

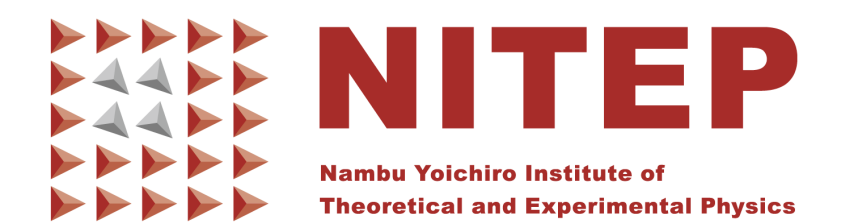
Review of ultra-high-energy cosmic rays (UHECRs) with air-shower experiments

FUJII, Toshihiro 藤井 俊博

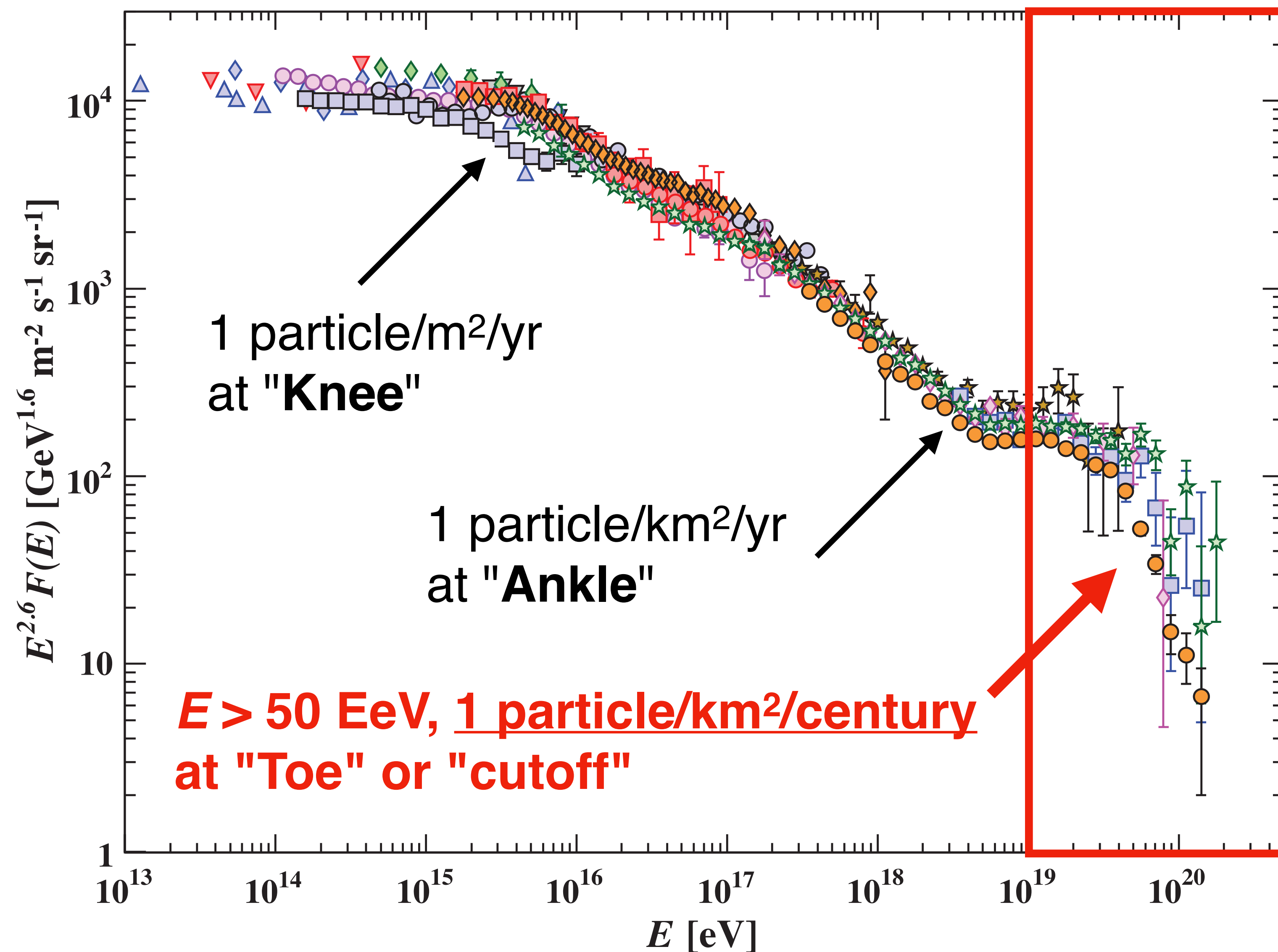
toshi@omu.ac.jp

Osaka Metropolitan University (OMU)
Nambu Yoichiro Institute of Theoretical
and Experimental Physics (NITEP)

Next Frontiers in Magnetic Monopole Searches
September 12, 2026, Beijing, China

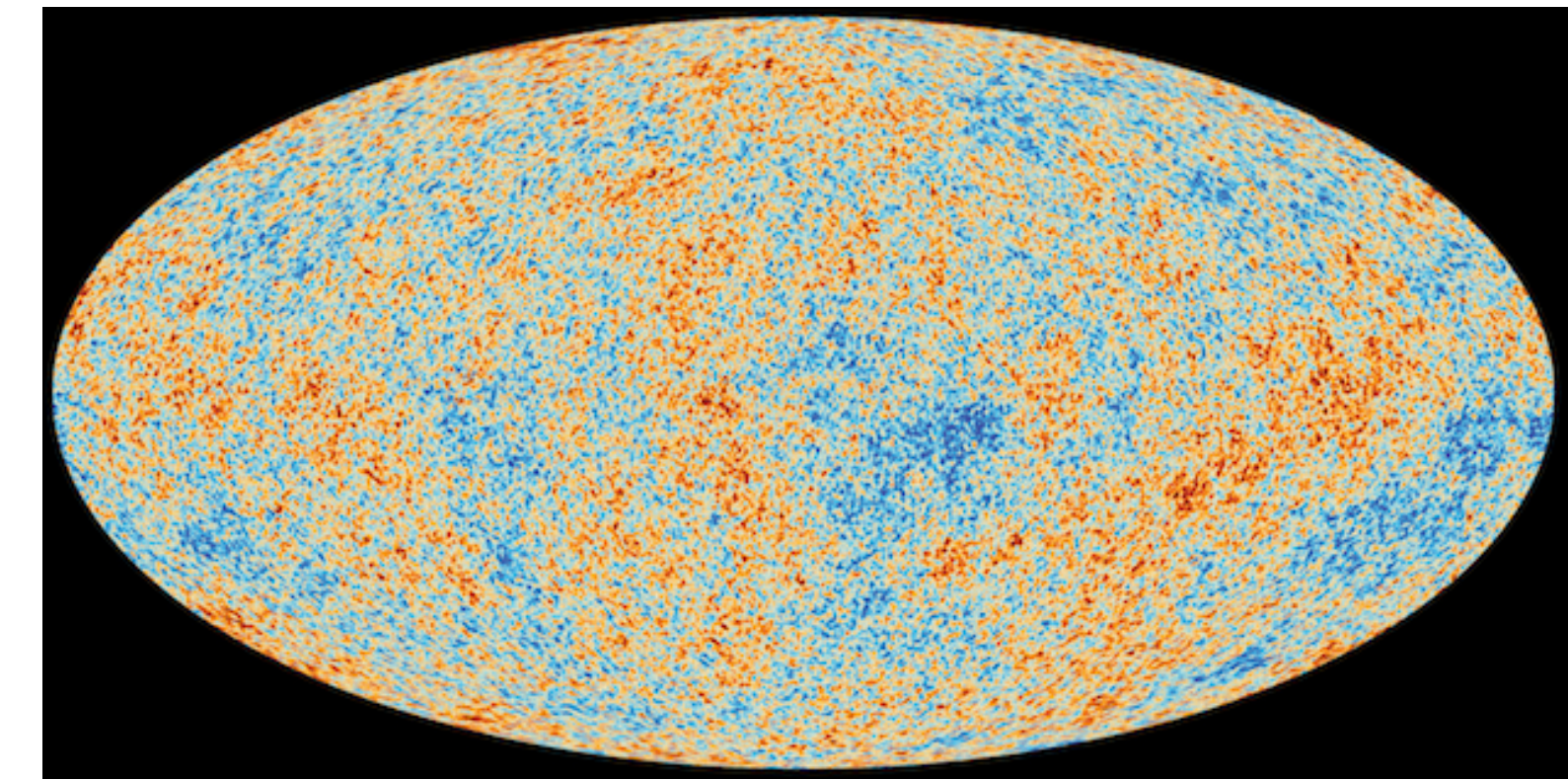
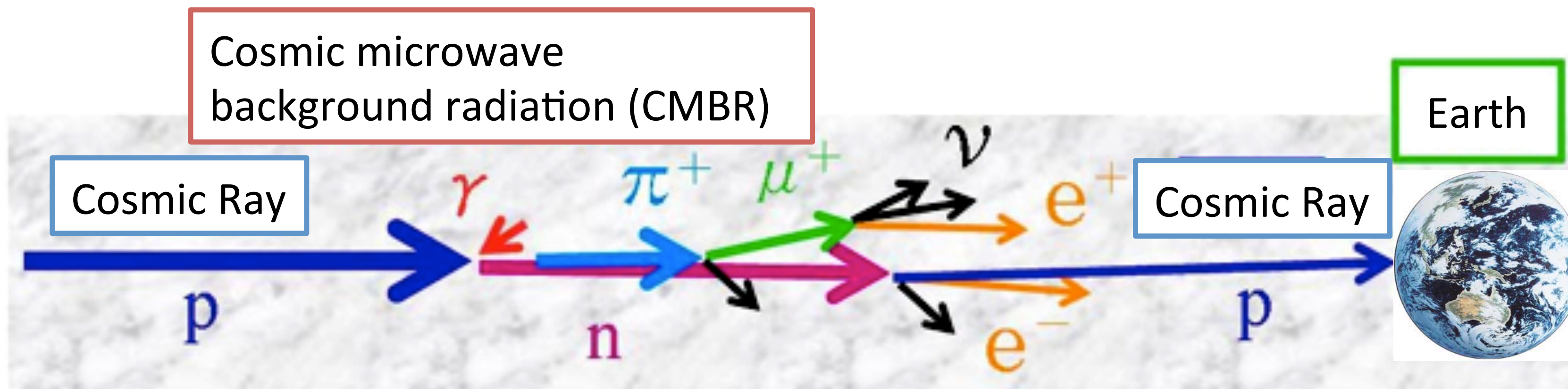


Energy spectrum of cosmic rays



- 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 $\sim 10^{13} \text{ eV}$ by the Earth's largest particle accelerator
- Extremely infrequent
- A huge effective area, $\sim 1000 \text{ km}^2$
- Long term observation in decades

Greisen–Zatsepin–Kuzmin (GZK) Cutoff ³



Planck Collaboration

- Interaction between >50 EeV proton and cosmic microwave backgrounds (CMB) via **pion production**
- Heavier nuclei also interact via **photo-disintegration**
- Mean free path: **50-100 Mpc (cosmological neighborhood)**
- Cutoff feature expected above 50 EeV**
- The universe's largest interactions** between the most energetic particles and the oldest photons

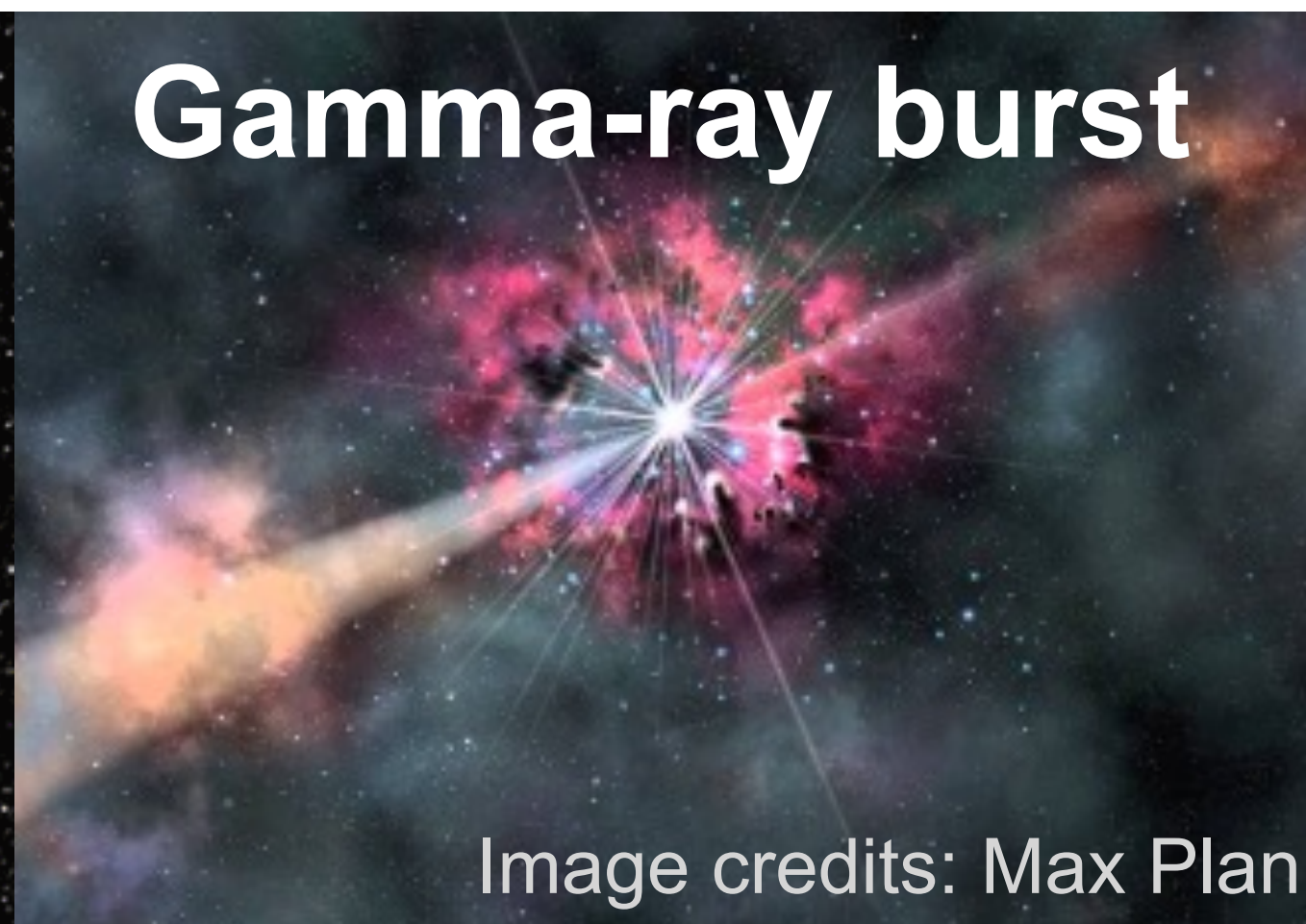
$$p + \gamma_{\text{CMB}} \rightarrow \Delta^+ \rightarrow p + \pi^0$$

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

Possible source candidates, next-generation astronomy⁴



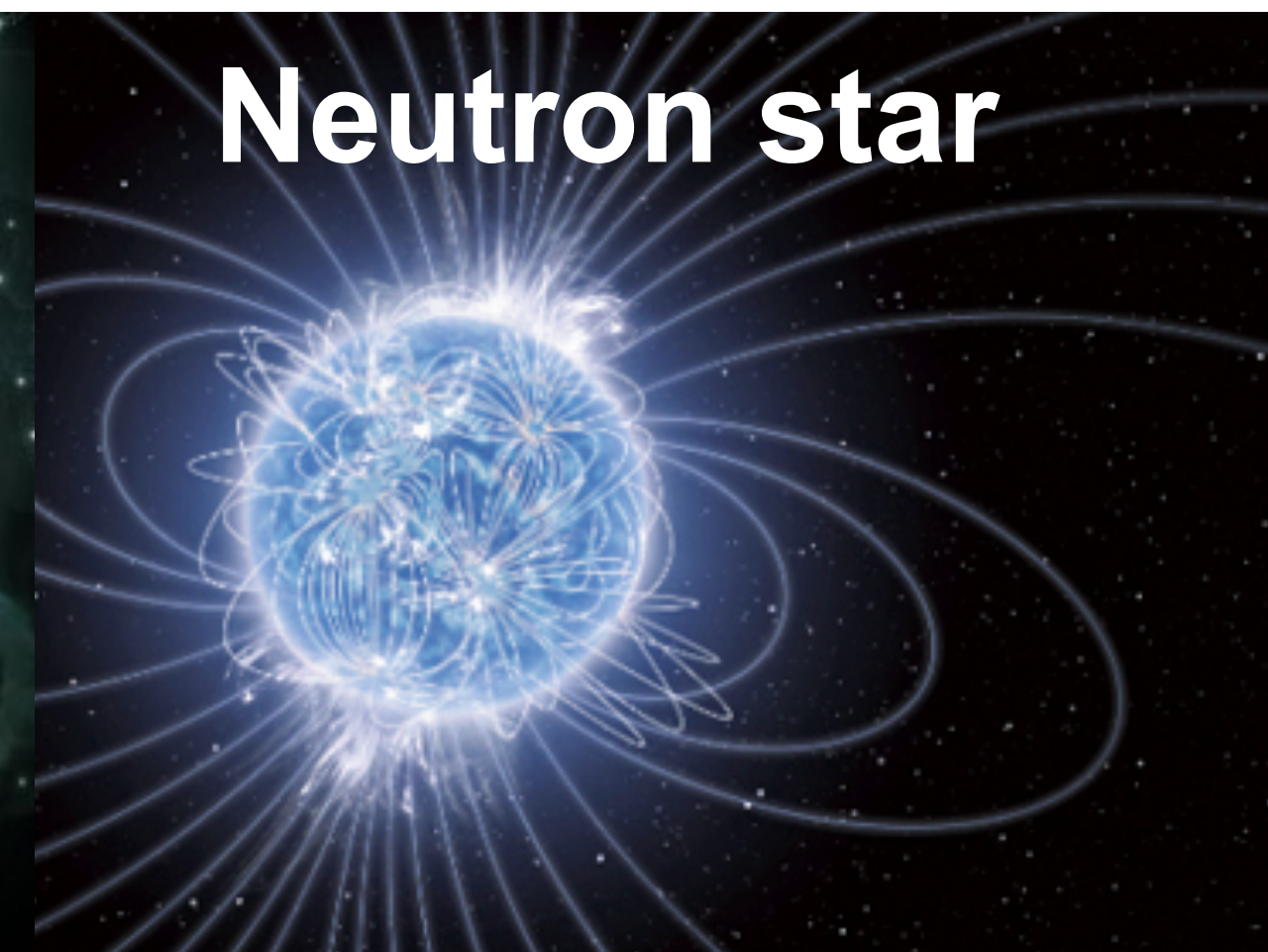
Supernova
remnant



Gamma-ray burst



Active
galactic nuclei



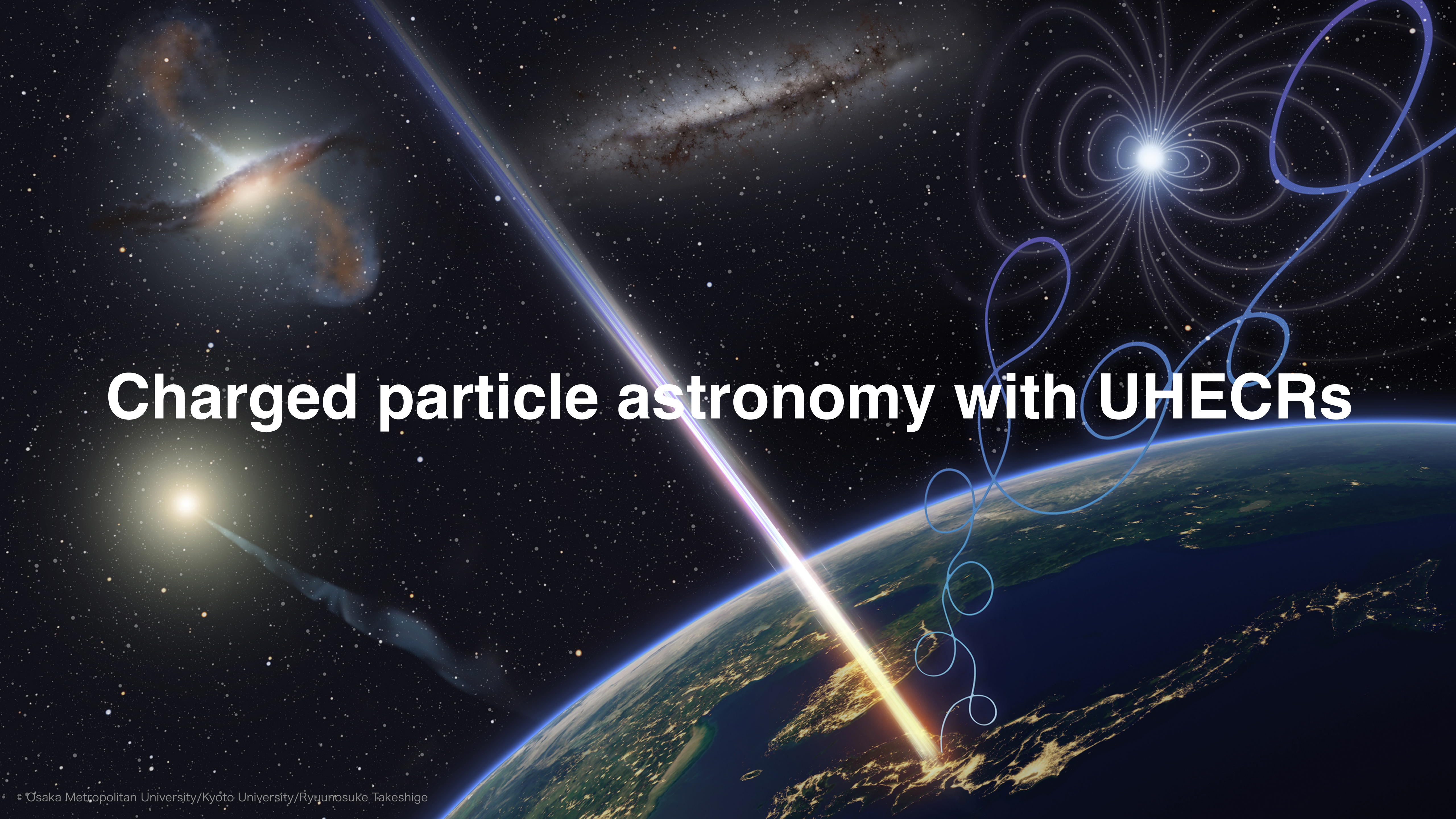
Neutron star

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

or "New physics", such as
magnetic monopoles

- 📌 **Limitation of nearby sources** due to GZK cutoff
- 📌 **Less deflections** by Galactic/extragalactic magnetic fields $\theta \sim 10^\circ Z \left(\frac{E}{10 \text{ EeV}} \right)^{-1}$
- 📌 Directional correlations between **UHECRs** and **nearby sources**
to identify their origins
- 📌 **A next-generation astronomy using charged particles**

Charged particle astronomy with UHECRs

The background of the slide is a deep space image featuring a bright yellow star in the lower-left, a blue and white nebula in the upper-left, and a distant galaxy in the upper-center. A vibrant, multi-colored streak (purple, blue, green, yellow) representing a particle track cuts diagonally across the frame. In the lower-right, the Earth's horizon is visible with city lights. Overlaid on the right side are blue, glowing magnetic field lines spiraling around a bright point, and a series of blue loops trailing from the particle track towards the Earth.

How to detect extremely infrequent UHECRs?

6



→ **Extensive air showers**

How to detect extremely infrequent UHECRs?

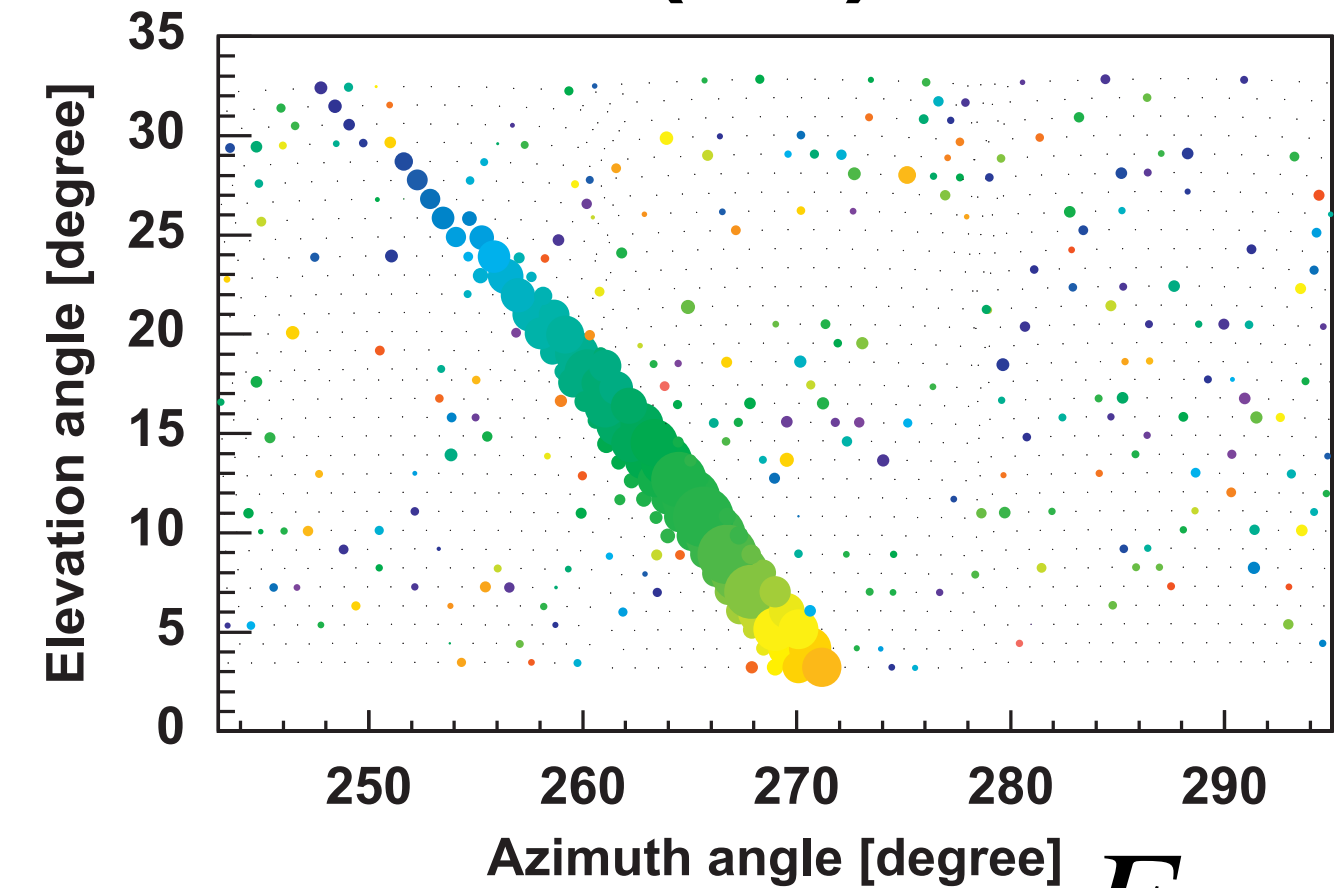
Extensive air showers

Surface detector array

Fluorescence detector

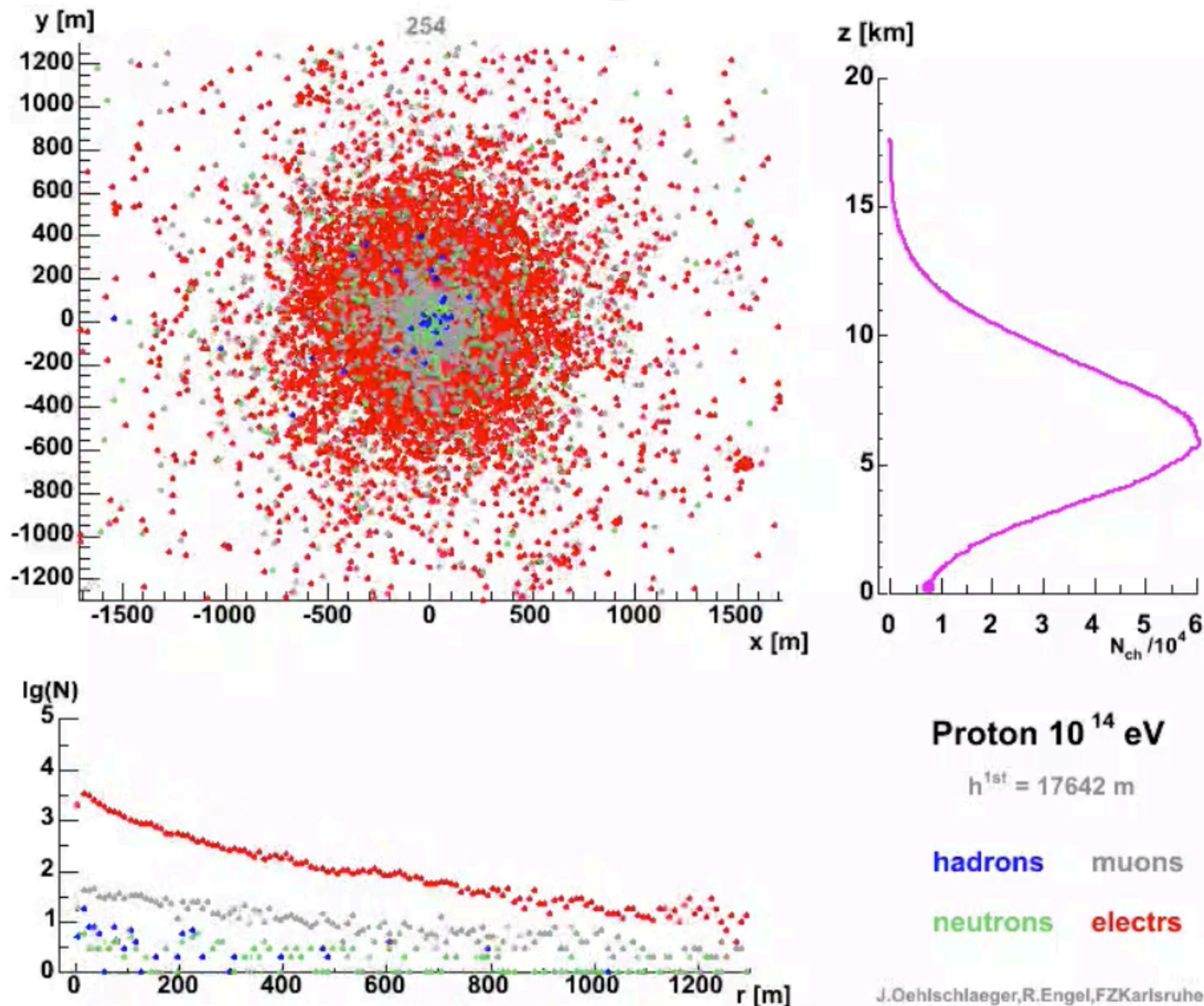
Observing extensive air showers and mass composition 8

Fluorescence detector (FD)



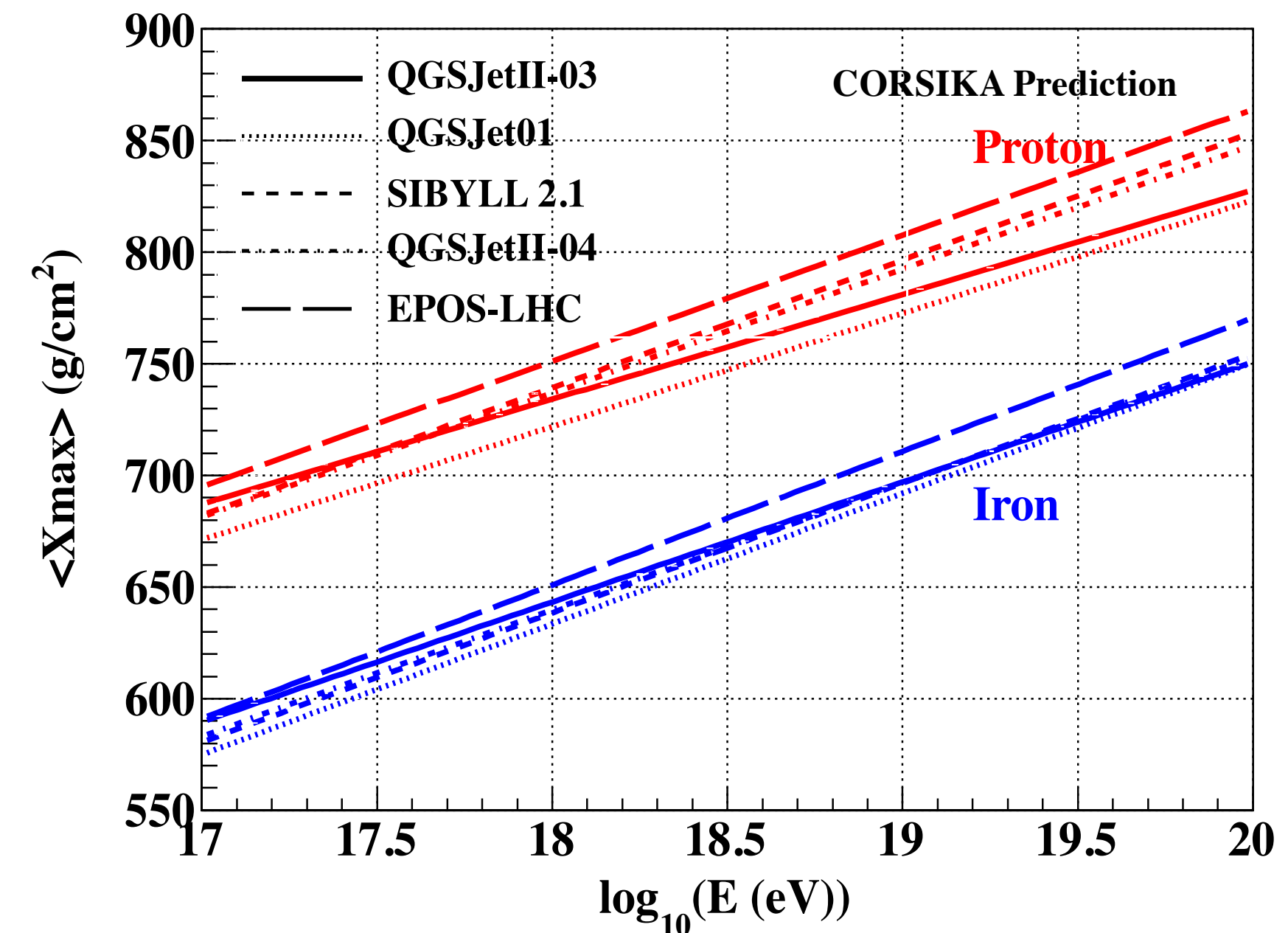
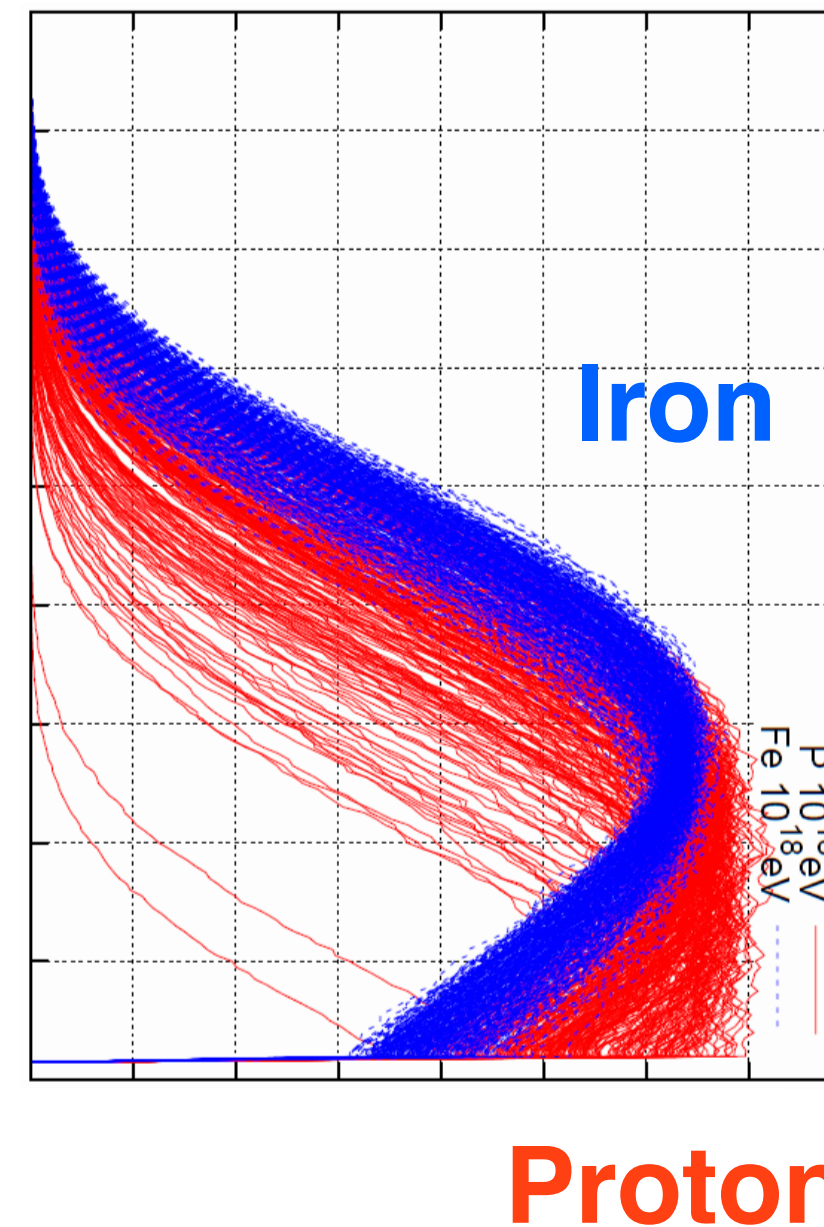
$X_{\max}$ measurements for
mass composition (Z)

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



Surface detector array (SD)

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



Latest UHECR observatories



Google Earth



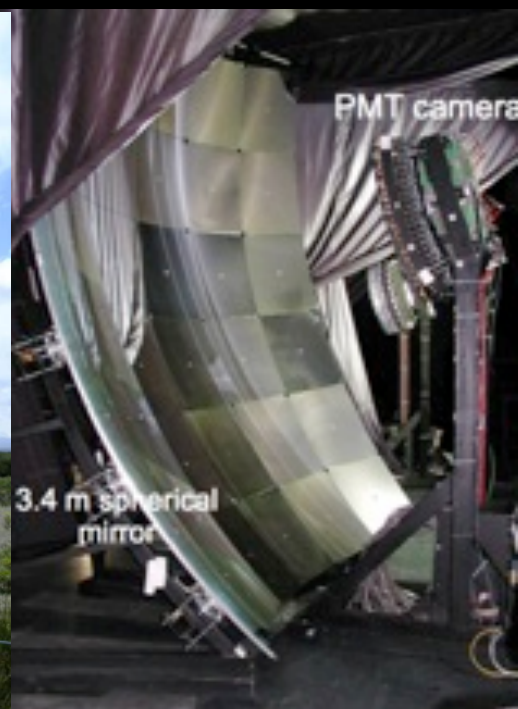
Telescope Array Experiment (TA)

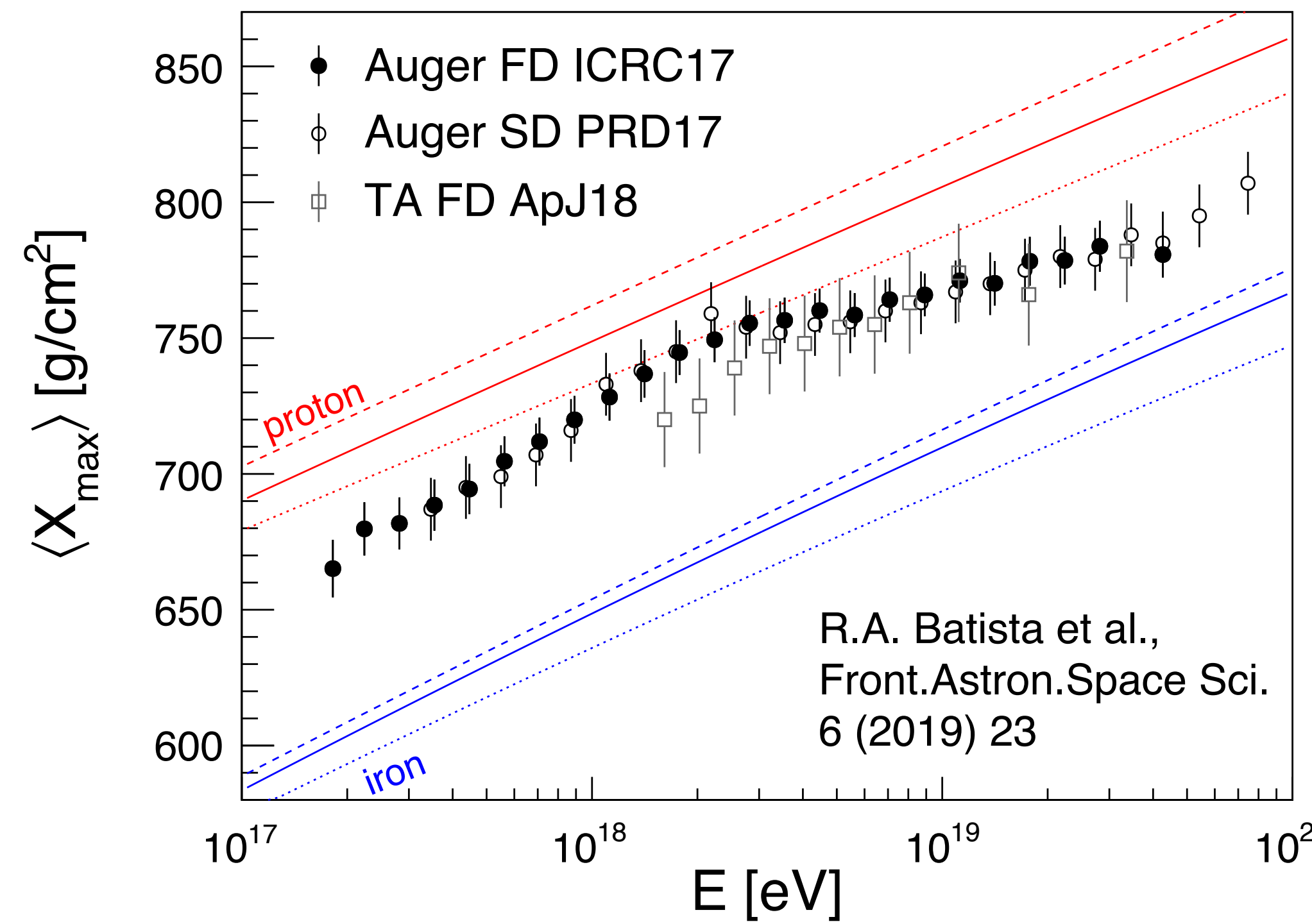
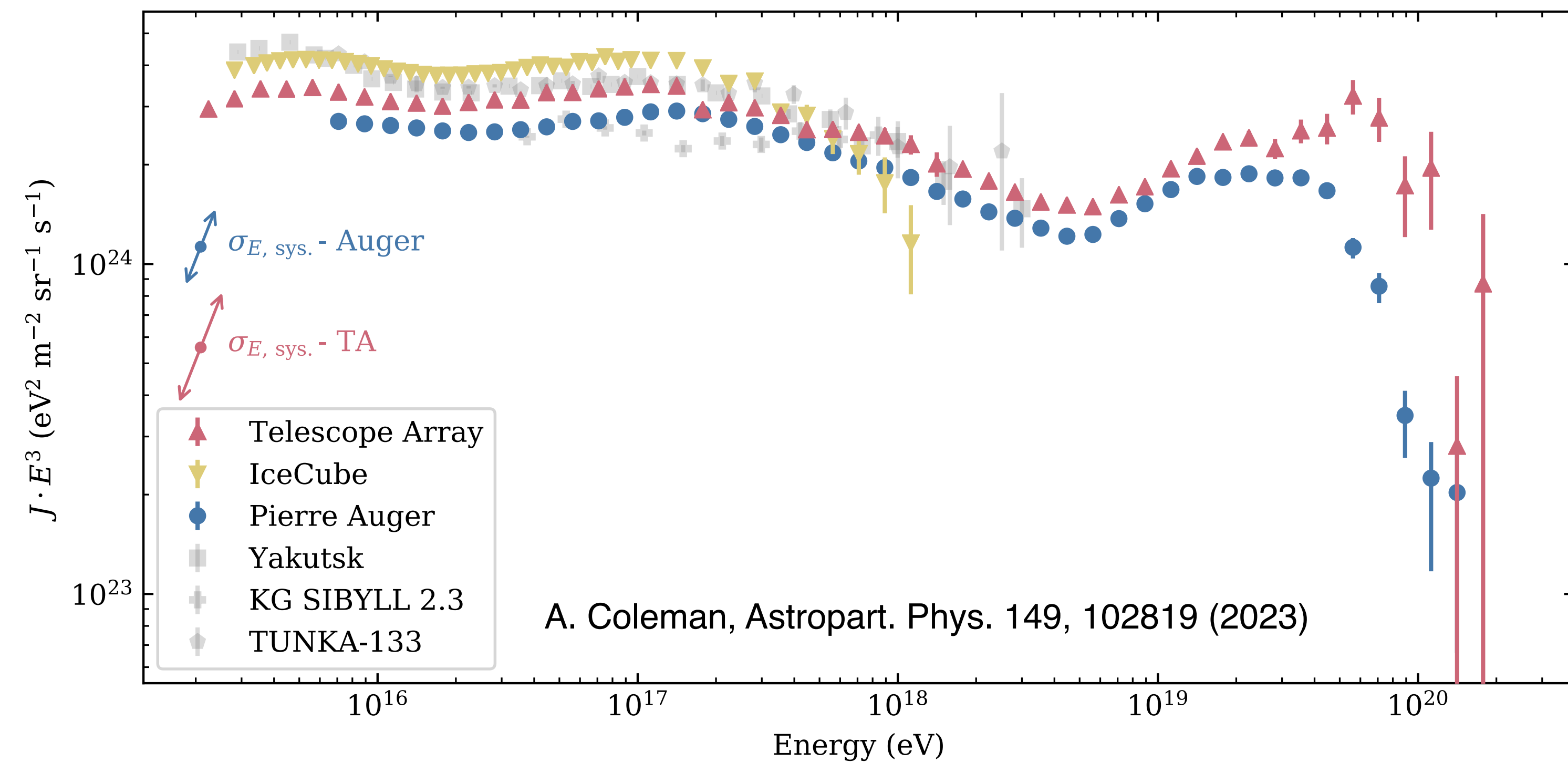
- Utah, USA
- 2008~, 700 km²
- TA×4 → 2800 km²



Pierre Auger Observatory (Auger)

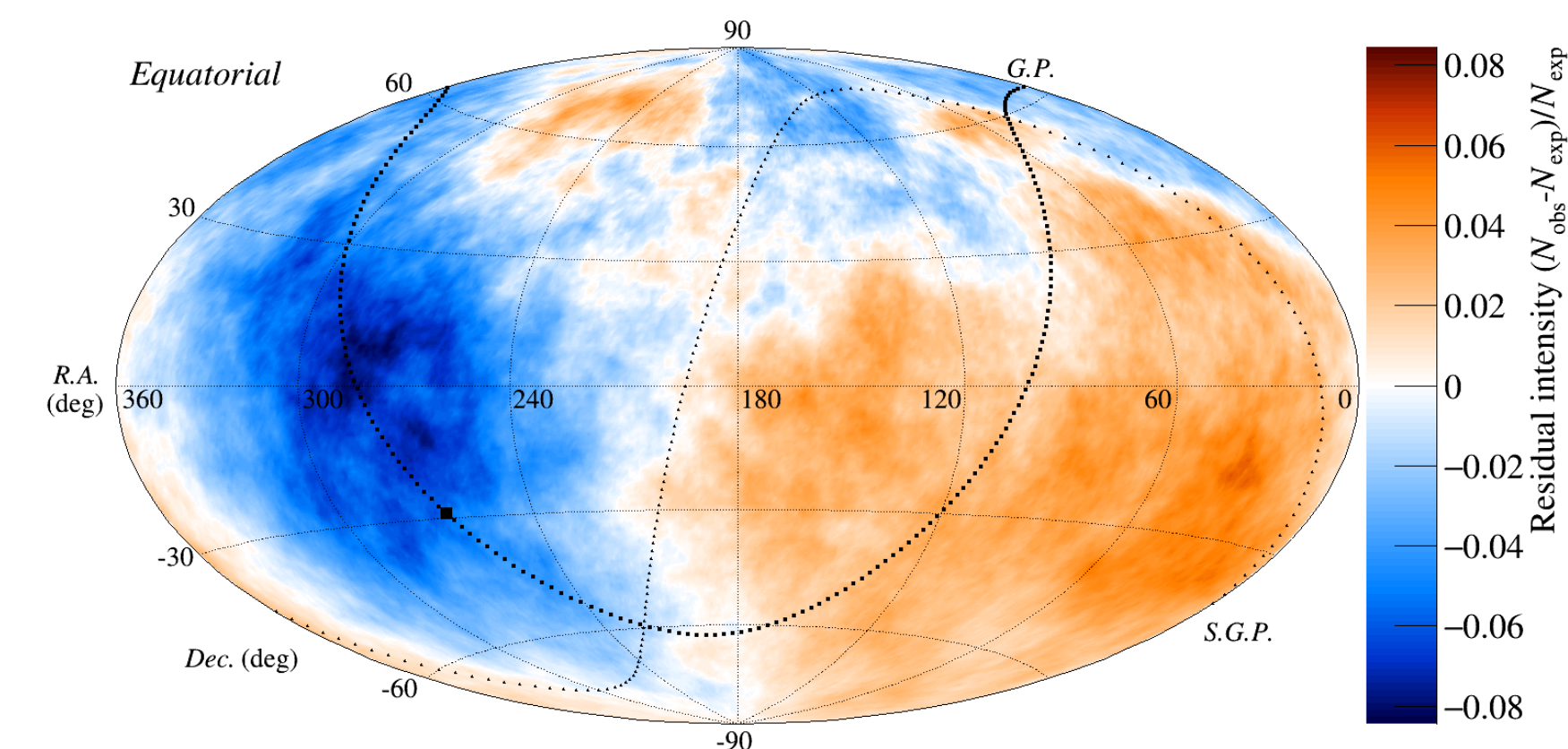
- Malargüe, Argentina
- 2004~, 3000 km²
- AugerPrime upgrade
scintillator + radio +
buried muon detector



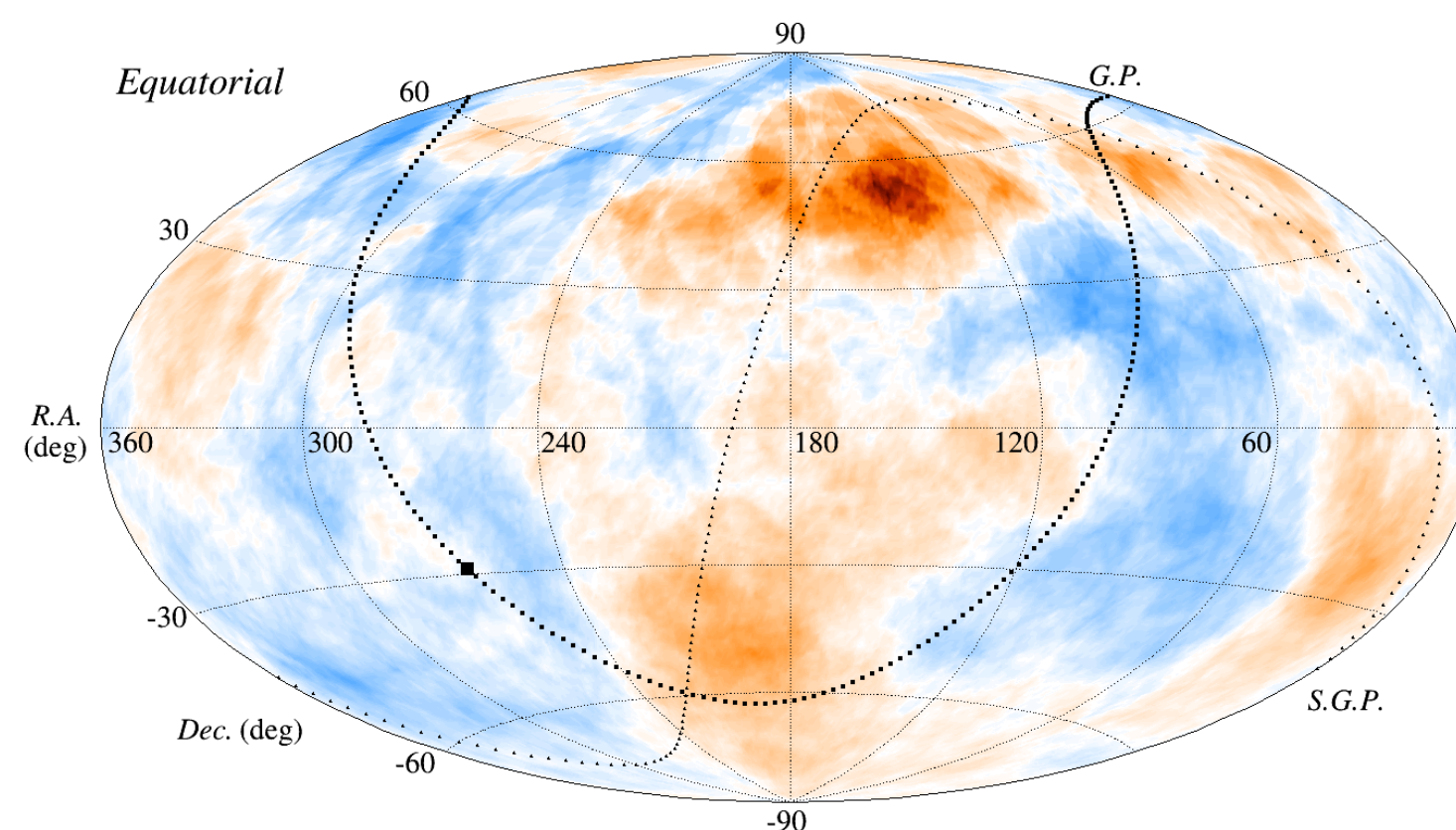


Latest results of UHECR

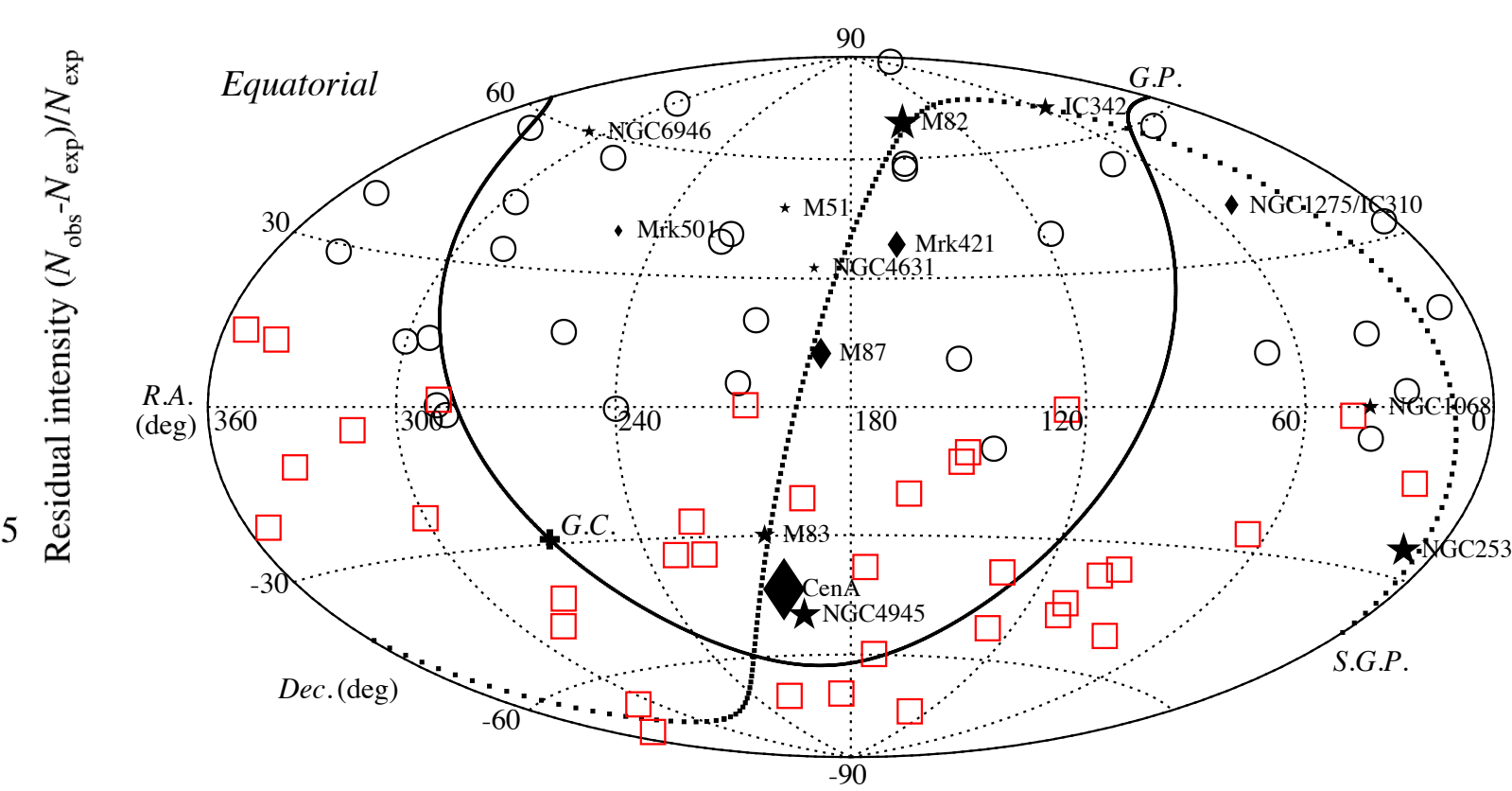
$$\theta \sim 10^\circ Z \left(\frac{E}{10 \text{ EeV}} \right)^{-1}$$



Ankle ($E > 10 \text{ EeV}$)

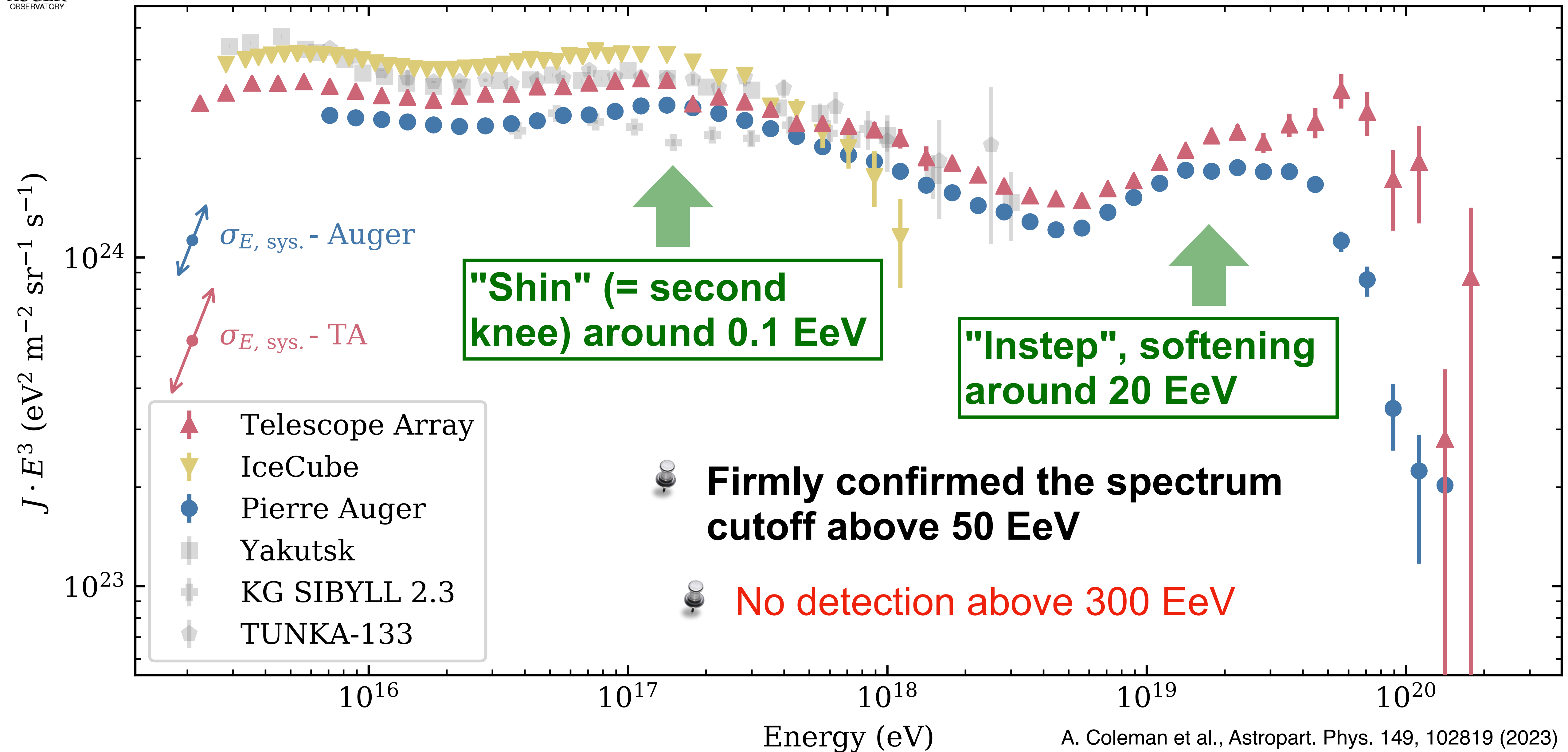


Cutoff ($E > 50 \text{ EeV}$)



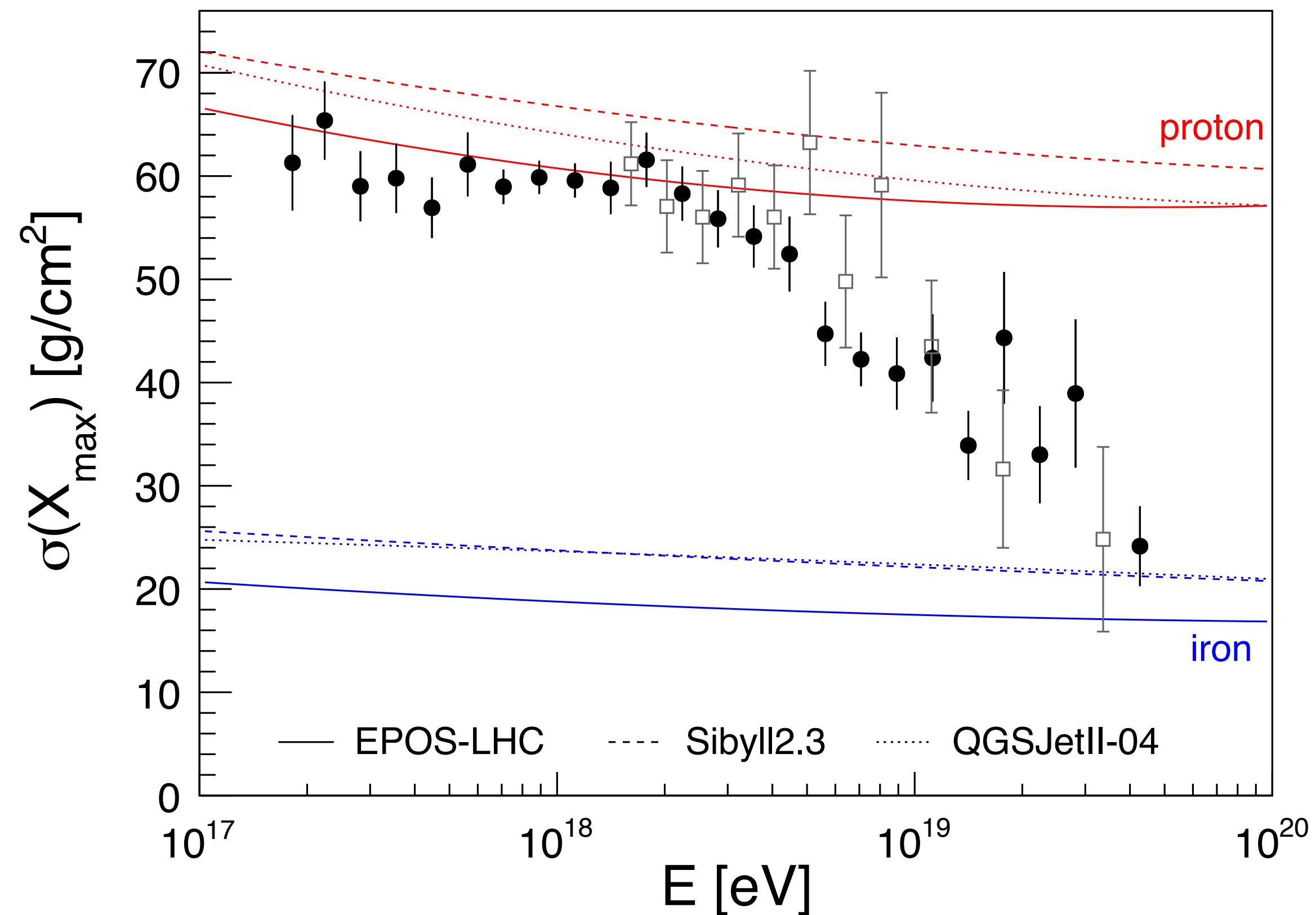
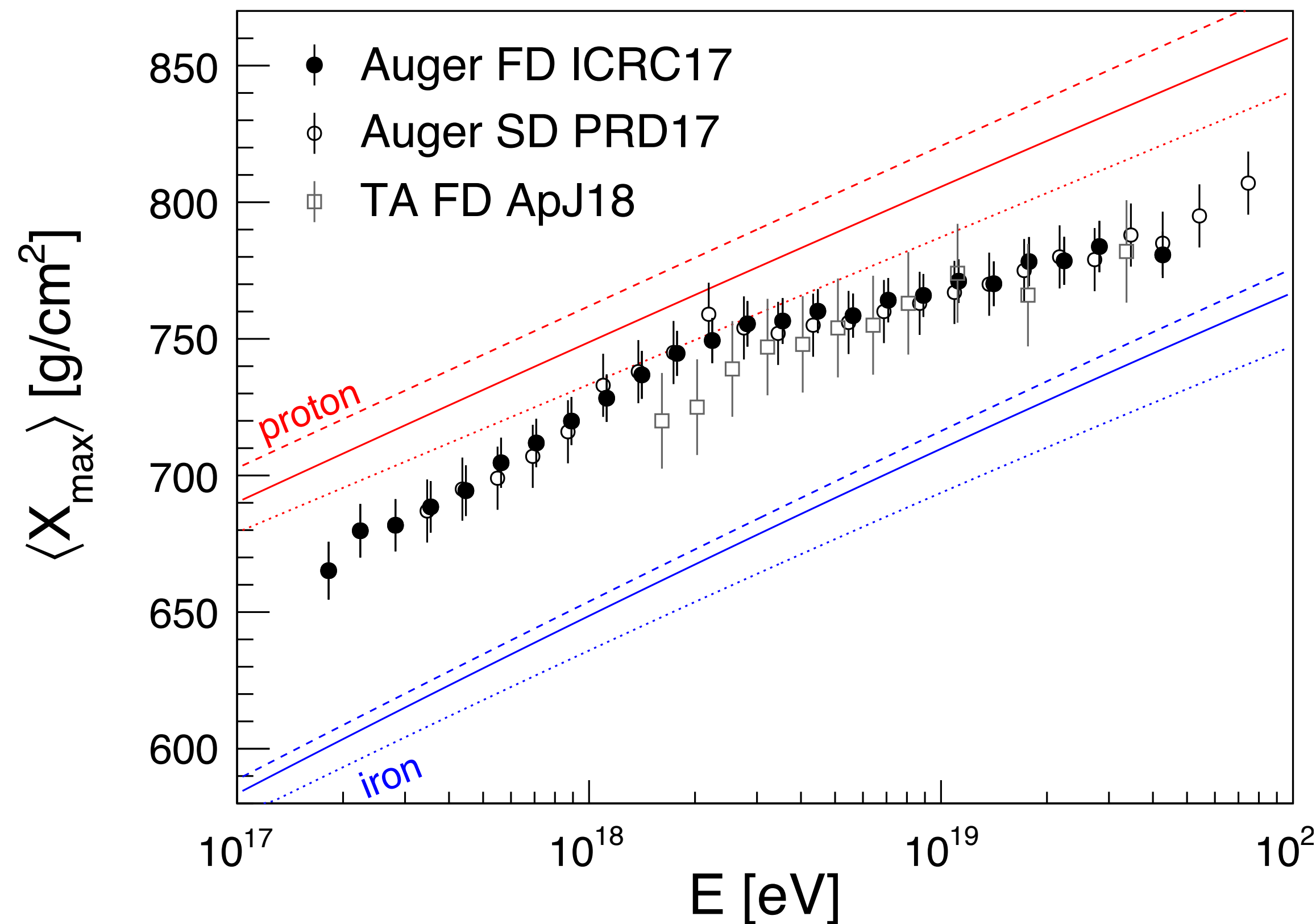
Beyond-cutoff ($E > 100 \text{ EeV}$)

Energy spectrum



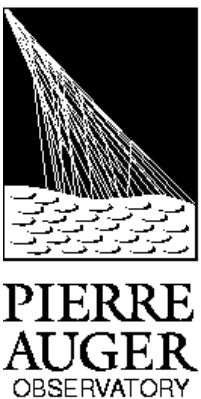
Mass composition, $X_{\max}$

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



Gradually increase to the heavier composition above 3 EeV

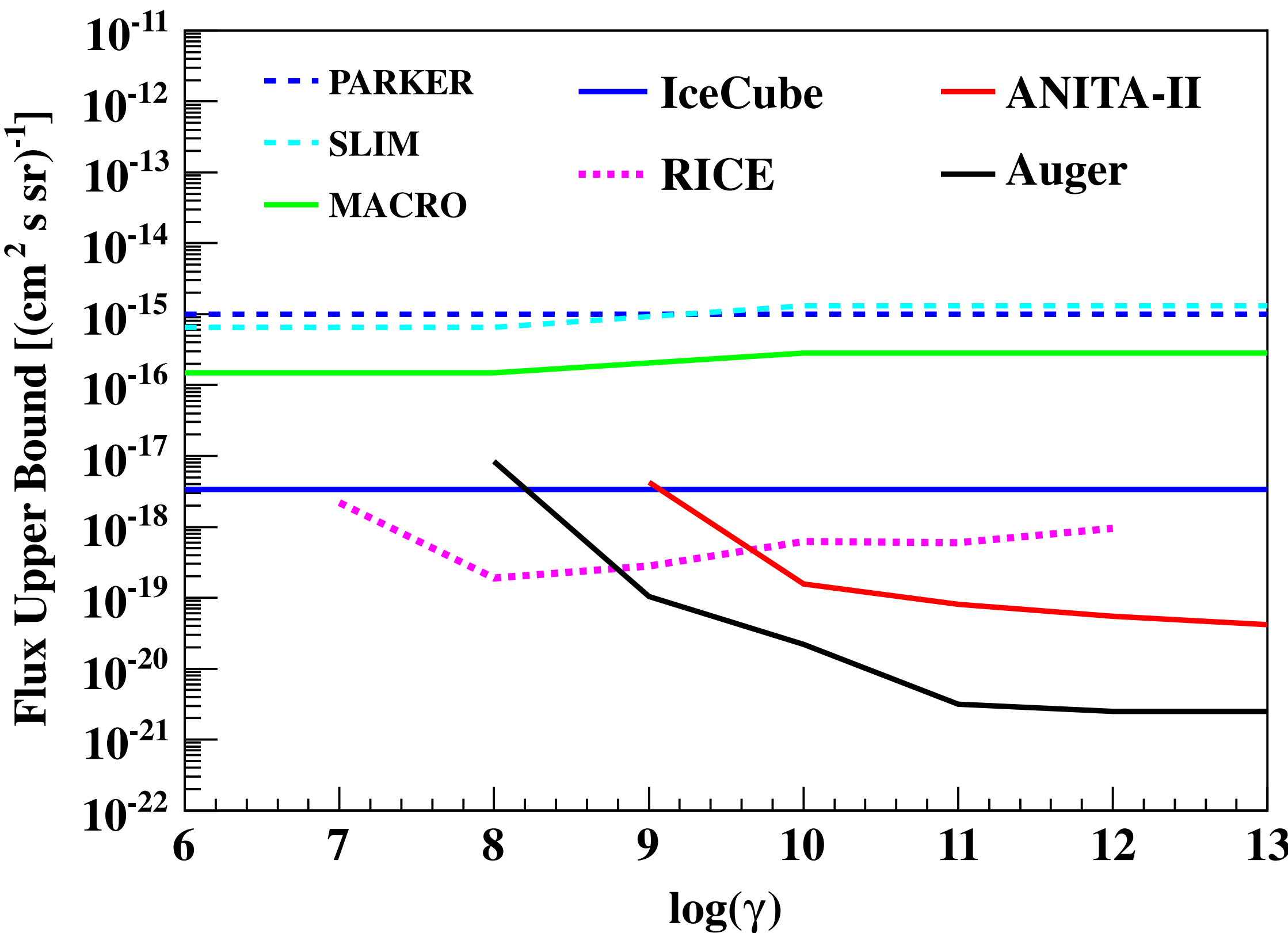
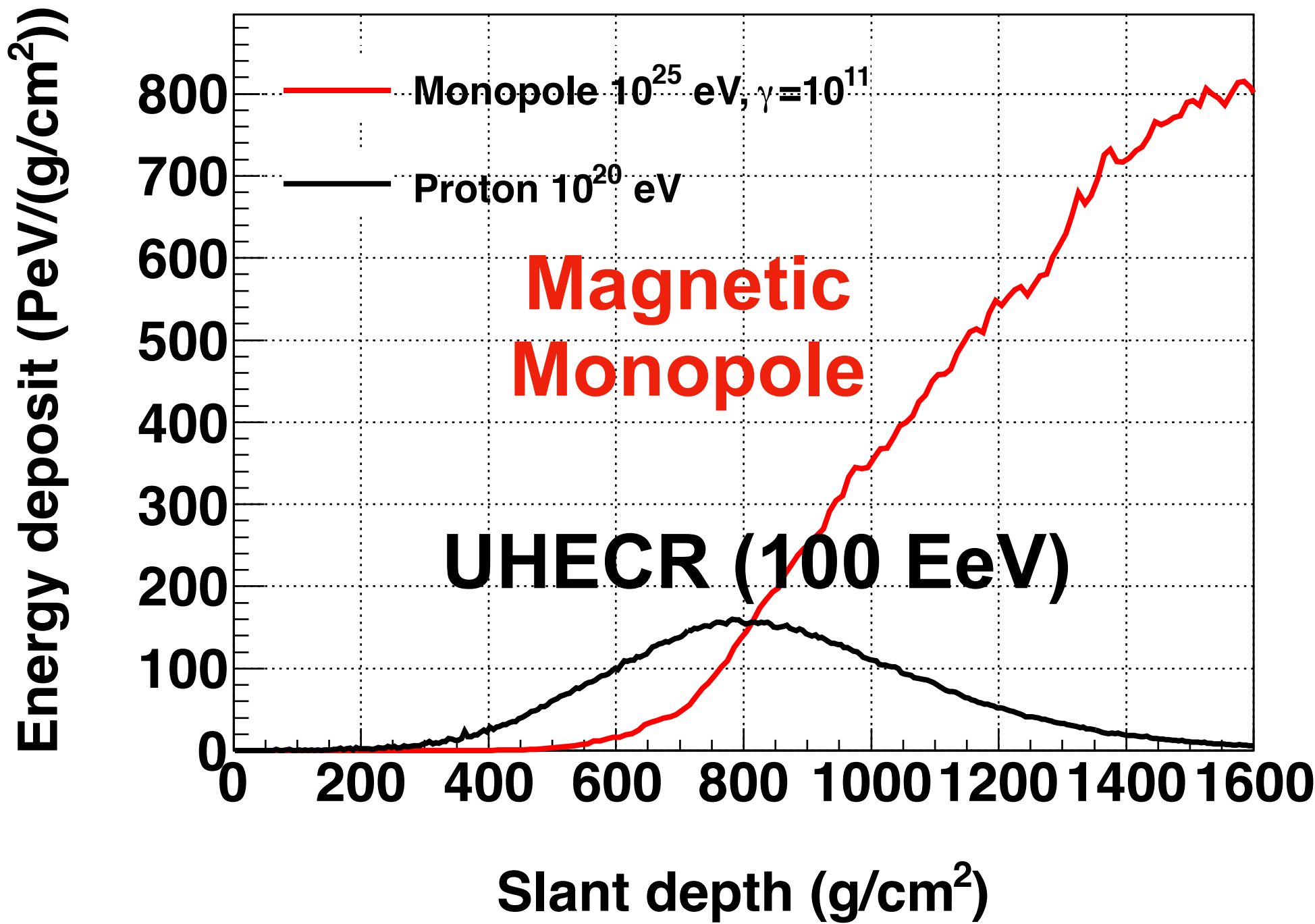
$$\theta \sim 10^\circ Z \left(\frac{E}{10 \text{ EeV}} \right)^{-1} \quad Z : \text{atomic number (mass composition)}$$



Magnetic monopole search in Auger

Search for ultra-relativistic magnetic monopoles in 10-year data of fluorescence detector of Pierre Auger Observatory

No candidates are found, and set the most stringent flux upper limit



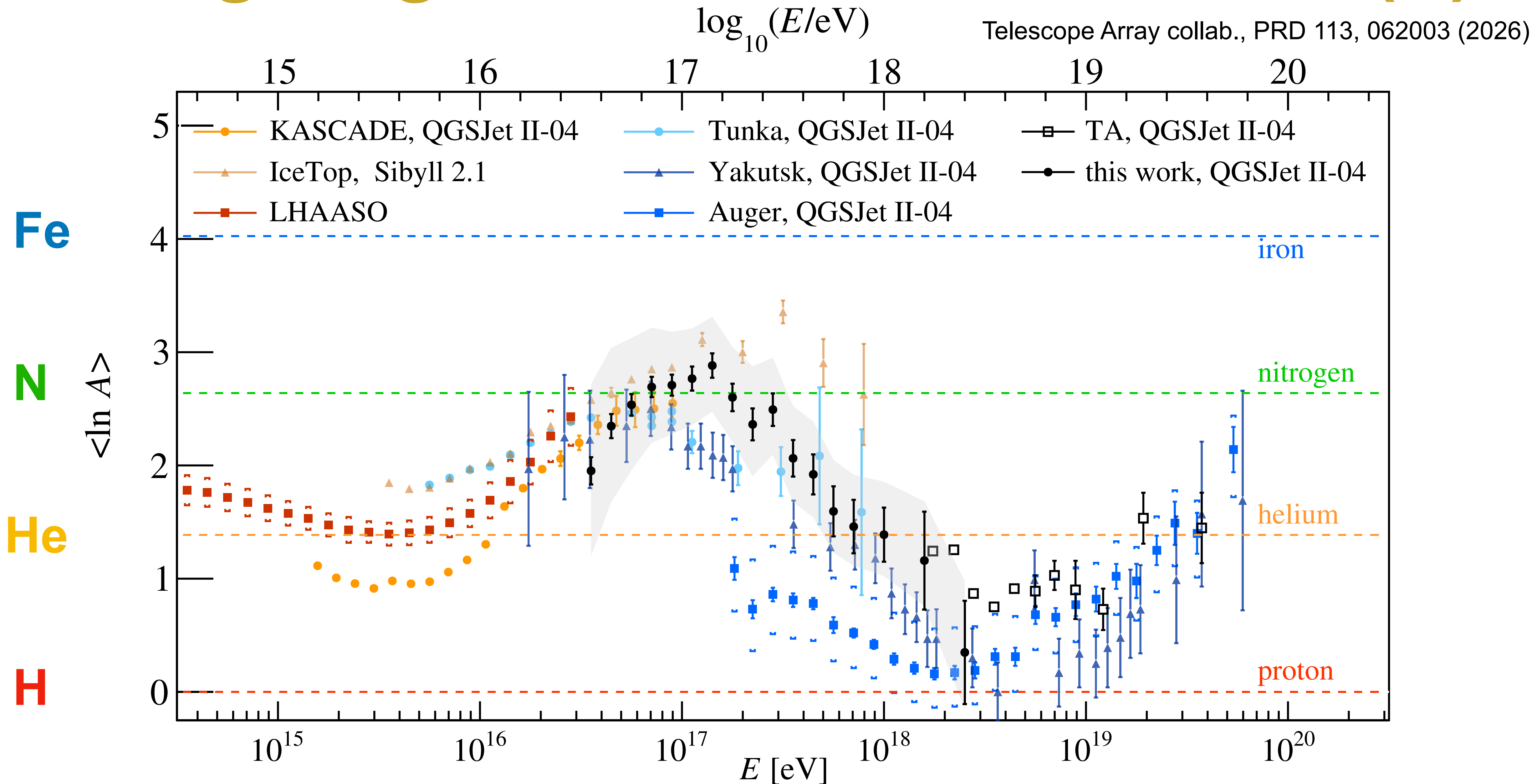
Pierre Auger collaboration, Phys.Rev.D, 94, 082002 (2016), Editors' suggestion

Monopole Flux — Cosmic Ray Searches

“Caty” in the charge column indicates a search for monopole-catalyzed nucleon decay.

FLUX (cm ⁻² sr ⁻¹ s ⁻¹)	MASS (GeV)	CHG (g)	COMMENTS (β = v/c)	EVTS	DOCUMENT ID	TECN
<2.5E-21		1	1E8 < γ < 1E13	0	¹ AAB	16 AUGER
<1.55E-18			β > 0.51	0	² AARTSEN	16B ICCB

Average logarithmic mass number, $\ln(A)$ ¹⁴

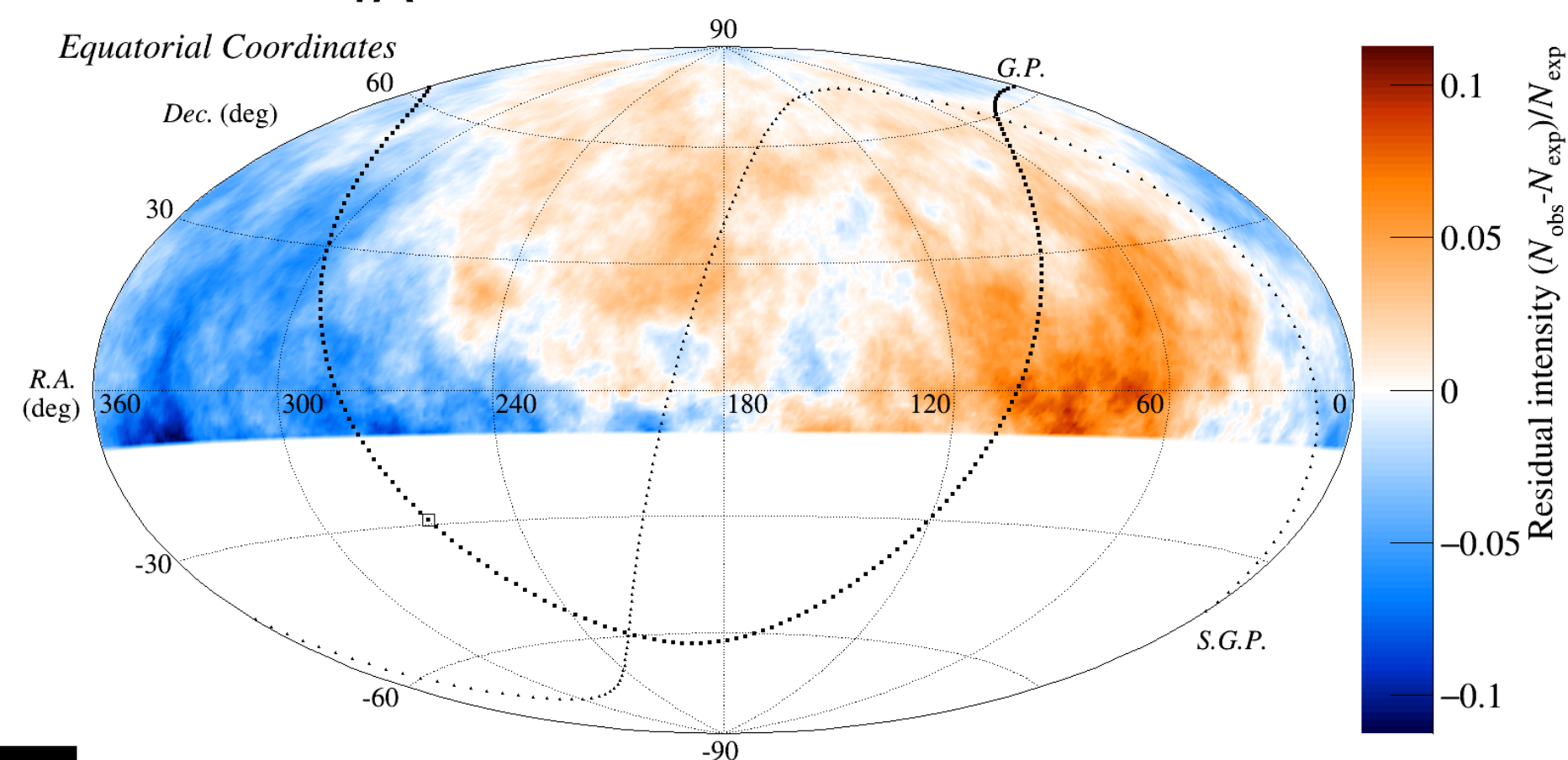


Anisotropy of UHECRs (>10 EeV)



Northern TA ApJL, 898:L28 (2020)

$E_{TA} > 8.8$ EeV



Significant ($> 5\sigma$) large-scale anisotropy observed by Pierre Auger Observatory



125 degrees away from Galactic Center



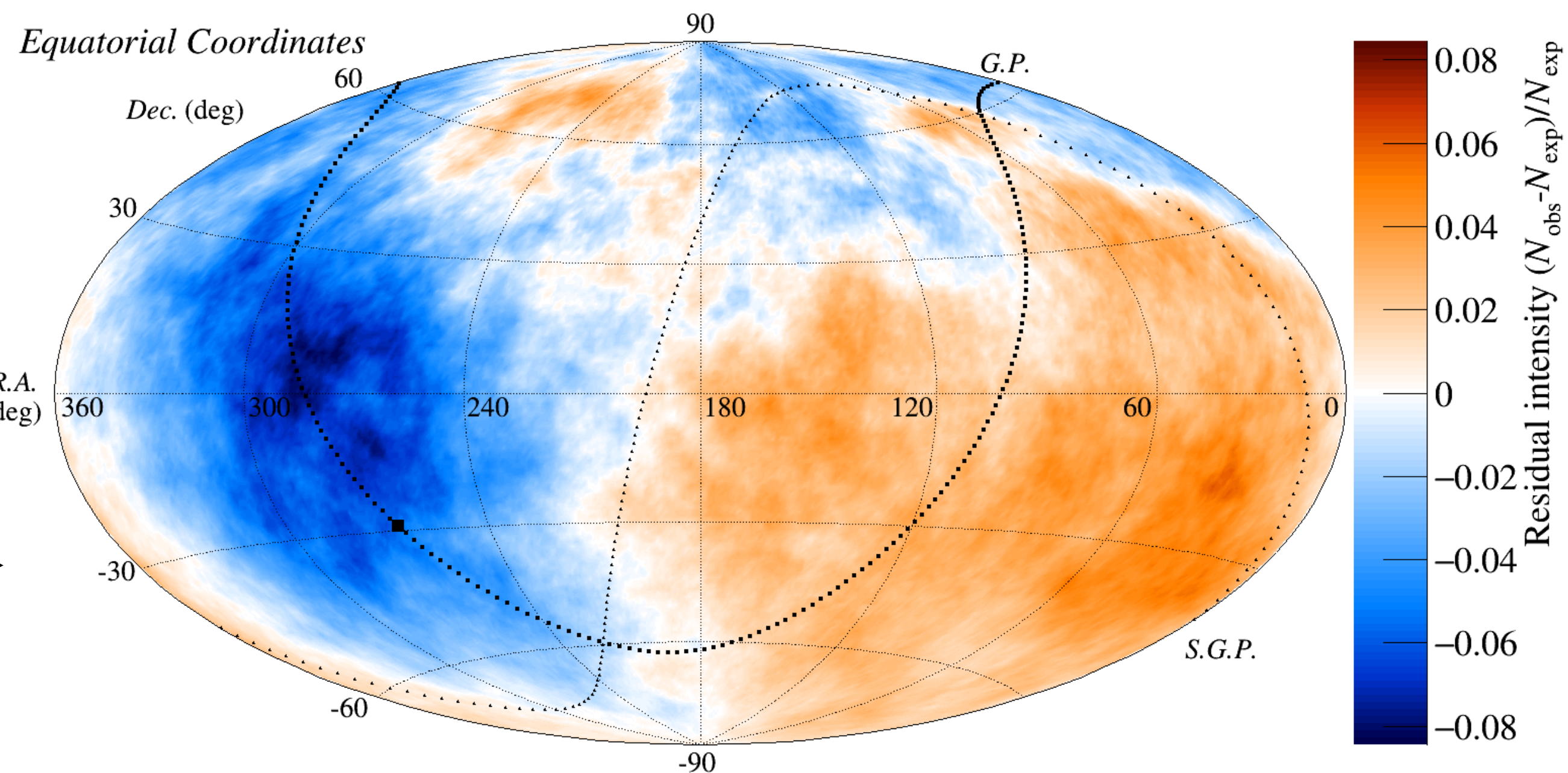
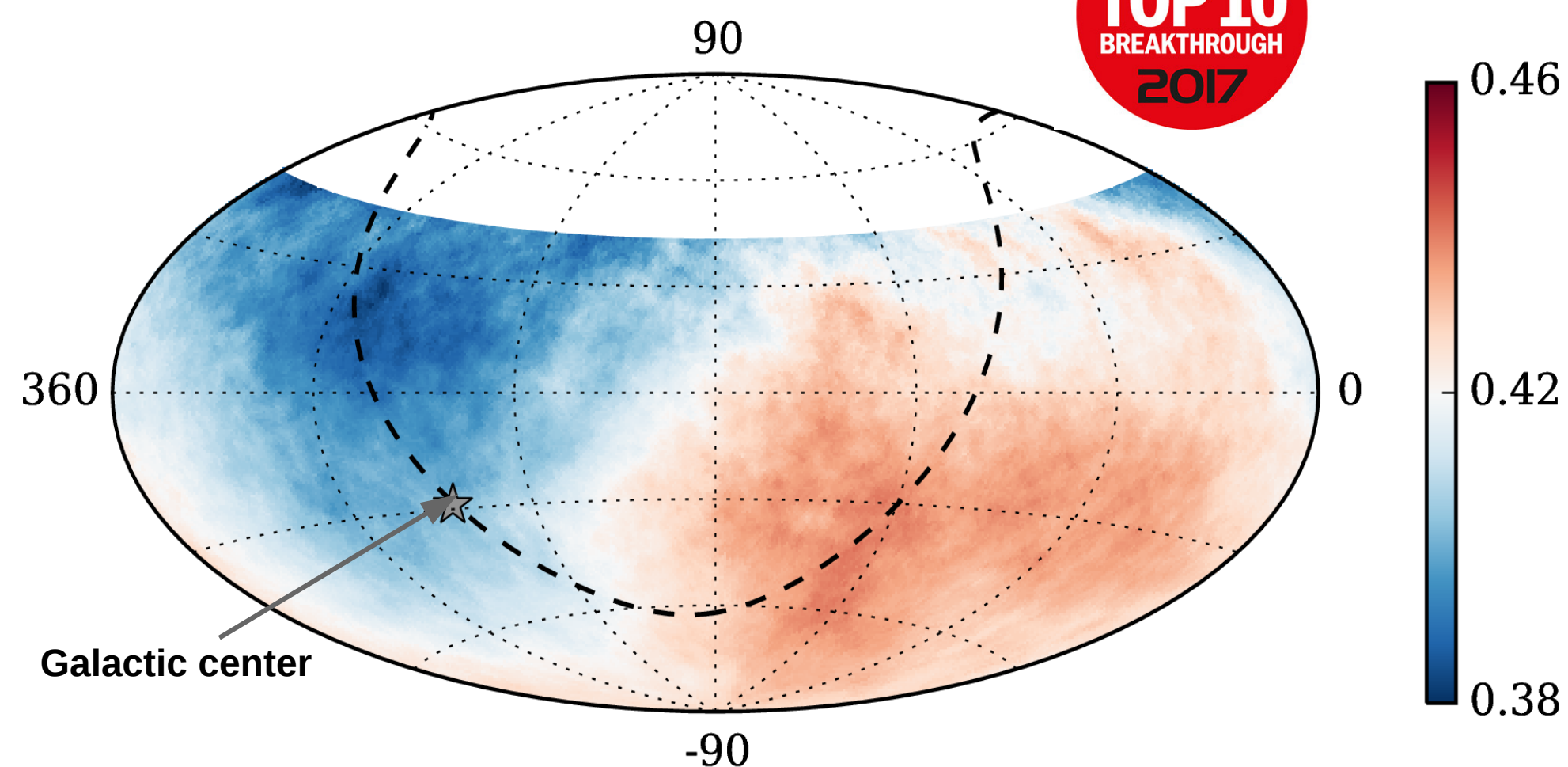
Supporting the extragalactic origins

Joint analysis

$\text{km}^{-2} \text{sr}^{-1} \text{yr}^{-1}$

Southern Auger Science 357, 1266 (2017)

$E_{Auger} > 8$ EeV

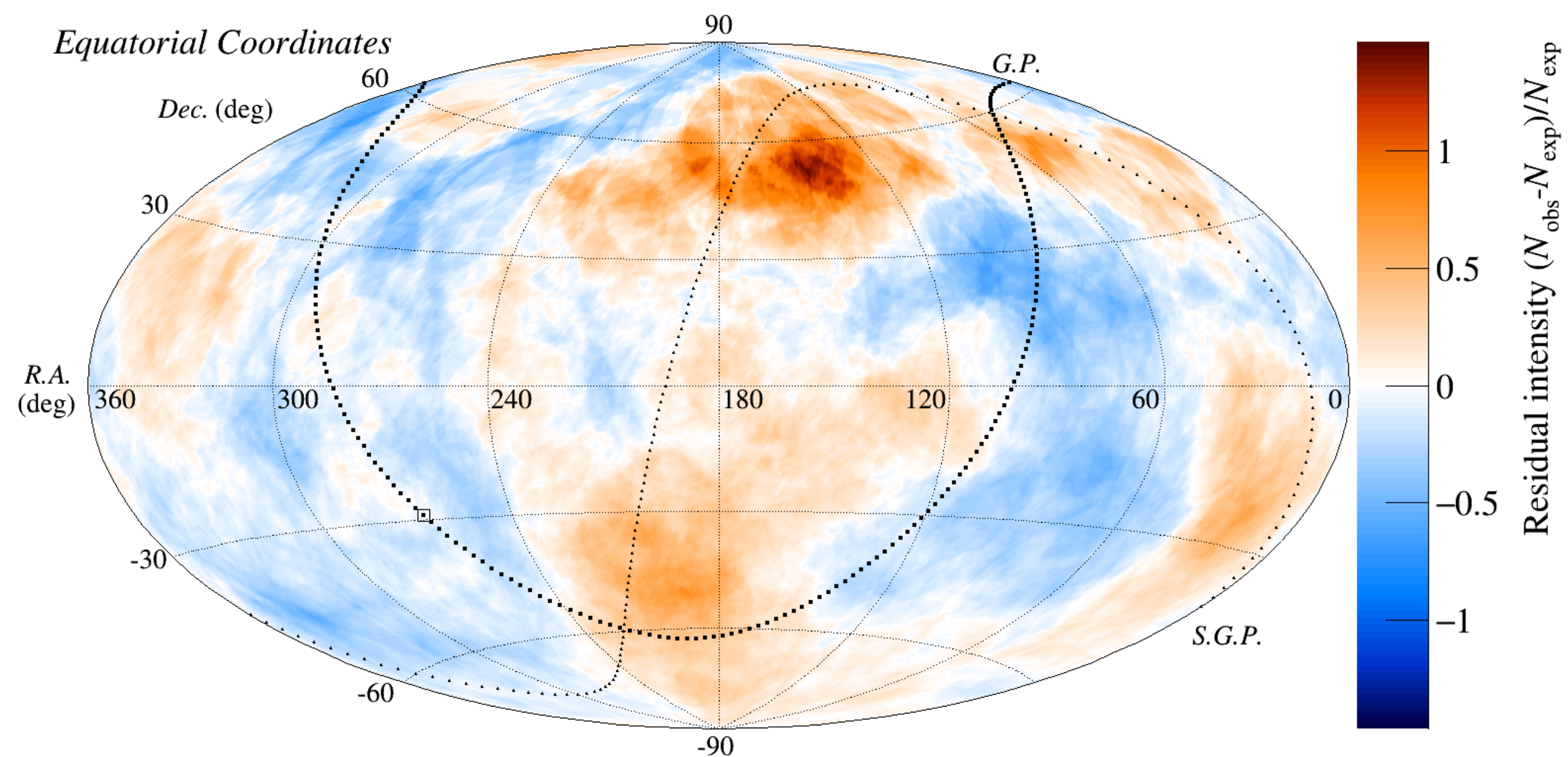
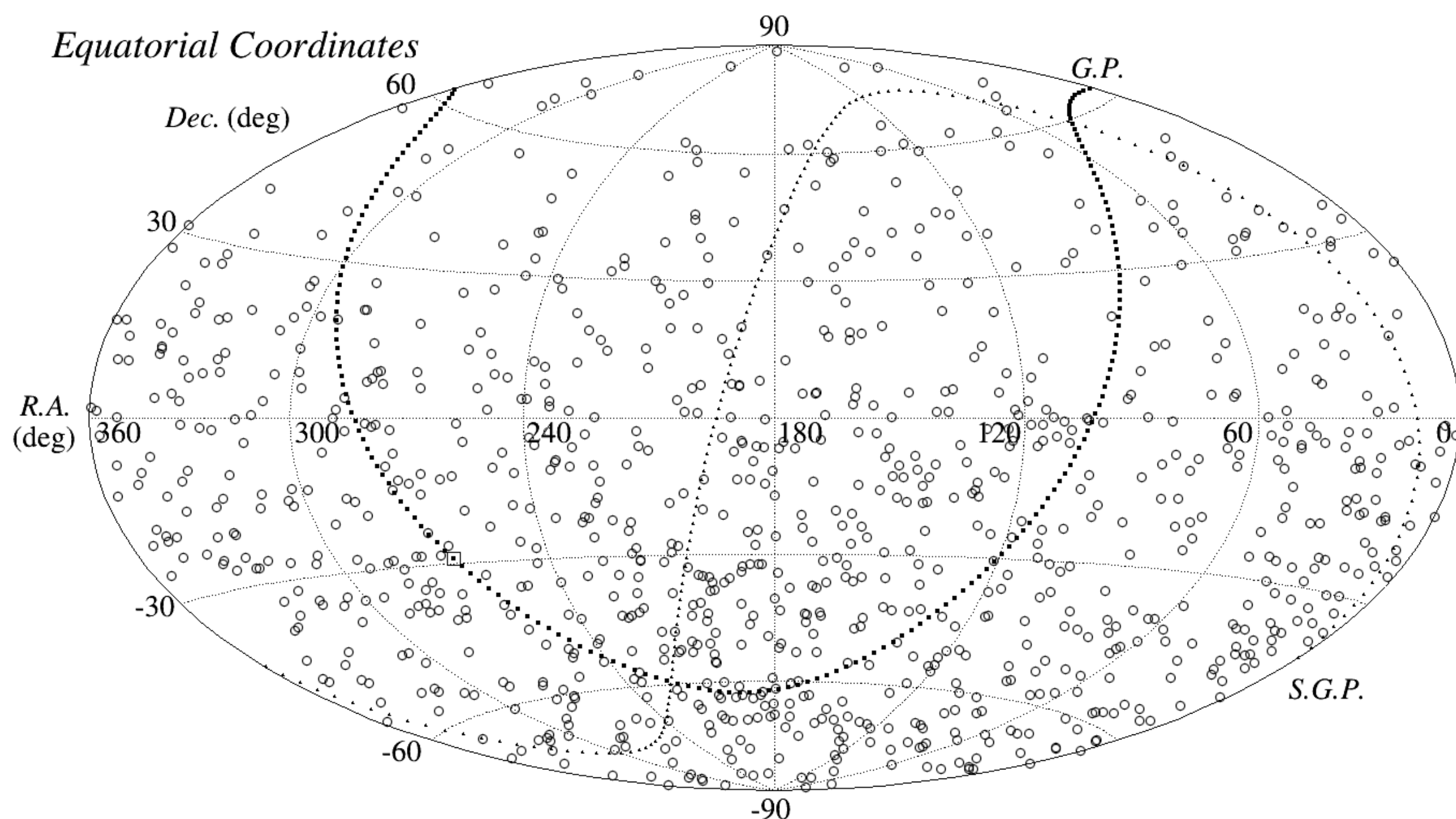


Ankle ($E_{TA} > 10$ EeV, $E_{Auger} > 8.86$ EeV)

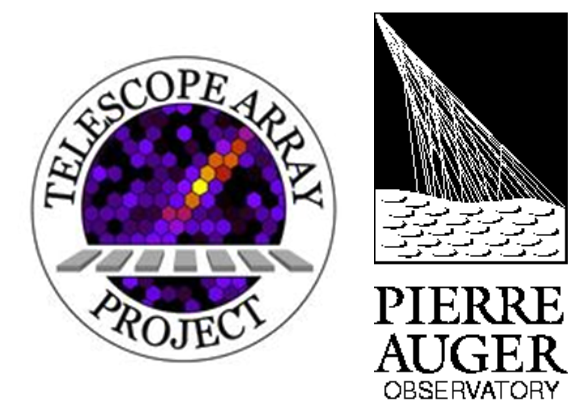
>50 EeV skymap

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

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



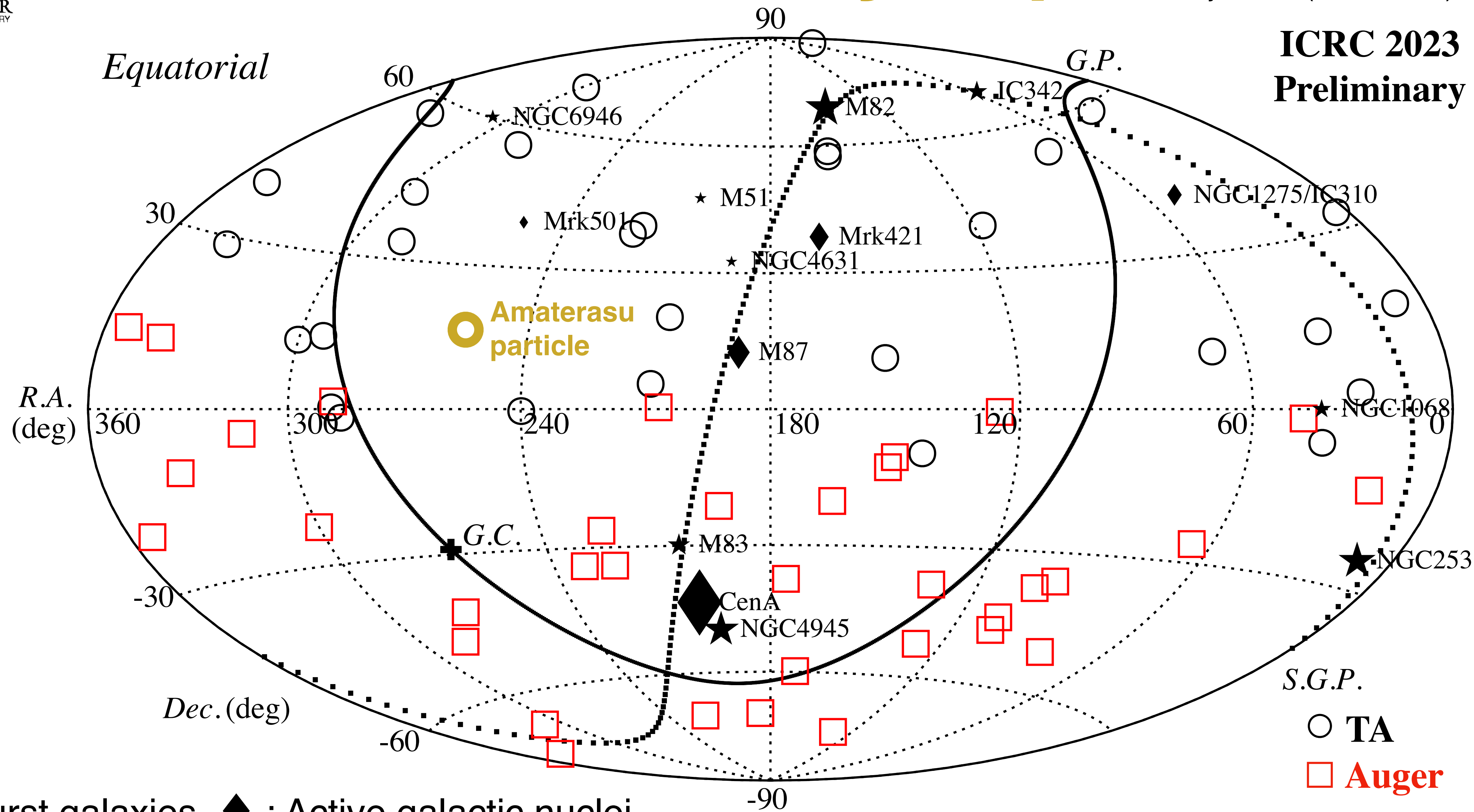
- Intriguing **intermediate-scale anisotropies** (~20 degrees) such as **hot/warm spots**
- No excess from Virgo cluster, dubbed "**Virgo scandal**"
- Isotropic distributions of UHECRs** than our (optimistic) expectation



>100 EeV skymap

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

**ICRC 2023
Preliminary**



★ : Starburst galaxies ◆ : Active galactic nuclei

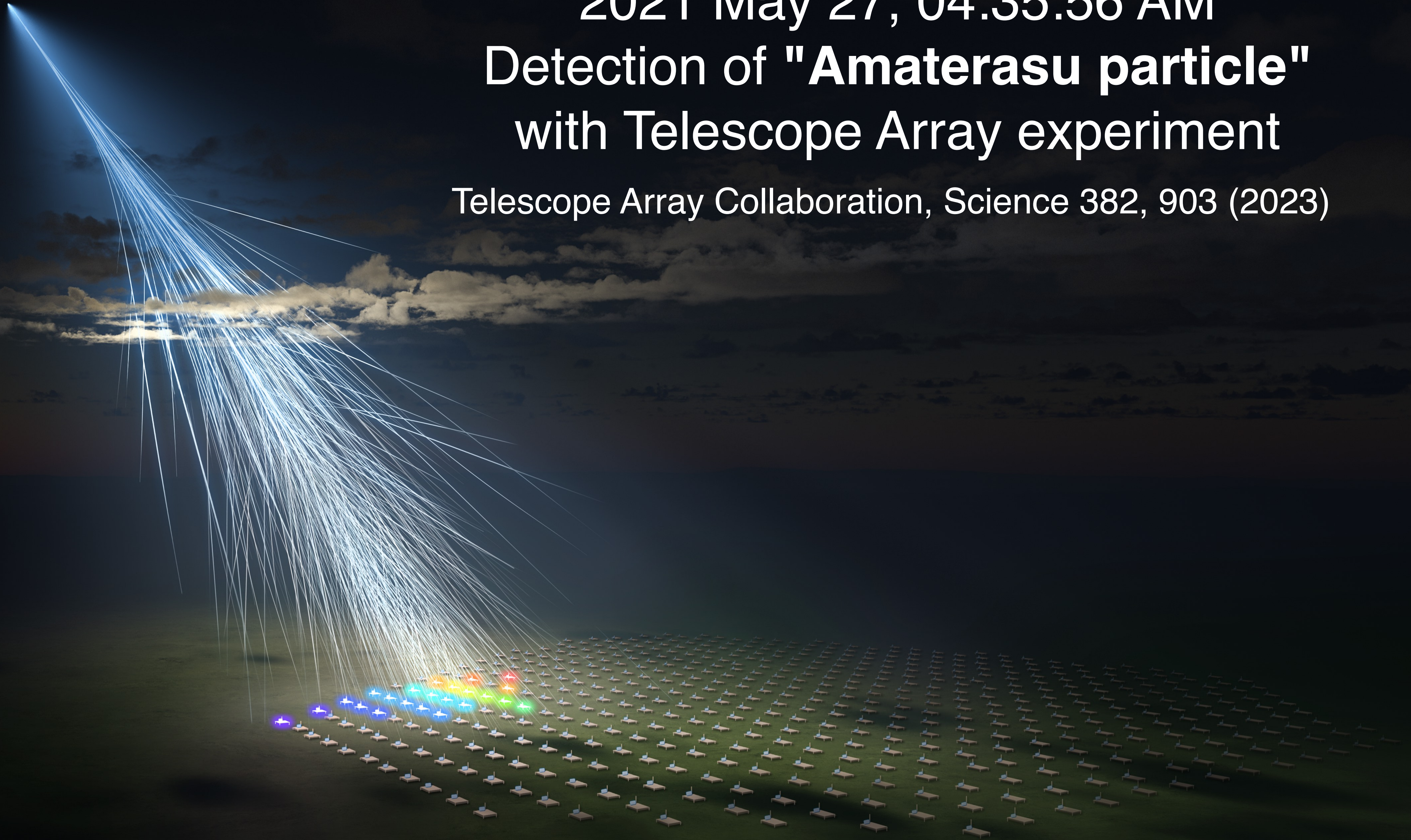
>100 EeV of TA 15-years and Auger 17-years

Need more statistics with mass identification capabilities

2021 May 27, 04:35:56 AM

Detection of "**Amaterasu particle**" with Telescope Array experiment

Telescope Array Collaboration, Science 382, 903 (2023)



20210526	225436.551339	9.393	7.004	6.74	35.22	110.52	0.541	0.00	1.65
20210526	232154.999225	-2.583	-0.124	20.62	33.07	237.89	0.156	0.00	6.25
20210526	232259.915571	-0.179	-16.096	10.36	31.73	198.26	0.404	0.00	2.47
20210526	234811.289968	2.478	9.314	4.69	21.00	115.48	0.493	0.00	1.06
20210527	001716.635727	5.737	-8.895	9.98	22.48	168.53	0.587	0.00	2.06
20210527	005753.524148	7.988	1.748	10.51	38.09	155.29	0.277	0.00	3.14
20210527	012459.385602	-5.703	-9.588	6.59	17.86	204.01	0.165	0.00	1.46
20210527	020622.327294	-4.091	-12.485	11.16	33.44	297.15	0.228	0.00	2.84
20210527	022215.026443	-5.554	-4.402	4.53	40.69	257.32	0.324	0.00	1.35
20210527	022953.053133	4.534	0.286	4.36	25.51	93.45	0.676	0.00	1.04
20210527	032730.128559	6.769	8.087	3.70	42.25	213.29	0.608	0.00	1.20
20210527	034324.408578	4.286	11.504	2.36	54.83	277.55	0.373	0.00	1.31
20210527	044710.753089	-2.208	6.068	6.57	23.24	213.93	0.200	0.00	1.38
20210527	045739.611334	3.358	-5.096	6.19	27.52	51.49	0.386	0.00	1.34
20210527	052456.616001	-8.802	-0.043	3.74	47.33	265.97	0.400	0.00	1.60
20210527	053039.195422	7.042	-0.775	5.07	51.50	253.88	0.338	0.00	3.25
20210527	060309.528577	7.681	-2.878	5.22	41.97	354.02	0.307	0.00	1.60
20210527	063750.948203	-9.893	-10.150	10.05	10.90	198.69	0.386	0.00	1.97
20210527	064513.310301	-0.567	-9.565	2.95	46.76	237.80	0.199	0.00	1.13
20210527	065111.717578	-2.120	2.494	5.77	40.51	246.21	0.142	0.00	1.70
20210527	072300.050046	5.441	12.539	2.87	48.35	327.27	0.538	0.00	1.22
20210527	073937.403223	8.820	-15.204	7.60	40.87	96.83	0.436	0.00	2.32
20210527	075907.626302	-0.188	-13.335	3.59	43.43	123.62	0.390	0.00	1.19
20210527	081936.883244	7.531	12.513	7.21	28.55	63.75	0.371	0.00	1.53
20210527	085544.355178	-3.884	3.239	9.03	41.35	233.83	0.416	0.00	3.03
20210527	103556.474337	-9.471	1.904	529.53	38.62	206.80	0.044	0.00	243.61
20210527	103819.341498	4.773	-16.531	3.90	52.08	21.79	0.250	0.00	2.39
20210527	122815.858965	-2.615	8.767	4.69	35.65	357.84	0.289	0.00	1.22
20210527	124726.186961	-4.969	-16.217	9.31	22.84	86.24	0.550	0.00	1.93
20210527	130030.400026	-6.704	-16.486	11.12	19.46	57.86	0.292	0.00	2.24
20210527	131652.649468	-2.707	2.834	8.41	30.48	159.44	0.317	0.00	1.85



The highest energy event of TA

May 27th 2021 10:35:56 UTC

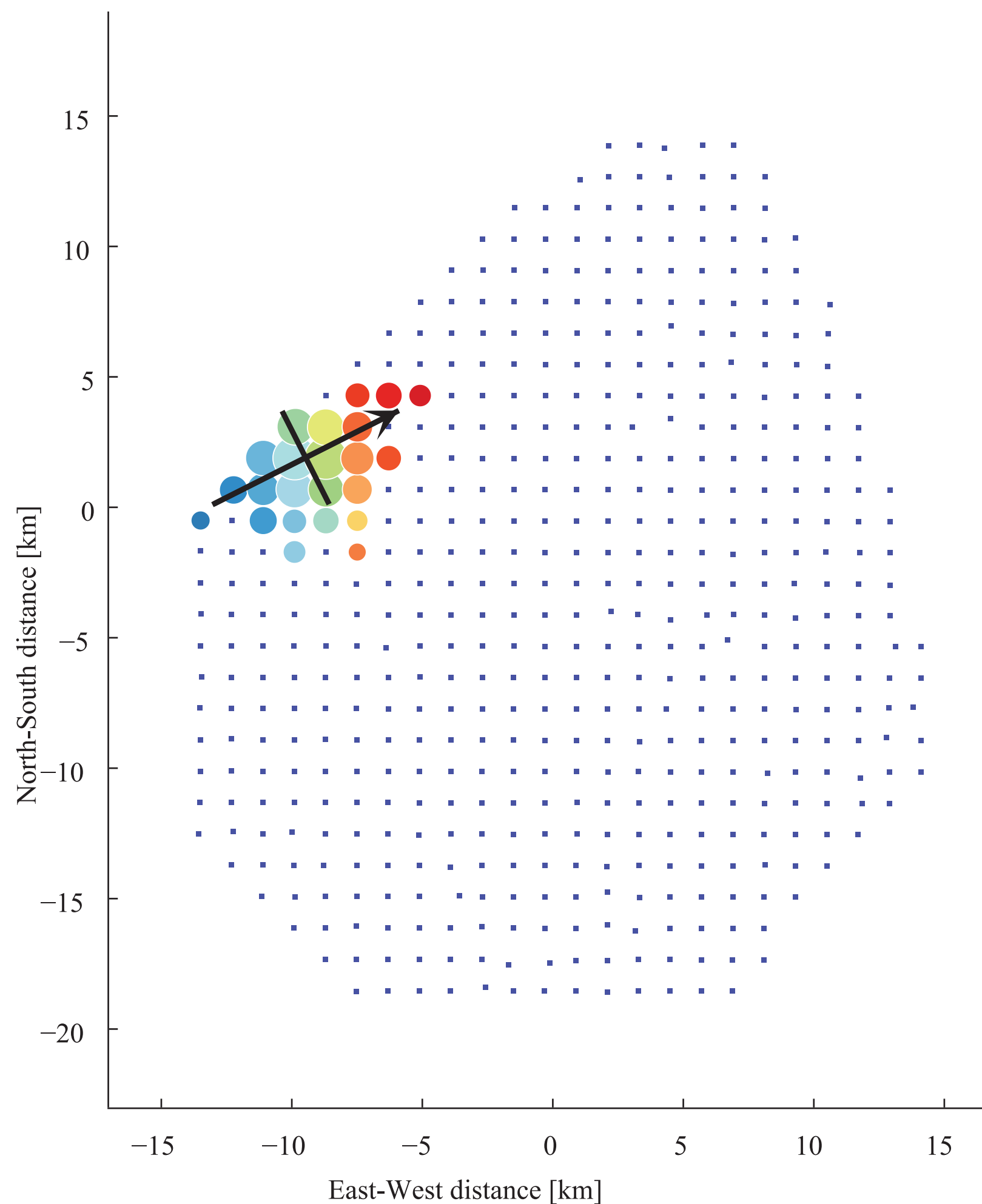
$E = 244 \pm 29$ (stat.)
 $+51, -76$ (syst.) EeV

Zenith angle = 38.6°

No operation of
fluorescence telescope
due to twilight

The most energetic event
in 18 years operation from
May 2008 to May 2026

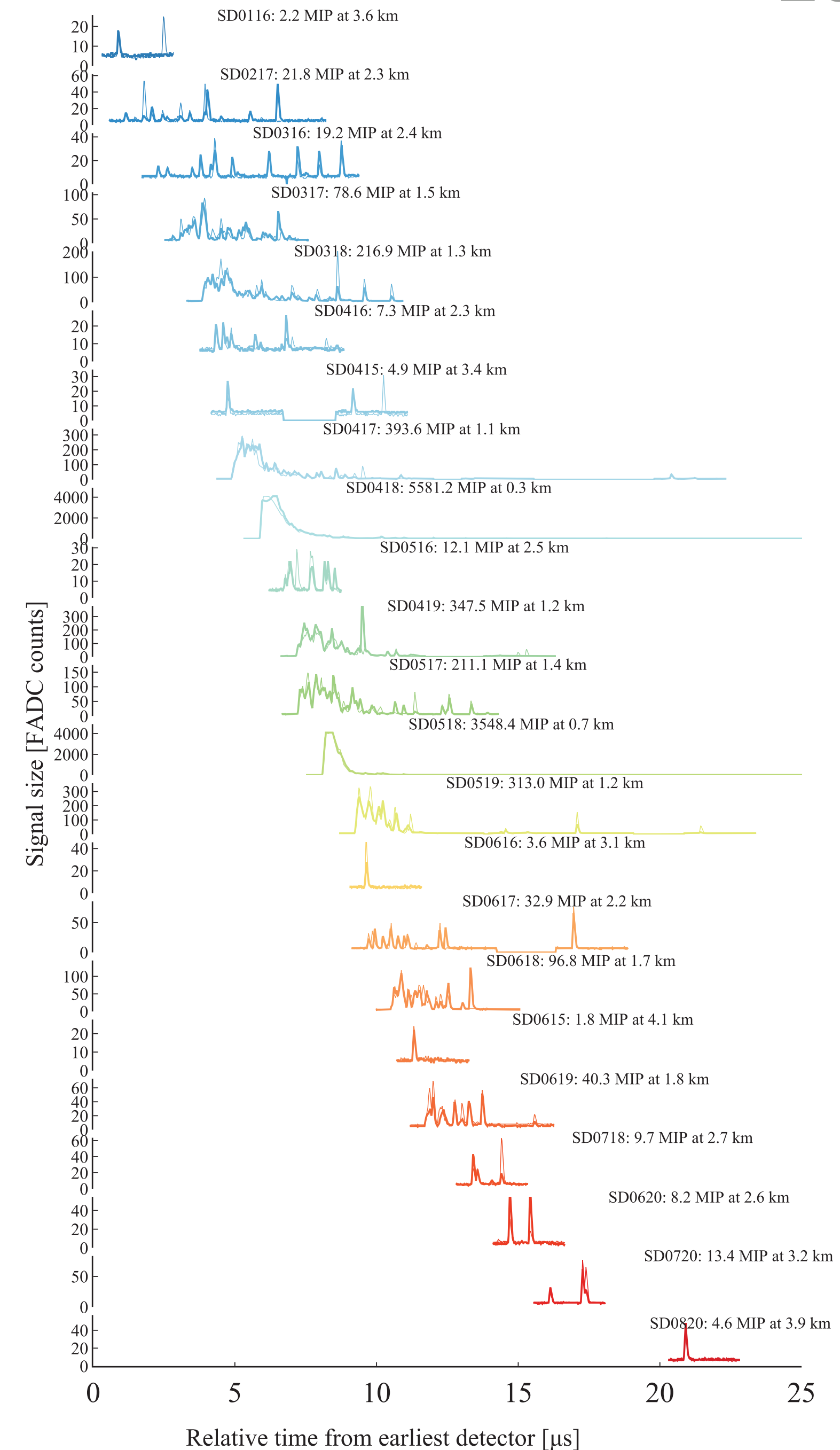
A Surface detector array of TA



Science 382, 903 (2023)

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

20

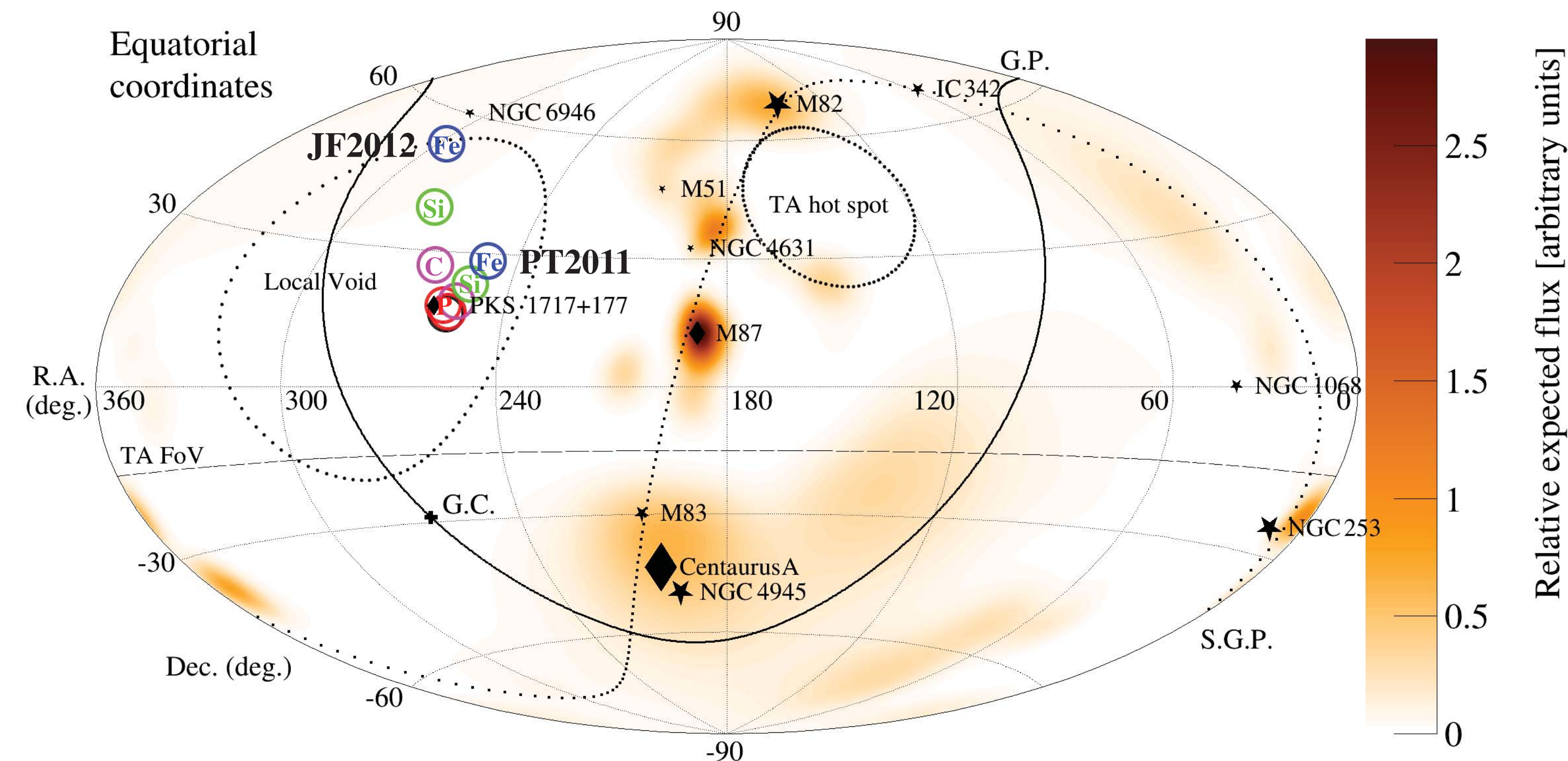


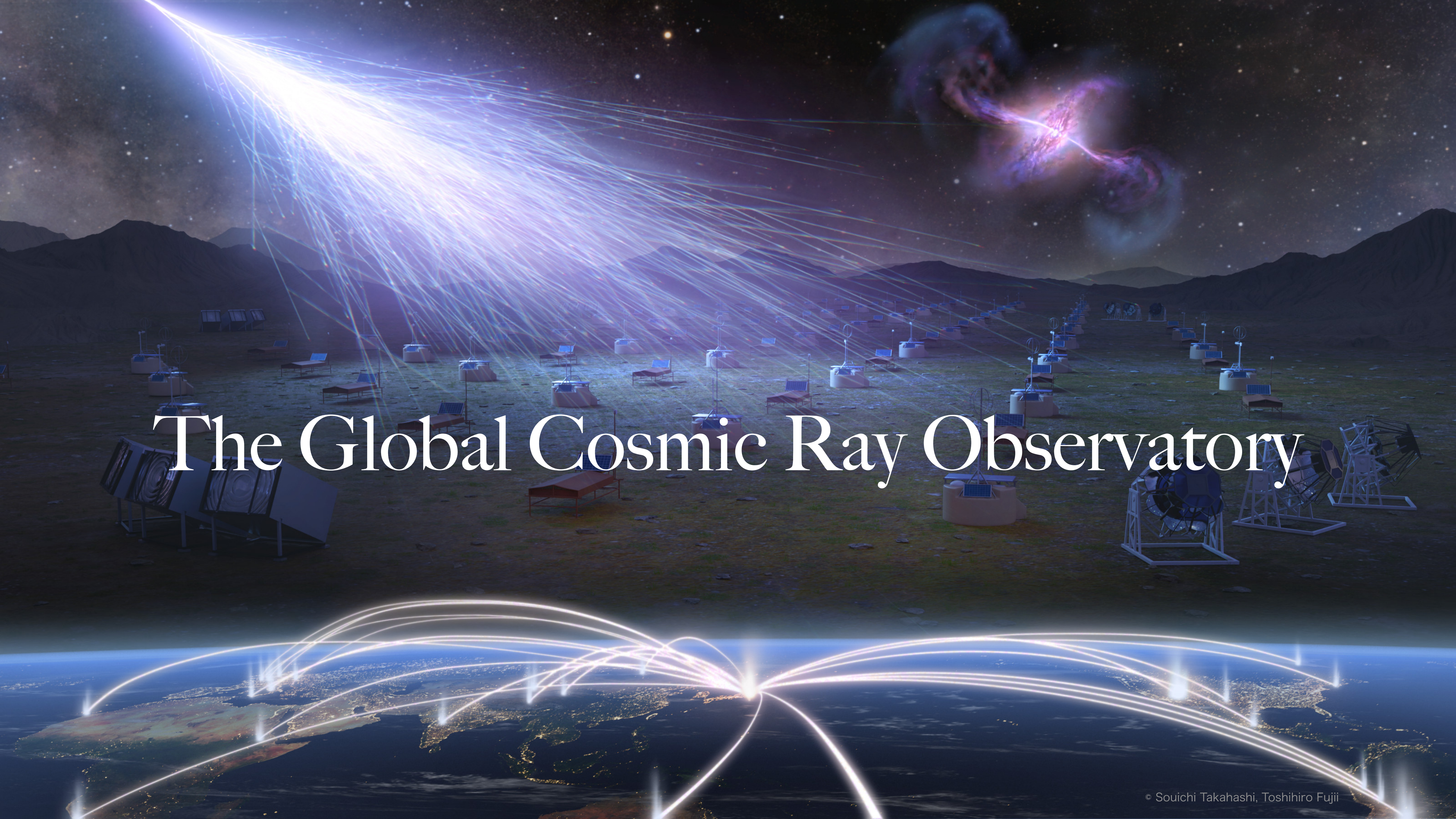


Arrival direction of the Amaterasu particle

- 📌 **Unexpectedly, came from the Local Void**
- 📌 **No promising astronomical source candidates**

- 📌 **Magnetic monopole origin** [Frampton, Phys.Lett.B 855, 138777 (2024), Cho et al., Phys.Lett.B 851 (2024) 138598]
- 📌 **Superheavy dark matter** [P. Sarmah, PRD 111, 0803048 (2025)]
- 📌 **Lorentz invariance violation** [Das, ApJL 988, L8 (2025)]
- 📌 **Binary neutron star merger** [Farrar, PRL 134, 081003 (2025)]
- 📌 **Ultra-heavy composition like Te or Pt** [Zhang et al, PRL 13, 181002 (2026)]
- 📌 **Bursting magnetar** [Shimoda and Wada, arXiv:2409.19915]

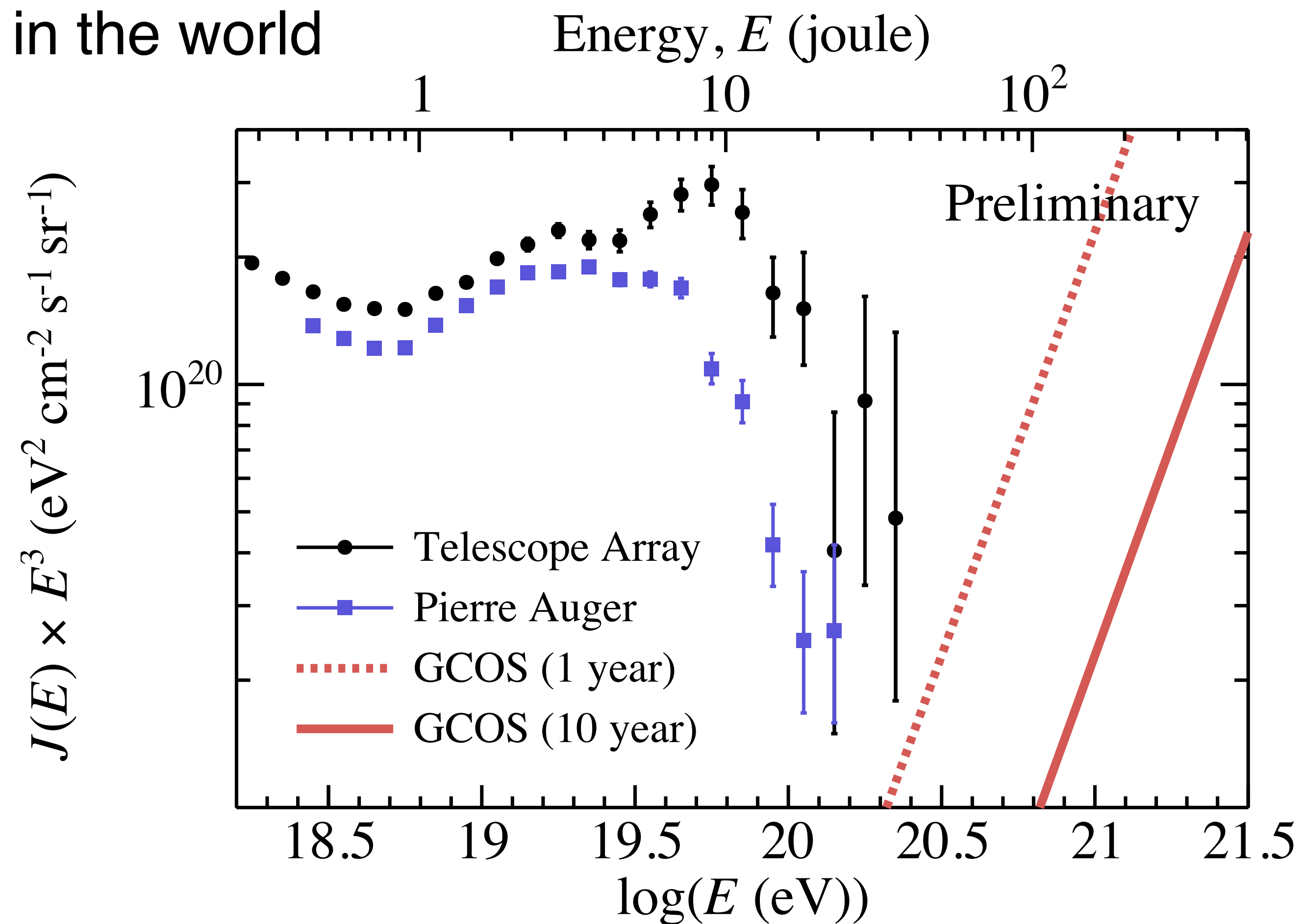
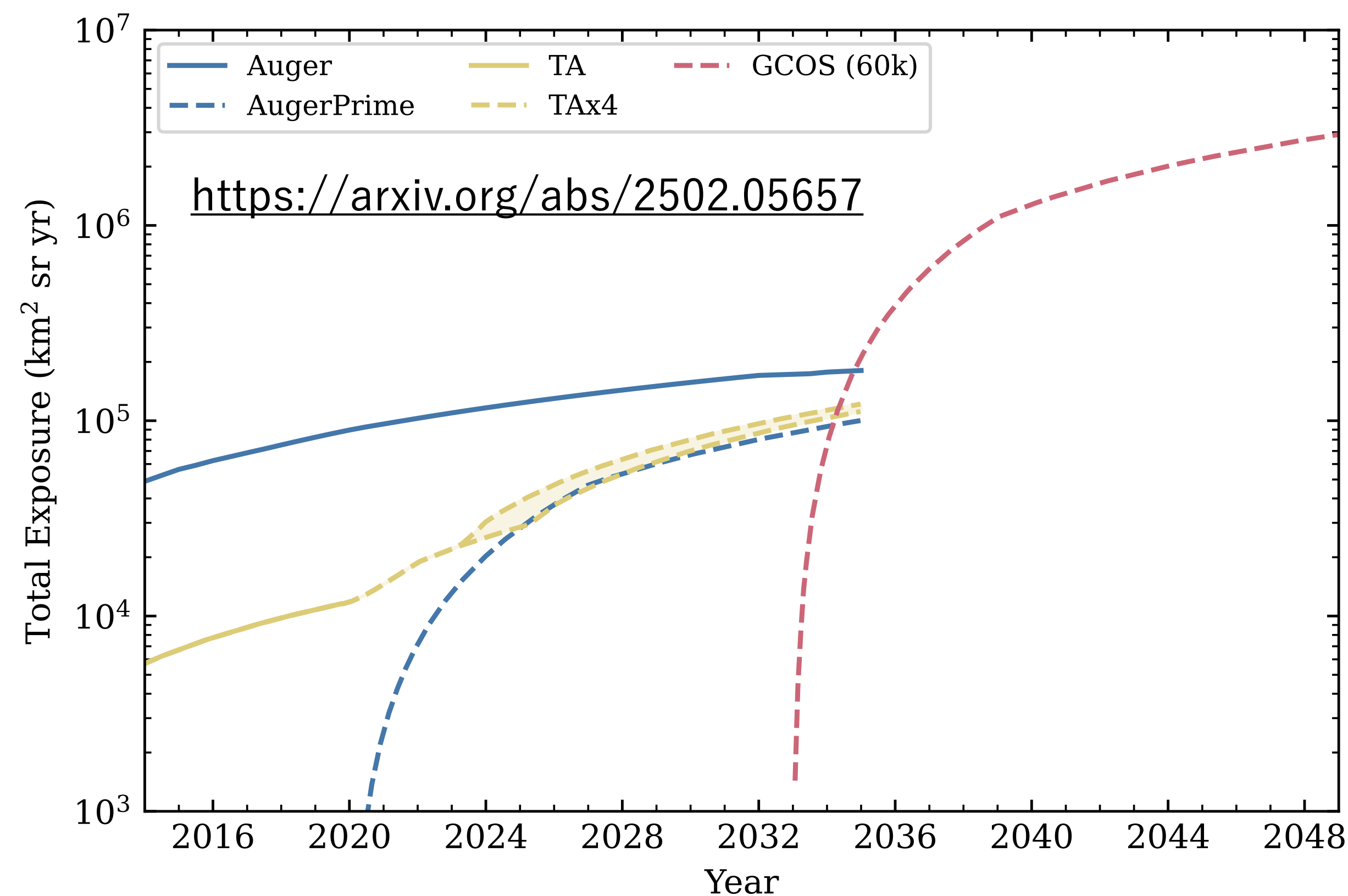




The Global Cosmic Ray Observatory

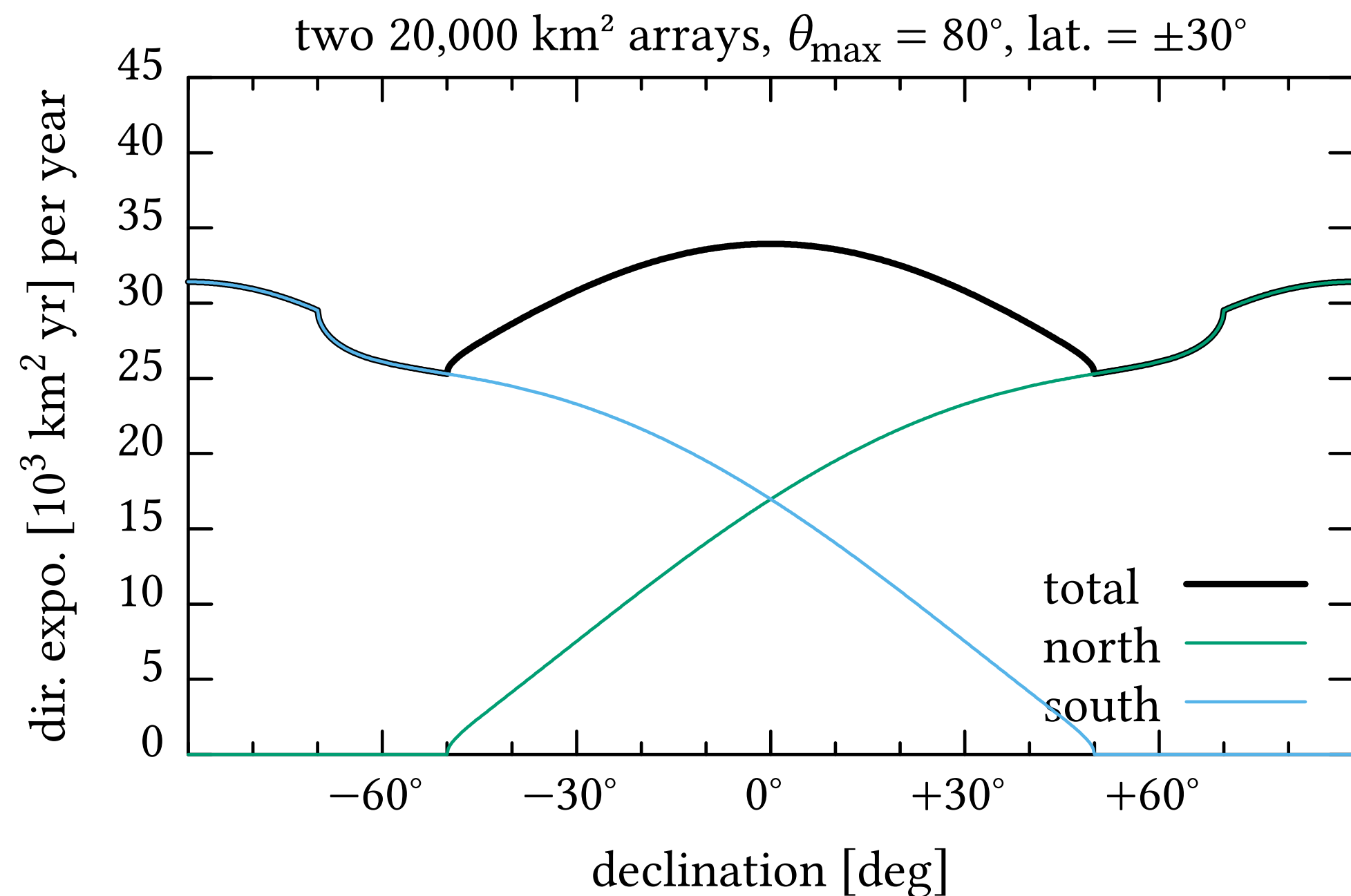
Science of the Global Cosmic Ray Observatory²³

- 📌 **Charged-particle astronomy** to clarify the origin and nature of the most energetic particles in the universe
- 📌 Unprecedented effective area, $\sim 60,000 \text{ km}^2$ 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: $\ln(A) \sim 1$ ($X_{\max} \sim 15 \text{ g/cm}^2$), arrival direction: **1 degree**
- Detector design and possible installation sites are under considerations



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

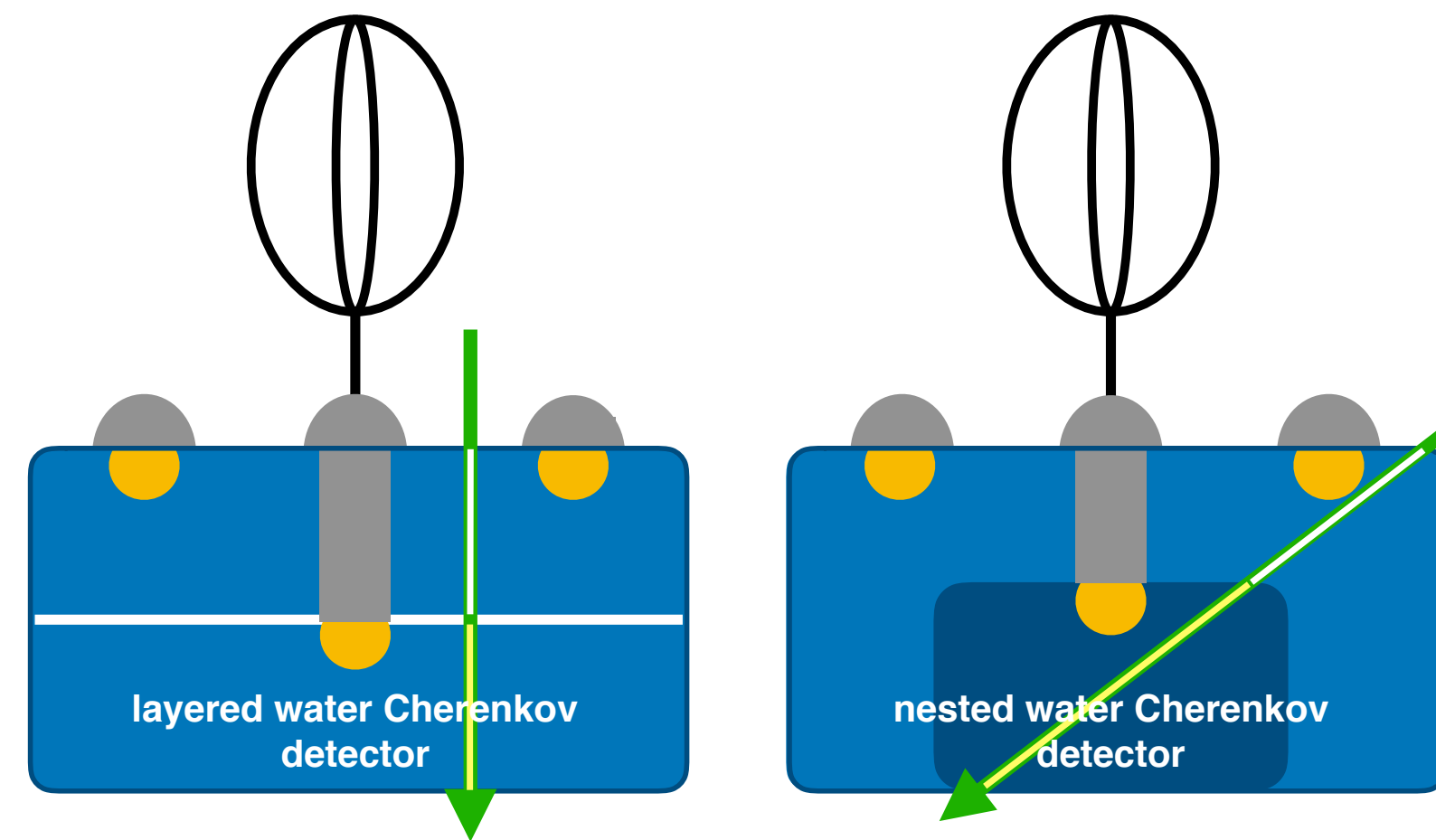


Figure 6: Detection concepts, using a layered (left) and a nested (right) water Cherenkov detector with a radio antenna on top.

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

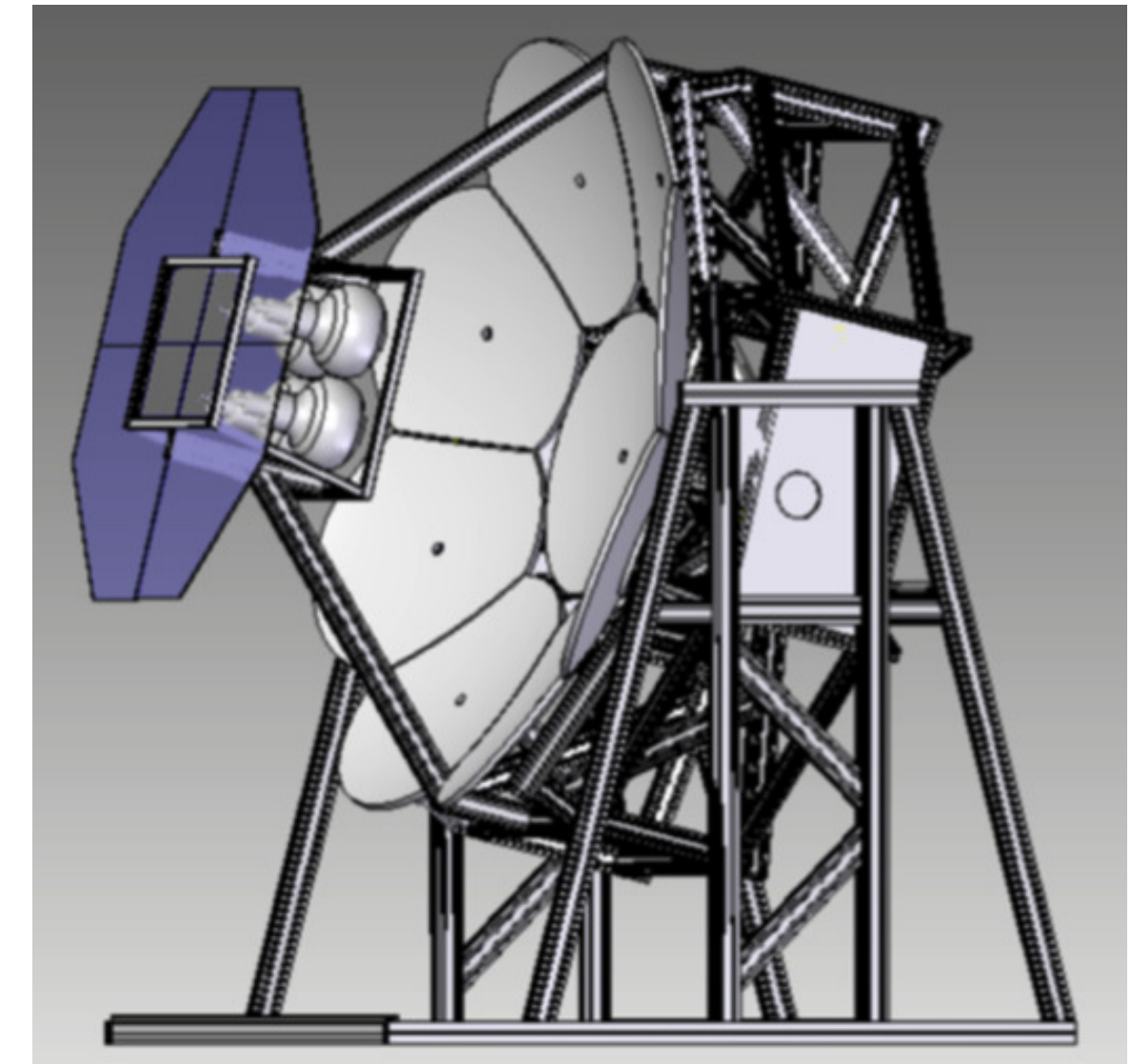


Figure 7: A FAST telescope frame, showing four PMTs at the focus of a 1.6 m diameter segmented mirror. The support structure is made from aluminium profiles. The UV band-pass filter can be seen attached to the periphery of the camera box [100, 101].

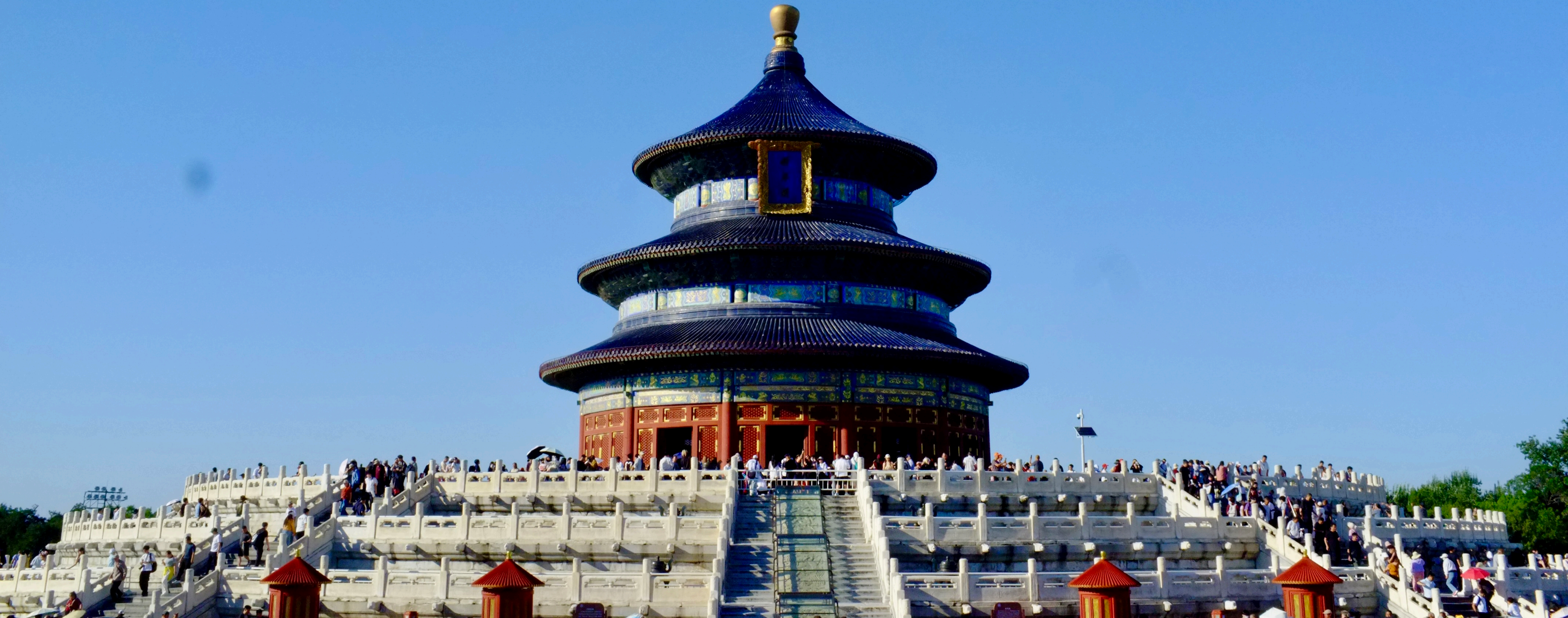
Y. Tameda in PoS (ICRC2025) 411
S. Sakurai in PoS (ICRC2025) 380

Summary and future perspectives

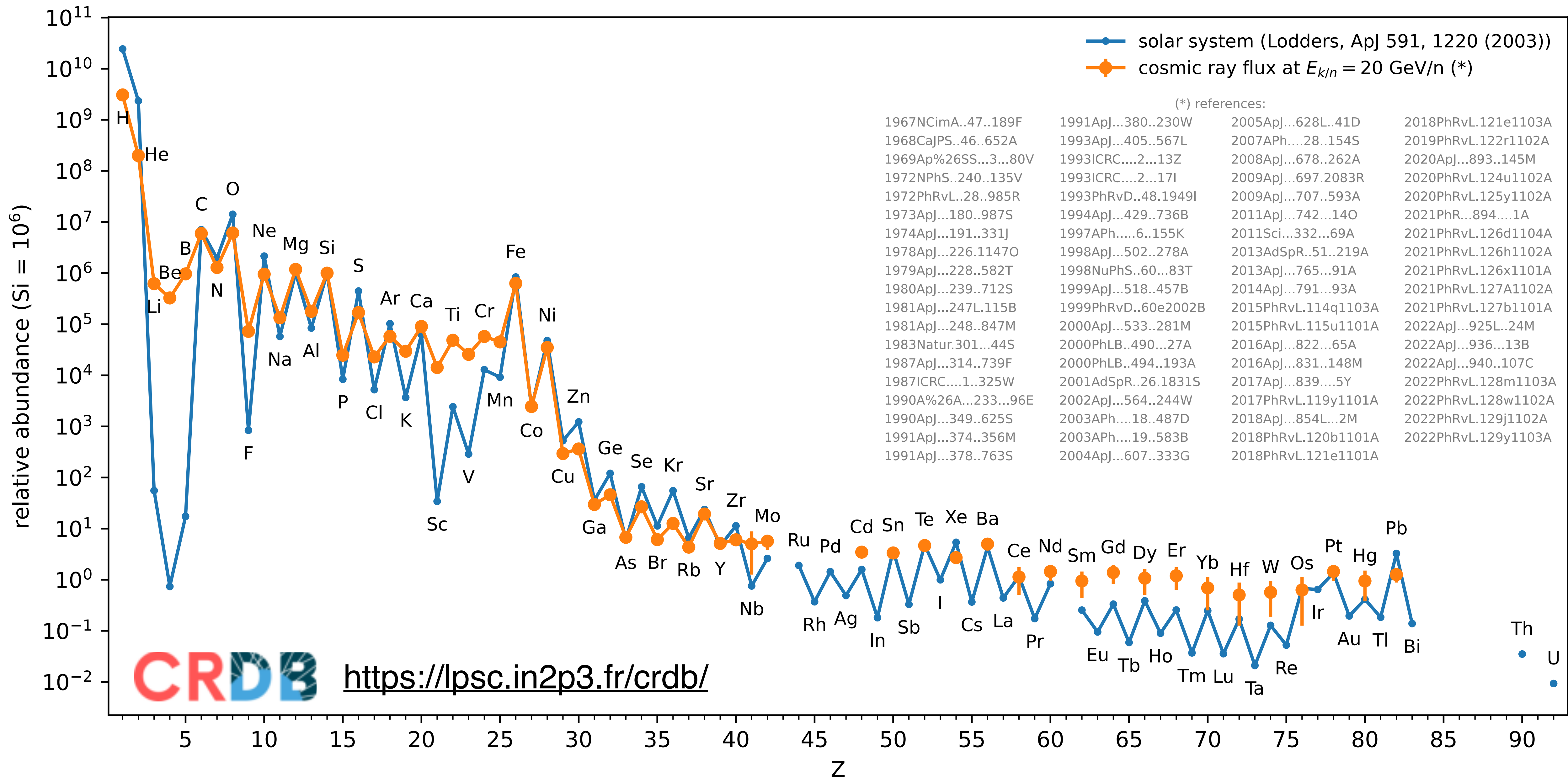
- 📌 **UHECRs**: the most energetic energetic and infrequent particles in the universe
- 📌 Challenging the **next-generation astronomy using UHECRs**
 - 📌 **Less deflections** of the Galactic/extragalactic magnetic fields
 - 📌 **Limitation of nearby sources** due to GZK cutoff
 - 📌 **Directionally correlations between UHECRs and nearby inhomogeneous sources to clarify their origins**
 - 📌 **Sensitive to signals induced by ultra-relativistic magnetic monopoles**
- 📌 The highest energy event of Telescope Array experiment on May 27th 2021
 - 📌 $E = 244 \pm 29$ (stat.) $+51, -76$ (syst.) EeV (~ 40 J), dubbed "Amaterasu particle"
 - 📌 **No obvious source candidates in arrival direction, possibly magnetic monopoles**
- 📌 Further data-collections of TA and Auger, and future observatories such as GCOS are essential to clarify origins of most energetic particles

UHECR observatories are a frontier for ultra-relativistic magnetic monopole searches

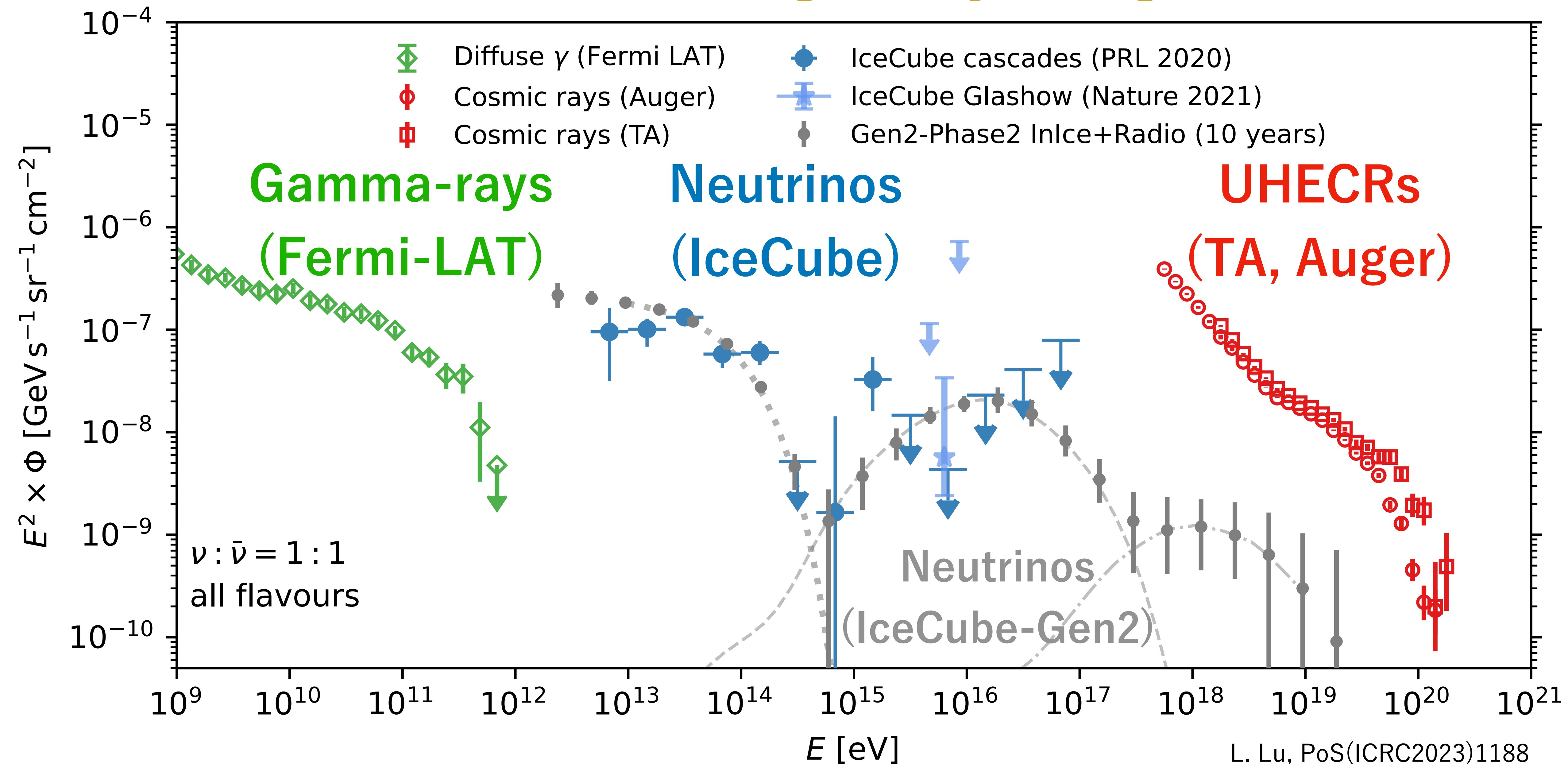
Thanks a lot 謝謝

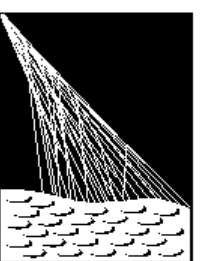


Mass composition of cosmic rays

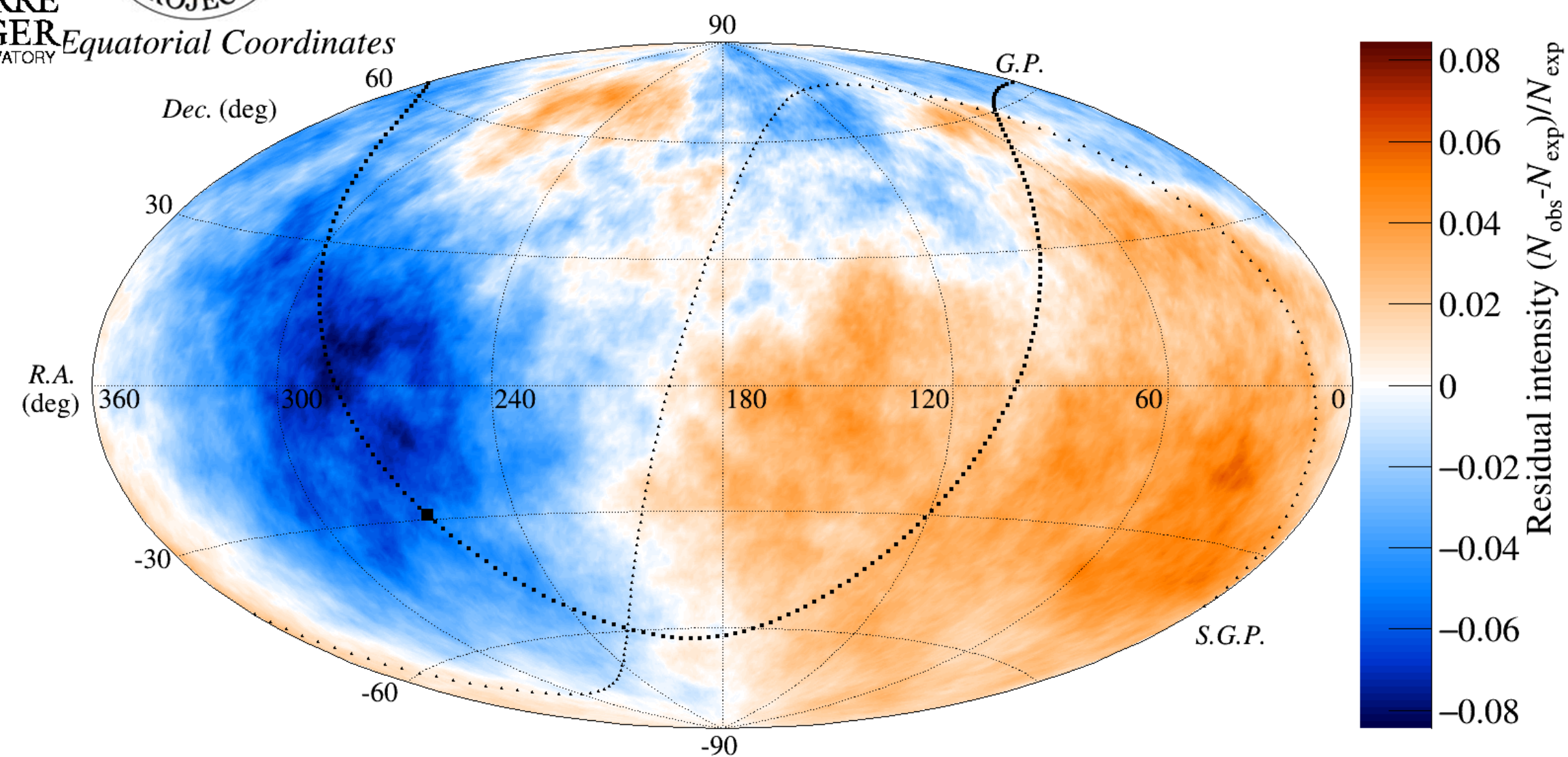


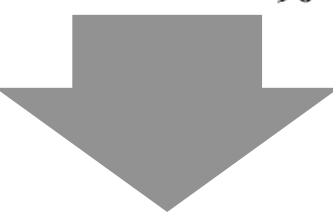
Multi-messenger synergies

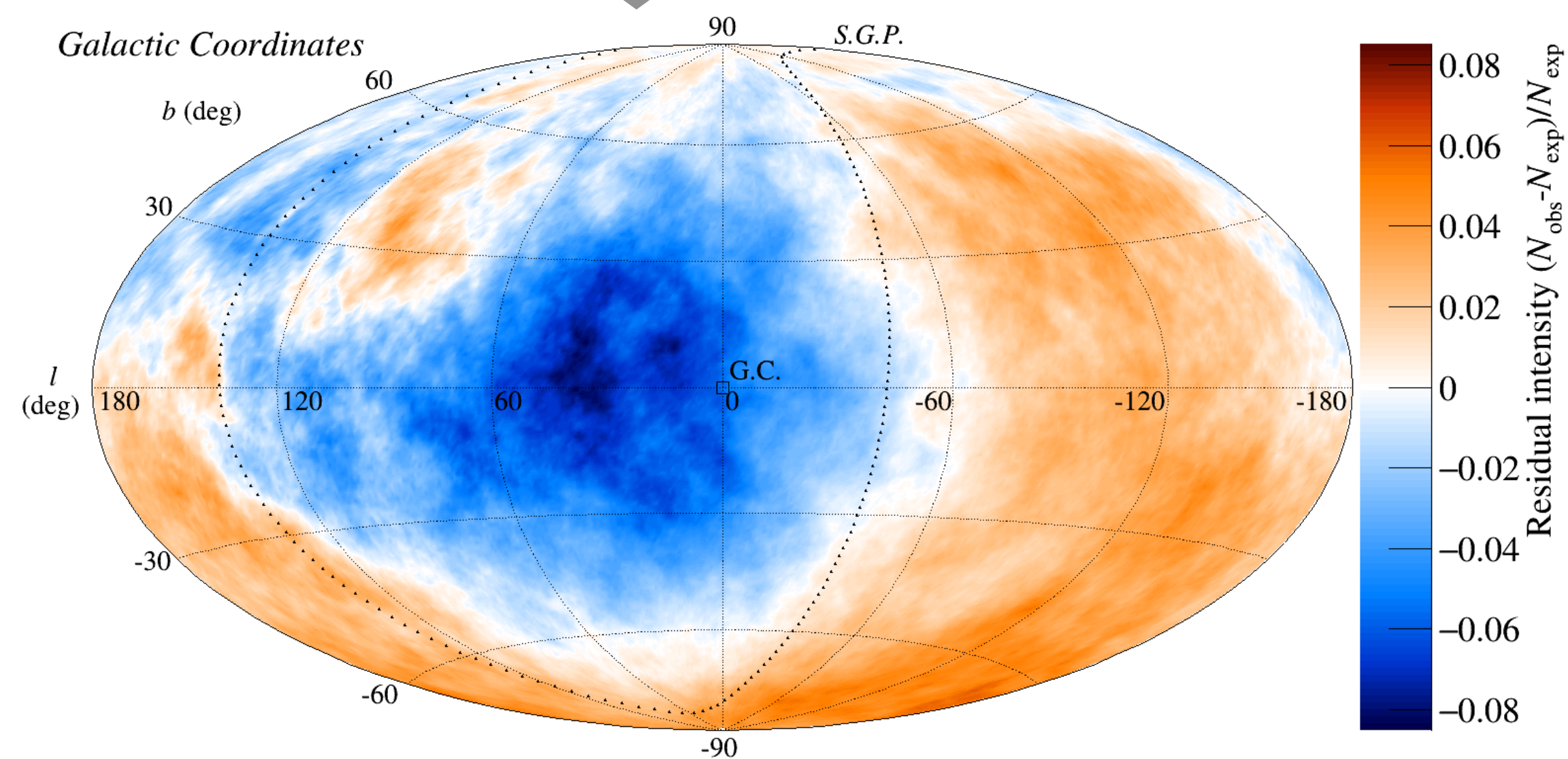




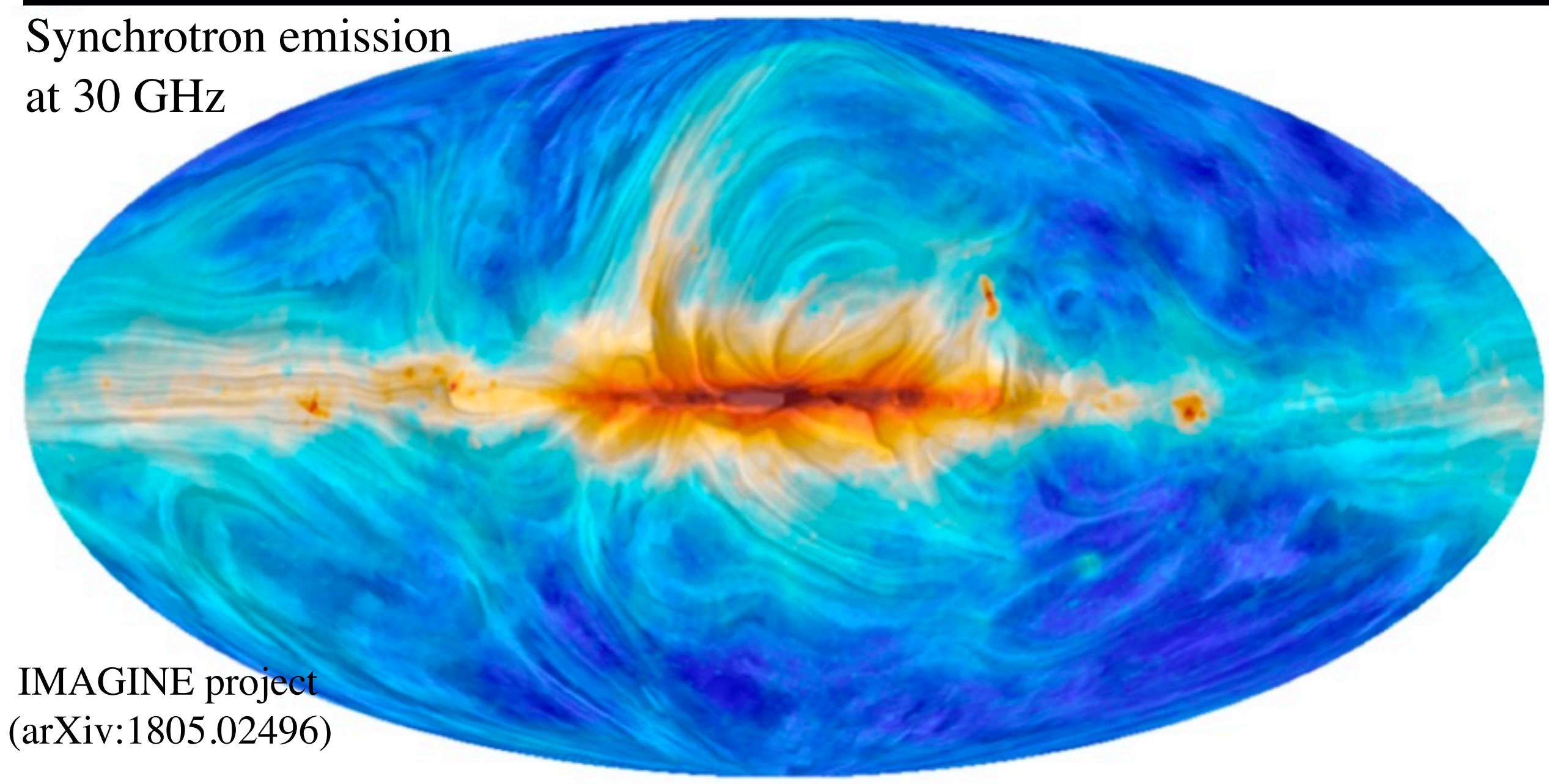
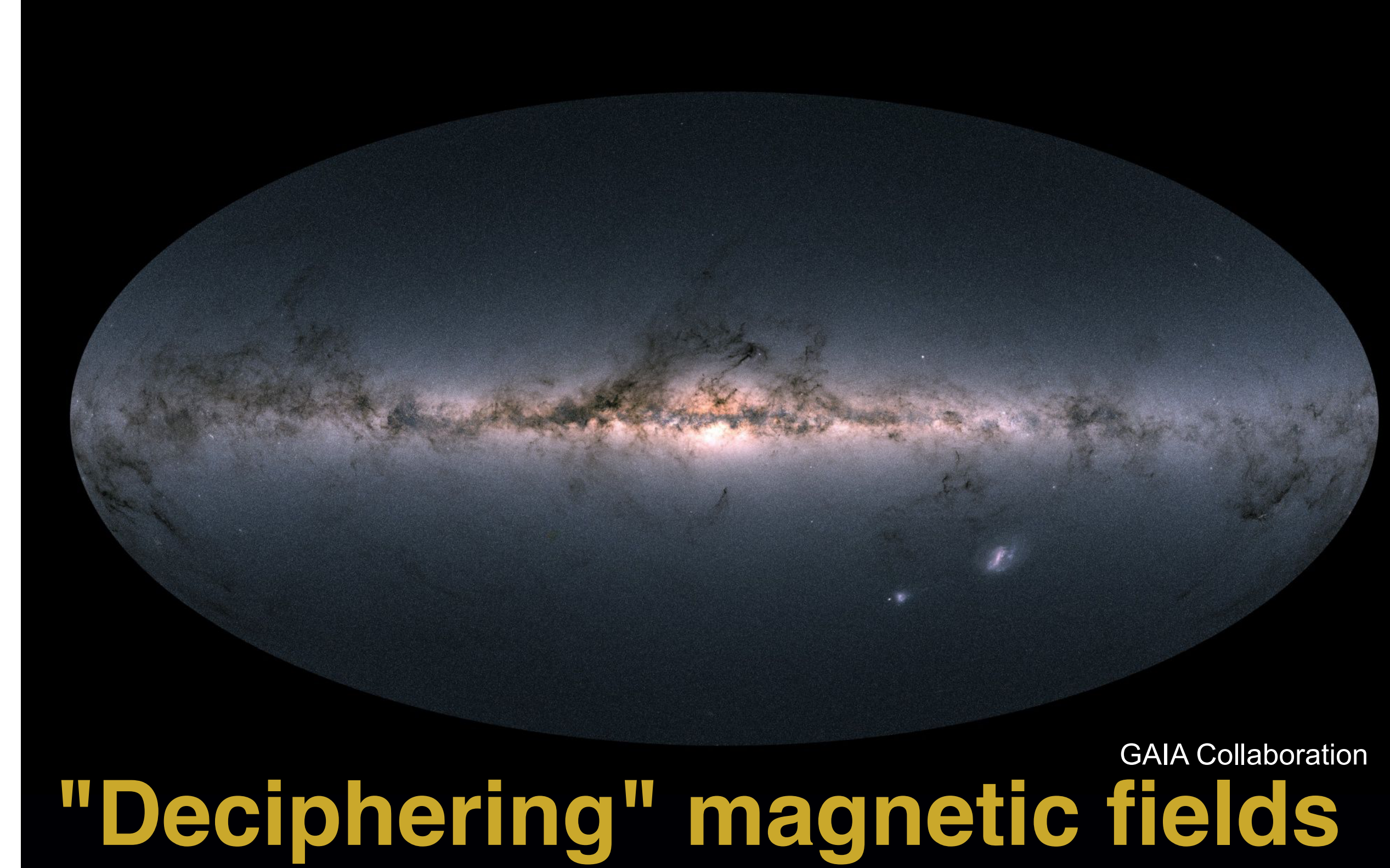
10 EeV skymap



Converted to  Galactic coordinates

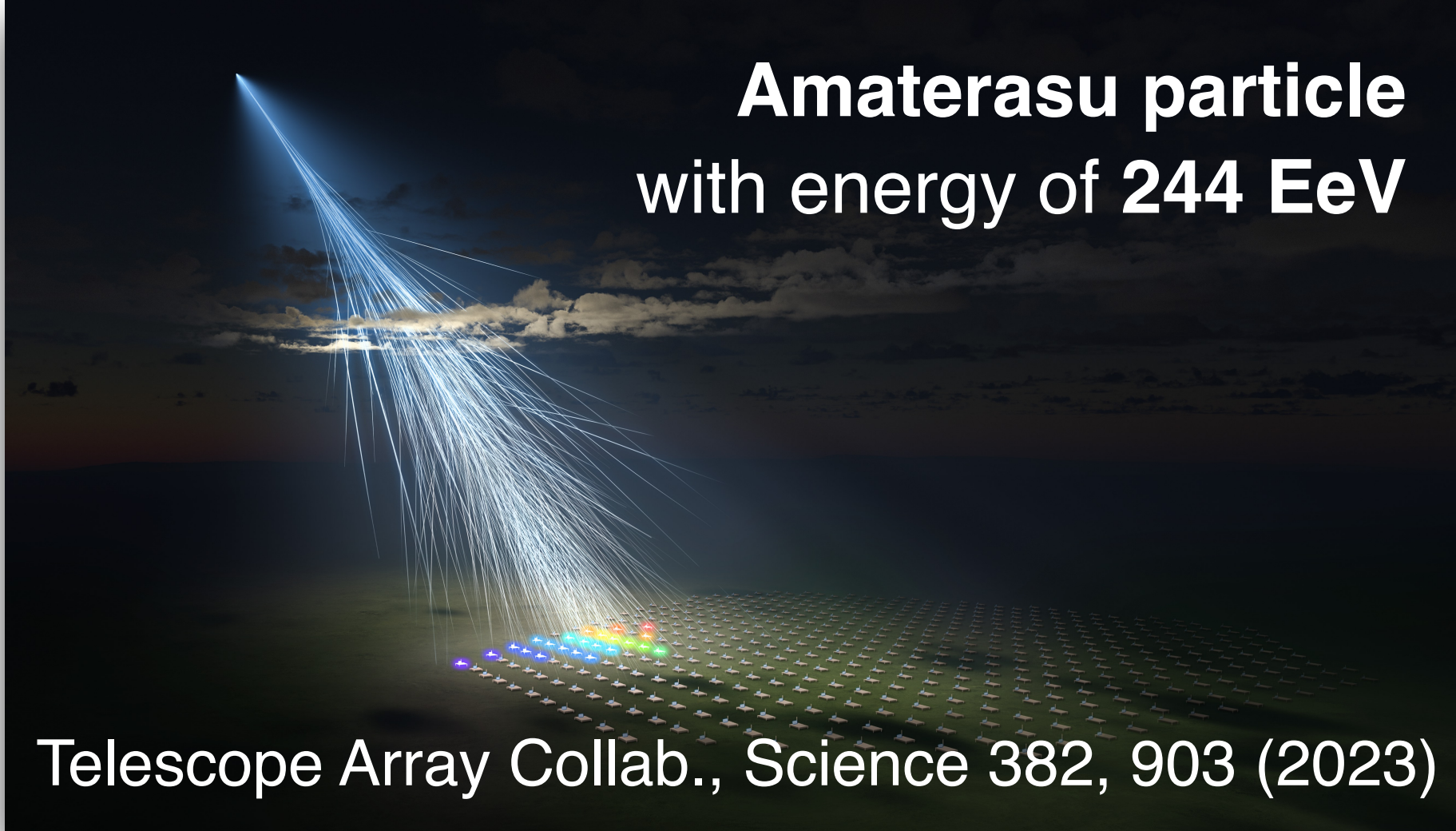


T. Fujii, PoS (ICRC2021) 402 (2021)



Data-driven Search for Origins of Amaterasu Particle³⁰

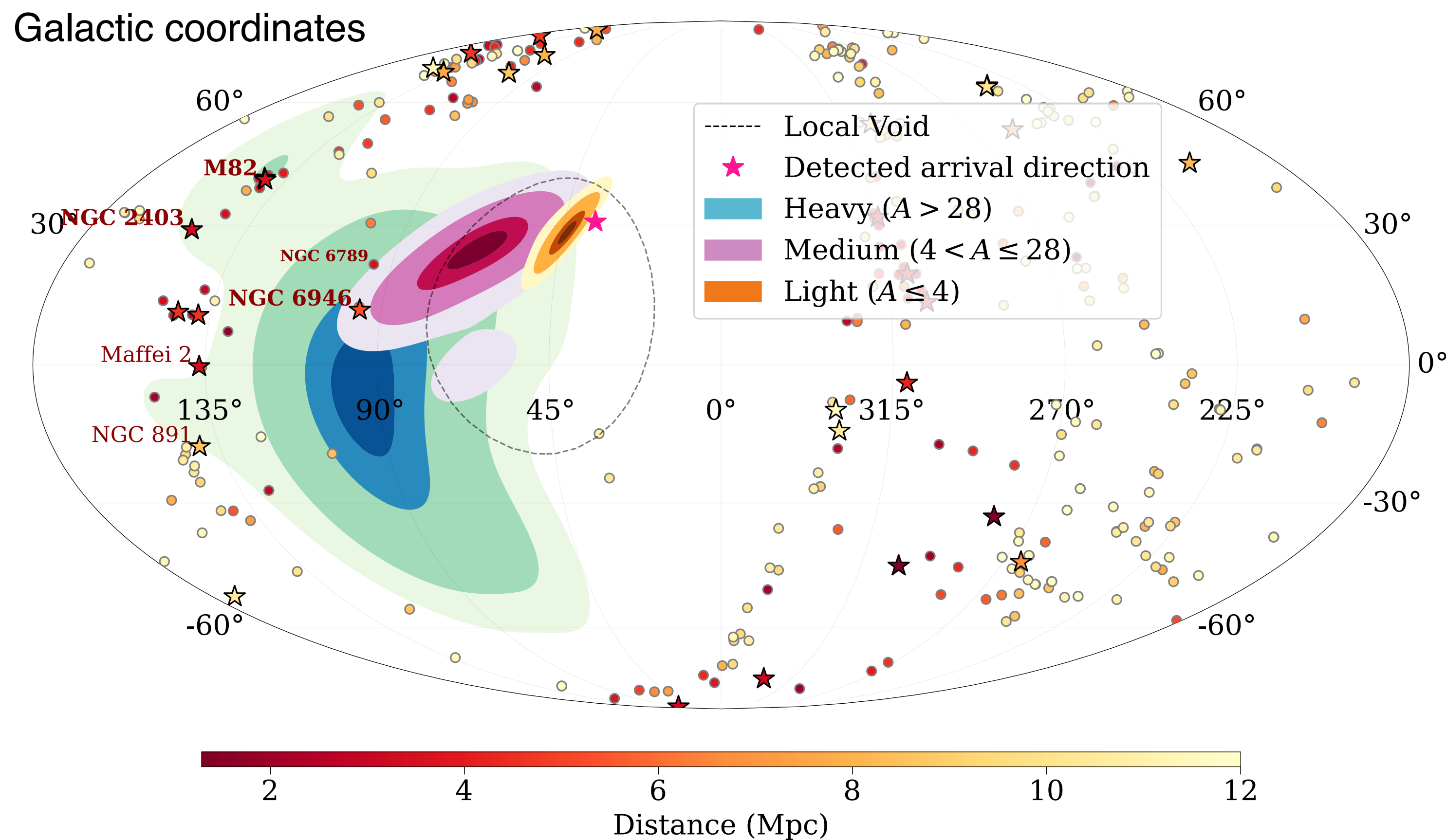
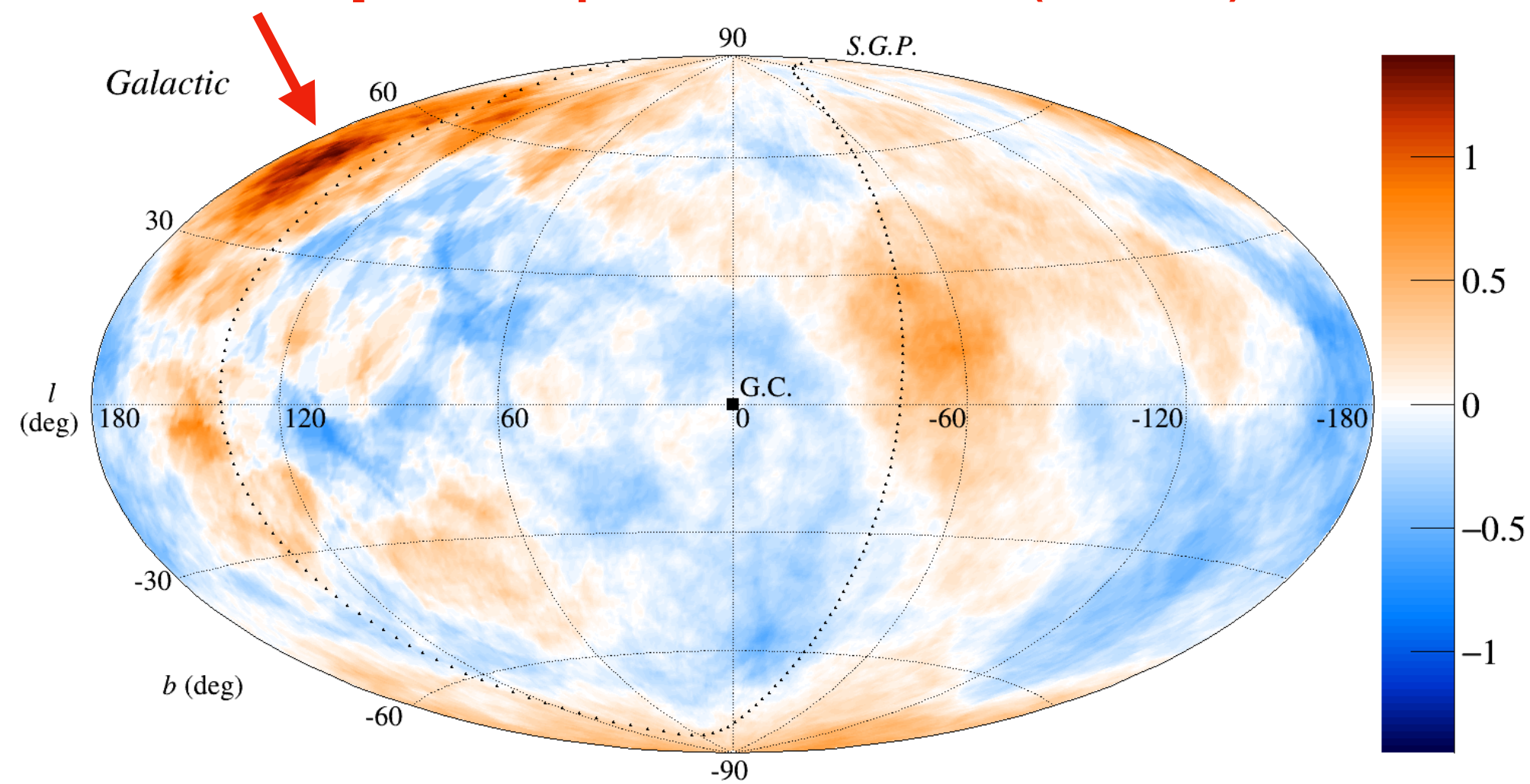
N. Bourriche and F. Capel 2026 ApJ 997 264 (2026)



- Source regions are estimated considering magnetic deflections in **both Galactic and extragalactic 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)



Energy dependence on the dipole amplitude

31

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Aab et al.

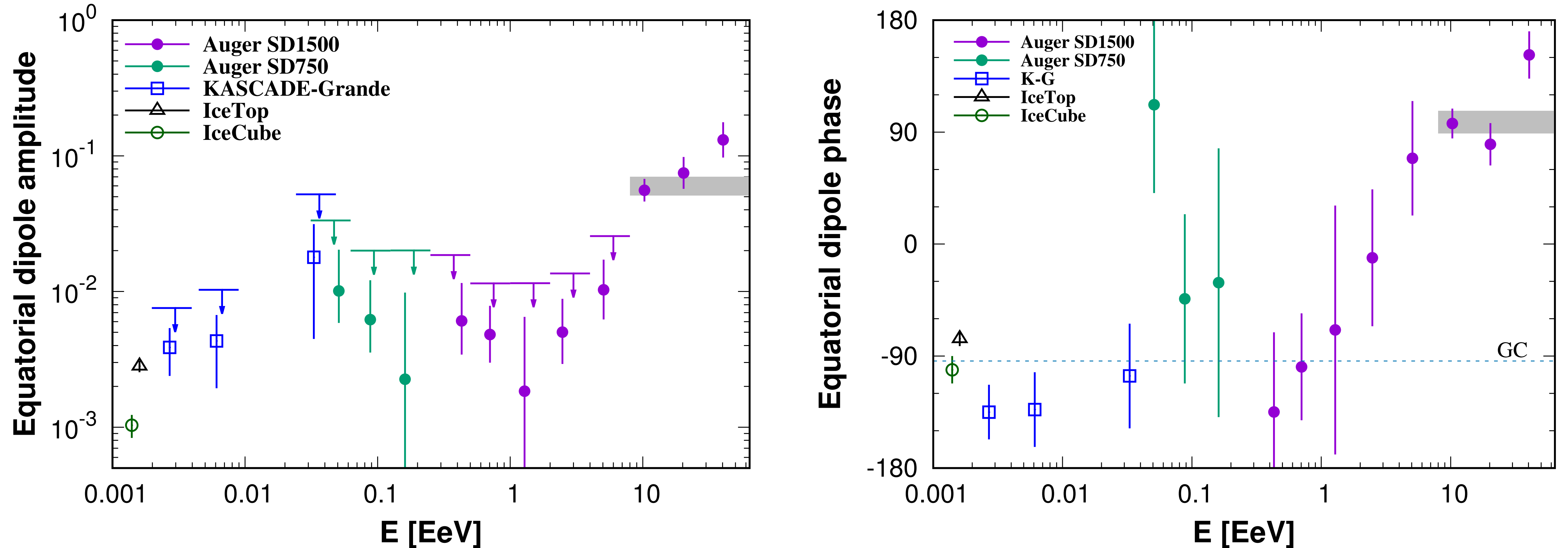
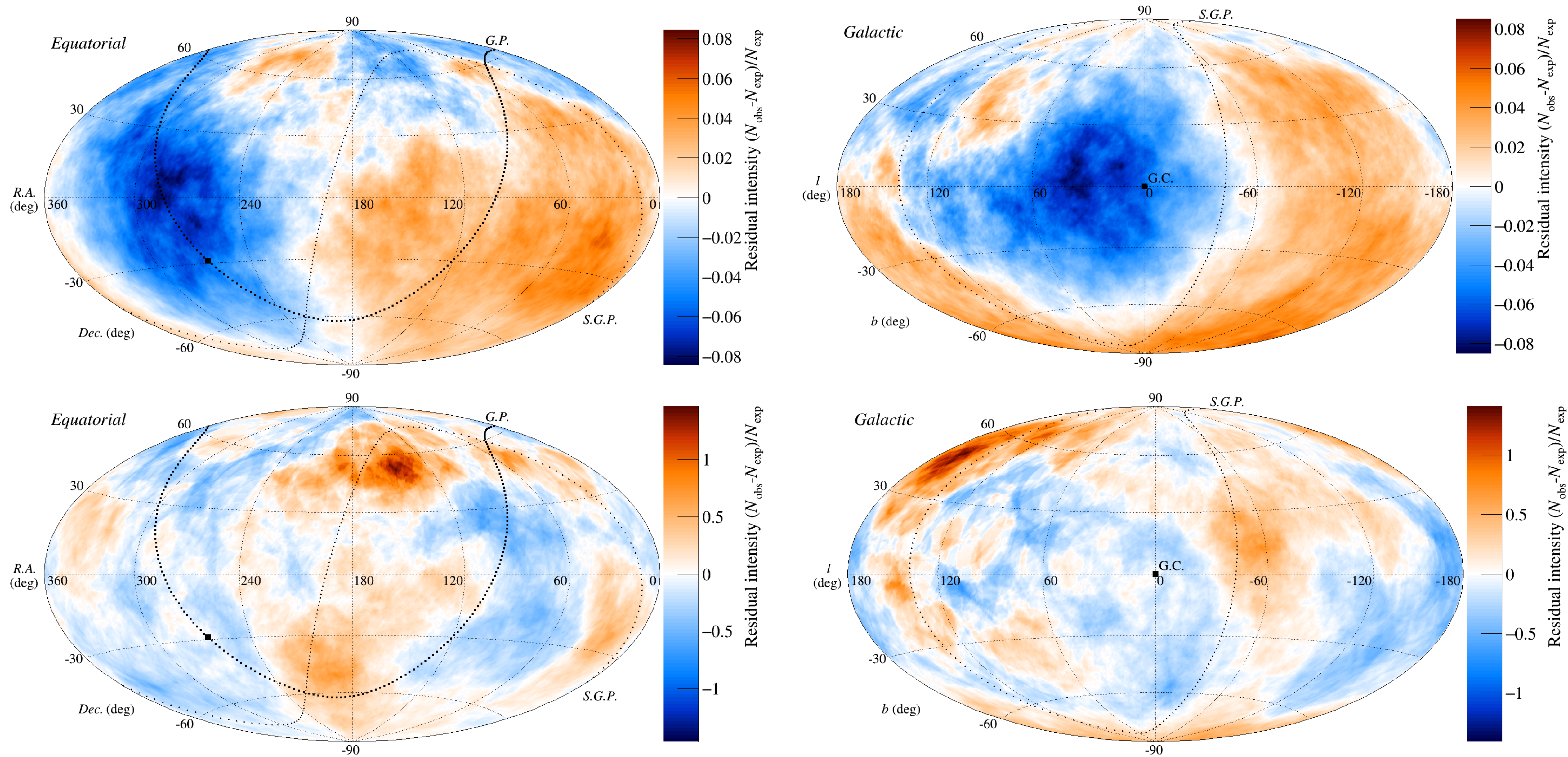


Figure 1. Reconstructed equatorial dipole amplitude (left) and phase (right). The upper limits at 99% CL are shown for all the energy bins in which the measured amplitude has a chance probability greater than 1%. The gray bands indicate the amplitude and phase for the energy bin $E \geq 8$ EeV. Results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

50 EeV skymaps



100 EeV skymaps

