Energy spectrum measured by the Telescope Array Surface Detectors

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on behalf of the Telescope Array Collaboration

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Outline

- Telescope Array Experiment
- Surface Detectors
- Surface Detector Event Reconstruction
- Spectral Features Measured by Telescope Array Surface Detectors
- Declination Dependence in the Cosmic Ray Spectrum
- Summary

Telescope Array Collaboration

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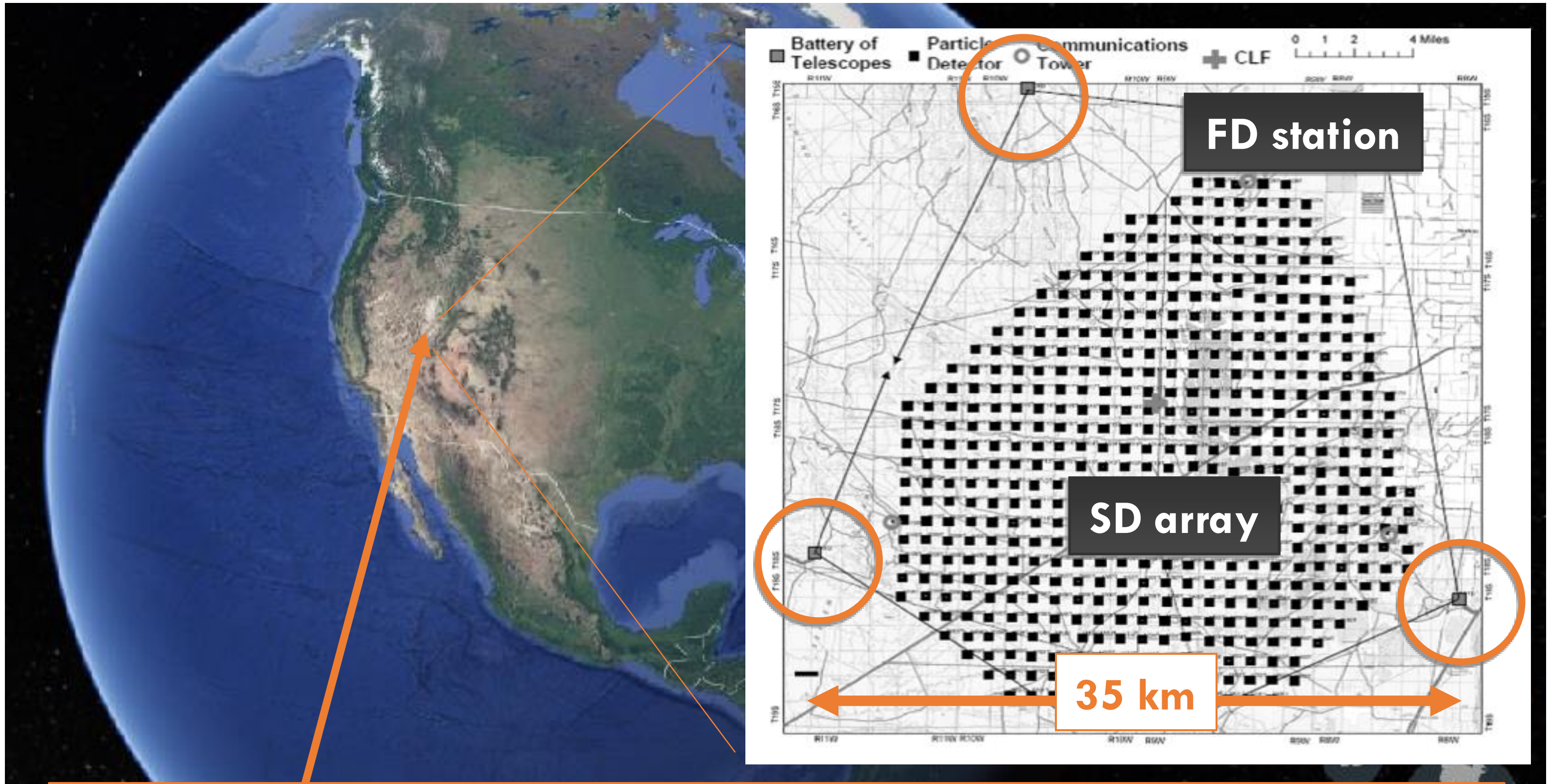
125 members, 36 institutes, 9 countries

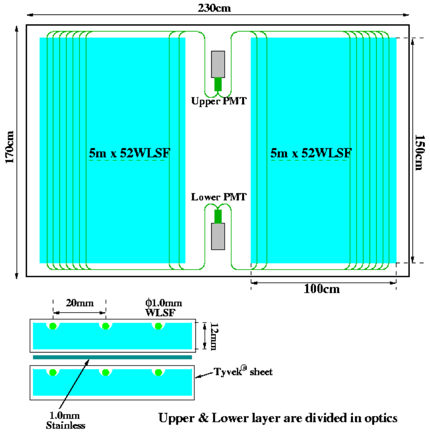
Telescope Array (TA) Experiment

- The largest cosmic ray observatory in the northern hemisphere



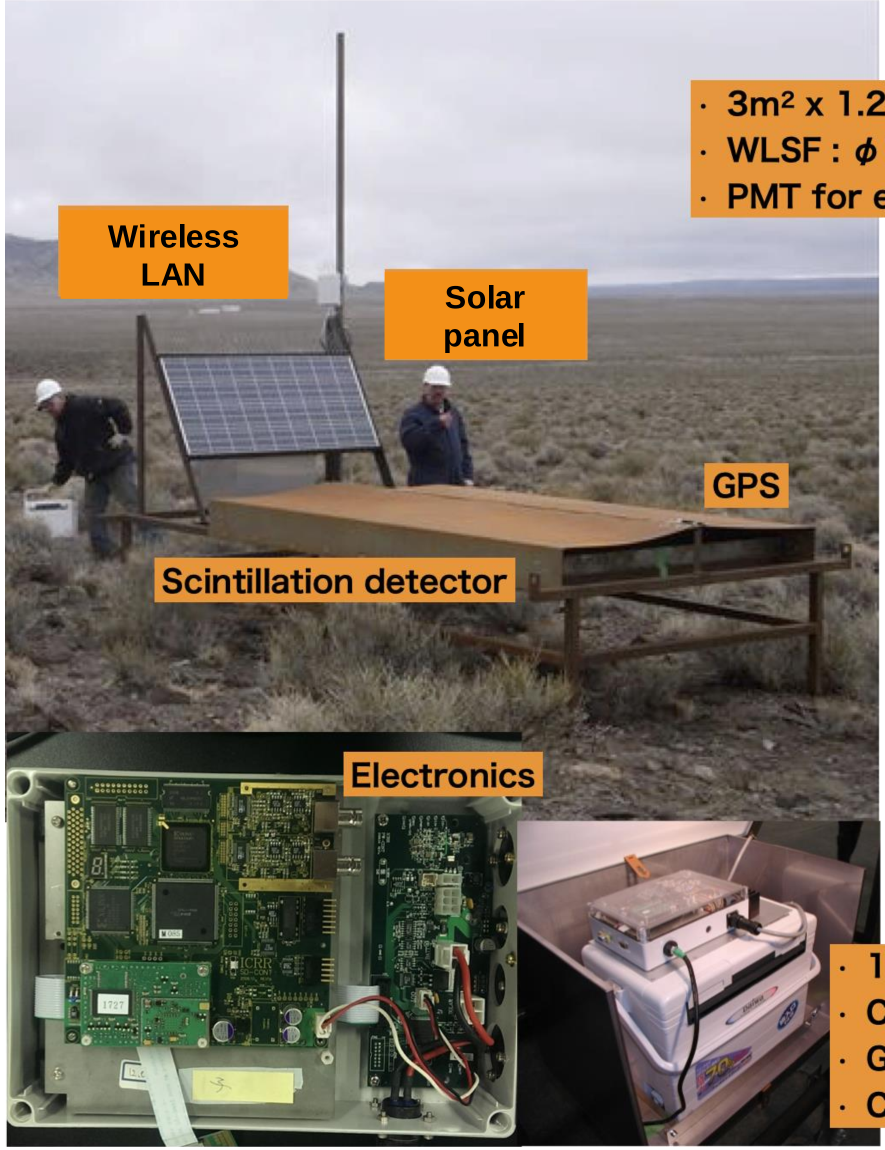
- Delta, Utah, USA. ~1400 m above sea level
- 507 surface detector array covers ~**700 km²**
- 38 telescopes in 3 stations look over the array

Surface Detector: Plastic Scintillator

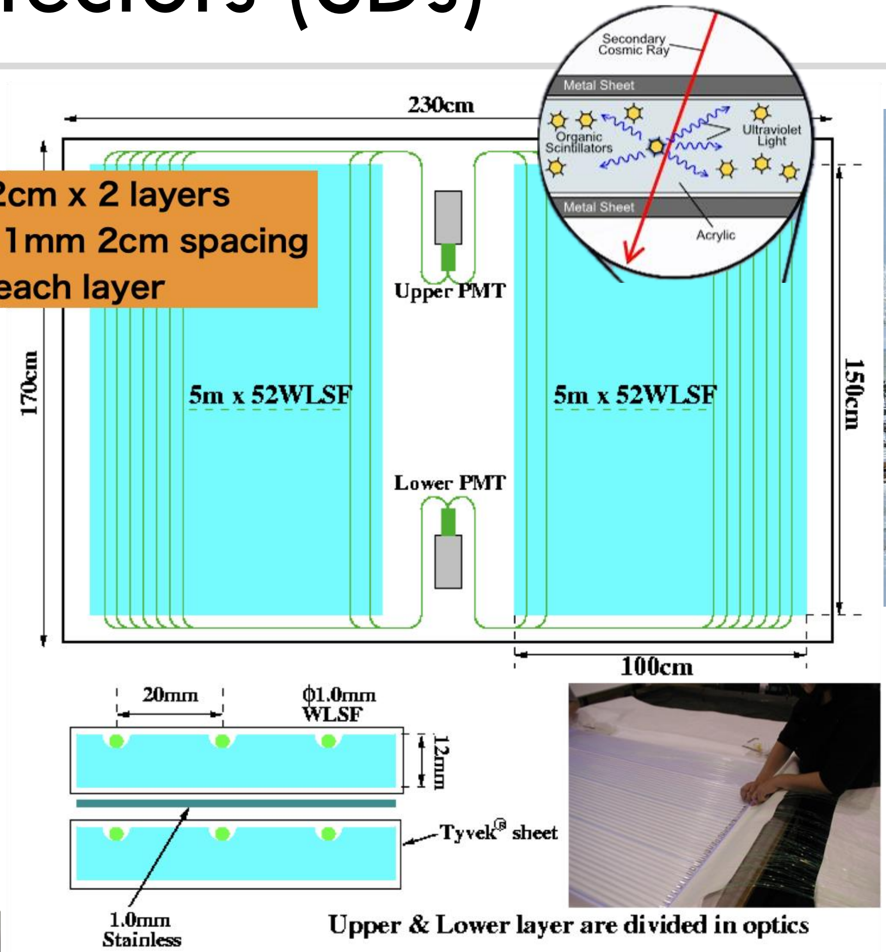


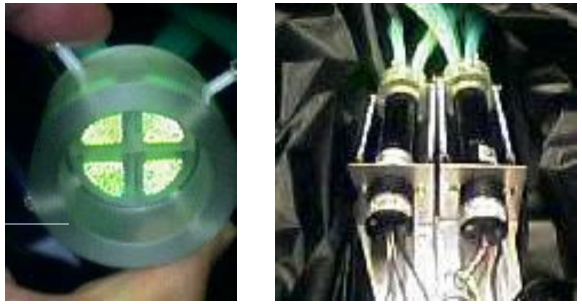
Fluorescence Detector: PMT camera

Scintillator Surface Detectors (SDs)



- 12bit 50MHz FADC x 2 layers
- CPU : Renesas SH4(25MHz)
- GPS, WLAN-modem
- Charge controller





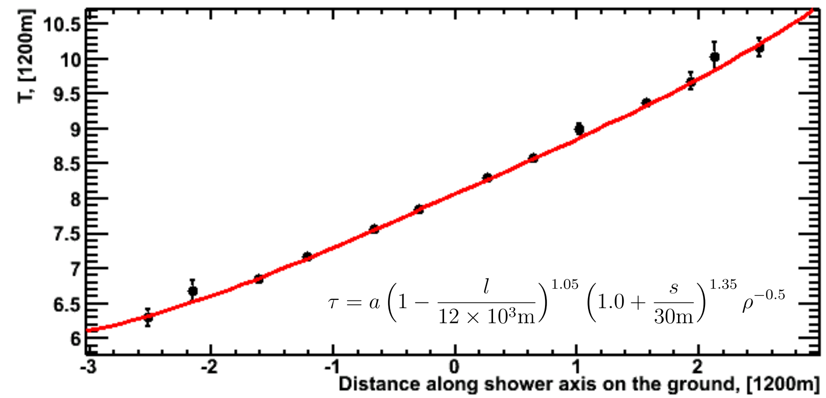
- 507 plastic scintillation counters
- 2 layers, 1.2 cm thick, 3 m^2 area
- 1.2 km square grid spacing covering **~700 km^2**

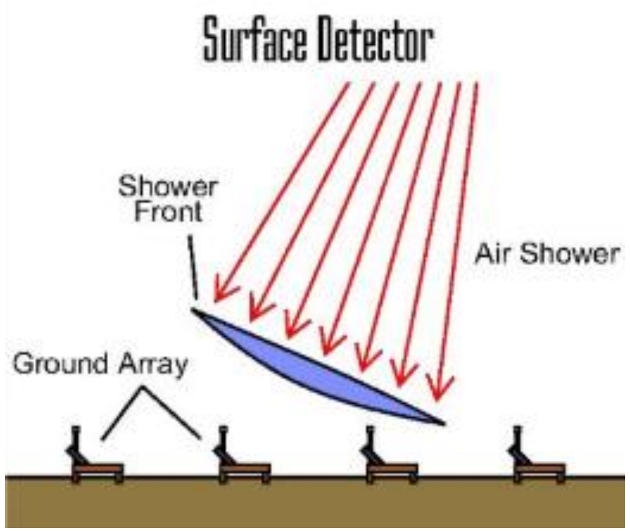
Surface Detector Event Reconstruction (1/2)

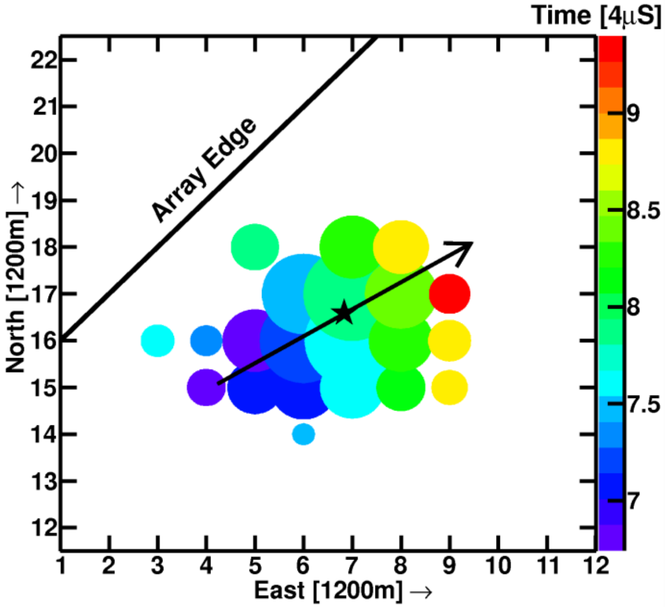
- Use counter location and timing to locate shower core and direction
- Fit counter signal size to find lateral distribution
- Signal size at 800 m, S800, is the energy indicator

SD Time Fit

Geometry Fit (modified Linsley)

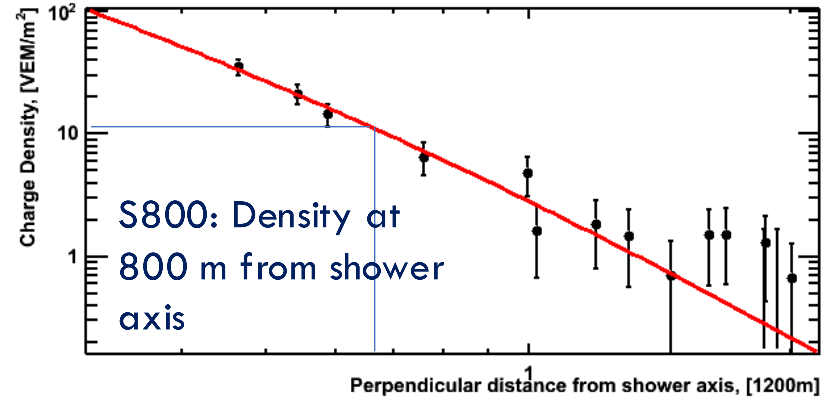






SD LDF Fit

Lateral Density Distribution Fit

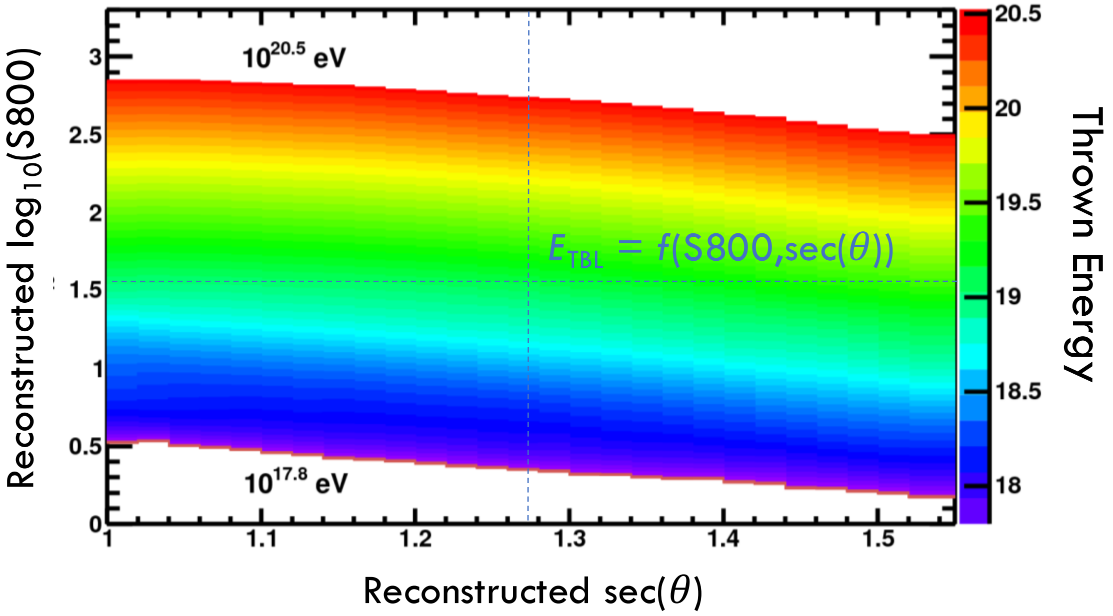


$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1+\frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1+\left[\frac{s}{1000\mathrm{m}}\right]^2\right)^{-0.6}$$

$$\eta(\theta) = 3.97 - 1.79\,[\sec(\theta)-1]$$

Surface Detector Event Reconstruction (2/2)

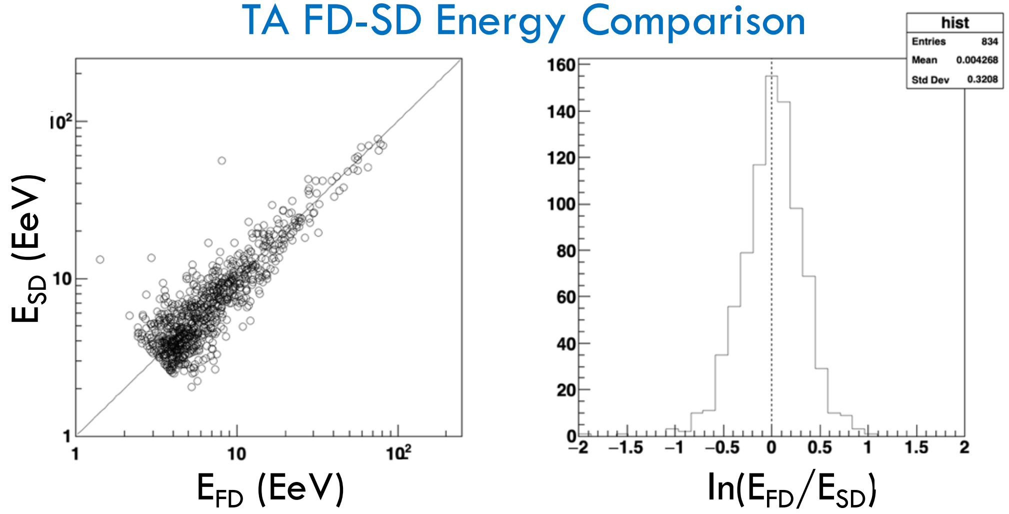
- Use S800 and zenith angle to look up energy (from CORSIKA-produced table)



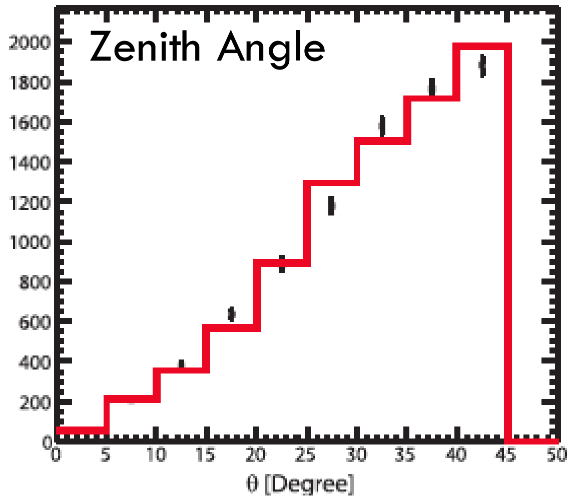
- Set the energy scale to the fluorescence detectors

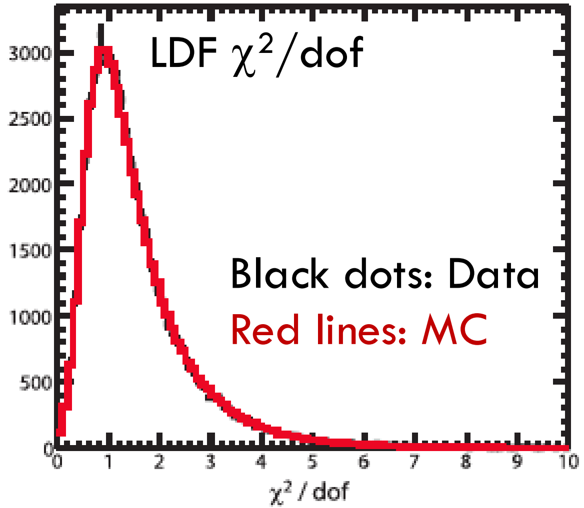
$$E_{Final} = E_{TBL}/1.27$$

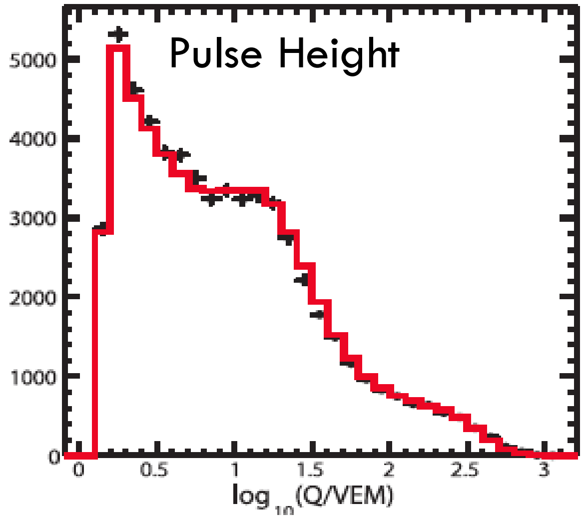
TA FD-SD Energy Comparison



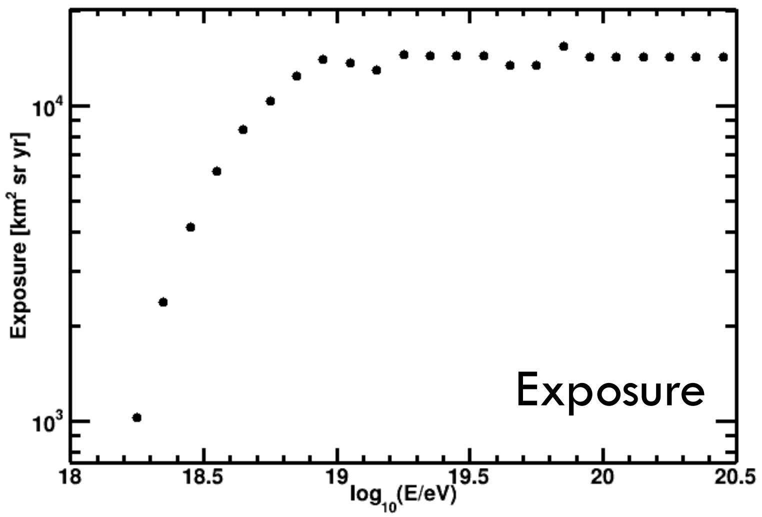
Resolution and Sensitivity by Monte Carlo Simulation





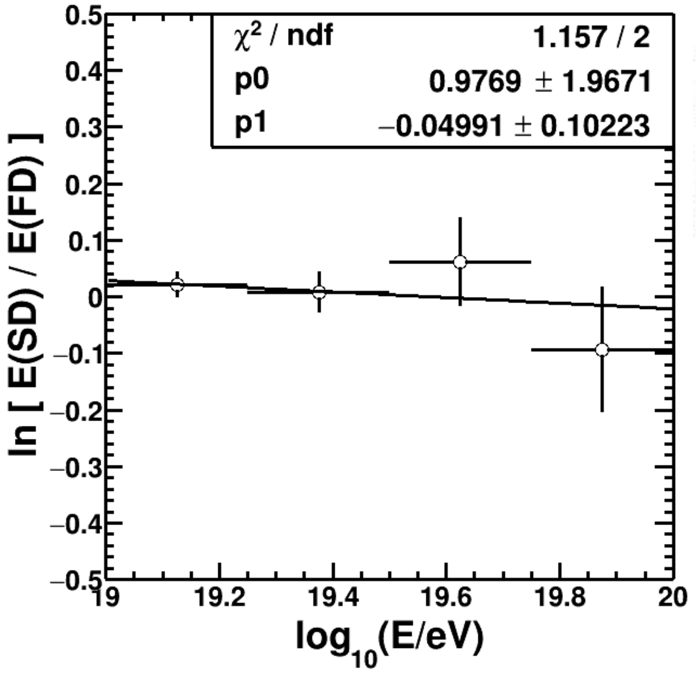


- Monte Carlo based on CORSIKA program used for resolution and exposure calculations.
- TA SD Resolution:
  - 19% energy, 1.4° angular, $E \geq 10^{19.0}$ eV
  - 29% energy, 2.0° angular, $10^{18.5}\text{eV} \leq E < 10^{19.0}$ eV
  - 32% energy. 2.4° angular, $10^{18.0}$ eV $\leq E < 10^{18.5}$ eV

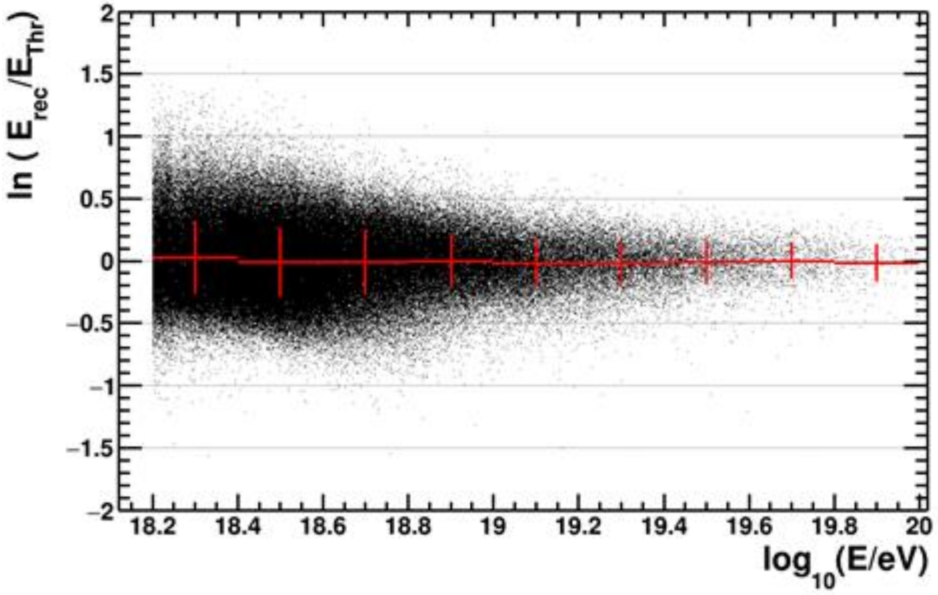


Linearity in Energy Reconstruction

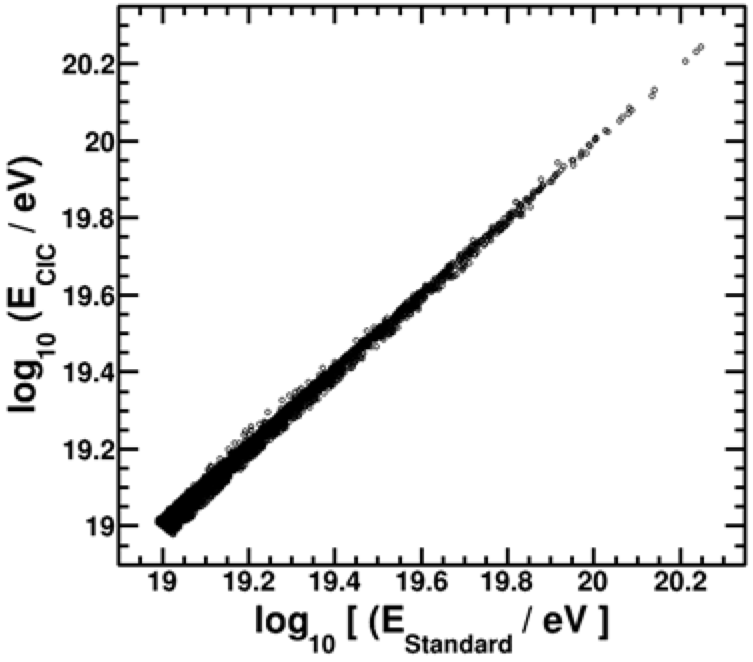
Standard TA SD and FD using hybrid events



MC Thrown energy and reconstructed energy



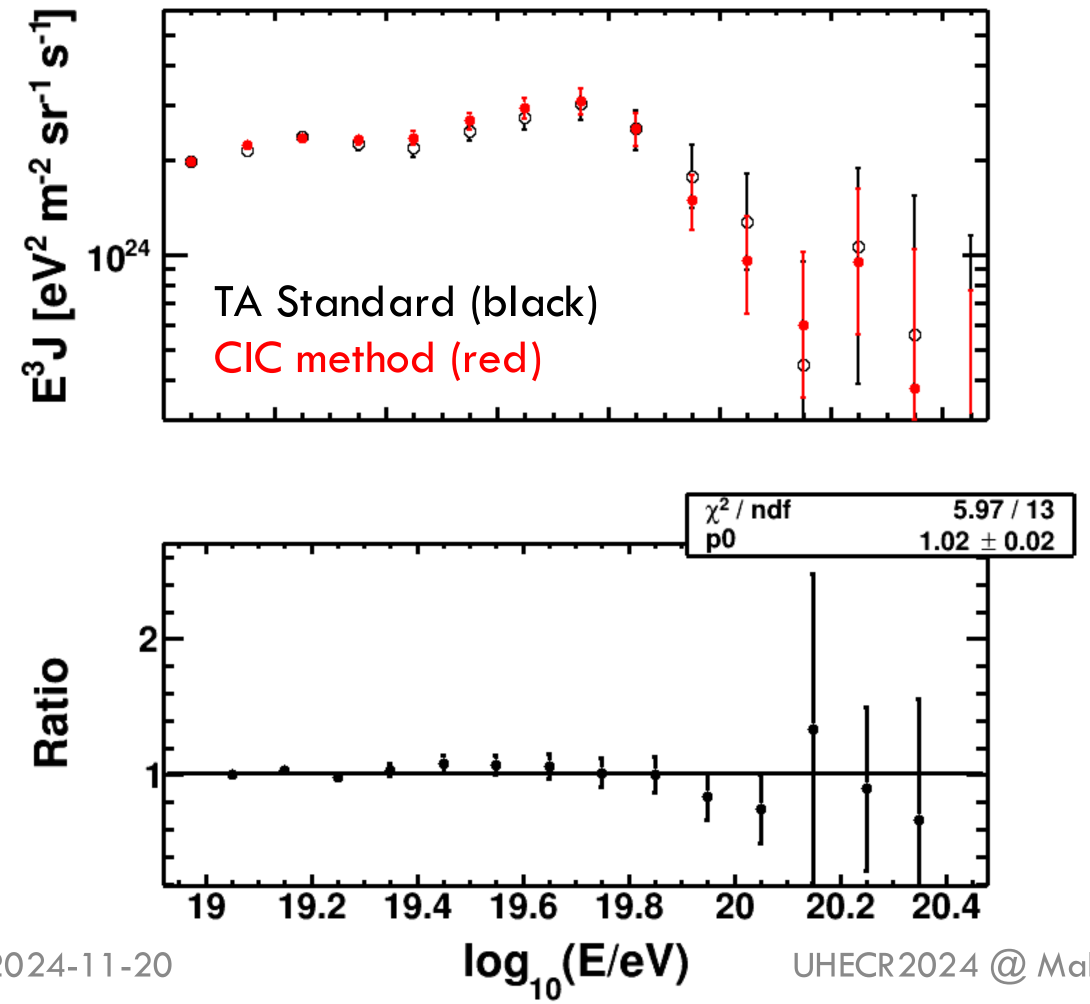
Constant intensity cut and standard TA reconstruction



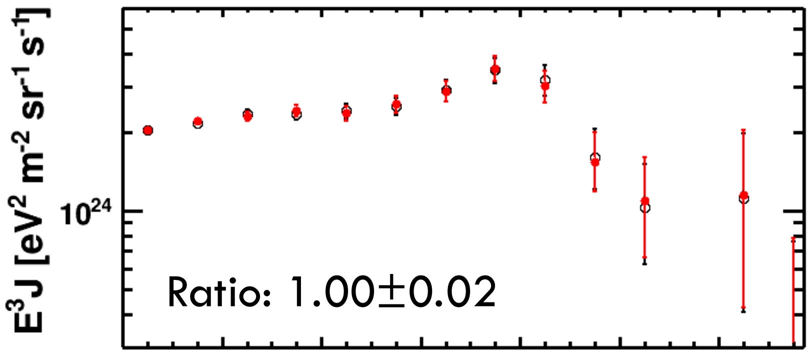
These show the linearity of the TA energy reconstruction.

Crosscheck using Constant Intensity Cut (CIC) Method

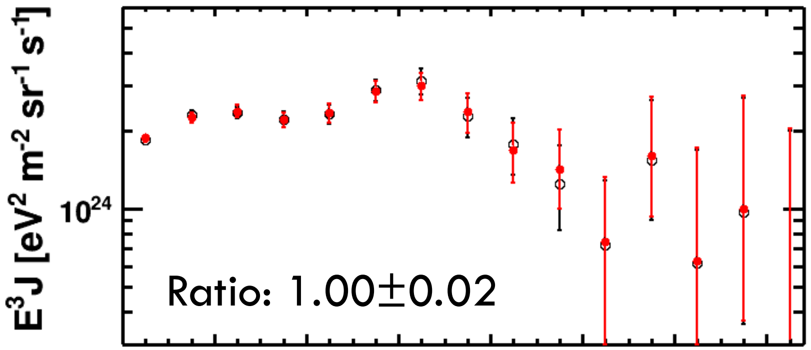
- Comparison with the energy spectra obtained using the CIC method shows consistent results within 2% uncertainties.



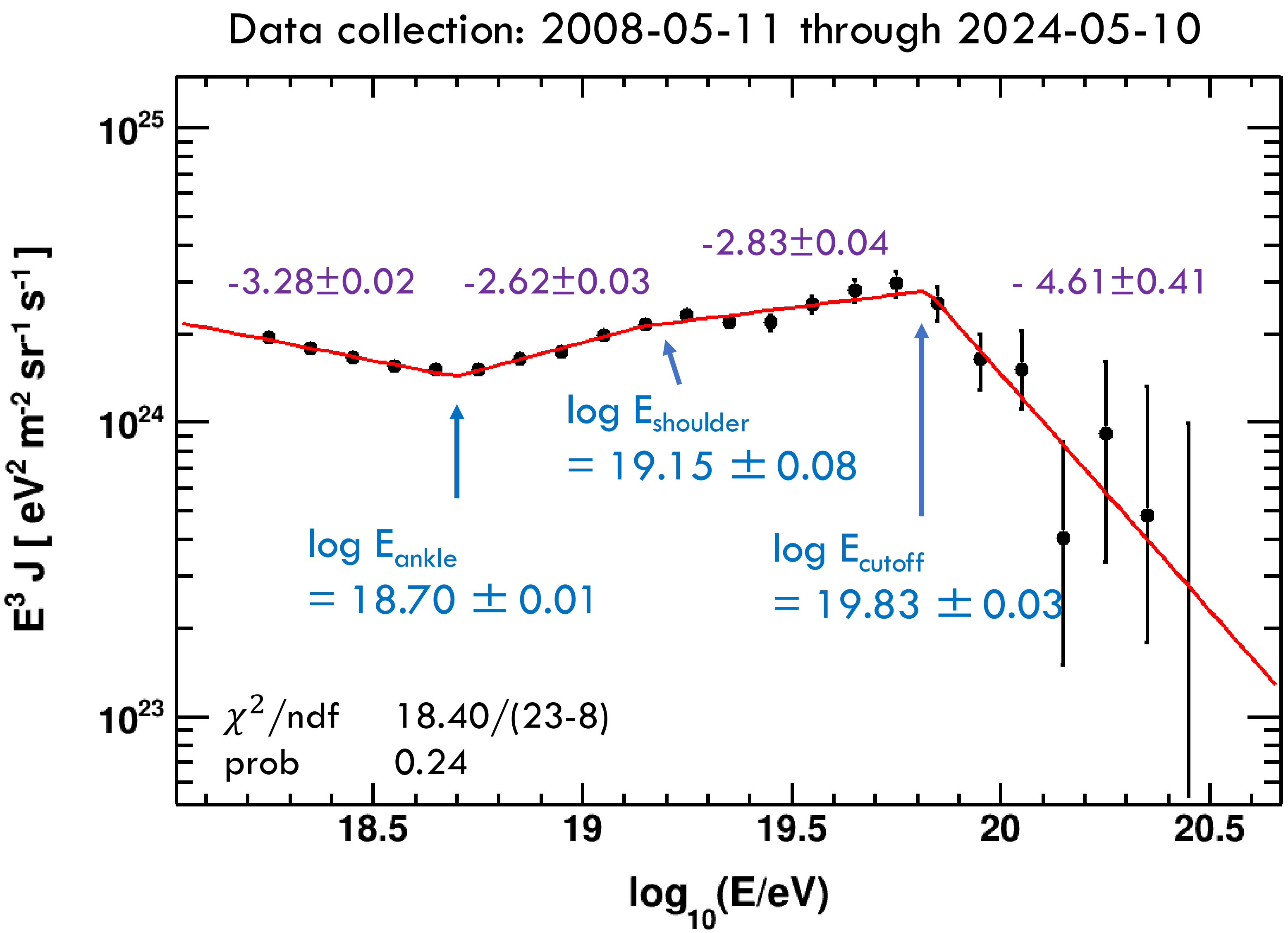
High Dec. (DEC ≥24.8°)



Low Dec. (-15.7°≤DEC<24.8°)



Spectral Features in 16-year TA SD Data

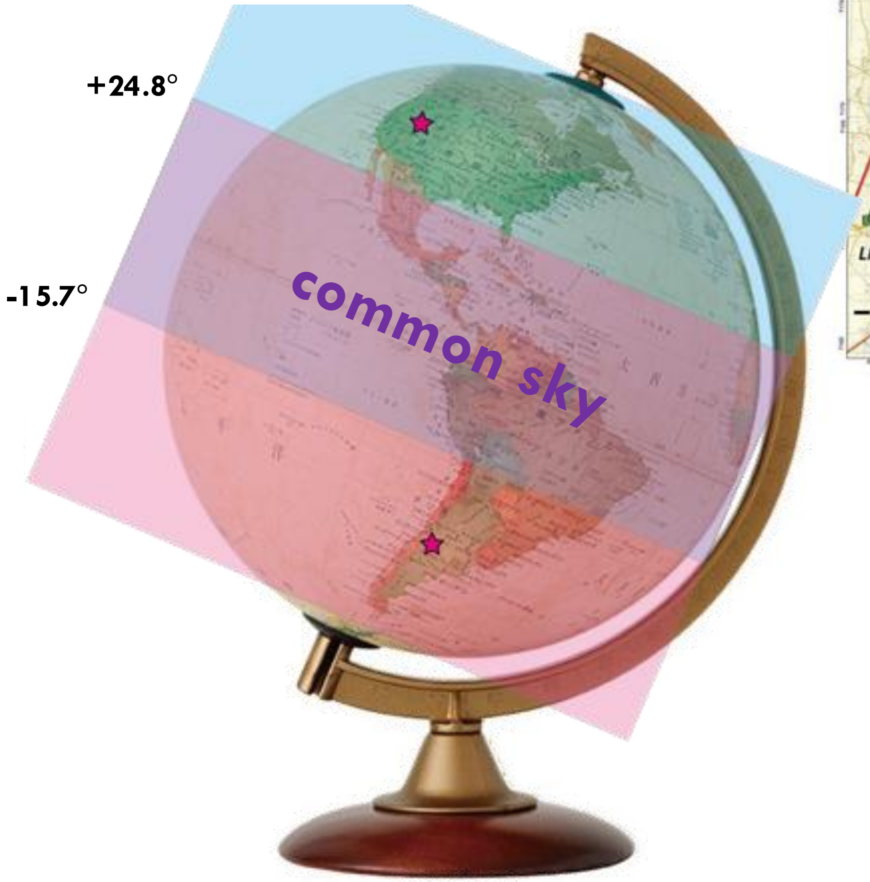


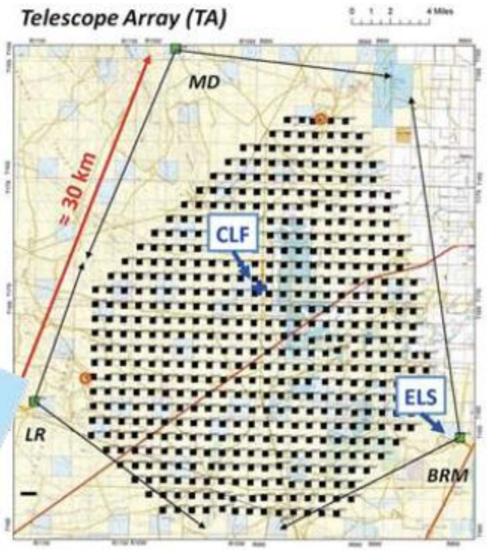
- **Cutoff** feature at $10^{19.83}$ eV
  N_{exp}: 173.7
  N_{obs}: 97
  Chance probability: 1.6×10^{-10}, $\sim6.3\sigma$
- **Shoulder** feature at $10^{19.15}$ eV
  N_{exp}: 2156.4
  N_{obs}: 1921
  Chance probability: 1.3×10^{-7}, $\sim5.2\sigma$
- We observe the softening feature in the northern hemisphere at $10^{19.15\pm0.08}$ eV with a 5.2σ significance, while Auger sees it at $10^{19.15\pm0.03}$ eV (with +9% energy rescaling).
- TA and Auger agree well.

Declination Dependence in the Cosmic Ray Energy Spectrum

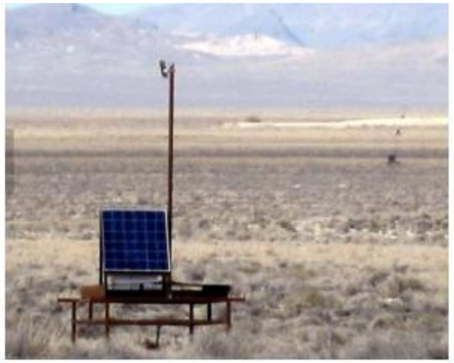
Two UHECR Observatories

Auger and TA

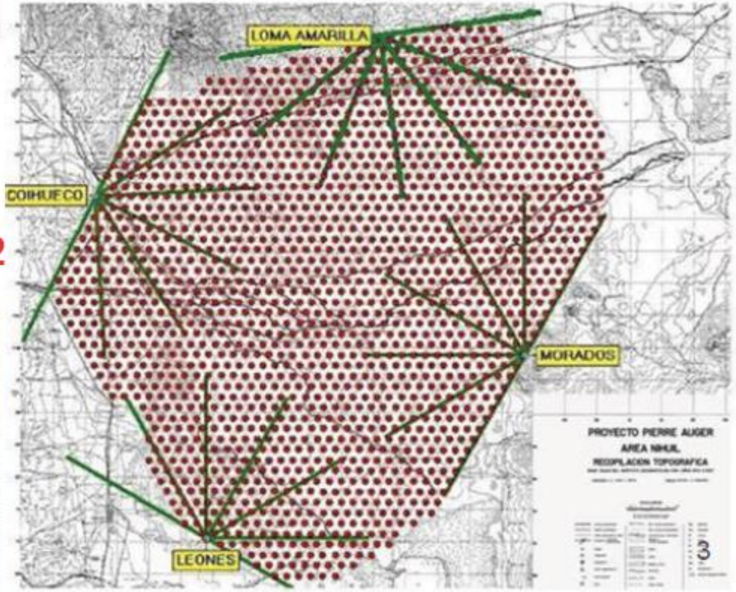




TA
39° N
700km²



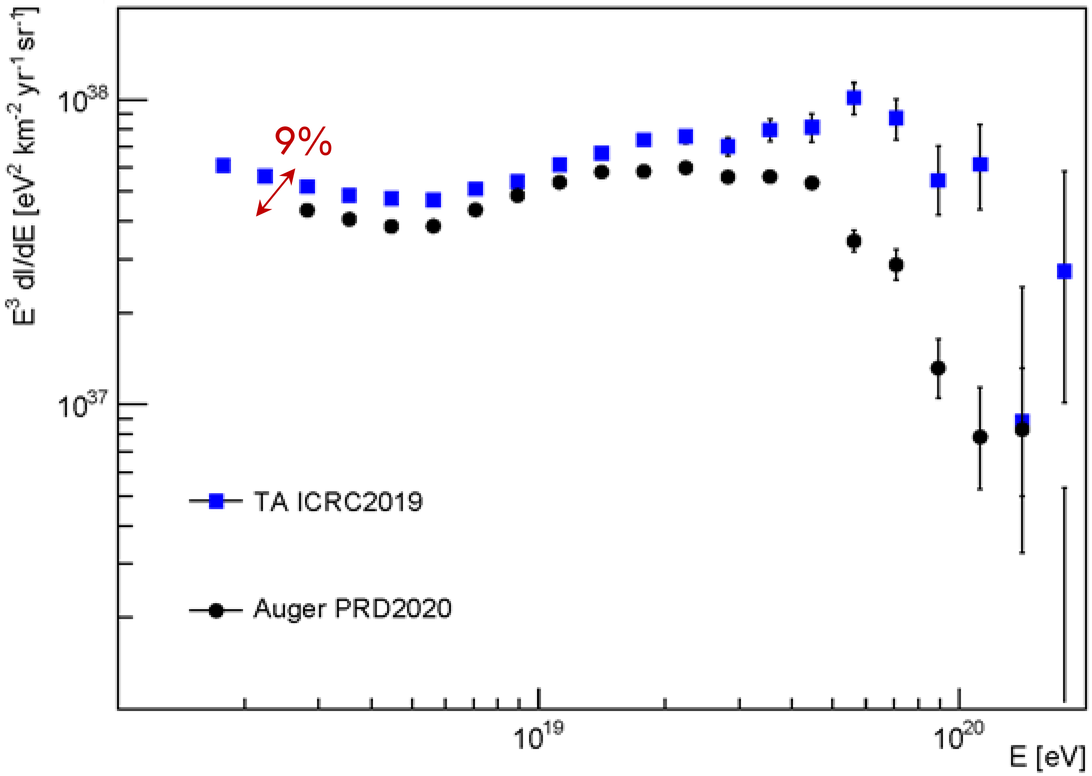
Auger
35° S
3000km²



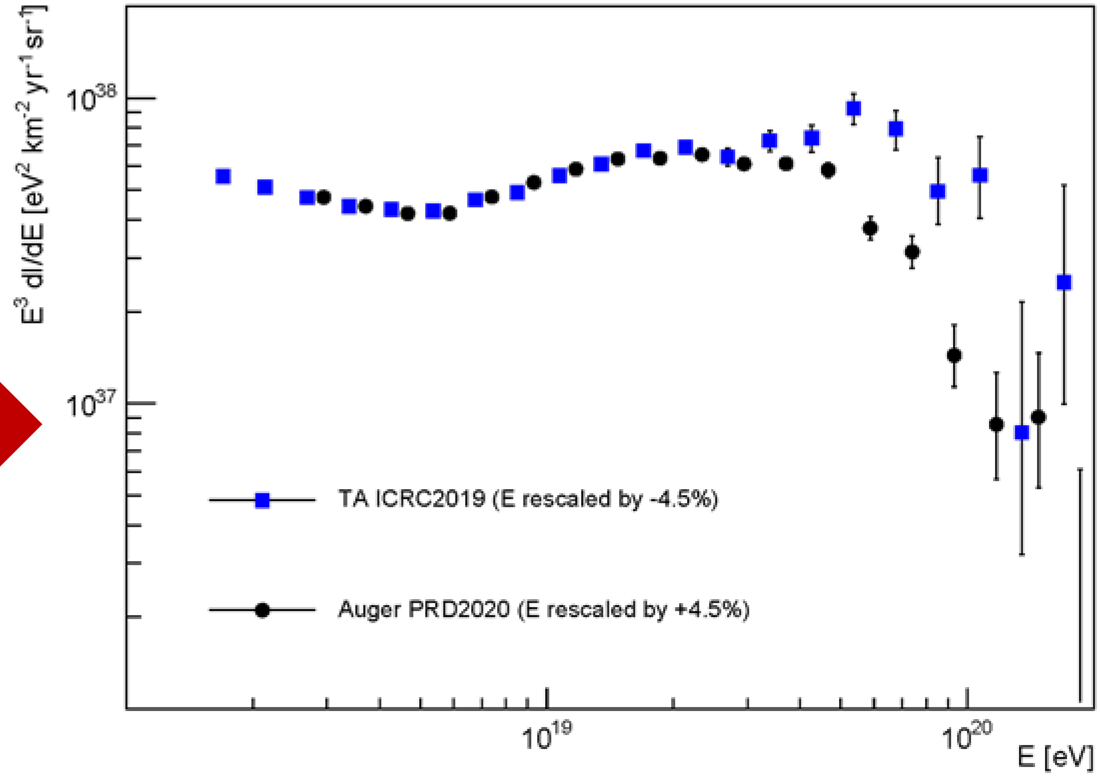
Energy Spectrum Measurements in Northern/Southern Skies

Energy systematic uncertainty:
21% for TA
14% for Auger

Y. Tsunesada+(Auger+TA Spectrum WG)
PoS(ICRC2021)337

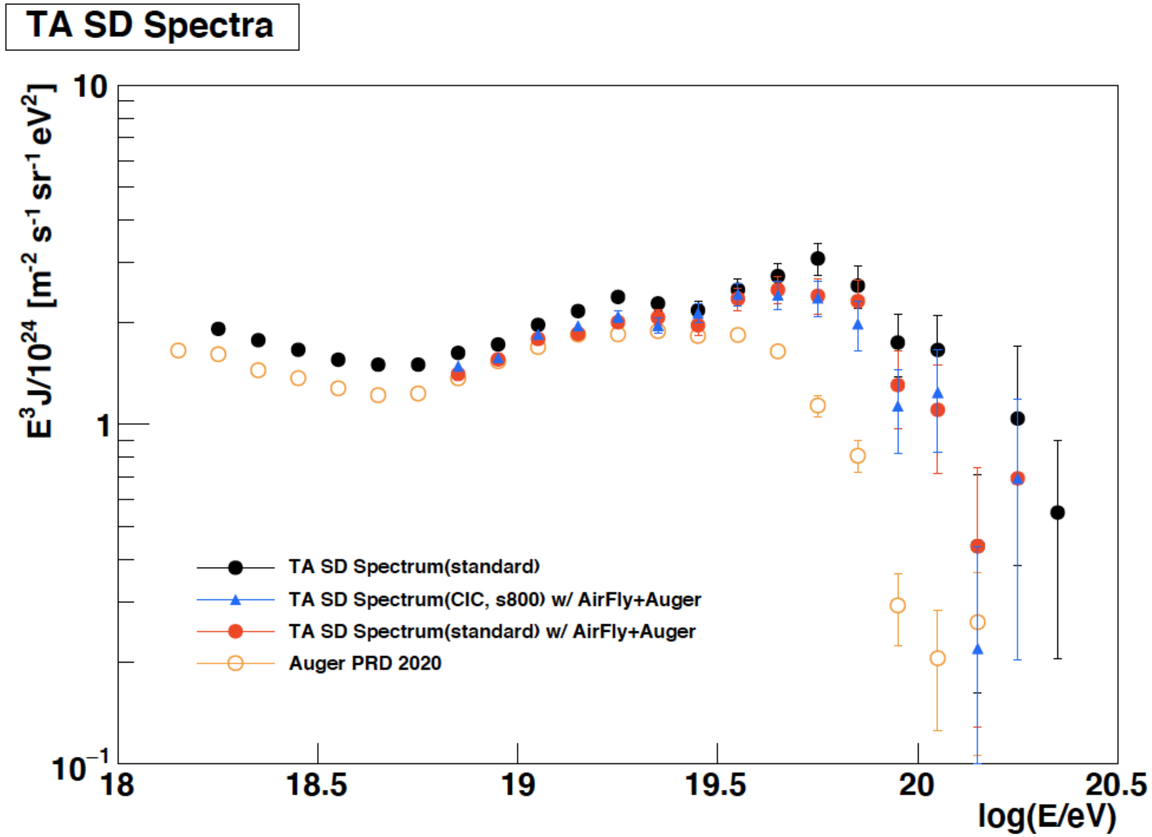


Relative energy rescaling with ±4.5%



Check using the Same Fluorescence Yield Model and Missing Energy

- Use the same fluorescence yield model as Auger.
- Use the same missing energy correction as Auger.
- The difference between TA and Auger above $10^{19.5}$ eV remains.



K. Fujita
More on PoS(ICRC2023)400

Simultaneous Fit: fit both spectra simultaneously

- Null hypothesis: Two spectra come from the same parent spectrum
- Binned log-likelihood, taken from Particle Data Group [S. Navas *et al.* (Particle Data Group), Phys. Rev. D 110, 030001 (2024)]

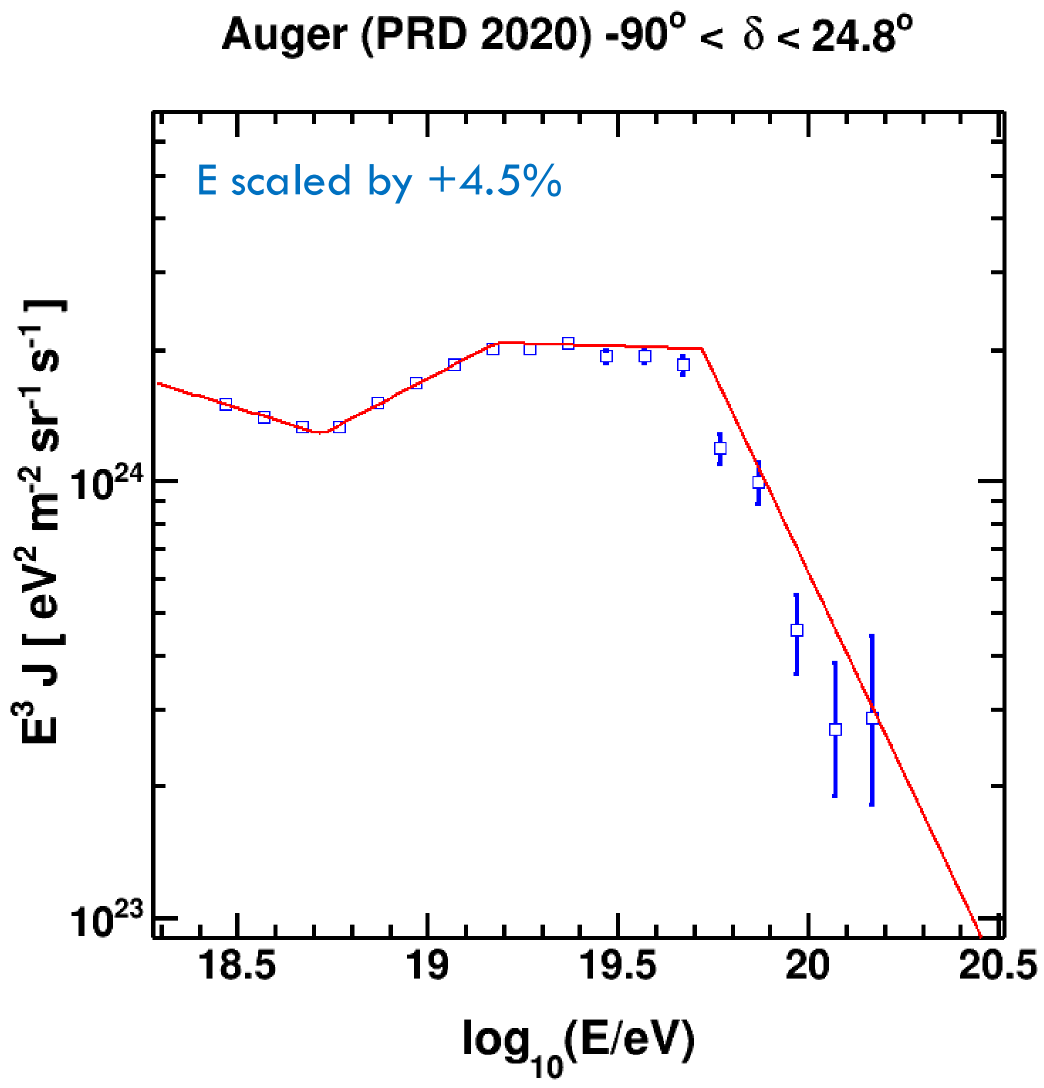
$$-2\ln\lambda(\boldsymbol{\theta}) = 2\sum_{i=1}^{N}\left[\mu_i(\boldsymbol{\theta}) - n_i + n_i \ln\frac{n_i}{\mu_i(\boldsymbol{\theta})}\right] , \qquad (40.16)$$

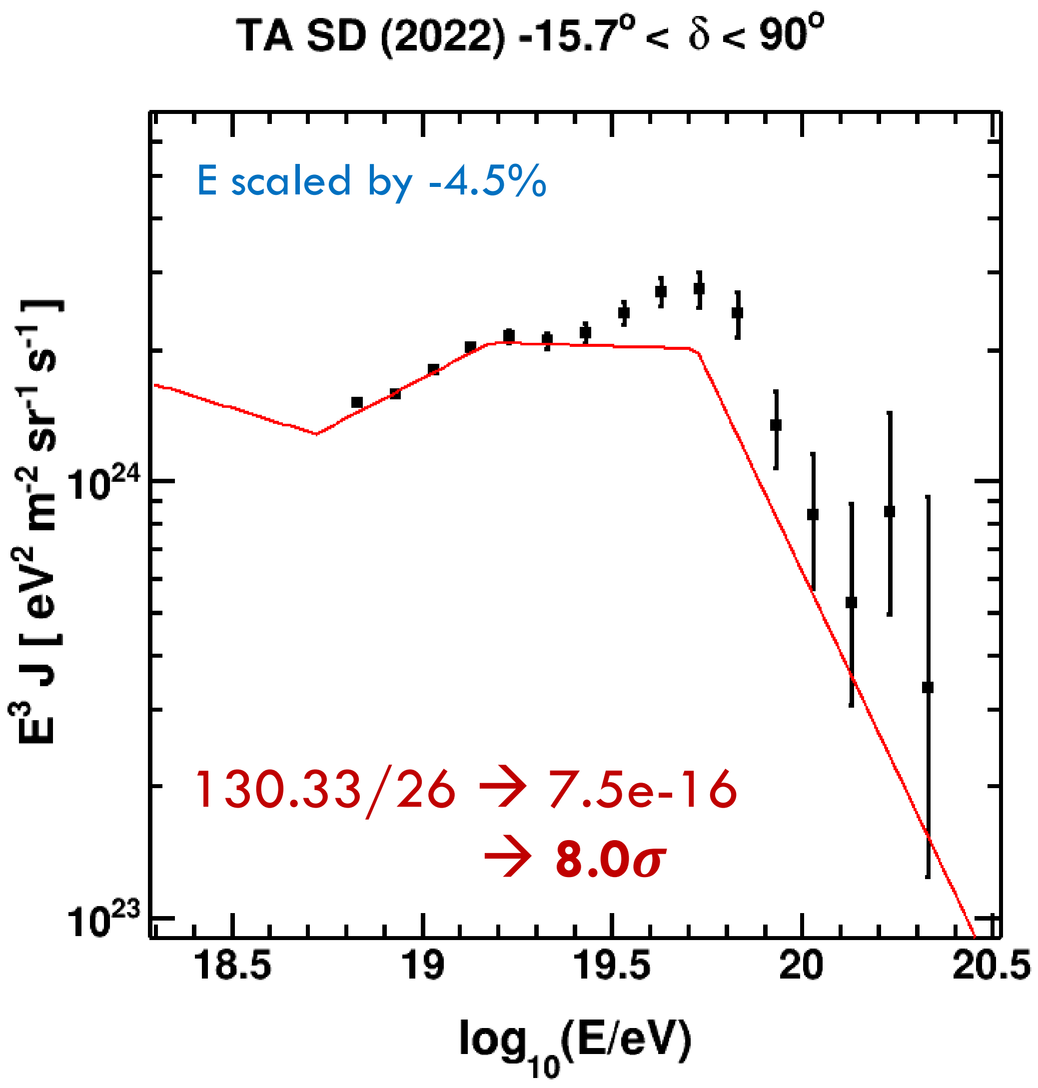
A smaller value of $-2\ln\lambda(\widehat{\boldsymbol{\theta}})$ corresponds to better agreement between the data and the hypothesized form of $\boldsymbol{\mu}(\boldsymbol{\theta})$. The value of $-2\ln\lambda(\widehat{\boldsymbol{\theta}})$ can thus be translated into a p-value as a measure of goodness-of-fit, as described in Sec. 40.3.3.1. Assuming the model is correct, then according to Wilks' theorem [10], for sufficiently large μ_i and provided certain regularity conditions are met, the minimum of $-2\ln\lambda$ as defined by Eq. (40.16) follows a χ^2 distribution (see, *e.g.*, Ref. [9]). If there are N bins and M fitted parameters, then the number of degrees of freedom for the χ^2 distribution is $N-M$ if the data are treated as Poisson-distributed, and $N-M-1$ if the n_i are multinomially distributed.

- Number of data points of Auger (PRD 2020): 18 bins ($E \geq 10^{18.4}$ eV)
- Number of data points of TA (this work): 16 bins ($E \geq 10^{18.8}$ eV)
- Free parameters of the broken power law fit: 8 (normalization + 3 break energies + 4 power indices)
- DOF = 18 + 16 – 8 = 26

Fit both spectra in their full apertures: **8.0σ**

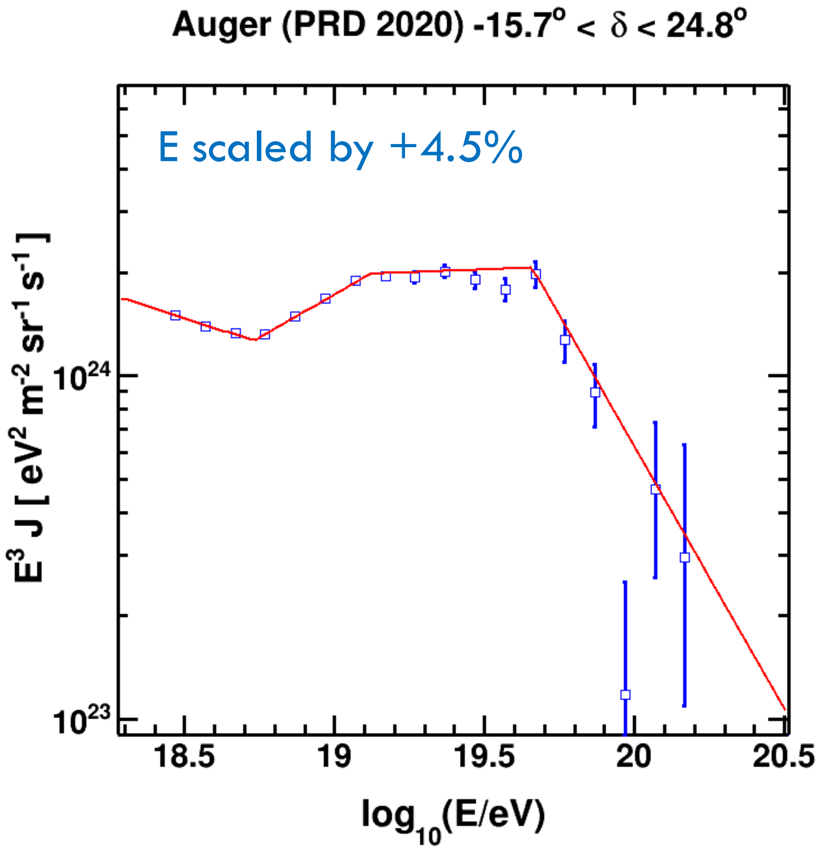
The red lines indicate the same broken power law function from the simultaneous fit.

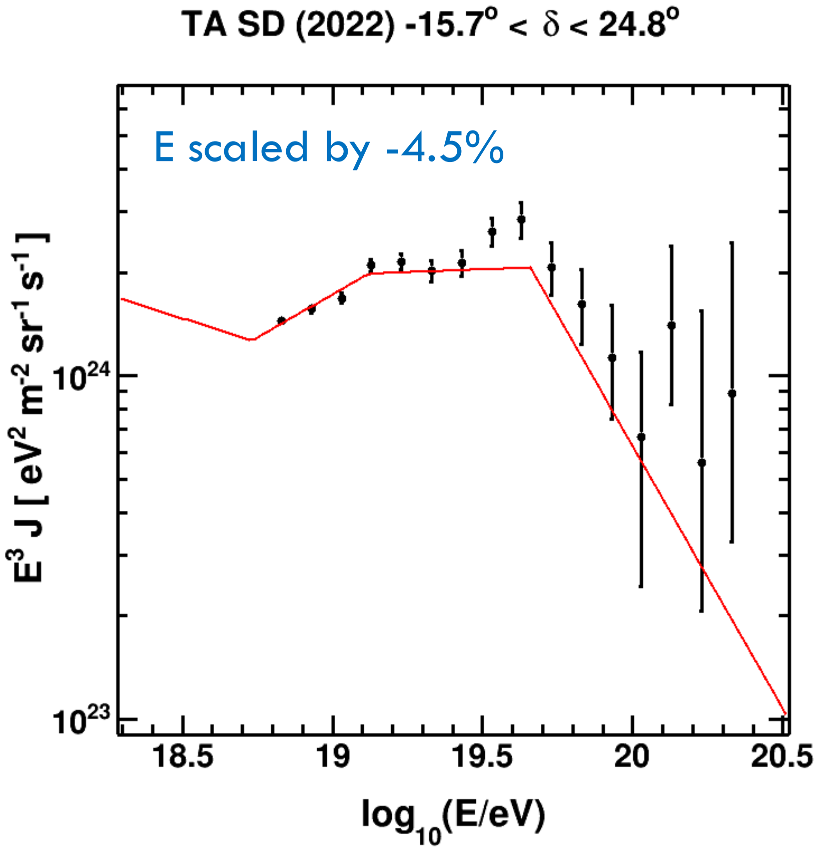




Test methodology: Fit both spectra in the common declination band

The red lines indicate the same broken power law function from the simultaneous fit.





- TA has seen two anisotropic regions in the northern sky that extend down into the common declination band.
- We hypothesize that this may affect the spectrum.

TA Hotspot & Perseus-Pisces supercluster excess

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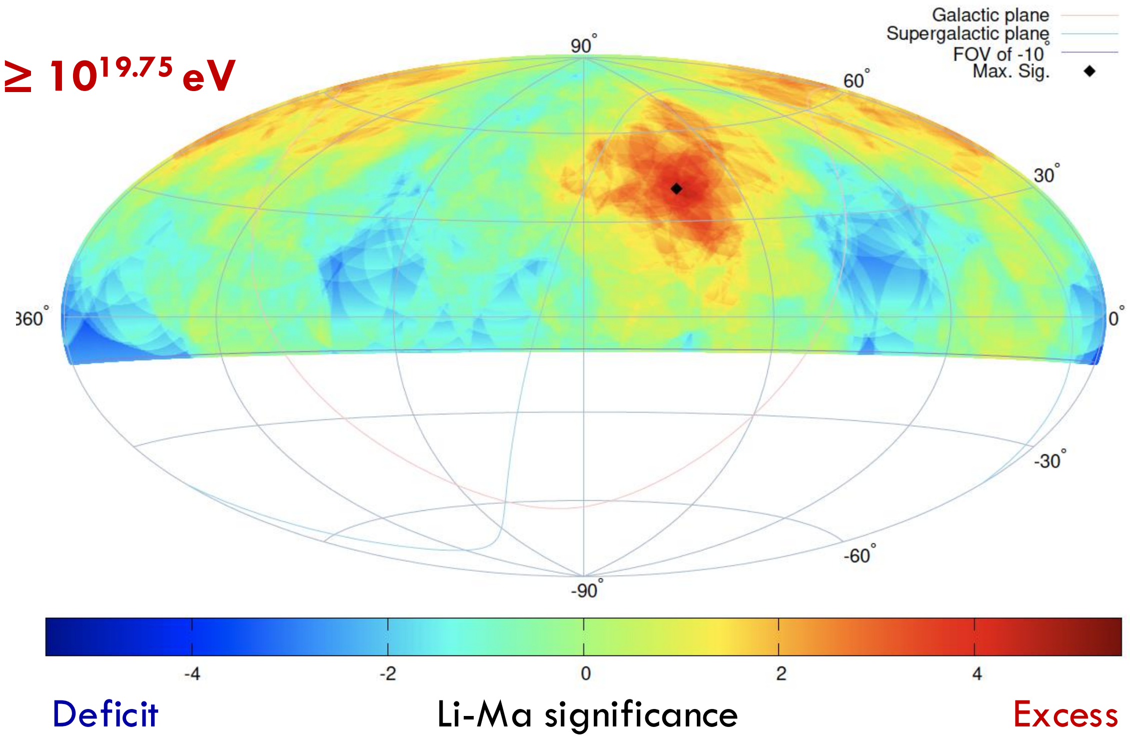
25°-radius oversampling

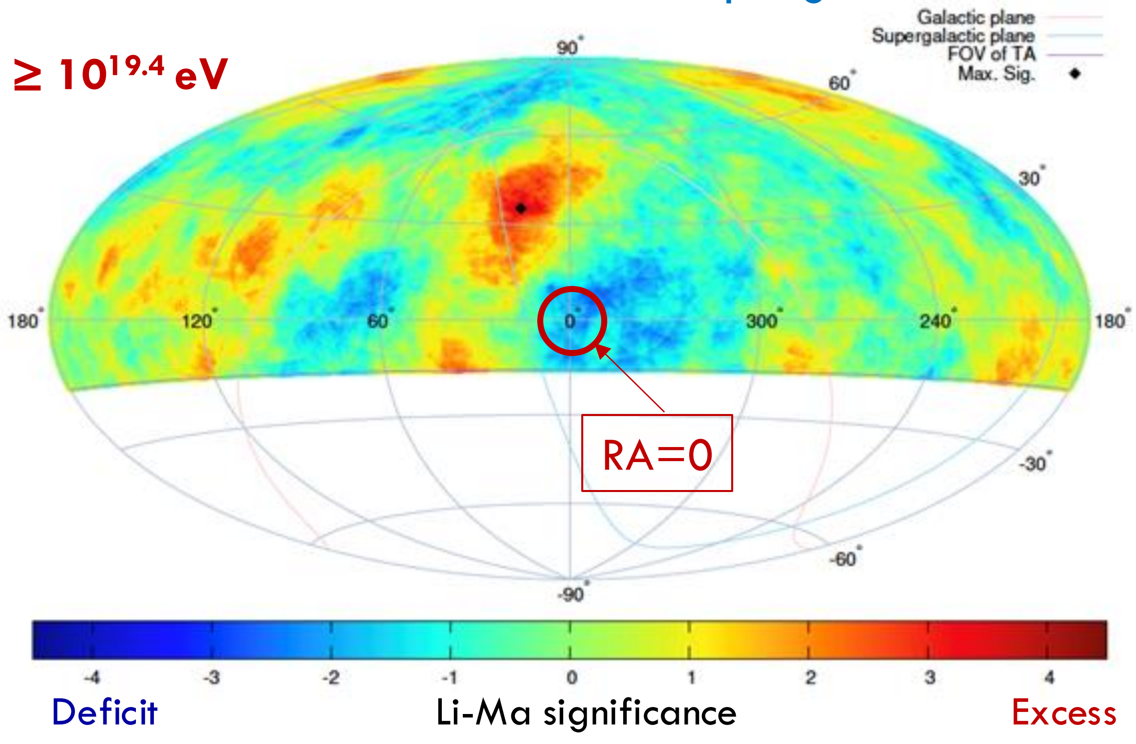
$E \geq 10^{19.75}$ eV



- 216 events (15-year TA SD data)
- Max local sig.: **4.8σ** at (144.0°, 40.5°)
- Post-trial prob.: $P(S_{MC} > 4.8\sigma)$=2.7×10^{-3}→ **2.8σ**

20°-radius oversampling

$E \geq 10^{19.4}$ eV

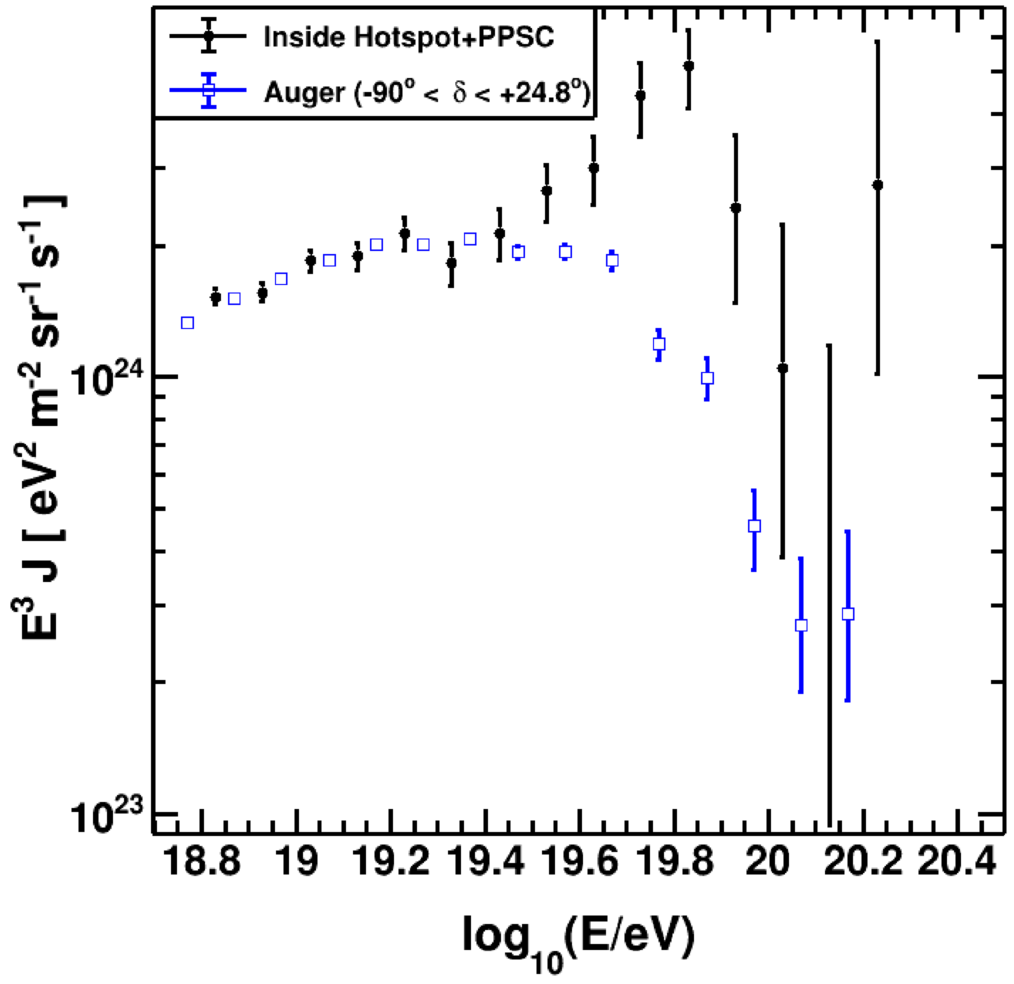


- 1125 events (15-year TA SD data)
- Max local sig.: **4.0σ** at (17.9°, 35.2°)
- Chance probability of having equal or higher excess close to the PPSC → **3.3σ**

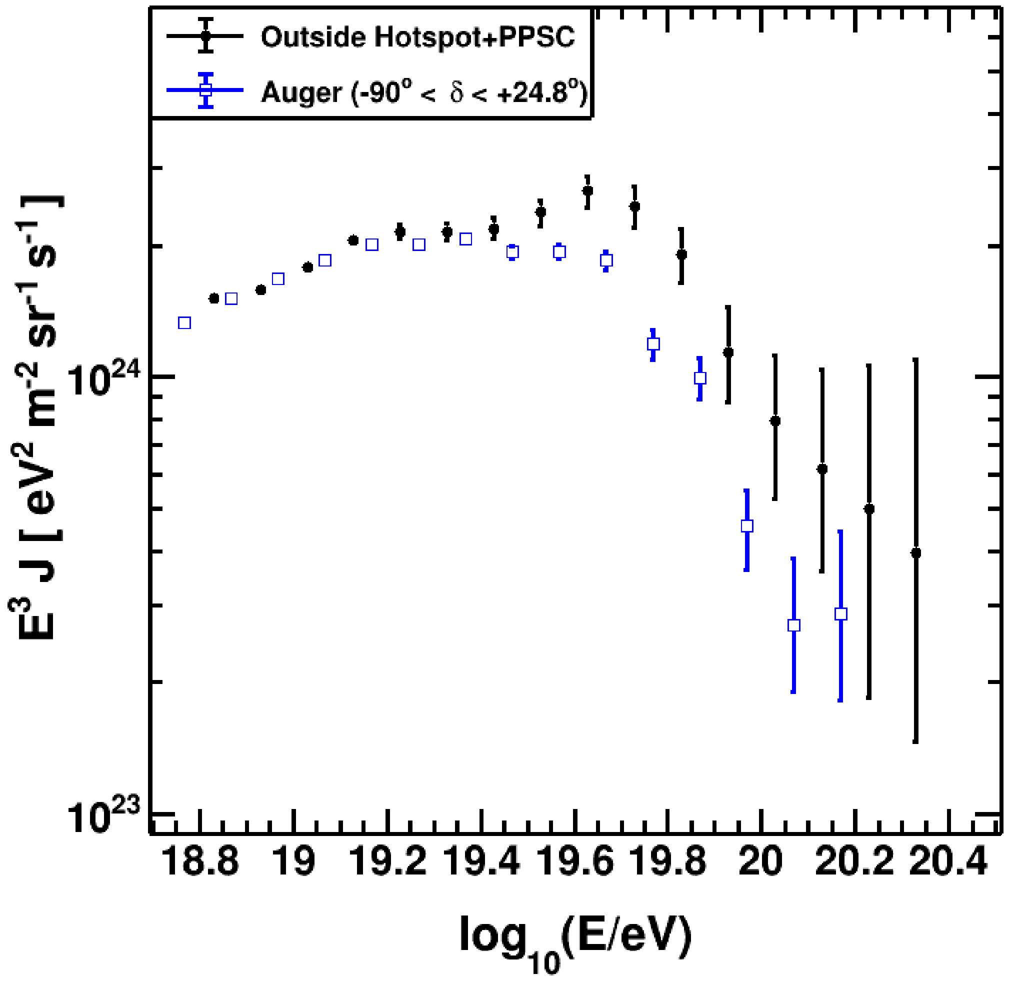
TA Inside/Outside Hotspot and PPSC excess regions

TA full aperture

Inside the excesses



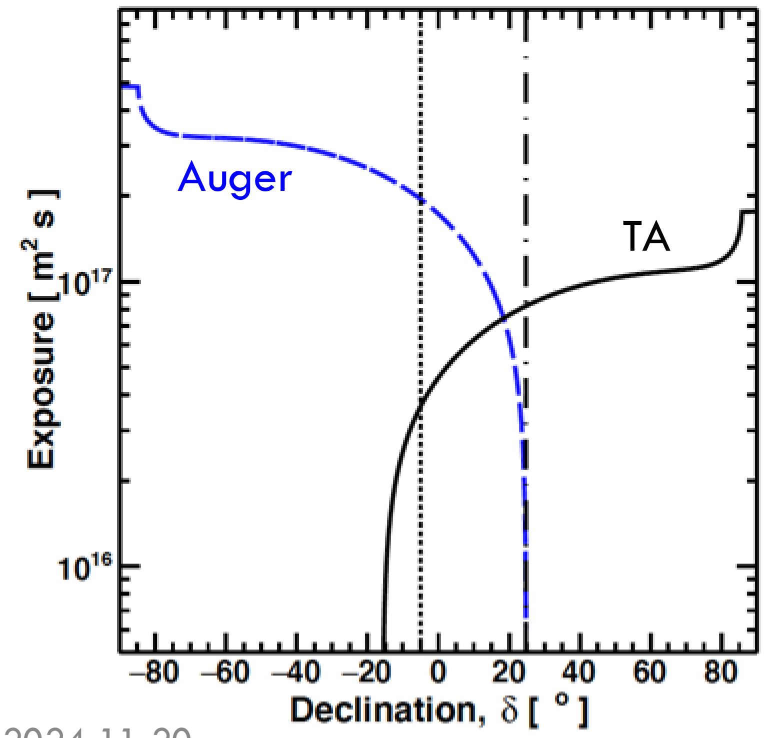
Outside the excesses

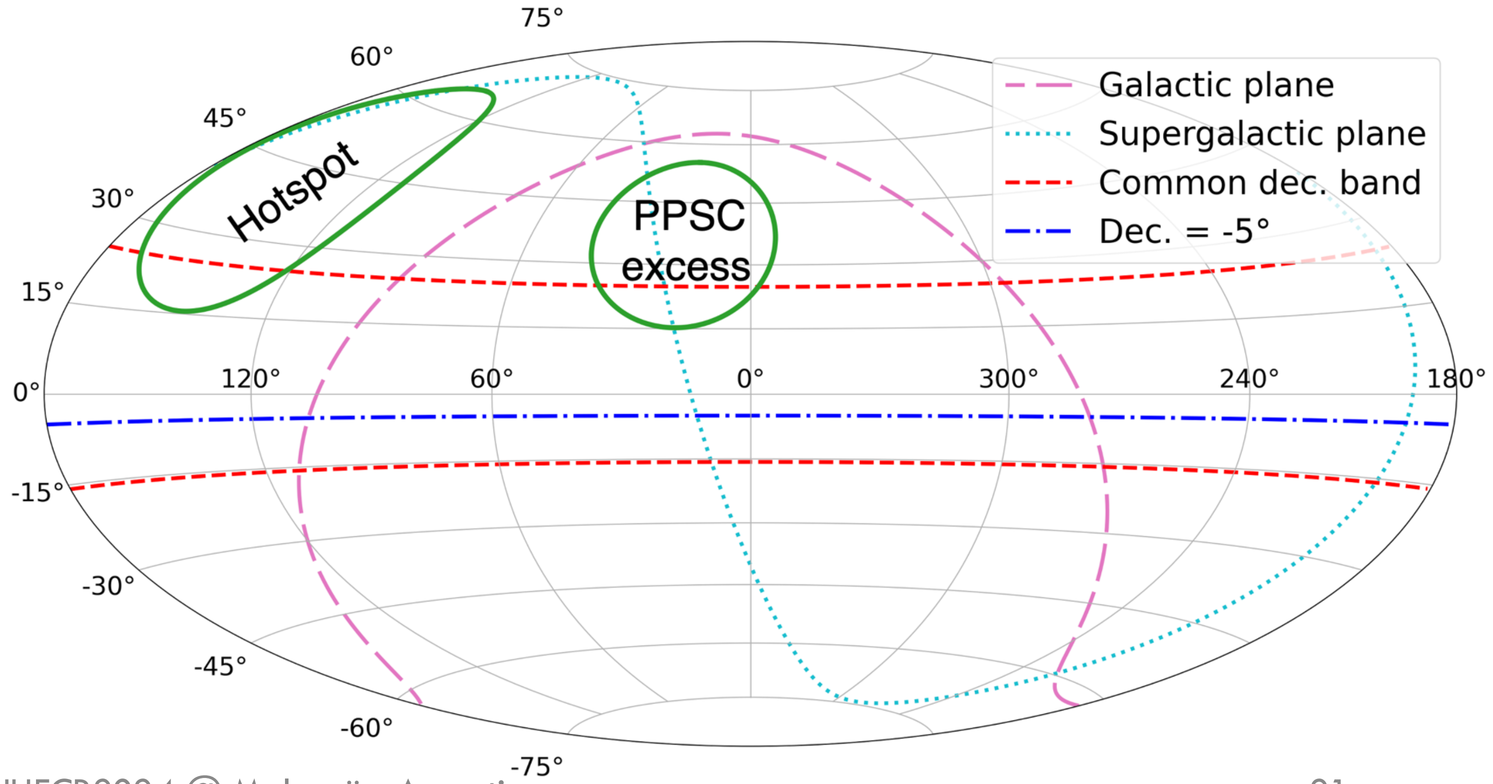


Validate the methodology by looking at the common sky

- Restrict the common declination band (-15.7°< δ <24.8° → **-5°**< δ <24.8°)
  - where TA exposure is very small and rapidly drops off
- Exclude all events within *a priori* established excess regions—masking the excess regions
  - where Auger exposure rapidly drops off

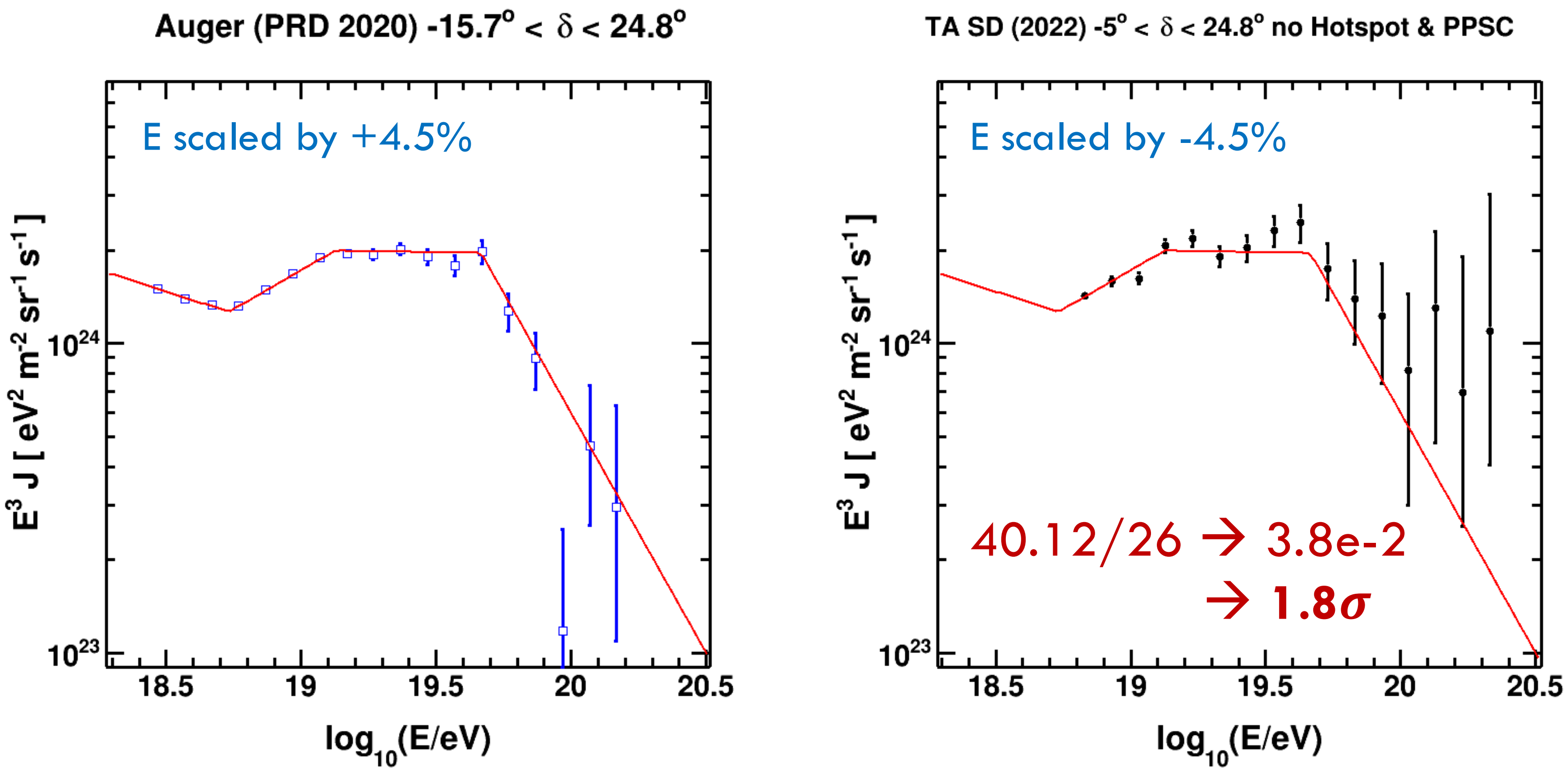
Exposure vs. Declination





Fit both spectra: TA in -5°≤δ<24.8° & excl. Hotspot+PPSC: **1.8σ**

The red lines indicate the same broken power law function from the simultaneous fit.

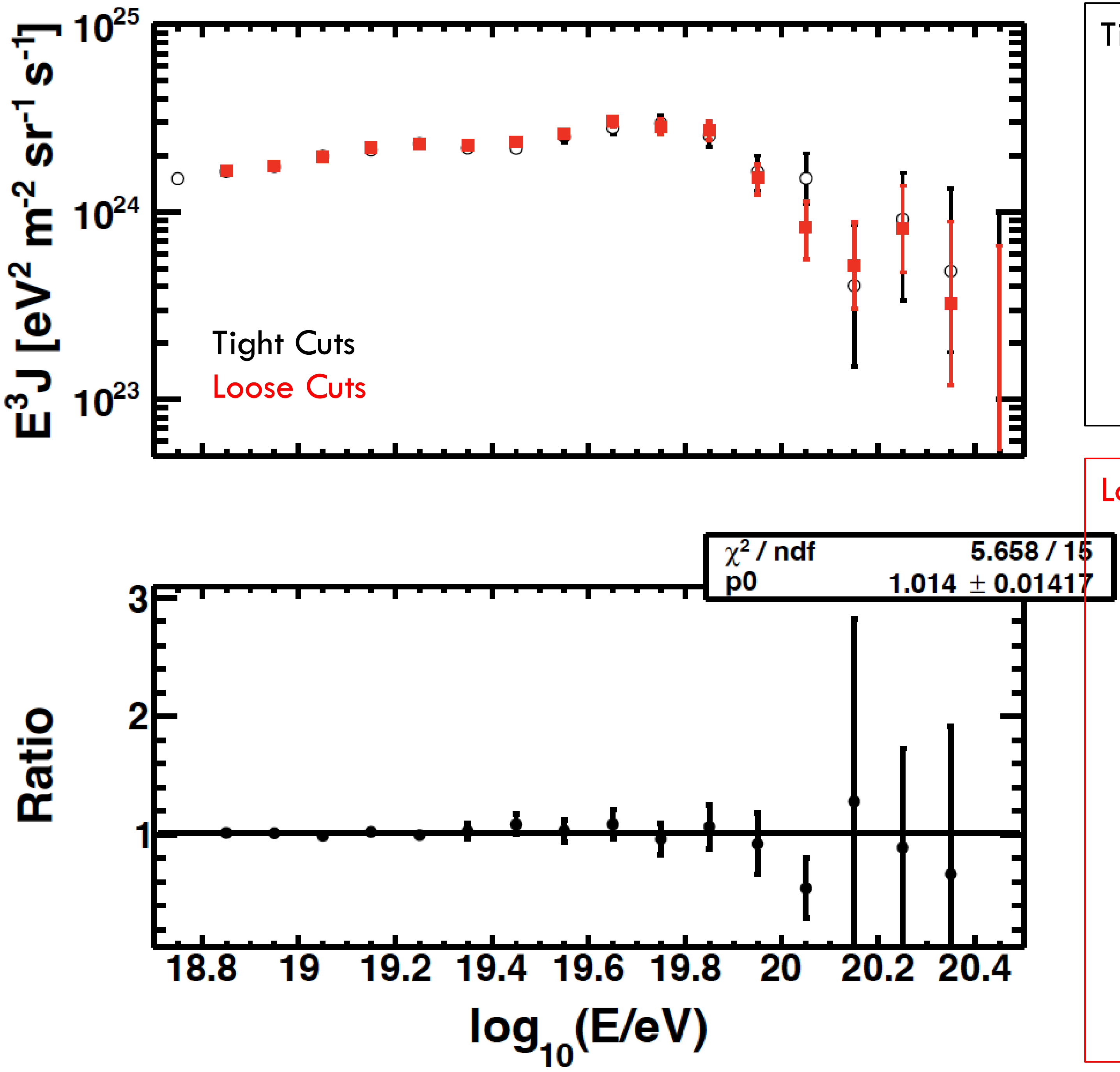


→ TA and Auger spectra are now in good agreement.

Summary

- We validated Monte Carlo carefully by comparing it with the distribution of the data.
- TA SD energy reconstruction is robust, as confirmed by three methods: 1) FD/SD comparison, 2) Monte Carlo, and 3) Constant intensity cut methods.
- The spectral features (ankle, *instep/shoulder*, and cutoff) in the 16-year TA SD data were presented.
- Simultaneous fit analyses were performed on the TA and Auger spectra.
- A log-likelihood sum per degree of freedom of **130.33/26** (**8.0σ**) was obtained from the simultaneous fit to both TA and Auger spectra in their full apertures.
- On the other hand, a log-likelihood sum per degree of freedom of **40.12/26** (**1.8σ**) was obtained using the simultaneous fit in the common sky region after applying cuts to isolate the causes of an apparent discrepancy.
- These results indicate that there is a difference in the cosmic ray energy spectrum between the northern and southern skies.

Backup



Tight Cuts

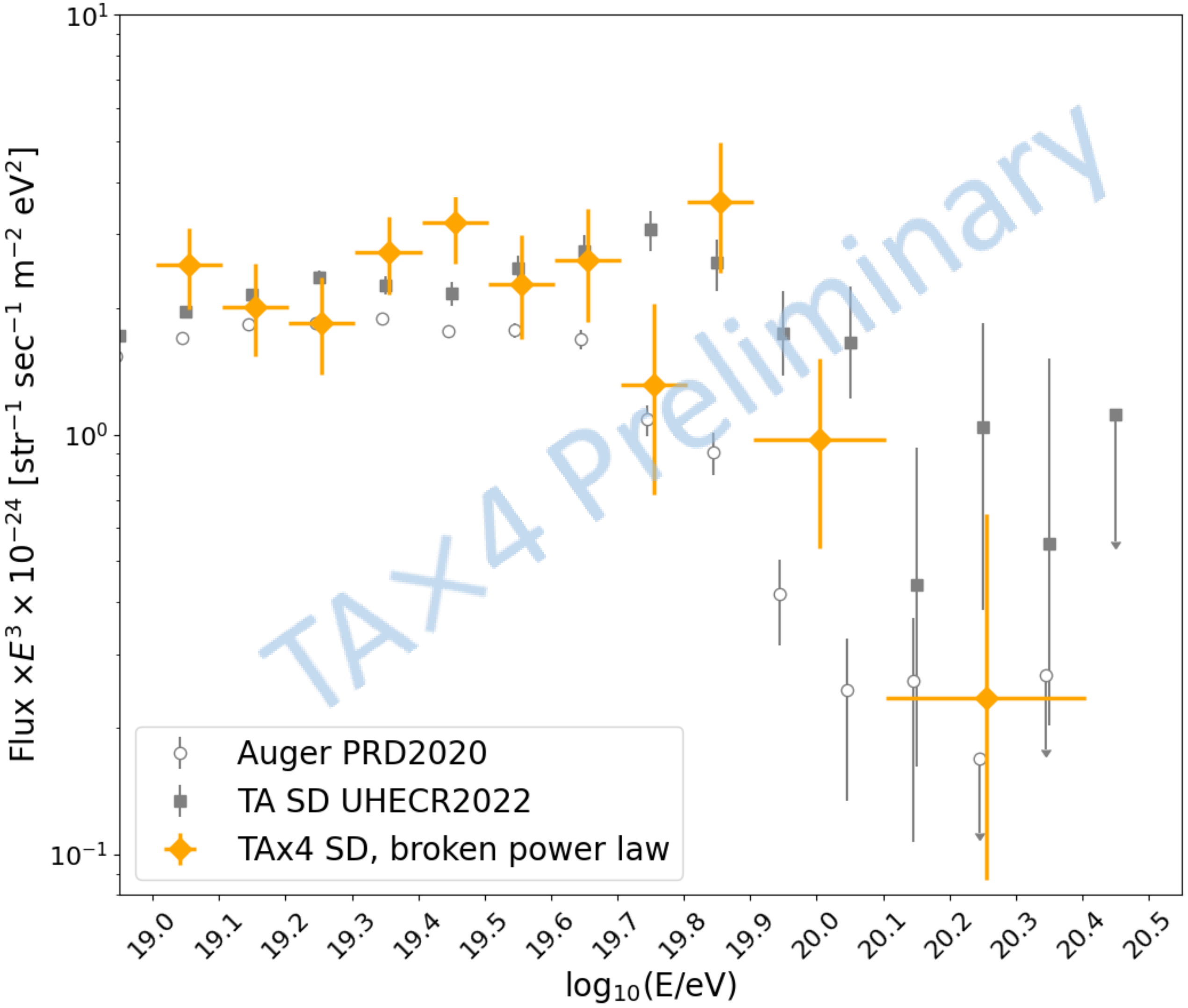
- Energy ≥ 10^{18} eV
- Zenith angle, $\theta < 45°$
- $N_{sd} \geq 5$ (number of good SDs that are part of the event)
- $D_{border} > 1200$ m
- chi2/d.o.f of geometry and LDF fits < 4
- Pointing direction error < 5°
- σ_{S800} / S800 < 0.25

Loose Cuts

- Energy ≥ $10^{18.8}$ eV
- Zenith angle, $\theta < 55°$
- $N_{sd} \geq 5$ (number of good SDs that are part of the event)
- chi2/d.o.f of geometry and LDF fits < 4
- Pointing direction error < 5°
- σ_{S800} / S800 < 0.25
- Largest VEM counter surrounded by 4 working counters, there must be one working counter to the left, right, down, up on the grid of the largest VEM counter but they do not have to be immediate neighbors of the largest VEM counter.

TA×4 SD Energy Spectrum

K. Fujisue



- The energy spectrum was measured by the TA×4 SD using data collected for 3 years (October 2019–September 2022).
- Note that the statistics of the TA×4 SD-only events has been limited due to the absence of the inter-tower trigger system in this period.
- Consistent with the energy spectrum measured by the TA SD array.

Energy-Dependent Systematic Uncertainties

D. Ivanov +(Auger+TA Spectrum WG)
EPJ Web of Conferences 210, 01002 (2019)

Table 1. Sources of energy-dependent reconstruction bias in TA

Source of nonlinearity	Amount (% per decade)
FD Invisible energy	1% ± 1%
FD Fluorescence yield	−1% ± 1%
FD Aerosols	1.7% ± 1%
SD and FD comparison	−2% ± 9%
Net	−0.3% ± 9%

Table 2. Sources of energy-dependent reconstruction bias in Auger

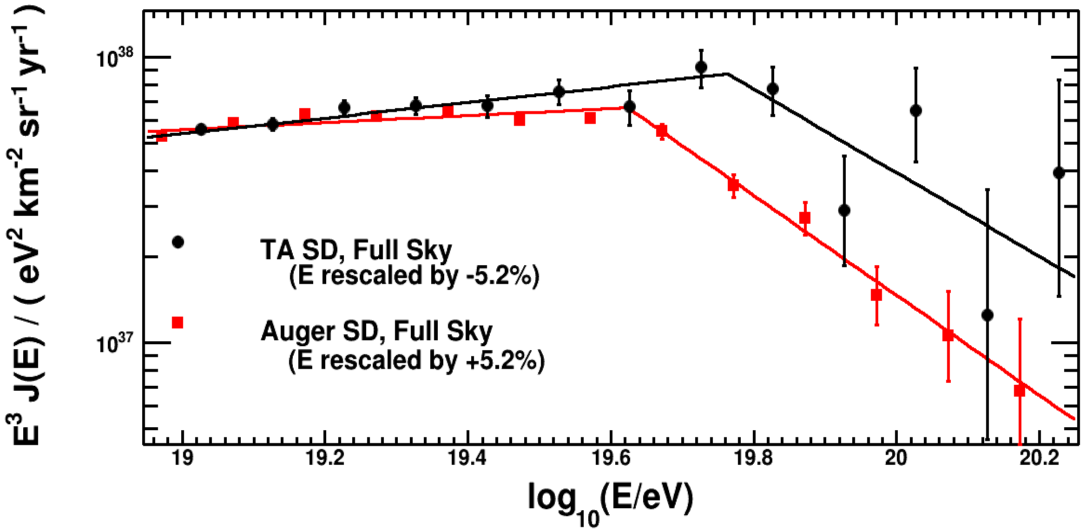
Source of nonlinearity	Amount (% per decade)
Aerosols	±1%
Calibration	±1%
SD and FD comparison	±2%
Constant Intensity Cut	±2%
Net	±3%

→ "We have investigated the systematic uncertainties of TA and Auger that would produce the energy-dependent biases in their energy spectra, and we have found that such biases are constrained to -0.3±9% for TA and ±3% for Auger."

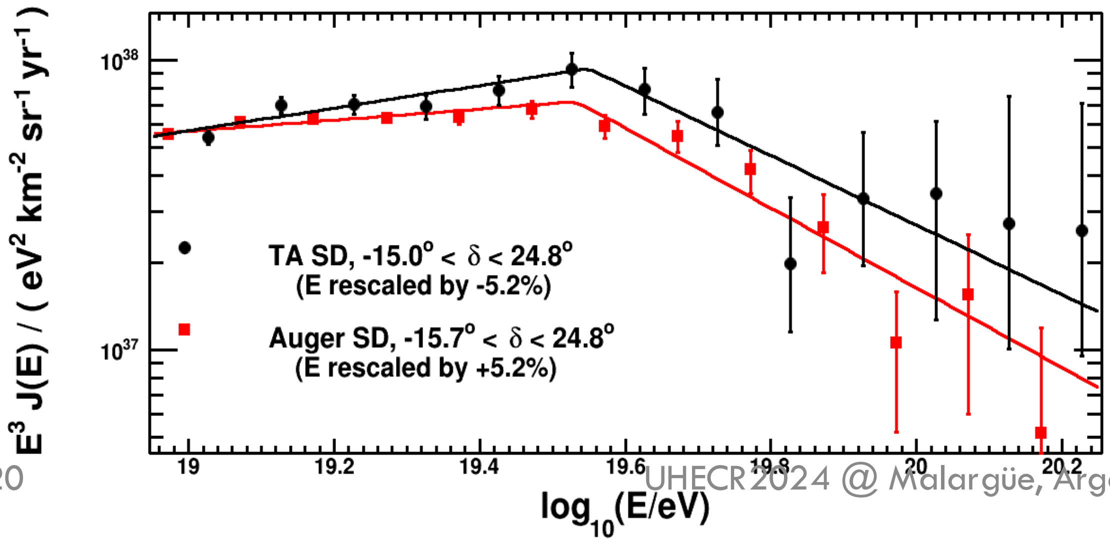
Previous Report from the Spectrum WG

D. Ivanov

Entire skies of Auger and TA



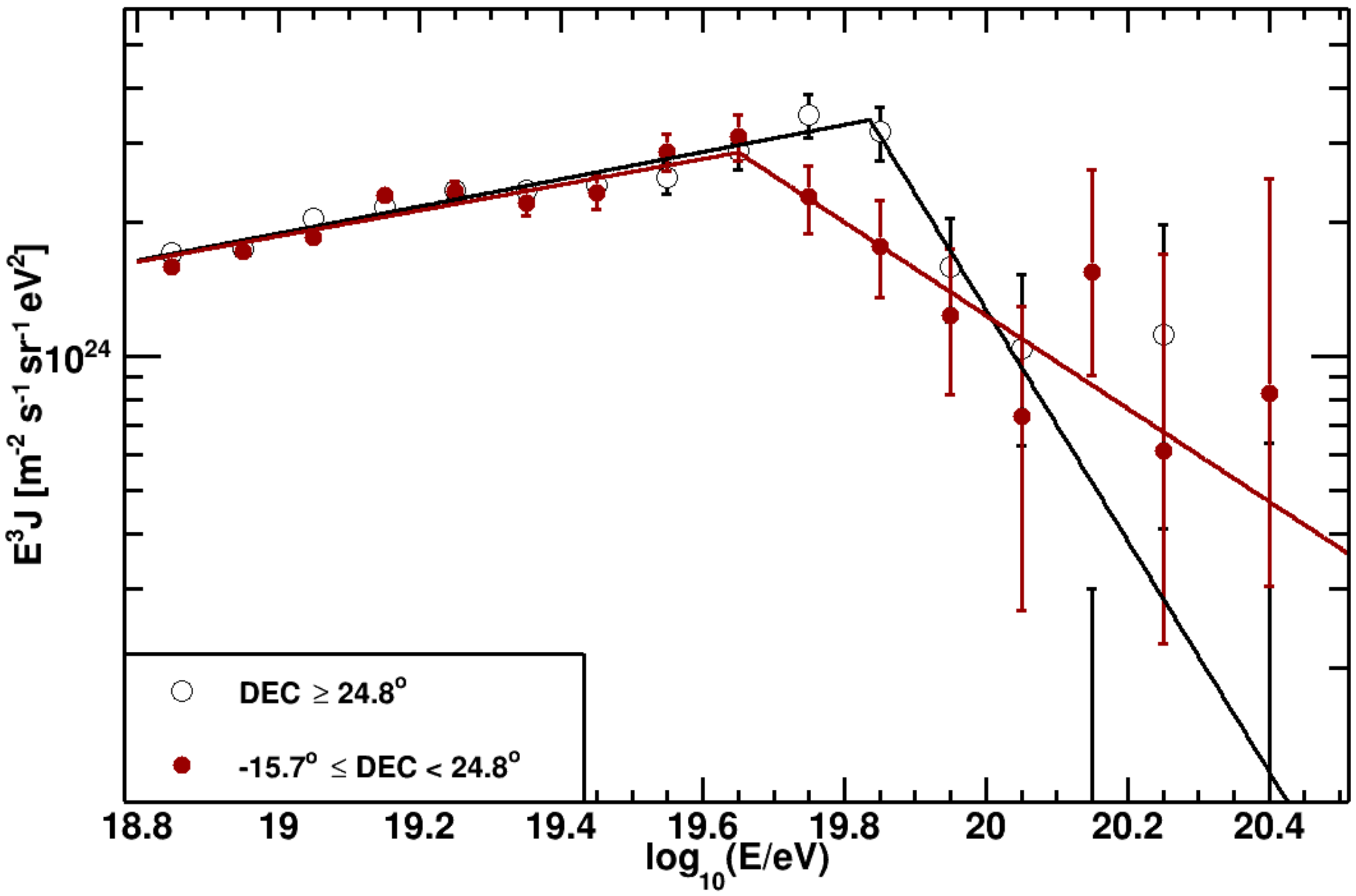
Auger-TA Common declination band



- **Auger-TA cutoffs agree** in the Auger-TA common declination band
- Disagreement across full sky and agreement in the common declination band has been seen consistently since UHECR 2014

Declination Dependence in the TA SD Spectrum

J. Kim+, PoS(ICRC2023)008



- Differences in the cutoff energies
  - log(E/eV)=**19.84 ±0.02** for higher declination (24.8°–90°)
  - log(E/eV)=**19.65 ±0.03** for lower declination (-16°–24.8°)
- The local significance is **4.8σ.**
- The global significance of the difference is estimated to be **4.4σ.**
- No instrumental causes were found. This difference implies it is astrophysical in nature.