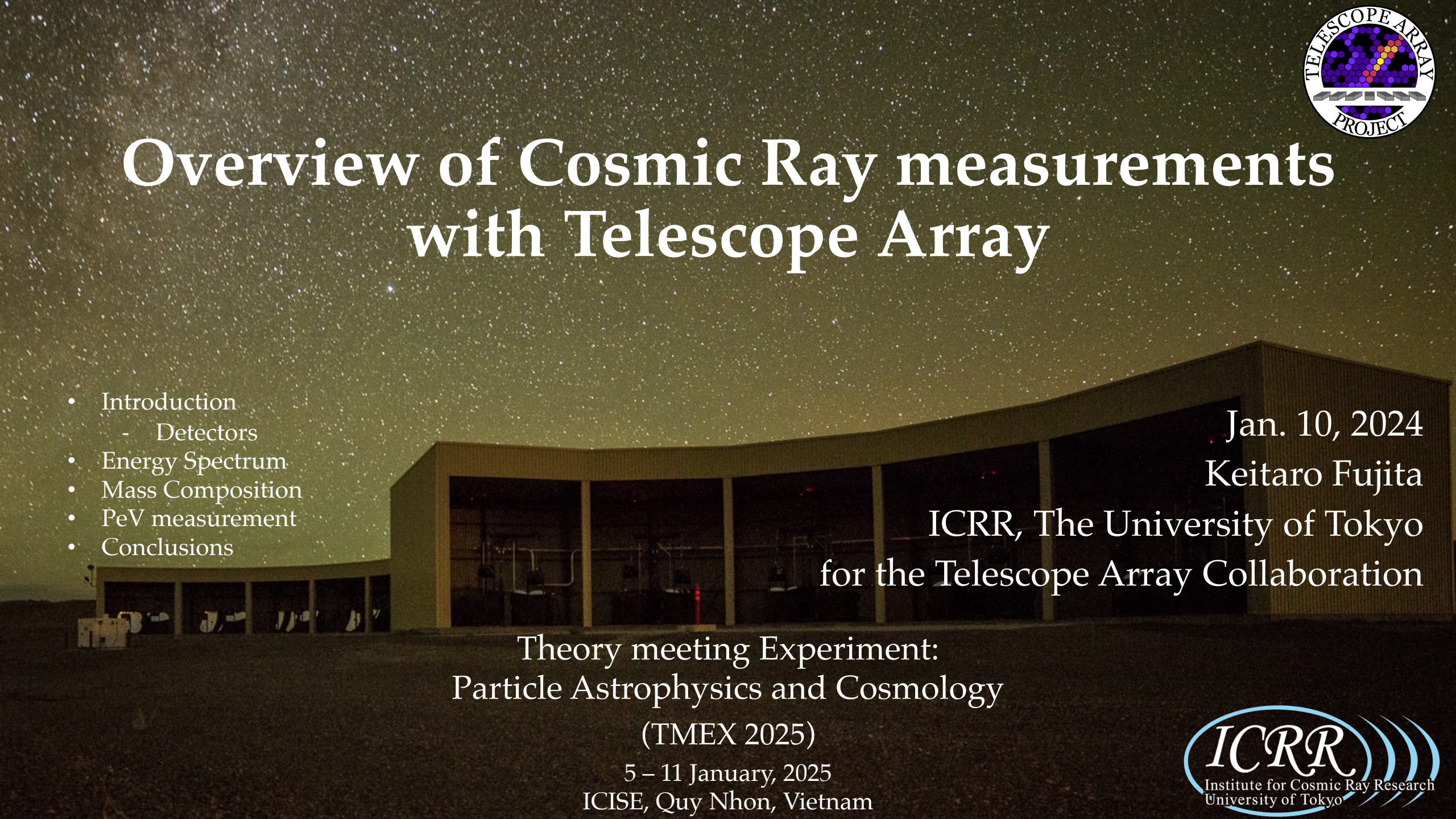


Overview of Cosmic Ray measurements with Telescope Array

- Introduction
  - Detectors
- Energy Spectrum
- Mass Composition
- PeV measurement
- Conclusions

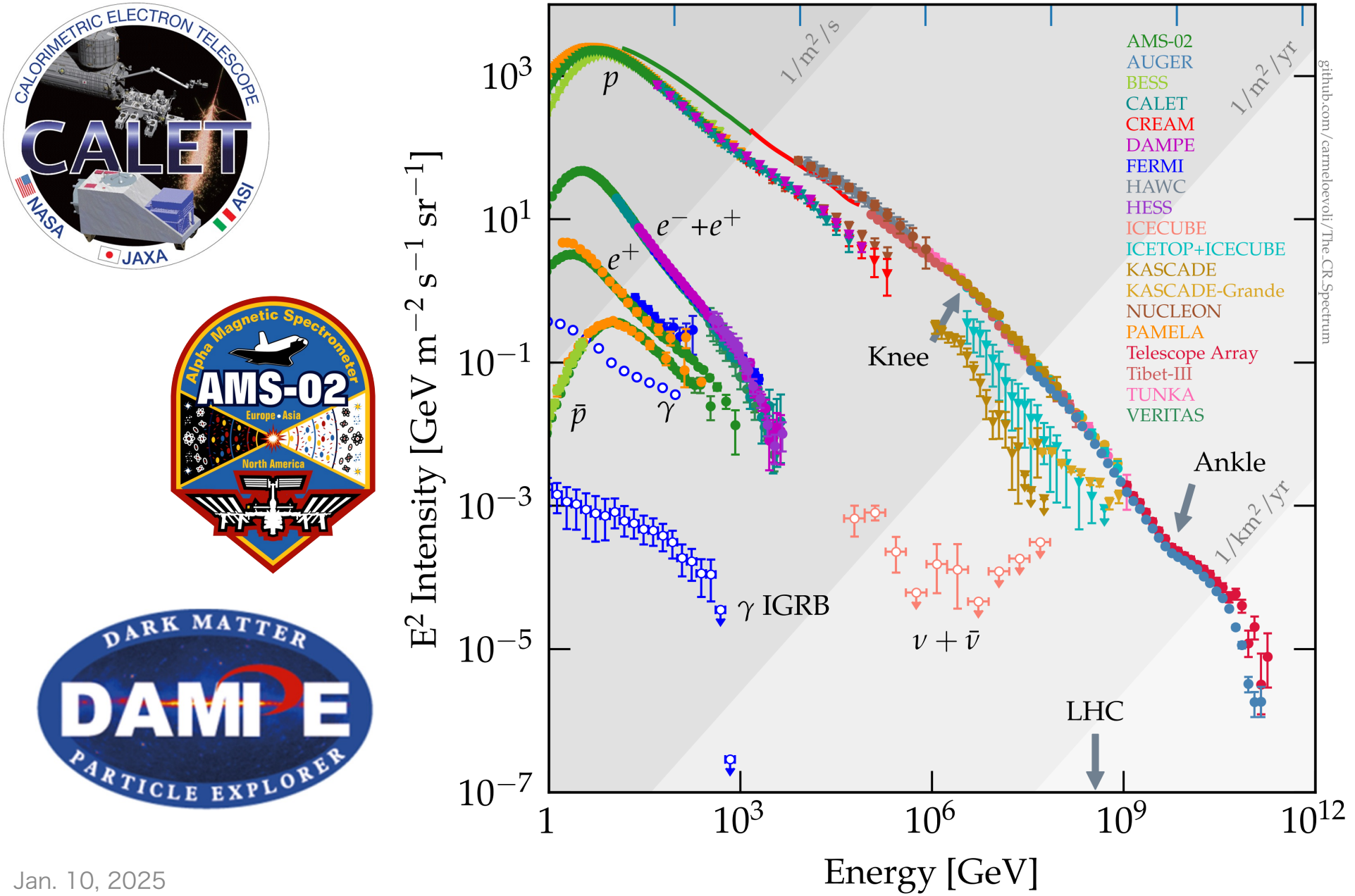
Jan. 10, 2024
Keitaro Fujita
ICRR, The University of Tokyo
for the Telescope Array Collaboration

Theory meeting Experiment:
Particle Astrophysics and Cosmology
(TMEX 2025)
5 – 11 January, 2025
ICISE, Quy Nhon, Vietnam

ICRR
Institute for Cosmic Ray Research
University of Tokyo

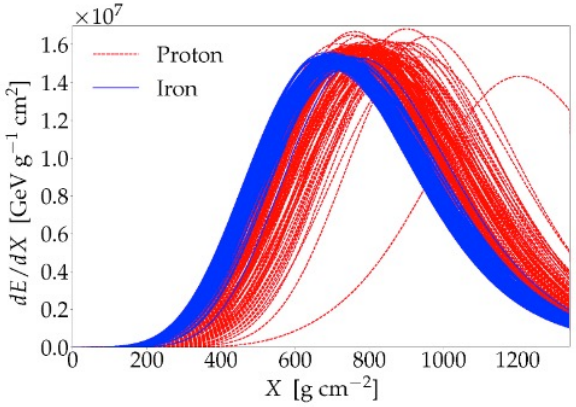
Direct

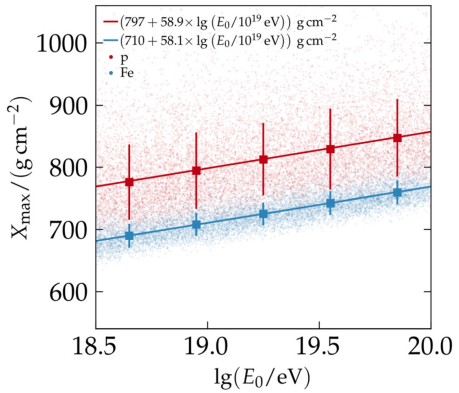
Indirect



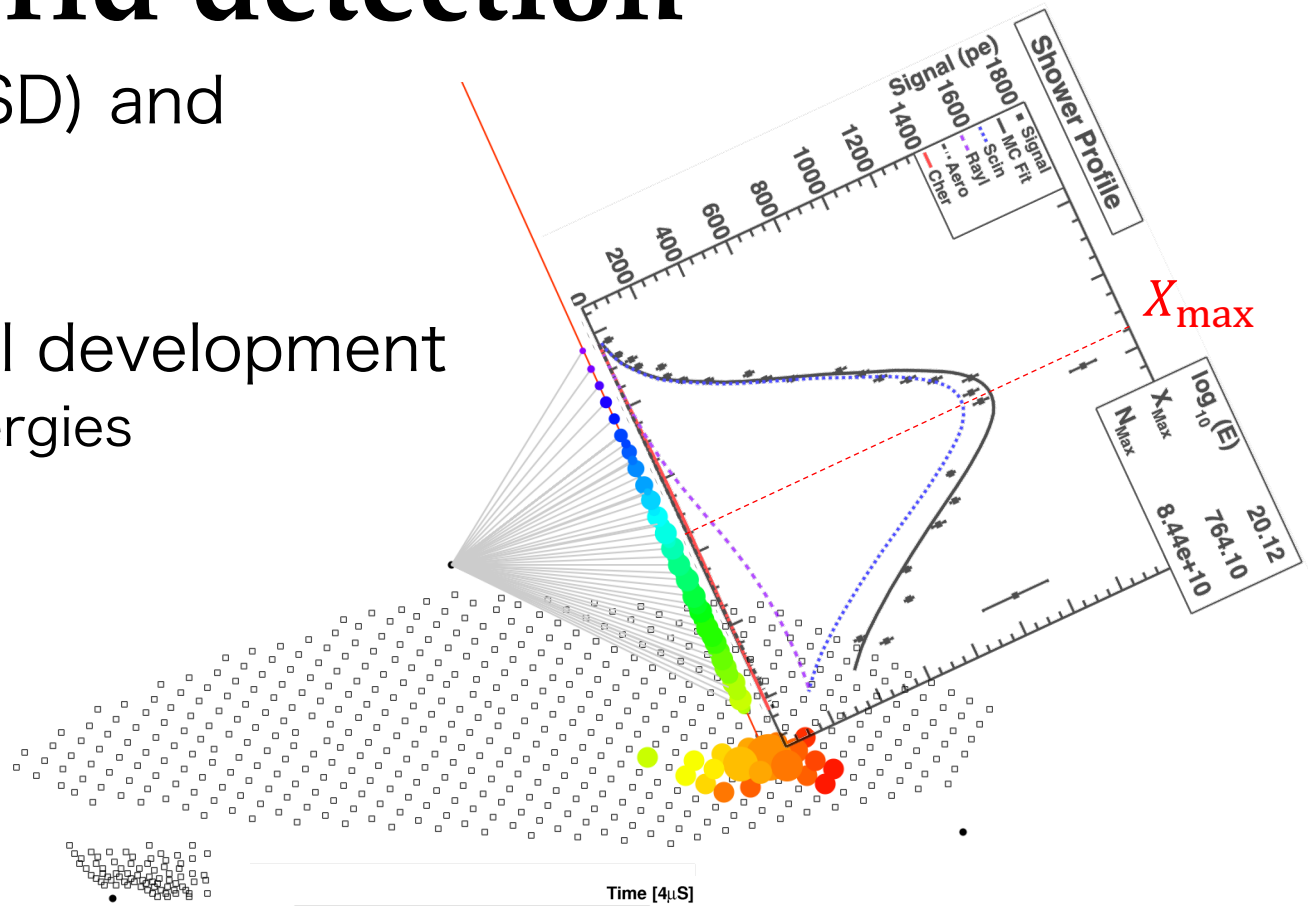
Key Technique → Hybrid detection

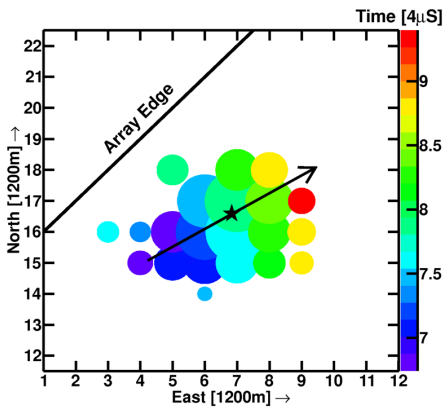
- Combination of Surface Detectors (SD) and Fluorescence Detectors (FD)
- FD:
  - Capable of measuring longitudinal development
    - calorimetric measurement of CR energies
    - mass composition by X_{max} measurement

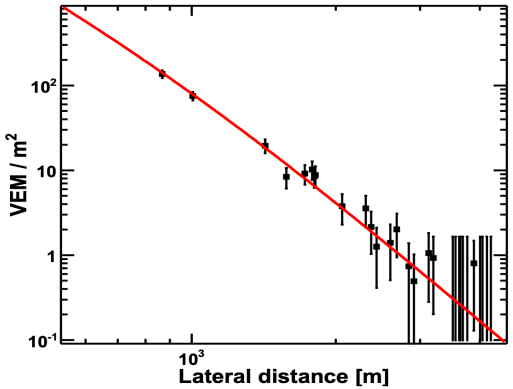




- SD:
  - 100% duty cycle
    - high statistics -> spectrum, anisotropy
  - calibrated SD energy to FD







Telescope Array

2008

TA

- TA starts 2008

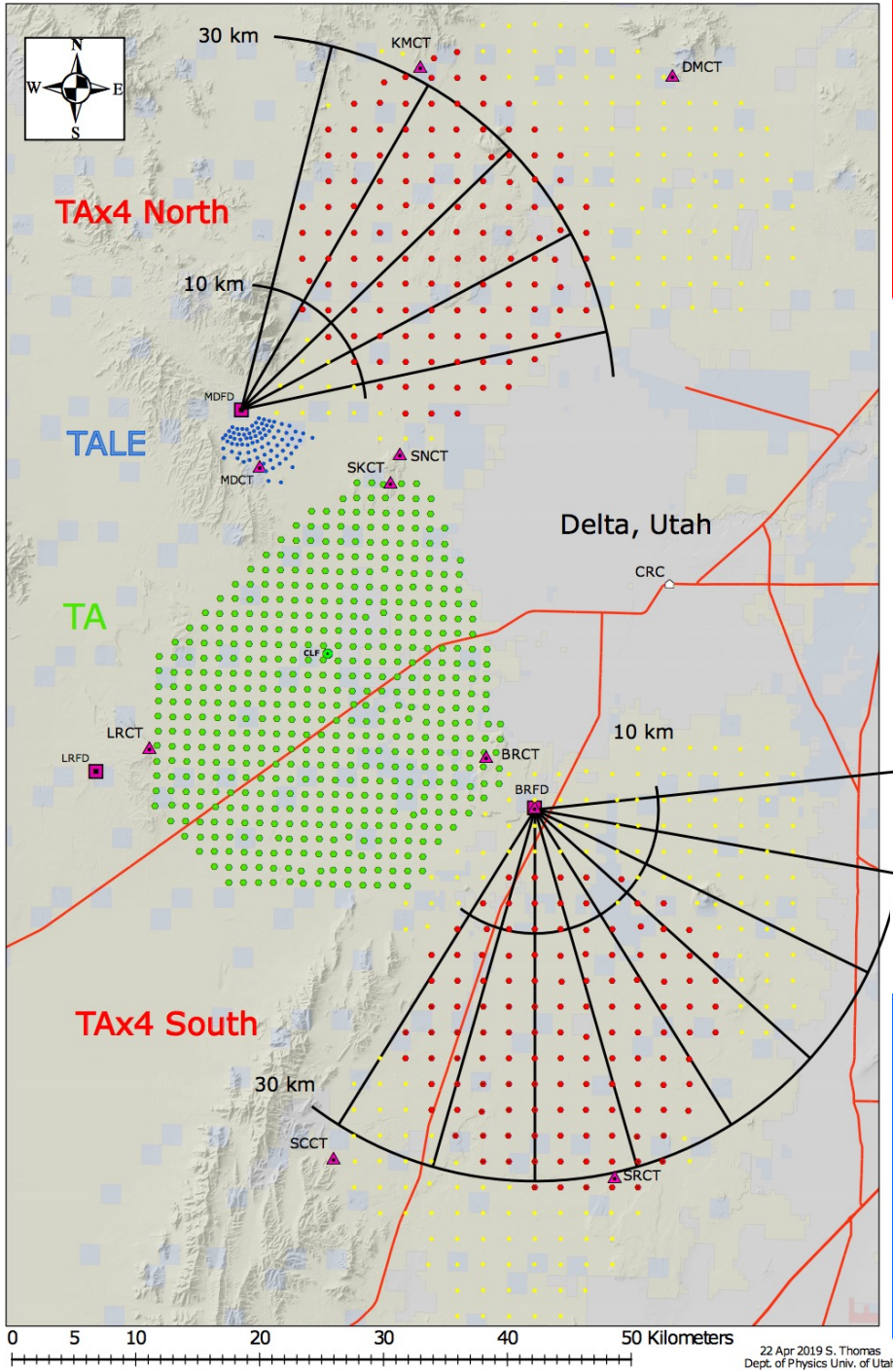
@ Utah, US

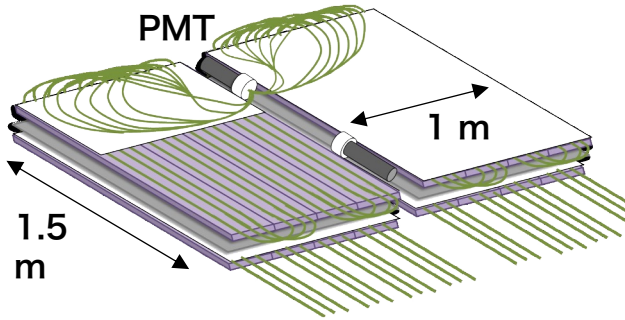
39° N, 113° W

  - SD: ●
    - plastic scintillator
    - 507SDs, 700km^2
    - 1.2km space
  - FD: ■
    - 3 sites
    - 38 telescopes

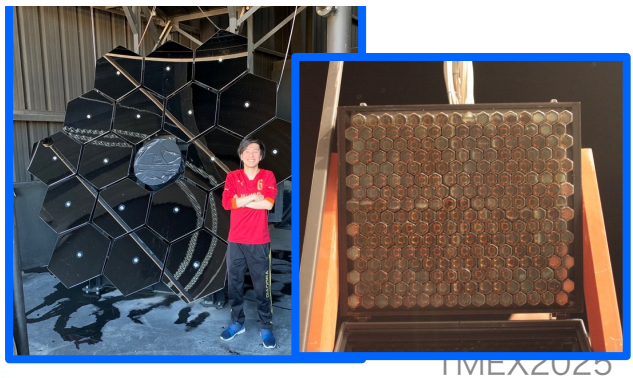
2019

- TAx4 starts 2019
  - extend SD coverage by a factor of four
  - additional 257SDs(●), 2.08km + 12 telescopes





Segmented mirrors
256 hexagonal PMTs/camera



Telescope Array Low-energy Extension

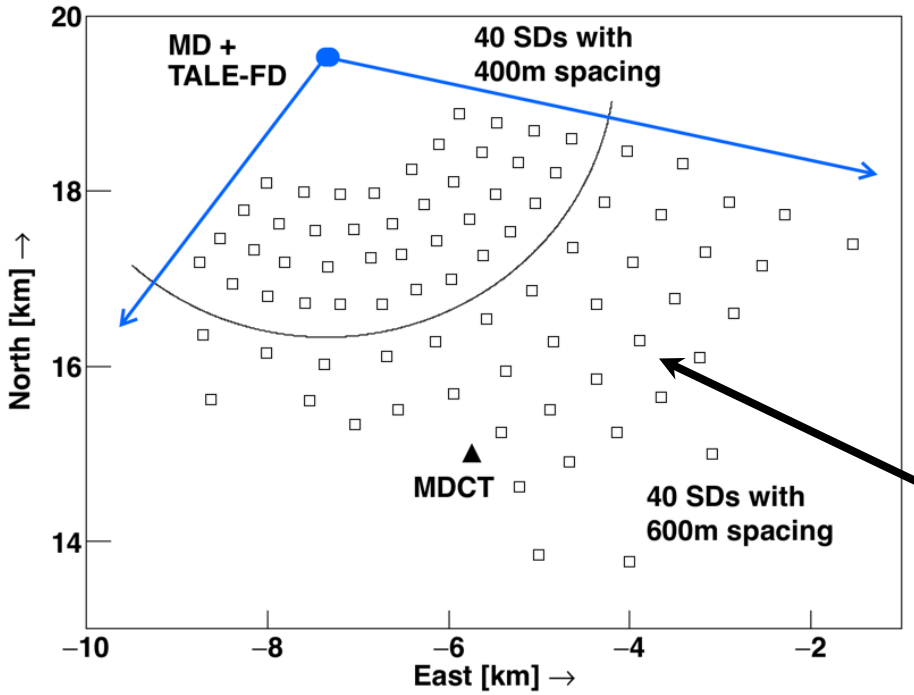
2008

TA

2013

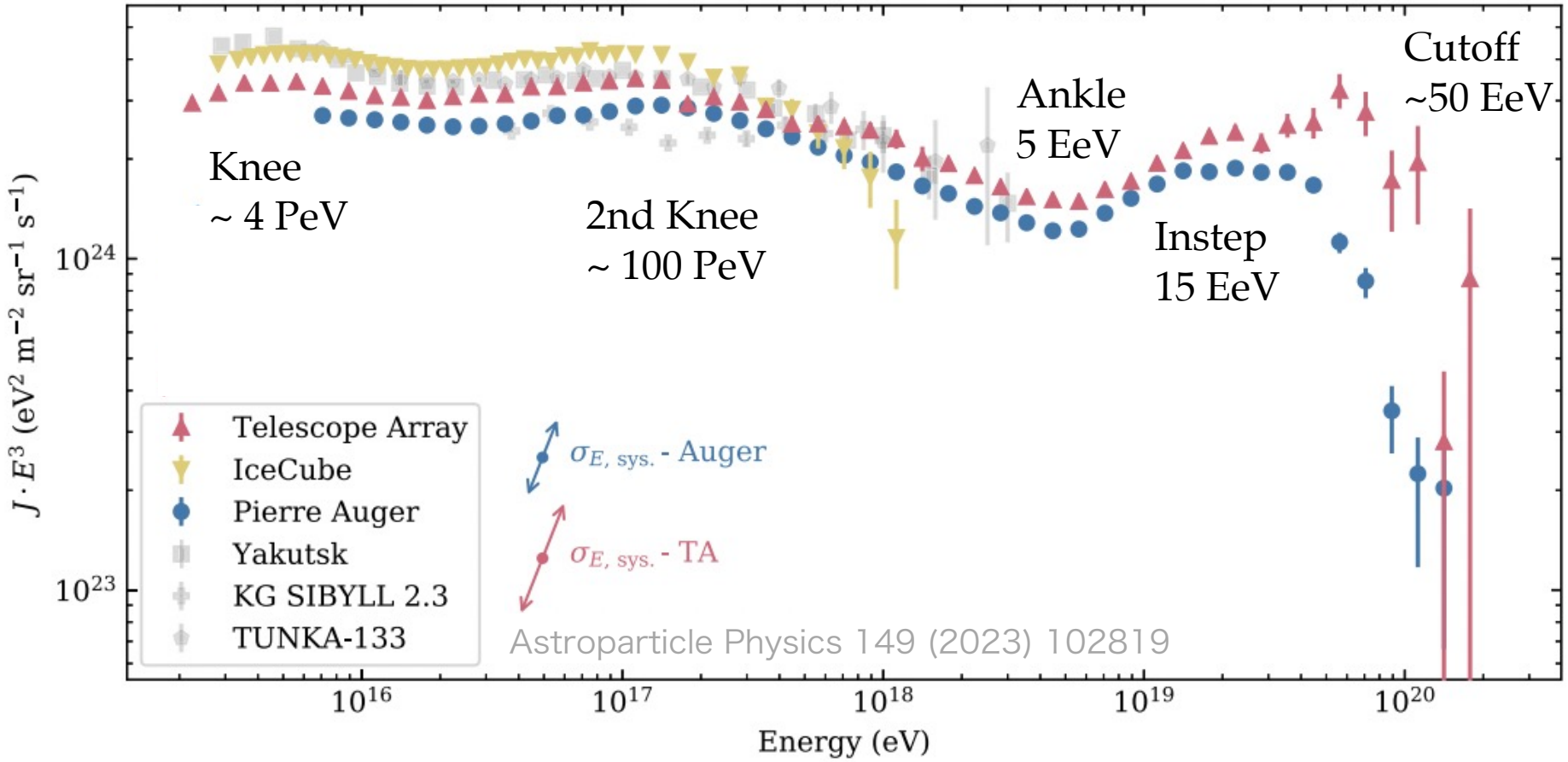
TA + TALE

- Extension in lower energies by hybrid detector → **TALE**



- Low energy CRs-induced shower
  - Not so bright, higher X_{max}
    → <u>high elevation telescope</u>
  - compact shower size
    → <u>dense SD array</u>
- Same concept as TA detector
  - 10 Fluorescence Telescopes
  - 80 Surface Detectors, 20 km^2
- Operation: FD since Sep. 2013
  SD since Nov. 2017

Open Questions of CRs above knee



- What are CR sources ? Mechanism ?
- Origin of break structure ?
- Where is galactic extra-galactic transition ? etc.

Reflect in { spectrum / mass composition / arrival direction

Extremely energetic cosmic ray observed by TA

Science 382, 6673 (2023)

May 27th 2021 10:35:56 UTC
No operation of FD due to twilight

$$E = 244 \pm 29\,(\text{stat.})^{+51}_{-76}(\text{sys.})\ \text{EeV}$$

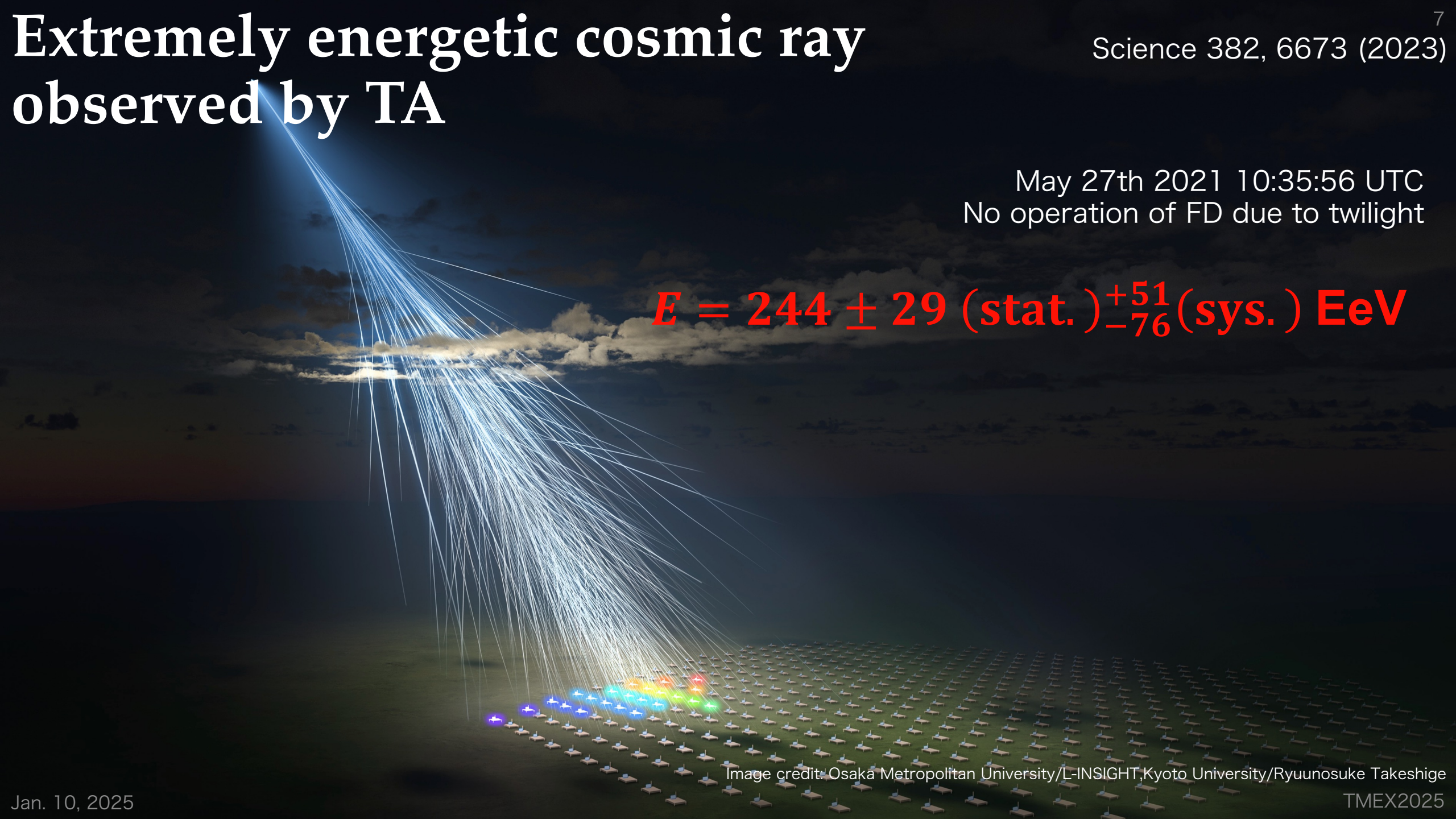
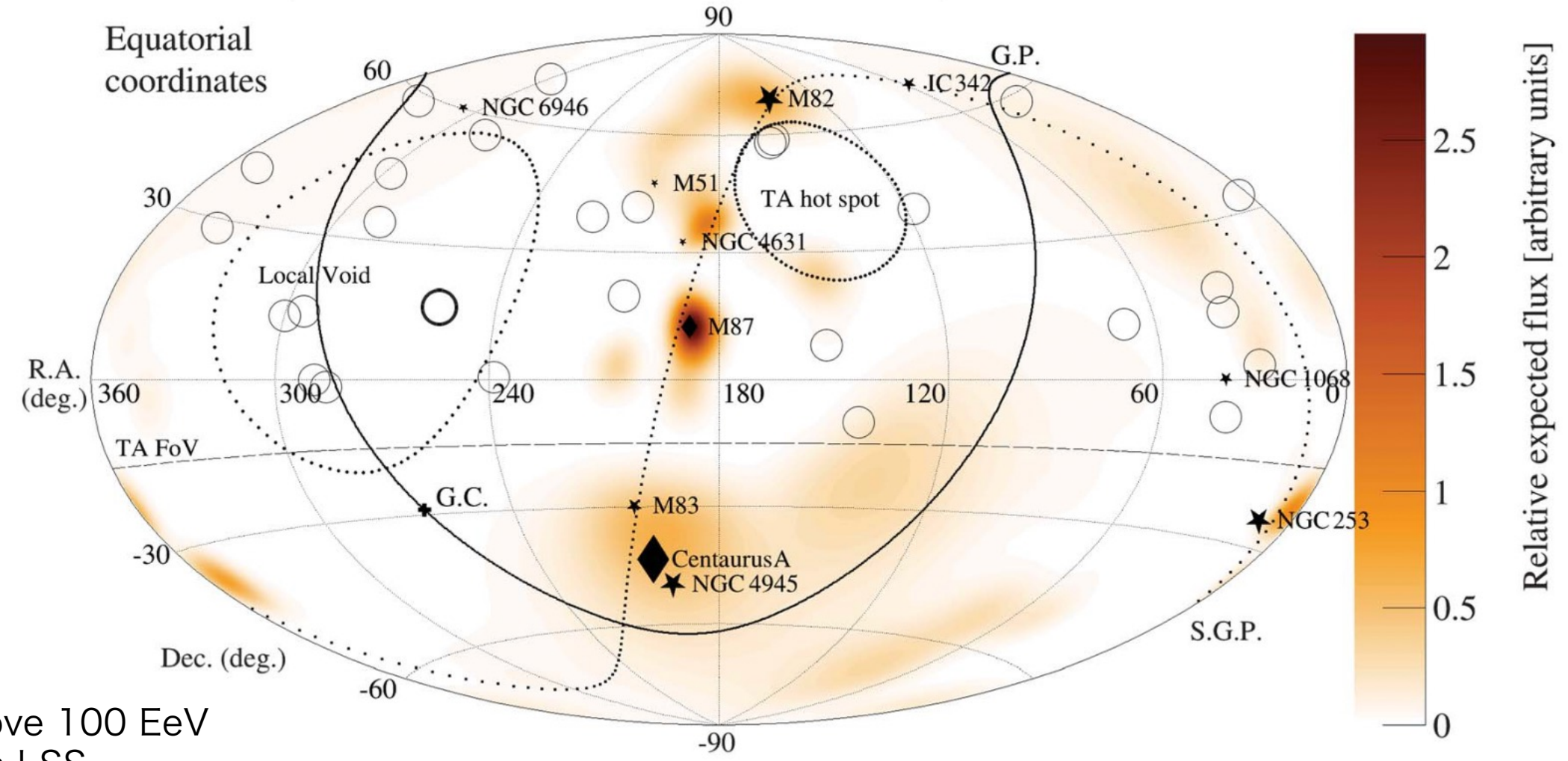


Image credit: Osaka Metropolitan University/L-INSIGHT,Kyoto University/Ryuunosuke Takeshige

Extremely energetic cosmic ray observed by TA

Science 382, 6673 (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.

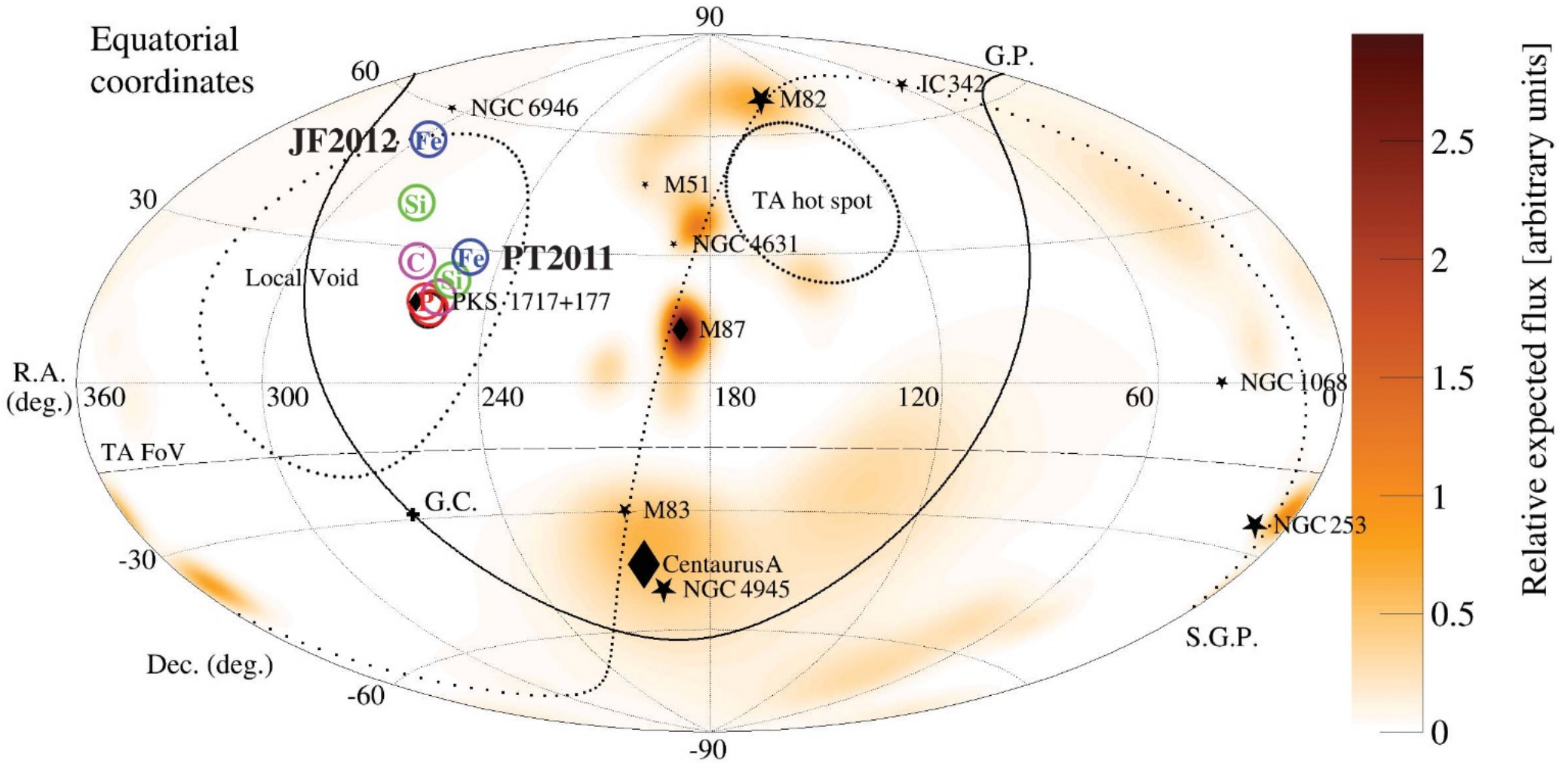


No clustering above 100 EeV
Uncorrelated with LSS

Extremely energetic cosmic ray observed by TA

Science 382, 6673 (2023)

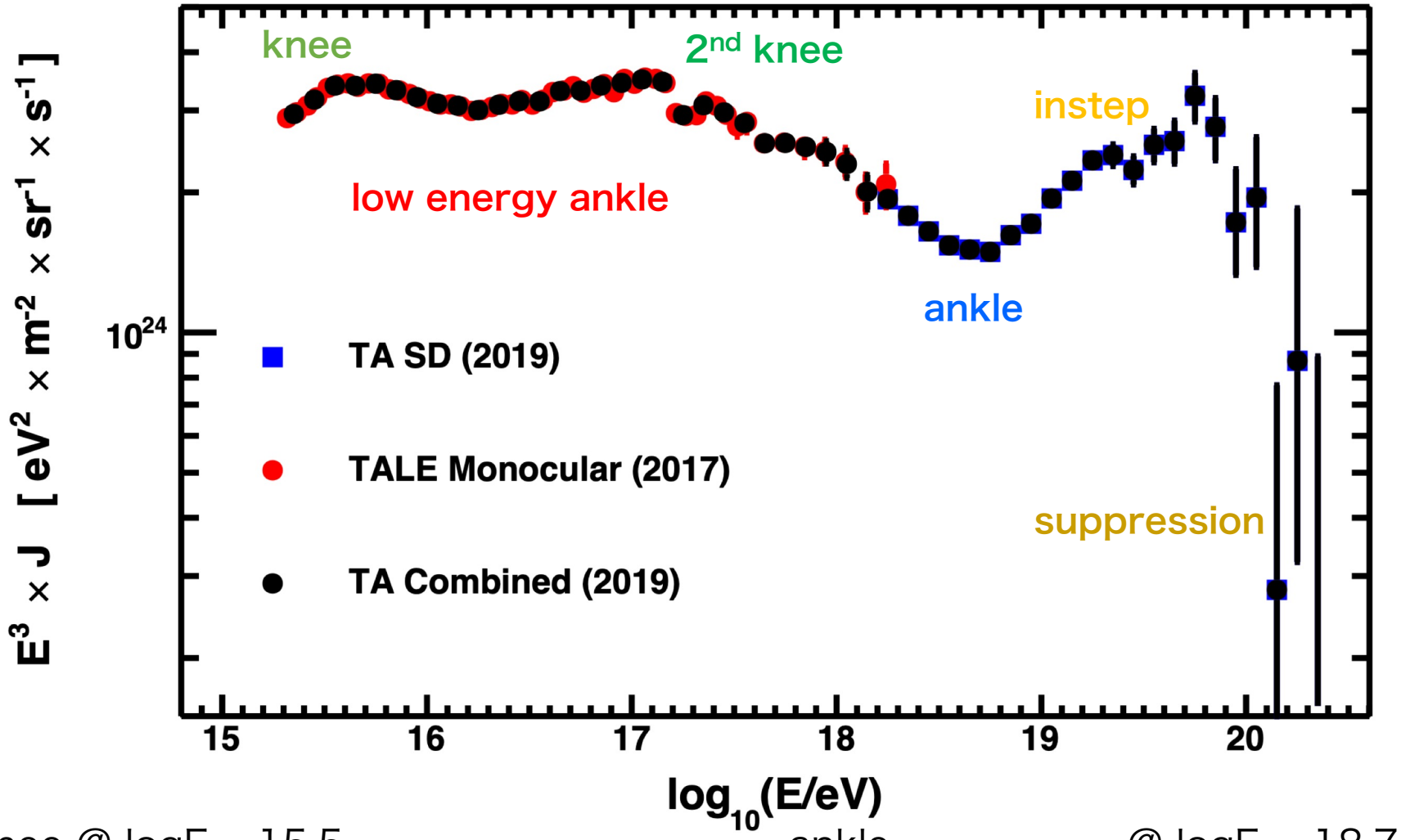
Fig. 2. Arrival direction of the high-energy event compared with potential sources. The arrival direction of the 27 May 2021 high-energy cosmic-ray particle (black circle) on a sky map in equatorial coordinates. Colored circles indicate calculated back-tracked directions assuming two models of the Milky Way regular magnetic field, labeled JF2012 (*31*) and PT2011 (*32*). For each model, different symbols indicate the directions calculated for four possible primary species: proton (P; red), carbon (C; purple), silicon (Si; green), and iron (Fe; blue).



No obvious source even if GMF deflection assuming

Energy Spectrum

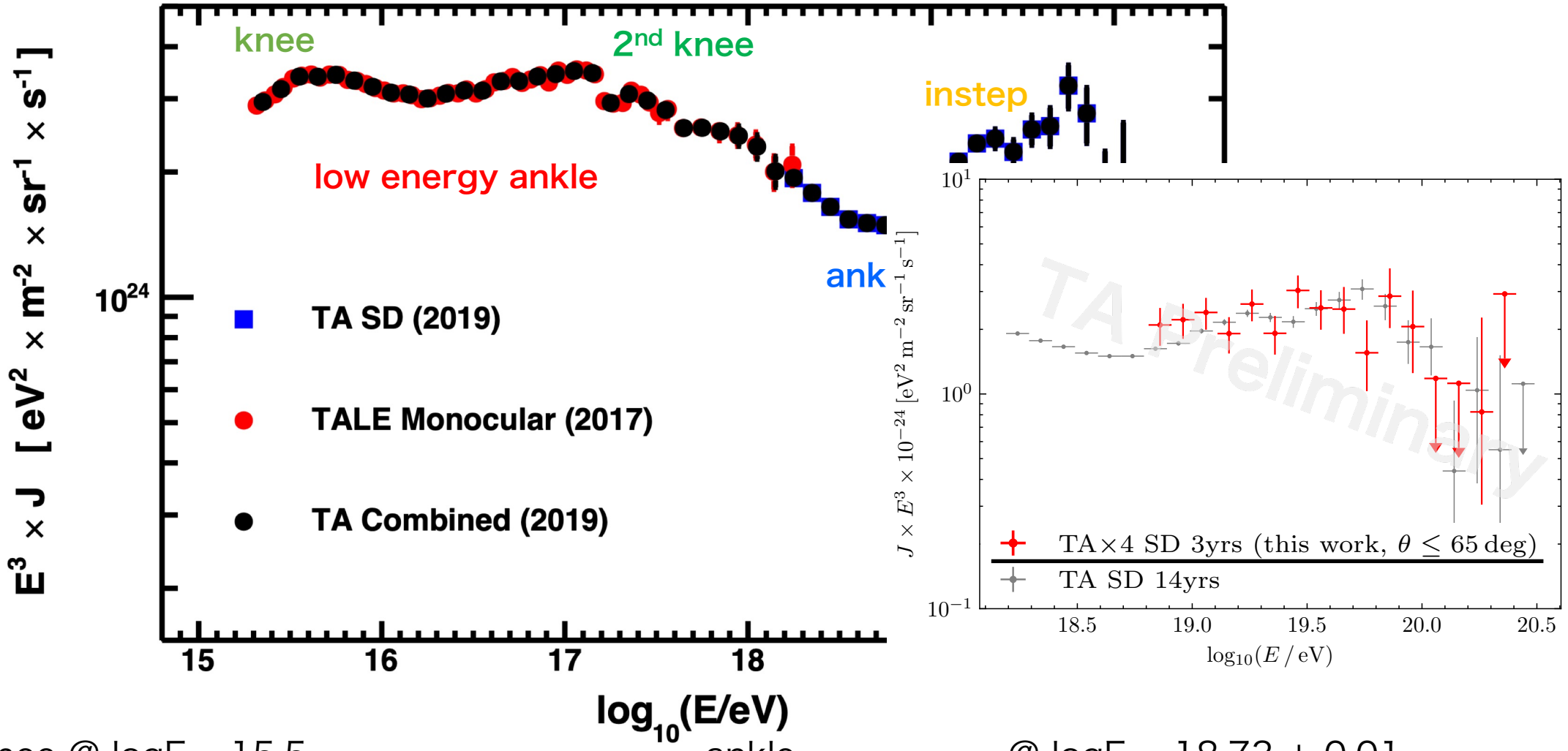
- 5 decades energy spectrum



knee @ logE ~ 15.5
low energy ankle @ logE = 16.22 ± 0.02
2nd knee @ logE = 17.04 ± 0.04
ankle @ logE = 18.73 ± 0.01
instep @ logE = 19.25 ± 0.03
cutoff @ logE = 19.85 ± 0.03

Energy Spectrum

- 5 decades energy spectrum



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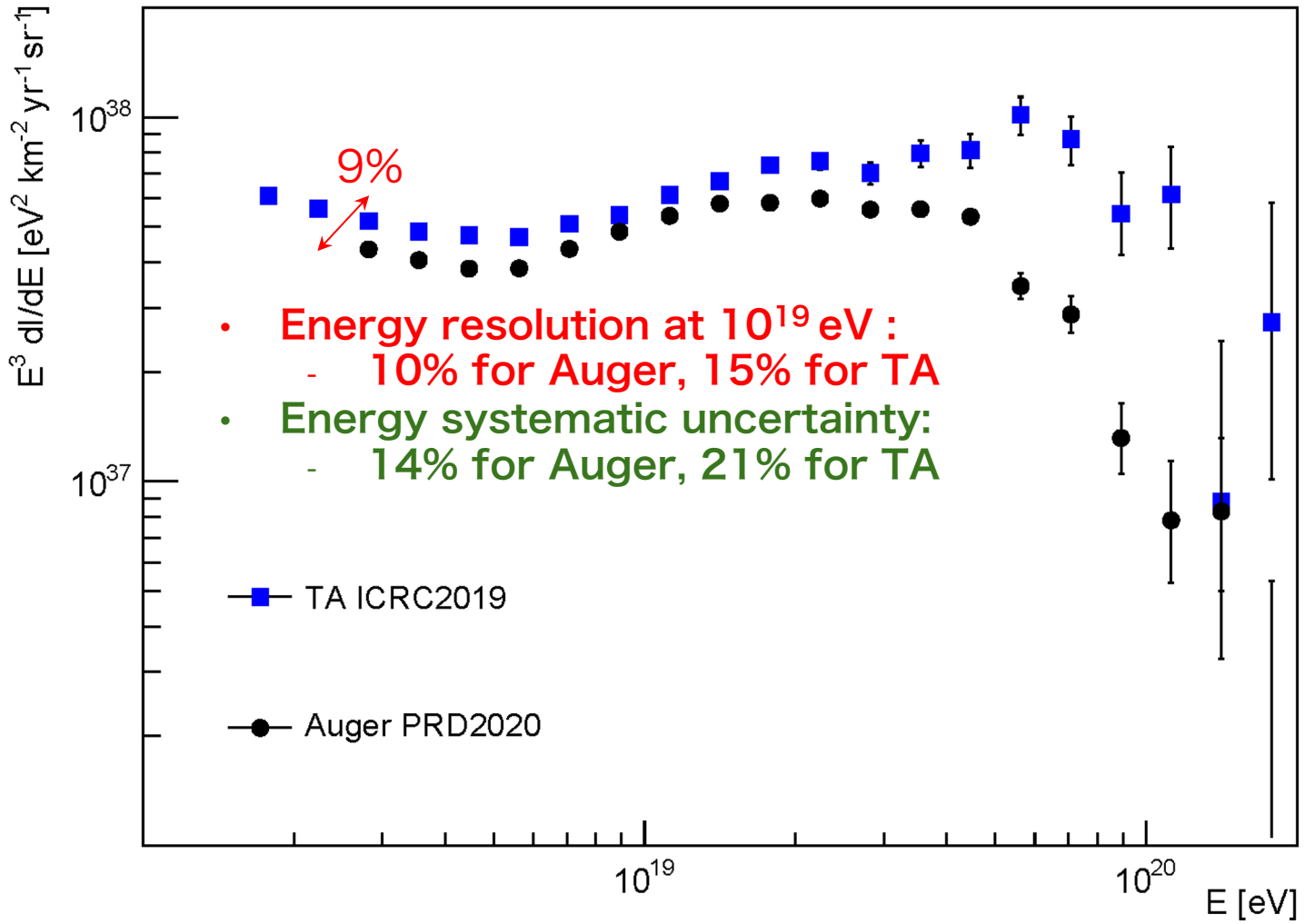
Energy Spectrum

- Focus on UHE region (E > 10^{18} eV)
  - comparison with Auger



difference between Auger and TA Spectra is ~9%, well within the uncertainty of either experiment

different energy reconstruction

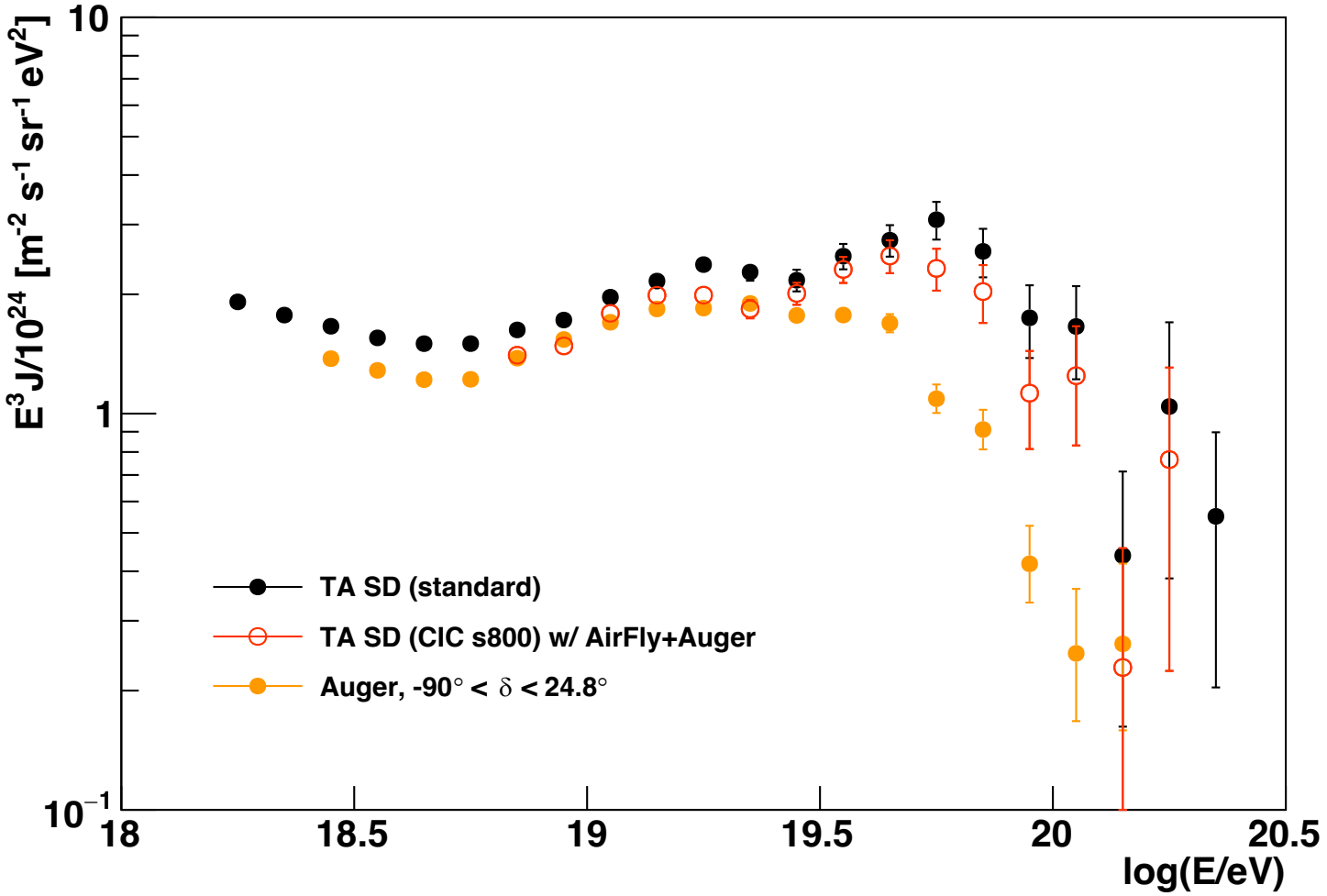
- fluorescence yield
  - TA/Auger ~ 1.14
- invisible energy correction
  - Auger: data-driven empirical formula
  - TA: estimated from proton MC
  - TA/Auger ~ 0.93
- energy estimation by SD
  - Auger: based on Constant Intensity Cut (CIC) - Data driven
  - TA: energy look-up table generated by proton MC

Tried reconstruction with same models as Auger, and CIC based energy estimation by TA

Energy Spectrum

- focus on UHE region (E > 10^{18} eV)
  - nice agreement within 1% below E = $10^{19.5}$ eV

TA SD Spectrum



difference between Auger and TA Spectra is ~9%, well within the uncertainty of either experiment

different energy reconstruction

- fluorescence yield
  - TA/Auger ~ 1.14
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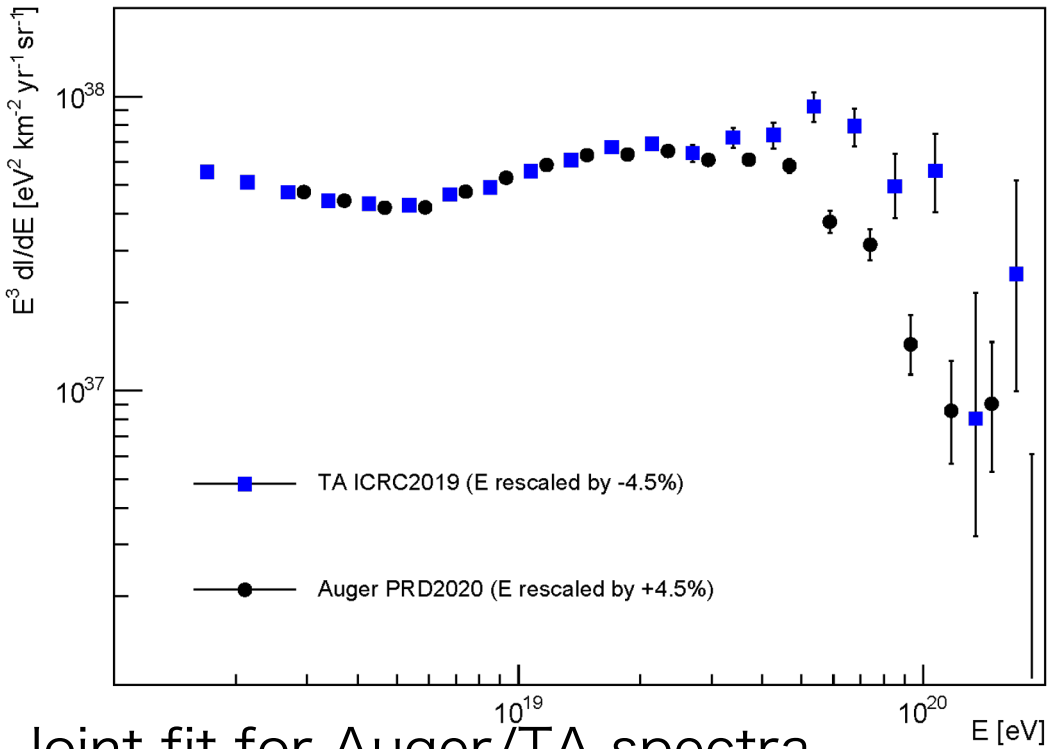
- energy estimation by SD
  - Auger: based on Constant Intensity Cut (CIC) - Data driven
  - TA: energy look-up table generated by proton MC

Tried reconstruction with same models as Auger, and CIC based energy estimation by TA (◯)

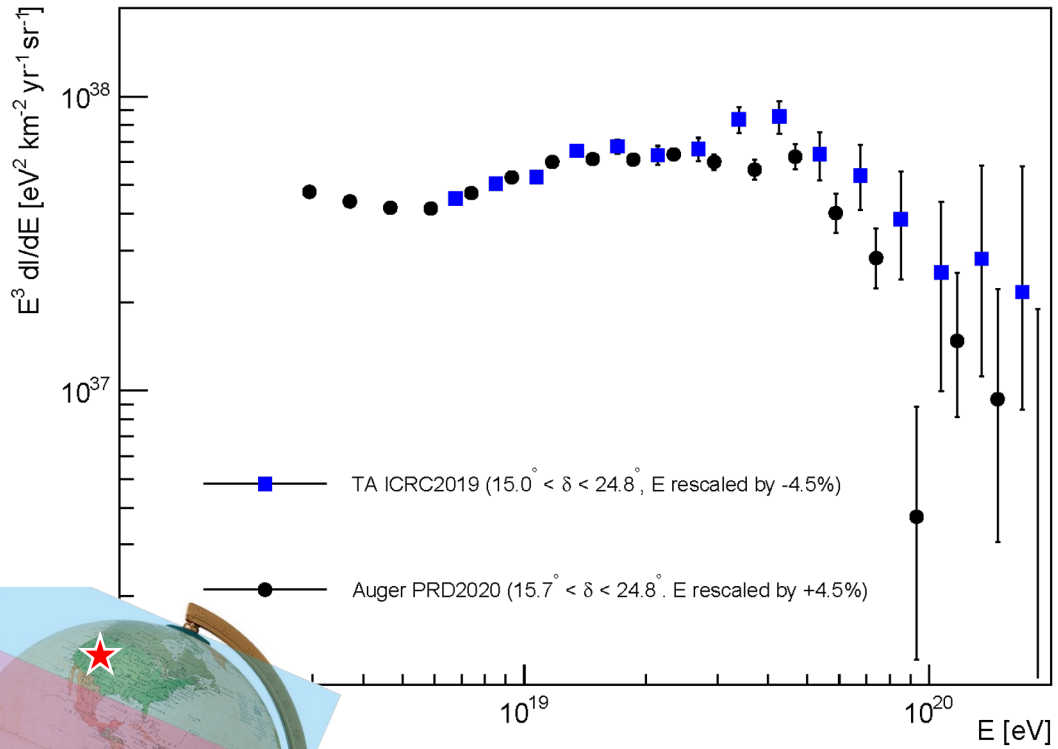
Energy Spectrum

- Focus on UHE region ($E > 10^{18}$ eV)
  - comparison with Auger

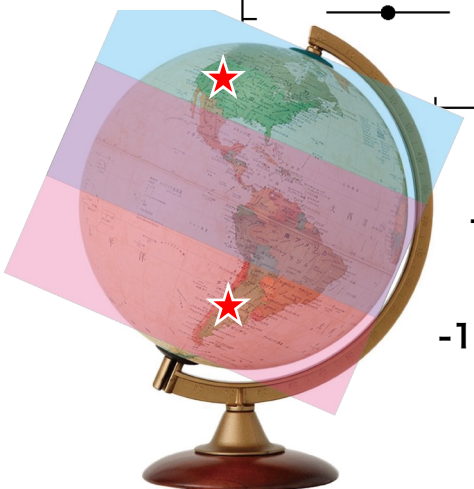
whole sky



common sky



- Joint fit for Auger/TA spectra
  - 8σ difference in whole sky
  - still 3σ difference in common sky



Auger: 35° S
- θ up to 60°

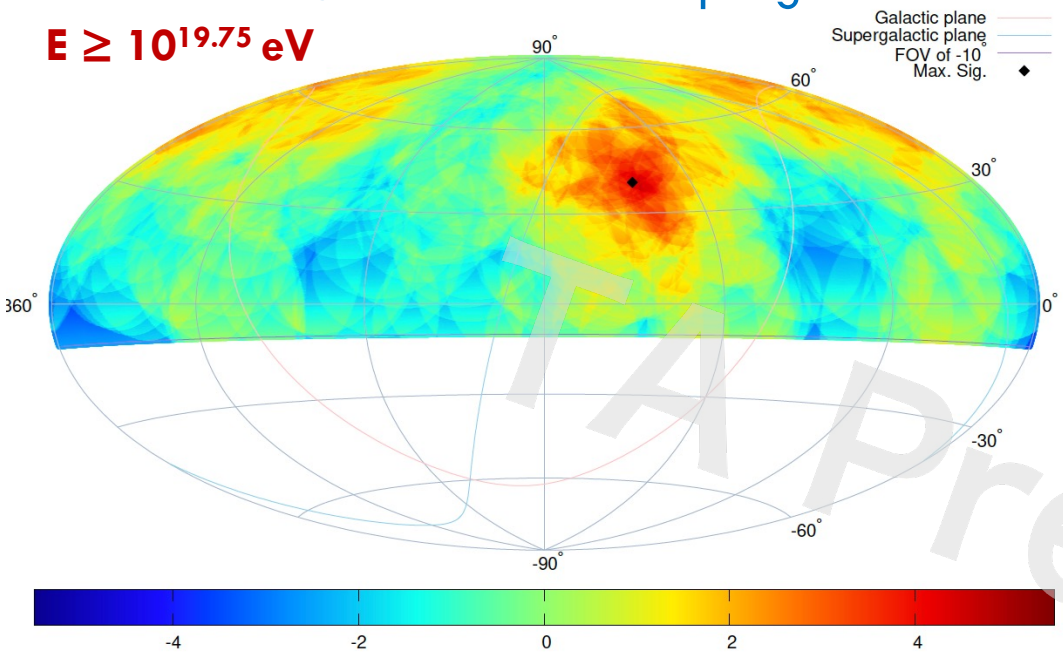
TA: 39° N
- θ up to 45°

Anisotropy

- anisotropy search

25°-radius oversampling

$E \geq 10^{19.75}$ eV



Deficit Li-Ma significance Excess

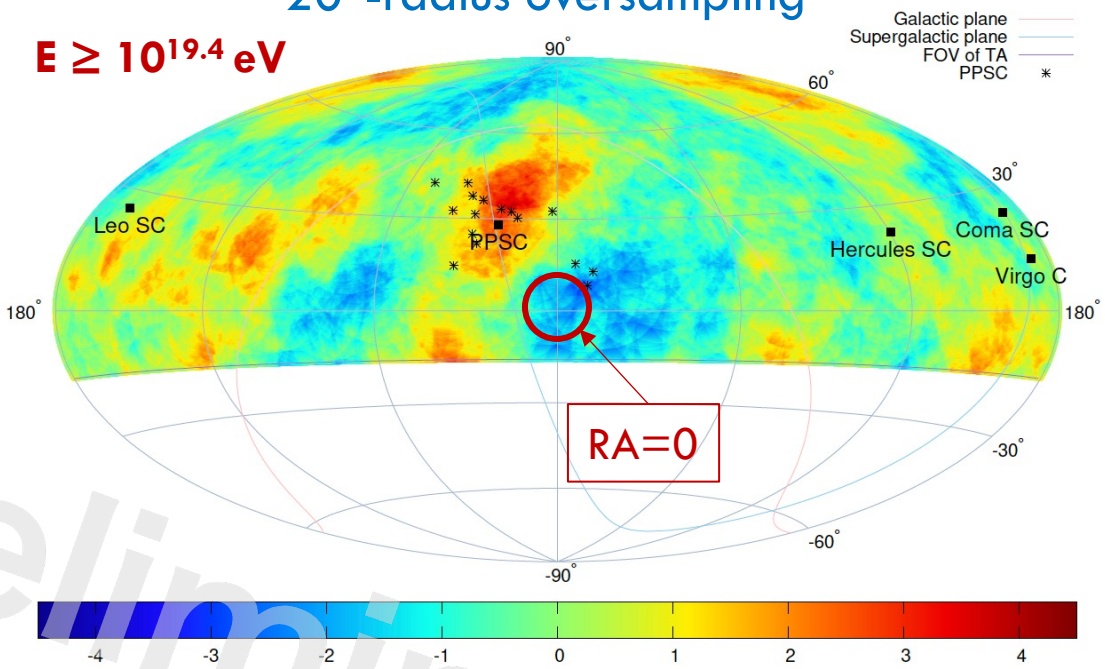
- 216 events (15-year TA SD data)
- Max local sig.: **4.8σ** at (144.0°, 40.5°)
  - Obs.: 44 events
  - N_{bg}: 18.0 events
- Post-trial probability:

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

Correlation with PPSC ?

20°-radius oversampling

$E \geq 10^{19.4}$ eV

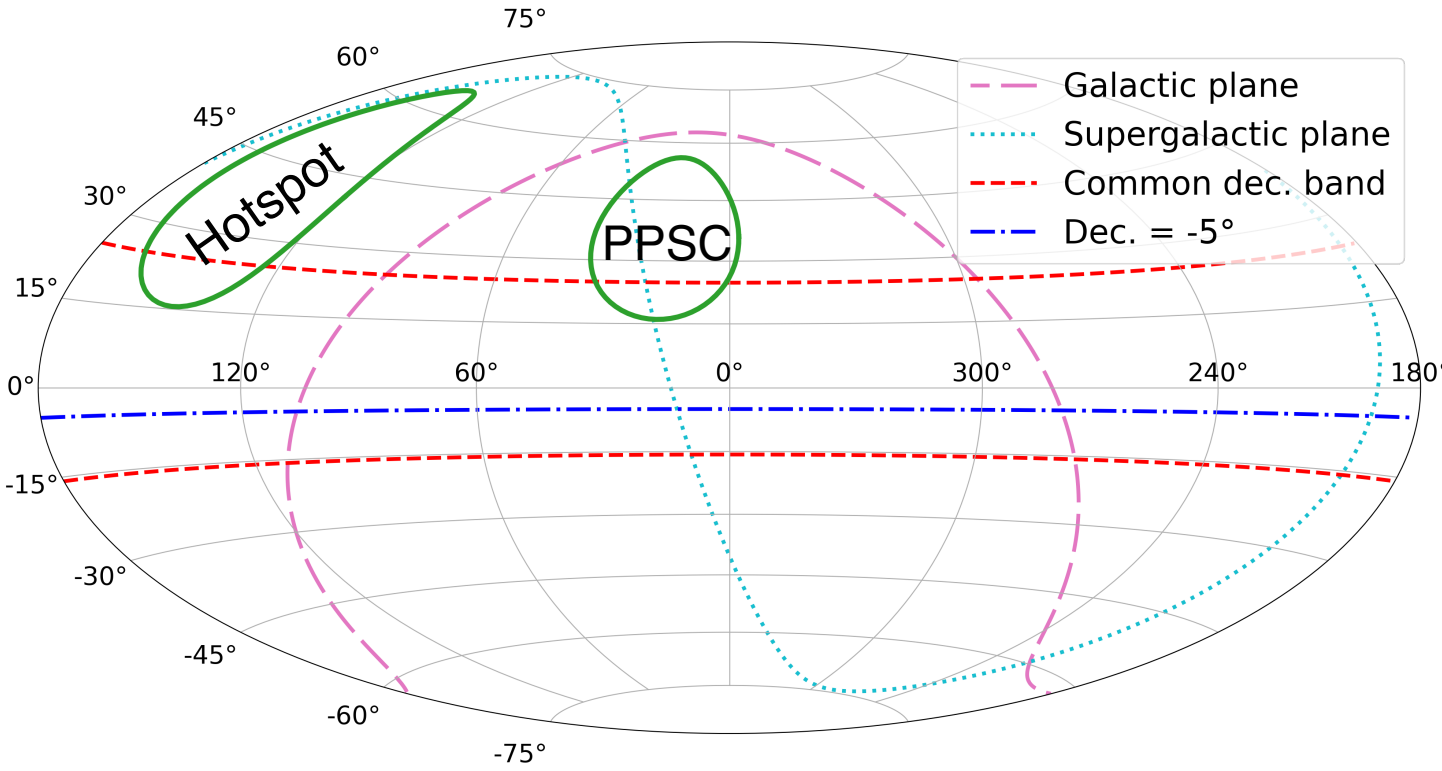


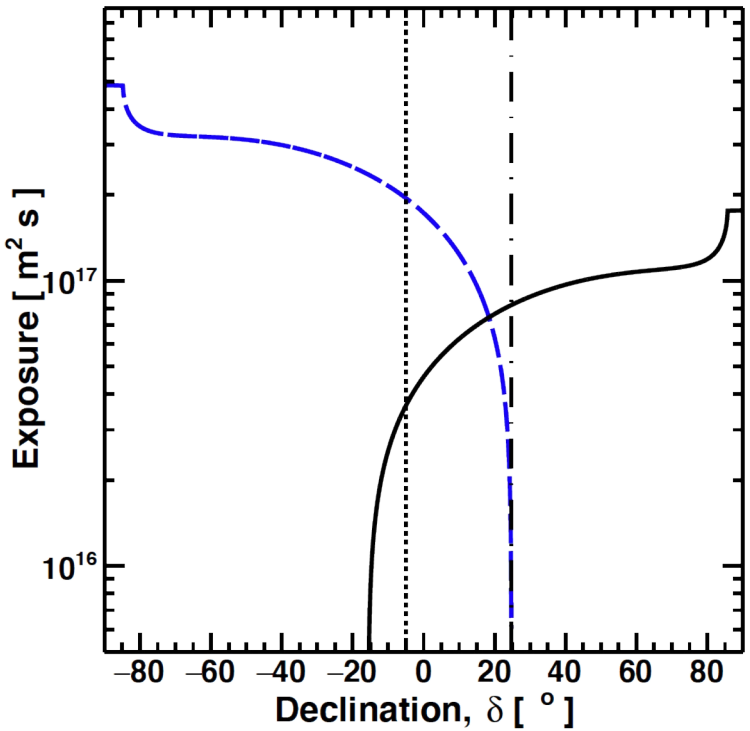
Deficit Li-Ma significance Excess

- 1125 events (15-year TA SD data)
- Li-Ma sig.: 4.0σ at (17.9°, 35.2°)
  - Obs.: 101 events
  - N_{bg}: 64.7 events
- Chance probability of having equal or higher excess on top of the PPSC → **3.3σ**

Energy Spectrum

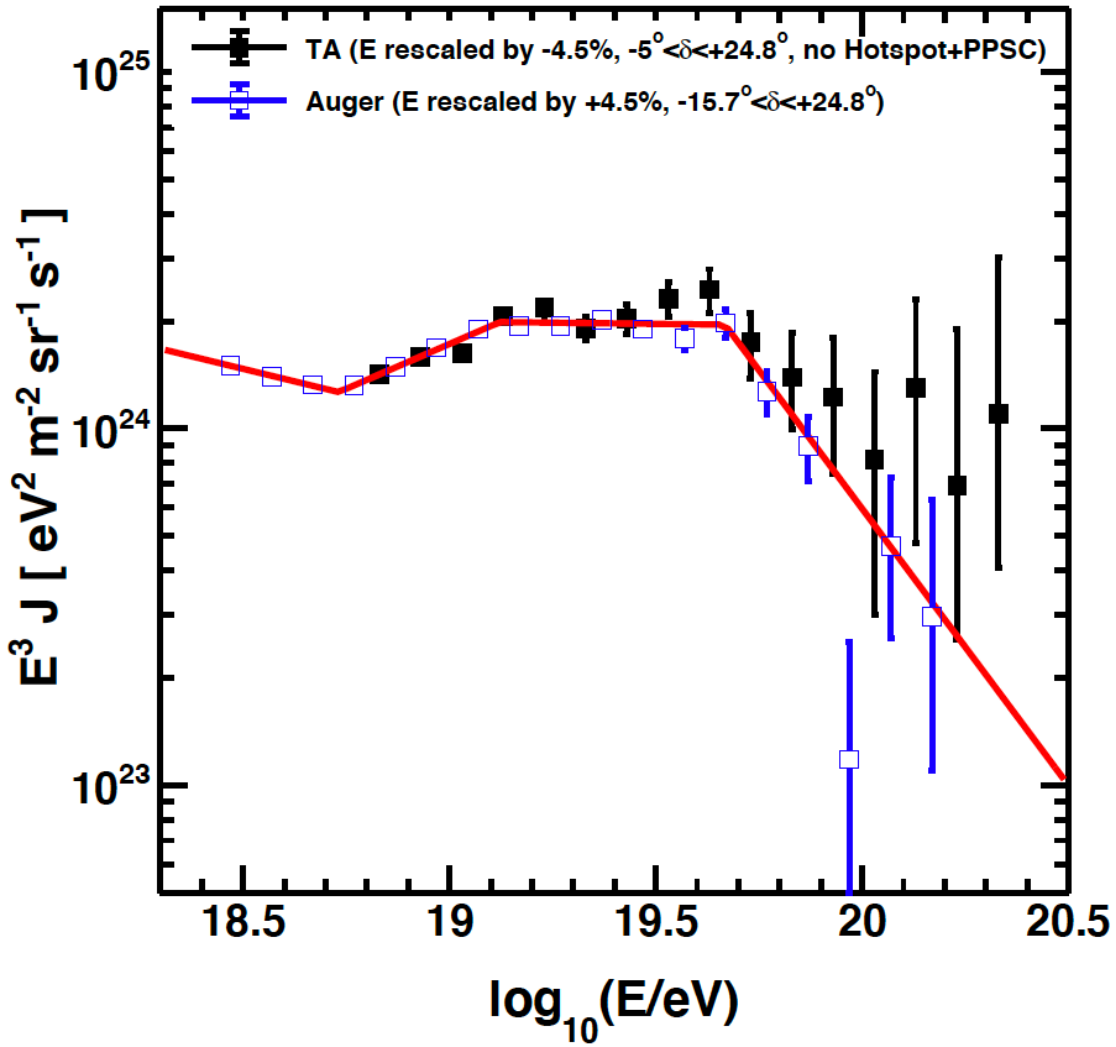
- Focus on UHE region (E > 10^{19} eV)
  - define the excess region
  - restrict common declination band ($-15.7° < \delta < 24.8° \rightarrow -5° < \delta < 24.8°$)
    - where rapidly drop off TA exposure





Energy Spectrum

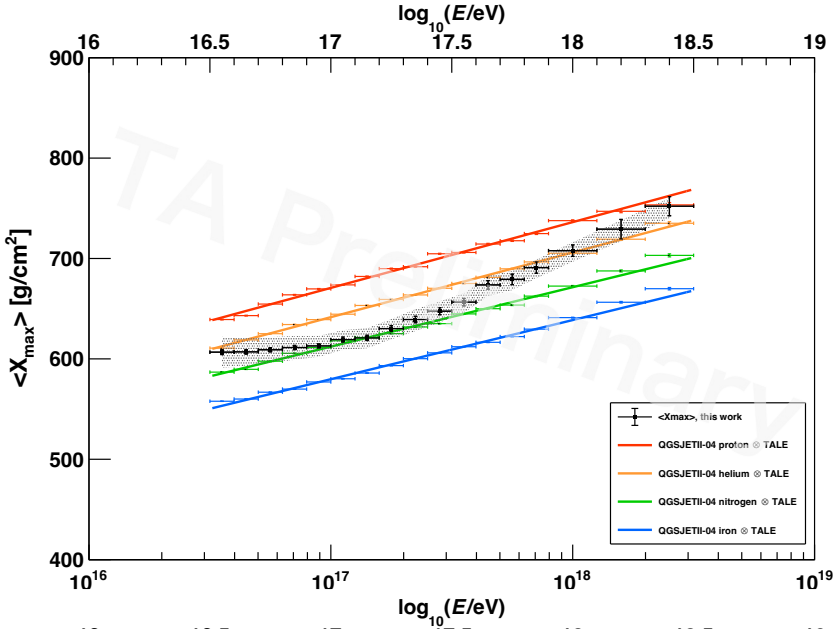
- Focus on UHE region (E > 10^{19} eV)
  - Auger ($-15.7° < \delta < 24.8°$) comparison with TA(no excess, $-5° < \delta < 24.8°$)
  - Joint fit for Auger/TA spectra: 1.8σ

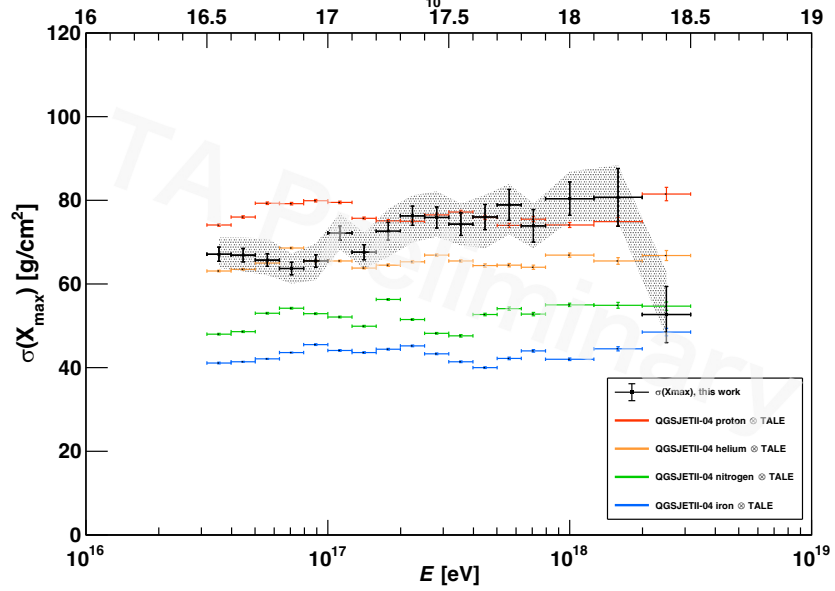


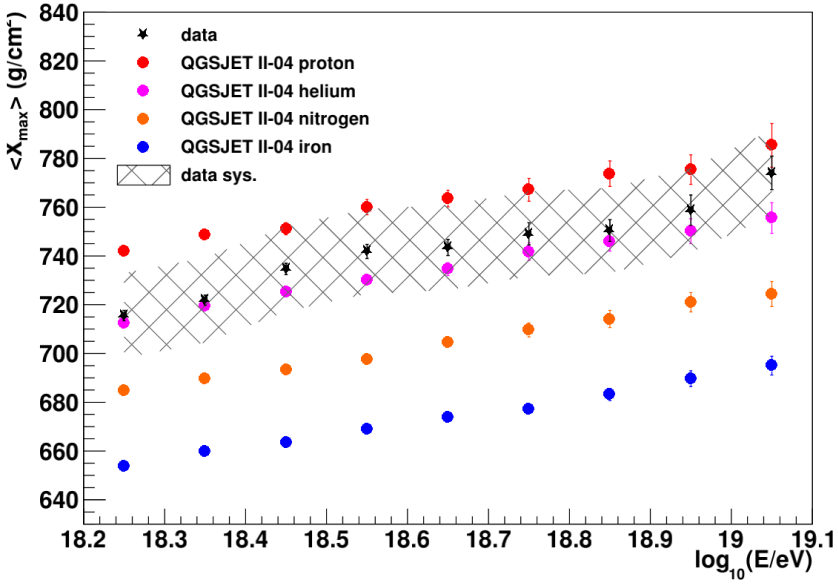
Mass Composition

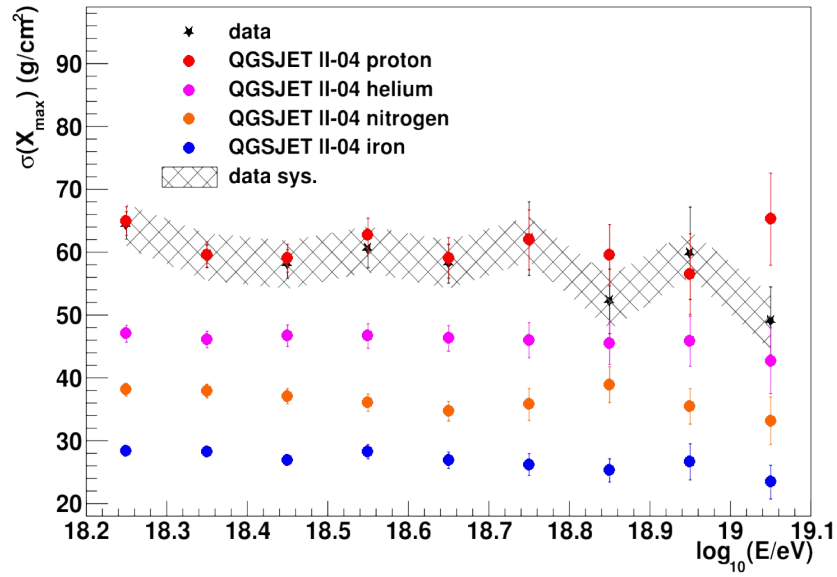
PoS(ICRC2019)280
PoS(ICRC2023)401

- Xmax measurement by TA and TALE hybrid mode









<Xmax> and Xmax dist. width(σ_{Xmax}) along with predictions of QGSJETII-04 proton, helium, nitrogen, iron

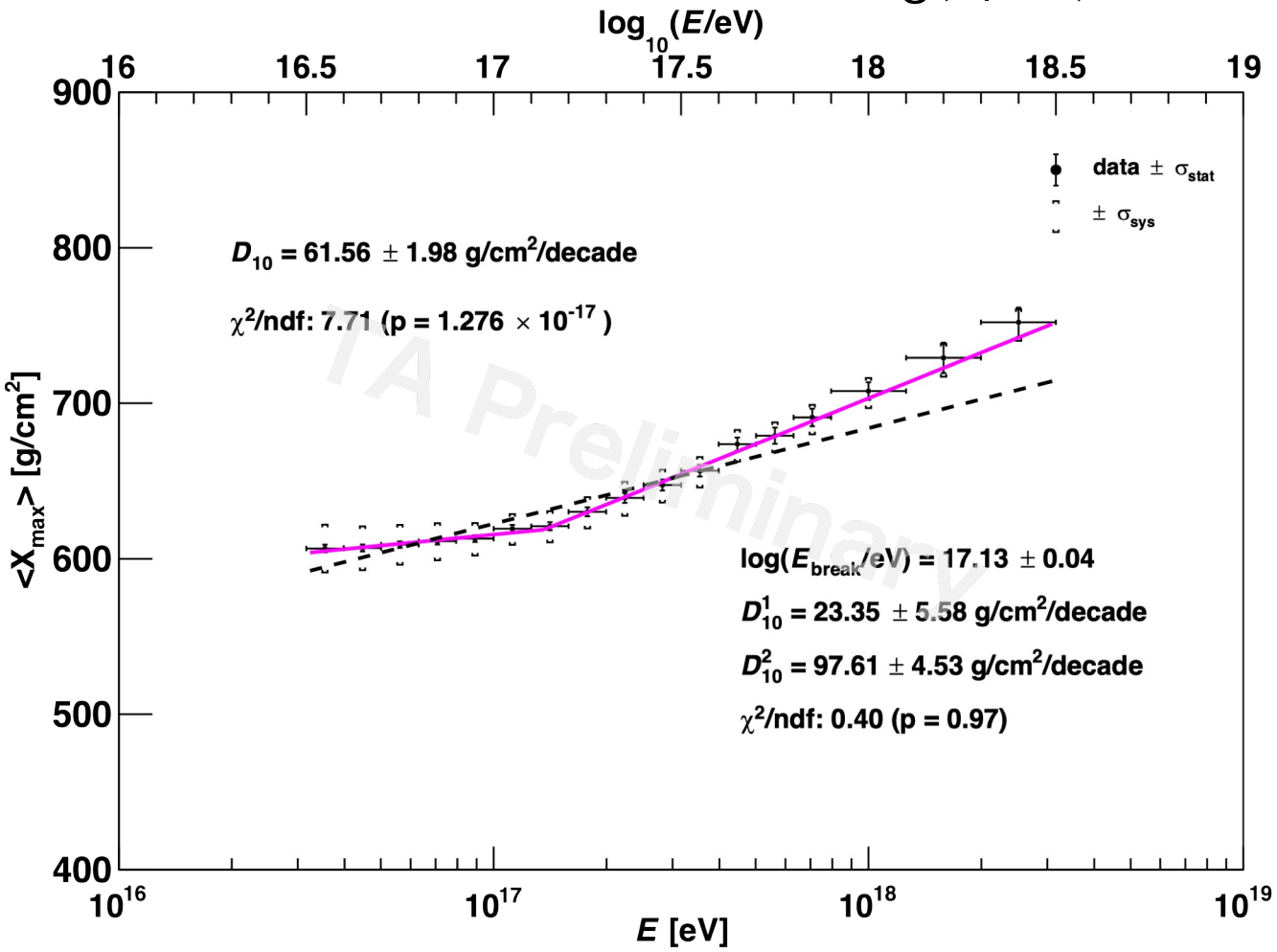
10yrs TA-Hybrid data $10^{18.2}$ to $10^{19.1}$ eV
3560 events after the quality cuts

5yrs TALE hybrid data $10^{16.5}$ to $10^{18.5}$ eV
9200 events after the quality cuts

$\langle X_{max} \rangle$: light → heavy → light
$\sigma(X_{max})$: constantly wide in all energies

Mass Composition

- Xmax measurement by TALE hybrid mode
- Measured $\langle X_{max} \rangle$ vs. shower energy
  - Nov. 2017 - Mar. 2023, 16.5 < log(E/eV) < 18.5



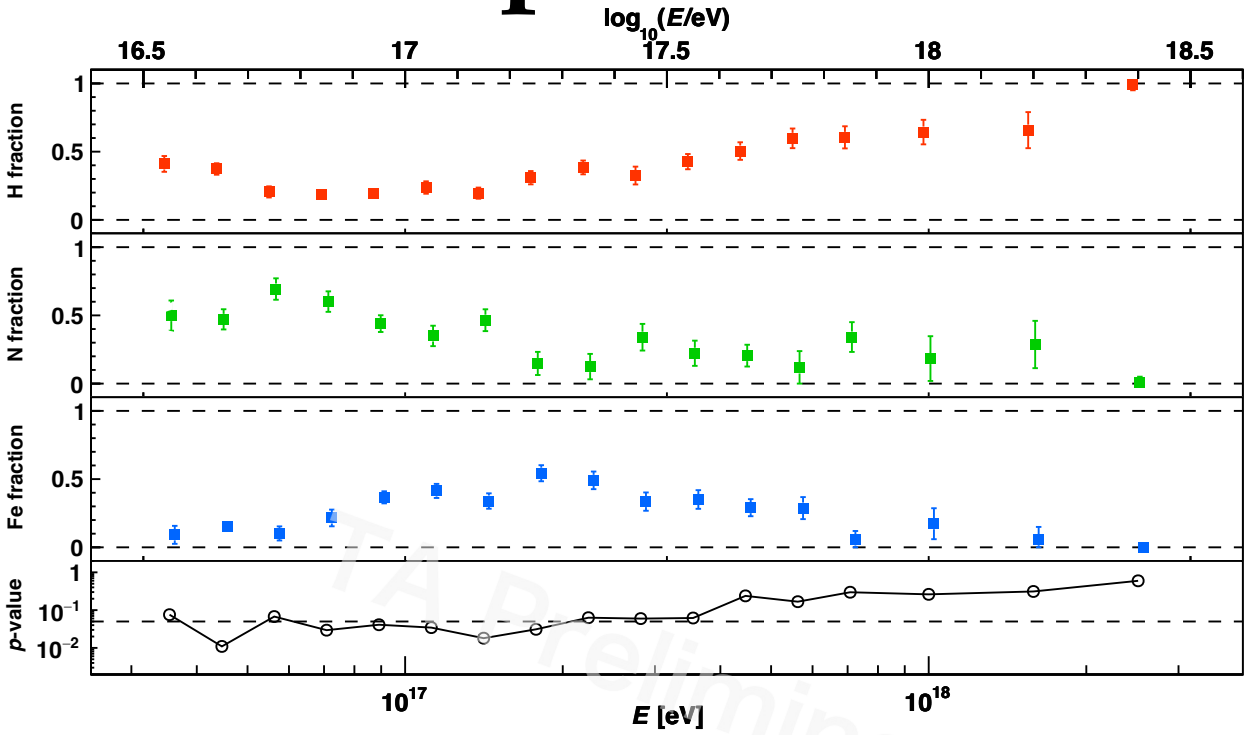
D_{10} = 62 ± 2 g/cm²/decade

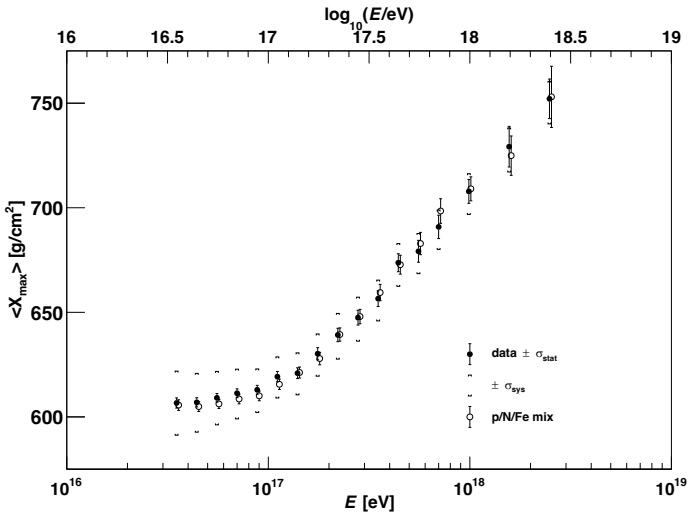
MC elongation rate [g/cm²/decade]

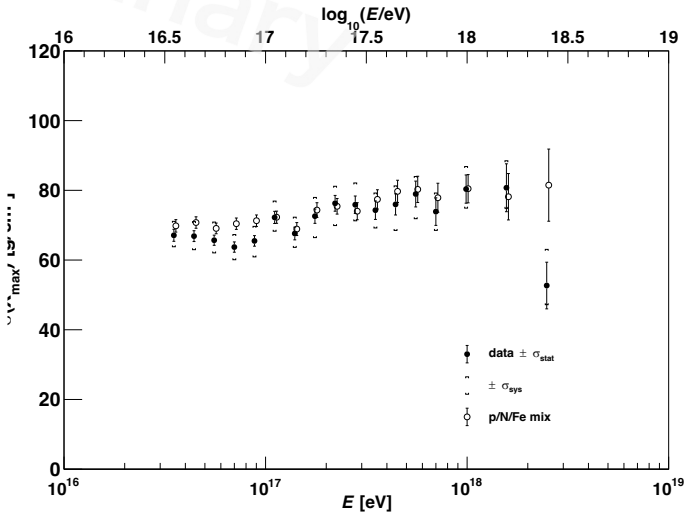
	proton	iron
D_{10}^{MC}	64 ± 2	61 ± 2

D_{10}^{before} = 23 ± 6 g/cm²/decade
D_{10}^{after} = 98 ± 5 g/cm²/decade
$\log_{10}(E_{break}/eV)$ = 17.1
~ 2nd knee

Mass Composition

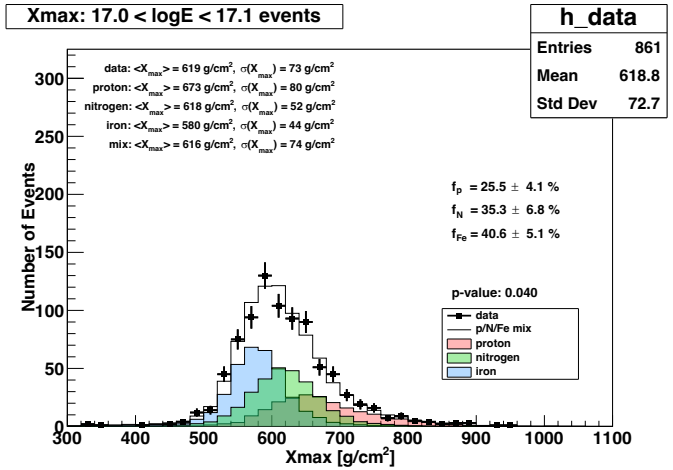






Energy evolution of nuclear fractions

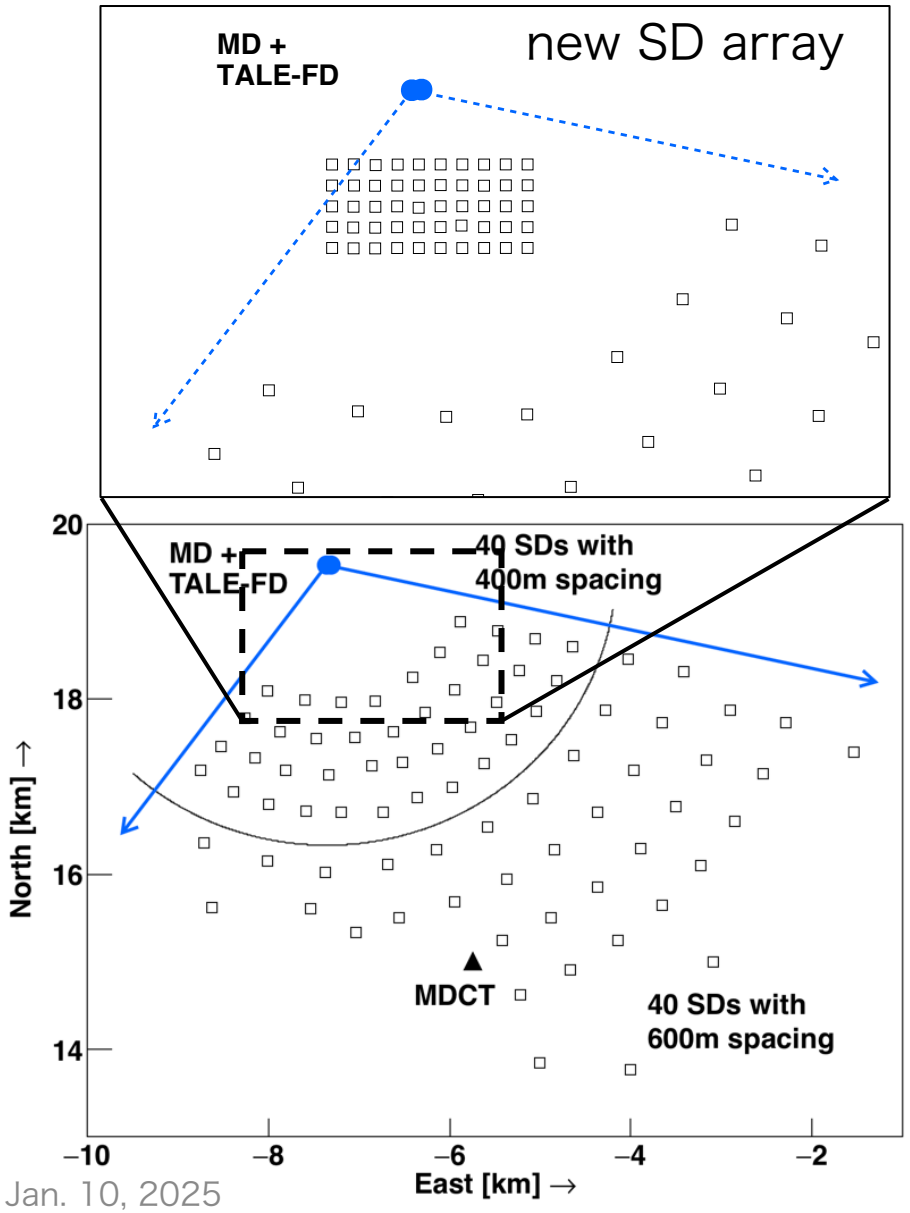
Fitting observed X_{max} distribution using MC (p/N/Fe) X_{max} distributions



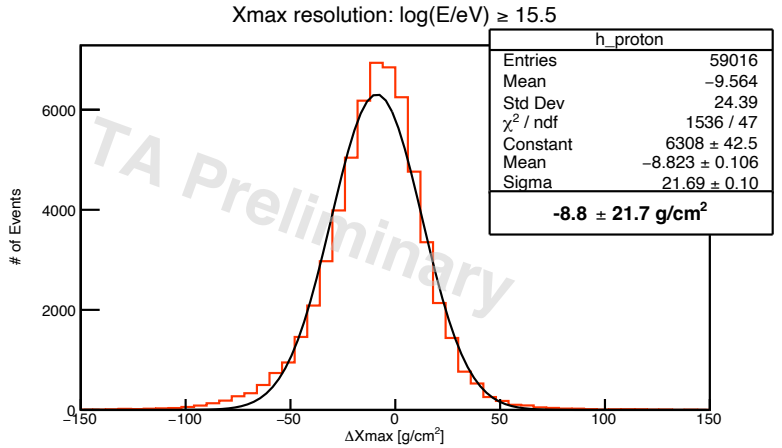
- proton
  - lowest fraction ~ 100 PeV
  - continue climb up to 3 EeV
- nitrogen
  - peak at ~ 50 PeV
  - low contribution in E >1 EeV
- iron
  - peak at ~ 150 PeV ~ 2nd knee
  - roughly 26/7x higher energy than nitrogen

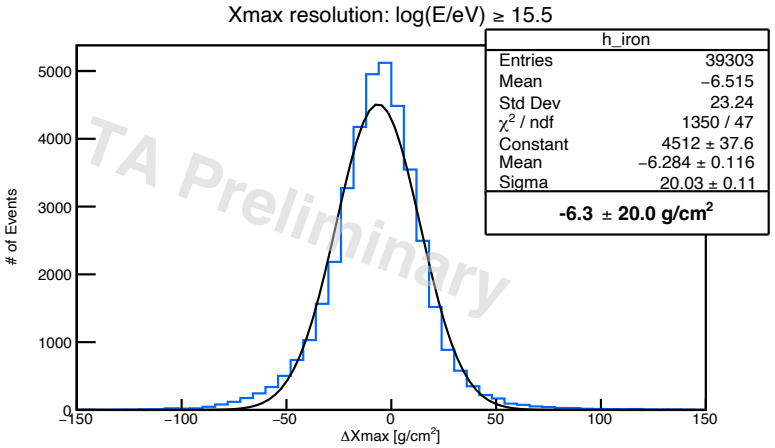
PeV measurement by TALE

- Upgrade TALE hybrid detector sensitivity down to PeV range



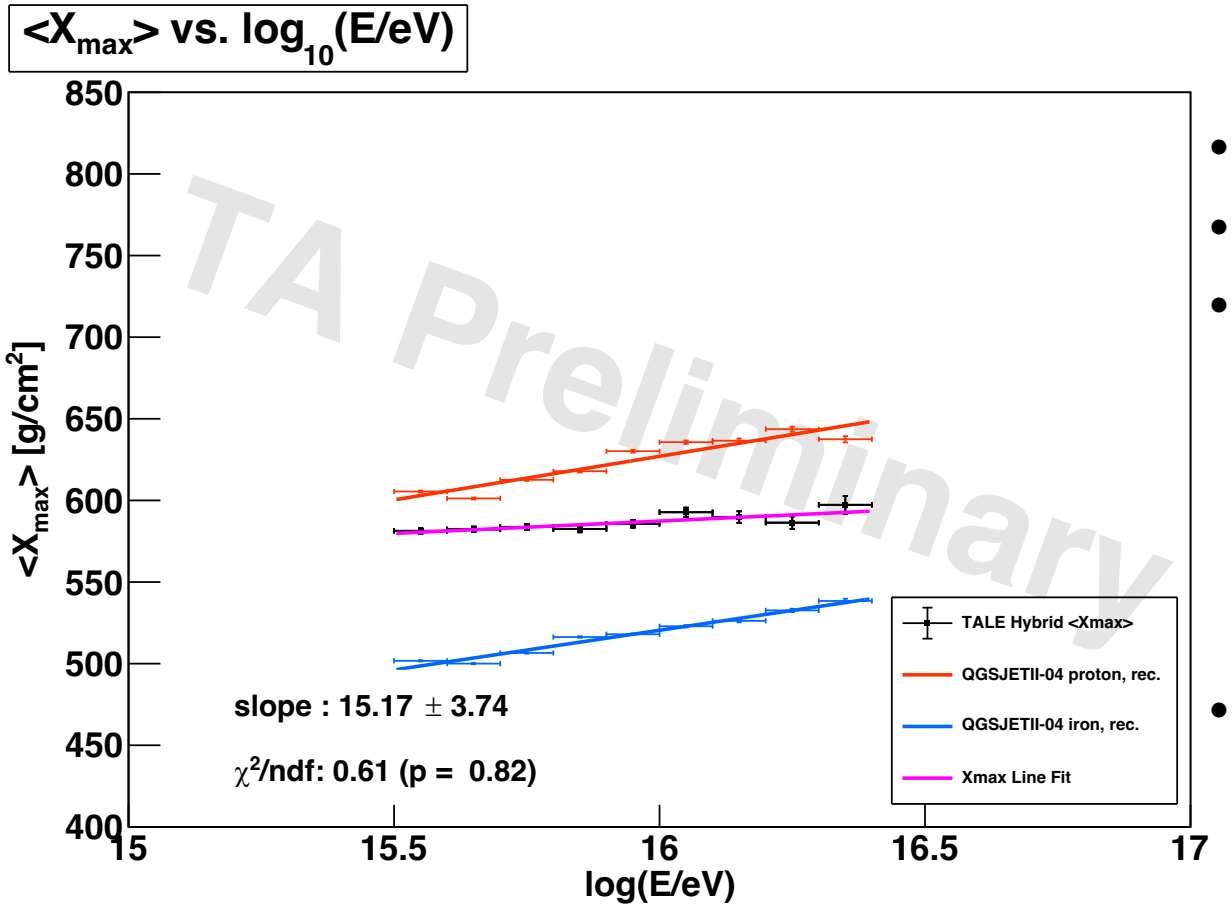
- Further dense SD array
  - **50**SDs with **100**m spacing
  - 2 layers Scintillation counter
  - trigger condition:
    5 adjacent SDs hit within 3μs
  - Started observation since Nov. 2023
  - duty cycle: > 98%
- Resolutions
  - $X_{\max}$ < 25 g/cm², Energy < 10%





PeV measurement by TALE

- Observed $\langle X_{\mathrm{max}} \rangle$ vs. shower energy
  - 540 hours observation data (Nov. 2023 - Jun. 2024)



- $\langle X_{\mathrm{max}} \rangle$ measurement with TALE FD + new SD array
- Energy range: 15.5 < log(E/eV) < 16.4
- Elongation rate
  - observation data: D_{10} = 15 ± 4 g/cm²/decade
  - MC case [g/cm²/decade]

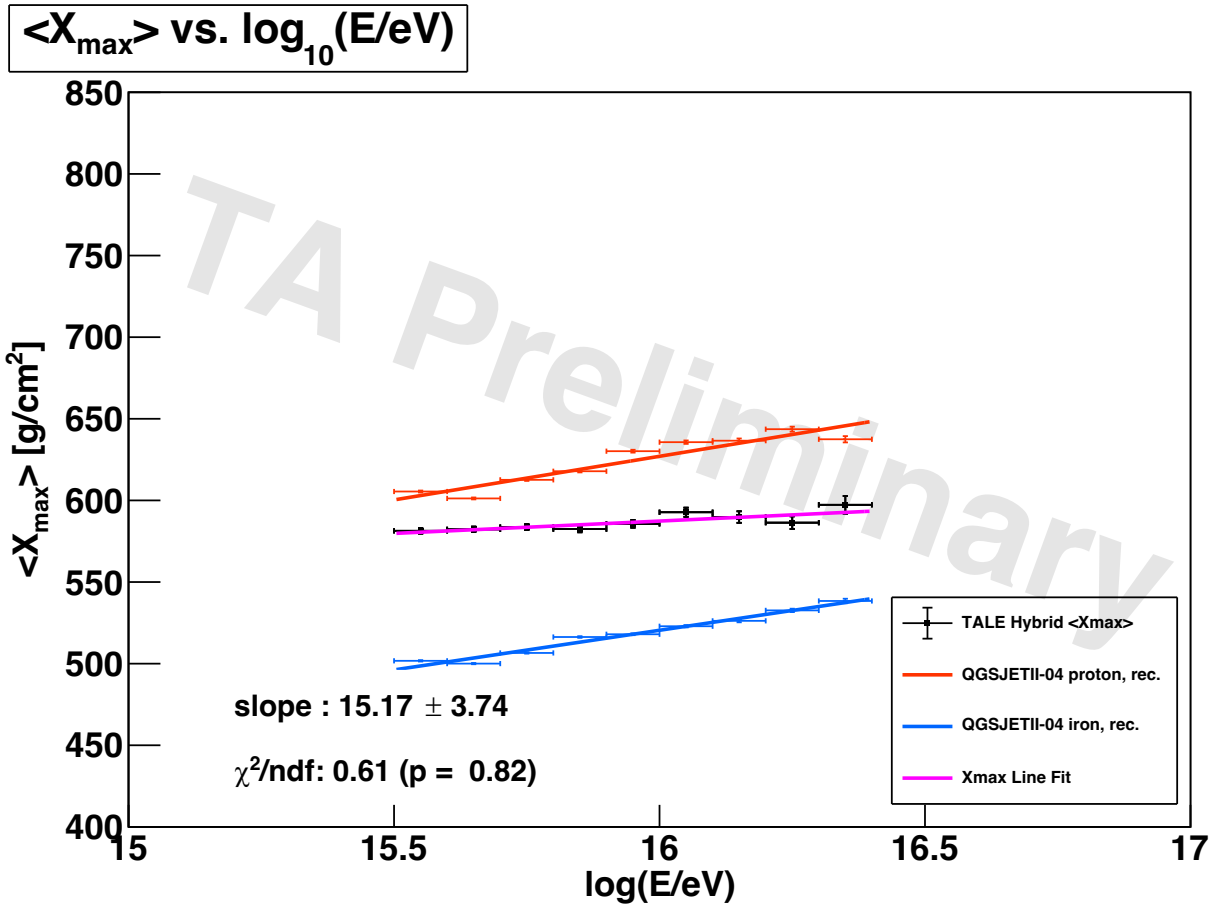
	proton	iron
D_{10}^{MC}	53 ± 2	48 ± 2

- This work indicates mean mass becomes heavier as the energy increases

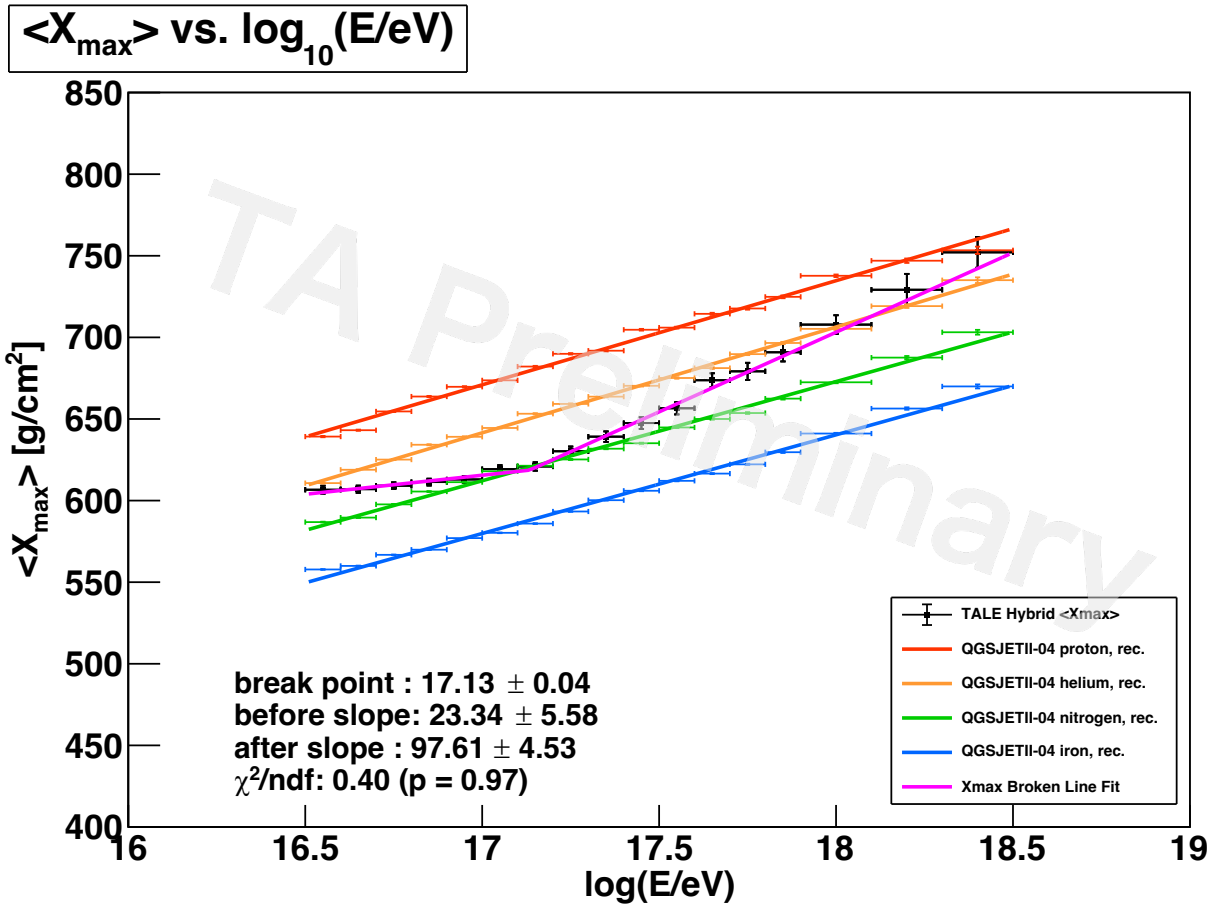
PeV measurement by TALE

- Observed $\langle X_{\mathrm{max}} \rangle$ vs. shower energy

TALE FD + new SD array hybrid measurement



TALE FD + TALE SD array hybrid measurement

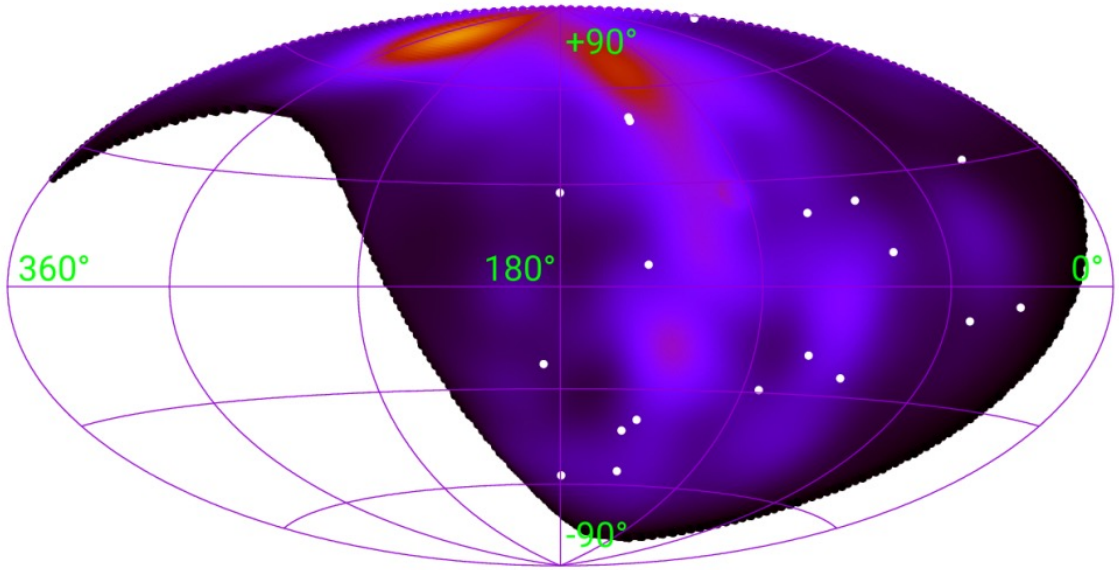


Elongation rates indicate mean mass show light -> heavy -> light
Covering energy range 15.5 < log(E/eV) < 18.5 by hybrid measurement

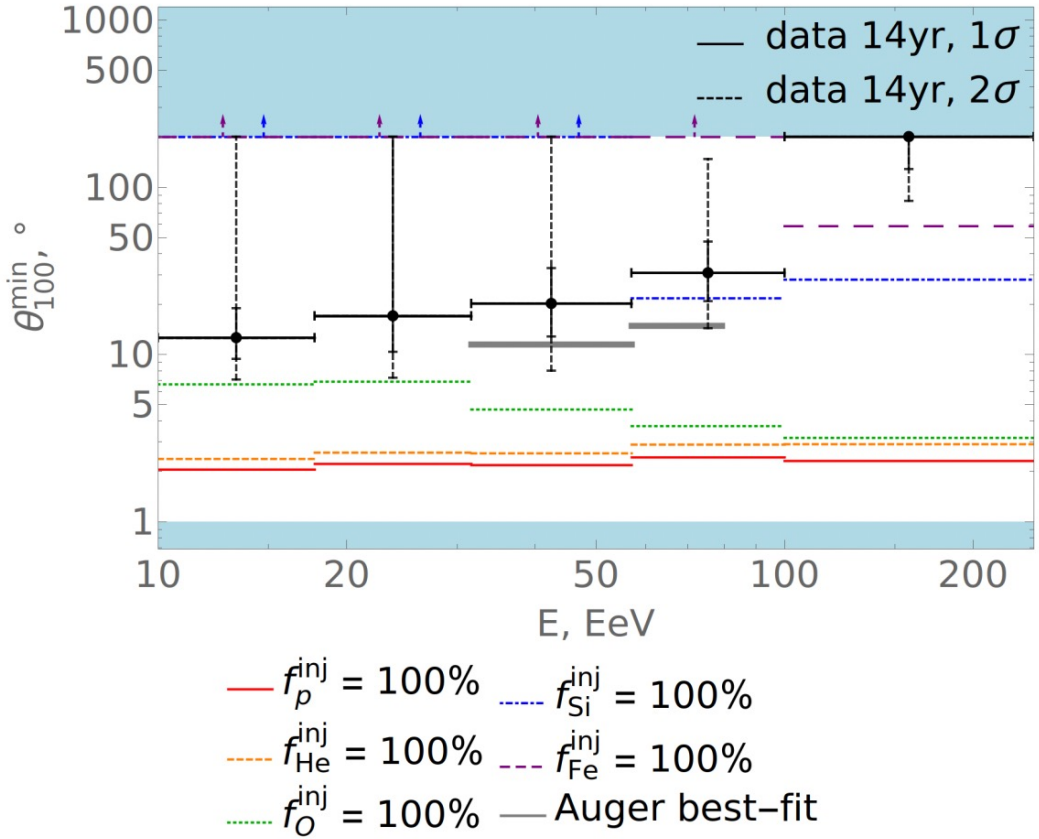
Arrival direction × mass composition

PRL 133(2024) 041001 24
PRD 110(2024) 022006

- Assumption: UHECR sources follow LSS, delivered from 2MRS catalog
  - eliminate galaxies beyond 250 Mpc
- Simulate realistic UHECR mock datasets originating LSS with various injection mass composition, considering GMF, etc.
- Calculate smearing angle θ from LSS



Example flux map with $\theta = 10°$ smearing angle from LSS, overlaid with the distribution of the TA SD events with E > 100 EeV



Events with E > 100 EeV imply heavy mass composition

Conclusions

- We have been operating the Telescope Array for more than 16 years
  - Combination of SDs and FDs
- Energy Spectrum
  - Spectrum measurements over 5 orders-of-magnitude in energy
  - 8σ difference HE spectrum between TA and Auger in the full field of view
  - Difference within common band can be reduced to 1.8σ by cutting excesses and exposure edge
- Mass Composition
  - X_{max} measurement in energy range of $10^{15.5}$ eV to 10^{19} eV by hybrid detection
  - light -> heavy -> light pattern observed
  - Arrival direction above $E > 10^{20}$ eV imply heavy mass composition
- Future
  - TAx4 to improve statistics especially for Anisotropy and Composition measurements