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Latest Measurement of the Ultra High Energy Cosmic Ray Spectrum with the Telescope Array Surface Detector

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on behalf of the Telescope Array Collaboration

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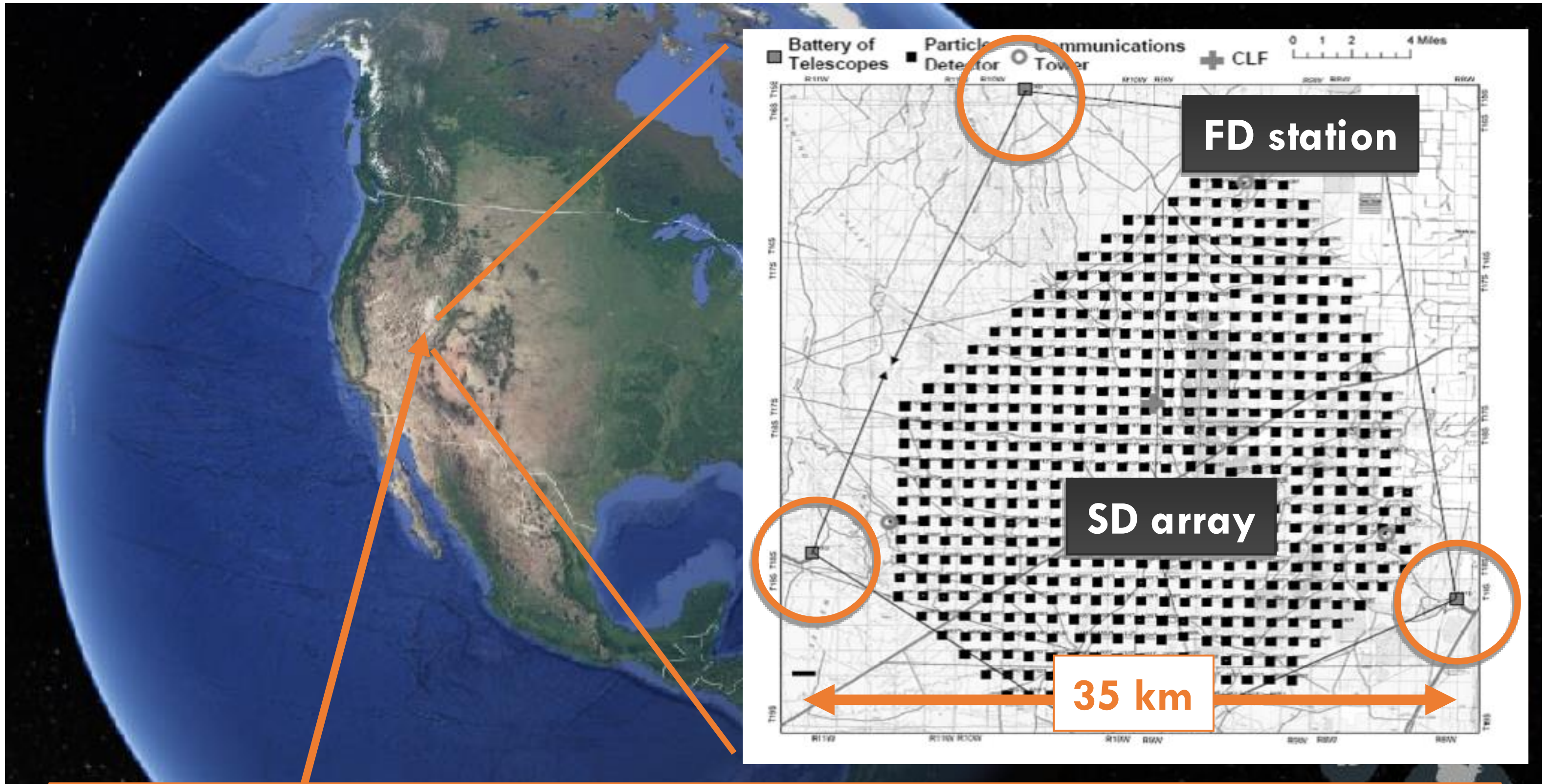
Outline

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

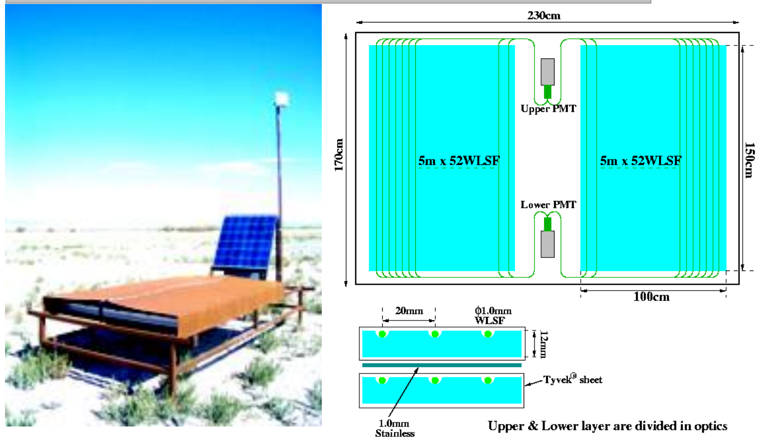
Telescope Array (TA) experiment

- The largest cosmic ray observatory in the northern hemisphere



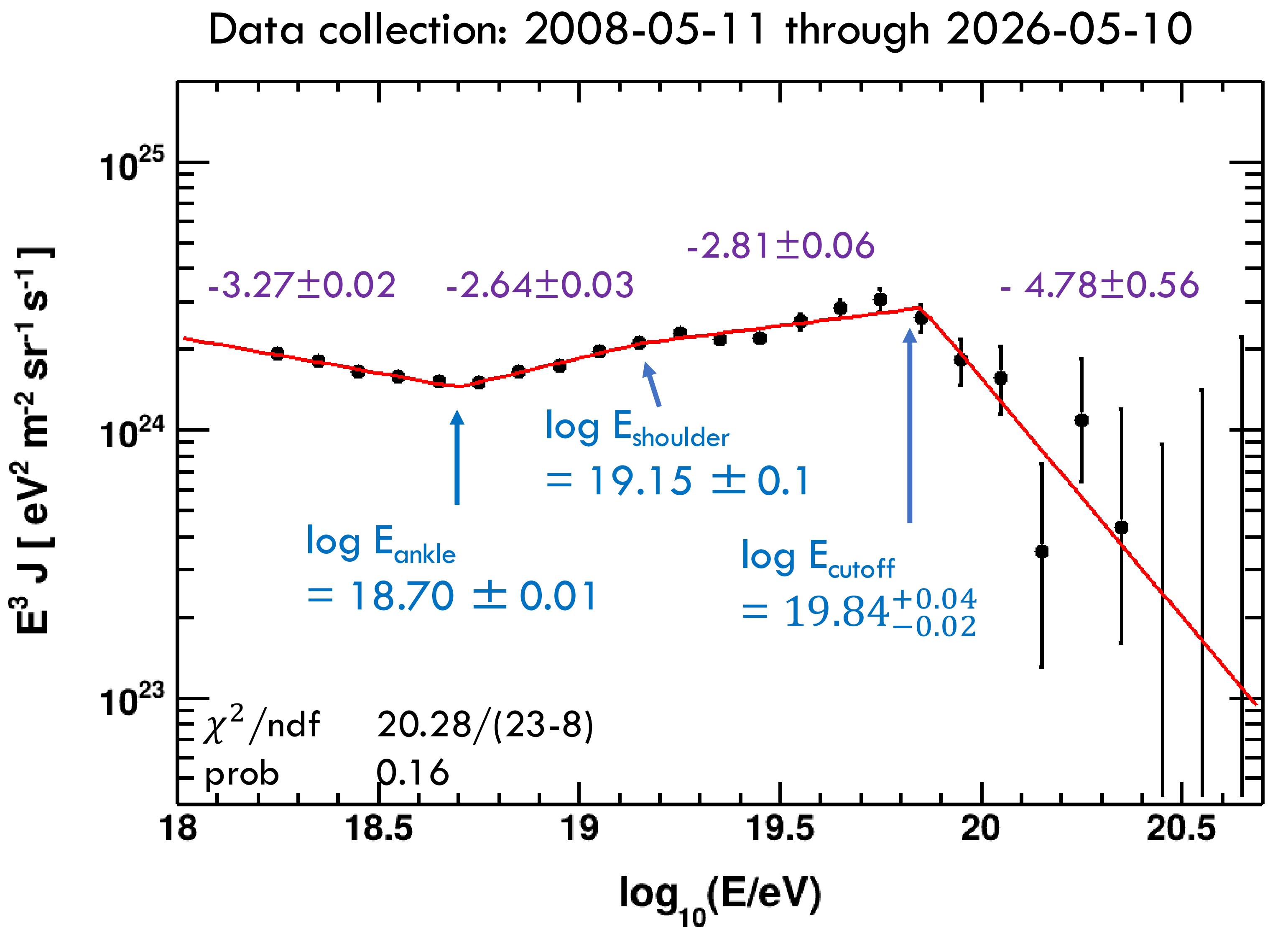
- Delta, Utah, USA. ~1400 m above sea level
- 507 surface detector array covers **~700 km²**
- 38 telescopes in 3 stations look over the array

Surface Detector: Plastic Scintillator



Fluorescence Detector: PMT camera

Spectral Features in 18-year TA SD Data: specCuts

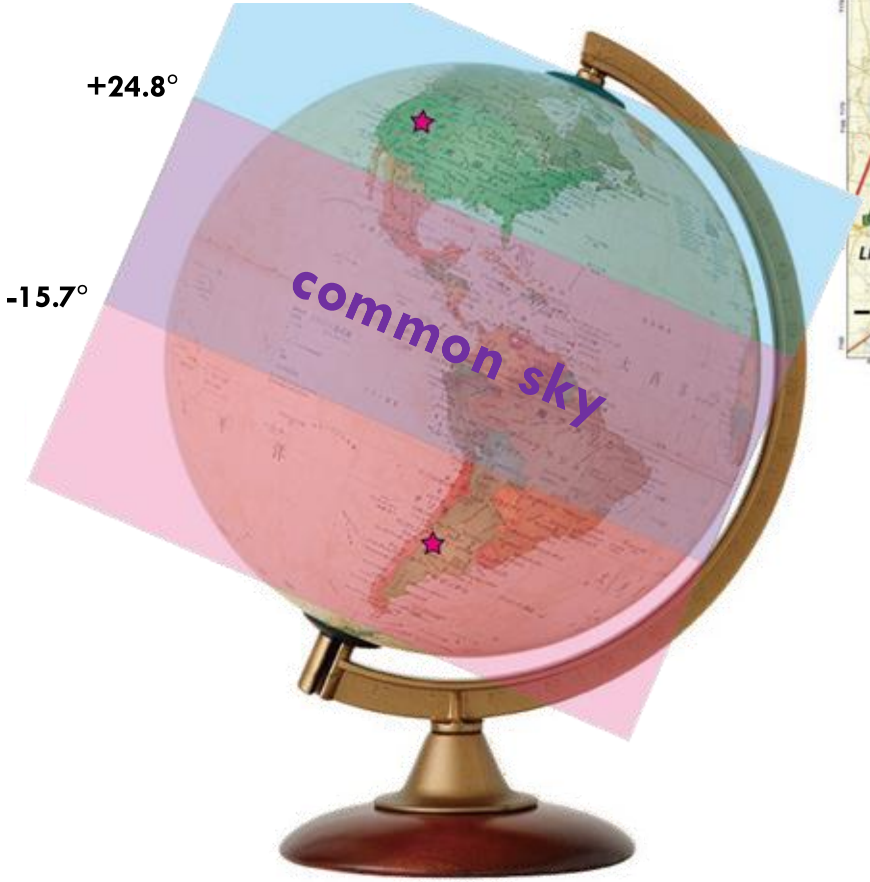


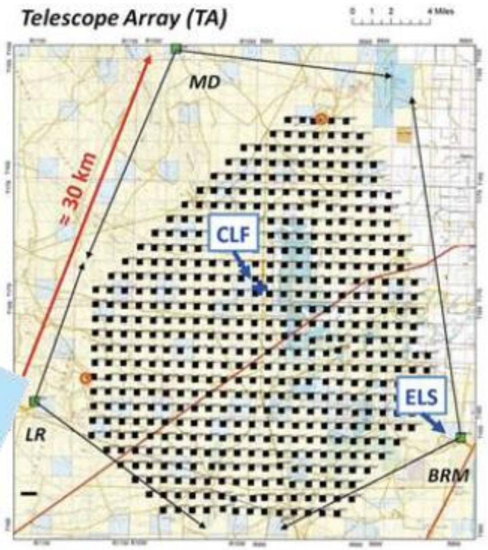
- **Cutoff** feature at $10^{19.84}$ eV
  N_{exp}: 125.4
  N_{obs}: 48
  Chance probability: 2.3×10^{-15}, ~7.8σ
- **Shoulder** feature at $10^{19.15}$ eV
  N_{exp}: 2425.6
  N_{obs}: 2193
  Chance probability: 8.5×10^{-7}, ~4.8σ
- We observe the softening feature in the northern hemisphere at $10^{19.15\pm0.05}$ eV with a 4.8σ 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

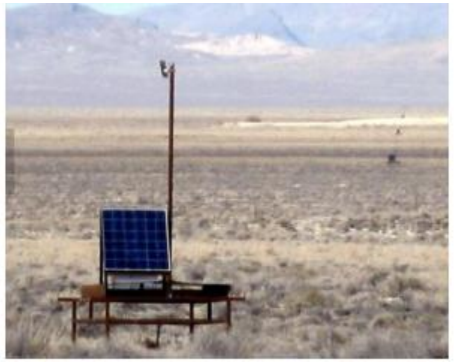
Two UHECR Observatories

Auger and TA

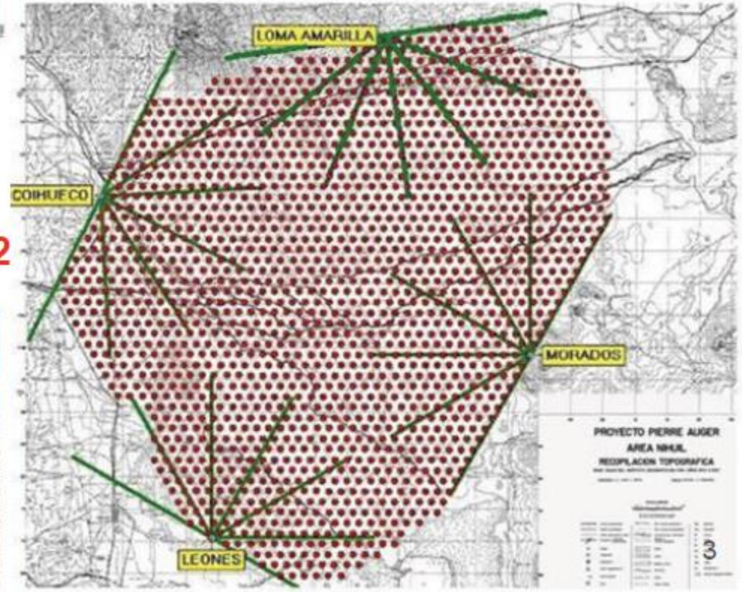




TA
39° N
700km²



Auger
35° S
3000km²



Energy Spectrum Measurements in Northern/Southern Skies

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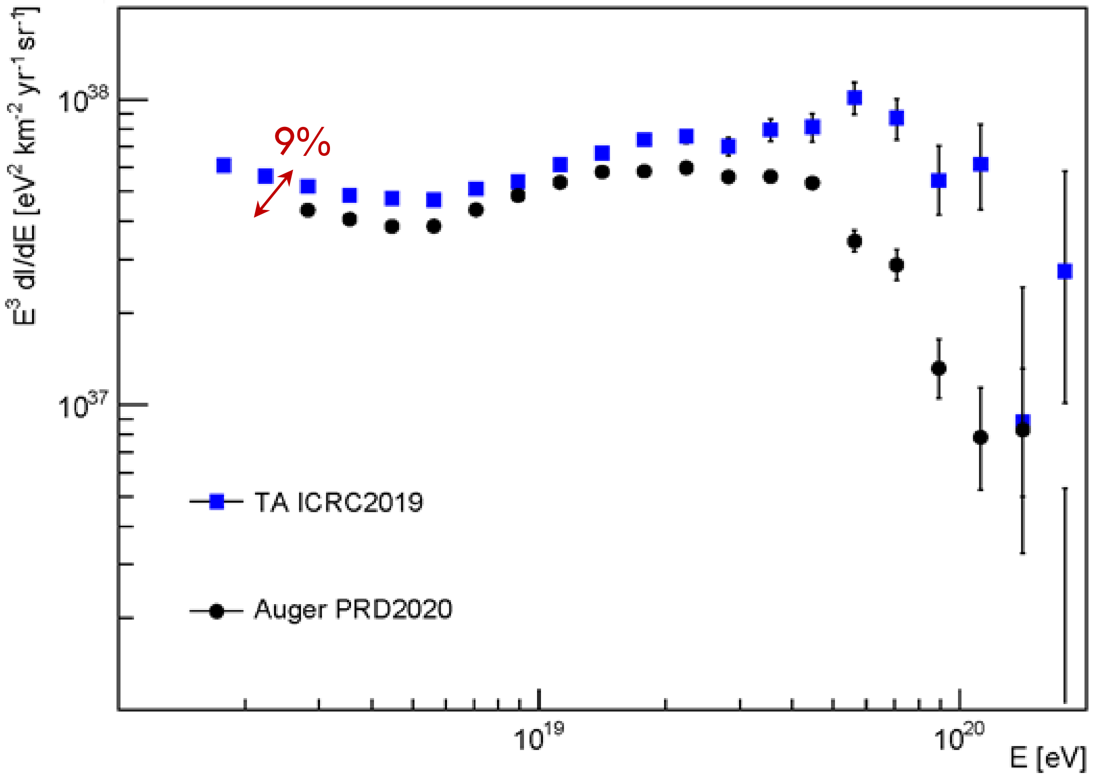
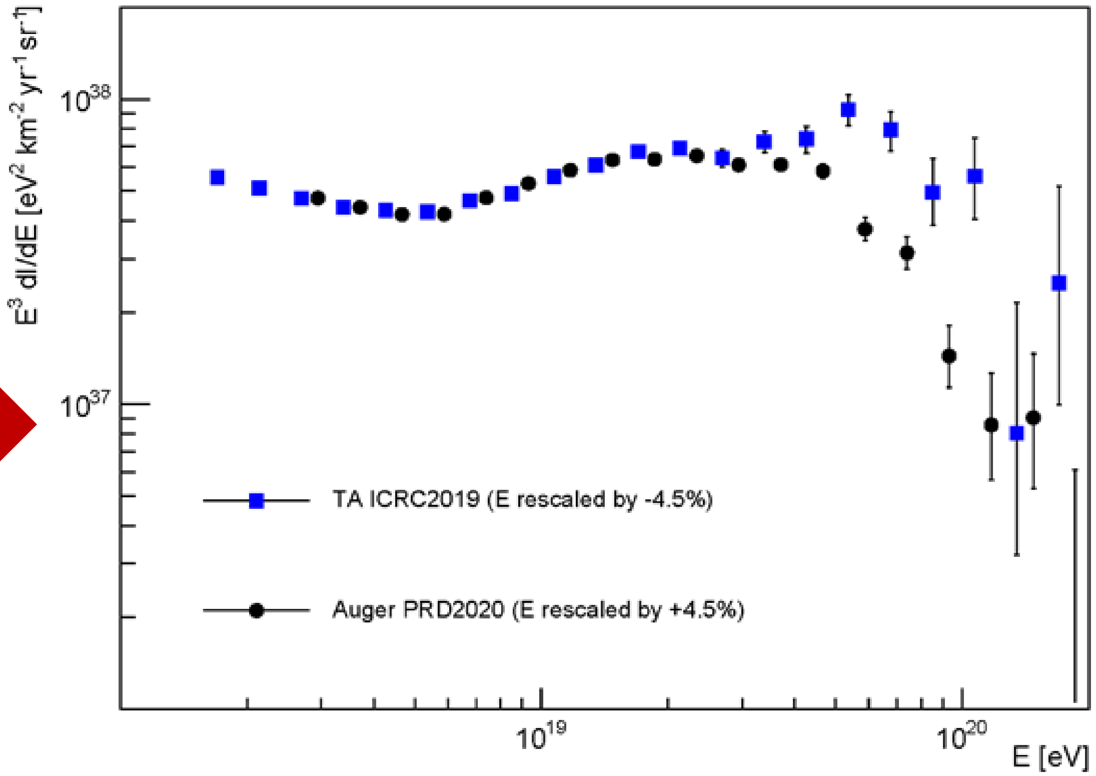
Energy systematic uncertainty:
21% for TA
14% for Auger

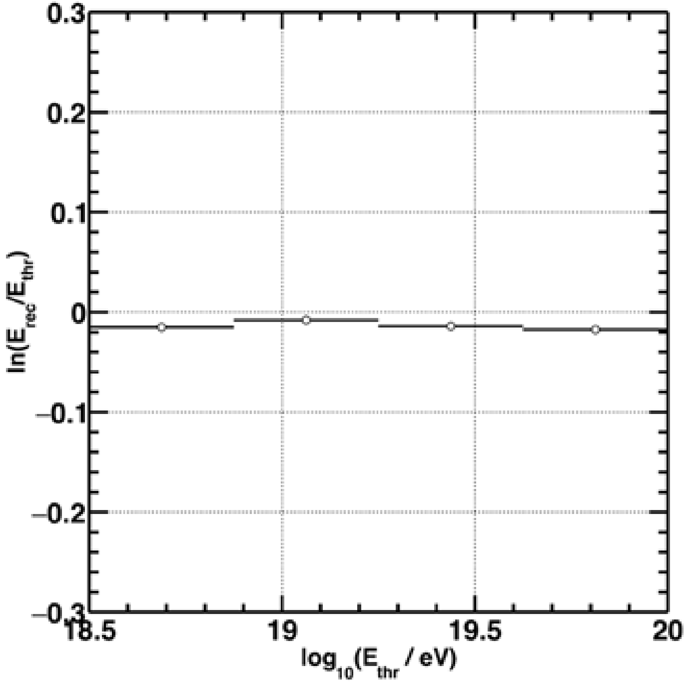
Relative energy rescaling with $\pm 4.5\%$



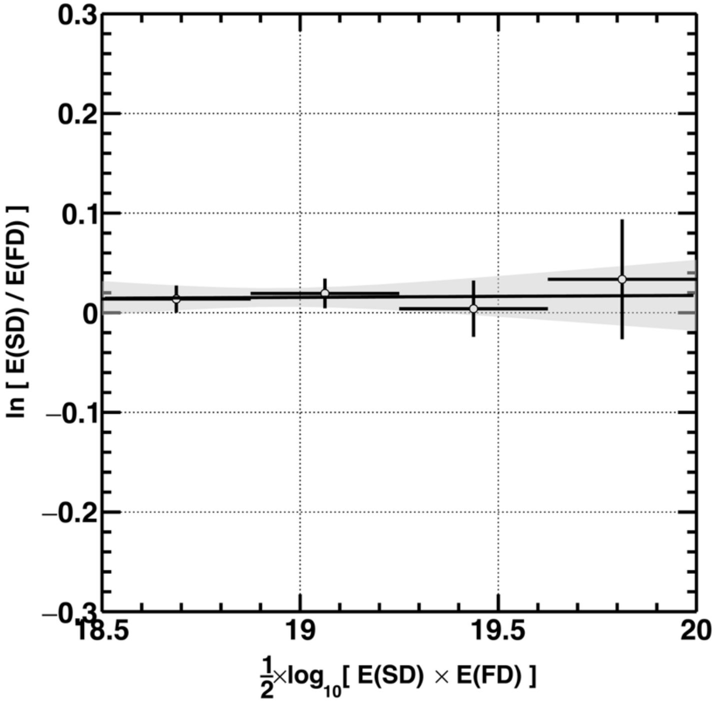


Linearity in Energy Reconstruction

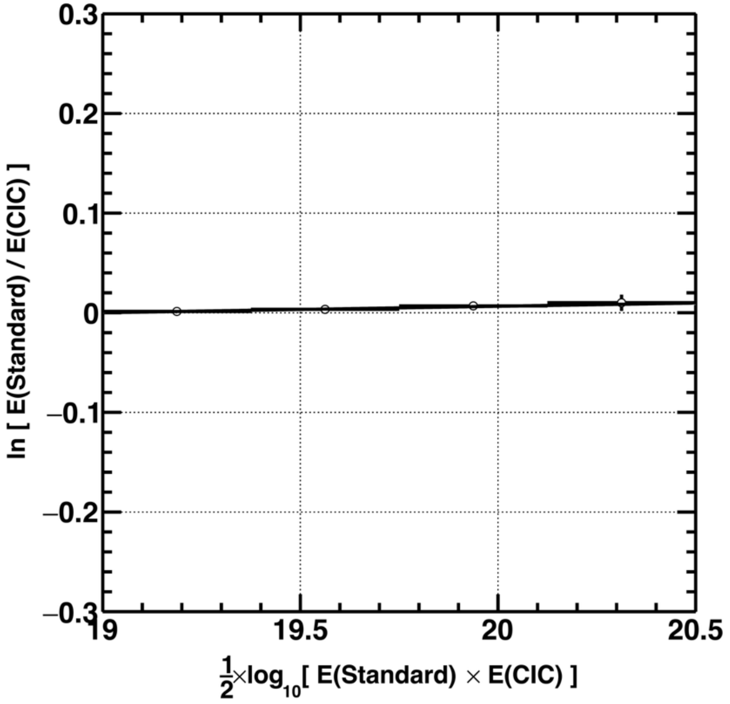
MC Thrown energy and reconstructed energy



TA SD and FD energies



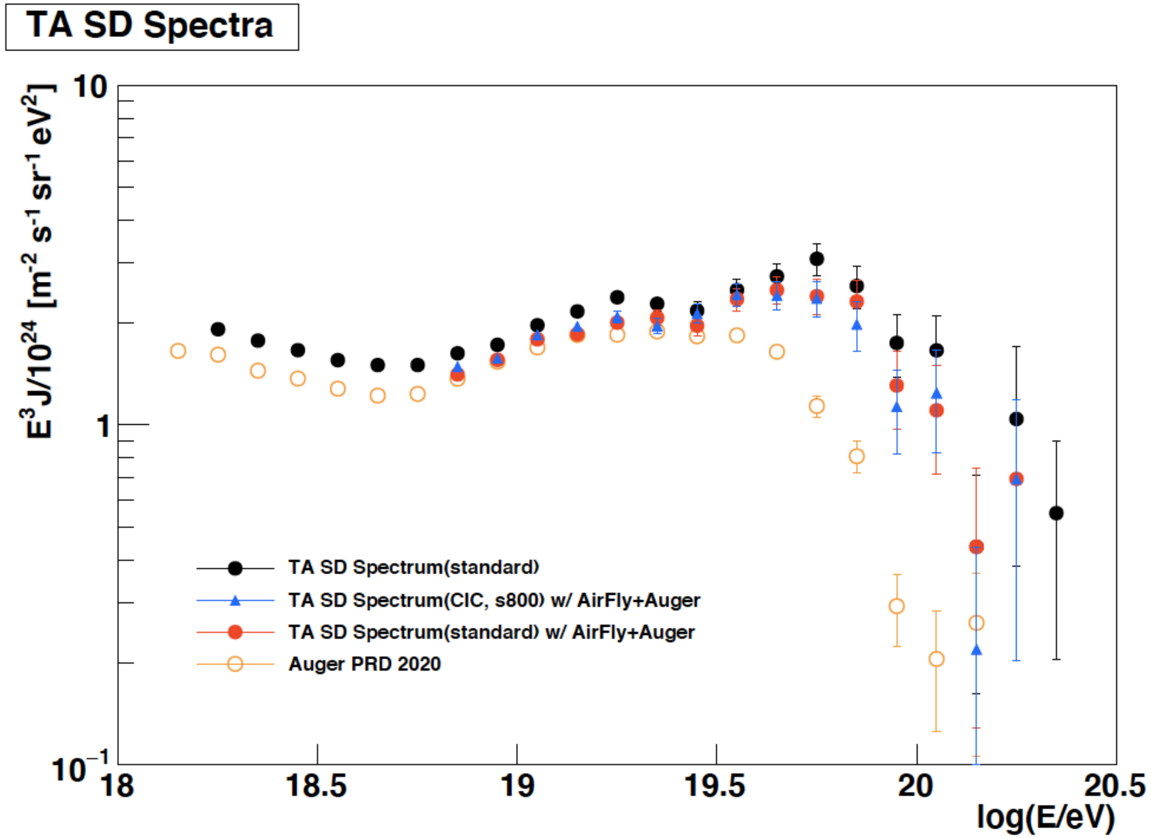
Constant intensity cut and standard TA reconstruction



These show the linearity of the TA energy reconstruction.

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.



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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)]

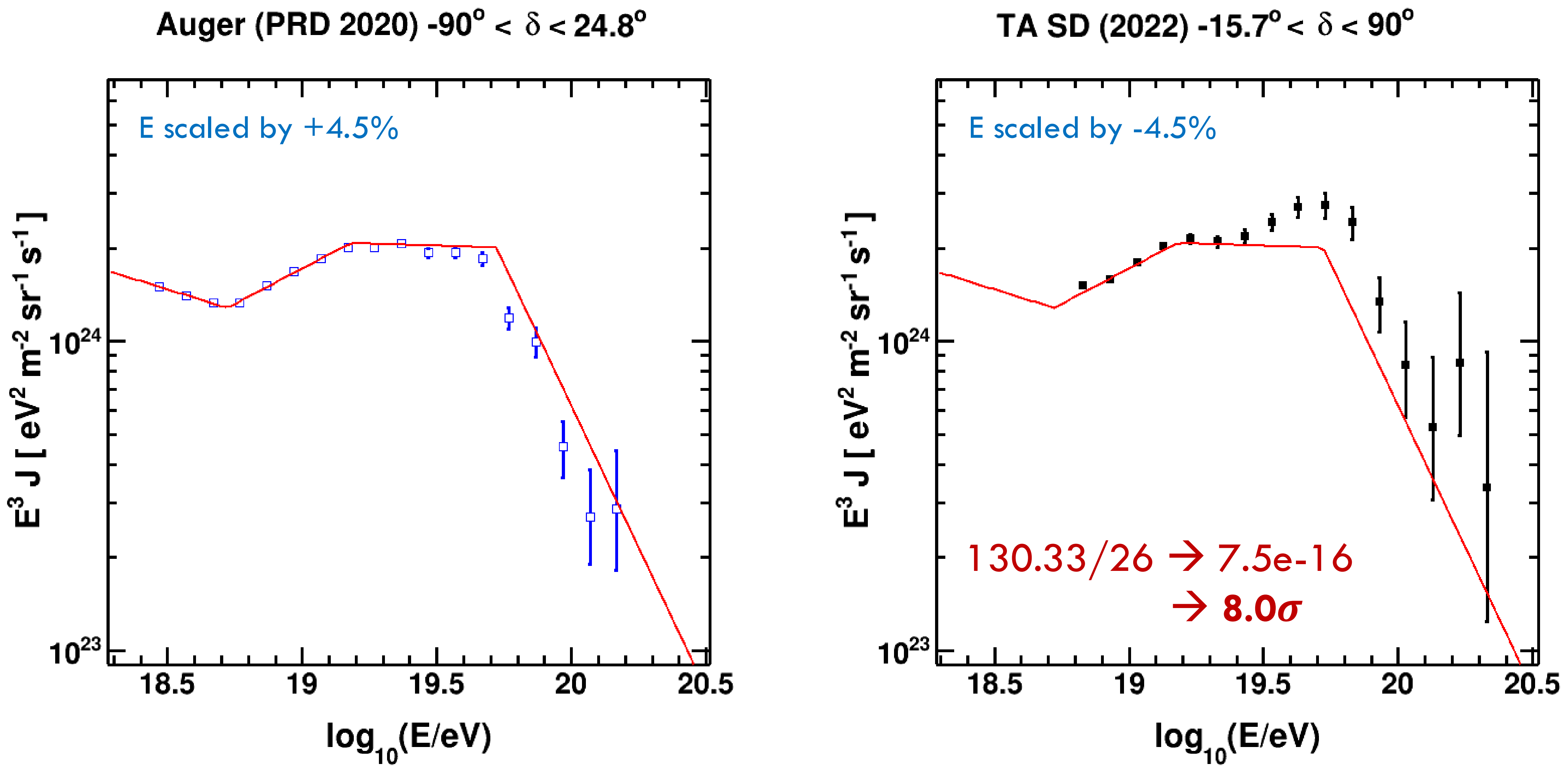
$$-2\ln\lambda(\boldsymbol{\theta}) = 2\sum_{i=1}^{N}\left[\mu_i(\boldsymbol{\theta}) - n_i + n_i \ln\frac{n_i}{\mu_i(\boldsymbol{\theta})}\right] , \qquad (40.16)$$

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

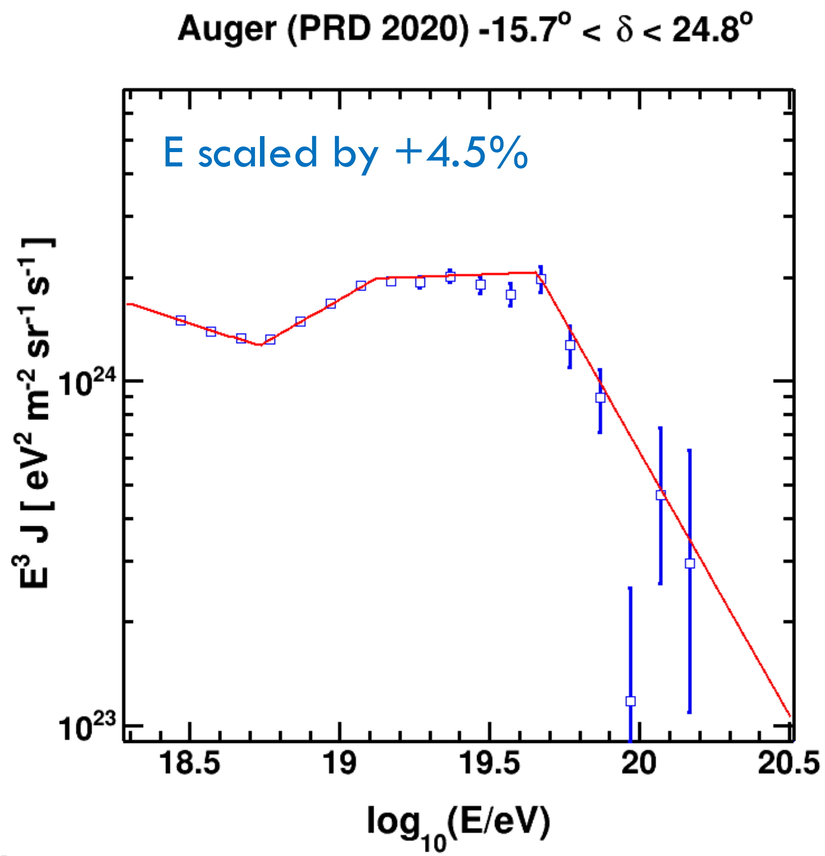
Fit both spectra in their full apertures: **8.0σ**

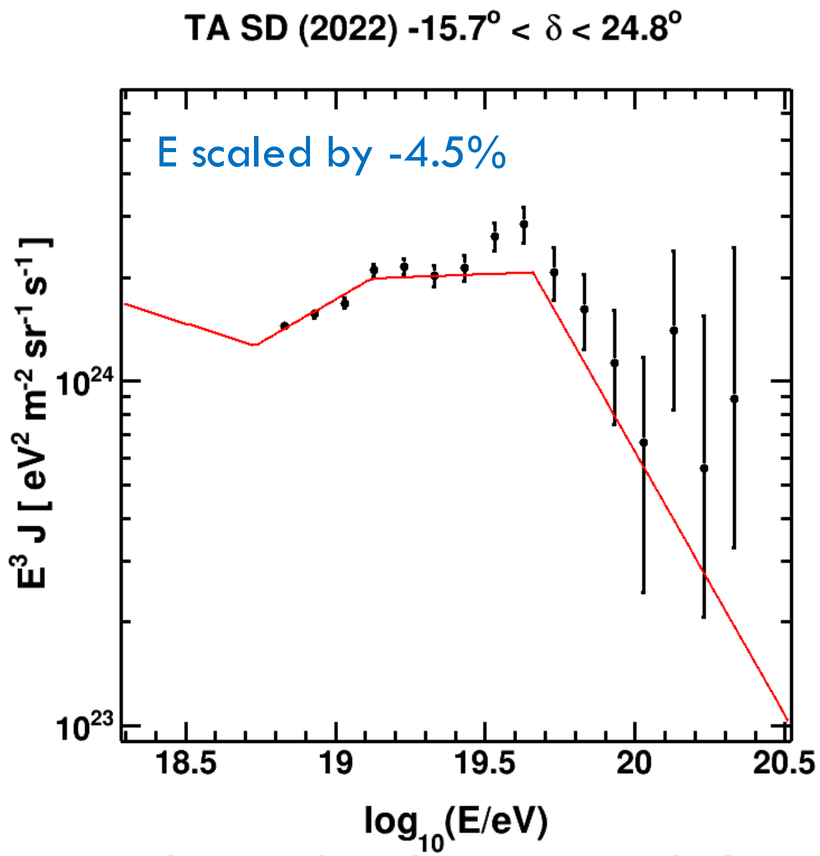
The red lines indicate the same broken power law function from the simultaneous fit.



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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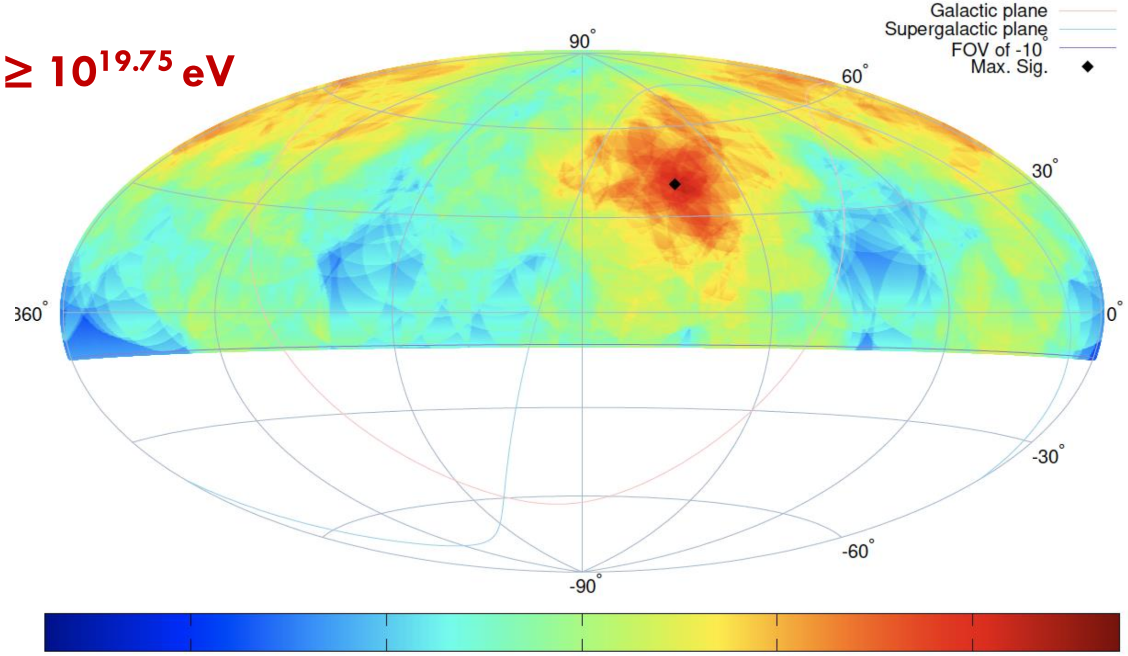
25°-radius oversampling

$E \geq 10^{19.75}$ eV

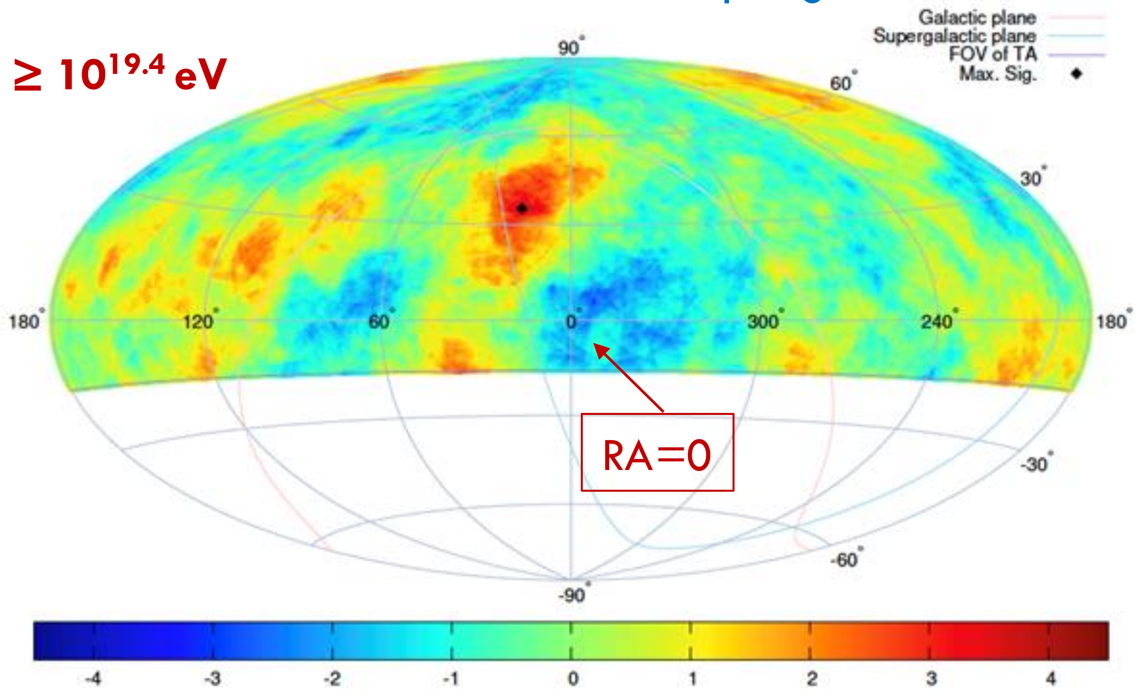


Deficit Li-Ma significance Excess

- 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



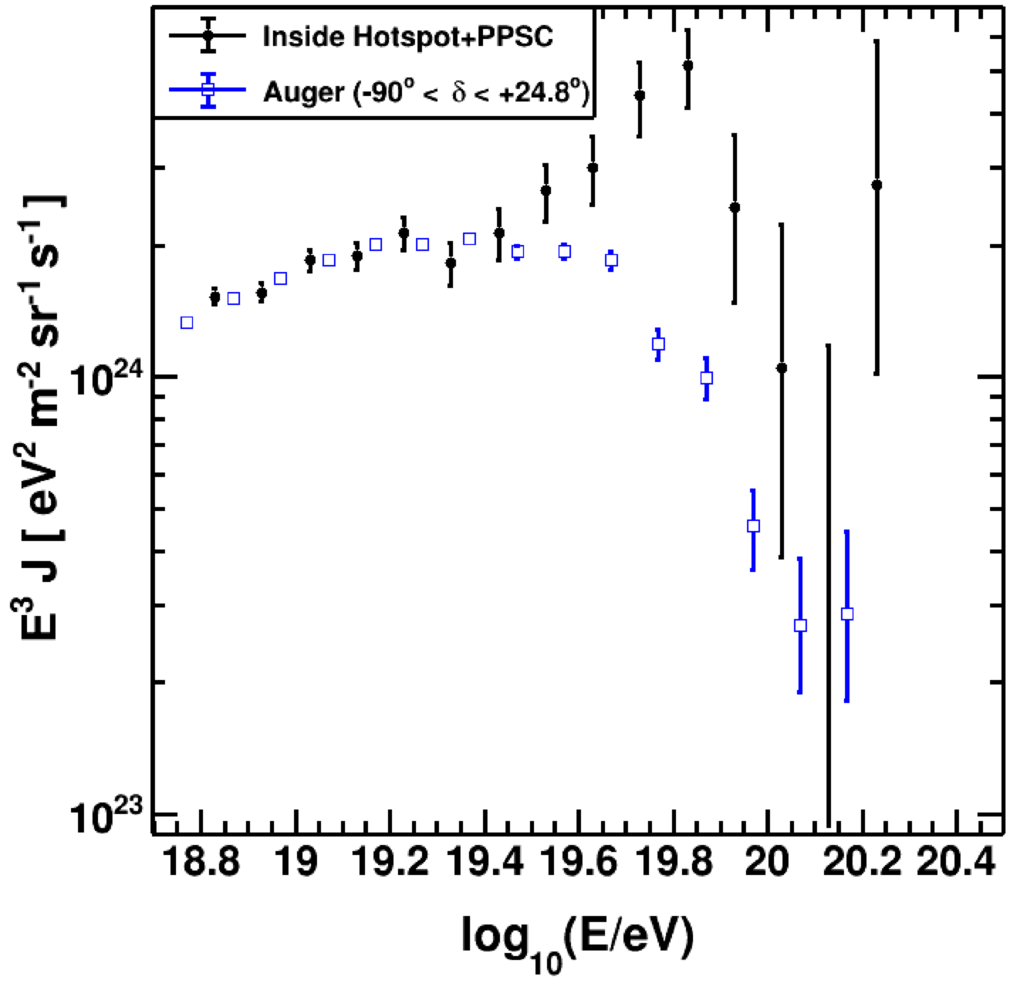
Deficit Li-Ma significance Excess

- 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**

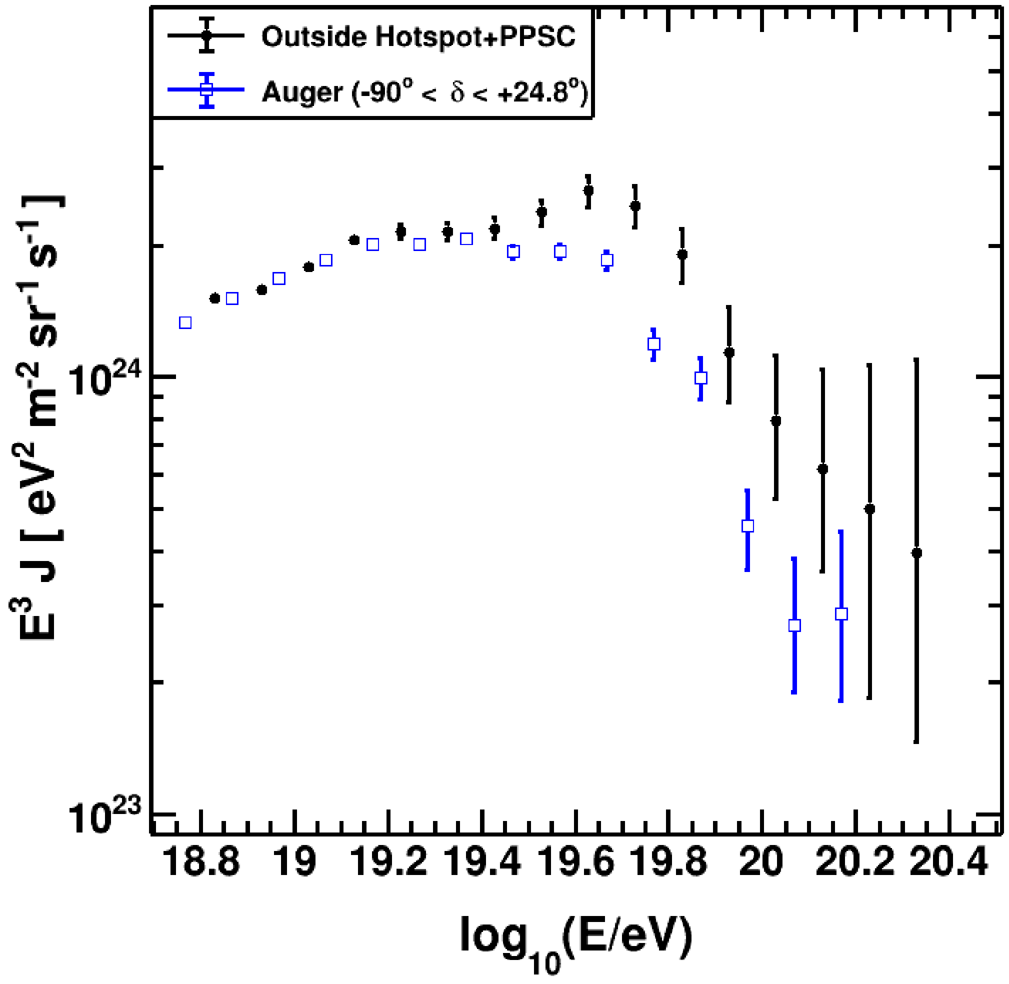
TA Inside/Outside Hotspot and PPSC excess regions

TA full aperture (-15.7°< δ <+90°)

Inside the excesses



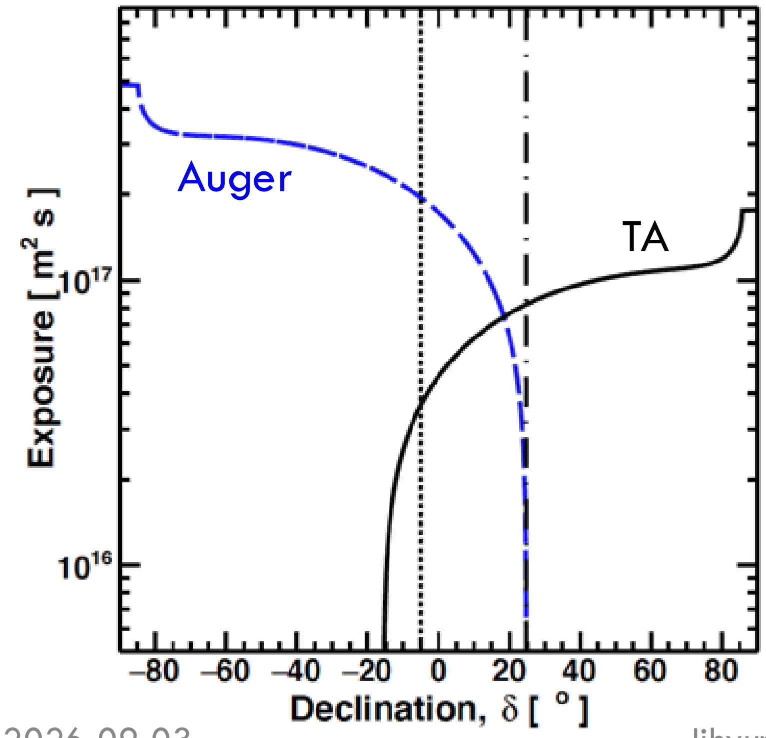
Outside the excesses

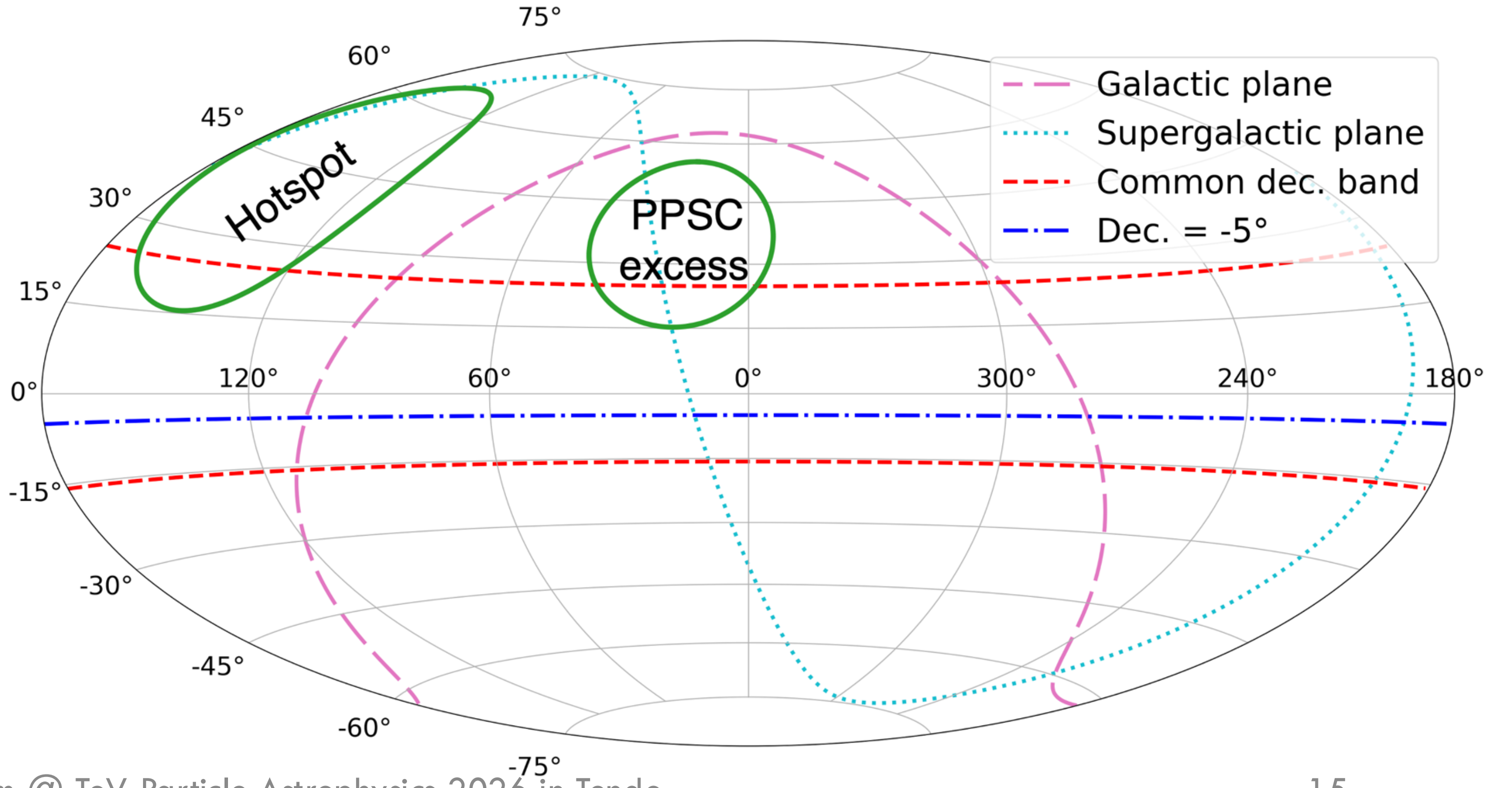


Validate the methodology by looking at the common sky

- 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

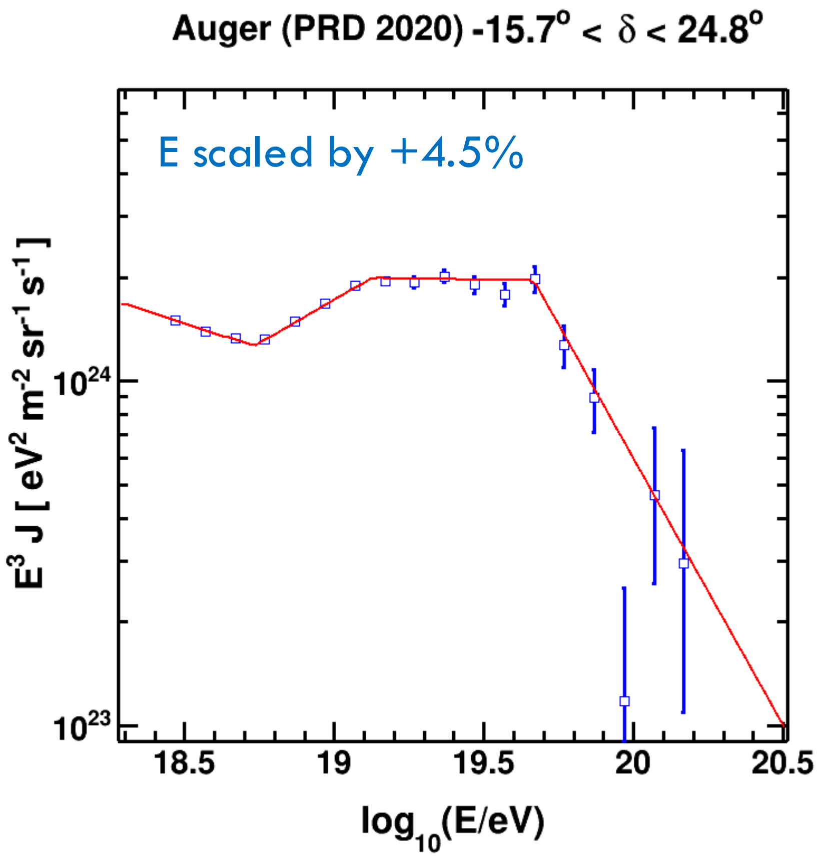
Exposure vs. Declination

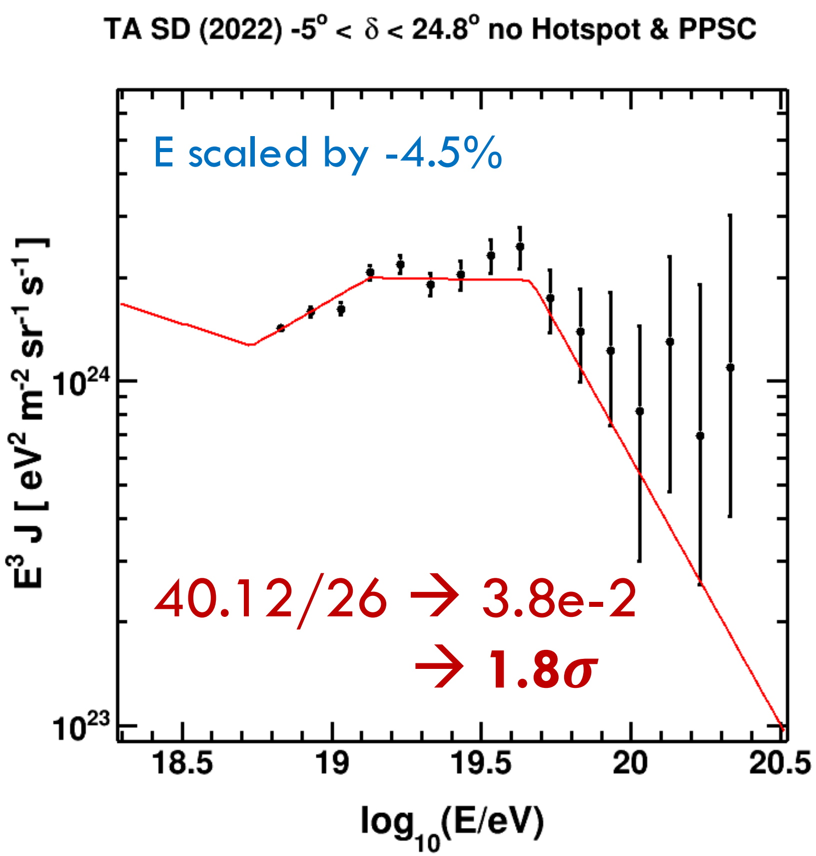




Fit both spectra: TA in -5°≤δ<24.8° & excl. Hotspot&PPSC: **1.8σ**

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

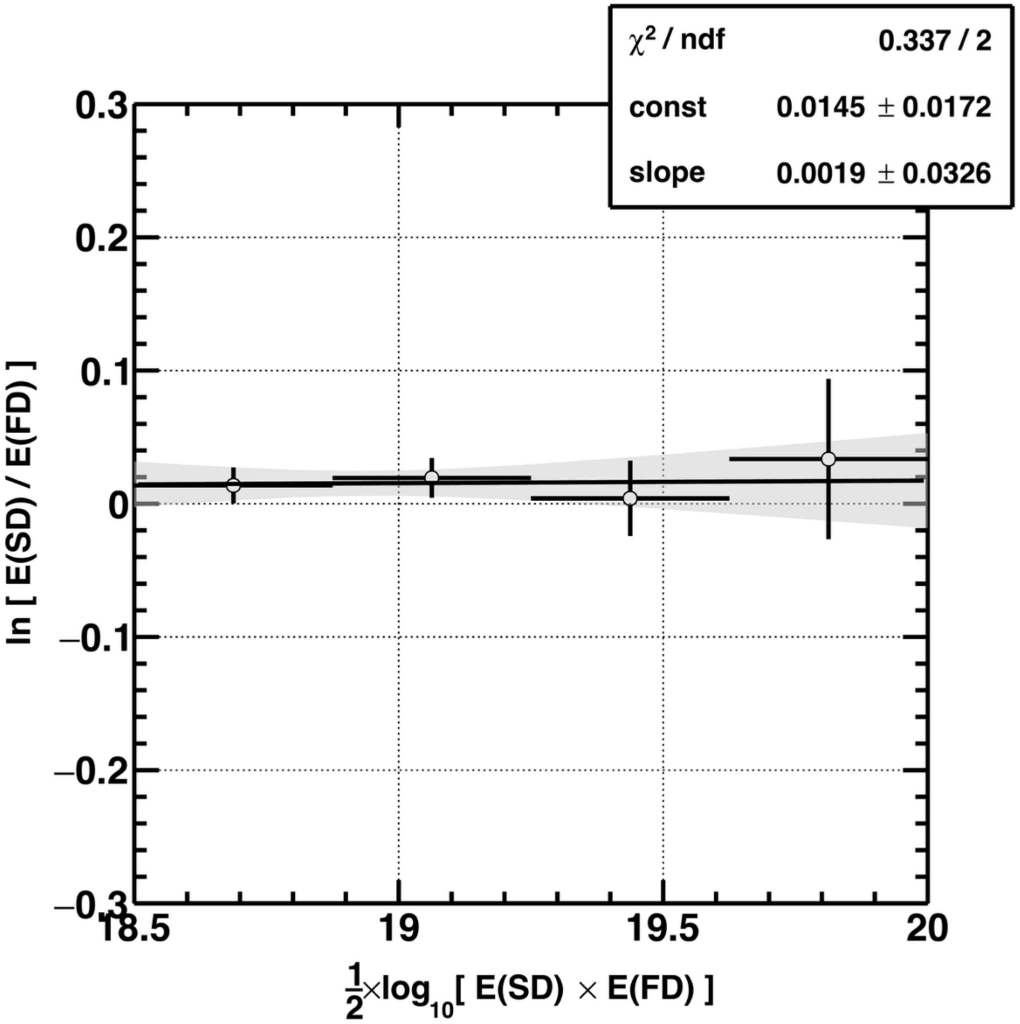




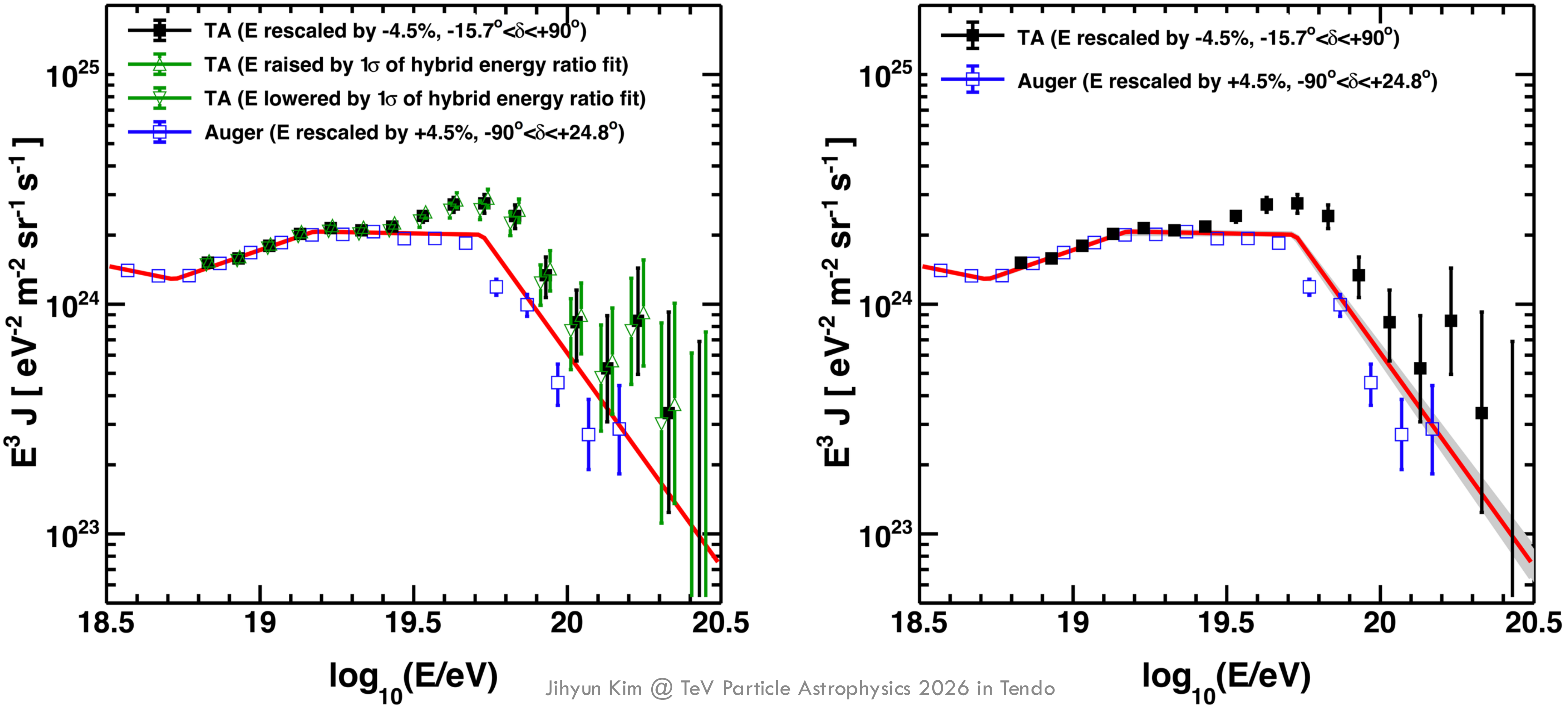
→ TA and Auger spectra are now in good agreement.

Evaluate the significance considering systematic uncertainty

- Rescale the energy by the $\pm 1\sigma$ uncertainty in $\ln(E_{SD}/E_{FD})$ (represented by the gray band) from the current TA energy and then perform a simultaneous fit.



Simultaneous Fit Plots: full apertures



Simultaneous Fit Results using the Gray Band in ln(E_{SD}/E_{FD})

Full apertures

- The original simultaneous fit result:
  - 130.33 / 26 → **8.0σ**
- When the energy is raised:
  - 173.17 / 26 → **10.0σ**
- When the energy is lowered:
  - 88.37 / 26 → **5.6σ**
- Taking energy scale uncertainty into account, the significance is $\mathbf{8^{+2.0}_{-2.4}\sigma}$.
- To be conservative, we choose our answer to be **5.6σ**.

Common dec. w/ applied cuts

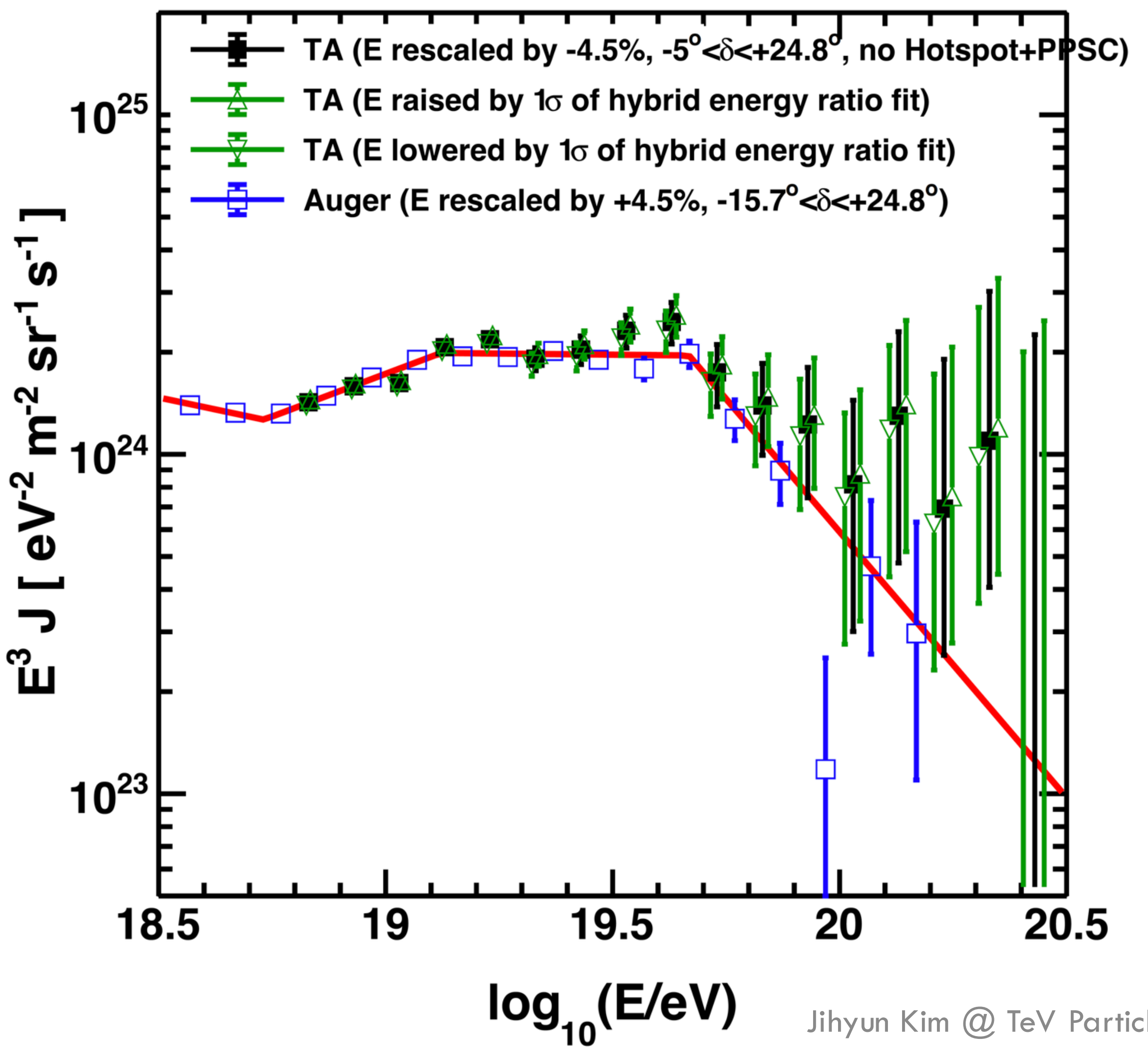
- The original simultaneous fit result:
  - 40.12 / 26 → **1.8σ**
- When the energy is raised:
  - 46.82 / 26 → **2.4σ**
- When the energy is lowered:
  - 35.70 / 26 → **1.3σ**

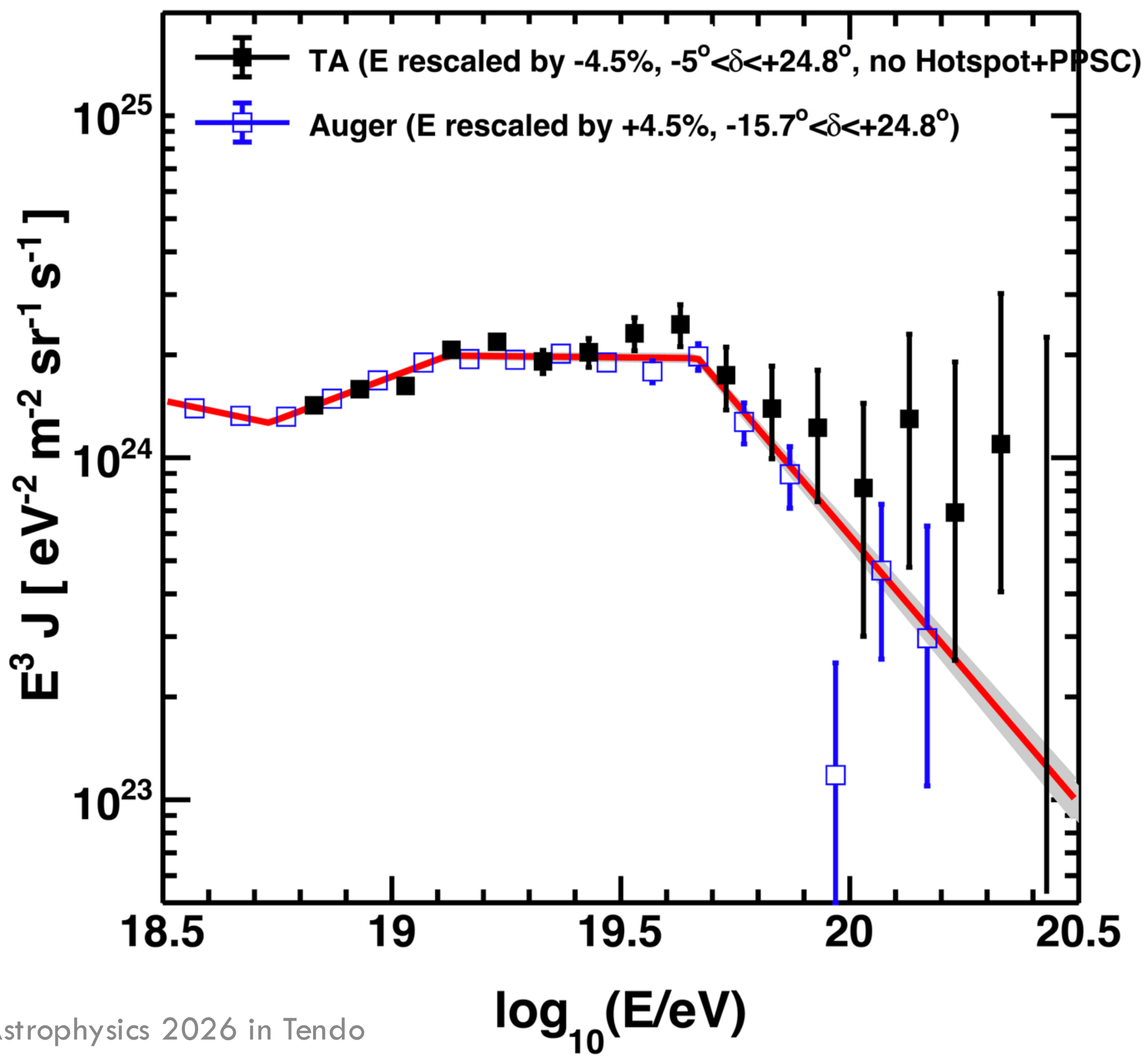
Summary

- 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 18-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

Simultaneous Fit Plots: common dec. w/ applied cuts





Check using Constant Intensity Cut (CIC) Method

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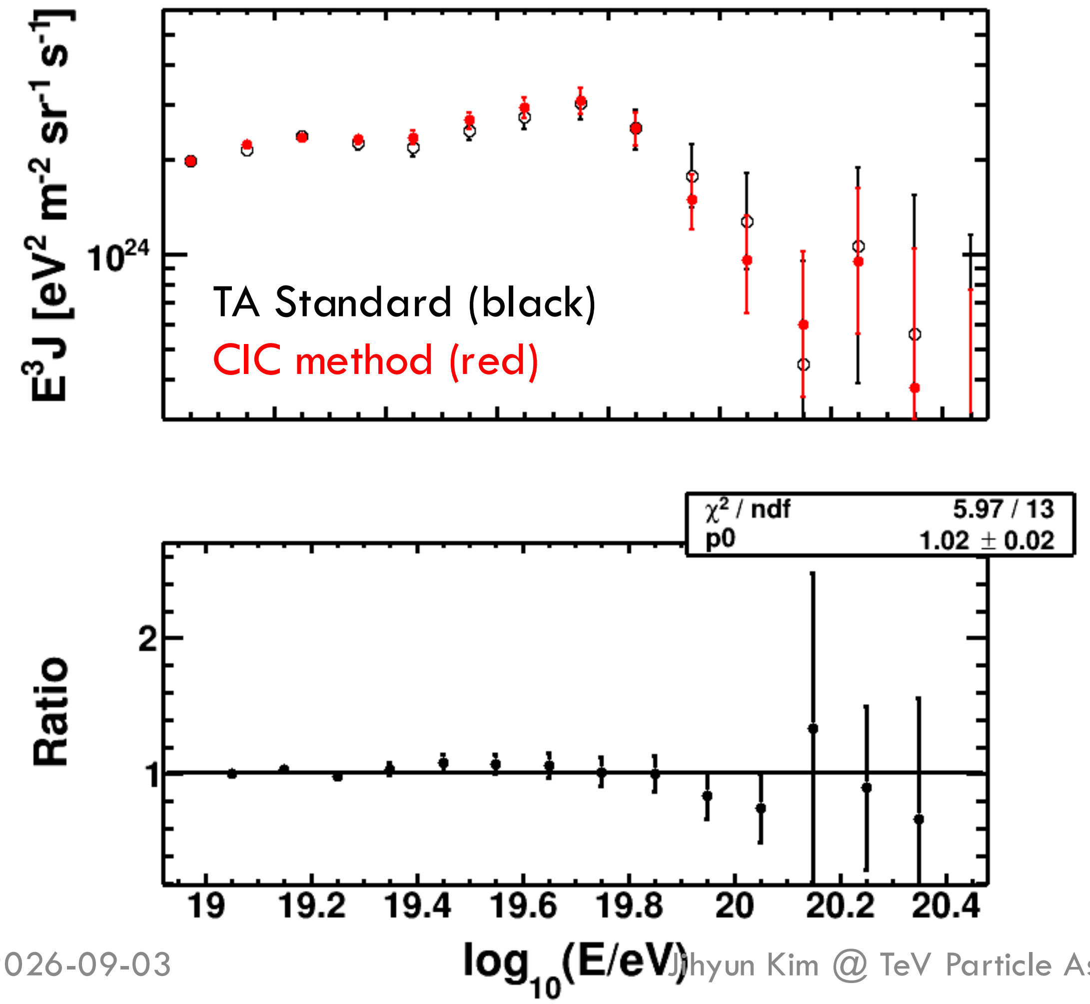
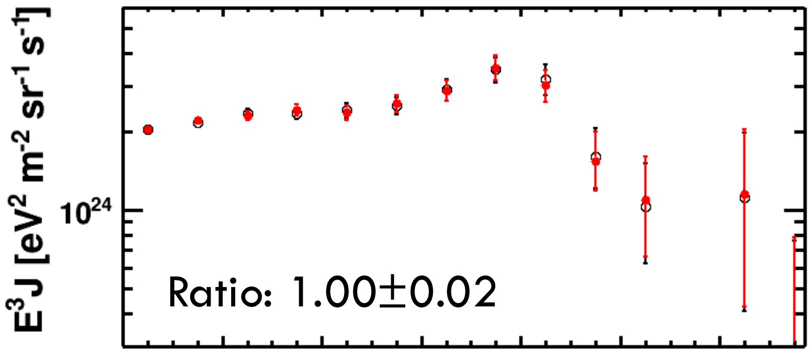
PoS(ICRC2023)008

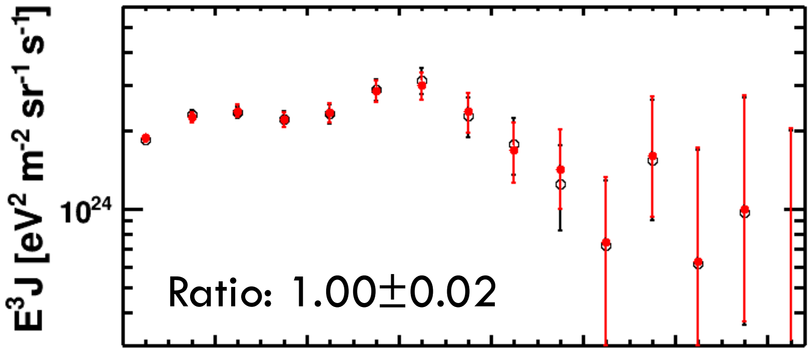
- Comparison with the energy spectra obtained using the CIC method shows consistent results within 2% uncertainties.



High Dec. (DEC ≥24.8°)

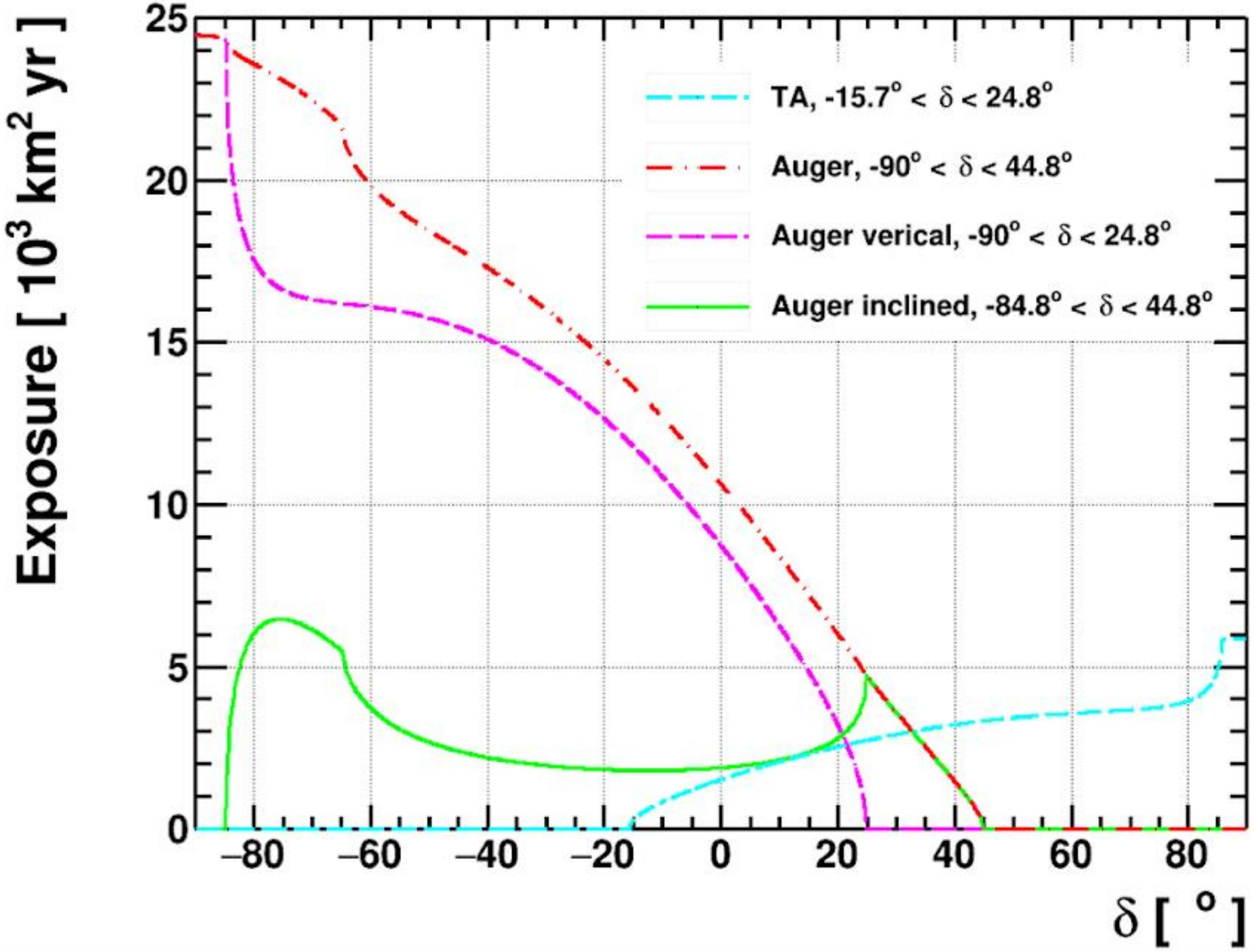


Low Dec. (-15.7°≤DEC<24.8°)

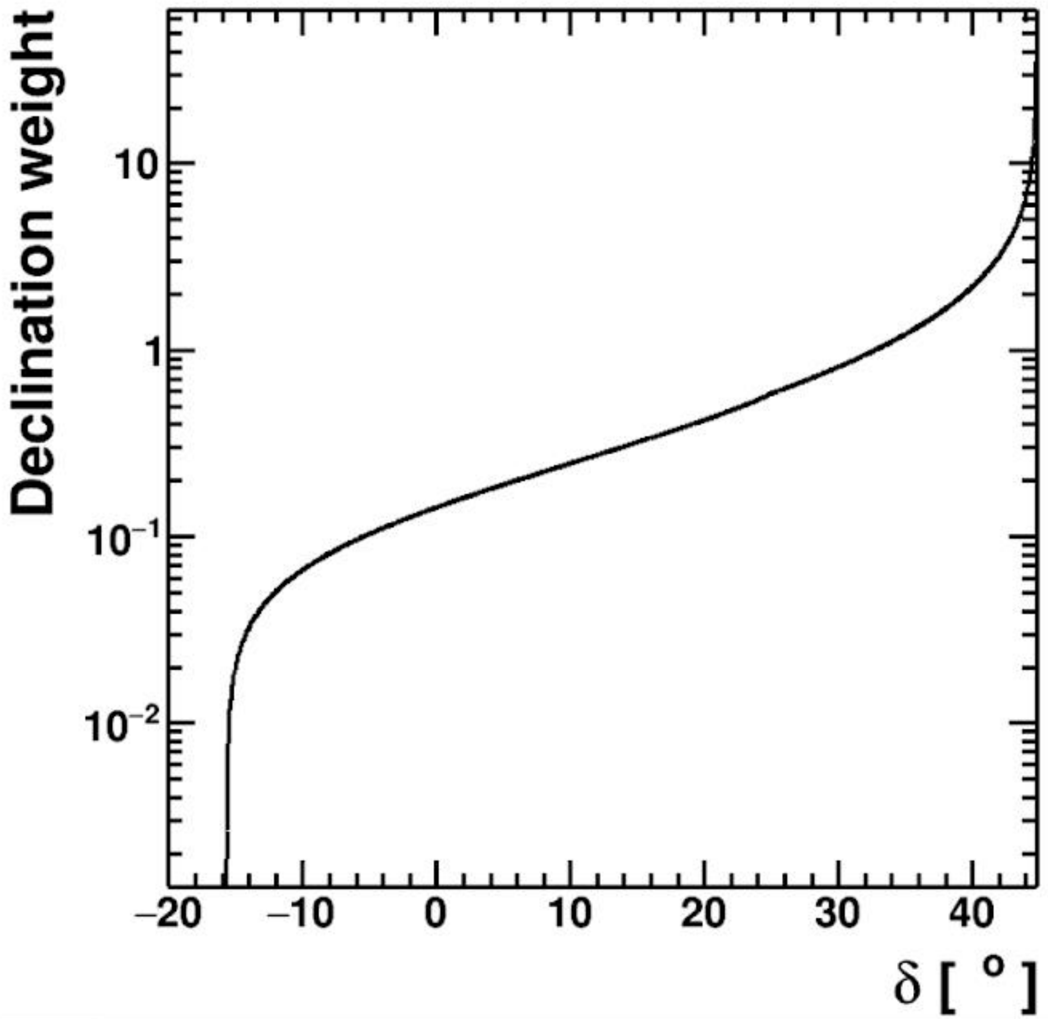


Why does Auger not observe the same results as TA?

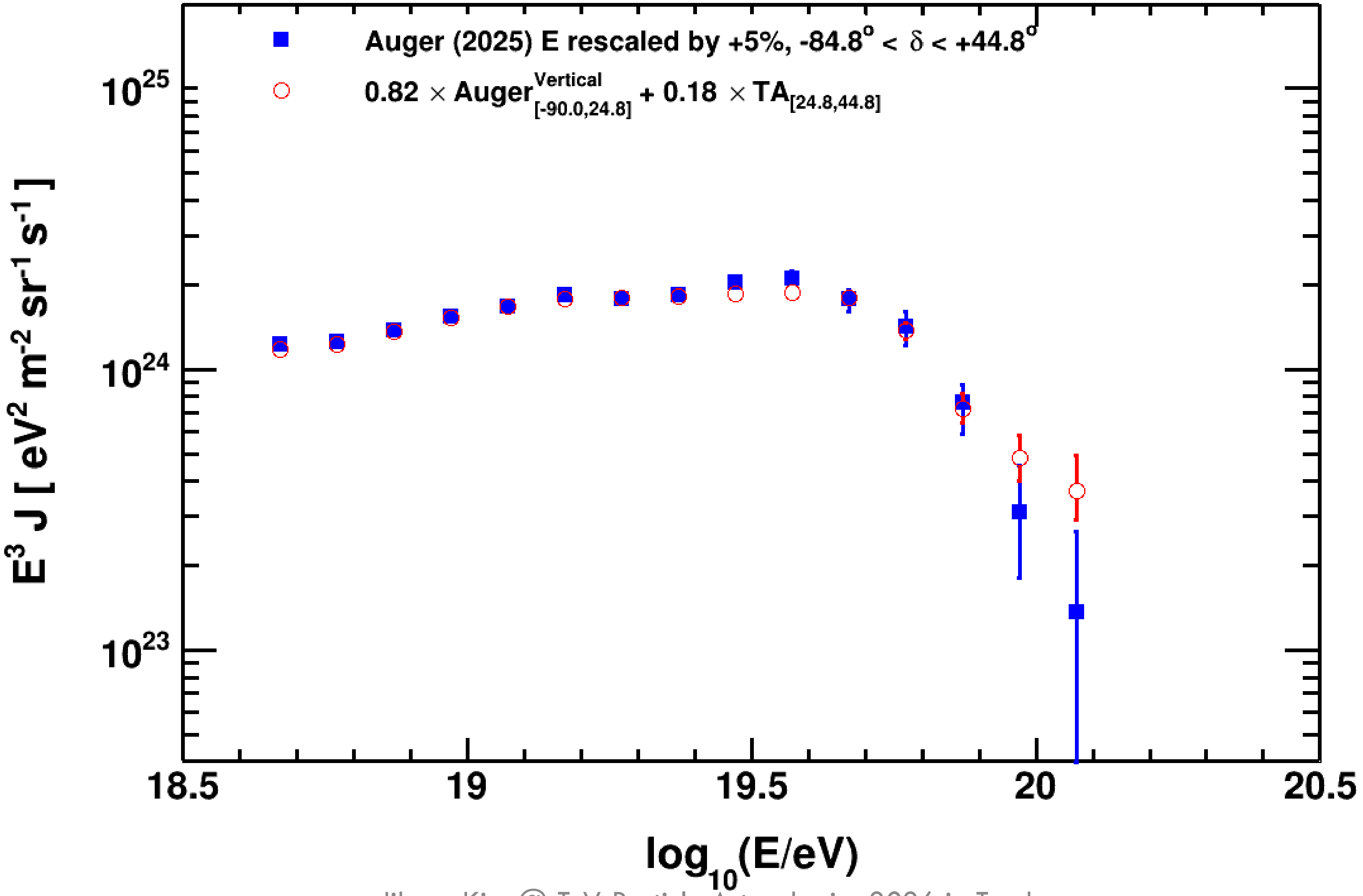
Exposures of TA and Auger



Exposure ratio of TA to Auger

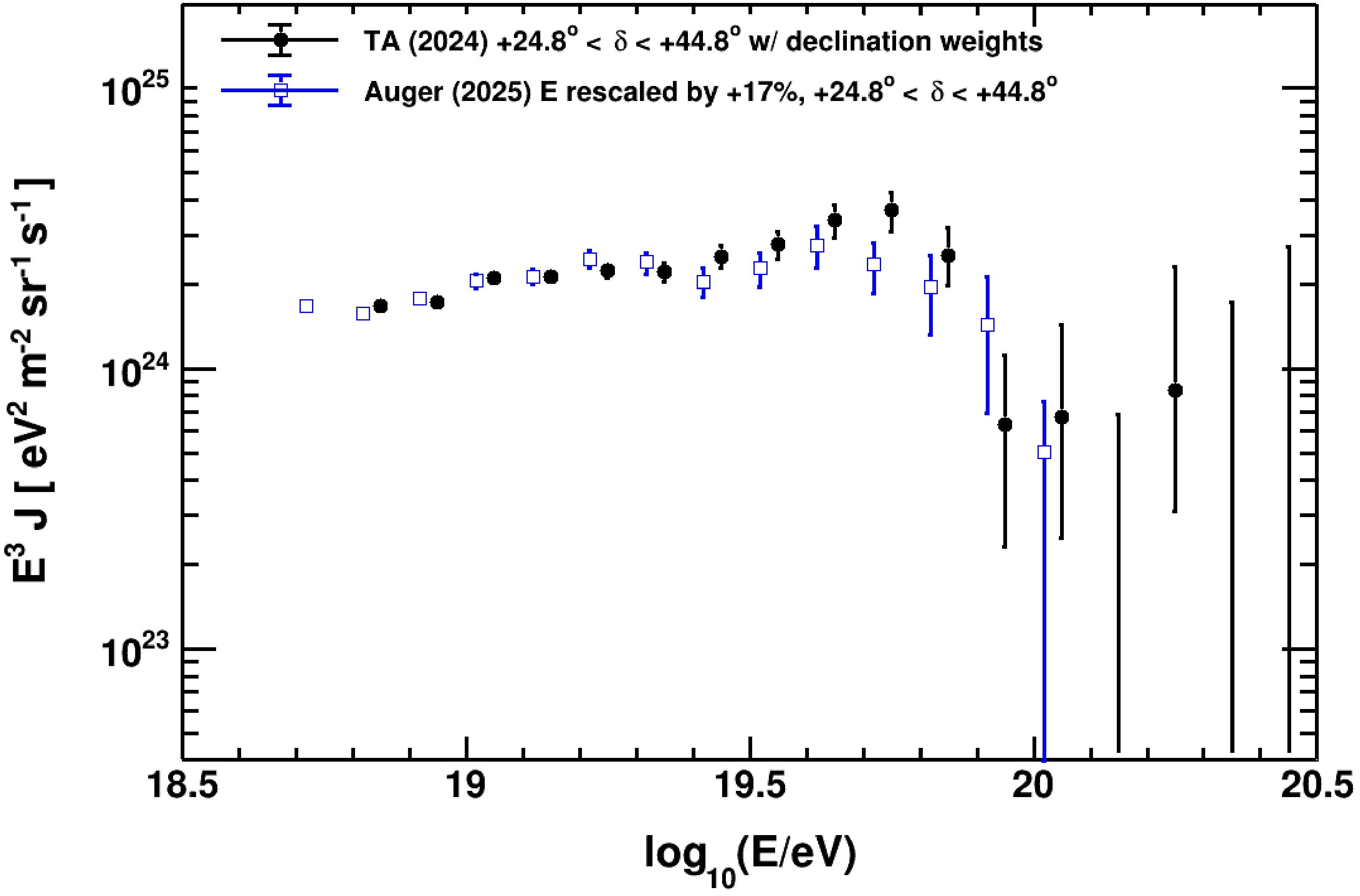


A demonstration: exposure-weighted combination of Auger and TA spectra



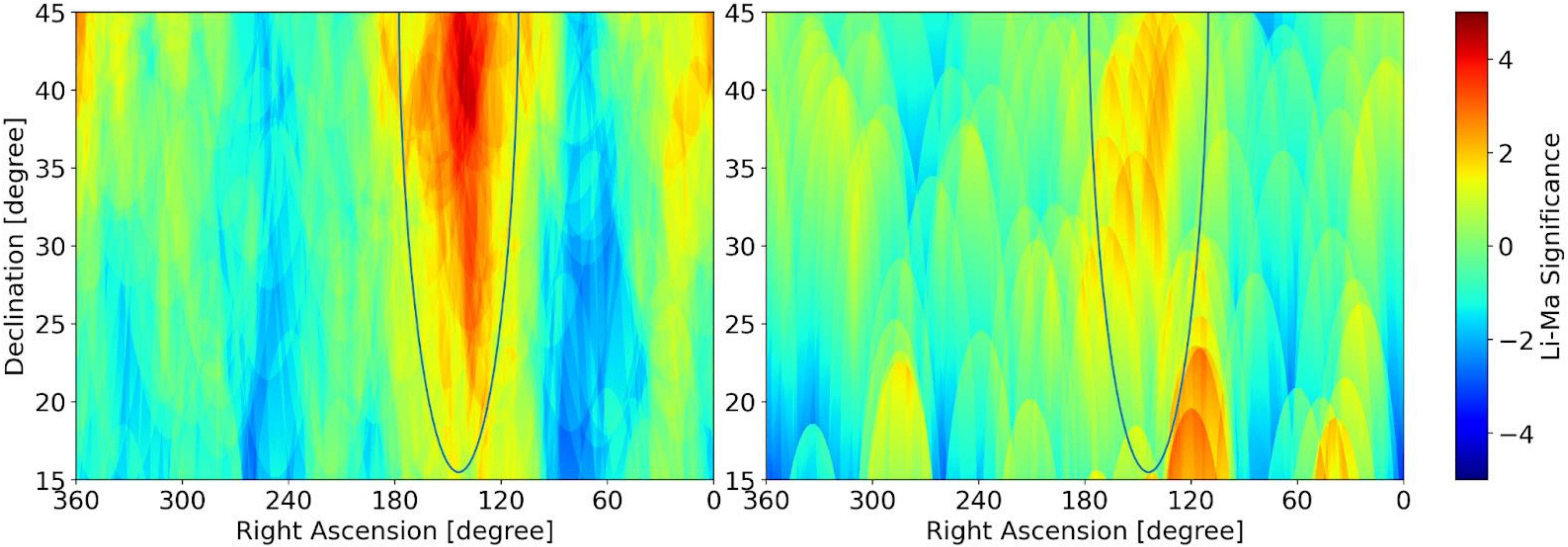
Auger data from
Pierre Auger Collab.
[arXiv:2506.11688](https://arxiv.org/abs/2506.11688)

Spectra in the same declination band of 24.8° < δ < 44.8°



Auger data from
Pierre Auger Collab.
[arXiv:2506.11688]

Comparison of the TA Hotspot using declination weights



(Left) The TA Hotspot as observed by TA. (Right) The TA Hotspot as it would appear to Auger, accounting for the declination weights of TA Hotspot events. The blue solid lines represent a 25° angular distance window from the Hotspot center.