

The energy spectrum measured with the  
Pierre Auger Observatory and its  
astrophysical interpretation

*Fabio Convenga on behalf of  
the Pierre Auger Collaboration*

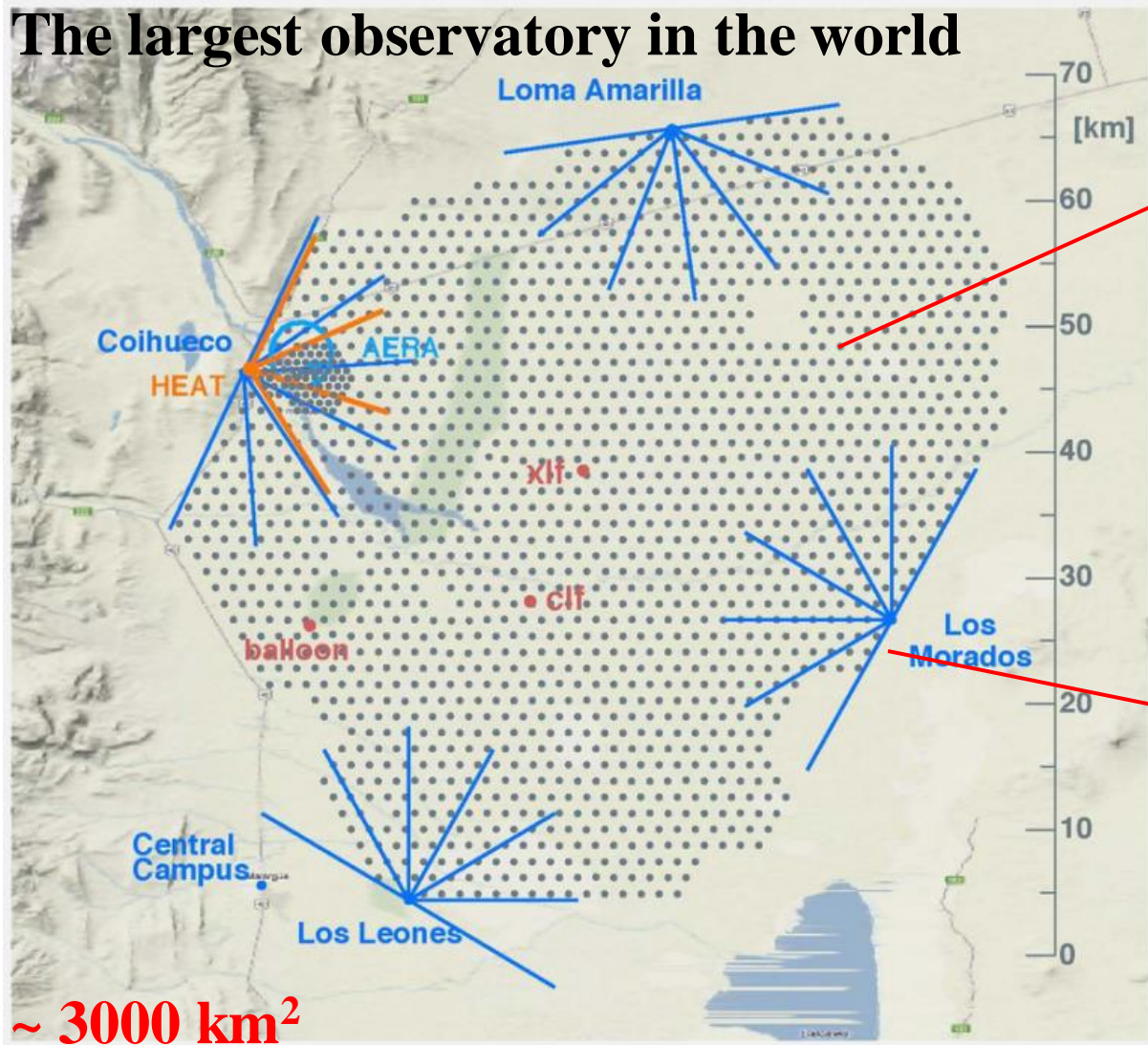


TEVPA  
2023



# THE PIERRE AUGER OBSERVATORY

## The largest observatory in the world



~ 3000 km<sup>2</sup>

## Extensive Air Showers (EAS) detection

### Surface Detector (SD)

secondary particles on ground



- Cherenkov detectors
- 1600 station
- different spacing

**SD1500**  
 3000 km<sup>2</sup>  
 1500 m grid  
 $E_{th} > 10^{18.4}$  eV

**SD750**  
 23.5 km<sup>2</sup>  
 750 m grid  
 $E_{th} > 10^{17}$  eV

**SD433**  
 1.9 km<sup>2</sup>  
 433 m grid  
 $E_{th} > 10^{16.8}$  eV

### Fluorescence Detector (FD)

fluorescence emitted in atmosphere



4 sites overlooking SD1500

24 telescopes  
 Elevation 0-30°  
 $E > 10^{18}$  eV

1 site overlooking SD750 – SD433

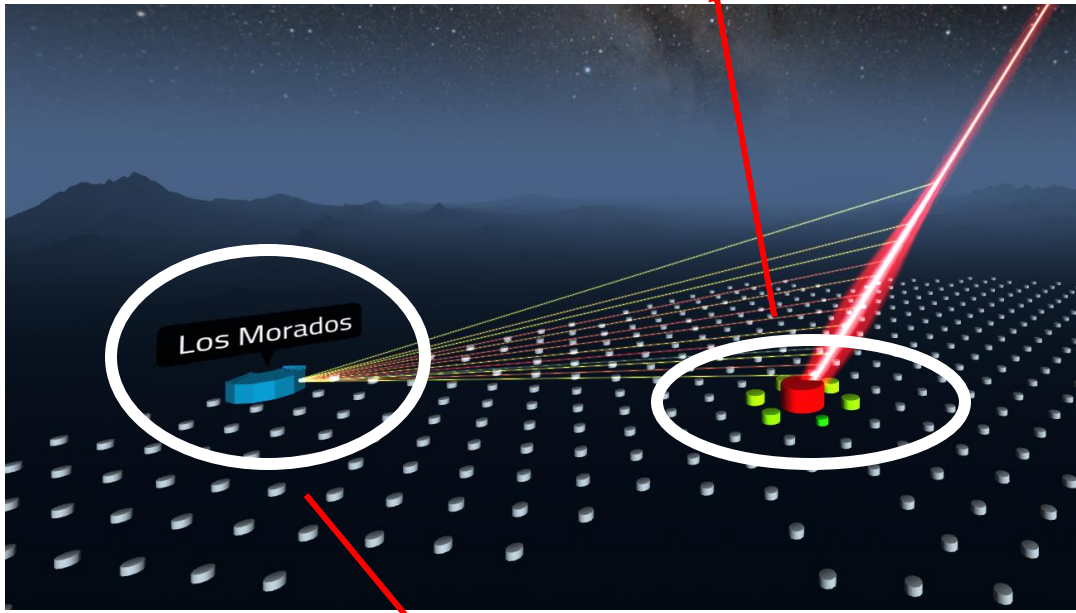
3 telescopes  
 Elevation 30°-60°  
 $E > 10^{15.8}$  eV

Atmospheric monitoring  
 XLF, CLF  
 Lidars, cloud camera

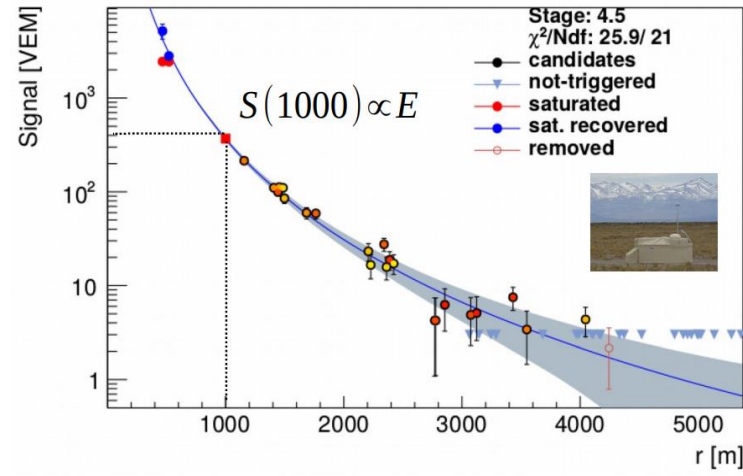
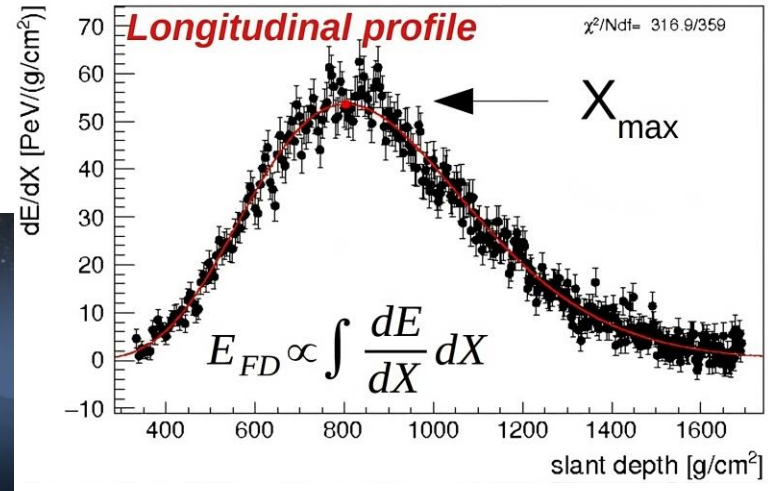
AugerPrime will add new detectors, station will become multi-hybrid instrument. (I. Allekotte, TevPa2023)

# THE HYBRID DETECTION

Duty Cycle ~ 100%



Duty Cycle ~ 13%



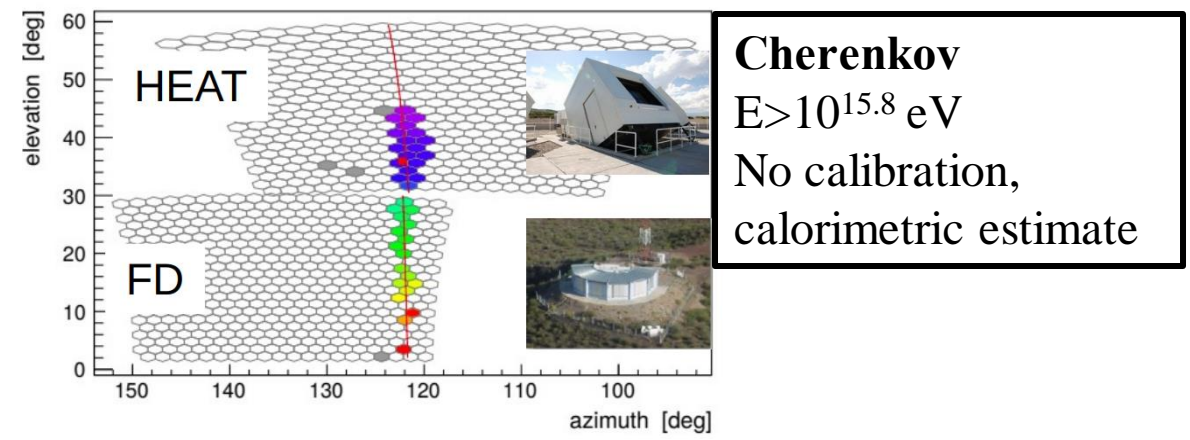
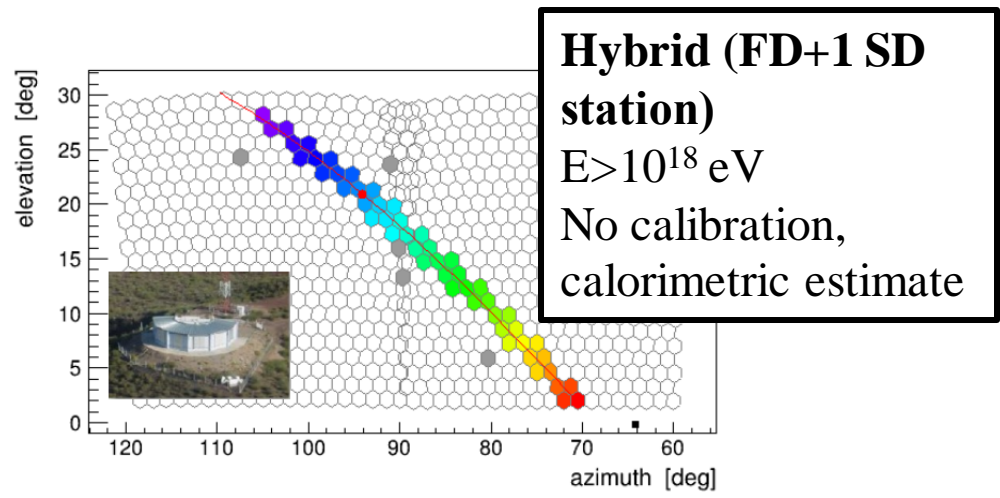
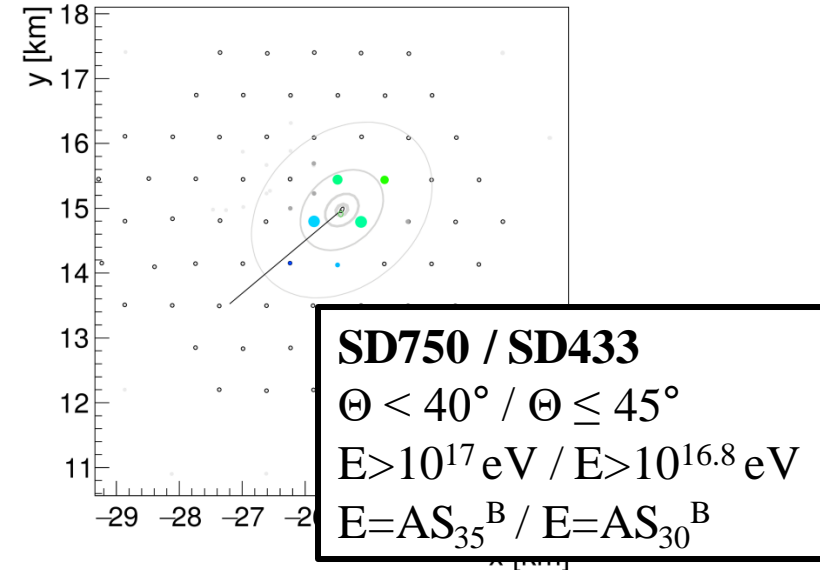
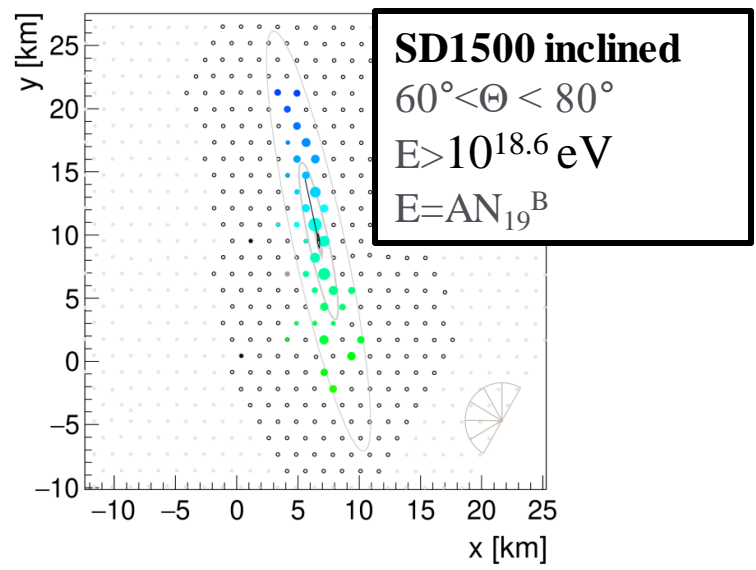
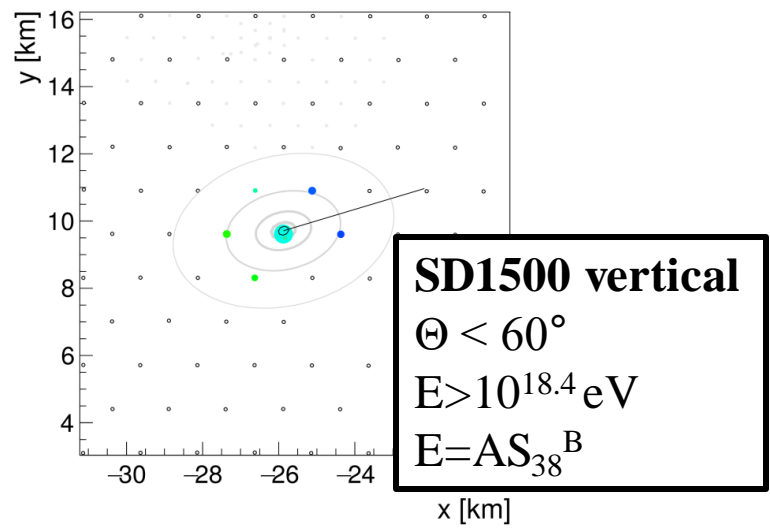
## Hybrid energy calibration

$S_{38}$  [VEM]  
 $E_{FD}$  [eV]  
 $D/m.d.f. = 3419/3336$

- Energy scale systematic uncertainty 14%
- Energy spectrum free of assumptions about hadronic physics

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

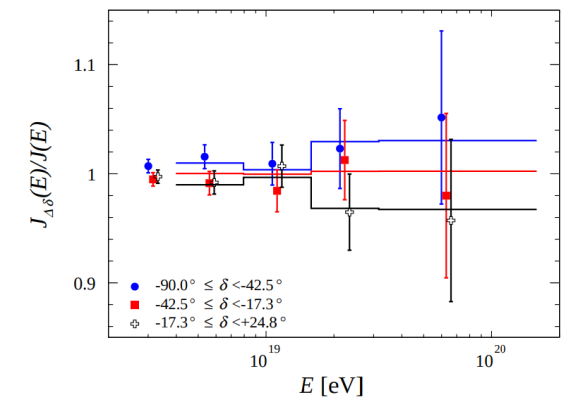
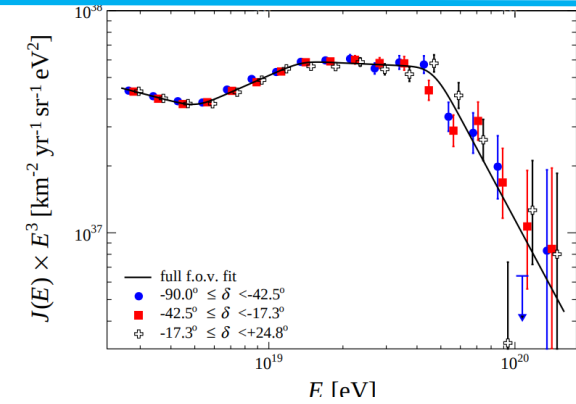
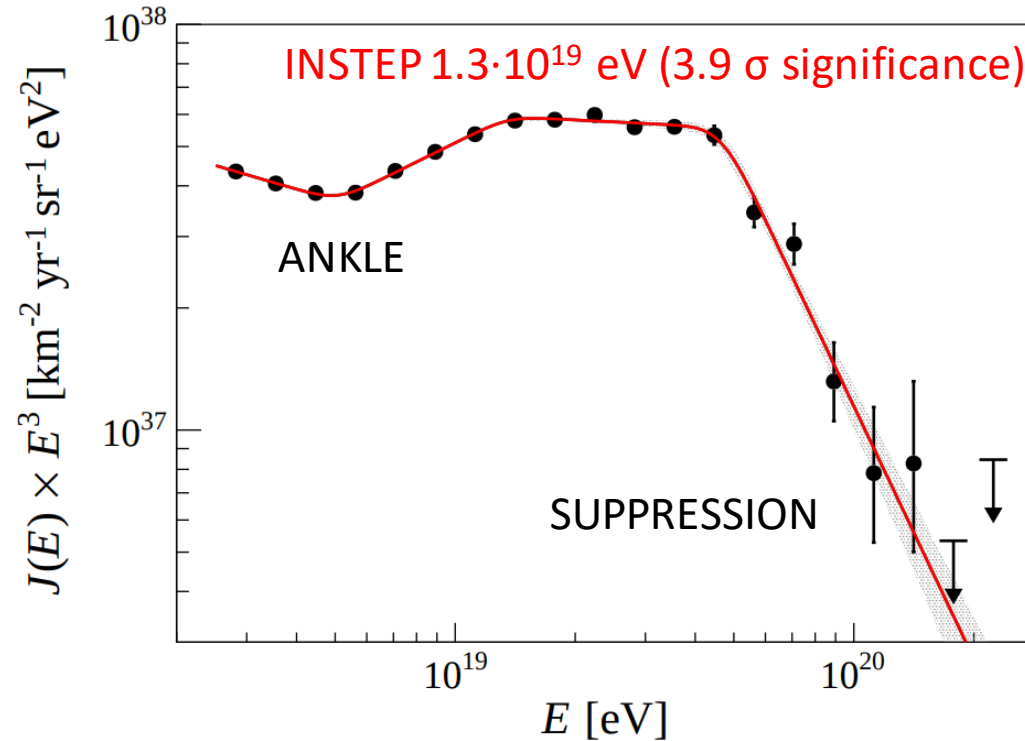
# DIFFERENT SPECTRUM MEASUREMENTS



# SD1500 VERTICAL SPECTRUM ( $\Theta < 60^\circ$ )

- High statistics of events reconstructed by SD1500
- From SD only energy estimator S(1000)
- **Correction of the attenuation** in atmosphere from S(1000) to  $S_{38}$
- Calibrate the energy estimator with hybrid events (SD+FD reconstructions)
- Full efficiency above  $10^{18.4}$  eV
- **Unfolding with resolution and bias from FD data**

**Reference:**  
[Phys. Rev. D 102, 062005 \(2020\)](#)



Highest statistics for the spectrum achieved so far

New features:  
**instep**

No (strong) declination dependence observed, Mild southern excess from dipole anisotropy

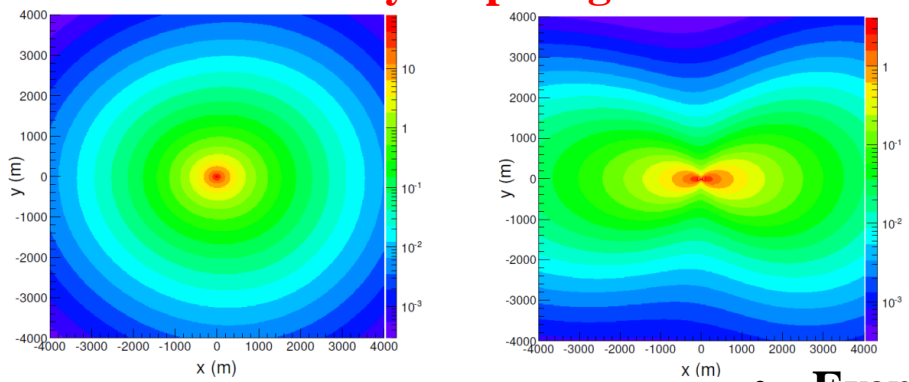
Removal of most model dependencies

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

**Ankle** confirmed

# SD1500 INCLINED SPECTRUM ( $60^\circ < \Theta < 80^\circ$ )

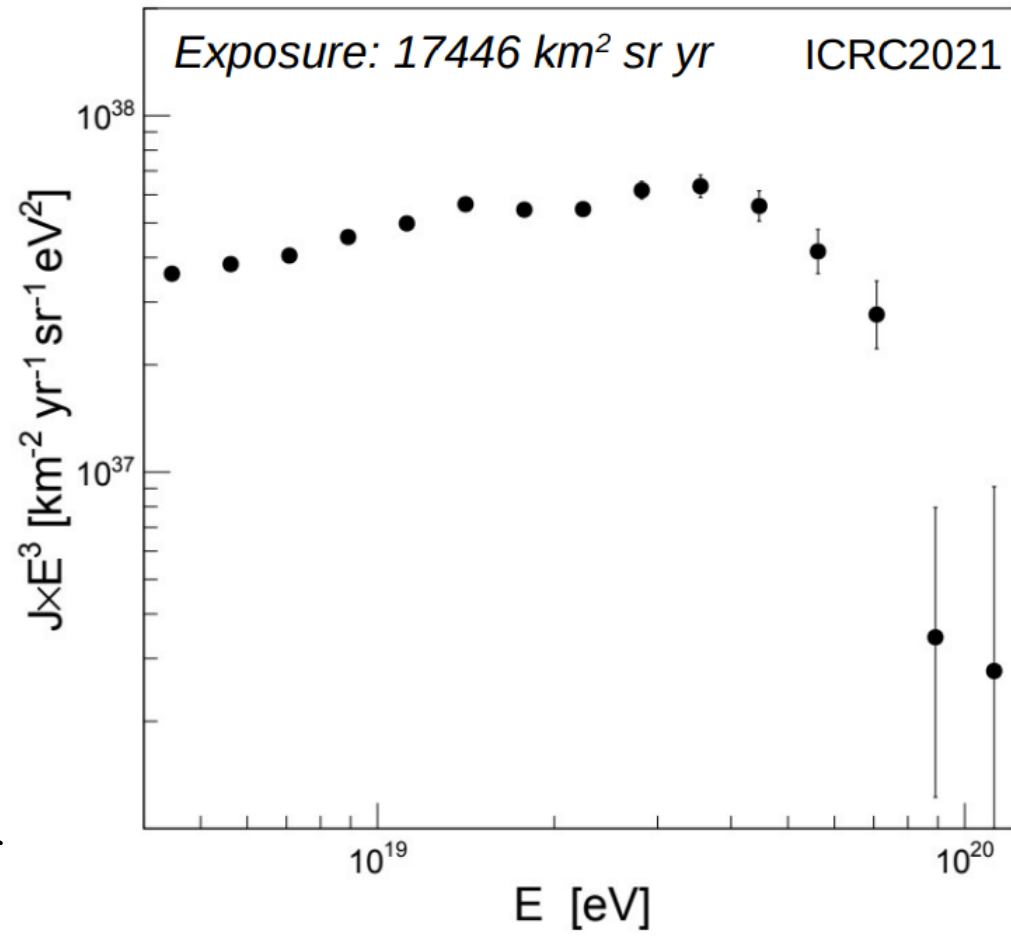
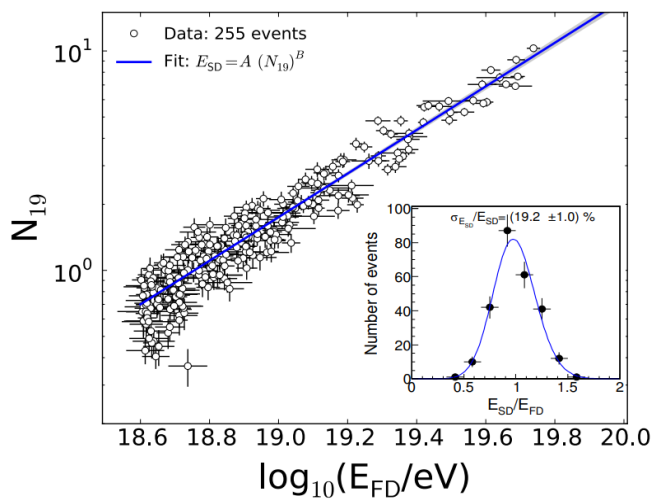
## Muon density map on ground



$N_{19}$  measure of the shower size: relative normalization with respect to a MC ground muon distribution

- Events dominated by muonic component (EM component is attenuated)
- Shape of the muon distribution is approximately universal for a given shower direction
- only the overall normalisation of the muon distribution depends on the shower energy and primary mass

## Calibration with Hybrid events

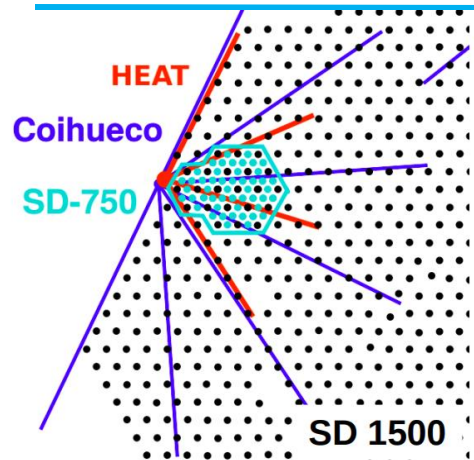


$$\rho_\mu(\vec{r}) = N_{19} \rho_{\mu,19}(\vec{r}; \theta, \phi)$$

- Fully efficient for  $E > 10^{18.6} \text{ eV}$

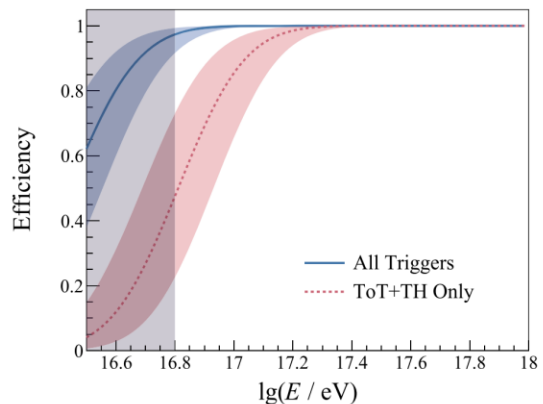
Reference:  
[JCAP 08 \(2015\) 049](#)

# SD750 – SD433 SPECTRA

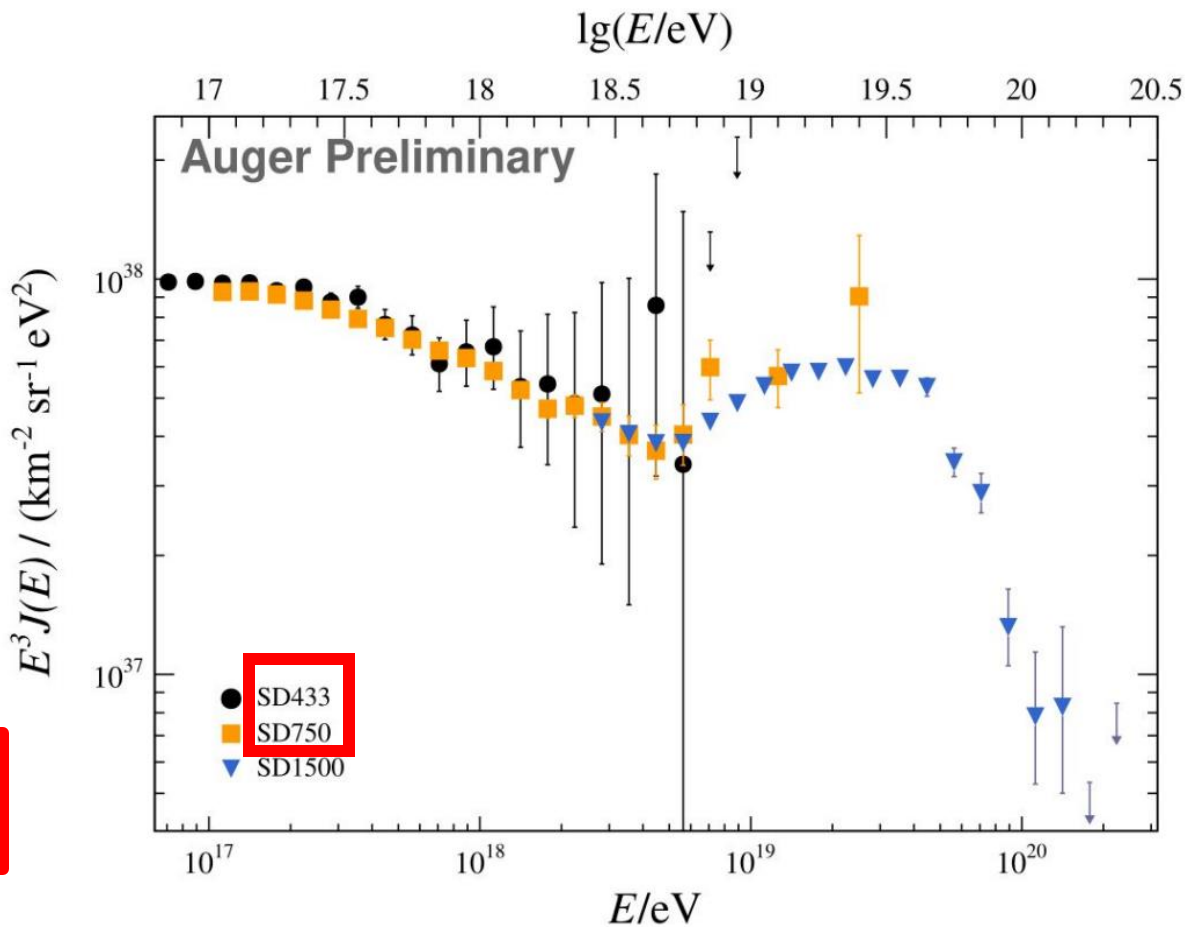


| SD750  | SD433  |
|--|--|
| Calibration with high elevation FD           | Calibration with events reconstructed with SD750 and SD433 |
| Fully efficient $10^{17}$ eV                 | Fully efficient $10^{16.8}$ eV                             |
| Energy estimator $S(450) \rightarrow S_{35}$ | Energy estimator $S(300) \rightarrow S_{30}$               |

- Low energy triggers used



Combination fundamental to study the galactic to extragalactic transition



**Reference:**  
[Eur. Phys. J. C \(2021\) 81:966](#)

**Reference:**  
[POS\(ICRC2023\)398](#)

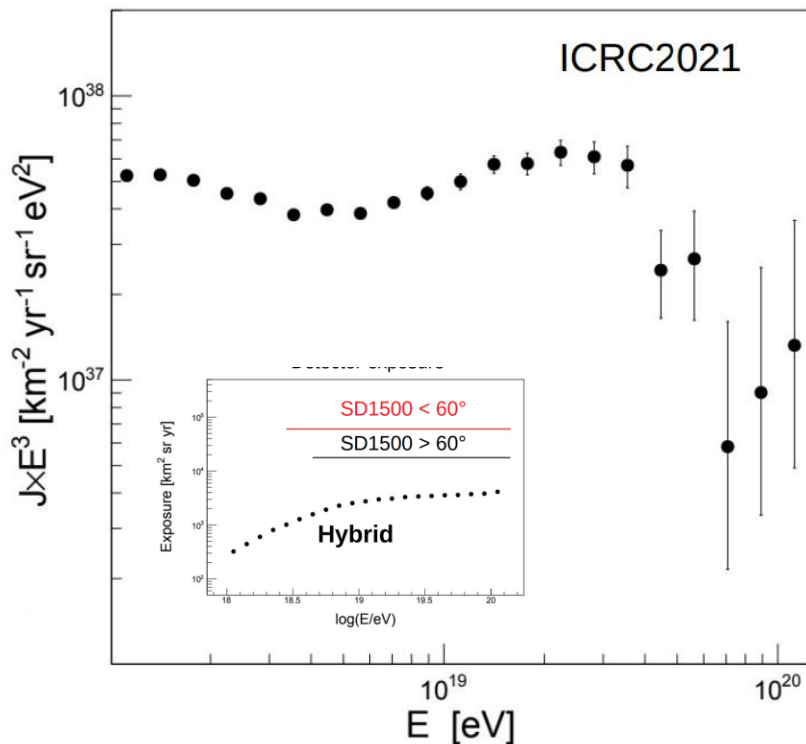
# HYBRID – CHERENKOV SPECTRA

- Spectrum using the **FD + 1 SD station**
- Single SD station triggered to **constrain geometry of the shower**
- $E > 10^{18}$  eV

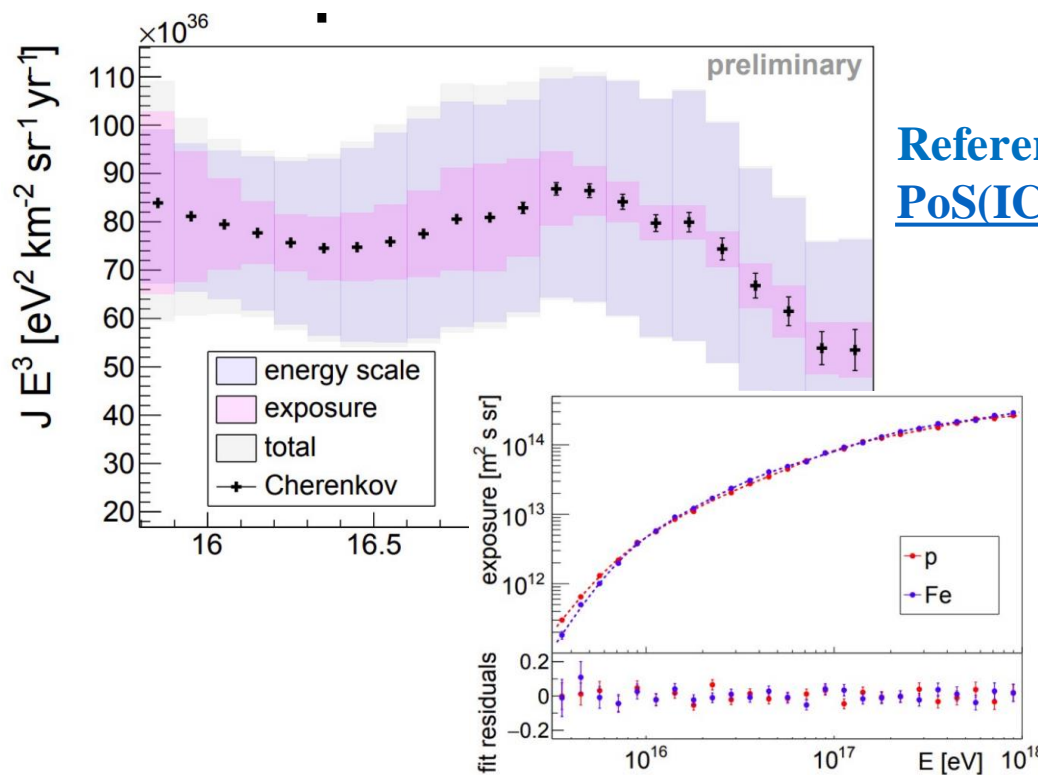
**No SD counterpart:** monocular mode only

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

Geometry determined with a constraint on the shower profile



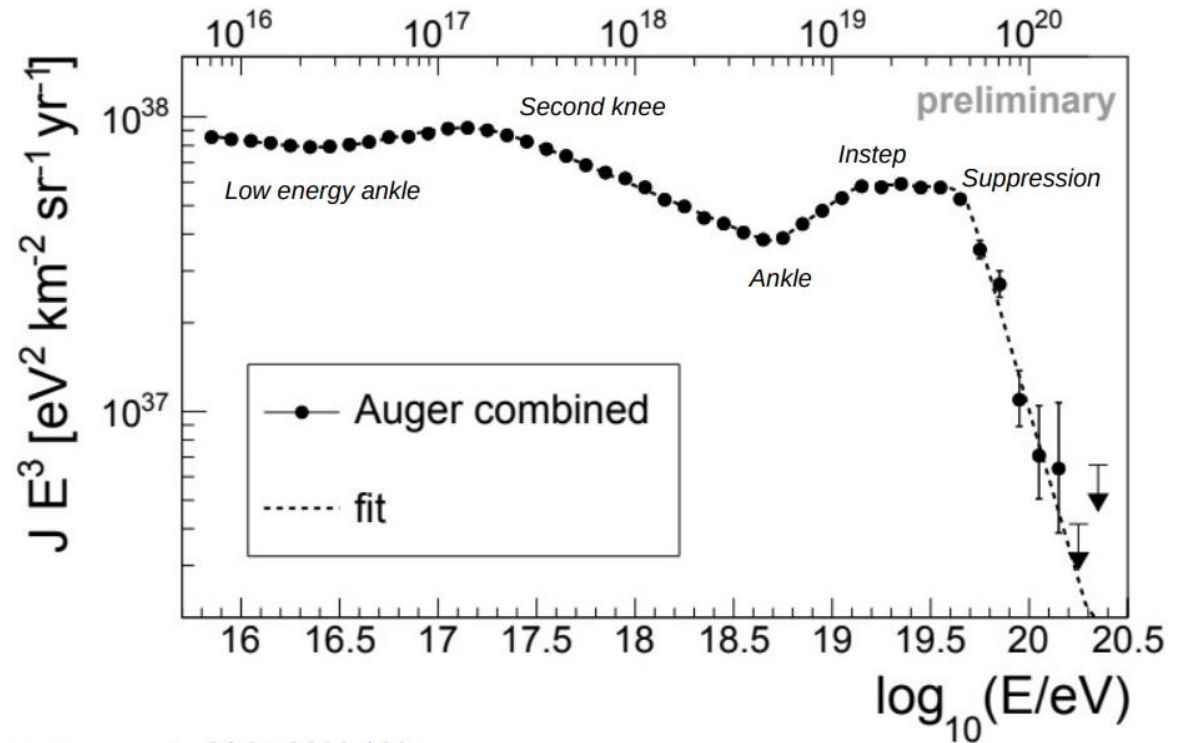
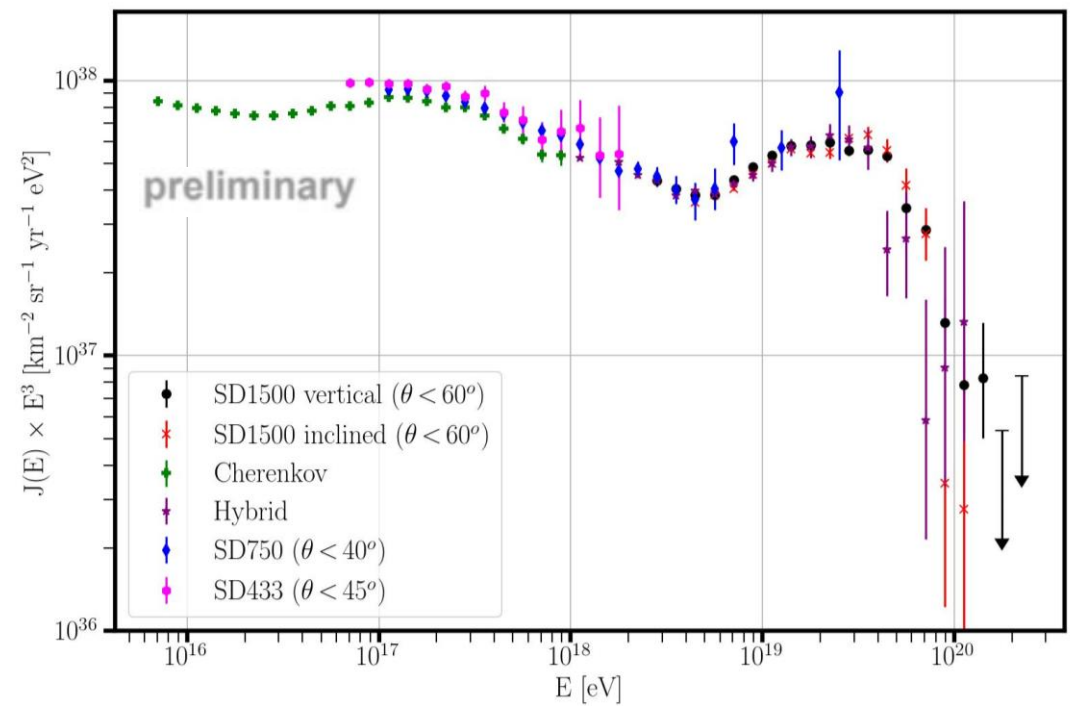
Reference:  
[EPJ Plus \(2012\) 127: 87](#)



Reference:  
[PoS\(ICRC2021\)324](#)



# COMBINED SPECTRUM



The contributing spectra are found to be in agreement within their uncorrelated systematic uncertainties

**Overall fit of all the spectra** accounting for systematics on exposure and energy

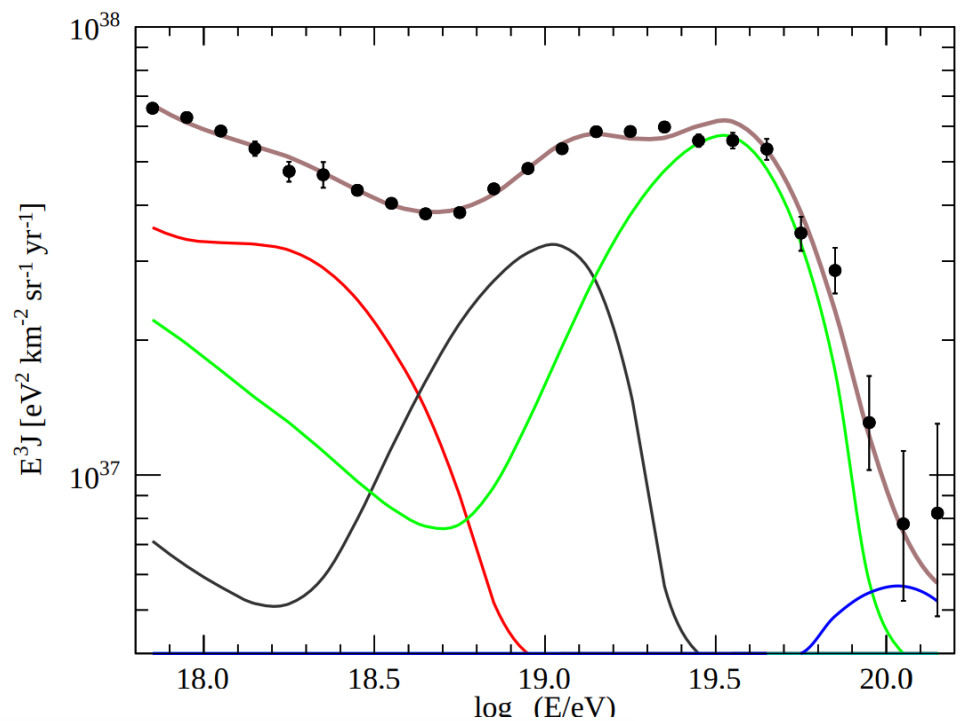
**Reference:**  
[PoS\(ICRC2021\)324](#)

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

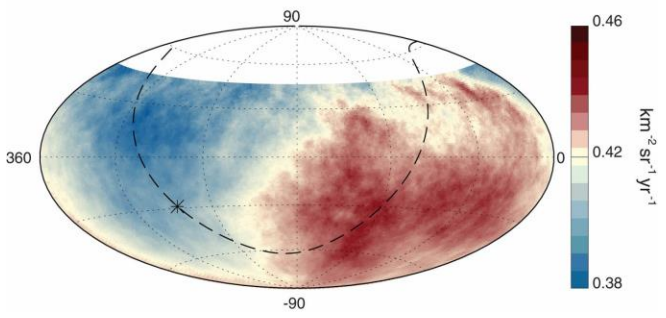
- low energy ankle*  $E_{01} = (2.8 \pm 0.3 \pm 0.4) \times 10^{16} \text{ eV}$
- 2<sup>nd</sup> knee*  $E_{12} = (1.58 \pm 0.05 \pm 0.2) \times 10^{17} \text{ eV}$
- ankle*  $E_{23} = (5.0 \pm 0.1 \pm 0.8) \times 10^{18} \text{ eV}$
- instep*  $E_{34} = (1.4 \pm 0.1 \pm 0.2) \times 10^{19} \text{ eV}$
- suppression*  $E_{45} = (4.7 \pm 0.3 \pm 0.6) \times 10^{19} \text{ eV}$

- $\gamma_0 = 3.09 \pm 0.01 \pm 0.10$
- $\gamma_1 = 2.85 \pm 0.01 \pm 0.05$
- $\gamma_2 = 3.283 \pm 0.002 \pm 0.10$
- $\gamma_3 = 2.54 \pm 0.03 \pm 0.05$
- $\gamma_4 = 3.03 \pm 0.05 \pm 0.10$
- $\gamma_5 = 5.3 \pm 0.3 \pm 0.1$

# INTERPRETATION



- Above the **ankle**: mixed composition with a hard spectrum and a low rigidity cutoff
- Below the **ankle**: component with very soft spectrum and a mix of protons and intermediate-mass nuclei
- **Instep**: interplay between He and CNO components
- GZK\* only scenario disfavored (**Phys. Rev. Lett. 16, 748 (1966)**)
- **Suppression**: combination of maximum accelerator energy + propagation effects



**Extragalactic origin above 8 EeV:** proven with arrival direction distribution  
(E. Martins, TeVPA2023)

**AugerPrime** will allow the measurement of the mass composition beyond the present limit, testing the presence of a possible sub-dominant light contribution at the highest energies .

**Reference:**  
[Phys. Rev. Lett. 125, 121106 \(2020\)](#)

- Different kinds of spectrum measurements
- New feature detected (instep)
- Suppression confirmed
- Ankle confirmed
- No strong declination dependence of spectrum
- SD750, SD433 and Cerenkov spectra cover the low energy region important to study the transition from galactic to extragalactic
- Suppression: combination of source maximum energy + propagation effects
- Instep: interplay between He to CNO components
- Ankle: interplay between (soft) LE and (hard) HE components

Gràzie assàje!