

The energy spectrum measured with the Pierre Auger Observatory

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The Pierre Auger Observatory



Surface Detector

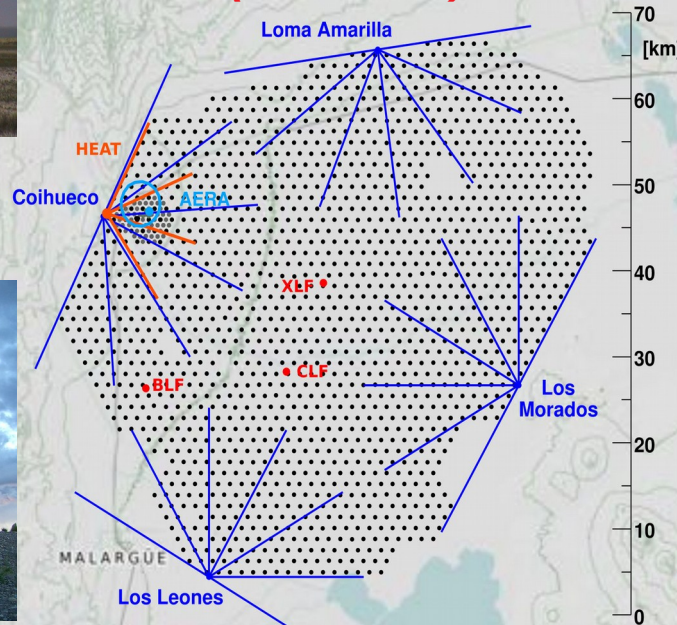
Detection of secondary particles on ground



Fluorescence Detector

Detection of fluorescence emitted in atmosphere by the CR shower

The largest Cosmic Ray detector ever built (~3000 km²)



Use the atmosphere as a giant target to detect UHECR
Low fluxes!

Surface detector (SD)

• 1500 m array

1600 detectors
3000 km², 1500 m grid
 $E > 2.5 \text{ EeV}$

• 750 m array

61 detectors
24 km², 750 m grid
 $E > 0.1 \text{ EeV}$

Fluorescence detector (FD)

• 24 telescopes

4 buildings
Elevation 0-30°
 $E > 1 \text{ EeV}$

• 3 additional telescopes

Elevation 30-60°
 $E > 0.1 \text{ EeV}$

AERA

• 153 radio antennas

17 km²
30-80 MHz
 $E > 0.1 \text{ EeV}$

Atmospheric monitoring

- XLF, CLF
- Lidars, cloud camera

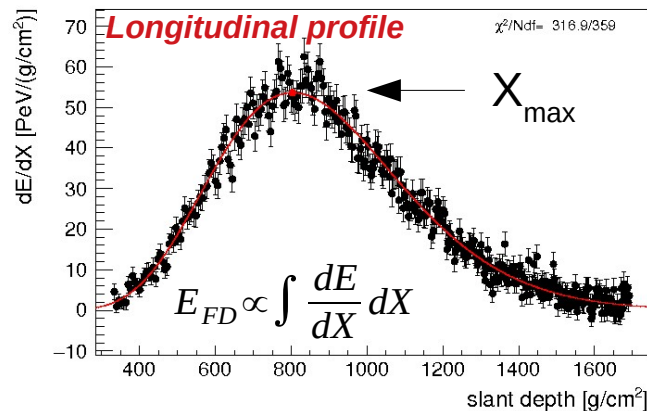
Duty Cycle ~ 13%



FD



The hybrid detection

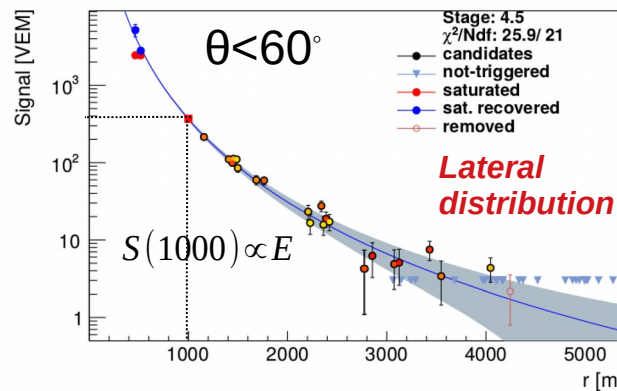


Energy scale
systematic uncertainty
14%

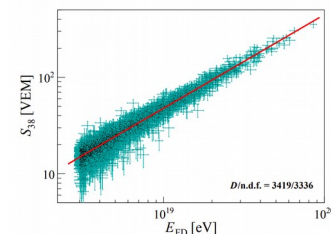
$X_{\max}$
systematic uncertainty
~10 g/cm²

Energy resolution:
20% @ $3 \cdot 10^{18}$ eV
7% $E > 2 \cdot 10^{19}$ eV

$X_{\max}$ resolution:
40 g/cm² @ 10^{17} eV
25 g/cm² @ 10^{18} eV
15 g/cm² $E > 10^{19}$ eV



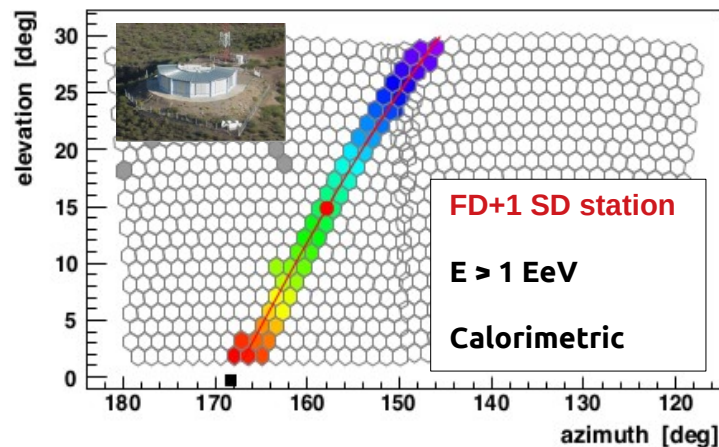
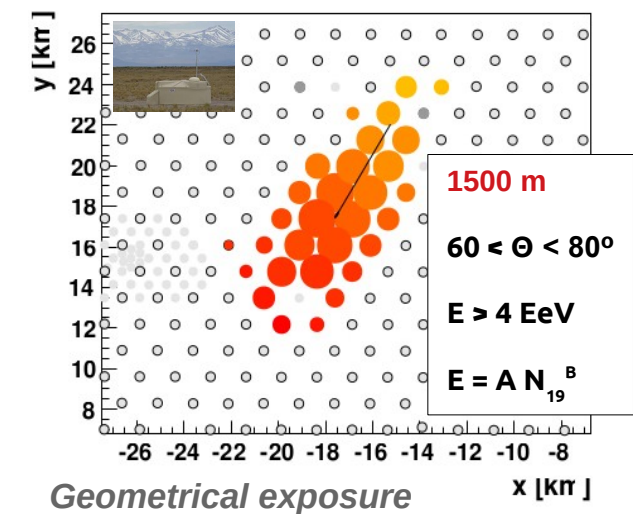
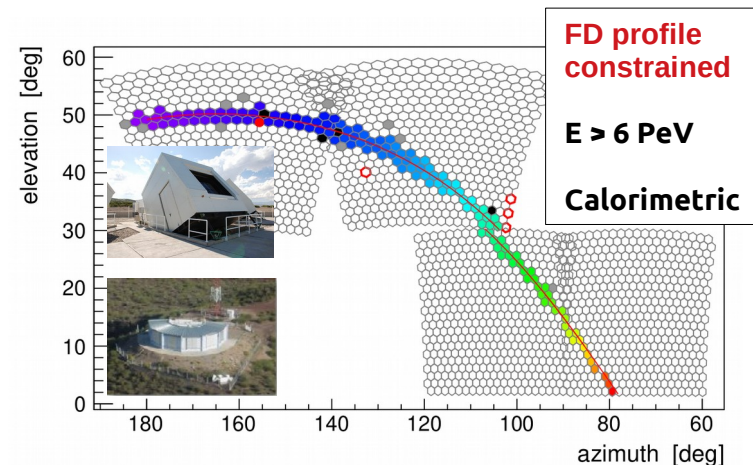
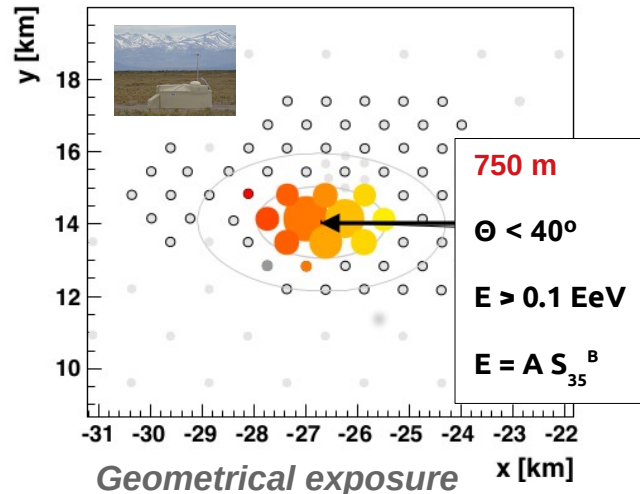
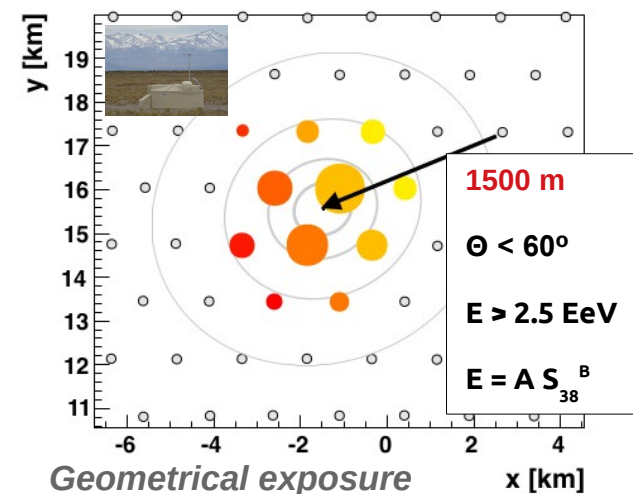
SD energy calibration



Hadronic interaction models
extrapolated from low energies

**Pierre Auger
scale based
on hybrid events**

Different techniques to measure the spectrum

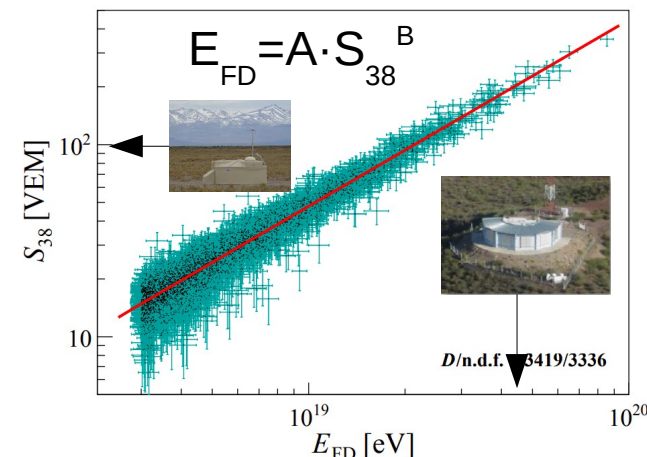
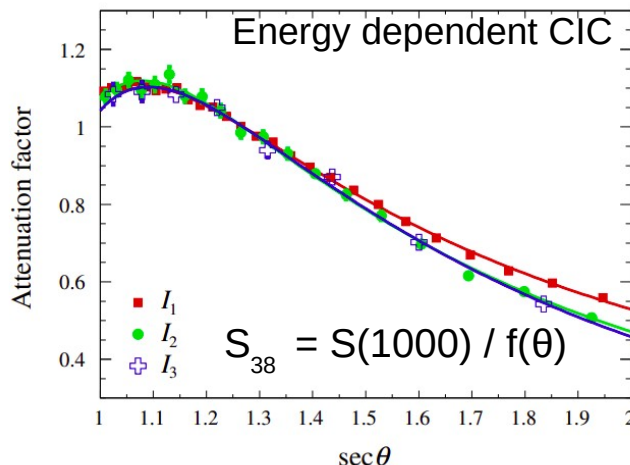
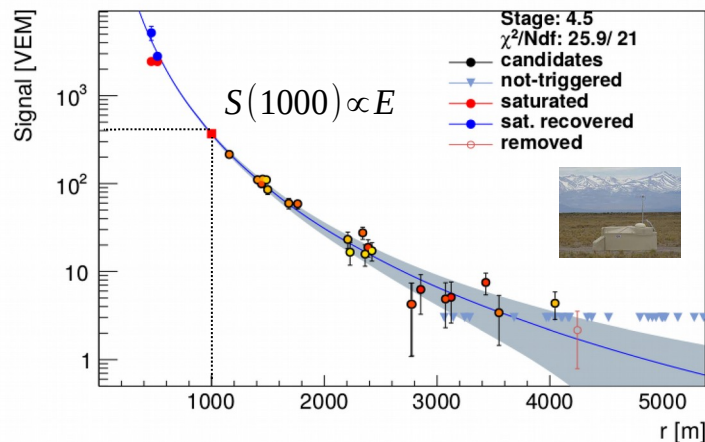


Coverage of ~5 orders of magnitude in energy

Coverage of the range $(-90, +45)^\circ$ in declination

Independent measurements of the spectrum

The SD1500 spectrum under 60 degrees



Bulk of the events reconstructed with SD

**Energy estimator from lateral distribution
 $S(1000)$ – Optimal distance, minimizing the uncertainty**

Calibrate the energy estimator with hybrid events (SD+FD reconstructions)

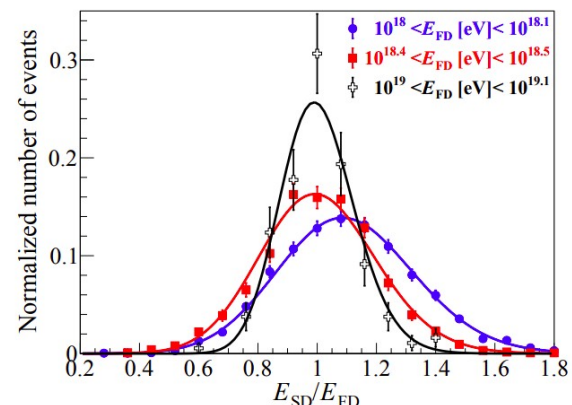
Full efficiency above ~ 2.5 EeV

Calculation of resolution and bias from FD data to unfold the spectrum

Data-driven invisible energy estimation

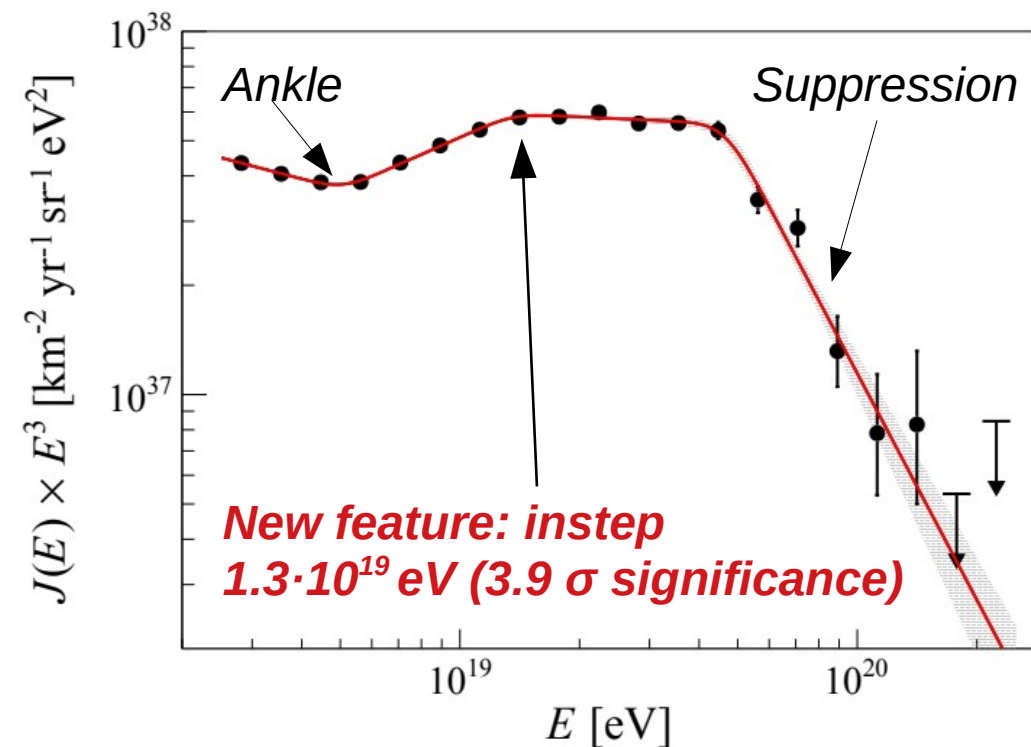
Trigger Efficiency from hybrid events

Energy dependent CIC for the correction of the attenuation



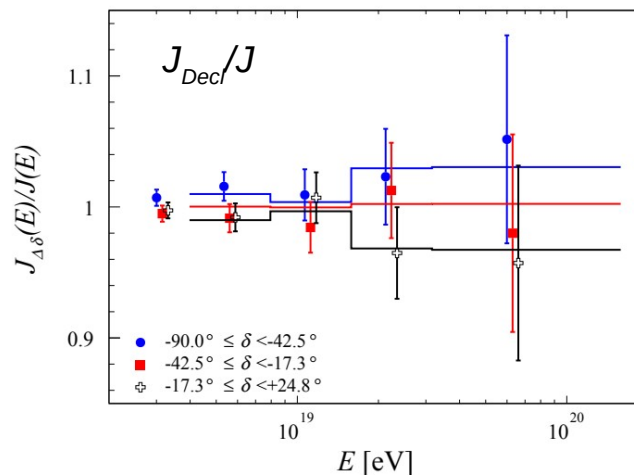
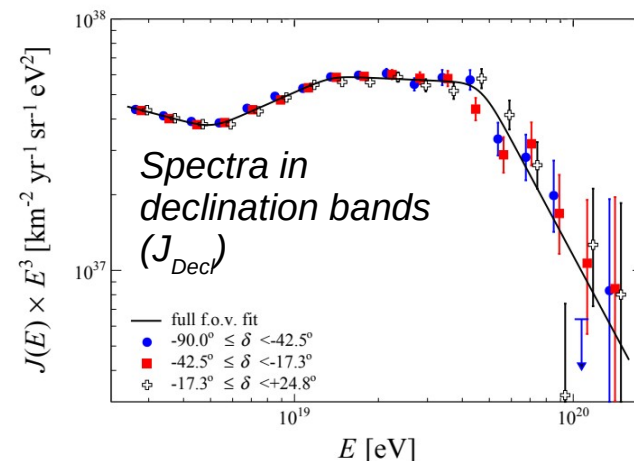
Removal of most model dependencies

The SD1500 spectrum under 60 degrees



Highest statistics for the spectrum achieved so far
 (60425 $\text{km}^2 \text{sr yr}$)

Mostly model independent estimate



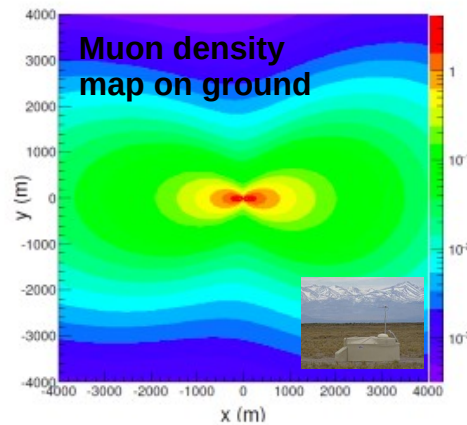
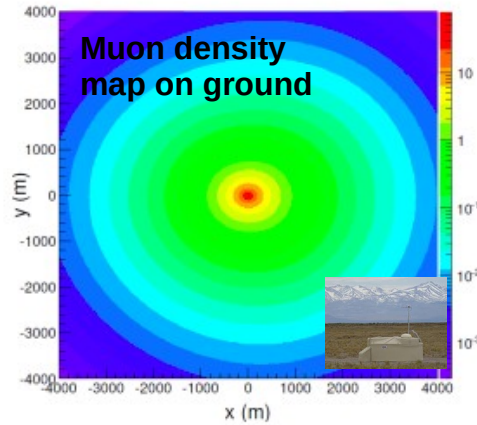
No declination
dependence
observed

Mild southern
excess
from dipole
anisotropy

Suppression
confirmed
 $4.6 \cdot 10^{19} \text{ eV}$

Ankle confirmed
 $5 \cdot 10^{18} \text{ eV}$

The SD1500 reconstruction above 60 degrees

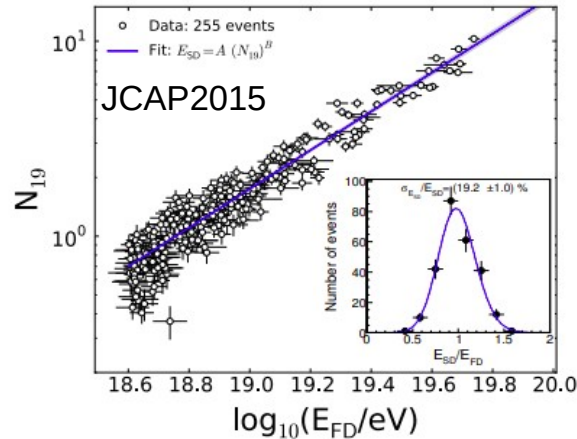


Events dominated by muonic component
(EM component is attenuated)

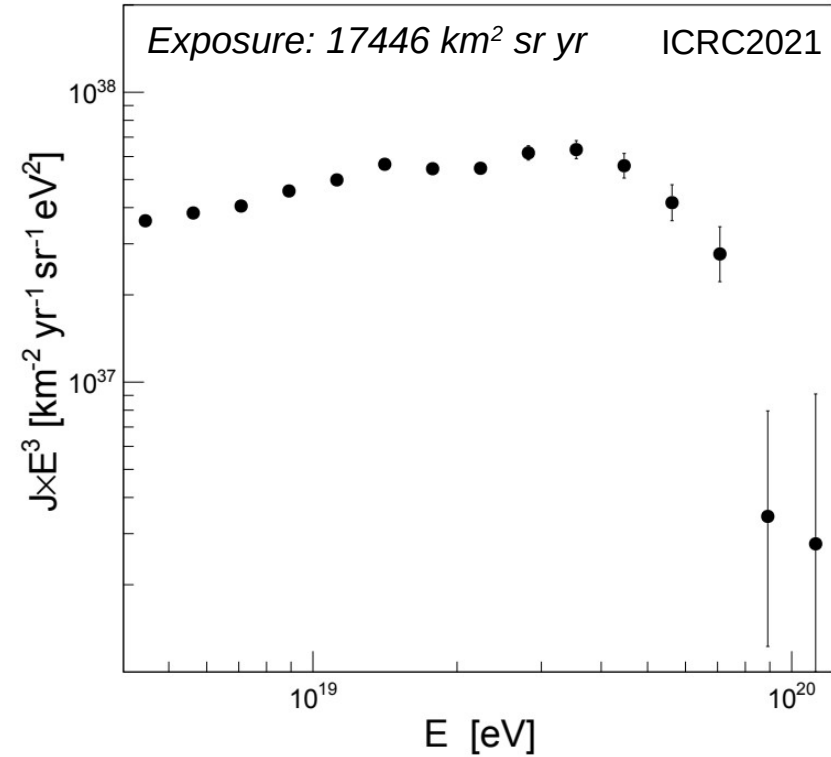
Distribution on ground estimated with MC (At 10¹⁹ eV for proton)

Energy estimator N_{19} : scaling factor to fit MC distribution to SD data

Calibration with Hybrid events



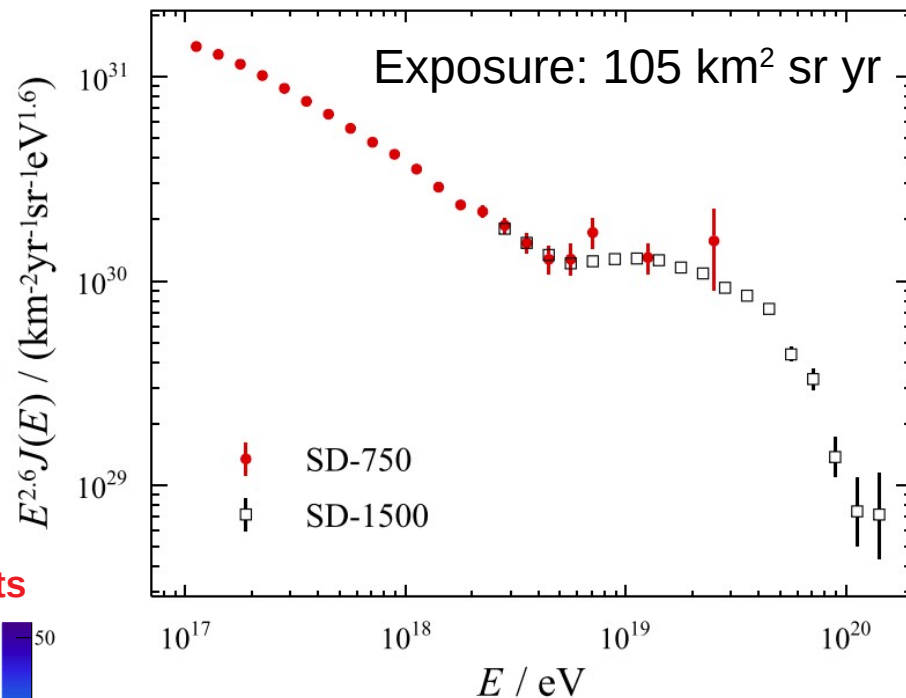
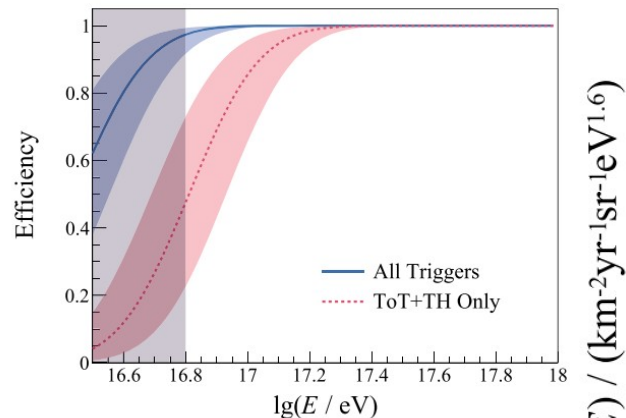
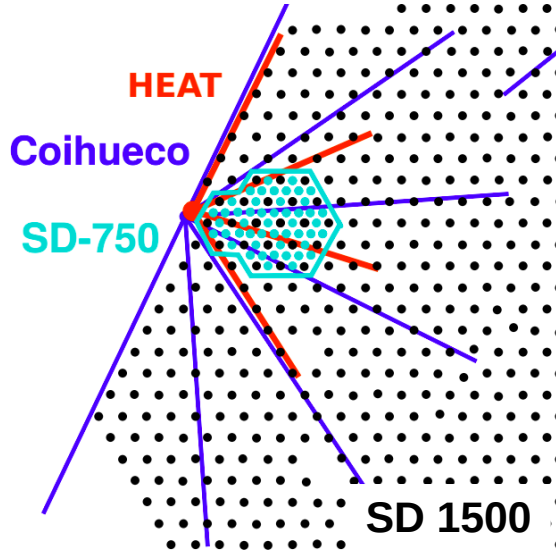
Fully efficient above ~4 EeV



**(60,80)° zenith angle
(-90,+45)° declination**

SD1500 exposure increased by 30%
85% of the sky covered

The SD750 spectrum



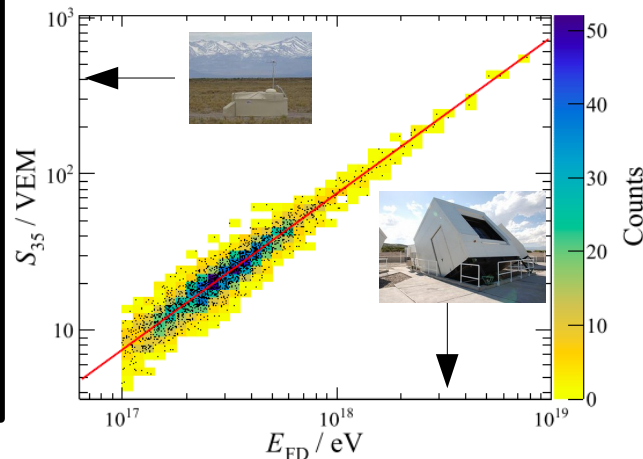
Extension to the low energies of the SD spectrum

Denser region of the array (750 m distance between SD detectors)

New triggers → **Fully efficient at 10^{17} eV**

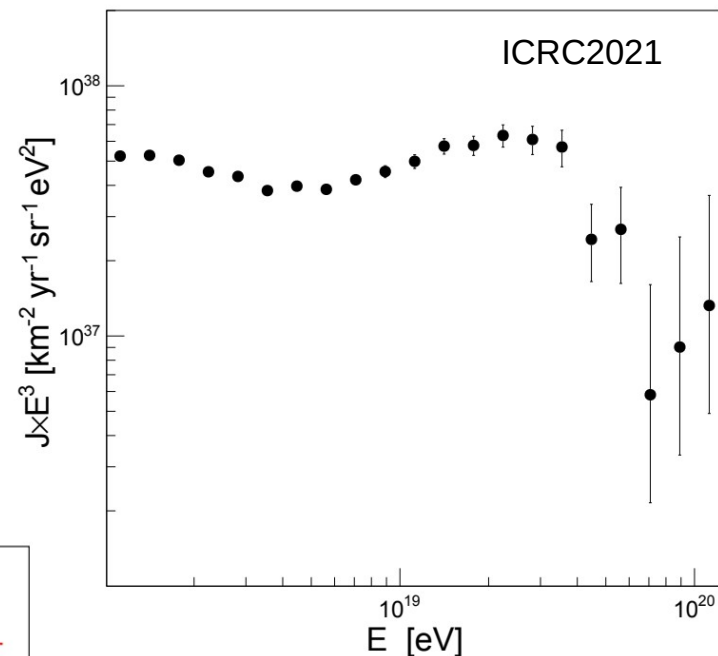
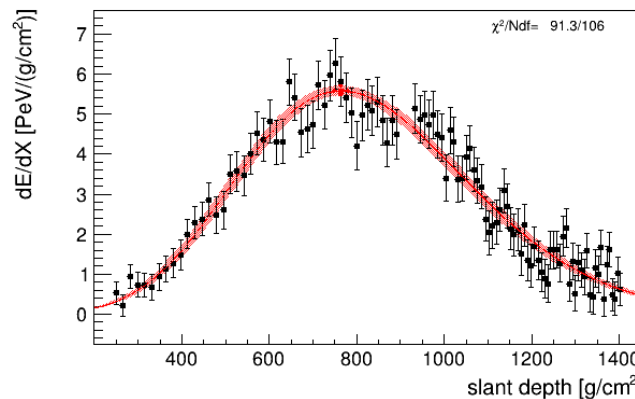
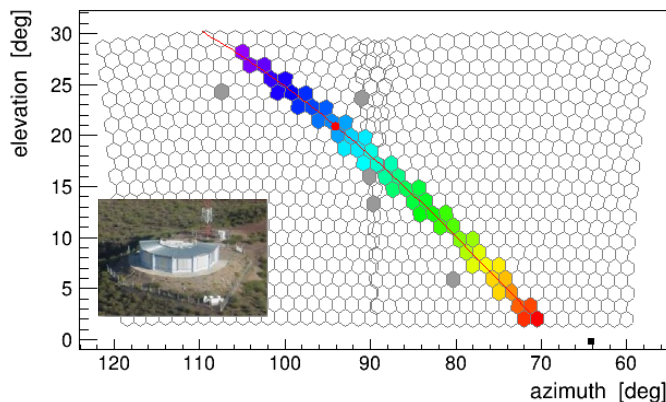
Energy estimator S(450)
Signal at 450 m from the core

Calibration with high elevation Hybrid events



SD1500+SD750 combination fundamental to study the galactic to extragalactic transition

The Hybrid spectrum



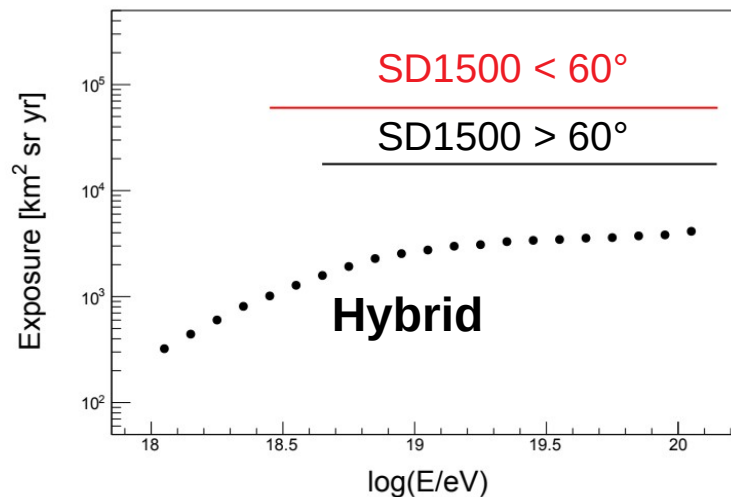
Measurement of the spectrum using the FD detector

Single SD detector triggered to constrain geometry of the shower

Exposure calculated with MC

Energy dependent exposure

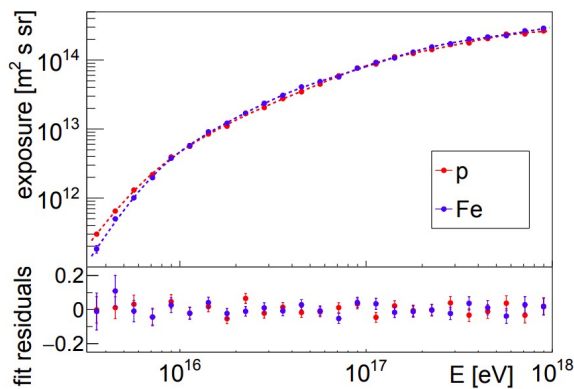
Detector exposure



$$\mathcal{E}(E) = \int_T \int_\Omega \int_S \varepsilon(E, t, \theta, \phi, x, y) \cos \theta \, dS \, d\Omega \, dt$$

Exposure based on real MC accounting for time dependent condition of the observatory

The Cherenkov spectrum

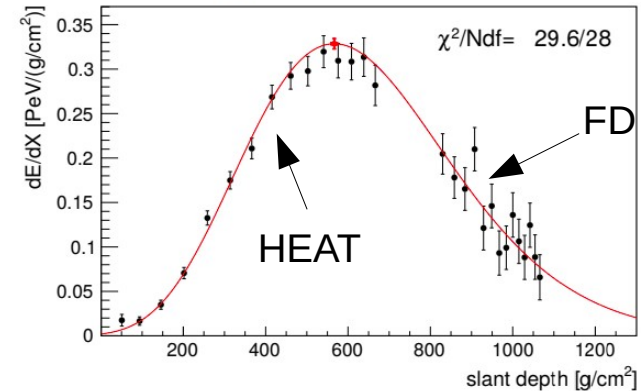
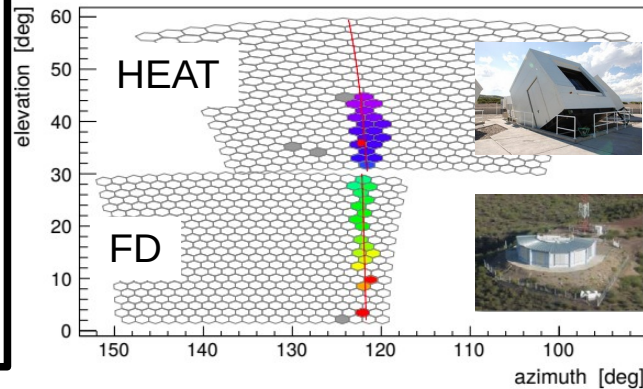
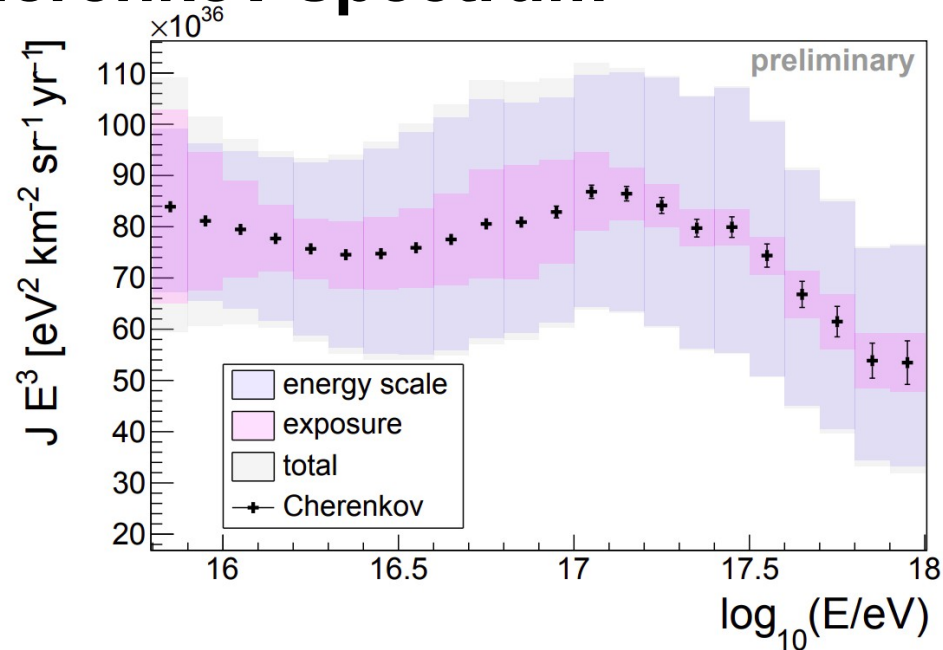


Measurement of the spectrum using the high elevation FD telescopes

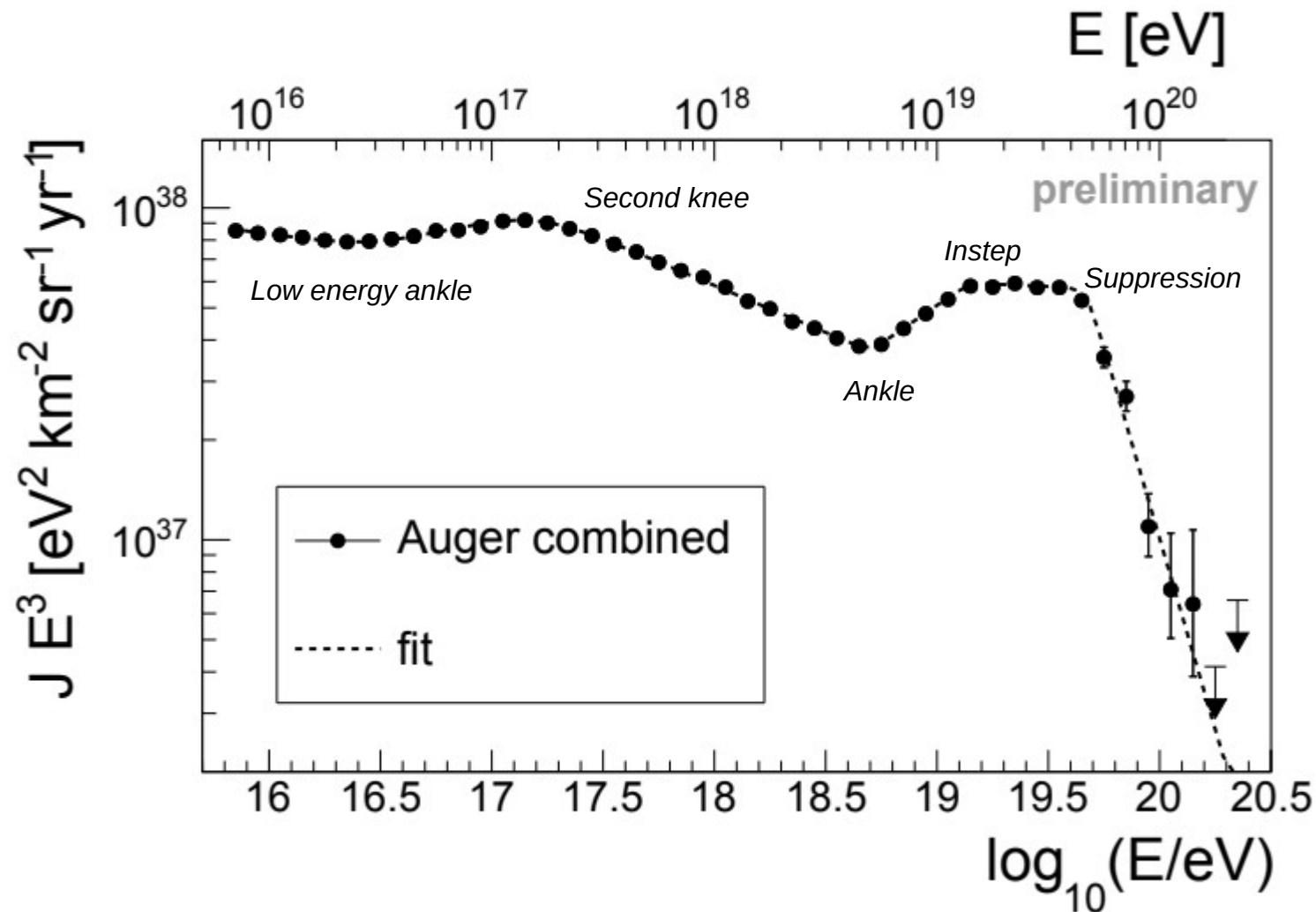
Lower the energy threshold to $10^{15.8}$ eV

No SD counterpart: monocular mode only

Profile Constrained Geometry Fit
Scan on the geometry+Constraint on the fit based on Gaisser Hillas profile



The combined spectrum



Parameter $\pm\text{stat.}\pm\text{syst.}$

$$J_0 = (8.34 \pm 0.04 \pm 3.40) \cdot 10^{-11} \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1} \text{ eV}^{-1}$$

$$\gamma_0 = 3.09 \pm 0.01 \pm 0.1$$

$$E_{01} = (2.8 \pm 0.3 \pm 0.4) \cdot 10^{16} \text{ eV}$$

$$\gamma_1 = 2.85 \pm 0.01 \pm 0.05$$

$$E_{12} = (1.58 \pm 0.05 \pm 0.2) \cdot 10^{17} \text{ eV}$$

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

$$E_{23} = (5.0 \pm 0.1 \pm 0.8) \cdot 10^{18} \text{ eV}$$

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

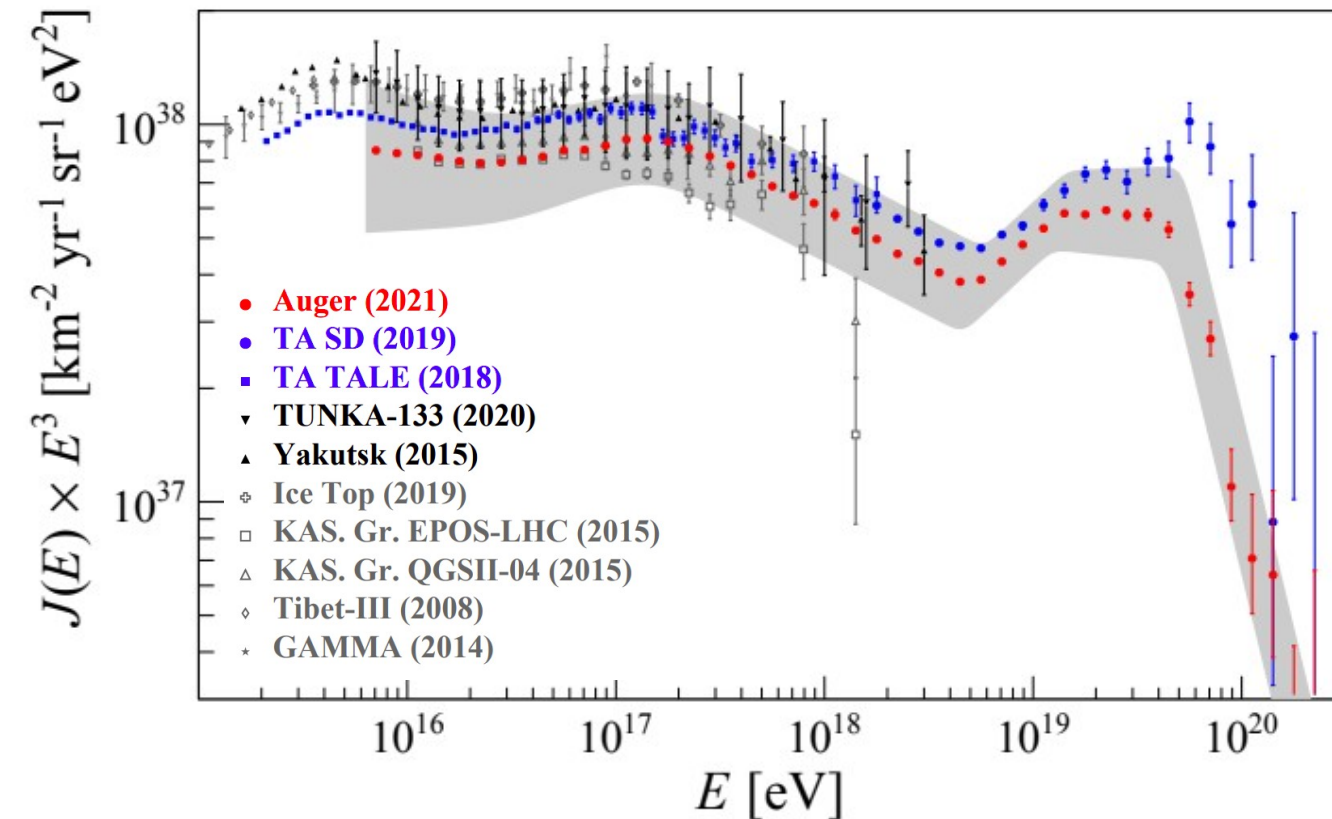
$$E_{34} = (1.4 \pm 0.1 \pm 0.2) \cdot 10^{19} \text{ eV}$$

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

$$E_{45} = (4.7 \pm 0.3 \pm 0.6) \cdot 10^{19} \text{ eV}$$

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

Comparison with other experiments



Generally consistent with other experiments within systematics

Above 10^{18} eV

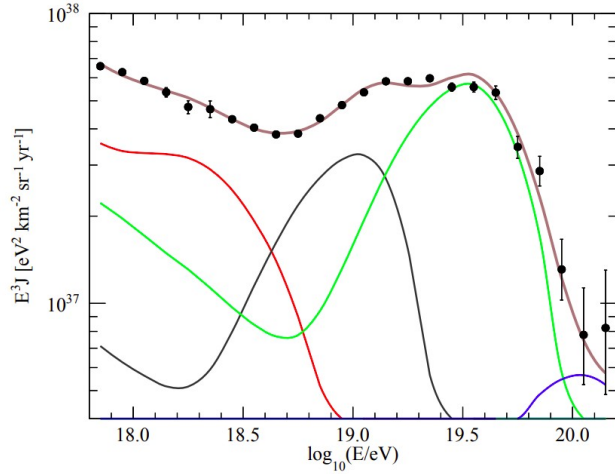
Agreement with Telescope Array* within systematics under 10^{19} eV

Above 10^{19} eV

$\pm 10\%$ per decade disagreement between Auger and TA (not explainable by known systematics)

Work in progress to explain the discrepancy above 10^{19} eV

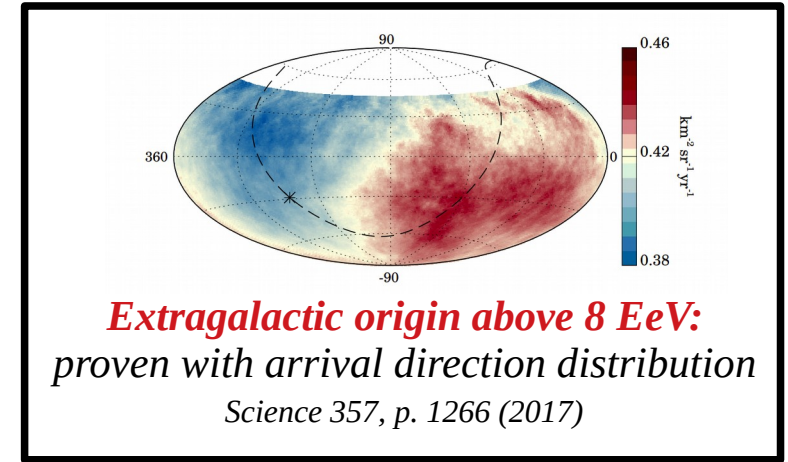
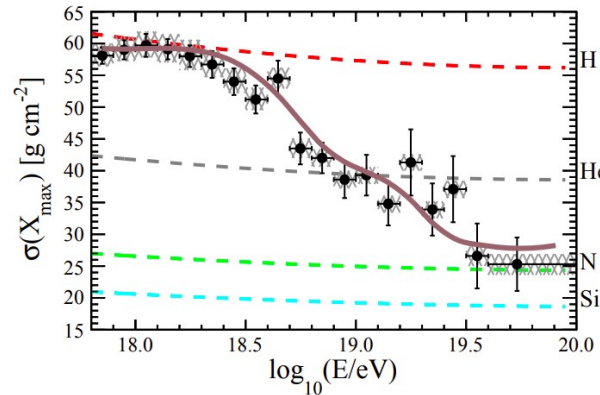
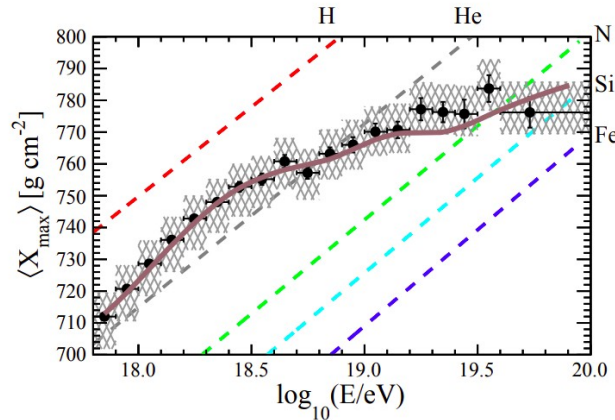
The astrophysical interpretation



**Astrophysical interpretation
based on a combined
spectral shape and
composition analysis**

Fit simple astrophysical model
to $J(E)$ and $X_{\max}^*$ distribution

Propagation and shower
development accounted for



Injected spectrum

$$J(E) = \sum_A f_A \cdot J_0 \cdot \left(\frac{E}{E_0} \right)^{-\gamma} \cdot \begin{cases} 1, & E < Z_A \cdot R_{\text{cut}}; \\ \exp \left(1 - \frac{E}{Z_A \cdot R_{\text{cut}}} \right), & E > Z_A \cdot R_{\text{cut}}. \end{cases}$$

Fit parameters

Luminosity of sources
Mass fraction (5 masses)
Steepness of escape spectrum (γ)
Cutoff energy (R_{cut})

The astrophysical interpretation

Suppression: combination of maximum accelerator energy + propagation effects

GZK* only scenario disfavored

*Phys. Rev. Lett. 16, 748 (1966); Pis'ma Zh. Eksp. Teor. Fiz, 4, 114 (1966)

Instep: interplay between He and CNO components

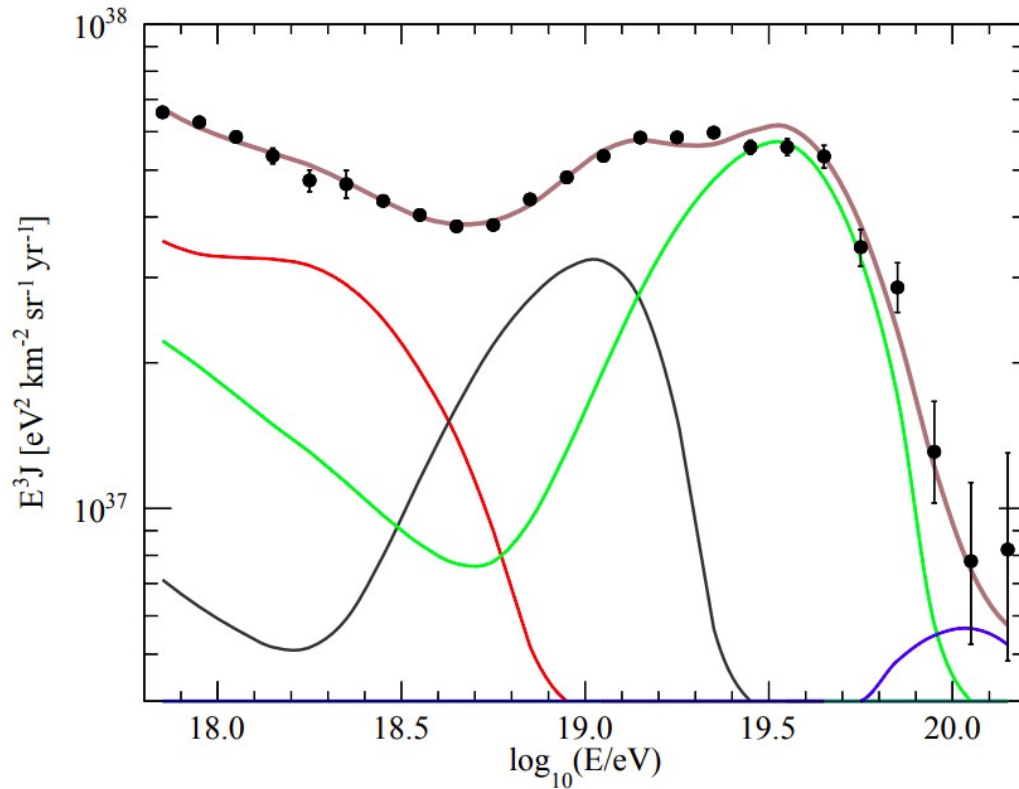
For the description of the spectrum across the Ankle:

Scenario 1

High Energy Extragalactic (Mixed)
Low Energy Extragalactic (Pure proton)
Low Energy Galactic (Medium mass CNO)

Scenario 2

High Energy Extragalactic (Mixed)
Low Energy Extragalactic (Mixed Nitrogen+ Proton)

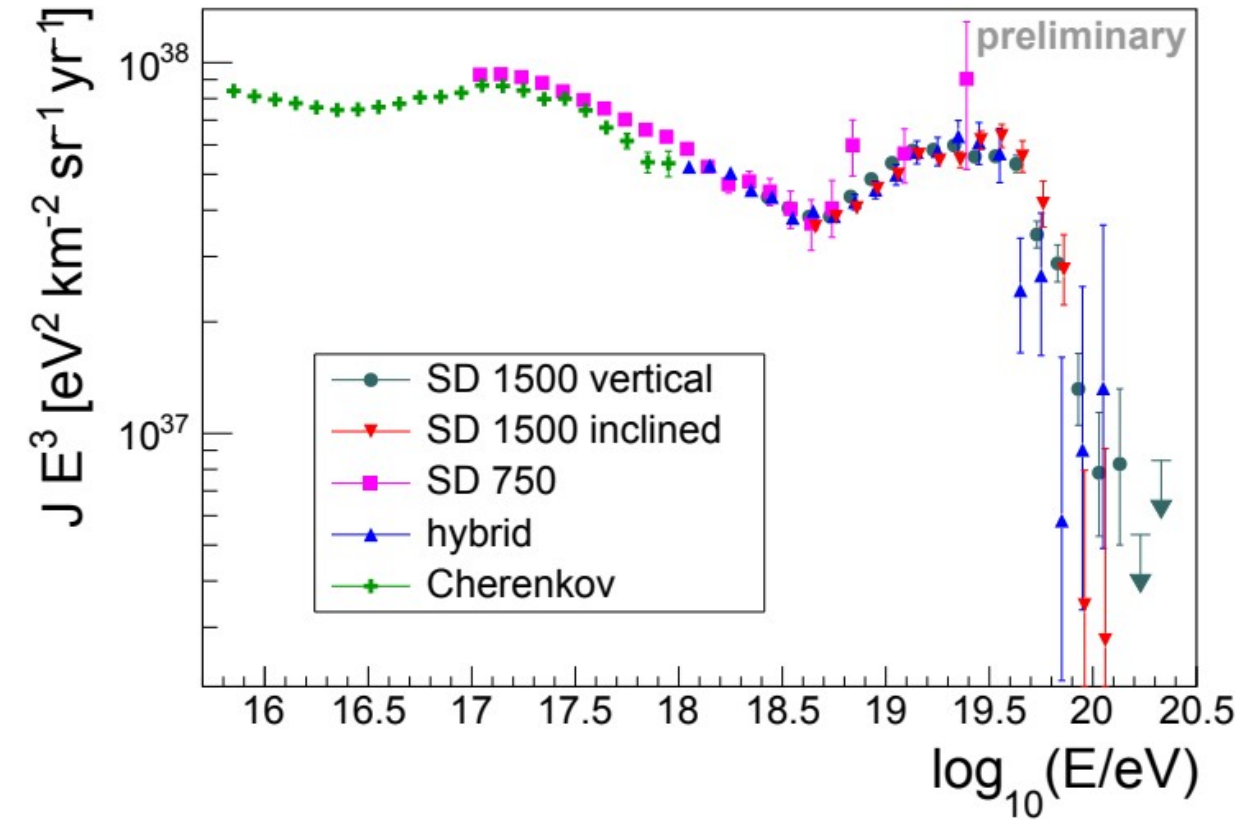


Conclusions

- Above 2.5 EeV: highest exposure achieved so far (60425 km² sr yr)
 - New feature detected (*in step*)
 - Suppression confirmed
 - Ankle confirmed
 - No declination dependence of spectrum
- Wide range in declination covered by the spectrum above 60°
- SD750 covers the region above 100 PeV
- Cerenkov spectrum covers the region from 6 PeV to EeV
- Suppression: combination of source maximum energy + propagation effects
- In step: interplay between He to CNO components
- Ankle: extra component needed across the ankle
 - Scenario 1: Galactic+extragalactic
 - Scenario 2: Extragalactic
- Transition from galactic to extragalactic: must happen between 100 PeV and 5 EeV

Backup slides

Overview of all the spectra



SD spectra

SD1500 < 60°: 60425 $\text{km}^2 \text{ sr yr}$

SD1500 > 60°: 17446 $\text{km}^2 \text{ sr yr}$

SD750: 105 $\text{km}^2 \text{ sr yr}$

FD Spectra

Hybrid: 2750 $\text{km}^2 \text{ sr yr}$
@ 10^{19} eV

Cherenkov: ~10 $\text{km}^2 \text{ sr yr}$
@ 10^{18} eV