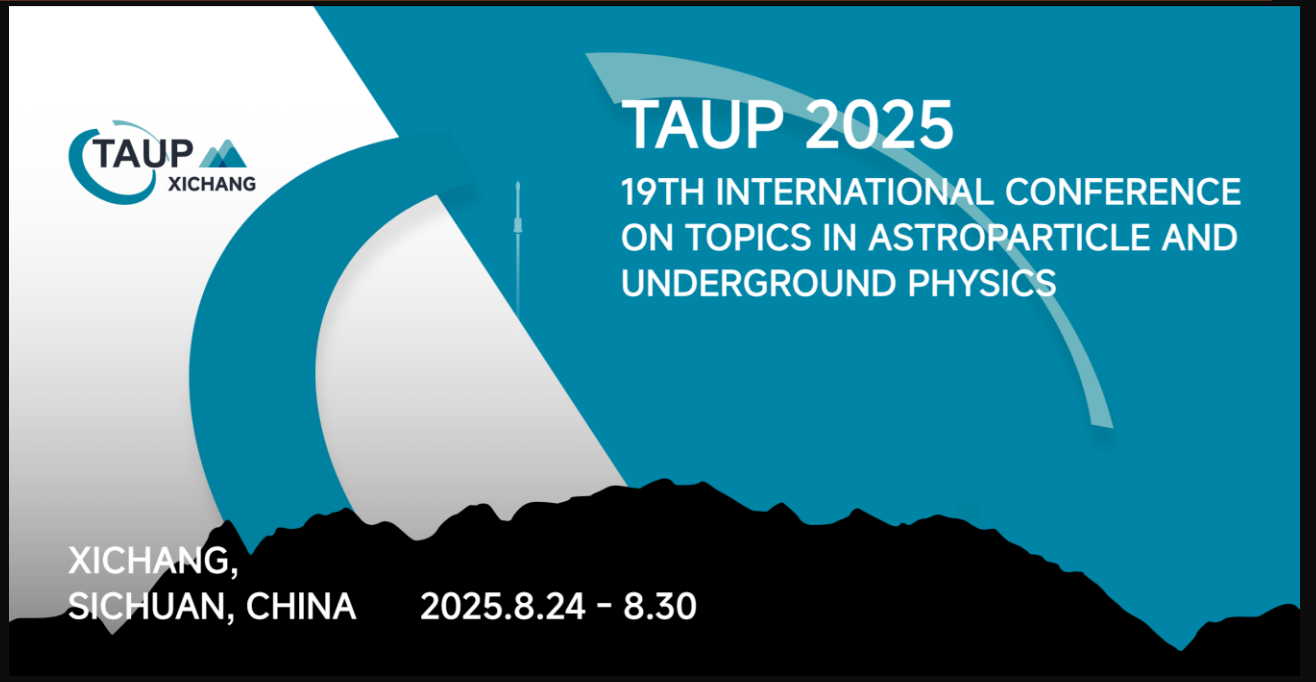
Recent Highlights from the Telescope Array

E. Kido on behalf of the

Telescope Array Collaboration



Outline

- Overview of the Telescope Array (TA) experiment
  - TA detectors
  - Extension to the lower energies (TALE) and higher energies (TAx4)
- Latest results
  - Energy spectrum
  - Anisotropy
  - Mass composition
- Summary

Telescope Array Collaboration

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30 institutions, 129 collaborators

TA detectors

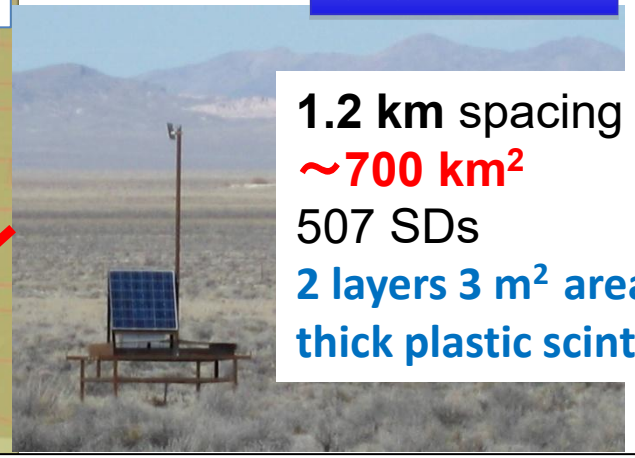
FD station

MDFD

TALE
SD array

SD array

Surface Detector (SD)



1.2 km spacing
~700 km²
507 SDs
2 layers 3 m² area 1.2 cm thick plastic scintillators

Latitude **39.30° N**
Longitude **112.91° W**
Height: 1382 m

CLF

LRFD

28km

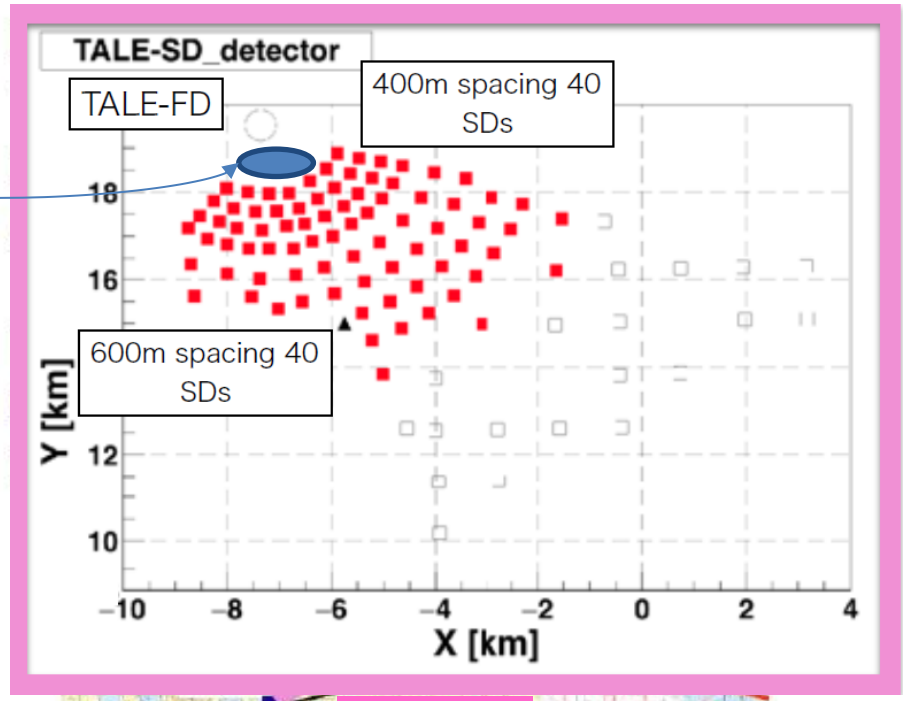
BRFD

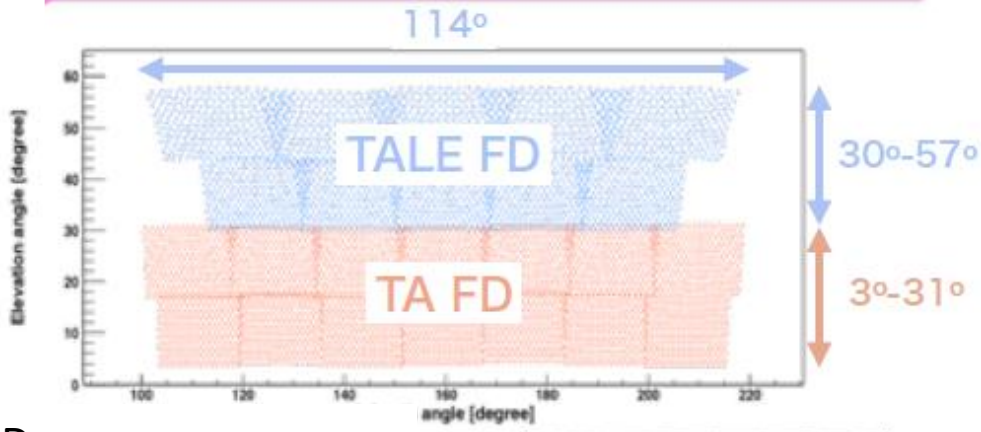
- **Largest cosmic-ray observatory in the northern hemisphere**
- **"Hybrid" observation**
  "Hybrid": SDs and FDs are simultaneously used to detect the same cosmic ray event.

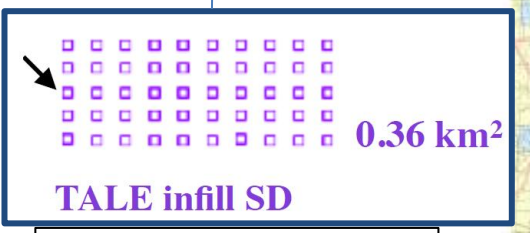
Fluorescence Detector (FD) station

Full operation since May **2008** @ **Utah, USA**

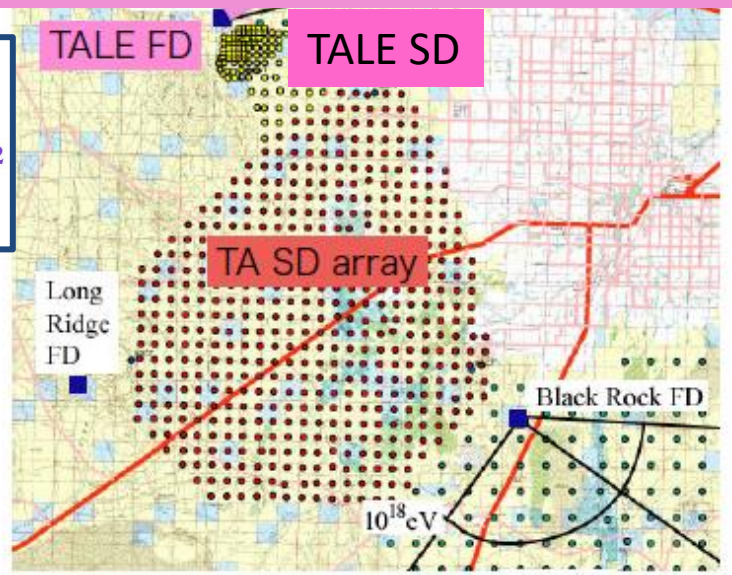
TALE (TA Low-energy Extension) Detectors







100m spacing
50 new SDs
Operation since
Oct. 2023



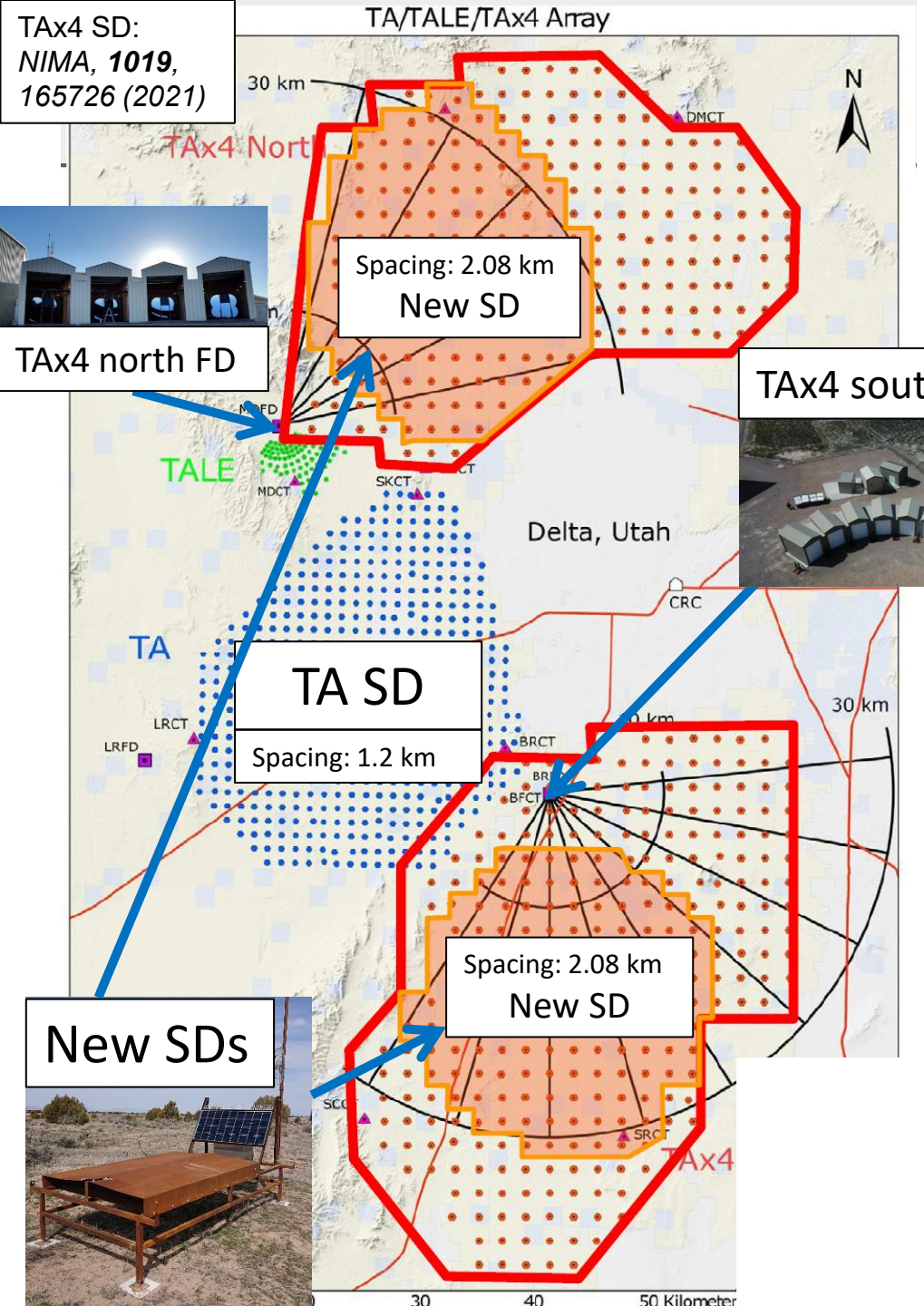
TALE FD was
installed in Nov. 2012

Operation since Sep. 2013

- **Extension for cosmic rays with lower energies**
- **Dense SD array**
  spacing: 100 m, 400 m, and 600 m
- **FD for higher elevation angles**
- **Hybrid observation by SD and FD since 2018.**

TAx4 SD:
NIMA, ***1019***, *165726 (2021)*

The TAx4 experiment



TAx4 was developed to accelerate the pace of data collection at the highest energies.

500 new SDs with **2.08 km** spacing (TASD: 1.2 km spacing)

New SDs and TA SDs plan to cover

4 × TA SD detection area (**~2800 km²**)

More than half of the new SDs (**257 SDs**) were deployed in 2019.

Deployed SDs are running stably since Nov. 2019.

Current detection area **~1700 km²**.

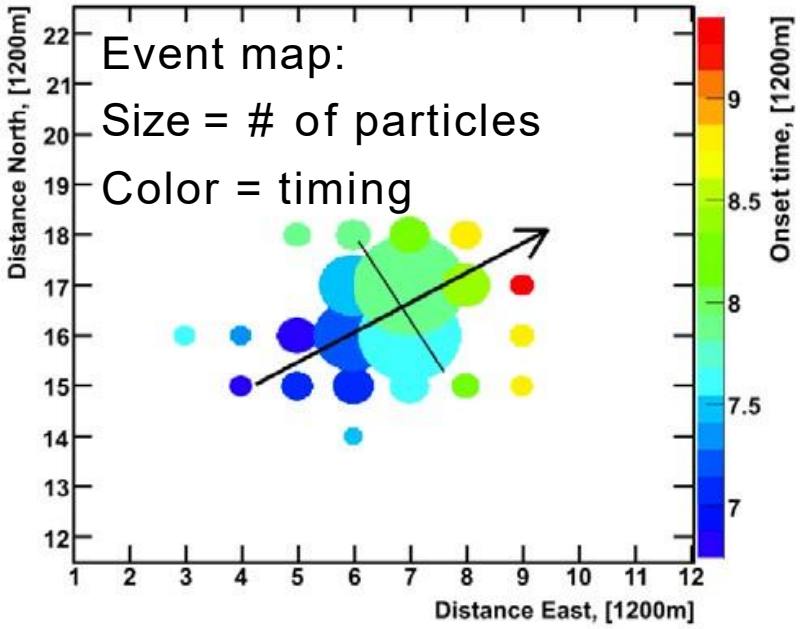
Two new Fluorescence Detector (FD) stations (4+8 HiRes Telescopes)

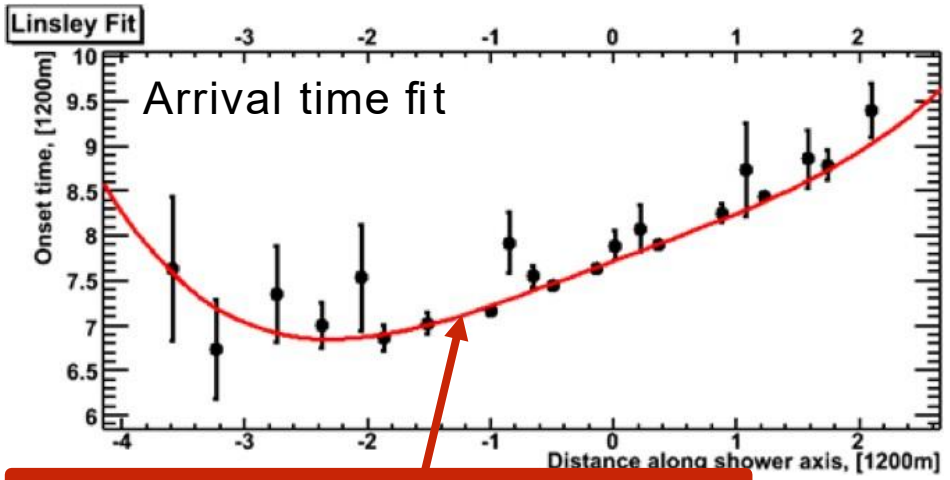
FD(north): stable run since Jun. 2018.

FD(south): stable run since Sep. 2020.

- **Extension for cosmic rays with higher energies**
- **Sparse SD array (spacing: 2.08 km)**
- **Two new FD stations**
- **Hybrid observation by SD and FD**

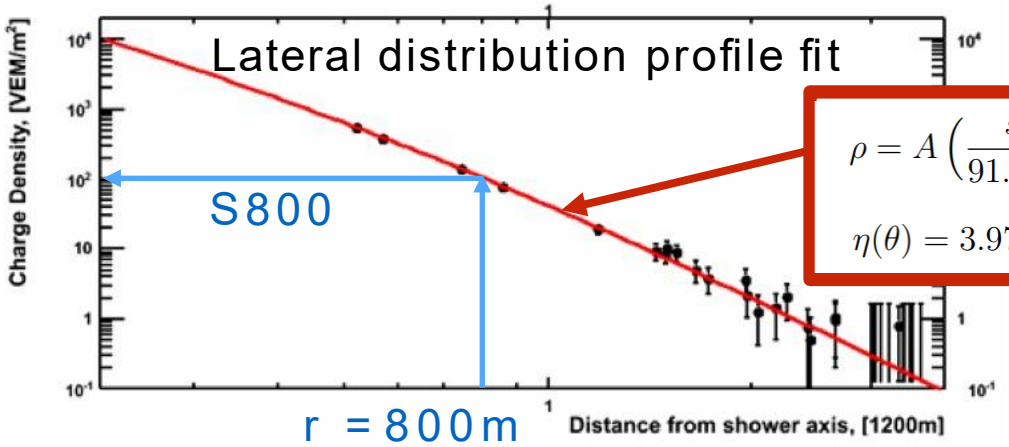
Event reconstructions with SDs





$$\tau = a\left(1-\frac{l}{12\times10^{3}\mathrm{m}}\right)^{1.05}\left(1.0+\frac{s}{30\mathrm{m}}\right)^{1.35}\rho^{-0.5}$$

Timing fit (modified Linsley)
-> shower geometry



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

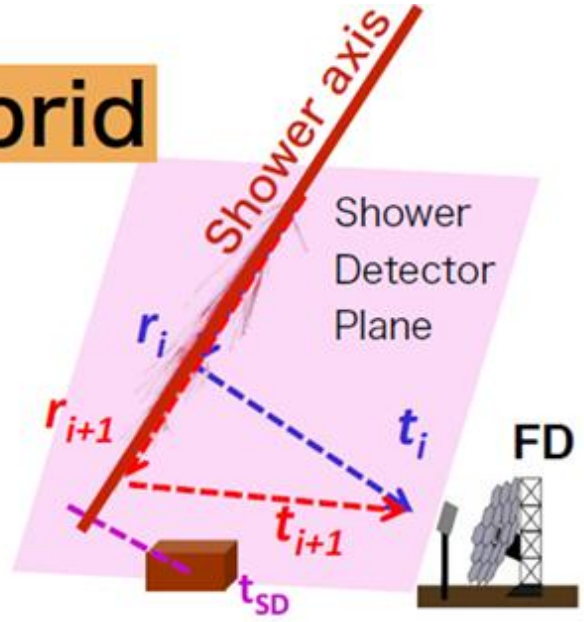
$$\eta(\theta) = 3.97 - 1.79\left[\sec(\theta)-1\right]$$

S800 -> primary energy

TAx4 SD (2.08 km spacing):
combined fit of timing and lateral

Event reconstructions with FDs

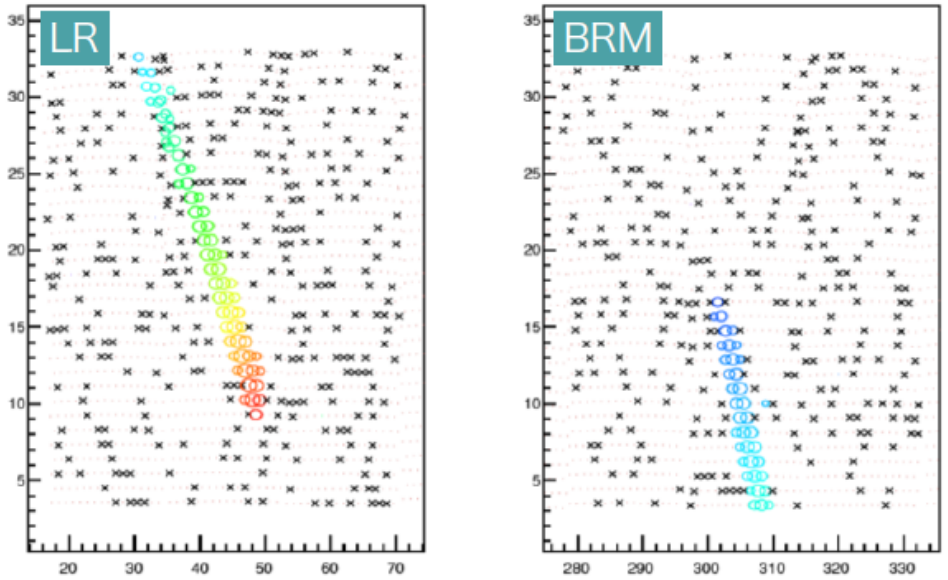
Hybrid



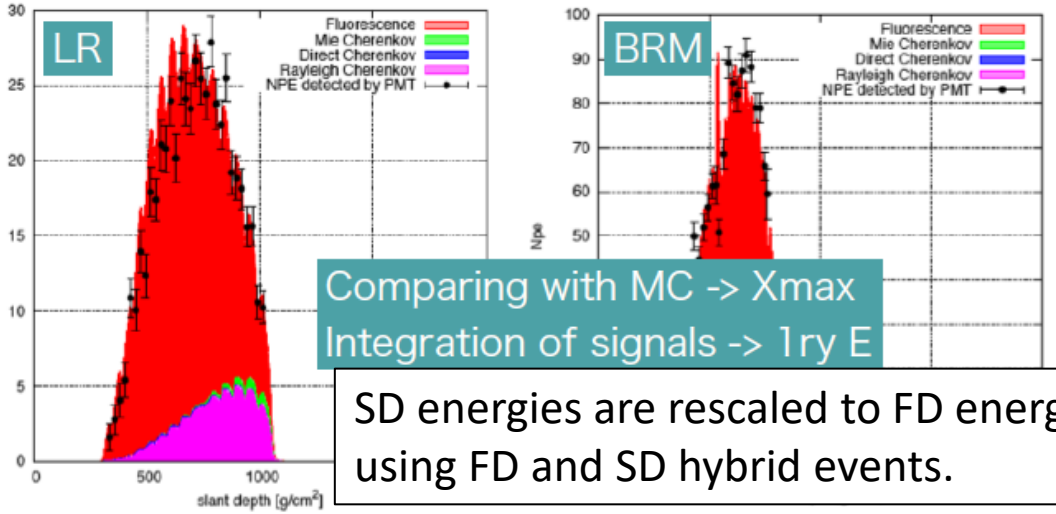
Schematic view of an event reconstruction of a hybrid event

"Mono" analysis:
analysis using only FD data

observed images



reconstructed shower profiles



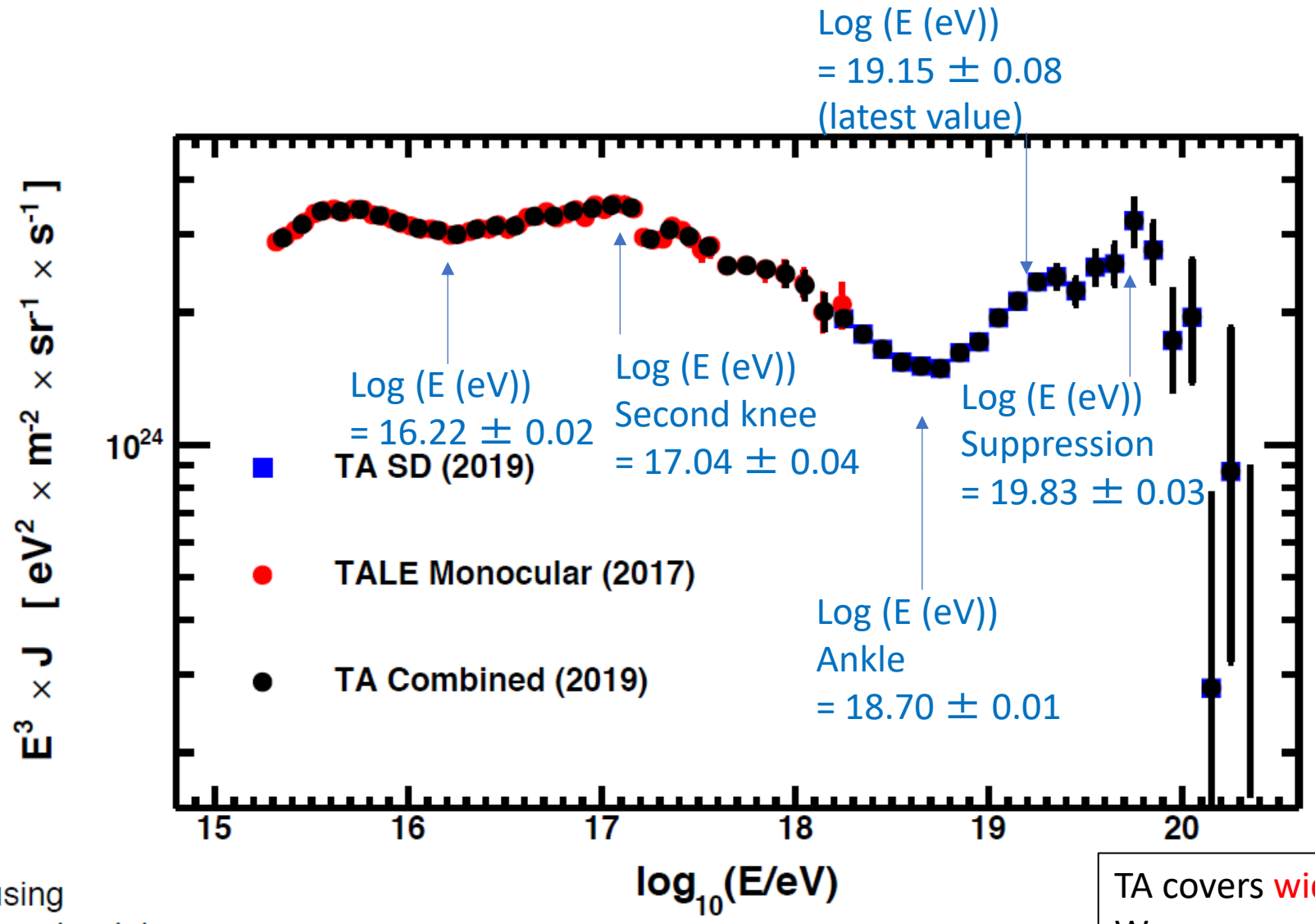
Comparing with MC -> Xmax
Integration of signals -> 1ry E

SD energies are rescaled to FD energies using FD and SD hybrid events.

Energy Spectrum

TA SD + TALE FD combined energy spectrum

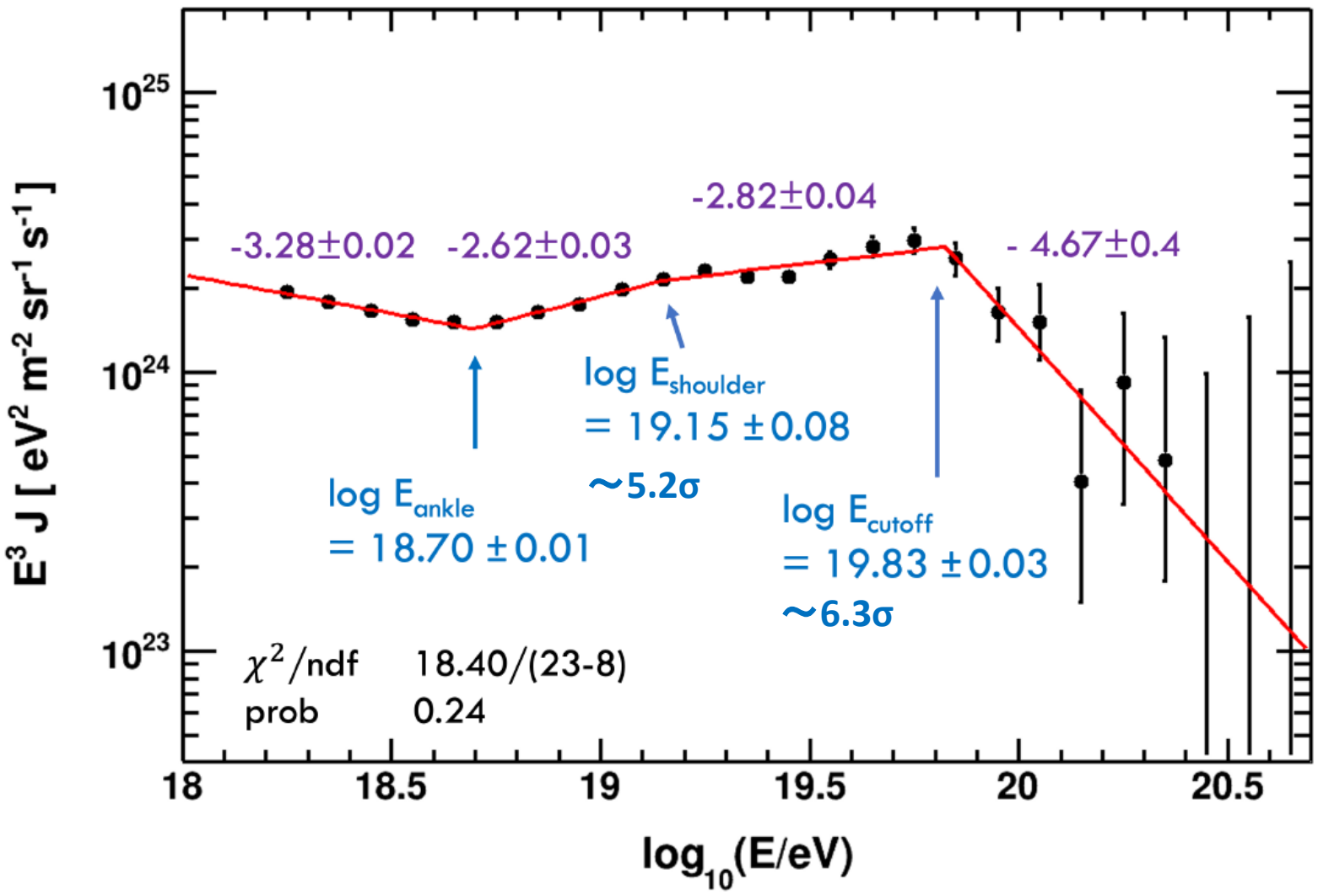
D. Ivanov, ICRC2019



Combined TA spectrum using
22 months TALE FD monocular data +
11 years TA SD data

TA covers wide energy range.
We can see several breaks
in the energy spectrum.

TA SD energy spectrum

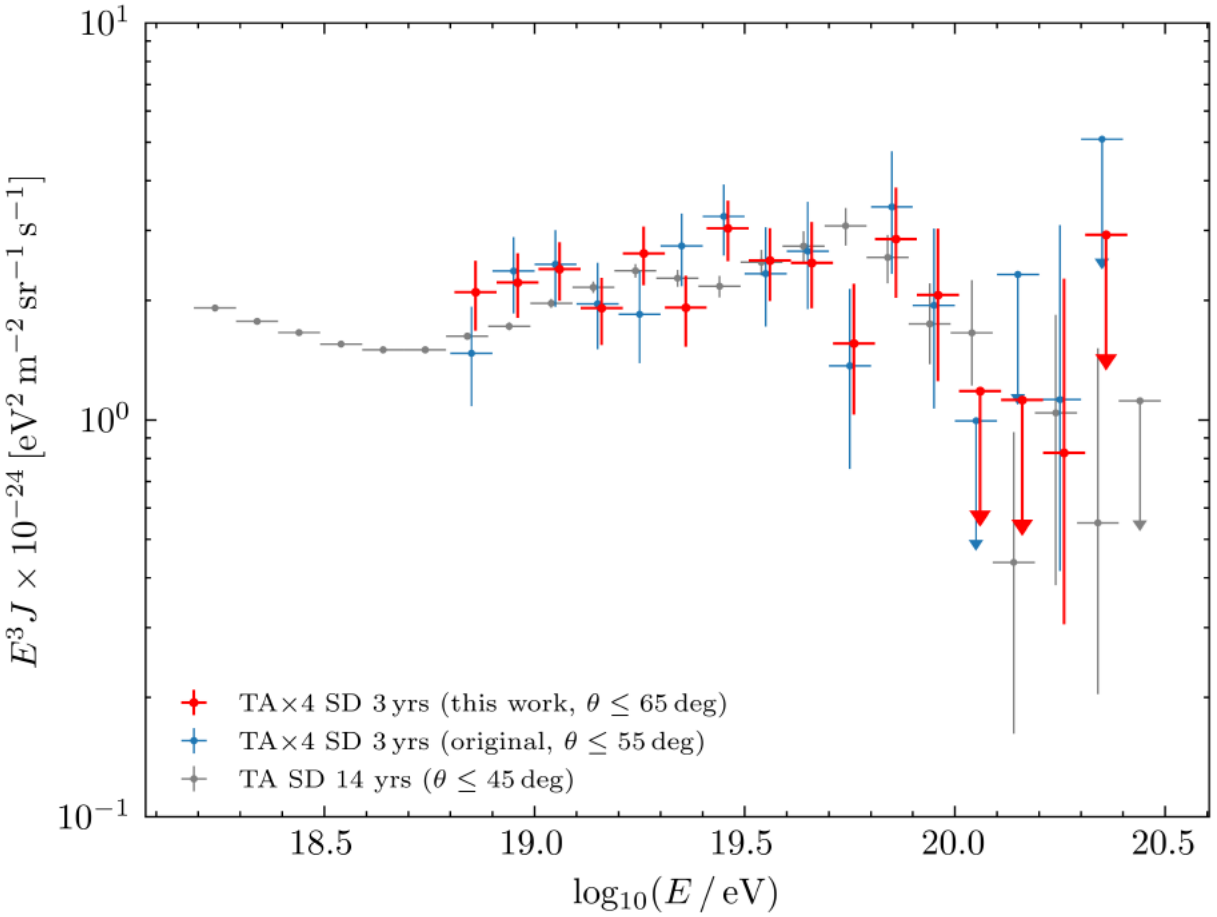


J. Kim, ICRC2025

- 16 years TA SD data
  - 2008-05-11 – 2024-05-10
- Three breaks are detected above 1 EeV.

TAx4 SD energy spectrum

C. Koyama,
ICRC2025

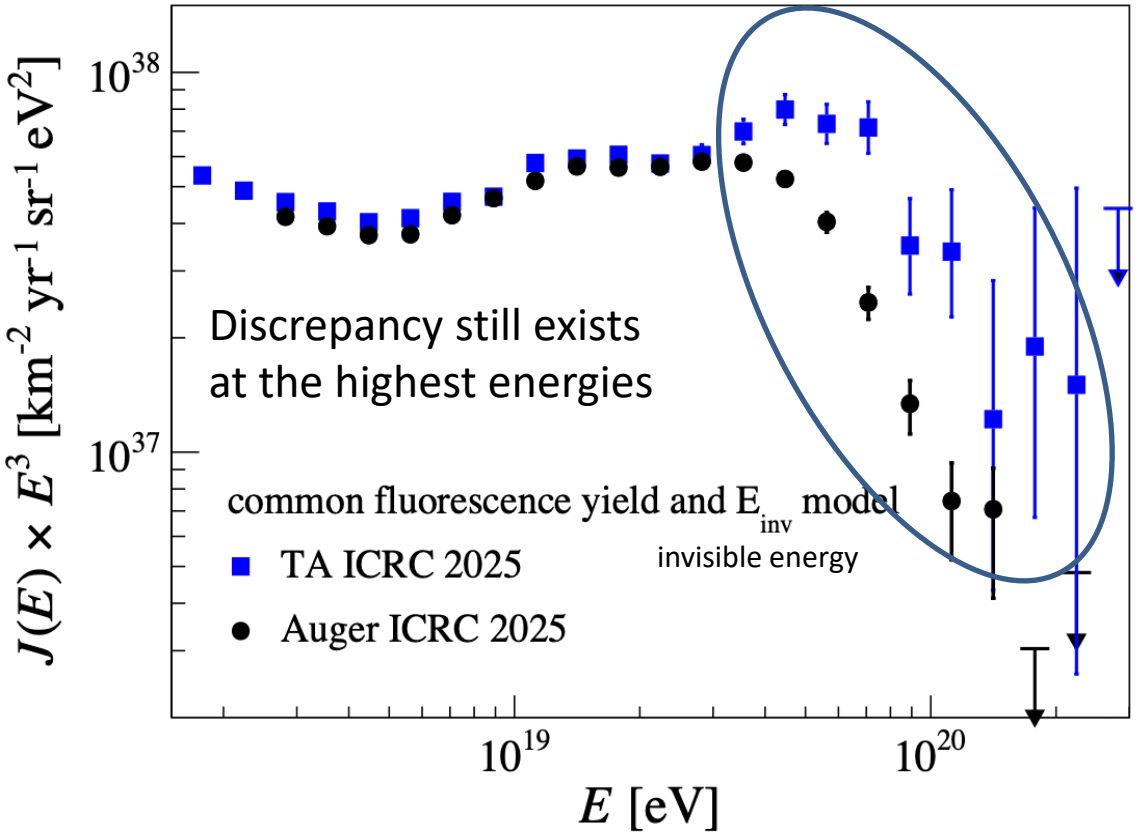


- 3 years TAx4 SD (2.08 km spacing) data
  - Oct. 2019 – Sep. 2022
- Reasonable agreement of the geometry between data and MC simulations.
- Event reconstructions with inclined shower (55-65 deg.) are newly included.
- Consistent with TA SD energy spectrum.

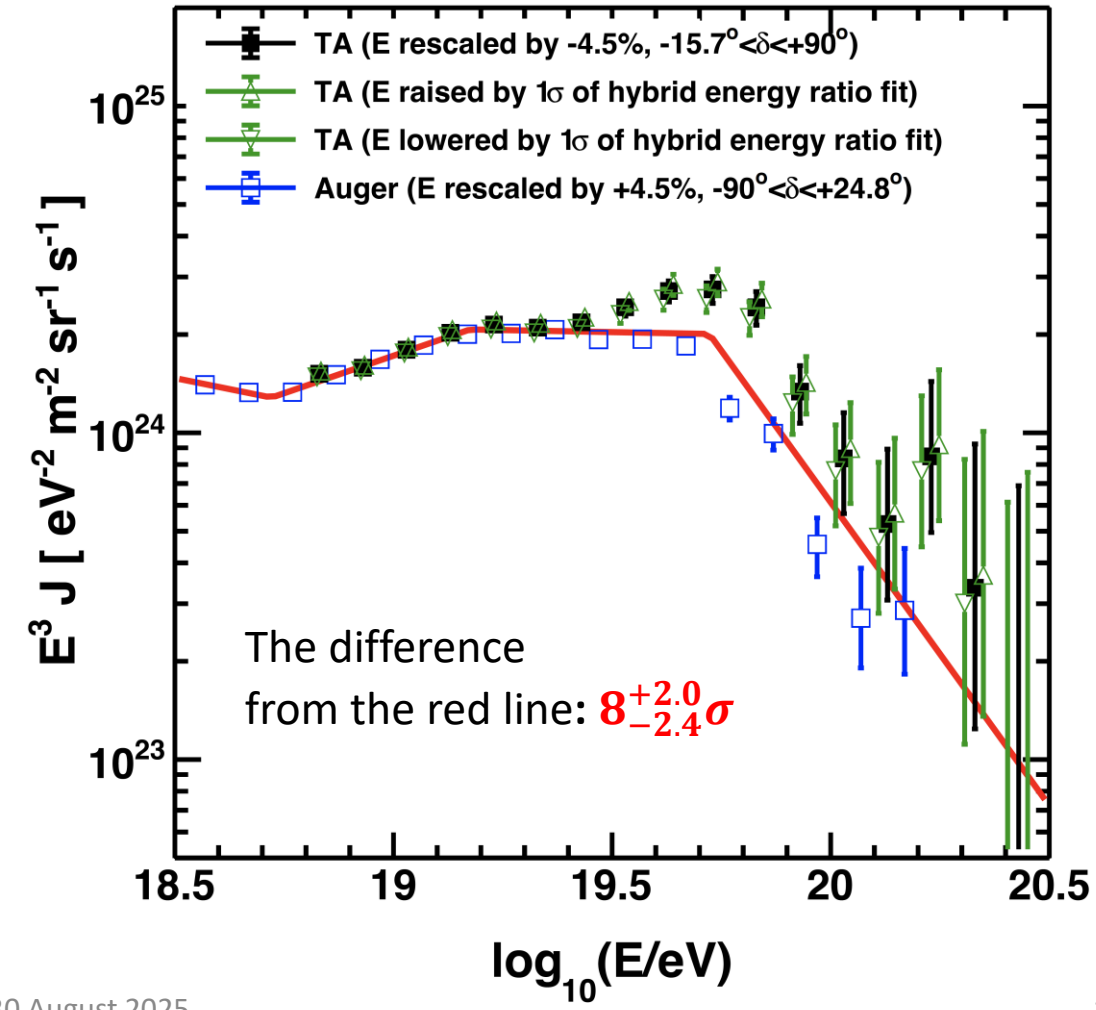
Comparison of TA SD energy spectra

F. Salamida, ICRC2025

Auger+TA spectrum working group

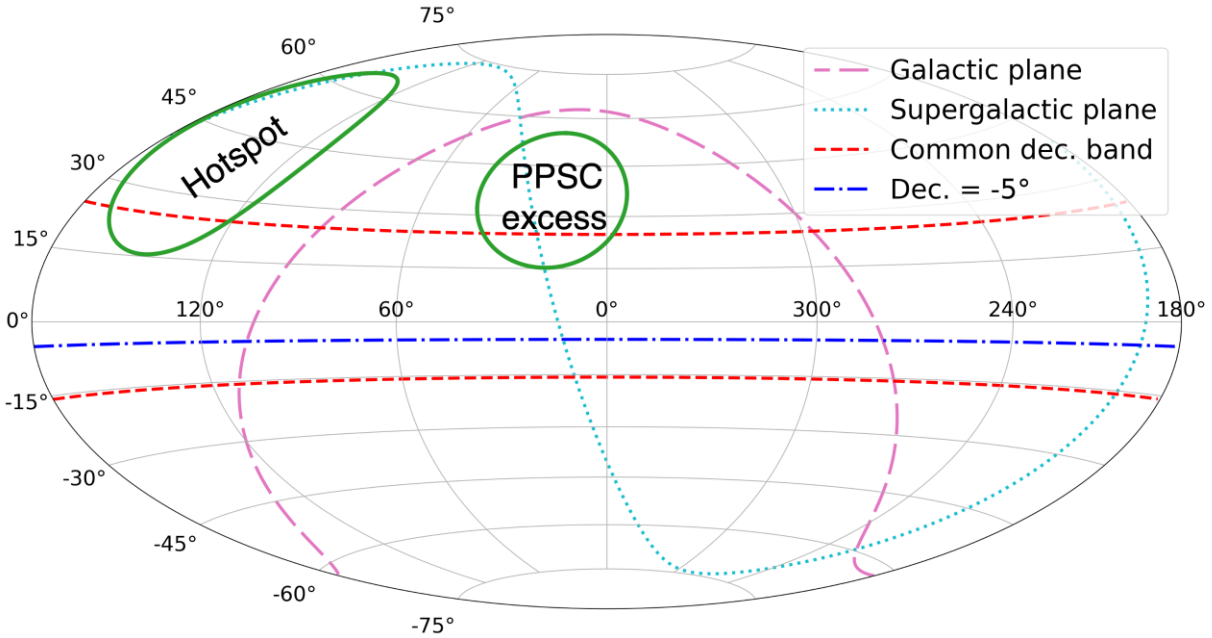


J. Kim, ICRC2025

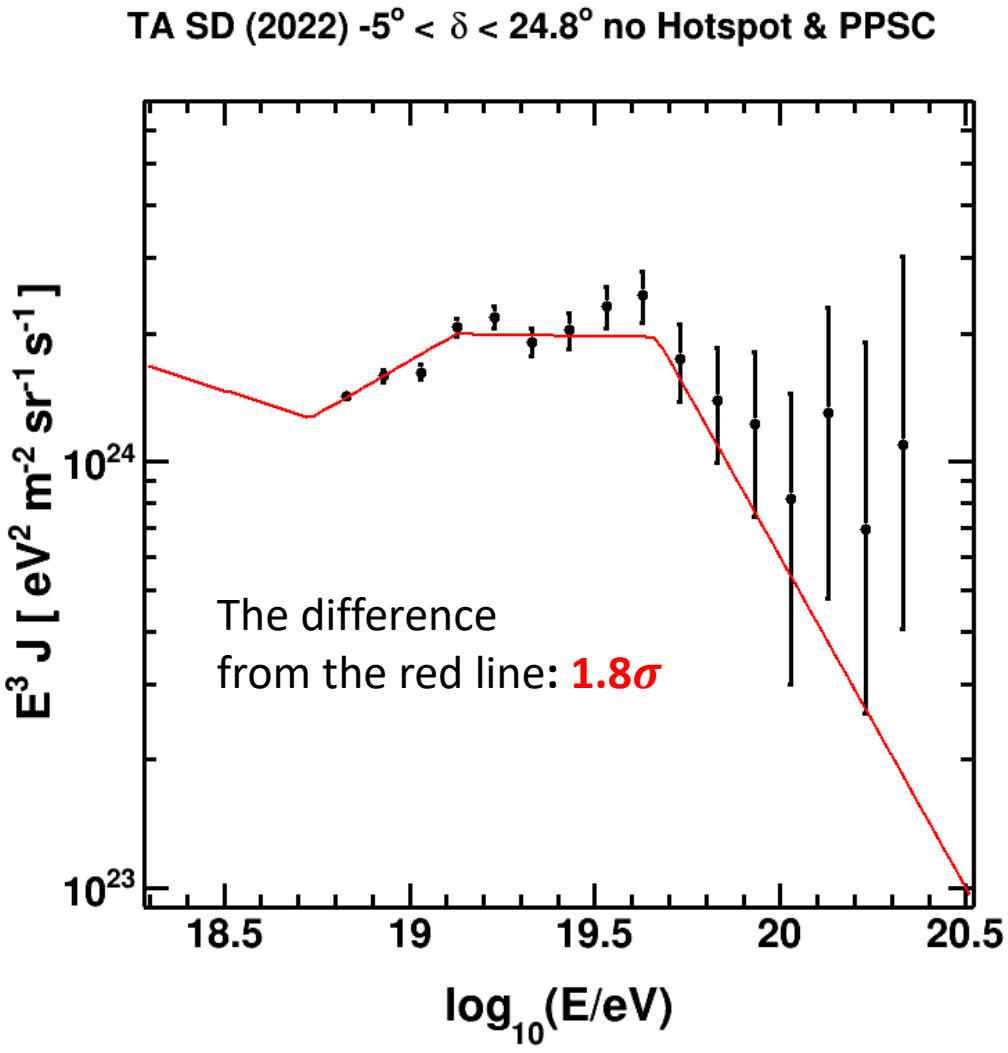


Energy spectrum in -5° < δ < 24.8° + excess region cuts

J. Kim,
ICRC2025

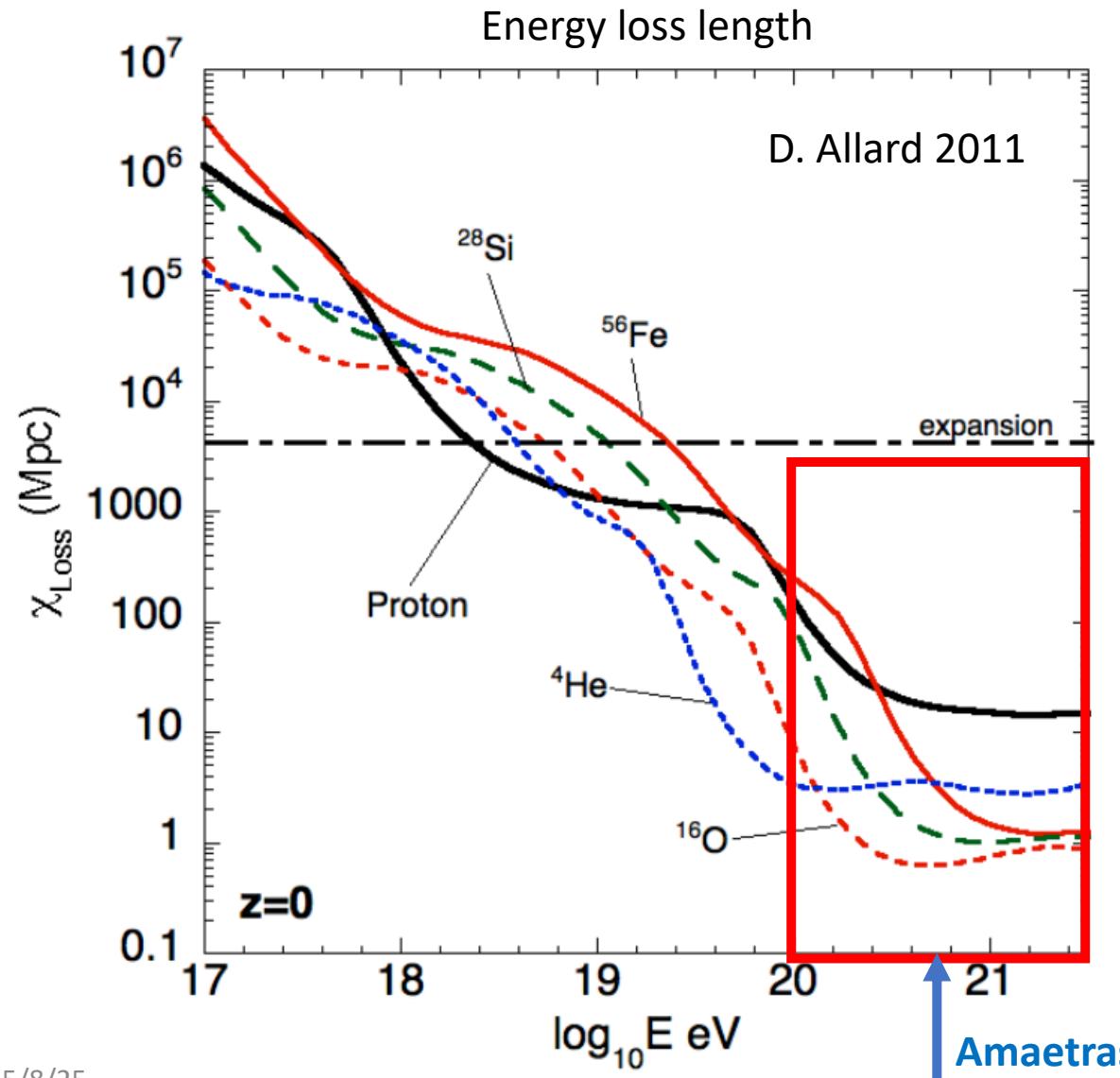


Hotspot and PPSC excess will be shown in the later slide.



Anisotropy

Energy loss length of UHECRs

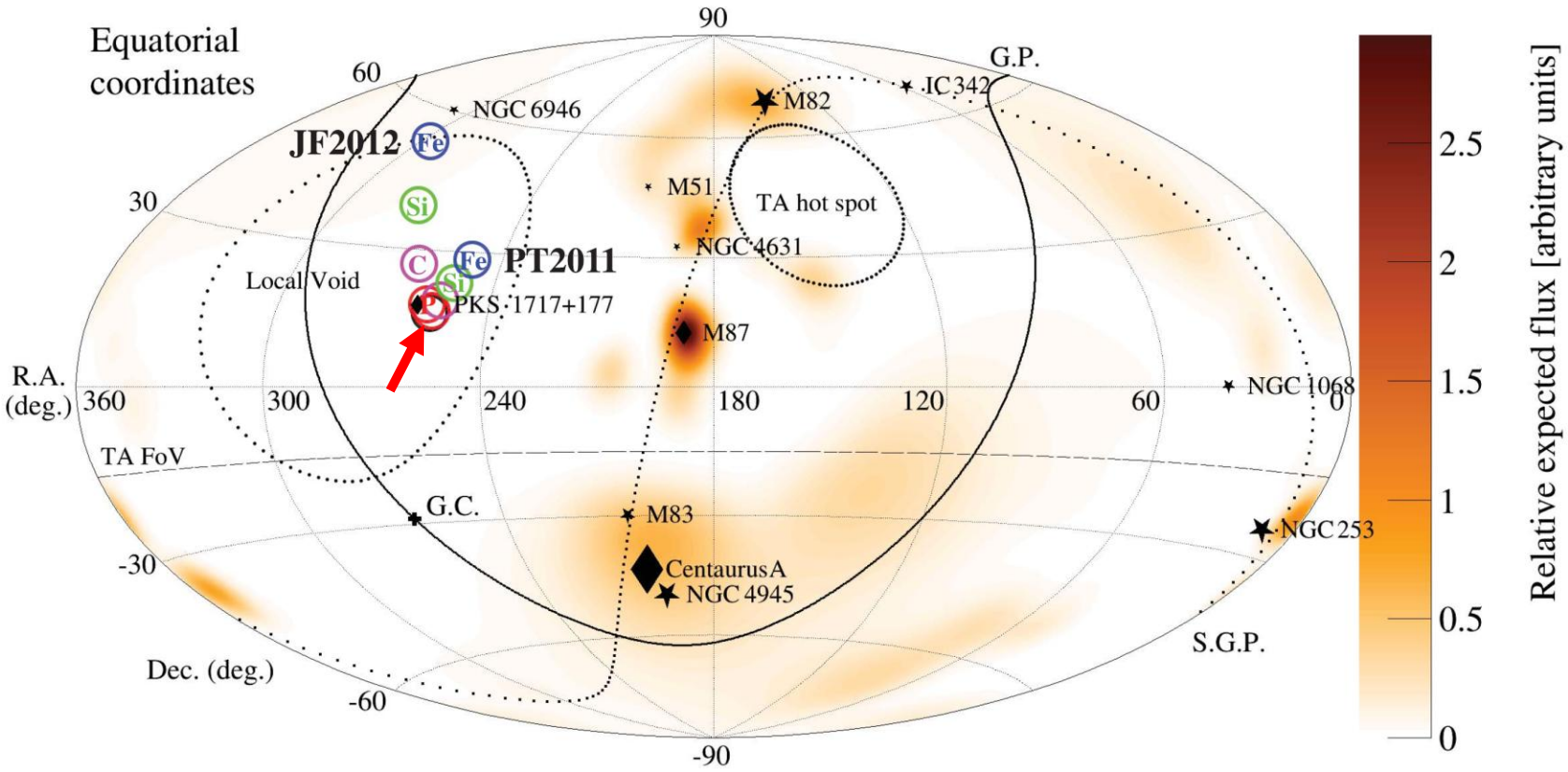


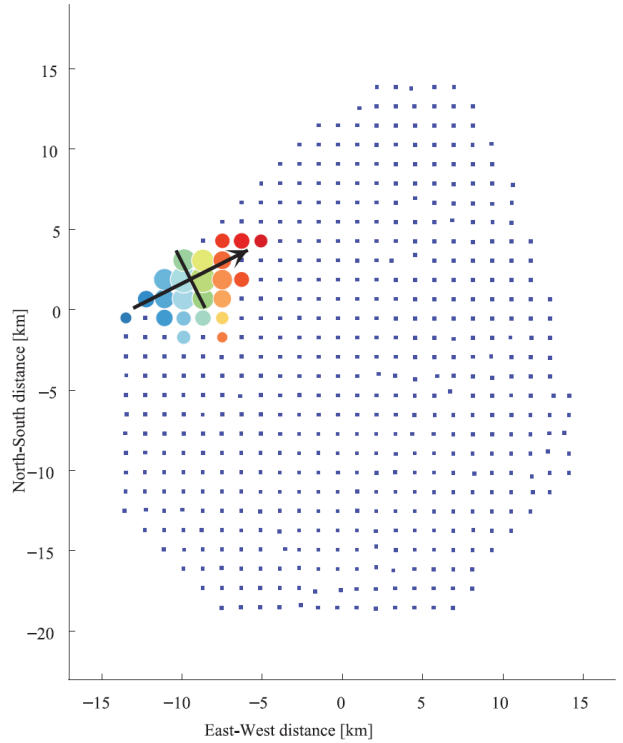
The drastic decrease of energy loss length of UHECR nuclei (protons) due to the giant dipole resonance (GZK process) with CMB photons at the highest energies

→ **Source candidates are limited** in short distances.

An extremely energetic cosmic ray event

TA Collaboration, Science,
***382**, 903 (2023).*

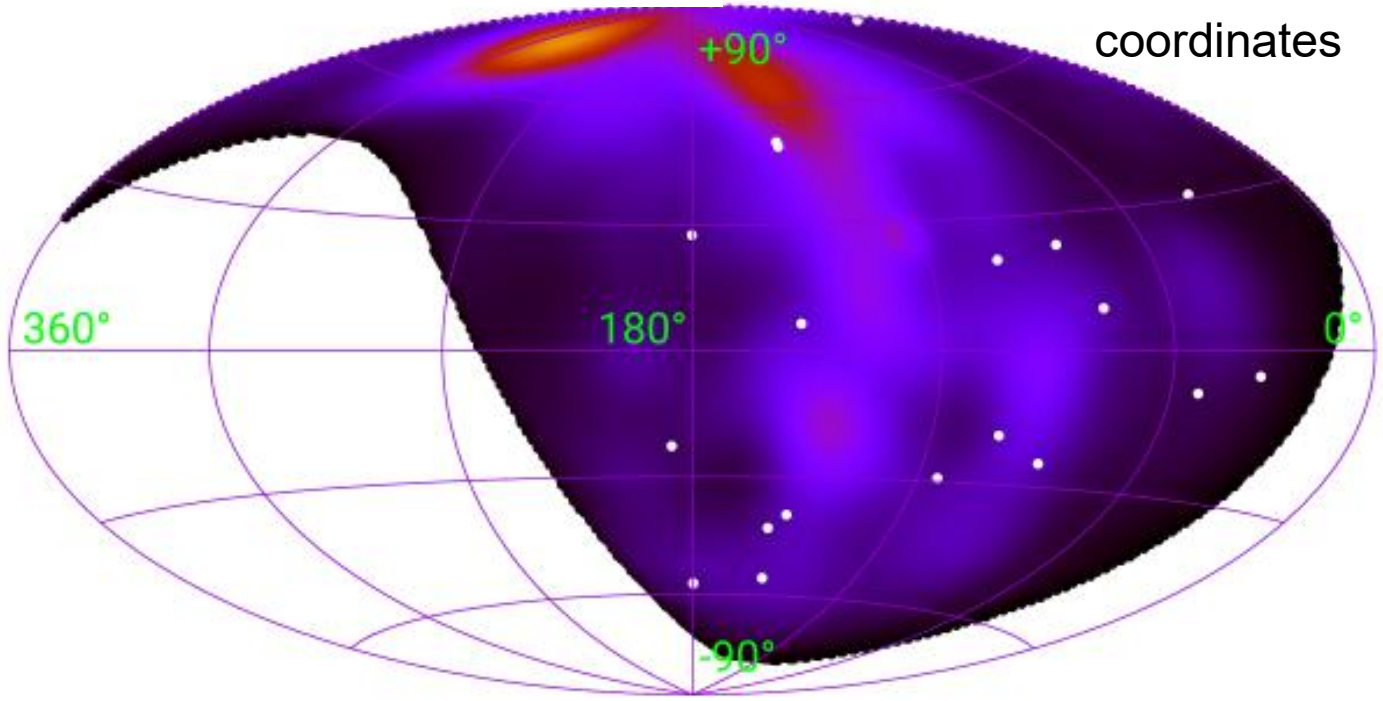




An event with
244±29(stat.)＋51-76(syst.) EeV
detected in the direction of
the **Local Void** (Tully+ 2008).
No apparent clustering with other E > 100 EeV events.

Mass composition from correlation study with nearby large scale structure (LSS)

TA Collaboration, *Phys. Rev. Lett.*, **133**, 903 (2024).



Flux map of UHECRs with E > 100 EeV LSS model (pure proton)
(red: large flux)
100 EeV smearing angle: 10° (von Mises Fisher dist.)
White points: observed 19 events with E > 100 EeV

- LSS model
  - Source distribution: 2Mass Redshift Survey catalog (distance <250 Mpc)
  - Propagation of UHECRs is simulated
  - Galactic magnetic field models considered
  - Free parameter: smearing angle
    (represents extragalactic magnetic fields)
- Arrival directions of 19 events with E > 100 EeV (14 years TA SD data) are compared with the LSS model.

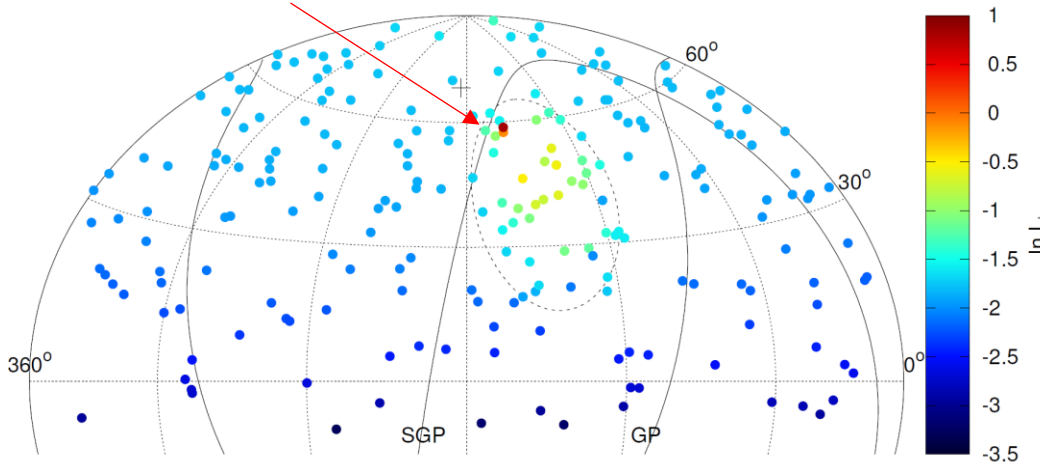
- Data is compatible with isotropy.
- LSS model has to assume
  - very heavy mass composition (> Fe)
  - extragalactic magnetic field has to be strong (> 20 nG, λ=1 Mpc) in case of proton or He

  to be compatible with the data within 2σ level.

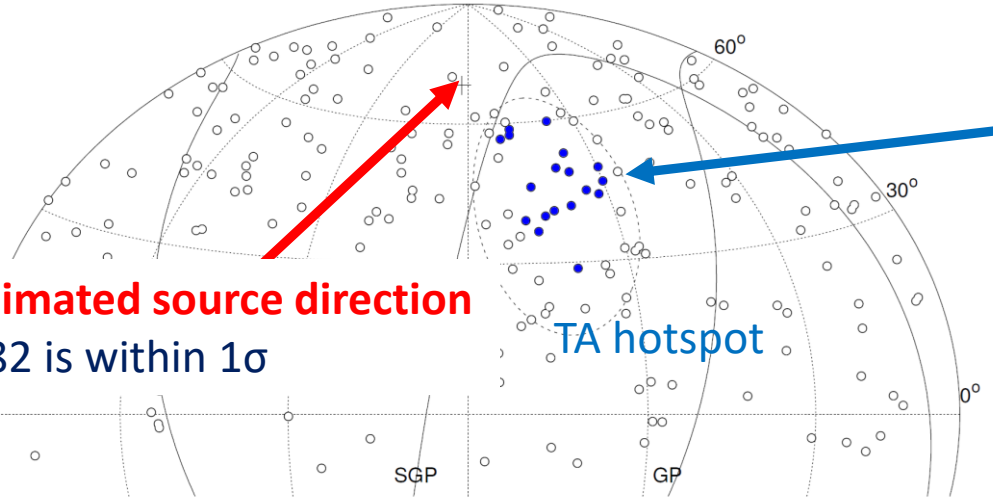
An energy structure inside of the TA hotspot induced by a single source?

E. Kido, ICRC2025

Max. likelihood function: **171 EeV**
2nd max. likelihood function:**107 EeV**



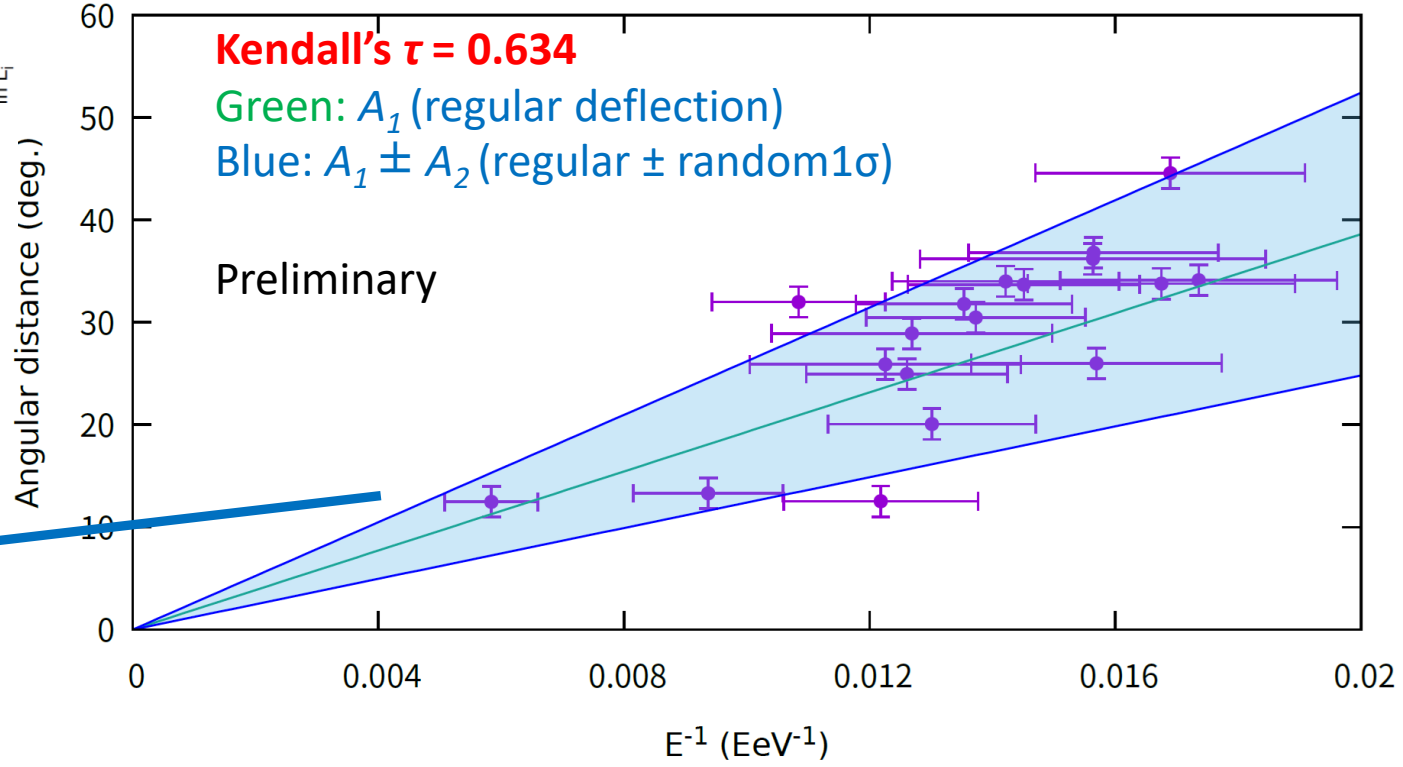
Likelihood function distribution



Estimated source direction
M82 is within 1σ

TA hotspot

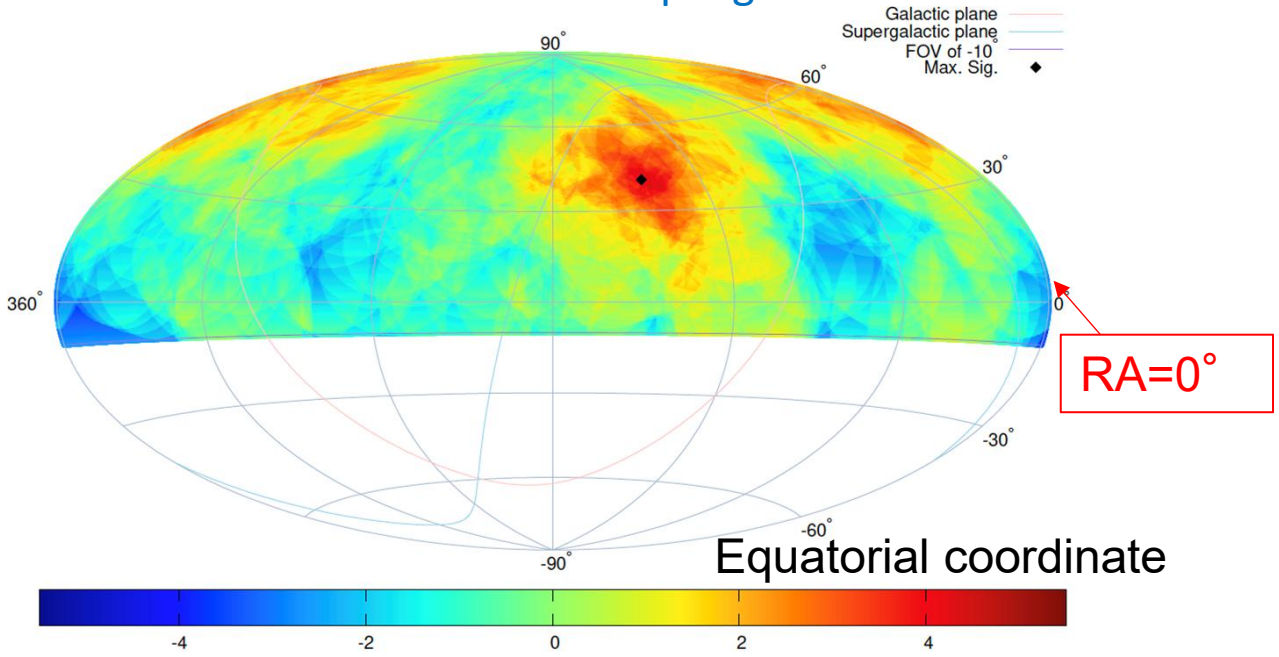
E > 100 EeV doublet @ north of the hotspot
We developed a likelihood analysis of a multiplet
→ TA hotspot event set
Pierre Auger public data: *H.-N. He talk CRD 422, 7/19*

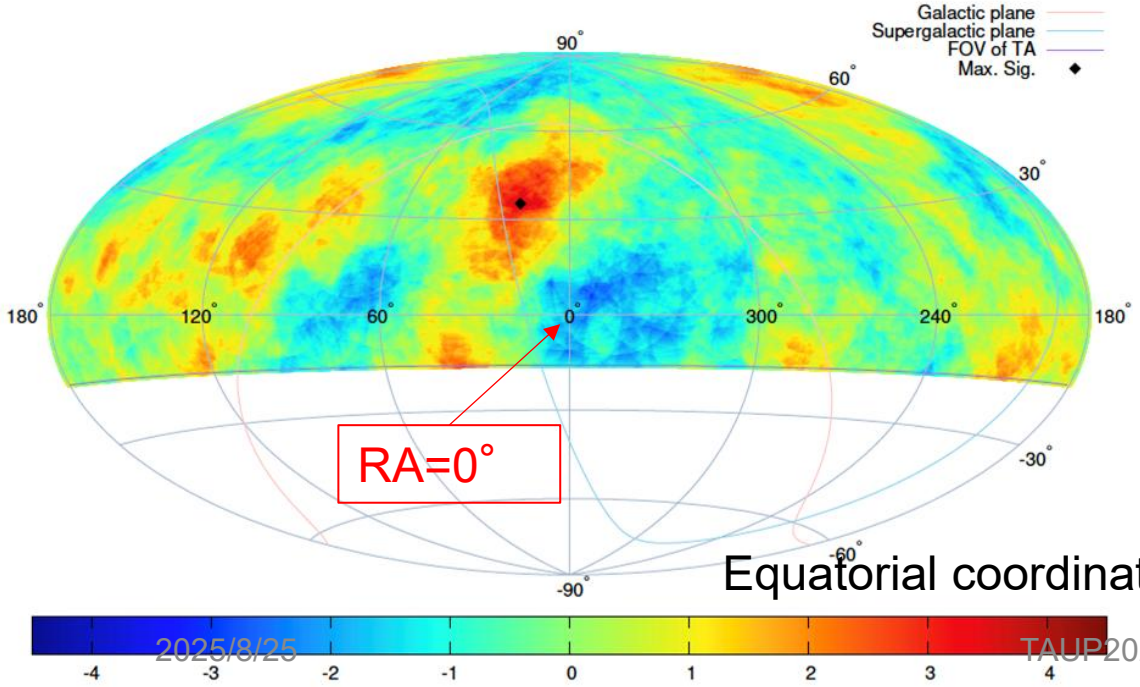


Global significance of the maximum likelihood function: **3.0σ**

E > 57 EeV

25°radius oversampling





Intermediate-scale anisotropy: Hotspot and a PPSC excess

J. Kim, ICRC2025

Analysis method (*ApJ 790, L21 (2014)*):

- Oversample number of UHECR events within a fixed radius circle from each arrival direction.
- Evaluate Li-Ma significance from isotropy expectation.
- TA SD data collected over 15 years was used.

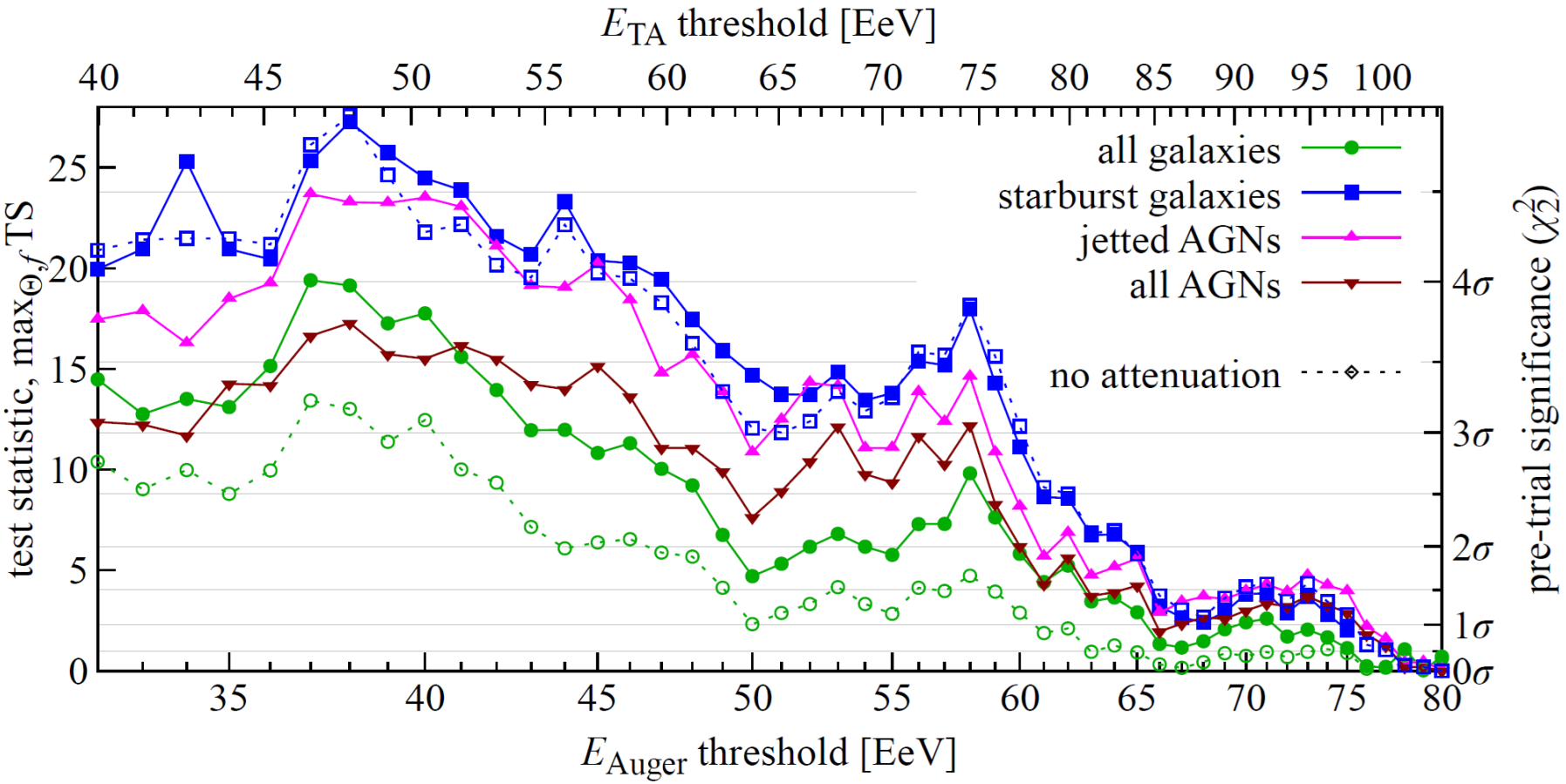
Hotspot (E > 57 EeV):

- 228 events
- max. local significance: 4.9σ at (144.0°, 40.5°)
- global significance: **2.9σ**

The Perseus-Pisces super cluster (PPSC) excess ($E > 10^{19.4,\ 19.5,\ 19.6}$ eV) (arXiv: 2110.14827):

- 1186, 767, 464 events
- significance: **3.1σ, 3.2σ, 3.0σ**

Correlation with catalog galaxies



A. Gálvez Ureña, ICRC2025

- Auger and TA anisotropy working group
- Joint Auger+TA data set
- Angular scales and energy thresholds were scanned.
- The galaxy selection and weighing come from an Auger-only study.
- Correlation with nearby starburst galaxies:

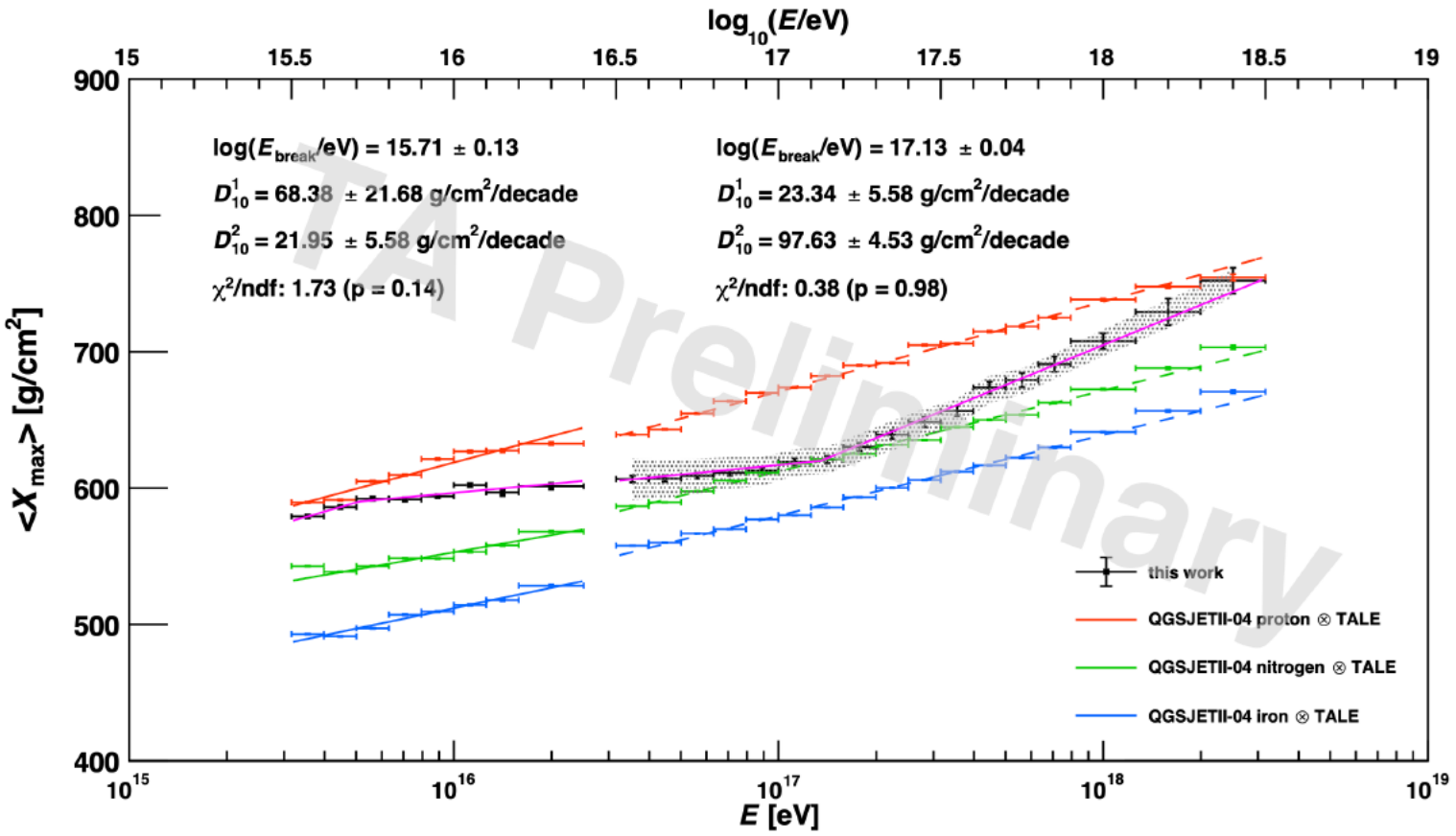
  4.2σ (post-trial)
- Correlation with nearby jetted AGNs:

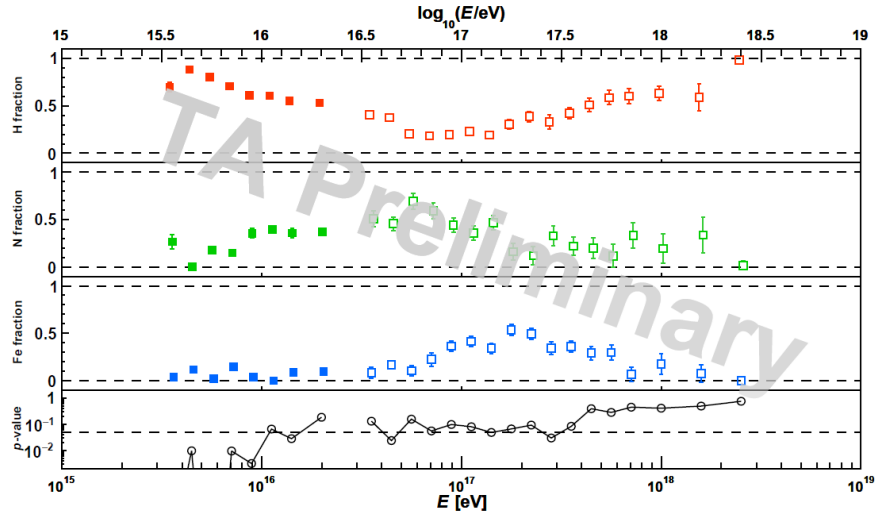
  3.8σ (post-trial)

Mass Composition

Mass composition measured by TALE hybrid and TALE-infill hybrid

K. Fujita,
ICRC2025

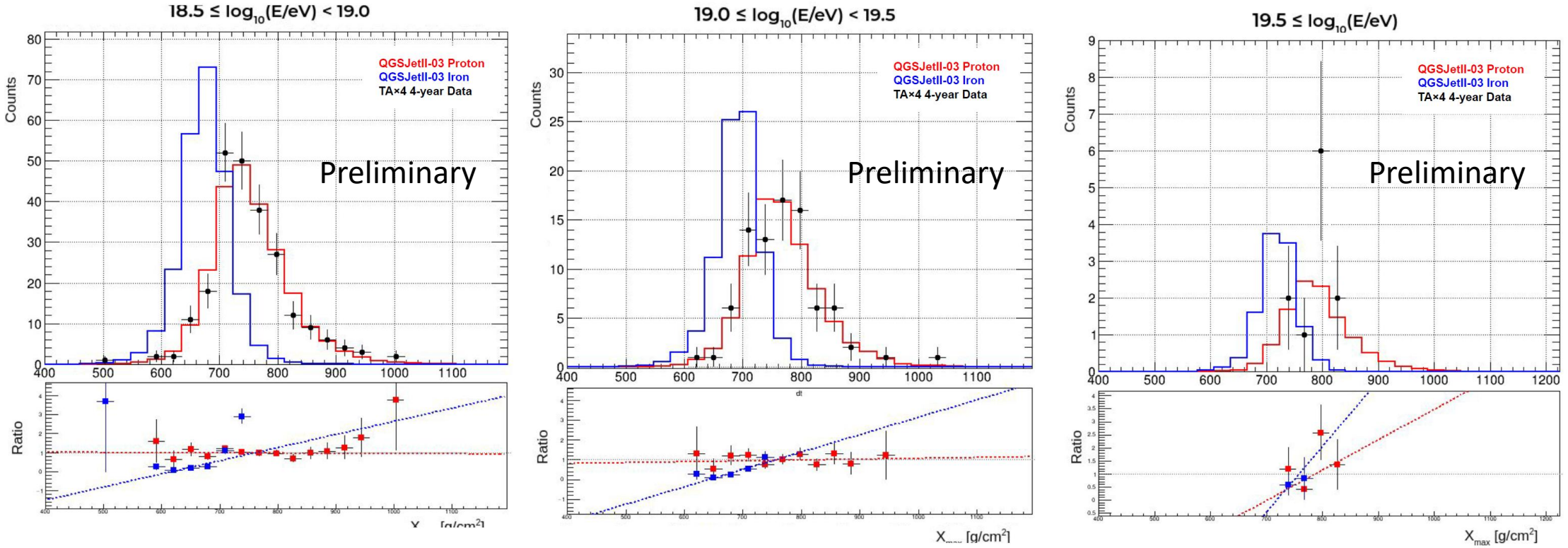




- Breaks in the $\langle X_{max} \rangle$ coincide with the knee and second knee.
- X_{max} distribution fits show a transition from light to heavy composition, peaking near $10^{17.2}$ eV.
- Further studies with He nuclei, and interaction model EPOS-LHC-R and QGSJET-III are ongoing.

TAx4 hybrid analysis

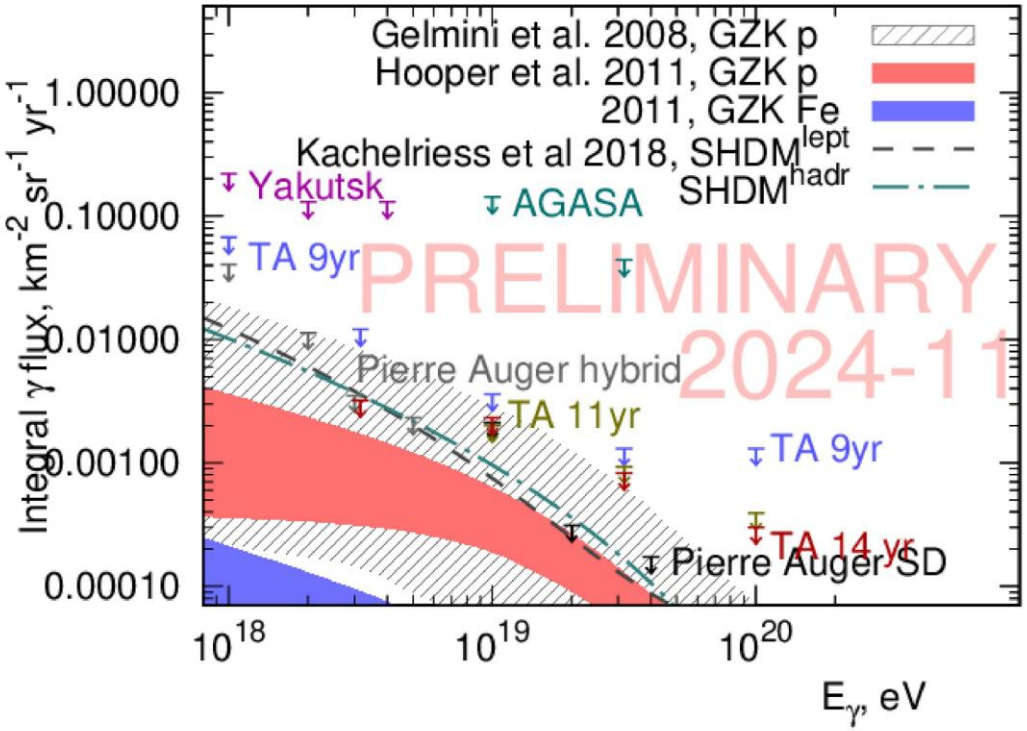
Z. Garber,
ICRC2025



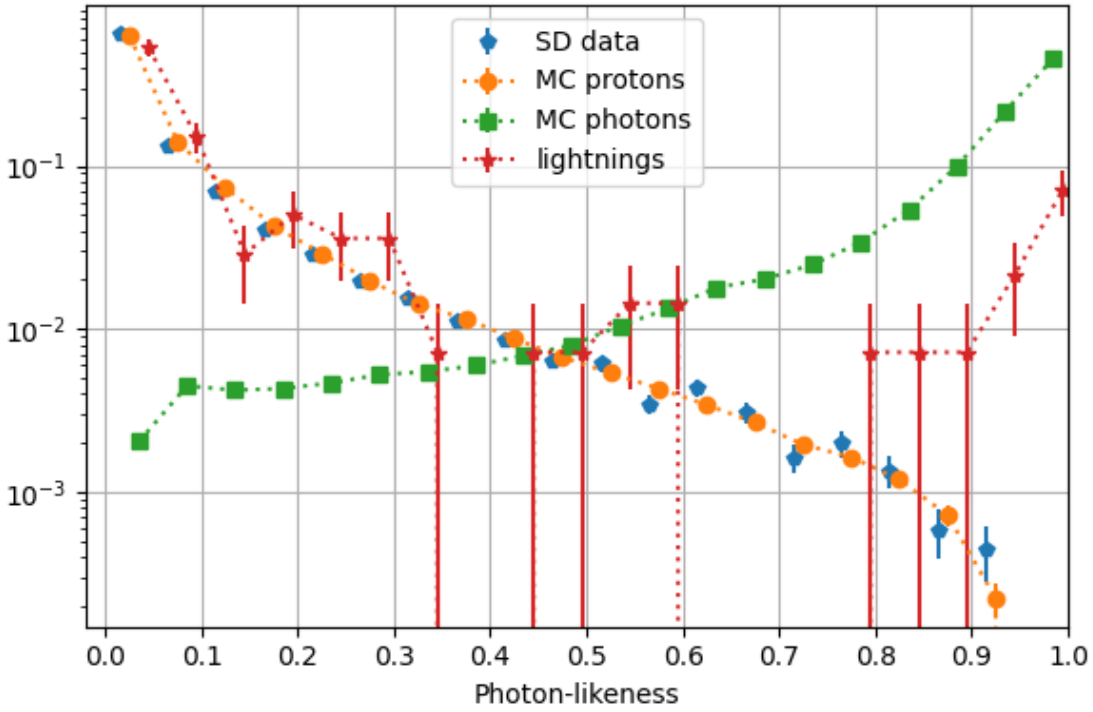
- 4 years TAx4 FD (new stations) and SD (2.08 km spacing) hybrid results.
- Consistent results with previous TA results were obtained. We need more statistics at the highest energies.
- **2 events** above 100 EeV were detected.

Upper limits of UHE photon flux

Astropart. Phys. ***110****, 8 (2019)*
updated in 2024. G. Rubtsov, UHECR2024



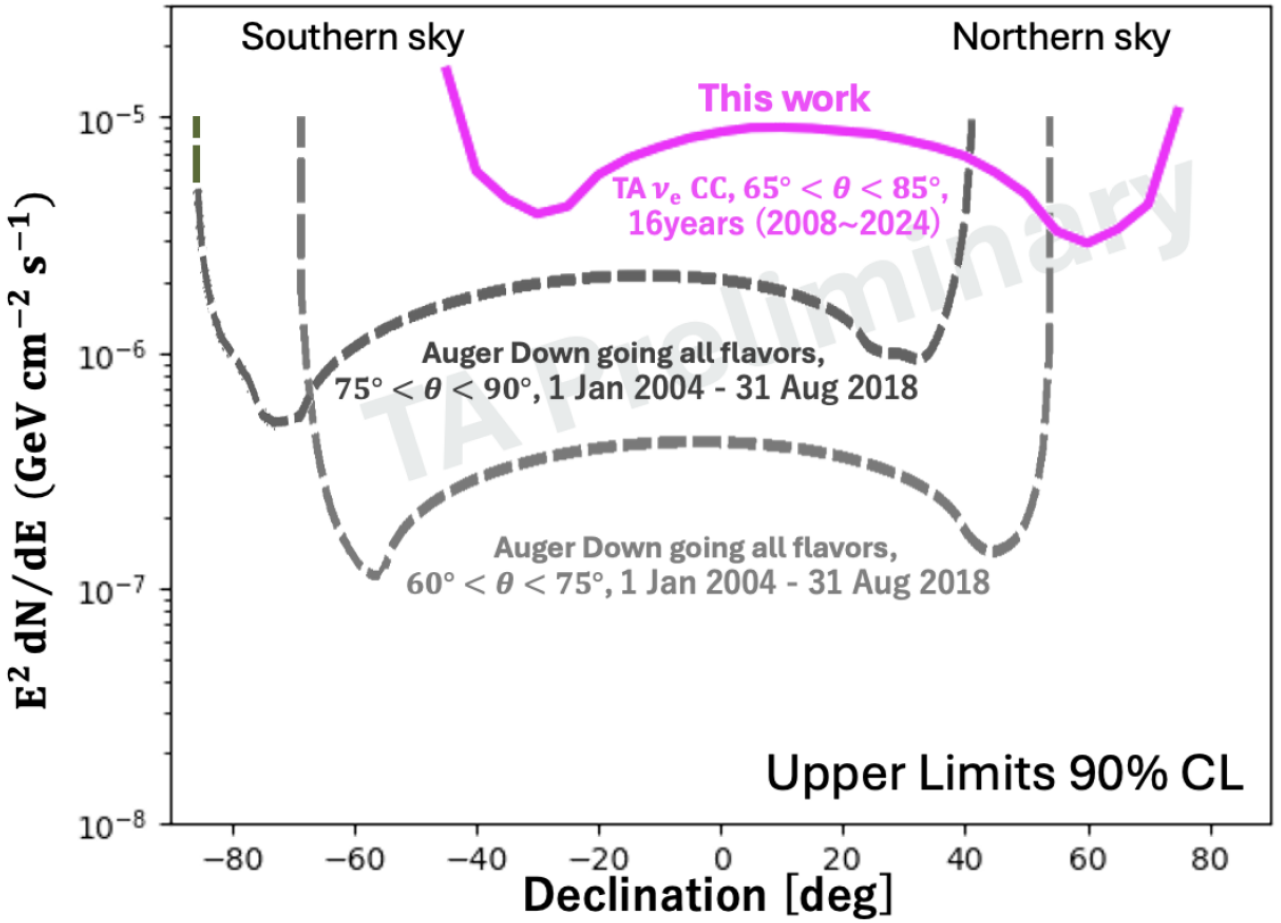
$E_\gamma > 10^{19.0}$ eV



- A neural network classifier is developed and trained on the photon-induced and proton-induced Monte-Carlo event sets.
- A classifier is fine-trained using the data events which are not photons with high confidence.
- The limits on the ultra-high-energy photon flux are established based on 14 years of TA SD data.

Upper limits of UHE neutrino flux

K. Takahashi, ICRC2025

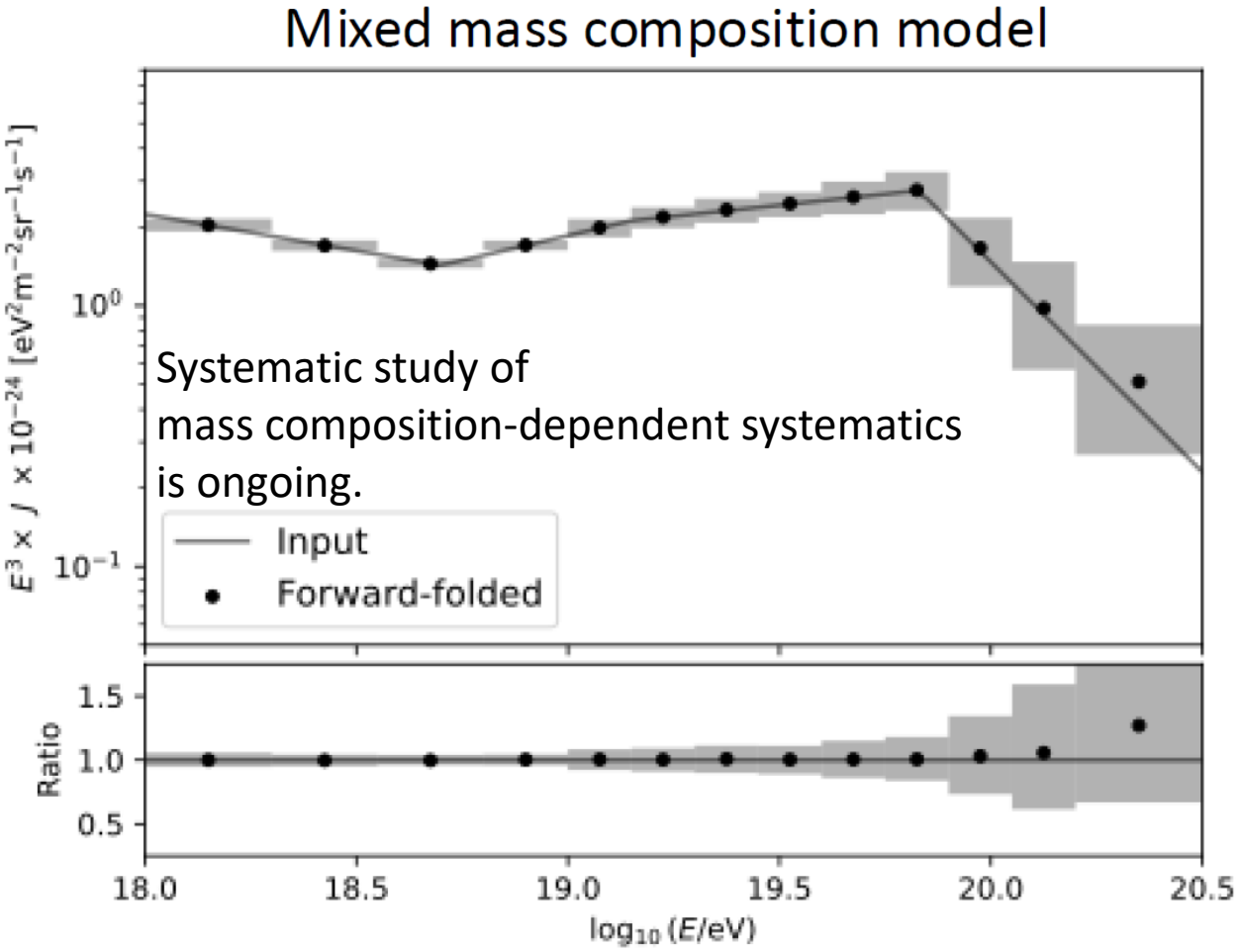


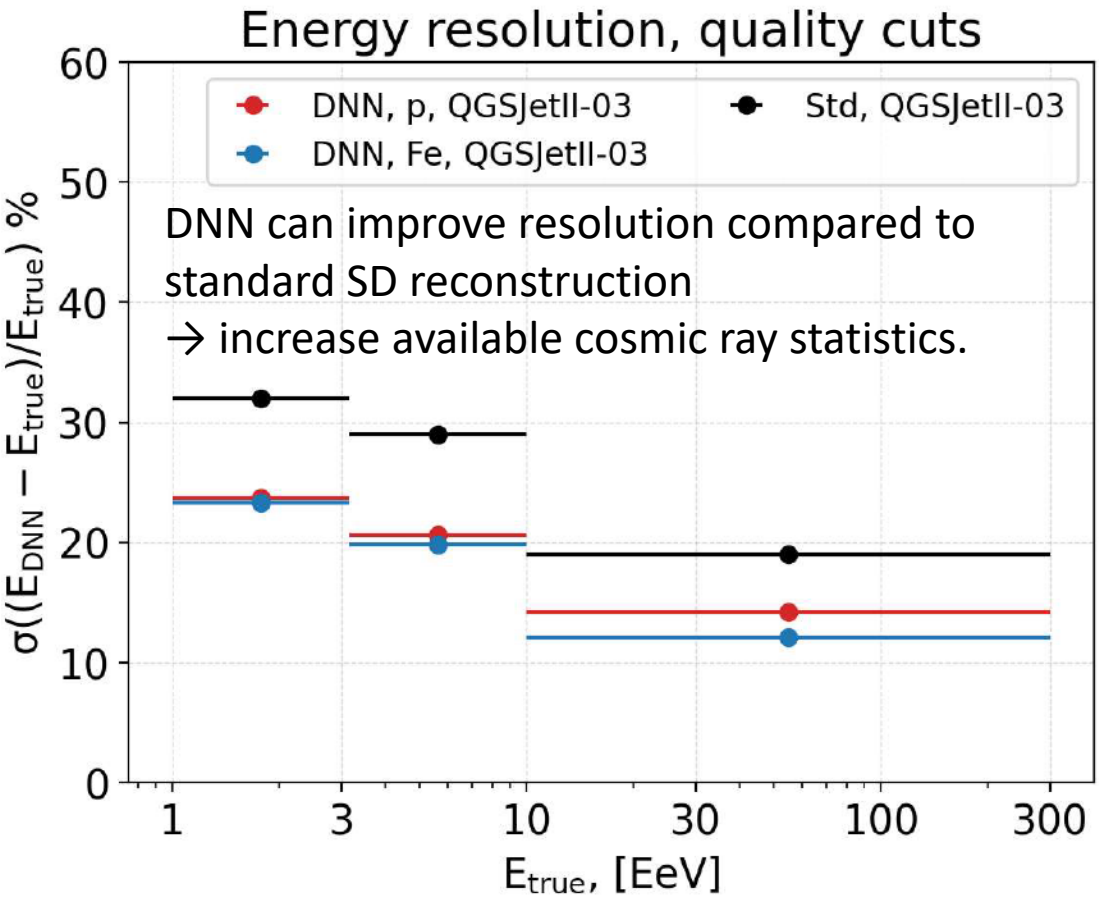
- Upper limits on UHE neutrinos are obtained with 16 years TA SD data.
- No neutrino event was observed (N_{exp} = 2.44).
- Inclined shower events : 65° < ϑ <85°
- Two observables
  - Shower curvature parameter
  - Area over peak

Software developments for SD event reconstructions

K. Fujisue, ICRC2025

A. Prosekin, UHECR2024





Summary

Thank you for your attention!

- TA detectors
  - TA: FDs and SDs are fully operated since May 2008.
  - TALE (low energy extension): FDs are operated since Sep. 2013. FD and SD hybrid triggers are operated since Sep. 2018.
    A **new dense array with 100 m** (TALE infill SD) spacing started to be operated since Oct. 2023.
  - TAx4 (high energy extension): 257 new SDs (out of 500) and two new FDs were completed. Coverage ~1700 km^2.
    North FD station stably runs since Jun. 2018, and south FD stably runs since Sep. 2020. SD stably runs since Nov. 2019.
- Energy spectrum
  - Declination dependence: discrepancy of full aperture energy spectrum with a fit energy spectrum
  - Energy spectrum obtained with new TAx4 SDs shows **compatible** energy spectrum with the TA SDs.
- Anisotropy
  - Hotspot (E > 57 EeV) (*ApJ 790, L21 (2014)*): **2.9σ**
  - An excess around the Perseus-Pisces super cluster (PPSC) (E > $10^{19.4}$ eV) (arXiv: 2110.14827): **3.0-3.2σ**
  - An extremely energetic cosmic ray event (**244**±29(stat.)＋51-76(syst.) EeV) detected in the direction of **the Local Void.**
  - The arrival directions of the data with E > **100 EeV** suggest that either a heavy composition or strong magnetic fields are required for consistency with the LSS model.
  - Correlation with nearby starburst galaxies (Auger+TA working group)): **4.2σ**
- Mass composition
  - Light-heavy-light transition in 10^{15} eV – 10^{18} eV and a break at ～$10^{17.2}$ eV in mean X_{max} were obtained with the TALE FDs.
  - Flux upper limits of UHE photons are updated. Flux upper limits of UHE neutrinos are obtained.
- **Future prospects**
  - **TAx4** SD and FD analyses → studies on **highest energy events**
  - Software for SD event reconstructions are being studied.
  - Hardware developments of current and future detectors are ongoing.