Hunting origins of ultrahigh-energy cosmic rays

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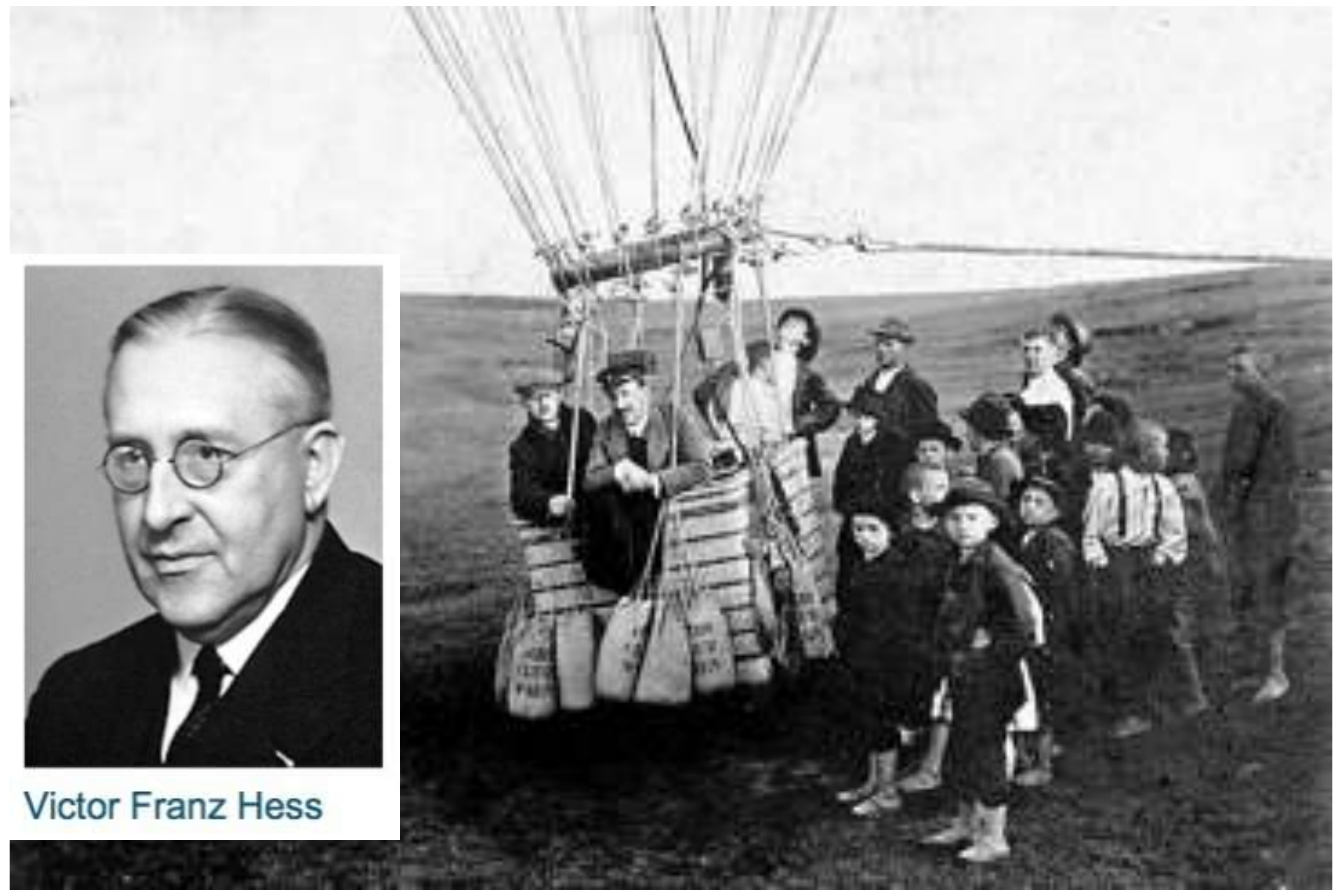
Nucleosynthesis and Evolution of Neutron Stars
January 30, 2025 @ YITP Kyoto University

Take-home message

- Detection of extremely energetic particle with 244 EeV (= 2.44 x 10^{20} eV), dubbed "Amaterasu particle" published in Science 382, 903 (2023)
  - Coming from **Local Void** in large-scale structure
  - **No promising source candidates**
- Large deflection angle due to heavier nuclei than iron?
  - **The highest energy particle might be r-process nuclei → Binary neutron star merger origin?**

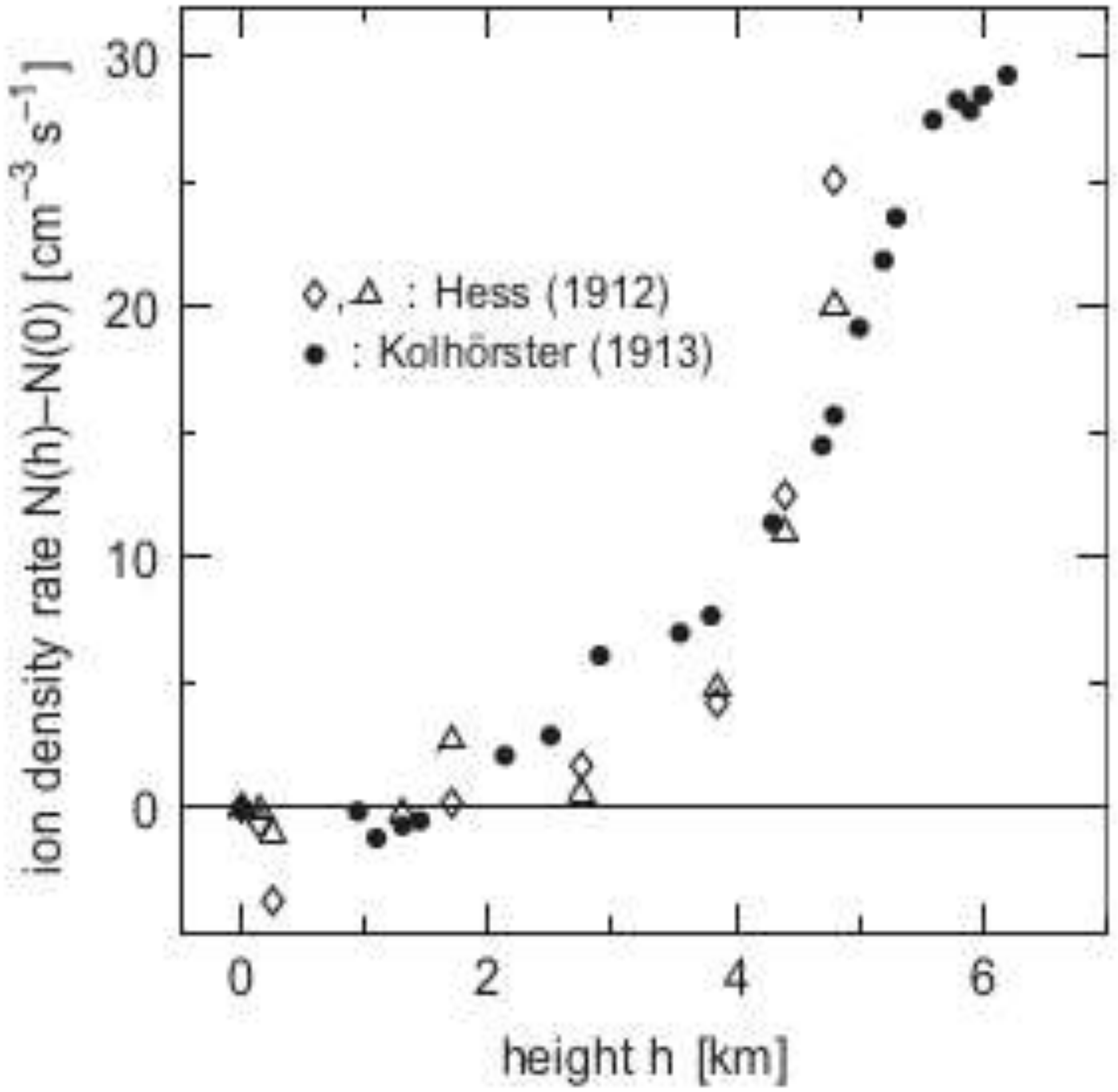
What are cosmic rays?

- Energetic particles in the universe
  - Discovered by V.F. Hess (1912), Nobel Prize in Physics (1936)
  - Proton(90%), Helium(8%), electron and heavier nuclei



V. F. Hess, Phys. Z. 13, 1804 (1912)

5350 m

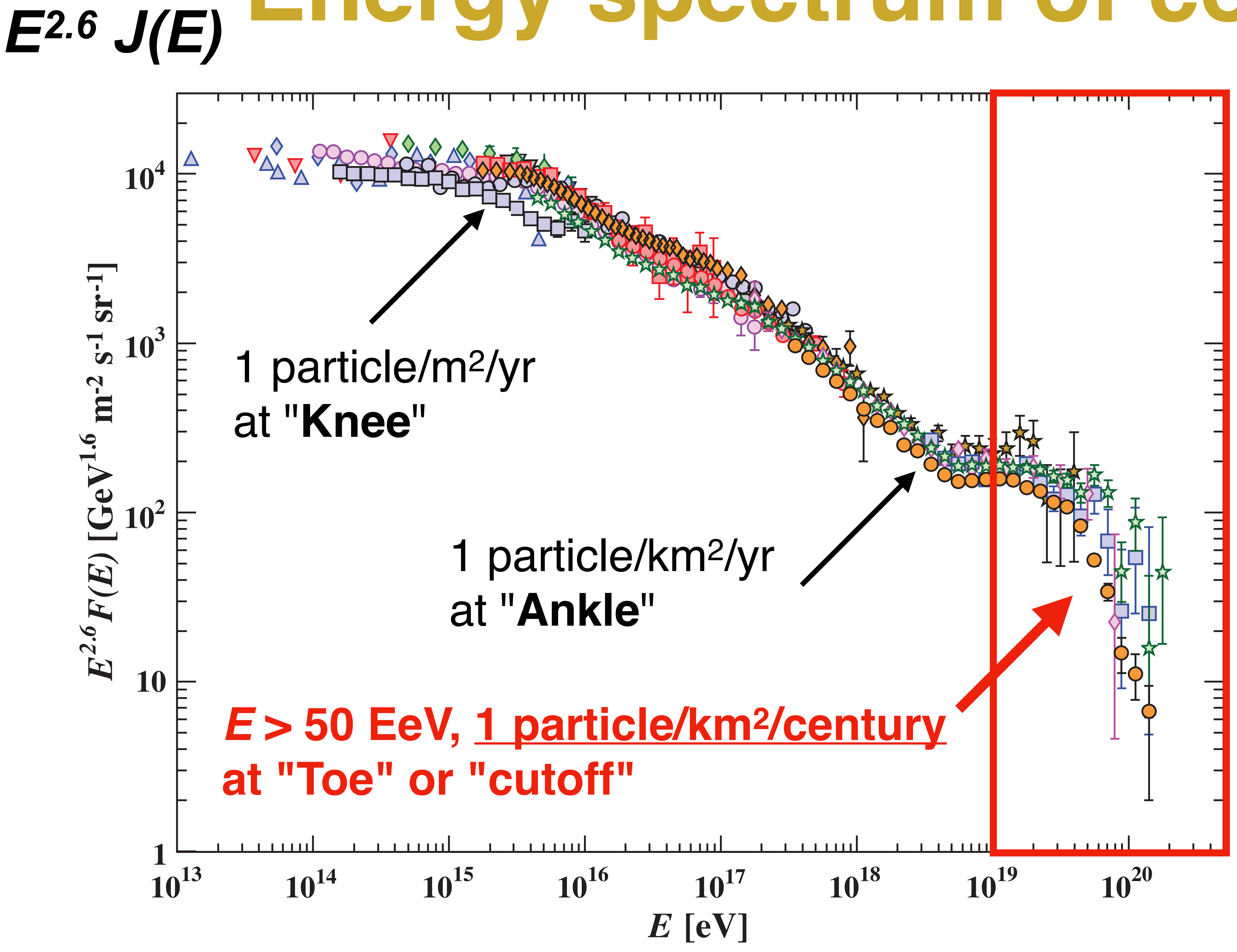


W. Kolhörster, Phys. Z. 14, 1153 (1913)

9300 m

Composition of cosmic rays

Energy spectrum of cosmic rays



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

- Measurements of cosmic rays from **10^9 eV** to **10^{20} eV**
  - **Origins 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 in decades

Less deflections in Galactic magnetic field (GMF)

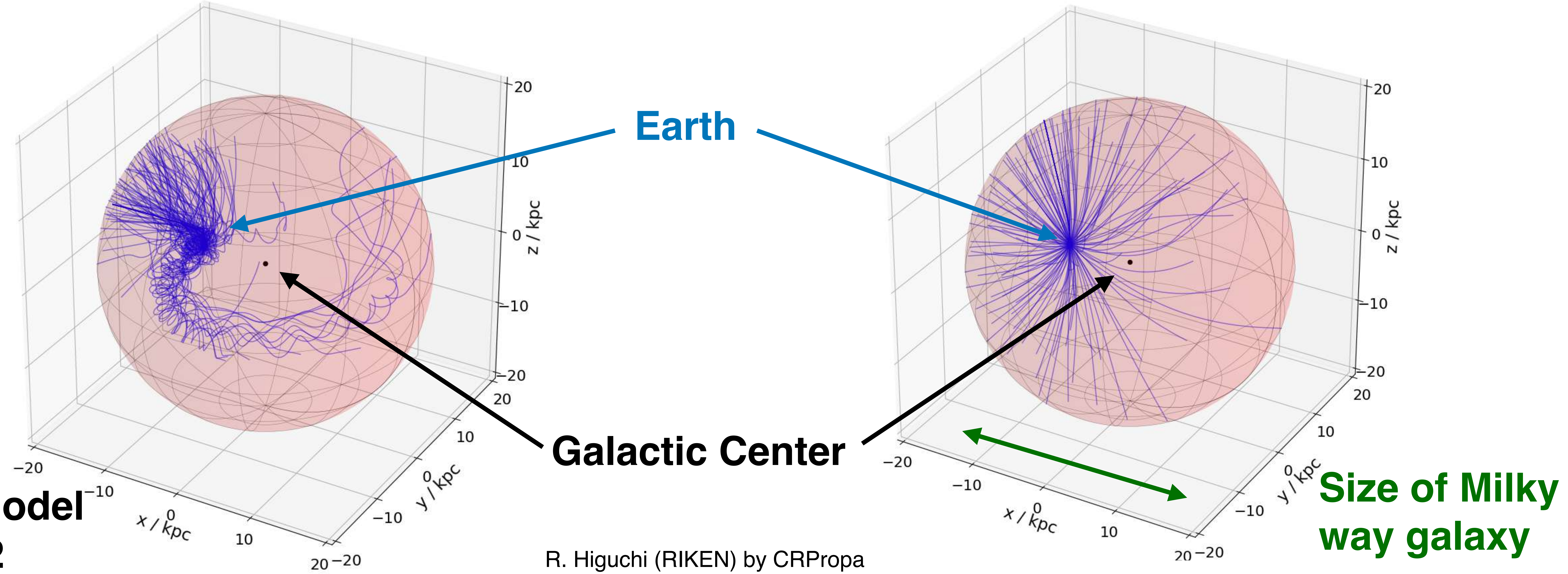
Deflection angle in Milky Way $\theta \sim 10^\circ Z \left(\frac{E}{10\,\mathrm{EeV}}\right)^{-1}$

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

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

1 EeV proton = O(8 EeV), Fe(26 EeV)

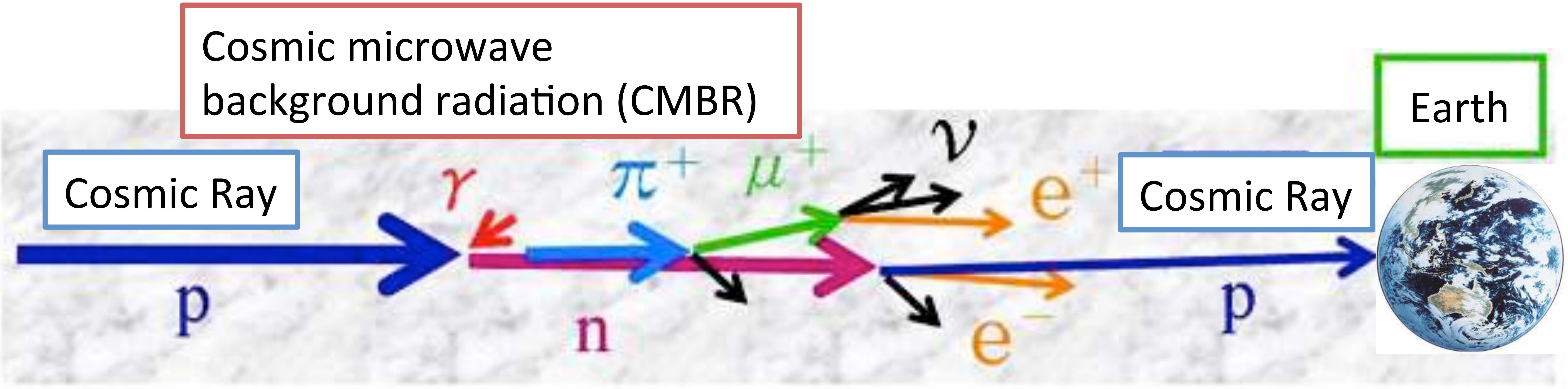
10 EeV proton = O(80 EeV), Fe(260 EeV)



GMF Model JF2012

R. Higuchi (RIKEN) by CRPropa

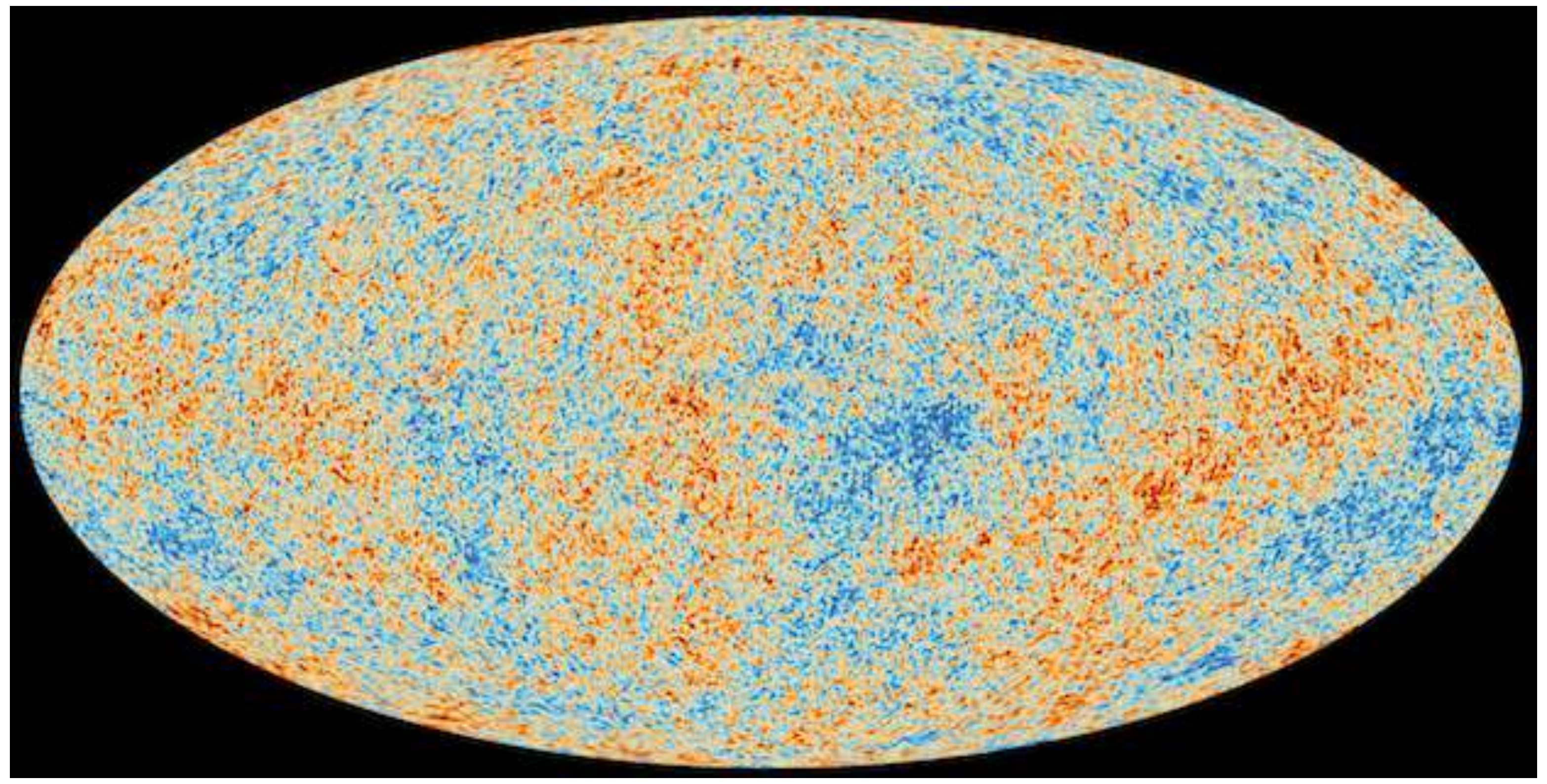
Greisen–Zatsepin–Kuzmin (GZK) Cutoff



- Interaction between >50 EeV proton and cosmic microwave background (CMB) via pion production
  - Heaver nuclei also interact via photo-disintegration
    - Mean free path: 50-100 Mpc (cosmological neighborhood)
  - **Cutoff feature of energy spectrum above 50 EeV**
- **The universe's largest-scale interactions between the <u>most energetic particles</u> and the <u>oldest photons</u>**

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0$$

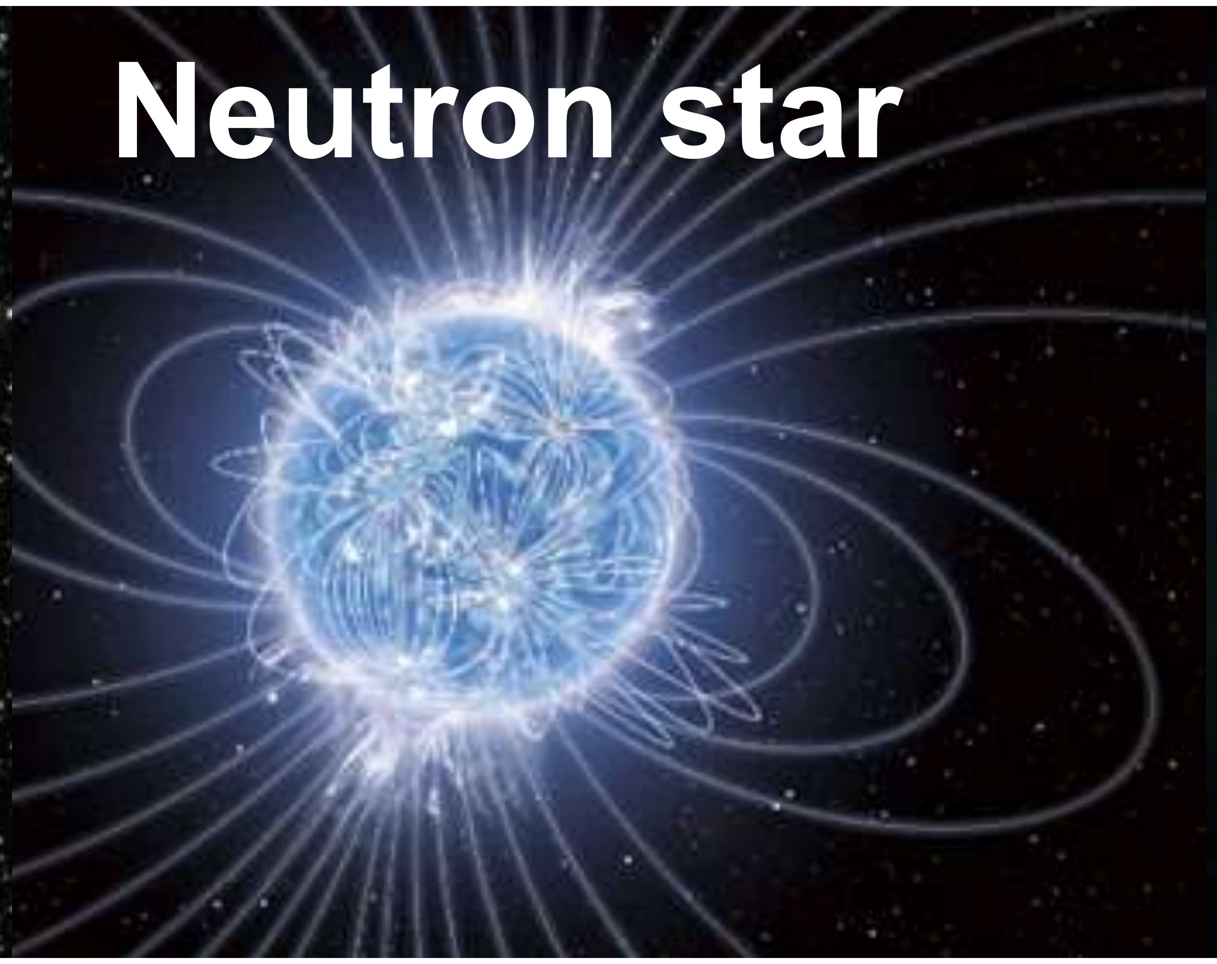
$$^A_Z N + \gamma_{\mathrm{CMB}} \rightarrow {}^{A-1}_{Z-1}N' + p$$



Planck Collaboration

K. Greisen, PRL 16 (17): 748–750. (1966), G.T. Zatsepin and V.A. Kuz'min, JETP Letters. 4: 78–80 (1966)

Source candidates



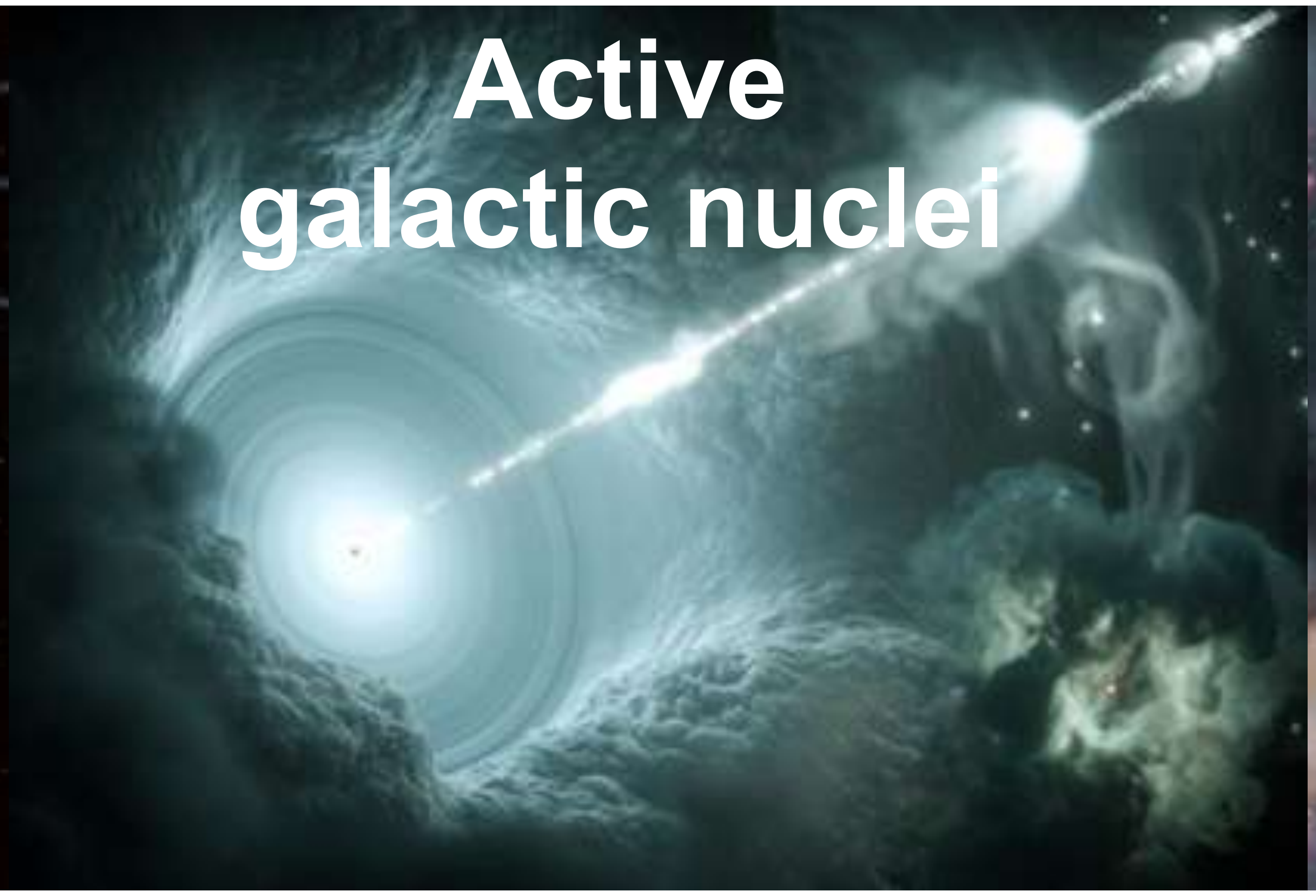
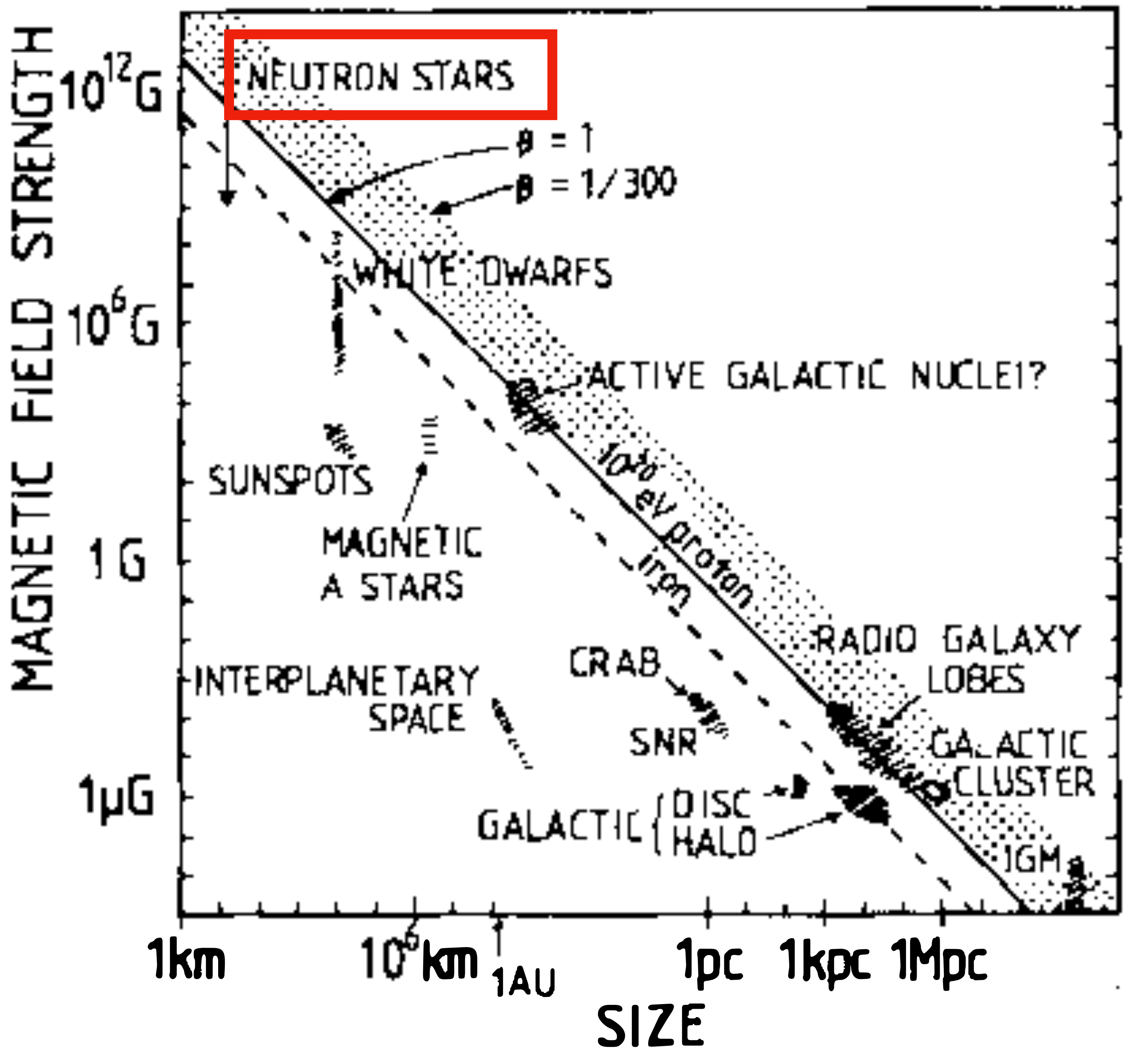


Image credits: Max Plank Inst./RIKEN/DESY/Science Comm

... or "New physics"



A. M. Hillas, Astron. Astrophys., 22, 425 (1984)

$$\left(\frac{E_{\rm max}}{100\,{\rm EeV}}\right) \leq Z \left(\frac{B}{10\,\mu{\rm G}}\right)\left(\frac{R}{10\,{\rm kpc}}\right)$$

Hillas condition

- **Limitation of nearby sources** due to GZK cutoff
- **Less deflections** of Galactic/extragalactic magnetic fields
  - Directionally correlations between **UHECRs** and nearby **inhomogeneous sources** to identify their origins
- **A next-generation "astronomy" using charged particles**


Centaurus A
M82
Neutron star
Next-generation astronomy using ultrahigh-energy cosmic rays (UHECRs)
Low energy cosmic rays
M87
© Osaka Metropolitan University/Kyoto University/Ryuunosuke Takeshige


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
Neutrinos
Galactic
TXS 0506+056
best-fit direction
IC170922A 50%
IC170922A 90%
Declination
Right Ascension
Fermi-LAT Counts/Pixel
IceCube Collaboration
Galactic Coordinates
S.G.P.
G.C.
UHECR?
Pierre Auger and Telescope Array Collaborations


UHECR is the "latest" messenger
(time-delayed and brand-new)
© Ryuunosuke Takeshige and Toshihiro Fujii (Kyoto University)

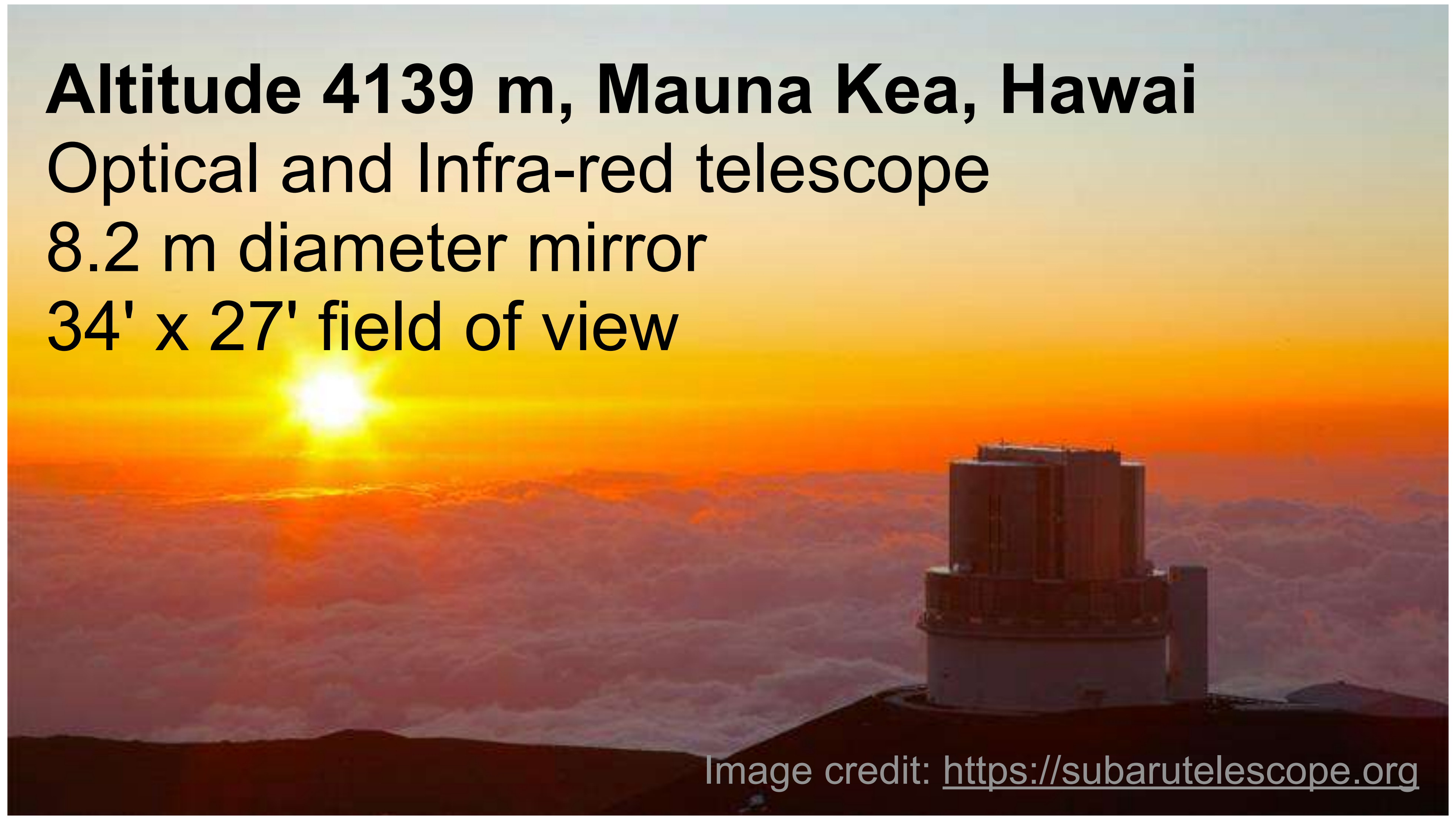
How to detect extremely infrequent UHECRs?

→ **Extensive air showers**

"Seeing" the extensive air showers by Subaru HSC

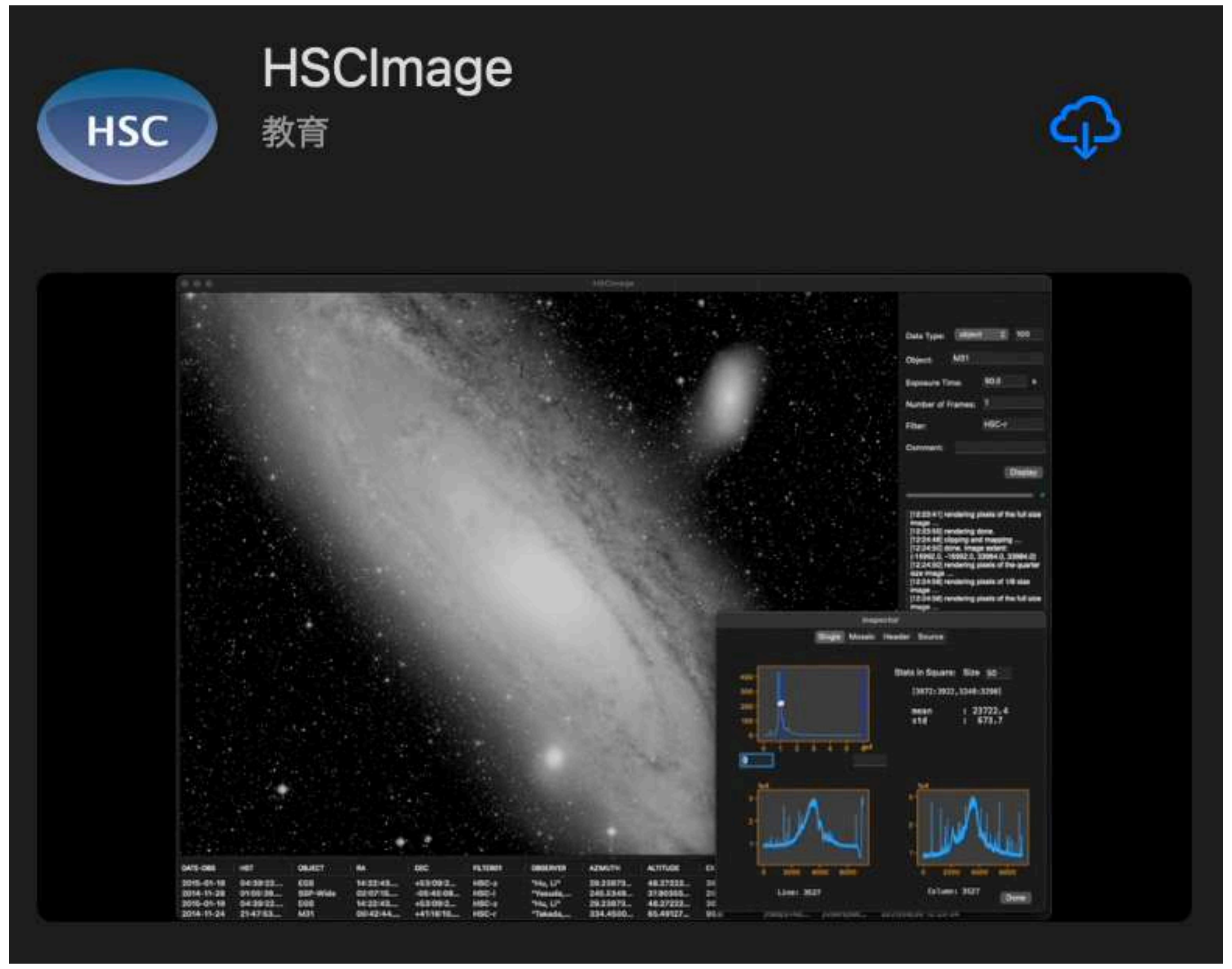
S. Kawanomoto, TF et al., Scientific Reports 13:16091 (2023)

"Direct" detection of Subaru HSC CCDs

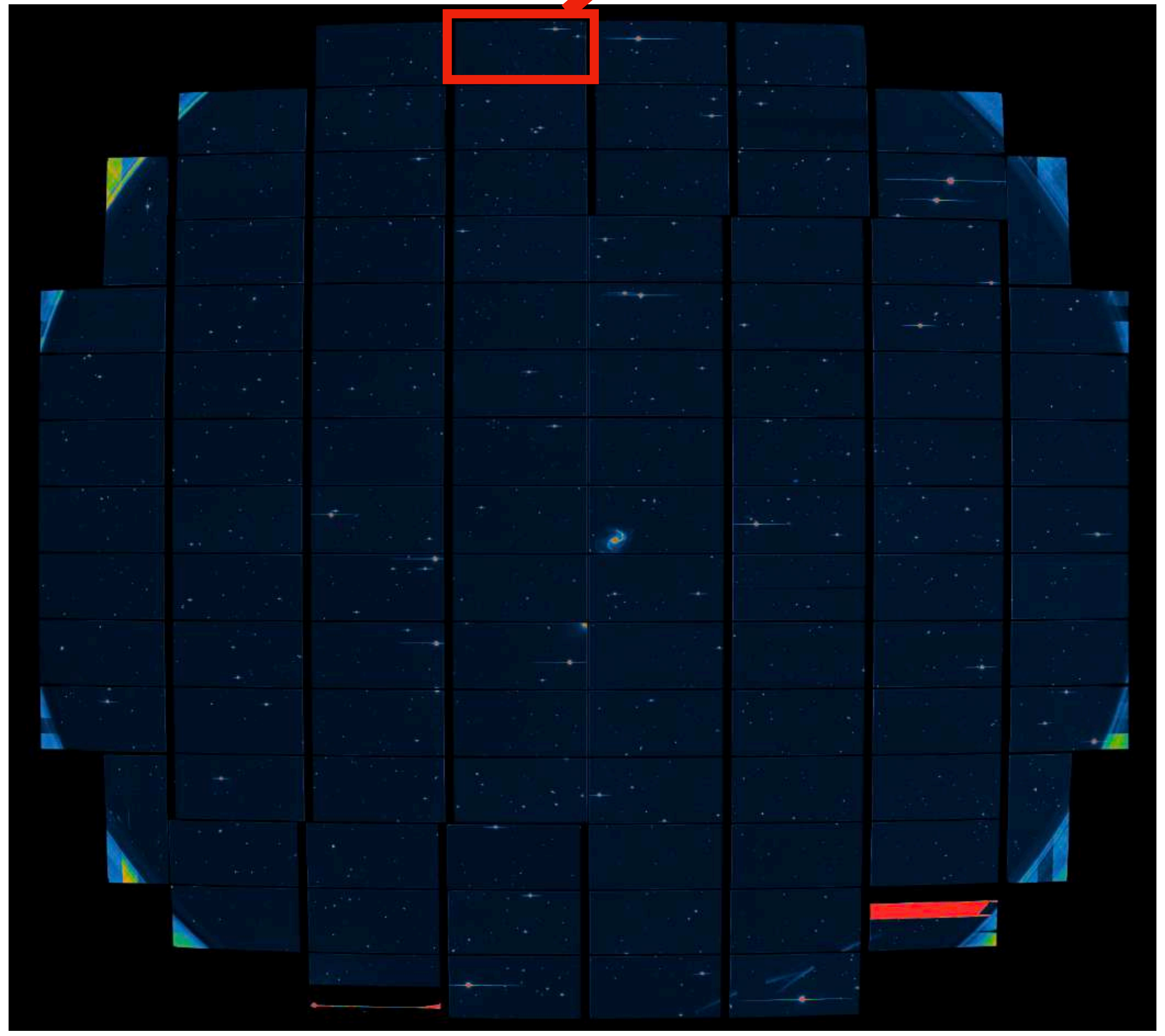


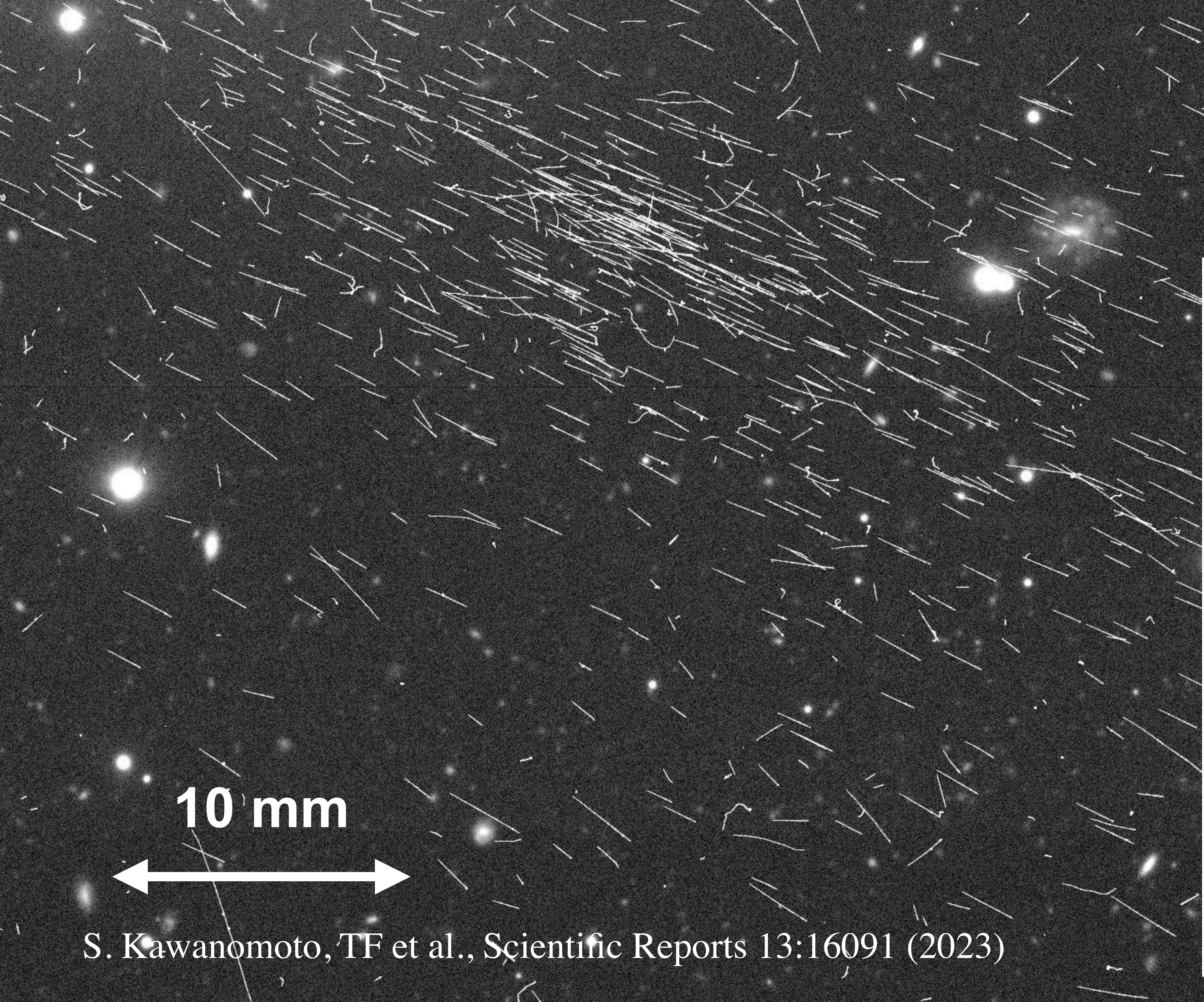
CCD size
30 mm x 60 mm
0.2 mm thickness
150 sec. exposure

116 CCDs



App Store (Mac)



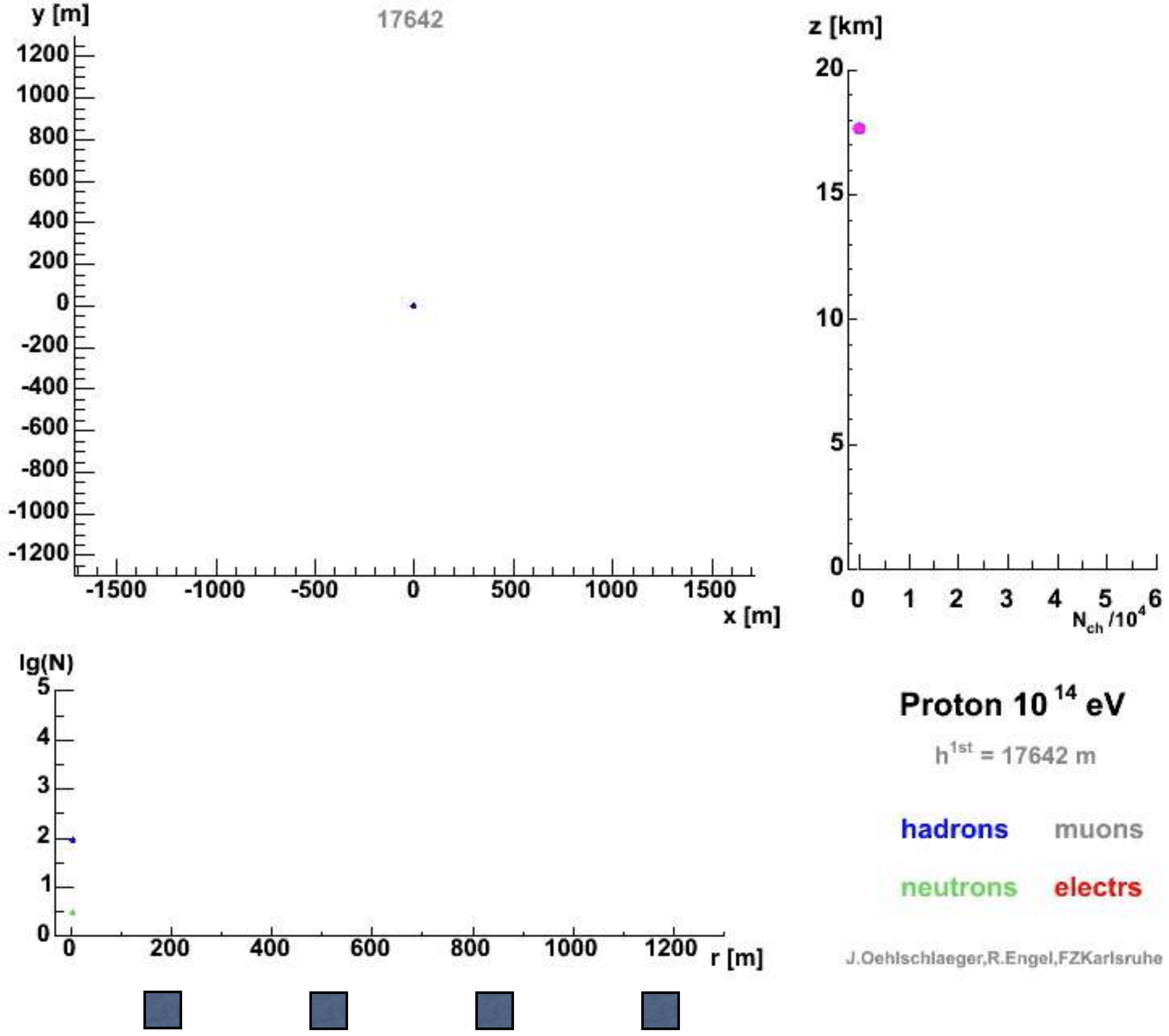

10 mm
S. Kawanomoto, TF et al., Scientific Reports 13:16091 (2023)

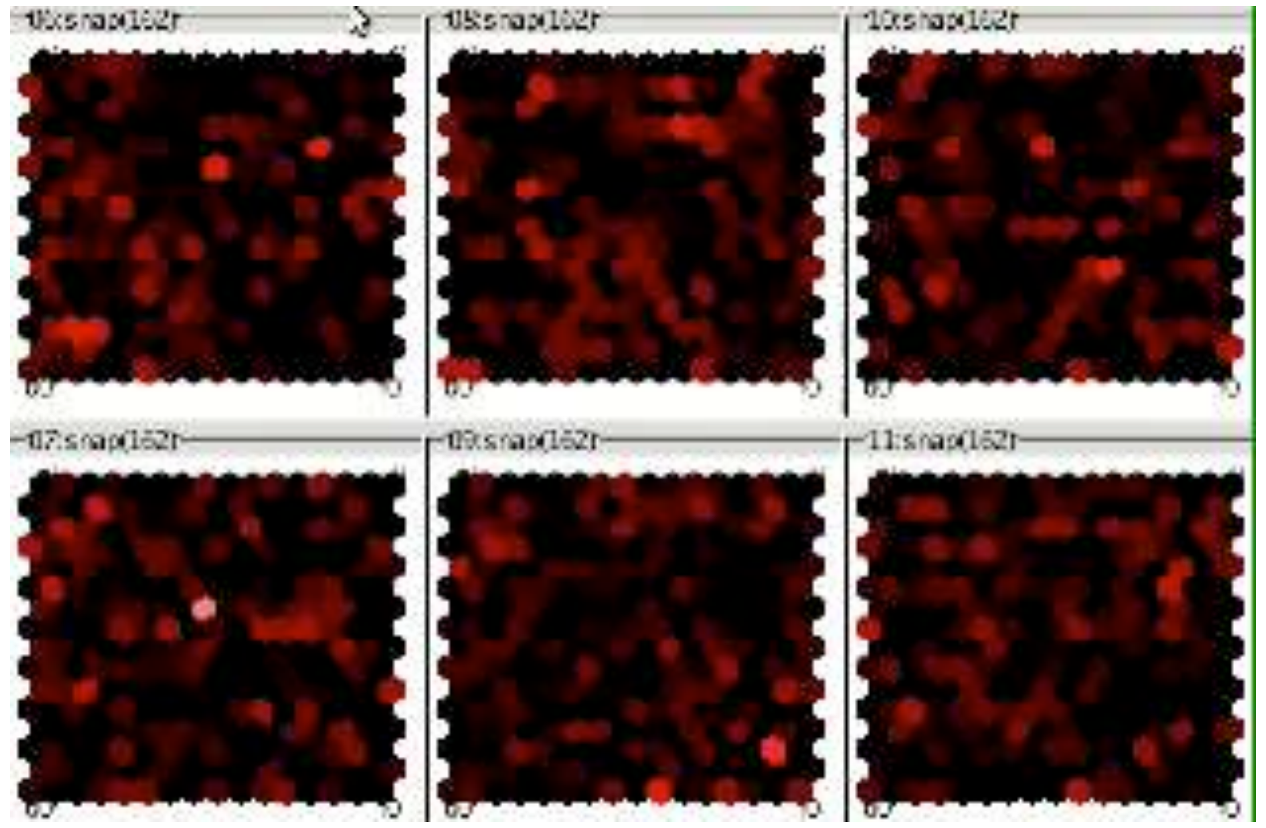

Dark Energy Survey
https://www.darkenergysurvey.org/

How to detect extremely infrequent UHECRs?

Observing extensive air showers and mass composition

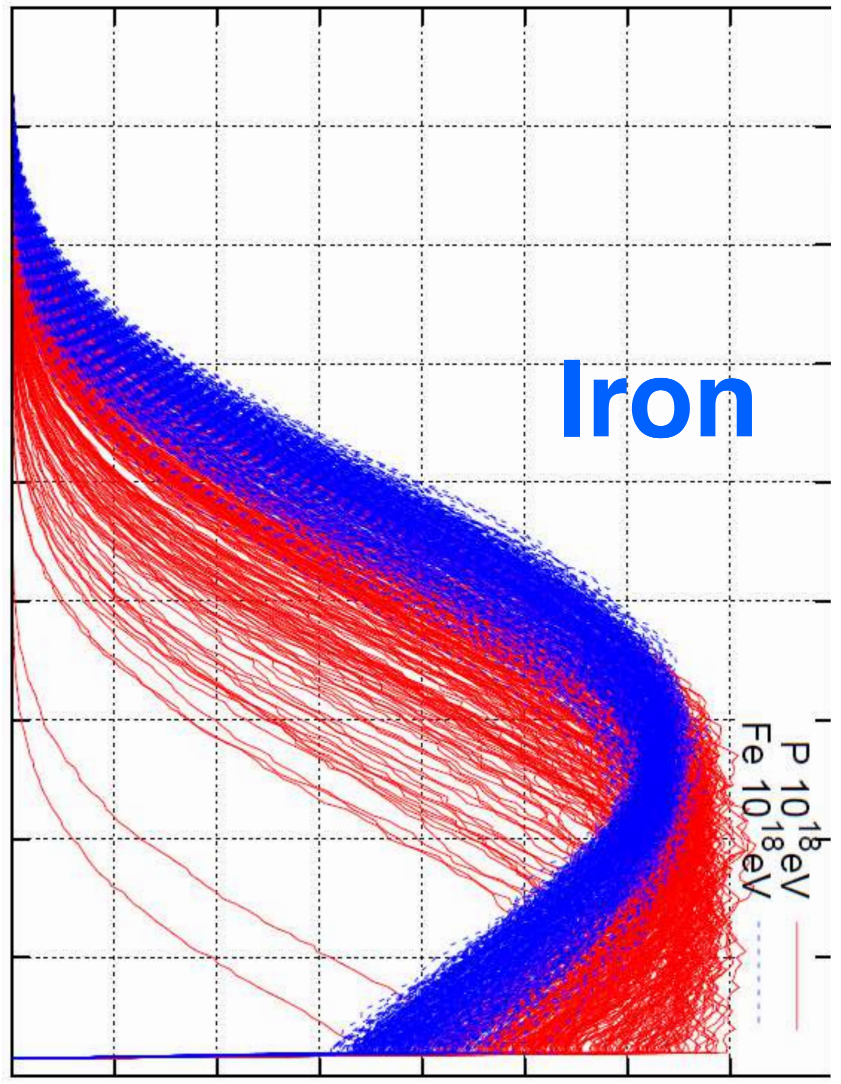
Fluorescence detector (FD)

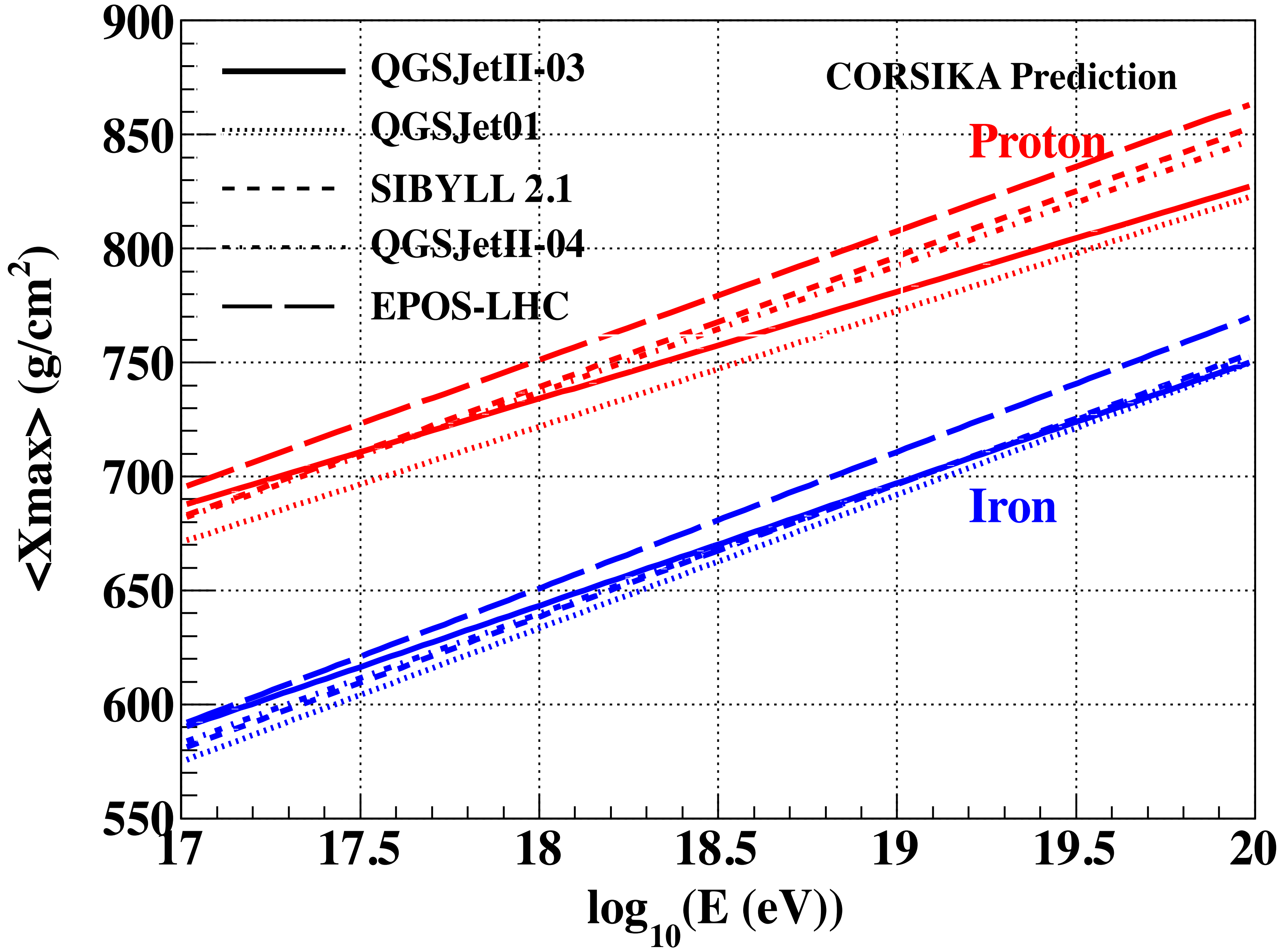




X_{max} measurements for **mass composition (Z)**

$$X_{max}^{A} \propto \ln \frac{E_0}{A}$$



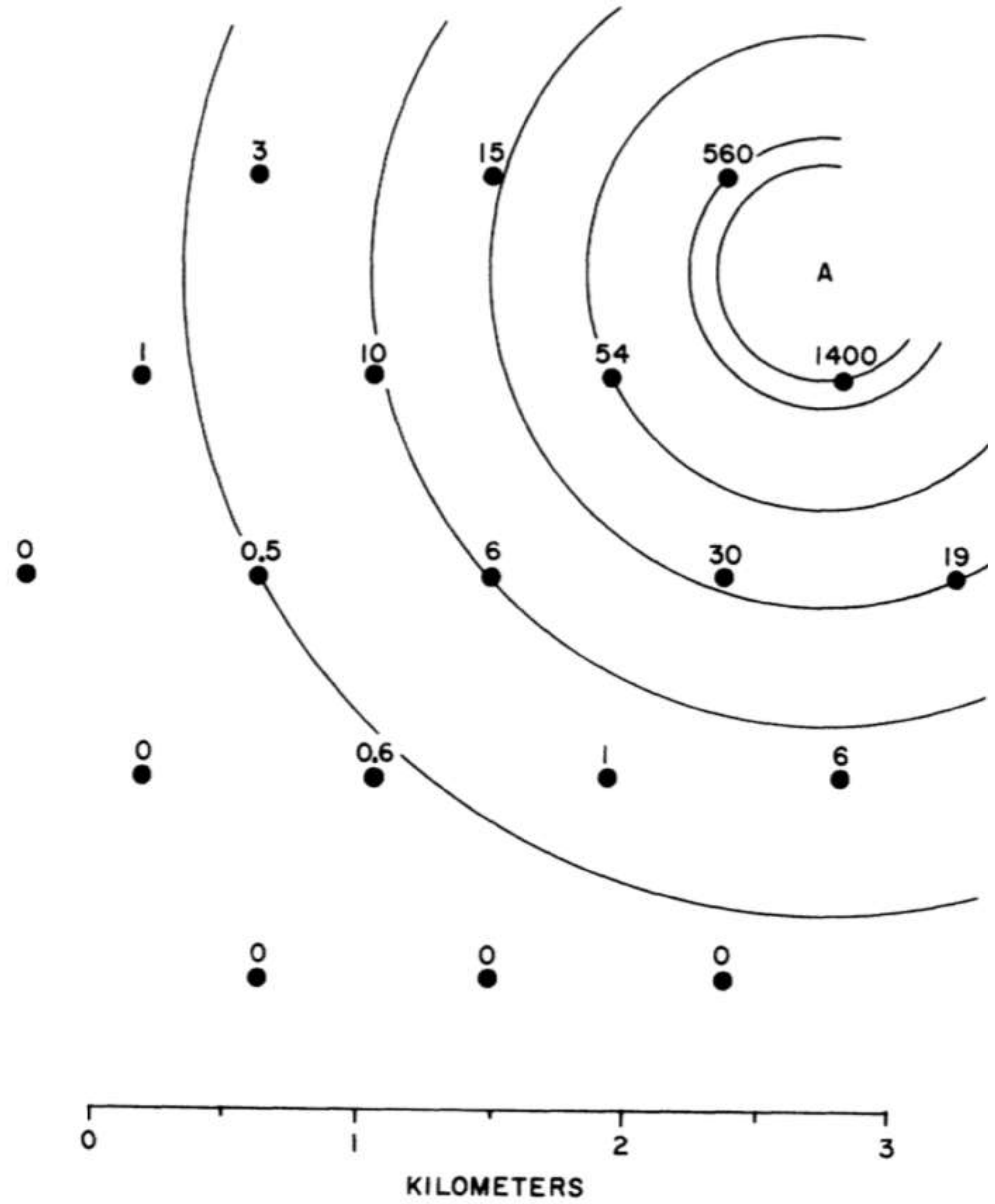


Surface detector array (SD)

CORSIKA webpage https://web.ikp.kit.edu/corsika/movies

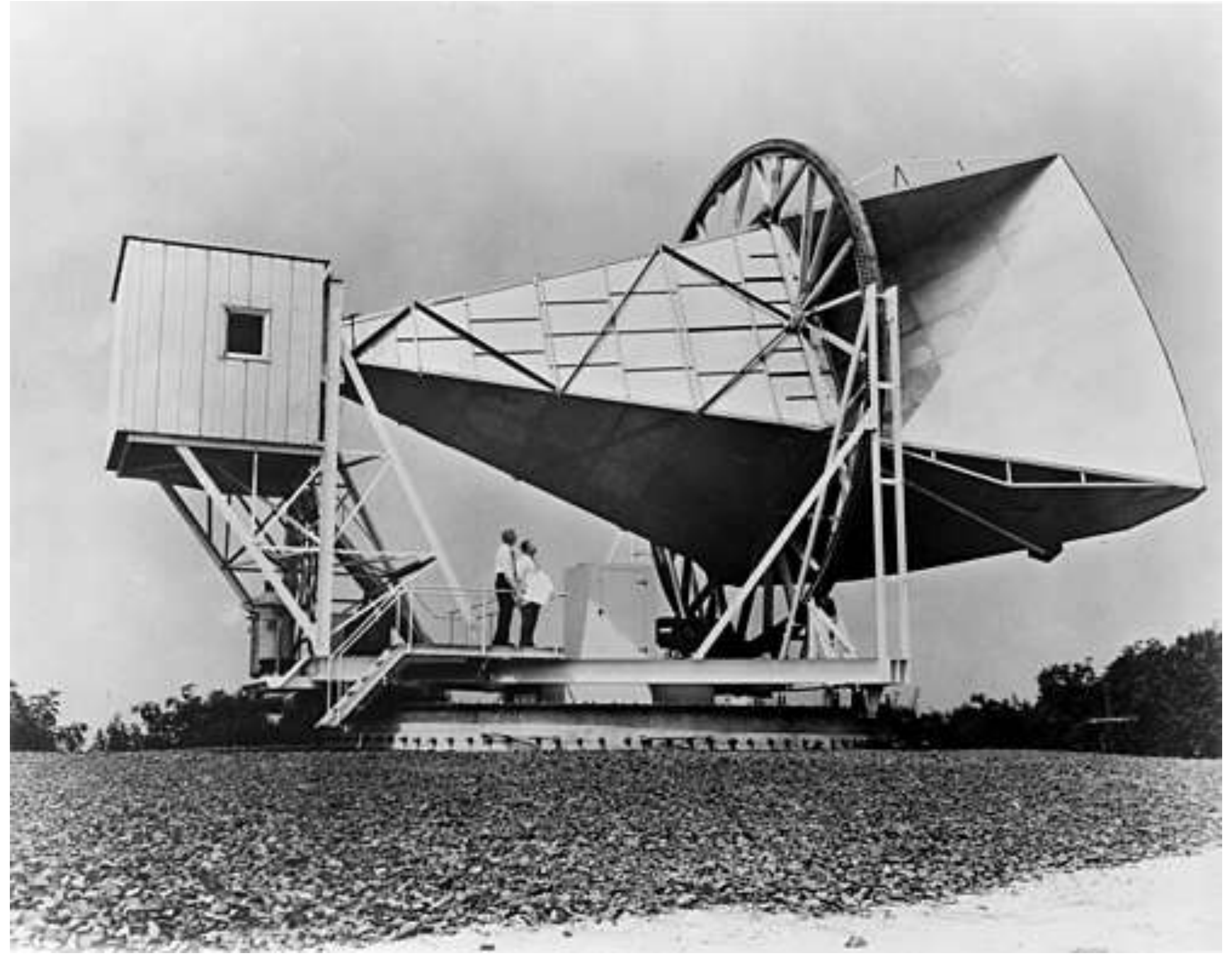
The beginning of 100 EeV (10^{20} eV) detection

First detection of 100 EeV at Volcano Ranch Array in 1963



J. Linsley, "Evidence for a Primary Cosmic-Ray Particle with Energy 10^{20} eV". *Phys. Rev. Lett.* 10 (4 Feb. 1963), 146–148

2.7K cosmic microwave backgrounds (CMB) by Penzias and Wilson in 1965



From wikipedia

A.A. Penzias and R.W. Wilson, "A Measurement of Excess Antenna Temperature at 4080 Mc/s", *Astrophys. J. Lett*. 142: 419–421 (1965)

Prediction of Greisen, Zatsepin and Kuzmin (GZK) Cutoff in 1966

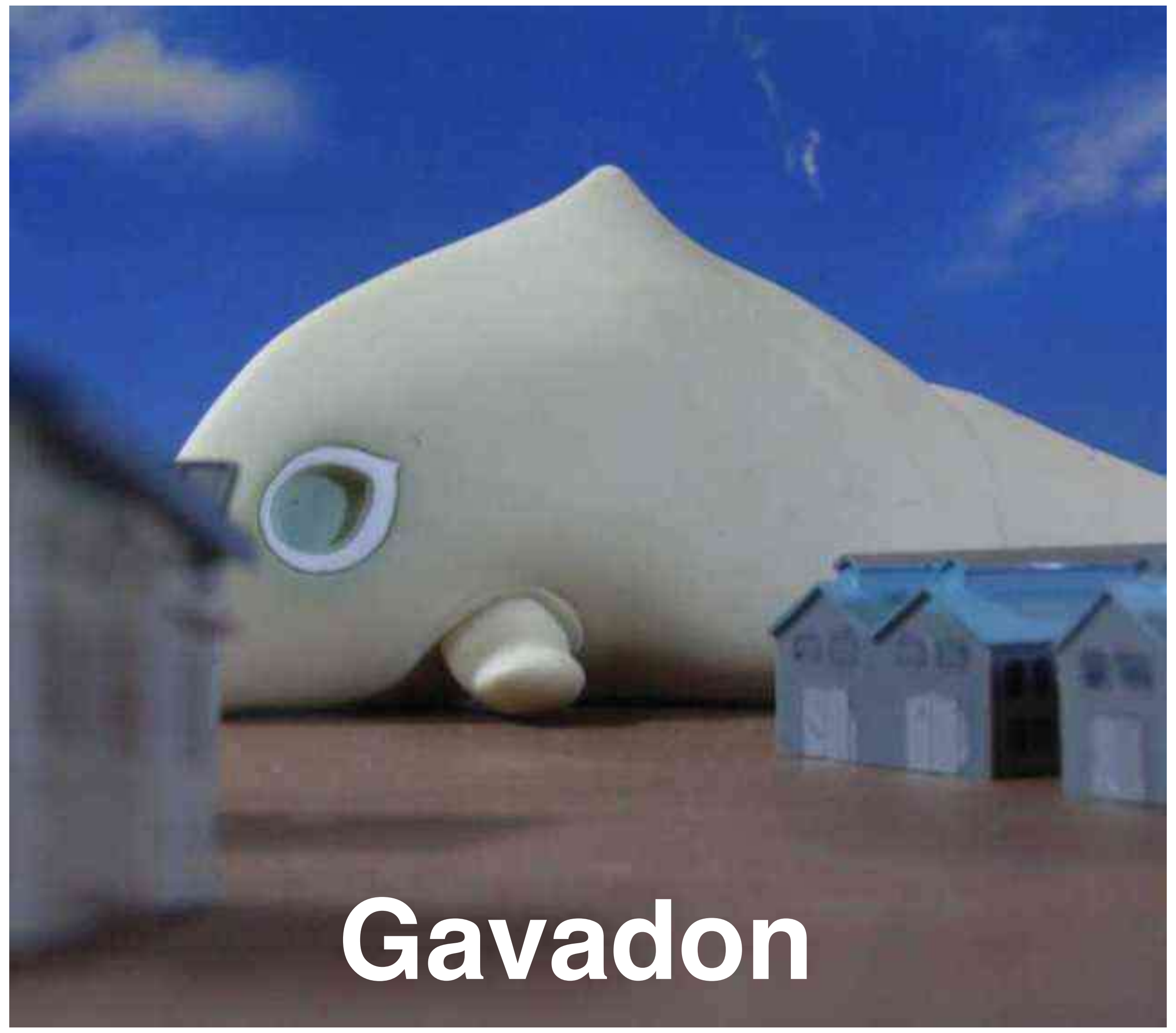
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0$$

K. Greisen, "End to the cosmic ray spectrum?" *Phys. Rev. Lett.* 16 (1966), 748–750

G.T. Zatsepin and V.A. Kuzmin, "Upper limit of the spectrum of cosmic rays". *JETP Lett.* 4 (1966), 78–80

Gavadon appeared in Ultraman (1966)

Ultraman (1966)
"*Feared* cosmic rays"



Remake version of
Ultraman blazar (2023)

第15話
朝と夜の間に

2023/10/21 放送

ゲントの息子ジュンには、一風変わったクラスメイト・アラタがいる。ある日アラタの秘密基地に連れられていったジュンは、アラタが描いた怪獣の絵の熱量と彼の自由さを受け、心を開いていく。ジュンが自主性をもって描いた怪獣はガヴァドンと名付けられた。
夜になり、秘密基地に空から怪光線がふりそそぐと、ガヴァドンの絵が鼓動し始める。

https://m-78.jp/videoworks/ultraman-blazar/

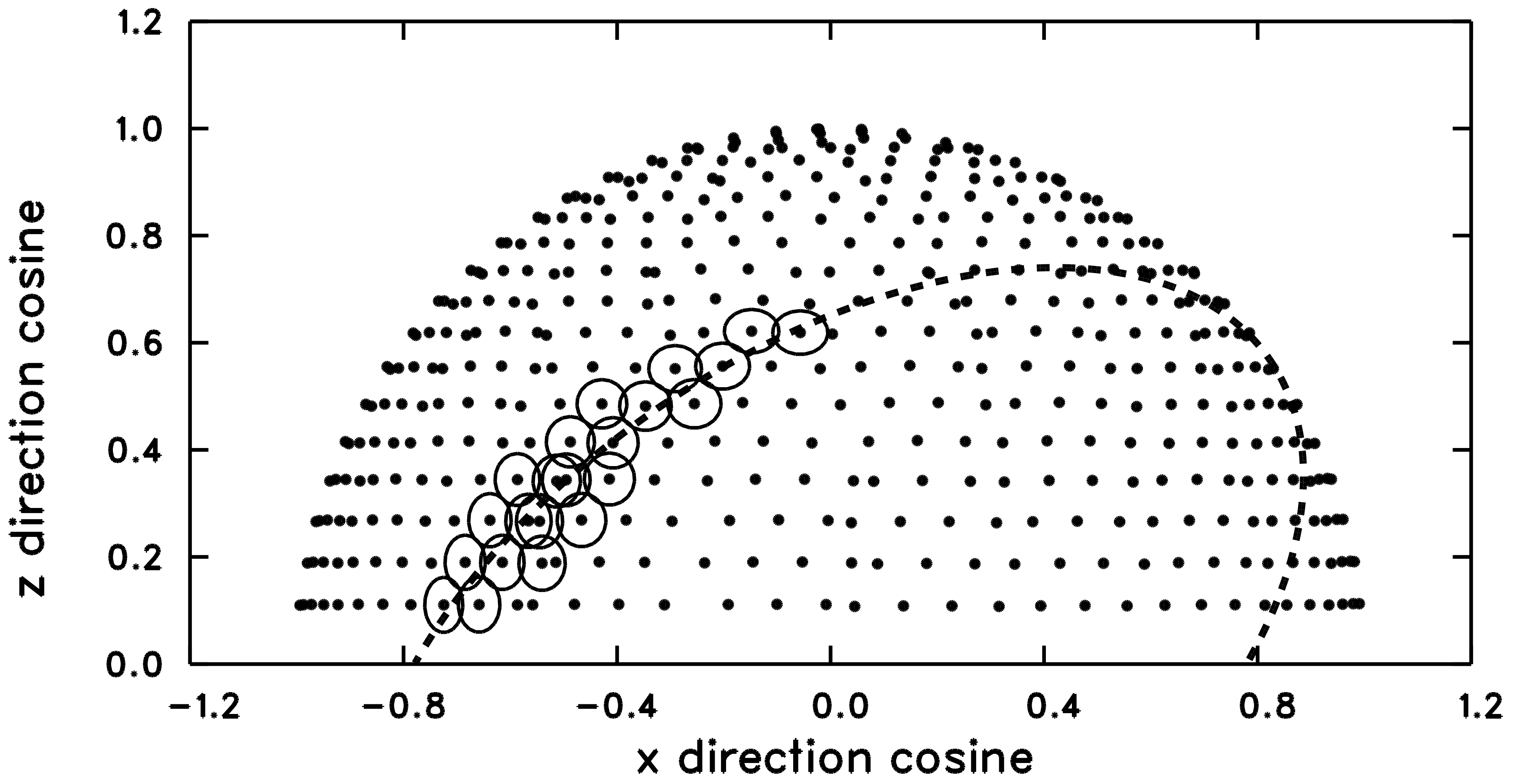
Gavadon in my office

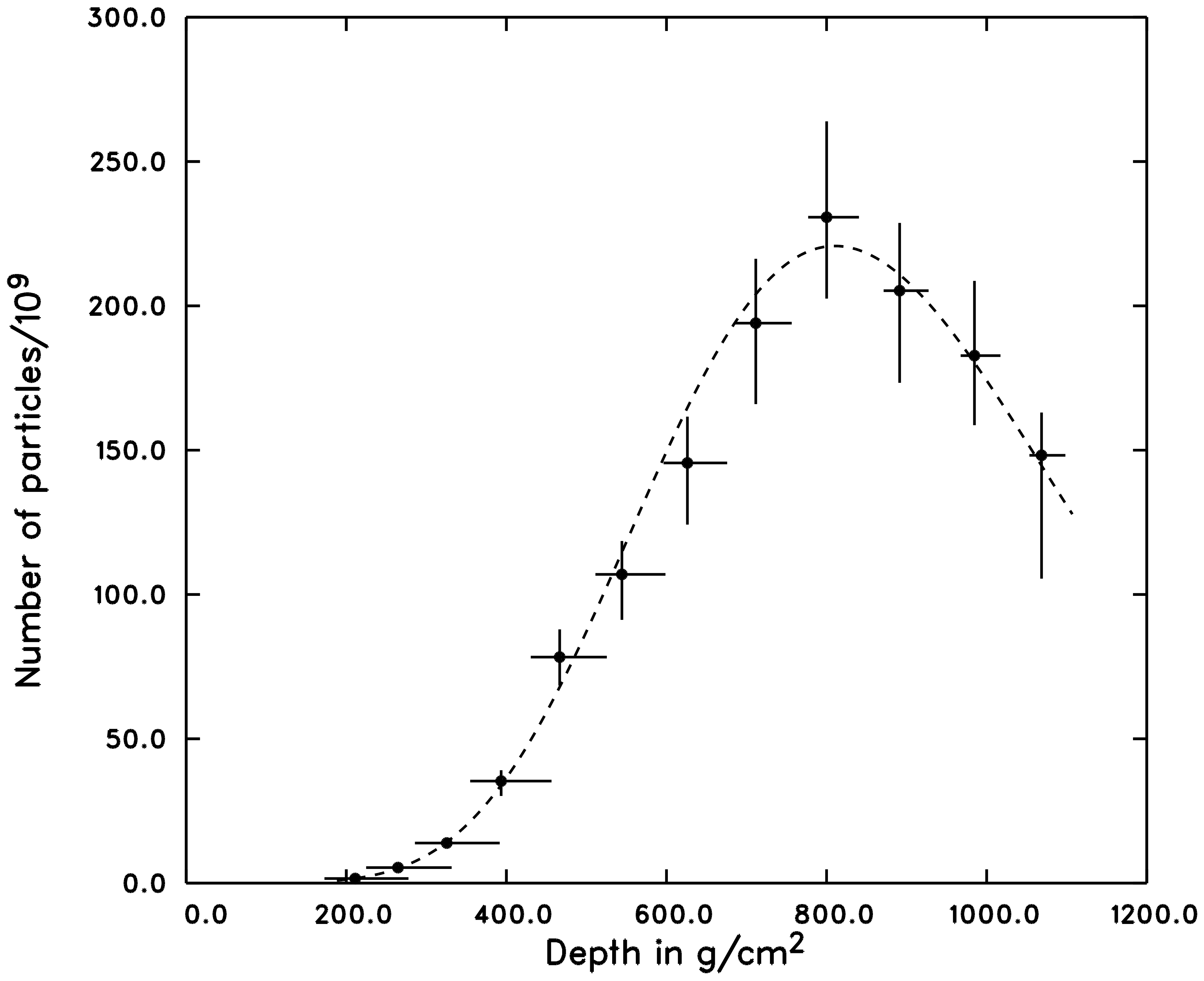
"Oh-My-God" particle by Fly's Eye

Fly's Eye (Utah, USA)
Construction started from 1976, after a confirmation of fluorescence signal at Volcano Ranch Array

Observed X_{max} is consistent with hadron primary, unlikely with gamma-ray

X_{max} = 815 ± 60 g/cm²





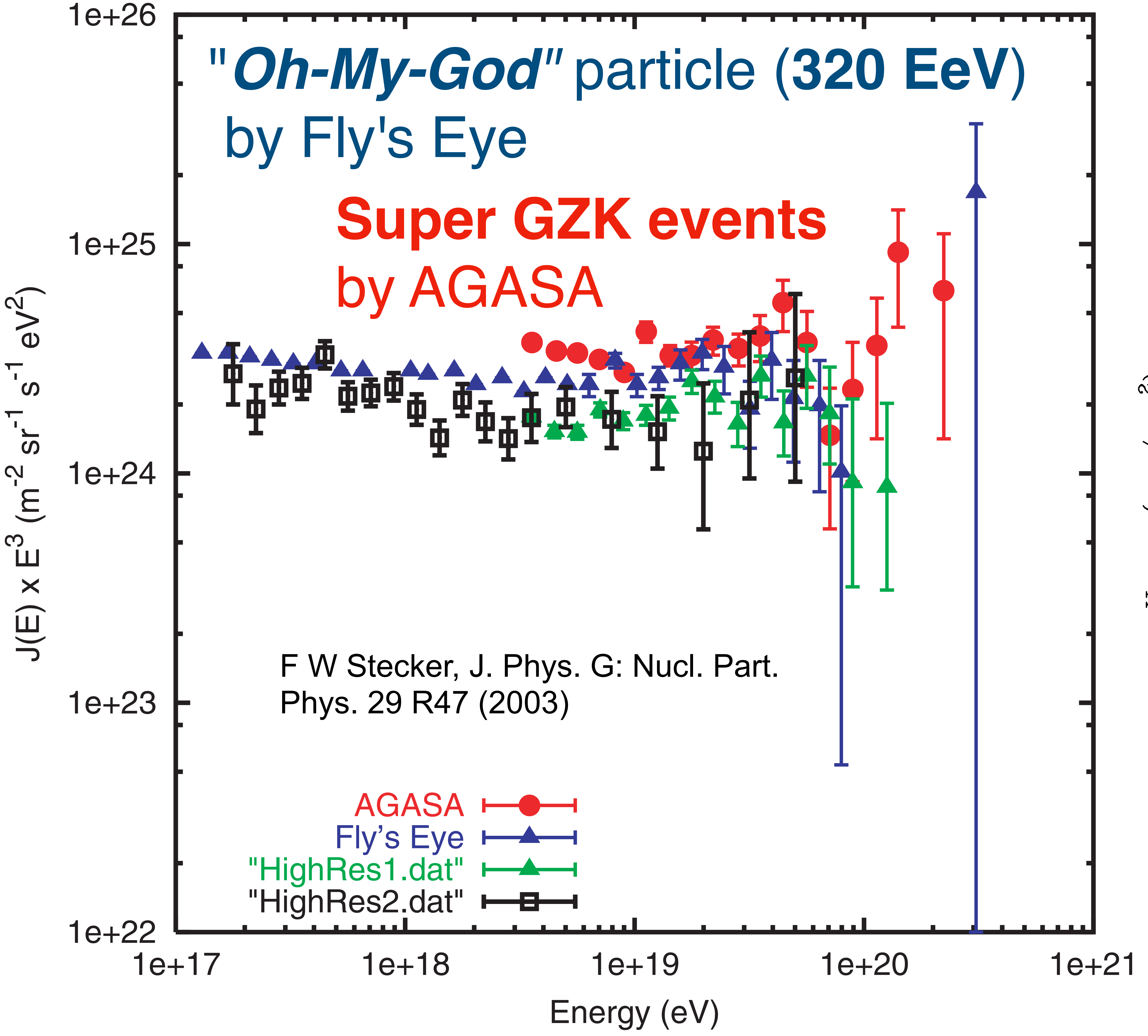
The highest energy cosmic ray on 15th October, 1991, dubbed Oh-My-God particle
320 ± 38 (stat.) ± 85 (syst.) EeV
Start the High Resolution Fly's Eye (HiRes-1) from 1994.

D.J. Bird et al., ApJ 441 (1995) 144

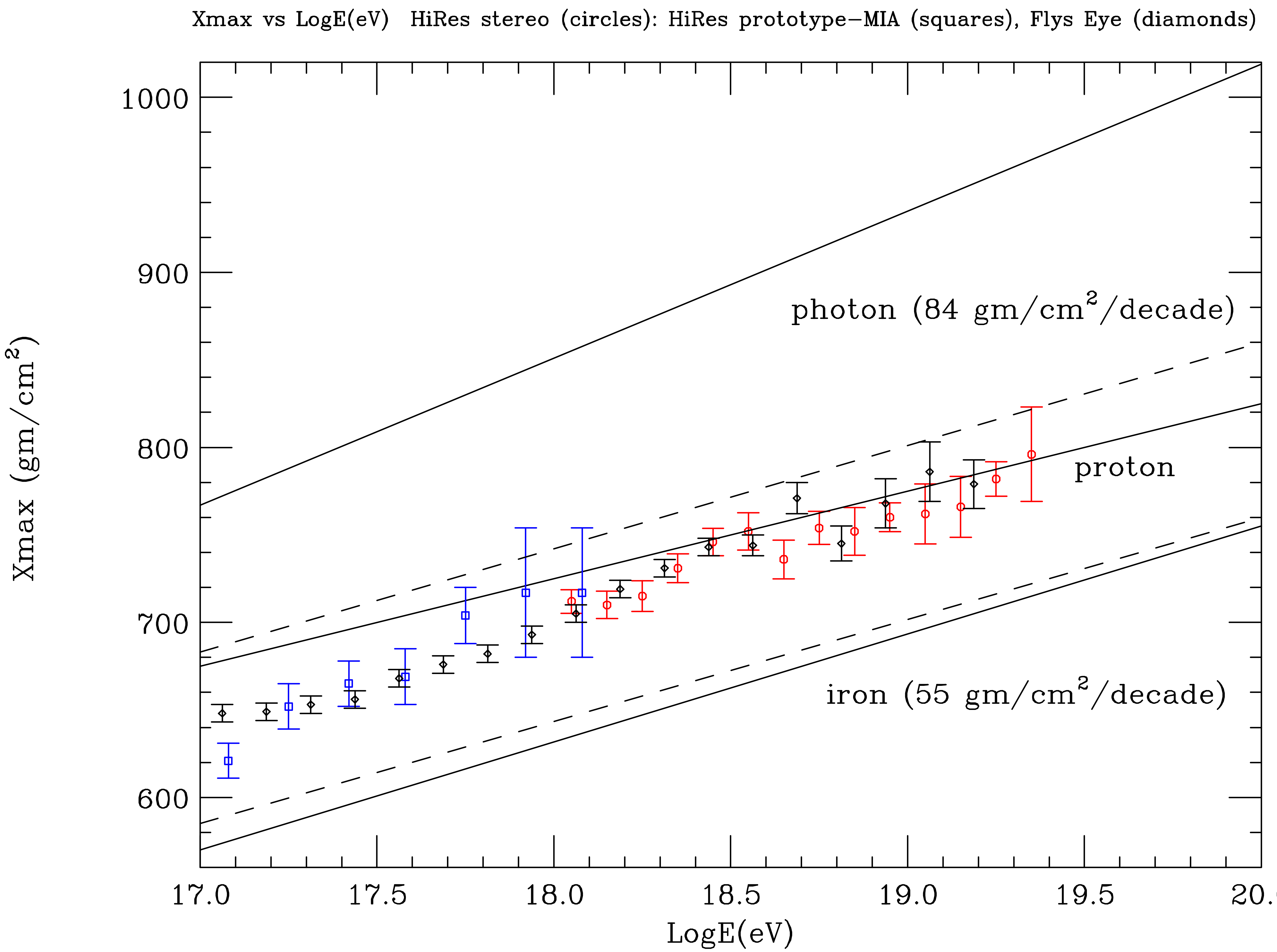
(R.A., Dec.) = (85.2°, 48.0°)

UHECR results 20 years ago

No GZK cutoff in spectrum?



Proton dominated composition at highest energies?



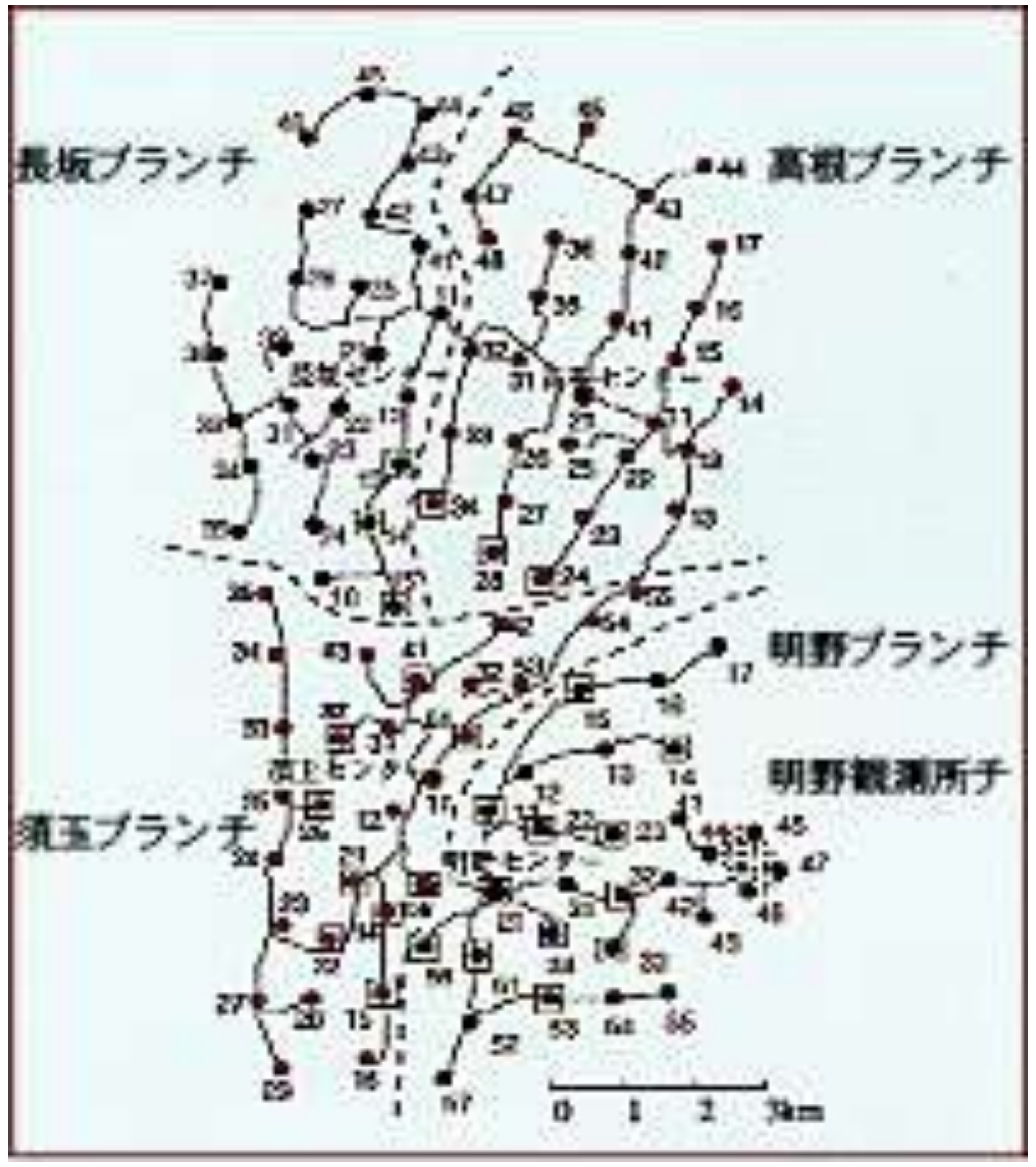
Extremely energetic events by AGASA

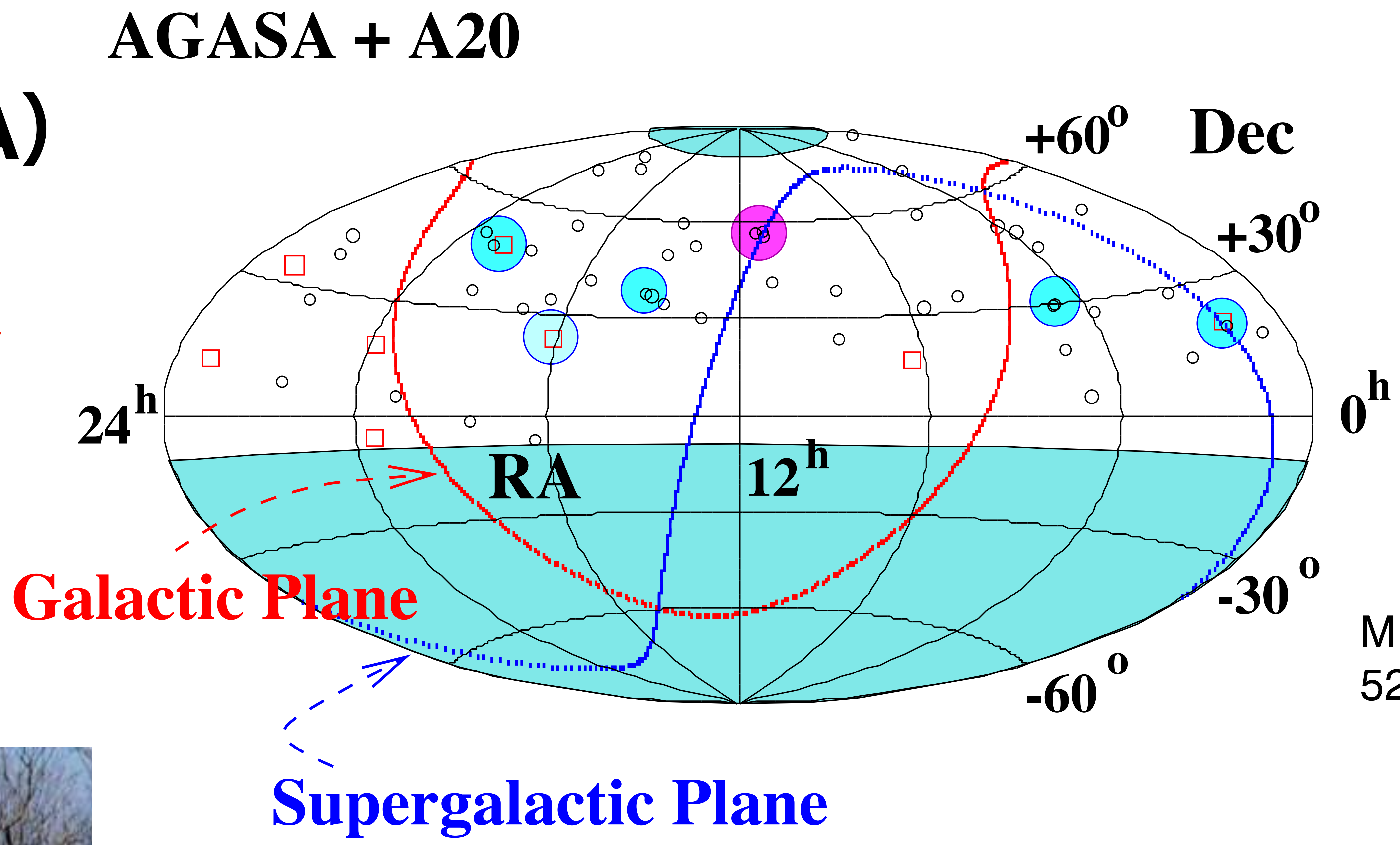
Akeno Giant Air Shower Array（AGASA）

1993~2004, Effective area of **100 km²**

December 3rd 1993, **213 (170 – 260) EeV**

May 10th 2001, **~280 EeV**

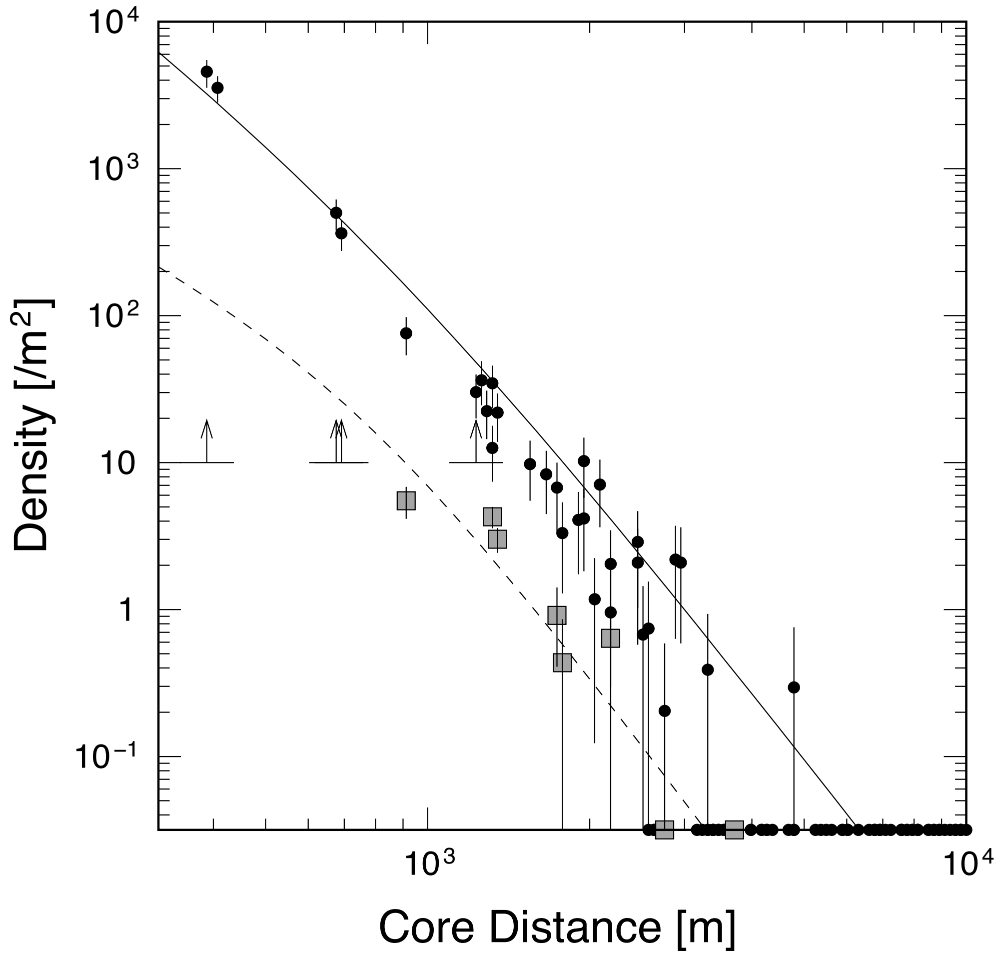


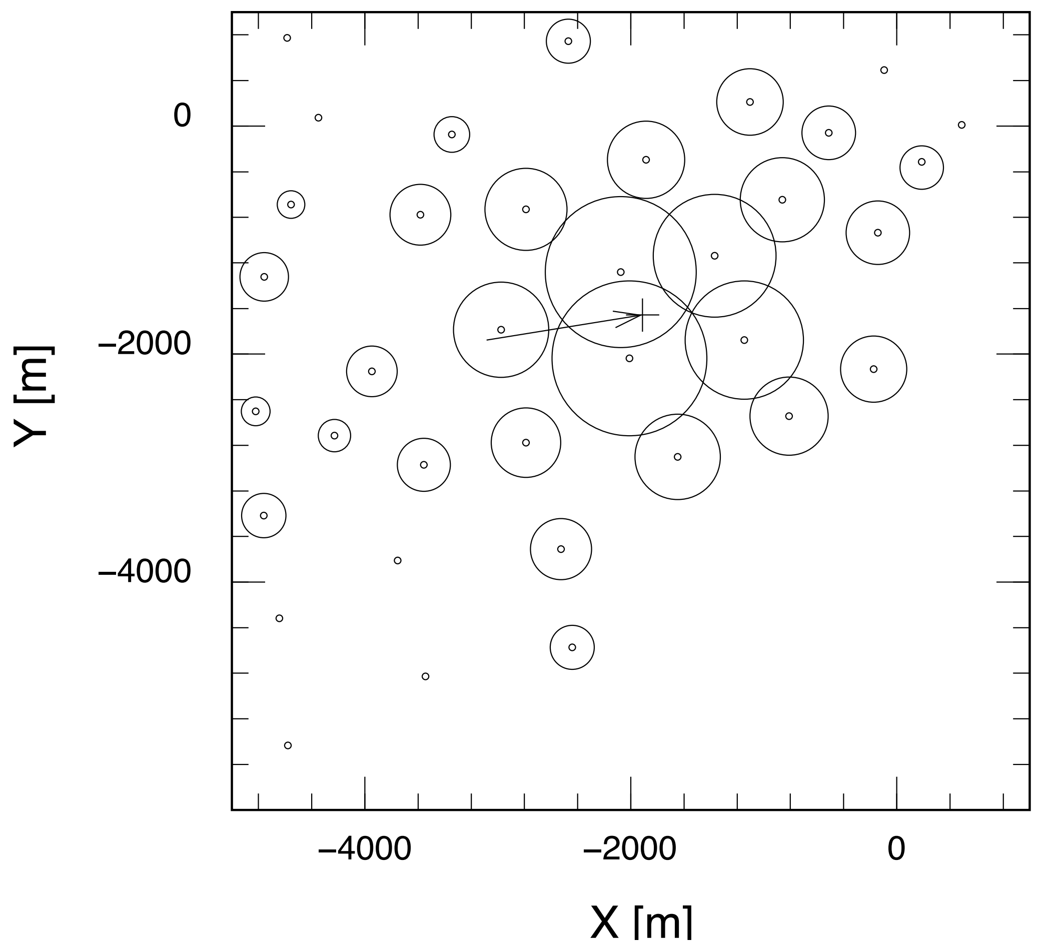


N. Hayashida, et al., Phys. Rev. Lett. 73, 3491 (1994)

M. Takeda et al., ApJ 522, 225 (1999)

N. Sakaki et al., Proceedings of ICRC 2001: 337

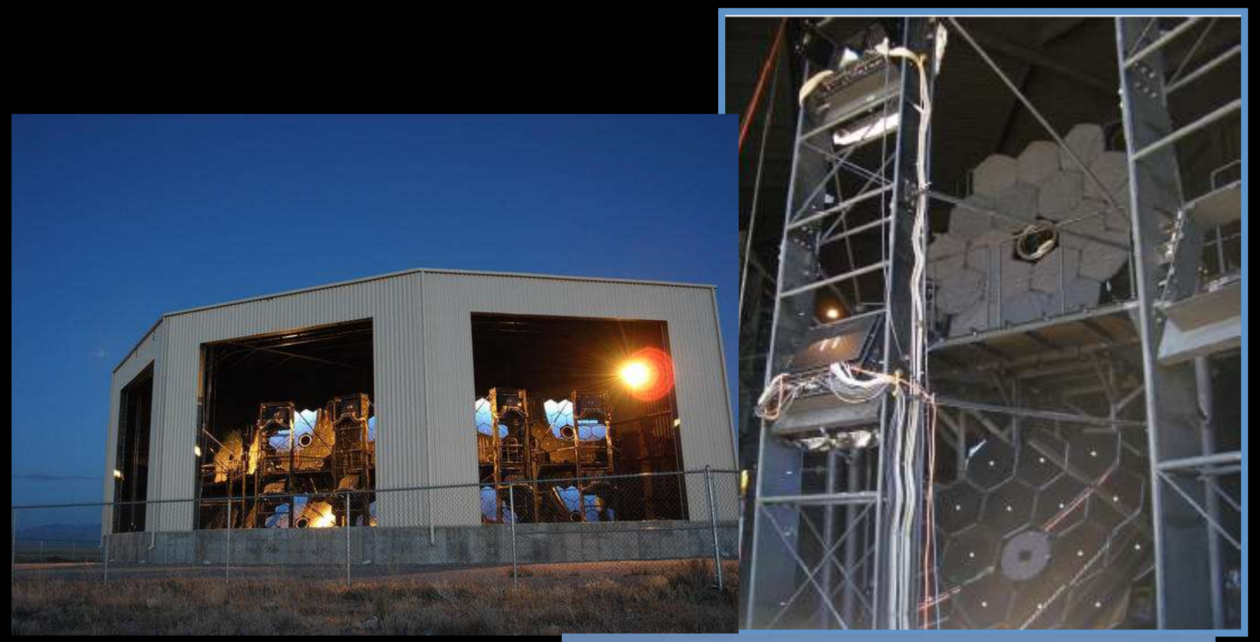




Latest UHECR observatories

Google Earth

- **Telescope Array Experiment (TA)**
  - Utah, USA
  - 2008~, 700 km²
    - **TA×4 → 3000 km²**



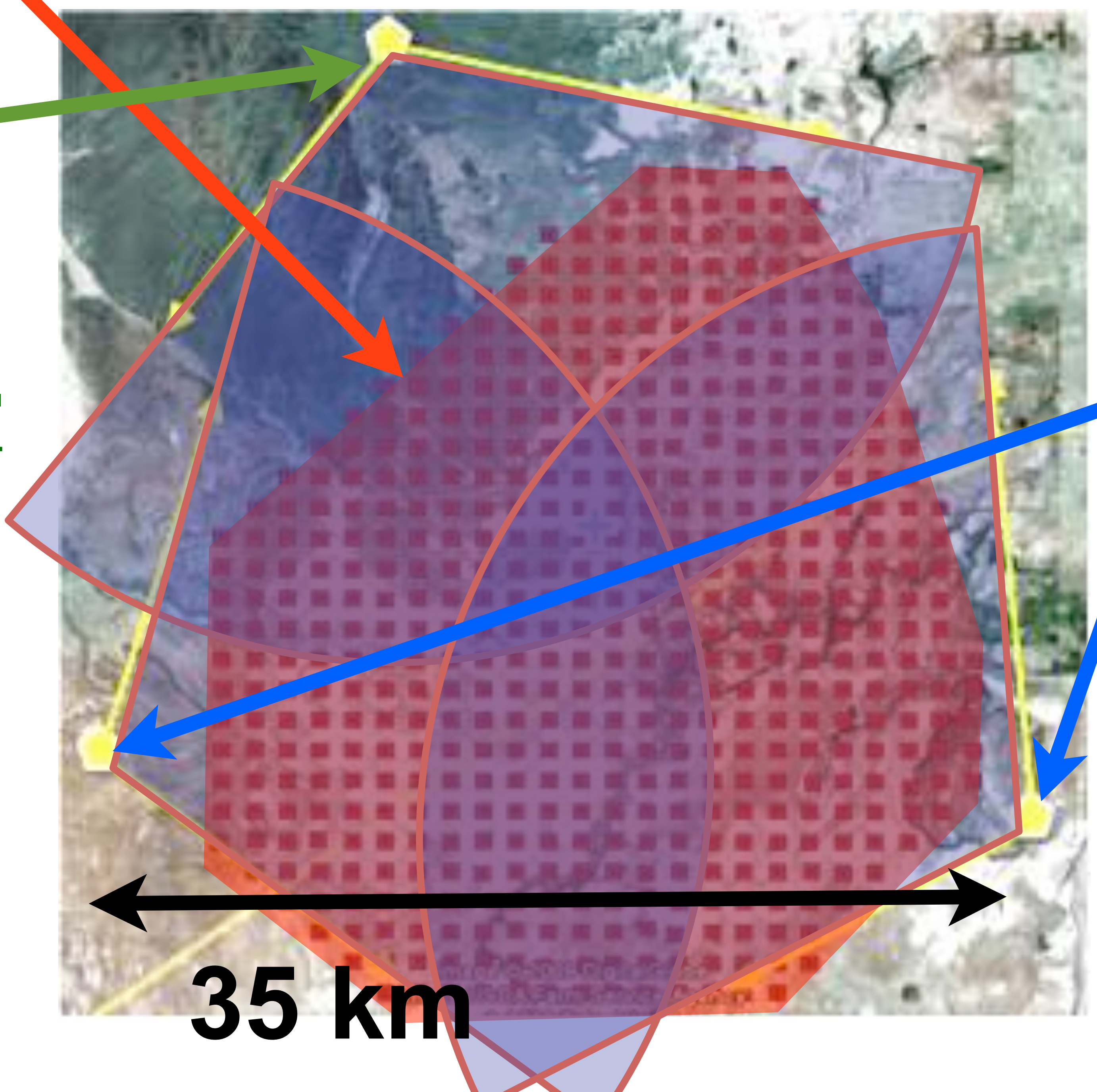
- **Pierre Auger Observatory (Auger)**
  - Malargüe, Argentina
  - 2004~, 3000 km²
    - **AugerPrime** upgrade scintillator + radio + buried muon detector

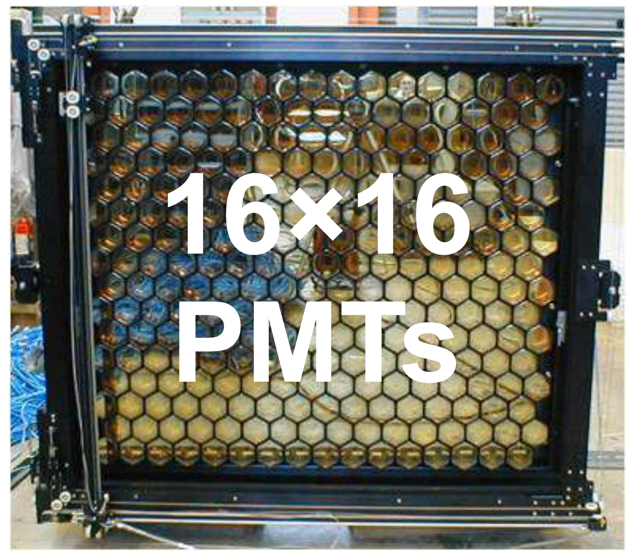
Telescope Array experiment (TA)

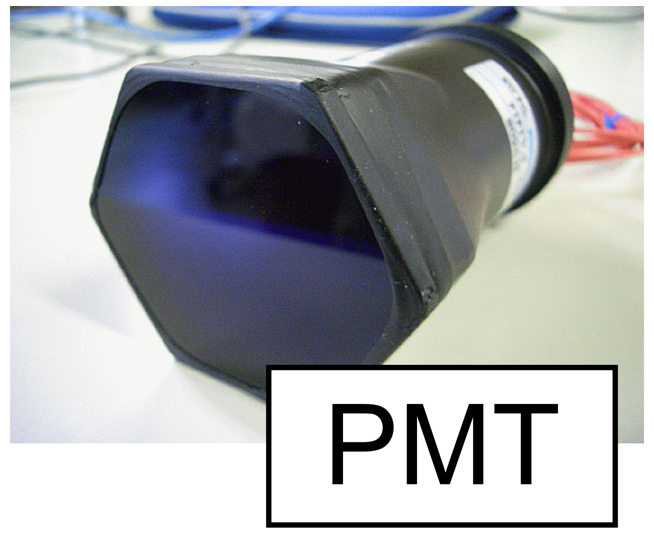
Surface detector array (SD)
507 scintillator, 1.2 km spacing
stand-alone data-taking

Fluorescence detector (FD) at southern stations
Mirror 6.8 m² + 256 Photomultiplier tubes (PMTs), 12 newly designed telescopes

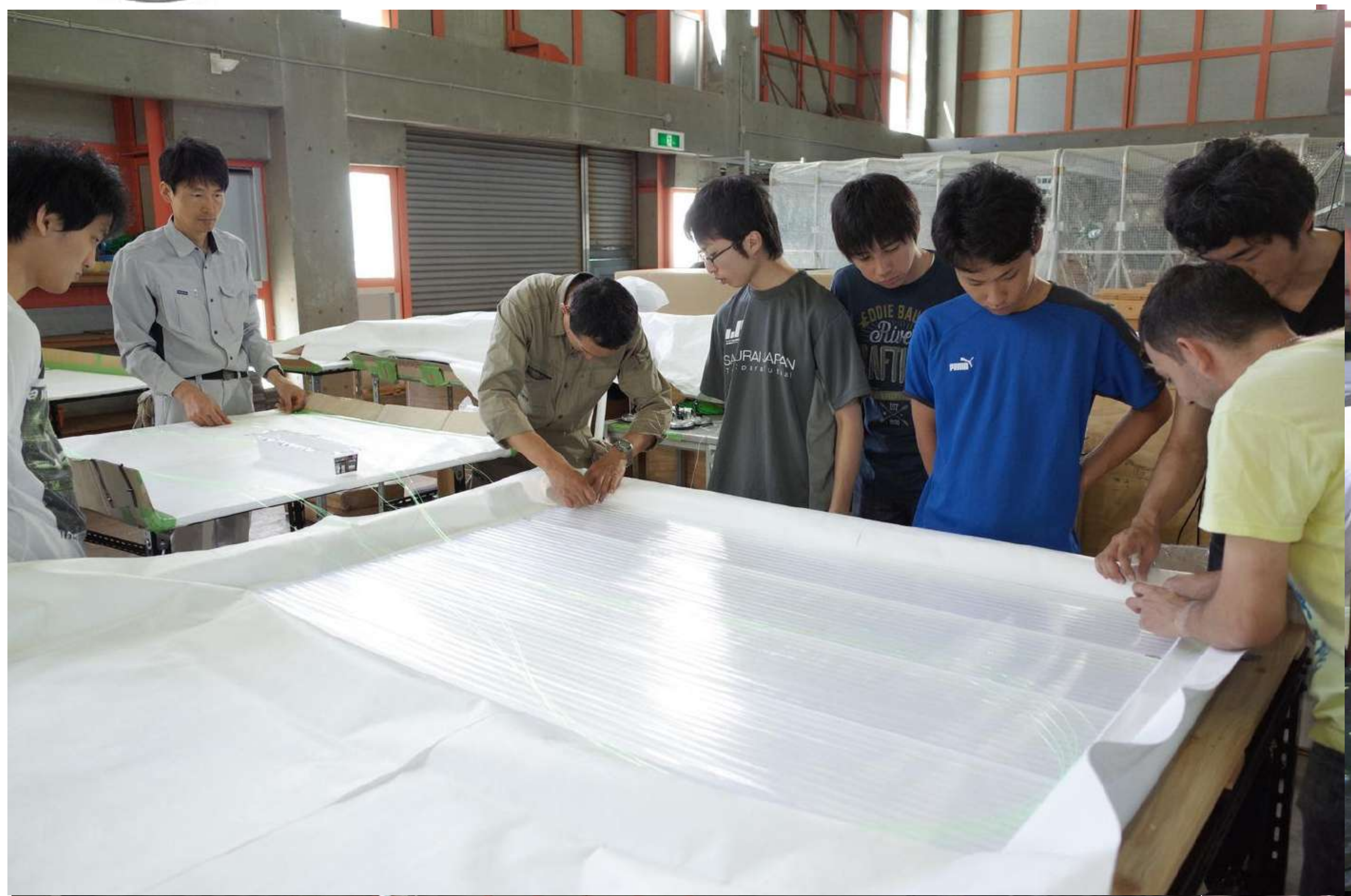
Fluorescence detector at a northern station
Refurbished
from HiRes experiment,
Mirror 5.2 m²,
256 PMTs, 14 telescope





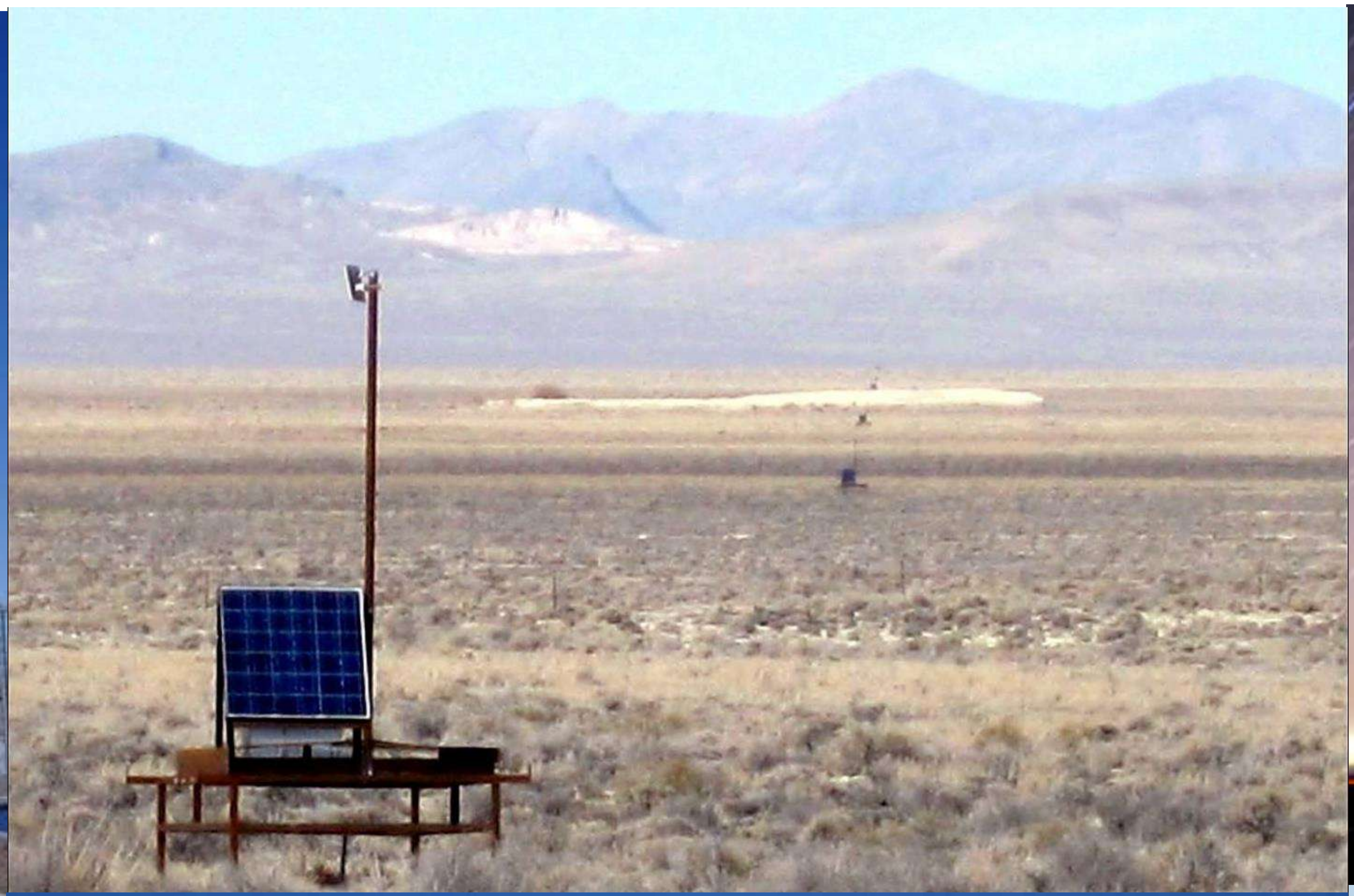


Hand-made detectors





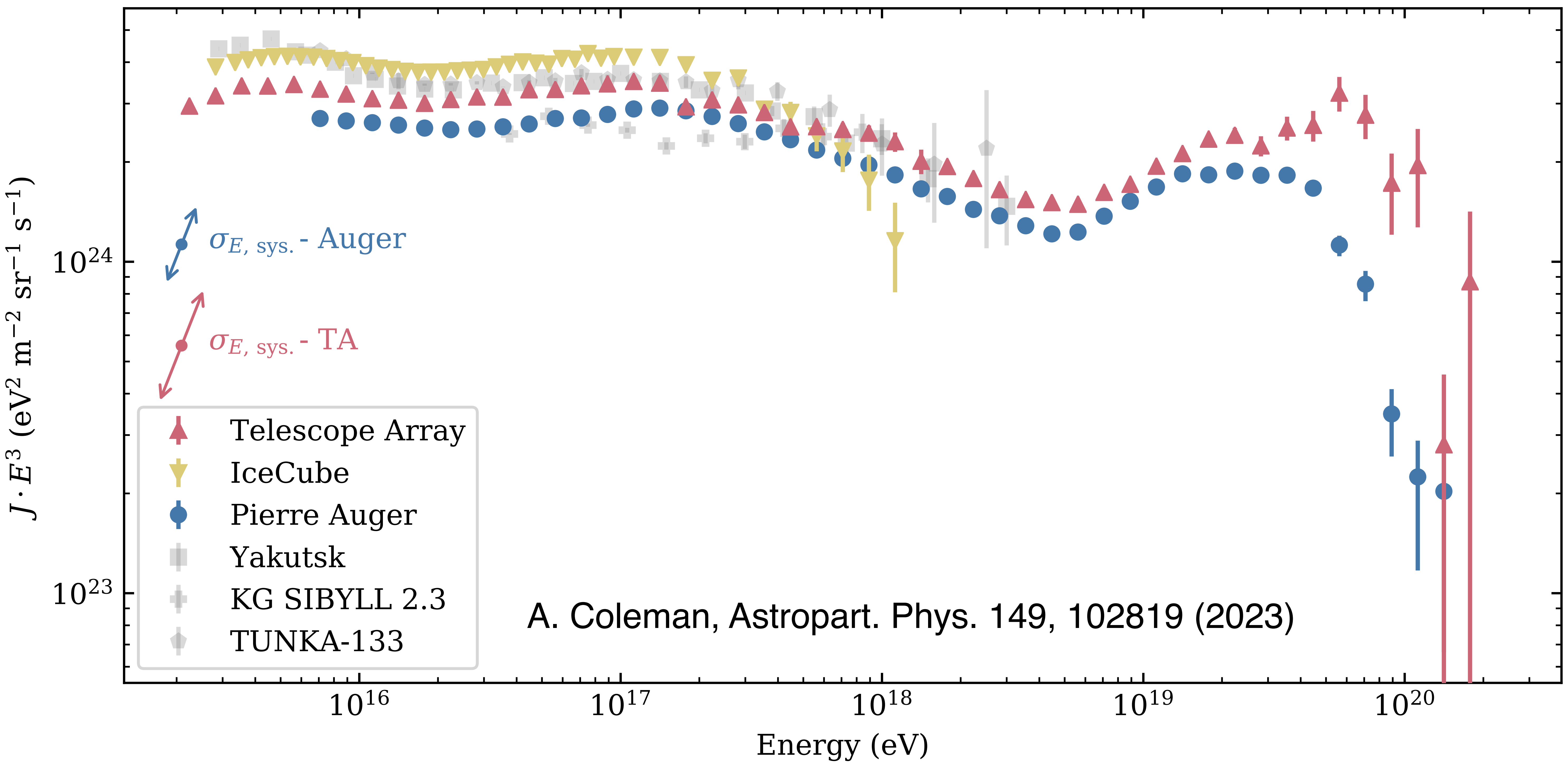

Telescope Array experiment @Utah

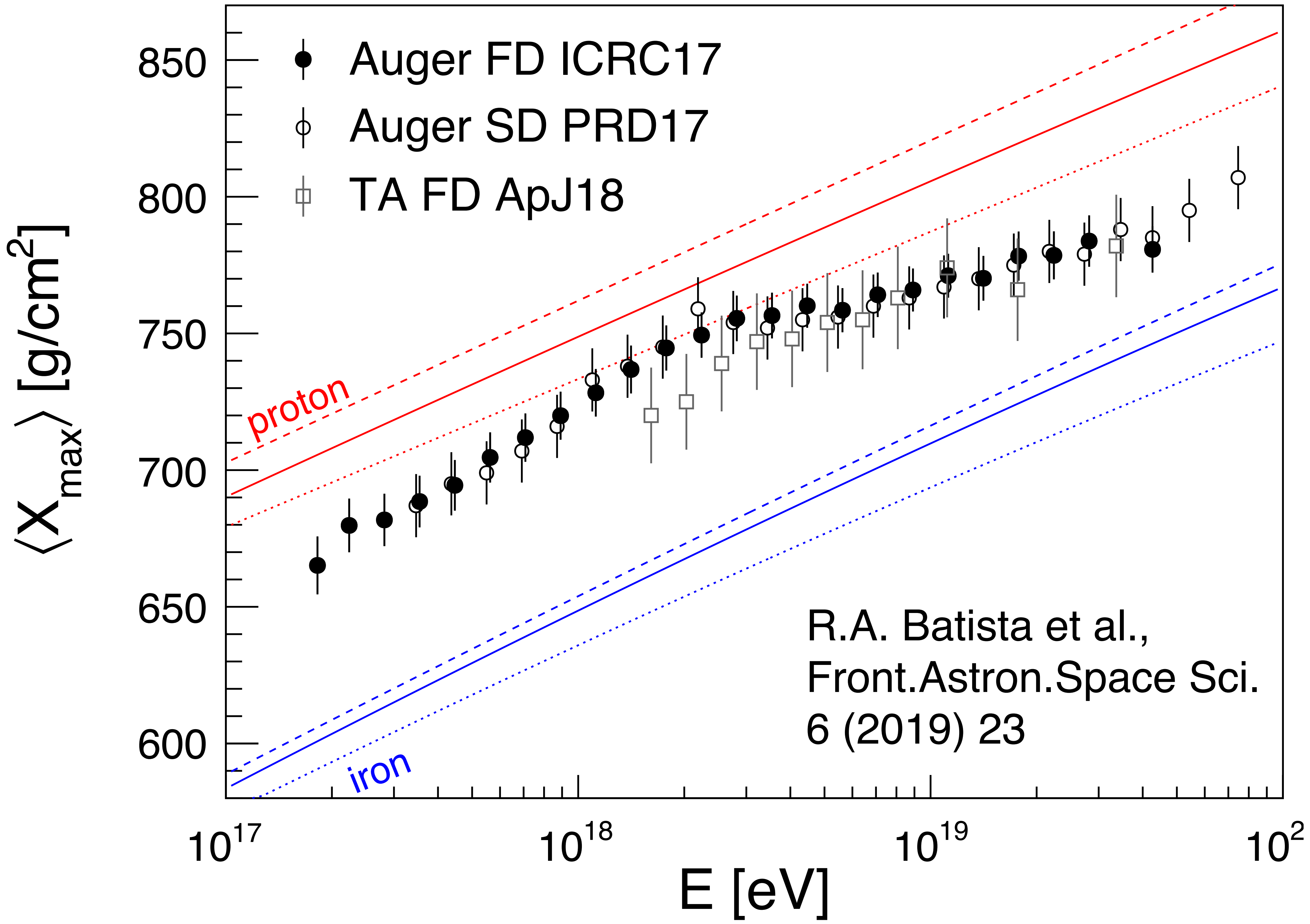


Credit: Telescope Array Collaboration, H. Oshima

PIERRE AUGER OBSERVATORY

Pierre Auger Observatory @Mendoza, Argentina

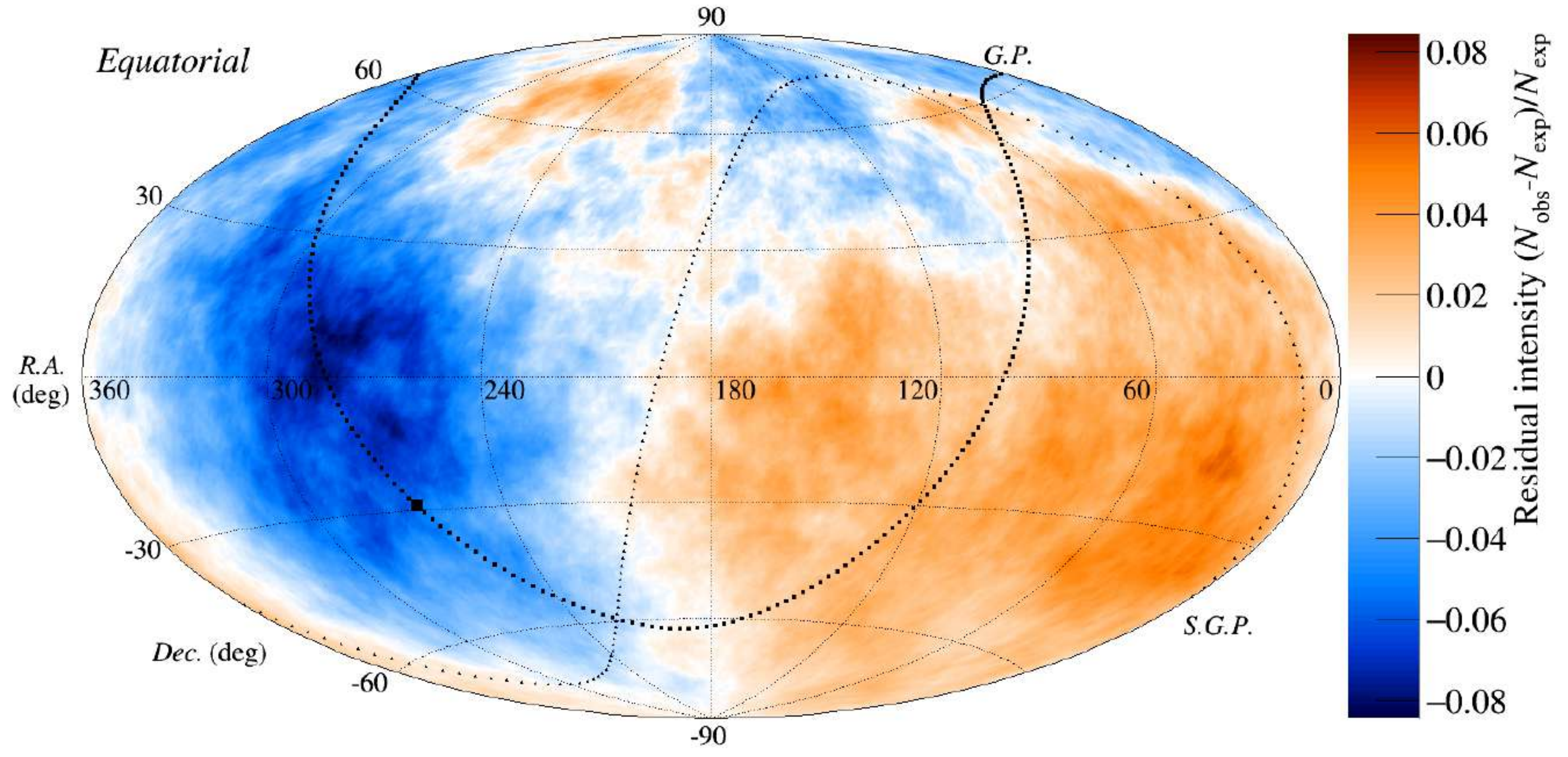




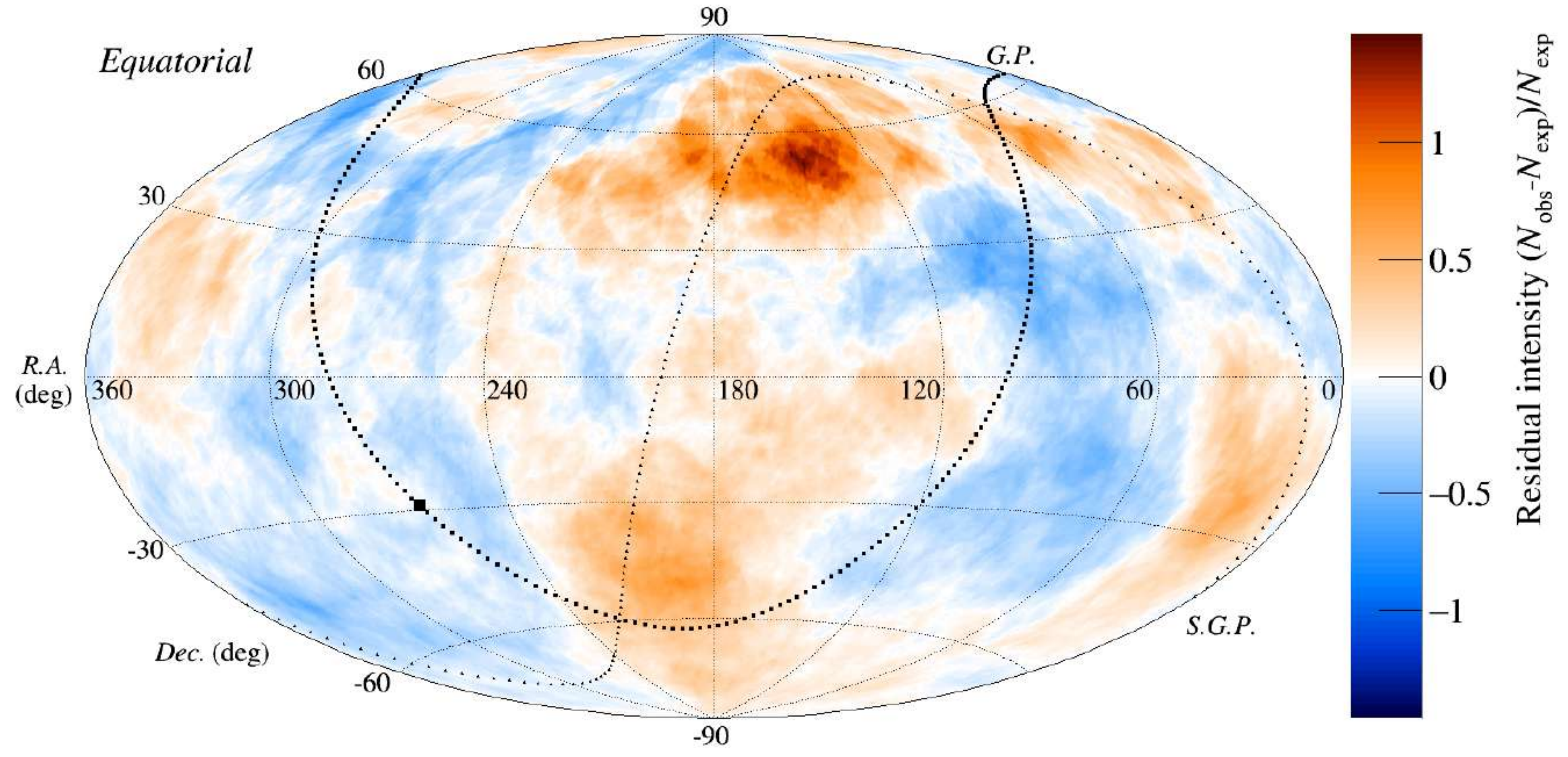
$$\theta \sim 10^\circ Z \left(\frac{E}{10\,\mathrm{EeV}} \right)^{-1}$$

Latest results of UHECR

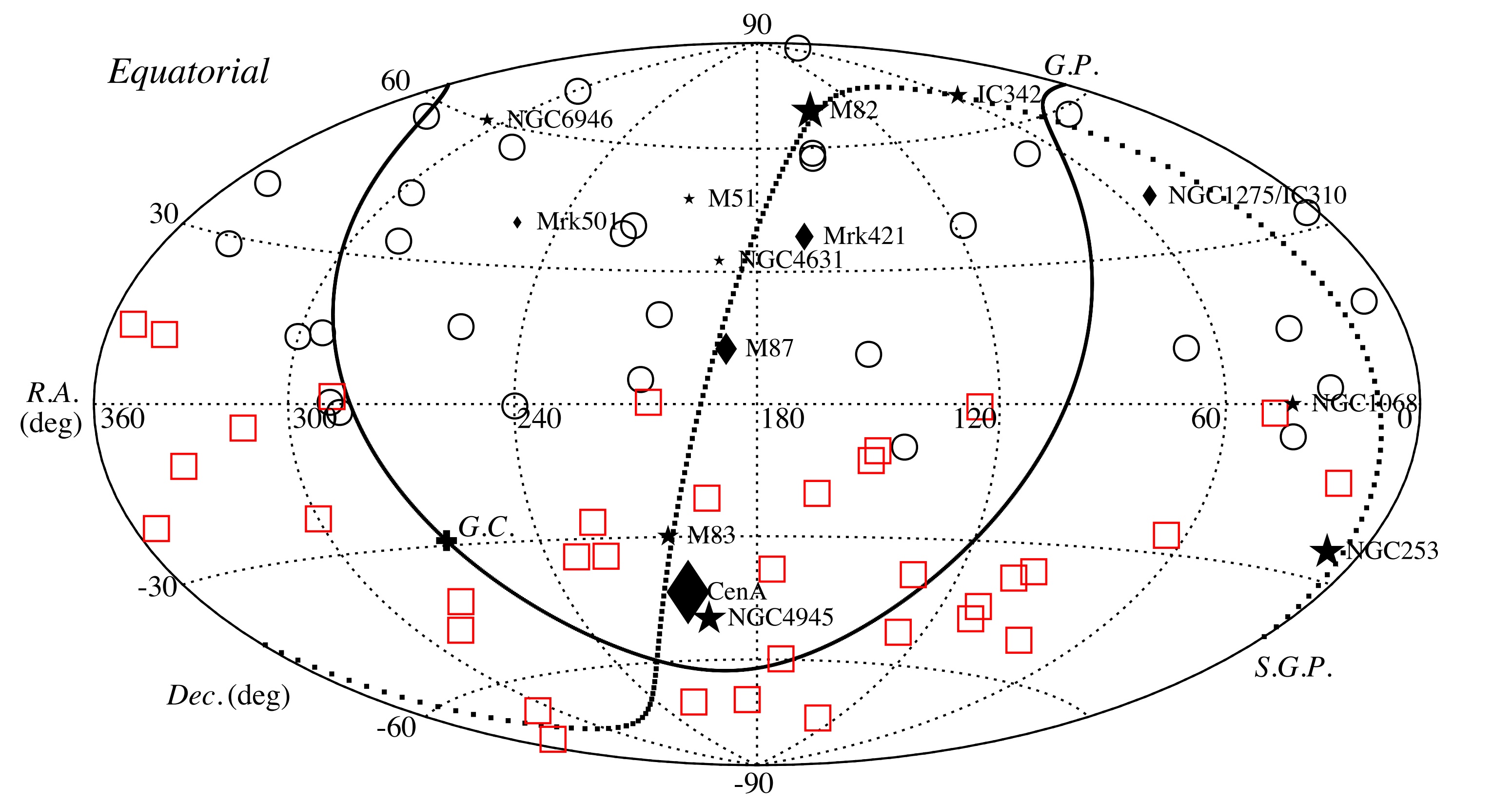
$$t_{\mathrm{delay}} \sim 100\, Z^2 \left(\frac{E}{10\,\mathrm{EeV}} \right)^{-2} \mathrm{yr}$$



Ankle ($E > 10$ EeV)



Cutoff ($E > 50$ EeV)



Beyond-cutoff ($E > 100$ EeV)

Energy spectrum

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

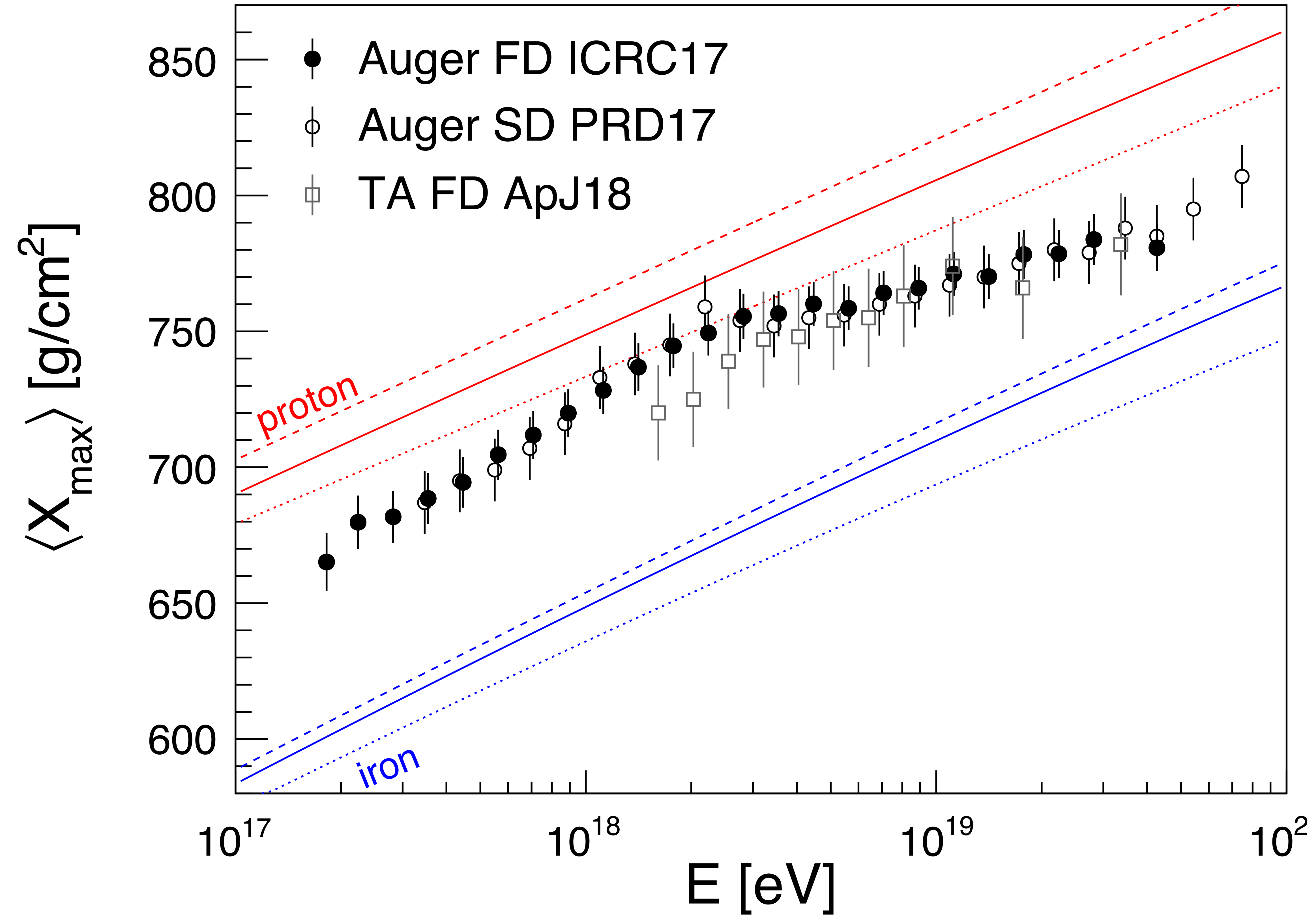
A. Coleman et al., Astropart. Phys. 149, 102819 (2023)

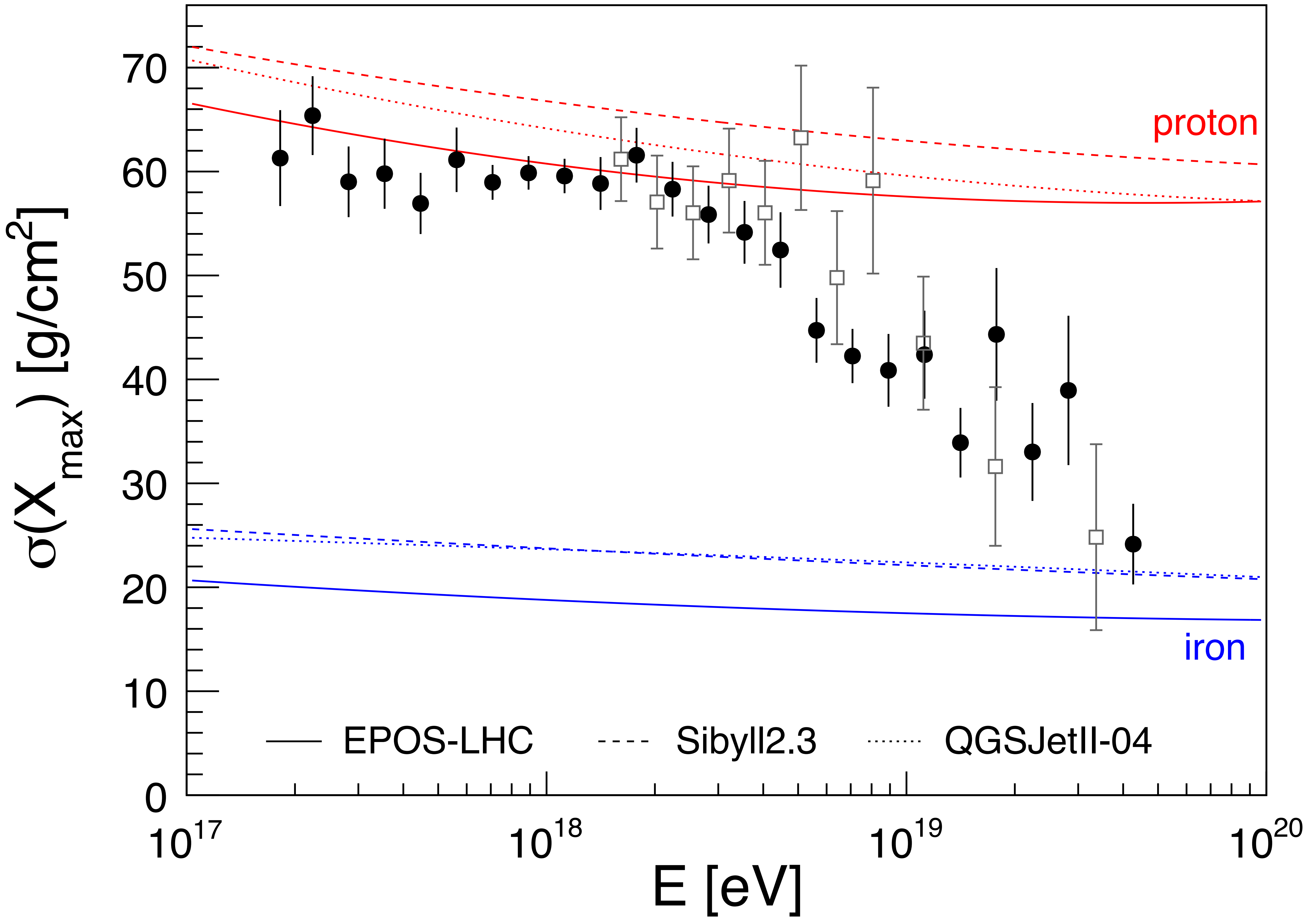
Mass composition

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

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

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





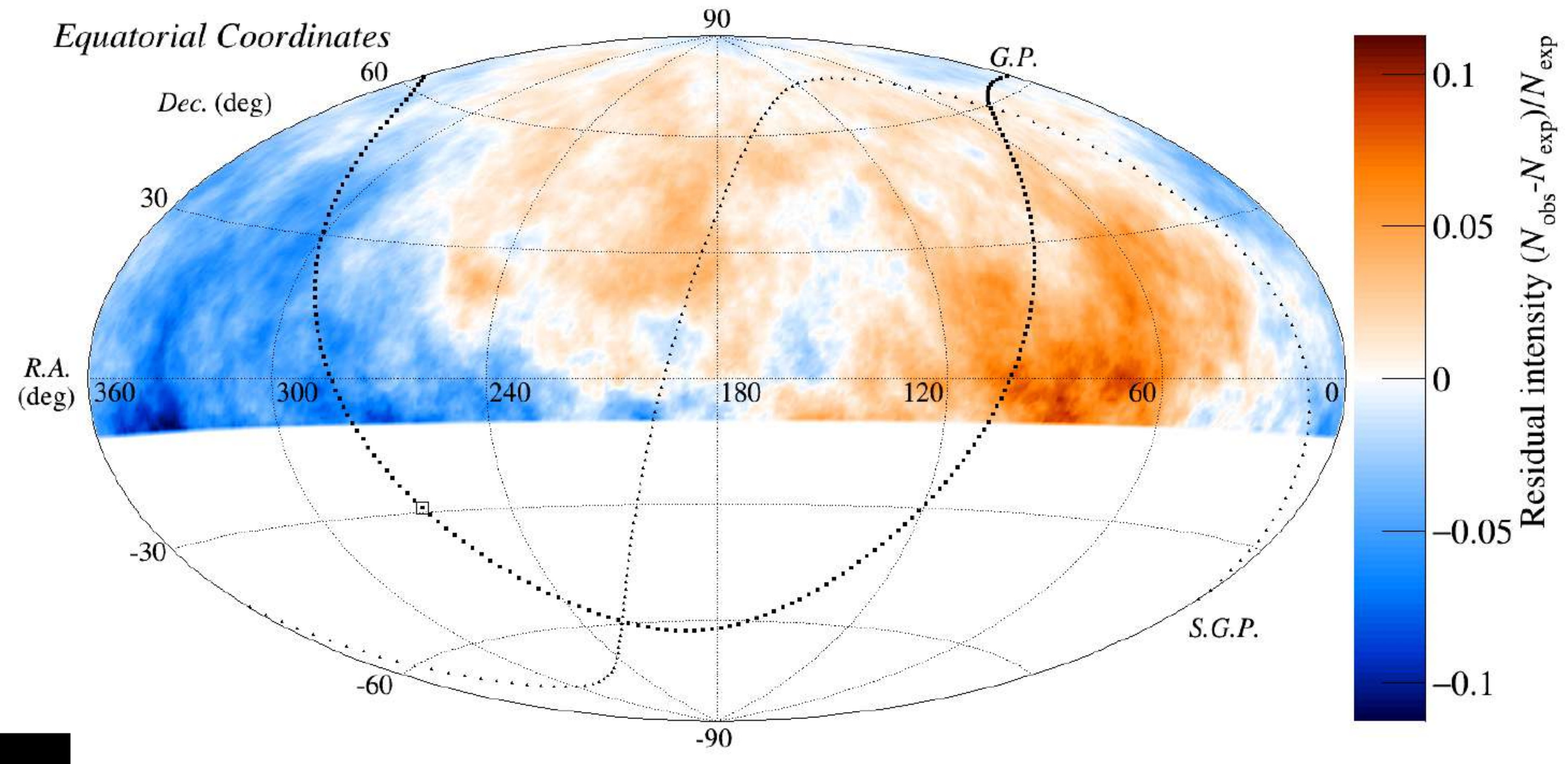
Gradually increase to the heavier composition above 3 EeV

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

Anisotropy of UHECRs (10 EeV)

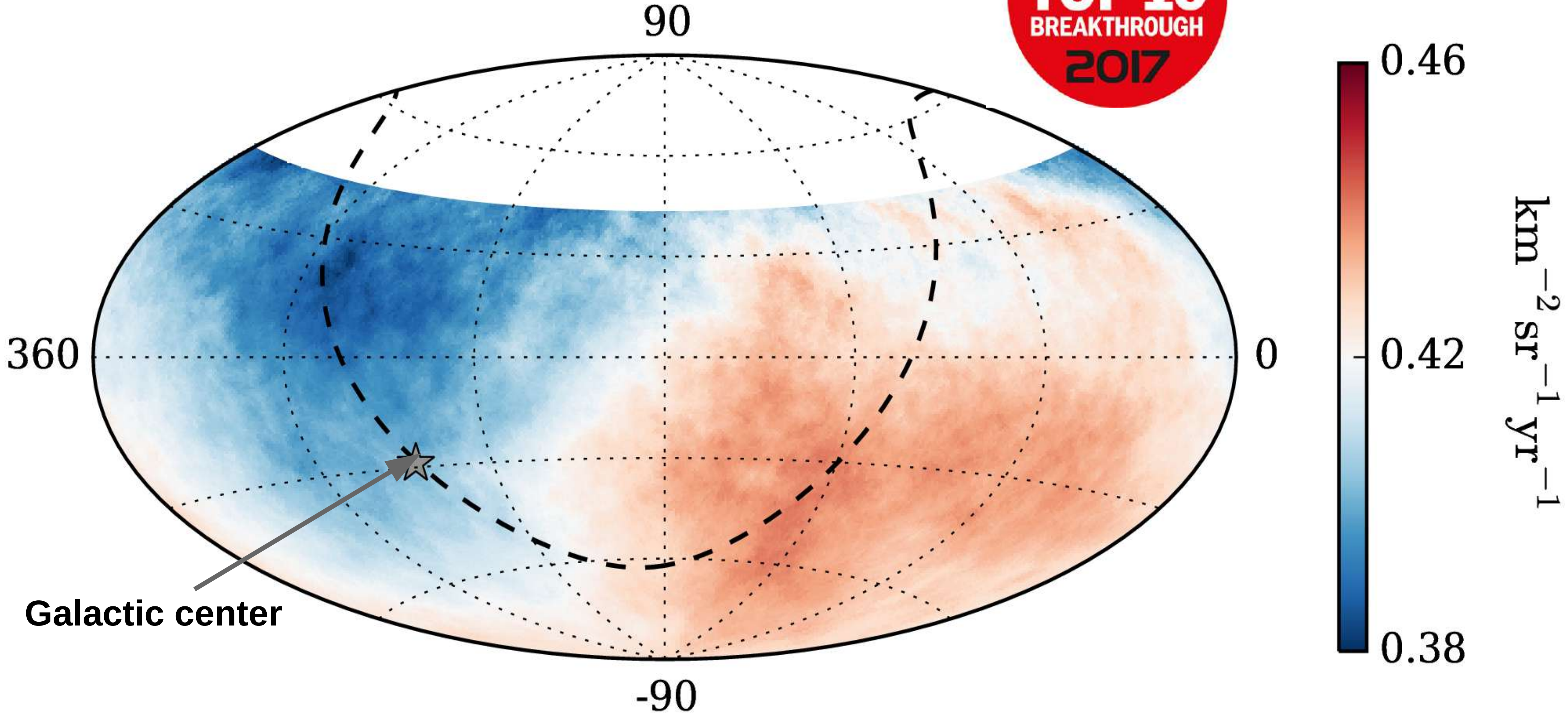
Northern TA ApJL, 898:L28 (2020)

E_{TA}> 8.8 EeV



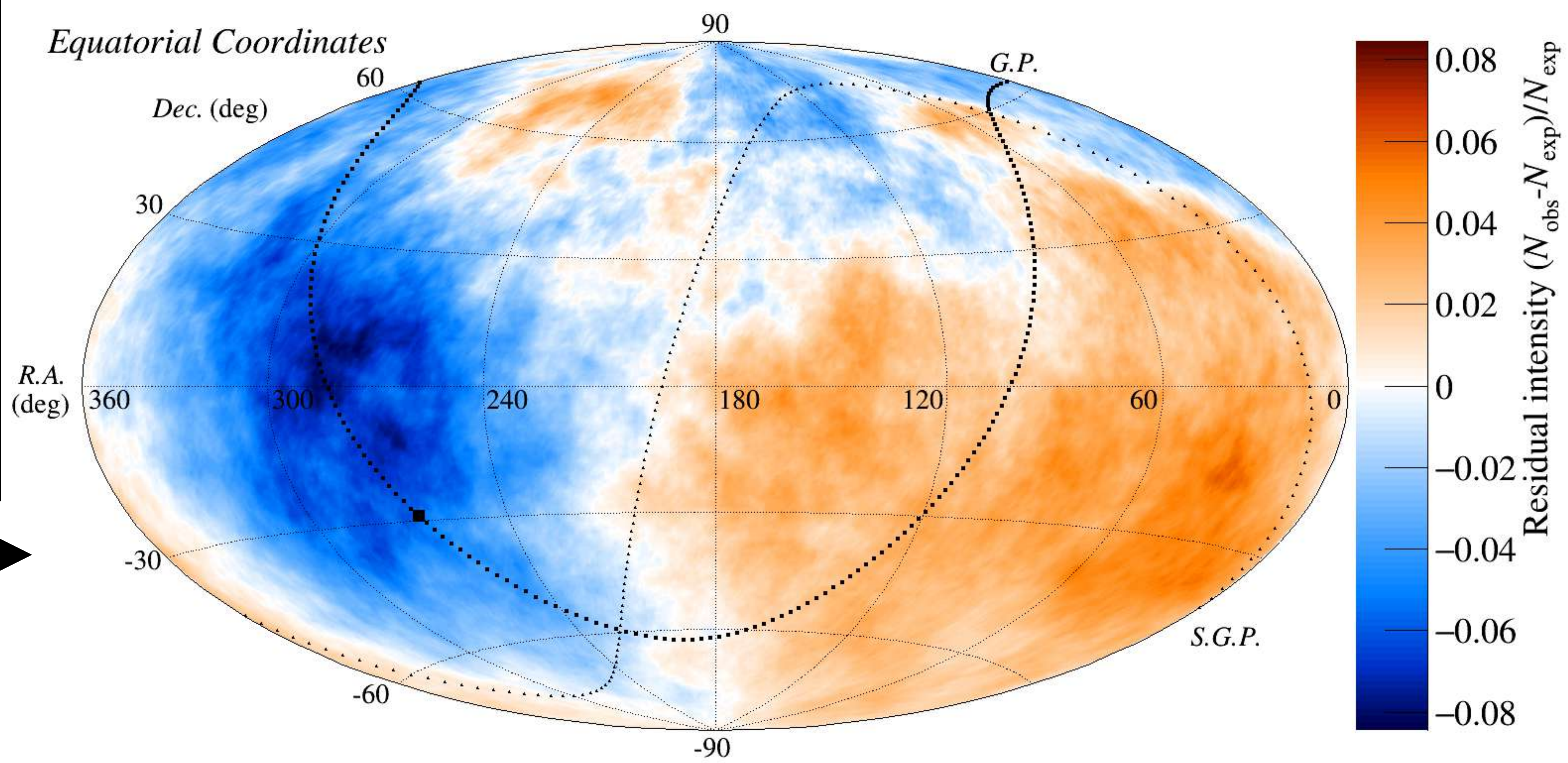
Southern Auger Science 357, 1266 (2017)

E_{Auger}> 8 EeV



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

Joint analysis



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

50 EeV skymap

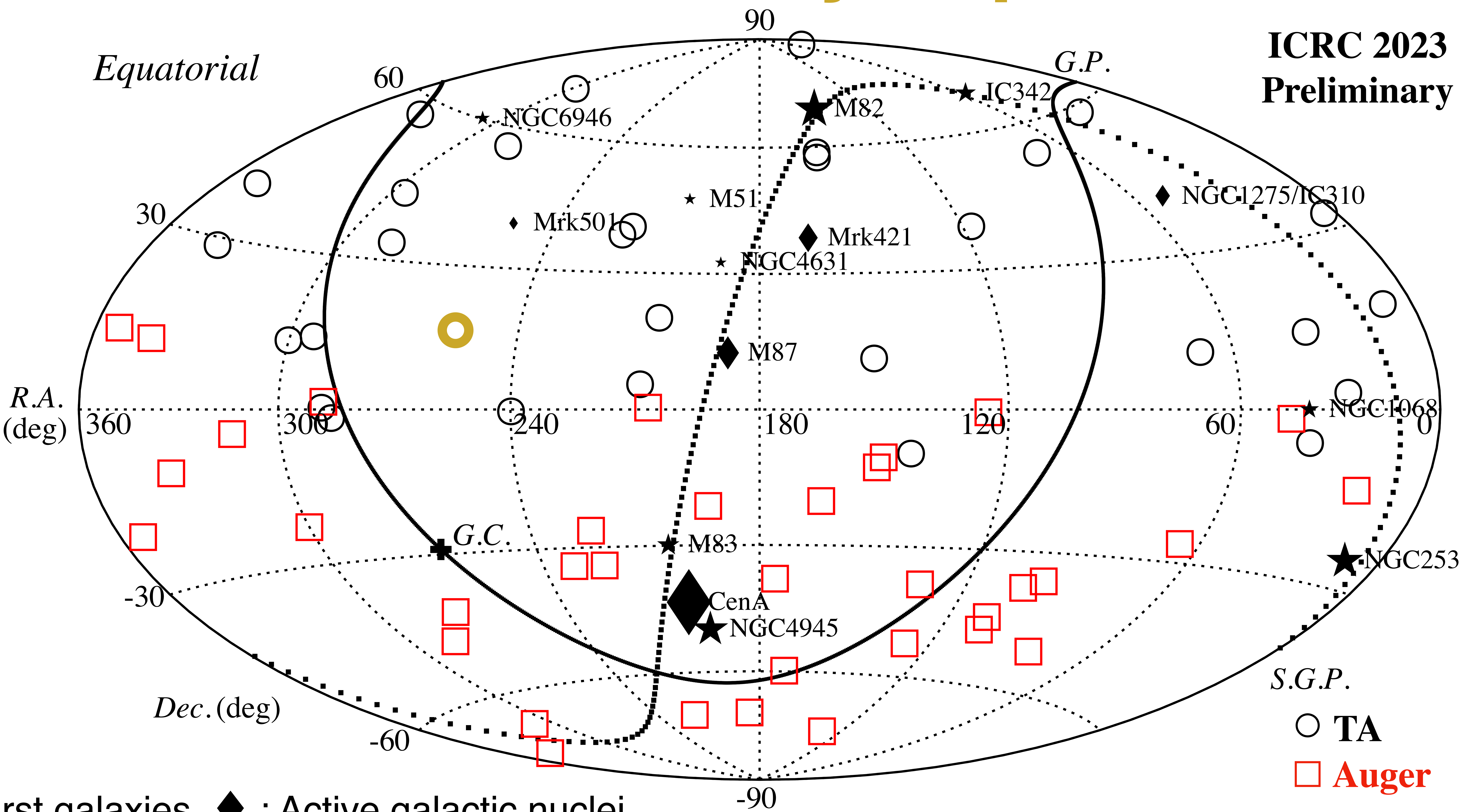
Cutoff (E_{TA}>52.3 EeV E_{Auger}>40 EeV), **~1000 events**

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**

100 EeV skymap

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

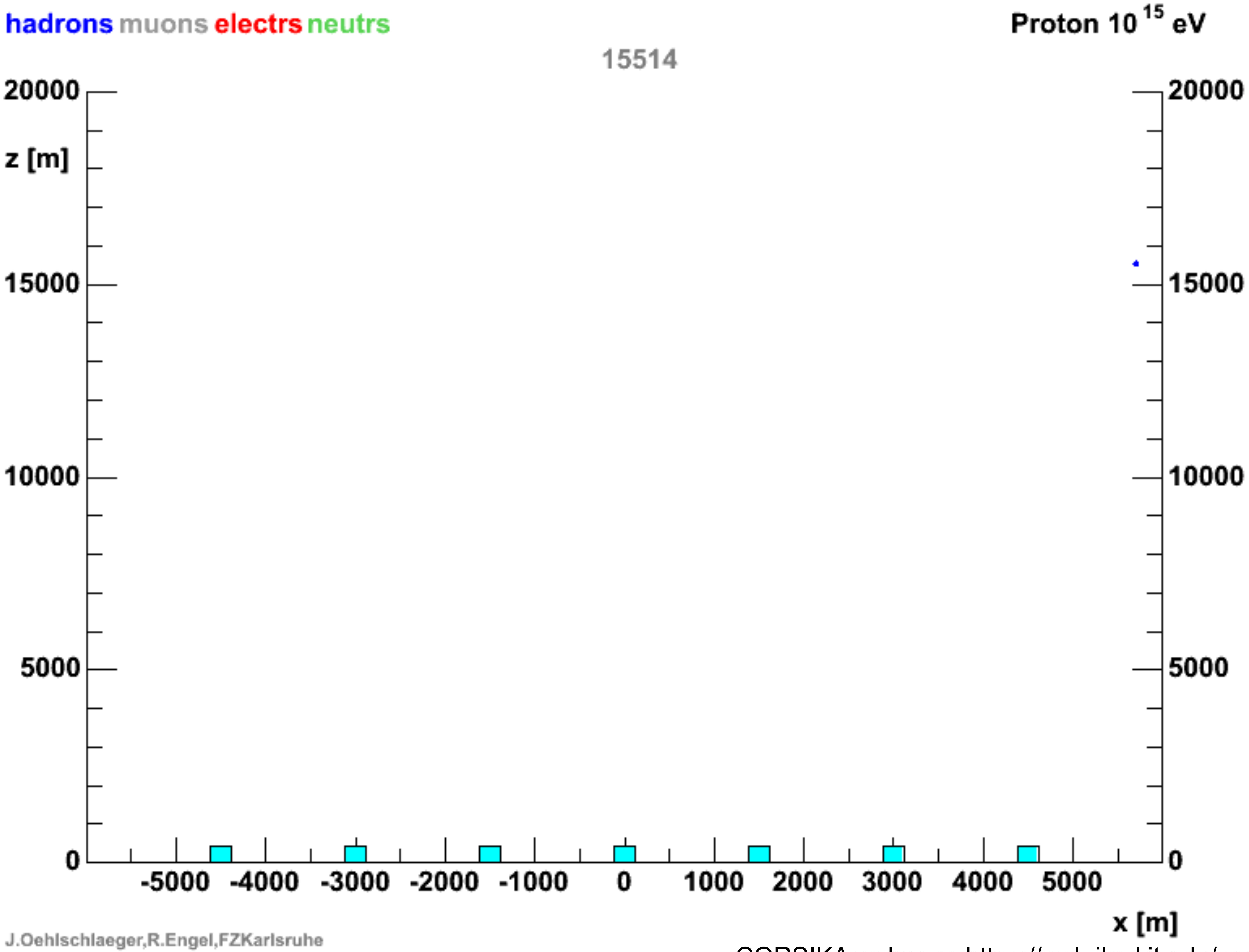


★ : Starburst galaxies ♦ : Active galactic nuclei

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

No obvious clustering appeared


2021 May 27, 04:35:56 AM
Detection of "Amaterasu" particle
© Toshihiro Fujii, L-INSIGHT, Kyoto University and Ryuunosuke Takeshige
Telescope Array Collaboration, Science 382, 903 (2023)



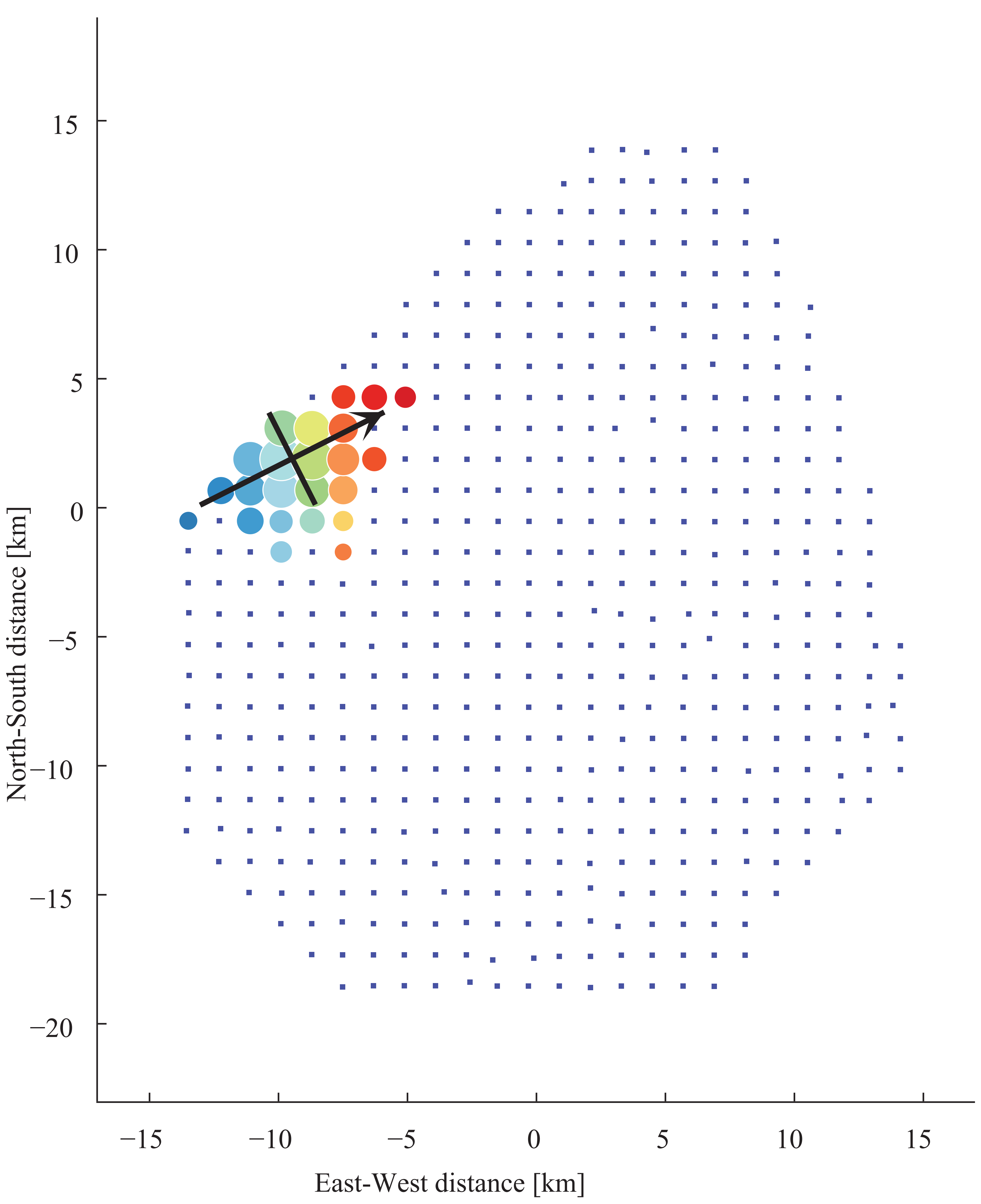
CORSIKA webpage https://web.ikp.kit.edu/corsika/movies

The highest energy event of TA

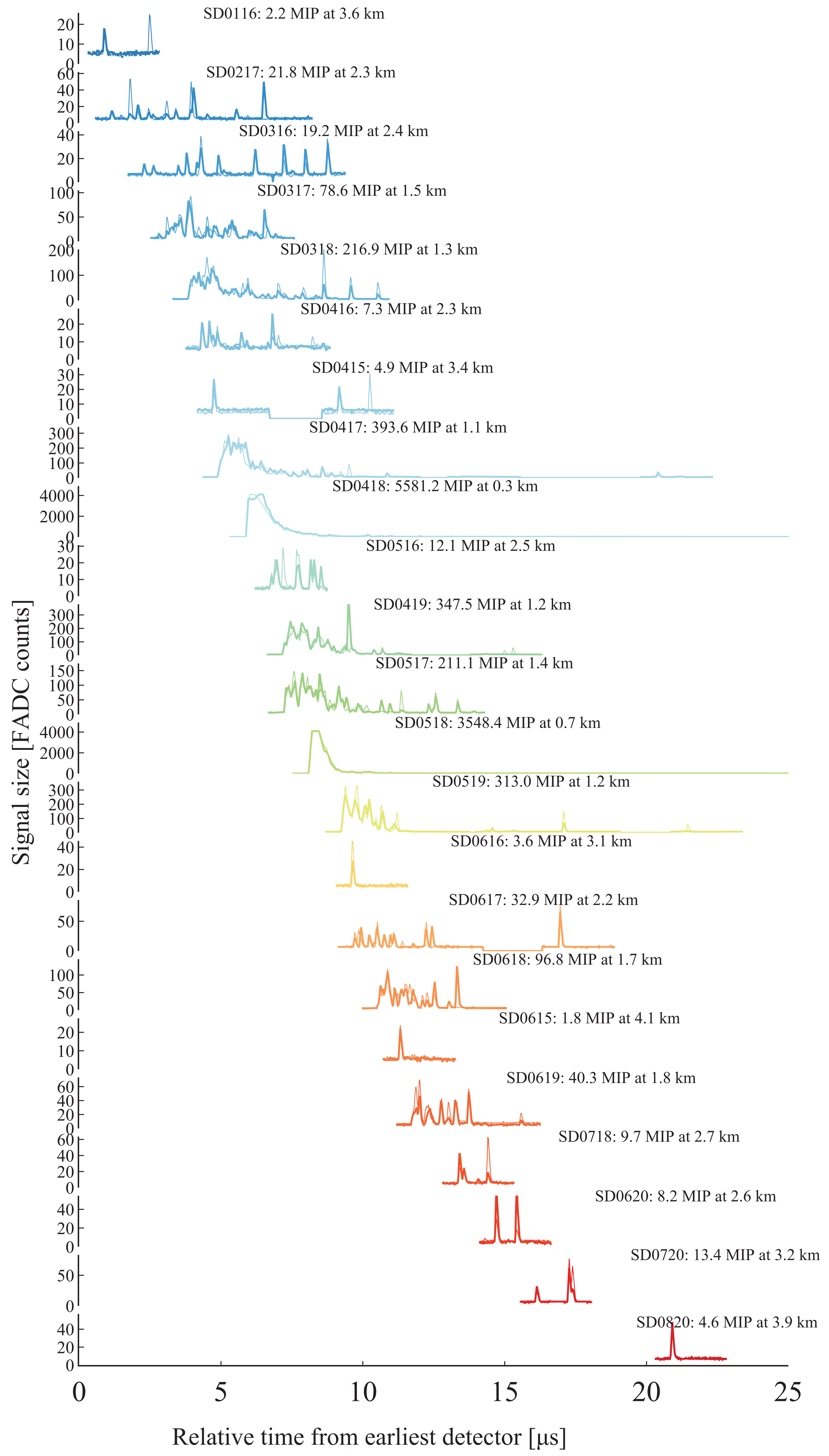
- May 27th 2021 04:35:56
- ***E* = 244 ± 29 (stat.) +51,-76 (syst.) EeV**
  - Zenith angle = 38.6°
- No operation of fluorescence telescope due to twilight

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

A Surface detector array of TA

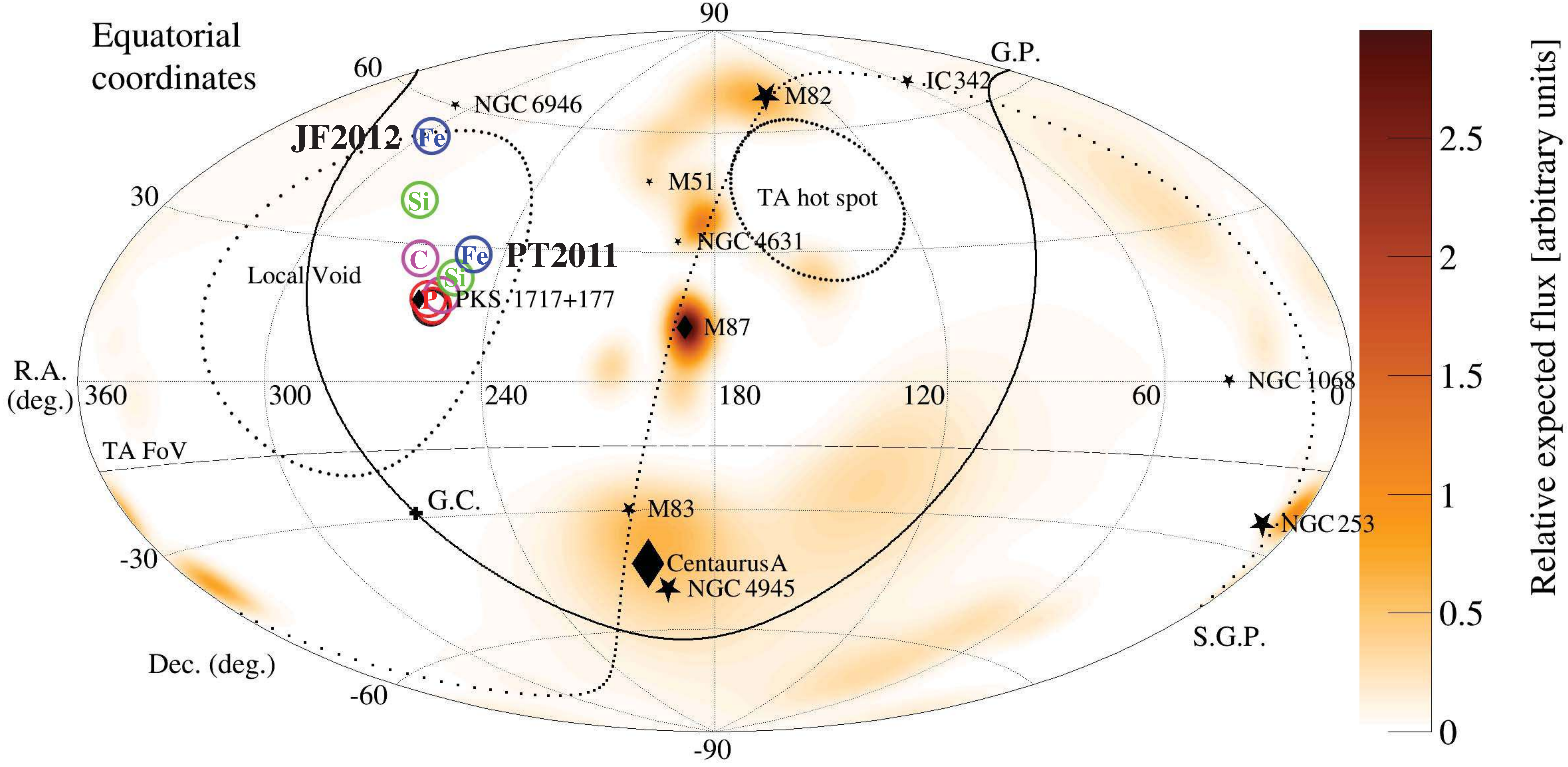


B Date: 27 May 2021 Time: 10:35:56.474337 UTC



Telescope Array Collaboration, Science 382, 903 (2023)

Arrival direction of Amaterasu particle



Telescope Array Collaboration, Science 382, 903 (2023)

Binary neutron star merger scenario

- **Binary neutron star merger** (Farrar, arXiv:2405.12004)
  - Energy injection rate of cosmic rays above 10 EeV → **6×10^{44} erg Mpc^{-3} yr^{-1}**
  - Energy in jet (Kiuchi+23) → **$10^{51.5}$ erg**
    - **BNS rate → 100 Gpc^{-3} yr^{-1}**
- **Ultra-heavy composition** like Te or Pt (Zhang, Murase et al., arXiv:2405.17409)

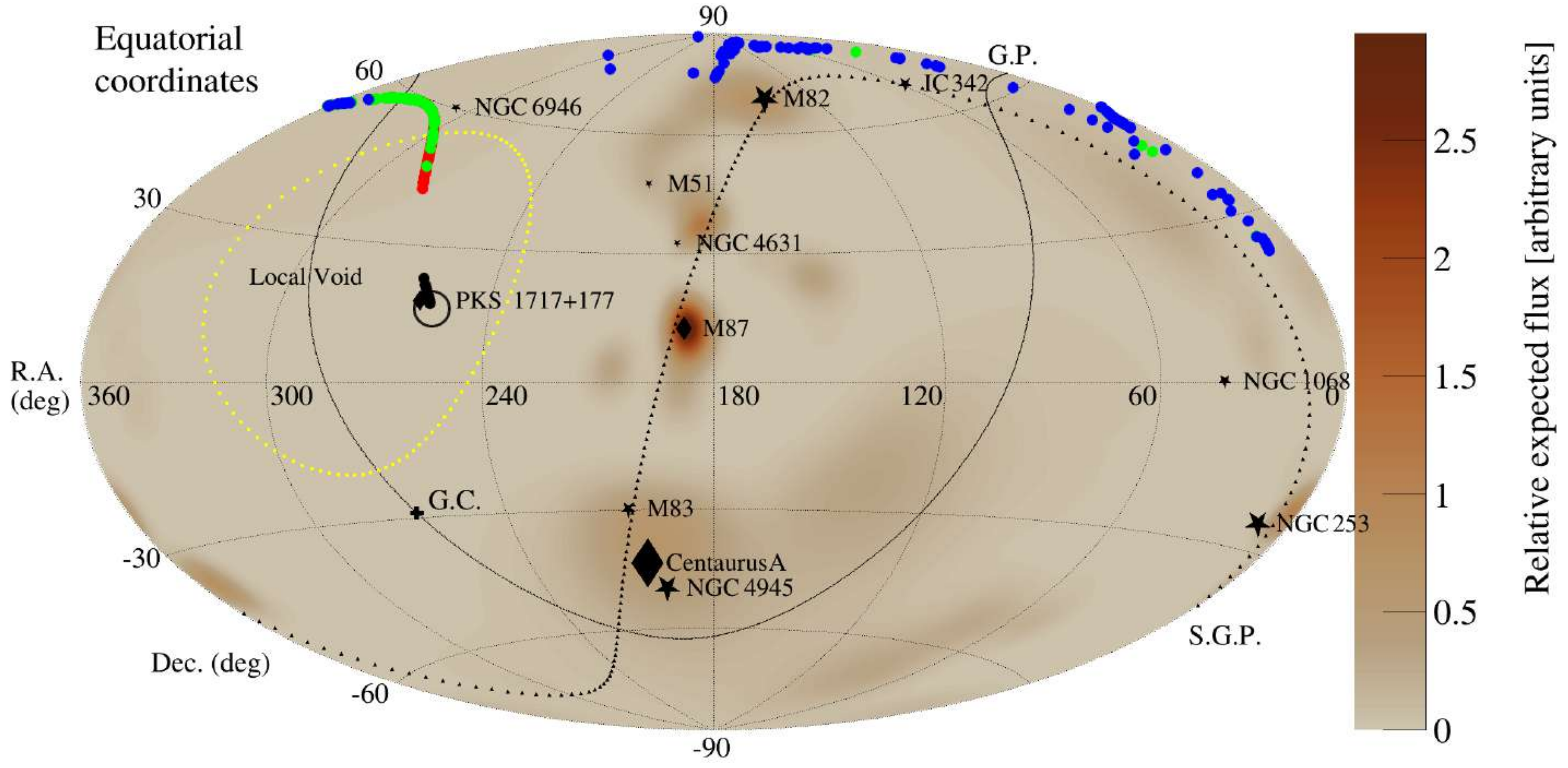


FIG. 3. Skymap of backtracked particles with mean energy $E = 244$ EeV and variation $E = 70$ EeV for p ($Z = 1$, black), Fe ($Z = 26$, red), Zr ($Z = 40$, green) and Pt ($Z = 78$, blue)

PHYSICAL REVIEW D **89,** 063006 (2014)

High-energy radiation from remnants of neutron star binary mergers

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(Received 25 July 2013; published 17 March 2014)

We study high-energy emission from the mergers of neutron star binaries as electromagnetic counterparts to gravitational waves aside from short gamma-ray bursts. The mergers entail significant mass ejection, which interacts with the surrounding medium to produce similar but brighter remnants than supernova remnants in a few years. We show that electrons accelerated in the remnants can produce synchrotron radiation in x rays detectable at ∼100 Mpc by current generation telescopes and inverse Compton emission in gamma rays detectable by the Fermi Large Area Telescopes and the Cherenkov Telescope Array under favorable conditions. Optical synchrotron radiation is also detectable by telescopes with good angular resolution. The remnants may have already appeared in high-energy surveys such as the Monitor of All-sky X-ray Image and the Fermi Large Area Telescope as unidentified sources. We also suggest that the merger remnants could be the origin of ultrahigh-energy cosmic rays beyond the knee energy, $\sim10^{15}$ eV, in the cosmic ray spectrum.

DOI: 10.1103/PhysRevD.89.063006 PACS numbers: 96.50.Pw, 97.60.Jd, 98.70.Sa

More details on next talk by R. Higuchi

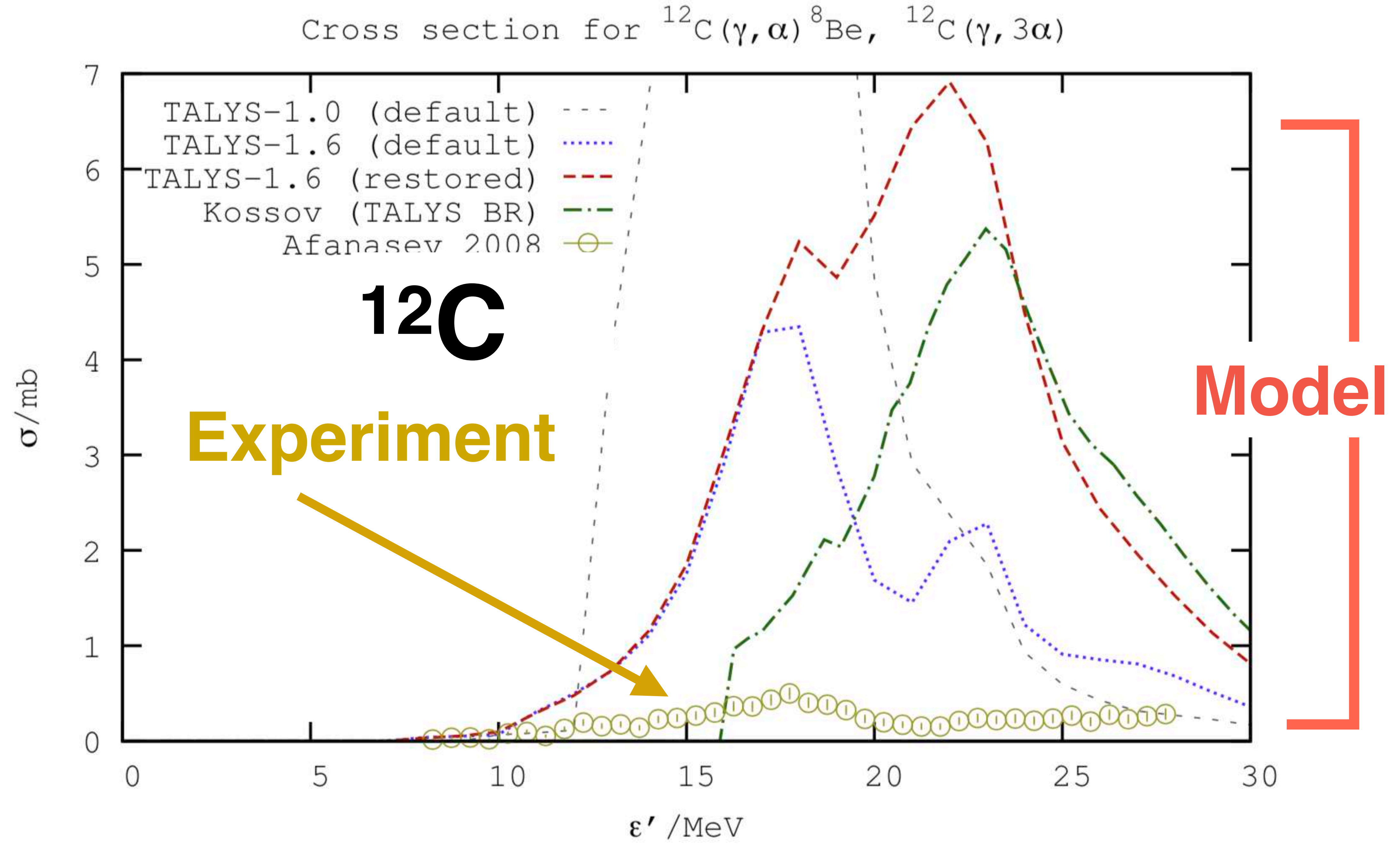
Nuclear Physics meets UHECRs (PANDORA project)

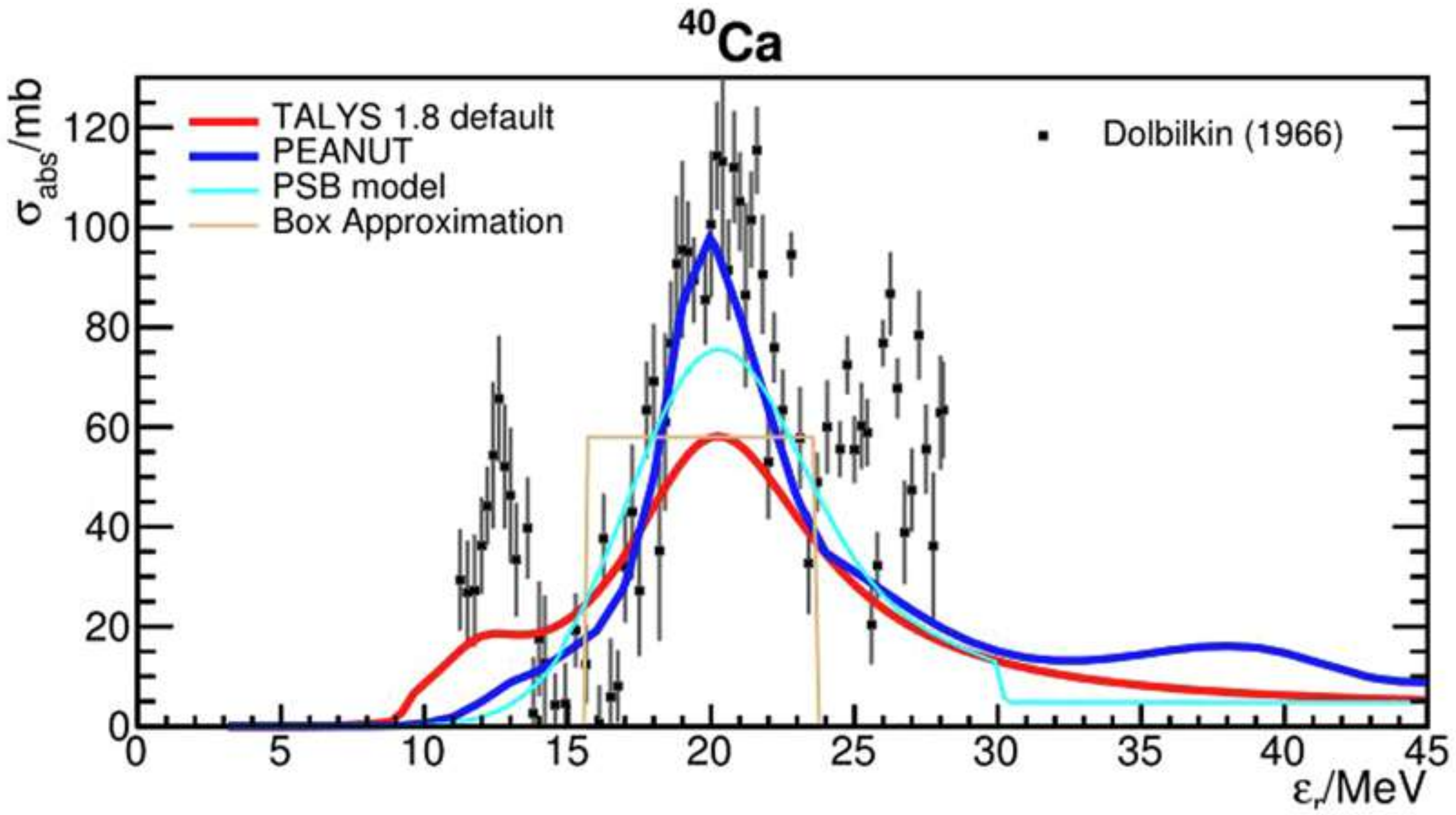
$$^{A}_{Z}N + \gamma_{\mathrm{CMB}} \rightarrow ^{A-1}_{Z-1}N' + p$$

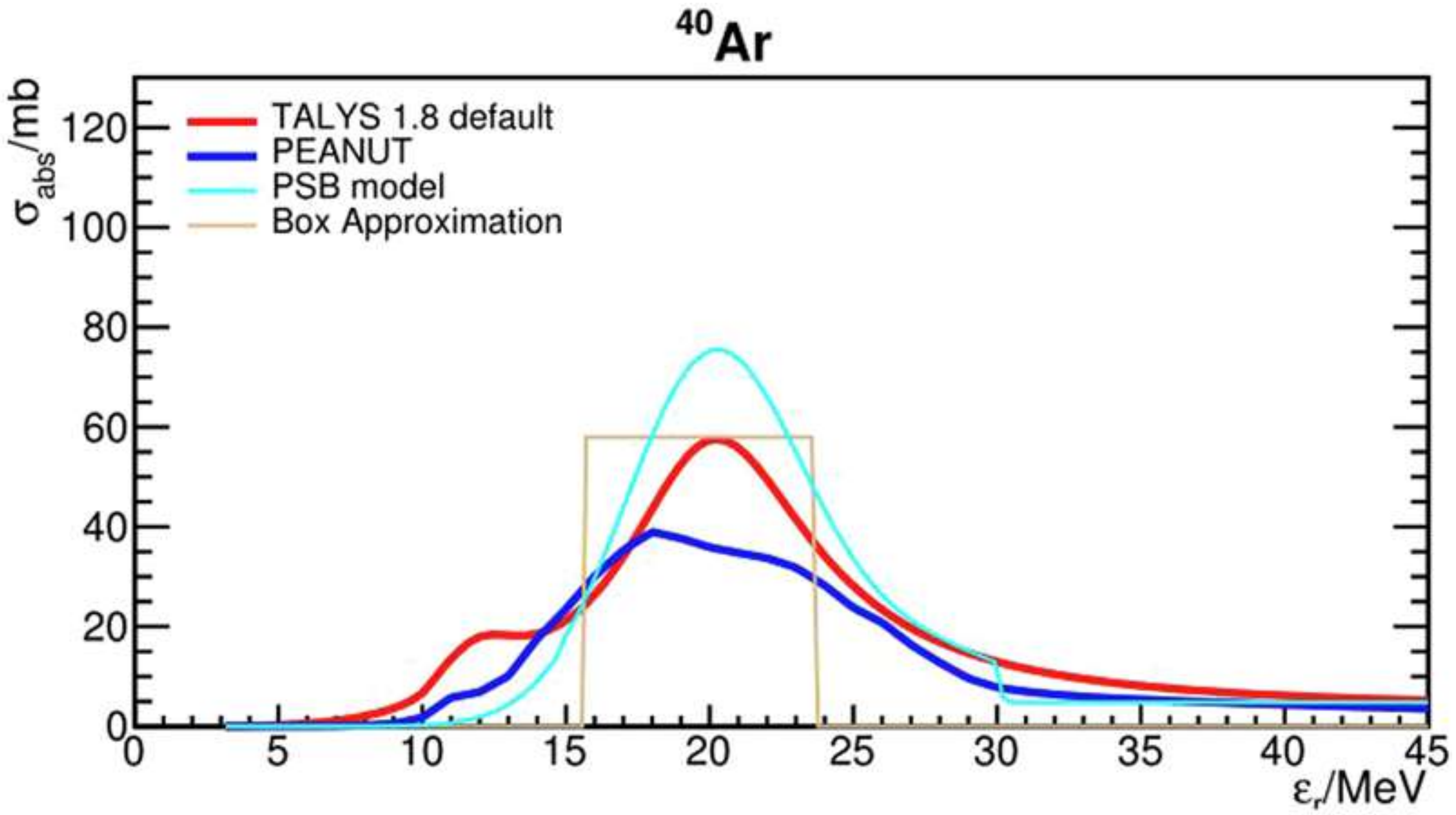
- Large uncertainty of the cross section from the giant dipole resonants for A < 60 nuclei
- Multi-disciplinary research among nuclear physics, UHECR and CMB

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

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

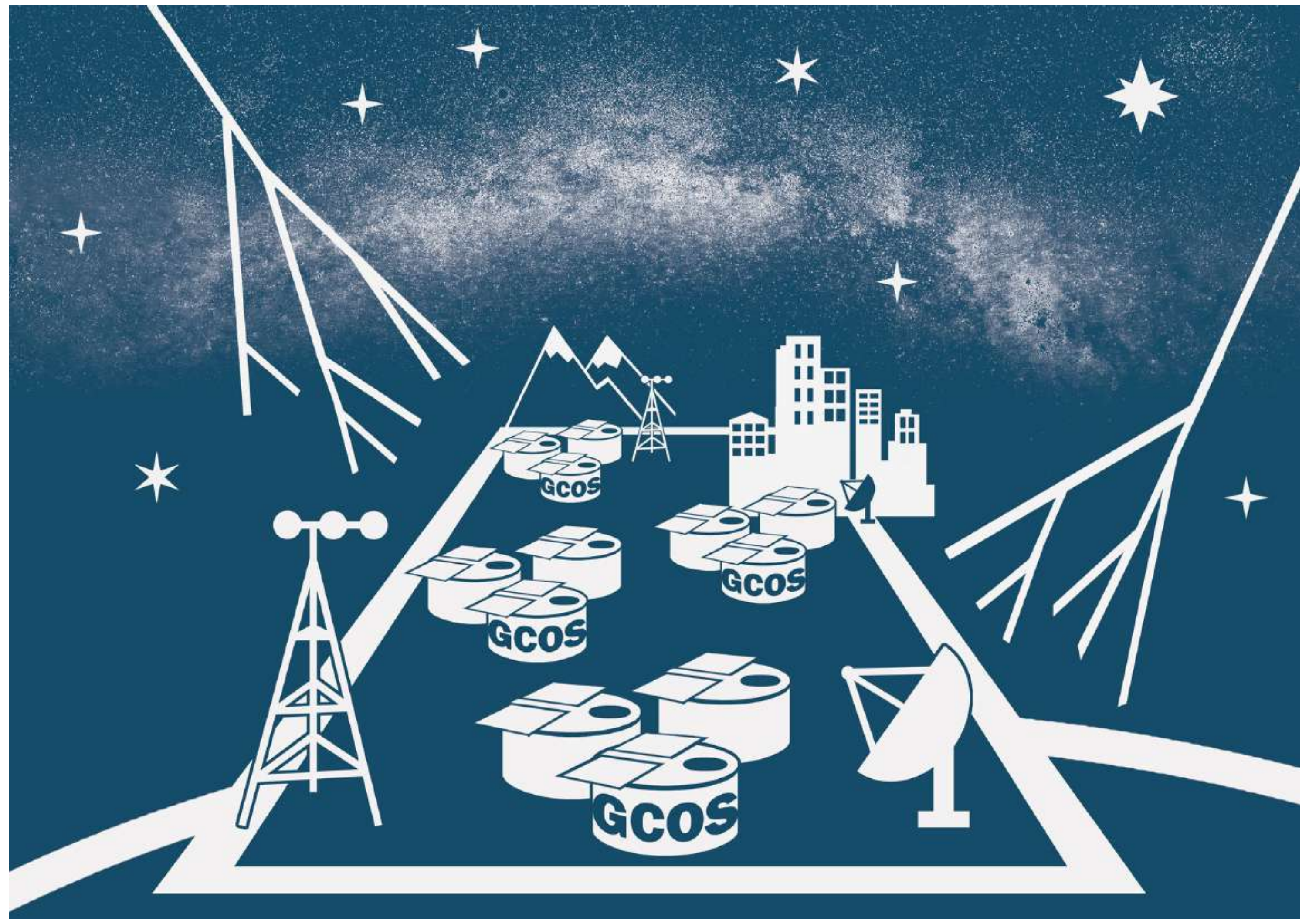


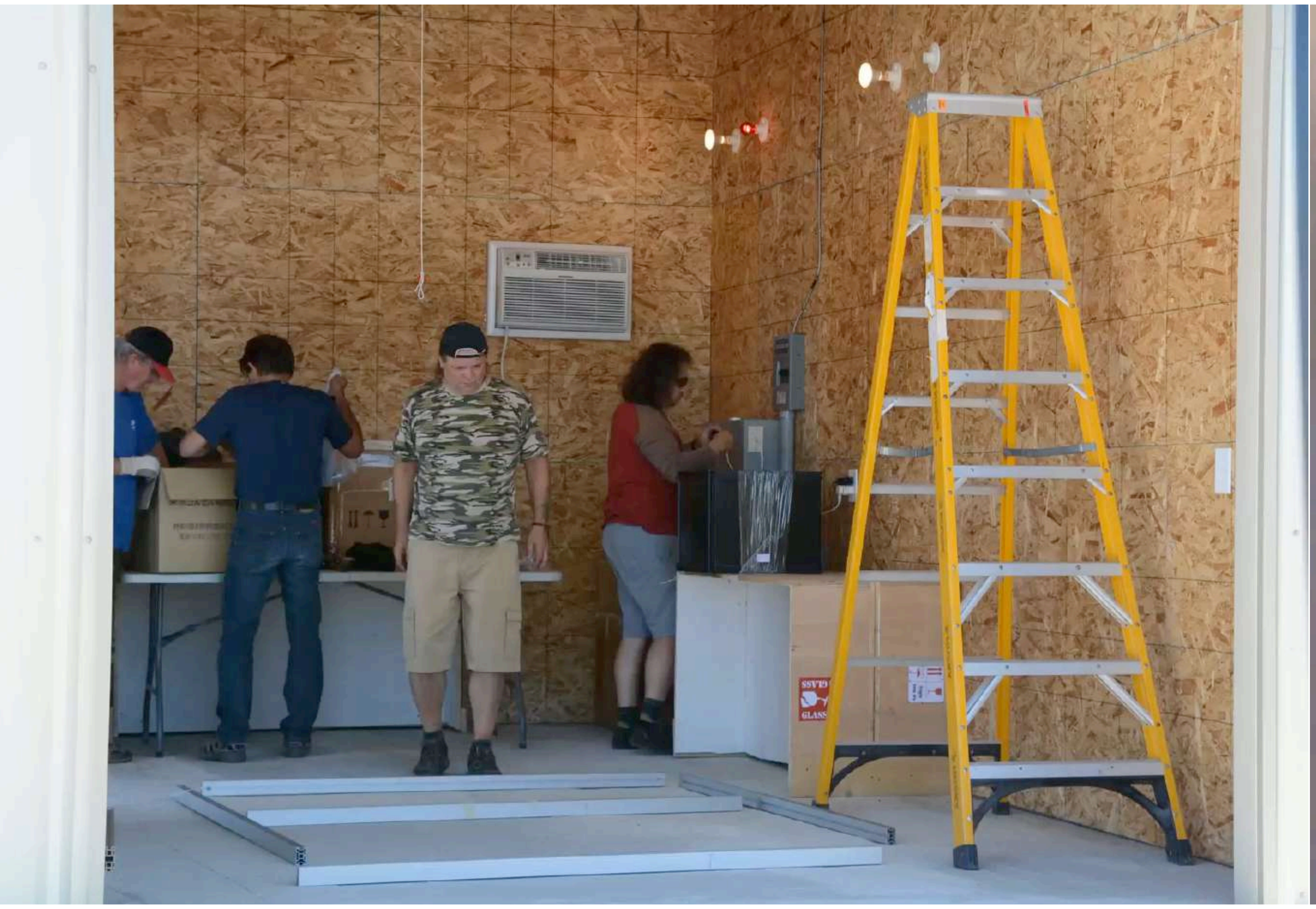




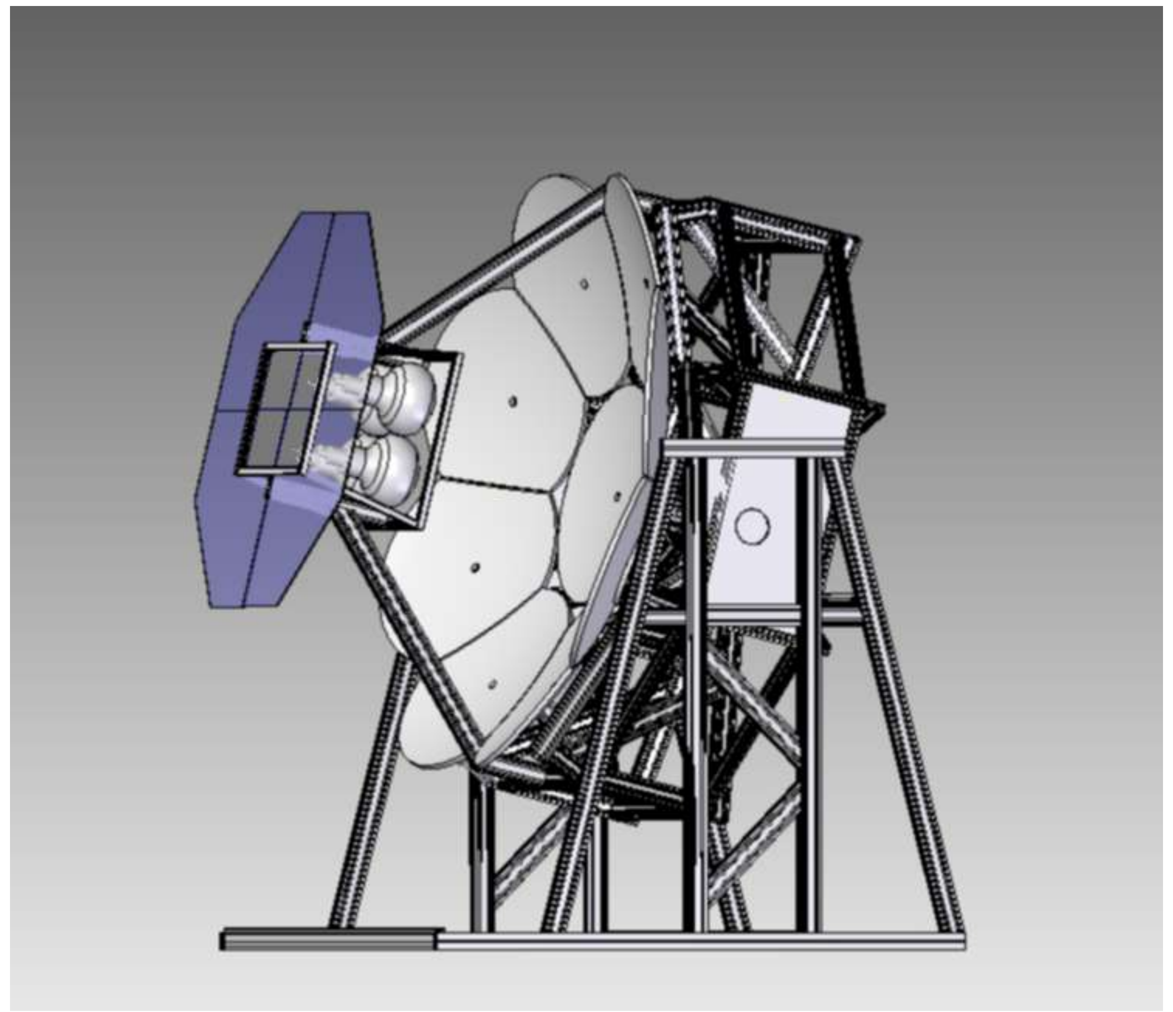
Detector developments for next-generation observatory

Global Cosmic Ray Observatory (GCOS) -- "GCOS-Japan consortium" was inaugurated. Your participations are highly welcome!!





Low-cost, easily deployable

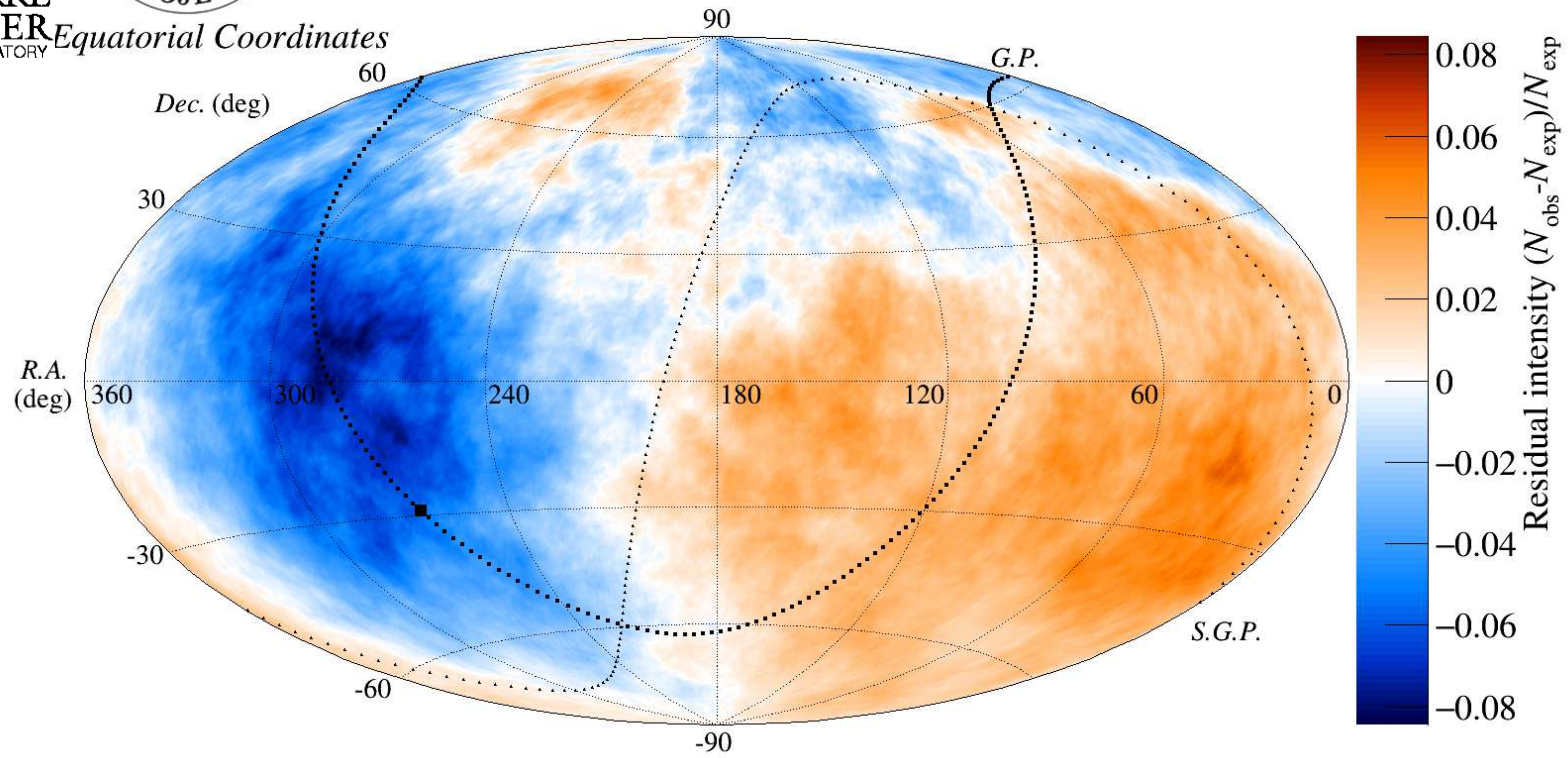


Summary and future perspectives

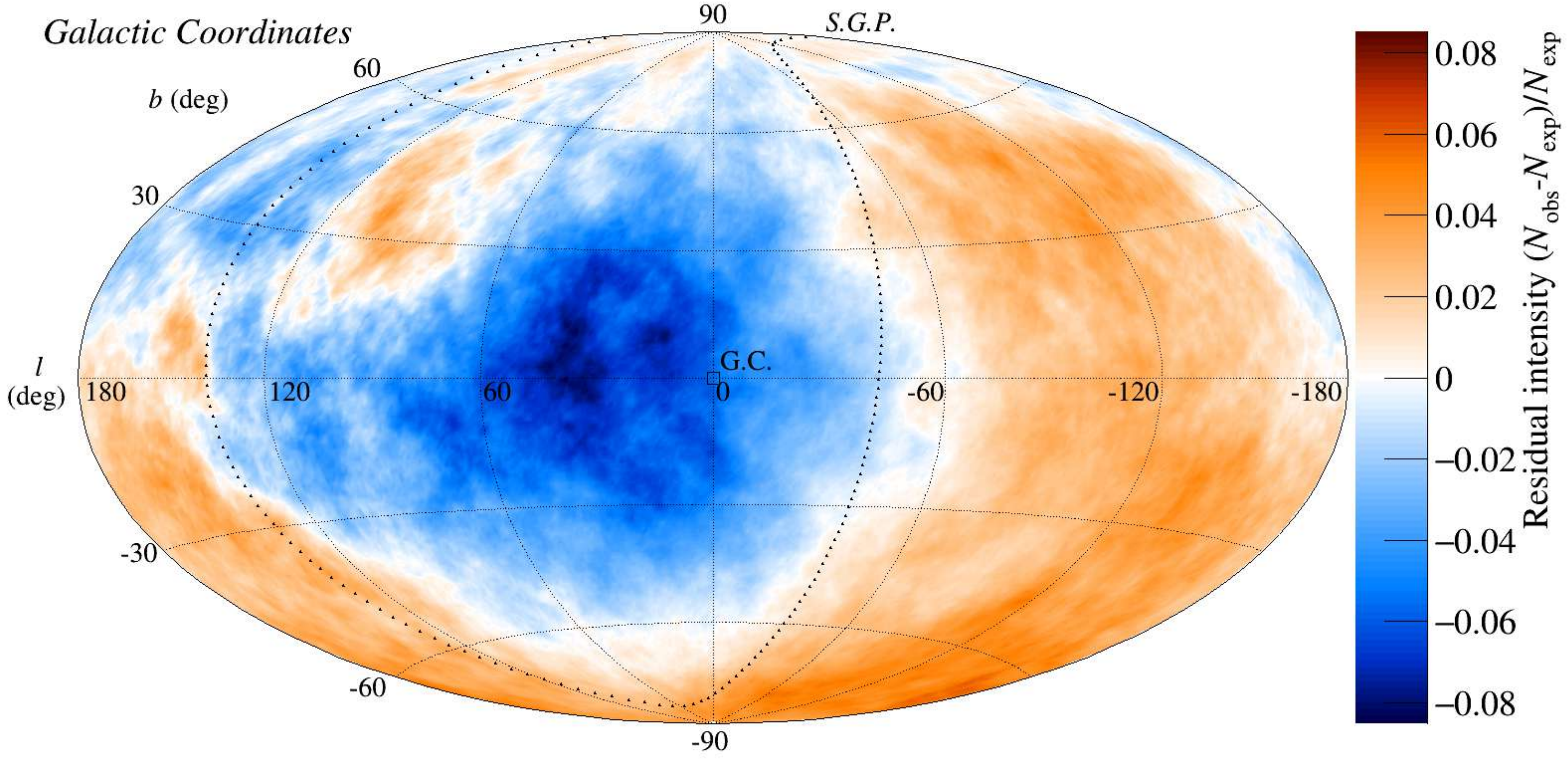
- **UHECRs**: the most energetic energetic and infrequent particles in the universe
  - Challenging the **next-generation astronomy using UHECRs**
    - **Less deflections** of the Galactic/extragalactic magnetic fields
    - **Limitation of "nearby" sources** due to GZK cutoff
      - **Directionally correlations between UHECRs and nearby inhomogeneous sources to clarify their origins**
- The highest energy event of Telescope Array experiment on May 27th 2021
  - **E = 244 ± 29 (stat.) +51,-76 (syst.) EeV** dubbed "Amaterasu" particle
    - **No obvious source candidates in arrival direction**
      - **R-process nuclei from Binary neutron star merger origin?**
- **Further data-collections of TA, its upgrade of TAx4 and future observatories are essential to clarify origins of most energetic particles**

Backup

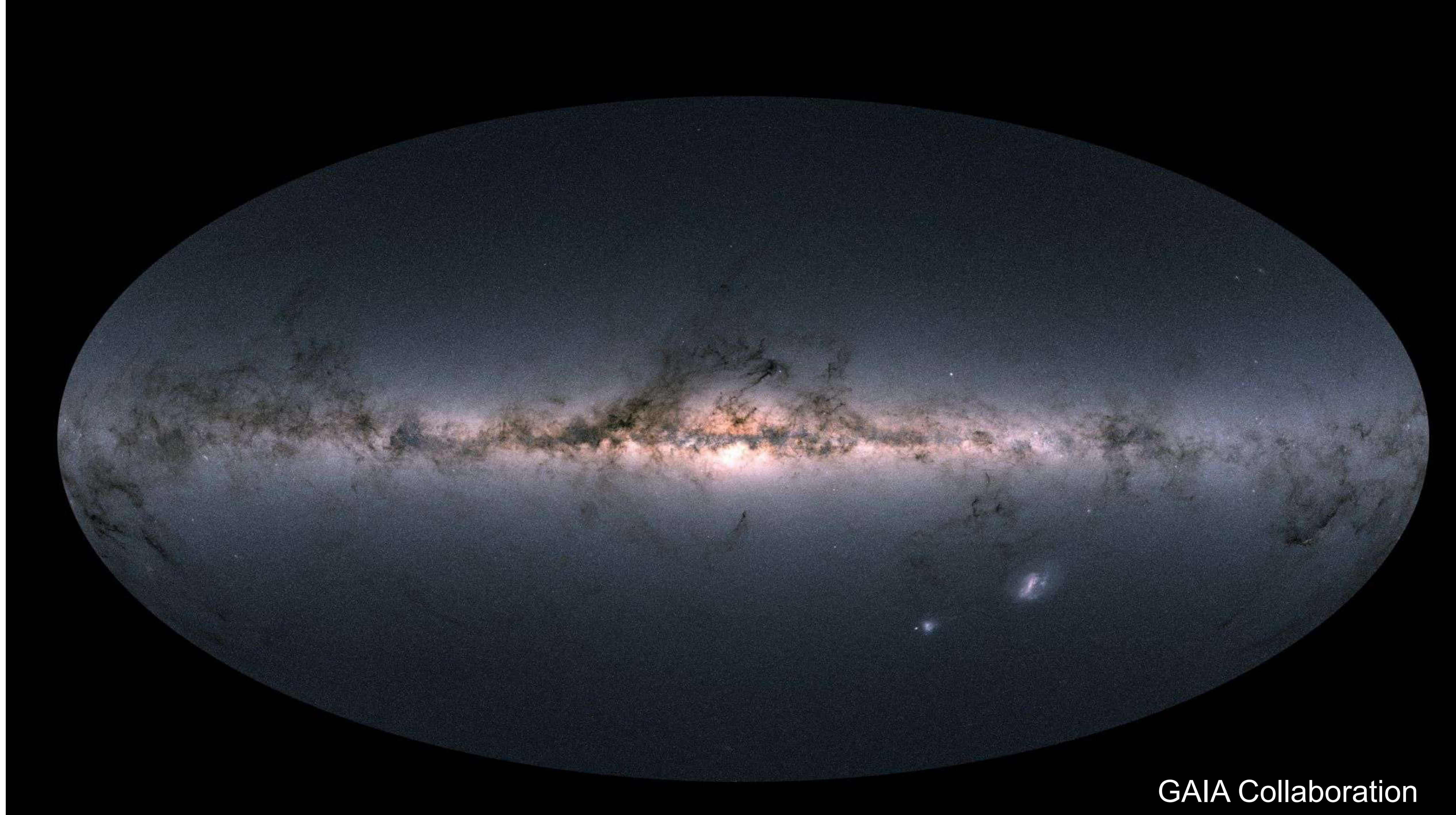
10 EeV skymap



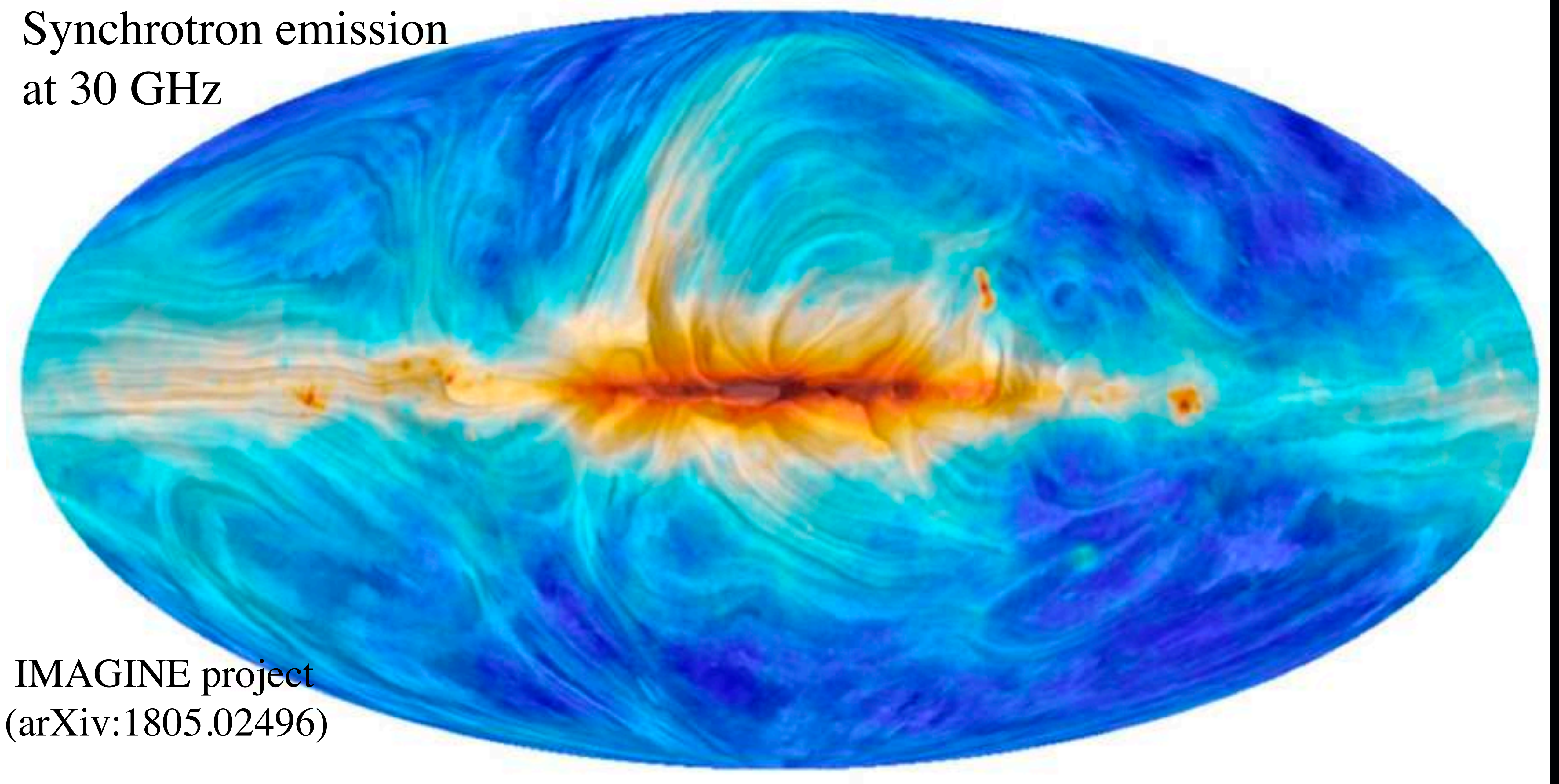
Converted to → **Galactic coordinates**



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



"Deciphering" magnetic fields

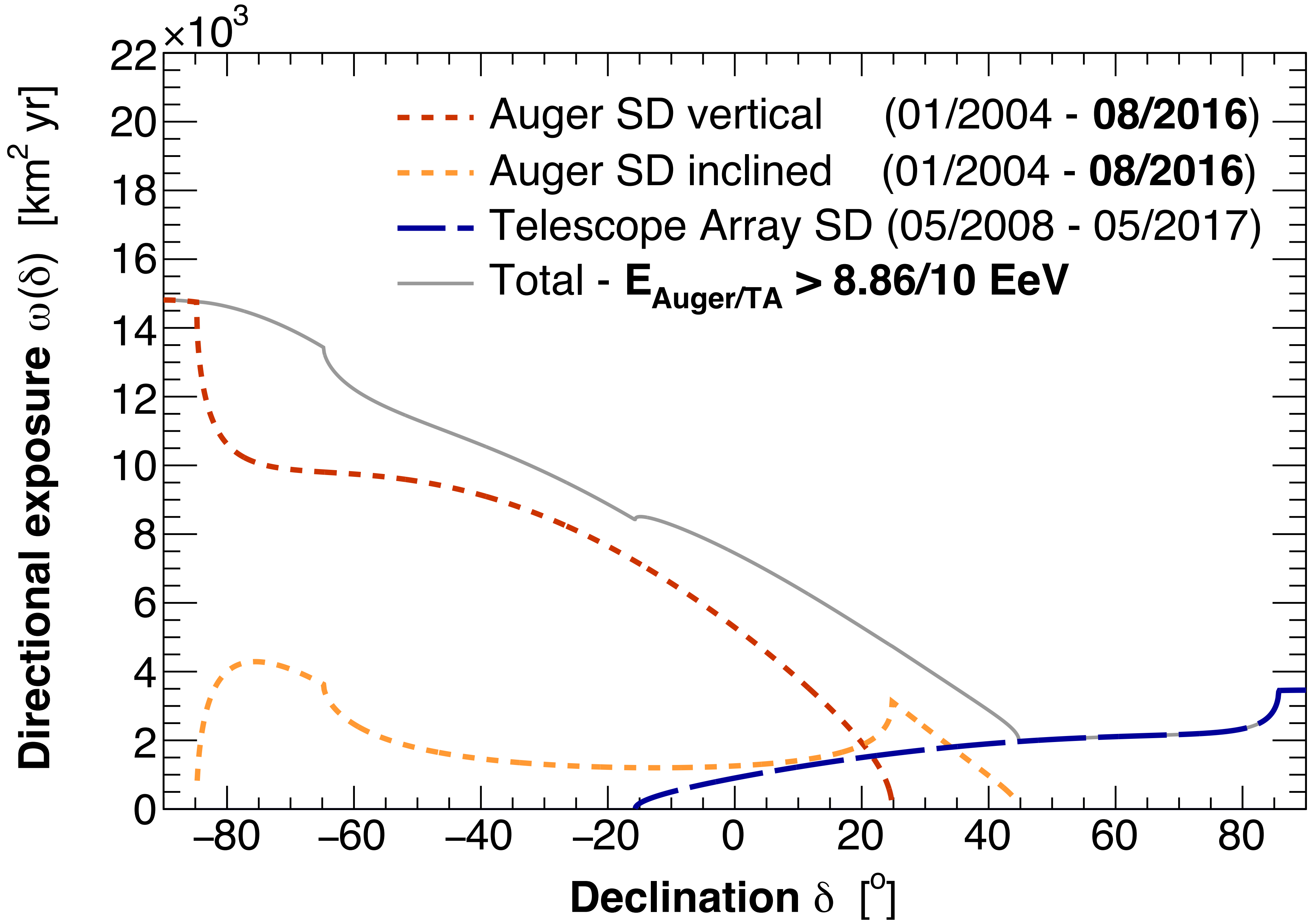


Multi-messenger synergies

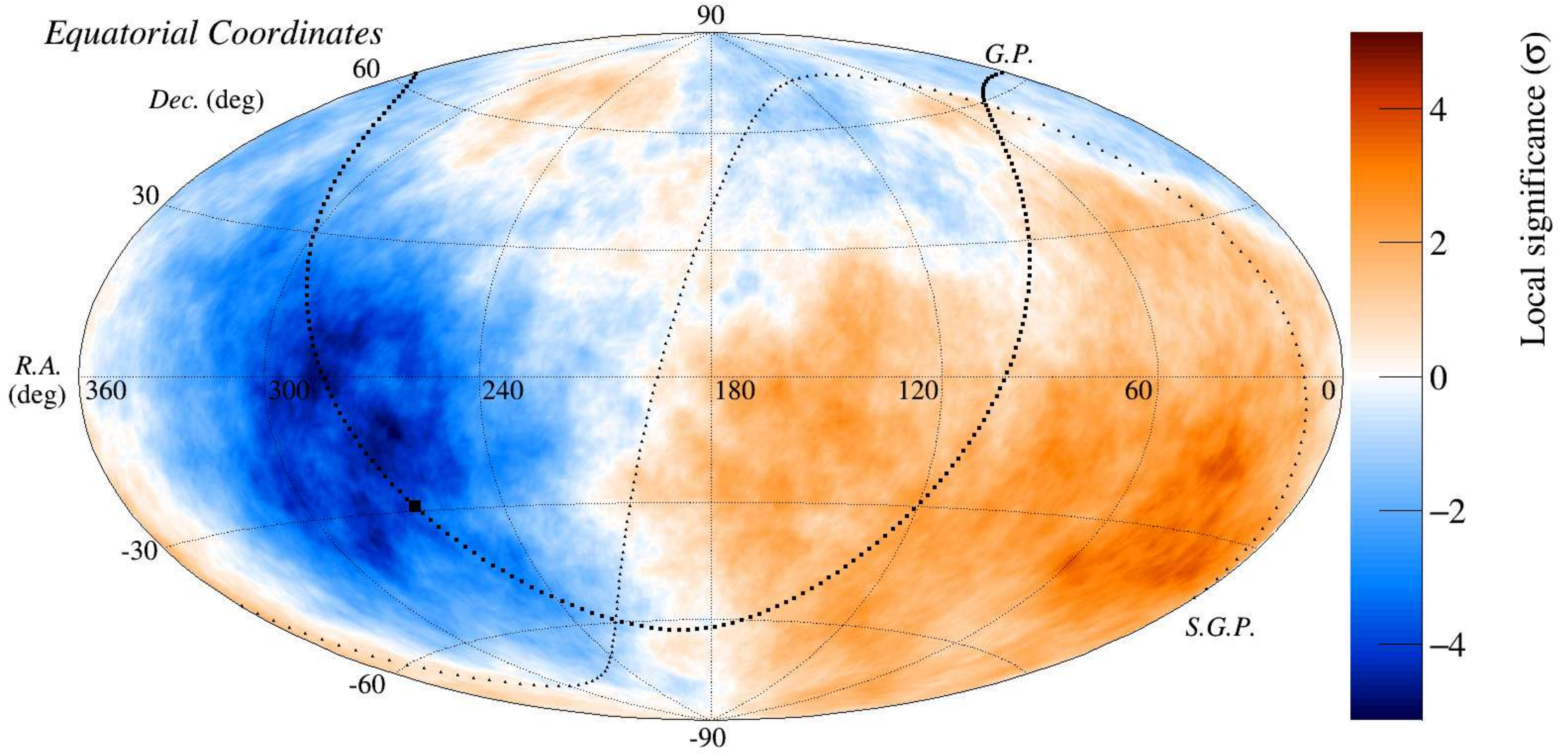
L. Lu, PoS(ICRC2023)1188

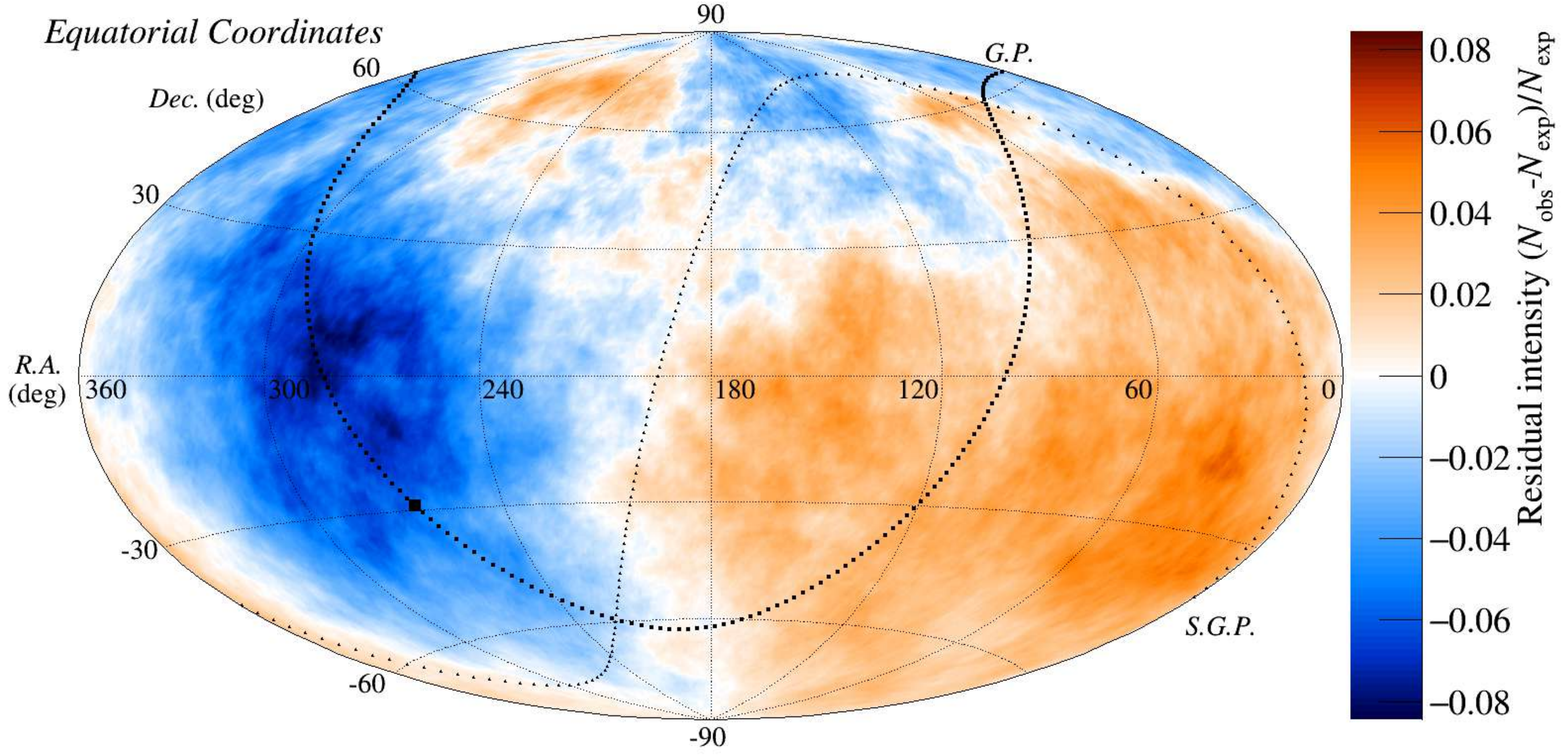
Auger and TA joint analysis for all-sky survey

- Energy calibration at common declination band



Auger/TA = 8.86/10 EeV

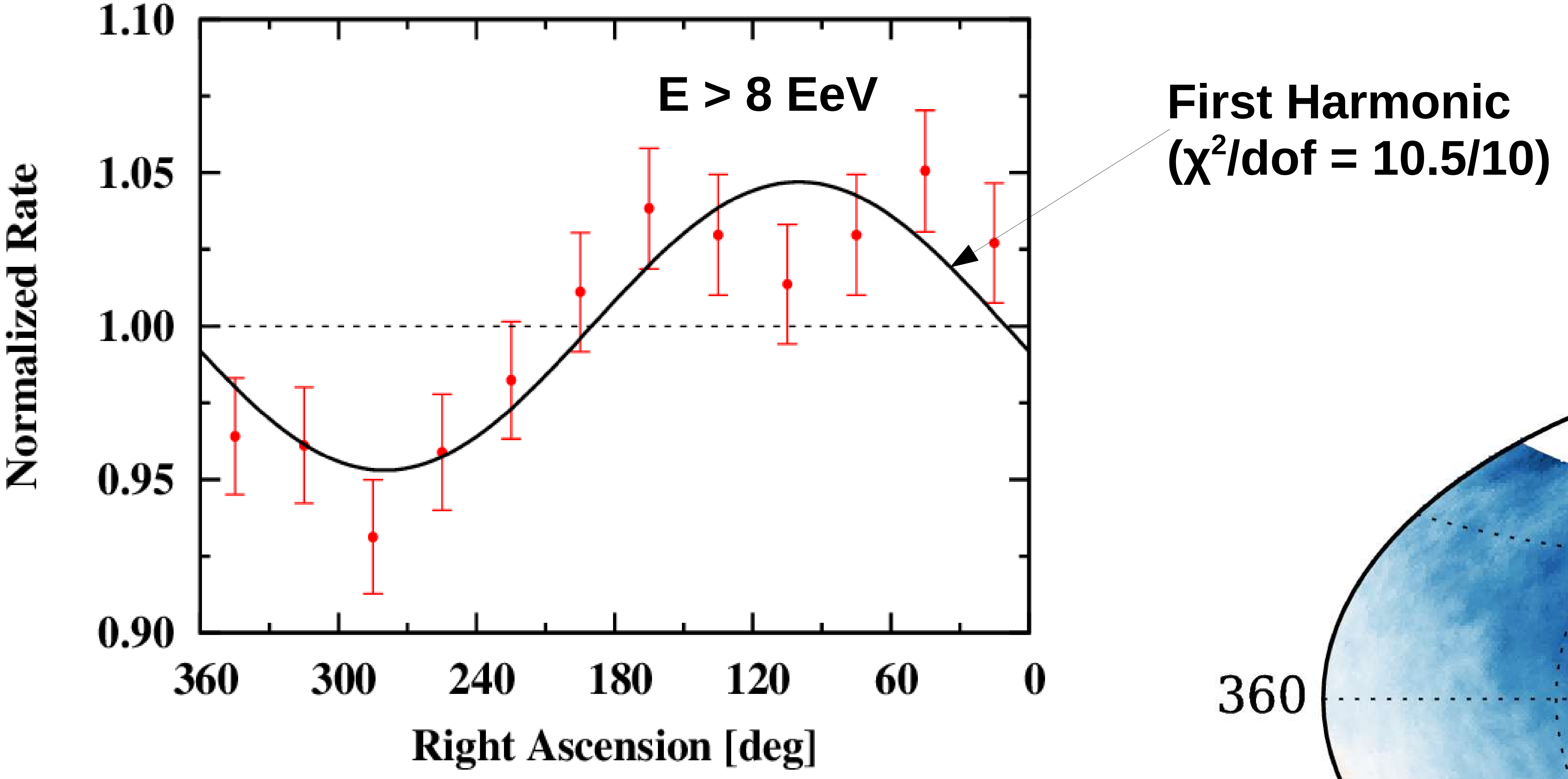




J. Biteau, TF et al., EPJ Web of Conferences 210, 01005 (2019) using a different color contour

Observation of dipole structure above 8 EeV

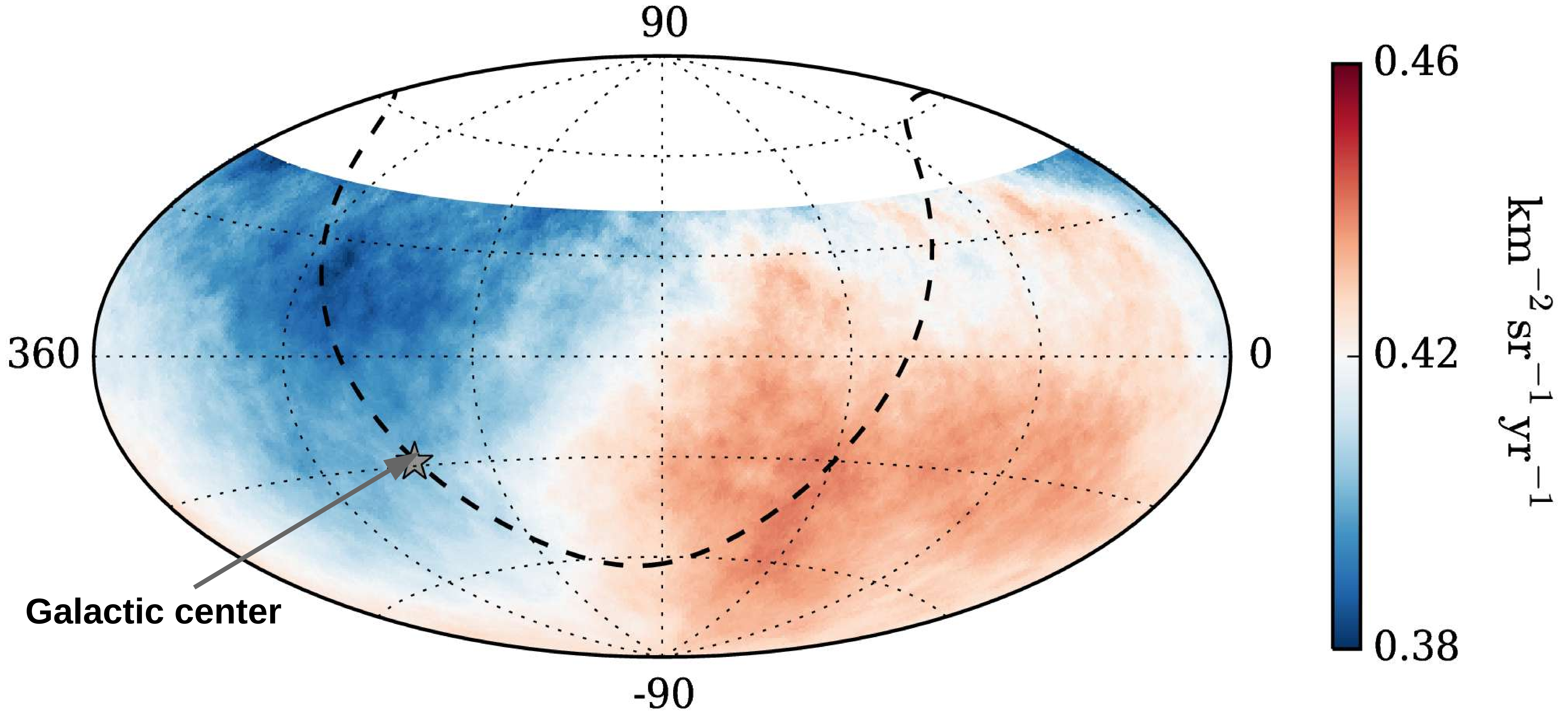
1 January 2004 - 31 August 2016, ~12 years



Harmonic analysis in right ascension α

E [EeV]	events	amplitude r	phase [deg.]	$P(\geq r)$
4-8	81701	$0.005^{+0.006}_{-0.002}$	80 ± 60	0.60
> 8	32187	$0.047^{+0.008}_{-0.007}$	100 ± 10	2.6×10^{-8}

significant modulation at 5.2σ (5.6σ before penalization for energy bins explored)



Energy dependence on the dipole amplitude

The Astrophysical Journal, 891:142 (10pp), 2020 March 10 Aab et al.

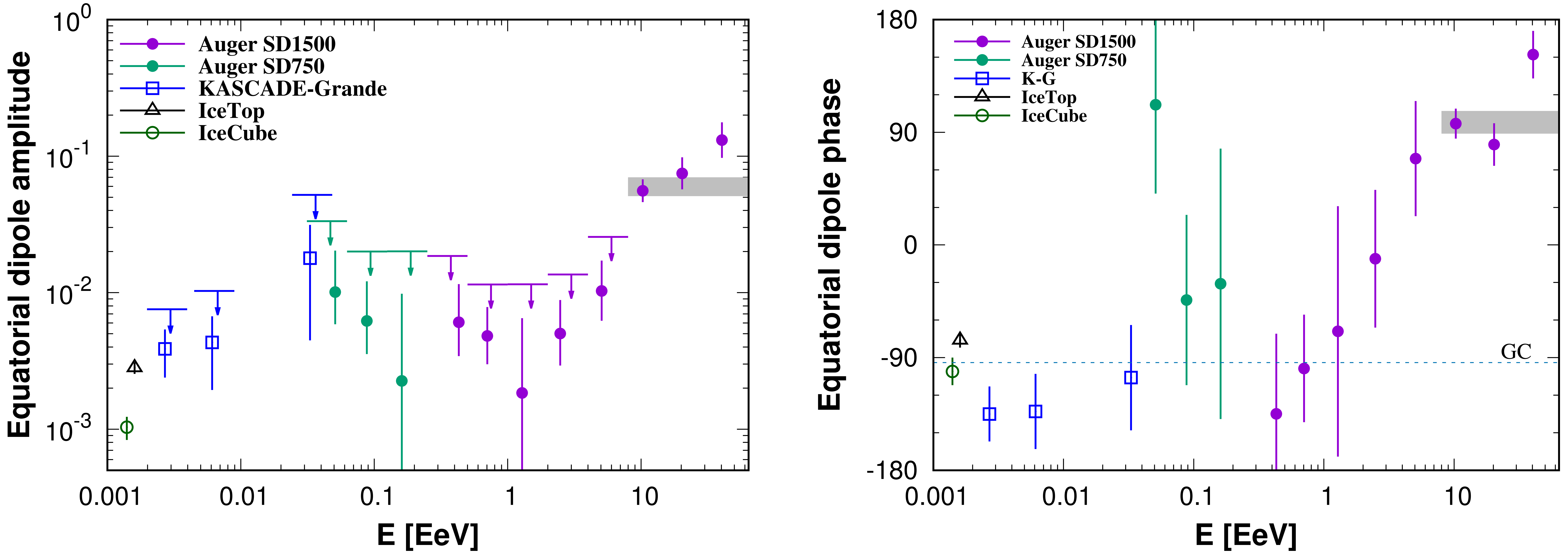
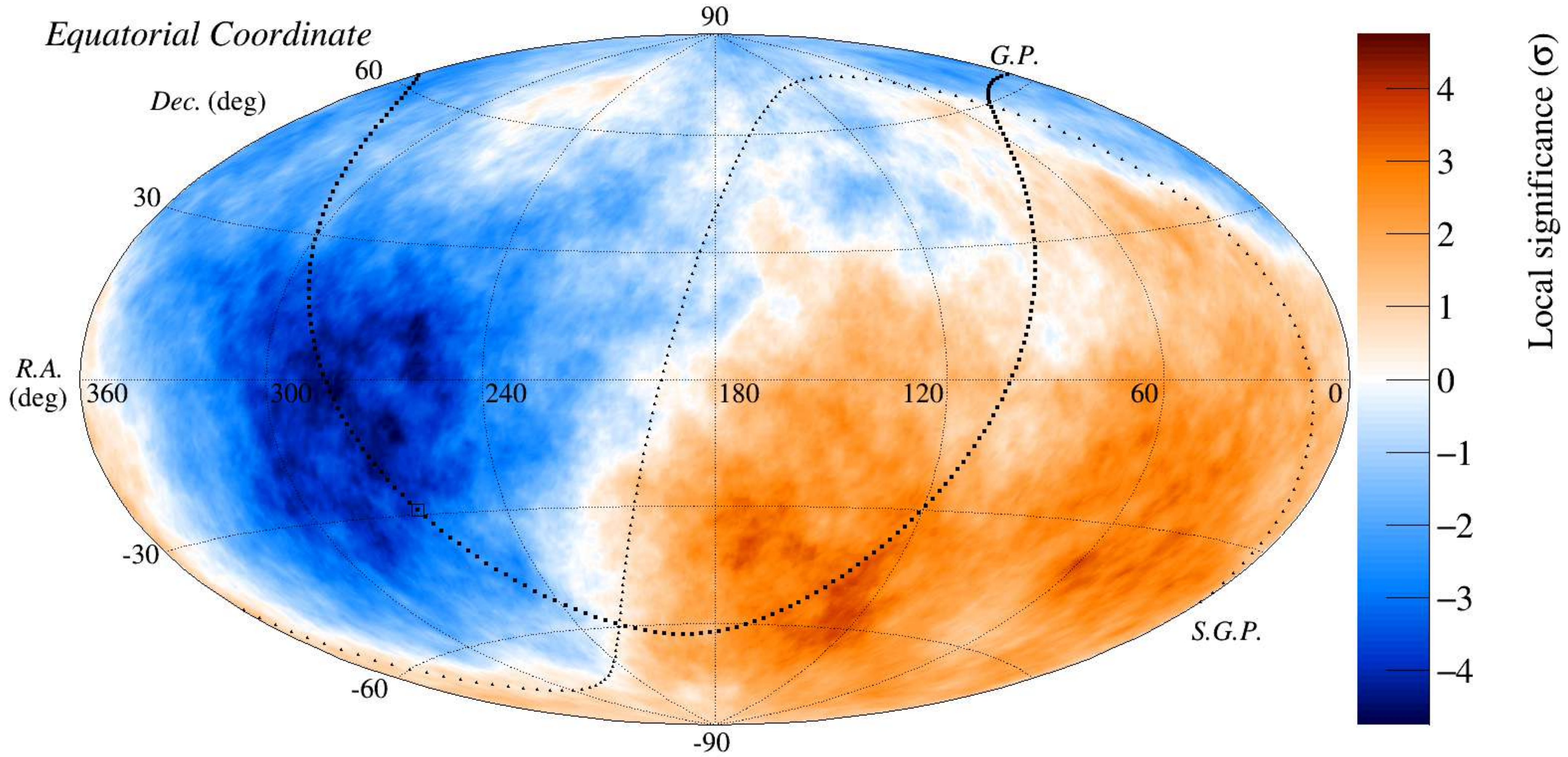


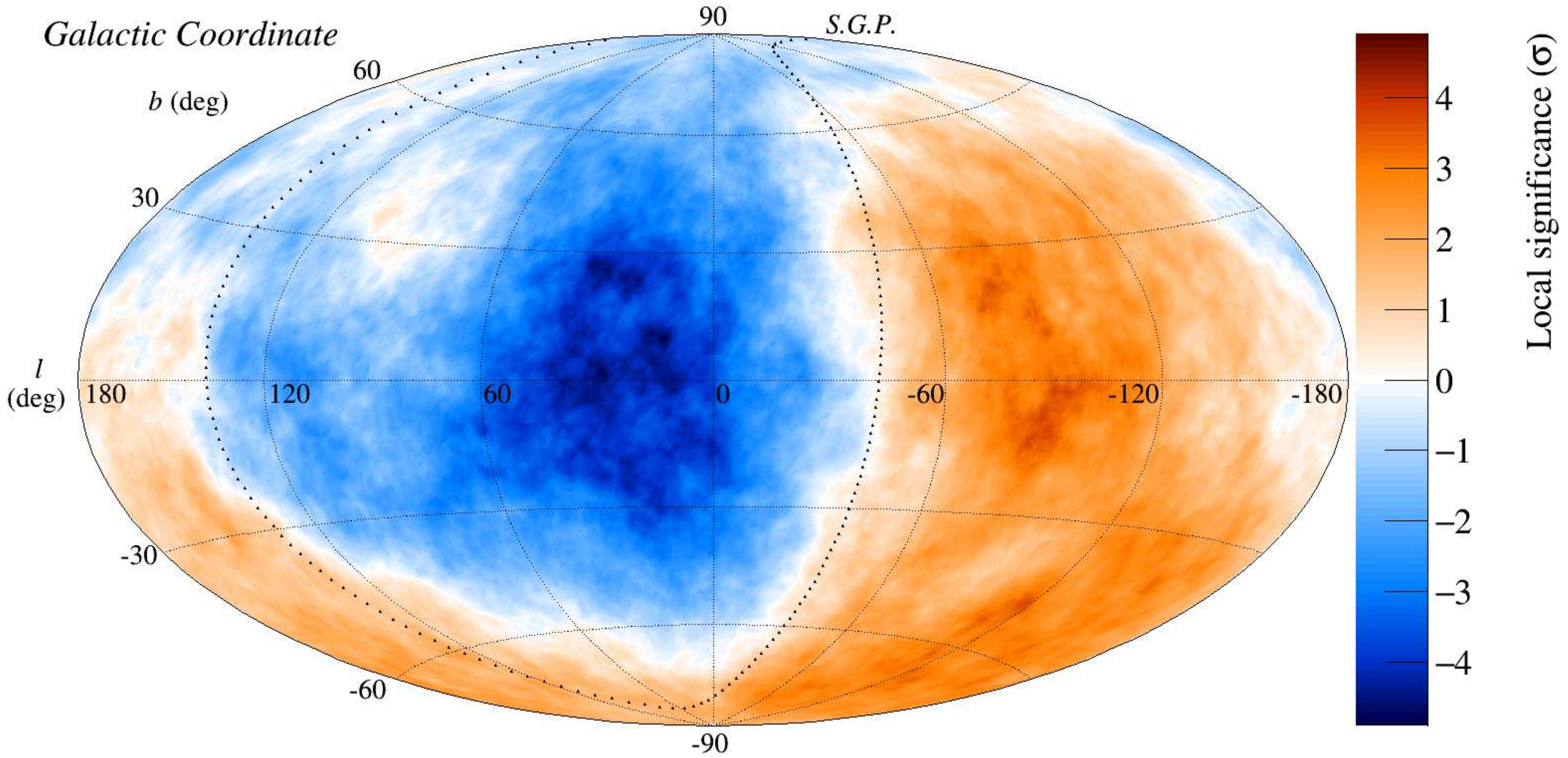
Figure 1. Reconstructed equatorial dipole amplitude (left) and phase (right). The upper limits at 99% CL are shown for all the energy bins in which the measured amplitude has a chance probability greater than 1%. The gray bands indicate the amplitude and phase for the energy bin $E \geqslant 8$ EeV. Results from other experiments are shown for comparison (IceCube Collaboration 2012, 2016; KASCADE-Grande Collaboration 2019).

Pierre Auger Collaboration, ApJ 891, 142 (2020)

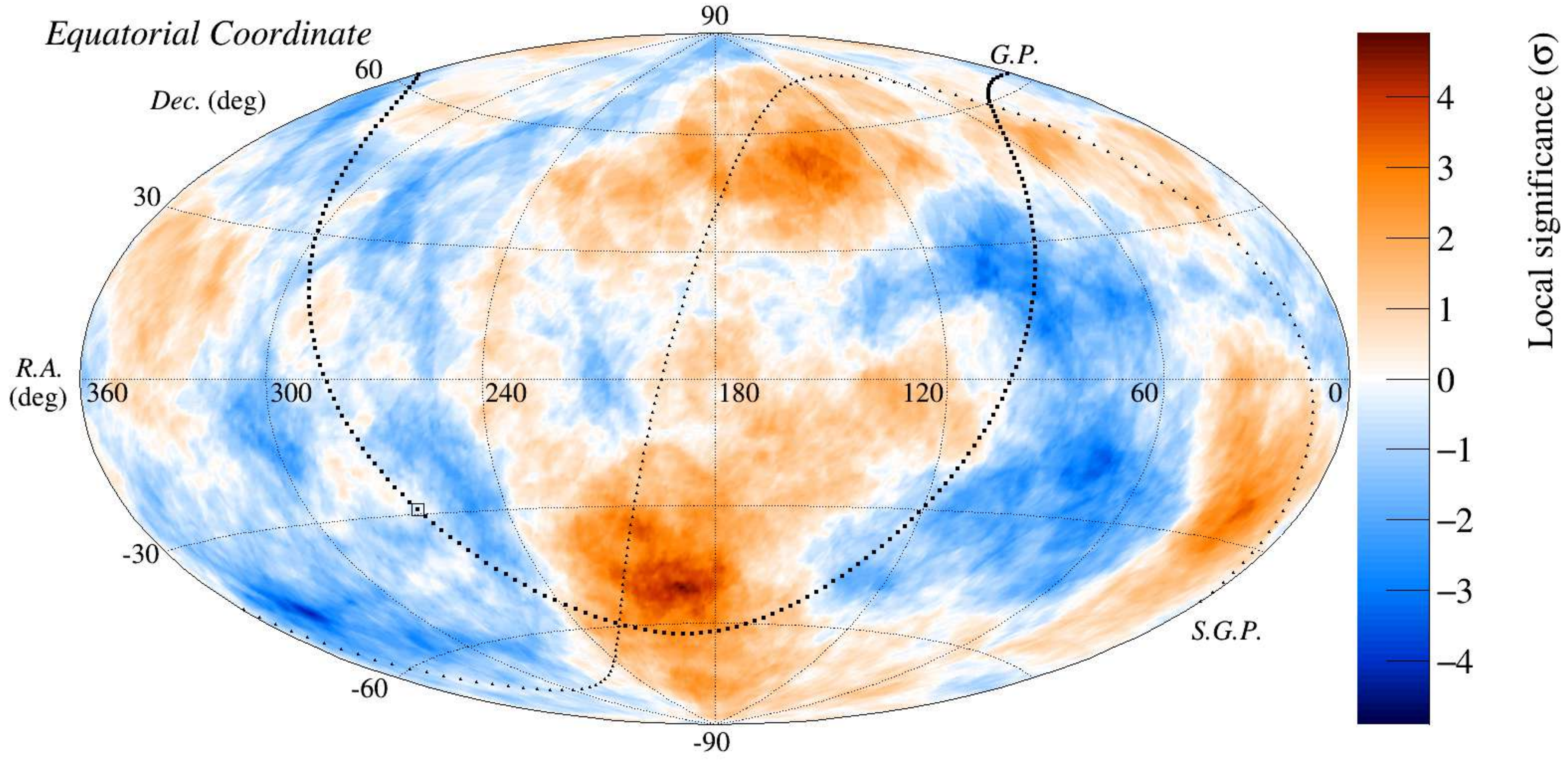
UHECR full-sky by TA and Auger

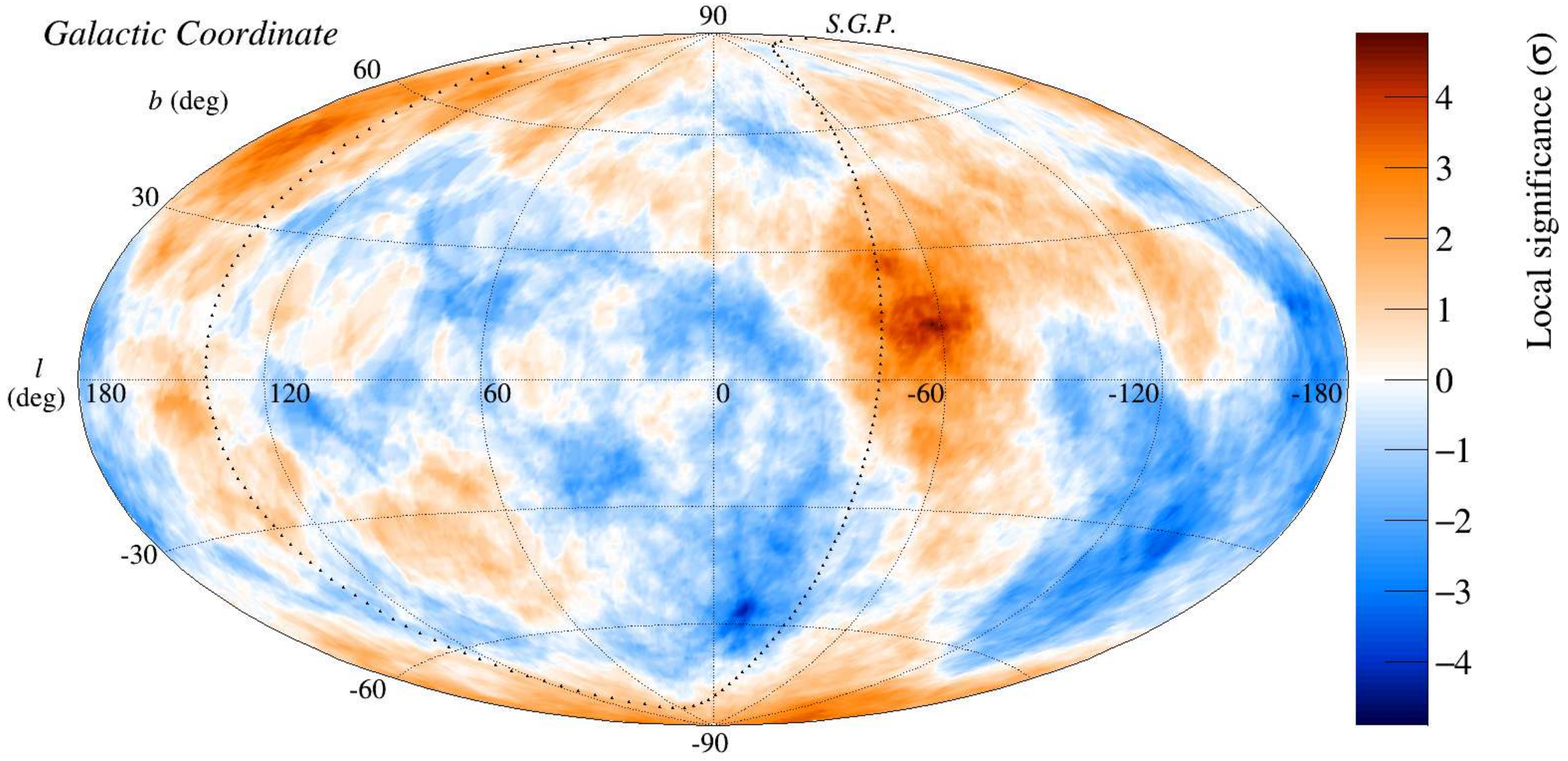
Ankle (E_{TA}>10 EeV, E_{Auger}>8.86 EeV) 45° circle



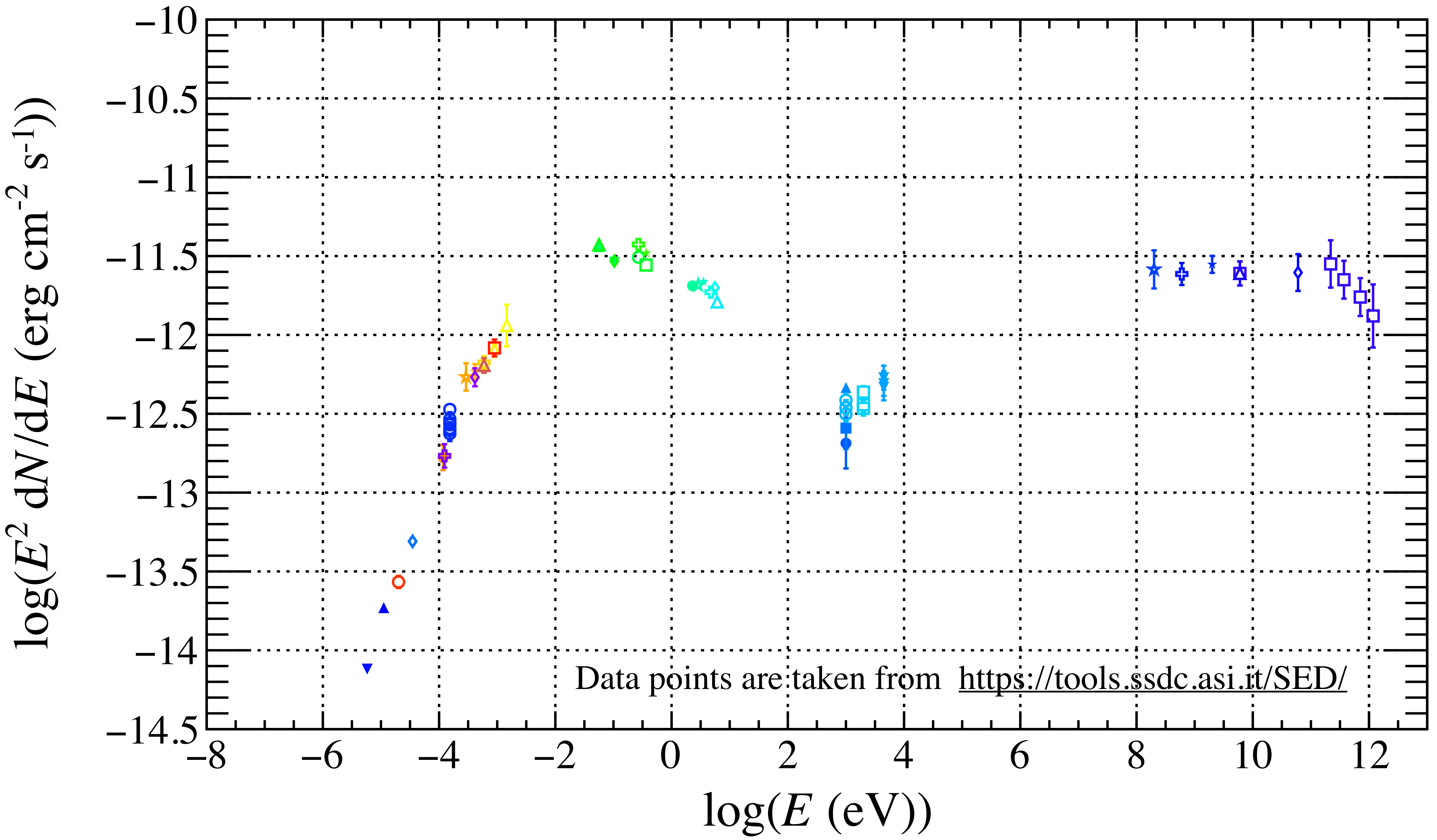


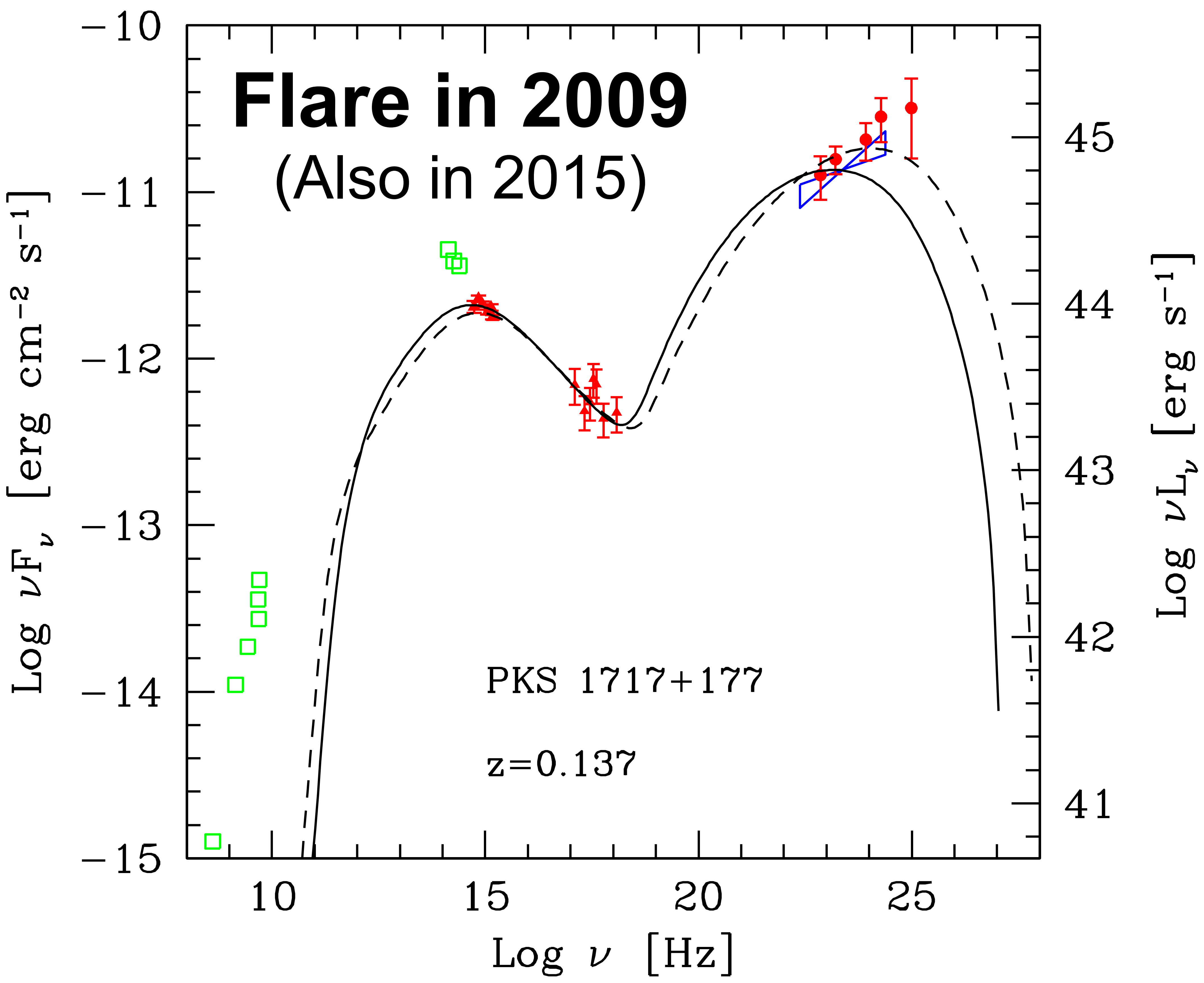
Suppression (E_{TA}>52.3 EeV E_{Auger}>40 EeV) 20° circle





Spectral Energy Distribution (SED) of PKS 1717+177





Cosmic ray with 300 EeV	P	He	Be	C	N	O	Si	Fe
Energy loss length (Mpc)	20	3	0.3	8	1.5	1.0	1.0	10

Too distant (~600 Mpc) to detect UHECR due to GZK cutoff