The ATLID laser beam observed by the cosmic ray observatories Pierre Auger (Argentina), Telescope Array (USA) and VERITAS (USA)

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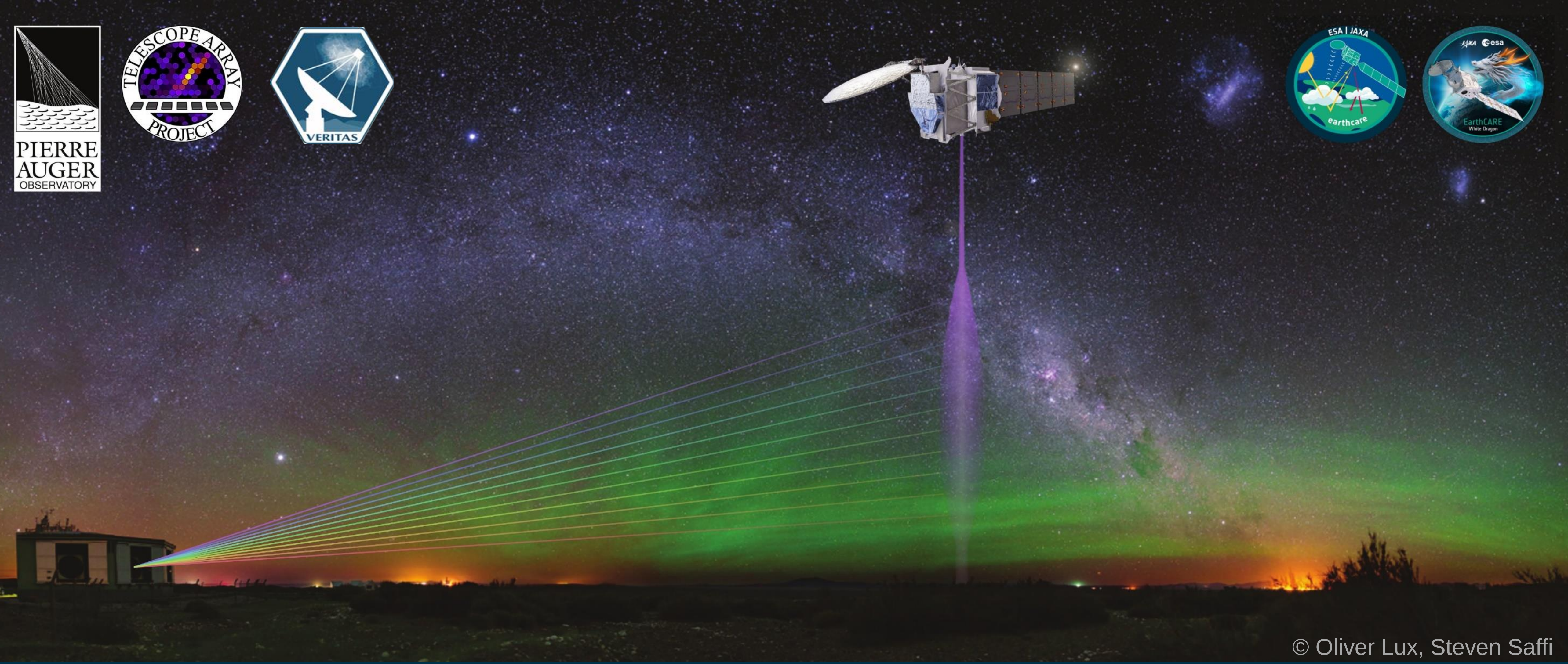


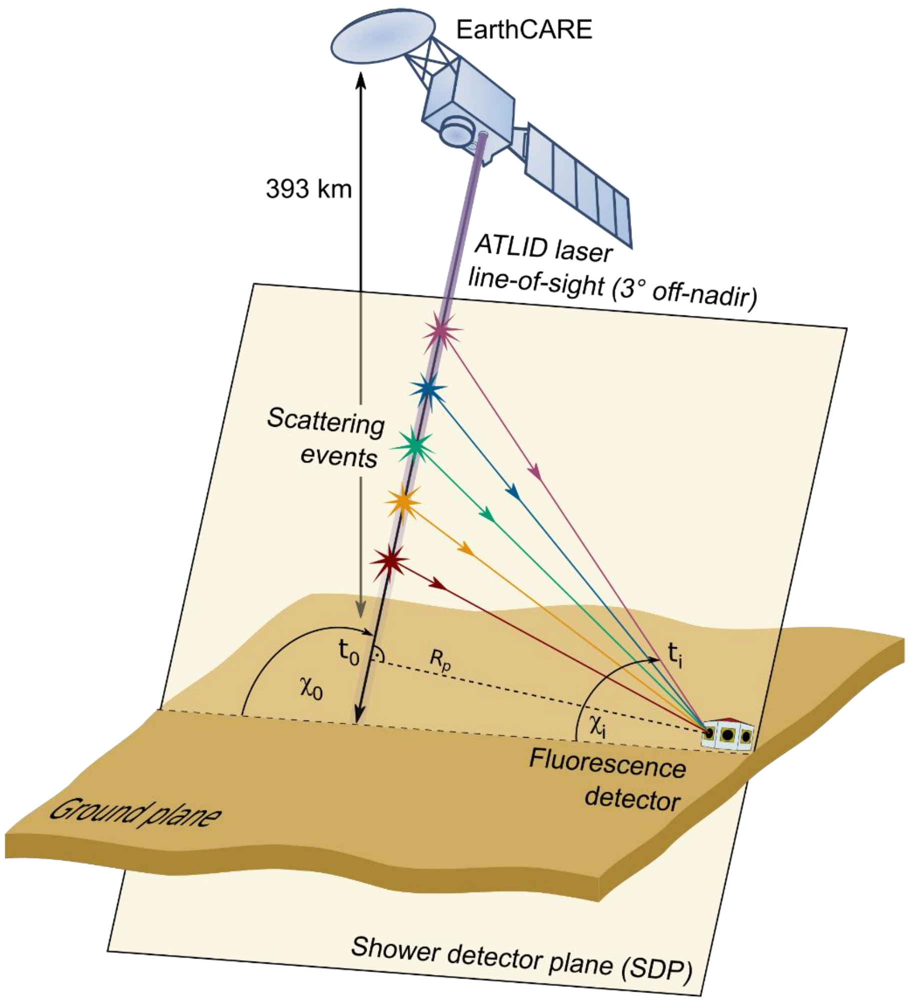
First observations of the laser beam of Aeolus by the Pierre Auger Observatory in 2019 (Auger Coll. et al. 2024, OPTICA).

ATLID laser beam is regularly measured at the Pierre Auger Observatory, the Telescope Array and VERITAS.

The ground-sites will be used to determine the geolocation of each laser shot and its laser energy.

ATLID laser beam will be exploited for inter-calibration between the two observatories: ATLID as a “calibration star”.

ATLID beam observations for each laser shot



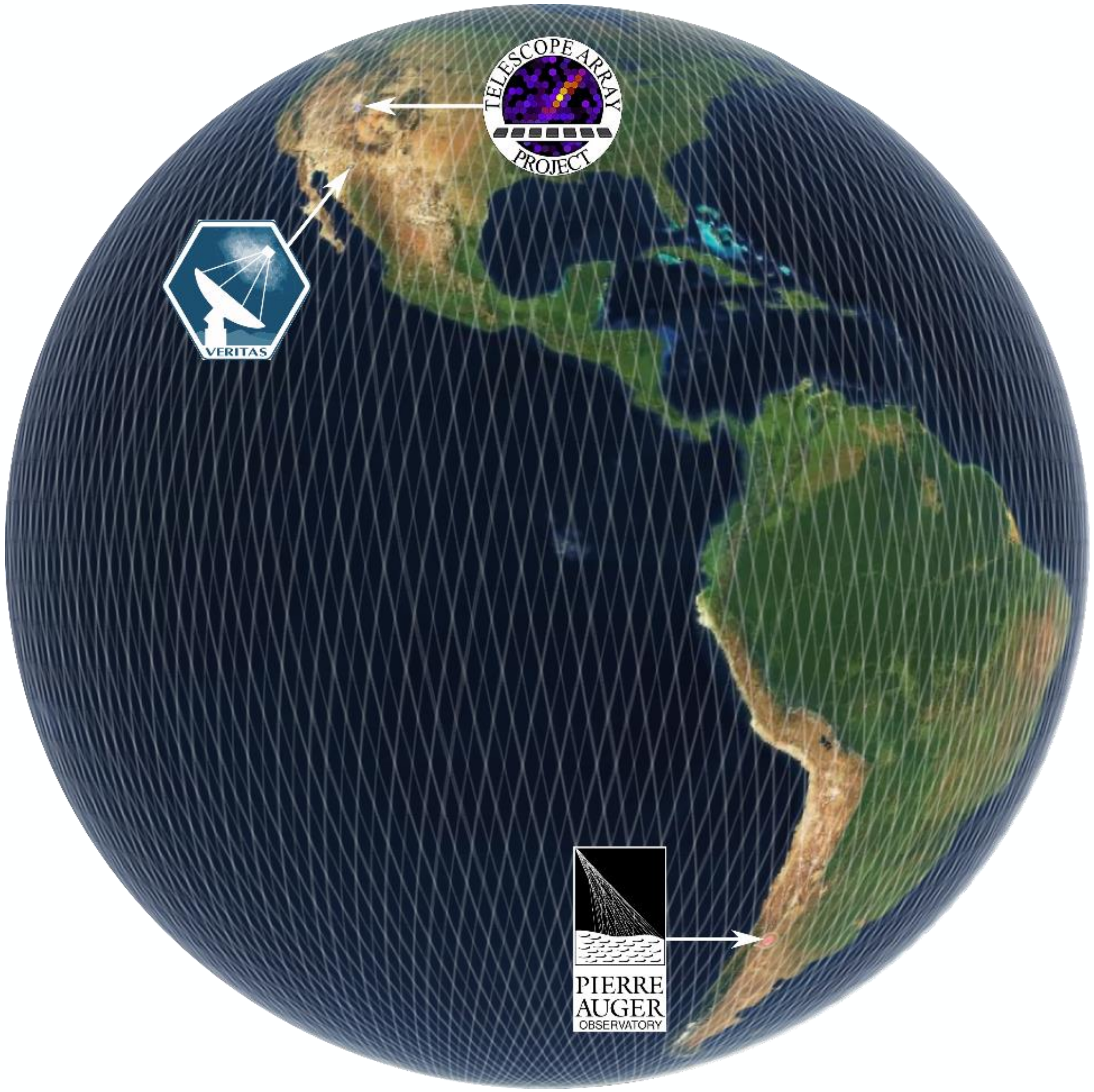
- Ground-based telescopes (Auger, TA) are used to **detect fluorescence light in the UV (380 nm – 430 nm)** from cosmic particles hitting N_2.
- **Observations of sideward Rayleigh and Mie scattering**
  => as ATLID laser beam is linearly polarized (in contrast to Aeolus, which was circular polarized), received light by ground-based telescopes depends on polarization direction and phase function.
- Reconstruction of **geo-location and LOS angles for every single laser shot possible** => with use of two ground-telescopes even stereo-reconstruction is possible with increased accuracy.
- Retrieval of **absolute laser energy from ATLID (in mJ) and its trend** is possible (as demonstrated for Aeolus with a few % accuracy); atmospheric transmission is used in the retrieval
  => preferably “clear-sky” Rayleigh atmosphere

Energy scales in astroparticle physics in eV (1 eV = $1.602 \cdot 10^{-19}$ J)

ATLID energy per photon @ 354.8 nm is 3.5 eV

ATLID energy per pulse 32 mJ = 200 PeV (10^{15} eV)

EarthCARE overpasses during its 25-d repeat cycle



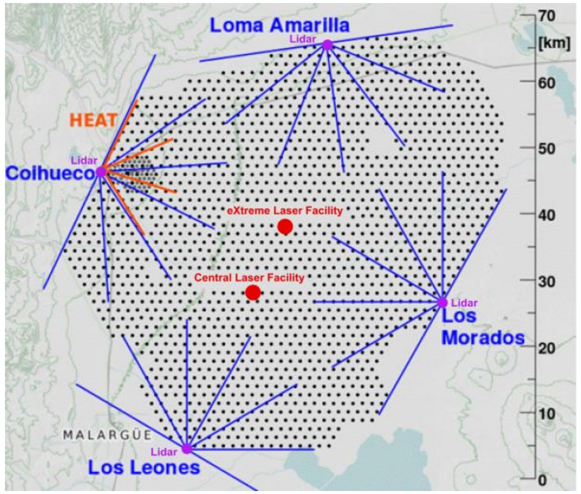
- **Each of the three observatories experiences two overpasses during each 25-day orbital repeat cycle** of EarthCARE; darkness for ascending orbits (2 am) is achieved during the complete year, in contrast to Aeolus on its dawn-dusk orbit (6 am/pm), which limited observations to a few months in the SH winter.
- **The two overpasses of the Telescope Array and VERITAS occur within just two minutes**, as they are aligned along the same orbit; **closest obser-vations (20–30 km) from TA and Auger occur within ~4 days.**

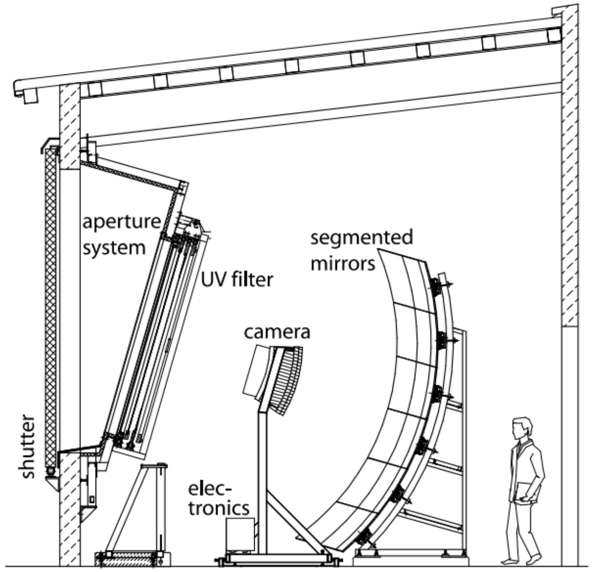
Observatories for ultra-high-energy cosmic ray particles with 10^{16} to 10^{20} eV

Pierre Auger Observatory Argentina

- 4 fluorescence detector sites spaced by 40 km, with a total of 24 telescopes of 13 m^2, 3 telescopes at additional site (HEAT)
- 440 photomultiplier tubes (PMTs) per telescope
- Elevation coverage: 1.5° to 30°
- 1,660 surface detector tanks filled with 12 t of ultra-pure water covering an area of ≈3,000 km²

The Pierre Auger Collaboration, The Pierre Auger Cosmic Ray Observatory, Nucl. Instrum. Methods Phys. Res. A: (2015).





Telescope Array Project Utah, USA

- 3 fluorescence detector sites on a 30 km triangle with a total of 38 telescopes
- 256 PMTs per telescope
- Elevation coverage: 3° to 33°
- 507 scintillator surface detectors on a square grid covering an area of about 700 km²

H. Tokuno et al., New air fluorescence detectors employed in the Telescope Array experiment, Nucl. Instrum. Methods Phys. Res. A (2012).

Observatories for gamma-ray photons with 10^9 to 10^{15} eV

VERITAS
Very Energetic Radiation Imaging Telescope Array System
Arizona, USA

- Detection of gamma rays (85 GeV to 30 TeV),
- Array of four atmospheric Cherenkov telescopes, each with a 12-meter segmented mirror consisting of 350 individual mirrors
- 499 PMTs on per telescope
- Field of view: 3.5°

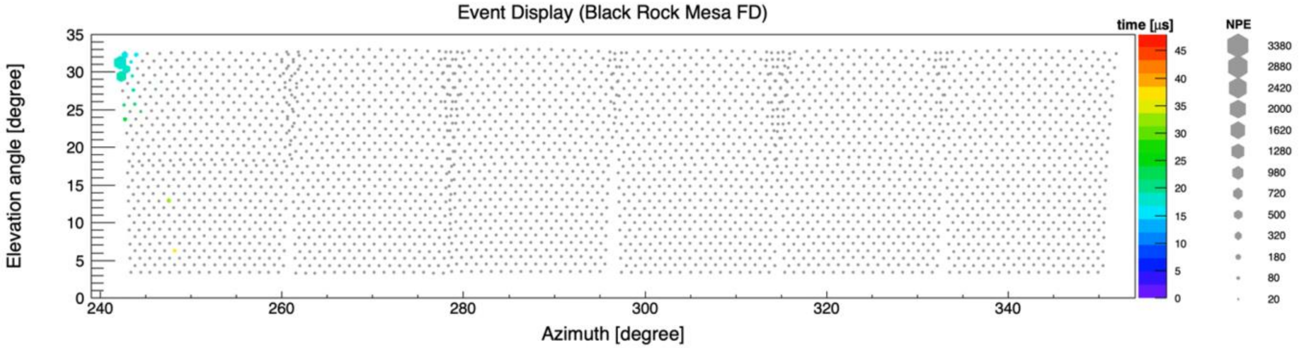
J. Holder et al. for the VERITAS Collaboration, The first VERITAS telescope, Astropart. Phys.: 25, 391-401 (2006).

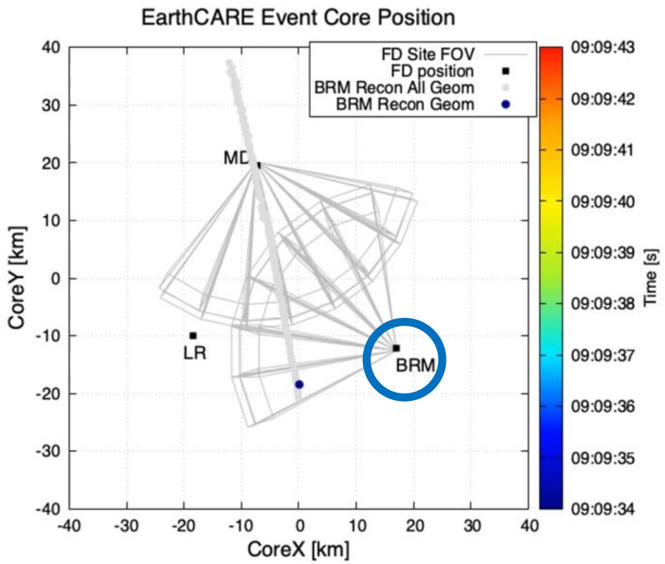
- Gammy-ray photons create Cherenkov light when hitting the atmosphere = > **detection in the UV to green.**
- Already laser beam from **CALIPSO and ICESAT-2** at 532 nm were detected by these telescopes.
- Observation at VERITAS requires **precise prediction of azimuth and elevation angles from ATLID,** since telescopes need to be accurately pointed towards ATLID due to the small field-of-view (3.5°).
- **Cherenkov Telescope Array Observatories (CTAO)** are built in the Northern (Island of La Palma, Spain) and Southern Hemisphere (Paranal, Chile).

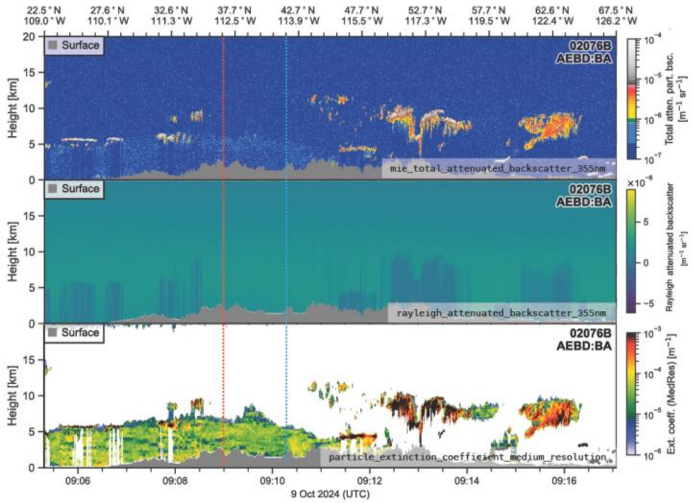
D. Hadasch and D. Mazin, Zukunft der Gammaastronomie, Phys. Zeit, 2025, DOI: 10.1002/piuz.70000

ATLID laser beam monitoring at Telescope Array

ATLID overpass from 9 Oct 2024 seen by telescopes at BRM site





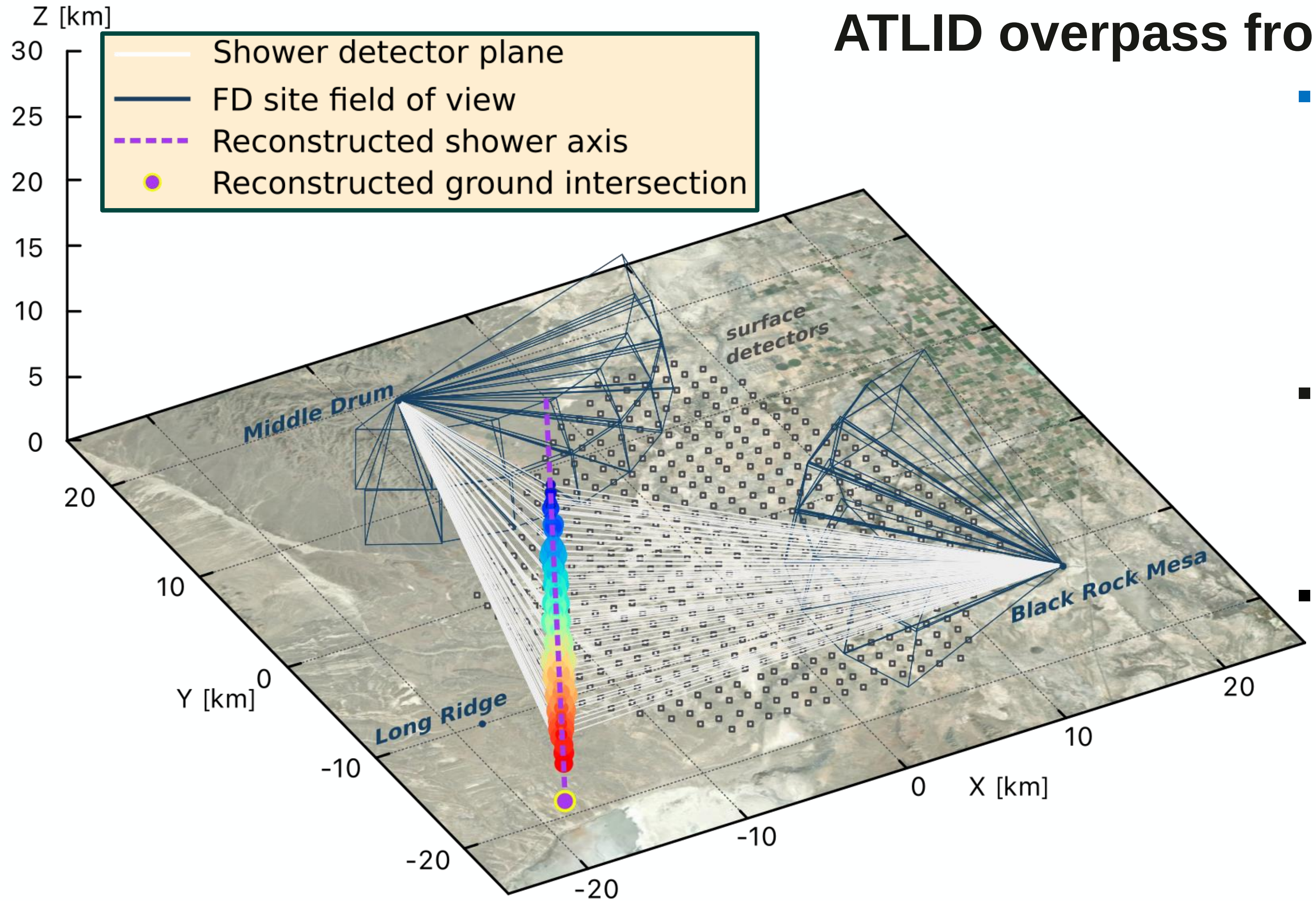


Result	Zenith [deg]	Azimuth [deg]	CoreX [km]	CoreY [km]	Rp [km]	Psi [deg]
Mono recon	3.000	144.147	0.721	-18.216	17.399	86.109

- Movie shows successive laser pulse detections at **Black Rock Mesa (BRM) telescopes** as function of elevation angle (y), azimuth angle (x), time (color) and number of photons (size of dot) for each detector PMT.
- **Geolocation for each pulse** using reconstruction with fixed ATLID zenith angle of 3°.
- **ATLID L1 (attenuated backscatter) and L2 (FM, TC)** are used for selection of clear-air events.

Movie by M. Teramoto (OECU)

Stereo-reconstruction by Telescope Array



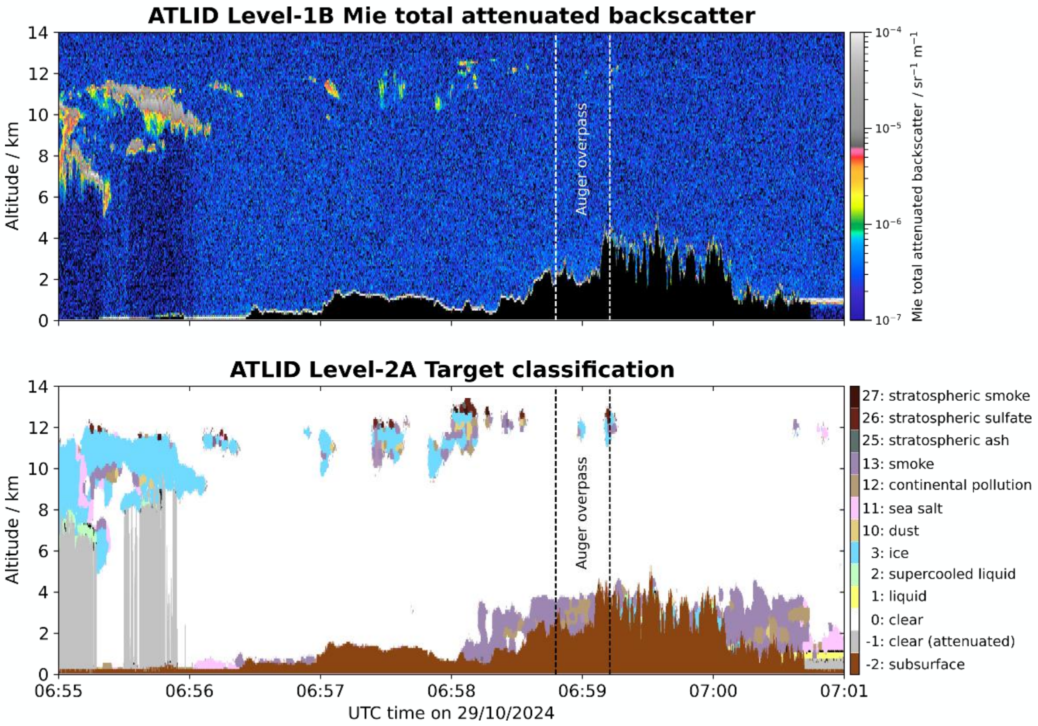
ATLID overpass from 22 May 2025

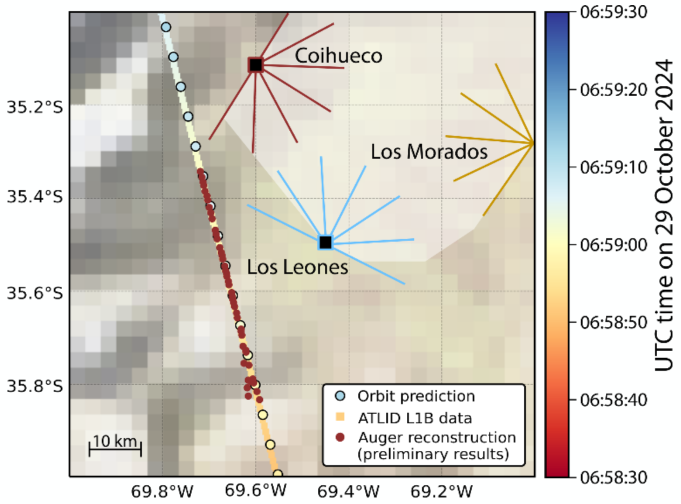
- **Stereo-reconstruction** using observations of ATLID laser beam by two ground-sites at the same time allows more precise reconstruction of geo-location and determination of ATLID pointing angles.
- Preliminary results indicate **zenith angle of larger than 3°**, confirming local zenith angles in Earth frame of 3.2° for ATLID.
- Using calibration data for TA energy and using linear depolarization of ATLID is on-going work; **preliminary estimates of the laser energy from TA indicate similar energies as reported by ATLID in L1 product for October 2024.**

Figure by M. Teramoto (OECU)

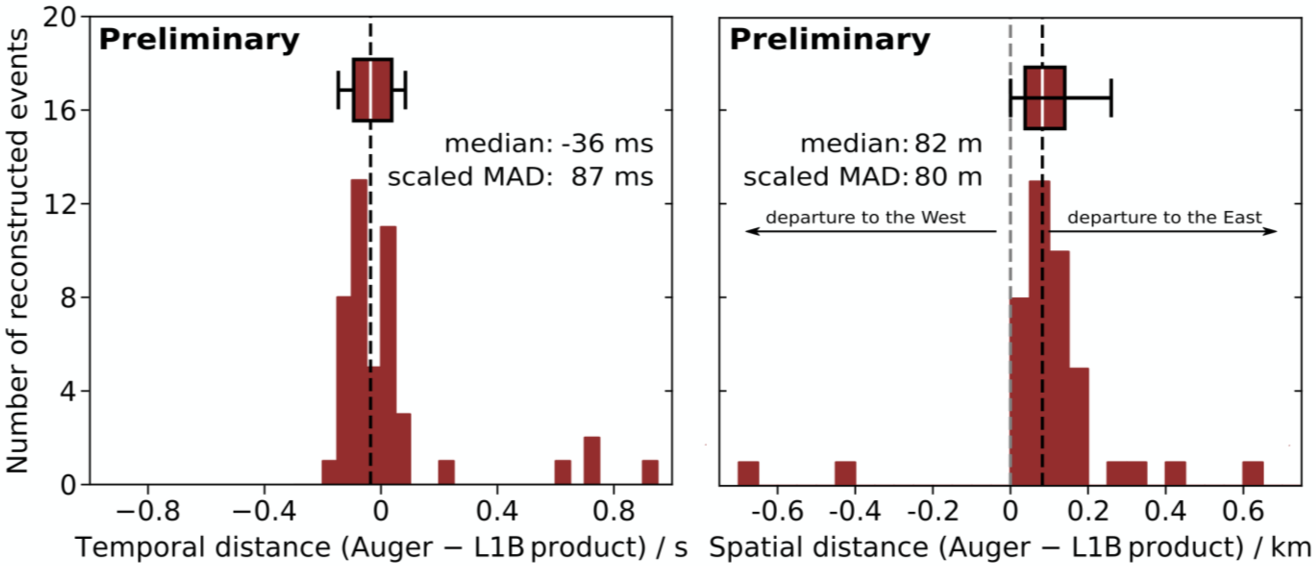
ATLID overpass from 29 October 2024

ATLID L1B-ATB and L2A-TC are used to assess aerosol/cloud content of overpass





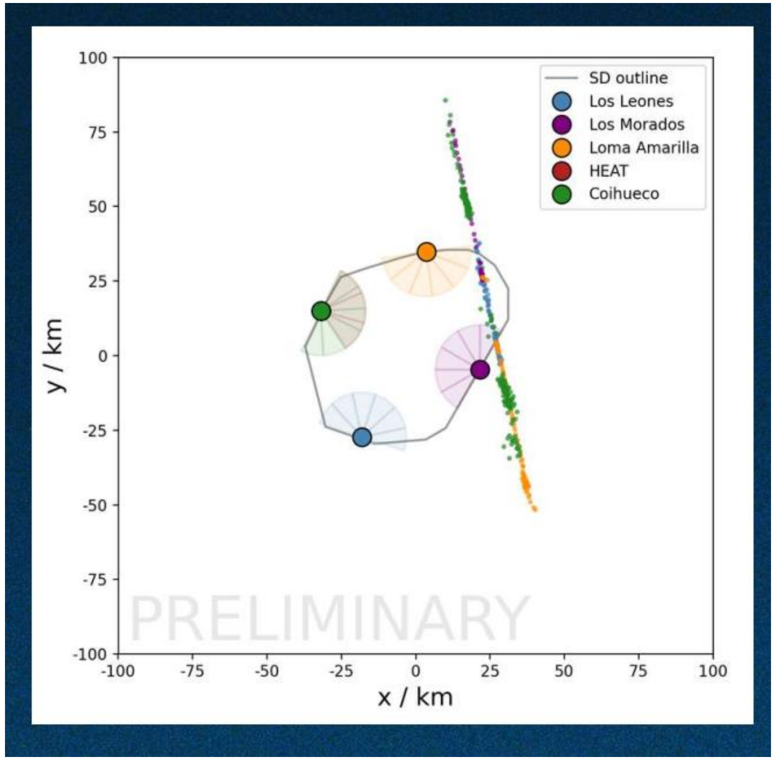
- Ground track predictions and L1 from ATLID L1 and Auger agree well.
- median temporal and spatial deviations are <100 ms and <100 m meters (preliminary).



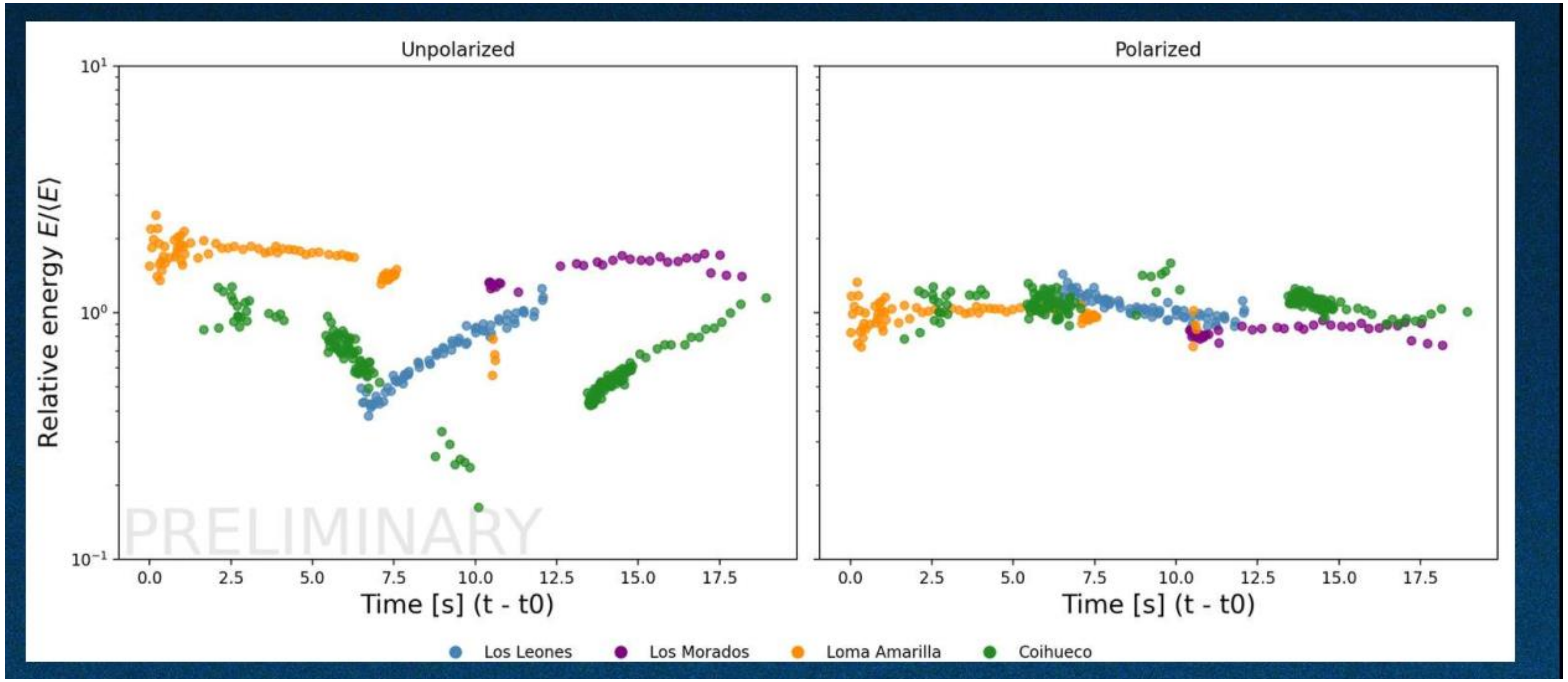
Figures by O. Lux (DLR) with data from T. Pineda (KIT)

Energy reconstruction by Auger observatory

ATLID overpass from 20 June 2025 seen by all 4 ground-based telescope sites



relative energy with unpolarized (left) and polarized laser light (right)



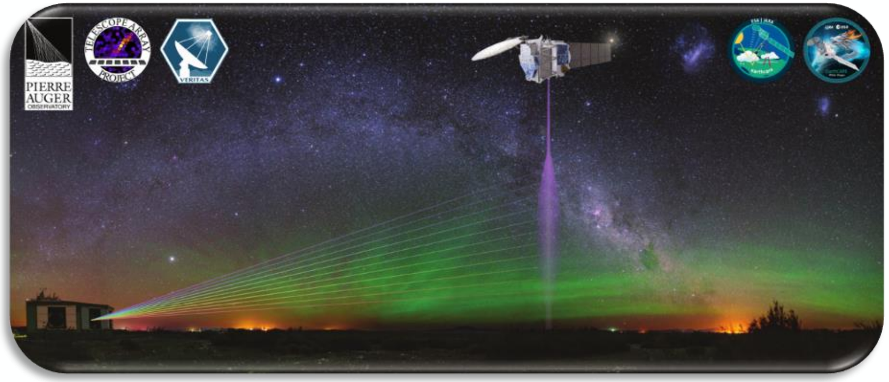
preliminary as average aerosol density and Auger calibration constants from 2023 are used

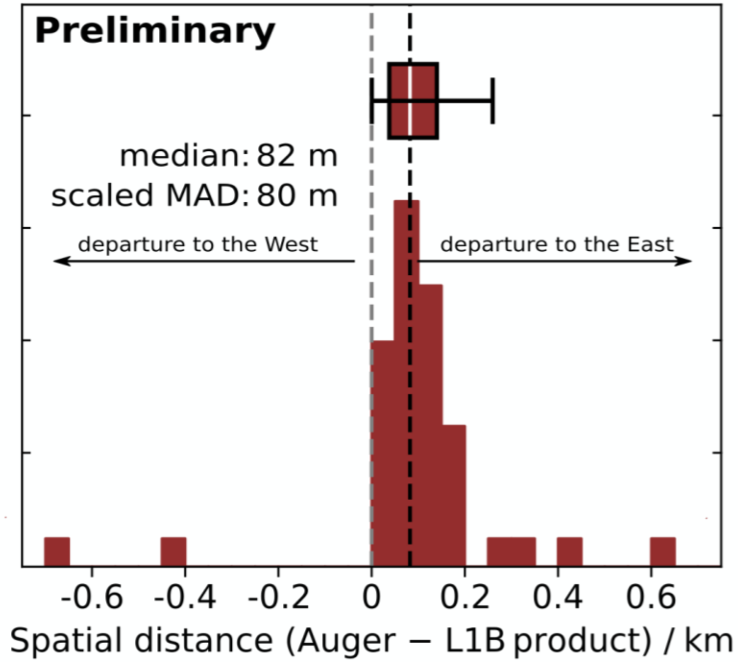
Figures by T. Pineda (KIT)

Conclusion: Earth Observation meets Astrophysics

- **First discovery of a space-borne ultraviolet laser beam from Aeolus in 2019** by an Earth-based observatory designed to detect ultra-high energy cosmic rays – the Pierre Auger Observatory.
- **EarthCARE ground-track** with 25 d repeat cycle and night-time ascending orbit **is favorable to be observed by the Pierre Auger Observatory, the Telescope Array and VERITAS**.
- First observations of the ATLID laser beam at Auger and Telescope Array in Oct-Nov 2024 **with median departures of geolocation of better than 100 m** (best case, preliminary) within mission requirements.
- First, preliminary estimates of the laser energy from TA **indicate similar energy as reported by ATLID for October 2024.**

- We will exploit, if **ATLID can be used as a "calibration star"** for inter-calibration of the energy of cosmic-ray observations* (Auger, TA) and Cherenkov Telescope Array Observatories (CTAO) under construction in the Northern and Southern Hemisphere.

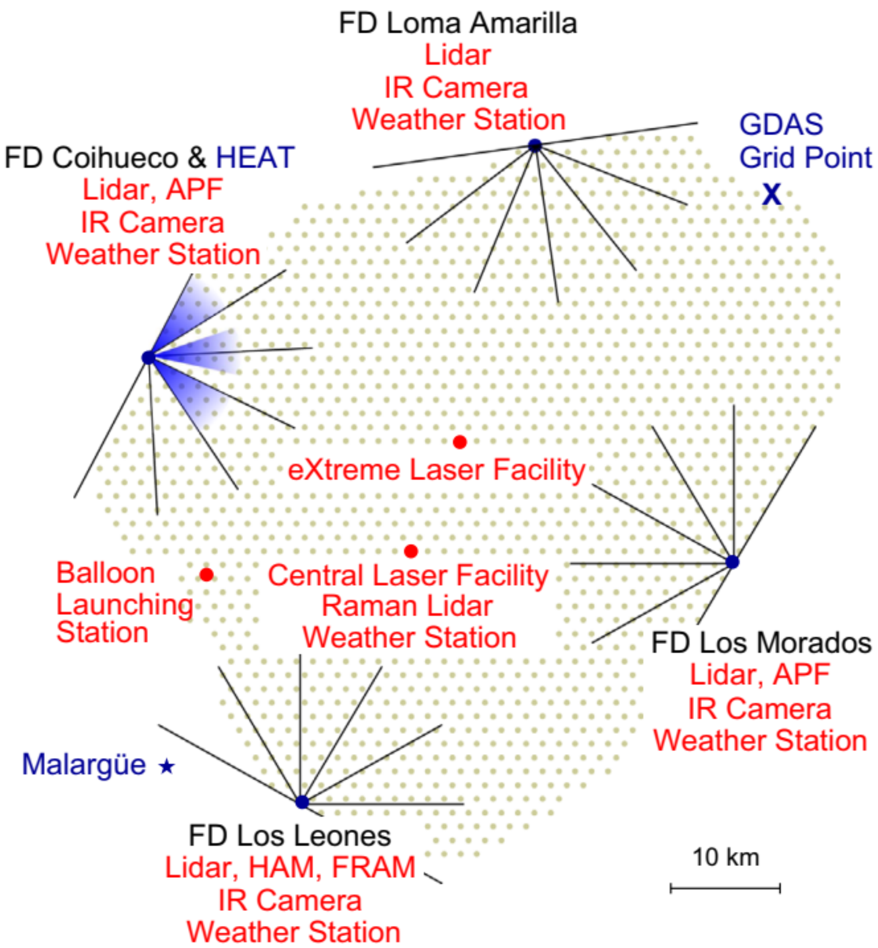




*The Pierre Auger Collaboration, ICRC 2025, https://pos.sissa.it/501/422

Backup slides

Atmospheric monitoring with lidars at Auger



- Characterization of aerosol optical depth and aerosol phase function (APF) for the 4 fluorescence detectors (FD) telescope sites.
- Each telescope site (FD) is equipped with an **elastic backscatter lidar** (Nd:YLF @ 351 nm) **with scanner.**
- **Central laser facility (CLF) is equipped with a Raman lidar** since 2013 (tripled Nd:YAG @ 354.7 nm, 6 mJ, 100 Hz) with N_2 and H_2O channel, aerosol α and β – retrieval by INFN, La Aquila, Italy.
- Scattering from the eXtreme Laser Facility (XLF) and CLF lasers (tripled Nd:YAG @ 354.7 nm) are recorded by the 4 telescope sites (FD).

The Pierre Auger Collaboration, The Pierre Auger Cosmic Ray Observatory, Nucl. Instrum. Methods Phys. Res. A: 798, 172–213 (2015)
Atmospheric Monitoring for High Energy AstroParticle Detectors AtmoHEAD workshops; last in 2024: E. Avocone, V. Rinzi, L. Valore, INFN//La Aquila,.Italy
B. Keilhauer, Atmospheric Monitoring for Astroparticle Physics Observatories, Proc. 38th International Cosmic Ray Conference (ICRC2023)