Measurement of the energy spectrum of cosmic rays with the Pierre Auger Observatory

Markus Roth for the Auger collaboration
Karlsruhe Institute of Technology (KIT)

Photo by S. Saffi

Existing CR detectors at highest energies

Telescope Array (TA)
Delta, UT, USA
507 detector stations, 680 km^2
36 fluorescence telescopes

Pierre Auger Observatory
Province Mendoza, Argentina
1660 detector stations, 3000 km^2
27 fluorescence telescopes

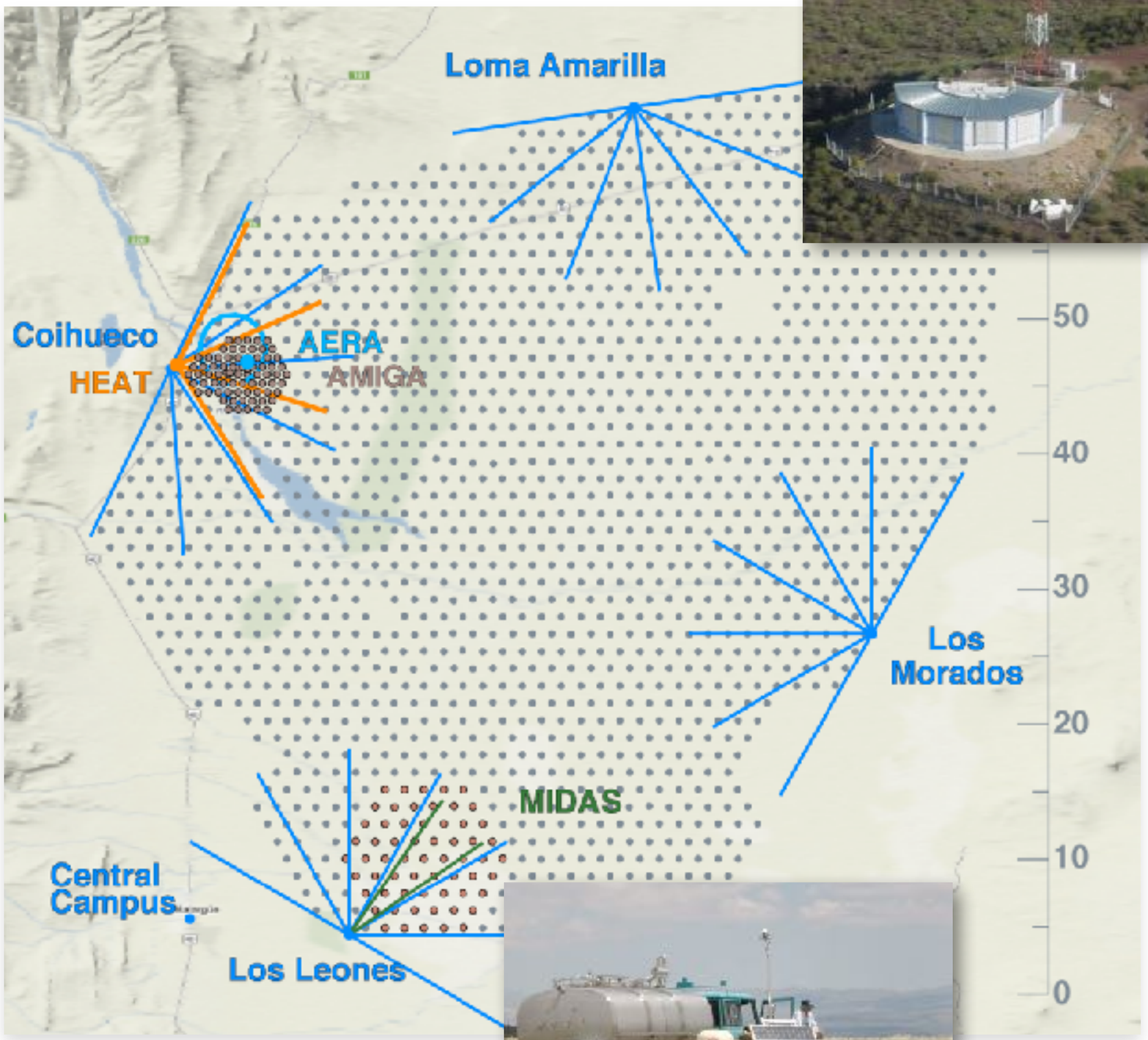
The Pierre Auger Observatory

Fluorescence detector (FD)

- 4 sites
  - 0-30°
  - **E>10^{18} eV**
- HEAT
  - 30°-60°
  - E>10^{17} eV

Surface detector array (SD)

- Grid of 1500 m
  - 3000 km^2
  - 1660 stations
  - **E>$10^{18.5}$ eV**
- Grid of 750 m
  - 24 km^2
  - 61 stations
  - E>$10^{17.5}$ eV



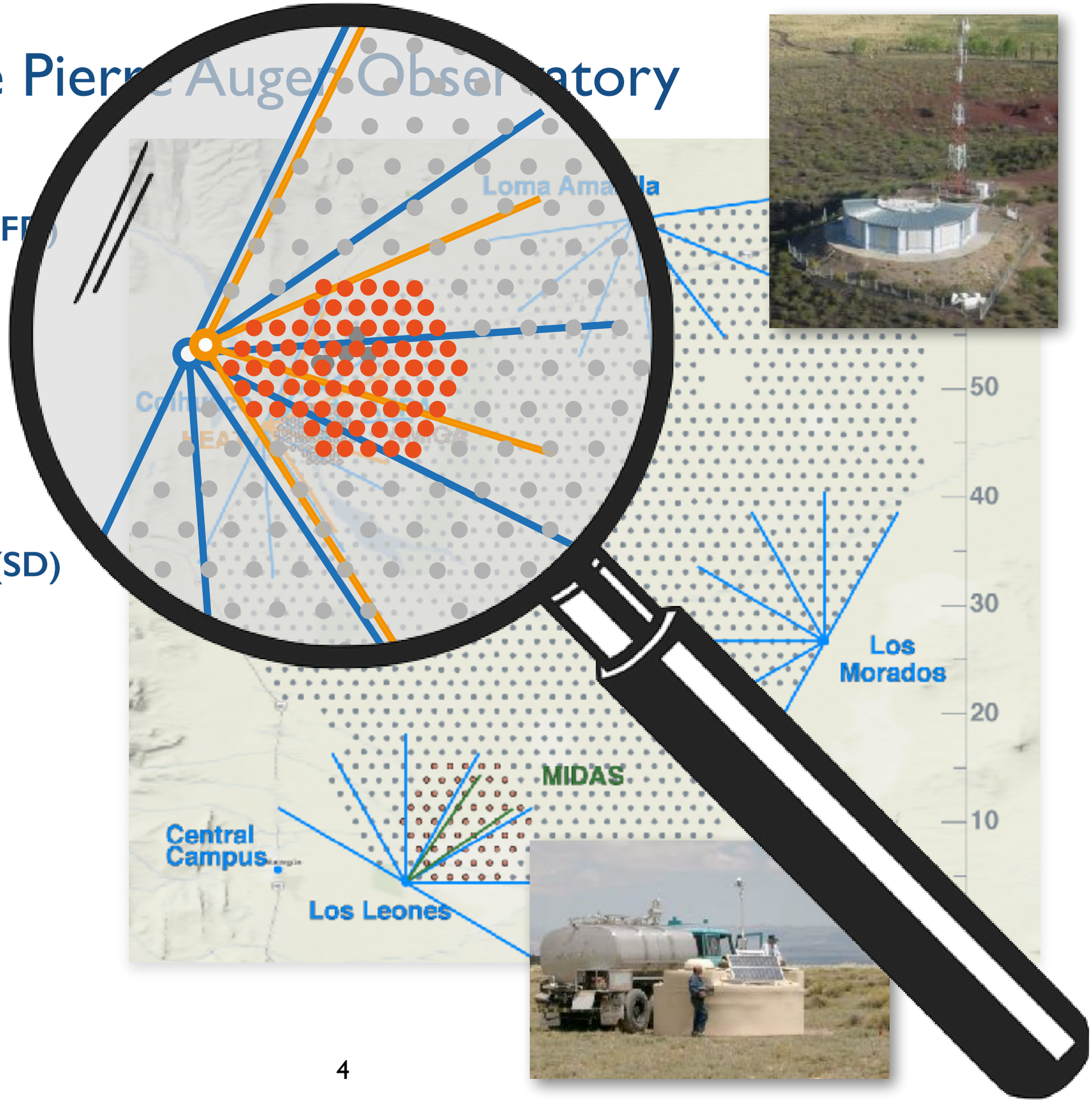
The Pierre Auger Observatory

Fluorescence detector (FD)

- 4 sites
  - 0-30°
  - E>10^{18} eV
- HEAT
  - 30°-60°
  - E>10^{17} eV

Surface detector array (SD)

- Grid of 1500 m
  - 3000 km^2
  - 1660 stations
  - E>$10^{18.5}$ eV
- Grid of 750 m
  - 24 km^2
  - 61 stations
  - E>$10^{17.5}$ eV



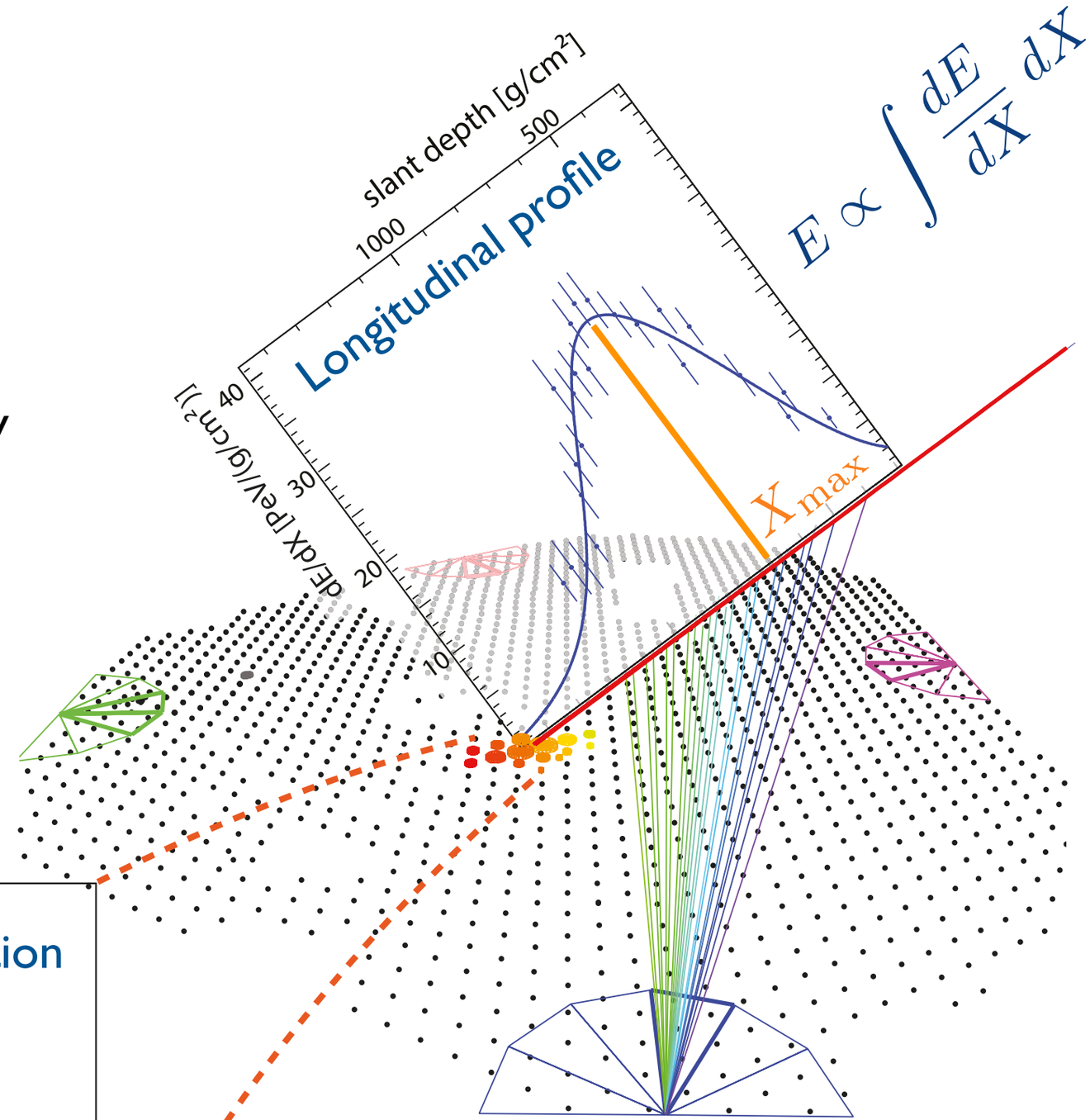
Hybrid detection

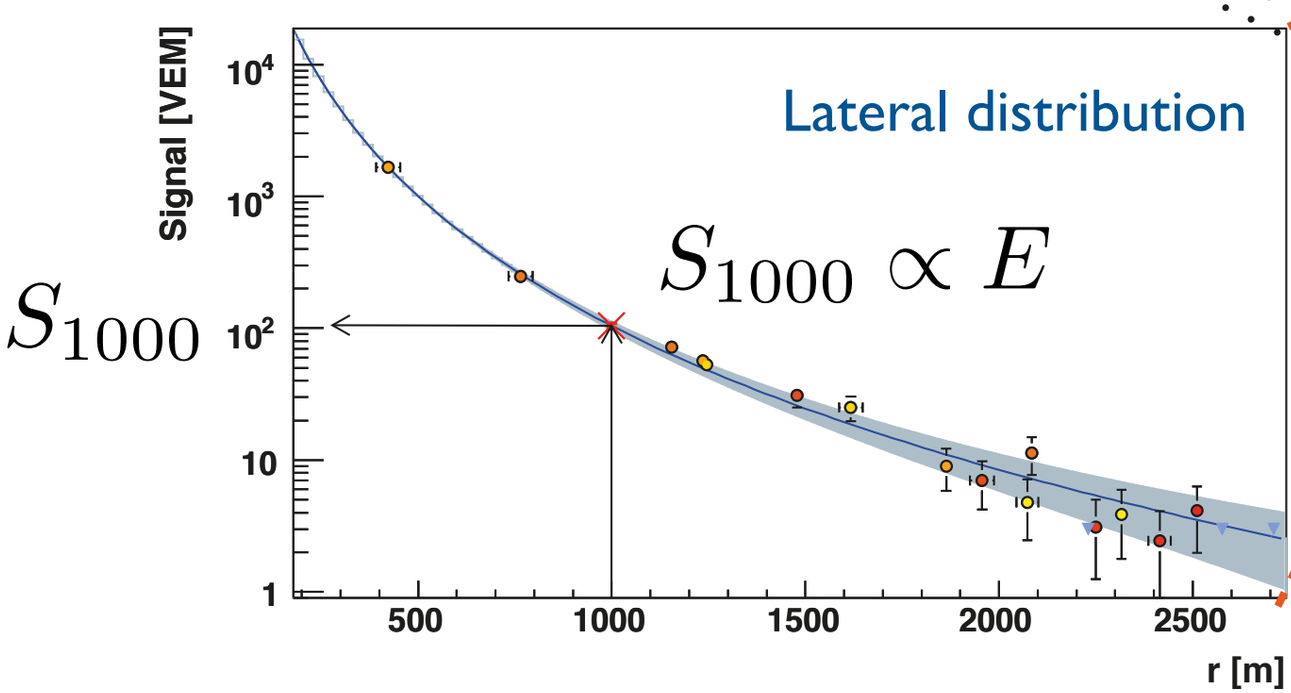
FD:

- calorimetric measurement of energy
- ca.13% duty cycle

SD:

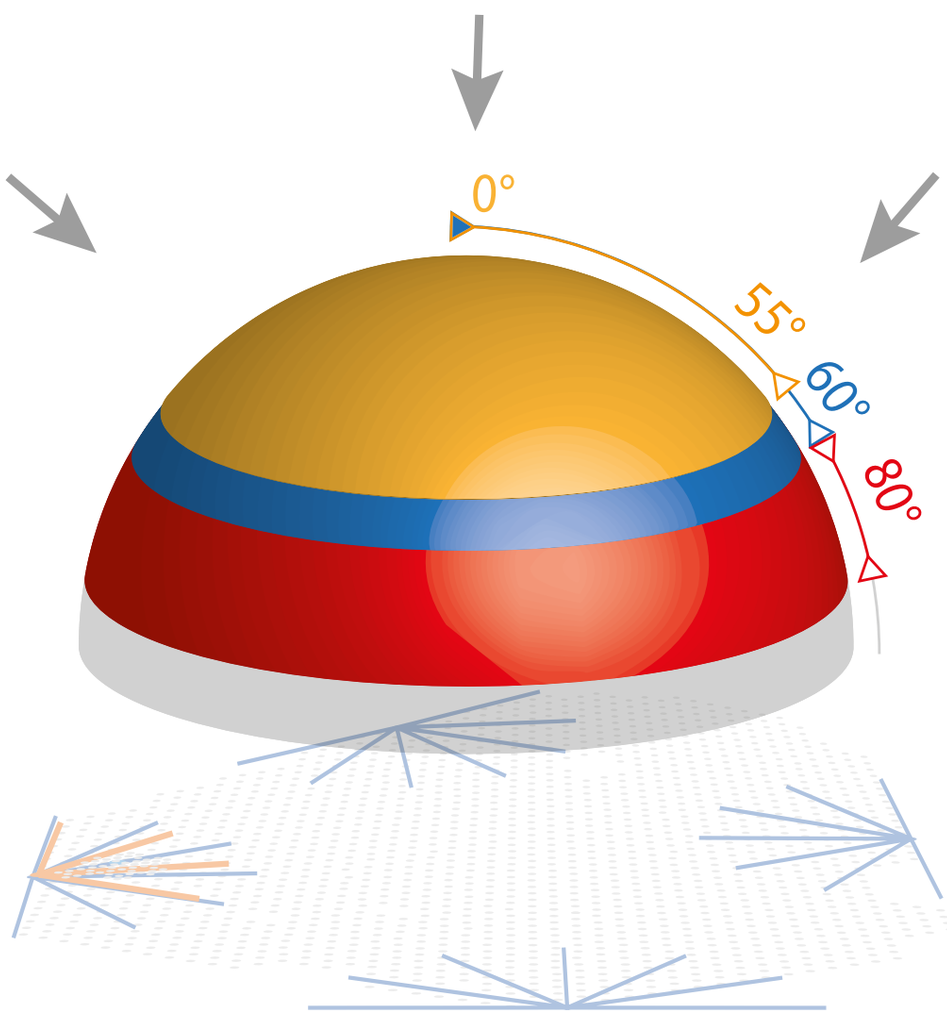
- data driven shape of LDF
- optimal distance at 1000 m
- ca. 100% duty cycle

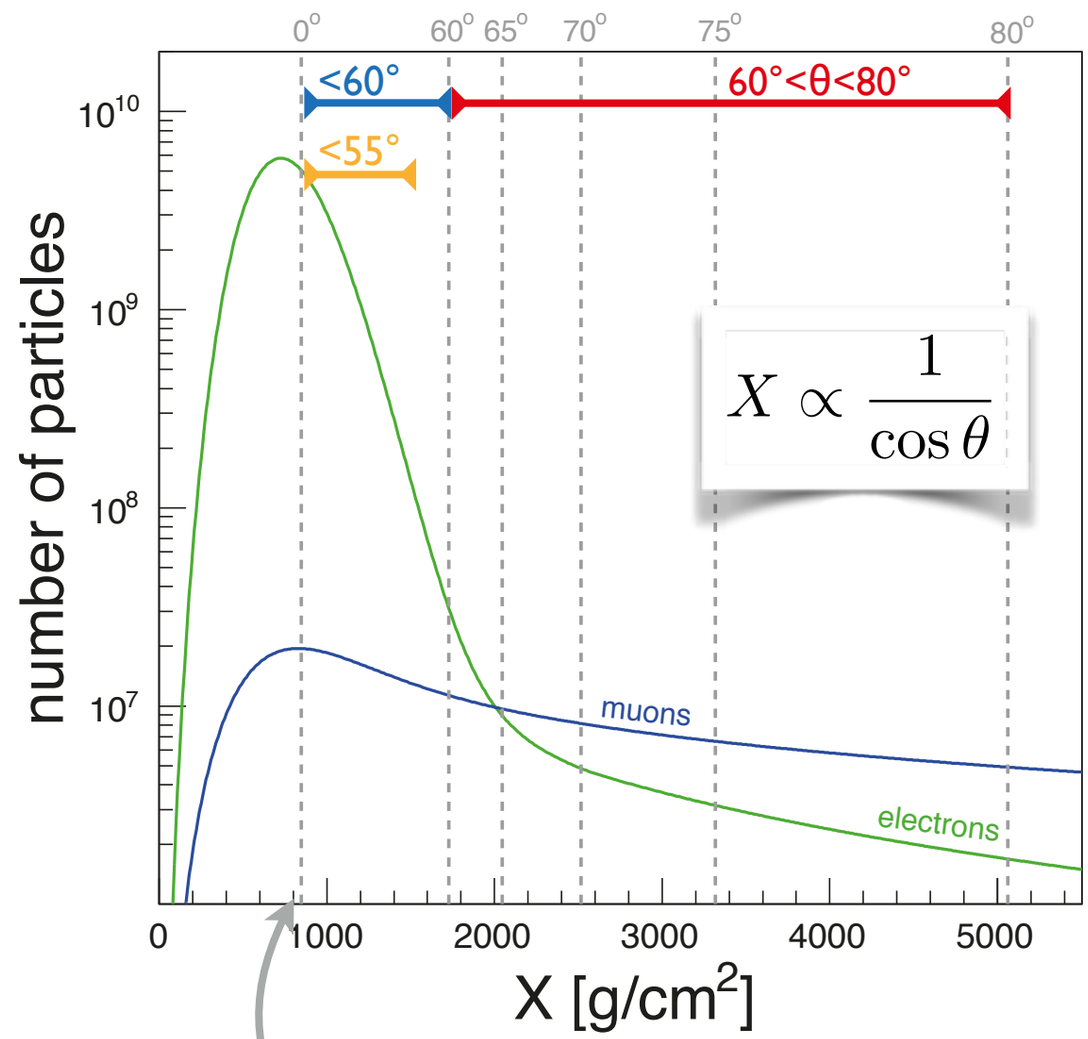




Zenith angle range of SD derived spectra

750m:	$0° < \theta < 55°$	$E > 3 \times 10^{17}$ eV	´vertical´
1500m:	$0° < \theta < 60°$	$E > 3 \times 10^{18}$ eV	´vertical´
1500m:	$60° < \theta < 80°$	$E > 4 \times 10^{18}$ eV	´inclined´



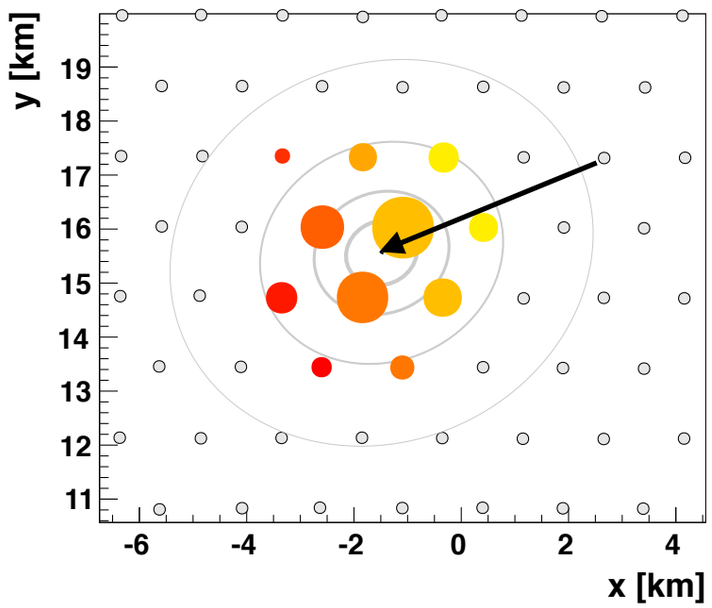


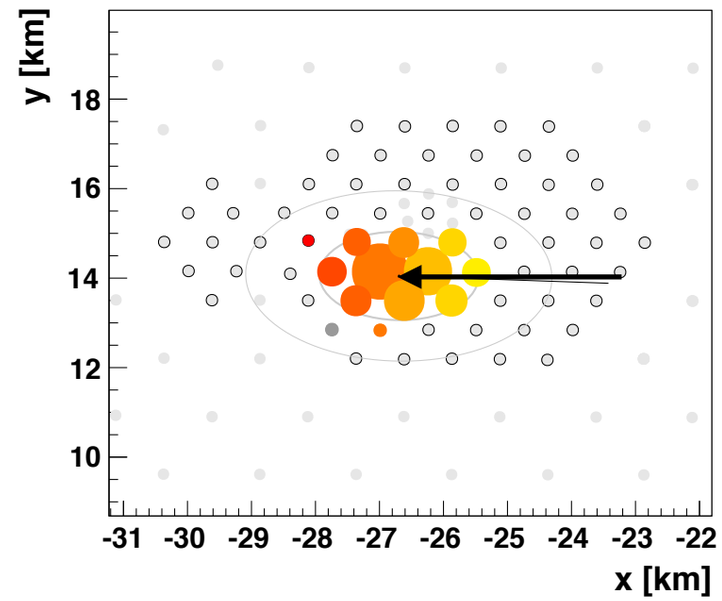
Depth of Malargüe site (870 g/cm²)

Footprint on ground depends on geometry and energy

- 1500 m
- θ < 60°
- 100% eff. @ 3 EeV

$E = A\ S_{38}^{B}$

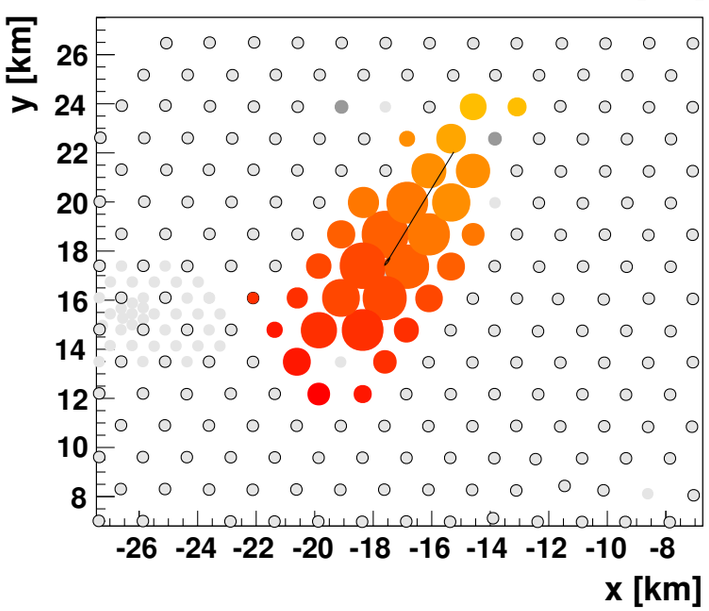


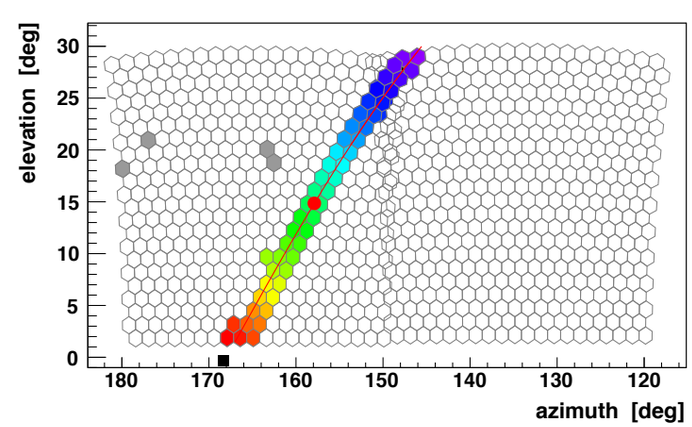


- 750 m
- θ < 60°
- 100% eff. @ 0.3 EeV

$E = A\ S_{35}^{B}$

- 1500 m
- 60°<θ < 80°
- 100% eff. @ 4 EeV
- $E = A\ N_{19}^{B}$
- N_{19} by definition independent of θ





- FD + 1 SD station
- θ < 60°
- 100% eff. @ 1 EeV

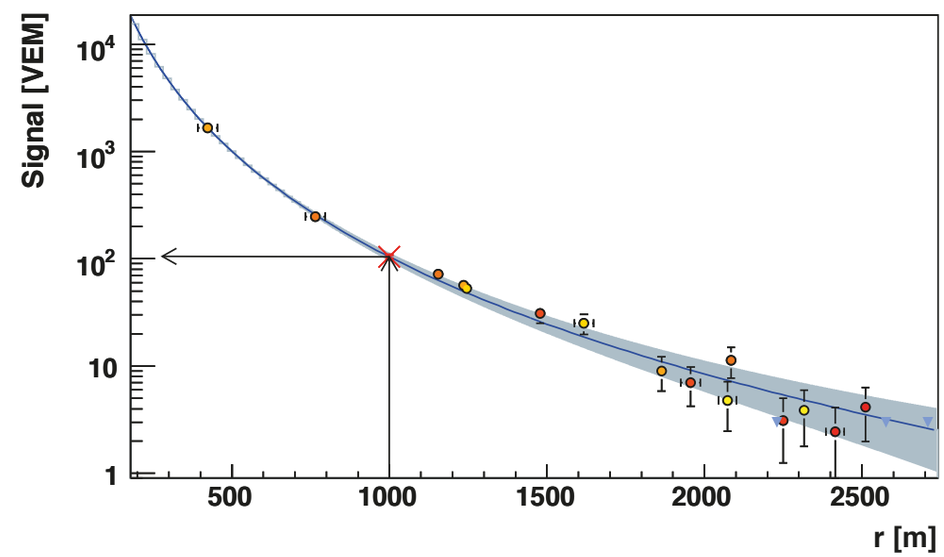
$E = E_{\mathrm{FD}}$

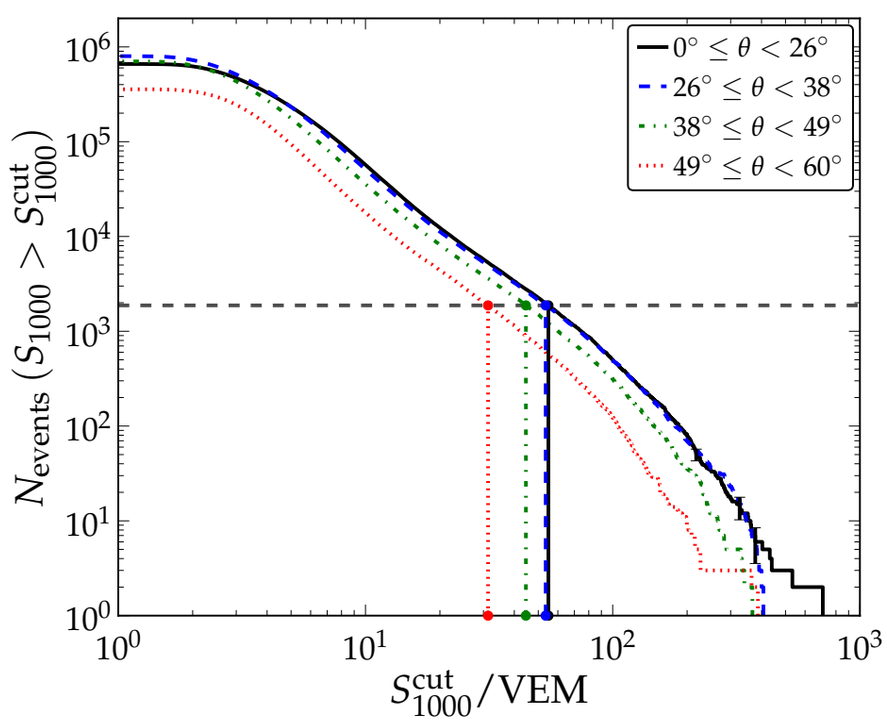
SD energy estimator for θ<60°

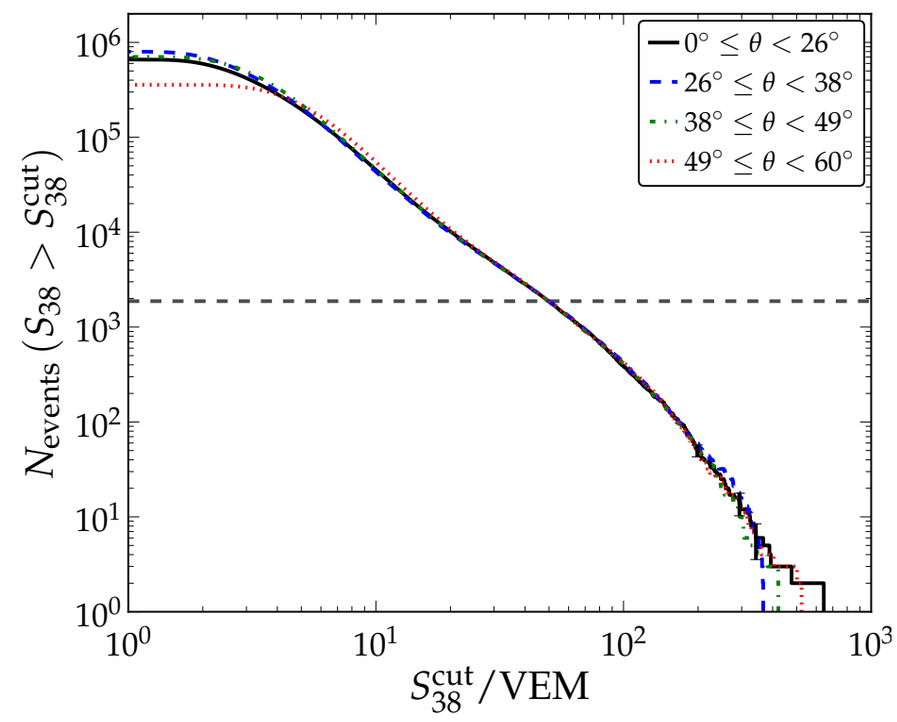
$$S(r) = S(r_{\rm opt}) f(r)$$

1500 m array: $S(r_{\rm opt}) = S1000$
750 m array: $S(r_{\rm opt}) = S450$

θ-dependence (attenuation in atmosphere) corrected for using CIC





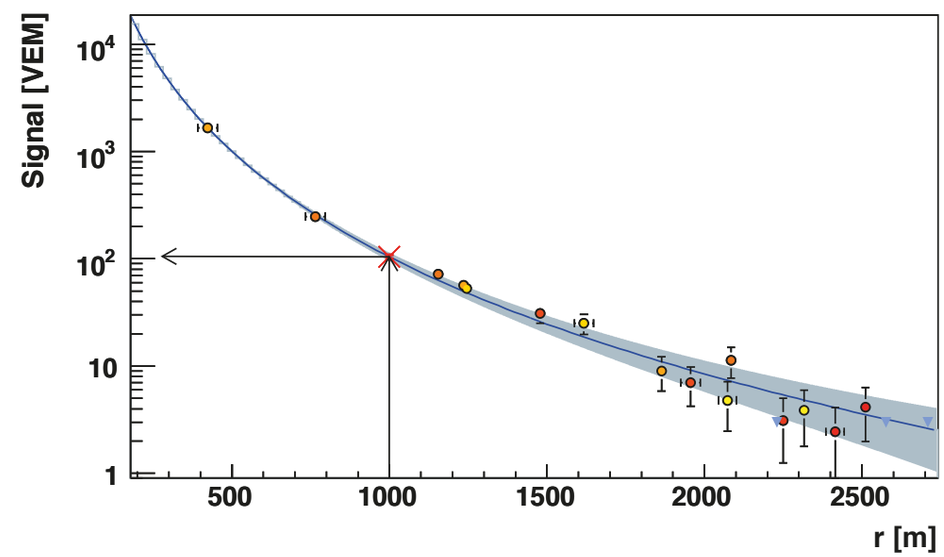


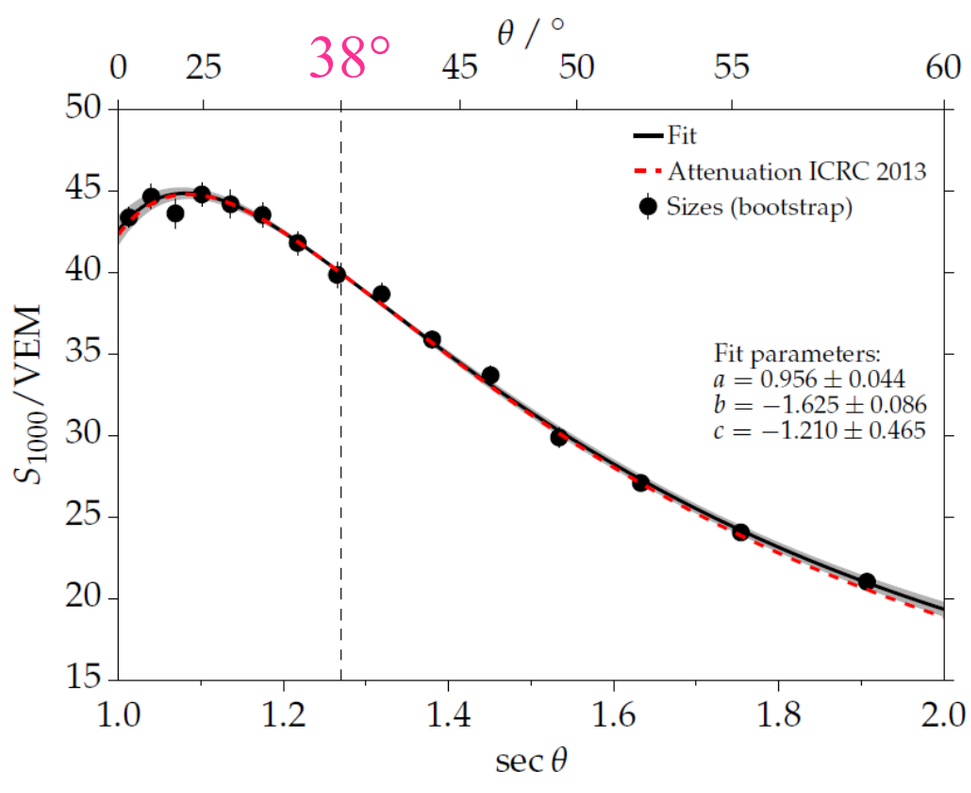
SD energy estimator for θ<60°

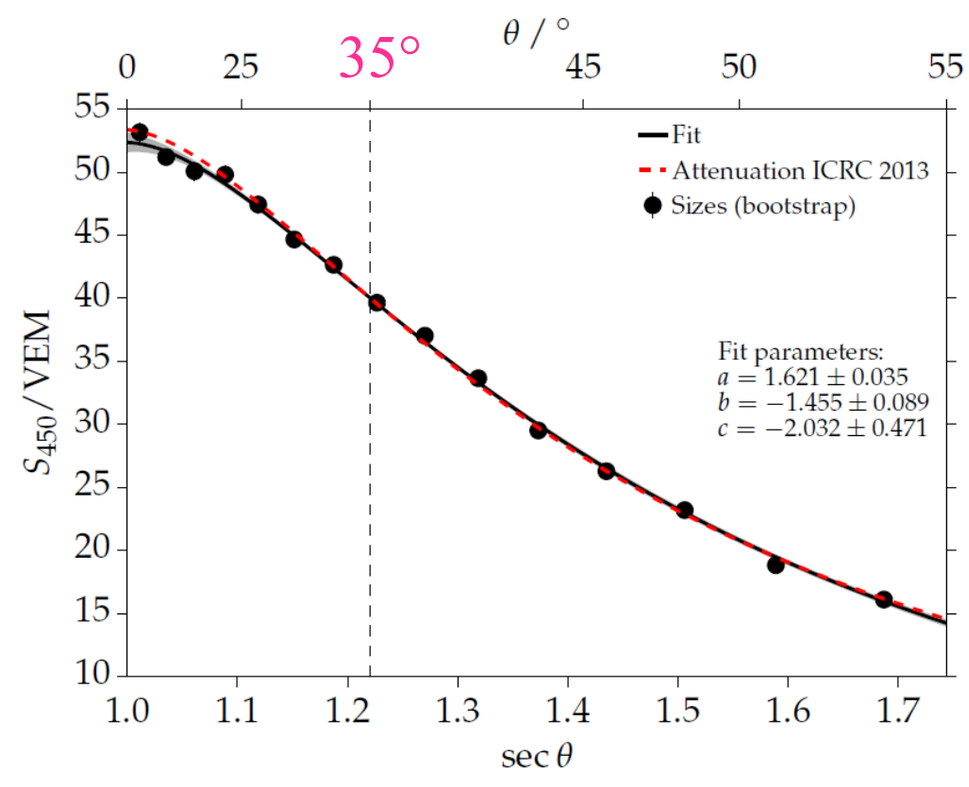
$$S(r) = S(r_{\rm opt}) f(r)$$

1500 m array: $S(r_{\rm opt}) = S1000$
750 m array: $S(r_{\rm opt}) = S450$

θ-dependence (attenuation in atmosphere) corrected for using CIC





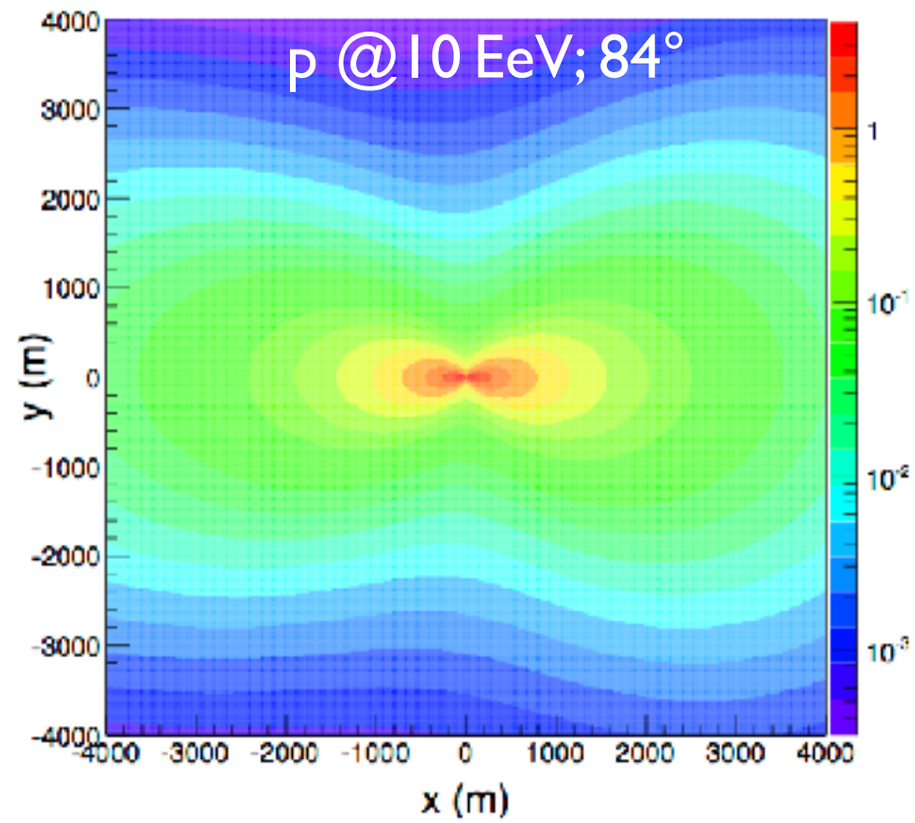


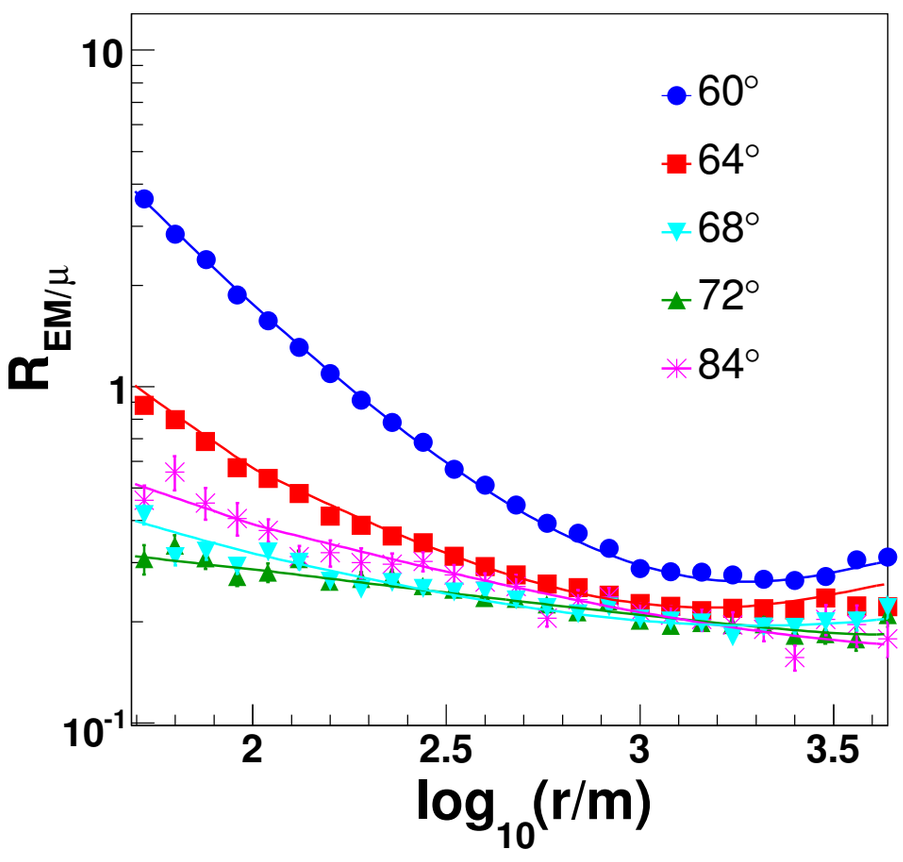
SD energy estimator for θ>60°

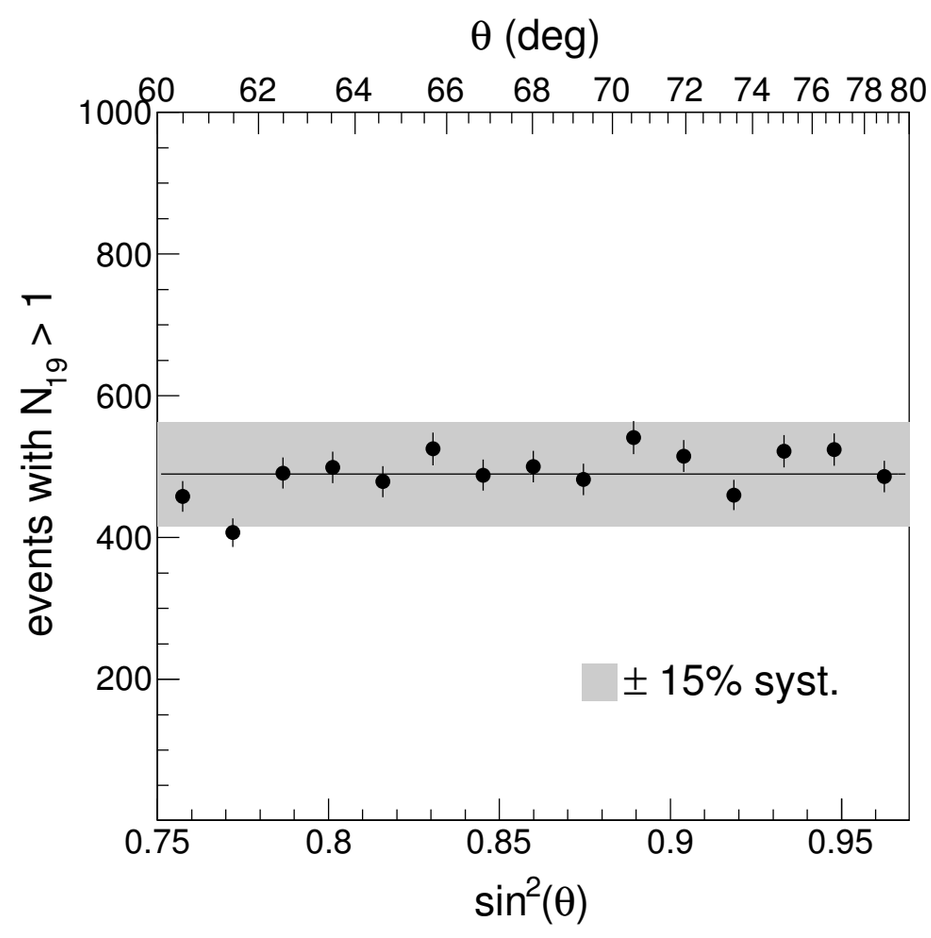
- Muonic component dominates
  - (≈ 20% residual e.m. component)
- Energy estimator N_{19}:

$$N_{19} = \rho_\mu / \rho_{\mu,\,19}(x, y, \theta, \phi)$$

- zenith angle independent

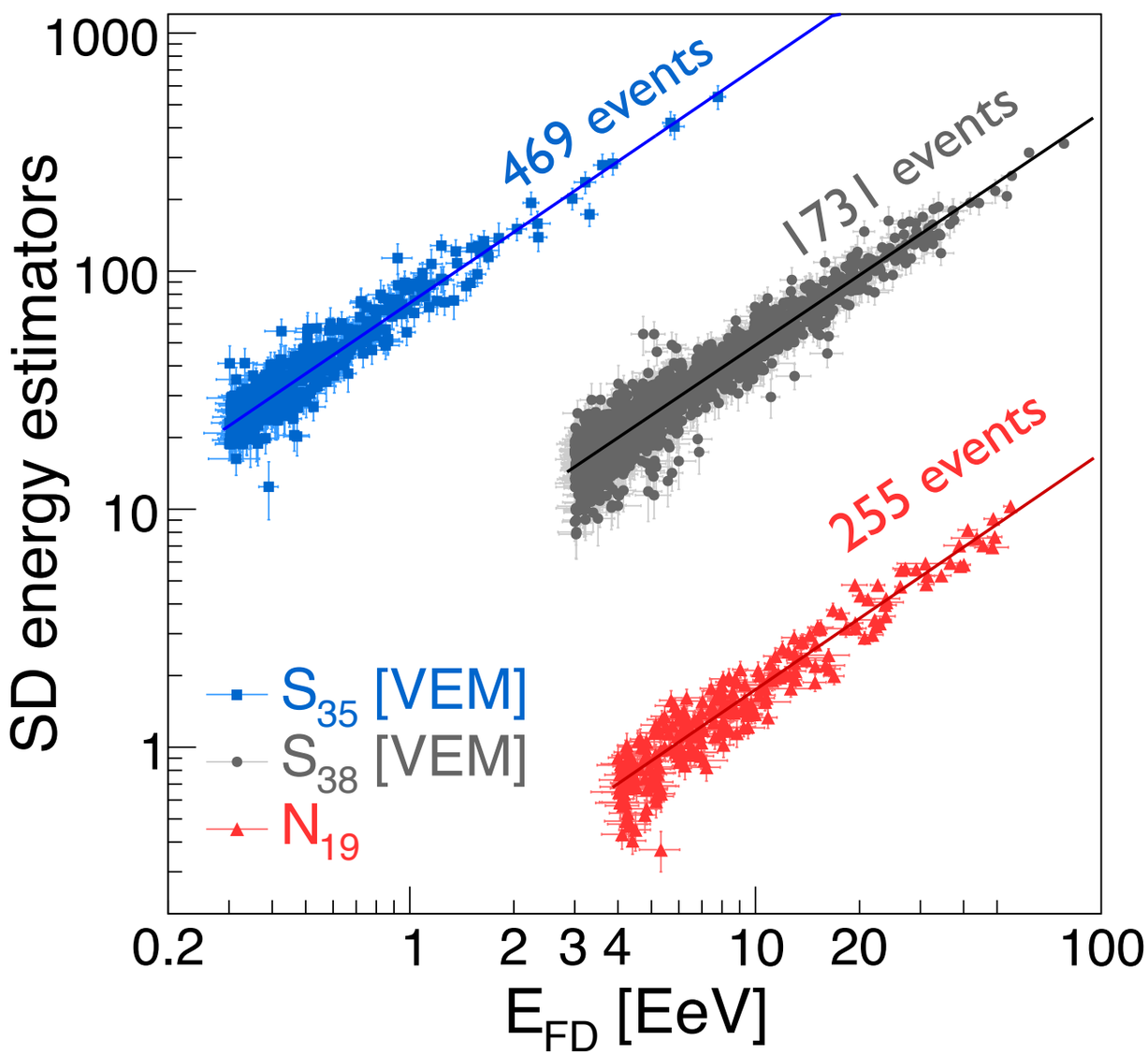






SD data: energy calibration

$$E_{\mathrm{FD}} = A\, S^{B}$$



Energy resolution

- 750m θ<55°: 13 ± 1% @ 0.3 EeV
- 1500m θ<60°: 15.3 ± 0.4% @ 3 EeV
- 1500m 60°θ<80°: 19 ± 1% @ 4 EeV

Data driven calibration
Air shower simulations are avoided

FD CORRELATED UNCERTAINTIES

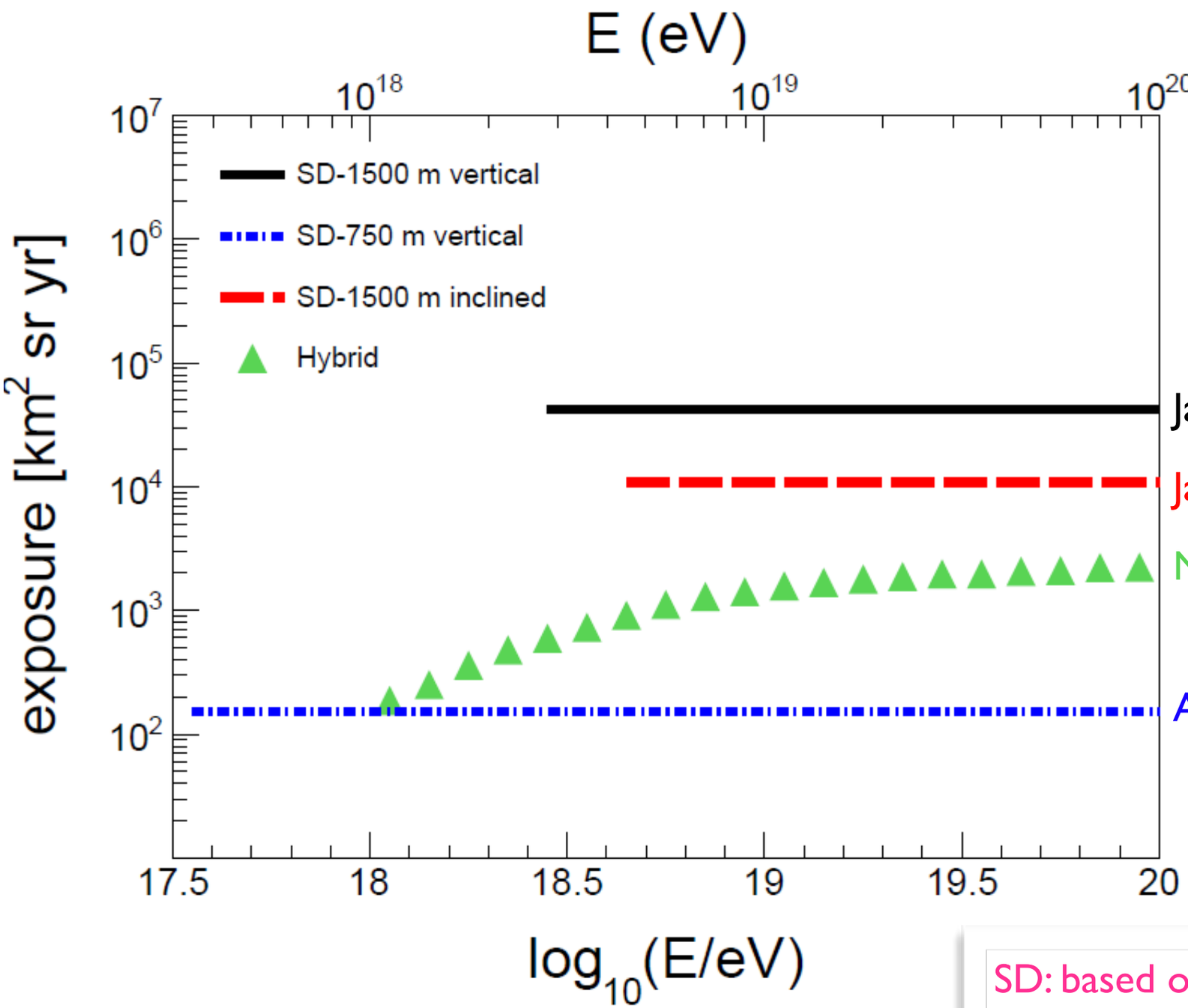
Total uncertainty: 14%
≈ energy independent

Absolute fluorescence yield	3,4 %
Fluores. spectrum and quenching param.	1,1 %
Sub total (Fluorescence Yield)	**3,6 %**
Aerosol optical depth	3 % — 6 %
Aerosol phase function	1 %
Wavelength dependence of aerosol scattering	0,5 %
Atmospheric density profile	1 %
Sub total (Atmosphere)	**3,4 % — 6,2 %**
Absolute FD calibration	9 %
Nightly relative calibration	2 %
Optical efficiency	3,5 %
Sub total (FD calibration)	**9,9 %**
Folding with point spread function	5 %
Multiple scattering model	1 %
Simulation bias	2 %
Constraints in the Gaisser-Hillas fit	**1 % — 3,5 %**
Sub total (FD profile rec.)	**5,6 % — 6,5 %**
Invisible energy	**1,5 % — 3 %**
Statistical error of the SD calib. fit	**0,7 % — 1,8%**
Stability of the energy scale	**5 %**
TOTAL	**14 %**

Largest contribution from FD calibration

1500 m array $\theta < 60°$

Exposure for flux measurements



Exposure in [km^2 sr yr]

Jan 2004 - Dec 2014: 42500

Jan 2004 - Dec 2013: 10900

Nov 2005 - Dec 2013: 1500 @ 10 EeV

Aug 2008 - Dec 2014: 150

SD: based on geometrical calculation

Hybrid: based on time-dependent MC simulations

Four measurements of the cosmic-ray flux

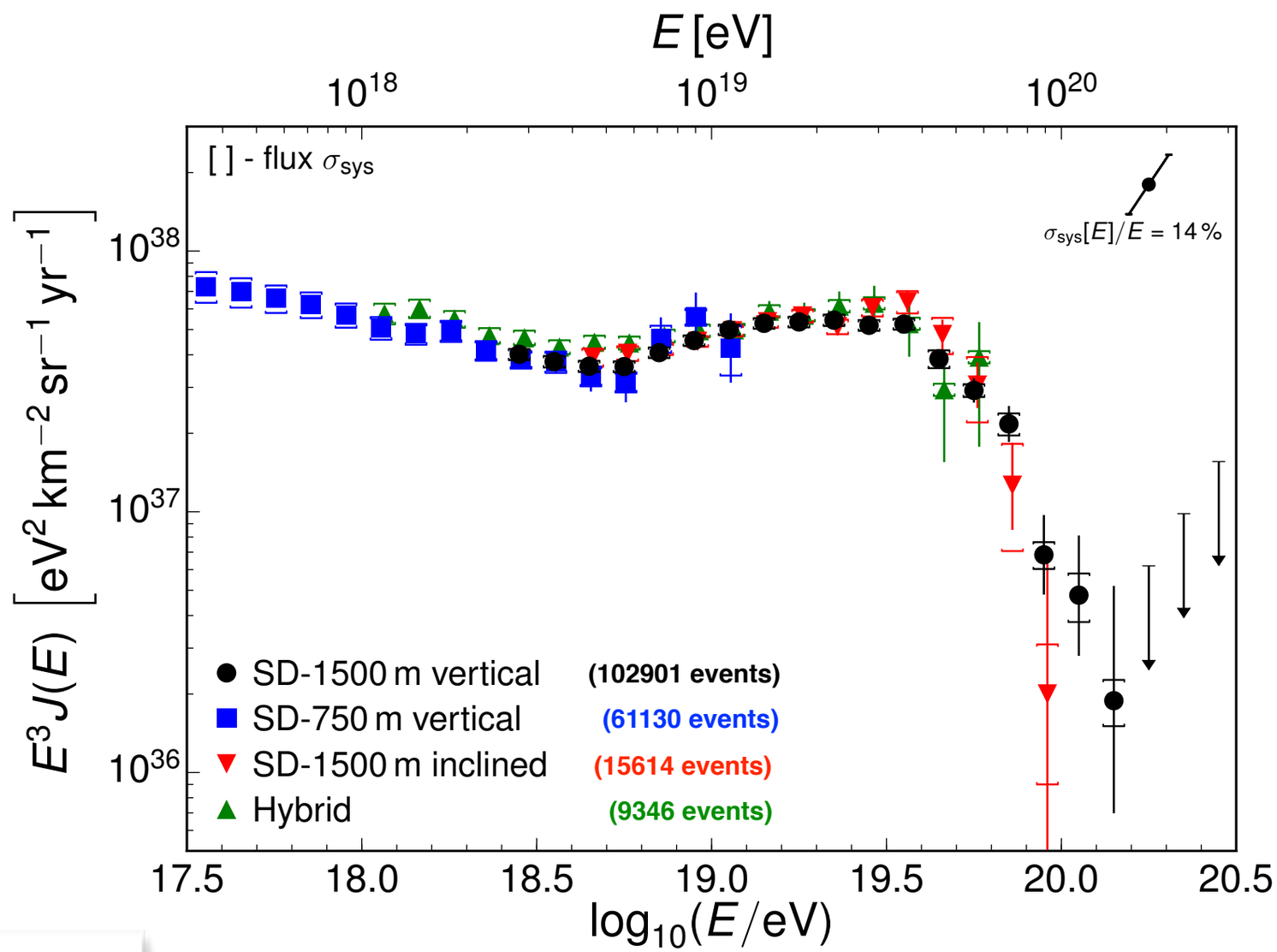
Systematic uncertainty on the flux

1500 m θ<60°: 5.8%

1500 m θ>60°: 5%

750 m: 14% (<7%) @ 0.3 (3) EeV

Hybrid: 10% (6%) @ 1 (10) EeV



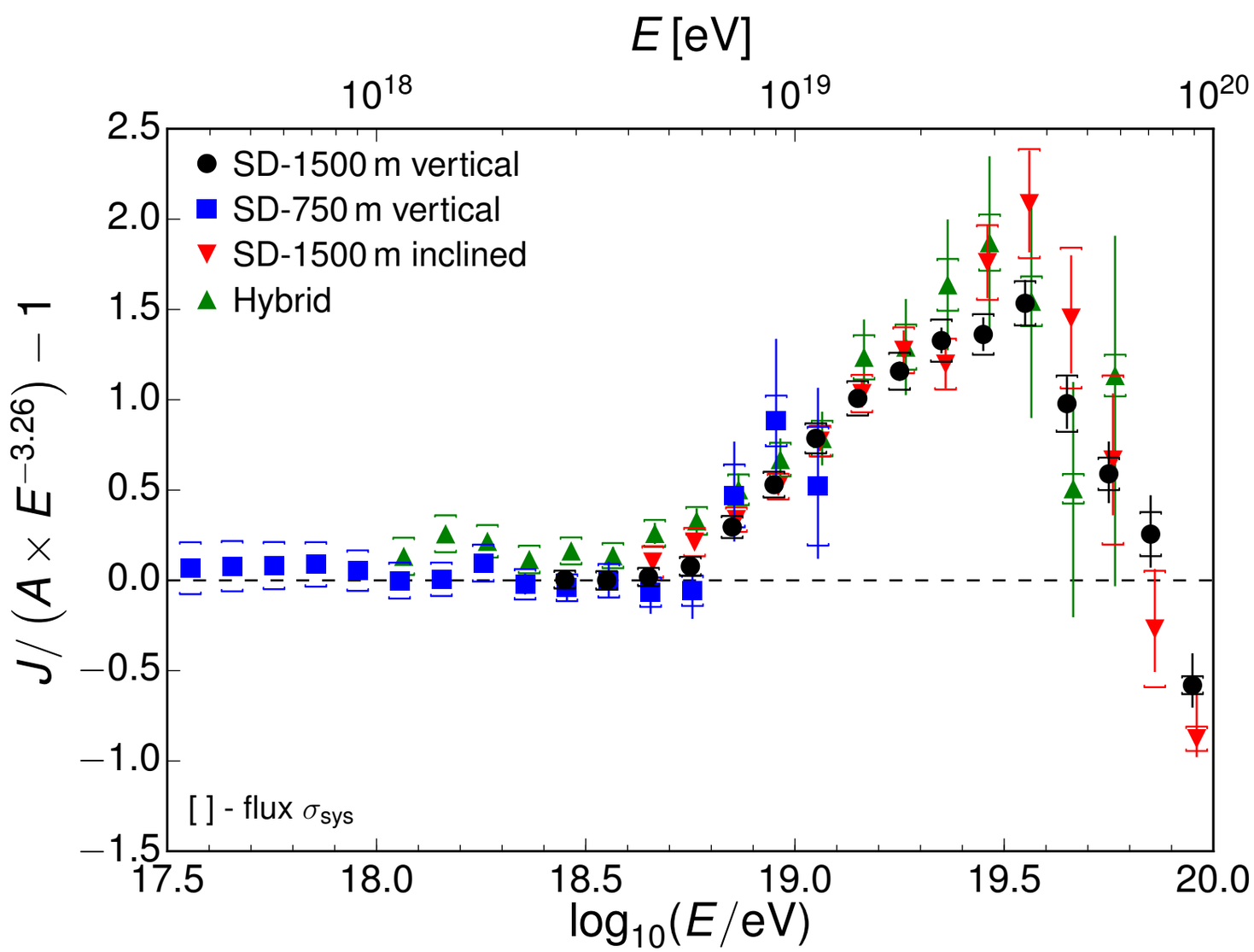
Deconvolution of SD spectra done to account for finite energy resolution (<15% SD, <3% Hybrid)

Fractional differences

Reference flux:

$$J(E) \propto E^{-3.26}$$

Positions of ankle and suppression consistent



Differences well within statistical and systematical uncertainties

⇒ Combined spectrum

Combined spectrum

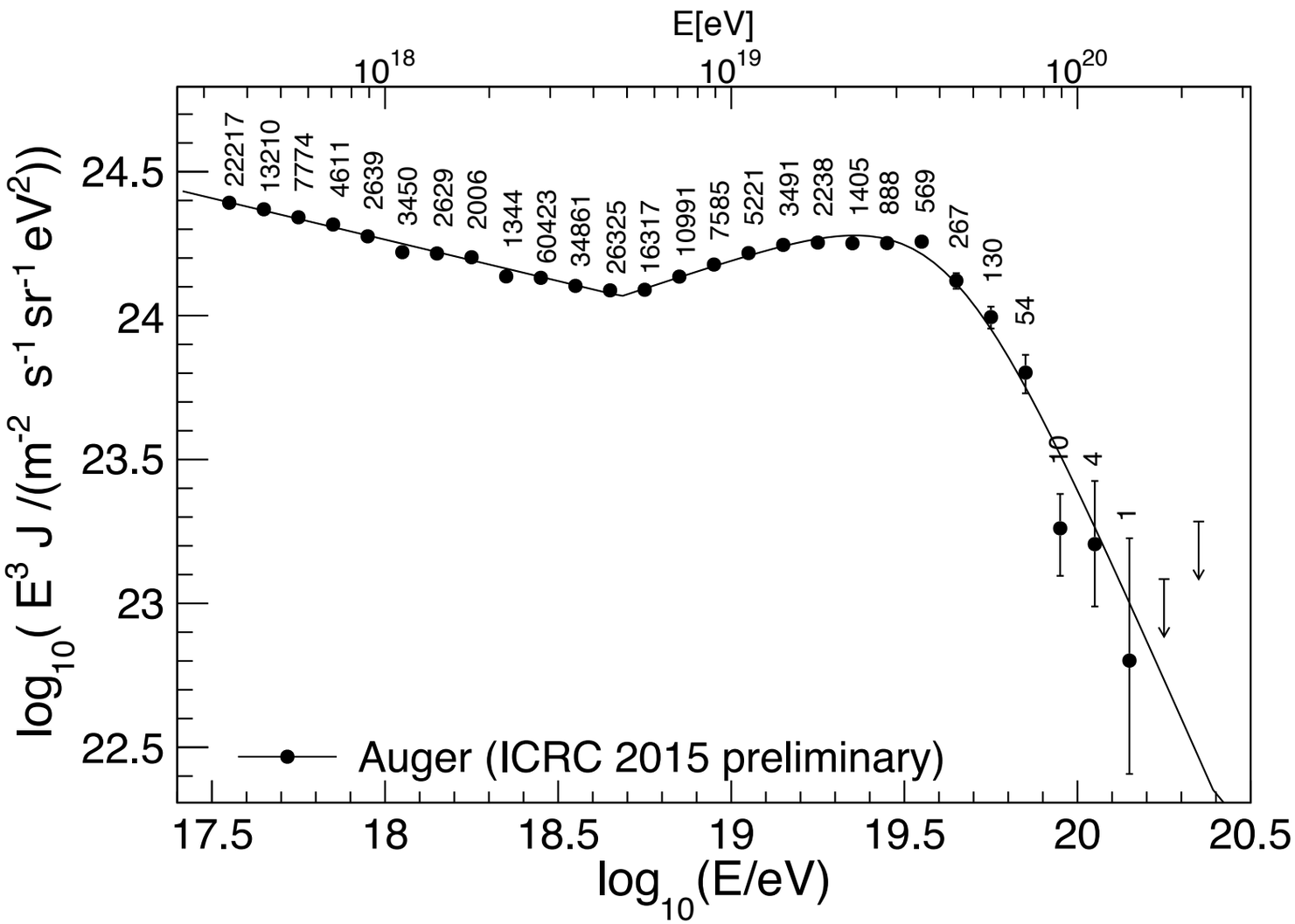
Flux normalizations:

1500 m vertical: 5.7%

1500 m inclined: -0.1%

750 m: 1.8%

Hybrid: -5.8%



Spectral features

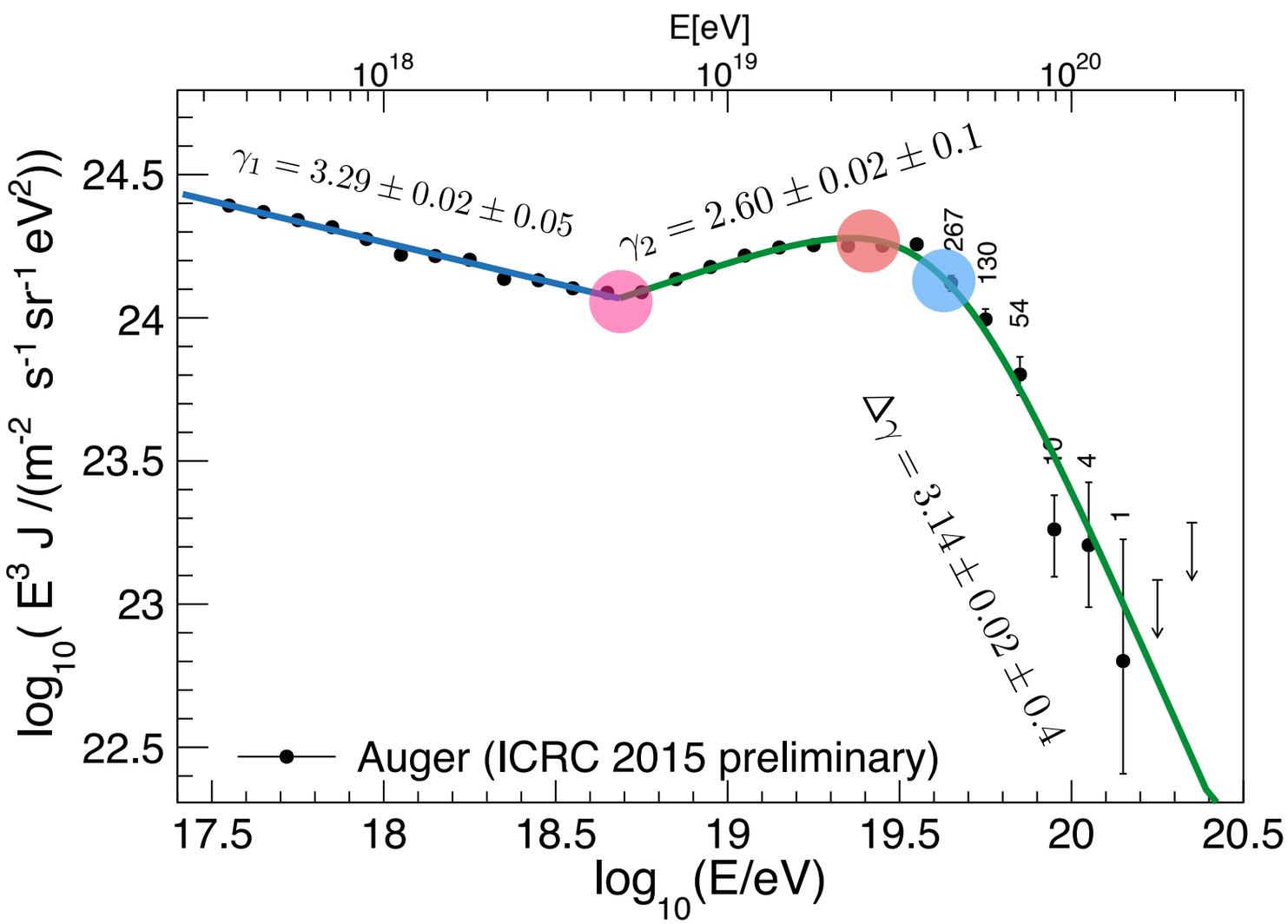
Flux model:

$E < E_{\text{ankle}}$:

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

$E > E_{\text{ankle}}$:

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



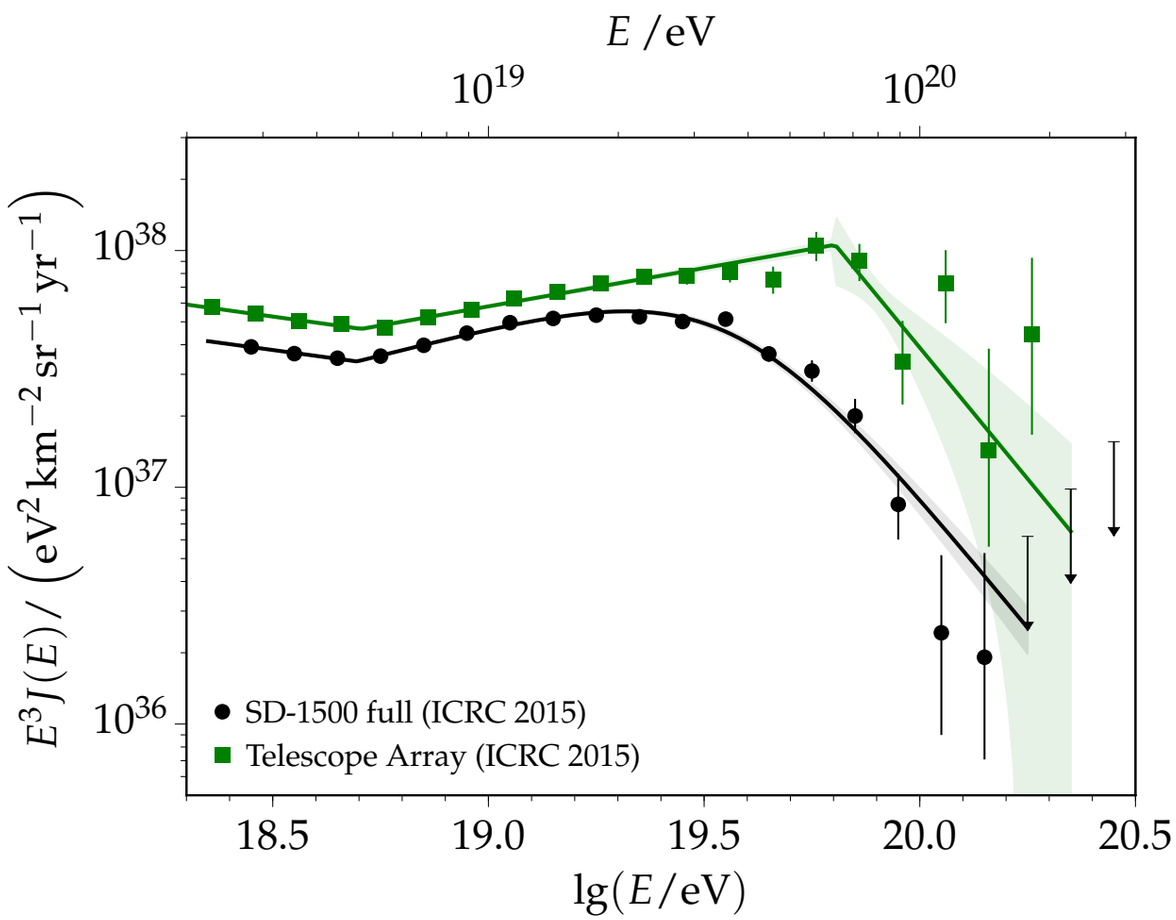
$$E_{\text{ankle}} = 4.8 \pm 0.1 \pm 0.8 \text{ EeV}$$

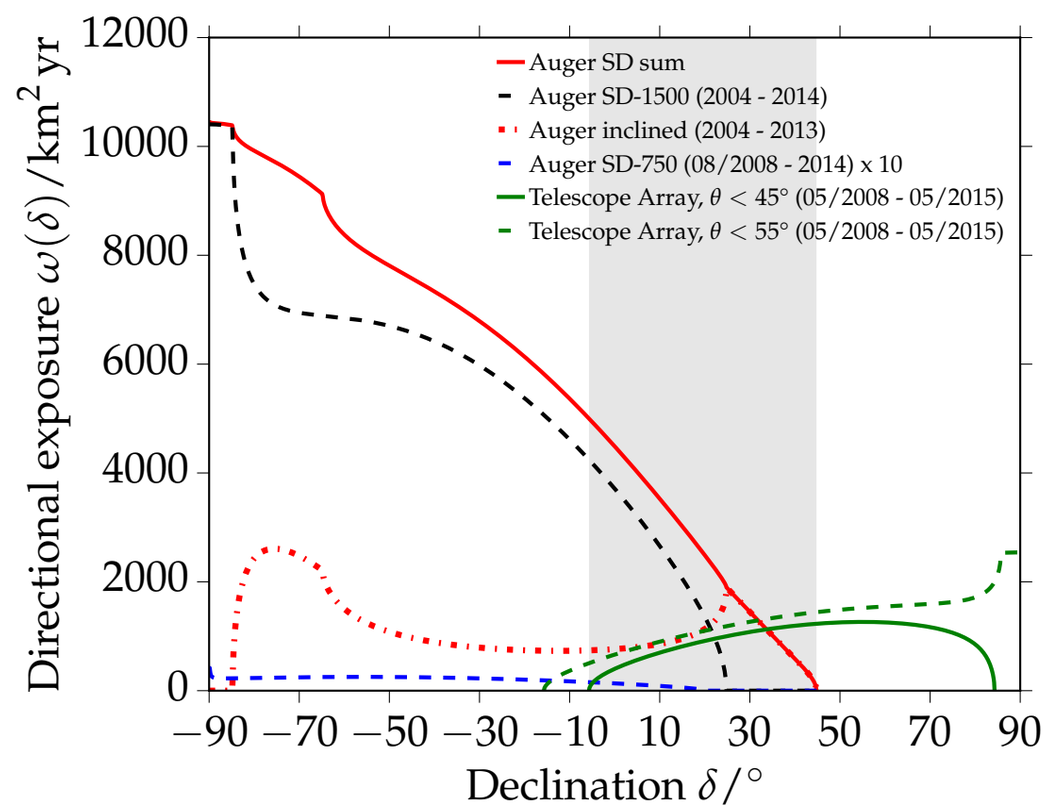
$$E_s = 42.1 \pm 1.7 \pm 7.6 \text{ EeV}$$

$$E_{1/2} = 24.7 \pm 0.1^{+8.2}_{-3.4} \text{ EeV}$$

$$I(E_{1/2}) = \frac{1}{2} \cdot I_0 \cdot \left(\frac{E_{1/2}}{E_s}\right)^{-\gamma_2+1}$$

Discrepancy between TA/Auger due to declination dependent flux?

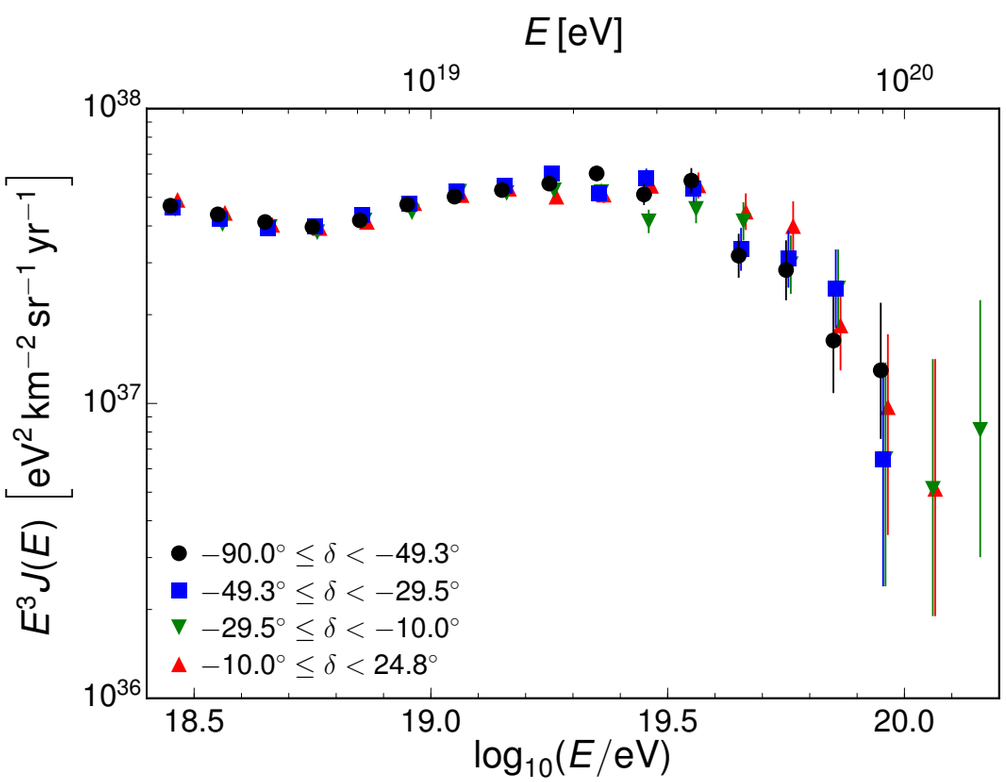




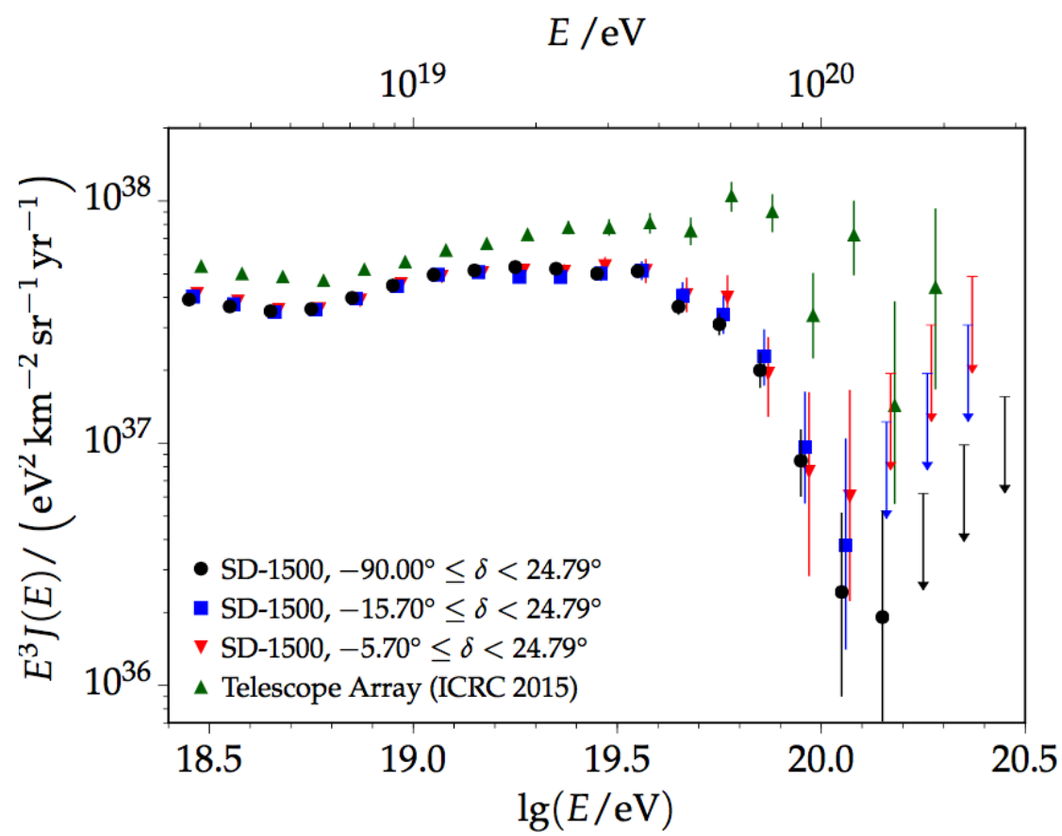
θ < 60° ⇒ Declination range: -90° to +25°

Discrepancy between TA/Auger due to declination dependent flux?

θ < 60°
⇒ Declination range: -90° to +25°



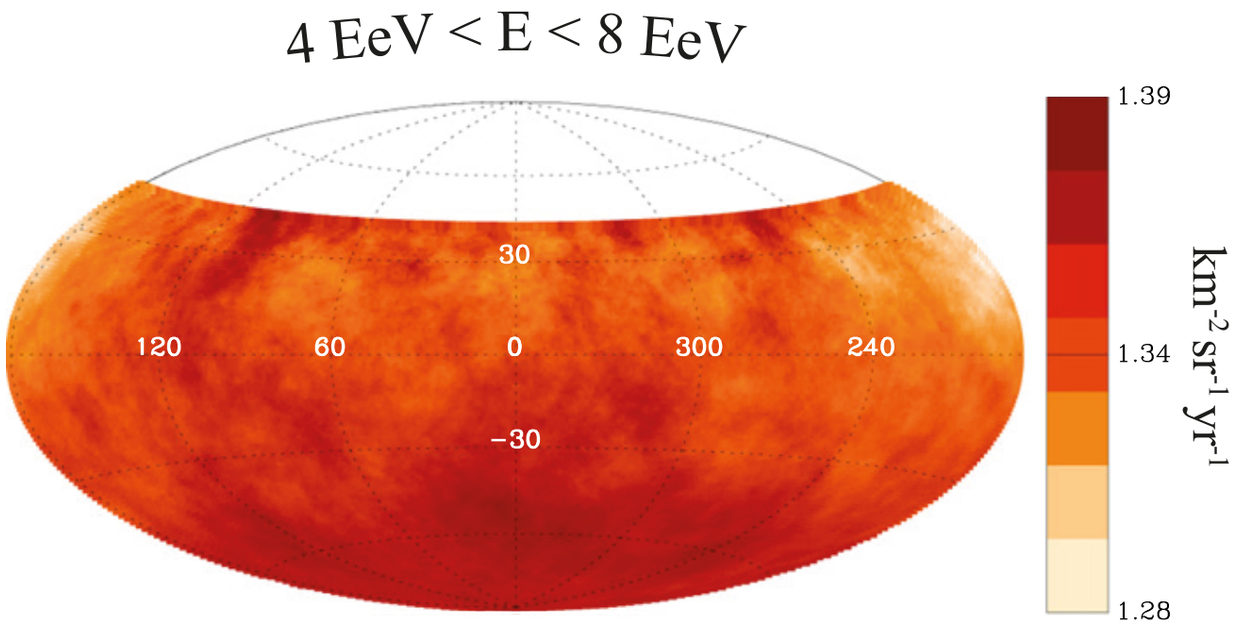
Experimental, atmospheric and geomagnetic effects accounted for

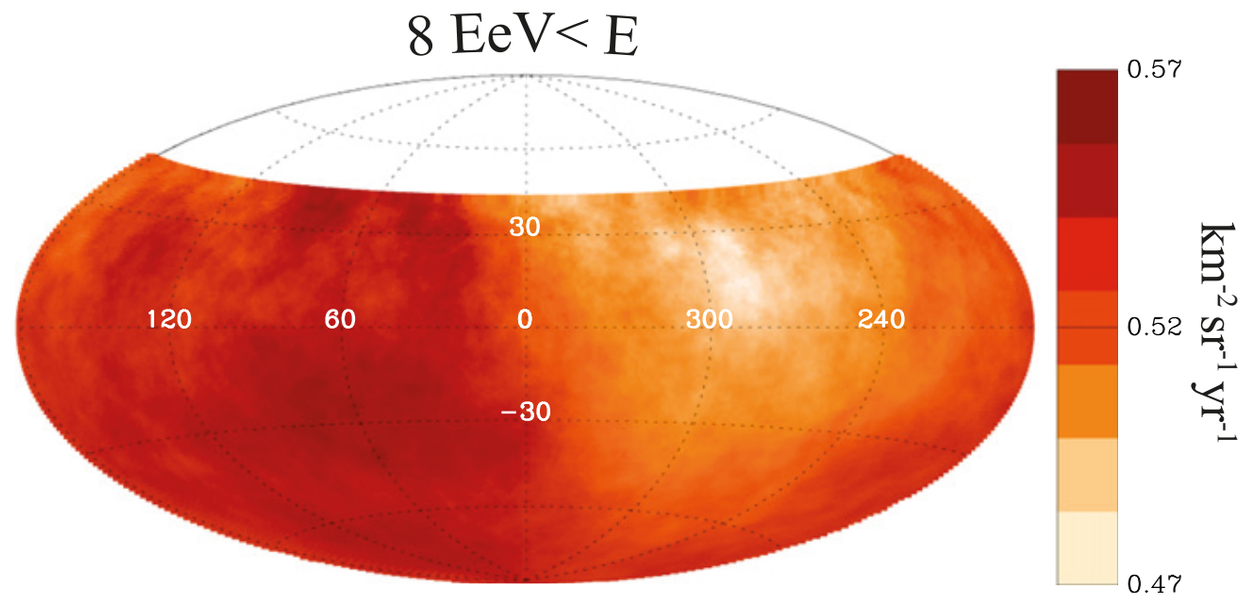


No indication of a declination-dependent flux
(differences between sub-spectra and all-sky flux < 5% below E_s and <13% above)

Auger-TA difference not explained
(still room, if TA flux is significantly larger above +25° than below)

Hint of a dipole anisotropy above 8 EeV



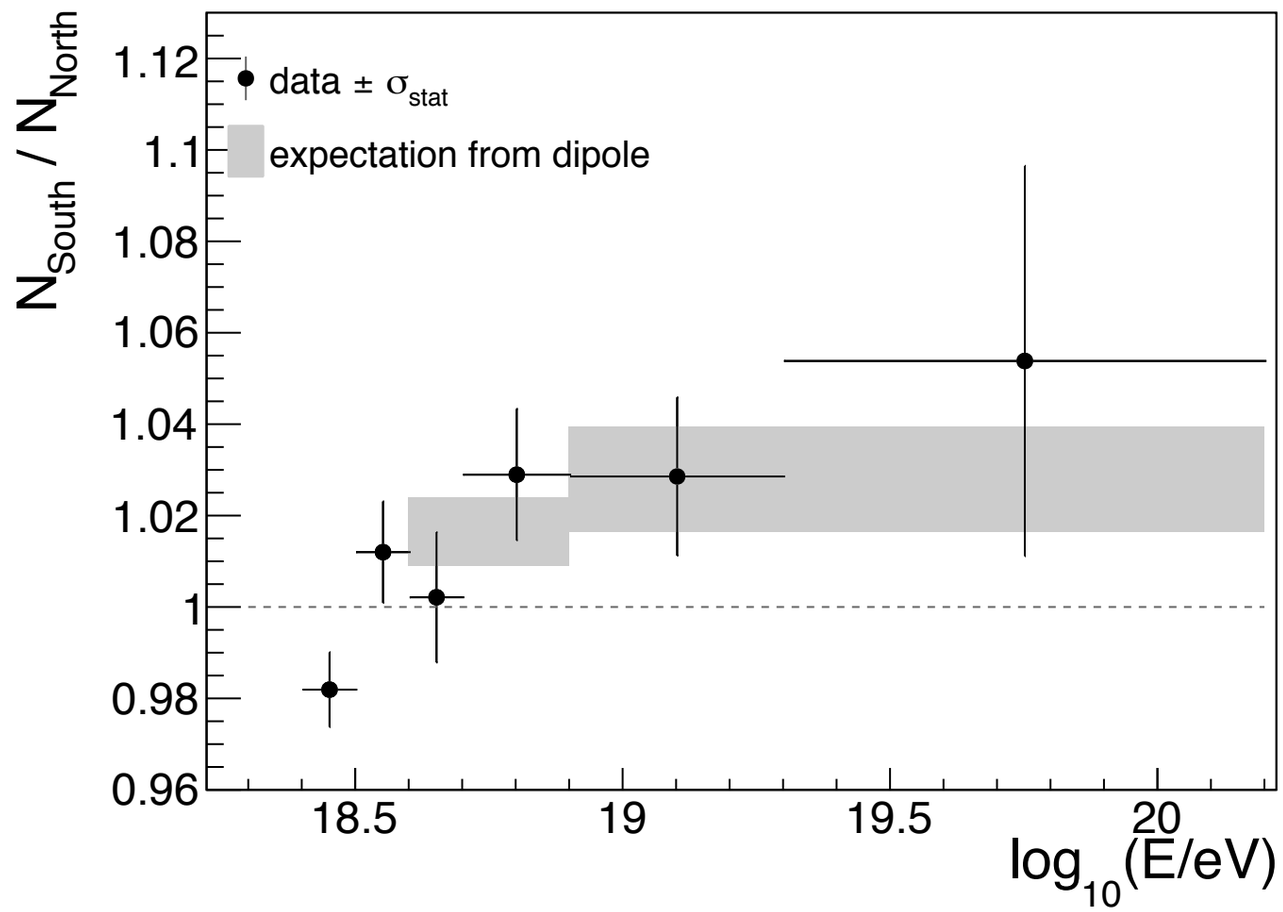


E [EeV]	d	d_d	a_d
4-8	(2.7±1.2)%	-81°±17°	15°±115°
>8	(7.3±1.5)%	-39°±13°	95°±13°

Amplitude in right ascension suggests a large-scale anisotropy with significance > 4σ

Declination dependence of the flux

Comparison with expectation from dipolar modulation measured obtained using data with θ < 80° (gray band)



Observed sky divided into 2 declination bands to compute:

$$\frac{N_{\mathrm{South}}}{N_{\mathrm{North}}} = \frac{N(\delta < -29.47^\circ)}{N(\delta > -29.47^\circ)}$$

Observation compatible with dipole expectation within uncertainties

Summary

- Four independent measurements using either SD and FD
- Using same energy scale derived from FD: Syst. uncertainty of 14%
- Combined spectrum above 3 x 10^{17} eV up to beyond 10^{20} eV using data collected over more than 10 years
- declination dependence of measured flux:
  - TA/Auger discrepancy: No significant indication of variation in 4 declination bands
  - Ratio N_{South}/N_{North} compatible with dipole anisotropy