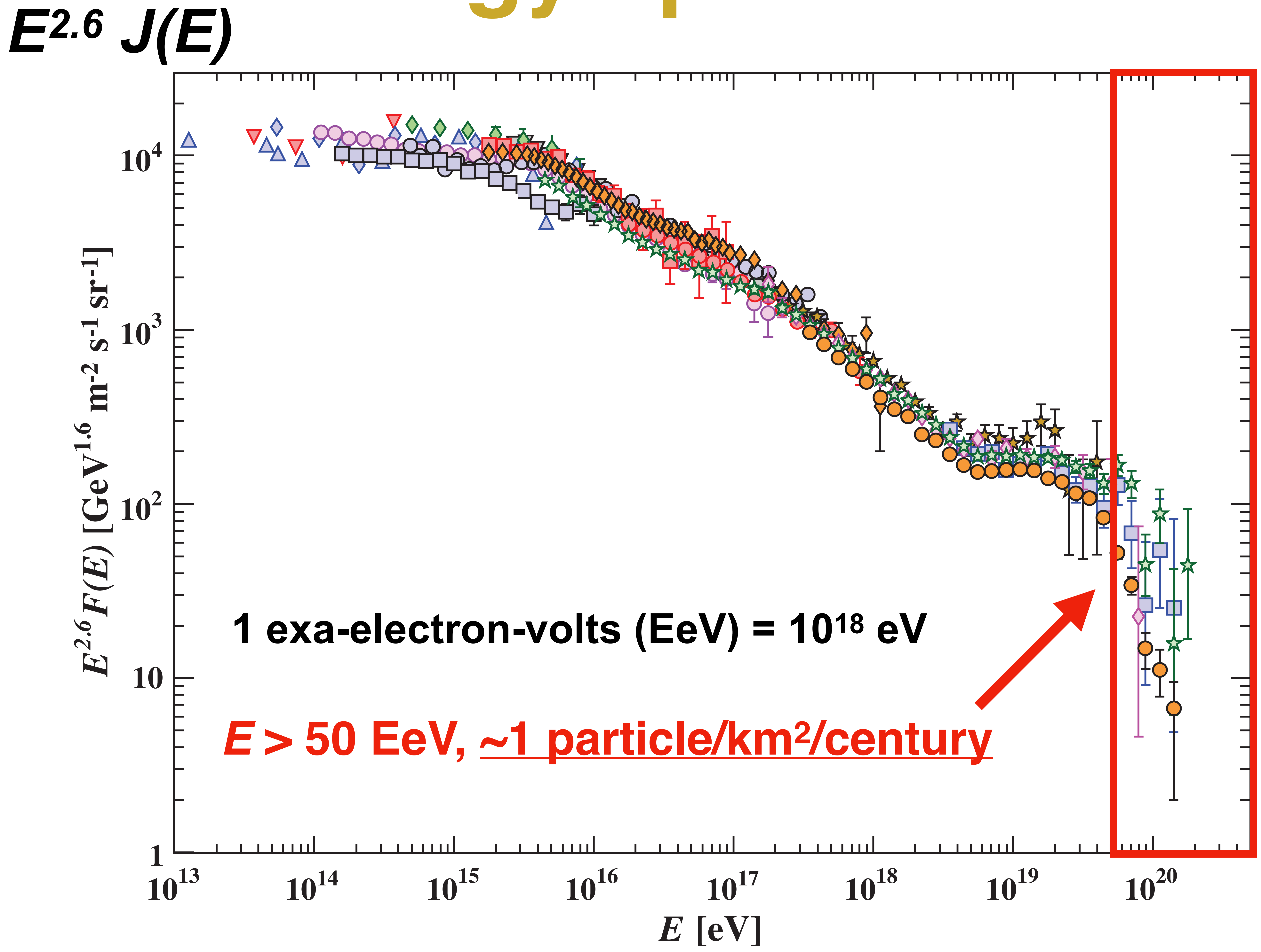
Scientific objectives and recent developments of the Global Cosmic Ray Observatory

Toshihiro Fujii (OMU, NITEP, toshi@omu.ac.jp) for the GCOS supporters
TeVPA2026, Tendo, Japan, September 1st, 2026

TeV Particle Astrophysics
TeVPA 2026
Tendo Japan
August 30 - September 4, 2026

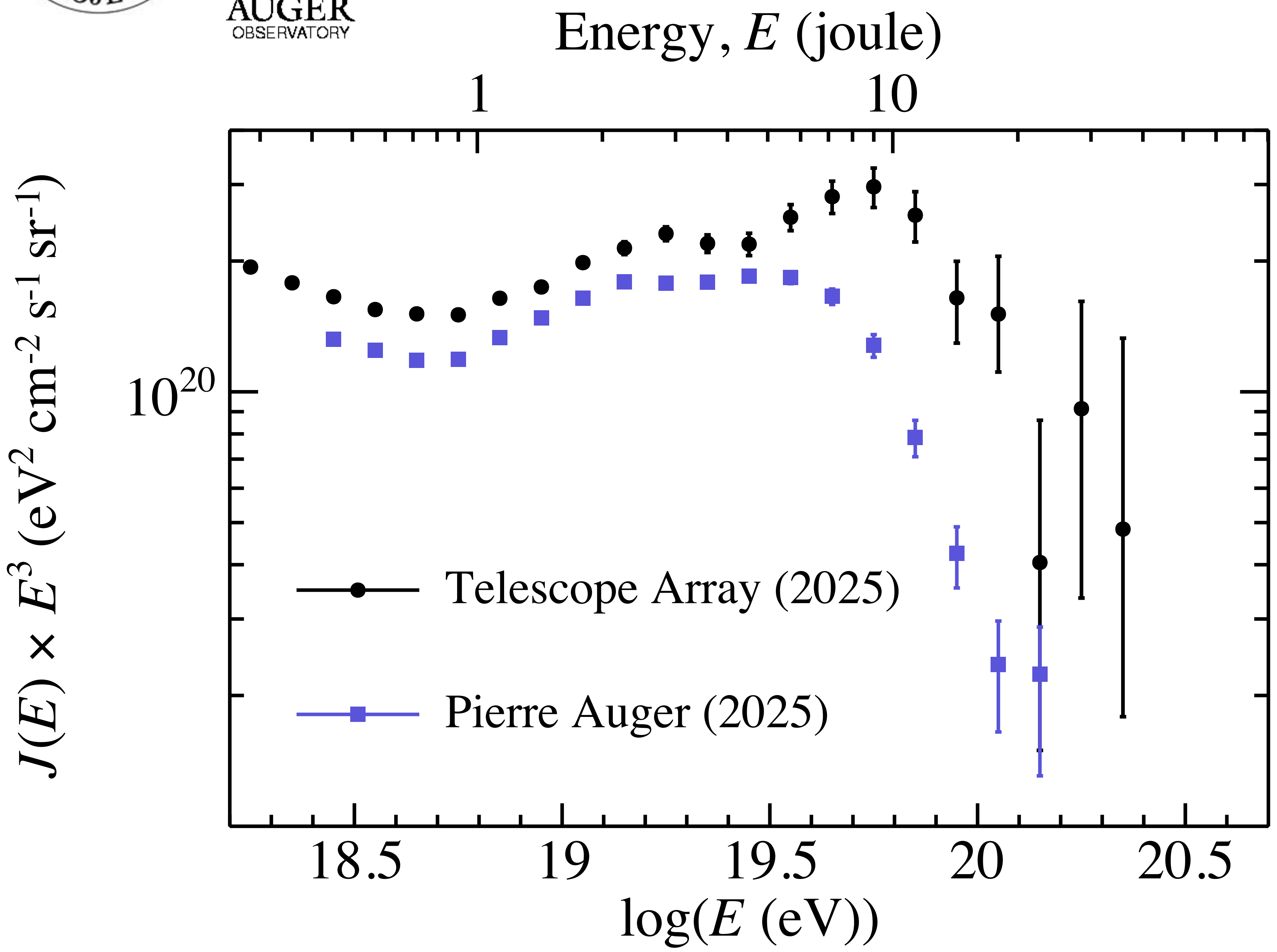
Energy spectrum of cosmic rays



Particle Data Group, Phys.Rev.D, 98, 030001 (2018)

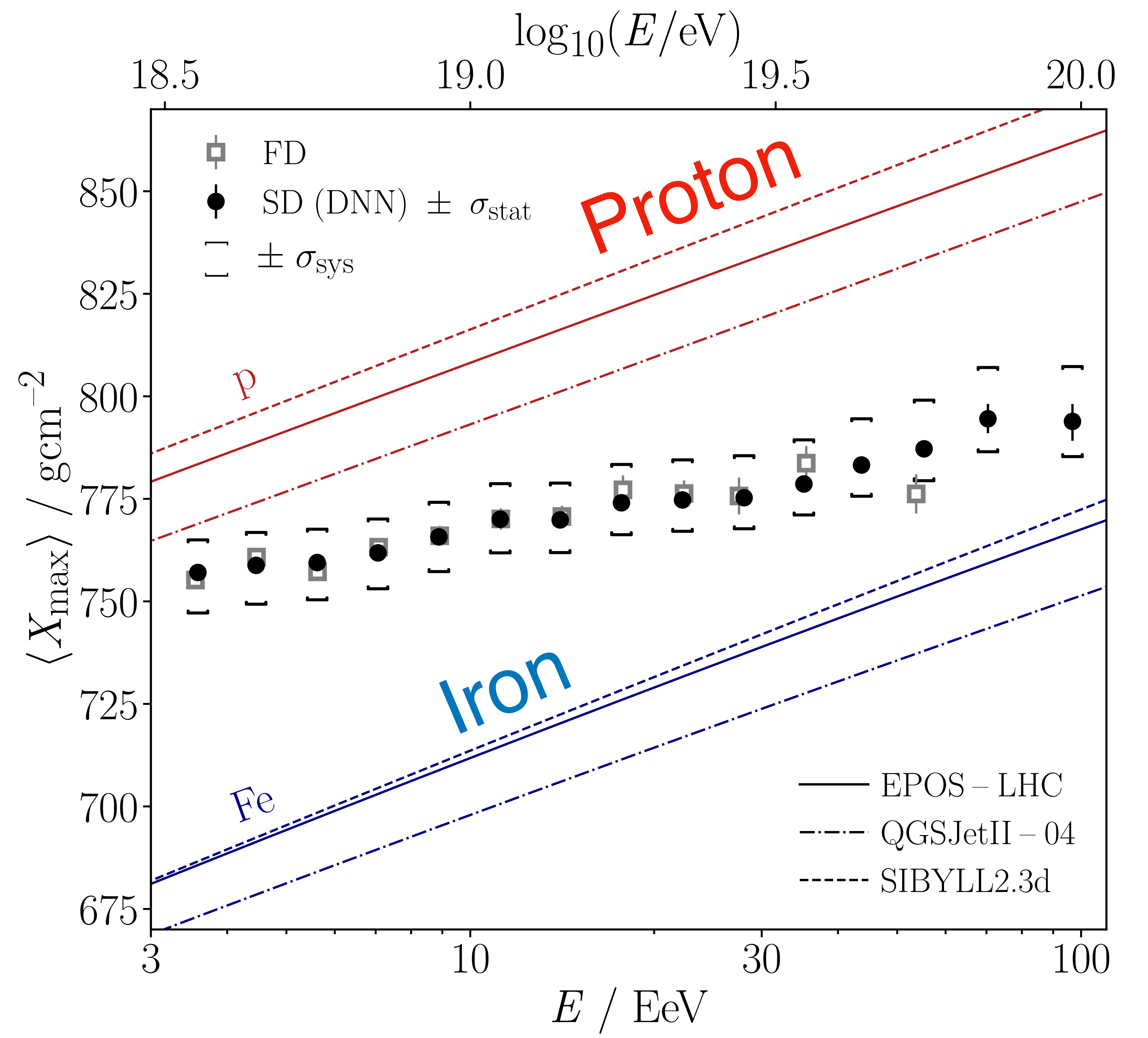
- Origins of ultra-high-energy cosmic rays (UHECRs) are still largely unknown
- **The most energetic particles in the universe**
  - Only ~10^{13} eV by the Earth's largest particle accelerator
- **Extremely infrequent**
  - A huge effective area, ~1000 km^2
  - Long term observation over decades

Latest results of UHECRs



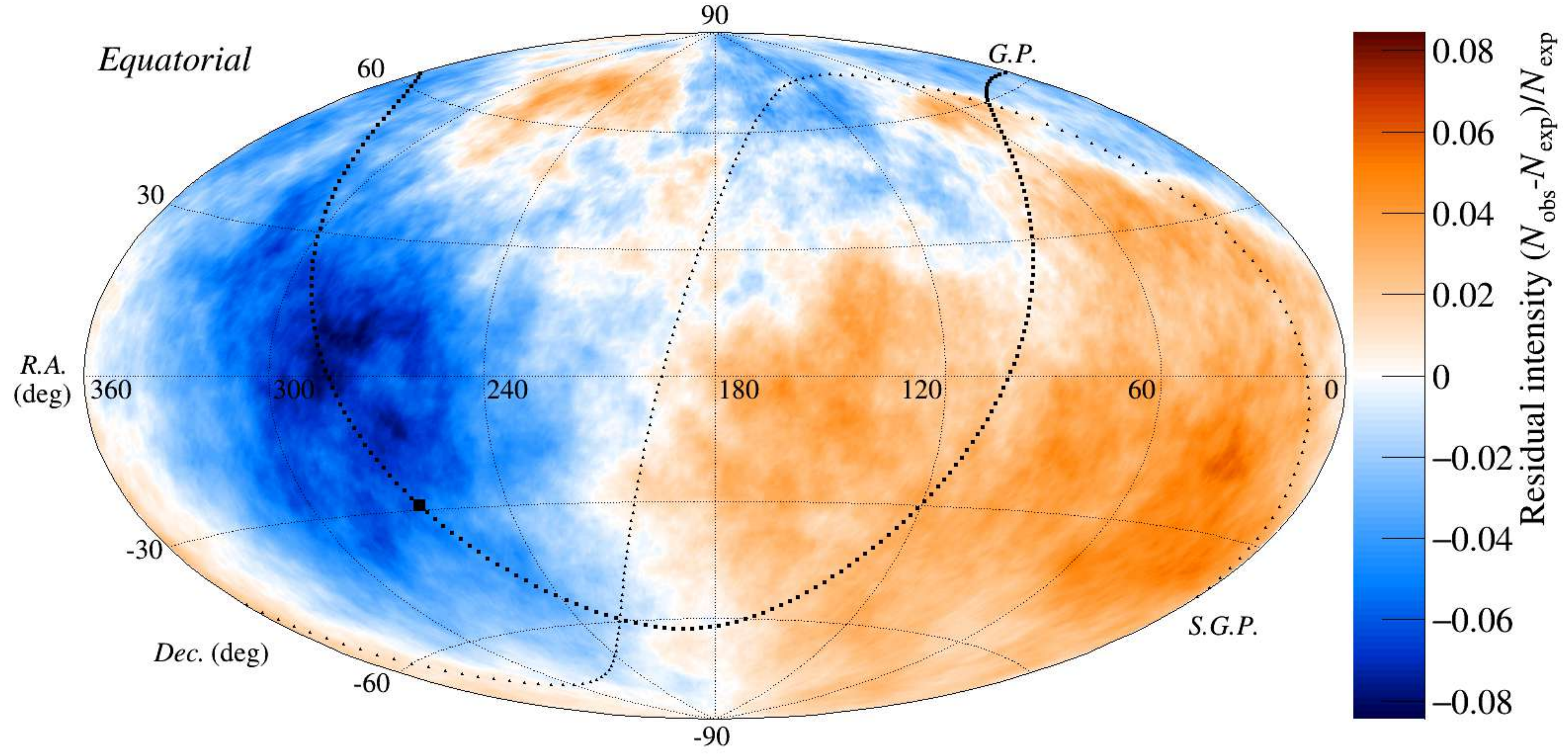
$$\theta \sim 10^\circ \boxed{Z} \left(\frac{E}{10\,\mathrm{EeV}} \right)^{-1}$$

Z: Atomic number
(Mass composition)

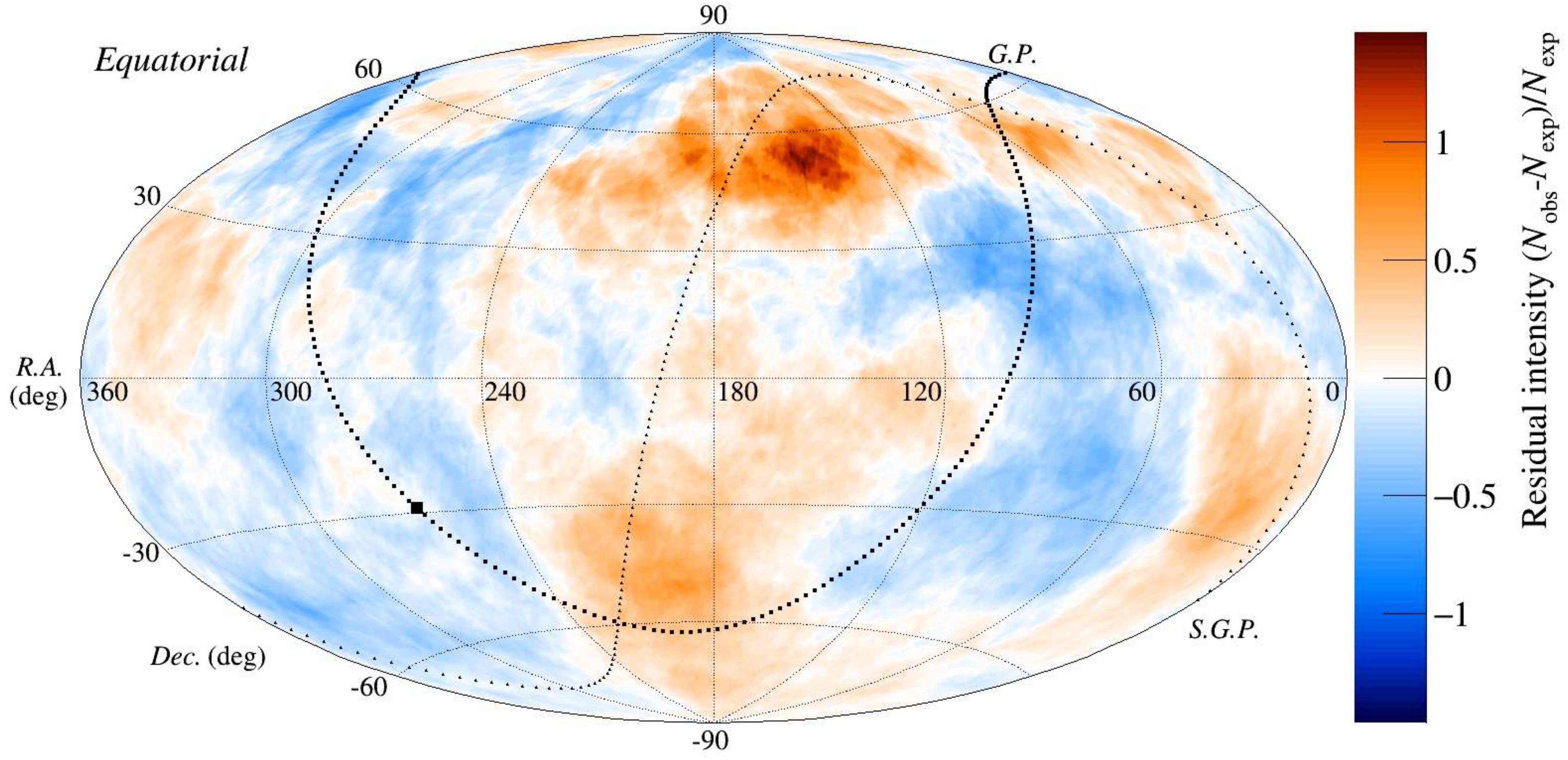


PRL 134, 021001 (2025)

"Ankle" region ($E > 10$ EeV)



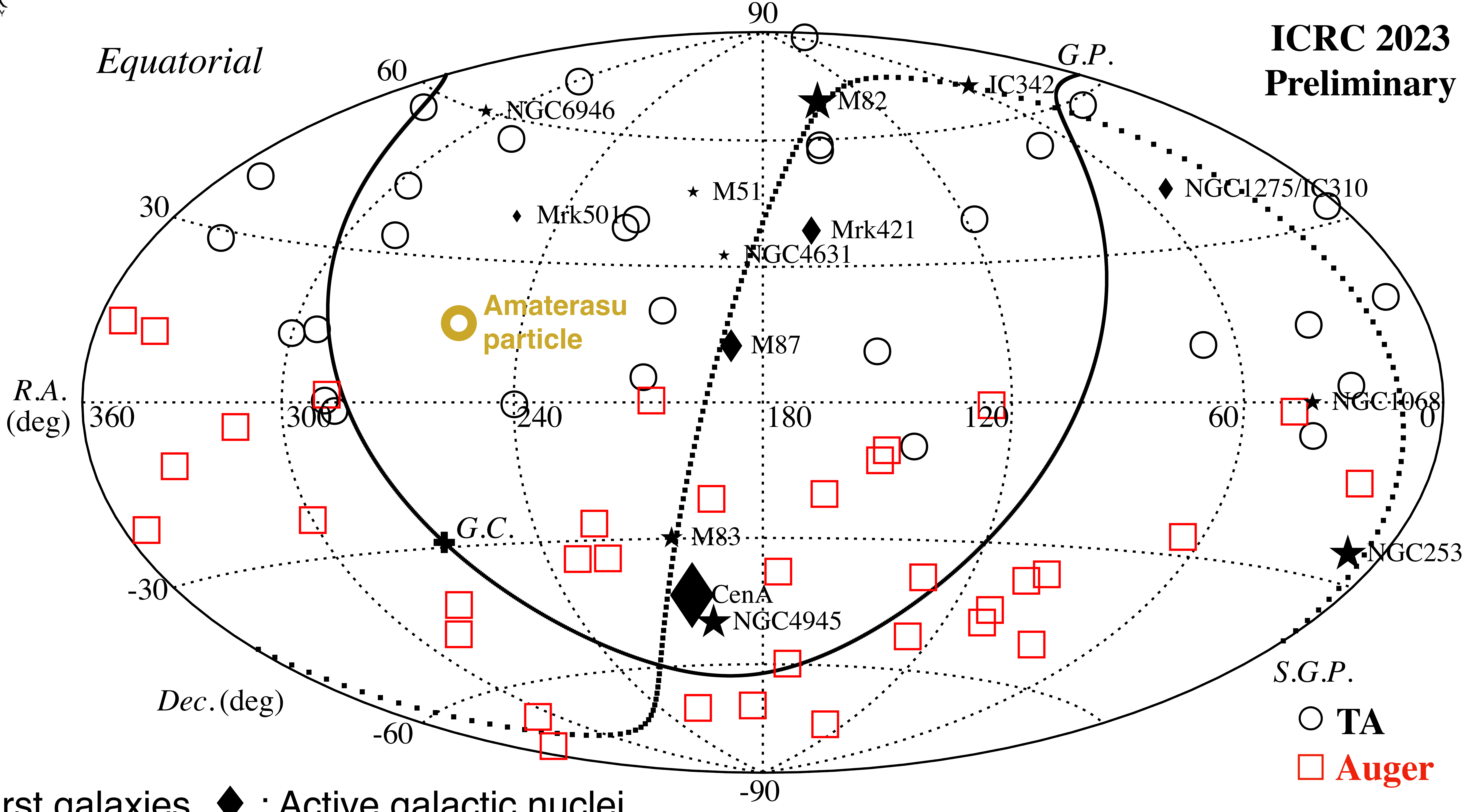
"Cutoff" region ($E > 50$ EeV)



- Constrain **proton fraction above 30 EeV to be <70%** by non-detection of UHE neutrinos
- PRL 135, 031001 (205)

>100 EeV skymap

T. Fujii, PoS (ICRC2023) 031 (2023)

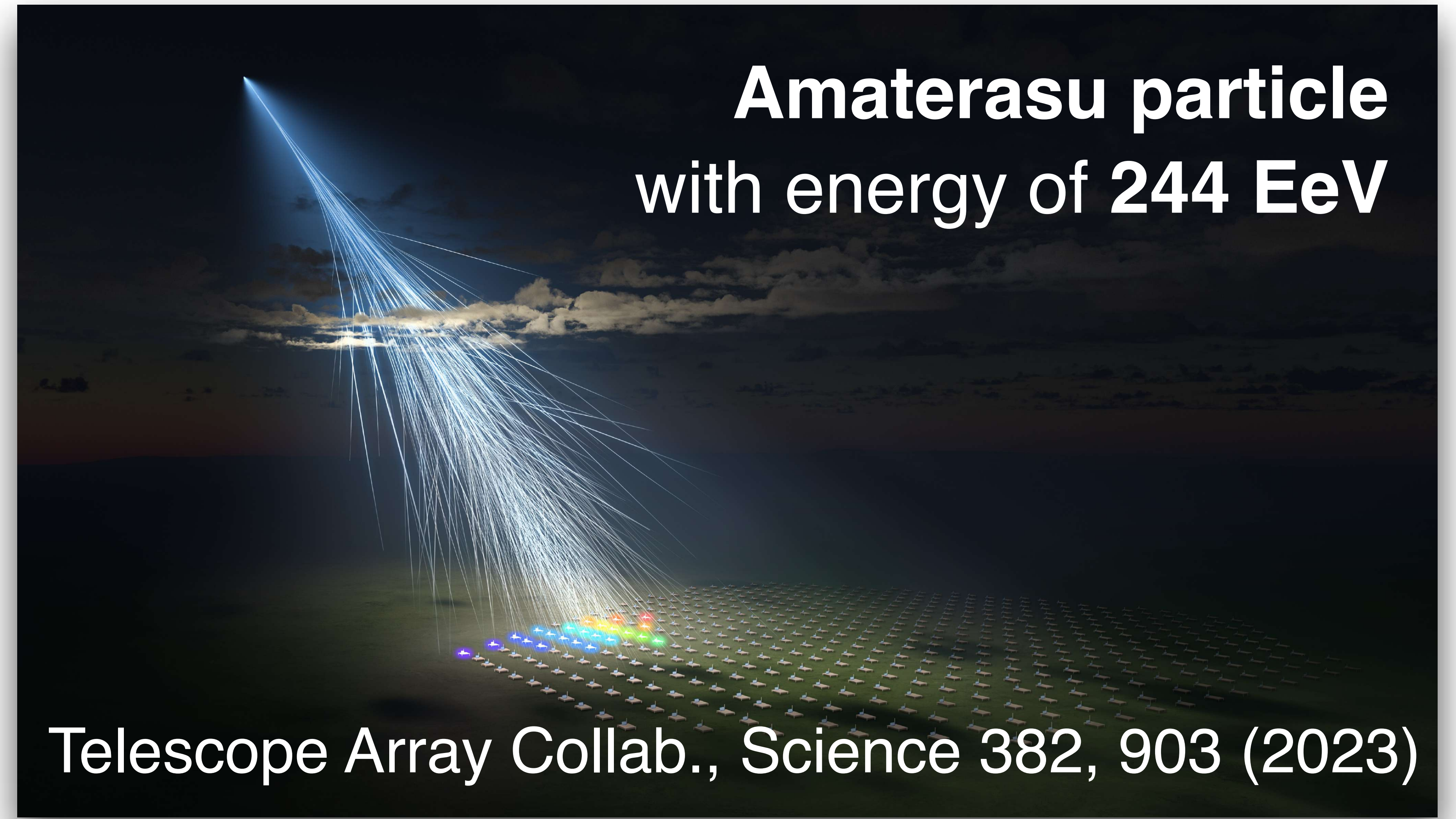


★ : Starburst galaxies ♦ : Active galactic nuclei

>100 EeV of TA 15-years and Auger 17-years

Need more statistics with mass identification capabilities

Data-driven Search for Origins of Amaterasu Particle

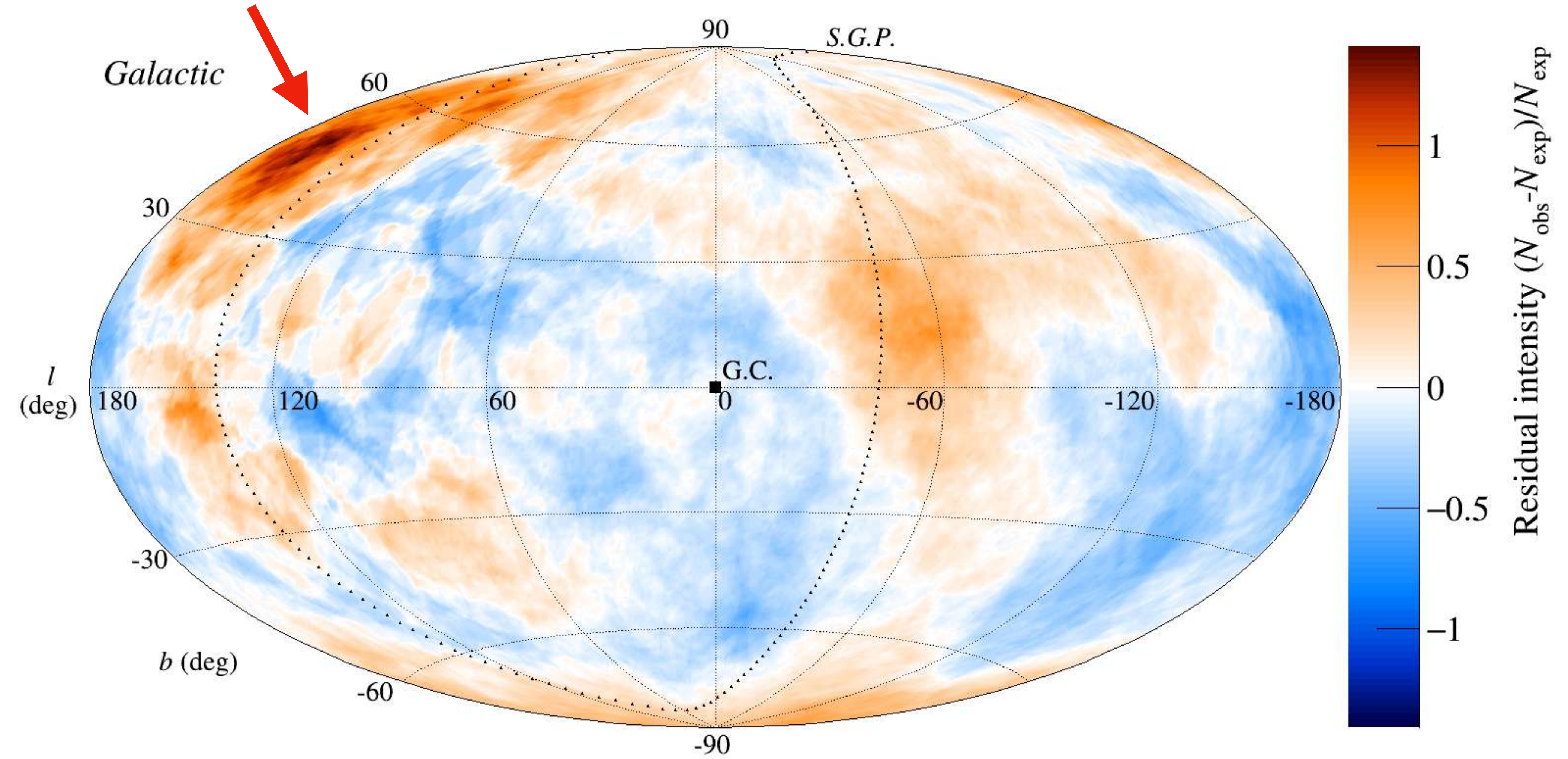


N. Bourriche and F. Capel 2026 ApJ 997 264 (2026)

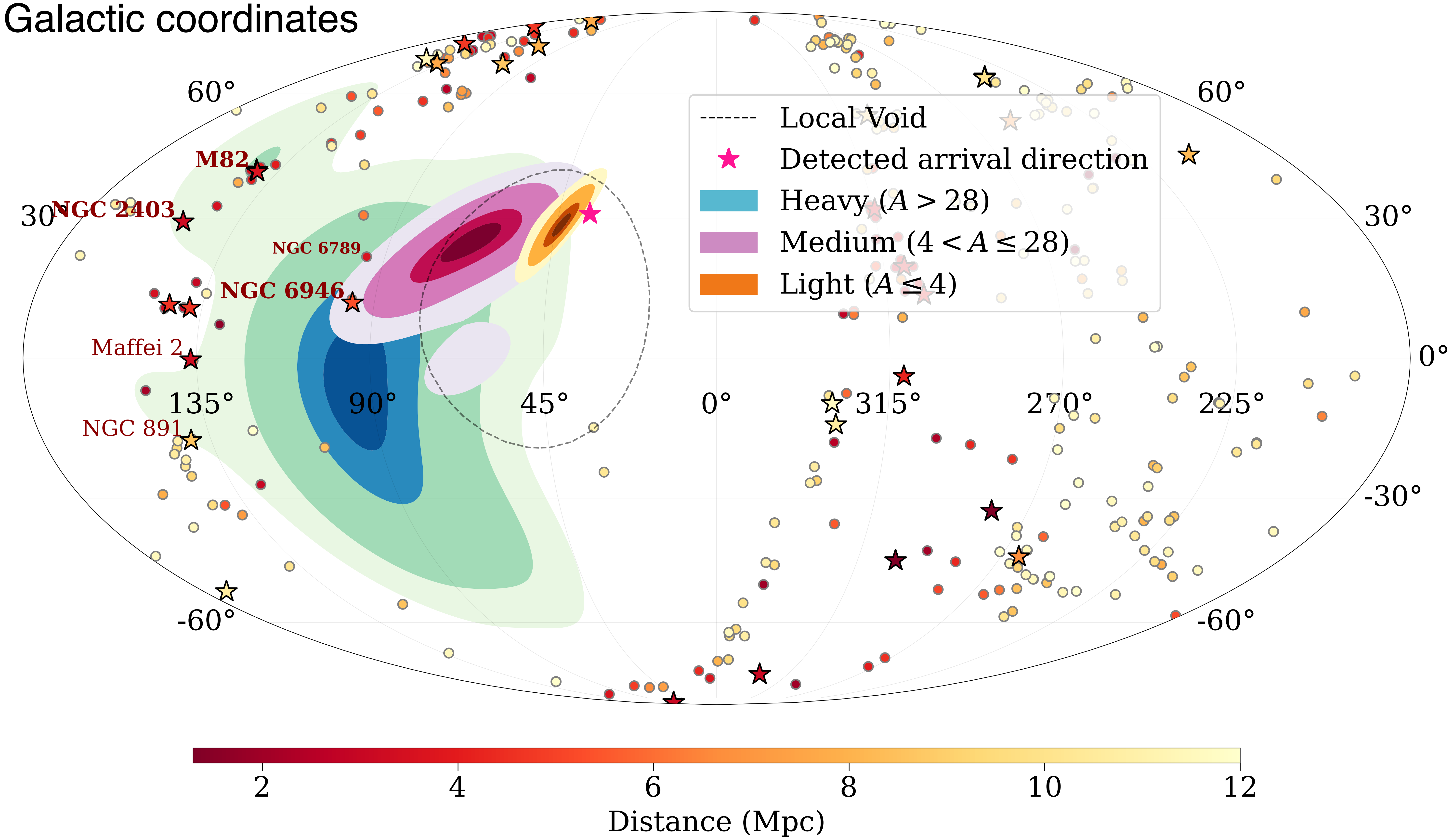
- Source regions are estimated considering both Galactic and extragalactic magnetic fields
  - For heavy nuclei, possible source candidates may be located **beyond the Local Void, nearby "TA hotspot"**

"Cutoff" region ($E > 50$ EeV)
in **Galactic coordinates**

TA hotspot, ApJL 790, 21 (2014)

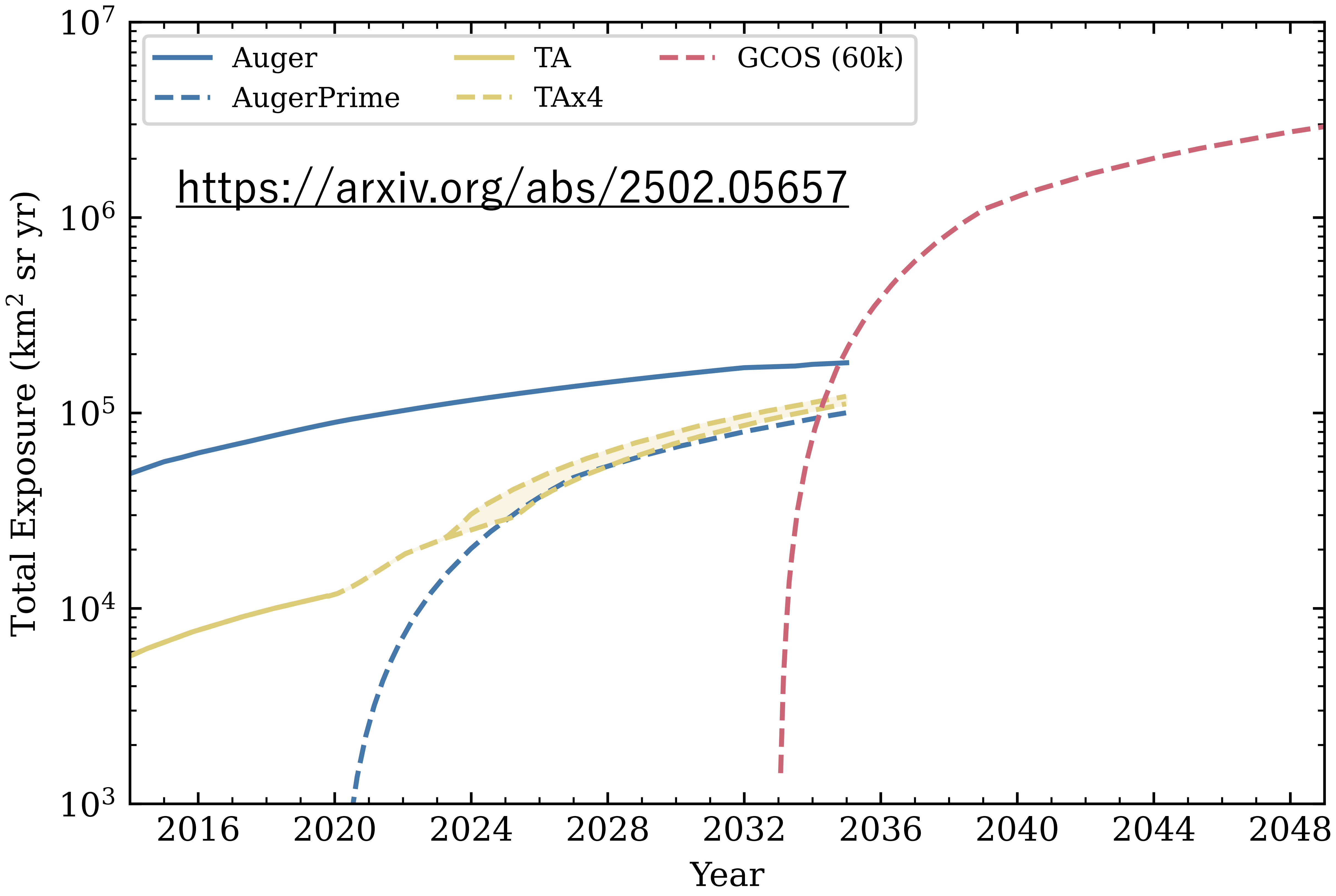


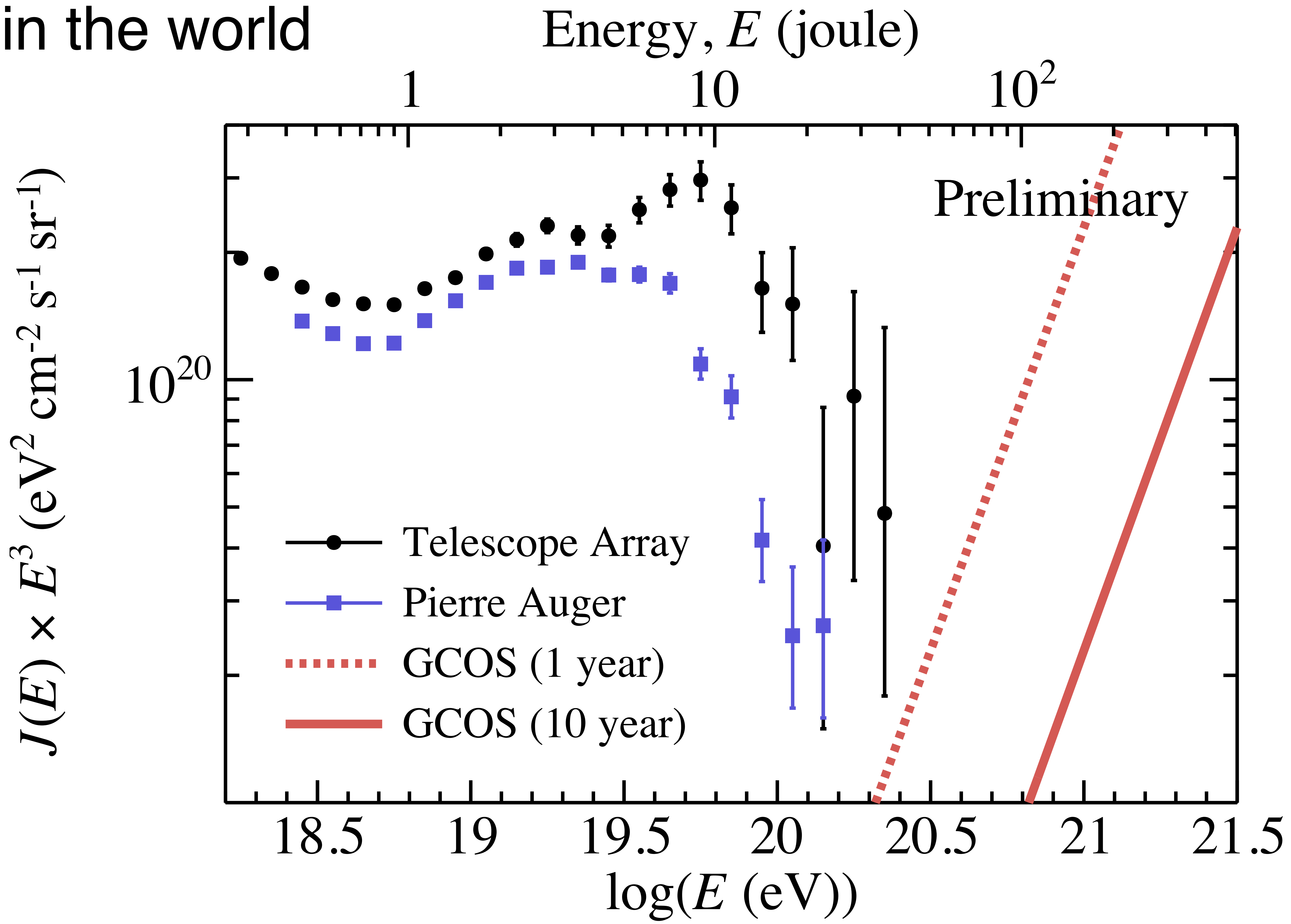
Galactic coordinates



Science of the Global Cosmic Ray Observatory

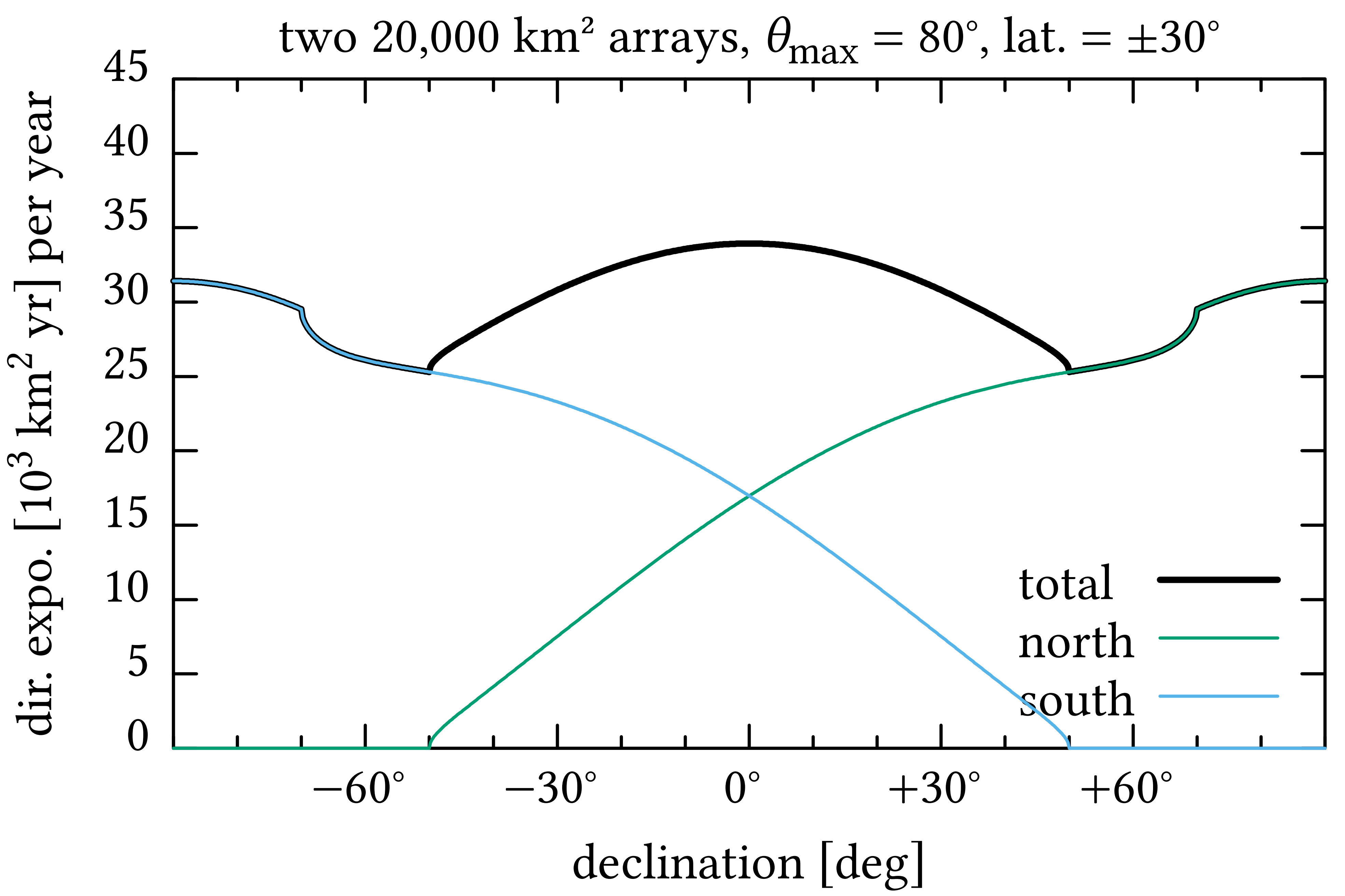
- **Charged-particle astronomy to clarify the origin and nature of the most energetic particles in the universe**
- **Unprecedented effective area, ~60,000 km²** and **mass identification capabilities**
- Begin operations in 2030s, **One team** in the world



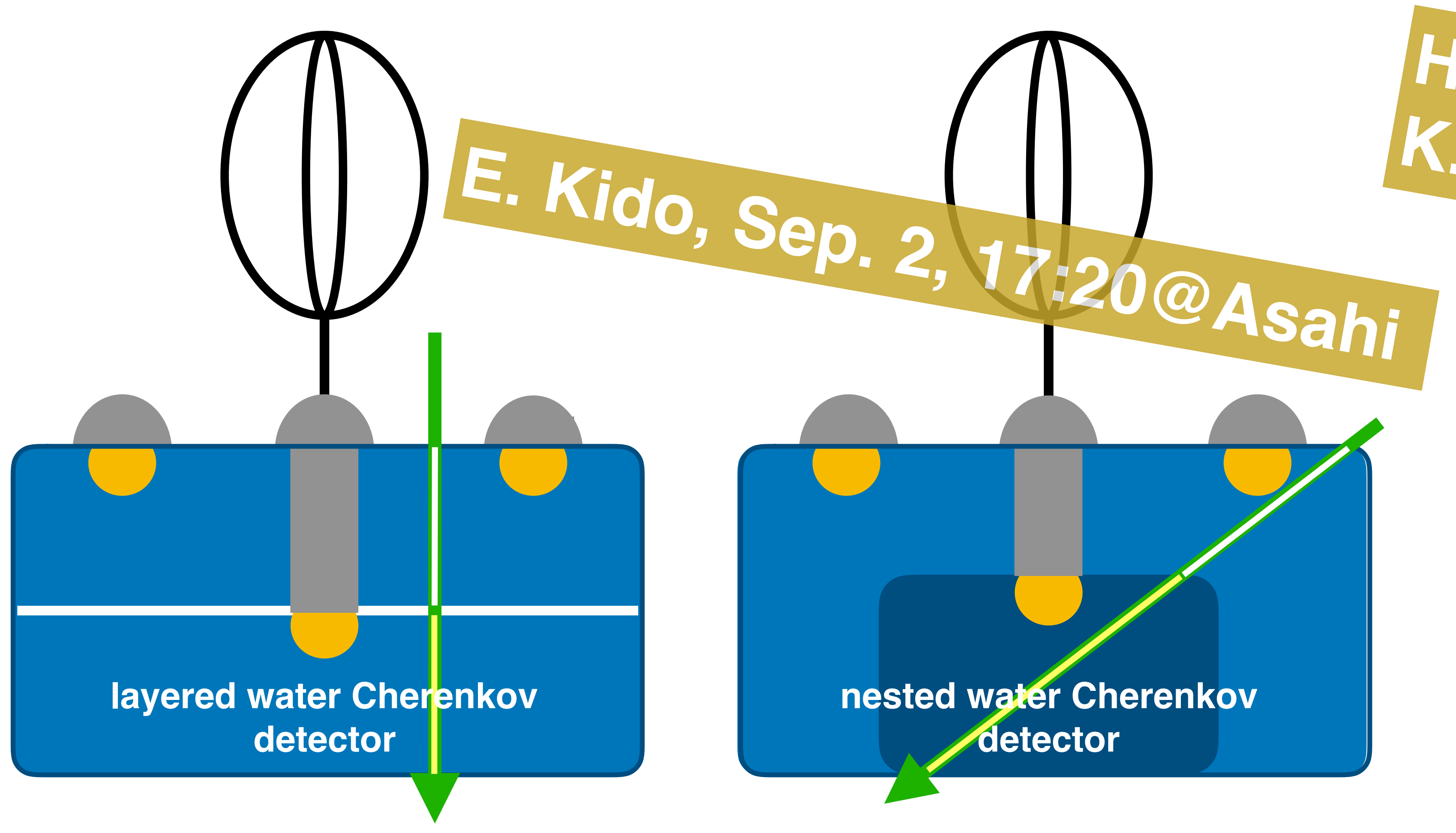


Detector of the Global Cosmic Ray Observatory

- **Number of sites ≧ 2**, Trigger energy threshold: **10 EeV**
  - Energy resolution: **10%**, mass resolution: **ln(*A*) ~ 1**, arrival direction: **1 degree**
- Detector design and possible installation sites are under considerations



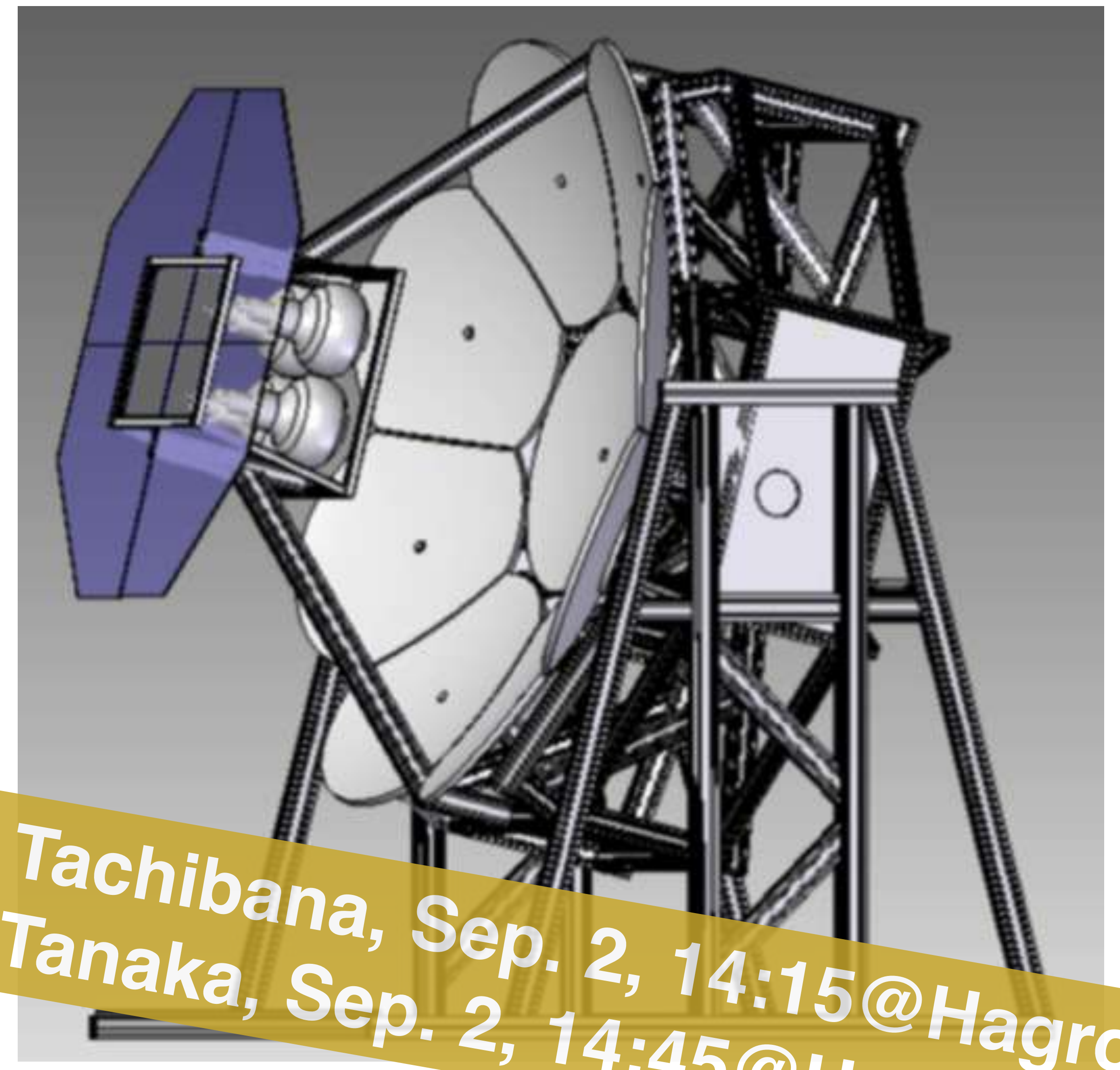
J.R. Hörandel et al. PoS (ICRC 2021) 027



E. Kido, Sep. 2, 17:20@Asahi

Figure 6: Detection concepts, using a layered (left) and a nested (right) water Cherenkov detector with a radio antenna on top.

A. Parenti in PO-1 PoS (ICRC2025) 354



H. Tachibana, Sep. 2, 14:15@Hagro
K. Tanaka, Sep. 2, 14:45@Haguro

Figure 7: A FAST telescope frame, showing four PMTs at the focus of a 1.6 m diameter segmented mirror. The support structure is made from aluminium profiles. The UV band-pass filter can be seen attached to the periphery of the camera box [100, 101].

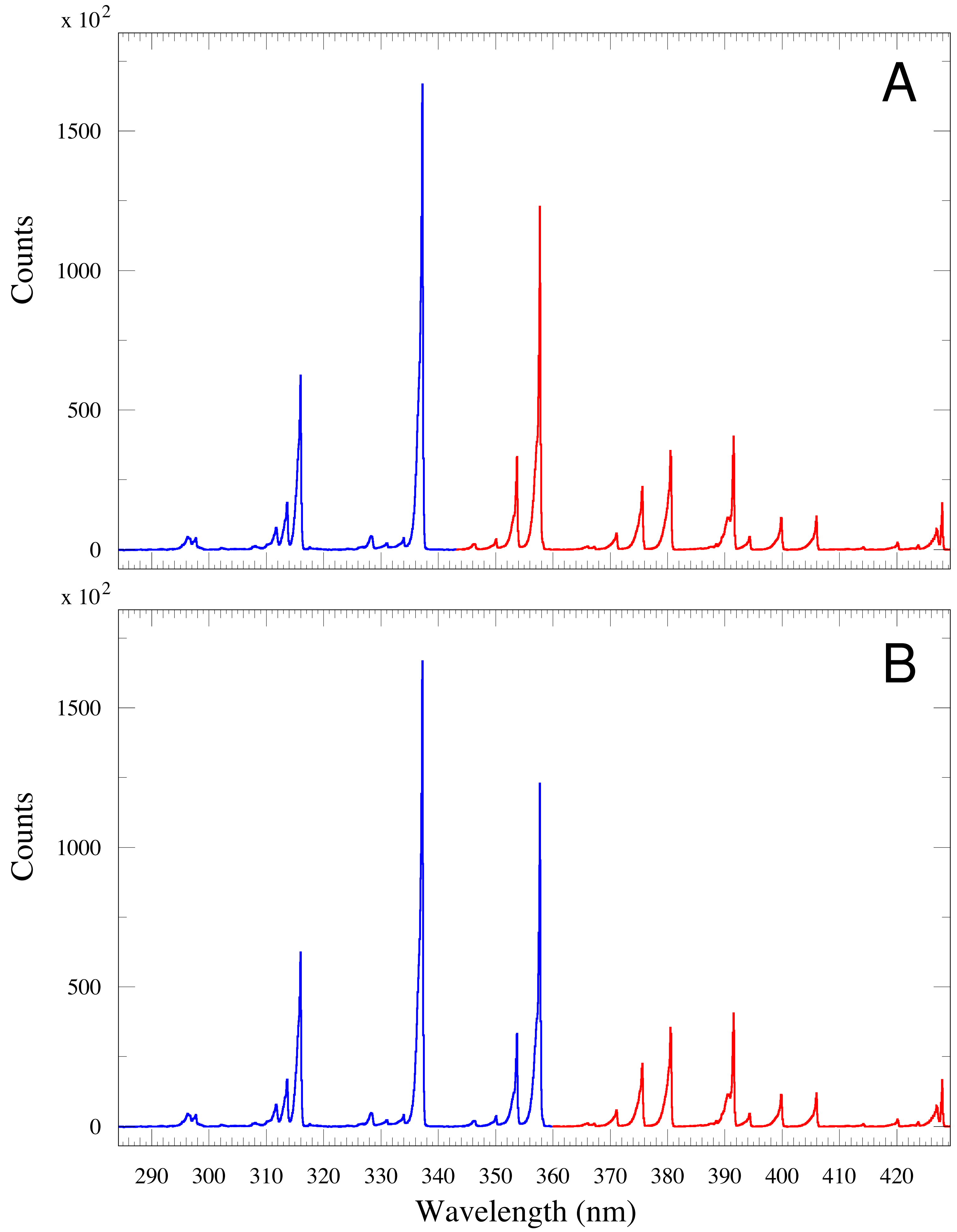
Y. Tameda in PoS (ICRC2025) 411
S. Sakurai in PoS (ICRC2025) 380

Ideas and Requirements for the Global Cosmic-Ray Observatory https://arxiv.org/abs/2502.05657

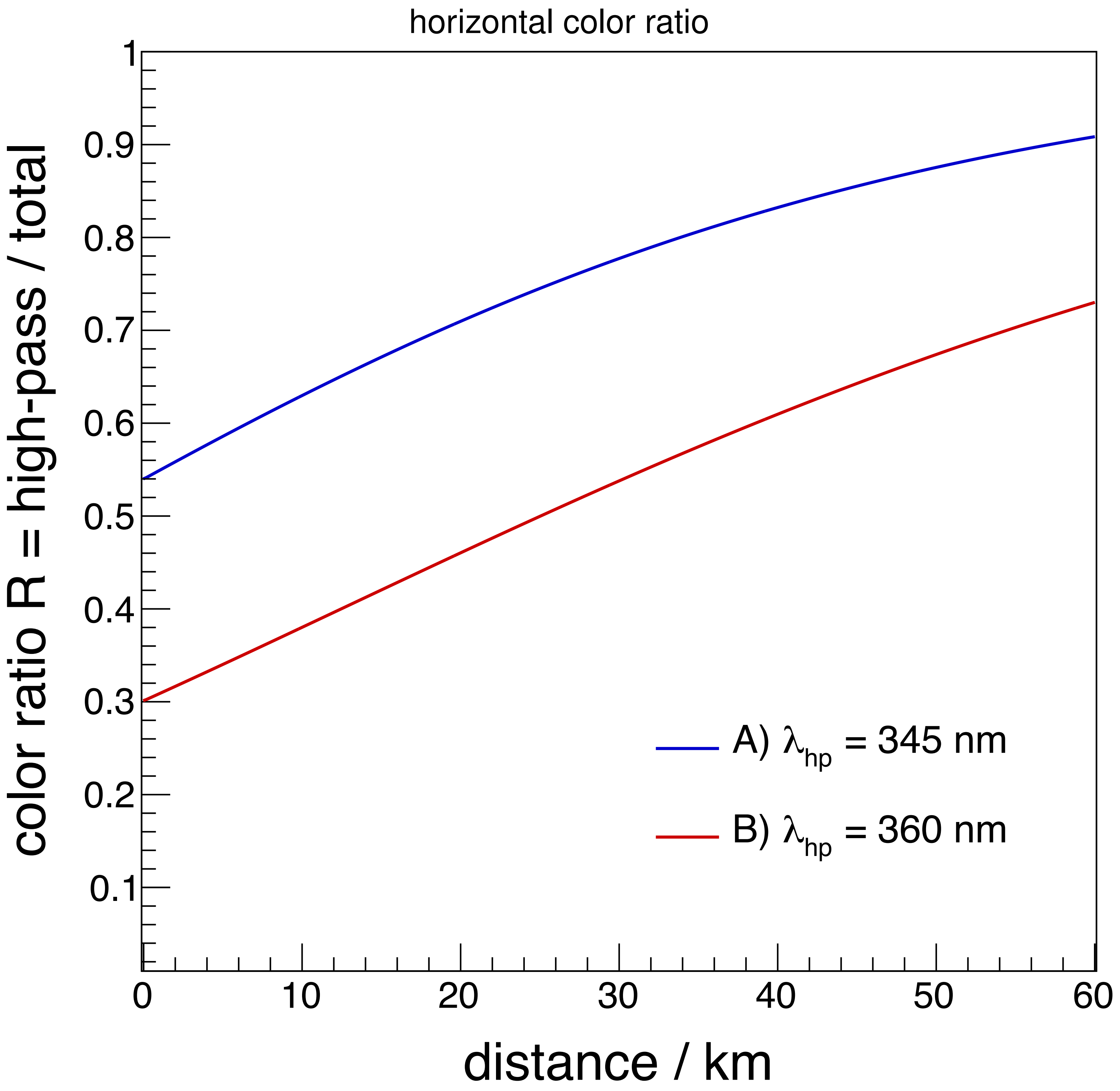
New concept: "Chromatic" Fluorescence detection

M. Unger (KIT)

fluorescence spectrum (AIRFLY 2007)



Chromatic Fluorescence Detection



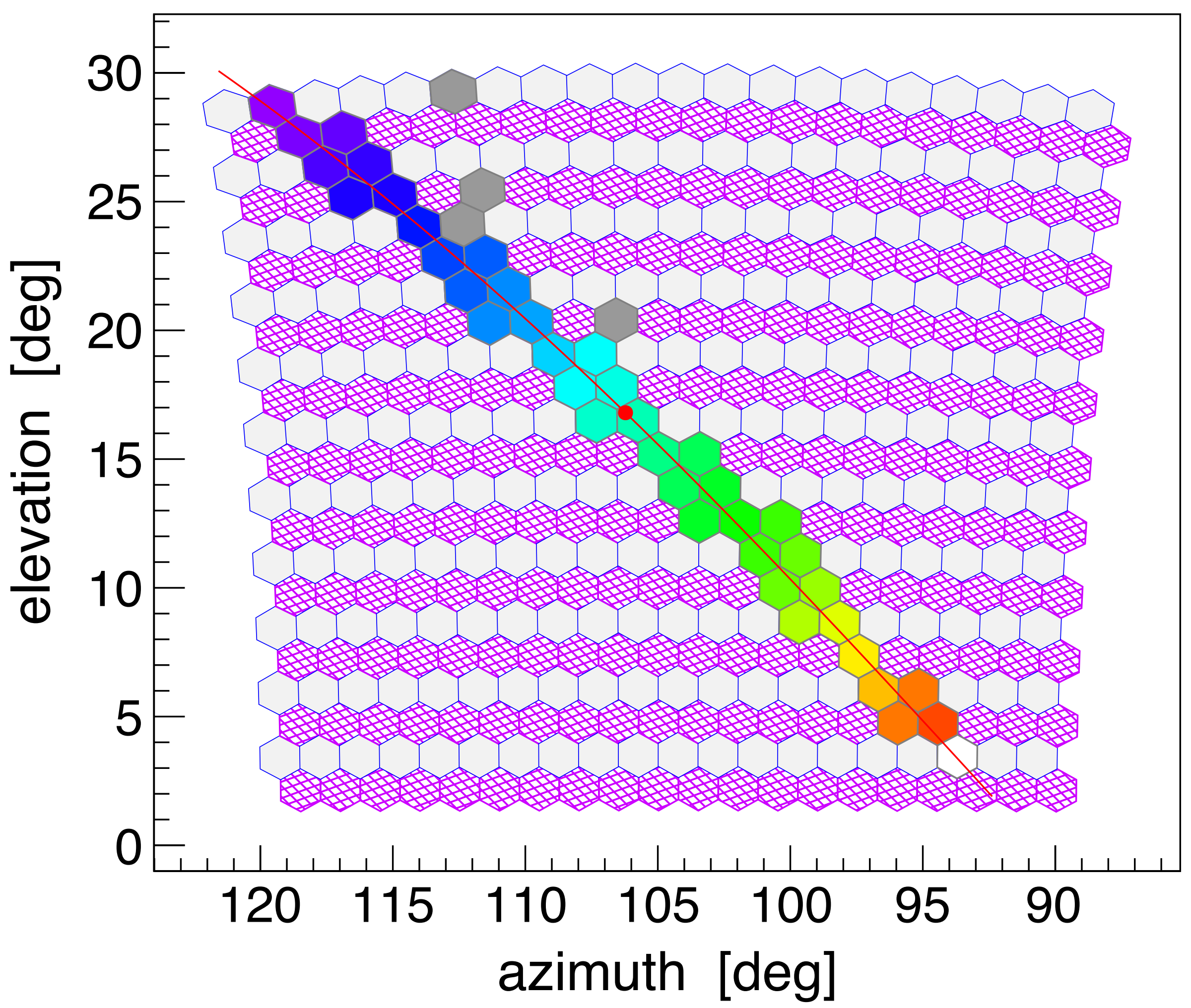
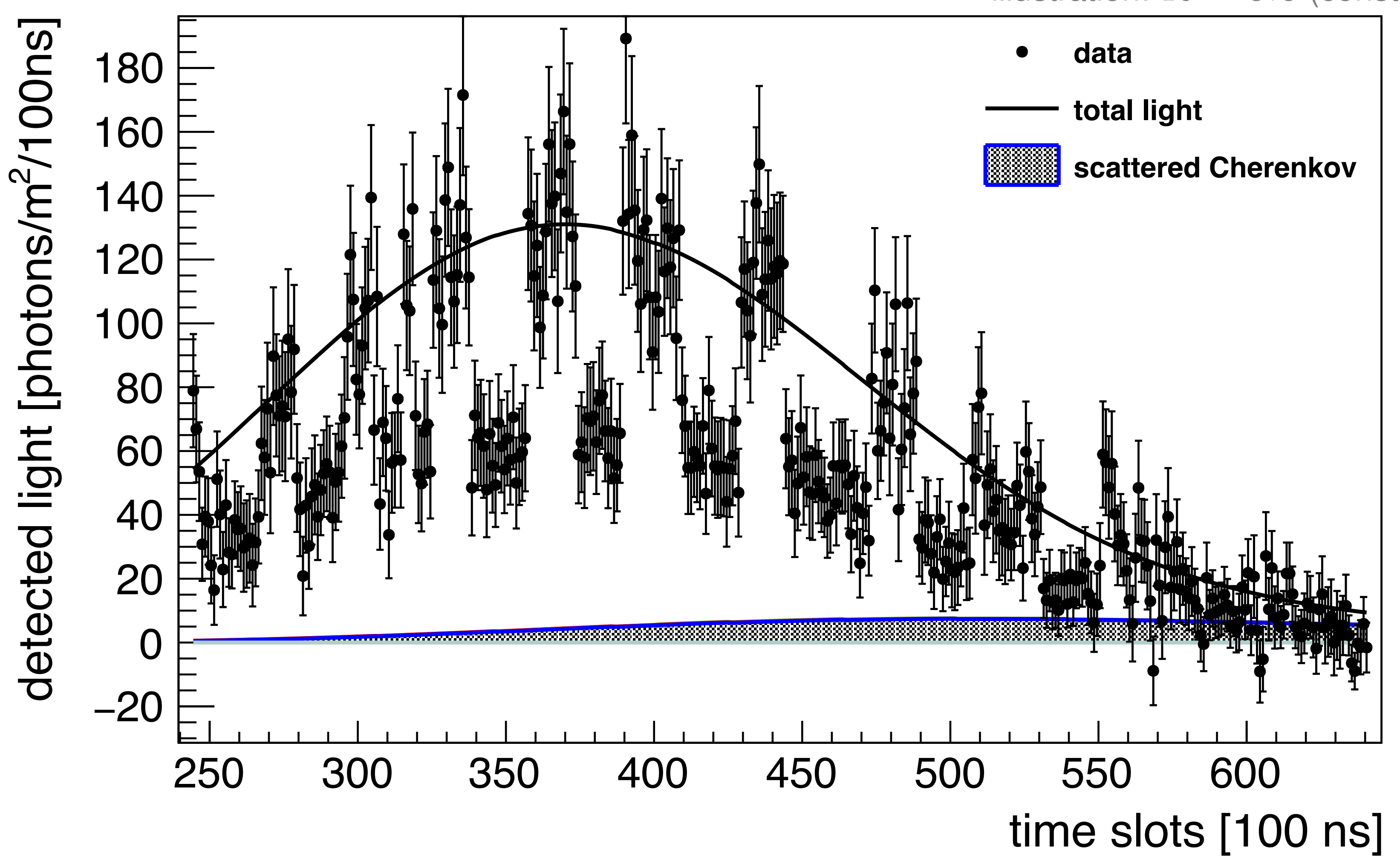
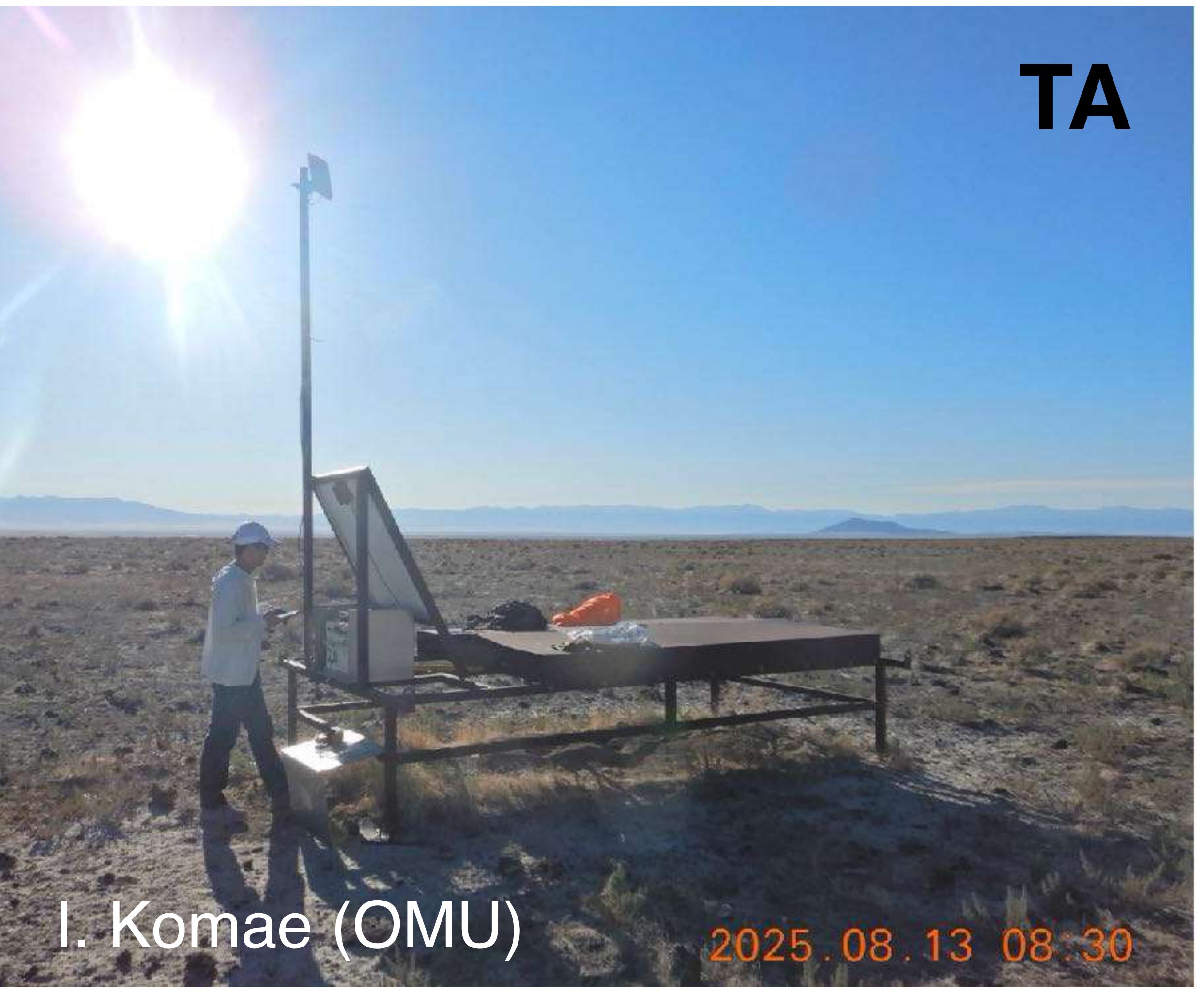


illustration: $R = 0.5$ (const.)



Color ratio = distance toward shower axis → better resolution even in monocular mode

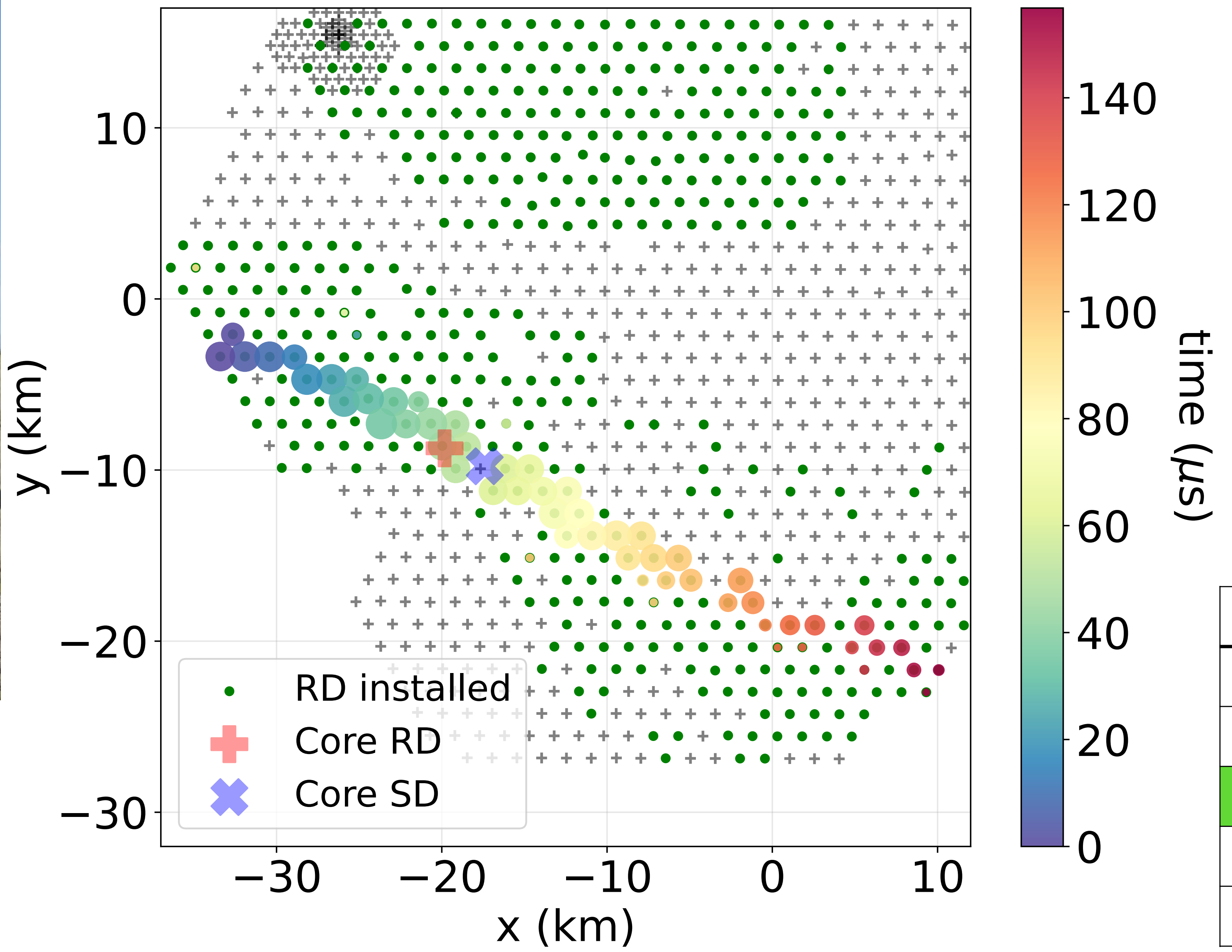
Developments of surface detector array

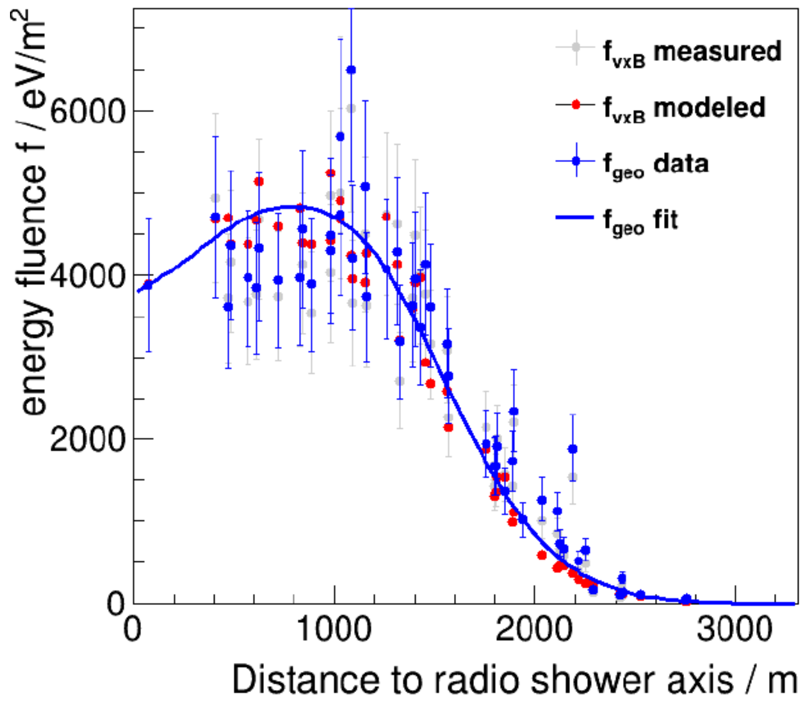


- **Optimization of detector** (Scintillator, Water-Cherenkov, Radio)
  - **Lead/Concrete shielded detector, two layered Cherenkov detector** to improve proton/iron identification capabilities
- Synergies with **machine learning technique**
- Satellite communication, **Starlink**

Radio detectors at Auger site

J.R. Hörandel (Radboud/VUB)



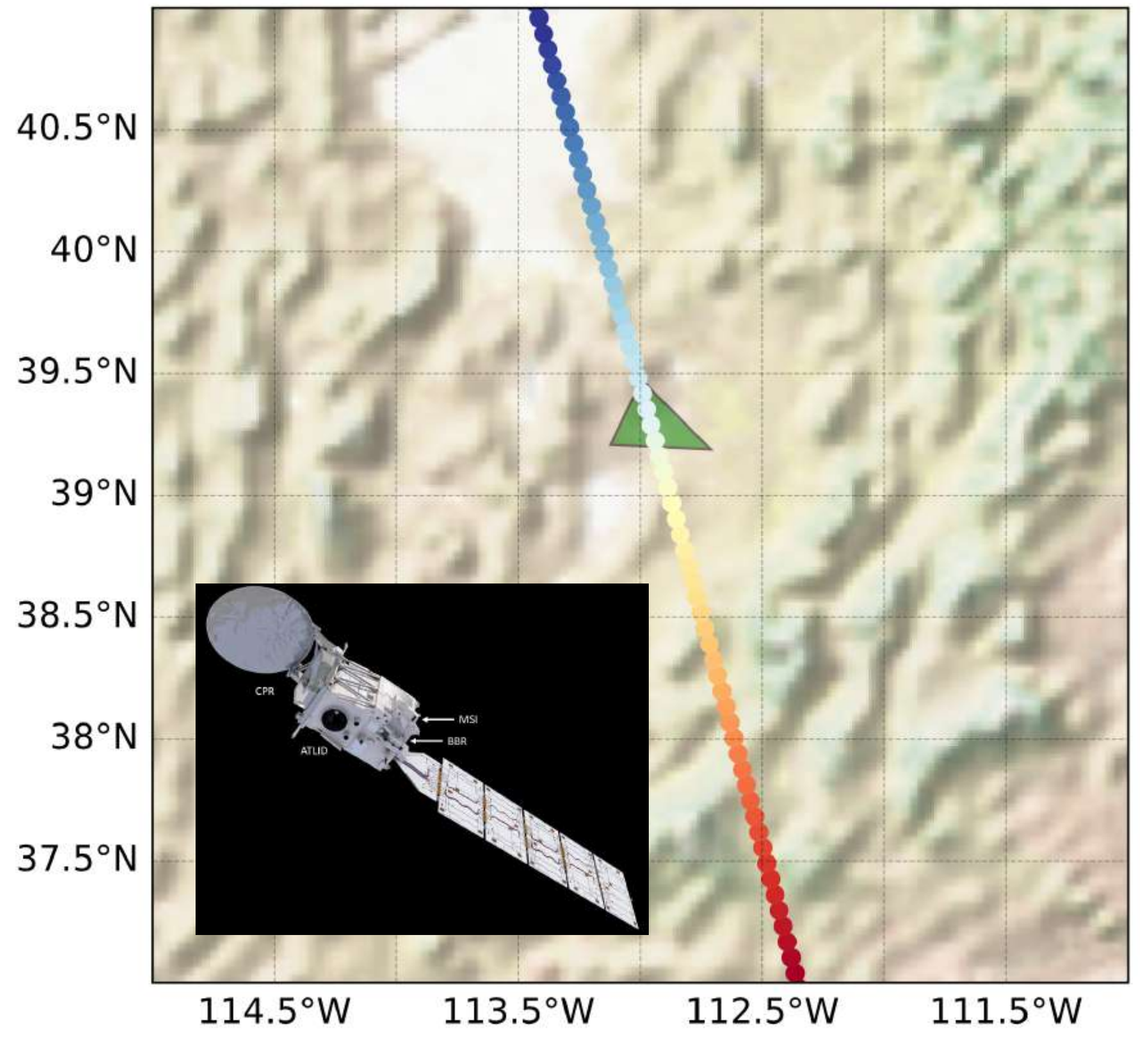


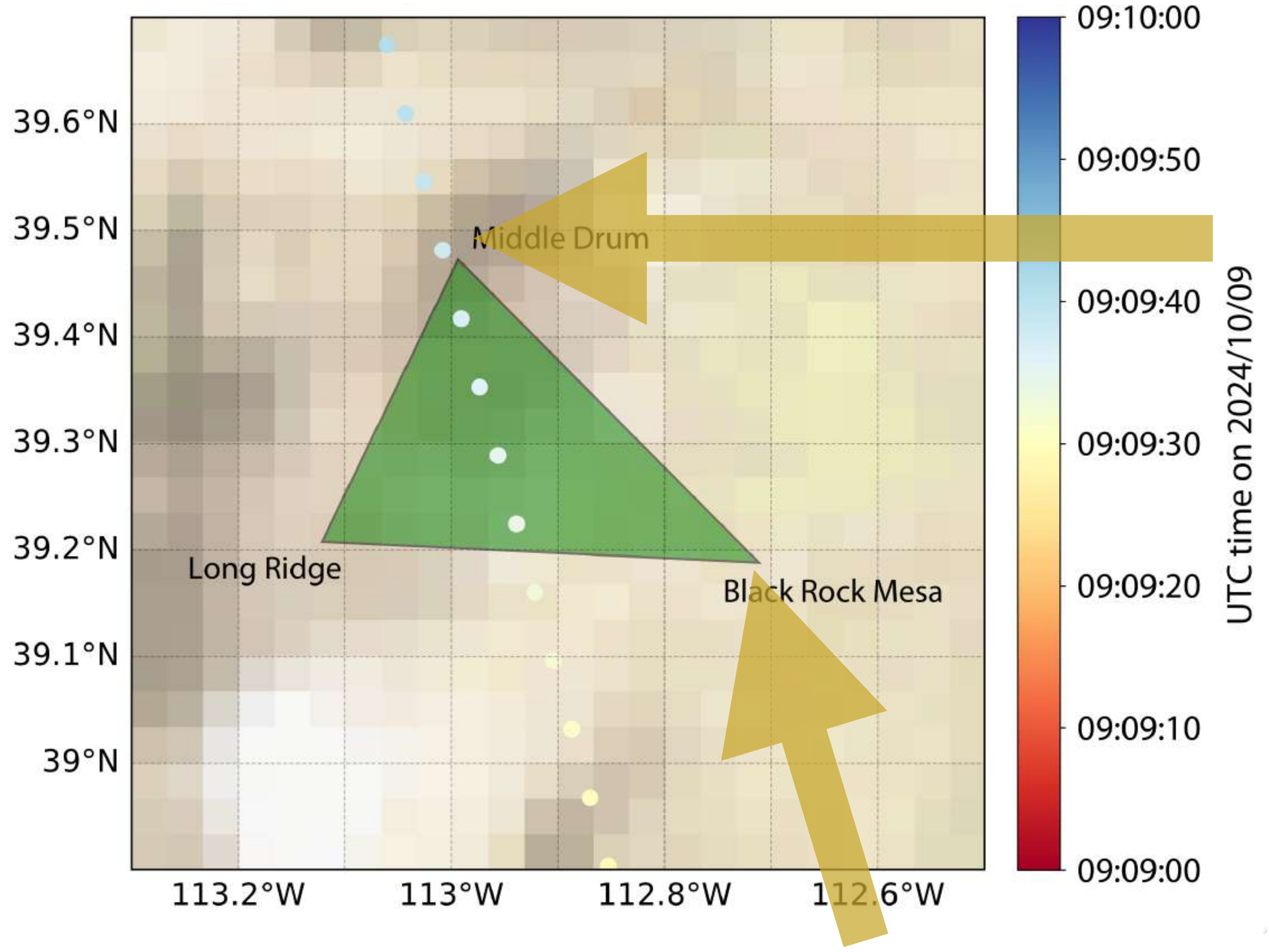
	RD	WCD
Azimuth (deg)	156.99±0.01	157±0.1
Zenith (deg)	84.7±0.01	84.7±0.1
Energy (EeV)	36.23 ± 3.34	38.55 ± 2.92
Core X (km)	-19.8	-17.40±0.88
Core Y (km)	-8.73	-9.78±0.45

Akeno Observatory as a test bench for detector developments

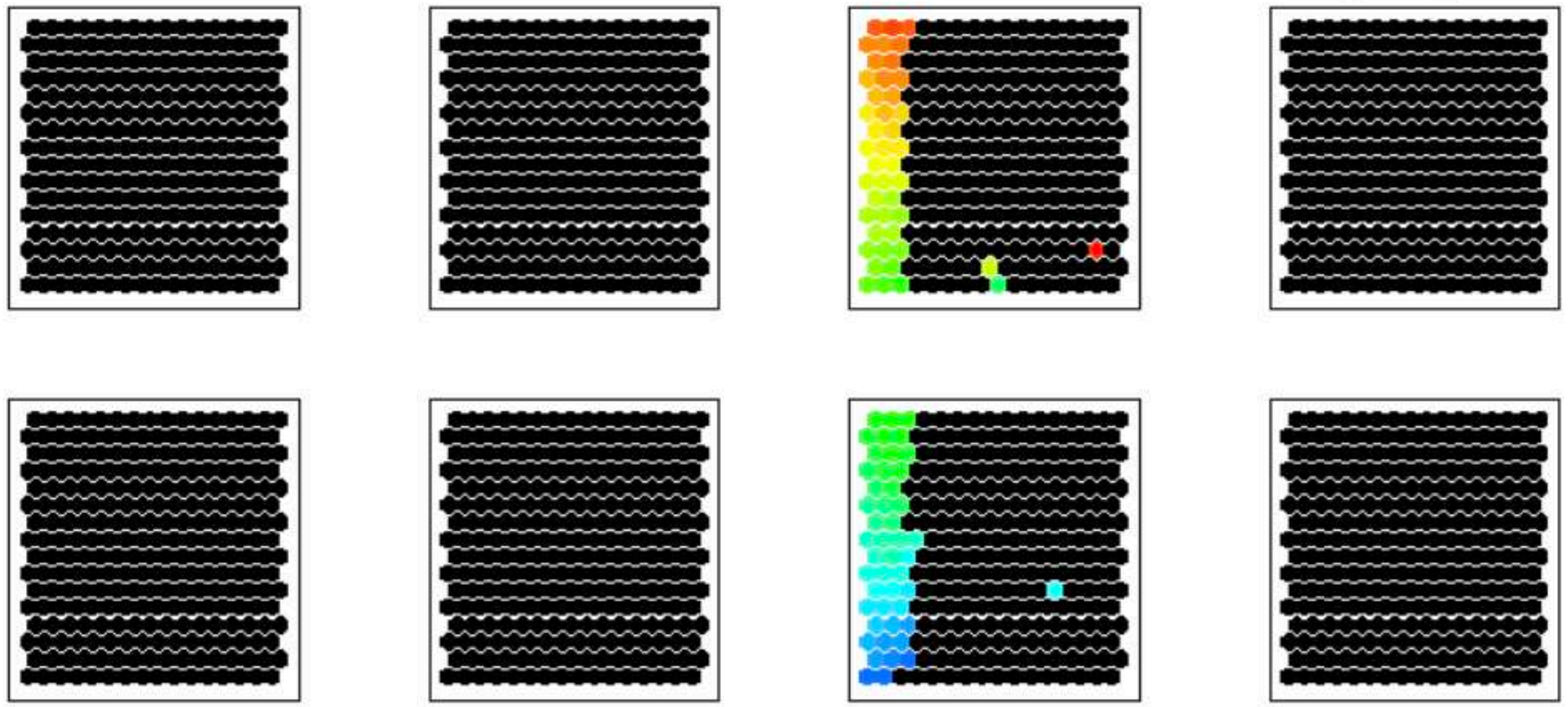
Intersection with Earth Science as "global light source"

TA overpass on 9 October 2024

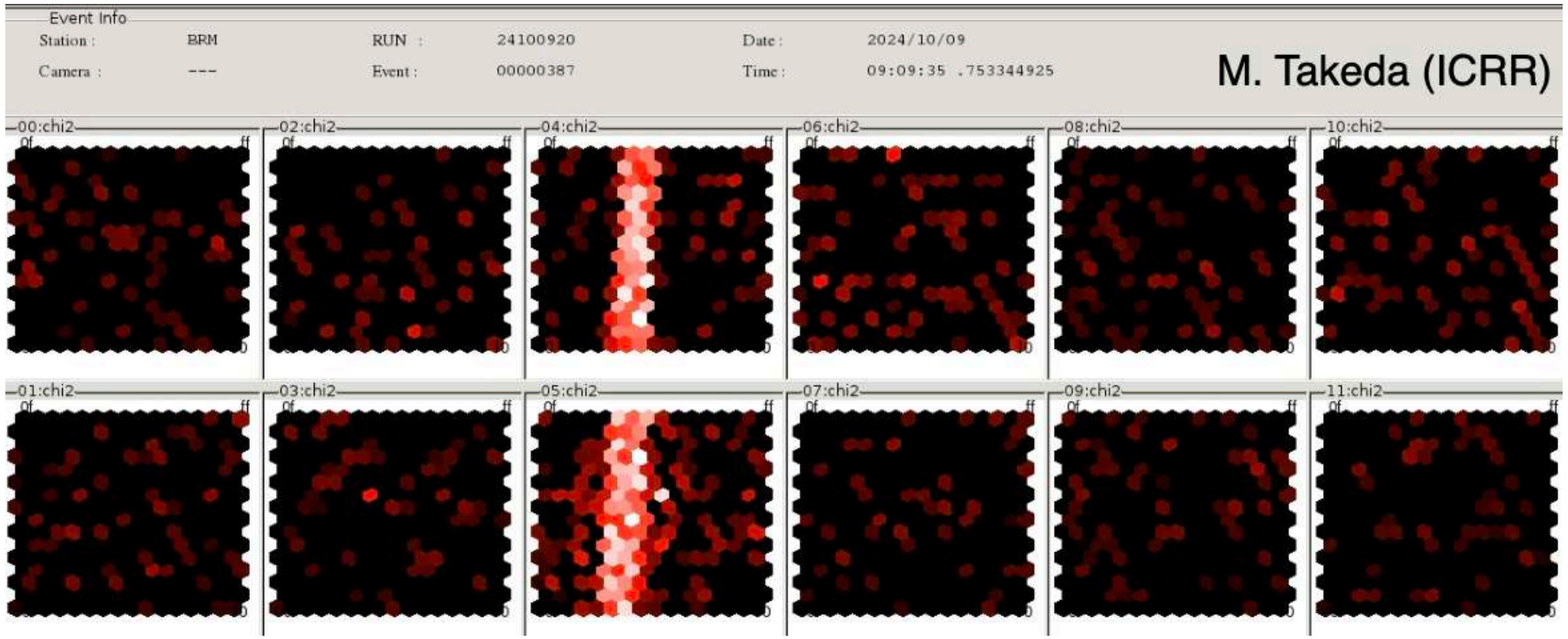




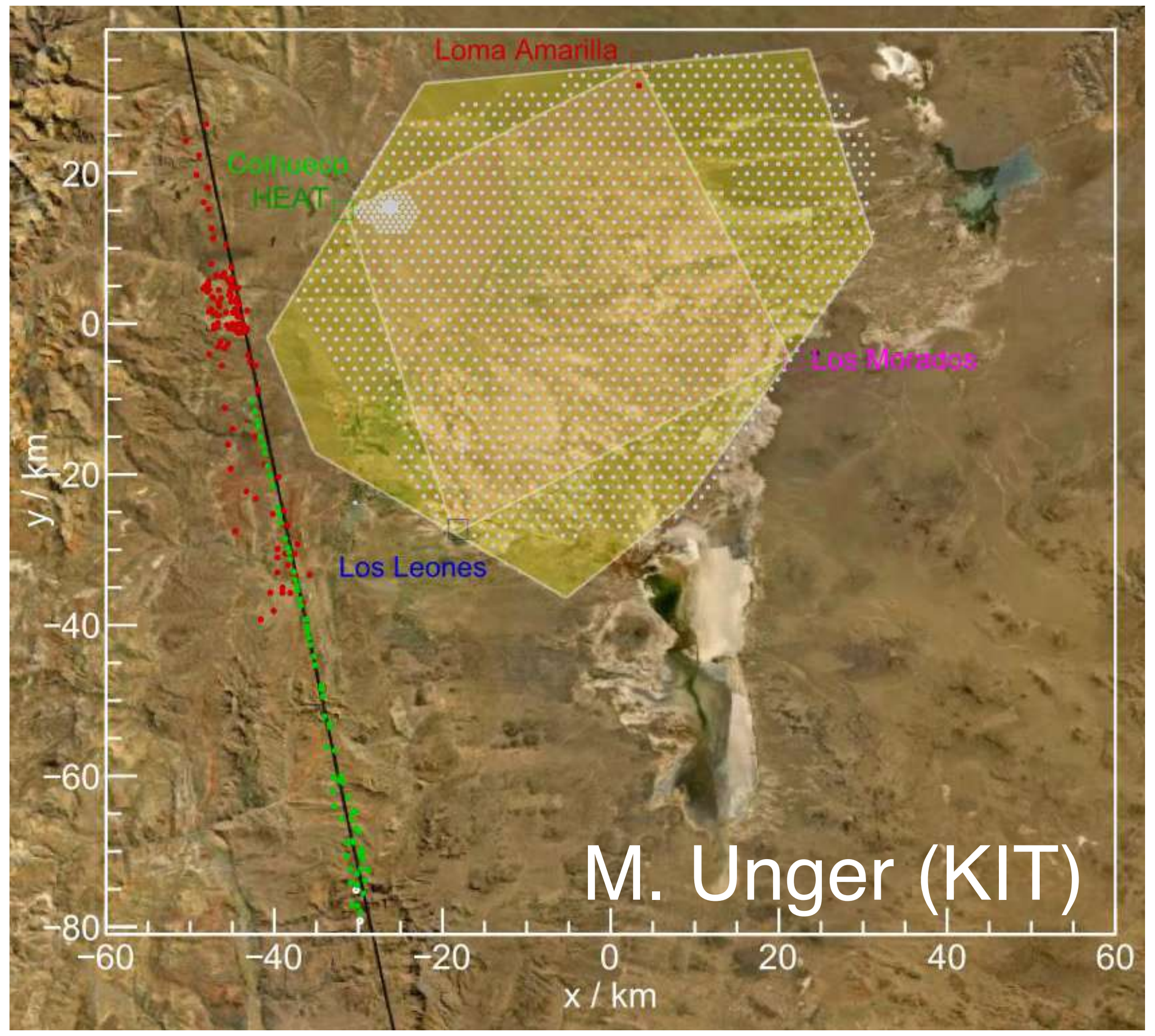
K. Fujita (ICRR)



Auger overpass on 29 October 2024



EarthCARE team: O. Lux and O. Reitebuch (DLR)



Summary and future

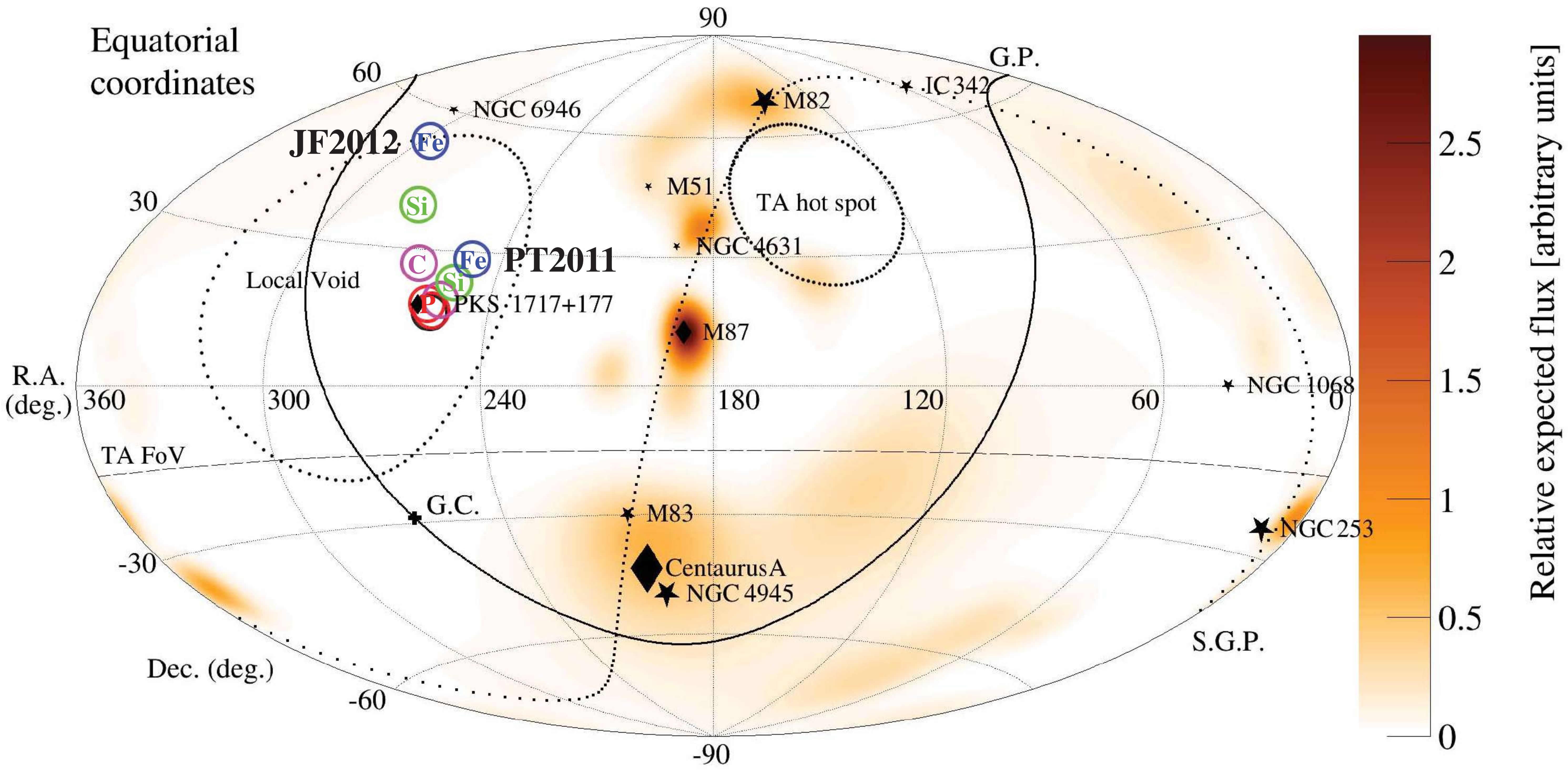
- **Scientific objectives of GCOS**
  - **Charged-particle astronomy** to clarify the origin and nature of UHECRs
    - Unprecedented effective area, **60,000 km²** and **mass identification capabilities**
  - **First detection of ultra-high-energy neutrinos and photons**, and search for new physics beyond standard model
  - Understand hadronic interaction and air-shower physics at the highest energies
  - Study geophysics and earth science as interdisciplinary research

GCOS-Japan workshop in Kanazawa, Aug. 3-5, 2026

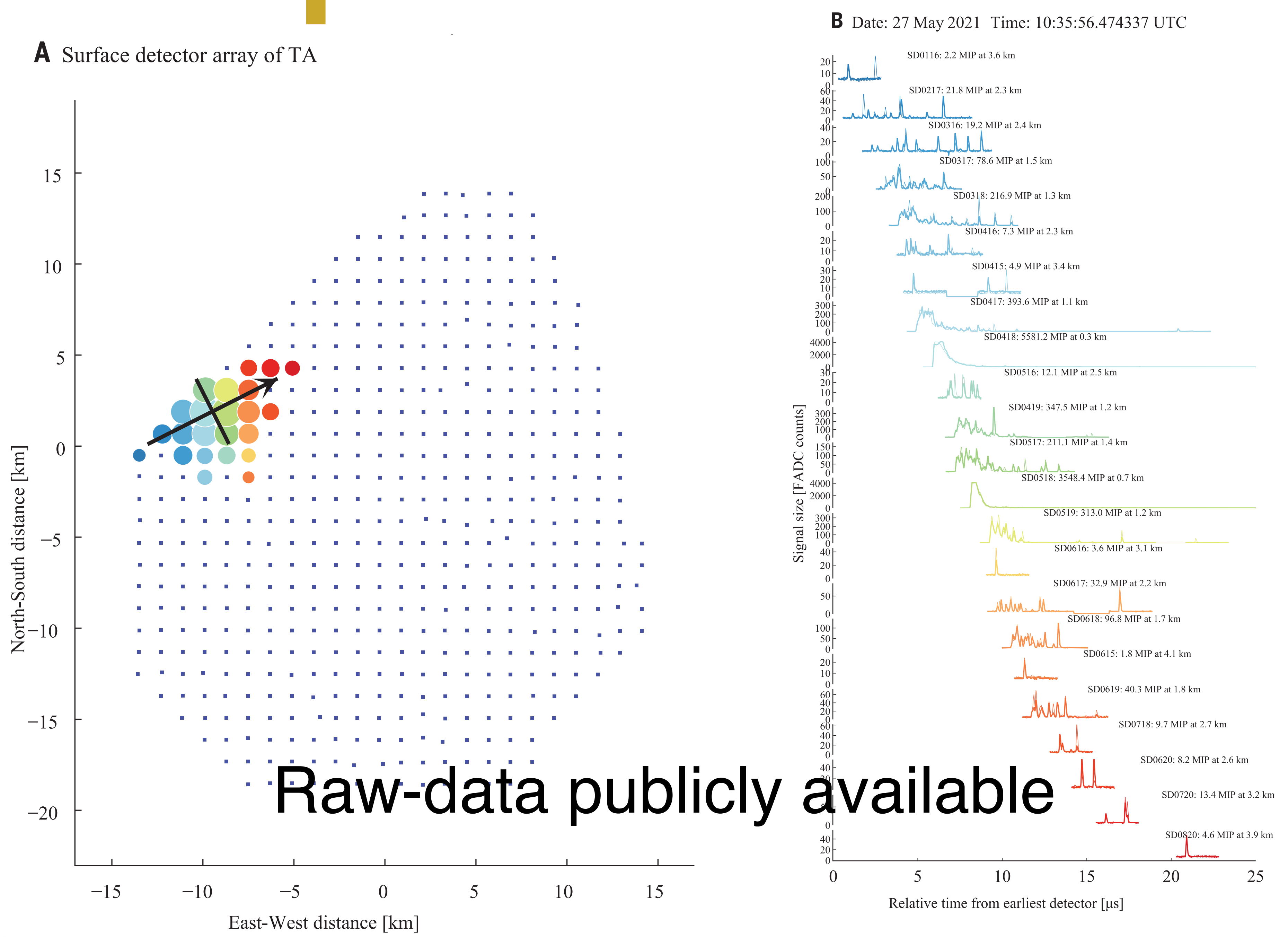
Backup

Arrival direction of Amaterasu particle

- E = 244 ± 29 (stat.) +51,-76 (syst.) EeV
  - **Unexpectedly, came from the Local Void**
  - No promising astronomical source candidates



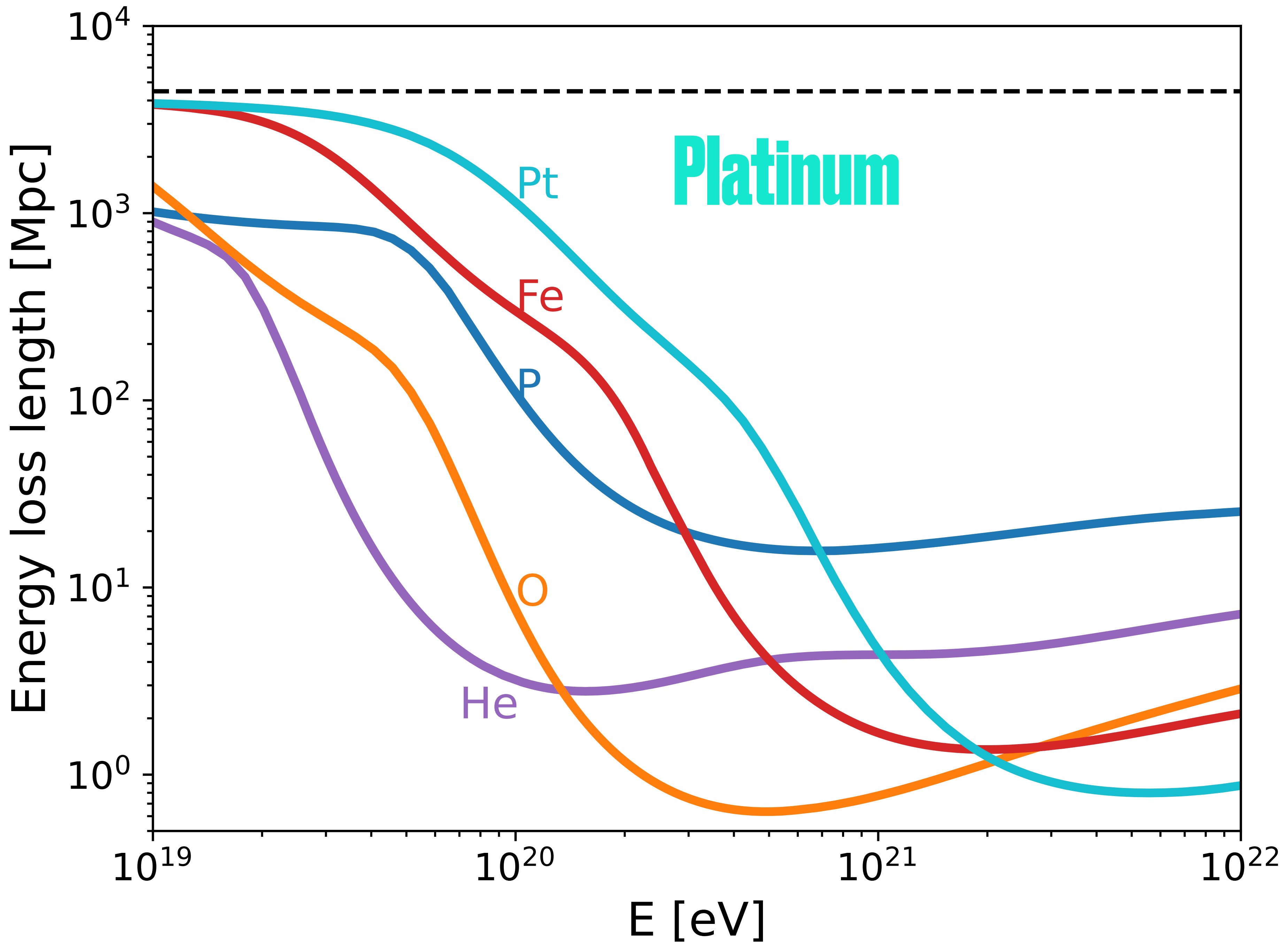
Telescope Array Collaboration, Science 382, 903 (2023)

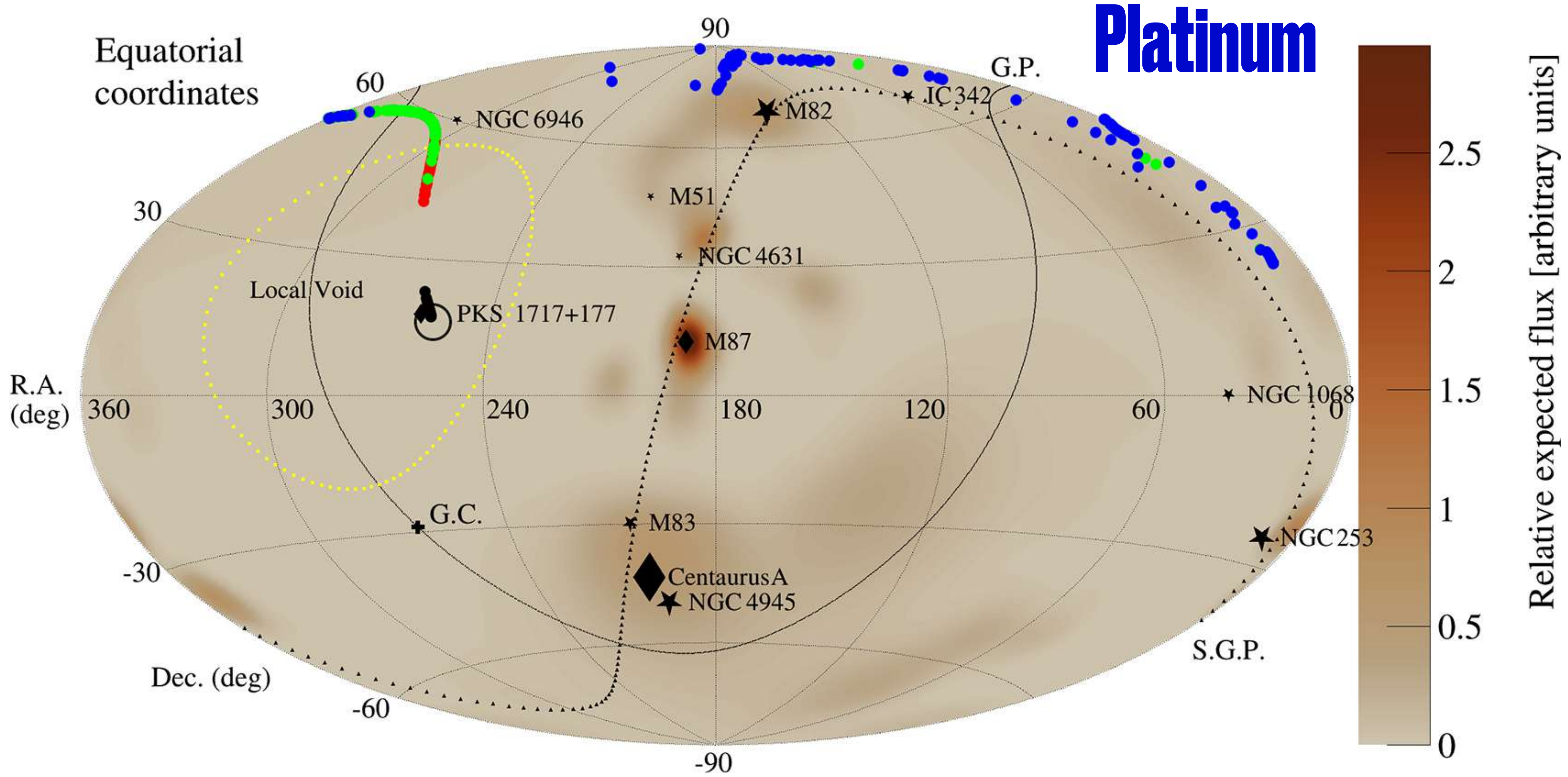


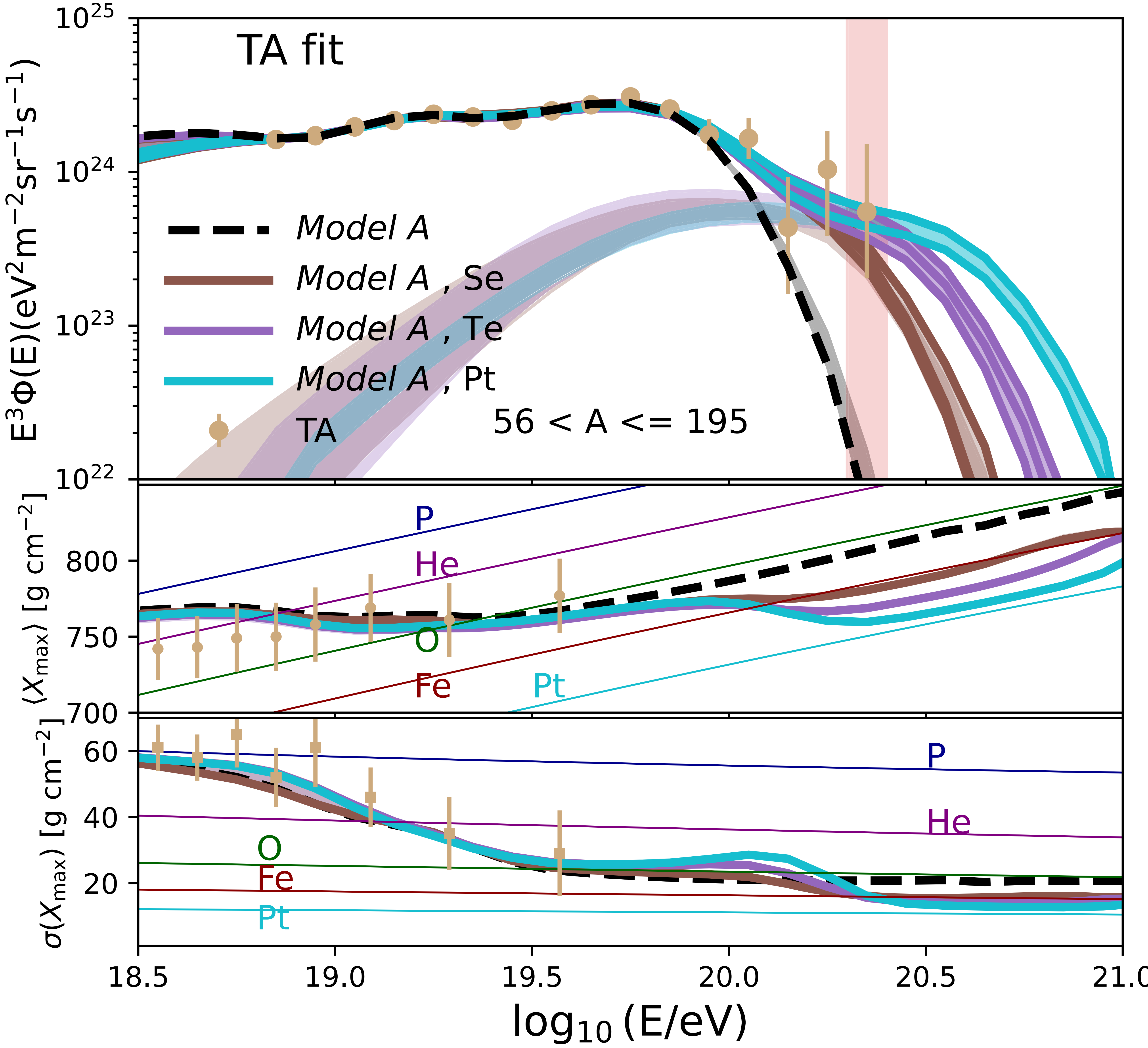
Raw-data publicly available

- **Possible source region** [Unger and Farrar, ApJL 962 L5 (2024)]
- **Magnetic monopole** [Frampton, Phys.Lett.B 855, 138777 (2024)]
- **Ultra-heavy composition** like Te or Pt [Zhang, Murase+, arXiv:2405.17409]
- **Binary neutron star merger** [Farrar, PRL 134, 081003 (2025)]
- **Bursting magnetar** [Shimoda and Wada, arXiv:2409.19915]

Ultraheavy ultrahigh-energy cosmic rays







B.T. Zhang et al., PRL 136, 181002 (2026)

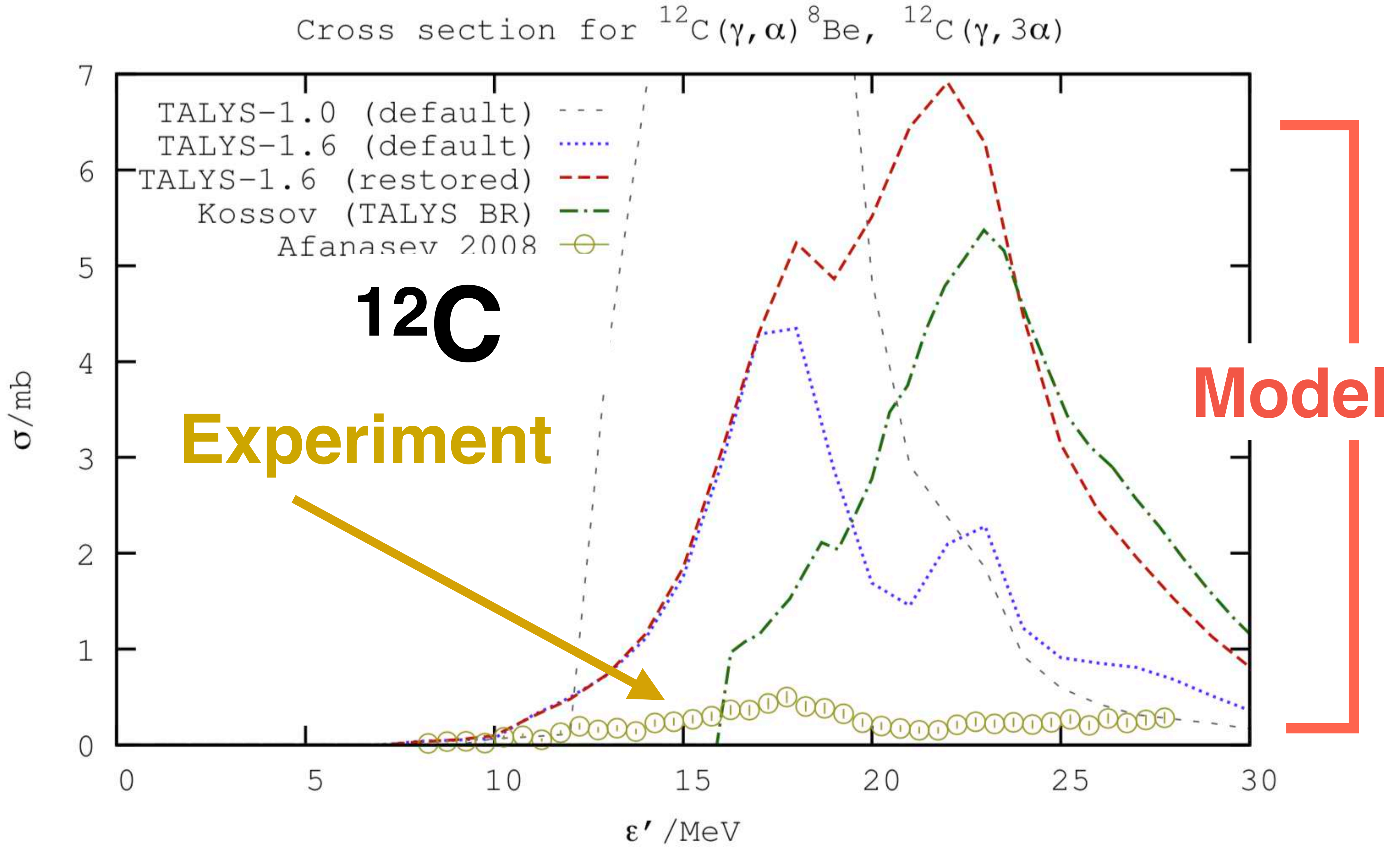
Nuclear Physics meets UHECRs (PANDORA project)

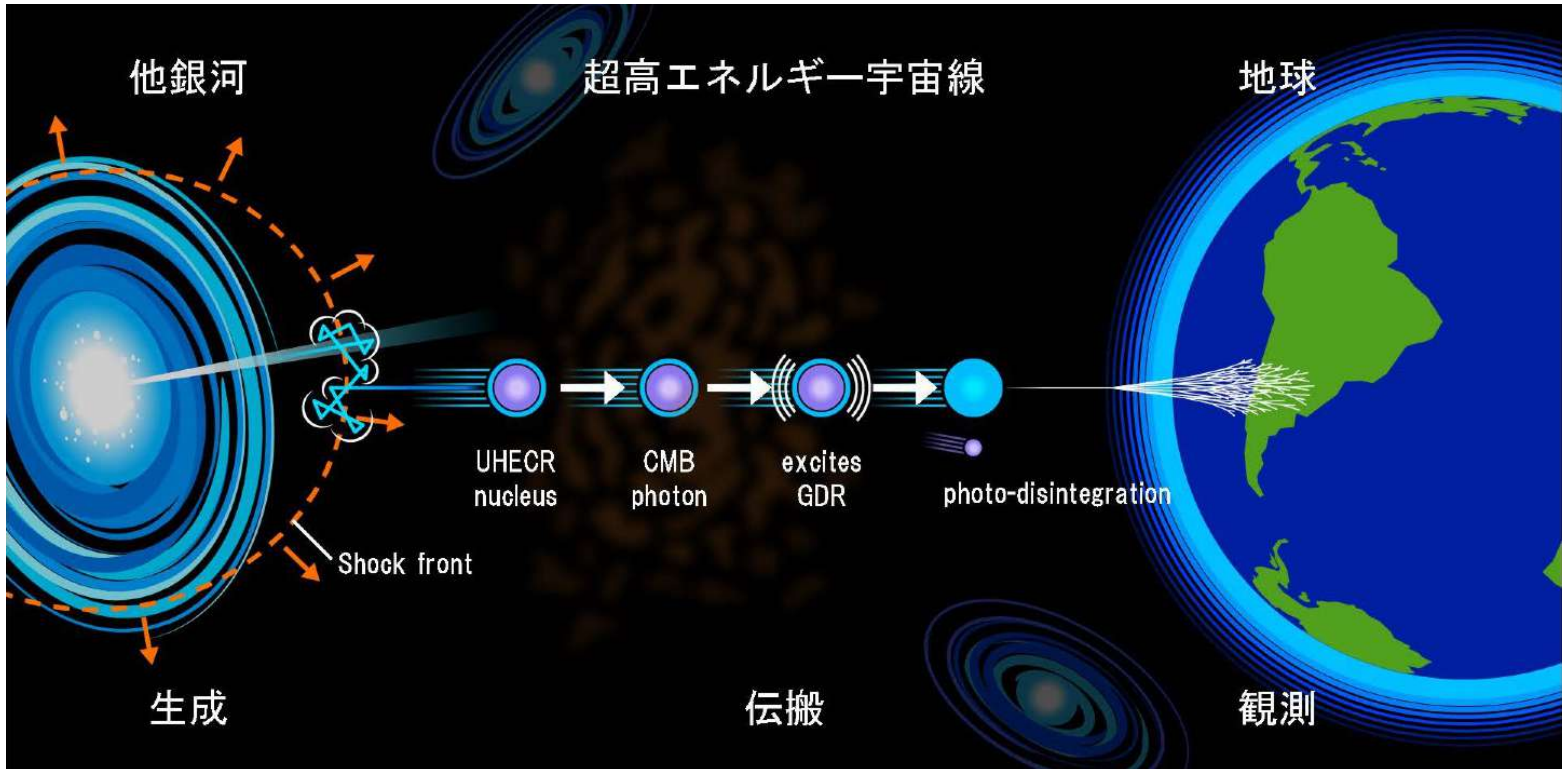
$$ {}^{A}_{Z}N + \gamma_{\mathrm{CMB}} \rightarrow {}^{A-1}_{Z-1}N' + p $$

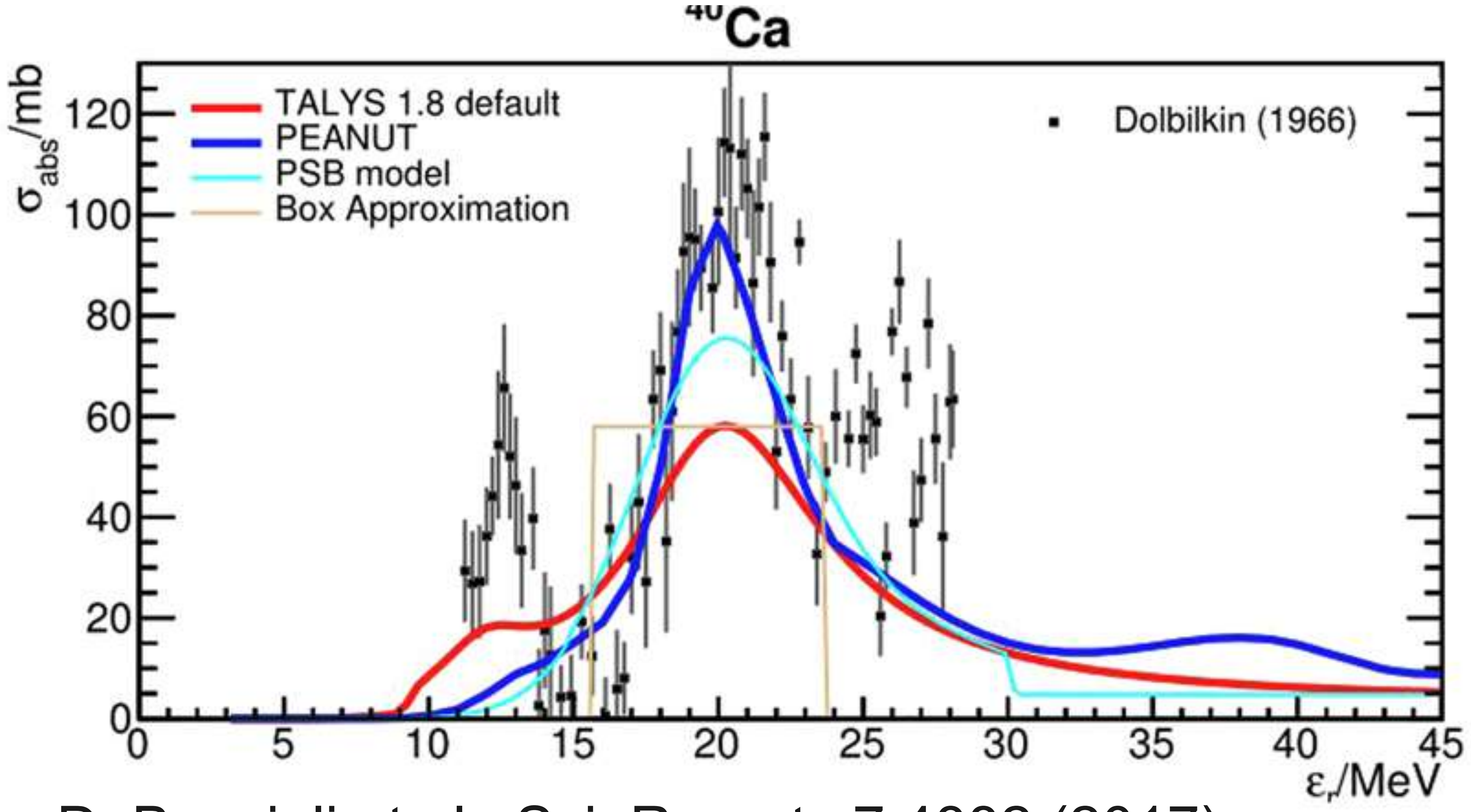
- Large uncertainty of the cross section from the giant dipole resonants for A < 60 nuclei
- Multidisciplinary research among nuclear physics, UHECR and CMB

A. Tamii, E. Kido et., Eur. Phys. J. A 59, 208 (2023)

E. Kido et al., *Astropart.Phys.* 152 (2023) 102866







D. Boncioli et al., Sci. Reports 7:4882 (2017)

Muon puzzle

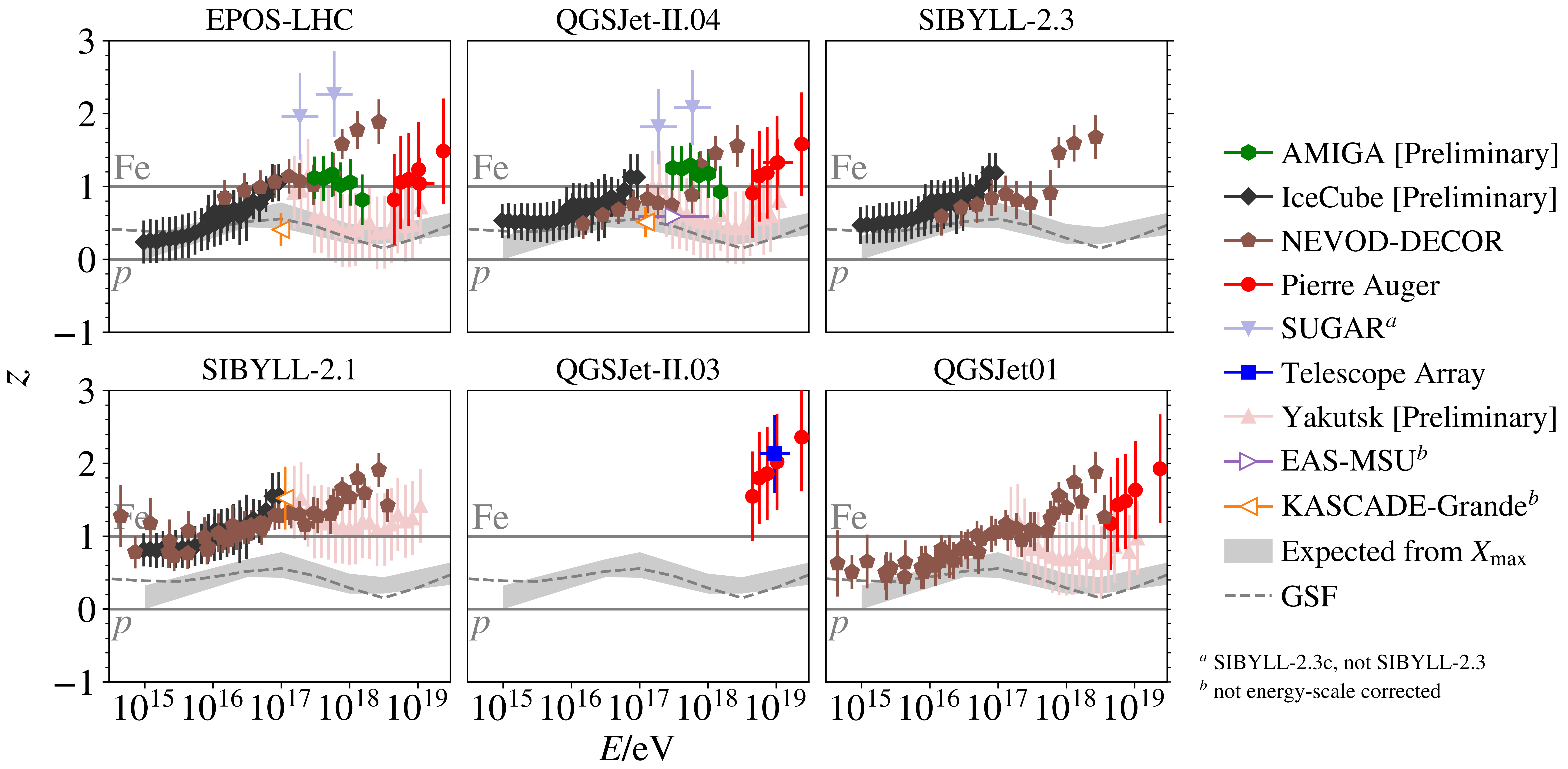


Fig. 3 Compilation of muon measurements converted to the abstract z-scale and after cross-calibrating the energy scales of the experiments as described in the text (image from Dembinski et al. (2019)). Shown for comparison are predicted z_{mass}-values based on air shower simulations and $X_{\max}$-measurements (grey band). The prediction from the GSF model (Dembinski et al. 2018) for z_{mass} is also shown (dashed line).

J. Albrecht et al., arXiv:2105.06138 (2021)

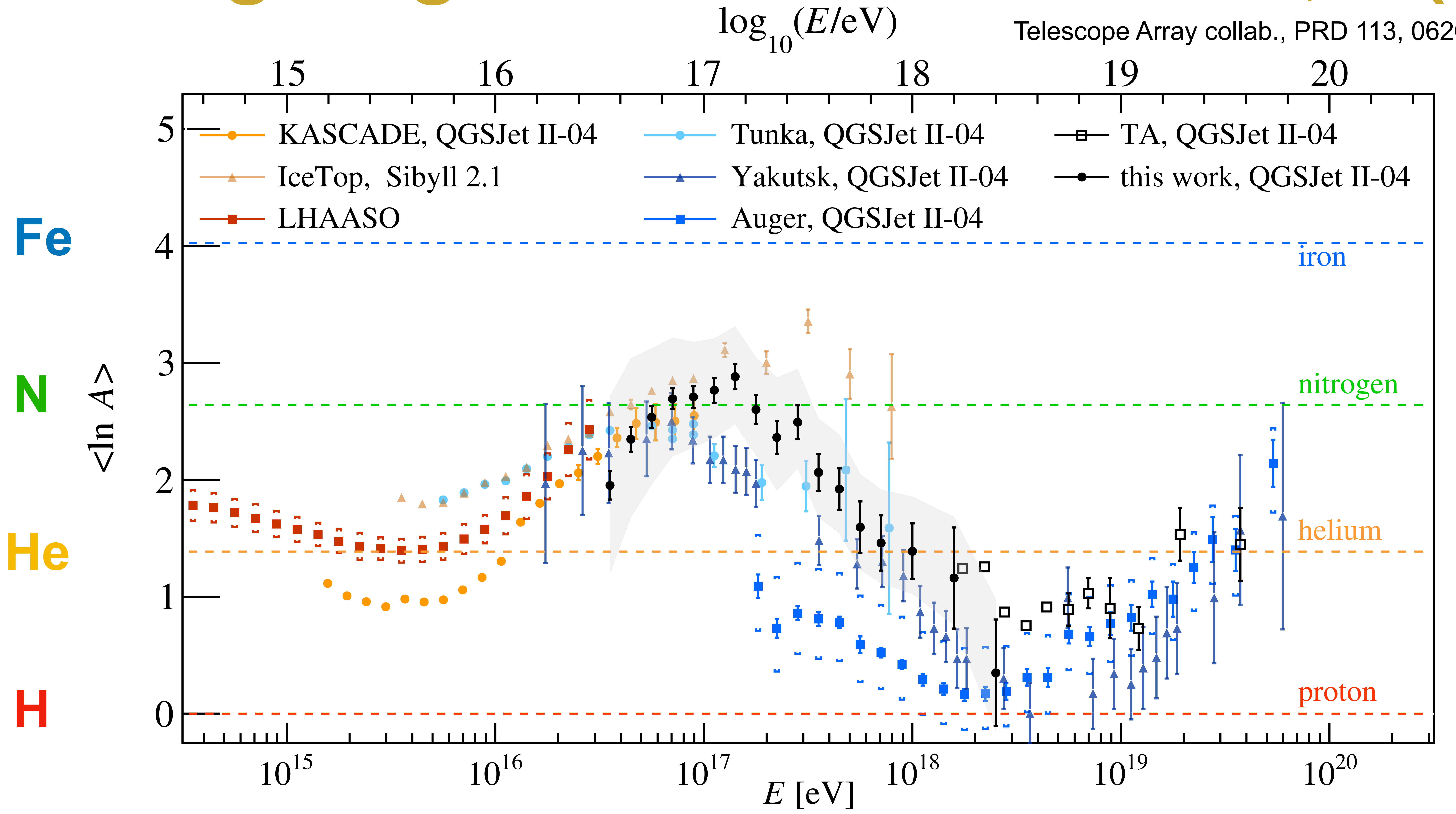
Energy spectrum

- Firmly confirmed the spectrum cutoff above 50 EeV
- No detection above 300 EeV

A. Coleman et al., Astropart. Phys. 149, 102819 (2023)

Average logarithmic mass number, ln(A)

Telescope Array collab., PRD 113, 062003 (2026)

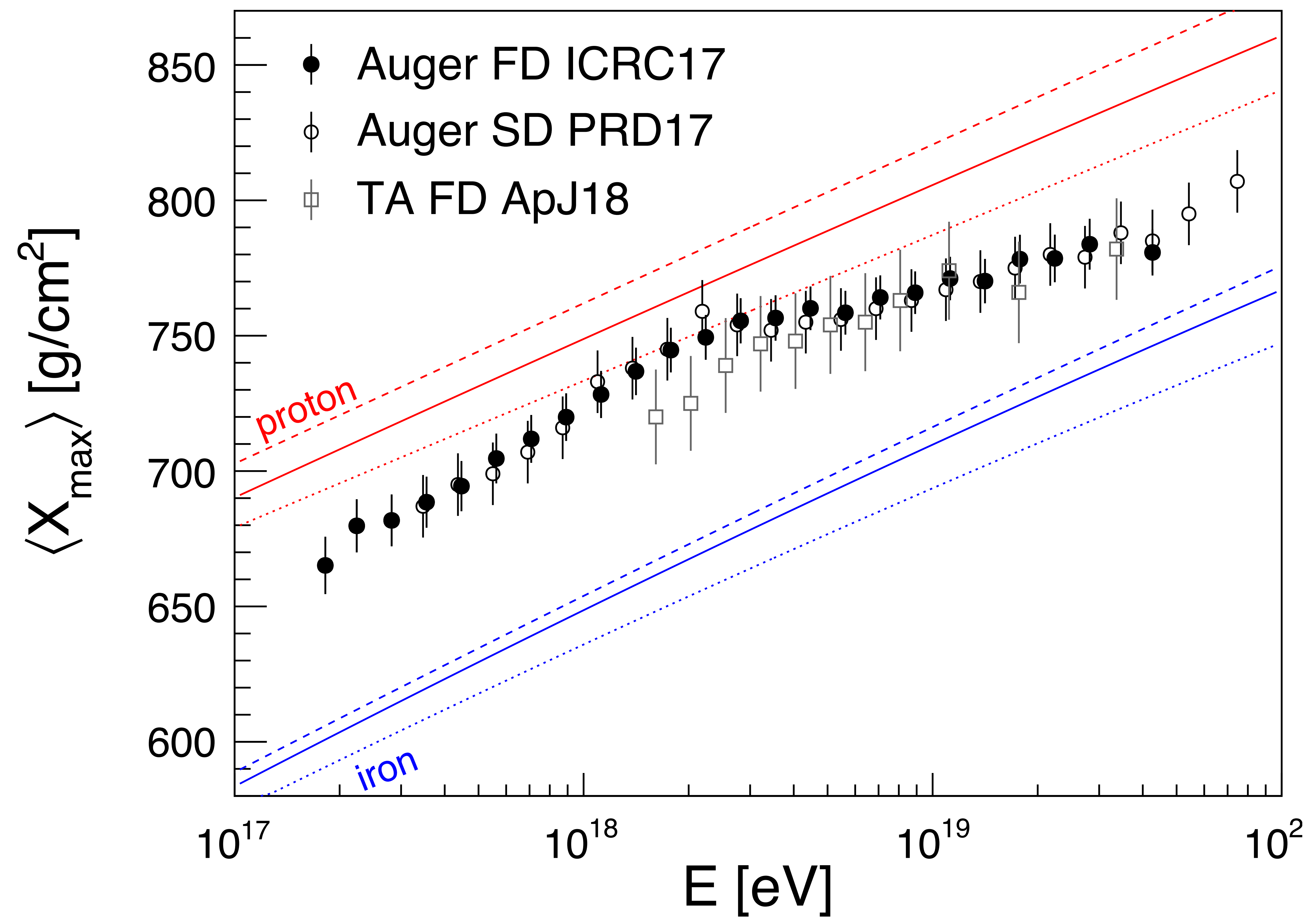


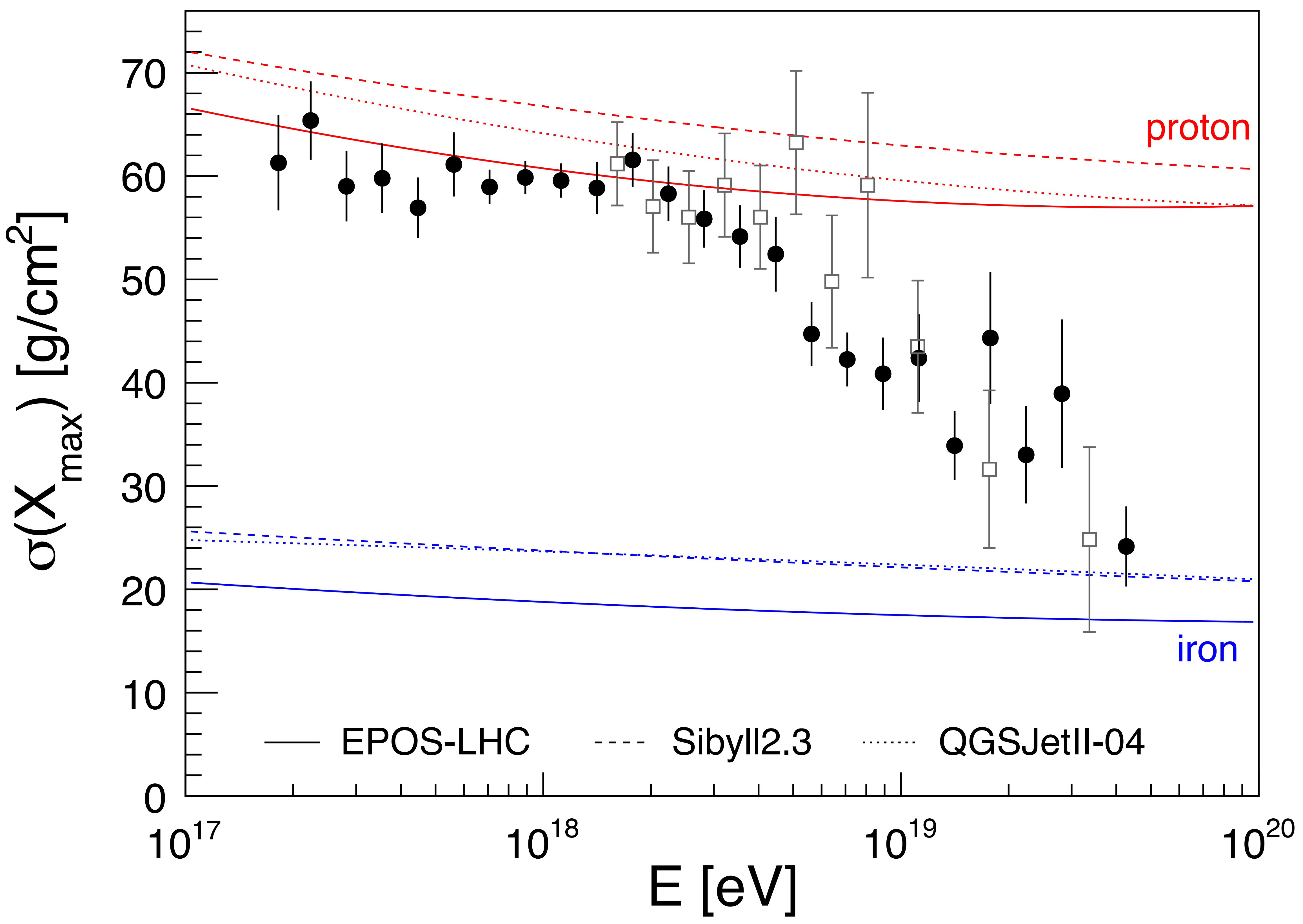
Mass composition

$$\theta \sim 10^\circ Z \left(\frac{E}{10\,\mathrm{EeV}} \right)^{-1}$$

Z : atomic number (mass composition)

$$t_{\mathrm{delay}} \sim 100\, Z^2 \left(\frac{E}{10\,\mathrm{EeV}} \right)^{-2} \mathrm{yr}$$





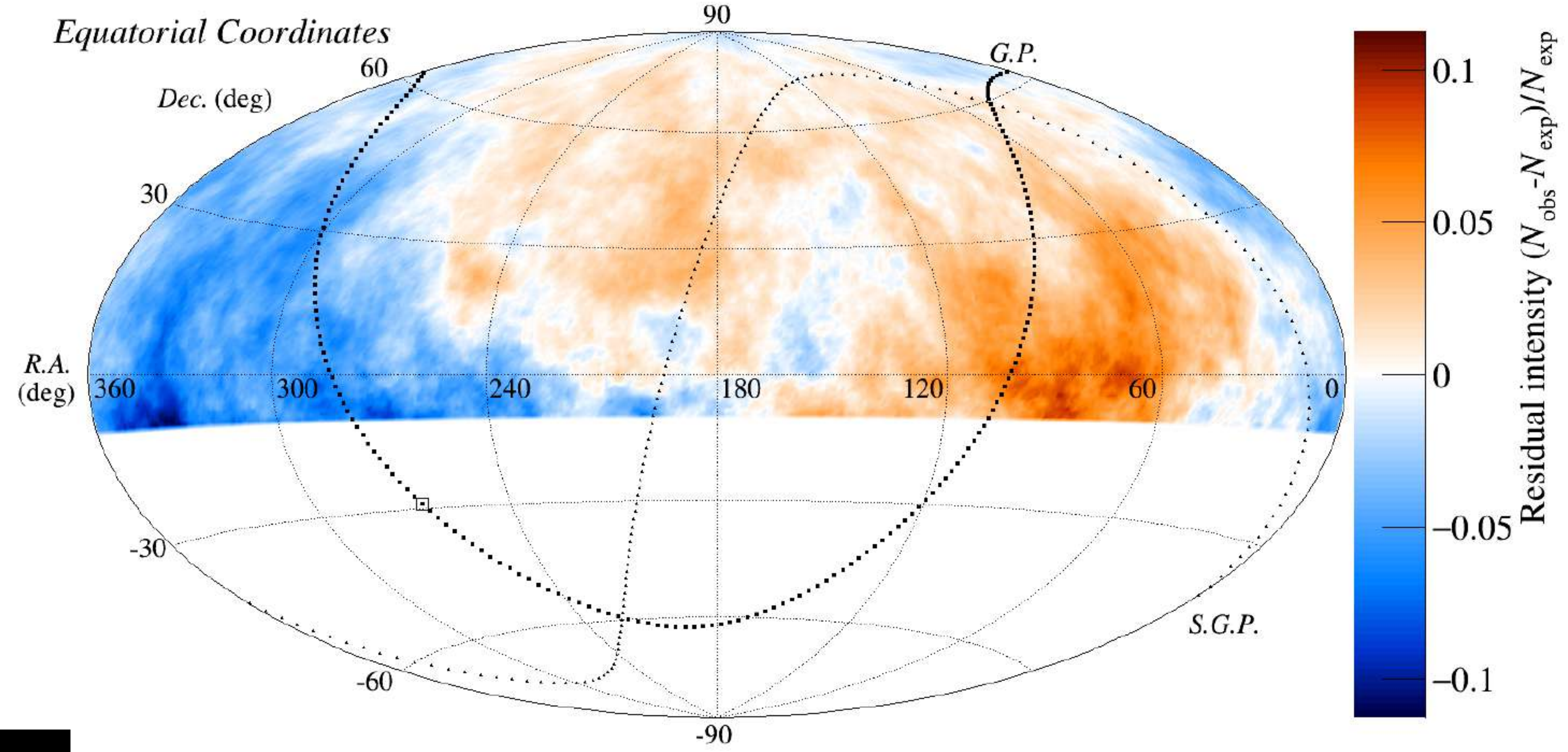
Gradually increase to the heavier composition above 3 EeV

R.A. Batista et al., Front.Astron.Space Sci. 6 (2019) 23

Anisotropy of UHECRs (10 EeV)

Northern TA ApJL, 898:L28 (2020)

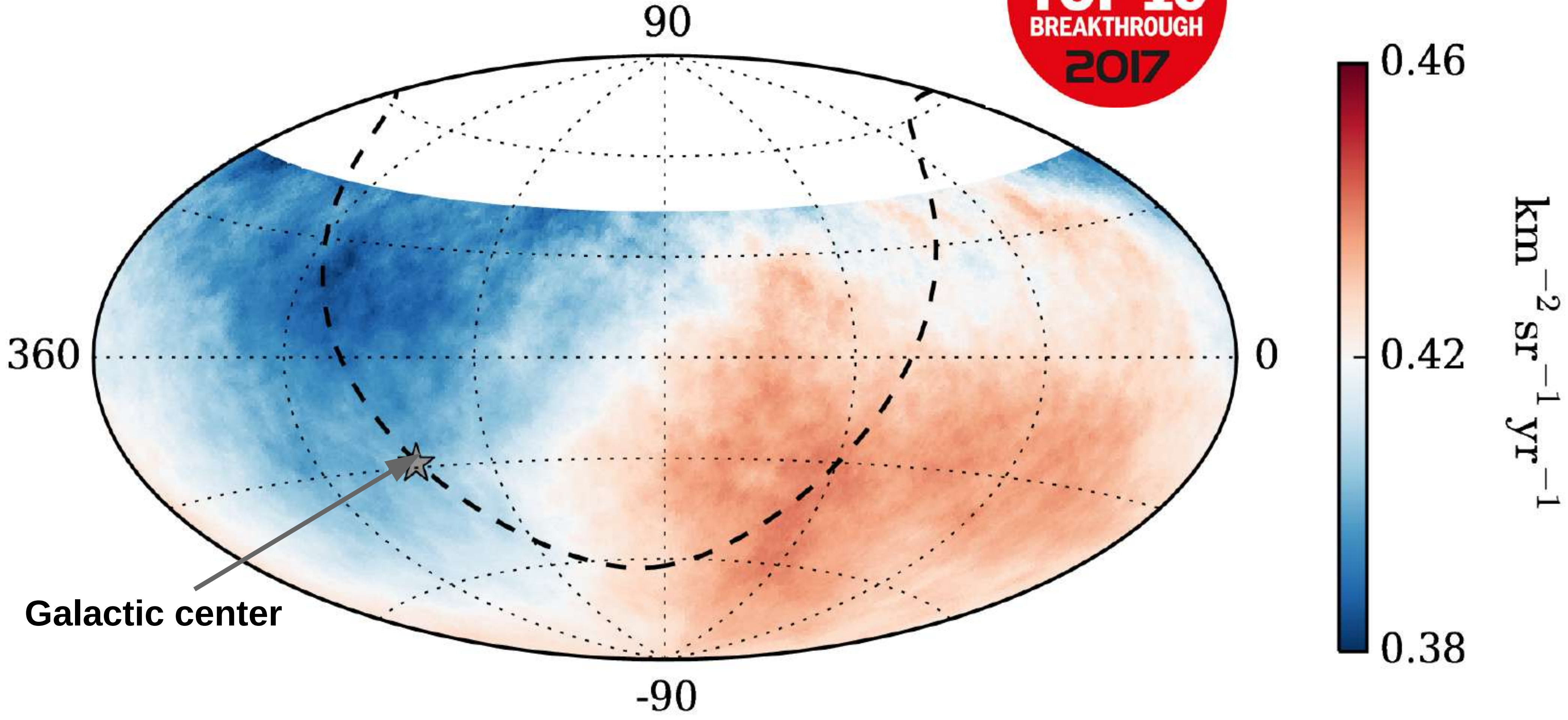
E_{TA}> 8.8 EeV



Southern Auger Science 357, 1266 (2017)

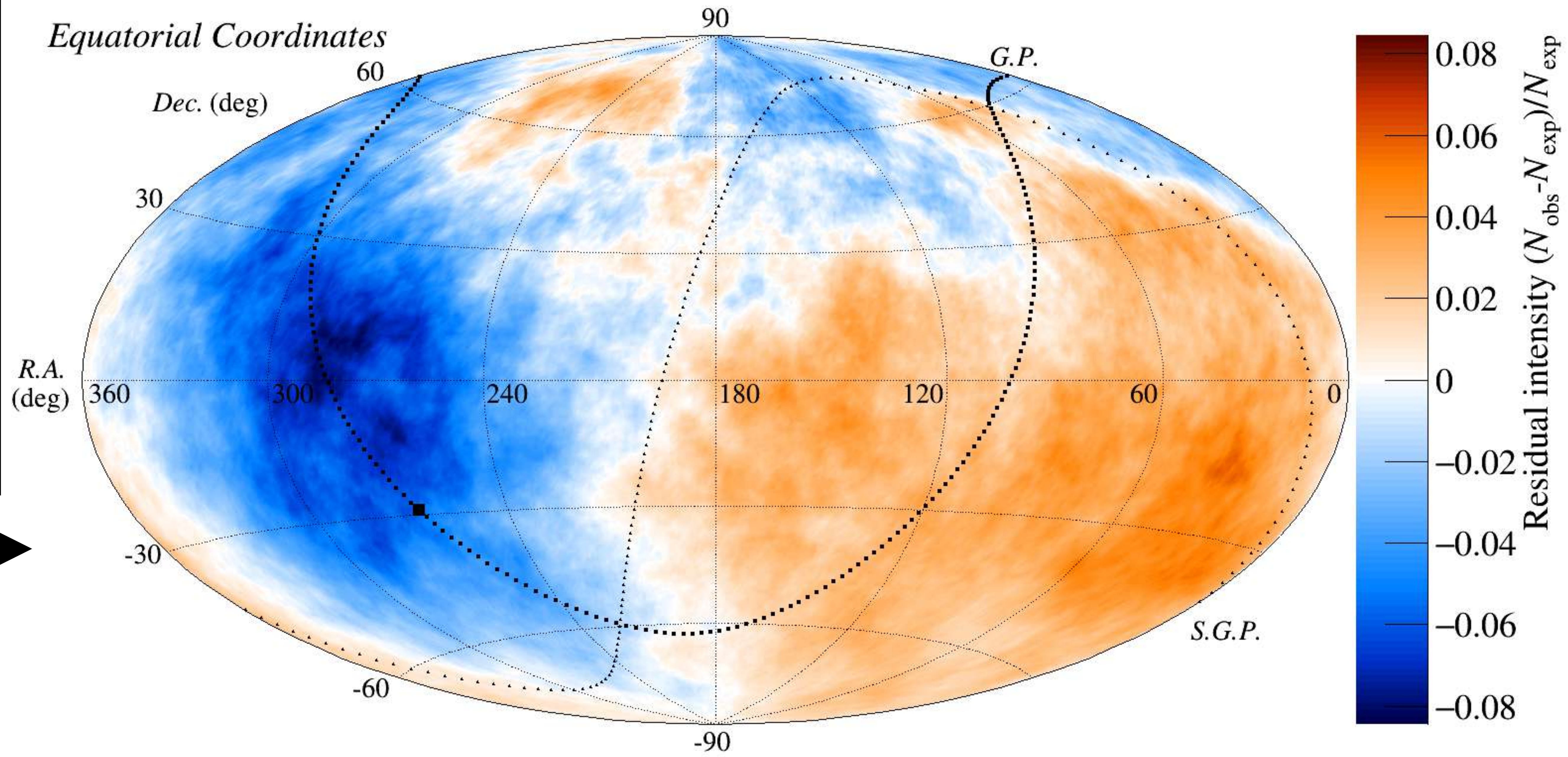
E_{Auger}> 8 EeV

physicsworld TOP 10 BREAKTHROUGH 2017



Joint analysis

- **Significant (> 5σ) large-scale anisotropy** observed by Pierre Auger Observatory
  - 125 degrees away from Galactic Center
  - **Supporting the extragalactic origins**



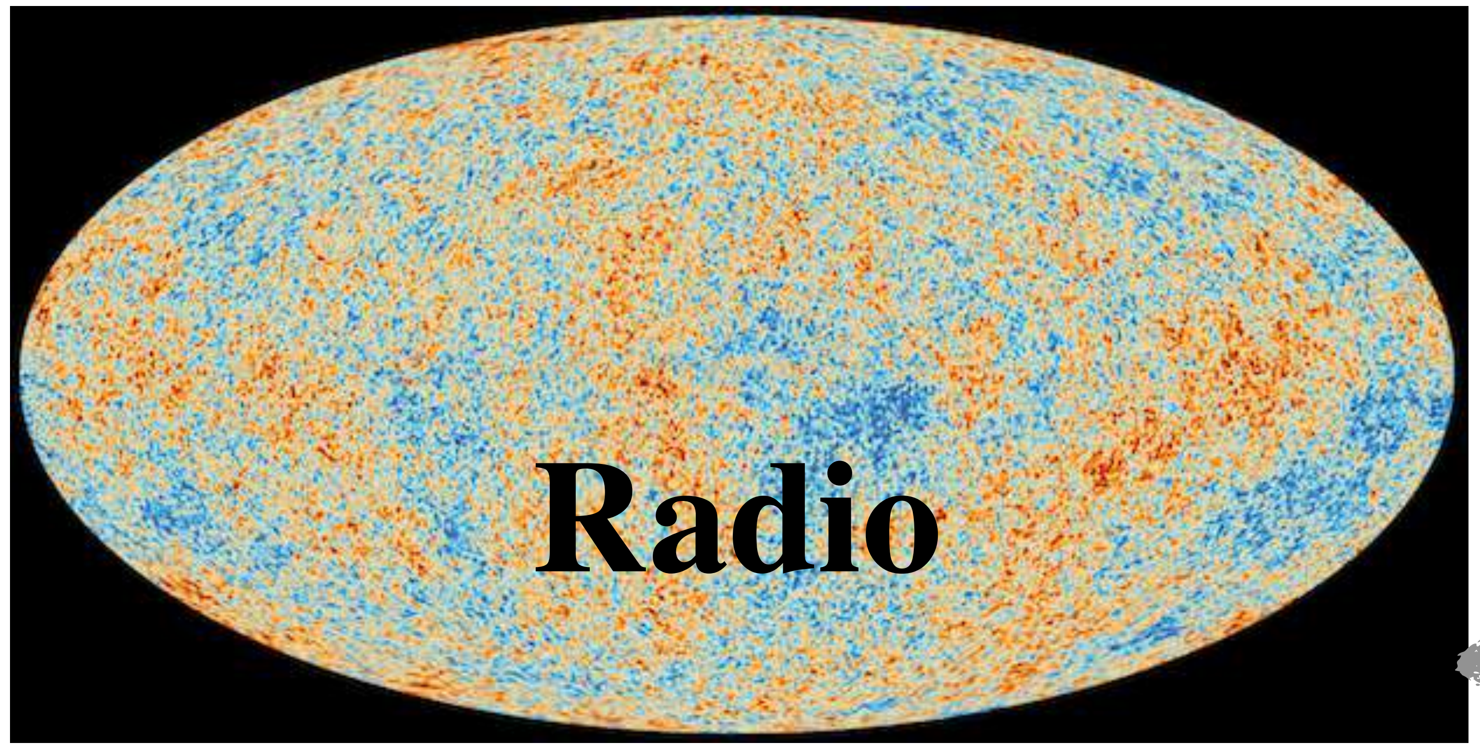
Ankle (E_{TA}>10 EeV, E_{Auger}> 8.86 EeV)

50 EeV skymap

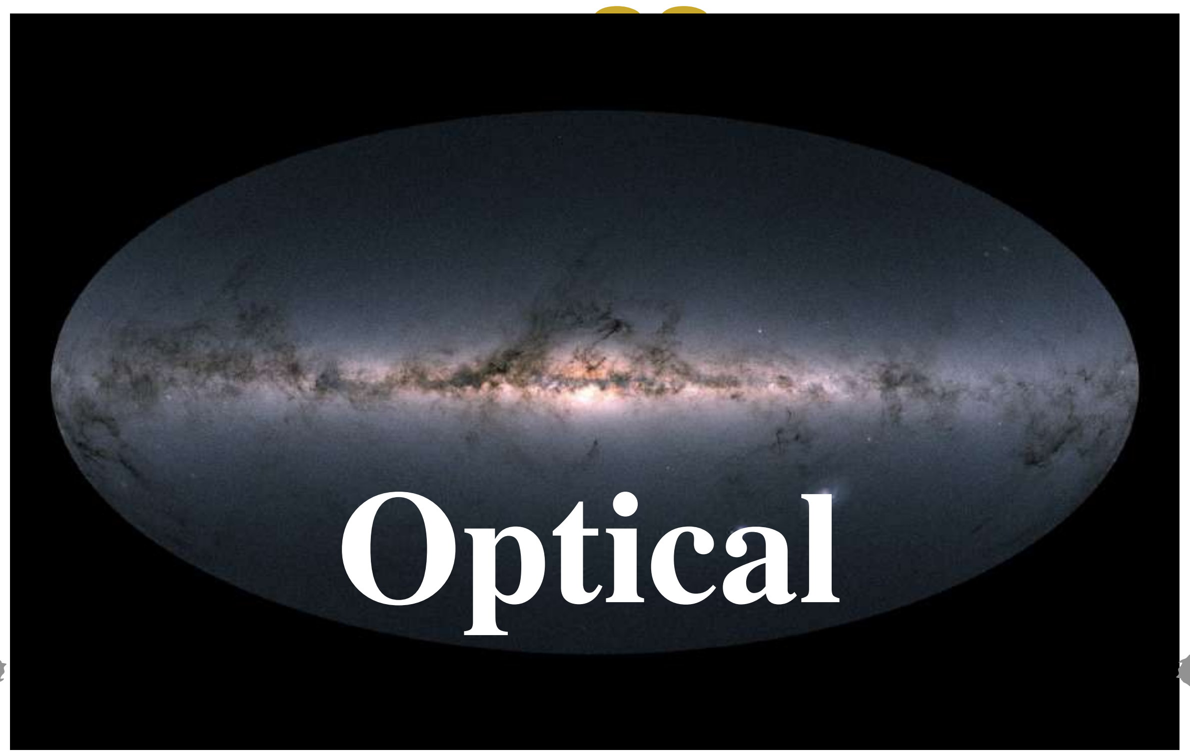
Cutoff (E_{TA}>52.3 EeV E_{Auger}>40 EeV), **~1000 events**

T. Fujii et al., PoS (ICRC2021) 291 (2020)

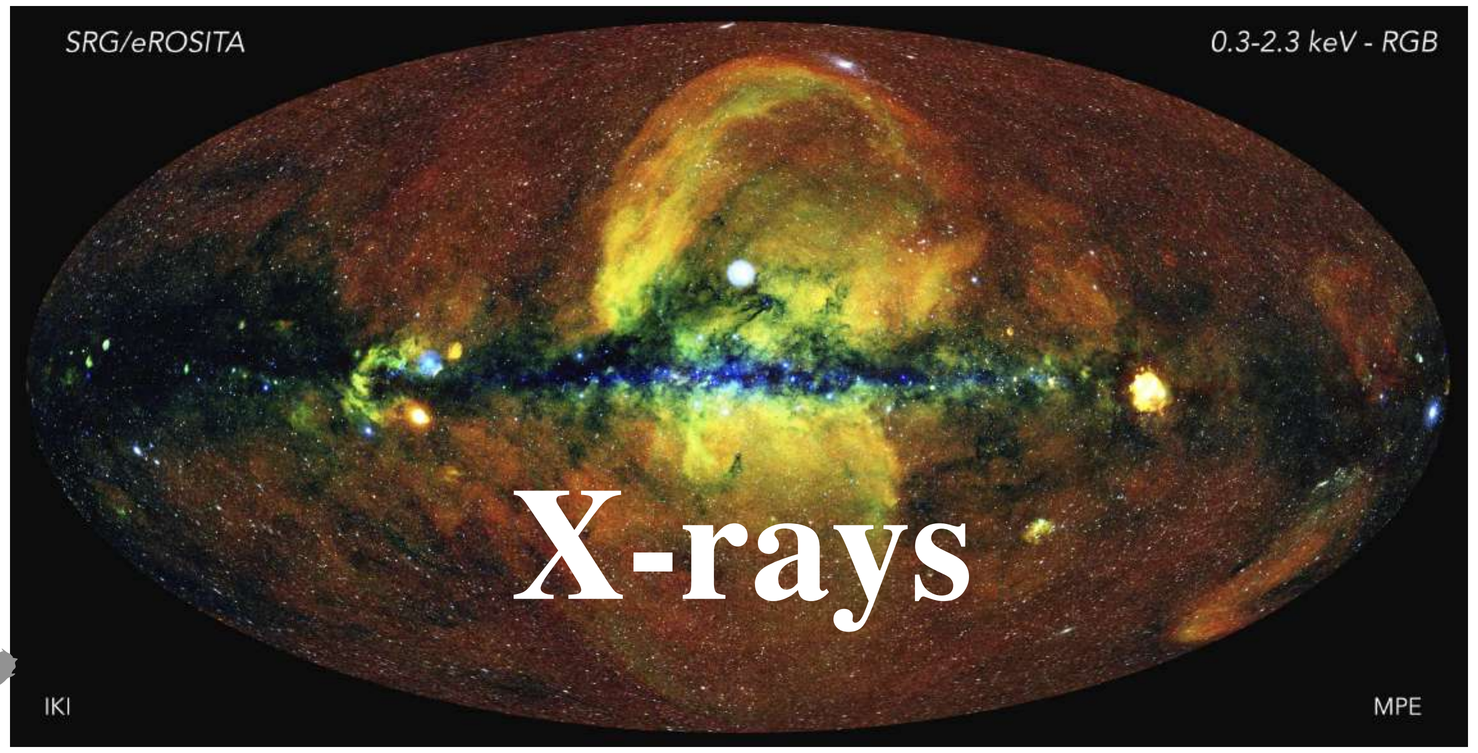
- Intriguing **intermediate-scale anisotropies** (~20 degrees) such as **hot/warm spots**
  - No excess from Virgo cluster, dubbed "***Virgo scandal***"
- **Isotropic distributions of UHECRs than our (optimistic) expectation**



Planck Collaboration

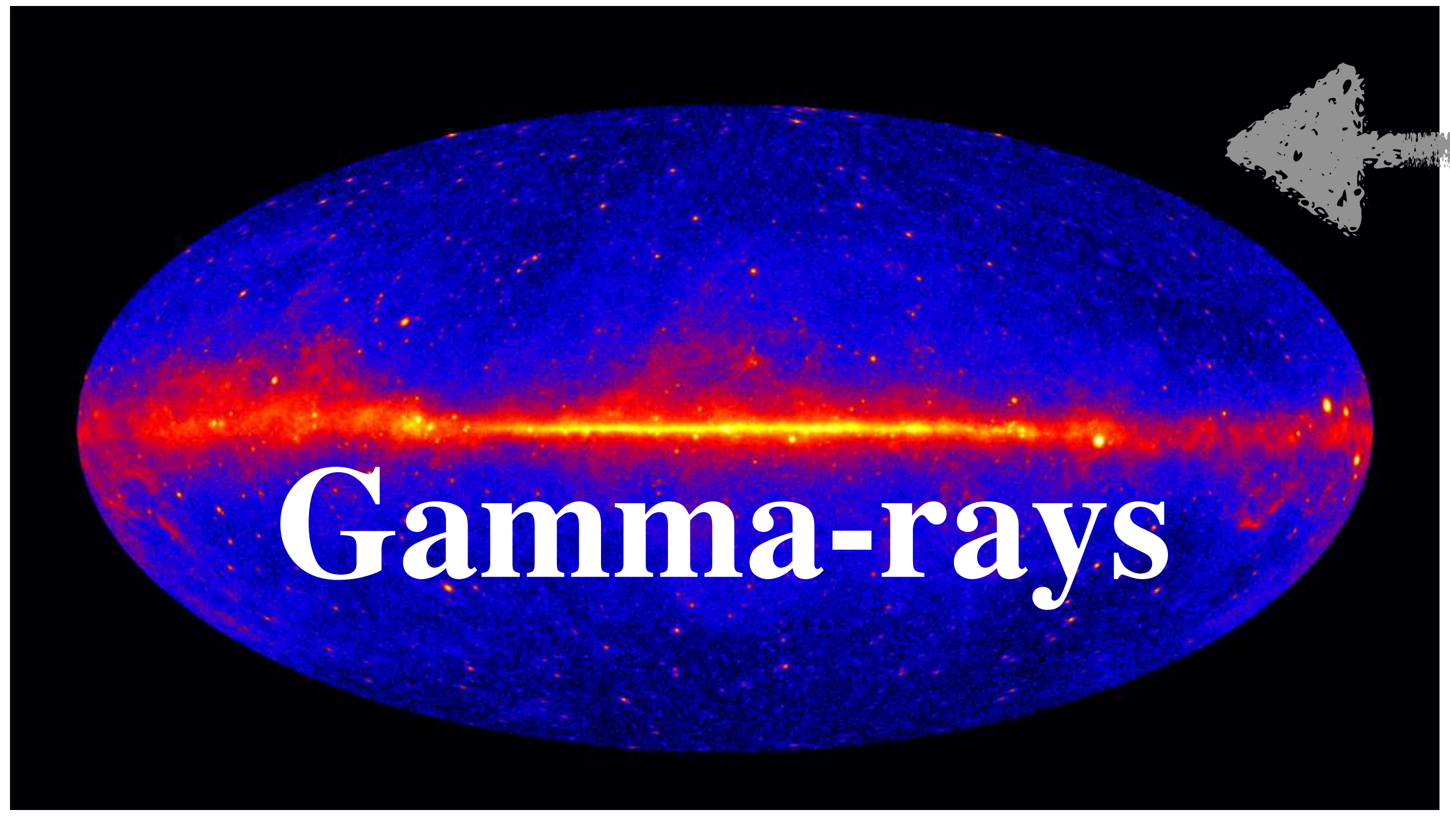


GAIA Collaboration

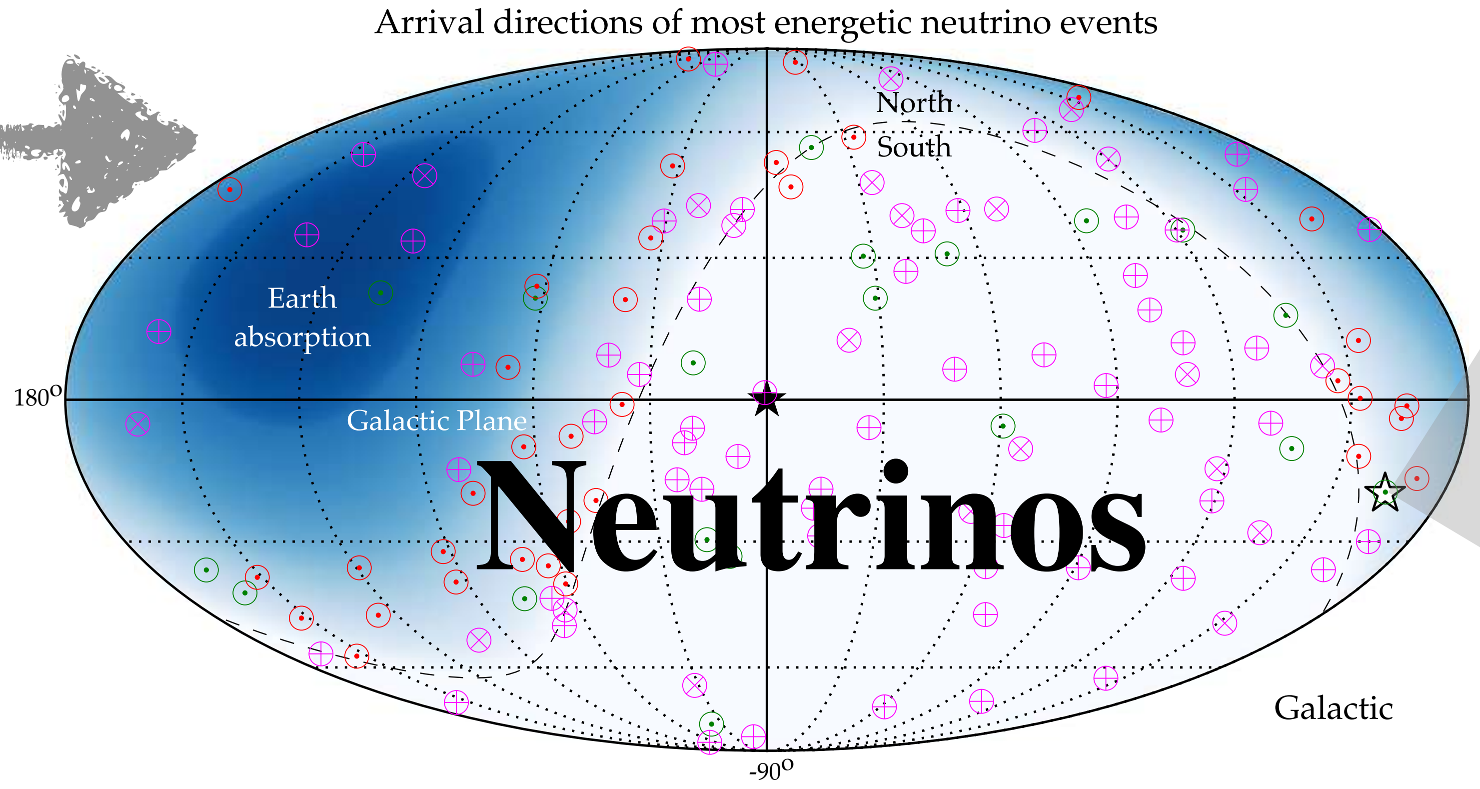


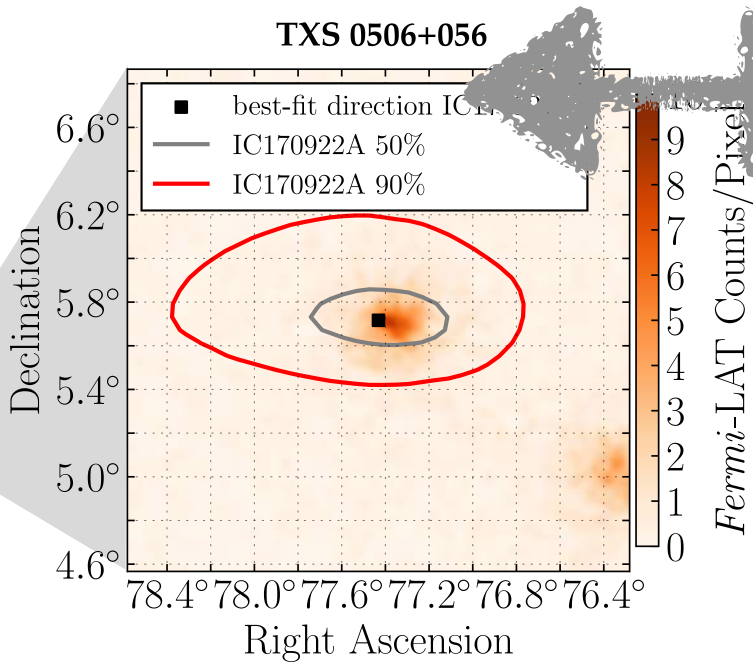
eROSITA Collaboration

Clarifying origins of extremely energetic particles by multi-wavelength and multi-messenger observations

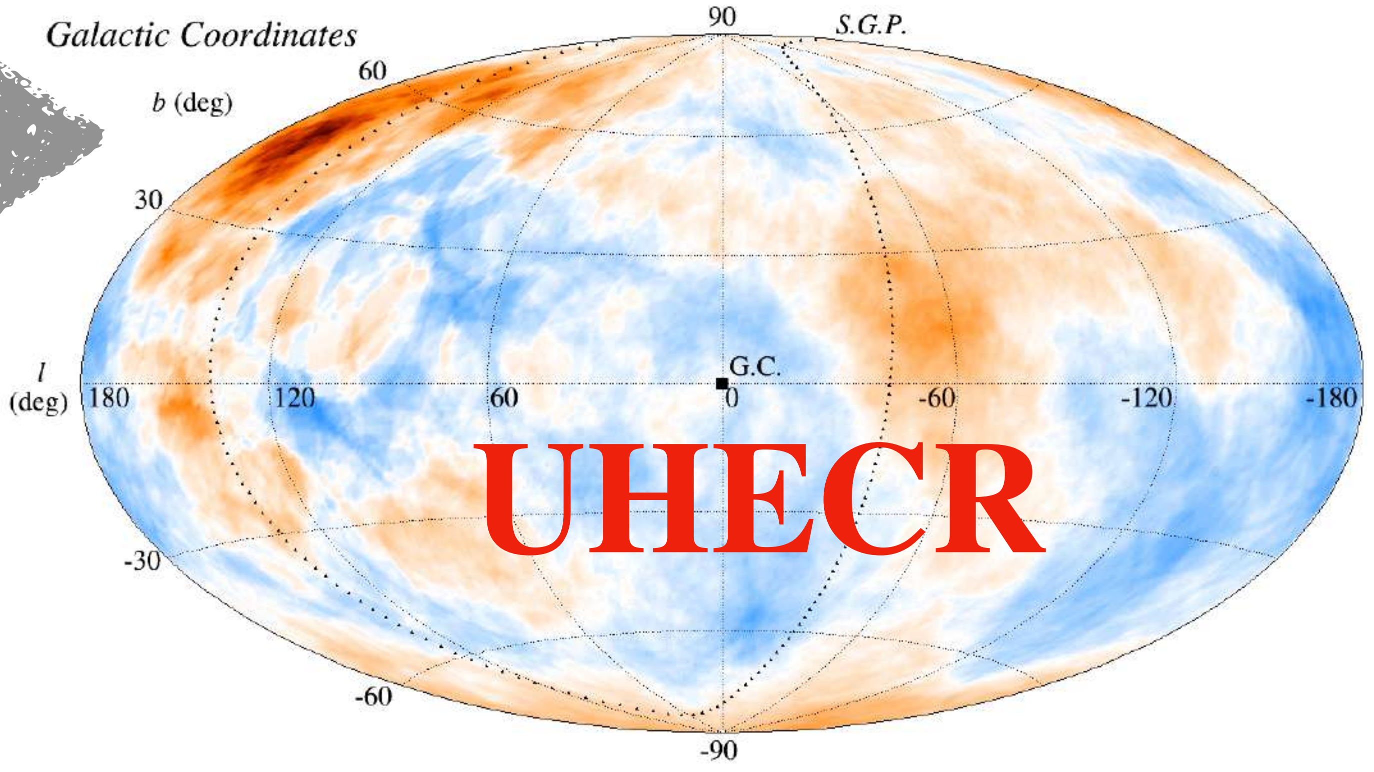


Fermi Collaboration



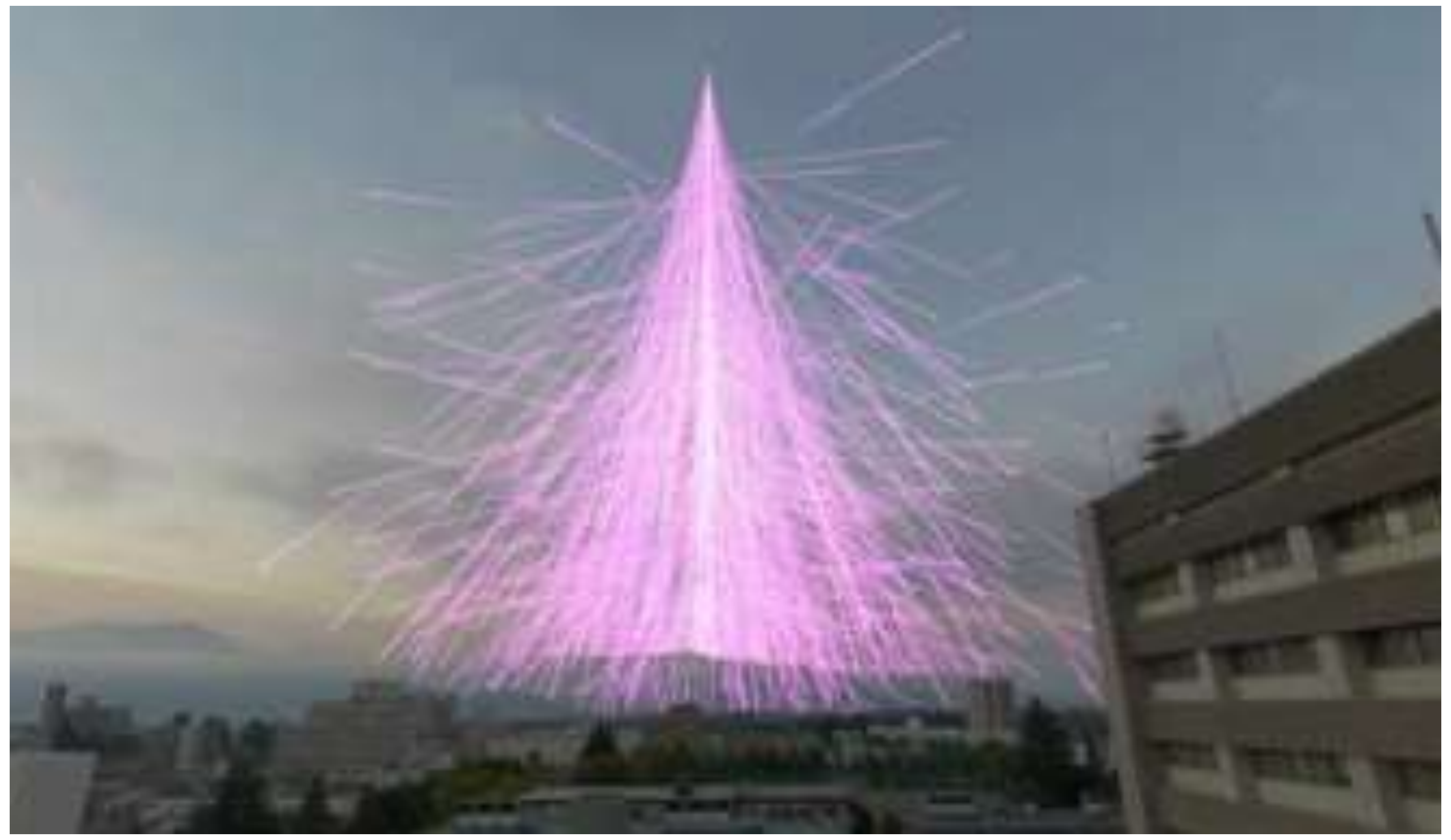


IceCube Collaboration



Pierre Auger and Telescope Array Collaborations

Outreach and Education



D. Ikeda (Kanagawa), T. Tomida (Shinshu)

K. Tanaka (Waseda, Accel Kitchen)

"Imakara Science", BS TV Tokyo

TBS CROSS DIG with Bloomberg 【ULTRASCIENCE】 Youtube