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The Astroparticle Physics Conference
34th International Cosmic Ray Conference
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The Hague, The Netherlands

The flux of ultra-high energy cosmic rays after 10 years of operation of the Pierre Auger Observatory

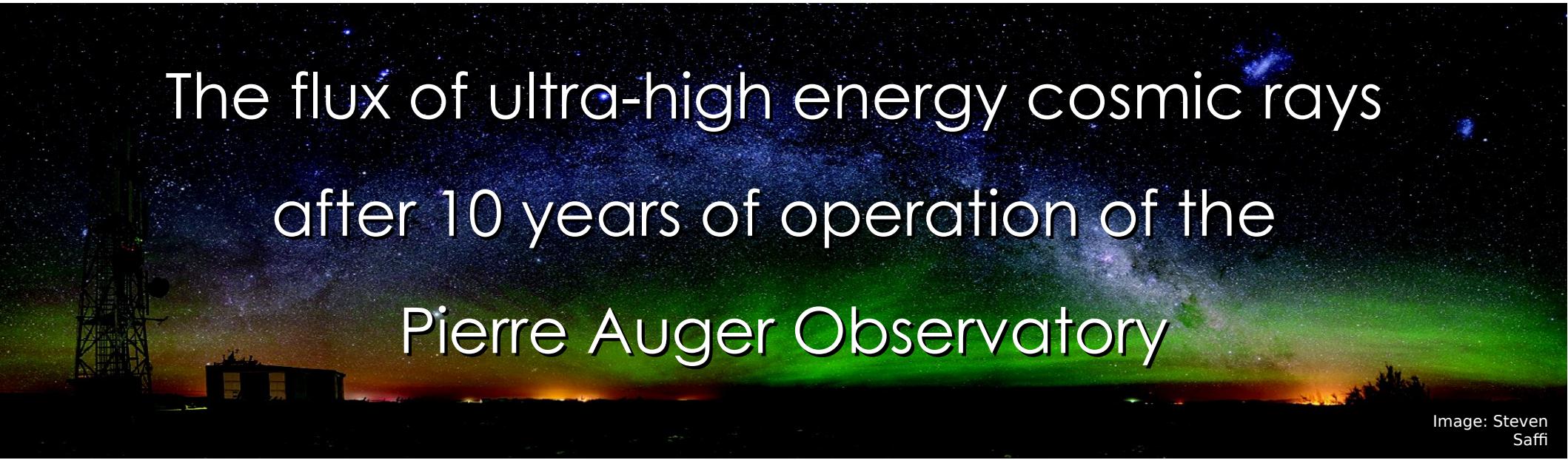

Image: Steven Saffi

PIERRE AUGER OBSERVATORY

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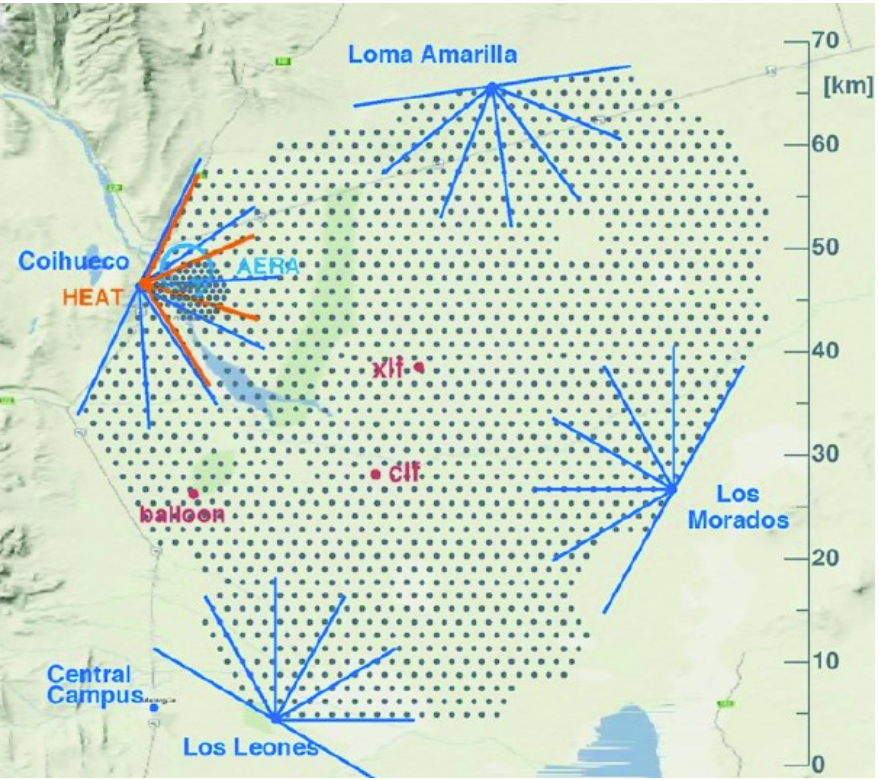
Outline

- Update of the cosmic-ray energy spectrum above 3×10^{17} eV obtained by combining four independent data sets collected by the Pierre Auger Observatory over more than 10 years.

- First results of the search for a dependence of the measured flux on the declination of the incoming cosmic rays.

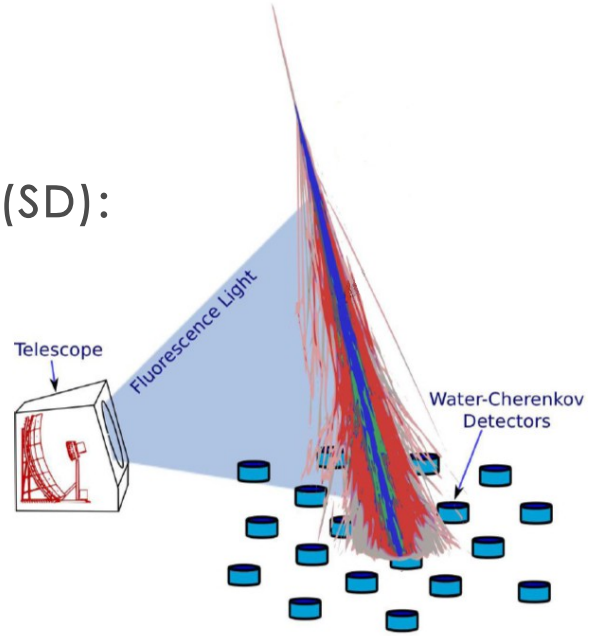


Hybrid detector:

- Surface detector array (SD):
  - SD-1500:

    1660 spaced by 1.5 km
    ~ 3000 km^2
  - SD-750:

    49 spaced by 750 m
    ~ 24 km^2



- Fluorescence detector (FD):

  27 fluorescence telescopes in 5 buildings

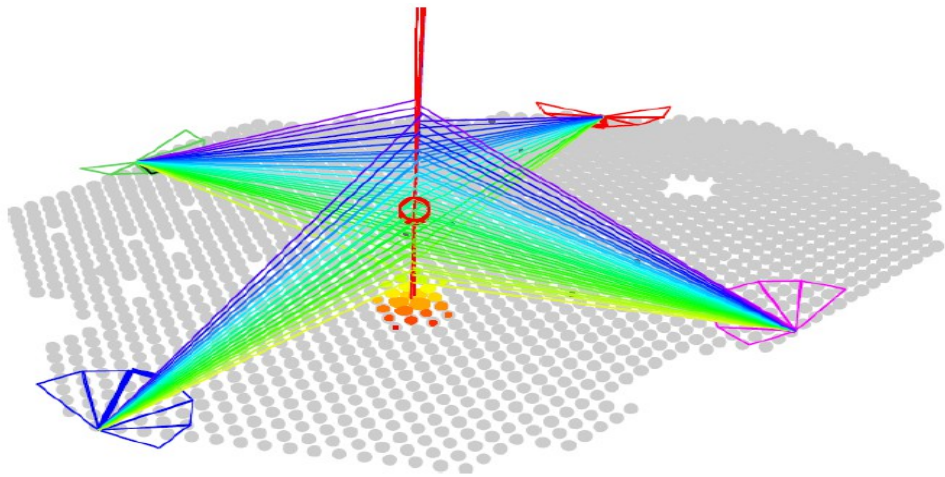
"The Pierre Auger Cosmic Ray Observatory" to appear in NIM A [arXiv: 1502.01323]

Measurements of the cosmic-ray energy

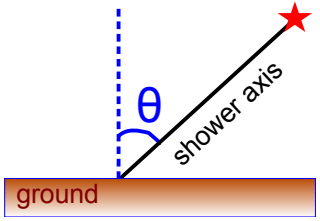
FD: calorimetric measurement of the energy; ~13% duty cycle

SD: provides an **energy estimator** = the shower size at the ground; ~ 100% duty cycle

SD absolute calibration using a subset of hybrid events reconstructed by both SD and FD, which allows an SD-energy estimation weakly reliant upon shower simulations.

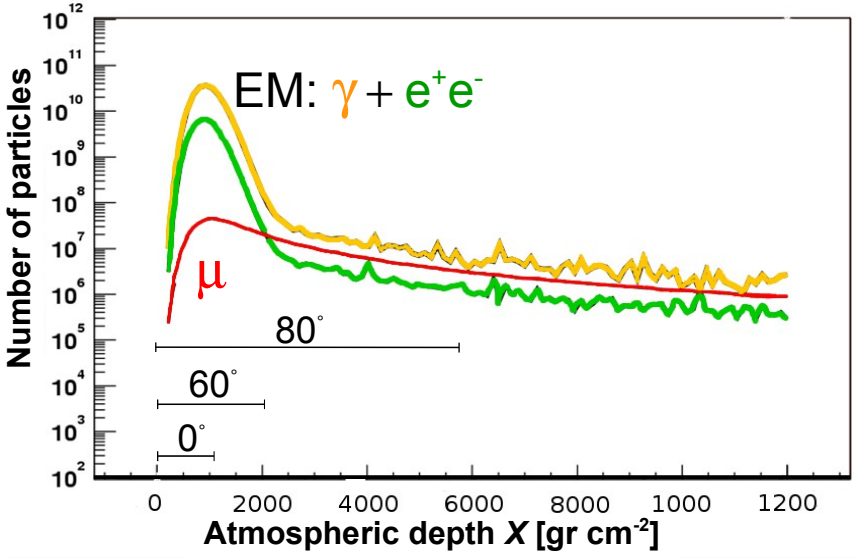


Measurements of the cosmic-ray energy



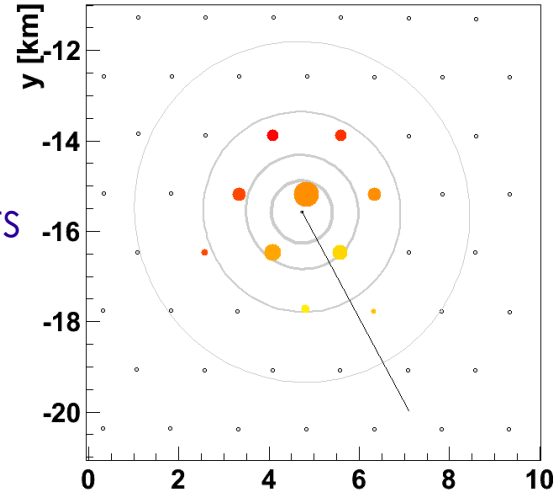
depth crossed by the shower :

$$\Delta X \propto \frac{1}{\cos\theta}$$

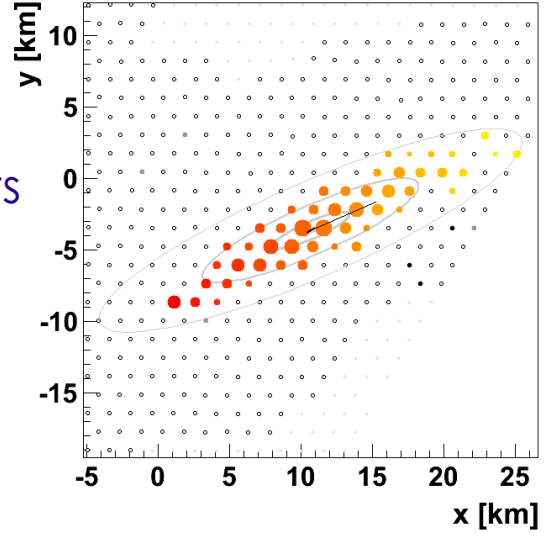


Muons travel long distances being deflected by the geomagnetic field

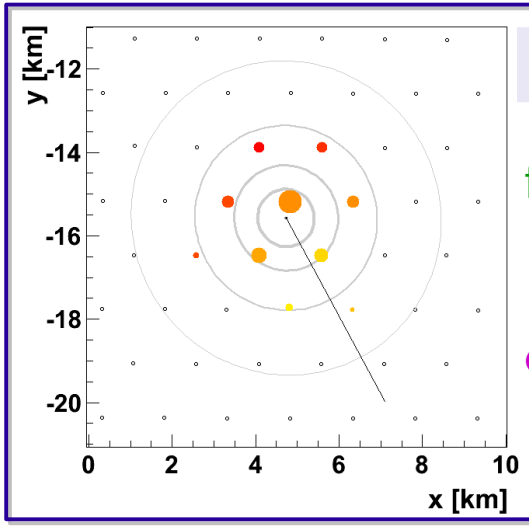
SD "vertical" events (θ<60°)



SD "inclined" events (θ>60°)



Measurements of the cosmic-ray energy

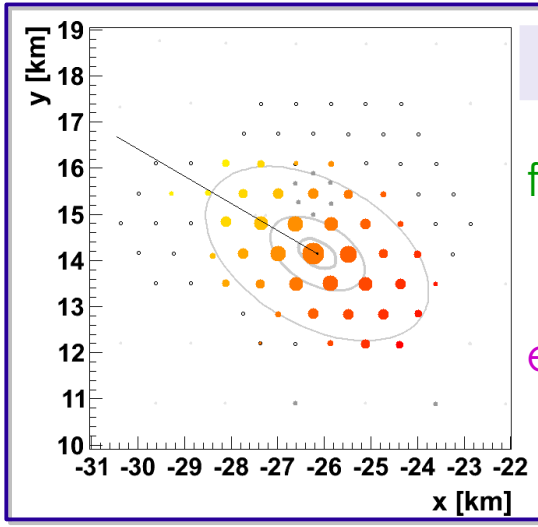


SD-1500 m (θ<60°)

fully efficient:

$E > 3 \times 10^{18}$ eV

energy estimator: S_{38}

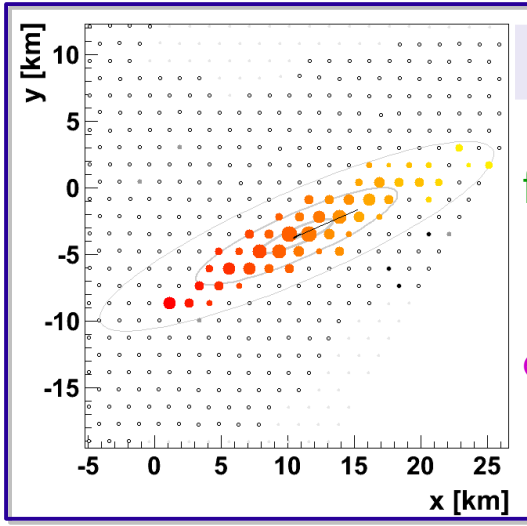


SD-750 m (θ<55°)

fully efficient:

$E > 3 \times 10^{17}$ eV

energy estimator: S_{35}

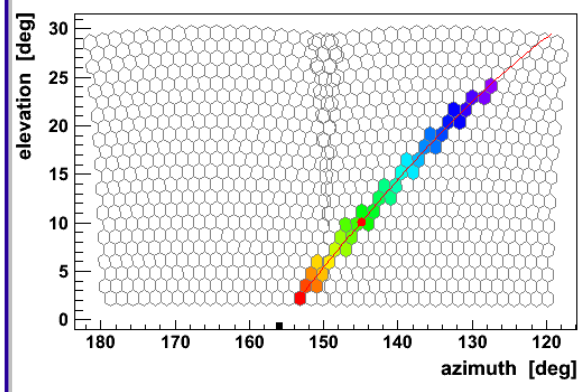


SD-1500 m (θ>60°)

fully efficient:

$E > 4 \times 10^{18}$ eV

energy estimator: N_{19}



Hybrid (θ<60°)

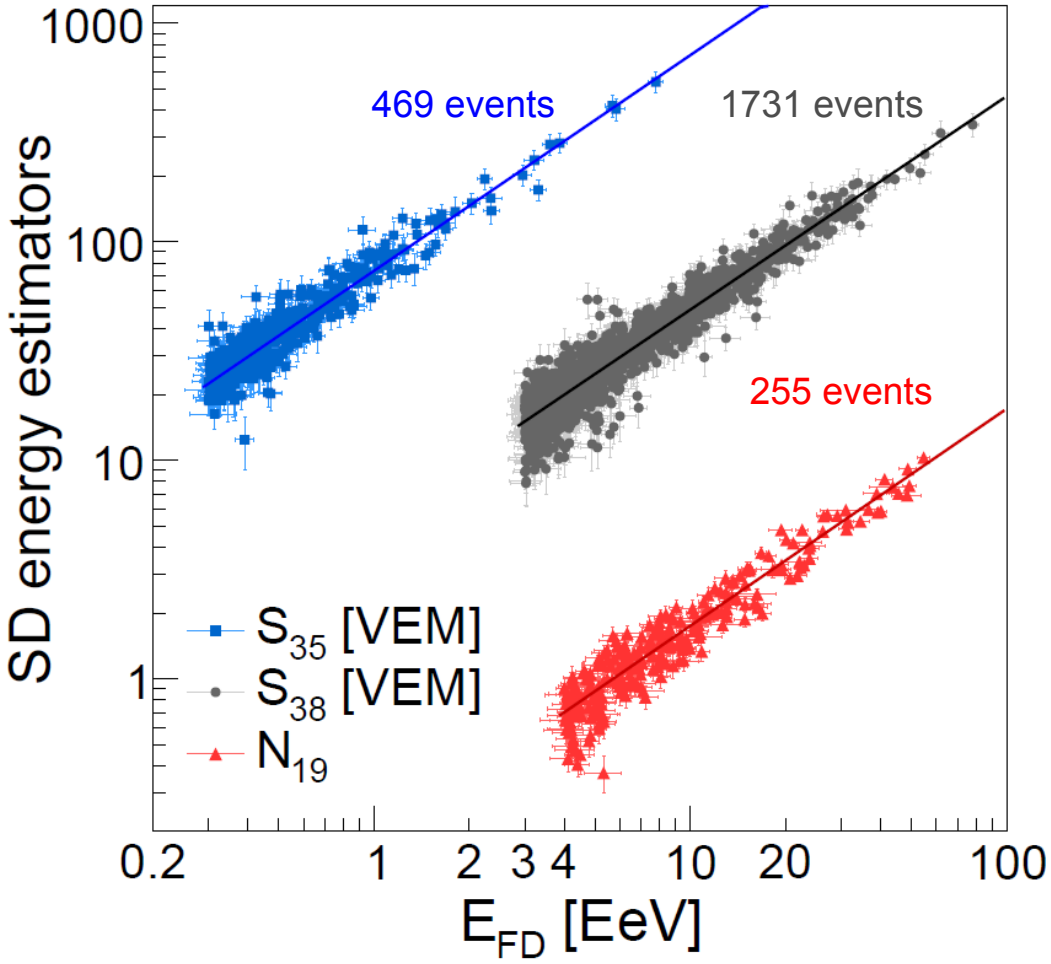
FD + ≥ 1 SD station

fully efficient:

$E \gtrsim 10^{18}$ eV

measurement: E_{FD}

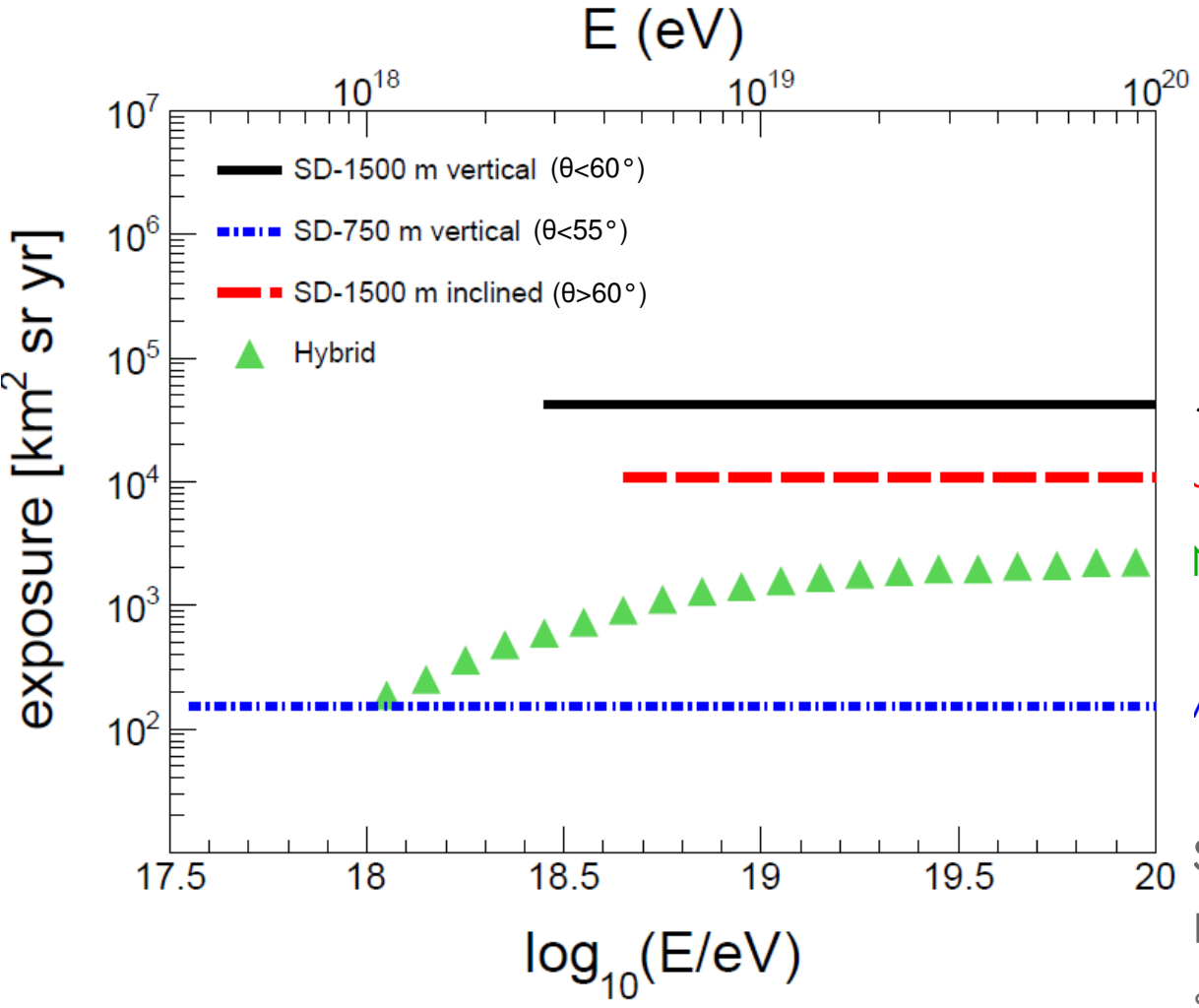
SD energy calibrations



Calibration function : $E_{FD} = A\,(\hat{S})^B$

- SD-1500 m "vertical" (S_{38}):
  - A = (0.1871± 0.004) EeV
  - B = 1.023 ± 0.006
  - energy resolution (E > 3 EeV)= **(15.3 ± 0.4)%**
- SD-1500 m "inclined" (N_{19}):
  - A = (5.71± 0.09) EeV
  - B = 1.01 ± 0.02
  - energy resolution (E > 4 EeV)= **(19 ± 1)%**
- SD-750 m (S_{35}):
  - A = (12.87± 0.63) PeV
  - B = 1.013 ± 0.013
  - energy resolution (E > 0.3 EeV) = **(13 ±1)%**

Exposure for the flux measurements



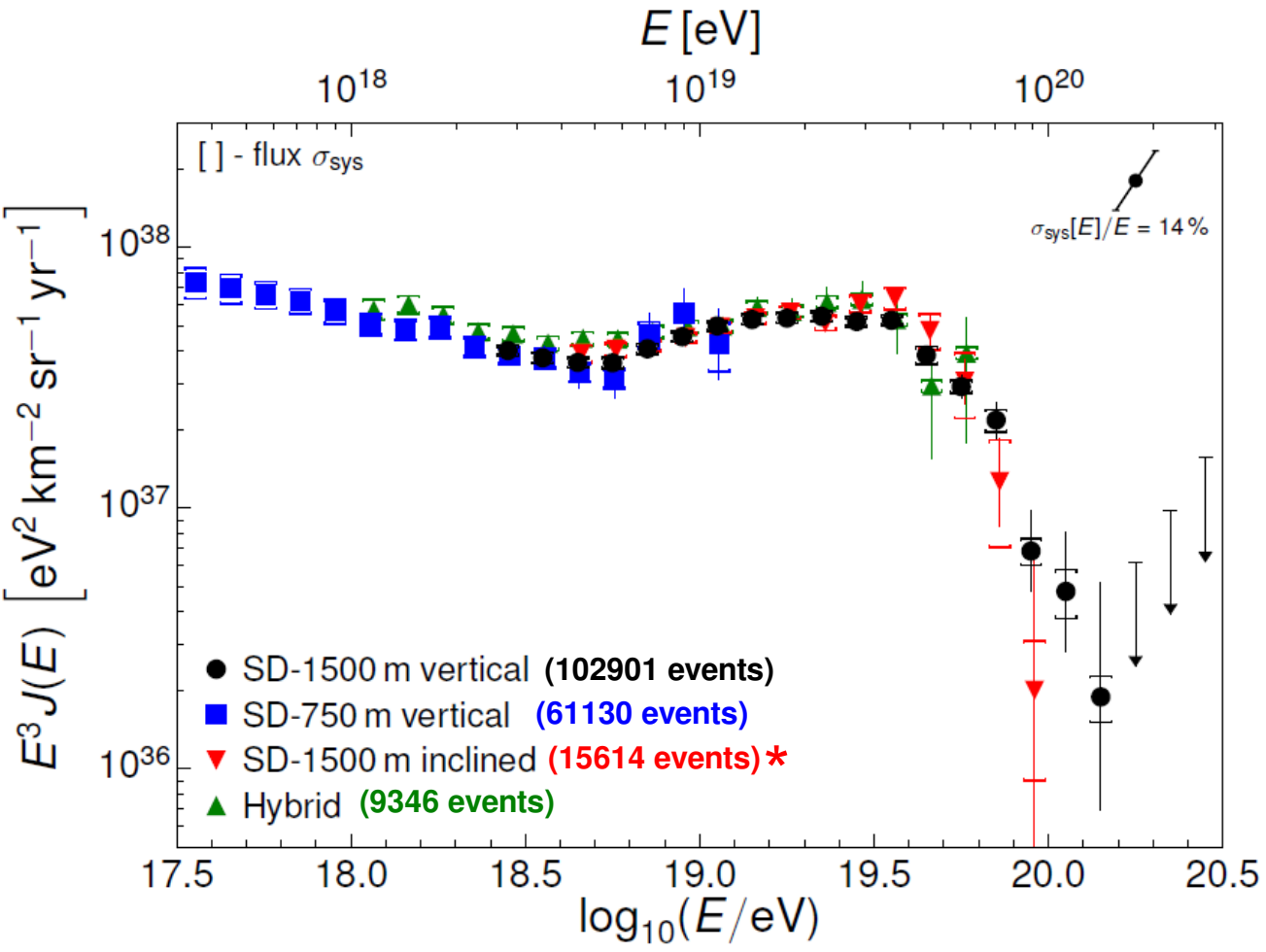
Exposure [km^2 sr yr]

Jan 2004 - Dec 2014:	**42500**
Jan 2004 - Dec 2013:	**10900**
Nov 2005 - Dec 2013:	**1500 at 10 EeV**
Aug 2008 - Dec 2014:	**150**

SD: based on geometrical calculation

Hybrid: based on time-dependent MC simulations

The four measurements of the cosmic-ray flux



* *to appear in JCAP [arXiv: 1503.07786]*

Flux systematic uncertainties

SD-1500 m θ<60°: **5.8%**

SD-1500 m θ>60°: **5%**

SD-750 m: **14%(<7%) at 0.3(3) EeV**

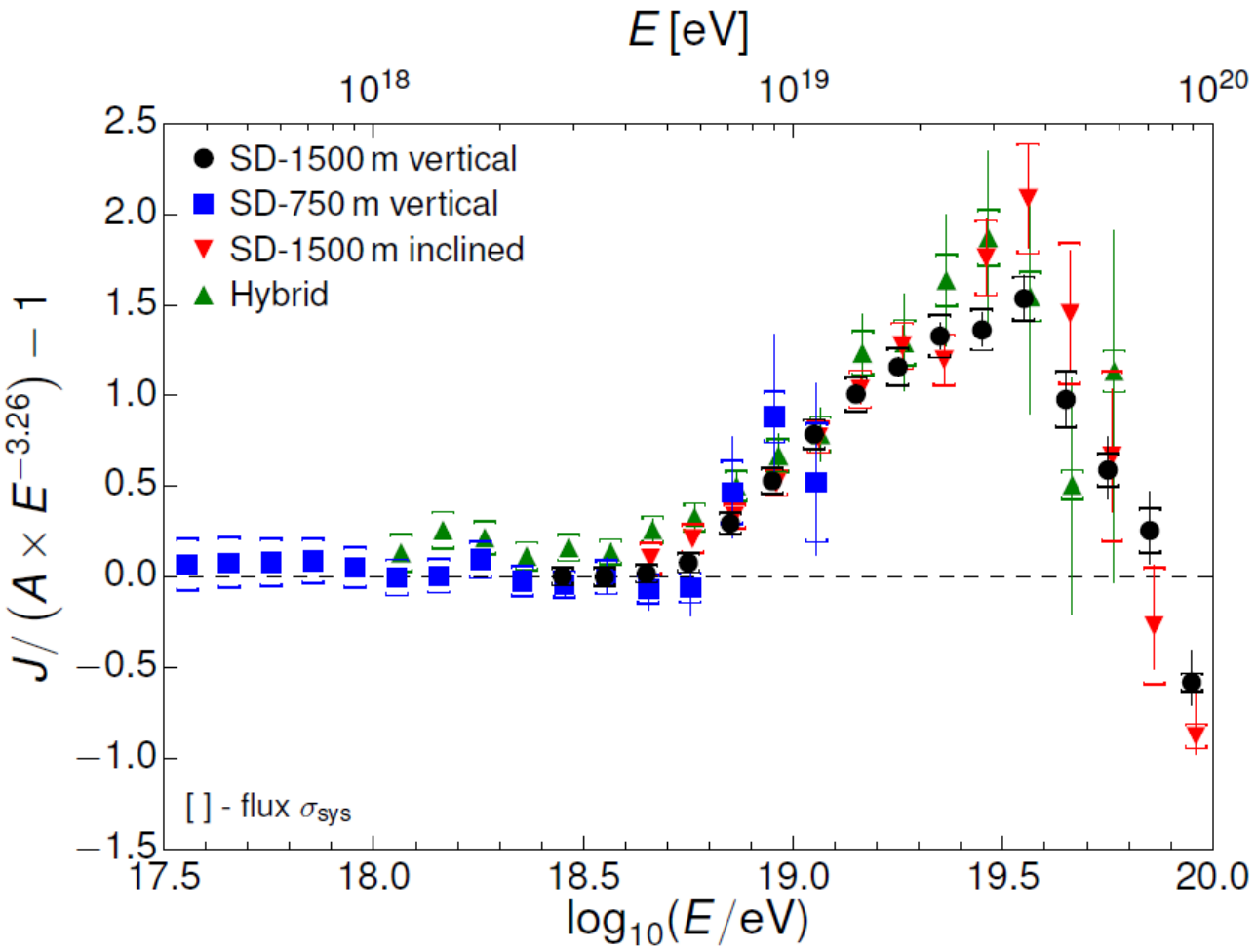
Hybrid: **10%(6%) at 1(10) EeV**

Energy systematic uncertainties

FD energy scale: **14%**

Spectra corrected for finite energy resolution, responsible for event-to-event bin migration (<15% SD, <3% Hybrid)

Fractional differences



Combined spectrum

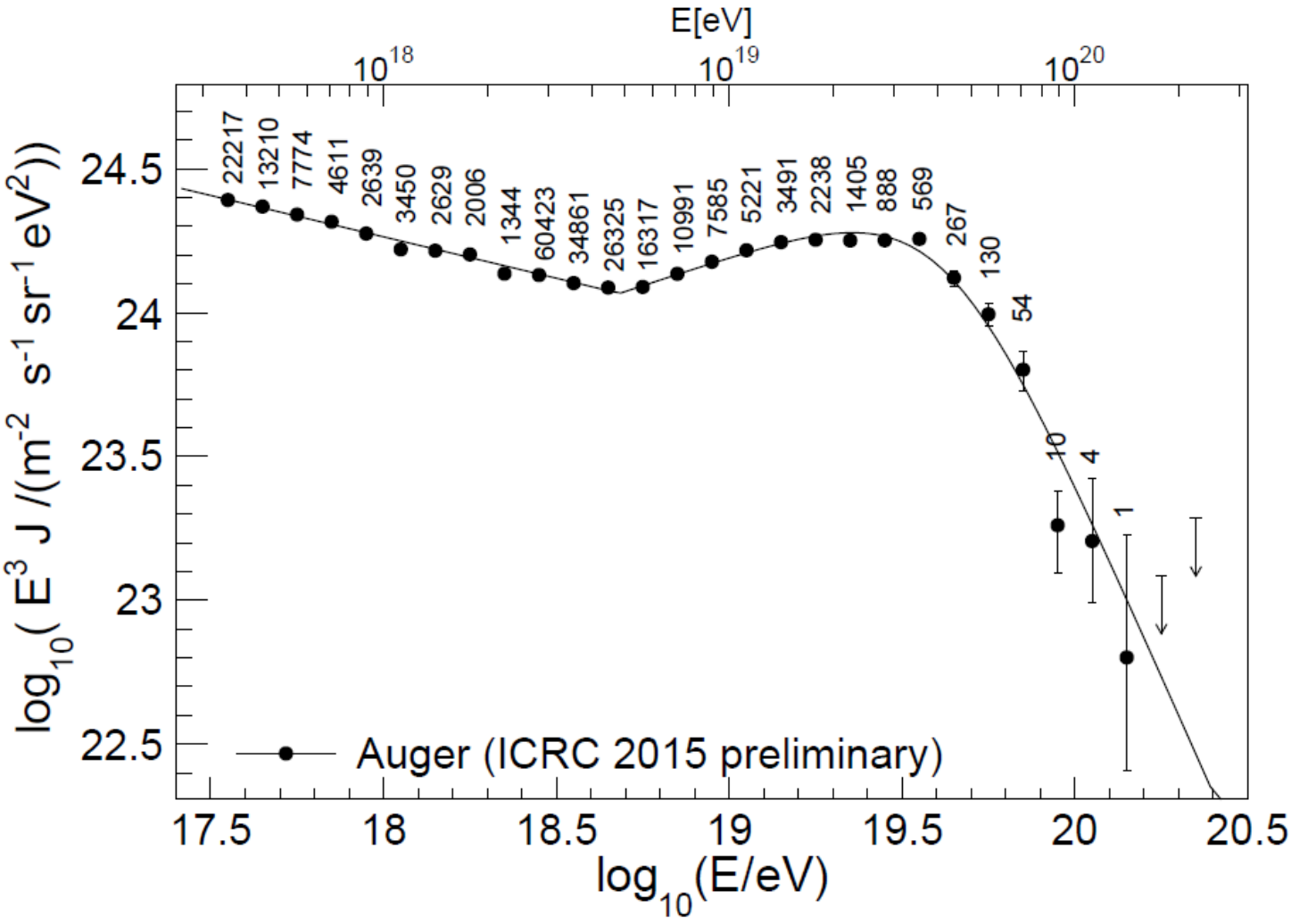
Flux normalizations:

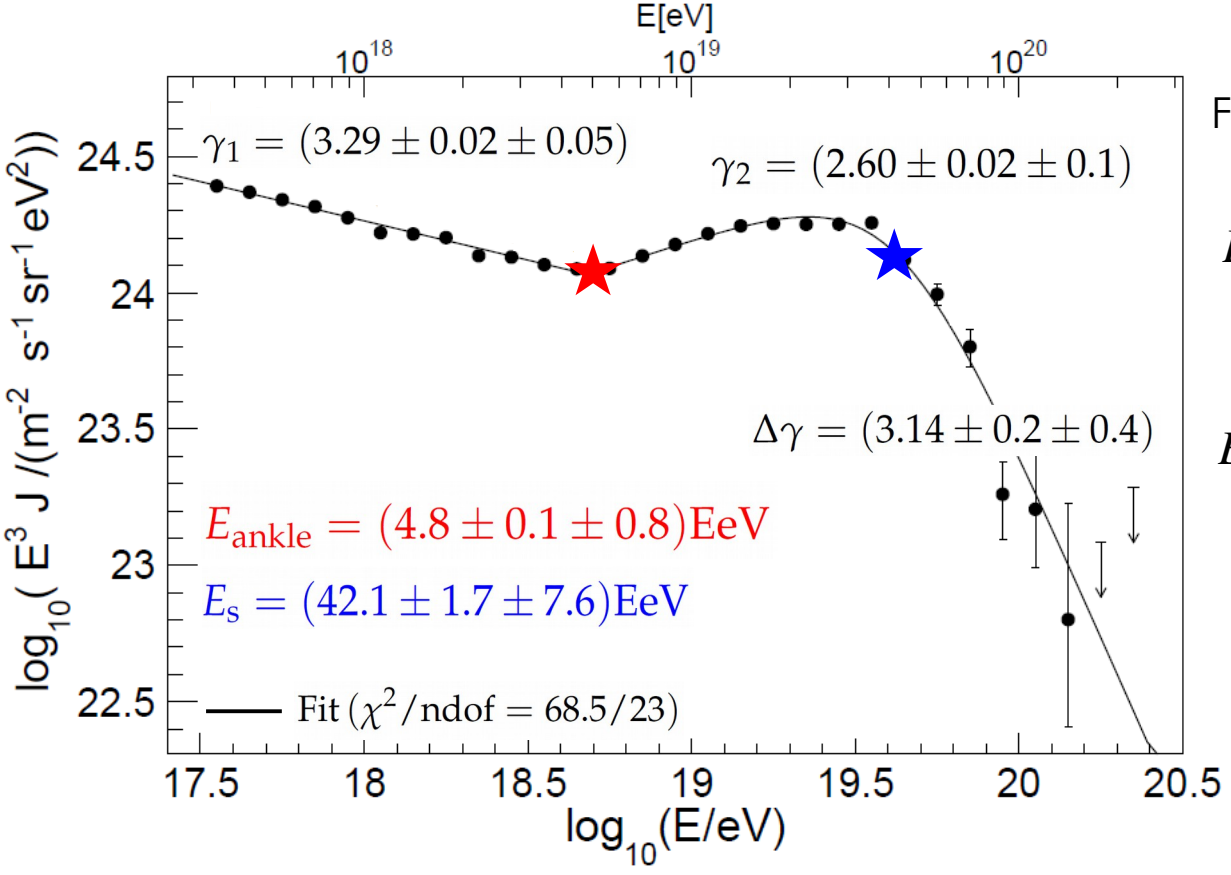
SD-1500 m vertical: **5.7%**

SD-1500 m inclined: **-0.1%**

SD-750 m: **1.8%**

Hybrid: **-5.8%**





Fit of the **differential flux** to the model:

$E < E_{ankle}$:

$$J(E) \propto E^{-\gamma_1}$$

$E > E_{ankle}$:

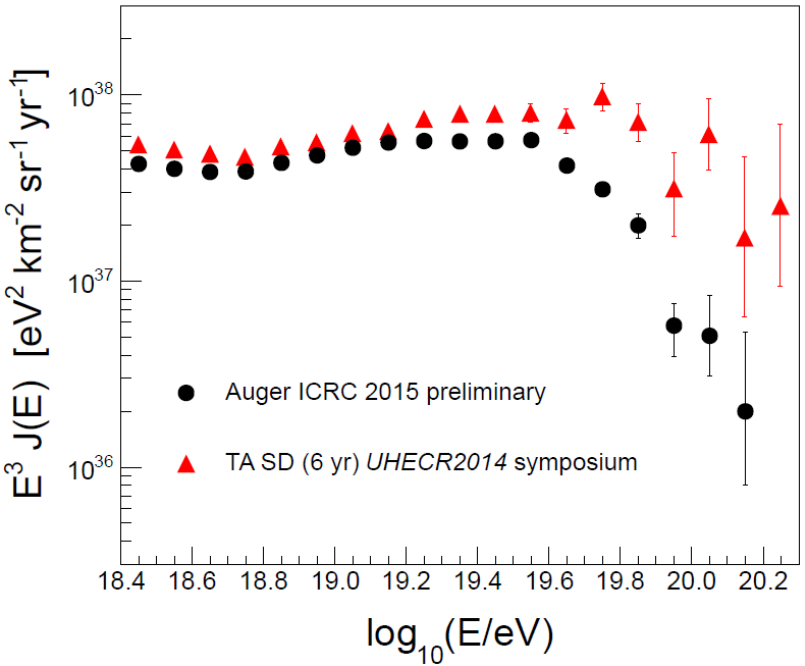
$$J(E) \propto E^{-\gamma_2} \left[1 + \left(\frac{E}{E_s}\right)^{\Delta\gamma}\right]^{-1}$$

$E_{1/2}$ at which the **integrated flux** drops by a factor of 2 below what expected without cutoff:

$$\mathrm{E}_{1/2} = (\mathbf{24.7 \pm 0.1}\ ^{+8.2}_{-3.4})\ \mathrm{EeV}$$

Declination-dependence on the flux : overview

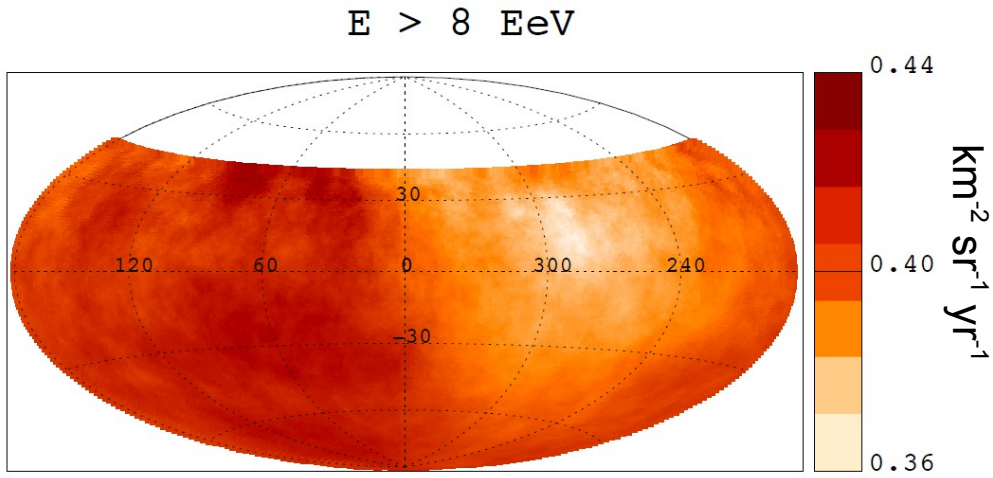
Difference between **Auger** and **Telescope Array spectra** at the highest-energy range.



under study by UHECR Spectrum WG (TA+Auger)

see for example I. C. Mariş UHECR2014

Hint of a **dipole anisotropy above 8 EeV** found with Auger data (see I. Al Samarai talk CR03)



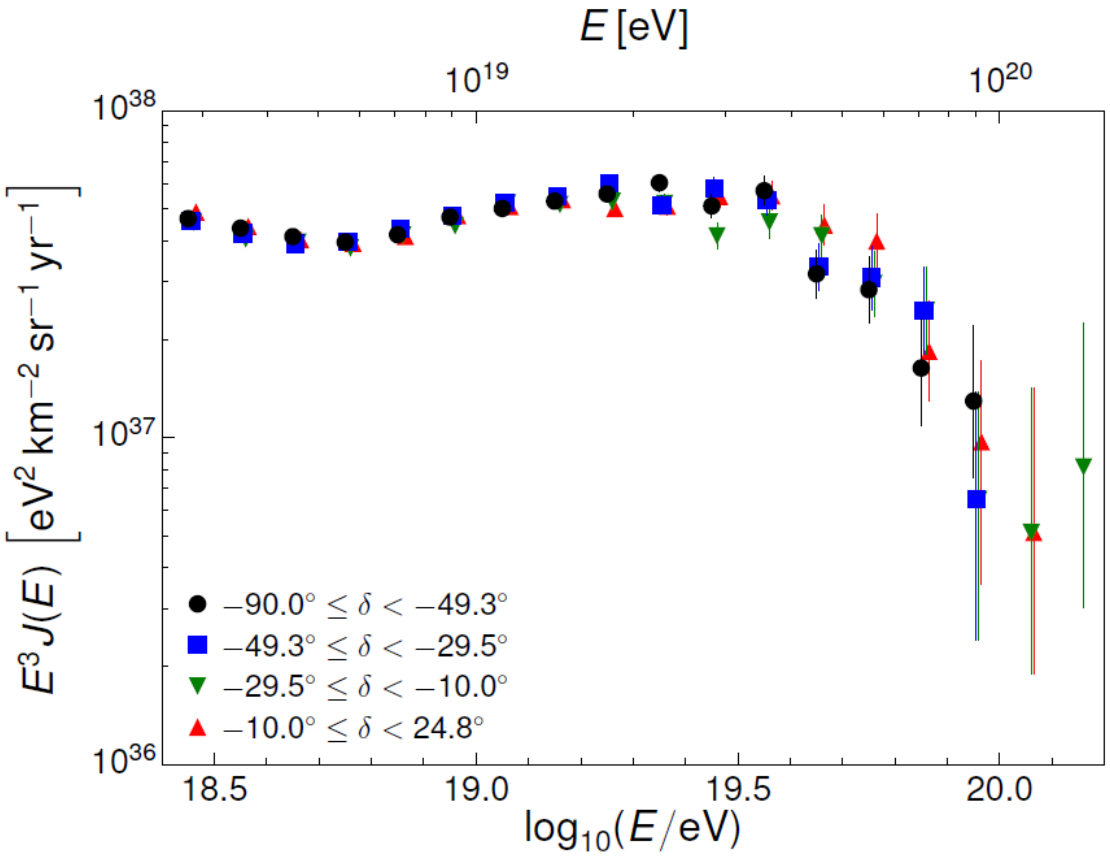
Observed amplitude in right ascension suggests a large-scale anisotropy with a **significance > 4σ**

Declination-dependence on the flux

- **Events with θ < 60°** (offer a large statistics) cover a wide range of **declinations from -90° to +25°**
- **Spurious** (experimental, atmospheric and geomagnetic) **effects** that **can module** the **flux** are taken into account in this analysis.

I) Observed part of the sky divided into 4 declination bands of equal exposure:

- **No indication of a δ-dependent flux**
  (**differences** between sub-spectra and all-sky flux **< 5%** below E_s and <13% above)
- **Auger-TA difference not explained**
  (still room if TA flux is much larger above +25° than below)



Declination-dependence on the flux

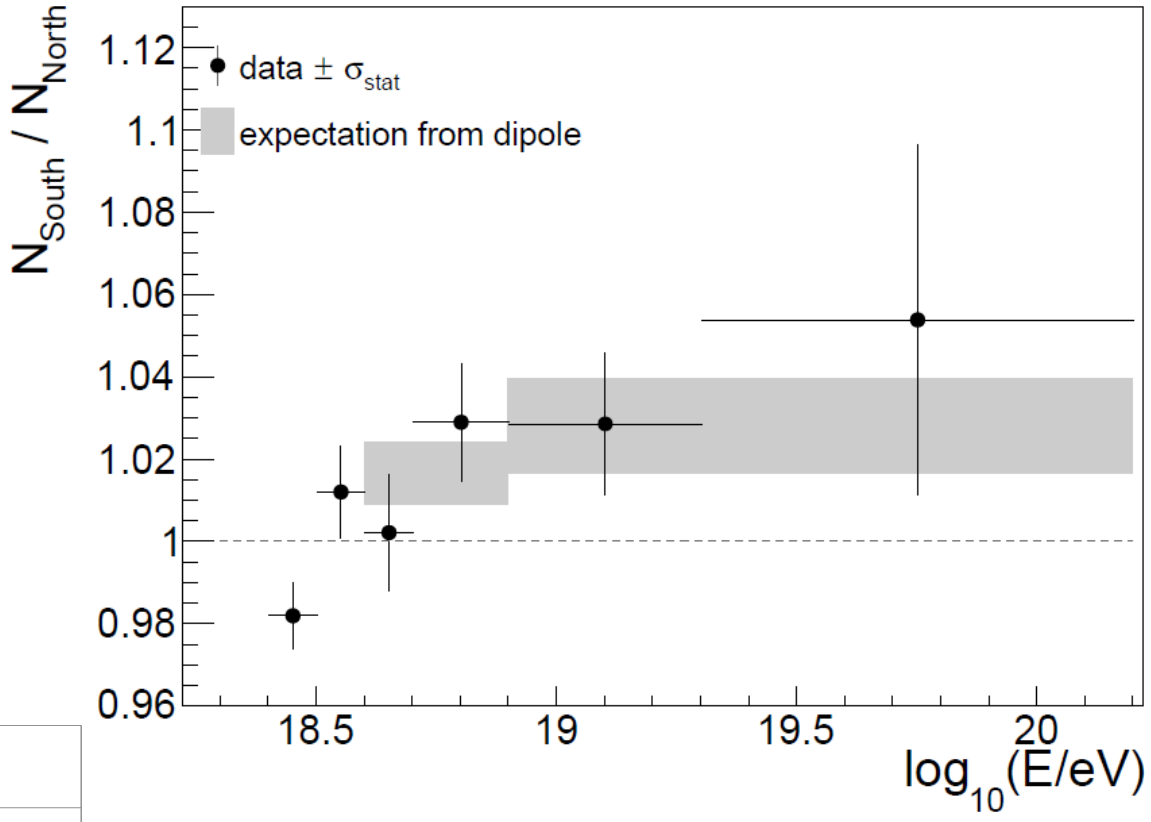
II) Observed sky divided into 2 declination bands to compute the ratio:

$N_{South}(\delta<-29.47°)/N_{North}(\delta>-29.47°)$

comparison with expectation from dipolar modulation measured obtained using data with $\Theta < 80°$.

E (EeV)	d	δ_d	α_d
4-8	(2.7 ± 1.2)%	-81° ± 17°	15° ± 115°
>8	(7.3 ± 1.5)%	-39° ± 13°	95° ± 13°

(I. Al Samarai talk CR03)



- Observation compatible with dipole expectation within uncertainties.

Summary

- **Four independent measurements of the UHECR flux** using both the SD and FD of the Pierre Auger Observatory.

- **Combined measurement** of the energy spectrum above 3 x 10^{17} eV up to its end at about 10^{20} eV using data collected over more than 10 years.

- **Spectral features** measured with unprecedented precision.

- **Preliminary search for a dependence of the measured flux on the declination** of the incoming cosmic rays:
  - No significant indication of variation in 4 declination bands.
  - Ratio N_{South}/N_{North} compatible with dipole anisotropy found with Auger data.