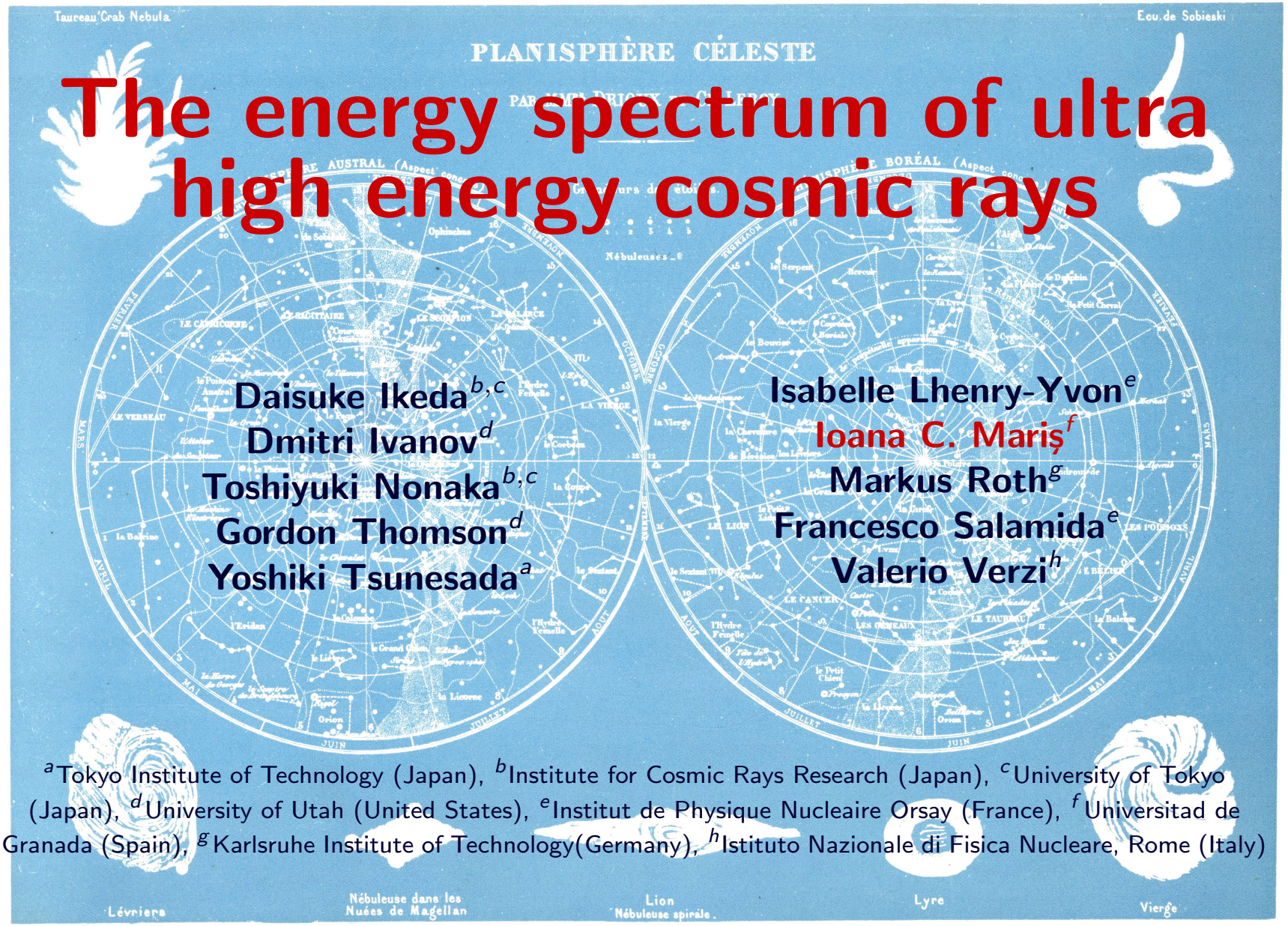

The energy spectrum of ultra high energy cosmic rays

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UHECR energy spectrum working group

Previous meetings

- The first UHECR symposium: Nagoya 2010
- CERN 2012: the first energy spectrum working group created between HiRes, Yakutsk, Telescope Array and Auger

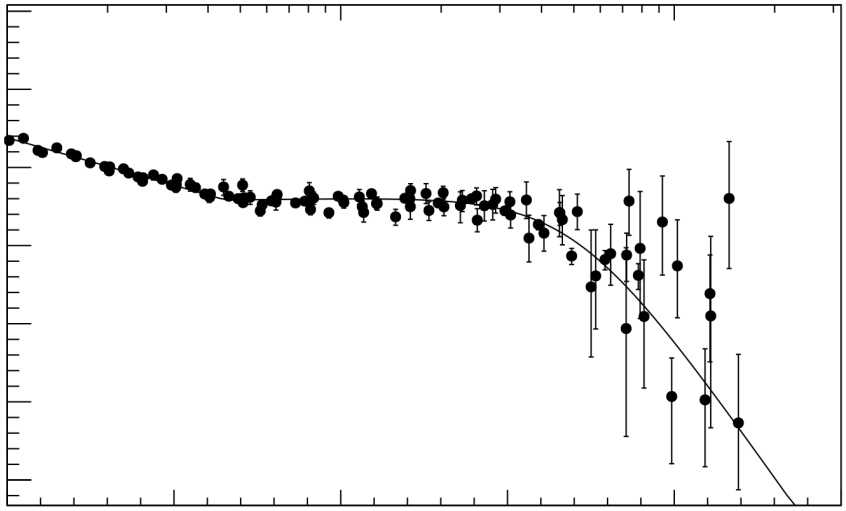
Where we started

- a large amount of information regarding the analysis differences and assumptions in each experiment has been exchanged
- thorough comparisons between energy spectra has been done
- high statistical precision measurements of the *ankle* and *flux suppression*

Where we were heading (discussions during 5 online meetings)

- Can the differences be explained by different systematic uncertainties when the same assumptions in the analysis are used?
- Is the *ankle* region solved regarding spectral indices and energy?
- Is there a difference between the flux of cosmic rays in the Northern/Southern hemispheres?

After UHECR 2012



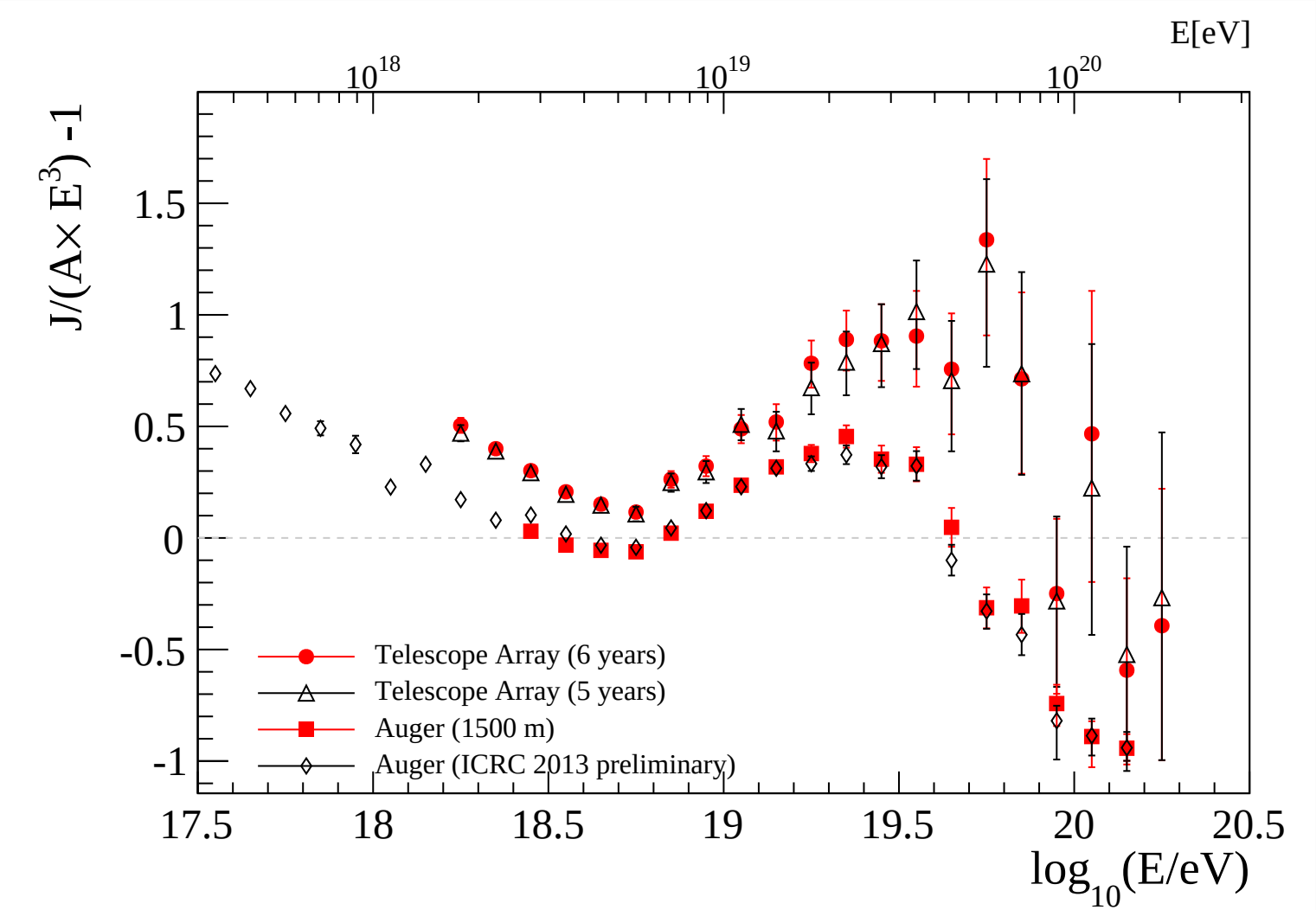
Highlights of UHECR 2012

- *ankle* confirmed (all experiments)
- flux suppression confirmed (TA/HiRes/Auger)
- 20% energy difference not fully explained
- continue collaboration and exchange of information between the experiments

What is new?

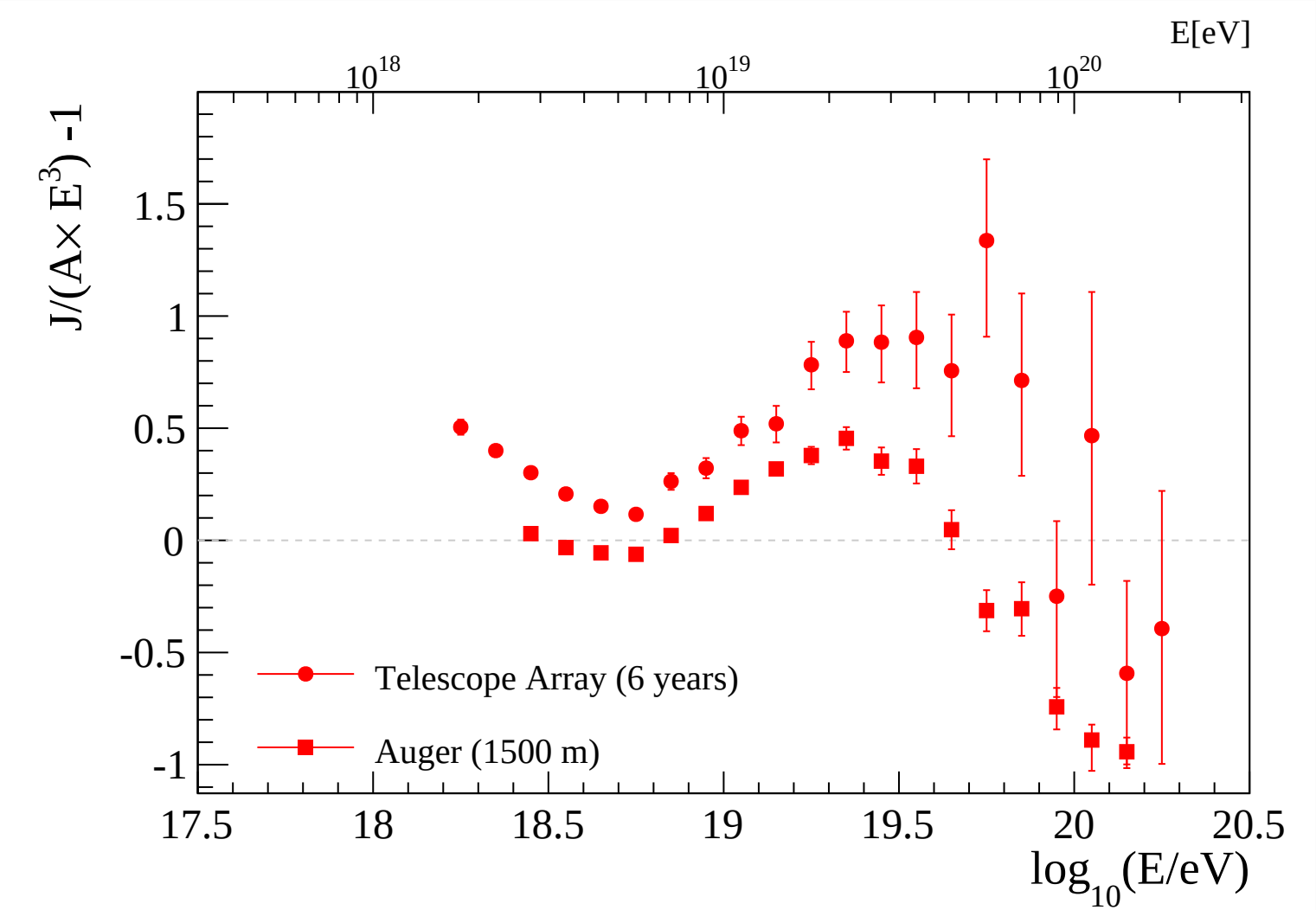
- Auger energy scale has changed and energy systematic uncertainties are largely reduced
- increased statistics for the Auger and TA data (6 years)

Where do we start from



$\Rightarrow$ Can the differences be explained by the systematic uncertainties and differences in the analysis?

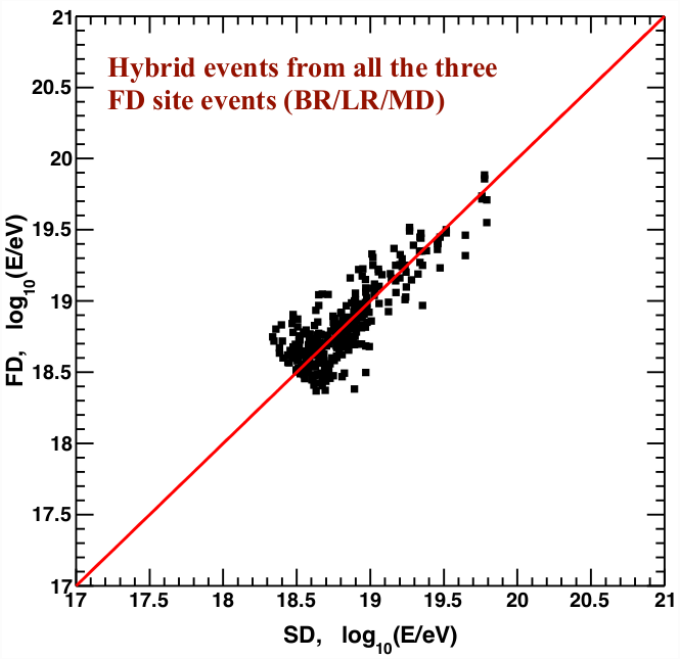
Where do we start from



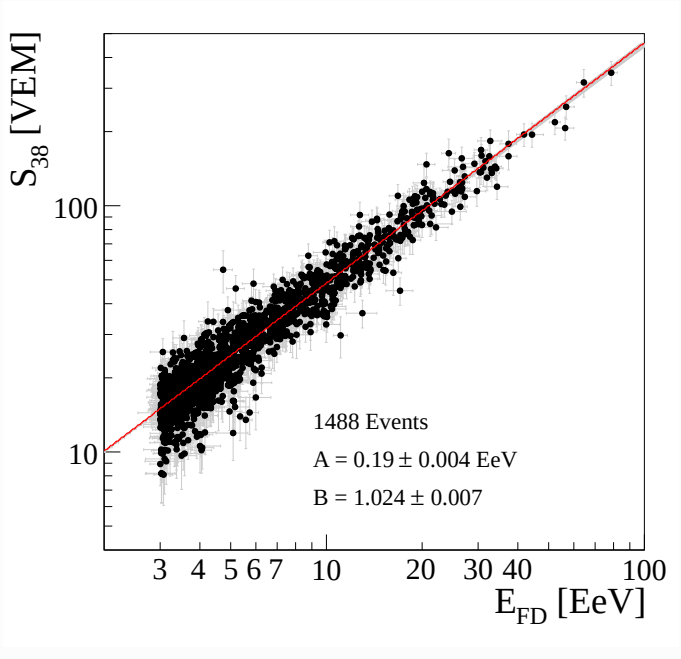
$\Rightarrow$ Can the differences be explained by the systematic uncertainties and differences in the analysis?

Energy calibration and systematic uncertainties

Telescope Array

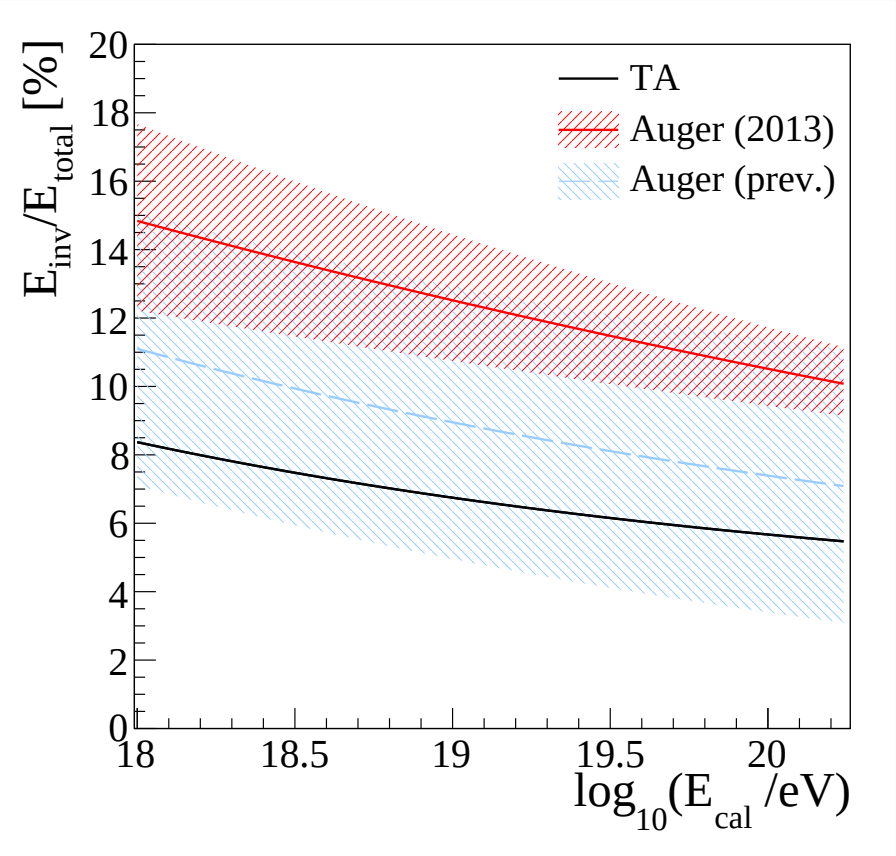


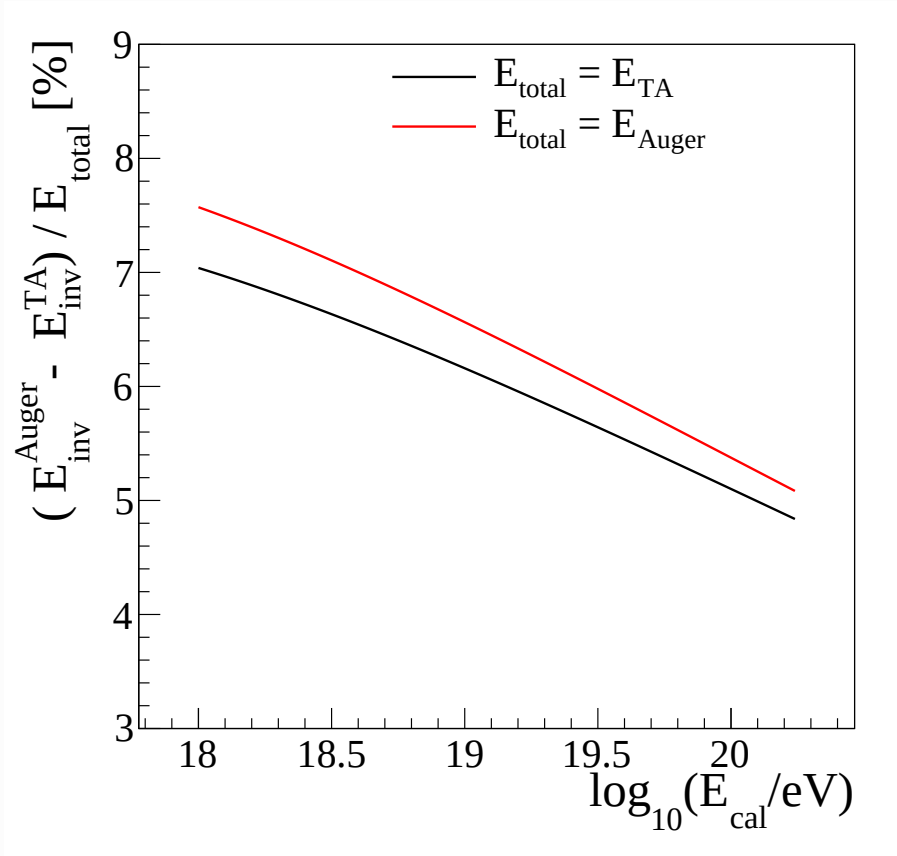
Auger



	Auger[%]	Telescope Array [%]
Atmosphere	3.4 - 6.2	11
Detector	9.9	10
Reconstruction	6.5 - 5.6	9
Stability of the energy scale	5	-
Sub-total	13	17
Invisible energy	3 - 1.5	5
Fluorescence yield	3.6	11
Total	14	21

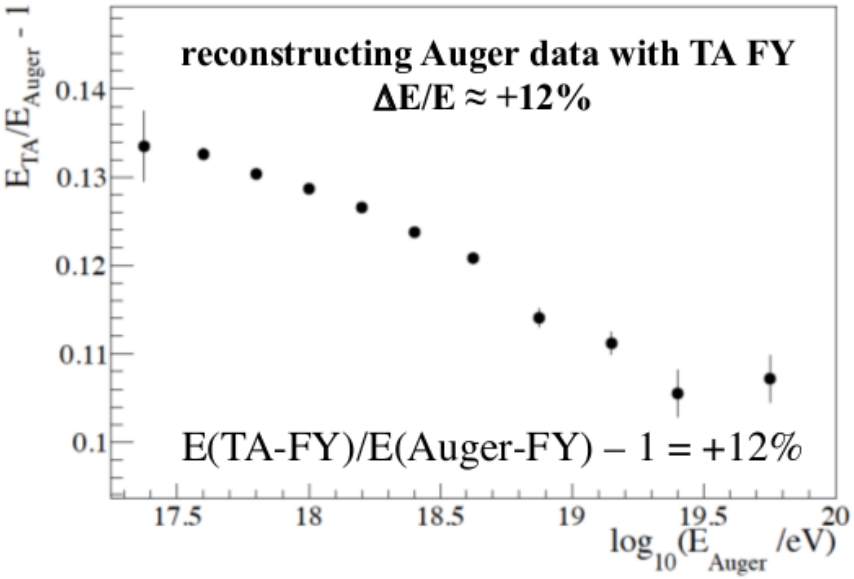
Invisible energy

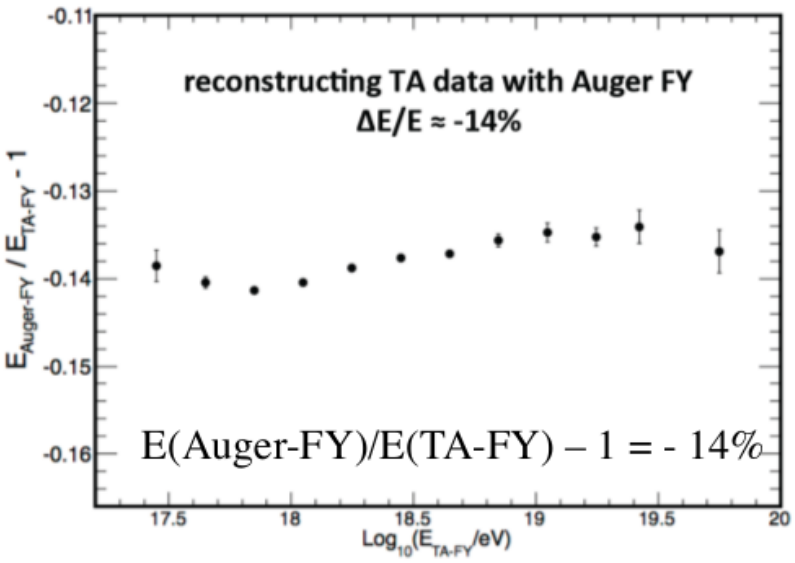




- Auger (prev): mixed composition (H. M. J. Barbosa et al.,Astropart. Phys. 22 (2004) 159)
- Auger (2013): data driven (M. Tueros ICRC 2013 #0705 arXiv:1307.5059)
- Telescope Array: proton composition (Astropart. Phys. 61 (2015) 93-101)

Fluorescence yield



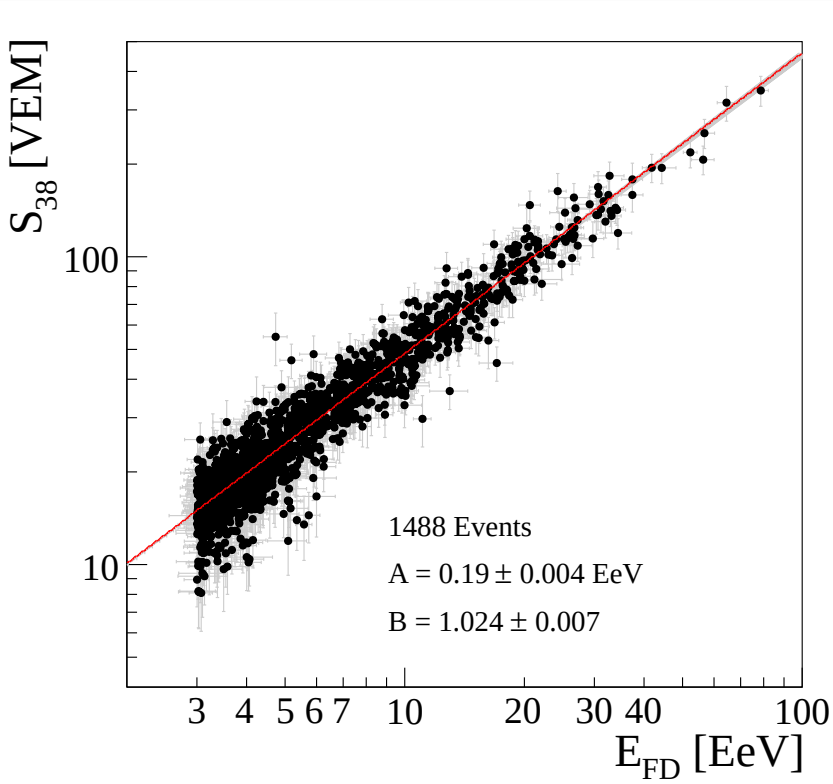


	E(TA-FY)/E(Auger-FY) - 1	E(Auger-FY)/E(TA-FY) - 1
Auger	+12%	-11%
TA	+16%	-14%

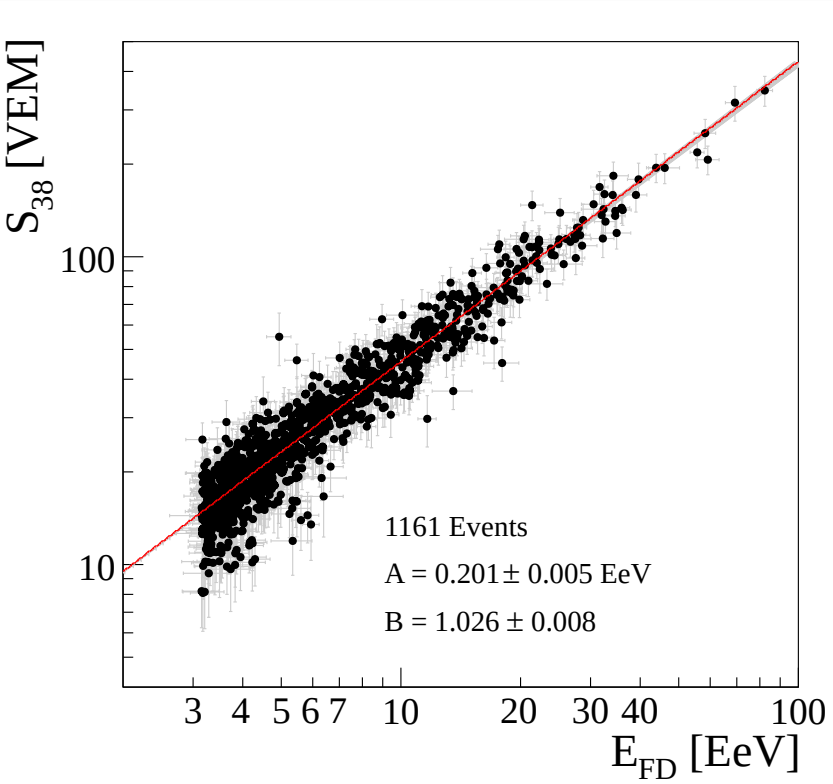
- Auger: AIRFLY (spectrum, absolute intensity, (p,T,h) dependency)
- TA: spectrum- FLASH, absolute intensity- Kakimoto, (p,T)- Kakimoto
- optical efficiency ($\approx$ 2%), wavelength dependence of the Rayleigh/ aerosol scattering cross-section, FD-shower distance, Cherenkov fraction...

The influence of the FY and of the invisible energy

Auger standard reconstruction

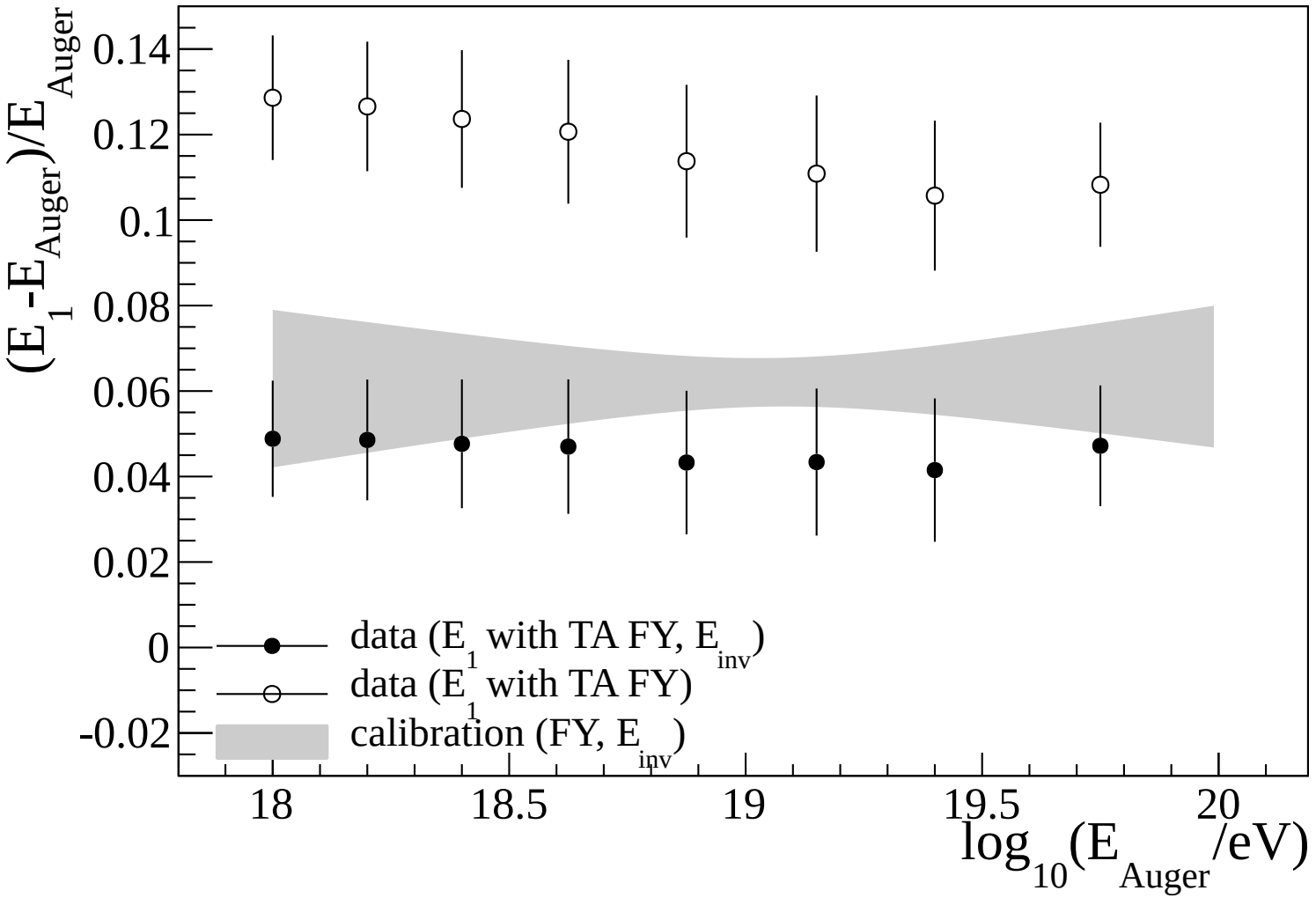


Auger using TA FY and invisible energy



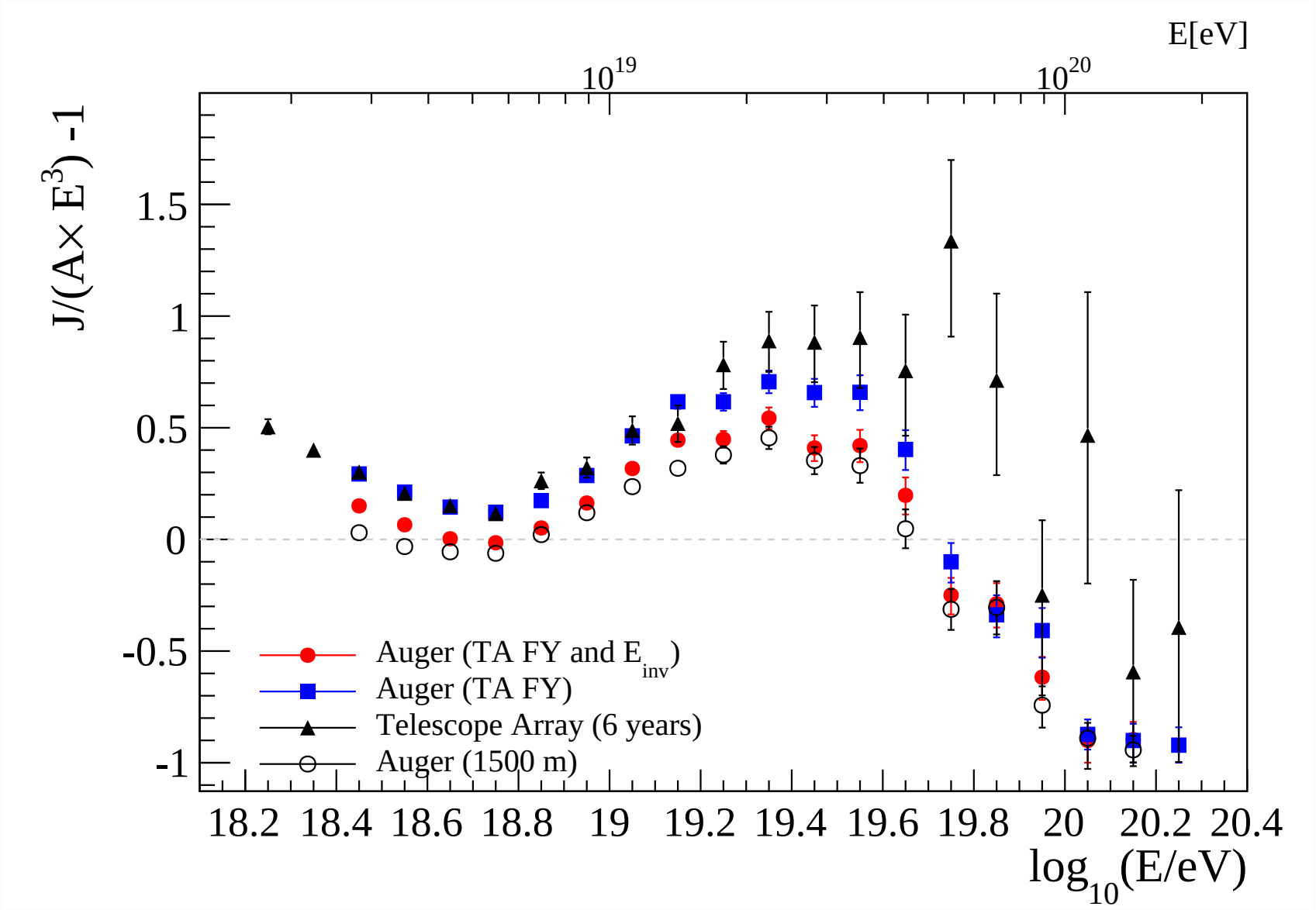
$\Rightarrow$ Perform end-to-end analysis of the SD energy spectrum

Energy changes with TA settings

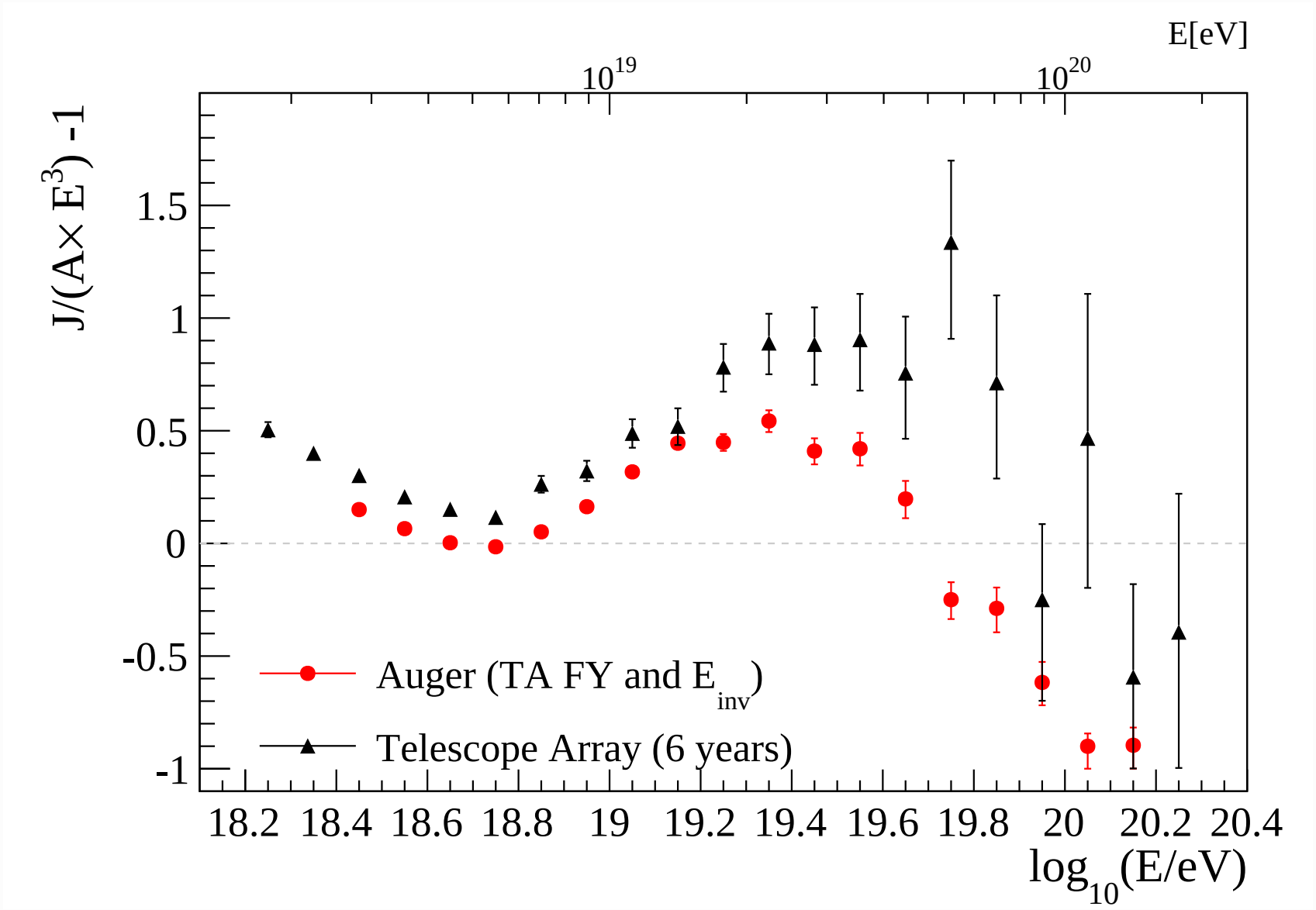


⇒ Using the TA FY and the TA invisible energy the Auger energy scale would change by 6%

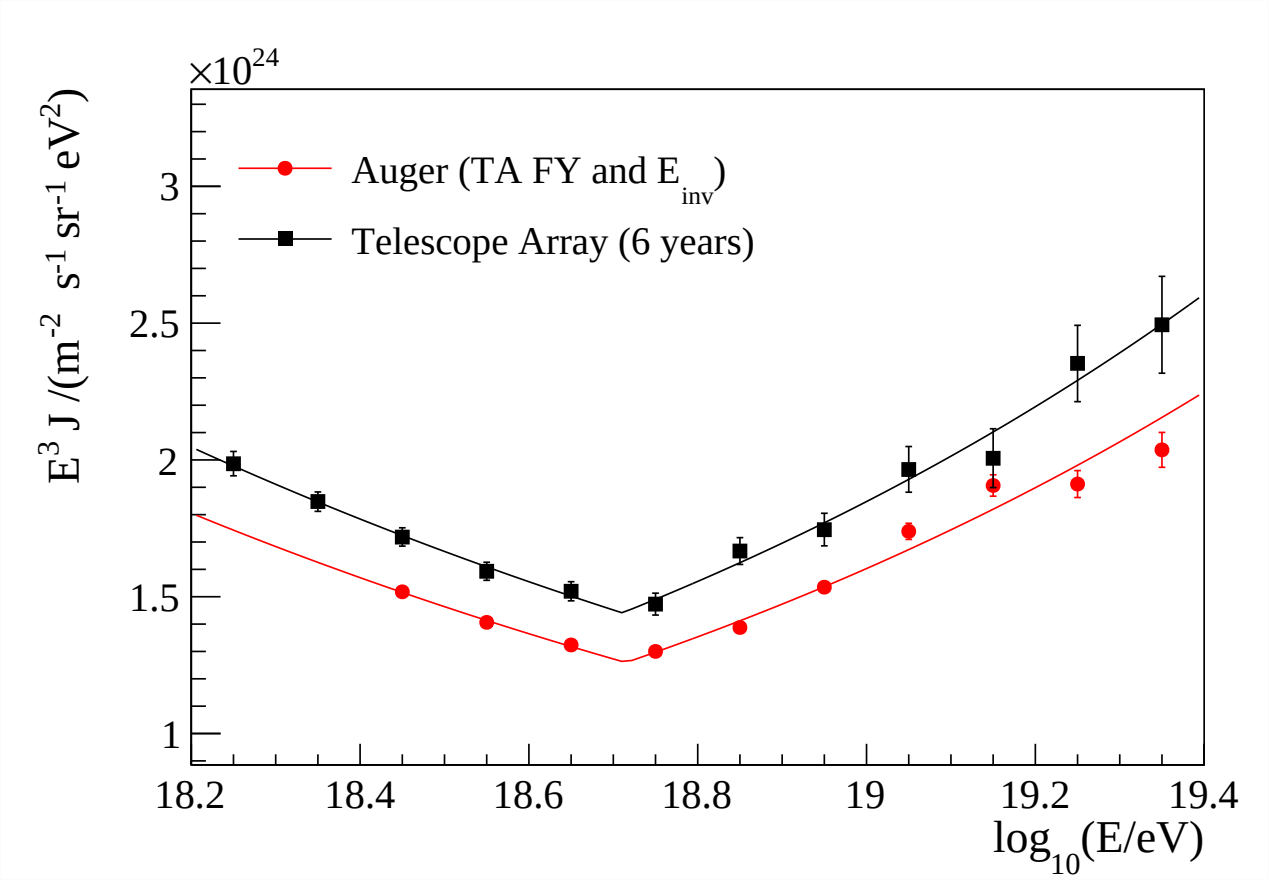
Energy spectra



Energy spectra

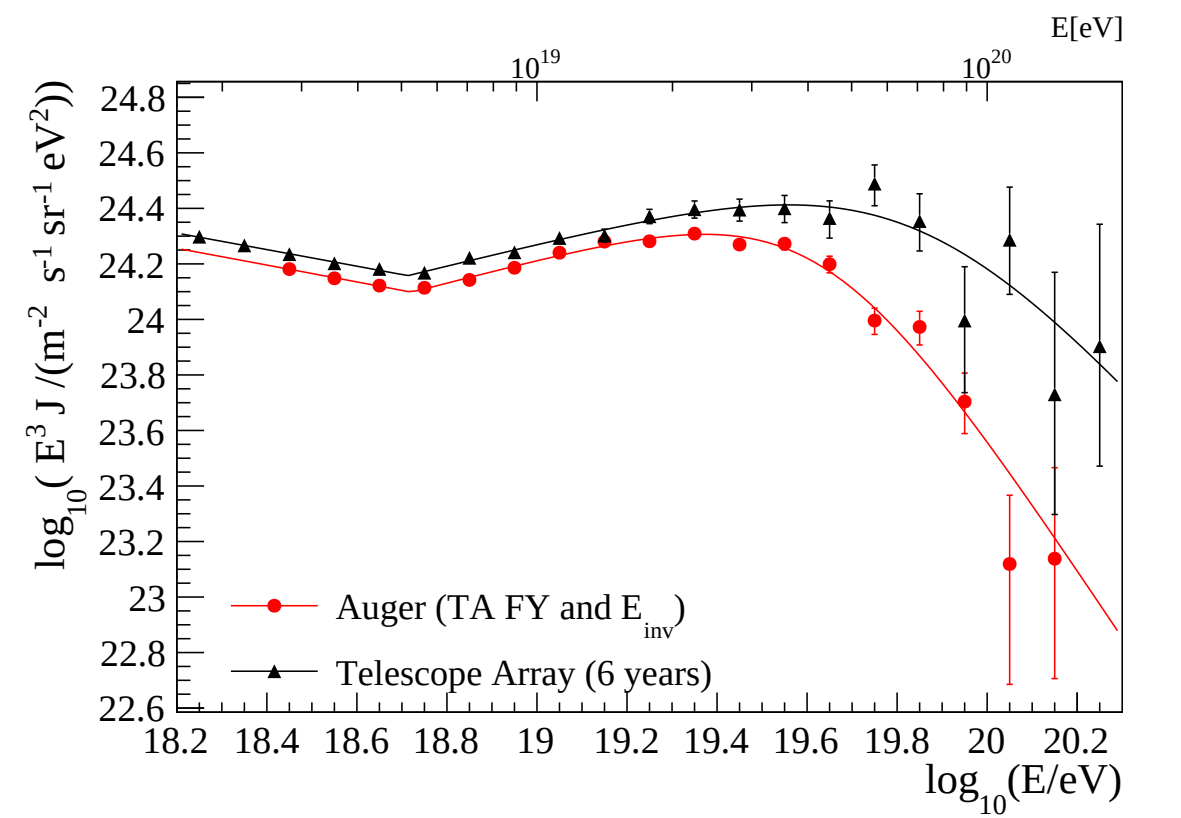


The ankle energy region



- $\log_{10}(E_{TA}/eV) = 18.70 \pm 0.02$, $\log_{10}(E_{Auger,TAset}/eV) = 18.71 \pm 0.004$
- $\gamma_{TA} = -3.30 \pm 0.03$, $\gamma_{Auger,TAset} = -3.30 \pm 0.03$
- $\gamma_{TA} = -2.67 \pm 0.03$, $\gamma_{Auger,TAset} = -2.63 \pm 0.02$

Spectral features



Auger (TA FY and inv. en):

$\gamma_1 = -3.30 \pm 0.03$, $\gamma_1 = -2.57 \pm 0.02$

$\lg(E_1/eV) = 18.72 \pm 0.01$

$\lg(E_{1/2}/eV) = 19.64 \pm 0.01$

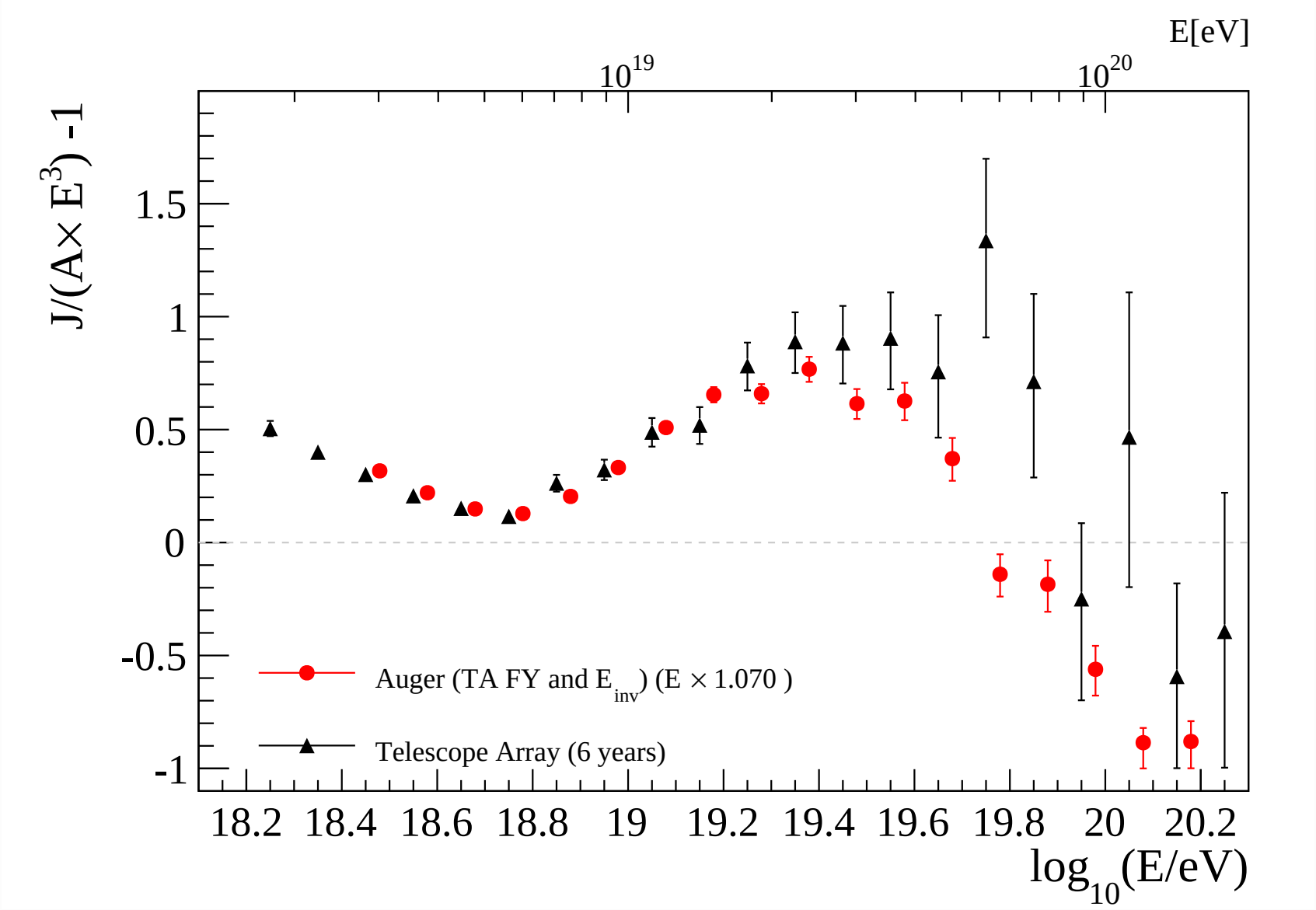
Telescope Array:

$\gamma_1 = -3.30 \pm 0.03$, $\gamma_2 = -2.62 \pm 0.05$

$\lg(E_1/eV) = 18.71 \pm 0.02$

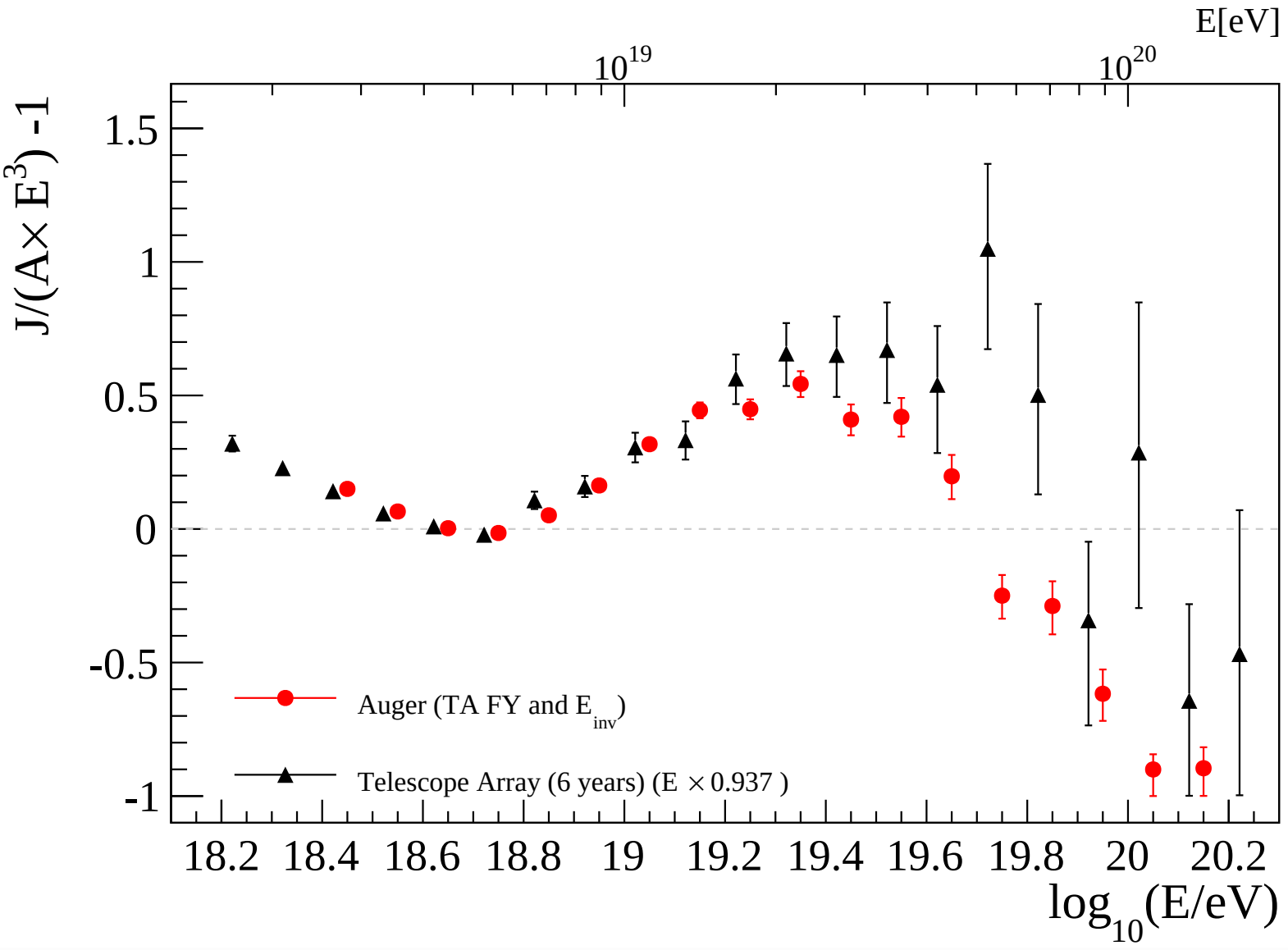
$\lg(E_{1/2}/eV) = 19.88 \pm 0.06$

Normalizing the energy spectra (constant energy shift)



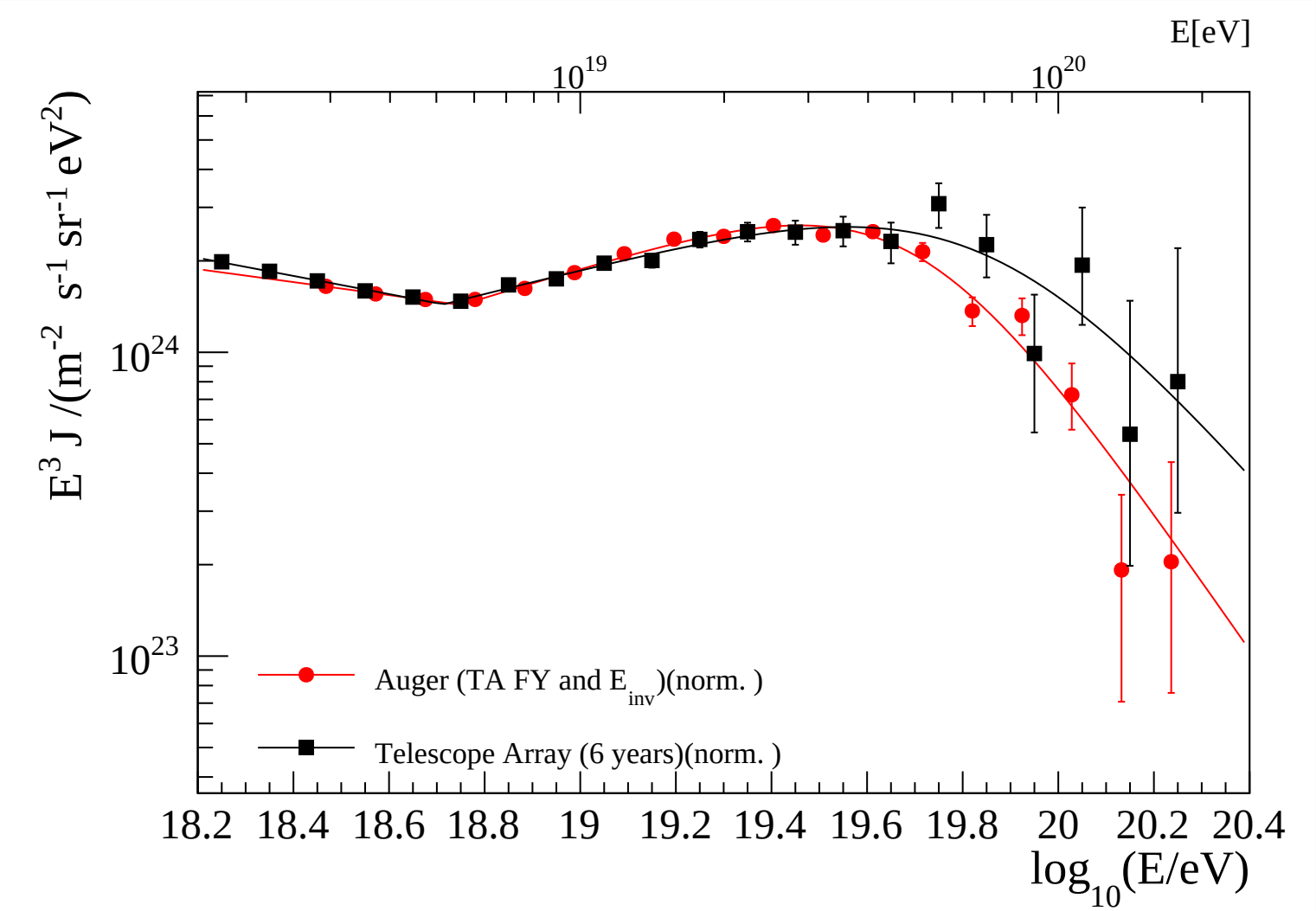
$\Rightarrow$ 7% difference on energy ($\chi^2/\mathrm{ndof} = 1.6$)

Normalizing the energy spectra (constant energy shift)



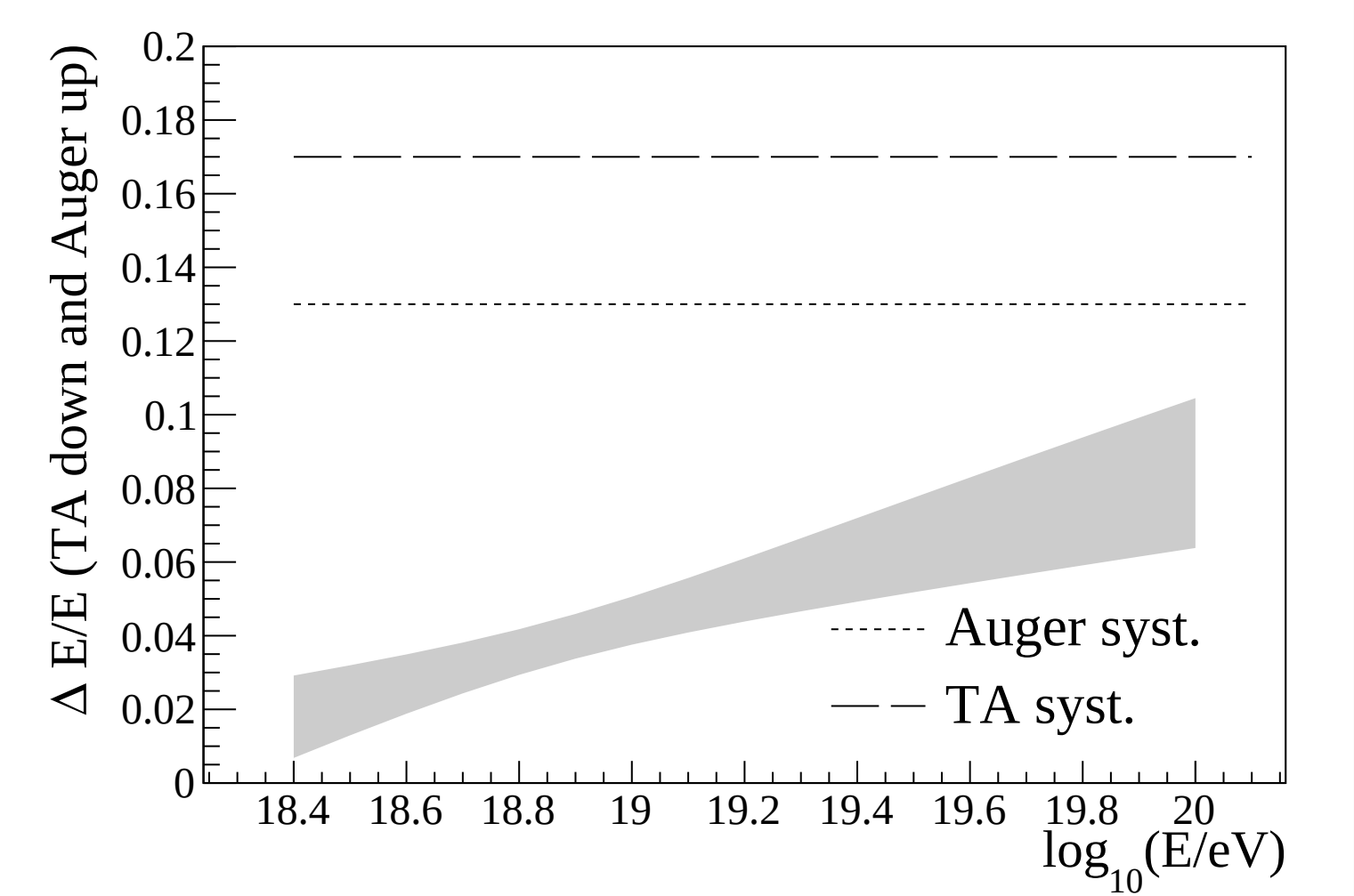
$\Rightarrow$ 7% difference on energy ($\chi^2/\mathrm{ndof} = 1.6$)

Energy dependent normalization



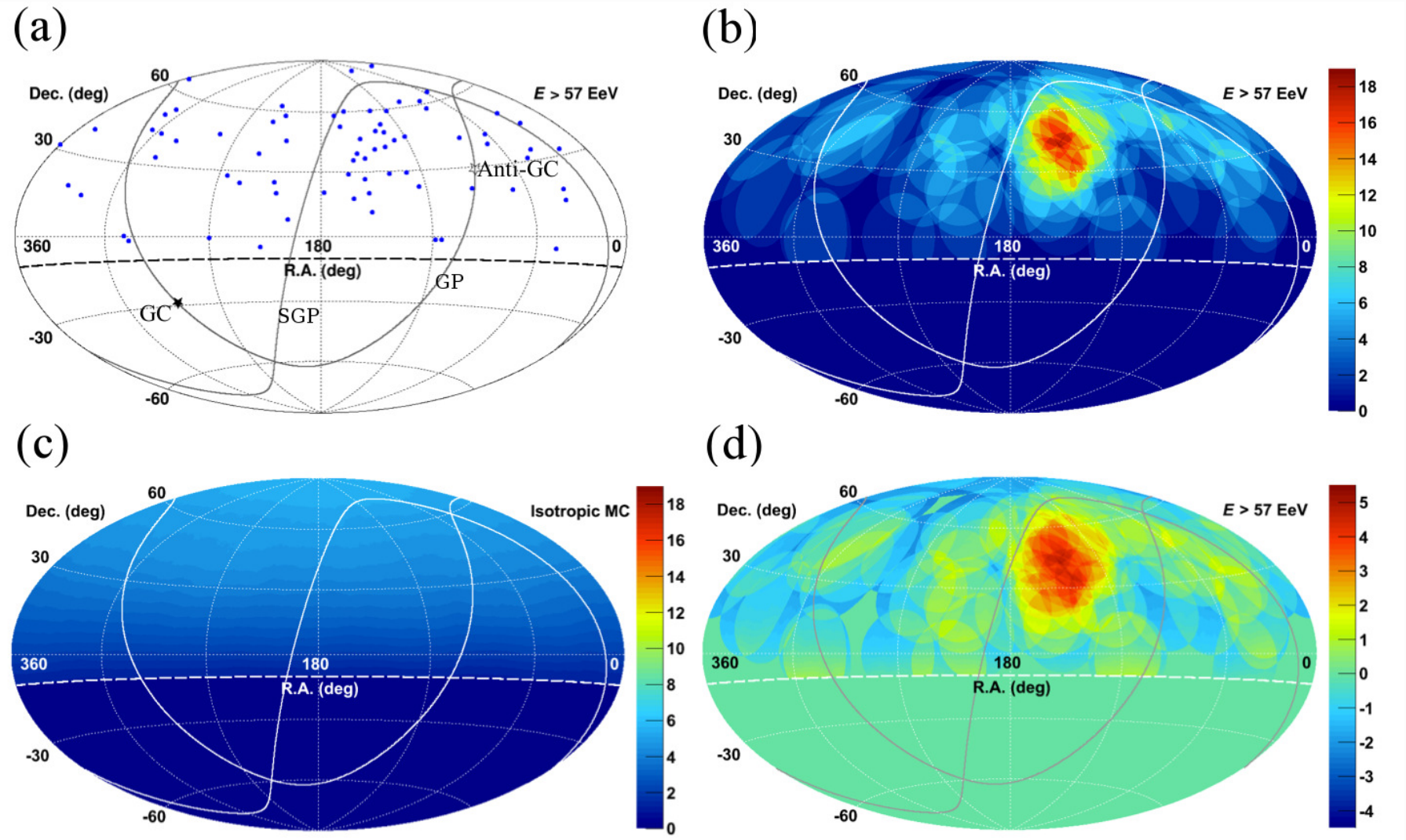
$\lg(E) = a + b \cdot \lg(E)$, $\chi^2/\mathrm{ndof} = 0.75(\mathrm{Prob} = 0.85)$

Energy dependent energy scaling

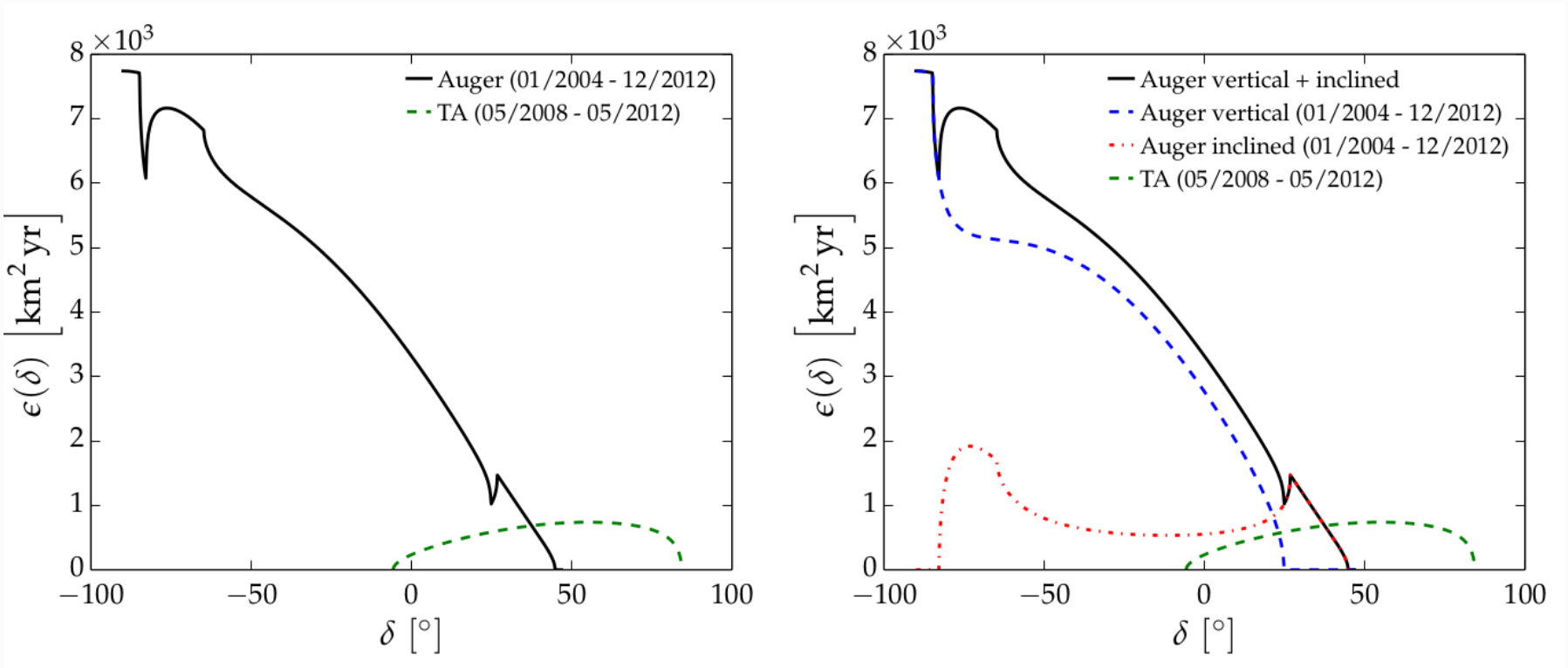


- after using the same FY and invisible energy, dividing the contribution naively in two
- can we find these systematic uncertainties dependency?

Is the TA hot-spot causing the flux differences?

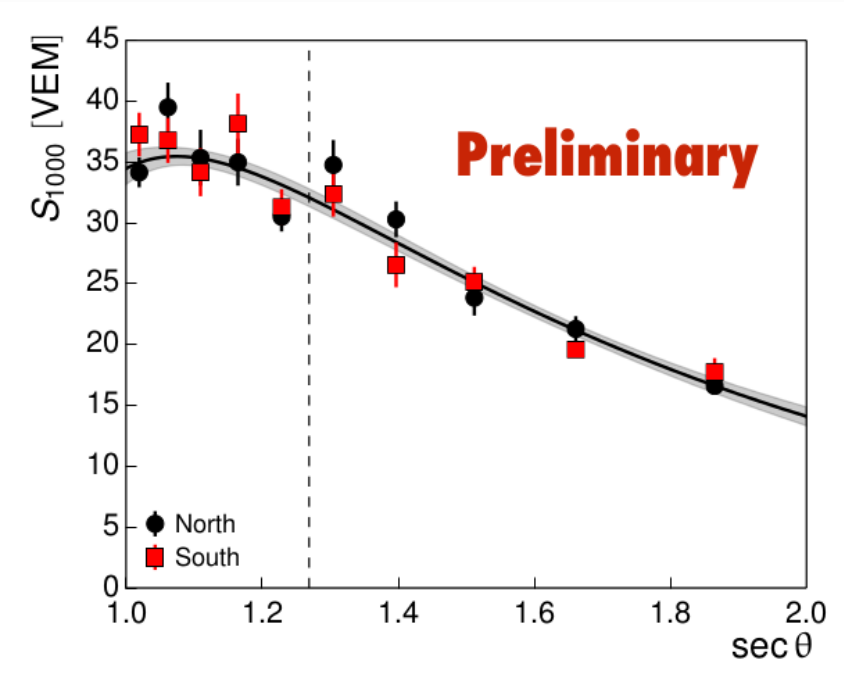


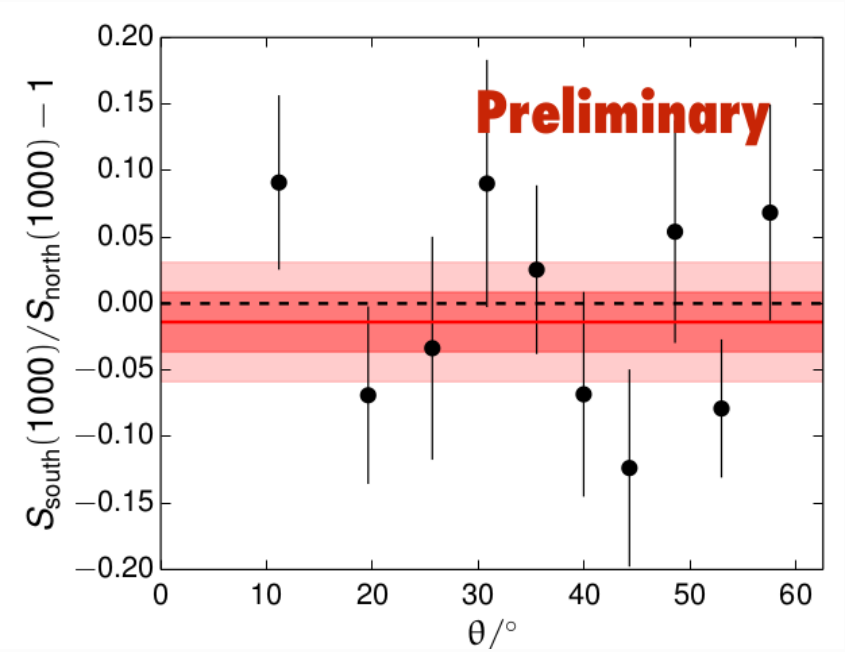
Declination dependent exposure



- TA: 05/2008 - 05/2012, Auger: 01/2004-12/2012
- Auger: divide the data set in four sky regions of equal exposure
- TA: divide the data in off/on-source and in two declination bands

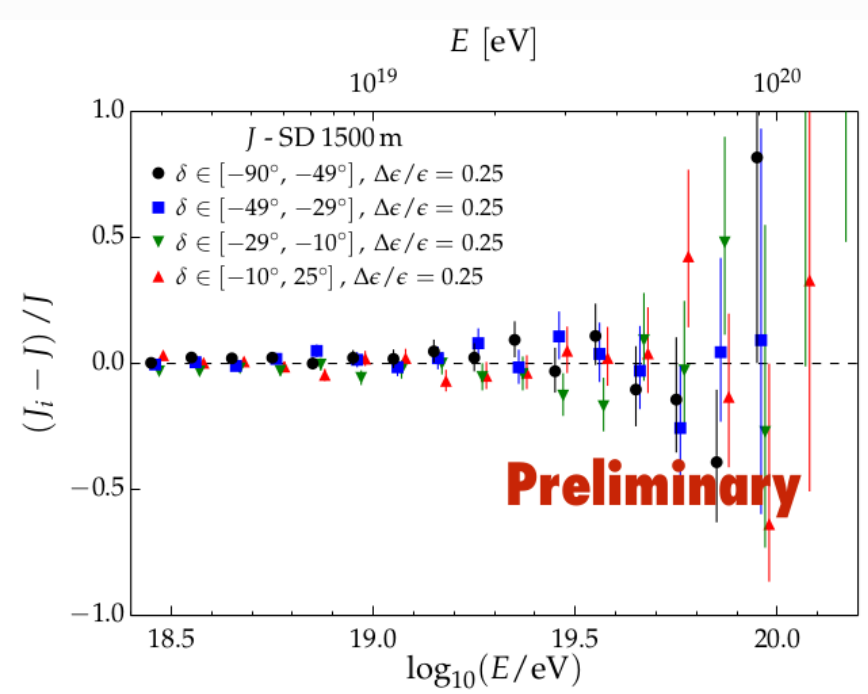
Auger:Constant intensity cut cross-check

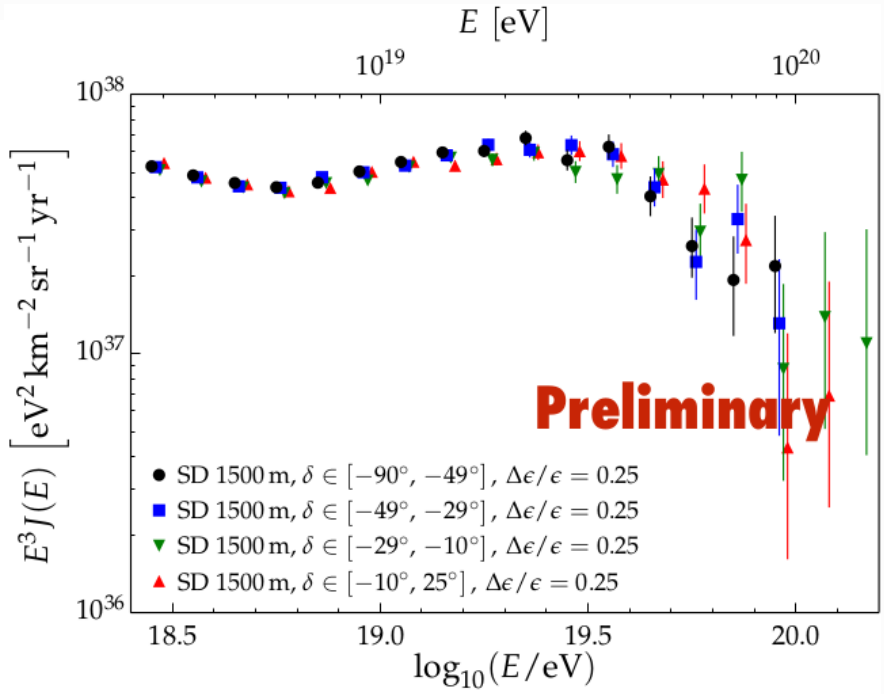




- for the zenith angle correction of S(1000), Auger assumes that the flux is independent of the zenith angle
- agreement between the attenuations from data taken in austral winter (enriched in small declination) and austral summer (enriched in large declination) of less than 2%

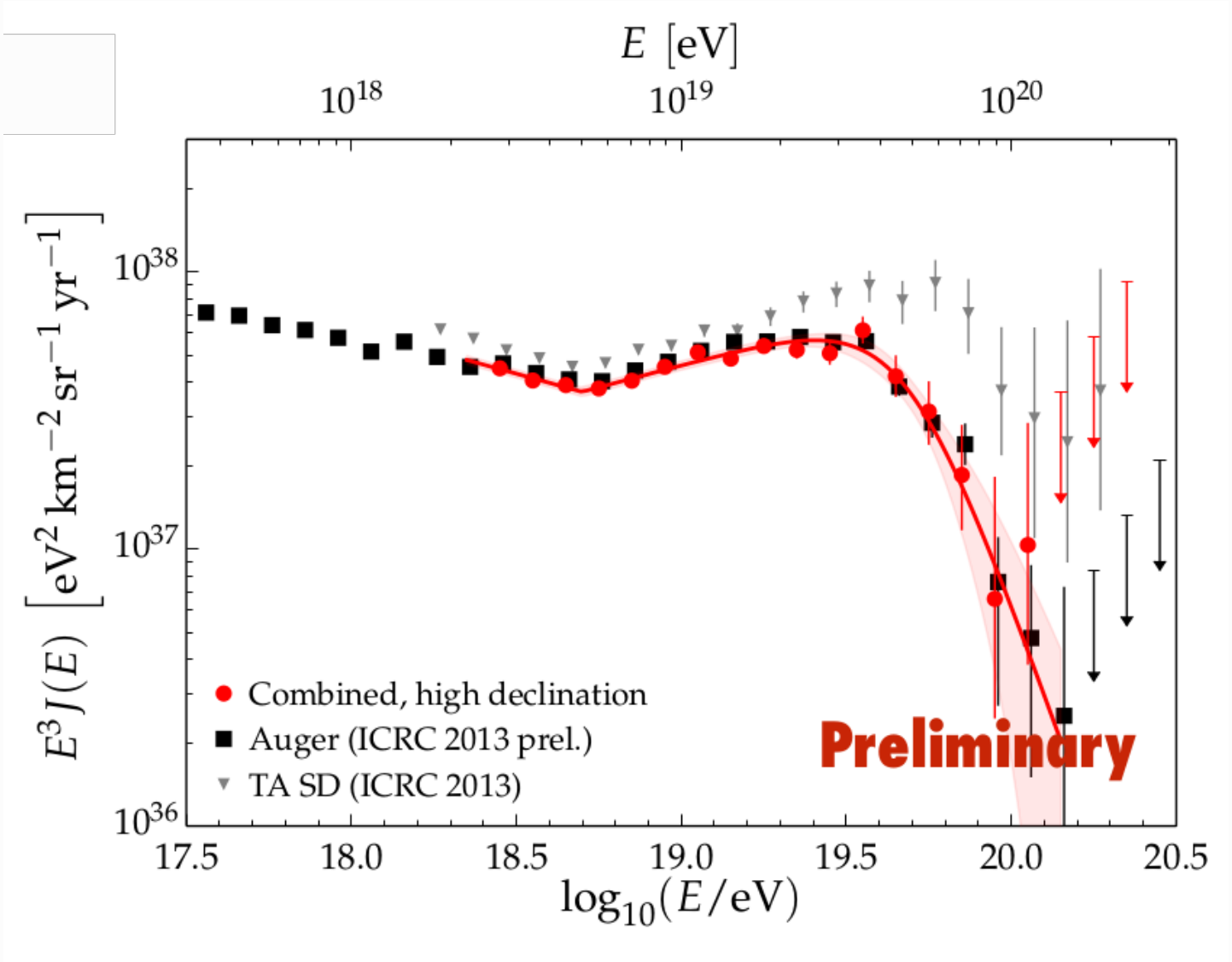
Auger energy spectra for different declination bands





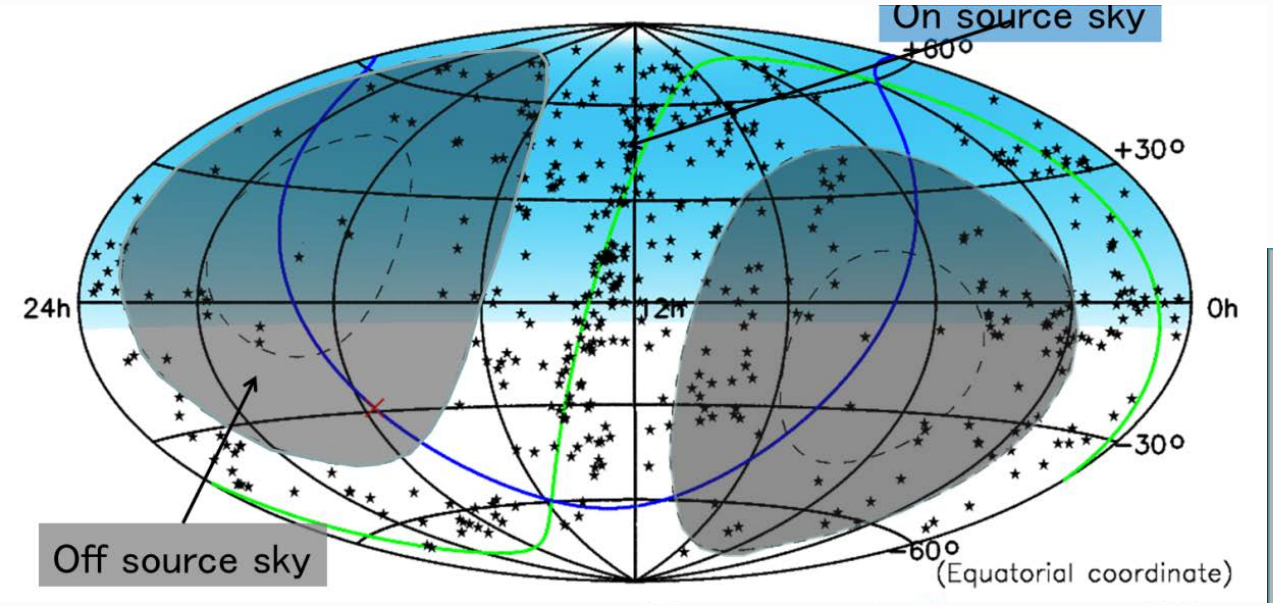
- relative difference to the total flux compatible with zero
- no indication of a declination dependent flux

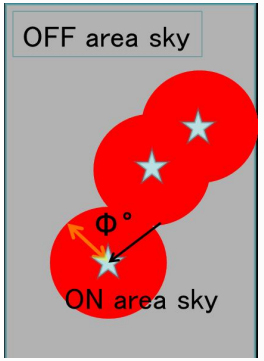
Auger energy spectrum in the common sky



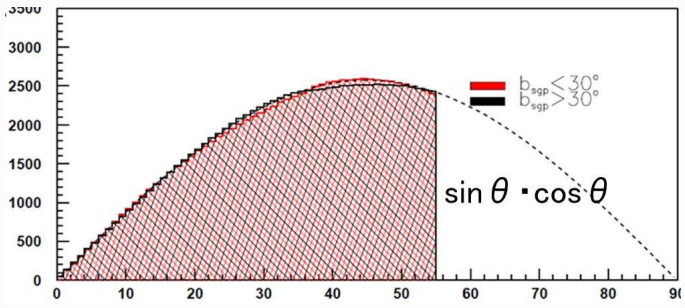
$\Rightarrow$ No difference observed with the Auger data ($0 < \delta < 45$)

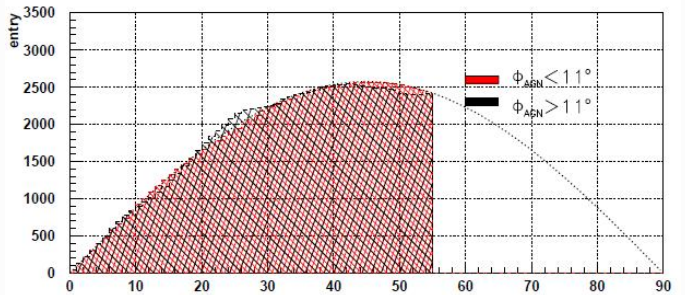
TA: On/off source definition



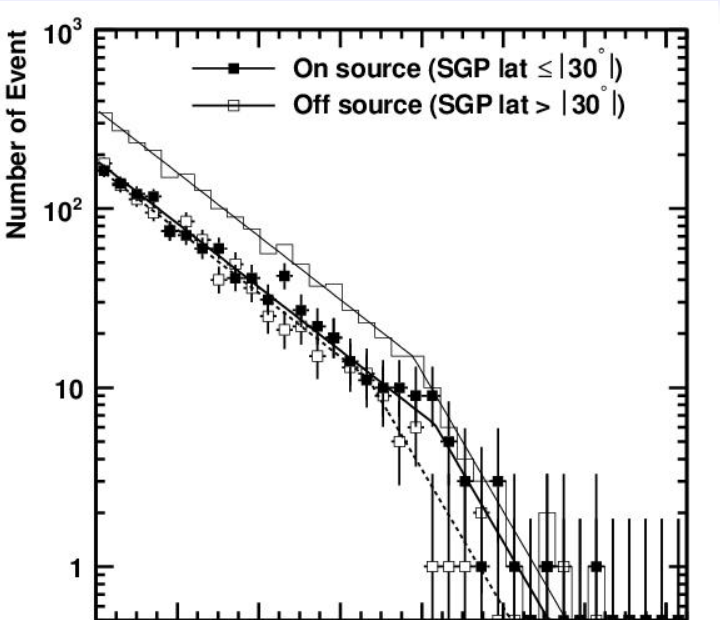


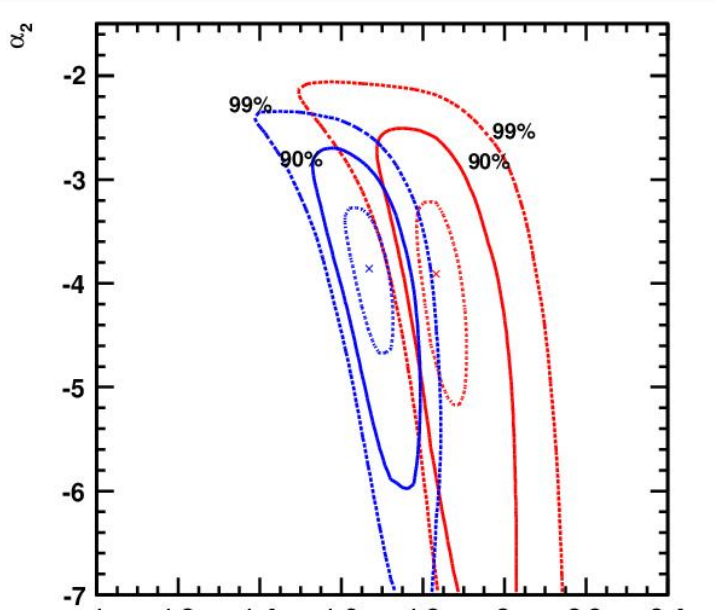
- On source 1: super galactic plane $\pm 30°$
- On source 2: VCV catalogue, $11°$ around sources (after scan to maximise N_{on}/N_{off})



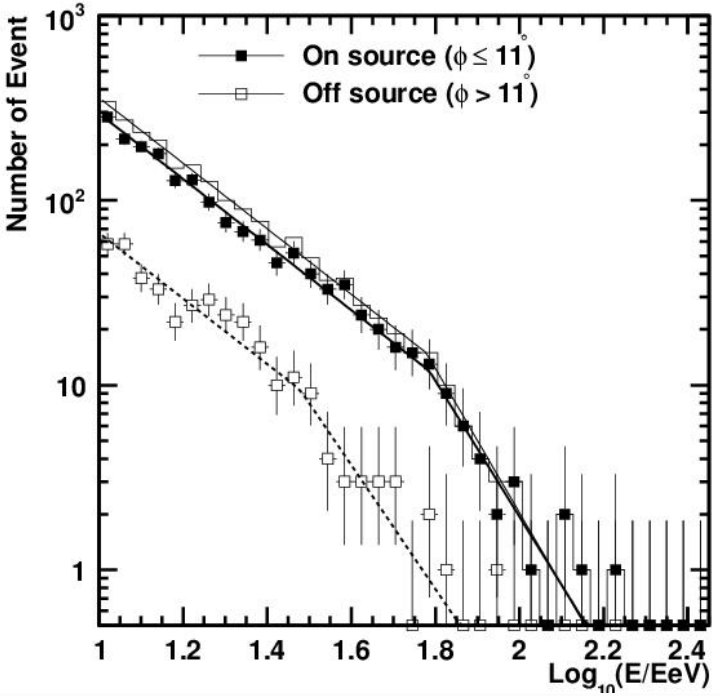


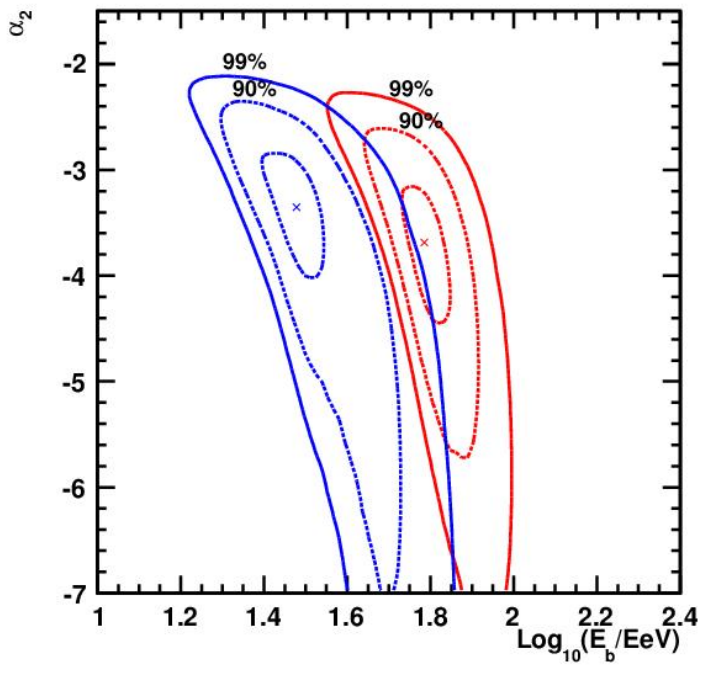
TA on/off sources, preliminary





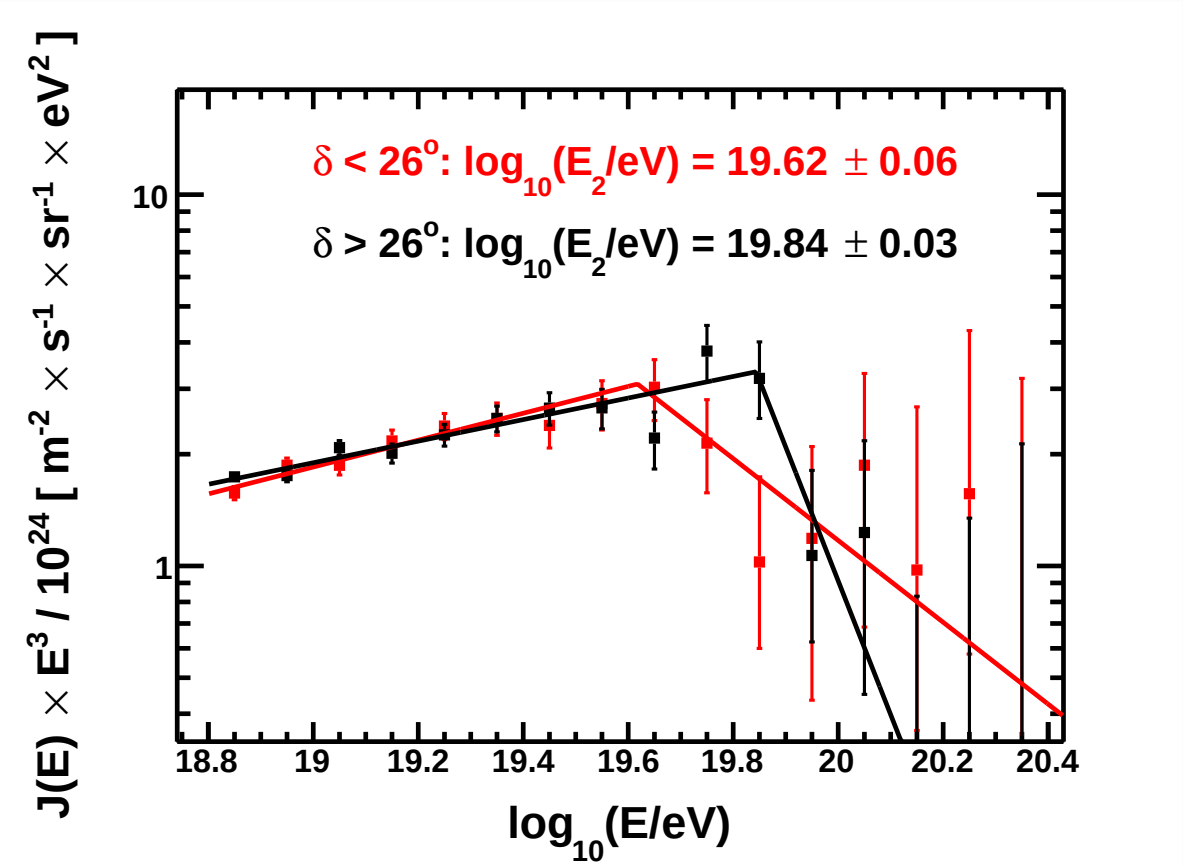
$\frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} = 0.34$
(exp. 0.48)
P = 0.0006

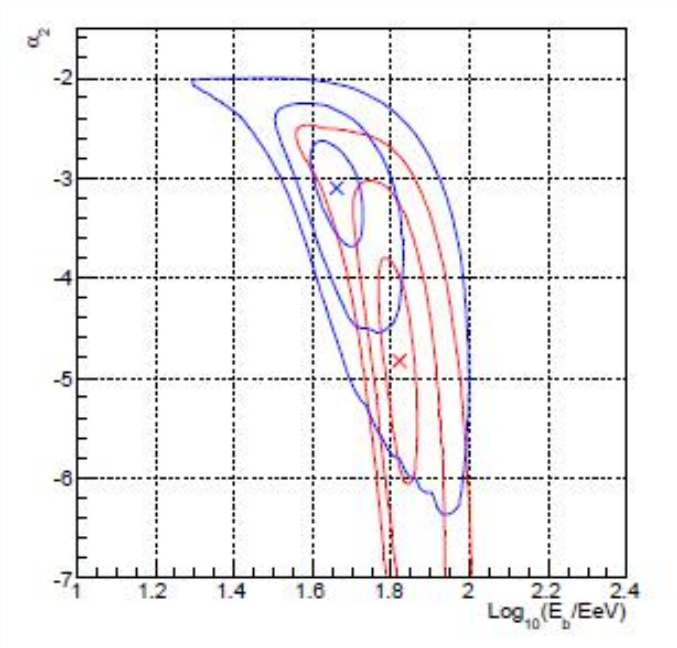




$\frac{N_{off}(E>E_b)}{N_{all}(E>E_b)} = 0.12$
(exp. 0.19)
P = 0.015
(with scan penalty)

Common sky TA-Auger ($\delta < 26^\circ$), preliminary





$\Rightarrow$ indication for a flux difference ($\approx 3\sigma$)

Conclusions

Features of the energy spectra

- the spectral slopes and the *ankle* energy are in a good agreement
- there is a flux difference at the highest energies (not quantified for now)

Flux suppression difference unclear

- explained by energy dependent systematic uncertainty?
- a different matter distribution in the North and South? Auger does not observe a declination dependency of the flux, while TA has indications of a dependency
- the number of events is too low in the overlapping regions
- more studies on energy dependent systematic uncertainty are needed to arrive at conclusive results

Thanks to several members of the TA and Auger collaboration that helped in the analysis!

Future

As a community and as individual experiments

- continue data taking
- obtain the TA energy spectrum with Auger FY and invisible energy (work in progress)
- understand how large can be the energy dependency of the energy systematic uncertainty
- knowing the energy systematic uncertainties quantify the flux suppression differences

Energy scale

- FD calibration: Auger octocopter flying in the field of view of TA
- SD calibration: Auger water Cherenkov tanks will be deployed at TA
- absolute calibration: TA electron laser source (ELS) data are analyzed