



Energy spectrum of cosmic rays measured with the Pierre Auger Observatory

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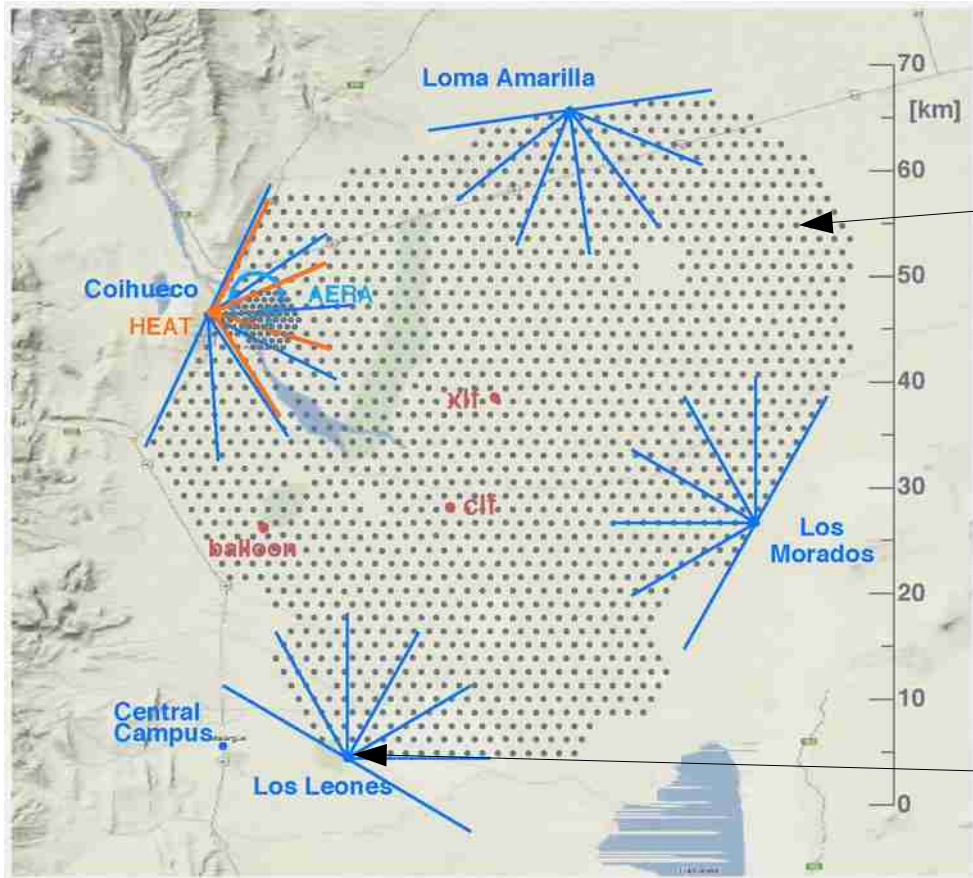
Very High Energy Phenomena in the Universe



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)

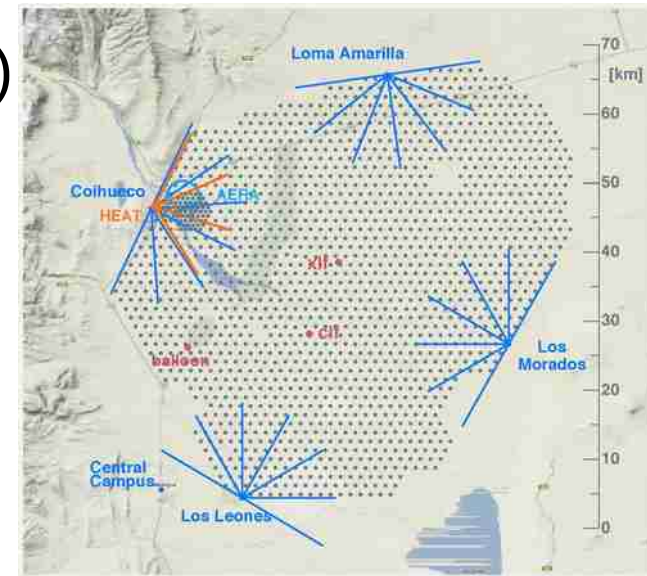
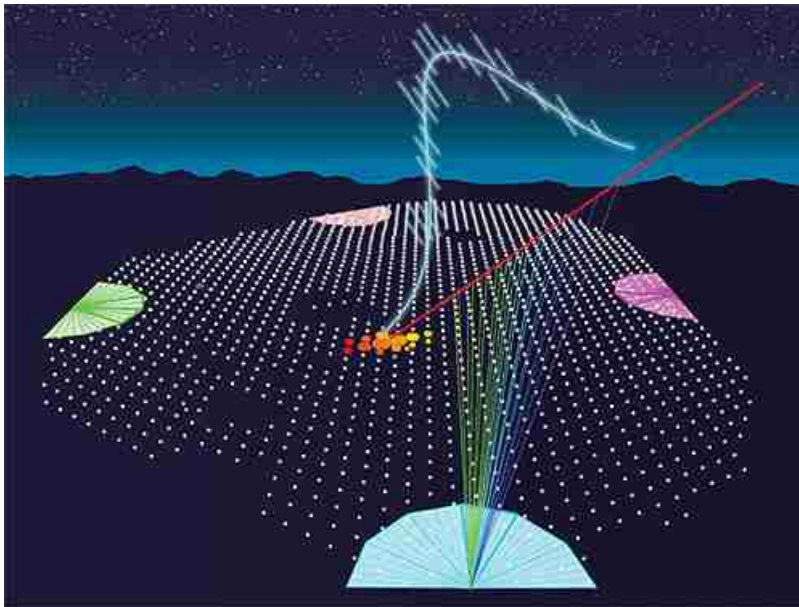


Fluorescence detector (FD)



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 ~ horizontally
 - 3 telescopes elevation ~ 30°-60° - HEAT

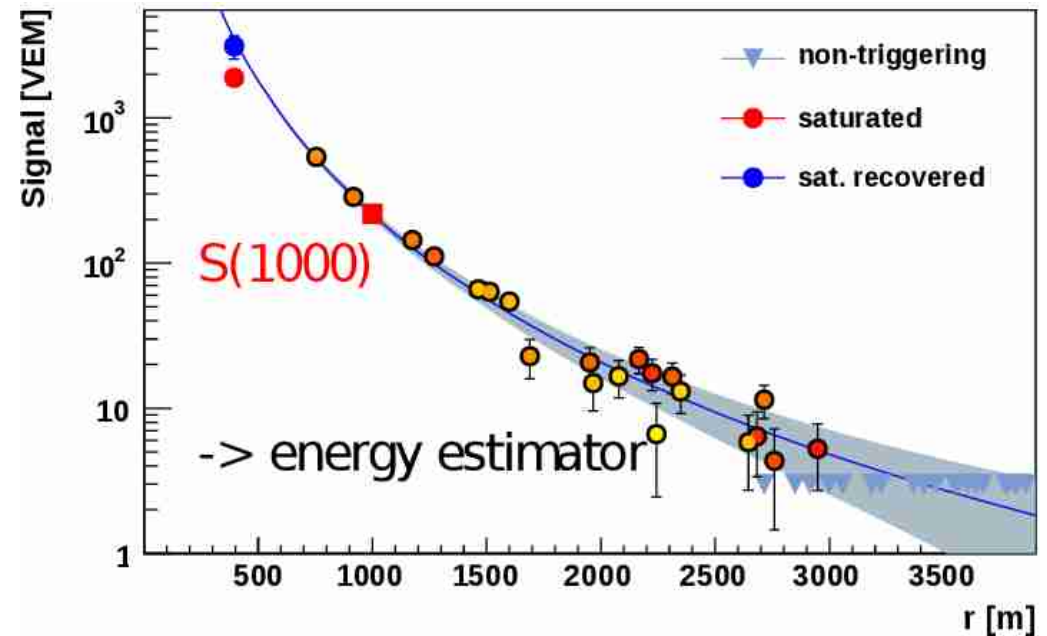
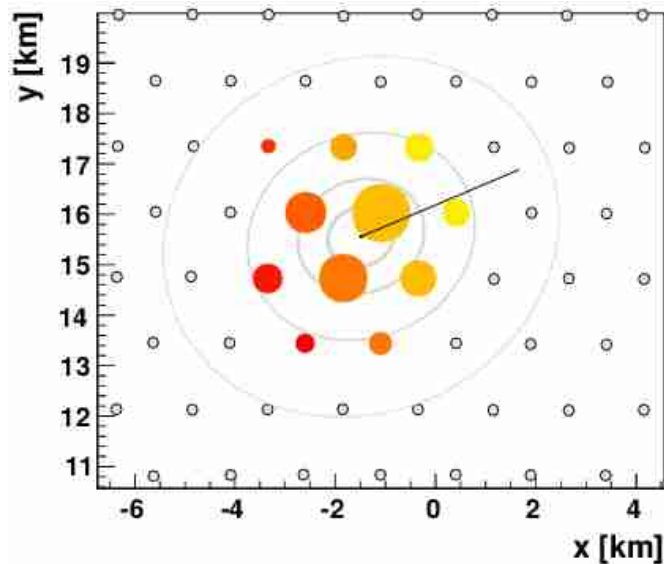


Desined to measure
the highest energies

Lower energy extensions

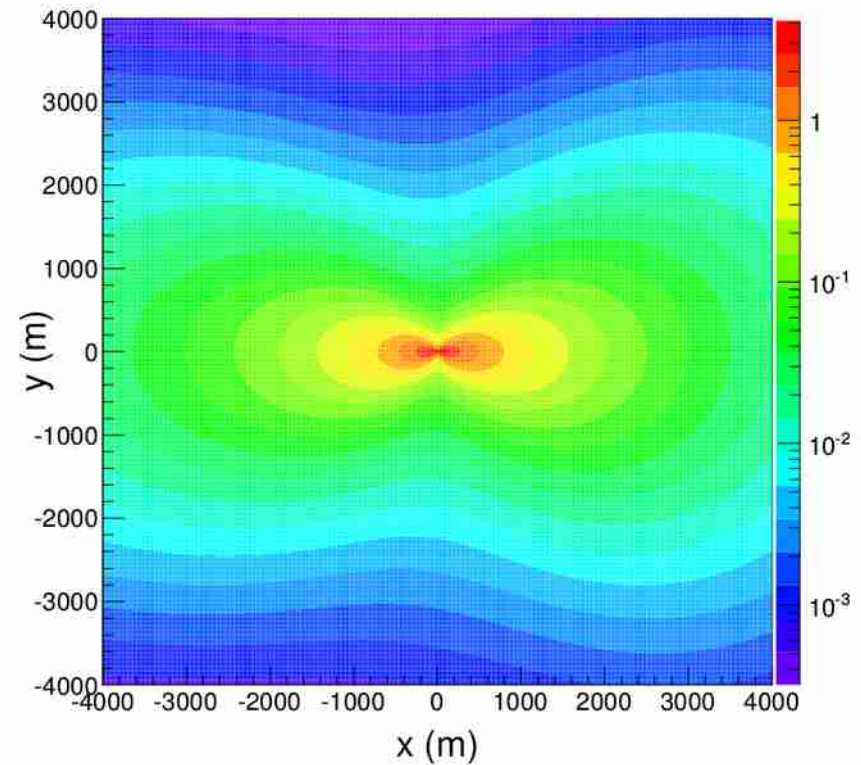
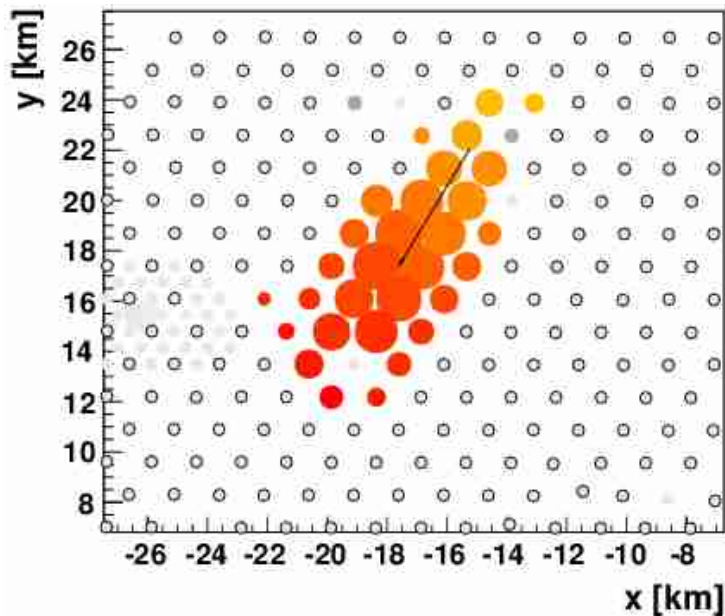
Event reconstruction

- SD vertical : $\theta < 60^\circ$ for 1500 m ($\theta < 55^\circ$ for 750 m)
 - fully efficient > 3 EeV (> 0.3 EeV) Lower energy extension
 - shower axis from WCD trigger times
 - energy estimator S_{38} (S_{35}) from lateral distribution
 - $S(1000) \rightarrow S_{38}$ by Constant intensity cut (zenith correction)
($S(450) \rightarrow S_{35}$)



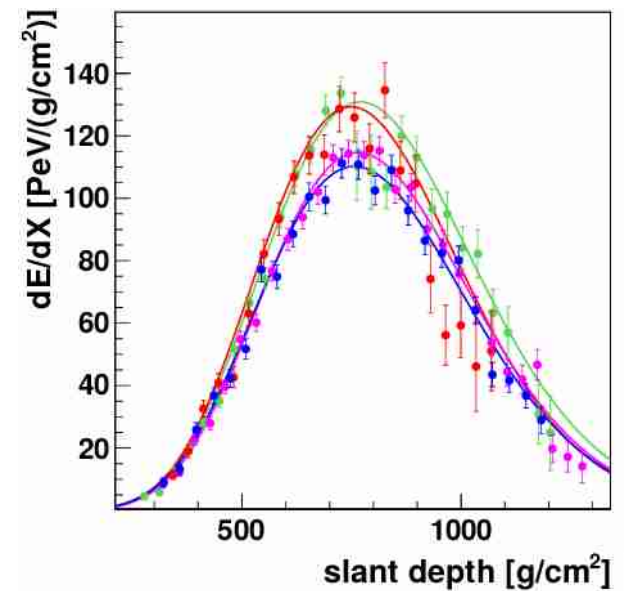
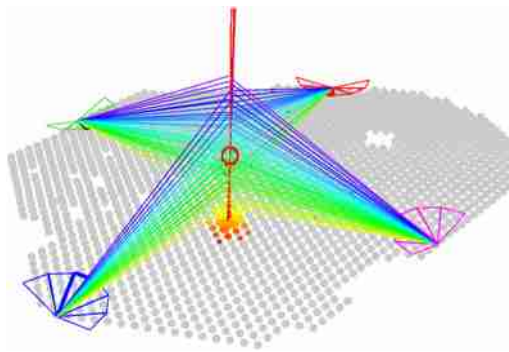
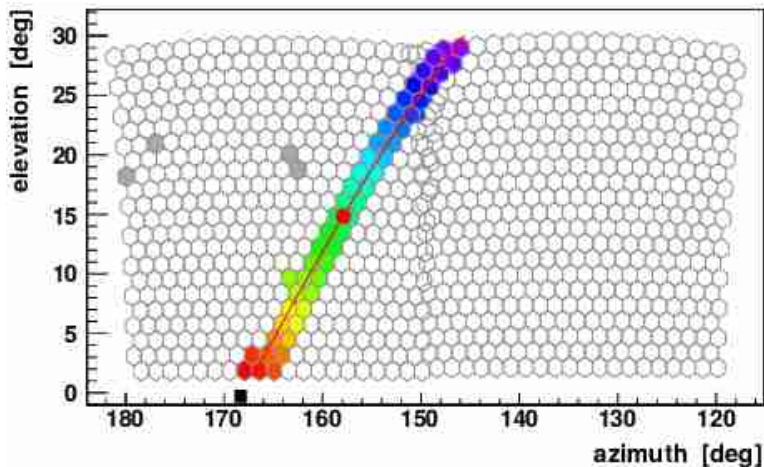
Event reconstruction

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



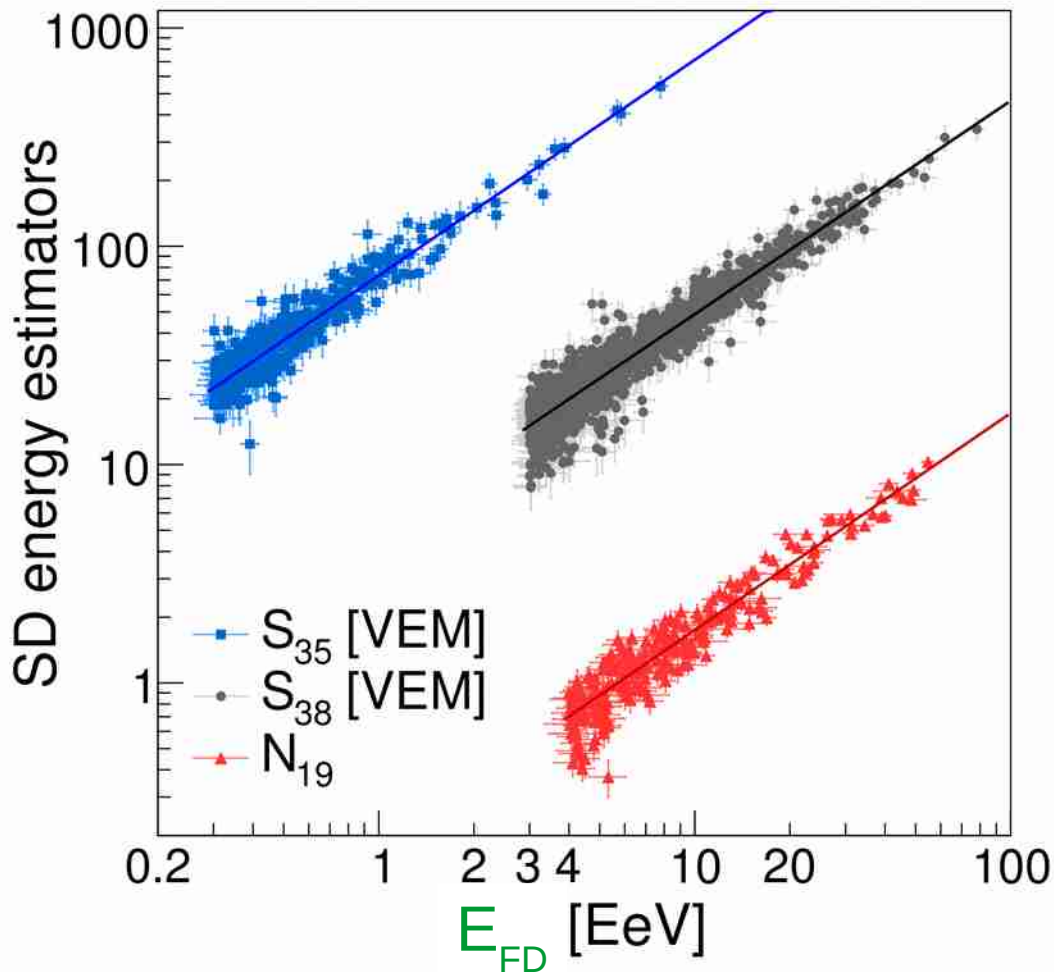
Event reconstruction

- Hybrid = FD + 1 WCD
 - fully efficient > 1 EeV
 - geometry from trigger times of FD pixels and 1 WCD
 - measurement of energy deposit in air \rightarrow 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 = independent SD and Hybrid rec.

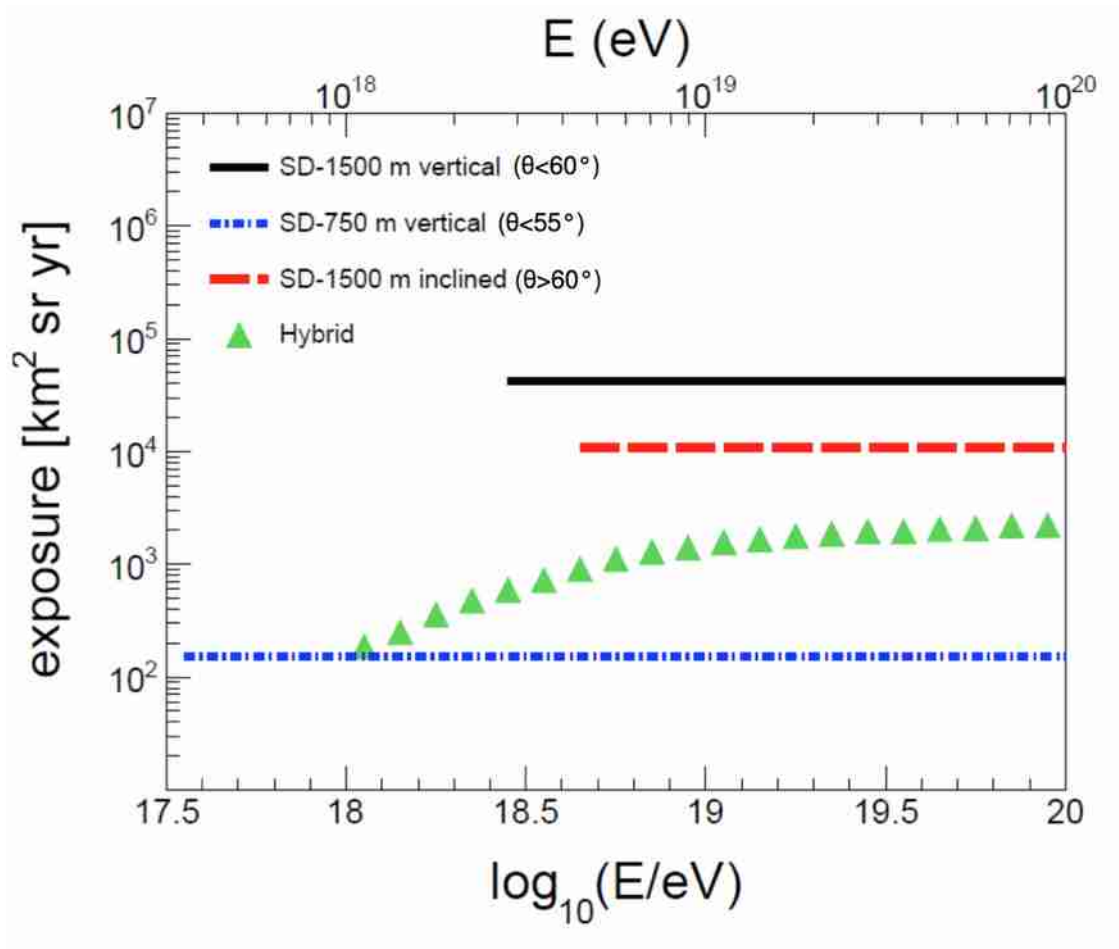


$$E = A \Sigma^B, \Sigma = S_{35}, S_{38}, N_{19}$$

- $A = (1.29 \pm 0.06) \times 10^{-2} \text{ EeV}$
 $B = 1.01 \pm 0.01$
 $E \text{ resolution } (13 \pm 1)\%$
- $A = (0.187 \pm 0.004) \text{ EeV}$
 $B = 1.023 \pm 0.006$
 $E \text{ resolution } (15.3 \pm 0.4)\%$
- $A = (5.71 \pm 0.09) \text{ EeV}$
 $B = 1.01 \pm 0.02$
 $E \text{ resolution } (19 \pm 1)\%$

Exposure

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

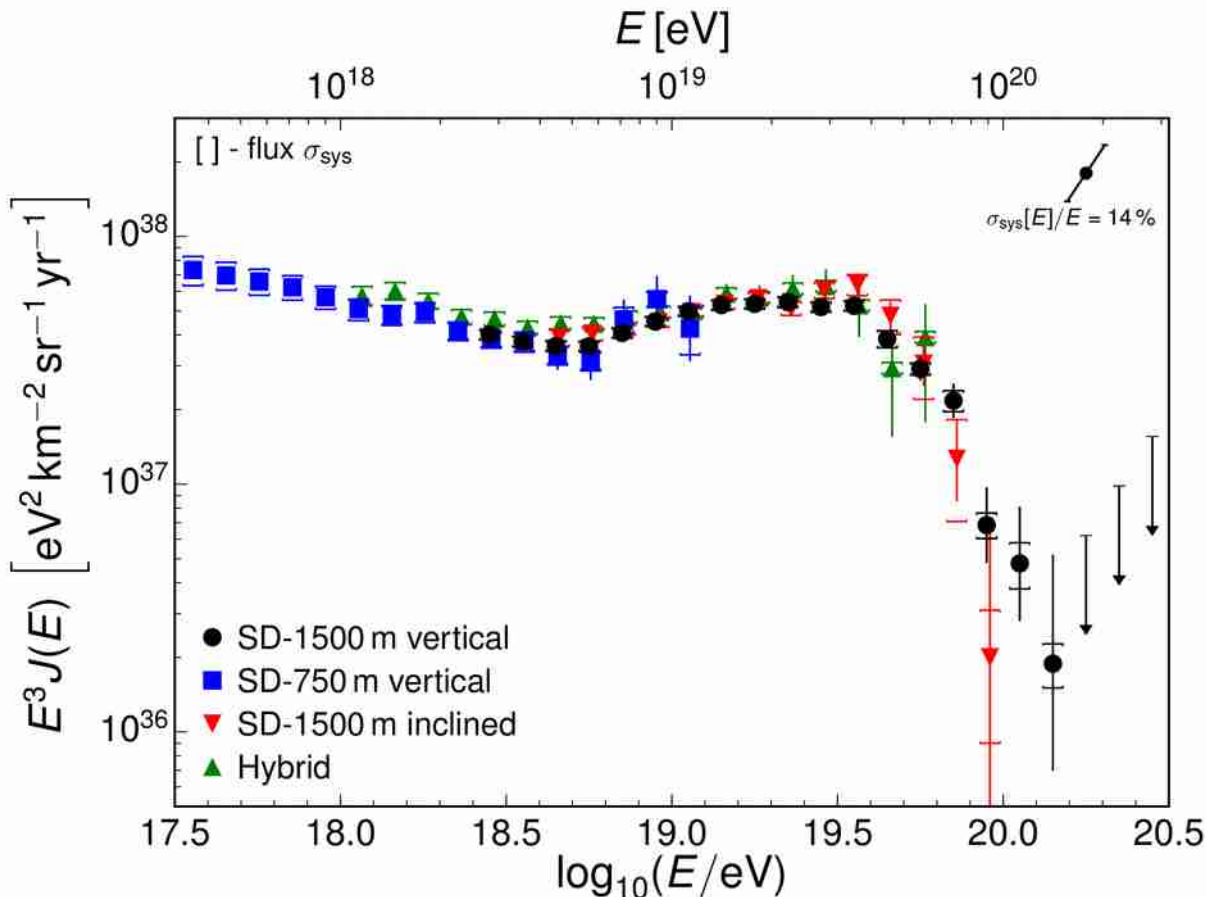


10 years of data:

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%

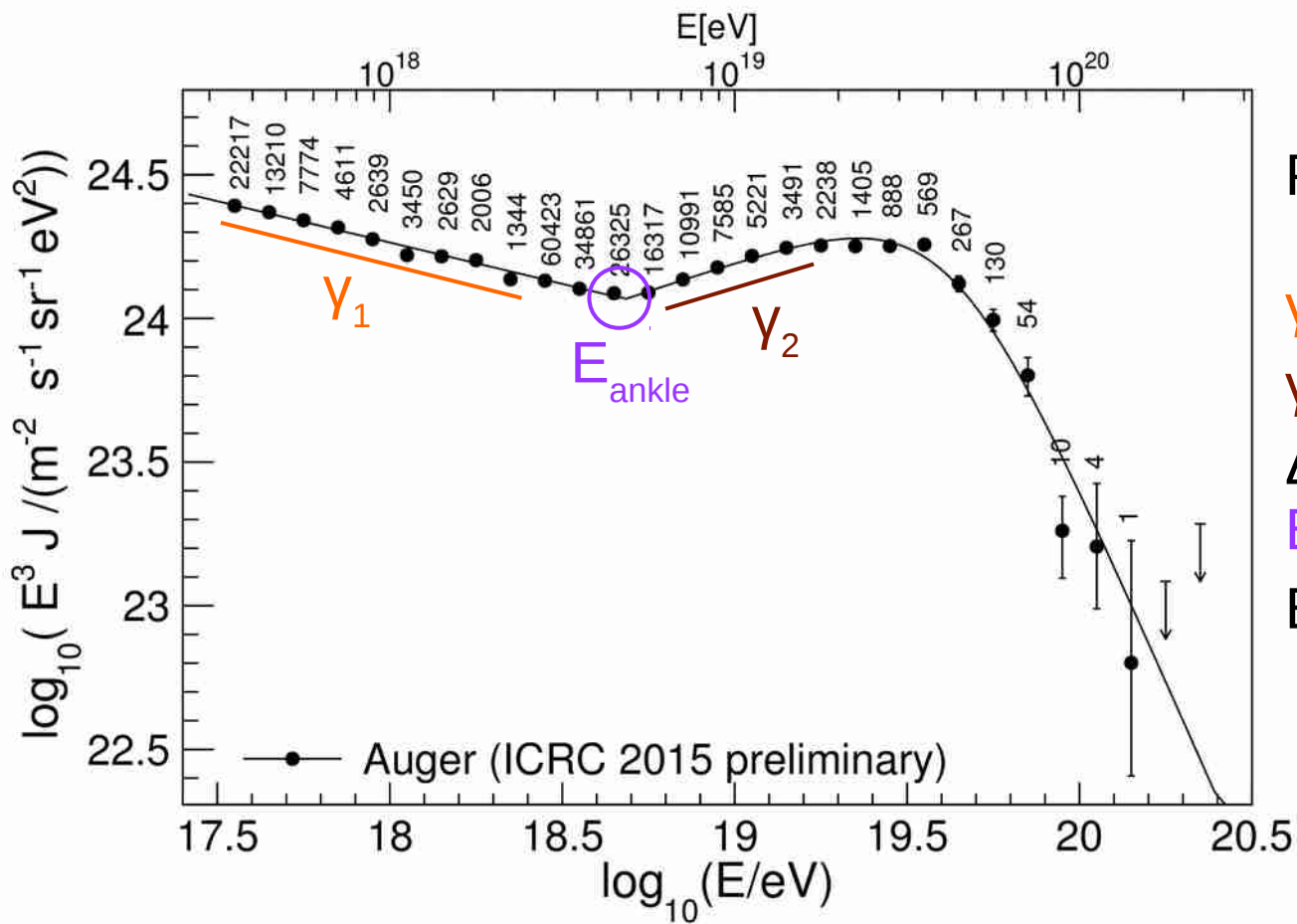
SD inclined: 5%

SD-750: 14% at 0.3 EeV
<7% at 3 EeV

Hybrid: 10% at 1 EeV
6% at 10 EeV

Combined spectrum

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

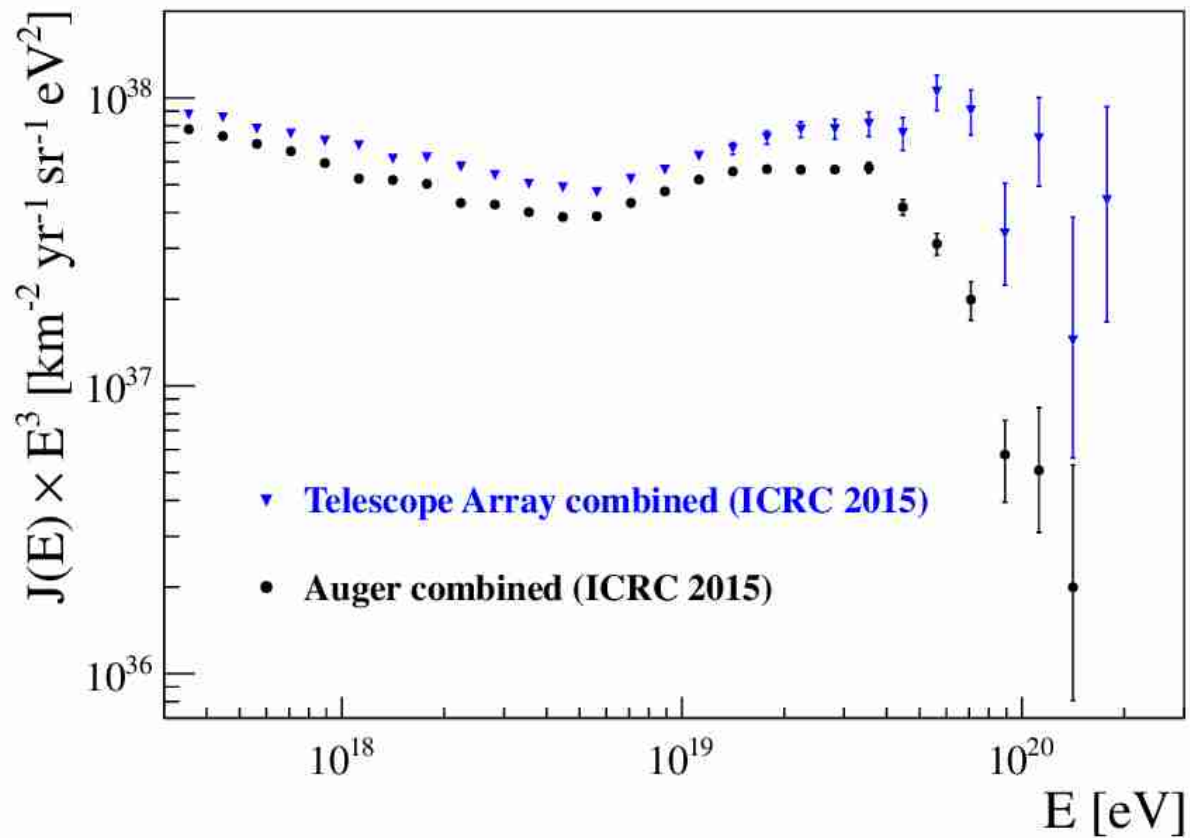


Parameters:

$\gamma_1 = 3.29 \pm 0.02 \pm 0.05$
 $\gamma_2 = 2.60 \pm 0.02 \pm 0.1$
 $\Delta\gamma = 3.1 \pm 0.2 \pm 0.4$
 $E_{ankle} = (4.82 \pm 0.07 \pm 0.8) \text{ EeV}$
 $E_S = (42.1 \pm 1.7 \pm 7.6) \text{ EeV}$

Comparison with TA spectrum

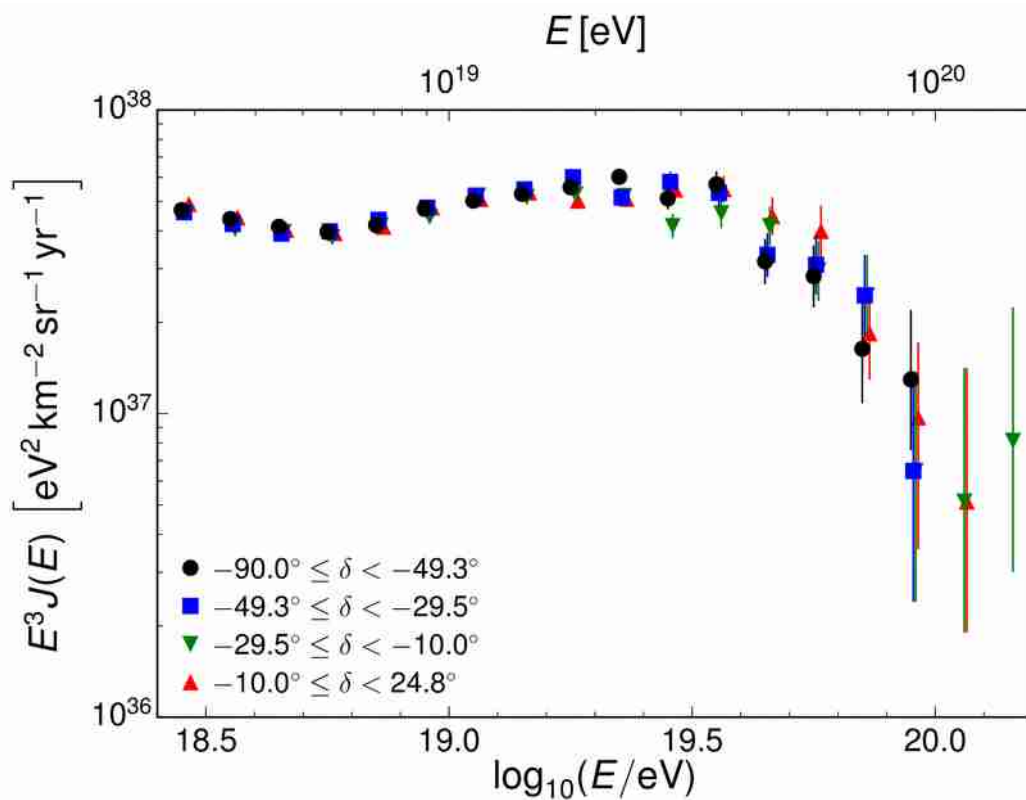
- Compatible within systematic errors up to $\sim 2 \times 10^{19}$ eV
- Tension at high energies not explained (sky region? instrument?)
 - Quantified by: $E_{1/2-Auger} = (24.7 \pm 0.1_{-3.4}^{+8.2}) EeV$ $E_{1/2-TA} = (60 \pm 7) EeV$



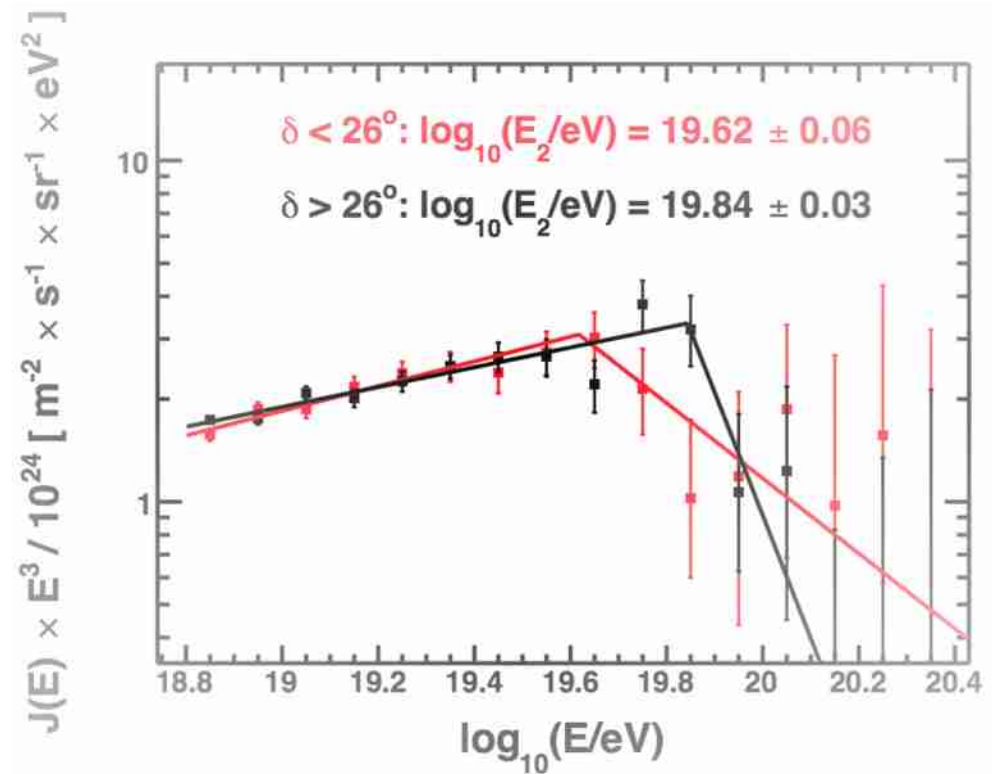
Declination dependence

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

Auger

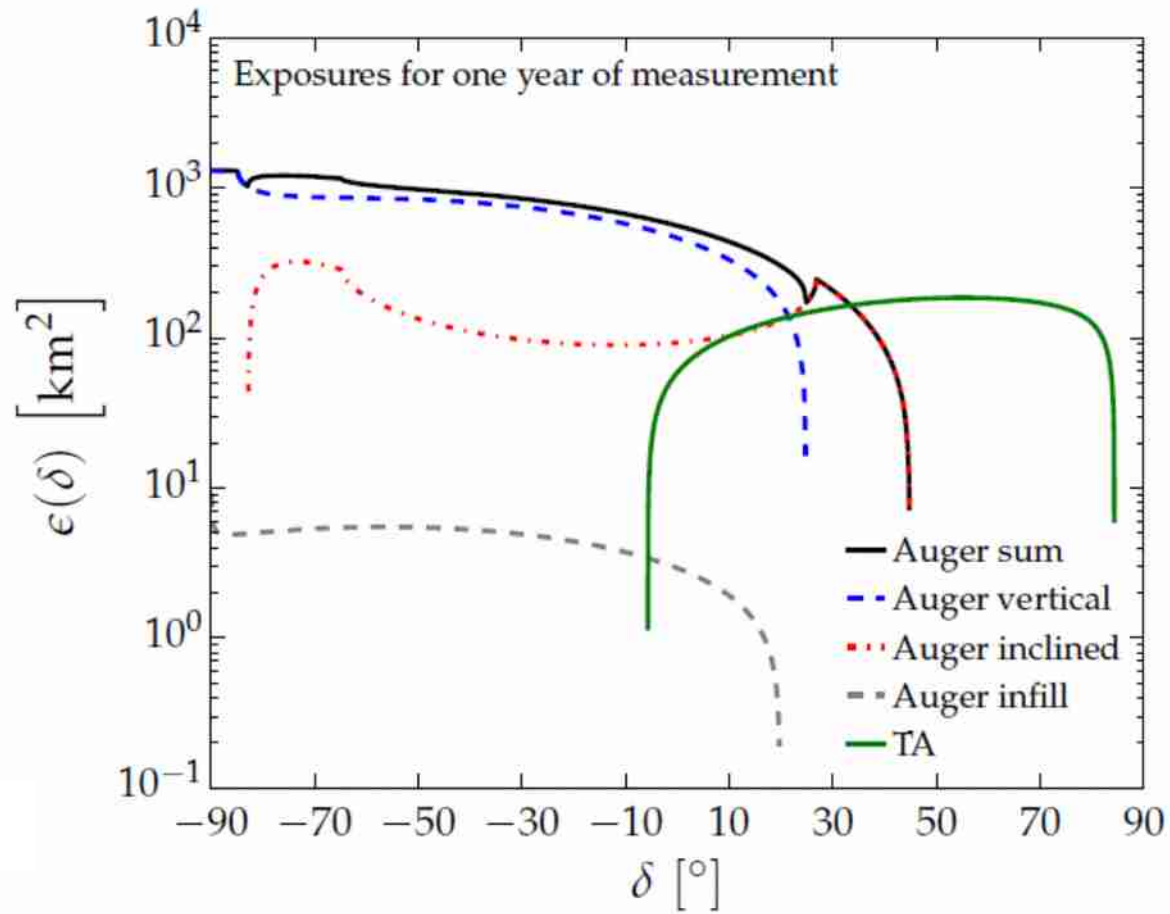


Telescope Array



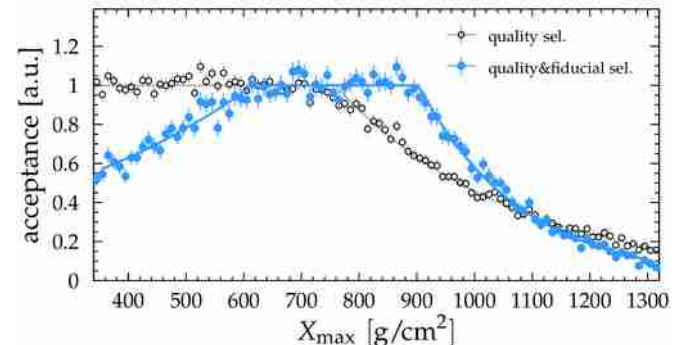
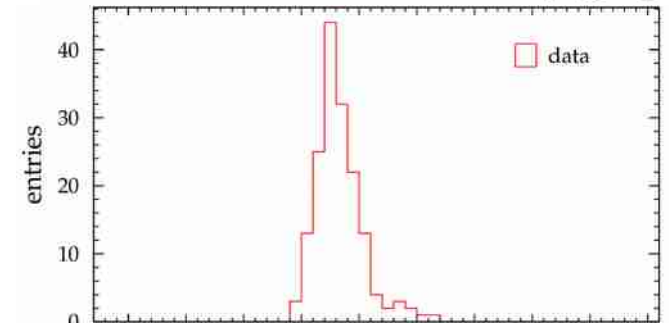
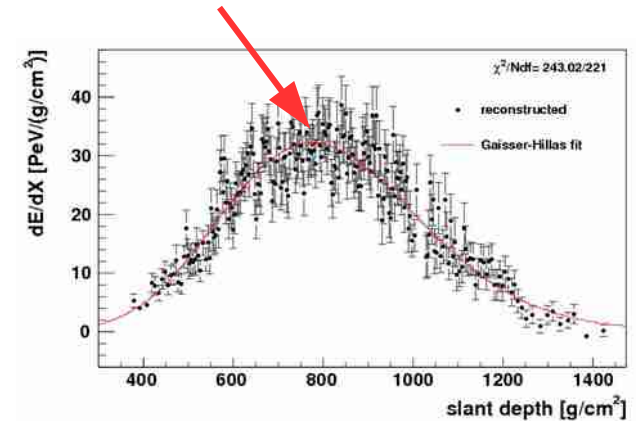
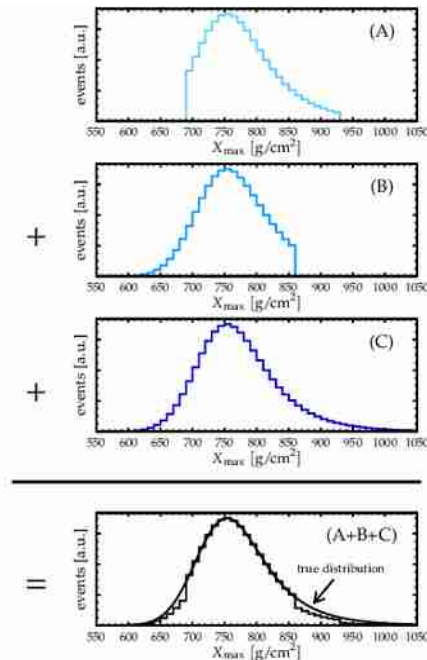
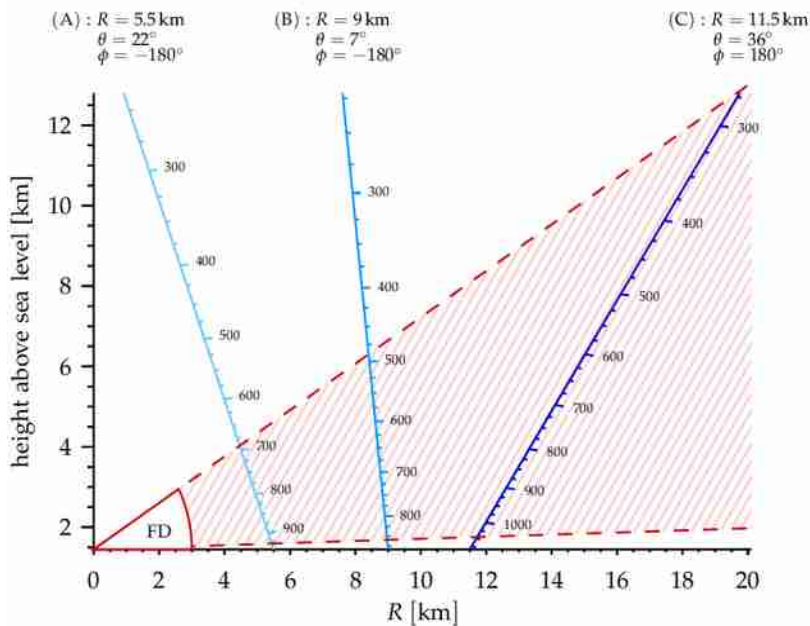
Exposure vs. declination

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



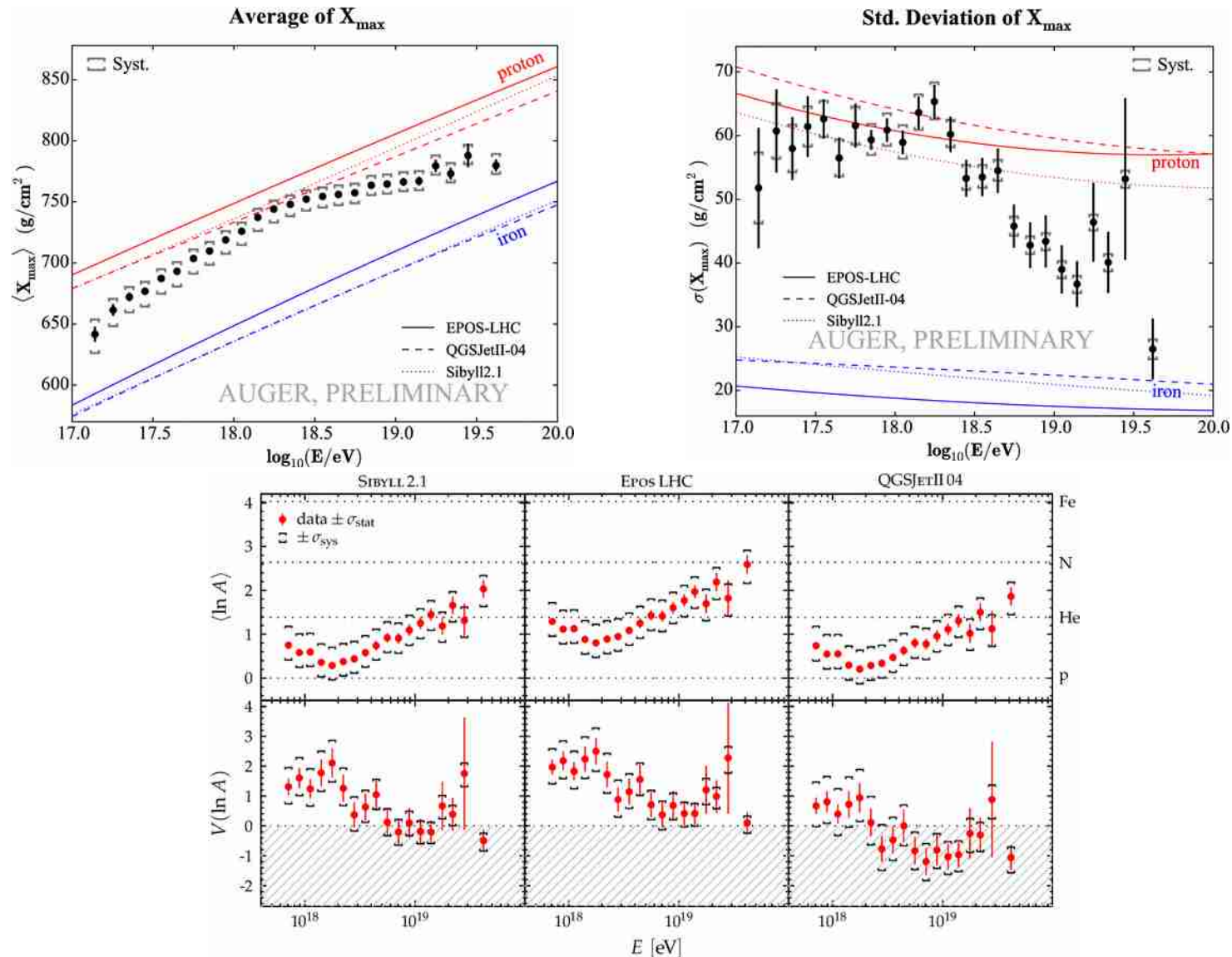
Composition measurement

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



X_{\max} moments

- From full X_{\max} distributions

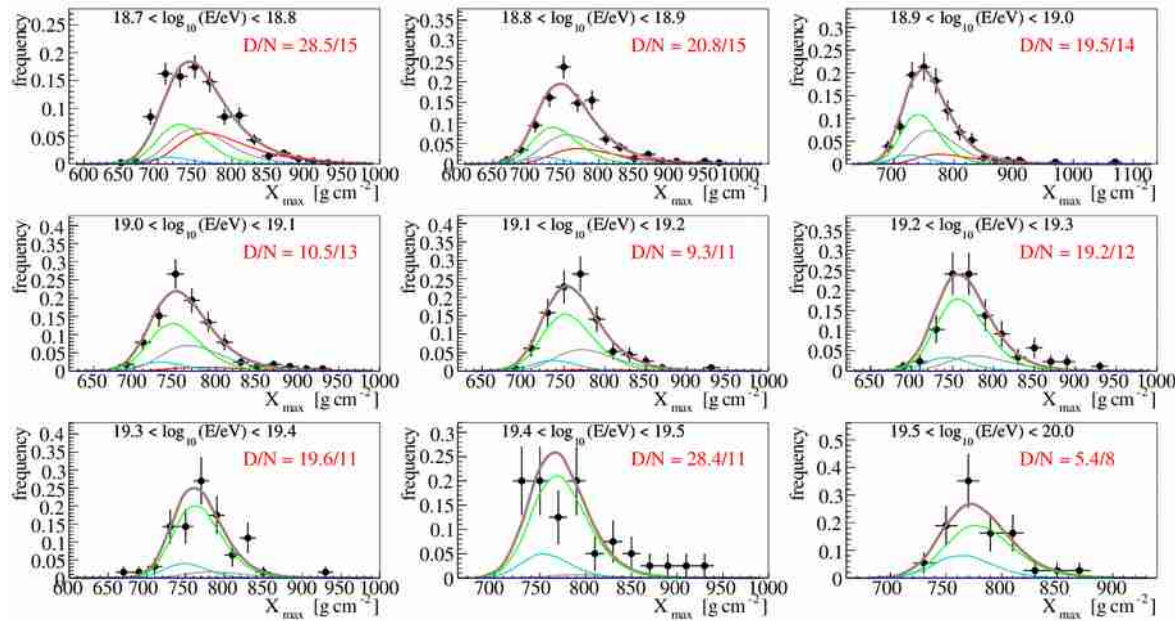


Combined fit

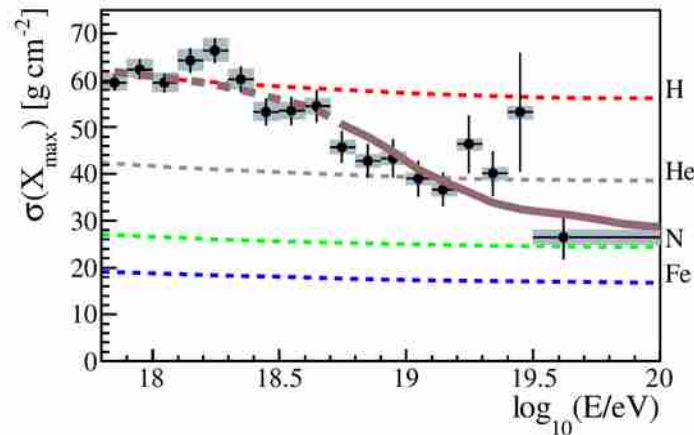
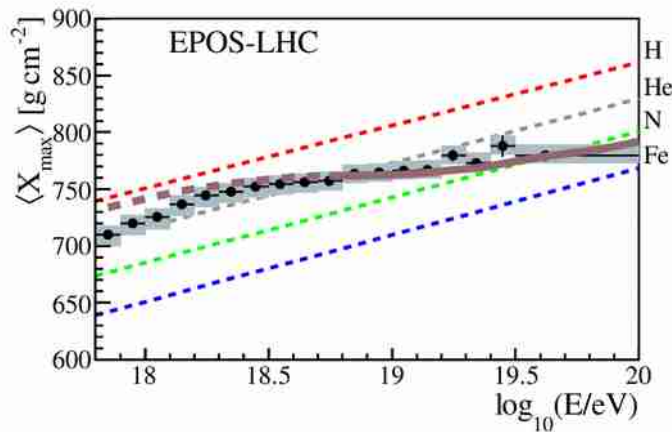
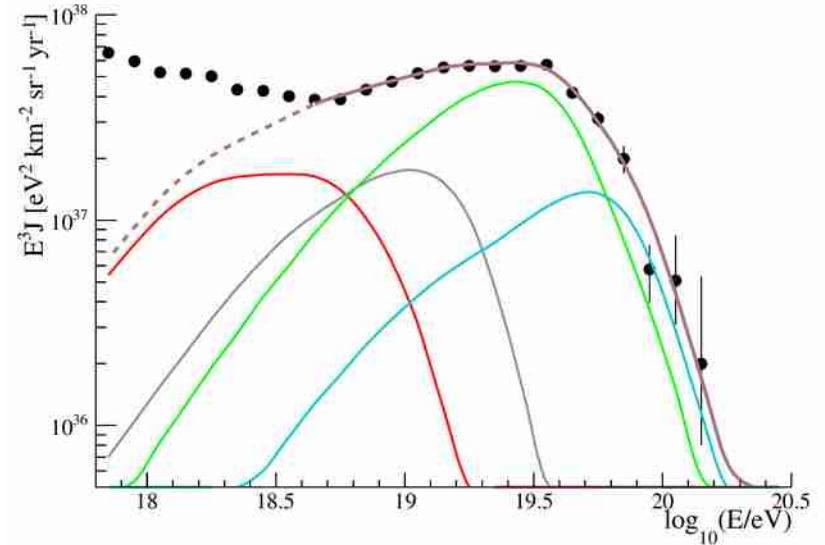
- Fit of energy spectrum together with X_{\max} distributions
- Sources modeled by
 - spectral index γ ($dN/dE \sim E^{-\gamma}$)
 - Composition fractions f_A – H, He, N, Si, Fe
 - maximum rigidity R_{cut}
- 1D simulation of propagation from source to Earth
 - CRPropa and SimProp
 - CMB
 - EBL – Gilmore 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

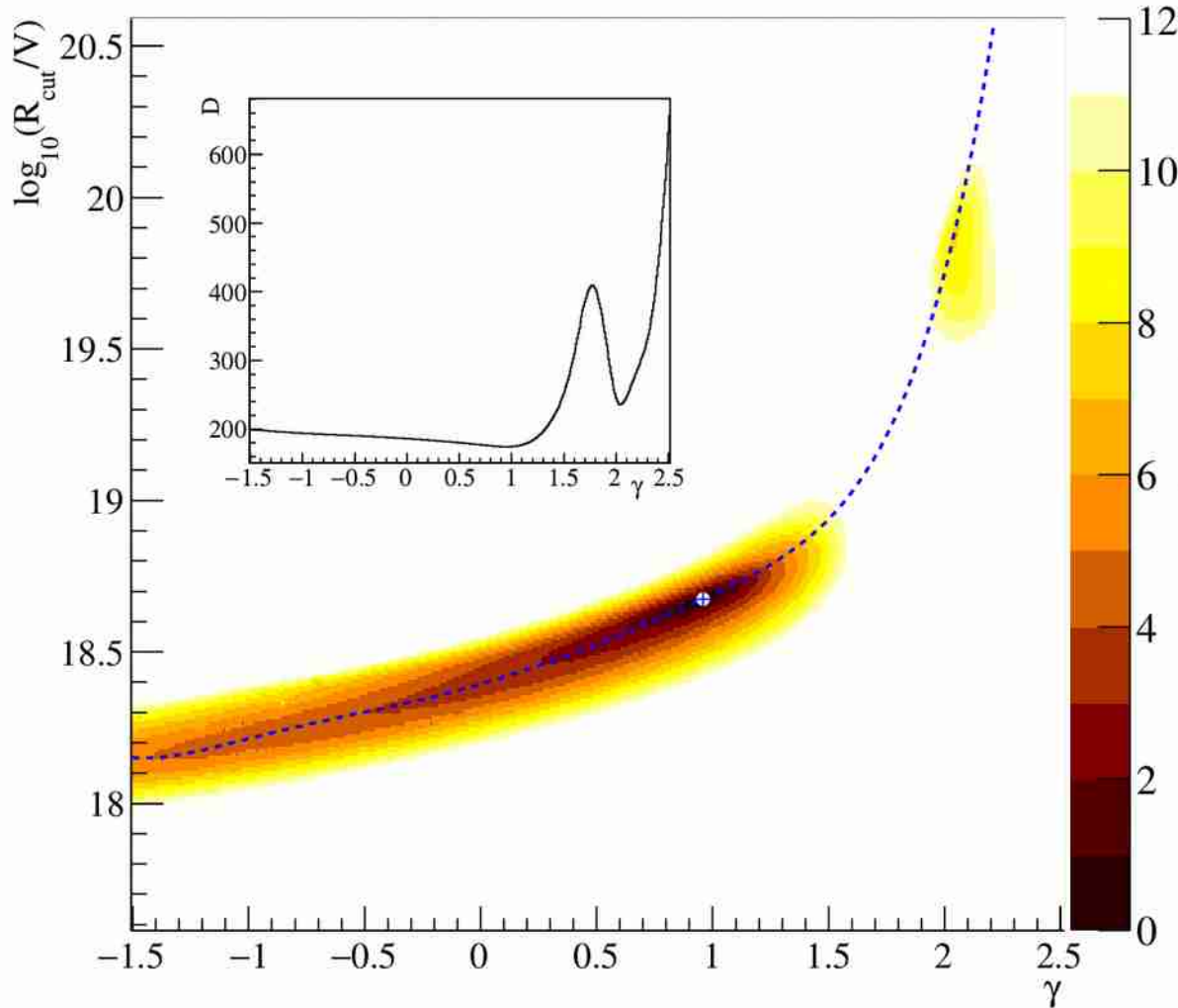


A = 1, 2-4, 5-22, 23-38, total



Source parameters

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



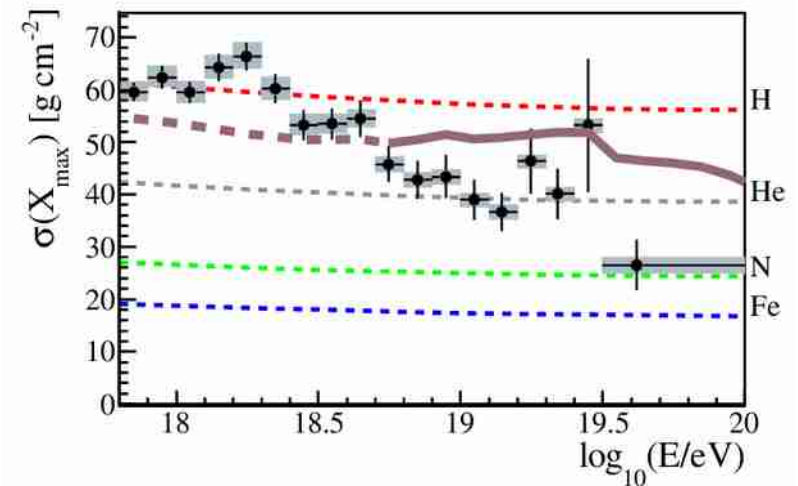
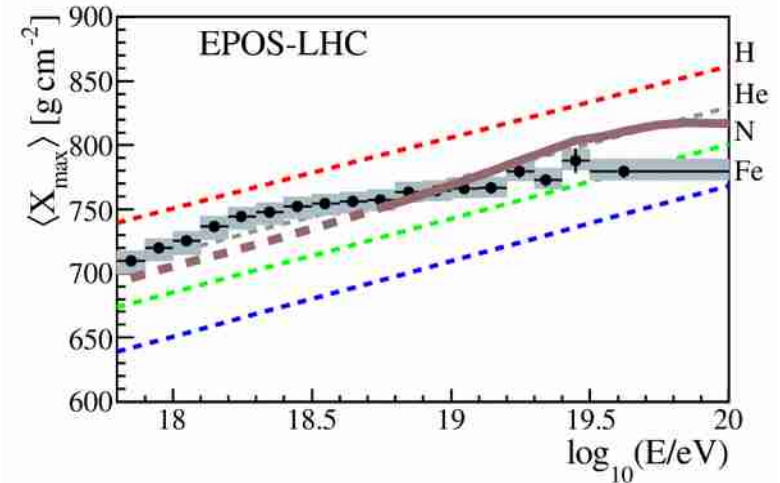
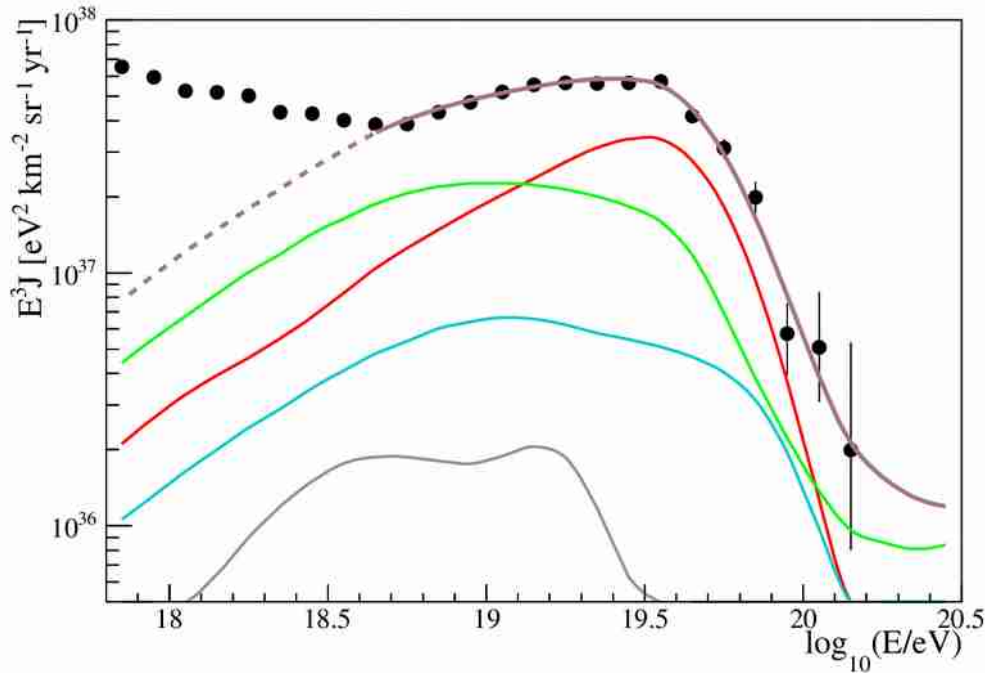
$$D = D(J) + D(X_{max}) = -2 \ln \frac{L}{L^{sat}} = -2 \ln \frac{L_J}{L_J^{sat}} - 2 \ln \frac{L_{X_{max}}}{L_{X_{max}}^{sat}}$$

	1 st minimum	2 nd 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

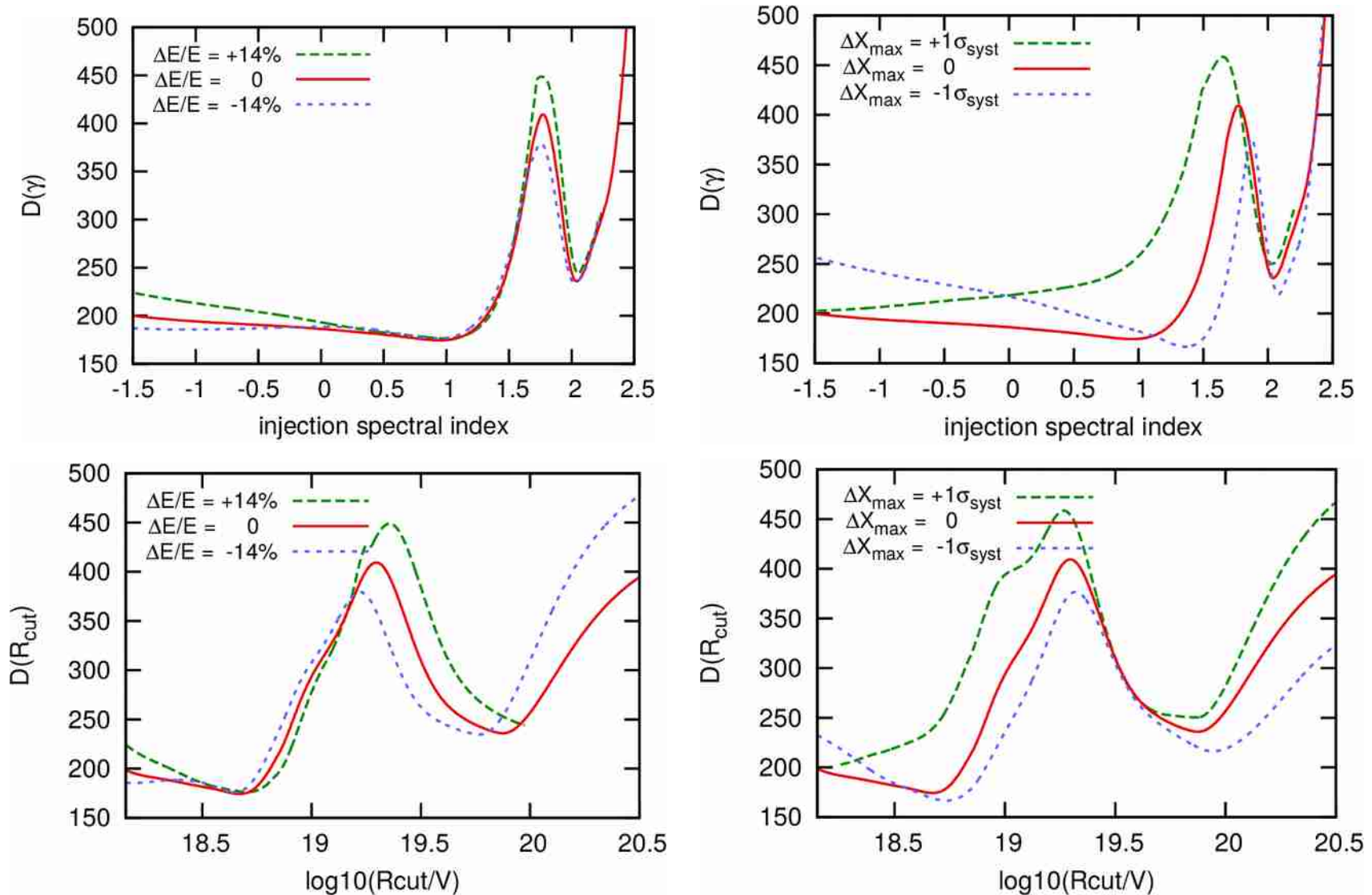
- R_{cut} larger \rightarrow photo-disintegration more important \rightarrow more protons

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

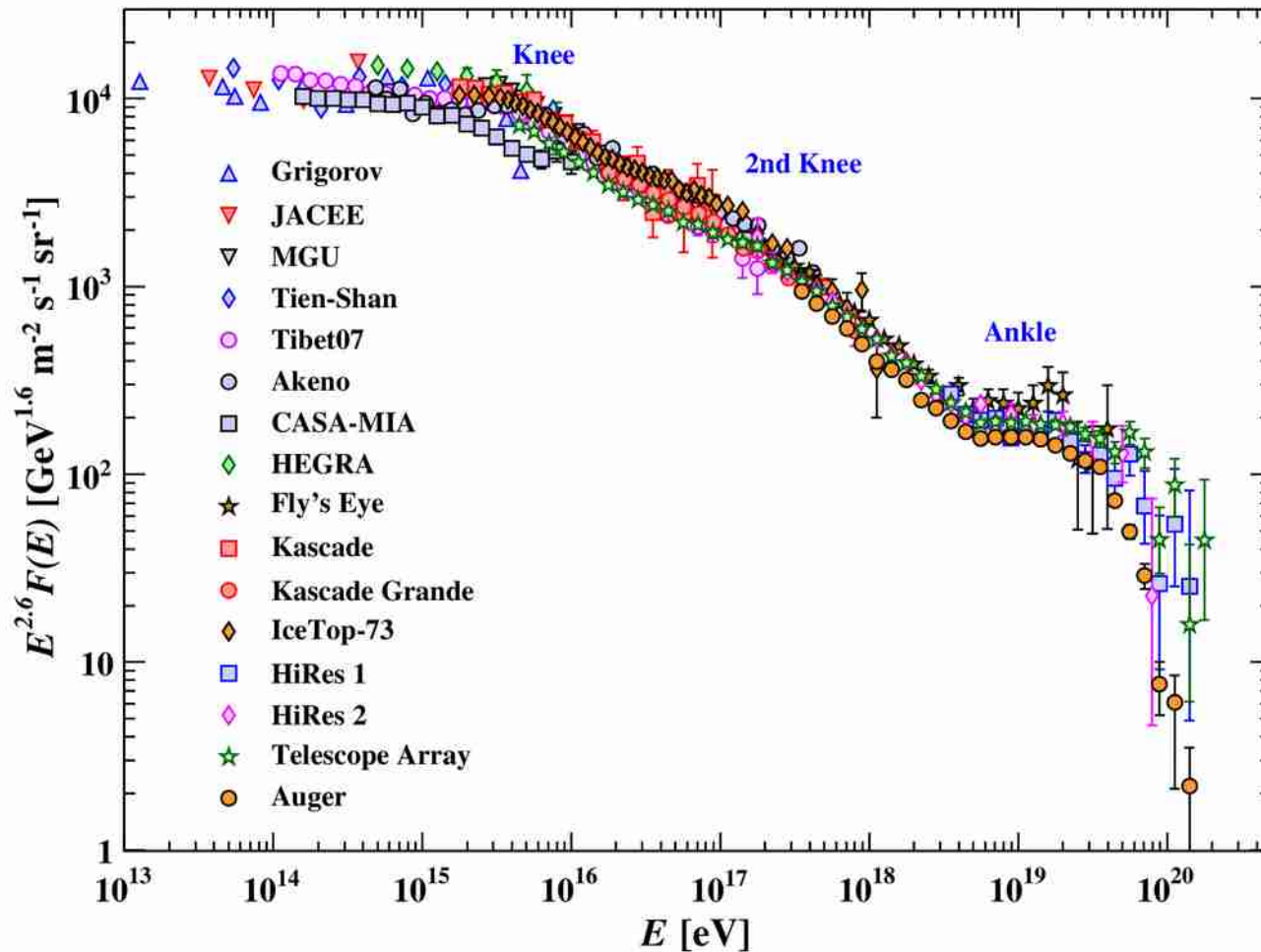


Stability

- Qualitative results robust 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 $\sim 2 \times 10^{19}$ 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%