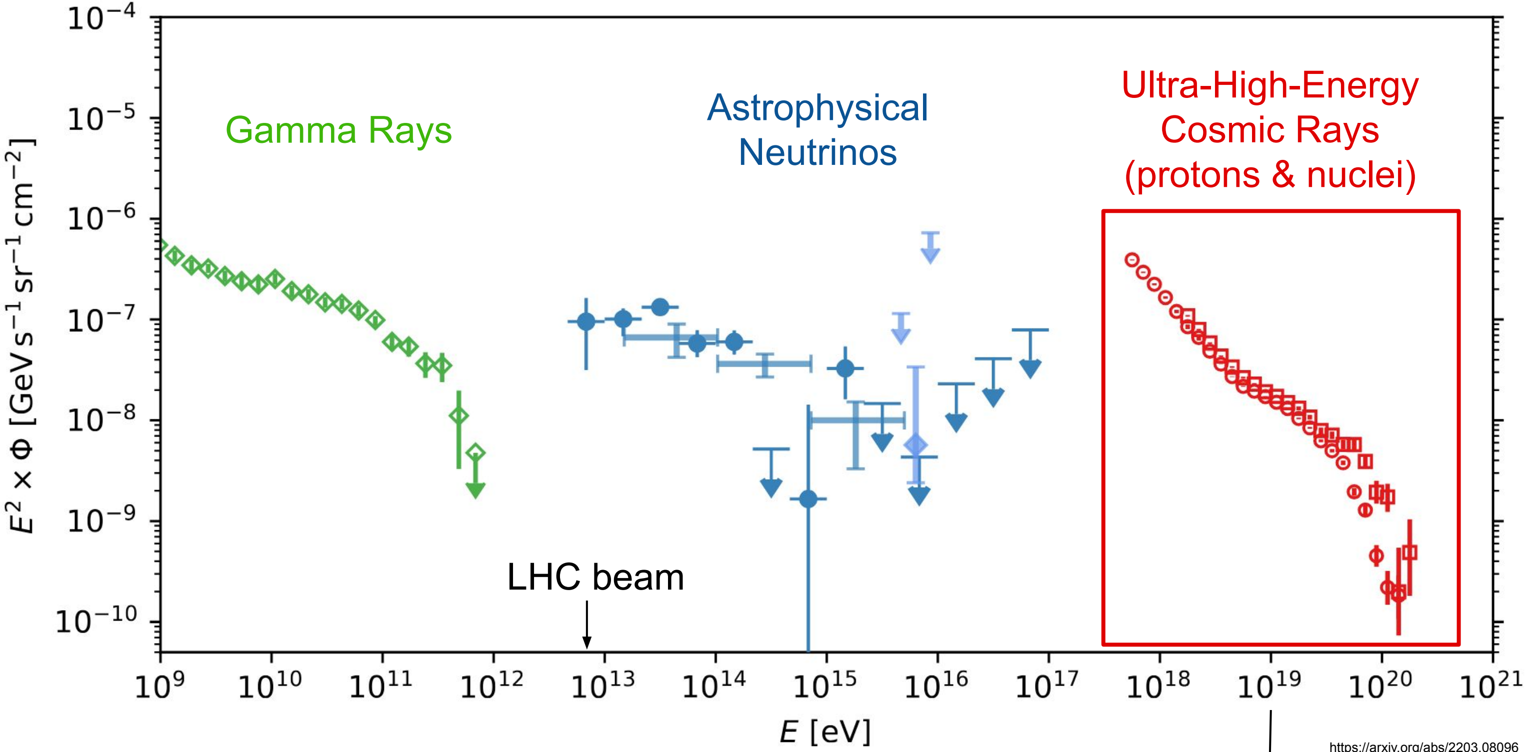
Ultra-High-Energy Cosmic-Ray and PeV-Photon Research @ IIHE

Ioana C. Mariș, Mateo Fernandez, Andrea Parenti (see IceCube talk), **Katarína Šimková**, Stijn Buitink (see SKA & LOFAR), Vincent Pelgrims, Ben Flaggs, (Yigit Aldirmaz, Nicolas Gonzalez)

IIHE Annual Meeting
10th November 2025, Brussels

Cosmic rays are the highest-energy particles known



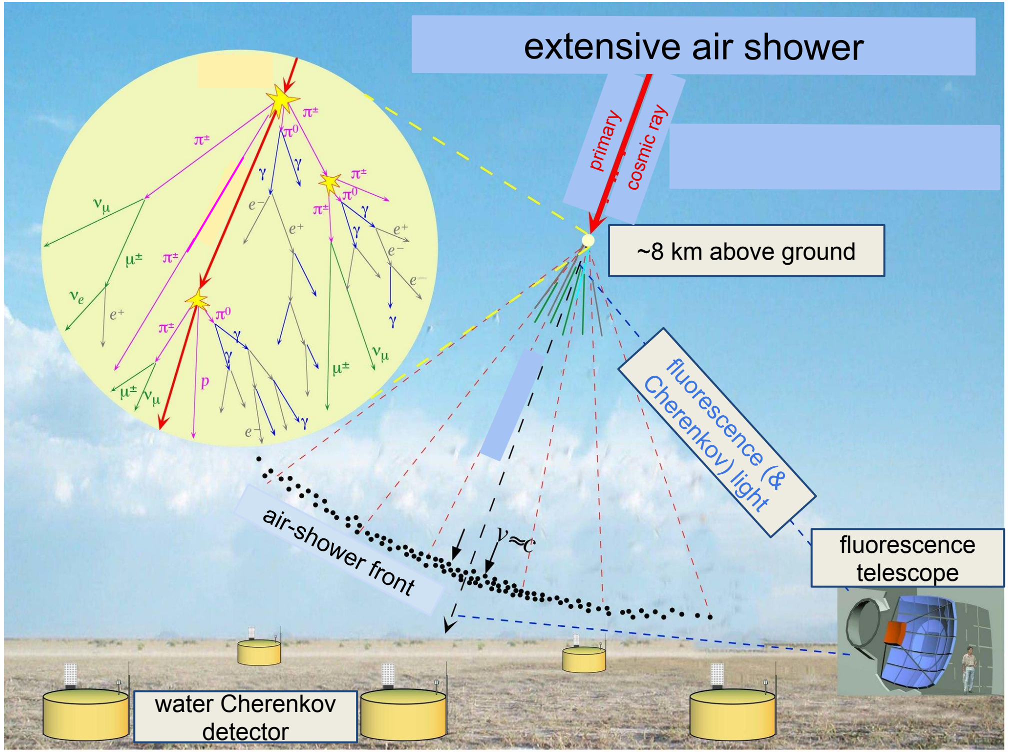
https://arxiv.org/abs/2203.08096

at 10 EeV ~1 particle/km^2/century

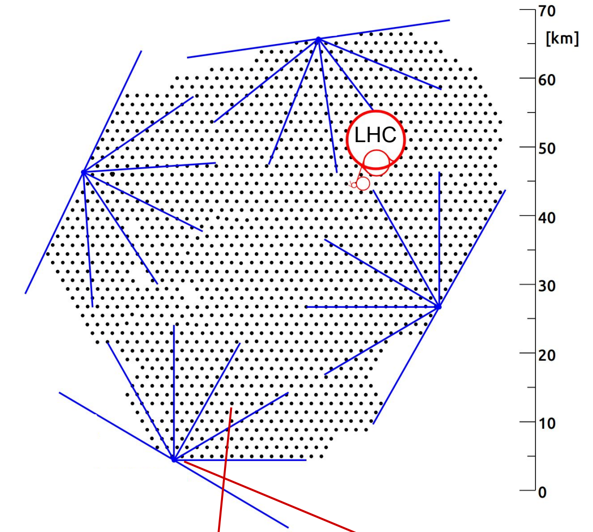
The Pierre Auger Observatory

World's largest cosmic-ray observatory spanning 3,000 km^2 in Argentinian pampa

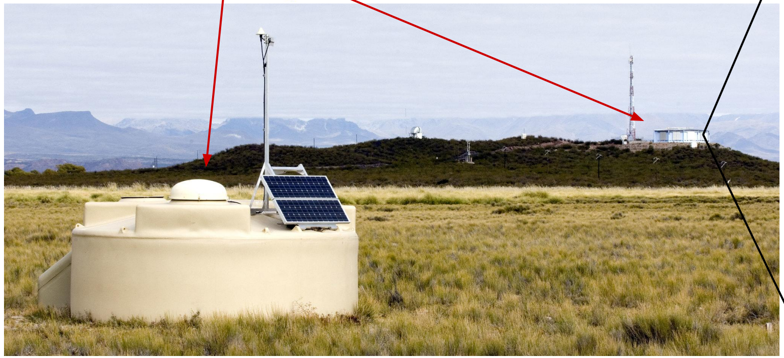
Operational since 2004, Auger group started at IIHE in 2018

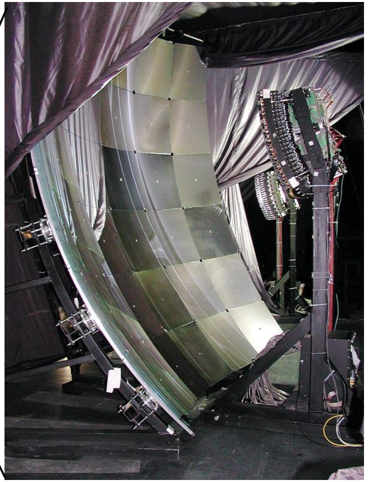


Surface and fluorescence detectors of Auger

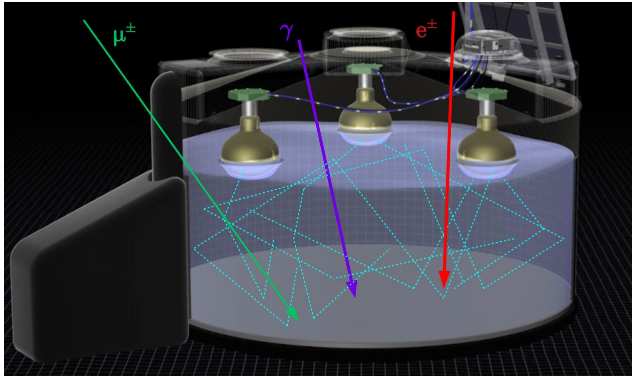


	surface det.	fluorescence det.
energy	✓	✓
arrival direction	✓	✗
primary mass	✓	✓
duty cycle	~100%	~15%





Water Cherenkov Detector (WCD)



We learnt much about UHECRs but questions remain

Spectrum above 10^{16} eV - observed cutoff

Composition heavier towards highest energies → maximum possible acceleration energy?

Muon puzzle: muon numbers in measurements > in hadronic models

Anisotropies:

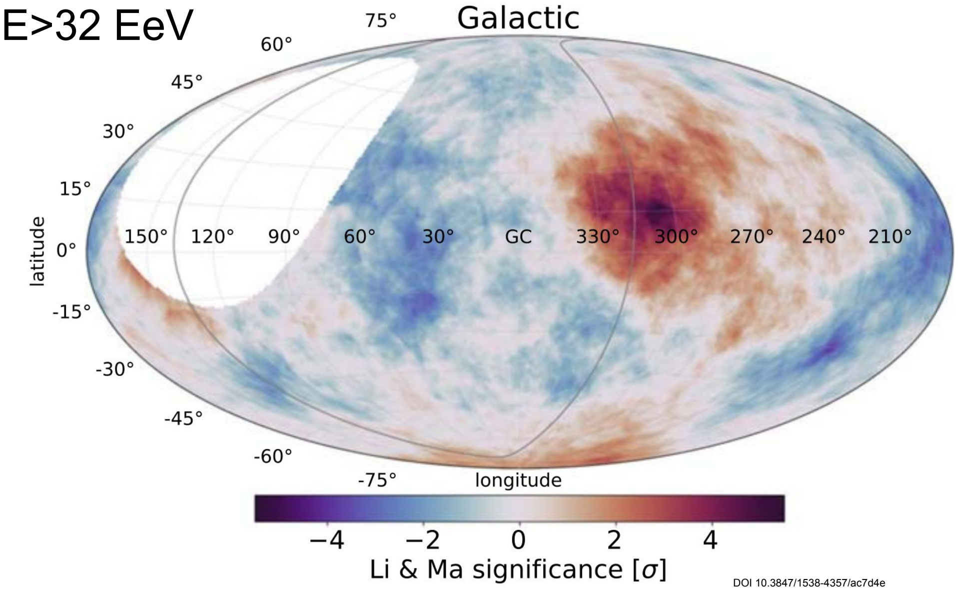
1. 6.8σ Dipole above 8 EeV → extragalactic sources
2. 4σ Anisotropy in Centaurus region at E>32 EeV

Persising questions:

What class(es) of sources?

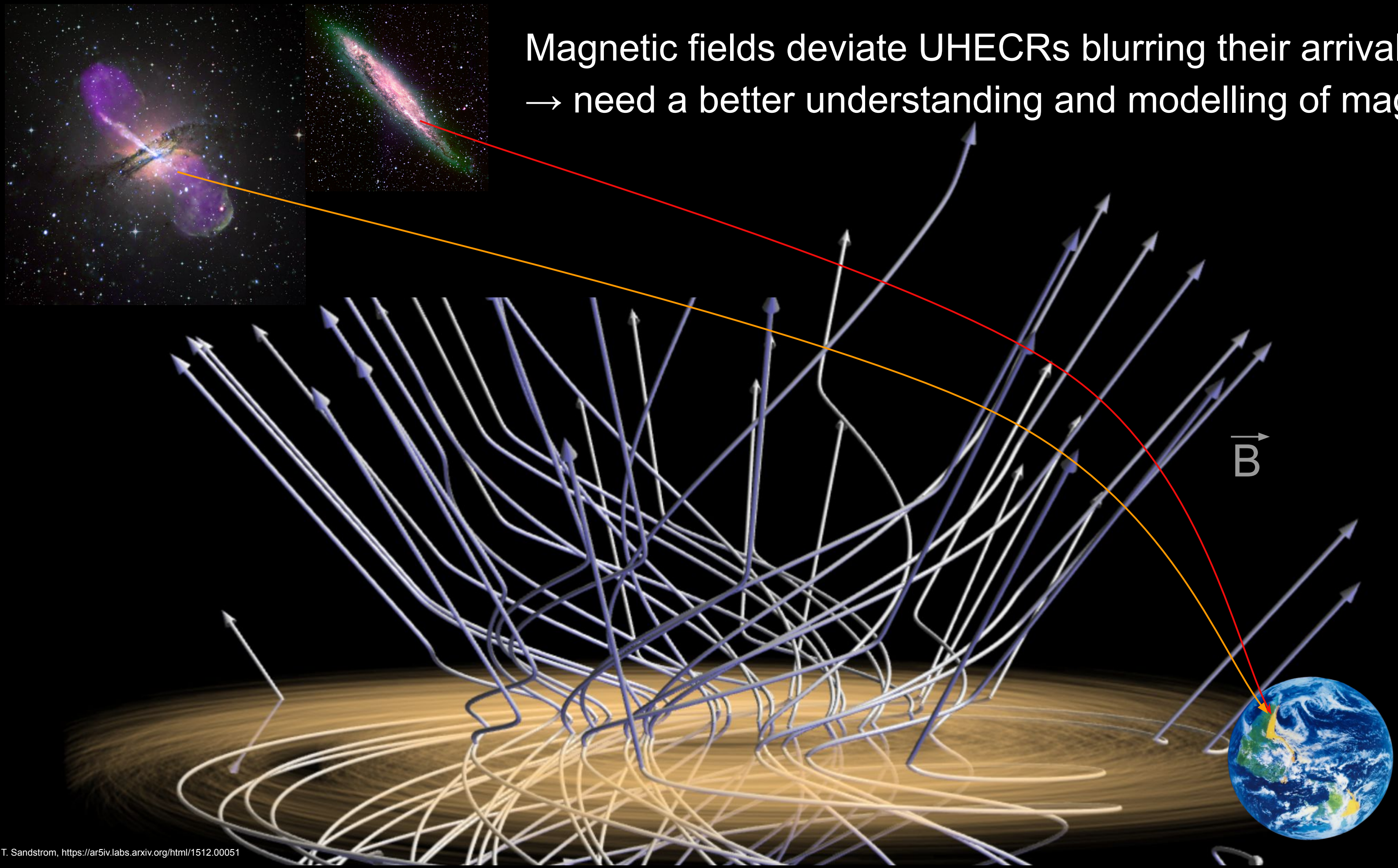
What acceleration mechanisms?

Any new fundamental physics?



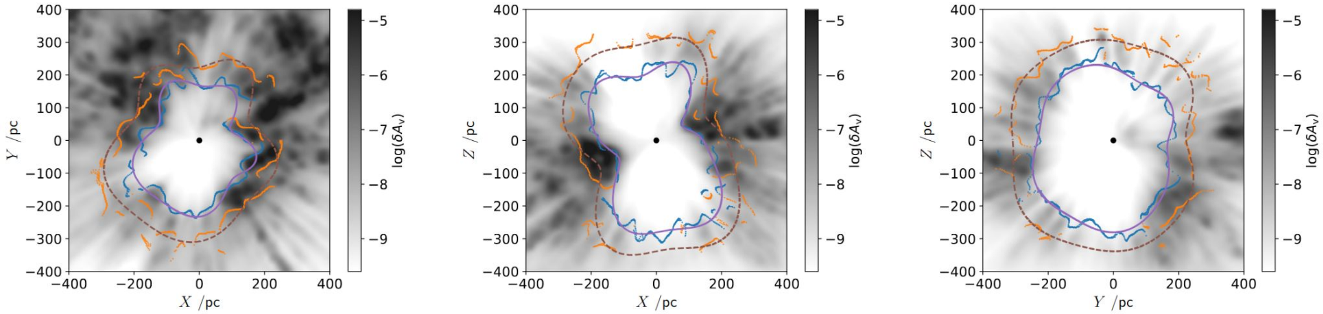
DOI 10.3847/1538-4357/ac7d4e

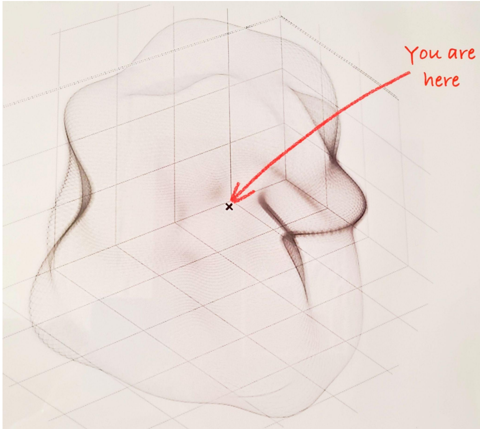
Magnetic fields deviate UHECRs blurring their arrival directions
→ need a better understanding and modelling of magnetic fields



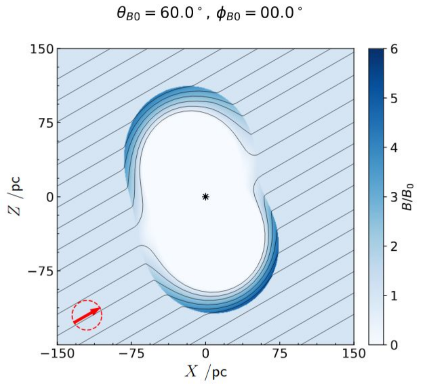
T. Sandstrom, https://ar5iv.labs.arxiv.org/html/1512.00051

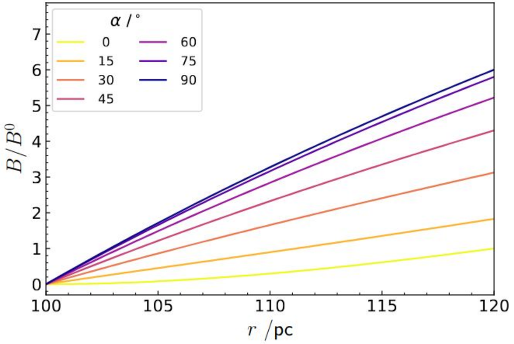
Modelling Local Bubble and incorporating it into $\vec{B}$ models





Thick-shell model:



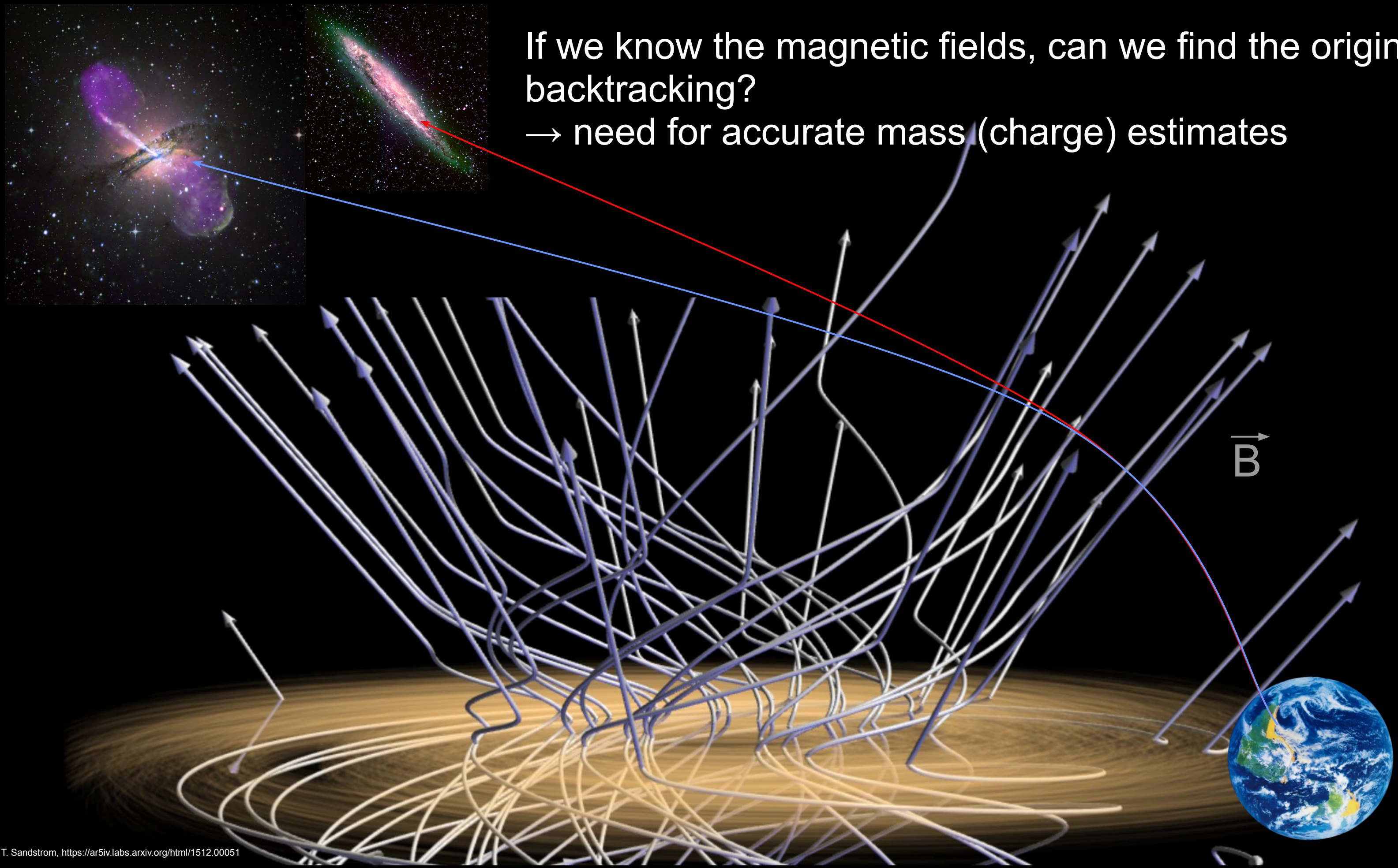


The bubble amplifies the initial magnetic field B^0

Conclusion: Negligible effect for UHECRs but important for lower-energy cosmic rays

Vincent, M. Unger and Ioana, published in A&A, DOI:[10.1051/0004-6361/202452943](https://doi.org/10.1051/0004-6361/202452943)

If we know the magnetic fields, can we find the original source via backtracking?
→ need for accurate mass (charge) estimates



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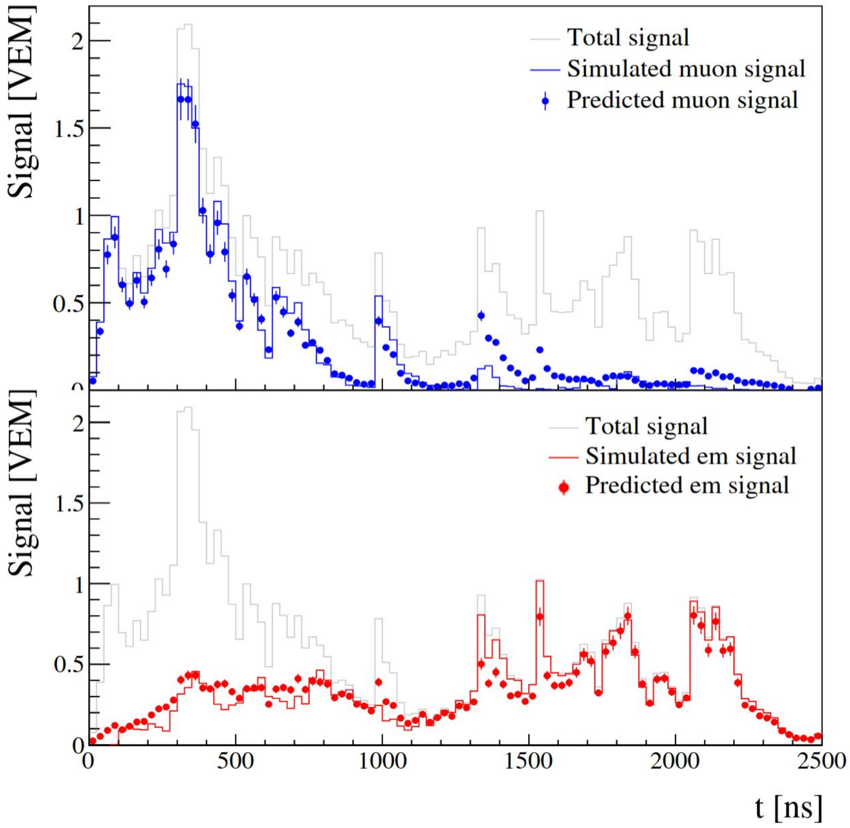
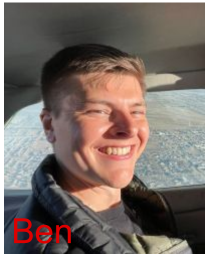
Neural Network to estimate muon signal



Muon number is helpful for primary mass estimate (heavier elements produce more muons) and photon/hadron separation

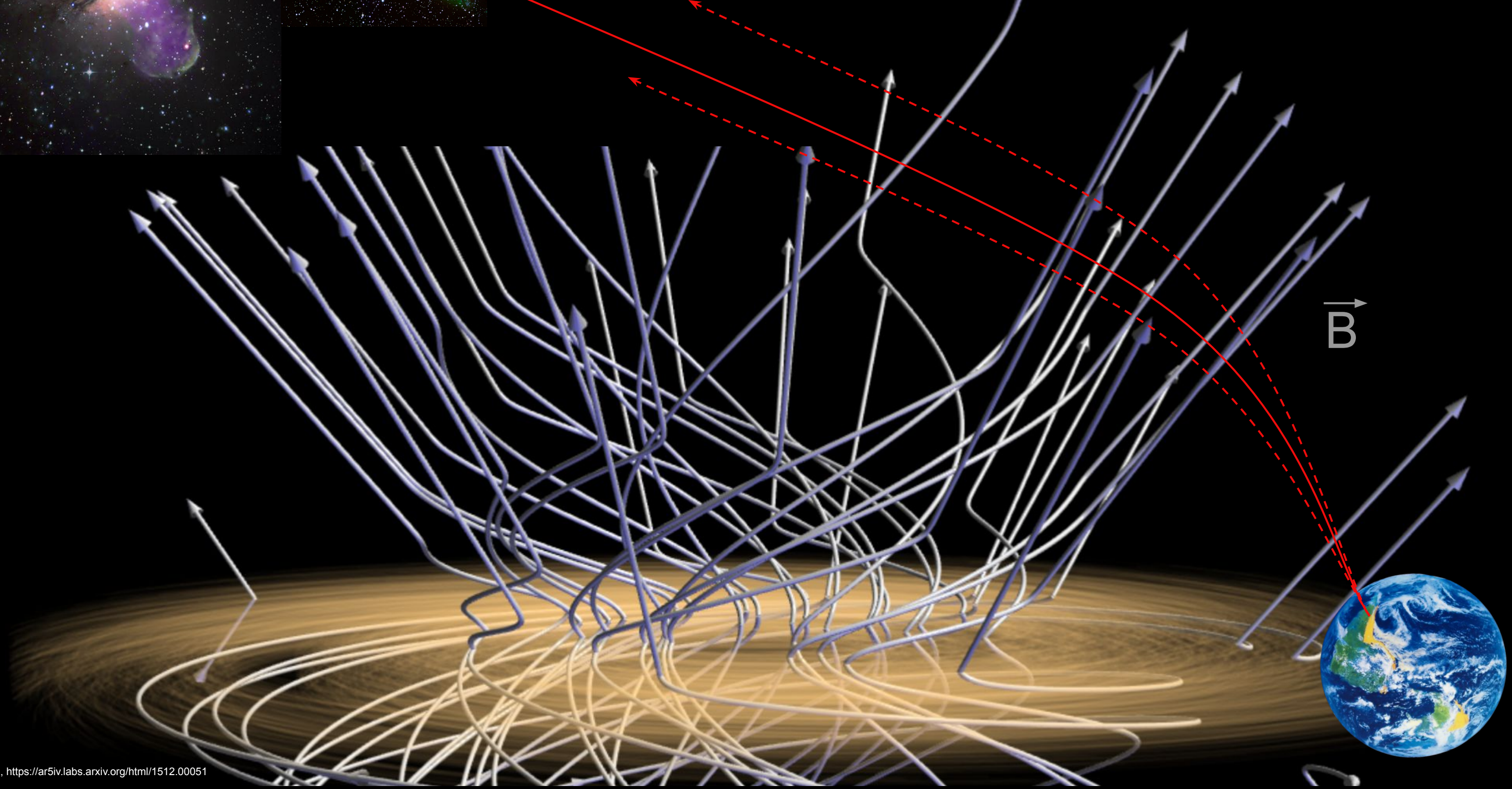
Orazio Zapparrata (defended in 2023) & Ioana included detector ageing effects

The NN is being reused by Ben, Mateo and Katarina



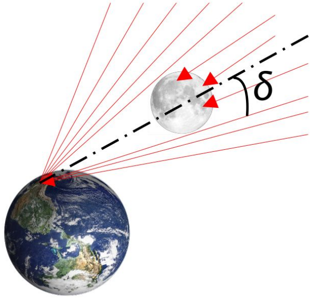
How accurate is our estimated arrival direction?

Can we improve it?



T. Sandstrom, https://ar5iv.labs.arxiv.org/html/1512.00051

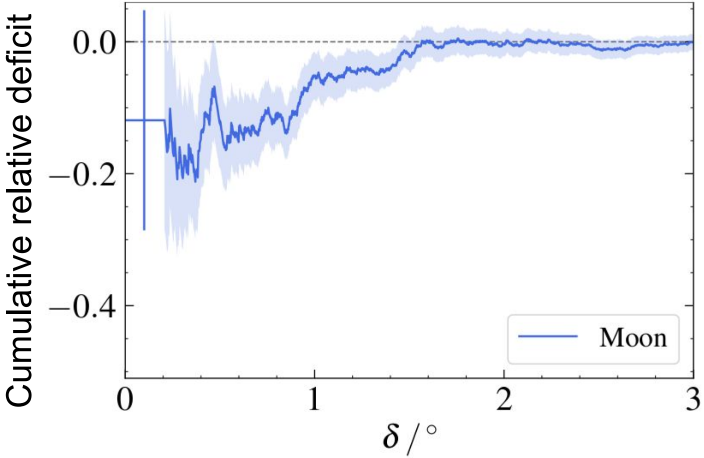
The first observation of the lunar and solar shadows above 10^{16} eV

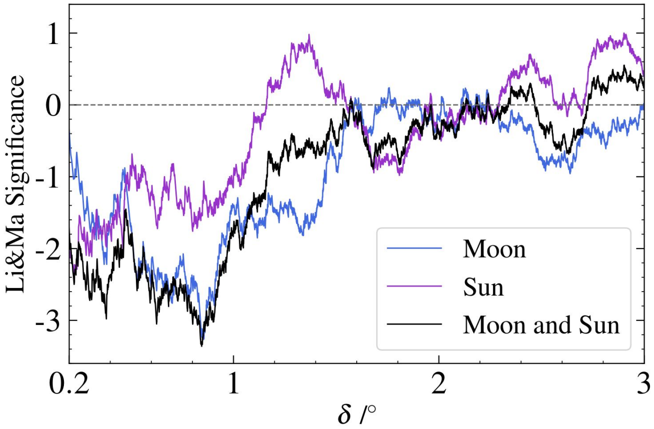


Cosmic rays are blocked by the Moon and the Sun with known position and angular radius of ~0.26°

Correct pointing and the effective angular resolution better than 1°

Unbinned likelihood fit significance of 3σ





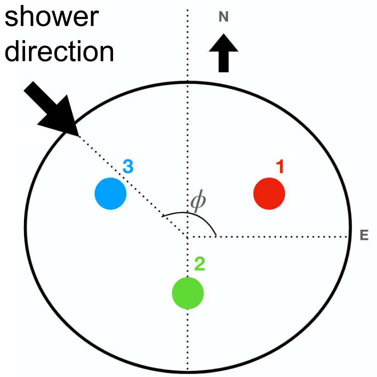
Katarina (FWO PhD fellow) supervised by Ioana & Stijn, PoS-ICRC2025-398

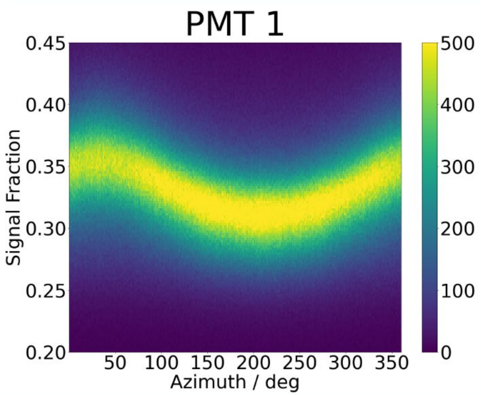
The detector upgrade AugerPrime

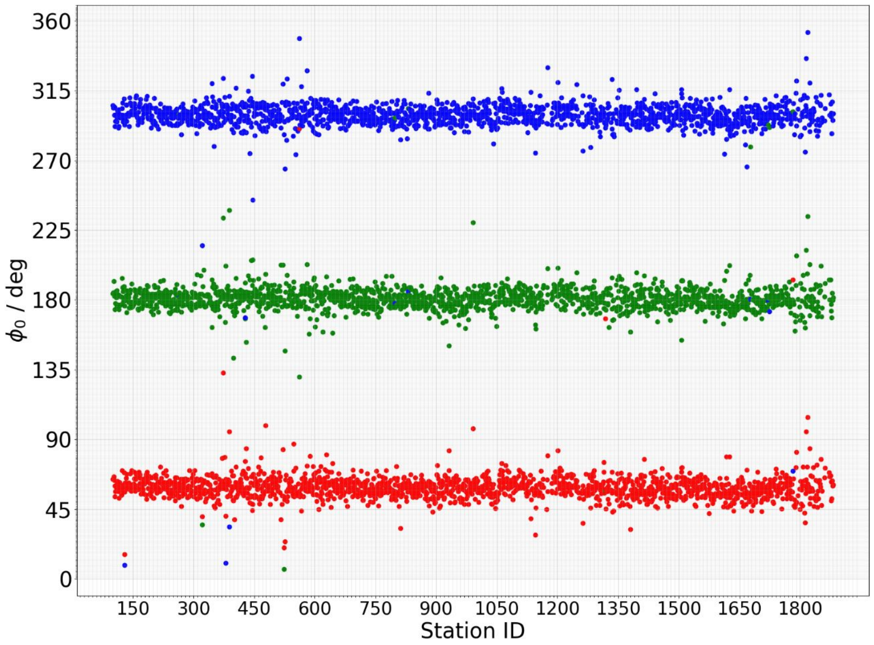
During 2021-24 surface detector stations equipped by new electronics, scintillator (SSD), radio detector and small PMT

PMT signal asymmetry revealed miscabled stations

Fractions of the signal in 3 PMTs are sensitive to azimuth ϕ of the shower direction







Fit for each station

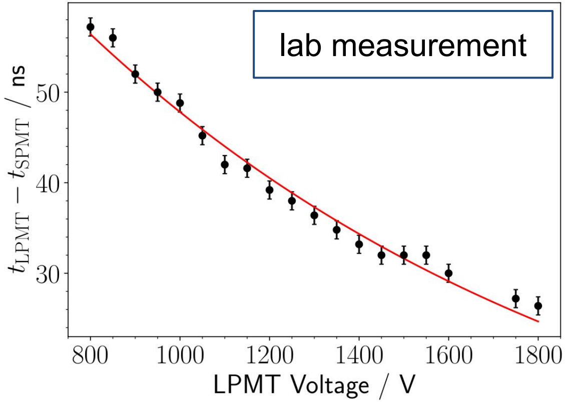
Look at stations with outlier fit parameter ϕ_0

Work of Mateo (& Ioana, Vincent) GAP2025_028

Outlook: use in event reconstruction for improved ϕ estimate

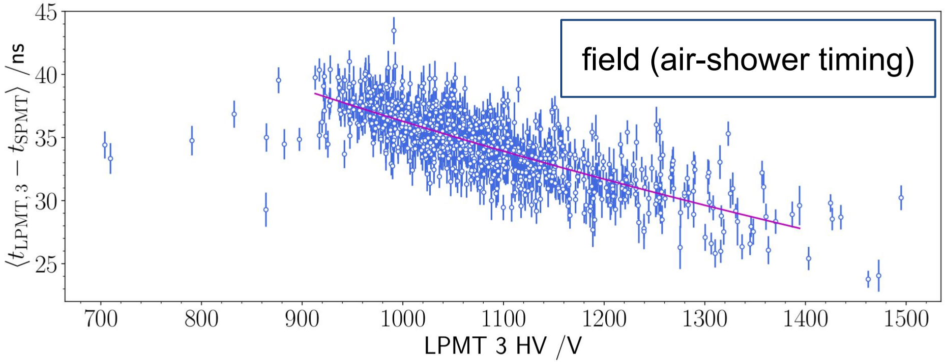
SSD commissioning: Accurate measurement of the time delays between the WCD and SSD

Analysis by Yigit, Ben, Ioana and Katarina, GAP-2025-006

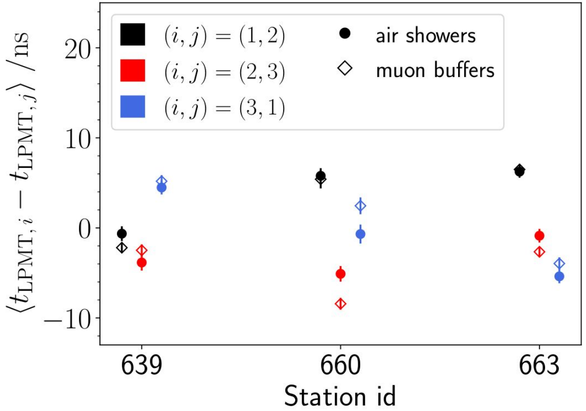


The first charaterisation of the PMT time delays as a function of the HV

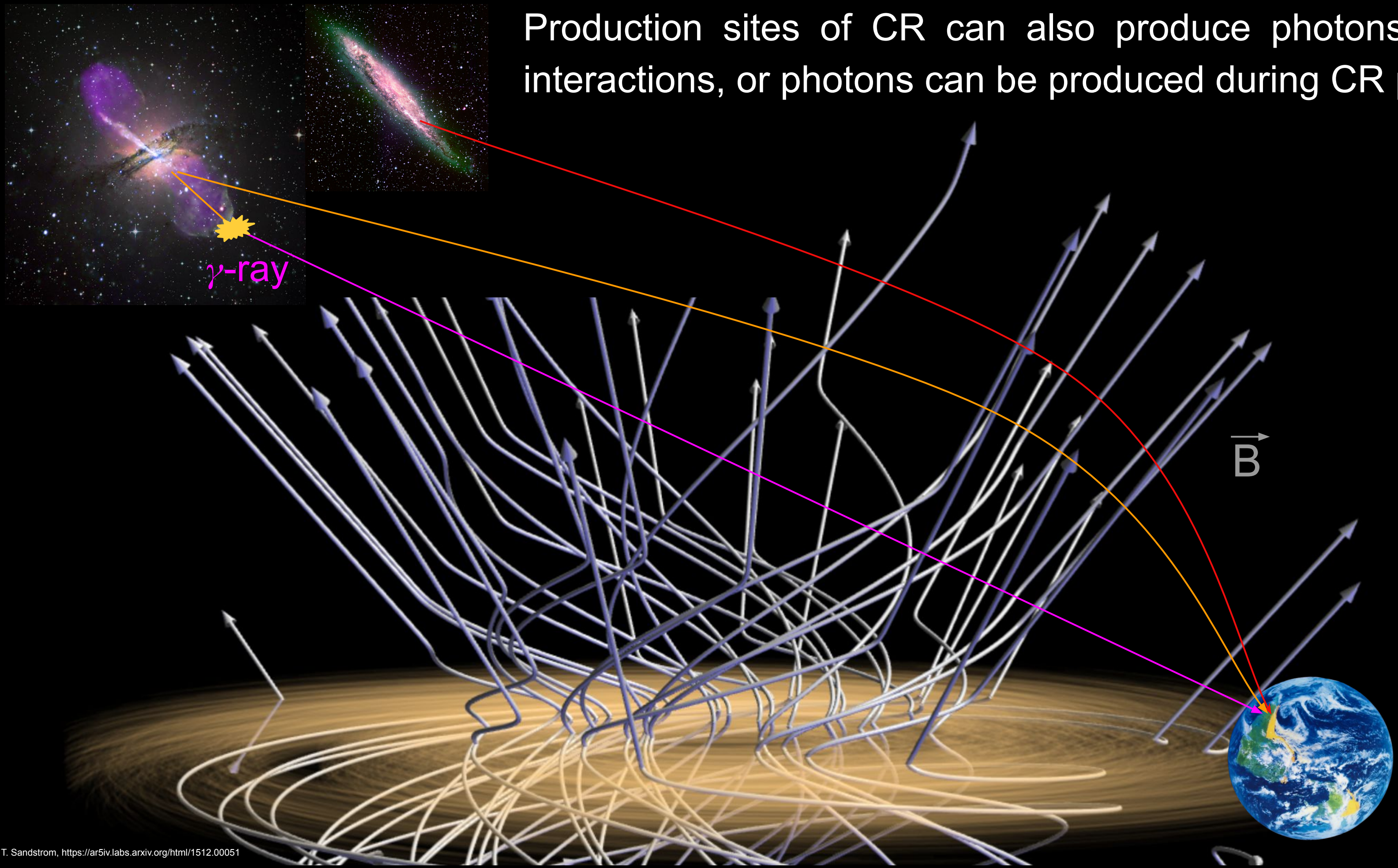
Average timing variance much lower than air-shower fluctuations



Two field-measurement methods in agreement



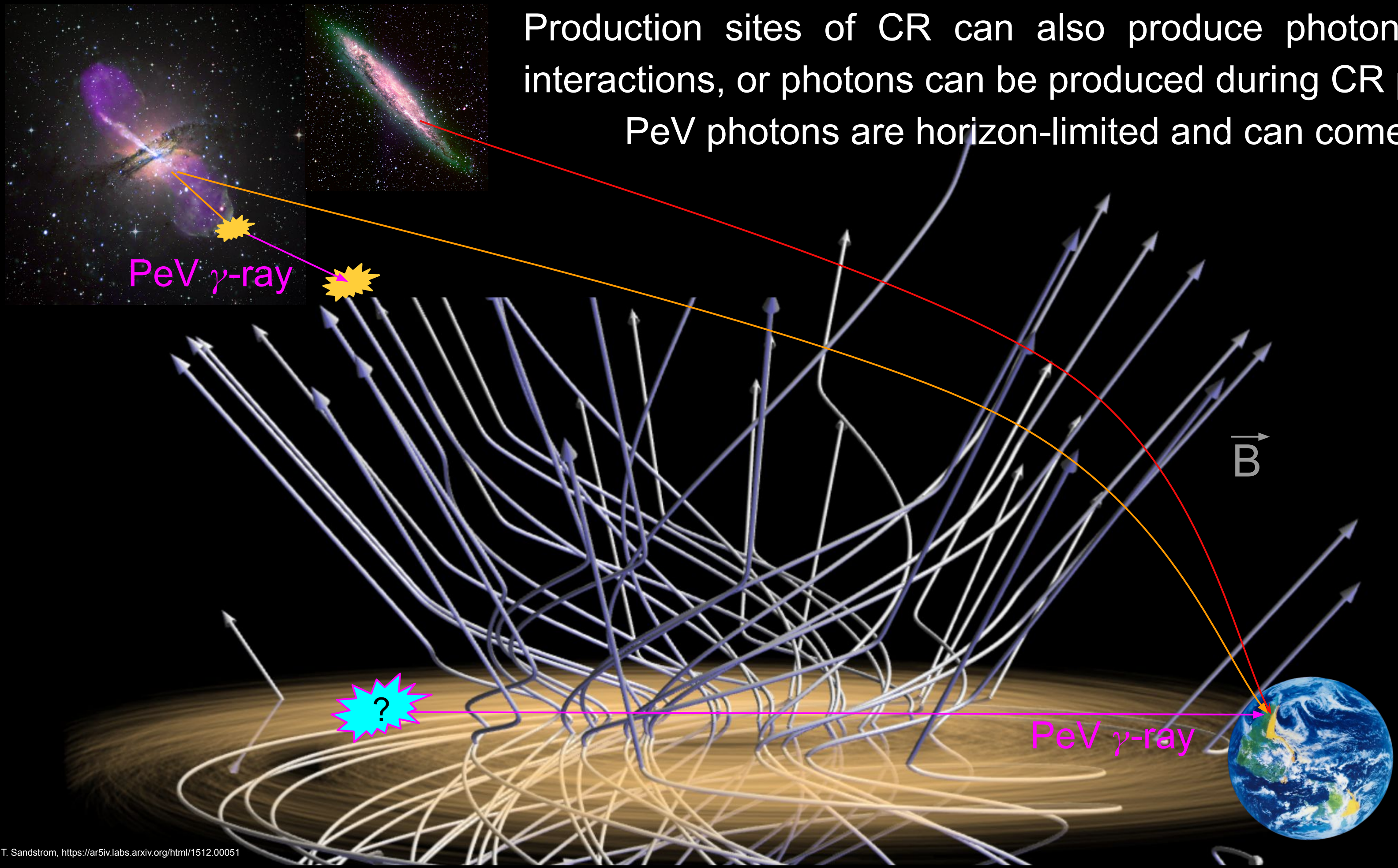
Production sites of CR can also produce photons in hadronic interactions, or photons can be produced during CR propagation



T. Sandstrom, https://ar5iv.labs.arxiv.org/html/1512.00051

Production sites of CR can also produce photons in hadronic interactions, or photons can be produced during CR propagation

PeV photons are horizon-limited and can come only from our Galaxy



T. Sandstrom, https://ar5iv.labs.arxiv.org/html/1512.00051

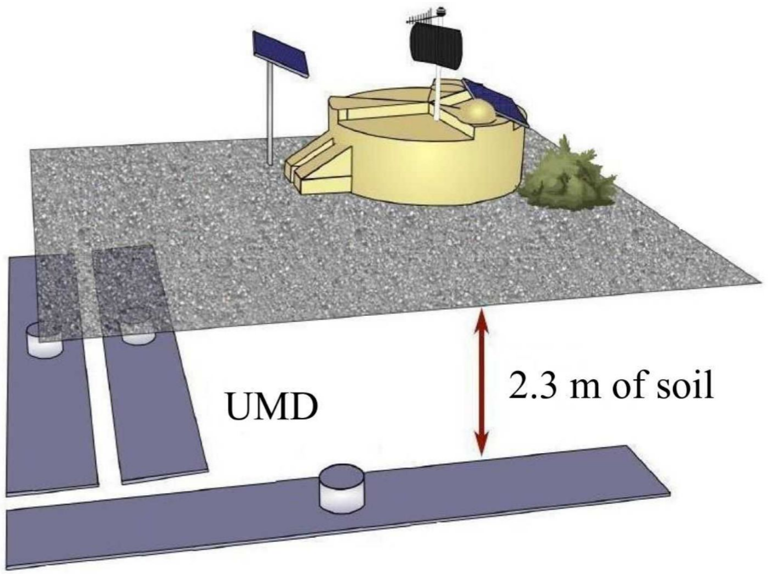
Search for a diffuse flux of photons above tens of PeV in Auger

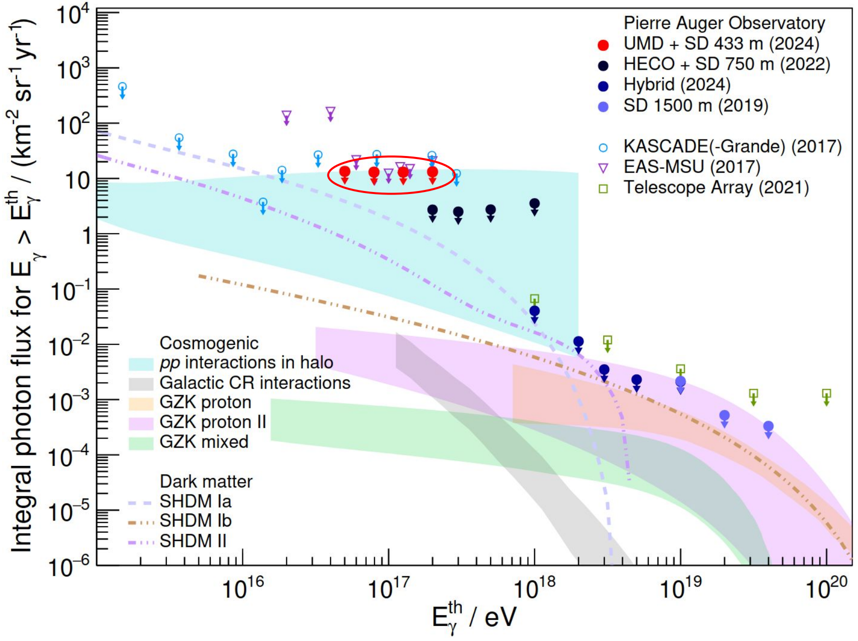
First use of the Underground Muon Detector in physics analysis

→ separation of photon air-showers from hadronic-shower background

Auger full-author-list publication coordinated by Nico, published in 2025 in JCAP

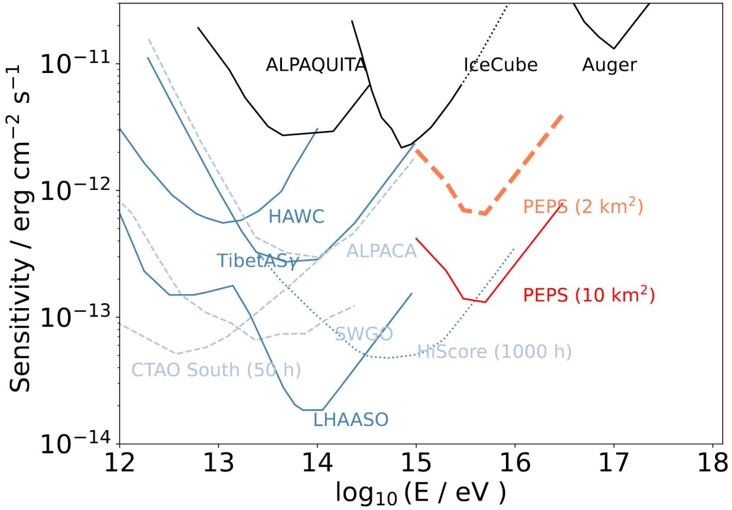
https://doi.org/10.1088/1475-7516/2025/05/061



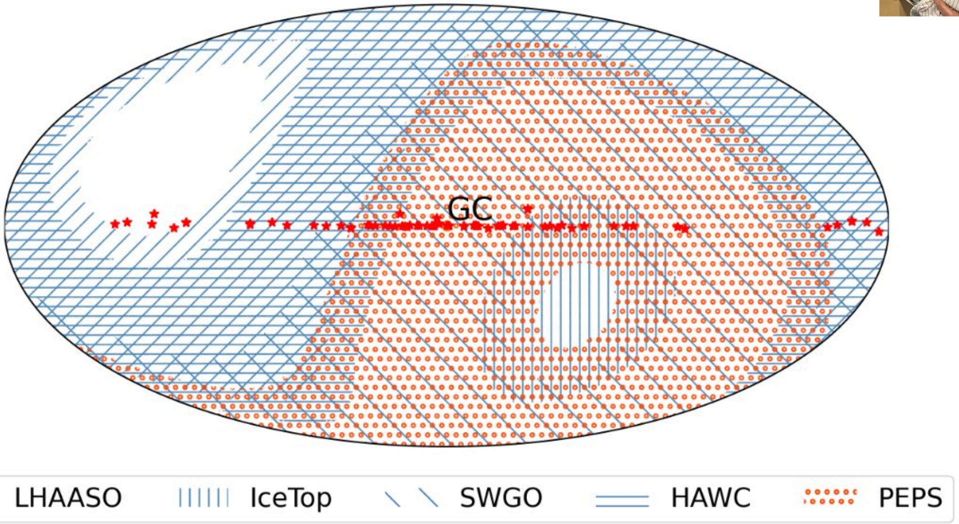


Probing Extreme PeVatron Sources (PEPS)

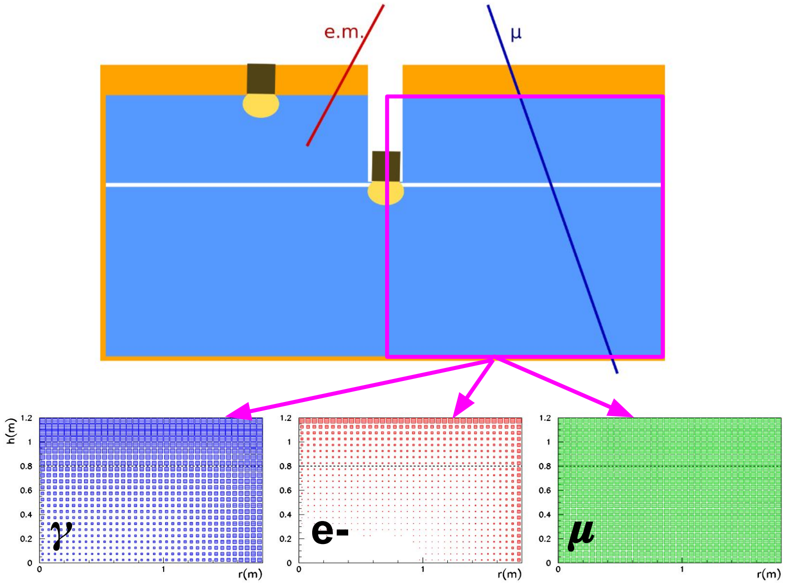
Detector of 10 km^2 to measure gamma-rays between 1-50 PeV @ Auger site

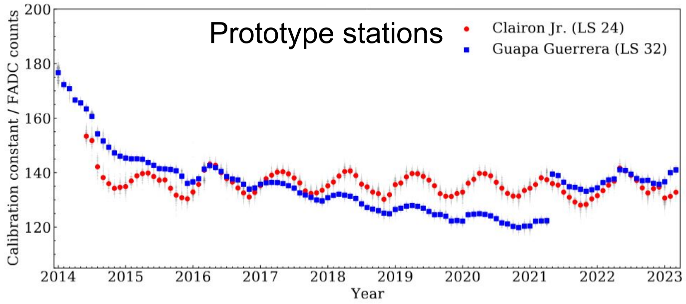


Very good sky coverage of the Galactic plane and Galactic center



Layered water Cherenkov detector to estimate muon signal





Prototype stations:
Preparation and tests of components in Brussels
First 2 detectors installed at Auger in 2014, 3 under construction

Envisioned array: 55 stations/km^2
Phase 1: 110 stations
Phase 2: 550 stations

Timeline since funding: 2-2.5 yr. completion
Phase 1 aimed at for 2027-2028
Total hardware cost < 10 M€

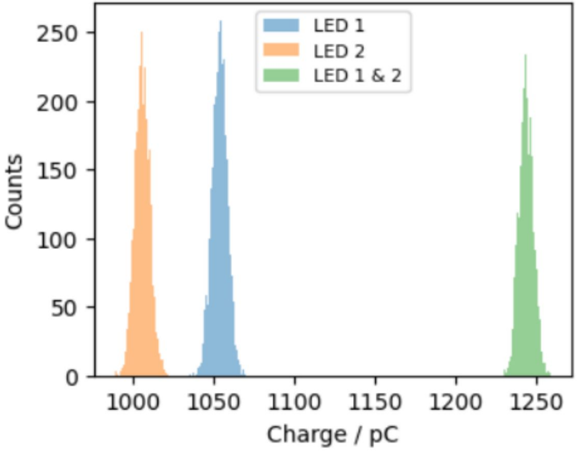
Popular design for next-generation UHECR observatories (GCOS)

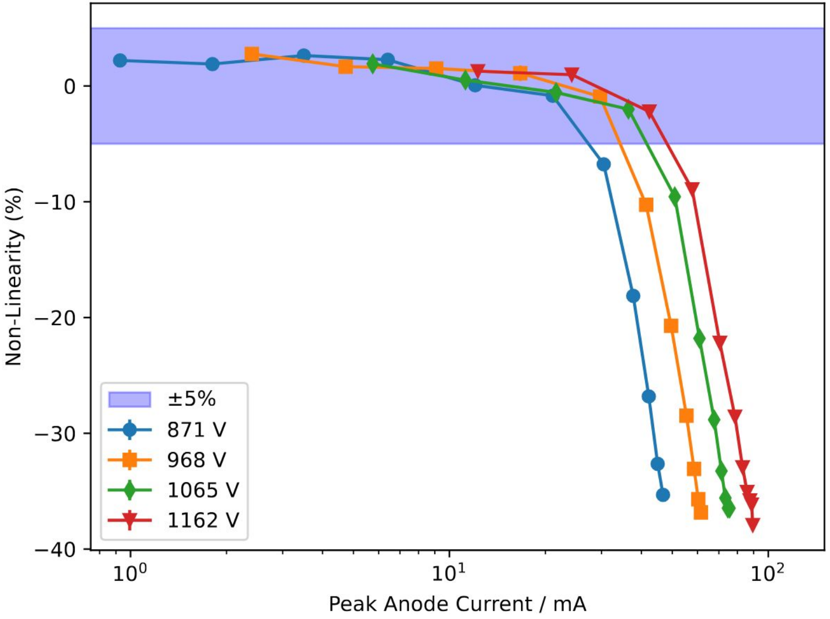
P. Billoir, Ben, Ioana and Andrea, PoS-ICRC2025-354

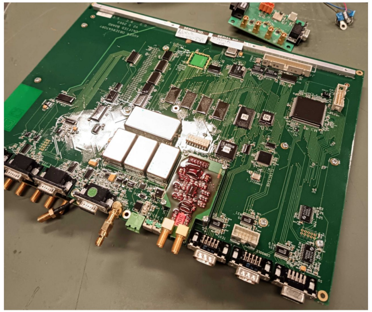
Technical developments for PEPS

Characterization of PMTs done in Prague (Mateo)

Linearity







Michael Korntheuer & Yifan Yang on electronics development
(unified board, communication systems)

Responsibilities and outreach

AUGERINFOCUS

6, October 2024 www.auger.org.ar

Over the past twenty years, the Pierre Auger Observatory has revolutionized the study of ultra-high energy cosmic rays (UHECRs), the most energetic particles known to humanity.

UHECR SPECTRUM MEASUREMENT

The observatory has confirmed a cutoff of UHECRs around 5×10^{19} eV, meaning that very few UHECRs are detected above 10^{20} eV, and none above 10^{21} eV. Additionally, new features in the spectrum have been discovered, providing input for models of their sources and propagation, which remain active areas of research.

EXTRAGALACTIC ORIGIN

It is now known that UHECRs above 8×10^{18} eV likely originate from outside our Galaxy. This conclusion is based on the measurement of dipolar anisotropy in their arrival directions, which differs significantly from the direction of the Galactic plane (Fig. 1).

HEAVIER COMPOSITION AT HIGHER ENERGIES

While UHECRs primarily consist of protons at 10^{18} - $10^{18.5}$ eV, they are composed of increasingly heavier nuclei, such as helium or nitrogen, at higher energies.

Despite these achievements, many questions remain unanswered. The next step is to measure the charge of UHECRs, as the trajectories of more charged nuclei are more deflected by magnetic fields in the Universe. This deflection blurs the pointing of UHECRs back to their original sources. If protons or helium nuclei, which have lower charges, can be isolated, the source pointing can become more precise.

Another puzzle is the discrepancy in the number of muons in the extensive air showers (EASs) initiated by UHECRs (see Auger in Focus 4). The number of muons is higher than expected from models, therefore improved measurements of the muon number in EAS are required.

FIGURE 1. UHECR ARRIVAL DIRECTIONS IN GALACTIC COORDINATES (GALACTIC PLANE IS HORIZONTAL ALONG 0 DEG IN LATITUDE)

AUGER PRIME

To address these challenges, the Pierre Auger Collaboration has initiated a significant upgrade to the observatory, known as AugerPrime. This upgrade includes the addition of scintillator detectors (SSD) and radio detectors (RD) to each existing surface detector station (Fig. 2). The new configuration enhances the ability to distinguish between the muonic and electromagnetic components of EASs due to the different responses of these detectors.

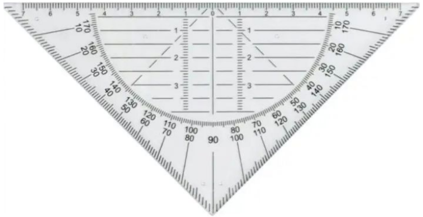
In the shower's core region, where particle density is highest, the three photomultiplier tubes (PMTs) in the surface stations may become saturated, causing inaccurate signal measurements. To mitigate this, AugerPrime introduces a small photomultiplier (sPMT) alongside the three existing large PMTs. The sPMT is designed to extend the dynamic range of the station's measurements, allowing for more accurate sampling of the shower.

The observatory's array also includes regions where the distance between tanks is less than the standard, 1500 meters. In one such region, where the stations are spaced 750 and 433 meters apart, the upgrade involves the installation of underground muon detectors (UMD). These detectors will provide critical direct measurements of the muonic component of atmospheric showers, as the electromagnetic part of the EAS is absorbed by the ground, while muons pass through and reach the UMD.
The surface detector electronics have also been enhanced to support the new detectors. The updated electronics board is not only compatible with the existing configuration but also with the SSD, RD, UMD, and sPMT. This advanced board features a faster sampling rate and improved timing accuracy.

Our special thanks to
AUGER Early Career Collaborators Assembly

FIGURE 2. UPGRADED SURFACE STATION

Observatorio Pierre Auger
info@auger.org.ar



Responsibilities:

Laurent Favart: Chair of the Finance Board of Auger

Katarina: Early-Career Co-Representative (2024-25) & Representative (2025-26) of Auger

Ioana:

- Task leader of "Auger as test environment"
- Co-director of the CosPa network
- Chair of Publication Committee of Auger (finished 10/2025)
- Member of the APPEC SAC
- Member of the GCOS core group

Outreach:

Masterclass with other astroparticle groups (Apr 2025)

Study accessories shipped from IIHE to students in Malargüe (Nov 2024) - thankful to Jorgen & Nina

Contributing to Auger outreach activities/social media

Organizing CosPA and PEPS workshop 27-29 October 2025