Overview of Cosmic Ray Measurements with the Telescope Array

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

Nov. 05, 2025

Keitaro Fujita

on behalf of the Telescope Array Collaboration

TeV Particle Astrophysics

(TeVPA 2025)

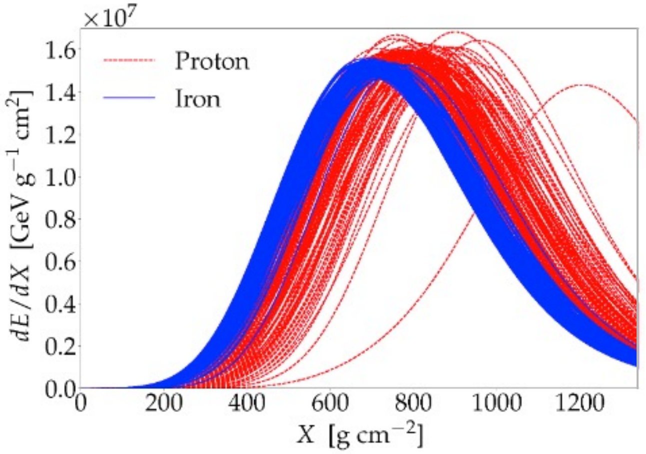
3 – 7 November, 2025

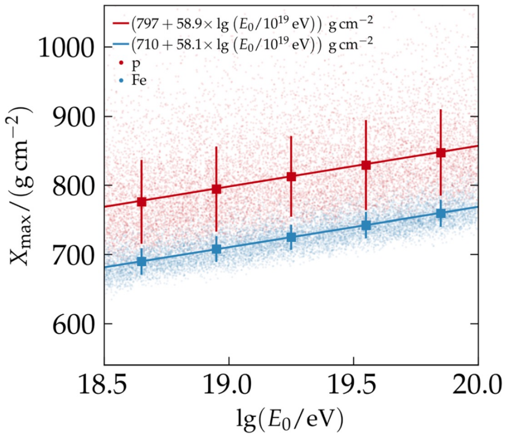
Valencia, Spain

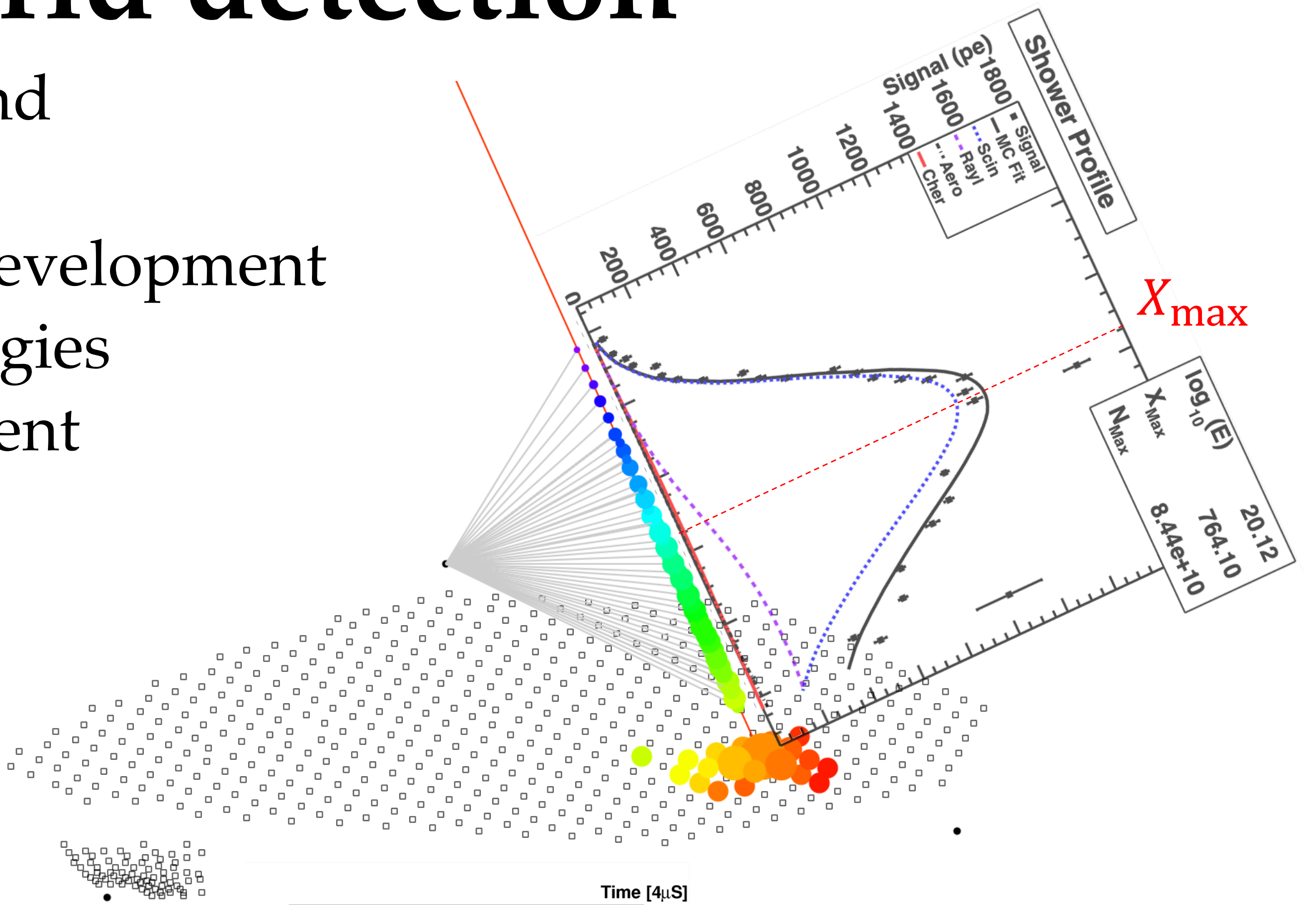
Institute for Cosmic Ray Research
University of Tokyo

Key Technique → Hybrid detection

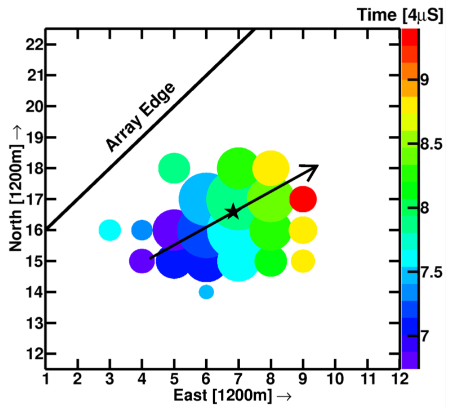
- Combination of Surface Detectors (SD) and Fluorescence Detectors (FD)
- FD: Capable of measuring longitudinal development
  - Calorimetric measurement of CR energies
  - Mass composition by X_{max} measurement

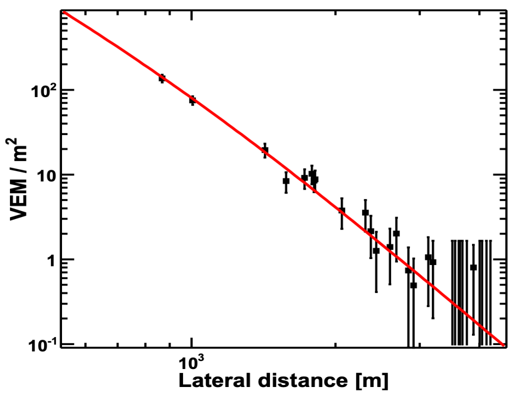






- SD: 100% duty cycle
  - high statistics -> spectrum, anisotropy
  - Calibrated SD energy to FD





Telescope Array

2008

TA

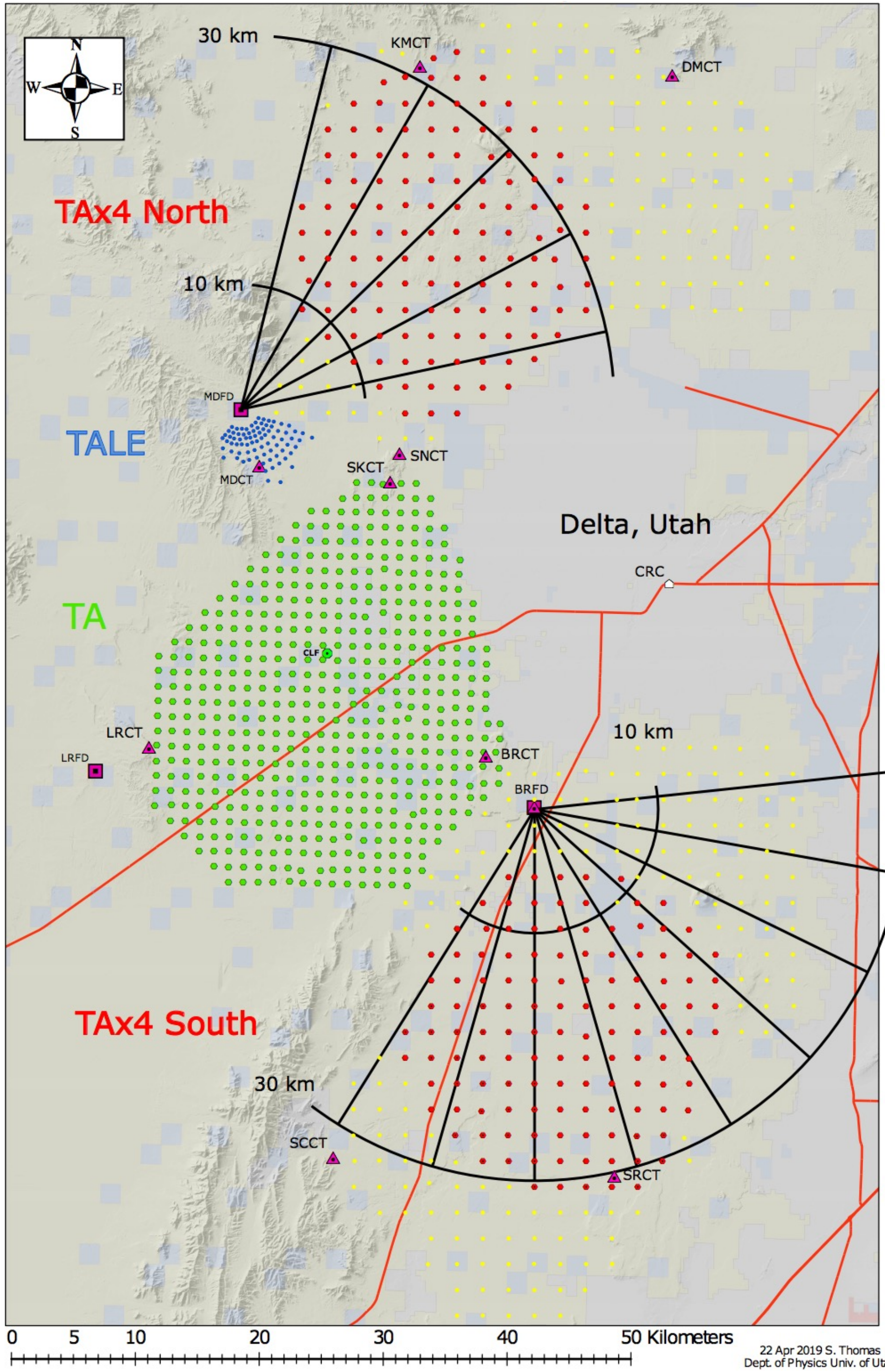
2019

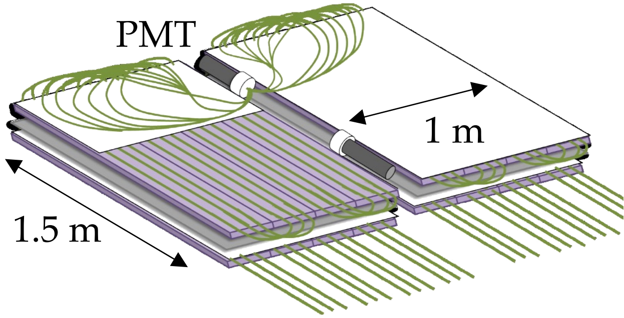
- TA starts 2008

@ Utah, US

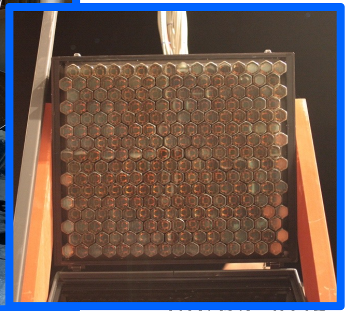
39° N, 113° W

  - SD: ●
    - plastic scintillator
    - 507 SDs, 700km²
    - 1.2km space
  - FD: ■
    - **3** sites
    - 38 telescopes
- TAx4 starts 2019
  - extend SD coverage by a factor of **four**
  - additional 257 SDs(●), 2.08km + 12 telescopes

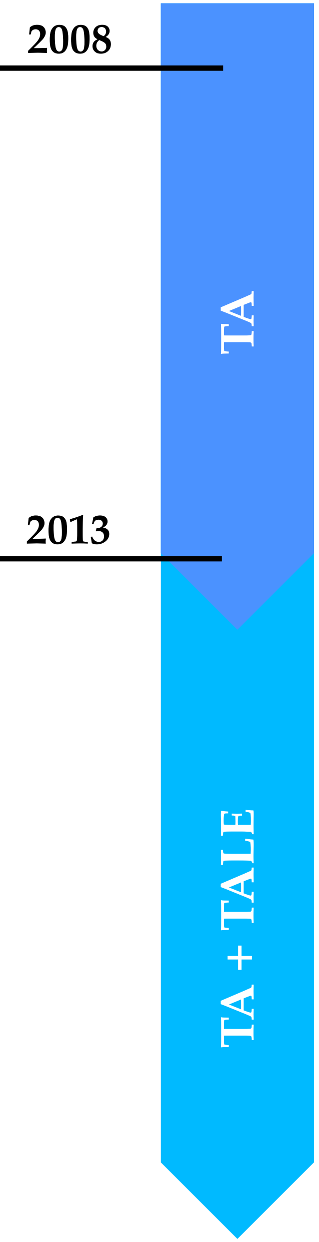




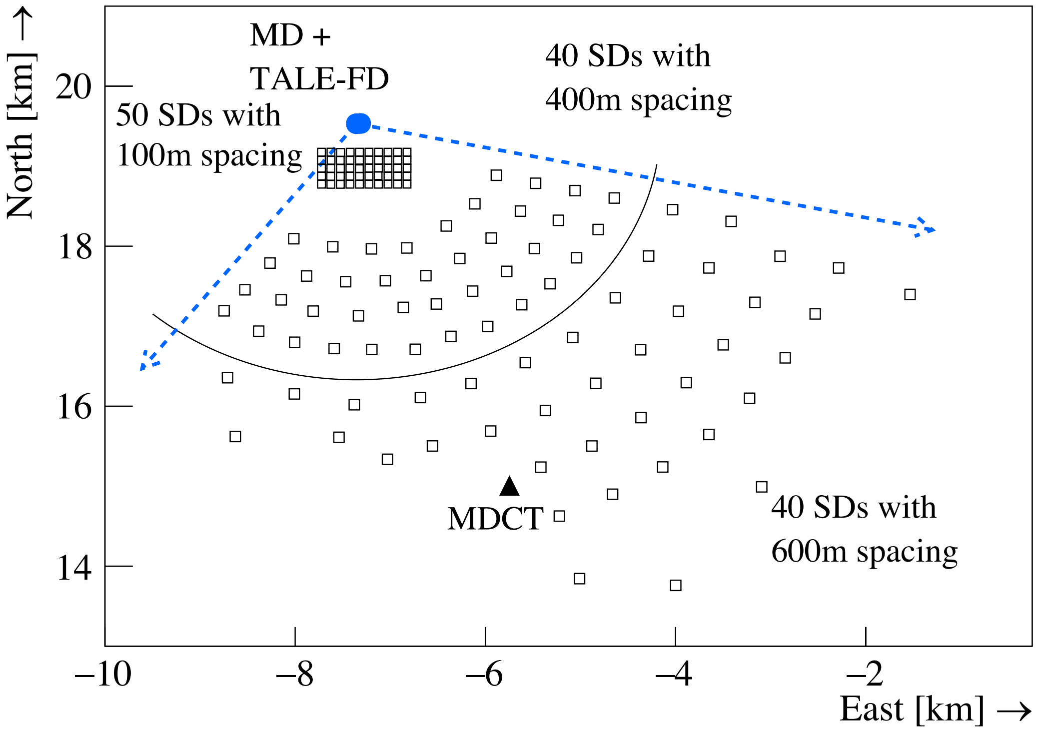
Segmented mirrors
256 hexagonal PMTs / camera



Telescope Array Low-energy Extension



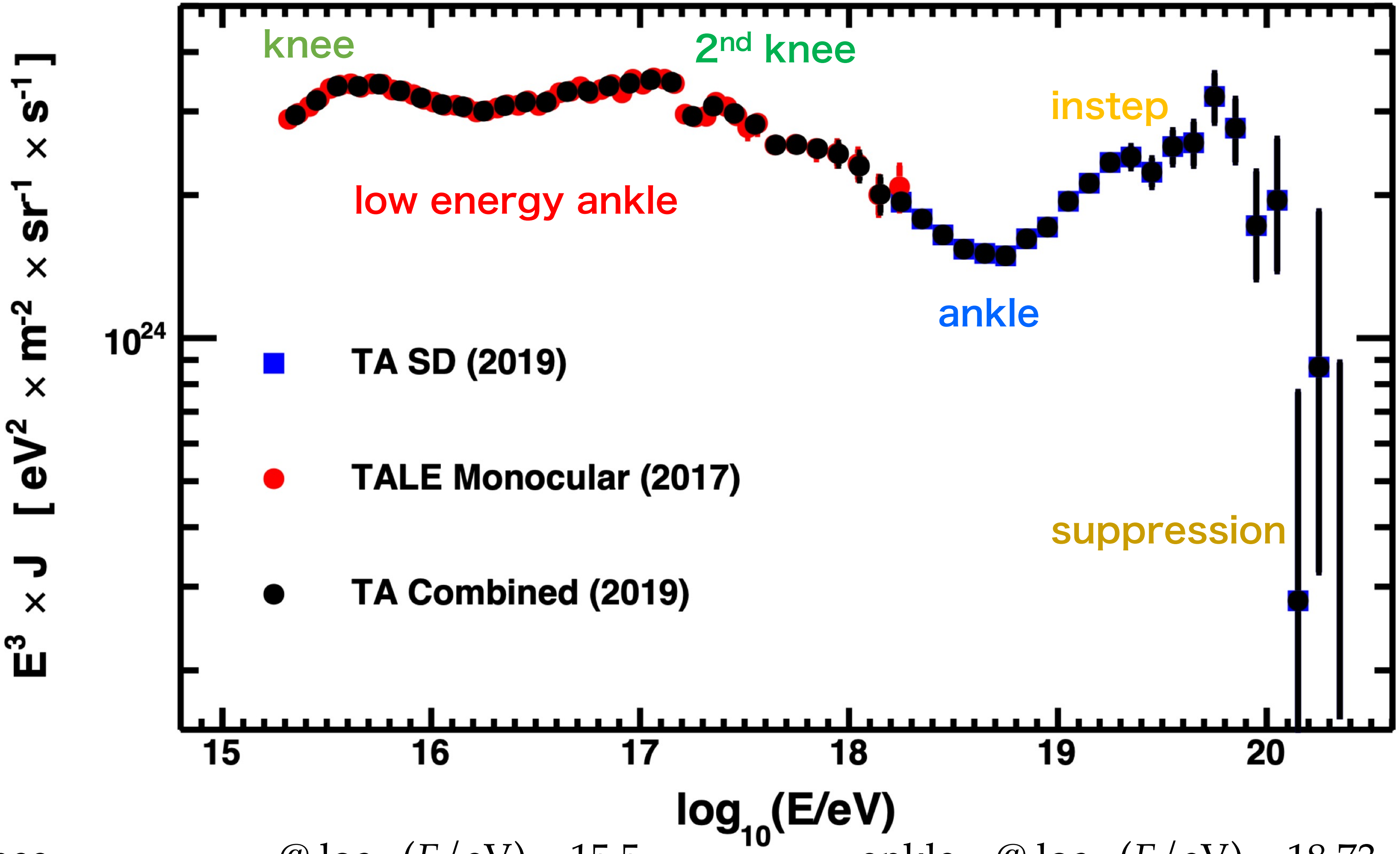
- Extension in lower energies by hybrid detector → **TALE**



- 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
  - 400m spacing of 40 SDs
    600m spacing of 40 SDs
  - Newly add 100m spacing of 50 SDs in 2022
- Operation: FD since Sep. 2013
  SD since Nov. 2017
  100m SD array since Nov. 2023
- Energy range coverage:
  TALE FD: ~1 PeV < E < 3 EeV
  100m array: ~1 PeV < E < 100 PeV
  400m + 600m array: E > 30 PeV

Energy Spectrum

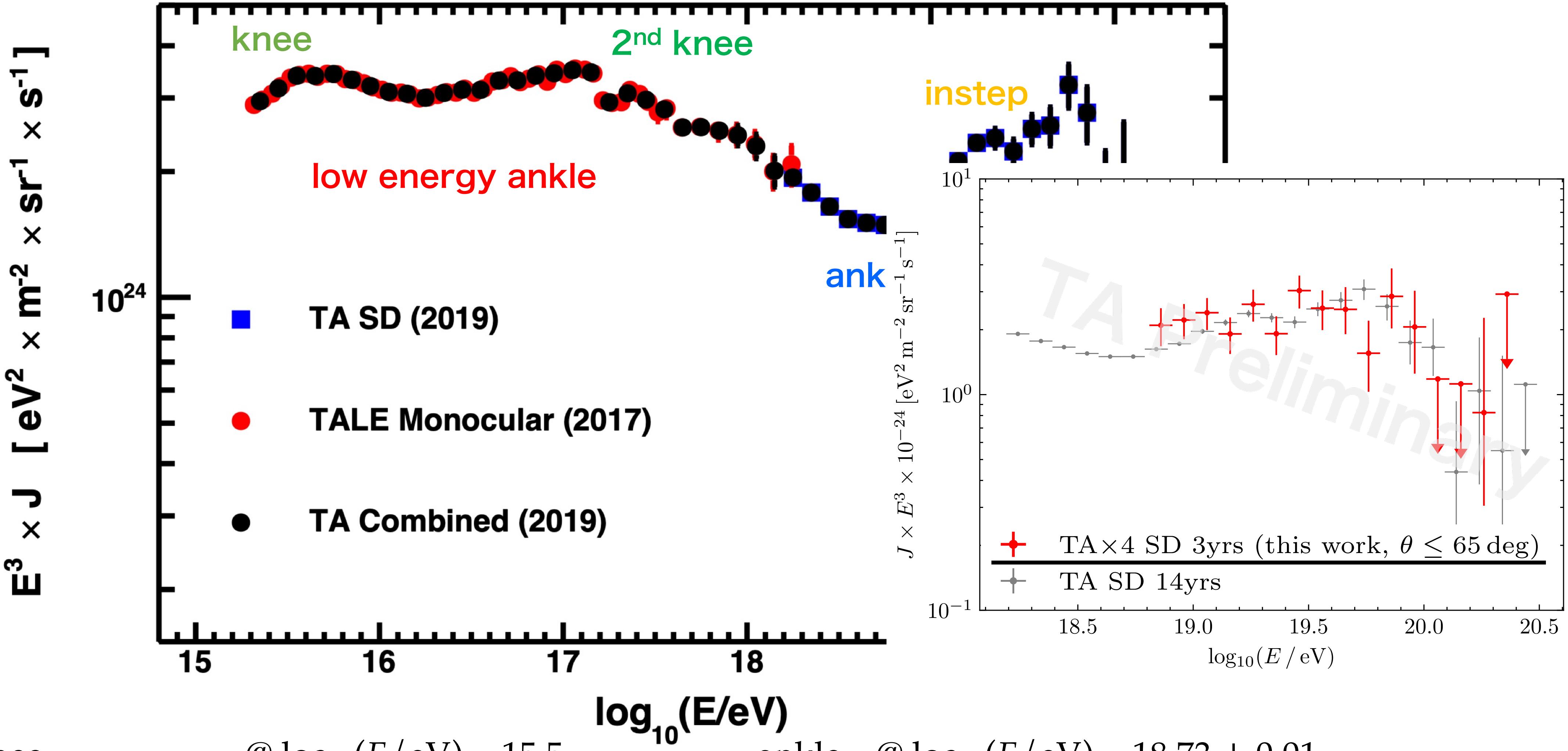
- Five-decade energy spectrum



knee	@ $\log_{10}(E/\mathrm{eV}) \sim 15.5$	ankle	@ $\log_{10}(E/\mathrm{eV}) = 18.73 \pm 0.01$
low energy ankle	@ $\log_{10}(E/\mathrm{eV}) = 16.22 \pm 0.02$	instep	@ $\log_{10}(E/\mathrm{eV}) = 19.25 \pm 0.03$
2nd knee	@ $\log_{10}(E/\mathrm{eV}) = 17.04 \pm 0.04$	cutoff	@ $\log_{10}(E/\mathrm{eV}) = 19.85 \pm 0.03$

Energy Spectrum

- Five-decade energy spectrum

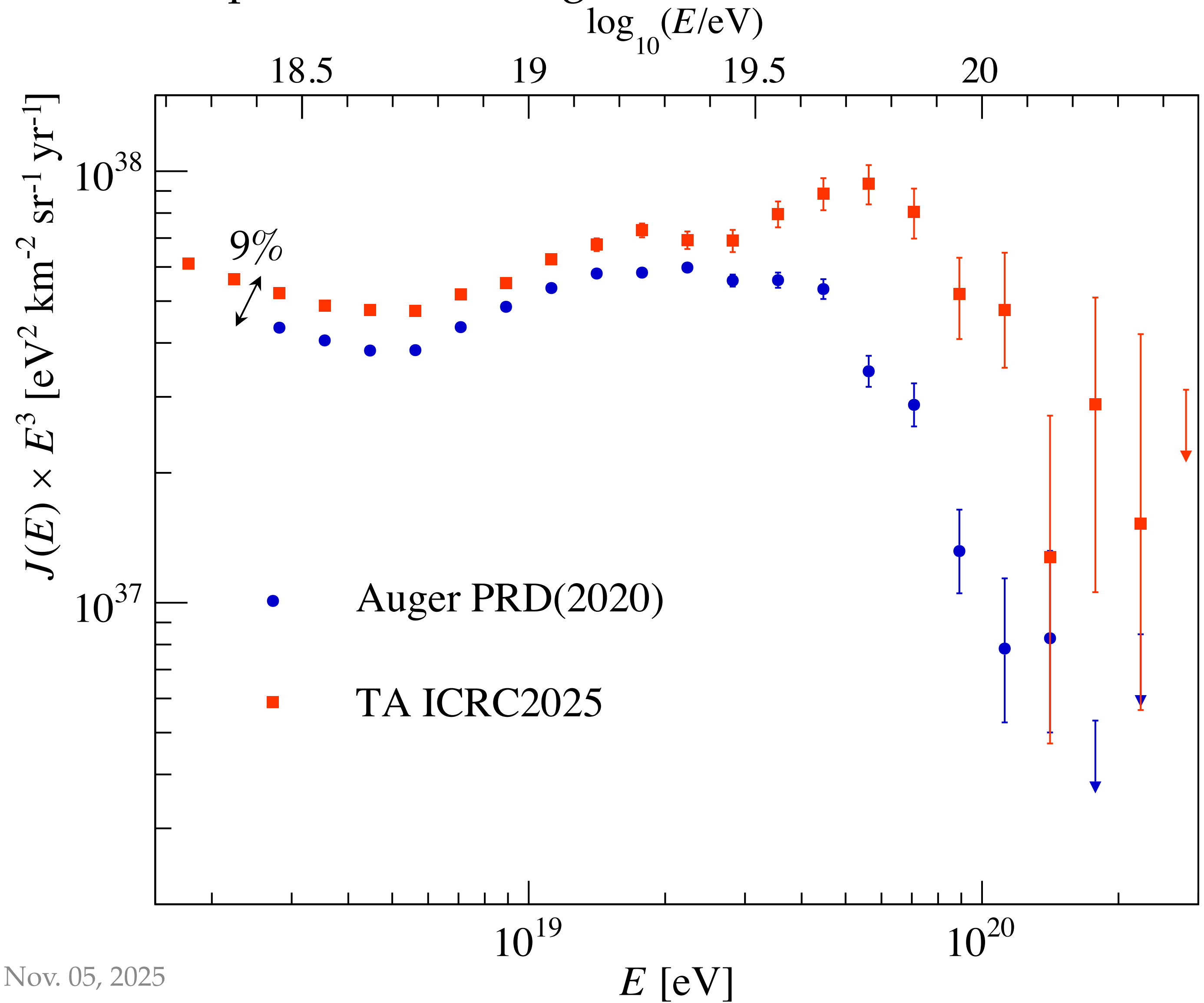


knee	@ $\log_{10}(E/\mathrm{eV}) \sim 15.5$	ankle	@ $\log_{10}(E/\mathrm{eV}) = 18.73 \pm 0.01$
low energy ankle	@ $\log_{10}(E/\mathrm{eV}) = 16.22 \pm 0.02$	instep	@ $\log_{10}(E/\mathrm{eV}) = 19.25 \pm 0.03$
2nd knee	@ $\log_{10}(E/\mathrm{eV}) = 17.04 \pm 0.04$	cutoff	@ $\log_{10}(E/\mathrm{eV}) = 19.85 \pm 0.03$

Energy Spectrum

Auger+TA Spectrum WG
PoS(ICRC2025)381

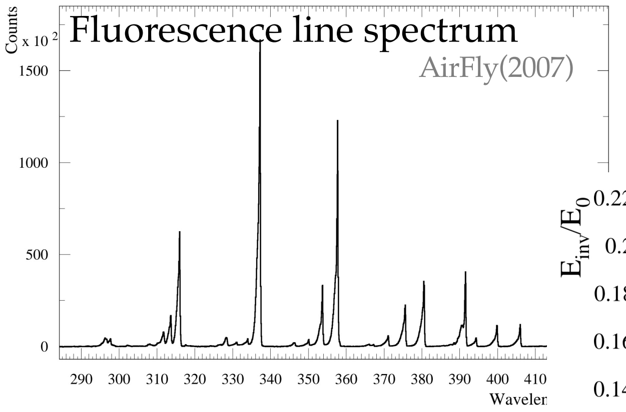
- Focus on UHE region ($E > 1$ EeV)
  - Comparison with Auger

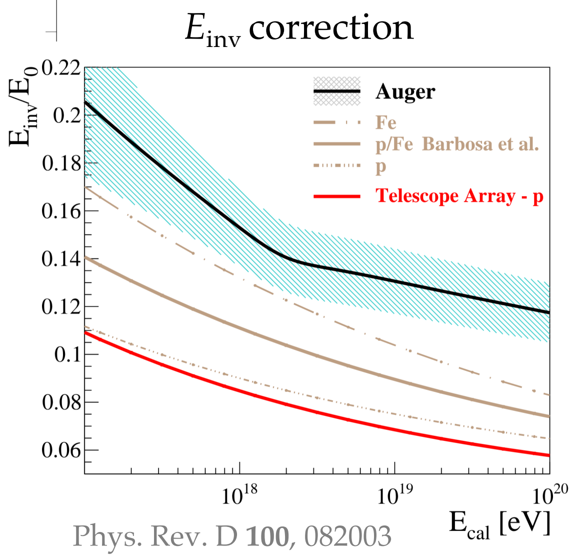


difference between Auger and TA Spectra is ~9%, well within the uncertainty of either experiment

differences in 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



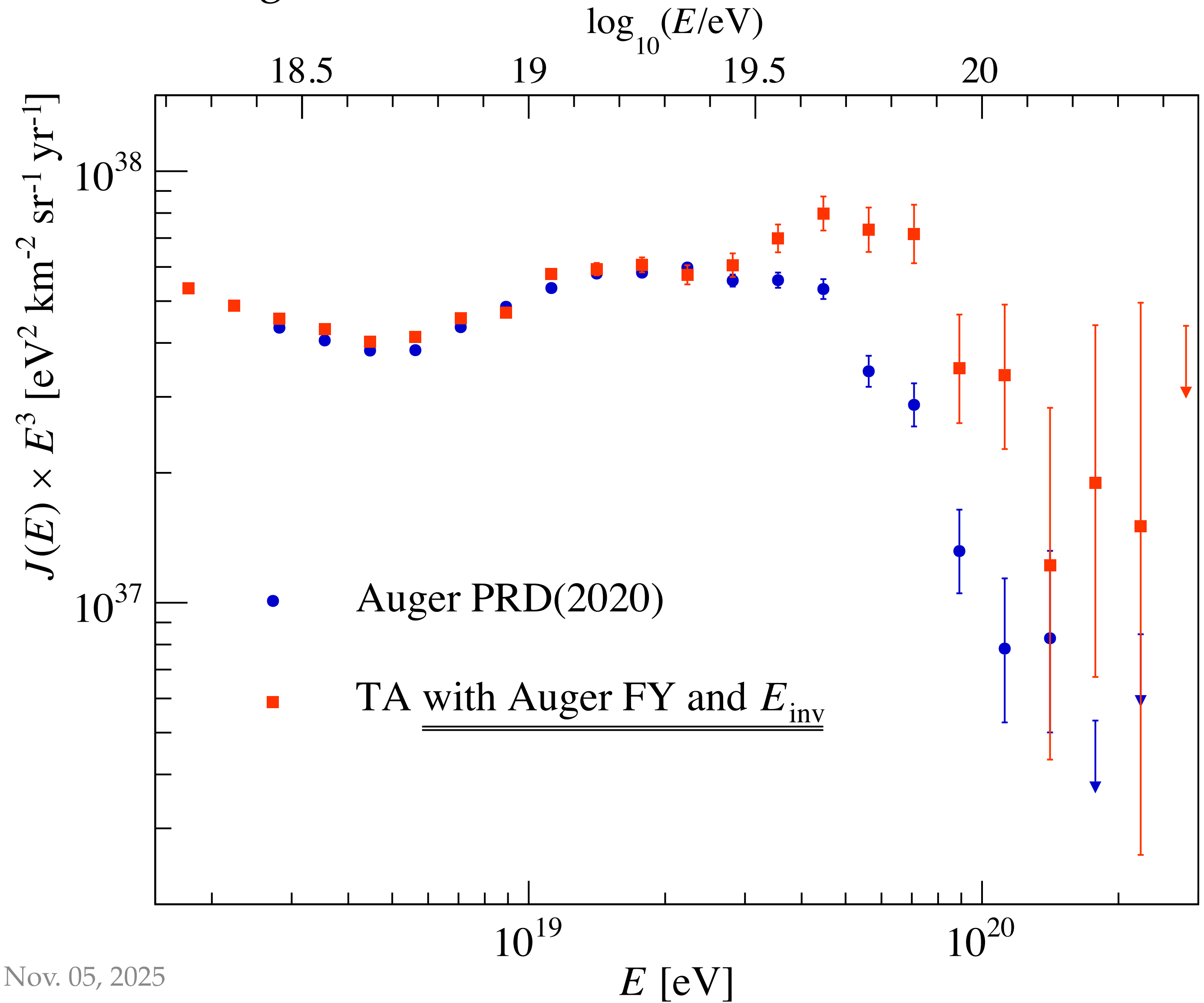


Phys. Rev. D **100**, 082003

Energy Spectrum

Auger+TA Spectrum WG
PoS(ICRC2025)381

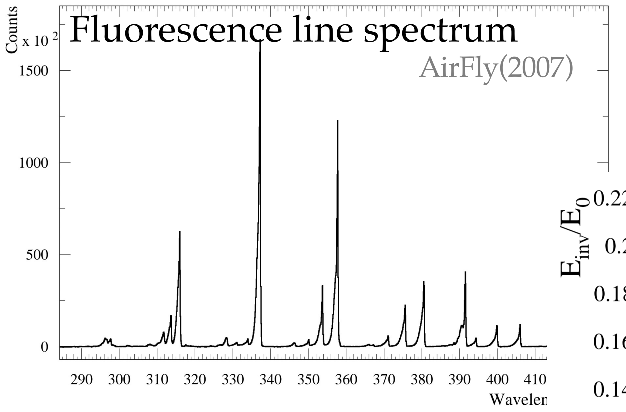
- Focus on UHE region ($E > 1$ EeV)
  - Nice agreement within a few % below $E = 10^{19.5}$ eV

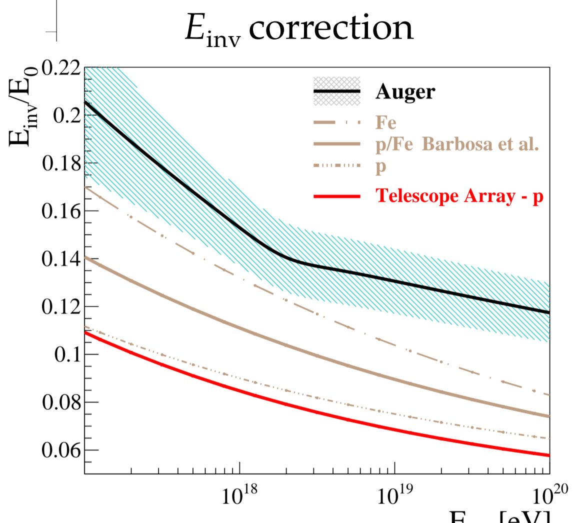


difference between Auger and TA Spectra is ~9%, well within the uncertainty of either experiment

differences in 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



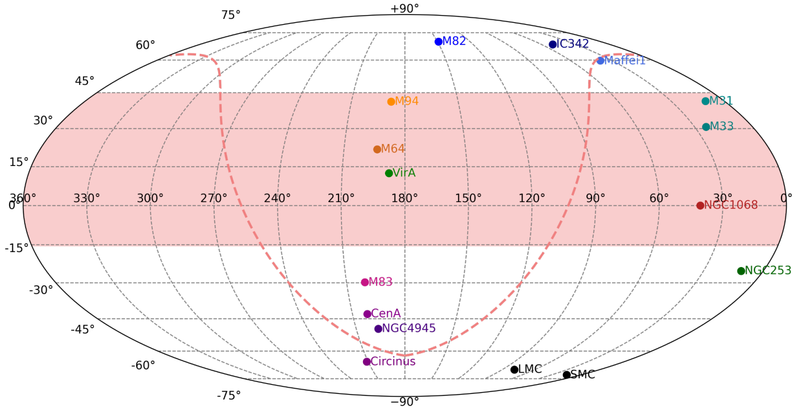


Phys. Rev. D **100**, 082003

Energy Spectrum

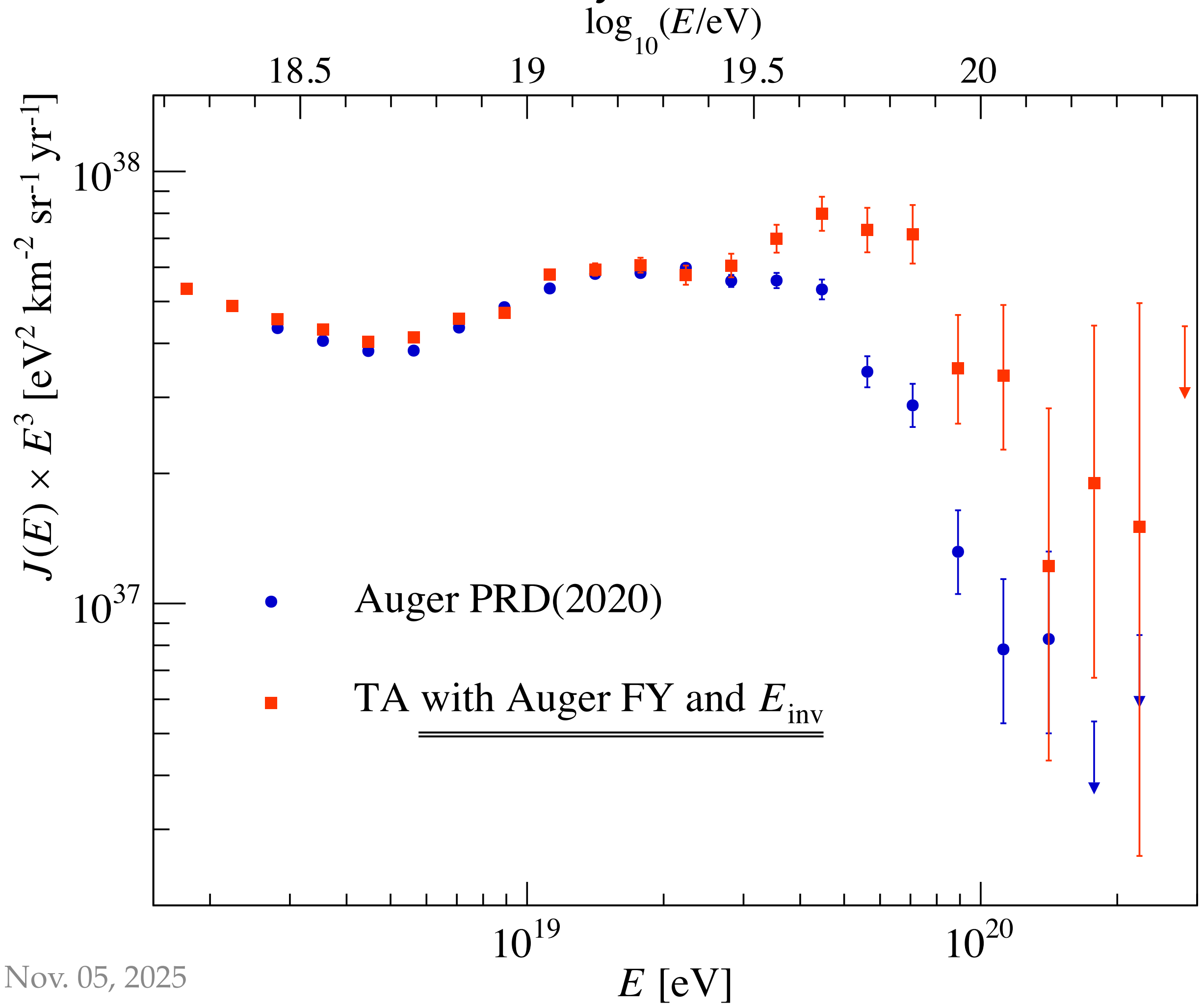
Auger+TA Spectrum WG
PoS(ICRC2025)381

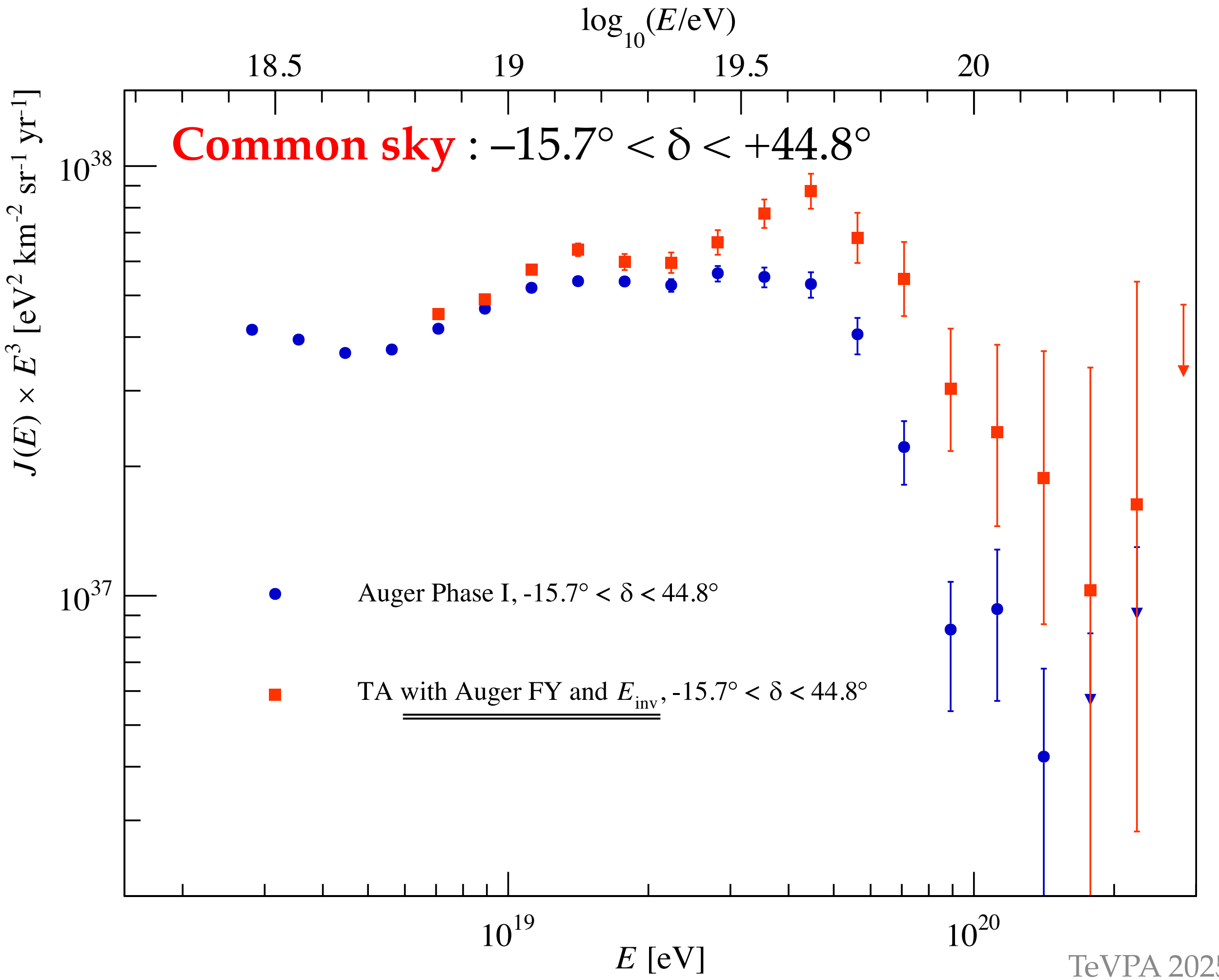
- Focus on UHE region ($E > 1$ EeV)
  - Comparison with Auger in **Common sky**
  - Remaining difference at the highest energies even in common sky — still under discussion



Auger: 35° S
- ***θ* up to 80°**

TA: 39° N
- ***θ* up to 55°**

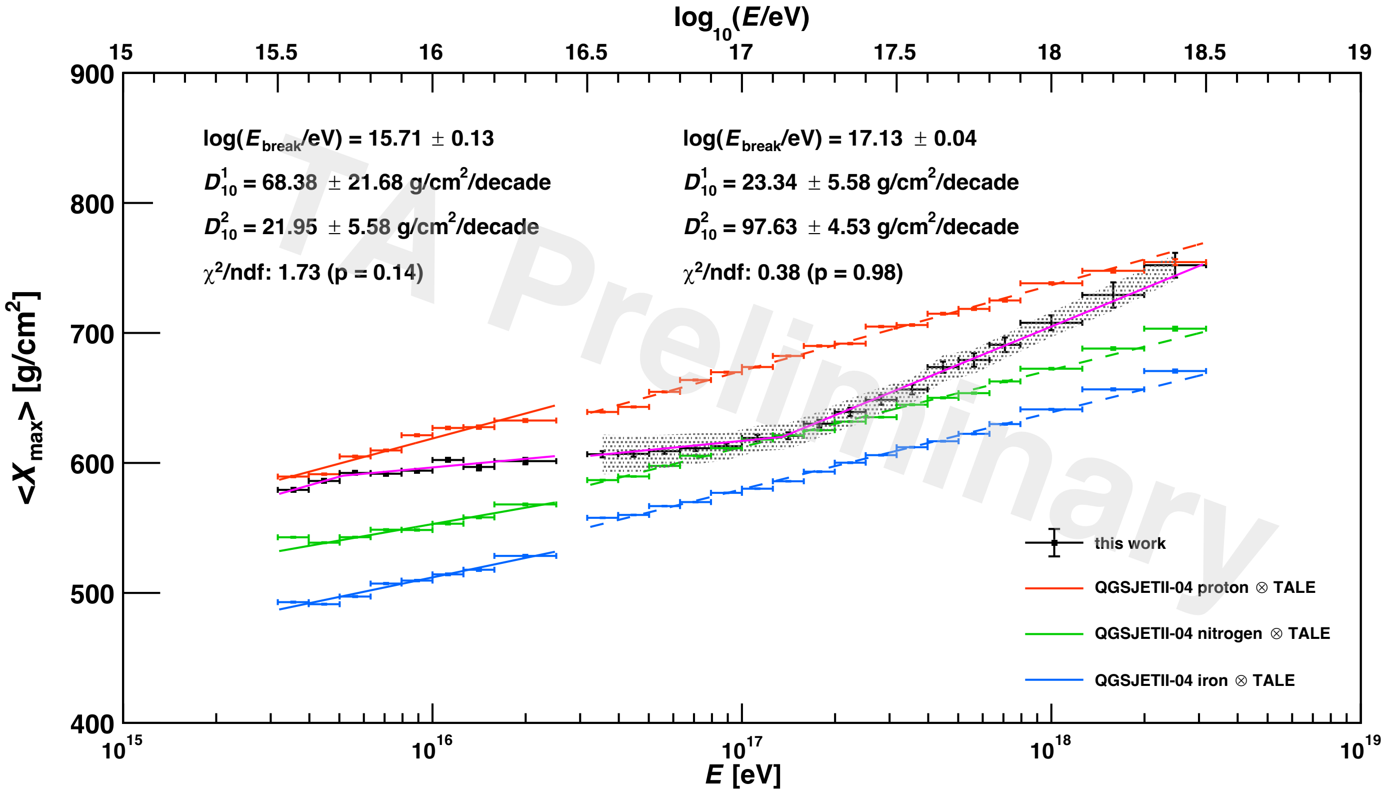


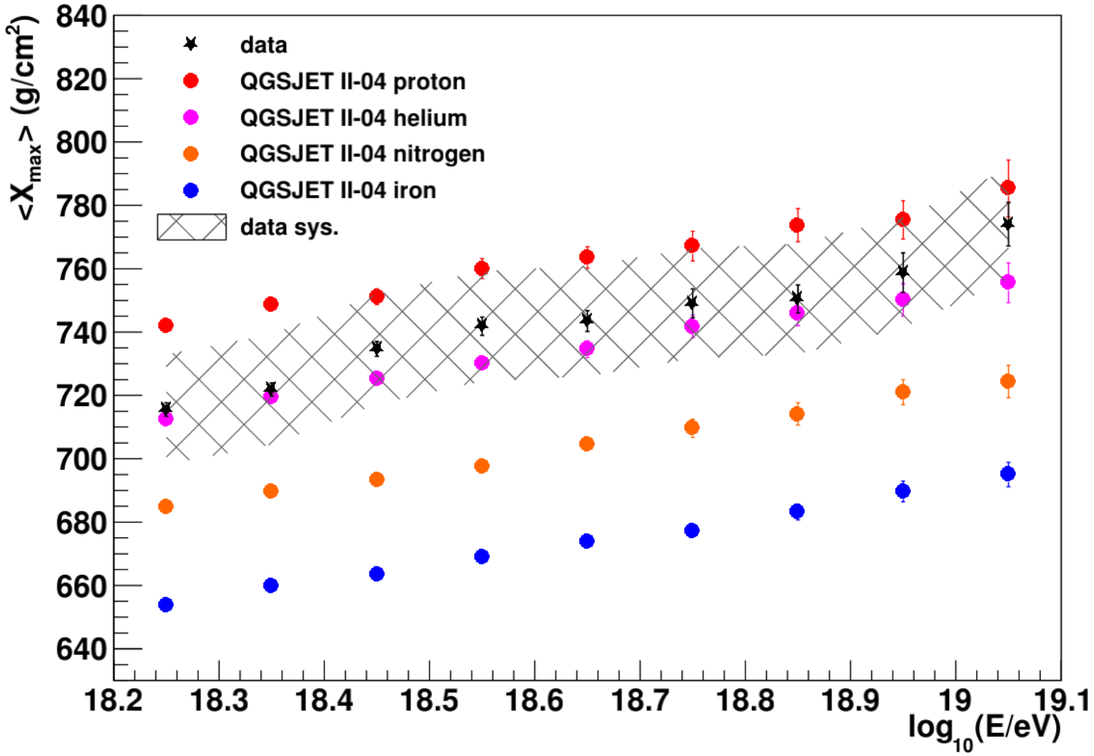


Mass Composition

Abbasi et al. 2018 *ApJ* 858 76
PoS(ICRC2025)261

- $X_{\max}$ measurements over a four-decade energy range





$\langle X_{\max}\rangle$ as a function of energy along with predictions of QGSJet II-04 proton, helium, nitrogen, iron

10yrs of TA-hybrid data $10^{18.2}$ to $10^{19.1}$ eV
5yrs of TALE-hybrid data $10^{16.5}$ to $10^{18.5}$ eV
1yr of 100m array + TALE-FD hybrid data $10^{15.5}$ to $10^{16.5}$ eV

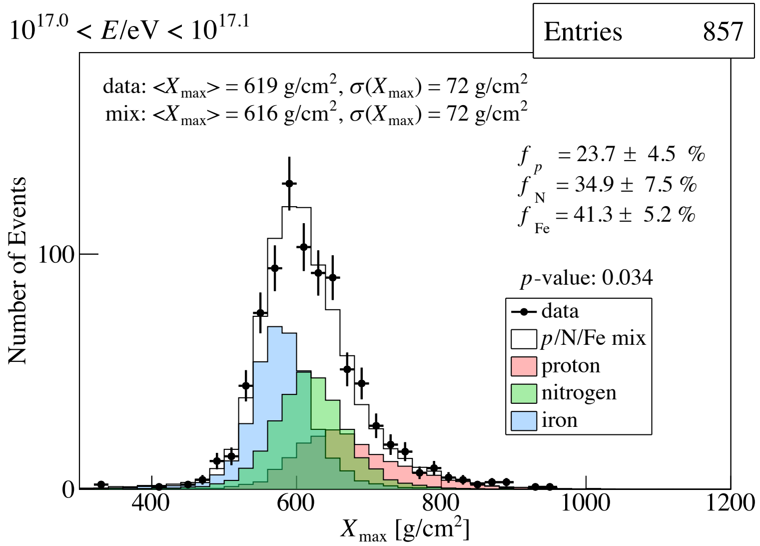
$\langle X_{\max}\rangle$: Light → Heavy → Light (up to 10 EeV)
2 breaks at $\log_{10}(E/\mathrm{eV}) = 15.7 \pm 0.1,\ 17.1 \pm 0.04$
close to knee and 2nd knee in the spectrum

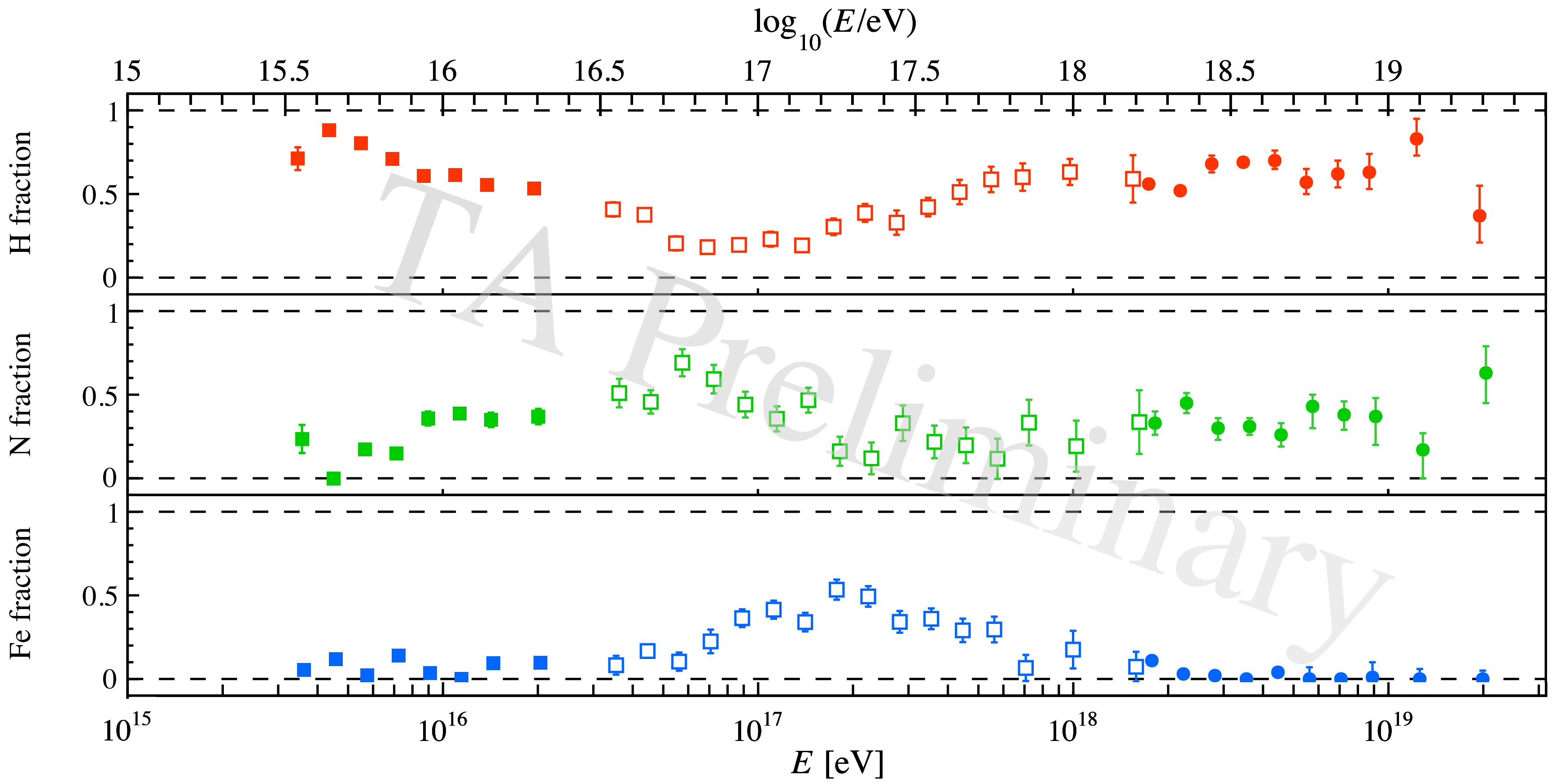
We couldn't conclude yet in the highest-energy range through our $X_{\max}$ measurement.

Mass Composition

PoS(UHECR2024)098
PoS(ICRC2025)261

- Energy evolution of nuclear fractions
  - Fitting observed $X_{\max}$ distribution using MC (p/N/Fe) $X_{\max}$ distributions
  - QGSJet II-04 used



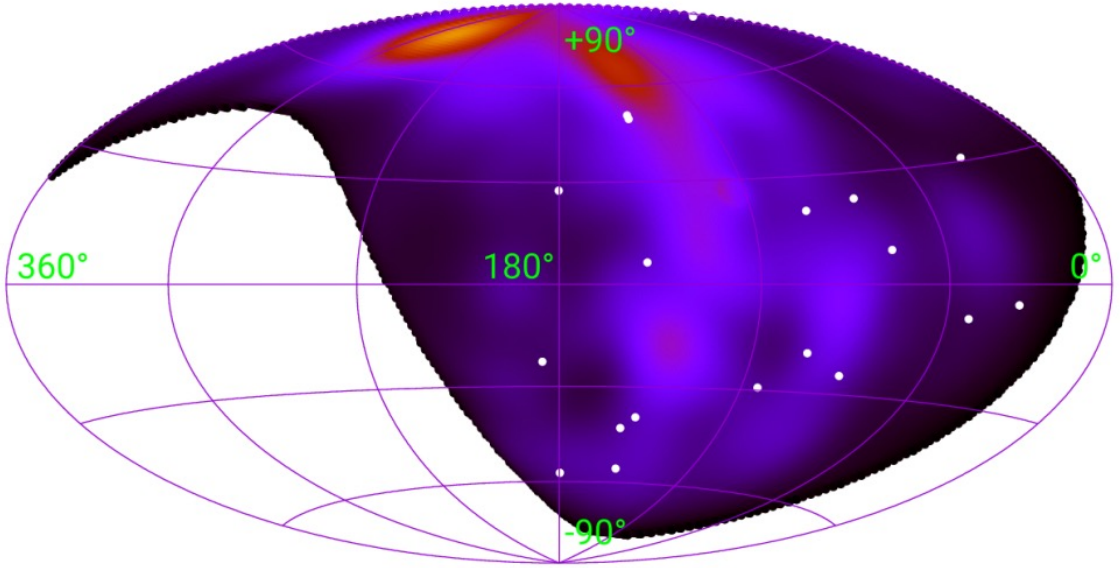


- proton
  - dominant at ~4 PeV
  - lowest fraction ~ 100 PeV
  - continue climb up to 3 EeV and constant up to 10 EeV
- Nitrogen
  - peak at ~ 50 PeV
  - low contribution in E >1 EeV
- Iron
  - peak at ~ 150 PeV ~ 2nd knee
  - roughly 26/7x higher energy than nitrogen

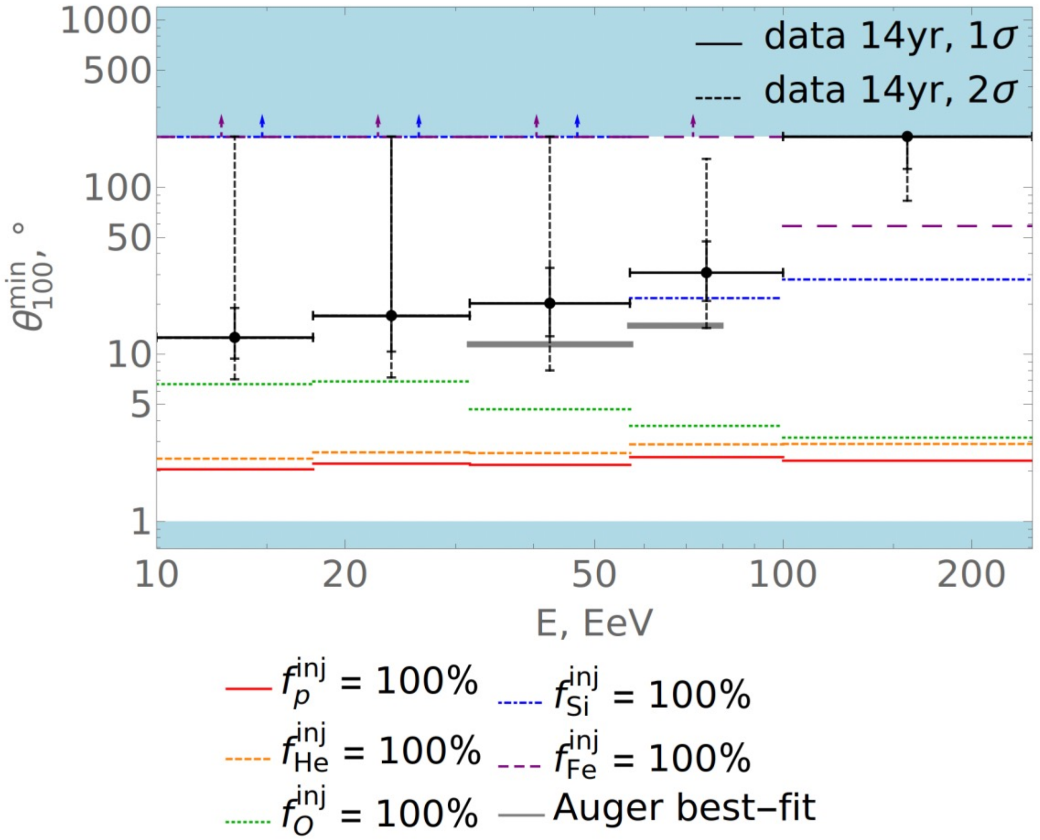
PRL 133(2024) 041001
PRD 110(2024) 022006

Arrival direction × mass composition

- 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
    - Nice agreement within few percent up to $10^{19.5}$ eV when use common FLY and invisible energy correction
    - Still under discussion in highest energies
- 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

Back up

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

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

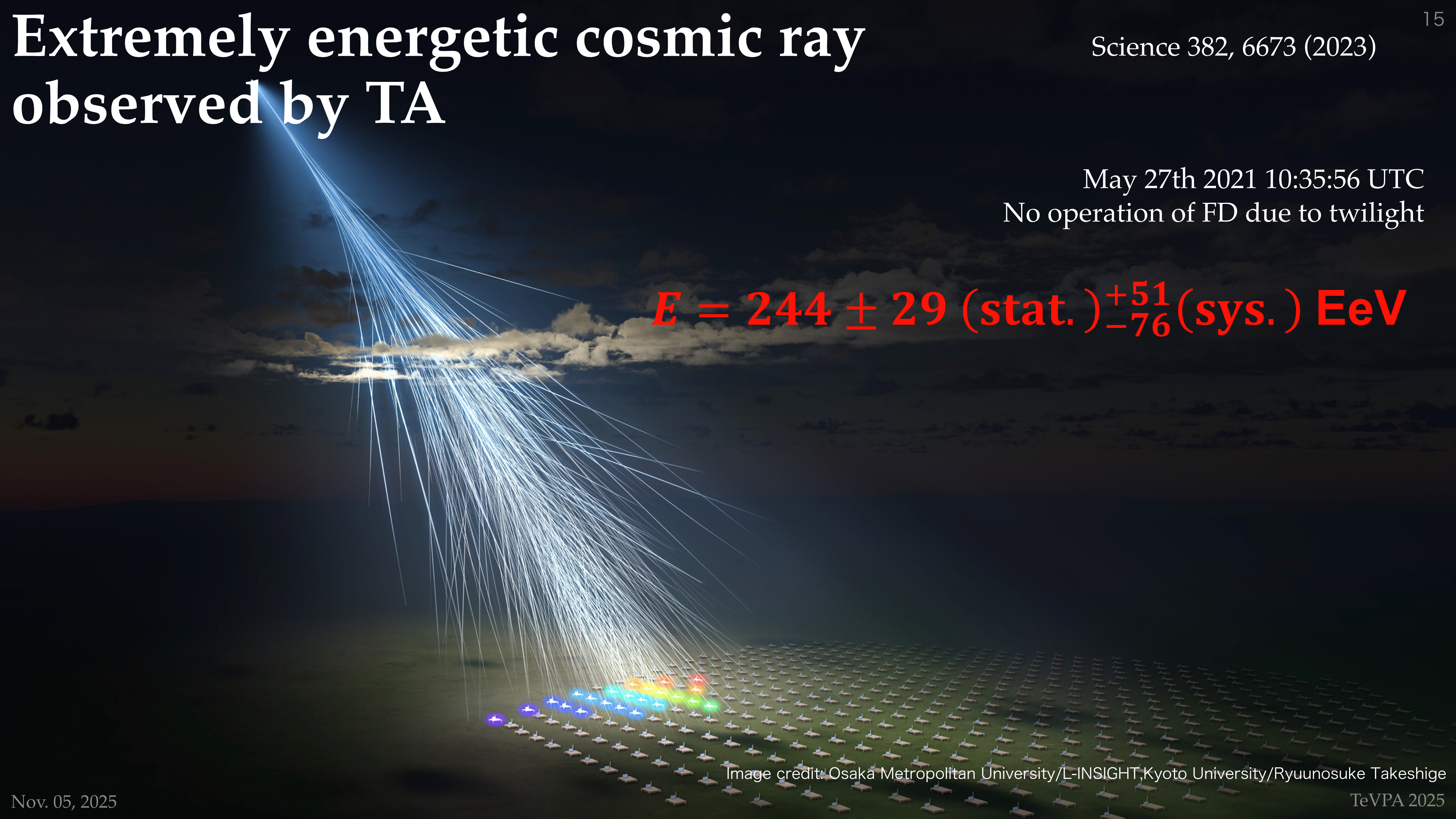
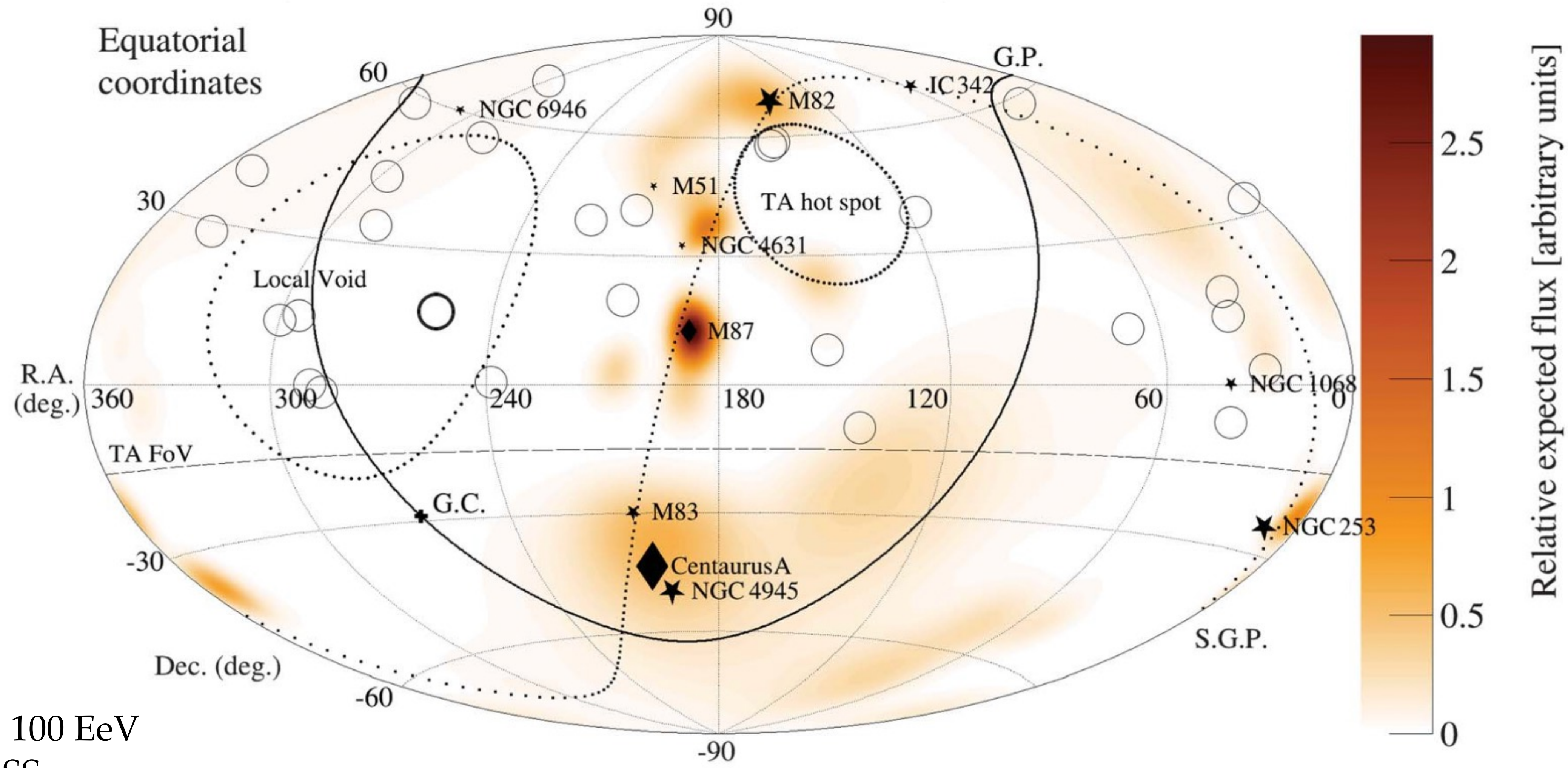


Image credit: Osaka Metropolitan University/L-INSIGHT,Kyoto University/Ryuunosuke Takeshige

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.

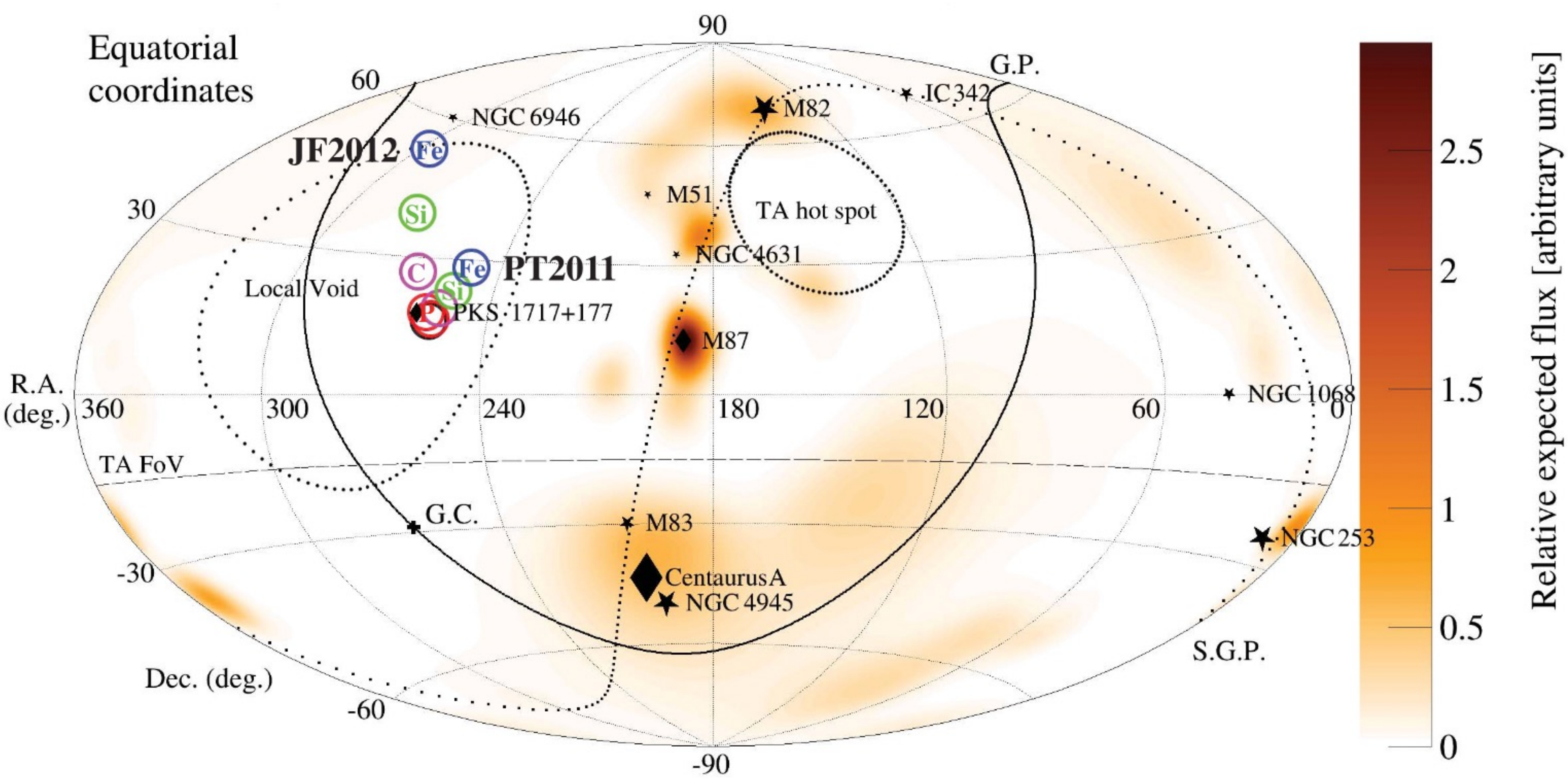


No clustering above 100 EeV
Uncorrelated with LSS

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).



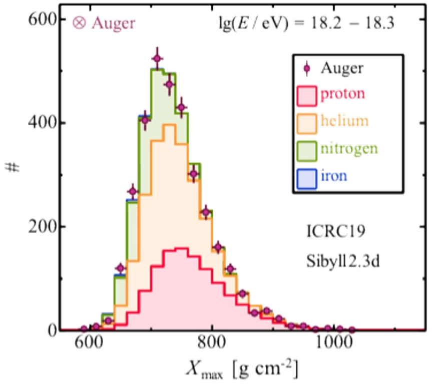
No obvious source even if GMF deflection assuming

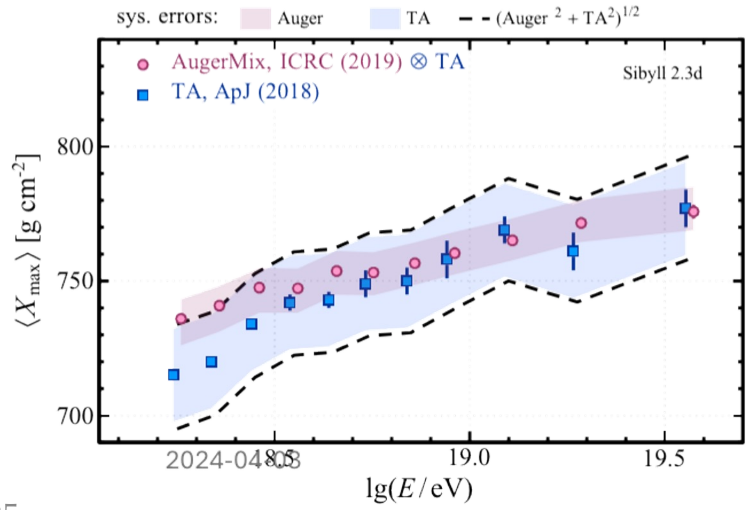
Auger/TA composition WG

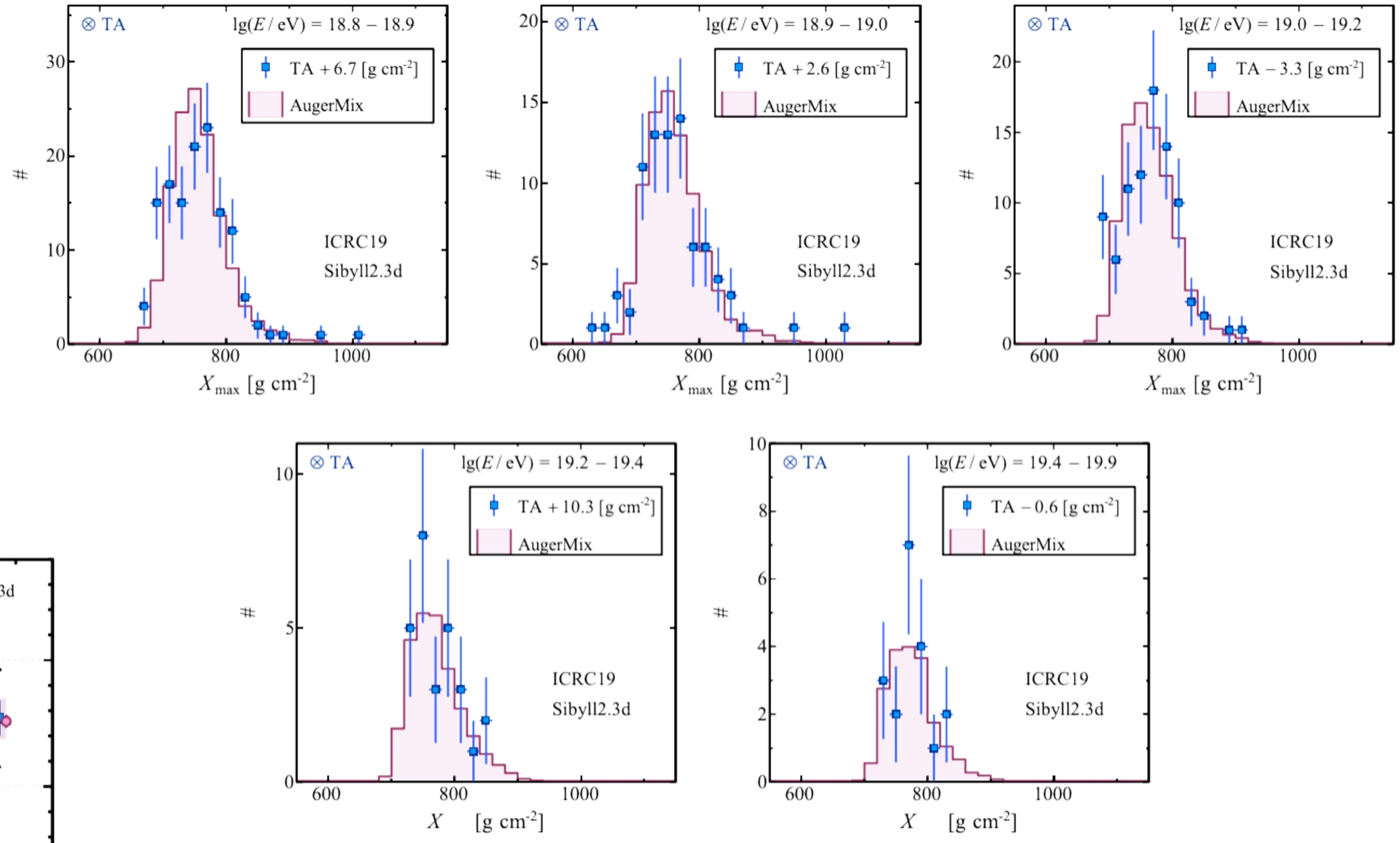
Alexey Yushkov et al.
PoS (ICRC2023) 249

- Reproduced observed Auger X_{max} distribution by combination of p/He/N/Fe, then simulate and reconstruction by TA

Combine (p, He, N, Fe) of Sibyll 2.3d to fit Auger X_{max} distributions





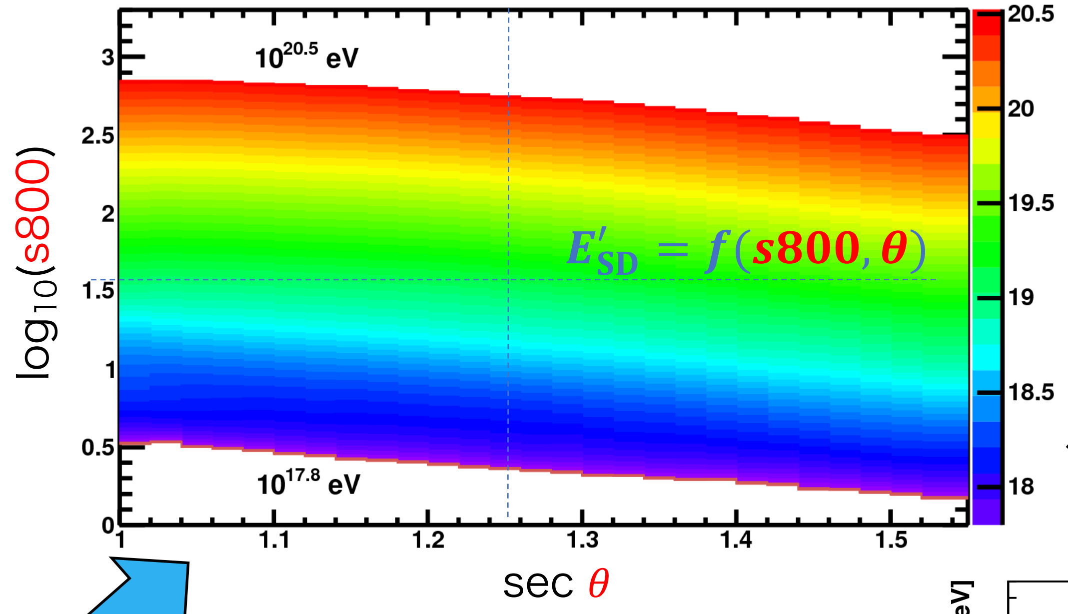


Auger and Telescope Array measurements are compatible at the current level of statistics and understanding of systematics

21

Energy determination, TA

→ Energy look-up table (S800, θ)



Scale to FD(Hybrid) energy

$$E_{SD} = E'_{SD} / 1.27$$