Highlights from the Telescope Array Experiment

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Outline

- Introduction to TA and TA×4
- Energy Spectrum
- Mass Composition
- Anisotropy
- Summary

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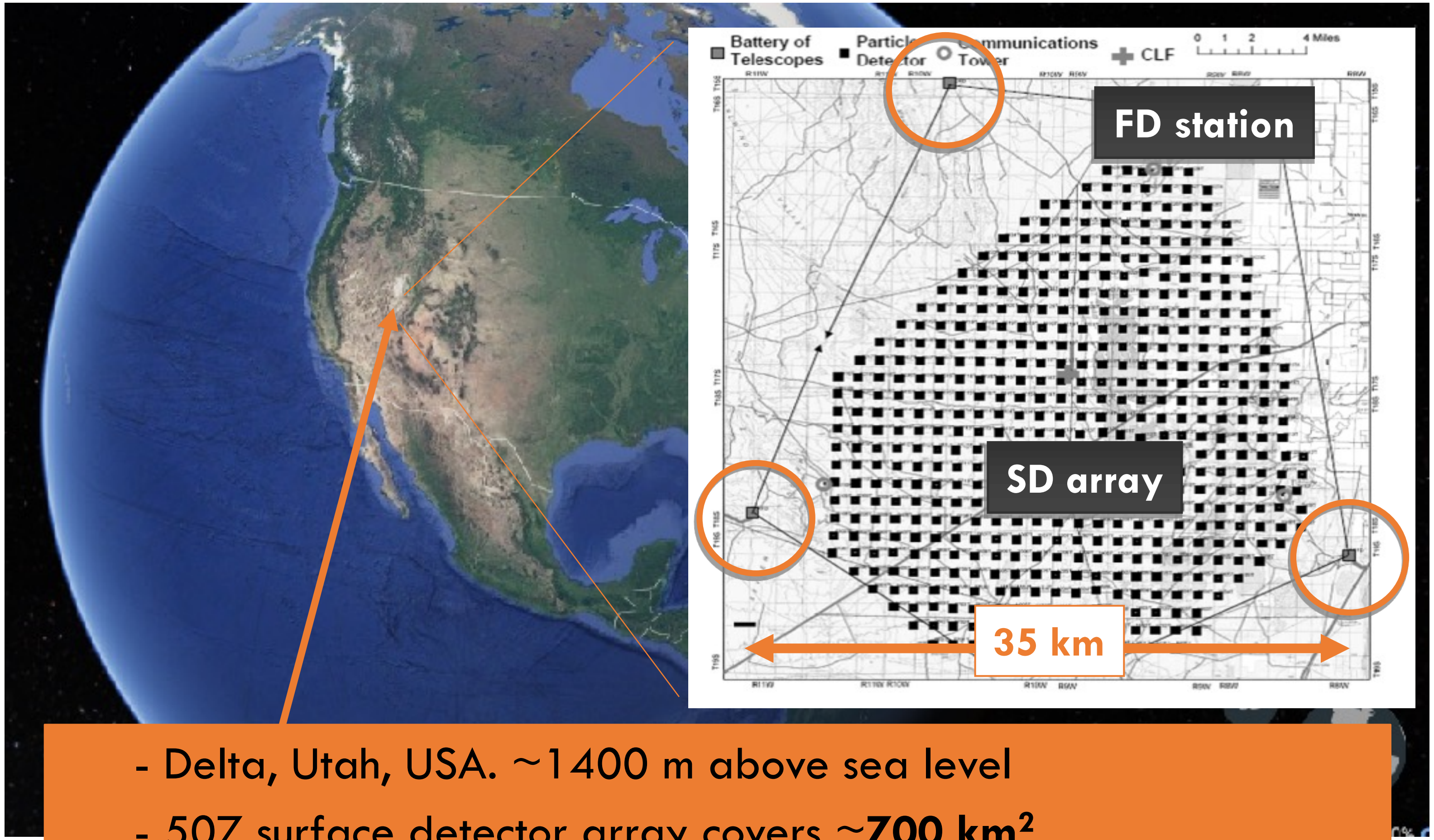
148 members, 33 institutes, 7 countries

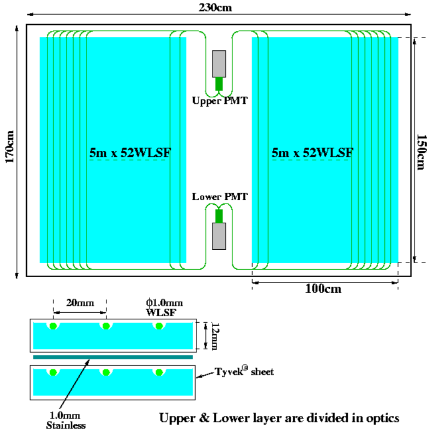
Telescope Array (TA) Experiment: hybrid observation

- The largest cosmic ray observatory in the northern hemisphere



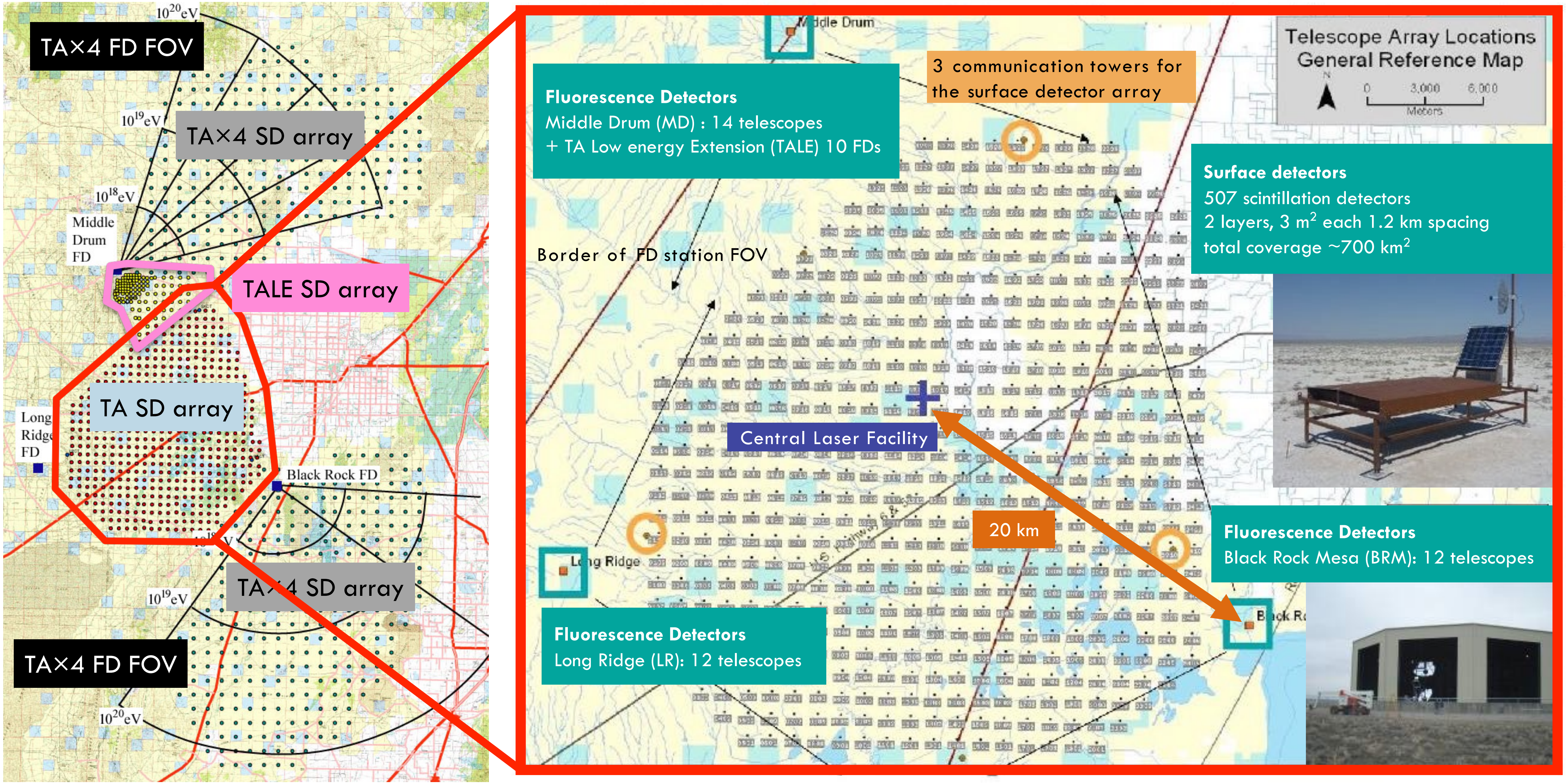
- Delta, Utah, USA. ~1400 m above sea level
- 507 surface detector array covers ~**700 km²**
- 38 telescopes in 3 stations look over the array

Surface Detector: Plastic Scintillator

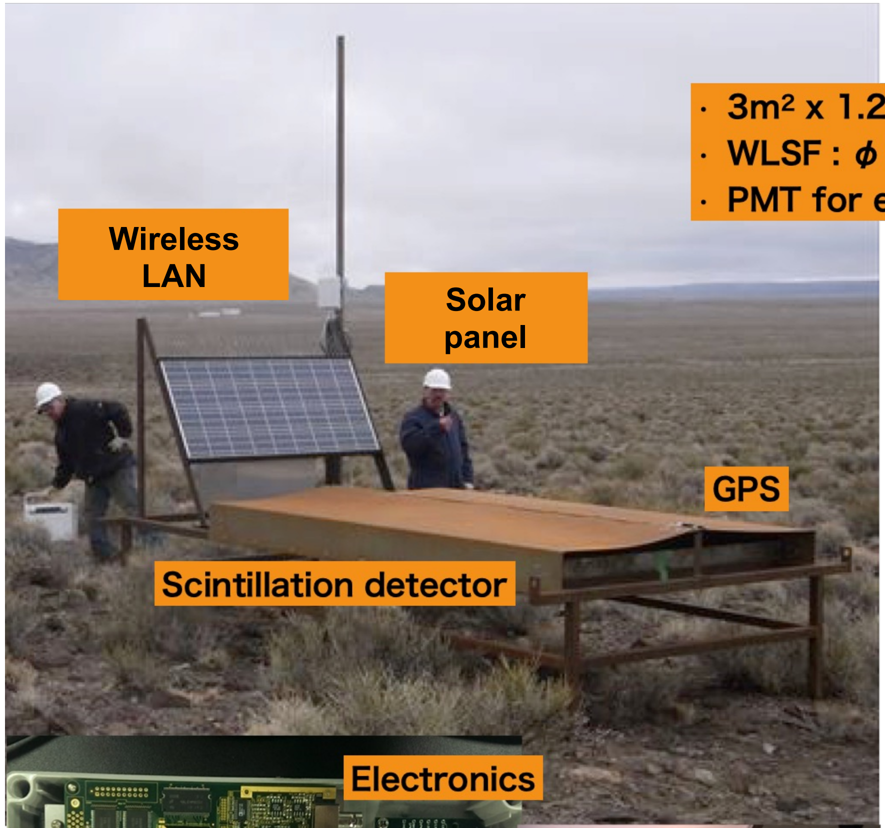


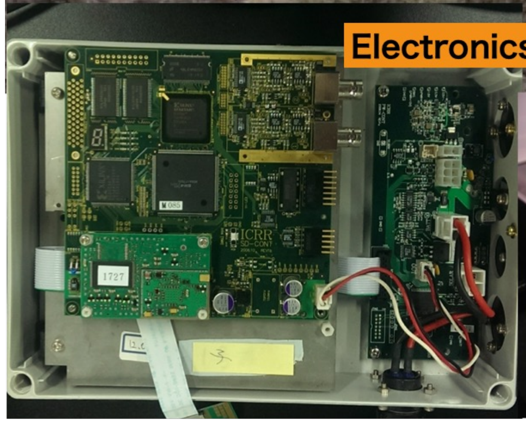
Fluorescence Detector: PMT camera

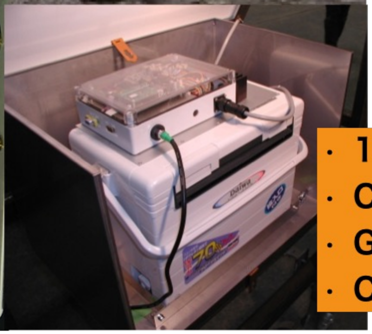
Map of the TA site



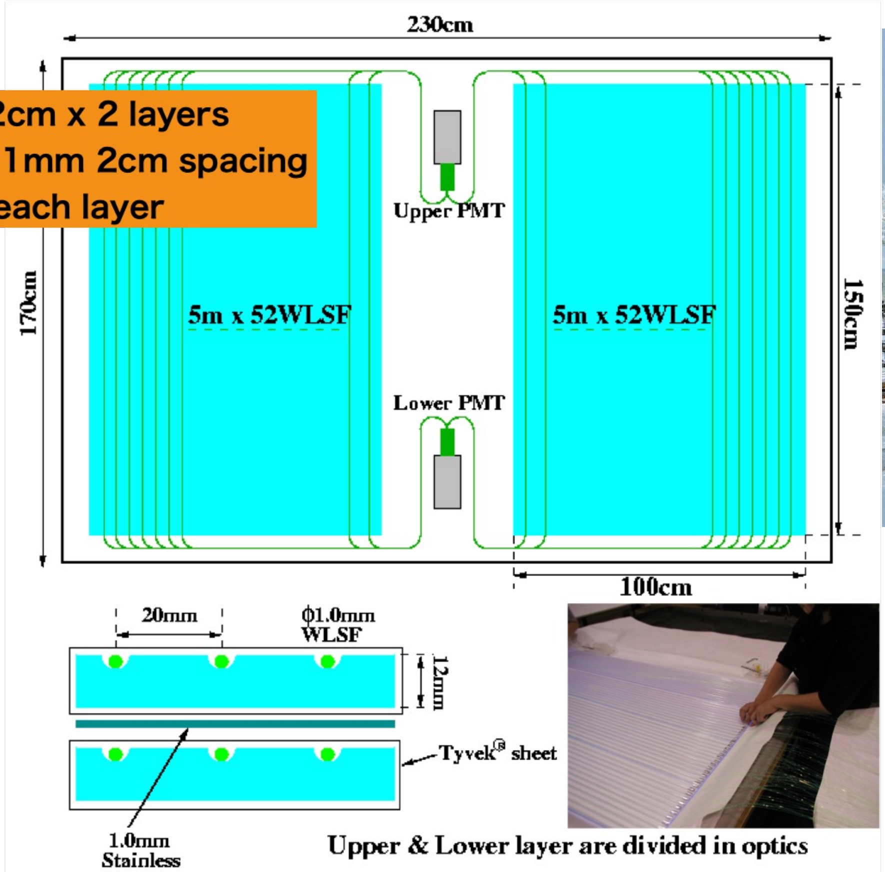
Scintillator Surface Detectors (SDs)







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

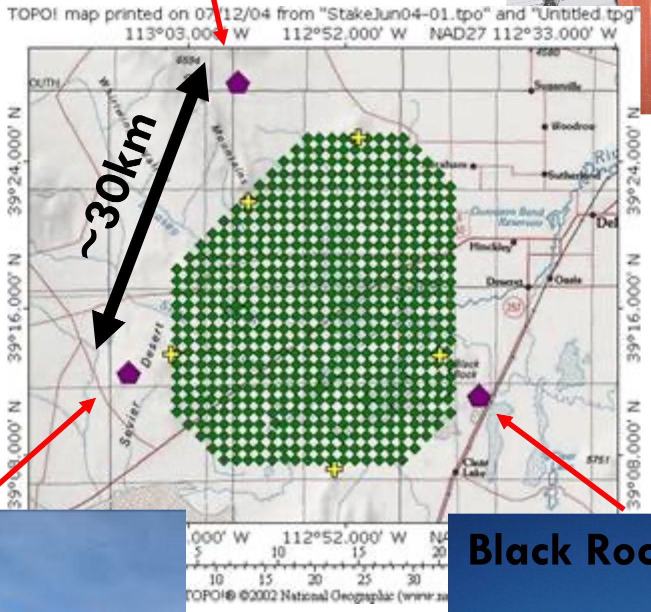


- 507 plastic scintillation counters
- 2 layers, 1.2 cm thick, 3 m^2 area
- 1.2 km square grid spacing covering

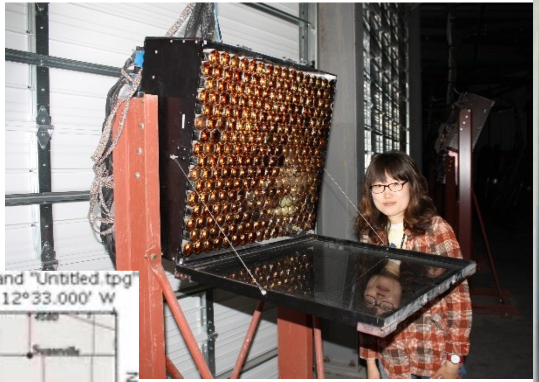
~700 km^2

Fluorescence Detectors (FDs)

Middle Drum



14 telescopes @ station
256 PMTs/camera



5.2 m^2

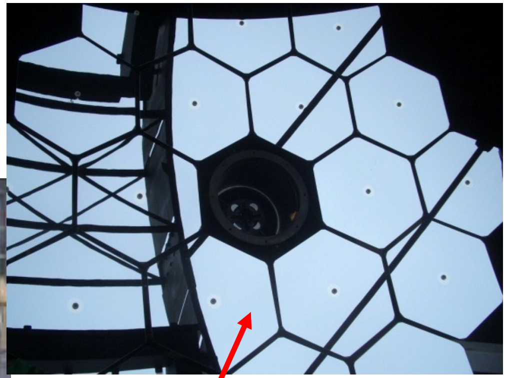
Reutilized from HiRes-I

Long Ridge

12 telescopes/station
256 PMTs/camera

Black Rock Mesa

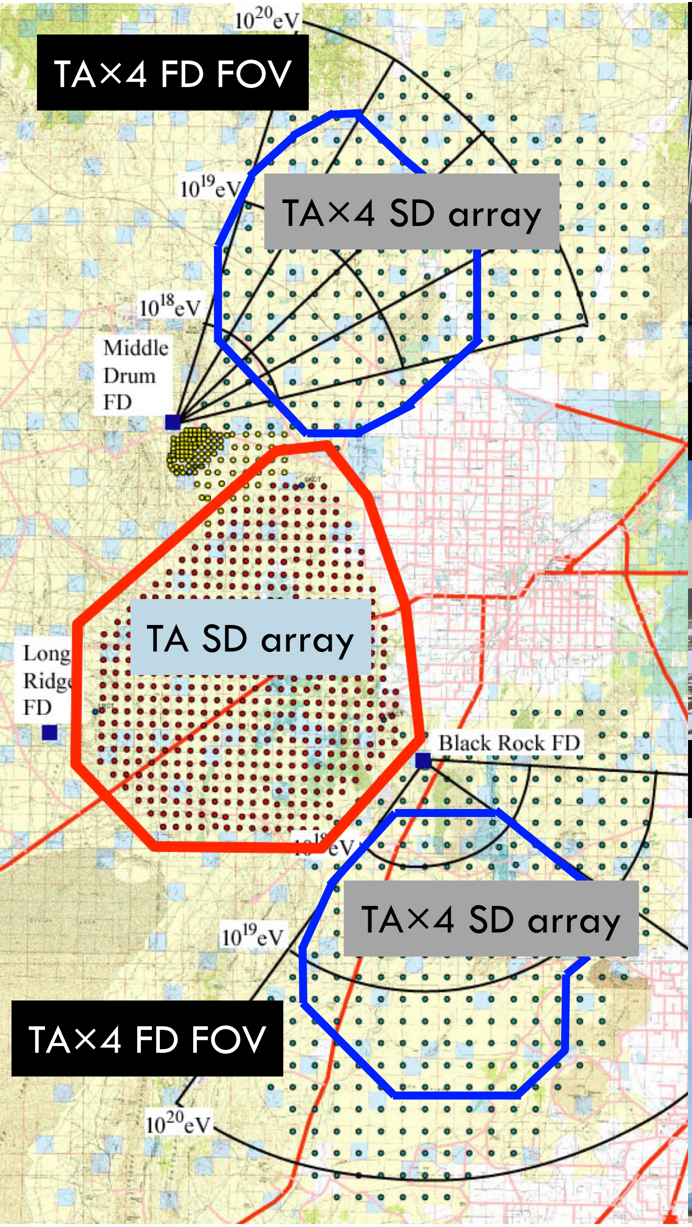
New Telescopes



6.8 m^2

- 3 stations
- 12–14 telescopes
- 256 hexagonal PMTs per camera
- 3°–31° elevation
- Look over the SD array for hybrid observation

TA×4 Project: Fourfold Extension of TA, ~2,800 km²



Initial Plan:

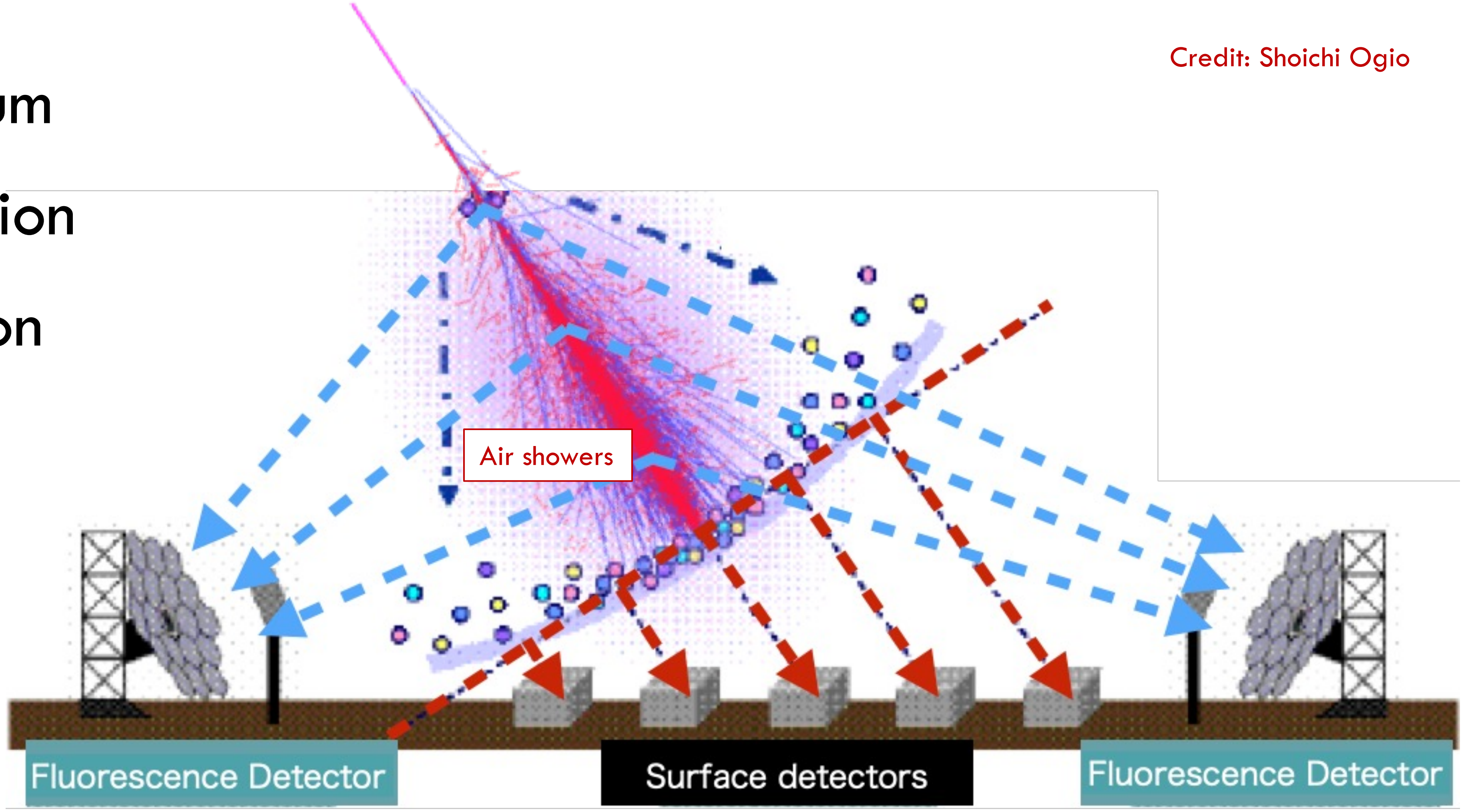
- Divide into 2 arrays: North, South
- 500 new SDs at **2.08 km** spacing
- 12 telescopes for hybrid observation

Current Status:

- Surface Detectors (SDs)
  - 257 detectors were deployed (blue lines)
  - began operation in November 2019
- Fluorescence Detectors (FDs)
  - 4 telescopes at North, started operation in June 2018.
  - 8 telescopes at South, started full operation after the pandemic shutdown in July 2020

Main Observables of UHECRs

- Energy spectrum
- Mass composition
- Arrival direction

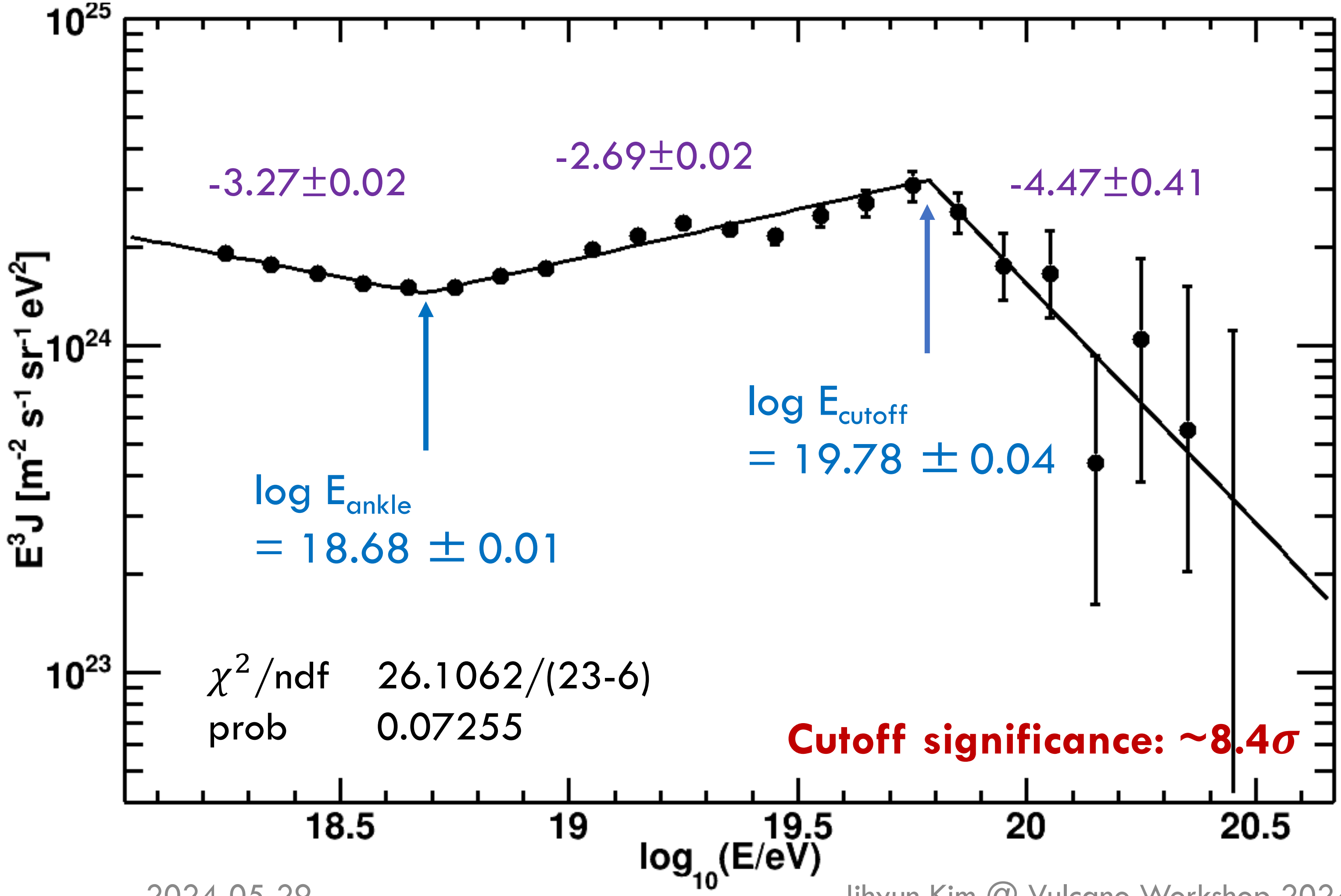


Credit: Shoichi Ogio

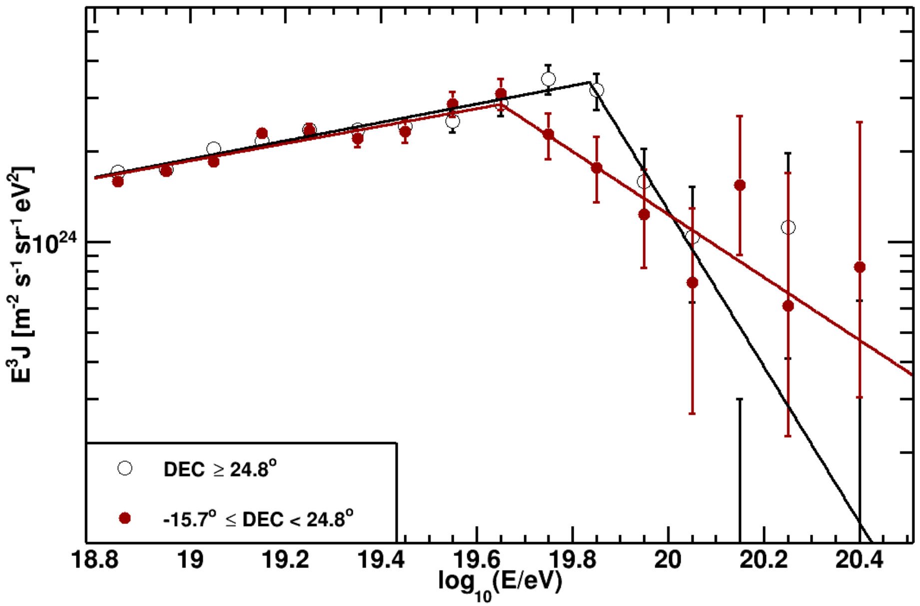
Energy Spectra

TA SD: Spectral Feature in 14-year Data (2008-05-11 to 2022-05-10)

- Spectral shape is indicative of collisions of the UHECR en route to us at Earth and the nature of source candidates.

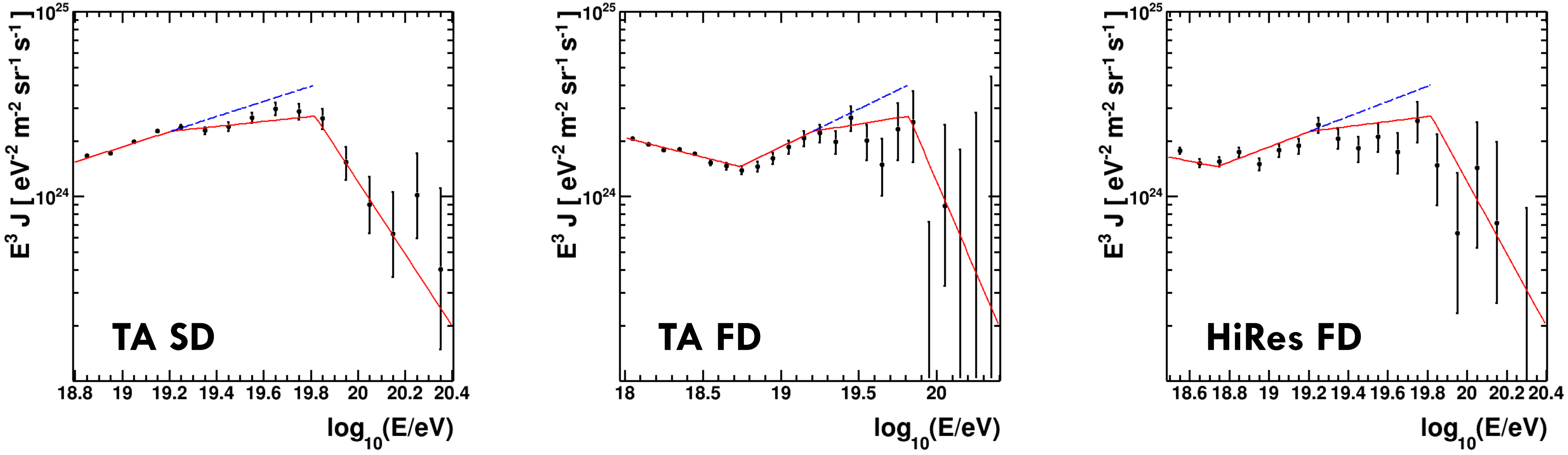


Declination Dependence



- Differences in the cutoff energies
  - log(E/eV)=**19.84 ±0.02** for (24.8°–90°)
  - log(E/eV)=**19.65 ±0.03** for (-15.7°–24.8°)
  - 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.

TA SD: Spectral Feature in 10^{19}–$10^{19.5}$ eV

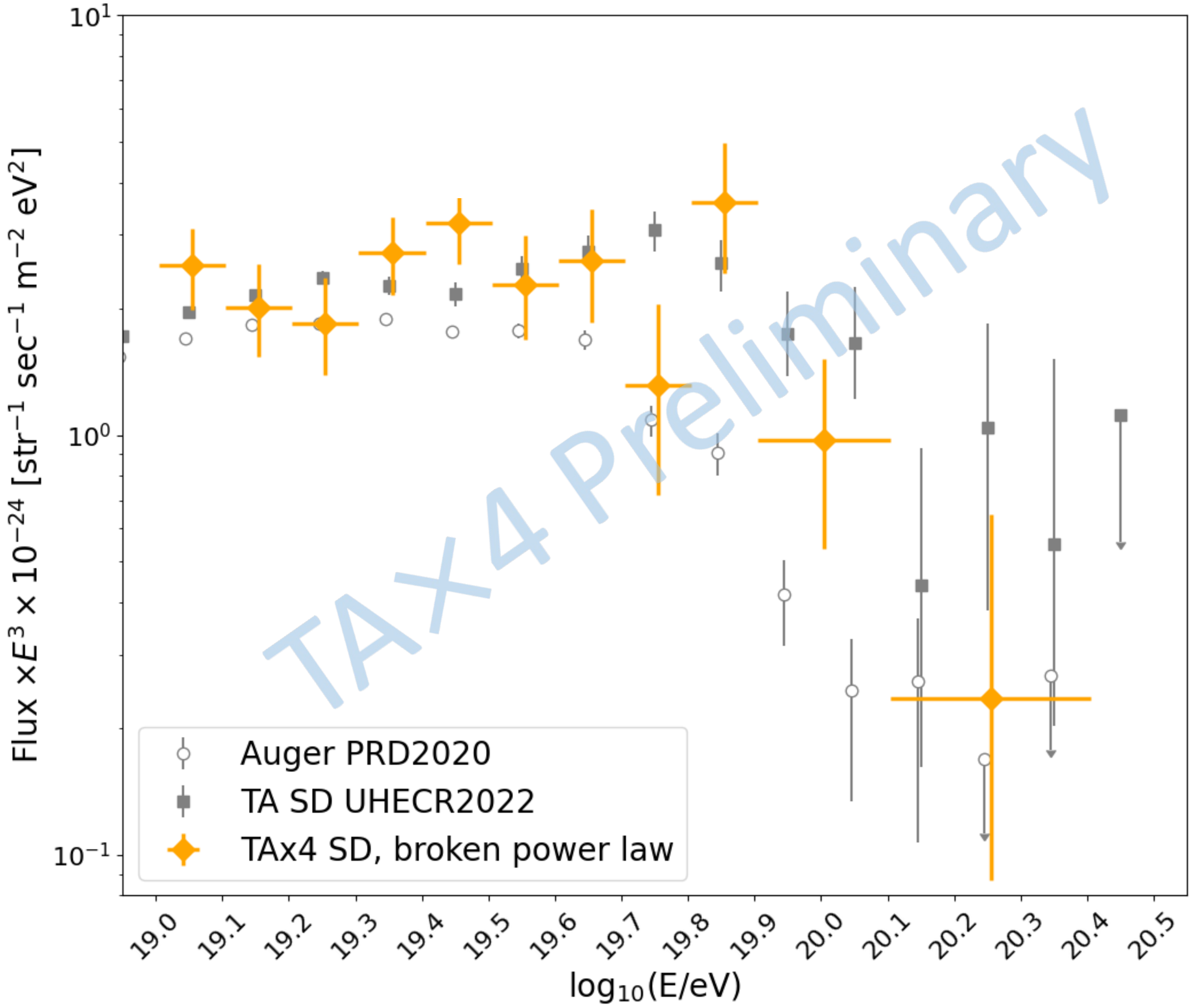


Fit parameter	HiRes—TA	Auger (PRD 2020)
p_1	-3.21 ± 0.01 (stat)	-3.29 ± 0.02 (stat)
p_2	-2.59 ± 0.01 (stat)	-2.51 ± 0.03 (stat)
p_3	-2.87 ± 0.03 (stat)	-3.05 ± 0.05 (stat)
p_4	-5.0 ± 0.3 (stat)	-5.1 ± 0.3 (stat)
$\log_{10}[E_{ANKLE}/eV]$	18.74 ± 0.01 (stat)	18.70 ± 0.01 (stat)
$\log_{10}[E_{SHOULDER}/eV]$	19.20 ± 0.03 (stat)	19.11 ± 0.03 (stat)
$\log_{10}[E_{CUTOFF}/eV]$	19.82 ± 0.02 (stat)	19.66 ± 0.03 (stat)

- Auger found a new spectral feature in 10^{19}–$10^{19.5}$ eV.
  (*instep/shoulder* feature)
- We observed the same softening feature in the northern hemisphere but at $10^{19.20\pm0.03}$ eV with a 6.5σ significance.
- TA and Auger agree within 1.2σ.

TA×4 SD Energy Spectrum

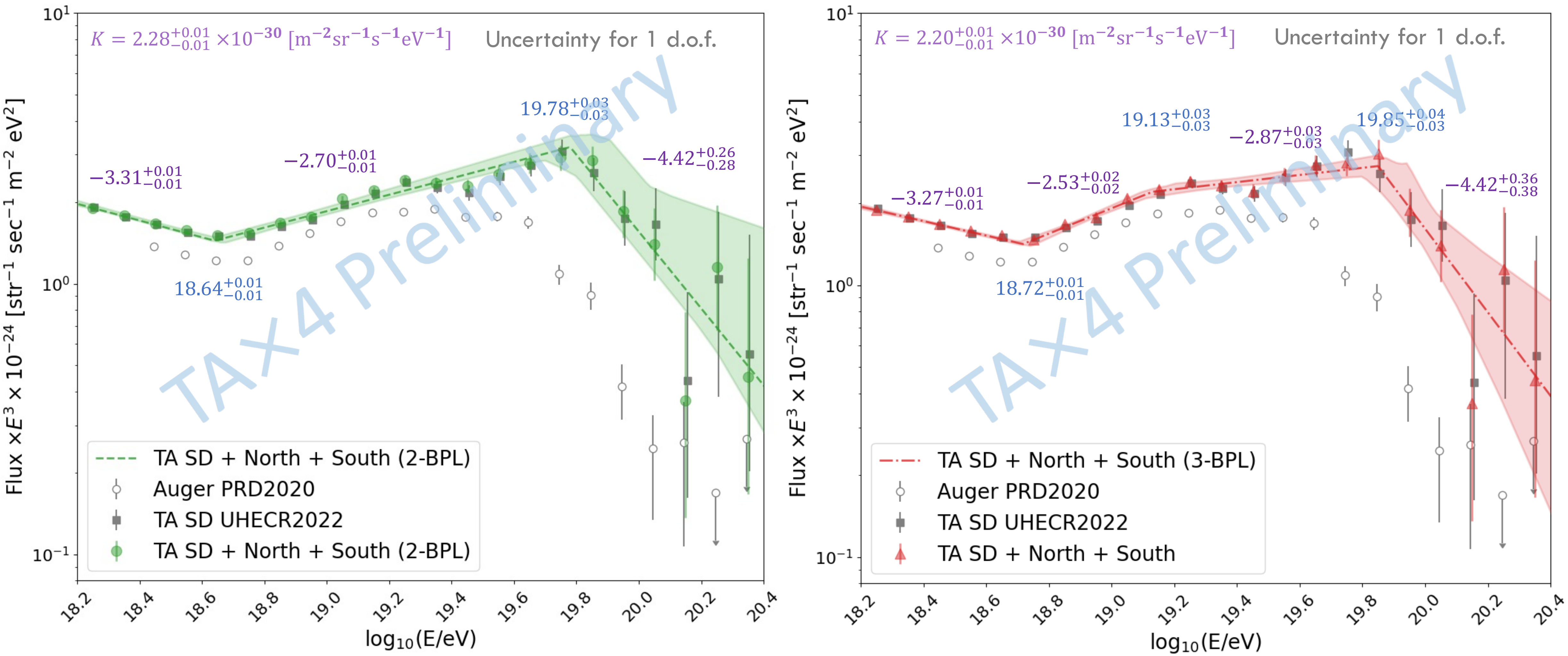
K. Fujisue



- 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 Spectrum: TA SD (14 years) + TA×4 SD (3 years)

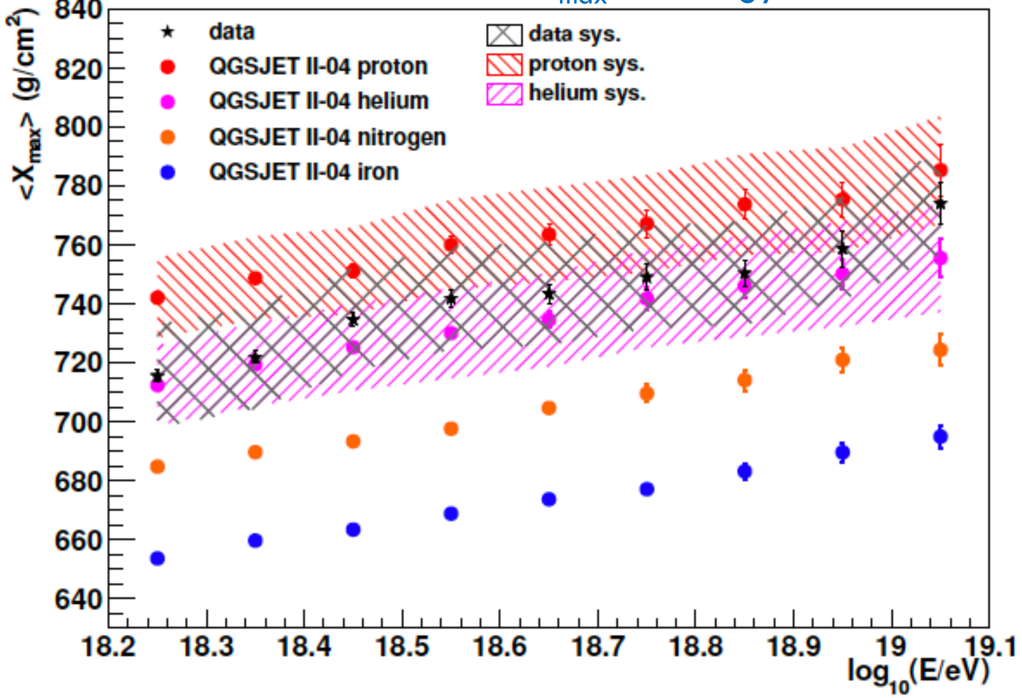
K. Fujisue



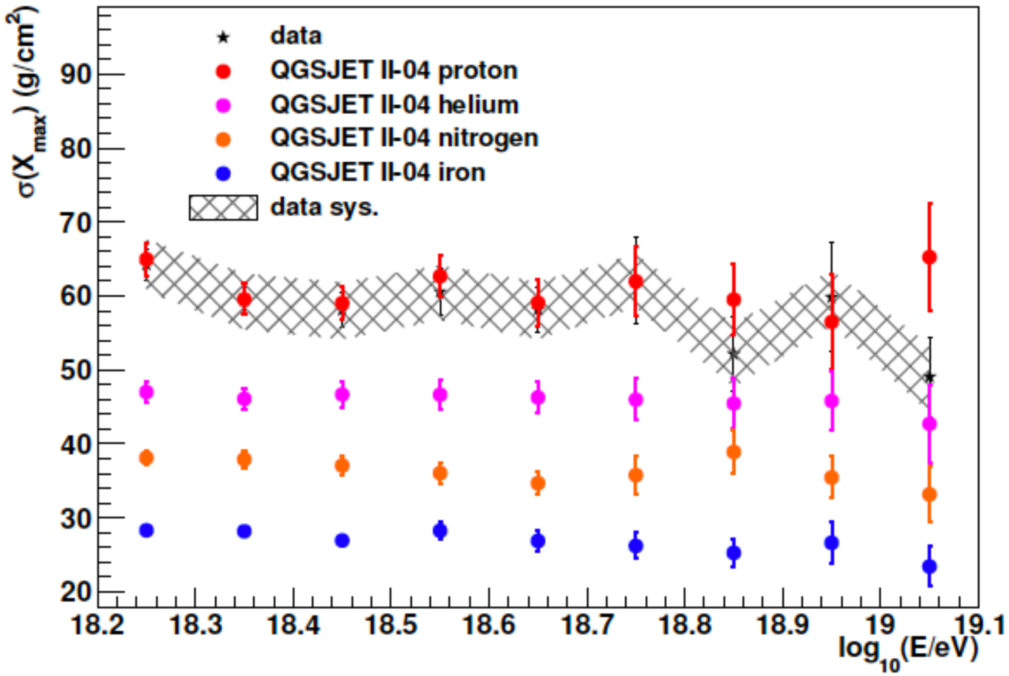
Mass Composition

TA Hybrid 10 years of data

TA Mean X_{max} vs energy



$\sigma(X_{max})$ vs energy

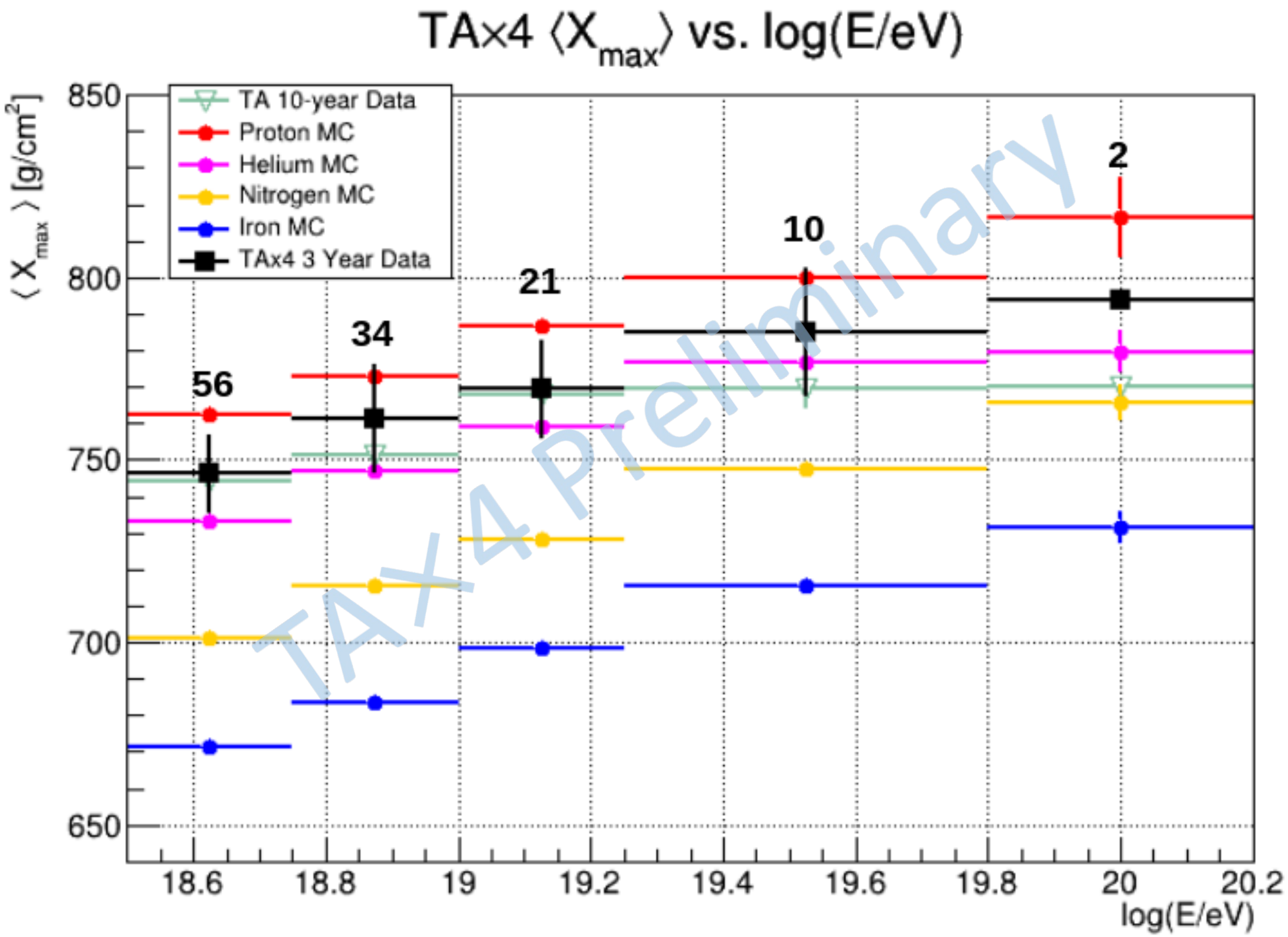


W. Hanlon, PoS(ICRC2019)280

- Energy Range: $10^{18.2}$–$10^{19.1}$ eV
- 3560 events after the quality cuts
- Systematic uncertainty of $\langle X_{max} \rangle$: ± 17 g/cm2
- QGSjetII-04 interaction model was compared with the data
  → agreement with light composition
- More events are needed to study the highest energies
- Work continues with more data and comparisons multiple models

TA×4 Hybrid 3 years of data (November 2020–December 2023)

Z. Gerber, APS April 2024

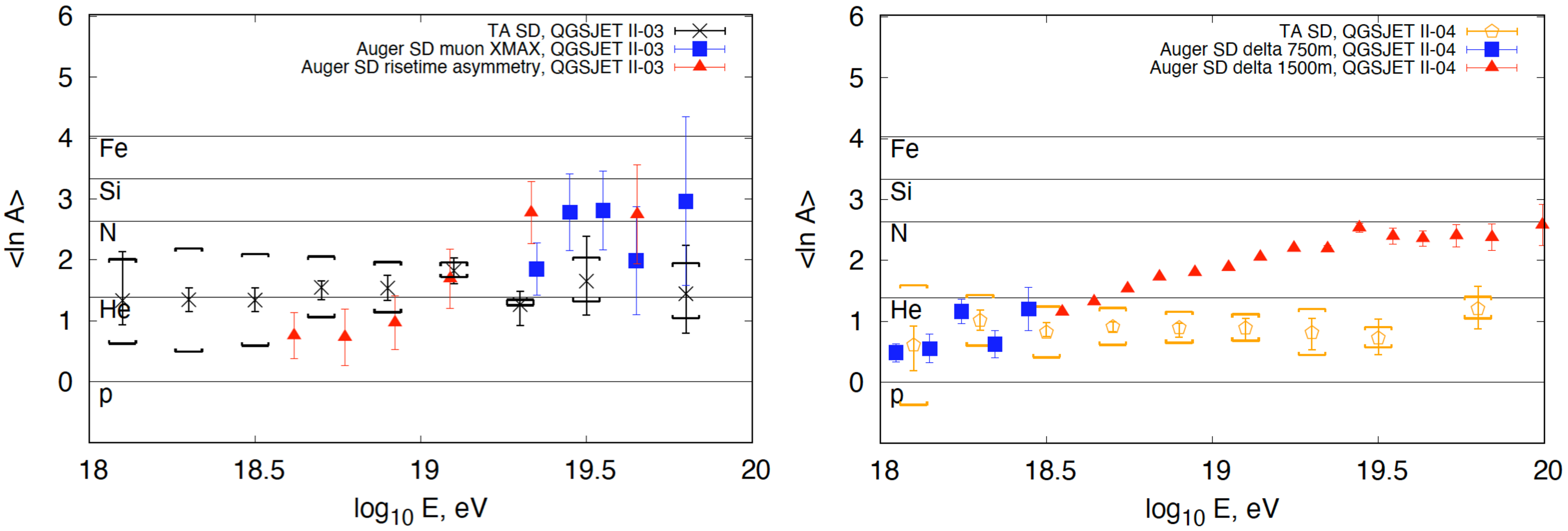


- ⟨X_{max}⟩ values are calculated as a function of energy for data collected for ~3 years.
- These values are compared to Monte Carlo simulations of single-element primary distributions using the QGSJET II-04 hadronic interaction model.
- These results indicate that cosmic ray mass composition is light and unchanging at the highest energies.
- Consistent with the previous results of TA.

TA SD 12 years of data

- Used machine learning technique based on BDT analysis
- Found light, unchanging composition above 10^{18} eV, with two different high-energy interaction models
- Plan to “calibrate” against hybrid data

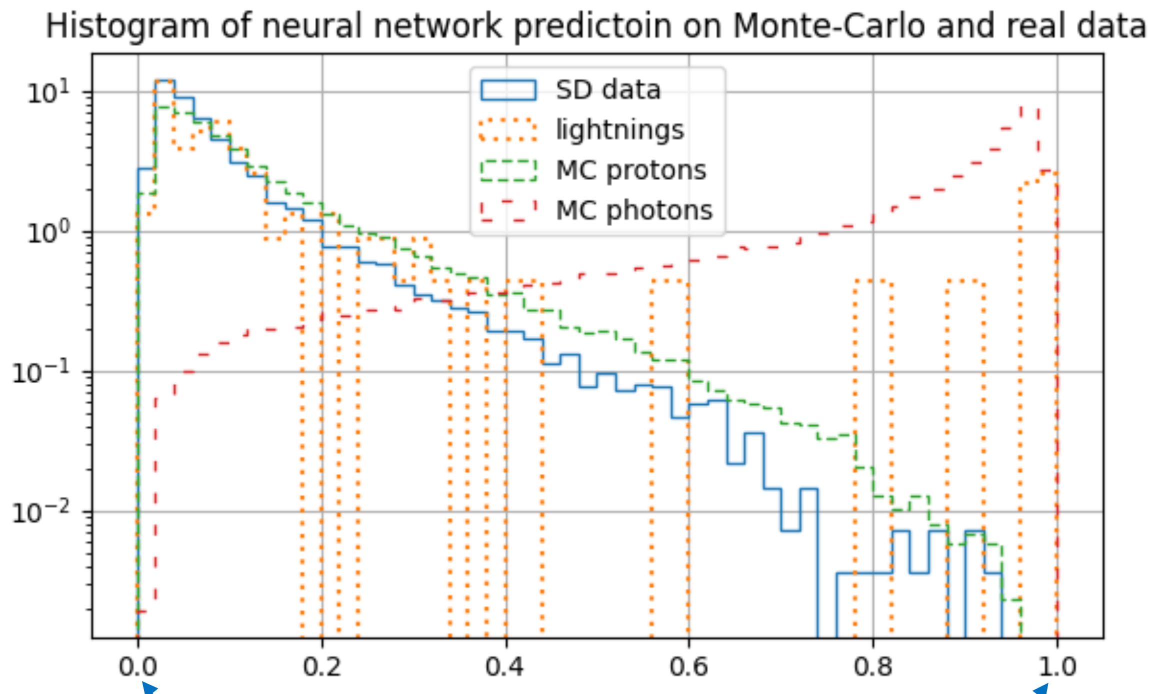
Y. Zhezher, PoS(ICRC2021)300



TA SD UHE Photon Search

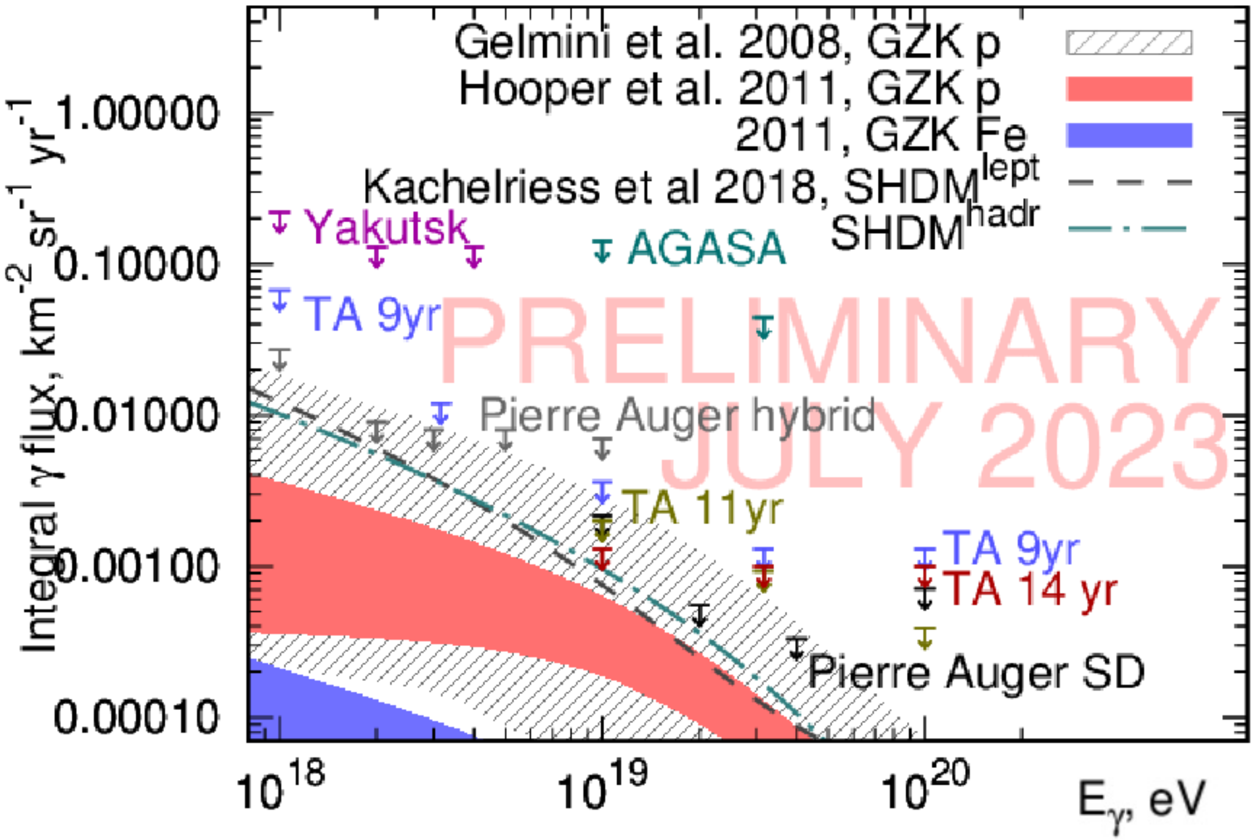
I. Kharuk, PoS(ICRC2023)324

- Neural network trained to classify protons and photons.
- No UHE photons detected but set the upper limits.



proton-induced air showers

photon-induced air showers



Estimation of the photon flux

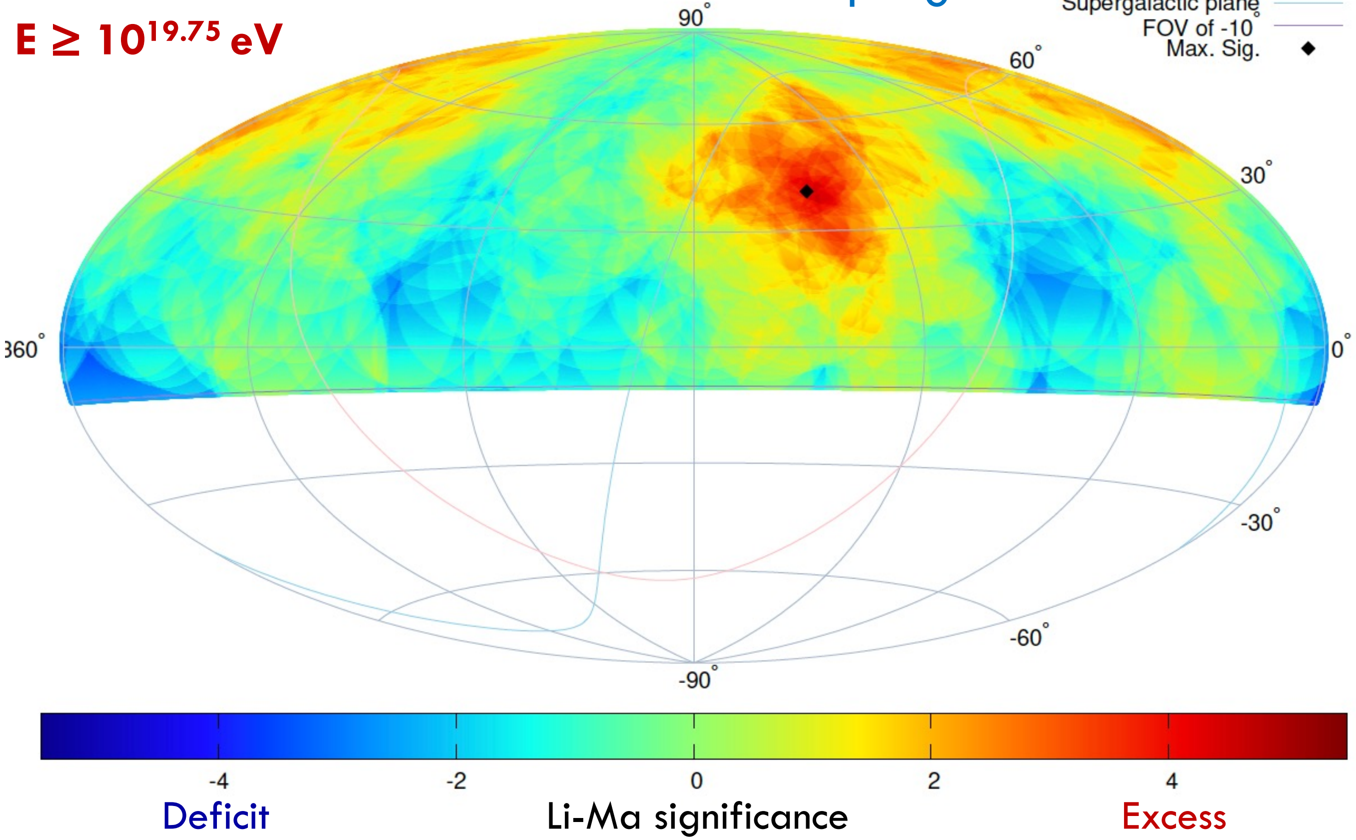
Anisotropies

Intermediate-scale Anisotropy: TA Hotspot

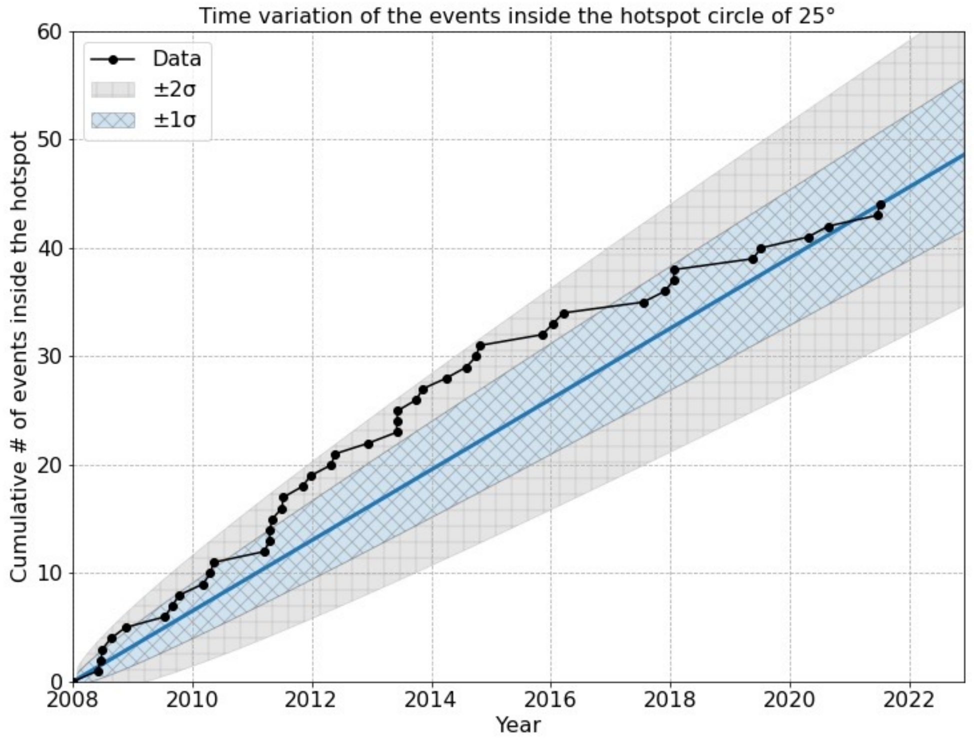
J. Kim, PoS(ICRC2023)244

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.: $P(S_{\mathrm{MC}} > 4.8\sigma) = 2.7\times10^{-3}$ → **2.8σ**



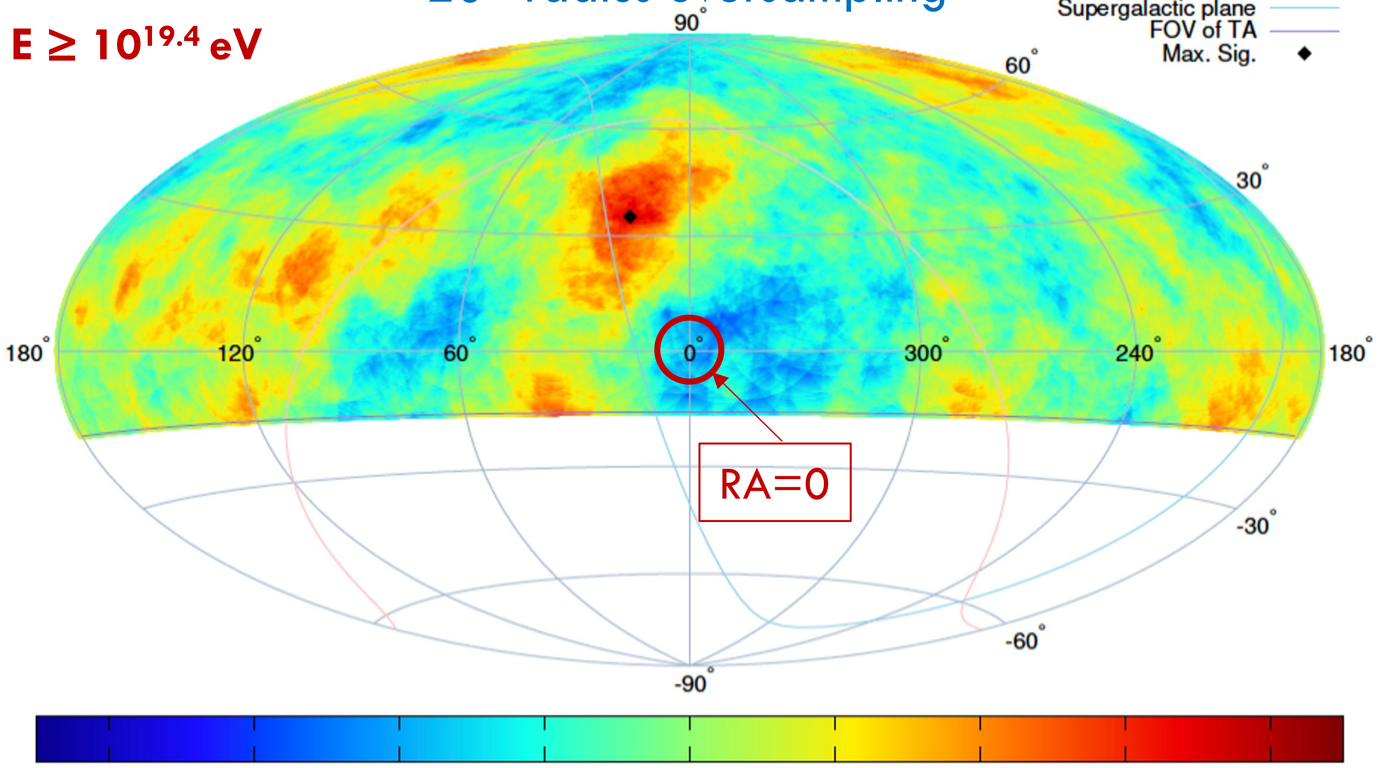
- The increase rate of the events inside the hotspot circle is **consistent with the linear increase within ~2σ.**

PPSC Excess in Slightly Lower Energy Events (1/2)

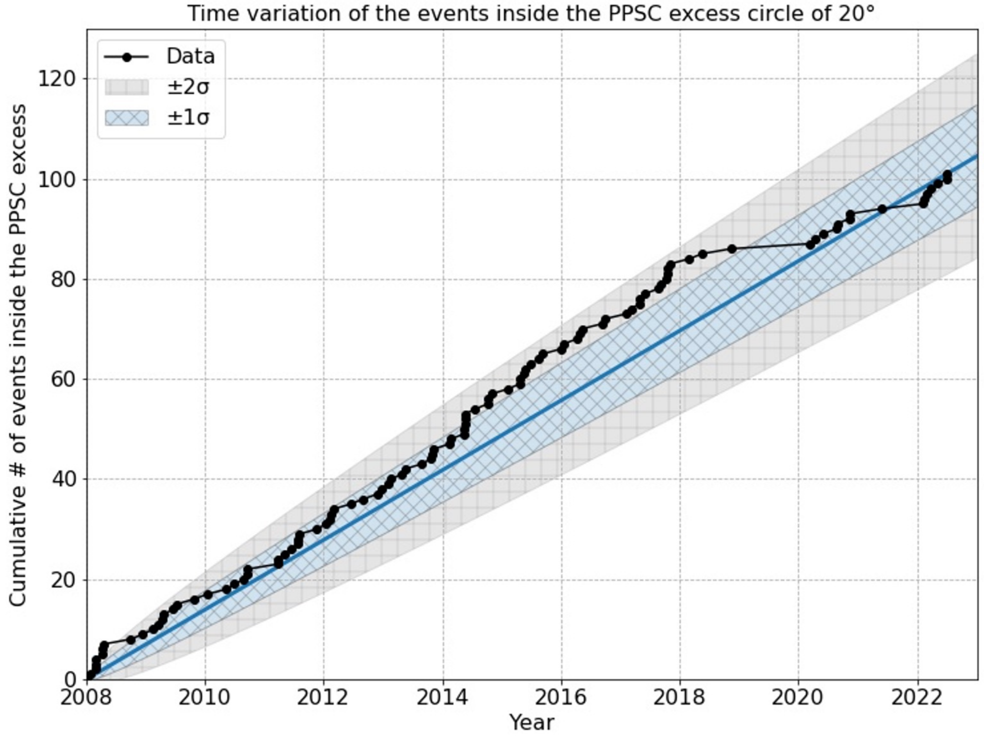
J. Kim, PoS(ICRC2023)244

20°-radius oversampling

E ≥ $10^{19.4}$ eV



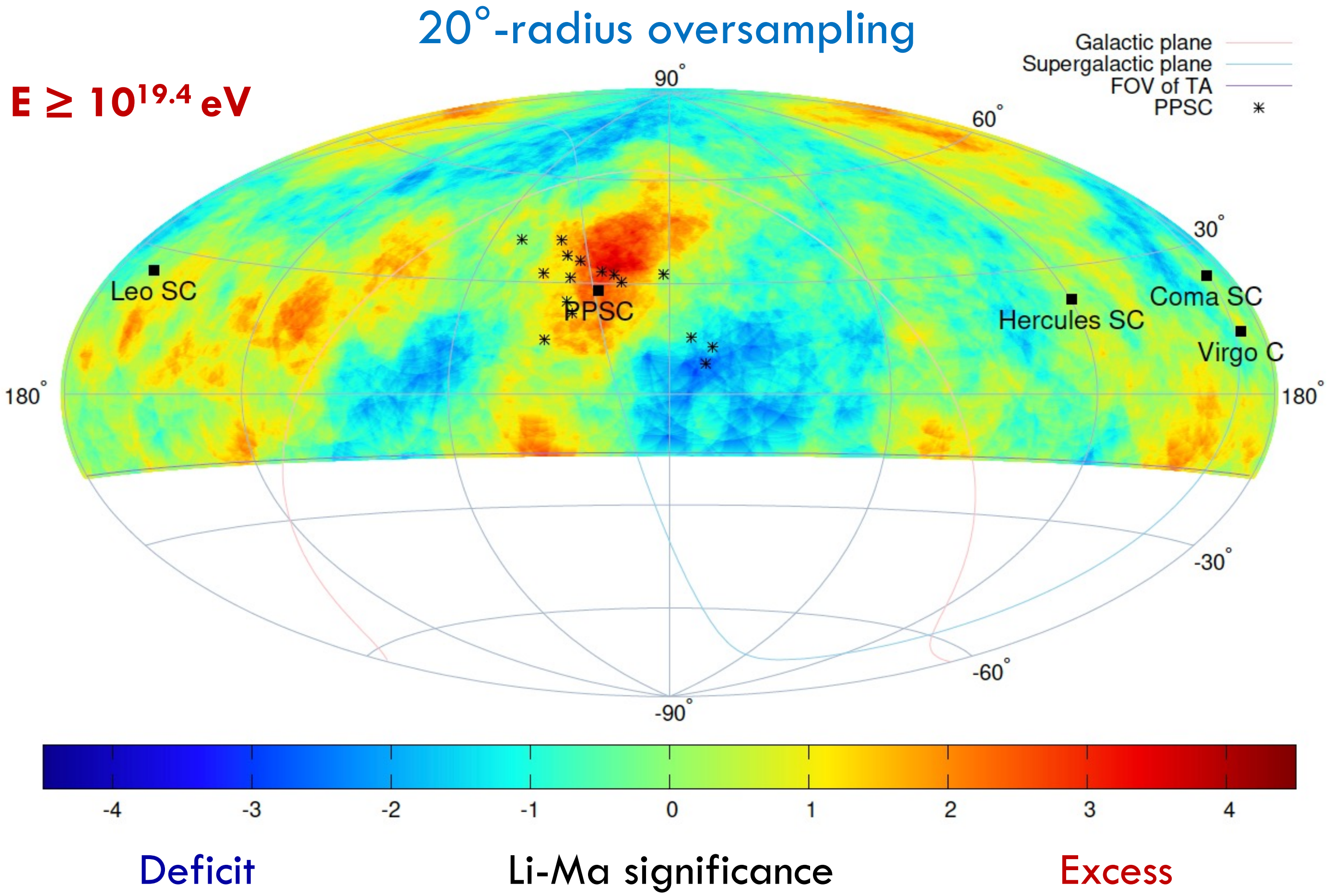
- 1125 events (15-year TA SD data)
- Max local sig.: **4.0σ** at (17.9°, 35.2°)



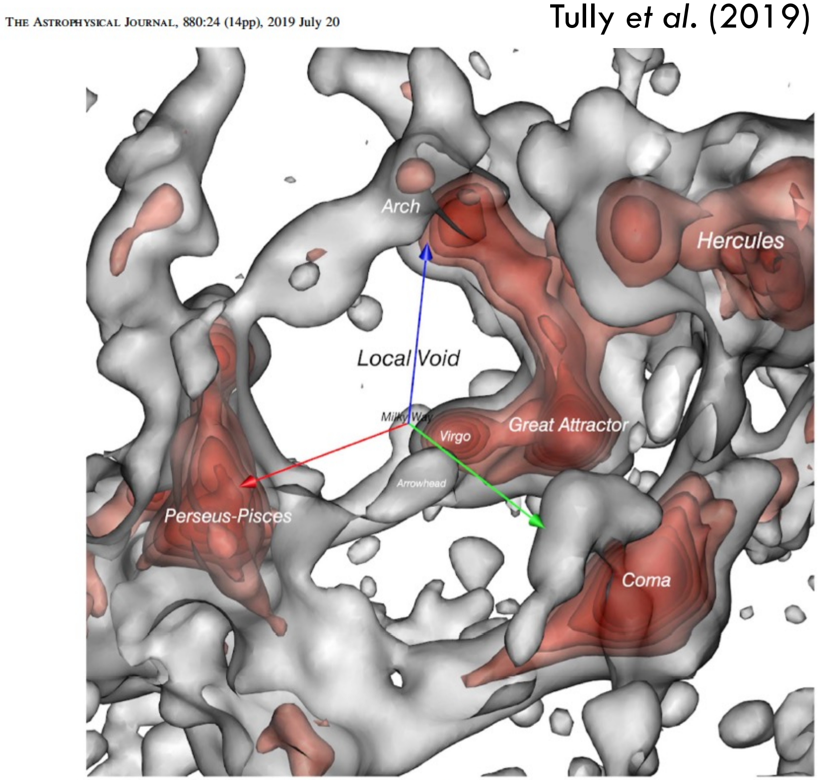
- The increase rate of the events inside the hotspot circle is **consistent with the linear increase within ~2σ.**

PPSC Excess in Slightly Lower Energy Events (2/2)

J. Kim, PoS(ICRC2023)244



Tully *et al.* (2019)



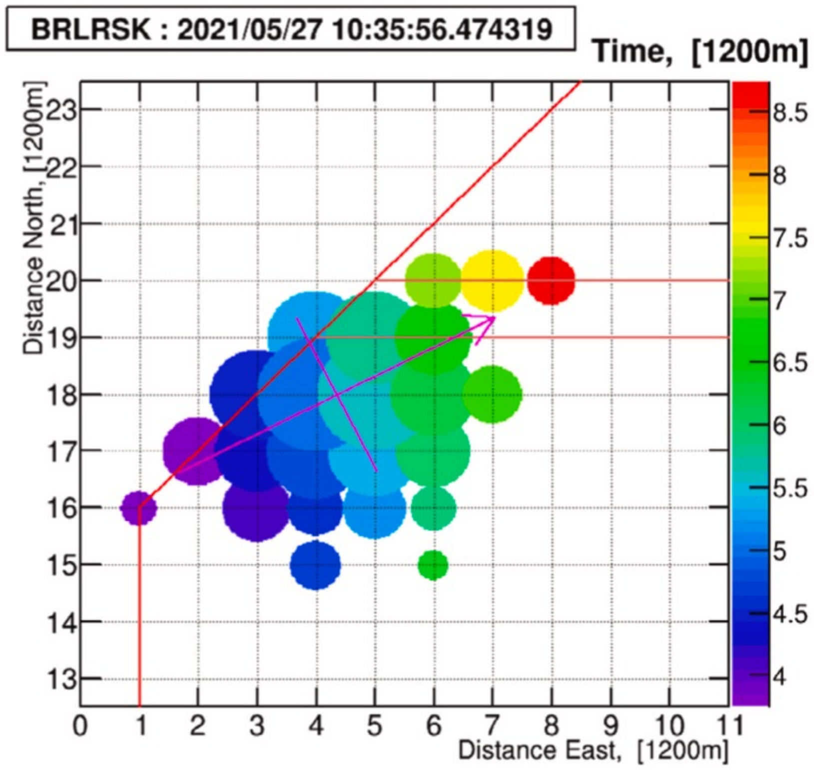
A new excess in slightly lower energy events in the direction of **the Perseus-Pisces supercluster** has been identified. The chance probability of having an excess as close to the PPSC as the data is estimate:

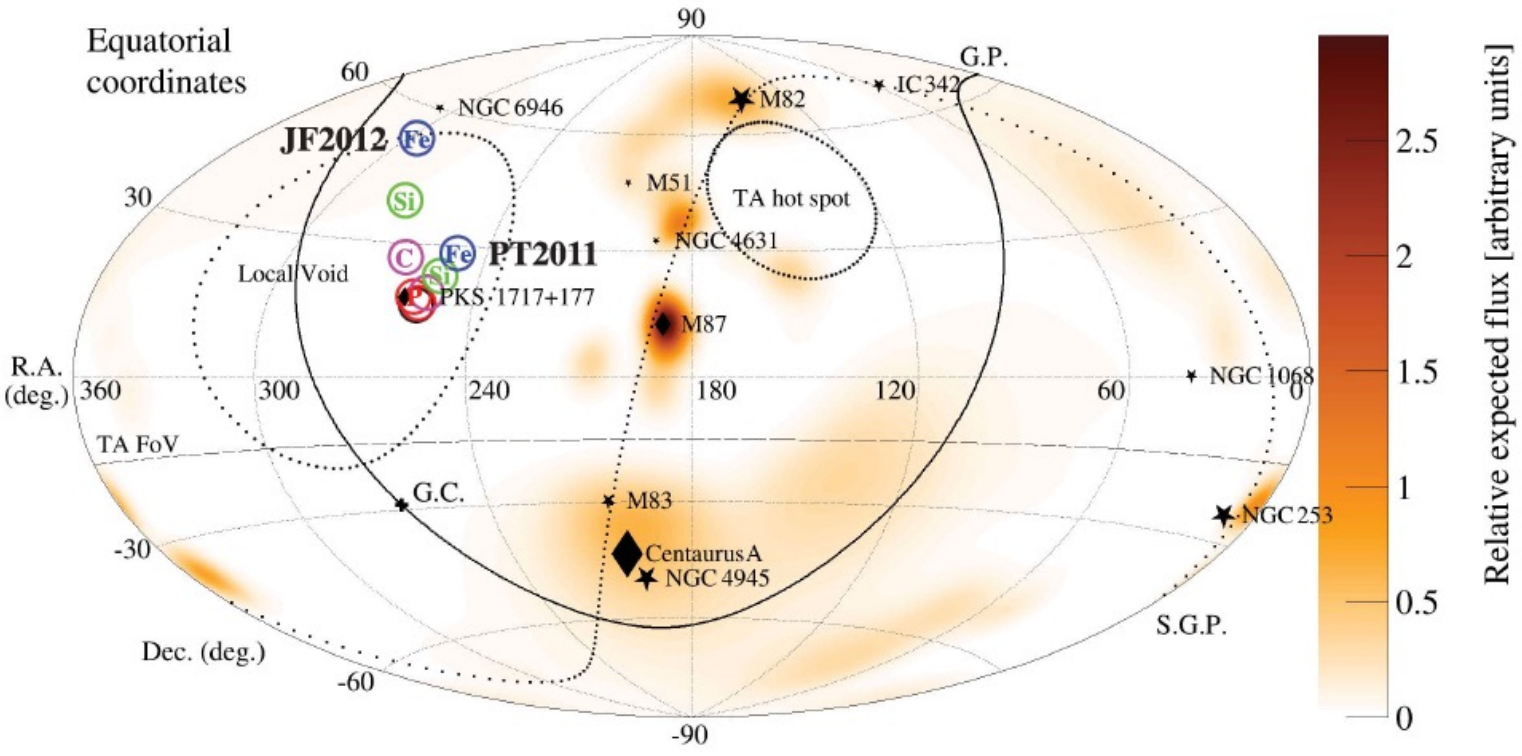
$$(S_{mc} \geq 4.0\sigma) \ \& \ (\theta_{mc} \leq 7.7°) \rightarrow \mathbf{3.3\sigma.}$$

Extremely Energetic Cosmic Ray Observed by TA

- 2021-05-27 10:35:56 UTC, No FD observation
- E = 244±29 EeV in the direction of (255.9°,16.1°) in the equatorial coordinates

Abbasi *et al.*, Science 382, 6673 (2023)





Summary

- **Energy Spectrum**
  - Measured over five orders of magnitude in energy by TALE+TA+TA×4, six spectral features (knee, low energy ankle, second knee, ankle, *instep/shoulder* feature, and cutoff)
  - Found strong evidence of the spectrum anisotropy in the northern hemisphere
  - Observed consistent spectrum from TA×4 SD data with the TA SD measurements
- **Mass Composition**
  - Light and steady in $10^{18.2}$–$10^{19.1}$ eV from TA hybrid data and in 10^{18}–10^{20} eV from TA SD data
  - Measured consistent mass composition results from TA×4 hybrid data
- **Anisotropy**
  - Hotspot persists near the direction of the Ursa Major constellation
  - New excess at slightly lower energy in the direction of the Perseus-Pisces Supercluster
  - An extremely energetic cosmic ray event (~245 EeV) in the direction of the Local Void
- **Future Prospects**
  - Need to improve statistics, especially for anisotropy and composition measurements
  - Complete TA×4 and take more data!!

We hope to better understand the nature and origin of UHECRs, thereby giving us a window to understanding the universe.

Thank you!