GR24 & Amaldi16



14 – 18 July 2025

Scottish Exhibition Centre, Glasgow, UK

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IOP Institute of Physics

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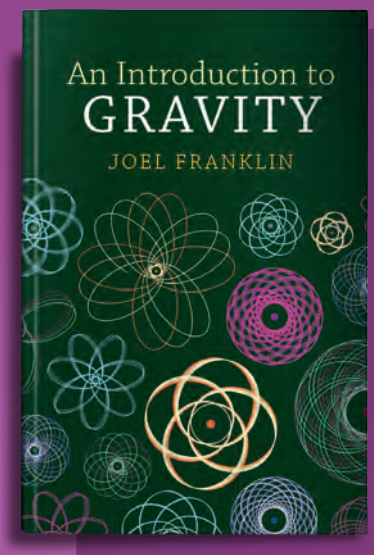
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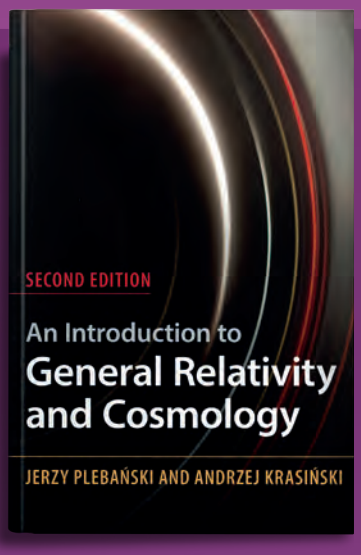


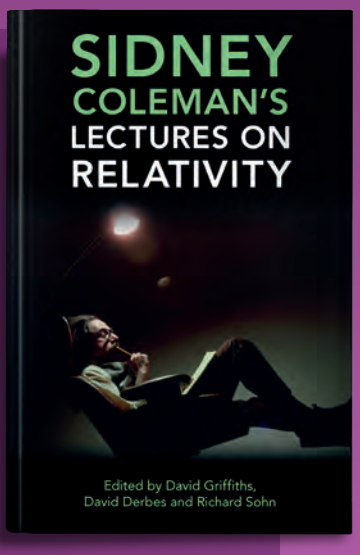
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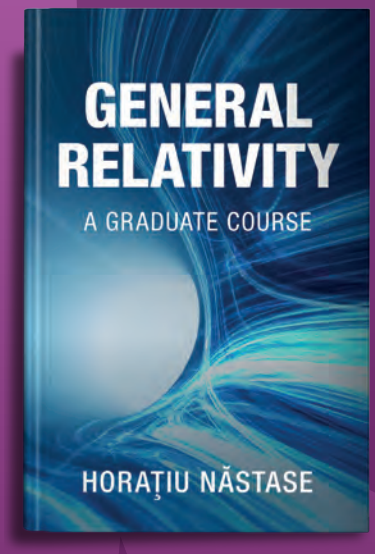


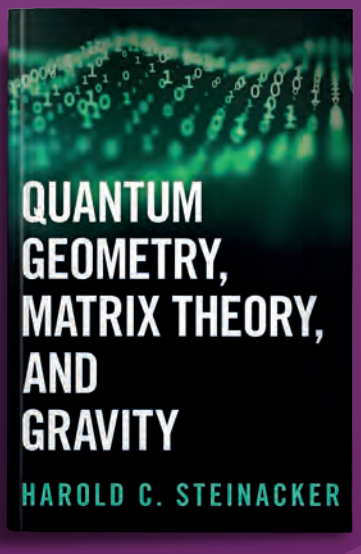


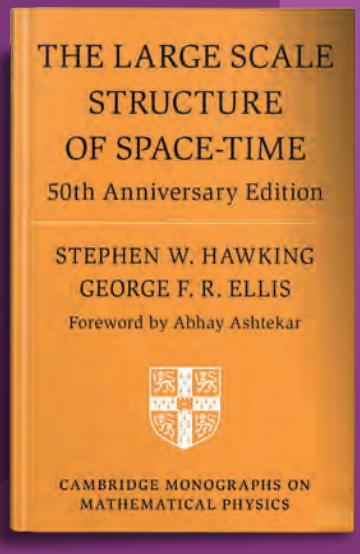


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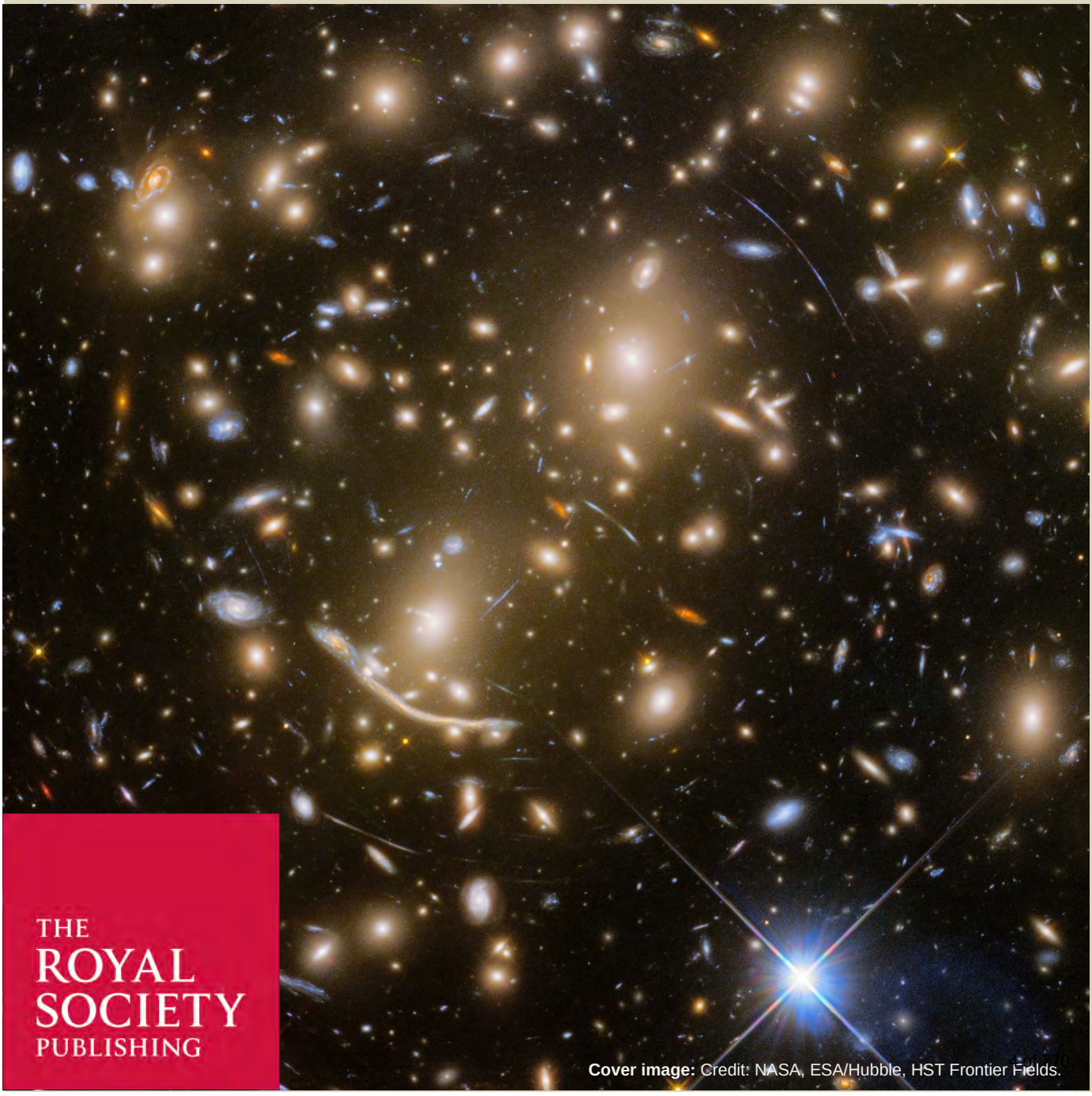
PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A

MATHEMATICAL, PHYSICAL AND ENGINEERING SCIENCES

Multi-messenger gravitational lensing

Theo Murphy meeting issue organised and edited by Graham P Smith, Martin A Hendry and Federica Bianco

Published April 2025



THE ROYAL SOCIETY PUBLISHING

Cover image: Credit: NASA, ESA/Hubble, HST Frontier Fields.

About this issue

The first multi-messenger (electromagnetic radiation and gravitational waves) detection of a gravitationally lensed cosmic explosion will have huge impact and unleash decades of novel science. This theme issue brings together experts from the relevant disciplines to review recent progress and chart the path to first detection, as the Vera Rubin Observatory nears first-light, and gravitational wave detector sensitivity continues to improve.

This issue is based on a Royal Society meeting held in March 2024.

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PART 1:

Preface to theme issue about multi-messenger gravitational lensing
Graham P Smith, Martin A Hendry and Federica Bianco

Electromagnetic follow-up of gravitational waves: review and lessons learned
Matt Nicholl and Igor Andreoni

False positives in gravitational wave campaigns: the electromagnetic perspective
Samantha Oates

Gravitational lensing in gamma-ray bursts
Andrew J Levan *et al.*

Strongly lensed supernovae: lessons learned
Ariel Goobar, Joel Johansson and Ana Sagués Carracedo

Fast radio bursts and the radio perspective on multi-messenger gravitational lensing
Inés Pastor-Marazuela

Properties of neural networks identifying strongly lensed gravitational waves in time domain
Arthur Offermans and Tjonnie GF Li

Finding black holes: an unconventional multi-messenger
Laura Elina Uronen *et al.*

lenscat: a public and community-contributed catalogue of known strong gravitational lenses
L Vujeva, RKL Lo, JM Ezquiaga and JCL Chan

PART 2:

Multi-messenger gravitational lensing
Graham P Smith *et al.*

Gravitational-wave lensing detection
Otto Akseli Hannuksela

A follow-up strategy enabling discovery of electromagnetic counterparts to highly magnified gravitationally lensed gravitational waves
Dan Ryczanowski *et al.*

False positives for gravitational lensing: the gravitational-wave perspective David Keitel

Kilonova simulations: connecting observations with the underlying physics Christine Collins, Luke Shingles and Vimal Vijayan

Challenges and opportunities for time-delay cosmography with multi-messenger gravitational lensing
Simon Birrer, Graham P Smith, Anowar J Shajib, Dan Ryczanowski and Nikki Arendse

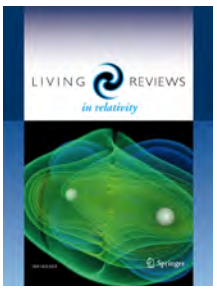
Gravitational lensing: towards combining the multi-messengers Anupreeta More and Hemanta Phurailatpam

Strong gravitational lenses from the Vera C. Rubin Observatory Anowar J Shajib *et al.*

HIGHLIGHTED TITLES

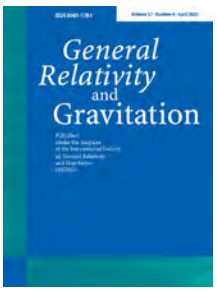
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Oral Presentations

New optimized mirror coatings for increasing the sensitivity of future Gravitational wave detectors.

. Diksha
[1]Maastricht university, [2]NIKHEF

Friday Session 4 - C4: Concept and research towards next-generation detectors

Gravitational wave detectors can measure small periodic distortions in spacetime known as gravitational waves. Improving detector sensitivity can help gain new insight into physics.
The detectors require mirror coatings made of low and high refractive index layers with very low coating thermal noise. Future detectors, such as the Einstein Telescope, will operate at cryogenic temperatures, requiring new coatings. Promising materials are amorphous silicon as the high-index material and silicon nitride as the low-index material, which have low mechanical loss but too high optical absorption.
Ways to reduce absorption while keeping mechanical loss low include 1) optimizing deposition process parameters 2) heat treatment 3) doping and passivation of dangling bonds using hydrogenation or fluorination 4) using a crystalline layer on top of an otherwise amorphous multilayer coating, which reduces the light field inside the layers underneath and consequently the coating absorption while adding negligible thermal noise.
This project explores using industrially available silicon on insulator (SOI) wafers with a device layer of the right thickness as the crystalline top layer. Suitable bonding technologies to bond the SOI wafer, coated with improved materials, to the mirrors will be investigated, as well as the etching procedure to obtain a final crystalline silicon top layer.
In this presentation, we will show the latest updates on producing a highly reflective multilayer coating with low optical absorption and low thermal noise.

Detection of a Baryon Acoustic Oscillation Ring at Redshift (z) 0.067?

Abdullah M[1]
[1]PhD Researcher, Faculty of Computing and Informatics, Multimedia University, Cyberjaya,
[2]International Society of General Relativity and Gravitation

Friday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

We believe we have detected a Baryon Acoustic Oscillation (BAO) ring? of ≈ 150 Mega parsecs (≈ 0.5GLY) radius at redshift (z) ≈ 0.067 with a recessional velocity of ≈ 20,100 kms per sec in our local universe (0.005 ≤ Redshift(z) ≤ 0.20). The separation size is consistent with Eisenstein et.al. (2005) statistical predictions of small excess clustering of two-point galaxy separation for 46,000 LRG galaxy samples in 0.16 ≤ z ≤ 0.47. Our detection also correlates with the first indirect BAO detection at z ≈ 0.068 by Tully et.al. (2023) using CosmicFlow-4 cataloged data in a 3-team study of bulk flow led by University of Honolulu, Hawaii.
Leveraged on SDSS (DR18) and NASA-SDSS Collaboration Catalogs we cover large-scale data and computing containing over ≈ 254,000 galaxies in multiple right ascension, declination and redshift intervals. The detection was realized based on our direct approach of selectively applying declination-redshift slices and coordinate flips through the large-scale webs of filamentary structures of the sampled galaxies. This is an adapted method from 1996 Las Campanas Redshift Survey (LCRS).
After 13.4 billion years of cosmic expansion gravitational instabilities and differential velocity fields had caused the ancient BAOs to lose their structural shapes making direct detection extremely challenging, without elaborate reconstructions. Being among the largest known structures in the universe, BAOs are actively studied by cosmologists. Importantly because of their useful characteristic scale which could be used as a standard ruler for cosmological distance measurements, especially for large-scale studies of the mysterious dark energy.

Electromagnetic Follow-up with GOTO during the O4 Observing Run

Ackley K[1]
[1]University Of Warwick

Tuesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

The fourth observing run (O4) of the LIGO-Virgo-KAGRA network is currently underway and there has been already been a wealth of gravitational wave (GW) detections and unique opportunities for multi-messenger astronomy. This talk will focus on the electromagnetic follow-up efforts conducted during O4 using the Gravitational-wave Optical Transient Observer (GOTO) network. GOTO is a wide-field optical telescope network dedicated to the follow-up of GW events. The network autonomously responds to alerts from both ground-based GW detectors and space-based gamma-ray observatories, providing rapid-response observations of multi-messenger events over nearly continuous 24-hour periods. I will discuss the strategies we've employed for real-time follow-up, including our prioritization of events, real-time processing and detection algorithms, and the challenges faced during the O4 run. Additionally, I will highlight some of the exciting events we have observed during O4 thus far and how we are continuing to improve our follow-up methods to pave the way for future discoveries.

Dimensional extension using likelihood reweighting for speeding up GW data analysis beyond GR

Agathos M[1], Romero-Shaw I[2]
[1]Queen Mary University Of London, [2]University of Cambridge

Friday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

Over the past 10 years, GW observations have enabled us to probe the strong-field dynamics of gravity and the nature of compact objects to unprecedented accuracy. A variety of parametrised tests have set out to explore extensions of the parameter space of BBH waveforms in GR, towards different directions in the infinite-dimensional space of non-GR waveforms. These exploratory re-analyses often come with a hefty multiplicative factor when it comes to computing costs. In this work we explore a Bayesian method of dimensional extension that can speed-up the extraction of posterior samples in the extended space, by leveraging pre-existing samples from vanilla PE runs, and performing a likelihood reweighting process when extending to the new dimension(s). We present initial results on the performance and fidelity of this method for constraining parameters that modify the binary inspiral dynamics, GW propagation, or the Kerr nature of the compact objects.

Efficient Analysis of Neutron Star Properties in f(R) Modified Gravity Using Physics-Informed Neural Networks

Ahmad M[1]
[1]National University of Computer and Emerging Sciences, Islamabad

Tuesday Session 4 - A3: Alternative and modified theories of gravity

This paper explores the characterization of neutron stars under f(R) gravity using physics-informed neural networks (PINNs) to solve the Tolman-Oppenheimer-Volkoff (TOV) equations.
We introduce a deep TOV solver that efficiently handles different f(R) gravity models, including the Starobinsky, Hu-Sawicki, and Exponential f(R) formulations. The solver is trained using a hybrid dataset incorporating synthetic numerical solutions and real astrophysical constraints from NICER, LIGO/Virgo/KAGRA, and pulsar timing observations. Bayesian inference techniques are employed to constrain the f(R) parameters, making use of a hierarchical modeling approach. Our results demonstrate that small curvature corrections are favored by current astrophysical constraints, while stronger deviations from General Relativity (GR) are disfavored. Future gravitational wave detections from LISA and Cosmic Explorer will refine these constraints further. This research presents a novel application of machine learning in modified gravity studies and highlights the potential of multi-messenger astrophysics for testing fundamental physics.

High power demands high precision: addressing challenges with innovative solutions in GW detector's aberration control

Aiello L[1,2], Cesarini E[2], Cifaldi M[2], Fafone V[1,2], Ianni M[1,2], Lorenzini M[1,2], Lumaca D[2], Minenkov Y[2], Nardecchia I[2], Rocchi A[2], Scacco V[1,2], Taranto C[1,2]
[1]Tor Vergata University Of Rome, [2]INFN Rome Tor Vergata

Friday Session 4 - C3: Progress and challenges in advanced ground-based detectors

One of the main limitations for the sensitivity of the current and future gravitational wave ground-based interferometers come from the thermally-induced aberrations, in the core optics. This impacts the possibility to operate the detector with high input and circulating power – a required condition to reduce the quantum noise contribution.
The Thermal Compensation System – devoted to the tackling and coping with this type of aberrations – already demonstrated in Virgo the importance of keeping under control these unwanted effects with dedicated sensors and actuators.
Looking ahead, all the plans for the near and long-term future forecast operations at increasingly higher power levels – making the aberrations' control even more crucial and posing a key challenge for preserving the detector's stability and sensitivity.
In this talk, the current status of the aberrations control strategy implemented in Advanced Virgo plus will be presented, together with the solutions presently being developed to help future runs – such as O5 and beyond – achieve the expected sensitivity.

Detecting non-Kerr signature in Sgr A* flares with current and future instruments

Aimar N[1], Rosa J[2], Tamm H[2]
[1]Centra, Faculdade De Engenharia Da Universidade Do Porto, [2]Institute of Physics, University of Tartu

Thursday Session 3 - C10: Experimental tests of the nature of compact objects

The heart of our galaxy harbors a supermassive compact object named Sagittarius A* (Sgr A*), with a mass of 4.3 million solar masses. Owing to its close proximity, certain general relativity tests have been executed using the orbits of S-Stars. However, these stars are situated too remotely to conduct tests of general relativity within the strongest regime, specifically at a few gravitational radii (rg). Fortunately, Sgr A* regularly produces radiation bursts known as flares, occurring around ~10 rg, which situates them within a strong gravitational regime. Despite significant astrophysical uncertainties, these flares provide a rare chance to investigate space-time characterized by intense curvature, particularly by employing polarization measurements. This is because polarization is influenced by the curvature of space-time and therefore can be utilized to unveil the properties of the compact object. In this presentation, I will discuss my research on the observability of non-Kerr, or exotic compact object signatures, in the flares of Sgr A* with GRAVITY, and explore the potential of future instruments.

Black Holes with Ringed Accretion Disks

Al Zahrani A[1]
[1]King Fahd University of Petroleum and Minerals

Monday Session 4 - B1: Relativistic astrophysics

We show that certain electromagnetic field configurations around black holes may lead to the formation of ringed accretion disks. These are structures made of disjoint rings of orbiting matter. The mechanism behind this effect lies in how the electromagnetic fields influence charged particle dynamics in such a way that they create a zone where stable circular orbits are forbidden. These forbidden regions can lead to breaking up the regular continuous disk into two distinct rings. This phenomenon may have implications related to the understanding of the particle dynamics in the vicinity of black holes and may help interpret future observational data more precisely.

An effective-one-body waveform model for large-mass-ratio black hole binaries

Albertini A[1]
[1]Charles University, Prague, [2]Astronomical Institute of the Czech Academy of Sciences

Wednesday Session 4 - B3: Approximations, perturbation theory, and their applications

The effective-one-body (EOB) approach is a powerful formalism that maps the two-body problem in general relativity into the motion of a single body in an effective metric. EOB-based models are nowadays providing fast and accurate gravitational wave (GW) templates for comparable-mass coalescing compact binaries, namely the events observed by the currently operating GW detectors. Third-generation detectors will instead allow us to detect signals from different sources, among which are black hole binaries with a larger mass ratio. I will present an EOB waveform model that has been adapted to better describe this kind of binaries, and that also includes eccentricity and precessing spins.

Measuring correlations in astrophysical gravitational-wave populations with PixelPop

Alvarez-Lopez S[1,2], Heinzel J[1,2], Mould M[1,2], Vitale S[1,2]
[1]LIGO Laboratory, Massachusetts Institute of Technology, [2]Kavli Institute for Astrophysics and Space Research and Department of Physics, Massachusetts Institute of Technology

Thursday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The origins of merging compact binaries observed by the LIGO-Virgo-KAGRA gravitational-wave (GW) detectors remain uncertain, with multiple astrophysical processes possibly contributing to the overall merger rate. Such formation channels result in nontrivial correlations in the underlying distribution of source parameters. Current understanding of these sources relies heavily on simplified parametric models that make strong assumptions about the population. PixelPop – a high-resolution Bayesian nonparametric population algorithm – offers a more flexible approach by inferring joint distributions and parameter correlations with minimal assumptions. In this work, we use PixelPop to analyze two-, three-, and four-dimensional correlations in the masses, spins, and redshift for simulated black-hole mergers from population synthesis simulations observable by LIGO-Virgo with current sensitivity. We show that neglecting correlations gives smaller uncertainties but limits and biases astrophysical insights. In contrast, modeling all correlations with PixelPop allows us to reduce biases and correctly measure the astrophysical merger rate in all source parameters without modeling assumptions, at the expense of larger uncertainties. Using the inference results from PixelPop, we also propose a method to distinguish between different formation channels. At current sensitivity, we find that formation channels can only be distinguished if the underlying astrophysical processes differ significantly. However, channels that share several evolutionary stages (like common envelope and stable mass transfer) remain indistinguishable. Given our uncertainty in the formation of GW sources, robust extraction of astrophysics from GW catalogs requires that we allow for potential nontrivial high-dimensional correlations with algorithms like PixelPop.

Multi-messenger astrophysics and cosmology with next-generation Gamma-Ray Bursts space missions

Amati L[1]
[1]Inaf - Oas Bologna, Italy

Tuesday Session 4 - C7: Multi-messenger astronomy of gravitational wave sources

The huge luminosity, the redshift distribution extending at least up to z~10 and the association with the explosive death of very massive stars make long GRBs extremely powerful probes for investigating the early Universe (pop-III stars, cosmic reionization, SFR and metallicity evolution up to the “cosmic dawn”) and measuring cosmological parameters. At the same time, as demonstrated by the GW170817 event, short GRBs are the most prominent electromagnetic counterpart of gravitational-wave sources like NS-NS and NS-BH merging events, and both long and short GRBs are expected to be associated with neutrino emission. Moreover, the combination of extreme distances, huge number of photons emitted over wide photon energy range and the variability down to few ms makes these phenomena a promising tool for performing tests of fundamental physics like Lorentz Invariance Violation (LIV). My review will include the status, concepts and expected performances of space mission projects, with particular emphasis on ESA/M7 candidate THESEUS, aiming at fully exploiting these unique potentialities of the GRB phenomenon, thus providing an ideal synergy with the large e.m. facilities of the future like LSST, ELT, TMT, SKA, CTA, ATHENA in the e.m. domain, advanced second generation (2G++) and third generation (3G) GW detectors and future large neutrino detectors (e.g., Km3NET).

A directed continuous-wave search from neutron stars in binary systems with the five-vector resampling technique

Amicucci F[1,2], Leaci P[1,2]
[1]Sapienza Università Di Roma, [2]INFN Sezione di Roma

Tuesday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Continuous gravitational-wave signals (CWs), which are typically emitted by rapidly rotating neutron stars with non-axisymmetric deformations, represent particularly intriguing targets for the Advanced LIGO-Virgo-KAGRA detectors. These detectors operate within sensitivity bands that encompass more than half of the known pulsars in our galaxy existing in binary systems (i.e., over 417 pulsars). However, the detection of these faint signals is especially challenged by the Doppler modulation due to the source's orbital motion, typically described by five unknown Keplerian parameters. This modulation spreads the signal across multiple frequency bins, resulting in a notable reduction of signal-to-noise ratio and potentially hindering signal detection. To overcome this issue, a robust five-vector resampling data-analysis algorithm has been developed to conduct thorough directed/narrowband CW searches at an affordable computational cost. We employ this methodology for the first time to search for CWs from the brightest Scorpius X-1, using data from the third observing run of the Advanced LIGO- Virgo-KAGRA detectors

The World's First Underground Facility for Interplatform Control and Seismic Isolation in Gravitational-Wave Detection

Andric T[1], Harms J
[1]Gran Sasso Science Institute

Monday Session 4 - C4: Concept and research towards next-generation detectors

We present the design and performance requirements of GEMINI, the first underground R&D facility dedicated to active seismic isolation and interplatform control for next-generation gravitational-wave observatories. The GEMINI site is located 1.4 km deep at the National Laboratories of Gran Sasso (LNGS). The facility consists of two actively isolated platforms operating in a vacuum, designed to achieve a record-low residual motion in the 1 mHz to 1 Hz band. For the Einstein Telescope (ET), GEMINI will test interplatform control in an underground environment for the first time. It will be essential in assisting the ET length and alignment control of auxiliary degrees of freedom and hence in enabling ET performance. We are also addressing the tilt-to-horizontal coupling, essential for meeting the stringent noise requirements of ET's underground interferometers. Furthermore, GEMINI will provide platforms to test novel, high-precision accelerometers at cryogenic temperature as will be required for the Lunar Gravitational-wave Antenna.

Cosmological and Astrophysical inference with Dark Sirens Number Counts: forecasts and astrophysical model relevance

Antinozzi G[1]
[1]SISSA - Scuola Internazionale Superiore di Studi Avanzati

Thursday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

A longstanding discrepancy in measurements of the Hubble constant, known as the Hubble tension, demands new methods for independent validation. Gravitational-wave observations offer an exciting path forward, however due to the scarcity of standard siren events, the gravitational wave community has been compelled to extract maximum information from Dark Sirens, i.e., events with no identified electromagnetic counterpart.
In this talk, I introduce a novel technique that derives cosmological parameters - with particular interest to the Hubble constant - solely from gravitational-wave data, bypassing assumptions about black hole masses or external galaxy catalogs. By comparing the expected number of Dark Sirens to those actually detected, we gain a powerful handle on cosmic expansion, particularly in view of the next-generation observatories, expected to significantly increase the gravitational-wave event sample.
I will showcase forecasts with this method for the Einstein Telescope and the Cosmic Explorer, then present its current challenges to LIGO–Virgo–KAGRA data. Finally, I will delve deeper into the astrophysical modeling aspect and highlight how significantly refining the merger rate evolution, star formation history, and binary population synthesis (via the SEVN code) further sharpens the cosmological constraints, offering a promising new angle on resolving the Hubble tension with gravitational waves.

Perturbations of black holes in quadratic gravity

Antoniou G[1]
[1]INFN Rome & Sapienza University Of Rome

Tuesday Session 3 - A3: Alternative and modified theories of gravity

In this talk I will discuss the perturbations of black hole solutions in the context of quadratic gravity, including ones that differ from those predicted in Genereal Relativity. The "hairy" branch of solutions only exists within a specific parameter range and is characterized by a richer spectrum of modes, since for gravitational perturbations in particular, two types of quasinormal modes emerge which we charcterize as massless-led and massive-led ones. This rich spectrum of modes arises due to the specific mixing of the metric perturbations and those of an auxiliary tensor field, associated with the presence of a massive spin-2 mode in the theory. Finally, I will discuss potential excitations of the various modes in the context of observations.

Improving the inference of the stellar quantities and equation of state using the extended I-Love-Q-δM relations

Aranguren E[1], Font J[2], Sanchis-Gual N[2], Vera R[1]
[1]University of the Basque Country (UPV/EHU), [2]Universitat de València

Thursday Session 4 - B1: Relativistic astrophysics

The I-Love-Q relations refer to the existence of various approximate equation of state-independent relations involving the moment of inertia, Love number, and quadrupole moment. These relations have an interesting applicability in observational astrophysics since they allow the inference of two quantities within the I-Love-Q trio out of a third one alone. However, the quantities involved in the I-Love-Q relations are normalized by the parameter M0, which arises in the usual perturbative analytical approach as the mass of the background configuration. However, since M0 is not the mass of the rotating star MS, it is not an observable quantity, and therefore the applicability of the relations to actual observations gets tainted. A common workaround consists on taking M0 to be the mass of the star. However, when the star is rapidly rotating this approximation is no longer valid and the problem is then overcome using some rotation-dependent I-Love-Q relations. In this talk, I will explain how to extract the value of M0 in the first place, using an extended version of the universal relations, which includes additional relations involving $\delta M \propto MS - M0$. Then, I will analyze the extent to which the use of these extended relations provides a more precise inference of the properties of the star, and its equation of state.

Beyond GR mergers: waveforms and more

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Tuesday Session 4 - B2: Numerical Relativity

I will discuss our latest results in Numerical Relativity simulations of compact binary mergers beyond GR. In particular I will present the obtained waveforms as well as the observables we have extracted from them. Finally I will give further details on alternative well-posed formulations that we have been investigating.

The LIGO-Virgo-KAGRA Observing Run 4

Arnaud N[1]
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Monday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The Observing Run 4 (O4, May 2023 – October 2025) is the longest data-taking period to date for the LIGO-Virgo-KAGRA (LVK) network of ground-based gravitational-wave (GW) detectors. Characterized by improved performance of its different detectors (the two LIGO instruments located at Hanford (WA) and Livingston (LA) in the USA; Virgo in Italy and KAGRA in Japan), this run has produced an unprecedented number of GW candidates in near-real time (significantly in excess of 200 by the time of the Amaldi Conference if the current performance holds up), publicly announced to allow astronomical multi-messenger follow-ups of these alerts.
The present talk will summarize the performance of the individual detectors and of the global LVK network during O4. It will also describe the framework that allows the LVK Collaboration to deliver vetted and accurate alerts in low latency. Finally, it will present the LVK plans for the coming years: a new series of upgrades is expected to further improve the performance of the detectors – and thus the LVK network prospects for GW detection – before the next data-taking phase.

Renormalized stress-energy tensor of scalar fields in stellar spacetimes

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Tuesday Session 4 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

We apply the extended-coordinate regularisation prescription to calculate renormalized expectation values of scalar fields in stars of uniform density. We will present results for the quantum vacuum polarization and the renormalized stress-energy tensor of scalar fields in the Boulware state, with special interest in the growth of both quantities as the maximum compactness limit of constant-density stars (the Buchdahl limit) is approached. Our investigations, which explore a broad range of values of the Ricci coupling, reveal the importance of semiclassical backreaction effects in highly compact stars. These effects might offer a way to bypass the Buchdahl theorem altogether.

Neural network method to search long transient gravitational waves

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Thursday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

I will introduce a novel approach for detecting long transient gravitational wave (GW) signals in interferometric detector data, particularly those predicted from rapidly spinning newborn magnetars (never observed). Traditional search methods struggle with these signals due to their rapid frequency variations, making them computationally impractical or highly demanding.
To address this, we explored a machine-learning-based alternative to develop a fast algorithm for identifying signal candidates. Specifically, we designed a classifier capable of distinguishing the presence or absence of a signal in time-frequency maps. Additionally, we created a denoiser to enhance classification accuracy by reducing noise in the time-frequency maps while preserving the signal track as effectively as possible.
We assessed the performance of both neural networks using simulated long transient signals and colored noise based on LIGO's interferometer design noise curves. I will demonstrate how integrating these two models significantly improves detection probability. Furthermore, I will show that our approach remains robust even when the exponent of the power law governing signal frequency evolution varies. Lastly, I will present preliminary findings from real data collected during the third LIGO-Virgo-Kagra scientific run.

Killing spinor gauge for Kerr perturbations

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Wednesday Session 3 - A2: Classical GR: Mathematical developments

The Kerr spacetime can be characterized using a valence (2,0) Killing spinor. We use this together with the GHP formalism to develop a framework to handle non-linear perturbations of the Kerr spacetime. With this setup, the framework is abstract enough to not cause coordinate or frame issues, but detailed enough for approximate symmetry operators to exist and as well as other structures needed for estimates.

Blind source separation in 3rd generation gravitational-wave detectors

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Wednesday Session 4 - C4: Concept and research towards next-generation detectors

The Einstein Telescope (ET) and Cosmic Explorer (CE), as next-generation gravitational-wave (GW) observatories, will achieve unprecedented sensitivity, detecting an immense number of GW signals across an extended frequency range. This improvement introduces a fundamental challenge: the presence of overlapping GW events in both time and frequency, complicating signal extraction and parameter estimation. Existing search pipelines assume isolated signals, but with BBH detection rates expected to reach 10^5–10^6 events per year, advanced signal processing techniques will be required to disentangle these overlaps effectively.
This work explores the application of Blind Source Separation (BSS) techniques—such as Independent Component Analysis (ICA), Non-Negative Matrix Factorization (NMF), and machine learning approaches—to gravitational-wave data. BSS methods, widely used in telecommunications and biomedical signal processing, offer a promising avenue for separating multiple overlapping sources without prior knowledge of their individual waveforms. We assess the feasibility of integrating these methods into next-generation GW data pipelines, considering constraints such as detector noise, real-time computational demands, and the evolving spectral characteristics of GW signals.
By adapting and optimizing BSS methods for the specific challenges of ET and CE we could enhance parameter estimation accuracy, mitigate biases in source characterization, and improve multi-messenger follow-up strategies. This study highlights the need for hybrid approaches combining BSS with traditional GW search algorithms to fully exploit the scientific potential of future GW observatories.

The Latest Results from the MeerKAT Pulsar Timing Array

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Monday Session 3 - C1: Pulsar timing array

The MeerKAT Pulsar Timing Array (MPTA) uses the SARAO 64-dish MeerKAT radio telescope to regularly monitor over 80 millisecond pulsars that it times with typically 1 microsecond accuracy over almost an octave of bandwidth. In its second data release, the MPTA showed some encouraging hints of the characteristic Hellings and Downs curve. By this July, the array will have another two years of data and in this talk I will present our latest findings, and highlight the issues faced with dispersion and red noise removal in pulsar timing arrays.

Towards Integration of Machine Learning for Sensing and Control in Next Generation Gravitational Wave Detectors

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Wednesday Session 4 - C4: Concept and research towards next-generation detector

Modern gravitational wave (GW) detectors are a complex weave of interconnected and cross-coupled linear time invariant (LTI) control systems. From laser stabilisation and orthogonalisation of mirror suspensions, to alignment control and non-linear effects in readout optics, there are a vast number of ways to optimise the sensitivity of a detector. We present a machine learning (ML) approach to these problems, utilising ML algorithms for a practical demonstration of orthogonalised suspension control and demonstrate how ML fitting techniques can be used to improve test mass optic measurements. Furthermore we discuss how ML can be wrapped into full GW detector control systems without compromising the tightly restricted calibration requirements.

Detecting new fundamental fields with asymmetric binaries and LISA and the effect of post-adiabatic corrections

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Thursday Session 4 - C6: Gravitational waves: Relativity and fundamental physic

Asymmetric binaries, i.e. compact binary systems with a large mass asymmetry, such as Extreme Mass Ratio Inspirals (EMRIs), are key sources for the future space detector LISA. Inspiralling around the central black hole (the primary), the smaller object (the secondary) generates gravitational waves (GWs) that harbour the potential for precise tests of fundamental physics.
In this talk, I will focus on a model of asymmetric binaries in theories of gravity with new fundamental scalar fields, where the primary scalar charge per unit mass is suppressed, so that the background spacetime is simply described by the Kerr metric. Moreover, at leading - adiabatic - order in the binary mass ratio, the imprint of the scalar field on the emitted waveform is fully captured by two extra parameters: the scalar charge per unit mass carried by the secondary and the scalar field mass. I will show how these two parameters affect the emitted GWs and, by analysing such signals, I will present the encouraging results on the LISA ability to detect the scalar charge and scalar field mass. Finally, I will present the latest results that include some post-adiabatic corrections to the model, and discuss how they affect the detectability of the scalar field.

Dynamical and thermal noise simulations of pendulum suspensions for next-generation gravitational wave detectors (aLIGO A+ and A#, Einstein Telescope and Cosmic Explorer) using Mathematica.

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Wednesday Session 3 - C4: Concept and research towards next-generation detector

Terrestrial gravitational waves detectors support test masses and other key optics on pendulum suspensions to isolate them from seismic noise, while minimizing the introduction of thermal noise. A toolkit in Mathematica for dynamical and thermal noise modeling of such systems has previously been developed at LIGO and has been used to model all the LIGO suspensions. The toolkit allows for rigid-body masses, springs, and wires/fibres, and maintains separate frequency-dependent complex damping functions on all stiffness terms so that thermal noise can be properly calculated.
Suspensions for next-generation detectors, especially cryogenic ones, present new modeling challenges. There will be new fibre materials such as silicon and sapphire. The fibers will be rather thicker (for strength and heat removal reasons), with bending stiffness that is relevant over the whole length (rather than just near the ends), and significant torsional stiffness. There is also the likelihood of temperature and other property gradients along the length.
We report on progress towards adding the required new physics to the toolkit and applying this to new configurations, especially the Einstein Telescope cryogenic payload and the Common Platform Triple (a technology demonstrator at Glasgow to suspend two 1 kg silicon optics on silicon or sapphire fibers and measure thermal noise), but also the ET room-temperature payload, aLIGO A+ and A#, and Cosmic Explorer.

A novel compact interferometric sensor for precise measurement of displacements below 1 kHz

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Wednesday Session 3 - C4: Concept and research towards next-generation detector

Third-generation gravitational wave detectors, like the Einstein Telescope, aim to improve the sensitivity of the detection band in the low-frequency region. For this, displacement sensors that provide high sensitivity between 200 mHz and 200 Hz are required for seismic isolation, and the scientific community is therefore investigating novel sensing techniques. We demonstrate a heterodyne interferometric displacement sensor design that aims to be compact while achieving a sensitivity in the sub-picometer region in the mentioned frequency range. Our sensor receives its compact nature by decoupling the interferometric readout and sensing units using a polarisation-maintaining optical fibre. By sending both the reference and the test beam through the same fibre, we can reduce the optical components in the sensing unit to a polarizing beam splitter and a mirror, while no electronics are required in the sensing unit at all. We present measurements from our tabletop sensor setup achieving a sensitivity better than 1 pm/√Hz for almost the entire range between 3 Hz and 600 Hz and better than 30 pm/√Hz down to 100 mHz. In addition, we show our sensor's nonlinear phase contributions are smaller than ±8 nm, and we also give an overview of how we aim to make our sensing unit even more compact using novel meta-structures. Based on our data, we are convinced that our design represents a compact displacement sensor that can be used to increase the sensitivity of a third-generation gravitational wave detector in the low-frequency regime.

A class of entangled and diffeomorphism-invariant states in loop quantum gravity: Bell-network states

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Wednesday Session 4 - D1: Loop quantum gravity and spin foams

Bell-network states constitute a class of diffeomorphism-invariant and entangled states of the geometry within loop quantum gravity that satisfy an area-law for the entanglement entropy in the limit of large spins. The fluctuations of the geometry for a Bell-network state are entangled, similar to those in the semiclassical limit as described by quantum field theory in curved spacetimes. We present a comprehensive analysis of the effective geometry and semiclassicality of Bell-network states on a dipole graph. This analysis provides a detailed characterization of the quantum geometry of a class of diffeomorphism-invariant, area-law states representing homogeneous and isotropic configurations in loop quantum gravity, which may be explored as boundary states for the dynamics of the theory. Regarding the effective geometry of a Bell-network state, we find that the average geometry at each node in the dipole graph with four links does not match that of a flat tetrahedron. Instead, the expected values of the geometric observables satisfy relations characteristic of spherical tetrahedra. Furthermore, we conduct a detailed semiclassical analysis of Bell-network states with respect to the angle operator on a dipole graph with an arbitrary number of links. The result shows that, for a large number of links, the expectation values of the angle operator are sharply peaked around a specific value, with minimal dispersion.

Developing a LISA optical ground-support equipment testing facility

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Thursday Session 3 - C5: LISA and other space-based detectors

Space-based gravitational wave detectors, such as the Laser Interferometer Space Antenna (LISA), use picometer-precision laser interferometry to detect gravitational waves at frequencies from 1 Hz down to below 0.1 mHz.
Laser interferometers used for on-ground prototyping and testing of such instruments are typically constructed by permanently bonding or gluing optics onto an ultra-stable bench made of low-expansion glass ceramic using coordinate-measurement-machine assisted alignment. These meticulous, complex and time-consuming designs do not allow rearrangements of the optical components.
Here, we present the study of a toolset for adjustable picometer-stable interferometers (TAPSI). With this concept, a given interferometer configuration can be realised very quickly due to a simplified and speed-up assembly process while still maintaining picometer length stability required for the LISA mission.
We built a corresponding test facility, consisting of a vacuum chamber, multilayer thermal shields and a specially developed temperature sensor (10 µK/√Hz down to 10 mHz) to provide insight into temperature coupling.
The toolset's stability has been demonstrated to meet the LISA requirements and is being used to set up new interferometers, such as a 4-signal Homodyne Quadrature Interferometer and a Concealed Noise experiment to probe the readout noise of our in-house developed phasemeters.

Quasinormal mode excitation in extreme mass ratio inspirals: signatures of eccentricity in late-time merger waveforms

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Wednesday Session 3 - B3: Approximations, perturbation theory, and their application

Black hole binaries with small mass ratios will be critical targets for the forthcoming Laser Interferometer Space Antenna (LISA) mission. They also serve as useful tools for studying the dynamics of compact binary systems and the gravitational waves they emit. Using an eccentric Ori-Thorne procedure, we build trajectories that describe the full inspiral and plunge of a small body on an initially eccentric orbit of a Kerr black hole. We then calculate the gravitational waves associated with these trajectories with a code that solves the Teukolsky equation in the time domain. The final cycles of these waveforms are a superposition of Kerr quasinormal modes. In this work, we examine the impact of orbital eccentricity and its associated phase parameters on quasinormal mode excitation. We find that a binary's eccentricity during its last orbital revolutions can have signatures on the relative mode excitation. If these signatures from the small-mass-ratio regime are present at less extreme mass ratios, then measuring gravitational ringdown modes from binary black hole mergers may provide key insight into a binary's geometry. A diagnostic of eccentricity in the late waveform could be a valuable tool for understanding the systems that create these signals for next-generation detectors like LISA, as well as the ground-based detectors operating today.

Towards robust gravitational wave detections from resolvable supermassive black hole binaries

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Monday Session 4 - C1: Pulsar timing arrays

The recent discovery of the stochastic gravitational-wave background via pulsar timing arrays will likely be followed by the detection of resolvable supermassive black hole binaries that stand out above the background. Even a single such detection would confirm the source of the background and provide a direct glimpse into supermassive black hole binary dynamics at sub-parsec scales. While recent analyses already found low-significance candidates, to confidently claim a detection, we will need not only more and better data, but also more sophisticated analysis techniques. Here we present two new approaches that can help us more robustly ascertain if a candidate found by a search algorithm is indeed a black hole binary: i) a direct comparison of the signal model with an incoherent model; ii) a model scrambling approach that builds null distributions of our detection statistic. Both rely on finding the coherence between pulsars characteristic to gravitational waves from a binary system. We test these methods on simple simulated datasets and explore how confidently coherence can be established depending on properties of the signal and the pulsar timing array.

A new model of spontaneous scalarization induced by curvature and matter

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Wednesday Session 4 - A3: Alternative and modified theories of gravity

We introduce a new model of spontaneous scalarization that unifies curvature and matter couplings to induce black hole scalarization. This model addresses known issues encountered in standard Gauss-Bonnet scalarization—such as stability and rigid bifurcation thresholds—by allowing the simultaneous interplay of two tachyonic instabilities originating from curvature and electromagnetic fields. By systematically adjusting these dual couplings, we achieve tunable scalarization thresholds and uncover a richer phenomenology, including multiple coexisting scalarized solutions and abrupt transitions between distinct scalarized states. Through numerical integration, we analyze novel scalarized black hole solutions, characterizing their scalar charges, horizon profiles, and thermodynamic properties, demonstrating how varying coupling parameters enhances or suppresses scalar "hair." These results broaden the landscape of modified gravity theories, offering new avenues for probing deviations from General Relativity.

Ultra-compact Objects of Non-minimally Coupled Dark Matter

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Thursday Session 3 - B1: Relativistic astrophysics

In the framework of a collisionless cold dark matter fluid which is non-minimally coupled to gravity, we investigate the existence and properties of static, spherically symmetric solutions of the general relativistic field equations.
We show that the non-minimal coupling originates an anisotropic pressure able to counteract gravity and to allow the formation of regular, horizonless ultra-compact objects of dark matter (NMC-UCOs). We then analyze the orbits of massive and massless particles in the gravitational field of NMC-UCOs and we effectively describe the gravitational lensing effects around them in terms of a pseudo-shadow.
Since for the non-minimal coupling to be efficient very high dark matter densities are required, we investigate its effects in the early Universe, finding that it naturally leads to an inflationary phase before radiation domination driven only by the dark matter fluid, without the need of an inflaton field.

Constraining cosmic expansion through full modelling of binary black hole-galaxy cross-power spectra on the sky

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Wednesday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

Gravitational wave (GW) emitting sources, which are routinely observed nowadays through the ground-based LIGO-Virgo-KAGRA detector network, serve as an independent probe towards inferring the cosmic expansion history. Such sources, also called the “standard sirens”, provide us with a direct measure of the cosmological distances through the observed GW strain. However, for the majority of the detected GW events, their redshift distribution remains unknown. For such sources, one can make use of their clustering properties with respect to the observed galaxies with known redshifts and the underlying dark matter distribution to infer the Hubble constant. Being part of the same large-scale structure, they are correlated with each other through structure formation history. In this talk, I will discuss how the angular correlation between the binary black holes and galaxies allows an unbiased inference of the Hubble constant. The cross-spectrum is modelled as a function of redshift from the matter power spectrum to extract the full redshift distribution of a given population of binary black hole mergers. Through a set of realistic number of simulated binary black holes with realistic noise simulations, and a mock galaxy catalogue, both simulated from the same underlying dark matter distribution, we show that this method successfully recovers the injected cosmic expansion rate parameter within the 68% confidence interval. I will also discuss the impact of weak lensing effects at different redshift ranges. With the growing number of such events in future observations, this technique will be imperative for a robust cosmological inference using GWs.

Curvature dependence of gravitational-wave tests: from observation to theory

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Wednesday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Next generation of gravitational wave detectors will have the sensibility to detect potential deviations in gravitational waveforms with respect to general relativity. However, current agnostic tests are plagued by a lack of realistic deviations, making it difficult to interpret such detections with respect to specific theories. In this talk, we bridge the gap between observations and theory by identifying the scaling of deviations with respect to the objects' mass, as well as the leading order post-Newtonian corrections. We use a local effective field theory (EFT) approach based on an expansion in curvature and potentially in additional scalar fields and we study the inspiral phase of compact binaries. The obtained results can be readily incorporated in all gravitational wave tests already under use by current detectors.

Communicating discoveries from LIGO-Virgo-KAGRA catalogues

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Thursday Session 4 - C8: Education and public outreach in gravitational physics

The LIGO-Virgo-KAGRA Collaboration have made a number of breakthrough discoveries in gravitational-wave astronomy. The field is currently moving from an era of first discoveries to one of producing large catalogues of detections. These discoveries are the result of an international collaboration of scientists. We will review some of the ways these breakthroughs are communicated to the public, using the case study of the third Gravitational-Wave Transient Catalog (GWTC-3). We shall highlight the challenges and benefits of communicating discoveries from a large collaboration, and where there are many complicated results as opposed to one single detection.

Interferometer Configuration and Commissioning of the Virgo Detector during the O4b/c Run

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Tuesday Session 3 - C3: Progress and challenges in advanced ground-based detectors

On 10 April 2024 the Virgo interferometer joined the international gravitational-wave network for the second and third parts of the fourth Observing Run, O4b and O4c, the latter of which will end on 7 October 2025. The Virgo detector is the first large-scale detector running with a marginally stable Signal Recycling Cavity, a configuration which poses significant challenges from the optical, thermal and control points of view. In this talk a description of such configuration of the Virgo detector will be given.
As a follow-up to the configuration in use at the beginning of the Run, an extensive report of the main Commissioning activities performed during the Run will be given. The goal for such activities is two-fold: one important aspect is maintaining, if not improving, the performance of the detector over time, profiting of the longer time scales during the Observing Run to better understand the behaviour of the detector. The second important aspect is to characterize better the noise content of the detector, and study in advance its characteristics in view of the future developments which are already planned for the next Observing Run O5. Both aspects will therefore shape the Virgo detector for the last part of the Observing Run, and will link to its evolution for the next years.

Some new developments in black hole spectroscopy

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Wednesday Session 3 - A1: Classical GR: Theoretical developments

According to general relativity, the remnant of a binary black hole merger is a perturbed Kerr black hole. Perturbed Kerr black holes emit "ringdown" radiation which is well described by a superposition of damped exponentials ("quasinormal modes”), with frequencies and damping times that depend only on the mass and spin of the remnant. The observation of gravitational radiation emitted by black hole mergers might finally provide direct evidence of black holes, just like the 21 cm line identifies interstellar hydrogen. I will discuss some recent interesting developments in the "black hole spectroscopy" program. I will focus on the modeling of nonlinearities in the ringdown, avoided crossings of quasinormal modes, and the possibility of resonant mode excitation.

Non-selfadjoint dynamics in black hole hyperboloidal foliations: Keldysh quasinormal expansions and low-regularity transients

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Tuesday Session 3 - B3: Approximations, perturbation theory, and their applications

Evolution systems driven by non-selfadjoint operators present certain genuinely dissipative dynamical features, absent in conservative systems. In a gravitational setting, the choice of a hyperboloidal foliation for the description of wave dynamics on a background spacetime with outgoing boundary conditions (e.g. black holes), casts the (linear) dynamics in terms of an evolution problem whose infinitesimal time generator is a non-selfadjoint operator. A general framework for non-conservative systems is given in terms of i) the spectral theory of non-selfadjoint operators and ii) the non-modal analysis associated with non-normal dynamics. They provide, respectively, complementary spectral and time-domain descriptions of non-conservative dynamics, sharing the key feature of being defined for normalisable states in a Hilbert (Banach) space. We focus here on two genuinely non-selfadjoint problems, illustrating this spectral/time-domain complementarity, namely: a) the construction of asymptotic resonant expansions and b) the assessment of dynamical linear transients. Regarding a), the so-called Keldysh expansion of the resolvent permits to express time-evolved fields as quasinormal mode expansions, with quasinormal frequencies characterised as eigenvalues of the non-selfadjoint operator. As a result, we provide general closed expressions for the spectral decomposition of the field that generalise (in an asymptotic sense) the standard (spectral-theorem) projection scheme in self-adjoint problems. Regarding b), and making use of Sobolev norms weigthing high-derivatives to assess the regularity/small-scale structure of solutions, we demonstrate the presence of an initial growth in the Sobolev-norm of evolving (linear) fields, indicating an initial transitory enhancement of the ''small scale/regularity'', akin to the Aretakis instability but not restrained to extremality.

Various aspects of photon ring visibility correlations

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Friday Session 4 - B1: Relativistic astrophysics

During recent years, attention at both the theoretical and phenomenological levels has been devoted to the so-called photon ring, a thin circle of light in black hole images formed by extremely lensed photons. Studies of the photon ring could eventually lead to one of the most straightforward ways to test the Kerr nature of black holes, and allow their characterization in real astrophysical systems. The famous resolved black hole images, captured by the Event Horizon Telescope (EHT) Collaboration, have inspired the planning of future extensions of this mission that hold the promise of a first direct detection of the photon ring. In order to prepare for these future data, a deeper theoretical understanding of potentially relevant observables is necessary. Typically, the quantities provided by EHT measurements are time series of interferometric complex visibilities. Using a variety of techniques, we explore the space of observables that may potentially be constructed from such visibilities. In particular, we compute their (auto-)correlation functions and examine their dependence on the black hole's parameters. We argue that detailed studies of such observables in simulated data, and in currently available EHT data, could help figure out how to best utilize them in order to reveal the black hole photon ring.

EECT: an Eccentricity Evolution Consistency Test for testing general relativity and identifying eccentricity mimickers

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Tuesday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

Binary eccentricity is one of the strong discriminators of different compact binary formation channels. However, identifying a real eccentric signal is challenging due to the degeneracy of binary eccentricity with eccentricity mimickers. Several eccentricity mimickers have been identified in the literature which include--but not limited to-- microlensing effect of gravitational waves by compact objects lying along the line of sight, spin-precession effect in the compact binaries where component spins are misaligned with the orbital angular momentum, dipole radiation and massive graviton effects of beyond-GR theories. To distinguish a real eccentric GR signal from an eccentricity mimicker, we propose an Eccentricity Evolution Consistency Test (EECT) based on GR-predicted frequency-evolution of eccentricity and eccentric-chirp mass (effective combination of chirp mass and eccentricity). This test will be respected in case of a real eccentric GR signal and violated if the incoming signal is from an eccentricity mimicker within GR or from a non-GR eccentricity mimicker. As a proof of principle demonstration, we focus on eccentricity mimickers like microlensing effect, dipole radiation and massive graviton effects and leave the spin-precession effect for future study

Rotating black holes experience dynamical tides

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Tuesday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Black holes, the simplest yet mysterious objects predicted by Einstein's general theory of relativity, pose various interesting questions. One of them is: How does a black hole respond to an external tidal field? In our recent work [Phys. Rev. D 111, L041504 (2025); arXiv:2406.09543 [gr-qc]], we calculated the tidal response of a rotating black hole from the Teukolsky equation in the near-zone and small-frequency regime. While the static tidal Love numbers of an arbitrarily rotating black hole are still zero, the dynamical tidal Love numbers are not zero for a non-axisymmetric external tidal field. To leading order, they depend quadratically on the black hole spin and linearly on the mode frequency. We demonstrated that these results hold true for an extremal rotating black hole as well, with the dynamical tidal Love numbers being non-zero. This implies that Kerr BHs are deformable under certain external, time-dependent perturbations. Since vanishing tidal Love numbers have been used in compact binary coalescences observed by the LIGO-Virgo-KAGRA Collaboration to test black hole nature of their components, our findings have important implications on such inferences in future gravitational wave observations. Additionally, in [arXiv:2412.15117 [gr-qc]], we showed that the non-zero dynamical tidal Love numbers are not only a property of gravitational perturbation but also of scalar and electromagnetic perturbations.

The gravitational-wave population of neutron star-black hole mergers

Biscoveanu S

Wednesday Session 2 - Prize Session

Neutron star-black hole (NSBH) mergers detected in gravitational waves have the potential to shed light on supernova physics, the dense matter equation of state, and the astrophysical processes that power their potential electromagnetic counterparts. In this talk, I will describe what we've learned about the population properties and multimessenger prospects of NSBH mergers, using the four candidate events reported through the end of the third LIGO-Virgo-KAGRA observing run and the exceptional event GW230529 from the ongoing fourth observing run. Either the most massive binary neutron star merger or the least massive NSBH merger, this event has important implications for the compact object mass distribution and electromagnetic counterpart probabilities for NSBH systems. As a single-detector event, the nature of the primary compact object cannot be definitively determined given large statistical uncertainties. I will also present a recent simulation study demonstrating that a higher signal-to-noise ratio in future observations of mass-gap gravitational wave mergers is critical for distinguishing between black hole and neutron star masses for such systems.

Probing Spin-Orbit Resonances with the Binary Black Hole Population

Biscoveanu S[1]
[1]Northwestern CIERA

Wednesday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Measurements of the binary black hole spin distribution from the growing catalog of gravitational-wave observations can help elucidate the astrophysical processes shaping the formation and evolution of these systems. Spin-orbit resonances are one such process of interest, in which the component spin vectors and the orbital angular momentum align into a common plane and jointly precess about the total angular momentum of the system. These resonances, which occur preferentially in systems formed via isolated binary evolution with strong tidal effects, lead to excesses in the distribution of the azimuthal angle between the projections of the component spin vectors onto the orbital plane at $\phi_{12}=0, \pi$. In this talk, I will present the first hierarchical analysis modeling the population-level distribution of ϕ_{12} simultaneously with the other mass and spin parameters for simulated binary black hole populations to determine whether spin-orbit resonances can be reliably constrained. I will show that while we are unlikely to find definitive evidence for spin-orbit resonances with a population of the size expected by the end of the ongoing LIGO-Virgo-KAGRA fourth observing run, we can qualitatively distinguish between different simulated ϕ_{12} distributions. Thus, I will argue that population-level measurements of the ϕ_{12} distribution offer a reliable, novel way to probe binary formation channels, dynamics, and mass transfer with gravitational-wave observations.

The interaction of gravitational waves with matter

Bishop N[1]
[1]Rhodes University

Thursday Session 3 - B3: Approximations, perturbation theory, and their applications

The interaction of gravitational waves (GWs) passing through matter is normally treated as being very weak. We have re-investigated this issue using linearized perturbations within the Bondi-Sachs formalism, with a model comprising a spherical shell of matter surrounding a GW source. The background geometry at the shell is either Minkowski or Schwarzschild. Even a shell of dust causes the GWs to be modified both in magnitude and phase; and if the shell is viscous, then the shear induced in the velocity field results in an energy transfer so damping the GWs and heating the matter in the shell. The effect is very weak when the matter is far from the GW source, but can be very significant when the shell radius is less than the GW wavelength. The applications to astrophysics include supernova explosions, the quasinormal mode regime after a neutron star merger, and a binary black hole merger at which matter is present, as well as to primordial gravitational waves in cosmology.

High Power Cryogenic Silicon 2um Technology Demonstrator and Detector

Blair C[1]
[1]University Of Western Australia

Friday Session 4 - C4: Concept and research towards next-generation detectors

In this presentation the proposal for high power cryogenic silicon experiments at Gingin will be described. These experiments aim to validate technologies proposed for the next generation of gravitational wave detectors. Combined these technologies potentially culminate in a 15kHz gravitational wave detector at the Gingin High Optical Power facility.

Linear Stability of Kerr black holes

Blue P[1]
[1]University Of Edinburgh

Wednesday Session 3 - A2: Classical GR: Mathematical developments

This talk will discuss decay of solutions to the linearised Einstein equation around a Kerr black hole. The nonlinear stability of black holes was a major open problem in mathematical relativity for many decades, and it has now been proven in the slowly rotating case in a series of paper by Klainerman, Szeftel, and coauthors. This talk will present our somewhat different approach from 2019 to the linear problem and our 2022 work introducing a new gauge for the full Einstein equation such that the linearisation of the metric is that in our earlier analysis of the linear problem. In 1972, Teukolsky discovered equations governing certain components of the linearised curvature that are invariant under linearised gauge transformations. In 1975, Chrzanowski introduced the "outgoing radiation gauge", a condition on the linearised metric that allows for the construction of the linearised metric from the linearised curvature. We begin from an assumption of a basic energy and Morawetz estimate for the Teukolsky curvature components, then improve this to more rapid decay, and then prove decay for some connections coefficients and for all metric components. We introduce a nonlinear version of Chrzanowski's linear gauge condition.

This is joint work with Lars Andersson, Thomas Backdahl, and Siyuan Ma.

Simulating Electromagnetic Wave Propagation and Phase Velocities in Highly Inhomogeneous Cosmological Models

Bochner B[1]
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Wednesday Session 3 - B2: Numerical Relativity

The propagation of energy in the form of waves (such as light) through extremely inhomogeneous and anisotropic gravitational metrics is not very well understood outside of the geometric optics ("light-ray") approximation. This approximation neglects a host of important wave-related effects, such as dispersion, energy exchange with gravitational background fields (photon creation), and nonadiabatic processes in general. A fuller understanding requires one to solve the Maxwell Equations in the curved spacetime to model these essentially wavelike behaviors. Here we consider the inhomogeneous and anisotropic (though planar-symmetric) class of "Kuang-Li-Liang" (KLL) cosmologies that possess many interesting features which can strongly violate the geometric optics approximation. These KLL metrics are non-vacuum (filled with moving planes of electromagnetic radiation), and have nonzero Weyl, Ricci, and Riemann tensors everywhere and at all times. Obtaining the wave equation for "test fields" of light injected into this metric, we see that it is not fully separable, and thus not easily analytically solvable. We have therefore constructed numerical simulation programs to solve the wave equations and evaluate propagation behaviors such as the phase velocity field and its time evolution. We find interesting departures from light-ray behavior, such as the throttling of wave speeds towards the initial time singularity, and significant deviations from null-ray phase velocities when the test fields briefly become resonant with the KLL planes of radiation. We are using use these simulations to fully characterize the behavior of wave propagation in these metrics for a variety of metric and test field wave parameters.

Modified gravity: a unified approach to metric and metric-affine models

Boehmer C[1], Jensko E[1]
[1]University College London

Thursday Session 3 - A3: Alternative and modified theories of gravity

The talk begins with a general overview of General Relativity focussing on the basic ingredients of its mathematical structure. This will naturally lead the way to consider various modifications or extensions of General Relativity, many of which have been studied recently. I will briefly review metric-affine models and how these fit into GR. Next I will discuss modified gravity models based on generalised geometries and on actions no longer linear in curvature. The main part of the talk will discuss how these many different theories can be studied using a single unified approach which also shows the equivalence of some of these models. We will finish off by showing a cosmological application where torsion drives a period of early-time inflation without affecting the late-time matter dominated behaviour. No matter sources are required to drive inflation and it becomes a purely geometrical effect.

Simulations of Sensing & Control for Advanced Virgo+ phase II

Boldrini M[1], Mantovani M[2], Casanueva Diaz J, Bersanetti D, De Rossi C
[1]INFN - Sezione Roma 1, [2]EGO - European Gravitational Observatory, [3]INFN - Sezione Genova

Wednesday Session 4 - C4: Concept and research towards next-generation detectors

The Phase II upgrade of Advanced Virgo+ aims to increase the sensitivity of the interferometer to gravitational waves, both by reducing control noise below 10 Hz and making the interferometer more robust to thermal effects, which allows to increase the input power without degrading the detector performances.
This upgrade radically modifies the optical layout, replacing the linear recycling cavities with longer, folded cavities that are geometrically stable but introduce four additional mirrors. These elements bring new, complex degrees of freedom that interact in nontrivial ways with the rest of the instrument, posing challenges for the control system.
Optical simulations are essential for guiding the design and implementation of this upgrade. They help develop the sensing scheme, model the coupling between degrees of freedom, establish requirements, and identify critical challenges.

We present the simulation groundwork to prepare the sensing and control scheme for Phase II.

Quasi-normal modes on black hole horizons

Bonga B[1]
[1]Radboud University

Monday Session 4 - C10: Experimental tests of the nature of compact objects

The gravitational waves emitted by a perturbed black hole ringing down are well described by damped sinusoids, whose frequencies are the so-called quasinormal modes. Until recently first-order black hole perturbation theory was used to calculate these frequencies. However, it is now clear that second-order effects are also necessary to model the gravitational-wave signal during the ringdown. In this talk, I will show that (1) the horizon of a newly formed black hole after the head-on collision of two black holes in numerical simulations also shows evidence of non-linear modes, and (2) compare these results with predictions from second-order black hole perturbation theory.

Synergies between numerical relativity and effective-one-body model for gravitational waves from eccentric binaries

Bonino A[1], Pratten G[1], Schmidt P[1]
[1]University Of Birmingham

Tuesday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

Binary systems of compact objects such as black holes or neutron stars tend to circularize due to the emission of gravitational waves as they approach merger. However, binaries formed through recent dynamical interactions can retain significant orbital eccentricity when entering the frequency band of gravitational wave detectors. Numerical relativity (NR) simulations and accurate waveform models are crucial for detecting eccentric signatures in gravitational wave signals. In recent years, considerable effort has been made to incorporate eccentricity into waveform models using various analytical techniques. The effective-one-body (EOB) approach is a successful paradigm for modelling gravitational waves emitted from binaries on arbitrarily eccentric orbits. In this talk I will discuss strategies to incorporate NR information in a EOB model for coalescing binary black holes. In the EOB framework, eccentricity effects are incorporated by including non-circular terms in the radiation reaction force, requiring modification of the radiation emitted in the circular case. We compare EOB and NR predictions for energetics and waveforms, quantifying the impact of eccentricity on the dynamics, waveform morphology and radiation emitted by the system. We find that the inclusion of higher order non-circular corrections to the dominant quadrupole radiation introduces significant effects, which can be detectable with future gravitational wave detectors.

Weak field approximations in modified theories of gravity

Booker N[1], Böhmer C[1]
[1]University College London

Friday Session 3 - A3: Alternative and modified theories of gravity

A recent topic of interest in modified theories of gravity is the so-called \(f(R)\) gravity, which replaces the Ricci scalar \(R\) with a function of it. One subset of \(f(R)\) gravity is \(f(\mathcal{G})\) gravity, which alters \(R\) as follows: The boundary term \(\mathcal{B}\), which does not contribute to the Einstein-Hilbert action, is removed, and the remaining \(\mathcal{G}\) is mapped to a function \(f(\mathcal{G})\).
In this thesis, we will examine linearised \(f(\mathcal{G})\) gravity and several of its interesting aspects. Firstly, there is a correspondence between the linearised \(\mathcal{G}\) and the Lagrangian of a rank-2 tensor field. Secondly, we discover that by one can recover the field equations with the cosmological term from the linearised \(f(\mathcal{G})\) field equations by a specific choice of \(f(\mathcal{G})\).
We then select a more generalised \(f(\mathcal{G})\) such that its gravitational wave solutions exhibit small deviations from GR. The simplest solution under this shows that the coupling constant \(\lambda\) of the \(f(\mathcal{G})\) term in the field equations is proportional to the angular frequency of the gravitational wave \(\omega\). Finally, this thesis closes with physical discussions of this solution.

Next-generation ground-based gravitational-wave detectors timing and the importance of LIGO-India

Borhanian S[1], Cole P[1], Renzini A[1], Pacilio C[1], Mancarella M[2], Gerosa D[1]
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Monday Session 4 - C4: Concept and research towards next-generation detectors

With the LISA mission set to launch in the mid-30s more attention has been directed towards the question about the next-generation of ground-based gravitational-wave detectors. Here, the Einstein Telescope and Cosmic Explorer proposals currently share the main spotlight. We use Fisher information theory to simulate the science capabilities of these detectors---alone, together, and in tandem with LIGO-India---for large source populations of binary black holes and binary neutron stars. We bootstrap the simulated populations to investigate and map the expected observation times to reach various targets for key science metrics in gravitational-wave astronomy, such as signal-to-noise ratio, sky localization, luminosity distance, and 3D localization. In particular, we investigate the the imapct on rare golden events and the effectiveness of LIGO-India in supporting a network of two next-generation detectors.

AION and the Global Atom Interferometry Frontier: Probing Dark Matter and Gravitational Waves

Bortoletto D

Monday Session 4 - C9: Experimental gravitation

Atom interferometry offers a powerful and versatile approach to exploring fundamental physics, astrophysics, and cosmology. It enables sensitive searches for ultralight dark matter and gravitational waves in the challenging frequency range around 1 Hz. The AION project is advancing this frontier through the development of single-photon, long-baseline atom interferometers based on the ^{87}Sr clock transition. AION's initial goal is the construction of a 10-metre prototype at the University of Oxford, serving as a stepping stone toward a planned 100-metre baseline facility. The project aims to operate in synergy with other detectors, notably the US-based 100-metre MAGIS interferometer, forming a global network for gravitational wave detection. This presentation will provide an update on the current status of AION and outline the vision of the Terrestrial Very-Long-Baseline Atom Interferometry (TVLBAI) Proto-Collaboration, which is coordinating a staged program of increasingly large-scale interferometers.

Magnetized Binary Neutron Star Mergers: Implications for the Remnant Dynamics and Post-Merger Gravitational Wave Signals

Bosch P[1]
[1]Utrecht University

Friday Session 4 - B2: Numerical Relativity

Binary neutron star mergers are critical for understanding the dynamics of dense matter, the origins of gravitational waves, and the formation channels for some of the heaviest elements through the r-process. Our aim is to elucidate whether merging generic neutron stars with small magnetic fields can develop large-scale, magnetar-strength fields in the post-merger dynamics and their implications for multimessenger signals. To this end, we investigate the effects of magnetic fields on the merger process and subsequent kilonova emissions. We perform ideal general relativistic magnetohydrodynamic simulations of ab initio magnetized neutron stars with various seed magnetic field configurations, focusing on their impact on dynamics, ejecta, and gravitational wave signatures. Regardless of the strength of the seed magnetic fields, the remnant consistently exhibits strong, large-scale magnetic field structures that develop after the initial contact of the neutron stars through the Kelvin-Helmholtz instability. Once this strong magnetic field is established, it acts as an effective viscosity, ultimately reducing differential rotation and influencing the remnant's evolution. Furthermore, it impacts the post-merger gravitational wave signature by shifting the f2 frequency and quenching the m=1 bar-mode emission, as well as the conditions leading to differences in the kilonova emission. This work aims to further our understanding of the growth and impact of magnetic fields in post-merger dynamics and their observable multimessenger signatures.

Orbital eccentricity in general relativity from catastrophe theory

Boschini M[1], Loutrel N[1], Georsa D[1], Fumagalli G[1]
[1]University Of Milano-Bicocca & INFN

Tuesday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

While the orbital eccentricity is a key feature of the gravitational unambiguous definition in general relativity poses significant issue, the eccentricity of binary black holes has important implications in gravitational-wave astronomy.
We present a novel approach to consistently define the orbital eccentricity in general relativity, grounded in the mathematical field of catastrophe theory. Specifically, we identify the presence of catastrophes, i.e., breakdowns of the stationary-phase approximation, in numerical relativity waveforms and exploit them to develop a robust and fully gauge-invariant estimator of the eccentricity. Our procedure does not require orbital fitting and naturally satisfies the Newtonian limit. The proposed eccentricity estimator agrees with and generalizes a previous proposal, though with a fully independent derivation. We extract gauge-free eccentricity estimates from about 100 numerical-relativity simulations and find that the resulting values are systematically lower compared to those reported alongside the simulations themselves.

Nonlinear quasinormal modes on a black-hole spacetime

Bourg P[1]
[1]Radboud University

Thursday Session 4 - C10: Experimental tests of the nature of compact objects

One of the major inquiries in the growing area of gravitational wave astronomy is in testing the nature of black holes (BHs). By measuring the characteristic frequencies of the BH spacetime in the so-called ringdown regime, the BH spectroscopy program probes if the dark compact objects are indeed well described by a Kerr black hole.
The ringdown of perturbed BHs has been theoretically studied since the 1970s, although most studies mostly focused on linear perturbations. However, steady advancements in detector sensitivity, as well as growing evidence from numerical simulations, show that future detection will allow us to test the nonlinear nature of gravity using the ringdown regime.
The well-known quasinormal modes (QNMs) frequencies at linear order in black-hole perturbation theory couple at second-order, giving rise to a new set of frequencies, called quadratic quasinormal modes (QQNMs). Since the QNM spectrum in the frequency space is sparse, the detection of these QQNMs is a clear signature of a nonlinear effect, as they are essentially fingerprinted with the order of perturbation theory that they arose from. This gives a clean split of the gravitational-wave signal into linear and non-linear pieces.
In this talk we will present a complete treatment of QNMs and QQNMs in second-order perturbation theory in a black-hole spacetime. We include novel methods for extracting QNMs and QQNMs amplitudes using a Laplace transform treatment, allowing for the inclusion of arbitrary initial data.

Semiclassical evolution of black holes with inner horizons

Boyanov V[1], Hilditch D[1]
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Tuesday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

I will present results on the full non-linear evolution of a dynamically formed charged spherical black hole, including the Polyakov approximation to the renormalised stress-energy tensor of a quantum scalar field as a semiclassical component. The result of this evolution involves the full evaporation of the trapped region, with both an inward motion of the outer horizon and an outward motion of the inner horizon. Additionally, a long-lived anti-trapped region appears in the wake of the evaporation.

An Interdisciplinary Site Suitability Analysis for Cosmic Explorer

Bristol W[1]
[1]Cosmic Explorer's Site Evaluation Team at The University of Arizona

Monday Session 3 - C4: Concept and research towards next-generation detectors

Cosmic Explorer, the next-generation gravitational-wave facility in the United States, is searching for observatory sites. CE is searching for two locations to fit an L-shaped observatory, one spanning 40 kilometers and the other 20 kilometers, in the United States. Suitable locations must be within appropriate cost boundaries, able to support CE's scientific goals, and retain a talented workforce in these areas. The site search poses unique challenges that CE is answering with an interdisciplinary approach. In recognition that the United States are on the ancestral homelands of sovereign Native Nations, CE also aims to involve Tribal Communities during all phases of the project from concept through decommissioning. This presentation will describe the mixed methods Geographic Information Systems (GIS) approach to do a national site suitability analysis to find a location for Cosmic Explorer. Suitability analysis is a form of GIS analysis that ensures a location meets the requirements of all stakeholders. This GIS National Suitability Analysis integrates social and scientific considerations and works in concert with efforts to characterize costs, gather information from location visits, and relationship building. An overview of the workflow and variables used to find potential sites at the national scale will be presented as well as a demonstration of the interactive web map we have built. Moreover, while some preliminary locations may now be deemed possible, Cosmic Explorer recognizes that further work is needed with local data along with community involvement through a proactive and iterative process long before a list of final sites is proposed.

Extreme mass-ratio inspirals into black holes surrounded by scalar clouds

Brito R[1]
[1]Centra, Instituto Superior Técnico

Thursday Session 3 - B3: Approximations, perturbation theory, and their applications

Scalar clouds can form through superradiant instabilities of massive scalar fields around spinning black holes and can also serve as a proxy for dark matter halos. In this talk I will present a novel framework to study extreme mass-ratio binary systems in which a stellar mass compact object spirals into a supermassive black hole surrounded by a scalar cloud. The framework is fully relativistic and assumes that the impact of the cloud on the geometry can be treated perturbatively. As a proof of concept, I will show how to use this framework to compute the leading-order power lost by the point particle due to scalar radiation for a point particle in circular, equatorial motion around a non-spinning black hole surrounded by a non-axisymmetric scalar cloud, but the framework can be generalized to generic black hole spins, as will be presented in other talks. This study confirms the presence of striking signatures due to the presence of a scalar cloud that had been predicted using Newtonian approximations, such as resonances that can give rise to sinking and floating orbits, as well as "sharp features" in the power lost by the particle at given orbital radii.

Mimicking the Luminosity Function Evolution

Brozzetti M[1], Turski C[2], Dálya G[3], Bilicki M[4], Ghosh A[2], Punturo M[5]
[1]Università Degli Studi Di Perugia, [2]Ghent University, [3]CNES , [4]CFT PAN, [5]INFN

Thursday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

UpGLADE is an upcoming extensive all-sky galaxy catalogue which will include more than a billion objects from various non-independent surveys, providing redshift information, which is fundamental for gravitational-wave (GW) cosmology – particularly for Hubble constant inference using dark sirens and galaxy catalogue. Moreover, UpGLADE will play a crucial role in multi-messenger astronomy by supporting GW follow-up campaigns and targeting possible electromagnetic counterparts.
Addressing the intrinsic incompleteness of galaxy catalogues is a key challenge in the statistical approach to GW cosmology, although assessing the completeness of UpGLADE is not trivial because it consists of multiple flux-limited samples covering different patches of the sky. This problem is tackled by analysing the luminosity function of the cross-matched catalogue using the Vmax method, which has been specifically adapted to account for its heterogeneity. The study reveals a behavior that could be interpreted as an evolution of the luminosity function over different redshift ranges. Our work aims to evaluate the impact of redshift uncertainties in the UpGLADE luminosity function, potentially mimicking its evolution.
Preliminary results suggest that redshifts error models may introduce systematic biases in the derived luminosity function, with implications for cosmological analyses. These findings motivate the use of a mock catalogue to interpret our results and provide a comparative framework, ultimately enhancing the reliability of UpGLADE for getting unbiased estimates of the Hubble constant.

Physical projector from Spin Foam amplitudes

Bruno M[1,2], Colafranceschi E[3], Mele F[3], Rovelli C[3]
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Friday Session 4 - D1 + D2 D+3,

In the quantum theory of gauge fields, the path integral is usually ill-defined.
A rigorous approach to the path integral formulation in a specific class of quantum field theories (Topological Quantum Field Theories) is provided by Atiyah's axioms. These theories are diffeomorphism-invariant quantum theories, thus offering promising tools for a rigorous analysis of the gravitational path integral. In quantum gravity, the path integral is typically controlled through a discretization procedure, as in Spin Foam models. The discretized picture represents a truncation of the theory, and the challenge is to recover the continuum properties from the discrete.
In this talk, we propose a set of axioms for Spin Foam models at the truncated level and derive the properties of the continuum. The main result is that, under some minimal assumptions, the amplitude picture associated with a model is sufficient to define a 'physical projector' in the sense of a rigging map, thereby allowing the construction of a proposal for the physical Hilbert space in the continuum.

The Quadratic Quasi-Normal Modes of a Schwarzschild Black Hole

Bucciotti B[1], Kuntz A[2], Trincherini E[1], Juliano L[1]
[1]Scuola Normale Superiore and INFN, Pisa, [2]Lisbon CENTRA, CFTP, and IST

Tuesday Session 3 - B3: Approximations, perturbation theory, and their applications

Black hole spectroscopy is a program that aims at testing black hole quasi-normal modes (QNMs), generated during the ringdown phase of a merger. Next-generation gravitational wave detectors will not only be sensitive to many linear QNMs, but also to non-linearities named quadratic QNMs. Understanding these corrections will be imperative in order to have sufficiently accurate templates. In addition, I will show that quadratic QNMs can be fully understood using black hole perturbation theory, which allows very clear and insightful computations.
While the frequencies of quadratic QNMs have long been known, their amplitudes and phases had remained poorly understood. In this talk I will introduce new master scalars regular at infinity and the black hole horizon that allow to compute amplitudes and phases for any parity, overtone and angular momentum of the perturbations for a non-rotating black hole.
I will confirm our predictions against existing numerical relativity waveforms, while also predicting new phenomenologically interesting modes. The large angular momentum limit is especially interesting and simple to study, analogously to the linear QNM case.

Addressing data gaps and assessing noise mismodeling in LISA

Burke O[1,2,3,4], Marsat S[2], Gair J[3,4], Katz M[3,5]
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Monday Session 4 - C5: LISA and other space-based detectors

Due to the sheer complexity of the Laser Interferometer Space Antenna (LISA) space mission, data gaps arising from instrumental irregularities and/or scheduled maintenance are unavoidable. In this talk we will discuss theoretical and practical consequences of missing interferometric data on time domain and frequency domain inference schemes. We will demonstrate that noise mismodelling with gaps is highly sensitive to the characteristics of the underlying noise process goverened by the behaviour of the noise curve. We will demonstrate that the assumption of independence between inter-gap segments appears to be a fair approximation, even if segments betweenn gaps are dependent on each other. However, rather alarmingly, we will show that if one assumes fictitious correlations between gap segments when the true data should be described as independent, then parameter recoveries may, in general, be inconsistent with the true parameters. We will finish with a quick discussion on how our algorithms could be incorporated into future global-fit pipelines.

Fact or FABLE: predictions for SMBH merger rates from cosmological simulations

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Wednesday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

The co-evolution of massive black holes and their host galaxies is well established within ΛCDM cosmology. The repeated mergers, accretion, and feedback that conspire to regulate this process can be studied in large-scale cosmological simulations, such as Illustris, FABLE, MillenniumTNG and Flamingo. These simulations resolve key galaxy formation processes at ~kpc scales, but are plagued with numerical inaccuracies at the smaller scales of black holes. This scale discrepancy presents significant challenges for investigating black hole properties and generating testable predictions, e.g. for future JWST, Gaia, LISA and IPTA observations of isolated and binary black holes. In this talk I will discuss the black hole population in FABLE. Our results show that the numerical treatment of black holes in cosmological simulations leads to a misleading picture, even at the well-resolved large scale of galaxies. In particular, a large fraction of black holes coalesce well before their host galaxies merge and thus require extra delays on the order of a few Gyrs. These delays, governed by the dynamical timescale of the merging host galaxies, occur before and in addition to any delays arising from unresolved 'sub-grid' physics describing black hole hardening mechanisms on parsec scales. This effect has profound implications for the black hole merger rates predicted from these large-scale cosmological simulations as well as for the multi-messenger predictions, once black hole growth during these dynamical galaxy merger delays is accounted for.

Premerger observation of massive black hole binaries with LISA

Cabourn Davies G[1], Harry I[1], Williams M[1]
[1]Institute of Cosmology and Gravitation, University Of Portsmouth

Friday Session 4 - C5: LISA and other space-based detectors

Using LISA to observe and characterise massive black hole binary signals before they merge offers a unique opportunity to observe across the spectrum one of the most energetic phenomena in our universe in real-time. Previous results have shown that that with minimal computational cost, we are able to reliably observe signals as early as 14 days pre-merger as long as the signal has accrued a signal-to-noise ratio of at least 8 in the LISA data. We add to this by considering the LISA data challenge dataset Sangria, which includes time-varying galactic binary foreground noise which can make detection more difficult. We present the challenges, solutions and results from including this complication.

Identifying the ancestors of LIGO-Virgo black holes and their host environments

Calderon Bustillo J[1], Wong H[2], Araujo Alvarez C[3], Romero-Shaw I[4], Liu A[2]
[1]University Of Santiago De Compostela, [2]The Chinese University of Hong Kong, [3]University of La Laguna, [4]University of Cambridge

Wednesday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Some black-hole mergers observed by the LIGO-Virgo-KAGRA network display component masses within the so-called pair-instability supernova gap, which suggests these black holes formed through hierarchical-formation channels in dense environments like e.g. globular clusters. We present a fully bayesian framework to derive the properties of the putative ancestors of these black holes as well as the corresponding gravitational recoil inherited at birth. These properties allow us to compute the probability that black holes in the PISN gap formed in given host environments -- characterised by their escape velocities -- leveraging all of the information contained in the parameter estimates of black-hole mergers. This talk will review our methodology and show its application to several black-hole mergers detected by LIGO-Virgo-KAGRA, considering both quasi-circular and eccentric scenarios.

Probing the Primordial Gravitational-Wave Background with LISA: Mitigating Astrophysical Confusion

Caliskan M[1], Anil Kumar N[1], Cheng S[2], Marsat S[3], Kamionkowski M[1]
[1]Johns Hopkins University, [2]Institute for Advanced Study, [3]Université de Toulouse

Friday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

The Laser Interferometer Space Antenna (LISA) will probe a primordial stochastic gravitational-wave background in an unexplored frequency window. Crucially, any primordial contribution must be distinguished from overlapping astrophysical backgrounds. We discuss prospects for disentangling a potential primordial signal by leveraging differences in spectral dependence among various sources. Finally, we consider the coexistence of multiple backgrounds, including the white dwarf galactic background, and outline broad strategies to reduce confusion among them.

Inextendibility of weak null singularities in 1+1 dimensions

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Friday Session 4 - A2: Classical GR: Mathematical developments

Dafermos and Luk have shown that dynamical black holes which settle down to Kerr in the exterior contain a Cauchy horizon to which the metric extends continuously (known as a "weak null singularity"). However, the strong cosmic censorship conjecture states that this spacetime is inextendible as a Lorentzian manifold with continuous metric and locally square integrable Christoffel symbols. In this talk I will discuss recent work with Sbierski where we prove the inextendibility of weak null singularities in 1+1 dimensions at this level of regularity. This represents the first spacetime inextendibility result below Lipschitz regularity.
We study 1+1 dimensional Lorentzian manifolds which admit a continuous spacetime extension across a null boundary. In particular we are interested in the degree to which such extensions are unique (up to the boundary). Firstly, we find that not even the C^0-structure of the extension is determined uniquely. However, we exhibit an interesting local-global relation which in particular entails the rigidity of the C^0-structure for "strongly spherically symmetric'' continuous extensions across the Cauchy horizon of the Reissner-Nordstrom spacetime. Secondly, we construct continuous extensions which have the same C^0-structure, but inequivalent C^1-structures. This construction carries over to weak null singularities in 3+1 dimensions. However, we argue that in physically relevant settings, any two C^0-extensions must be C^{0,α}-equivalent for all 0<α<1. Using this we are able to extend recent work of Sbierski to prove our inextendibility statement for weak null singularities using a curvature blow-up assumption.

Rotating hairy Black Holes in scalar-tensor theories using Numerical Relativity

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Wednesday Session 3 - A3: Alternative and modified theories of gravity

In General Relativity, stationary Black Holes are entirely determined by their mass, angular momentum, and electric charge if coupled with Maxwell theory. They are said to have "no hair". However, this is no longer the case in many alternative theories of gravity. In scalar-tensor theories, which consist in adding a scalar field to the theory, no hair theorem can be evaded and static hairy solutions have already been found. Although, very few rotating solutions have been found so far. The search for rotating solutions is astrophysically motivated, as Black Holes in nature are expected to have a non-zero angular momentum. The goal of the work presented here is to find rotating hairy Black Hole solutions in scalar-tensor theories, using tools from Numerical Relativity. Theories investigated are the ones with a known analytical static solution, with a focus on shift-symmetric Horndeski and DHOST theories. Equations of motion are written in the 3+1 formalism, and are solved in a unique spatial slice with no time derivative, as we are looking for stationary solutions only. The existence of an event horizon is imposed using boundary conditions, then metric field and scalar field are computed in the exterior region using spectral methods.

Numerical simulations of gravitational collapse of a massive quantum scalar field

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Friday Session 3 - B2: Numerical Relativity

Recent work by Berczi et al. has investigated the gravitational collapse to a black hole of a massless quantum scalar field using numerical relativity methods. We moderately extend this work to consider the effects of including a mass term for the scalar field, and investigate the consequences of this modification on the dynamics of the collapse. We also improve the numerical efficiency of the method by parallelisation of the algorithm on a GPU.

A Methodological Framework for Black Hole Spectroscopy in Time Domain

Caneva Santoro G[1]
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Thursday Session 4 - C10: Experimental tests of the nature of compact objects

This talk presents a comprehensive methodological framework for performing black hole spectroscopy, the study of the ringdown phase of binary mergers through superpositions of quasi-normal modes, as it provides one of the most clear probes of the Kerr nature of astrophysical black holes. We aim to build the foundation for the upcoming fourth observing run TGR (Tests of General Relativity) analysis. Building on insights from the pyRing pipeline, we address key challenges such as multimodalities, sky localization, and template selection, offering a step-by-step guide to robustly extract QNMs from GW signals. Using controlled injections of both damped sinusoid and Kerr-modified templates with well-defined mode content, we validate our approach under idealized conditions and extend it to more realistic waveforms. We implement a systematic analysis plan, including injections with varying mass ratios, inclinations, and distances, and employ a range of templates across a grid of starting times to ensure robustness. Our results demonstrate precise recovery of injected quasi-normal modes and accurate estimation of the black hole parameters, while also identifying biases that arise when specific modes are neglected in the template models.

Accretion Disks in Gravitational Wave Physics: Tidal Love Numbers and Hydrodynamic Drags

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[1]Istituto Superior Tecnico, Lisbon, [2]Niels Bohr Institute, [3]La Sapienza University of Rome, [4]University of Pennsylvania

Thursday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

In recent years, it was recognized how the environments surrounding black holes (BHs) may play a crucial role during a binary coalescence, leaving detectable imprints on the waveform which may contaminate our ability to test general relativity using gravitational wave (GW) observations. In particular, accretion disks around BHs are ubiquitous phenomena in astrophysics, which form when matter spirals towards the BH due to gravity. In this talk, I will discuss how accretion disks drastically affect GW phenomenology in two different systems. First, I will discuss the tidal deformability of black holes surrounded by thin accretion disks. I will show how the love numbers could be large enough to mask any effect of modified gravity and how the tidal parameters could be measured with high precision using next-generation GW detectors; this provides a powerful tool to probe the environment around coalescing binary systems. In the second part of the talk, I will discuss how a stellar-mass object in an eccentric, inclined orbit around a supermassive BH is highly affected by the disk surrounding the latter, due to accretion and dynamical friction. I will show how eccentricity and inclination are modified by the presence of the disk, and how this phenomenology affects the GW signal measurable by LISA.

Direct Nuclear Parameter Estimation from Gravitational Waves

Capano C[1,2]
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Wednesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

Understanding the nuclear equation of state (EOS) is one of the foremost science goals of gravitational-wave astronomy. Most Bayesian analyses of gravitational waves have sampled over macro parameters (the neutron stars' mass and tidal deformability), then inferred EOS constraints in a two-step process. A more comprehensive probe of the underlying nuclear physics can be realized by directly sampling over nuclear parameters. However, this requires both generating EOS and solving the Tolman-Oppenhimer-Volkoff (TOV) equations on the fly, which is computationally expensive. We use machine learning to develop an emulator that quickly generates the EOS and solves the TOV equations given a set of nuclear parameters. By using the emulator with a heterodyne likelihood function, we are able to directly sample over nuclear parameters in a full Bayesian analysis of GW170817 in ~2 minutes utilizing 256 CPU cores. This represents a 100-fold speedup compared to using a standard TOV solver. The resulting posterior yields direct constraints on nuclear parameters, such as the symmetry energy of nuclear matter and the speed of sound at supra nuclear densities.

Exploring suspension thermal noise from thin tapered fibers at the AEI 10 m Prototype

Carlassara M[1]
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Tuesday Session 4 - C3: Progress and challenges in advanced ground-based detectors

Suspension Thermal Noise (STN) is one of the dominant noise contributors to ground based gravitational wave detectors (GWD), particularly at low frequencies (below 10 Hz).
The use of quasi-monolithic suspensions has been adopted for all current GWDs to reduce STN. This uses fibers of the same material as the mirror substrate to reduce mechanical losses in the surface, bulk, or thermal-elastic losses. These losses at the last stage heavily impact the noise performances. This effect can be optimized by changing the geometry of the fibers and reducing imperfections.
At the AEI 10m Prototype, we are planning to build a Fabry-Perot Michelson interferometer to test technologies to improve current and future GWDs. Specifically, we target research on quantum noise suppression, which will be enabled by using 100 g fused silica mirror masses quasi-monolithically suspended with 20 μm diameter fibers.
This presentation will explore progress in understanding the surface thermal noise of these thin tapered fibers, and its effect on interferometer sensitivity with simulations made with pygwinc.
In this Python library, some approximations and assumptions are made to estimate the STN, and not all are valid for these thin fibers. The studied parameters include the geometrical factor μ, the surface-to-volume ratio, and the second moment of inertia. The results of this study can be used to guide the design of fibers for future small-scale suspensions.

A portal to public access for SKA pulsar timing data

Carli E[1]
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Thursday Session 3 - C1: Pulsar timing arrays & C8: Education and public outreach in gravitational physics

Regular observations or ‘timing’ of radio-emitting pulsars, the most precise clocks in the Universe, offer access to regimes of physics not attainable in the laboratory, such as studies of relativistic gravity, neutron star interiors, and the detection of the nanoHertz gravitational wave background. I will present a new radio pulsar timing online portal, https://pulsars.org.au, that provides public access to tens of thousands of pulsar timing observations and related scientific data products, suitable for astronomical research in a user-friendly manner. The initial version of the portal provides most of the pulsar timing data ever recorded by MeerKAT, the mid-frequency precursor telescope of the Square Kilometer Array (SKA) Observatory. Notably, most of the MeerKAT Pulsar Timing Array data is public, except for the most recent observations under a proprietary period. The site is extensible to other radio observatories and is being considered in collaboration with the Australian SKA Regional Centre as the future portal to SKA pulsar timing products.

Midisuperspace foam and the cosmological constant

Carlip S[1]
[1]University of California at Davis

Thursday Session 4 - D3: Causal sets, causal dynamical triangulations, non-commutative geometry, asymptotic safety, and other approaches to quantum gravity

Standard quantum field theory arguments predict a huge cosmological constant. But what would this mean observationally? For a homogeneous universe the answer is clear, but if the universe is inhomogeneous at the Planck scale the question becomes more subtle: for a large class of initial data, rapidly expanding and contracting regions coexist and give an average expansion near zero. Classically, though, such data develop singularities, and we need a quantum description of their evolution. I describe results from a spherically symmetric midisuperspace model -- a model in which most degrees of freedom are frozen out but an infinite number remain -- in which the wave function can become "trapped" for long periods in regions in which the average expansion remains small, effectively hiding a large cosmological constant.

Testing Gravitation with Long-Baseline Atom Interferometry

Carroll A[1]
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Monday Session 4 - C4: Concept and research towards next-generation detectors

MAGIS and AION are a pair of next-generation quantum sensors that aim to explore fundamental physics with atom interferometry. This new regime of experiment is capable of probing a diverse range of physical phenomena such as detecting mid-band (0.1-10 Hz) gravitational waves and measuring the gravitational Aharanov-Bohm effect, as well as capabilities in precision metrology to measure Newton's constant and test the Equivalence Principle. MAGIS-100 will be a strontium atom interferometer located at Fermilab with a 100-meter vertical baseline, building on previous work done over 10-meter scales, and with the intention of providing a development platform for future kilometre-scale experiments. AION is a sister project which is planning to build a 10 m prototype at the University of Oxford, with plans to upgrade to a 100-meter baseline. The collaboration between MAGIS and AION will facilitate the development of the technologies required to build such an ambitious experiment, as well as providing multiple independent observatories for gravitational wave detection.

Analytical computation of quasi-normal modes excitation amplitudes in generic binary configurations

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Wednesday Session 3 - B3: Approximations, perturbation theory, and their applications

Current waveform models of binary black hole mergers incorporate a large amount of analytical information during the inspiral phase, in the form of post-Minkowskian/Newtonian perturbative expansions (eventually resummed). On the other hand, the post-merger waveform component only uses a phenomenological ansatz informed by numerical simulations. These “templates” carry very limited analytical information, purely restricted to the quasinormal modes frequencies.
To tackle this problem, we develop the first analytical model predicting the late-time quasinormal modes amplitudes for generic orbital configurations, including highly eccentric ones. Our perturbative computation explains from first principles the impact of the inspiral on quasinormal modes amplitudes, that was previously observed a-posteriori from numerical relativity fits.
Our model shows very good agreement with a numerical solution of the binary merger, around the percent level. The proposed approach offers an extremely promising way to extract physical quasinormal modes contributions, avoiding ambiguities and overfitting issues when assuming phenomenological ansatze, and to construct analytically informed ringdown models.

New exact GR solutions: interior spacetimes sourced by stationary rotating cylindrical fluids.

Celerier M[1]
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Thursday Session 4 - A1: Classical GR: Theoretical developments

For mathematical simplicity reasons, vacuum solutions of the GR equations have been more studied than their corresponding interiors. Among them, the Lewis-Weyl vacuum, gravitationally sourced by a stationary rotating cylinder of matter, has long been known and studied, while its interior spacetimes were left aside. Now, in a recent series of seven papers, a set of interior solutions matching to a Lewis-Weyl exterior has been displayed. These new exact solutions to the field equations correspond to different configurations of fluid equations of state and rotation type, rigid and non rigid. Here, both perfect fluid cases, rigidly and differentially rotating, will be described and their physical properties will be analysed.

Fullshape power spectrum for the Symmetron modified gravity model

Cervantes-cota J[1]
[1]Inin

Tuesday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

We make use of the perturbation theory scheme for modified gravity models that we developed in previous works and apply it to construct the fullshape galaxy power spectrum for the Symmetron modified gravity model. First, we study the growth rate, that is a scale dependent quantity, and compare our results with Hu-Sawcki (HS) model. Later, we apply the fk-PT approximation to reduce the computation time of nonlinear kernels, to find the fullshape galaxy power spectrum for the Symmetron, and study the differences with HS model. We integrate this theory to an MCMC sampler and validate our results by fitting our parameters to NSeries simulations to recover the parameters that bring the model to GR.

Curb Your Eccentricity?: The Role of Astrophysical Environments on the Eccentricity Evolution of Stellar Binaries in the LISA Band

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Monday Session 3 - B1: Relativistic astrophysics

Gravitational-wave emission causes binary systems to inspiral and circularize over time. However, when a binary is embedded in an astrophysical environment, torques induced by this environment can compete with the effects of gravitational-wave emission, modifying the evolution of the system. In this talk, I will show how accretion disk effects, such as dynamical friction and Eddington mass accretion, influence the eccentricity evolution of stellar binaries as they chirp through the LISA frequency band. Additionally, I will compare these environmental effects to those induced by a third body, highlighting which effects dominate across a wide range of astrophysical parameter spaces. This work emphasizes the crucial role that astrophysical environments play in the formation and evolution of eccentric stellar binaries.

Millisecond waveforms for eccentric, non-precessing extreme mass ratio inspirals into spinning black holes

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Wednesday Session 3 - B3: Approximations, perturbation theory, and their applications

The Laser Interferometer Space Antenna is expected to observe numerous mHz gravitational-wave sources including extreme mass ratio inspirals (EMRIs) of stellar-mass compact objects into massive black holes (MBHs). While EMRIs enable precise mass and spin measurements, they also require highly accurate waveform models that maintain coherent phasing over thousands to millions of orbits. The FastEMRIWaveforms (FEW) project aims to build tools for rapid and accurate EMRI template generation, previously achieving millisecond waveform generation for eccentric inspirals into non-spinning MBHs. However, many MBHs are expected to be rapidly spinning, which significantly affects waveform morphology and, therefore, the scientific potential of EMRIs for these systems. In this talk, I will present a significant advancement of FEW that incorporates MBH spins up to 99.9% of their maximal rate. I will first describe the modifications to the framework necessary to meet accuracy requirements in this regime (which is verified with convergence studies), followed by a discussion of EMRI science prospects for eccentric inspirals into spinning MBHs informed by a fully-relativistic waveform model for the first time. I will conclude by outlining the next stage of FEW development: to further generalise the framework to support precessing (inclined) and eccentric inspirals for spin-aligned binaries.

The impact of astrophysical priors on parameter inference for GW230529

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Friday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

We investigate the effects of prior selection on the inferred mass and spin parameters of the neutron star-black hole merger GW230529_181500. Specifically, we explore models motivated by astrophysical considerations, including massive binary and pulsar evolution. We examine mass and spin distributions of neutron stars constrained by radio pulsar observations, alongside black hole spin observations from previous gravitational wave detections. We show that the inferred mass distribution highly depends upon the spin prior.
Specifically, under the most restrictive, binary stellar evolution models, we obtain narrower distributions of masses with a black hole mass of $4.1^{+0.2}_{-0.3} \,M_\odot$ and neutron star mass of $1.3^{+0.1}_{-0.1} \,M_\odot$ where, somewhat surprisingly, it is the prior on component spins which has the greatest impact on the inferred mass distributions. Re-weighting using neutron star mass and spin priors from observations of radio pulsars, with black hole spins from observations of gravitational waves, yields the black hole and the neutron star masses to be $3.8^{+0.5}_{-0.6} \,M_\odot$ and $1.4^{+0.2}_{-0.1} \,M_\odot$ respectively. The sequence of compact object formation --- whether the neutron star or the black hole formed first --- cannot be determined at the observed signal-to-noise ratio. However, there is no evidence that the black hole was tidally spun up.

Nuclear physics versus Astrophysics with multi-messenger neutron star data

Chatziioannou K
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Wednesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

The properties of neutron stars depend both on the nuclear physics that governs their interiors and the astrophysical processes that created them. Neutron star observations can therefore inform both large-scale astrophysics and dense matter. In this talk, I will present a joint analysis of the neutron star equation of state and their astrophysical mass distribution using gravitational-wave, radio, and X-ray data. I will discuss similarities and differences between neutron star subpopulations and whether it is nuclear physics or astrophysics that dictates the properties of the most massive neutron star in the universe.

Measuring the cosmic dipole with golden dark sirens

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Thursday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves

The tensions between cosmological parameter measurements from the early-universe and the late-universe datasets offer an exciting opportunity to explore new physics, if not accounted for unknown systematics. Apart from the well-known Hubble tension, there also exists a ~4.9σ tension in the cosmic dipole, which is induced by the observer's kinetic motion or possible intrinsic anisotropy of the universe. If the intrinsic anisotropy is true, it can be a dark energy mimicker that creates an illusion of the cosmic accelerating expansion. As a new and powerful tool, gravitational waves can serve as an independent probe to the cosmic dipole. With next-generation ground-based detectors, near-by well-localized binary merger events can be detected, whose host galaxies can be determined directly due to precise localization. As shown in my talk, these "golden dark sirens" can provide a strict constraint on the cosmic dipole magnitude down to 10 to the power of -4.

Extremal Black Branes from the Near-Horizon

Chen C[1]
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Friday Session 3 - D1 + D2 D+3

In this talk, I will present the Kaluza-Klein spectrum of background perturbations to Freund-Rubin compactifications, which are the near-horizon geometry of a class of extremal black branes. The purpose of this is twofold.
The effective masses of fields in the near-horizon geometry determine the scaling exponents of (tidal) deformations to extremal black branes, so the spectrum characterises the horizon of certain extremal black branes which are continuously connected to the undeformed geometry. A large class turns out to be non-smooth or singular, generalising a recent result for extremal black holes.
We also argue that the severity of the Aretakis instability of black branes is determined by the scaling dimensions of the perturbations on the Anti-de Sitter factor in the near-horizon geometry. Our results therefore show that extremal black branes suffer from an Aretakis instability even in the absence of additional fields --- in some cases, the dominant mode itself is non-decaying.

Studying astrophysics with Pulsar Timing Arrays

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Tuesday Session 4 - C1: Pulsar timing arrays

Pulsar Timing Arrays (PTAs) are entering a new era of nano-Hertz gravitational wave (GW) astronomy with evidence for a GW signal found in several PTA data sets, CPTA, EPTA, InPTA, NANOGrav, PPTA and MPTA. They are working together in the IPTA to combine the data sets and analyze the truely best upcoming global PTA data set, IPTA DR3, to be able to conclusively confirm the detection of nano-Hertz GWs. In addition, the GammaPTA project is also advancing and offers a complementary observing frequency range to radio PTAs. In my presentation I will focus on tackling the challenge of the identification and characterization of the source of the GWs.
One of the main targets are super massive black hole binaries (SMBHBs), which are formed when two galaxies merge. Several processes will drive the evolution of the binary orbit. Measurements of a GW background can help to address the question on how SMBHBs evolve over a cosmic time scale. Given that direct observations in the electromagnetic spectrum are difficult, we can turn to cosmological simulations for further tests. Finding an individual SMBHB as a GW source will not only allow for the possibility to distinguish different population models of SMBHBs, but also for multi-messenger astrophysics. I will attempt to review the current status of astrophysical interpretation efforts from the PTA community and how we will move forward into the post-detection era.

Quasinormal modes of gravitational perturbation for uniformly accelerated black holes

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Tuesday Session 3 - B3: Approximations, perturbation theory, and their applications

We first show that the master equations for massless perturbations of accelerating rotating black holes can be transformed into the Heun's equation. The quasinormal modes of the black holes can be easily calculated in the framework of the Heun's equation. We identify three modes for the tensor perturbations: the photon sphere modes, which reduce to the quasinormal modes of Kerr black holes when the acceleration parameter vanishes; the near-extremal modes, which branch from the first set and become dominant when the spin is near extremal; and the acceleration modes, which are closely related to the acceleration horizon. We calculate the frequency spectrum of the QNMs in various spin and acceleration parameters. We choose an angular boundary condition that
keeps the angular function regular at $\theta = 0$ and π, which is consistent with the boundary condition of the Kerr black hole. The conical singularity caused by the acceleration influences this boundary condition. We find that the $m0 = 1$ modes have an anomalous behavior at particular accelerations.

A Unified Approach to Dark Siren Cosmology in Harmonic Space

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Wednesday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves

Dark siren methods aim to infer cosmological parameters from gravitational waves (GWs) without an electromagnetic counterpart by leveraging features in the mass distribution and statistically averaging over possible host galaxies. The latter method, known as the “galaxy catalog method”, is uninformative at moderate to high redshifts where galaxy catalogs are highly incomplete. On the other hand, cross-correlating GW sources and galaxies relaxes the requirement that the host galaxy is in the catalog. We present a unified hierarchical Bayesian formalism under which the cross-correlation method is an extension of well-known existing methods, incorporating both GW and galaxy selection effects. Furthermore, by sampling from the full joint likelihood of population and individual event parameters, we demonstrate how one can obtain both the galaxy catalog and the cross-correlation posterior with a simple re-weighting of a fiducial population inference hyperposterior. Under unified assumptions, we present results on GWTC-3 data and project the constraining power of these different methods for future observing runs.

A search for extra polarisations using a Gaussian process in Gravitational-Wave Transient Catalogue 3

Cheung S[1], Passenger L[1], Lasky P[1], Thrane E[1]
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Wednesday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

General relativity only predicts two polarisations, the plus + and cross ×, while alternate theories of gravity allow up to six polarisations. By combining data from three or more observatories, we construct a null stream where the + and × signals destructively interfere, leaving behind noise and/or extra polarisations. We develop a Gaussian process as a model-agnostic method to search for extra polarisations beyond general relativity. Using data from all 52 three-detector event from the third gravitational-wave transient catalogue (GWTC-3), we apply our search on null stream, and find that there is no evidence of extra polarisations in the GWTC-3 events. We set upper limits on the maximum deviation from general relativity, and constrain the strain amplitude of signal from extra polarisations.

The AEI 10 m Prototype Facility

Chiarini G[1]
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Tuesday Session 4 - C3: Progress and challenges in advanced ground-based detectors

As gravitational wave detectors evolve, improving their sensitivity remains a key challenge, with several noise sources limiting performance, including seismic noise, thermal noise, and quantum noise. Techniques to overcome these limitations are essential for expanding the observational range and the detection rates of events, opening new opportunities for multimessenger astronomy.
The AEI 10 m Prototype facility, located at the Albert Einstein Institute (AEI) in Hannover, Germany, serves as a testbed for developing and testing new techniques aimed at improving the performance of gravitational wave detectors. This facility plays a critical role in bridging the gap between small-scale proof-of-principle experiments and full-scale gravitational wave observatories, since it consists of a Fabry-Pérot Michelson interferometer with ~10 m suspended cavities, housed in a vacuum system. The interferometer is designed to be limited by the standard quantum limit between 65-200 Hz, proving a unique test-bed for quantum noise reduction method. Additionally, the facility is ideal for testing new sensors and techniques to address other classical noise sources, such as seismic and thermal noise.
This presentation will provide an update on the current status of the prototype, highlighting recent developments and progress. Some of them are the suspension platform interferometer for relative control between the tables, a dedicated welding machine to cleave and weld ⌀20 µm fibers and the implementation of balanced homodyne detection.

LISA Gravitational Reference System: consolidating the perfect free-fall environment for LISA Test Masses

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Thursday Session 3 - C5: LISA and other space-based detectors

LISA will use a constellation of free-falling test masses in space to measure gravitational waves in the mHz frequency range. The Gravitational Reference System (GRS) is one of the key systems of LISA, including the reference masses themselves and much of the environment needed to ensure their near-perfect geodesic motion: more precisely, spurious accelerations must be kept lower than 3 fm/s²/√Hz at 1 mHz, a requirement that surpasses the performance of previous missions by more than five orders of magnitude. This goal was considered so ambitious that an entire mission was dedicated to demonstrating its feasibility, LISA Pathfinder, whose great success paved the way for LISA.
I will provide an overview of the GRS, its performance during LISA Pathfinder flight and some of the remaining open questions. These include forces arising from the outgassing environment around the test masses, effects linked to the surface properties of conductors, and noise in the test mass control forces. These currently drive further theoretical and experimental studies of the GRS instrument, as well as a critical review of the system hardware and handling, which are briefly described in this contribution. A significant portion of these studies are conducted at the University of Trento with dedicated facilities, including torsion pendulums.

Effect of generic dark matter halo on transonic accretion onto galactic black holes

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Monday Session 4 - B1: Relativistic astrophysics

The environment surrounding a black hole or black hole binaries is generally expected to play an important role in understanding various astrophysical phenomena around them. In this work, we study relativistic, low angular momentum, inviscid, and advective hot accretion flow onto a galactic supermassive black hole dressed with a cold dark matter halo. Focusing on different relativisticdark matter distributions with an inner density spike, we analyze the effect of the dark matter halo on the topology and properties of the accretion flow. Our results show enhancement of diskluminosity in the presence of dark matter, which depends on the nature and properties (halo mass and compactness) of the dark matter distribution. Since the dominant contribution to the diskluminosity for compact and massive halo comes from the inner region of the accretion disk, our analysis suggests that luminosity measurement can indeed be useful to probe the exact nature of the dark matter density spike.

Locally asymptotically hyperbolic initial data sets with negative mass

Chrusciel P[1]
[1]Bimsa And Cft Pan
Monday Session 3 - A2: Classical GR: Mathematical developments

I will present the construction of asymptotically locally hyperbolic manifolds with higher genus conformal infinity and with mass of arbitrary sign. Based on joint work with Erwann Delay and Rafaela Wutte, arXiv:2207.14563 and 2112.00095

METRICS and its use in extracting fundamental physics from gravitational-wave ringdown signals

Chung A[1]
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Monday Session 4 - C10: Experimental tests of the nature of compact objects

Gravitational-wave ringdown signals emitted by the remnant black holes formed by binary black-hole coalescence allow us to extract rich fundamental physics, such as the validity of general relativity near the event horizon. Nonetheless, due to the challenges of computing the quasinormal-mode of spectra of a black hole under different circumstances, these ringdown tests have been carried out mostly in a model-agnostic way. The recent breakthrough in quasinormal-mode computations brought by METRICS (Metric pErTuRbations wIth speCtral methodS) has made physics-informed ringdown tests of general relativity possible. In this talk, I will sketch the skeleton of METRICS, and show the results of the first accurate computations of the quasinormal-mode spectra of rapidly rotating black holes in Einstein-scalar-Gauss-Bonnet gravity and dynamical Chern-Simons gravity, well-motivated beyond-general-relativity extensions. Then, I will discuss the projected constraints on these beyond-Einstein extensions with ground-based detection of gravitational-wave ringdown signals, and the implications of the projected constraints on fundamental physics.

Kerr Geodesics in Terms of Weierstrass Elliptic Functions

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Friday Session 4 - A2: Classical GR: Mathematical developments

I will present a derivation of novel analytical solutions describing timelike and null geodesics in the Kerr spacetime. The solutions are parameterized explicitly by constants of motion - the energy, the angular momentum, and the Carter constant - and initial coordinates. A single set of formulas is valid for all null and timelike geodesics, irrespective of their radial and polar type. This uniformity is achieved using a lesser-known theorem by Biermann and Weierstrass concerning solutions to a specific class of ordinary differential equations. Our solution is explicitly real for all types of geodesics. In particular, transit orbits have been expressed for the first time in terms of real Weierstrass functions. I will present the solution in both Boyer–Lindquist and Kerr–Schild coordinates. I will also discuss the solution's behavior in the limiting case—the Schwarzschild solution.
This talk is based on four papers: Class. Quantum Grav. 39 225003 (2022); Phys. Rev. D 108, 024056 (2023); Acta Phys. Pol. B Proc. Suppl. 16, 6-A10 (2023); Class. Quantum Grav. 42 015004 (2024), co-authored by Patryk Mach, Eva Hackmann, Zuzanna Bakun, Angelika Łukanty and Anastasiia Untilova.

Precise Orbit Determination and Clock Bias Estimation of Galileo FOC satellites for Fundamental Physics Measurements within the Galileo for Science 2.0 Project

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Tuesday Session 3 - C9: Experimental gravitation

The Galileo for Science 2.0 (G4S_2.0) project is an Italian initiative funded by the Italian Space Agency (ASI), bringing together the Center for Space Geodesy (ASI-CGS) in Matera, the Istituto di Astrofisica e Planetologia Spaziali (INAF-IAPS) in Rome, and the Politecnico di Torino (POLITO). This collaboration aims to conduct Fundamental Physics measurements by leveraging the Galileo-FOC (Full Operational Capability) Constellation, particularly the two satellites in elliptical orbit (Doresa and Milena).
Beyond its primary focus, the project encompasses several ambitious goals: a novel measurement of gravitational redshift, evaluation of relativistic precessions, constraints on potential dark matter in our galaxy in the form of Domain Walls (DWs), exploration of a purely relativistic positioning system, development of advanced models for non-gravitational forces (e.g., Solar Radiation Pressure), and the design of an innovative accelerometer concept for next-generation Galileo satellites.
Critical to achieving these Fundamental Physics objectives is the highly accurate Precise Orbit Determination (POD) of Galileo satellites and precise estimation of their clock bias. Accurate POD enables the application of the so-called orbital residual method for estimating relativistic precessions —a technique previously implemented for geodetic satellites like LAGEOS. Additionally, analysing the atomic clock bias aboard these satellites yields two significant outcomes: measurement of gravitational redshift as a test of Local Position Invariance (LPI), and exploration of potential DWs of Galactic origin.
The ongoing activities conducted using the software packages considered by the project, GEODYN II (NASA/GSFC) and Bernese (AIUB) software, for POD and clock bias estimation will be presented.

Rapidly spinning dark matter-admixed neutron stars

Cipriani L[1,2], Giangrandi E[3,4], Sagun V[5], Doneva D[6], Yazadjiev S[7,8]
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Thursday Session 3 - B1: Relativistic astrophysics

Radio and X-ray observations provide measures of neutron stars mass and moment of inertia, that could be influenced by the accumulation of self-interacting dark matter. To study this possibility, we have extended the RNS code to simulate rotating neutron stars that include a dark matter component, at their mass-shedding limit. Dark matter is treated as a self-interacting bosonic fluid governed by a quartic repulsive potential, allowing for both core and halo configurations. Our simulations indicate that the resulting mass–radius relationships and moments of inertia remain similar to those of neutron stars composed solely of baryonic matter; effects due to the dark matter component may be misinterpreted as properties of the baryonic equation of state.

Resumming Post-Minkowskian and Post-Newtonian gravitational waveform expansions

Cipriani A[1]
[1]University Of Rome "Tor Vergata"

Friday Session 3 - D1 + D2 D+3

In this presentation we analyze the gravitational waveform emitted by a particle moving inside a Schwarzschild geometry. In perturbation theory, using tools developed in the realm of supersymmetric gauge theories, this waveform can be written as a double series expansion in z=2M/r and y=2iωr in the limit where distances are large with respect to the size of the horizon, (z<<1,PM approximation), but small with respect to the gravitational wavelength, (y<<1,PN approximation). The main result is the derivation of all order formulae for the two expansions of the waveform, where the dependence on y or z is completely resumed under the assumption that x=ωM <<1. This is possible thanks to a novel hypergeometric representation of the confluent Heun functions. Indeed the propagation of the emitted gravitational waves is described by the radial part of Teukolsky equation, which can be recast as a confluent Heun equation. Finally, in the case of circular orbits, we compute our formulae at order 30 PN and show an evident agreement with the solutions obtained via numerical integration and the MST method, improving the known results in literature for the luminosity of the system. Based on 2501.19257.

An Einstein@Home Survey for Gamma-ray Pulsars in the Inner Galaxy

Clark C[1]
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Wednesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

The Fermi Large Area Telescope (LAT) has revealed a mysterious extended excess of GeV gamma-ray emission around the Galactic Centre, which has been interpreted as possible evidence of dark matter particle annihilation. However, it can also potentially be explained by emission from an as-yet unresolved population of pulsars, particularly millisecond pulsars (MSPs), in the Galactic bulge. Recent models suggest that the brightest members of this putative population should now be individually detectable as point sources of gamma-ray emission. With the goal of identifying these brightest members, we used the Einstein@Home distributed volunteer computing system, and methods adapted from ontinuous gravitational wave searches, to search for gamma-ray pulsations from unidentified point sources in the inner Galaxy. I will present the four new pulsars discovered by this survey, including the closest known gamma-ray pulsar to the Galactic Centre (by angular separation), and one new isolated MSP. I will explain how our gamma-ray timing solutions for two of these pulsars enabled follow-up searches in public LIGO data for continuous gravitational waves that reach close to the spin-down limit. While the distances to these pulsars remain uncertain, we find it more likely that these are foreground sources from the Galactic disk than from the putative Galactic bulge population. I will explain that our results are not inconsistent with a pulsar origin for the Galactic Centre excess, and how future gamma-ray and radio pulsar surveys may soon provide sensitive tests of this hypothesis.

Simulation based inference for extreme mass ratio inspirals

Cole P[1]
[1]University Of Milan-bicocca

Friday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

Extreme mass ratio inspirals are a key target for next generation space-based gravitational wave detectors because they have a rich phenomenology that could offer new astrophysics and fundamental physics insights. However, their dynamics are complicated to model, and they will be buried amongst a large population of other sources in the milliHertz frequency band, with a background of non-stationary and non-Gaussian noise. Searching for these systems and measuring their parameters therefore presents a difficult challenge.
Simulation-based inference methods could offer solutions to some of these challenges. I will show parameter estimation results for extreme mass ratio inspiral systems achieved using sequential simulation-based inference. I will highlight the benefits of this approach with respect to traditional likelihood-based methods, and discuss the broader context in which such a pipeline will need to be embedded, including in the context of searching for new fundamental physics signatures.

Exploring the astrophysical origins of binary black holes using normalising flows

Colloms S[1], Berry C[1], Veitch J[1], Zevin M[2,3]
[1]University Of Glasgow, [2]Adler Planetarium, [3]Northwestern University

Thursday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The growing number of gravitational-wave detections from binary black holes enables increasingly precise measurements of their population properties. The observed population is most likely drawn from multiple formation channels. Population-synthesis simulations allow detailed modelling of each of these channels. Comparing population-synthesis models with the observations allows us to constrain the uncertain physics of binary black hole formation and evolution. However, the most detailed population-synthesis codes are highly computationally expensive. We demonstrate the use of normalising flows to emulate five different population synthesis models, reducing the computational expense, and allowing interpolation between the populations predicted for different simulation inputs. With the trained normalising flows, we measure the branching ratios of different formation channels and details of binary stellar evolution, using the current catalogue of gravitational-wave observations. Given our set of formation channel models, we infer the natal spin to be between 0.03 and 0.08, and the common-envelope efficiency to be >3.7 at 90% credibility, with the majority of underlying mergers coming from the common-envelope channel. Our framework allows us to measure population synthesis inputs where we do not have simulations and better constrain the astrophysics underlying current gravitational-wave populations.

Characteristic gluing in D-dimensional spacetimes with cosmological constant

Cong W[1], Chruściel P[1], Gray F[1]
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Monday Session 4 - A2: Classical GR: Mathematical developments

It is well known that the Einstein's equations admit a well-posed initial value formulation. However, the initial data is subjected to a set of constraint equations making it a non-trivial task to come up with permissible initial data. An interesting question is: given two sets of initial data, can one find a third which "glues" the two data together. The spacelike problem has been answered in the affirmative by Corvino and Schoen, specifically for the gluing of asymptotically flat data to Kerr data at large distances. In a series of recent papers, Aretakis, Czimek and Rodnianski considered the analogous problem for characteristic Cauchy data. I will discuss how characteristic gluing can be extended to higher spacetime dimensions and to spacetimes with non-zero cosmological constants.

Turbulence in Magnetised Neutron Stars

Cook W[1]
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Thursday Session 4 - B1: Relativistic astrophysics

The magnetic field configuration in the interior of Neutron Stars is an open problem and may be impacted by the influence of a turbulent cascade within the star. Assessing the impact of turbulent flow with numerical simulations requires incredibly high resolution as well as long lived simulations covering multiple Alfven times. We present a series of high resolution simulations of magnetised neutron stars lasting at their longest 1.2s, to assess this issue; the longest lasting and highest resolution such simulations to date. At the highest resolution we find evidence for a turbulent cascade absent in an unmagnetised star which cannot be captured with lower resolution simulations, consistent with a k^{-5/3} power law. The presence of turbulence triggers an inverse cascade of helicity, while at late times the net helicity appears to vanish, suggesting that a twisted-torus is not formed in the magnetic field. We find that the presence of the magnetic field excites a characteristic oscillation in the l=2, m=0, sector of the density profile of 145Hz, consistent with Alfvenic modes proposed as the source of quasi-periodic oscillations observed in magnetars.

The implications of stochastic gas torques for asymmetric binaries in the LISA band

Copparoni L[1,5], Speri L[2,4], Sberna L[3], Derdzinski A[6,7], Barausse E[1,5]
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Thursday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Gravitational waves from asymmetric mass-ratio black-hole binaries carry unique information about their astrophysical environment. For instance, the Laser Interferometer Space Antenna (LISA) could potentially measure the amplitude and slope of gas torques in binaries embedded in the accretion disks of Active Galactic Nuclei, helping differentiate competing accretion disk models. However, this relies on simplified analytic models, which do not account for the stochastic variability of torques seen in hydrodynamic simulations. In this work, we use hydrodynamic simulations to create gravitational waveforms for extreme and intermediate mass-ratio inspirals in the LISA band. We then analyze these simulated waveforms using simpler templates that assume analytic torques, without stochastic time variability. By performing realistic Bayesian parameter estimation, we find no bias at 90% confidence in the binary parameters; however, estimates of accretion disk parameters, such as torque amplitude and slope, may be biased. Typically, the posterior distribution is centered around the average value of the torques, but when stochastic variability is large, the posterior can indicate no torques, even though they are present in the simulation. Our results suggest that while simplified analytic torque models work well for estimating binary parameters, caution is needed when using them to infer properties of the accretion disk.

Reformulation of Einstein equations in the Fully Constrained Formulation: local uniqueness, post-Newtonian expansion and initial data

Cordero-Carrión I[1], Santos-Pérez S[1], Cerdá-Durán P[1]
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Wednesday Session 4 - B2: Numerical Relativity

Einstein equations can be written in the so-called Fully Constrained Formulation (FCF). This formulation has two different sectors: the elliptic sector, formed by the Hamiltonian and Momentum constraints together with the equations derived from the gauge choice; and the hyperbolic sector, formed by the evolution of the rest of the spacetime metric variables, which encodes the gravitational radiation. In this work, we present a modification of both sectors that keeps local uniqueness properties of the elliptic system of equations and includes a hierarchical post-Newtonian structure of all the elliptic and hyperbolic equations. This reformulation can have potential applications in cosmology and relativistic astrophysics. Moreover, we show how initial stationary data can be computed numerically using this formulation without assuming a conformally flat spatial metric, with the illustrative example of a rotating neutron star.

Nonlinear echoes from black holes in Einstein-Maxwell-scalar theory

Melis M[1,2], Corelli F[1,2], Croft R[1,2], Pani P[1,2]
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Friday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Gravitational wave echoes are studied especially for exotic compact objects, for which the (partially) reflective surface and the peak of the effective potential close to the photon sphere form a cavity-like structure where modes can be trapped.
Interestingly, it has recently been noticed that a similar phenomenon can also occur for black holes in the Einstein-Maxwell-scalar extension to General Relativity. Indeed, in a certain region of the parameter space, this theory admits additional hairy black hole solutions whose effective potential for scalar or gravitational perturbations features multiple maxima and minima, exhibiting cavities that are suitable for echo generation.
In this talk, I will present the results of a recent study in which we explored this scenario with multiple different approaches. In particular, by working in both the time and the frequency domains we observed the presence of echoes in the perturbative regime. Furthermore, by performing fully-fledged simulations of the collapse of scalar wave packets onto these black hole configurations in spherical symmetry, we have been able to show that echoes appear even in scenarios where the dynamics are in the nonlinear regime.
Reference: M. Melis, F. Corelli, R. Croft and P. Pani, arXiv:2412.14259 [gr-qc], accepted for publication in Phys. Rev. D

Signatures from metastable oppositely-charged black hole binaries in scalar Gauss-Bonnet gravity: Part II

Corman M[1], Lara G[1], Nee P[1], Pfeiffer H[1], Vu N[2]
[1]Max Planck Institute For Gravitational Physics, [2]California Institute of Technology

Wednesday Session 3 - A3: Alternative and modified theories of gravity

Gravitational wave observations of compact objects have provided new opportunities to test our understanding of gravity in the strong-field, highly dynamical regime. To perform model-dependent tests of General Relativity with these observations, as well as to guide theory-agnostic tests, it is crucial to develop inspiral-merger-ringdown waveforms in alternative theories of gravity. In this talk, we present an example of a type of binary system in an alternative theory of gravity that undergoes a sudden state transition during the inspiral. This gives rise to telltale signatures such as a change in the multipolar character of the scalar radiation and the introduction of eccentricity in the orbit.

Axisymmetric critical collapse with bamps

Cors D[1]
[1]University of Cambridge

Friday Session 3 - B2: Numerical Relativity

32 years after its discovery, critical phenomena in gravitational collapse has been found in many matter models in spherical symmetry. Nevertheless, a complete description of this type of phenomena near the threshold of collapse beyond spherical symmetry is still missing. Focusing on type II critical phenomena, we find that numerical evolutions of some initial data seem to lead to different scaling exponents, bifurcating horizons and only approximate discrete self-similarity. In this talk I will present results of axisymmetric critical collapse simulations performed with the pseudo-spectral code bamps, occurring in evolutions of gravitational waves in vacuum and of massless scalar fields. I will explain the tools required to perform these studies and how the results bring us a step closer to a description of threshold dynamics beyond spherical symmetry.

Plenary Talk - Alessandra Corsi

Corsi A

Thursday Session 2 - Plenary Talks

The direct detection of gravitational waves is transforming our view of the universe and has opened a new era in the field of time-domain multi-messenger astronomy. In this talk, I will summarize key open questions on the astrophysics of stellar-mass compact objects associated with multi-messenger transients. Then, I will describe the scientific reach and discovery potential of current and future ground-based gravitational-wave detectors, from LIGO-Virgo-KAGRA to next generation detectors such as Cosmic Explorer. I will emphasize synergies with present and future electromagnetic facilities, and conclude with a few highlights on prospects for extending multi-messenger studies to compact objects at the higher end the mass spectrum.

Reference frames in General Relativity and the galactic rotation curves

Costa F[1,2], Frutos-Alfaro F[3], Natário J[2], Soffel M[4]
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Thursday Session 3 - B1: Relativistic astrophysics

The physical interpretation of the exact solutions of the Einstein field equations is, in general, a challenging task, part of the difficulties lying in the significance of the coordinate system. I will discuss the extension of the International Astronomical Union (IAU) reference system to the exact theory, retaining the crucial property of being non-rotating with respect to asymptotic inertial frames. This is shown to be possible in spacetimes admitting non-shearing congruences of observers which, at infinity, have zero vorticity and acceleration. The construction is demonstrated in the FLRW, Kerr, and NUT spacetimes, and in the van Stockum rotating dust cylinder. It is finally used to refute the Balasin-Grumiller (BG) model, and the claims that it can explain the galactic rotation curves through gravitomagnetic effects without the need for Dark Matter. The BG model is shown to be actually static with respect to the asymptotic inertial frame, held in place by unphysical singularities which originate its gravitomagnetic effects, and the obtained rotation curves stem from an invalid choice of reference frame---the congruence of zero angular momentum observers, which are being dragged by the singularities. The same types of flaws affect other akin gravitomagnetic galactic models in the recent literature.

Can we identify primordial black holes? Analysis and physical implications of candidate subsolar gravitational-wave events

Crescimbeni F[1], Franciolini G[4], Pani P[1], Riotto A[2], Vaglio M[3]
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Thursday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

The detection of a subsolar object in a compact binary merger is regarded as one of the smoking gun signatures of a population of primordial black holes (PBHs). We critically assess whether these systems could be distinguished from stellar binaries, for example composed of white dwarfs or neutron stars, which could also populate the subsolar mass range. At variance with PBHs, the gravitationalwave signal from stellar binaries is affected by tidal effects, which dramatically grow for moderately compact stars as those expected in the subsolar range. We forecast the capability of constraining tidal effects of putative subsolar neutron star binaries with current and future LIGO-Virgo-KAGRA (LVK) sensitivities as well as next-generation experiments, such as Einstein Telescope. We show that, should LVK O4 run observe subsolar neutron-star mergers, it could measure the (large) tidal effects with high significance. Also, we show possible consequences of the detection of such important candidates, both from the cosmological and the nuclear-physics points of view.

The Search for Gravitational Echoes with Collisions of Einstein Maxwell Scalar Black Holes

Croft R[1,2], Corelli F[1,2], Melis M[1,2], Pani P[1,2]
[1]Sapienza, Universita di Roma, [2]Istituto Nazionale di Fisica Nucleare

Tuesday Session 4 - B2: Numerical Relativity

We will discuss the gravitational, scalar, and electromagnetic radiation emitted during head-on collisions of hairy black holes (BH) in Einstein-Maxwell scalar theory and characterise their remnant. Isolated BHs in this theory can exhibit gravitational echoes and their mergers could provide a unique probe of echo phenomenology in highly dynamic spacetimes. The aforementioned collisions are performed with a 2D-cartoon version of GRChombo, a modern numerical relativity code with fully adaptive mesh refinement.

Creation of a black hole bomb instability in an electromagnetic system

Cromb M[1], Braidotti M[2], Vinante A[3,4], Faccio D[2], Ulbricht H[1]
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Monday Session 4 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

The amplification and generation of electromagnetic radiation by a rotating metallic or lossy cylinder, first theorized by Zel'dovich in the 1970's, is tightly connected to the concepts of energy extraction from rotating black holes and runaway mechanisms such as black hole bombs. Recent advances include acoustic analogues of the Zel'dovich effect and the observation of a negative resistance in a low-frequency electromagnetic model. Here, we demonstrate experimentally that a mechanically rotating metallic cylinder not only definitively acts as an amplifier of a rotating electromagnetic field mode but also, when paired with a low-loss resonator, becomes unstable and acts as a generator of such a mode, seeded only by noise. The system exhibits an exponential runaway amplification of rotating electromagnetic modes thus demonstrating the electromagnetic analogue of Press and Teukolsky's 'black hole bomb'. The exponential amplification from noise supports theoretical investigations into black hole instabilities and is promising for the development of future experiments to observe quantum friction in the form of the Zel'dovich effect seeded by the quantum vacuum.

Numerical construction of asymptotically hyperboloidal perturbed Kerr initial data without logarithmic singularities

Csukás K[1]
[1]Wigner Rcp

Wednesday Session 4 - B2: Numerical Relativity

It is well known that the solutions of the constraint equations exhibit polyhomogeneous behavior near the future null infinity. The exact conditions restricting the solution space to initial data smooth on scri were developed by Andersson and Chrusciel for the conformal framework, and recently by Beyer and Ritchie for the parabolic-hyperbolic framework. We numerically construct perturbed Kerr initial data, extending the latter work to a wider class of solutions. Based on analytic arguments, we derive falloff conditions for various physically adequate quantities and show that the numerical data support these analytic rules. We also determine the Bondi mass by studying the asymptotic behavior of the Hawking mass.
Joint work with István Rácz. Based on the paper arXiv:2503.11804. Part of this work was supported by the Hungarian Scientific Research fund NKFIH Grant No. K-142423 and NSF CAREER Award PHY-2047382.

Gravitational memory: new results from post-Newtonian and self-force theory

Cunningham K[1], Kavanagh C[1], Pound A[2], Trestini D[2], Warburton N[1], Neef J[1]
[1]University College Dublin, [2]University of Southampton

Monday Session 4 - B3: Approximations, perturbation theory, and their applications

Gravitational memory is the name given to persistent effects caused by the passage of gravitational waves, in this case a permanent displacement.
I will present new displacement memory results calculated using gravitational self-force techniques, a double self-force/post-Newtonian expansion, and post-Newtonian theory and demonstrate their accuracy and agreement.
Comparisons to numerical relativity demonstrate that our second order self-force calculations are remarkably accurate for mass ratios up to 1:10.
I will briefly mention the importance of these calculations for future self-force work.

Phase-coherent gravitational-wave sky maps with the MeerKAT Pulsar Timing Array

Curylo M[1]
[1]Monash Universit

Monday Session 3 - C1: Pulsar timing arrays

Pulsar timing arrays, which probe nanohertz-frequency gravitational waves, have recently produced the very first evidence for the presence of a stochastic background. This background most likely originates from a superposition of inspiraling supermassive black hole binaries. However, more speculative sources such as cosmic strings and phase transitions cannot be ruled out. Mapping the gravitational-wave sky is one of the most promising methods to identify and characterise the source of the signal. In particular, any sign of anisotropy or hot spots would suggest the signal is a superposition of black hole binary signals. Initial studies, which map gravitational-wave power, suggest the signal is consistent with an isotropic background. In the talk, I describe a phase-coherent approach to gravitational-wave cartography in which one measures the plus and cross polarisation states of gravitational waves across the sky. I apply this framework to data from the MeerKAT Pulsar Timing Array and argue that the phase coherent approach creates lossless maps, which help us to discriminate between different types of signals.

Black hole quasinormal modes beyond General Relativity

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[1]University Of Nottingham

Friday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Black hole quasi-normal modes (QNMs) provide a powerful probe of deviations from General Relativity. We analyze the distinct contributions given by shifts in the QNM spectrum of Kerr black holes and by the presence of additional modes sourced by extra fields in a theory-agnostic framework. By exploring different regimes, we identify when each effect dominates and propose suitable ansätze for the corresponding waveforms. We provide an example of this phenomenon in the context of a recently derived effective field theory scheme for QNMs in shift-symmetric scalar-tensor theories with second order equations, showing how the QNM calculation can be drastically simplified.

Site identification and evaluation for Cosmic Explorer

Datrier L[1]
[1]California State University Fullerton

Monday Session 3 - C4: Concept and research towards next-generation detectors

Cosmic Explorer (CE) is a proposed US next generation terrestrial gravitational-wave observatory. CE is currently in its design phase, with plans to begin operations in the 2030s together with the Einstein Telescope (ET) in Europe. CE's conceptual design consists of two widely separated L-shaped interferometers, one with 20km arms and one with 40km arms, each based on technology proven by the highly successful Laser Interferometer Gravitational Wave Observatory (LIGO). This order of magnitude upscaling on the 4km LIGO design comes with unique challenges towards identifying suitable detector locations across the conterminous United States.
This talk will review some of the current efforts towards identifying suitable locations that could host the Cosmic Explorer observatories. Cosmic Explorer's approach to site evaluation integrates social, cultural and physical criteria. Here we present improvements to the Cosmic Explorer Location Search (CELS) code for minimising building costs incurred by the geology, geography and topography of the land. We also report on efforts to integrate astrophysical requirements established by the Cosmic Explorer Science Traceability Matrix into our site search.

A multi-parameter expansion for Extreme Mass Ratio Inspirals in astrophysical environments

Datta S[1]
[1]Gran Sasso Science Institute

Thursday Session 3 - B3: Approximations, perturbation theory, and their applications

Asymmetric binaries have attracted increasing attention as golden sources for probing the astrophysical environment in which they evolve. Black holes do not exist in isolation; they inhabit diverse environments where particles and fields, possible of unknown nature, interact with each others and with compact objects. For example, massive BHs are surrounded by accreting matter, dark matter halos, which may consist of exotic fields or beyond-standard-model candidates. Moving beyond vacuum general relativity presents significant challenges due to the lack of relativistic solutions describing BHs embedded in matter and the complexities introduced by metric-matter couplings. As a result, modeling environmental effects on extreme mass ratio inspirals often relies on post-Newtonian approaches, though fully relativistic descriptions remain key to confidently extract small deviation from vacuum predictions. I along with Prof. Andrea Maselli, develope a multi-parameter framework to describe environmental effects on BHs, where the surrounding matter is modeled as a fluid stress-energy tensor. We adopt a general anisotropic prescription, incorporating both radial and tangential pressure components. We compute axial and polar perturbations at first order in the mass ratio, induced by the secondary on the geometry of a non-rotating BH embedded in an environment. We discuss practical, ready-to-use expressions for computing gravitational and fluid perturbations, as well as the resulting GW emission, as functions of environmental parameters and the secondary's orbital motion.

Inflation in non-local hybrid metric-Palatini gravity

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Friday Session 4 - A3: Alternative and modified theories of gravity

Within the framework of hybrid metric-Palatini gravity, we incorporate nonlocalities introduced via the inverse of the d'Alembert operators acting on the scalar curvature. We analyze the dynamical structure of the theory and, adopting a scalar-tensor perspective, assess the stability conditions to ensure the absence of ghost instabilities. Focusing on a special class of well-defined hybrid actions – where local and non-local contributions are carried by distinct types of curvature – we investigate the feasibility of inflation within the resulting Einstein-frame multi-field scenario. We examine how the non-minimal kinetic couplings between the fields, reflecting the non-local structure of the original frame, influence the number of e-folds and the field trajectories. To clarify the physical interpretation of our results, we draw analogies with benchmark single-field inflation scenarios that include spectator fields

Gravitational wave oscillations in bimetric cosmology

de Cesare M[1,2]
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Friday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

Gravitational wave oscillations represent a distinctive signature of some gravitational theories beyond general relativity, notably bimetric gravity. In this theory, gravitational waves are generated as a superposition of massless and massive graviton states, which undergo mixing as they propagate through spacetime. This phenomenon, which displays some analogies to neutrino oscillations, is characteristic of theories with extra tensor modes and does not have an analogue in general relativity. In this talk, I will present analytical techniques to study the propagation of tensor modes in an expanding universe and extract accurate predictions for the redshift-dependent corrections to the amplitude and phase of the gravitational wave signal. In particular, our results allow for a detailed exploration of the phenomenology of gravitational waves in bimetric gravity in regions of parameter space where the theory is still viable.

Inferring population properties of Galactic compact binaries in LISA with Simulation Based Inference

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Friday Session 3 - C5: LISA and other space-based detectors

The LISA space mission, set to launch in the mid 30s, is expected to open a new window on the “gravitational wave universe”. Thanks to its exceptional sensitivity in the low frequency spectrum ~10^-4-10^-1 Hz, it will observe a variety of different sources all at the same time: from massive black hole binaries to extreme mass ratio inspirals or Galactic compact binaries. Among these, Galactic compact binaries of double white dwarves, emitting nearly monochromatic waves, are expected to be the dominant source in the mHz band. Of ~10^7 binaries in the Milky Way, a small fraction of tens to thousands will be actually resolvable by LISA. The unresolved ones are indeed expected to produce a foreground (“confusion”) stochastic noise which must be accounted for in the recovery of the other sources.
Recent works have shown that different astrophysical mechanism driving the binary evolution can affect the overall astrophysical population. In particular, different interacting binary populations can produce sensibly different foreground noises. However, the extraction of the astrophysics from confusion noise still remains a non-trivial challenge in the context of the Global Fit.
In this talk, I will describe an alternative approach to overcome this challenge based on Simulation Based Inference. By simulating several catalogue realizations from different astrophysical populations we train a Neural Posterior Estimator to map the simulated confusion noises to the parameters of the populations. Our model represents a first step towards the linking of astrophysical populations to the output of a Global Fit analysis.

On formal integrability of PDEs in general relativity

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Friday Session 3 - A2: Classical GR: Mathematical developments

Partial differential equations (PDEs) remain notoriously difficult to work with and, in many cases, are unsolvable. An alternative approach to studying PDEs, known as the formal theory of PDEs, treats PDEs as submanifolds of a specific vector bundle called the jet bundle. This perspective allows the extensive machinery of differential geometry to be applied to the analysis of PDEs.
Einstein's Equation, the cornerstone of General Relativity, is known to be formally integrable, a property that can be demonstrated using Spencer cohomology. In this work, I will provide a brief overview of this process and explore the advantages of formal integrability. Finally, I will discuss obstacles for setting up the Einstein-Vlasov equation in this framework.

Quantum anomalies and asymmetric particle creation in analogue systems.

Del Rio A[1]
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Monday Session 4 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

In quantum field theory in curved backgrounds, the vacuum expectation value of the Noether charge associated to classical chiral symmetries typically fails to be preserved in time. This is a consequence of a chiral anomaly in the quantum theory. The connection of this phenomenon to particle pair creation with net helicity is usually ignored or somewhat confusing in the literature, lacking some contributions. In this talk we will illustrate and clarify this connection for the chiral fermion anomaly in 1+1 dimensions [arXiv:2308.06330]. We will then describe similar ideas that relate the electric-magnetic duality anomaly in 3+1 dimensions, a chiral anomaly for spin 1 fields induced by a gravitational background [arXiv:1607.08879, arXiv:1810.08085, arXiv:2002.01593, arXiv:2106.08350], with photon pair asymmetric excitation in accelerated optical waveguides.

McFACTS: A population synthesis code for dynamic AGN mergers

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Friday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

After a decade since GW190514, we are still in the dark about how the binary black hole progenitors for LIGO/Virgo/KAGRA observations form. Past work has explored various isolated and dynamic formation channels by comparing the properties of observed binaries with simulated populations, in order to find statistical preferences and explanations for populations and individual events toward one formation channel or another. One of the tools for this analysis is rapid population synthesis, which enables us to sample star formation histories which inform isolated binary evolution models. We now present the open source population synthesis code McFACTS to provide a similar method for predicting populations of binaries forming dynamically around AGN. By running McFACTS on a realistic AGN population, we predict rates and properties from first-generation and hierarchical mergers through the AGN channel.

Timing gravity in the strong field

Della Monica R[1]
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Tuesday Session 3 - C9: Experimental gravitation

The centre of the Milky Way has been subject of an intense observational program over the past thirty years. This led to the discovery of a point source supermassive object named Sagittarius A* (Sgr A*) whose inferred mass is ~ 4 million solar masses. Thanks to the precise tracking of the motion of stars in its surroundings and the direct imaging of accreting matter in this region, we can now unambiguously identify this object as a supermassive black-hole (SMBH). A promising possibility to reach new experimental frontiers in black hole physics is the existence of detectable pulsars on tight relativistic orbits in the Galactic Center. While, up to date, no pulsar has been directly observed in orbit around Sgr A*, future observing facilities like the Square Kilometer Array (SKA) promise not only to reach this goal, but also to be able to perform timing analysis of such sources. In this talk I will show the recent progress in the modeling of pulsar timing in the Galactic Center and the avenues that the successful detection of a pulsar in this environment would open for unparalleled tests of gravity.

Quasi normal modes of gravitational atoms

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Monday Session 4 - C10: Experimental tests of the nature of compact objects

Ultra-light scalar fields have been proposed in various contexts, e.g. as dark matter candidates. A black hole embedded in a cloud of ultra-light scalar field can form a long-lived, meta-stable self-graviting configuration, known as scalar wig or gravitational atom.
These scalar field clouds could affect the gravitational wave signals emitted in binary black hole coalescences, in particular in the ringdown stage, in which the final black hole oscillates in a superposition of damped harmonic signals, whose complex frequency only depend on the nature of the remnant. Next-generation ground-based interferometers, such as the Einstein Telescope and Cosmic Explorer, may detect ringdown signals with sufficient precision to observe multiple modes, offering new insights into both the remnant's properties and its surrounding environment.
I this talk I will discuss how scalar wigs can affect the ringdown signal, and assess the detectability of these deviations by third generation ground-based interferometers like the Einstein Telescope of Cosmic Explorer

Agnostic analysis of correlations between tests of general relativity and astrophysics

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Monday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

A prominent category of tests of general relativity (GR) involves measuring specific parameters to account for potential deviations from GR predictions. In the so-called parametrized tests, for example, a theory-agnostic deviation parameter is added to the waveform model.
Whereas individual events can in principle lead to evidence of GR violation, such parameters are also studied at a population level - assuming a common distribution - but often not correlated to astrophysical parameters in these analyses.
In this talk, I will show how neglecting such correlations can hinder the detection of possible GR violations and, making use of a Bayesian non-parametric method, I will present a novel approach for simultaneously inferring the astrophysical distribution and deviation from GR parameters while accounting for potential correlations.

The Cosmological Constant and Trapped Surfaces

Demmie P[1]
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Monday Session 4 - A1: Classical GR: Theoretical developments

The cosmological constant is a model of dark energy that is one explanation for the accelerated expansion of the universe. The concept of a trapped surface provides a precise characterization of gravitational collapse that has proceeded beyond the point of no return, resulting in a black hole. Therefore, because their importance, we examined spherically symmetric spacetimes with a cosmological constant to determine its impact on the characteristic development of trapped surfaces. The principal result of this study is a relationship between the mass (m) and the cosmological constant (Λ) that is a necessary and sufficient condition for trapped surfaces to develop to the future of a branch of a perfect null hypersurface. For the cosmological constant obtained from the Planck-satellite data, there is a maximum mass for a black hole. We determined the value for the cosmological constant for a Planck-mass black hole and showed that it is 120 orders of magnitude larger than the cosmological constant obtained from the Planck-satellite data. Finally, we argue that that our universe is too massive to be closed and spatially bounded given the value of the cosmological constant obtained from the Planck-satellite data.

Binary black hole subpopulations revealed by model-free iterative reconstruction

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Thursday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The binary black hole systems identified by LIGO-Virgo observations - close to 100 catalogued prior to the O4 run and 200-odd new candidates during it - form a previously unsuspected astrophysical population. Efforts to explain their origin face many challenges: from the observation side alone low number statistics, high measurement uncertainties and selection biases must be accounted for. Recent advances in non-parametric inference endeavour to avoid further bias from oversimplified or incorrect modelling, but recovering correlations across the multi-dimensional space of binary properties is proving computationally demanding.
We present an alternative methodology to uncover correlations and sub-populations in the compact binary catalogue with minimal assumptions, using a computationally cheap KDE-based maximum likelihood framework. For binary black holes in GWTC-3 we find partly independent binary and secondary mass distributions, invalidating some commonly-made model assumptions, and a subpopulation with a broad, flat distribution of spins above primary mass ~35 Msun, suggesting a distinct formation channel. We also demonstrate the method using a set of simulated LISA IMBH light seed binary observations.

Continuous gravitational wave atlas.

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Wednesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

The latest atlas of continuous gravitational waves will be presented. Because continuous gravitational waves persist, it is possible to achieve sensitivity to gravitational strains far smaller than what is seen in short transient events, such as black hole and neutron star collisions. The comprehensive atlas includes measurements of upper limits, signal-to-noise ratios (SNRs), signal parameters of SNR peaks and novel polarization specific upper limits. Some of the results have been followed up, but the majority are unexplored.
The atlas data is conveniently provided in the MVL file format, designed for efficient analysis even on smaller computing devices, such as personal notebooks. There is also an MVL version of Gaia DR3 data, which can be used to explore Falcon atlas, or on its own.

Bias in astrophysical and cosmological inference due to inaccurate gravitational-wave models

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Monday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Gravitational-wave (GW) observations of binary black-hole (BBH) coalescences are expected to address outstanding questions in astrophysics, cosmology, and fundamental physics. Inference of BBH parameters relies on waveform models, and realizing the full discovery potential of upcoming LIGO-Virgo-KAGRA observing runs and new ground-based facilities (such as the Einstein Telescope and Cosmic Explorer) hinges on the accuracy of these waveform models. Using linear-signal approximation methods and Bayesian analysis, we assess our readiness for what lies ahead using two state-of-the-art quasi-circular, spin-precessing models: SEOBNRv5PHM and IMRPhenomXPHM. We ascertain that current waveforms can accurately recover the distribution of masses in the LVK astrophysical population but not spins. Upon exploring the broader parameter space of BHs, we find that systematic biases increase with detector-frame total mass, binary asymmetry, and spin-precession, with most such binaries incurring parameter biases, extending up to redshifts ~ 3 in future detectors. Moreover, highly asymmetric systems within the lower BH mass-gap exhibit biased measurements of the secondary-companion mass, which impacts the physics of both neutron stars and formation channels. Similarly, we deduce that the primary mass of massive binaries ($> 60M\odot$) will also be biased, affecting supernova physics. We employ a population diagnostic within the hierarchical inference framework to assess the accuracy of the population likelihood. Our findings reveal that a high-mass processing subpopulation as small as 5% of the GWTC-3 population can lead to identifiable systematic biases of the Hubble constant in the O5 network.

First eccentric search for spinning neutron star binaries in the third observing run of Advanced LIGO and Virgo

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Wednesday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

With almost 100 binary merger observations using publicly available gravitational waves (GWs) data, our understanding of the astrophysical population of compact binaries is improving, but the fundamental question of how compact binaries are formed and evolved remains elusive. The orbital eccentricity is a robust indicator of a binary's formation history – by the time GWs enter the sensitive band of current detectors isolated binaries have negligible eccentricity, whereas non-negligible eccentricity is expected in dynamical scenarios. Eccentric binaries are rare, and the search for these systems is both computationally expensive and limited by current waveform models. I will present the results for the first eccentric search for neutron star binaries in the data from the third observing run of Advanced LIGO and Virgo. I will then discuss our observational constraints on four different astrophysical models. Finally, I will present our predictions on eccentric observations by upcoming 2G and 3G observatories, and discuss the astrophysical implications of such observations.

Investigating All-sky Frequency Hough performances for neutron stars (isolated and in a binary system)

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Monday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

Between the population statistics for Neutron Stars (NSs) and the actual number present in the catalogs, there is a huge gap: O(10^8−9) vs O(10^3). Among the different search techniques for Continuous gravitational waves (CWs), the All-sky could help to reduce the discrepancy.
We have been working with the All-sky CW pipeline Frequency Hough (FH), where no parameter of the quadruplet (f, spindown, longitude, latitude) is known. This pipeline has been built with the purpose of detecting CW from isolated neutron stars, therefore correcting for the Earth's Doppler effect and Following-up the candidates according to a statistical parameter called Critical Ratio (CR): an imperfect Doppler correction translates into a lower CR. A question arose: how far can we go with the FH pipeline in the case of CW from an NS in a binary system (very far from coalescence)? We have been investigating this topic with O3 data and various combinations of orbital period and projection of the semi-major axis, i.e. (Porb, ap). In this scenario, the imperfect Earth's Doppler correction sums up with the Rømer effect of the binary system, changing the assumption on CR related to the positions: candidates with the strongest CR are not correctly representing the quadruplet of the signal.
Moreover, a preliminary implementation of Machine Learning (ML) technique(s) has been made, producing Houghmaps (HMs) (frequency, spindown) with the FH pipeline to distinguish between Signal/Noise and eventually Isolated/Binary thanks to the different shapes of the signal in the HMs.

The Galileo for Science (G4S_2.0) Project: Galileo GNSS Atomic Clocks and Fundamental Physics

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Tuesday Session 3 - C9: Experimental gravitation

Galileo for Science (G4S_2.0) is an ongoing project funded by the Italian Space Agency (ASI) and carried
out by the Istituto di Astrofisica e Planetologia Spaziali (IAPS/INAF) in Rome, the Politecnico di Torino (POLITO) in Turin and by the Center for Space Geodesy (ASI-CGS) in Matera. The project addresses two key challenges by utilizing the GNSS : conducting fundamental physics measurements and developing advanced technological tools.
Regarding the first challenge, the project focuses on: i) a novel measurement of the gravitational redshift to further constrain the Local Position Invariance (LPI), ii) investigating the possible presence of dark matter in the Milky Way in the form of scalar field domain walls, and iii) a precise measurement of the relativistic precessions of satellites in elliptical orbits to test the validity of the Newton's inverse-square law of gravity ($\sim 1/r2$) at the corresponding altitudes.
As for the second challenge, the project aims to: i) explore the feasibility of an (inverse) purely relativistic positioning system, and ii) develop an advanced accelerometer for the direct measurement of inertial accelerations acting on next-generation Galileo satellites.
In this talk, we will present an overview of the G4S_2.0 project and the fundamental activities conducted at IAPS-INAF in Rome on GNSS clock data. These data are crucial for optimizing gravitational redshift measurements and setting reliable constraints on domain wall dark matter. In particular, we will also discuss the preliminary results concerning the statistical properties of the Galileo Rubidium and Maser clock network and its potential to detect domain walls-signatures.

Einstein-Podolsky-Rosen quantum entanglement for future gravitational-wave detectors

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Friday Session 3 - C4: Concept and research towards next-generation detectors

Quantum Noise (QN) limits the sensitivity of terrestrial Gravitational Wave (GW) interferometers across all the frequency bandwidth (10Hz - 10kHz) [1]. Current detectors are designed to achieve broadband QN Reduction (QNR) via frequency-dependent squeezing (FDS) generated in reflection of a 300 m long detuned filter cavity (FC) that is coupled with a frequency-independent squeezing (FIS) source [2, 3, 4]. However, the infrastructure required for the FC is extensive, and this issue is particularly critical for the future generation of GW detectors such as the Einstein Telescope (ET) [5]. Looking ahead to the post-O5 era and third-generation detectors like ET, more compact, cheaper, and more flexible technologies for broadband QNR without the need for external filter cavities are desirable [5]. One promising technique involves using Einstein-Podolsky-Rosen (EPR) quantum entanglement [6]. To explore this, we are developing an experiment in Virgo's R&D squeezing laboratories to measure the effect of EPR-FDS in the audio band region of interest for terrestrial GW detectors [7]. This experiment involves 20 members from several Italian universities and related INFN groups (Roma1, Napoli, Perugia, Genova), and South Korean institutions like KASI, Kyung Hee University, and Yonsei University. This talk will overview the current status of the EPR project and highlight its future potential.

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Connecting Gravitational Waves and Neutrino Emissions in Core Collapse Supernovae: Insights from Empirical Mode Decomposition

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Tuesday Session 4 - C7: Multi-messenger astronomy of gravitational wave sources

Core Collapse Supernovae are some of the most energetic events in the Universe. Despite extensive efforts to understand the key factors driving these explosions, we still lack definitive evidence regarding the exact mechanisms behind them. Core collapse supernovae are predicted to generate gravitational waves due to the asymmetric motion of mass in the collapsing core, and simultaneously emit neutrinos from the interactions in their high-density surroundings. Both gravitational waves and neutrinos offer a unique way to investigate the inner workings of these processes. Among the various detectable signatures of core collapse supernovae, one in particular—Standing Accretion Shock Instabilities —connects gravitational wave emission with the outgoing neutrino flux. In this study, (Embedded) Empirical Mode Decomposition has been employed to analyse a set of GW time series derived from a selected sample of 3D numerical simulations. This method enables the identification of Standing Accretion Shock Instabilities contributions and their instantaneous frequencies.

Decoding Neutron Star Mergers: From Numerical Relativity to Multi-Messenger Inference

Dietrich T

Wednesday Session 2 - Prize Session

The interpretation of binary neutron star mergers, including gravitational waves and electromagnetic counterparts, relies on accurate theoretical models that can be consistently cross-correlated with observational data. For gravitational-wave signals, such models can be constructed by combining ab initio numerical-relativity simulations with analytical waveform approximations, enabling precise and computationally efficient predictions. Similar modelling strategies can be applied to electromagnetic signals, such as the kilonova and the GRB afterglow. By combining all these components, one can develop a coherent multi-messenger analysis framework that enables us to extract fundamental physics from observations -- placing tighter constraints on the equation of state of supranuclear dense matter, measuring the Hubble constant with higher precision, and quantifying the production of heavy elements in neutron star mergers.

Simulating and Interpreting the Multimessenger Picture of Neutron Star Mergers

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Wednesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

Neutron stars are among the most compact objects in the Universe, and their collisions rank among the most energetic events observed. The groundbreaking multimessenger detection of gravitational waves and electromagnetic signals from such events has revolutionized astronomy, providing profound insights into fundamental physics. The correct interpretation of multimessenger data, including gravitational waves and electromagnetic counterparts, requires accurate theoretical predictions that can be cross-correlated with observations. These models can be constructed by combining ab initio numerical-relativity simulations with derived analytical knowledge. Finally, an efficient Bayesian framework for multimessenger analysis is indispensable for extracting meaningful information from observational data. We will discuss how numerical-relativity simulations and multimessenger data analysis go hand in hand to provide valuable insights into neutron star mergers and fundamental physics principles.

Machine-Learning based classification of GRBs and implications for gravitational wave astronomy

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Tuesday Session 4 - C7: Multi-messenger astronomy of gravitational wave sources

We will discuss the classification of Gamma-Ray Bursts (GRBs) observed by Swift and Fermi detectors using machine learning (ML) algorithms UMAP in conjunction with Principal Component Analysis. Using the prompt emission light curves of GRBs in these two detectors, the ML algorithms identify five distinct classes of GRBs. We superimpose the information about those GRBs that are associated with supernovae (SNe) and kilonovae (KNe) on this classification. We find the KNe-associated GRBs lie in two distinct clusters potentially indicating two different progenitors for them. Hypothesizing these two populations are binary neutron star (BNS) and neutron star–black hole (NS-BH) mergers, we compare the rate of these GRBs with gravitational wave estimates of BNS and NSBH mergers, after correcting for beaming and other selection effects. This further allows us to place limits on the GRB-bright NS-BH mergers to be 1.3–63% for Fermi and 0.4%-15% for Swift. As we start detecting more multimessenger NS binary mergers, ML-based GRB tools can play a pivotal role in shaping our understanding of GRB progenitors and classes.

Probing Star Formation and Compact Binary Origins with Future Gravitational Wave Networks

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Wednesday Session 4 - C4: Concept and research towards next-generation detectors

Current gravitational wave (GW) detectors are observing hundreds of binaries in the low-redshift universe, but to fully understand formation mechanisms we must probe the high-redshift regime. Next-generation detectors, such as Cosmic Explorer and Einstein Telescope, will allow us access to redshifts greater than 20, and even upgrades to existing detectors may allow us to probe the star-formation peak. In this work, we explore the capabilities of next generation observatories, and upgrades of existing GW detectors such as A#, to map the black hole and neutron star population of the Universe. In particular, we investigate the ability of different networks to accurately characterize the star formation peak at redshift 1-3. We focus on measurement of the merger rate for different populations of black holes and neutron stars and the possibility of using this information to distinguish formation scenarios.

Probing the gravitational wave source population via orphan afterglows

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Tuesday Session 4 - C7: Multi-messenger astronomy of gravitational wave sources

The discovery of the first neutron star merger, GW170817, heralded the dawn of a new era in time domain astronomy. GW170817 answered many questions, but raised even more – for example, what is the underlying relation between neutron star mergers and gamma-ray bursts? How much energy do mergers release? Do they all launch jets, and how beamed are the jets? Comprehensively answering these questions will require follow-up of a population of gravitational wave detections but nearly a decade later we are yet to discover a second electromagnetic counterpart.
In the absence of GW-detected mergers with which to answer these questions, studying gamma-ray bursts (GRBs) is a natural alternative but comes with an enormous selection bias - the gamma-ray emission from GRBs is tightly collimated and in order to detect one it must be beamed towards Earth. However, the synchrotron afterglows produced by GRBs are quasi-isotropic and hence there should be a large population of “orphan afterglows”, i.e. GRBs that are inclined away from Earth.Orphan afterglows can reveal vital information about the gravitational wave source population - e.g. the beaming fraction can be used to measure the total energy released and the overall burst rate. However, discovering them requires sensitive large-area surveys and hence finding them has only recently become feasible. In this talk I will present the results of recent searches for orphan afterglows, expectations for the next generation of astronomical facilities (Rubin Observatory and the Square Kilometre Array) and their broader implications for gravitational wave astrophysics.

Laser welding of crystalline sapphire for use in next generation gravitational wave detector suspensions

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Wednesday Session 3 - C4: Concept and research towards next-generation detectors

With many next-generation gravitational wave detectors planning to implement crystalline materials as replacements for fused silica, there is an increasing need for novel techniques in suspension jointing. In current aLIGO systems, fused silica fibres are laser welded to the test mass ears, achieving low thermal noise joints. This work will report on the development and characterisation of a laser welding technique for crystalline sapphire. Utilising a CO_2 laser within a crystal growth machine, specifically designed for laser-heated pedestal growth, we have established a repeatable method for laser welding sapphire rods of varying millimetre diameters. Experimental characterisation of tensile strength, crystallography, and cryogenic measurements of thermal conductivity and mechanical loss revealed promising results that support the feasibility of this technique. Additionally, we demonstrated a laser polishing method that greatly enhanced tensile strengths to over 1 GPa with no observed failure in the welded joint. These initial findings indicate significant potential for sapphire laser welding as a viable concept in next-generation cryogenic detector suspensions and provide strong justification for further development of this jointing method.

Post-Newtonian Tidal Effects in the Gravitational Waveform from Binary Inspirals in Scalar-Tensor Theories

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Tuesday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

In this talk, we investigate tidal effects on gravitational waveforms emitted by compact binary inspirals within scalar-tensor theories of gravity. While general relativity has been the standard framework for waveform modeling, the expected precision of next-generation detectors requires waveform templates that account for potential deviations from general relativity. In particular, observations of neutron star binaries present a significant challenge: distinguishing between tidal effects arising from neutron star matter and those due to modifications of gravity.
We focus on generalized Brans-Dicke theories, which extend general relativity by introducing a massless scalar field minimally coupled to the metric. These theories allow for a natural extension of the post-Newtonian formalism to predict modified dynamics and possibly observable imprints on the emitted gravitational waves. In this context, a neutron star experiences tidal deformations induced both by its companion and by the scalar field.
Assuming that the star remains in a state of equilibrium at each instant, we derive the tidal corrections to the system's Lagrangian, equations of motion, and conserved quantities up to second post-Newtonian order. Using the post-Newtonian multipolar post-Minkowskian formalism, we compute corrections to both scalar and gravitational energy fluxes, as well as to the waveform's phase and amplitude modes, at the same level of accuracy.
Our results show that tidal effects in scalar-tensor theories induce phase shifts, especially in the late inspiral phase. These effects might be detectable with upcoming gravitational wave observations, particularly with the Einstein Telescope, and provide valuable tools for precision tests of gravity.

Targeted search for continuous gravitational waves from known pulsars using O4 LVK data

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Monday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

In this talk, I present the latest results on behalf of the LIGO-Virgo-KAGRA (LVK) Collaboration describing the targeted search for CWs from 45 known pulsars using data from the first part of the fourth LVK observing run (O4a). Three independent analysis methods were applied, considering both single-harmonic and dual-harmonic emission models. No CW signals were detected, and upper limits were set on the signal amplitude and neutron star ellipticity. The tightest ellipticity constraint, 8.8e−9, is obtained for J0437-4715. These results improve our constraints on neutron star properties and gravitational wave emission mechanisms. In this talk, I will also describe the status of the targeted searches considering the full O4 run.

Prospects for an EMRI + precessing disk framework for QPE timings: Constraining astrophysics and optimizing observing strategies

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Wednesday Session 4 - C7: Multi-messenger astronomy of gravitational wave sources

Quasi-Periodic Eruptions (QPEs) are luminous, periodic X-ray outbursts observed from the nuclei of nearby galaxies, with timescales ranging from hours to weeks. While their origin remains under debate, leading models invoke either accretion disk instabilities or the interaction of a supermassive black hole (SMBH) with a lower-mass secondary object in an extreme mass ratio inspiral (EMRI). EMRI-based scenarios provide an increasingly promising framework for interpreting QPEs. EMRI models offer a robust framework for characterizing observational signatures associated with the secondary's orbital dynamics, facilitating the extraction of the SMBH's physical properties. In this study, we employ a precessing disk model and analytic expressions for Kerr geodesics to efficiently resolve the trajectory of the secondary object. Using these tools, we explore observing strategies that optimize the extraction of astrophysical parameters, such as the orbital characteristics of the secondary, the spin of the SMBH, and its mass. Our analysis demonstrates how long-term monitoring campaigns and tailored observational cadences can improve constraints on key system parameters, enabling a deeper understanding of the dynamics driving QPEs. This work highlights the promise of QPE observations as probes of galactic nuclei, revealing insights into SMBH properties and uncovering potential EMRI sources for the LISA mission.

Wet Eccentric Extreme-Mass-Ratio Inspirals

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Monday Session 3 - B1: Relativistic astrophysics

In this talk, we will discuss the evolution of eccentric, equatorial extreme-mass-ratio inspirals (EMRIs) immersed in the accretion disks of active galactic nuclei. We will see how single gravitational-wave observations from these systems could provide measurements with ~ 10% relative precision of, simultaneously, the disk viscosity and mass accretion rate of the central supermassive black hole. This is possible when the EMRI transitions, within the observation time, from supersonic to subsonic motion relative to the disk gas, for eccentricities e >~ 0.025-0.1. The estimate of the accretion rate would assist in the identification of the EMRI's host galaxy, or the observation of a direct electromagnetic counterpart, improving the chances of using these sources as cosmological sirens, highlighting the rich phenomenology of binary evolution in astrophysical environments and the need to improve the modelling and analysis of these systems for future gravitational-wave astronomy.

Tracking Topology in Dynamical Triangulations: Toy Models in 1+1 and 2+1.

Duston C[1]
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Tuesday Session 4 - D3: Causal sets, causal dynamical triangulations, non-commutative geometry, asymptotic safety, and other approaches to quantum gravity

We will present an approach to track topology change in dynamical triangulations, using a decorated graph in a sphere. The decorated graph will be used as a branch locus to track the topology in a covering space representing the spatial section. Identifying such a branch locus as part of the existing triangulation amounts to simply adding a label to it. Standard techniques from dynamical triangulations would then apply, but with the ability to study topology change. This specific work will elucidate the approach by constructing toy models in 1+1 and 2+1 dimensions, highlighting some of the choices that need to be made to create such models, particularly the effect of the Pachner moves on the resulting topology. We will present the resulting actions, discuss what you can learn about topology in these toy models, and briefly discuss some initial results for a 3-dimensional spatial section.

Novel Approaches to Black Hole Ringdown Fits

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Thursday Session 4 - C10: Experimental tests of the nature of compact objects

Following a merger, a perturbed black hole relaxes into its final Kerr state, in part by radiating quasinormal modes (QNMs) — oscillations at specific complex frequencies with angular structures dictated by black hole perturbation theory. QNMs are widely used in waveform modelling and underpin key tests of general relativity and the nature of compact objects. While routinely identified in numerical relativity waveforms, challenges remain, including selecting the appropriate set of QNMs to avoid overfitting and accurately determining the ringdown start time. In this talk, I will introduce novel techniques for detecting and analysing QNMs. These include a Bayesian approach to QNM fitting, offering a robust alternative to the conventional least-squares method, and spatial mapping—part of a program we call black-hole cartography—to extract the angular structure of modes. In both cases, I will present results obtained using the latest high-fidelity Cauchy characteristic extraction (CCE) simulations from the SXS collaboration and discuss how these methods provide insight into the role of overtones and nonlinear effects, both of which will be important for future gravitational wave observations.

Environmental effects in extreme mass ratio inspirals: perturbations to the environment in Kerr

Dyson C[1], Spieksma T[1], Brito R[2], van de Meent M[1,3], Dolan S[4]
[1]Niels Bohr Institute, [2]Instituto Superior Técnico, [3]Albert Einstein Institute , [4]University of Sheffield

Thursday Session 3 - B3: Approximations, perturbation theory, and their applications

Future gravitational wave observatories open a unique avenue to study the environments surrounding black holes. Intermediate or extreme mass ratio inspirals will spend thousands to millions of cycles in the sensitivity range of detectors, allowing subtle environmental effects to accumulate in the gravitational waveform. Working in Lorenz gauge and considering equatorial circular orbits, I will present recent results where we calculate the fully relativistic perturbation of a black hole environment due to an inspiraling secondary in the Kerr geometry. I will focus on the calculation wherein the environment is that of a superradiantly grown scalar cloud, though our framework is generalizable to other scenarios.

Nonlinear corrections to black hole ringdown

East W[1]
[1]Perimeter Institute

Tuesday Session 3 - B2: Numerical Relativity

As a black hole formed from a merger or other process settles down to a stationary state, it emits a ringdown gravitational wave signal. This can be cleanly interpreted as a measurement of the properties of the final black hole, as well as a test of general relativity, provided one understands the potential impact of nonlinearities. In this talk, I will introduce methods for studying nonlinear ringdown based on starting from a black hole perturbed by linear quasinormal modes, but numerically solving the fully equations of general relativity to include all nonlinear corrections as a function of the amplitude. I will describe the application of these methods to identify and quantify corrections that are quadratic, cubic, and higher order in the amplitude of a least damped quasinormal mode of a spinning black hole.

On the uncertainty in modeling the astrophysical GW background

Ebersold M[1]
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Tuesday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The astrophysical gravitational wave background (AGWB), formed by the superposition of unresolved signals from numerous compact binaries throughout the universe, is expected to become detectable in the near future. Such a detection will offer profound insights into the population of compact objects over cosmic time.
I will discuss the various uncertainties in modeling the AGWB, including factors like the mass and spin distribution of the underlying compact binary population as well as the evolution of the merger rates. Additionally, potential conclusions that can be drawn about the compact binary population from an eventual detection are explored, highlighting the importance of stochastic background searches alongside transient GW searches.

Constructing new wormhole solutions in generalized geometry-matter coupling gravity using Einstein clusters as fluid-like dark matter models

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Thursday Session 4 - A3: Alternative and modified theories of gravity

This investigation centers on the concept of traversable wormholes within the framework of $f(R, L_m, T)$ gravity, a theory that enhances traditional gravitational concepts by incorporating the matter Lagrangian and the trace of the energy-momentum tensor. We represent this modification as: $ f(R, L_m, T) = R + \lambda L_m + \chi T$, where λ and χ are coupling constants. By focusing on the matter Lagrangian defined as $L_m = -\rho$, with ρ indicating energy density, and employing a constant redshift function $\hat{\nu}(r)$, we analyze the properties and gravitational lensing effects associated with Einstein clusters. These clusters, formed by weakly interacting massive particles that serve as dark matter halos, demonstrate a dominance of tangential pressure. This is described by an equation of state in which the tangential pressure P_t is proportional to the energy density ρ (i.e., $P_t = \sigma \rho$, where σ is a constant), enabling adjustments in anisotropy to effectively model galactic rotation curves. We derive the shape function influenced by these Einstein clusters and investigate how the null energy condition affects matter distribution within anisotropic fluids. The stability of the resulting wormhole solutions is confirmed through the Tolman-Oppenheimer-Volkoff formalism. Our exploration of photon deflection along null geodesics reveals that for σ values in the range $[0, 0.25]$, the deflection angle is negative, causing photons to bend outward. In contrast, for σ values between $[-0.25, 0]$, the angles are positive, indicating that light rays curve inward toward the wormhole throat.

Testing gravity's attraction on quantum vacuum: the state of art of ARCHIMEDES experiment.

Errico L[1,2]
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Monday Session 3 - C9: Experimental gravitation, July 14, 2025

According to the paradigm of General Relativity (GR), gravitational attraction is a geometric phenomenon of spacetime experienced by both massive bodies and massless fields, such as the electromagnetic field. As a consequence of such deep change of perspective, the concept of “weight” must also be reformulated, because this physical quantity turns out to depend not only on the amount of matter but also on internal energy. Since GR is a classical theory, the effect of attraction on classical fields is considered plausible; on the other hand, it is not obvious to imagine this phenomenon on quantum fields, due to divergences in the calculation of vacuum energy. Such divergences cannot be physical and the regularizations proposed in literature cannot be accepted, because the vacuum energy density would be so high as to have consequences on a cosmological scale that have not been observed.
The ARCHIMEDES experiment (INFN - CSN2) aims to measure the weight change of a superconducting BSCCO crystal while an internal vacuum energy variation is induced by the phase transition. The expected weight variation is so small (0.5 fN) that a high-precision opto-mechanical balance had to be built ad hoc at the future SUN Laboratory (Lula, NU), Sardinia being one of the places with the lowest seismic noise in Europe. The state of art of the experiment will be presented with the latest results about the sensitivity of the apparatus.

Simulations of Ellipsoidal PBH Formation and the impact of Non-Spherical effects on the PBH mass function

Escrivà A[1]
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Wednesday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

Numerical simulations have been instrumental in advancing our understanding of Primordial Black Hole (PBH) formation and in providing precise estimates of their abundance in the Universe. Traditionally, these simulations have assumed spherical collapse, but indeed, the most realistic initial configuration is an ellipsoid. In this presentation, I will discuss recent findings on non-spherical PBH formation, focusing on its dynamics and the effect of non-sphericities on the threshold of formation. Our results indicate, for the cases tested, that non-spherical effects are crucial when the fluctuation amplitude is near the collapse threshold (critical regime), preventing a significant number of configurations from forming black holes. However, when considering these effects in the statistical estimation of the PBH mass function, their overall impact is minimal.

Renormalized stress-energy tensor of an electromagnetic field in the Kerr spacetime

Ester E[1], van de Meent M[1]
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Tuesday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

It is a fundamental problem of Quantum Field Theory in curved spacetime to find an expression for the expectation value of the stress tensor for quantized matter fields in a curved background. This is an obstacle one faces before considering the backreaction of Hawking radiation on a black hole geometry. Backreaction effects are significant even before a black hole reaches the Planck scale, when a yet to be formulated quantum gravity theory is expected to control the process. Black holes radiate thermally all types of existing particles, however it is expected that most of the Hawking radiation emitted is in the form of massless fields. We therefore consider the vacuum expectation value of the only confirmed massless free field in the Standard Model, the photon. We employ Levi and Ori's pragmatic mode-sum regularization method to numerically implement point-splitting regularization of the divergences in the stress-energy tensor. Pragmatic mode-sum regularization can be applied to any background metric, provided it displays an isometry. We apply it to a Kerr background, exploiting its time-translation symmetry. The challenge in Kerr spacetime is the non-separability of the Maxwell equations, therefore we solve the spin-1 Teukolsky equation and reconstruct the electromagnetic field from its solution. We conclude by evaluating the expectation value in different vacuum states, e.g. Boulware, Unruh (physically representing BH evaporation).

Gravitational-wave signatures of boson stars mergers: using numerical relativity simulations to inform current and future gravitational-wave observations

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Friday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Gravitational-wave signals detected to date are commonly interpreted under the assumptions that they originate from pairs of black holes or neutron stars. However, many alternative proposals of exotic compact objects (ECOs) have been put forward to challenge this paradigm. In this talk, we focus on a specific class of ECOs -- boson stars -- and present the latest numerical relativity results of binary boson star coalescences, highlighting their key gravitational-wave signatures. We discuss whether their gravitational-wave signals may be detected and differentiated from signals originating from binary black holes and neutron stars.

Pseudospectral implementation of the Einstein-Maxwell system with Boundary Stability

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Friday Session 3 - B2: Numerical Relativity

We are interested in studying the Einstein-Maxwell system, both to investigate the physics of fundamental fields, as well as a proxy for general gravity-matter interaction. To that end, here I present a boundary-stable formulation of the system as an initial-boundary-value problem, and its implementation in the pseudospectral numerical relativity code BAMPS. Our formulation and discretization choices are aimed at obtaining the best possible accuracy to cost ratio. Finally, I present a suite of numerical tests of the implementation, focusing on convergence, and the code's ability to reproduce well-known physics, e.g. black hole quasinormal modes.

What Comes Next in Gravitational Wave Cosmology

Ezquiaga J

Wednesday Session 2 - Prize Session

Every time that we have looked further into the Universe, we have found fascinating surprises. Most notably, we observe that an omnipresent dark energy drives the Universe to expand ever faster, and that its large-scale structures hold together only because of an invisible dark matter. Yet, we do not fully understand how cosmic structures form, or whether our laws of gravity are valid at all scales. Gravitational waves – ripples in space and time produced by extreme gravitational systems such as binary black holes – offer a unique opportunity to answer these fundamental open questions. In this talk, I will argue that the next frontier in gravitational wave cosmology is gravitational lensing. In particular, I will discuss how lensed gravitational waves can test the uncharted wave optics regime, probe dark matter substructures, and shed light on the origin of the observed binary black holes.

LISA’s Potential to Test the Kerr Hypothesis: Symmetry-Breaking Effects in Extreme-Mass-Ratio Inspirals

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Monday Session 3 - C10: Experimental tests of the nature of compact objects

Extreme-Mass-Ratio Inspirals (EMRIs) are one of the main sources of gravitational waves in the low-frequency band, where space-based detectors like LISA will operate. These systems consist of a stellar-mass compact object (sCO), known as the secondary object—typically a neutron star or a stellar-mass black hole— orbiting a massive black hole (MBH), the primary, in an evolutionary phase dominated by gravitational-wave emission. Due to their high precision as gravitational-wave sources, EMRIs provide a powerful framework in which to perform fundamental physics studies, such as probing the nature of the primary object and checking whether it corresponds to a Kerr black hole or a more exotic compact object.
In this work, we take advantage of the rich multipolar structure of self-gravitating bodies beyond the constraints imposed by General Relativity for black holes. We analyze the impact of gravitational radiation on generic orbits around a primary object modified by an arbitrary mass quadrupole and its non-axisymmetric component, as well as a mass octupole and its non-axisymmetric component, at leading post-Newtonian order and linear order in the mass ratio.
For this study, we use the Analytic Kludge waveform model and perform parameter estimation via Fisher analysis for our extended parameter space. We evaluate how accurately LISA will constrain the non-axisymmetric mass quadrupole and octupole moments, providing insights into the detector’s ability to detect symmetry-breaking effects. This analysis will shed light on LISA’s potential to probe deviations from the Kerr hypothesis.

Modeling coupled constellation dynamics and validating payload architecture & pointing control strategies for TianQin

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Monday Session 3 - C5: LISA and other space-based detectors

TianQin is a proposed mission for space-based gravitational-wave detection that features a triangular constellation in circular high Earth orbits. The mission entails three drag-free controlled satellites and long-range laser interferometry with stringent beam pointing requirements at remote satellites. For the payload architecture and pointing control strategies, having two test masses per satellite, one for each laser arm, and rotating entire opto-mechanical assemblies for constellation breathing angle compensation represent an important option for TianQin. Besides, the suspension and drag-free control keep the two test masses centered and aligned within their housings while maintaining drag-free conditions along the laser-arm directions. This results in orbit-attitude coupled dynamics for the constellation, which are further accentuated by satellite self-gravity. We develop a detailed model to thoroughly analyze these dynamics model, which can propagate the full 15-body dynamics inter-dependently under the inter-satellite pointing and drag-free conditions. This presentation is threefold. First, based on the coupling relationship, the required electrostatic forces and torques for the test mass suspension control are estimated and found to be sufficiently small for the acceleration noise budget. Second, to meet the constellation stability requirements, it is found that the DC common self-gravity in the flight direction should be minimized, or kept close for the three satellites. Third, the required control forces and torques on the satellites are calculated, and thrust allocation solutions are found under the constraint of having a flat-top sunshield on the satellite with varying solar angles.

Plenary Talk - Amanda Farah

Farah A

Monday Session 2 – Plenary Talks

The rapidly-expanding catalog of gravitational wave signals is steadily honing our understanding of the neutron stars and black holes from which they are sourced. In turn, this population of compact objects can help answer pressing questions in astronomy such as the metal content of the high-redshift Universe, properties of star clusters, the supernova mechanism, interactions within massive binary star systems, and the expansion history of our Universe. In this talk, I will give a broad overview of the population of compact object binaries as inferred from the current gravitational wave data, highlighting several open questions brought about by the discovery of features in this population. I will additionally present the astrophysical implications of the distributions of compact object masses, spins, and redshifts and comment on areas that will be improved by imminent gravitational-wave catalogs. Finally, I will present the latest results from the LVK and discuss how they relate to our understanding of the compact binary population.

Eccentricity and GR tests

Favata M[1], Saini P[2], Bhat S[3], Arun K[4], Gandevikar C[5], Mishra C[5]
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Tuesday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

Gravitational wave (GW) observations over the past decade have opened up new avenues for testing general relativity (GR). In the next decade (or two), third generation ground and space-based detectors will allow for higher precision GR tests. Most current GR tests presume that binary orbits are circularized. But we expect that 3G detectors will find nonnegligible numbers of binaries with measurable eccentricity. If these systems are analyzed with circular waveform families, eccentricity can easily bias these GR tests, falsely indicating a GR violation. I will summarize several recent works where we quantified this eccentricity-induced bias. This is considered in the context of post-Newtonian (PN) parametrized tests of GR and the inspiral/merger/ringdown consistency test. I will also discuss efforts to develop parametrized null tests of GR that directly incorporate binary eccentricity. One approach extends the standard parametrized test of GR by adding additional deviation parameters to the eccentric part of the GW phasing. Another approach involves modifying the periastron advance rate. We explore the bounds that can be set on the resulting deviation parameters for a range of detectors and systems.

Radiation reaction effects in the dynamics of compact binaries at the fourth and a half post-Newtonian order

Blanchet L[1], Faye G[1], Trestini D[2]
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Thursday Session 4 - B3: Approximations, perturbation theory, and their applications

Compact binaries constitute the main sources for the first generations of gravitational-wave detectors. To extract physical information from the ensuing signal, one must model the theoretical waveforms to very high accuracy, typically beyond the third post-Newtonian (PN) order of general relativity. In this context, we investigate the radiation-reaction effects affecting the companion dynamics at the 4.5PN order, using an appropriate extension of the Burke-Thorne coordinate system. This allows us to proof explicitly the validity of the PN balance equations for the ten integrals of motion, at the 2PN approximation. We point out that the relative acceleration as given in the centre-of-mass frame contains non-local-in-time contributions, which have been overlooked in the past literature.

TiO2:GeO2 optical coatings: progress and challenges towards improving the sensitivity of ground-based detectors

Fazio M[1], Gier C[1], Ben-Yaala M[1], Armstrong S[1], Reid S[1]
[1]University Of Strathclyde

Tuesday Session 4 - C3: Progress and challenges in advanced ground-based detectors

Upgrades to ground-based gravitational-wave observatories will require mirror coatings with reduced thermal noise, enabling improved detector sensitivity and extended astrophysical reach.
The high refractive index material chosen for A+ LIGO, germanium dioxide mixed with titanium dioxide (TiO2:GeO2), shows lower mechanical loss than the current material in Advanced LIGO. We report on multilayer optical coatings fabricated using TiO2:GeO2 and silicon dioxide (SiO2) for the low index material. Coatings were grown by ion beam deposition (IBD) at the Extreme Performance Optical Coatings laboratory. Optical absorption at 1064 nm below 1 part-per-million (ppm) is observed in the multilayer stacks after heat treatment. Depending on the base pressure of the process, the formation of blisters induced during the annealing process can be suppressed. We also report on the evolution of the structure and optical properties of TiO2:GeO2 coatings as a function of the annealing temperature. Understanding this material is key to reaching the design sensitivity of future ground-based gravitational-wave detectors.

Singularity at the demise of a black hole

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Thursday Session 4 - A3: Alternative and modified theories of gravity

In this talk, I consider the conformal diagram for a 1+1 evaporating black hole in a "baby universe" scenario and argue that the "pinch off" point is a kind of quasiregular singularity characterized by points possessing two future-directed light cones and two past-directed light cones (in fact this spacetime is conformal to a region of the 1+1 trousers spacetime). I then discuss a Euclidean signature shift-symmetric scalar-tensor theory from which one can extract a Lorentzian structure, and show how this theory can provide a microscopic description for the aforementioned singularities. I discuss some recent developments indicating that this theory contains a tensor degree of freedom that propagates with a Lorentzian dispersion relation.

The canonical ensemble of a self-gravitating matter thin shell in asymptotically AdS space

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Wednesday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

The canonical ensemble of a matter thin shell in asymptotically AdS is constructed using the Euclidean path integral approach. By imposing spherical symmetry and the Hamiltonian constraint, we obtain the reduced action, which can be regarded as a generalized free energy. We then perform the zero loop approximation by minimizing the reduced action. We obtain the equations of stationarity and stability in general, showing that full stability is guaranteed if the gravitational radius increases as temperature increases and if the shell is mechanically stable. We use a specific equation of state for the shell and find four solutions for the shell, with one solution being stable. We obtain the thermodynamic quantities of the ensemble. The ensemble is thermodynamically stable if the heat capacity is positive, while the mechanical stability cannot be described by thermodynamic variables of the system. We compare the stable shell solution with the stable black hole solution of Hawking and Page in the context of phase transitions. The favorable solution is found for fixed temperatures by analyzing which solution has the lowest free energy. The analysis shows that the phase transition involving the shell mimics the Hawking-Page phase transition.

Inferring astrophysics and cosmology with individual compact binary coalescences and their gravitational-wave stochastic background

Ferraiuolo S[1,2,3], Mastrogiovanni S[2,3], Escoffier S[1], Kajfasz E[1]
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Thursday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

Gravitational waves (GWs) from compact binary coalescences (CBCs) offer a novel method to probe cosmic expansion, particularly the Hubble constant H0. A key technique in GW cosmology is the spectral sirens method, which utilizes GW luminosity distance and source-frame mass distribution to infer redshift. With GW detectors, populations of CBCs can be either observed as resolved individual sources or implicitly as a stochastic gravitational-wave background (SGWB) from the unresolved ones. This study explores how both resolved and unresolved CBCs contribute to constraining cosmic expansion within the spectral siren framework. The SGWB provides additional constraints on CBC population properties, potentially enhancing precision in cosmic expansion measurements. Using a five-detector network at O5-designed sensitivity, we find that incorporating the SGWB helps exclude lower values of H0 and the dark matter energy fraction Ωm. It also helps in refining the redshift distribution of CBCs, improving the determination of a possible CBC peak in redshift. However, while SGWB improves constraints on low values of H0 and Ωm, resolved spectral sirens remain the dominant source of precision for H0. We also performed a spectral siren analysis for 59 resolved binary black hole sources detected during the third observing run with an inverse false alarm rate higher than 1 per year jointly with the SGWB. We obtain that with current sensitivities, the cosmological and population results are not impacted by the inclusion of the SGWB.

SMBH accretion and merger history: a study of its impact on the PTA gravitational wave background with L-Galaxies simulations

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Tuesday Session 4 - C1: Pulsar timing arrays

Understanding how supermassive black holes (SMBHs) form and grow is a key question in astrophysics. Their growth is thought to occur by two main mechanisms: radiatively efficient accretion and mergers with other SMBHs. While accretion has been extensively studied using the quasar luminosity function (QLF), mergers can be studied using the stochastic gravitational wave background (SGWB) produced by SMBH binaries (SMBHBs). Recent evidence for an SGWB from Pulsar Timing Array (PTA) experiments provides a new way to probe the evolution of SMBHs.
This work explores how the growth history of SMBHs influences PTA observables using realistic SMBH merger trees from L-Galaxies simulations, which track the evolution of galaxies and SMBHs within cosmological dark matter merger trees generated by N-body cosmological simulations. We study a simulated SMBH population that matches both the observed present-day SMBH mass function and the SGWB amplitude measured by PTAs. The structure of the simulations allows us to study individual merger trees in detail, as well as average quantities that reflect the evolutionary history of the SMBH population. For example, a quantity that compares the simulated SMBHBs population to an extreme scenario where SMBHs form exclusively by equal-mass mergers at z=0 provides insight into the SMBH growth history and its anti-hierarchical nature.

Instability of nonlinear scalar field on asymptotically AdS black hole backgrounds

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Tuesday Session 3 - A2: Classical GR: Mathematical developments

We discuss how the dynamics of a conformal cubic scalar field on the Reissner-Nordström-anti-de Sitter background depends on the black hole size, charge, and the choice of the boundary condition. In particular, we observe a new instability mechanism that emerges for large black holes at the specific critical value of the charge. Similarities between Reissner-Nordström and Kerr black holes let us suspect that a similar effect may also occur for rotating black holes.

GWSurrogate: A user-friendly Python package for rapid evaluation of numerical relativity waveform surrogate models

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Monday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Surrogate models efficiently replicate gravitational waveforms originally computed by computationally demanding numerical relativity simulations. Within their training domains, surrogate waveforms achieve accuracies comparable to direct numerical relativity solutions while evaluating in milliseconds, thus enabling data analyses and parameter estimation studies. Thanks to the maturity and robustness of numerical relativity codes producing the necessary training datasets, surrogate models now cover extensive regions of the binary black hole (BBH) parameter space, incorporating all relevant physics. In this talk, I will discuss GWSurrogate, an open-source Python package that allows access to a comprehensive suite of numerical relativity surrogate models. Currently supported models include generically precessing BBHs, models with non-linear memory effects, and mass ratios ranging from intermediate to extreme. I will provide a summary of current models as well as ongoing surrogate model-building efforts extending the parameter range of existing models, BBH systems with eccentric orbits, and highly accurate ringdown models.

On the features and challenges of fitting ringdown overtones

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Thursday Session 4 - C10: Experimental tests of the nature of compact objects

The physical significance of ringdown overtones remains an open question in both numerical-relativity simulations and gravitational-wave observations. In this work, we take a pragmatic approach and investigate (assuming the ringdown can be modeled as a sum of many overtones) the practical utility of each additional overtone in extracting information from the ringdown. Using numerical-relativity waveforms, we apply both least-squares (i.e., maximum-likelihood) and Bayesian fitting methods to assess the contribution of each overtone to the ringdown, highlighting some key features. This includes the dependence of ringdown start time on the number of overtones, the feasibility of detecting deviations from general relativity in the frequencies, and the strong correlations between neighboring overtone amplitudes.

Causal Fermion Systems - A Relational, Background Independent Candidate for a Unifying Theory

Fischer P[1]
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Friday Session 4 - D1 + D2 D+3

The theory of causal fermion system (CFS) is a mathematically well-posed approach to fundamental physical. It is based on a non-linear variational principle of the so-called causal action, from which both the standard model and the Einstein field equation can be derived. In addition, CFS provides an effective collapse model and explanation for the matter/antimatter asymmetry in the universe. Minimizer of the action of CFS describe a physical model for spacetime and all the matter content. Starting from a vacuum solution, which defines the continuum limit of CFS, one can treat particle creations and interactions perturbativly. Then, the Euler Lagrange equation of CFS constrain the perturbations giving rise to the equations of motion of the standard model and the Einstein field equation.
The vacuum minimizer requires a UV regularization length scale ε. This parameter then determines the gravitational coupling constant (ε ~ √G), while the coupling constants of the standard model are independent of it. Thus, CFS also provides a natural solution of the hierarchy problem and a nice explanation, why gravitational effects, hence the UV cutoff scale can be neglected in the standard model.
Fundamentally, a CFS is only described by the correlations between one-particle wave functions, which are constructed as operators on an abstract Hilbertspace. Thus, the spacetime is an "emergent" physical quantity of the theory and determined by the Euler-Lagrange equation of CFS. This makes the theory background independent and purely relational.

An Algorithmic Approach to the Cauchy Problem for Einstein's Field Equations

Fischer A[1]
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Monday Session 4 - A2: Classical GR: Mathematical developments

Using results regarding first order quasilinear symmetric hyperbolic systems, rather than the usual second order quasilinear strictly hyperbolic systems, we approach the Cauchy problem for Einstein's vacuum field equations in an algorithmic manner, as two distinct cases. The first case, Case A (the harmonic case), is the base case, which is the classical case where the original Cauchy data satisfies both the necessary constraint equations and also the harmonic coordinate conditions on the Cauchy data, which in turn fixes harmonic coordinates for the solution. We then discuss the general Case B (the non-harmonic case), where the original Cauchy data satisfies the constraint equations but does not satisfy the harmonic coordinate conditions. This case is resolved in two steps. Firstly, as an intermediate solution, we show how the general case can be explicitly reduced to the harmonic case by modifying the original non-harmonic Cauchy data to become harmonic Cauchy data, which is then solved as in Case A. The general non-unique solution to the original problem is then achieved by pulling the intermediate solution back by any diffeomorphism that also pulls back the non-original intermediate harmonic Cauchy data to the original non-harmonic Cauchy data.
Other aspects of the Cauchy problem are discussed, including the internal structure of the Ricci tensor, how the covariance of the scalar curvature gives rise to the constraints on the Cauchy data, and the relation of the Cauchy problem to the problem of isolating and parameterizing the space of true degrees of freedom for the gravitational field.

Nonlinear evolution of vacuum tensor fluctuations during inflation

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Wednesday Session 3 - B2: Numerical Relativity

The primordial gravitational-wave background (PGWB), if detected, would provide key information about the inflationary period, complementary to scalar perturbations. Typical calculations of the PGWB decouple tensor and scalar perturbations; however, for non-standard models of inflation such as ultra-slow-roll, tensors and scalars can interact strongly to produce large non-Gaussian signatures in late-time correlators. We use the numerical relativity code GRChombo/GRTeclyn to predict the shape of these correlators by evolving a stochastic gravitational-wave background according to the fully-relativistic Einstein's equations during slow-roll inflation. We outline the methodology and validation of our GRChombo example, which initialises a stochastic background according to the linearised Mukhanov-Sasaki solution for a massless scalar field, and extracts the statistics of this background before, during and after horizon crossing. We show excellent agreement with the Mukhanov-Sasaki equation in the linear regime, and present hints of the emergence of a bispectrum for sufficiently large initial tensor perturbations.

Emission of W bosons by electrons and decays of W bosons in the early universe

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Thursday Session 4 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

This presentation concerns the study of the transition rates for two processes in the early universe: first the emission of a W boson by an electron in de Sitter spacetime, a process forbidden in the Minkowski geometry due to the simultaneous conservation of energy and momentum; and also the leptonic decay of a W boson in de Sitter spacetime, a process for which we recover the Minkowski tranisition rate (up to a numerical factor) as a limiting case from the rate computed in an expanding universe.
We employ the QFT methods of flat spacetime and define the amplitudes for the aforementioned transitions in the first order of perturbation theory. This can be done by using the minimal coupling of the matter fields to gravity, and also by using the tetrad formalism to define a local chart which describes the expanding portion of de Sitter spacetime. We also make use of the Proca field solutions in de Sitter spacetime, to describe the massive W bosons, while for leptons we utilize the massive and massless Dirac field solutions in de Sitter spacetime.
The resulting probabilities and rates depend on the particle masses and the Hubble parameter. In order to establish finite expressions for these probabilities and transition rates, we make use of dimensional regularization and the minimal substraction method.

Plenary Talk - Emmanuel Fonseca

Fonseca E

Friday Session 2 - Plenary Talks

Pulsars are spinning neutron stars typically observed as pulses emitted at radio wavelengths. These pulsations exhibit a rotational stability that rival the best atomic clocks, making pulsars one of the most important tools for resolving gravitational phenomena in extreme environments. I will present an overview of the ways in which radio pulsars can be used to test strong-field gravity and observe gravitational radiation, both in the context of historical and ongoing experiments. I will also describe how these measurements can be translated to sought-after quantities like the masses and moments of inertia of neutron stars.

Measuring the speed of gravity in short distances: improving signal strength

Frajuca C[1]
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Tuesday Session 3 - C9: Experimental gravitation

In order to investigate the speed of gravitational signals traveling in air and through a different medium a experiment is proposed. The experiment contains 2 masses vibrating (emitters), the masses will emit a periodic tidal gravitational signal and one sapphire device that behaves as a detector is located between the two vibrating masses. This detector is suspended in vacuum and cooled down to 4.2 K will. The vibrational amplitude of the sapphire detector is measured by a microwave signal with ultralow phase-noise that uses resonance in the whispering gallery modes inside the detector device. Sapphire has quite high mechanical and electrical Qs which implies a very narrow detection band thus reducing the detector sensitivity but amplifies the phase difference of the signal coming from the emitters. With the aid of a finite element program the normal mode frequencies of the detector can be calculated with high precision. The results show that to improve the sensitivity of the experiment is necessary to improve the signal strength. A new emitter is proposed then the new best operational frequency is calculated showing a better design for the experiment.

Non-adiabatic dynamics of eccentric black-hole binaries in post-Newtonian theory

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Tuesday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

Eccentric black-hole binaries are among the most awaited sources of gravitational waves, yet their dynamics lack a consistent framework that provides a detailed and physically robust evolutionary description due to gauge issues. We present a new set of non-orbit-averaged equations, free from radiation-reaction gauge ambiguities, that accurately describe the evolution of orbital elements for eccentric, non-spinning black-hole binaries. We derive these equations by mapping the Keplerian orbital elements to a new set of characteristic parameters using energy and angular momentum definitions combined with near-identity transformations. The resulting framework is valid for arbitrary eccentricities, including parabolic and hyperbolic limits. Using this framework, we demonstrate the strictly observable effects of the non-adiabatic emission of gravitational waves — characteristic of eccentric binaries— on the orbital parameters. Furthermore, we assess the regime of validity of the widely used orbit-averaged equations first derived by Peters in 1964. Importantly, their breakdown becomes evident at the first pericenter passage, implying that the validity of the orbit-averaged approximation cannot be inferred solely from binary initial conditions. The formalism we introduce, accurate up to 2.5 post-Newtonian order, aims to provide a robust tool for making reliable astrophysical predictions and accurately interpreting current and future gravitational wave data, paving the way for deeper insights into the dynamics of eccentric black hole binaries.

Creases, corners and caustics: properties of non-smooth structures on black hole horizons

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Wednesday Session 3 - A1: Classical GR: Theoretical developments

Dynamical black holes are known to develop non-smooth structures on their event horizons. We begin by reviewing a classification of all generic non-smooth structures that may appear on black hole horizons in four-dimensional spacetimes. Introducing a time function, we describe how these features evolve, and in particular discuss processes known as ‘perestroikas’, where the non-smooth structure on a horizon cross-section changes qualitatively. Finally, we demonstrate by means of an explicit example that these perestroikas provide an exact local description of how black holes merge.

Supernovae evidence for foundational change to cosmological models

Wiltshire D[1], Seifert A[1,2,3], Lane Z[1], Galoppo M[1], Ridden-Harper R[1]
[1]University of Canterbury, [2]Universität Heidelberg, [3]Perimeter Institute

Friday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

We present a new statistical analysis of the Pantheon+ Type Ia Supernovae data set. Our new techniques apply to any cosmology with a notion of statistical homogeneity and isotropy, including models with non-Friedmann–Lemaitre–Robertson–Walker (non-FLRW) evolution. Within this framework we compare the standard spatially flat Λ cold dark matter (ΛCDM) cosmology and the timescape cosmology, which invokes backreaction of inhomogeneities. Timescape departs from average FLRW evolution and replaces dark energy by kinetic gravitational energy and its gradients, explaining independent cosmological observations. When considering the entire Pantheon + sample, we find very strong evidence ($\ln B > 5$) in favour of timescape over ΛCDM. Furthermore, even restricting the sample to redshifts beyond any conventional scale of statistical homogeneity, $z > 0.075$, timescape is preferred ΛCDM with $\ln B > 1$. The relation of our results and those of other surveys (DES, DESI etc) that find increasing tensions for ΛCDM, will be discussed. These results provide evidence for a need to revisit the foundations of theoretical and observational cosmology.
References: [1] A. Seifert, Z.G. Lane, M. Galoppo, R. Ridden-Harper, D.L. Wiltshire, "Supernovae evidence for foundational change to cosmological models", MNRAS Letters 537 (2025) L55-L60; [2] Z.G. Lane, A. Seifert, R. Ridden-Harper, D.L. Wiltshire, "Cosmological foundations revisited with Pantheon+", MNRAS 536 (2025) 1752-1777.

Accurate waveforms for eccentric binary black holes within the effective-one-body formalism

Gamboa A[1], Buonanno A[1,2], Enficiaud R[1], Khalil M[3], Ramos-Buades A[4], Pompili L[1], Estellés H[1], Pfeiffer H[1]

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Friday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Coalescing compact binaries gradually circularize over time due to gravitational wave (GW) emission, making quasi-circular binaries the primary expected sources of GW signals for current detectors. However, upcoming LIGO-Virgo-KAGRA observing runs are expected to detect a subpopulation of signals exhibiting signatures of orbital eccentricity. Measuring eccentricity in GWs will provide unique insights into the astrophysical origin of binary systems; conversely, neglecting eccentricity in GW analyses could introduce significant biases in parameter estimation and tests of General Relativity. This highlights the importance of developing accurate waveform models for coalescing binaries in eccentric orbits. The effective-one-body (EOB) formalism combines various analytical approximation methods with information derived from numerical-relativity simulations, and it has proven reliable in modeling the inspiral-merger-ringdown waveform of binaries on generic orbits. In this talk, we will present a recently developed EOB waveform model, SEOBNRv5EHM, designed for eccentric binary black holes with spins aligned (or antialigned) with the orbital angular momentum. The model's accuracy, robustness, and computational efficiency make it well-suited for data analysis and astrophysical applications, including searches for eccentric GWs, parameter estimation, waveform systematics tests, and binary black hole population studies. Lastly, we will discuss the first results of the extension of the SEOBNR models to generic (eccentric, spin-precessing) binaries. This is crucial for a complete understanding of the formation channels of coalescing binaries.

Towards a spacelike characterization of the null singularity inside a black hole

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Friday Session 3 - B2: Numerical Relativity

Numerical simulations typically use a foliation of spacetime by spacelike surfaces. However, we expect that at least part of the singularity inside a black hole is null. This leads to the issue of how to identify the presence of a null singularity in a simulation that uses spacelike surfaces. This talk will explore a method using harmonic time slices and rescaled tetrad. As a proof of concept, I will present a demonstration that the method works well in the Reissner-Nordstrom spacetime.

Scattering of Scalar Fields of Cosmological Black Hole Spacetimes: the Case of Cosmic String Fluid

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Monday Session 4 - B3: Approximations, perturbation theory, and their applications

Black holes provide an excellent laboratory for probing fundamental physics, including potential candidates for dark matter. In this study, we explore black hole dynamics using a generalization of Einstein's equations in General Relativity that accounts for the effects of surrounding matter. As a specific example, we consider a cosmic string case modeled as an anisotropic ideal fluid. How does the presence of this cosmic string gas alter the black hole's structure and influence the behavior of perturbations in its surroundings?
We addressed this question by analyzing the horizon structure, the perturbations of a charged, massless scalar field, and the associated effective potential. We characterized how perturbations around the black hole evolved over time by studying its characteristic vibrations, known as quasinormal modes, which are analogous to the ringing of a bell and reveal how the system responds to perturbations. To carry out this analysis, we developed a precise numerical technique based on the well-known Leaver's method.

The conformal Killing spinor initial data equations and Petrov type D initial data

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Monday Session 4 - A2: Classical GR: Mathematical developments

It is discuss how to obtain necessary and sufficient conditions for an initial data set for the vacuum conformal Einstein field equations to give rise to a spacetime development in possession of a Killing spinor. The fact that the conformal Einstein field equations are used in our derivation allows for the possibility of the initial hypersurface intersecting non-trivially with (or even being a subset of) null infinity. For conciseness, these conditions are derived assuming that the initial hypersurface is spacelike. Hence, in particular, these conformal Killing spinor initial data equations encode necessary and sufficient conditions for the existence of a Killing spinor in the development of asymptotic initial data on spacelike components of null infinity. Furthermore, it is discussed how to use these (conformal) Killing spinor initial data equations to obtain a covariant characterisation of initial datasets for Petrov type D vacuum spacetimes.

Morphology of Relativistically Broadened Emission Lines from Accreting Black Holes

Gates D[1], Truong C[2], Sahu A[2], Cardenas-Avendano A[3]
[1]Harvard University, [2]Princeton University , [3]Los Alamos National Laboratory

Monday Session 3 - B1: Relativistic astrophysics

Emission from hot gas near a black hole (BH) experiences extreme frequency shifts due to relativistic motion and the intense gravitational field. The observer's inclination, the gas proximity to the BH, and the BH spin influence these shifts. Consequently, over the past decades, the broadened spectra of accreting systems have been used to constrain BH spin and observer inclination. In this talk, I will explicitly show how features of the emission line profile—such as their extent, kinks, and fall-off—are mapped onto the BH spin, observer inclination, and disk boundaries.

Accumulation of Charge on an Extremal Black Hole's Event Horizon

Gelles Z[1], Pretorius F[1]
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Monday Session 3 - A1: Classical GR: Theoretical developments

Extremal black holes are known to develop a horizon instability in the presence of external scalar fields. In this talk, I will discuss the extension of this Aretakis instability to charged perturbations, demonstrating that a linear instability manifests in the electric field itself. Specifically, when the electromagnetic coupling to the scalar field is sufficiently large, matter can accumulate on the extremal horizon and produce a constant, nonzero charge density at late times. In demonstrating this result, I will discuss a new gauge-invariant formalism for computing the dynamics of the charged fields, and I will introduce a compactified coordinate system that allows us to numerically evolve the equations of motion to null infinity, thus capturing the appropriate power-law tails at the boundaries of the spacetime. I will conclude by presenting updates on the non-linear problem, where metric backreaction is included and may be able to mitigate the instabilities.
Based on arXiv: 2503.04881

Which black hole? The labeling uncertainty in gravitational-wave astronomy

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Wednesday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Compact objects observed in gravitational-wave astronomy (at least so far) come in pairs and not individually. Identifying the two components of a binary system is a delicate operation that is often taken for granted. The labeling procedure (i.e., which is object “1” and which is object “2”) effectively acts as systematics, or, equivalently an unspecified prior, in gravitational-wave data inference. The common approach is to label the objects solely by their masses (m1>m2), on a sample-by-sample basis. We show that object identification can instead be tackled using the posterior distribution as a whole. We frame the problem in terms of constrained clustering —a flavor of semi-supervised machine learning— and find that unfolding the labeling systematics can significantly impact, and arguably improve, our interpretation of the data. In particular, the precision of black-hole spin measurements improves by up to 50%, multimodalities and tails tend to disappear, posteriors become closer to Gaussian distributions, and the identification of the nature of the object (i.e. black hole vs. neutron star) is facilitated. We estimate that about 10% of the LIGO/Virgo/KAGRA posterior samples are affected by this relabeling, i.e. they might have been attributed to the other compact object in the observed binaries. (PRL, 2025)

A χ^2 statistic for the identification of strongly lensed gravitational waves from compact binary coalescences.

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Friday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Gravitational waves (GWs) emanated by stellar mass compact binary coalescences (CBCs), and lensed by galaxy- or cluster-scale lenses, will produce two or more copies of the GW signal. These will have identical phase evolution but differing amplitudes. Such lensing signatures are expected to be detected by the end of the LIGO-Virgo-Kagra's (LVK's) fifth observing run (O5). In this work, we propose a novel χ^2-lens statistic to segregate pairs of detected GW events as either lensed or unlensed, using templates typically used in GW searches. The statistic is an application of the generalized χ^2 discriminator described in Dhurandhar et al. 2017 tailored to probe the similarity (or lack thereof) between the phase evolutions of two CBC signals. We assess the performance of χ^2-lens on a realistic astrophysical dataset of lensed and unlensed CBCs detectable in O4, assuming a single LIGO-like detector at design sensitivity. We find that we can correctly identify lensed events with efficiencies comparable to existing Bayesian and machine learning methods. Evaluating χ^2-lens is orders of magnitude faster than Bayesian methods. Moreover, the statistics of χ^2-lens, in stationary Gaussian noise, are fully understood, in contrast to machine learning methods. χ^2-lens can, therefore, be used to rapidly and accurately weed out the vast majority of unlensed candidate pairs and identify lensed pairs.

Beyond galaxy catalogues for dark standard sirens

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Thursday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

Compact binaries observed in gravitational waves (GWs) are standard distance indicators or standard sirens. With complementary resdhift information, they open up a parallel avenue to independently measure cosmological parameters such as the Hubble constant. The idea of "dark" standard sirens -- where the redshift comes statistically from a set of potential host galaxies in an electromagnetic (EM) catalogue -- is of compelling interest, given that we have observed only one bright standard siren till date. The method is however limited by the incompleteness of traditional galaxy catalogues, which currently show little to no support at redshifts beyond z ~ 0.3. This limitation is expected to become more and more significant with upcoming observing runs of LIGO-Virgo-KAGRA as we observe compact binaries to higher and higher distances.
In this work, we explore the use of alternate tracers of the high-redshift universe to complement the GW distance information. In particular, we focus on luminous red galaxies (LRGs), and galaxy clusters obtained from X-ray observations as well as using the Sunayev-Zel'dovich (SZ) effect. For the first time we see significant information coming from the EM sector beyond the "spectral" contribution from GW mass distributions. We discuss the potential systematic effects of our method, and a roadmap to tackle them.

Tidal dissipation in binary neutron star inspiral : A novel probe of exotic matter at neutron star cores

Ghosh S[1,2]
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Tuesday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

During the inspiral of binary neutron stars, viscous processes in the neutron star fluid can damp out the tidal energy induced by its companion and convert it to thermal energy. This tidal dissipation(or equivalently tidal heating) process introduces a net phase shift in the gravitational wave signal. Earlier studies suggested that tidal dissipation due to viscosity from nuclear matter does not have any detectable effect on the gravitational wave signal. But non-leptonic processes involving exotic particles at neutron star cores like hyperons and quark matter can produce bulk viscosity that are several orders higher than the nuclear matter viscosity. We demonstrate that tidal dissipation from this high bulk viscosity could have a detectable phase shift in the gravitational-wave (GW) signal in the next-generation GW detectors. If tidal dissipation is not accounted for in waveform models, we show that it induces a systematic bias in tidal deformability measurements and thus biasing any equation of state(EoS) inference. Lastly, we develop a frequency domain waveform model incorporating the effects of tidal dissipation and perform a full Bayesian parameter estimation with our model to show how accurately we can measure the additional phase due to tidal dissipation in future GW observations and discuss its significance in extreme matter studies.

Quintessence and phantom scalar field from the affine connection in Einstein-Palatini theory

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Tuesday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

In this presentation, we will demonstrate that it is possible to introduce two scalar fields using the affine connection in the Einstein-Palatini action that is linear in the scalar curvature. The resulting Einstein's equation is consistent with the Bianchi identity. Along with the cosmological constant, this provides us with a general version of Einstein's equation, excluding torsion. One of the scalar fields contributes a positive stress tensor and behaves like quintessence, while the other behaves like a phantom scalar field. We will generalize the action to introduce interaction terms that may be useful in explaining inflation and dark energy. Additionally, we will comment on the stability of the theory. We will give a brief discussion on the coupling between
these scalar fields and ordinary matter. We will conclude with a few geometrical significances of the new scalar fields.

References:

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Constraining the Hubble constant from the Cross-Correlation of Individual Gravitational Wave Events with Galaxies

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Thursday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

Gravitational waves (GWs) from the inspiral of binary compact objects provide a direct measurement of the luminosity distance to the event, which is crucial for estimating the expansion rate of the Universe, called the Hubble constant. However, unlike binary neutron stars, the inspiral of binary black holes is not expected to be accompanied by electromagnetic radiation. Thus, a subsequent determination of its redshift using the traditional host identification method is not feasible. Therefore, independent redshift measurements of such GW events are necessary to measure the Hubble constant. Current state-of-the-art methods that perform statistical host identification in existing galaxy catalogs are limited by the completeness of such catalogs. In this study, we present a novel Bayesian method, which is less sensitive to the completeness of the galaxy catalog, to infer the Hubble constant from the cross-correlation between galaxies with known redshifts and individual binary black hole merger events. We demonstrate the efficacy of our method with 250 simulated GW events distributed within 1 Gpc in colored Gaussian noise of Advanced LIGO and Advanced Virgo detectors operating at O4 sensitivity. We show that such measurements can constrain the Hubble constant with a precision of 8% or less (90% highest density interval). We also discuss the potential improvements that are required before applying this method to the real data.

Relational dynamics and Page-Wootters formalism in group field theory

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Wednesday Session 4 - D1: Loop quantum gravity and spin foams

Group field theory posits that spacetime is emergent and is hence defined without any background spacetime; dynamical questions are formulated in relational terms, in particular using (scalar) matter degrees of freedom as time. Unlike in canonical quantum gravity, in group field theory there is no obvious notion of coordinate transformations or constraints, and different canonical formalisms for group field theory have been discussed in the literature. We address these issues using a parametrised version of group field theory, in which all (geometry and matter) degrees of freedom evolve in a fiducial parameter. There is a constraint associated to reparametrisations and the Dirac quantisation programme can be implemented. Using the "trinity of relational dynamics", we show that the resulting "clock-neutral" theory is equivalent to a deparametrised canonical group field theory, interpreted in terms of the Page-Wootters formalism. Hence, the deparametrised quantisation is fully covariant and can be seen as encoding the dynamics of joint quantum matter and geometry degrees of freedom. We show extensions to a setting in which many independent gauge symmetries are introduced, which connects to the "multi-fingered time" idea in quantum gravity.

Mixmaster chaos in a quantum scenario: a Deformed Algebra approach

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Thursday Session 3 - D1: Loop quantum gravity and spin foams

The Bianchi IX model, whose primordial phase is also called Mixmaster model, has been widely studied for its chaotic properties near the initial singularity. Here, we face the question about the fate of chaos when quantum gravity effects come into play. In particular, we construct a framework in which the Misner anisotropic variables obey Deformed Commutation Relations inspired by different Quantum Gravity theories. We consider three deformations, two of which have been able to remove the initial singularity similarly to Loop Quantum Cosmology when implemented to the single volume variable. Here, the two-dimensional Algebras naturally implement a form of Non-Commutativity between the space variables that affects the dynamics of the anisotropies. In particular, we implement the modifications in their classical limit, where the Deformed Commutators become Deformed Poisson Brackets. We derive the modified Belinskii-Khalatnikov-Lifshitz map in all the three cases, and we study the fate of the chaotic behavior that the model classically presents. Depending on the sign of the deformation, the dynamics will either settle into oscillations between two almost-constant angles, or stop reflecting after a finite number of iterations and reach the singularity as one last simple Kasner solution. In either case, chaos is removed.

Interface modes in inspiralling neutron stars: A smoking-gun gravitational-wave signature of first-order phase transitions

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Thursday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

Quantum chromodynamics predicts a phase transition from hadronic matter to deconfined quarks at extreme densities, yet its exact nature remains uncertain. Neutron stars offer a unique opportunity to probe this transition, but bulk properties---mass, radius and tidal deformability---provide only indirect signatures, which require many detections to resolve and are ineffective if the discontinuity exists at lower densities. In this talk, I report on a smoking-gun gravitational-wave signature of a first-order phase transition, identifiable in a single event: the resonant tidal excitation of an interface mode. I demonstrate the detectability of this resonance using general-relativistic perturbation calculations for an ensemble of nuclear-matter equations of state informed by chiral effective field theory. The results suggest that this signature is within reach of third-generation interferometers and may even be observable with LIGO A+ in sufficiently loud events.

Extreme mass-ratio inspirals in dark matter halos: dynamics and distinguishability of halo models

Gliorio S[1]
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Thursday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

The LISA satellite, recently adopted by ESA, is ready to open a new gravitational wave window, targeting sources that are inaccessible to ground-based detectors like LIGO and Virgo.
Extreme mass-ratio inspirals (EMRIs), composed by a massive black hole and a stellar mass secondary, are a among the most peculiar of such new family of binaries. The inspiral phase of these systems falls within the mHz regime of the LISA band. Depending on their mass ratios, EMRIs will be continuously observed over long periods, ranging from months to years. Such long evolution is key to provide a measurement of the source parameters with exceptional accuracy, and to allow to perform precise tests of gravity.
In this talk, I will discuss how, from a theoretical perspective, we can model the dynamics of EMRIs in the presence of dark matter halos within a fully relativistic framework. Building on this, I will show how different dark matter profiles, such as Hernquist, Navarro-Frenk-White, and Einasto, affect the inspiral dynamics and whether LISA observations could detect their imprints and distinguish between these models.

Characterizing LIGO detector data in the fourth observing run

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Monday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The Laser Interferometer Gravitational-wave Observatory detectors are currently collecting data in the fourth observing run at unprecedented sensitivity to astrophysical gravitational wave signals. Characterizing detector data is crucial to enable detection of signals and accurate parameter estimation of source properties. During the current observing run, new detector hardware is in-use, environmental noise couplings have evolved and new noise sources are observed since the previous observing run. These changes require investigation and understanding in order to characterize the data and maximize the scientific benefit of the detectors. The LIGO detector characterization effort spans a wide range of investigation, analysis, monitoring, noise mitigation, and close collaboration between on-and off-site scientists. I will present the efforts of LIGO Scientific Collaboration scientists to characterize the detectors in the fourth observing run, examples of noise sources from both LIGO detectors, and how this information is used to maximize scientific benefits.

Targeted coherent CBC searches in multimessenger astronomy.

Gomez Lopez S[1], Pannarale F[1]
[1]La Sapienza Università Di Roma | INFN sezione di Roma

Tuesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

The multimessenger observational campaign that connected the transients GW170817, GRB 170817A, and AT2017gfo to the binary neutron star merger in the galaxy NGC 4993 was extremely successful. Such coincidence of electromagnetic (EM) and gravitational-wave (GW) observations of compact binary mergers and the direct implications in astrophysics and cosmology may be viewed as a testament of all the physics we can probe with mutlimessenger events. In recent years, the GW community has implemented and incrementally improved software in preparation for the analysis of two possible future scenarios: 1) An external trigger reported first by EM observers such as Fermi-GBM, Swift or CHIME. 2) A well-localized GW trigger, uncovered by low-latency all-sky all-time pipelines.
In this talk, I will focus on the first case and describe the ideas behind PyGRB, a modelled coherent search for compact binaries. PyGRB was used in the first three LIGO-Virgo-KAGRA observing runs, on GW170817A, and it has recently undergone major development changes. I will dive deep into the latest implementation, which offers new flexibility, and will discuss performance metrics. Finally I will discsuss the PyGRB use cases, and future prospects.

Black-hole - neutron-star mergers: new numerical-relativity simulations and multipolar effective-one-body model with spin precession and eccentricity

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Friday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

We present 52 new numerical-relativity (NR) simulations of black-hole-neutron-star merger (BHNS) mergers and employ the data to inform a multipolar effective-one-body model for complete waveforms from arbitrary mergers. Our simulations target quasicircular mergers and the parameter space region characterized by significant tidal disruption of the star. Convergent gravitational waveforms are produced with a detailed error budget after extensive numerical tests. We study in detail the multipolar amplitude hierarchy and identify a characteristic tidal signature in the (l,m)=(2,0), and (3,0) modes. We also develop the most updated NR-informed model for the remnant black hole and a new model for the recoil velocity. The numerical data is then used to inform next-to-quasicircular corrections and the ringdown of TEOBResumS-Dali for BHNS. We show an overall order of magnitude improvement in the waveform's amplitude at merger and more consistent multipoles over our older TEOBResumS-GIOTTO for BHNS. TEOBResumS-Dali is further validated with a new 12 orbit precessing simulation, showing phase and relative amplitude differences below 0.5 (rad) throughout the inspiral. The computed mismatches including all the modes lie at the one percent level for low inclinations. Finally, we demonstrate for the first time that TEOBResumS-Dali can produce robust waveforms with both eccentricity and precession, and use the model to identify the most urgent BHNS to simulate for waveform development.

Injection system improvement for AdV+ phase II

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Tuesday Session 3 - C3: Progress and challenges in advanced ground-based detectors

To achieve a geometrically stable configuration, the Advanced Virgo+ gravitational wave detector will undergo a major upgrade, increasing the length of its recycling cavities. This infrastructural change significantly impacts the injection subsystem, particularly its in-vacuum part, which had to be completely redesigned to align with the new interferometer optical layout. This presentation will detail the key modifications planned for the injection system, along with the enhancements based on the O4 commissioning experience, while ensuring the beam deliver to the interferometer meets the stringent performance requirements.

Current status of Direct Dark Matter Searches with LIGO/Virgo/KAGRA in the Fourth Science Run

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Friday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

Despite the overwhelming observational evidence for dark matter, and decades of research into numerous theories, its nature remains unknown. Various candidates, such as axions, dark photons, macroscopic dark matter, WIMPs, and dark-matter spikes imply unique signatures that could be detected by ground-based laser interferometers like LIGO/Virgo/KAGRA. These types of dark matter can be probed through their effects on gravitational-wave signals from inspiraling compact objects and isolated black holes or neutron stars, or through direct interactions with detector components. The search for dark matter with LIGO/Virgo/KAGRA not only complements traditional gravitational-wave detections but also pioneers new data analysis techniques. These techniques are crucial for identifying the prolonged signals characteristic of dark matter, which differ significantly from the seconds-long mergers typically observed.
From expanding and contracting mirrors, to accelerating them, to modifying the behaviour of laser beams, this talk provides an overview of direct dark matter searches with the LIGO/Virgo/KAGRA detectors and the innovative techniques developed by the LVK collaboration to overcome associated challenges. We also provide an update on the status of those searches on the LVK's fourth science run, in a mass range from about 1e-14 eV to 1e-11 eV, framed within the broader context of dark matter investigations.

A Prototype Interferometer for 3rd Generation Detectors: the Glasgow Cryogenic Interferometer Facility

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Monday Session 3 - C4: Concept and research towards next-generation detectors

The current generation of gravitational wave detectors revolutionised the scientific community with the first detection in 2015. Over the past 10 years humanity's insight into the universe has deepened through key findings such as validations of general relativity and the Hubble constant measurement. However, these detectors have a sensitivity limit, preventing detection of many theorised GW sources. Next generation detectors will utilise innovative techniques to decrease limiting noise sources such as building underground, lengthening of arm cavities, and cooling to cryogenic temperatures, with prototype interferometer facilities of fundamental importance to the development of the next generation. At this point in time we urgently need to adapt known science, test novel technologies, and demonstrate the integration of standalone experiments and techniques into interferometer configurations.
One prototype working to this goal is the Glasgow Cryogenic Interferometer Facility: the 2024 upgrade to Glasgow's 10m prototype. This site will utilise a double-cavity configuration with cryogenic silicon optics to demonstrate necessary technologies for next-generation detectors, while taking direct measurements of coating thermal noise. This ambitious project will have impact in quasi-monolithic suspensions including silicon and sapphire fibres and jointing techniques, cryogenic substrates and coatings, and cryogenic sensors and actuators. Other key demonstrations include long-wavelength laser stabilisation and cavity control. This talk will give a status update on the facility, present results from laser development work and the design of the silicon cryogenic cavity suspensions from both conceptual and technical viewpoints, and outline the planned R&D which will contribute to the group's research goals.

The First Law of Binary Black Hole Mechanics with Dissipation

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Tuesday Session 4 - B3: Approximations, perturbation theory, and their applications

The first law of binary mechanics generalizes the usual first law of black hole mechanics to binary systems of compact objects, and shows how changes in the energy and angular momentum are related to the area and surface gravity of the central black hole and the mass and a "redshift observable" for the orbiting body. Using this law, one can derive a formula for the binding energy of such a system, the evolution of which can be determined from fluxes of gravitational radiation to infinity. This can provide a shortcut in computing gravitational waveforms from quasicircular, extreme mass-ratio inspirals such as those predicted to be seen by LISA. However, most formulations of this first law are performed in a regime where the system is conservative, possessing a helical Killing vector field. Such a discussion cannot account for dissipation, and so determining the evolution of the binding energy from fluxes is not consistent. In this talk, I will show how to account for dissipation in the first law within the extreme mass-ratio regime, up to second order in perturbation theory.

Real-time neural simulation-based inference for binary neutron stars and beyond

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Friday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The increasing detection rate of gravitational waves by LIGO-Virgo-KAGRA demands rapid, accurate parameter estimation, especially for binary neutron star (BNS) mergers. Timely inference is critical for electromagnetic follow-up and multi-messenger astronomy. I will discuss our recent deep-learning method, built upon the DINGO simulation-based inference pipeline, which leverages heterodyning and multi-banding to perform full Bayesian inference for BNS mergers in just one second. Our approach improves sky localization by about 30% compared to traditional low-latency methods, and accurately infers all binary parameters, including sky position, luminosity distance, inclination, and component masses, thus enabling efficient allocation of telescope time. DINGO-BNS further supports pre-merger inference and can analyze hour-long signals for next-generation observatories. I will conclude by highlighting ongoing developments, including in population inference, improved network flexibility, and applications of DINGO to astrophysical discovery.

From the Virgo interferometer calibration to the bias and uncertainty of the h(t) detector strain during the O4 run

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Tuesday Session 3 - C3: Progress and challenges in advanced ground-based detectors

Since the first gravitational wave detection in 2015, ground-based interferometer sensitivities have significantly improved, requiring highly precise calibration to ensure accurate reconstruction of the h(t) strain signal.
In this talk we will outline the Virgo interferometer calibration steps performed in preparation of the O4b run started in April 2024. We will first describe the Photon Calibrator power devices intercalibration within the LVK, allowing for a 0.56% precision for the PCal. Which is then used to calibrate every Virgo mirror actuator.
We will also discuss the monitoring of the h(t) strain reconstruction during the run showing that, on the 20 Hz to 2kHz band, the reconstructed strain achieves a precision of 2% in modulus and 30 mrad in phase. Special emphasis will be given on the newly developed frequency-dependent bias and uncertainty computation method and the resulting online unbiasing of the h(t) strain.

Mapping the Gravitational Wave Sky using the MeerKAT Pulsar Timing Array 4.5 year data set

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Monday Session 3 - C1: Pulsar timing arrays

Since 2023, Pulsar Timing Array (PTA) collaborations have been reporting the presence of a quadrupole-correlated common red noise signal in their data sets - the smoking gun of a nanohertz gravitational wave background (GWB).
With the growing statistical evidence for the presence of the signal, and in particular due to the major PTA GWB search results published in recent years, the driving scientific goal of nanohertz GW research has shifted from simply detecting such a background signal towards identifying its astrophysical origin.
A gravitational wave background may emanate from a variety of sources such as interacting supermassive black hole binaries, phase transitions in the early Universe or other more exotic scenarios. One key method of discrimination is the distribution of GW power across the sky.
GW sky maps allow the identification of spatially constrained areas of significantly enhanced GW power, so-called "hot spots" arising from stand-out supermassive black hole binaries, or statistically insignificant large-scale fluctuations indicating an isotropic background.
In this talk, we will present the most recent study of the GW power sky distribution, taking advantage of the unique quality of the latest dataset of pulsar observations with the MeerKAT radio telescope, comprising 83 pulsars and spanning 4.5 years.
We put a special focus on the improvements we have made to the data analysis framework currently used to compute the GW sky map by combining techniques developed by both the LIGO and PTA communities.

Ultra-high resolution temperature sensing using Whispering-Gallery-Mode resonators.

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Monday Session 4 - C4: Concept and research towards next-generation detectors

As ultra-high resolution thermometry gains prominence in fields of experimental and applied physics, the demand for diverse and innovative technologies becomes imperative. This is particularly crucial as applications extend to lower frequency windows, as exemplified by space-borne gravitational wave observatories like LISA (Laser Interferometer Space Antenna), operating in the Hz-mHz window. To address this challenge, existing solutions based on resistive sensors can achieve micro-kelvin sensitivities (until limited by electronic or fundamental noise). Optical sensors present an opportunity to further enhance resolution capabilities.
In this work we showcase the efforts and steps being taken into developing a thermometry subsystem using optical devices with potential to reach 1 nKHz−1/2 in the Hz-0.1mHz window, as well as the test-bench designed for the characterisation of such a challenging noise floor requirement. The sensor itself is a Whispering Gallery Mode Resonator (WGMR), that is a MgF2 birefringent monolithic disc shaped cavity whose resonant modes are very sensitive to environment fluctuations. This makes them very precise sensors for temperature, humidity, pressure and as bio-sensors. This kind of opto-mechanical device has already been used as thermal sensor before, achieving remarkable sensitivities in the order of nKHz−1/2 in high frequency band (Hertz).

Remarks on the |s|=1 Teukolsky Equation

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Tuesday Session 4 - A2: Classical GR: Mathematical developments

The mathematical problem of stability of Kerr black hole spacetimes has been a major subject in mathematical and theoretical studies of the Einstein equations of general relativity.
In 1970s, a major breakthrough was achieved when Teukolsky was able to construct a master equation for the gauge-invariant ('extreme') Newman-Penrose scalars. The structure of the linearized Einstein equations is such that the Teukolsky master equation does not admit a natural variational formulation for higher spin fields, such as the Maxwell and the linearized Einstein fields. As a result the energy methods are not directly applicable for this equation.
In this talk, we shall present the construction of a positive-definite energy for the Teukolsky variables for the Maxwell fields (spin |s|=1) in the special case of axial symmetry. The origin of this positive-definite energy is a Hamiltonian principle and the construction is based on using certain 'twist' potentials as the main canonical variables as opposed to the vector potential.

Numerical simulations of gravitational collapse on null cones with a regular centre

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Friday Session 3 - B2: Numerical Relativity

The use of null coordinates in numerical relativity has focused either on spherical symmetry (in particular, collapse and black hole interiors) or, with less symmetry, on situations where data are posed on an ingoing null cone, or a timelike inner boundary, as well as an outgoing null cone. By contrast, I present the first simulations of black hole formation from regular initial data posed on an outgoing null cone with a regular centre (vertex), constructing the spacetime on the full domain of dependence of these data. In particular, I present results on critical phenomena at the threshold of black hole formation for a scalar field coupled to gravity in axisymmetry. The coordinates can be adapted to critical collapse in order to make fine-tuning to the black hole threshold much cheaper than with a 3+1 code with adaptive mesh refinement.

Determining and Detecting Gravitational Waves from Cosmological Phase Transitions

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Wednesday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

I will discuss some of the recent progress on the calculation of the gravitational wave spectrum from cosmological first phase transitions, one of the most important for particle physics and cosmology. I will also discuss the detection of such gravitational wave spectrum using data from LIGO/Virgo/KAGRA and detection prospect with future space based detectors like LISA/Taij/Tianqin.

The population properties of eccentric binary black holes: a gravitational wave perspective

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Wednesday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The discovery of binary black holes (BBHs) in elliptical orbits would provide compelling evidence for their dynamical formation through two- or three-body encounters. Fortunately, "eccentric" BBHs generate gravitational waves (GWs) that are measurably distinct from those of quasi-circular BBHs, producing bursts of radiation during close passages.
In this work, we analyze GW events detected by the LIGO-Virgo-KAGRA (LVK) collaboration and find evidence for eccentricity in the observed BBH population. Specifically, our results indicate a greater than 99.5% probability that at least some BBHs possess nonzero eccentricity. Using hierarchical Bayesian inference, we extend individual event analyses to place constraints on the fraction of BBHs formed through dynamical interactions. Looking ahead to the upcoming fourth LVK observing run, we forecast how GW signals from eccentric BBHs can provide insights into formation channels of BBHs. These discoveries are driven by 1) recent advances in waveform modeling and numerical relativity, which have enabled highly accurate eccentric aligned-spin waveform models and 2). machine-learning techniques in simulation-based inference that have facilitated fast and robust parameter estimation of GW events.

Magnetic field effects in binary neutron star mergers: post-merger remnant and disk evolution

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Friday Session 4 - B2: Numerical Relativity

Magnetic fields play a crucial role in shaping both the dynamics and observational signatures of binary neutron star (BNS) mergers. In this talk, I will present results from general relativistic magnetohydrodynamic (GRMHD) simulations performed with the GR-Athena++ code, investigating the impact of different initial magnetic field configurations on the evolution of BNS mergers. Our study explores the amplification of magnetic fields, the structure of the post-merger remnant and accretion disk, and the properties of the ejected material. I will discuss how pre-merger magnetic field configurations influence the thermodynamic and magnetic evolution of the remnant and disk, with implications for electromagnetic counterparts. Finally, I will highlight recent advancements in our numerical methods that enhance the accuracy of magnetized neutron star merger models, improving predictions for multimessenger signals from these extreme astrophysical events.

Geodesic Motion and Forced Deviations

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Tuesday Session 4 - B3: Approximations, perturbation theory, and their applications

Binary systems with extreme mass ratios, such as the supermassive black hole Sagittarius A* (Sgr A*) and a stellar-mass companion, are key targets for upcoming observatories. These include gravitational wave detections with LISA and pulsar searches near Sgr A* with the Square Kilometer Array. In such systems, the motion of the secondary object is well approximated by geodesic trajectories. However, perturbations from the gravitational self-force, third bodies, or surrounding material can significantly alter its motion.
In this presentation, we first review analytical solutions for geodesic motion, that can also be extended to spinning particles, covering all orders for (anti-)aligned spins and first-order corrections for generic spin orientations. We then discuss the framework of osculating geodesics for a specific choice of constants of motion and analyze various perturbative effects, such as those arising from modified spacetimes or astrophysical environments like accretion disks.

Extreme lensing-induced correlations in black hole signals

Hadar S[1], Harikesh S[1], Chelouche D[1]
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Friday Session 4 - B1: Relativistic astrophysics

Rapid progress in electromagnetic black hole observation presents us with a challenge: how can we efficiently distill the universal signatures of extreme gravitational lensing from the stochastic astrophysical signals in upcoming data? Motivated by the prospect of conceiving novel techniques to do so, I will describe an approach focusing on correlation functions of observed signals across image positions, times, and frequencies. These observables can show peaks of enhanced correlation arising from multi-path propagation, or echoes, which are a result of extreme lensing. We use simple geometric-statistical emission models, allowing a semi-analytical treatment, with complete analytical control over the contributions which arise solely from extremely lensed light rays. I will then present numerical results for the image-integrated spectrotemporal correlation function, which transcend the analytical approximations and account for it in full. The latter observables could be relevant, for example, for future X-ray spectroscopic light-curve measurements. We compute correlation maps for many combinations of black hole and emission parameters within a simple source model, and use the results to train convolutional neural networks which can be used for parameter estimation, achieving promisingly low evaluation errors within the model.
Based on:
- S. Hadar, M. D. Johnson, A. Lupsasca, and G. N. Wong, Phys. Rev. D 103 no. 10, (May, 2021) 104038
- S. Hadar, S. Harikesh, and D. Chelouche, Phys. Rev. D 107 no. 12, (June, 2023) 124057
- S. Harikesh, S. Hadar, and D. Chelouche, arXiv:2502.12053

PhenomXPNR: high precision modelling of quasi-circular binary-black-holes with generic spins

Hamilton E[1], Colleoni M[1], Thompson J[2], Hoy C[3], Heffernan A[1], Kinnear M[4], Ramis Vidal F[1], Valencia J[1], Garcia Quiros C[5], Ghosh S[6], London L[7], Hannam M[4], Husa S[8]
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Friday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Highly accurate gravitational wave signal models are essential for a robust analysis of gravitational wave signals, from parameter estimation to astrophysical and cosmological inferences, as well as tests of general relativity. With the increasing sensitivity of detectors, we are already pushing the boundaries of the capability of current generation gravitational wave models. I will present the cutting-edge IMRPhenomXPNR model for precessing black-hole-binaries. IMRPhenomXPNR combines an improved post-Newtonian description of the precession dynamics during inspiral with the calibration of precession effects and dominant multipole asymmetry to numerical simulations through merger and ringdown. This enables us to take advantage of the evolution of the individual black hole spins. These developments lead to a more accurate model for generically-spinning binaries, which in turn results in improved parameter estimation and estimates of the remnant properties and kick velocities.

Nonparametric reconstructions of dynamical dark energy via flexknots

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Friday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

Recent cosmological surveys have provided unprecedented datasets that can be used to reconstruct the history of the dark energy equation of state. In this work, a free-form "flexknot'' parameterisation is employed to represent w(a) as a linear spline between free-moving nodes, the number of which may vary. By combining DESI Baryon Acoustic Oscillation measurements with Pantheon+ or DES5Y supernovae, the functional posteriors of w(a) reveal an unexpected W-shaped structure. While the Bayesian evidence may still favour ΛCDM, the robustness of these results suggests the structure is indeed present in the data. The tension R-statistic and suspiciousness have been marginalised over models, and demonstrate that while the reconstructions from DESI and Pantheon+ agree, DESI and DES5Y do not. We conclude that, while there is no smoking gun for dynamical dark energy, the structure unearthed in this work is generally too complex to be captured by the restrictive wCDM or CPL parameterisations. https://arxiv.org/abs/2503.08658

A robust method to assess numerical-relativity accuracy requirements

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Tuesday Session 3 - B2: Numerical Relativity

It is generally assumed that next-generation detectors and LISA will require vastly more accurate numerical relativity calculations to achieve their science goals. Given the high computational cost of large simulation campaigns, and the long lead-time to develop new numerical methods and codes, it is essential that we have reliable estimates of future NR accuracy requirements. One standard estimate, that the mismatch uncertainty must be lower than ~1/SNR^2, is far too conservative. We present an improved method to accurately quantify the mismatch requirements for the measurement of each individual source parameter. We illustrate the method with the example of aligned-spin binaries, and discuss how this method could be extended to generic binaries, and applied to calculate NR accuracy requirements across the black-hole binary parameter space.

The impact of Vegh-modified massive gravity on stellar structure.

Hansraj S[1]
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Wednesday Session 4 - A3: Alternative and modified theories of gravity

While Einstein's general relativity (GR) has earned immense acclaim from experimental evidence as a viable theory of gravity, there are many reasons to believe that GR is in need of modification. Specifically it is not renormalizable like its counterpart in quantum theory and relies on exotic matter fields to explain the observed accelerated expansion of the universe. Massive gravity was proposed as an alternative to general relativity. We probe the implications of a massive graviton on stellar structure. It has already been shown that the DRGT (de Rham-Gabadadze-Tolley) construction solves a number of issues inherent in the original formulation by Fierz and Pauli such as extra degrees of freedom for a spin-2 particle as well as ghosts of the theory. Recently Vegh introduced a modification making it easier to study how stars behave under the influence of massive gravitons. The resulting governing differential equation of pressure isotropy is now inhomogeneous. In the limit of vanishing mass general relativity is regained. However in general the effects of a massive particle responsible for curvature are significant. The vacuum solution of Schwarzschild and the incompressible interior metric will now be augmented by new terms influencing the dynamical behaviour. Specifically we study the equation of state, stability criteria and energy conditions. Several mathematical configurations such as algebraically special spacetimes such as conformal flatness, metrics admitting groups of conformal motions as well as the embedding problem are studied. We find exact stellar models and analyze their physical contribution to the standard theory models.

Curvature singularities and mass gap phenomenon in EGB gravity

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Thursday Session 3 - A3: Alternative and modified theories of gravity

The Einstein-Gauss-Bonnet (EGB) gravity framework, as a natural extension of general relativity, provides an approach to explore the effects of higher-order curvature corrections in spacetime dynamics. We first look at N-dimensional cosmology within the Einstein-Gauss-Bonnet framework, investigating the nature of singularities, the occurrence of bounces, and the evolution of the Universe in nonstandard conditions. Using a transformation, we show that no black hole singularity is possible in N-dimensional Einstein-Gauss-Bonnet perfect fluid collapse. Further, we provide a geometrical explanation for the mass gap phenomenon in 5D Einstein-Gauss-Bonnet black holes. The central zero mass singularity is weak, conical and naked, and the horizon forms only when a finite amount of matter, that depends on the coupling constant of the Gauss-Bonnet term, falls into the central singularity. We show in the case of self-similar radiation collapse in the modified theory, the central singularity is not a sink for timelike geodesics and is extendable. These studies clearly demonstrate how the Gauss-Bonnet invariant affects the nature of the final state of collapse in this modified theory.

Singularity resolution and regular black hole formation in gravitational collapse in asymptotically safe gravity

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Tuesday Session 4 - D3: Causal sets, causal dynamical triangulations, non-commutative geometry, asymptotic safety, and other approaches to quantum gravity

We adopt an effective action inspired by asymptotically safe gravity, in which the effective gravitational constant is parameterized as $G(\epsilon) = G_{N} [1 + \tilde{\omega} (G_{N}^{2} \epsilon)^{\alpha}]^{-1}$, where G_{N} and ϵ denote Newton's gravitational constant and the energy density of the matter field, respectively, with two dimensionless model parameters, $\tilde{\omega}$ and α. Within this framework, we investigate the complete gravitational collapse of a homogeneous ball of perfect fluid and find that the singularity is completely resolved for $\alpha > 1$ but not for $1/2 \le \alpha \le 1$. The case $0 < \alpha < 1/2$ is inconsistent with asymptotic safety. Moreover, we note that although the singularity cannot be fully resolved for $\alpha = 1$, it is significantly weakened by quantum gravity effects. Furthermore, we successfully construct a static exterior metric which, together with the interior solution, describes the dynamical formation of regular black holes in an asymptotically flat spacetime for the perfectly resolved case $\alpha > 1$. The resulting regular black hole, obtained as the final static state, contains a de Sitter core and admits a static metric fully expressible in terms of the Lerch transcendent for general cases and in elementary functions for certain values of α, including $\alpha = 2$. We also discuss the formation of gravastars and the late-time evaporation process of the regular black holes.

A foundation for nonlinear self-force problems

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Wednesday Session 4 - A1: Classical GR: Theoretical developments

An important organizing principle for essentially all known self-force results is that self-interacting objects move like test bodies in certain effective fields: Charged particles accelerate according to the Lorentz force equation in a particular effective electromagnetic field, uncharged particles fall on geodesics of a particular effective metric, etc. This talk will describe a large class of nonlocal effective fields which preserve the laws of motion in this sense. It will explain why known results exist and how they can be generalized. The Detweiler-Whiting effective fields which arise in linear self-force problems are special cases. More complicated examples allow one to understand motion in new, nonlinear settings, in general relativity and in other theories.

Spherical Lens Mass Models in Strong Gravitational Lensing for Statistical Cosmology

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Wednesday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

Over the last couple of decades, strong gravitational lenses have been observed with an increased number; the current largest compilations are being regularly updated with Euclid and DES data. The next generation of surveys are posed to vastly increase the number of lenses observed by 3 orders of magnitude. Nonetheless, current compilations are already sufficient to enable statistical analyses of lens properties and to constrain cosmological parameters.
Typically, these investigations implement spherical power law lens mass models. However, many lensing systems are poorly described by these models, even though they may adequately represent the average lens galaxy. We investigate the lens models (inter-)dependence with two specific cosmological models - (i) the standard spatially flat FLRW models (including ΛCDM) and (ii) the inhomogeneous timescape cosmology with backreaction. We find that no combination of lens model and model cosmology adequately fits with the present data. Overall, we conclude that the application of a global spherical power-law lens model to the entire catalogue of systems leads to unphysical distance ratio estimates, introducing bias to the dataset during cosmological fitting.

Eccentricity Reduction for High-Mass Ratio Compact Binaries

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Thursday Session 4 - B2: Numerical Relativity

Gravitational wave astronomy requires precision waveform models for accurate parameter estimation and the resulting science. Numerical relativity supplies a key ingredient to all present waveform models: accurate models of the inspiral, merger and ringdown. As current ground detectors become more sensitive and with future ground detectors as well as LISA approaching, the need for more coverage of the parameter space of compact binaries is becoming acute; in particular, higher mass ratio simulations. In this project, we examine the eccentricity reduction techniques required for the initial data of quasi-circular, high-mass ratio compact binaries. We compare both previously known techniques and newer variations to optimise the eccentricity reduction and lower the number of (expensive) simulations required.

Phasemeter development and experiments for LISA at AEI Hannover

Heinzel G[1]
[1]AEI Hannover

Thursday Session 3 - C5: LISA and other space-based detectors

The Phasemeter is a core instrument of LISA. AEI Hannover has developed prototypes for many years, and the flight hardware will now be built be industry. In this talk I will summarize the design and status of the phasemeter as well as some other related experiments that are ongoing at the AEI.

Energy extraction from black holes via charged particle collisions revisited

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Monday Session 3 - A1: Classical GR: Theoretical developments

When Bañados, Silk and West noticed that under idealised conditions, particles coming from rest at infinity can collide close to a black hole with unbounded centre-of-mass collision energy, it inspired a surge of research revolving around the question of what is the best-case scenario for the Penrose process, which we believe is still not settled. Whereas in the vacuum case, the energy of an escaping particle is unconditionally bounded even under the most favourable conditions, no such bound exists whenever both the black hole and the escaping particles are charged. In our previous research [PhysRevD.100.064041, PhysRevD.105.024014], we generalised this conclusion to black holes with arbitrarily small charge, working under the assumption of the black hole being extremal and in the limit of the collision happening infinitely close the horizon. It is known that with deviation from extremality, a tight bound on the rest mass of the produced particles appears, disallowing the option to probe processes with hypothetical super-heavy particles, but significant energy extraction is still possible in principle. However, as we previously demonstrated, the most striking question in all cases is whether the kinematically favoured way of energy extraction is compatible with processes involving particles with realistic properties. Thus, in the present talk, we will consider a couple of model processes and show how they fare at finite coordinate distance from the horizon and under deviation from extremality.

Numerical relativity in effective field theories of gravity

Held A[1]
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Tuesday Session 4 - B2: Numerical Relativity

Constraining potential strong-field deviations from General Relativity requires reliable waveform predictions, not just in GR, but also when higher-curvature corrections contribute to the dynamics. Recent developments on,
(i) mathematical well-posedness of the initial value problem,
(ii) classical time evolution in the presence of ghosts,
(iii) numerical relativity simulations to obtain full nonlinear waveforms,
combine into a novel scheme to perform numerical relativity simulations in general effective field theories of gravity. I will briefly review this progress and then present the first black-hole binaries and waveforms in quadratic gravity.
Items (i) to (iii) are based on three ongoing collaborations:
2407.08775 (with P. Figueras and A Kovacs);
2305.09631 (with C. Deffayet, S. Mukohyama, and A. Vikman);
2104.04010, 2306.04725, 2503.13428 (with H. Lim).

Developing an Early Career Mentorship and Training Programme for the Einstein Telescope Collaboration

Hendry M[1]
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Thursday Session 4 - C8: Education and public outreach in gravitational physics

The Einstein Telescope (ET) Preparatory Phase project is a Horizon Europe-funded infrastructure project that aims to support critical activities of the ET community in the preparatory phase of the experiment, including technical design, costing and site selection for the observatory and identification of ET's scientific, socio-economic and environmental impact. Work Package (WP) 10 of ET-PP concerns "Education, Outreach and Citizen Engagement" and has the mandate to promote to the widest possible audience the enormous scientifical potential of ET.
A key deliverable of WP10 is to develop a plan for an Early-Career Scientist Mentorship and Training programme for the ET Collaboration. The proposed contribution will provide an overview of the work being carried out towards this deliverable. It will first review the many examples of good practice that exist in related mentorship and training programmes within the gravitational-wave community and beyond. It will then facilitate an open dialogue with early-career scientists attending the Amaldi Meeting; this will tease out and reflect upon early-career colleagues' mentorship and training needs – particularly those which are distinct or bespoke compared with those of other gravitational-wave projects. This dialogue will help to shape the WP10 deliverable outcome report which will be submitted to the EU in autumn 2025.

The balance problem for n aligned black holes

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Wednesday Session 3 - A2: Classical GR: Mathematical developments

Black hole uniqueness theorems establish that the Kerr and Kerr-Newman solutions are the only possible stationary, asymptotically flat vacuum black hole spacetimes, provided that only a single black hole is present. However, the existence of multi-black-hole solutions and whether they can form in gravitational collapse remains an open question. The repulsive spin-spin interaction of rotating objects, combined with the additional electromagnetic repulsion in the charged case, suggests the possibility of such exotic configurations. We investigate this problem by studying a linear matrix problem that is equivalent to the Einstein (-Maxwell) equations for stationary, axisymmetric (electro-) vacuum spacetimes with n aligned black holes. This approach yields the most general boundary data on the symmetry axis in terms of a finite number of parameters. In the simplest case n=1, we recover a constructive uniqueness proof of the Kerr (-Newman) solution. For n=2 in vacuum, we obtain a non-existence result for stationary two-black-hole configurations. However, for n=2 in electrovacuum, as well as for larger n, it remains an open question whether the resulting finite families of solutions contain any physically acceptable spacetimes, i.e. solutions free of naked singularities, magnetic monopoles and struts.

Detecting strongly lensed gravitational waves using the null stream

Heynen J[1], Janquart J[1], Roy S[1]
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Friday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy, July 18

Gravitational lensing of gravitational waves is expected to be observed in current and future detectors' data. In view of the growing numbers of gravitational wave detections, to claim a confident detection, a false alarm probability is required and for this a background needs to be constructed. Current detection pipelines are expensive which makes constructing a background unfeasible. We present a novel strong lensing detection method, whose detection statistic can be constructed using the null stream of a detector network. A coherent analysis between the detectors' data of two (or more) events provides measurements of the likelihood energies, which helps us identifying lensed pairs. This waveform model independent method has the advantage of being cheap while remaining accurate enough to make statistical claims about the lensing hypothesis. We show this by constructing an O4-like background and lensed foreground and exhibiting the method performance by providing its ROC curve. We also apply our method on GWTC-1 and find preliminary evidence for the lensed hypothesis between the pair GW170814-GW170818.

Ray Tracing and Cosmography in Szekeres Cosmological Models

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[1]University of Canterbury, [2]Niels Bohr Institute

Tuesday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

Inhomogeneous cosmological models provide a natural means of tackling various cosmological tensions and anomalies through the construction of fully general relativistic descriptions of the local universe. We use the exact Szekeres solutions to model our local void with adjacent over-densities that simulate the distribution of structure in our local cosmic neighbourhood. We perform full general relativistic ray tracing in these simulations, and compare results to the cosmographic predictions given by the generalised luminosity-distance expansion of Heinesen [1]. We systematically assess the accuracy and convergence properties of the expansion to fourth order, and find an early breakdown of the cosmographic approximation. This provides important insight into the applicability of cosmographic methods in markedly inhomogeneous local environments.
Reference: [1] A. Heinesen, JCAP 05 (2021) 008, "Multipole decomposition of the general luminosity distance 'Hubble law': A new framework for observational cosmology"

Exact Solutions for Realistic Compact Stars

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Thursday Session 3 - B1: Relativistic astrophysics

New exact solutions for realistic spherically symmetric compact stars are constructed in assuming a quartic density profile. These solutions extend the Tolman-VII solutions that provide physically viable exact models of gravitating spheres. The metric coefficients are obtained by solving the appropriate differential equations. One metric function is in terms of a polynomial of the radial coordinate and the other in terms of a Jacobi elliptic integral. The pressure is then computed for cases where $P=0$ at the fluid-vacuum boundary (natural models) and where P is non-vanishing (self-bound models). In addition to closed form solutions for density, pressure and metric components, the equation of state $P=P(\rho)$ can be written in analytic form. This allows one to compute causal sound speeds, adiabatic indices and M/R ratios. Solutions having a distinct core, crust and atmosphere arise out a single equation of state that can be approximated with a sequence of polytropes. The models are compared to neutron stars whose masses and ratios are known through observations including those from LIGO, and NICER. It is shown that the observational mass to ratios of a number of neutron stars can be obtained with an appropriate choice of free parameters appearing in these solutions.

Hybrid waveform model for rapidly spinning binaries

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Wednesday Session 3 - B3: Approximations, perturbation theory, and their applications

Extreme mass ratio inspirals (EMRIs) will be primary sources for the future space-based mission LISA. An approximation scheme tailored for these binaries is the gravitational self-force expansion (SF); it leverages the binary's extreme mass ratio to expand the Einstein field equations and the orbital dynamics in powers of the mass ratio. Waveform faithfulness requirements for parameter estimation indicate that expanding the field equations and the orbital dynamics to second order in the gravitational self-force (2SF) is both necessary and sufficient. Despite significant efforts to extend 1SF computations to 2SF, 2SF results may still not fully cover the parameter space by the time LISA launches. To mitigate that risk, we propose approximating the 2SF and higher-order corrections to phase space quantities through a truncated post-Newtonian (PN) approximant. In this talk, based on joint work with G. Compère and A. Pound, I will describe how we integrate recent advances from both self-force and post-Newtonian communities to build a new state-of-the-art PN-SF hybrid waveform model for quasi-circular spinning binaries. I will then assess the accuracy of the hybrid waveform model against other state-of-the-art models such as effective one-body models by comparing mismatches with numerical relativity simulations.

Two quadrupole formulae in de Sitter ! What are we missing?

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Monday Session 4 - A1: Classical GR: Theoretical developments

Gravitational radiation from an isolated system is mainly dictated by the time-varying quadrupole moment of the source. The quadrupole formula also provides an estimate of the energy loss due to gravitational radiation. The first proposed quadrupole formula for gravitational waves in de Sitter was derived by Ashtekar, Bonga, Kesavan (ABK). However, together with G. Compère and E. S. Kutluk, we pointed out that the quadrupolar truncation was inconsistently performed in the work of ABK since it was conflicting with stress-energy tensor conservation. In another recent study by Bonga, Bunster and Perez (BBP), an alternative quadrupole formula was derived which we will denote as “Formula 1”. Together with G. Compère and E. S. Kutluk, we rederived the quadrupole formula in the consistent quadrupolar truncation and obtained an adjusted quadrupole formula that upgrades the proposal of ABK, which we will denote as “Formula 2”. We also rederived the quadrupole formula derived in the work of BBP and proved that it differs from Formula 2 by a distinct definition of energy. Both Formula 1 and Formula 2 admit the standard flat limit and are negative definite in de Sitter. The existence of several proposals for the quadrupole formula in de Sitter suggests that fundamental requirements on the uniqueness of the quadrupole formula, such that the enforcement of gauge invariance, are still missing.

Incorporating model accuracy into gravitational-wave Bayesian inference

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Friday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Inferring the properties of colliding black holes from gravitational-wave observations is subject to systematic errors arising from modelling uncertainties. Although the accuracy of each model can be calculated through comparison to theoretical expectations from general relativity, Bayesian analyses are yet to incorporate this information. As such, a mixture model is typically used where results obtained with different gravitational-wave models are combined with either equal weight, or based on their relative Bayesian evidence. In this talk, I will present a novel method to incorporate the accuracy of multiple models in gravitational-wave Bayesian analyses. By analysing simulated gravitational-wave signals in zero-noise, I will show that this technique uses 30% less computational resources, and more faithfully recovers the true parameters than existing techniques. I will further present results from applying this technique to real gravitational-wave signals observed by the LIGO-Virgo-KAGRA collaboration. We envisage that this method will become an essential tool within ground-based and space-based gravitational-wave astronomy.

Solving tough inference problems for the next-generation gravitational wave detectors with machine learning: long signals and overlapping signals

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Tuesday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The third-generation (3G) gravitational wave (GW) detectors are expected to detect signals with significantly increased signal duration and detection rates, leading to a major computational burden in the 3G era. In particular, the hours-long binary neutron star (BNS) signals and overlapping signals are two of the major challenges in source parameter estimation (PE). In this talk, we demonstrate solutions to PE of long signals and overlapping signals using machine learning.
For long BNS signals, we employ efficient compression techniques on GW data using neural networks, based on which we construct neural density estimators (NDEs) for inference. Our model can infer BNS properties—including full spin effects and Earth's rotational effects—within a second, compared to the thousands to millions of CPU hours required by traditional stochastic sampling methods. This demonstrates the potential for processing large event catalogs in the future.
For overlapping signals, it has been reported that hierarchical inference with signal subtraction may amplify errors, while joint estimation yields more accurate results but is significantly more computationally intensive. However, we show that hierarchical subtraction can achieve accurate results with a sufficient number of iterations, and on the other hand, NDEs, being able to generate posterior samples rapidly, make it possible to perform signal subtraction and inference repeatedly. Our method provides fast and accurate inference for overlapping GW signals and is highly flexible, accommodating any type of overlapping sources and time differences, therefore has the potential to serve as a general solution to the inference of overlapping GW signals.

EMRIs with spinning secondaries: An approximate scheme for quickly computing spin's effect

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Tuesday Session 4 - B3: Approximations, perturbation theory, and their applications

Extreme mass ratio inspirals (EMRIs) are sources for the low-frequency gravitational-wave antenna LISA. They are expected to make possible exquisitely precise measurements of black hole properties, though such measurements will require waveform templates that faithfully track the system's phase through tens of thousands of orbits. Leading order adiabatic templates are now understood, and work is underway to develop fast public codes and data for producing them. A great deal of theoretical effort now focuses on understanding post-adiabatic effects which also impact the phasing of EMRIs. One such effect is due to the smaller body's spin coupling to spacetime curvature, causing spin-orbit precession and additional "forces" relative to the leading-order motion. In this talk, I will describe work in progress to exploit a useful approximation for quickly computing how secondary spin affects gravitational-wave emission in EMRI systems. By taking advantage of the fact that the leading effect of spin-curvature coupling is akin to "shifting" the orbit of a non-spinning body, we show that a high-quality estimate of a spinning body's backreaction can be computed using simple modifications of a code based on geodesic orbits. This promises to provide rapid estimates of how secondary spin affects EMRI evolution, allowing us to map out where in parameter space its effects are particularly important, and for which non-approximate followup may be necessary.

Speed of Gravity and Cosmology Constraints from Binary Neutron Stars using Time Delays between Gravitational Waves and Short Gamma-ray Bursts

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Thursday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

The landmark detection of a gravitational wave (GW) from the Binary Neutron Star Merger (BNS) GW170817 and its electromagnetic counterparts allowed us to study the Universe in an entirely new way. Among the several discoveries made possible by GW170817, we can find the tightest constraints on the speed of gravity and the measurement of the Hubble constant (H0). Both of these measurements were made thanks to several assumptions and conditions that might not hold for future detections. Specifically, the speed of gravity was measured using agnostic assumptions on the prompt time delay between the GW and the short Gamma-ray burst (sGRB), while the measurement of H0 was made thanks to the identification of the source host galaxy. I will show that relaxing the assumptions on the GW-sGRB prompt time delay, as well as the need for the identification of the host galaxy, still allows us to infer the speed of gravity and H0 with populations of GW sources. By simulating populations of GW-sGRB detections with future observing runs, we find that: (i) it will be possible to jointly fit the GW-sGRB prompt time delay distribution together with the speed of gravity and (ii) it will be possible to measure the Universe expansion even when the source host galaxy is not observed. In particular, the latter result is made possible thanks to a new technique that I explored, which can assign a redshift to the source using the GW-sGRB observed time delay.

Hybridization of second-order gravitational self-force and numerical relativity waveforms for quasi-circular and non-spinning black hole binaries

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Wednesday Session 4 - B3: Approximations, perturbation theory, and their applications

In the past few decades, the waveform community has made advances in producing waveforms that span the inspiral-merger-ringdown of comparable-mass-ratio black hole binaries using numerical relativity (NR) as well as state-of-the-art gravitational wave models. Current methods in NR have shown progress towards producing stable simulations reaching mass ratios of 1:100; however, the computational cost becomes prohibitively expensive as the mass ratio and the length of the simulation increases. The gravitational self-force (GSF) community has developed waveform models that can not only generate extreme mass ratio inspiral (EMRI) waveforms, but also generate near-equal-mass-ratio waveforms with surprising accuracy. To assess the limits of both the GSF and NR waveforms and alleviate computational costs, we present hybridized GSF-NR waveforms with the inspiral of GSF for non-spinning black hole binary systems. The hybrid waveforms are generated from a set of 65 non-spinning NR waveforms with mass ratios $q \leq 10$ and include the (2,2), (2,1), (3,3), (3,2), (4,4), and (4,3) spin-weighted spherical harmonic modes. In this talk, I will highlight a selection of these hybrid waveforms and examine the error in the hybridization procedure. To address the feasibility of hybridizing GSF inspirals with short, high mass ratio NR waveforms, thereby alleviating computational costs, I will discuss the relationship between mass ratio and the placement of the matching window. Finally, I will present a preliminary parameter estimation analysis of the hybrid waveforms with models valid for large mass ratios.

Statistical biases in parameterized searches for gravitational-wave polarizations

Imafuku H[1]
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Wednesday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

In tests of gravity using gravitational waves (GWs), GW events analyzed are often selected based on specific criteria, particularly the signal-to-noise ratio (SNR). However, such event selection can introduce bias into parameter estimation unless the selection effect is appropriately taken into account in the analysis. In this talk, we investigate how event selection with certain prior information affects parameter inference within the scalar-tensor polarization framework, focusing on the measurement of the scalar mode amplitude parameters. We find that for the Tensor+Scalar(dipole) model, the amplitude of the scalar dipole radiation is overestimated when its true value is nonzero while there is no false deviation in the absence of the scalar mode. The same bias is expected to occur also for the Tensor+Scalar(quadrupole) model. However, error typically exceeds the bias as the scalar quadrupole mode is difficult to be distinguished from the tensor mode.

Two years of LISA gravitational waves observations: the simulated Common Dataset 1 of the LISA Distributed Data Processing Center

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Monday Session 4 - C5: LISA and other space-based detectors

The LISA Distributed Data Processing Center (DDPC) has kicked off in June 2024, aiming at designing and implementing the data processing and data analysis software and infrastructure to interpret LISA measurement data-streams. An important component of DDPC is the simulation of a representative, synthetic dataset feeding all the building blocks of data processing and analysis in order to design, optimize and challenge the different pipelines.
The first Common Dataset CD1, code-name «Mojito», is currently under construction. It will eventually contain a rich cocktail of about 100 MBHB mergers, 100 plunging and non-plunging EMRIs, covering a wide region of the parameter space, a galaxy of ~7 millions detached and interacting white-dwarf binaries, completed with two extra-galactic hot-spots (LMC and Andromeda), a few tens of stellar mass black holes binaries including a subset of multi-band systems, and 3-4 different flavors of cosmological stochastic background with different spectral morphologies. The whole being combinable and customizable in a lego-type dataset collection. On the instrument side, two different levels of noise complexity are foreseen, adjusting noise models and properties, or adding glitches and gaps. The main elements of the common dataset will be publicly released eventually.
In this talk, we will detail the source population, the waveform models and the signals included, highlighting the rationale on the physical and astrophysical sides, as well as the constraints and objectives regarding the data processing and data analysis preparation of LISA DDPC.

Learning the neutron star equation of state with Normalising Flows: the dangers of structured data

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Thursday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

We discuss using Normalising Flows to perform the conditional mapping of nuclear equation of state data given observed parameters from gravitational wave signals of binary neutron star mergers. We use a convolutional autoencoder to compress unified high density equations of state - including data from the neutron star crust - to a lower dimensional representation, preserving unique features of the individual equations of state. We find that the Normalising Flow shows evidence of learning underlying structure of high density phenomenological equations of state but struggles to interpolate between training samples regardless of Flow complexity. To address this issue, we present an additional Normalising Flow method to augment data during training, mitigating inherent grid-like structure and alleviating cost associated with traditionally expensive equation of state data generation. This work promotes the rapid inference of the neutron star equation of state from multiple gravitational wave events. This is especially important for next generation ground based detectors where neutron star merger events are expected to be frequent and the assumption of a unique fixed crust is no longer valid.

Quantum reference frames for spacetime symmetries and large gauge transformations

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Monday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

Symmetries, for instance those given by isometries of the spacetime background, have long since provided a guide in our understanding of structural aspects of quantum fields. However, their presence also poses a challenge for an operational treatment of the observables for a QFT: How to distinguish between observables related by a symmetry transformation? The framework of operational quantum reference frames (QRFs) provides a means to describe observables in terms of their relation to a physical reference system, yielding relational (or relative) observables that are invariant under the relevant symmetry group. We discuss a number of applications of these reference frames in the context of quantum field theory on curved backgrounds: 1) A type reduction result for algebras of observables associated with the deSitter static patch. Here we consider observables defined relative to a QRF for a group of spacetime isometries, and provide conditions on the QRF for which these observables admit a well-behaved trace. 2) A gluing procedure for states of the electromagnetic field. We describe observables of the electromagnetic field on a finite region of spacetime (with boundaries and corners), including `edge mode observables' covariant under large gauge transformations acting non-trivially on the corner of this region. Treating these degrees of freedom as a QRF for large gauge symmetries, we can construct gauge invariant observables on non-trivial backgrounds using observables associated with some finite subregions. Using this method, we can construct states on the full gauge invariant algebra of observables from states on these finite subregions.

Asymptotics and Universality in Black Holes: the black hole quasinormal Weyl's law case

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Wednesday Session 3 - A1: Classical GR: Theoretical developments

Current state-of-the-art approaches to black hole (BH) dynamics, encompassing numerical relativity, perturbation theory including self-force calculations, Post-Newtonian theory and other effective approximation schemes offer a remarkable control of the quantitative aspects of strong gravity. Beyond such quantitative description, and together with crucial mathematical relativity inputs, they also provide key insights into some qualitative aspects of the problem. In spite of this, there remain blind spots that hinder the understanding of the mechanisms underlying some observed phenomena, in particular concerning simplicity and universality in BH spacetimes. Adopting an asymptotic approach to a given phenomenon, by filtering non-essential degrees of freedom, can potentially unveil universality patterns by identifying some underlying structural-stability mechanism. Here we illustrate such an asymptotic approach by focusing on recent work on the BH quasinormal (QNM) Weyl's law, that accounts for the universal asymptotics of the QNM "counting function'', complementing previous work by Dyatlov & Zworski. This permits to identify light-trapping and the (local) redshift effect as the underlying mechanisms, also offering a bridge to the universal patterns found in BH QNM spectral instability that we have explored in recent years. As a by-product, Weyl's law universality formally opens an observational access to spacetime (effective) dimensionality. We conclude, more heuristically, by sketching a program recently put forward (with B. Krishnan and C.F. Sopuerta) to apply such "asymptotic reasoning'' in an attempt to address observed simplicity and universality patterns in binary BH merger dynamics in terms of a hierarchy of asymptotic models, potentially making contact with integrability theory in gravity.

Energy extraction from boson stars

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Tuesday Session 4 - B2: Numerical Relativity

Superradiance, first studied by Ginzburg and Frank in the 1940s, refers to the amplification of radiation during a physical process. While extensively studied in rotating or charged black holes, I will show that scalar field solitons, such as boson stars, can also exhibit superradiance. Boson stars are powerful as hypothetical, horizonless compact objects that can mimic black holes and serve as dark matter models. We demonstrate that stable rotating and static boson stars with a polynomial scalar potential can superradiantly amplify incident radiation through a novel mechanism involving mode interactions and coherent field rotation.

Friedmann cosmology with hyperfluids

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Friday Session 3 - A3: Alternative and modified theories of gravity

In metric-affine gravity, both the gravitational and matter actions depend not just on the metric, but also on the independent affine connection. Thus matter can be modeled as a hyperfluid, characterized by both the energy-momentum and hypermomentum tensors. The latter is defined as the variation of the matter action with respect to the connection and it encodes extra (micro)properties of particles. For a homogeneous and isotropic universe, it was recently shown that the generic cosmological hypermomentum possesses five degrees of freedom: one in dilation, two in shear, and two in spin part. The aim of the current work is to present the first systematic study of the implications of this perfect hyperfluid on the universe with Friedmann-Lemaître-Robertson-Walker metric. We adopt a simple model with non-Riemannian Einstein-Hilbert gravitational action plus arbitrary hyperfluid matter, and solve analytically the cosmological equations for single and multiple component hypermomentum contributions using different assumptions about the equation of state. It is remarkable, that in a number of cases the forms of the time evolution of the Hubble function and energy density still coincide with their general relativity counterparts, only the respective indexes w_eff and w_ρ start to differ due to the hypermomentum corrections. The results and insights we obtained are very general and can assist in constructing interesting models to resolve the issues in standard cosmology.

Cosmological Implications for Gravitational Axions

Jenks L[1]
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Friday Session 3 - A3: Alternative and modified theories of gravity

Axions are a compelling dark matter candidate. In this talk, I will discuss a production mechanism and subsequent cosmological implications for gravitational axions - pseudoscalar fields that couple to the parity-odd RR* curvature invariant. I will outline how a mass term for the gravitational axion can be generated via Euclidean wormhole effects, and enumerate several phenomenological consequences. These include applications to dark matter and dark energy, as well as modifications to Chern-Simons gravity.

From the LISA global fit to a catalog of Galactic binaries

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Friday Session 4 - C5: LISA and other space-based detectors

In the next-generation space-based gravitational-wave detector, LISA, gravitational-wave signals from millions of ultra-compact binaries will exist in the detector at any moment during the mission's lifetime. Detecting tens of thousands of these sources is made possible by a simultaneous fit of all sources in the detector data stream, sometimes called the ``global fit.'' However, turning a global fit posterior into a catalog of astrophysical sources presents several nontrivial challenges. First, the global fit uses a trans-dimensional sampling algorithm that includes sources in some iterations which are not present in others. Second, the posteriors for some sources may be multi-modal or lack an individual identity due to overlapping posteriors of two or more sources. Finally, swapping labels of parameters in the posterior chain doesn't change the likelihood, resulting in the label switching problem, which in the limit of perfect sampling will result in all marginalized posteriors being identical in distribution. Here we present a novel method using parameterized distributions to fit the global fit posterior to label individual sources from a trans-dimensional global fit posterior chain and create a catalog of individual sources with specific application to galactic binaries in LISA.

Quantum Gravity can explain the rotation problem and the corresponding acceleration problem

Jones R[1]
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Tuesday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

Arbitrary initial conditions allow solutions of Einstein's field equations for General Relativity to have arbitrarily large relative rotation or acceleration of matter and inertial frames. However, measurements of the cosmic microwave background radiation indicate very small relative rotation or acceleration for our universe (approximately 10^{-20} radians per year and 10^{-19} to 10^{-16} m s^{-2}, respectively). Although we do not have a universally accepted theory of quantum gravity, nearly any reasonable theory of quantum gravity can explain such small relative rotation or relative acceleration by phase interference because the action is an extremum at zero rms relative rotation or acceleration. Even as early as about a quarter of a second after the initial singularity, quantum cosmology would limit the cosmologies that contribute significantly to a path integral calculation to have relative rms rotation less than about 10^{-51} radians per year and relative rms acceleration to be less than about 10^{-50} m s^{-2}. In addition, although inflation dominates the calculation, even if there had been no inflation, the cosmologies contributing significantly to the path integral would have relative rotation rates less than about 10^{-32} radians per year and relative acceleration less than about 10^{-31} m s^{-2} at about a quarter of a second after the initial singularity. The calculations include inflation for 50, 55, and 60 e-foldings, and for values of the dependence of relative rotation or relative acceleration on cosmological scale factor a as a^{-m} for various values of m.

Gravitational wave emission from accreting neutron stars

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Friday Session 3 - B1: Relativistic astrophysics

Accreting neutron stars are promising candidates for producing detectable continuous gravitational wave signals. For this emission to occur, a mechanism must exist to create an asymmetry in the star's mass distribution. We present such a mountain-building mechanism, where temperature asymmetries are created via the anisotropy of the star's thermal conductivity, induced by its magnetic field. These temperature symmetries then produce asymmetries in the mass distribution, via the small but no-zero finite temperature dependence of the high density equation of state. Our calculations are of use in assessing the detectability of such signals, and in interpreting the significance of non-detections and any future detections.

Black Holes, Covariant Entanglement Entropy, and Causal Set Theory

Jones J[1,2]
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Thursday Session 4 - D3: Causal sets, causal dynamical triangulations, non-commutative geometry, asymptotic safety, and other approaches to quantum gravity

Motivated by the frame independence of the Bekenstein-Hawking black hole entropy, and the possibility of it being entanglement entropy in nature, I will present a covariant spacetime definition for the entanglement entropy of free quantum fields. This definition is a spectral formulation, and conducive to frame independent regularisation. Such a regularisation can be provided by causal set theory, wherein this formulation finds a natural place.

The first dedicated search for ultralight vector bosons around merger remnant black holes

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Monday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

Ultralight bosons, if they exist, could form clouds around rapidly rotating black holes through the superradiance mechanism. These boson clouds may produce long-lasting gravitational waves, providing a unique astrophysical probe for physics beyond the Standard Model. Merger remnant black holes from compact binary coalescences are particularly well-suited for such searches due to their known formation history and well-measured properties. In particular, they can host ultralight vector boson clouds that may emit detectable signals within the sensitivity range of current gravitational-wave detectors. In this talk, I will describe a statistical framework that accounts for uncertainties in black hole properties, providing a foundation for setting robust constraints on the existence of ultralight vectors. We apply this framework to the first dedicated search for ultralight vector bosons around merger remnant black holes observed in the latest gravitational-wave observing run.

Advances in semiclassical gravity

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Tuesday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

In semiclassical gravity (SG), quantum fields curve spacetime in an effective way through the expectation value of their stress-energy tensor, while propagating in the spacetime they curve. I discuss some advances in SG in three directions: (i) in understanding structural properties or special solutions of SG in spacetimes with isometries (e.g. static, conformally static, maximally symmetric) and for special Hadamard states (ii) in understanding the initial value formulation and (iii) in black hole evaporation and why information is (very likely) not lost.

A Search for Low-Mass Neutron Stars in the Third Observing Run of Advanced LIGO and Advanced Virgo

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Tuesday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Neutron stars with masses around 1.4 solar masses are consistent with current formation theories, but no sub-solar mass neutron star has been observed so far. Detecting such a low-mass neutron star would be a significant milestone, providing critical constraints on the nuclear equation of state, revealing a new population of neutron stars, and enhancing our understanding of their formation mechanisms. We present the first targeted gravitational-wave search for tidally deformed sub-solar mass binary neutron star (BNS) systems, using data from the Advanced LIGO and Advanced Virgo detectors during their third observing run. We search for binaries with primary masses between 0.1 and 2 solar masses and secondary masses ranging from 0.1 to 1 solar mass, while also accounting for tidal deformabilities up to 10,000. Tidal effects are crucial because low-mass neutron stars are more easily distorted by gravitational forces. Previous searches ignored tidal effects, and potentially lost sensitivity for more than 30% of signals from binaries with a chirp mass of 0.6 solar masses.

Optical studies of core optics for next generation of gravitational wave detectors

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Friday Session 4 - C4: Concept and research towards next-generation detectors

Future gravitational-wave detectors such as Cosmic Explorer and Einstein Telescope are envisioned to operate with better optical coatings and substrates to reduce the impact of thermal noise and optical losses. Cosmic Explorer is designed to be a 40km laser interferometer building on LIGO A+ technologies. To mitigate coating thermal noise in A+ and beyond, new designs of optical coatings need to be rigorously tested. The air annealing scatterometer at Cal State Fullerton is equipped to characterize optical coatings up to 850C. Annealing these samples using a suitable temperature ramp can help determine the onset of scatter and crystallization which is crucial to determining the optimal recipe for low coating noise. In collaboration with Caltech and MIT, these samples undergo various calibrations and measurements across different experiments to determine the overall scatter and coating loss angle.
Crystalline silicon (cSi) is planned to be used as test mass optic in Einstein Telescope as it has desirable thermal properties at cryogenic temperatures. However, the optical properties of cSi require thorough investigation, particularly regarding birefringence and surface/bulk scatter, as these factors influence the overall optical losses in an interferometer. Our lab focusses on studying temperature dependent scatter of cSi at 2 microns between 10K and 295K. A second experiment using a scanning cavity with a cSi sample is being set up to measure the birefringence in silicon at 2 microns. Understanding both these properties is key towards operating a cryogenic interferometer and may have implications on determining the type of silicon and crystal orientation.

Constraining Nuclear Parameters using numerical simulations of BNS Mergers

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Friday Session 4 - B2: Numerical Relativity

The Skyrme formalism for construction of neutron star (NS) equation of state (EOS) parameterizes the same in terms of the nuclear parameters that are constrained by the scattering experiments of heavy nuclei. These paramters along with their allowed values can also be constrained by the gravitational wave (GW) as well as electromagnetic observations of the binary neutron star mergers. In this talk, I will present some preliminary results of hydrodynamical simulations of BNS mergers and signatures of nuclear parameters on the multimessenger signals from them.
In particular, we find that higher values of K_{sat} lowers the maximum density achieved during the merger and post-merger evolution keeping the maximum temperature almost the same. We also find lower neutrino luminosity for lower values of K_{sym}. Total mass of high-speed matter increases with L_{sym} and ϵ_{sym}. GW frequency with peak power decreases with a combination of parameters, K_{sat} and K_{sym}. I will discuss some of the ways nuclear physics community can help us interpret the BNS multimessenger observations for improved understanding of nuclear forces in the strong regime. Here, $K_{\text {sat }}$ is the isoscalar incompressibility modulus, $\epsilon_{\text {sym }}$ is the symmetry energy, L_{sym} is related to the slope of symmetry energy in the direction of increasing density, $K_{\text {sym }}$ is the isovector incompressibility modulus.

Searches for gravitational waves from the 2024 Vela pulsar glitch

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Tuesday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Among known neutron stars, the Vela pulsar is one of the best targets for gravitational-wave searches. It is also one of the most prolific in terms of glitches, sudden frequency increases in a pulsar's timing. Such glitches could cause a variety of transient gravitational-wave signals. This talk gives an update on searches for signals associated with a Vela glitch on 29 April 2024 in data from the fourth LIGO-Virgo-KAGRA observing run. These searches cover both seconds-scale burst-like emission, primarily from f-mode oscillations, and longer quasi-monochromatic transients up to four months in duration, primarily from quadrupolar deformations. Finding such signals, or putting significant non-detection constraints on the gravitational-wave amplitude in either channel, holds great promise in probing the dynamics and interior structure of the pulsar in synergy with electromagnetic observations.

Cosmic Explorer Observatory Conceptual Design

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Monday Session 3 - C4: Concept and research towards next-generation detectors

The Cosmic Explorer observatory will detect gravitational waves as a next-generation ground-based facilty to begin operations in the 2030s. During the design phase, the project is investing in evaluation to understand the impacts on the local region and the field of gravitational wave astrophysics. Cosmic Explorer prioritizes mutually beneficial relationships with local and Indigenous communities, building these relationships as an essential component for identification of potential locations for the observatory. Members of the Cosmic Explorer Consortium contribute to scientific gains and form a community for collaboration, training, and education. As a large scientific facility, Cosmic Explorer will expand the reach of observational gravitational-wave astronomy while impacting the people who interface with the project.

Black Holes and Banking: Inter-sector collaboration to deliver explainable uncertainty quantification.

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Friday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Analysis pipelines that ingest data and either output results from algorithms or predictions from models are ubiquitous in the modern world. Be it a bank that searches for anomalous fraudulent activity in the data steam of customer activity or gravitational wave astronomers searching for chirps in interferometer data streams, both use cases have significant interest in methods to quantify the systematic uncertainty in the inputs and outputs from analysis pipelines as they are a promising way to reduce the risk of errors arising from evaluating code/models in regions outside their expected input/output space.
We have developed a novel explainable generative machine learning model framework to model any tabular data that can be used to both generate synthetic data and evaluate the likelihood of samples which naturally leads to anomaly scores and anomaly detection.
Our method is general and can be used to build a model for the expected behaviour of any tabular dataset which can then be implemented in real-time monitoring software to search for the existence of anomalous data. This method has potential to reduce analysis errors and to discover novel behaviour in the data.
We analyse LIGO triggers generated by the Omicron analysis pipeline during O3a and O3b observation runs to demonstrate how, by adding a layer of uncertainty quantification, that our method can identify potentially anomalous noise triggers which may lead to more robust noise analysis and an improvement in data quality.

Scattered Light Noise mitigation for the AEI 10m Prototype

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Tuesday Session 4 - C3: Progress and challenges in advanced ground-based detectors

Scattered light noise is a significant limitation to the sensitivity of gravitational wave (GW) detectors. Mitigation of this noise is essential for enhancing detector performance and facilitating the detection of weaker gravitational signals. This work focuses on scattered light noise mitigation strategies for the AEI 10m Prototype. We have characterized over 18 different materials as prospective candidates for baffles and high-power beam dumps, aiming to minimize scattering while safely managing high-power laser beams. Additionally, we employed the optical engineering software FRED to conduct scattered light simulations to design and optimize the cavity baffles of the prototype. The optimal materials and baffle design have been modeled in FRED to simulate and calculate the scattered light noise budget, as well as to assess the radiation pressure induced by scattered light on the interferometer's optics. These results provide critical insights into material selection and optical design strategies that effectively reduce scattered light noise, contributing to the overall improvement of GW detector sensitivity.

General-Relativistic Hydrogenic Ions

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Monday Session 3 - A2: Classical GR: Mathematical developments

Gravitational effects between a nucleus and the electron in hydrogenic ions have traditionally been considered too weak to merit consideration. This is a compelling assessment at the non-relativistic level, where Newton's gravitational pair energy and Coulomb's electrical pair energy are qualitatively identical yet differ by approximately 40 orders in magnitude quantitatively. However, general-relativistic gravity is a qualitatively different force of nature. Many surprising results were obtained in quantum-mechanical studies of general-relativistic hydrogenic ions, starting with the Bohr-Sommerfeld-type investigations and continuing for now with mathematically rigorous studies of the quantum-mechanical Dirac operator for an electron in a classical general-relativistic spacetime of a nucleus. After briefly recalling some historical milestones, the talk summarizes our own contributions to this research topic produced over the past several years, in part with our postdocs Ebru Toprak and Eric Ling. The talk concludes with a list of important open problems.

The Quantization and Unruh state forTeukolsky scalars on Kerr spacetimes

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Monday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

One of the big open questions in theoretical physics is the quantization of gravity or, as a first step, its linearized version. A major challenge in this process is the large gauge freedom of the theory. However, on Kerr spacetimes, which describe stationary rotating black holes, there is a way to circumvent this issue. Most solutions to the vacuum Einstein equations linearized around a Kerr spacetime can be obtained from spin-weighted, gauge-invariant scalars satisfying a Teukolsky equation. Similarly, solutions to the Maxwell- and wave-equations can be related to solutions to a Teukolsky equation. Motivated by this, we study the quantization of the spin-s Teukolsky scalars on Kerr spacetimes and construct an analogue of the physically well-motivated Unruh state for this theory.

Identifying loud gravitational-wave bursts from galactic black hole binaries with LISA

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Friday Session 3 - C5: LISA and other space-based detectors

Stellar-mass black hole binaries (BHBs) in galactic nuclei are gravitationally perturbed by the central supermassive black hole (SMBH) of the host galaxy, potentially inducing binary eccentricity oscillations detectable by the Laser Interferometer Space Antenna (LISA), a planned space-based gravitational-wave (GW) detector. These highly eccentric binaries emit GWs during each periastron passage, producing a train of short GW bursts in the LISA mHz band. Detecting binary eccentricity oscillations will have important implications for our understanding of BHB formation channels and dynamics. In this work, we consider the scenario in which multiple BHBs orbit our galaxy's SMBH and subsequently undergo eccentricity oscillations. We develop a methodological framework, based on a wavelet decomposition of the LISA time-delay interferometry (TDI) channels, to identify these GW bursts with LISA, yielding the timing and signal-to-noise ratio (SNR) of each burst event. This timing information can then be passed to a wavelet reconstruction algorithm for the purposes of fitting and subtracting these sources from LISA data.

Late-time dynamics of standing waves in the massive nonlinear Klein-Gordon equation with cubic-quintic terms: a hyperboloidal approach

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Tuesday Session 4 - A2: Classical GR: Mathematical developments

We consider a simplified model of boson stars and investigate a family of time-periodic solutions known as Q-balls in the 3+1 dimensional complex nonlinear Klein-Gordon equation with cubic and quintic nonlinearities on a Minkowski background. The spectral stability of these solutions is analyzed using the Vakhitov-Kolokolov criterion. We further study the long-time evolution of unstable stationary solutions under small perturbations, employing a hyperboloidal foliation of Minkowski spacetime to track their relaxation dynamics.

Gravitomagnetic tidal response of relativistic stars in partially screened scalar-tensor theories

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Tuesday Session 4 - A3: Alternative and modified theories of gravity

In scalar-tensor theories beyond Horndeski, the Vainshtein screening mechanism is only partially effective inside astrophysical bodies. We investigate the potential to detect this partial breaking of Vainshtein screening through the tidal response of fluid bodies. Specifically, we calculate the gravitomagnetic tidal Love numbers and analyze how deviations from general relativity depend on parameters governing the breaking of Vainshtein screening in the weak-gravity regime. For fixed parameter values, the relative deviations increase with higher multipoles and larger compactness. However, we demonstrate that these parameters alone are insufficient to fully characterize the tidal response of relativistic bodies in scalar-tensor theories beyond Horndeski.

Distinguishing Galactic Compact Binaries in LISA’s Observations

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Friday Session 3 - C5: LISA and other space-based detectors

The Laser Interferometer Space Antennae (LISA), a joint ESA-NASA mission set to launch in 2035, will revolutionise our understanding of gravitational waves, targeting a frequency range of 0.1 mHz to 1 Hz. Among its many observational challenges, one key question is whether Galactic compact binaries composed of black holes and neutron stars can be distinguished from the abundant double white dwarf binaries that are expected in the same frequency band. In this study, we perform a mock analysis of 300 binary systems consisting of black holes and neutron stars. By recovering the system masses from fiducial gravitational wave signals, drawn from an astrophysically motivated Galactic population, we explore the feasibility of distinguishing these systems from the larger population of Galactic double white dwarfs. Our results provide insight into the potential of LISA to resolve these systems, contributing to the mission's capability to discern astrophysical populations and advance our understanding of compact binary evolution in the Milky Way.

Penrose inequality for integral energy conditions

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Wednesday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

The classical Penrose inequality, a relation between the ADM and the area of any cross section of the black hole event horizon, was introduced as a test of the weak cosmic censorship: if it fails, the trapped surface is not necessarily behind the event horizon and a naked singularity could develop. Since that original derivation, a variety of proofs have developed mainly focused on the initial data formulation on maximal spacelike slices of spacetime. Most of these proofs are applicable for classical fields, as the energy conditions required are violated in the context of quantum field theory. In this talk, I will present two generalizations of the Penrose inequality: a proof of a classical inequality using an initial data formulation and an average energy condition and a proof of a generalized inequality for evaporating black holes with a connection to the weak cosmic censorship. The latter case is also applicable to quantum fields. Finally, I will present physically motivated examples for both.

Hyperloss destroys quantum squeezed light: Impact of mode mismatch on future gravitational-wave detectors

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Friday Session 4 - C3: Progress and challenges in advanced ground-based detectors

Quantum squeezed light is a key technology in gravitational-wave detection, enabling high sensitivity in current and future detectors. However, taking full advantage of it requires minimizing all sources of optical decoherence. A newly identified — but not yet directly observed — source of decoherence is hyperloss, caused by mismatches between the spatial shapes of optical modes at different interfaces within the detector. When such mismatch occurs, squeezed field coherently couples into a high-order spatial mode, and can re-couple at subsequent interfaces. Due to differences in propagation between two modes, they re-couple with some relative phase offset. This phase offset lead to decoherence due to the coupling of a strong anti-squeezed quadrature. Even at moderate mismatch levels expected in future detectors, the effect can be severe, potentially turning squeezed state into a thermal state. Notably, the effect is much stronger than what would be expected from the nominal level of mode mismatch, making accounting for this effect crucial in the detector design. We experimentally demonstrate hyperloss, observing a complete decoherence of 7dB of squeezed light, leading to a thermal state that exceeds the shot noise level by 2dB with only a 15% total mode mismatch. This effect has major implications for future detectors, such as Einstein Telescope, influencing their sensitivity, design, and the technological advancements required to mitigate decoherence. We discuss these implications and highlight the directions of future research.

Well-posed initial value formulation of general effective field theories of gravity

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Wednesday Session 3 - A3: Alternative and modified theories of gravity

In this talk, I will argue that all higher-derivative effective field theories of vacuum gravity admit a well-posed initial value formulation when augmented by suitable regularising terms. These regularising terms can be obtained by field redefinitions and allow rewriting the resulting equations of motion as a system of second-order nonlinear wave equations. I will also show that the regularising terms introduce auxiliary (non-physical) massive degrees of freedom. However, the masses of these extra degrees of freedom can be chosen to be non-tachyonic and heavier than the cutoff scale, so these modes do not affect the dynamics in the regime of validity of effective field theory. Our well-posed formulation is manifestly covariant and neither requires fine tuning of free parameters nor involves prescribing arbitrary equations. I will explain how our result applies to the quadratic, cubic, and quartic truncations of the effective field theory of gravity that have previously appeared in the literature.

EPR Speedmeter proof-of-principle: measuring mirror speed with two polarization modes in a triangular cavity

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Friday Session 3 - C4: Concept and research towards next-generation detectors

The sensitivity of interferometric gravitational wave detectors is fundamentally limited by quantum noise. One way to overcome this limitation is to perform quantum non-demolition measurement, for example by measuring speed of the interferometer mirrors instead of their position. Several optical layouts to realize these so-called speedmeters have been proposed, but are not yet mature compared to the conventional interferometer topologies. The EPR Speedmeter is based on measuring the position of the interferometer mirrors with two polarization modes, which have different bandwidths and different optical circulating powers, and combines the position information of the two modes with an additional beamsplitter to achieve a back-action free measurement. We use a triangular cavity with two different bandwidths for p- and s-polarization modes to create an equivalent optical system in a tabletop experiment. We control the cavity length to keep it resonant for the p-polarization and shift the frequency of the s-polarization to be resonant in the cavity at the same time. By analyzing the cavity reflection, we aim to show that this optical system enables the measurement of the cavity end mirror's speed, thus realizing a speedmeter configuration that could be implemented in interferometric gravitational wave detectors with minimal infrastructure changes.

A Testbed for Validating Second-Generation TDI and Clock Noise Correction for LISA

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Monday Session 3 - C5: LISA and other space-based detectors

The Laser Interferometer Space Antenna (LISA) will rely on Time-Delay Interferometry (TDI) to cancel laser frequency noise and enable the detection of gravitational waves in the millihertz regime. While TDI has been well studied through software simulations, there have been few experimental demonstrations using hardware capable of generating LISA-like signals. Previous setups have not tested the combination of dynamic delays in combination with clock noise removal in a single system. We present a testbed designed to replicate the dominant noise sources of LISA's interferometric measurement system: laser frequency noise and clock jitter. It implements a two-arm Michelson-X configuration, where inter-satellite beatnotes include time delays consistent with spacecraft motion, Doppler shifts, and a gravitational wave strain signal. A key component of the setup is the FPGA-based delay line, which has been tested and confirmed to introduce very limited additional phase noise beyond LISA's requirements. The testbed also introduces clock sidebands with realistic delays and frequency shifts, allowing for an experimental investigation of both laser noise suppression through second-generation TDI and clock noise correction. This setup provides the first hardware validation of these techniques using data streams that closely mimic LISA's measurement conditions.

Inspiral-merger-ringdown waveforms from gravitational self-force theory

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Wednesday Session 3 - B3: Approximations, perturbation theory, and their applications

The prospect of observing asymmetric compact binaries with next-generation gravitational-wave detectors has motivated the development of fast and accurate waveform models in gravitational self-force theory. These models are based on a two-stage process: in a (slow) offline stage, waveform ingredients are pre-computed as functions on the orbital phase space; in a (fast) online stage, the waveform is generated by evolving through the phase space. This framework has traditionally been restricted to the inspiral stage of a binary, leading to post-adiabatic waveforms that describe the quasi-circular inspiral around a non-spinning black hole with sub-radian accuracy, in remarkable agreement with numerical relativity simulations. In recent work we have extended this framework model across the transition to plunge, where the small companion crosses the innermost stable circular orbit around the primary black hole, and through the final plunge, which generates the binary's merger-ringdown signal. In this talk I present the three regimes (inspiral, transition and plunge) and discuss how they can be combined to construct full inspiral-merger-ringdown waveforms for asymmetric binaries. Finally, I will discuss the late-time comparison with a quasinormal mode sum that has been self-consistently calculated within our framework.

Accounting for the Known Unknown: A General Approach to Account Waveform Systematic Errors in Gravitational Waves Parameter Estimation

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Friday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The parameter estimation for gravitational wave merger events relies on the accuracy of the waveform model. As the sensitivity of gravitational wave detectors keeps increasing, systematic errors can hinder precision science with GW merger events. In this work, we present a framework to account for the waveform systematic errors by introducing relative and absolute phase changes to the reference waveform model. We use the cubic spline curves as a function of frequencies to allow deviation from the reference waveform model.
When the waveform errors are known, those error budgets can be used as a prior distribution in the Bayesian framework. However, the conservative/broader priors can account for waveform systematic errors, even in the absence of these error budgets. Furthermore, we explain how to distinguish waveform systematic errors from other potential systematic errors, such as those from detector calibration uncertainties.
We utilize zero noise injection and recovery campaigns to evaluate the framework's ability to correct waveform systematic errors. We introduce arbitrary systematics to the reference waveform model and demonstrate that even 1-2 percent errors in the cumulative phase of the reference waveform can significantly bias the estimated source parameters of interest. The proposed framework effectively corrects these biases.
Through simulations, we further illustrate the framework's ability to identify signs of missing physical effects not accounted for in waveform modeling and demonstrate its ability to identify data analysis artifacts. These methods are essential to be employed in the analysis pipeline, specially in the era of signals with high signal-to-noise ratio.

Spacetime Penrose Inequality for Cohomogeneity One Initial Data

Kunduri H

Monday Session 3 - A2: Classical GR: Mathematical developments

We outline a proof of the spacetime Penrose inequality for asymptotically flat 2(n+1)-dimensional initial data sets for the Einstein equations, which are invariant under a cohomogeneity one action of SU(n+1). Analogous results are obtained for asymptotically hyperbolic initial data that arise as spatial hypersurfaces in asymptotically Anti de-Sitter spacetimes. More precisely, it is shown that with the dominant energy condition, the total energy is bounded below by an explicit function of the outermost apparent horizon area. Furthermore, the inequality is saturated if and only if the initial data isometrically embed into a Schwarzschild(-AdS) spacetime. This generalizes the only previously known case of the conjectured spacetime Penrose inequality, established under the assumption of spherical symmetry. The proof relies on the generalized Jang equation approach of Bray-Khuri.

Multi messenger constraints from neutron star mergers

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Tuesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

Kilonovae and short gamma-ray bursts (sGRBs) are powerful probes of neutron star mergers, including binary neutron star (BNS) and neutron star-black hole (NSBH) mergers. We produce realistic simulations of neutron star merger events for the upcoming LIGO/Virgo/KAGRA (LVK) observing runs. We use these source properties to generate a population of kilonova light curves and explore the dependence of kilonova detectability on key binary parameters, including mass, distance, inclination, and spin. Furthermore, we present updated multi-messenger neutron star merger detection rates, accounting for uncertainties in the equation of state and volumetric merger rates. Given the recent likely mass-gap neutron star–black hole (mgNSBH) events detected by the LVK, we also investigate possible kilonova emission from such systems. At last, we combine the current BNS and NSBH merger rate estimates with our simulated predictions to assess the fraction of sGRBs produced through each channel and constrain the half-opening angle of the resulting jets. Establishing this link between merger rates and SGRBs will provide insights into the dominant progenitors of sGRBs and the efficiency of jet formation in different merger environments.

Probing stochastic length fluctuations with the QUEST experiment: First results, outlook and single-photon readout.

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Monday Session 4 - C4: Concept and research towards next-generation detectors

The QUEST experiment aims to measure correlated length fluctuation signals by averaging the cross-correlation spectrum of two co-located table-top interferometers over an extended period of time. Being the most sensitive table-top interferometric system to date, QUEST has set the first broadband constraints for a stochastic gravitational wave background from 13 to 80 MHz, reaching a strain sensitivity of 3×10^{-20} 1/√Hz in a coincident run of 10,000 s. In this talk, I present these first results and the techniques used to achieve this sensitivity. Next, I will present the results from our squeezed light sources, which are characterised using the balanced-homodyne detection technique. The application of these squeezed states of light to each interferometer, along with increased circulating power will aid in reaching the design strain sensitivity of 4×10^{-22} 1/√Hz in the next coincident observing run of 1 million s. Further, I will talk about the design and commissioning of the single-photon readout and how this technique could be used to surpass the quantum noise limit in the 5-m long successor of the QUEST experiment. At its design sensitivity, the QUEST experiment can probe a wide variety of stationary signals such as signatures of quantum gravity, scalar field dark matter candidates, and stochastic and continuous gravitational waves.

A covariant formulation of violations of the Equivalence Principle

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Monday Session 3 - C9: Experimental gravitation

In the Newtonian framework a violation of the Equivalence Principle can be described by introducing inertial and graviational masses. Within General Relativity it is not obvious how to couple different particles differently to the same space-time geometry. Here we propose a scheme where - within GR - in a given geometrical background a violation of the universality of free fall as well as of the universality of frame dragging can be formulated. This extends the geometrizitation from translational degrees of freedom to rotational degrees of freedom. This procedure can be applied to a more specific analysis of the recent best test of the Universality of Free Fall from the space mission MICROSCOPE and also to the tests of the Schiff effect by the space mission Gravity Probe B.

(In)stability of black hole ringdown with localized matter distributions

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Tuesday Session 3 - B3: Approximations, perturbation theory, and their applications

Recent studies have shown that small, far-field perturbations to a black hole may destabilize its quasinormal mode spectrum. However, the destabilized spectrum does not necessarily translate into significant differences in the time-domain ringdown signal. In this work, we study the quasinormal mode spectrum and ringdown behavior of a Schwarzchild black hole with a simple physical far-field perturbation (entirely within the framework of General Relativity) -- a thin matter shell with finite surface tension. After accounting for the dynamics of the interaction between GWs and the matter shell, we find that for certain configurations, the spectrum is destabilized, and in the polar sector, the coupling between the metric perturbations and the oscillations of the shell sources QNMs with nearly-real frequencies. The existence of these weakly-damped modes alters the ringdown behavior of polar metric perturbations, introducing a weakly-damped component at late times, but due to the lack of coupling between axial perturbations to the motion of the spherical shell, axial ringdown is essentially unchanged despite also displaying a destabilized QNM spectrum. In an effort to understand how the presence of a thin spherical shell could be inferred from data analyses, we also study whether least-squares QNM fits or the full and rational ringdown filters can clearly identify the signatures of the shell on a radial infall ringdown waveform.

Adaptive optic for mode matching correction

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Friday Session 4 - C3: Progress and challenges in advanced ground-based detectors

Quantum noise limits the sensitivity of the gravitational waves detectors. Its effect is damped using a technique named the “frequency dependent squeezing” which consists in injecting a squeezed vacuum beam into the interferometer by its output port. However, this technique is effective only if the spatial distribution of the squeezed vacuum beam matches the spatial distribution of the interferometer laser beam. The difference between the spatial distributions of the two beams is called “Mode mismatch”. This effect is one the main limitation of the quantum noise cancellation. In addition, the shape of the interferometer main beam changes due to the interferometer operation. To adapt continuously the squeezing beam shape to the interferometer beam, and so correct the mode mismatch, two kinds of adaptive mirror have been developed in the university of Trento: One to correct the beam focusing, the other to correct the astigmatism defect. These mirrors are meant to be installed on the Virgo site, and on the future detector Einstein-Telescope.

Cosmic Variance Effects on Gravitational Wave Background Spectra

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Monday Session 4 - C1: Pulsar timing arrays

A Gravitational Wave Background (GWB) is the confusion noise from overlapping gravitational waves (GWs) of astrophysical or cosmological origin. Typically, it is modelled as a stochastic, isotropic, and Gaussian process. However, these assumptions are only valid for a cosmological GWB source, or in the large number limit of a finite population of astrophysical GW sources, as recent work shows (e.g. Allen 2023). Cosmic variance introduces uncertainties in the predicted astrophysical GWB strain due to wave interference effects and Poisson statistics, which also results in anisotropies and non-Gaussianity in certain regimes. In this talk, we will present our work on analytically deriving the astrophysical GWB spectrum observed by pulsar timing arrays (PTAs) and its statistics after incorporating cosmic variance effects. We will discuss the limits it may place on astrophysical parameter estimation in PTA data analysis, and how it may affect our ability to distinguish between GWBs of different sources across the gravitational wave spectrum.

Oscillatory spacelike singularities: The Bianchi type VI_{-1/9} vacuum models

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Friday Session 3 - A2: Classical GR: Mathematical developments

The Bianchi type VI_{-1/9}, VIII and IX vacuum models all have 4-dimensional Hubble-normalized state spaces and are expected to have a generic initial oscillatory singularity, but the invariant boundary sets responsible for the oscillations are much more complicated for type VI_{-1/9} than those of type VIII and IX. For the first time, we explicitly solve the equations on these type VI_{-1/9} boundary sets and also introduce a new graphic representation of the associated network of heteroclinic chains (i.e. sequences of solutions describing the oscillations). In particular, we give examples of networks of entangled cyclic heteroclinic chains and show that only some of these cyclic heteroclinic chains are asymptotically relevant.

Signatures from metastable oppositely-charged black hole binaries (Part I)

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Wednesday Session 3 - A3: Alternative and modified theories of gravity

Gravitational wave observations of compact objects have provided new opportunities to test our understanding of gravity in the strong-field, highly dynamical regime. To perform model-dependent tests of General Relativity with these observations, as well as to guide theory-agnostic tests, it is crucial to develop inspiral-merger-ringdown waveforms in alternative theories of gravity. In this talk, we present an example of a type of binary system in an alternative theory of gravity that undergoes a sudden state transition during the inspiral. This gives rise to telltale signatures such as a change in the multipolar character of the scalar radiation and the introduction of eccentricity in the orbit.

Stochastic Inflation in Numerical Relativity

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Wednesday Session 3 - B2: Numerical Relativity

The absence of general non-perturbative methods in quantum field theory on curved spacetimes has highlighted the importance of numerical studies in classical regimes. This work presents an overview of our recent advances in solving the equations of general relativity (GR) for inhomogeneous inflation, driven by vacuum quantum fluctuations.
A key contribution of this work is the transition from a cosmological framework—such as knowledge of curvature perturbations on comoving hypersurfaces—to a numerical relativity framework. This transition introduces a consistent method for incorporating perturbative initial conditions that satisfy GR constraints. Moreover, it naturally defines a coarse-graining procedure for an inflating spacetime, enabling the construction of a stochastic model for inflation in full GR. We explain the subtlety between an initial input of perturbations and stochastic sources, which relates to the concept of quantum diffusion.
Finally, we report on our latest simulations, which appear to be among the first stochastic PDE systems solved within GR. These include non-perturbative phenomena arising from perturbative sources, highlighting the potential of numerical relativity to probe these regimes.

Progress on second-order self-force for Kerr

Leather B[1], Bourg P[2], Dolan S[3], Dyson C[4], Nasipak Z[5], Osburn T[6], Pound A[5], Spiers A[7], Upton S[5], Wardell B[8]
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Monday Session 3 - B3: Approximations, perturbation theory, and their applications

To achieve the stringent accuracy requirements for the Laser Interferometer Space Antenna (LISA), second-order, first post-adiabatic (1PA) waveforms are required over the full parameter space of astrophysically realistic configurations. These 1PA waveforms, derived from gravitational self-force (GSF) theory in combination with a multiscale expansion framework, provide a principled and computationally efficient modelling strategy capable of generating accurate waveforms grounded in first principles within milliseconds.
Recently, 1PA waveforms have become available for quasi-circular inspirals involving non-spinning or slowly spinning primary black holes. Initially developed for extreme-mass-ratio inspirals (EMRIs), 1PA waveforms have demonstrated robust accuracy across a broader range of mass ratios, extending into the intermediate mass-ratio regime. However, binaries involving a rapidly spinning (Kerr) primary are expected to be significantly more relevant in realistic astrophysical scenarios. Accurately modelling these systems necessitates carefully treating spin effects at second order in the mass ratio, which the second-order Teukolsky formalism uniquely addresses.
In this talk, I will review the current state of the art in second-order GSF theory and discuss recent advances in extending these calculations to spinning primaries—an essential step toward accurate, efficient, and astrophysically realistic waveform models for future gravitational-wave observations.

What is the Topology of the Observed Universe?

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Tuesday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

Cosmology is based on observations made within the observable universe. The widely accepted Lambda cold dark matter (ΛCDM) cosmological model, suggests a topology of M ≈ R1 × S3, indicating a universe of compact spaces. However, current observational data are not sufficient to determine the size of the universe. Exploring the universe from an external viewpoint yields interesting insights. Through astronomical observations and daily experience, we first show that the universe is not spatially finite. We then prove that spacelike hypersurfaces in the globally hyperbolic space–time, including the ΛCDM model and all other cosmological models, lead to topologically Euclidean three-spaces, challenging traditional belief. This establishes that the globally hyperbolic space–time is topologically R4, settling the long debate on the universe's sizes. This is especially clear in light of the recent discovery of the accelerated expansion of the universe. Our proof is topological yet easy to understand, and is independent of detailed gravitational theories. Classical notions of a closed oscillating universe, multi-universe, wormholes as well as very recent work in Physical Review Letters [1] are ruled out. We reinterpret the ΛCDM model, provide new insights, highlight challenges in quantum gravity, and provide a proper area for string theory.

Null surfaces, Carrollian Hydrodynamics and non-linear behavior of black holes

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Wednesday Session 4 - A1: Classical GR: Theoretical developments

The behavior of null surfaces has been found to be dual to that of (a subset) of Carrollian fluids. The underlying dual description can be exploited to shed light on both such fluids and the dynamical behavior of null surfaces. In particular, to explore the non-linear regime and its transition to the linear one as black holes relax to equilibrium

Folding black-hole spin and recoil estimates in multi-messenger observations of black-hole mergers in AGN disks

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[1]The Chinese University of Hong Kong, [2]Universidade de Santiago de Compostela, [3]The Pennsylvania State University

Wednesday Session 4 - C7: Multi-messenger astronomy of gravitational wave source

Binary black-hole mergers in dense environments can produce electromagnetic counterparts as the remnant black-hole recoils through the host environment, such as the accretion disks of AGNs, enabling multi-messenger observations that can deliver independent estimates of the Hubble parameters. While several such candidates exist, their assessments are based solely on the consistency of their sky locations inferred from the electromagnetic (EM) and gravitational-wave signals, ignoring the consistency of the binary parameters that underlie the emission mechanism. For instance, considering a jet produced via the Blandford-Znajek mechanism, the visibility of the EM flare will depend on the alignment of the final spin and recoil of the remnant black hole with the line of sight. In this talk, I will show how including such information can help confirm existing candidates and rule out the unphysical ones, even for current gravitational-wave detectors, with a special focus on GW190521.

Perturbative framework to compute spectral and modal shifts of a Kerr black hole

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Thursday Session 3 - C10: Experimental tests of the nature of compact objects

Black hole ringdowns are described for much of their evolution by quasinormal modes. Due to the dissipative nature of the system, these modes have complex frequency and do not in general form a complete set. It was recently shown, however, that under an appropriate product, quasinormal modes are orthogonal to each other [Green+ PRD (2023)]. Exploiting this product, we develop a perturbative framework analogous to quantum-mechanical perturbation theory. We use this framework to calculate spectral shifts and mode corrections to Kerr quasinormal modes due to a small deformation of the Kerr background.

A pseudo-Hamiltonian framework for Gravitational Self-force

Lewis J[1]
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Tuesday Session 4 - B3: Approximations, perturbation theory, and their applications

In recent years, gravitational self-force theory has been established as a framework for modelling compact binaries, particularly extreme mass-ratio inspirals (EMRIs), both quickly and accurately at adiabatic (0PA) and first post-adiabatic (1PA) orders. In particular, the separation of timescales in an EMRI is exploited via a multiscale expansion of the Einstein equations. In this talk, we present a gauge-invariant waveform-generation framework at first post-adiabatic (1PA) order, circumnavigating the direct calculation of the gauge-dependent self-force. To achieve this, we recast the established multiscale framework in a pseudo-Hamiltonian form, incorporating dissipation and deriving local-in-time equations of motion. We find a conservative Hamiltonian structure can be naturally embedded into the complete, dissipative 1PA pseudo-Hamiltonian dynamics, giving rise to natural definitions of the conserved energy, angular momentum, and action variables. As a by-product, we clarify that the on-shell value of the conservative Hamiltonian is equal to the binding energy historically predicted by the first law of binary black hole mechanics

Model Extreme Mass-Ratio Inspiral within an Ultralight Scalar Cloud

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Thursday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Gravitational wave detections provide novel opportunities to study both fundamental physics and astrophysical environments around black holes. Extreme mass-ratio inspiral (EMRI), as one major target of future space-based gravitational wave detectors, can carefully probe the environment around a supermassive black hole via its thousands of wave cycles. Although the modeling of EMRI waveforms has gained great success within vacuum environments in general relativity, it has been limited to simple cases, such as static and spherically symmetric central black holes, in theories beyond general relativity and non-vacuum environments due to the lack of a unified framework. The recent development of the modified Teukolsky formalism has made modeling the EMRI waveforms of more astrophysically relevant, spinning black holes in the complicated settings above possible. The modified Teukolsky formalism has gained success in studying ringdown in theories beyond general relativity, and here we would like to present the first application of this formalism in modeling the EMRI waveform of a spinning black hole within an ultralight scalar cloud formed by superradiance. We first calculate the scalar radiation driven by the EMRI particle and the associated scalar flux, showing their consistencies with other calculations. We then combine this information with the backreaction of the cloud to the supermassive black hole's geometry to compute the additional gravitational flux via the modified Teukolsky formalism. In the end, we present the additional phase shifts due to these fluxes and discuss the potential application of this approach to other scenarios, including theories beyond general relativity.

Effective Gravitoelectric Lagrangian for Neutron Star Dynamical Tides

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Tuesday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

The tidal deformations of neutron stars in binary systems can have a significant impact on the emitted waveforms of gravitational waves. Studying these effects provides a direct window into the internal dynamics of neutron stars, in particular their still unknown equation of state [Abbott et al. (LIGO Scientific, Virgo) (29 May 2018)]. We characterize the tidal dynamics of a rotating neutron star in an external gravitational field by a systematic construction of a Lagrangian in the framework of effective field theory. This Lagrangian is constructed from the degrees of freedom describing the leading order gravitoelectric effects for neutron stars modeled as a perfect fluid as is done e.g. in [Gupta, Steinhoff, Hinderer (2021)]. Using these degrees of freedom we reduce the description to the minimal physically relevant number of terms and characterize the tidal spin via an analysis of the symmetries in the Lagrangian. Further we show that the equations of motion as well as the stress-energy tensor attained from the Lagrangian reproduce the Mathisson–Papapetrou–Dixon (MPD) equations of motion describing general extended objects in General Relativity. Resulting from this analysis we find a discrepancy between the spin defined as the conjugate momentum of the angular velocity and the Dixon spin in the MPD equations.

Magnetic Flux--Disk Mass Correlation in Black Hole--Neutron Star Mergers

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Thursday Session 4 - B1: Relativistic astrophysics

We perform numerical relativity simulations of black hole--neutron star (BH--NS) mergers with a fixed mass ratio, varying the BH spin to produce a wide range of post-merger accretion disk masses. Our high-order numerical scheme, fine resolution, and Large Eddy Simulation techniques enable us to achieve likely the most resolved BH--NS merger simulations to date, capturing the post-merger magnetic field amplification driven by turbulent dynamo processes. Following tidal disruption and during disk formation, the Kelvin-Helmholtz instability in the spiral arm drives a turbulent state in which the magnetic field, initialized to a realistic average value of $10^{11}\, \rm{G}$, grows to an average of approximately $10^{14}\, \rm{G}$ in the first $\approx 20\, \mathrm{ms}$ post-merger. Notably, the dimensionless magnetic flux on the BH, $ \phi $, evolves similarly across nearly two orders of magnitude in disk mass. This similarity, along with estimates from longer numerical simulations of the decay of the mass accretion rate, suggests a universal timescale at which the dimensionless flux saturates at a magnetically arrested state~(MAD) such that $ \phi \approx 50 $ at $t_{\rm MAD} \gtrsim 10\,{\rm s}$. The unified framework of Gottlieb et al. (2023) established that the MAD timescale sets the duration of the resulting compact binary gamma-ray burst, implying that all BH--NS mergers contribute to the recently detected new class of long-duration compact binary gamma-ray bursts.

Innermost stable circular orbit of comparable-mass compact binaries at the fourth post-Newtonian order

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Tuesday Session 3 - B3: Approximations, perturbation theory, and their applications

We compute by means of post-Newtonian (PN) methods the innermost stable circular orbit (ISCO) of comparable-mass compact binaries. Two methods are used, with equivalent results: one based on the equations of motion in harmonic coordinates and one on the Hamiltonian formalism in ADM coordinates.
The ISCO is deduced from an invariant stability criterion, extending the 3PN criterion of Blanchet and Iyer (2003) to the 4PN order. The heart of the derivation of this 4PN criterion is the study of the perturbation of the tail integrals appearing in the dynamics, which are non-local in time.
Our results for the ISCO are in good agreement with self-force and numerical relativity ones. We also explicitly show that the 4PN Lagrangian and 4PN Hamiltonian intermediate results are equivalent by deriving the relation between harmonic and ADM coordinates.

Dynamics Of Quadratic f(r) Cosmology With A Perfect-fluid: Jordan And Einstein Frames

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Friday Session 4 - A3: Alternative and modified theories of gravity

The f(R) theory of gravity extends General Relativity, leading to two mathematically equivalent but physically distinct representations: the Jordan frame and the Einstein frame. In the Jordan frame, the modifications appear explicitly in the gravitational sector, while the Einstein frame is obtained via a conformal transformation, recasting the theory as General Relativity coupled to a scalar field. In this frame, the additional degree of freedom manifests as a dynamical scalar field with a potential, making it particularly useful for studying the cosmological implications of f(R) gravity, such as inflation and late-time acceleration.
Understanding the relationship between these frames is essential for assessing the viability of f(R) models and their compatibility with observations. In our work, we analyse the dynamics of the quadratic f(R) theory in a flat Friedmann–Robertson–Walker (FRW) cosmology with a perfect fluid, obeying a linear equation of state. We introduce global and regular dynamical system formulations in both frames, enabling us to identify solutions that are globally mapped between the Jordan and Einstein frames—and those that are not—within a global state space picture.

Relativistic single-electron wavepacket in quantum electromagnetic fields: coherence, radiation, and the Unruh effect

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Thursday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

We present a linearized effective theory using a Gaussian wavepacket description for a charged relativistic particle coupled to quantum electromagnetic fields to explore the interplay between single electrons and quantum fields in free space, at a scale well below the Schwinger limit. The proper values of the regulators in our effective theory are determined according to the data from individual experiments, and will be time-dependent in the laboratory frame if the single electrons are accelerated. Using this theoretical tool, we study quantum decoherence of flying electrons in free space, quantum radiation emitted by them, and the Unruh effect on the accelerated electrons.

Violation of weak cosmic censorship in de Sitter space

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Monday Session 4 - A1: Classical GR: Theoretical development

Inspired by the recent discovery of a violation of strong cosmic censorship (SCC) for the near-extremal Reissner-Nordström black holes in de Sitter space (RN-dS), we investigate if the weak cosmic censorship conjecture (WCCC) can also be violated in RN-dS with a fixed cosmological constant. Our method is based on the recent formulation of examining WCCC by the constraint of the second law, which in this case requires the sum of areas of the event and cosmic horizons cannot decrease during the infall process of Wald's gedanken experiment. We find that the WCCC can be violated for the near-extremal RN-dS in some regimes of second-order perturbation of field configurations. Given the charge parameter of RN-dS, we can find the lowest value of the subextremality parameter, beyond which the WCCC holds. Our results imply that there might be possible correlations between the violation of SCC and WCC. Because of a lack of an unambiguous relation between the gravitational mass and matter's kinematic mass in asymptotically de Sitter space, we cannot compare the corresponding regimes of parameter space for the violations of SCC and WCCC. We also discuss the subtlety in formulating the first- and second-law approaches to examine WCCC.

Remote Helicon Plasma Sputter Deposition of Ta2O5 Optical Coating for Gravitational Wave Detection

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Friday Session 4 - C4: Concept and research towards next-generation detectors

Mirror coatings for gravitational wave detectors are required to meet a variety of specifications including low optical absorption, high reflectance, and low thermal noise as well as high resistance against damage by laser power radiation, long term optical stability and high uniformity. With next generation detectors such as ALIGO+ and ALIGO# looking to increase sensitivity by at least a factor of 2, the mirror coatings must be improved to meet this demand. There are several methods under investigation to improve the mirror coatings such as alternative materials, multi-material coatings, crystalline coatings and alternative deposition techniques. In this work, we present the characterisation of the mechanical, optical, and structural properties of Ta2O5 thin films deposited by remote Helicon plasma sputtering deposition, analysing the effects of thermal annealing on these properties, and evaluating the potential of this advanced sputtering method to produce high index materials for GWDs. The results of this study show that an annealing temperature of 400oC reduced mechanical loss of Ta2O5 down to $\phi = 1.8 \times 10{-}4$, with low optical absorption and extinction coefficients of around 2.15ppm and $k = 1.2 \times 10{-}6$ (at 1064nm). Furthermore, the results of this study show a low stress of -52.80 MPa and 6.39 MPa pre and post annealing respectively with a theoretical zero-stress point achievable under specific annealing conditions. Additionally, we discuss the potential of remote Helicon plasma sputter deposition as a complementary technique to ion beam sputtering (IBS) for deposition of gravitational wave detector coatings.

On Hidden Degeneracies of Spacetimes

Linley J

Friday Session 4 - A2: Classical GR: Mathematical developments

We present carefully constructed examples of spacetimes whose metrics are geometrically degenerate at limiting points and therefore not extendible to those points. After a coordinate transformation, these same metrics appear non-degenerate; that is, their component matrices become regular. This apparent contradiction arises because the new coordinate map is itself degenerate in such a way as to mask the true degeneracy of the metric.
These examples highlight a serious issue: no coordinate representation of a metric alone can reliably be used to assess degeneracy. In practice, one often treats a metric as non-degenerate simply because its component matrix is invertible in some coordinate chart. But this always involves the hidden assumption that the map which pushes forward the coordinate system to the manifold-level metric is itself non-degenerate. In general, there is no independent way of knowing whether this is true.
These observations impose strong limitations on how extendibility and singularities are assessed in general relativity. However, we also present a constructive geometric method that provides a sufficient condition for identifying genuine degeneracy, offering a coordinate-independent resolution to this ambiguity.

The ongoing International Pulsar Timing Array data release: Characterizing the noise components of the gravitational wave detector

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Monday Session 4 - C1: Pulsar timing arrays

The detection of nanohertz gravitational waves using the pulsar timing array (PTA) experiment is at the forefront of fundamental physics. Recently, regional (PTA) collaborations have released crucial evidence for the existence of a gravitational wave background. These collaborations have also formed a joint force under the International Pulsar Timing Array (IPTA) consortium, to advance toward the first conclusive detection of nanohertz gravitational waves. In this talk, I will first provide a brief introduction to the ongoing IPTA Data Release 3 (DR3) project. This will include the scope of the IPTA DR3 dataset and the standardized procedures for combining data from different regional PTAs. I will then focus on the methodologies used to quantize the noise components in the combined dataset, with a highlight on how to determine the optimal model describing the noise properties. Following this, I will present analysis results primarily based on the early DR3 dataset, discuss key insights gained so far, and outline next-step plans towards the completion of full DR3. Finally, I will briefly touch upon how the SKA is poised to significantly enhance the capabilities of PTA in advancing nanohertz gravitational wave science.

Determination of G with time-of-swing method by using single-crystal silicon spheres

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Tuesday Session 3 - C9: Experimental gravitation

The time-of-swing method was used in our last measurement of G in 2018, which gave the value of G as 6.674184(78)×10^−11 m^3kg^-1s^−2 with an uncertainty of 12 ppm. The distance between the geometric centers of the source masses is the main error source, a 0.36 μm uncertainty of geometric distance introduces an uncertainty of 9.3 ppm to the G value. If the measurement precision of the geometric distance can be reduced to 0.1 μm, its contribution to the G value is less than 2 ppm, as a result it is no longer the main error source in the experiment.
In the on-going G measurement, the single-crystal silicon spheres are going to be used in G measurement due to the higher sphericity and more uniform homogeneity. The laser interferometry is used to measure the geometric distance between the spheres, which is a non-contact measurement method, has a very high precision, and can be carried out on the site to improve the reliability of measurement result. We have constructed a laser interferometric measurement system, with geometric distance measurement uncertainty reaching 11 nm. Furthermore, we have developed some other improvement, such as reducing the deformation of the suspension point and the electromagnetic effects generated by the motor, which can further improve the precision of G measurement. The on-going G measurement is expected to give a new result in a few years.

A Generic Algorithm for Building Hybrids of Precessing Systems

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Monday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

The demand for long and accurate gravitational waveforms is increasing as we prepare for the next generation of detectors and seek to improve the calibration of current waveform models. However, numerical relativity (NR) waveforms, while highly accurate, are often too short for these applications due to their high computational cost. To extend their inspiral phase, hybridization with longer waveforms derived from post-Newtonian (PN), effective-one-body (EOB), or phenomenological models is necessary. While hybrid waveform construction is well established for non-precessing systems, precessing cases pose additional challenges related to frame dependence and multi-mode alignment. In this communication, we present a systematic approach for constructing hybrid precessing waveforms. Among the possibilities of hybridizing in an inertial frame or in the non-inertial coprecessing frame, we find that the latter is preferred. Our method is designed to be robust and broadly applicable, imposing minimal constraints on the input waveforms. We validate our approach through mismatch studies and parameter estimation injections, demonstrating its effectiveness in producing accurate hybrid waveforms.

Eigenvalue repulsion in Kerr quasinormal mode spectra

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Tuesday Session 3 - B3: Approximations, perturbation theory, and their applications

Theoretical understanding of the characteristic oscillations of a perturbed black hole, also referred to as quasinormal modes (QNMs), is crucial to interpreting the late stage of binary black hole mergers that we now routinely observe in gravitational wave detectors. In this work, we introduce a new approach, based on the generalized Sasaki-Nakamura formalism, to compute the QNM spectra and quantify their ease of excitation with quasinormal excitation factors (QNEFs), for scalar, electromagnetic and gravitational perturbations. Using this approach, QNM wavefunctions remain finite at the horizon and spatial infinity. Our results in general agree with previous calculations that were performed using different methods, though we further clarify that the values for QNEFs and their scaling with the mass of the black hole depend on the spin weight of the perturbation. We demonstrate that eigenvalue repulsion, originating from branch point singularities, still plays an important role in the QNM spectra, despite the spectra depend only on the angular momentum of the black hole that only takes a real value. Importantly, the real or the imaginary part of the eigenvalues can cross each other but not both simultaneously, and when crossing occurs in one part, repulsion follows in the another part.

Highly accurate simulations of asymmetric black hole scattering and cross validation of effective-one-body models

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Tuesday Session 3 - B2: Numerical Relativity

The study of unbound binary black hole encounters provides a gauge-invariant method to explore strong-field two-body gravitational interactions. In this work, we present a new set of highly accurate numerical relativity (NR) simulations of black hole scattering, generated using the Spectral Einstein Code (SpEC). Our simulations include both spin-aligned systems and unequal mass ratios extending up to q=8. We perform the first direct comparison of scattering angles computed using different NR codes, finding good agreement. Additionally, we compare our NR scattering angle results to effective-one-body (EOB) models, specifically the closed-form SEOB-PM and wPM models, as well as the evolved model SEOBNRv5HM. We find that the EOB models match NR results within a few percent accuracy throughout most of the parameter space. Furthermore, we present the first computation of asymmetric scattering angles arising from asymmetric gravitational wave emission and provide a comparison with the SEOB-PM model.

Black holes and other exact solutions in six-derivative gravity

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Wednesday Session 4 - A3: Alternative and modified theories of gravity

Higher-derivative terms are relevant to several approaches to quantum gravity; they occur in the perturbative quantization of Einstein gravity and can be used to construct (super-)renormalizable quantum gravity models. In this talk, we present the first results regarding the classification of exact, static spherically symmetric vacuum solutions to a generic six-derivative gravity (i.e., without assuming specific relations between the coupling constants). By using modified Schwarzschild coordinates and Frobenius analysis we are able to identify six main classes of solutions and determine their number of free parameters. We find novel solutions absent in quadratic gravity, including those with extreme horizons (and their near-horizon limits) that exist without matter sources. We also find asymptotically (anti-)de Sitter spacetimes, giving rise to an effective cosmological constant. The solutions around the origin are contained in a single class, and they are necessarily regular. Together with the existence of double-degenerate horizons, this may indicate the existence of regular black holes in six-derivative gravity. We shall also discuss how the exact solutions can be compared with the previously known linearised solutions.

Eccentric binary black hole simulations with numerical relativity

Lousto C[1]
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Thursday Session 4 - B2: Numerical Relativity

We perform a systematic study of eccentric orbiting nonspinning
black hole binaries. We first make a technical study of the optimal
full numerical techniques to apply to these studies.
We find the grid structure and global resolution
that optimize accuracy and speed of current computational resources,
while choosing different gauge parameters and Courant factors,
$c=dx/dt$, find its optimal value of 0.45.
With these choices we perform a study of the merger times $t_m(e)$
as a function of eccentricity, e,
for configurations with comparable orbital energy content and find that
its dependence is well represented by the post-Newtonian factor
$F(e)=(1+73e^2/24+37e^4/96)/(1-e^2)^{7/2}$, when merger times are
normalized to their quasicircular values, i.e. $t_m(e)\approx t_m(0)/F(e)$.
We then perform a systematic coverage of five small-medium eccentricities
up to $e\sim0.45$ and six mass ratios up to 8.5:1 producing a total of 30
simulations covering up to 25 orbits to merger to further model the
unequal mass ratio dependence of merger times and as a seed study to
a forthcoming new systematic catalog of gravitational
waveforms from eccentric binary black holes to allow directly perform parameter
estimations of gravitational waves events.

Intrinsic rigidity of extremal horizons

Lucietti J

Friday Session 3 - A2: Classical GR: Mathematical developments

I will present a recent proof which shows that the intrinsic geometry of compact cross-sections of any vacuum extremal horizon, possibly with a cosmological constant, must admit a Killing vector field. In particular, this implies that the extremal Kerr horizon is the most general such horizon in four-dimensional General Relativity and completes the classification of the associated near-horizon geometries.

Efficient Eccentric Effective-One-Body Dynamics via Near-Identity Averaging Transformations

Lynch P[1], Buonanno A[1,2], van de Meent M[3,1], Gamboa A[1]
[1]Max Planck Institute for Gravitational Physics, Potsdam, [2]University of Maryland, [3]Neils Bohr Institute, Copenhagen

Wednesday Session 4 - B3: Approximations, perturbation theory, and their applications

Next-generation gravitational wave detectors, such as LISA, the Einstein Telescope, and Cosmic Explorer, will require accurate modelling of long-lived black hole binary signals, including those with orbital eccentricity. A major challenge in using eccentric effective-one-body (EOB) models for parameter estimation is the high computational cost of evolving long-lived eccentric dynamics. We address this by first recasting the EOB equations of motion using the method of osculating orbital elements and then applying near-identity averaging transformations during the inspiral phase.

By implementing these transformations up to second post-adiabatic order, we obtain averaged equations of motion that faithfully capture the long-term dynamics of comparable-mass systems. This approach eliminates the need to resolve rapidly oscillating orbital dynamics, significantly improving computational efficiency. Furthermore, this parametrisation enables the adaptation of fast waveform generation techniques previously developed for extreme mass ratio inspirals, paving the way for more efficient gravitational wave data analysis.

Science Opportunities of Wet Extreme Mass-Ratio Inspirals

Lyu Z[1], Pan Z[2,3], Mao J[4], Jiang N[5,6], Yang H[4]
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Wednesday Session 4 - C7: Multi-messenger astronomy of gravitational wave sources

Wet extreme mass-ratio inspirals (wet EMRIs), which arise from stellar-mass black holes (sBHs) inspiral into supermassive black holes (SMBHs) within the gas-rich environments of Active Galactic Nuclei (AGN), are primary sources of gravitational waves (GWs) for space-borne detectors like LISA, TianQin, and Taiji. Unlike "dry EMRIs", which form through gravitational scattering in nuclear star clusters, wet EMRIs are naturally accompanied by interactions with accretion disks, offering rich multi-messenger science opportunities. They are distinct in generating transient electromagnetic (EM) signals, such as quasi-periodic eruptions (QPEs), which serve as valuable probes of accretion disk physics and SMBH environments. Their GW signals provide an unprecedented precision of the order of $\mathcal{O}(10^{-4}\sim 10^{-6})$ in measuring SMBH mass and spin, enabling the calibration of traditional EM techniques and offering insights into jet formation models. Additionally, wet EMRIs serve as bright and dark sirens for cosmology, facilitating percent-level precision measurements of Hubble parameter through AGN host identification or statistical association. These systems hold immense potential for advancing our understanding of black hole dynamics, accretion physics, and cosmology.

Monte Carlo methods for stationary solutions of general-relativistic Vlasov systems

Mach P[1], Cieślik A[2], Odrzywołek A[1]
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Thursday Session 4 - B1: Relativistic astrophysics

I will present a Monte Carlo type method for computing stationary solutions of the general-relativistic Vlasov equation, describing a gas of non-colliding particles in a curved spacetime. Our approach consists of three key steps: (1) selecting a representative set of trajectory parameters that reflect the assumed properties of the distribution function (e.g., initial, asymptotic, or boundary conditions); (2) numerically solving the corresponding geodesic equations; and (3) implementing a coarse-graining scheme to approximate relevant physical quantities, such as the particle current density and the energy-momentum tensor. I will highlight the main challenges associated with steps (1) and (3), illustrating these difficulties with examples concerning stationary accretion onto the Schwarzschild black hole, either at rest or moving. This talk is based on two papers: Phys. Rev. D 108, 124057 (2023) and Phys. Rev. D 110, 084014 (2024), co-authored by Adam Cieślik and Andrzej Odrzywołek.

Hunting for new glitches in LIGO data using community science

Mackenzie E[1], Berry C[1]
[1]University Of Glasgow

Tuesday Session 3 - C3: Progress and challenges in advanced ground-based detectors

Data from ground-based gravitational-wave detectors like LIGO contains many types of noise. Glitches are short bursts of non-Gaussian noise that may hinder our ability to identify or analyse gravitational-wave signals. They may have instrumental or environmental origins, and new types of glitches may appear following changes in the detectors. The Gravity Spy project studies glitches and their origins, combining insights from volunteers on the community-science Zooniverse platform with machine learning. Here, we review volunteer proposals for new glitch classes, discussing links between these glitches and disturbances in the detectors, reviewing the challenges of identifying the causes of glitches, and examining how new glitch classes pose a challenge for machine-learning classifications. Our results demonstrate how Zooniverse empowers non-experts to make discoveries, and the importance of monitoring changes in data quality in the LIGO detectors.

Gear Up for the Action Replay: Leveraging Lensing for Enhanced Gravitational-wave Early Warning

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Tuesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

An early warning from the Gravitational-wave (GW) detectors of Binary Neutron Star (BNS) and Neutron star Black hole (NSBH) merger could enable the electromagnetic (EM) telescopes to capture the premerger and the merger of these events. We propose an astrophysical scenario that could provide early-warning times of hours to days before coalescence with subarcsecond localization, provided that these events are gravitationally
lensed. The key idea is that if the BNS/NSBH is lensed, then so is the host galaxy identified via the EM counterpart. From the angular separation of the lensed host galaxy images, as well as its redshift and the
(foreground) lens redshift, we demonstrate that, for galaxy-scale lenses, we can predict the time delays/arrival time
differences assuming standard lens models. We construct realistic time delay distributions of detectable
lensed BNSs/NSBHs to forecast the early-warning times we might expect in the future observing scenarios. To assess the feasibility of our lensing-driven idea, we extract time delays directly from galaxy-galaxy strong lensing images observed using two telescopes: a space-based telescope with Hubble Space Telescope (HST) resolution and a ground-based telescope with Hyper Suprime-Cam (HSC) resolution. We then compare the time delay uncertainties between these two observations. Additionally, we explore the viability and advantages of this approach across different lensing systems and GW observing runs, including those of the current LIGO–Virgo–KAGRA network, Voyager, and third-generation detectors.

Ringdown tests of general relativity with spin-precession

Maggio E[1], Pompili L[1], Silva H[2], Buonanno A[1,3], Enficiaud R[1]
[1]Max Planck Institute For Gravitational Physics (Albert Einstein Institute), Potsdam, [2]University of Illinois Urbana-Champaign, [3]University of Maryland

Monday Session 3 - C10: Experimental tests of the nature of compact objects

The coalescence of black-hole (BH) binaries provides a unique arena to test general relativity (GR) in the dynamical and strong-field regime. The ringdown phase, where the merger remnant relaxes to a stationary state, offers a direct probe of the theory. It is dominated by the oscillation frequencies of the remnant, the so-called quasinormal modes, which reveal the nature of the remnant.
In this talk, we present a parametrised test of general relativity that constrains deviations in the quasinormal modes for spin-precessing binaries. We show that neglecting spin-precession can lead to false detections of GR deviations, even at current detector sensitivities, emphasising the need for accurate modelling. Finally, we reanalyse the events of the third Gravitational-Wave Transient Catalog. Using a hierarchical combination of these events, we accurately constrain fractional deviations in the frequency and damping time of the dominant quasinormal mode.

Possible binary neutron star merger history of the primary of GW230529

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Thursday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

Black holes (BHs) with masses between $\sim 3-5M_{\odot}$, produced by a binary neutron star (BNS) merger, can further pair up with a neutron star or BH and merge again within a Hubble time. However, the astrophysical environments in which this can happen and the rate of such mergers are open questions in astrophysics. Gravitational waves may play an important role in answering these questions. In this context, we discuss the possibility that the primary of the recent LIGO-Virgo-KAGRA binary GW230529_181500 (GW230529, in short) is the product of a previous BNS merger. Invoking numerical relativity (NR)-based fitting formulas that map the binary constituents' masses and tidal deformabilities to the mass, spin, and kick velocity of the remnant BH, we investigate the potential parents of GW230529's primary. Our calculations using NR fits based on BNS simulations reveal that the remnant of a high-mass BNS merger similar to GW190425 is consistent with the primary of GW230529. This argument is further strengthened by the gravitational wave-based merger rate estimation of GW190425-like and GW230529-like populations. We show that around 18% (median) of the GW190425-like remnants could become the primary component in GW230529-like mergers. The dimensionless tidal deformability parameter of the heavier neutron star in the parent binary is constrained to 67^{+163}_{-61} at 90% credibility. Using estimates of the gravitational-wave kick imparted to the remnant, we also discuss the astrophysical environments in which these types of mergers can take place and the implications for their future observations.

Semiclassical signatures in black hole perturbations and light rings using Padé approximation

Maharana S[1], Simovic F[1], Soranidis I[1], Terno D[1]
[1]Macquarie University

Thursday Session 3 - C10: Experimental tests of the nature of compact objects

The Event Horizon Telescope image of a dark central object surrounded by light rings (LRs) has provided compelling evidence for astrophysical black holes. This has been further substantiated by the LIGO-Virgo-KAGRA detection of gravitational waves due to two colliding black holes, where the late-time signal consists of quasinormal modes (QNMs) as the resulting compact object settles into equilibrium. While these features are typically studied using the vacuum Schwarzschild and Kerr solutions in classical general relativity (GR), they also appear in various models incorporating quantum effects, matter field contributions, or modifications to GR. A precise analysis of QNMs and LRs can reveal deviations from classical GR and provide insights into the matter distribution around compact objects. A model-independent approach to parameterizing black hole metrics was introduced earlier using the C-fraction expansion called the Rezolla-Zhidenko expansion. In this work, we employ a two-point Padé approximation based on an M-fraction expansion to interpolate between the near-horizon region and the asymptotic structure. Using these Padé-based metrics, we numerically compute the quasinormal mode frequencies of gravitational perturbations in Schwarzschild-like spacetimes via the matrix method. Additionally, we analyze the locations of light rings and their dependence on near-horizon geometries. We also present a concise comparative analysis of various parameterization schemes, assessing their accuracy in reproducing established QNM and LR results from the literature and identifying the contexts in which each is appropriate.

Development of compact interferometric displacement sensors for local test mass readout Using Deep Frequency Modulation Interferometry.

Mahesh M[1], Gerberding O[1], Eckhardt T[1]
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Wednesday Session 4 - C4: Concept and research towards next-generation detectors

To enhance the sensitivity of ground-based detectors at low-frequency range (1 - 10 Hz), we need to improve the local sensing to minimize the noise associated with the seismic isolation system and control. This motivate the deployment of precise local displacement sensors at the mirror suspensions. We have combined Deep frequency modulation and compact interferometric techniques to develop a compact sensor with high displacement sensitivity for the readout of local test masses in future gravitational wave detectors. A sinusoidal laser frequency modulation (~3GHz modulation depth with a rate of 1kHz) is applied and the beat notes are generated from the interference of two homodyning beams that have a time-delay due to an intentional arm-length mismatch. A nonlinear algorithm implemented partly in FPGAs is employed to extract the signal parameters including modulation depth, phase and amplitude from the signal in real time. Here we present the latest design, infrastructure and performance test results of our Compact Balanced Readout Interferometer (COBRI) which is 35 mm long and fits inside a half inch mirror mount. It contains a single quasi-monolithic optic which results in an unequal arm length Michelson interferometer with a dual port readout enabling balance detection. Our precision goal is to achieve sensitivities below 100f$m/$ rt Hz between 0.1-10 Hz.

Black Hole Statistical Mechanics for Near Horizon Observers: Shape fluctuations

Major S[1], Takis T[1]
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Tuesday Session 3 - D1: Loop quantum gravity and spin foams

The statistical mechanics of black holes based on the quasi-local energy for constantly accelerating observers in the near-horizon exterior is explored. The model builds on the statistical mechanics of a gas of non-interacting quanta of geometry, which condenses in the large area limit setting a natural microscopic scale for the system. This talk focuses on the statistical mechanics of `shape fluctuations', or gravitational modes, induced by the Hawking process. These modes reflect off the potential barrier and do not make it out to asymptotic infinity. Modeled using perturbations of Schwarzschild spacetime, the mode frequencies are lower than quasi-normal mode frequencies. The statistical mechanics of shape fluctuations is captured by a two dimensional Debye model. The entropy of the model is computed and compared to the Bekenstein-Hawking entropy. Implications of the results for loop quantum gravity, including the Barbero-Immirzi parameter, as well as implications for physics in the neighborhood of a black hole are discussed.

Time-periodic solutions of the conformally invariant wave equation on the Einstein cylinder

Maliborski M[1], Ficek F[1]
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Tuesday Session 3 - A2: Classical GR: Mathematical developments

As a first step in exploring time-periodic solutions of the Einstein equations with negative cosmological constant, we study the cubic conformal wave equation on the Einstein cylinder. Using a combination of numerical and perturbative techniques, we discover that time-periodic solutions form an intricate bifurcation patters.

Sampling the full hierarchical population posterior distribution in gravitational-wave astronomy

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Thursday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Gravitational-wave population studies and spectral-siren cosmology rely on hierarchical Bayesian inference to extract parameters that describe the astrophysical population of merging compact binaries and the expansion of the Universe. Currently, population inference methods estimate hyperparameters by marginalizing over individual-event parameters, often relying on costly and potentially inaccurate Monte Carlo integrations.
In this presentation, I will discuss a method for sampling the full posterior distribution in the high-dimensional space of both population-level and single-event parameters using modern probabilistic programming languages and Hamiltonian Monte Carlo. This approach enables direct access to "population-informed" individual event parameters, population properties, and their correlations. I will demonstrate this technique with an application to the GWTC-3 catalog, addressing the intrinsic parameter space of binary masses, spin magnitudes, spin directions, and redshift alongside population hyperparameters.
While challenges remain, particularly related to the Monte Carlo integration required for computing the selection function, this method could offer advances towards more accurate and efficient population inference.

Mitigation of Parametric Instabilities in Gravitational Wave Detectors using Mechanical Dampers

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Friday Session 4 - C3: Progress and challenges in advanced ground-based detectors

Increasing laser power is necessary to reduce shot noise and enhance the sensitivity of gravitational wave detectors at high frequencies.
However, when the mirrors have very high quality factors and the circulating laser power in the optical cavity reaches several hundred kilowatts, parametric instabilities may occur.
These instabilities arise from the interaction between cavity optical modes and mirror mechanical modes, negatively impacting the detector's performance.
A mitigation system has to be designed to prevent these instabilities from occurring.
This approach consists of bonding small oscillators with low quality factors, resonating at critical frequencies, to the lateral surfaces of the mirrors.
This reduces the quality factor of the mirror mechanical modes and, consequently, the likelihood of instability.
We present the recent simulations and experimental results from tests on various types of dampers, conducted on a suspended fused silica sample in a vacuum chamber at room temperature.
These tests support the ongoing effort to develop effective damping solutions for the fifth observation run of the Advanced Virgo interferometer.

Methodological approach to evaluate control requirements for gravitational wave detectors

Mantovani M[1], Bersanetti D[2], Boldrini M[3], Casanueva Diaz J[1], De Rossi C[1], Melo S[1], Pinto M[1]
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Friday Session 4 - C3: Progress and challenges in advanced ground-based detectors

The assessment of the requirements for the maximum allowable displacement of optics (both in RMS and within the detection band) is a crucial aspect of designing a new gravitational wave detector. Since these requirements must be defined in order to ensure an optimal performance of a detector, they should account not only for the residual motion of the optics but also for potential defects that could degrade the overall detector response.
This study plays a fundamental role in the design of suspension, sensors and thermal compensation systems.
In this work, we present a methodological approach for computing these requirements, which can serve as a guiding principle for the design of all gravitational wave detectors.

Singularity resolution in the backreacted Schwarzschild geometry from 2D matter with negative central charge

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Tuesday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

2D dilatonic gravity theories provide insightful models to study the dynamics of semiclassical black holes. They are often coupled to conformal 2D scalar fields, since the resulting QFT implements some quantum effects (such as the trace anomaly) while often being simple enough to be solved analytically. Purely from a 2D QFT perspective, the central charge is positive for unitary theories. However, 2D theories with negative central charge are expected to mimic some effects of unitary QFTs in 4D of renewed interest (e.g. dimensionless scalar fields). Recent studies in the CGHS model with an RST term concluded that a negative central charge removes the singularity in the 2D backreacted geometry. In this work, we discuss that the singularity resolution mechanism is a consequence of the negative central charge and not the specific dynamics of the model. For that, we present similar results in spherically reduced Einstein's gravity, a different dilatonic model; and also show that the backreacted geometry of the CGHS model remains nonsingular even without the RST term.

[1] Potaux, D. Sarkar and S. N. Solodukhin, Phys. Rev. Lett. 130, 261501 (2023)
[2] A. del Río, F. J. Marañón-González and J. Navarro-Salas, Phys. Rev. D 111, 045025 (2025)

Timing the gap

Marka S[1]
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Monday Session 3 - C5: LISA and other space-based detectors

The discovery of gravitational waves has revolutionized astrophysics, opening new windows into the universe. As detector technologies advance, a synergistic approach that unites observations across multiple messengers is enabling deeper, more comprehensive cosmic insights. Yet, a crucial frequency band—between 0.1 and 1 Hz—remains beyond the reach of current detectors. This gap holds immense scientific potential, including the study of intermediate-mass black hole mergers, early inspirals of compact binaries, and coordinated multiwavelength campaigns with next-generation observatories like the Einstein Telescope.
To address this challenge, I will introduce the concept of the Artificial Precision Timing Array (APTA)—a novel, space-based gravitational-wave detector inspired by pulsar timing arrays. By using satellites with high-precision clocks to send signals to a central receiver, APTA aims to probe this unexplored band. As clock technologies rapidly advance, APTA represents a bold step toward unlocking a new era in gravitational-wave science.

Stability Properties of Ultracompact Black Hole Mimickers: Radial Stability and Beyond

Marks G[1], Staelens S[1], Evstafyeva T[1], Sperhake U[1]
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Tuesday Session 4 - B2: Numerical Relativity

Motivated by a conjectured dynamical instability brought on by the presence of stable light rings, we study the radial stability properties of a class of ultracompact black hole mimickers modelled as boson stars with a solitonic potential. Fundamental radial oscillation frequencies are computed, and compared to the results of dynamical evolutions using an appropriate dimensional reduction of the BSSN and CCZ4 formalisms. These will be compared to the results of runs in axisymmetry and full 3+1 evolution with no symmetry assumption, with the goal of presenting strong numerical evidence for the long-term stability of these models.

Coating designs using alumina layers for reduced thermal noise in future detectors

Martin I[1], Murray P[1], McGhee G[1], Hill S[1], Fitzgerald S[1], Rowan S[1], Hough J[1], Johnston R[1]
[1]University Of Glasgow

Friday Session 4 - C4: Concept and research towards next-generation detectors

Developing mirror coatings with suitably low thermal noise and optical absorption remains a key challenge for future gravitational wave detectors. This challenge is likely to be solved by a combination of alternative coating materials, optimised coating designs and careful studies of the effects of coating deposition parameters on coating performance. This talk will present recent work in these areas, particularly highlighting the potential for using alumina coating layers as a replacement for low-index silica layers at cryogenic temperatures. Unlike the commonly-used silica low-index layers, the mechanical loss of alumina does not show a cryogenic peak, making it an attractive replacement for reducing thermal noise. Measurements of the mechanical loss and optical absorption of alumina will be presented, and multi-material coating designs in which alumina is partnered with ultra-low loss amorphous silicon layers will be analysed. Such designs will require some top layers of low absorption materials to reduce the absorption contribution of the amorphous silicon, and the parameter space of potential materials will be explored.

Simulation-based Inference of Massive Black Hole Binaries using Sequential Neural Likelihood

Martin Vilchez I[1], Sopuerta C[1]
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Friday Session 3 - C5: LISA and other space-based detectors

We propose a machine learning-based approach for parameter estimation of Massive Black Hole Binaries (MBHBs), leveraging normalizing flows to approximate the likelihood function. By training these flows on simulated data, we can then generate posterior samples via Markov Chain Monte Carlo with a relatively reduced computational cost. Our method enables iterative refinement of smaller models targeting specific MBHB events, with significantly fewer waveform template evaluations. However, dimensionality reduction is crucial to make the method computationally feasible: it dictates both the quality and time efficiency of the method. We present initial results for a single MBHB with Gaussian noise and aim to extend our work to increasingly realistic scenarios, including waveforms with higher modes, non-stationary noise, glitches, and data gaps. Most of this work is based on the article "Efficient Massive Black Hole Binary parameter estimation for LISA using Sequential Neural Likelihood" (arXiv:2406.00565; accepted for publication in JCAP).

Updated Stray Light Induced Noise Simulations in the Einstein Telescope main Arms

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Friday Session 3 - C4: Concept and research towards next-generation detectors

We present an updated estimation of the noise induced by scattered light inside the main arms of the Einstein Telescope (ET) gravitational wave detector. Both ET configurations for high- and low-frequency interferometers are considered. The new studies consider both 10km and 15km arms, and explore possible mis-alignments of the laser beam inside the cavity. As it is already the case in the existing experiments, baffles are used to mitigate and suppress the noise inside the vacuum tubes. New improved simulations are employed including the presence of the baffles and their serrated edges. We propose updated baffle layouts for ET and re-compute the remaining scattered light noise contribution to ET sensitivity.

Combining concurrent all-sky gravitational wave transients searches with coherentWaveBurst-2G

Martini A[1], Prodi G[1], Miani A[1], Bini S[2], Lazzaro C[3], Salemi F[4], Drago M[4], Tiwari S[5], Xu Y[6]
[1]University Of Trento and INFN, [2]Caltech, [3]Università di Cagliari e INFN, [4]Università di Roma La Sapienza and INFN, [5]UZH Universität Zürich, [6]UIB Palma

Thursday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The most general searches for gravitational wave transients are based on data analysis methods that do not assume prior knowledge of the signal s waveform, direction, and arrival time on Earth. These searches are crucial for discovering expected and unexpected sources, providing a data-driven and minimally biased signal reconstruction. Here we discuss the latest deployed methods and achieved performances of the coherentWaveBurst-2G software framework, which is highly adaptable for agnostic or loosely modelled searches for gravitational wave transients (GWTs). Enhancements include the use of a ranking statistic fully based on multivariate classification with eXtreme Gradient Boosting, a deeper validation of the accuracy of the statistical significance of GWT candidates, and the measurement of the correlations of false alarms and simulated detections between different concurrent searches. Various search configurations for GWTs are examined using approximately 14.8 days of observation data from the latest public LIGO-Virgo-KAGRA (LVK) release, i.e., the third observing run, O3. We provide for the first time a comprehensive comparison of search performances on both Hanford-Livingston and Hanford-Livingston-Virgo data. This enables to design advantageous combinations of concurrent searches, offering essential insights for assessing data analysis strategies in the current LVK fourth observing run, O4.

Cosmology on a Gravitational Waves Background

Matos T[1]
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Tuesday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

There is no doubt that we live in a Gravitational Wave Background (GWB). In this talk, we start from this hypothesis and show that, if we consider the energy generated by the GWB, we must extend Einstein's equations with a term $\mathcal{M}=2\pi^2/\lambda^2$, where λ is the Compton wavelength of primordial gravitons. We find that the energy of GWB today is of the order of 10^{-33}eV and the term $\mathcal{M}$ has the same order of magnitude as the cosmological constant, but varies with time. We call this model the Compton Mass Dark Energy (CMaDE). With these equations, we study the corresponding cosmology and, using the SimpleMC code, we find that this model fits the Pantheon + BAO + CC data better than the LCDM model. Then, using the same parameter values and using the CLASS code, we compared this model to the CMB data and found excellent agreement with the CMB and MPS profiles, even significantly reducing the H0 tension. We conclude that the CMaDE model is an excellent candidate for explaining the accelerated expansion of the universe, without cosmological constants, extra matter, or modifications to Einstein's equations. Ref: arXiv:2303.07111 and MNRAS 529, 3013, (2024).

The Impact of Black Hole Spin on Black Hole–Neutron Star Mergers

Matur R[1], Hawke I[1], Andersson N[1]
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Friday Session 4 - B2: Numerical Relativity

The GW230529 event demonstrated that black hole–neutron star systems can contain low-mass black holes, making them particularly favourable for multimessenger observations. Such observations are crucial, as they allow us to extract more information from a single event. They carry direct imprints of the source objects, enabling constraints on key parameters such as spin magnitude and orientation. Most importantly, they provide essential insights into the equation of state of neutron stars. However, the role of black hole spin in these mergers is not well understood. In this talk, we present our latest numerical relativity simulation results, focusing on how black hole spin influences both the gravitational wave signal and the properties of the ejected matter. We further examine whether these effects can be detected and constrained with current and next-generation ground-based gravitational wave observatories.

Spin two field superradiance beyond the linear story

May T[1], East W[1]
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Tuesday Session 3 - A3: Alternative and modified theories of gravity

Massive spin-2 particle models have been proposed in the context of dark matter and beyond standard model physics. Constraints on these particles have been places under the assumption that the phenomenology for black hole superradiance follows the same story as in the case of particles with spin one or zero. Here we consider a particular non-linear theory, quadratic gravity, to study the behaviour of spin two particles that undergo superradiance around black holes.

Gravitational wave propagation beyond General Relativity: geometric optic expansion and lens-induced dispersion

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Friday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

GW propagation tests of theories beyond Einstein's general relativity (GR) are constrained by the high symmetry of the average cosmological spacetime. In the presence of inhomogeneities (i.e., gravitational lenses) deviations from GR can give rise to new interactions, e.g., between standard GW polarizations and additional scalar or vector fields with different spin, leading to potentially observable phenomena.

Relying on the short-wave expansion, this talk presents a novel framework to describe beyond geometric optics corrections to GW amplitude and phase in scalar-tensor theories of gravity. These corrections represent dispersive phenomena, analogous to how a prism splits light into its component frequencies. In this picture, gravitational lenses induce frequency-dependent signatures on the GW signal, a phenomenon we term lens-induced dispersion (LID). These effects arise from interactions with zero derivatives, which are expected in any modified theory of gravity. While analogous effects exist in GR, they do not impact GW polarizations and leave no observable imprint on the signal. LID phenomena are therefore a universal prediction beyond GR. They can be tested on any GW signal, without requiring an electromagnetic counterpart, and offer a new tool for new tests of GR.

Approximately universal relations for the average stiffness of neutron stars and applications to tests of General Relativity

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Tuesday Session 4 - A3: Alternative and modified theories of gravity

Universal relations (i.e., insensitive to the equation of state) linking macroscopic and microscopic properties of neutron stars can provide a clean window into the behavior of nuclear matter. In this talk, we discuss a tight correlation between certain macroscopic properties of a neutron star—its compactness, moment of inertia, and tidal deformability—and a suitably defined average of the squared speed of sound within the star. This quantity provides a meaningful measure of the star's average stiffness and offers insights into the underlying nuclear matter properties.

We describe key properties of this stiffness measure for both static and rotating neutron stars, assess the approximate universality of the associated relations, and explore their physical origins. We then discuss the implications of these findings in light of recent and future neutron star observations. In particular, we explore the possibility that the averaged speed of sound squared exceeds the so-called conformal limit. This property, that holds for highly compact neutron stars obeying many (though not all) realistic equations of state, would turn these objects into valuable laboratories for testing various scalar extensions of general relativity.

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Classification and stability of black hole event horizon births: a contact geometry approach

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Wednesday Session 3 - A2: Classical GR: Mathematical developments

A classical result by Penrose establishes that null geodesics generating a black hole event horizon can only intersect at their entrance to the horizon in “crossover” points forming the “crease set”. Such “crease sets” finish at points where light rays focus on “caustics”. This can be paraphrased by saying that black hole horizons “are born” at their crease set. A natural question in this context refers to the classification and stability of crease sets,
that is, of the structural possibilities in which black holes can be born. In this talk we revisit the strategy adopted by Gadioux & Reall for such a classification in the setting of singularity theory in contact geometry. Specifically, in such contact geometry setting, the black hole event horizon is identified as a section (not connected to null infinity) of a so-called “bigfront”. The characterisation of bigfronts as Legendrian projections of Legendrian submanifolds of appropriate contact manifolds permits to classify the possible crease sets and “cuspidal sets” (the latter corresponding, in the contact geometry terminology, to Penrose’s caustics) by applying classical results established by the school of V.I. Arnol’d. Here we extend the work by Gadioux & Reall by focusing on refining the stability discussion of the relevant structures. This analysis permits to establish the causal connection with null infinity of the other (connected) components of the crease set and (most of) the cuspidal set of the entire bigfront. Such visibility of “caustics” by distant observers invites to consider potential observational signatures of black hole births.

All-Sky Search for Continuous Gravitational-Wave Signals from Unknown Neutron Stars in Binary Systems Using O4a Data

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[1]University Of The Balearic Islands

Tuesday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Rapidly rotating, non-axisymmetric neutron stars (NSs) are expected to emit continuous gravitational waves (CWs). Detecting these signals would significantly enhance our understanding of the galactic NS population and matter under extreme conditions, while also providing valuable tests of general relativity. NSs in binary systems likely constitute a substantial fraction of the unobserved galactic population and, due to potential mass accretion, may emit stronger CW signals than their isolated counterparts. The LIGO-Virgo-KAGRA (LVK) Collaboration employs various techniques to search for CWs, with blind all-sky searches for NSs in binary systems being among the most computationally challenging. These searches must account for a large orbital parameter space, Doppler modulation effects, and the need for all-sky coverage. The GPU-accelerated FastTracks pipeline has been developed to address these challenges, enabling an efficient and highly sensitive search at reduced computing cost.
In this talk, after a general introduction to the FastTracks analysis method and the target source populations, we will discuss implementation, performance, and results from analysis of LVK observing run O3a. Additionally, we will present the latest progress of the ongoing search for the first part of the fourth observing run (O4a), optimized to target the most sensitive frequency range of the LIGO detectors.

Enhanced Laser Stability and Diagnostic Tools for Gravitational-Wave Detectors

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Friday Session 3 - C4: Concept and research towards next-generation detectors

Gravitational-wave detectors require exceptional stability of their laser sources to minimize noise coupling via optical asymmetries. While active and passive stabilization techniques are effective, the development of inherently lowest-noise lasers and amplifiers remains crucial. We present a next-generation non-planar ring oscillator laser, achieving a tenfold reduction in laser power and frequency noise. The improvement in frequency noise persists through amplification, enabling a tenfold reduction in laser-system frequency noise. For sensor noise-limited systems, this advancement could potentially relax stabilization requirements.

To perform a full characterization of such laser systems, a novel diagnostic tool combining fiber-optic and free-space techniques in a compact design is introduced. It measures laser power and frequency noise from 1 Hz to over 100 MHz, using FPGA-based digital control for processes like demodulation and feedback control, traditionally handled by analog systems.

These advancements in laser sources and their characterization not only address limitations in gravitational-wave detectors but also open new possibilities in quantum optics and optical communications, where reduced noise enhances sensitivity and performance.

Extending Starobinsky's formalism to general relativity (favourite)

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Thursday Session 4 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

The continual production of long wavelength gravitons during primordial inflation endows graviton loop corrections with secular growth factors. During a prolonged period of inflation these factors eventually overwhelm the small loop-counting parameter of GH2, causing perturbation theory to break down. A technique was recently developed for summing the leading secular effects at each order in non-linear sigma models, which possess the same kind of derivative interactions as gravity. This technique combines a variant of Starobinskys stochastic formalism with a variant of the renormalization group. Generalizing the technique to quantum gravity is a two-step process, the first of which is the determination of the gauge fixing condition that will allow this summation to be realised. Moreover, I will briefly discuss the second step which shall obtain the Langevin equation in which secular changes in gravitational phenomena are driven by stochastic fluctuations of the graviton field.

Plenary Talk - Yuta Michimura

Michimura Y

Monday Session 2 – Plenary Talks

Since the first detection in 2015, over 300 gravitational wave events have been observed by the LIGO-Virgo-KAGRA collaboration, revealing the population of stellar-mass black holes and raising new questions about compact binary formation. The 2017 binary neutron star merger marked the beginning of multi-messenger astronomy, providing insights into the origin of heavy elements, neutron star physics, theories of gravity, and cosmology. However, such multi-messenger observations have only been achieved once so far. To improve this situation, enhancing detector sensitivity and expanding the global network are essential. In particular, upgrades to KAGRA and the addition of LIGO-India will significantly improve sky localization and polarization measurements. In the late 2030s, next-generation observatories such as the Einstein Telescope and Cosmic Explorer will enable observations of compact binary mergers across the entire universe. This talk will highlight the scientific potential of ground-based gravitational wave observatories and the key technologies that will make it possible.

The LIGO Magazine

Middleton H[1], Green A, Rieger S, Bhagwat S, Bolingbroke G, Burtnyk K, Chalathadka-Subrahmanya S, Chatterjee D, Colloms S, Diab R, Di Fronzo C, Fornal B, Freise A, Fulda P, Gonzalez G, Kijbunchoo N, Kolitsidou P, Milde S, O'Hanlon T, Schiworski M
[1]University Of Birmingham

Thursday Session 4 - C8: Education and public outreach in gravitational physics

The LIGO Magazine is published twice a year by the LIGO Scientific Collaboration. Articles focus on the people behind the science, featuring personal stories, interviews, and advice, as well as news from across the gravitational-wave community. Ever wondered what it is like working at the LIGO observatory sites, or being on-call to look at gravitational-wave event triggers as they come in (day or night)? The LIGO Magazine aims to capture these personal insights of working in a large-scale collaboration. It is free to read online at www.ligo.org/magazine and is aimed at both the gravitational-wave community and the public.

The MeerKAT Pulsar Timing Array: Results of the first searches for gravitational waves

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Monday Session 3 - C1: Pulsar timing arrays

The signal that is most sought after in pulsar timing array experiments is that of a stochastic gravitational wave background: the superposition of all nanohertz-frequency gravitational waves emitted in the observable Universe. Recently, a number of pulsar timing arrays have unveiled the first evidence of a spatially correlated signal. This signal, if correct, is thought to be representative of a background of gravitational waves from inspiralling supermassive black hole binaries. However, in order to make a definitive detection, it is necessary to observe pulsars over a longer timing baseline, monitor a larger ensemble of pulsars, time pulsars to higher precision, or all. Here, we introduce The MeerKAT Pulsar Timing Array. The array monitors a large number of pulsars (83), to high precision, and at the highest cadence of any extant pulsar timing array. In the pursuit of a definitive detection of nanohertz-frequency gravitational waves, it now joins the others in searching its dataset for signals indicative of a stochastic gravitational wave background, and entertains more exotic explanations for the surprising results found in this search.

In this presentation, we describe the process of analysing the highly sensitive data of the array, and present the detailed results of these searches.

Perturbative gauge-invariants in the Schwarzschild interior for hybrid quantization

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[1]Instituto de Estructura de la Materia (IEM)

Tuesday Session 3 - D1: Loop quantum gravity and spin foams

In this work, we aim to present a Hamiltonian formulation for the interior perturbations of the Schwarzschild spacetime. Our analysis is based on a truncated action at quadratic order in perturbations. Both background and perturbative degrees of freedom are treated dynamically, forming a unified system endowed with the canonical structure derived from the truncated action. First-order perturbations of the metric are expressed through perturbative gauge-invariants, linear perturbative constraints, and their associated canonical variables. For the quantum description, we employ a hybrid approach: the background is quantized using loop quantum gravity techniques, while the perturbations are treated with conventional quantum field methods.

A Spacetime Interpretation of the Confluent Heun Functions in Black Hole Perturbation Theory

Minucci M[1]
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Tuesday Session 4 - A2: Classical GR: Mathematical developments

In Black Hole Perturbation Theory (BHPT), confluent Heun functions emerge as solutions to the radial Teukolsky equation, which governs the dynamics of perturbations in black hole spacetimes. While these functions have traditionally been studied for their analytic properties, their connection to the underlying spacetime geometry has been less explored. In this talk, I will present a spacetime interpretation of the confluent Heun functions, showing how their distinctive behaviour near their singular points reflects the structure of key surfaces in Kerr spacetimes. By interpreting homotopic transformations of the confluent Heun functions as changes in the spacetime foliation, I will establish a connection between these solutions and various regions of the black hole's global structure. Additionally, I will examine the relationship between these solutions and the hyperboloidal formulation of the Teukolsky equation. Although confluent Heun functions are not directly tied to hyperboloidal slices, I will show that the spacetime framework retains a structure that can be analysed using methods akin to those employed for Heun functions.

Narrowband search for continuous gravitational waves from known pulsars using O4 LVK data

Mirasola L[1]
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Wednesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

Known pulsars are promising targets for the search of continuous gravitational waves (CWs) that can give crucial insights on the interior structure of these kinds of compact objects. Narrowband searches are more robust regarding the emission model with respect to single-template searches since they explore possible mismatches between electromagnetic and gravitational emissions. In this talk, I will present the latest results on behalf of the LIGO-Virgo-KAGRA (LVK) collaboration of a narrowband search for CWs from 16 known pulsars using data from the first part of the fourth LVK observing run (O4a). No CW signals were detected, and upper limits were set on the signal amplitude. I will also present the status of the full O4 analysis.

Capturing turbulence in neutron stars with a sub-grid model

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[1]University of Southampton, [2]Universitat de València

Thursday Session 4 - B1: Relativistic astrophysics

Insufficient numerical resolution of grid-based, direct numerical simulations (DNS) hampers the development of instability-driven magnetohydrodynamic (MHD) turbulence at small (unresolved) scales. As an alternative to DNS, sub-grid models can potentially reproduce the effects of turbulence at small scales in terms of the resolved scales. They can capture physical effects with fewer computational resources. In this talk, I will present the MHD-instability-induced-turbulence (MInIT) mean-field model, which is based on solving partial differential equations for the turbulent kinetic energy densities. These energy densities are directly related to the turbulent stress tensors, which are the quantities that arise in the mean-field MHD equations and represent the effect of the small-scale physics. I will talk about the application of this model to the MHD instabilities that play an important role in the merger of two neutron stars: The Kelvin-Helmholtz instability, which is triggered in the interface between the two neutron stars, and the magnetorotational instability, which arises during the neutron star postmerger phase (and in other scenarios such as protoneutron stars' formation). The effects of small-scale turbulence can impact the neutron star's stability and its consequent gravitational wave and electromagnetic emission.

Outreach via Olympiad Problems

Miritescu C[1]
[1]IFAE Barcelona

Thursday Session 4 - C8: Education and public outreach in gravitational physics

Data analysis tasks are a key component of the International Olympiad on Astronomy and Astrophysics, a prestigious competition for high school students. Each participating country has its own selection process, open to students with an interest in Astronomy. Exam questions are an excellent way to introduce students to novel topics, provided the required knowledge to solve them is within the high school level. As a former competitor in Romania and one of the current organizers of the national selection, I created a data analysis problem based on my 6 weeks research stay at the Virgo gravitational waves (GW) detector, where I worked on magnetic noise characterization. The problem begins by explaining the importance of noise hunting campaigns prior to observing runs, the procedure and the equipment used for magnetic noise injections (such as coils, amplifiers, and single-axis magnetometers). It then introduces the concept of a coupling function between the magnetometers (witness sensors) and the GW channel, and its upper limit. A data table is provided, depicting measurements obtained during injections in both the GW channel and the magnetometers, together with the frequency of the coil's voltage. Students are tasked with calculating the coupling functions, plotting them on a logarithmic scale, and determining the slope to extract a power dependency between them and frequency. This approach tests students' understanding of logarithmic scales and their ability to fit data using the least squares method, while also exposing them to a cutting-edge research topic.

Developments of the LISA QPR with an Outlook Towards IDS Performance and Operations.

Mistry T[1], van Bakel N[1], van Beuzekom M[1], Uminska A[3], Barranco G[3], in 't Zand J[2], Frericks M[2], Laubert P[2], Aitink-Kroes G[2], Kaune B[3], Hewitson M[4], Visser G[1], Dubbeldman L[2], Cornelissen R[1]
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Monday Session 3 - C5: LISA and other space-based detectors

The Interferometric Detection System (IDS) encapsulates the Optical Bench Assembly (OBA) which hosts interferometers Optical Bench Mechanisms Control Unit, and Phase/Signal Detection and Processing Chain responsible for continuous sensing the interferometric light for LISA. A subset of these instruments form the LISA Metrology System (LMS) that measures the phase of the incident light over a bandwidth between 03 - 30 MHz, as determined by the beat note frequency of the heterodyne interferometers. Multiple Quadrant Photoreceivers (QPRs) are used throughout the spacecraft, and are the first step in the chain, which converts the incident light into an output voltage via a Quadrant Photodiode (QPD) and transimpedance amplifier. This signal is sent to a Phase Measurement System (PMS) that utilises multiple phasemeters to create the desired readout data streams useful for science detection and instrument monitoring. Whilst the technology used is grounded in well established techniques, the challenge lies in achieving the low noise, large bandwidth and high sensitivity in addition to surviving the harsh environment of a rocket launch and operating in space. This talk will cover development of the instruments that are apart of the IDS chain. In particular, a detailed look at the QPR development and performance including its' impact on the signal chain though the performance and operation of the LISA IDS.

Charged isotropic solutions with linear barotropic equations of state in Einstein-Gauss-Bonnet gravity

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Thursday Session 3 - A3: Alternative and modified theories of gravity

In the present work we have investigate new class of charged isotropic solutions with linear barotropic equation of state (EoS) in the framework of Einstein-Gauss-Bonnet (EGB) gravity for 5 and 6 dimensional spherically symmetric static distributions. Imposing such restriction of EoS, one more further assumption on metric potentials must be chosen in order close the system. For example the constant gravitational potential which is responsible for isothermal distribution in Einstein gravity is well studied and as well as different form of temporal potential are analyzed. Through graphical analysis we demonstrate that the obtained exact models satisfy the basic elementary astrophysical requirement for physical plausibility.

GPU and PSO accelerated low-latency fully-coherent all-sky search for compact binary coalescences

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Monday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Progress in Gravitational Wave data analysis is often limited by global optimization challenges rooted in the fitting of complex signal models. The fully coherent all-sky (FCAS) search for compact binary coalescences (CBCs), which requires the global optimization of the likelihood function of network data over CBC signal parameters, is particularly demanding in this respect. Despite its potentially higher sensitivity and one-step parameter estimation capability, a low-latency FCAS search is impossible with traditional deterministic or Markovian parameter space sampling methods. Building on our earlier work, we introduce a solution combining Particle Swarm Optimization (PSO) with GPU acceleration that achieves an approximate 48-fold speed-up over real-time analysis, resulting in a potential 5 sec (or less) detection latency for a double neutron star signal in the demanding scenario of a 4-detector current-generation network. With large-scale simulation of Frequentist parameter estimation errors made possible by this code, we show that regularizing the FCAS search using automated gain selection is extremely important as it can substantially reduce the area on the sky -- in some cases by more than 50% for a two-detector network -- that needs to be searched for electromagnetic counterparts. In addition, we will demonstrate how a PSO-based search enables a particularly innovative glitch veto strategy by allowing the search to naturally extend over unphysical sectors of the CBC parameter space. A sub-solar mass FCAS search on all open GW data using the new pipeline is under implementation and the results will be reported.

Localising Binary Black Hole Mergers to Active Galactic Nuclei through Angular Cross-Correlation

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Wednesday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The detection of gravitational waves from black hole mergers in the pair-instability mass gap suggests that some proportion of mergers occur hierarchically in dense astrophysical environments. Astrophysical models suggest that a significant fraction of such mergers could occur in Active Galactic Nuclei disks (AGN). The dynamics of binaries in the gas rich AGN could produce an associated electromagnetic flare coincident with the gravitational wave signal, opening up binary black holes to study through multiple-messengers.

However, determining the host galaxy origin of binary mergers is not possible through gravitational wave localisation alone, and current coincidences of AGN flares and gravitational waves are not robust enough to claim association. Furthermore, discriminating between different hierarchically merging scenarios - such as AGN disks vs nuclear star clusters - by analyzing the binary parameters is also challenging due to uncertainties in astrophysical modeling.

We assess the feasibility of determining the fraction of hierarchical mergers occurring in AGN disks, by computing the angular cross-correlation between gravitational wave sky localisation posteriors and galaxy catalogs. We forecast when the clustering of gravitational wave sky localisations can be measured accurately enough to distinguish the AGN origin scenario from hierarchical mergers in star-forming galaxies. We find that if the observed merging population is dominated by binaries formed dynamically in AGN, then this could be determined with ~5000 mergers detected at projected A# sensitivity.

GWB anisotropy studies on eccentric and circular SMBHB populations

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Tuesday Session 4 - C1: Pulsar timing arrays

Recent evidence from Pulsar Timing Arrays (PTAs) is for a stochastic Gravitational Wave Background (GWB) that may be produced by the superposition of GWs generated by a population of supermassive black hole binaries (SMBHBs). Since the number of SMBHBs is discrete, these systems produce a level of anisotropy in the GWB, which can be used to study astrophysical properties of this population.
In this talk, I will present our analysis of an anisotropic GWB generated by different SMBHB populations. We thus investigate the possibility of breaking the degeneracy of the observed GWB spectrum slope caused by some level of environmental coupling and eccentricity of the sources. We did this analysis by first investigating the expected anisotropic GWB signatures using different realizations of the SMBHB population and then simulating a realistic PTA.

Direct Searches for Ultralight Dark Matter Using Gravitational-Wave Detectors and an Optimal Detection Statistic

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Tuesday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

An ultralight boson, with a mass smaller than 1 eV, emerges as an intriguing candidate for dark matter (DM). It behaves as classical waves within the Galaxy due to its large occupation number, and its frequency is determined by the boson's mass. Notably, these waves can interact with mirrors or laser light of gravitational-wave interferometers, and hence this type of dark matter can be searched for using detectors like LIGO, Virgo, and KAGRA. In the first half of the talk, I will briefly introduce recent studies in this direction including our works on searches for dark photon and axion using LIGO and KAGRA.
In the latter half, I will discuss the statistical properties of the signal caused by ultralight DM and introduce an optimal detection method that we recently proposed in arXiv:2503.04484. I will introduce a method to calculate the signal's auto-correlation function and explain how we have constructed an optimal detection statistic using those information. With analytic arguments and numerical simulations, I will demonstrate that our new method surpasses the performance of the conventional data analysis method.

pyEFPE: An improved post-Newtonian waveform model for inspiralling precessing-eccentric compact binaries

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Thursday Session 4 - B3: Approximations, perturbation theory, and their applications

The modeling of spin-precession and orbital eccentricity in gravitational-wave (GW) signals is crucial for understanding the astrophysical formation of compact binaries and ensuring that GW detector data is explored fully and without biases. However, describing these effects accurately and efficiently remains a challenge. In this talk, I will present pyEFPE, a frequency-domain post-Newtonian (PN) waveform model for precessing-eccentric inspirals. pyEFPE improves upon previous models by introducing analytical expressions for the eccentric amplitudes, enhancing the numerical stability of the spin-precession description, and adding recently derived post-Newtonian corrections, critical for accurately describing signals in GW detectors. Additionally, we introduce an amplitude interpolation scheme that improves computational efficiency and makes the model practical for data analysis. I will demonstrate these improvements by comparing pyEFPE against existing models and showcasing its application in parameter estimation studies.

Geometry and topology of trapped photon region in Kerr-Newman and Kerr-Sen spacetime

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Tuesday Session 4 - A2: Classical GR: Mathematical developments

Consider the trapped photon region in the domain of outer communication of sub-extremal Kerr spacetime. Cederbaum and Jahns proved that the canonical projection of this trapped photon region in the (co-)tangent bundle is a five-dimensional submanifold of topology $SO(3)\times \mathbb{R}^2$. By
adapting the latter's methodology, we generalize this result to two stationary axisymmetric classes of spacetimes admitting black hole horizon, namely Kerr-Newman spacetime and Kerr-Sen spacetime. The former is a solution of Einstein-Maxwell equations, while the latter is a solution of Einstein-Maxwell-Dilaton-Axion equations. These include both sub-extremal and extremal cases. The result has potential applications in various areas of mathematical relativity, like black hole uniqueness theorems, black hole dynamical stability, gravitational lensing, black hole shadows, and cosmic censorship conjecture. (This is a joint work with Carla Cederbaum).

Multi-messenger transients from merging magnetically arrested supermassive black hole binaries

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Wednesday Session 4 - C7: Multi-messenger astronomy of gravitational wave sources

Merging supermassive black hole (SMBH) binaries will likely be surrounded by a circumbinary accretion disk. Close to merger, gravitational radiation-driven inspiral will happen on timescales faster than the effective viscous time at the disk cavity wall, leading to a decoupling of the inner binary dynamics from the surrounding gaseous environment. Here we present the first simulation of this decoupling process from a magnetically arrested circumbinary accretion disk. In this regime, the central cavity is filled with very strong vertical magnetic flux, regulating accretion onto the binary. Our simulations identify three main stages of this process: (1) Large-scale magnetic flux loss prior to decoupling. (2) Rayleigh-Taylor-driven accretion streams onto the binary during and after decoupling, which can power magnetic tower-like outflows, resembling dual jets. (3) Post merger, the cavity wall becomes unstable and the magnetic flux trapped inside the cavity will get ejected in large coherent outbreak episodes with implications for potential multi-messenger transients to merging SMBH binaries.

Greybody factors of d-dimensional string-corrected black holes

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Friday Session 3 - D1 + D2 + D3

We compute analytically greybody factors for asymptotically flat spherically symmetric black holes with Gauss-Bonnet higher derivative corrections in d dimensions in the high frequency limit. Our calculations include both the eikonal limit - where the real part of the frequency of the scattered wave is much larger than the imaginary part - and the highly damped case - where the imaginary part of the frequency is much larger than the real part -, addressing the emission of gravitons and test scalar fields, and yielding full transmission and reflection scattering coefficients. We comment our results considering the recently established correspondence between greybody factors and quasinormal modes, whose frequencies we previously computed for the same black holes. This correspondence becomes exact in the high-frequency (eikonal) regime.

Averaging over inhomogeneous structures in relativistic cosmology: backreaction effects and impact of the choice of spatial foliation

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Tuesday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves

The geometric simplicity of the homogeneous and isotropic background of the concordance model of cosmology (with the formation of matter structures described as linear perturbations or Newtonian dynamics on top of this background) comes at a cost. To match observations, its expansion must be accelerating in recent times, which requires either an exotic Dark Energy fluid, or a cosmological constant with ad hoc magnitude. It has also seen several observational tensions emerge in recent years, most famously discrepancies in measurements of the current expansion rate H0. On a more fundamental level, there is no clear a priori prescription of how such a homogeneous background is extracted from the actual inhomogeneous Universe: this is the "averaging problem".

A specific issue of defining such a smoothing operation in a relativistic spacetime is the many ways one can define "space" as 3-dimensional slices to characterize spatial observables evolving with time. This has led to concerns about the dependence in this choice of the resulting averaged dynamics. I will show how to define a spatial averaging framework for scalar observables within any spatial slicing, especially useful e.g. for the interpretation of relativistic cosmological simulations. The resulting effective dynamics include "backreaction" terms from the presence of local structure that can, in principle, contribute to the effects of dark energy and/or dark matter at different scales. I will then discuss the dependence of spatial averages on the slicing, and show how physical restrictions on possible slicings can ensure an approximate invariance of averages.

An update on the development of searches for binaries using LISA

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Friday Session 4 - C5: LISA and other space-based detectors

The space based laser interferometer LISA, expected to be operational in the next decades, will be able to probe the millihertz frequency band. This will make it sensitive to a vast array of compact object mergers including that of the massive black hole (MBH) binaries. These black holes, straddling the intermediate and supermassive types of black holes, have masses extending above a minimum of 1000 M⊙. It would be in general important to work on developing the science ground segment to enable the designing of searches for the binaries that LISA will be sensitive to, fitting of multiple diverse sources and the generation of simulated data to test and calibrate such searches. The MBHs are expected to be observable within the LISA band for several weeks to months before they merge, making them excellent candidates for low latency, pre-merger observations. Also, some mergers of MBHs are expected to have electromagnetic counterparts which makes it important to send out pre-merger alerts with sky location information from LISA data analysis to the astronomy community for early detections of such mergers in multiple electromagnetic bands. It would also be important to assess the precision up to which we can measure the parameters of MBHs. In my talk I explore some developments towards the designing of the search for MBHs in LISA data, especially at low-latencies.

Gravitational memory contributions to waveform and effective action

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Wednesday Session 4 - A1: Classical GR: Theoretical developments

In this talk, I will present a study on quadrupole-quadrupole contributions to gravitational-wave emission using effective field theory techniques. We derive a waveform in agreement with previous results found within the multipolar post-Minkowskian approach, emphasizing the role of radiation-reaction terms in the energy-momentum balance between source and radiation. Additionally, we construct an in-in effective action and demonstrate how it yields energy and angular momentum balance equations consistent with fluxes carried by gravitational waves to infinity.

A pipeline for searching and fitting instrumental glitches in LISA data

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Monday Session 4 - C5: LISA and other space-based detectors

In January 2024, the European Space Agency officially adopted the Laser Interferometer Space Antenna (LISA) mission to detect gravitational waves (GW) in the millihertz regime. LISA is expected to observe a complex superposition of astrophysical signals, including Massive Black Hole Binaries, Galactic Binaries, and Extreme Mass Ratio Inspirals. However, as LISA lacks an independent measurement of instrumental noise, robust methodologies are essential to characterize noise and mitigate instrumental artifacts, ensuring accurate parameter estimation of GW signals from astrophysical sources. In this talk, we present an approach based on Reversible Jump Markov Chain Monte Carlo with parallel tempering to identify and model noise artifacts, specifically glitches. Our work contributes to the global fit development for LISA, which aims at simultaneously characterizing all detected sources while estimating instrumental noise. Using the open-source sampler Eryn, we perform astrophysical signal searches and parameter estimation to disentangle glitches from Massive Black Hole Binary signals while accounting for stochastic instrumental noise.

Dynamical formation of regular black holes

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Wednesday Session 4 - A3: Alternative and modified theories of gravity

Recently, it has been shown that the addition of an infinite tower of higher-curvature terms to the Einstein-Hilbert action in dimensions greater or equal than five regularises the Schwarzschild black hole singularity. In this talk, I will present a dynamical process of thin-shell collapse which leads to the formation of these regular black holes. Starting at some finite radius, the shell collapses until it reaches a minimum radius inside the regular black hole inner horizon. This is followed by a bounce which makes it emerge in a new universe until reaching a turning point, from which the process of collapse is restarted.

Light rings and causality for nonsingular ultracompact objects sourced by nonlinear electrodynamics

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Thursday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

We study observational signatures of nonsingular ultracompact objects regularized by nonlinear electrodynamics. The phenomenon of birefringence causes photons of different polarizations to propagate with respect to two distinct metrics, which manifests itself in the appearance of additional light rings surrounding the ultracompact object. We analyze the observational consequences of this result and illustrate our findings based on three regular black hole models commonly considered in the literature. We find that nonsingular horizonless ultracompact objects sourced by nonlinear electrodynamics possess an odd number of light rings and discuss the viability of this model as an effective description of their properties. In addition, we compare the phase velocities of polarized light rays propagating in nonsingular geometries sourced by nonlinear electrodynamics to the corresponding phase velocity in the Schwarzschild spacetime and demonstrate that regularizing the singularity by means of a theory that does not adhere to the Maxwell weak-field limit may lead to the emergence of acausal regions.

Second-order self-force calculations in the radiation gauge: a rescue mission

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Monday Session 3 - B3: Approximations, perturbation theory, and their applications

Gravitational self-force is an approximation scheme used to model extreme-mass-ratio inspirals by expanding the spacetime metric in the small ratio of the two bodies' masses. To produce sufficiently accurate predictions for LISA, this expansion must be carried to second order. While such second-order calculations have been performed for a nonspinning secondary object with a Schwarzschild primary, several challenges stand in the way of generalising to a spinning secondary and Kerr primary. One challenge is an apparent breakdown of the traditional radiation gauges due to pathological gauge singularities that lead to ill-defined distributional source terms at second order. In this talk, I present a scheme that bypasses this obstacle, constructing a well-defined source for the second-order Teukolsky equation in the radiation gauge. Among other things, this should facilitate analytical calculations at second order, extending the combined post-Newtonian and self-force expansions commonly used at first order. I demonstrate the source-construction method in that analytical approach.

Probing the population of pop III remnants using gravitational wave observations

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Wednesday Session 4 - C4: Concept and research towards next-generation detectors

The properties of the first stars in the Universe, known as Population III (Pop III) stars, and their remnants are still poorly understood. However, the increased sensitivity of next-generation gravitational wave observatories offers the potential to detect mergers of these early compact binaries at redshifts greater than 15. A fraction of these detections will be loud enough, that is, the signal-to-noise ratio greater than 20 in the third-generation gravitational wave detector network, and are suitable for accurately understanding the astrophysical processes behind the formation and evolution of these very first compact binaries in the Universe. Using parametric population models, we explore the detectability and parameter inference accuracy of the early Universe binary black hole populations and determine the astrophysical population properties, such as the mass, spin and redshift distributions. Furthermore, we assess the gravitational wave network requirements necessary to differentiate the properties of compact binary populations in the early Universe from those in the present-day Universe.

Identifying and Mitigating Machine Learning Biases for the Gravitational Wave Detection Problem

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Monday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Matched filtering is a long-standing technique for optimal detection of known signals in stationary Gaussian noise. However, it performs suboptimally when applied to unknown signals in real noise and suffers from computational inefficiencies. Deep learning has emerged as a promising alternative for gravitational wave detection, but we demonstrate that numerous learning biases hinder generalization, leading to significant loss in detection sensitivity. Our work identifies 11 interconnected biases present in the supervised learning of the gravitational-wave detection problem and offers mitigation tactics and training strategies to address them. We show that current detection sensitivity metrics are unreliable for machine learning-based pipelines, questioning the trustworthiness of previous results. Using gravitational-wave domain knowledge, we developed a machine-learning-based binary black hole search pipeline, Sage, which addresses these biases. In the Machine Learning Gravitational-Wave Search Challenge, Sage detects ~11.2% more signals than the benchmark PyCBC analysis at a false alarm rate of one per month in O3a noise. It also outperforms the previous best-performing machine-learning pipeline by detecting ~48.29% more signals on the same dataset. We demonstrate that Sage can: [i] handle out-of-distribution noise power spectral densities, [ii] reject non-Gaussian transient noise artifacts, and [iii] achieve higher detection sensitivities using less data than similar-sized architectures. Through empirical investigations, we aim to improve interpretability and address the need for understanding the performance changes in machine learning methods for gravitational-wave science.

Spherically symmetric static models in higher dimensional Einstein-Gauss-Bonnet gravity

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Tuesday Session 4 - A3: Alternative and modified theories of gravity

A framework to study spherically symmetric static stellar models in Einstein-Gauss-Bonnet (EGB) gravity is presented. EGB gravity is a class of Lovelock gravity in which Lovelock gravity represents a natural extension of general relativity to higher dimensions. We provide a foundation for modelling astrophysical objects in EGB gravity and investigate the influence of the higher order curvature corrections arising in EGB gravity on the gravitational dynamics of these stellar objects. The matter distribution considered is a neutral fluid. The EGB field equations for such a matter distribution are generated in N dimensions. Solving these field equations will provide insights on the physical features of the stellar model. This is done by assuming isotropic pressure and solving the resulting differential equation. The condition of pressure isotropy is an Abel differential equation of the second kind, a complicated first order nonlinear differential equation. Such equations are difficult to solve however we illustrate a method to reduce it to a canonical differential equation. This systematic approach allows for exact solutions to the canonical equation to be found, which is unique from the methods considered in general relativity. The solutions found represent a new family of solutions to the EGB isotropic pressure condition equation. This process is fundamental for stellar modeling and advances the number of exact solutions in EGB gravity. Earlier results are contained in the solutions found and the difference between general relativity and EGB gravity is provided. We further discuss the physics of the resulting stellar model.

Effects on gravitational waves emanating from core-collapse supernovae

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Thursday Session 3 - B1: Relativistic astrophysics

Core-collapse supernovae (CCSNe) have long been touted as potential sources of detectable gravitational waves (GWs). However, with predicted GW waveforms from CCSNe, detection expectations are limited to galactic events at a detection rate of a couple per century at current detector sensitivity. Increasing detector sensitivity and the potential of deep learning to improve detection and analysis of GW data, would seem to indicate GW detection from CCSNe is imminent. However, it may also be that we may need to revise our expectations down based on other effects in the CCSNe environment. It is generally believed that GW traversing through matter would not suffer any discernible effect. Using linearised perturbations within the Bondi-Sachs formalism for various scenarios of matter surrounding a GW source, we found several novel results which contradicted this prevailing notion. As an initial investigation, taking a Minkowski or Schwarzschild background, we found that for a spherical dust shell surrounding a GW source, GWs can be modified both in magnitude and phase, but without the transfer of energy. Introducing viscosity, we found that GW heating of the surrounding matter occurred as a consequence of the transfer of energy, resulting in damping of GWs. Using parameters expected from the progenitors of CCSNe in our models, we find that the damping can be significant including up to the point where complete GW damping occurs, in which case no GW signal will escape the CCSNe. These results suggest that optimism for detectable GWs from CCSNe may need to be damped itself.

Investigating the Formation Pathway of Heavy Binary Neutron Stars: Part I

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Monday Session 4 - B1: Relativistic astrophysics

Approximately 30 Galactic binary neutron star (BNS) systems have been identified via radio pulsar timing, with total binary masses ranging from 2.50 to 2.89 M⊙. Gravitational-wave (GW) observations have yielded two detections of binary neutron star (BNS) mergers so far: GW170817, with a total binary mass of 2.74 M⊙, is the only GW event associated with an electromagnetic counterpart. GW190425, with a combined mass of 3.4 M⊙, has a significantly higher total mass than any known Galactic BNS system, suggesting a non-standard formation pathway. To investigate the formation of heavy double neutron star binaries, we explore the late stages of the evolution of helium stars with masses between 2.5 and 9.8 M⊙ in binary systems with a 1.4 M⊙ neutron star companion, modeled using the detailed 1D stellar evolution code — Modules for Experiments in Stellar Astrophysics (MESA). We test proposed alternative formation channels to determine which pathway(s) are more likely to produce heavy systems like GW190425. We calibrate our models to ensure they can reproduce the observed Galactic BNS mass distribution. After accounting for the limits imposed by ultra-stripped and electron capture supernovae in the kick prescription, our models produce an improved agreement over prior binary population synthesis codes. We conclude that the population synthesis of our models rules out the formation of heavy BNS systems through the second unstable mass transfer phase (common envelope evolution).

Can HI Intensity Mapping shed light on Dark Sirens?

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Wednesday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

Gravitational wave (GW) detections of compact binary mergers without electromagnetic counterparts, commonly referred to as “dark sirens,” have been measured in abundance by the LIGO-Virgo-KAGRA network. These events hold a tremendous potential for constraining cosmological parameters such as the Hubble constant H0, notably famous due to the 8 sigma tension separating the SH0ES and Planck results.
A critical step in the determination of H0 is the inference of the GW’s redshift. One method to do so consists in constructing a redshift prior informed by the underlying matter distribution. Galaxies naturally host compact objects, but incomplete catalogues at high redshifts limit their efficiency. With this work, we investigate how neutral hydrogen (HI) 21-cm intensity maps, measured by MeerKAT and the upcoming Square Kilometre Array Observatory (SKAO), can provide us with an alternative tracer for constructing redshift priors for dark sirens.
Using simulated GW and HI datasets, we quantify the precision with which H0 can be measured in the LVK-SKAO era. To anticipate limitations associated with the use of real data, we assess the impact of instrumental and astrophysical systematics. Our results demonstrate the power of bridging gravitational wave cosmology with tracers of large-scale structure, providing a pathway to precise measurements of the Universe’s expansion history with multi-tracers.

Will art tell the story of multi-messenger astronomy? Engaging communities with art and science

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Thursday Session 3 - C1: Pulsar timing arrays & C8: Education and public outreach in gravitational physics

Artistic reworking of scientific content can often succeed in illuminating aspects and meanings that are 'collateral', and not immediate for the scientists themselves, but which can be of great impact for society and other audiences.
In recent years, the European Gravitational Observatory (EGO) and the National Institute of Nuclear Physics (INFN) have developed collaborations and dialogues with several artists, interaction designers, video makers…focusing on some crucial ideas or achievements of our contemporary vision of the cosmos: from Einstein's Theory of General Relativity up to the discovery of gravitational waves and Multimessenger Astronomy.
Some outcomes of these collaborations are the exhibitions "Gravity. Imagining the Universe after Einsten" MAXXI, Rome, 2017, "The Rhythm of Space" Palazzo Lanfranchi, Pisa, 2018, "Uncertainty. Interpreting the Present, Predicting the Future", Palazzo delle Esposizioni, Rome, 2021 with internationally renowned artists such as Tomas Saraceno, Laurent Grasso, Liliane Liyn, Allora & Calzadilla and others.
Recently EGO has developed also a program of residencies with young artists (Lulù Nuti, Pedro Torres, Alice Paltrinieri, Attila Faravelli, Massimo Magrini), presenting this during the public program of the Italian Pavilion at the Venice Art Biennale 2024, at the Spoleto Festival dei due Mondi 2024 and other Science and Art Festivals in Europe.
The talk will propose a more general reflection on the method deployed in the interaction between scientists and artists and on the initiatives of contemporary art museums, that are in fact experimenting with new formats of communicating science, broadening its perspective and values.

Constructing the Hamiltonian for eccentric, precessing compact binaries in the small mass ratio limit

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Tuesday Session 4 - B3: Approximations, perturbation theory, and their applications

In this talk, I present computations of the spacetime metrics of eccentric, precessing compact binaries to first order in the mass ratio using the self-force framework. I make these computations publicly available in the Python package pybhpt, which has already been used to generate data for waveform models such as Fast EMRI Waveforms and for second-order perturbations of Kerr spacetime. From the spacetime metric, I construct the Hamiltonian that governs the system's dynamics. This Hamiltonian is obtained directly from the redshift, which I calculate for the first time for eccentric, precessing binaries. Finally, I discuss how this Hamiltonian calculation not only advances self-force methods but also offer a promising bridge to post-Newtonian and effective-one-body frameworks.

Improving pulsar-timing solutions through dynamic pulse fitting

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Monday Session 4 - C1: Pulsar timing arrays

Precision pulsar timing is integral to the detection of the nanohertz stochastic gravitational-wave background as well as understanding the physics of neutron stars. Conventional pulsar timing often uses fixed time and frequency-averaged templates to determine the pulse times of arrival, which can lead to reduced accuracy when the pulse profile evolves over time. We illustrate a dynamic timing method that fits each observing epoch using basis functions. By fitting each epoch separately, we allow for the evolution of the pulse shape epoch to epoch. We apply our method to PSR J1103 - 5403 and demonstrate that it undergoes mode changing, making it the fourth millisecond pulsar to exhibit such behaviour. Our method, which is able to identify and time a single mode, yields a timing solution with a factor of 1.78 improvement over template fitting on both modes. This boosts the signal-to-noise ratio of a gravitational-wave background signal for this particular pulsar by 32%.

Impact of eccentricity and mean anomaly in numerical relativity mergers

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Thursday Session 4 - B2: Numerical Relativity

Accurate modelling of black hole binaries is critical to achieve the science goals of gravitational-wave detectors, which relies heavily on numerical-relativity (NR) simulations. While binaries on quasi-circular orbits have been widely explored with NR, extension to eccentric orbits remains limited. In this talk, I will discuss recent progress in the coverage of the eccentric parameter space with NR simulations. First, I will present a new waveform-based eccentricity control procedure, allowing a precise control over the eccentricity, mean anomaly, as well as the length of the simulation. Next, I will demonstrate the importance of considering the entire 2-dimensional eccentric parameter space. We find that, for fixed eccentricity, many merger-related quantities show an oscillatory dependence on the mean anomaly. For eccentricities explored, we find that quantities such as the merger amplitude and peak luminosity can deviate as much as ~5% where, depending on the mean anomaly, the quasi-circular value can be enhanced or diminished. These deviations scale almost linearly with the eccentricity. Finally, with these findings in hand, we interpret eccentric phenomena reported to date in the literature. These simulations serve as a test-bed to explore the consequences of orbital eccentricity, and will help guide efficient coverage of the eccentric parameter space.

Expanding the two body problem - Analytical approaches for second order self force

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Monday Session 3 - B3: Approximations, perturbation theory, and their applications

The self force formalism is the leading approach to obtaining waveforms for binary sources with extreme mass ratios. Accuracy requirement of the upcoming LISA mission necessitate results at second order in the mass ratio. The second-order problem is tackled predominantly with numerical methods, which are notoriously challenging. Complementing these methods with analytical approximations can massively reduce the computational cost. Motivated by this I will present the most recent endeavors in analytical second-order approaches, which feature an additional expansion around the Newtonian limit. I will present a new addition to the black hole perturbation toolkit, which arms numerical tools for the Teukolsky equation with analytical counterparts. These tools are then used to compute a second order Teukolsky source directly from the first order retarded field, bypassing major computational difficulties of previous approaches.

Effective Dimension and Topology via Matter Fields in Lattice Quantum Gravity

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Tuesday Session 4 - D3: Causal sets, causal dynamical triangulations, non-commutative geometry, asymptotic safety, and other approaches to quantum gravity

Causal Dynamical Triangulations (CDT) is a lattice approach to quantum gravity that has emerged in recent years as a leading candidate for a nonperturbative description of Quantum General Relativity. Numerical simulations within this framework reveal the emergence of four-dimensional de Sitter spacetimes, exhibiting intriguing features such as a nontrivial ultraviolet spectral dimension, hinting at underlying fractal properties. Coupling scalar fields to the dynamical geometry induces phase transitions, accompanied by changes in the dimensionality and topology of spacetime. The coupling of Yang-Mills fields to gravity will also be discussed, with a focus on the topological charge as a physical observable.

Higher Order Black Hole Perturbations with Backreaction

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Tuesday Session 3 - D1: Loop quantum gravity and spin foams

Black hole perturbations are mostly considered up to second order. In this talk, we consider higher-order perturbations and explore the new technical challenges that arise. Our approach is based on the Hamiltonian formulation of general relativity using ADM variables and systematically incorporates backreaction effects. A canonical quantization of the theory will provide new insights into the quantum nature of black holes. Looking ahead, we aim to investigate black hole evaporation, with the goal of deriving corrections to existing semiclassical computations and clarifying the fate of evaporating black holes.

Quantum corrections from unitary evolution of de Sitter space

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Thursday Session 4 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

One of the main obstacles in our attempts to find a consistent quantum framework for gravity arises from the different concepts of time in general relativity and quantum mechanics. In an attempt to canonically quantise general relativity, having no privileged time means that one needs to choose an internal variable as clock. In the frame of unimodular gravity, a natural choice for such a clock arises as the conjugate to the cosmological constant. We show that requiring unitary time evolution "resolves" the de Sitter horizon where the flat slicing breaks down and leads to strong quantum effects there, even though classically nothing special happens at this surface. This model illustrates the fundamental clash between general covariance and unitarity in quantum gravity.

Expectations for the Fourth Observing Run of Advanced LIGO/Virgo/KAGRA

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Monday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

We present our predictions for the fourth observing run of Advanced LIGO, Virgo, and KAGRA. Using information gleaned from the public alerts, we will discuss some of the most interesting candidates, including the loud binary black hole merger GW250114. We will discuss the opportunities the growing population presents to improve our understanding of the merger population and gravitational-wave science going forward.

Ringdown mode amplitudes of precessing binary black holes

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Tuesday Session 3 - B3: Approximations, perturbation theory, and their applications

The ringdown phase of a binary black-hole merger encodes key information about the remnant's properties and provides a direct probe of the strong-field regime of General Relativity. While quasi-normal mode frequencies and damping times are well understood within black-hole perturbation theory, their excitation amplitudes remain challenging to model, as they depend on the merger phase. The complexity increases for precessing black-hole binaries, where multiple emission modes can contribute comparably to the ringdown. In this paper, we investigate the phenomenology of precessing binary black hole ringdowns using the SXS numerical relativity simulations catalog. Precession significantly reshapes the ringdown excitation amplitudes and the related mode hierarchy.
Using Gaussian process regression, we construct the first fits for the ringdown amplitudes of the most relevant modes in precessing systems.

Can you fall into a McVittie black hole?

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Thursday Session 3 - A1: Classical GR: Theoretical developments

McVittie's spacetime is a spherically symmetric, time-dependent solution of the Einstein equations with perfect fluid source that embeds the Schwarzschild field in a background Friedmann-Lemaitre-Robertson Walker universe. Studies of the radial null geodesics of the have revealed its black hole nature: ingoing radial null geodesics meet a non-singular boundary at finite affine distance that does not lie in the past of future null infinity. However, the fluid particles of the spacetime do not reach the horizon, extending instead to infinite radius as the cosmic time (and proper time) approaches infinity. We ask here: are there other material particles that can reach the black hole event horizon in a finite amount of proper time? And if so, do curvature and matter invariants remain finite along the trajectories of these particles as they cross the horizon? We answer both questions in the affirmative.

Testing beyond-LCDM cosmologies with gravitational waves

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Wednesday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Beyond LCDM cosmologies generically introduce new degrees of freedom, e.g. associated with dynamical theories of dark energy. These degrees of freedom can affect both the emission and propagation of gravitational waves and imprint characteristic signatures on gravitational wave observables in the process. In this talk I will discuss this in the context of the quasi-normal modes emitted during ringdown as well as for propagation effects captured by modified dispersion relations, highlighting where tight constraints on beyond LCDM physics have already been obtained using LVK observations as well as forecasting future constraints.

Signature of ultralight dark matter in pulsar timing arrays

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Monday Session 3 - C1: Pulsar timing arrays

Pulsar timing arrays (PTAs) provide a way to detect gravitational waves (GWs) at nanohertz frequencies. To ensure the detection of GWs, observational data must exhibit the Hellings-Downs angular correlation. It is also known that PTAs can probe ultralight dark matter. This presentation considers possible contamination of the Hellings-Downs angular correlation by the ultralight dark matter. We find that ultralight vector dark matter can give rise to the deformation of the Hellings-Downs correlation curve. Thus, the Hellings-Downs correlation curve could contain information on ultralight dark matter with a spin.

Quantum Field Simulator with Ultracold Gases: Particle Production in Oscillating Spacetime

Oberthaler M

Monday Session 3 - C9: Experimental gravitation

The study of space-continuous physics in the many-body quantum limit is the natural regime of ultracold degenerate quantum gases. Recently, we have shown that the evolution of phononic excitations follows a Friedman-Lemaître-Robertson-Walker metric. The experimental control allows full control of the curvature and scale factor of the metric as well as the initial condition.

Here I will give a brief summary of the results demonstrating particle production in expanding spacetime and the realisation of positive and negative curvature [1]. Building on the unique capabilities of the simulator, we have explored particle production in oscillating spacetime and linked the result to the solution of a simple one-dimensional scattering problem [2].

The longtime dynamics of oscillating universes reveal an emergent spacetime with peculiar properties that go beyond the perturbative regime. There we found that the cosmological principle, i.e. the homogeneity and isotropy of spacetime, is spontaneously violated and a periodic spatial modulation of the metric emerges. We show that this phenomenon can be understood as a drift towards an attractive nonlinear fixed point [3]. Using the quantum field simulator, we show that the emergent structure can be understood as a recently discussed superfluid smectic-A liquid crystal phase [4].

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Next generation cosmological analysis with a re-usable library of machine learning emulators across a DiRAC-enabled grid of cosmological models and datasets

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Friday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

In recent years, disparities have emerged within the context of the concordance model regarding the values of the H_0 [1907.10625], σ_8 [1610.04606] and ΩK [1908.09139, 1911.02087] when estimated with different datasets. Determining the level of discrepancies between different observed datasets, which are predicted to be in agreement theoretically by a cosmological model, is called tension quantification [1902.04029].

We approach this problem by producing a re-usable library of MCMC chains, Nested sampling runs, and machine learning emulators across a grid of cosmological models through detecting cosmological tensions between datasets from the DiRAC allocations DP192 & DP264.

This library is available as part of the pip-installable package unimpeded (https://github.com/handley-lab/unimpeded) and serve as an analogous grid to the Planck Legacy Archive (PLA), but machine learning enhanced and expanded to enable not only parameter estimation (currently available with the MCMC chains on PLA), but also allowing cosmological model comparison and tension quantification, as well as including pairwise comparisons between modern cosmological datasets (CMB, BAO, Supernovae, Weak Lensing). In addition, we provide machine learning emulators [2205.12841] of these marginalised likelihoods for use in future analyses as a fast and flexible alternative to MCMC chains and nested samples for re-use in future analyses. Currently, a systematic coverage of 10 cosmological models and 60 datasets (to be extended, including to gravitational wave data) are easily accessible via the unimpeded package using a few lines of code.

Schwarzschild black hole revisited: analytic models for gravitational collapse

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Thursday Session 3 - A1: Classical GR: Theoretical developments

Within the framework of general relativity, we explore the interior of the Schwarzschild black hole before complete collapse occurs, finding that the exterior is perfectly compatible with a source much more complex than a pointlike mass. We provide a set of inner geometries for singular and regular black holes that smoothly joint the Schwarzschild exterior at the horizon r=h=2M, and which can therefore be regarded as suitable initial conditions for collapse. In particular, the regular solutions might be an alternative to the Schwarzschild black hole as the final stage of gravitational collapse, and thus useful to study the validity of general relativity in environments of high curvature. Finally we present an exact analytical model showing the final stage of Schwarzschild black hole formation. The model describes the gravitational collapse of regular (non-exotic) matter, which at all times maintains its physical acceptability. The scheme used shows great potential for studying in detail the appearance of singularities in general relativity.

A new class of rotating black holes with non-aligned electromagnetic field

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[1]Charles University

Monday Session 3 - A1: Classical GR: Theoretical developments

We present a new class of expanding and twisting solutions to the Einstein-Maxwell equations of algebraic type D, where the principal null directions of the Faraday tensor are not aligned with those of the Weyl tensor. After deriving this novel solution we explore its various metric forms and parameterizations. In suitable coordinates, the solution depends on six physical parameters, namely mass m, Kerr and NUT twist parameters a and l, com-
plex charge c, acceleration α, and parameter β that governs the interplay between electric and magnetic charges in the aligned part of the Faraday tensor. This parameterization, as the Griffiths-Podolsky form of the Plebanski-Demianski solution, facilitates explicit special subcases, such as Kerr-Newman black holes, and a deeper physical interpretation. Notably, we find that the electromagnetic field becomes aligned when the acceleration parameter vanishes. Additionally, in the static limit, our solution reduces to previously known cases. These findings offer new insights into the role of acceleration in modifying electromagnetic field alignments in black hole spacetimes.

Multi-messenger detectability of continuous gravitational waves with future detectors

Owen B[1]
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Wednesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

While gravitational wave detections of compact binary mergers have become commonplace at high frequency (the LVK band), and a stochastic background of them has been detected at low frequency (the pulsar timing band), detections of other signals remain elusive. I evaluate the detectability of continuous gravitational waves from various known astronomical objects with a variety of future high frequency detectors. Current theories suggest that continuous wave sources are likely to be detected first in the next few years and frequently in the era of next generation detectors.

Suppression of tilt-to-length noise in LISA data processing

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Thursday Session 3 - C5: LISA and other space-based detectors

In 2024, the European Space Agency (ESA) began the implementation phase of the LISA mission, bringing gravitational wave observations in the frequency range from 0.1mHz to 1Hz closer to reality than ever before. The raw data from the LISA satellites will be processed in several steps before a catalog of gravitational wave sources can be produced. The initial data treatment will include unit-level calibrations and reformatting. In this presentation, I will summarize how we further process this data, including the interferometer measurements from the three satellites, to obtain data ready for astrophysical analysis. This processing suppresses several sources of noise, including tilt-to-length noise. For this example, I will show some results from dedicated simulations where we were able to show that the planned subtraction works under current assumptions.

Horizon entropies from simplicial Lorentzian path integrals

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Thursday Session 3 - D1: Loop quantum gravity and spin foams

Recent advances have argued how gravitational entropies can be computed directly from Lorentzian path integrals, avoiding the problems of Euclidean methods associated with the conformal factor problem. In particular, how the de Sitter horizon entropy can be recovered from a real-time path integral that computes the dimension of the Hilbert space associated with a spatial ball. Similarly, the swap entropy of an evaporating black hole (central to the replica paradigm resolution of the black hole information paradox) can be computed in this way. In this talk, I will discuss how Quantum Regge Calculus, a lattice-like approach to quantum gravity, enables concrete realizations of these scenarios, providing insights beyond continuum methods. This perspective clarifies aspects of gravitational path integrals and may have implications for approaches such as causal dynamical triangulations and spin foams, where Regge-like formulations play a fundamental role.

Determining the neutron star maximum mass with subthreshold gravitational wave emission from binary neutron star post-merger remnants

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Friday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Gravitational waves from the remnants of binary neutron star mergers provide one of few places in the Universe to study the hot nuclear equation of state. However, those gravitational-wave signals are weak, and may not be detected until gravitational-wave observatories such as Cosmic Explorer or Einstein Telescope come online in the mid-to-late 2030s. Before that time, we expect many binary neutron star mergers to emit post-merger signals that are below the threshold for detection in gravitational-wave observatories. In this work, we develop a technique for calculating the maximum, non-rotating neutron star mass, the so-called Tolman-Oppenheimer-Volkoff (TOV) mass, using information from subthreshold gravitational-wave mergers. We show how to calculate the fraction of binary neutron star mergers that result in prompt collapse to a black hole. This fraction, combined with the binary neutron star mass distribution as determined by the inspiral component of the signals, provides a measurement of the maximum rotating mass threshold for hot neutron stars. We demonstrate that by combining data from 10-20 marginally detected (log(Bayes Factor) ~ 1-3, SNR ~ 4-5) binary neutron star post-merger remnants it is possible to constrain the maximum rotating mass threshold. This latter quantity can be related back to the TOV mass using theoretical models to inform the nuclear equation of state. We perform simulations to demonstrate how the method performs in simulated Gaussian noise, and re-colored real gravitational-wave detector noise.

Inferring Cosmic Expansion from a Combined Compact Binary Coalescence Population

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Thursday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

Gravitational Waves (GW) provide an independent probe of cosmological parameters, in particular the Hubble Constant. Underpinning this is the 'spectral siren' method, which relies being able to infer structure in the mass distribution of GW sources. We present the novel combined-population approach, which allows for unified analyses with binary black hole (BBH), neutron star-black hole (NSBH), and binary neutron star (BNS) events. This framework enables a comprehensive analysis without the need for segregating GW events by binary classification and allows for constraints on the relative astrophysical fractions of each source type. We introduce two versions of this combined population model and demonstrate its application to both simulated GW events and a reanalysis of the GWTC-3 catalog. Furthermore, we detail a method for GW event classification that integrates cosmological and population information, applying it to the GW event GW230529.

Algebraic classification of 2+1 geometries

Papajčík M[1], Podolský J[1]
[1]Charles University

Tuesday Session 4 - A2: Classical GR: Mathematical developments

Study of exact solutions in 3D gravity theories, which are conceptual models for quantum gravity, AdS/CFT, black hole thermodynamics, etc., requires a robust classification procedure. We present a new and practical method of algebraic classification of all 2+1 geometries, analogous to the Newman–Penrose formalism of 4D general relativity based on the Weyl tensor. Our approach employs five real scalars Ψ's, defined as projections of the Cotton tensor onto a null basis. The algebraic type of a spacetime is then determined by gradual vanishing of these scalars, leading to types I, II, D, III, N and O. We also derive the corresponding Bel–Debever criteria, together with the multiplicity of the Cotton aligned null directions (CANDs). We provide a useful frame-independent algorithm for classification based on the polynomial curvature invariants, and show its equivalence to approaches previously developed by García-Díaz, and others. Finally, we illustrate our method on explicit examples and discuss some interesting applications.

Overlapping signals in 3G detectors: an approach based on Transformers

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Tuesday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Third-generation ground-based gravitational wave detectors such as the Einstein Telescope are expected to significantly advance our understanding of compact binary coalescences. One of the most critical challenges in data analysis for the Einstein Telescope is that of overlapping signals. With a tenfold improvement in sensitivity, the Einstein Telescope will be able to detect binary black hole and binary neutron star coalescences with expected rates of up to ~10^5 events per year. Moreover, the extended range toward lower frequencies will allow the detector to observe these signals for longer durations compared to current-generation detectors. While this creates the opportunity to deepen our knowledge of these sources, detectable signals will inevitably overlap. This poses a severe challenge to parameter estimation analysis pipelines. We need a faster, unbiased parameter estimation strategy.

In this talk, we will describe a promising solution to address this challenge: a deep learning approach that combines the power of two state-of-the-art machine learning architectures, Transformers and Normalizing Flows. In particular, we present the first application of a Transformer encoder for gravitational wave data analysis. This architecture is capable of capturing complex, varying-range dependencies, and we use it to extract the information in the data. We then employ Normalizing Flows to estimate the high-dimensional posterior distributions of the overlapped signals.
We will present the results from training this network architecture, demonstrating its effectiveness in handling three overlapping signals simultaneously, and discussing how this deep learning method represents a promising solution to the problem, along with its potential extensions and improvements.

Thermodynamics of asymptotically flat quantum black holes in 1+1 dimensions

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Wednesday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

We study the entropy of static dilatonic black holes at both classical and semiclassical levels. Including back-reaction effects, the model can be solved exactly by adding a term to the action, with the BPP and RST models as special cases. We find that in these models, the total entropy—the sum of black hole entropy and entanglement entropy—matches the entropy of the classical black hole. Additionally, we derive numerical black hole solutions with back-reaction, without introducing extra terms in the action. The numerical results show that the constant entropy found in the BPP and RST family of models arises from the inclusion of the additional term in the action.

Hairy Black Holes by Spontaneous Symmetry Breaking in ESGB theory

Park M[1]
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Wednesday Session 4 - A3: Alternative and modified theories of gravity

We study hairy black hole solutions in Einstein(Maxwell)-scalar-Gauss-Bonnet theory. The scalar coupling function includes quadratic and quartic terms, so the gravitational action has a U(1) symmetry. We argued that when the e ective mass of the scalar field is at the critical value, hairy black holes are generated in a symmetry-broken vacuum via spontaneous symmetry breaking, where the Goldstone bosons are trivial. Moreover, we found that the spontaneous symmetry breaking associated with local U(1) is unlikely to occur in this theory. To examine such process, we introduce a scalar field perturbation on the newly formed background spacetime. We solve the linearized perturbation equation using Green's function method. We begin by solving the branch cut contribution. This allows us to analytically investigate the late-time behavior of the perturbation at both spatial and null infinity. We found that late-time behavior only differs from the Schwarzschild black hole by a mass term. We then proceed to calculate the quasinormal modes (QNMs) numerically, which arise from the presence of poles in the Green's function. Our QNM analysis shows that hairy black holes in the symmetric phase become unstable when the quadratic coupling constant exceeds a critical value for a fixed value of the quartic coupling constant. In contrast, hairy black holes in the symmetry-broken phase are always stable at the critical value. These numerical results provide strong evidence for a dynamical process that unstable black holes without hairs transition into stable hairy black holes in the symmetry-broken phase through the spontaneous symmetry breaking.

A Gaussian process framework for testing general relativity with gravitational waves

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Monday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Gravitational-wave astronomy provides a promising avenue for the discovery of new physics beyond general relativity as it probes extreme curvature and ultra-relativistic dynamics—precisely the regime where one might expect to see hints of new physics. However, in the absence of a single compelling alternative to general relativity, it is difficult to carry out a search that allows for a wide range of deviations. To that end, we introduce a Gaussian process framework to search for deviations from general relativity in gravitational-wave signals from binary black holes with minimal assumptions. We employ a kernel that enforces our prior beliefs that—if gravitational waveforms deviate from the predictions of general relativity—the deviation is likely to be localised in time near the merger with some characteristic frequency. We demonstrate this formalism with simulated data and apply it to gravitational-wave events from Gravitational-Wave Transient Catalog 3. We find no evidence for a deviation from general relativity.

Eccentric parameter estimation in minutes with physical insights from eccentric harmonics.

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Wednesday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Eccentricity is a crucial aspect of gravitational wave (GW) science, providing a unique view into the formation of binary black hole systems in the Universe. Performing a full Bayesian analysis of eccentric signals is, however, highly resource-intensive due to the increased computational cost of generating eccentric waveforms and the expanded parameter space that includes eccentricity and mean anomaly dimensions. To address this, we have developed a novel framework that efficiently decomposes existing eccentric waveform models into eccentric harmonics [cite?]. These harmonics offer direct physical insights into the eccentric information within the signal, enabling extremely rapid parameter estimation. We have successfully leveraged this approach to develop a pipeline capable of extracting posterior estimates, including eccentricity and mean anomaly, from GW signals in just a few minutes. In this talk, I will review the eccentric harmonic decomposition and present parameter estimation results for a population of GW signals.

Development of 30-cm GaAs/AlGaAs crystalline mirror coatings for the next LIGO upgrade

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Tuesday Session 4 - C3: Progress and challenges in advanced ground-based detectors

Currently, the sensitivity of the LIGO detectors is limited in the central frequency band by thermal noise in the test mass mirror coatings. Substrate-transferred GaAs/AlGaAs crystalline coatings provide the most significant improvement in the coating thermal noise, with a measured reduction of 80-90%, while maintaining LIGO's strict optical noise limits. The Advanced LIGO mirrors use an ion beam sputtered, amorphous dielectric mirror coating of titania-tantala/silica. Since their development in 2007, the thermal noise reduction in amorphous coatings research has been limited to about 30%.

The main challenge for the development of "AlGaAs" mirrors has been scaling production methods up to 30 cm. GaAs-based semiconductor development is currently limited to a 20-cm wafer size. Funding the retooling to a 30-cm production process, including boule growth, waferization, coating growth, and bonding was quoted to be > $20M and require 4 years.

The authors have developed an alternative production process that utilized MBE growth of GaAs on Ge wafers and composite test mass mirrors to reduce the coating cost to $2M with prototype mirrors expected this year. We will detail the sensitivity gains and instrumentation challenges of this new mirror production method. We will also review the status of investigations into other potential noise sources unique to crystalline semiconductor coatings including birefringence and free-carrier noise.

Test of local Lorentz invariance with the LAGEOS satellites

Lucchesi D[1,2,3], Visco M[1,2], Peron R[1,2], Rodriguez J[4], Bassan M[5,2], Pucacco G[5,2], Anselmo L[3], Cinelli M[1,2], Di Marco A[1,2], Lucente M[1,2], Magnafico C[1,2], Pardini C[3], Sapio F[1,2]
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Tuesday Session 3 - C9: Experimental gravitation

In the framework of the Parametrized-Post Newtonian (PPN) formalism, valid in the weak-field and slow-motion (WFSM) limit of General Relativity (GR), the Preferred Frame Effects (PFEs) are described by the parameters α1, α2 and α3, all equal to zero in GR and in tensor-scalar theories of gravity. A test of PFEs is equivalent to a test of Local Lorentz Invariance (LLI), which represents a pillar of GR and states that the result of any local (in space and time) non-gravitational test experiment is independent of the speed of the free-falling apparatus in which the experiment is conducted.
We present a measurement of the PPN parameter α1, In the WFSM limit of GR, based on the analysis of the orbital residuals of the two LAGEOS satellites over a time interval of 28 years. LAGEOS satellites are very well tracked through the Satellite Laser Ranging technique. We considered the possible existence of PFEs due to the motion of the Earth-Sun-satellite system with respect to the Cosmic Microwave Background radiation.
LLI is well tested in high-energy physics experiments but is much more difficult to test in the gravitational context. In the weak-field regime, the current best results in constraining the parameters α1 and α2 were obtained through the Lunar Laser Ranging (LLR) technique.
The result we obtained is in line with a null value for the α1 parameter and improves the constraint obtained with LLR. Therefore, this improved limit for the PPN parameter constrains further the possible existence vector-tensor theories of gravity.

The LISA Optical Bench

Taylor A[1], Earle A[1], Perreur-Lloyd M[1], Robertson D[1], Watt A[1], Ward H[1], Ali Z[2], Brzozowski W[2], Carruthers J[2], Cochrane W[2], Clarkson D[2], Fitzsimons E[2], Keogh J[2], Kovacs S[2], Kraus M[2], Leavey S[2], Rinaldesi M[2], Sharman R[2], Tamas L[2], Thurairethinam V[2]
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Thursday Session 3 - C5: LISA and other space-based detectors

The LISA optical bench is at the heart of the LISA instrument mounted between the telescope and the Gravitational Reference Sensors at each end of the 2.5 million Km laser interferometer arms. In order to detect gravitational waves, LISA must be sensitive to relative displacements of picometres per √Hz.

We will describe the interferometric function of the optical bench – a 450mm diameter, 80mm thick disk of ultra-stable Zerodur® populated with optics, and opto- and electro-mechanical units on both sides - and update on the status of the key technologies. With a total of six optical benches required for space flight, and several more for the engineering and qualification phases of the mission, a major effort led by ESA is being undertaken by the UK optical bench team, and across Europe and the United States to develop all required technologies and their assembly and integration procedures. We will present highlights of the current optical bench design and how it addresses the many optical, engineering and integration challenges.

Stray light management on the LISA optical bench

Perreur-Lloyd M[1], Taylor A[1], Earle A[1], Robertson D[1], Ward H[1], Watt A[1], Ali Z[2], Brzozowski W[2], Clarkson D[2], Fitzsimons E[2], Thurairethinam V[2]
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Thursday Session 3 - C5: LISA and other space-based detectors

Stray light poses a significant risk to LISA as noise from phase-instable light directly imparted onto the quadrant photodetectors acts in the same way as the signature from a gravitational wave passing through the LISA constellation. The LISA optical bench has a predominantly polished glass/glass-ceramic architecture with numerous metallic sub-systems performing the manipulation of the laser beam as it traverses the bench. Where the light interacts with any unstable or jittering structure on the optical bench or the spacecraft, phase instability will be imparted on the stray light.

One of the key mitigations to suppress stray light is the use of low-scatter beam dumps to absorb stray and rejected light on the optical bench. We will present a detailed design of the baseline beam-dump for use on the LISA optical bench and describe how this integrates into the broader strategy of suppressing stray and scattered light.

Stability of the wave equation on 1+4 dimensional Myers-Perry black holes.

Peters P[1]
[1]Eth Zürich

Wednesday Session 3 - A2: Classical GR: Mathematical developments

Myers–Perry black holes are (d + 1)-dimensional analogues of the celebrated Kerr family of black holes; they admit ⌊d/2⌋ − 1 commuting angular Killing vectors, corresponding to rotations in multiple orthogonal planes. The Myers-Perry metric is a stationary, asymptotically flat solution of Ric(g) = 0; the case d+1 = 5 is the last one to admit a notion of subextremality.

Our main result is a proof of Price’s law, i.e. sharp t^{−4} pointwise decay, for linear scalar waves on (4+1)-dimensional Myers-Perry black holes in the full subextremal range. Our proof has two main ingredients.
The first is the real mode stability in the full subextremal range, which we prove by combining the integral transform of Cvétic et al. '22 (which starts off with the separability of the wave equation) with
the methods of Shlapentokh-Rothman '15. The second main ingredient is a complete description of the null-geodesic
flow; in particular, we show that the trapped set in phase space is r-normally hyperbolic for every r using a highly nontrivial modification of Dyatlov '15 to our setting. The proof of Price’s law via a careful low energy resolvent analysis, finally, follows the template of Hintz '22.

Non-linear hyperboloidal evolution in Generalized Harmonic Gauge

Peterson Bórquez C[1], Hilditch D[1]
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Wednesday Session 4 - B2: Numerical Relativity

In this talk I will discuss recent progress in the numerical evolution of the Einstein field equations in their generalized harmonic formulation with the use of compactified hyperboloidal coordinates. This slicing of spacetime is ideally suited to extract asymptotic quantities from numerical simulations, being radiation extraction the main target of this line of research.
I will show how we can recover the expected physics at future null infinity with spherically symmetric evolutions. I will finish by discussing ongoing efforts to implement these ideas without symmetry assumptions.

Environmental imprints on black hole ringdowns: quasinormal modes in matter halos

Pezzella L[1]
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Monday Session 3 - C10: Experimental tests of the nature of compact objects

Black hole spectroscopy offers insights into the properties of black hole remnants. However, most models assume idealized, vacuum spacetimes, neglecting the astrophysical environments in which black holes reside.

Our most recent results show that the presence of matter halos, such as dark matter distributions, affects the quasinormal modes (QNMs) of black holes. We examined black holes embedded in a variety of matter profiles, including Hernquist and Navarro-Frenk-White distributions.

Our analysis shows that the surrounding environment leads to a universal redshift of QNM frequencies and damping times, proportional to the halo's compactness. In this talk I will describe the numerical techniques used to construct these black hole spacetimes and compute their QNMs, and discuss the implications of these findings for gravitational wave observations with next-generation detectors like LISA and the Einstein Telescope.

Geometric template bank for eccentric compact binaries and the LIGO-Virgo selection function for eccentric sources of gravitational waves

Phukon K[1]
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Wednesday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Orbital eccentricity is one of the most powerful tracers of compact binary formation. Detecting eccentric signatures in gravitational waves can help constrain different formation pathways, as these pathways also manifest in orbital eccentricities. While current gravitational-wave searches excel at detecting quasi-circular mergers, the origins of binaries in the growing catalog remain uncertain. Developing search methods for eccentric compact binary mergers is a pressing priority, given their immense potential to unlock new astrophysical insights. Current gravitational-waves search methods that employ quasi-circular template banks can significantly underestimate the presence of eccentric binaries. We show that quasi-circular template banks can miss up to approximately 40% of moderately eccentric ($e > 0.15$ at 15 Hz) binaries in the low mass region of compact binary parameter space. To mitigate these limitations, we develop the first geometric template bank to detect eccentric compact binaries by incorporating eccentricity into the four-dimensional binary search parameter space that comprises component masses and component spins along the binary's orbital angular momentum. The eccentric template bank is highly effectual and loses up to only 6% eccentric compact binaries due to discreteness in the template placement. Using this template bank, we present selection functions of eccentric searches for various populations of binaries with eccentricity and spin precession by considering the configuration of LIGO-Virgo detectors with projected O4 sensitivity, which are crucial for the accurate inference of compact binary population properties. From this analysis, we also present the correlation between eccentricity and spin-precession parameters in a detectable population of binaries.

Probing increasingly younger neutron stars through continuous gravitational waves with higher-order spin-down parameters.

Pierini L[1]
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Monday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

Wide-band searches for continuous gravitational waves are essential to reveal unknown neutron stars that may be close enough to us to be detectable. However, such searches cover a huge parameter space that makes them computationally bounded. Neutron stars are predicted to slow down their rotation by losing energy through a variety of physical mechanisms, including, e.g, electromagnetic and gravitational-wave emission. The simplest possible model describes neutron stars slowing down at a constant rate by a first-order spin-down parameter that, for one-year long observing runs, is expected by neutron stars that are about thousands of years old, or even older. In this talk I will show that, thanks to the algorithm optimization, it is possible to enlarge the parameter space to search for signals with an higher order spin-down, with a specific focus to the Frequency-Hough algorithm. I will discuss the complications induced by this choice and show that in this way we can broaden the search to younger neutron stars, up to hundreds of years old or less.

The spin magnitude of stellar-mass black holes evolves with the mass

Pierra G[1]
[1]Infn Roma

Thursday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

Using gravitational-wave (GW) data from the latest GW Transient Catalog (GWTC-3), we investigate the relationship between the masses and spin magnitudes (χ) of binary black holes (BBHs). Our focus is on identifying potential correlations and exploring their astrophysical implications in terms of formation channels.

We employ hierarchical Bayesian methods and new population models for spin-mass distributions to analyze the GW data, validating our results with several sanity checks.

Analyzing 59 GW signals, we find statistical evidence for an evolution of BBH spin magnitudes with mass. We interpret this evolution in two ways. First, using population models that parameterize spin evolution with mass, we observe a transition from a population of BBHs with lower spin magnitudes ($\chi \sim 0.2$) at lower masses to higher, but less constrained, spin magnitudes at higher masses. This transition occurs around 45 $M_\odot$−55 $M_\odot$. Additionally, using models mixing independent BBH populations, we find the observed GW signals can be interpreted as ∼98% low-spin black holes with masses $\lesssim$40 $M_\odot$ and ∼2% high-spin black holes with masses $\gtrsim$40 $M_\odot$.

Using different prescriptions for the interplay between BBH spins and masses, we find evidence of a characteristic mass scale at 45 $M_\odot$−55 $M_\odot$, where the spin magnitude distribution changes. This may support the hypothesis that most low-mass, low-spin BBHs form through isolated stellar binary evolution, while a smaller fraction of higher-mass, high-spin BBHs likely originate from dynamical assembly or hierarchical mergers.

Dynamical Cosmology Constant

Pilo L
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Tuesday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

The dynamical realisation of the equation of state p +rho =0
is studied. A non-pathological dynamics for the perturbations of such a system mimicking a dynamical cosmological constant (DCC) requires to go beyond the perfect fluid paradigm. It is shown that an anisotropic stress must be always present.
The Hamiltonian of the system in isolation resembles the one of a
Pais-Uhlenbeck oscillator and linear stability requires that it cannot be positive definite. The dynamics of linear cosmological perturbations in a DCC dominated Universe is studied in detail showing that when DCC is minimally coupled to gravity no dramatic instability is present.
In contrast to what happens in a cosmological constant dominated Universe, the non-relativistic matter contrast is no longer constant and exhibits an oscillator behaviour at small scales while it grows weakly at large scales. In the gravitational waves sector, at small scales, the amplitude is still suppressed as the inverse power of the scale factor while it grows logarithmically at large scales. Also the vector modes propagate, though no growing mode is found.

Semiclassical backreaction on extremal black holes

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Tuesday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

Working within the framework of semiclassical gravity, we provide a mode-sum prescription to directly compute the renormalized stress-energy tensor (RSET) for scalar fields in the Boulware vacuum state. The method generalizes the recently developed extended coordinate method which was previously only applicable to Hartle-Hawking states and enables the study of semiclassical effects in spacetimes without such states, including extremal black holes and stellar spacetimes.

We demonstrate the accuracy and efficiency of the method by calculating the RSET in both sub-extremal and extremal Reissner-Nordström spacetimes, finding numerical evidence for the regularity of the RSET at the extremal horizon regardless of the field mass or coupling. In addition, we compute the semiclassical backreaction by employing the numerical results obtained for the RSET to source the static semiclassical Einstein equations. Our results indicate that extremal horizons are unstable under quantum perturbations: if the RSET is considered as a static perturbation, it will either de-extremalize the black hole or convert it into a horizonless object.

The development of this methodology opens a window to computing semiclassical backreaction in previously unexplored scenarios, particularly in stellar spacetimes.

Reference:
J. Arrechea et al., arXiv preprint arXiv:2409.04528 (2024).

A mode-free description of general relativistic dynamical tides in binary inspirals.

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Tuesday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

In the context of a neutron star in a binary system, the emitted gravitational waves are influenced by the tidal deformation caused by its companion. Initially, during the early stages of the inspiral, the interaction is accurately described by the static tides approximation, and all time derivatives can be ignored. However, as the inspiral progresses and the stars get closer, the dynamical effects of the tidal interactions cannot be neglected. The existing literature employs a spectral approach linked to the star's normal modes, which is well established in Newtonian physics, to describe these dynamical effects. Unfortunately, this approach poses challenges when extending the model to general relativity. Alternatively, our model provides a mode-independent description of the dynamical tides applicable to both Newtonian gravity and general relativity by assuming a slowly evolving tidal field and utilizing a time-derivative expansion, in which the characterization of the tidal deformation now involves both static and dynamic Love numbers. To overcome the limitations introduced by the assumption of a slowly evolving tidal field, we move to the frequency domain in the final step and invert the expansion to achieve a good level of accuracy when the tidal field evolves more rapidly.

Tests of beyond Einstein gravity with gravitational waves. Applying the parameterised post-Newtonian formalism to gravitational waves. A theory independent approach to the early inspiral.

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Wednesday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

Gravitational waves (GW) from compact binary systems provide a novel opportunity to test theories of gravity beyond General Relativity. However, most of the study of this problem has been limited to theory dependent approaches, in this talk we propose a novel theory agnostic method. We unite the parameterised post-Newtonian formalism (PPN) with a new set of sensitivity parameters to generate a theory independent equation of motion for compact binary systems. We derive the corresponding Lagrangian, then demonstrate how these results can be used to obtain expressions for the early in-spiral gravitational wave phase and amplitude. We then see how constraints from GW data can be used to place bounds on our new parameters, more specifically on the variation of the PPN parameters over cosmic time, complimenting existing applications of the PPN formalism to cosmology.

Eccentric or circular? Re-analyzing gravitational wave events for orbital eccentricity signatures with IMRPhenomTEHM

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Wednesday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The first three observing runs of the LIGO-Virgo-KAGRA (LVK) Collaboration have led to the detection of over 90 gravitational wave (GW) events from compact object binaries, but understanding their formation channels still remains an open question in GW astrophysics. While most inspiraling binaries detected by ground-based detectors likely form through isolated binary evolution and are expected to circularize before entering the detector band, other formation channels may preserve significant orbital eccentricity. Detecting eccentricity in GW signals will provide crucial insights into binary formation and evolution, which requires accurate waveform models for robust parameter estimation.
We present IMRPhenomTEHM, the first time-domain eccentric multipolar phenomenological waveform model for aligned-spin binaries with two eccentric parameters. Built upon the quasi-circular IMRPhenomTHM model, IMRPhenomTEHM includes post-Newtonian eccentric and spin corrections up to the third order, providing an accurate and computationally efficient full inspiral-merger-ringdown description. Using this model, we perform a systematic re-analysis of binary black hole and neutron star–black hole mergers from the first three LVK observing runs, focusing on events identified as potentially eccentric, precessing, or significantly asymmetric in mass. Our results demonstrate the efficiency and accuracy of IMRPhenomTEHM, enabling the first eccentric study using standard parameter estimation techniques for quasi-circular binaries—without relying on resampling or machine learning methods. We identify events with a strong preference for the eccentric hypothesis, highlighting the importance of eccentric waveform modeling in GW astrophysics to avoid biases in parameter estimation.

Various metric forms of all type D black holes, and their application

Podolsky J[1]
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Thursday Session 4 - A1: Classical GR: Theoretical developments

Several recent results concerning the complete class of type D solutions to the Einstein-Maxwell-Lambda equations with an aligned electromagnetic field will be summarized. This large class of spacetimes includes charged black holes with rotation, NUT parameter, and acceleration. In particular, we will present their Plebanski-Demianski, Griffiths-Podolsky-Vratny, and Astorino metric representations, discuss mutual relations between them, and demonstrate their usefulness for investigation of physical and geometrical properties (singularities, horizons, conformal diagrams, ergoregions, rotating strings causing the acceleration, thermodynamics). It includes the proof that such black holes emit gravitational radiation if, and only if, they accelerate.

This contribution is based on several recent joint papers with Hryhorii Ovcharenko, Marco Astorino, Adam Vratny, Francisco Fernandez-Alvarez and Jose Senovilla, namely:

[1] Black holes of type D revisited: relating their various metric forms,
Ovcharenko, Podolsky, Astorino, Phys. Rev. D 111, 024038 (2025)

[2] Revisiting black holes of algebraic type D with a cosmological constant,
Ovcharenko, Podolsky, Astorino, arXiv:2501.07537 [gr-qc]

[3] New improved form of black holes of type D,
Podolsky, Vratny, Phys. Rev. D 104, 084078 (2021)

[4] New form of all black holes of type D with a cosmological constant,
Podolsky, Vratny, Phys. Rev. D 107, 084034 (2023), 108, 129902(E) (2023)

[5] Analysis of gravitational radiation generated by type D black holes with positive cosmological constant,
Fernandez-Alvarez, Podolsky, Senovilla, Phys. Rev. D 110, 104029 (2024)

Inspiral into a Black Hole Surrounded by Matter: A Modified Teukolsky Equation Approach

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Thursday Session 3 - B3: Approximations, perturbation theory, and their applications

Extreme Mass Ratio Inspirals (EMRIs) are among the key gravitational wave sources expected to be observed by the Laser Interferometer Space Antenna (LISA). Accurately modeling their waveforms requires accounting for various astrophysical effects, including the influence of surrounding matter, as black holes are rarely isolated. The presence of matter can break spacetime symmetries, making standard techniques inapplicable. However, by treating both the inspiraling body and the surrounding matter as independent perturbations, we can formulate the problem using the modified Teukolsky equation. In this presentation, we demonstrate how this equation can be solved in the spacetime of a Schwarzschild black hole surrounded by a ring, approximated by its leading multipoles. This calculation is a first step toward relativistic modeling of EMRIs in general spacetime backgrounds.

Supermassive black hole binaries as objects of synergistic gravitational waves

and very long baseline interferometry studies

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Wednesday Session 4 - C7: Multi-messenger astronomy of gravitational wave sources

The existence of supermassive black hole binaries (SMBHBs) is predicted by various cosmological and evolutionary scenarios for active galactic nuclei. These objects are contributors into the gravitational wave (GW) background detected by Pulsar Timing Arrays. They are also considered as the generators of GW to be detected by prospective spaceborne gravitational wave detectors. However, SMBHBs remain a rather elusive class of extragalactic objects.
We present a new approach to identifying SMBHBs via their `oscillating' pattern detectable in astrometric VLBI (Very Long Baseline Interferometry) observations. As examples, we describe two such sources, J2102+6015 and J2236+2828, and consider them as potential SMBHB systems. We analyse evolution of SMBHB as a generator of GW using as input properties of these sources obtained in VLBI observations. We also present a `toy' model of SMBHB consistent with the detected astrometric oscillations. It allows us to make verifiable quantitative predictions for detectability of such the sources as multi-messengers by the current and prospective GW facilities. This also allows us to describe an evolutionary track of these SMBHB systems and estimate the link between the GW emission and the SMBHB orbital evolution for the objects in our study.
We conclude that astrometric VLBI monitoring has a potential for future detections of SMBHBs which could become multi-messenger targets for both electromagnetic (in radio domain) and gravitational wave astronomy. We also describe a synergy between prospective GW and space-borne VLBI facilities in direct studies of SMBHBs.

Plenary Talk - Adam Pound: Theoretical progress in waveform modelling

Pound A[1]
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Tuesday Session 1 - Plenary Talks

Gravitational waveform modeling has a central role in gravitational-wave astronomy and in modern gravitational physics more broadly. After decades of development, there are now several mature methods of constructing these models: numerical relativity, post-Newtonian and post-Minkowskian theory, gravitational self-force theory, and black hole perturbation theory---along with the methods of combining them into fast, extensive models. I describe recent breakthroughs and synergies in these methods and their readiness for next-generation detectors.

Core-collapse supernovae and their impact for gravitational waves

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Tuesday Session 4 - C7: Multi-messenger astronomy of gravitational wave sources

Explosive massive stars are powerful emitters of gravitational waves. In the last 10 years, significant progress has been made in understanding the characteristics of their gravitational-wave emission. However, better coverage of the core-collapse supernova progenitor parameter space is still needed to fully understand the gravitational-wave detection prospects, the explosion dynamics, and the birth properties of neutron stars and black holes. Here we show results from 150 supernova simulations with progenitor star masses between 9 and 36 solar masses, 3 nuclear equations of state, and a variety of different rotation rates. We describe the impact of the rotation and equation of state on the explosion dynamics and neutron star birth properties. We describe the differences in the gravitational-wave emission, and discuss the detection prospects for next generation ground and space observatories.

Low-cost, Precision Gravimetry Using Micromechanical Sensors

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Monday Session 4 - C9: Experimental gravitation,

Mapping spatial and temporal changes in local gravity is essential for detecting and characterising subsurface density anomalies, enabling critical applications in geophysics, hydrology, volcanology, and resource exploration. Traditional gravimeters, although accurate, are typically bulky, costly, and complex to operate, significantly limiting their widespread deployment and accessibility. Microelectromechanical Systems (MEMS) technology has opened new avenues for developing, compact, cost-effective, and robust gravity sensors suitable for deployment and long-term monitoring applications.
In this talk, we introduce “Wee-g”, which is the world’s first true MEMS on-chip gravimeter. This relative gravimeter features a unique mass-on-a-spring design that allows the device to reach an exceptional acceleration sensitivity (< 5 uGal where 1 Gal = 1 cm/s2) and long-term stability (a drift rate of < 270 uGal/day) which is sufficient to track Earth Tides. The sensor is batch-fabricated from silicon, significantly reducing overall costs and simplifying instrument assembly. The excellent SWaP-C (Size, Weight, Power, and Cost) characteristics of Wee-g position it as the first gravimeter specifically optimized for large-scale array deployments for survey and continuous monitoring applications.
Experimental validation of Wee-g in real-world field environments demonstrates its potential to enable broader adoption of gravimetric surveys for geophysical exploration, natural hazard assessment, and groundwater resource management. This advancement in MEMS gravimetry also opens exciting new possibilities in previously inaccessible applications, including drone-based gravimetry and gravity-aided navigation systems.

On the Kerr-Schild double copy for Kundt spacetimes

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Thursday Session 3 - A3: Alternative and modified theories of gravity

For certain classes of spacetimes, one can relate exact vacuum solutions of Einstein's gravity with solutions to the Maxwell equations in a flat spacetime. In both main approaches (the Kerr-Schild double copy and Weyl double copy), the vacuum gravity solutions correspond in a precisely defined way to two copies of Maxwell solutions, hence the term double copy.
In this talk, we focus on vacuum type N Kundt spacetimes in an arbitrary dimension. We have shown that these spacetimes obey the Kerr-Schild double copy in any dimension employing a coordinate-independent approach of higher-dimensional Newman-Penrose formalism. We will also discuss two kinds of non-uniqueness of an electromagnetic field corresponding to a given KS metric and the origin of this non-uniqueness. Since vacuum type N Kundt spacetimes are universal solutions of virtually any higher-order gravity and null fields in such backgrounds are immune to higher-order electromagnetic corrections, the KS-Kundt double copy that we demonstrated also applies to large classes of modified theories. The case with a non-vanishing cosmological constant will also be briefly discussed.

All-sky search for short gravitational-wave bursts in the LVK O4a data

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Thursday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

We present the status of a search for generic short-duration gravitational-wave transients in LIGO data from the first eight months of the fourth observing run of Advanced LIGO-Virgo-KAGRA. The search employs three analysis pipelines, each of which identifies transient signals using a variant of the coherent WaveBurst algorithm and then applies a machine-learning classification method to suppress background.
The search is designed to identify any short gravitational-wave transients in the frequency range 16-4096 Hz, but our focus here is to identify signals of different nature than those interpreted as compact binary coalescences.
For this reason, we exclude from the search the binary merger candidates already reported in low-latency alerts.
The sensitivity of the analysis pipelines will be discussed in terms of a variety of other signals, including standard ad-hoc waveforms plus a selection of core-collapse supernova waveforms and plausible signals from transient neutron star f-modes.

A quantum computing software package for gravitational wave parameter estimation

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Tuesday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The third-generation (3G) gravitational-wave (GW) observatories are poised to detect orders of magnitude more GWs from compact binary coalescences. While these detections will significantly advance GW astronomy and multimessenger astrophysics, it also presents considerable computational challenges in parameter estimation. In our previous study, we introduced a hybrid quantum algorithm qBIRD, which performs quantum Bayesian inference using renormalization and downsampling to infer GW parameters. However, this algorithm is limited to estimating up to 6 parameters, a constraint not imposed by hardware but the algorithm itself. In this work, we present a new algorithm capable of estimating more than 6 parameters, moving toward the typical 15 parameters required for full GW parameter estimation. We validate this new algorithm using both simulated and observed GWs from binary black hole mergers on both classical simulators and partially on quantum hardware.

Toward Precision Cosmology with Dark Sirens in O4: Constraints and Biases in Galaxy Catalog Methods

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Tuesday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

Standard sirens based on gravitational-wave (GW) detections offer an independent avenue for measuring the Hubble constant (H_0), especially in the absence of electromagnetic counterparts—so-called dark sirens. In this work, we present updated H_0 constraints using five new GW events detected during the fourth LIGO/Virgo/KAGRA observing run (O4) in combination with previous 10 dark sirens, analyzed via the galaxy catalog method with photometric redshifts from the Legacy Survey. We obtain $H_0 = 70.4^{+13.6}{-11.7} , \rm{km} ,\rm{s}^{-1} \rm{Mpc}^{-1}$ (68% confidence), a 23% improvement over previous dark siren analyses. When combined with the bright siren GW170817, this refines to $H_0 = 68.0^{+4.4}{-3.8}, \rm{km} ,\rm{s}^{-1} \rm{Mpc}^{-1}$.
To understand future prospects and limitations, we also investigate the impact of systematic uncertainties arising from catalog incompleteness and redshift estimation errors. Using simulated photometric redshifts, we forecast that by the end of O4, dark sirens alone could reach a precision of $\sim12%$–$17%$ on H_0. We quantify potential biases due to incorrect weighting schemes for galaxy host assignment, such as using stellar mass or star formation rate as tracers. We show that unbiased H_0 estimates are achievable when appropriate corrections are applied and when catalogs are volume-limited. A precision of $\sim3%$ on H_0 may be attainable with ~100 GW detections during O4–O5, provided that localization regions are sufficiently constrained and that catalog coverage is adequate.

Together, our results highlight the current constraining power of dark sirens from O4 and the path toward percent-level precision with upcoming GW observations—while cautioning about the need to control catalog related systematics.

Induced gravity from quantum field theory in discrete spacetime

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Thursday Session 4 - D3: Causal sets, causal dynamical triangulations, non-commutative geometry, asymptotic safety, and other approaches to quantum gravity

We show that gravitational interactions emerge as an effective phenomenon from quantum field theory in discrete spacetime.

In our approach, quantum field theory in discretized spacetime manifold is formulated using compositional quantum field theory [1] and tensor network methods [2]. Focusing for concreteness on free scalar field theory in 2d simplicial spacetime, we show that renormalizing the model (i.e., integrating out high energy degrees of freedom) leads to terms in the effective action, which correspond to a discrete gravity action. This mechanism is similar to Sakharov's induced gravity [3] in the continuum case.

Our results suggest a new unified model for quantum gravity and matter obtained by first considering quantum field theory in discrete spacetime (without explicit gravitational dynamics), which induces the gravitational action for the spacetime geometry, and then finally summing over the different discrete spacetime structures, akin to causal dynamical triangulations [4]. Moreover, the sum over amplitudes for different discrete manifolds can be implemented as a tensorial state-sum model, relating our work to random tensor models [5].

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Hyperboloidal initial data without logarithmic singularities

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Thursday Session 3 - A1: Classical GR: Theoretical developments

It is well-known that generic asymptotically hyperboloidal initial data solutions to the elliptic form of the constraint equations have polyhomogeneous asymptotic expansions. This talk revisits related analytic issues within the framework of the parabolic hyperbolic formulation of the constraints. Our main result asserts that the existence of well-defined Bondi mass and angular momentum, subject to certain restrictions on the free data, ensures that the generic solutions to the parabolic-hyperbolic form of the constraint equations are completely free of logarithmic singularities.

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Hawking and Schwinger Effects via Lorentzian Worldline Path Integral Formalism

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Wednesday Session 4 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

We revisit the Schwinger effect and Hawking radiation using the Lorentzian worldline formalism to shed light on some of their common and distinct features. The positive frequency solutions of the Klein-Gordon equation -- in a constant electromagnetic case for the Schwinger effect and a dynamical black hole spacetime for the Hawking radiation -- encode useful details of the pair creation process. The solutions, in turn, admit Lorentzian worldline path integral representations with mixed boundary conditions. We explore how tunneling and pair-creation effects manifest in such an explicitly real-time-based path integral. While we confirm the generally held notion that complex worldlines play a crucial role in the semi-classical interpretation of the pair-creation process in both the Schwinger and Hawking effect, how they arise is found to be interestingly different. In the Schwinger effect case, we show explicitly how complex worldline instantons arise naturally as relevant saddle points of the proper time integral. In the Hawking radiation case, in contrast, the tunneling is interestingly described by a `real' worldline, which acquires complex coordinates values merely because it extends beyond the corresponding coordinate patch. Moreover, while the worldline instanton in the Schwinger case serves as a proxy for spacelike correlations in the vacuum, in the case of Hawking radiation, it represents non-radial correlations that contribute to the zero-angular momentum modes."

IMRPhenomXHM_NSBH: A Fast and Accurate Gravitational-Wave Model for Neutron Star–Black Hole Coalescences

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Monday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

We present IMRPhenomXHM_NSBH, a new phenomenological model for graviational-wave (GW) emission from neutron star–black hole (NSBH) coalescences. This model features a newly developed numerical relativity (NR)-calibrated amplitude prescription incorporating tidal contributions up to 7.5PN order, a phasing model tuned to NR simulations incorporating dynamical tidal effects (NRTidalv3), and the inclusion of higher GW strain harmonics also including tidal corrections calibrated to numerical relativity.

This model represents a significant improvement over previous phenomenological GW models for NSBHs, providing smooth and well-behaved waveforms across the parameter space with enhanced physical fidelity while introducing minimal computational overhead compared to its baseline binary black hole model, IMRPhenomXHM. As a result, it is the fastest NSBH model including higher-order harmonics, with its (2,2) mode being roughly an order of magnitude faster than previous NSBH models for this mode.

Finally, we discuss the prospects of extending the model to incorporate spin-precession and orbital eccentricity effects.

Fast and accurate frequency-domain inspiral-merger-ringdown phenomenological waveforms for eccentric binary black holes with aligned spins

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Wednesday Session 4 - B3: Approximations, perturbation theory, and their applications

A non-negligible population of binary black holes (BBHs) forming dynamically in active astrophysical environments is predicted to radiate graviational waves (GWs) in the frequency band of ground-based LIGO, Virgo and KAGRA (LVK) GW detectors. Thus, strong evidence for orbital eccentricity in GW detections will play a pivotal role in unveiling the astrophysical origins of BBH mergers. Despite recent progress on modelling GWs from eccentric binaries, GW data analysis of BBH mergers is still limited to systems on quasi-circular orbits, due to the lack of waveform models that accurately predict the signals of eccentric BBH mergers in a computationally efficient manner. In this work, we present an inspiral-merger-ringdown phenomenological waveform model in frequency domain for binary black holes with non-precessing spins in ellitpical orbits. Eccentric corrections are incorporated in the waveform multipoles, and validated against eccentric numerical relativity waveforms finding unfaithfulness below 2%. Additionally, we perform parameter estimation runs on GW events detected by the LVK and demonstrate that the computational efficiency of the model enables routine GW data analysis and systematic studies of large populations of generic BBHs.

The Future is Bright... Sort of: Leveraging Simulations to (Potentially) Enhance the Dark Siren Technique

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Thursday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

Gravitational waves (GW) offer a promising avenue to resolve the current tension in the Hubble constant (H0), caused by the inconsistencies in the methods that use different probes to measure this value. Given the plethora of GW events from binary black hole (BBH) mergers, the dark siren technique is at the forefront of techniques to provide an estimate of the Hubble constant. However, current measurements with this technique still face challenges, such as large relative errors and potential biases due to systematics. This highlights the need for novel approaches to constrain H0. Utilising outputs from simulations and mock catalogues may hold the key to robust testing of the impact of systematics in the dark siren technique and shed light on what aspects of the technique need improving. In this talk, I will show how outputs from simulations of BBH mergers in host galaxies can be used to place informative and astrophysically motivated priors on the galaxies more likely to host GW events, to determine if the H0 posterior can be constrained. I will also discuss the pilot studies being conducted in OzGrav for a southern hemisphere dark siren follow up program.

A Two-Step Procedure to Detect Cosmological Gravitational Wave Backgrounds with Next-Generation Terrestrial Detectors

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Tuesday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Primordial gravitational waves are expected to produce a cosmological stochastic background, offering insights about the early Universe that no other probe can access. The next-generation terrestrial detectors Einstein Telescope and Cosmic Explorer will be uniquely positioned to probe this background in the ~[1,100] Hz regime. However, the cosmological background will be buried beneath an astrophysical foreground of gravitational waves from compact binary mergers. In this talk, I will present a novel framework to detect the cosmological background in the presence of binary black hole and binary neutron star signals. Our approach strategically combines (i) efficient subtraction of binary black hole signals through masking in the time-frequency domain; (ii) a joint Bayesian inference method to simultaneously analyze individually resolved binary neutron star signals, the astrophysical foreground and the target cosmological background. We test our procedure on a flat cosmological background with realistic amplitude, finding that a confident detection can be achieved within just a few months of observation.

Singularity Resolution of Quantum Black Holes in (A)dS

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Friday Session 4 - D1 + D2 + D3

Black holes serve as key testing grounds for quantum gravity due to their singular nature and have been extensively studied in various quantum gravity approaches. In this talk, I apply the Henneaux-Teitelboim formulation of unimodular gravity to the symmetry-reduced Schwarzschild-(Anti-)de Sitter model. We perform a canonical quantization, leading to a Wheeler-DeWitt equation that takes the form of a Schrödinger equation in unimodular time. By enforcing unitary evolution in this time coordinate, we naturally treat the cosmological constant as an observable. We find a family of quantum theories in each of which the classical singularity is resolved, and we derive an analytical expression for the quantum-corrected Schwarzschild-(Anti-)de Sitter metric. Furthermore, we show that each quantum theory permits only semi-classical states corresponding to either positive, negative, or zero-mass black holes. Therefor we avoid problems that would otherwise occur in singularity free theories with arbitrarily large negative energy states.

Free-surface correlations on analogue black-hole water flows

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Monday Session 4 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

As a realisation of field theory in curved spacetime, Analogue Gravity finds great utility in correlation functions. In particular, such correlations capture the pairwise nature of the analogue of Hawking radiation in an effective spacetime with a black-hole horizon [1-3]. More generally, they can provide valuable information about the behaviour and structure of the effective spacetime and the wave scattering induced on it.

In this talk, I will report on correlation patterns observed in the free-surface deformations on an accelerating transcritical water flow. In an Analogue Gravity context, such flows are described by an effective metric with a black-hole horizon, with waves on the supercritical side being unable to return upstream and thus being trapped in the ``black-hole interior''. The correlation patterns are dominated by a particular scattering process triggered by a large influx of co-current waves, the scattering of which is analogous to backscattering of incident waves on a black-hole spacetime and was experimentally studied in [4] via stimulation by a wave maker. Here instead, the wave scattering and their associated correlations are induced by the intrinsic noise in the system, making our study complementary to that of [4]. The observed correlations are compared with those expected due to the analogue Hawking effect.

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Evolution of the event horizon of binary mergers in modified gravity

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Wednesday Session 3 - A3: Alternative and modified theories of gravity

The collision of compact objects, such as black holes and neutron stars, is a spectacular cosmic event of great interest to gravitational wave astronomy. In recent years elementary ray-tracing techniques have been shown to capture the main characteristics of black hole mergers by considering the extreme mass ratio limit in an unorthodox way. In this regime, the evolution of the event horizon, when a large black hole merges with a small compact object, can be easily computed (semi-)analytically.
In this talk, this approach will be exploited in the context of compact object mergers in modified gravities respecting the equivalence principle. Several examples will be discussed: the collision between two black holes in cubic gravity, the merger of two hairy black holes in Einstein-scalar-Gauss-Bonnet theory, and the fusion between a large black hole and a small traversable wormhole supported by a phantom scalar field. Differences with respect to black hole mergers in General Relativity will be highlighted.

Homothetic expansion of polyhedra in loop gravity

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Thursday Session 3 - D1: Loop quantum gravity and spin foams

Loop quantum gravity (LQG) proposes a quantization of gravity based on wave functions (spin-networks), defined over graphs with a spin label on the links, related with quanta of area, and intertwiners at the nodes that are related with chunks of volume. The twisted geometries framework, parametrized using the spinorial formalism, offers a classical interpretation of the spin-networks as a collection of convex polyhedra glued together by faces of equal area. The use of this framework to study the dynamics of the LQG truncation known as the two-vertex model (two nodes with an arbitrary number of links) has recently provided interesting results. In particular, the evolution of a symmetry reduced sector, identified with the homogeneous and isotropic sector due to its sole dependence on the total area (not on the specific link or node), eventually recovers the Friedmann equations. In this talk we exploit the use of frame bases as a tool to exhaust the study of the evolution of the geometry of the polyhedra in the reduced sector of the two-vertex model. The main result is that the polyhedra only suffer an homothetic expansion.

Hamiltonian renormalisation of the U(1)^3 model for 3+1 quantum gravity

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Wednesday Session 4 - D1: Loop quantum gravity and spin foams

We apply Hamiltonian renormalization to Smolin's U(1)^3 model for 3+1 quantum gravity, which can be interpreted as the weak Newton constant regime of the full theory. Our analysis shows that the renormalization group flow identifies known solutions of the model as fixed points, demonstrating the scheme's consistency. This suggests that the renormalization approach could be extended to the full theory to help resolve quantization ambiguities.

Can we form gravitational wave sources from binaries? The role of stellar winds and envelope structure in the formation of the most massive black holes

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Friday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

The formation of black holes, especially those seen in Gaia binaries and gravitational wave events, is still not fully understood due to gaps in our knowledge of how massive stars evolve. Stellar winds play a key role in mass loss and significantly affect these evolutionary paths. However, existing models are hampered by outdated methods and considerable differences in their underlying assumptions. In this talk, I will share a detailed mapping of stellar winds and envelope structure for massive stars, examining how different physical choices impact their evolution and therefore the formation of gravitational wave sources. From all the uncertainties, robust evolutionary patterns emerge, which are common to most models. These patterns provide important insights into the progenitors of the black holes we observe, including their isolated (spectroscopic) evolution and the chances of binary mass transfer, thus serving as an essential resource for interpreting both current and future observational data.

The growing evidence for dynamically-formed and triple-origin mergers in the gravitational-wave transient catalogue

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Wednesday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Several hundred merging compact objects have been detected by the LVK via their GW emission. However, the formation mechanisms of this abundant population remains elusive.
Binary compact objects may form and merge in isolation, in either long-lived binaries or hierarchical field triples; or they may become bound through dynamical interactions in densely-populated environments.
Several properties of compact object binaries can indicate distinct formation channels.
For example, dynamically-formed mergers can have higher masses, higher and more misaligned spins, and higher orbital eccentricities than those evolving in isolation.
Meanwhile, binaries with a tertiary companion may also have detectable eccentricities, but different mass and spin profiles than dynamical mergers.
In this talk, I review exciting recent work that builds evidence for dynamically-assembled and tertiary-influenced in our detected GW population.
I show that around ~20% of the BBHs in LVK's detected mergers have masses and spins consistent with predictions from globular cluster models.
I discuss the growing evidence for eccentric binary compact objects in the population, revealing the surprising implications of these results in support of triple-origin binary mergers.
Finally, I present new measurements of orbital eccentricity and spin-induced precession, using a full insprial-merger-ringdown waveform model with higher-order modes, that remove ambiguity in these measurements—providing a first step towards a "final word" on the proposed eccentricity of the detected events.

On the maximum mass and stability of differentially rotating neutron stars

Rosinska D[1], Szewczyk P[1]
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Friday Session 3 - B1: Relativistic astrophysics

An understanding of differentially rotating relativistic stars is key to many areas of astrophysics, in particular to the emission of gravitational waves. A newly born, proto-neutron star or a compact remnant of neutron stars binary merger are expected to rotate differentially and to be important sources of gravitational radiation. A highly accurate and stable, relativistic spectral code is used to explore the whole solution space for broad ranges of the degree of differential rotation. Staying within an astrophysically motivated range of rotation profiles, we investigate the characteristics of neutron stars and strange quark stars with maximal mass for all types of sollution and different equations of state. We find various types of configurations, which were not considered in previous work, mainly due to numerical limitations. The maximum allowed mass for the new types of configurations and moderate degree of differential rotation can be even 2-4 times higher then the maximum mass of non-rotating neutron stars with the same equation of state. Differential rotation can temporarily stabilize a hyper-massive neutron star against gravitational collapse. I will discuss the stability properties of such stars. This result may have important consequences for the gravitational wave signal expected from coalescing neutron star binaries or from some supernova events.

Modeling the complete (l=2,m=0) mode in aligned-spin and precessing binary black holes: applications to parameter estimation

Rosselló Sastre M[1], Husa S[2], Bera S[3], Valencia J[1]
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Friday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Gravitational waves from binary black hole mergers encode astrophysical information in multiple spherical harmonic modes. While dominant and subdominant modes have been extensively studied, the (l=2, m=0) mode has only recently been incorporated into waveform models.
We present a phenomenological waveform model for the (2,0) mode, capturing its two components: the non-oscillatory displacement memory and the quasi-normal ringdown. Incorporating this mode refines waveform accuracy, especially in the merger and post-merger regimes. Additionally, the displacement memory effect, which is mainly contained in this mode, remains undetected and this waveform model can be used to study its detectability. The model is first developed for aligned-spin binaries and then extended to precession, expanding its applicability across a wider parameter space. Our implementation builds upon the computationally efficient IMRPhenomTHM and IMRPhenomTPHM models, which are optimal for Bayesian parameter estimation. Through extensive studies, we quantify the biases introduced when this mode is omitted, demonstrating its crucial role in accurately recovering individual mass and spin components and constraining the distance-inclination degeneracy. We present results for the Advanced LIGO A# sensitivity and the Einstein Telescope.
Targeting the modeling of generic waveforms, we also present preliminary results regarding the (2,0) mode in eccentric systems.
By incorporating this missing piece of the gravitational wave signal, our work not only enhances the precision of parameter estimation, but also takes a step forward the possible detection of the displacement memory.

Women in science tell their stories - communication strategies and experiences to promote gender diversity in science

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Thursday Session 3 - C1: Pulsar timing arrays & C8: Education and public outreach in gravitational physics

There is still much to do to improve gender diversity in science, and each aspect of the scientific research system has its role in this fundamental process, including of course communication and outreach. In communicating the community of the European Gravitational Observatory (EGO) and the science of Virgo this has been a central mission and many approaches and actions have been explored in the past few years.

We will share the communication actions developed by the communication office of EGO in the past few years concerning the representation of women in science, such as events, social media activities and a theatre show. We will share the questions and issues that came up, and the solutions and strategies developed to face them, resulting in some of the infinite possible communication approaches to this theme.

Vacuum axisymmetric gravitational collapse, revisited

Rostworowski A[1]
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Friday Session 3 - B2: Numerical Relativity

I will discuss my efforts to reproduce the results of the renown Abrahams&Evans (AE) paper on a critical axisymmetric gravitational collapse [Abrahams&Evans, PRL70 2980 (1993)]. There were some such tries in the past but, as far as I know, no one has really succeeded so far. In particular, I will discuss AE ansatz, its linearized approximation, the initial data choice and the bases of the pseudospectral code that I have constructed. I will also try to briefly summarize the efforts undertaken in the last 30 years to repeat AE results and check their conclusions.

Full self-force merger-ringdown waveforms in scalar field theories of modified gravity

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Monday Session 3 - B3: Approximations, perturbation theory, and their applications

Gravitational self-force theory (GSF) has proved to be a viable method of solving the general relativistic 2-body problem for asymmetric binaries, with state-of-the-art GSF inspiral waveforms now exhibiting minimal phase error across all mass ratios smaller than ~1/10. Recent work has extended these GSF inspiral waveforms to include beyond-GR effects in a broad class of scalar-tensor theories. At the same time, GSF inspiral models have now also been extended to include the final merger and ringdown. In this talk we tie together these two themes by calculating first-principles GSF merger-ringdown waveforms in scalar-tensor gravity.

Testing General Relativity at the Galactic center with GRAVITY(+) and the ELT

Sadun Bordoni M[1]
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Thursday Session 3 - C10: Experimental tests of the nature of compact objects

Since 2016, the GRAVITY interferometer at ESO's Very Large Telescope has enabled us to obtain astrometric data with unprecedented accuracy for the S-stars orbiting Sagittarius A*, offering a unique laboratory to test General Relativity (GR) near the supermassive black hole at the center of our Galaxy. In particular, for the star S2, we have detected the effects that arise at first order in the post-Newtonian (PN) expansion of GR, namely the in-plane, prograde Schwarzschild precession of the pericenter angle and the gravitational redshift of its spectral lines.

The imminent upgrade of GRAVITY to GRAVITY+ (to be completed by 2026) and the first light of the Extremely Large Telescope (ELT) in 2029 will revolutionize our understanding of the Galactic center. These advancements could lead to the discovery of fainter stars on significantly tighter orbits around Sagittarius A*, providing an opportunity to measure its spin and quadrupole moment—thus testing the no-hair theorem.

The Lense-Thirring precession caused by the spin of Sagittarius A* arises at 1.5 PN order and is orders of magnitude smaller than the Schwarzschild precession, making it too weak to be detected for S2. Detecting this effect would require a star with a pericenter distance at least three times smaller, while an even tighter orbit would be necessary to measure quadrupole effects and rigorously test the no-hair theorem. However, these measurements could be complicated by perturbations from stellar-mass black holes in the region, which may affect spin and quadrupole moment estimates, as I will discuss.

COSMOLOGICAL PARAMETERS FROM MEASUREMENTS IN THE NONLINEAR REGIME

Safi S[1], Farhang M[1]
[1]Shahid Beheshti University

Tuesday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

As upcoming large-scale structure surveys aim to probe the mildly nonlinear regime with high precision, accurate theoretical modeling becomes essential for reliable cosmological inferences. This study explores the impact of different nonlinear prescriptions on parameter estimation in cosmic shear measurements for a Euclid-like survey and galaxy clustering observations, focusing on the Halofit fitting scheme and the Effective Field Theory of Large Scale Structure (EFTofLSS). We assess their effects across various cosmological models, including ΛCDM, wCDM, and (w0, wa) CDM, while investigating the consequences of different nonlinear cutoff schemes.

Our findings indicate that including smaller scales significantly reduces predicted errors on most parameters, with the extent of reduction dependent on the choice of nonlinear prescription and cutoff method. We observe notable biases—approximately 5σ for certain parameters—when employing the Halofit model, specifically affecting σ8 and ns. Furthermore, our analysis demonstrates that marginalizing over nuisance parameters related to nonlinear theory and galaxy bias amplifies the measurement errors of standard cosmological parameters, thereby limiting the effectiveness of different nonlinear prescriptions in parameter estimation. Ultimately, enhancing the modeling of these nuisance parameters is crucial to maximize the cosmological insights derived from the mildly nonlinear regime in future surveys.

Thermal Power Region around BH, probing BH's strong gravity

Saida H[1]
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Monday Session 3 - B1: Relativistic astrophysics

Let a body (radiation source) be falling into BH with emitting radiations to far observer. I show that, once the falling body goes into the vicinity of BH, r < 4M (Schwarzschild case), then the observed power spectrum of the radiation becomes proportional to the thermal spectrum of Hawking temperature.

Note that the appearance of this Hawking thermal power is completely a classical physics phenomena, no quantum field theory is considered in its derivation. The appearance of this Hawking thermal power can be an observable signature of the strong gravity at the vicinity of BH (r < 4M). This strong gravity region, r < 4M, may be named "thermal power region around BH".

Now, I am considering how to detect the thermal power region/Hawking thermal power with the "Black Hole Explorer (BHEX)" project. BHEX is the radio-satellite-telescope project for enhancing the "Event Horizon Telescope" resolution to take the image of lights circling around BH, being promoted by USA and Japan (I'm a member of Japanese team).

Why do we need a vacuum system in space? How Brownian noise affects the LISA detection, and the vacuum system design

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Monday Session 3 - C5: LISA and other space-based detectors

Detecting sub-milliHertz gravitational waves requires the free-falling reference bodies – the LISA test masses – to follow a nearly perfect geodesic trajectory. At the femtoNewton level – which is the LISA target –, no physical effect is negligible. The random collision of residual gas molecules with the test masses is definitely a source of disturbance, known as the “Brownian” noise: as individual molecules hit the test masses, they transfer momentum, ultimately generating a shot noise which can potentially hinder gravitational wave detection. This is why the LISA GRS (gravitational reference system) will be a flying vacuum system, with, at the same time, the cleanliness/outgassing level of a particle accelerator, and the crowdedness of a space-qualified instrument. I will discuss the LISA vacuum system design, the results from LISA Pathfinder, and the testing strategies foreseen to comply with the Brownian noise requirement.

Enhancing the Reach of cWB in Sky-Targeted Searches

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Thursday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The Coherent WaveBurst (cWB) pipeline is renowned for its ability to continuously survey the entire sky in search of gravitational-wave transients (GWTs), operating with minimal assumptions about the waveform models of the signals. Despite its capacity to constrain the incoming direction of these signals, this feature has yet to be utilized in practical applications.
In this work, we present two case studies focusing on sky-targeted searches associated with core-collapse supernovae and pulsar glitches. These cases serve as a platform to explore and evaluate new methodological advancements tailored for such targeted searches. We provide an analysis of typical sensitivities and achievable distance ranges for various gravitational-wave emission models. Our investigations are based on archival gravitational-wave data from the third observing run of Advanced LIGO and Advanced Virgo.

Geometric Invariants on Asymptotically corresponding initial data sets

Sancassani A[1]
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Monday Session 3 - A2: Classical GR: Mathematical developments

As first pointed out by Chruściel and Tod, there exists a correspondence between initial data sets with constant mean curvature and different values of the cosmological constant. A key example of this correspondence is the relationship between hyperbolic space in Anti-de Sitter (AdS) spacetime and the hyperboloid in Minkowski space. This relationship has been extensively used to transfer knowledge from the asymptotically flat realm to the asymptotically AdS hyperbolic setting, as seen in the work of Cha and Khuri. In this talk, I will present results from a detailed investigation of this correspondence, with a focus on its implications for Killing Initial Data (KIDs). I will define asymptotically corresponding initial data sets and prove a result concerning the associated geometric invariants, as defined by Michel. These findings enable us to generalize the cited results and clarify the extent to which this correspondence can be exploited to gain insights into spacetimes arising from corresponding initial data.

Cosmological spacetimes with spatially constant sign-changing curvature

Sánchez M
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Friday Session 3 - A2: Classical GR: Mathematical developments

In spite of common assertions about the implications of symmetry in Cosmology, globally hyperbolic spacetimes endowed with a time function t whose spacelike slices $t=t_0$ have constant curvature c_0, and where the sign of c_0 (as well as the topology of the slice) varies with t_0, have been constructed in [1], see also [2].

Because of global hyperbolicity, these spacetimes also admit Cauchy temporal functions τ, whose levels are all necessarily diffeomorphic and yield a global orthogonal splitting of the spacetime [4]. However, the levels of the time t above might be physically more appealing.

Indeed, the finiteness of the total matter and energy after the Big Bang might imply a closed model with a spatial part of positive constant curvature at early stages, while observational evidence would suggest an Euclidean spatial part later. Both conditions are incompatible for cosmologies based on FLRW spacetimes (or, in general with a privileged Cauchy temporal function τ). However, they are compatible with the requirement of constant curvature for each level of a different time function t.

In this talk, examples and properties of these models will be explained. Ongoing work in collaboration with B. Janssen, G. García and A. Jiménez (U. Granada), M. Mars (U. Salamanca) and R. Vera (U. País Vasco) will be included.

[1] M. Sánchez: Portugaliae Math. 80, No. 3/4 (2023).
[2] R. Ávalos: Lett Math Phys 113, 98 (2023).
[3] A. N. Bernal, M. Sánchez: Commun. Math. Phys. 257 (2005).

Killing and homothetic initial data for general hypersurfaces

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Thursday Session 3 - A1: Classical GR: Theoretical developments

In this talk we present a novel framework to address the homothetic Killing initial data problem for general hypersurfaces. Specifically, we present a collection of general identities relating the deformation tensor $\mathcal{L}_\eta g$ of an arbitrary vector field η with the tensor $\mathcal{L}_\eta \nabla$ on an abstract (i.e. viewed as a detached object from the spacetime) hypersurface H of any causal character. As an application we establish necessary conditions on H for the existence of a homothetic Killing vector in the spacetime where H is embedded. Their sufficiency is then analyzed in three specific settings. For spacelike hypersurfaces, we recover the well-known homothetic KID equations [Coll, García-Parrado–Khavkine] in the language of hypersurface data. For two intersecting null hypersurfaces, we generalize a previous result [Chruściel-Paetz] (valid for Killings) to the homothetic case and, moreover, demonstrate that the equations can be formulated solely in terms of the initial data for the characteristic Cauchy problem, i.e., without involving a priori spacetime quantities. This puts the characteristic KID problem on equal footing with the spacelike KID problem. Furthermore, we highlight the versatility of the formalism by addressing the homothetic KID problem for smooth spacelike-characteristic initial data. Other initial value problems, such as the spacelike-characteristic with corners, can be approached similarly. This talk is based on arXiv:2502.07767.

Quantum energy inequalities bound the singular behaviour of quantum fields

Sanders K[1]
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Wednesday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

Quantum energy inequalities for the stress tensor of a quantum field can be used to express the stability of a theory in analogy to the classical energy conditions in GR. In this talk, however, I will argue that they also have another important application: they can be used to bound the high energy behaviour of quantum fields in analogy to Hamiltonian bounds known for quantum fields in Minkowski space. This potentially opens up the way to manipulate pointwise quantum fields and operator product expansions in a rigorous way, also for quantum fields in curved spacetimes.

Testing the spin-induced multipole moments of compact binary coalescences using a Flexible Theory-Independent framework

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Thursday Session 3 - C10: Experimental tests of the nature of compact objects

The no-hair conjecture tells us that the multipole moments of a black hole in General Relativity are completely determined by its mass and spin. This is not in general true for compact objects: neutron stars or exotic compact objects can have spin-induced multipole moments that are different from the ones of black holes with the same mass and spin. Gravitational waves can thus be used to test the nature of compact binary coalescences. We present a test for the spin-induced quadrupole and octupole moments of compact objects using the Flexible Theory-Independent (FTI) framework. FTI is a parameterized inspiral test of General Relativity that allows for deviations in the post-Newtonian coefficients in the gravitational wave phase. We use this new test on synthetic signals to study the measurability of the quadrupole and octupole moments. We then apply the test to signals observed by the LIGO and Virgo detectors. Lastly, we present forecasts for next-generation ground-based detectors.

Optomechanical technologies for gravitational-wave observatories

Sanjuan J, Guzman F[1]
[1]University Of Arizona

Friday Session 3 - C4: Concept and research towards next-generation detectors

High sensitivity displacement interferometers and optomechanical systems have wide range of applications in gravitational-wave observatories, both on ground and in space. This can not only cover the main science laser-interferometric observations, but also ancillary sensing systems to characterize and monitor critical parts of the observatories.

We will discuss some of the optomechanical technologies that we have been developing in our laboratory to monitor ground motion and seismic effects in ground-based gravitational-wave observatories, as well as novel optical truss interferometer systems with subpicometer sensitivity, which can be used for the characterization of critical systems in space-based observatories, such as LISA.

Weak cosmic censorship and the rotating quantum BTZ black hole

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Tuesday Session 4 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

Tests of the weak cosmic censorship conjecture examine the possibility of a breakdown of predictivity of the gravitational theory considered, by checking if curvature singularities are cloaked behind an event horizon at all times, during the time-evolution of an initial regular configuration. The conjecture has been a subject of intense scrutiny, but no convincing counter-example has been found yet for classical theories of gravity.

A natural question to ask, therefore, is what is the impact (if any) of quantum gravity effects on the conjecture. In this talk, we will address this problem by focusing on an extremal, rotating, quantum version of the BTZ black hole. This has been holographically constructed some years ago starting from a solution for a black hole localized on a brane in anti de Sitter space in four dimensions, and it has recently been reconsidered and re-analyzed in details. The holographically-dual three-dimensional metric encodes the exact backreaction from strongly coupled quantum conformal fields. Our analysis reveals that, despite the inclusion of quantum effects and akin to the classical scenario, these attempts to destroy the black hole are doomed to be unsuccessful. Particles carrying the maximum angular momentum and still falling into an extremal quantum BTZ black hole can, at most, leave it extremal. We found numerical evidence that large backreaction of the quantum fields tends to disfavor violations of cosmic censorship.

Modelling the accretion-ejection flow around the supermassive black hole at the centre of the Milky Way

Santos J[1]
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Monday Session 3 - B1: Relativistic astrophysics

Over the past decade, the study of compact objects has seen an increase in interest and overall research in the field. With this, Sagittarius A* (Sgr A*), our galaxy's supermassive black hole, and, thus, the closest supermassive black hole candidate to Earth, has been highlighted as a unique laboratory for relativistic astrophysics. The most recent developments in the area is the 2022 Event Horizon Telescope Collaboration reconstructed image of Sgr A*'s close environment. In turn, these allow for better constraints to be put on state-of-the-art models.

As such, the goal of my master's thesis is to accurately reproduce the observed spectrum, image, and light polarization of Sgr A* (by the EHT), using the General Relativistic Ray-tracing code, GYOTO, as the chosen software to simulate new and more realistic models for the black hole jets and disk.

So far, the work done with GYOTO has allowed us to learn about relativistic effects and how these impact both the resulting spectrum and the synthetic images of the emitting disk and jet's plasma. In this talk, I will present our new disk + jet analytic model, which aims to reproduce both the non-thermal properties of the observed spectrum and the image observables from the EHT observations. I will present our parameter-space exploration and highlight the most critical parameters. With this work we aim to derive new constraints on the accretion-ejection mechanism for Sgr A*.

Relativistic dissipative fluids from kinetic theory using the trace-fixed particle frame

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Monday Session 4 - A1: Classical GR: Theoretical developments

We discuss a new dissipative fluid theory on an arbitrary curved spacetime background. This theory is obtained from kinetic theory by applying a new version of the relativistic Chapman-Enskog method to derive the constitutive relations to first order in the Knudsen parameter. The novelty of our approach consists in applying a suitable projection method to solve the linearized Boltzmann equation and to use the so-called trace-fixed particle frame, which determines the state variables n,T,u (particle density, temperature parameter and four-velocity) by fixing the trace of the stress-energy tensor in addition to the particle current density. As we show, this leads naturally to a dissipative fluid theory which, in contrast to the traditional first-order theories (Eckart and Landau), is hyperbolic, causal, and stable at global equilibrium configurations. Moreover, we prove that the full nonlinear system of equations can be cast into a first-order quasilinear system which is strongly hyperbolic and yields a well-posed Cauchy problem.

Applying quantum state preparation algorithms to gravitational wave data analysis

Sarell E[1], Girish A[2], Spencer-Wood H[1], Puerrer M[2], Messenger C[1], Speirits F[1], Croke S[1]
[1]University of Glasgow, [2]University of Rhode Island

Tuesday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The potential for successfully applying quantum algorithms to gravitational wave data analysis is rapidly becoming a reality, with the development of quantum algorithms that offer significant speed up over classical algorithms. However, these techniques require encoding the observational gravitational wave data into a quantum computer.
Quantum State Preparation is an increasingly important part of quantum computing and ensuring waveforms can be loaded efficiently is essential for the future of quantum algorithms. Here, we look at improving the efficiency of amplitude encoding for gravitational waveforms. We load in the amplitudes of two gravitational waveform models. The first waveform is an approximation of the inspiral section and the second is a numerical representation of an inspiral merger and ringdown of a binary black hole system. By inducing a small error into the Grover-Rudolph algorithm, we can greatly reduce the number of gates needed as the number of qubits grows. We achieve this by asymmetrically discretising our distribution, prioritising areas with large amounts of change so that we can more uniformly map the number of gates used to the amount of information in that section.

Silicon Nitride and Silicon Oxy-nitride Films Deposited by Plasma-enhanced Chemical Vapour Deposition for Mirror Coatings of the Cryogenic Laser Interferometer Gravitational Wave Detectors.

Saunders K[1], Clark C[2], Ried S[3], Martin I[1], Gibson D[4], Garcia Nunez C[1]
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Friday Session 4 - C4: Concept and research towards next-generation detectors

Gravitational wave detectors (GWDs) have transformed our understanding of Astrophysics and fundamental Physics by enabling direct observations of cosmic events such as black hole mergers and neutron star collisions [1]. To further enhance detector sensitivity, next-generation GWDs will operate at cryogenic temperatures and longer laser wavelengths, such as 1550 nm, to reduce thermal noise and optical absorption losses. However, current high-reflectivity (HR) coatings used in interferometric mirrors suffer from high mechanical loss and optical absorption at cryogenic temperatures, limiting their performance.
A promising alternative is the use of silicon nitride (SiNx) and silicon oxynitride (SiOxNy) as high and low refractive index materials, respectively, to form an HR coating optimised for cryogenic operation. These materials exhibit superior mechanical and optical properties, including low absorption and reduced mechanical loss, while maintaining high reflectance at 1550 nm. Furthermore, plasma-enhanced chemical vapor deposition (PECVD) allows control over film composition, thickness, and uniformity, facilitating the development of this type of coatings tailored for GWD requirements [2]. This work will present a thorough theoretical and experimental study of optical and mechanical properties of PECVD SiNx and SiOxNy thin films, as well as the design, fabrication and characterisation of SiNx/SiOxNy based HR coating for the next generation of GWDs.
[1] Cheung, et al. Classical and Quantum Gravity 41 (2024) 115010.
[2] Kirstin Saunders, et al. SPIE Optical Systems Design Proceedings 13020 (2024)

Relativistic corrections in black hole superradiance

Sberna L[1]
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Friday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Calculations for superradiant clouds around black holes are often performed in the non-relativistic limit, where the cloud states resemble the hydrogen atom's. We develop a relativistic perturbation theory for scalar clouds around rotating black holes. We first introduce a relativistic product and corresponding orthogonality relation between scalar modes, both quasibound and quasinormal. We then derive the analog of perturbation theory in quantum mechanics, and apply it to calculate self-gravitational frequency shifts. This brings close agreement with numerical relativity. This approach can also be applied to computing transitions between the cloud states, and reveals that the cloud can dissipate not only by transitioning into the free spectrum, but also into quasinormal modes.

Geometric description of gravitational singularities

Sbierski J[1]
[1]University Of Edinburgh

Friday Session 4 - A2: Classical GR: Mathematical developments

A hallmark of a gravitational singularity is the divergence of scalar curvature invariants. This, in itself, gives us however very little information about different singularity structures and strengths. By the examples of Schwarzschild and FLRW spacetimes we focus in this talk on capturing the singularity structure at the level of the connection and the metric, determining which geometric quantities blow up and in which regularity class the solution breaks down. The latter is of particular importance for our understanding of the strong cosmic censorship conjecture.

Non-vanishing Yukawa interactions in asymptotically safe quantum gravity

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Tuesday Session 4 - D3: Causal sets, causal dynamical triangulations, non-commutative geometry, asymptotic safety, and other approaches to quantum gravity

Asymptotically safe quantum gravity might provide a unified description of the fundamental dynamics of quantum gravity and matter. The realization of asymptotic safety—i.e., scale symmetry at high energies—constrains the possible interactions and dynamics of a system. For asymptotically safe quantum gravity to be a phenomenologically viable description of nature, it needs to cure the Landau poles of the Standard Model. In this talk, I will focus on the Yukawa sector, where the presence of a Landau pole indicates that only vanishing Yukawa couplings can emerge from a UV-complete theory. I will review the state-of-the art of quantum gravity coupled to a single Yukawa sector, where gravitational fluctuations can cure the Landau pole, by turning the Yukawa coupling into a relevant direction in theory space, if the gravitational fixed point lies in a specific regime. I will then argue that two types of couplings, namely induced and non-induced couplings will contribute to the critical exponent of the Yukawa coupling at next-to-leading order. Taking those couplings into account, we find indications that the Yukawa coupling is actually relevant at the gravitational fixed point (from fluctuation-computations). Finally, I will present an error-estimate of the region in the gravitational coupling space, where the Yukawa coupling becomes relevant based, on Monte-Carlo simulations of the next-next-to-leading order.

Asymptotic conservation laws in GR

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Wednesday Session 4 - A1: Classical GR: Theoretical developments

Associated with solutions to the standard wave equation in Minkowski space, there are an infinite number of conservation laws on each light cone. The corresponding conserved quantities are known as Newman-Penrose (NP) constants. Inspired by these conservation laws, I derive a covariant and conformal representation of NP constants for massless fields of arbitrary spin --- including the electromagnetic field, Weyl fermions, and the linearized Weyl tensor --- using a novel conformal extension of the Geroch-Held-Penrose formalism. This covariant representation may be extrapolated to curved space-times, where they define generalized NP charges satisfying approximate conservation laws. These approximate conservation laws rapidly approach conservation laws at null infinity, and may be integrated to determine the asymptotic solution of various wave equations.

Primordial Black Holes, Charge, and Dark Matter: Rethinking Evaporation Limits

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Wednesday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

Earlier studies investigating the allowed fraction of dark matter as primordial black holes (PBHs) tend to completely rule out PBHs with masses smaller than ~10^{-15} solar masses. This is due to the lack of evidence for Hawking radiation coming from the final evaporation stages of such small PBHs. These limits, however, make the key assumption that these PBHs can be modelled as uncharged, non-rotating Schwarzschild black holes. In this talk, we will present changes to these lower mass bounds when charge is included, i.e., by going to Reissner–Nordström black holes as models for PBHs. Concretely, we will add a "dark" U(1) charge, present in the early universe when the PBHs was formed; while not present in today's universe, it might still appear as a black hole charge. We use the Hiscock and Weems model of charged black hole evaporation, to correctly include the Schwinger effect. We then investigate and present the updated mass bounds for PBHs as dark matter candidates and their dependence on mass and charge of the corresponding "dark" electrons.

A+ LIGO Output Mode Cleaner Cavities and Investigation of Polarisation Balanced Homodyne Detection

Seetharamu T[1]
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Tuesday Session 3 - C3: Progress and challenges in advanced ground-based detectors

The first direct detection of gravitational waves by the Advanced LIGO (aLIGO) detectors in 2015 [Phys Rev A, 116, 061102 (2016)], followed by multiple observations of black hole (BH) and neutron star (NS) mergers, has profoundly shaped our understanding of the cosmos. To build upon these achievements, the Advanced LIGO Plus (A+) upgrade aims to enhance the detectors' sensitivity, doubling the GW detection range [Phys Rev D 91, 062005 (2015)]. The UK with LIGO Lab has played a significant role in this effort, contributing to key upgrades in optics and suspension systems and one of these major upgrades is incorporation of the Balanced Homodyne Readout scheme which will enable maximal utilisation of existing frequency dependant quantum squeezing [Phys. Rev. X 13, 041021 (2023)].

The new Output Mode Cleaners (OMCs) were developed and constructed at Caltech through a collaboration between LIGO Laboratory and IGR at the University of Glasgow. These optimised optical cavities play a crucial role in squeezing-enhanced interferometer performance by suppressing unwanted optical modes and minimising excess noise. These OMCs have an efficiency exceeding 98%, fully meeting the stringent requirements of the A+ upgrade [LIGO-T1800447-v7]. Furthermore, given the pivotal role of Balanced Homodyne Detection in A+, we investigated the feasibility of implementing Balanced Homodyne Readout using a single Output Mode Cleaner cavity rather than two—a novel approach termed Polarisation Balanced Homodyne Detection [Kuns, K. A. (2019). Future Networks of Gravitational Wave Detectors: Quantum Noise and Space Detectors. UC Santa Barbara] [LIGO-G1802013 (2018)].

A description of cosmological particle creation using an equal-time quantum kinetic formalism

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Thursday Session 4 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

When considering quantum fields in an expanding spacetime, it is well known that the expansion rate can produce particles. However, as long as the expansion persists there is no unique way of defining the particle content, which is at odds with our classical notion of particles. A similar situation occurs in strong-field quantum electrodynamics (QED), where a strong background electric field can produce electron-positron pairs through the Schwinger effect. In the QED context, relativistic quantum kinetic methods have been used to great success to study complex scenarios with applications to plasma physics, and to obtain intuition about the transition between the classical and quantum regime. Inspired by this success, we have applied a recently developed equal-time quantum kinetic method to study the production of massive scalar particles on flat FLRW spacetimes [1]. This formalism is based on a set of phase-space functions which are obtained by performing certain Wigner transforms on the real scalar field and its conjugate momentum. The resulting phase-space functions act as quasi-distribution functions for the energy momentum tensor, and through this relation we are able to make a natural definition of the particle content. To highlight similarities and differences with other approaches, we then compare this definition with the Bogoliubov approach and commonly used adiabatic particle definitions.

[1] P. Semrén, “Cosmological particle creation using an equal-time Wigner formalism,” Phys. Rev. D110 (2024) no.8, 085004 doi:10.1103/PhysRevD.110.085004

Characterization of gravitational radiation at infinity with a cosmological constant

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Tuesday Session 3 - A2: Classical GR: Mathematical developments

The existence or absence of gravitational radiation escaping from the spacetime at scri is characterized in the presence of a cosmological constant Λ of any sign. To that end the properties of the asymptotic super-momentum are used. The characterization is equivalent, when $\Lambda=0$, to that based on the News tensor. For $\Lambda\neq0$, it provides the first reliable definition of existence of radiation at scri, and it gives fully satisfactory results in known exact solutions.

Evolution of Energy and Linear Momentum in Asymptotically Hyperboloidal Initial Data Sets

Senthil Velu S[1], Sancassani A[1]
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Monday Session 4 - A2: Classical GR: Mathematical developments

Gravitational radiation in the null setting is characterized by the Bondi mass loss formula, which describes the decrease in energy due to radiation at null infinity. We study asymptotically hyperboloidal initial data sets, which are spacelike at null infinity, and analyze the evolution of energy and linear momentum defined in this context. Introducing E-P chargeability, we show that it is preserved under Einstein's equations, ensuring well-defined charges throughout the evolution. We obtain energy-loss and momentum-loss formulae that recover the Bondi loss formula under weaker asymptotic assumptions. This approach provides an alternative to conformal compactifications and null coordinates, offering a new perspective on mass loss in asymptotically hyperboloidal initial data sets.

Effective theory reproducing MOND phenomenology based on a Yang-Mills graviphoton

Seraille E[1]
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Friday Session 4 - A3: Alternative and modified theories of gravity

Despite the remarkable success and relative simplicity of the standard ΛCDM model, some phenomena remain unexplained. Most notably, the puzzling relationship between galaxy rotation curves and the observed baryon density that motivated the development of MOND. However, most field theories attempting to reproduce MOND predictions have to rely on ad hoc free functions, preventing them from being considered fundamental.
In this presentation, I will introduce a new theory that reproduces MOND phenomenology, built on a fundamental Yang-Mills gauge field based on SU(2), with a gravitational coupling constant that emerges in a low-acceleration regime. Using a mechanism of gravitational polarization within the dark matter medium, I will discuss how certain solutions of this theory naturally recover the deep MOND regime.
Within this new framework, we can connect the observed MOND effect to the existence of a new sector of particle physics, which fundamentally involves a violation of local Lorentz invariance. Nevertheless, I will show how general covariance can be restored by introducing an additional gravitational degree of freedom in the form of the Khronon scalar field.

Inspiral tests of general relativity and waveform geometry

Seymour B[1], Golomb J[1], Chen Y
[1]Caltech

Wednesday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

The phase evolution of gravitational waves encodes critical information about the orbital dynamics of binary systems. In this work, we test the robustness of post-Newtonian coefficients against unmodeled deviations from general relativity. We demonstrate that the parameterized tests are flexible and sensitive in detecting generic deviations in the waveform. This universality arises from examining the inherent geometry of the waveform signal and understanding how biases manifest. We calculate how the Bayes factor detects evidence for violation from general relativity, and intuitively explain the effectiveness of a mismodeled test. Finally, we demonstrate that the parameterized tests contain sizable overlaps with each other, and propose a new singular value decomposition method to construct generic tests of general relativity.

From a rumble to a roar: the International Pulsar Timing Array's third data release

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Monday Session 4 - C1: Pulsar timing arrays

Recent analyses of pulsar timing array (PTA) datasets by 5 collaborations have presented compelling evidence for a gravitational-wave background (GWB), sparking excitement about the far-reaching implications for astrophysics and fundamental physics. The relatively loud background is particularly intriguing, as it challenges simple models of a GWB produced by circularized supermassive black hole binaries, suggesting a more complex or exotic origin. To achieve the formal 5-σ detection and push these investigations forward, the International PTA is undertaking its most expansive data combination to date—merging pulsar timing observations from every functioning PTA into a unified dataset of around 120 pulsars. In this talk, I will discuss how this effort poses significant technical hurdles, such as harmonizing data across diverse telescopes and rigorously identifying and mitigating potential biases, but stands poised to unlock profound new insights. A confident GWB detection would not only shed fresh light on supermassive black hole dynamics but also enable stringent tests of general relativity and open up the tantalizing possibility of detecting new physics beyond the Standard Model.

Fundamental Physics with Pulsars around Sgr A*

Shao L[1], Hu Z[1]
[1]Peking University

Friday Session 4 - B1: Relativistic astrophysics

Searches for radio pulsars around the supermassive black hole at our Galactic Centre (Sgr A*) are ongoing for many years, and in the imminent era of the Square Kilometre Array telescope, the perspective of finding such pulsars is promising. We built the first numerical timing model to analyze radio pulsars around Sgr A*, and used it to investigate a number of fundamental physics questions, including the Kerrness of the Sgr A* black hole, modified theories of gravity, small-scale dark-matter properties, and so on. We found that timing of radio pulsars around Sgr A* will undoubtfully go beyond current experiments, and deepen our understanding of gravitation, spacetime, and dark matters.

Bulk-boundary correspondence for vacuum asymptotically Anti-de Sitter spacetimes

Shao A[1]
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Tuesday Session 3 - A2: Classical GR: Mathematical developments

The AdS/CFT conjecture in physics posits the existence of a correspondence between gravitational theories in asymptotically Anti-de Sitter (aAdS) spacetimes and field theories on their conformal boundary. In this presentation, we prove a rigorous mathematical statement toward this conjecture in the classical relativistic setting.

In particular, we show there is a one-to-one correspondence between aAdS solutions of the Einstein-vacuum equations and a suitable space of data on the conformal boundary (consisting of the boundary metric and the boundary stress-energy tensor), provided the boundary satisfies a geometric condition. We also discuss applications of this result to symmetry extension, as well as its connection to unique continuation problems.

This is joint work with Gustav Holzegel, and refers to joint works with Athanasios Chatzikaleas, Simon Guisset, and Alex McGill.

Reading off correlation of spacetime fluctuations from interferometric output

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Monday Session 4 - C9: Experimental gravitation

To understand the fundamental nature of gravity, high-precision interferometers, namely, Holometer (Fermilab), QUEST (Cardiff) and GQuEST (CalTech), seek possible evidence of spacetime fluctuations. These spacetime fluctuations, a feature common to both quantum and semiclassical models of gravity, could be characterised by two-point correlation functions. A two-point correlation function of any typical physical process dictates the correlation to decay as the separation increases, with the decay being either exponential or an inverse power law. This leads to two possible classes of correlation functions. We compute the spectral densities of interferometric output signal from a single Michelson interferometer, corresponding to when the light beam traverses through spacetime fluctuations with different correlation functions. From the high and low frequency behaviours of such spectral densities, we identify the characteristic signatures of each class of these correlation functions. We show that detection of these characteristic signatures in the interferometric output, in turn, will help identifying the underlying correlation function. To fully capture these signatures, we find that interferometers require sensitivity in a frequency range between O(0.1) and O(10) times the light round-trip frequency c / 2 L, for an interferometer with arm length L. We also find the high and low frequency trends of the spectral density for more sophisticated setups such as Holometer-type colocated interferometers and LIGO-type interferometers with Fabry-Perot arm cavities. Comparing such findings allow us to identify from current interferometers, setups best suited for investigating spacetime fluctuations. Our work can also be used to guide the design of future interferometers.

Resonant Locking Between Binary Systems Induced by Gravitational Waves

Sharpe C[1]
[1]The University Of Oxford

Wednesday Session 4 - B3: Approximations, perturbation theory, and their applications

The interaction of gravitational waves (GWs) with matter is typically thought to be negligible in the Universe. In this talk, we identify a possible exception in the case of resonant interactions, where GWs emitted by a background binary system such as an inspiraling supermassive black hole (SMBH) binary cause a resonant response in a stellar-mass foreground binary and the frequencies of the two systems become, and remain, synchronized. We point out that such locking is not only possible, but can significantly reduce the merger time for thousands of binaries in the host galaxy of the merging SMBHs of $10^{9-11}\Msun$ in standard general relativity and even more either in ‘wet’ SMBH mergers or in certain modified theories of gravity where the inspiral rate is reduced. This could leave an imprint on the period distribution of stellar mass binaries in post-merger galaxies which could be detectable by future GW detectors, such as LISA. As such, GW-induced resonant locking may offer new avenues to test gaseous dynamics, theories of modified gravity, the merger history of galaxies, and the formation pathway of SMBHs.

Null horizon dynamics under linear perturbations

Sherif A[1]
[1]Henan Academy Of Sciences

Tuesday Session 4 - A2: Classical GR: Mathematical developments

The symmetry of locally rotationally symmetric (LRS) spacetimes allows for a neat covariant formulation of perturbations of these solutions providing a straightforward way of making a choice of the set of gauge invariant quantities. For a null horizon embedded in a LRS background, with an assumed foliation by marginally outer trapped surfaces (MOTS), we consider the dynamics of the causal character of the horizon in this covariant formulation when the background is subjected to (linear) perturbations. Specifying to the Schwarzschild background and spatially homogenous backgrounds, the particular fields contributing to such dynamics under the perturbations are clarified. Some aspects of the MOTS stability operator in our setting are also discussed.

Measuring the wormhole with Krylov complexity

Shir R[1]
[1]University of Luxembourg

Friday Session 3 - D1 + D2 + D3

Within the framework of the AdS/CFT correspondence, the time dynamics of black holes in the bulk hints to the existence of boundary observables that evolve for very long time-scales. It was conjectured that quantum complexity has the correct features to be a candidate boundary observable. However, none of the proposed notions of quantum complexity yielded a precise bulk-boundary correspondence until recently. In this talk we will provide such a precise match by focusing on a particular notion of quantum complexity, known as Krylov complexity. We will show that in the limit where double-scaled SYK is dual to JT gravity, Krylov complexity of the infinite-temperature thermofield double state evolving in time on the boundary has a precise gravitational description in the bulk — making it the first microscopic instance of complexity to have a precise geometric description.

Cosmic Explorer: Observatory and Instrument Project Status

Shoemaker D[1]
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Monday Session 3 - C4: Concept and research towards next-generation detectors

NSF's LIGO, with Virgo and KAGRA, were designed to succeed in launching the new epoch of gravitational-wave astronomy, on a ‘best effort’ basis. The next generation of terrestrial observatories, exemplified here by Cosmic Explorer, can take a more structured approach to observatory and initial instrument design. For CE, priorities are to enable an initial reach some 10x greater for neutron-star coalescence while managing cost and risk. A Science Traceability Matrix approach, as developed by NASA, is used to link the broader astrophysics goals to design decisions. The observatory and initial detector are firmly based in LIGO experience, with surface observatories of 40km and 20km arm lengths each housing a single detector. The initial detector will be an evolution from the current LIGO detectors, using next-generation mechanical and optical designs. The US National Science Foundation is supporting both design and experimental activities, complemented by work in the UK, Germany, Australia and Canada. The current status of CE and the plan going forward will be given.

Simulating neutron stars with dissipative hydrodynamics

Shum L[1], Abalos F[2], Bea Y[3], Bezares M[1], Figueras P[4], Palenzuela C[2]
[1]University of Nottingham, [2]Universitat de les Illes Balears, [3]Universitat de Barcelona, [4]Queen Mary University of London

Friday Session 4 - B2: Numerical Relativity

In this talk, I will discuss our work in modelling neutron stars using the recently developed formulation for relativistic dissipative hydrodynamics, known as the BDNK theory. By performing numerical simulations of neutron stars in spherically symmetric spacetimes, we will study how incorporating dissipation using the BDNK theory affects the physical predictions of the system.

Gravitational waves from triple systems: Doppler shifts, aberration and QNMs

Sieiro dos Santos J[1], Cardoso V[1,2], van de Meent M[2,3], Natário J[4]
[1]CENTRA - Instituto Superior Técnico, [2]Niels Bohr International Academy - Niels Bohr Institute, [3]Max Planck Institute for Gravitational Physics, [4]CAMGSD - Instituto Superior Técnico

Wednesday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

We consider the gravitational waves generated by a stellar-mass binary orbiting a supermassive Kerr black hole, a system often denoted as b-EMRI. Previous results established that these systems are expected to form in active galactic nuclei and globular clusters. The corresponding gravitational wave signal contains a high-frequency part due to the inner motion of the stellar mass binary and a low-frequency part due to the motion of its center of mass around the supermassive black hole. This makes it a candidate for multiband detections when LISA and the LVK collaboration start working simultaneously. Furthermore, a plethora of interesting phenomenology is expected to appear: doppler shift, beaming, gravitational redshift, lensing, quasinormal mode excitation, and tests of the black hole paradigm. In this work, using the Dixon formalism for extended mass distributions and black hole perturbation theory, we develop a self-consistent and relativistic model for this triple system and analyse the resulting waveforms.

Nonlinear Treatment of a Black Hole Mimicker Ringdown

Siemonsen N[1]
[1]Princeton University

Thursday Session 4 - C10: Experimental tests of the nature of compact objects

Black hole mimickers and their dynamical properties are playing an important role in understanding and testing the black hole paradigm. In this talk, I will present the first nonlinear, self-consistent treatment of such objects with stable light rings during their merger and ringdown. Using full Einstein-Klein-Gordon simulations of binary boson star collisions in the large-mass-ratio regime, we explore the gravitational wave signals from the resulting spinning, horizonless remnants. Our findings confirm features predicted by perturbative methods: the prompt response resembles that of a Kerr black hole in the high-compactness limit, while subsequent emissions include high-frequency bursts reminiscent of gravitational wave echoes—though sourced by the remnant's internal degrees of freedom. Additionally, we identify a long-lived signal component comparable in frequency to black hole quasi-normal modes. I will discuss the characteristics of these emissions, key scaling relations, and the energy released in gravitational waves, offering insights into the observational prospects of black hole mimickers.

Self-similar collapse of spherically symmetric elastic stars.

Silva D[1]
[1]CENTRA - Instituto Superior Técnico

Thursday Session 3 - A1: Classical GR: Theoretical developments

Self-similar solutions of collapsing compact objects are a special class of solutions wherein matter and metric functions display an invariance with regards to a spatial and temporal rescaling. The application of a scale invariant set of coordinates allows the description of such systems by means of a set of ordinary differential equations. More than a simplification, self-similar solutions provide a bridge to study critical phenomena. These describe the threshold separating the formation of a black hole from the dissipation of the collapsing matter distribution. Black holes that do form are those of the smallest mass possible and, thus, are surrounded by an exposed neighborhood of high curvature. Critical solutions have been thoroughly studied for a variety of different matter models, but elastic matter models stand as an exception. Generalizing perfect fluid models, elasticity provides a more complex description of matter that may be important for the description of stellar dynamics. In this talk I discuss self-similar solutions of spherically symmetric collapsing elastic distributions of matter and their features. I show they generalize the perfect fluid models, exhibiting also continuous self-similarity, but that tuning the elastic parameters introduces richer and more realistic behaviors.

Head-to-head comparisons of moving puncture codes

Silva R[1]
[1]Cardiff University

Thursday Session 4 - B2: Numerical Relativity

The increased sensitivity of the next generations of gravitational wave detectors will require an increase in the accuracy of our waveform models, which will depend on both the accuracy and efficiency of our numerical relativity codes. Technological developments in supercomputing will also require us to adapt our codes to the changing infrastructure. While some older codes will evolve to meet these challenges, others may be abandoned and replaced. These steps must be taken carefully, with appropriate comparisons and tests based on real world detection and analysis goals.

Some research groups who previously used a version of the BAM code for the production of binary black hole waveforms have more recently switched (or are in the process of switching) to the Einstein Toolkit (ETK). ETK has the advantage of being open source, with ongoing development by a relatively large community of users, and also has the option to use multiple spherical grid patches for greater efficiency over an extended wave zone. I will present results from comparisons of these two codes, BAM and ETK, in terms of their accuracy and efficiency for binary black hole waveform production.

Constraints on EMRI Populations from LISA data

Singh S[1], Berry C[1], Veitch J[1]
[1]University Of Glasgow

Friday Session 3 - C5: LISA and other space-based detectors

Gravitational waves from extreme mass ratio inspirals (EMRIs), which are the inspirals of stellar-mass black holes into massive black holes are predicted to be detected by Laser Interferometer Space Antenna (LISA). A sufficiently large number of EMRI detections will provide unique insights into the massive black hole population. We have developed a hierarchical Bayesian inference framework capable of constraining the EMRI population parameters given the LISA data accounting for SNR-based selection biases. Additionally, we leverage the capacity of a simple feed-forward neural network as an emulator enabling SNR calculations of ~10^5 EMRI signals in fraction of seconds speeding up the analysis up to 5 orders of magnitude. We validate our framework on a phenomenological EMRI population that captures key dynamical complexities of massive black hole environments. Our results show how well we can constrain EMRI population parameters such as the spin distribution of massive black holes, the slope of both the massive and stellar-mass black hole mass spectra and the branching fractions of different formation channels. These results allow further investigation into the different evolution scenarios of massive black holes.

Optimizing Early Warning and Sky Localization from Eccentric Compact Binaries

Sinha P[1]
[1]International Centre for Theoretical Sciences (ICTS)

Tuesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

Realizing the full promise of multi-messenger astronomy relies on our capacity for swift and precise gravitational wave event localization. While early warning for circularized binaries are mature, the anticipated detection of eccentric mergers, originating from dynamically dense environments like globular clusters, introduces a substantial analytical complexity. Specifically, accurate sky localization for early warning requires precise signal-to-noise ratio (SNR) calculations, which traditionally initiate integration upon signal entry into the detector band. For circular binaries, with their monotonic frequency evolution, this approach is straightforward. However, eccentric binaries exhibit oscillatory instantaneous frequency evolution, featuring multiple occurrences of a given frequency and heightened frequencies at periastron passages. Critically, cycles of this instantaneous frequency enter the detector band before than the orbit-averaged frequency, which itself increases monotonically. This raises a fundamental question: where should integration commence for accurate SNR and sky area determination? We examine two distinct approaches: (1) initiating integration upon entry of the orbit-averaged frequency into the detector band, and (2) utilizing periastron passage entry as the starting point. We discuss these two choices for different observing scenarios and determine the appropriate approach to effectively localize eccentric sources in the sky. Furthermore, we investigate the contribution of sub-dominant modes, in conjunction with the dominant mode, on the sky localization of eccentric signals across a range of mass and spin parameters.

Using machine learning to detect and localise unmodelled GW signals fast. MLy Pipeline and O5.

Skliris V[1]
[1]Cardiff University

Thursday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The search for unmodeled gravitational wave (GW) transients, or "bursts," presents unique challenges. In a morphology-agnostic approach, any signal that cannot be identified as a glitch could be of astrophysical origin. However, to date, no non-CBC (compact binary coalescence) signals have been detected by coherent WaveBurst (cWB) , and their detection probability remains significantly lower than that of CBCs. The MLy pipeline is a novel machine learning-based search framework designed to identify unmodelled candidates, prioritizing latency over efficiency. First deployed in December 2024, its primary goal is to rapidly identify and localize signals that are well-suited for electromagnetic follow-up. In this talk, we will explore the structure of this search, the current challenges we face, and our plans for O5.

Analytic solution for the motion of spinning particles in Kerr space-time

Skoupý V[1], Witzany V[1]
[1]Charles University

Tuesday Session 4 - B3: Approximations, perturbation theory, and their applications

The motion of massive test particles around Kerr black holes is famously separable in Boyer-Lindquist coordinates, as shown by Carter. However, this powerful property is lost when the particles possess classical spin. In this talk, I demonstrate that separability can be restored—at least to linear order in spin—by an elegant shift of the worldline, derived from the hidden symmetry of Kerr spacetime. This allows the equations of motion to be solved in closed form, in direct analogy with the spinless case. The result deepens our understanding of separability and integrability in Kerr dynamics and has crucial implications for modeling gravitational wave sources, particularly inspirals of spinning compact objects into massive black holes.

Numerical Relativity Simulations of Zoom-Whirl Orbits in High-Energy, Equal-Mass Black Hole Binaries: An Investigation of Black Hole Charge

Smith M[1], Paschalidis V[1], Bozzola G[2]
[1]The University of Arizona, [2]California Institute of Technology

Thursday Session 4 - B2: Numerical Relativity

Numerical relativity simulations of high-energy binary black hole (BBH) collisions provide exceptional opportunities to investigate fundamental physics. For binaries with impact parameters near the scattering threshold, non-linear effects -- like zoom-whirl (ZW) orbits -- begin to dominate the dynamics of the systems. Investigating this transient regime in high-energy binaries provides a fertile testing ground for unexpected effects of black hole properties like spin or charge. Here we present our recent work using fully non-linear simulations of equal-mass, like-charged BBH mergers to investigate the effects of charge on merger remnants, radiated quantities, and ZW behavior. Among other conclusions, our work identified a potential universality for BBHs with like charge. Future work investigates the effects of unlike charge and aligned spin on binaries with impact parameters near the scattering threshold.

Isolated but Not Alone: Binary Black Hole Merger Rates from Galaxy Evolution

Smith T[1], Kaplinghat M[1]
[1]University Of California, Irvine

Friday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

As the LIGO-Virgo-KAGRA (LVK) collaboration continues through its fourth observing run, it is set to significantly expand upon the 90 gravitational wave events detected thus far. This growing dataset necessitates the development of robust models to accurately predict the population of compact objects. In particular, binary black hole systems represent the overwhelming majority of these observations. Our study builds upon galaxy formation and cosmological relations integrated with stellar evolution theory using the state-of-the-art Stellar EVolution N-body (SEVN) code to model isolated binary black holes. Our model calculates the population dynamics, merger rates, and its derivatives, to first order, and finds general agreement with the mass spectrum and redshift evolution inferred by the LVK collaboration. The results deviate at the pair-instability mass gap as our analysis assumed standard stellar evolution theory, however we propose that dynamically formed BBH mergers from our single black hole population can help alleviate this tension at the high end tail of the mass spectrum. Built upon decades of empirical observations, our model is well-positioned to align with and interpret the forthcoming observational data.

PINNGraPE: A Physics-Informed Neural Network for gravitational wave parameter estimation with unmodeled search algorithms

Scialpi M[1,2], Smith L[3,4], Di Clemente F[2], Bejger M[2,5]
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Thursday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Unmodeled searches for gravitational waves are essential for ensuring that all potential sources are accounted for in detection efforts, as they make minimal assumptions regarding source morphology. While these searches primarily target generic transient sources, they are also highly effective at identifying a broad range of compact binary coalescences (CBCs), demonstrated by the unmodeled search algorithm coherent Waveburst (cWB) being the first to detect GW150914. Despite their ability to detect CBCs with diverse properties, the accurate estimation of source parameters remains to be a challenging task in unmodeled searches due to the absence of waveform template banks. To overcome this, we leverage Physics-Informed Neural Networks (PINNs), which serve as a powerful tool for parameter estimation by applying physical constraints through the universal differential equation governing a compact binary system. In this work we introduce the PINNGraPE algorithm, which accurately and rapidly infers key source parameters of a binary black hole (BBH) merger system, such as the mass components, from only the gravitational wave signal through the implementation of a physics-informed convolutional neural network. We demonstrate the algorithm's effectiveness through the application to time-frequency signal representations output from the cWB search.

Quasinormal Modes of a Dispersive, Confined Gravity Simulator

Solidoro L[1]
[1]University Of Nottingham

Monday Session 3 - C9: Experimental gravitation

Gravity simulators enable the study of black-hole quasinormal modes (QNMs) in controlled experimental settings. However, realistic laboratory setups introduce two key effects absent in traditional gravitational QNM analyses: dispersion and spatial confinement. The former introduces Lorentz-breaking terms in the wave equation, as encountered in modified gravity theories, whereas the latter significantly alters the QNM spectrum, as widely explored in recent studies on spectral stability. The recent development of a rotating spacetime simulator in superfluid helium offers an ideal platform where these effects can be observed. In this talk, I show how ray tracing and spectral-stability techniques can be used to predict the resonances observed in finite-size, highly dispersive systems, providing new insights into laboratory-based black hole spectroscopy.

Kinematics of EMRIs: From event rates to waveform computations.

Sopuerta C[1], Martin Vilchez I[1], Muguruza P
[1]Institute of Space Sciences (ICE-CSIC), [2]Institute of Space Studies of Catalonia (IEEC)

Wednesday Session 4 - B3: Approximations, perturbation theory, and their applications

Binary with systems with mass ratios in the range from 1/100 to 1/1000000 emit gravitational waves (GWs) detectable by next decade GW observatories both from the ground and from space. Due to the mass ratios involved, a separation of time (and spatial) scales occurs that allows us to simplify the modelling of the binary evolution and its GW emission. Indeed, in the extreme-mass-ratio limit, of particular interest for future space-based observatories as LISA, we can separate the dynamics into an effective one-body conservative description (short-time scale) plus a radiation-reaction prescription (long-time scale) which can be obtained from the combination of different perturbative schemes (post-Newtonian, post-Minkowskian and black hole perturbation theory). This separation of scales can be used to accelerate significantly the computations. In this talk, I will describe how this can be done by combining in an optimal way analytical knowledge with numerical computations that use parallel computing and, in particular, GPUs. I will also describe how this can benefit the estimation of event rates as well as the production of waveforms for detection and parameter estimation.

A Superattenuator for the Einstein Telescope

Spada F[1]
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Wednesday Session 3 - C4: Concept and research towards next-generation detectors

The Superattenuator is a cornerstone in seismic isolation systems for ground-based interferometers and is indicated as the reference solution for the isolation of the test masses of the Low-Frequency Einstein Telescope.
However, the need for an update of the Superattenuator arises not as much from the increased sensitivity requirements, as from the need to suspend a heavier, cryogenic payload, which makes the mechanics more demanding and imposes constraints on the materials, that must be compatible with both vacuum and cryogenic conditions. As seismic isolation system design progresses, evaluating the impact of targeted interventions on the performance of existing solutions is essential.
The upgrade detailed here allows the Superattenuator to meet the more demanding requirements of a third-generation interferometer while preserving its well-established reliability and performance.

Progressing technologies in crystalline test mass suspensions

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Wednesday Session 3 - C4: Concept and research towards next-generation detectors

Crystalline materials play a key role in defining the design and the thermal and structural behaviour of suspensions used for the test masses in upcoming gravitational wave interferometers that will employ cryogenic payloads.

The requirements are demanding and multi-fold and thereby present an incredible challenge to the next-generation gravitational wave detector community. The test mass suspension system has to employ thin fibres of single crystal material. The fibres and associated joints to the test masses are required to have sufficient strength to suspension the large mass mirrors of a gravitational wave detection, high thermal conductivity to allow for conductive cooling of the mirror to below 20K, low mechanical loss to reduce thermal noise in the detector, and geometries that optimise the dynamic performance of the pendulum suspension.

This talk will highlight the latest advancements from a collaborative research effort involving several laboratories, research centers, and private companies focused on developing cryogenic test mass suspensions capable of supporting 200 kg substrates with exceptional thermal and mechanical performance.

The study specifically focuses on the analysis of manufacturing techniques for thin monocrystalline fibres, including those related to advanced surface treatments. It also investigates welding methods, mechanical energy dissipation modelling, and fracture stress testing. Finally, some of the implemented designs are described.

Unlocking the Science Objectives of Extreme Mass Ratio Inspirals

Speri L[1]
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Friday Session 3 - C5: LISA and other space-based detectors

The upcoming mission, Laser Interferometer Space Antenna (LISA), will be the first space-based gravitational wave observatory, opening a new window in the millihertz regime. Among the sources LISA is expected to observe, Extreme Mass Ratio Inspirals (EMRIs) are binary systems composed of stellar-mass compact objects orbiting massive black holes at the centers of galaxies.
EMRI observations are expected to address key scientific objectives of the LISA mission, including testing the nature of gravity and exploring the environments surrounding massive black holes. In this talk, I will discuss how these objectives can be achieved and the challenges involved. Specifically, I will demonstrate how to incorporate effects beyond vacuum in EMRI waveforms and forecast our ability to achieve some of the key scientific objectives of the LISA mission. Additionally, I will outline recent progress in searching for EMRI signals in LISA simulated data and conclude with the path forward in preparing for LISA's launch and the future of EMRI science.

From Nano- to Millihertz Gravitational Waves: Bridging Methods Across the Spectrum

Speri L

Wednesday Session 2 - Prize Session

Gravitational wave astronomy is rapidly expanding our understanding of the Universe, but as detector sensitivity increases, data analysis methods and models must improve as well. In this talk, I will present work from my PhD focused on maximizing the scientific return from both space-based detectors like LISA and Pulsar Timing Arrays (PTAs). I will discuss the development of accurate and efficient waveform models for Extreme Mass Ratio Inspirals (EMRIs), enabling robust parameter estimation and multimessenger studies. On the PTA side, I will present the use of trans-dimensional sampling techniques applied to the second European Pulsar Timing Array data release, targeting both a stochastic gravitational wave background and individual supermassive black hole binaries. I will conclude by highlighting the synergies between LISA, PTA, and ground-based detectors, and explore how sharing modeling and data analysis methodologies across these regimes can enhance our ability to extract insights from the gravitational wave spectrum.

Exploring environments surrounding black holes: galactic halos and superradiant boson clouds.

Spieksma T[1]
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Thursday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Black holes in our Universe are not expected to reside in vacuum. Their environments—such as accretion disks or dark matter distributions—can alter the dynamics of binary systems through effects like accretion or dynamical friction. As a result, environmental effects can leave imprints on the emitted gravitational waves, offering both challenges and opportunities for gravitational wave astronomy. Understanding the interplay between the binary and the environment is not only essential for detecting these signals, but could also inform us on the specific matter distribution. In this way, black holes could serve as detectors of new physics.

In this talk, I will explore two scenarios where environmental effects could play a role. First, I will examine whether galactic environments can influence the ringdown signal. Second, I will investigate how superradiant boson clouds affect binary evolution, particularly during the early inspiral, assessing the likely configurations of both the cloud and the binary as they enter LISA's sensitivity band. These findings point towards distinct observational signatures for future detectors.

Fix the Frame, Resolve the Memory: The Bondi--Sachs Gauge in Black Hole Perturbation Theory

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[1]University of Nottingham, [2]California Institute of Technology, [3]University of Southampton

Monday Session 4 - B3: Approximations, perturbation theory, and their applications

Understanding gauge and frame dependence is crucial for comparing binary models and extracting physics. Black hole perturbation theory calculations are extending to second-order, where increased gauge dependence brings new challenges: gauge-invariant quantities at linear order become gauge-dependent at second-order, and nonlinear source terms can produce infrared divergences. We address these issues by constructing a gauge invariant second-order field equation associated with an asymptotically flat gauge. The Bondi–Sachs gauge, designed to analyze gravitational waves at future null infinity, retains residual freedom under the BMS symmetry group. Our framework transforms perturbations from any initial gauge to the Bondi–Sachs gauge (avoiding infrared divergences) and fixes the BMS frame. By choosing an appropriate BMS frame, memory effects can be extracted from black hole perturbation theory calculations. These effects will be detectable with future gravitational wave detectors. Additionally, our formalism can transform self-force and ringdown calculations to the BMS frames associated with post-Newtonian theory and numerical relativity simulations to help compare results.

Simulation-Based Hierarchical Inference of Galactic Binaries with LISA

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[1]SISSA, [2]Observatoire de la Côte d'Azur

Friday Session 4 - C6: Gravitational waves: Relativity and fundamental physics

The upcoming space-based gravitational wave detector, LISA, holds great potential for detecting a wide range of sources, the most numerous of which are galactic binaries (GBs). However, inferring their population poses significant challenges for traditional Bayesian methods due to the vast number of overlapping sources (~30×10^6) within LISA's extensive data set (~6×10^6 frequency bins). In this talk, I will present a simulation-based inference framework designed to address these challenges. Our approach enables hierarchical inference of GB population characteristics. We leverage GPU-accelerated forward simulators to efficiently generate synthetic LISA data, exploring inference efficacy under a variety of astrophysical models. To handle the high dimensionality of the data, we develop a robust summary statistic that preserves essential population information while significantly compressing the input data. Our results demonstrate the potential for fast, scalable, and accurate inference from LISA data, paving the way for deeper insights into the properties of GBs and the structure of the Milky Way.

Cosmological inference using gravitational waves and normalizing flows

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[1]University Of Glasgow

Thursday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

We present CosmoFlow, a machine-learning-based framework leveraging normalizing flows (NFs) to infer cosmological parameters from gravitational wave (GW) events. Our methodology is general to any compact binary coalescence event and cosmological model, relying on the generation of training data that represents distributions of GW event parameters. These parameters are conditioned on the underlying cosmology and incorporate prior information from galaxy catalogues. We demonstrate that NFs can effectively model the electromagnetic (EM)-dependent prior of GW parameters, allowing us to account for selection effects and parameter uncertainties in detected GW events.
The approach involves training an NF model prior to the detection of GWs. For each observed event, we input parameter estimation results to compute the cosmological parameter likelihood in just $\sim$1 ms per parameter set. This enables a computationally efficient analysis, achieving results in O(1) s, and allows direct comparison with traditional Bayesian approaches such as gwcosmo. As a proof of concept, we infer the Hubble constant (H_0) using binary black hole (BBH) mergers detected in the O1, O2, and O3 observational runs of Advanced LIGO and Virgo. We obtain a Bayesian posterior on H_0, estimating $H_0 = 74.51^{+14.80}_{-13.63}$ km s^{-1} Mpc^{-1}.
Our results highlight the potential of NFs to enable fast, reliable, and expressive probability distributions over cosmological parameters, paving the way for future applications of machine learning in GW cosmology.

Stable evolutions of ultracompact black hole mimickers in 3+1 dimensions.

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Tuesday Session 4 - B2: Numerical Relativity

Ultracompact black hole mimickers formed through gravitational collapse under reasonable assumptions obtain light rings in pairs, where one is unstable and the other one is not. Stable light rings are believed to be a potential source for dynamical instability due to the trapping of massless perturbations, as the decay of these modes is relatively slow.

Motivated by the stability results in 1+1 dimensions, we perform fully nonlinear dynamical evolutions of spherically symmetric, ultracompact solitonic boson stars in 3+1 dimensions. We find no evidence of an instability after evolving the objects for ~1000 light crossing times, suggesting that the proposed mechanism may not be efficient after all to effectively destroy ultracompact black hole mimickers. We also discuss the properties of ray-traced images associated with these models, and their signatures in Fourier space.

The SXS Collaboration's third catalog of binary black hole simulations

Stein L

Friday Session 4 - B2: Numerical Relativity

We present a major update to the Simulating eXtreme Spacetimes (SXS) Collaboration's catalog of binary black hole simulations. Using highly efficient spectral methods implemented in the Spectral Einstein Code SpEC, we have nearly doubled the total number of binary configurations from 2,018 to 3,756. The catalog now densely covers the parameter space with precessing simulations up to mass ratio q=8 and dimensionless spins up to $|\chi|\leq 0.8$ with near-zero eccentricity. The catalog also includes some simulations at higher mass ratios with moderate spin and more than 250 eccentric simulations. We have also deprecated and rerun some simulations from our previous catalog (e.g., simulations run with a much older version of SpEC or that had anomalously high errors in the waveform). The median waveform difference (which is similar to the mismatch) between resolutions over the simulations in the catalog is 4×10^{-4}. The simulations have a median of 22 orbits, while the longest simulation has 148 orbits. We have corrected each waveform in the catalog to be in the binary's center-of-mass frame and exhibit gravitational-wave memory. We estimate the total CPU cost of all simulations in the catalog to be 480,000,000 core-hours. We find that using spectral methods for binary black hole simulations is over 1,000 times more efficient than much shorter finite-difference simulations of comparable accuracy. The full catalog is publicly available through the sxs Python package and at https://data.black-holes.org.

Linear three-mirror cavity for quantum noise reduction: resonant behavior, stability and meter-scale prototype

Stevens P[1]
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Friday Session 3 - C4: Concept and research towards next-generation detectors

Fabry-Perot cavities are used in present GW interferometers for the frequency-dependent squeezing technique, which reduces quantum noise across the entire observation frequency range. However, they may not offer sufficient control over the squeezing properties required for next-generation detectors, in particular the Einstein Telescope. To this end, different filtering system configurations are currently being explored. Among these, linear three-mirror cavities are of particular interest due to their unique characteristics, especially resonance peak splitting and their equivalence to two-mirror cavities with variable finesse. I will discuss simulations we conducted to examine how the resonant behavior and stability of these systems vary with different configurations, as well as experimental measurements taken from a meter-scale prototype that demonstrates variable finesse and resonance splitting.

The formation of merging compact binaries from massive binary stars

Stevenson S[1]
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Monday Session 4 - B1: Relativistic astrophysics

Several hundred compact binary mergers have now been observed in gravitational waves by LIGO, Virgo and KAGRA. Most of these are binary black hole mergers. The origin of these merging binaries is currently uncertain; they may originate from massive binary stars, be dynamically formed in star clusters or galactic nuclei, or may have contributions from multiple formation channels. We study the formation of merging compact binaries using the rapid population synthesis suite COMPAS. We present the current state of COMPAS, detailing recent updates in modelling physics relevant to compact binary formation, including the mass-loss rates of massive stars. We show that current population synthesis models are already in tension with (ruled out by) existing gravitational-wave observations. Using a simple mixture model, we show that while more than half of observed gravitational-wave events are not formed through massive binary evolution, the vast majority of compact binaries merging in the local universe originate from massive binary stars.

Tidal resonances of stars in precessing orbits around a spinning black hole

Stockinger M[1]
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Friday Session 4 - B1: Relativistic astrophysics

Tidal disruptions of stars on the equatorial plane orbiting Kerr black holes have been widely studied. However thus far, there have been fewer studies of stars in inclined precessing orbits around a Kerr black hole.

We use the tensor virial equations to analyze perturbatively the influence of the precession on the star.

We show the presence of possible resonances in these systems for typical physical parameters of black hole-neutron star binaries in close orbits or of a white dwarf/an ordinary star orbiting a supermassive black hole.

This suggests the presence of a new instability before the tidal disruption limit is encountered in such systems.

Constraining Domain Wall Dark Matter with LIGO

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Wednesday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Domain walls associated with a low-mass (sub-eV) scalar field have been proposed as a possible solution to the dark matter problem. Gravitational-wave detectors such as LIGO offer a unique way to search for this phenomenon, as a domain wall passing through the detector will interact directly with the interferometer test masses to produce a transient signal in the gravitational-wave data stream. We present a search for domain wall signatures in LIGO data from 2015-2020. We find no evidence for a domain wall passage. Assuming that domain walls constitute the bulk of the dark matter, we set limits on the scalar field coupling energy scale that are approximately 5 orders of magnitude stronger than previous limits for walls with thicknesses in the range 1m - 10km.

A Semi-analytic Approach to Ringdown Gravitational Waves

Suzuki M[1]
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Thursday Session 3 - C10: Experimental tests of the nature of compact objects

Gravitational Waves (GWs) are ripples in spacetime that travel at the speed of light. They were detected by LIGO in 2015, and so far, about 300 GW events have been detected. All of their sources are considered to be compact binary coalescences, i.e., binaries of compact objects such as black holes and neutron stars. GWs emitted by them can be separated into three phases: inspiral, merger, and ringdown. The ringdown phase is the stage in which the merged black hole settles down by emitting GWs. Its theoretical waveform is described as a superposition of damped sinusoidal modes, which are called Quasi-Normal Modes (QNMs). In the near future, as the sensitivity of GW detectors improves, more QNMs can be extracted. Consequently, in order to extract more QNMs, the template waveform needs to include more modes. However, conventional methods require a high computational cost. Therefore, we have developed a method to accelerate the computation by using orthonormalized QNMs and marginalizing some parameters analytically. Furthermore, we found that using these modes makes it easier to extract the amplitude of each mode compared to using original QNMs since orthonormalized-QNMs analysis reduces the correlation between mode amplitudes. In this presentation, I will show the methodology and the results of the analysis.

Strong-Field Scattering of Black Holes

Swain S[1], Pratten G[1], Schmidt P[1]
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Tuesday Session 3 - B2: Numerical Relativity

Recent developments in post-Minkowskian (PM) calculations have led to a fast-growing body of weak-field perturbative information. As such, there is major interest within the gravitational wave community as to how this information can be used to improve the accuracy of theoretical waveform models. In this talk, I will highlight the key features of three recently proposed resummation schemes and make detailed comparisons with a new suite of high-energy numerical relativity simulations. I will discuss the challenges faced at high energies and the need for higher-order PM information. I will also demonstrate that further resummation of the EOB radial potentials could be a powerful strategy in improving the accuracy and robustness of the models in this regime.

Accelerating the Galaxy Catalog Method: Improved Constraints on Cosmology and Modified Gravitational Wave Propagation with Standard Sirens

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Thursday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

Gravitational waves (GWs) from compact binary mergers are powerful probes of cosmology and General Relativity (GR). However, the increasing volume of data from current and future GW observatories demands efficient and robust codes. In this talk, we present CHIMERA 2.0, a GPU-accelerated framework for hierarchical Bayesian inference of cosmological, modified gravity (MG), and population hyperparameters using dark sirens and galaxy catalogs. This code enables the analysis of a few thousands of events, a crucial step for next-generation interferometers, such as the Einstein Telescope, Cosmic Explorer, and LISA. We use CHIMERA 2.0 to analyze three mock populations of 300 dark sirens detected at SNR>20, assuming the nominal O5 sensitivity of the LIGO-Virgo-KAGRA network. Each population is characterized by a different value of the MG parameter Ξ0: 0.6, 1 (corresponding to GR), and 1.8. Leveraging the computational efficiency of CHIMERA 2.0, we perform several Markov Chain Monte Carlo (MCMC) tests, allowing us to analyze about 5000 sources. In these tests, we explore different MCMC configurations and assumptions about galaxy redshift errors. With spectroscopic galaxy catalogs, the fiducial Ξ0 is recovered with a precision of 22%, 7.5%, and 10% for Ξ0 = 0.6, 1, and 1.8, respectively; while the precision on the Hubble constant H0 is 2 − 7 times worse than when Ξ0 is not inferred. Photometric redshifts degrade the constraints by 3.5 times on average and fail to reduce parameter correlations that spectroscopic redshifts can resolve, underscoring the importance of future spectroscopic surveys to fully exploit the potential of standard sirens.

Classical and Quantum Laws of Motion for Singularities of Spacetime

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Friday Session 3 - A2: Classical GR: Mathematical developments

I will briefly explain the necessary conditions under which worldlines of charged particles can be identified with time-like singularities of spacetime, and show examples of classical as well as quantum laws of motion for them. I will elaborate on the crucial role that the geometry of spacetime in the neighborhood of these singularities plays in formulating these laws, including whether or not the weak form of the second Bianchi identity is satisfied. I will connect this with Bray's Zero Area Singularities and his notion of mass for them.

Electrovac space-times with null aligned electromagnetic field

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Monday Session 3 - A1: Classical GR: Theoretical developments

We consider Einstein-Maxwell (electrovac) space-times, where the the Maxwell spinor is null and aligned. Such a spinor has only one complex component, which in coordinates describes polarized waves propagating in one direction, so we call this field an “outgoing (or ingoing) one-way null” field. For the gravitational field, we impose the same condition, i.e. the Weyl spinor is of Petrov type N. We prove that such space-times admit geodesic, shear-free and non-diverging null congruence and that the system of Maxwell equations and Bianchi identities is compatible.
The model considered can describe gravitational waves of a certain type induced by electromagnetic free waves. The constraints on the congruence determine that such induced gravitational waves can only propagate in a space-time in which the null congruence is non-diverging, i.e. the null congruence neither expands nor rotates. Outgoing one-way null electromagnetic waves can nevertheless induce gravitational waves of a more complex kind.

Balanced homodyne detection with AEI 10 m Prototype facility

Takano S[1]
[1]Max Planck Institute For Gravitational Physics

Tuesday Session 4 - C3: Progress and challenges in advanced ground-based detectors

Now that the sensitivity of the gravitational wave detectors is approaching the standard quantum limit (SQL), it becomes important to investigate technologies to surpass the limit. Balanced homodyne detection (BHD) is an interferometer readout technique which can suppress technical noise, and has been adopted for the upgrade plan of the current detectors. BHD can also surpass the SQL at specific frequencies by tuning the local oscillator phase and exploiting correlations between quantum radiation pressure noise and shot noise. However, it is not trivial to control the interferometer with a BHD configuration, and its demonstration has not been well tested in large-scale suspended interferometers.
The AEI 10 m Prototype facility is aiming to reach the SQL and be a test-bed for new technologies to overcome it. The facility will contain a 10 m-long Fabry-Pérot Michelson interferometer (the 'Sub-SQL Interferometer'). We are working towards implementing BHD and demonstrating sub-SQL sensitivity. This presentation will report on recent progress of the Sub-SQL Interferometer and results from the interferometric simulations to implement a BHD control scheme.

Quantum decoherence of gravitational waves

Takeda H[1], Tanaka T[1]
[1]Kyoto University

Friday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

The quantum nature of gravity remains an open question in fundamental physics, lacking experimental verification. Gravitational waves (GWs) provide a potential avenue for detecting gravitons, the hypothetical quantum carriers of gravity. However, by analogy with quantum optics, distinguishing gravitons from classical GWs requires the preservation of quantum coherence, which may be lost due to interactions with the cosmic environment causing decoherence. We investigate whether GWs retain their quantum state by deriving the reduced density matrix and evaluating decoherence, using an environmental model where a scalar field is conformally coupled to gravity. Our results show that quantum decoherence of GWs is stronger at lower frequencies and higher reheating temperatures. We identify a model-independent amplitude threshold below which decoherence is negligible, providing a fundamental limit for directly probing the quantum nature of gravity and the inflation mechanism. In the standard cosmological scenario, the low energy density of the universe at the end of inflation leads to complete decoherence at the classical amplitude level of inflationary GWs. However, for higher energy densities, decoherence is negligible within a frequency window in the range 100 Hz-100 MHz, which depends on the reheating temperature. In a kinetic-dominated scenario, the dependence on reheating temperature weakens, allowing GWs to maintain quantum coherence above 10 MHz.

Black Hole Statistical Mechanics for Near Horizon Observers: Quantum Statistics for the Quanta of Geometry

Takis T[1], Major S[1]
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Tuesday Session 3 - D1: Loop quantum gravity and spin foams

The thermodynamics of black holes is examined in the near-horizon limit for uniformly accelerating observers. The area spectrum of loop quantum gravity is incorporated into the quasi-local energy for these observers, with quantum particles of geometry treated as indistinguishable using the standard 2j+1 spin degeneracy. Both bosonic and fermionic statistics with nonzero chemical potentials are considered under the assumption of large horizon areas. In the bosonic case, the system condensates into the lowest area state, while for fermions, a degenerate Fermi gas forms. The entropy of these large area configurations is low but the resulting quantum geometry gives a simple model for studying fluctuations of the near horizon geometry.

An information-based approach to gravitational-wave population inference at scale

Talbot C[1]
[1]University Of Chicago

Thursday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The population of observed gravitational-wave transients allow us to learn about the formation processes of compact objects, measure the cosmic expansion history of the Universe, and test the nature of spacetime in extreme dynamic environments.
However, the methods employed to perform these analyses come at a large computational cost and have systematic uncertainties that grow rapidly with the size of the observed catalogue.
In this talk, I will introduce a novel simulation-based population inference framework based on information-theoretic arguments that can be used to analyze populations of gravitational-wave events of the size expected not only with current detectors, but future observatories with acceptable computational cost.
The new approach provides two additional advantages over the current methods: we provide an absolute method to diagnose model mis-specification that does not rely on comparison with a reference model, furthermore, our method provides a natural method to determine when we will be able to resolve distinct features in the population of gravitational-wave transients.

Dynamics of Spinning, Eccentric Binary Black Holes at Second Post-Newtonian Order

Tanay S[1], Colin T[1], Bernard L[1]
[1]Paris Observatory

Thursday Session 4 - B3: Approximations, perturbation theory, and their applications

Accurate and efficient modeling of binary black hole (BBHs) dynamics is crucial for detecting the gravitational waves they emit. We will discuss our recent progress on determining the dynamics and the solution of spinning, eccentric BBHs at 2PN order. It starts with five constants of motion of the system, followed by the solution of the system in time. These, then, enable us to define the 2PN orbital elements (eccentricity, semi-major axis, mean motion). The solution also lets us extract the four non-zero frequencies of the system, which helps us locate their resonances (including the already-discovered ones). Finally, for the so-called "orbit-averaged" version of the system, we construct the action-angle variables using the recently introduced mathematical method of fictitious position-momentum variables. With these action-angle variables, we discover a new "separatix-like" region in the phase space where the nature of the solution changes abruptly. Resonances and separatrices are important in that, in the presence of a perturbation, they are potential regions of chaos, where the analytical solution might break down.

Localizing Gravitational-wave Signals & Identifying Galaxy Hosts with Pulsar Timing Arrays

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Tuesday Session 4 - C1: Pulsar timing arrays

If the origin of the gravitational-wave background---for which pulsar-timing array (PTAs) collaborations announced first evidence in 2023---is a population of supermassive black-hole binary systems, then an inevitable consequence is the breakdown in apparent stochasticity of the signal as more pulsars and data are added. Over time, individual binary signals will become resolvable, allowing for single-event characterization following the same qualitative workflow as in LVK and as expected in LISA. But how well can PTAs resolve the origin of a signal, and how is this localization capability tethered to the three-dimensional geometry of the pulsar network, the precision with which the pulsar distances are known, the noise in each pulsar, and the timespan over which a pulsar has been monitored? In this talk, we will explore these factors and present galaxy host ranking protocols based on synthetic data that mirrors the near-future sensitivity of the International Pulsar Timing Array. Understanding the factors governing the angular resolution of a PTA detector, and establishing procedures for host ranking, will be essential to understanding the relationship between supermassive black-hole binaries and their galaxies.

SFTs: a scalable data-analysis framework for long-duration gravitational-wave signals

Tenorio R[1], Gerosa D[1]
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Wednesday Session 4 - C4: Concept and research towards next-generation detectors

We introduce a framework based on Short-time Fourier Transforms (SFTs) to analyze long-duration gravitational wave signals from compact binaries. Targeted systems include binary neutron stars observed by third-generation ground-based detectors and massive black-hole binaries observed by the LISA space mission. In short, ours is an extremely fast, scalable, and parallelizable implementation of the gravitational-wave inner product, a core operation of gravitational-wave matched filtering. By operating on disjoint data segments, SFTs allow for efficient handling of noise non-stationarities, data gaps, and detector-induced signal modulations. We present a pilot application to early warning problems in both ground- and space-based next-generation detectors. Overall, SFTs reduce the computing cost of evaluating an inner product by three to five orders of magnitude, depending on the specific application, with respect to a standard approach. We release public tools to operate using the SFT framework, including a vectorized and hardware-accelerated re-implementation of a time-domain waveform. The inner product is the key building block of all gravitational-wave data treatments; by speeding up this low-level element so massively, SFTs provide an extremely promising solution for current and future gravitational-wave data-analysis problem.

Physical black holes: geometry, matter, observational signatures

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Thursday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

For a distant observer gravitational collapse concludes in three possible scenarios: it may proceed indefinitely, approaching an event horizon asymptotically; form an ultra-compact object with a surface beyond the gravitational radius; or create a light-trapping region in finite time—a physical black hole. Classical solutions, such as Schwarzschild or Kerr, correspond to the first scenario and fit current data. Exotic ultra-compact objects represent the second scenario. However, only the physical black holes allow discussions of transient black holes or the formulation of the information loss problem.

Imposing this third scenario and a weak form of cosmic censorship (curvature scalars remain finite at the apparent horizon), constrains near-horizon geometries. In spherical symmetry, only two dynamic solution classes emerge, each describing evaporating black holes and expanding white holes. The outer horizon is a timelike surface, and the null energy condition is violated in its vicinity. It may appear as a mild negative energy density firewall. The only consistent generalization of surface gravity—linked to Hawking temperature in static black holes—vanishes at black hole formation and evaporation. Physical black holes currently do not couple to the cosmological background and their equation of state renders them unsuitable candidates for dark energy. A Pade-like interpolation scheme directly links parameters of the near-horizon geometry to quasinormal modes and light rings.

This analysis also applies to wormholes. Static traversable wormholes are not static limits of semiclassical dynamical solutions, and allowed static limits are non-traversable, violating quantum energy inequalities and involving divergent tidal forces.

Fully non-linear gravitational wave simulations from past to future null-infinity

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[1]University Of Canterbury, [2]University of Otago

Wednesday Session 4 - B2: Numerical Relativity

We present the first numerical simulations of asymptotically flat space-times whose computational domain includes past and future null-infinity. As an application, we explore the scattering of a gravitational wave in a Schwarzschild black hole space-time. The study is conducted in the fully non-linear regime using an initial boundary value problem formulation of Friedrich's generalised conformal field equations. We calculate the Bondi energy, Bondi news and gravitational information at both past and future null-infinity and discuss their relationships.

Precision gravitational wave science on the Moon

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Monday Session 3 - C5: LISA and other space-based detectors

Preparations for the new generation of gravitational wave detectors are ongoing, with ground-based interferometers in the audio band and space-based ones in the milli-Hertz band.
The Lunar Gravitational Wave Antenna (LGWA) is a planned mission to fill the gap between them, with a sensitivity curve achieving its best values in the deci-Hertz band.
It will employ the elastic response of the Moon to a passing gravitational wave, measuring the resulting ground motion with an array of seismometers placed in a permanently shadowed crater at the lunar pole, whose conditions allow for low-noise cryogenic operation.

Precision sensors in this band offer a diverse science case, not limited to gravitational waves since they can also gather information about the Moon's geology and its interior.
The potential astrophysical sources include intermediate-mass black holes, supernovae, tidal disruption events, and light compact binaries with neutron stars and white dwarfs.

I will describe the first full Bayesian parameter estimation for the LGWA, performed for sources in a comparatively well-known population: stellar-mass black hole and neutron star binaries.
While the estimated overall sensitivity of the LGWA to them is comparable to the current one of the LIGO-Virgo-KAGRA network, the way their signals appear is very different.
They remain in band for days to years, allowing for ample early warning and exquisite measurement of phase and all related parameters, such as sky position and chirp mass - a blessing and a curse, since it also poses significant technical challenges in data analysis.

Profiling stellar environments of gravitational wave sources

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Wednesday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Gravitational waves (GWs) have enabled direct detections of compact binary coalescences (CBCs). However, their poor sky localisation and the typical lack of observable electromagnetic (EM) counterparts make it difficult to confidently identify their hosts, and study the environments that nurture their evolution. In this work, we show that detailed information of the host environment (e.g. the mass and steepness of the host potential) can be directly inferred by measuring the kinematic parameters (acceleration and its time-derivatives) of the binary's center of mass using GWs alone, without requiring an EM counterpart. We consider CBCs in various realistic environments such as globular clusters, nuclear star clusters, and active galactic nuclei disks to demonstrate how orbit and environment parameters can be extracted for CBCs detectable by ground- and space-based observatories, including the LIGO detector at A+ sensitivity, Einstein Telescope of the XG network, LISA, and DECIGO, on a single-event basis. These constraints on host stellar environments promise to shed light on our understanding of how CBCs form, evolve, and merge.

Simulating a Multi Messenger Detection of a Core Collapse Supernova

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Tuesday Session 4 - C7: Multi-messenger astronomy of gravitational wave sources

The mechanism driving supernova explosion post core-collapse is unknown. It is not known how the stalled shock is revived but current models favour neutrino-driven explosion mechanisms, where neutrinos escaping from the proto-neutron star heat the shock. Electromagnetic observations cannot allow us to see into the core of the star during core collapse and so cannot aid us in constraining the mechanism. Here we perform a simulation of a multi-messenger detection of a core collapse supernova, using both electromagnetic and gravitational waves to build a picture of what information we could gain if such an event occurred within the Milky Way. We found that the electromagnetic light curve can be used to describe the star at zero age main sequence, telling us about its past and can also be used to inform the parameter estimation via gravitational waves. For the gravitational waves, we found that we can probe the core 1 second after collapse, allowing us to understand the events leading up to the supernova explosion and constrain the driving mechanism. Our results demonstrate that by combining multiple mediums, we can build a more comprehensive picture of a core collapse event and understand what is occurring in the core right after collapse. In the event of a core collapse supernova within the Milky Way, our method could be used to gain valuable insight into the core of an exploding star and help us with our understanding of the life cycle of stars.

Low-latency gravitational-wave searches in the fourth observing run of the International Gravitational-Wave Network

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Tuesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

As the fourth observing run of the International Gravitational-Wave Network (O4) continues, so does the search for gravitational-wave counterparts, including gamma-ray bursts and kilonovae. Observations of gravitational waves and their counterparts, like GW170817 and AT2017gfo, are crucial for our understanding of the neutron star equation of state and of r-process nucleosynthesis which is expected to take place in the ejecta of compact binary mergers with at least one neutron star. There have been approximately 200 online gravitational-wave discoveries so far during O4, more than twice the number of catalogue events through O3. Here, we present a summary of public alerts in O4, the current data products used to classify compact binary mergers, and those under development.

Research towards large scale heavy suspensions for next generation gravitational wave detectors

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Wednesday Session 3 - C4: Concept and research towards next-generation detectors

Current generation room temperature gravitational wave detectors utilise fused silica for their monolithic suspension stages due to its superior mechanical and thermal properties. There is a desire however for the next generation detectors to scale up various aspects compared to current generation designs. For the monolithic suspensions, this involves larger and heavier test masses to help reduce radiation pressure noise, as well as keeping optimal thermal noise performance through suspension fibre design.

Research is already underway at the Institute for Gravitational Research (IGR) within the University of Glasgow to investigate the modelling and engineering challenges associated with assembling and suspending next generation test masses. This includes the installation of a bespoke large scale vacuum chamber that can house a multi-stage suspension chain for up to 400kg test masses, as well as the development of new tooling and assembly techniques that would be required to create a monolithic suspension stage. In addition, failure mechanisms of fused silica fibres at high stresses (>4GPa) are also being investigated, with the aim of providing data that could potentially support increasing the applied stress on the suspension fibres for future detectors.

This presentation provides a detailed update on the above suspension activities related to next generation gravitational wave detectors that aim to mitigate the risks associated with developing suspension chains with up to 400kg test masses.

Reconciling PTA and JWST and preparing for LISA with POMPOCO: a Parametrisation Of the Massive black hole POpulation for Comparison to Observations

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Thursday Session 3 - C1: Pulsar timing arrays & C8: Education and public outreach in gravitational physics

Over the past few years, we've gained an expanding range of probes into the massive black hole population, with even more expected in the next decade, particularly through the space-based gravitational wave detector LISA. Developing an approach that efficiently combines these observations is essential to deepen our understanding of the formation and evolution of massive black holes. In this talk, I will introduce our newly developed model, POMPOCO, and demonstrate its application to recent PTA and JWST data.

We find that the observed black hole luminosity function is consistent with the (likely) nHz gravitational wave signal detected by PTAs, provided we allow for an increased luminosity function at high redshift (z = 4–7), as recently indicated by JWST results. Our model successfully reproduces both the bulk of the Mstar-Mbh relation at z = 0 and its outliers—a challenge for cosmological simulations. This offers a fresh perspective on the apparent tensions between the black hole luminosity function and recent JWST and PTA findings.

Our LISA predictions, informed by these observations, remain broad and align with the wide spread seen in other models, underscoring LISA's immense potential to refine our understanding of massive black hole formation and evolution. The flexibility of POMPOCO makes it an ideal tool to fully exploit the potential of future gravitational wave observations of massive black hole binaries with LISA.

Hybrid waveform models for quasielliptic orbits: self-force meets post-Newtonian theory

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Thursday Session 4 - B3: Approximations, perturbation theory, and their applications

Post-Newtonian (PN) waveforms work well for comparable-mass binaries but break down for extreme and intermediate mass ratio inspirals (EMRIs/IMRIs), where self-force (SF) methods are more reliable. While SF techniques accurately describe leading-order (0PA) waveforms for eccentric orbits, achieving LISA's required precision demands control over post-adiabatic (1PA) corrections—especially for IMRIs, though not to very high accuracy. We introduce a hybrid model that combines numerical SF methods for the 0PA waveform and the conservative piece of the 1PA waveform with 3PN results for the 1PA dissipative corrections. To ensure gauge-invariant inputs, we express 3PN fluxes in terms of radial and azimuthal frequencies, requiring a new calculation for the 4PN periastron advance, including tail effects. We also determine numerically the 2SF-accurate relation between the frequencies with energy and angular momentum. Finally, we test our model against numerical relativity and EOB, as well as 2PA waveforms for circular orbits.

Symbolic regression in gravitational wave science: low and high latency strategies for inferring physical knowledge from unmodeled data

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Monday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

A whole branch of gravitational wave astronomy is carried out with burst methods, that is, methods which make tiny to no physical assumption on the system generating the observed signal. In contrast with matched filtering techniques, burst methods do not allow a straightforward physical interpretation of the collected data. Symbolic regression addresses the problem of inferring physics from unmodeled data. It accounts for several strategies aiming at recognizing the most human-readable functional form reproducing the data. Two main approaches exist, and they are both applicable to the observation of gravitational waves. The first one is sparse regression, a linear method with limitations on the amount of physical information it can infer. However, it can be extremely important for detection pipelines, since it recognizes dynamic-patterns via Dynamic Mode Decomposition, and thus can be used for online event vetting. Secondly, there is genetic programming, which samples different combinations of basis functions until reaching optimality. Of course, this method is much more computationally intensive and less algebraically rigorous than the previous one, yet the amount of physical information it can infer from completely unmodeled data makes it worth the burden. A peculiar procedure when using genetic programming is the implementation of Bayes theorem: while keeping the prior information minimal, Bayesianism allows to perform a Metropolis-Hastings sampling of a Hilbert space while forcing a low complexity (and thus improved human-readibility) on the obtained physics. These approaches are being reviewed and used in a novel tool for symbolic regression on gravitational waves unmodeled data.

Oscillatory modes of relativistic tori and their implications for QPOs in Low-Mass X-ray Binaries

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Friday Session 4 - B1: Relativistic astrophysics

We investigate the oscillatory behavior of relativistic, non-self-gravitating, fluid tori in the Kerr metric, focusing on their implications for black hole and neutron star mass and spin measurements in low-mass X-ray binaries (LMXBs). By conducting a local analysis within a general relativistic framework, we determine the radial epicyclic and orbital frequencies of a perfect fluid torus. The model assumes a non-Keplerian distribution of specific angular momentum, allowing us to explore how different angular momentum profiles affect the oscillation properties. These frequencies are then linked to high-frequency quasi-periodic oscillations (QPOs) observed in LMXBs, providing constraints on the mass and spin of the central compact object.

Deep neural networks to investigate single-detector times in gravitational wave data

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Monday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The search for gravitational wave signals in the data collected by the current ground-based interferometers is a complex problem, especially when only one detector operates. Modern deep learning approaches could contribute to find a solution. I'll discuss the detection problem and present an update of the work detailed in the paper https://iopscience.iop.org/article/10.1088/1361-6382/ad40f0 where we investigate the performance of neural network classifiers based on three types of architectures: convolutional neural network, temporal convolutional network, and inception time. The last two architectures are specifically designed to process time-series data. We apply the trained classifiers to LIGO data from the O1 science run, focusing specifically on single-detector times. We find a promising candidate on 2016-01-04 12:24:17 UTC compatible with a black hole merger with masses 50 M⊙ and 24 M⊙.

BMS asymptotic symmetries in the Carroll and Galilei limits

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Friday Session 4 - D1 + D2 + D3

There are two threads in the research on symmetries of space-time that originated in the 1960s but have been recently reinvigorated by the much more widespread interest: BMS symmetry (later extended by Barnich and Troessaert) and the kinematical symmetries other than Poincare or (anti-)de Sitter (especially the Carroll and Galilei ones). The former is related to the spacetime geometry at the infinities or horizons, the latter to expansions around the strong/weak gravitational coupling. At their intersection, one may consider the Carrollian and Galilean contraction limits of BMS algebras. It turns out that we can consistently define such contractions for 3D BMS and (partially) 3D Lambda-BMS algebras, while in the case of 4D BMS (in the sense of Barnich and Troessaert) we only obtain quasi-Carrollian/Galilean BMS algebras. This can be compared with the recent studies of contractions of the original BMS algebra, in which their authors came to quite different conclusions. Furthermore, the results have potential applications in the context of quantum gravity, in particular in the quantum-group deformations of spacetime symmetries.

Primordial black hole formation from a type II perturbation in the absence and presence of pressure

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Wednesday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

We investigate primordial black holes (PBHs) formed from nonlinearly large amplitudes of primordial curvature fluctuations, classified as type II. Type II fluctuations differ from type I by the presence of a stationary point (neck, belly, or saddle) on the initial time slice. Starting from these type II perturbations, the nonlinear evolution governed by the Einstein equations generally results in two distinct types, A and B, of horizon configurations, respectively characterized by the presence and absence of a bifurcating trapping horizon where past and future trapping horizons meet. In this paper, using the Lemaître–Tolman–Bondi solution, we show that type I/II and type A/B classifications are equivalent for a spherically symmetric dust fluid system regardless of the fluctuation profile.

Calculating the effective source for use in second-order self-force calculations

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Monday Session 3 - B3: Approximations, perturbation theory, and their applications

The primary method used for the modelling of extreme-mass-ratio inspirals (EMRIs), important sources for the space-based gravitational-wave detector LISA, is gravitational self-force theory. It has long been known that one must go to second order in this perturbative method in order to correctly track the motion of the small object as it spirals into the central black hole. The puncture scheme (or effective source method) is a key ingredient in extant calculations used to generate gravitational waveforms from EMRIs. In this scheme, one uses a puncture field, which is a local approximation to the small object's self-field describing its multipole structure, to generate a source that regularises the perturbed Einstein field equations. From this, one can then determine the motion of the small object.

In this talk, I will detail the method used to generate the source for the second-order Einstein field equations that forms a part of current EMRI waveform calculations in Schwarzschild. I will also discuss extending the current punctures to include higher-order-in-distance terms and present these punctures in the Kerr spacetime for the first time. These punctures are a crucial and core component for future calculations that use the effective source method to solve the second-order Teukolsky equation using m-modes in Kerr; see talk by Leather.

Bounds on fuzzy and warm dark matter from JWST SMBH observations

Urrutia J[1]
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Wednesday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

In the talk, I will introduce a new semianalytical model (SAM) for supermassive black hole (SMBH) growth that departs from traditional EPS-based merger tree methods by directly tracking differential SMBH growth via mergers. I will show that this model reveals a clear preference for heavy SMBH seeds across diverse datasets—including recent JWST observations—except in cases of extremely efficient merging, where a light-seed scenario uniquely fits the JWST data. I will also discuss the interplay between galaxy–SMBH co-evolution and dark matter (DM) models. I will show that, by incorporating the effects of warm and fuzzy DM on large-scale structure formation and halo evolution, the latest JWST measurements of the UV luminosity function and SMBHs can be used to place novel constraints on DM properties. Notably, this uncovers a previously unexplored link between the initial SMBH seed mass and DM characteristics, establishing SMBH evolution as a remarkably sensitive tracer of DM. Finally, I will also comment on what are the prospects of future GW observatories, namely LISA and the atom interferometers, to complement current observations and severely constrain or discover deviations from cold DM.

Black Hole Scattering in the Self Force Approach

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Tuesday Session 4 - B3: Approximations, perturbation theory, and their applications

Self Force Analytical computations has been used in the past years as an useful tool to calibrate the numerical simulations of waveforms for EMRIs. At the same time, in the field of Scattering Amplitudes, a lot of parallel work has been done in trying to compute observables related to the unbound two-bodies scattering. It has also emerged a theoretical argument that shows how it is possible to map information from scattering orbits results to the bounded case, through the so-called unbound-to-bound mapping. Because of this, also in the Self Force community, it is increased the interest in the description of the unbound motion.
I will present the approach to compute analytic correction to the unbound motion in the Self-Force formalism, relying on a double Post-Minkowskian and Post-Newtonian (low velocity) expansion. I will discuss a general strategy to study both gravitational and non-gravitational Self Force. In order to validate these techniques, I will show firstly how to study the scattering of a scalar charge against a Schwarzschild black hole, then I will present how to use the same procedure to compute the waveform and the fluxes of energy and angular momentum for the gravitational scattering at high precision in both PN/PM.

Novel seismic isolation systems at low-frequency for third-generation gravitational wave observatories

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Wednesday Session 3 - C4: Concept and research towards next-generation detectors

Gravitational waves have reshaped our understanding of the Universe. Second-generation interferometers Adv-LIGO, Adv-Virgo, and KAGRA are preparing for upcoming observational runs and upgrades, while future third-generation detectors, such as the Einstein Telescope and Cosmic Explorer, will achieve an improvement in sensitivity of at least a factor 10. Notably, improved low-frequency sensitivity is crucial for detecting high-mass or high z systems, improving source localization, enabling timely alerts for electromagnetic follow-ups, and facilitating the detection of predicted gravitational waves from sources like rotating pulsars. In this contribution, we will present ongoing experimental and simulation efforts to develop novel prototypes for mitigating low-frequency seismic noise. Such prototypes aim at reducing the height and complexity of current attenuation systems, lowering cost and work needed to build the Einstein Telescope detector.

Waveform systematic bias in LISA ringdown analysis

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Friday Session 4 - C5: LISA and other space-based detectors

The inaccurate modeling of gravitational-wave templates, whether due to unknown physics or an incomplete description of known effects, can introduce systematic biases in the estimated binary parameters. With next-generation detectors expected to observe events at increasingly higher signal-to-noise ratios, addressing this issue becomes crucial. In this work, we analyze the ringdown signal from supermassive black hole binaries in LISA, assessing biases introduced by an incomplete description of the ringdown stage—specifically, the exclusion of certain modes from the waveform template used in recovery. We first examine the mode hierarchy across different events and then compare a reference template, which includes a maximal set of N_max = 12 modes, against approximations with fewer modes (N < N_max). Within the linear signal approximation, we determine the minimum number of modes required for unbiased parameter estimation and explore how this threshold varies across the parameter space.

A hybrid time-domain approach to the LISA response: performance and applications

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Monday Session 4 - C5: LISA and other space-based detectors

We address the challenge to evaluate the response of the Laser Interferometer Space Antenna (LISA) in an accurate and computationally efficient way. Without approximations, the full LISA response is computationally expensive and traditional approaches, such as the long-wavelength approximation, accelerate the response calculation at the cost of reducing accuracy at high frequencies. Here we introduce a novel hybrid time-domain response for LISA, that balances computational efficiency and accuracy across the binary's evolution. Our method implements a fast low-frequency approximation using central finite differences during the early inspiral —where most binaries spend most of the time in the sensitive frequency band of LISA— while reserving the computationally intensive full-response calculations for the late inspiral, merger, and ringdown phases. This hybrid approach supports CPU and GPU implementations, TDI generations 1.5 and 2.0, and flexible time-delay complexity, and has potential to accelerate parts of the global fit, and reduce power consumption. As an application we present parameter estimation results using state-of-the-art phenomenological waveform models for LISA, which include orbital eccentricity, and the oscillatory and memory parts of the (2,0) spherical harmonic.
Additionally, we evaluate the low-frequency response efficacy in early-warning pipelines by performing inspiral-only Bayesian inference.

Geometric scattering methods for the conformal Einstein field equations

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Tuesday Session 3 - A2: Classical GR: Mathematical developments

In this contributed talk I will discuss how methods from Melrose's School of Geometric Scattering can be used, together with the conformal Einstein field equations and a gauge based on conformal invariants to obtain sharp statements about the asymptotic behaviour of asymptotically flat solutions to the vacuum Einstein field equations in the region of spacetime near null and spatial infinity. This approach, which combines asymptotic expansions computed with the aim of computer algebra with detailed estimates obtained through the positive commutator method within the framework of b-calculus allows to relate, in a precise way, the behaviour of the gravitational field near spatial and null infinity to the properties of Cauchy data. In particular, one can identify the pieces of the data responsible for the development of logarithmic singularities at the intersection of spatial infinity and null infinity —thus providing a detailed description of the formation of polyhomogeneous asymptotics from smooth data. It is hoped that the approach described in this contribution will allow to obtain a complete understanding of the so-called problem of spatial infinity in General Relativity —that is, an understanding the consequences of the singularity in the conformal structure of spacetime at spatial infinity due to the presence of a non-vanishing ADM mass.

The above research is part of a collaboration with Jordan Marajh (QMUL), Edgar Gasperín (CENTRA, Instituto Superior Técnico, Lisbon) and Grigarius Taujanskas (Cambridge).

Curvature Correlators in Nonperturbative Lorentzian Quantum Gravity

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Tuesday Session 4 - D3: Causal sets, causal dynamical triangulations, non-commutative geometry, asymptotic safety, and other approaches to quantum gravity

Correlation functions are crucial tools in quantum field theory from both a fundamental and practical point of view. Additionally, they are ubiquitous in early-universe cosmology, a regime where quantum gravity may provide measurable predictions.
However, thus far the use of correlation functions in fully nonperturbative theories of quantum gravity has been limited, due to difficulties associated with diffeomorphism-invariance and the dynamical nature of geometry. Causal Dynamical Triangulation (CDT) is such a nonperturbative Lorentzian quantum gravity framework that has been successful in determining a number of observables, like the Hausdorff and spectral dimension as well as the de Sitter shape of the universe. We present an analysis of a manifestly diffeomorphism-invariant, nonperturbative two-point curvature correlator using the CDT framework in a pure gravity setting with the so-called quantum Ricci curvature. Our analysis sheds light on the difficulties and subtleties in defining connected correlation functions and provides a good basis for the ongoing investigations in full 4D CDT and possibly other nonperturbative theories of quantum gravity.
[van der Duin, J., Loll, R. Curvature correlators in nonperturbative 2D Lorentzian quantum gravity. European Physical Journal C (2024). + work in progress.]

Tidal effects in gravitational waves from neutron stars in scalar-tensor theories of gravity

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Tuesday Session 4 - A3: Alternative and modified theories of gravity

We compute tidal signatures in the gravitational waves (GWs) from neutron star binary inspirals in scalar-tensor gravity, where the dominant adiabatic even-parity tidal interactions involve three types of Love numbers that depend on the matter equation of state and parameters of the gravitational theory. We calculate the modes of the GW amplitudes and the phase evolution in the time and frequency domain, working up to first order in the post-Newtonian and small finite-size approximations. We also perform several case studies to quantify the dipolar and quadrupolar tidal effects and their parameter dependencies specialized to Gaussian couplings. We show that various tidal contributions enter with different signs and scalings with frequency, which generally leads to smaller net tidal GW imprints than for the same binary system in General Relativity.

The ETpathfinder experiment

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Monday Session 3 - C4: Concept and research towards next-generation detectors

Third-generation gravitational wave observatories, such as the Einstein Telescope (ET) and Cosmic Explorer, aim for sensitivity improvements of at least a factor of ten over a wide frequency range compared to the current operational detectors. To finalize the design of these 3G detectors and to further develop and qualify their subsystems, dedicated test facilities are required. The ETpathfinder prototype consists of full interferometer configurations and aims to provide a high sensitivity test facility in a similar environment as ET. The key technologies that will be implemented are lasers and optics at 1550 nm and 2090 nm, silicon test masses, cryogenic cooling techniques, and advanced quantum-noise reduction schemes. In this overview talk, we will present a general status update of the ETpathfinder experiment.

Absolute Calibration of the Virgo Interferometer Using a Newtonian Calibrator

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Tuesday Session 3 - C3: Progress and challenges in advanced ground-based detectors

The precise calibration of gravitational wave detectors is essential to ensure the accuracy of astrophysical observations. In the Virgo interferometer, absolute calibration has traditionally relied on Photon Calibrators (PCal), which use laser radiation pressure to induce controlled mirror displacements. However, during previous observation runs, we have developed and implemented a Newtonian Calibrator (NCal), which utilizes the well-characterized gravitational field of moving test masses to produce a known displacement. This method provides improved accuracy and long-term stability compared to PCal-based calibration. We present the latest results from the Virgo NCal, which is the absolute calibration reference for Virgo since the beginning of the ongoing O4 observing run.

Free hyperboloidal evolution: 4D reference metrics and status of 3D simulations

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Wednesday Session 4 - B2: Numerical Relativity

Gravitational wave radiation is only unambiguously defined at future null infinity - the location in spacetime where light rays arrive and where global properties of spacetimes can be measured. Future null infinity is thus very important for extracting correct waveforms from numerical relativity simulations. A convenient way to reach it is using hyperboloidal slices, which can be tackled with conformal compactification. Current efforts in this approach rely on a 4D time-independent background reference metric for the calculation of the source functions in the gauge conditions, which are a crucial part of the implementation. I will present suitable choices of reference metrics, tested in spherical symmetry, and update on the ongoing efforts towards hyperboloidal simulations in full 3D.

Gravitational waves from supermassive black holes at pulsar timing arrays

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Tuesday Session 4 - C1: Pulsar timing arrays

Inspiralling supermassive black hole (SMBH) binaries constitute a natural astrophysical explanation of the gravitational wave (GW) background discovered in pulsar timing array (PTA) data. In this talk, I present a fast semianalytical computation of the expected GW background from SMBHs that allows for systematical studies of the effects of binary environments and eccentricities on the total GW background. I will discuss the fit of the SMBH model to the PTA data that shows evidence of environmental effects or binary eccentricities. I will also identify signatures that can be used to distinguish between these effects and to confirm whether the signal comes from SMBH binaries. Finally, I will discuss how the PTA GW observations can be linked to the JWST observations of dual AGNs and little red dots and how these observations point towards strong environmental effects due to which the final-parsec problem is avoided.

Ultrarelativistic motion in curved spacetime through Penrose limits

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Monday Session 4 - B3: Approximations, perturbation theory, and their applications

Understanding the motion of point-like objects in arbitrary spacetimes can be quite difficult, especially if the underlying spacetimes don't possess a certain degree of symmetry. This often leads to the construction of various perturbative formalisms that leverage the symmetries of some "base" spacetime. In this talk, I present a perturbative formalism that is valid for objects that are in the vicinity of null geodesics in arbitrary spacetimes. The key ingredient in this formalism is the Penrose limit -- the idea that the metric around a specified null geodesic, when expanded in the appropriate coordinates, looks like a plane wave metric at leading order. Objects whose worldlines remain close to the fixed null geodesic are ultrarelativistic, and their motion is determined by the structure of the associated plane wave metric, the latter of which generically possesses a higher degree of symmetry. This talk will describe ongoing work on using this formalism to simplify the equations of motion of an ultrarelativistic point-like particle in arbitrary spacetimes.

Black Hole Solutions of Palatini Nonlinear Electrodynamics and their Characteristics

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Monday Session 3 - A1: Classical GR: Theoretical developments

The general subject of this talk is the formalism for electromagnetism and its non-linear generalizations, which is analogous to the Palatini formalism of General Relativity and its extensions and modifications. There exist already studies of non-linear electrodynamics (NLED) in first order formalism of a limited type where it is always equivalent to the second order formalism. The advantage of this first order approach is mainly technical in that it facilitates the study of certain NLED theories which are difficult to handle in second order. However, it turns out that it is possible to construct a large family of first order NLED theories which we call Palatini non-linear electrodynamics (PNLED for short), by relinquishing the condition of equivalence between the first and second order formalism. In this talk I will introduce novel spherically-symmetric PNLED Black Hole solutions presented analytically, either directly in terms of r-dependent functions, or using a parametric representation. This allows relatively simple expressions for (and among) the main BH parameters, like mass, charge, horizon radius, temperature, entropy, photon sphere radius etc. Subsequently, some of the BH main characteristics are studied from various perspectives, from thermodynamic aspects to optical phenomena like gravitational lensing and shadows. This talk is partially based on https://arxiv.org/abs/2412.20989 .

Virgo h(t) reconstruction for O4 and O5

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Monday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The precise online reconstruction of the Virgo detector strain h(t)
induced by gravitational waves is the main detector output
used for astrophysical observations. Its latency is critical for the low-latency alert generation.
Since the start of the O4 run, a new version of the Virgo h(t) reconstruction process in the frequency domain is used and provides an unbiased and noise-mitigated h(t) with frequency-dependent uncertainties around 2% on modulus and 30 mrad on phase, with a latency of about 10 seconds.
In parallel, a time domain h(t) reconstruction is under study to provide at least the same features and performances while improving the latency down to below one second. The principle, main features and results of those two types of h(t) reconstruction, developped within the Virgo calibration team, are presented here.

Evolution of structures in modified gravity

Verma M[1]
[1]University Of Lucknow

Friday Session 3 - A3: Alternative and modified theories of gravity

We explore the structure formation in the modified gravity background with the equivalent contributions from the scalar degree of freedom. The behavior of evolution is analysed across the epoch $z=1$. It is found that the late-time accelerated expansion affects the formation of large scale structures by slowing down the growth of matter density. The observations on structure formations are consistent with the fact that the scalar contributions from modified gravity enhance the matter density perturbations. A consistent model of f(R) theory is developed for the detailed analysis for observational compliance.

Searching for spacetime fluctuations with interferometers

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Monday Session 4 - C9: Experimental gravitation

Spacetime fluctuations are a ubiquitous feature of proposals to reconcile quantum mechanics and gravity. Interferometers could potentially be used to detect these fluctuations and provide the first detection of quantum gravity phenomena. We discuss the GQuEST experiment, which uses photon-counting interferometry to evade the standard quantum limit and thus allows unprecedented sensitivity to spacetime fluctuations. Moreover, we will discuss how new high-frequency data from LIGO is used to constrain holographic theories of quantum gravity; specifically we discuss a search for geontropic spacetime fluctuations as predicted by Verlinde & Zurek.

Elevated p-astro: Increased significances with multi-messenger coincidences

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Tuesday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

Coincident multi-messenger observation of cosmic sources can offer numerous benefits, especially when used contextually via synergistic astrophysics. One significant advantage is enhancing the detection significance of separate detectors by correlating their data and assuming joint emission. We have formulated an approach for updating the Bayesian posterior probability of an astrophysical origin, namely p-astro, relying on multi-messenger coincidences assuming an emission model. The description is applicable to any combination of messengers. We demonstrated the formalism for the gravitational waves and high-energy neutrinos case. Applying our method to the public data of candidate coincident high-energy neutrinos with subthreshold gravitational-wave triggers, we found that in the case of highly energetic neutrino coincidences, p-astro can increase from approximately 0.1 to 0.9. The amount of improvement depends on the assumed joint emission model. If models are trusted, the marked improvement makes subthreshold detections much more confident. Moreover, the model dependency can also be used to test the consistency of different models. This work is a crucial step toward the goal of uniting all detectors on equal footing into a statistically integrated, Earth-sized observatory for comprehensive multi-messenger astrophysics.

Modifying general relativity as function of the topology of the universe: motivations and consequences for cosmology

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Friday Session 3 - A3: Alternative and modified theories of gravity

I will present a parameter-free modification of general relativity depending on the topology of the Universe. I will first focus on the original motivation for this theory, i.e. requiring the existence of a Newtonian limit in any topology. Then I will present the main consequences for cosmology and inflation. In particular, this theory allows for the construction of a parameter-free model of inflation with a non-zero background curvature, something not possible in general relativity.

A highly accurate, efficient, and parallelizable numerical scheme to simulate gravitational waves from black holes with extreme masses

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Tuesday Session 3 - B2: Numerical Relativity

Laser Interferometer Space Antenna (LISA), a future space-borne gravitational wave detector, is primarily sensitive to Extreme Mass Ratio Inspirals (EMRIs), which are black hole mergers with a mass ratio greater than 100,000. We require an extremely precise template wave bank for the matched filtering procedure. In this talk, I will discuss about a Discontinuous Galerkin (DG) technique for gravitational wave simulations of EMRI systems. The Teukolsky equation, which governs the behavior of EMRIs, is first reduced to a set of coupled 1+1D wave equations with a delta source term that functions as the secondary black hole in an EMRI system. Our DG approach, in contrast to previous numerical schemes, can precisely incorporate the smaller black hole's point particle behavior in the form of a delta function. Compared to previous methods, our efficient method produces very accurate waveform due to the scheme's spectral (super)convergence property and exact treatment of the Dirac delta function that models the smaller black hole. Our time domain solver now includes hyperboloidal layers, which allow us to retrieve the solution at null infinity and horizon. We verify our computation by calculating Kerr and Schwarzschild energy fluxes from circular orbits at null infinity and Price tail power laws. We also demonstrate an exponential (super)convergent solution to energy fluxes and self-force from circular orbits of the smaller secondary black hole.

Black Hole Scattering and Integrability : a Hyperboloidal Approach

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Wednesday Session 3 - A1: Classical GR: Theoretical developments

Integrability structures are known to play a key role in one-dimensional scattering. In the gravitational context, the analysis emphasizing the role of the so-called Darboux covariance and its intimate connection with KdV conserved quantities was recently introduced by Lenzi & Sopuerta. In a second stage, this led in particular to the identification of the structural role of the "KdV-Virasoro-Schwarzian derivative" triangle in this problem. Such a gravitational scattering description dwells naturally on a Cauchy foliation of the spacetime. In this talk, we recast this problem in a hyperboloidal foliation scheme, where the infinitesimal time generator of the dynamics is a non-selfadjoint operator. Our focus is on identifying a Lax-pair formulation that underlies the integrability features. Specifically, the main results presented here are i) the explicit proposal of a ("weak") Lax-pair, valid under suitable conditions involving fields at null infinity, and ii) the related discussion of isospectrality under such a Lax-pair deformation. From a broader perspective, the very form of the non-selfadjoint infinitesimal time operator, which neatly separates into two components corresponding to bulk and boundary structures, paves the way for the description of the gravitational dynamics in terms of a "semi-direct action" of bulk degrees of freedom onto boundary degrees of freedom. This is akin to the "wave-mean flow" approach for black hole strong-gravity dynamics recently proposed by the authors.

MONET - Mechanical Oscillators in Non-Equilibrium Thermodynamics

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Friday Session 4 - C4: Concept and research towards next-generation detectors

To reach higher sensitivities in the frequency band below 10 Hz in third generation terrestrial gravitational wave detectors, such as the Einstein Telescope, the individual noise sources must be addressed and their impact on the system reduced. One of these noise sources is thermal noise, to be addressed through operating ET at cryogenic temperatures.

The cooling of the detector will introduce a temperature gradient along the suspensions at which the optical components are located. It is crucial to understand and characterise any effect of this thermal gradient onto heat dissipation and therefore the mechanical behaviour of the suspensions. This behaviour is complex, and current models, based on the fluctuation-dissipation theorem, do not capture all aspects of it, creating the need for experimental work toward understanding these effects.

The "Mechanical Oscillators in Non-Equilibrium Thermodynamics (MONET)" project aims to investigate, define and quantify the changes in mechanical properties of a suspension when a temperature gradient is introduced to a system along the suspension. To explore this, we use an experimental setup, where a mirror is suspended on thin wires, along which we create a temperature gradient of up to 60 K. To monitor the changes to the mechanical properties of the suspension, we used a high dynamic range interferometer, based on homodyne quadrature interferometry.

In this contribution, we will present the results of the experimental work, its conclusions and limitations, outlining the next steps towards better understanding of thermal noise is such systems, and through this reaching higher sensitivities in cryogenic detectors.

Solving the gravitational self-force problem with numerical relativity methods

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Tuesday Session 3 - B2: Numerical Relativity

For the upcoming space-based gravitational-wave detector LISA we will need to simulate binary black holes with extreme mass ratios (EMRIs). To achieve the required accuracy for these simulations we will have to compute the gravitational self-force acting on a small body in Kerr spacetime to second order in perturbation theory. In this talk I present a computational approach towards this goal based on numerical solutions of elliptic partial differential equations, which is made feasible using technology developed for large-scale numerical relativity simulations. I demonstrate how we use discontinuous Galerkin methods, task-based parallelism, and the iterative elliptic solver algorithms developed for binary black hole initial data problems to solve for the self-force acting on a scalar charge in Kerr spacetime, and present progress towards solving the gravitational self-force problem with this technology.

Best of both worlds: integrating principled matched-filtering searches with AI/ML tools

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Monday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

In the limit of infinite data and computational resources, machine learning (ML) methods can be optimal, however this idealistic situation is not often realized in practice. On the other hand, principled data-analysis methods are robust, but they make simplistic assumptions (e.g., the noise is roughly Gaussian). I will present how ML algorithms can enhance matched-filtering pipelines by: (i) generating optimal template banks (ii) weighting templates to downplay unphysical binary configurations (iii) mitigating non-Gaussian noise. Incorporating these advancements in the IAS search pipeline, I will present new detections of black holes in the astrophysically significant pair-instability mass gap and IMBH mass ranges.

Oscillon Formation in Modified Gravity using Numerical Relativity

Waeming A[1]
[1]Queen Mary University of London

Wednesday Session 3 - B2: Numerical Relativity

Formed in the early universe, oscillons are solitonic objects that may seed primordial black holes and leave imprints in the form of a gravitational wave background. I will describe work using non-linear relativistic simulations that include gravitational backreaction to study oscillons forming in a preheating phase of the post-inflationary universe. In particular, we study whether their compactness can reach levels sufficient to form black holes from generic initial perturbations. I will also show how modifications to gravity, inspired by the effective field theory approach, may change the dynamical strong field evolution.

Probing gravity using black hole ringdown

Wagle P[1], Li D[2,3], Chen Y[3], Yunes N[2]
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Monday Session 4 - C10: Experimental tests of the nature of compact objects

The detection of gravitational waves from compact binary mergers by the LIGO/Virgo collaboration has opened new avenues for testing relativistic gravity in the strong, dynamical, and nonlinear regimes. With the advent of future ground- and space-based gravitational wave detectors, we are poised to extract further insights into astrophysical events and investigate the implications for Einstein's theory of relativity in contexts where gravitational fields are both strong and dynamical. In this presentation, I will discuss recent advancements in the study of gravitational perturbations related to gravitational wave ringdown. I will highlight the necessity for these investigations and outline prospective research directions. Central to my discussion will be a novel approach that enables us to derive a "modified Teukolsky equation", a set of linear, decoupled differential equations that characterize the dynamical perturbations of non-Kerr black holes through the radiative Newman-Penrose scalars Ψ0 and Ψ4. This foundational work facilitates the examination of gravitational waves emitted during the ringdown phase of black hole coalescence within modified gravity frameworks applicable to black holes of any spin. Additionally, I will discuss the application of this approach in the context of a quadratic theory of gravity, where the metric and scalar fields exhibit non-minimal coupling, and calculate the quasinormal mode frequencies. I will conclude by discussing the prospects for detecting modifications to gravitational wave ringdown signatures in future observations, thereby enhancing our understanding of gravity beyond general relativity.

An Introduction to Cauchy Slice Holography

Wall A[1]
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Monday Session 3 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

A holographic duality is an equivalence between a higher dimensional gravitational theory, with a lower dimensional field theory (defined on a nondynamical background metric). The most famous example is the AdS/CFT duality, in which the CFT lives on a timelike boundary at asymptotic infinity.

In this talk, I will give a basic overview of a different way of doing holography, in which the lower dimensional theory lives on a spacelike Cauchy slice. Thus, time is the emergent dimension. I will explain the "dictionary" relating the gravitational description to the field theory description. Although the field theory is not a CFT, it becomes one in the large volume (infrared) limit. This opens up new possibilties for trying to give a short distance definition of quantum gravity.

(This talk is intended to be accessible to relativists familiar with canonical GR, but who may not know much about holography.)

Hamilton-Jacobi vs Separate Universe approach to inflation beyond slow roll

Wands D[1], Artigas D[2], Frion E[3], Miranda T[4], Vennin V[5]
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Tuesday Session 4 - B4: Cosmology: Theory and observations (including gravitational waves)

The Hamilton-Jacobi approach is a powerful tool to describe the non-linear evolution of large-scale fluctuations during inflation in the early universe. A key assumption in this approach is to neglect anisotropic perturbations on large scales. We show that neglecting the anisotropic part of the momentum constraint corresponds to discarding the non-adiabatic mode of scalar field perturbations at leading order in a gradient expansion. Consequently, the Hamilton-Jacobi approach cannot be used to describe the general evolution of large-scale perturbations during inflation beyond slow roll, where non-adiabatic field fluctuations play an important role on due to the absence of an attractor trajectory. We contrast this to the more general Separate Universe approach. As an example, we analyse the case of linear perturbations during a phase of ultra-slow-roll inflation.

Initial conditions and analytical studies of linear cosmological perturbations in (modified) loop quantum cosmologies

Wang A[1]
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Thursday Session 3 - D1: Loop quantum gravity and spin foams

In loop quantum cosmology (LQC), the classical big bang singularity is replaced by a quantum bounce. This is also true in modified loop quantum cosmologies (mLQCs). A challenging question of cosmological perturbations in such a background is how to impose the initial conditions. Another challenging question is the computation of mode functions after quantum geometric effects are taken into account, as the resultant Mukhanov-Sasaki (MS) equations are so complicated that often require very expensive numerical calculations. In this talk, I am going to report our recent investigations on both of these questions. In particular, we first show that in the remote contracting phase, a stable initial state still exists, while to the second problem we further develop the uniform asymptotic approximation method and apply it to the linear cosmological perturbations in mLQC-I, and find the explicit expressions of the mode functions to the modified MS equations. The analytical solutions trace the numerical ones very well, and the upper bound of the errors are usually no larger than 15$\%$ to the first-order approximation. The approximations can be extended to high-order, with which the errors are expected to be much smaller. More specifically, to the third-order approximation the upper bound is normally no larger than 0.15$\%$, which is accurate enough for the current and forthcoming cosmological observations.

Quasi-periodic lensed light curves of stars by supermassive black hole binaries

Wang H[1], Zumalacarregui [2], Kocsis B[1]
[1]University Of Oxford, [2]Max Planck Institute for Gravitational Physics

Friday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

Supermassive black hole binaries (SMBHB) form in galactic nuclei after galaxy mergers. In this presentation, I will demonstrate that inspiraling SMBHBs detectable with LISA may act as a binary gravitational lens leading to a new class of electromagnetic (EM) counterparts. The caustic (i.e. the curve on which the magnification diverges) of the binary lens is more complex than that of a single point mass, and the orbit and inspiral of the binary leads to the rotation and decreasing size of the caustic curve. This opens the possibility that a background source such as a star can cross the caustic multiple times during the binary orbital period leading to strong quasi-periodic time-dependent magnification. I will show examples where this EM signal may be detected, where the recurring peak magnification due to the SMBHB lens reaches a factor of 10^5 for giant stars with particular features which makes it possible to extract the properties of the supermassive binary such as the orbital period and eccentricity. These electromagnetic events may be targets for surveys such as LSST to identify inspiraling supermassive black holes even without a coincident gravitational wave detection.

Searching for gravitational waves from eccentric binary black holes

Wang Y[1]
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Wednesday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Eccentricity serves as crucial diagnostics for constraining formation channels of coalescing compact binaries. Thanks to recent breakthroughs in waveform modeling on the aligned-spinning eccentric binary coalescence, we have implemented the first matched-filtering search for gravitational waves with an effective one body waveform template bank incorporating eccentricity. This search considers component masses spanning 5 to 200 solar masses and eccentricity reaching 0.5 at 10 Hz orbital separation. I will present the technique to construct the template bank, the search strategy, and the search results.

Hierarchical search method for gravitational waves from stellar-mass binary black holes in noisy space-based detector data

Wang Y[1], Fu Y[1], Mohanty S[2]
[1]Huazhong University Of Science And Technology, [2]University of Texas Rio Grande Valley

Friday Session 4 - C5: LISA and other space-based detectors

Future space-based detectors, such as LISA and TianQin, will detect gravitational waves from stellar-mass binary black holes (SmBBHs), offering insights into astrophysical formation channels, fundamental physics and multi-wavelength GW astronomy. However, the detection and characterization of GWs from SmBBHs poses a formidable data analysis challenge, arising from the large number of wave cycles that make the search extremely sensitive to mismatches in signal and template parameters in a likelihood-based approach. This makes the search for the maximum of the likelihood function over the signal parameter space an extremely difficult task, with grid-based deterministic global optimization methods becoming computationally infeasible. We propose a GPU-accelerated hierarchical data analysis method combining semi-coherent F-statistic computations with particle swarm optimization (PSO). The approach partitions the parameter space across multiple stages, progressively changes the search statistic from semi-coherent to fully-coherent F-statistic, and narrows the search ranges to avoid noise-induced false maxima. Tested on 2.5 years of simulated LISA time-delay interferometry data for SmBBH signals (SNR \approx 11–14), and searching over [20, 80] M_sun in detector frame chirp mass, [0, 0.05] in orbital eccentricity at a fiducial frequency, and the whole sky, the method achieves: (i) chirp mass relative error <0.01%, (ii) coalescence time precision ~100 sec, (iii) sky localization ~0.2 deg^2, and (iv) orbital eccentricity error <1% at 10 mHz. These results are among the best achieved so far on this challenging data analysis problem.

Mitigation of tilt-to-length coupling noise in space-based missions

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Thursday Session 3 - C5: LISA and other space-based detectors

Angular and lateral jitter coupling is a common noise source in ground- and space-based gravitational wave detectors, in LISA Pathfinder, and likewise in the GRACE-FO mission and its successors. In space missions, this noise type is mostly referred to as tilt-to-length coupling noise, while lateral jitter coupling in LISA is often referred to as line-of-sight alignment noise. Mitigating these noise types comprises three important aspects: suppression by dedicated design choices, by optimization of the alignment, and by noise subtraction in data processing. In this presentation, I will give an overview from my perspective on this noise type and its suppression in the different missions with a focus on LISA, and our experience from LISA Pathfinder.

Including more physics in fast EMRI waveform models

Warburton N[1], FastEMRIWaveform developers .
[1]University College Dublin

Wednesday Session 3 - B3: Approximations, perturbation theory, and their applications

With the recent release for the FastEMRIWaveform (FEW) model for inspirals in the equatorial plane of a spinning primary, attention now turns to extending the parameter space and adding additional physics. In this talk I will discuss recent additions to FEW for modelling orbital and tidal resonances and the extension to complete inspiral-merger-ringdown models which are important for intermediate mass ratio binaries. I will also discuss plans to extend the model to cover the full parameter space and highlight how the modularity of the model allows additional physics (environmental, beyond GR, etc) to be added with ease.

Post-innermost stable circular orbit ringdown of a rapidly spinning black hole

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Monday Session 3 - C10: Experimental tests of the nature of compact objects

In a binary merger with an extreme mass ratio, as the secondary body approaches the innermost stable circular orbit (ISCO) of the primary black hole, the motion transitions from the adiabatic inspiral to the plunge governed by the geodesic equation. The plunge orbit is expected to excite the ringdown gravitational wave, which encodes information about the primary black hole's geometry. The details of the transition regime depend on the binary's mass ratio through radiation fluxes, which in turn influence the initial conditions for the plunge. As such, the mass ratio affects the post-ISCO gravitational wave excitation.

In our recent study [D.Watarai, PhysRevD.110.124029 (2024)], we numerically investigate the mass ratio dependence of higher harmonic quasi-normal mode excitations in the post-ISCO gravitational waves of rapidly spinning black holes, based on the Teukolsky-Sasaki-Nakamura formalism. The effect of the mass ratio on the gravitational waves is consided by accounting for the energy and angular momentum losses during the transition regime according to the Ori-Thorne procedure.

In this talk, we focus on how the mass ratio affects higher harmonic quasi-normal mode excitations and discuss the implications for future observations with space-based gravitational wave interferometers.

Resonantly enhanced deep frequency modulation interferometry (ReDFMI)

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Friday Session 3 - C4: Concept and research towards next-generation detectors

Current gravitational-wave detectors are limited by control noises at frequencies below 10 Hz. This noise originates primarily from the sensitivity of the currently used local displacement sensors. Newer interferometric displacement sensors are limited to a sensitivity of up to 10 $fm/\sqrt{Hz}$.
With Resonantly enhanced deep frequency modulation interferometry (short: ReDFMI), a multi-fringe displacement sensing technique with absolute ranging that uses a strong frequency modulation (DFM) in combination with optical resonators, sensitivities below 1 $fm/\sqrt{Hz}$ can be achieved, according to analysis of the Cramer Rao lower bound. Compared to other interferometry techniques, ReDFMI doesn't rely on complex optical layouts and quasi-monolithic setups.

Can Dirac Fields Source Traversable Wormholes?

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Thursday Session 4 - A1: Classical GR: Theoretical developments

Traversable wormholes have captivated the interest of the public and of theoretical physicists since their inception, with a recent resurgence of interest in the context of holography. While wormhole geometries are permissible within the framework of general relativity, they require matter with "negative energy" to sustain them, specifically matter that violates the null energy condition on a sufficiently large scale. Typical classical matter, however, does not possess the necessary properties to support such geometries.

The question remains open as to whether a Dirac field can generate sufficient violations of the null energy condition to source a traversable wormhole. In this talk, I will present recent progress in exploring this possibility for positive-frequency, classical Dirac fields within static, spherically symmetric wormhole spacetimes. I will examine whether solutions to the Dirac equation can provide the "negative energy" needed to make static, spherically symmetric wormholes viable without resorting to introducing nonphysical exotic matter.

Classifying Isospectrality Breaking Beyond General Relativity

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Monday Session 4 - C10: Experimental tests of the nature of compact objects

Accurately modeling a gravitational-wave ringdown signal, dominated by quasinormal modes, is crucial to test the accuracy of general relativity (GR). Many modified theories of gravity predict the even- and odd-parity ringdown modes have different quasinormal mode frequencies, violating the symmetry (isospectrality) found in GR. In this paper, we use the recently developed modified Teukolsky equations to classify how isospectrailty breaking can occur in effective-field-theory extensions of GR. We find that in a broad range of modifications, isospectrality is lost, leaving possible evidence for parity-violating gravity and the existence of additional scalar, vector, or tensor fields. Additionally, we use numerical relativity simulations to model the signal-to-noise ratio of modified waveforms in next-generation detectors, forecasting the optimal properties of progenitor binaries that could produce a detectable isospectrality-breaking signal.

Probing black holes and exotica through gravitational-wave spectroscopy

Westerweck J[1]
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Monday Session 3 - C10: Experimental tests of the nature of compact objects

First observational bounds are now being placed on deviations from general relativity and properties of alternatives to black holes through gravitational-wave observations. Recent advances in data-analysis methods enabled these, which we applied in studies covering multi-mode ringdown observations, additional fields, and signatures of horizonless or exotic compact objects. I provide an overview of these methods' capabilities and limitations, and the bounds we obtained on black holes and their alternatives.

Black-hole spectroscopy studies the characteristic modes emitted in the ringdown phase of a binary merger as the perturbed remnant object settles down to its final state. Tests of the no-hair black hole uniqueness theorem in general relativity require measurement of multiple modes, excluding influence from pre-ringdown data. This is now becoming an observational reality, overcoming data-analysis challenges preventing to account for uncertainty in the merger time and sky location of the source. Its application to current spectroscopy results allows us to reliably evaluate the evidence for multiple ringdown modes.

Signatures of exotic compact objects can be revealed through methods derived from those of spectroscopy. We find constraints on properties of several proposed alternatives to black holes from current gravitational-wave data and predict future instruments' prospects. This includes scalar/vector-fields near black holes; long-lived modes from classes of horizonless compact objects, yielding strict bounds on their space-time geometry; and modes from oscillating currents in dense-fluid compact objects sourcing gravitational waves, providing insight into matter properties beyond neutron-star densities.

Brill Waves of Slow Fall-off

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Monday Session 3 - A2: Classical GR: Mathematical developments

Obtaining their namesake from D. Brill's proof of the positive mass theorem in a simple and specialized setting, Brill waves are simple solutions to the Einstein vacuum constraint equations representing initial data for an axially- and time-symmetric distribution of gravitational waves. I present joint work with Lydia Bieri and David Garfinkle in which we demonstrate both analytical results towards the existence and uniqueness of Brill-type initial data exhibiting slower decay towards asymptotic flatness at spatial infinity, as well as numerical realizations of such solutions. These provide particularly simple models of general asymptotics demonstrated by Bieri in settings with slow fall-off, as well as a testing ground for the robustness of desirable physical features enjoyed by systems with faster fall-off, namely the antipodal symmetry of certain limiting curvatures at spatial infinity that allow for identifying the BMS groups on future and past null infinity.

LIGO-Virgo-KAGRA Searches for Continuous Gravitational Waves from Scorpius X-1

Whelan J[1], for the LIGO-Virgo-KAGRA collaboration
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Tuesday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

The low-mass X-ray binary Scorpius X-1 is a promising source of continuous gravitational waves. Its high X-ray luminosity indicates a large rate of accretion, which may power GW emission. A variety of methods have been developed and applied to search for a GW signal, which presents challenges because of the unknown signal frequency and residual uncertainties in orbital parameters. Searches with advanced gravitational wave detectors have begun to probe astrophysically plausible signal models. I will summarize results from the first three observing runs of LIGO, Virgo and KAGRA, along with the status of searches in the ongoing LIGO-Virgo-KAGRA O4 run.

Frequency-domain self-force scatter calculations using the Gegenbauer procedure

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Monday Session 3 - B3: Approximations, perturbation theory, and their applications

Recent years have seen significant cross-disciplinary interest in the problem of relativistic black hole scattering, driven by the potential to advance theoretical waveform models for gravitational wave astronomy and to explore the interface between different modeling approaches and regimes. This talk will focus on the self-force approach, and in particular the use of frequency-domain numerical techniques to calculate the self-force along hyperbolic scatter geodesics. Such methods have found great success in bound-orbit self-force calculations, but suffer from increasing loss of precision in the limit of large eccentricity due to numerical cancellation between low-frequency modes. Frequency-domain methods have been demonstrated to work for self-force scatter calculations (within a scalar-field toy model), and to possess significant advantages over time-domain numerical techniques during the periapsis portion of strong-field scatter orbits, but the cancellation problem causes a precipitous decline in precision when the orbital separation becomes much larger than its periapsis value. In this talk we will discuss how the Gegenbauer reconstruction procedure can be applied to the self-force problem, reconstructing the self-force from frequency modes without the cancellation problem inherent in the conventional frequency-domain approach. The procedure is demonstrated with numerical results for the spherical harmonic modes of the scalar-field and its derivatives, evaluated on the worldline of a small scalar charge scattering off a Schwarzschild black hole. We conclude by discussing the merits of this approach, and the challenges that remain for a full self-force calculation using the Gegenbauer procedure.

A Bound on Gravitational Wave Luminosity from Non-Perturbative Quantum Effects

Wieland W[1]
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Thursday Session 3 - D1: Loop quantum gravity and spin foams

In classical field theory, a state of the system is characterized by initial data on a Cauchy surface. At the quantum level, different states correspond to different (normalised) vectors in the Hilbert space of the theory. In field theory, gauge redundancies can bring in further complication. Points on the same gauge orbit represent the same physical state of the system. In vacuum general relativity, the relevant gauge symmetries are four-dimensional diffeomorphisms. Loosely speaking, depending on which gauge sections we choose, we land on different Cauchy hypersurfaces in spacetime. In my talk, I will present a research programme in quantum gravity based on the idea to perform a non-perturbative quantization of initial data on light-like surfaces. I will report on three new results on this frontier. First, I provide a non-perturbative characterization of the gravitational phase space on a null boundary for tetradic gravity with the parity violating γ-term (Holst term) in the action. Second, the description is taken to the quantum level. Third, an immediate physical implication is found: in the model, the Planck luminosity separates the eigenvalues of the radiated gravitational wave power. Below the Planck power, the spectrum of the radiated power is discrete. Above the Planck power, the spectrum is continuous and the resulting physical states contain caustics that can spoil the semi-classical limit. The talk is based on arXiv:2402.12578, arXiv:2401.17491, arXiv:2104.05803.

Equations of motion for compact binaries in general relativity: Do they depend on internal structure at the third post-Newtonian order?

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Thursday Session 4 - B3: Approximations, perturbation theory, and their applications

We discuss the possibility, derived from work carried out 20 years ago, that the equations of motion for binary neutron stars at the third post-Newtonian (3PN) order in general relativity might actually depend on the internal structure of the bodies. These effects involve integrals over the density and internal gravitational potentials of the bodies that are independent of the mass and radius of the bodies, but dependent on their equations of state. These effects could alter the coefficients in the 3PN equations derived using "point mass" methods by as much as 100 percent. They were found in independent calculations done at Washington University using the Direct Integration of the Relaxed Einstein Equations (DIRE) approach, and at the Institut d'Astrophysique de Paris using the Multipolar post-Minkowskian (MPPM) approach. Neither calculation was completed because of the enormous complexity of the algebraic computations and the limitations of software of the day (Maple, Mathematica), and because of an assumption (hope) that the effects would somehow cancel or be removable by some transformation. If these structure-dependent effects are real, but are not incorporated into gravitational waveforms, they could severely impact efforts using next-generation gravitational-wave interferometers to extract information about the equation of state for neutron star matter from gravitational-wave signals from binary neutron star or black hole-neutron star mergers. Conversely, if they exactly cancel or can be absorbed into renormalized masses or shifted positions of each body, this would provide further support for the Strong Equivalence Principle of general relativity.

Wave optical imaging by point-source scattering for a TNdS black hole

Willenborg F[1]
[1]University of Bremen, ZARM

Monday Session 4 - B3: Approximations, perturbation theory, and their applications

Several methods offer a theoretical description of these observations. Already mentioned are ray-optical methods by geodesics or the calculation of the scattering by the so-called amplification factor F by the description of time-delays td. In our work, we describe the calculation by a full wave equation using the Teukolsky equation, which allows access to all frequencies. To obtain fully analytical solutions, a small cosmological constant is considered, generalising the solution to Taub-NUT-de Sitter (TNdS). We observe the scattering of a monochromatic point source to an observer at a larger distance from the black hole. Afterwards, we briefly discuss the method and present results for Schwarzschild-de Sitter at very low frequencies in a wave-optical approach as a simple model. Finally, we present results for TNdS and how these change with the parameter variation.

Parameter estimation for binary black hole signals including waveform model uncertainty

Williams D[1], Veitch J[1], Heng I[1]
[1]University Of Glasgow

Friday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

As GW detectors improve in sensitivity, systematic uncertainty due to waveform models is becoming increasingly important relative to statistical uncertainty due to noise. Our work aims to incorporate this systematic uncertainty during inference. Gaussian processes can be used to quantify the uncertainty in a given model, or between models. We will present the methodology for performing inference using these Gaussian process models, and our initial results for analysis of real gravitational wave signals.

Investigating the impact of quasi-universal relations on neutron star properties with third generation detectors

Williams N[1], Puecher A[1], Grams G[1], Dietrich T[1,2]
[1]University of Potsdam, [2]Max Planck Institute for Gravitational Physics

Friday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Gravitational wave observations of binary neutron star systems have the potential to shed light on the currently unknown neutron star equation of state. The equation of state determines a wide array of neutron star properties, which can result in a highly dimensional problem. Quasi-universal relations between neutron star properties tackle this challenge by providing an equation of state quasi-independent mapping between neutron star observables, and are commonly employed within waveform modelling and parameter estimation. However, quasi-universal relations have been demonstrated to break down for equations of state with extreme features. In this work, we explore the applicability of quasi-universal relations within a binary neutron star population as observed by upcoming third-generation detectors. We simulate two extreme equations of state, and test the effect of a selection of quasi-universal relations in turn. We explore if biases are induced in the binary parameters when assuming quasi-universal relations, and the impact this has on the resulting equation of state measurement.

Quantum corrected anti-de Sitter space-time

Winstanley E[1], Thompson J[1]
[1]University Of Sheffield

Tuesday Session 4 - D4: Quantum fields in curved space-time, semiclassical gravity, quantum gravity phenomenology, and analog models

We study the back-reaction of a quantum scalar field on anti-de Sitter (AdS) space-time. The renormalized expectation value of the stress-energy tensor operator (RSET) for a quantum scalar field on global AdS spacetime acts as a source term on the right-hand-side of the Einstein equations for the quantum-corrected metric. We find the RSETs for rotating and nonrotating thermal states on global AdS and compare them with results from relativistic kinetic theory. We then solve the quantum-corrected Einstein equations. We interpret these quantum-corrected metrics as asymptotically-AdS solitons.

You may not need to look that FAR out

Wolfe N[1], Mould M[1], Vitale S[1]
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Thursday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

From catalogs of gravitational-wave transients observed by the LIGO-Virgo-KAGRA (LVK) collaboration we can infer the population-level distribution of merging compact object properties, and in turn, constrain the physics of massive binary stellar evolution. However, estimating the population-level likelihood suffers from Monte Carlo uncertainty that grows with increasing catalog size and can yield biased conclusions. Further, current catalogs likely admit noise transients which may bias astrophysical population inference. Computational solutions to these challenges may also scale poorly with the number of events, becoming infeasible for future catalogs. Here, we propose a simple remedy: increasing the significance threshold for inclusion in astrophysical population inference. First, we re-analyze the binary black hole mergers observed during the LVK's third observing run. Down to a false alarm rate threshold of 1 per 100,000 years, we find that qualitative conclusions about the population of merging binary black holes remain unchanged, though statistical uncertainties are correspondingly larger. Next, we analyze catalogs of up to 1600 black-hole mergers simulated with full Bayesian parameter estimation to assess the efficacy of our solution. We find that measurement uncertainties of the power-law index of the primary mass distribution and the location and scale of the spin distribution do not grow significantly until signal-to-noise ratio thresholds above 20. Simultaneously, Monte Carlo uncertainty in the likelihood is dramatically reduced with increasingly stringent thresholds. Therefore, analyzing smaller catalogs of more significant events is a promising approach to ameliorate contamination from noise transients and sampling artefacts, enabling unbiased astrophysical interpretation of gravitational-wave catalogs.

Reproducing Cosmology with Nonlocal Gravity

Woodard R[1]
[1]University Of Florida

Thursday Session 4 - A3: Alternative and modified theories of gravity

This talk is based on arXiv:2402.11716 with Cedric Deffayet. I construct a nonlocal, modified gravity model which reproduces all the cosmological successes of cold dark matter, including the CMB, BAO and linearized structure formation. The technique is to take the dark matter people at their word, that dark matter consists of a pressureless perfect fluid which only interacts with gravity. This means that its stress tensor is separately conserved, which provides enough equations to completely determine the pressure and a scalar whose gradient produces a timelike 4-velocity field. I then discuss the prospects for modifying the model so that, for static, gravitationally bound systems it reduces to Milgrom's MOdified Newtonian Dynamics. I also discuss the prospects for deriving this model from a nonperturbative resummation of graviton loop effects during inflation.

LensingFlow: An Automated Workflow for Gravitational Wave Lensing Analyses

Wright M[1,2], Janquart J[3,4], Cremonese P[5]
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Friday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

As the current LIGO-Virgo-KAGRA network of gravitational wave detectors continues to get more and more sensitive with each upgrade, the number of events detected during each observing run also continues to increase allowing searches for various phenomena that can happen to the signals. One such phenomenon is gravitational lensing---in which the signal experiences deflection due to passing by a massive object on its path to the observer. This
can leave a number of signatures from waveform distortions to repeated signals being detected. Searches for lensing must therefore cover a broad number of possible phenomenologies and must analyse not just each individual GW event but combinations of them leading to a significantly larger number of analyses than for standard searches. Some of these searches are also computationally expensive to conduct. It is therefore vital to have infrastructure available to rapidly work through the data and communicate between the different phenomenologies to ensure that any potential candidates for lensing are analysed with priority. For this, we present LensingFlow which brings together a variety of existing search pipelines for lensing into an automated workflow handling communication and prioritisation of analyses to ensure efficient searches for lensing.

LISA+3G coherent multiband parameter estimation of stellar-mass BBHs using PyCBC

Wu S[1], Nitz A[2], Harry I[3], Babak S[4], Williams M[3]
[1]Max Planck Institute For Gravitational Physics In Hannover, [2]Syracuse University, [3]University of Portsmouth, [4]AstroParticule et Cosmologie

Monday Session 4 - C5: LISA and other space-based detectors

I will introduce the latest development of PyCBC pipeline for LISA data analysis, focusing especially on optimizing the combination of the information from LISA and next-generation ground-based detectors for stellar/intermediate-mass binary black holes. According to the GWTC-3 population model, stellar-mass binary black holes will most likely have an SNR less than 5, but the most state-of-the-art multiband parameter estimation method, such as archivally using 3G posterior as prior for LISA, can only get good results when LISA SNR is greater than 5. We developed a novel coherent multiband parameter estimation method that can maintain the amplitude and phase consistency between LISA and 3G for the same signal, together with the multiband marginalization of the extrinsic parameter space, which can work robustly even when the LISA SNR is down to 3. Using our new method, we can almost double the number of usable BBH events for LISA. For the first time, we show population-scale and efficient multiband Bayesian parameter estimation. The paper will be on arXiv in April.

Hyperbolic Mass in 2+1 Dimensions

Wutte R[1], Chruściel P[2,3]
[1]Department Of Physics And Beyond Center, Arizona State University, [2]Beijing Institute of Mathematical Sciences and Applications, [3]Center for Theoretical Physics of the Polish Academy of Sciences

Monday Session 4 - A2: Classical GR: Mathematical developments

Solutions to general relativity with a negative cosmological constant have received significant attention due to the conjectured AdS/CFT correspondence, a particularly well-understood example of which is exhibited in 2+1 dimensions.
I will review known vacuum solutions to general relativity with a negative cosmological constant in 2+1 dimensions and discuss the difficulties in defining mass, which are resolved via minimisation using a positive energy theorem. I will present a gluing theorem for vacuum time-symmetric general-relativistic initial data sets in two spatial dimensions. By gluing two given time-symmetric vacuum initial data sets at conformal infinity, we obtain new time-symmetric vacuum initial data sets. I will sketch the derivation of the mass formulae of the resulting manifolds. Our gluing theorem yields complete manifolds with any mass aspect function, which are smooth except for one conical singularity.

Bayesian search of massive scalar fields from LIGO-Virgo-KAGRA binaries

Xie Y[1], Chung A[1], Sotiriou T[2], Yunes N[1]
[1]University of Illinois Urbana-Champaign, [2]University of Nottingham

Wednesday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

Massive scalar fields are promising candidates for addressing many unresolved problems in fundamental physics. We report the first model-agnostic Bayesian search of massive scalar fields that are nonminimally coupled to gravity in LIGO/Virgo/KAGRA gravitational-wave data. We find no evidence for such fields and place the most stringent upper limits on their coupling for scalar masses $\lesssim 2 \times 10{-}12$ eV. We exemplify the strength of these bounds by applying them to massive scalar-Gauss-Bonnet gravity, finding the tightest constraints on the coupling constant to date, $\sqrt{\alpha_{\rm GB}} \lesssim 1$ km for scalar masses $\lesssim 10{-}13$ eV to 90% credible level.

Jetstream Genesis: Simulating the Lifespan of Cosmic Relativistic Jets

Xie X[1]
[1]Max Planck Institute For Gravitational Physics, Potsdam

Monday Session 4 - B1: Relativistic astrophysics

Relativistic jets, observed across diverse astrophysical environments—from stellar black holes in X-ray binaries to supermassive black holes in active galactic nuclei (AGN) and gamma-ray bursts (GRBs)—serve as powerful laboratories to probe fundamental plasma physics, particle acceleration, and high-energy radiation mechanisms under extreme conditions.

Capturing relativistic jets' complete lifecycle—from their violent formation near compact objects through extensive interactions with their environments to eventual dissipation—remains a major computational challenge. Current numerical simulations typically address isolated phases, such as jet launching or propagation, failing to simultaneously resolve the full jet evolution and its complex interplay of relativistic magnetohydrodynamics, microphysical processes, and radiation mechanisms.

Building upon my recent development of a state-of-the-art general relativistic moving-mesh hydrodynamics framework, I introduce a comprehensive general relativistic moving-mesh magnetohydrodynamics (GRMMHD) simulation methodology. This innovative approach systematically explores the entire jet lifecycle, from the initial "Spark of Life" phase (launching and collimation) to the final "Golden Reflections" phase (dissipation). My framework uniquely resolves energy conversion processes from Poynting-flux-dominated to kinetically driven regimes, clarifying the mechanisms influencing jet structure, stability, and radiation properties.

Moreover, by integrating multi-messenger astrophysical signatures, my research establishes direct connections between jet dynamics, ultra-high-energy cosmic ray (UHECR) production, and electromagnetic and neutrino emissions from binary neutron star mergers. This approach provides predictive, observationally testable models, significantly advancing our understanding of relativistic jets in high-energy astrophysics.

Improved analytic solution of Kerr (-Newman) black hole superradiance

Xu Q[1]
[1]Instituto Superior Técnico

Monday Session 4 - B3: Approximations, perturbation theory, and their applications

The study of black hole superradiance relies on calculating bosonic quasi-bound states with complex eigenfrequencies. A widely used analytic approximation in the small α (“gravitational fine structure constant”) limit has been proposed for more than forty years; however, it does not agree well with results obtained from the numerical continued fraction method. In this study, we refine the analytic solution by employing a power-counting strategy to achieve a next-to-leading order (NLO) approximation. This improved solution applies to the analysis of superradiant instabilities in Kerr and Kerr-Newman black holes with charged or uncharged massive spin-0 fields. It has a compact form and demonstrates good agreement with existing numerical calculations. Moreover, the refined solution is straightforward to use and has already been applied in studies related to superradiance.

Deep learning for ringdown gravitational waves

Yamamoto T[1], Tanaka T[2]
[1]Resceu, University Of Tokyo, [2]Kyoto University

Thursday Session 4 - C10: Experimental tests of the nature of compact objects

Ringdown gravitational waves are emitted from a perturbed black hole (BH) and are occupied by BH's quasi-normal modes (QNMs). QNM frequencies are complex-valued and characterized only by BH's mass and spin in general relativity. By this feature, QNM frequencies are useful for testing general relativity in the strong gravity region. Ringdown gravitational waves can extract the last part of gravitational waves from a binary black hole merger. However, its transition from inspiral part is not trivial. We employ neural networks to extract the QNM frequencies from the ringdown part of binary black hole mergers. We generate the training data by using the flexible waveform model that has manually modified ringdown parts. We will present the performance of our algorithm and the results from the real data.

Generalised focusing theorem and dynamical horizon entropy in diffeomorphism-invariant theories

Yan Z[1]
[1]University of Cambridge

Thursday Session 4 - A3: Alternative and modified theories of gravity

On a Killing horizon background, we extend the null Raychaudhuri equation and the focusing theorem to encompass general diffeomorphism-invariant theories with arbitrary bosonic matter fields. An entropy formula (Wall entropy) for the horizon can be extracted from the Raychaudhuri equation, and it obeys both the first and the second laws of thermodynamics, providing a natural generalisation of Wald entropy when dynamical perturbations are present. Moreover, for higher-spin matter fields, we show that a "focusing condition" must be imposed to ensure that light rays converge under a positive energy flux, which in turn guarantees that the horizon entropy is well-defined. We speculate that focusing could be a necessary condition for the physical consistency of higher-spin theories.

Modulations of Gravitational Waves due to Non-static Gravitational Lenses

Yang X[1]
[1]Korea Institute for Advanced Study (KIAS)

Friday Session 3 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Gravitational waves (GWs) offer a new observational window into the universe, providing insights into compact objects and cosmic structures. Gravitational lensing, commonly studied in electromagnetic waves, also affects GWs, introducing magnification, time delays, and multiple images. While existing studies focus on static lenses, many astrophysical lenses are dynamic, with time-varying mass distributions such as moving stars or orbiting binaries. We develop a general theoretical framework to describe non-static lenses and demonstrate how they modulate GW signals, inducing unique time-varying amplitude modulations and spectral broadening. By examining uniformly moving and orbiting binary lenses, we show that these modulations provide new observational signatures, enhancing our understanding of lensing objects and the dynamics of the universe. Our findings have important implications for GW astronomy, offering novel ways to probe lens dynamics and improve the interpretations of GW signals.

The Gregory-Laflamme Instability of Five-dimensional Black Strings in Lovelock Gravity

Yao S[1], Figueras P[1], Kovács Á[1]
[1]Queen Mary University Of London

Wednesday Session 3 - B2: Numerical Relativity

Einstein's general theory of relativity (GR) remains the cornerstone of our understanding of gravity, but it is known to suffer from pathologies that challenge its predictive power. The Gregory-Laflamme (GL) instability of higher-dimensional black strings serves as a critical probe for the breakdown of GR. On the one hand, the nonlinear evolution of GL instability leads to the fragmentation of the black string horizon, which suggests the occurrence of naked singularity. On the other hand, the higher derivative terms in the effective field theory correction to GR may play a crucial role in determining the fate of the instability as the scale of the black string shrinks.

In this talk, we explore the Gregory-Laflamme instability of black string in the context of Lovelock gravity, specifically Einstein-Gauss-Bonnet theory, the leading higher-derivative extension to GR in five-dimensional spacetime. Using a recently developed well-posed formulation for Lovelock gravity, we implement the numerical study on the nonlinear evolution of five-dimensional black strings in the presence of non-negligible Gauss-Bonnet coupling. Our numerical simulations reveal distinct differences in the strong-field dynamics of black strings in Lovelock gravity compared to Einstein gravity, providing insight into how UV theory such as string theory could potentially offer a resolution to the singularity.

Statistical Fluctuations in the Causal Set-Continuum Correspondence

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Thursday Session 4 - D3: Causal sets, causal dynamical triangulations, non-commutative geometry, asymptotic safety, and other approaches to quantum gravity

Causal set theory is an approach to quantum gravity that proposes that spacetime is fundamentally discrete and the causal relations among the discrete elements play a prominent role in the physics. Progress has been made in recognizing and understanding how some continuumlike features can emerge from causal sets at macroscopic scales, i.e., when the number of elements is large. An important result in this context is that a causal set is well approximated by a continuum spacetime if there is a number-volume correspondence between the causal set and spacetime. This occurs when the number of elements within an arbitrary spacetime region is proportional to its volume. Such a correspondence is known to be best achieved when the number of causal set elements is randomly distributed according to the Poisson distribution. I will discuss the Poisson distribution and the statistical fluctuations it induces in the causal set-continuum correspondence, highlighting why it is important and interesting. I will also discuss new tools and techniques that facilitate such analyses.

Systematic biases from the exclusion of higher harmonics in parameter estimation on LISA binaries

Yi S[1], Iacovelli F[1], Marsat S[2], Wadekar D[1], Berti E[1]
[1]Johns Hopkins University, [2]Laboratoire des 2 Infinis - Toulouse

Friday Session 4 - C5: LISA and other space-based detectors

The remarkable sensitivity achieved by the planned Laser Interferometer Space Antenna (LISA) will allow us to observe gravitational-wave signals from the mergers of massive black hole binaries (MBHBs) with signal-to-noise ratio (SNR) in the hundreds, or even thousands. At such high SNR, our ability to precisely infer the parameters of an MBHB from the detected signal will be limited by the accuracy of the waveform templates we use. We explore the systematic biases that arise in parameter estimation if we use waveform templates that do not model radiation in higher-order multipoles. This is an important consideration for the large fraction of high-mass events expected to be observed with LISA. We examine how the biases change for MBHB events with different total masses, mass ratios, and inclination angles. We find that systematic biases due to insufficient mode content are severe for events with total redshifted mass $\gtrsim 10^6\,M_\odot$. We then compare several methods of predicting such systematic biases without performing a full Bayesian parameter estimation. In particular, we show that through direct likelihood optimization it is possible to predict systematic biases with remarkable computational efficiency and accuracy. Finally, we construct approximate waveforms including angular multipoles with $\ell \geq 5$ to better understand how many additional modes (beyond the ones available in current approximants) might be required to perform unbiased parameter estimation on the MBHB signals detected by LISA. We then investigate whether these techniques can be used to quantify similar sources of systematic bias in the context of ground-based detection.

Neutron star oscillations in the post-Newtonian approximation

Yin S[1], Andersson N[1], Gittins F
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Thursday Session 4 - B3: Approximations, perturbation theory, and their applications

During a binary neutron star (NS) inspiral, the stars' internal structure becomes important as the orbital separation approaches the size of the bodies. We are expecting to extract information about the stars' inner structure through the impact of static and dynamical tides on the corresponding GW signals. One possible way to describe dynamical tides in NS binaries is via a mode-sum. In the Newtonian case, the solution to this problem relies on the orthogonality and completeness of the star's oscillation modes. In general relativity the modes are known not to be complete due to the GW damping. However, the set of stellar oscillation modes will remain complete in the post-Newtonian (pN) description (at least up to 2pN order). With the aim of giving a more accurate description of dynamical neutron-star tides using the mode-sum approach, we extend the Newtonian stellar oscillation problem into the post-Newtonian regime.

How a remnant object and AGN disk environment influence the electromagnetic couterparts of gravitational wave events

Yu Y[1]
[1]Central China Normal University

Friday Session 3 - C7: Multi-messenger astronomy of gravitational wave sources

The merger of double neutron stars can result in the formation of a Keplerian - rotating massive magnetar. Such a magnetar could have a long lifespan and drive a powerful relativistic wind. The interaction between the magnetar wind and the ejecta from the previous merger significantly affects the emission characteristics of the so-called kilonova. First, a shock can rapidly traverse the ejecta and trigger a breakout emission prior to the kilonova. Second, the energy injection from the magnetar wind can substantially enhance the kilonova emission, while the opacity of the ejecta changes. Finally, as the ejecta expands and becomes transparent, the emission from the magnetar wind can leak and give rise to a non - thermal component in the tail of the kilonova. In principle, even if the remnant object is a black hole, the above - mentioned processes can still occur if there is a persistent fallback accretion. Given that a large number of merger events can take place in the accretion disk surrounding active galactic nuclei (AGN), we also studied the impact of the dense disk material on the dynamical evolution of the merger ejecta and the relativistic jet that may generate a gamma - ray burst (GRB) emission. It has been found that only when the jet has an extremely high luminosity and the central engine can operate for a sufficiently long time can the jet eventually break through the AGN disk to produce a detectable GRB emission.

Can causality-violation arguments constrain modified gravity?

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Tuesday Session 3 - A3: Alternative and modified theories of gravity

Causality arguments from flat-spacetime amplitudes, based on the eikonal limit of gravitational scattering, have been recently used to attempt to place constraints on modified gravity theories. In this talk, we will discuss how these arguments are only valid in the weak-gravity regime (even for transplanckian scattering). We will also show that such constraints are much less stringent than astrophysical ones, obtained, for example, from gravitational waves emitted in black hole coalescence. Special attention will be given to the weakness of causality constraints on dynamical Chern-Simons gravity, but our results apply to general classes of modified gravity theories.

Searching for gravitational waves in real LIGO noise using neural networks

Zelenka O[1,2,3], Brügmann B[2,3], Ohme F[4,5]
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Monday Session 4 - C2: Gravitational wave astronomy: searches, data analysis, parameter estimation and multi-messenger astronomy

Conventional searches for gravitational wave signals in detector data are computationally demanding and struggle when certain transient noise sources are present. Recently, machine-learning algorithms have been proposed to address current and future challenges. We present a neural-network based algorithm to search for binary black hole waveforms. We also apply our algorithm to real O3b data and recover the relevant events of the GWTC-3 catalog.

Inside Black Holes, Singularity or Complementarity?

Zeng D

Thursday Session 4 - A1: Classical GR: Theoretical developments

Through two exact solutions to the Einstein equation with dynamical sources, we show that general relativity allows two complementary descriptions for the microscopic state of BHs formed through gravitational collapse: (1) continuously contracting collapsars with asymptotically implementable but never successfully implemented horizon in the Schwarzschild time definition, and (2) over-cross oscillatory solid-balls ergodically but unpredictably crossing the singularity in the Lemaitre time definition. This complementarity emerges naturally from the general coordinate invariance of GR rather than apriori assumptions required of any unknown quantum gravitation theory. The area-law formula of Bekenstein-Hawking entropy arises from the degeneracy of the quantised wave functional of the collapsing matter configurations. Our work provides a resolution for the contradiction between the statistic feature BH thermodynamics and the deterministic scenario of singularity theorems. It suggests that BHs maintain extended matter distributions of their progenitors rather than developing successfully implmented singularities or event horizons. This is a remarkable prediction testable through gravitational wave spectroscopy and multi-messenger astronomy.

Aimed registration themes: Classic GR, theoretical developments

Chiral Gravitational Waves Background Search with a Network of Triangular Detectors

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Wednesday Session 3 - C6: Gravitational waves: Relativity and fundamental physics

The circularly polarized gravitational wave backgrounds are predicted in many well-motivated models of inflation and phase transitions involving spontaneous parity violation. In this work, we investigate the detection of such parity-violating signals with the network of two space-borne triangular detectors. We derive the general analytical formula for the overlap reduction functions of networks composed of two triangular detectors, by exploiting the system's symmetrical properties under the long-wave approximation. Based on these results, we further assess the detectability of a parity-violating background with alternative LISA-Taiji network configurations. We find that the sensitivity to the parity-violating component can be significantly enhanced at low frequencies by adjusting the orientation of Taiji's constellation plane. This sensitivity gain is approximately an order of magnitude around the millihertz band, making the peak sensitivity comparable to the total intensity. This provides a promising opportunity to constrain various parity-violating theories in the millihertz band with upcoming space-borne detectors.[2410.18916 &2411.08691 & 2412.18420]

A treatment to gravitational perturbations and Lorentz-violating effects with Lagrangian analysis

Zhang C[1]
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Tuesday Session 3 - A3: Alternative and modified theories of gravity

Since the first direct detection to the gravitational wave (GW), i.e., the event GW150914, it has emerged as a blockbuster during the past decade within the realm of theoretical physics. Specially, it provides us with an unprecedented opportunity in testing theories of gravity that beyond the scope of general relativity (GR), especially in the strong-field regime. One common way for extracting physical information and observables from a theory's Lagrangian is to execute the gravitational perturbations on it. Unfortunately, due to the sophisticated structure of, e.g., the Lorentz-violating (LV) theory, which predicts multiple horizons that beyond GR and plays an important role in constructing the quantum gravity, many attempts in this area are meeting a great challenge under the traditional treatment. To eliminate this challenge, here we will introduce a novel treatment for this sort of problems, which can be expediently referred as Lagrangian analysis. It can not only reveal the inherent stability of the theory but also lead us to the effective derivation process of the corresponding GWs. Hopefully, several research sub-branches, including the study of modified theories of gravity and their combinations with GW observations, will benefit from the development of this novel treatment to gravitational perturbations. More details will be given in the talk.

ExaGRyPE: Numerical Relativity Solvers Based upon the Hyperbolic PDEs Solver Engine ExaHyPE

Zhang H[1,2], Li B[1], Weinzierl T[2], Barrera-Hinojosa C[3]
[1]Institute for Computational Cosmology, Durham University, [2]Department of Computer Science, Durham University, [3]Instituto de Física y Astronomía, Universidad de Valparaíso

Thursday Session 4 - B2: Numerical Relativity

ExaGRyPE is a suite of solvers for numerical relativity based on ExaHyPE 2, our second-generation Exascale Hyperbolic PDE Engine. This code tackles the Einstein equations/relativistic hydrodynamics equations under a 3+1 foliation, with a focus on compact object spacetimes. The implementation utilizes a block-structured Cartesian grid with higher-order Finite Difference schemes and adaptive mesh refinement while enabling massive parallelism through message passing, domain decomposition, and task parallelism.
Our approach formalizes simulation creation as a sequence of lowering operations, where abstract logical tasks are broken down into progressively finer tasks until reaching a C++ executable level. The program logic is specified through a domain-specific Python interface, which maps to numerical tasks, then to technical tasks for parallelization, and finally to task graphs containing PDE evaluations, initial conditions, and boundary conditions. This architecture creates a rigorous separation of concerns, shielding users from technical details and simplifying the development of novel physical models. This approach enables researchers to efficiently develop and deploy novel physical models while leveraging the full computational potential of exascale systems.
In this talk, we are going to present the ExaGRyPE architecture and demonstrate its capabilities through comprehensive benchmarks. We will also highlight our unique solver-coupling feature, which allow us seamlessly integrates finite volume scheme for relativistic hydrodynamics within our high-order finite difference framework for spacetime evolution.

Gravitational ringing of a spherically symmetric black hole surrounded by dark matter spike

Zhao Y[1]
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Thursday Session 3 - B3: Approximations, perturbation theory, and their applications

Supermassive black holes at the center of each galaxy may be surrounded by dark matter. Such dark matter admits a spike structure and vanishes at a certain distance from the black hole. This dark matter will impact the spacetime near the black hole and the related ringing gravitational waves can show distinguished features of the black hole without dark matter. These features can be used in future gravitational wave detection about extremal mass ratio inspiral systems to probe the existence of dark matter around supermassive black holes.

In the present work, we focus on the quasi-normal modes of the axial gravitational perturbation who dominate the ringdown process of the perturbed black holes surrounded by dark matter spikes. The relativistic modification results in less impact on QNMs. Besides, we analyze how varying the equation of state of the dark matter influences the properties of the spacetime in the black hole's vicinity. In particular, we identify deviations in both the ringing frequency and damping time, reaching magnitudes of up to $10^(-3)$ for certain parameter values. These variations can potentially be detected by upcoming space-borne detectors.

Wave-optics phenomena in lensed gravitational waves

Zumalacarregui M[1]
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Wednesday Session 3 - B4: Cosmology: Theory and observations (including gravitational waves)

Just like light, gravitational waves (GWs) are gravitationally lensed by massive objects in the Universe. Moreover, their low frequency, phase coherence and lack of absorption make GWs complementary to lensed electromagnetic sources. Hence, in addition to well known effects (such as the formation of multiple images), lensed GWs allow for new wave-propagation phenomena like diffraction, the bending of the signal's wavefront. Lensing diffraction causes a frequency-dependent modulation of the signal, which encodes information about lens' mass and distribution. I will describe the rich phenomenology of lensing diffraction, its observational prospects and its potential to probe the dark matter distribution and identify strongly lensed signals.

Board No.	First Name	Last Name	Paper Title
1	Judy	Shir	The symplectic geometry of the photon shell
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5	Susmita	Jana	Exploiting gravitational wave memory in cosmological background for studying gravity and cosmology
6	David	Hobill	Discrete Self-Similar Bianchi-IX Dynamics and the Golden Ratio
7	Clémentine	Dassy	Light deflection in the gravimagnetic dipole spacetime
8	Gabriel	Sánchez-pérez	Transverse expansion of the metric at null hypersurfaces and application to Killing horizons
9	Jordan	Marajh	Controlled regularity at future null infinity from past asymptotic initial data: the wave equation
10	Raya	Mancheva	Two spherically symmetric perfect fluids near a weak null singularity
11	Junbang	Liu	Probing singularity existence and structure via the abstract boundary construction
12	Carsten	Gundlach	Recent developments in our understanding of critical collapse
13	Takeshi	Chiba	Hidden Symmetries of Power-law Inflation
14	Murli Manohar	Verma	Impact of f(R) gravity on gravitational waves propagation
15	David	Trestini	Post-Newtonian waveforms for elliptic and hyperbolic orbits in scalar-tensor theories
16	Edwin J.	Son	Limits on the mass of compact objects in Horava-Lifshitz gravity
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20	Sabina	López Espinoza	Introduction to Vector-tensor Gravity
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25	Barbora	Bezdekova	Light deflection near gravitational objects surrounded by a warm plasma
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Posters

Improved gravitational wave parameter estimation with SBI and secondary mode marginalisation

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Simulation-based inference (SBI) has emerged as a powerful tool for parameter estimation, particularly in complex scenarios where traditional Bayesian methods are computationally intractable. In this work, we build upon a previous application of SBI, based on truncated neural posterior estimation (TNPE), to estimate the parameters of a gravitational wave post-merger signal, using real data from the GW150914 event. We extend this approach by incorporating marginalisation over secondary modes, which are often neglected in standard analyses under the assumption that their contribution is weaker than noise and can therefore be absorbed into a Gaussian noise model. However, when secondary modes have a non-negligible impact, this assumption can introduce biases in the inferred parameters of the dominant mode. By explicitly accounting for these contributions within the SBI framework, we investigate whether this refinement improves both the accuracy and robustness of parameter estimation compared to standard Bayesian methods.

Generation of non-local quantum entanglement through non-inertial motion

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General relativity and quantum mechanics represent two of the most important pillars of modern physics. However, even after nearly 100 years since their conception, observations where the two theories intersect are scarce. Recently, several theoretical and experimental advances have been made in this area, where quantum phenomena are probed in non-inertial frames of reference. These schemes in non-inertial frames utilize Einstein's equivalence principle, making them analogous to conducting experiments in a uniform gravitational field. Here, we propose a Sagnac-based interferometer to generate non-local quantum entanglement between two independent single photons through mechanical rotation. We show the generated entangled state can maximally violate the CHSH inequality. Our results pave the way for exploring the connection between non-inertial motion and quantum non-locality, with implications for experimental endeavors into the quantum nature of curved spacetime.

Reconstructing source motion from gravitational wave strain

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The identification of burst gravitational wave signals can be challenging due to the lack of well-defined waveform models for various source types. In this study, we propose a novel approach to understanding the mass dynamics of the system that produced the burst signal by reconstructing the possible motions of masses that could generate the detected waveform within certain constraints. Our method involves training a normalising flow motions of masses, which allows us to explore a wide range of possible mass configurations and their corresponding waveforms. By employing this technique, we can reconstruct all feasible mass dynamics that may have contributed to the observed gravitational wave signal.
We present some results from our analysis, as well as discuss its limitations and potential extensions. These methods could provide valuable insights into the nature of burst gravitational wave sources and point towards a better understanding of their astrophysical origins.

Next Gen Gravitational Waves – The UK Collaboration for technology progress towards 3rd generation ground-based detectors

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Our Collaboration will enable the UK to co-develop the Conceptual Design of the next generation of gravitational-wave observatory infrastructure. While the current 'Advanced' generation of GW observatories continue to deliver science from GW signals coming from our local Universe, new, 'next-generation' infrastructure is needed to realise the full transformative potential of GW astronomy. The next-generation GW network, consisting of US 'Cosmic Explorer' (CE) and European 'Einstein Telescope' (ET) observatories, will provide guaranteed discoveries in astrophysics, cosmology, and fundamental physics. CE and ET are in a design phase, which will deliver conceptual designs a factor of 10 more sensitive than current detectors. By building on UK expertise in these areas, conceptual designs for relevant subsystems and components of the next-generation observatories will be developed. The UK contribution to next-generation GW infrastructures targets integration within the CE and ET projects. It has six technical Work Packages (WP1-WP6):
WP1 Suspensions: to develop a conceptual design for the suspensions systems for the heavier masses in next-generation observatories that are essential for sensitivity improvement; WP2: mirror coatings: to develop characterisation and optimisation strategies for development of coatings of greater than 600mm diameter; WP3 inertial control: development of aspects of suspension/active seismic sensing and control; WP4 interferometer sensing and controls: conceptual design of a robust interferometer sensing and control scheme for interferometers of extended baselines; WP5: Science traceability matrix: determination of the impact of instrument design on target science deliverables; WP6: Digital infrastructure: design/prototyping of digital infrastructures for real-time operation in the signal rich era.

Light deflection near gravitational objects surrounded by a warm plasma

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Analytical description of the light bending in a dispersive medium near compact sources, e.g., black holes or neutron stars, has been currently frequently performed in terms of the Hamiltonian formalism. This formalism is very convenient to derive equations of motion which are needed to obtain quantities characterizing the light propagation, such as the deflection angle. While it is possible to formulate equations for a general refractive index, which some studies do, most attention in the literature is given to the particular case of cold plasma. Cold plasma has many advantages in terms of practical calculations (light propagation in cold plasma is independent of the medium velocity), and it is a well understood non-magnetized type of plasma suitable for the applied formalism. However, cold plasma approximation was derived under an assumption that the thermal velocities of plasma species are very low, effectively reaching zero. This is a restrictive assumption which does not correspond to the media surrounding compact sources in real astrophysical situations. As a step forward towards a more realistic analytical description of the light propagation in the discussed system, we chose a warm plasma for a medium characterization. In a warm plasma, the thermal velocities of individual species are still low, but not negligible. We calculated the deflection angles for both a spherically symmetric static and axially symmetric stationary objects surrounded by a warm plasma. In the spherically symmetric case, we also analyzed photon sphere radii. We compared the derived results with previously studied vacuum and cold plasma cases.

Gravitomagnetic Vorticity Generation in Accretion Discs: Implications for Plasma Flow Stability in the Weak-Field Limit

Bhattacharjee C

We explore vorticity generation in accretion discs around slowly rotating black holes within the weak-field, low-velocity limit of general relativity. Our analysis highlights the role of the gravitomagnetic field, induced by black hole rotation, as a novel source of vorticity (both magnetic field and flow vortex) in plasmas with non-negligible vertical structure. We derive the vorticity generation rate, which vanishes at the disc's mid-plane but increases with vertical height, potentially influencing plasma flow stability. Additionally, we calculate the enstrophy density generation rate as a measure of turbulence and dissipation, observing its growth away from the mid-plane. While our weak-field approximation limits precise conclusions near the innermost stable circular orbit, our findings suggest that gravitomagnetic effects may constrain the vertical structure of accretion discs, particularly in tenuous discs around low-mass, rapidly rotating black holes. This work offers new insights into the interplay between relativistic frame-dragging and plasma dynamics.

Probing the Temporal Fine Structure of the Hubble Tension with Linear Cosmography

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Given recent re-confirmations of the Hubble Tension, such as in the ACT DR6 data release, the potential of this tension to have a real cosmological origin persists. From a model-independent standpoint, this impels one to precisely locate the source of the problem with the concordance cosmological model. The extraordinarily good fit to the CMB data shows that LambdaCDM was once truly an excellent match to the real universe; yet, at some point between the last scattering surface and the more local region with standard-candle-measured expansion, the universe has "gone off the track" of simple LambdaCDM (with fixed value of H0), if the tension is to be believed. Much as a doctor probes the patient and asks, "Where does it hurt?", linear cosmography can be used to map out the temporal evolution of the Hubble parameter to ask the question, "When (and how) did the Universe begin to go wrong?" Our studies of the DES Supernova data have shown hints of interesting temporal behaviors; and further study is ongoing to examine how statistically significant these hints can be found to be, and how sensitive they may be to different choices of supernova redshift binning.

Searching for Non-Gaussian Stochastic Gravitational Wave Background with a Network of Terrestrial Detectors

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We present an approach for moving beyond the standard Gaussian framework in searches for stochastic gravitational wave backgrounds using higher-order correlation functions in terrestrial detector networks. This method enables the incorporation of empirical models to characterize generic non-Gaussianities. We outline the theoretical framework, highlight key challenges, and discuss relevant simulation techniques as well as sensitivity analyses for implementing such searches.

Formation of binary black holes from stellar binaries and in massive star clusters: a cosmological approach

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The two main formation channels generally considered to explain the formation of tight binary black holes (BBHs) are: the isolated evolution of stellar binaries, and the dynamical assembly in dense star clusters.
Here we present a consistent implementation of these two formation channels in a cosmological volume simulation and focus on understanding the role played by galactic environment.
To this end, we apply a model of star cluster formation to a large catalogue of individual galaxies in the cosmological volume simulation FIREbox. Combined with the code for star cluster evolution CMC, we are able to produce realistic populations of star clusters and dynamically formed merging BBHs across cosmic time. We complement this analysis with simulations of binary stellar evolution using the code COSMIC and include BBHs from the isolated channel in this same catalogue of galaxies.
While merging BBHs from isolated stellar binaries mostly originate from low-metallicity environments, massive star clusters preferentially form in the most massive galaxies. Therefore, we expect the BBH mergers stemming from these two formation channels to trace different physical properties of their host galaxies. Furthermore, massive clusters can host hierarchical BBH mergers, where a massive second-generation BH, formed from an earlier merger and retained within the cluster, pairs with a first-generation stellar origin BH. These particular events are expected to have unique physical properties. Identifying the formation channel of some of the observed BBH mergers could be the first step towards identifying their host galaxies, thus providing valuable information about their astrophysical origin.

Challenges for searches with next-generation gravitational-wave detectors

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Next-generation ground-based gravitational-wave detectors will present an opportunity to observe more and more varied events than ever before. With all opportunities come challenges though, and this situation is no different. We present some of the difficulties that would be faced by matched-filter based search analyses on future detector data, and highlight avenues of investigation for solutions.

Searching for boson-star mergers in LIGO-Virgo-KAGRA data

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While black holes and neutron stars are the most likely sources of the gravitational waves observed to date, several theoretical proposals exist of horizonless "exotic" compact objects that can mimic such emission. One of the most appealing ones, due to their simplicity and well understood formation and stability mechanisms is that of boson stars. In this talk I will describe current efforts to search for a particular type of mergers of boson stars through the comparison of existing gravitational-wave events to numerical simulations of mergers of a particular type of boson-star known as Proca stars. Additionally, I will describe a technique to obtain evidence for the existence of these across boson-mass coincidences across many events, even if none of these can conclusively rule out the black-hole merger hypothesis.

Impact of Power Spectral Density Estimation on Black Hole Spectroscopy

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Accurate parameter estimation from gravitational wave observations requires careful treatment of noise and data selection effects, particularly in the time-domain analysis of black hole ringdown signals. In this study, we investigate how different analysis settings—such as data segment duration, the length of the noise chunk used for computing the autocorrelation function (ACF), and the roll-off time applied to the noise chunk—impact posterior distributions. If not chosen carefully, these settings can introduce biases or alter the inferred posteriors. We demonstrate that there exist optimal configuration choices that maximize the recovery of the correct posterior distribution, ensuring reliable analysis of ringdown signals.

Glass sensors as an inertial sensing solution for future gravitational wave detectors.

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[1]AEI Hannover, [2]Fraunhofer Institute for Applied Optics and Precision Engineering

Future gravitational wave observatories require significant advances in all aspects of their seismic isolation; inertial sensors being a pressing example. Inertial sensors using gram-scale, high Q factor, glass mechanical resonators combined with compact interferometric readout are promising alternatives to kilogram-scale conventional inertial sensors. We have developed a novel technique for manufacturing glass resonators based upon wafer bonding, which removes the previous size limitations on the design of such sensors, which otherwise limited their performance. The manufacturing technique works with fused silica for room-temperature applications and is adaptable to silicon for cryogenic ones. We have produced fused silica resonators using this method and demonstrated that Q factors of over 100,000 are possible. One resonator we produced was combined with a state-of-the-art interferometric readout to form an inertial sensor. The resulting sensor was tested against other commercial, bulky inertial sensors in AEI's 10m prototype gravitational wave detector. In addition to showing the best performance demonstrated by any gram-scale sensor to date, we achieve comparable sensitivity to the significantly bulkier sensors used in gravitational wave detectors today. The scalability of the novel manufacturing method will be used to make much larger fused silica resonators, which will significantly improve future sensor sensitivity. These resonators are already in production. The compact size, inherently precise self calibration, and vacuum compatibility of these sensors make them ideal candidates for the inertial sensing requirements in future gravitational wave detectors.

Representing the late inhomogeneous Universe: the Szekeres cosmological model.

Celerier M[1]
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The homogeneous and isotropic LambdaCDM model, together with its linear and higher order perturbations, constitute the roots of contemporary cosmology. They allow us to understand roughly the geometry and the evolution of our Universe. Now, the observed late Universe exhibits structures at many different scales whose magnitude increases with the sophistication of observation technologies. Moreover, with the advent of more precised large surveys, anomalies and tensions have developed in the framework of this standard model. The Szekeres model is an exact solution of Einstein's equations, inhomogeneous and without symmetry. It is able to represent the matter/cosmological constant dominated region of our Universe: its gravitational source is a pressureless fluid and the cosmological constant can be incorporated in its equations. Since it includes the homogeneous and isotropic Friedmann solution as a limiting case, it is able to reproduce naturally the homogeneity/inhomogeneity transition. The most robust predictions of the early Universe cosmology can therefore be maintained. The Szekeres solution will be described here, together with its main properties necessary for a cosmological purpose. How the different observational data will be of use to constrain the model will de described and commented. Will we thus be contemplating the advent of a new cosmological paradigm?

Detecting Environmental effects on the Stochastic Gravitational-Wave Background from Stellar-Mass Black Hole Binaries in LISA

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The stochastic gravitational-wave background (SGWB) from stellar-mass black hole binaries is a promising target for detection by the Laser Interferometer Space Antenna (LISA). Astrophysical environmental effects, such as dynamical friction and accretion, modify the gravitational-wave energy spectrum at low frequencies, introducing potentially detectable deviations from the vacuum signal. In this talk, I will explore how these environmental effects imprint onto the SGWB and assess their detectability within the LISA frequency band. We also develop a generalized parametric phenomenological template and perform Bayesian parameter estimation to distinguish the environmental effects from a vacuum signal, and also constrain the disk density and mass accretion rate.

Persistent gravitational radiation from glitching pulsars

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Neutron star glitches may be caused by the sudden unpinning and collective movement of vortices in the superfluid condensate inside the star, also known as vortex avalanches. The metastable vortex configuration between avalanches is determined by the far-from-equilibrium avalanche dynamics and is nonaxisymmetric in general, producing a small but nonzero current quadrupole moment which generates persistent, quasi-monochromatic gravitational waves as it rotates. In this work, we use an N-body simulation of vortex avalanches to calculate an empirical scaling of this current quadrupole, and extrapolate that scaling to estimate the characteristic wave strain for this mode of emission. We also develop analytic upper- and lower-bound characteristic wave strain, which corresponds to idealized regimes in vortex dynamics and bracket the empirical scaling.

Hidden Symmetries of Power-law Inflation

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A scalar field with an exponential potential has been proposed as a model of inflation (called power-law inflation). Although it admits an exact solution, the integrability of the system has not been shown. We uncover the hidden symmetries behind the system by utilising the Eisenhart lift of field theories. We find that a conformal Killing vector field in the field space exists only for a particular combination of exponential functions that includes a single exponential potential. This implies the existence of additional conserved quantity and explains the integrability of the system.

Sky marginalization in black hole spectroscopy and tests of general relativity

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The observation of gravitational waves (GW) unlocked the ability to conduct high-precision tests of general relativity on real astrophysical data. Specifically, tests of the no-hair theorem can be conducted via black hole (BH) spectroscopy, and require accurate accounting of the quasinormal modes (QNMs) present in the post-merger signal of GWs. There has been considerable debate in the literature regarding whether subdominant modes — QNMs other than the dominant (ℓ, m, n) = (2, 2, 0) mode — are detectable in GW signals observed from binary BH mergers. At least some of this contention is caused by fixing the arrival time of the signal in each GW detector, which has traditionally been done due to technical challenges. Here, we surmount these challenges and fully marginalize over sky location and coalescence time uncertainties in post-merger QNM analyses of GW signals. We apply this method to a reanalysis of the event GW150914, which has been debated to have a (2, 2, 1) overtone present in the post-merger signal. We find low evidence in support of the overtone model for this event due to large timing uncertainties inherent to the data. We also apply this method to a reanalysis of GW190521 to probe the detectability of subdominant fundamental (n = 0) QNMs.

Can relativistic effects explain galactic dynamics without the need for dark matter?

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In recent works it has been claimed that "gravitomagnetism" and/or non-linear general relativistic effects can play a leading role in galactic dynamics, partially or totally replacing dark matter. Using the 1+3 "quasi-Maxwell" formalism, and generalizing it for null geodesics, we show, on general grounds, such hypothesis to be impossible. We demonstrate that (i) the observed gravitational lensing effects rule out any galactic model based on gravitomagnetism, and (ii) the non-linear contributions to the gravitational field actually weaken gravitational attraction, thereby only aggravating the need for dark matter. The misunderstandings underlying the recently proposed 'relativistic galactic models' shall also be briefly dissected.

Theory-agnostic searches for non-gravitational modes in black hole ringdown

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In any extension of General Relativity (GR), extra fundamental degrees of freedom couple to gravity. Besides deforming GR forecasts in a theory-dependent way, this coupling generically introduces extra modes in the gravitational-wave signal. We propose a novel theory-agnostic test of gravity to search for these nongravitational modes in black hole merger ringdown signals. To leading order in the GR deviations, their frequencies and damping times match those of a test scalar, vector, or tensor field in a Kerr background, with only amplitudes and phases as free parameters. This test will be highly valuable for future detectors, which will achieve signal-to-noise ratios higher than 100 (and as high as 1000 for space-based detectors such as LISA). By applying this test to GW150914, GW190521, and GW200129, we find that the current evidence for an extra mode is comparable to that for the first gravitational overtone, but its inclusion modifies the inferred remnant spin.

Resonance-induced modulations of multimessenger emission in core collapse supernovae

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Core-collapse supernovae (CCSNe) are among the most powerful explosions in the universe, playing a crucial role in the chemical enrichment of galaxies. They also represent one of the primary formation channels for neutron stars and black holes. Understanding the mechanisms that power CCSNe requires a multimessenger approach, as these events emit gravitational waves (GWs), neutrinos, and electromagnetic radiation. The emissions are strongly influenced by various properties of the progenitor star, including its metallicity, mass, composition, and the presence of rotation or magnetic fields.
In the present study we focus on neutrinos, which provide estimates of the explosion energy, and GWs, which offer a unique probe into the newly formed compact object, the proto-neutron star (PNS), and its surrounding matter. In particular, we investigate the rotation contribution in a series of state-of-the-art CCSN simulations.
By analyzing neutrino luminosities and the GW signal, we identify a pre-collapse rotation regime where a resonance emerges between the core normal modes and its rotationally driven oscillations. This resonance amplifies the GW signal and induces a correlated modulation in the neutrino emission. Our analysis reveals that the excited oscillations can be traced back to the fundamental mode within the PNS.
Resonance-driven bursts produce high-amplitude enhancements lasting hundreds of milliseconds at kilohertz frequencies, making them key observables for current and next-generation interferometers. In conclusion, our study provides the first known description of long time resonance emerging in complex astrophysical scenarios and highlights the complex interplay among the multimessenger signals.

On-ground testing of the LISA Gravitational Reference System

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The Gravitational Reference System (GRS) that flew in the LISA Pathfinder mission exhibited outstanding acceleration noise performance, surpassing LISA's requirements across the whole frequency band. Building on this success, the GRS for LISA will be based on the Pathfinder's design. However, with approximately a decade since the final assembly of the Pathfinder, additional on-ground testing for the newly-built engineering models of the LISA's GRS is essential for risk mitigation. To address this, an updated and improved verification strategy for LISA's GRS is needed.
The on-ground verification strategy for the LISA's GRS encompasses measurements of the electrode housing parameters (capacitive sensing and actuation performance, upper limits on total force noise, stiffness measurements, thermal effects, stray potentials, …), the investigation of the surface properties at a sample level (chemical composition of the surface layers and bulk of the coating, local topology and work-function, outgassing rates, …) the functional and performance verification of the updated front-end electronics (provided by TASCH and ETHZ) and of the charge management system (provided by NASA and UFL).
Notably, the torsion pendulums at the University of Trento will be invaluable tools to test the newly built electrode housing for LISA, as they can measure small forces acting on test masses to a level comparable with the LISA requirements ensuring the system's performance and reliability in the mission's context.
Through this multifaceted testing approach, we aim to mitigate risks and ensure the GRS operates with the precision necessary for successfully reaching the ambitious scince goals of LISA.

LISA Phasemeter based on MicroTCA as ground-support equipment

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We present an electrical ground-support equipment phasemeter, or phasemeter simulator, based on the MicroTCA.4.1 standard. The development is done in parallel to, and in collaboration with, the flight hardware phasemeter. This EGSE phasemeter shall be available for assembly, integration, verification and testing (AIVT) phase of the mission and for the technology development of payload items. The MicroTCA.4.1 standard, developed for, and deployed in, large scale accelerators like the European XFEL, is uniquely suited for realizing a LISA-type phasemeter with more than 48 readout channels, providing further extensibility, high reliability and various interfaces.
We present the system design, the phasemeter software for controlling and data acquisition and provide performance measurements of the new custom developed ADC module.

Light deflection in the gravimagnetic dipole spacetime

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The gravimagnetic dipole is an asymptotically flat, stationary axisymmetric solution to the vacuum Einstein equations. It represents a system of two non-extreme black holes with equal masses and opposite NUT charges connected by a Misner string (the gravitational equivalent of the Dirac string in the context of magnetic monopoles) with tension. The tension in this string is attractive or repulsive depending on its length.
By carefully defining a value for the length of the Misner string that depends on the mass and the NUT charges, (ie. choosing the distance between the black holes), the string can be tensionless, which gives rise to a stable configuration of two black holes rotating in opposite direction at a fixed distance.
With the help of numerical simulations, we explore the geodesic equations for massless particles around such a configuration. In particular, we investigate the gravitational lensing around such a system, both for extended sources at infinity and for punctual sources at a finite distance, on the equatorial plane as well as on the axis of the black holes. This allows for a complete construction of the deviation of light rays. We also examine the impact of the NUT charge/mass ratio on the different paths of light.

Tidal Heating: Hunt for the black hole horizon

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With the observation of the multiple binary inspirals, we begin to question whether the components of the binary are black holes or some exotic compact objects (ECOs). The "black holeness" or the deviation from it can be tested in several ways. The distinguishing feature of a black hole from ECOs in the presence of the horizon. This surface acts as a one-way membrane that absorbs energy. Due to this different behavior from ECOs, in the last stages of an inspiral black hole exchange energy. These backreact on the orbit, transferring energy and angular momentum from their spin into the orbit. This effect is called tidal heating. I will discuss how tidal heating can be used to test "black hole ness"; and distinguish black holes from other compact objects. The presentation will primarily be based on Phys.Rev.D 99 (2019) 8, 084001, Phys.Rev.D 101 (2020) 4, 044004, Phys.Rev.D 104 (2021) 8, 084006, and Phys.Rev.D 110 (2024) 2, 024048.

Is JWST's Early Universe Better Portrayed by Using Einstein's 1915 Coordinates?

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The James Webb Space Telescope has discovered a large population of bright compact galaxies in the early universe. Their abundance suggests that the universe may not have expanded as rapidly as Big Bang cosmology implies, that it may have been relatively more compact over a longer period of time. It is plausible that the physical issue with the Robertson-Walker metric form in this regard is Friedmann's 1922 coordinate condition, which doesn't accommodate gravitational time dilation or limit speed. In contrast, Einstein's observationally well-supported 1915 coordinate condition enforces Lorentz covariance by equating the metric's determinant to -1, which rules out a Big Bang singularity. We transform the Robertson-Walker metric form to Einstein coordinates, and we work out the radial evolution of the simplest expanding-dust-sphere model universe in both Friedmann and Einstein coordinates. In Einstein coordinates the model universe's expansion always accelerates, but that inflation peaks shortly after the occurrence -- in Friedmann coordinates -- of the model universe's Big Bang singularity, and then wanes with a long tail.

BART: Beam-like Application of Radiation on Test-masses – A Beam Test to Investigate LISA TM Charging Effects

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The Laser Interferometer Space Antenna (LISA) will detect millihertz gravitational waves using free-falling test masses (TMs) as inertial references. However, TMs accumulate electric charge due to cosmic rays and solar particles, leading to Coulomb noise that limits sensitivity. While previous experiments, including LISA Pathfinder (LPF), have quantified this effect, simulations using FLUKA and GEANT4 consistently underestimate the observed net charging. This discrepancy is attributed to low-energy electrons (LEE), which are difficult to model and have not yet been confirmed experimentally. To address this, we propose BART (Beam-like Application of Radiation on Test-masses), an experiment designed to replicate the charging environment of LISA in a controlled setting using proton beams from the TIFPA ProtonTherapy facility. The apparatus includes a flight-representative capacitive sensor (LPF Qualification Model), housing a gold-coated TM inside a molybdenum electrode housing, placed within a vacuum chamber with realistic spacecraft shielding.
By irradiating the sensor with proton beams (70–230 MeV), we simulate cosmic-ray interactions and measure induced charging currents using a fempto-ampere precision leve electrometer. By varying the TM potential, we aim to observe the signature of LEE re-attraction, a mechanism that could explain the equilibrium potentials measured in LPF.
Simulations predict measurable currents (~pA), enabling high-precision validation of charging dynamics. I will present the data gathered from the first issue of the BART experiment and their importance regarding the first direct constraints on LEE contributions and the improvement of the reliability of simulation toolkits used for LISA's charge management strategy.

Residual neural likelihood estimation for gravitational-wave astronomy

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Bayesian inference is the standard approach for estimating the properties of observed gravitational-wave signals and relies on an approximate analytical likelihood. This approximation assumes that detector noise is Gaussian and stationary—conditions that are violated in 20% of detected short-duration signals from binary black hole mergers and in all longer signals from binary neutron star inspirals. These limitations can introduce systematic biases and affect the reliability of parameter estimation. To address this challenge, we introduce Residual Neural Likelihood Estimation (RNLE), a novel extension of the Neural Likelihood Estimation (NLE) method developed in simulation-based inference. RNLE models the distribution of residual data after subtracting a deterministic signal model, leveraging the assumption that signal and noise processes are additive. We validate and demonstrate that, for a fixed number of simulations, RNLE reduces the systematic uncertainty in the likelihood introduced by the Machine Learning algorithm. This novel algorithm will allow us to perform a more robust and reliable low-latency analysis of future signals by enabling simultaneous inference of both the astrophysical signal and the noise characteristics.

Reconstructing parametric gravitational-wave population fits from non-parametric results without refitting the data

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With the growing number of gravitational-wave detections, population studies are becoming increasingly relevant, providing access to more details about the astrophysics underlying gravitational-wave sources. A critical component of such studies is the assumed population model, which can range from astrophysically motivated functional forms to non-parametric treatments that are flexible but difficult to interpret. In practice, the current approach is to fit the data multiple times with different population models to identify robust features. Current analyses rely on hierarchical Bayesian methods, which are powerful but computationally expensive. Computational costs are further increased by the need to carefully correct the dataset for selection effects, a procedure that must be repeated each time a new population model is assumed. We propose an alternative strategy: assuming the data have already been fit with a flexible model, we present a practical recipe to reconstruct the population distribution of a different model. As our procedure postprocesses existing results, it avoids the need to access the underlying gravitational-wave data again and handle selection effects. Additionally, our reconstruction metric provides a goodness-of-fit measure to compare multiple models. We apply this method to the mass distribution of black-hole binaries detected by LIGO/Virgo/KAGRA. Our work paves the way for streamlined gravitational-wave population analyses by fitting the data once and for all with advanced non-parametric methods and careful handling of selection effects, while the astrophysical interpretation is then made accessible using our reconstruction procedure on targeted models. The key principle is that of conceptually separating data description from data interpretation.

Using interferometer Time-Domain Simulation (ifoTDS) to simulate the influence of ghost beams inside a compact interferometric sensor

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Current gravitational wave detectors are limited in the frequency range below 10 Hz by alignment and control noise, to which the precision of current displacement sensors contributes significantly. We are focusing on the development of new sensors that offer increased precision, especially in the lower frequencies. The advancement of these displacement sensors is also necessary for future third generation gravitational wave detectors, such as the Einstein Telescope.
In the Gravitational Wave Detection Group at the University of Hamburg, we are developing a new displacement sensor called COmpact Balanced Readout Interferometer (COBRI). This on-axis sensor consists of a quasi-monolithic component (QMC) and implements deep-frequency modulation of the laser light. Currently, our sensor's performance is most probably limited by scattered light inside the QMC and other non-linearities. We currently investigate the source of the scattered light to create an analytic model and reduce their impact through post-processing techniques. This is done by simulating the light behaviour inside the QMC using a Time-Domain and node-based simulation tool. This tool is called Interferometer Time-Domain Simulation (ifoTDS), originally designed in our group for tunable coherence in scattered light suppression simulation.
By introducing imperfections in the simulation such as scattering from optical surfaces and non-polarization-maintaining optics, we study the possibility of recreating the influence of the ghost beams inside the QMC. We plan to make this simulation tool available as a python package, which can also be used for simulating other optical configurations, such as homodyne quadrature Interferometers.

Continuous gravitational waveforms from triaxially deformed precessing neutron stars in tight binaries

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Spinning neutron stars (NSs) can emit continuous gravitational waves (GWs) that carry a wealth of information about the compact object. If such a signal is detected, it will provide us with new insight into the physical properties of matter under extreme conditions. According to binary population synthesis simulations, future space-based GW detectors, such as LISA and TianQin, can potentially detect some double NSs in tight binaries with orbital periods shorter than 10 minutes. The possibility of a successful directed search for continuous GWs from the spinning NS in such a binary system identified by LISA/TianQin will be significantly increased with the proposed next-generation ground-based GW observatories, such as Cosmic Explorer and Einstein Telescope. Searching for continuous GWs from such a tight binary system requires highly accurate waveform templates that account for the interaction of the NS with its companion. In this spirit, we derive analytic approximations that describe the GWs emitted by a triaxial nonaligned NS in a binary system in which spin-orbit coupling has been incorporated. The difference with the widely used waveform for the isolated NS is estimated and the parameter estimation accuracy of an example signal using Cosmic Explorer is calculated. The effect of orbital eccentricity on the GWs from NS is estimated for different double NS populations.

The Geometric Berry phase in Twistor theory

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The Geometric (Berry) phase can be written in terms of the holonomies of several natural geometric structures in complex projective space. Whilst geometric phases in the projective Hilbert spaces occurring in Quantum theory have been well studied, the corresponding phases in Twistor theory have received relatively little attention.
Twistor space for Minkowski space is a 4-dimensional complex vector space with a pseudo-Hermitian metric. The corresponding projective twistor space is a complex projective 3-space whose points represent spinning massless particles. Helicity is equal to half the twistor norm, the vanishing of which defines the 5-dimensional space of light rays in (compactified) Minkowski space. Twistor space has a symplectic structure given by its Kähler form, which is understood physically as the degree of rotation of a pair of abreast rays about a third. The symplectic potential provides a measure of non-abreastness of photons, its exterior derivative is the symplectic form. As in the process of pre-quantisation in the geometric quantisation approach, the symplectic potential and two-form may be thought of as a connection and curvature. The Berry curvature turns out to be proportional to the Kähler form and its associated geometric phase is the first Chern invariant of the circuit of the ray in projective twistor space. Furthermore, the connection and curvature are shown to be proportional to the U(1) part of the Riemannian connection and curvature of the Kähler metric on twistor space. The connection is shown to be related to a potential first introduced by Infeld and van der Waerden.

Quasilocal Newtonian limit of general relativistic galactic dynamics

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We develop a new self-consistent perturbative expansion for realistic isolated differentially rotating systems – disc galaxies. At leading order it is formally equivalent to Ehler's Newton-Cartan limit, which we reinterpret in terms of quasilocal energy and angular momentum. The self-consistent coupling of these quasilocal terms leads to first-order differences from the conventional Newtonian limit. A modified Poisson equation is obtained, along with modifications to the equations of motions of the effective fluid elements. The results may have major implications for all gravitational physics on galactic and cosmological scales. We show by fitting to astrophysical data that the phenomenology of collisionless dark matter for disc galaxies can be reproduced.
Reference: arXiv:2408.00358

Coherent search method for finding faint images of strongly lensed gravitational waves

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Strong gravitational lensing occurs when radiation, in the form of electromagnetic or gravitational waves, passes by a massive object, being deflected and magnified. This effect has been observed and used successfully many times in electromagnetic astronomy, but a first detection of lensed gravitational waves remains yet to be made.
One promising way of finding lensed gravitational waves would be to look for faint images that could have fallen under the statistical thresholds of the standard search pipelines. Previous searches for such “subthreshold” images have used the known events in the gravitational wave catalogs as templates for performing matched filtering on each detector separately and recording the single-detector candidates, then testing the consistency in arrival time between detectors. We have developed a new pipeline to coherently analyse data streams of a detected event at different times. We will discuss the improvement that can be gained with this method, which restricts the power to the two polarizations of the gravitational wave and allows for the creation of a null stream that can be used to discriminate signal from noise. Furthermore, we have implemented the B-statistic method, which marginalizes the amplitude parameters with a physical prior instead of maximizing them.

Leveraging cross-detector parameter consistency measures to enhance sensitivities of gravitational wave searches

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The Advanced LIGO and Advanced Virgo detectors routinely observe gravitational wave (GW) events. So far, all observed events are consistent with Compact Binary Coalescence (CBC) mergers. However, these detectors are sensitive to a more diverse array of astrophysical GW transient sources - such as core-collapse supernovae, cosmic strings, neutron star glitches, etc. Many of these signals have complex morphologies and are only weakly modelled due to our lack of complete understanding of the physics of their sources. The LIGO-Virgo-KAGRA (LVK) collaboration designs unmodeled and weakly-modeled searches for detecting generic burst signals with minimal assumptions on signal morphology. Often, coincident loud noise transients limit the search sensitivity by increasing false alarm rates and reducing the significance of detected events. For the first time, we utilize parameter estimation-based consistency measures to enhance the sensitivity of a search algorithm. We revise the detection statistic of a search algorithm using Jensen Shannon Divergence (JSD) so that noise triggers are heavily penalized, and signals remain almost untouched - thus leading to search sensitivity improvements. We demonstrate this idea with the cWB-GMM search (Coherent Waveburst (cWB) enhanced by Gaussian Mixture Modelling (GMM)). We test our method on an injection campaign comprising Gaussian pulses, Sine-Gaussians, and White Noise Bursts as well as a suite of core-collapse supernova simulations - which are commonly used waveforms for assessing burst search sensitivity. Our method shows a 10-20% improvement in the sensitivity to these burst signals. The proposed method is implementable in the post-processing stage of most GW searches.

Affine Connection and Quantum Theory in Curved Spacetime

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In a few recent manuscripts, we used the affine connection to introduce two massless scalar fields in the Einstein-Palatini action. These fields lead to non-metricity. In this article, we will discuss the significance of these fields in inflation and dark energy. We will construct a Lagrangian formalism to include these scalar fields in a theory of gravity coupled with ordinary matter and radiation. We will find that these fields need not to be included in the actions of interacting gauge theories coupled with conserved fermionic vector currents as a part of the connection. The same remains valid for ordinary scalar fields. We can couple the connection-scalars with ordinary matter by adding suitable interaction terms. In this context, we will find that Stokes' theorem leads us to include the right-handed neutrinos in the electroweak theory in curved spacetime even with the Levi-Civita connection. This is required to obtain consistent equations of motion and anomaly-free conserved vector current for the neutrinos. Axial vector currents for different Dirac fields may remain anomalous depending on the theory. The right-handed neutrinos can be useful to explain neutrino oscillation and dark matter.

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Extreme Mass-Ratio Inspirals and scalar fields on generic orbits: characterization of the gravitational wave spectrum with MEW

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The LISA satellite, recently adopted by ESA, is set to open a new gravitational wave window, targeting sources that are inaccessible to ground-based detectors like LIGO and Virgo.
Extreme mass-ratio inspirals (EMRIs), consisting of a massive black hole and a stellar-mass secondary, are among the most distinctive members of this new class of binaries. The inspiral phase of these systems falls within the mHz regime of the LISA band. Depending on their mass ratios, EMRIs will be continuously observed over long periods, ranging from months to years. This prolonged evolution is key to enabling exceptionally precise measurements of source parameters and performing stringent tests of gravity.
In this poster, I consider a beyond-GR theory in which the secondary compact object is endowed with a scalar field. I show how to compute the scalar energy fluxes emitted by such EMRIs when the secondary follows the most general orbits, both eccentric and inclined. This computation has been performed implementing a new C++ code, MEW (Modified EMRI Waveforms), which computes not only the scalar energy fluxes but also the gravitational ones. I present the first results obtained with this code.
The total energy flux is expressed as a sum over radial, polar, and azimuthal modes. I will show the spectra of these scalar energy fluxes, an essential first step toward performing an efficient mode summation, which is, in turn, crucial for studying the evolution of EMRIs.

3+1 GRHD simulations of NSBH mergers with light black holes

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The astrophysical evidence for the existence of compact objects with masses lying in unexpected regions of their respective mass spectrum has recently triggered a new set of numerical studies of compact binary coalescenses including these type of objects.

I will present new neutron star-black hole simulations with light black hole masses carried out end to end with public codes. A description of the constraint-solved neutron star-black hole initial data computed using FUKA will be illustrated, along with its evolution using thorns available for the Einstein Toolkit, including WhiskyTHC for the neutron star matter. I will discuss comparisons of physical observables, such as the extracted gravitational waveforms across the simulations using different equations of state.

Recent developments in our understanding of critical collapse

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This talk presents highlights of our 2025 update of the 2007 Living Review on critical phenomena in gravitational collapse. It focuses on three developments: 1) better numerical understanding of vacuum collapse; 2) recent rigorous mathematical developments on naked singularity formation and the existence and stability of self-similar blowup solutions for various PDEs as well as the Einstein equations;) 3) the extremal critical collapse conjecture; and how these interact.

GPU Accelerated Nested Sampling for next-generation gravitational wave analysis

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Nested Sampling is a Monte Carlo method that performs parameter estimation and model comparison robustly for a variety of high dimension and complicated distributions. It has seen widespread usage in the physical sciences, in particular in cosmology and gravitational wave data analysis, however in recent years increasingly it is viewed as part of a legacy code base, with GPU native paradigms such as neural simulation based inference coming to the fore. In this work we demonstrate that we can effectively reformulate Nested Sampling to a form that is highly amenable to modern GPU hardware, taking unique advantage of vectorization opportunities to accelerate numerical inference to state of the art levels, for example for real-time follow-up or large-scale search strategies. We provide a public implementation of this code in blackJAX, and in this talk will explore its application to a number of inference problems such as Gravitational Wave parameter estimation and CMB cosmology.

Composite Test Masses for Next Generation Ground based detectors

Hennig M

The success of the next generation of ground based GW detectors will require large diameter test mass optics that can be operated at cryogenic temperatures. Silicon test masses of >45cm diameter, ~200kg are leading contenders for the mirror substrates, however currently there is no one who can provide such substrates. Researchers at the IGR, at the DZA (Deutsches Zentrum für Astrophysik) and the IKZ (Leibniz Institut für Kristallzüchtung) are working together to come up with a design for a composite test mass, which will bond together high quality float zone silicon to attain a composite test mass for installation into 3G detectors.

Deci-Hz gravitational waves from the self-interacting axion cloud around the rotating stellar mass black hole

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Gravitational waves from condensates of ultra-light particles, such as axion, around rotating black holes are a promising probe to search for unknown physics. For this purpose, we need to characterize the signal to detect the gravitational waves, which requires tracking the evolution of the condensates, including various effects. The axion self-interaction causes the non-linear coupling between the superradiant modes, resulting in complicated branching of evolution. Most studies so far have considered evolution under the non-relativistic approximation or the two-mode approximation. In this paper, we numerically investigate the evolution of the axion condensate without these approximations, taking higher multipole modes into account. We also investigate the possible signature in gravitational waves from the condensate. We show that the higher multipole modes are excited, leading to the gravitational wave signal by the transition of the axion between different levels. The most prominent signal of gravitational waves arises from the transition between modes with their angular quantum numbers different by two. The gravitational wave signal is emitted in the deci-Hz band for stellar mass black holes, which might be observable with the future gravitational wave detectors.

Multimaterial optical coating designs for future ground-based interferometric gravitational wave detector upgrades

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Coating thermal noise remains a significant source of noise in current ground-based interferometric gravitational wave detectors. Various materials are currently being researched and considered for future upgrades to both Advanced LIGO and VIRGO. This poster showcases various designs using multi-material methods that are being researched by the University of Glasgow and collaborators, with designs based on data from the Extreme Performance in Optical Coatings (EPOC) facility. These designs aim to meet the coating thermal noise specification of future detector upgrades and maintain the required optical properties.
This poster will present the most recent data obtained for these coatings including mechanical loss and optical absorption, showing that these are improvements on designs used in current-generation detectors. The poster will also discuss the coating process and future research plans that aim to reduce noise in current ground-based detectors.

Experimental investigation and comparison of three backlink designs for space-based gravitational-wave detection

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Future space-based gravitational-wave detectors consist of three spacecrafts arranged in a triangular formation and interconnected via laser links. Each spacecraft houses two optical benches which carry the information from the corresponding distant satellite. These are joined via the “backlink”, an optical interface through which the two counter-propagating beams travel towards the respective adjacent optical bench. Due to asymmetries in the optical pathlengths, unwanted noise can couple into the nominal beams, leading to an increased differential pathlength noise that will reduce the overall sensitivity of the detector. This additional noise is referred as the non-reciprocity and it must remain below a certain value to meet the mission’s requirement. In the framework of the Laser Interferometer Space Antenna (LISA) mission, the non-reciprocity in the backlink must be below 1pm/sqrt(Hz). In this context, the Albert Einstein Institute (Hannover, Germany) has developed a test facility, the Three Backlink Experiment, that aims to demonstrate the feasibility of three potential backlink concepts in one single setup. Two are fiber-based, the Direct Fiber Backlink and the Frequency Separated Fiber Backlink, while the third travels in free space using active steering mirrors, the Free Beam Backlink. Comparing three links allows to disentangle the individual noise levels. Here, we report on the current performance, which is very close to the LISA requirement.

Discrete Self-Similar Bianchi-IX Dynamics and the Golden Ratio

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Dynamical solutions to the Einstein equations for Bianchi IX cosmologies are examined through the use of Ellis-MacCallum-Wainwright (expansion normalized) variables. Using an iterative map, derived from the Einstein equations, that describes Bianchi-II transitions from one Kasner solution to the next, one can construct an infinite number of periodic solutions. The simplest periodic solutions of the map consist of 3-cycles. It is shown that for 3-cycles the time series of the logarithms of the expansion normalized spatial curvature components vs normalized time parameter (which is runs backwards towards the initial singularity), generates a set of self-similar golden rectangles. In addition the golden ratio and its inverse appear in other aspects of the same time series representation, such as the scaling of the oscillations. The existence of period-3 oscillations implies that the dynamics exhibit deterministic chaotic behaviour.

Costs of Bayesian Parameter Estimation in Third-Generation Gravitational Wave Detectors

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Bayesian inference with stochastic sampling has been widely used to obtain the properties of gravitational wave (GW) sources. Although computationally intensive, its cost remains manageable for current second-generation GW detectors because of the relatively low event rate and signal-to-noise ratio (SNR). The third-generation (3G) GW detectors are expected to detect hundreds of thousands of compact binary coalescence events every year with substantially higher SNR and longer signal duration, presenting significant computational challenges. In this study, we systematically evaluate the computational costs of source parameter estimation (PE) in the 3G era by modeling the PE time cost as a function of SNR and signal duration. We examine the standard PE method alongside acceleration methods including relative binning, multibanding, and reduced order quadrature. We predict that PE for a one-month-observation catalog with 3G detectors could require billions to quadrillions of CPU core hours with the standard PE method, whereas acceleration techniques can reduce this demand to millions of core hours. These findings highlight the necessity for more efficient PE methods to enable cost-effective and environmentally sustainable data analysis for 3G detectors. In addition, we assess the accuracy of accelerated PE methods, emphasizing the need for careful treatment in high-SNR scenarios.

Fiber-Optic Listening: Distributed Acoustic Sensing for Gravitational Wave Site Monitoring

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Ground-based gravitational wave detectors face fundamental sensitivity limits due to seismic and Newtonian noise. Distributed Acoustic Sensing (DAS), which transforms fiber-optic cables into dense seismic sensor arrays, offers new opportunities to address these challenges. With thousands of sensing points per kilometer, DAS provides unmatched spatial resolution for detecting, localizing, and mitigating environmental noise.
Since May 2021, we have developed a hybrid seismic network on a scientific campus in Hamburg, Germany, home to DESY, the European XFEL, and other major research infrastructures including experiments for gravitational wave detectors. The network combines traditional seismometers and geophones with a 19 km DAS loop installed in existing fiber infrastructure. This deployment enables nearly real-time mapping of anthropogenic and natural vibrations and their coupling into precision measurement facilities.
We present initial results from this network, including DAS sensor self-noise characterization and examples of how spatially distributed sensing reveals previously undetected noise sources. We discuss the implications for gravitational wave observatories, particularly the potential for identifying unknown noise sources and coherent noise cancellation strategies using DAS arrays. Early studies indicate that DAS may contribute not only to seismic noise suppression but also to future Newtonian noise mitigation, a key step toward improving low-frequency sensitivity.
Our findings suggest that DAS-enabled networks can significantly enhance noise monitoring capabilities and support the next generation of gravitational wave detectors. We also share lessons learned from deploying fiber within operational infrastructure and outline future directions for integrating DAS into gravitational wave research.

An analytic joint prior of effective spin parameters and inference of the spin distribution of binary black holes

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We derive an analytical form of the joint prior of effective spin parameters assuming an isotropic and uniform-in-magnitude spin distribution. This is a vital factor in performing hierarchical Bayesian inference to study the population properties of merging compact binaries observed with gravitational waves. In previous analyses, this was evaluated numerically using kernel density estimation (KDE). However, we find that this numerical approach is inaccurate in certain parameter regions, where both |χ_eff| and χ_p are small. Our analytical approach provides accurate computations of the joint prior across the entire parameter space and enables more reliable population inference. Employing our analytic prior, we reanalyze binary black holes in the Gravitational-Wave Transient Catalog 3 (GWTC-3) by the LIGO-Virgo-KAGRA collaboration. While the results are largely unchanged, log-likelihood errors due to the use of inaccurate prior evaluations are O(1). Since these errors accumulate with the increasing number of events, our analytical prior will be crucial in future analyses.

Supersubstrates: toward a theory of spacetime curvature as an elastic response to intersecting higher-dimensional structures, and the implications thereof for quantum gravity.

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General relativity describes how mass-energy curves spacetime but leaves its mechanism unexplained. Extending the accepted characterization of spacetime via elasticity principles—given gravitational-wave behavior—to higher-dimensional geometry enables an account of spacetime curvature as a secondary aspect of higher-dimensional tensile behavior. Objects with mass-energy are 3+1D surfaces of structures with higher-dimensional geometries (“supersubstrates”) intersecting spacetime at those regions; volume reflects 3+1D intersection aperture; mass-energy reflects the intersecting component's hypervolume. Supersubstrates’ intrusions stretch spacetime along a higher-dimensional axis—requiring compensatory contraction along spacetime’s intrinsic dimensions. Adapting Hooke's law, the EFEs' stress-energy tensor encodes higher-dimensional stress from intersecting supersubstrates; the curvature tensor encodes lateral strain.
This preserves—and explains—all significant aspects of GR. Density determines curvature because reduced volume deepens higher-dimensional intrusion—thus greater stress/strain. Hypervolume conservation requires nonzero volume—no singularities. Progressive tightening of spacetime approaching intersections increases effective velocity (strong equivalence principle)—also entailing relativistic time dilation under Lorentz invariance.
Higher-dimensional substrates beyond spacetime could flout 3D-geometric constraints within spacetime and contain unobservable fluctuations producing variance in intersecting regions’ observable behavior—enabling a nonlocal deterministic account of QM consistent with Bell’s theorem and observed probability distributions (consider a Boltzmann-like mechanism producing Born's rule). If vacuum fluctuations are those same fluctuations and reside outside spacetime, they cause no stress—no cosmological constant problem. Gravity as spacetime’s structural response to intrusion requires no field-quantization or bosons (gravitons).
The result is an outline of a novel unification of gravity with QM/QFT without superposition-curvature paradoxes. Gravity arises not from objects themselves, but because their substrates displace spacetime—causing compensatory tightening within observable spatial dimensions.

Exploiting gravitational wave memory in cosmological background for studying gravity and cosmology

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Despite of successfully explaining the late-time accelerated expansion of the universe, various observations suggest that the widely accepted ΛCDM model significantly deviates from correct cosmological model. Finding the cosmological models with correct parameters is still an open problem in gravity and cosmology. Leveraging the improved sensitivity of next-generation gravitational wave(GW) detectors at higher redshift up to z~100, we propose that GW memory in cosmological background can provide constraints on cosmological model parameters. GW, originated from an astrophysical event, perturbs the background 2-D surface orthogonal to its propagation direction, or it generates secondary GWs, which subsequently creates a permanent distortion or 'memory' in the 2-D surface. As secondary GWs or the memory propagates over cosmological distances, it captures the signature of the cosmological background, accumulating an integrated effect of the background. We show, the integrated cosmological memory(ICM) gets amplified while traveling cosmological distances. Specifically we show, the enhancement of the ICM by a factor of 100 for higher redshift sources—well within the sensitivity range of next-generation detectors like Cosmic Explorer and the Einstein Telescope. Furthermore, we show that if the astrophysical event produces GW of different amplitude depending on the plus or cross polarization modes, supported the parity violating dynamical Chern-Simons(dCS) theory then the amplitude difference between two polarization modes gets amplified through the ICM. Finally, we show that the distinct enhancement in the ICM for two polarization modes lead us to an independent constraint on the dCS parameter (α), leveraging the detection possibilities of the next generation GW detectors.

Global Portraits of Inflation

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In the phase space perspective, scalar field slow roll inflation is described by a heteroclinic orbit from a saddle type fixed point to a final attractive point. In many models the saddle point resides in the scalar field asymptotics, and thus for a comprehensive view of the dynamics a global phase portrait is necessary. For this task, in the literature one mostly encounters dynamical variables that either render the initial or the final state singular, thus obscuring the full picture. In this work we construct a hybrid set of variables which allow the depiction of both the initial and final states distinctly in nonsingular manner. To illustrate the method, we apply these variables to portray various interesting types of scalar field inflationary models like metric Higgs inflation, metric Starobinsky inflation, pole inflation, and a nonminimal Palatini model.

Black hole ringdown modelling: Linking the horizon dynamics to gravitational wave observations

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The last phase of a black hole merger is accompanied by a train of damped gravitational radiation known as the ringdown. It can be described linearly at late times, as a sum of discrete modes: the quasi-normal modes (QNMs) of the final Kerr black hole. As a consequence of the black hole no-hair theorem, the QNM frequencies are fully determined by the mass and spin of this black hole. Measures of these frequencies then enable tests of this prediction of GR e.g. by comparison between multiple QNMs. It has been suggested that ringdown signals may be modelled by QNMs already from the merger onwards using a large enough number of modes (overtones), which could remove the need to analyse much quieter late-time signals. I will present and discuss the results of further tests of this claim from numerical relativity results in two regimes: the local dynamics of the final horizon, and the closely related gravitational radiation itself when modelled with many QNM overtones. I will in particular discuss the stability of the recovery of individual QNM tones and the resulting prospects for spectroscopic tests of GR; as well as comparisons to a few phenomenological models beyond the linear QNMs.

LISA - Mission Performance Assessment and Status Update

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The mission preparation activities for the Laser Interferometer Space Antenna (LISA), selected by the Science Programme Committee (SPC) in 2017 for the Cosmic Vision L3 opportunity, have been successfully completed. On 25 January 2024, the LISA mission was formally adopted, confirming that the mission concept and technology are sufficiently advanced, giving the go-ahead to build the spacecraft and instruments.
Led by the European Space Agency (ESA) in partnership with NASA, LISA will survey the sky for Gravitational Waves in the 0.1 mHz to 1 Hz frequency band, which will enable the study of a vast number of objects ranging from Galactic binaries and stellar mass black holes in the Milky Way, to distant massive black-hole mergers and the expansion of the Universe.
Since adoption, the LISA Performance and Operations (P&O) team has been established. Led by ESA, it gathers members from international partner instrument and data processing teams, with the primary objectives to support:

- Modelling and simulation of the LISA system
- Analysis and optimisation of LISA's performance
- Design, preparation, and execution of mission operations

An ESA-led review was conducted at the end of 2024, setting a performance baseline before the start of the implementation phase, which is now underway. Based on the outcome of this review, the presentation will provide an update on the LISA mission performance status.

Covariant Spectral Entanglement Entropy for Free Fields

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Motivated by the possibility of the Bekenstein-Hawking black hole entropy being entanglement entropy, I will present a spectral definition for the entanglement entropy of free quantum fields, defined over regions of spacetime. This formulation allows for frame independent regularisation, relevant for black hole entropy, as well as allowing for the calculation of entanglement entropy between regions not confined to a single spatial hypersurface.

Rotating version of the static R = 0 Lorentzian wormhole: geometry, matter and shadow

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We obtain a new, three-parameter, rotating version of a known static, spherically symmetric, zero Ricci scalar (R=0) Lorentzian wormhole. First, we show how the standard Newman-Janis algorithm or its generalisation do not yield an explicit metric for a rotating wormhole and, therefore, an alternative method pioneered by Azreg-A\"inou (AA) has to be employed. Rather than being a Teo-type wormhole, our new rotating solution constructed using the AA method, belongs to the Kerr like wormhole class. However, the rotating spacetime, has a non-zero Ricci scalar, though its geometry and especially, its wormhole character, can be ascertained through detailed analysis. Further, the regular nature of the metric is confirmed via the smooth and continuous behaviour of the six independent Zakhary- McIntosh (ZM) invariants. In the framework of general relativity (GR) and the Einstein equations, we show that the matter required to support such a geometry does violate the energy conditions, as expected. Interestingly, the extent of violation can be controlled (and lessened) by varying the metric parameters. Finally, we obtain the shadow profile of this rotating geometry and match our results with EHT observations. It is found that all theoretically permissible values of the metric parameters respect the constraint from the shadow of M87*. However, there is a limit on the parameters when the theoretical shadow profile is compared with SgrA* data.
Based on: A. Kar, S. Jana and S. Kar, Phys. Rev. D 111, 064010 (2025), arXiv:2411.09202 [gr-qc]

LISA’s Science Objectives with EMRIs: The Role of Relativistic Waveforms

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Extreme-mass-ratio inspirals (EMRIs) are among the most exciting targets for the future LISA, offering a unique window into fundamental physics and astrophysics. However, to fully unlock their scientific potential, we need the most accurate and up-to-date waveform models.
In this presentation, we present results based on a fully relativistic Teukolsky-based waveform model for circular equatorial orbits in Kerr spacetime, developed as part of this work and made publicly available. Using this model, we show the impact of using relativistic waveforms on the objectives of the LISA EMRI science, considering both vacuum and non-vacuum environments. We examine how far into cosmic history LISA can probe EMRIs and demonstrate that using inaccurate waveform models leads to significant under- or overestimation in the horizon redshift predicted for EMRI sources. This shift arises from the presence of beyond dominant modes (l, m) = (2,2) in the relativistic waveform model.
To probe the surroundings of massive black holes in the local universe, one of LISA's main science goals, we studied beyond-vacuum effects by including two environmental scenarios in the waveforms: power-law migration torques (modeling accretion disks) and superradiant scalar clouds. For the migration case, we find that accurate waveform modeling enhances the sensitivity to the environmental effect, improving parameter estimation, and allowing even weaker disk-induced signatures to become detectable by LISA—compared to non-relativistic models. For scalar clouds, we present—for the first time—fully relativistic waveforms that include these effects, enabling precise parameter estimation.
All waveform models and data products used in this study are publicly available.

Deep Learning Classification of Gravity Wave Transient Noises using LIGO's Auxiliary Channel Data

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We demonstrate that a deep learning classifier utilizing only the auxiliary channel data from gravitational wave (GW) detectors can accurately distinguish various types of non-Gaussian noise transients (glitches) with an accuracy exceeding 80%. To achieve this, we employ multi-scale neural networks (MSNN) implemented using PyTorch. Glitches pose a significant challenge to the detection and parameter estimation of GW signals as they degrade the sensitivity of gravitational wave detectors. While numerous efforts have been made to trace the origins of glitches and mitigate their impact, many glitches remain of unknown origin. We apply the MSNN classifier to publicly available GravitySpy glitch samples from the LIGO O1 run, using only auxiliary channel data without incorporating GW strain data. This approach is advantageous for identifying the sources of glitches, as auxiliary channel data record the physical and environmental conditions of the detector, as well as the status of its various components, at the time glitches occur in the GW strain channel. Furthermore, by utilizing explainable AI (XAI) techniques, specifically occlusion sensitivity analysis, this classifier can provide an independent assessment of data quality and potentially offer insights into the origins of glitches.

Impact of Temporally Overlapping Gravitational-Wave Signals on Parameter Estimation: A Simulation Study

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As gravitational-wave (GW) detectors such as LIGO, Virgo, and KAGRA continue to improve in sensitivity, the detection rate of GW events is steadily increasing. In the near future, we expect multiple events to be detected daily, increasing the likelihood that signals from different astrophysical sources may arrive at detectors nearly simultaneously or with small time offsets.
We investigate how such temporally overlapping GW signals affect source characterization, focusing on potential biases and uncertainties in parameter estimation. Using simulated injections of independent GW signals—primarily from binary black hole and neutron star–black hole mergers—we analyze cases with varying time separations between arrivals. We perform parameter estimation on the overlapped signals to quantify the degradation in inference performance.
Our analysis incorporates the current sensitivities of the LIGO-Virgo-KAGRA detector network to evaluate realistic scenarios. Future work will extend this study to include the projected sensitivity of next-generation detectors such as the Einstein Telescope (ET), to assess the impact of overlapping signals in the high-event-rate regime of future observatories.
This study provides early insight into the challenges posed by overlapping GW events and highlights the need for robust data analysis strategies for the next era of GW astronomy.

Boosted Trumpet Initial Data

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Improving the accuracy and efficiency of numerical relativity simulations is a serious challenge for gravitational wave astronomy. One potential improvement would be to construct initial data in a gauge better suited to numerical evolution. For moving-puncture simulations we know the analytic solution for the Schwarzschild spacetime in 1+log slicing, but the corresponding solution for boosted and/or spinning black holes has been a long-standing problem in the field. In this work we present first steps to solve the axisymmetric Einstein equations for advecting Bowen-York trumpet data, first in Maximal slicing and then in 1+log slicing.

Quantum Corrections to Einstein's Field Equations and Their Observational Signatures in Large-Scale Structure and Gravitational Waves

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The interplay between quantum fluctuations and relativistic gravitation is a key unresolved issue in modern physics. While Einstein's field equations provide a classical description of spacetime, quantum corrections arising from effective field theories introduce higher-order curvature terms that could leave measurable imprints on cosmic structures. This work explores the observational consequences of these modifications, focusing on deviations in the cosmic microwave background (CMB), large-scale structure, and gravitational wave propagation.
We formulate an extended gravitational action incorporating leading-order quantum corrections:
$S = \int d^4x \sqrt{(-g)} [R + \alpha R^2 + \beta C_{\mu\nu\rho\sigma} C^{\mu\nu\rho\sigma} + \mathcal{L}_m]$,
where R is the Ricci scalar, $C_{\mu\nu\rho\sigma}$ the Weyl tensor, and α, β encode the strength of quantum-induced corrections. Perturbative solutions in a Friedmann–Lemaître–Robertson–Walker background reveal modifications to metric fluctuations that impact structure formation, gravitational lensing, and black hole environments.
We propose empirical tests of these effects using next-generation mm-wave observatories, gravitational wave detectors (LISA, Einstein Telescope), and multi-messenger signals from neutron star mergers. Detecting such quantum signatures would provide crucial insights into quantum gravity, potentially constraining modifications to general relativity at cosmological scales.
This study bridges theoretical developments with upcoming observational capabilities, offering a pathway toward empirical validation of quantum gravitational effects.

General relativity predicts tensor-polarized gravitational waves (GWs) with plus (h+) and cross (h×) polarization modes.

Klimesova E

General relativity predicts tensor-polarized gravitational waves (GWs) with plus (h+) and cross (h×) polarization modes. The unmodeled GW burst analysis pipeline, BayesWave, offers two tensor-polarized signal models: the elliptical polarization model and the relaxed polarization model. Future expansion of the global GW detector network will enable more accurate studies of GW polarizations. In this talk, we present a multi-detector analysis comparing the performance of the elliptical and relaxed models in characterizing elliptical and nonelliptical GW polarizations. We first present a study on simulated precessing and nonprecessing binary black holes (BBHs), comparing the waveform reconstruction accuracy and the Bayesian evidences of the two polarization models. We then present results comparing the two polarization models using publicly available BBH events from the third LIGO-Virgo-KAGRA observing run. We will also discuss how the relaxed model can measure generic GW polarization content using Stokes parameters, and examine how detector network size affects the recovery of this polarization information.

Impact of Spin Priors on the Population Inference of Merging Binary Black Holes

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This study focuses on the population estimation of binary black holes (BBHs) using gravitational-wave data. In particular, we examine the distribution of spins, which is crucial for understanding the formation processes of BBHs. The prior probability distribution of the effective spin in the Bayesian parameter estimation of individual events, as used in previous studies, imposes constraints on the region of large absolute values of the effective spin. This is because the prior distribution assumes uniform magnitude and isotropic orientation for component spins. Therefore, in this study, we investigate the bias introduced in the population estimation of BBHs due to this prior probability distribution. Specifically, we implemented a prior probability distribution that ensures a uniform effective spin and reanalyzed BBHs observed up to the third observing run (O3) by the LIGO-Virgo-KAGRA (LVK) collaboration. Furthermore, using this reanalyzed data, we conducted population estimation under the same conditions as previous studies to assess the extent of differences that arise. Additionally, using mock data, we examined the bias introduced in analyses that consider a subpopulation with large spins.

A multiphysics perspective on the equation of state for neutron star matter

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The multimessenger event GW170817 demonstrated poignantly how binary neutron star (BNS) mergers deliver important information about the equation of state (EOS) of neutron star matter. However, to fully constrain the EOS across its entire scope, it is necessary to consider a variety of data, including information from nuclear theory, nuclear experiments, and further astrophysical observations. This talk provides an overview of the multiple data points regarding neutron star matter and how to combine them consistently to constrain the EOS in a model-agnostic fashion. This allows to compare the impact different data points have on specific parts of the EOS, to perform mutual consistency checks between different data points, and eventually delivers stringent limits on the neutron star maximum mass and the radius of a canonical neutron star. However, without additional assumptions about the degrees of freedom in matter at higher densities, the microphysical EOS remains relatively unconstrained.
Focusing particularly on Bayesian data analysis of multimessenger BNS events, we also review current state-of-the art modeling for the different messengers in such signals and demonstrate how surrogate modeling of the electromagnetic part makes full Bayesian inference feasible.

3D numerical study of gravitational-wave signatures from magnetorotational effects in extreme core-collapse supernovae

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Core-collapse supernovae are among the most energetic explosions in the universe. Their evolution is shaped by hydrodynamics, neutrino transport, and magnetic fields at work in the first seconds after collapse. We investigate these processes through 3D simulations of an extremely compact 39 Msun progenitor using the FLASH M1 magnetohydrodynamics code. Our study explores three models – a nonmagnetized nonrotating baseline model, a nonmagnetized rotating model, and a magnetized rotating model – to highlight the roles of rotation and magnetic fields in shaping the explosion mechanisms and associated gravitational-wave (GW) and neutrino signatures.
We evolve each model from core collapse through bounce into the early post-bounce phase. We employ a three-species, energy-dependent M1 moment scheme for neutrino transport, incorporating a state-of-the-art nuclear equation of state and advanced treatments of deleptonization and neutrino heating/cooling. All models undergo similar gravitational collapse and bounce. However, during post-bounce, rotation and magnetic fields significantly impact the shock dynamics, explosion morphology, protoneutron star evolution, and variations in neutrino emission.
We specifically analyze GW signals derived from quadrupole moment calculations and neutrino emission asymmetries, emphasizing how rotation and magnetization distinctly shape these signals. We highlight key features in the GW emission patterns, such as frequencies, amplitudes, and time evolution, that could aid observational identification of magnetorotational effects. Our results underscore the potential of GW astronomy to differentiate magnetorotationally influenced explosions from more spherical scenarios. Future work will extend our gravitational wave analysis by refining neutrino microphysics, incorporating full general-relativistic treatments, and exploring a broader range of progenitor conditions.

When to use semi-classical GR instead of QFT to probe cosmological correlation functions; a quantitative view

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A growing number of ever more ambitious numerical studies of inhomogeneous inflation such as lattice simulations, numerical relativity, and stochastic inflation, constitutes a great leap in theory predictions because of the possibility to compute correlation functions for any models of inflation and at all orders in perturbation theory or beyond. These numerical systems all evolve according to the classical equations of motion (EOM), sourced by initial or stochastic noise, the spectra of which are motivated by the fluctuations of the quantum vacuum. Unfortunately, the precise time from which the non-linear dynamics can be described by the EOM is usually unknown or ignored. This work shows that there can be a quantitative answer for each scenario and regime.
We calculate the Keldysh contributions to the leading order bispectrum from past infinity, showing for instance that the squeezed limit is dominated by the on-shell evolution. By truncating the time integrals in the analytic expressions for contributions to the bispectrum, we define a 'quantum interactivity' and quantitatively identify scales and times for which it is sufficient to only assume classical GR evolution, given a fixed precision. In contrast to typical perceptions inspired by free two-point functions, we show that common non-linear contributions to inflationary perturbations can be well-described by classical evolution even prior to horizon crossing.

Modelling High Mass Ratio Compact Binary Black Hole Inspirals in Eccentric Orbits.

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Detection of gravitational waves (GW) from unequal mass black hole binaries such as intermediate mass ratio inspirals (IMRIs) and extreme mass ratio inspirals (EMRIs) will allow us to map the gravity in strong field regime. Since these sources lies in the range of millihertz to few hertz frequency band, therefore they can be detected by the future space based detectors (LISA/DECIGO) and in some cases the multiband detection is possible with third generation ground based and space based detectors as well. We compute the spherical harmonic modes (upto $l=m=12$) for such high mass ratio compact binary black hole system in eccentric orbits by combining the post-Newtonian approximation and the black hole perturbation theory approaches.

Multi-detector characterization of gravitational-wave burst tensor polarizations with the BayesWave algorithm

Lee Y

General relativity predicts tensor-polarized gravitational waves (GWs) with plus (h+) and cross (h×) polarization modes. The unmodeled GW burst analysis pipeline, BayesWave, offers two tensor-polarized signal models: the elliptical polarization model and the relaxed polarization model. Future expansion of the global GW detector network will enable more accurate studies of GW polarizations. In this talk, we present a multi-detector analysis comparing the performance of the elliptical and relaxed models in characterizing elliptical and nonelliptical GW polarizations. We first present a study on simulated precessing and nonprecessing binary black holes (BBHs), comparing the waveform reconstruction accuracy and the Bayesian evidences of the two polarization models. We then present results comparing the two polarization models using publicly available BBH events from the third LIGO-Virgo-KAGRA observing run. We will also discuss how the relaxed model can measure generic GW polarization content using Stokes parameters, and examine how detector network size affects the recovery of this polarization information.

The capacity of Constant Torsion Emergent Gravity (CTEG) to resolve cosmological tensions

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We investigate constraints on the cosmological parameters of Conformal Torsion Extended Gravity (CTEG) using Planck 2018 Cosmic Microwave Background (CMB) data. CTEG is a critical case of Poincaré Gauge Theory (PGT)—a formulation of gravity motivated by the gauge field theories underlying fundamental forces in particle physics. This model is parity-invariant, ghost-free, tachyon-free, and power-counting renormalizable. Unlike GR, CTEG incorporates intrinsic torsion degrees of freedom while maintaining second-order field equations. At specific parameter values, it reduces to the ΛCDM model, providing a natural extension to standard cosmology.
CTEG introduces two additional parameters in addition to ΛCDM: the initial value of the torsion scalar field, and the bare dark energy density parameter. To constrain these parameters, we use PolyChord nested sampling algorithm, interfaced via Cobaya with a modified version of CAMB. Our results indicate that CTEG allows for a larger inferred Hubble constant, offering a potential resolution to the Hubble tension. Furthermore, Bayesian model comparison suggests that while ΛCDM is preferred with Planck 2018 data alone, CTEG is favoured when including SH0ES measurements, alleviating the tension between the two datasets.
This study highlights CTEG as a compelling alternative gravitational framework, demonstrating its potential to address cosmological tensions and motivating further investigations of gravity theories within a cosmological context.

Probing signatures of mirror asymmetry in the Universe using gravitational waves from binary black hole mergers.

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The Cosmological Principle states that the Universe should be homogeneous and isotropic on a large scale. By extension, one would expect that the Universe does not favour any particular handedness, so an ensemble of binary black-hole mergers should not emit more gravitational wave (GW) of one particular polarisation than the other. In this work, we introduce a gravitational analogue of the Stokes parameter as a measure of the imbalance of GW emissions in opposite helicities and further investigate the measurability of this quantity through GW observations. Moreover, we demonstrate that this quantity, as a pseudoscalar, strongly correlates with the recoil of the remnant black hole of the merger. Finally, using the latest catalogue of GW events, we show that mirror symmetry is still globally respected across the Universe.

Using gravitational wave dark sirens to choose between host galaxy models

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Binary black hole (BBH) mergers, an important source of gravitational-waves (GW), are assumed to be hosted in galaxies. The probability of a galaxy to host a BBH is related to its properties, for example stellar mass and star formation rate. These properties are estimated from observables such as the luminosity in certain observation bands. This relationship among BBH merger rate, galaxy properties, and observables is called the host galaxy model. However, it has yet to be accurately determined. Population synthesis has provided a variety of host galaxy models. Here we investigate whether it is possible to distinguish different host galaxy models using a data driven approach. We use the GW cosmology tool gwcosmo with a simulated LIGO-Virgo-KAGRA fifth observation run-like scenario. We also construct a mock spectroscopic galaxy catalogue from MICECATv2. Our analysis compares the Bayes factors among three simple luminosity weighting models, r-band, g-band, and uniform weighting. The Bayes factors among different host galaxy weighting models show a minor preference for the true model for a ~200-detection case, and a decisive preference for the true model over the uniform model for a ~1000-detection scenario, which is strongly driven by a small number of events.

Bipartite Relativistic Quantum Information from Effective Field Theory Approach with Implications to Contextual Meanings of Locality and Quantumness

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The effective field theory (EFT) has been adopted to consider the quantum decoherence of a near-horizon Unrhu-DeWitt (UDW) charged qubit in a macroscopic cat state. We generalize this EFT approach to study the relativistic quantum information (RQI) of two static UDW-charged qubits with or without a black hole. This EFT is obtained by integrating out a massless mediator field, yielding the direct Coulombic interactions among intrinsic multipole moments of UDW detectors and the induced one on the black hole. The RQI of the quantum state of the mediator field can be probed by the reduced final states of UDW detectors by tracing out the induced internal states of the black hole. From the reduced final state, we find the patterns of entanglement harvesting agree with the ones obtained by the conventional approach based on master theory. However, the more detailed study suggests that the contextual meanings of (non-)locality may or may not be the same in quantum field theory (QFT) and RQI. To explore the contextual meanings of quantumness and locality more, we also calculate quantum discord and locality bound of the Bell-type experiments, with the former characterizing the non-classical correlations and the latter the (non-)locality in the hidden-variable context of RQI. We find that QFT and RQI agree on quantumness based on different physical reasons but may not agree on locality.

Break the mass-redshift degeneracy in gravitational waveforms

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There is a mass-redshift degeneracy in the gravitational waveforms emitted by compact binaries. The source-frame mass parameter M and the redshift z usually appear in the combination M(1+z). Messenger et al. find that using the inspiral signal of binary neutron stars or the postmerger signal of binary neutron stars together with the inspiral signal can break this degeneracy. Here, we propose to use only the postmerger signal to extract the redshift. Considering the observations of the postmerger signal by the Neutron Star Extreme Matter Observatory, based on the Fisher analysis, we find that the redshift z can be measured with fractional uncertainties of ~30% for sources at redshifts z=0.01 - 0.09.

Probing singularity existence and structure via the abstract boundary construction

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Boundary construction method studies, how to describe the structure of a singularity following the Penrose and Hawking singularity theorem via some specific families of curves. A construction to describe singularities using the topological endpoint of geodesics with a bounded affine parameter continues to be studied. In this talk, I will introduce a more comprehensive and recent construction, present our result on the topological relation between singularities, and elucidate the connection between the singularity theorems and the curvature blowup feature in solutions of the Einstein field equation using the strong curvature condition.

Introduction to Vector-tensor Gravity

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There was a time when Newtonian Physics, along with Galilean transformations, seemed to explain our Universe with precision. To maintain the invariance of all laws of Physics given a change of reference frame, Lorentz transformations were introduced, leading to Special Relativity, a theory that would explain local phenomena with excellence. To explain slight disagreements between observations and theory, Einstein's General Relativity provided a great solution. Now, in an effort to unify gravity and Quantum Mechanics or to explain phenomena such as dark matter and dark energy, alternative theories of Gravitation have been proposed. One of these theories is vector-tensor gravity, where instead of only considering a metric tensor to find the field equations, a vector field is incorporated. An introduction to this theory and some of its results is presented.

A fast and accurate selection function for LVK compact binary searches.

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Despite nearly 100 detections of binary black hole (BBH) events catalogued up to now, fundamental questions remain unanswered regarding their formation mechanisms and the environments in which they originate. Rigorous population analysis with careful control of uncertainties and biases, including selection bias, is needed in order to address them. We present a physically motivated model of the search sensitivity for CBC events to estimate the probability of detection of GW signals from binary black hole mergers, as well as binary neutron stars (BNS), neutron star - black hole (NSBH) and intermediate-mass black hole (IMBH) mergers. In contrast to the standard method of re-weighting injections (importance sampling), our approach describes selection effects via an analytic function of masses, spins and distance, with adjustable parameters that are fit to LVK injection results. This estimate is aimed at enhancing the accuracy and efficiency of population reconstructions, and it's particularly useful for population models whose signal distribution over parameter space differs significantly from the injection distribution. Our model has already been used in some population studies such as reconstructing the BBH merger rate dependence on redshift, and it will bring increasing benefits with the larger catalogues expected for current (with over 200 candidates in O4) and future runs.

An extended body moving in a black hole spacetime: the center of the mass issue

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We discuss the Mathisson-Papapetrou-Dixon (MPD) equations in the pole-dipole-(spin induced)quadrupole approximation along with spin supplementary conditions (SSCs) defining the center of mass of an extended body in the MPD framework. By focusing on circular equatorial orbits around a Kerr black hole, we see what happens when we shift the center of mass by changing the SSC. Finally, we address the issue whether an a SSC is a gauge choice or not.

Models of regular black holes from higher-derivative effective delta sources

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We discuss a method to generate models of regular black holes based on the effective source formalism applied to higher-derivative and non-local gravity theories. We stress the ambiguities involved in this procedure, and compare the results obtained with some exact solutions, when available. In particular, we focus on the case of Lee-Wick black holes, analyzing their structure of horizons and evaporation process. [Based on: JCAP 11 (2023) 067 and Nucl. Phys. B 1007 (2024) 116674.]

Experimental demonstration of femtosecond-level timing stability for the Phasemeter Instrument in the LISA Mission

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The Phase Measurement Subsystem (PMS) is a core payload instrument of the Laser Interferometer Space Antenna (LISA) mission responsible for the phase extraction of the interferometric signals with microradian precision. This requires critical timing functions such as timestamping, clock noise transfer and clock distribution with up to femtosecond-level phase stability.
Thermal noise in the sub-system interface with the platform couples into the phase and timing noise performance, potentially compromising the instrument's performance. Therefore, achieving the necessary precision in thermal vacuum posed a significant technological challenge.
A flight-like PMS has been modelled, analysed, manufactured, and tested at the AEI in Hannover. The PMS timing performance was verified at representative conditions and across different set points within its operating temperature range. Transfer function measurements were also conducted to determine the coupling coefficients between temperature and phase fidelity within the LISA observation band. This talk presents the latest results and upcoming activities.

Revealing subdominant modes in black hole ringdowns with the quasi-normal mode rational filter

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Measuring quasi-normal modes (QNMs) in the ringdown phase of binary black hole coalescence provides crucial insights into merger dynamics and enables tests of the no-hair theorem. The recently introduced QNM rational filter offers a powerful method for identifying subdominant QNMs in gravitational wave signals by removing dominant modes. In this talk, I will present recent work quantifying the statistical confidence of subdominant mode detections in real gravitational wave observations. I will demonstrate the validity of this technique using synthetic signals from numerical relativity waveforms and discuss its application to real gravitational wave data.

Unaccounted Energy Aspects of the Gravifrequency and Electromagnetic Interactions. With the Addition

Lunin Y[1]
[1]independent researcher

The electric charge definition is formulated. The refined formula of the electric charge non-invariance is given. The electric charge momentum conservation law was obtained. The concept of "the charged particle spin" is clarified. The angular momentum conservation law for electric charge was obtained. The frequency moment definition (the magnetic moment analog) is formulated in gravidynamics. The formula for the kinetic energy of the translational motion of an electric charge was constructed. Steiner's theorem for electrodynamics was formulated. The rotational motion dynamics equation was constructed for electric charge. The formula for the kinetic energy of the rotational motion of an electric charge was constructed. A Planck formula analog for the magnetic field was obtained. Formula for the interval s between two events was constructed in the electric charge space. Another kind of uncertainty ratio was obtained. The value of the gravifrequency interaction constant was calculated:
alpha_g = \frac{Gm^2}{ħc}, alpha_g = 17.49\times10^{-46}; (it's the analog of a fraction 1/137).
A Reynolds number analog for electromagnetism was obtained:
Ř = ρ e v D/H = I D/(s H) = 4I/(π D H). The experiments results on finding the Reynolds number in electrodynamics are given.
Keywords: The angular momentum of electric charge, The rotational motion dynamics equation for electric charge, A Planck formula for the magnetic field, The gravifrequency interaction constant, Reynolds number in electrodynamics.

Theoretical analysis of physical proprieties of a mirror for interferometric gravitational wave detection

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We report a study on a thermally-actuated adaptive mirror for use in gravitational wave detectors inspired by a work by H. T. Cao et al. [1]. The optic is a fused-silica mirror captured within an aluminum ring through a shrink-fitting process. We performed a theoretical analysis of this mirror considering variations of its physical properties. We compare our results with those found in [1].
[1] CAO, H et al. Enhancing the dynamic range of deformable mirrors with compression bias. Optics Expr., 28 (2020) 38480-38490.

Measurement of 2D birefringence maps of substrate materials and coatings.

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The birefringence that can occur in the optics that will be used in the Einstein Telescope (ET) interferometer is an essential phenomenon to be considered to ensure the desired sensitivity for gravitational wave (GW) detection. The birefringence of the optics directly depends on the substrate and coating materials and is mainly induced by stress in these materials (residual internal stress, externally induced stress, intrinsic stress fluctuations). The scheme of the ET-Ferrara polarimeter for transmission measurements is based on a linearly polarised beam (either 532 nm, 1064 nm or 1550 nm wavelength) passing through two half-wave plates co-rotating at a frequency ν_o between which is placed the sample. Heterodyne detection is used to extract the ellipticity signal. Measurements are also feasible in reflection to study mirrors and coatings with a minor modification of the transmission scheme. A rotating magnetic field is used for calibration using the Cotton Mouton effect of air. In both the transmission and reflection configurations the sensitivity to optical path difference is $\Delta D = \int \Delta n \, dL \approx 5 \times 10e{-}13$ m, limited by the spurious ellipticity generated by the rotating half-wave plates. We will present transmission and reflection maps for various substrate and coating materials.

Symmetry reduction of gravitational Lagrangians

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Derivation of the Schwarzschild solution by substituting a spherically symmetric ansatz for the metric directly into the Einstein-Hilbert action instead of the Einstein field equations is known as the Weyl trick. Although it is a violation of the variational principle, surprisingly, this trick gives the correct result, which was later justified by the principle of symmetric criticality (PSC), first studied rigorously by Palais and later by Fels and Torre. PSC imposes two conditions on the infinitesimal symmetry group action (it should be stressed that these conditions are independent of the gravitational theory in question), and when satisfied, it allows one to symmetry-reduce any Lagrangian and guarantees that its field equations are fully equivalent to the reduced field equations.
We analyze all possible symmetry reductions of Lagrangians that yield fully equivalent field equations for any 4-dimensional metric theory of gravity. Specifically, we present a complete list of 44 infinitesimal group actions obeying PSC. We identify the corresponding invariant metrics and analyze their simplest form allowing for a successful symmetry reduction of Lagrangians. It turns out that PSC is satisfied not only by the infinitesimal symmetry group action of the Schwarzschild black hole, but also by, for example, the Taub-NUT solution, FLRW cosmologies, or NHEK geometry.

Calibrated uncertainty quantification for improved signal detection efficiency and robust noise classifications in gravitational wave astronomy

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There is significant excitement within gravitational wave astronomy about the potential of machine learning (ML) to dramatically speed up or improve analyses. However, many ML algorithms only provide black box point estimates, but reliable scientific results also require well-calibrated and explainable uncertainty estimates. Conformal prediction (CP) is a framework for quantifying uncertainties in any prediction algorithm, ensuring trustworthy results. My talk will introduce CP and how it can be applied to two ML-driven tasks. First, we show that by providing robust uncertainty quantifications, CP enhances confidence in glitch classification, enabling improved mitigation processes and data quality. Second, we demonstrate that applying CP to a combination of search pipelines can boost signal detection efficiency, increasing confidence in sub-threshold candidates identified by multiple pipelines. By integrating CP into gravitational wave analysis, we unlock the potential of ML by providing robust uncertainty estimations.

Two spherically symmetric perfect fluids near a weak null singularity

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In this work we contrast the behaviour of two spherically symmetric matter models in a class of spacetimes which feature a weak null singularity, such as generic spherically symmetric perturbations of subextremal Reissner-Nordstrom under the Einstein-Maxwell scalar field system. This black hole interior is bounded to the future by a Cauchy horizon which is a weak null singularity.
Firstly, we consider the Cauchy problem of dust falling into the Cauchy horizon where the initial dust velocity is normal to a smooth spacelike curve with bounded second fundamental form. We prove that, under some physically reasonable assumptions, the flow of the dust velocity does not experience any shell-crossing before or at the singularity, and that the dust energy density remains bounded as matter approaches the singularity.
Secondly, we consider the characteristic initial value problem for stiff perfect fluid falling into the Cauchy horizon. By relating the stiff fluid velocity and energy density to a scalar field satisfying the homogeneous linear wave equation, we prove that this energy density blows up as we approach the weak null singularity.

Controlled regularity at future null infinity from past asymptotic initial data: the wave equation

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We study the relationship between asymptotic characteristic initial data for the wave equation at past null infinity and the regularity of solutions at future null infinity on the Minkowski spacetime. By constructing estimates on a causal rectangle which contains the portions of the conformal boundary, we prove that the solution admits an asymptotic expansion near null and spatial infinity whose regularity is controlled quantitatively in terms of the regularity of the data at past null infinity. Our approach makes use of Friedrich's conformal representation of spatial infinity in which we prove delicate non-degenerate Grönwall estimates. We describe the relationship between the solution and the data in terms of the usual physical coordinates on Minkowski space. This is work in collaboration with Juan A. Valiente Kroon and Grigalius Taujanskas.

Ensuring ethical and appropriate sharing of credit within the gravitational-wave community

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Coordinating scientific observations involves intricate interactions among distinct groups with limited insight into each other's life, including observers, instrument and data scientists, software engineers, and theorists. These professional interactions form a complex web that not only influences careers but can also impact human longevity and happiness. Embracing a variety of perspectives, goals, and experiences is essential for fostering scientific progress in collaborative environments, making it crucial to ensure that meritorious minds, including women, are not only allowed to contribute but also that their contributions are visible, recognized, valued, and rewarded. Being recognized as a major contributor to significant advancements, publications, and discoveries or gaining the opportunity to present breakthrough results at conferences are types of recognition that only a designated few receive, especially when there are myriads of pressures, biases, and interests. Even the ability to participate in the field at all can be diminished through ever-existent power differentials. In this presentation, I will advocate for an ethical, merit-based, comprehensive, and open scientific community where all members feel welcome and valued solely on the basis of their scientific merit, vision, and performance, and do not face the negative consequences of managerial obstructions, manipulation, and power games.

Performance of an instrumented baffle placed at the entrance of Virgo’s end mirror vacuum tower during O5

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We present results on the simulated performance of an instrumented baffle installed at the entrance of the vacuum towers hosting the end mirrors of Virgo's main Fabry-Pérot cavities. The installation of instrumented baffles is part of the Advanced Virgo Plus upgrade in time for the O5 observing run. They were originally envisaged to be suspended, mounted on new payloads and surrounding new larger end mirrors.
We demonstrate that placing the instrumented baffles just beyond the cryotrap gate valve and in front of the end mirrors would be equally effective for monitoring scattered light inside the cavities. This new location, more than a meter away from the mirror, further reduces the risk of contamination and any potential interference with the mirrors, preserves the full capability to monitor scattered light, and decouples the instrumented baffle timeline from the plans for installing large mirrors in the experiment. We provide an estimate of the light distribution the baffles would encounter under both nominal and non-nominal conditions, as well as an assessment of the scattered light noise introduced by these baffles in this new location, confirming that they would not compromise Virgo's sensitivity.

Peering into the "Eccentric" side of Black Hole Binaries using ESIGMAHM

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Orbital eccentricity leaves a strong imprint in the gravitational waves (GWs) emitted by coalescing compact binaries. Its presence indicates at dynamically assembled binaries in dense stellar environments like globular clusters, nuclear star clusters, etc., thus making it an excellent tracer of their formation channels. As a result, the GW community has lately begun to focus on including eccentricity in GW data analysis. One such effort in this direction is our recently developed inspiral-merger-ringdown (IMR) waveform model with higher-order GW modes, ESIGMAHM, for black holes on moderately eccentric orbits with non-precessing spins. We present results from the Bayesian parameter estimation studies of all the binary black hole (BBH) GW events detected till LIGO-Virgo's 3rd observing run using ESIGMAHM. We find that most events are consistent with having negligible eccentricity, but a few exhibit some indications of being eccentric in nature.
While ESIGMAHM matches other eccentric IMR models in evaluation speed, these parameter estimation studies remained computationally expensive, requiring approximately a week to complete for a GW150914-like event on considerable computing resources. This problem will be exacerbated even more in future as our detectors become more sensitive at lower frequencies, necessitating even longer waveforms to be computed for the analyses. To address this, we also present a novel parameterization to build a scalable, long-duration, yet efficient surrogate model of ESIGMAHM capable of analyzing BBH events from frequencies as low as 10Hz, thus making ESIGMAHM a valuable eccentric IMR waveform model for the current and future GW data analysis needs.

The International Gravitational-Wave observatory Network

McIver J[1], Anderson S[2], Ando M[3], Arun K[4], Barsuglia M[5], Brady P[6], Carbognani F[7], Carpinelli M[7], Fafone V[8], Fairhurst S[9], Freise A[10], Gemme G[11], Kanda N[3], Kajita T[3], Lazzarini A[1], Lee H[12], Lee R[13], Lee S[14], Martinez M[15], McClelland D[16], Miyoki S[3], Masatake O[3], Reitze D[1], Rowan S[17], Sordini V[5], Tagoshi H[3], van den Broeck C[18], Yokoyama J[3]
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The International Gravitational-Wave observatory Network (IGWN) is a consortium of ground-based, interferometric gravitational-wave detectors that will explore the fundamental physics of gravity and observe the universe. The inaugural IGWN detectors are LIGO, Virgo, and KAGRA. In contrast to the LIGO-Virgo-KAGRA Collaboration, IGWN aims to undertake fully joint development, ommissioning and operation of member gravitational-wave detectors in addition to development and deployment of techniques for gravitational-wave observation and interpretation of gravitational-wave data. IGWN may be operating in parallel with the LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration as early as 2026, and could become the flagship unified organization for LIGO, Virgo, and KAGRA researchers as soon as the next observing run (Observing run 5).

Application of physics informed neural networks for the solution of the Tolman–Oppenheimer–Volkoff equation

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Using a physics-informed-neural-network (PINN), we calculate the mass, density and pressure functions of a neutron star by solving the Tolman–Oppenheimer–Volkoff (TOV) equation in radial coordinates. The outputs are these solutions to the TOV equation for a range of polytropic equations of state (EOS), specified by the trainable parameter space. The resulting model is a proof-of-concept method that is pretrained and can rapidly solve the TOV equation for radial solutions and total radius for a given EOS and therefore the total mass of a neutron star can be inferred from these functions. The PINN method allows for an accurate machine learning solution for a differential equation and is compared to current numerical methods.

Extreme mass ratio inspirals around topological stars

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Topological stars are regular, horizonless solitons that emerge from the dimensional compactification of five-dimensional Einstein-Maxwell theory. They are promising candidates to describe qualitative properties of microstate geometries for astrophysical black holes. As ultracompact objects arising from a well-defined theory, topological stars exhibit all the phenomenological features typically associated with black hole mimickers, including a (stable) photon sphere, long-lived quasinormal modes, and echoes in the ringdown. We study a point scalar charge in circular orbit around a topological star. This is the first step towards studying extreme mass-ratio inspirals around these objects. We show that when the particle probes the spacetime close to the object, the scalar-wave flux is significantly different with respect to the black hole case. Furthermore, when the topological star approaches the black hole limit, the inspiral can excite its long-lived modes, producing resonances in the emitted flux. While such resonances are too narrow to produce detectable dephasing, we estimate that one year of inspiral up to the innermost stable circular orbit produces O(100) radiant worth dephasing relative to the black hole case. Although a dedicated parameter estimation is required, such large deviation should be detectable with future space-based interferometers.

LISA Consortium Demographic Survey Data Brief

Das S, Steinle N, Reginbau T, Vagenas E, Farmer H, Waibel R, Middleton H[1], Redondo-Yuste J, Safi-Harb S, Key J, Luetzgendorf N
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A demographic survey of the LISA Consortium was implemented by the LISA Consortium Diversity, Equity, and Inclusion (DEI) Committee and analysed by the Center for Evaluation and Research for STEM Equity (CERSE). The anonymous survey was sent to members of the LISA Consortium in September 2023 to collect consortium and demographic information including education, position, and working group participation. The data collected on the composition of the Consortium provides a representative view of Consortium membership as input for the efforts of the DEI committee. The CERSE Associate Director served as the external evaluator to prepare the data brief of the survey responses presented in this poster. 547 total responses were recorded, of which those from postdoctoral researchers were the most common followed by those from faculty and from graduate students.

A Search for Stochastic Gravitational Waves Backgrounds in the O1-O3 LVK Data Motivated by Domain Walls Behaviour in the Early Universe

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Several theories beyond the Standard Model predict the occurrence of Domain Walls (DW), topological defects expected to arise from the breaking of a discrete symmetry in the early universe. The motion and the eventual annihilation of these objects are expected to generate a stochastic background of gravitational waves (SGWB), that could in principle be probed by ground-based gravitational waves detectors. In this work we build upon our previous search for a double-peaked domain wall motivated SGWB in the O1-O3 LVK data by introducing a novel multi-break power law function, in addition to a more intuitive parametrization of the double peak signal. We follow this mathematical implementation with a phenomenological approach, in order to place constraints on the physical parameters characterizing the DWs and to determine new parameter exclusion zones.

Detecting gravitational waves system using convolutional neural network.

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The first detection of the gravitational wave event GW150915 in 2015 opened the doors for the gravitational astronomy. Since then, over 90 such events have been detected. Some of these have been particularly significant, such as GW170817, the first binary neutron star merger. This detection enabled a measurement of electromagnetic counterpart marking the beginning of the multi messenger astrophysics. Detecting such events is extremely challenging. From noise isolation in interferometers, up to the data analysis techniques used to extract signal from the stream. In this context, machine learning techniques have been deeply explored and applied to boost the gravitational wave detection. In this work, we explore a possible solution in data analysis for triggering binary neutron stars events. Exploiting simulated data of both gaussian noise and signals, a Residual Network is trained and tested to recognize whether an event is present or not in the data. Also, to simulate non-Gaussian noise, transient glitch events have been artificially injected. Finally, a comparison between the performances obtained by the algorithm against the classical approach has been reported.

Korteweg-de Vries Integrals for Modified Black Hole Potentials: Instabilities and other Questions

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Quasi-normal modes (QNMs) and greybody factors are some of the most characteristic features of the dynamics of black holes (BHs) and represent the basis for a number of fundamental physics tests with gravitational wave observations. It is therefore important to understand the properties of these quantities, naturally introduced within BH perturbation theory, in particular the stability properties under modifications of the BH potential. Instabilities in the QNMs have been recently shown to appear in the BH pseudospectrum under certain circumstances. In this work, we give a novel point of view based on the existence of some recently discovered hidden symmetries in BH dynamics and the associated infinite series of conserved quantities, the Korteweg-de Vries (KdV) integrals. We provide different motivations to use the KdV integrals as indicators of some crucial BH spectral properties. In particular, by studying them in different scenarios described by modified BH barriers, we find strong evidence that the KdV conserved quantities represent a useful tool to look for instabilities in the BH spectrum of QNMs and in their greybody factors.

Gravitational waves from compact binary systems: observational prospects for Advanced Virgo

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The detection of gravitational waves has estabilished a new way to see the Universe. The LIGO-Virgo-KAGRA collaboration, following the current observing run O4, has planned a future one, O5, within this decade. Furthermore, in 2030s third-generation gravitational wave detectors, such as Einstein Telescope and Cosmic Explorer, will become opertive. During the transition phase from second to third generation another observing run is planned, the so-called postO5, in which current advanced interferometers will be further upgraded, in order to achieve the best sensitivity possibile: this is the case of Virgo_nEXT, the upgrade program for Advanced Virgo.
This work presents the observational prospects for the LIGO-Virgo-KAGRA detector network during postO5. We consider compact binary coalescences as sources of gravitational waves, while, for what concerns the detectors, we focus on different noise configurations for Advanced Virgo. The predictions presented will be functional to design the upgrades of current ground-based interferometers in order to maximize the scientific outcome.
We produced a realistic population of compact binary systems by appling accurate astrophysical population synthesis models for the evolution of binary stars across cosmic time and eventually their merger; therefore we simulated the gravitational wave signal expected for these sources. Consequently, the observing scenarios for future runs are derived, in terms of detection rates and localization regions of the detected sources.
In conclusion, this talk shows the observing scenario for the LIGO-Virgo-KAGRA detector network during postO5, highlighting how different noise configurations simulated for Advanced Virgo can impact on the detection and localization capabilities of the network.

Testing Black Hole Event Horizons with LISA

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Planned for launch in the mid-2030s, the Laser Interferometer Space Antenna (LISA) will detect gravitational waves (GWs) in the millihertz frequency band. LISA will therefore observe GWs emitted by massive black hole binary (MBHB) coalescences for the first time. Due to their large signal-to-noise ratios when compared with LIGO-band stellar-origin black hole binaries, LISA MBHBs will allow for tests of general relativity (GR) with unprecedented precision. In particular, such bright signals will allow for significant detection of the ringdown phase of the compact binary coalescence, when the post-merger remnant settles into a stationary configuration. The ringdown can be modeled as a superposition of damped sinusoids, whose frequencies and damping times are related to the characteristic oscillation frequencies of the remnant, known as quasinormal modes. By measuring these quasinormal modes, we can thus test whether the merger remnant is compatible with black holes as predicted by GR. In contrast, several extensions of GR instead predict the existence of horizonless compact objects, which propose to solve the paradoxes of black holes such as the presence of singularities. We present a theory-agnostic test for identifying GR deviations in the ringdown phase of MBHB signals, which allows us to probe the presence of a horizon in a MBHB post-merger remnant. Employing Bayesian analysis techniques, we demonstrate how this test can be applied to LISA MBHB signals and indicate that this method is promising for establishing strong bounds on the reflectivity and compactness of massive objects.

Gravity-induced birefringence in spherically symmetric spacetimes

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Geometric optics effectively describes the propagation of electromagnetic waves when the wavelength is much smaller than the characteristic length scale of the medium, making wave phenomena like diffraction negligible. As a result, light propagation in a vacuum is typically modeled by rays that follow null geodesics. However, general relativity predicts that polarization-dependent deviations from these geodesics occur in an inhomogeneous gravitational field. In this article, we evaluate the corrections for the deflection and emission of light by a massive gravitating body. Additionally, we derive the scaling behavior of the physical parameters characterizing the trajectories. The calculations are performed at leading order in frequency. We use these results to assess the significance of the birefringence effect in various astrophysical observations. We find that the effect cannot be measured with current instruments but may be detectable in the near future.

Gravitational wave probes of compact binaries and observational constraints on alternative models

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Gravitational wave signals from merging compact binary systems provide unique avenues for testing the general theory of relativity (GR) predictions in the strong-field, dynamic, and relativistic regimes. As the gravitational wave (GW) transient catalogue grows in number and source diversity, designing and implementing tests for these predictions in model-agnostic ways and for specific alternative theory predictions is mandatory. In this presentation, I will introduce the routinely employed model-agnostic tests of the nature of compact objects using the observed binary population and implications of such constraints to alternative models. Then, I will describe theory-specific tests of the nature of compact objects, focusing on spinning black holes in modified GR theories and discuss the possible constraints on such models from current and future GW observations. Mostly based on [https://doi.org/10.1103/PhysRevD.109.124047] and follow up studies.

Spin-induced moments test for inspiralling compact binaries on eccentric orbits

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Testing the binary black hole nature of compact binaries relies on the “no-hair” conjecture, which posits that a Kerr black hole's properties are fully characterized by its mass and spin. This conjecture underpins tests applied to circular compact binaries detected by gravitational wave (GW) detectors, where the quadrupole moment depends solely on mass and spin. In contrast, exotic compact objects may require additional parameters, such as the equation of state, encoded in spin-induced quadrupole moments. Extending previous tests to binaries on eccentric orbits, we use Fisher matrix analysis to quantify parameter uncertainties and assess eccentricity's impact. This method independently measures spin-induced quadrupole moments, helping to distinguish black holes from exotic compact objects in GW observations. With their enhanced low-frequency sensitivity, next-generation detectors like the Einstein Telescope and Cosmic Explorer will make these tests more powerful, allowing for tighter constraints on higher-order multipole moments.

Search for Neutrino Counterparts to Gravitational Wave Events in Super-Kamiokande during the LIGO/Virgo/KAGRA O4 Observing Run

Nascimento Machado L

Super-Kamiokande (SK) is a 50-kiloton water Cherenkov detector located in Japan, designed to detect neutrinos from various sources. In recent years, SK has contributed to multi-messenger astronomy by searching for neutrino signals in coincidence with gravitational wave events.
The fourth observing run (O4) of the LIGO/Virgo/KAGRA collaborations started on 24 May 2023 and is scheduled to continue until November 2025. During the initial phase, known as O4a, which concluded on 16 January 2024, the LIGO detectors identified 81 gravitational wave candidate events. While an official catalog for O4a has not yet been released, SK data have been analyzed for time-coincident neutrino signals across an energy range from a few MeV to few hundred GeV.
We present preliminary results from these searches, covering different types of gravitational wave candidates. We also describe the methods used for the coincidence search, including event selection and background estimation. Finally, we outline plans to develop an online follow-up system to improve SK's response to future gravitational wave alerts.

Reconstructing the Density Perturbations for a Minimally Modelled Gravitational Wave Source using Normalising Flows

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The detection of new and exotic gravitational wave sources is a key frontier of gravitational wave science. All detected gravitational wave signals to date come from compact binary coalescences, which rely on detailed physical templates. An outstanding problem is the reconstruction of physical parameters for minimally modelled sources, such as core-collapse supernovae. A promising new method is Normalising Flows, which allow to construct posterior distributions for unknown parameters without requiring a detailed physical model. We present a method using Normalising Flows to reconstruct the time-dependent coefficients of a mode decomposition of the source density for a burst source, specifically a toy model designed to resemble a core collapse supernova.

Exploring the feasibility of neural likelihood estimators to speed up gravitational wave inference

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Gravitational-wave (GW) astronomy has become routine with almost 200 GW detections in the ongoing observing run of the current network of ground-based detectors. With the next generation of GW detectors with higher sensitivities being planned, the volume and the complexity of the detected signals are expected to rise dramatically, increasing the computational cost and resources of running Bayesian analysis to unsustainable levels. Many alternatives to classic stochastic sampling algorithms have recently been proposed, particularly implementing machine learning components in the Bayesian frameworks. In this work we explore the capabilities and the limits of neural likelihood estimators (NLE) in the context of GW analysis, comparing computational costs and accuracy with standard samplers. We apply our method to simulations as well as real GW signals and show that we are capable of reproducing the posterior probability distribution functions of parameters with a reduction in computational costs by a factor of ~50. Although our proposed method has its limitations, we show NLEs to be a cheap and flexible framework for GW data analysis.

Characterisation of Crystalline Silicon Fibres for Cryogenic Suspension Systems in Next-Generation Gravitational Wave Detectors

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The next generation of gravitational wave detectors, such as the proposed Einstein Telescope and Cosmic Explorer, will require advanced low-noise mirror suspensions to reach their sensitivity goals. Fused silica, currently used in room-temperature detectors, is not a viable candidate for cryogenic suspension systems, as it generates excessive thermal noise at low temperatures. To overcome this limitation, a transition to crystalline materials is necessary. Crystalline silicon is a promising candidate for suspension elements due to its favourable properties at cryogenic temperatures such as high-quality factor and thermoelastic nulling at 20K and 123K — the proposed operating temperatures of future cryogenic interferometers. In this study, we present the characterisation of the first silicon fibres grown for suspension systems using the float-zone technique by IKZ Berlin. We examine material purity levels, crystal orientation, and diameter uniformity, alongside in-depth mechanical tensile strength testing via along-axis linear drive and four-point bending techniques. Additionally, we evaluate the thermal conductivity of the fibres to ensure efficient heat extraction from test masses. These initial findings demonstrate promising results for the production of high-quality silicon fibres. They also suggest that, with further optimisation, the fibres have the potential to achieve the necessary low thermal noise performance, reinforcing silicon's suitability as a candidate material for next-generation gravitational wave detectors.

Quantum Teleportation for Advanced Gravitational-Wave Detectors

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We propose several quantum noise reduction schemes for gravitational-wave detectors based on quantum teleportation. Gravitational-wave detectors, as highly precise displacement-measurement devices, are ultimately limited by quantum shot noise and radiation pressure noise. The trade-off between these two noise sources imposes the so-called standard quantum limit (SQL), as a natural consequence of Heisenberg’s uncertainty principle. Numerous schemes to enhance the quantum-noise-limited sensitivity beyond the SQL have been proposed, some of which require nontrivial modifications to the basic Michelson configuration of the detectors. Recently, it has been found that the principles of quantum teleportation can solve this issue; the detector's sensitivity can be enhanced beyond the SQL at minimal cost via parallel processing, which is a key concept in quantum information processing. We theoretically demonstrate ways to implement quantum teleportation in (1) frequency-dependent squeezing/readout and (2) quantum speed measurement, without requiring additional infrastructure or the manufacture of optics. We conclude that these ideas can be viable candidates for future detectors.

A lightweight low-latency algorithm for early detection and characterization of massive black hole binaries with LISA

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We present a lightweight, low-latency algorithm for detecting and characterizing massive black hole binary signals in the inspiral phase with the LISA space-based gravitational-wave observatory. Our method analyzes time-frequency representations to identify significant power excess over a modeled background in data segments ranging from 5 to 10 days. Processing approximately ten days of data takes about 1.5 seconds to generate candidate triggers with an associated significance score. We employ a clustering strategy to consolidate information from multiple triggers, providing robust preliminary estimates of the source's chirp mass and coalescence time. We validate our approach using the Sangria LDC dataset, successfully detecting all embedded sources and issuing early warnings up to 15 days before merger. Timely detection and characterization of these signals are essential for enabling rapid multimessenger follow-up observations and optimizing LISA's observational strategy in preparation for high-significance merger events.

Graviton-photon conversions in magnetic environments

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Graviton-photon conversions in a given external electric or magnetic field, known as the Gertsenshtein mechanism, are usually treated using the four-potential for photons. In terms of the electric and magnetic (EM) fields, however, proper identification of the fields in curved spacetime is important. By misidentifying the fields in Minkowski form, as is often practiced in the literature, we show that the final equation for photon conversion is correct in transverse-tracefree gauge {\it only} for planar gravitational waves in a uniform and constant external field. Even in the former method, to recover the EM fields from the four-potential in curved spacetime, one should properly take into account the metric involved in the relation. By including the metric perturbation in the graviton conversion equation, we show that a magnetic environment can cause tachyonic instability term in gravitational wave equation.

Experimental phase readout performance and electrical phase bias measurements for Space-borne Gravitational Wave detectors

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Gravitational wave detectors are highly sensitive instruments that use laser interferometry to measure changes in the time travel of light, expressed as small changes in phase. Quadrant photodetectors are often used in such optical experiments to measure angles between light beams by extracting the phase differences between four nominally identical electrical channels (Differential Wavefront Sensing). In concrete applications, such as LISA, each channel passes through an analog front end and an ADC, and is then processed by Digital Phase-Locked Loops. Together they must have micro-radian performance for the expected gravitational waves to be measured. In addition, small differences in the transfer function of such nominally identical channels will introduce differential phase biases that must be well characterized and stable.
This talk presents experimental measurements of the phase performance
and electrical phase bias of a LISA-like phase measurement system using flight representative hardware. The phase performance measurements are below the required micro-radian accuracy and approach the limits of the noise model. In addition, the measured electrical phase bias is below 2 milliradians and is also planned to be measured with an optical experiment.

Constraining dark-sector effects using gravitational waves from compact binary inspirals

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Gravitational wave observations are a powerful tool to constrain fundamental physics. This work considers dark matter that carries charge under a dark abelian massive vector field. If such dark matter is bound inside coalescing neutron stars, the presence of the new force will modify the total energy of the binary, and the emission of dark radiation modes will impact the rate of inspiral. At leading order, the dark matter corrections introduce a Yukawa term to the potential energy and a dipole radiation mode. We calculate modifications to the binary inspiral waveform to first post-Newtonian order, incorporate these corrections into a state-of-the-art waveform model for neutron star binaries, and use this model in a Bayesian parameter estimation analysis on real data collected by current, second-generation ground-based detectors. Through this study, we place the first robust constraints on the Yukawa interaction strength and dipole emission parameter.

Probing ringdown physics in asymmetric black hole mergers: from plunge dynamics to quasi-normal mode excitations

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The post-merger phase of a binary coalescence, during which gravitational wave emission can be described as a superposition of quasi-normal modes (QNMs), provides a valuable source of information for studying the system's properties.
For comparable-mass systems detected by current interferometers, the amplitude of this ringdown phase can be determined using numerical relativity simulations. However, future detectors will target a wider range of systems, potentially with greater mass asymmetry.
In this poster, I will present recent work on characterizing the dependence of ringdown signals on binary parameters in asymmetric mergers. Specifically, I will demonstrate how plunge trajectories can be parametrized and how key aspects of binary dynamics, such as inclination and eccentricity, influence QNM excitations. Understanding these signatures is crucial for developing more accurate waveform models, ultimately improving our ability to extract astrophysical information and test fundamental physics with future gravitational wave observations.

A parametrized test of General Relativity applied to LISA Massive Black Hole Binaries

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LISA observations of Massive Black Hole Binaries (MBHBs) will provide high signal-to-noise ratio (SNR) data, ideal for testing General Relativity (GR) in the strong field regime. MBHBs with masses between 10^4 and 10^7 solar masses produce inspiral signals in LISA's frequency band, well-modeled by the Post Newtonian (PN) approach, followed by loud merger-ringdown signals. We present a framework for parametrized inspiral GR tests with gravitational waves (GWs) from MBHBs, inspired by existing LIGO-Virgo-KAGRA (LVK) tools. This approach introduces generic deviations to the PN coefficients of the frequency-domain GW phase, effectively identifying potential GR violations by constraining deviations in the PN phasing formula.
Our results demonstrate that parameter constraints depend significantly on both mass and SNR, as LISA's sensitivity to different gravitational wave phases—inspiral, merger, and ringdown—varies across MBHB's parameter space. We also investigate the interplay between inspiral-only versus inspiral-merger-ringdown analyses in constraining deviation parameters.
Complementary analyses using Fisher matrix and full Bayesian approaches confirm that LISA observations could improve constraints on deviations from GR by at least two orders of magnitude compared to the most recent LVK measurements.
Additionally, using different waveform models for signal recovery allows for waveform systematics investigation, highlighting potential sources of bias that could mimic GR violations.
This work contributes to the development of robust tests of GR with LISA, enhancing our ability to probe the nature of gravity.

Accounting for Tidal Deformability in Binary Neutron Star Template Banks

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Modelled searches for gravitational waves emitted by compact binary coalescences currently filter the data with template signals that ignore all effects related to the physics of dense-matter in neutron stars interiors, even when the masses in the template are compatible with a binary neutron star or a neutron star–black hole source. The leading neutron star finite-size effect is an additional phase contribution due to tidal deformations induced by the gravitational coupling between the two inspiralling objects. We show how neglecting this effect reduces the search sensitivity close to the detection threshold. This is particularly true for binary neutron stars systems, where tidal effects are larger. In this work we therefore propose a new technique for the construction of binary neutron star template banks that accounts for neutron star tidal deformabilities as degrees of freedom of the parameter space to be searched over. A first attempt in this direction was conducted by Harry & Lundgren [Physical Review D 104, 043008 (2021)], who proposed to extract randomly the tidal deformabilities of the stars over a uniform interval, regardless of the system component masses. We show that this approach yields 33% additional templates with respect to the equivalent point-like template bank. Our proposed approach, instead, adopts a more physically motivated tidal deformability prior with a support that is informed by the value of the neutron star mass and compatible with the neutron star equation of state constraint provided by the observation of GW170817. This method significantly reduces the needed additional templates to 8.2%

Differential-Wavefront-Sensing performance measurements for LISA

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LISA’s ambitious sensitivity of pm/Hz1/2 presents many technical challenges; one of the main issues is the coupling of the angular jitter of the spacecraft and test masses to the interferometrically-measured longitudinal displacement (Tilt-To-Length coupling, or TTL). LISA will use the Differential-Wavefront-Sensing (DWS) method to keep the satellites aligned, which uses a Quadrant PhotoDiode (QPD) and combines the individual phase readouts from the four segments to obtain an angular readout. An ultra-stable interferometer testbed representative of a LISA spacecraft's Optical Bench (OB) has been developed to validate critical interferometric techniques for the LISA mission. The testbed features a pair of steering mirrors that can induce synthetic tilts between the beams to simulate spacecraft or test mass motion. This testbed has previously demonstrated the optical reduction of TTL by using imaging systems to image the point of rotation of the beams into the detector plane. Current work focuses on reducing the optical noise sources down to a DWS angular sensitivity at the few nrad/Hz^(1/2) levels in the LISA heterodyne detection band, which is required for LISA’s operation. The degradation of DWS performance in conditions of weak light or beam tilts, which are crucial for LISAs inter-satellite interferometer and test mass interferometer, respectively, has been characterized. Finally, the experiment will also serve as an optical testbed for a new method to readout the DWS signals from the QPDs.

Accelerated nested sampling with posterior repartitioning and simple-pe

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We present a novel approach to accelerate gravitational-wave data analysis by combining simple-pe, a pipeline which uses intuitive arguments to rapidly constrain parameters, with a technique called posterior repartitioning. Nested sampling is a powerful method for inference in the gravitational wave community, but its computational cost can be prohibitive for accurate waveform models. By leveraging the initial parameter estimates provided by simple-pe, we demonstrate an acceleration method that enhances nested sampling convergence. Specifically, we train a normalizing flow on the simple-pe output, and construct a repartitioned prior to use for a full nested sampling run. By merging the capabilities of posterior repartitioning and simple-pe, this combined pipeline offers a swift and dependable inference method for gravitational wave parameter estimation with enhanced accuracy and efficiency.

Combining concurrent all-sky gravitational wave transients searches with coherentWaveBurst-2G

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The most general searches for gravitational wave transients are based on data analysis methods that do not assume prior knowledge of the signal s waveform, direction, and arrival time on Earth. These searches are crucial for discovering expected and unexpected sources, providing a data-driven and minimally biased signal reconstruction. Here we discuss the latest deployed methods and achieved performances of the coherentWaveBurst-2G software framework, which is highly adaptable for agnostic or loosely modelled searches for gravitational wave transients (GWTs). Enhancements include the use of a ranking statistic fully based on multivariate classification with eXtreme Gradient Boosting, a deeper validation of the accuracy of the statistical significance of GWT candidates, and the measurement of the correlations of false alarms and simulated detections between different concurrent searches. Various search configurations for GWTs are examined using approximately 14.8 days of observation data from the latest public LIGO-Virgo-KAGRA (LVK) release, i.e., the third observing run, O3. We provide for the first time a comprehensive comparison of search performances on both Hanford-Livingston and Hanford-Livingston-Virgo data. This enables to design advantageous combinations of concurrent searches, offering essential insights for assessing data analysis strategies in the current LVK fourth observing run, O4.

A Realistic Projection for Constraining Neutron Star Equation of State with the LIGO-Virgo-KAGRA Detector Network in the A+ Era

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The upcoming A+ era of the LIGO-Virgo-KAGRA network, with upgrades to both Advanced LIGO and Advanced Virgo, will enable more frequent and precise observations of binary neutron star (BNS) mergers, leading to improved constraints on the neutron star equation of state (EOS). In this study, we applied reduced-order quadrature (ROQ) techniques for full parameter estimation of 3,000 simulated gravitational wave signals from BNS mergers injected at A+ sensitivity, the largest full parameter estimation simulation to date, made possible by the hundreds of times speedup enabled by the ROQs. We considered three EOS models: HQC18, SLY230A, and MPA1. Our results show that tidal deformability is generally overestimated at higher masses and underestimated at lower masses. With the anticipated detection of a few tens of BNS mergers during a three-year observing run at A+ sensitivity (e.g., O5), we post-processed the parameter estimation results using statistical approaches to assess our EOS recovery accuracies, identify biases in the EOS constraints and their causes, and quantify the necessary corrections.

Unified Recipe for the First Law of Black Hole Thermodynamics

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Diffeomorphism invariance is essential for deriving the first law of black hole thermodynamics. However, in gravitational theories formulated in the Cartan formalism, there are also symmetries associated with gauge transformations, in addition to symmetries under diffeomorphisms. In this talk, I will explore how to translate metric calculations into the Cartan formalism, demonstrating that the results are independent of gauge transformations, a topic that has generated some controversy recently. Finally, I will present a generic recipe for deriving the first law of thermodynamics for black holes that are solutions to generalized gravitational theories, thus broadening our understanding of these solutions.

The LISA Optical Bench Imaging Systems

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On the LISA optical bench many of the interfering beams are tilting relative to each other. These tilts are caused by, for example, spacecraft orbits and spacecraft. These time-varying beam tilts will cause apparent length changes in the optical paths (Tilt-to-Length, TTL) coupling and are one of the largest noise sources in the LISA interferometry. To supress this potential noise source imaging systems are used in all of the interferometers on the optical benches. The target is to reduce the TTL coupling to below 13 µm/rad over a +/-500 µrad field of view and with a wavefront degradation of <λ/20. The system must be contained within a tightly constrained physical envelope and have a design robust enough to maintain performance in a space environment.
We describe the design choices and the specification and tolerancing of a baseline design. A test system has been procured to this design. We describe the building and testing of this baseline imaging system.

Greybody factors as robust gravitational observables: insights into post-merger signals and echoes from ultracompact objects

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The quasinormal mode spectrum plays a crucial role in modeling post-merger ringdown signals in binary coalescences, encompassing both black holes and ultracompact horizonless objects. However, quasinormal modes are highly sensitive to small deformations of the system and only describe the linear response within a limited and imprecisely defined timeframe after the merger. Motivated by a recently discovered connection between greybody factors and post-merger black hole signals, we study the robustness of greybody factors as gravitational observables, furnishing a complementary approach to quasinormal modes. We show that greybody factors are stable under small perturbations and unaffected by specific ambiguities that undermine the reliability of the quasinormal modes. We demonstrate that greybody factors play a significant role in characterizing also the signals emitted by wormholes and other horizonless ultracompact objects. The greybody factors of ultracompact objects exhibits both low-frequency resonances and high-frequency, (quasi-)reflectionless scattering modes. We show that these high-frequency (quasi-)reflectionless scattering modes, rather than low-frequency resonances, are directly responsible for the echoes observed in the time-domain response of ultracompact objects or black holes surrounded by matter fields localized at large distances. Our study is focused both on non-rotating and rotating solutions.
Based on: https://arxiv.org/abs/2406.01692, https://arxiv.org/abs/2501.16433, forthcoming works.

Strategy to detect Long Transient GWs from Newborn magnetars using Current and Next-Generation Detectors

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Long transient gravitational waves (GWs) from newborn magnetars provide a promising target for next-generation GW searches. These signals, though weaker than binary mergers, persist over extended timescales, allowing detection with specialized data analysis techniques. We present improvements to the Generalized Frequency Hough (GFH) pipeline to enhance sensitivity and computational efficiency in the search for these signals. By refining the GFH method, we optimize detection prospects. Currently, we are applying this modified GFH pipeline to a search for the remnant of SN 2023ixf which was observed in May 2023. With the upcoming LIGO/Virgo/KAGRA O5 run we explore an improved approach that can increase the search sensitivity. Our methods aim to enhance the detectability of long transient GWs to probe extreme astrophysical events.

Transverse expansion of the metric at null hypersurfaces and application to Killing horizons

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In this talk we present a novel framework to obtain the full transverse expansion of the metric at a general null hypersurface in terms of the tower of derivatives of the ambient Ricci tensor. Our main identities generalize several well-known results in the literature such as the homothetic horizon case [Fefferman-Graham] and the Killing horizon one [Moncrief, Petersen-Kroencke, Lucietti-Katona]. As an application, we prove general existence and uniqueness results when initial data is posed on a single null hypersurface. Our approach is entirely covariant, independent on any field equations and does not make any assumptions regarding the topology or dimension of the hypersurface. Particularizing our results to the Killing horizon case, we show existence and uniqueness of Λ-vacuum spacetimes from initial data at a non-degenerate Killing horizon of any topology, dimension and possibly with bifurcation surfaces. The contents of this talk can be found in arXiv:2405.05377 and arXiv:2501.03983.

The gravitational field outside a bounded matter distribution in General Relativity – Combined Rotational and Tidal deformations beyond the quasi-spherical Hartle-Thorne approximation

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Understanding rotating stars is crucial for many developments in Astrophysical Relativity, and within the last decade more attention has been given to tidal effects - both with and without rotation. While the Kerr Black hole and its various mechanisms are now quite well-understood, for a non-collapsed bounded matter distribution relatively little progress has been made beyond the quasi-spherical approximation, and this is due to the strong non-linearity in the Field Equations even for the stationary exterior region.
To break the impasse, here we separately consider two alternative perturbation limits which make no prior assumptions about the deformation of the matter distribution or the form of the final expressions, but nevertheless turn out to be consistent with the quasi-spherical limit. Further, unlike other previous investigations we also include axisymmetric tidal deformations following the author's Doctoral research, and the new approach for the vacuum builds on this as follows: (i) The matter distribution is highly compact; where the exact Kerr metric is the unperturbed limit. Physically this is not a completely unreasonable assumption as it is expected that many rapidly-rotating Neutron stars are highly compact. (ii) The matter distribution is strongly deformed but its rotation rate is actually quite slow, and the unperturbed limit is the exact 'static' axisymmetric solutions. Such a configuration could describe a core with a weakly bound outer layer.
For various scenarios involving strong departure from spherical symmetry, the relative simplicity of these two approximate vacuum solutions makes them more practical to use than the corresponding exact solution.

Residual test to search for microlensing signatures in strongly lensed gravitational wave signals

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When a gravitational wave signal encounters a massive object, such as a galaxy or galaxy cluster, it undergoes strong gravitational lensing, producing multiple copies of the original signal. These strongly lensed signals exhibit identical waveform morphology in the frequency domain, allowing analysis without the need for complex lens models. However, stellar fields and dark matter substructures within the galactic lens introduce microlensing effects that alter individual signal morphologies.
Identifying these microlensing signatures is computationally challenging within Bayesian frameworks. In this study, we propose a novel residual test to efficiently search for microlensing signatures by leveraging the fact that current Bayesian inference pipelines are optimized solely for the strong lensing hypothesis. Using cross-correlation techniques, we investigate the microlensing-induced deviations from the strong hypothesis, which are imprinted in the residuals. Our simulated signals from realistic microlensing populations reveal that while most events exhibit small mismatches, a fraction exhibit significant deviations.
We find that 29% (56%) and 37% (69%) of microlensed events with mismatch > 0.03 and > 0.1, respectively, can be discerned with O4 (O5) detector sensitivities, which demonstrates that high-mismatch events are more likely to be identified as microlensed. Including all events from a realistic population, 12% (21.5%) are identifiable with O4 (O5) sensitivity using our approach.

Magnetic Diagnostics for LISA

Serrano Rubio D[1], Nofrarias M[1], Roma D[1], Pérez A[1]
[1]Ieec & Ice-csic

The LISA mission will be the first observatory to detect gravitational waves from space within the millihertz frequency band. Its operation principle revolves around measuring distance variations between free-falling test masses (TMs) when perturbed by passing gravitational waves. Its precision with interferometric measurements reaches down to picometers. At such levels of precision, any external perturbation other than gravitational effects can affect the performance of the mission. Magnetic forces have an important impact on the instruments sensitivity below the millihertz as they can perturb the TMs from their geodesic motion. Hence, monitoring the magnetic environment within each of the LISA spacecrafts is of utmost importance. We present the instruments that will be employed for the study of the magnetic environment at each of LISA's spacecrafts as part of the Science and Diagnostics Subsystem. It is planned to implement 6 anisotropic magnetoresistance magnetometers to continuously measure the magnetic field on-board each spacecraft. Additionally, 2 coils will also be implemented to monitor audio-band frequency magnetic signals originated from the electronics on-board, since their amplitude modulations could down-convert to the frequency band of LISA. We will also introduce the status of a CubeSat mission, expected to launch in 2026, in which we will test some of the LISA diagnostics technologies.

A practical Bayesian method for gravitational-wave ringdown analysis with multiple modes

Shao L[1], Dong Y[1], Wang Z[1]
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Gravitational-wave ringdown signals from binary black hole mergers encode valuable information about the perturbative properties of the spacetime of the remnant black hole. When the signal-to-noise ratio of gravitational-waves gets larger in the next-generation ground-based detectors, the usefulness of ringdown signals is boosted if higher modes and overtone modes are sufficiently identified. However, the computational cost easily becomes a problem because of the inclusion of these modes where they quickly enlarge the dimensionality of the parameter space. Inspired by the F-statistic method in the studies of continuous gravitational waves, we develop a robust algorithm, as well as a standalone code, to deal with extra parameters. We illustrative the effectiveness and efficiency of our algorithm by carefully comparing its results with that from a full-scale Bayesian analysis for various cases. We show that without losing accuracy, our algorithm is faster by two orders of magnitude, and is readily applicable for real data analysis of events from the next-generation gravitational-wave detectors.

The symplectic geometry of the photon shell

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The images of supermassive black holes published by the Event Horizon Telescope (EHT) collaboration show a bright annulus of light with a dark center, the detailed structure of which is still not resolved. General relativity predicts that within this annulus of light there is a thin bright ring known as the ``photon ring", resulting from nearly-bound photons which orbit the black hole a number of times on the way from the source to the detector. This set of nearly bound null geodesics defines a submanifold of the null geodesic phase space known as the ``photon shell". In this work, we study a new property of the famous Kerr solution: the symplectic geometry and differential phase-space volume of the photon shell. We begin by considering exactly critical, bound photon orbits, which theoretically orbit the BH an infinite number of times. We give special attention to the near extremal limit, in which the near-horizon-extremal-Kerr (NHEK) geometry is known to govern a significant fraction of the photon orbits. With our calculations, we quantify the relative volume of phase space in the (near-) NHEK region. We also explore the differential phase space volume of the near-critical photon orbits, which are able to reach an observer at infinity. Going forward, our approach, combined with the stochastic nature of the astrophysical emission, could be applied to provide new insights into properties of black hole images.

All-sky search for continuous gravitational waves from isolated neutron stars with the Frequency-Hough pipeline

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A fast-rotating, non-axisymmetric neutron star is expected to emit persistent quasi-monochromatic continuous gravitational waves (CWs). The Frequency-Hough (FH) search is aimed at the detection of CWs emitted by isolated neutron stars, blindly exploring a wide range of parameters covering the whole sky, the whole frequency range of Advanced LIGO-Virgo-KAGRA detectors and a spin-down term in the range [-10, 2] nHz/s. We will firstly describe the method, and then focusing on the adaptation of the computing workflow to integrate with computing centers in the International Gravitational-Wave Network (IGWN) community. We will hence present the status of current search for the first part of the fourth observing run (O4), showing the main differences and implementations with respect to the third observing run (O3).

Rapid and Insightful Gravitational-Wave Parameter Estimation with Simple-PE: Validation and Application to GWTC-3

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Performing rapid parameter estimation of gravitational wave (GW) signals is crucial for multi-messenger follow-up observations. The stochastic methods currently used for inference are computationally expensive, often taking hours to days. Based on an intuitive understanding of the GW signal, Fairhurst et al (2023) introduced the simple-pe algorithm to measure the astrophysical parameters in CPU minutes. Simple-PE not only accounts for the power in the dominant mode of the GW waveform but also checks for the contribution from various subdominant features, such as the second GW polarization, higher multipoles, and orbital precession, to improve the accuracy of the parameter measurement. In this talk, I will discuss the robustness of simple-pe across the parameter space of binary mergers observed by ground based detectors. I will also demonstrate its performance against GWTC-3 observations. Additionally, I will highlight the potential role that simple-pe can play in low-latency alerts and aiding the detailed parameter estimation routines in the upcoming observing runs of LIGO-Virgo-KAGRA.

Limits on the mass of compact objects in Horava-Lifshitz gravity

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It is known that there exist theoretical limits on the mass of compact objects in general relativity: One is the Buchdahl limit for an arbitrary matter equation-of-state that turns out to be the limit for the matter of uniform density and another one is the causal limit that is stronger than the Buchdahl limit. We calculate similar theoretical limits on the mass of compact objects in Horava-Lifshitz gravity. Interestingly, the curves of the uniform density limit and the causal limit converge to the extremal black hole that is the minimum of the event horizon, assuming the Kehagias-Sfetsos solution that is an asymptotic flat solution in HL gravity.

Simulation-Based Inference for Real-Time Massive Black Hole Binary Detection with LISA

Srinivasan R[1], Copparoni L[1], Barausse E[1]
[1]SISSA

The upcoming space-based gravitational wave detector, LISA, promises unprecedented access to a wide range of sources, including massive black hole binary (MBHB) mergers that may be observed concurrently with telescopes. Rapid detection of merging MBHBs is crucial for enabling timely electromagnetic follow-up. However, traditional Bayesian methods face significant challenges in achieving this due to the high dimensionality of MBHB data (~10^4 frequency bins) and the need for daily updates. In this talk, I will present a novel simulation-based inference framework that addresses these challenges through fast and accurate parameter estimation. Our approach leverages GPU-accelerated forward simulators to efficiently generate synthetic LISA data, covering a broad range of parameter priors. To overcome the data dimensionality bottleneck, we develop a robust summary statistic that compresses the input data while preserving critical source information. This framework enables (i) early detection of inspiraling MBHBs and (ii) precise estimation of key parameters, including masses, time-of-merger, and sky localization. Our results demonstrate the potential for rapid, scalable, and reliable inference from LISA data, paving the way for multi-messenger observations of MBHB mergers and advancing real-time gravitational wave astronomy.

Optimization of the cWB2G-GMM pipeline for unmodeled all-sky short searches

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Gravitational wave (GW) transients are emitted by various astrophysical sources, with some signals remaining poorly defined or even unknown. These signals require unmodeled searches that do not assume prior knowledge of their morphology. The Gaussian Mixture Modeling (GMM) enhanced Coherent WaveBurst 2G (cWB2G) pipeline (cWB2G-GMM), is one such unmodeled transient search method that employs the GMM machine learning algorithm to effectively differentiate GW signals from glitches. By generating two separate models, one for signal and one for noise, cWB2G-GMM uses the log-likelihood ratio of a given trigger in multi-dimensional parameter space as its detection statistic. We present recent updates to the cWB2G-GMM pipeline aimed at improving performance for the second part of the fourth observing run of Advanced LIGO-Virgo-KAGRA. These updates focus on optimizing computational efficiency, streamlining the overall workflow, and ensuring coherency with cWB2G, with improvements demonstrated using publicly available data from the third observing run.

Large gauge transformation in cosmological perturbation theory

TANAKA T

Cosmological perturbation theory plays an important role in linking models of the early universe with observed density fluctuations. Various pathologies can seemingly occur when considering quantum loop corrections, but many of these can be resolved by understanding a symmetry called Large gauge transformation. This symmetry is a symmetry for global transformations derived from the symmetry for general coordinate transformations that inevitably exists in the framework of relativistic theories. One of the problems solved by this symmetry is the problem of infrared divergence. By requesting that the state of the universe preserves this symmetry, it can be shown that the IR divergence appearing in the loop calculations cancels out completely. It also allows us to guarantee that the theoretical predictions of cosmologically observed fluctuations are robust predictions, independent of what has happened on smaller scales. This has received much attention in recent years due to the upsurge in research on primordial black hole formation scenarios. Furthermore, the equation between correlation functions, called the consistency relation in cosmological perturbations, can also be understood naturally from the standpoint of respecting the Large gauge transformation. It can be said that this principle has been unconsciously respected as a result of actual honest calculations. On the other hand, in exotic scenarios, pathologies can occur because this symmetry is not respected.

Investigating Hardware Injections in LIGO O3 Data: Simulated Continuous Signals from a Neutron Star in a Low-Mass X-Ray Binary

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Simulated continuous gravitational wave (CW) signals, known as hardware (HW) injections were added to the data during the LIGO detectors' third observing run (O3), including two periodic signals mimicking a spinning neutron star in a binary system, similar to the low-mass X-Ray binary Scorpius X-1 (Sco X-1). HW injections, which add the simulated signal to the interferometer control loop, serve as an important validation of a search method, as they occur before data cleaning and preparation. We searched for these injections using a cross-correlation pipeline, which searched for CWs from Sco X-1 in the O3 run. To simulate a realistic search, we used a search region of orbital parameter space of similar size to the plausible parameter ranges for Sco X-1, but containing the parameters of each HW injection. We report the results of the searches for both injections, as well as targeted searches at the true injection parameters.

Post-Newtonian waveforms for elliptic and hyperbolic orbits in scalar-tensor theories

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Recently, there has been much progress in studying gravitational waves in alternative theories of gravity, especially in a class of mass scalar-tensor theories. However, the waveform modelling effort has mostly focused on the case of circular orbits. Here, I will present recent work extending these results to elliptic and hyperbolic orbits. I will present the construction of the quasi-Keplerian parametrization in these theories, which solves the equations of motion with second post-Newtonian (2PN) accuracy. This parametrization has been obtained both in the bound case (where we find in particular the radial frequency and the periastron advance) and in the unbound case (where we find the scattering angle and the impact parameter). I then present energy and angular momentum loss, and how this backreacts onto the system. For bound orbits, this leads to the secular evolution of the orbital parameters, whereas in the unbound case, the radiation reaction leads to dissipative contributions to the scattering angle.

Design and manufacturing of superconducting coils for cryogenic (inertial) sensing and actuation for Einstein Telescope and the Lunar Gravitational-wave Antenna

Ellenbroek V[1] , Sharma M[2] ,Van Heijningen J[1] , Singh S[3], , Zeoli M[5], Gatti A[6], Collette C[5], Harms J[7], Perali A[4], Tavernier F[6], Vool U[2]
[1]Nikhef , [2]CPFS at MPI Dresden , [3]National Physics Laboratory , [4]Univerity of Camerino, [5]PML - ULiège, [6]ESAT - KULeuven, [7]Gran Sasso Science Inistitute

Future gravitational-wave (GW) detectors such as Einstein Telescope (ET) will be cryogenic to decrease thermal noise to be sensitive to low-frequency GWs. In addition to this thermal noise reduction, there is an opportunity for superconductive technology introduction. We can just make our current interferometric sensing and coil-magnet actuation cryo-compatible, but superconductivity solutions thrive – instead of survive – in the cold.
Using the Meissner effect, these devices enable extremely precise actuation and (inertial) sensing that can be deployed near the suspended mirrors of ET. There, they can monitor or actively mitigate tiny, unwanted vibrations. For instance, the heat links from cryocoolers to the bottom of ET's suspensions can transfer such vibrations, and we aim to develop the world's first sensors that have sufficient sensitivity - sub-fm/√Hz from 1 Hz onwards - to deploy so near to the mirror. Additional to vibration monitoring, an array of superconducting inertial sensors can be deployed in a permanently shadowed lunar crater with stable cryogenic temperatures. Ultra-sensitive inertial sensors can detect gravitational-wave-induced lunar deformations, using the Moon itself as part of the Lunar Gravitational-wave Antenna (LGWA).
Here we present the sensing and actuation concepts, our approach to designing and manufacturing the geometry of the coils and the first milestone in manufacturing: a thin-film niobium nitride coil in the superconducting state.

Glitch + compact binary inference with a data-driven glitch model

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Gravitational wave signal parameter estimation typically assumes a stationary noise process, but instrumental glitches can coincide with true signals and cause bias in parameter estimates. In LIGO-Virgo-KAGRA analyses, glitches are subtracted in a pre-processing step before parameter estimation, or a glitch model can be included made from an agnostic wavelet basis (e.g. BayesWave). In this work we take another approach, and build a parameterised model of glitches based on the GravitySpy glitch catalogue. We train a normalising flow to produce an informative prior on the glitch model. The inference of glitch and signal is then performed simultaneously with Bilby. We demonstrate the performance of our method in terms of bias reduction, glitch identification and model selection between glitch, signal and glitch+signal models.

Understanding photo-emission on Au-coated surfaces of LISA gravitational reference sensor

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As part of the LISA test campaign, we've developed a ground-based facility to measure the photo-electric yield of the LISA gravitational reference sensor Au-coated surfaces. In space, the LISA test masses will be exposed to a charging flux of 10-100 e/s (1-100 aA) from solar energetic particles (SEP) and galactic cosmic rays since the test masses are free-falling inside the spacecrafts. To keep the charge on the test masses below the required limit of $|Q| < 2.4$ pC, we shine UV light (4.9 eV) onto the surfaces to discharge them using the photoelectric effect. Our facility includes a replica of the LISA Pathfinder electrode housing with inside a hollow test mass, all under vacuum. An electrical interface allows us to set voltages on the housing and individual electrodes, while an electrometer measures the current flowing through the test mass-electrode housing capacitor. We've shown that the facility can achieve a current resolution of 1 fA, which is comparable to the in-flight maximum photo-current of 4 fA. We characterized the photoelectric yield of the surfaces as a function of applied voltages, emulating the in-flight electrical fields the photo-electrons move in, and time. In addition, we built a second facility, dedicated to calibrate test mass charging simulations, where we repeated some measurements, getting compatible results, which shows the stability of the measurement technique.

Impact of f(R) gravity on gravitational waves propagation

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We explore the propagation of gravitational waves (GWs) in context of metric f(R) gravity under weak field approximation. We observe the scalar degree of freedom arising from f(R) gravity modify the wave equation for GWs leading additional scalar modes of polarization. The background matter distribution influences GWs propagation, affecting their speed. Our study also focuses on the observational constraints that limit the detection of these deviations in GWs signals from General relativity (GR) thus providing insights into the challenges of testing extended gravity theories.

Galactic suppression of polarization modes of gravitational waves

Verma M[1], Dash U[2]
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We explore the suppression of the scalar modes of polarisation of gravitational waves travelling across the evolving galaxies. This is done in a specific model in the the modified f(R) gravity background. The observation of such modes is found to be dominantly suppressed by a chameleon mechanism in the gas rich environment of the galaxies. The degree of suppression is found to constrain the future observations which are dominated by tensor modes. It is proposed that the influence on the polarisation by the varying density galactic backgrounds serves as a new and strong approach to distinguish the LambdaCDM model from the alternative gravity theories. We carry out consistency checks of viability of our model with the current galactic observations.

First demonstration of Tunable Coherence in a power-recycled Michelson interferometer

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As straylight is an important limitation for the sensitivity of gravitational wave detectors, we investigate new laser operation concepts and interferometer topologies for a more straylight-resilient detector configuration.
Our main focus is the use of tunable coherence realized by phase modulation following a pseudo-random-noise (PRN)-sequence on the interferometer laser. This breaks the coherence of the delayed straylight reducing its intrusive impact with the remaining coherence length only depending on the PRN frequency. Thus, effectively realizing a pseudo white-light interferometer with tunable coherence length.
In addition to our successful concept demonstration in a Michelson interferometer and optical cavities individually, we effectively reduced the resonant enhancement of these cavities to a delays in the µm range.
Now, we present first results from a power-recycled Michelson at increased PRN frequencies up to 10 GHz reducing the coherence down to only several wave lengths.

On point-ahead angle control strategies for TianQin

Wang D[1], Zhang X[1]
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In space-based gravitational wave detectors, the ranging noise caused by beam pointing deviation and jitter constitutes a significant noise source, with the point-ahead angle (PAA) compensation serving as a critical component of the pointing control system. In LISA's design, the compensation of PAA is implemented via a single-axis rotating mirror directly inserted into the outgoing beam path to ensure the transmitted beam tracking with distant satellite. However, the adjustment of the mechanism may introducing path-length variations during PAA modulation, potentially degrading the measurement data quality through additional noise. Based on TianQin's high-precision numerical orbital data, we characterize its PAA evolution and propose a static bias compensation strategy tailored to TianQin's constellation configuration. Preliminary simulations of intensity and tilt-to-length (TTL) coupling noise validate the strategy's feasibility while establishing essential wavefront quality requirements for TianQin.

A gating-and-inpainting perspective on GW150914 ringdown overtone

Wang Y[1]
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I will present a result analyzing the ringdown overtone signals in GW150914 with a gating-and-inpainting technique. We address several data analysis subtleties, including noise estimation. The data analysis results show mild support for the existence of a ringdown overtone signal in GW150914.

A+ Upgrade to Advanced LIGO

Webster S[1], Barton M[1], Hammond G[1], Hough J[1], Jones R[1], Rowan S[1], Seetharamu T[1], Martinov D[2], Vecchio A[2], O'Dell J[3], Huddart A[3], Robertson C[3], Dooley K[4], Grote H[4], Reid S[5]
[1]University of Glasgow, [2]University of Birmingham, [3]STFC Rutherford Appleton Laboratory, [4]Cardiff University, [5]University of Strathclyde

Advanced LIGO (Laser Interferometer Gravitational-Wave Observatory) is designed to measure the quadrupolar strain of space itself arising from passing gravitational waves and in 2015 made the first observation of a binary black hole merger [Abbot et al, Phys Rev A, 116, 061102 (2016)]. With subsequent improvements to the interferometer, detections of such events now occur at a rate of 2-3 per week, with sources located at distances of up to 3 billion light years.
The A+ upgrade to aLIGO aims to reduce the noise floor of the instrument and, so, to further extend its reach into the Universe. Improvements to large-scale optics (reduced coating thermal noise, increased aperture), active optics for optimizing mode-matching, and the implementation of a balanced homodyne detection scheme, to maximise the efficacy of frequency-dependent squeezing, are the primary features of the upgrade.
We will report on the UK's contribution to A+, in core optics, suspensions, and the optical design for the balanced homodyne detection scheme, together with future plans for improving the sensitivity of the interferometer.

The CW Vista: Depth vs Breadth

Wette K[1]
[1]Australian National University

Searches for continuous gravitational waves may be characterised by two properties: depth, representing the sensitivity of the search relative to detector performance; and breadth, representing the relative size of the search parameter space. I will use these two properties to give a big-picture overview of the last two decades of searches for continuous gravitational waves using LIGO/Virgo/KAGRA data, and illustrate the different trade-offs made between sensitivity and parameter space coverage.

Gauge Independent Effective Field Equations for Quantum Gravity

Woodard R[1]
[1]University Of Florida

This talk is arXiv:1702.05694 (with Shun-Pei Miao and Tomislav Prokopec), arXiv:2107.13341 (with Sanjib Katuwal) and arXiv:2402.05452 (with Drazen Glavan, Miao and Prokopec). I describe a technique for purging gauge dependence from the linearized effective field equations induced by loops of gravitons. This means that effective field equations can be used the same way as classical field equations, without recourse to the S-matrix. There are important implications for cosmology for which the S-matrix is not observable and may not even exist. Explicit results have been obtained on flat space background for graviton corrections to scalars and to electromagnetism, along with a proof of gauge independence. Most recently, a result has been obtained for scalars on de Sitter background, although the proof of gauge independence is still in progress.

Relativistic effects in extreme-mass-ratio inspirals in scalar clouds: inclined and eccentric orbits

Xu Q[1]
[1]Instituto Superior Técnico

We study extreme-mass-ratio inspirals (EMRIs) in scalar clouds including orbital inclination and eccentricity. We also assess the importance of relativistic effects. EMRIs are binary systems in which a stellar-mass compact object spirals into a supermassive black hole, and are key sources for space-based gravitational wave detectors like LISA. Recent studies have explored EMRIs within scalar clouds formed via superradiant instabilities around rotating black holes. Building upon prior work, we extend the analysis to include the effects of orbital inclination and eccentricity on the dynamics of EMRIs in such environments. We employ a fully relativistic framework to assess how these orbital parameters influence energy loss through scalar radiation and gravitational waves.

Ground test of locking and releasing scheme in space-borne gravitational wave detection

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Measurement, and School of Physics, Huazhong University of Science and Technology
In space-borne gravitational wave detection, the construction of multiple sets of high-precision inertial reference is required. Its core is the test mass which is free-falling in space. To achieve this goal, the test mass is locked during the launch phase of the spacecraft and then released during the scientific exploration phase, allowing it to go into free fall, providing an inertial reference for the laser interferometry system. After the test mass is released, limited by the capture control ability of the electrostatic force, the release impulse of the test mass is required to be less than 1*10-5 kg m/s, and the release impulse moment is less than 5*10-8 kg m2/s, respectively. Since actual on-orbit verification experiments are difficult to carry out, it is particularly important to verify and evaluate the locking and releasing scheme on the ground. As a result, the torsion pendulum is built to test the locking and releasing scheme on the ground.
In order to meet the test requirements under different conditions, we propose the ground testing based on the compound pendulum, the simple pendulum, and two-stage pendulum. At present, the torsion pendulum can meet the test requirements of releasing impulse up to 10-6 kg m/s and releasing impulse moment of 4*10-9 kg m2/s. The on-orbit locking and releasing control strategies and schemes under different working conditions can be verified and evaluated on the ground, which provides the theoretical and technical support for the future application of locking and releasing schemes in real space environment.

Waveform reconstruction of core–collapse supernova gravitational waves with improved multisynchrosqueezing transform

Yuan Y[1], Wang A[2], Li Z[3], Yu G[2], Lü H[4], Xu P[1], Fan X[5]
[1]Institute Of Mechanics, Chinese Academy Of Sciences, [2]University of Jinan, [3]SUPA, University of Glasgow, [4]Guangxi University, [5]Wuhan University

Gravitational waves (GWs) from core–collapse supernovae (CCSNe) have been proposed as a means to probe the internal physical properties of supernovae. However, due to their complex time-frequency structure, effectively searching for and extracting GW signals from CCSNe remains an unsolved challenge. In this paper, we apply the improved multisynchrosqueezing transform (IMSST) method to reconstruct simulated GW data based on the advanced LIGO (aLIGO) and Einstein Telescope (ET) detectors. These data are generated by the rotational and neutrino-driven mechanisms, and we use the match score as the criterion for evaluating the quality of the reconstruction. To assess whether the reconstructed waveforms correspond to true GW signals, we calculate the false alarm probability of reconstruction (FAPR). For GW sources located at 10 kpc and data sets where the waveform amplitudes are normalized to 5 × 10^−21 observed by aLIGO, FAPR are 2 . 1 × 10^−2 and 6 . 2 × 10^−3, respectively. For GW sources at 100 kpc and with waveform amplitudes normalized to 5 × 10 −21 observed by ET, FAPR are 1 . 3 × 10^−1 and 1 . 5 × 10^−2, respectively. When the GW strain reaches 7 × 10^−21 and the match score threshold is set to 0.75, the IMSST method achieves maximum reconstruction distances of approximately 37 and 317 kpc for aLIGO and ET, respectively . Finally ,we compared the performance of IMSST and STFT in waveform reconstruction based on the ET. The results show that the maximum reconstructable distance using STFT is 186 kpc.

Research on detecting the interaction through mediating axions with the milligram torsion pendulum

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[1]Huazhong University of Science and Technology

The axion, as one of the most important candidates for dark matter, exhibits an extremely small coupling with ordinary matter. The milligram torsion pendulum has an ultrahigh measurement sensitivity of force and torque. Here we propose a scheme to detect the axion-mediated potential interaction by using the milligram torsion pendulum. In the scheme, a SiO_2 block serves as the unpolarized nucleon source, while two SmCo blocks act as the polarized electron spin sources. The nucleon source is suspended by a micrometer diameter silica fiber. The signal to be measured is the monopole-dipole interaction.
To measure the axion-induced signal, the surface separation between the nucleon source and the electron spin sources is periodically modulated within the range of 30-100 μm. Two SmCo blocks with opposite spin polarization directions are symmetrically positioned to cancel out the Newtonian gravitational torques acted on the nucleon source. The noise sources are evaluated, such as the temperature fluctuation, the disturbance of electromagnetic field, the ground vibration, the drift and fluctuation of laser power, the shot noise, and the noise caused by the quantum. Around and below the natural frequency of the torsion pendulum, the combined noise is 2.0×10^{-22} $Nm/Hz^{0.5}$. When the duration of each measurement is three days, the combined noise is 4.4×10^{-21}Nm. Under this level, the coupling coefficient of the interaction mediated by axions will be determined, and the precision is expected to be two orders of magnitude higher than that of the previous work when the interaction path is tens of microns.

Mass Transfer and Common Envelope Evolution of Ultralight Boson Clouds in Black Hole Binaries

Zhang J[1]
[1]International Centre for Theoretical Physics Asia-Pacific

Clouds of ultralight bosons can form around spinning black holes through superradiance. In this talk, we discuss the dynamical evolution of such clouds in binary black hole systems. Focusing on comparable mass binaries, we will demonstrate that the cloud can resonantly transfer between the two black holes and eventually form a common envelope during the late inspiral phase. The mass transfer of clouds happens at larger orbital separation than the Roche Lobe transfer and differs from that of particle-like matter, providing a unique prob of new physics. We shall also discuss the back-reaction on the orbital dynamics and the resulting signatures in gravitational wave observations.

Towards a reliable reconstruction of the power spectrum of primordial curvature perturbation on small scales from GWTC-3

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Primordial black holes (PBHs) are considered to be both candidates for dark matter and progenitors of binary black holes (BBHs) detected by the LIGO-Virgo-KAGRA (LVK) collaboration. The gravitational collapse of primordial density perturbations in the early Universe provides a formation channel for PBHs, making the statistical properties of gravitational-wave-observed BBH populations a powerful probe of the primordial curvature power spectrum. In this work, we employ a more reliable systematic approach to reconstruct the primordial curvature power spectrum from GWTC-3 data using hierarchical Bayesian inference, by considering the measurement uncertainties and LVK detector-induced selection effects (particularly sensitivity thresholds). We present results from both the single-component PBH population model (assuming primordial black holes solely) and the multi-population model (which incorporates a mixture of PBHs and astrophysical black hole binaries). The reconstructed primordial curvature power spectrum exhibits a peak amplitude of ~0.025 at O(10^5) /Mpc scales, aligning with inflationary models that generate PBHs through small-scale power spectrum enhancements.

GR Bootstrapping For Venusians

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According to a familiar piece of physics folklore, made famous by Feynman, one can derive General Relativity (GR) from a purely field-theoretic perspective. In this ”Venusian” approach, one begins with the linear theory of a spin-2 field on Minkowski space and introduces, order by order, the "gravitational energy" terms dictated by energy-momentum conservation. This is believed to lead inevitably to the full Einstein’s Field Equation.
However, no such an independently motivated iteration procedure is actually found in the literature. Rather, all of the existing approaches import knowledge and concepts from our "Earthly", geometry-based understanding of general relativity, such as the gauge symmetry corresponding to diffeomorphism invariance [R.P. Teynman 1962, R. Wald 1986] or auxiliary variables engineered to represent a connection [S. Deser 1970]. This lacuna has led some [T. Padmanabhan 2008, L.M. Butcher et al 2009, C. Barcelo et al 2014] to argue that the claim is false - that a purely ”Venusian” analysis is not sufficient to determine the theory.
Here, we fill that gap by presenting an explicit method to derive the required terms to all orders, making it clear that they are indeed unique up to field redefinition. The procedure, and the reasoning leading to it, require no knowledge of Riemannian geometry. Our method relies solely on requiring that the field equation must arise as the Euler-Lagrange equation of some action, using the conditions formulated long ago by Helmholtz [H von Helmholtz 1887].

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