'Galaxy chemistries across cosmic time: a key window into the evolution of galaxies from observations and modelling (GalChem)' Abstracts

Talks

Chemodynamical simulations of galactic dust formation and evolution across cosmic time

Authors
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Abstract
The evolution of dust is important for understanding galactic chemical evolution as a significant amount of metals are predicted to be locked inside dust grains. Current models of dust formation and evolution are able to explain the dust scaling relations in galaxies in the local Universe. However, the same models often struggle to reproduce the high dust content in z~7 galaxies observed with ALMA, as well as the carbonaceous dust in z~8 galaxies observed with JWST. The latter is particularly difficult to explain with our current theories of dust formation which depend on Asymptotic Giant Branch (AGB) stars to be the main factories of carbonaceous dust but whose lifetimes are too long to have made significant contributions to the dust budget at these times. Therefore, we introduce dust into our cosmological chemodynamical simulations together with the latest nucleosynthesis yields. This allows us to robustly trace the mass of ten different dust species in the ISM from initial conditions: a variety of silicates, as well as carbonaceous, iron and alumina dust. This dust mass increases through production in supernovae and AGB stars, as well as accretion from gas phase metals. The dust is destroyed through star formation, supernova shock waves and thermal sputtering. Our results successfully reproduce scaling relations at low redshift. We show also where our model is able to reproduce these high redshift observations, taking account of observational selection bias, and discuss possible reasons behind any discrepancies including the limitations of current simulations.

The bursty baryon cycle: how differential galactic winds shape the chemistry of the first galaxies

Authors

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Abstract

The cycling of baryons between the ISM and CGM is a fundamental driver of galaxy evolution, yet this process remains poorly understood at high redshift. In this talk, I present results from THESAN-ZOOM, a suite of high-resolution cosmological simulations combining a cutting-edge ISM model with on-the-fly radiative transfer, with a focus on how bursty star formation shapes the gaseous environments of early galaxies. I show that the highly stochastic star-formation histories of high-redshift galaxies drive temporally differential galactic winds where starbursts expel oxygen-rich supernova ejecta into the CGM. This produces a chemically stratified CGM-ISM system in which the composition of inflowing and outflowing gas differs dramatically depending on the phase of the burst cycle, and naturally leads to nitrogen-rich galaxies, reproducing JWST observations without requiring exotic stellar yields. I demonstrate that these differential winds cause the canonical gas-phase fundamental metallicity relation to break down and invert for low-mass galaxies, as regular dilution by low-metallicity inflows dominates over the expected equilibrium behaviour. To robustly connect these predictions to observations, I present COLT, a state-of-the-art MCRT code that forward-models nebular line and continuum emission in cosmological simulations from first principles, bringing microphysics previously restricted to 1D photoionization codes to the full galaxy scale. Applied to THESAN-ZOOM, COLT reproduces observed high-redshift emission line ratios and enables direct predictions for how chemical abundances measured from ionized gas trace different phases of the baryon cycle.

Measuring the detailed stellar chemical abundances of z>3 massive quiescent galaxies

Authors
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Abstract
The stellar chemical abundances in galaxies preserve a wealth of information about the physical processes and conditions when each star formed. One particularly useful measurement is the alpha abundance in quiescent galaxies, which, due to the elements' different production channels compared to iron-peak elements, can be used to trace the duration of past star formation in galaxies. The alpha abundance of lower redshift quiescent galaxies has been well studied in the past two decades, and measurements are beginning to be obtained for z>2 galaxies.

Using a sample of the earliest massive quiescent galaxies at z>3 observed through JWST NIRSpec R~1000 spectroscopy, we test the measurement of their stellar metallicity and alpha-abundance jointly with their star formation histories. We found significant disagreements between abundance estimates from different stellar population models, different fitted wavelength ranges and fitting codes. This demonstrates the difficulty of probing detailed stellar chemical abundances of high-redshift galaxies, a result of their younger ages and lower data quality.

Despite the disagreements, we show that z>3 massive quiescent galaxies are generally alpha-enhanced. They likely have comparable stellar metallicity to lower redshift quiescent galaxies with the same stellar mass. We also uncovered evidence that archaeological downsizing was already in place by z~4.

The importance of measuring nebular attenuation curves for accurate gas-phase metallicity measurements

Authors

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Abstract

Correcting emission line fluxes for dust attenuation is an integral first step in measuring gas-phase metallicities from spectra. However, the shape of the nebular attenuation curve we use to de-redden these emission-line fluxes is typically assumed to follow the Milky Way extinction curve or the Calzetti+00 attenuation curve with little physical reasoning. Measurements of this nebular attenuation curve have proven challenging even at low redshifts, and at high redshifts, few studies have accurately constrained its shape due to the need for high signal-to-noise measurements of several Hydrogen Balmer lines. Here, we present recent results accurately constraining the shape of the nebular attenuation curve at cosmic noon for a sample of 15 galaxies from the Blue Jay survey between the rest-optical and the rest-NIR.

Our results indicate that the common assumption of a fixed Milky-Way-like attenuation curve for nebular emission is invalid, since several of our low mass galaxies (log(M*/M_sol)<~10) show substantial variation in the slopes of the attenuation curves. This diversity can be attributed to variations in the dust composition or star-dust geometry (such as the dust covering fraction), and can introduce a significant systematic uncertainty in measurements of metallicity from strong-line calibrations and from the direct method. With JWST NIRSpec, this systematic uncertainty is of a similar order to the measurement uncertainty, and therefore, studying the shape of these nebular attenuation curves for even larger samples of galaxies is essential for constraining metallicity for high-redshift galaxies.

Galactic Morpholography: Linking Galaxy Structure to Chemical Evolution and Assembly Histories

Authors

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Abstract

We show that galaxy structure encodes key information about chemical enrichment and star formation histories. Using the 200m6 run of the COLIBRE cosmological hydrodynamical simulation, we analyse stellar populations across the mass–size plane at z=0. We find that structural compactness strongly correlates with chemical abundance ratios, in particular [Mg/Fe], as well as with luminosity-weighted stellar age, specific star formation rate, and ex-situ stellar mass fraction.
These correlations indicate that compact galaxies experienced rapid, early star formation and short enrichment timescales, while extended systems formed more gradually. We interpret these trends as a structural–chemical mapping, in which present-day galaxy structure encodes information about chemical evolution histories. By analogy with optical holography, we refer to this mapping as morpholography.
Applying this framework, we identify a population of ultra-compact massive galaxies with enhanced [Mg/Fe] and negligible merger growth, consistent with relic systems. Our results highlight a direct connection between galaxy structure, chemical enrichment, and evolutionary pathways, and provide a new avenue for comparing simulations and observations.

Probing feedback and metal enrichment with the Circumgalactic Medium

Authors

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Abstract

The circumgalactic medium (CGM) acts as both the reservoir of gas that fuels star formation and galaxy growth, as well as the interface where galaxies deposit the products of stellar evolution and feedback, making it a crucial site for constraining galaxy formation physics. The column densities and covering fractions of ions in the CGM provide powerful observational probes of gas flows across the CGM. Different ions (Mg II, O VI, C IV) trace distinct phases of the CGM, and their combination can provide strong constraints on feedback and metal enrichment. In this talk, I will present a systematic study exploring how variations in galaxy formation parameters, particularly those governing stellar feedback and the metal loading of outflows, impact these observables. Using cosmological zoom-in simulations of Milky Way-mass galaxies from the Auriga simulations, I quantify how changes in feedback parameters influence metal transport in the CGM and alter the distribution and ionisation state of the gas. By connecting cosmological simulations to CGM observables, this work provides a framework for interpreting observations and serves as a benchmark for constraining galaxy formation models.

Decoding the Drivers of Gas-Phase Metallicity across Cosmic Time

Authors

Maria Koller (1)

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Abstract

Tracing the chemical evolution of galaxies provides a window into the interplay between star formation, feedback, and gas flows. While the primary drivers of gas-phase metallicity are well-established in the local Universe (e.g., Koller et al. 2026), their evolution toward the earliest cosmic epochs remains unclear. Using JADES data ($0.5 < z < 10$), we apply Random Forest regressions and Partial Correlation Coefficients to isolate causation from correlation, directly comparing the high-redshift baryon cycle to local benchmarks.

Our analysis reveals a fundamental transformation in the drivers of chemical enrichment. We find that stellar mass dominates gas-phase metallicity at high redshift, while gravitational potential becomes negligible. Notably, while a Fundamental Metallicity Relation (FMR) is in place, the contribution of SFR is significantly weaker than that of stellar mass. Conversely, galaxy size emerges as a much more critical driver than in local galaxies, even surpassing SFR in importance.

We observe a positive correlation between gas-phase metallicity and effective radius, a stark reversal of the negative correlation observed for the local Universe. We find that more compact galaxies exhibit the strongest negative offsets from the local FMR, becoming increasingly metal-deficient. We interpret these combined findings in terms of compaction phases; in this regime, rapid infalls of pristine gas simultaneously trigger bursty star formation, compact the galaxy, and dilute the gas-phase metallicity.

We complement these observations with an identical analysis of the Thesan-Zoom simulations, providing insights into the galaxy assembly from the first billion years to today. This framework provides a vital benchmark for interpreting upcoming massive datasets from next-generation facilities like the ELT and MOONS/MOONRISE.

Connecting individual H II Region Abundances and Star Formation in M31

Authors

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Abstract

Understanding the evolution of galaxies requires linking the physics of cloud-scale star formation to galaxy-wide chemical abundance variations in the interstellar medium (ISM). The Andromeda galaxy (M31) provides a unique laboratory in which individual giant molecular clouds (GMCs) and their associated H II regions can be resolved across an entire galaxy disc. We present results from a multi-wavelength study combining high-resolution (approx.15 pc) Submillimeter Array observations of dust continuum and CO emission with optical spectroscopy of HII regions from the MMT/Hectospec. From these data, we calculate both the CO-to-dust mass conversion factor (alpha'CO), and the chemical abundances of nearby H II regions for the same clouds.

The combination of these data enabled a direct test of the metallicity dependence of alpha'CO at resolved GMC scales across the disc of M31. Despite significant metallicity variation, α'CO remains approximately constant, challenging theoretical predictions if we assume a constant gas-to-dust ratio. In parallel, we find significant local scatter in 12 + log(O/H), 12 + log(N/H), and log(N/O) at all galactocentric radii (4 - 22 kpc). The observed trend in log(N/O) vs 12 + log(O/H) supports theoretical evidence that M31 formed from a more intense and rapid starburst than the Milky Way, leading to higher N/O at a given metallicity.

By linking GMC structure to H II region chemical abundances, this work connects the physical conditions of star formation within molecular clouds to galaxy-wide chemical enrichment, thus providing insight into the star-forming properties and evolutionary history of galaxies across cosmic time.

Chemical networks and the multiphase ISM in galaxy simulations (Invited)

Authors

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Abstract

We infer the properties of gas in and around galaxies from emission and absorption tied to specific chemical processes. In a wide variety of simulations, from individual patches of gas to cosmological simulations of galaxy formation, modelling this chemistry is essential both for comparing simulations with observations and for setting the thermodynamic and dynamical state of the gas. Yet fully detailed chemical networks are often computationally prohibitive, forcing compromises between cost and fidelity.

I will review commonly used chemical models and frameworks, including Grackle, CHIMES, Cloudy, and Hyacinth, and how they are applied in different simulation projects. I will focus on their treatment of key processes in atomic and molecular gas (ionisation, recombination, molecular formation and destruction, photo- and cosmic-ray heating, and metal-line cooling), and on how these choices shape the emerging multiphase interstellar medium in simulations. I will highlight trade-offs among network size, accuracy, and performance and outline current challenges. The goal is to provide a practical map of where improved chemistry is most likely to change physical conclusions.

The chemical enrichment of galaxies across the cosmic time (Invited)

Authors
Roberto Maolino (1)

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Abstract
The chemical enrichment of galaxies is the fingerprint of the many physical mechanisms and processes at work during the formation, evolution, and transformation of galaxies. In recent years, major progress has been made in obtaining observational constraints on the metallicities and relative chemical abundances of galaxies in the local Universe and at high redshift, as well as in developing new models and numerical simulations capable of reproducing many of the observed properties. However, recent data have also revealed new puzzling and intriguing features, some of which are challenging to explain within current chemical evolutionary scenarios. In this talk, I will provide a brief overview of recent results in this field, highlight the major open problems, and discuss how further progress will be enabled in the coming years by the next generation of observational facilities.

Posters

Nitrogen enhancement of GN-z11 due to the pollution from supermassive stars

Authors

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(4) Kavli Institute for Cosmology, University of Cambridge
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Abstract

The James Webb Space Telescope revealed that GN-z11 has nitrogen-rich chemical abundance compared to local galaxies (Cameron et al. 2023, Isobe et al. 2023, Senchyna et al. 2024). Possible origins of such nitrogen-rich interstellar medium are, for example, stellar wind from Wolf-Rayet stars, gas ejection from AGB stars, and tidal disruption events. Stellar winds of supermassive stars (SMSs) are also a possible origin, but so far, almost all previous studies have used one-zone models to study SMS pollution. We performed a more realistic galaxy chemo-dynamical simulation of a GN-z11-like galaxy using a cosmological zoom-in galaxy-formation simulation with the N-body/SPH code ASURA (Saitoh et al. 2009) and the chemical evolution library CELib (Saitoh et al. 2017). As a post-processing step, we added metal pollution from SMSs. Our simulated galaxy showed a higher log(N/O) than the solar abundance for a short time (<10 Myr) only with the pollution from WR stars, but it was typically below the GN-z11's value, log(N/O)>-0.25. Using stellar evolution calculations for 10^{3-5} Msun SMS (Nagele & Umeda 2023), we added the ejecta from the SMSs to the region estimated to be ionized by the SMSs. We found that SMS pollution can reproduce the log(N/O) and log(C/O) of GN-z11 if the pollution mass fraction ranges 10-30 %. Such a pollution fraction can be realized with the gas density of 10^{4-5} cm^-3, assuming a Strömgren sphere for the ionized region. We also compared the abundance ratios with those of other observed N/O-enhanced galaxies. Some of them can also be explained with our SMS model.

Stripped and Enriched: the role of ram–pressure in shaping chemical enrichment of galaxies at intermediate redshift

Authors

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Abstract

The chemical evolution of galaxies is shaped by their star formation histories and the exchange of gas with their environments. Metallicity provides key insights into these processes, reflecting the interplay between star formation and gas flows. A fundamental aspect of this evolution is the mass—metallicity relation, which captures the strong correlation between a galaxy stellar mass ($M_\star$) and its gas-phase oxygen abundance. In this study, we use MUSE observations to analyse star-forming disc galaxies in 12 clusters within the redshift range $0.3<z<0.5$. Galaxies were classified into three groups: ram-pressure stripping (RPS), control cluster, and control field. For the first time, we investigate the impact of RPS on gas-phase metallicities across a wide mass range of galaxies at intermediate redshift, comparing RPS galaxies to counterparts in both cluster and field environments. By analysing the integrated flux within galactic discs, our result reveals that, on average, RPS induces a metallicity enhancement of 0.2 dex over non-stripped galaxies. Contrary to the prevailing view that cluster membership alone drives metallicity enrichment, we find that control cluster galaxies exhibit metallicities comparable to field galaxies at a given $M_\star$, with only RPS galaxies displaying significantly higher metal content, highlighting the unique role of RPS in shaping the chemical properties of galaxies. These differences become more pronounced at lower $M_\star$, indicating that environmental influences play a more critical role in shaping the chemical evolution of lower-mass galaxies. Our findings suggest that both enhanced star formation rates and suppressed gas inflows — consequences of ram pressure stripping — drive the elevated metallicity observed in RPS galaxies.

Metal Trends in Dwarf Galactic Fashion

Authors

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Abstract

In this work, we investigate dwarf galaxy evolution across a broad parameter space by probing combinations of dark matter halo properties with different star formation efficiencies and supernova feedback strengths. Using high-resolution hydrodynamical simulations that includes the latest stellar physics, we study how structural parameters and star formation histories regulate gas mixing and chemical enrichment in dwarf galaxies ($M_* < 10^9 M_\odot$). Our models incorporate state-of-the-art, metallicity-dependent stellar yields and non-instantaneous enrichment from multiple channels, including hypernovae, pair-instability supernovae, sub-Chandrasekhar mass Type Ia supernovae, and neutron star mergers. This allows us to predict abundance patterns for all stable elements, from hydrogen to uranium, as well as gas-phase abundances (C, N, O, Ne, S, and Ar) and predicted stellar abundances. We explore how distinct evolutionary pathways give characteristic signatures in chemical space, such as [α/Fe] trends and the dispersion of r-process elements like Eu. Furthermore, we show the impact of halo concentration on metal retention, showing how diffuse halos struggle to expel gas through feedback-driven outflows. By isolating specific enrichment channels, we identify chemically peculiar stars that serve as observable tracers of underlying nucleosynthetic events. As large spectroscopic surveys provide new data, our models can be used as powerful tools to understand the physical phenomena behind the chemical diversity of the Universe.

Using gamma-ray bursts to probe the faint, distant galaxy population; consistency with the general star forming galaxy population at different redshift ranges.

Authors

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Abstract

Gamma-ray bursts (GRBs) are the most energetic explosions in the universe, often outshining their host galaxies. They have been discovered out to redshifts of ~9, revealing their host galaxies, which can go undetected in large galaxy surveys due to their faintness and distance. We can therefore use GRBs to probe the faintest, most distant galaxies in the universe, and use their imprint on the GRB afterglow to measure their properties such as metallicity. Due to the connection between GRBs and massive stars, these measurements are used to expand the star forming galaxy population measured in emission to lower masses and metallicities.

However, in this process, two assumptions are made that are highly uncertain. Firstly, much remains uncertain about whether the GRB host galaxy sample follows the same fundamental relations as general star forming galaxies and therefore if these two populations are actually the same. And secondly, it is currently unknown whether the line of sight metallicities obtained through the afterglow spectra of GRBs are probing the same component of galaxies as the emission line metallicities of galaxy samples obtained through integrated spectra, and therefore if we can even use the metallicity obtained from the GRB afterglow to compare to emission spectra obtained metallicites.

In this talk I will tackle the first of these issues, comparing the largest sample of GRB host galaxies (~100) for which we have a mass estimate through SED fitting and a metallicity from emission spectra, to large galaxy samples at similar redshifts, to investigate if GRB hosts are indeed part of the same population and follow the same fundamental relations as general star forming galaxies in different redshift bins.

Detailed Insights into the Evolution of the Gas-Phase Metallicity and Scaling Relations of a Large Sample at z > 3

Authors

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Abstract

With the launch of JWST and the superior capabilities of NIRSpec and NIRCam, our ability to study the interstellar medium (ISM), probing chemical enrichment, and structural properties of early galaxies has advanced immensely. Understanding what drives early chemical enrichment is a crucial, yet understudied aspect of galaxy formation. Recent JWST results show that galaxies at $z > 4$ deviate from the fundamental metallicity relation (FMR), suggesting an epoch where gas enrichment, accretion and feedback are not yet balanced. New strong-line diagnostics, independent of ionisation state, now allow for improved metallicity estimates where galaxies lack temperature-sensitive lines.

I will present a comprehensive study combining imaging from several surveys with spectroscopy from the Dawn JWST Archive, analysing 650 galaxies at $z > 3$ with a combination of metallicities obtained through the direct method and strong-line diagnostics. This large sample allows an exploration of how the mass-metallicity and size-metallicity relations evolve and how FMR deviations could correlate with structure and other physical parameters, revealing how chemical enrichment and galaxy growth interplay in galaxy evolution.

Environment as the origin of the plateau and scatter in the Stellar Mass-Metallicity Relation in dwarf galaxies

Authors
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Abstract
Below $M_\star\sim10^5\ \mathrm{M_\odot}$, dwarf galaxy satellites of the Milky Way (MW) depart from the canonical stellar mass--metallicity relation (SMZR), producing a `plateau' with markedly increased scatter. The origin of this feature is unresolved. We use data for Local Group dwarfs and the high-resolution radiation--hydrodynamical EDGE2 (Engineering Dwarfs at Galaxy formation's Edge 2) simulations to explore the origins of this plateau. We find that strong tidal stripping can displace individual systems (producing clear outliers) but is rare and insufficient to explain the full plateau population. Instead, we find isolated EDGE2 dwarfs naturally develop a large intrinsic scatter at low stellar mass ($M_\star\lesssim10^5\ \mathrm{M_\odot}$) driven by three coupled processes: (i) variations in central dark-matter density that set early star-formation and enrichment rates, (ii) merger-driven or inflow-induced dilution that temporarily lowers the mass-weighted metallicity, and (iii) differential metal retention controlled by confinement in dense filamentary circumgalactic environments. Rapid self-enrichment to ${\rm [Fe/H]} \sim-3$ within $\lesssim100$\,Myr establishes a lower metallicity floor in the plateau region, while early quenching (by reionisation for the lowest-mass systems or by infall for larger dwarfs) freezes galaxies in at different enrichment stages. We show that, together, these effects naturally populate the observed plateau without any need for additional physics. Our results imply that the plateau is an imprint of early dwarf formation and should be present in all environments.

Outside-in evolution with a twist: metallicity gradients and asymmetries in the SMC

Authors

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Abstract

Taking advantage of the near-infrared calcium triplet lines, we determine metallicities for a sample of more than 3500 red giant stars in the field of the Small Magellanic Cloud. We find a median metallicity of [Fe/H] = −1.05+/-0.01 dex with a negative metallicity gradient of −0.064+/-0.007 dex/deg between 1.2 and 6.0 degrees from the SMC centre, consistent with an outside-in evolution scenario. For the first time, we detect hints of a positive metallicity gradient within 1.2 deg, likely reflecting radial migration or centralized chemical enrichment. Azimuthal metallicity asymmetries are detected, with flatter gradients in the eastern and southern quadrants and steeper ones in the north and west. They are consistent with tidal interaction effects from the Large Magellanic Cloud. Finally, in spite of a clear distance and velocity bifurcations in the east, they seem to share a common chemical origin, in agreement with other studies.