Challenging Charged Particle Astronomy with the Global Cosmic Ray Observatory (GCOS)

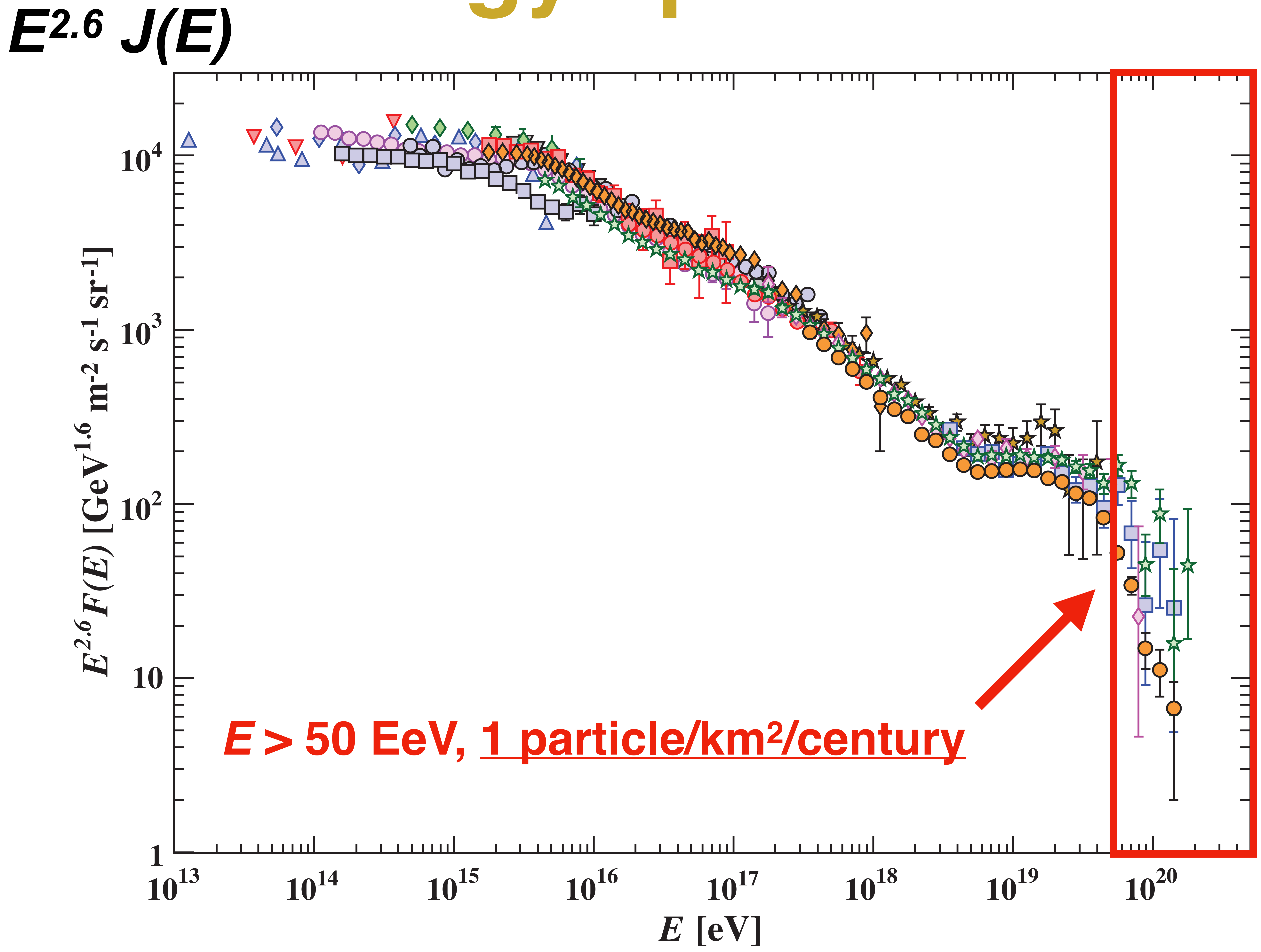
Toshihiro Fujii (OMU, NITEP, toshi@omu.ac.jp)
on behalf of the GCOS supporters

Multi-messenger Annual Conference 2025, Miyagi, Japan, Nov 19, 2025

総合知で、超えていく大学。

NITEP
Nambu Yoichiro Institute of Theoretical and Experimental Physics

Energy spectrum of cosmic rays



1 exa-electron-volts (EeV) = 10^{18} eV

- **Origins and nature 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 km²
  - Long term observation over decades

Source candidates and next-generation astronomy

Image credits: Max Plank Inst./DESY/Science Comm/RIKEN

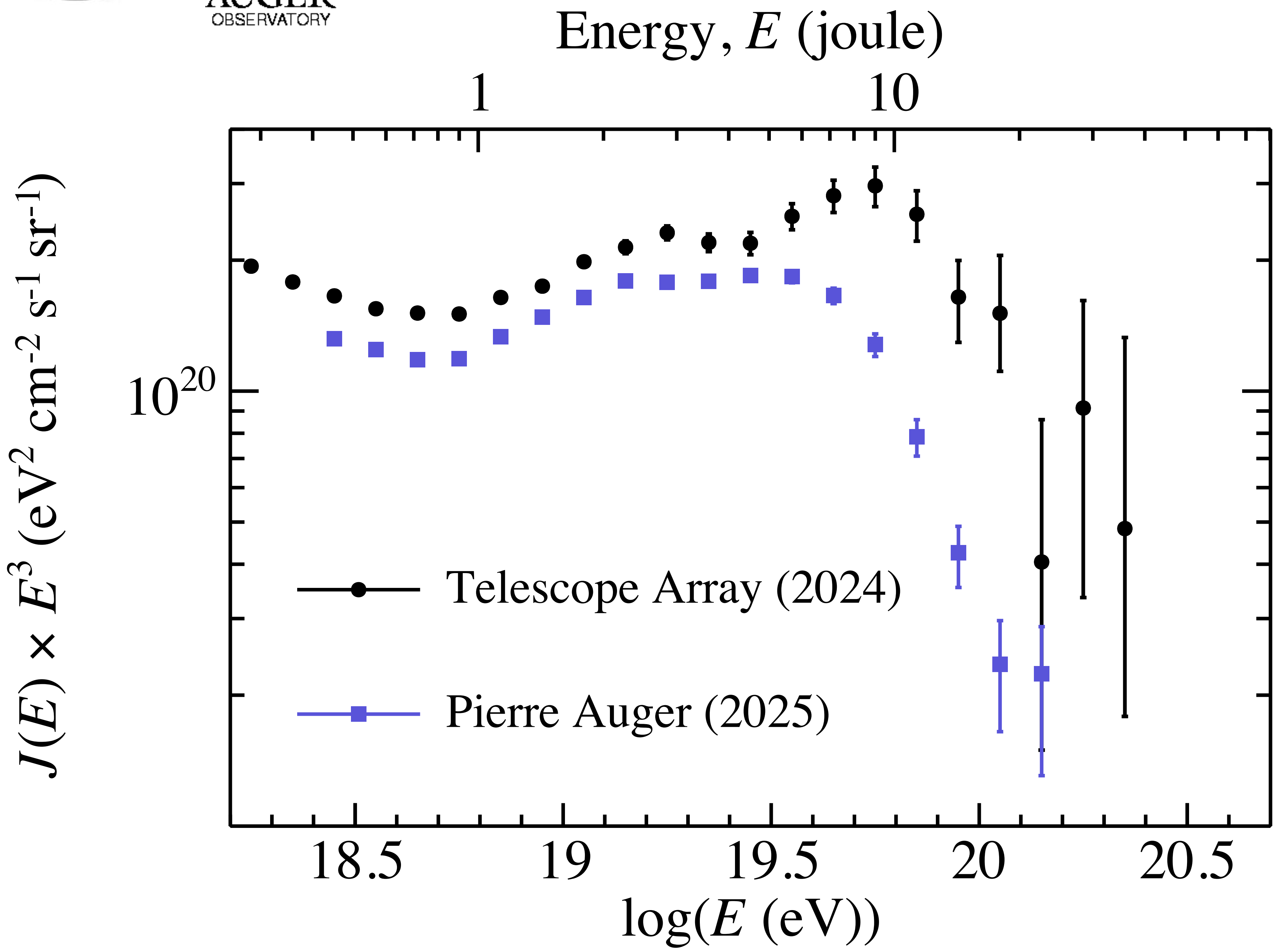
or "New physics"

- **Limitation of nearby sources** due to "GZK cutoff"

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0 \qquad {}^{A}_{Z}N + \gamma_{\mathrm{CMB}} \rightarrow {}^{A-1}_{Z-1}N' + p$$

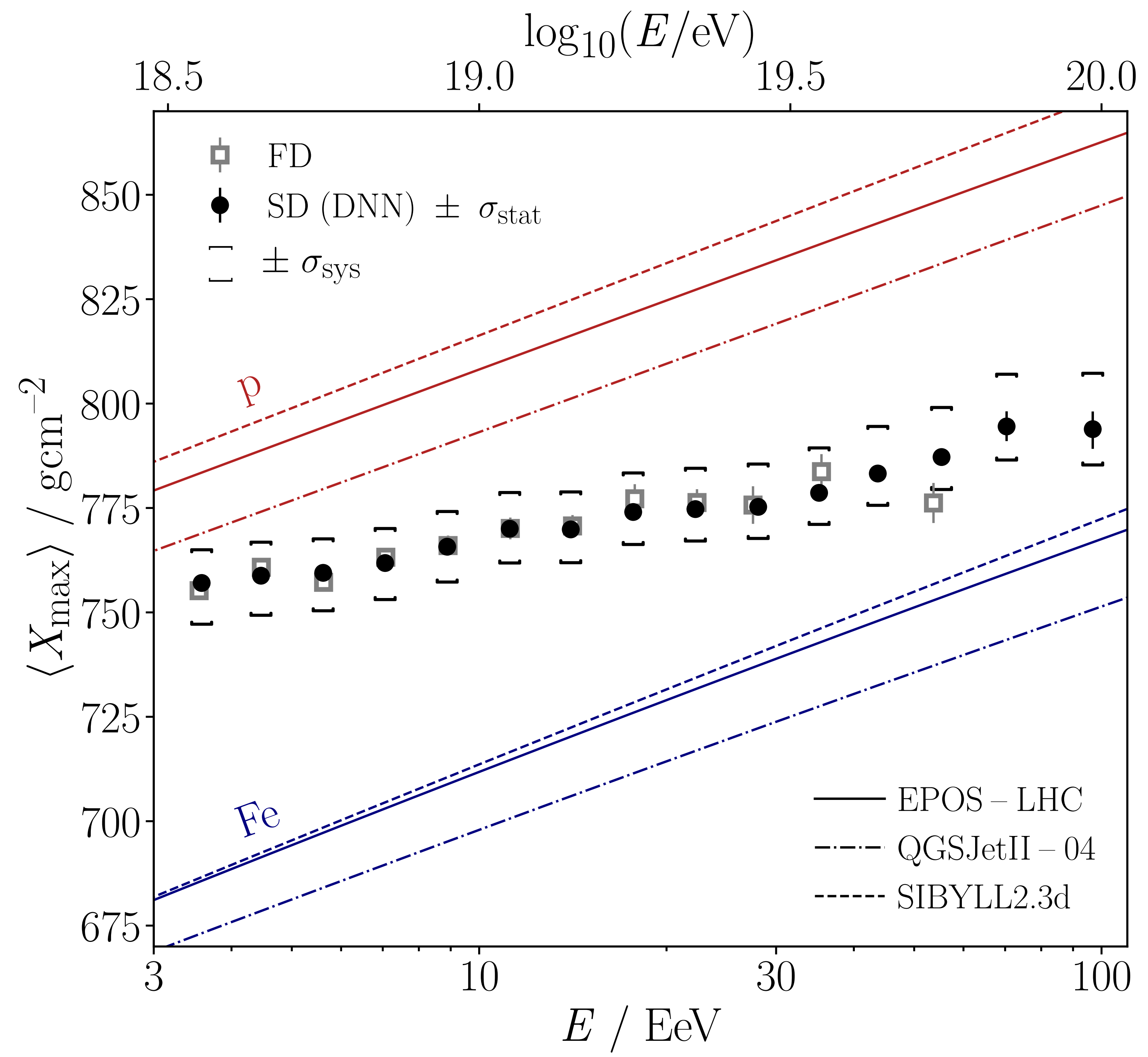
- **Less deflections** by Galactic/extragalactic magnetic fields $\theta \sim 10^\circ Z \left(\frac{E}{10\,\mathrm{EeV}}\right)^{-1}$
  - Directional correlations between **UHECRs** and nearby **inhomogeneous sources** to identify their origins
  - **A next-generation "astronomy" using the charged particles**

Latest results of UHECRs



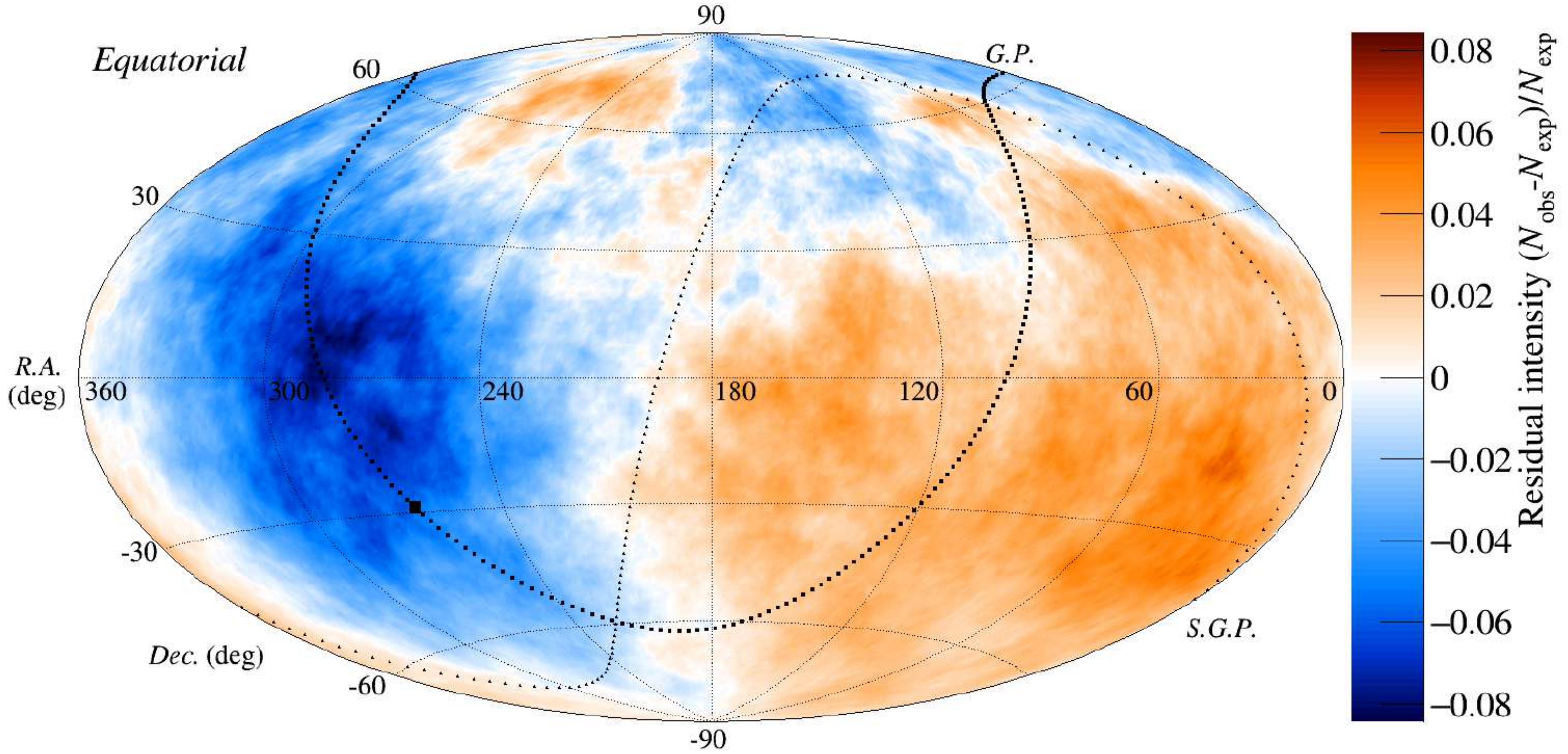
$$\theta \sim 10^\circ \boxed{Z} \left(\frac{E}{10\,\mathrm{EeV}}\right)^{-1}$$

Z: Atomic number
(Mass composition)

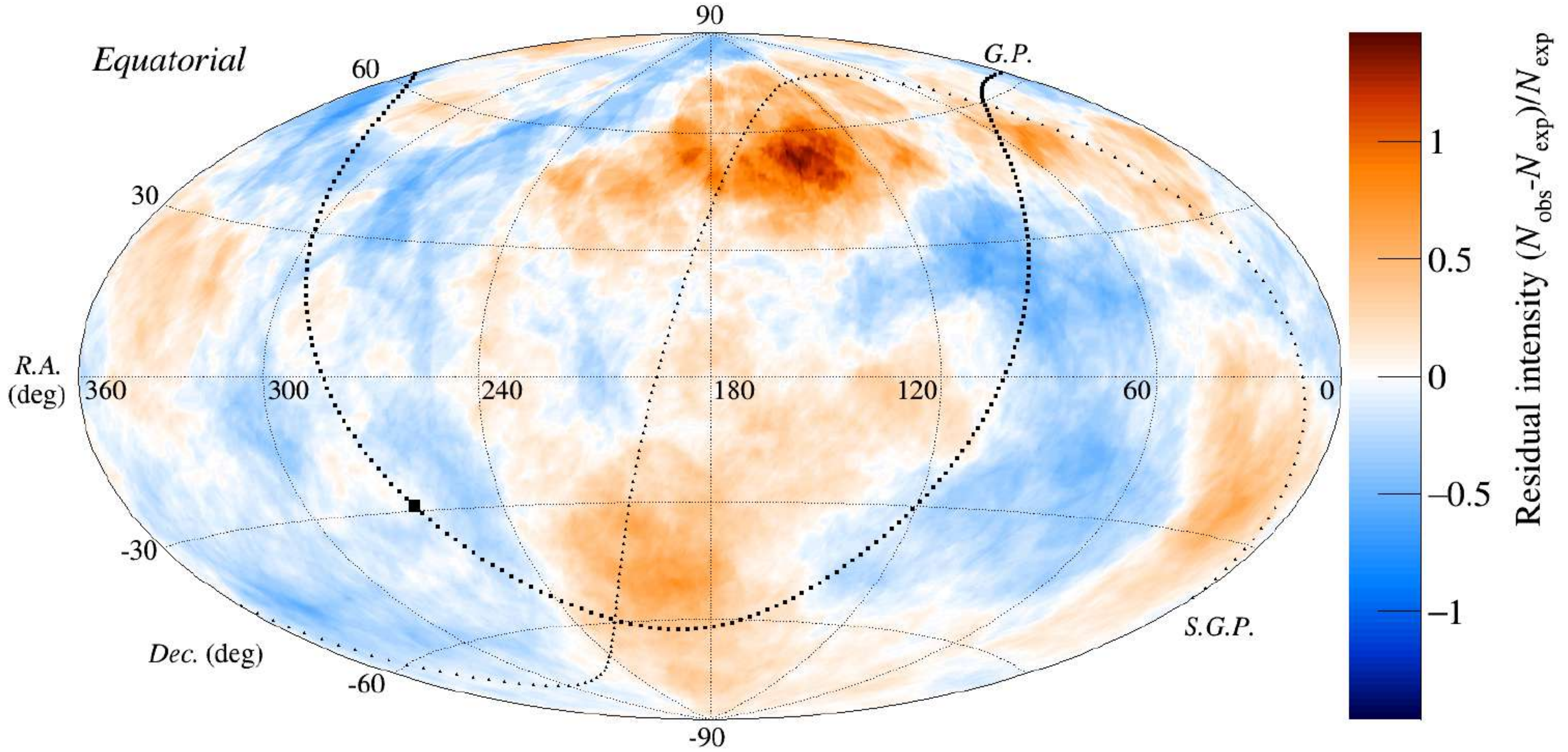


PRL 134, 021001 (2025)

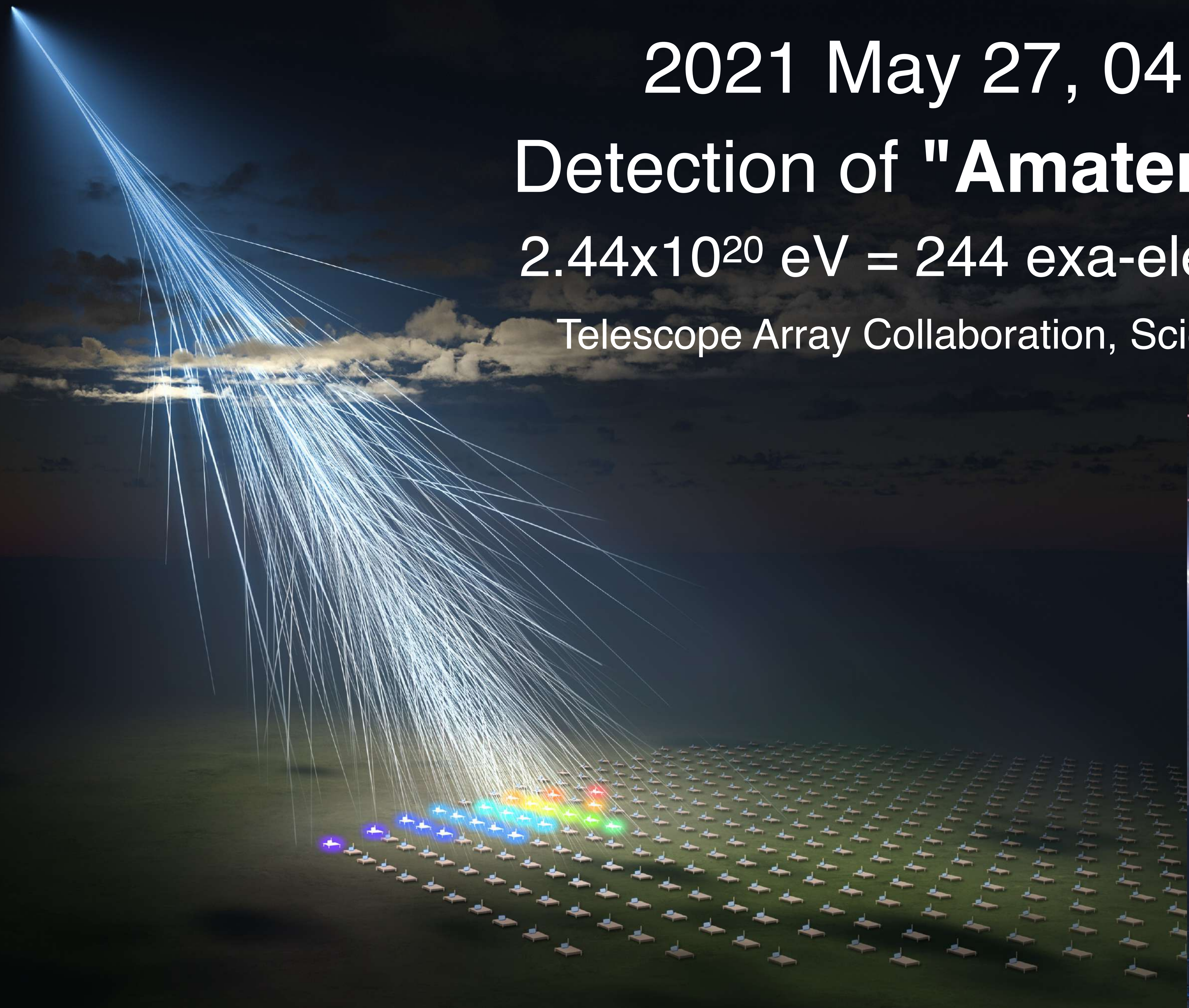
Ankle ($E > 10$ EeV)



Cutoff ($E > 50$ EeV)



- Constrain **proton fraction above 30 EeV to be <70%** by non-detection of ultra-high energy neutrinos
  - PRL 135, 031001 (2025)



2021 May 27, 04:35:56 AM

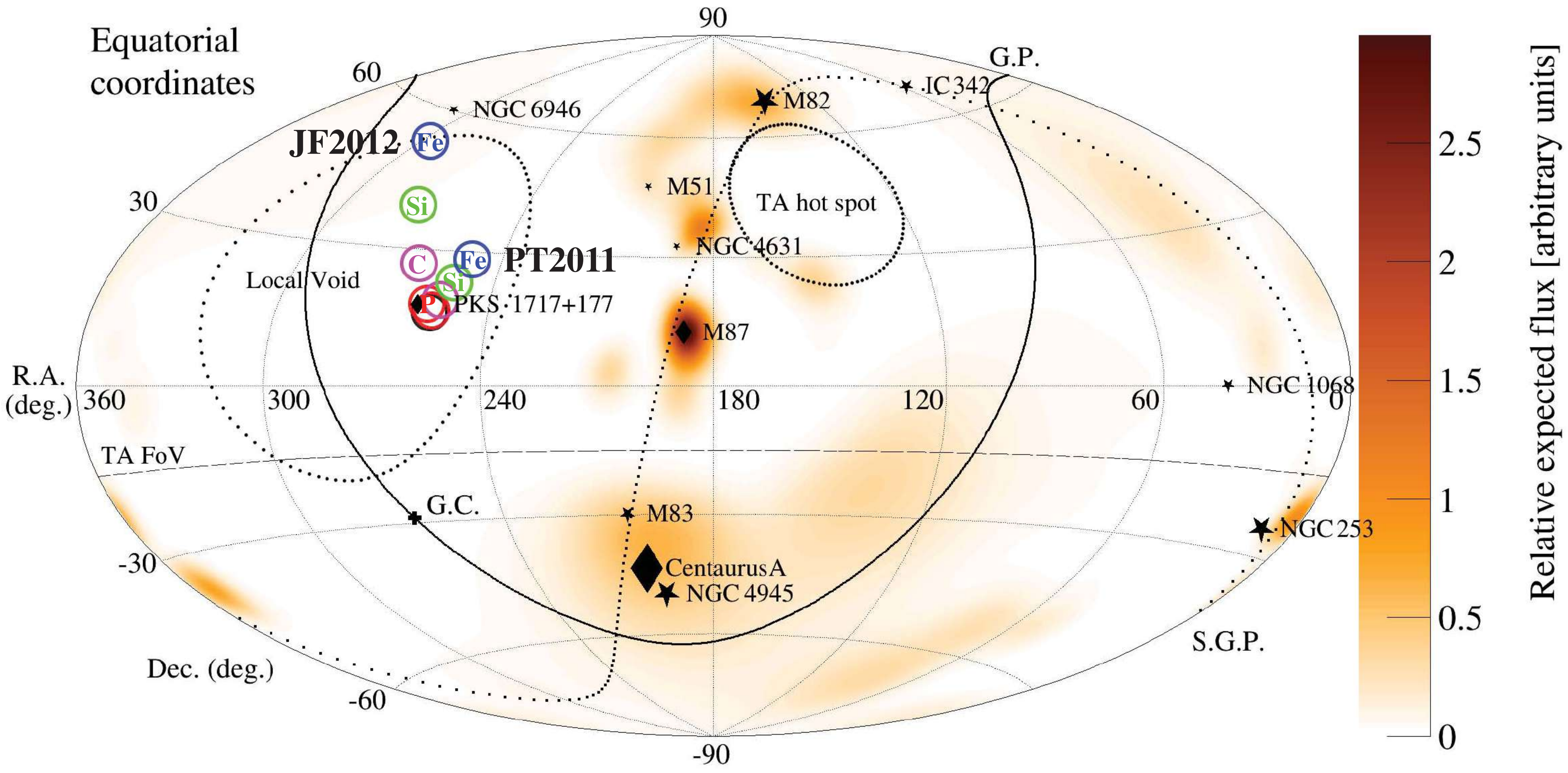
Detection of **"Amaterasu particle"**

2.44×10^{20} eV = 244 exa-electron volts (EeV)

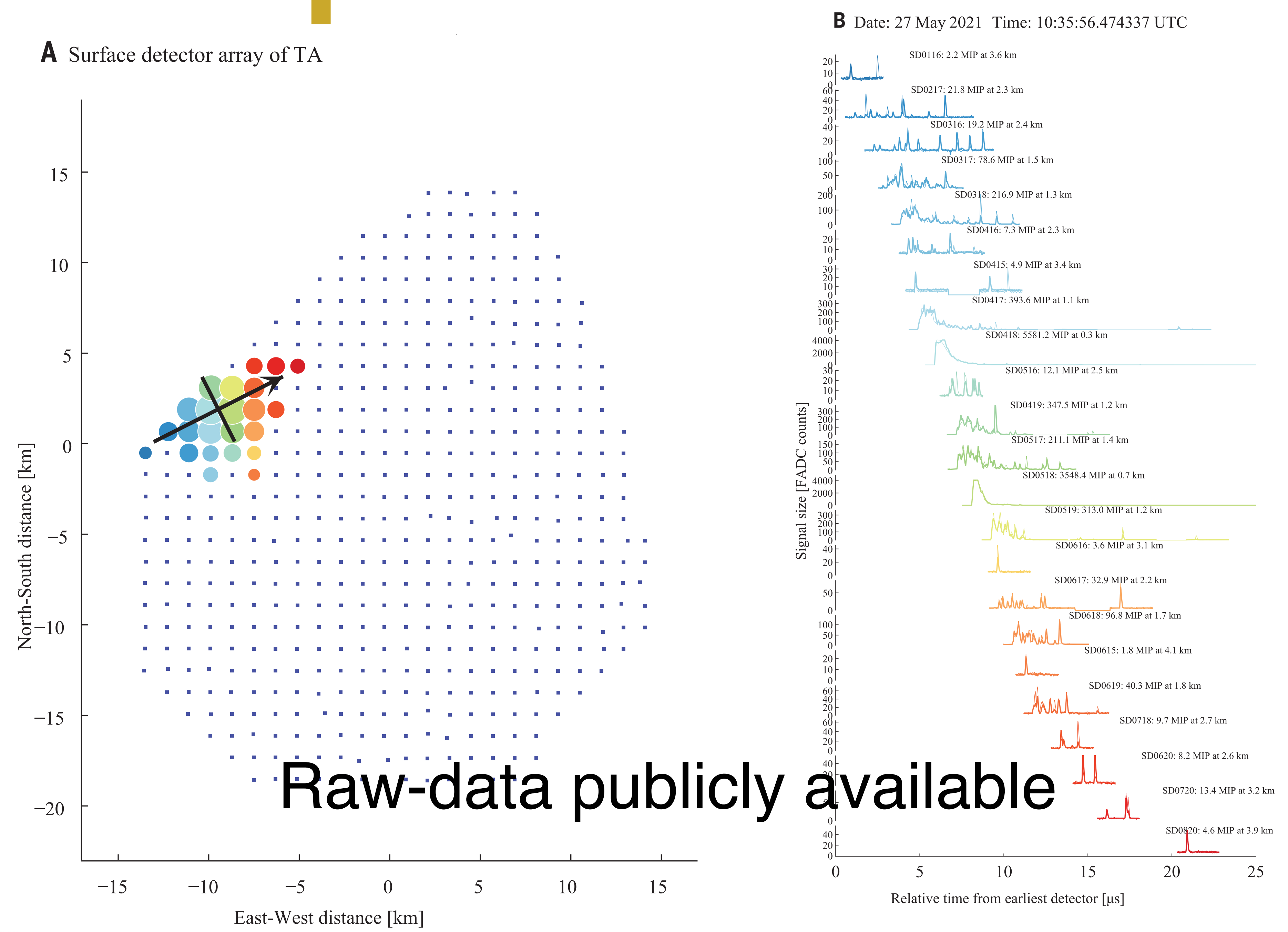
Telescope Array Collaboration, Science 382, 903 (2023)

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)

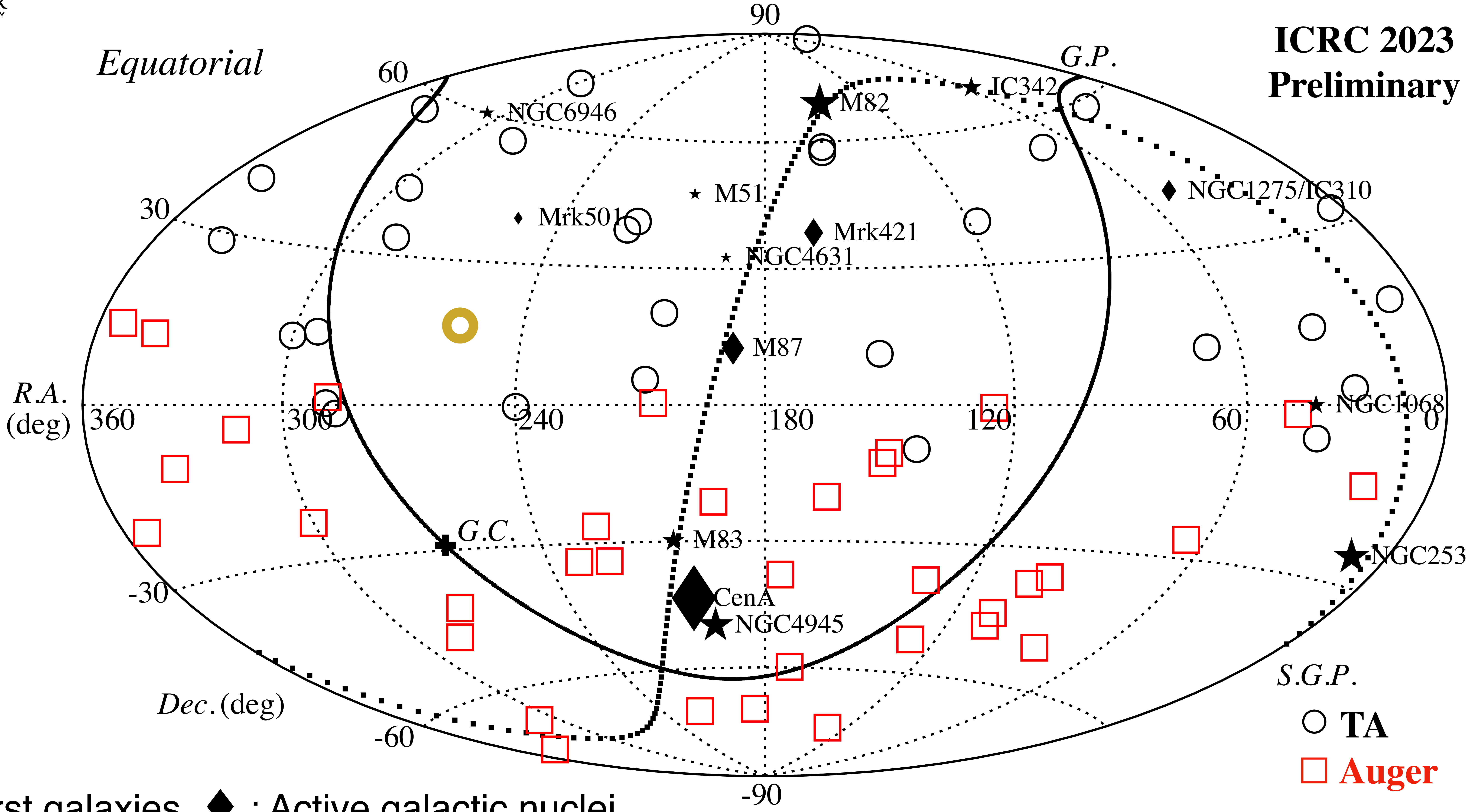


Raw-data publicly available

- **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]

>100 EeV skymap

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



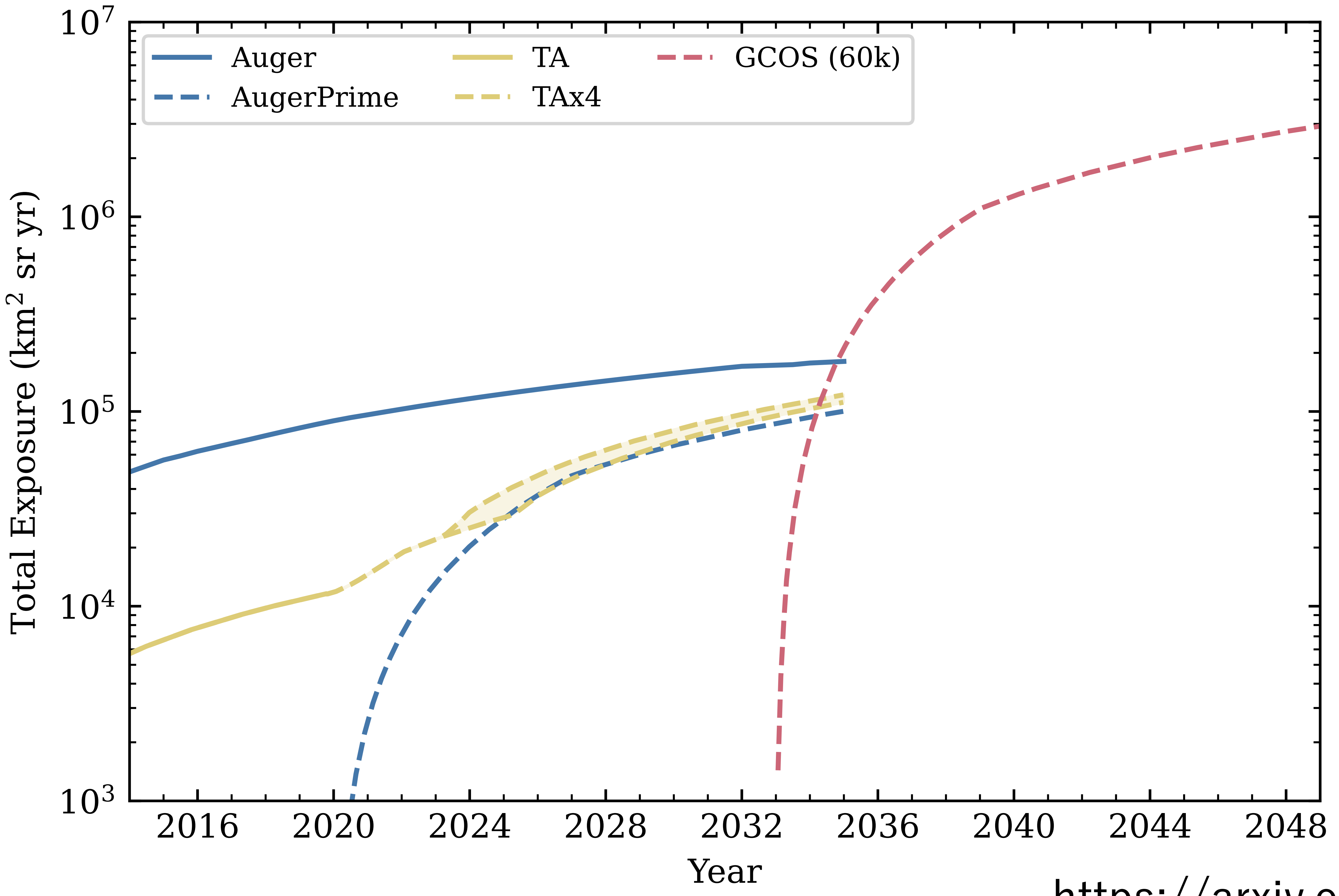
★ : Starburst galaxies ♦ : Active galactic nuclei

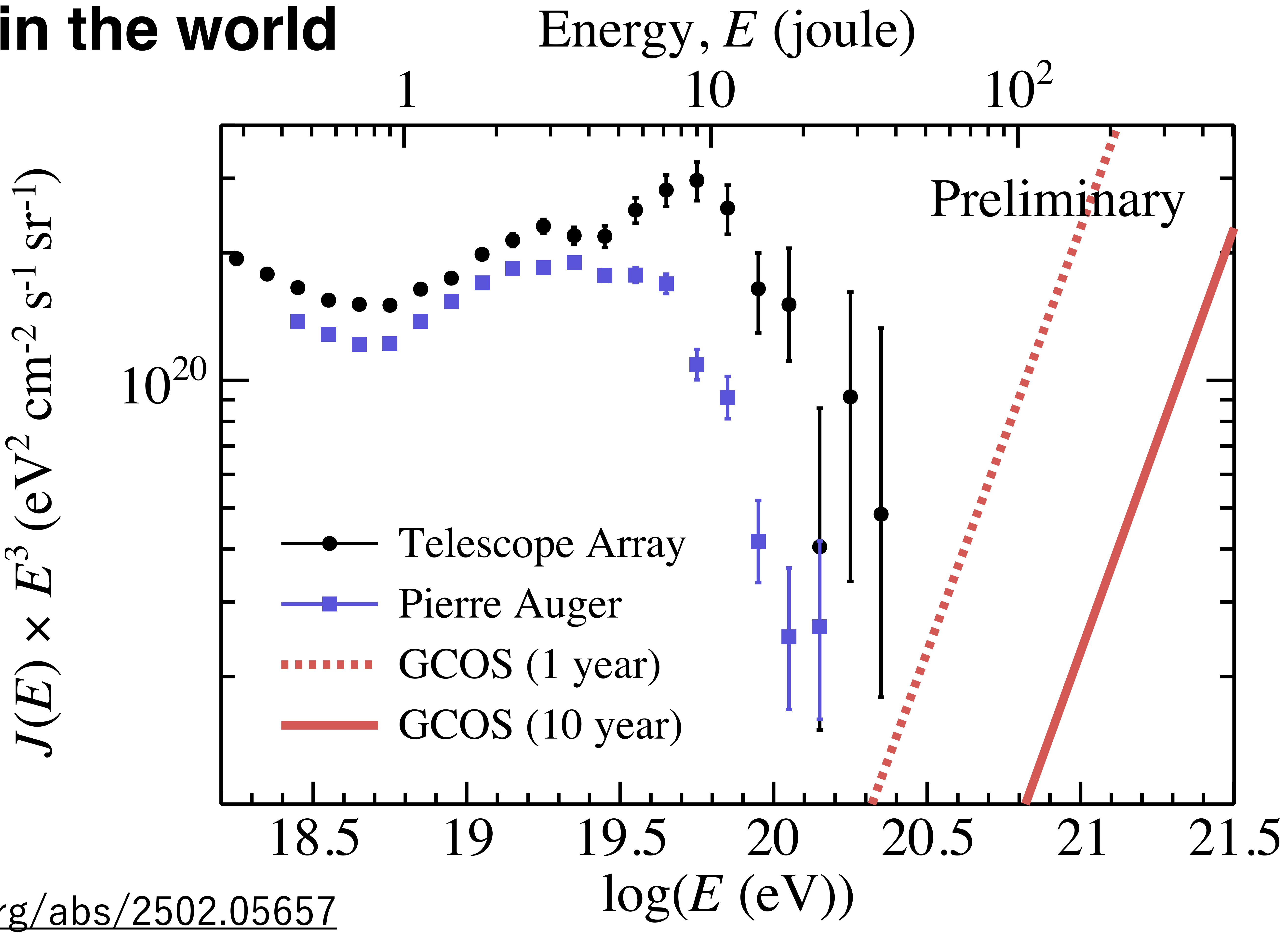
>100 EeV of TA 15-years and Auger 17-years

Need more statistics with mass identification capabilities

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, ~60000 km²** and **mass identification capabilities**
- Begin operations in 2030s, **One team in the world**

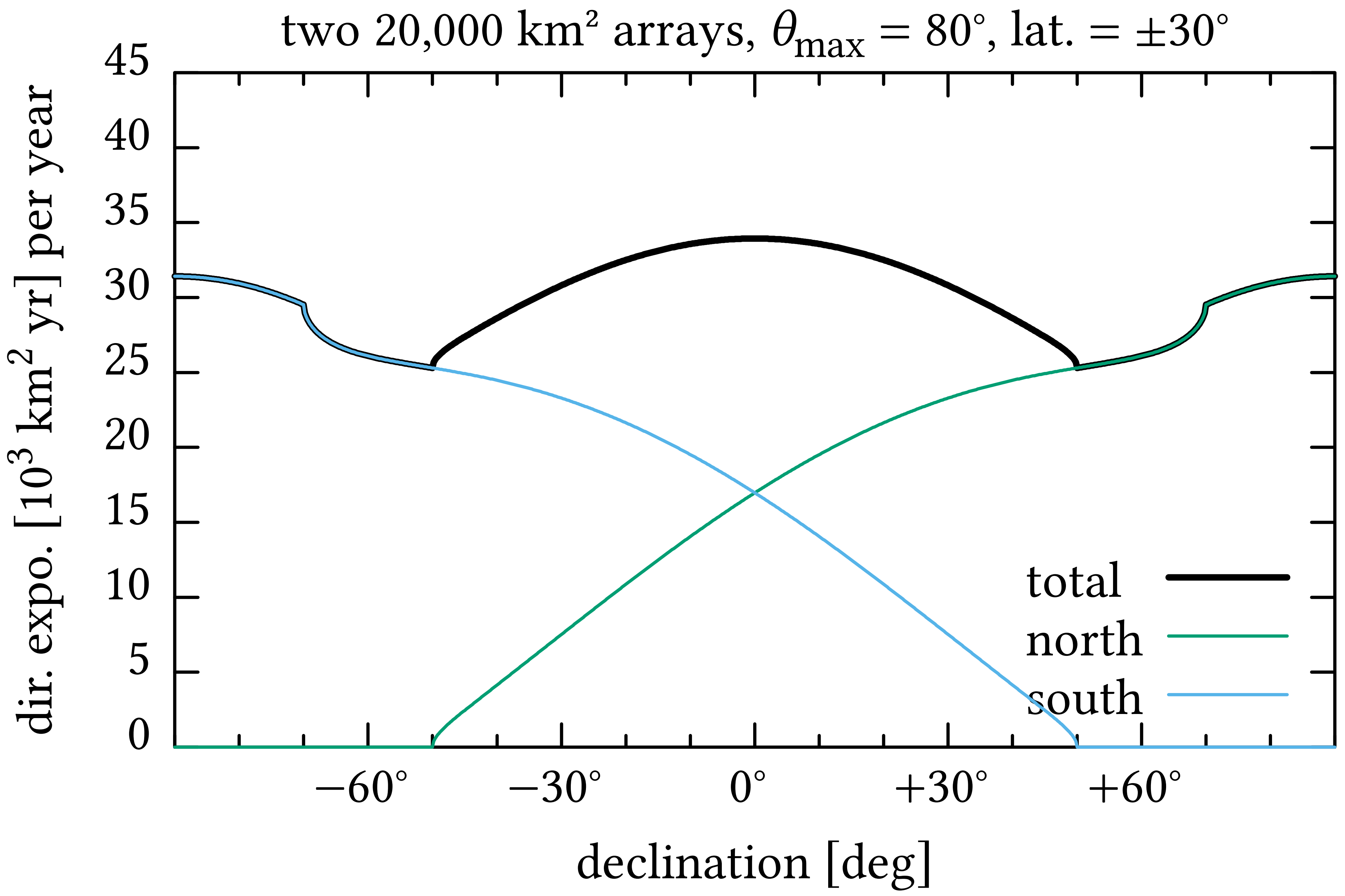




https://arxiv.org/abs/2502.05657

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. Horandel et al. PoS (ICRC 2021) 027

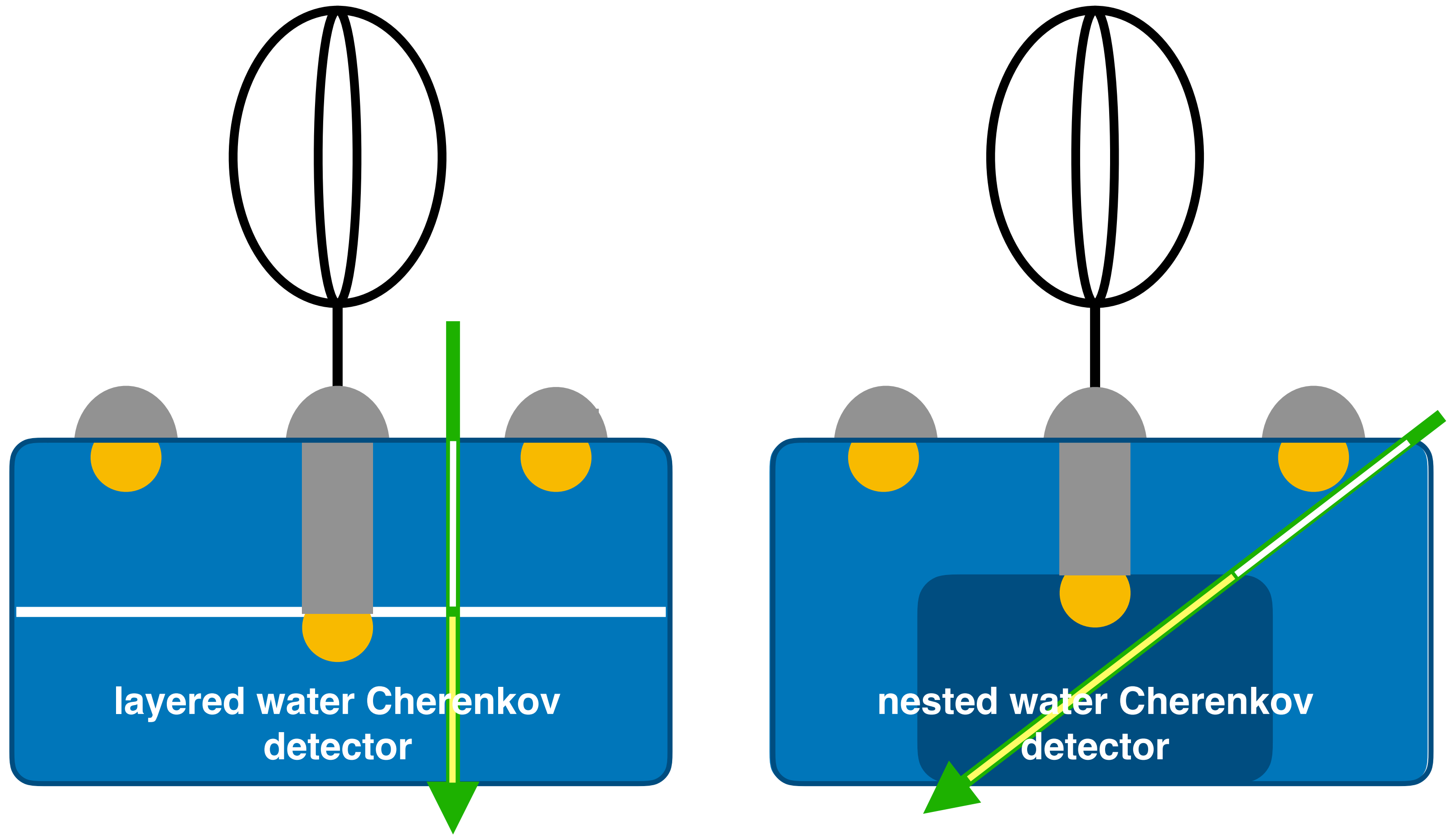


Figure 6: Detection concepts, using a layered (left) and a nested (right) water Cherenkov detector with a radio antenna on top.

A. Parenti in PoS (ICRC2025) 354

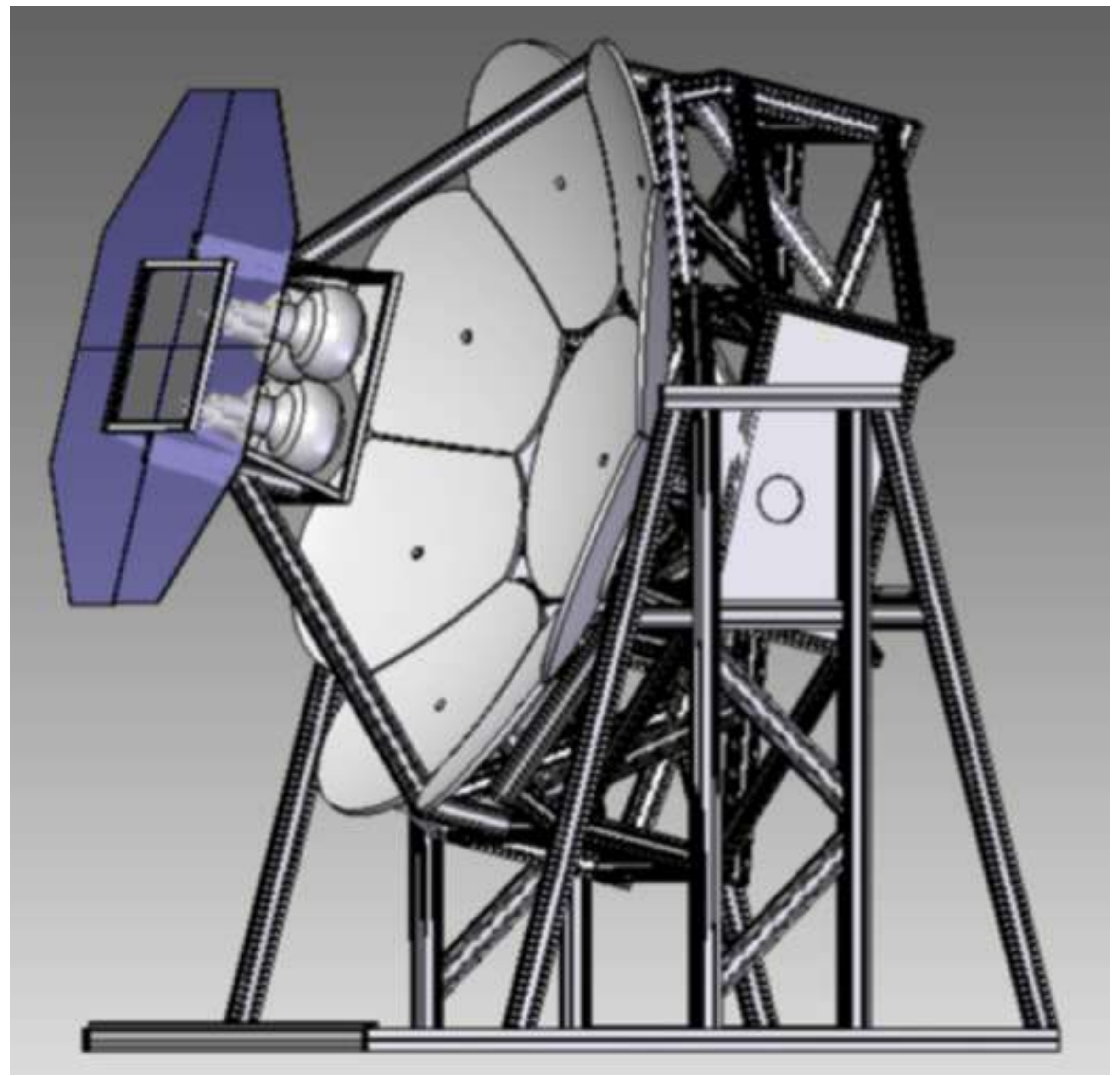


Figure 7: A FAST telescope frame, showing four PMTs at the focus of a 1.6 m diameter segmented mirror. The support structure is made from aluminium profiles. The UV band-pass filter can be seen attached to the periphery of the camera box [100, 101].

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

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

Summary and future

- **Scientific objectives of GCOS**
  - **Charged-particle astronomy** to clarify the origin and nature of UHECRs
    - Unprecedented effective area, **~60000 km^2** and **mass identification capabilities**
      - Constrain a detailed structure of the Galactic magnetic field
  - **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
- **We warmly welcome your participations!!**

Task leaders of GCOS-Japan consortium



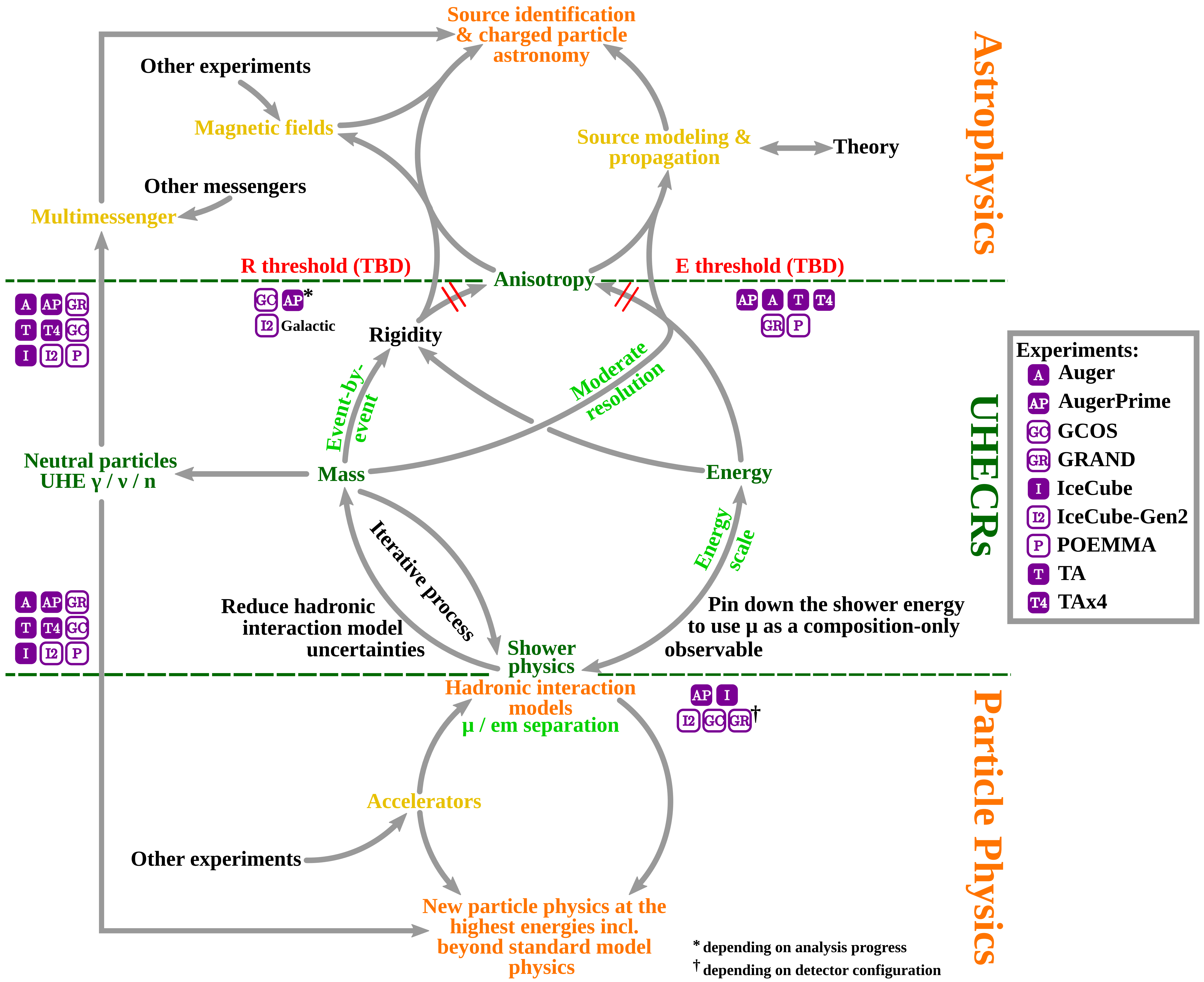



The greatest pleasure in life is
doing what people say you cannot do.
Walter Bagehot

Backup

Mass composition of cosmic rays

Strong connections to astrophysics and particle physics



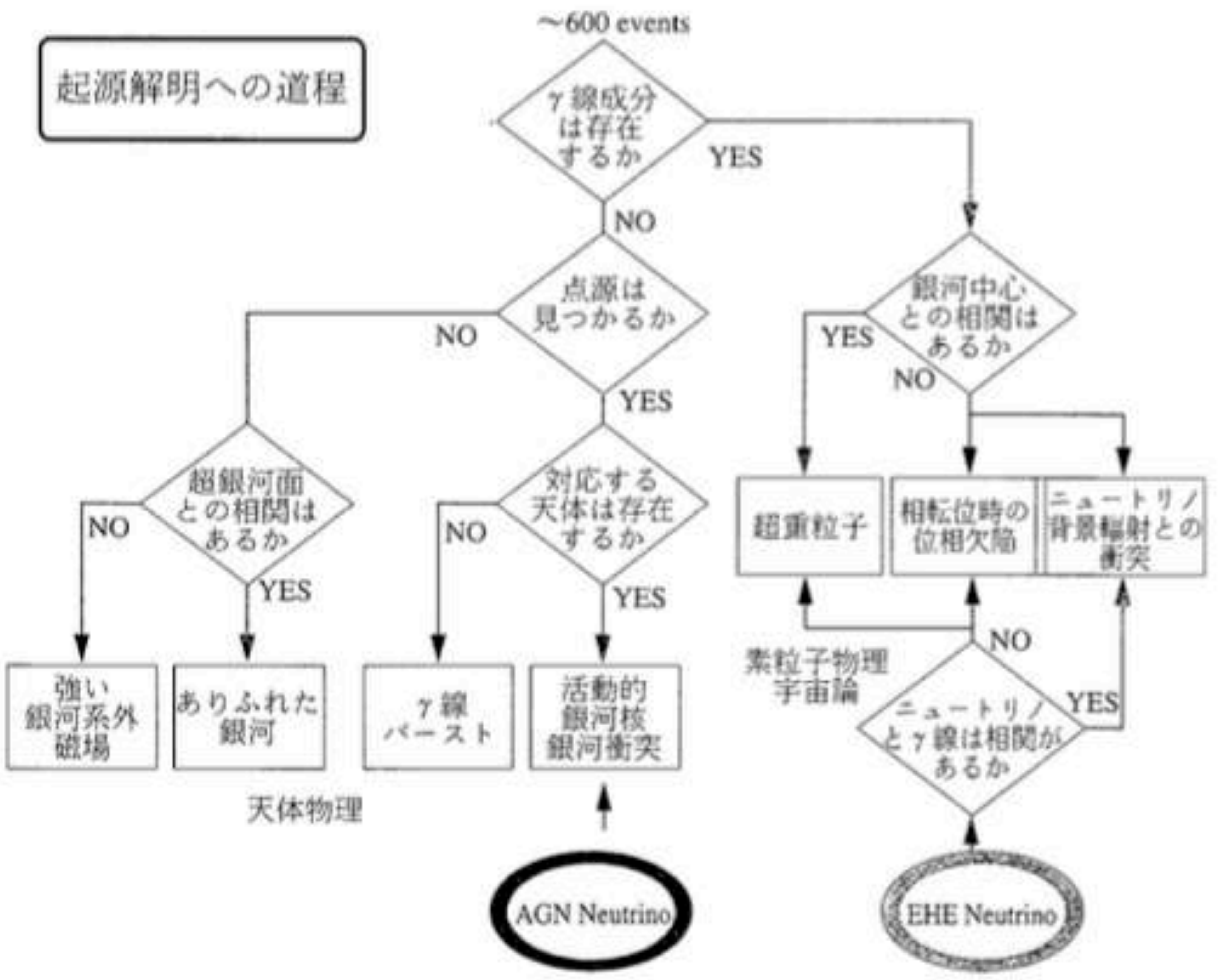
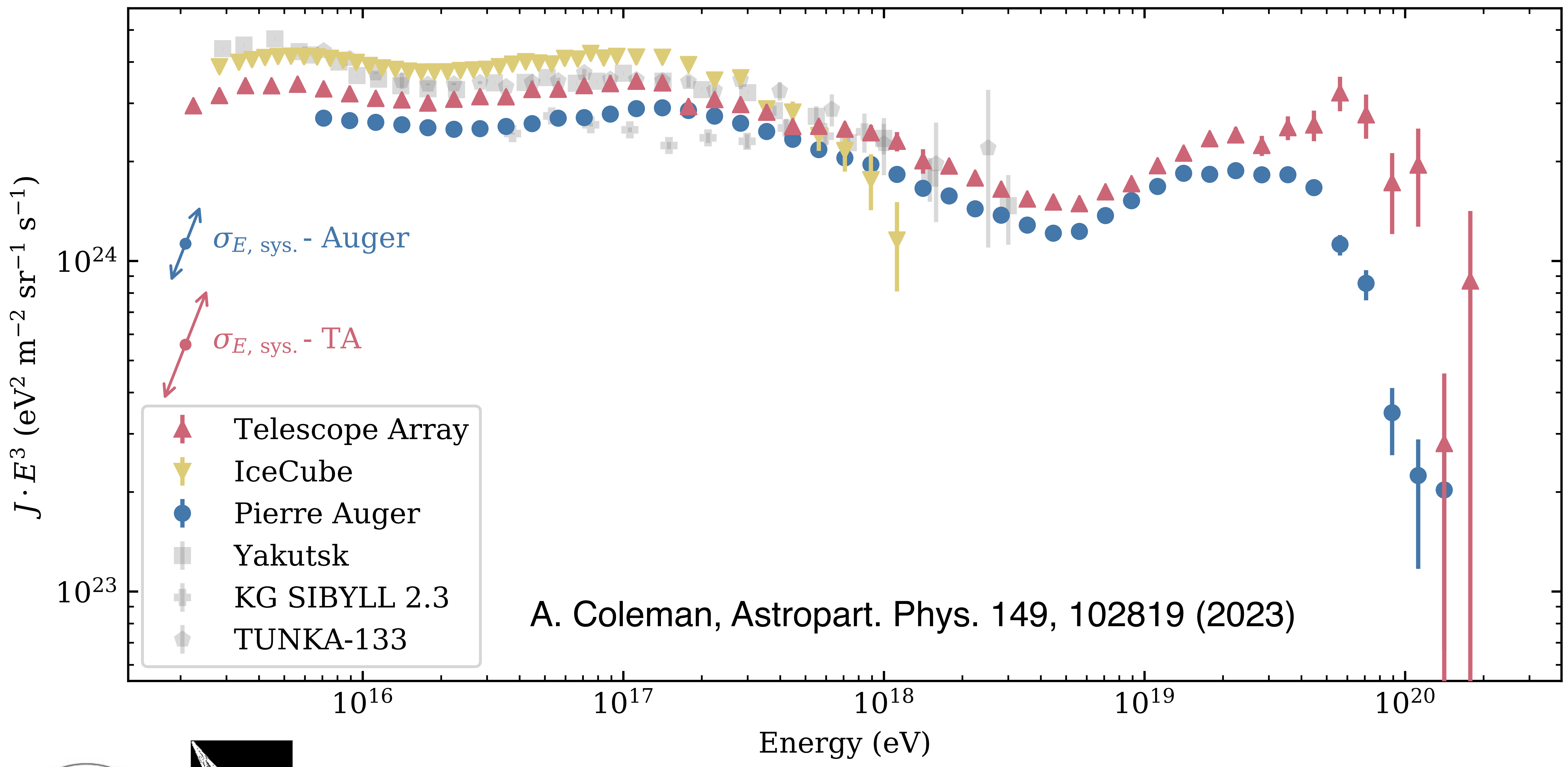
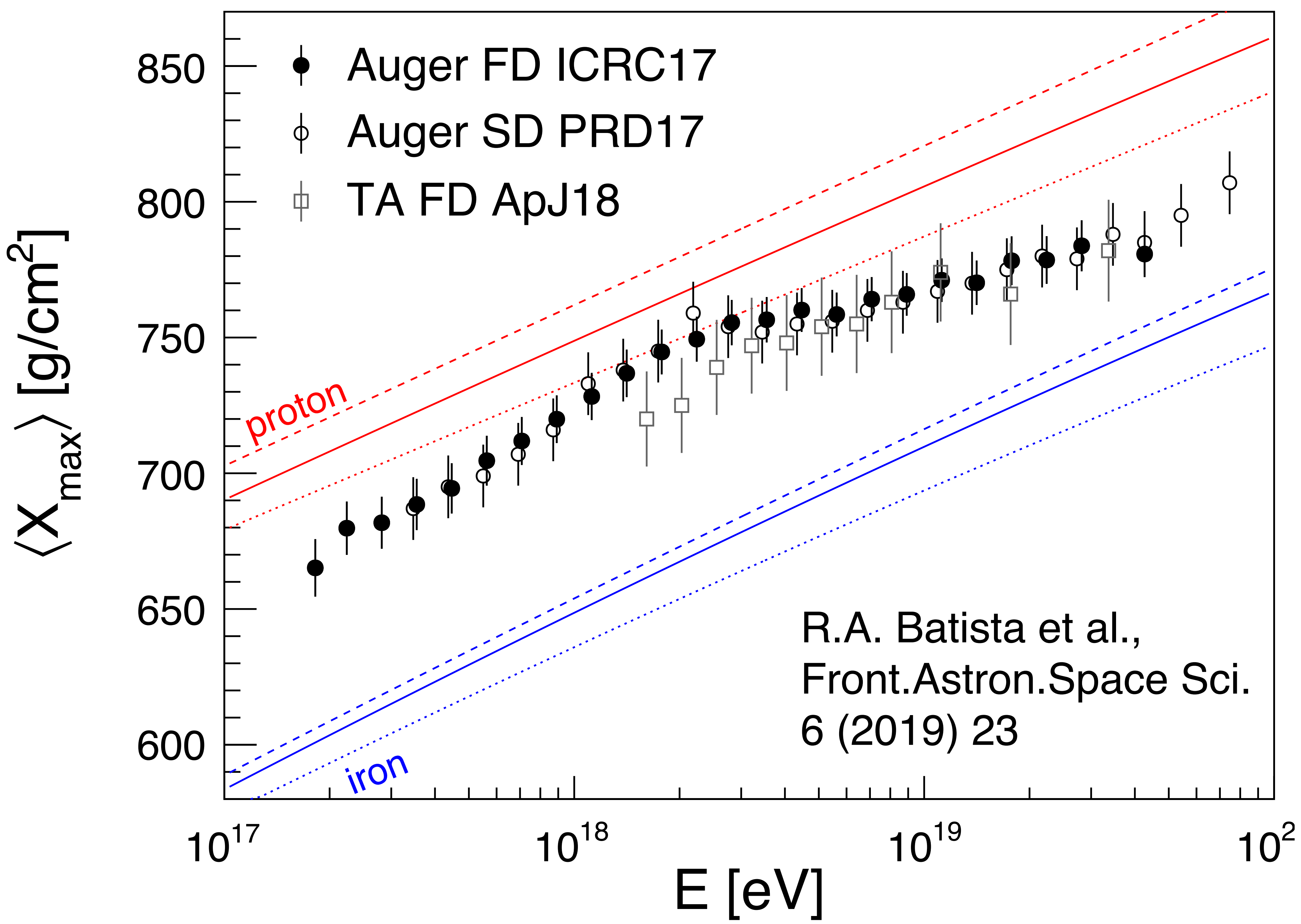


図10 宇宙からくる超高エネルギー粒子放射の起源を観測によって解明する道筋を示した。到来方向分布や既知の天体との相関、ガンマ線やニュートリノ成分の検出によって、提案されている様々なモデルの真偽を確かめることができる。

A. Coleman et al., Astroparticle Physics 149 (2023) 102819

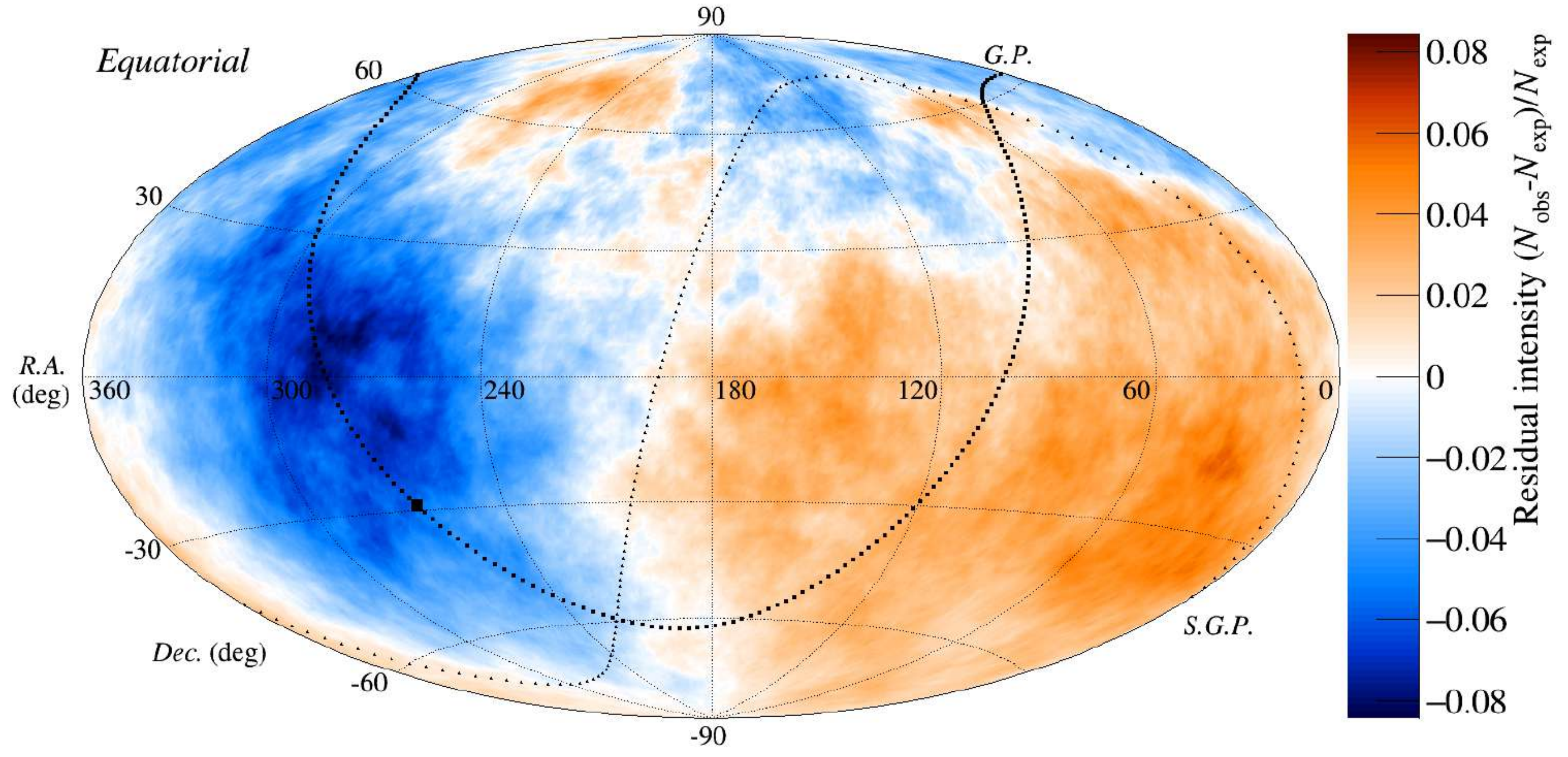
物理学会誌 2000年 福島・吉田



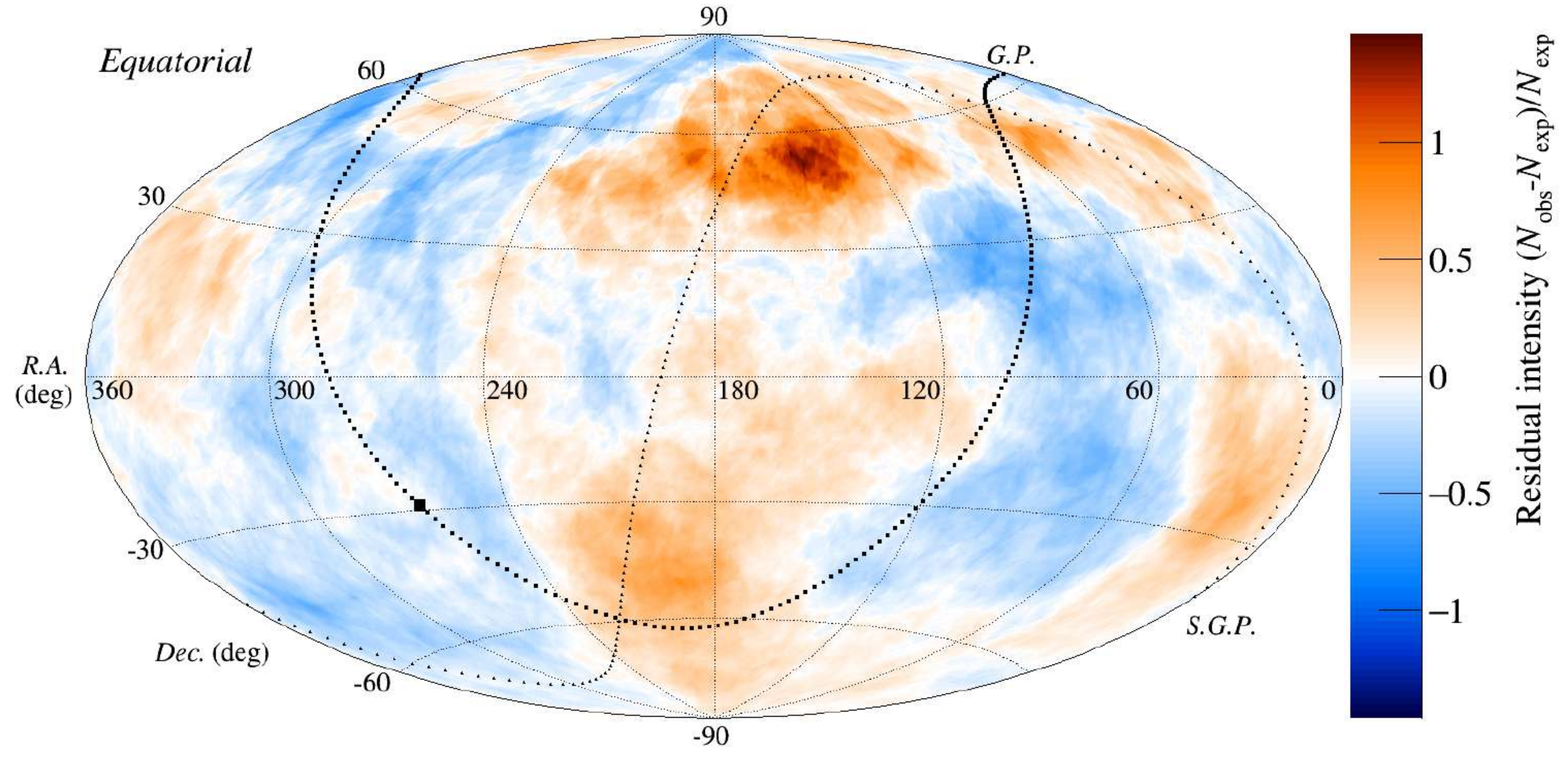


Latest results

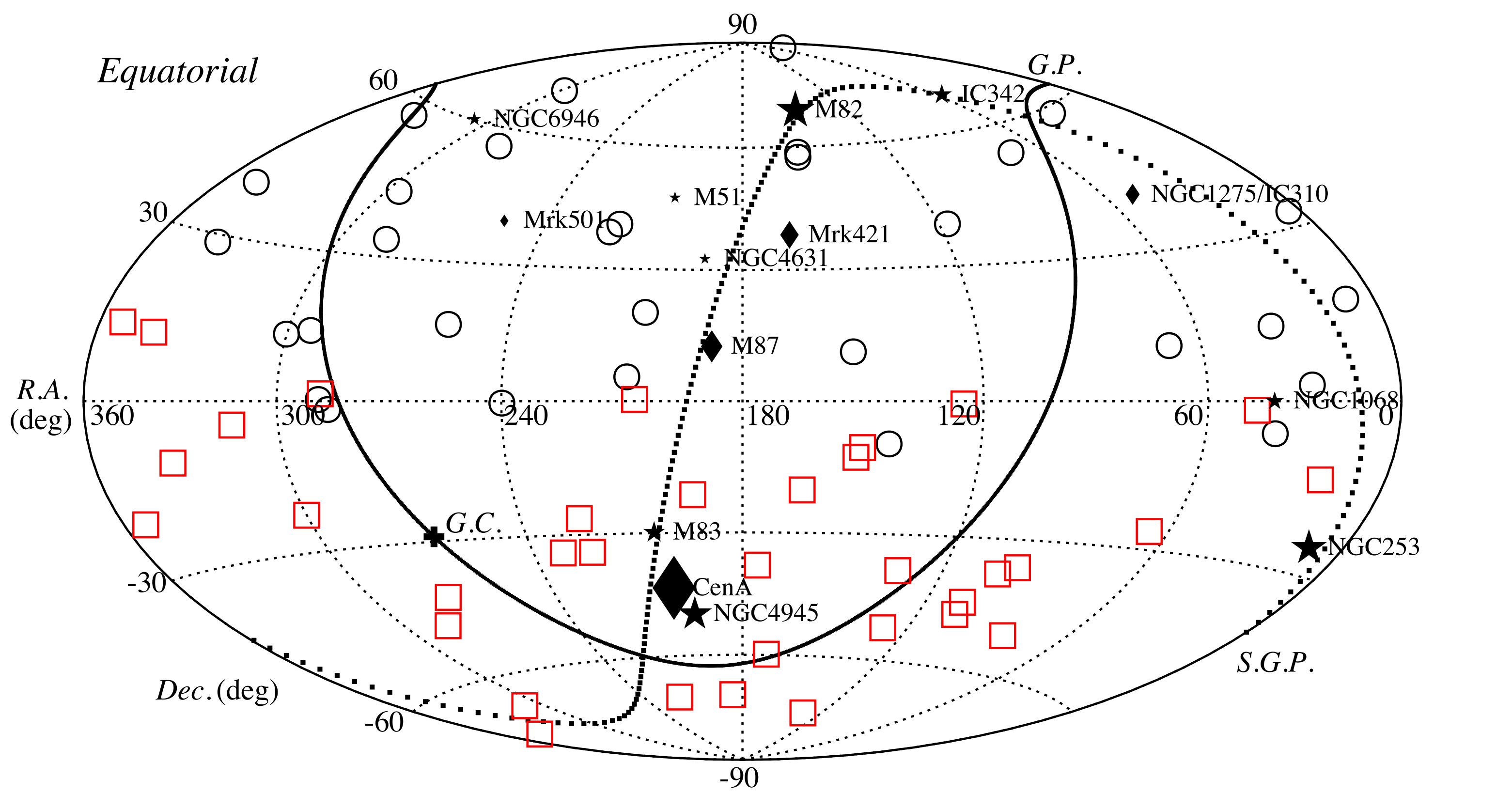
$$\theta \sim 10^\circ Z \left(\frac{E}{10\,\mathrm{EeV}}\right)^{-1} \qquad t_{\mathrm{delay}} \sim 100\, Z^2 \left(\frac{E}{10\,\mathrm{EeV}}\right)^{-2} \mathrm{yr}$$



Ankle ($E > 10$ EeV)

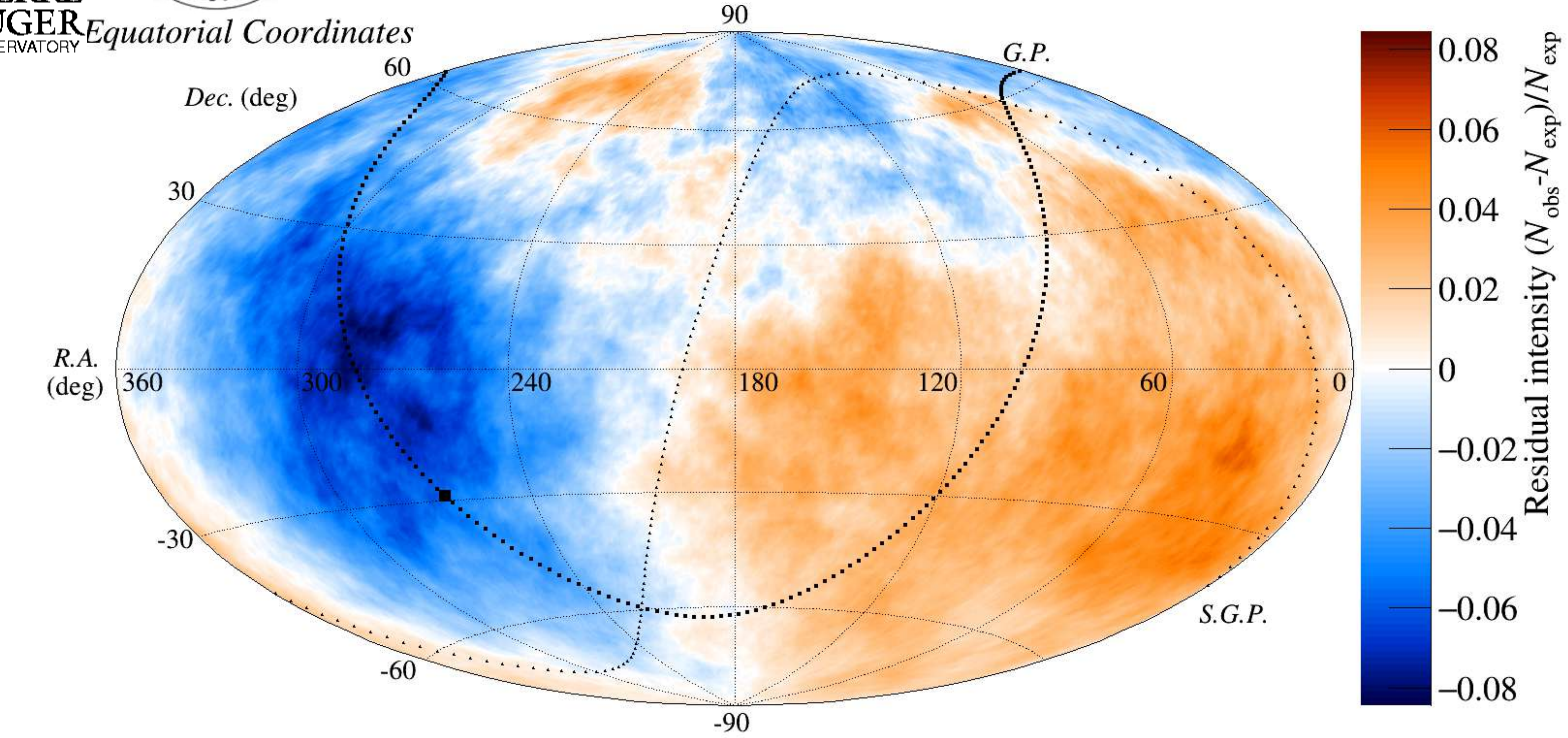


Cutoff ($E > 50$ EeV)

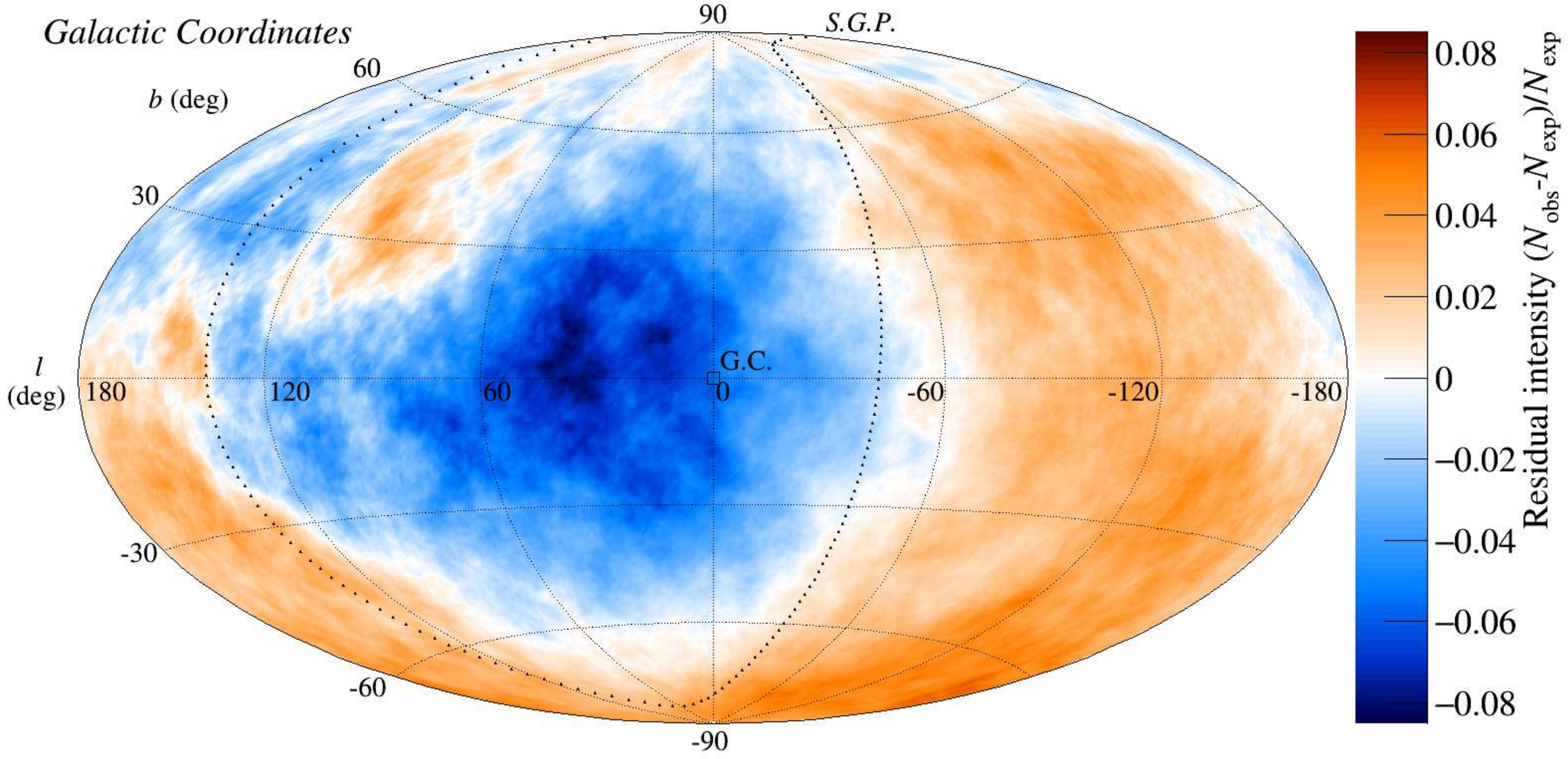


Beyond-cutoff ($E > 100$ EeV)

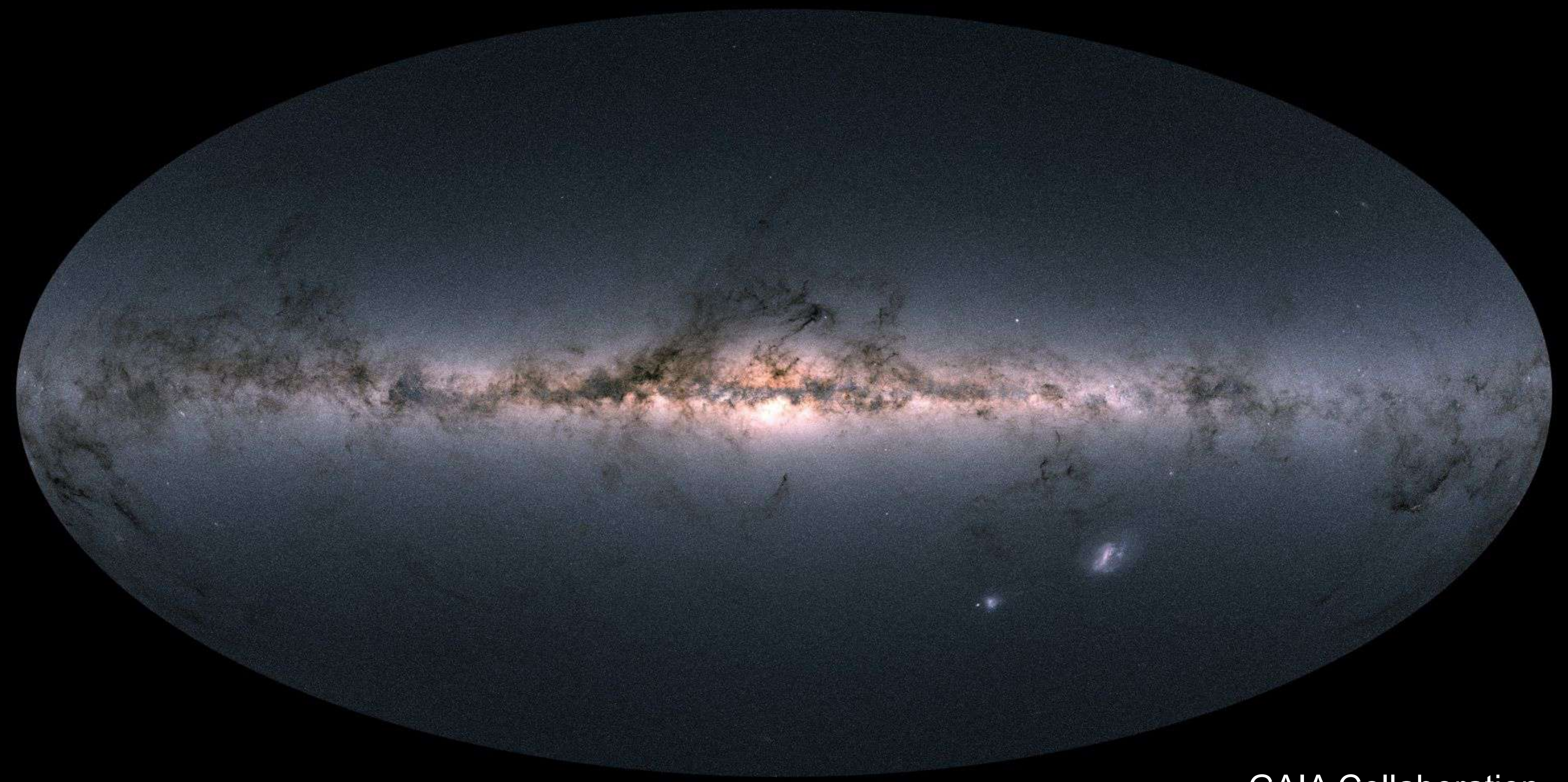
10 EeV skymap



Converted to **Galactic coordinates**



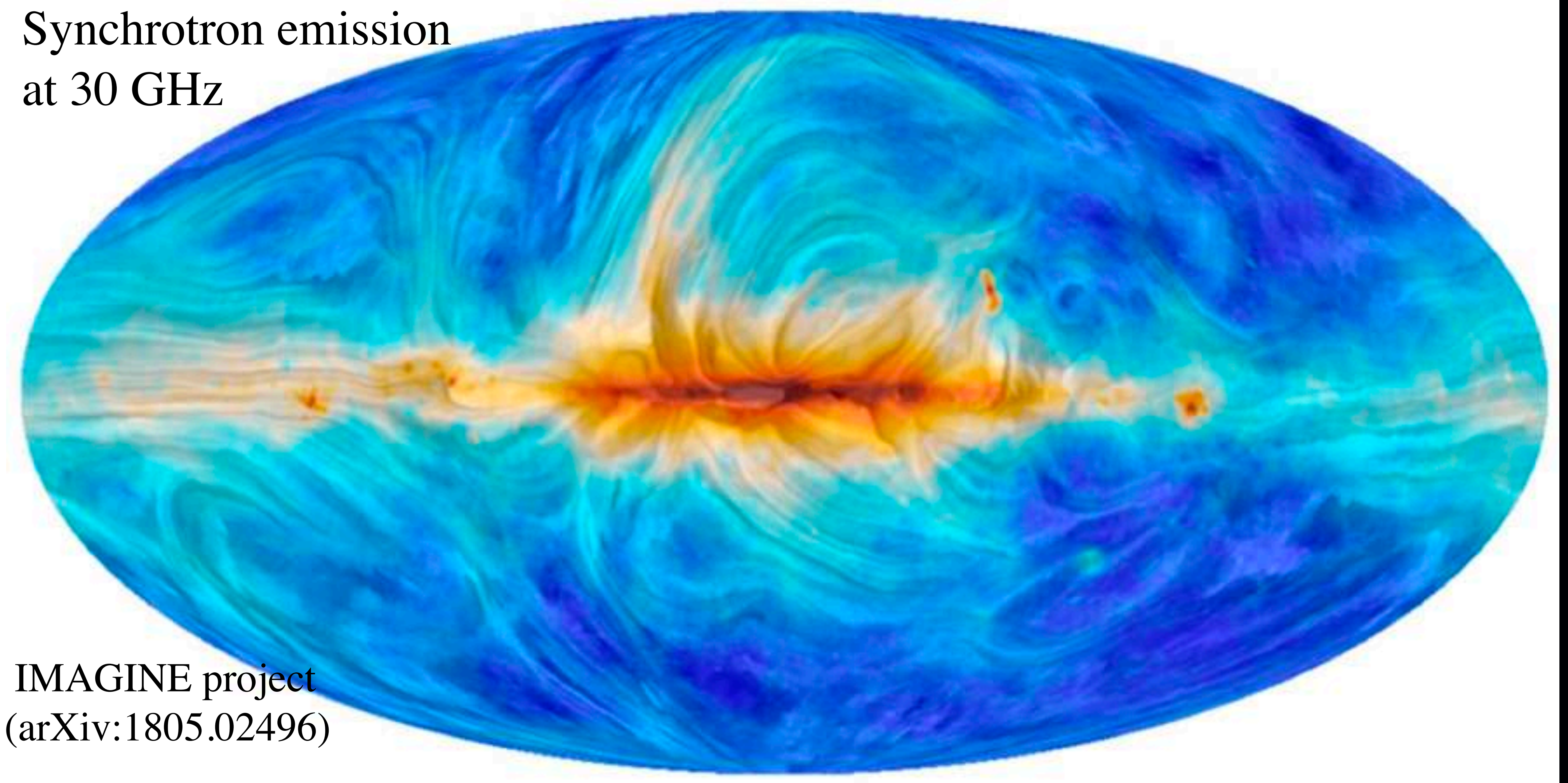
T. Fujii, PoS (ICRC2021) 402 (2021)



GAIA Collaboration

"Deciphering" magnetic fields

Synchrotron emission at 30 GHz



IMAGINE project (arXiv:1805.02496)

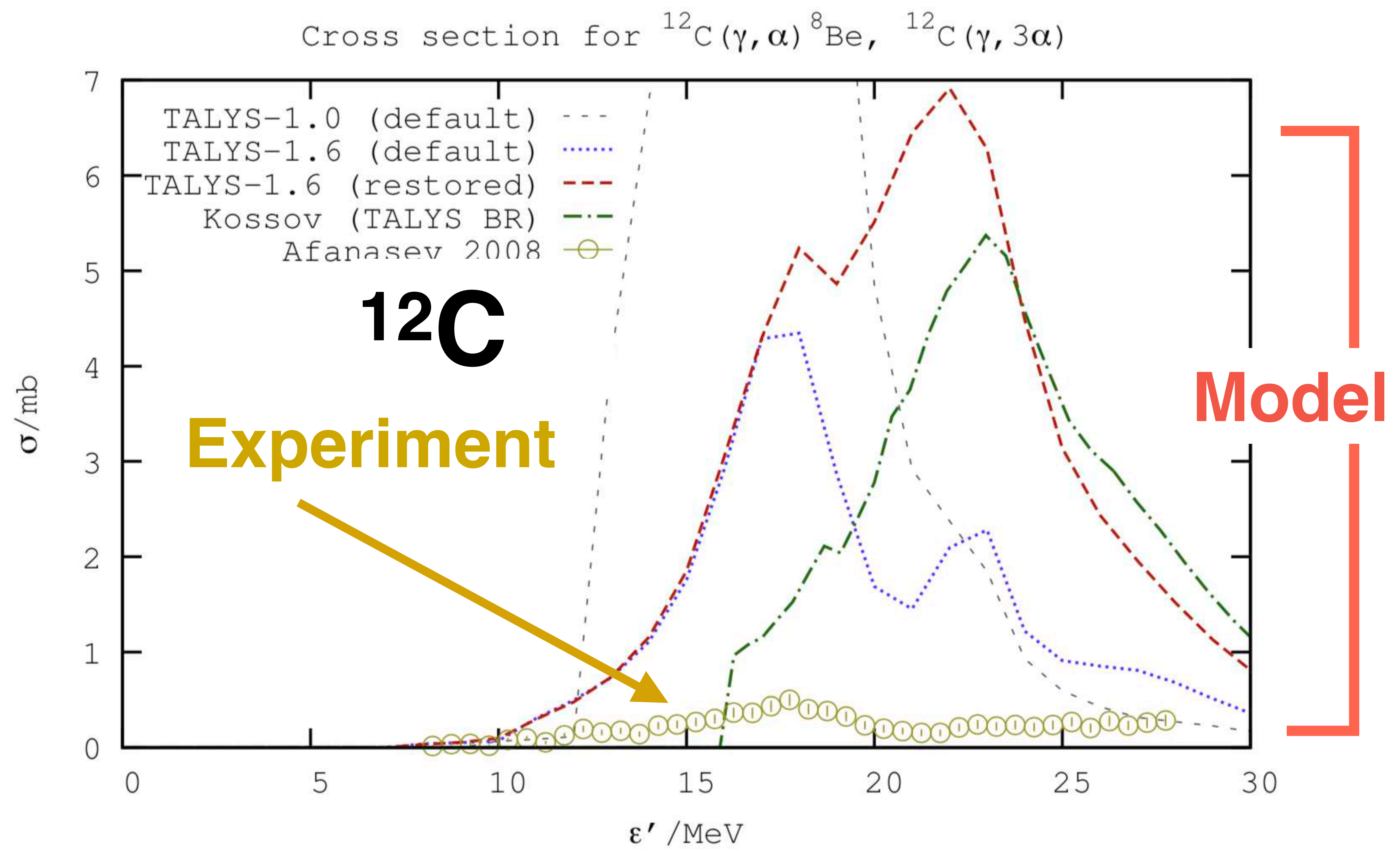
Nuclear Physics meets UHECRs (PANDORA project)

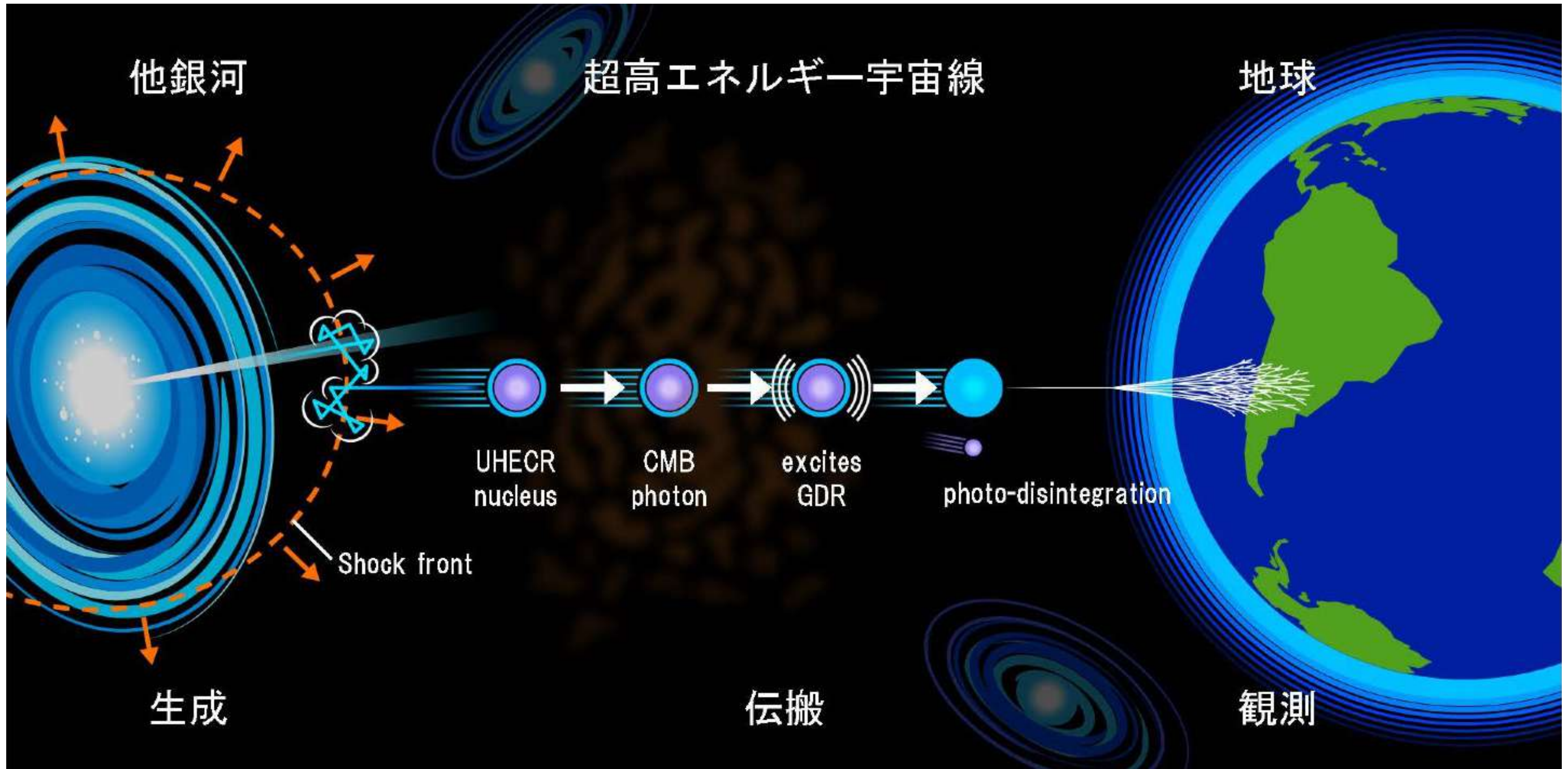
$$ {}^{A}_{Z}N + \gamma_{\mathrm{CMB}} \rightarrow {}^{A-1}_{Z-1}N' + p $$

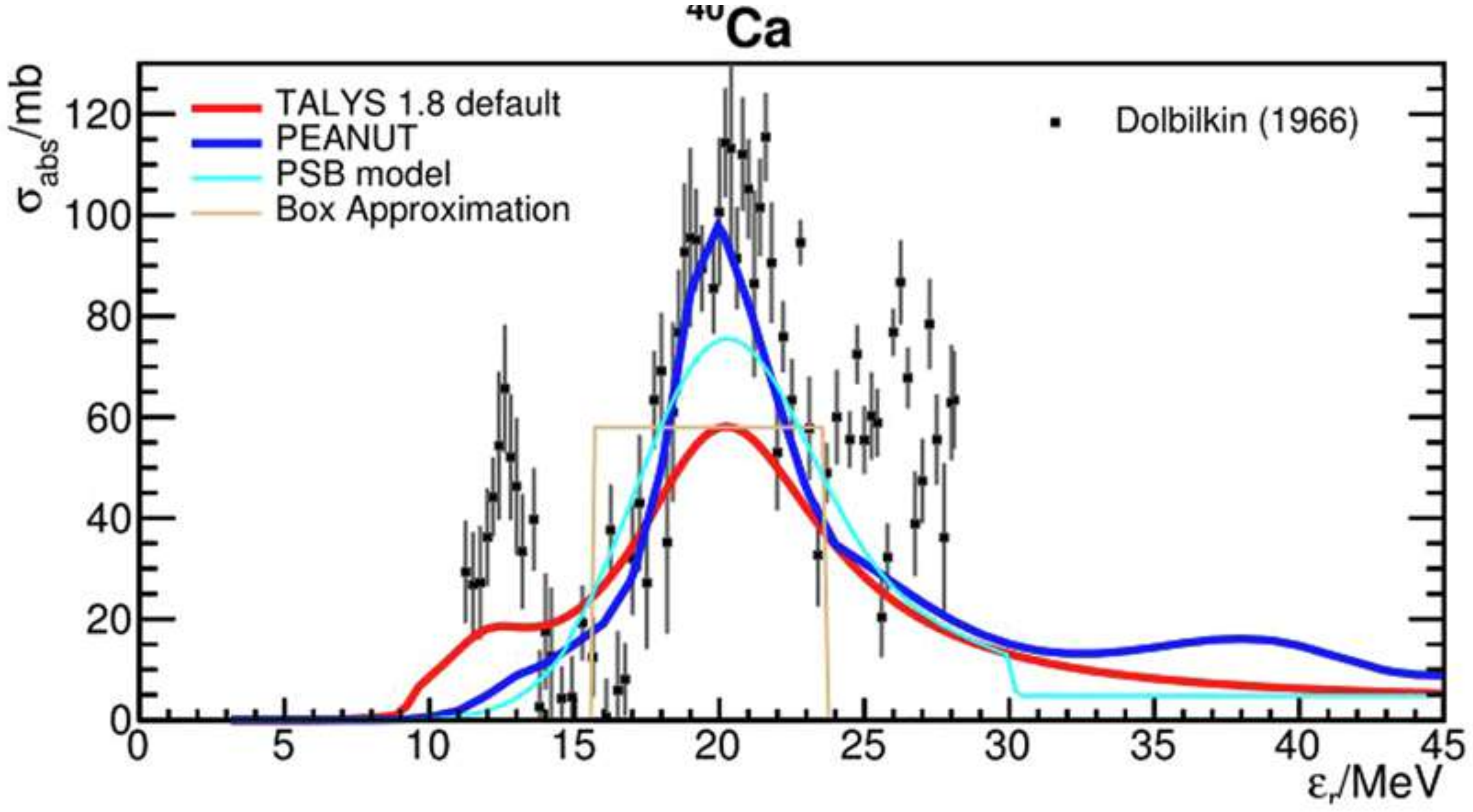
- Large uncertainty of the cross section from the giant dipole resonants for A < 60 nuclei
- Multidisciplinary research among nuclear physics, UHECR and CMB

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

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







Muon puzzle

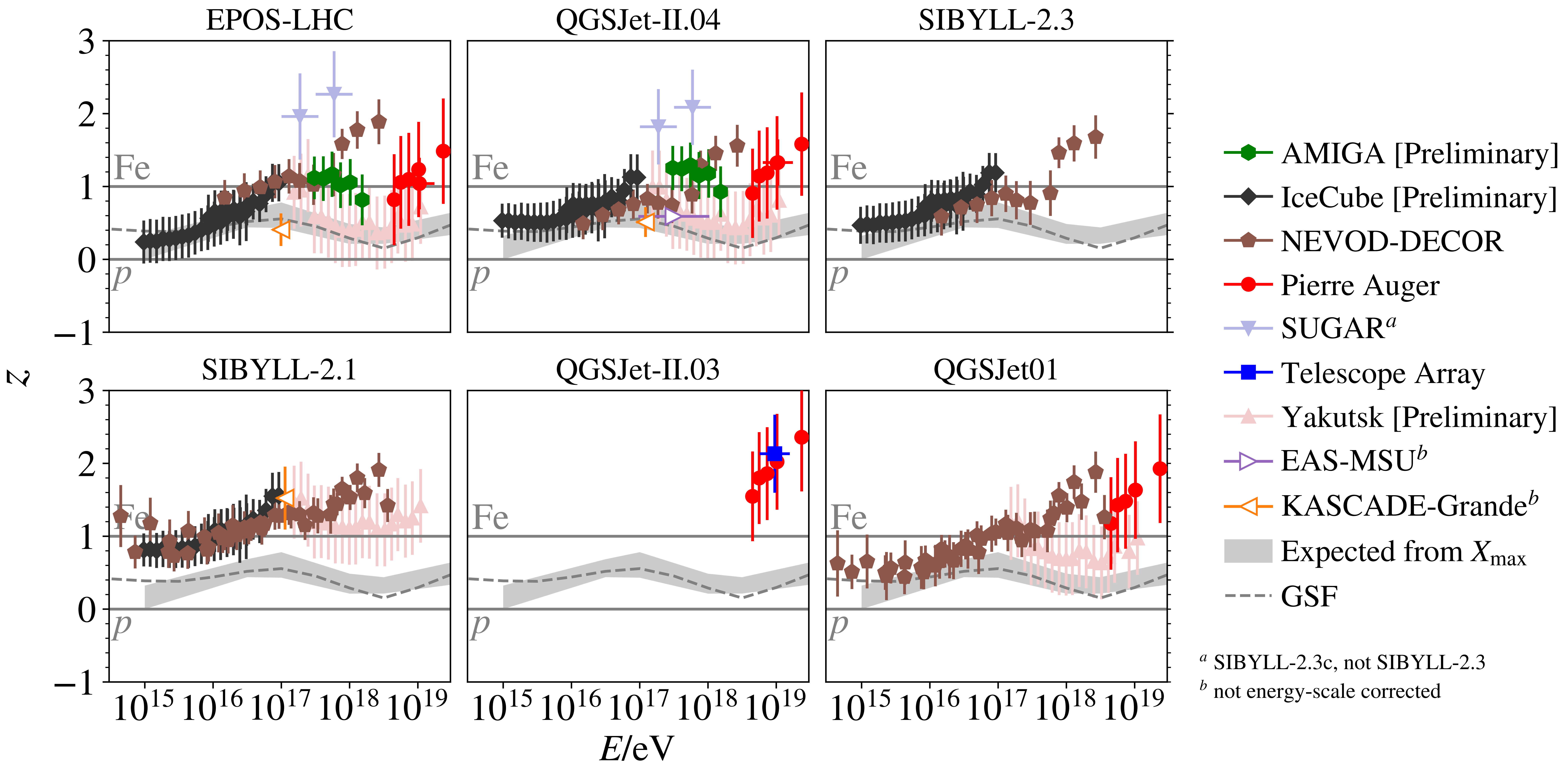


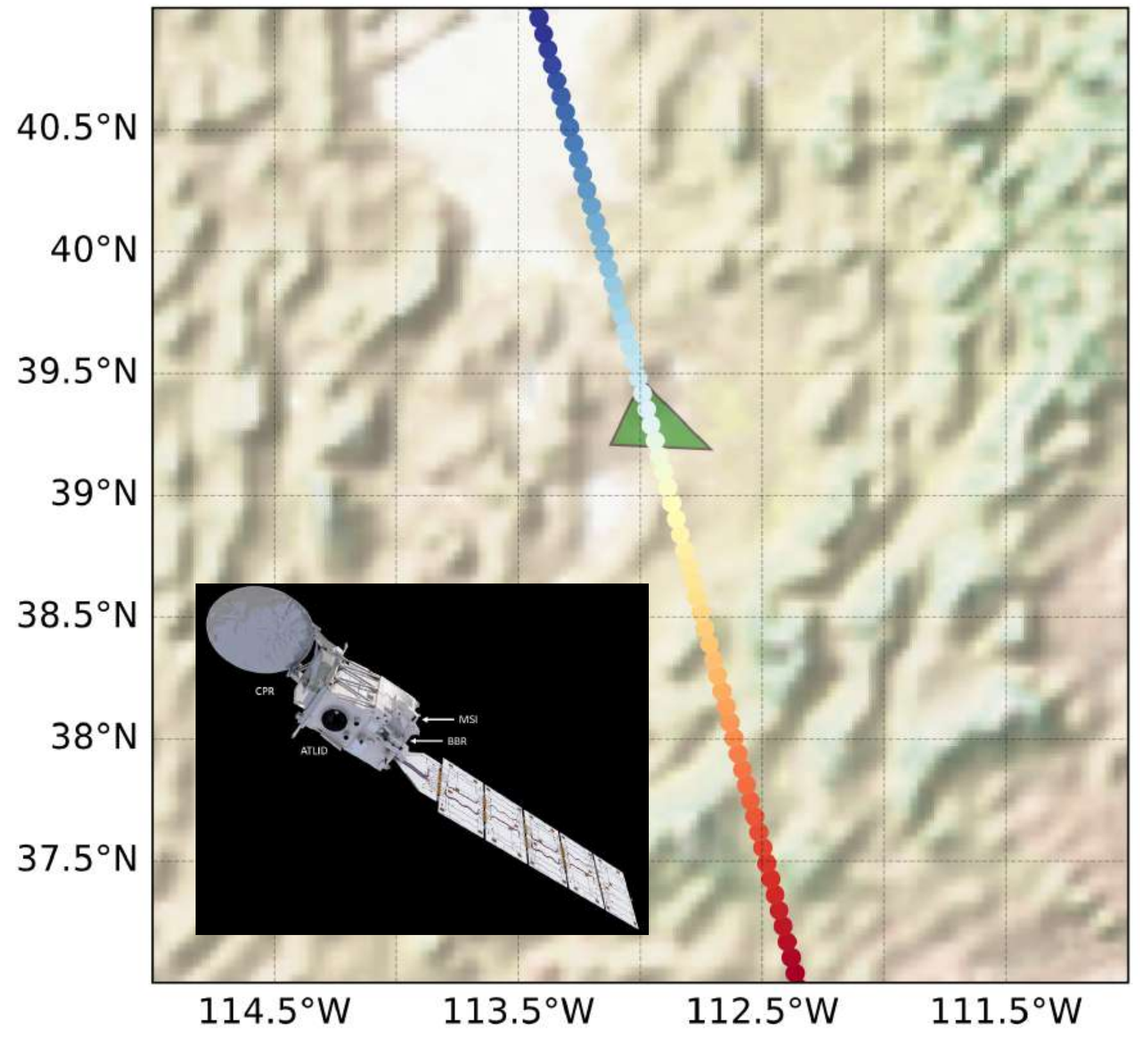
Fig. 3 Compilation of muon measurements converted to the abstract z-scale and after cross-calibrating the energy scales of the experiments as described in the text (image from Dembinski et al. (2019)). Shown for comparison are predicted z_{mass}-values based on air shower simulations and X_{max}-measurements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

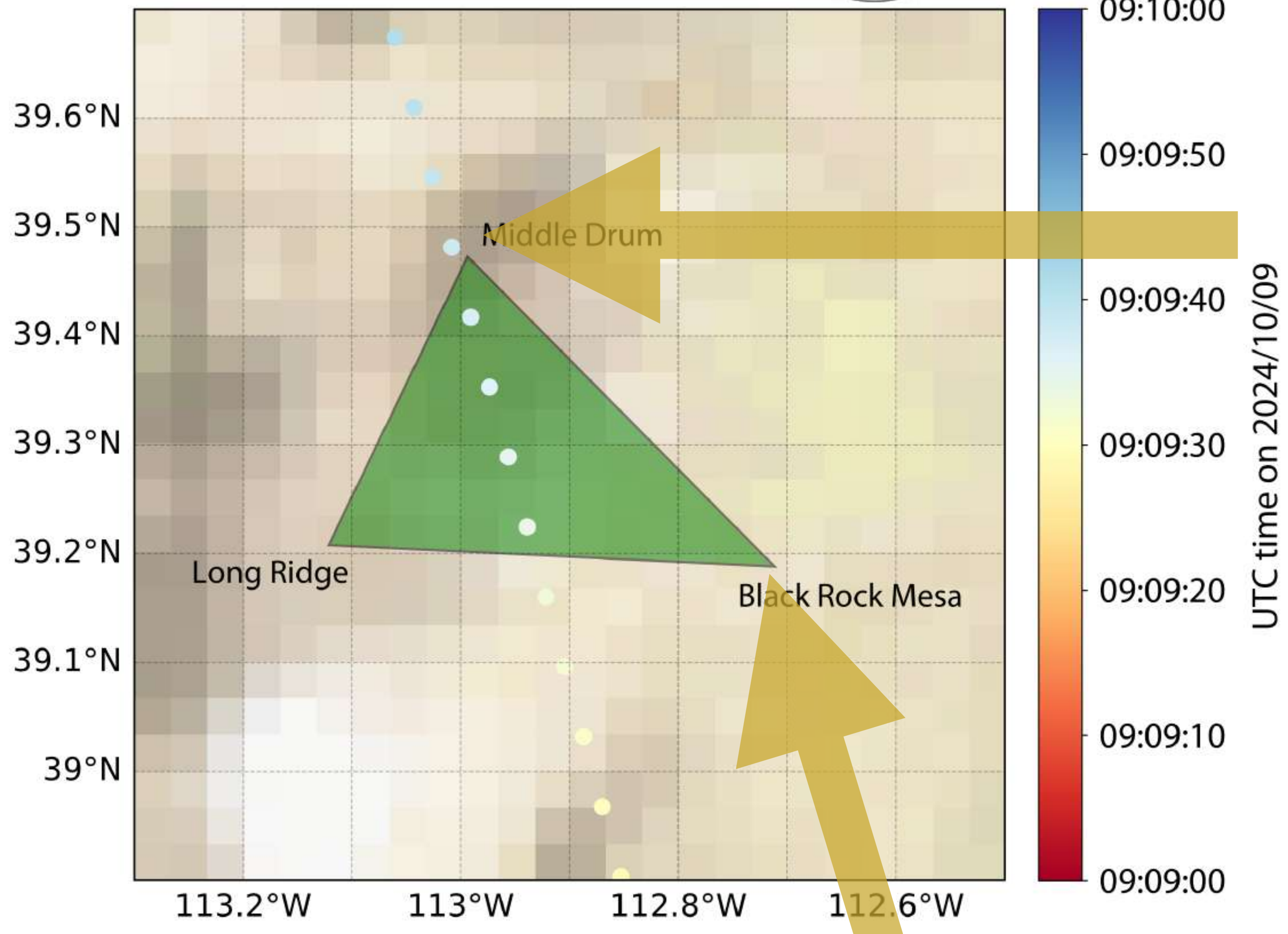
J. Albrecht et al., arXiv:2105.06138 (2021)

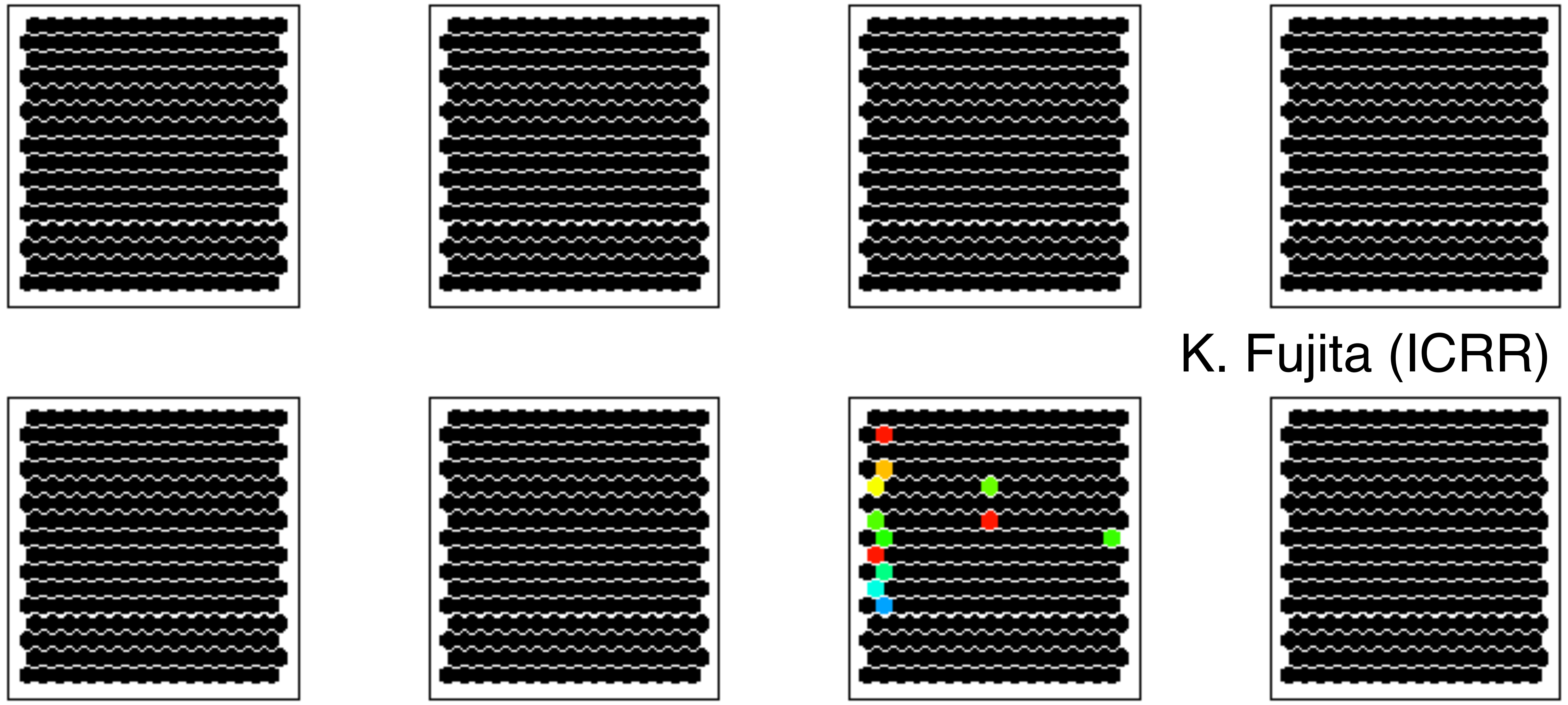

Radio
Planck Collaboration
Optical
GAIA Collaboration
SRG/eROSITA
0.3-2.3 keV - RGB
X-rays
IKI
MPE
eROSITA Collaboration
Gamma-rays
Fermi Collaboration
Arrival directions of most energetic neutrino events
North
South
Earth absorption
Galactic Plane
180°
-90°
Galactic
Neutrinos
TXS 0506+056
best-fit direction IC170922A
IC170922A 50%
IC170922A 90%
Declination
Right Ascension
Fermi-LAT Counts/Pixel
IceCube Collaboration
Galactic Coordinates
b (deg)
l (deg)
S.G.P.
G.C.
UHECR?
Pierre Auger and Telescope Array Collaborations

Intersection with Earth science as "global light source"

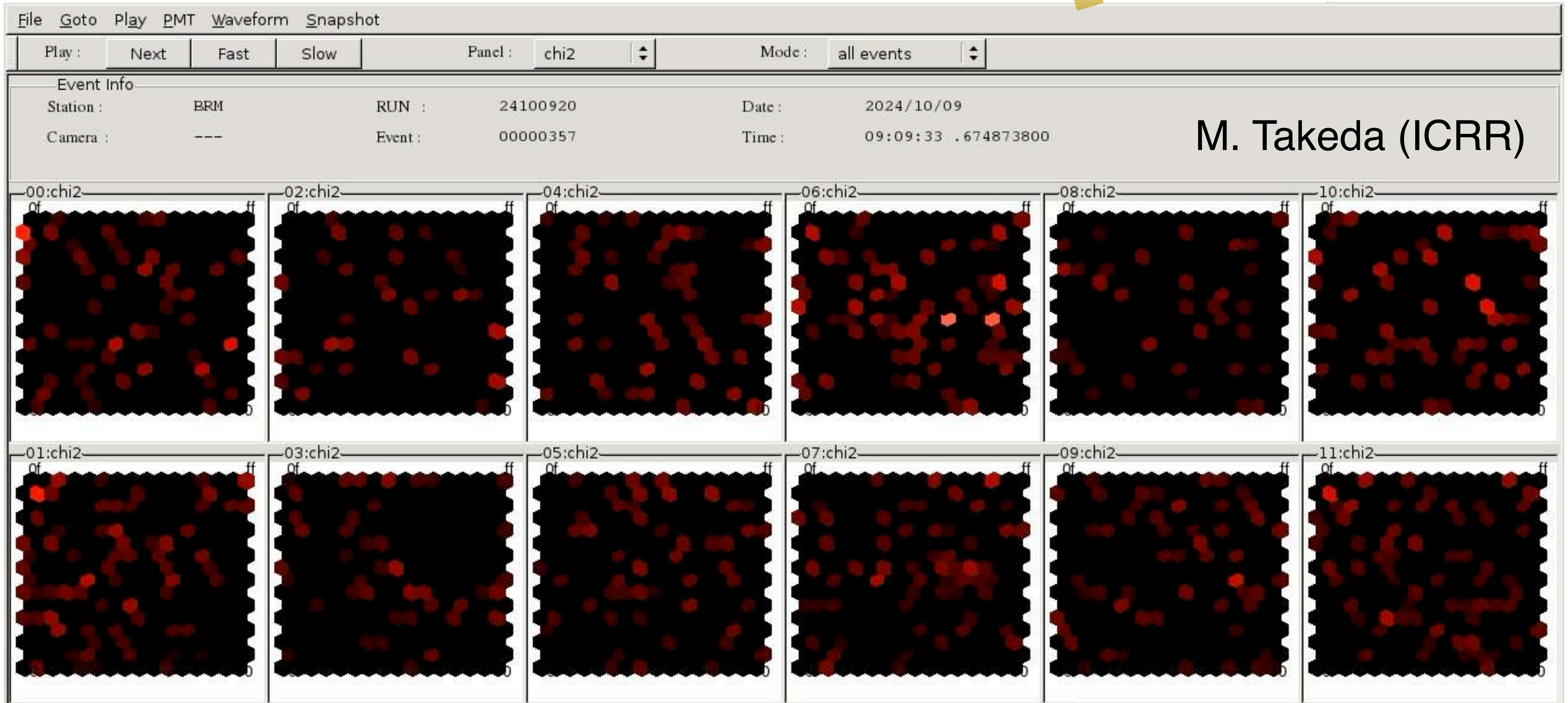
TA overpass on 9 October 2024





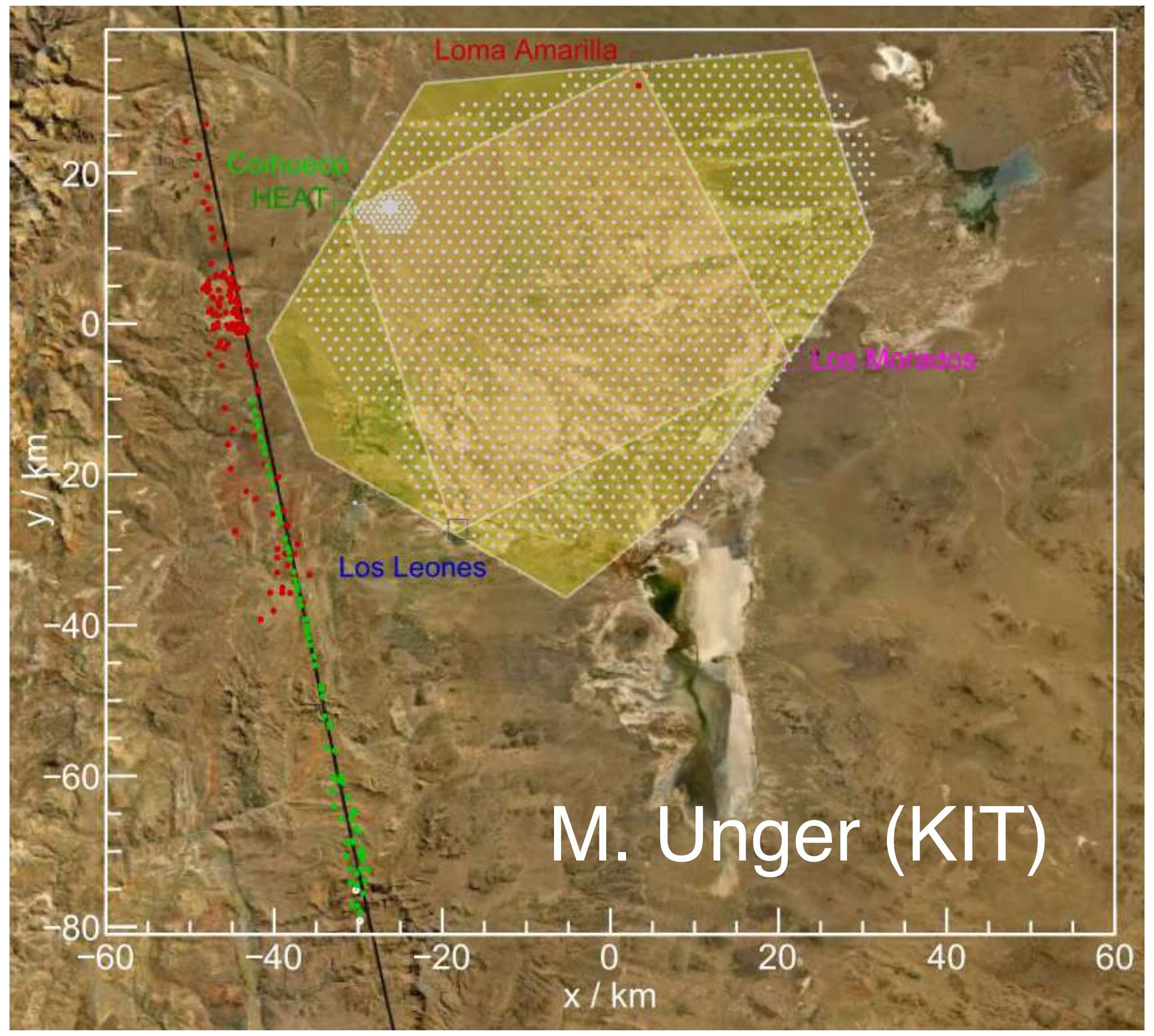


K. Fujita (ICRR)



M. Takeda (ICRR)

Auger overpass on 29 October 2024



M. Unger (KIT)

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

Energy spectrum

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

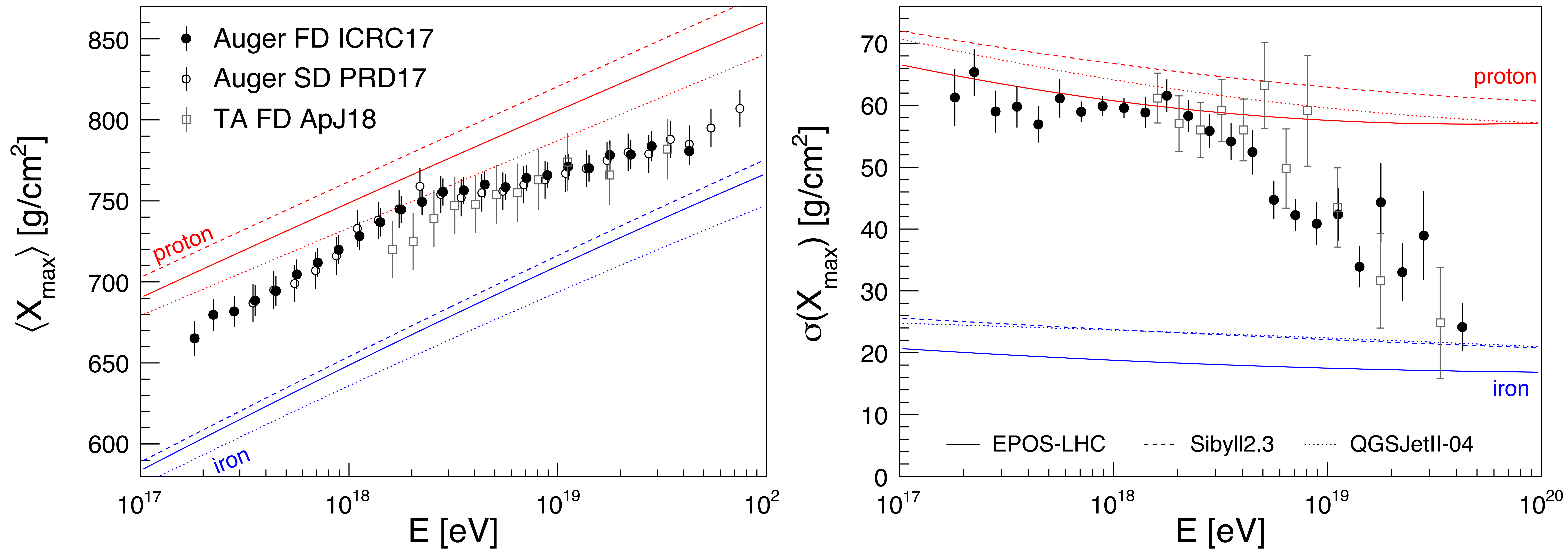
A. Coleman et al., Astropart. Phys. 149, 102819 (2023)

Mass composition

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

Z : **atomic number (mass composition)**

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



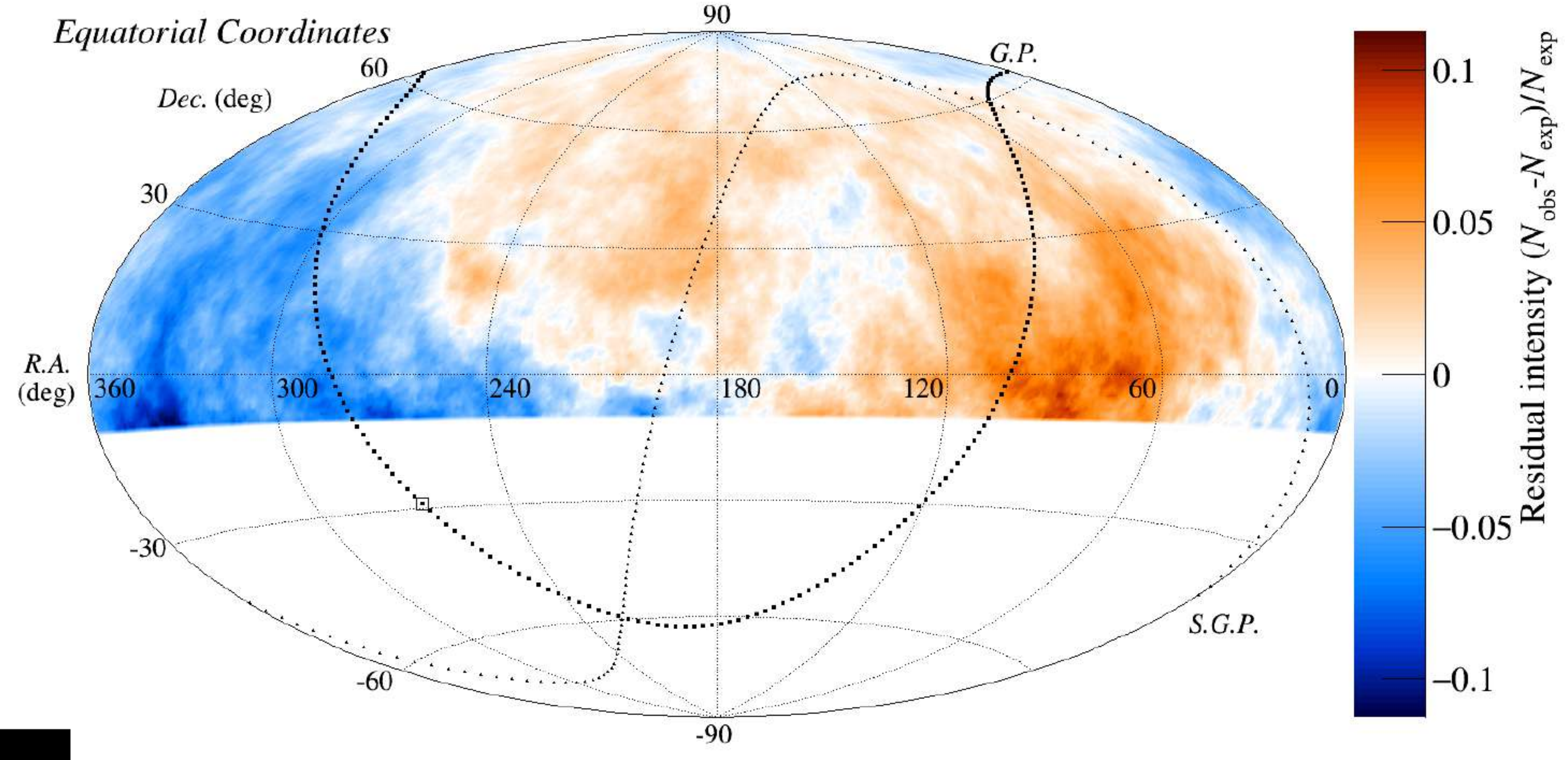
Gradually increase to the heavier composition above 3 EeV

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

Anisotropy of UHECRs (10 EeV)

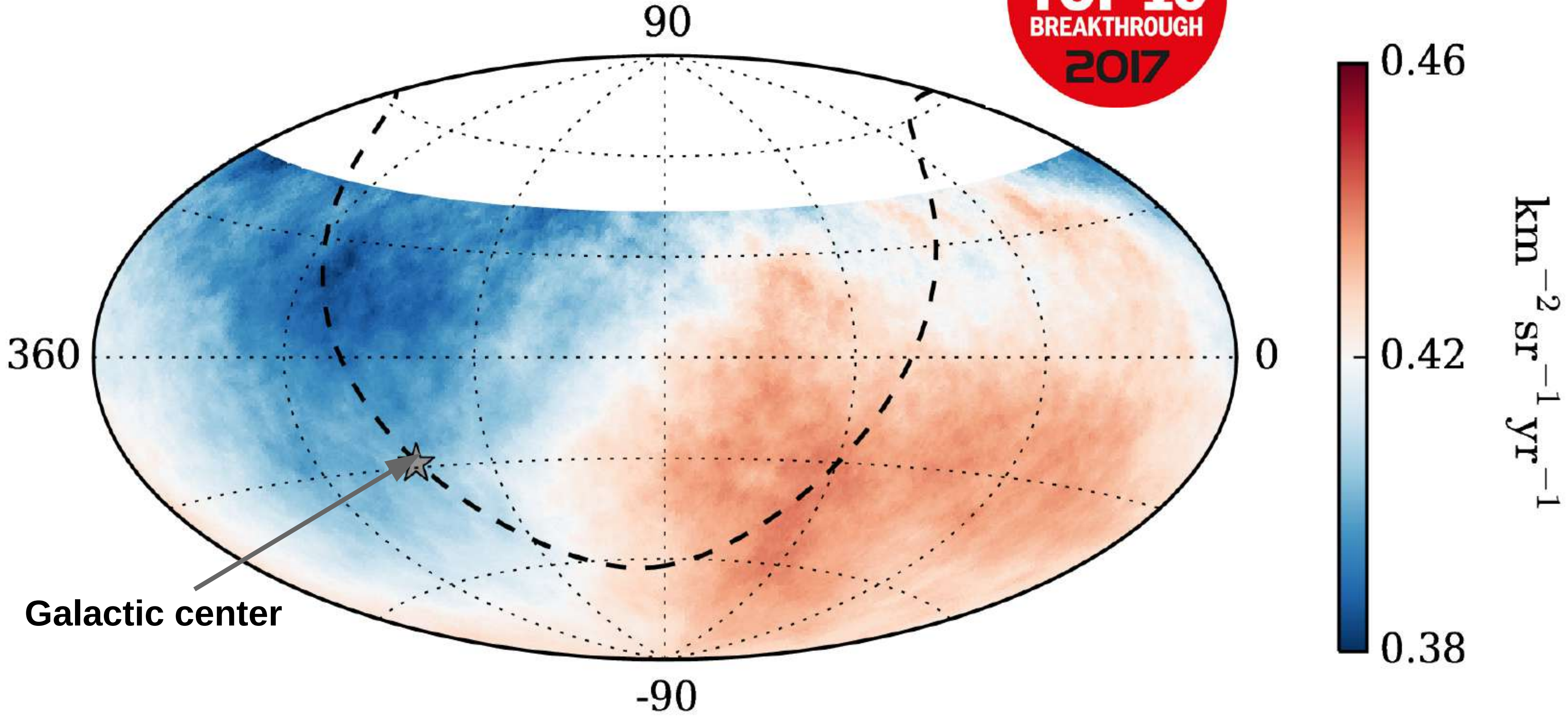
Northern TA ApJL, 898:L28 (2020)

E_{TA}> 8.8 EeV



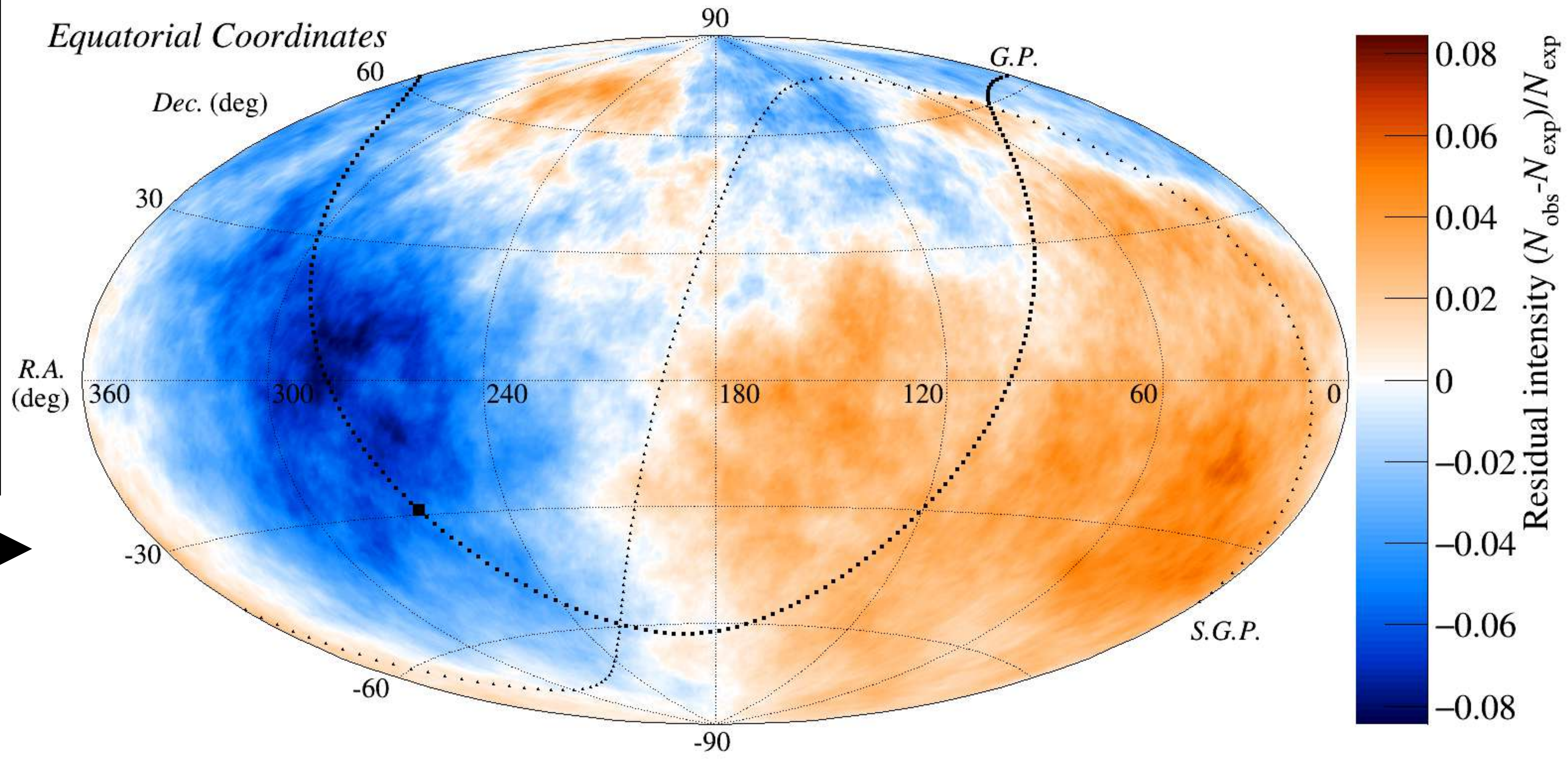
Southern Auger Science 357, 1266 (2017)

E_{Auger}> 8 EeV



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)

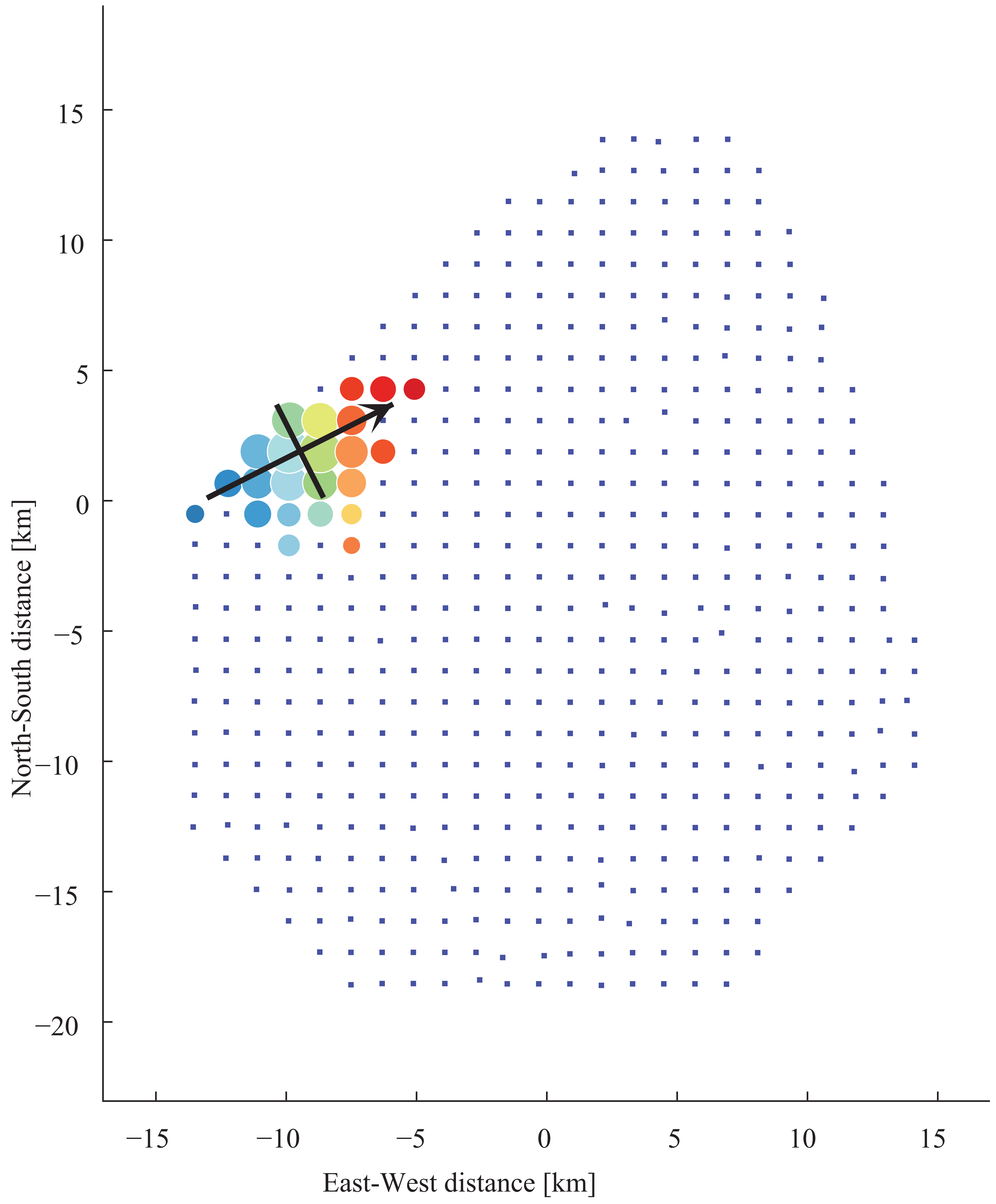
- Intriguing **intermediate-scale anisotropies** (~20 degrees) such as **hot/warm spots**
    - No excess from Virgo cluster, dubbed "***Virgo scandal***"
- **Isotropic distributions of UHECRs than our (optimistic) expectation**

The highest energy event of TA

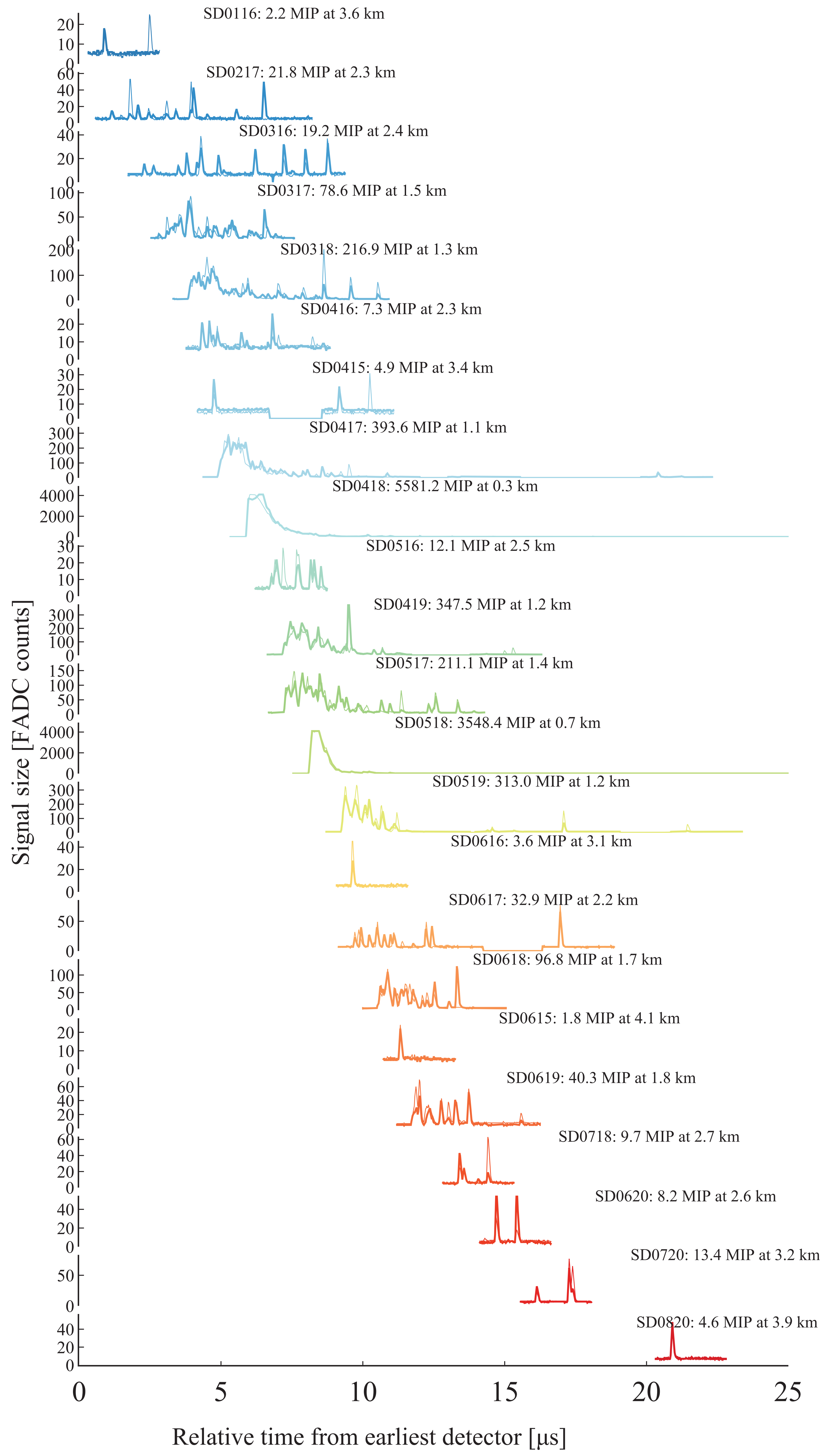
- May 27th 2021 04:35:56
- ***E* = 244 ± 29 (stat.) +51,-76 (syst.) EeV**
  - Zenith angle = 38.6°
- No operation of fluorescence telescope due to twilight

The most energetic event in 16 years operation from May 2008 to May 2024

A Surface detector array of TA



B Date: 27 May 2021 Time: 10:35:56.474337 UTC



Telescope Array Collaboration, Science 382, 903 (2023)


https://indico.cern.ch/e/gcos2025
Workshop for the Global Cosmic Ray Observatory
Challenging Next-Generation Multi-Messenger Astronomy with Interdisciplinary Research
September 9 - 11 2025, Koshiba Hall, University of Tokyo, Japan
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