



Osaka
Metropolitan
University



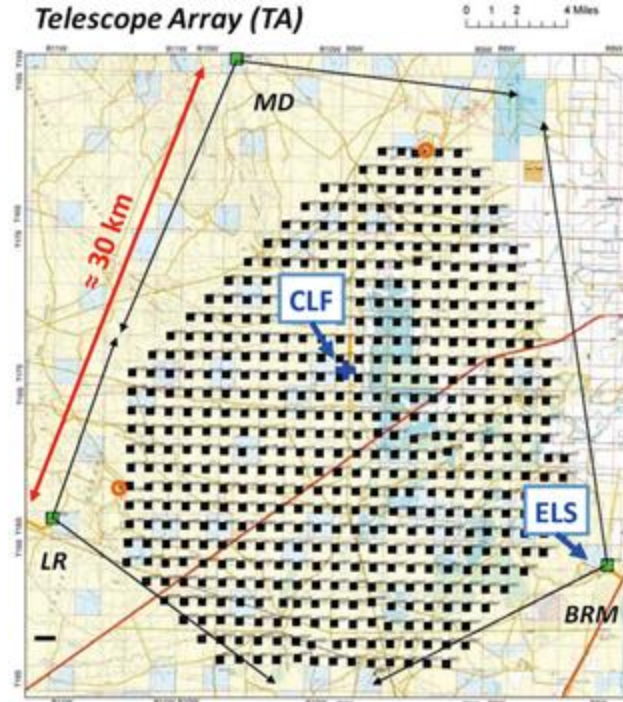
Telescope Array Results

Yoshiki Tsunesada

Osaka Metropolitan University

Cosmic Rays and Neutrinos in the Multi-Messenger Era,
APC Laboratory, Paris, December 9, 2024

TA Site



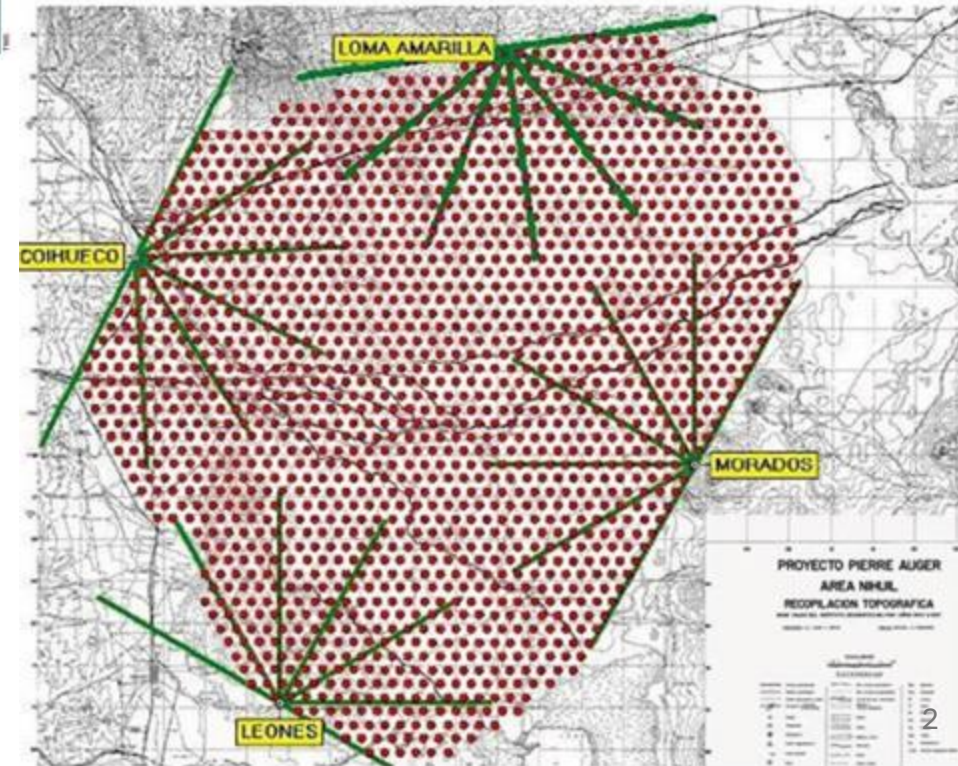
TA: Utah, USA

39° N

700km²

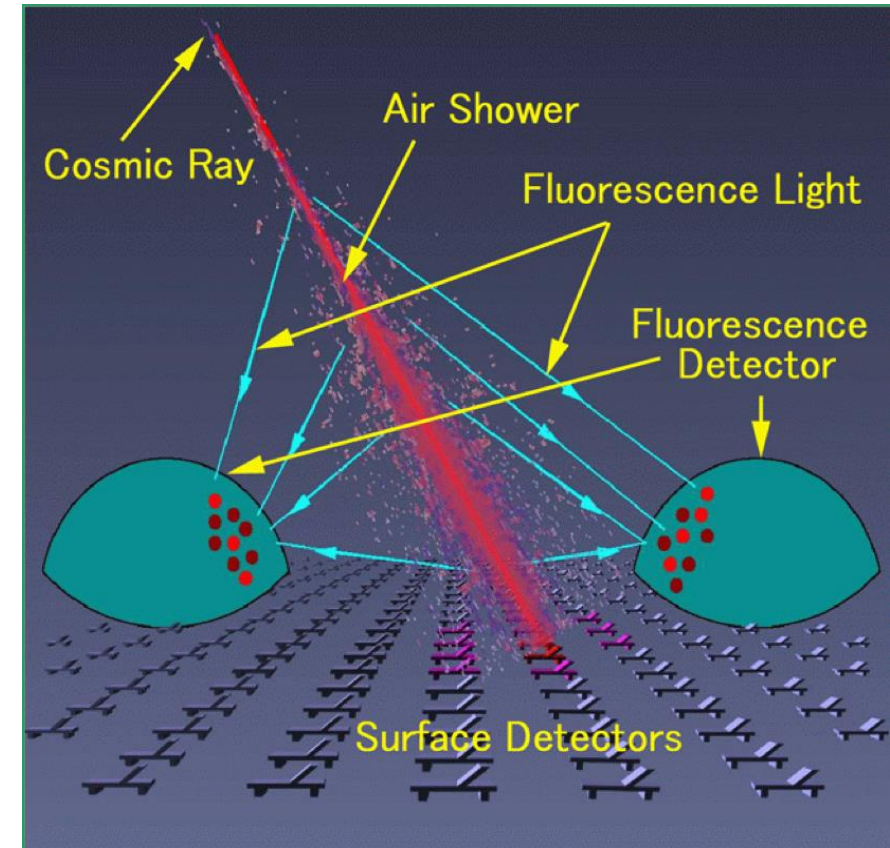
Operational since May
2008

Auger:
Malargue, Argentine
35° S
3000km²
Operational since
2004



Telescope Array (TA)

- The largest cosmic ray detector in the northern hemisphere.
 - Constructed in Utah, USA, by Japan, US, Russia, and Korea
 - 700km² (c.f. Singapore)
 - c.f. AGASA - 100km²
- Use both types of detectors: fluorescence detectors (FD) and surface detectors (SD)



TA Detectors

• Millard county, Utah, US

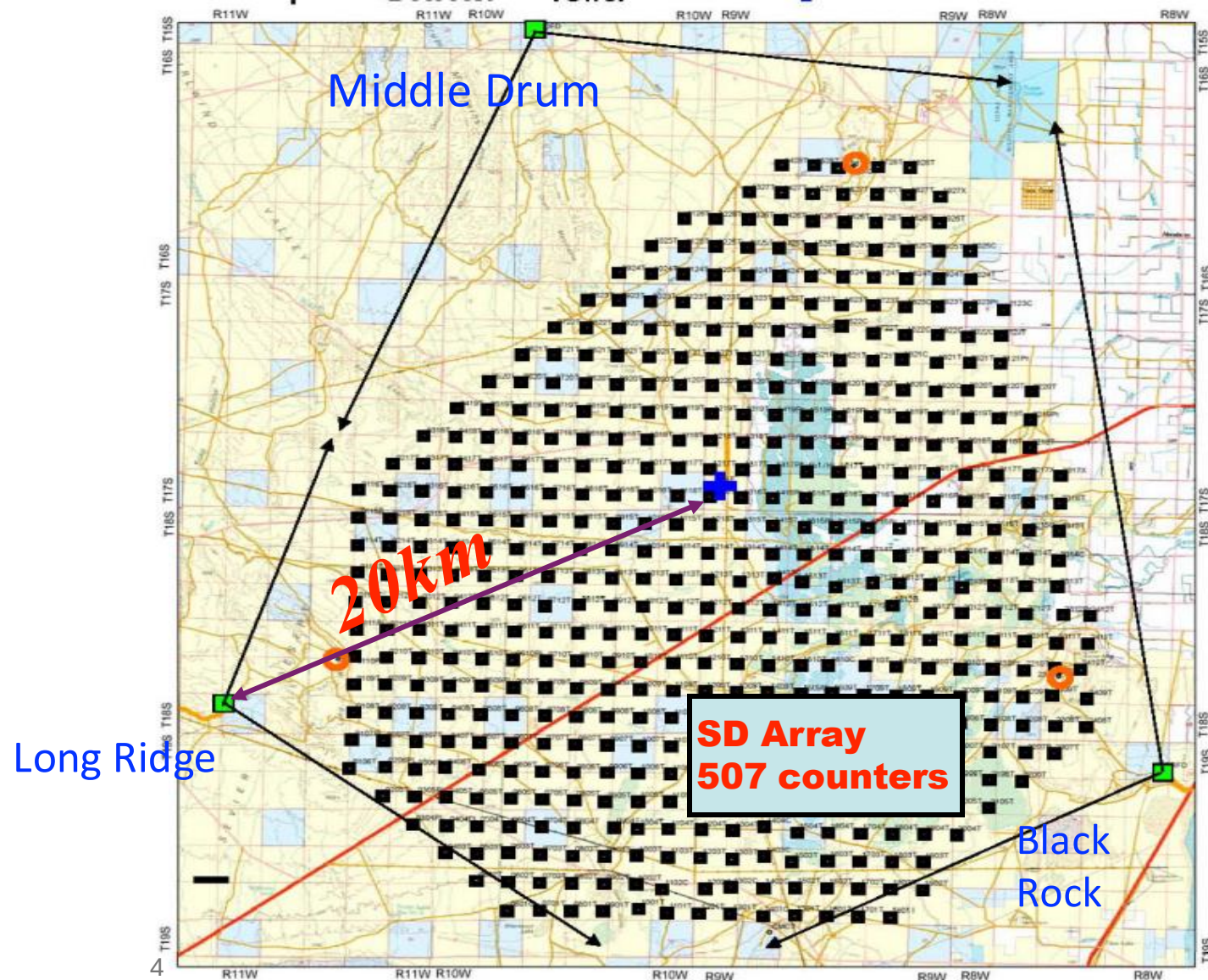
39N, 141W

• 507 SDs

- 3m² double-layered plastic scintillators
 - Water Cherenkov tanks in Auger
- 40MHz digitization (cf. AGASA 10us integrated)
- 1.2km separation
- 700 km²
 - cf. AGASA 100km², Auger 3,000km²
- 100% duty cycle

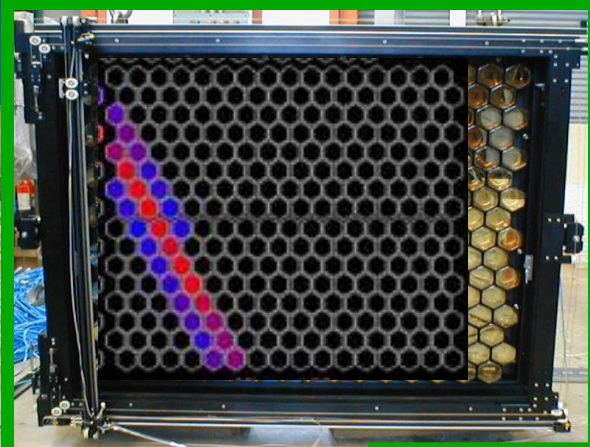
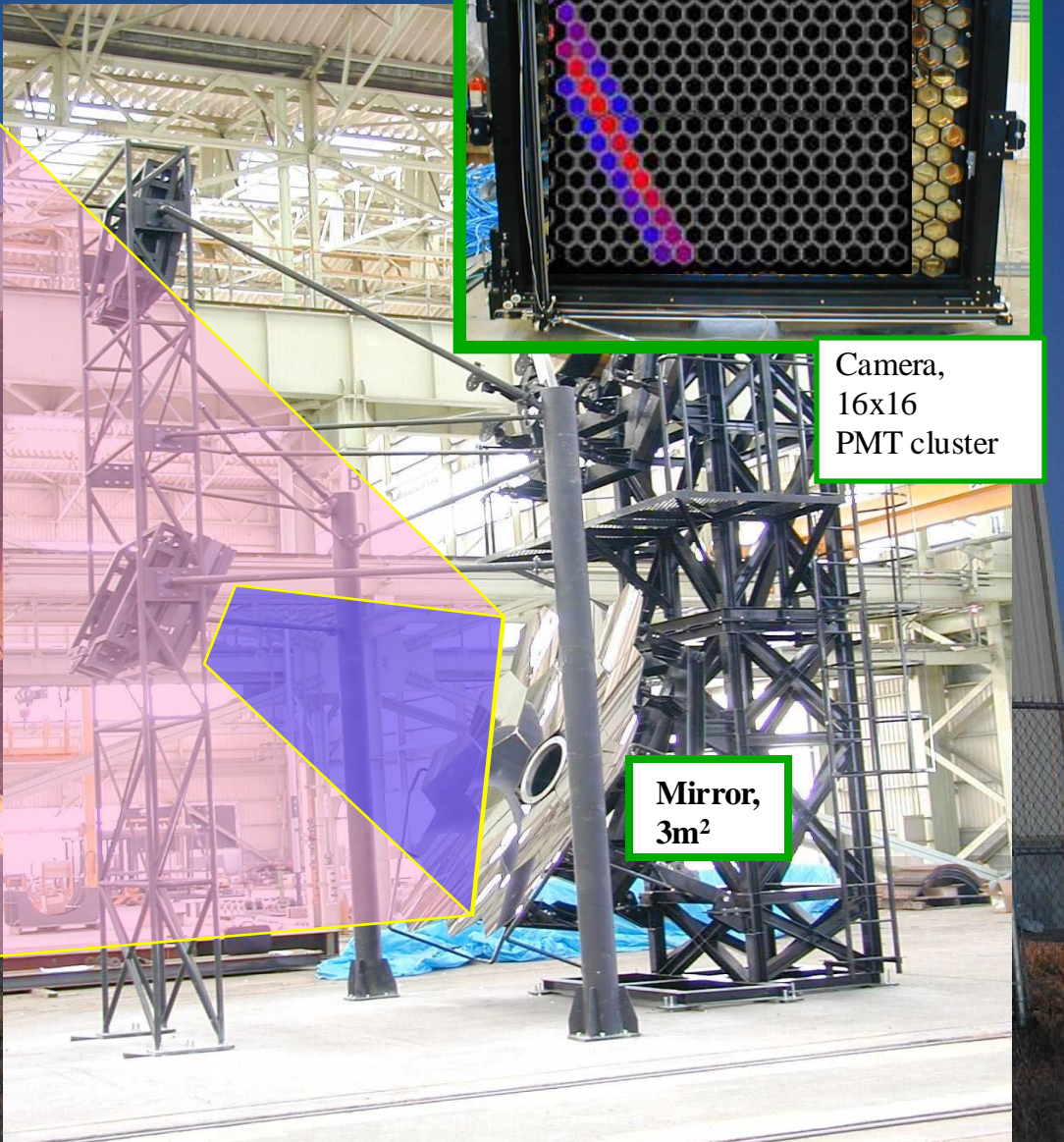
• 3 FD stations

- Black Rock - 12
- Long Ridge - 12
- Middle Drum – 14 (refurbished HiRes)
- 10% duty cycle



TA Fluorescence Detectors

BR site



Camera,
16x16
PMT cluster

Mirror,
3m²

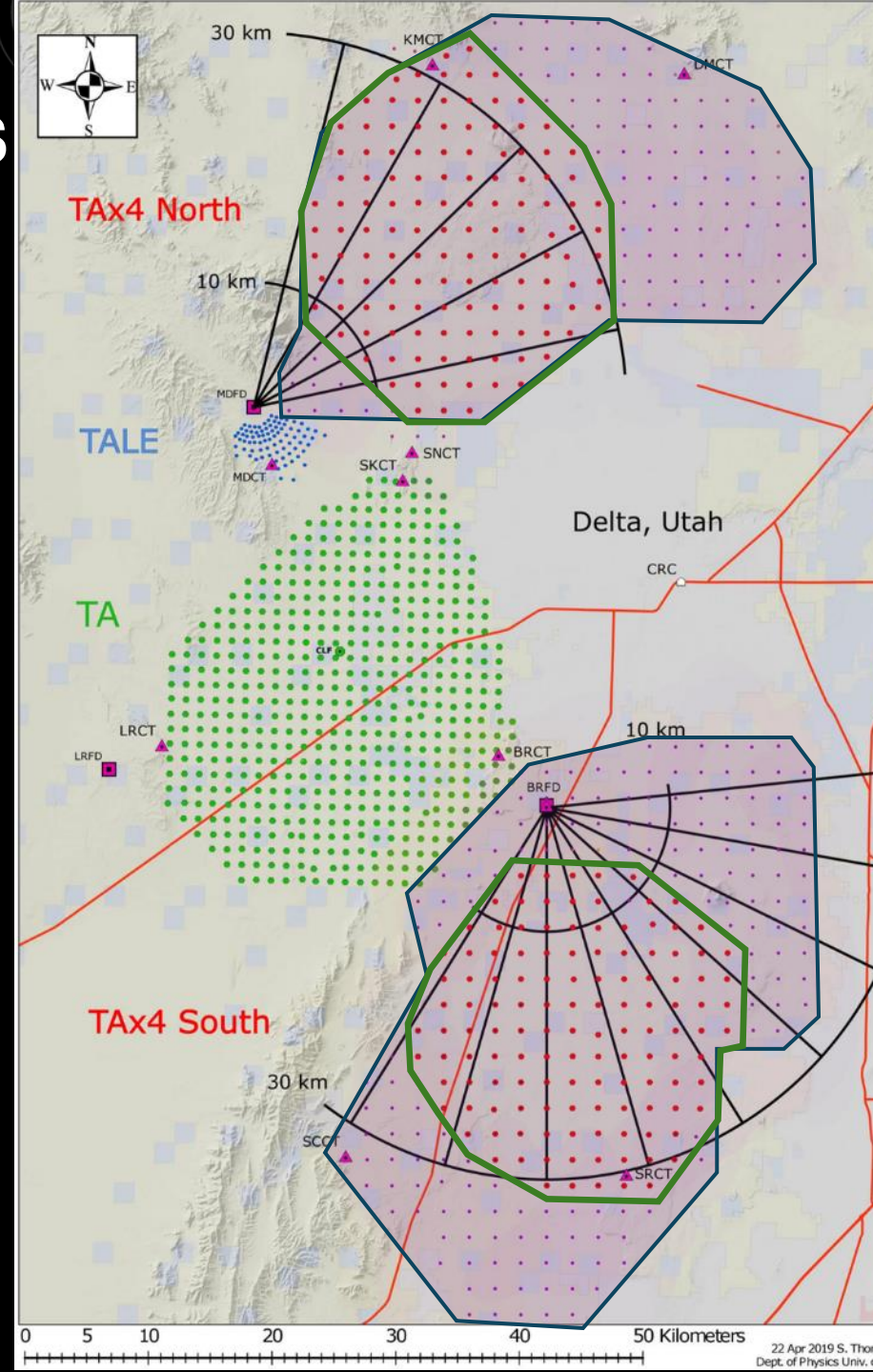
TAx4 detectors

Expanded Surface Array

- 2.08km spacing (1.2km TA)
- SDs similar design as TA
- **257** of planned **500** deployed (operational since Nov/2019)

Fluorescence Telescopes

- 4 telescopes viewing NE lobe (since Jun/2019)
- 8 telescopes viewing SE lobe (since Aug/2020)
- 3° – 17° elevation



TA Highest Energy Event "Amateras particle"

SCIENCE

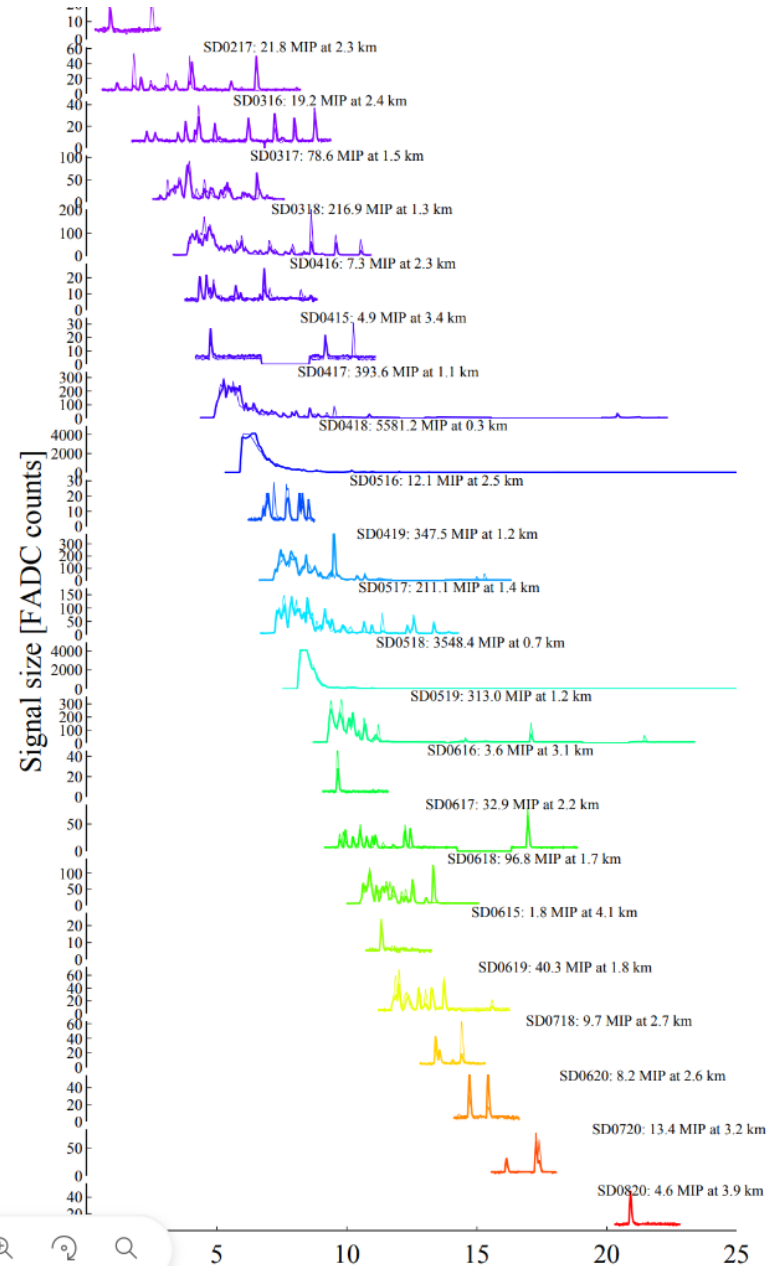
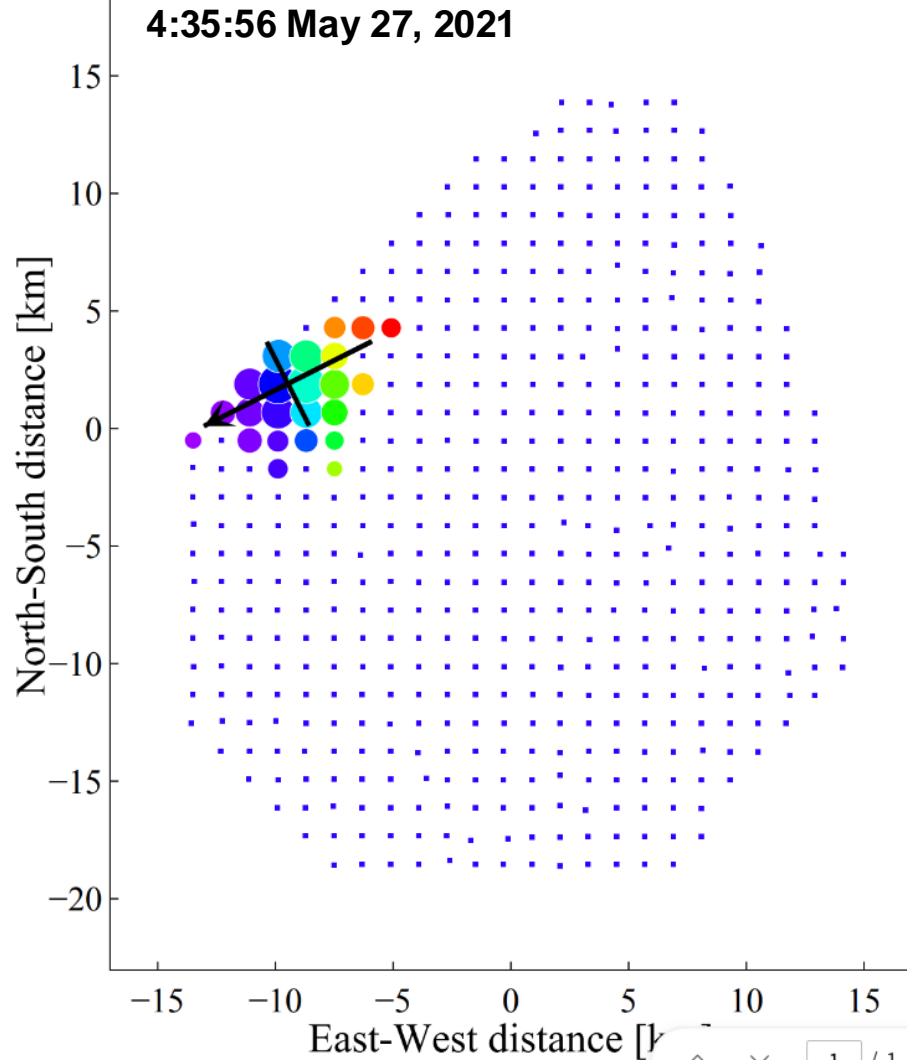
23 Nov 2023

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pp. 903-907

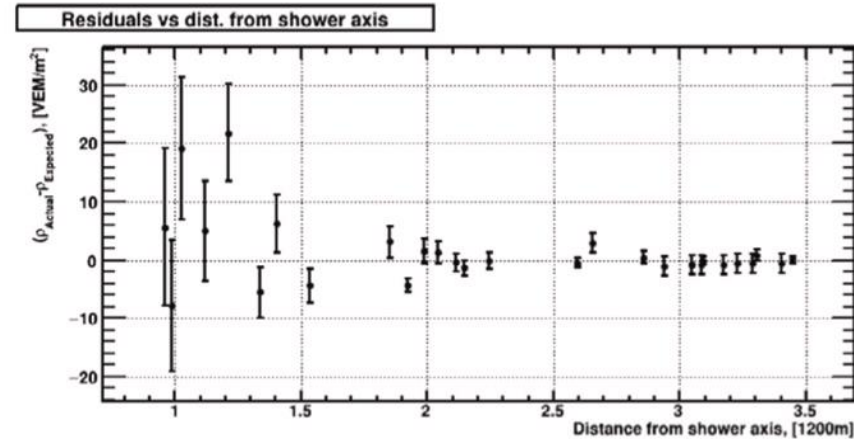
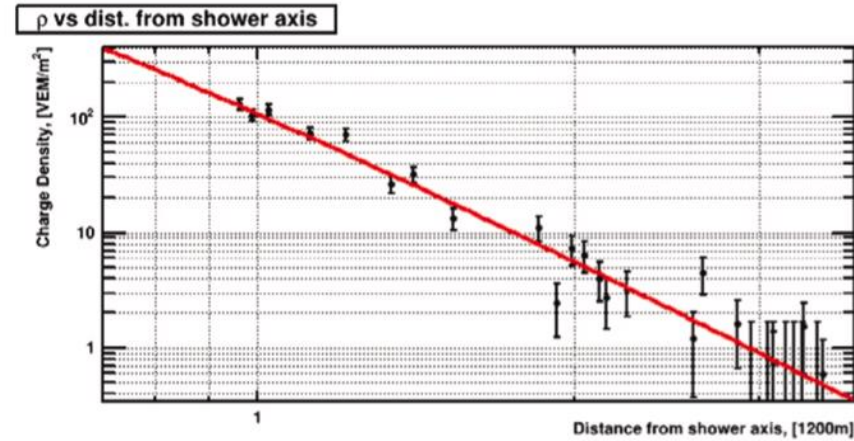
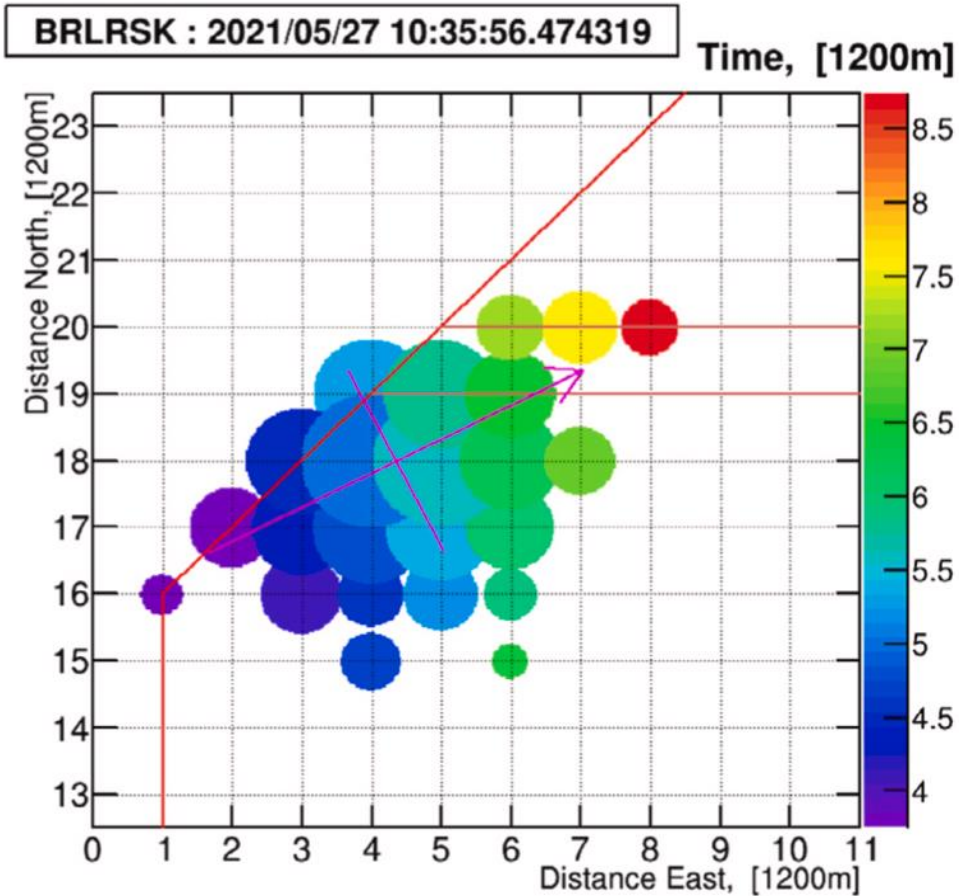
DOI: [10.1126/science.abo5095](https://doi.org/10.1126/science.abo5095)

Surface detector array of TA



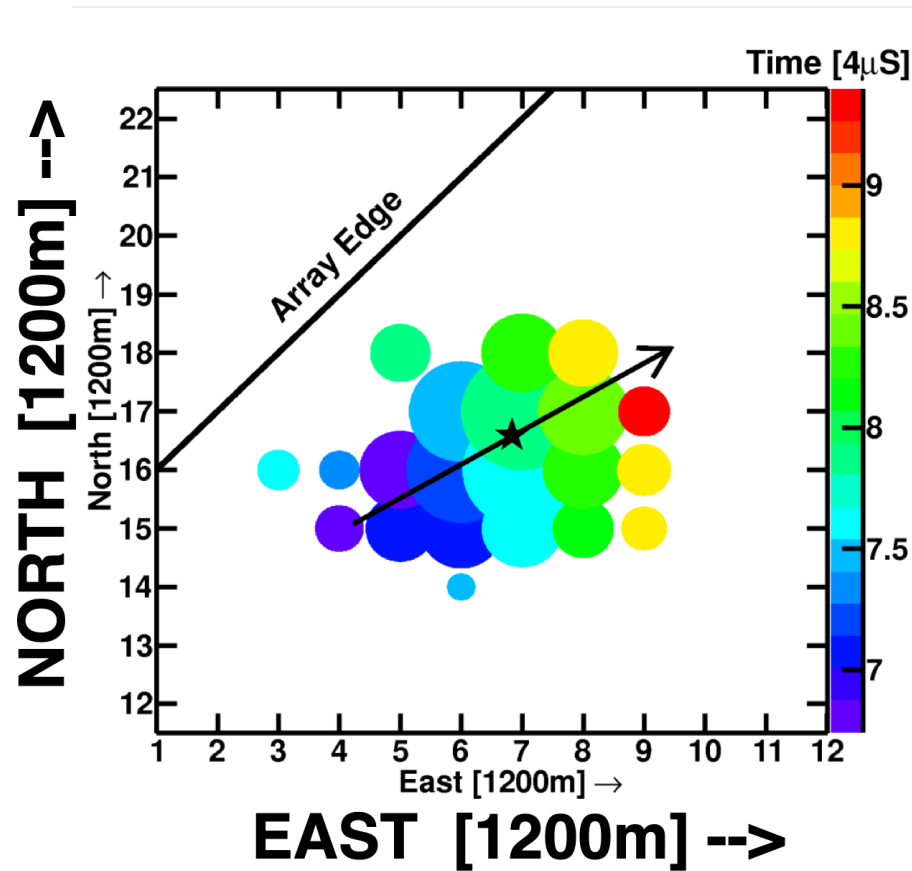
TA highest event "Amateras"

2021-05-27 10:35:56.47, No FD observation



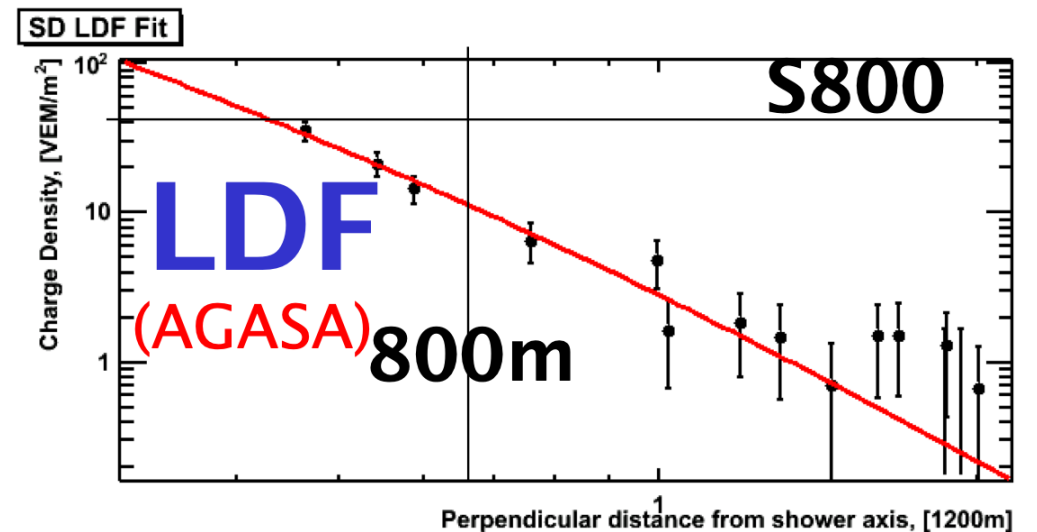
Date (UTC)	Energy (EeV)	S_{800} (m ⁻²)	Zenith angle	Azimuth angle	R.A.	Dec.	Directional uncertainty
May 27 2021 10:35:56	244±29(stat.) +51 -76 (syst.)	530±57	38.6°	206.8°	255.9°	16.1°	0.8°

SD Event Reconstruction

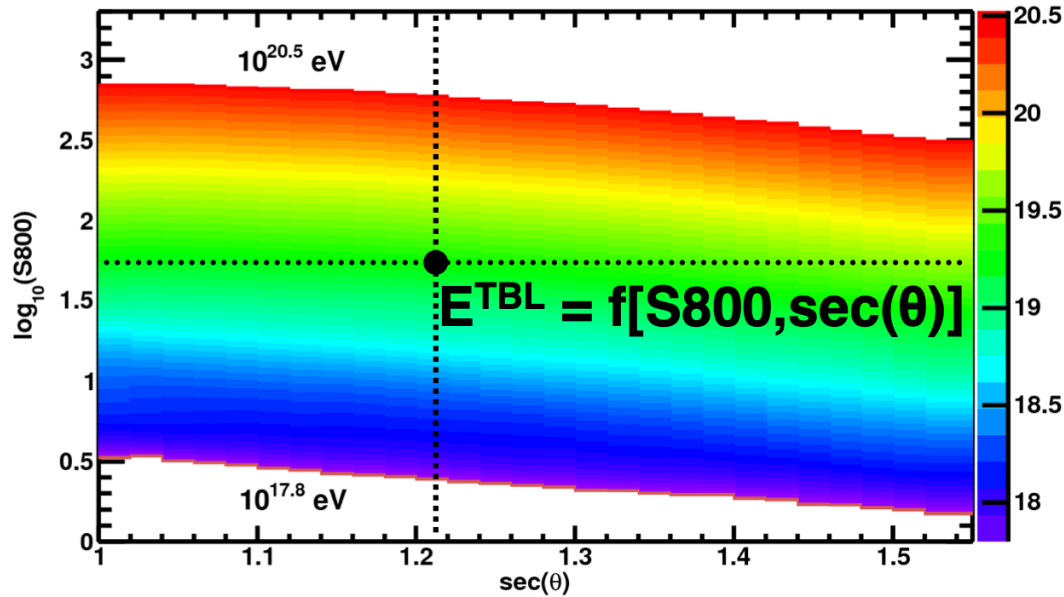


The SD array measures the “footprint” of a shower

Use “S800” as an energy estimator



TA SD Energy Determination



- 1st energy estimate: A lookup table by MC (S800, θ) $\rightarrow E^{\text{TBL}}$

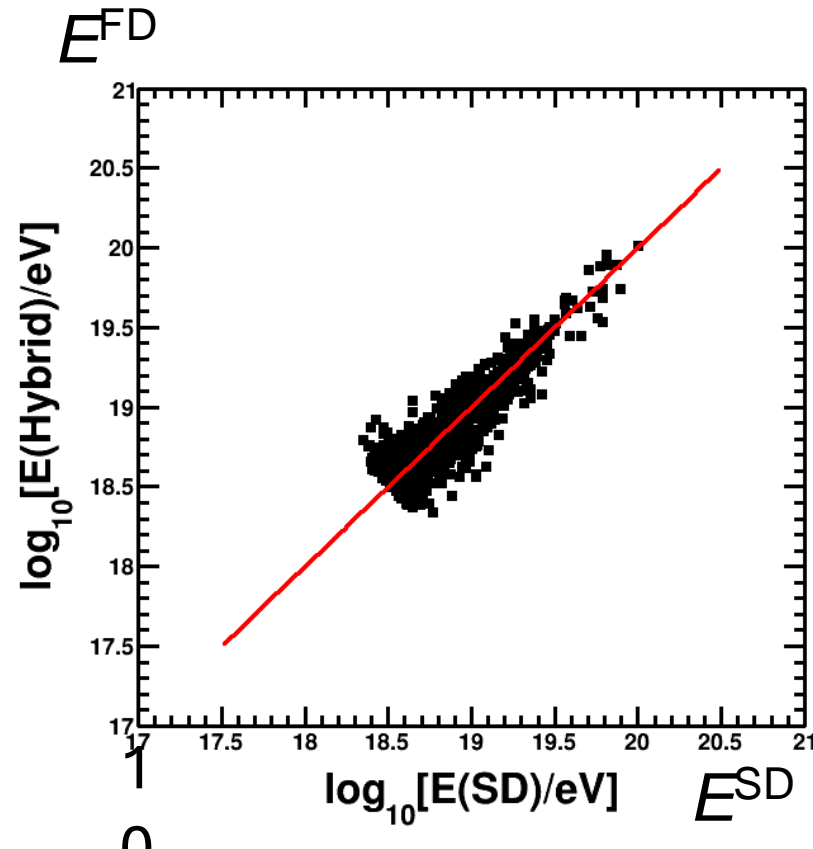
Using hybrid events,

$$\left\langle \frac{E^{\text{TBL}}}{E^{\text{FD}}} \right\rangle_{\text{hyb}} = 1.27$$

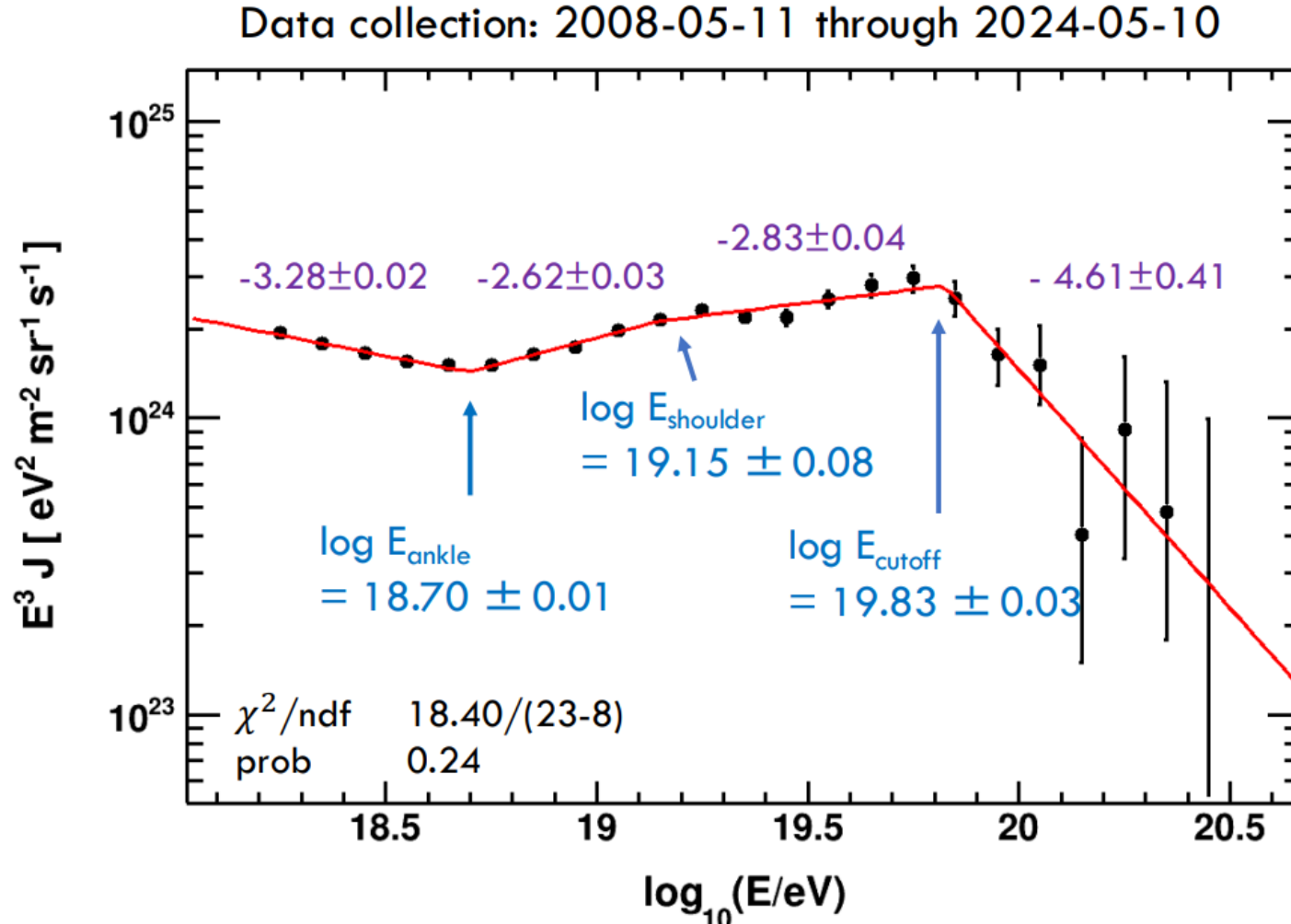
cf. AGASA/HiRes = 1.25

- Final energy is by scaling E^{TBL} :

$$E_{\text{SD}} = E^{\text{TBL}} / \left\langle \frac{E^{\text{TBL}}}{E^{\text{FD}}} \right\rangle_{\text{hyb}}$$



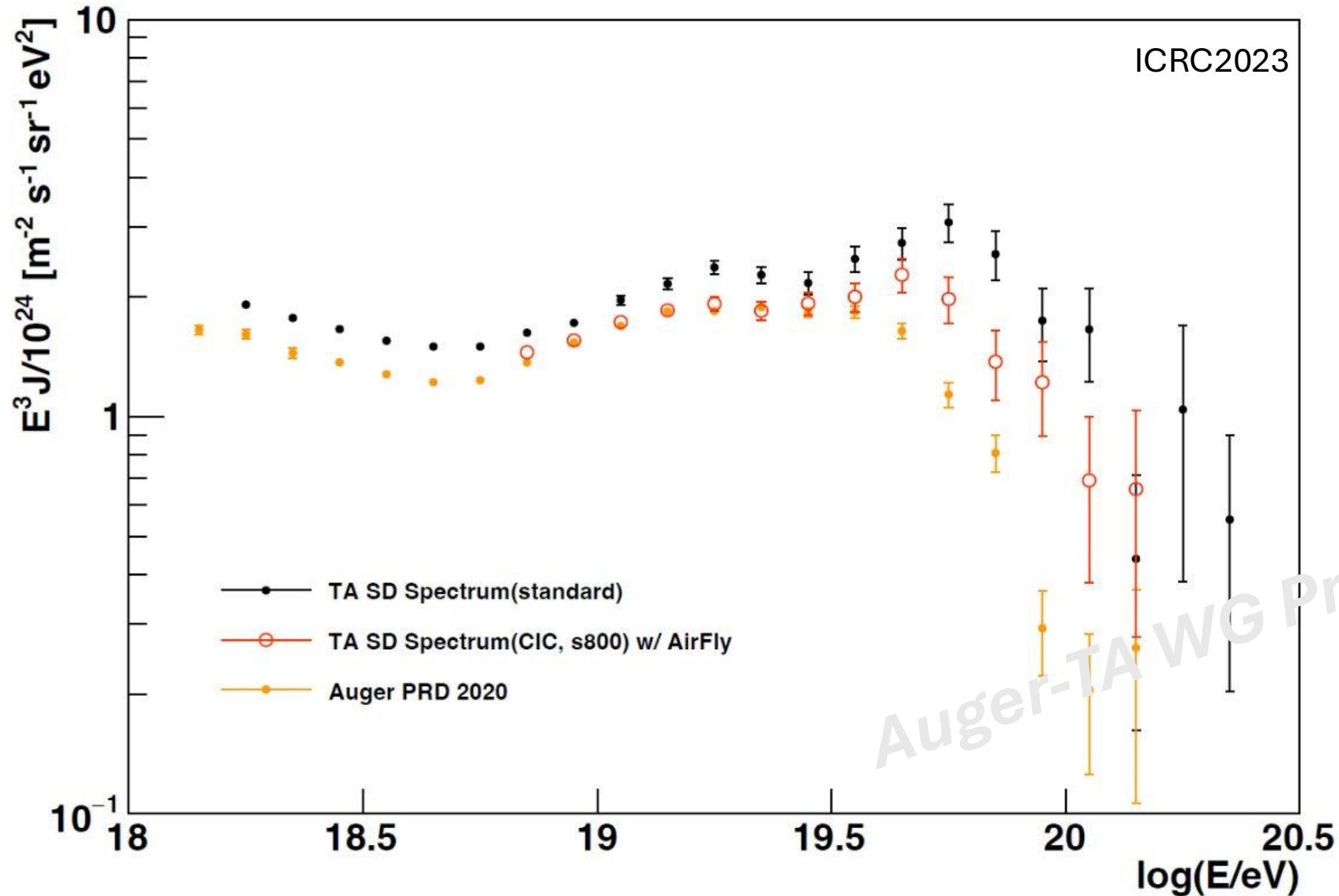
Spectral Features in 16-year TA SD Data



- Spectral steepening at $\log E = 19.83$
 - $N_{\text{exp}}: 173.7, N_{\text{obs}}: 97$
 - $P = 1.6 \times 10^{-10}, 6.3\sigma$
- "Instep" or "shoulder" found at $\log E = 19.15$
 - $N_{\text{exp}}: 2156.4, N_{\text{obs}}: 1921$
 - $P = 1.3 \times 10^{-7}, 5.2\sigma$

Recalculated the spectrum (common δ band)

TA event are reconstructed using AirFly, CIC, and other parameters kept unchanged

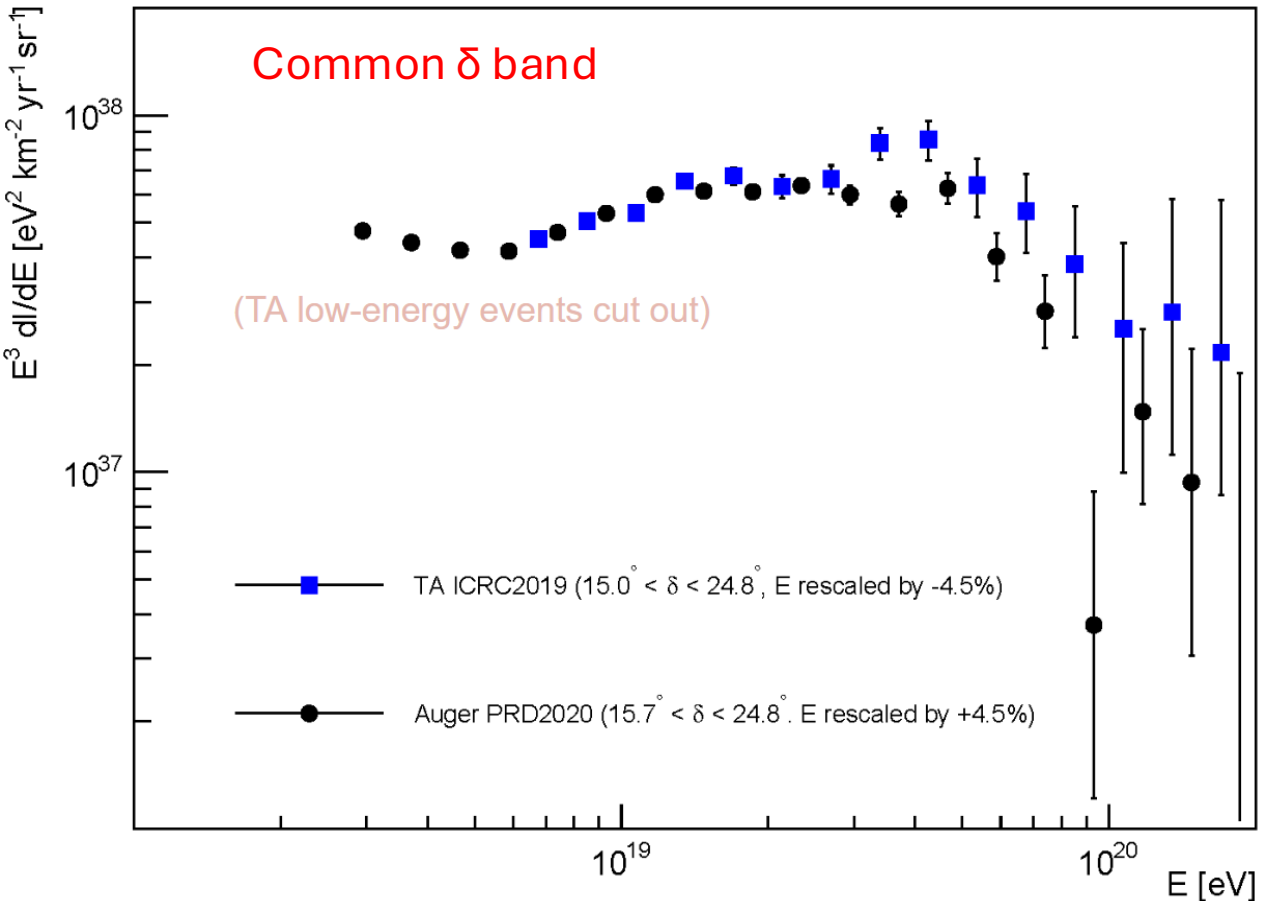
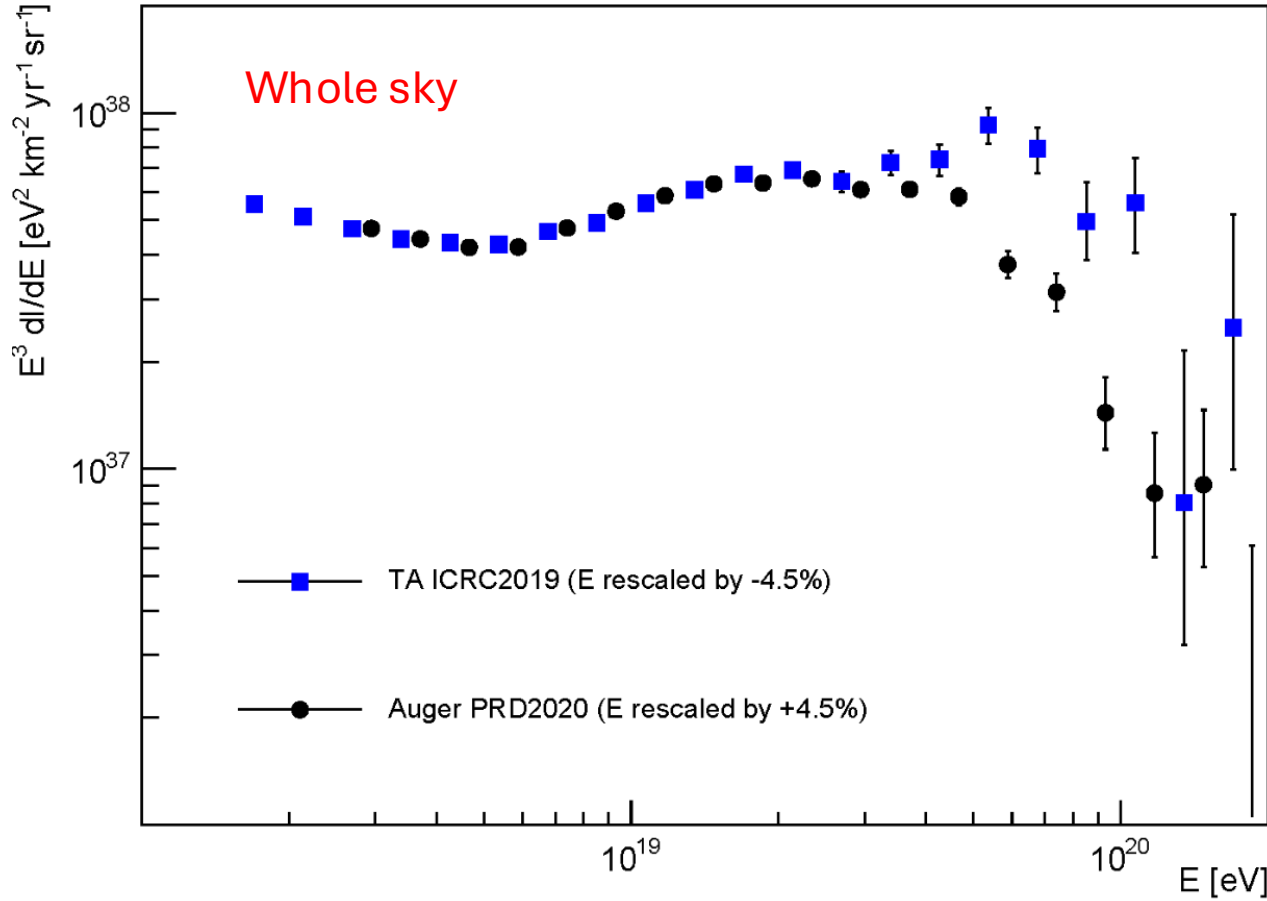


Comparison with Auger

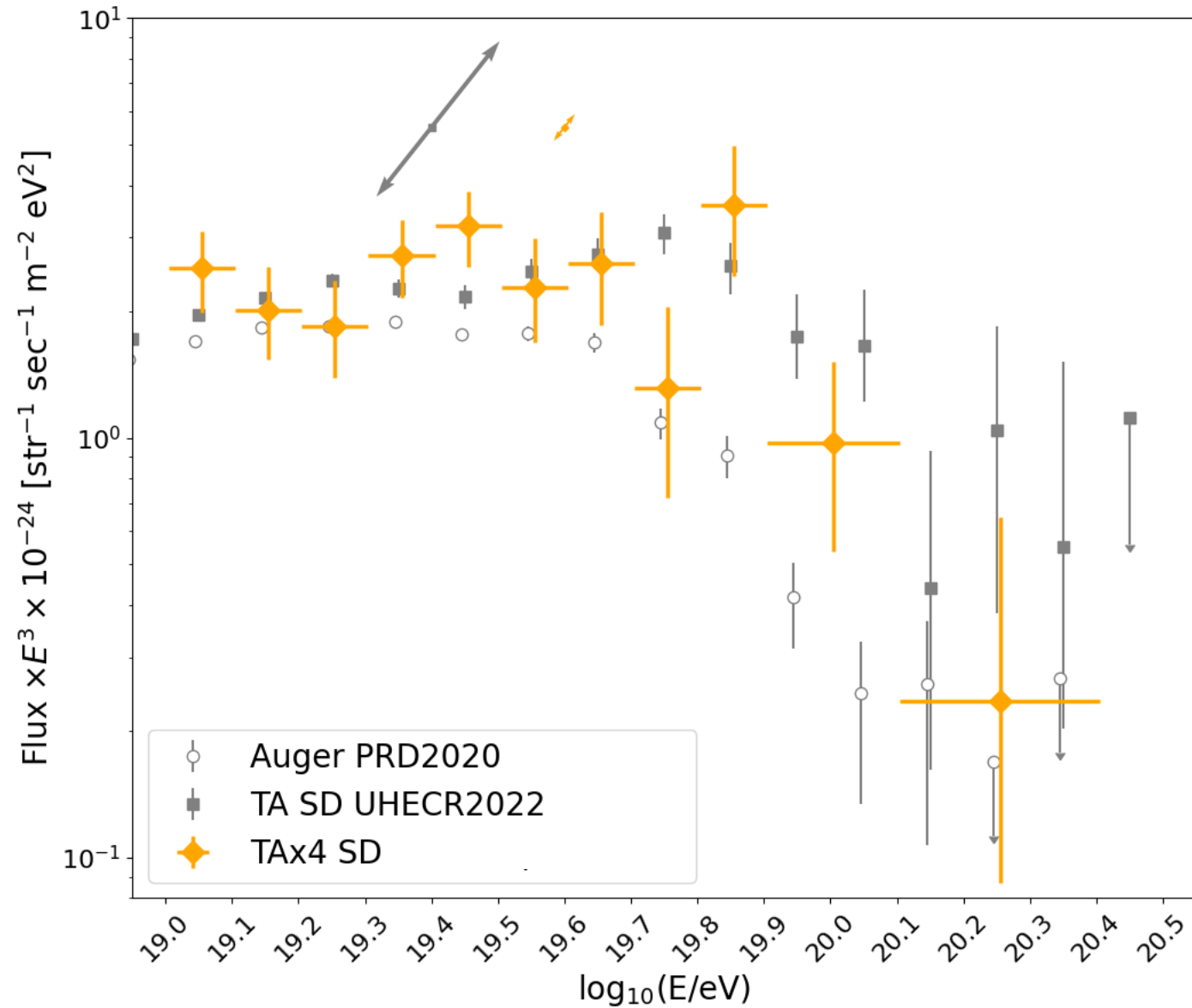
- Auger: 35°S
 - θ up to 60°
- TA: 39°N
 - θ up to 55°
- Common declination band
 - $-15^\circ < \delta < 24.8^\circ$



ICRC2021

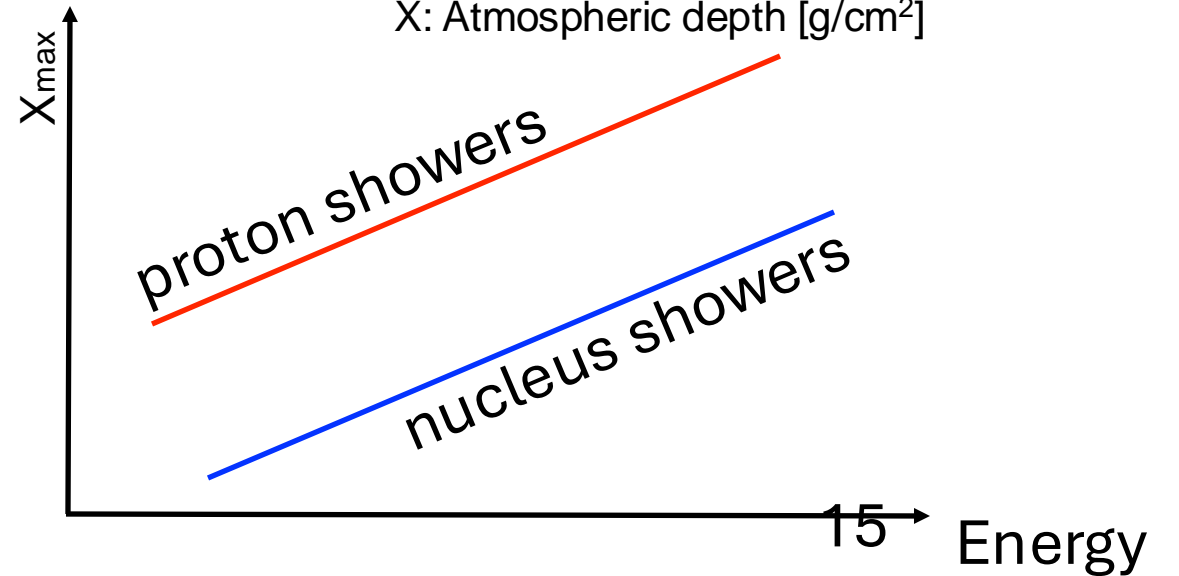
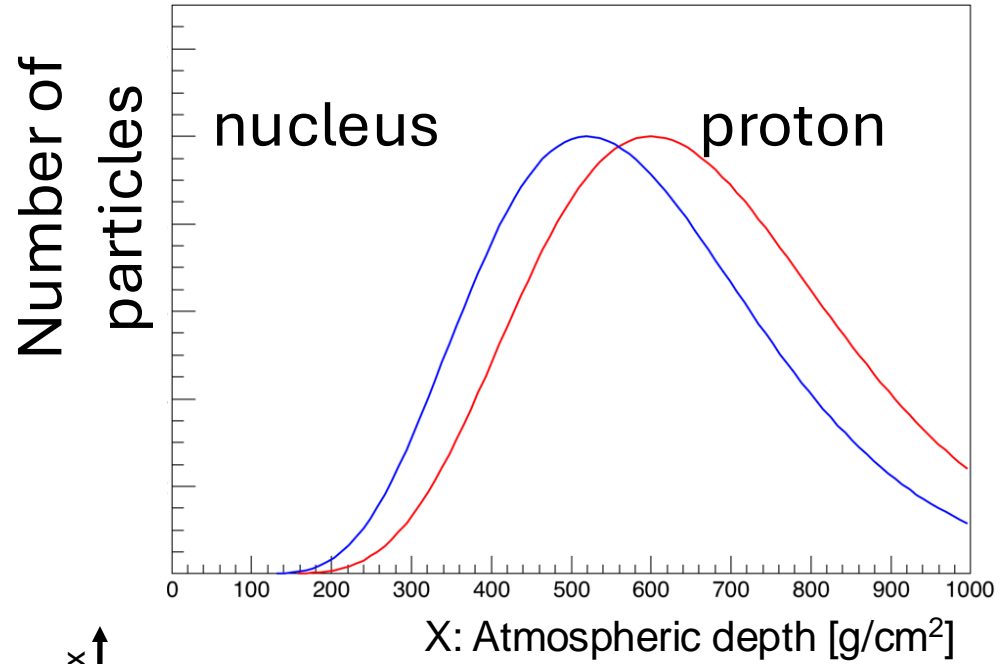
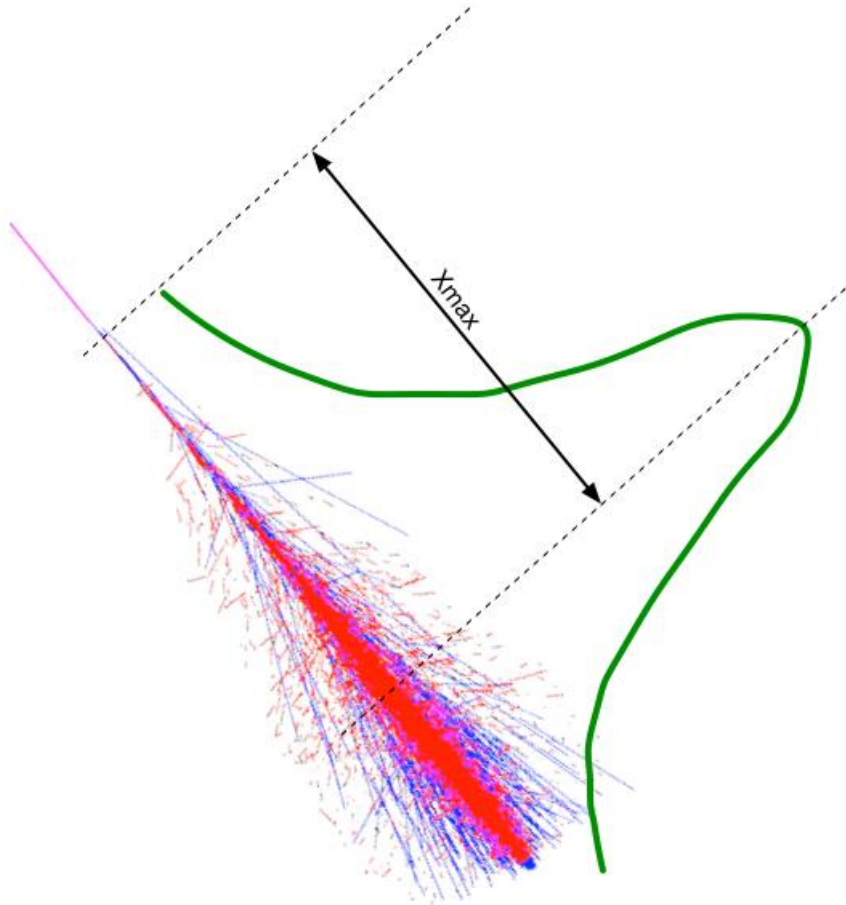


TAx4 Spectrum



- TAx4 spectrum 2019-2022
- No inter-subarray triggers
- Consistent with TA SD

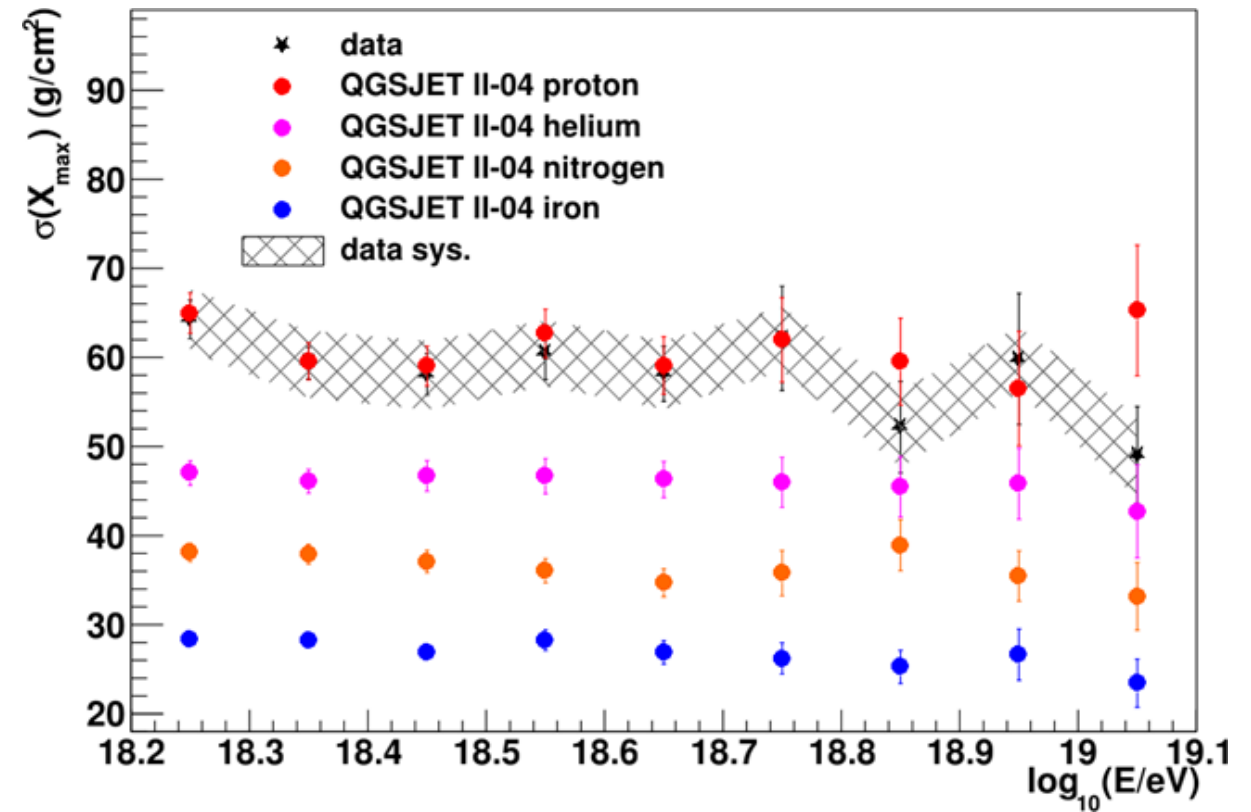
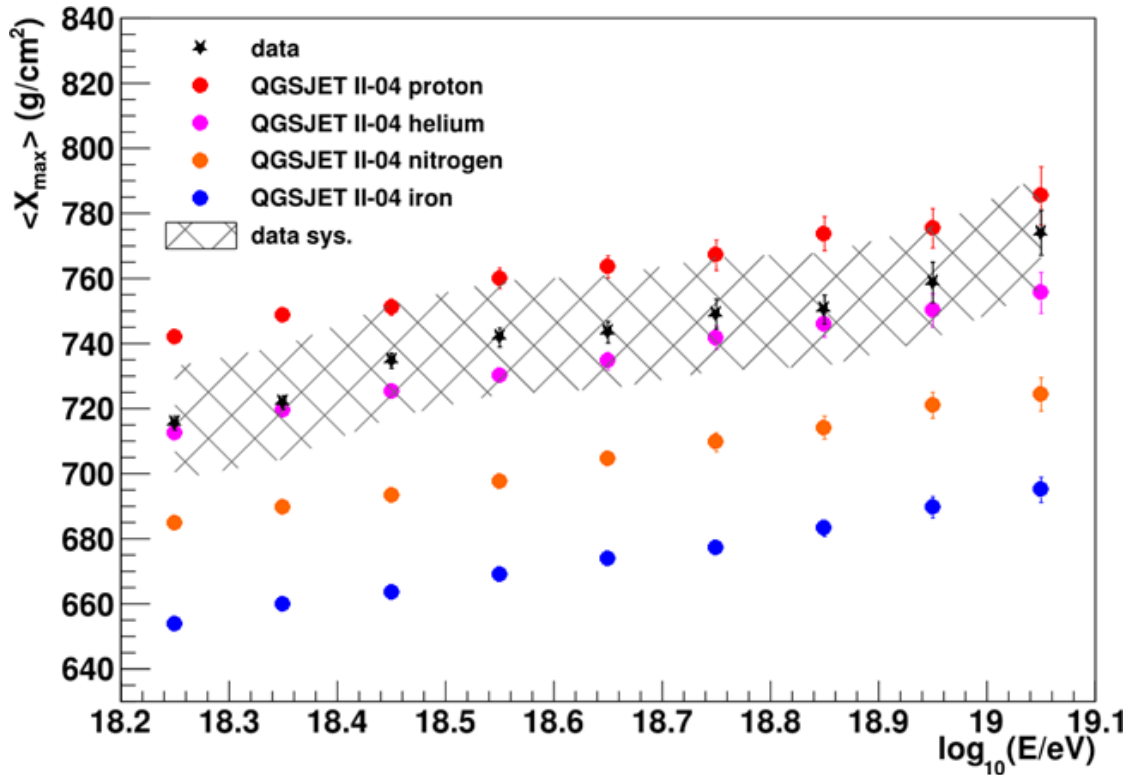
Measurement of X_{\max}



TA Xmax Measurement: BR/LR FD-SD Hybrid

R. U. Abbasi *et al* 2018 *ApJ* **858** 76

PoS(ICRC2019)280

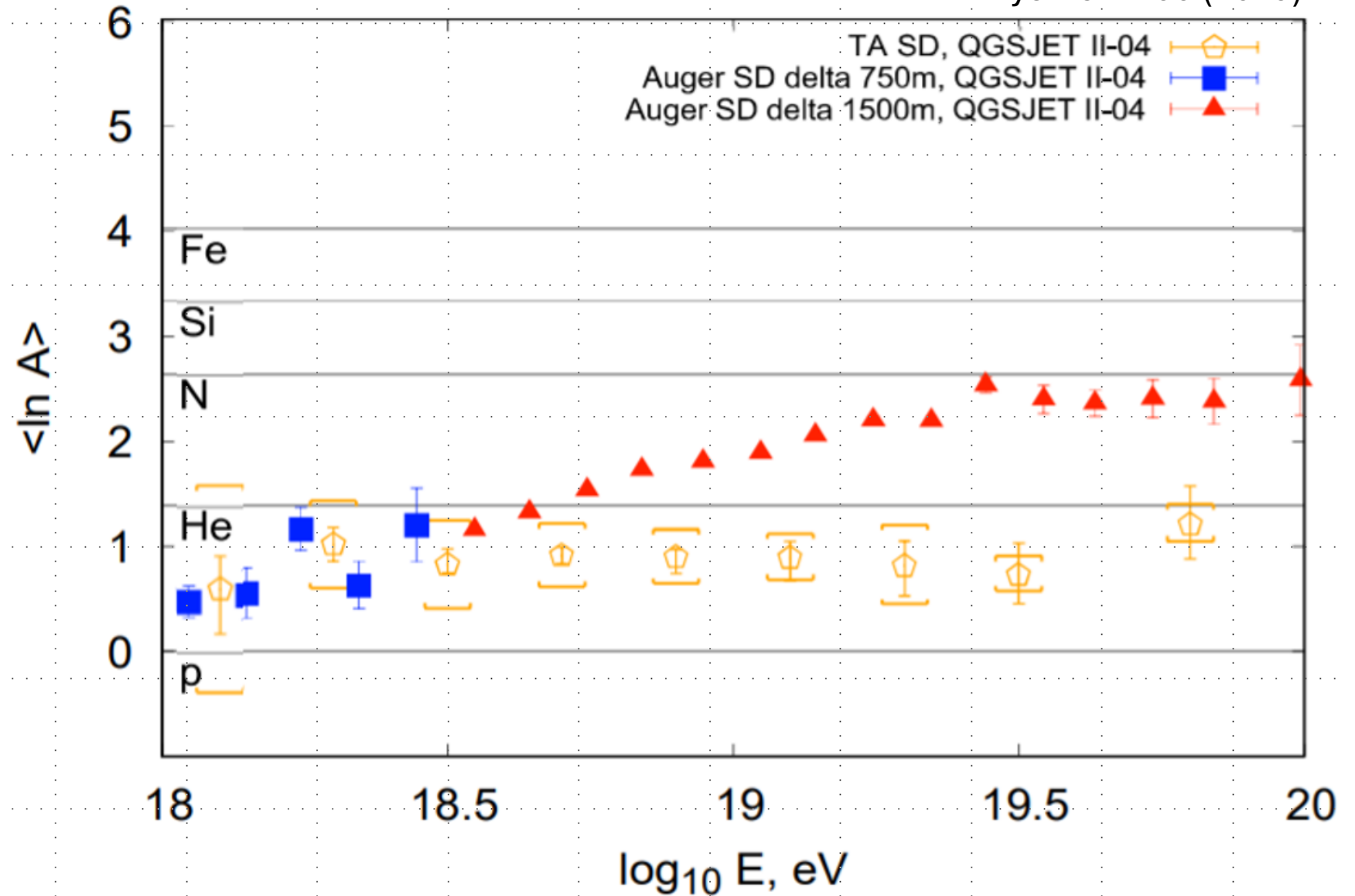


- 10-years FD+SD data
- Agreement with light composition up to 1019.1 eV
- Need more data for higher energies

SD Composition Study

Y. Zhezher, ICRC2021
Phys.Rev.D 99 (2019) 2

- SD data, composition-sensitive parameters like Linsley curvature, number of peaks in traces,
- BDT classifier

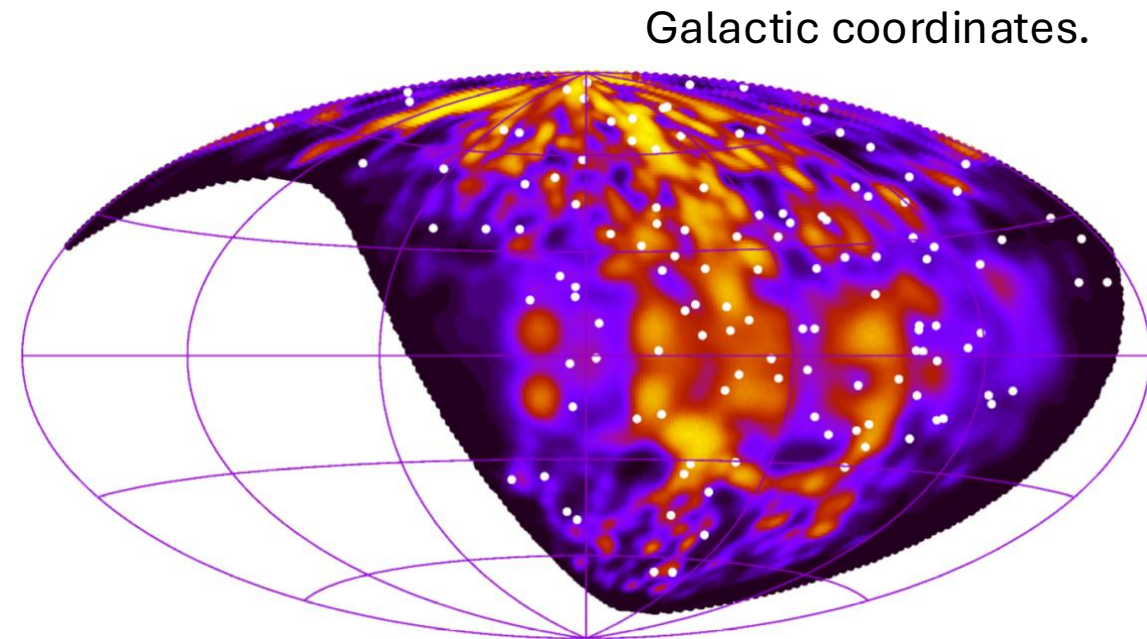


Implication of mass composition from the arrival direction distribution

- Use 2MRS galaxy map as the tracer of LSS-mass distribution
- Introduce the *smearing angle* θ to blurr the cosmic ray source due to the magnetic field
- Employ a *flux sampling method* and compare the TA data in terms of the test statistic,

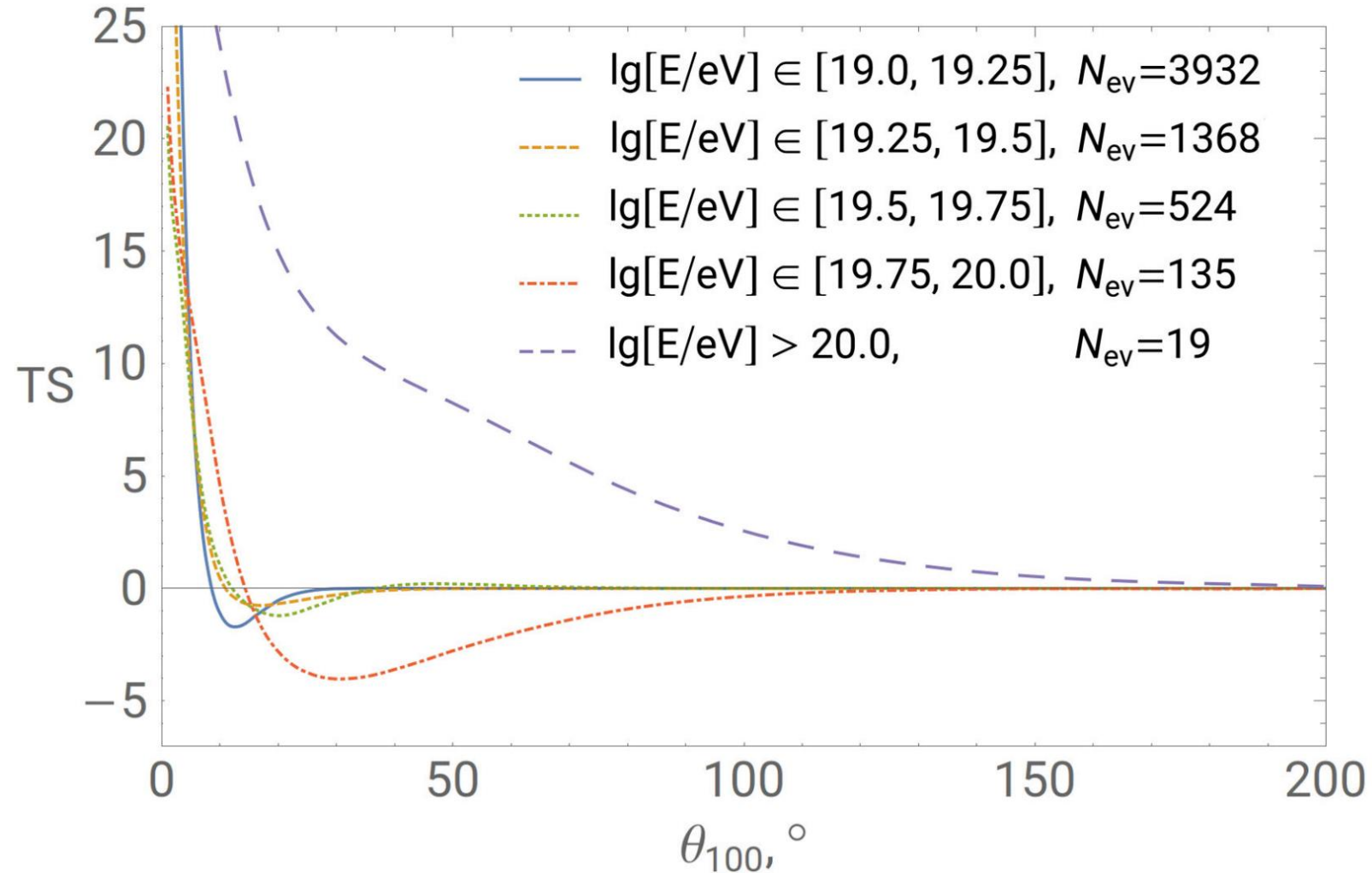
$$TS(\theta_{100}) = -2 \sum_k \left(\sum_i \ln \frac{\Phi_k(\theta_{100}, \mathbf{n}_i)}{\Phi_{\text{iso}}(\mathbf{n}_i)} \right).$$

- \mathbf{n}_i : i -th TA event direction
- $\theta = \theta_{100}/E_k$
- θ_{100} : Smearing angle at 100EeV



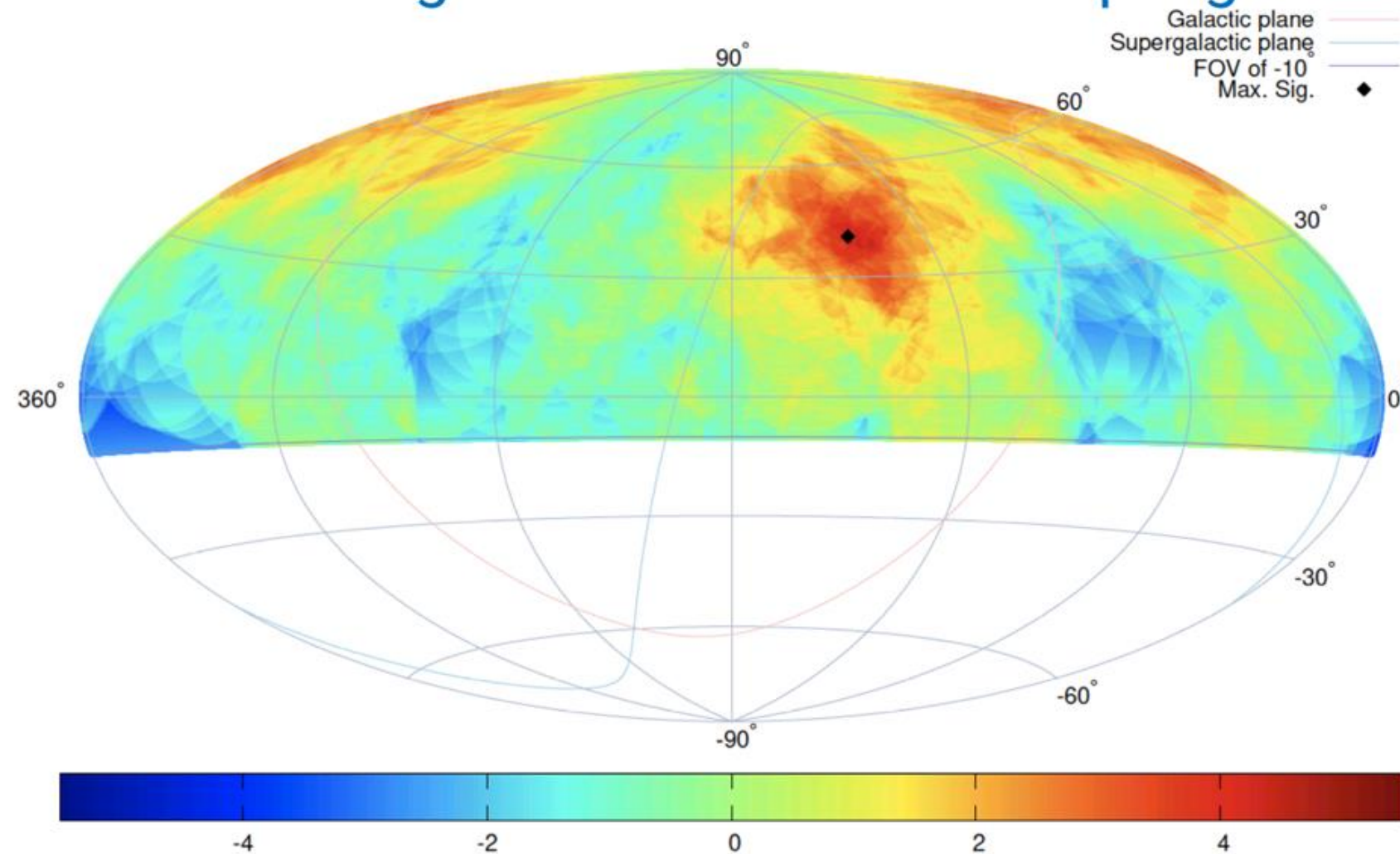
TA highest energy SD events are isotropic

- Small deflections ($< 10^\circ$) is not compatible at all energies
- Θ_{100}^{\min} found around 10-30 degrees below $\log E < 20$: Compatible with LSS at 2σ level
- Prefers complete isotropy for $\log E > 20$, which implies heavy composition at the highest energies



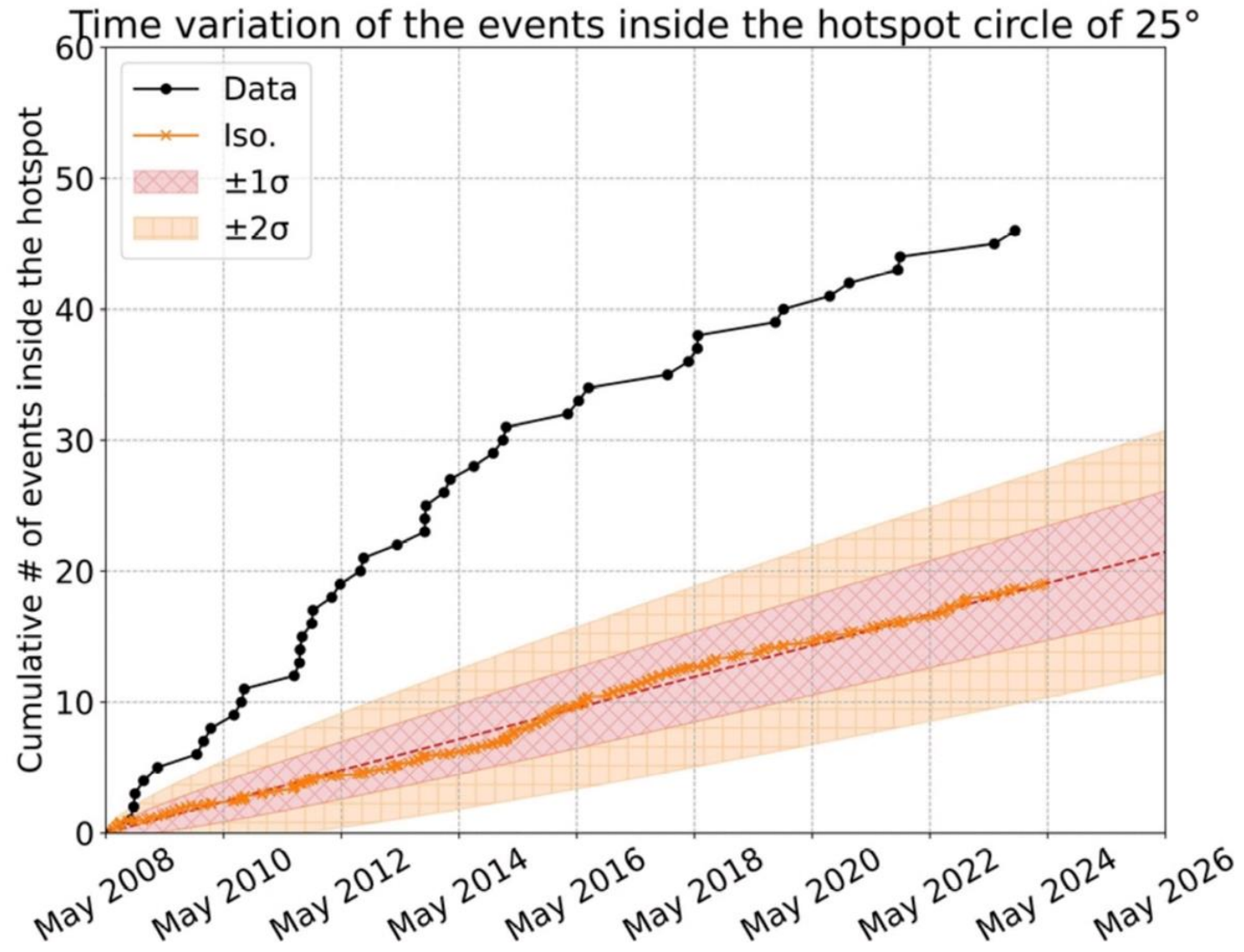
TA Hot Spot

25° angular distance oversampling



- $E > 57$ EeV, 228 events
- Local significance 4.9 sigmas at (144.0, 40.5)
 - Nobs: 46
 - Nexp: 19.1
- Global significance 2.9 sigmas

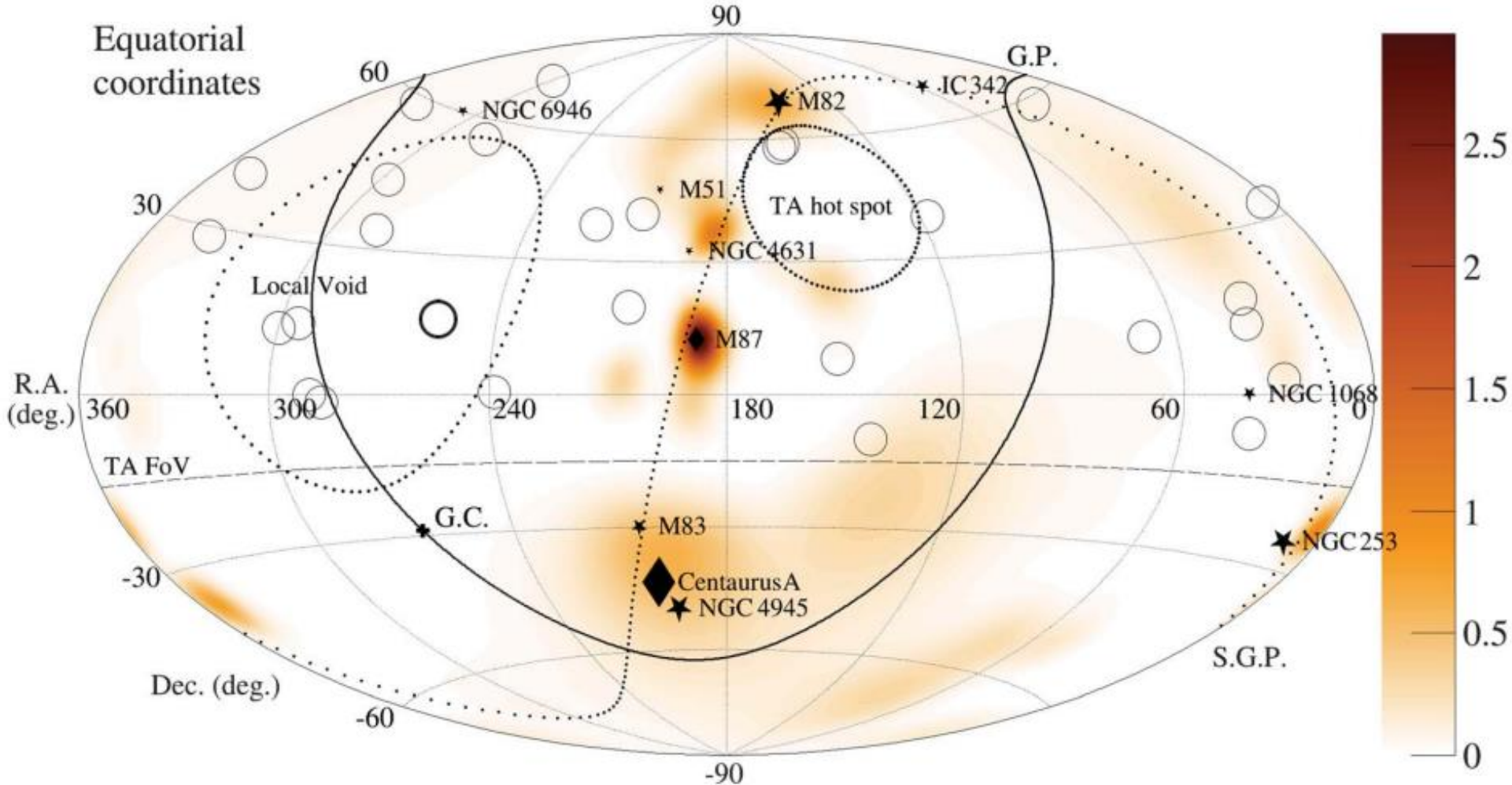
TA Hot Spot Is Still Hot



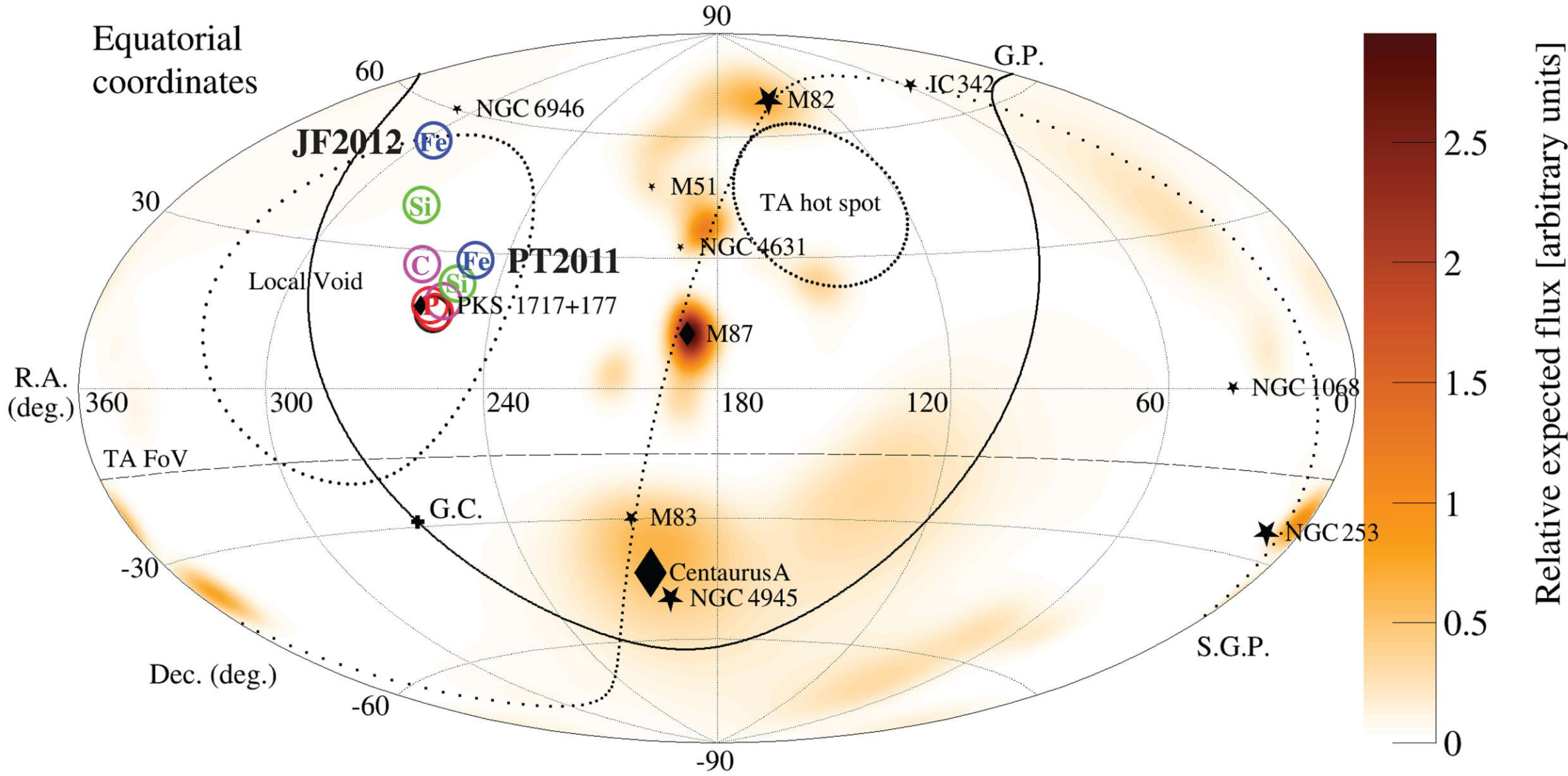
Amateras is uncorrelated with LSS

Telescope Array Collaboration,
Science 382, 903–907 (2023)

Fig. 3. Arrival directions of all >100-EeV cosmic rays. Empty circles indicate the arrival directions of all cosmic rays observed by TA SD over 13.5 years of operation that had energies >100 EeV. The background and other symbols are the same as in Fig. 2. No clustering around the highest-energy event (thick circle) is evident.



Amateras is uncorrelated with LSS



Summary

- TA is operational more than 16 years since 2008
- Energy spectrum updated
 - Highest-energy steepening at $\log E = 19.83$, 6.3 sigmas
 - "Instep" structure confirmed at $\log E = 19.15$, 5.2 sigmas
 - Good agreement with Auger for $\log E < 19.5$
 - Northern/southern sky tension
- Composition studies
 - "Light" composition up to $10^{19.1}$ eV by FD, $10^{19.7}$ by SD
 - Heavy composition favors from the arrival direction distribution for $E > 10^{20}$ eV
- TA hotspot is still hot at (144.0, 40.5) for $E > 57$ EeV
- Amateras particle
 - May 27, 2021
 - 244 EeV, the 2nd highest energy all the time, the highest energy event detected by an SD array
 - No FD data
 - Identification of the primary particle type ongoing

Backup

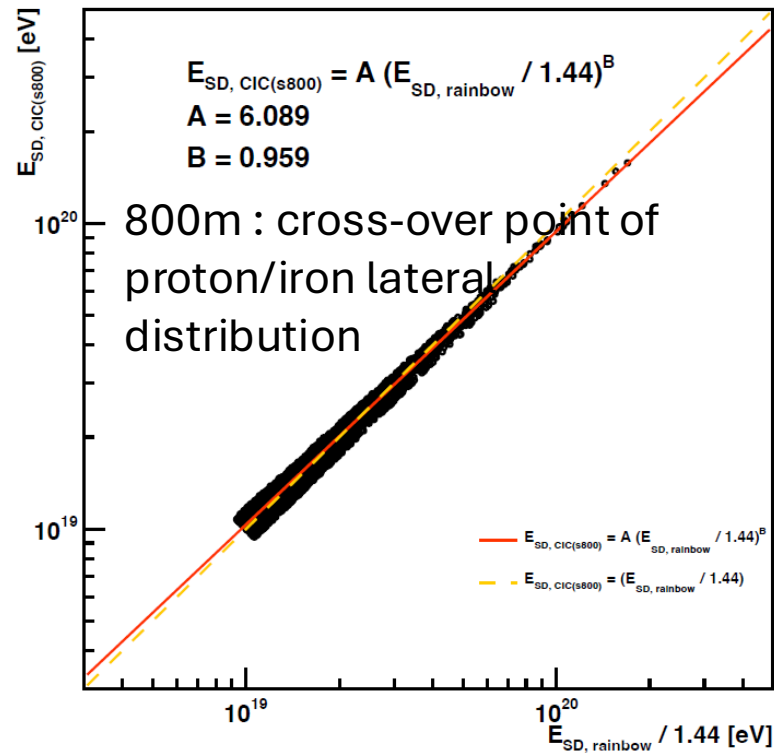
Attempt 2: Rainbow table vs CIC

using 14yrs T ASD data

$E_{SD, \text{rainbow}}$ vs. E_{CIC}

- Energy comparison

$E_{SD, \text{rainbow}}$ vs. $E_{SD, CIC(s800)}$



$E_{SD, \text{rainbow}}$ vs. $E_{SD, CIC(s1300)}$

