The energy spectrum of ultra-high energy cosmic rays measured using the Pierre Auger Observatory

TeVPA Chicago 2024

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KIT

PIERRE AUGER OBSERVATORY

Deriving a spectrum

→ Event rate N_i
→ Derive exposure ε from detector geometry, event selection and measurement time
→ Energy bin width ΔE
→ **Raw spectrum:**

$$J_i^{\mathrm{raw}} = \frac{N_i}{\epsilon\, \Delta E},$$

→ **Forward-folding:**

- Account for the finite resolution κ of the energy reconstruction (forward folding)

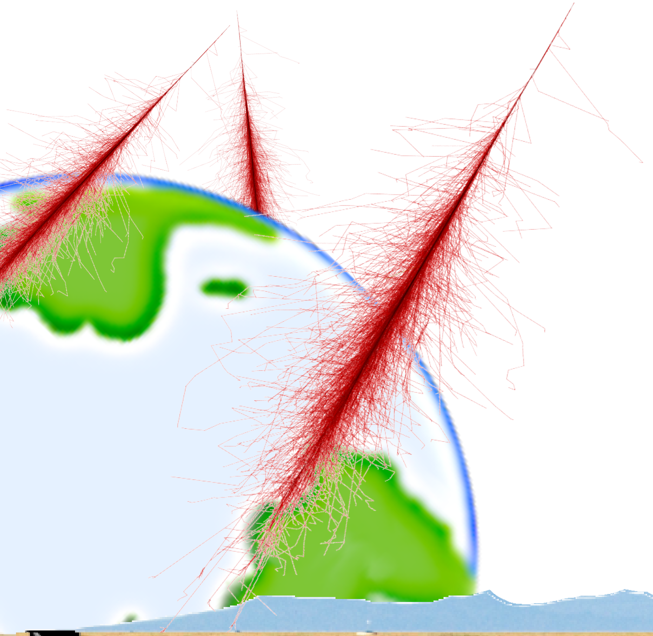
$$J^{\mathrm{raw}} = \frac{\int \mathrm{d}\Omega \cos\theta \int \mathrm{d}E \epsilon\, \kappa\, \mathbf{J}}{\int \mathrm{d}\Omega \cos\theta},$$

- Model the spectrum by a sequence of power laws with soft transitions:

$$J(E) = J_0 \left(\frac{E}{E_0}\right)^{-\gamma_1} \prod_{i=1}^{n} \left[1 + \left(\frac{E}{E_{ij}}\right)^{\frac{1}{\omega_{ij}}}\right]^{(\gamma_i - \gamma_j)\omega_{ij}} \qquad J_i = c_i\, J_i^{\mathrm{raw}}$$

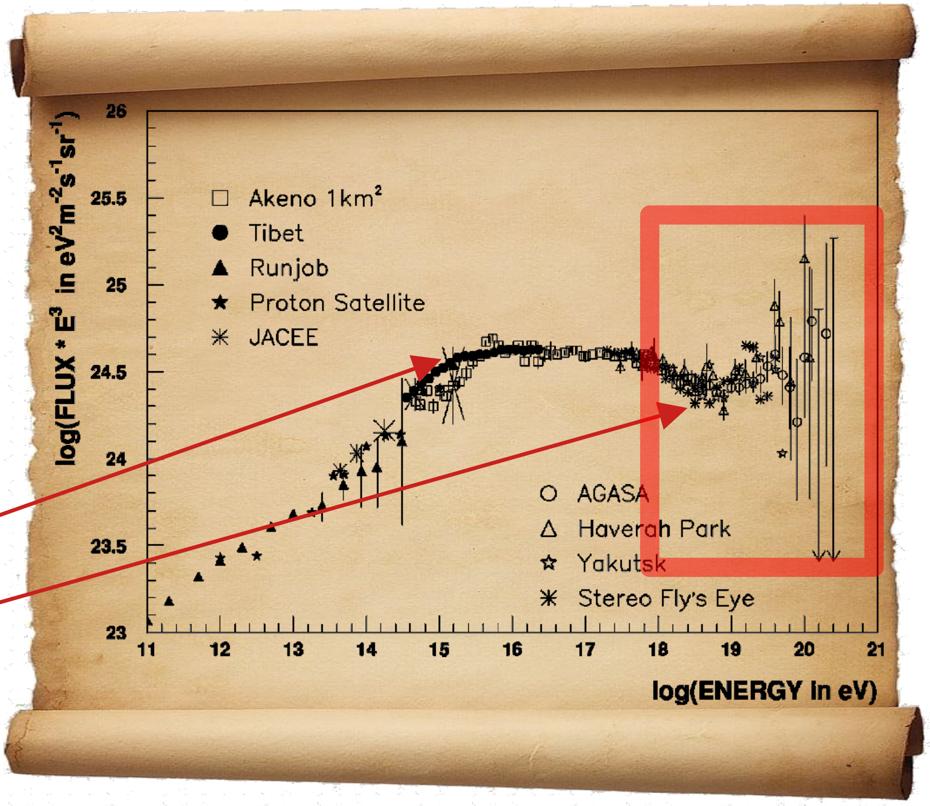
Motivation

- → The energy spectrum of cosmic rays in 2000
- → Large uncertainties at the highest energies
- → GZK cutoff or source exhaustion???



1 particle per m^2 year

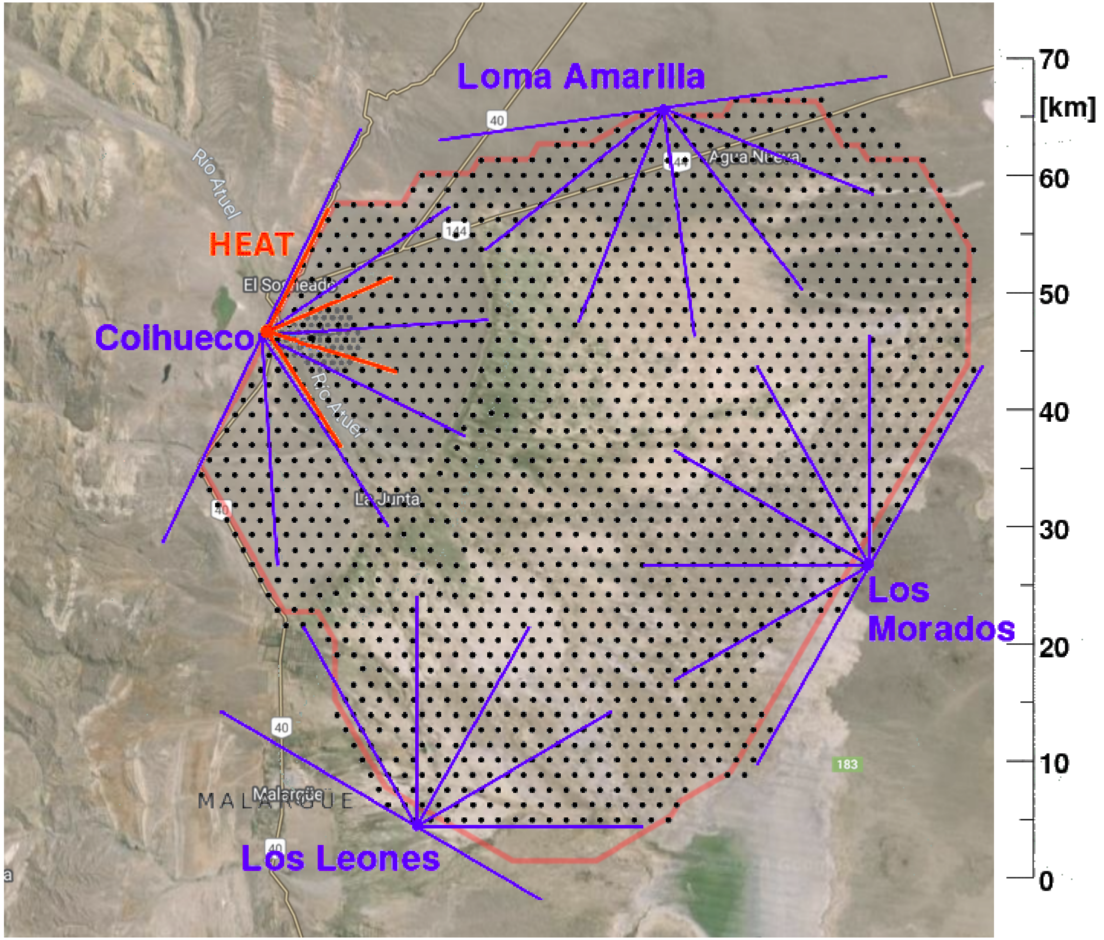
1 particle per km^2 year



Rev. Mod. Phys. 72, 689 (2000)

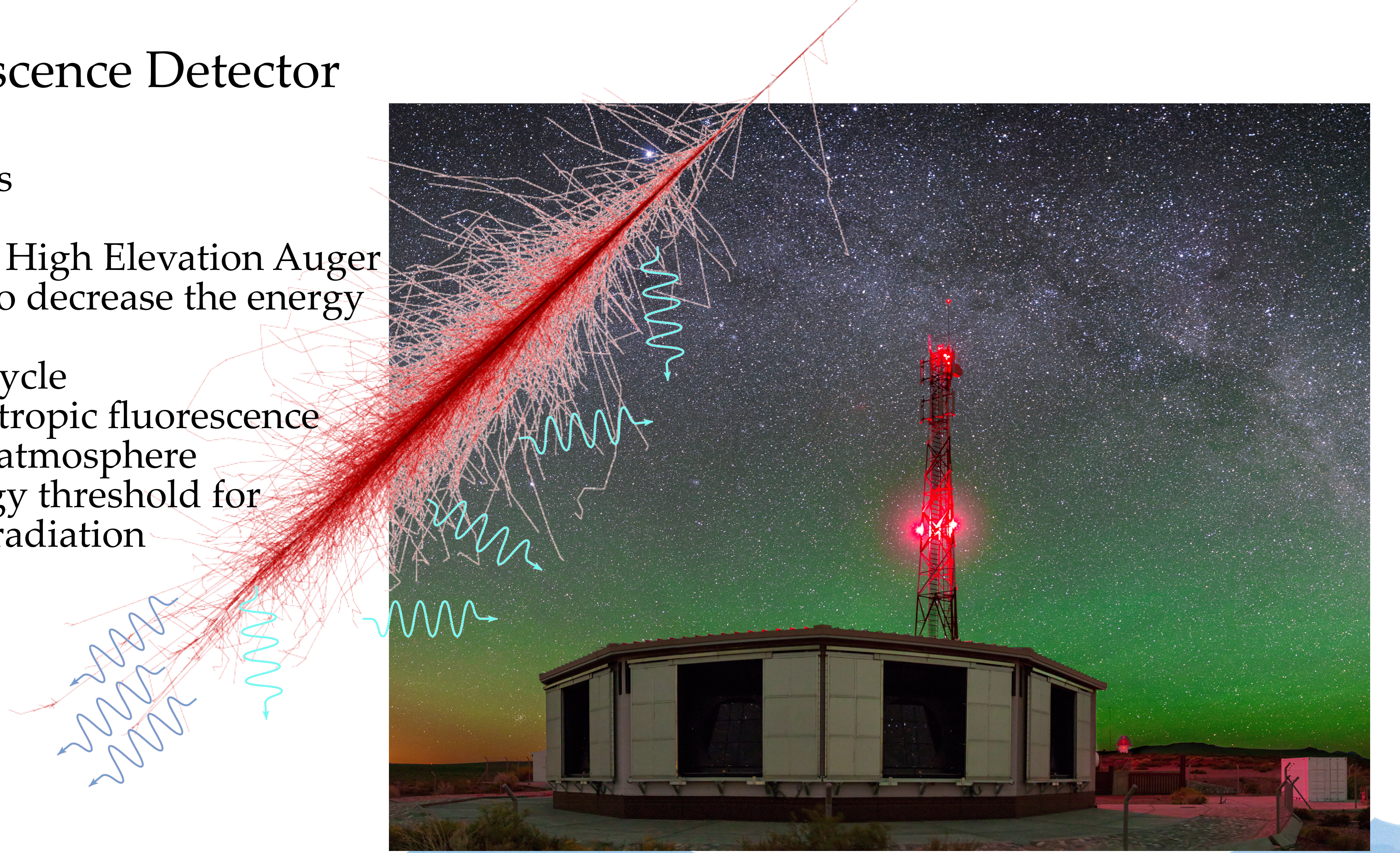
The Pierre Auger Observatory

- → 1400m altitude
- → 3000 km²
- → Designed to detect secondary particles of extensive air showers
- → Hybrid detector layout
  - Fluorescence Detector
  - Surface Detector



The Fluorescence Detector

- → 24 telescopes
- → 4 buildings
- → 3 additional High Elevation Auger Telescopes to decrease the energy threshold
- → ~15% duty cycle
- → Measure isotropic fluorescence emission in atmosphere
- → Lower energy threshold for Cherenkov radiation



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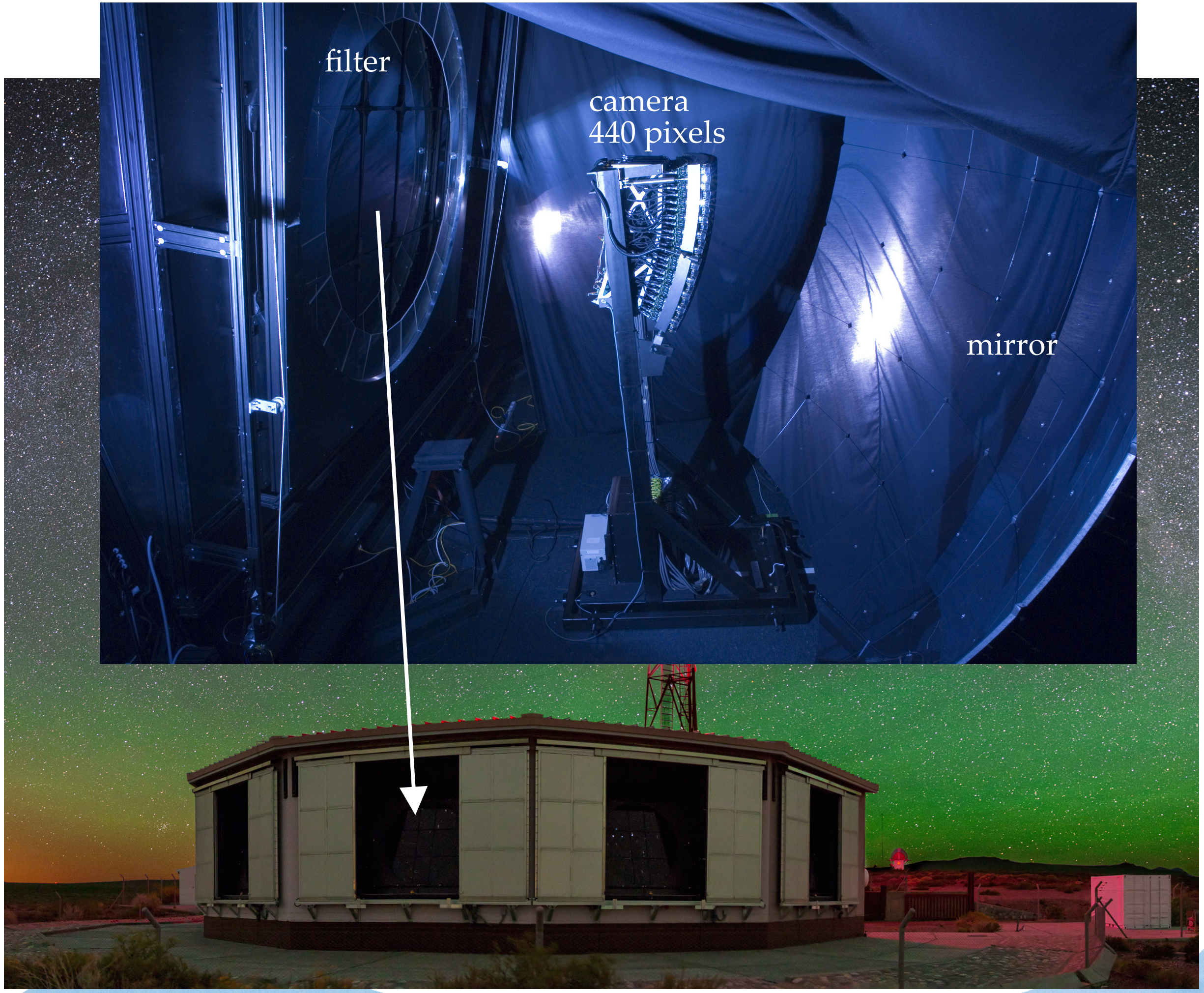
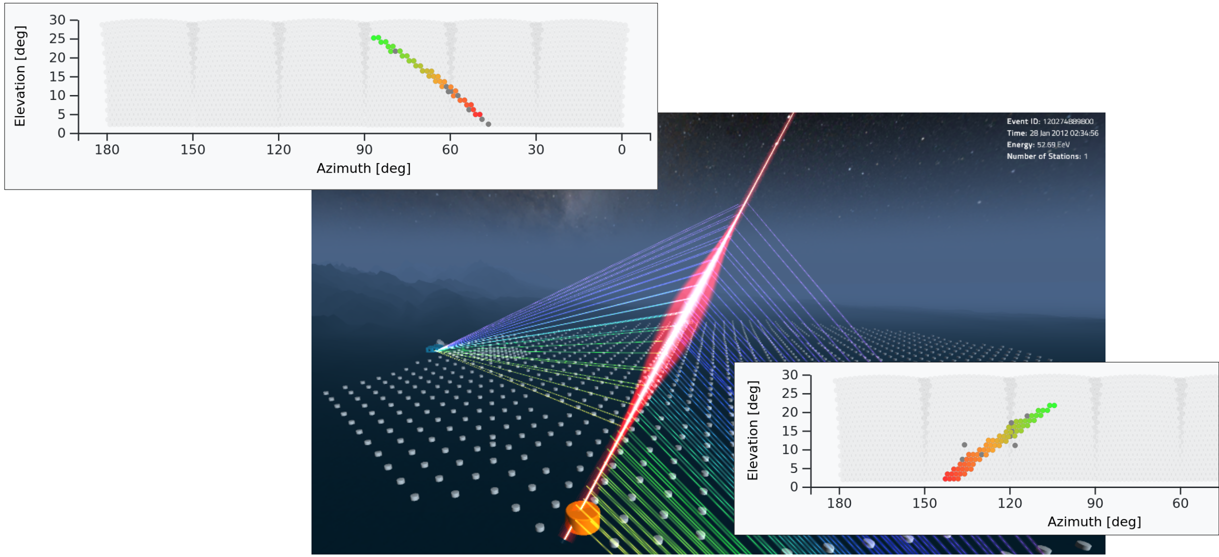
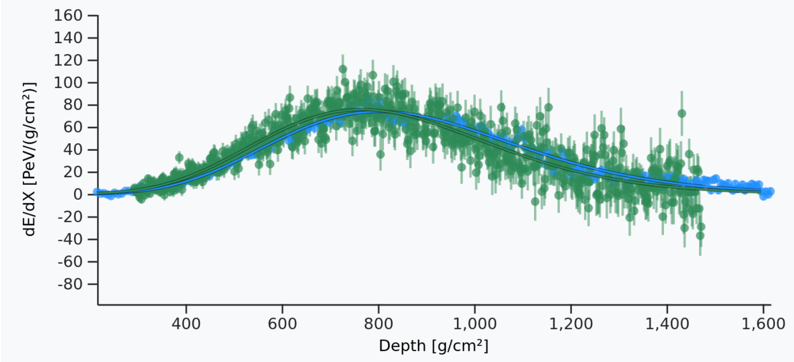


The Fluorescence Detector

→ 24 telescopes
→ 4 buildings
→ 3 additional High Elevation Auger Telescopes to decrease the energy threshold
→ ~15% duty cycle
→ **Geometry constrained by single triggered SD station**

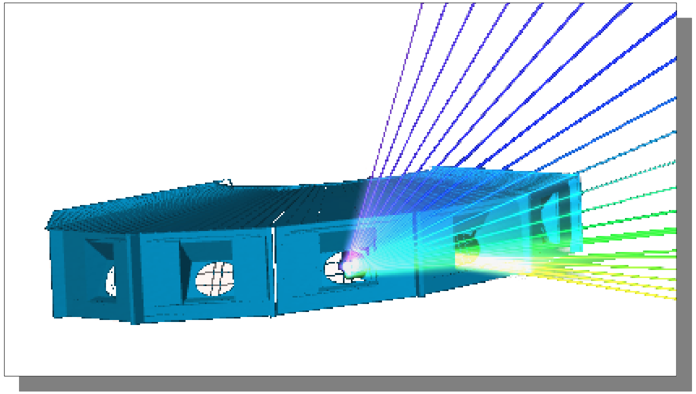


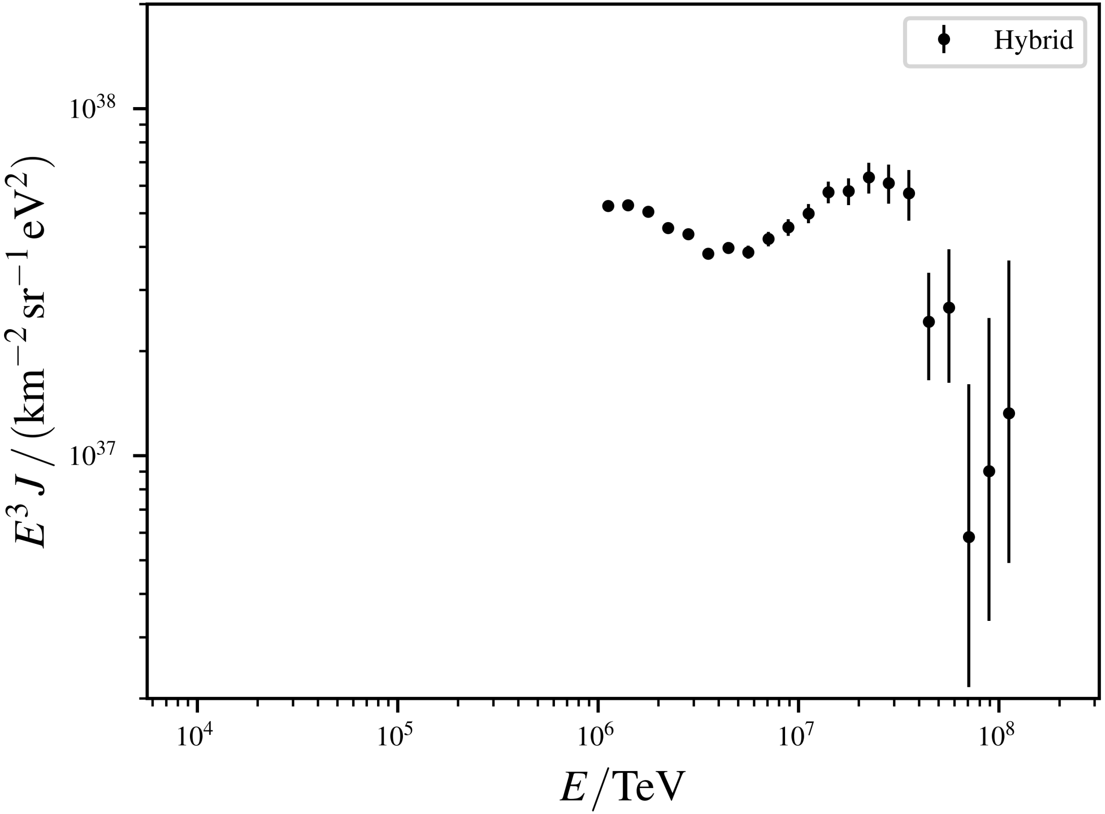
→ Integral gives calorimetric energy
→ Corrected for "invisible" energy (μ, ν) ~10% (data-driven)
→ Shower maximum in field of view
→ Exposure derived from simulations



The Hybrid Spectrum

- → 01/2007 - 12/2017
- → ~15 000 events
- → Zenith: 0-60°
- → Energy threshold: 10^{18} eV





Eur. Phys. J. Plus 127, 87 (2012)

The Surface Detector (SD)

- → >1600 water-Cherenkov detector stations
- → triangular grid
- → 3 arrays with different densities
  - 1500 m spacing
  - 750 m spacing
  - 433 m spacing
- → 100% duty-cycle
- → Calibrated with atmospheric muons

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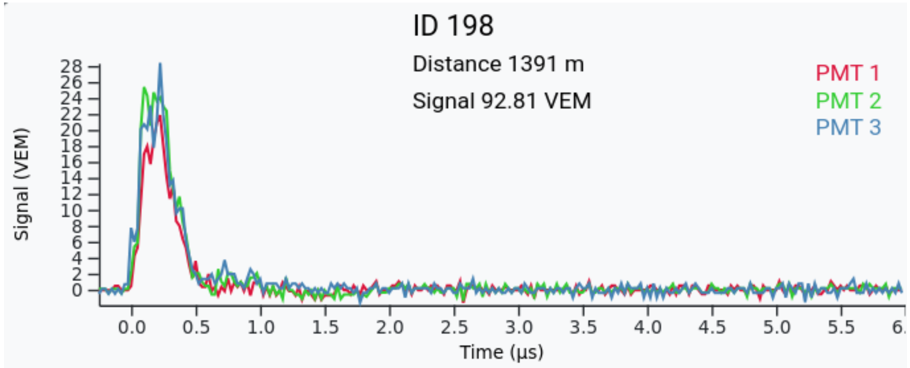
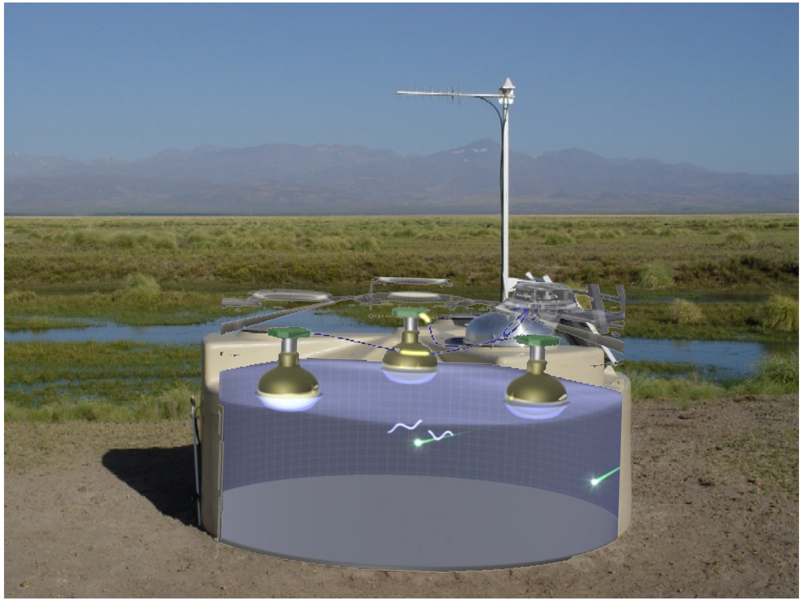
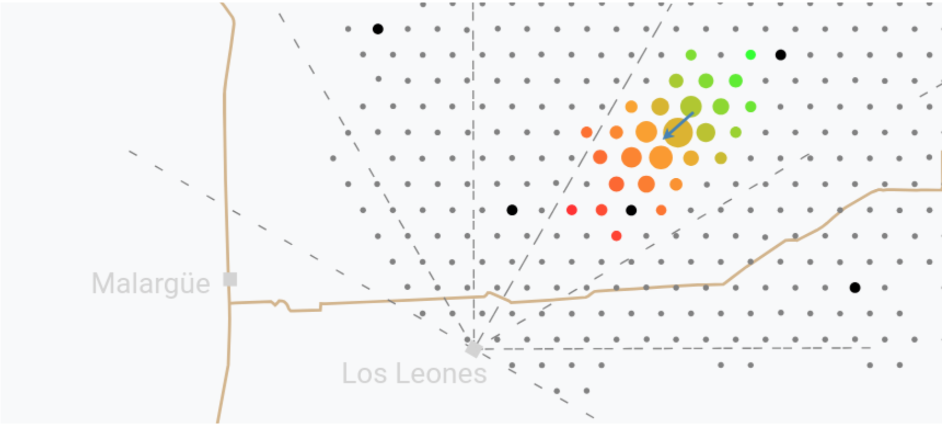


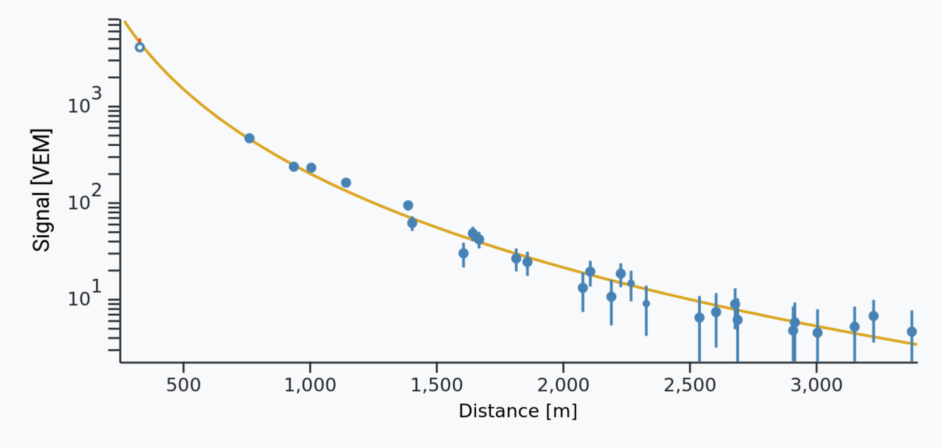


The Surface Detector (SD)

- → Reconstruction based on lateral distribution of signals
- → Correction for attenuation depending on inclination
- → Energy calibration with “golden” hybrid events
  - Uncertainty of the energy scale: ~14%
- → Purely geometric exposure at full efficiency

PRD 102, 062005 (2020)

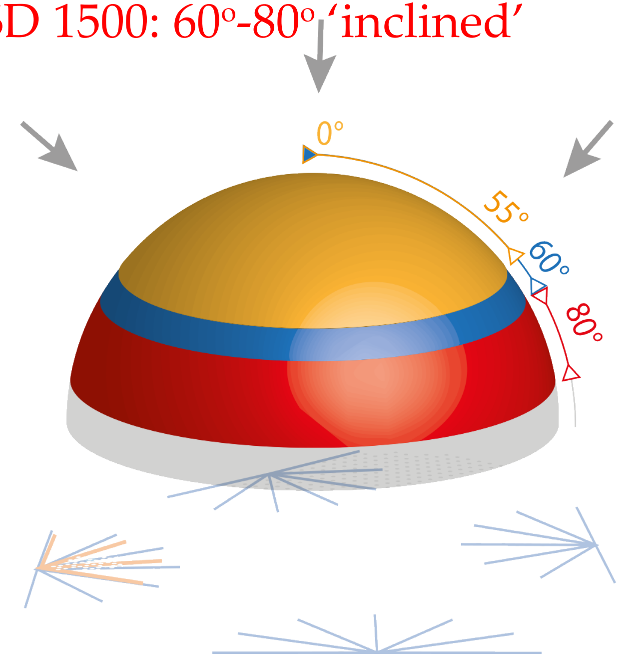


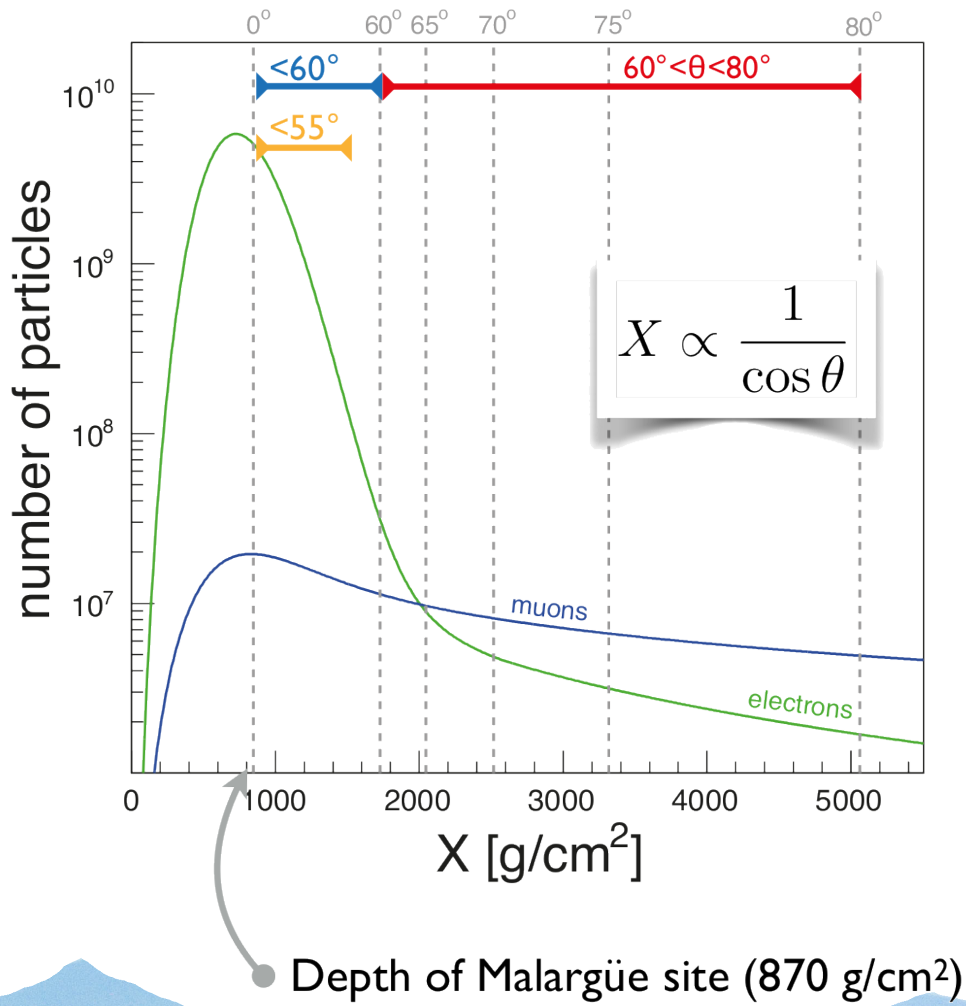


The Surface Detector (SD)

→ Zenith angle ranges

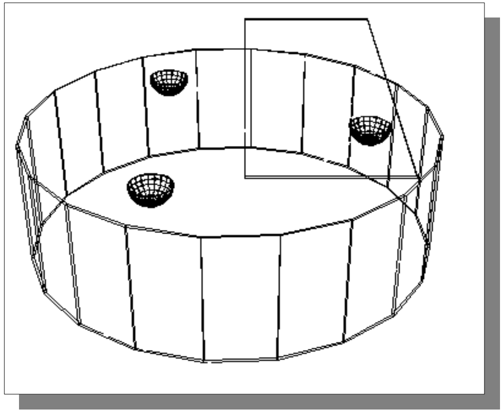
- SD 750:   0° - 55° 'vertical'
- SD 1500: 0° - 60° 'vertical'
- SD 1500: 60°-80° 'inclined'

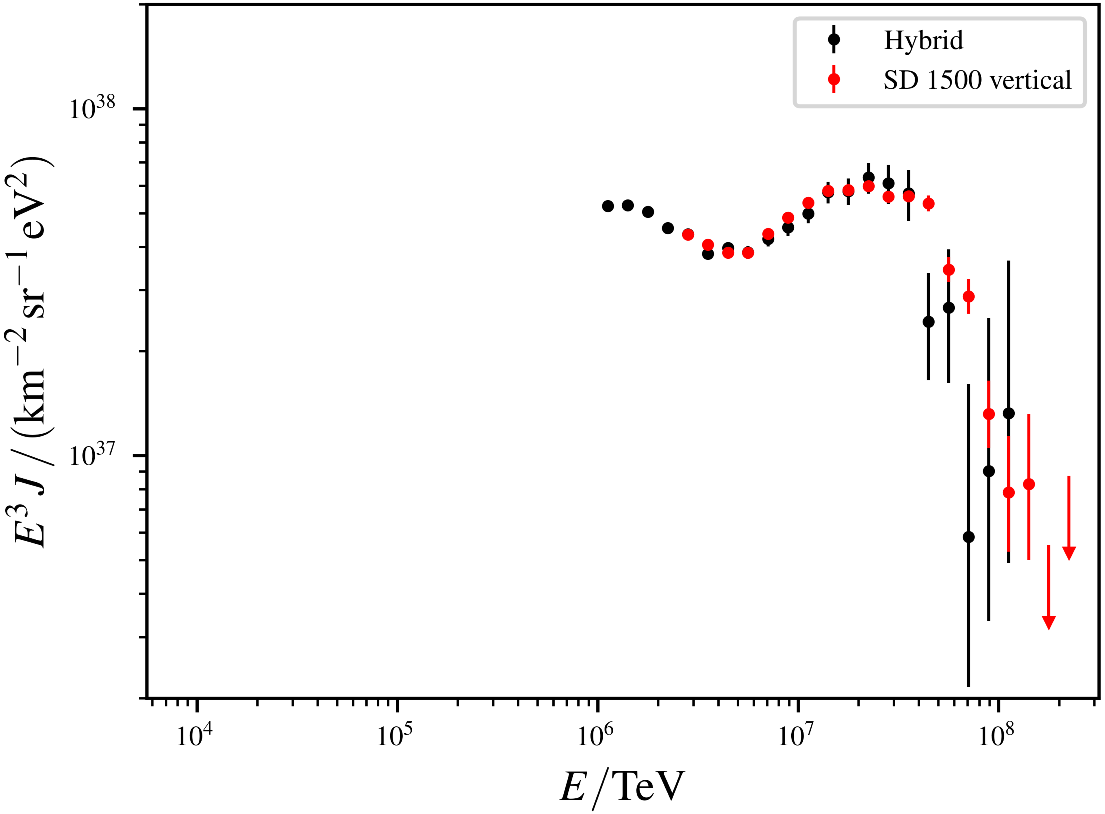




The SD 1500 Spectrum

- → 01/2004 - 08/2018
- → ~215 000 events
- → Zenith: 0 – 60°
- → Energy threshold: $10^{18.4}$ eV



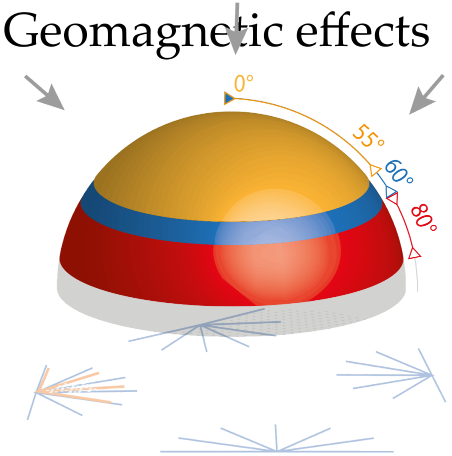


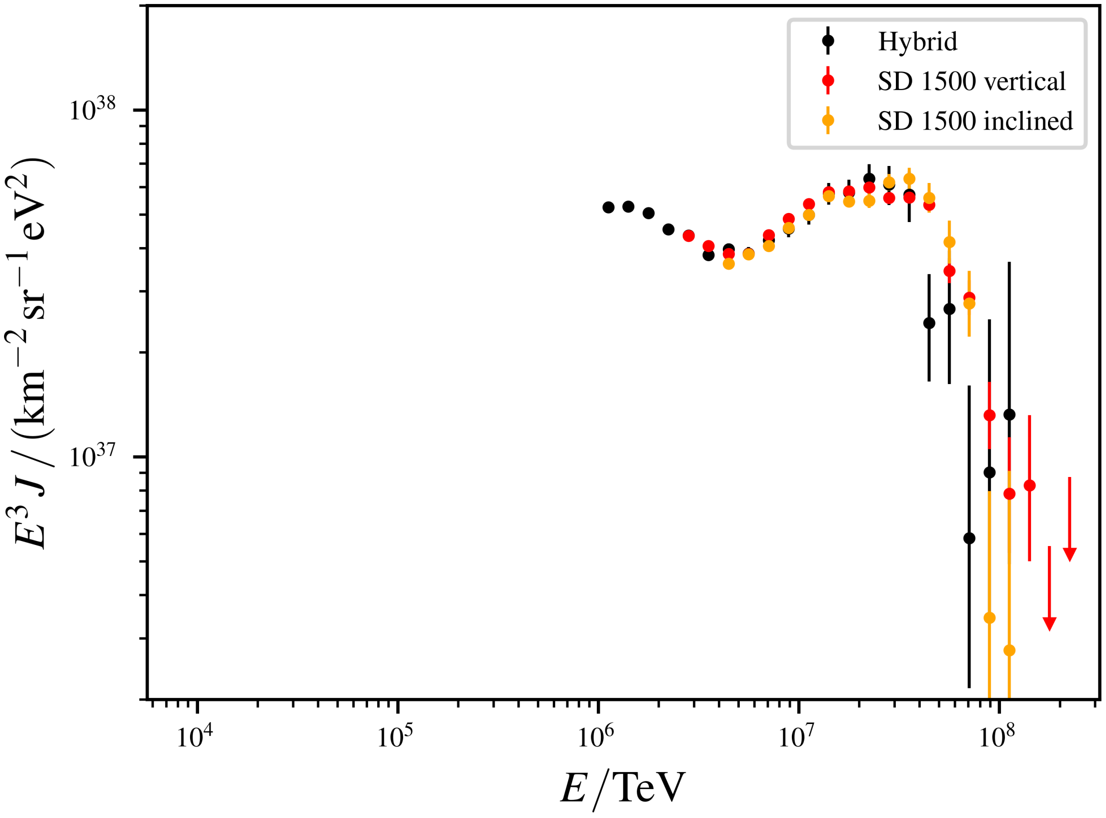
PRD 102, 062005 (2020)

The SD 1500 Inclined Spectrum

- → 01/2004 - 08/2018
- → ~24 000 events
- → Zenith: 60 – 80°
- → Energy threshold: $10^{18.6}$ eV

- → Large attenuation
- → Dominated by muon component
- → Geomagnetic effects

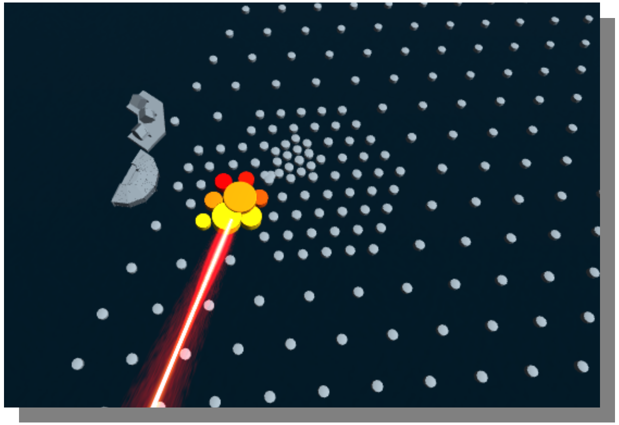


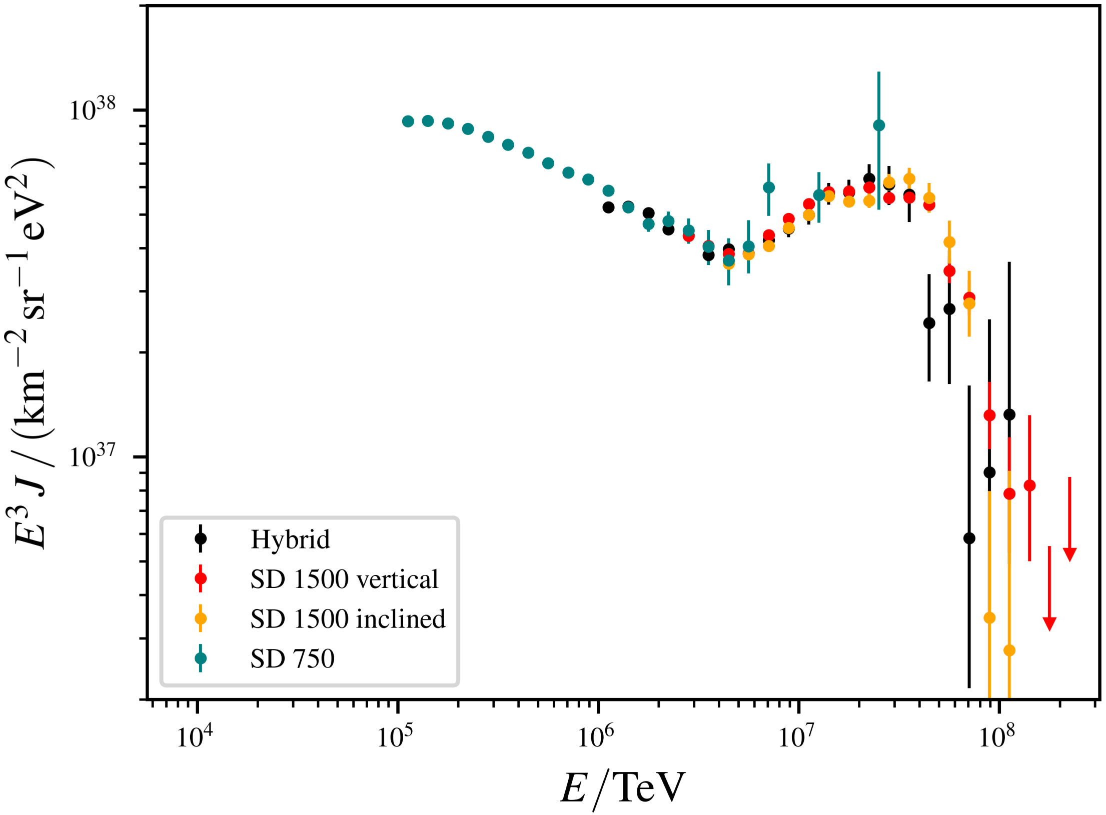


JCAP 08, 049 (2015)

The SD 750 Spectrum

- → 01/2014 - 08/2018
- → ~545 000 events
- → Zenith: 0 – 40°
- → Energy threshold: 10^{17} eV

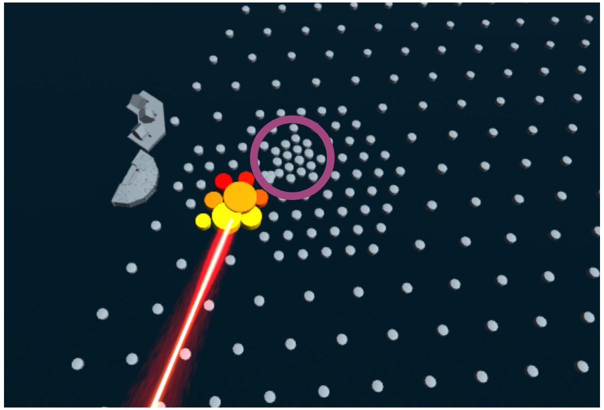


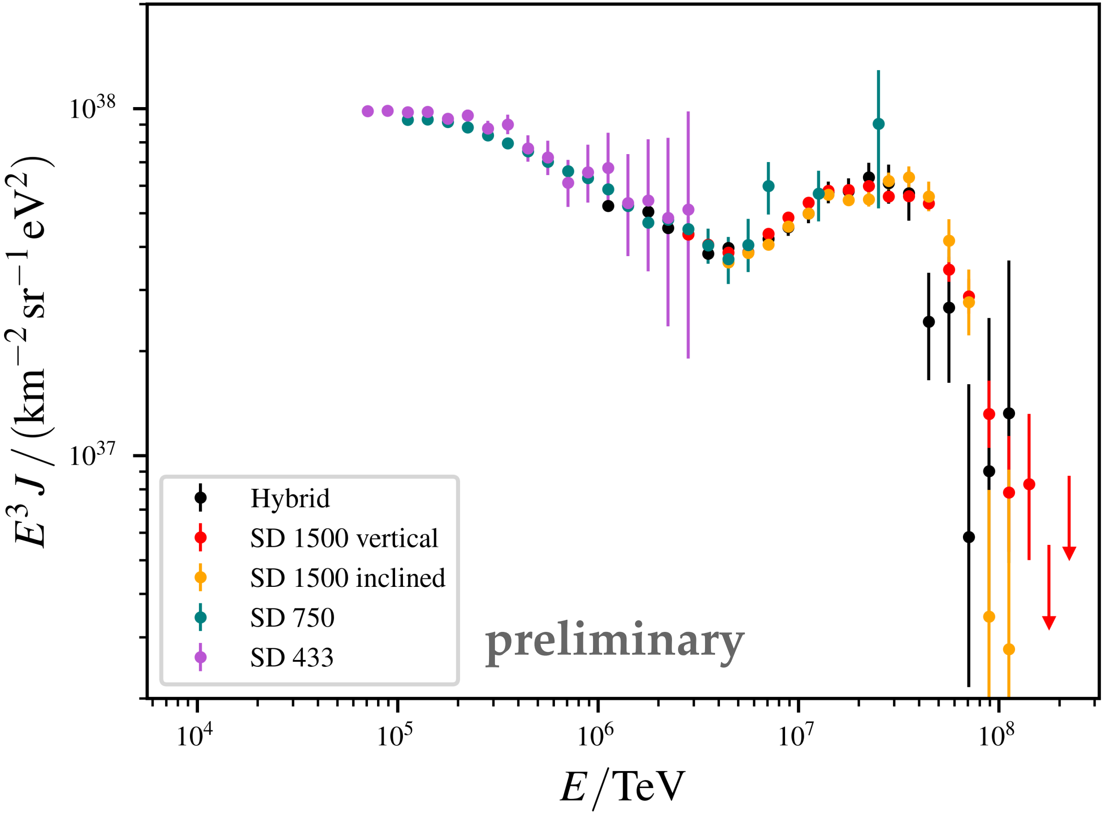


Eur. Phys. J. 81, 966 (2021)

The SD 433 Spectrum

- → 01/2018 - 12/2021
- → ~50 000 events
- → Zenith: 0 – 45°
- → Energy threshold: $10^{16.8}$ eV

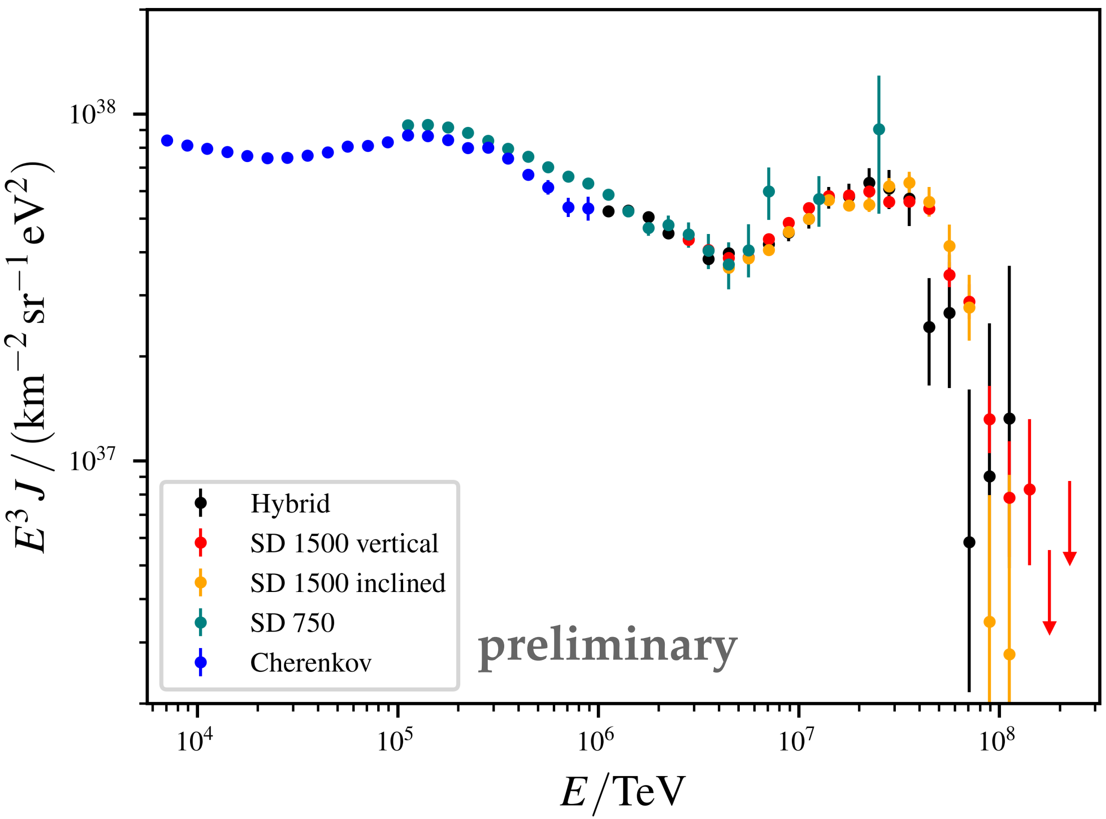




PoS(ICRC2023)398

The combined spectrum

- → Forward-folding approach
- → Estimate uncorrelated **systematic uncertainties**
  - Changes of exposure δε
  - Changes in energy calibration δA, δB
- → Combined likelihood fit
  - Correction factors for each spectrum
  - (Δε, δA, δB)
- → Combined spectrum
  - Effective exposure
  - Weighted sum of number of events



PoS(ICRC21)324

The combined spectrum

→ Forward-folding approach

→ Estimate uncorrelated **systematic uncertainties**

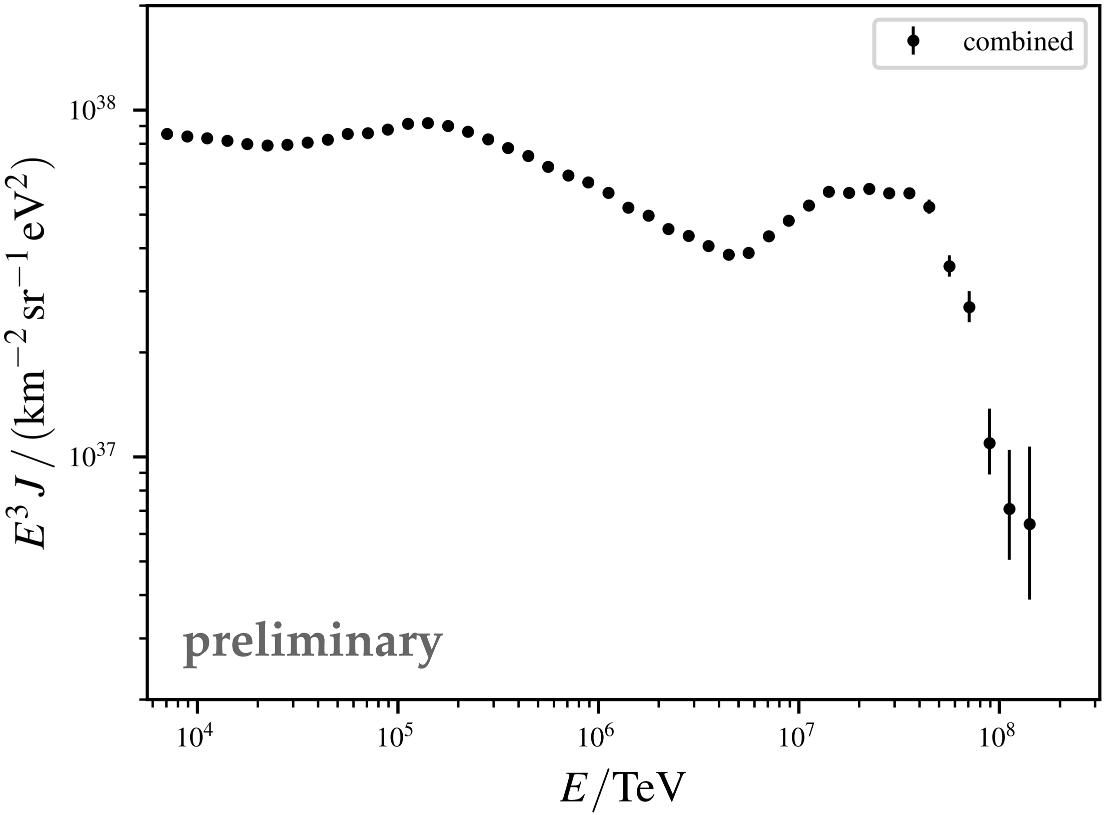
- Changes of exposure δε
- Changes in energy calibration δA, δB

→ Combined likelihood fit

- Correction factors for each spectrum
- (Δε, δA, δB)

→ Combined spectrum

- Effective exposure
- Weighted sum of number of events



PoS(ICRC21)324

The combined spectrum

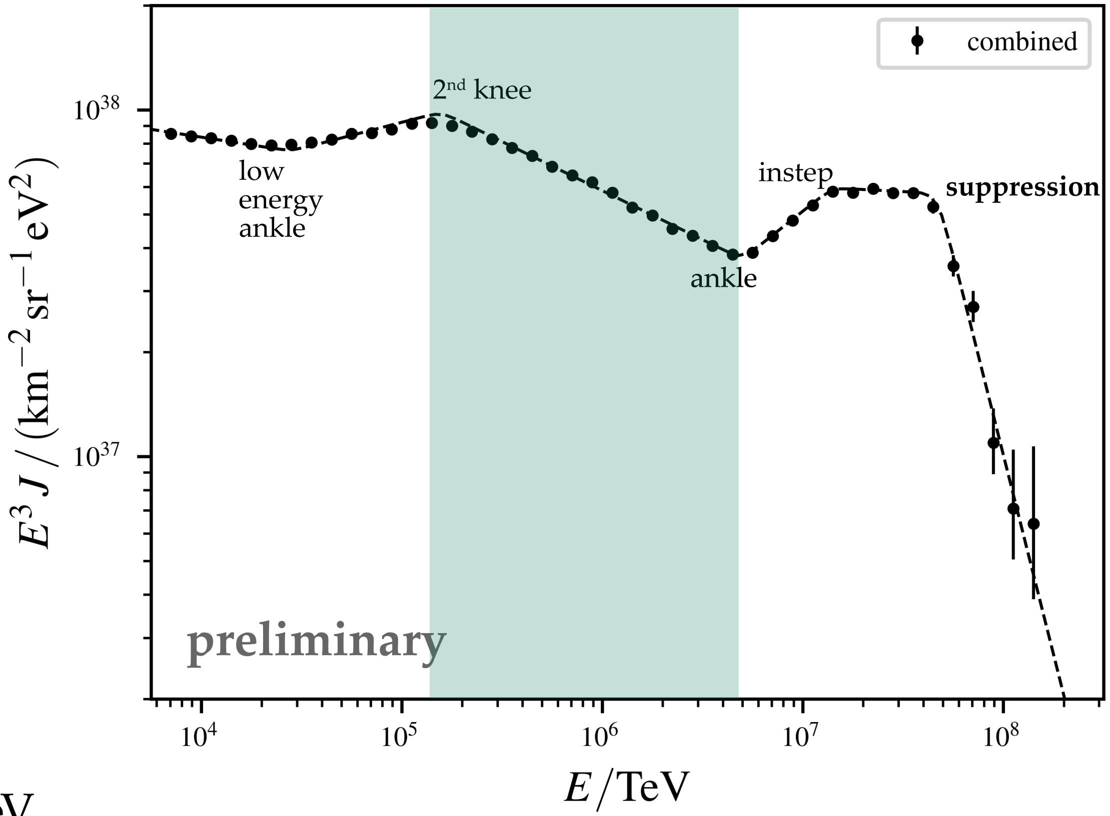
Possible explanations:

→ Maximum energy of acceleration of the heaviest nuclei for galactic sources

→ Transition from galactic to extragalactic sources

More about **arrival directions**:
Joao de Mello Neto [Today 4:15 PM]

More about **mass composition**:
Miguel Martins [Today 4:35 PM]



2nd knee $E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^5$ TeV

$\gamma_2 = 3.283 \pm 0.002 \pm 0.10$

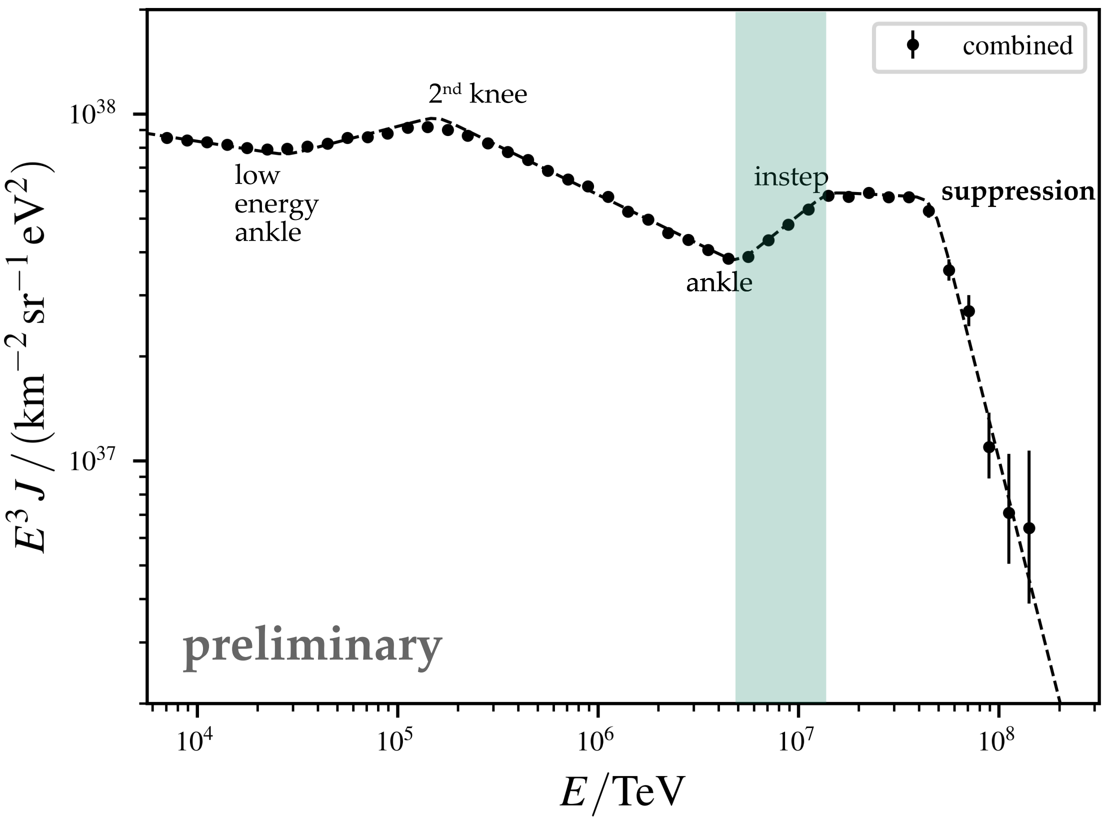
PoS(ICRC21)324
PRL 125, 121106 (2020)
JCAP 05, 024 (2023)

The combined spectrum

Possible explanations:

→ Below: lighter composition with soft spectrum

→ Above: mixed composition with harder spectrum



ankle $E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^6$ TeV

$\gamma_3 = 2.54 \pm 0.03 \pm 0.05$

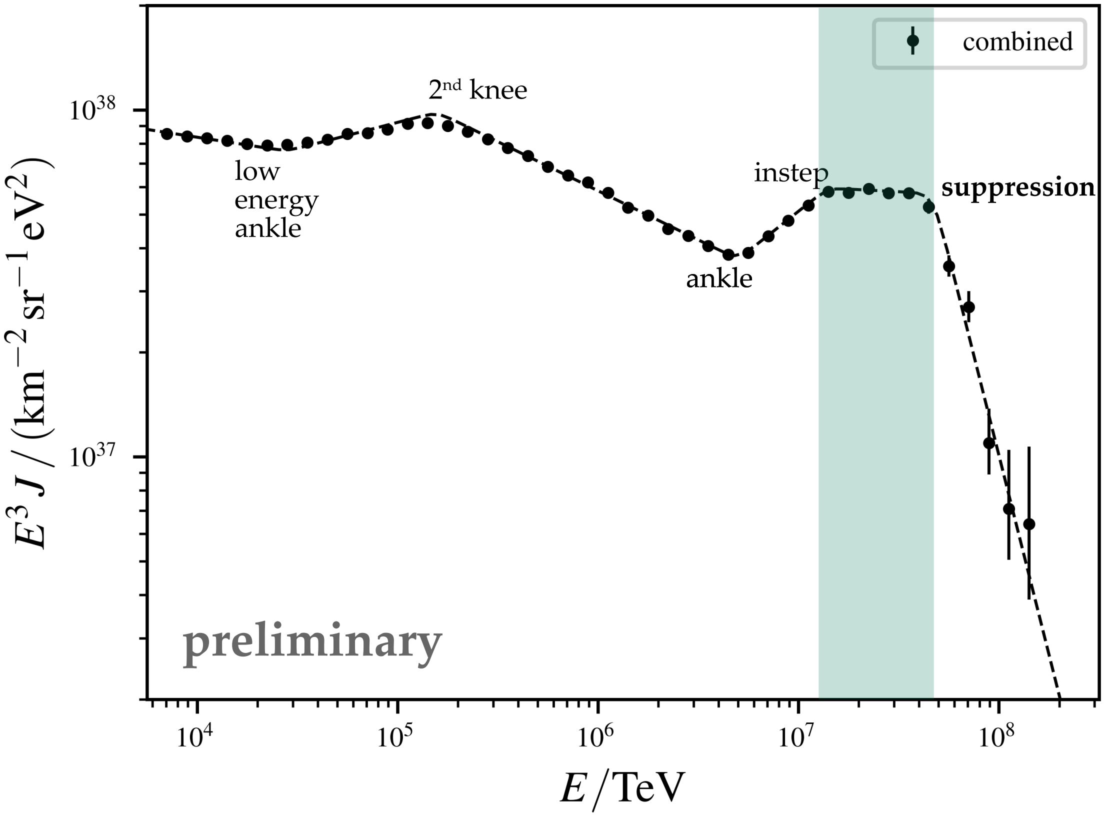
PoS(ICRC21)324

PRL 125, 121106 (2020)

The combined spectrum

Possible explanations:

→ Interplay between flux contributions of helium and carbon-nitrogen-oxygen



instep $E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^7$ TeV

$\gamma_4 = 3.03 \pm 0.05 \pm 0.10$

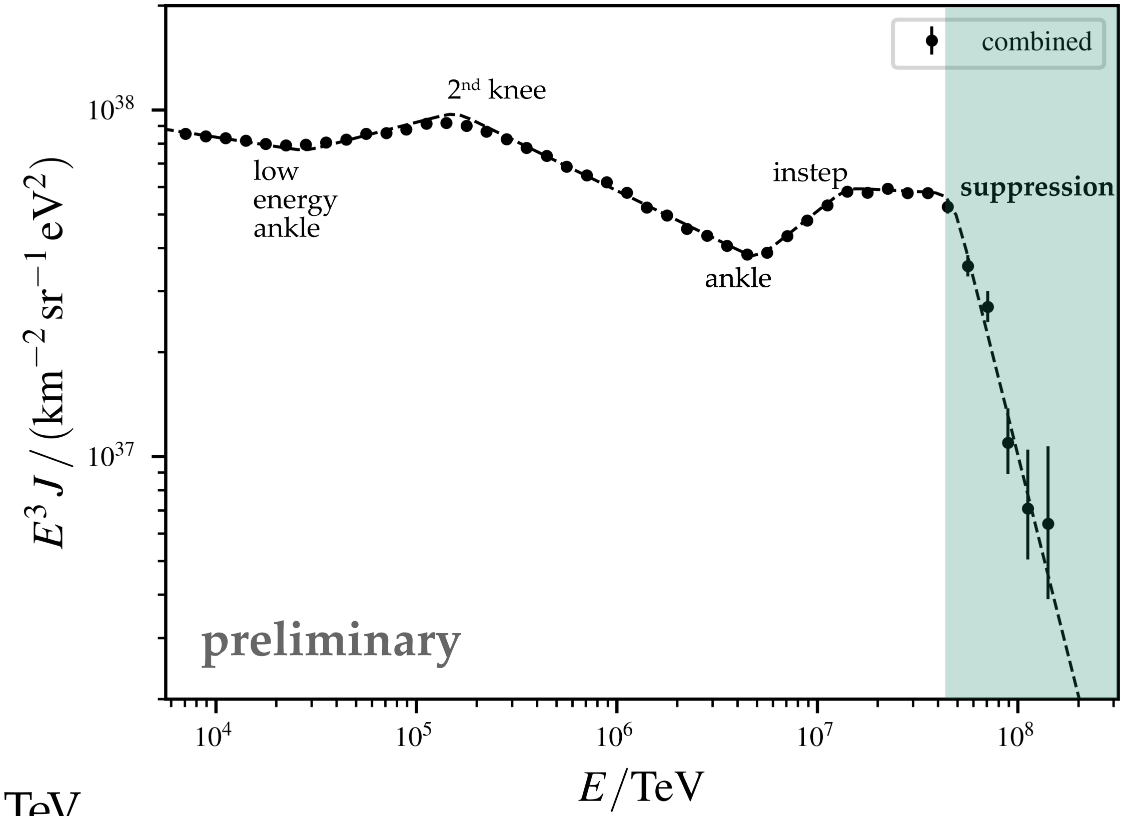
PoS(ICRC21)324
PRL 125, 121106 (2020)

The combined spectrum

Possible explanations:

→ Maximum energy of acceleration of the heaviest nuclei

→ Propagation effects (GZK, ...)



suppression $E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^7$ TeV

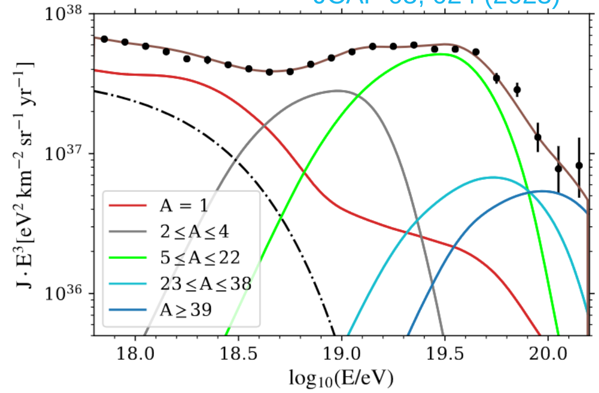
$\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

PoS(ICRC21)324
PRL 125, 121106 (2020)

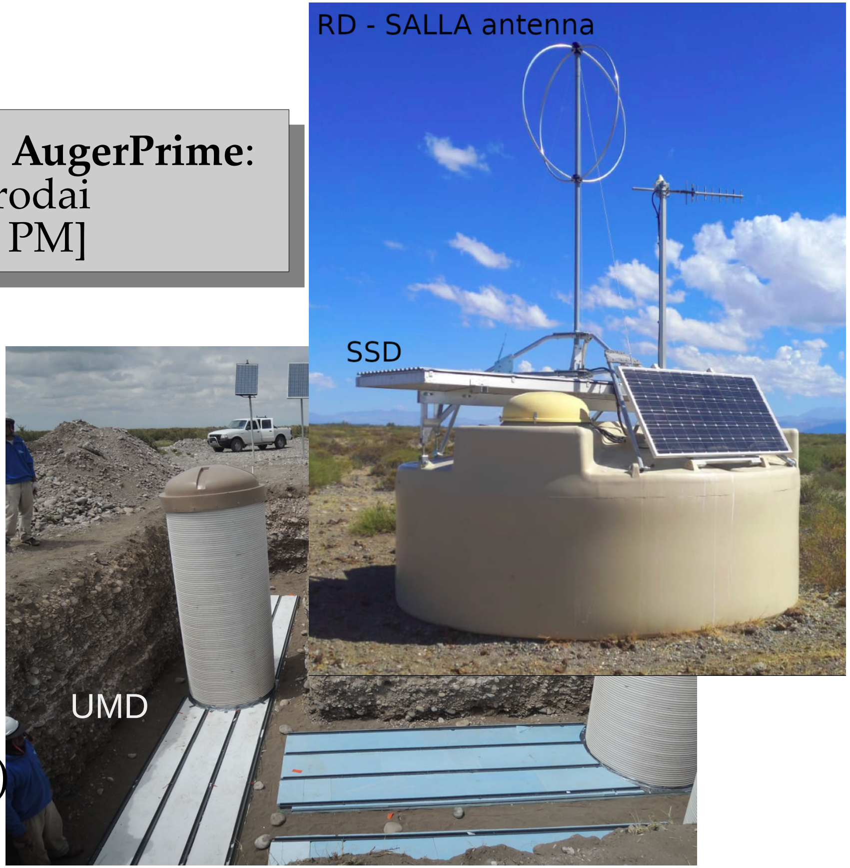
Outlook

→ Combined fit with source models

JCAP 05, 024 (2023)



More about **AugerPrime**:
Nataliia Borodai
[Today 4:50 PM]



→ Combined spectrum for all Auger phase I data
→ Improved triggers lower the energy thresholds
→ Detector upgrades for phase II enhance

- composition sensitivity (scintillation detectors)
- dynamic range (new electronics + small PMT)
- calorimetric energy scale accuracy (radio)
- Underground muon detectors