Measurement of the cosmic ray spectrum with the Pierre Auger Observatory

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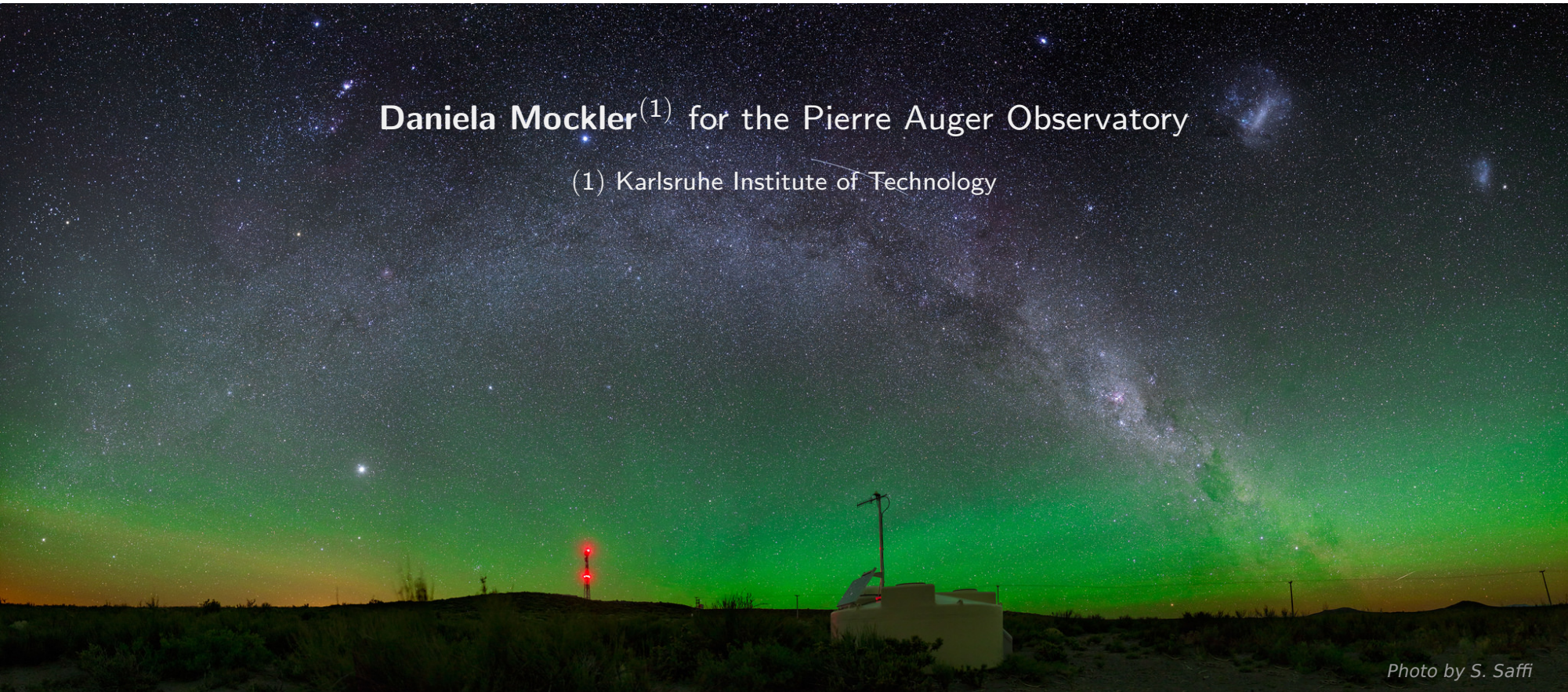


Photo by S. Saffi

The Pierre Auger Observatory

Fluorescence Detector

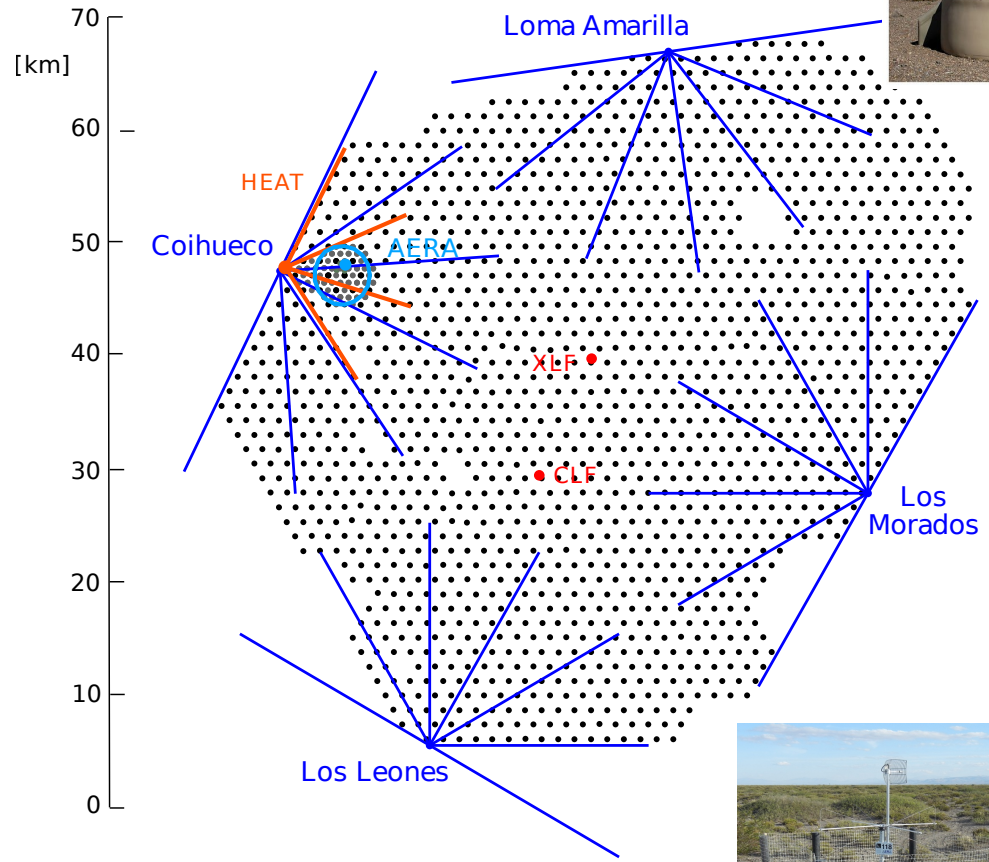
4 sites
$0 - 30^\circ$
$E > 10^{18}$ eV

HEAT
$30 - 60^\circ$
$E > 10^{17}$ eV

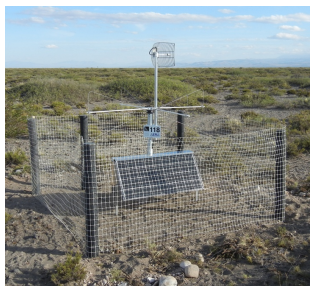
Surface Detector

Grid of 1500 m
3000 km^2
1600 stations
$E > 10^{18.5}$ eV

Grid of 750 m
27 km^2
71 stations
$E > 10^{17.5}$ eV



153 radio antennas



Hybrid detection of air showers

FD

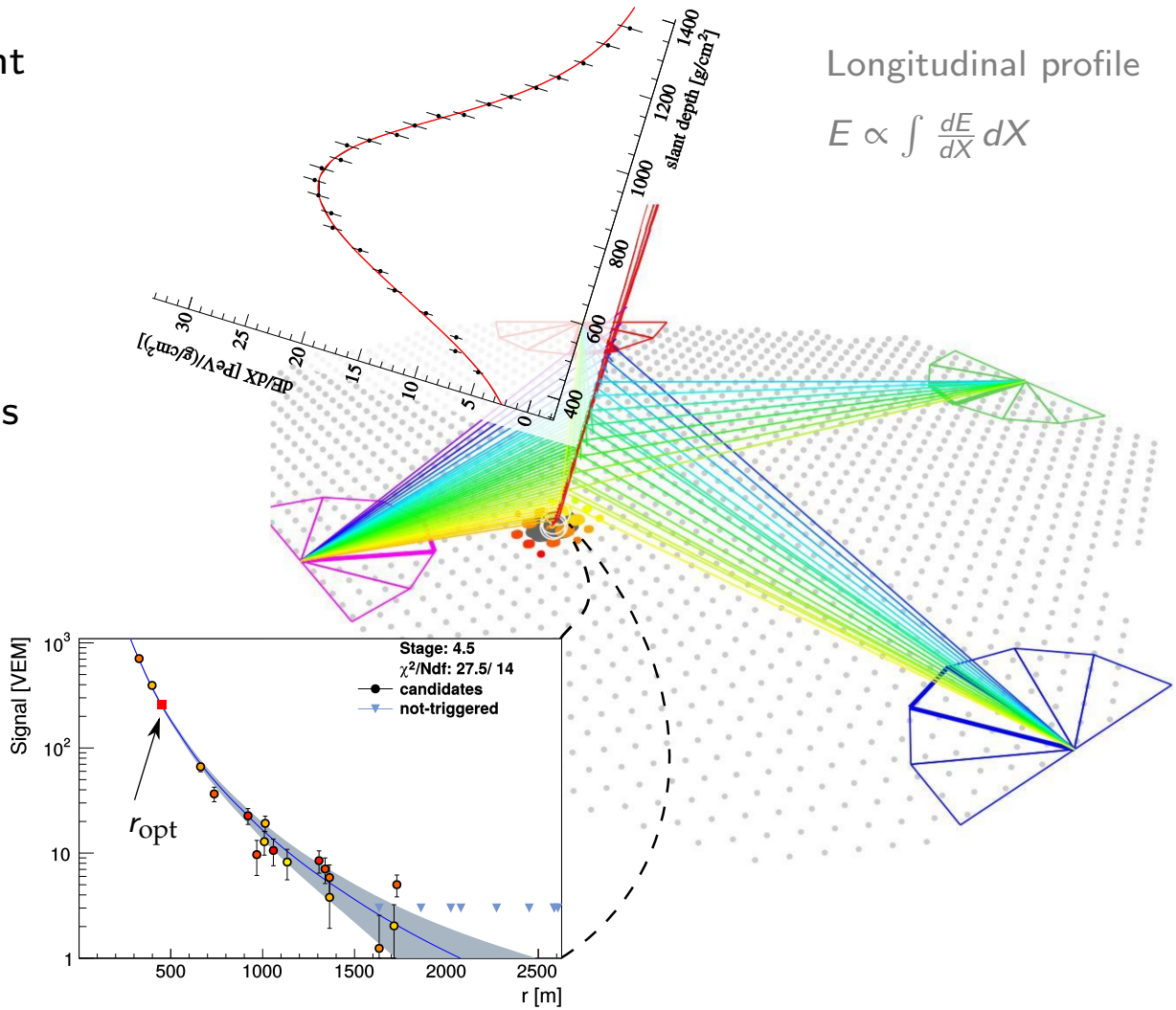
- calorimetric measurement of energy
- ∼15 % duty cycle

SD

- fit to station data
- optimal distance depends on grid spacing
- ∼100 % duty cycle

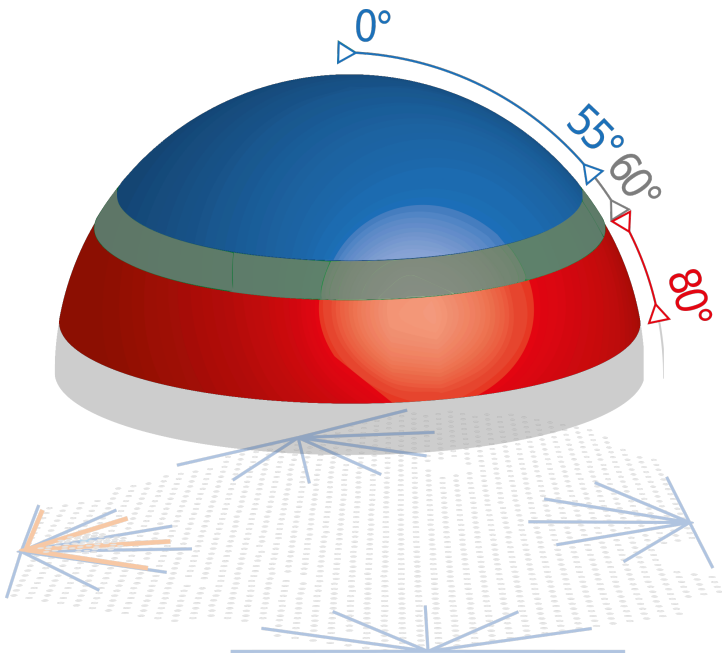
Hybrid

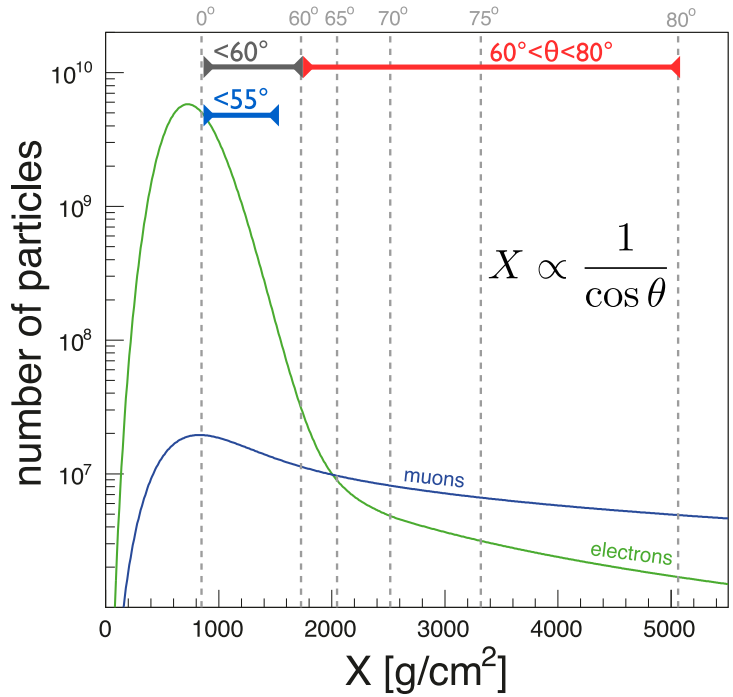
- FD + timing from SD station



Zenith range of SD derived spectra

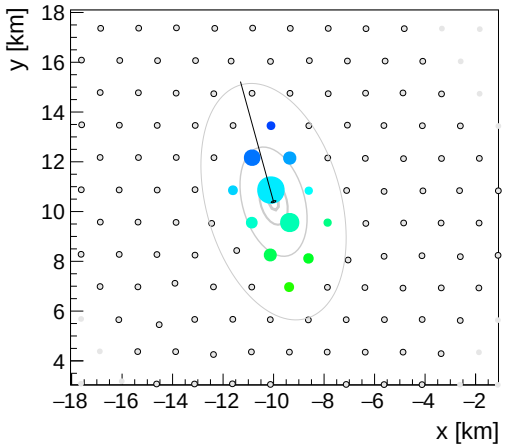
750 m: $0° < \theta < 55°$, **vertical**
1500 m: $0° < \theta < 60°$, **vertical**
1500 m: $60° < \theta < 80°$, **inclined**





Depth of Malargüe site: $870\,\mathrm{g\,cm^{-2}}$

Four different data sets

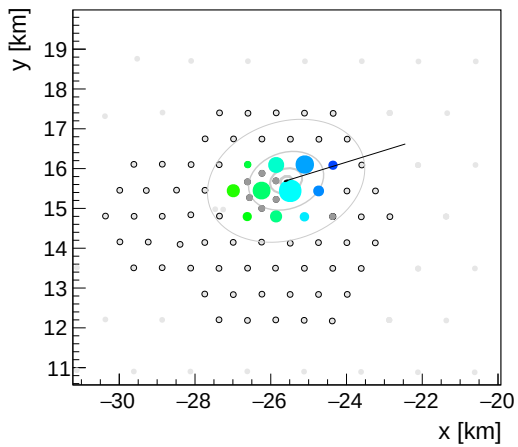


SD-1500 m vertical

events with $\theta < 60^\circ$

full efficient: $E > 3\,\mathrm{EeV}$

energy estimator: S_{38}

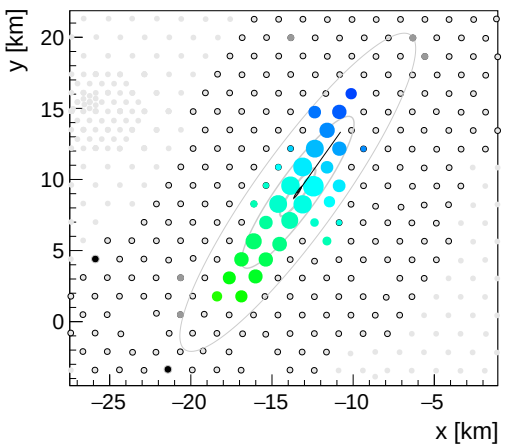


SD-750 m vertical

events with $\theta < 55^\circ$

full efficient: $E > 0.3\,\mathrm{EeV}$

energy estimator: S_{35}

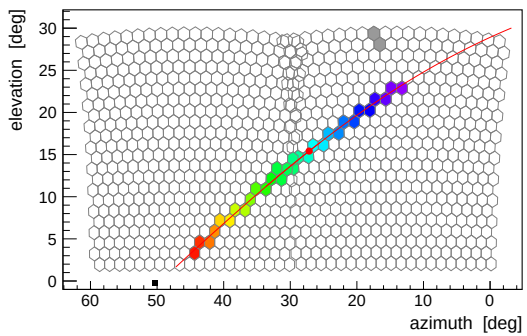


SD-1500 m inclined

events with $\theta > 60^\circ$

full efficient: $E > 4\,\mathrm{EeV}$

energy estimator: N_{19}



Hybrid

events with $\theta < 60^\circ$

full efficient: $E > 1\,\mathrm{EeV}$

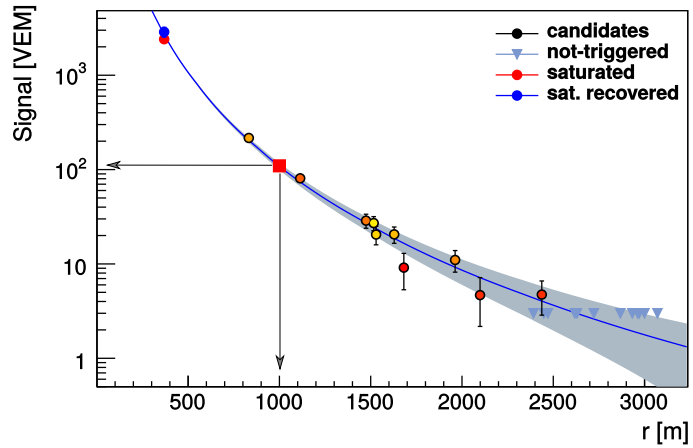
calorimetric energy

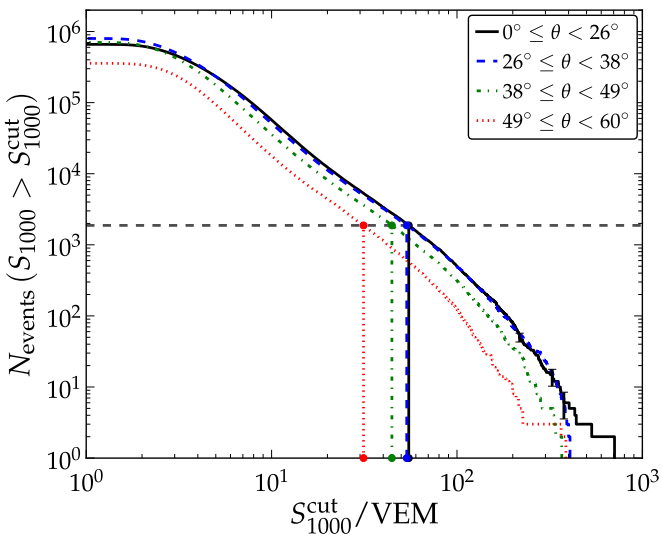
SD energy estimator for $\theta < 60^\circ$

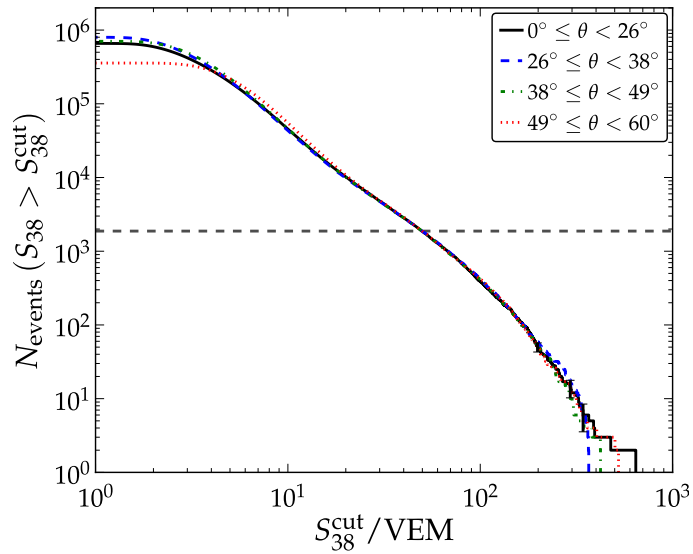
$$S(r) = S(r_{\rm opt})\, LDF(r)$$

$$S(r_{\rm opt}) = \begin{cases} S(450) & \text{for SD-750 m} \\ S(1000) & \text{for SD-1500 m} \end{cases}$$

But: θ-dependence due to attenuation in atmosphere





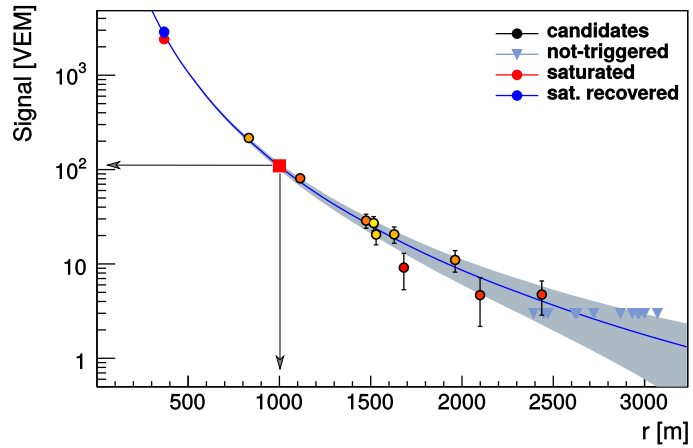


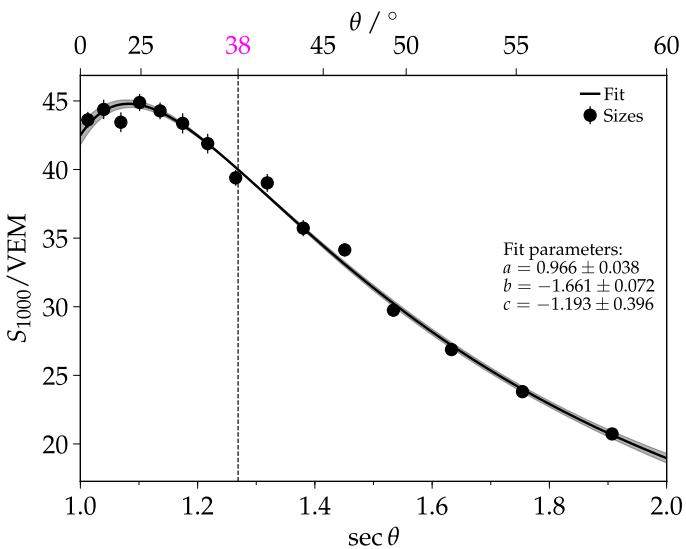
SD energy estimator for $\theta < 60^\circ$

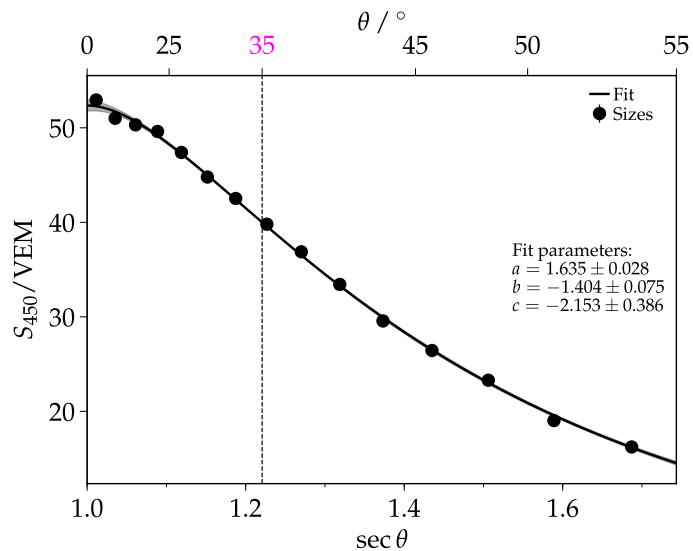
$$S(r) = S(r_{\text{opt}})\, LDF(r)$$

$$S(r_{\text{opt}}) = \begin{cases} S(450) & \text{for SD-750 m} \\ S(1000) & \text{for SD-1500 m} \end{cases}$$

But: θ-dependence due to attenuation in atmosphere

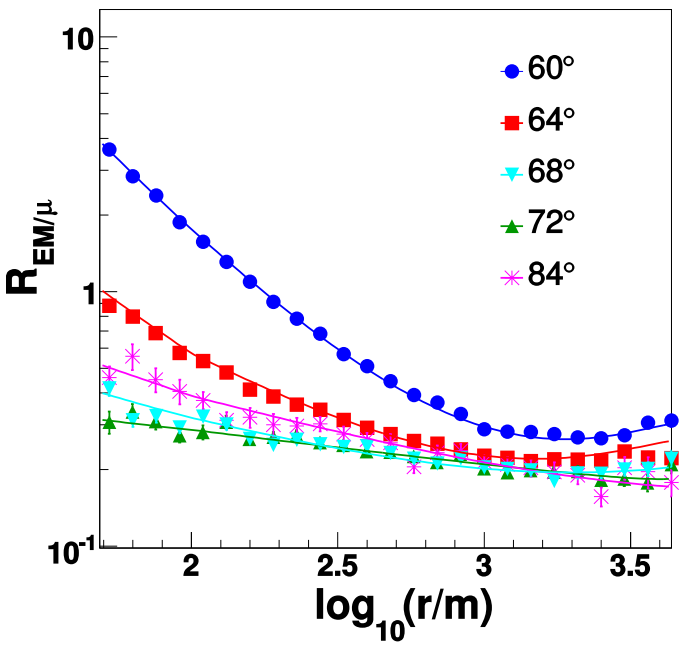


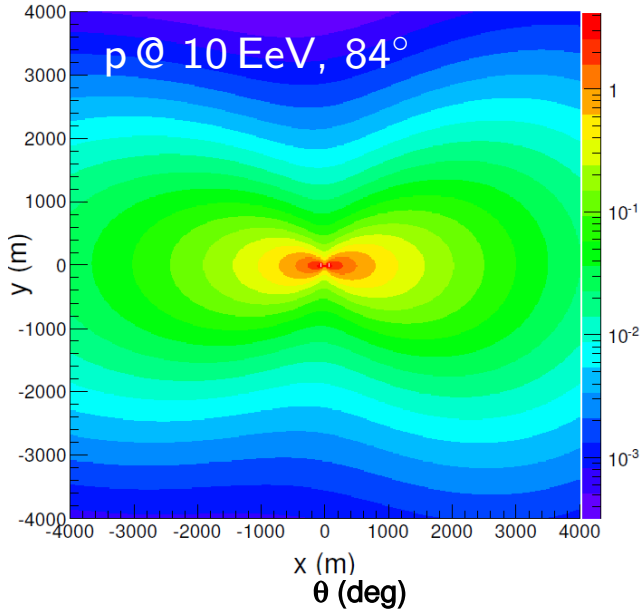


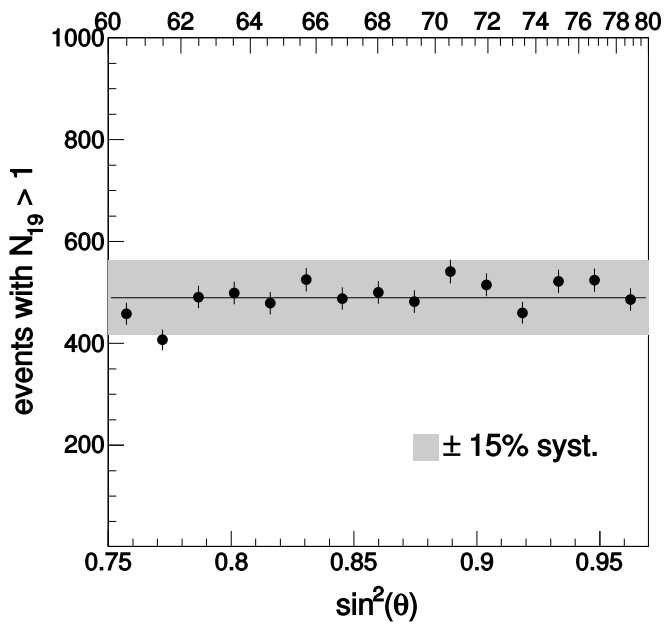


SD energy estimator for $\theta < 80°$

- Muonic component dominates
- Energy estimator N_{19}:
  $N_{19} = \rho_\mu / \rho_{\mu,19}(x, y, \theta, \phi)$
- Zenith angle independent







Reconstruction of the FD energy

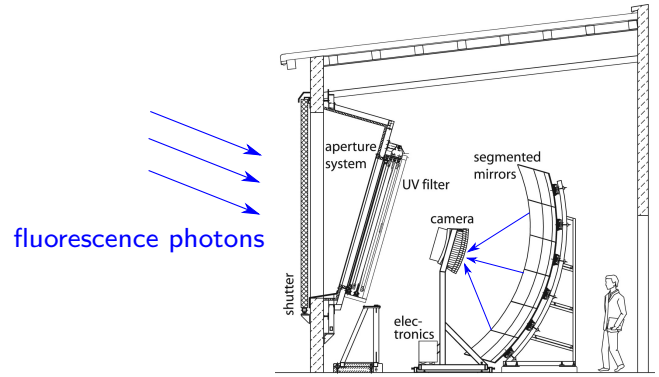
Measures the calorimetric shower energy:

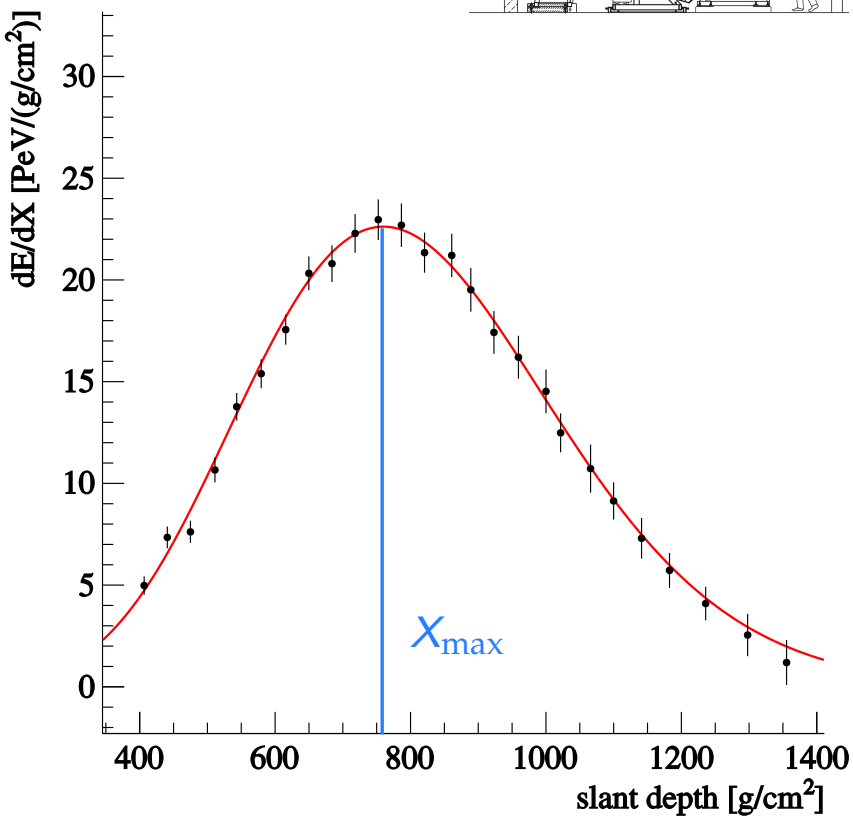
$$E_{\text{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\mathrm{d}X$$

Total energy:

$$E = E_{\text{cal}} + E_{\text{invisible}}$$

$\hookrightarrow$ neutrinos and high-energy muons





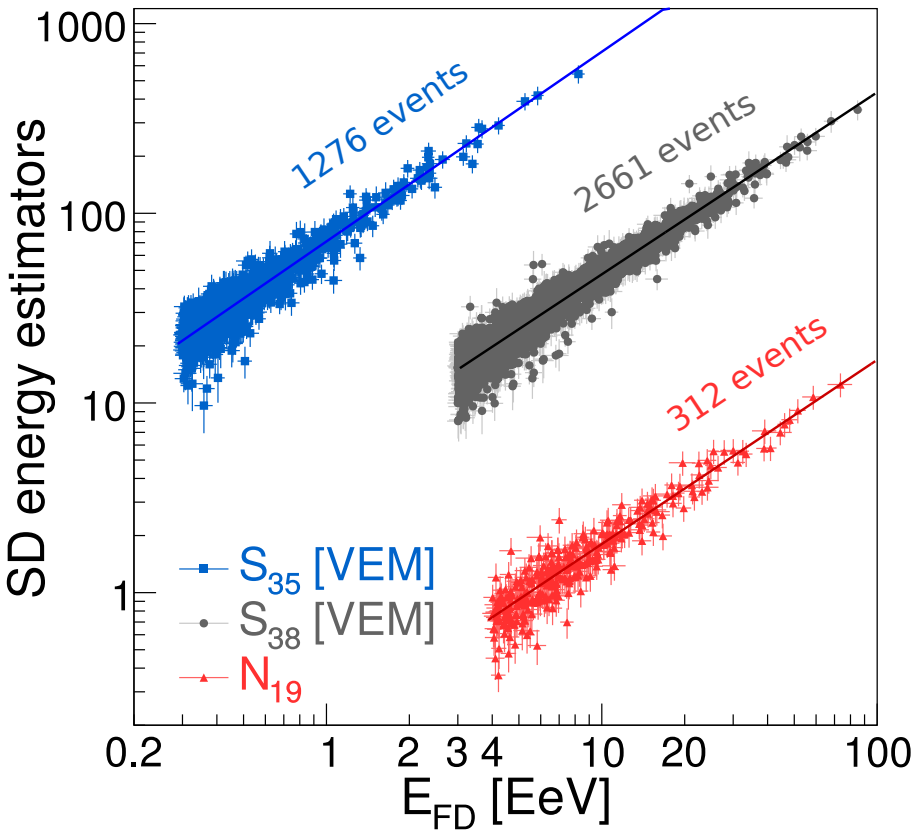
Reconstructed profile of the energy deposit in the atmosphere

Systematic uncertainty in FD energy: 14 %

- Fluorescence yield: 3.6 %
- Atmosphere: 3.4 % ÷ 6.2 %
- FD calibration: 9.9 %
- FD profile rec.: 6.5 % ÷ 5.6 %
- Invisible energy: 3 % ÷ 1.5 %
- Other contrib.: ≈ 5 %

Energy calibration

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

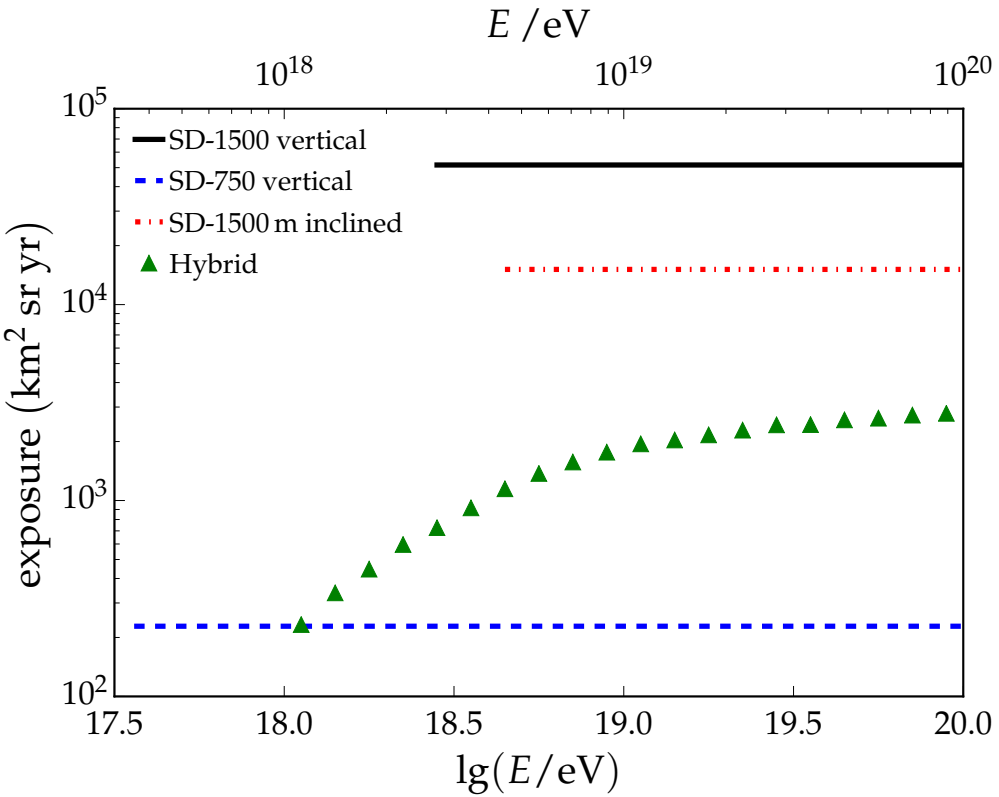


Energy resolution

- 750 m $<$ 55° : $13 \pm 1\,\%$ @ 0.3 EeV
- 1500 m $<$ 60° : $15 \pm 0.4\,\%$ @ 3 EeV
- 1500 m $>$ 60° : $19 \pm 1\,\%$ @ 4 EeV

Data driven calibration
Air shower simulations are avoided

Exposure for flux measurements



Exposure in $[\mathrm{km}^2\,\mathrm{sr}\,\mathrm{yr}]$

01/2004 - 12/2016: 51588

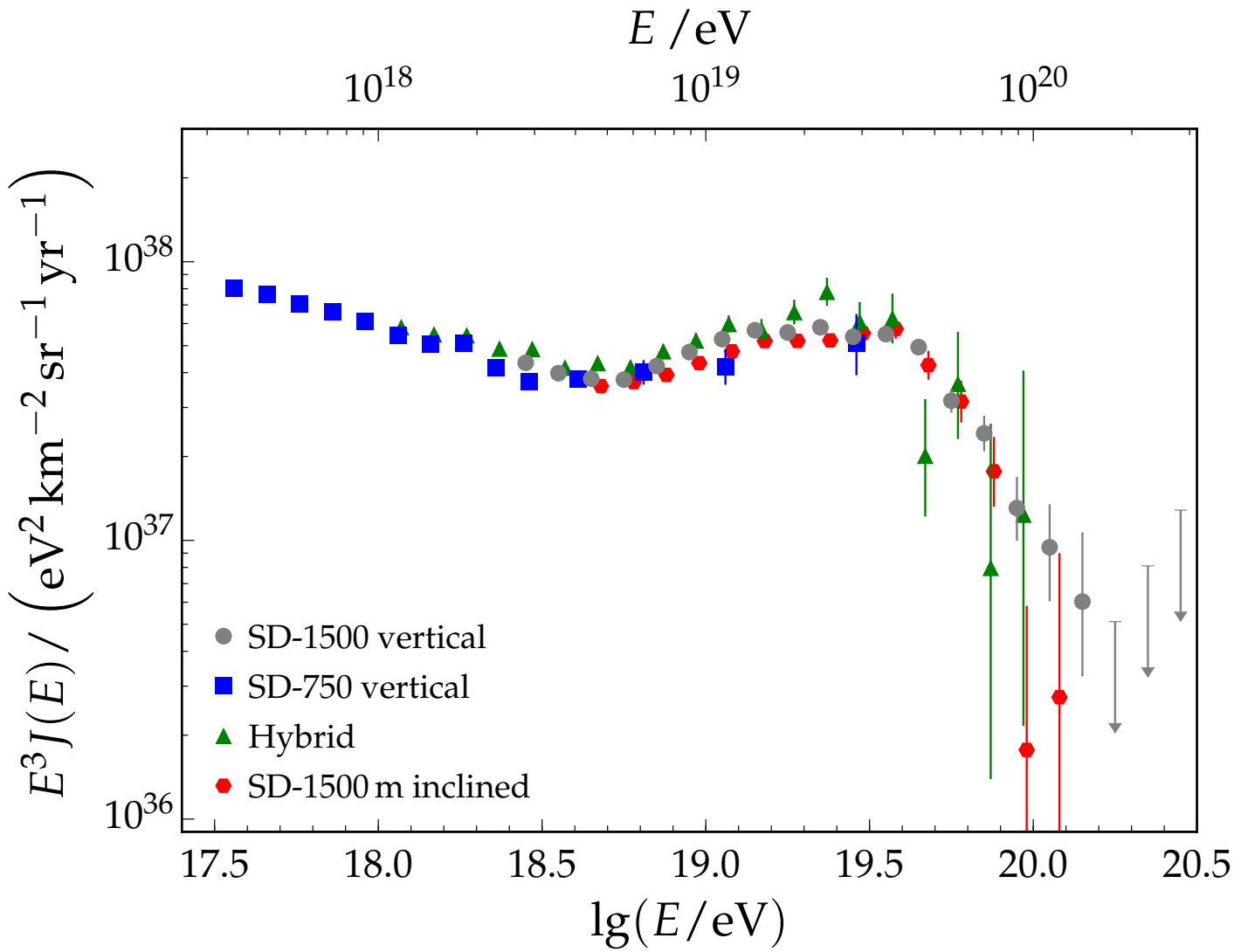
01/2004 - 12/2016: 15121

01/2007 - 12/2015: 1946 @ 10^{19} eV

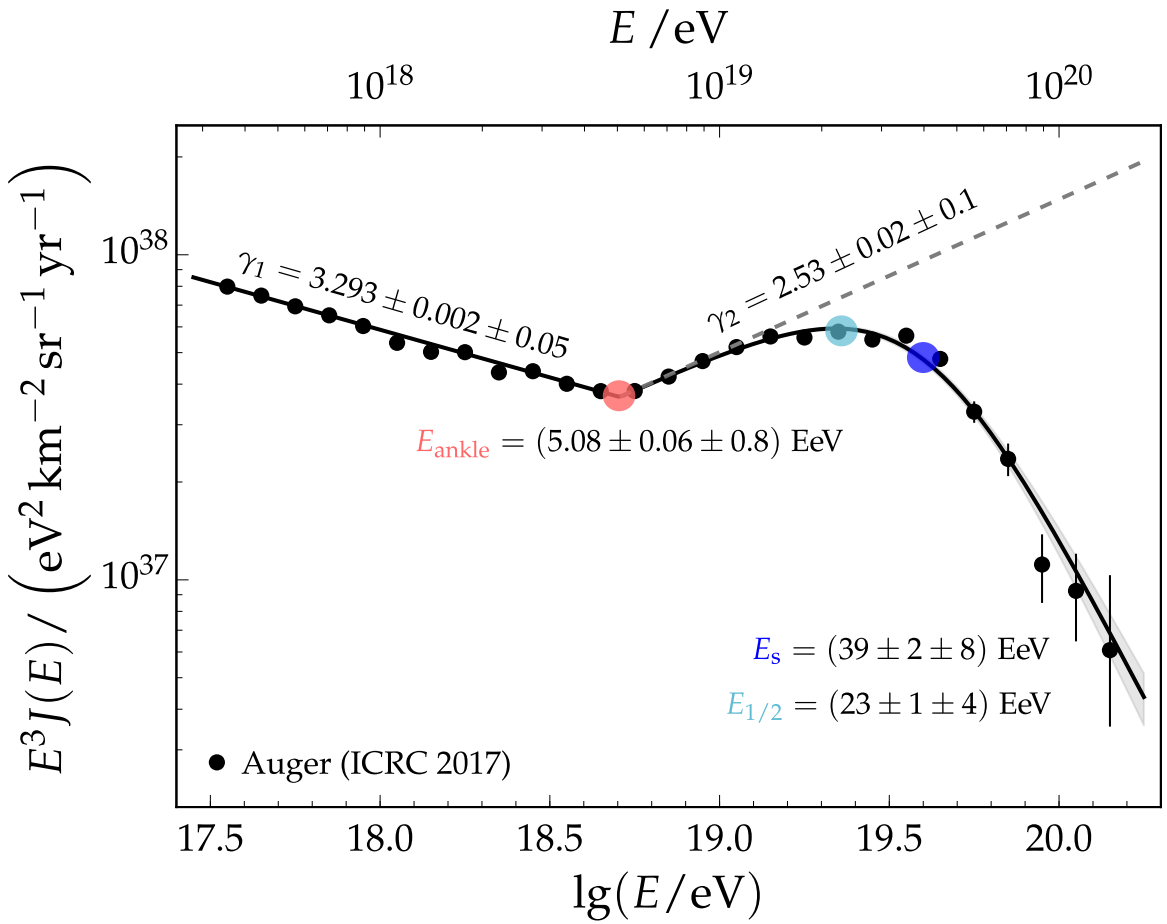
08/2008 - 12/2016: 228

SD: based on geometrical calculation
Hybrid: based on time-dependent MC simulations

The four measurements of the cosmic-ray flux



Spectral features



Flux models

- $E < E_{\mathrm{ankle}} : J(E) \propto E^{-\gamma_1}$
- $E > E_{\mathrm{ankle}} : J(E) \propto E^{-\gamma_2} \left[1 + \left(\frac{E}{E_S}\right)^{\Delta\gamma}\right]^{-1}$

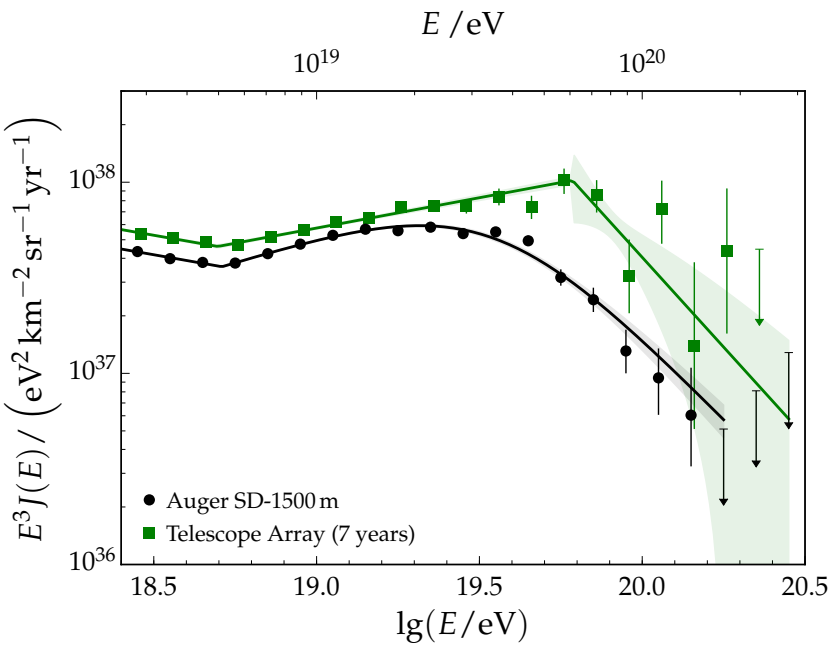
- Deconvolution of SD spectra to account for finite energy resolution

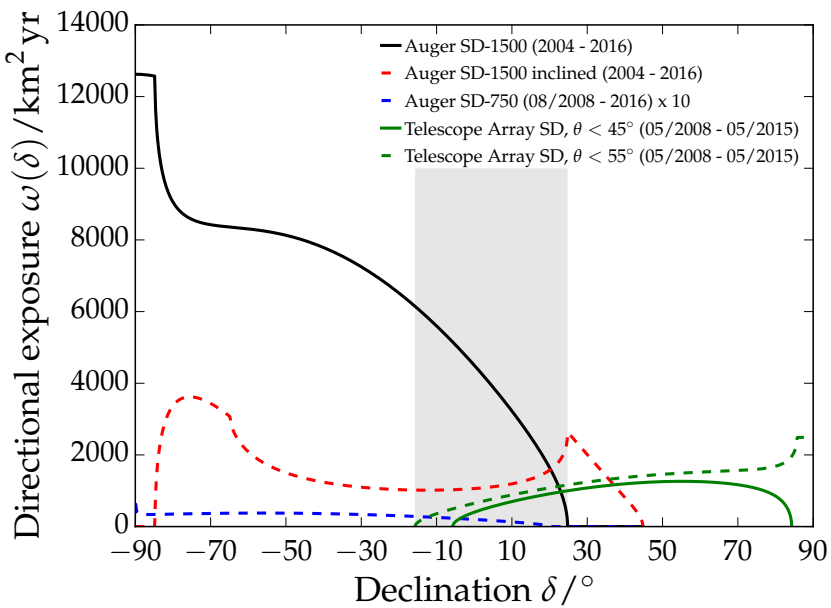
Comparison with Telescope Array

Auger: latitude $= -35.21^\circ$

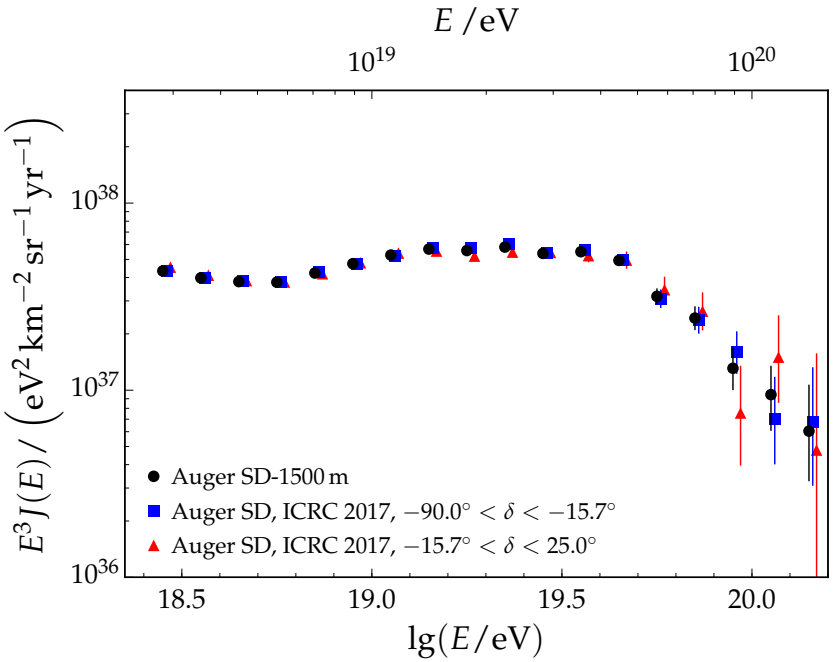
TA: latitude $= 39.3^\circ$

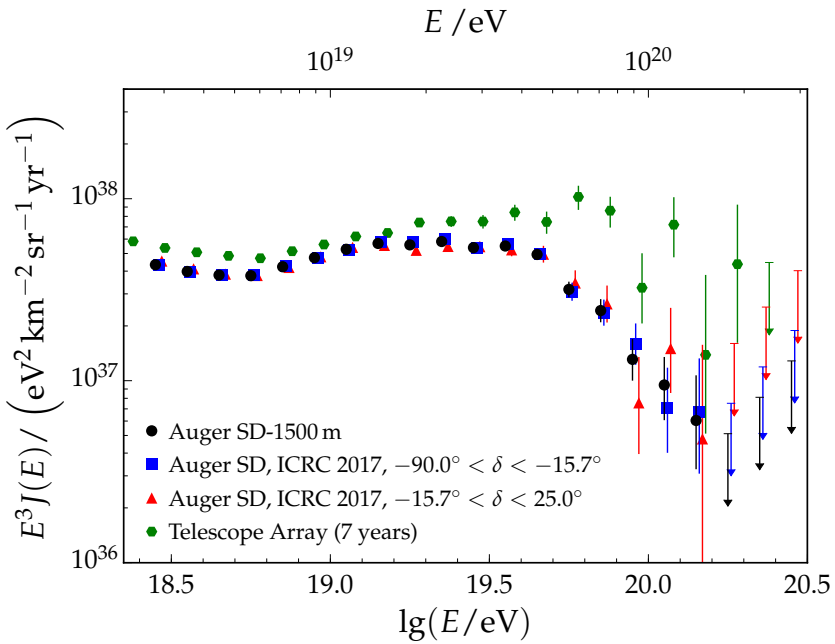
$\theta < 60^\circ : -90^\circ$ to $+25^\circ$





Discrepancy due to declination dependent flux?





SD-1500 m data split in:

- Auger-only ($-90° < \delta < -15.7°$)
- TA-overlapping ($-15.7° < \delta < 25°$)

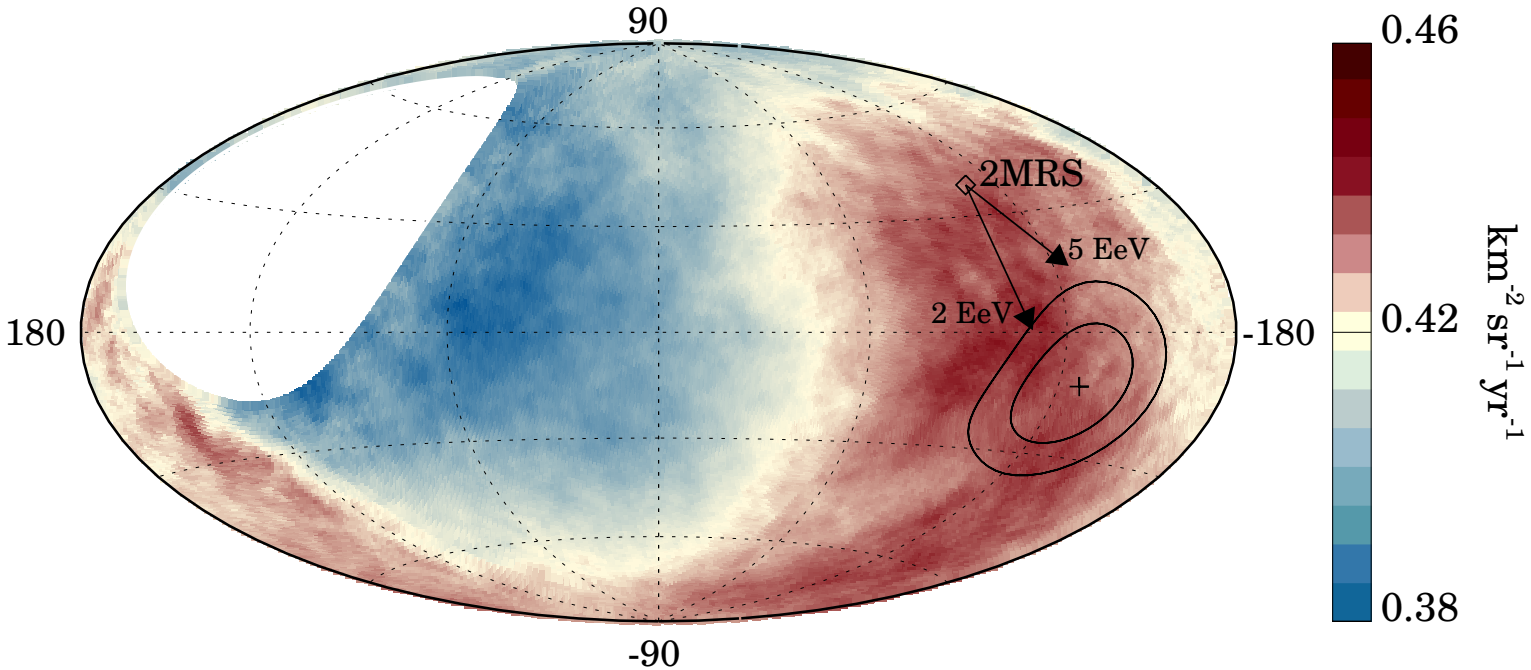
SD-1500 m data corrected for:

- atmospheric & geomagnetic effects
- experimental effects

No indication of δ-dependent flux. Auger-TA difference not explained.

Dipole anisotropy above 8 EeV

Combination of vertical and inclined showers



gal. coord.: $(l, b) = (233^\circ, -13^\circ)$

3-d dipole above 8 EeV:

$(6.5^{+1.3}_{-0.9})\%$ at $(\alpha, \delta) = (100^\circ, 24^\circ)$

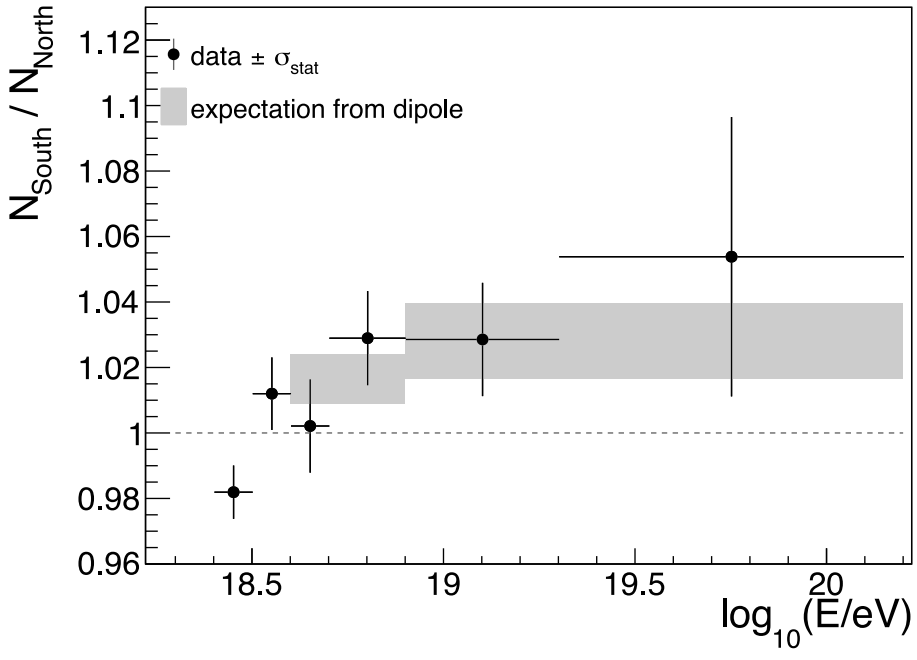
Significant modulation at 5.2σ

Declination dependence of the flux

SD-1500 m data divided into two declination bands:

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

Compared to expectation from dipolar modulation measured using data with $\theta < 80^\circ$

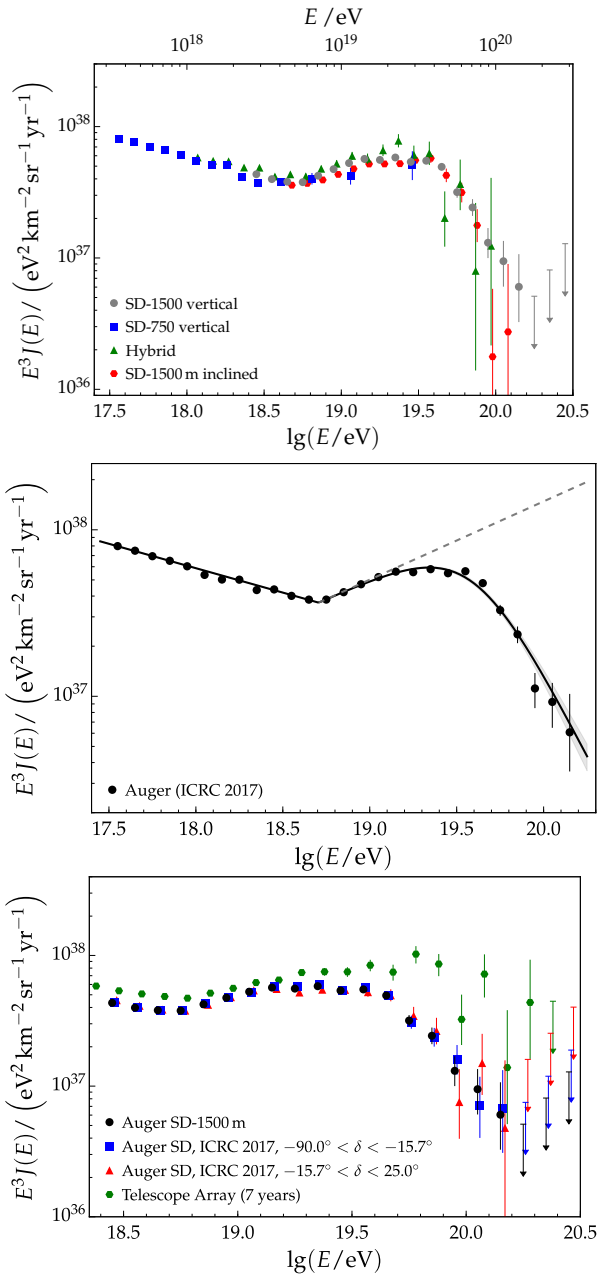


Observation compatible with dipole expectation within uncertainties

Summary

- **Four independent** measurements, three SD and one FD
- All share the **same energy scale** derived from FD with a syst. uncertainty of 14 %
- Combined spectrum covers **three decades** in energy
- **No significant indication of variation** in declination-binned spectra
- **Ratio** $N_{\mathrm{South}} / N_{\mathrm{North}}$ **compatible** with dipole expectation
- **Composition** information needed

Thanks for your attention!



Backup slides

Combined Auger spectrum