Universität Siegen

PIERRE AUGER OBSERVATORY

The Pierre Auger Observatory: Results and Prospects

uni-siegen.de

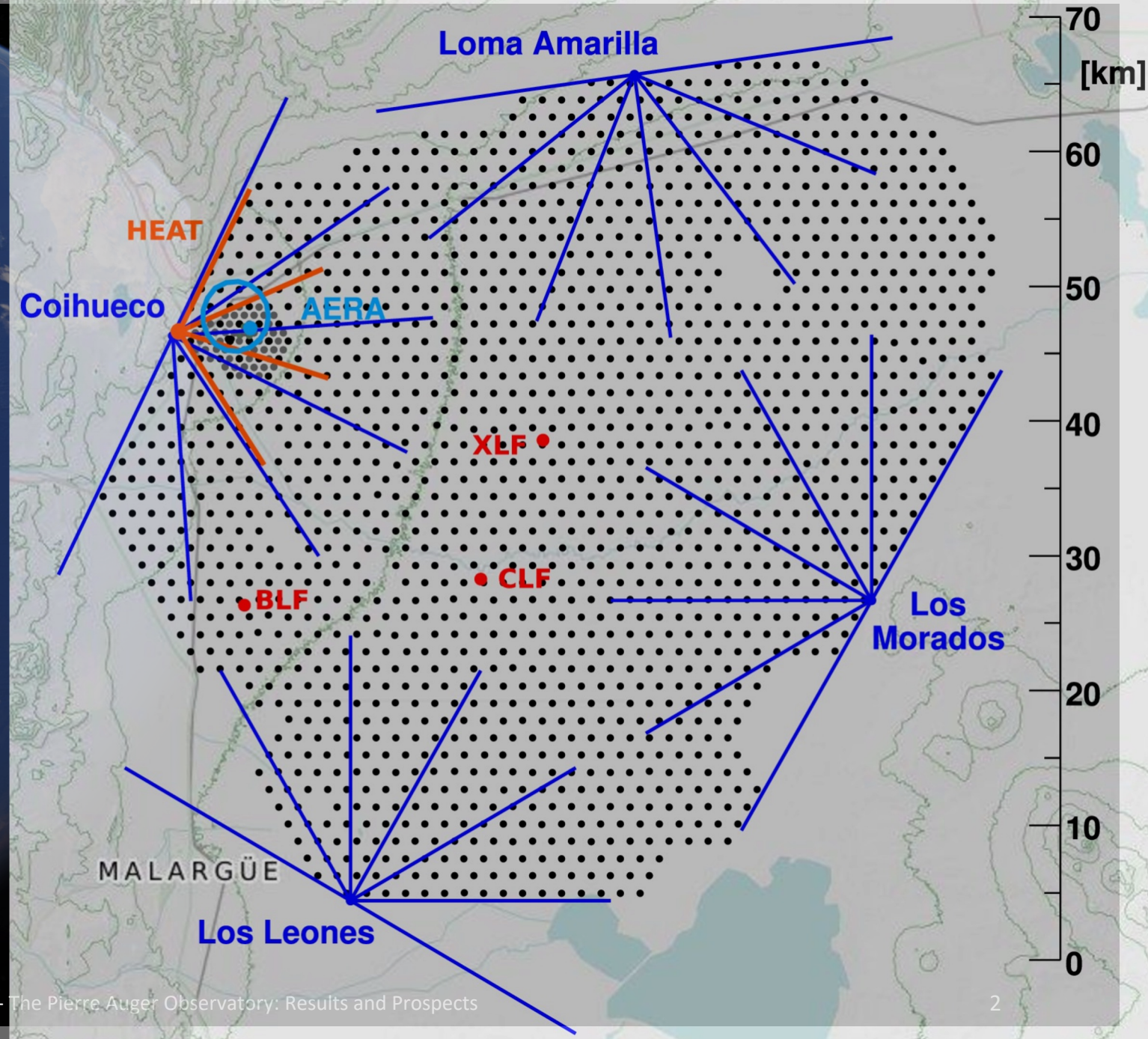
Qader Dorosti

The Pierre Auger Observatory

- Area: 3000 km^2
- Altitude: 1400 m a.s.l.
- Collaboration: 18 countries, 95 institutes

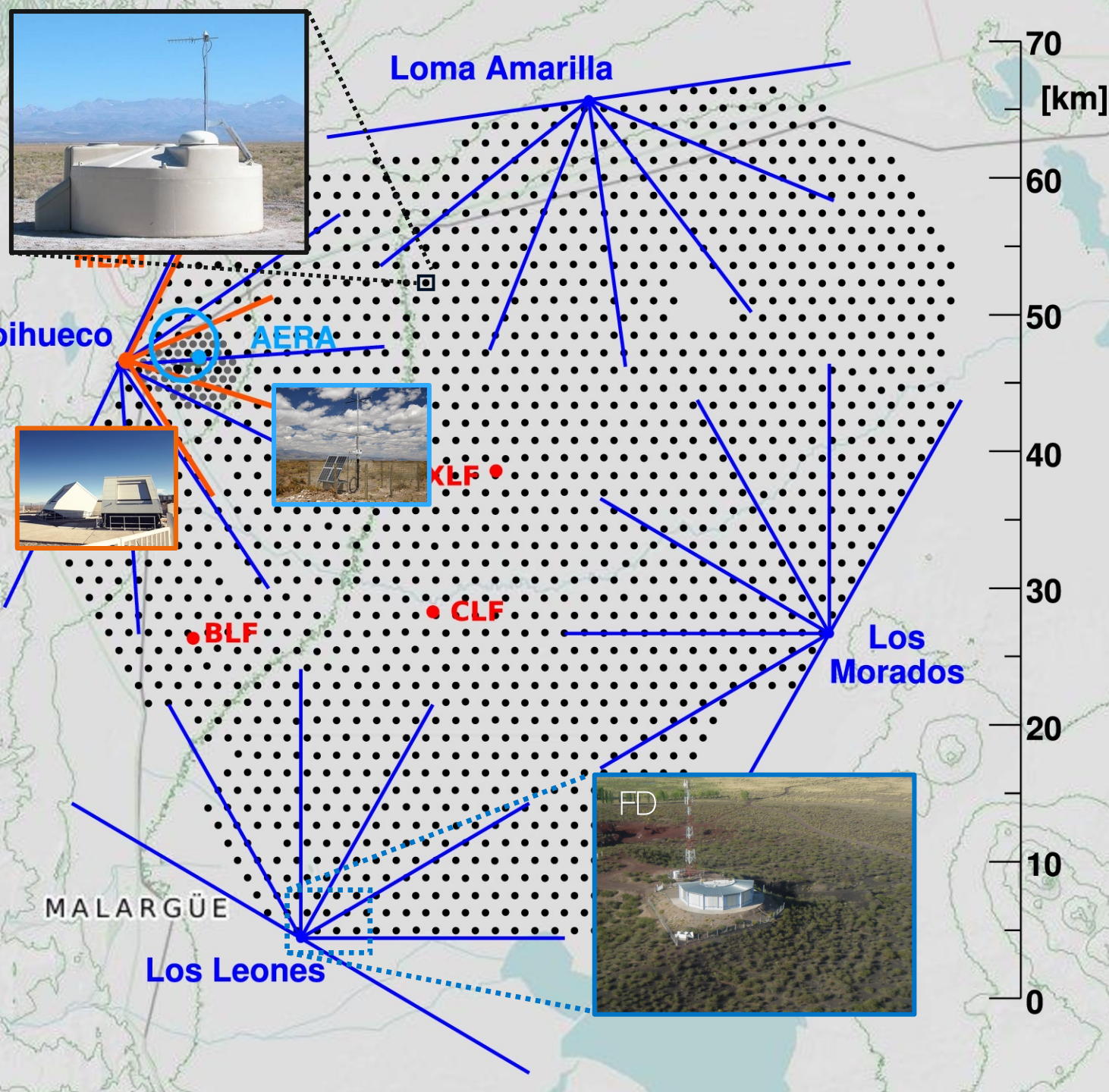
  → over 400 members

Pierre Auger Observatory
Province Mendoza, Argentina

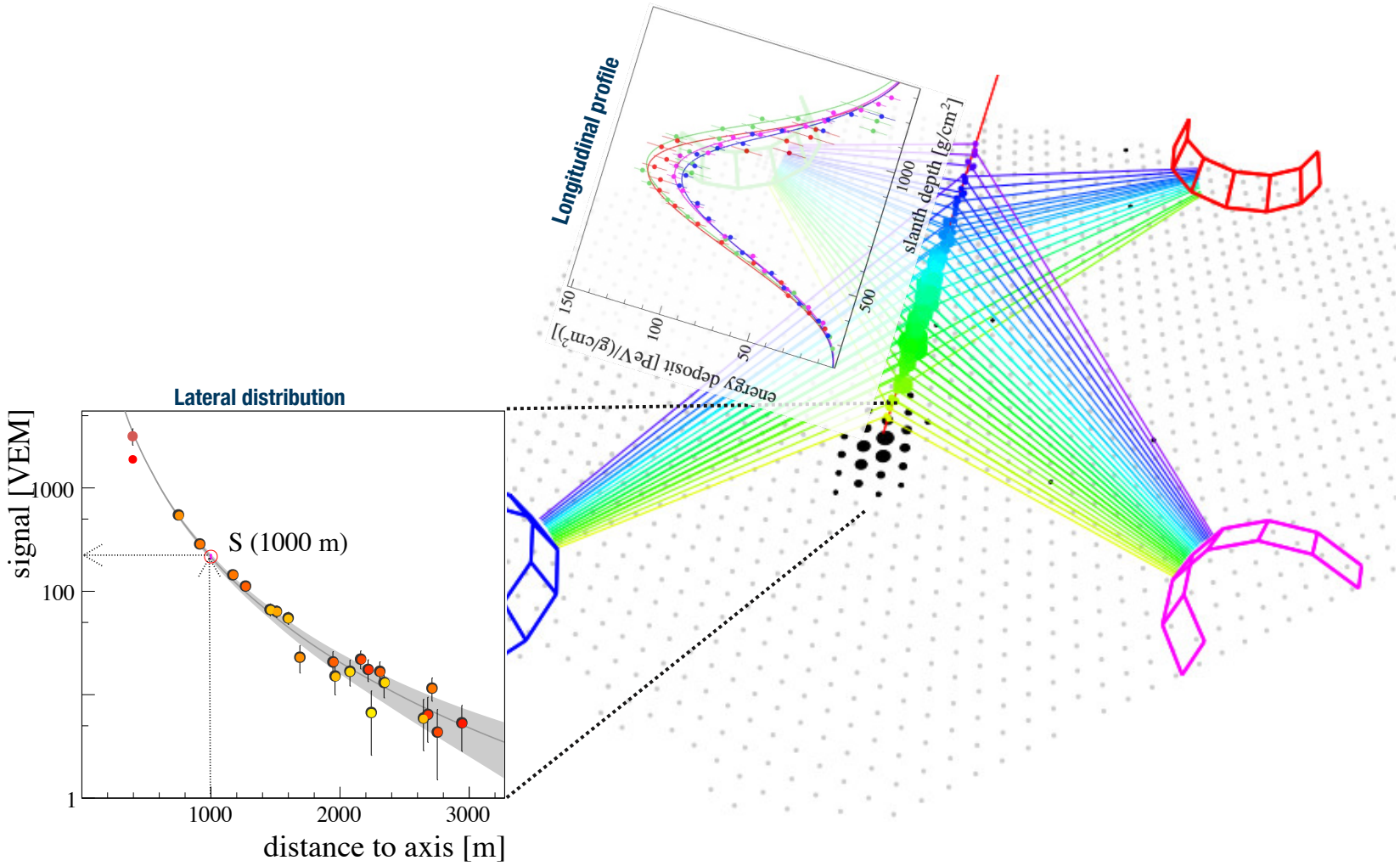


The Pierre Auger Observatory

- Surface Detectors (SD):
  - 1,600 water-Cherenkov detectors
  - 1.5 km grid spacing
- Fluorescence Detectors (FD):
  - 4 buildings, each 6 telescopes
  - around the observatory perimeter
- Infill array (enhancement area):
  - 60 SD: 750 m grid spacing
  - Underground muon detectors (UMD): 30 m^2 scintillators
  - High elevation telescopes (HEAT)
  - Auger engineering radio array (AERA)



Principle of Measurement



- Fluorescence Detectors (FD):
  Measures UV light from N_2 excitements
  Tracks shower development, energy, and direction
  Night-only (15% duty cycle)

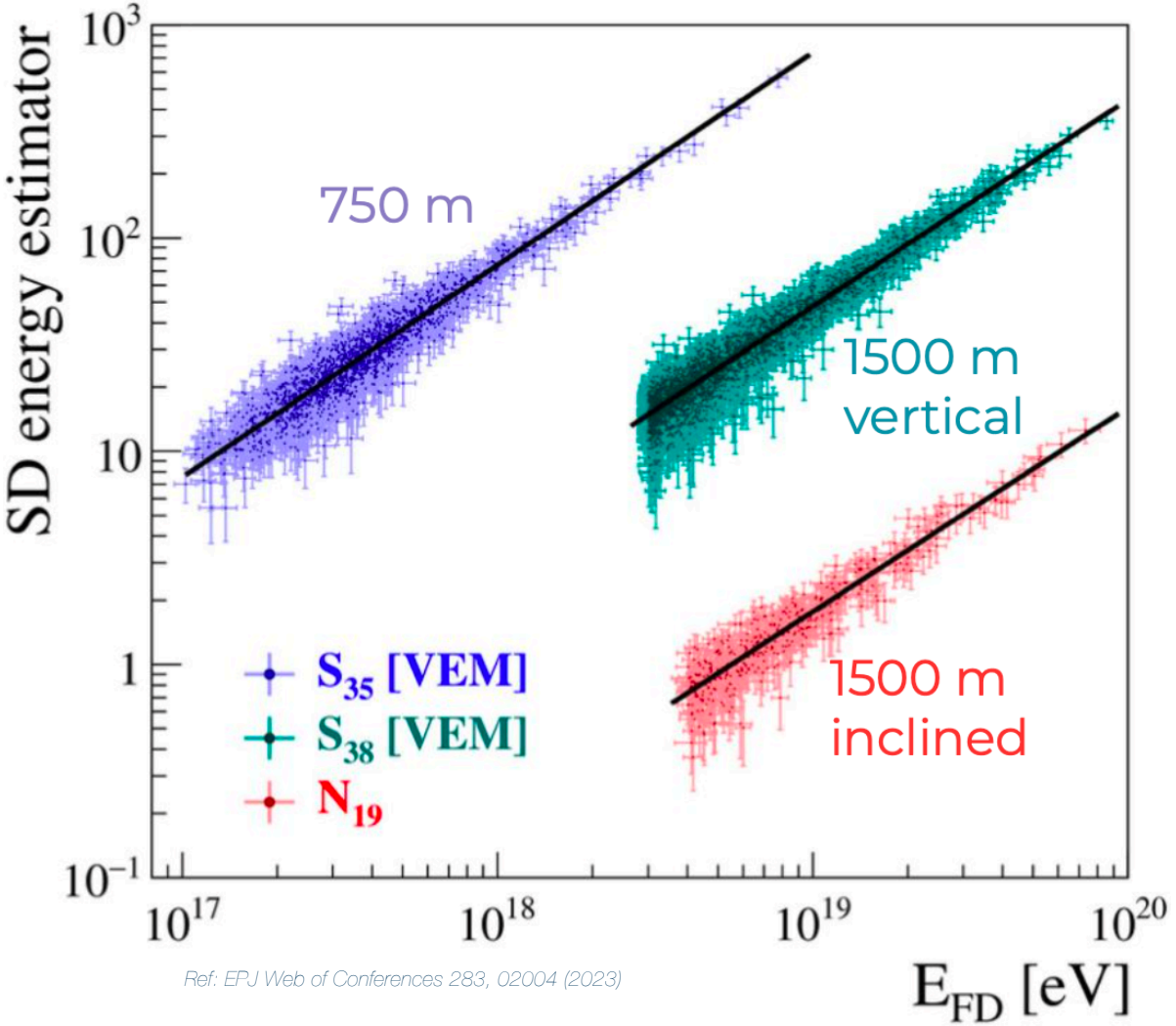
- Surface Detectors (SD):
  Detects particles via Cherenkov light
  Measures energy and direction
  Continuous (100% duty cycle)

Hybrid Detection Technique

Calibration of SD with FD:

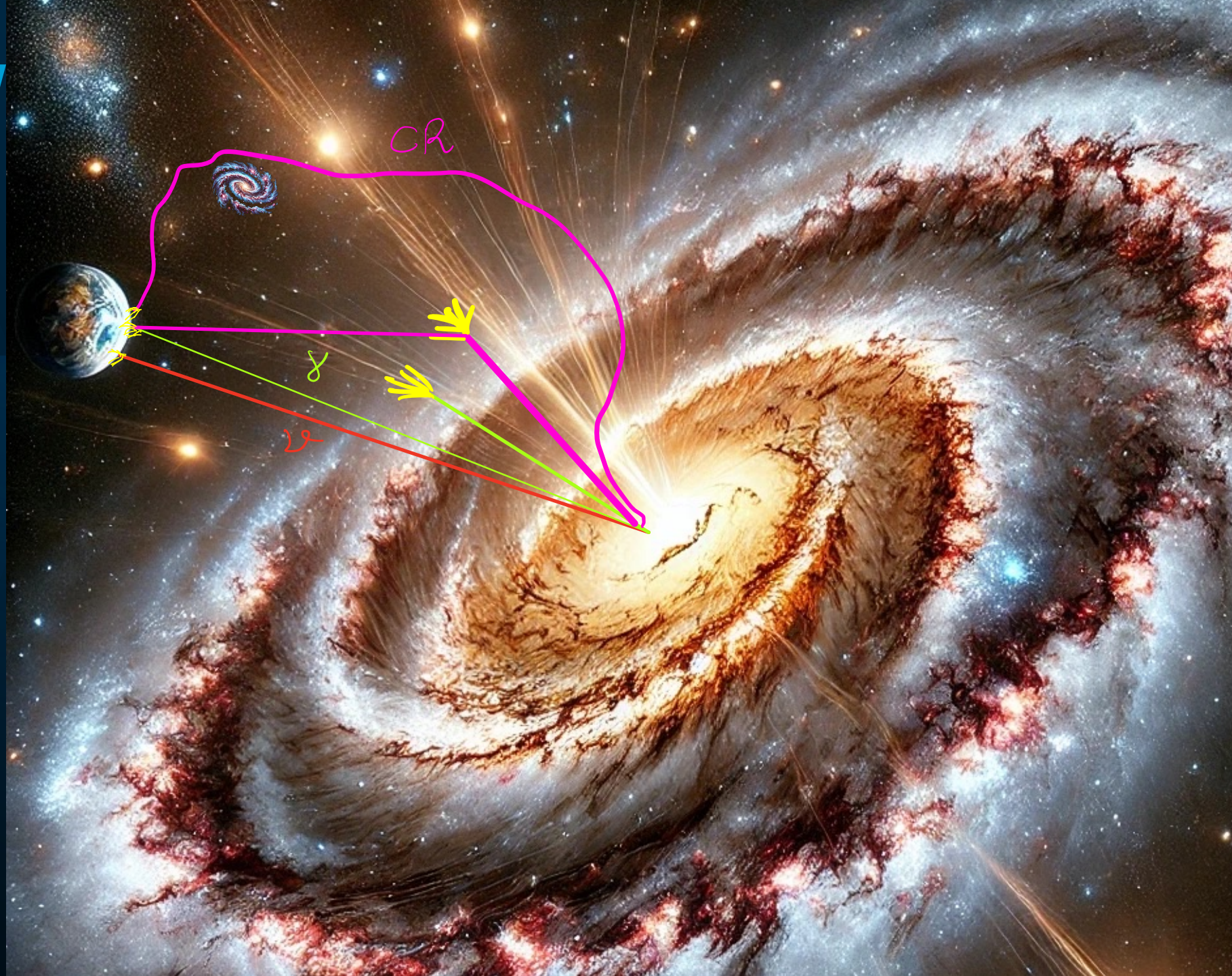
- FD provides a quasi-calorimetric energy measurement
- Improves geometry reconstruction for hybrid events
- Enhances control of systematic uncertainties

SD energy estimators for vertical (two baselines) and inclined events vs. FD energy



Ref: EPJ Web of Conferences 283, 02004 (2023)

What are we after?



UHCR Energy Spectrum

- 14 years of data with over 200,000 events
- Deviations from a power law:

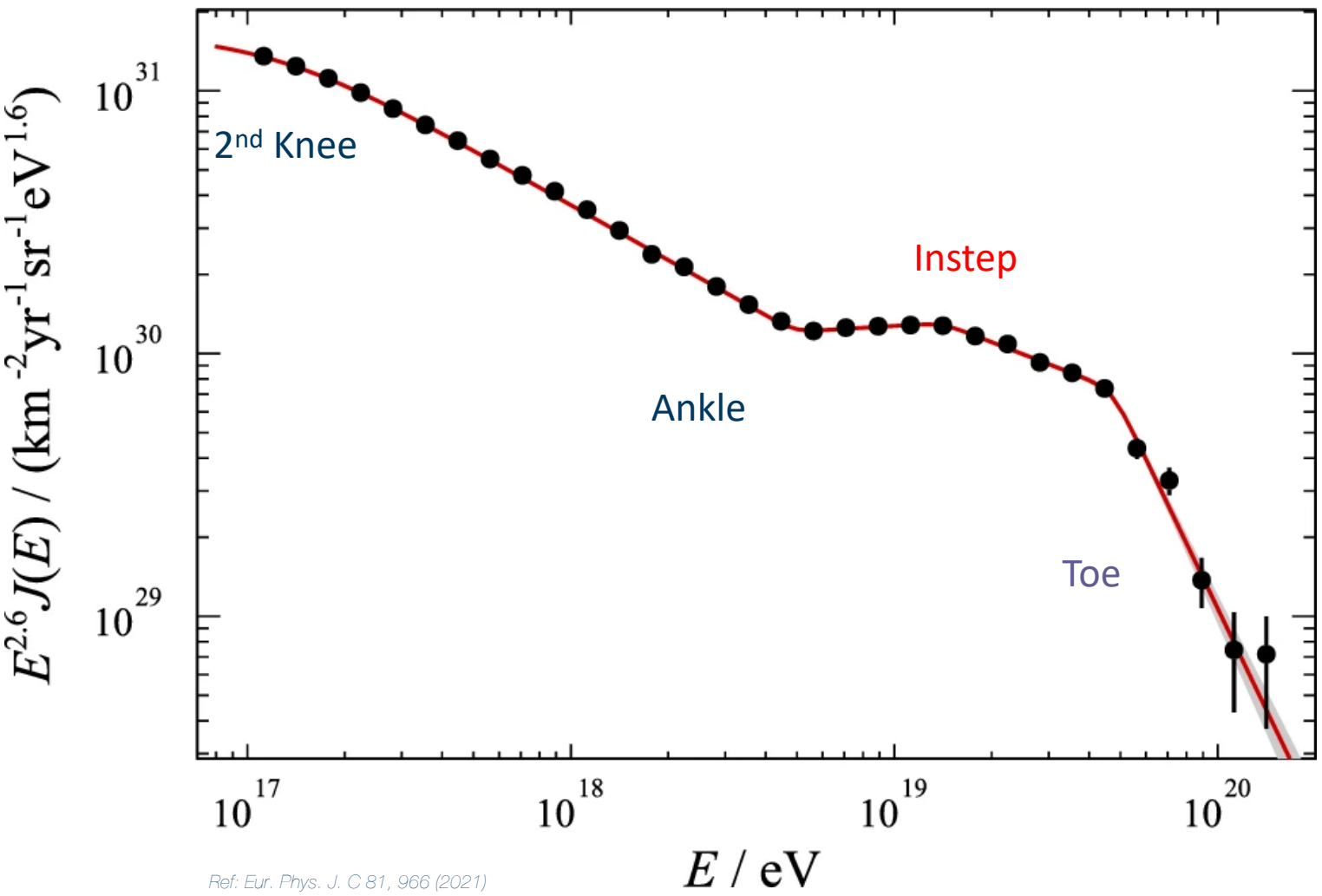
distinct features observed

- UHE features incompatible with

single mass models

- Suppression due to propagation effects

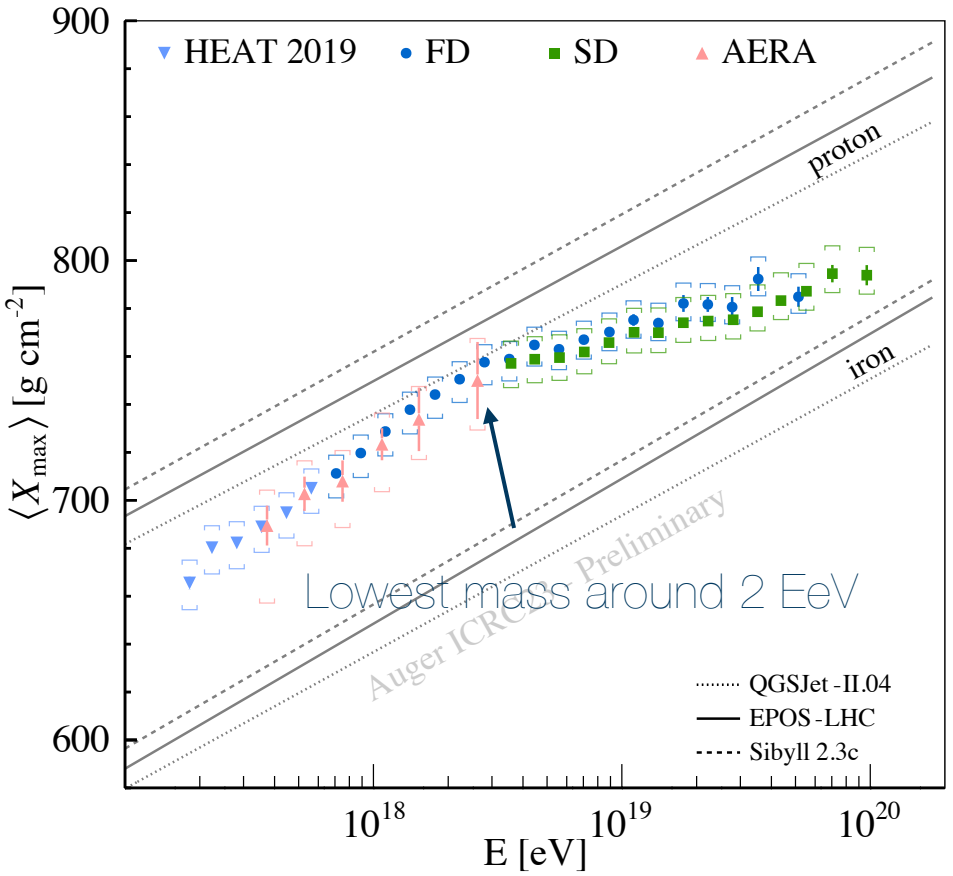
and/or source exhaustion

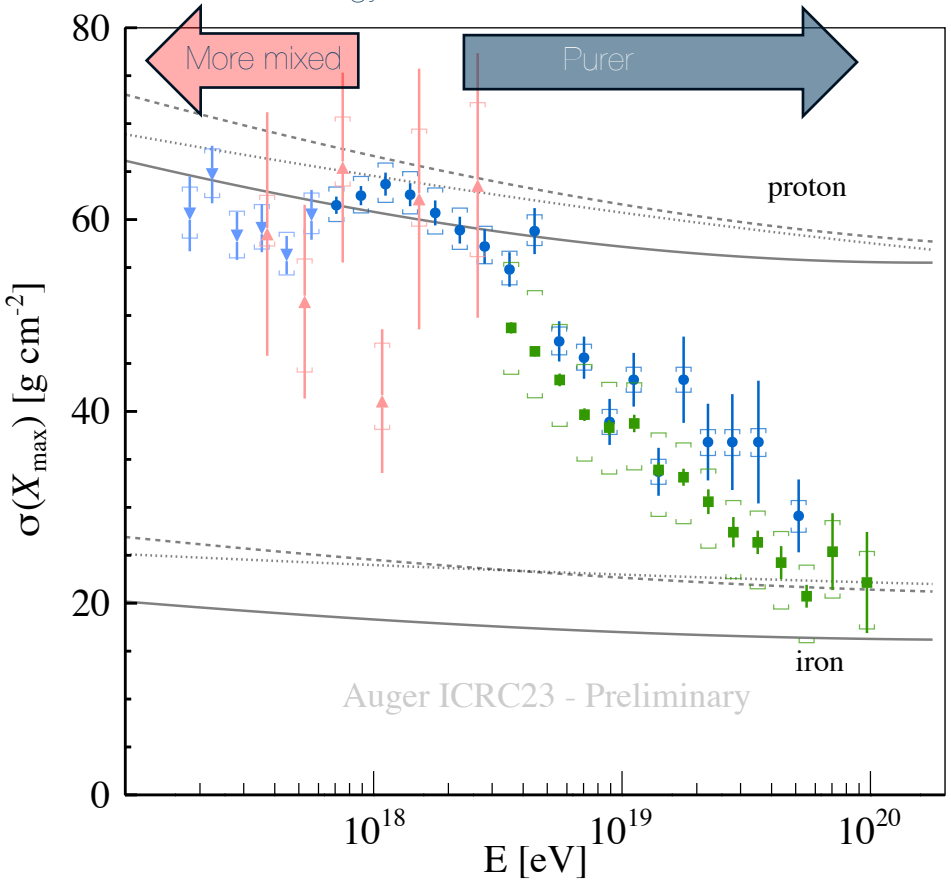


Ref: Eur. Phys. J. C 81, 966 (2021)

Mass Composition

First and second moments of the X max distributions Vs. Energy



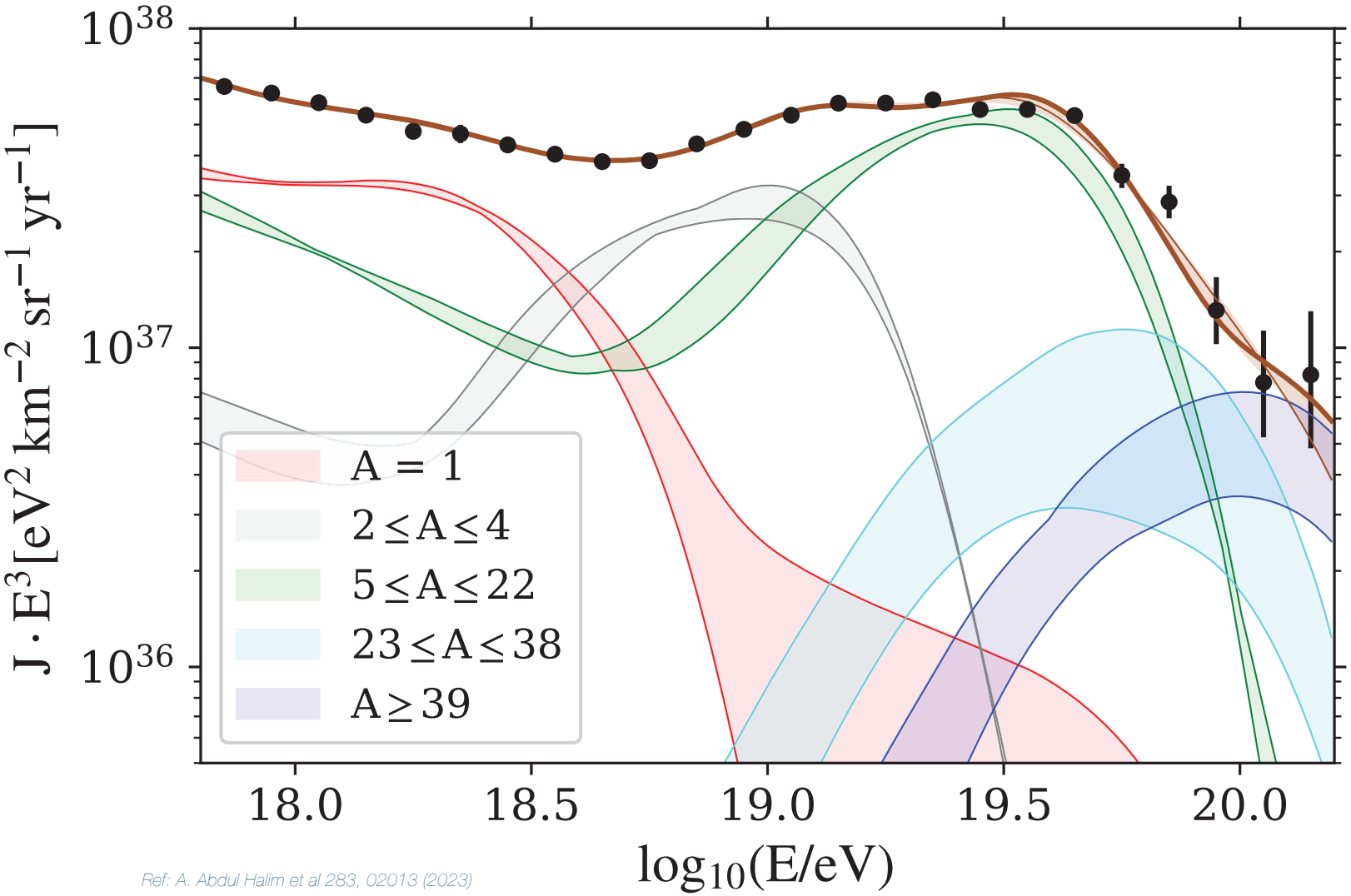


- The primary composition shifts from lighter to heavier elements as energy increases
- The composition becomes progressively purer above the ankle

Ref: ICRC2023)365

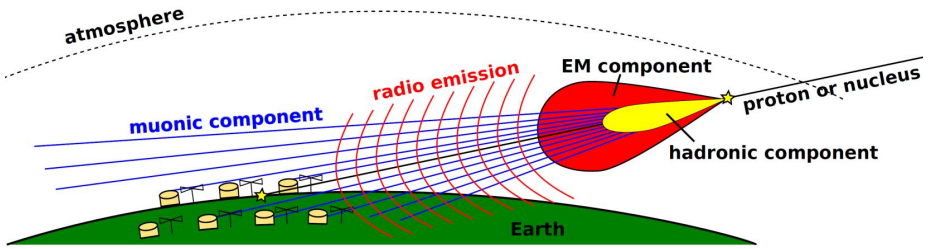
Composition Enhanced Spectrum

- Protons are minimal above the ankle and rare at the highest energies
- Iron is nearly absent from 10^18.4 to 10^19.4 eV
  →
- Sources have low cutoff energies ($E_{cut} \lesssim Z{\times}5$ EeV)
- hard spectra ($\gamma \lesssim 1$)
- heavy composition

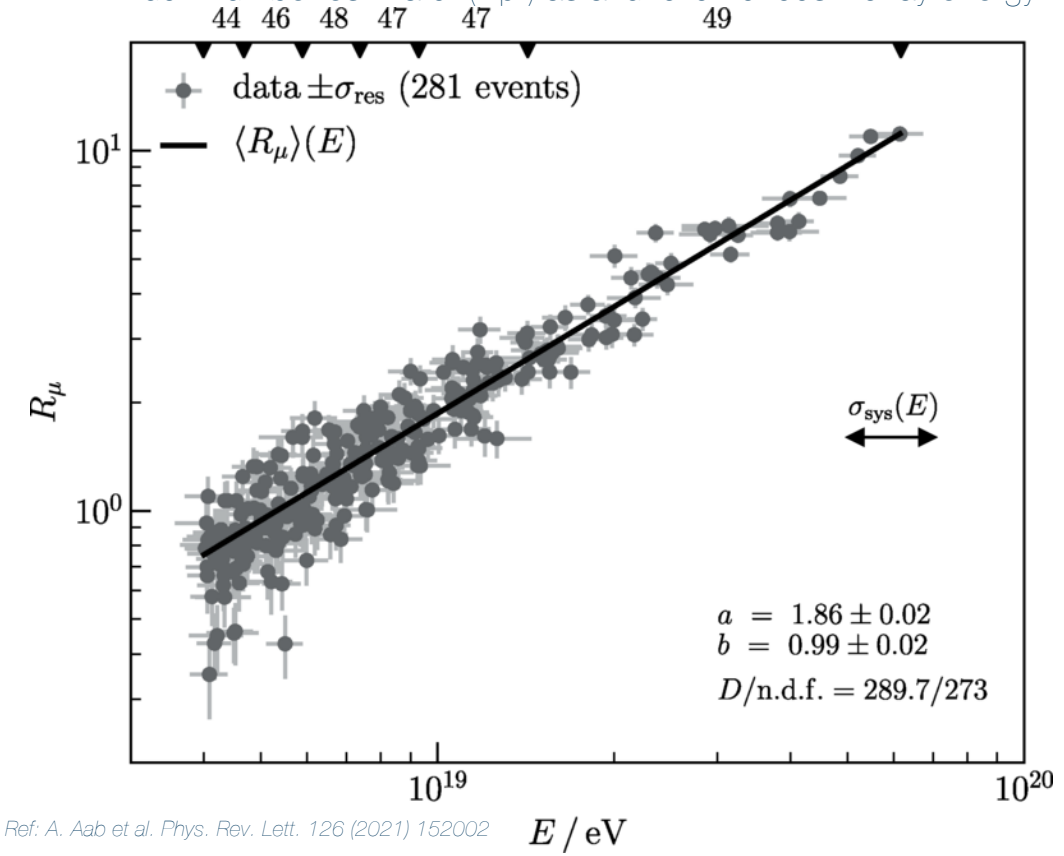


Ref: A. Abdul Halim et al 283, 02013 (2023)

Assessing Muon Contributions in Air Showers



Muon number estimator (Rμ) as a function of cosmic ray energy



Ref: A. Aab et al. Phys. Rev. Lett. 126 (2021) 152002

- Data selection:
  - Golden hybrid events: 281 events over 14 years
  - Zenit angels: 62° to 80°
  - Energy: $E > 4 \times 10^{18}$ eV
- Measurements:
  - FD: Energy measurements
  - SD: Muon number estimation

→ Relate muon count to primary energy

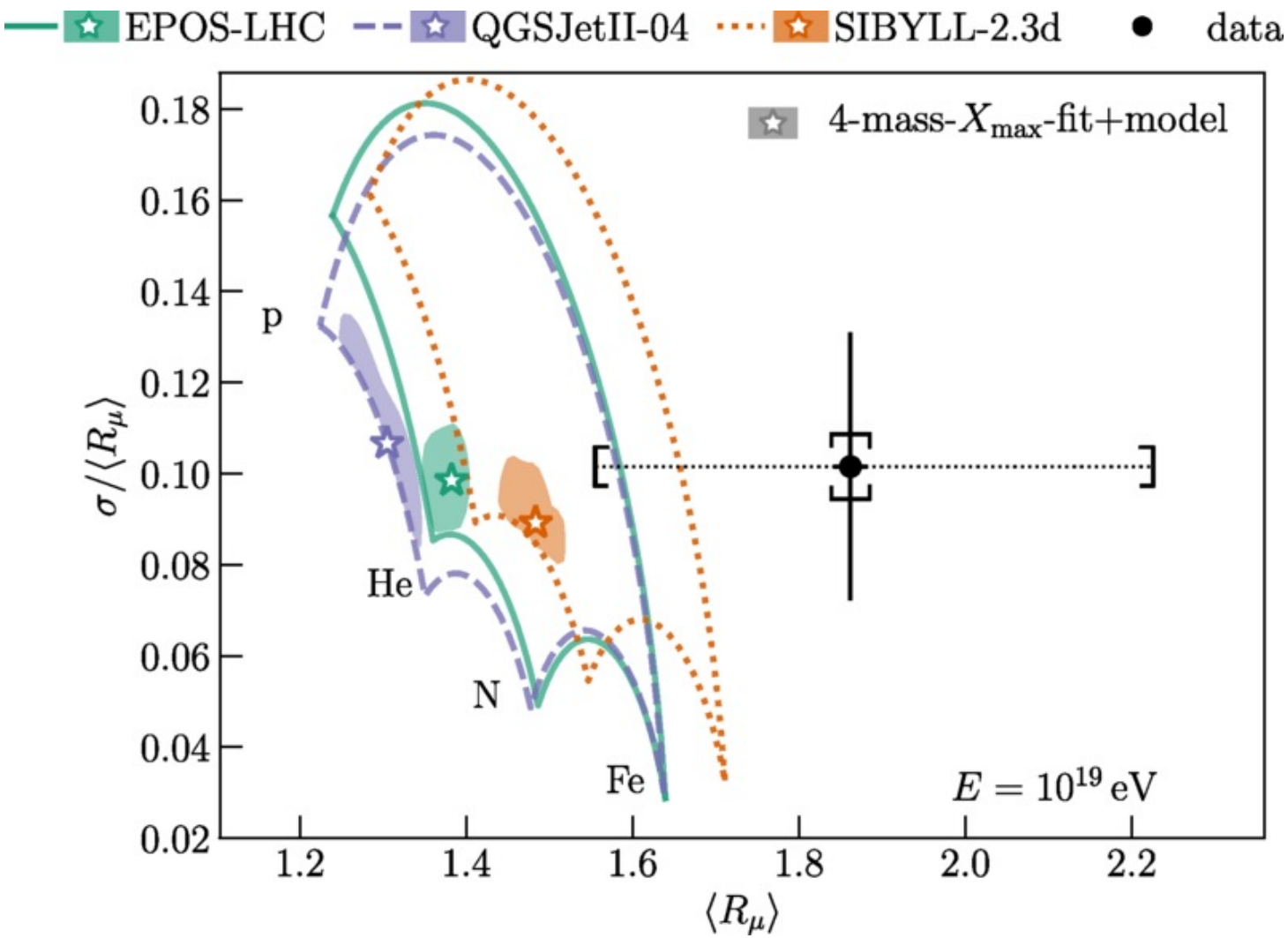
Muon Puzzle

Result: Muon fluctuations align with models, but muon counts do not!

Remedies:

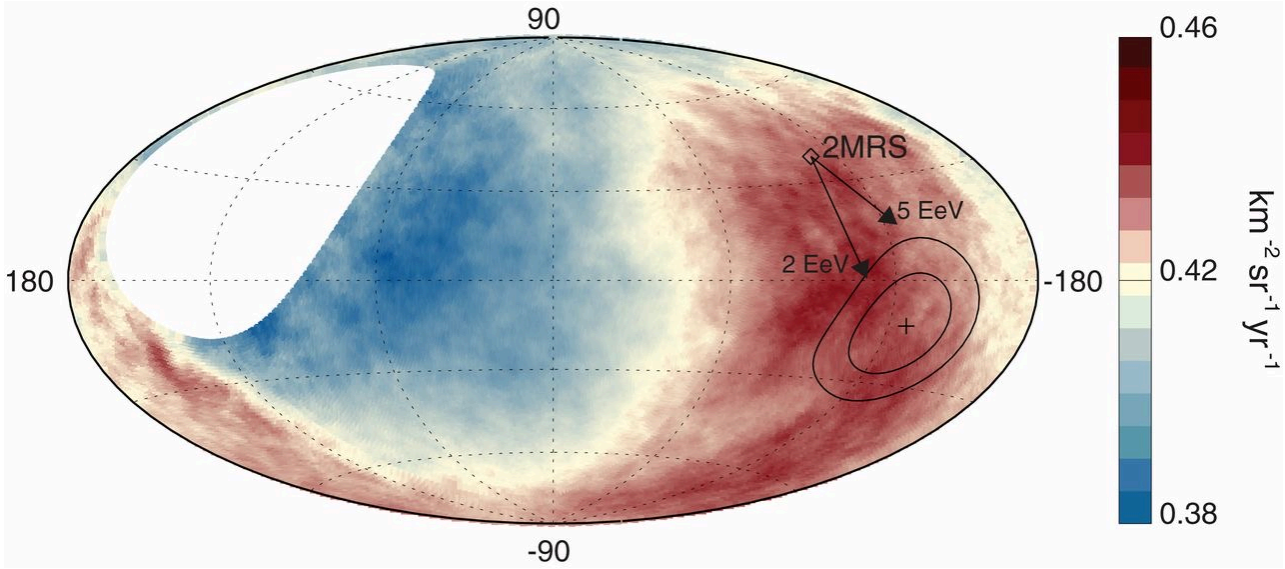
- Increase hadronic energy fraction $\boldsymbol{\alpha}$ in the first interaction
  → Impractical due to fine-tuning

- Introduce $\boldsymbol{\delta\alpha}$ across all generations:
  → Not supported by LHC data



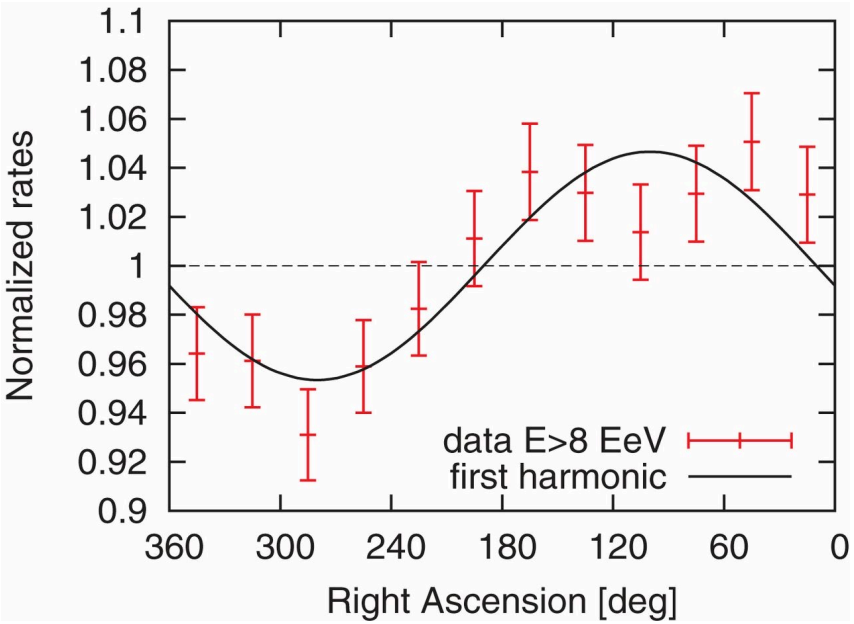
Arrival direction: Large Scale

Cosmic-ray flux map in galactic coordinates for energies E≥8 EeV



Ref: The Pierre Auger Collaboration, Science 357, 1266–1270 (2017)

Normalized rate of events as a function of right ascension

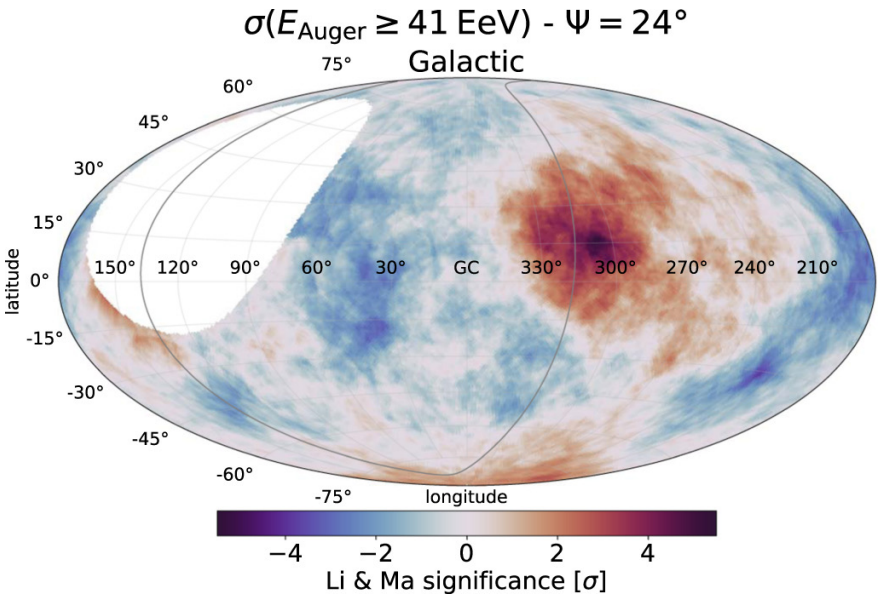


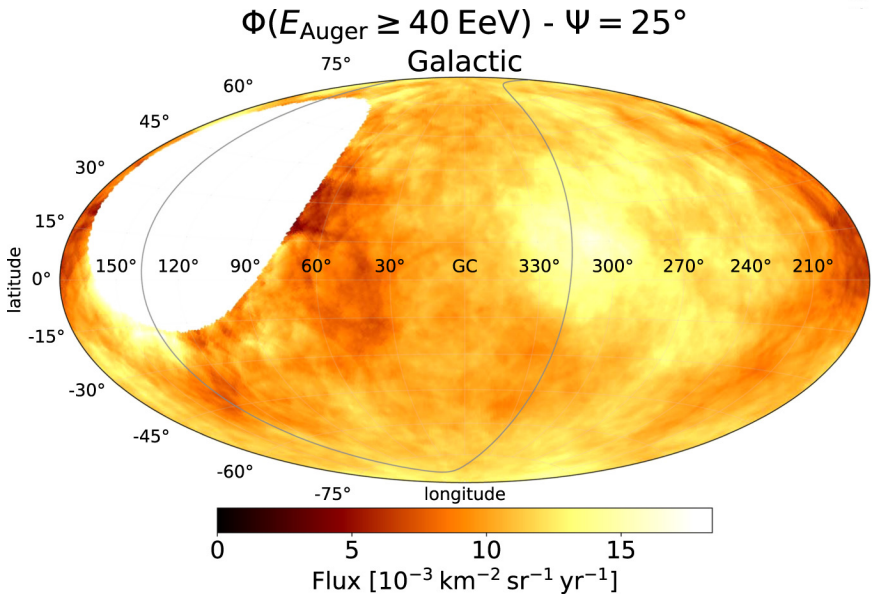
The first-harmonic modulation aligns well with the data (X2/n = 10.5/10); the dashed line represents a constant function

- The 3D dipole above 8 EeV is oriented ~125° from the galactic center
- Its position aligns with mixed composition deflected by galactic magnetic fields
- Arrows indicate expected particle deflections by the galactic magnetic field for E/Z = 5 or 2 EeV

Arrival Direction: Intermediate Scale

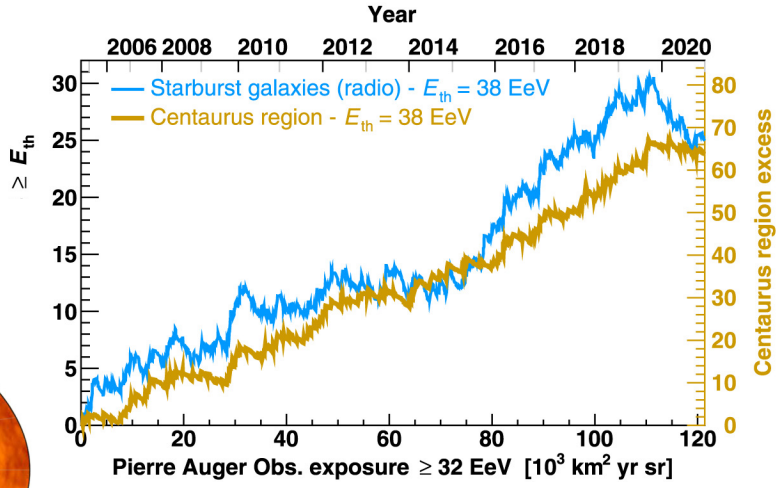
Cosmic-ray flux map in galactic coordinates for energies E≥40 EeV





Whole sky blind search: Excess 5.4σ, Ψ=24° & E=41EeV

- Tested 4 different catalogues, including starburst galaxies and AGNs
- A model-independent analysis of the Centaurus region finds a 4.1σ significance



A 5σ discovery is expected by late 2025 with Ψ = 27°

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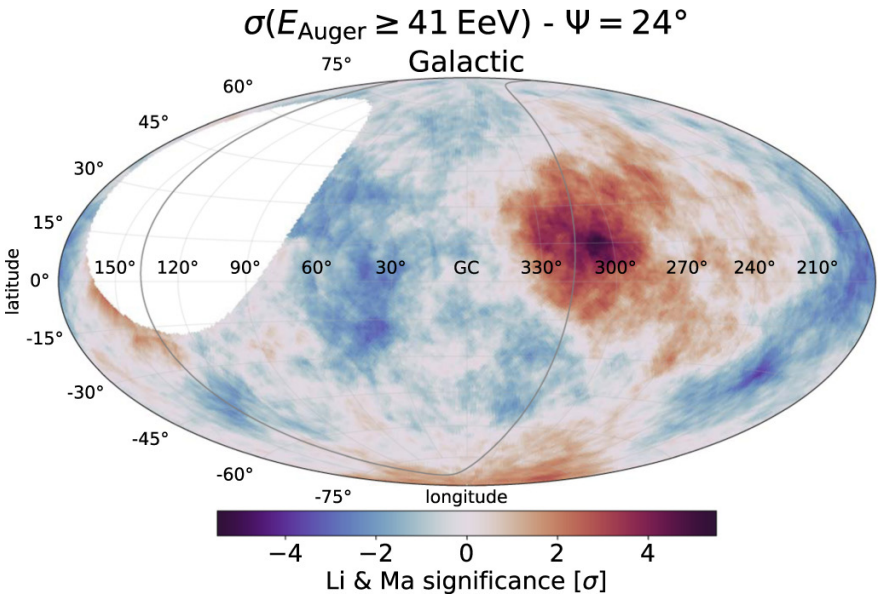

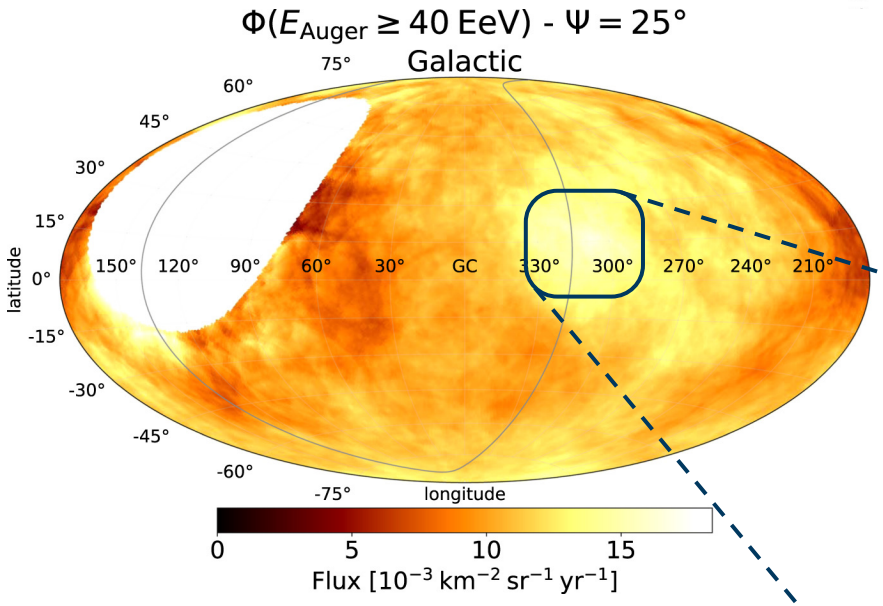

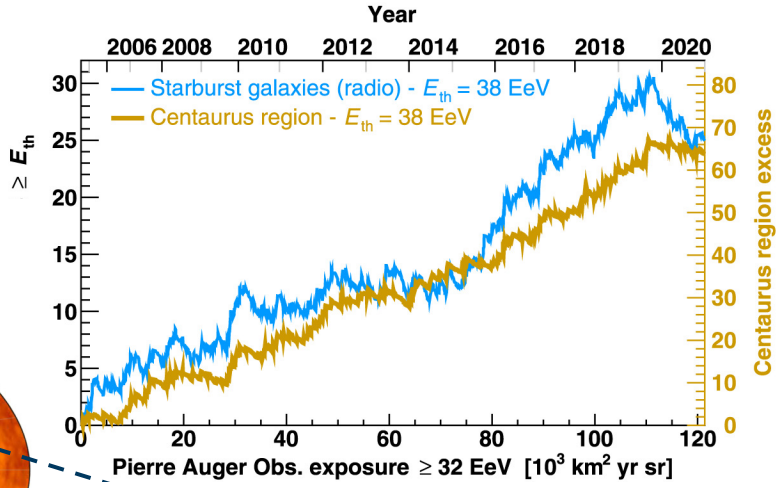

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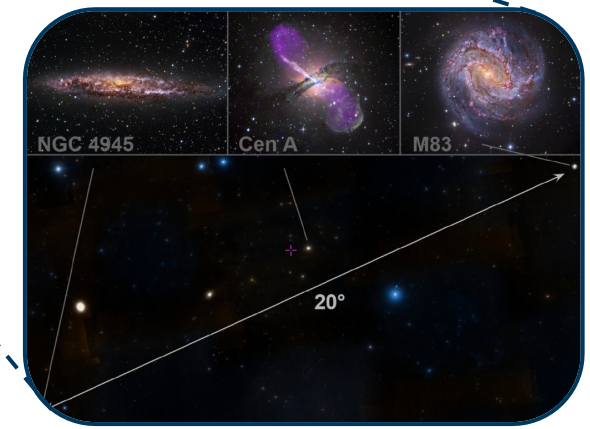

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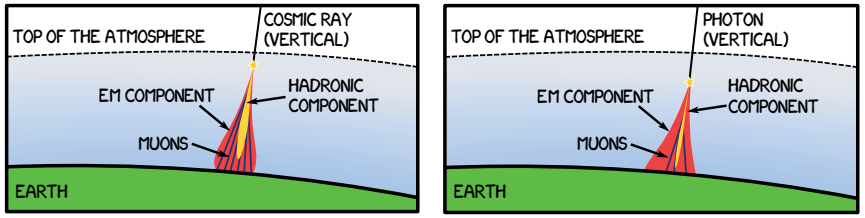
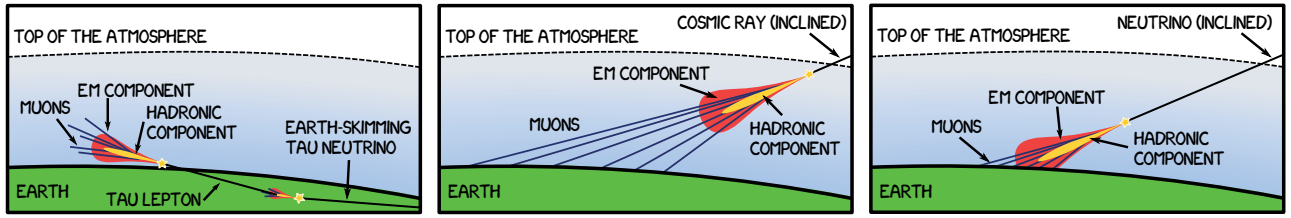
→ Auger Phase II: event-by-event primary mass information – composition enhanced anisotropy studies

Searching for Neutral Particles

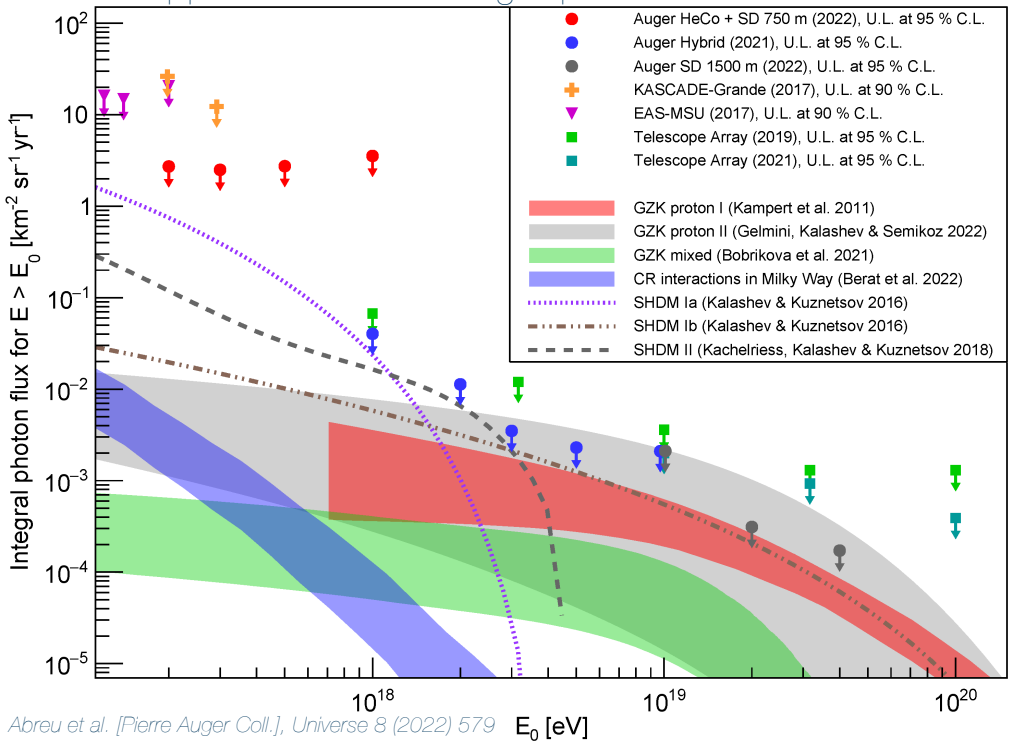
cosmic rays vs. photos



shallowly up-going (Earth skimming) neutrinos, cosmic rays, down-going neutrinos

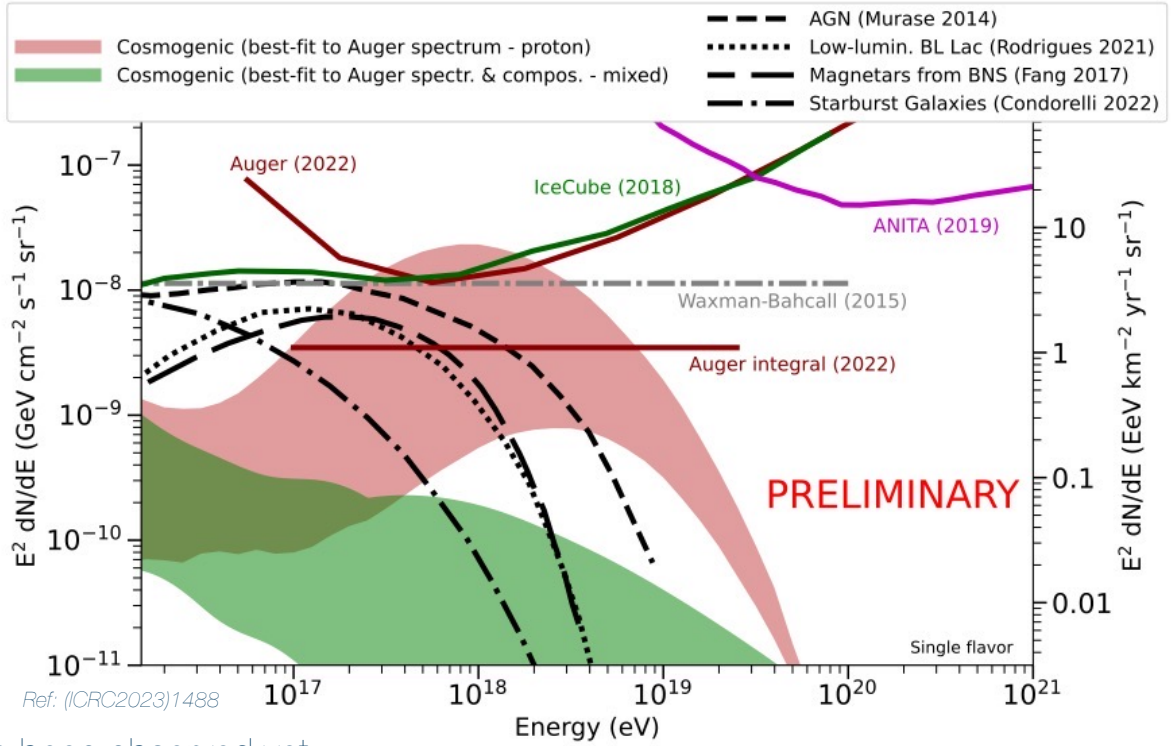


Upper limits on the integral photon flux at 95% C.L.



Ref: P. Abreu et al. [Pierre Auger Coll.], Universe 8 (2022) 579

Upper limits on the diffuse flux of neutrinos at 95% C.L.

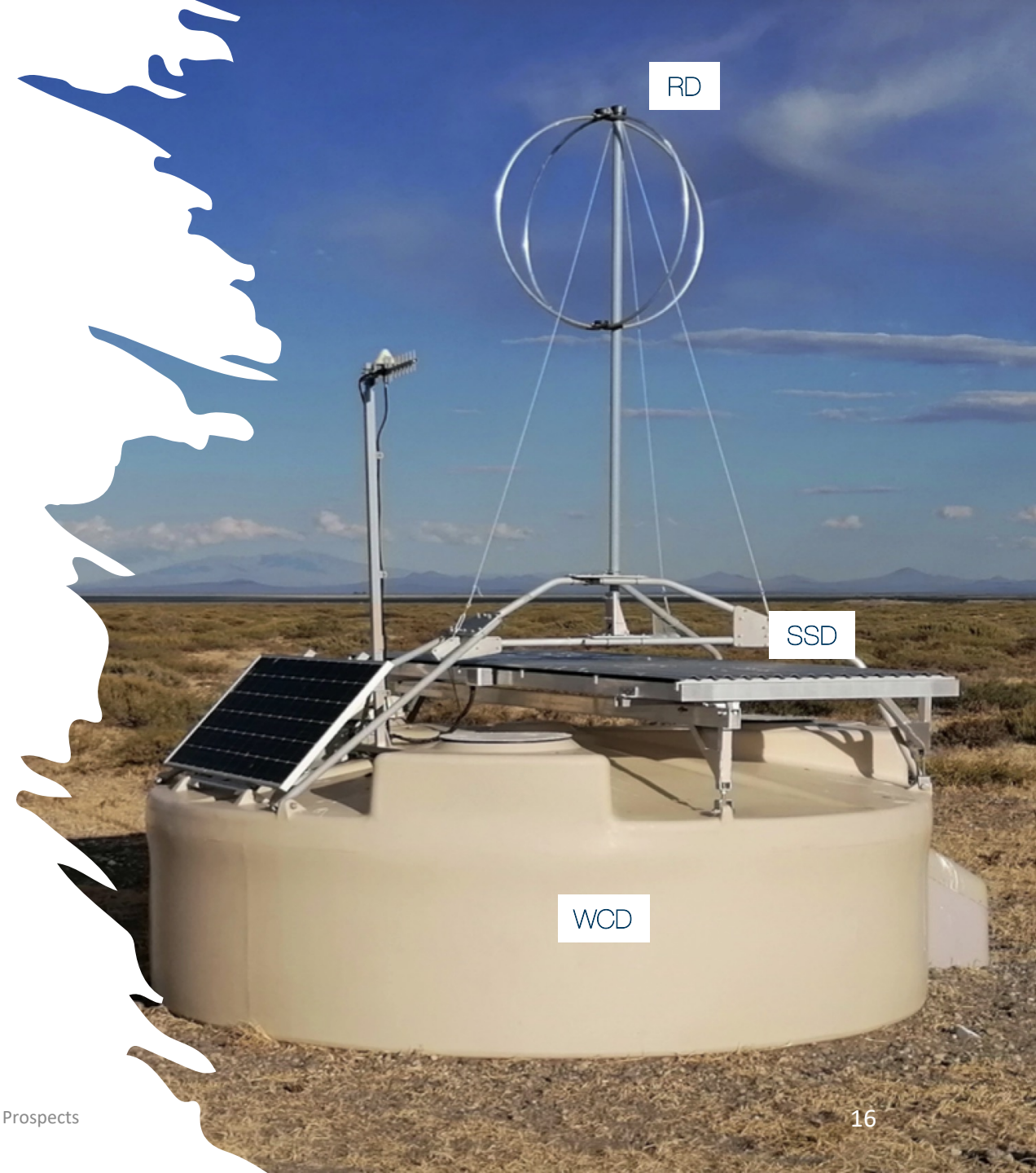


Ref: (ICRC2023)1488

No UHE photons or neutrino have been observed yet

AugerPrime: Observatory Upgrade

- Scintillator-based Surface Detector (SSD) on Water Cherenkov Detector (WCD)
  → measure shower e/μ
- Added smaller PMT in WCD
  → increase dynamic range
- New upgraded electronics board (UUB)
  → improve data processing.
- Radio Detector (RD) atop WCD
  → enhance composition measurements, particularly for horizontal events



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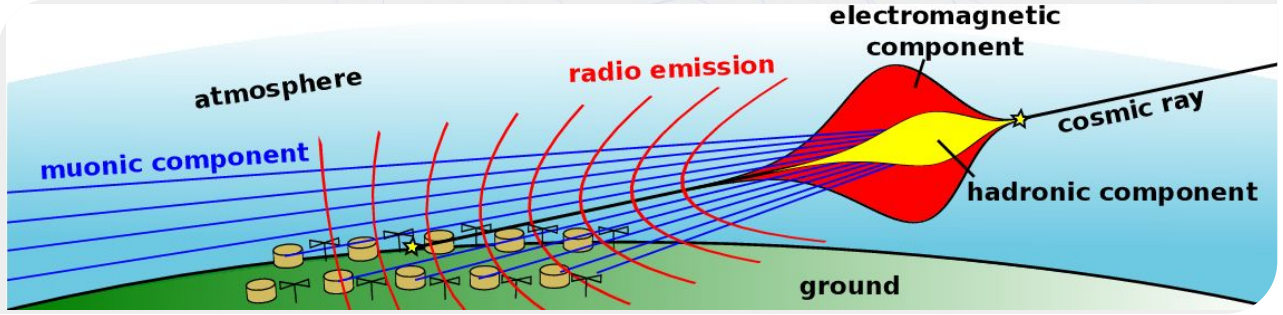
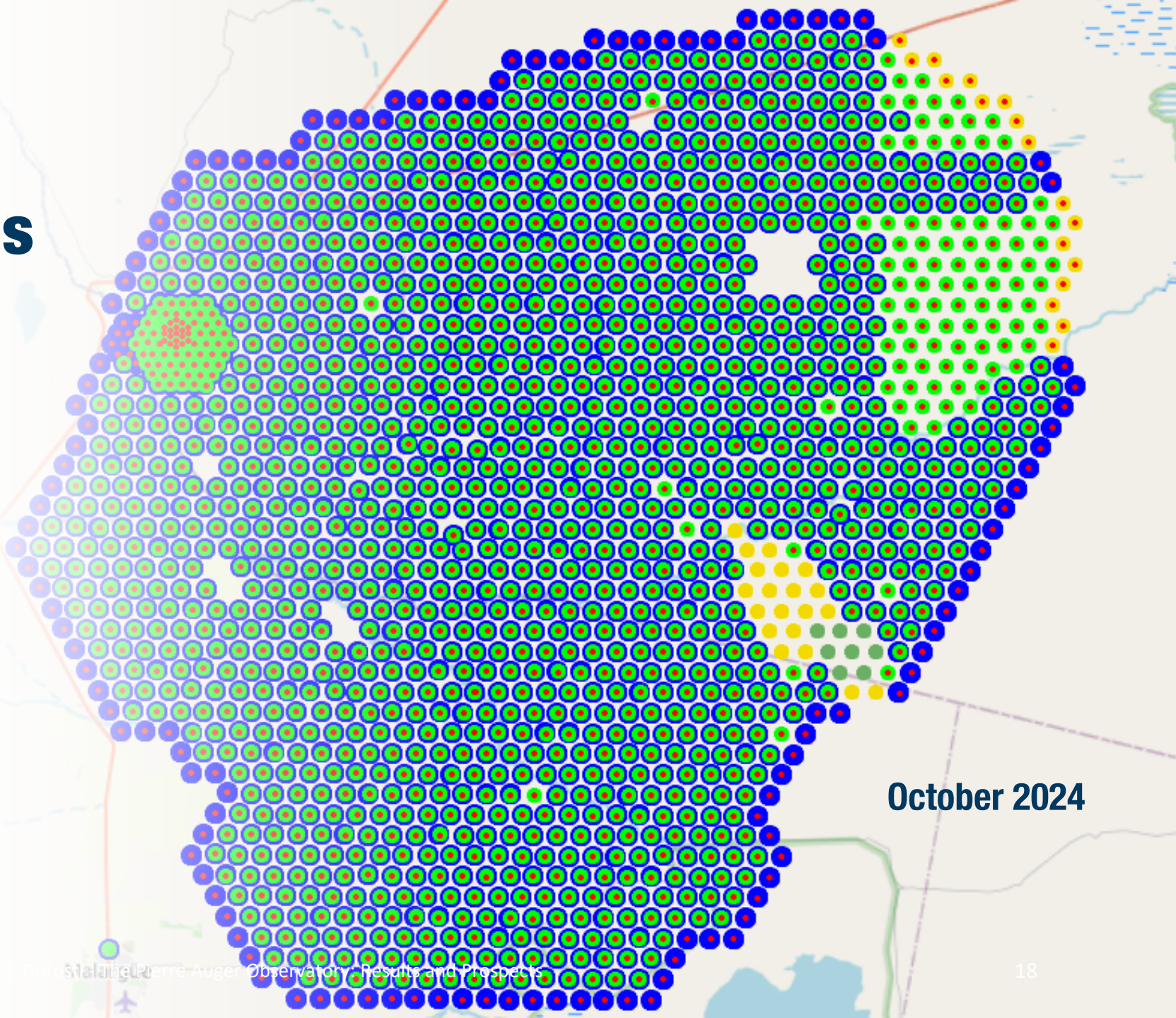


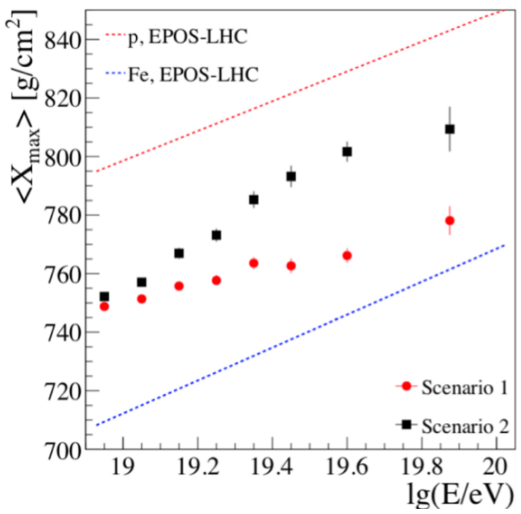
AugerPrime: Deployment Status

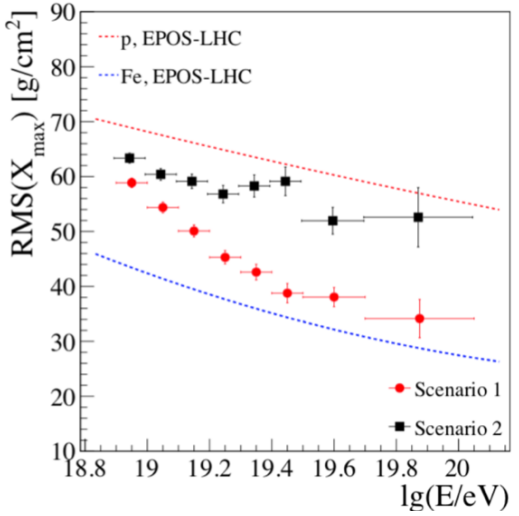


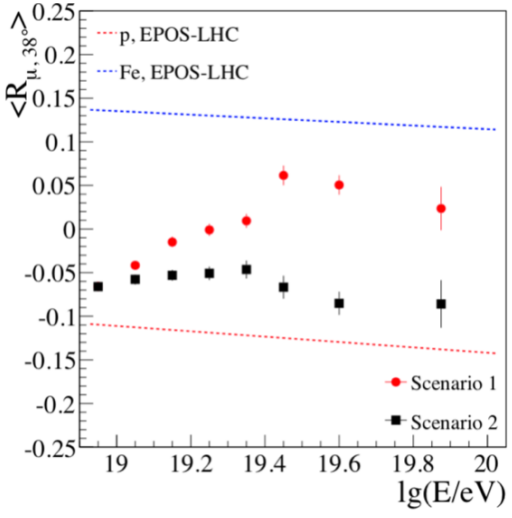
Auger Phase 2: Enhanced Era with AugerPrime

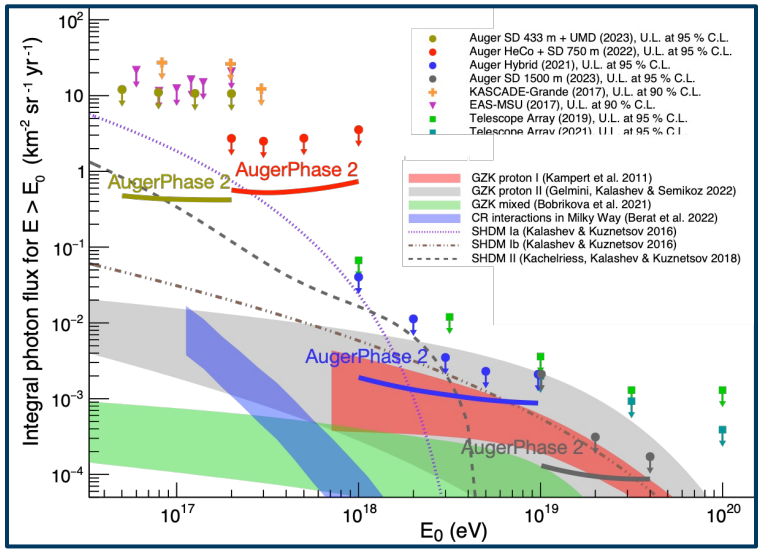
- Measure mass composition on an event-by-event basis
- Investigate the nature and origin of UHECRs
- Detect UHE neutrinos and photons
- Test new physics at the UHE scale
- Explore geophysical sources of high-energy particles, and more

Xmax, Fluctuations, and Muon Number for Rigidity for Different Source Models









Ref: EPJ Web of Conferences 210, 06002 (2019)