Energy spectrum of cosmic rays measured with the Pierre Auger Observatory

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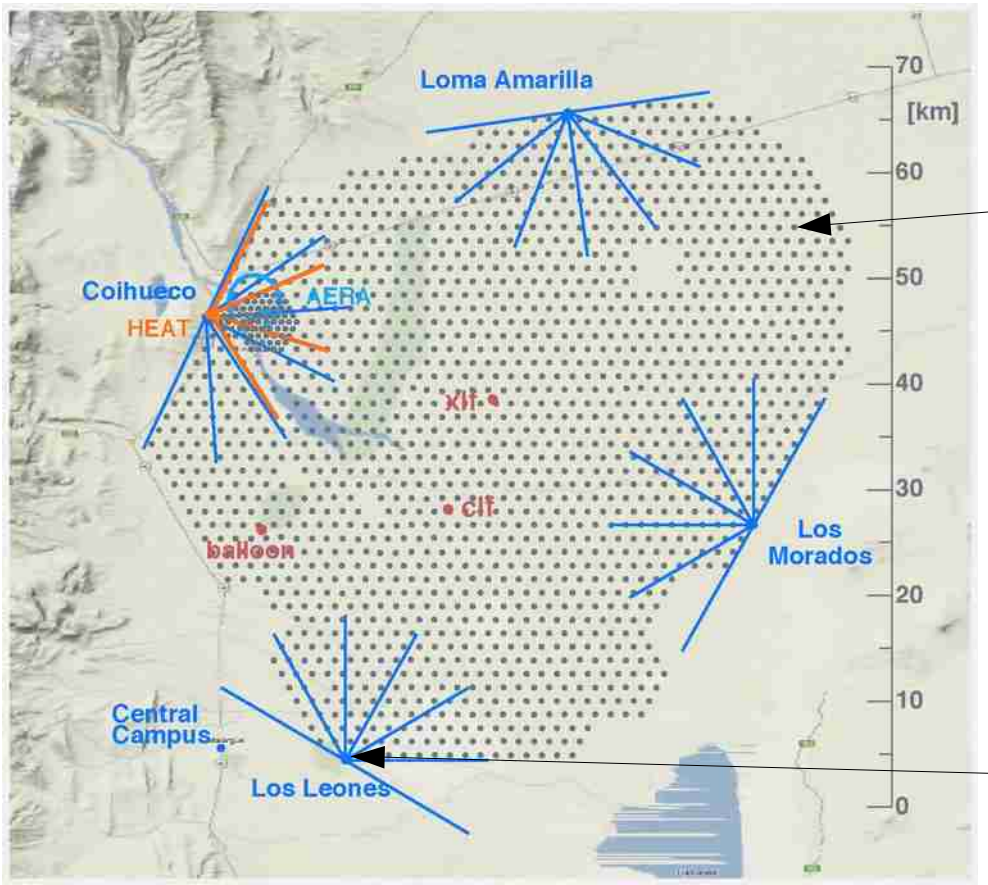
Very High Energy Phenomena in the Universe

Pierre Auger Observatory

- Detector of extensive air showers induced by high energy CR
- Located near Malargüe, Argentina – 69° W, 35° S, 1400 m a.s.l.

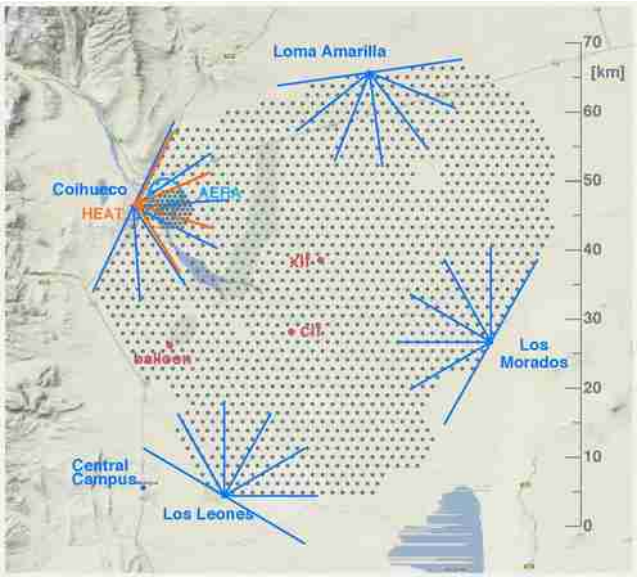


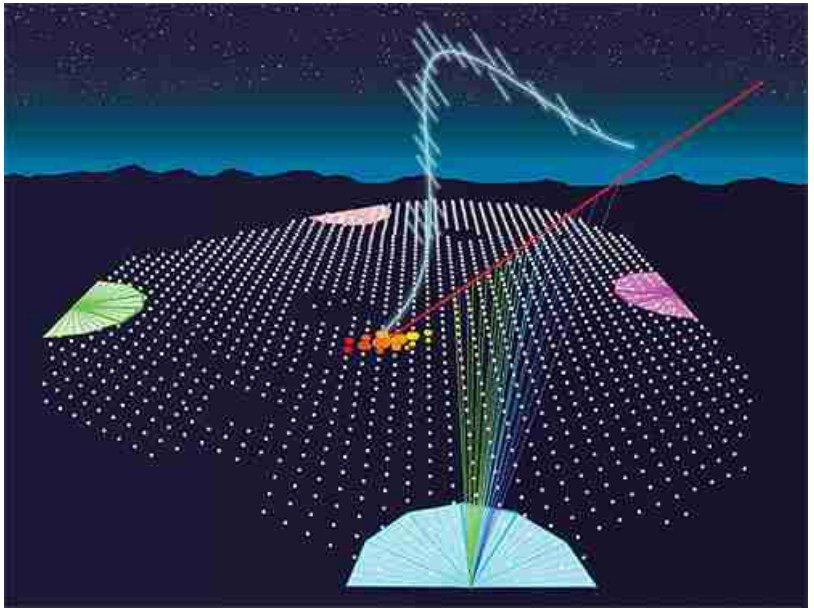
Surface detector (SD)

Fluorescence detector (FD)

SD+FD = Hybrid detector

- Surface detector – day+night (~100% duty cycle)
  - Triangular grid of 1660 WCD with 1500 m spacing
  - 49 additional WCD with 750 m – Infill
- Fluorescence detector – clear nights (~13%)
  - 24 telescopes looking ~ horizontaly
  - 3 telescopes elevation ~ 30°-60° - HEAT





Desined to measure the highest energies

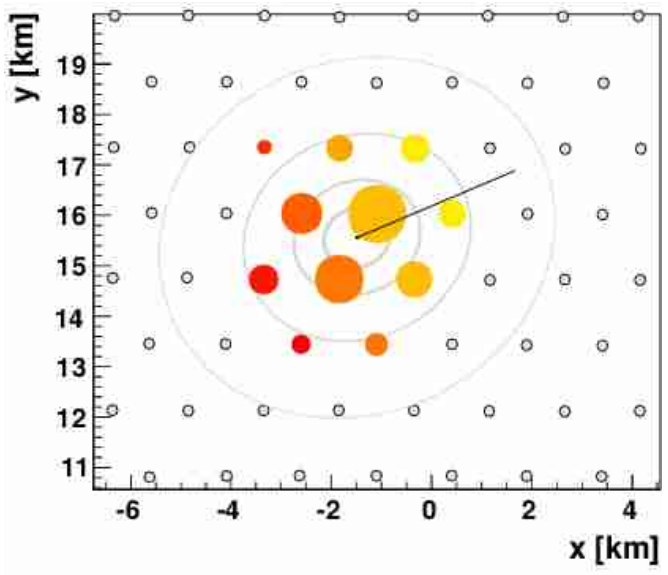
Lower energy extensions

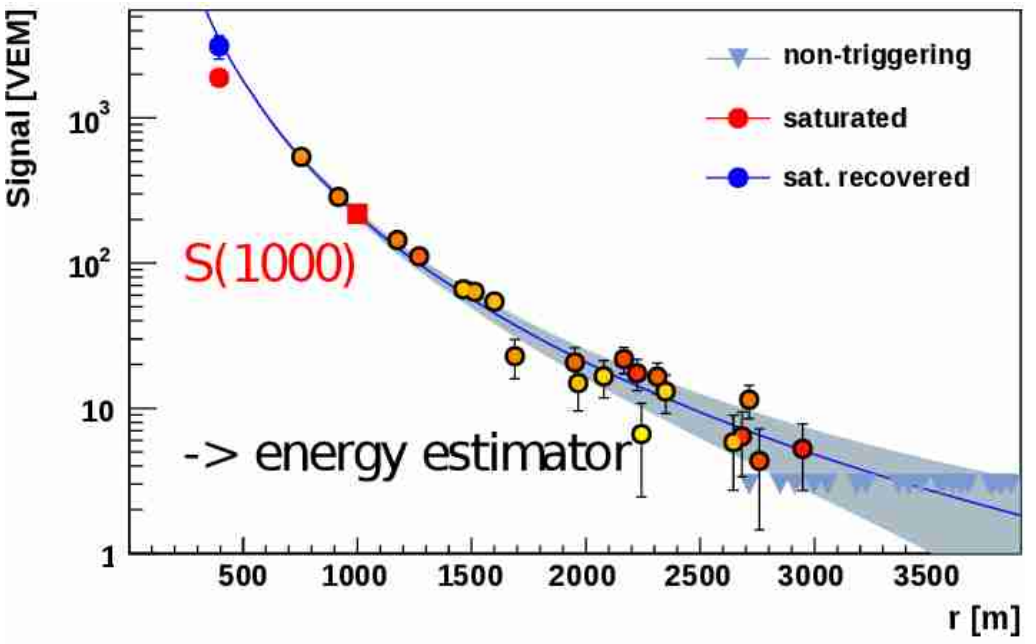
Event reconstruction

- SD vertical : θ < 60° for 1500 m (θ < 55° for 750 m)
  - fully efficient > 3 EeV (> 0.3 EeV)
  - shower axis from WCD trigger times
  - energy estimator S_{38} (S_{35}) from lateral distribution
  - S(1000) → S_{38} by Constant intensity cut (zenith correction)

    (S(450) → S_{35})

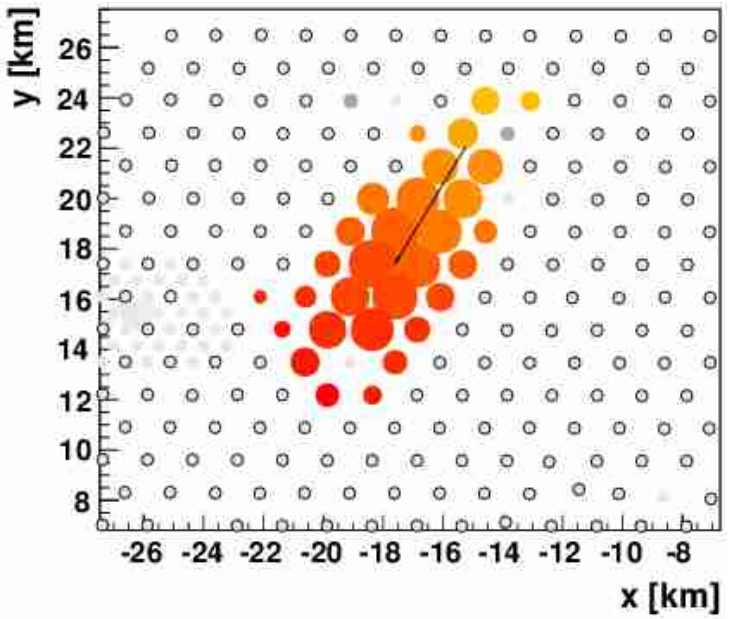
Lower energy extension

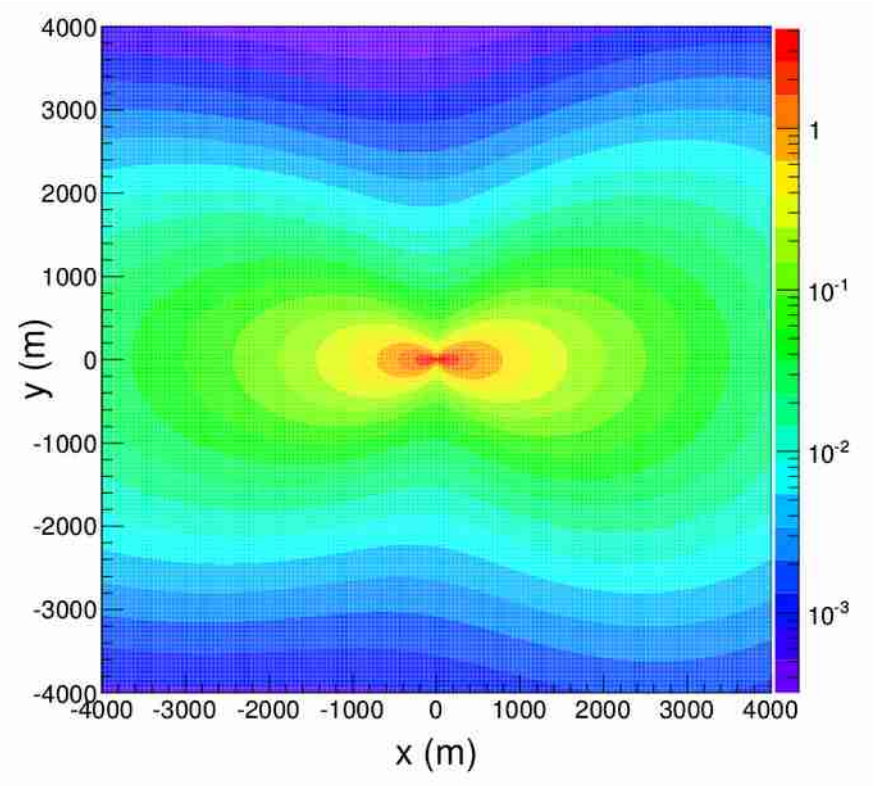




Event reconstruction

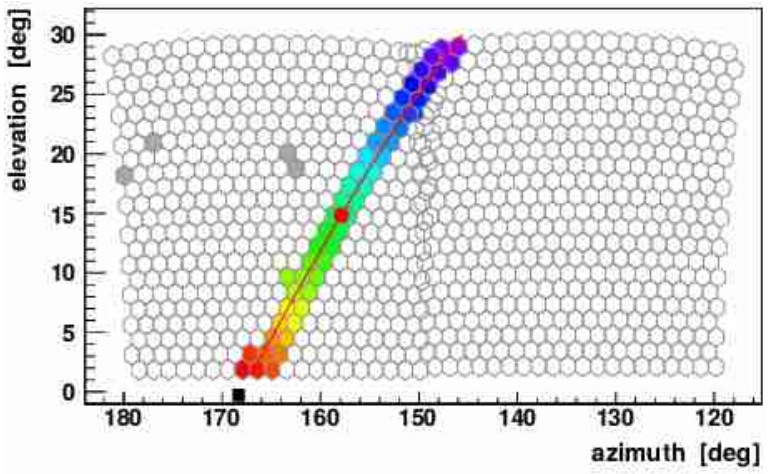
- SD inclined : 62° < θ < 80° for 1500 m
  - fully efficient > 4 EeV
  - signal dominated by muons (EM ~ 20%)
  - shower axis from map of muon distribution on ground
    - $\rho_\mu(\boldsymbol{r}) = N_{19}\, \rho_{\mu,19}(\boldsymbol{r}; \theta, \varphi)$
  - energy estimator N_{19}

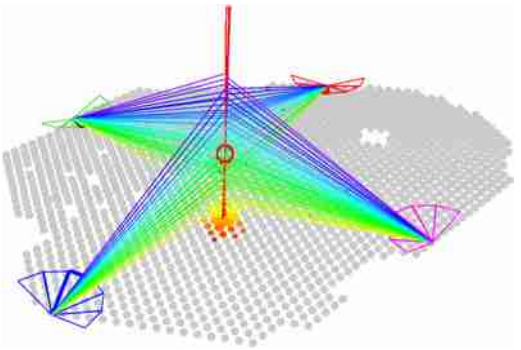


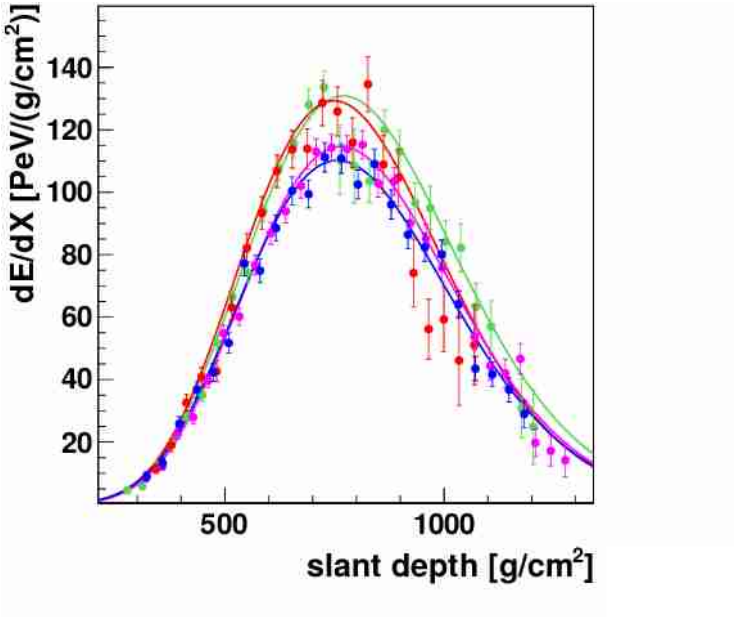


Event reconstruction

- Hybrid = FD + 1 WCD
  - fully efficient > 1 EeV
  - geometry from trigger times of FD pixels and 1 WCD
  - measurement of energy deposit in air → longitudinal profile
  - energy estimator E_{FD}
    - integral of longitudinal profile + invisible energy

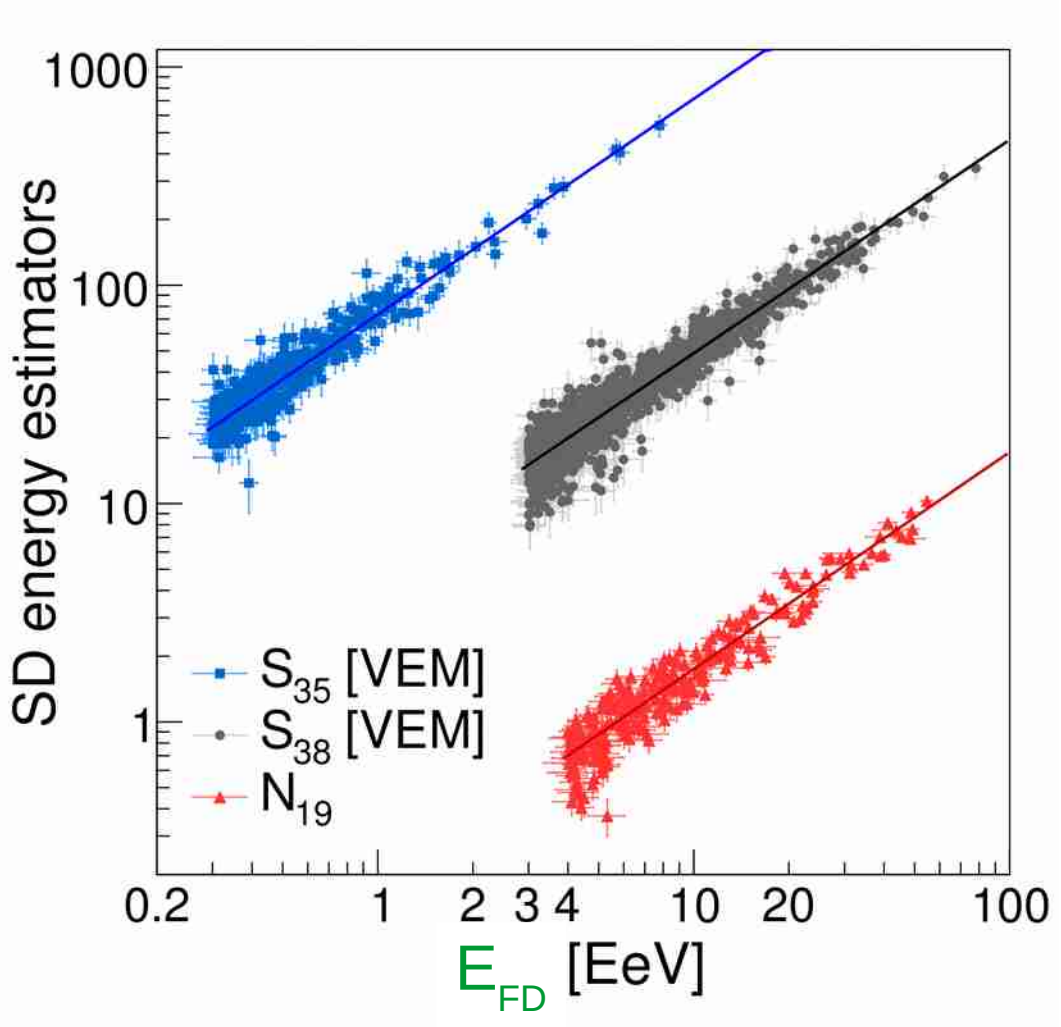






Energy calibration

- SD calibrated to Hybrid measurements → common energy scale
- subset of Golden events = independet SD and Hybrid rec.

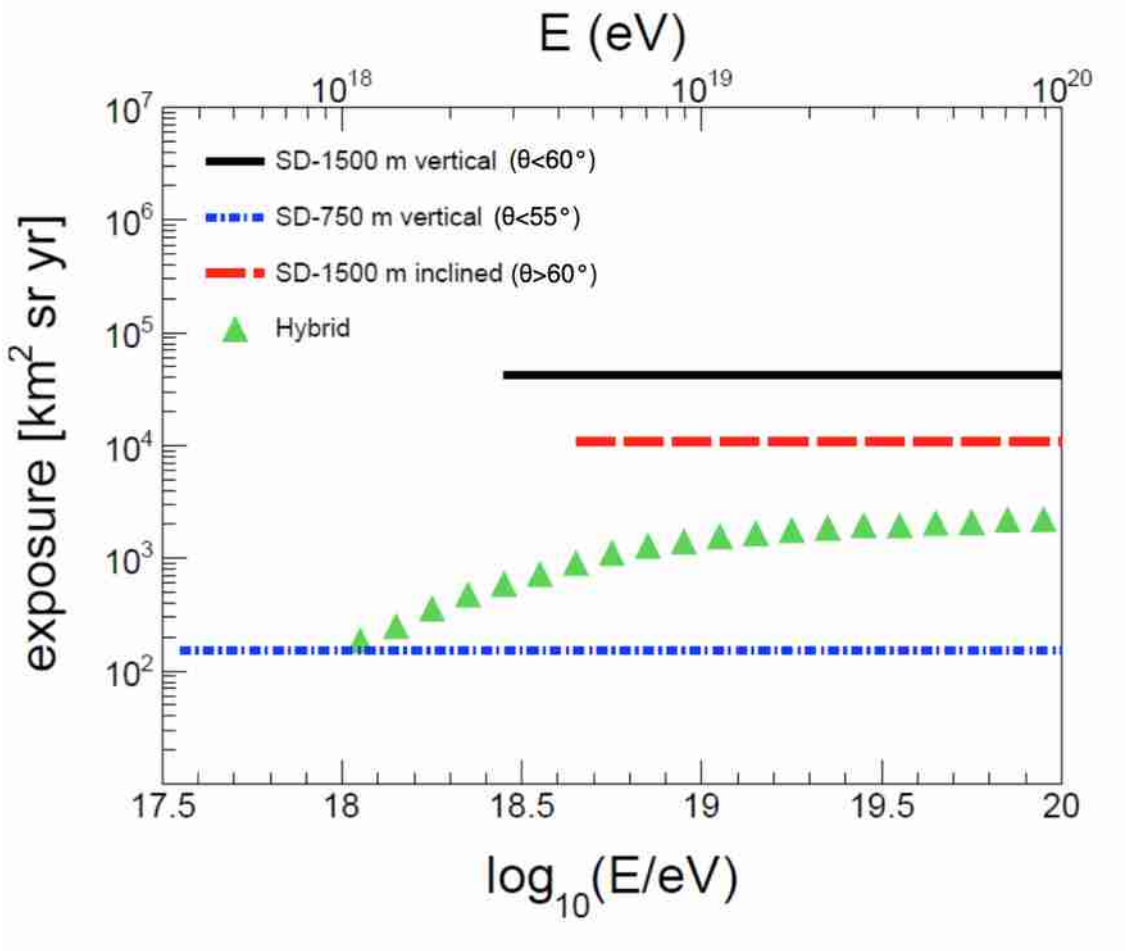


$E = A\,\Sigma^B$, $\Sigma = S_{35}, S_{38}, N_{19}$

- $A = (1.29 \pm 0.06)\times10^{-2}$ EeV
  $B = 1.01 \pm 0.01$
  E resolution $(13 \pm 1)\%$
- $A = (0.187 \pm 0.004)$ EeV
  $B = 1.023 \pm 0.006$
  E resolution $(15.3 \pm 0.4)\%$
- $A = (5.71 \pm 0.09)$ EeV
  $B = 1.01 \pm 0.02$
  E resolution $(19 \pm 1)\%$

Exposure

- SD exposure purely geometrical (number of hexagons)
- Hybrid based on time dependent MC simulations

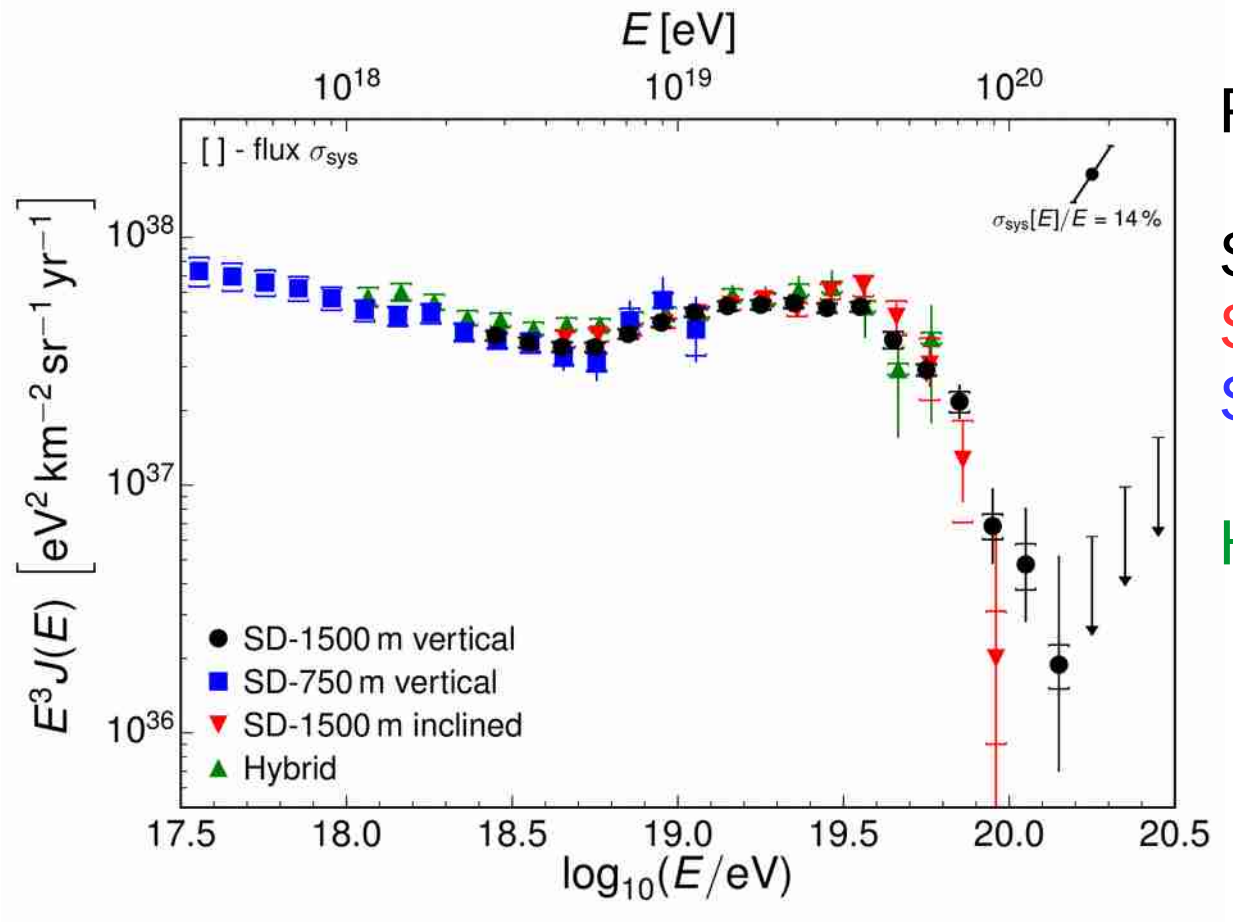


10 years of data:

SD vertical: 42 500 km² sr yr
SD inclined: 10 900 km² sr yr
SD-750: 150 km² sr yr
Hybrid: 1 500 km² sr yr at 10 EeV

Cosmic ray flux

- Energy scale systematic uncertainty 14%

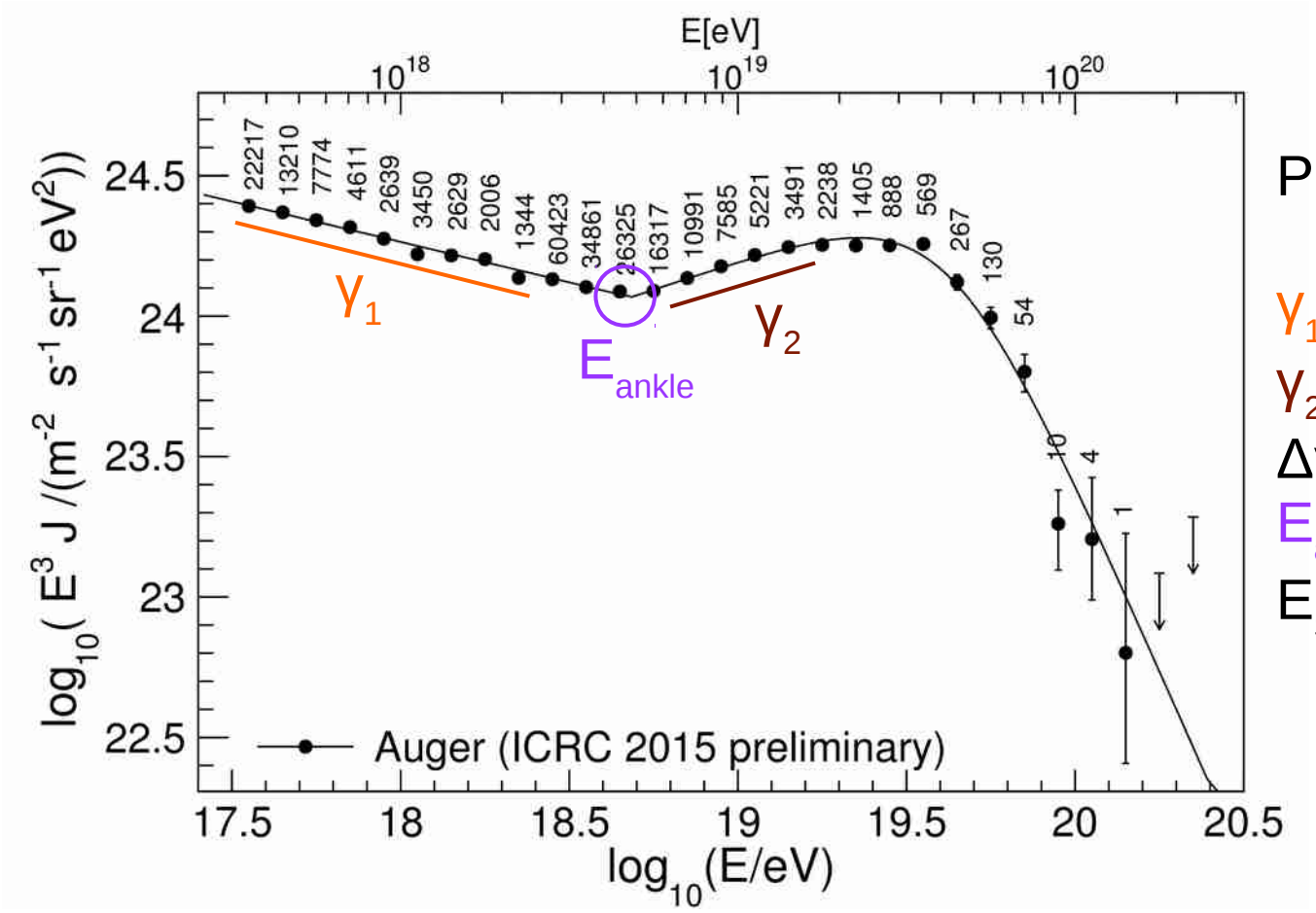


Flux systematic uncertainties

SD vertical: 5.8%
SD inclined: 5%
SD-750: 14% at 0.3 EeV
<7% at 3 EeV
Hybrid: 10% at 1 EeV
6% at 10 EeV

Combined spectrum

Fitted by: $J(E)=J_0\left(\frac{E}{E_{ankle}}\right)^{-\gamma_1}, E<E_{ankle}$ $J(E)=J_0\left(\frac{E}{E_{ankle}}\right)^{-\gamma_2}\left[1+\left(\frac{E_{ankle}}{E_S}\right)^{\Delta\gamma}\right]\left[1+\left(\frac{E}{E_S}\right)^{\Delta\gamma}\right]^{-1}, E>E_{ankle}$



Parameters:

$\gamma_1 = 3.29 \pm 0.02 \pm 0.05$

$\gamma_2 = 2.60 \pm 0.02 \pm 0.1$

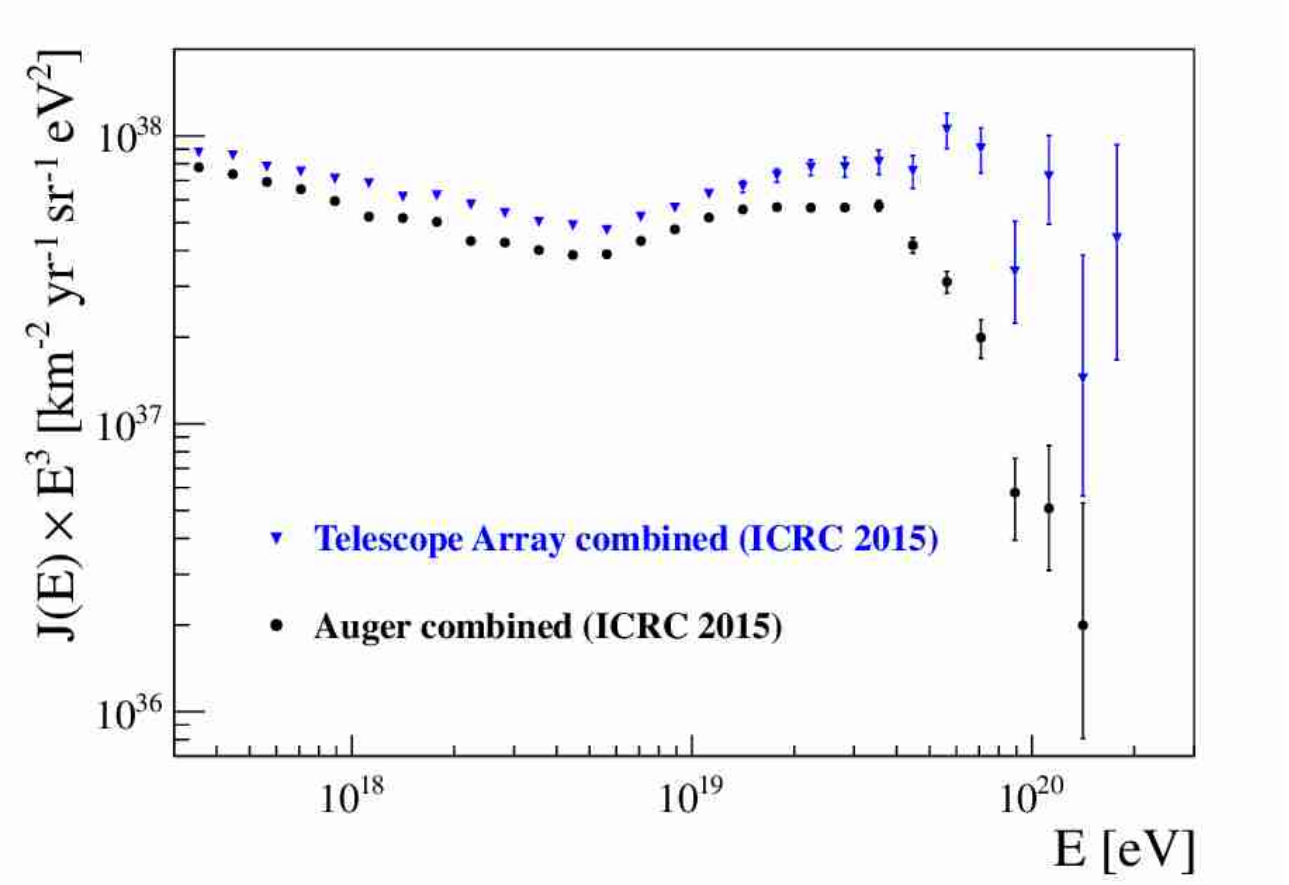
$\Delta\gamma = 3.1 \pm 0.2 \pm 0.4$

$E_{ankle} = (4.82 \pm 0.07 \pm 0.8)$ EeV

$E_S = (42.1 \pm 1.7 \pm 7.6)$ EeV

Comparison with TA spectrum

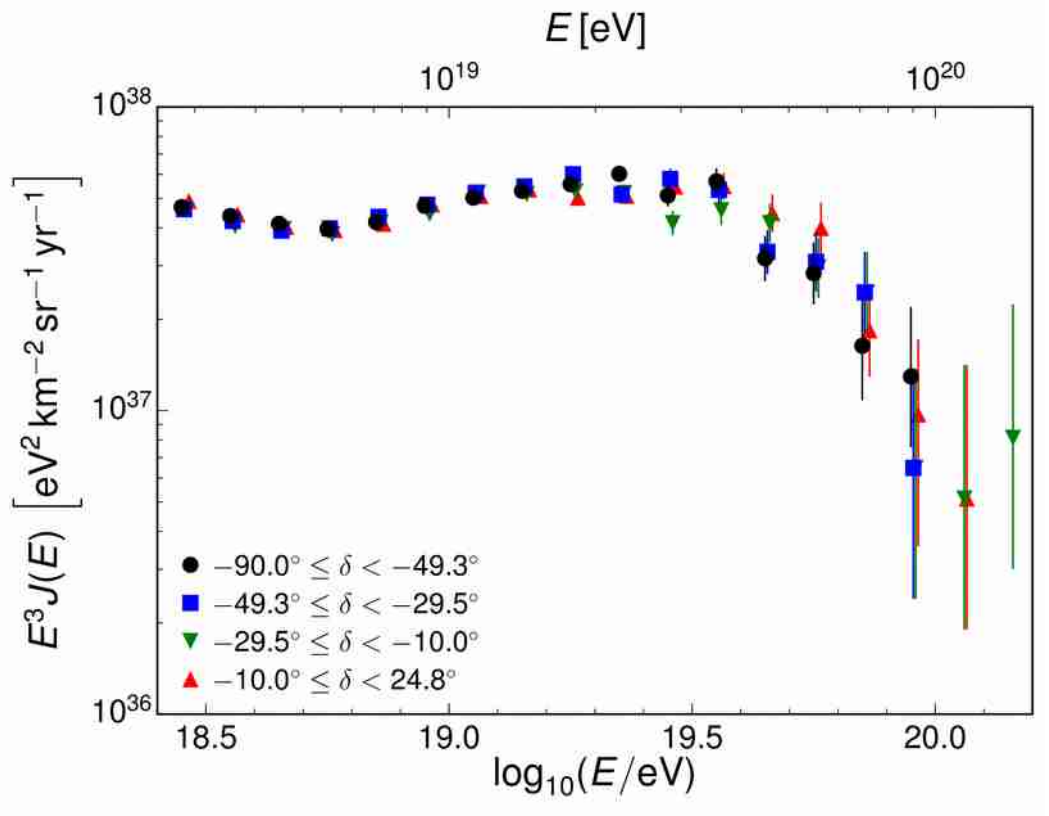
- Compatible within systematic errors up to ~ 2x10^{19} eV
- Tension at high energies not explained (sky region? instrument?)
  - Quantified by: $E_{1/2-Auger} = (24.7 \pm 0.1^{+8.2}_{-3.4})\,EeV$ $E_{1/2-TA} = (60 \pm 7)\,EeV$



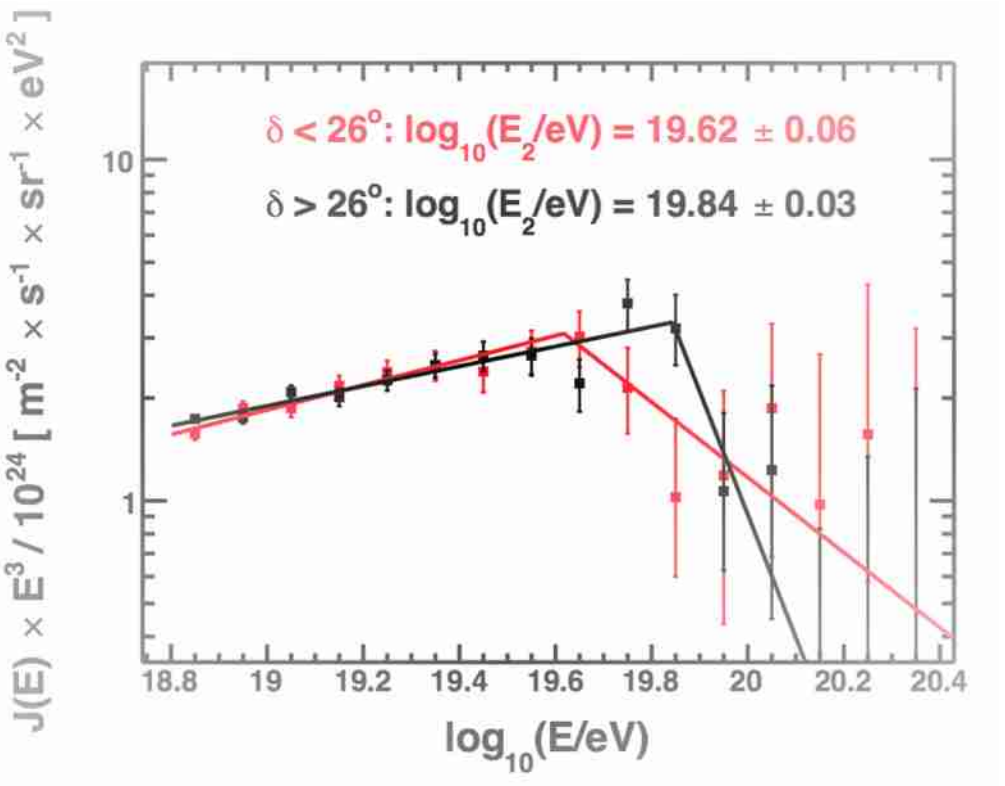
Declination dependence

- Not seen by Auger – SD vertical only
- Telescope Array sees it

Auger

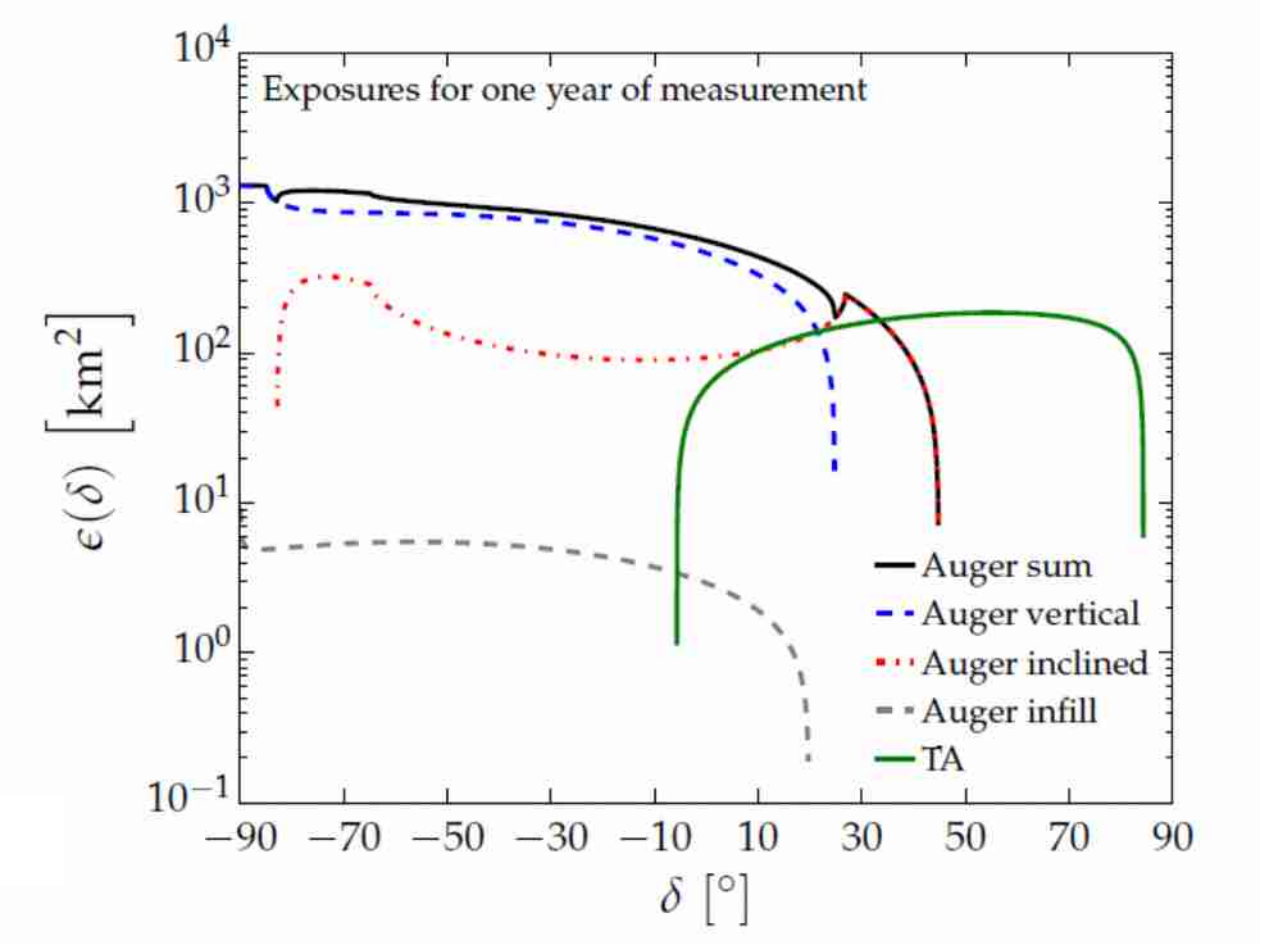


Telescope Array



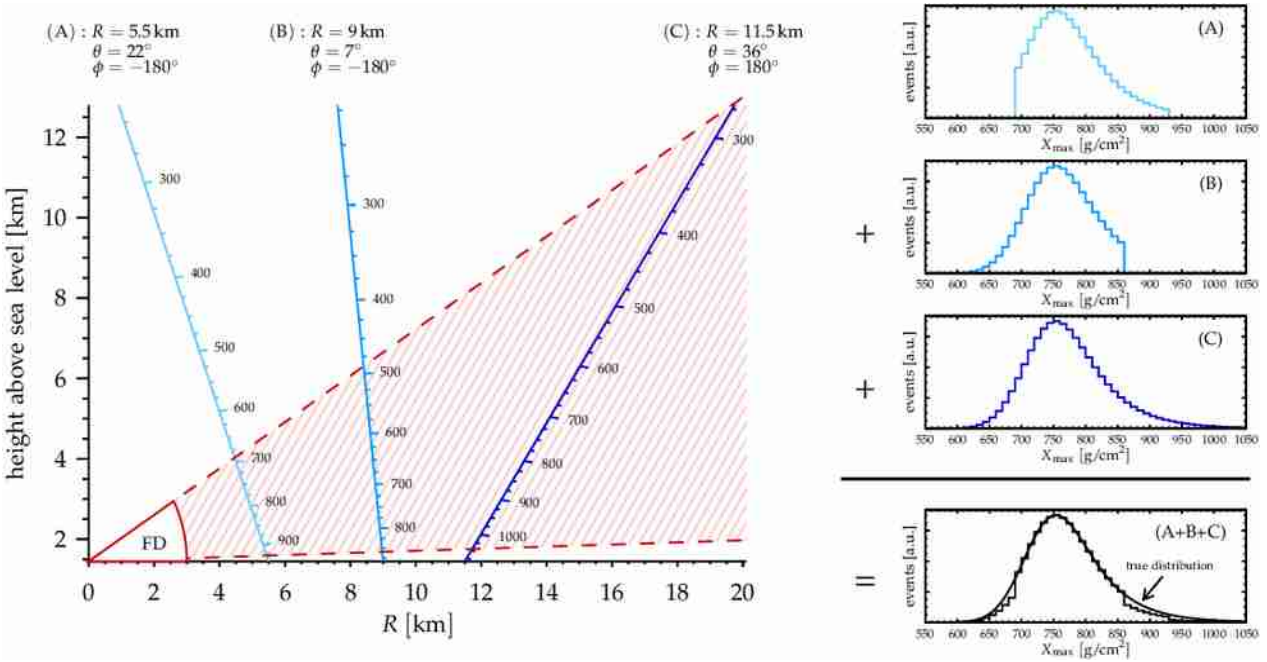
Exposure vs. declination

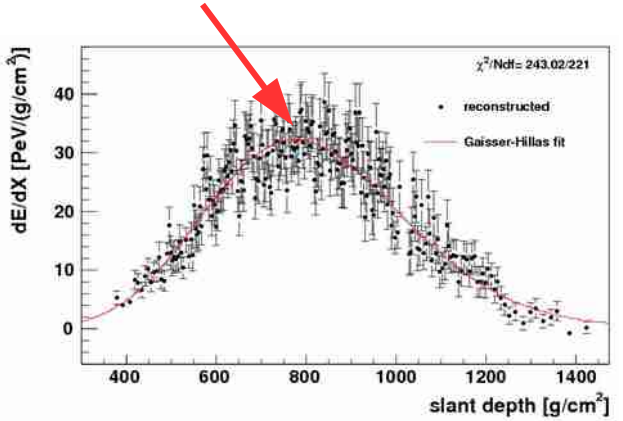
- Different shape for Auger SD vertical and TA
- Similar shape for SD inclined and TA – analysis not finished

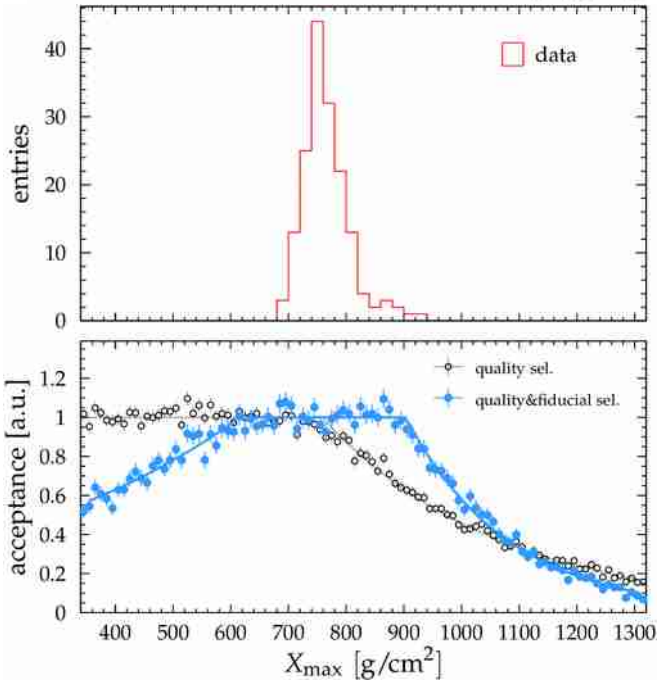


Composition measurement

- Measurement of maximum of longitudinal profile = X_{max}
- Field of view cuts → unbiased distributions
  - Directly comparable with MC output

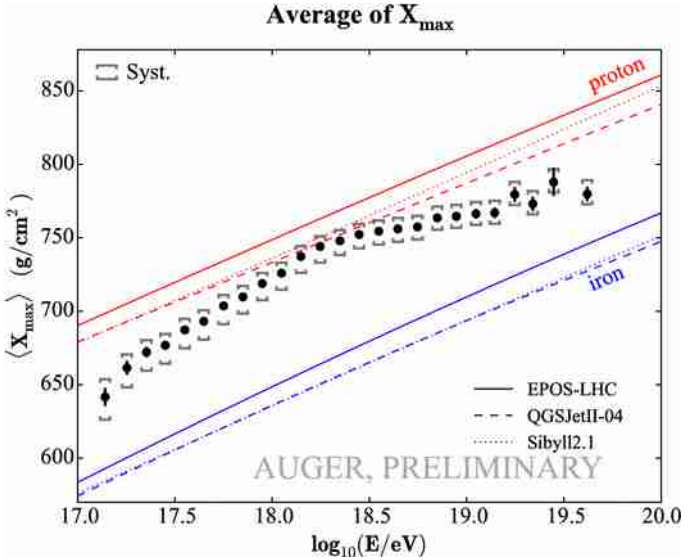


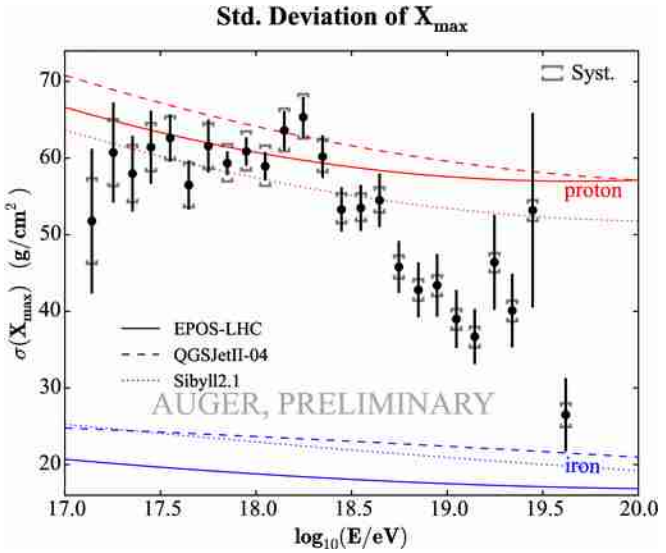


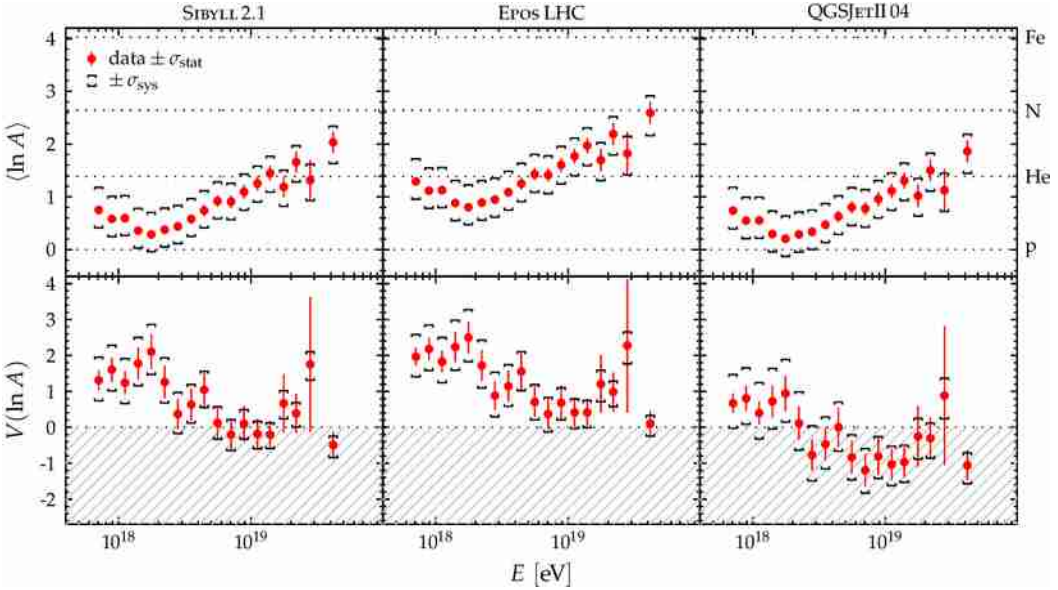


X_{max} moments

- From full X_{max} distributions





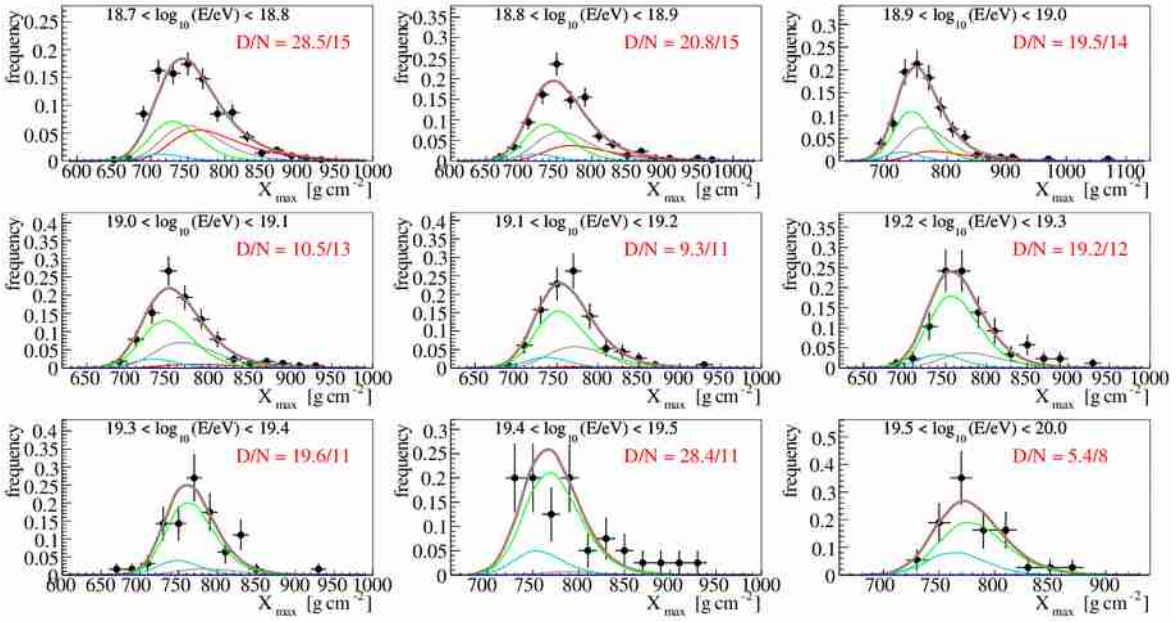


Combined fit

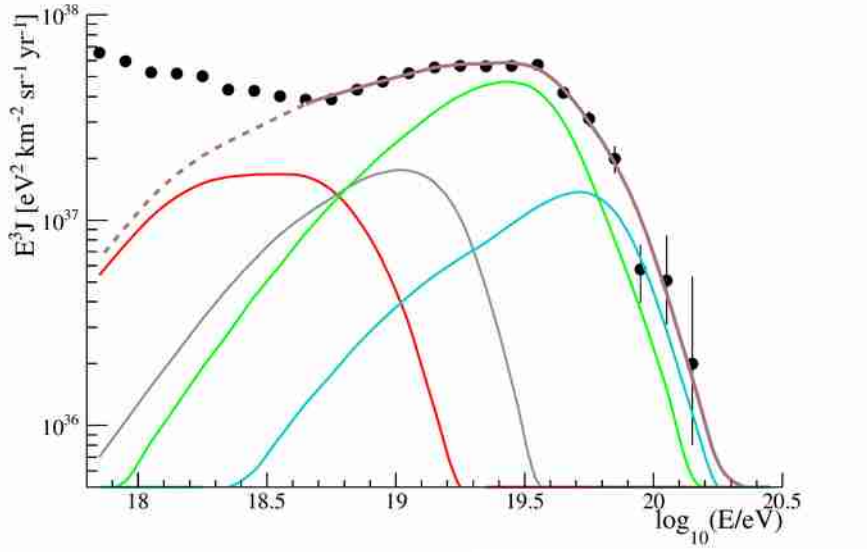
- Fit of energy spectrum together with X_{max} distributions
- Sources modeled by
  - spectral index γ ($dN/dE \sim E^{-\gamma}$)
  - Composition fractions f_A – H, He, N, Si, Fe
  - maximum rigidity R_{cut}
- 1D simulation of propagation from source to Earth
  - CRPropa and SimProp
    - CMB
    - EBL – Gilmore and Domínguez models
    - photo-disintegration – PSB, TALYS and Geant4 models
- Identical sources, isotropic distribution, no evolution with redshift
- X_{max} sampled by generalized Gumbel distributions
- SD and FD detector response taken into account

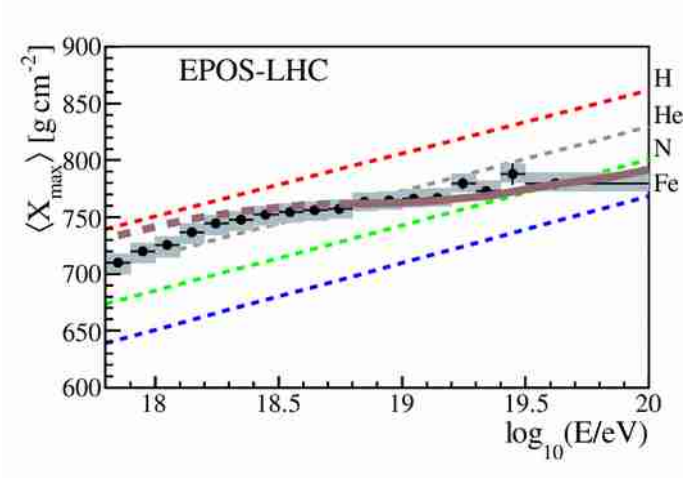
Fit results

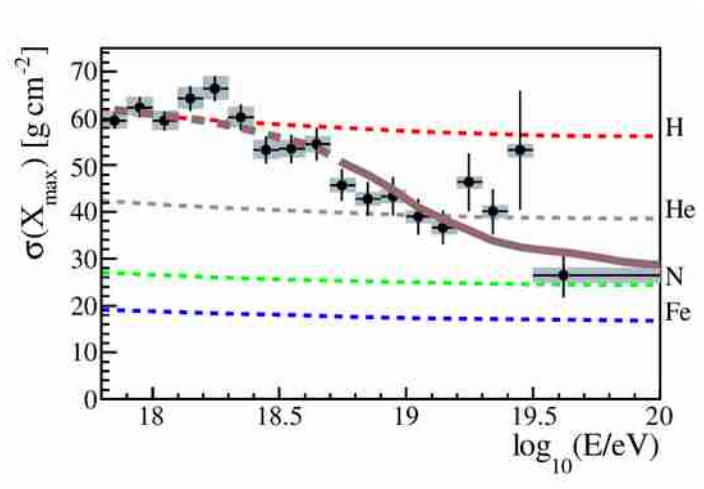
- The best fit of X_{max} distributions and spectrum



A = 1, 2-4, 5-22, 23-38, total

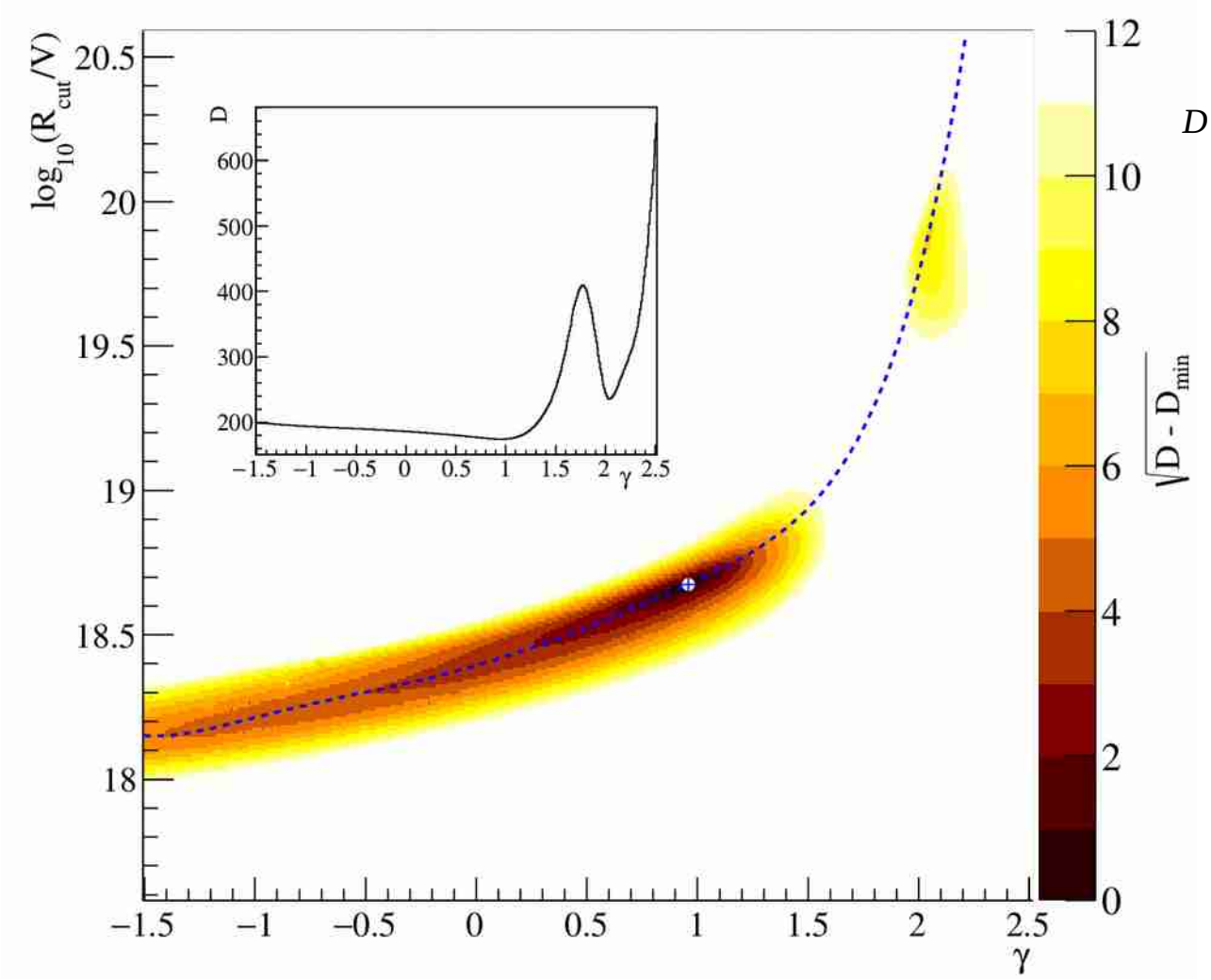






Source parameters

- The best fit model: SPG (SimProp, PSB, Gilmore) + EPOS LHC



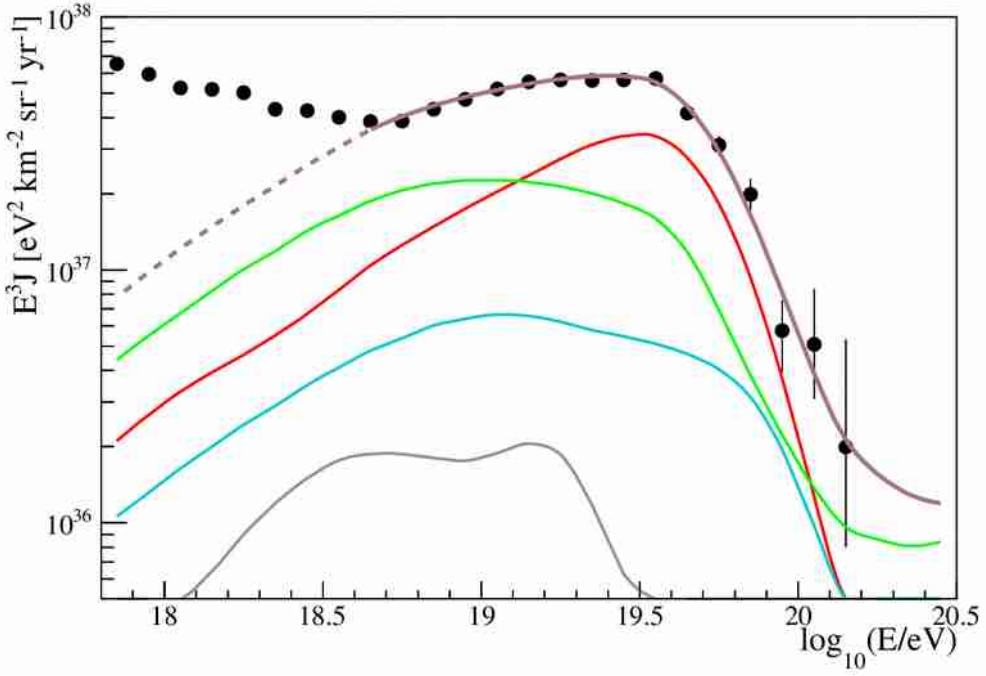
$$D = D(J) + D(X_{max}) = -2\ln\frac{L}{L^{sat}} = -2\ln\frac{L_J}{L_J^{sat}} - 2\ln\frac{L_{X_{max}}}{L_{X_{max}}^{sat}}$$

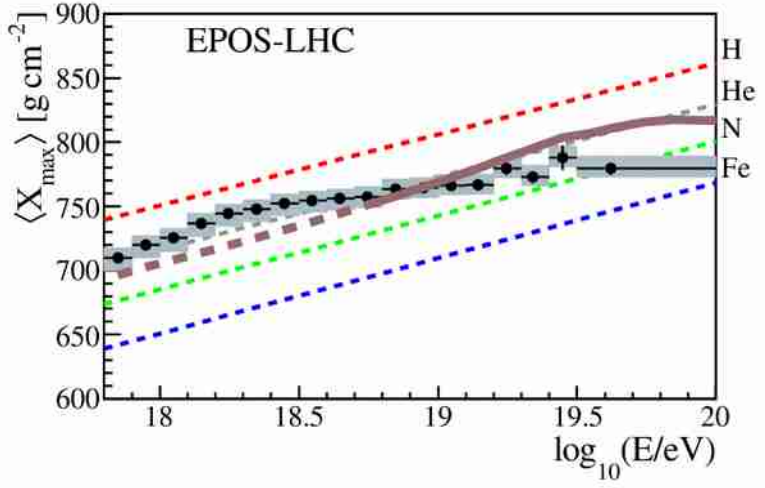
	1st minimum	2nd minimum
γ	$0.96^{+0.08}_{-0.13}$	2.04 ± 0.01
$\log_{10}(R_{cut}/V)$	$18.68^{+0.02}_{-0.04}$	19.88 ± 0.02
f_H (%)	0.0	0.0
f_{He}(%)	67.3	0.0
f_N (%)	28.1	79.8
f_{Si}(%)	4.6	20.2
f_{Fe}(%)	0.0	0.0

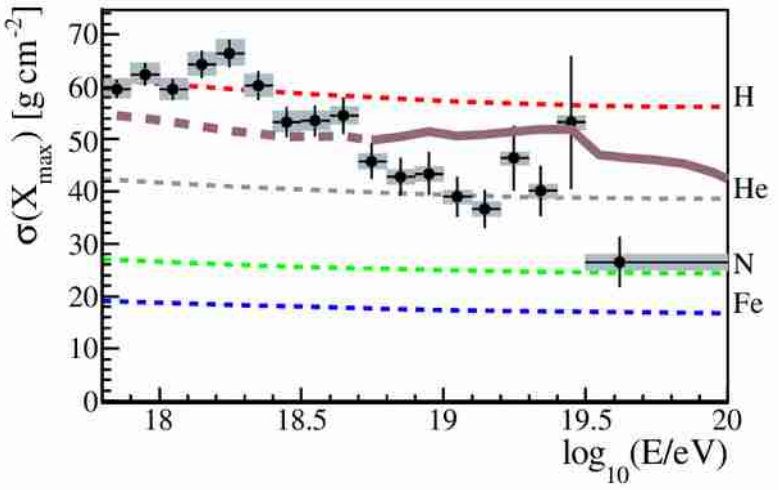
Second minimum

- R_{cut} larger → photo-disintegration more important → more protons

A = 1, 2-4, 5-22, 23-38, total

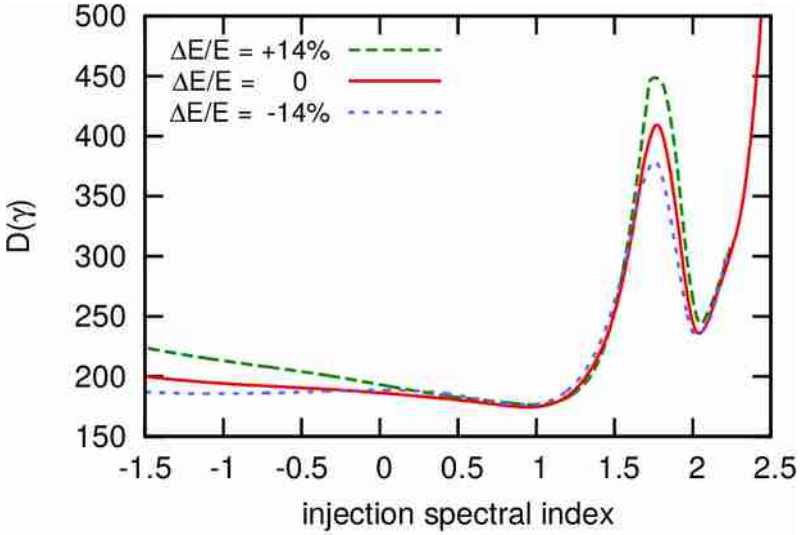


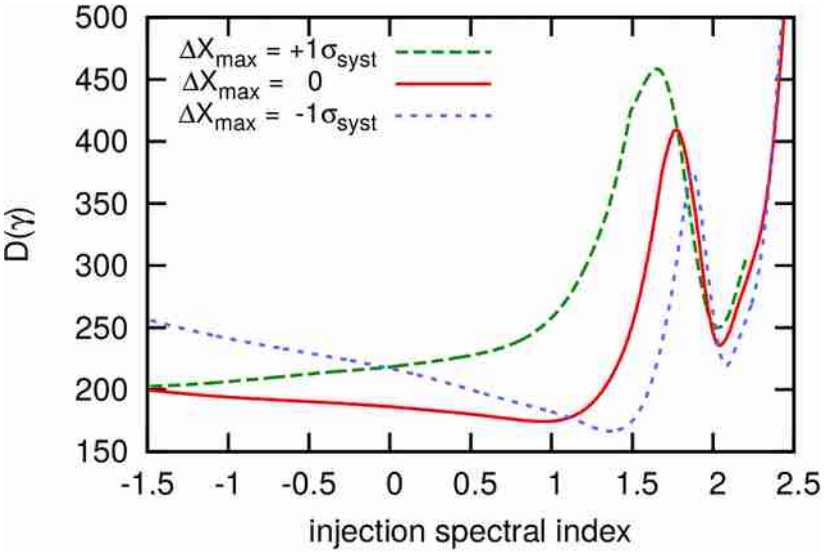


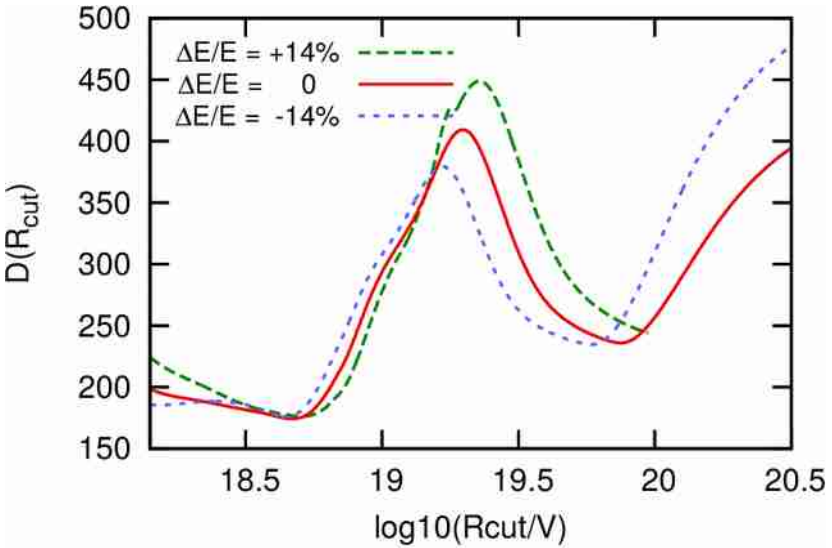


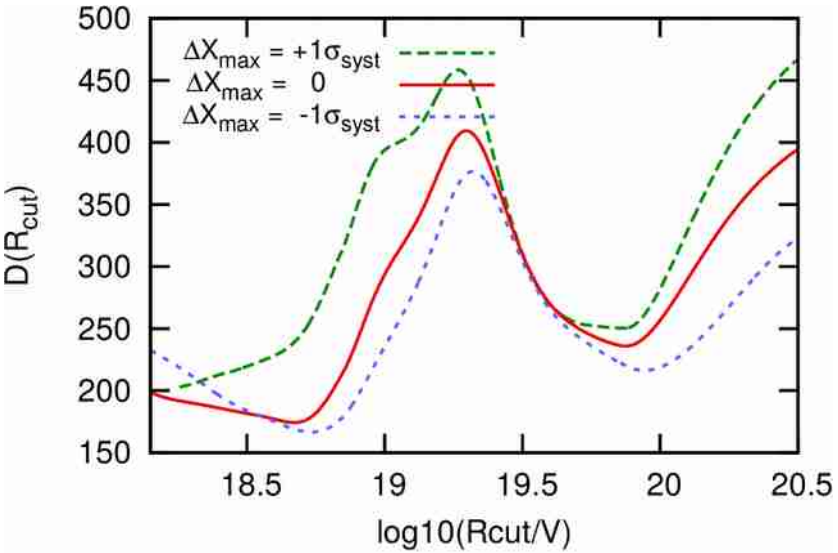
Stability

- Qualitative results rubust with respect to systematic on E and X_{max}

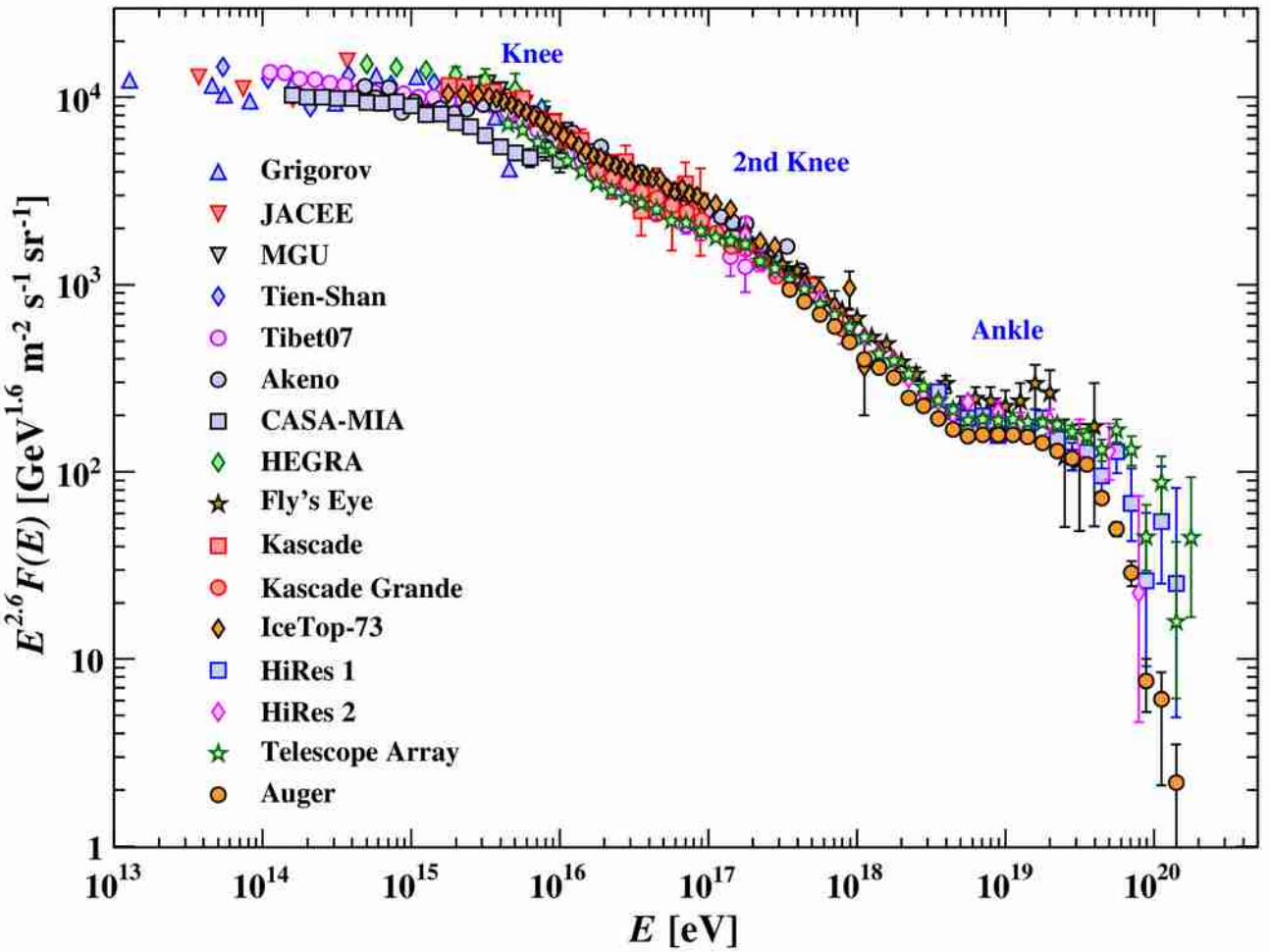








Spectrum comparison



Conclusions

- All particle energy spectrum measured by four methods
  - SD vertical, SD inclined, SD-750 vertical, Hybrid
  - in preparation – HEAT hybrid and HEAT Cherenkov
- Tension with TA spectrum above ~ 2×10^{19} eV not explained
- Combined fit of spectrum and composition done
  - hard injection spectrum and low R_{cut} favoured
  - depends on Auger interpretation of data – mixed composition
  - 3D simulations + magnetic fields – work in progress

Energy scale systematics

Systematic Uncertainties on the Energy Scale		
	TA	Auger
Fluorescence Yield	11%	3.6%
Atmosphere	11%	3.4%÷6.2%
FD Calibration	10%	9.9%
FD Reconstruction	9%	6.5% ÷5.6%
Invisible Energy	5%	3%÷1.5%
Other Contributions		5%
Total	21%	14%