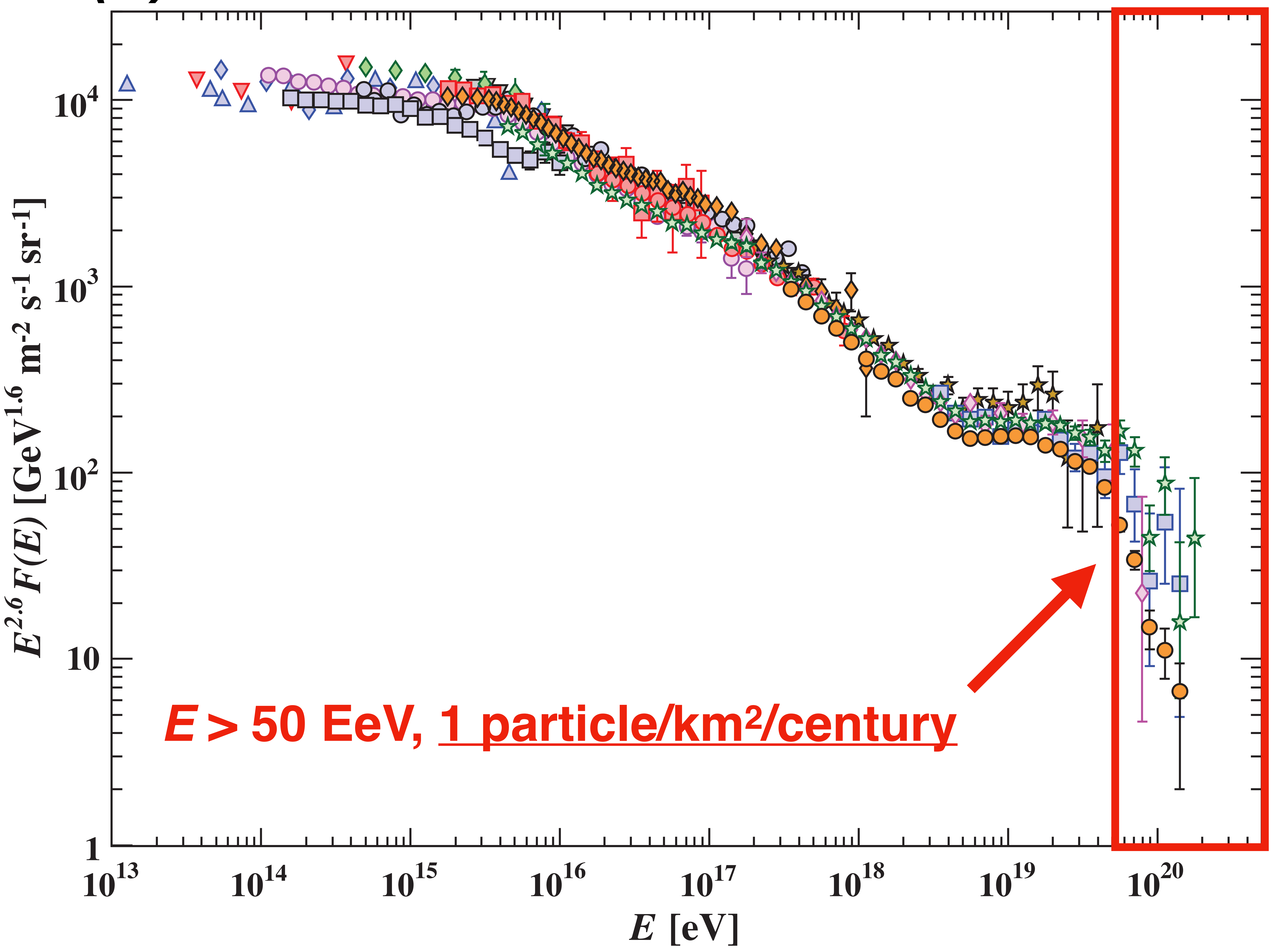
Machine Learning for the Global Cosmic Ray Observatory

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

TADAML workshop, Taipei, Taiwan, October 16, 2025

Energy spectrum of cosmic rays

$E^{2.6}\ J(E)$



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

- **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 km²
  - Long term observation over decades

Source candidates and next-generation astronomy

or "New physics"

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

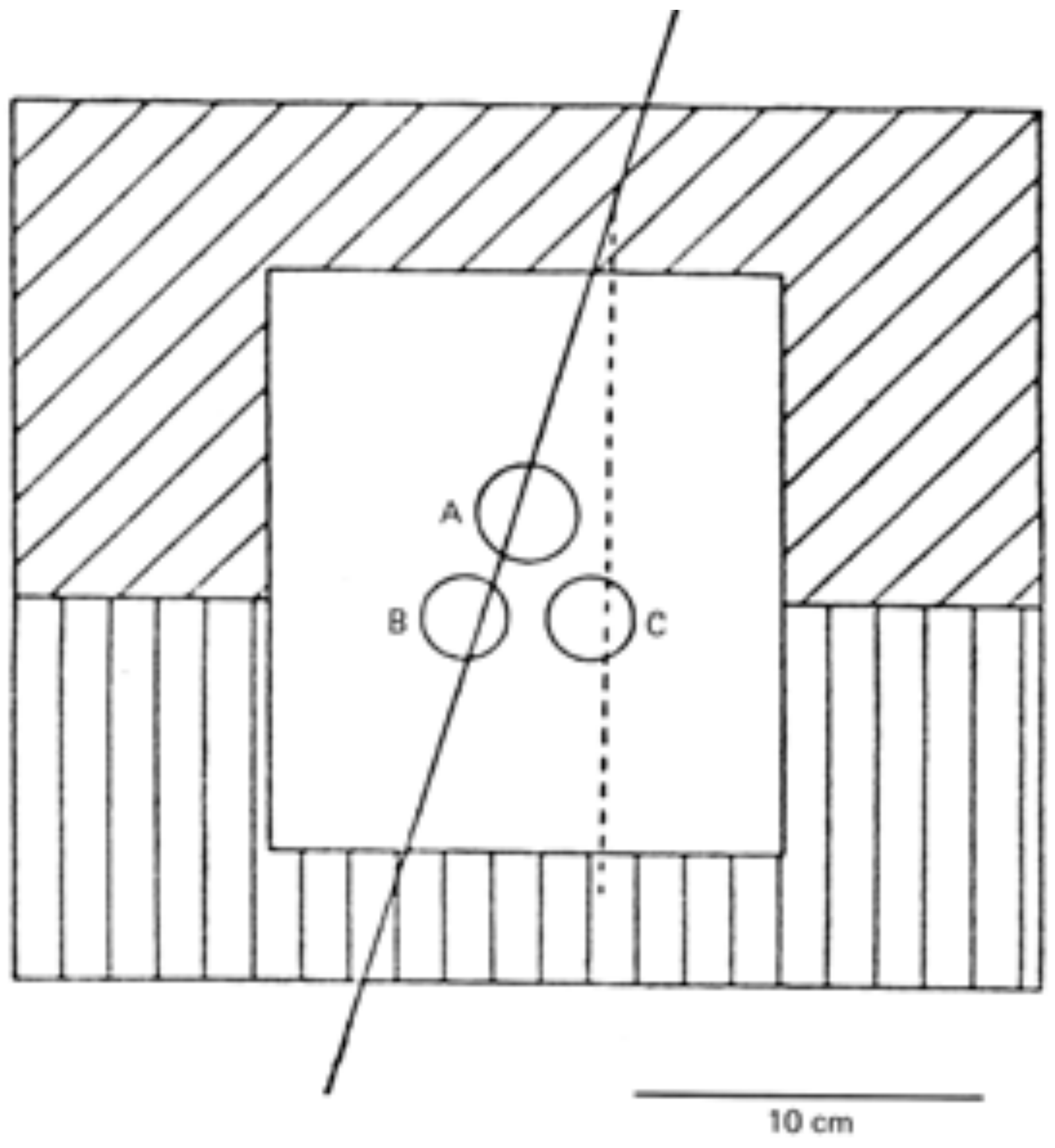
$$p + \gamma_{\mathrm{CMB}} \to \Delta^{+} \to p + \pi^{0} \qquad {}^{A}_{Z}N + \gamma_{\mathrm{CMB}} \to {}^{A-1}_{Z-1}N' + p$$

- **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 charged particles**

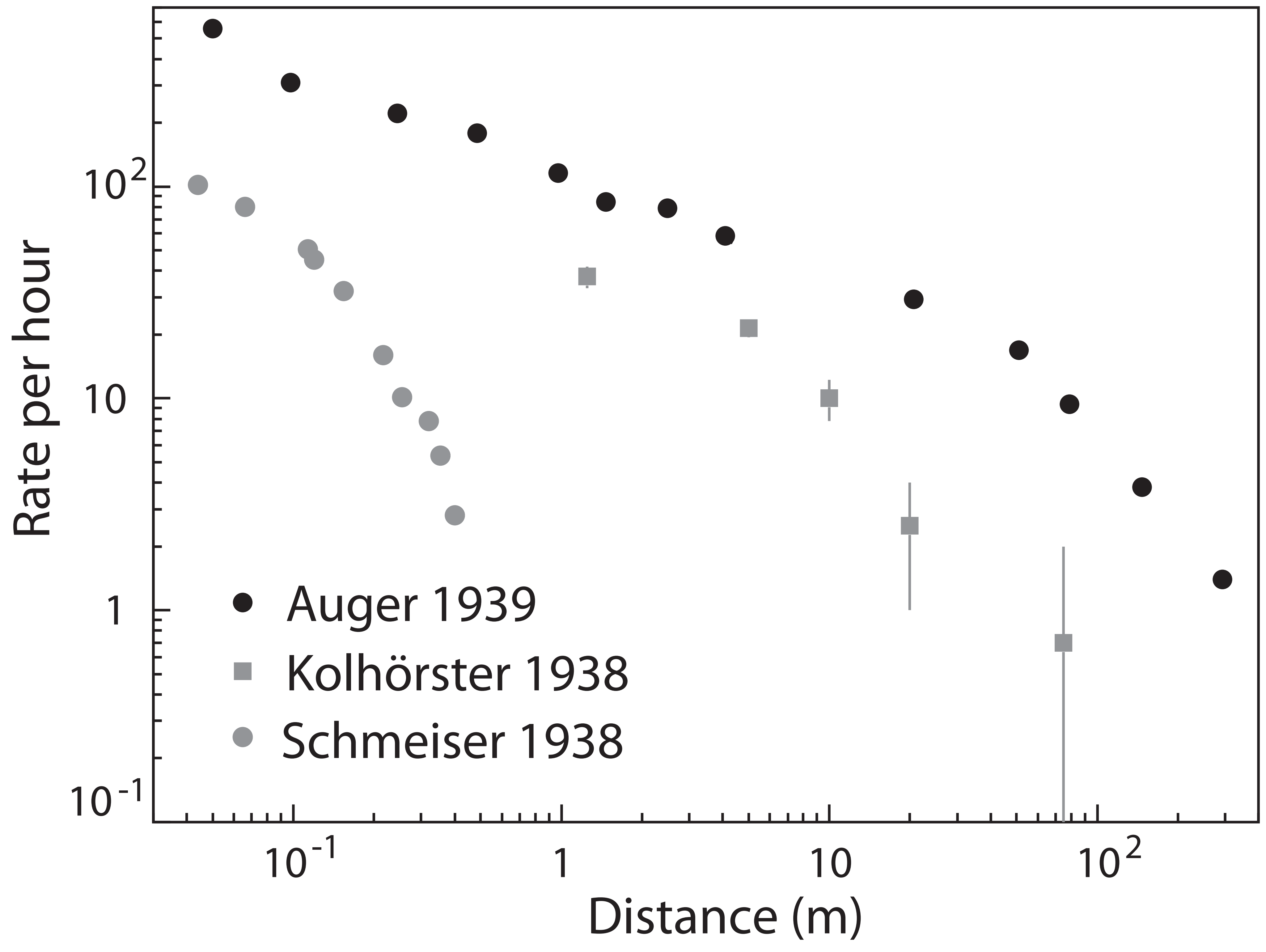
How to detect extremely infrequent UHECRs?

Discovery of extensive air shower

- Development of coincidence method within 0.4 millisecond (B. Rossi, 1931)



- Discovered coincidence signals of distant detectors with 150 m spacing at 3450 m (P. Auger, 1939)

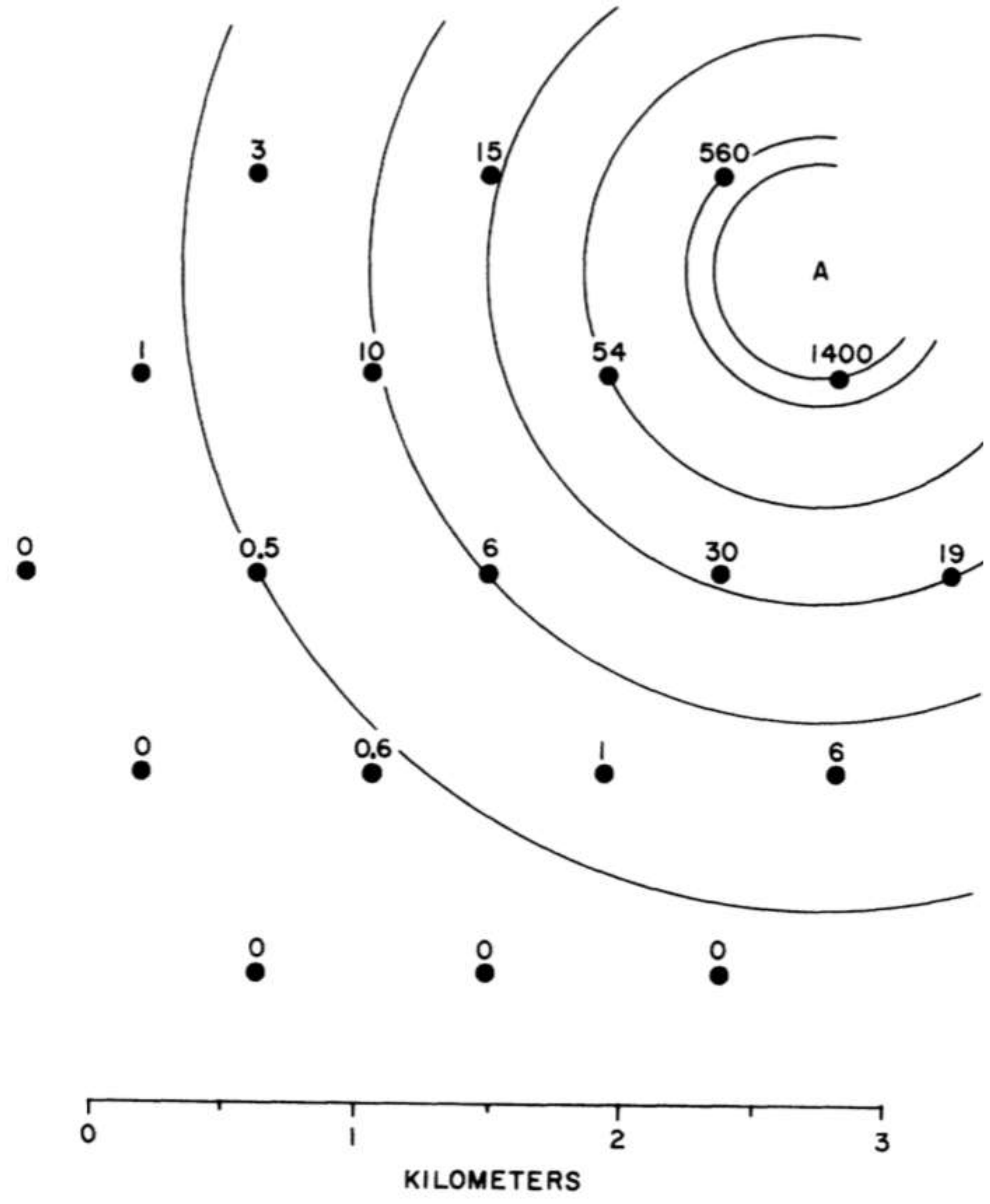


- Particle shower at 3027 m (W.B. Fretter, 1949)

K.H. Kampert, A.A. Watson, Eur. Phys. J. H 37, 359–412 (2012)

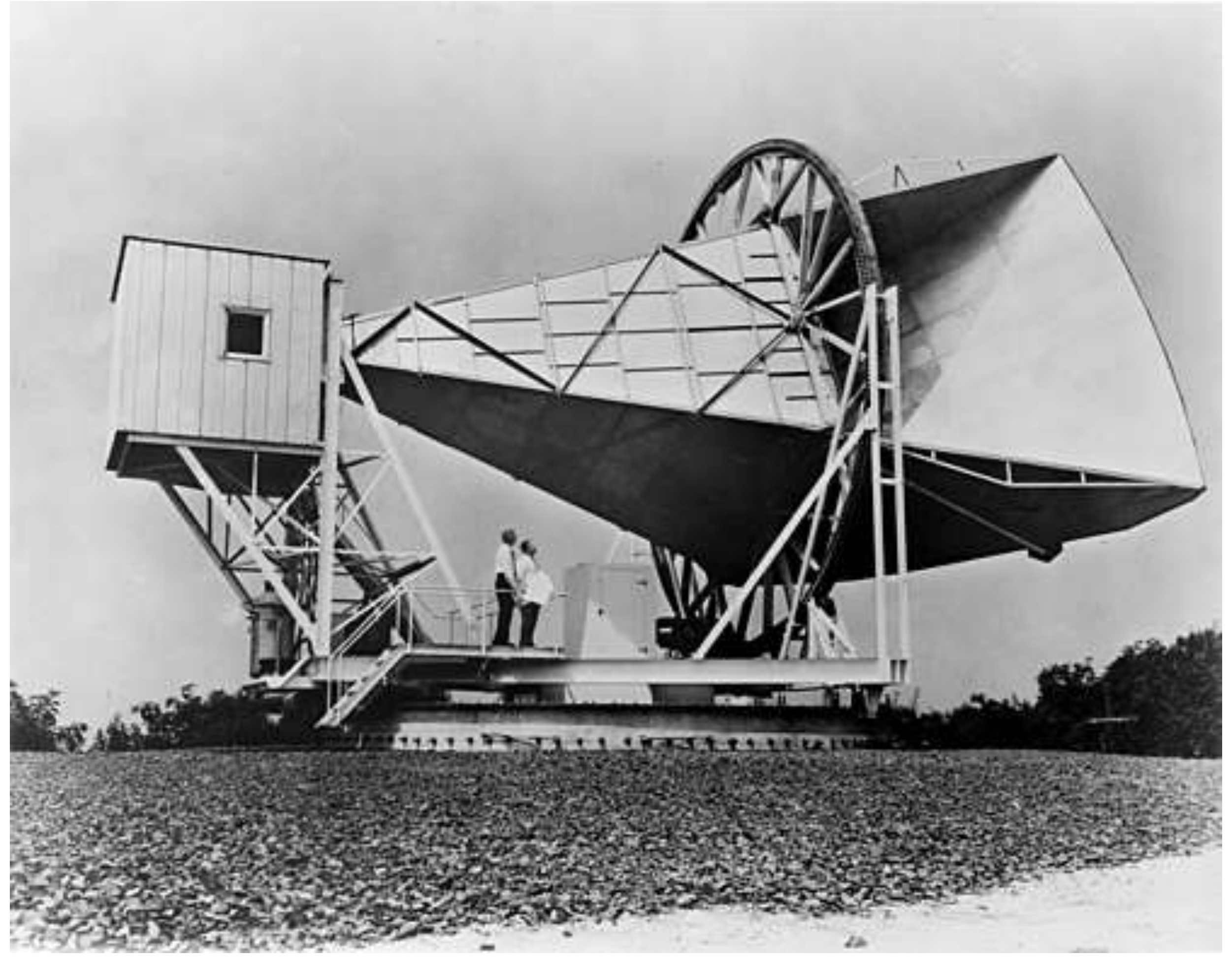
The beginning of 100 EeV (10^{20} eV) detection

First detection of ~100 EeV at Volcano Ranch Array (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 (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 (1966)

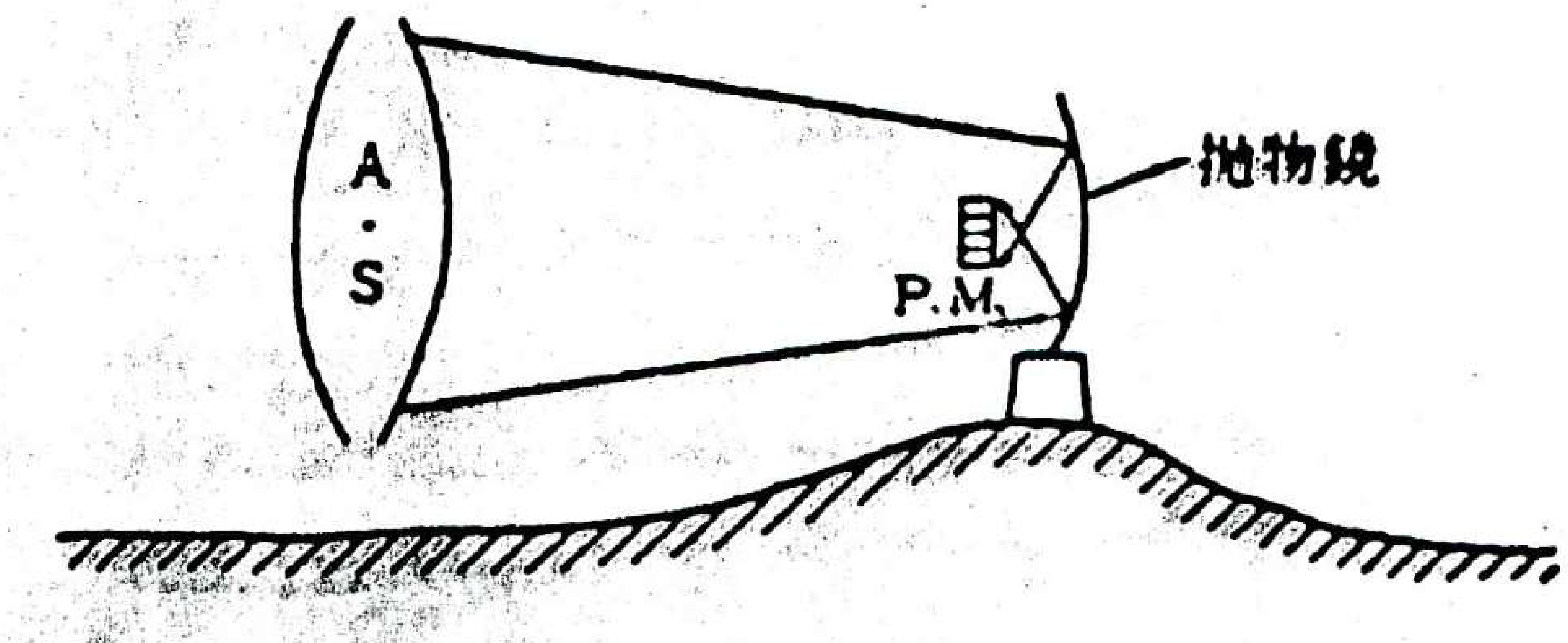
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

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

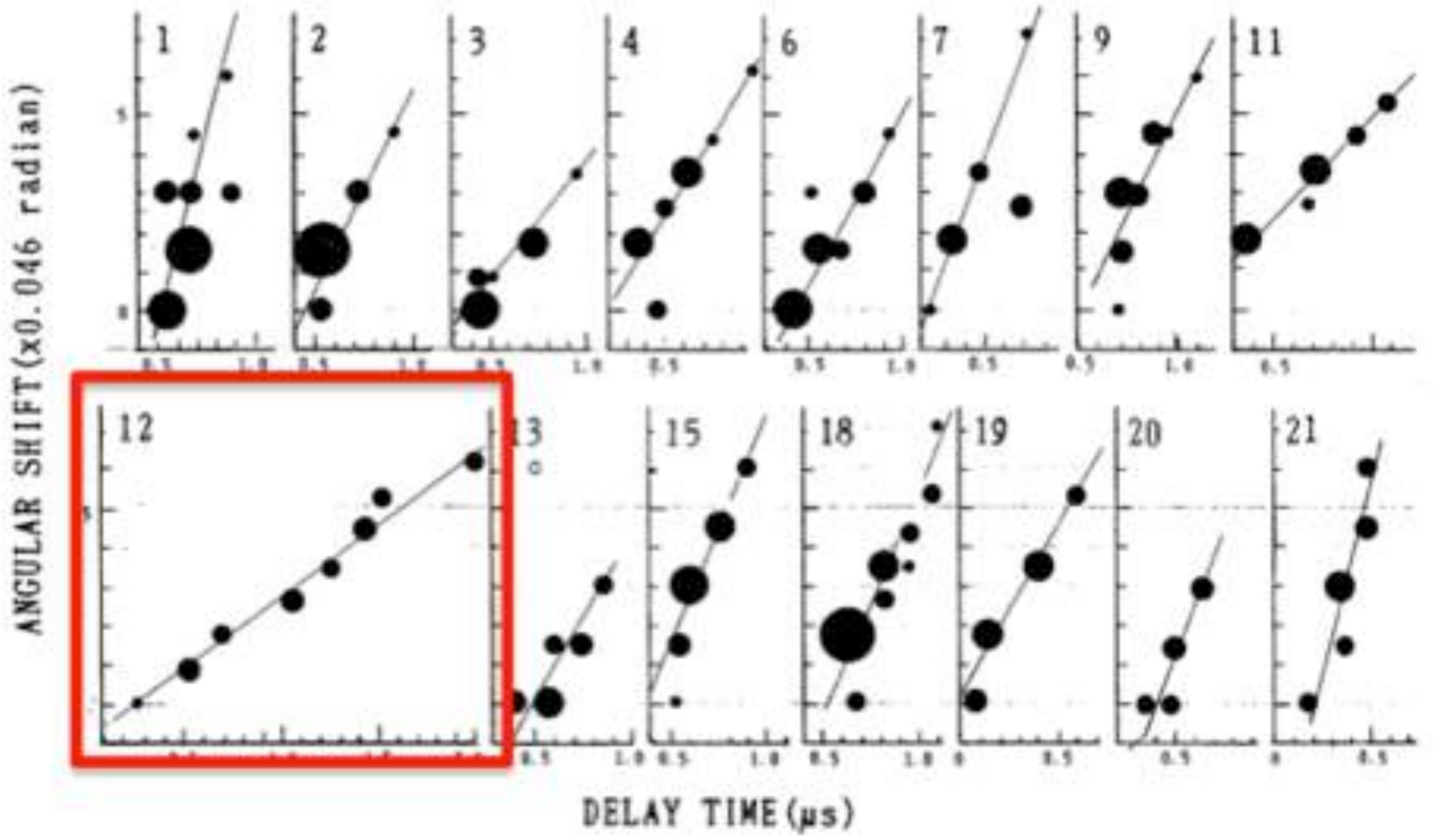
How to detect extremely infrequent UHECRs?

History of fluorescence detector

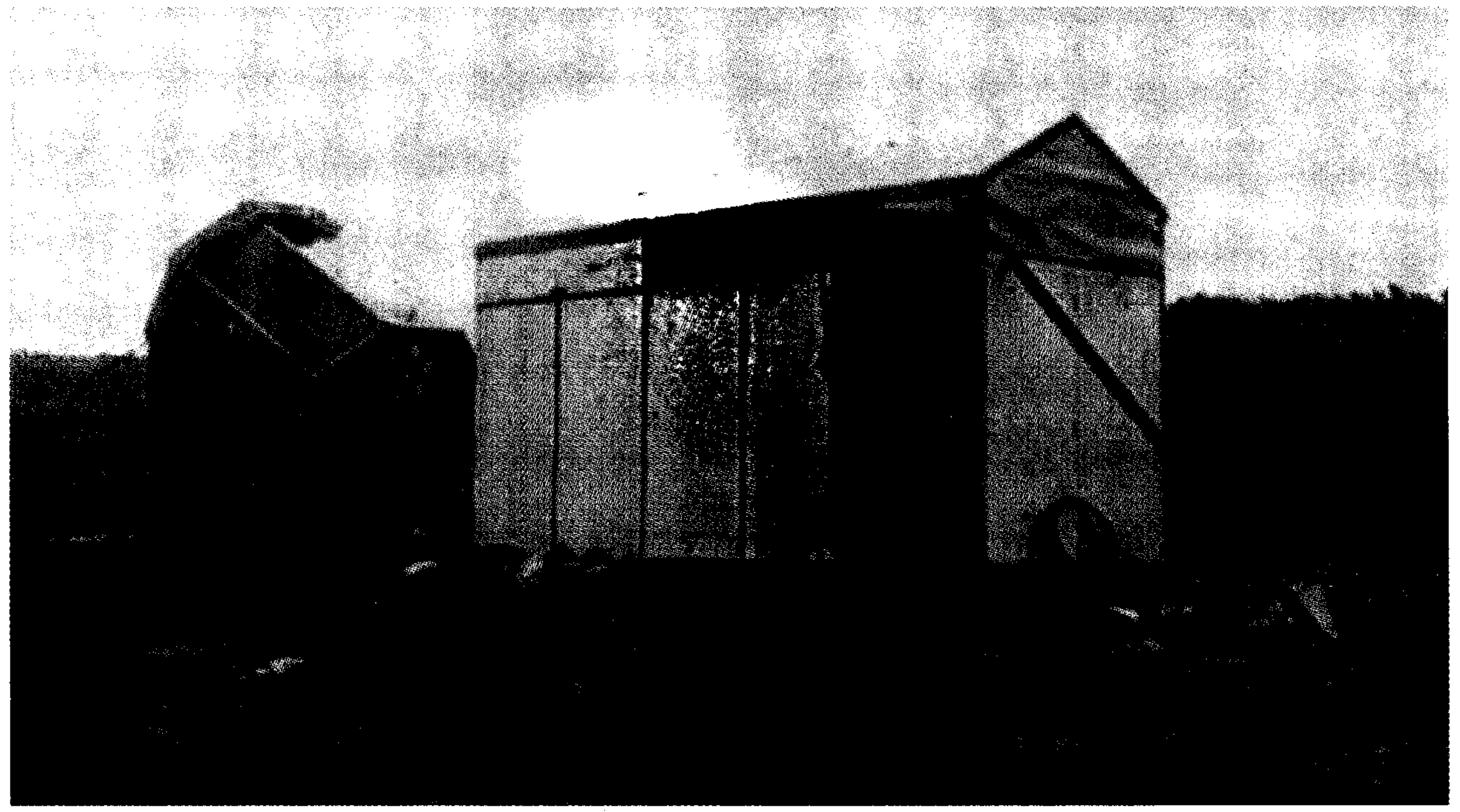


第3図 1958年乗鞍シンポジウムで話されたシャワー・カーブ測定の提案

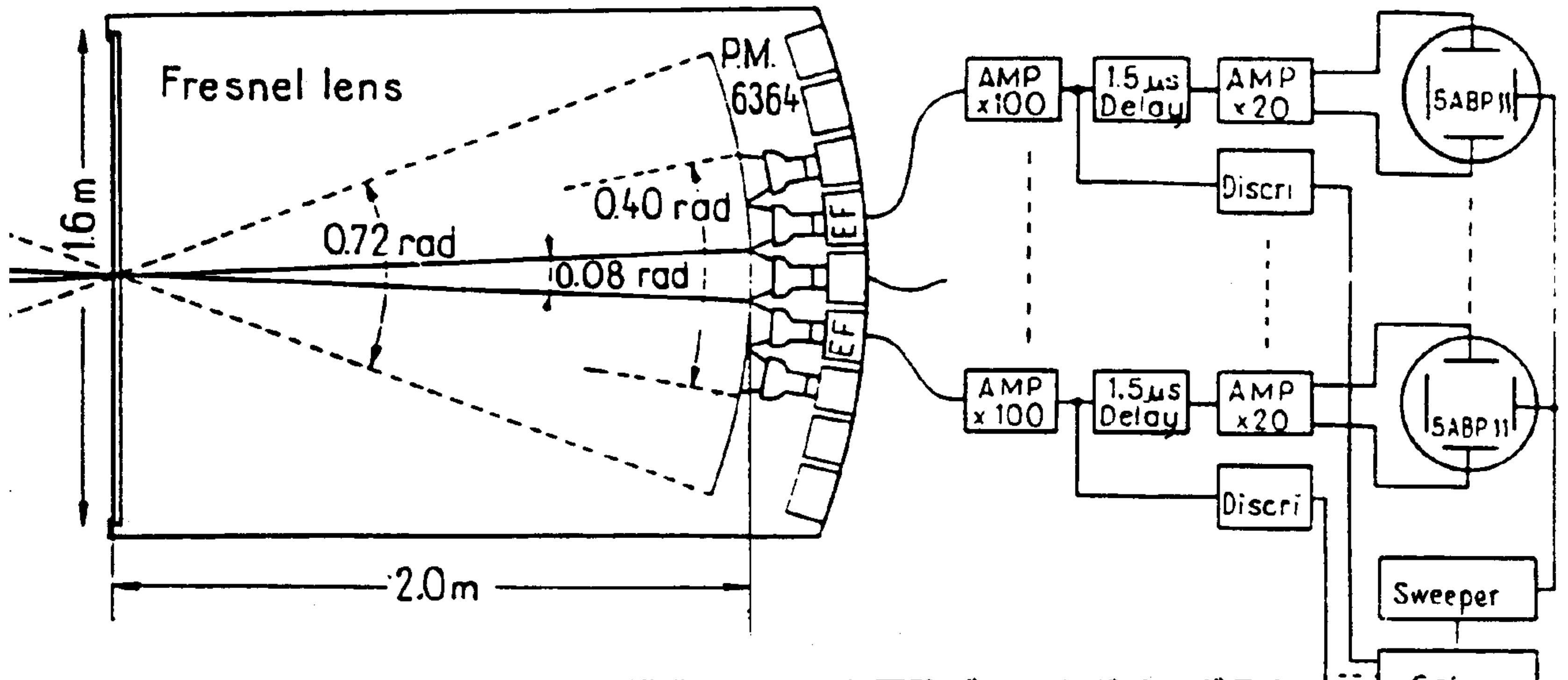
- Proposed by K. Suga and M. Oda (1958), also by Greisen and Chudakov at the same time
- First detection by Fresnel lens and 55 PMTs, TOKYO-1 (**1969**)



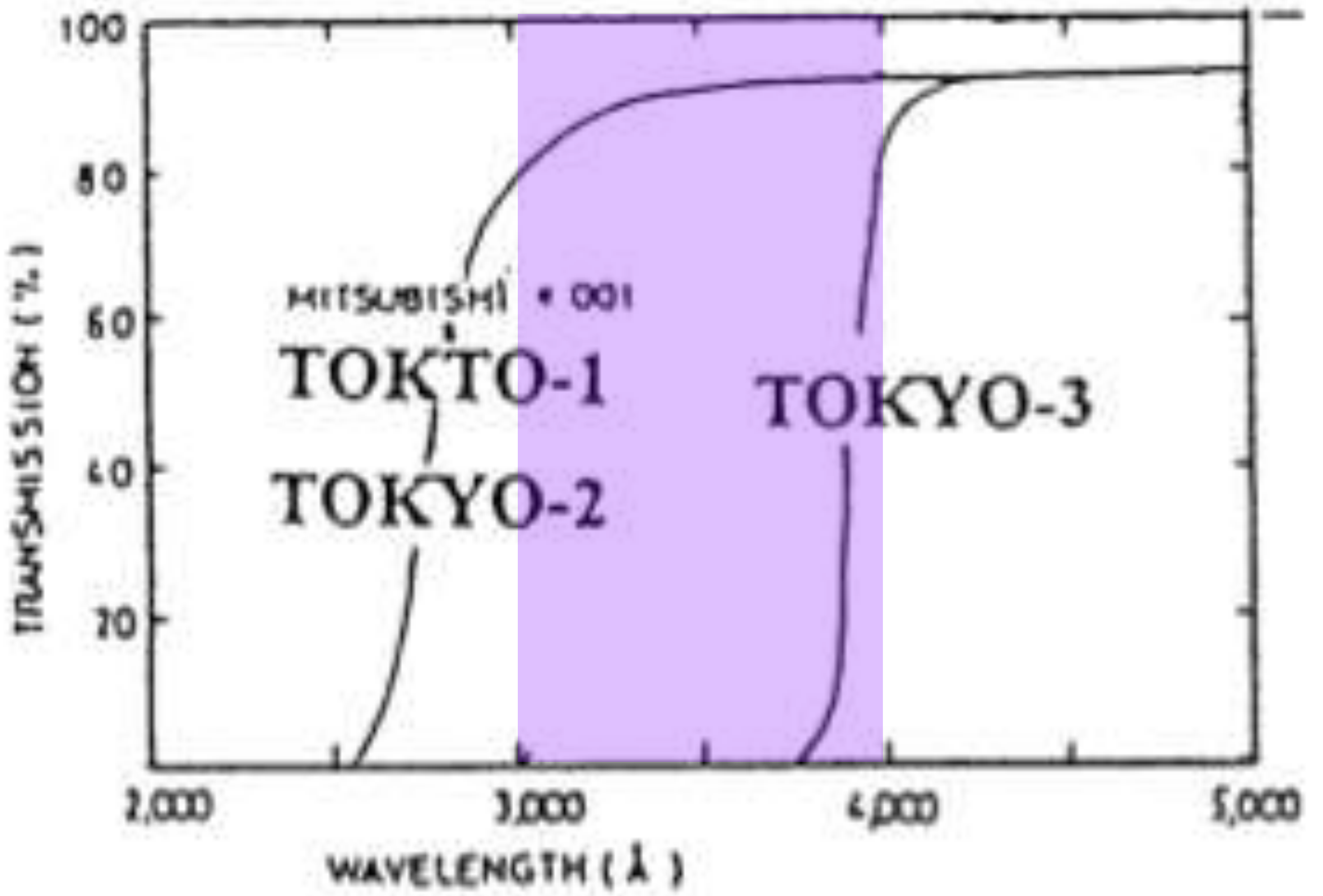
5×10^{18} eV, 680 g/cm^2 analyzed by B. Dawson, arXiv:1112.5686 (2011)



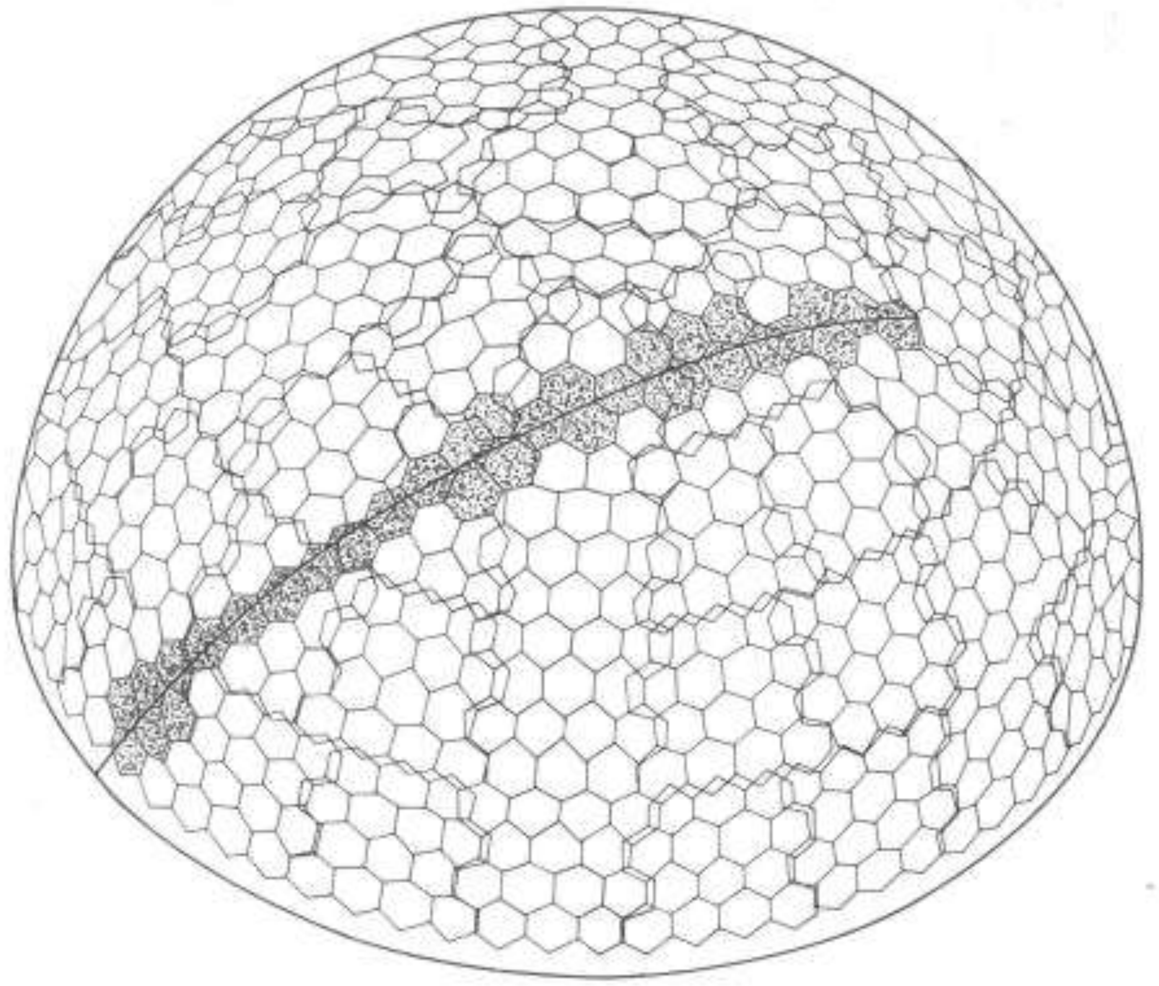
第8図 TOKYO−1の設置写真



第7図 TOKYO-1の構造スケッチと回路ブロックダイアグラム



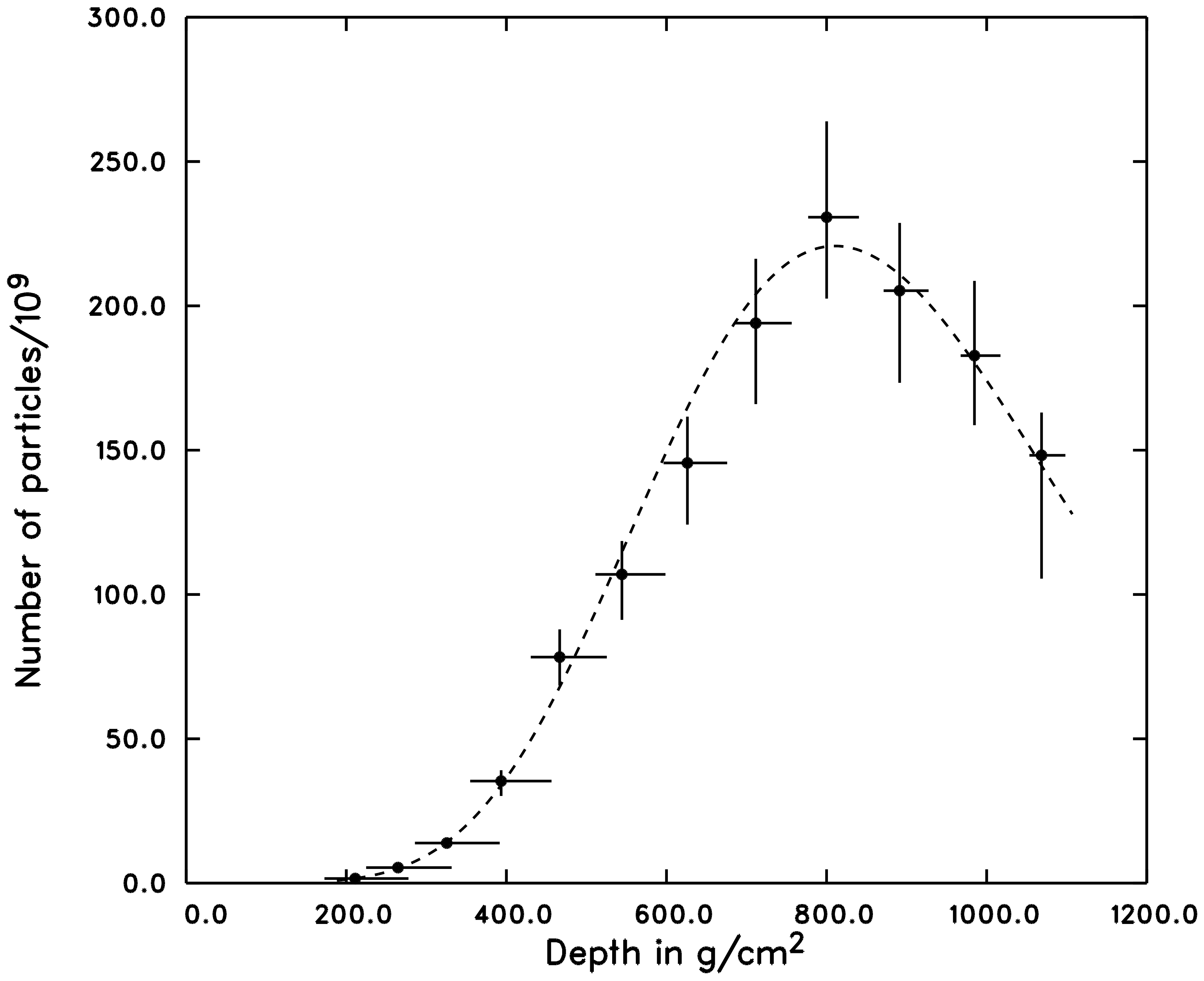
The Universe's most energetic particle



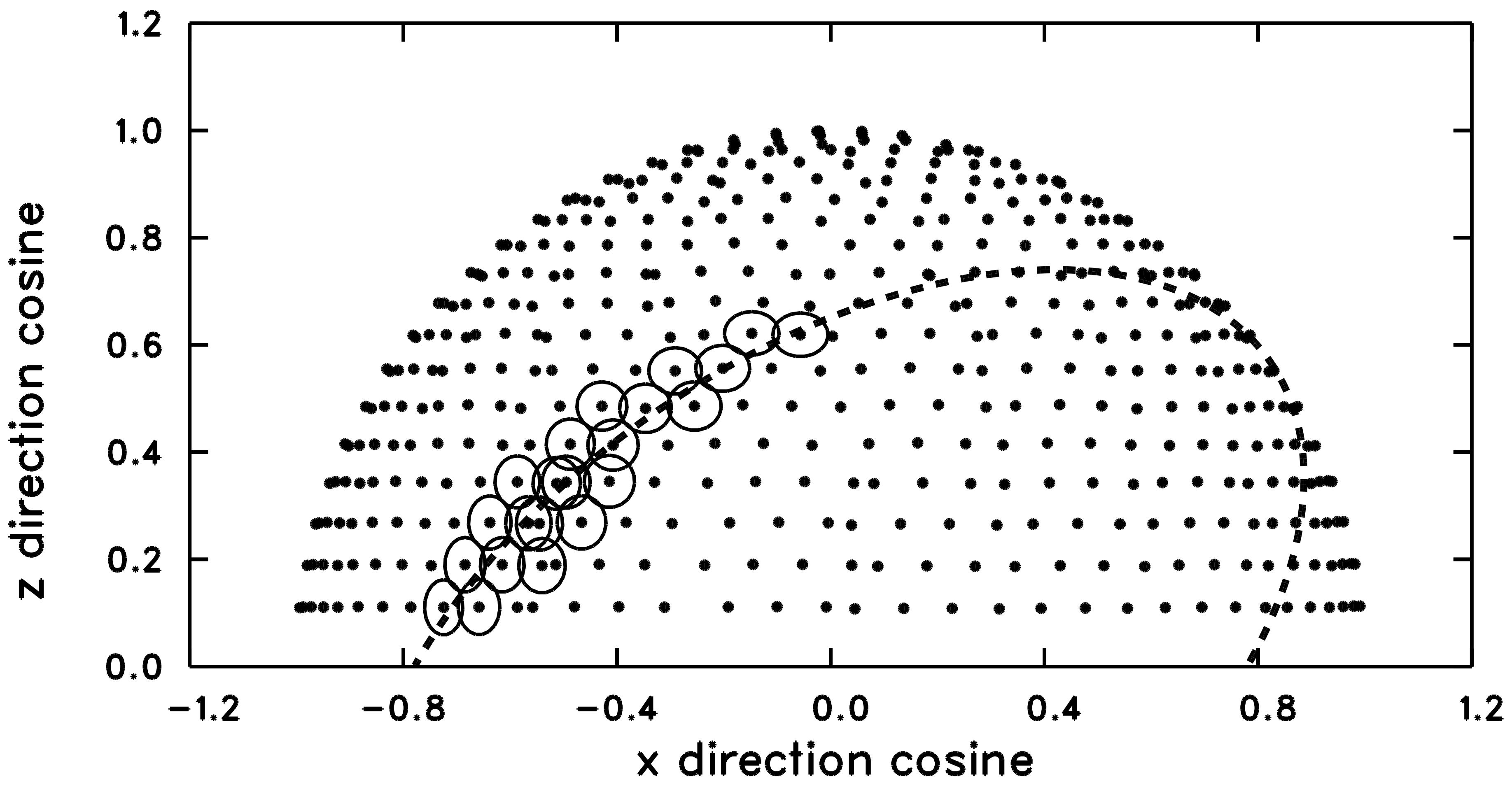
Fly's Eye (Utah, USA)
Construction started from **1976**, after a confirmation of fluorescence signal at Volcano Ranch Array

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

$$\boldsymbol{X_{max} = 815 \pm 60\ \mathrm{g/cm^2}}$$



The highest energy cosmic ray so far, 15th October, 1991
320 ± 38 (stat.) ± 85 (syst.) EeV, *"Oh-My-God" particle*



(R.A., Dec.) = (85.2°, 48.0°)

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

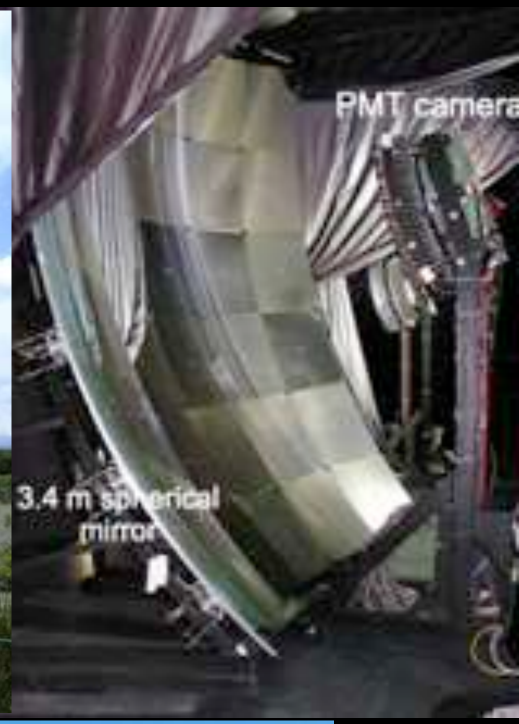
Start the High Resolution Fly's Eye (HiRes-1) from 1994.

Latest UHECR observatories

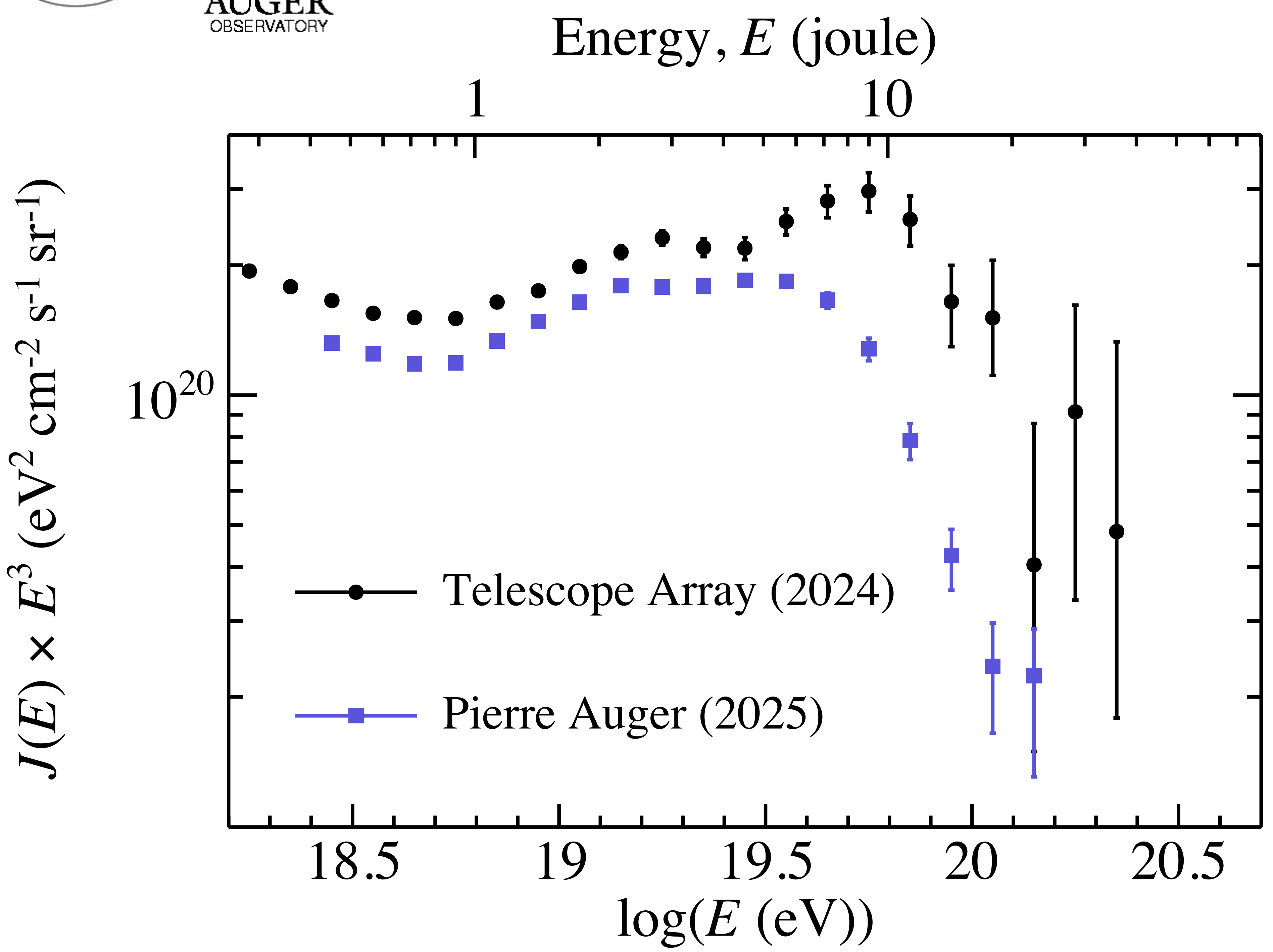
Google Earth

- **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 + small PMT + radio + buried muon detector + high speed electronics

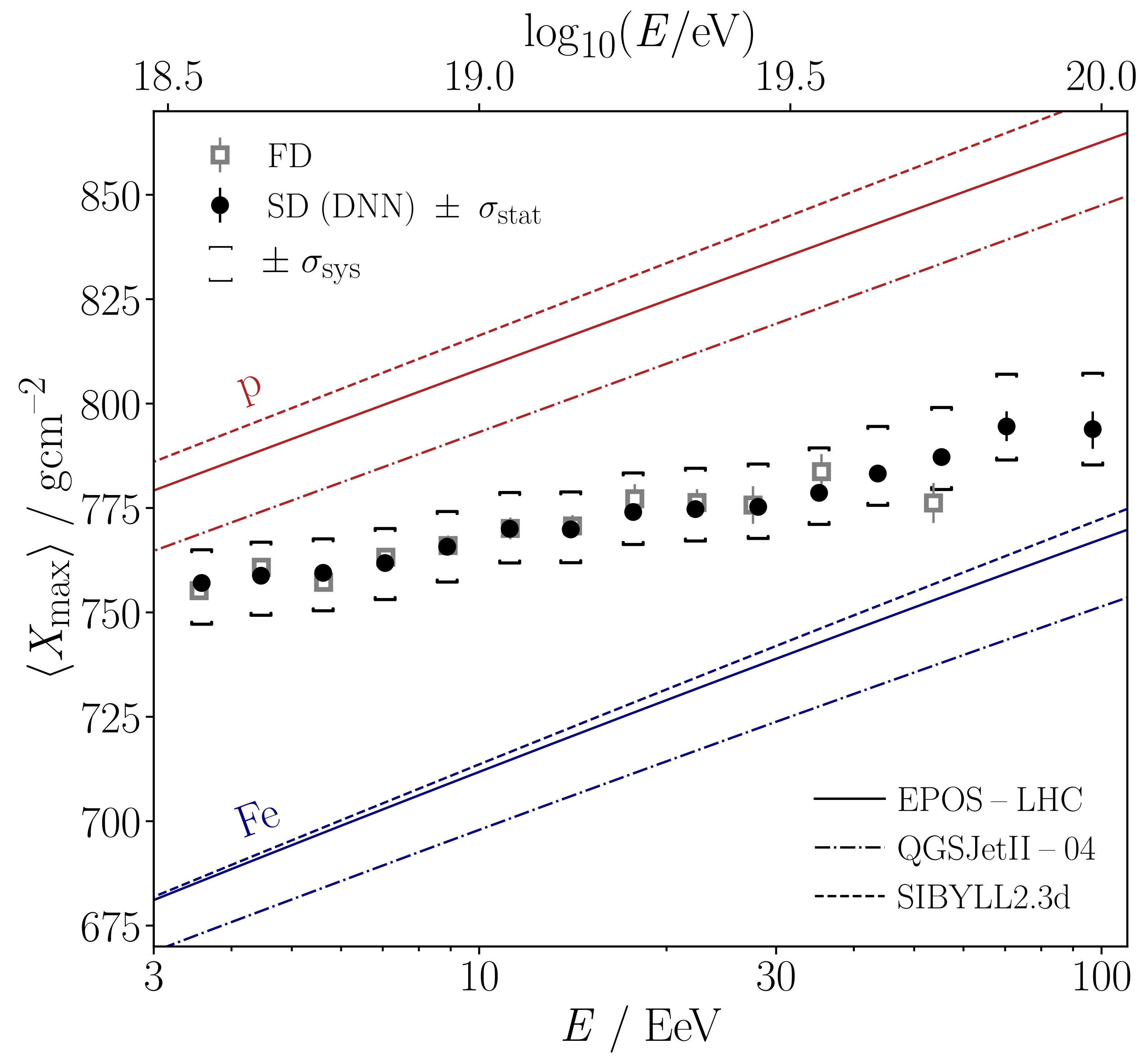


Latest results of UHECRs



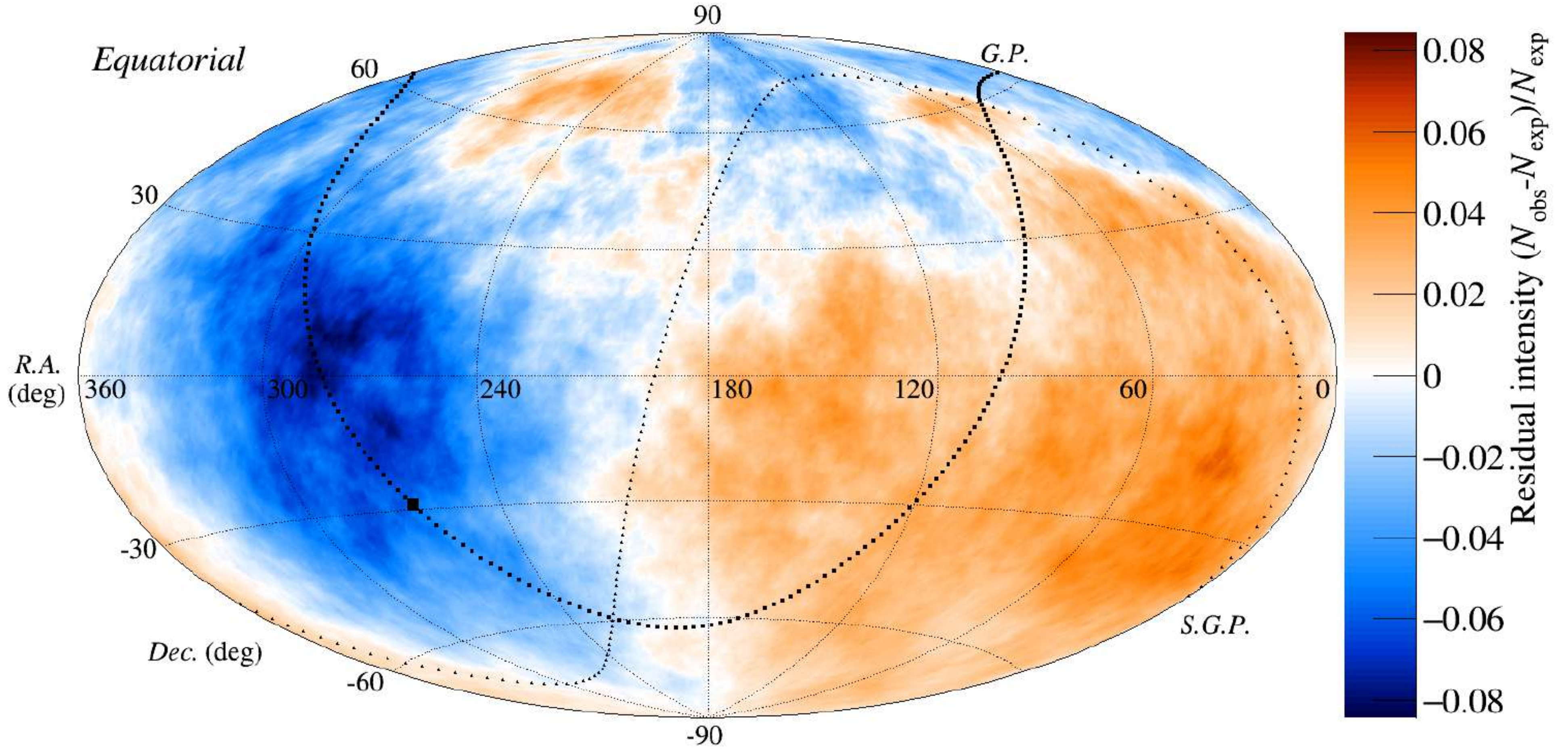
$$\theta \sim 10^\circ \boxed{Z} \left(\frac{E}{10\,\mathrm{EeV}} \right)^{-1}$$

Z: Atomic number
(Mass composition)

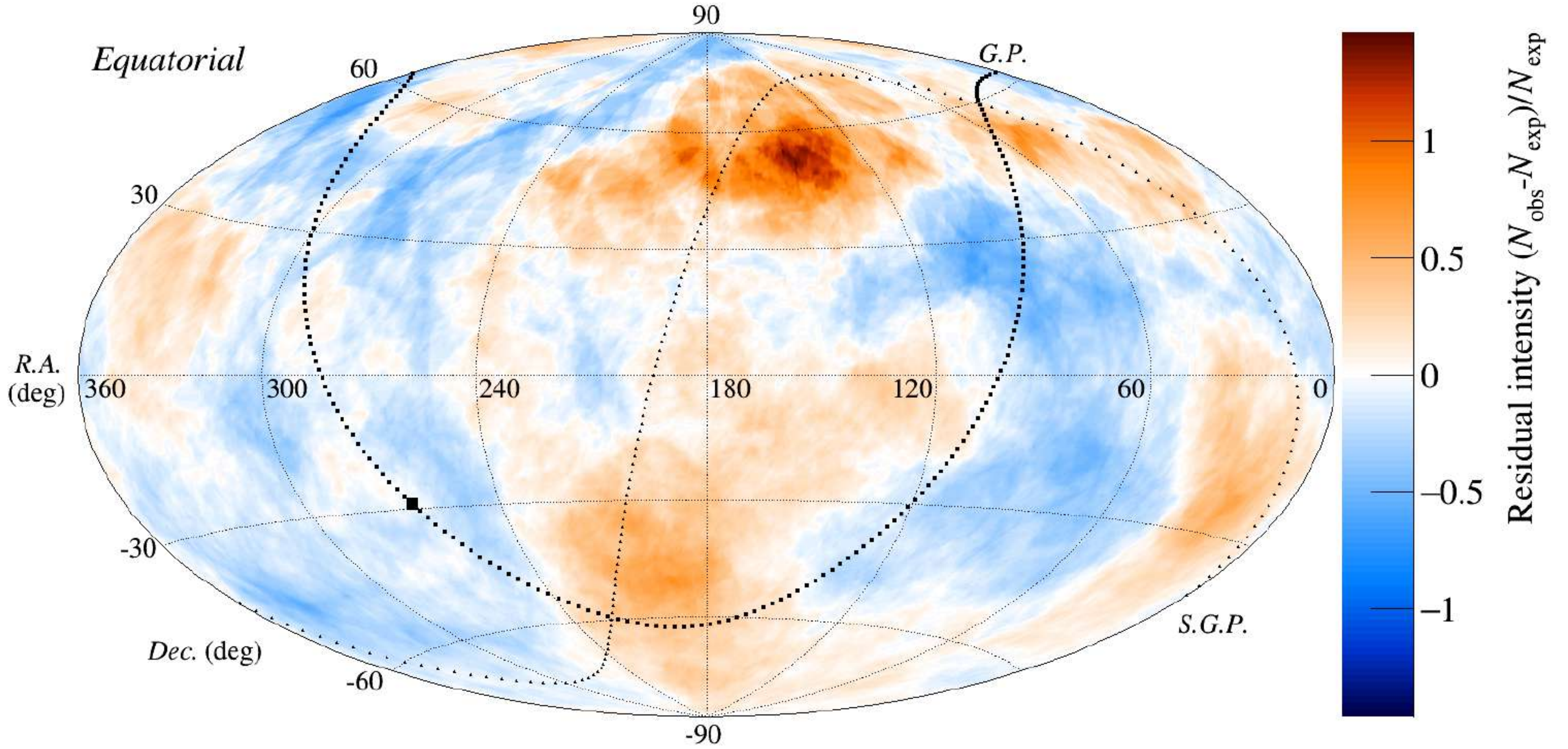


PRL 134, 021001 (2025)

Ankle ($E >$ 10 EeV)

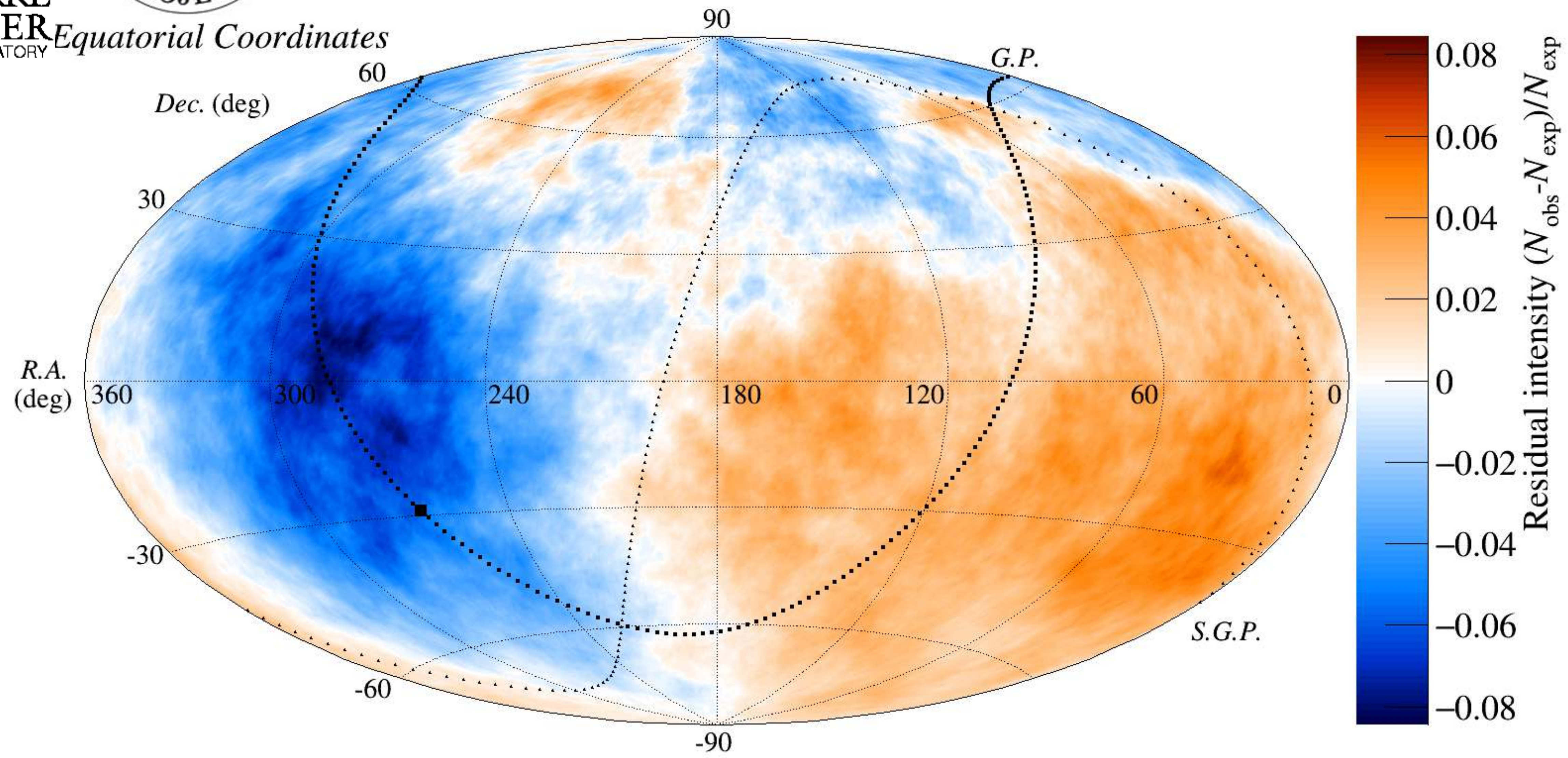


Cutoff ($E >$ 50 EeV)

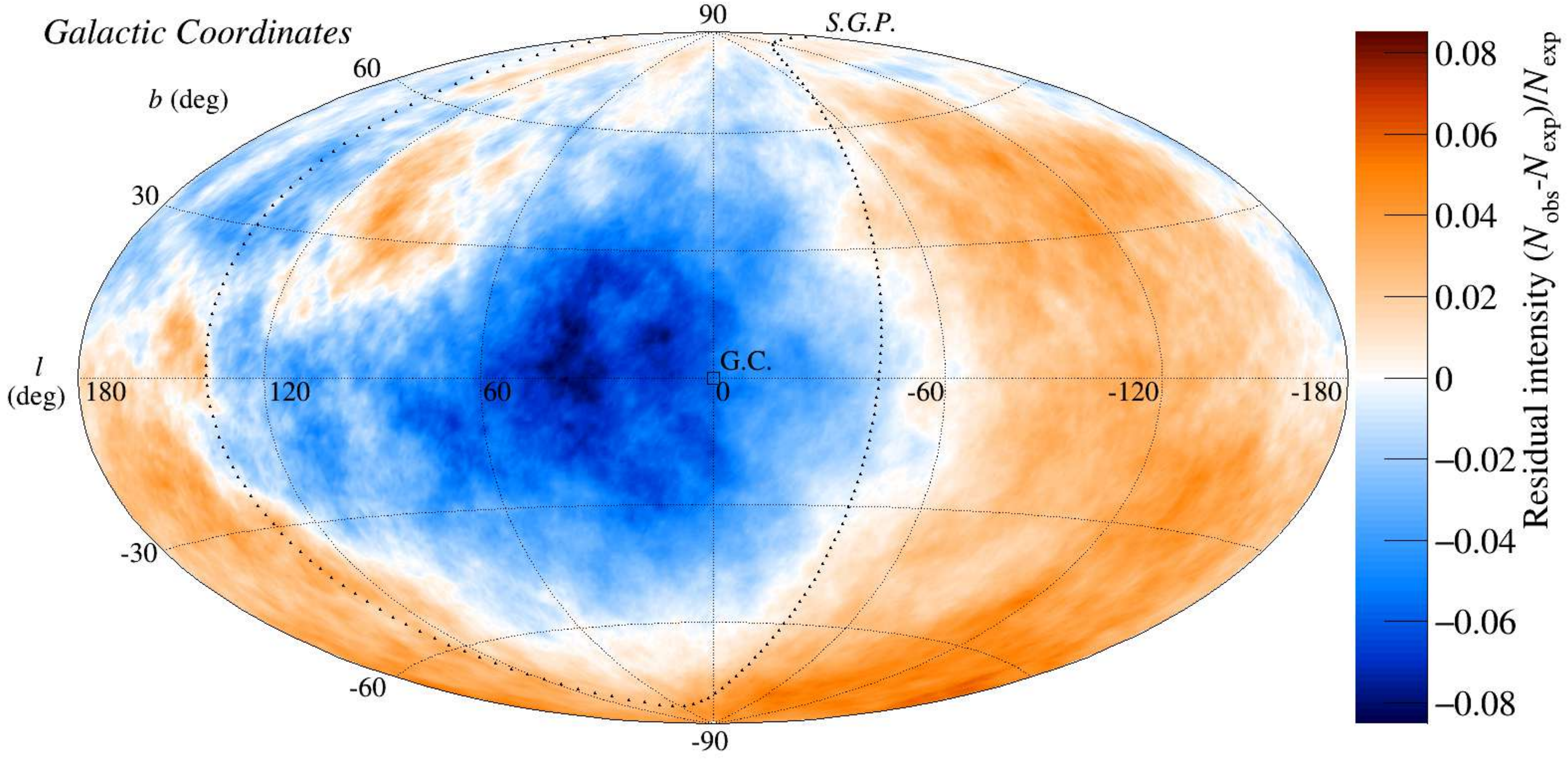


- Constrain proton fraction above 30 EeV to be <70% by non-detection of UHE neutrinos
- PRL 135, 031001 (2025)

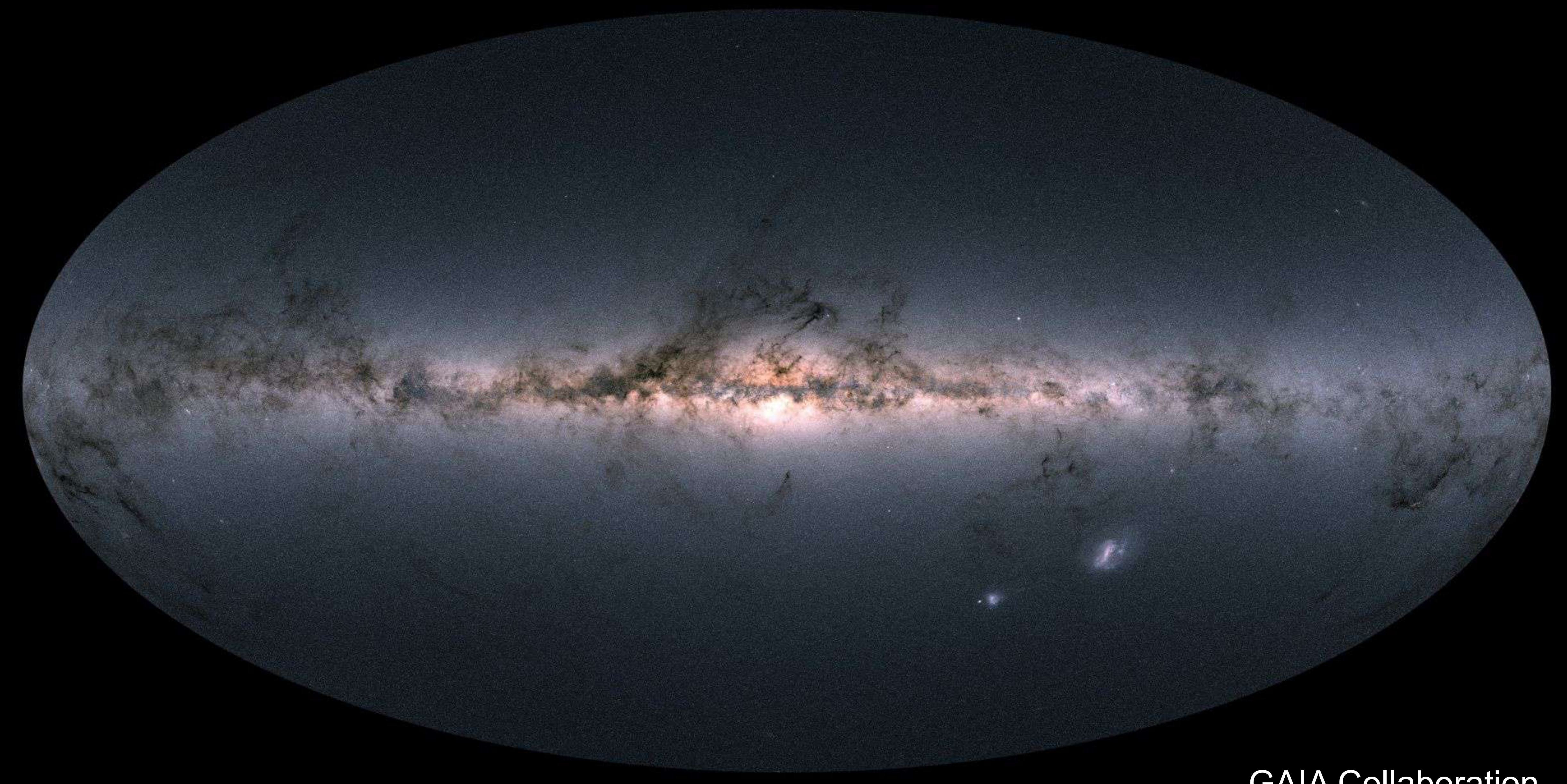
10 EeV skymap



Converted to Galactic coordinates



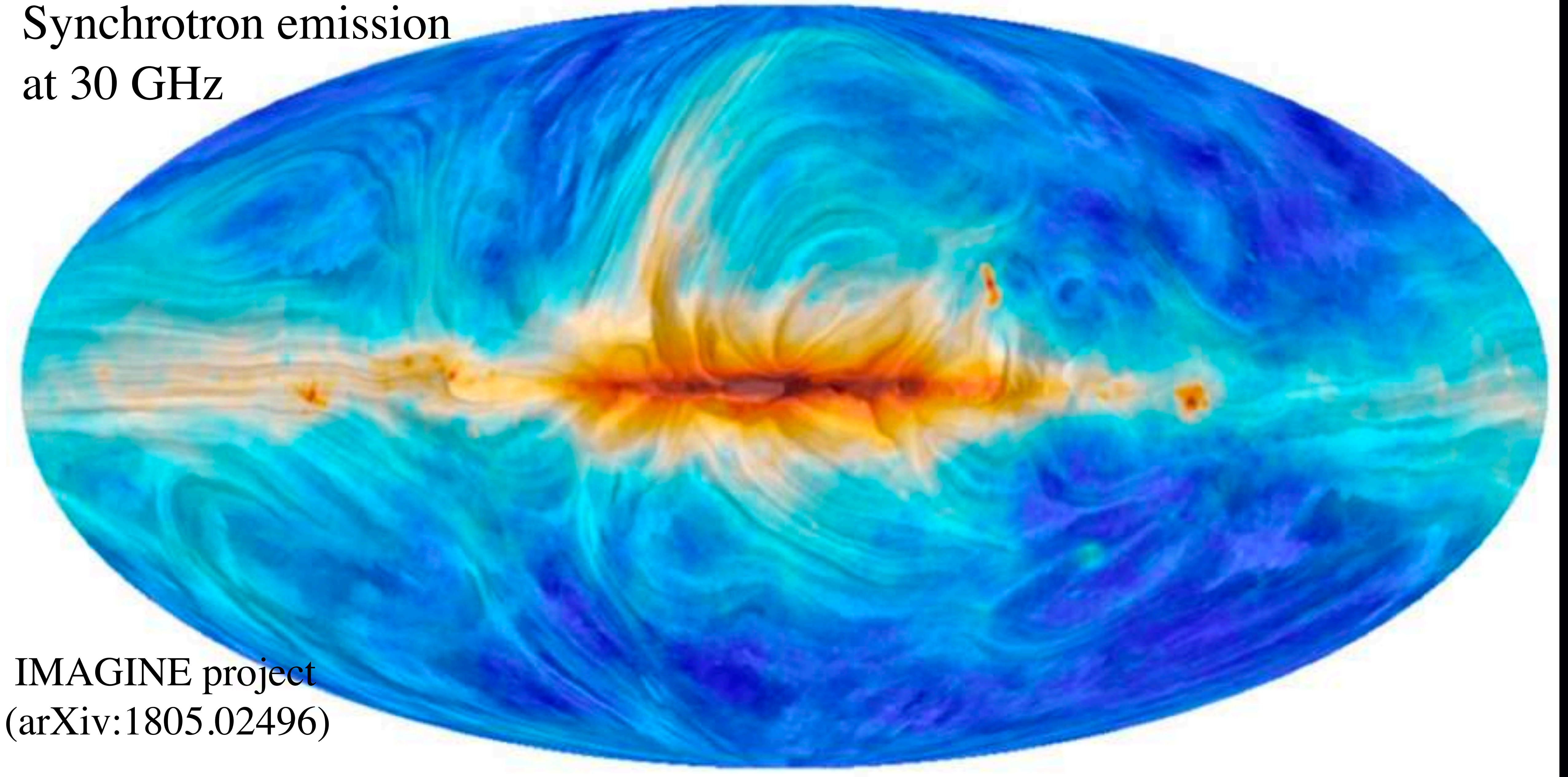
T. Fujii, PoS (ICRC2021) 402 (2021)



GAIA Collaboration

"Deciphering" magnetic fields

Synchrotron emission at 30 GHz



IMAGINE project (arXiv:1805.02496)

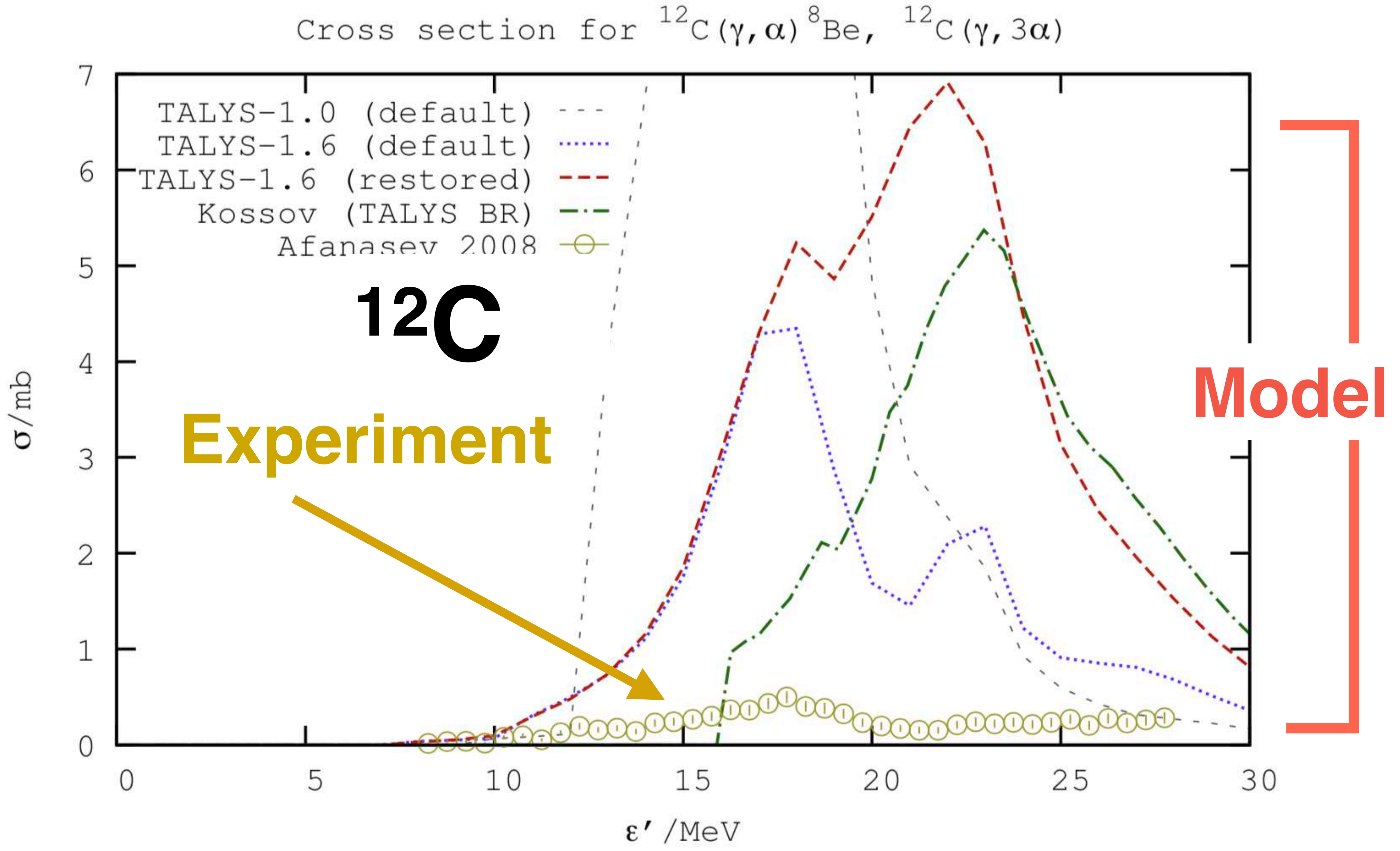
Nuclear Physics meets UHECRs (PANDORA project)

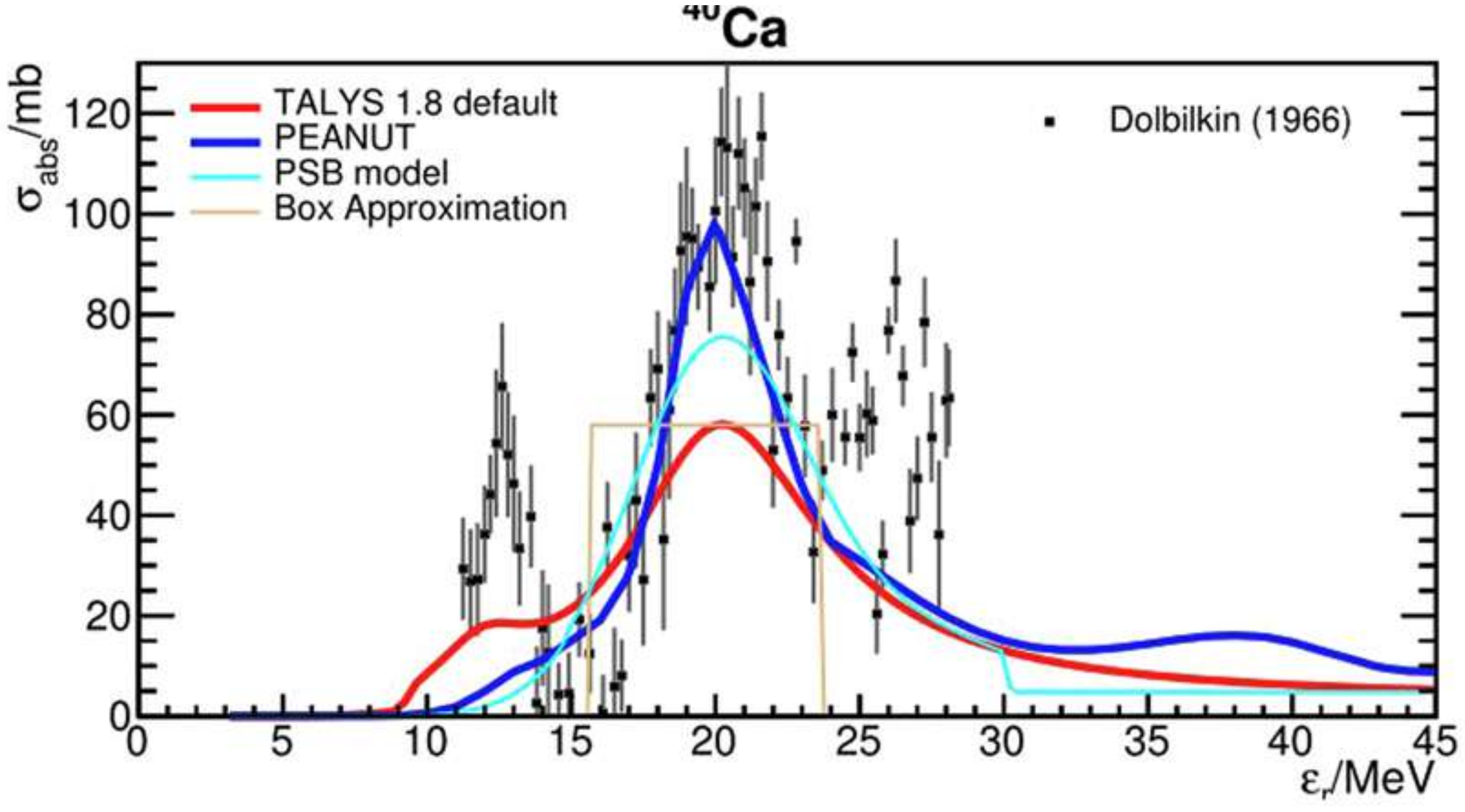
$$^{A}_{Z}N + \gamma_{\mathrm{CMB}} \rightarrow {}^{A-1}_{Z-1}N' + p$$

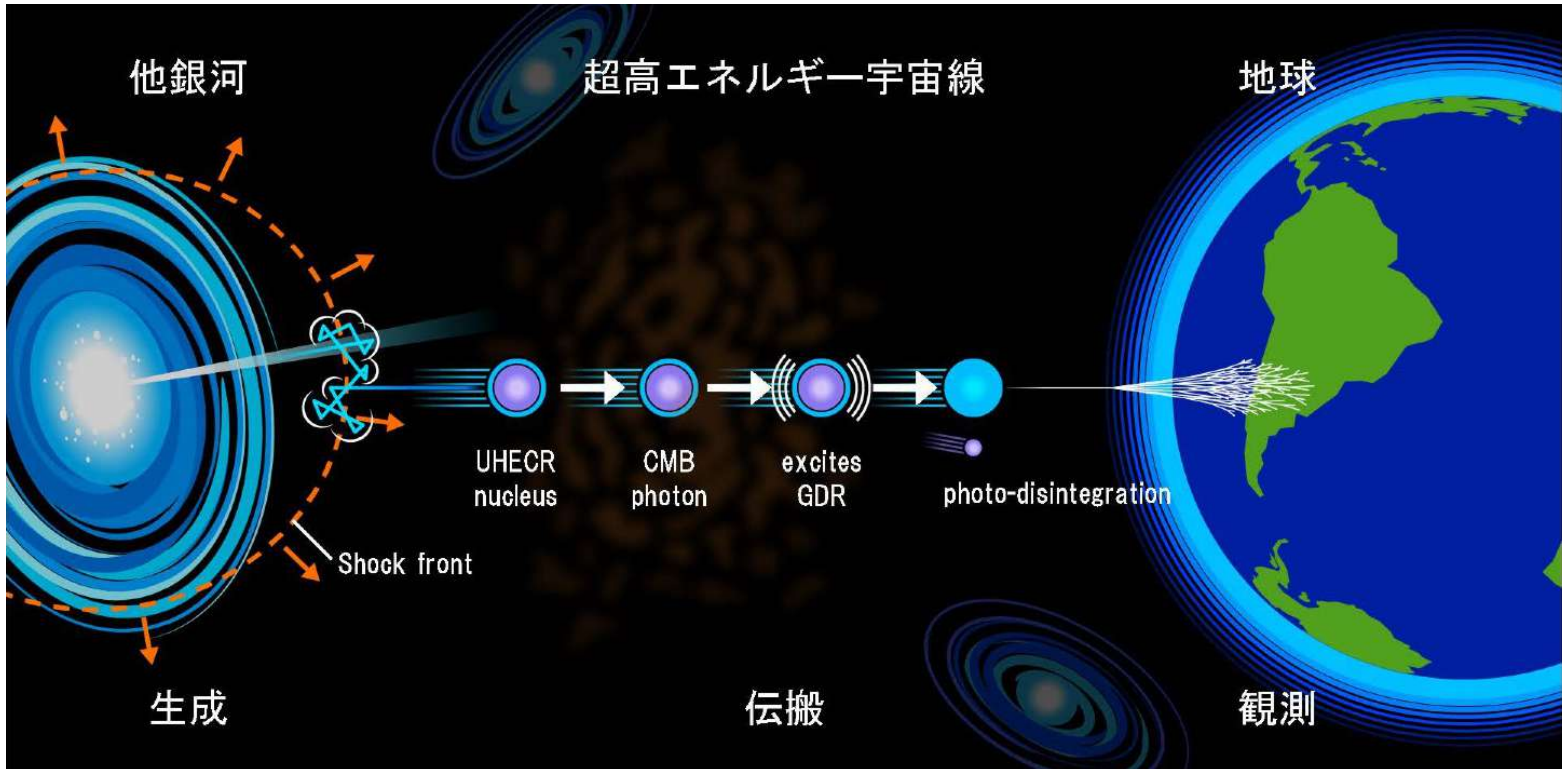
- Large uncertainty of the cross section from the giant dipole resonants for A < 60 nuclei
- Multidisciplinary research among nuclear physics, UHECR and CMB

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

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







Challenging to "Muon puzzle"

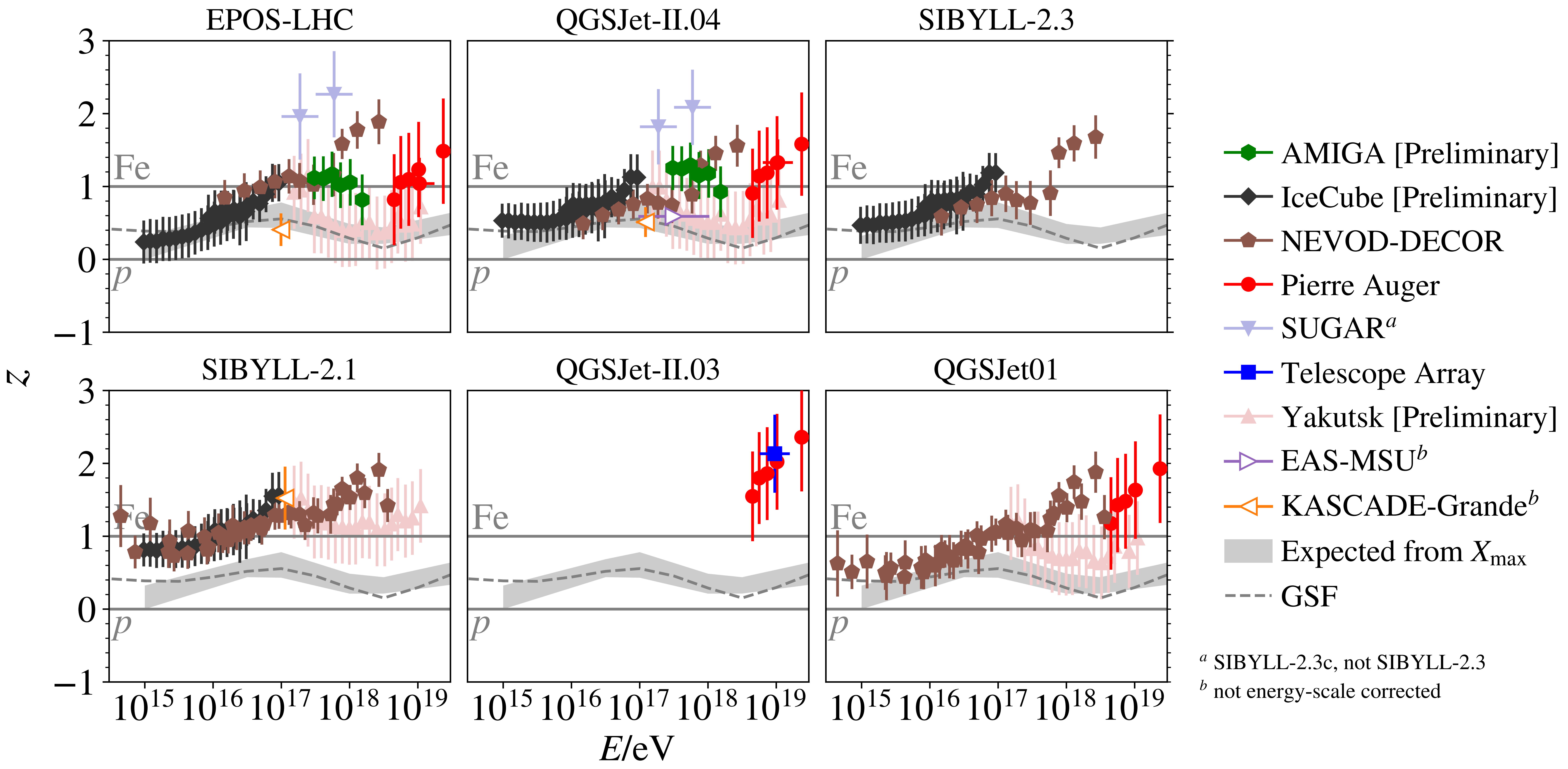


Fig. 3 Compilation of muon measurements converted to the abstract z-scale and after cross-calibrating the energy scales of the experiments as described in the text (image from Dembinski et al. (2019)). Shown for comparison are predicted z_{mass}-values based on air shower simulations and X_{max}-measurements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


2021 May 27, 04:35:56 AM
Detection of **"Amaterasu particle"**
2.44x10^{20} eV = 244 exa-electron volts (EeV)
Telescope Array Collaboration, Science 382, 903 (2023)
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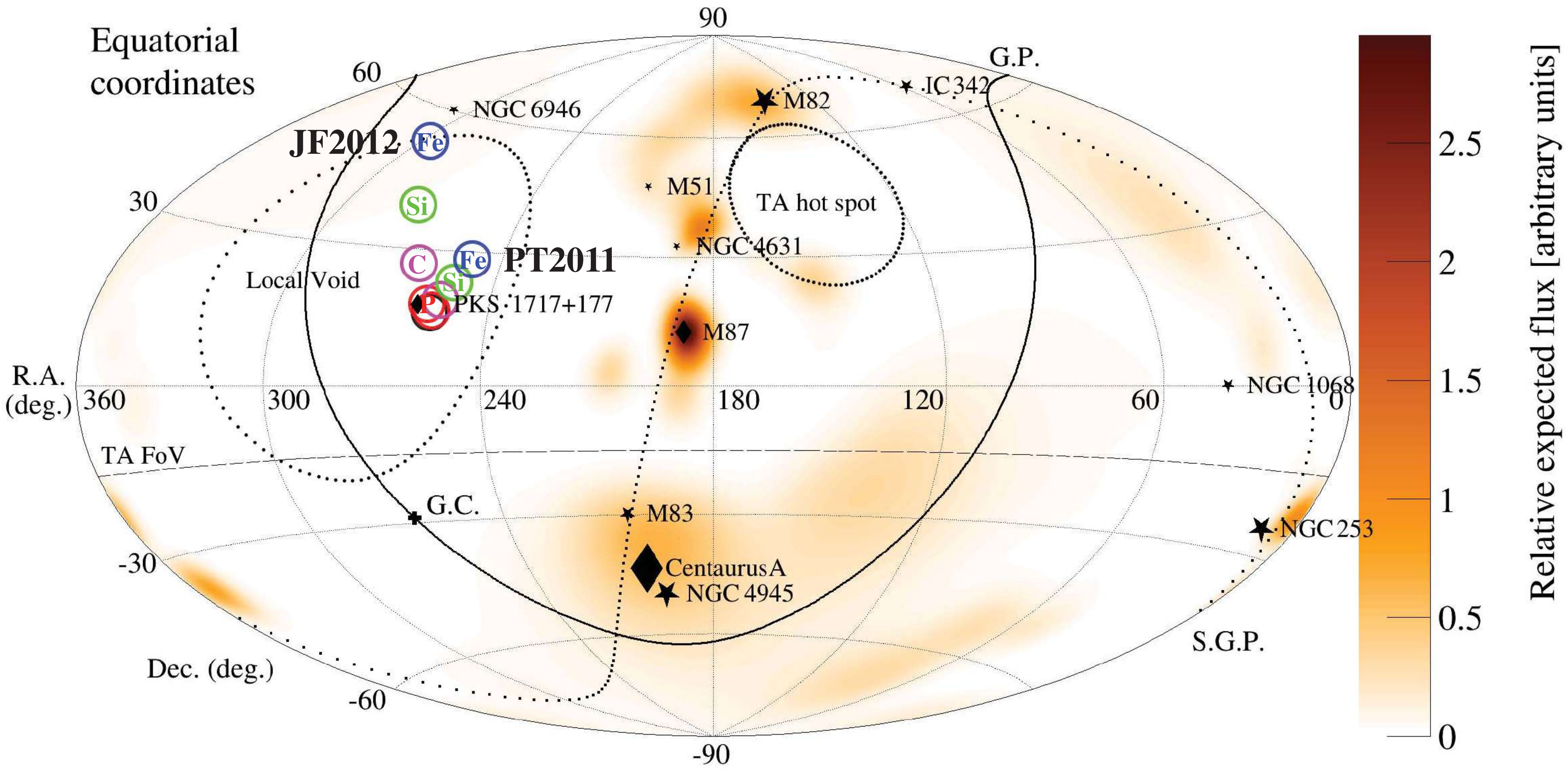
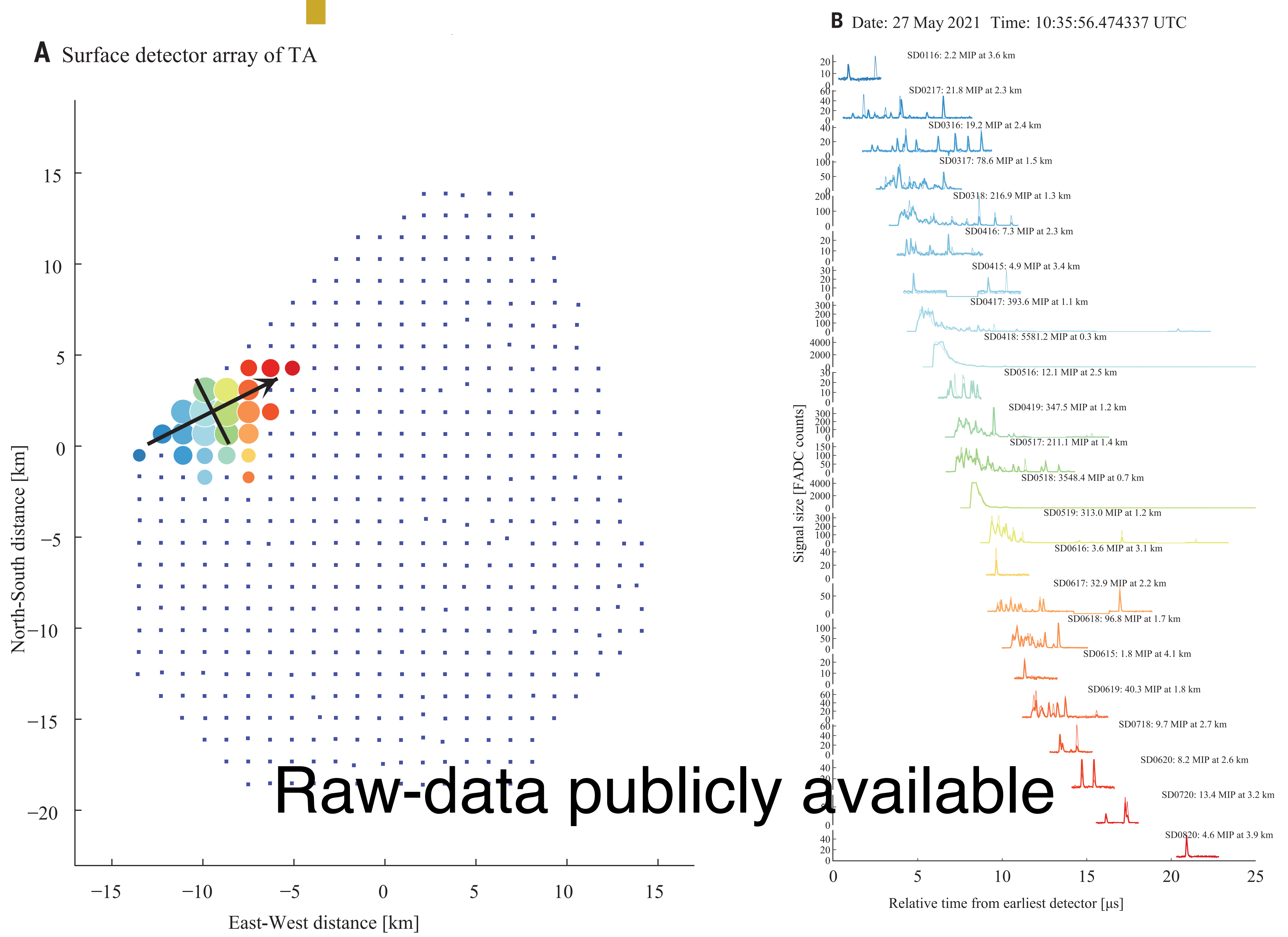
20210527	001716.635727	5.737	-8.895	9.98	22.48	168.53	0.587	0.00	2.06
20210527	005753.524148	7.988	1.748	10.51	38.09	155.29	0.277	0.00	3.14
20210527	012459.385602	-5.703	-9.588	6.59	17.86	204.01	0.165	0.00	1.46
20210527	020622.327294	-4.091	-12.485	11.16	33.44	297.15	0.228	0.00	2.84
20210527	022215.026443	-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
20210527	131931.788147	3.315	-18.699	7.52	38.62	277.76	0.506	0.00	2.05
20210527	135753.703832	-11.351	-6.900	6.24	25.40	113.13	0.446	0.00	1.42
20210527	143154.113642	-6.137	-17.021	10.56	34.18	200.72	0.205	0.00	2.77

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)

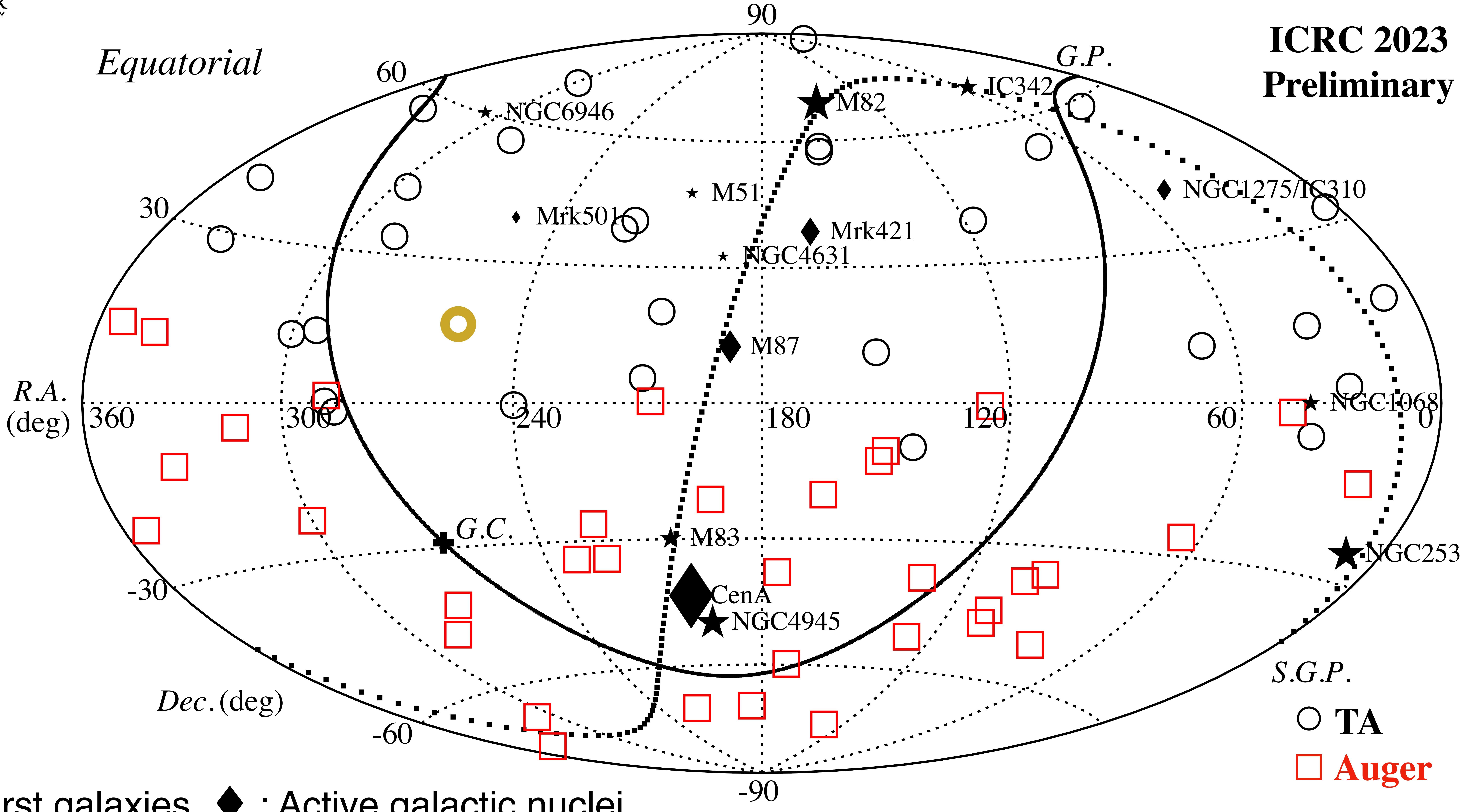


Raw-data publicly available

- **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


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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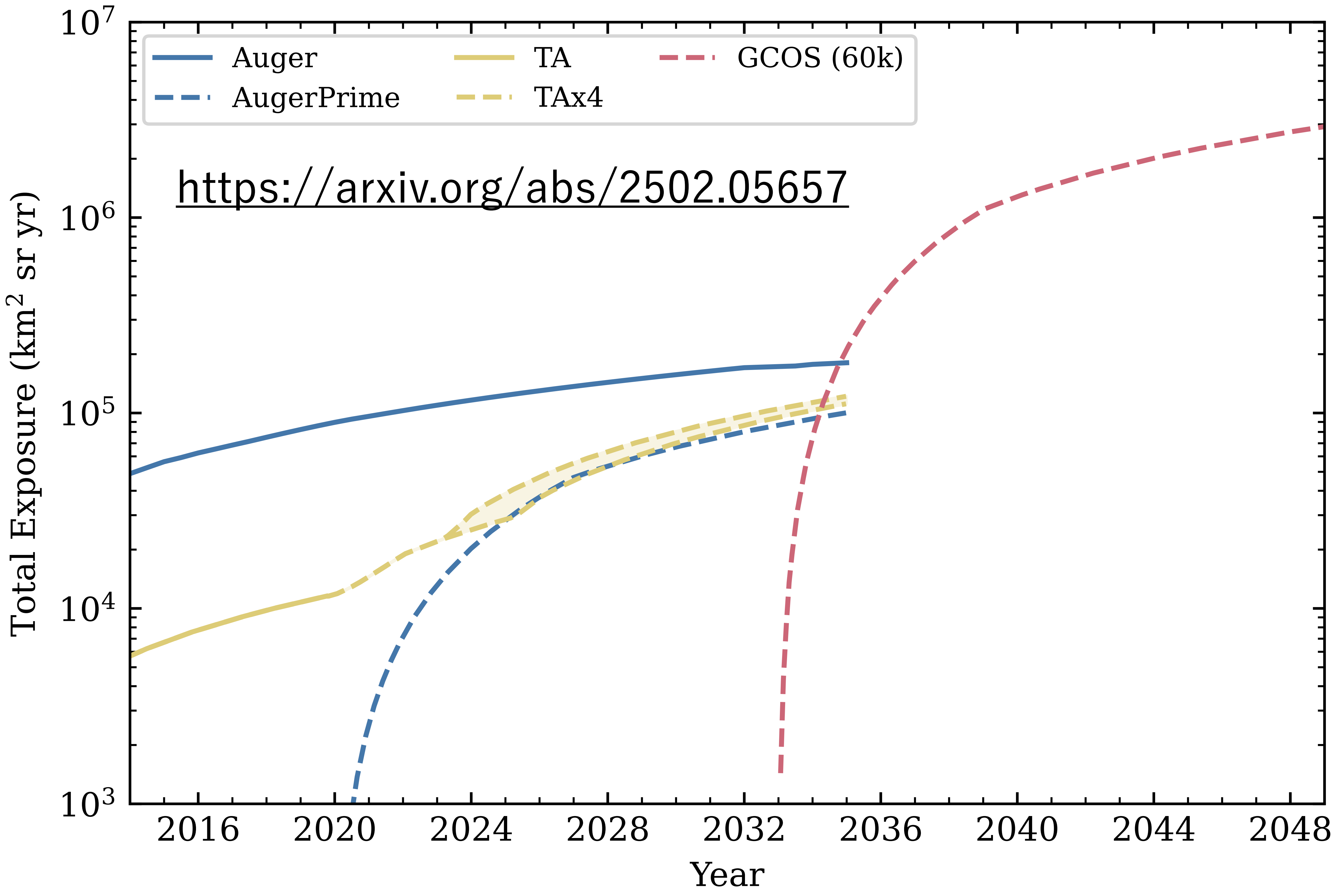
Workshops for the Global Cosmic Ray Observatory

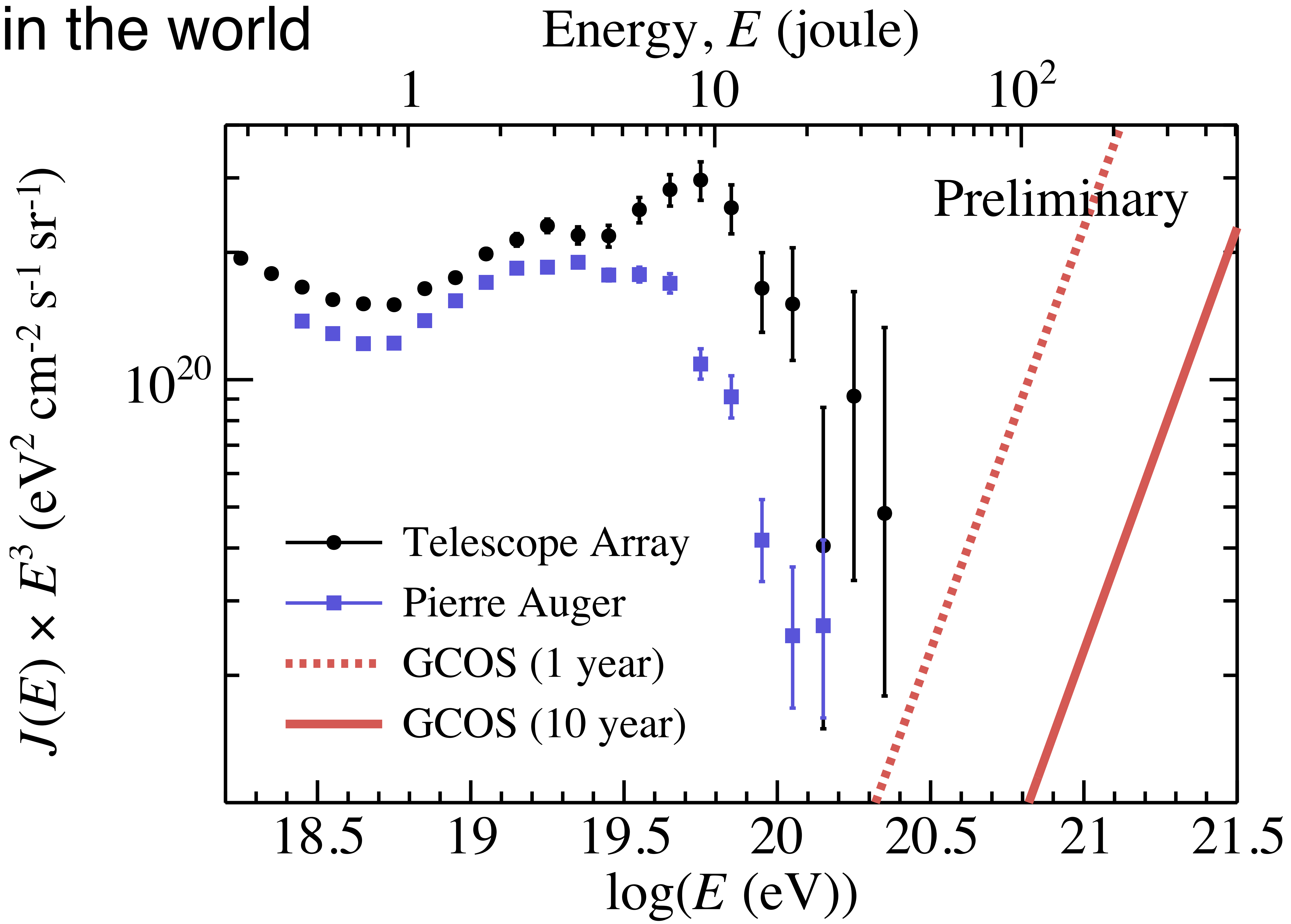
- 1st GCOS workshop 2021 online
  - https://agenda.astro.ru.nl/event/18/
- 2nd GCOS workshop 2022 Wuppertal
  - https://agenda.astro.ru.nl/event/21/

- 3rd GCOS workshop 2023 Brussels (June 10 - 11, 2023)
  - https://indico.iihe.ac.be/event/1729/
- **4th GCOS workshop 2025 Tokyo (September 9 - 11, 2025)**
  - **https://indico.cern.ch/e/gcos2025**

Science of the Global Cosmic Ray Observatory

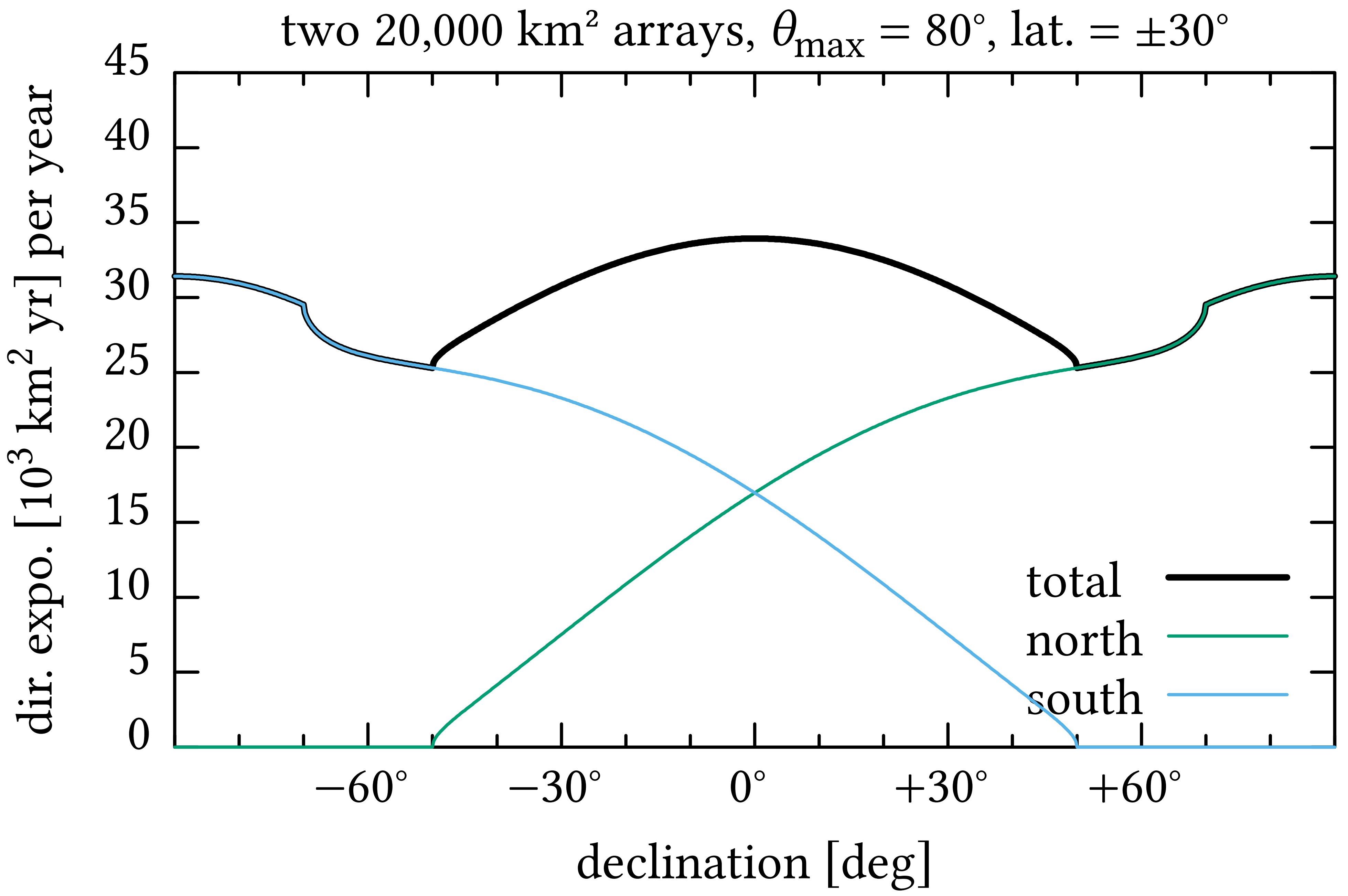
- **Charged-particle astronomy to clarify the origin and nature of the most energetic particles in the universe**
- **Unprecedented effective area, ~60,000 km²** and **mass identification capabilities**
- Begin operations in 2030s, **One team** in the world





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

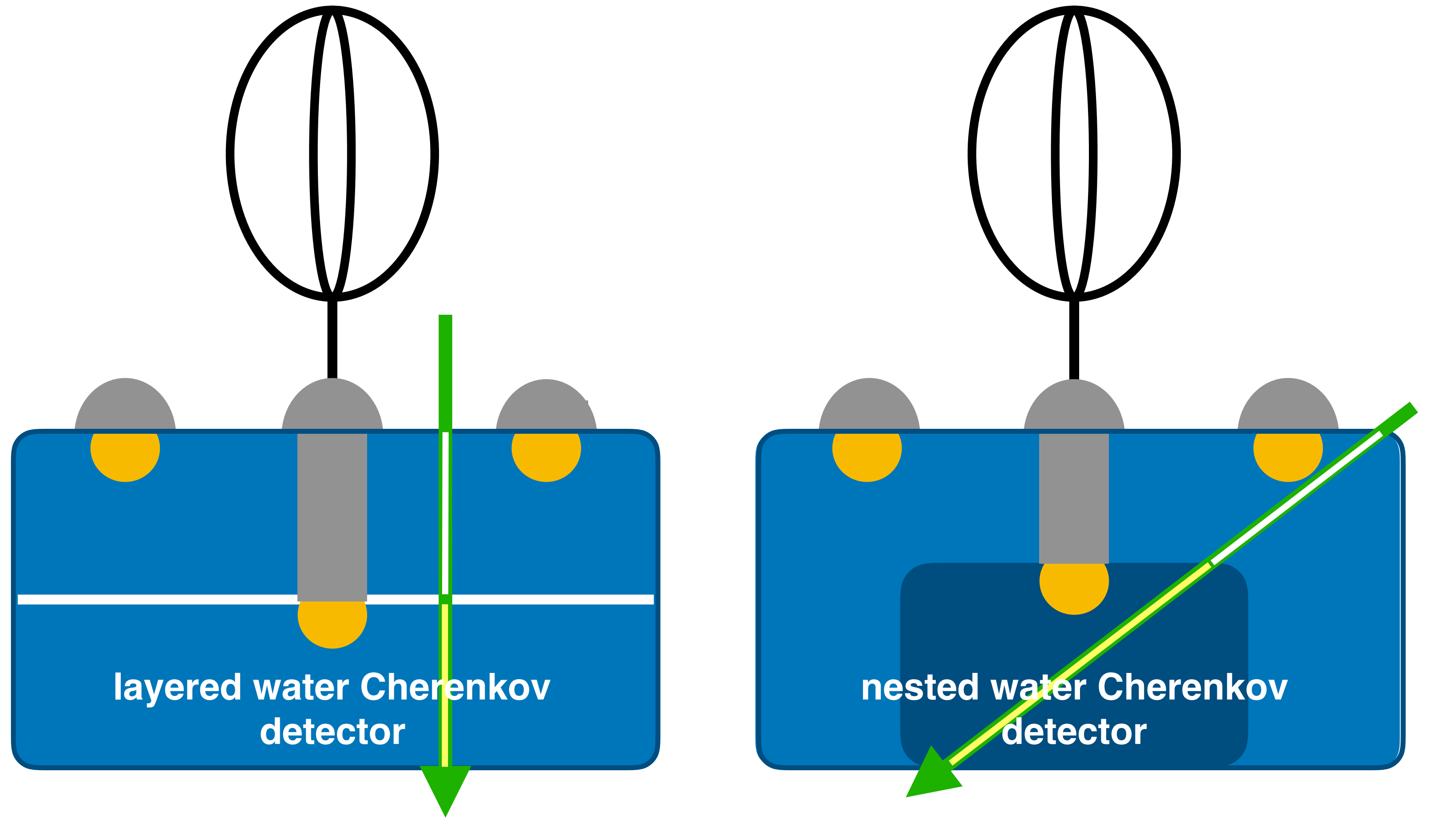


Figure 6: Detection concepts, using a layered (left) and a nested (right) water Cherenkov detector with a radio antenna on top.

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

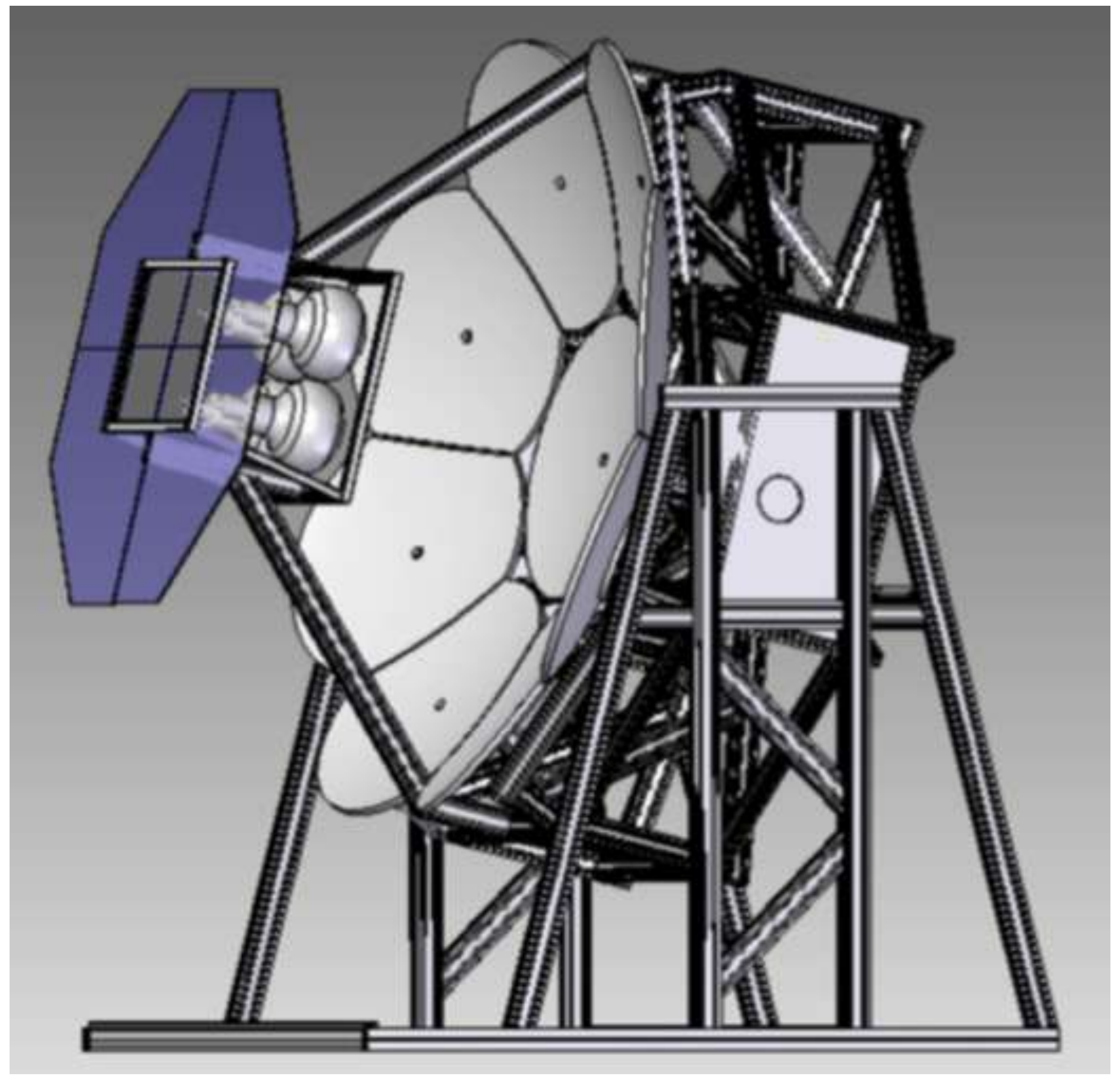
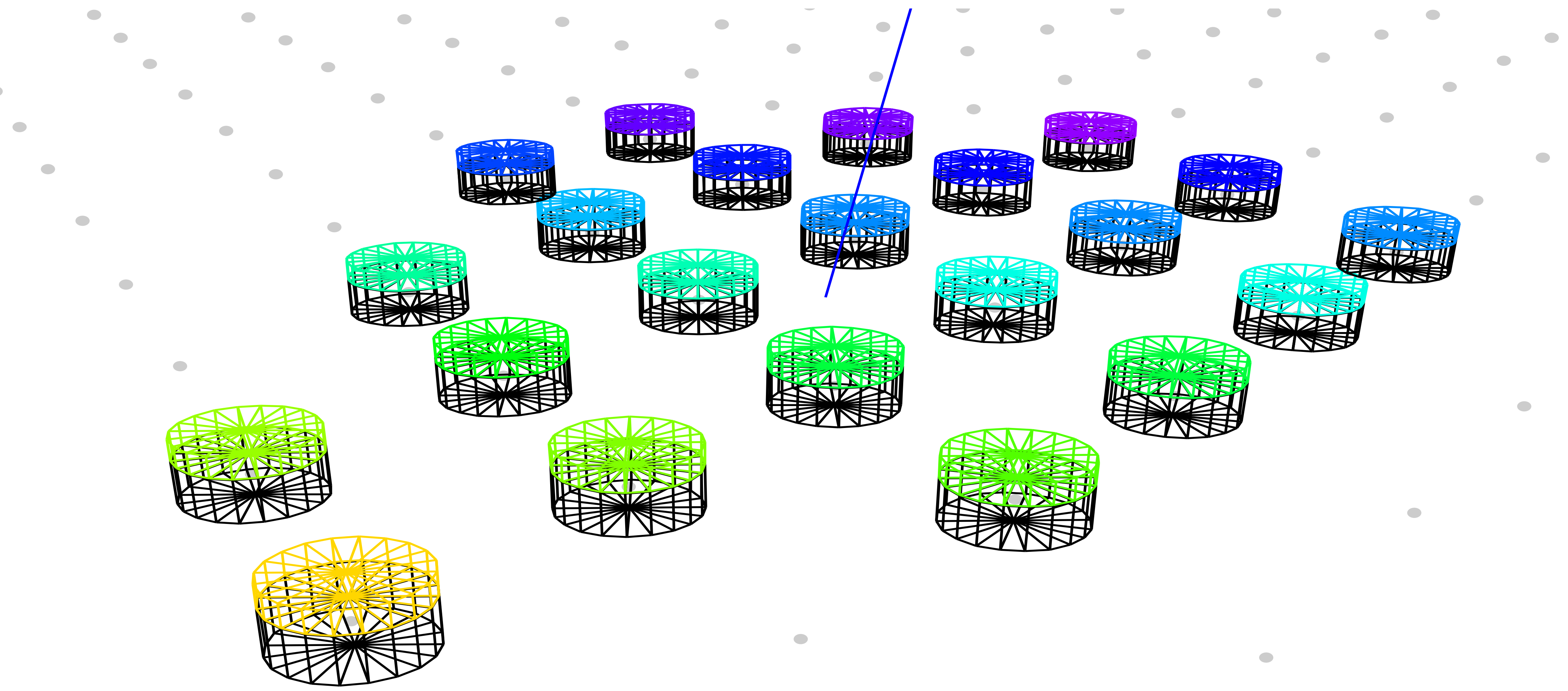


Figure 7: A FAST telescope frame, showing four PMTs at the focus of a 1.6 m diameter segmented mirror. The support structure is made from aluminium profiles. The UV band-pass filter can be seen attached to the periphery of the camera box [100, 101].

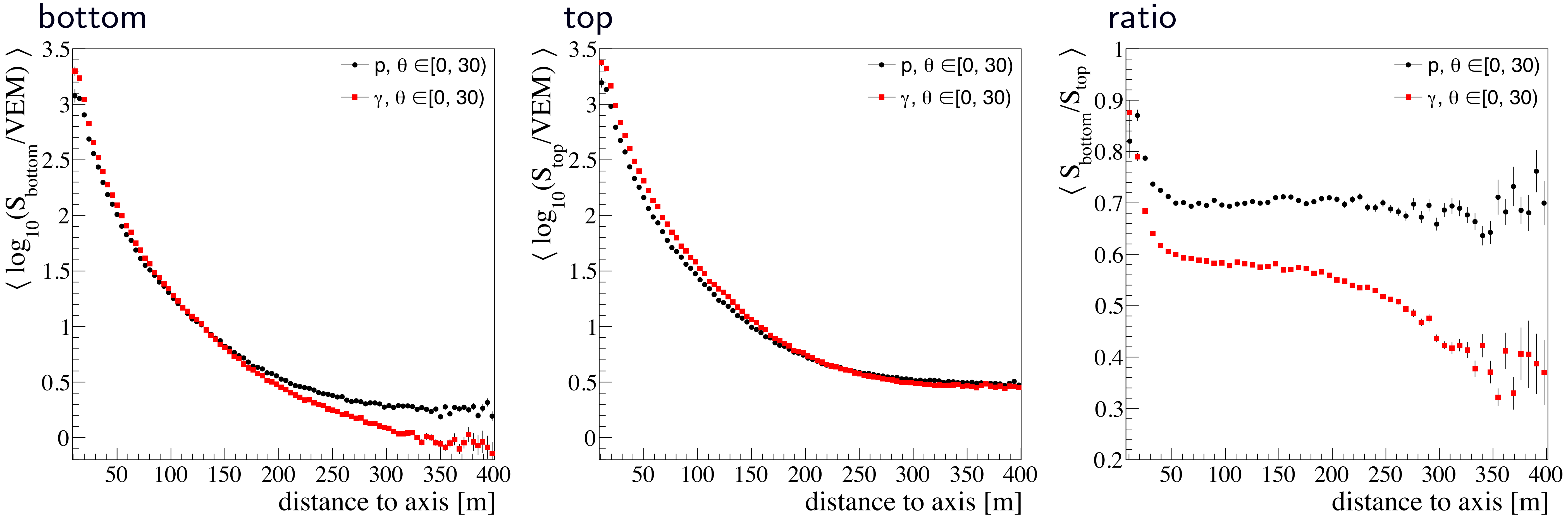
Y. Tameda et al., (CRAFFT)
S. Sakura et al., (FAST)

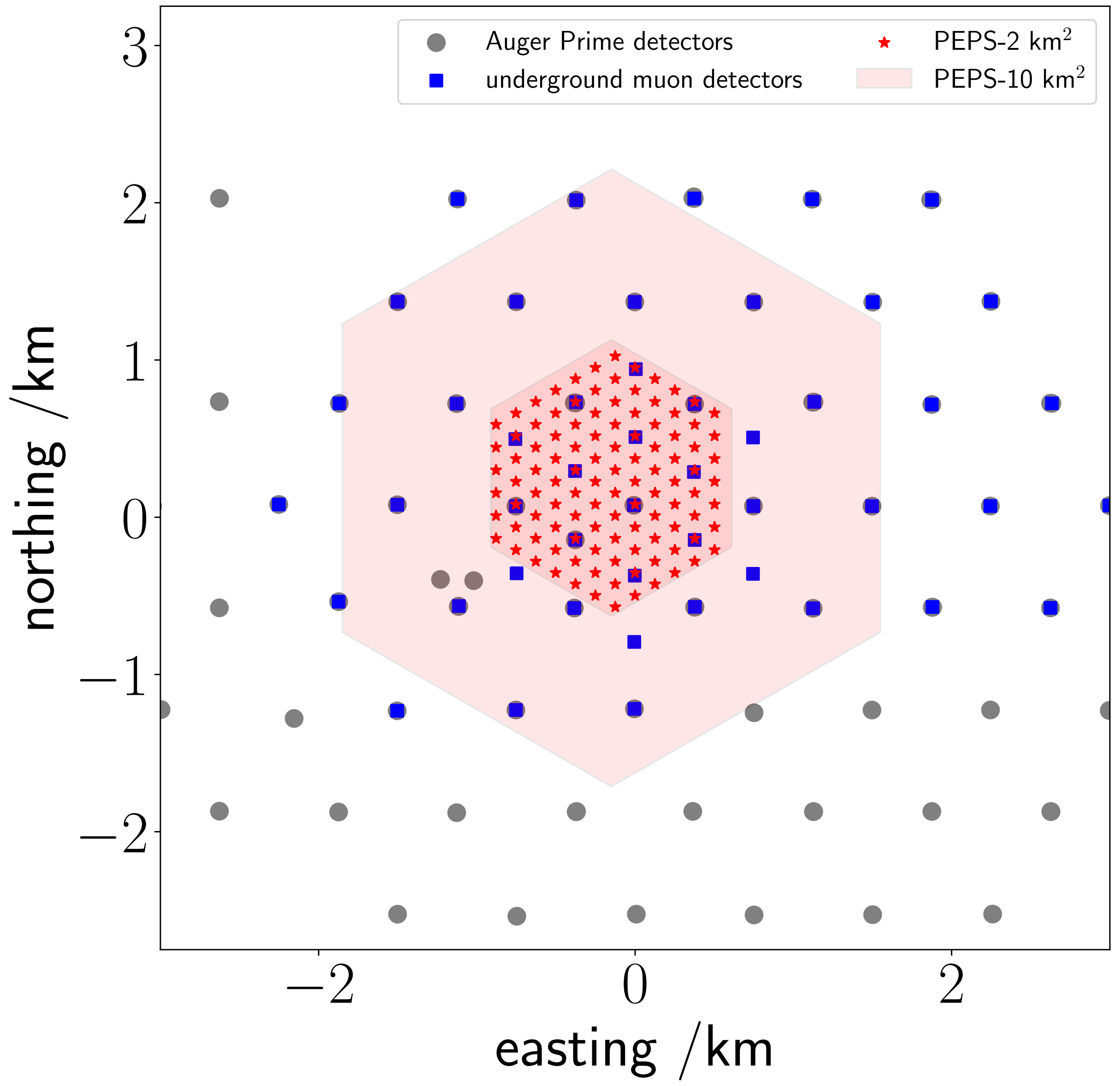
Ideas and Requirements for the Global Cosmic-Ray Observatory https://arxiv.org/abs/2502.05657

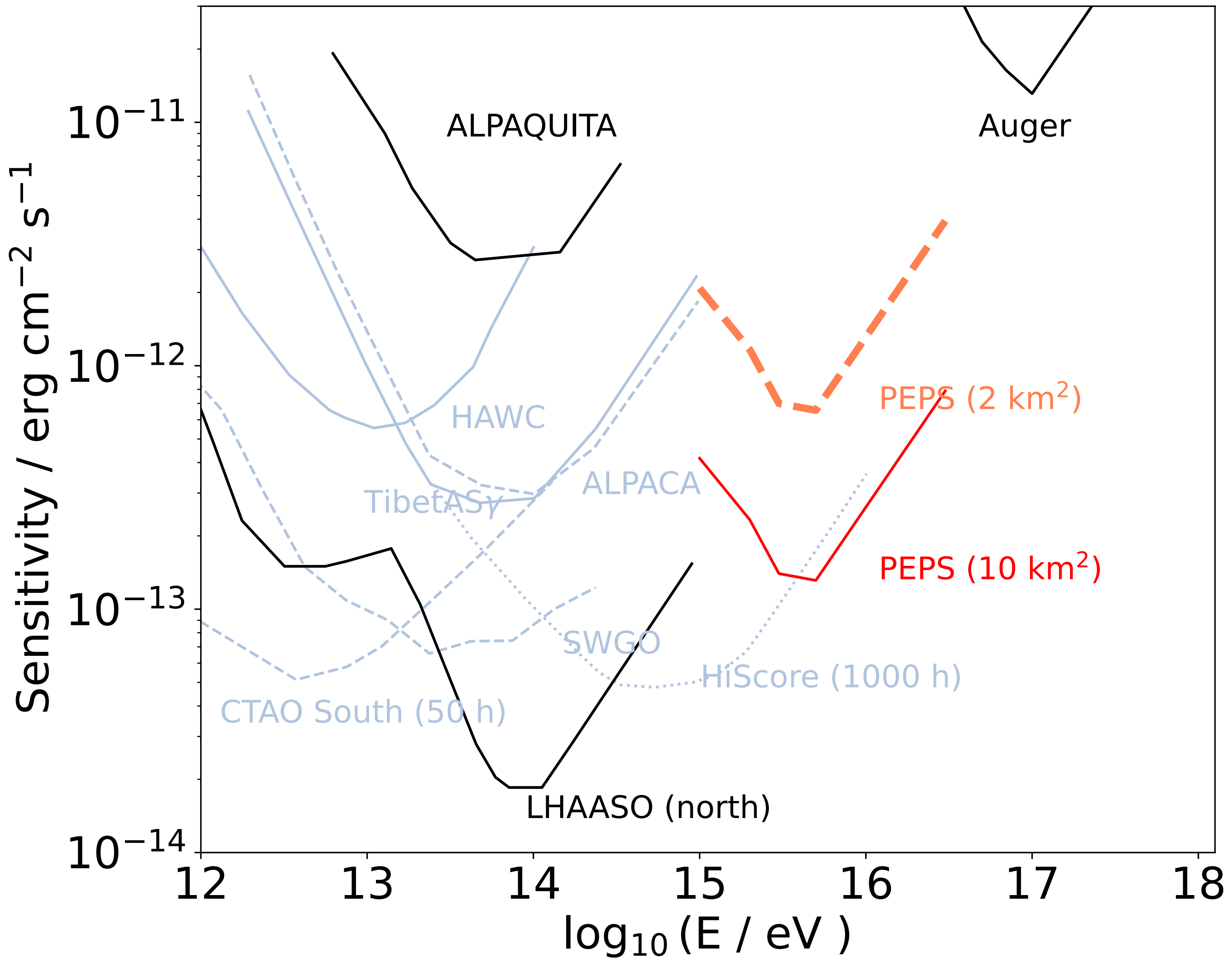
GCOS SD developments: PEPS

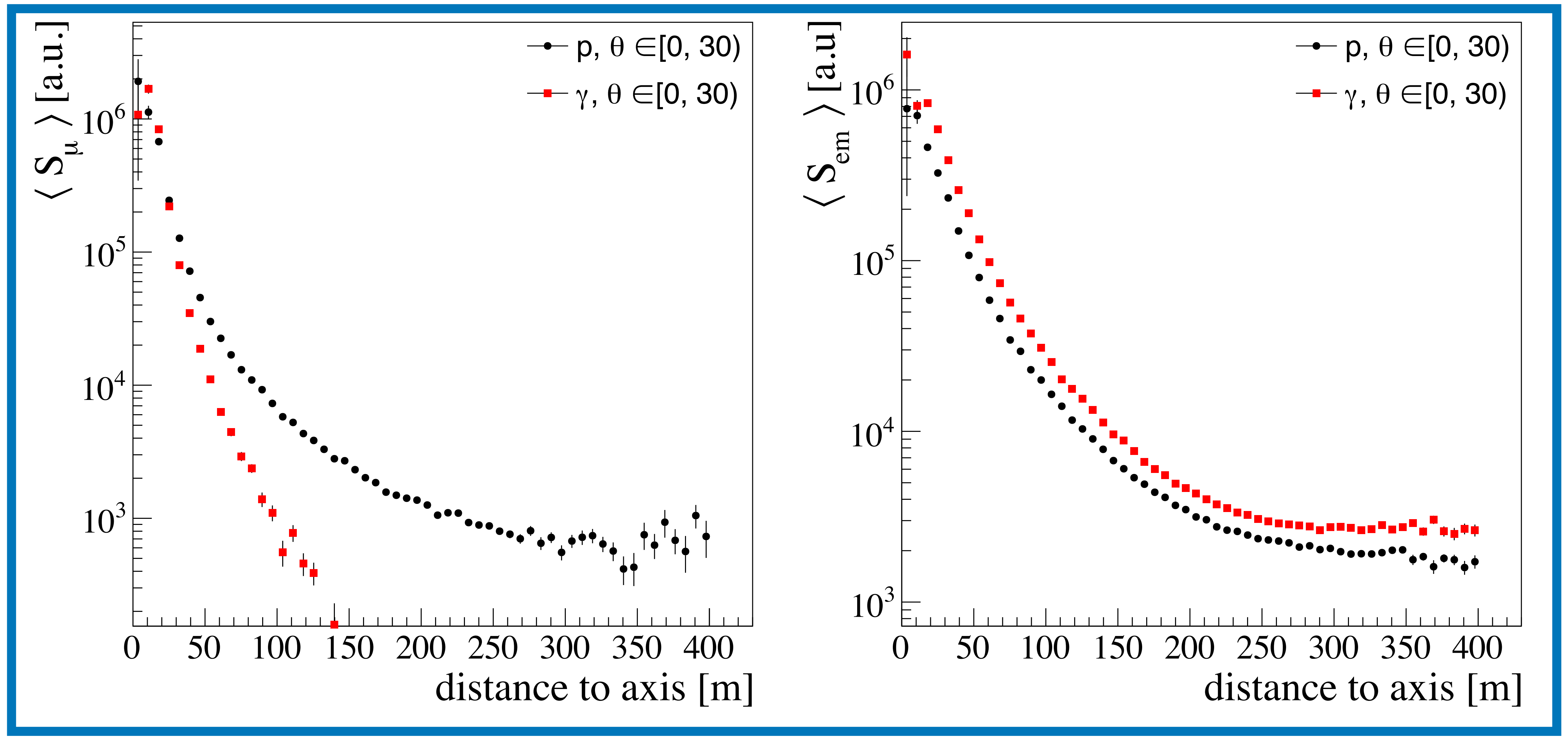


2 km² array to be installed (if funded)





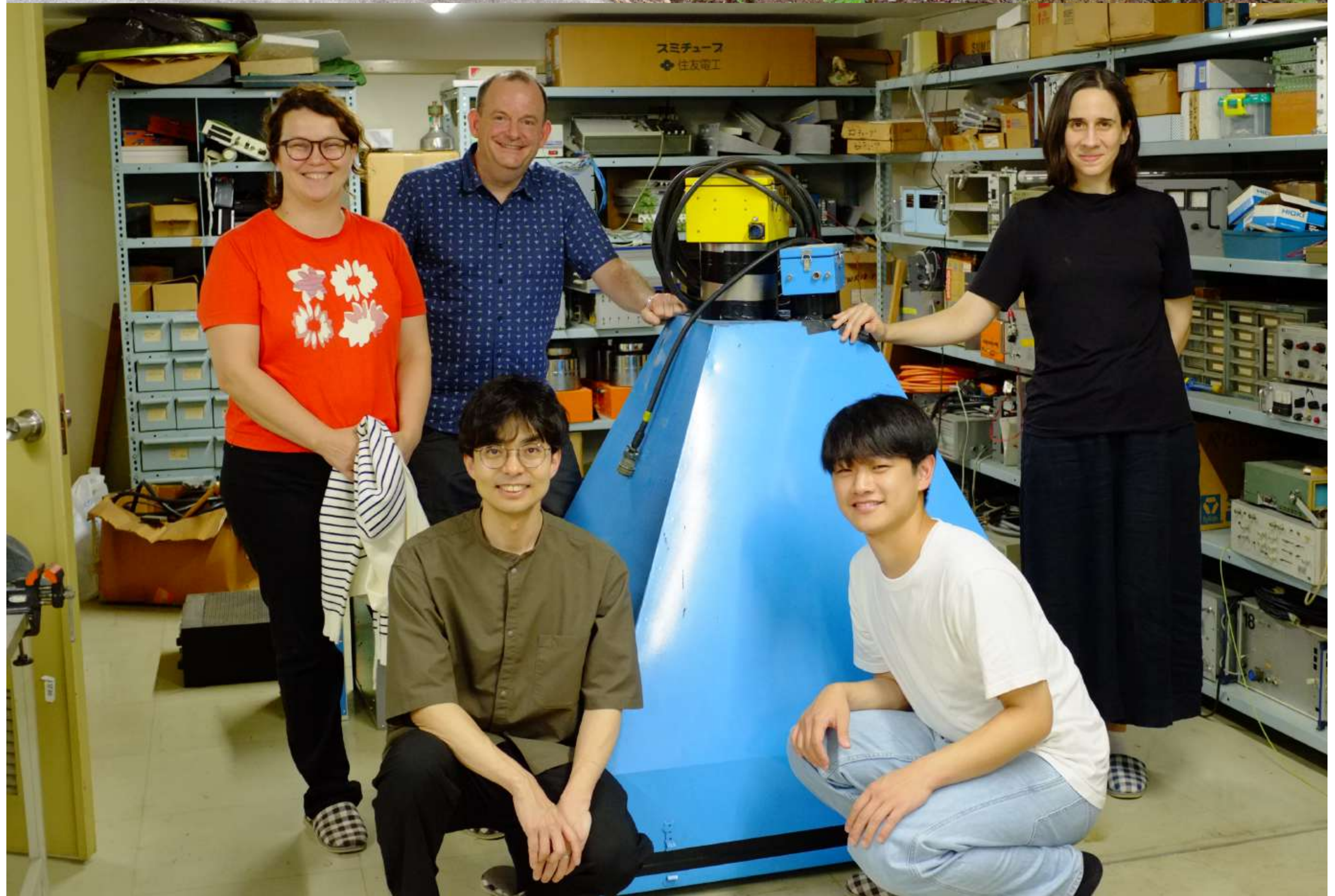




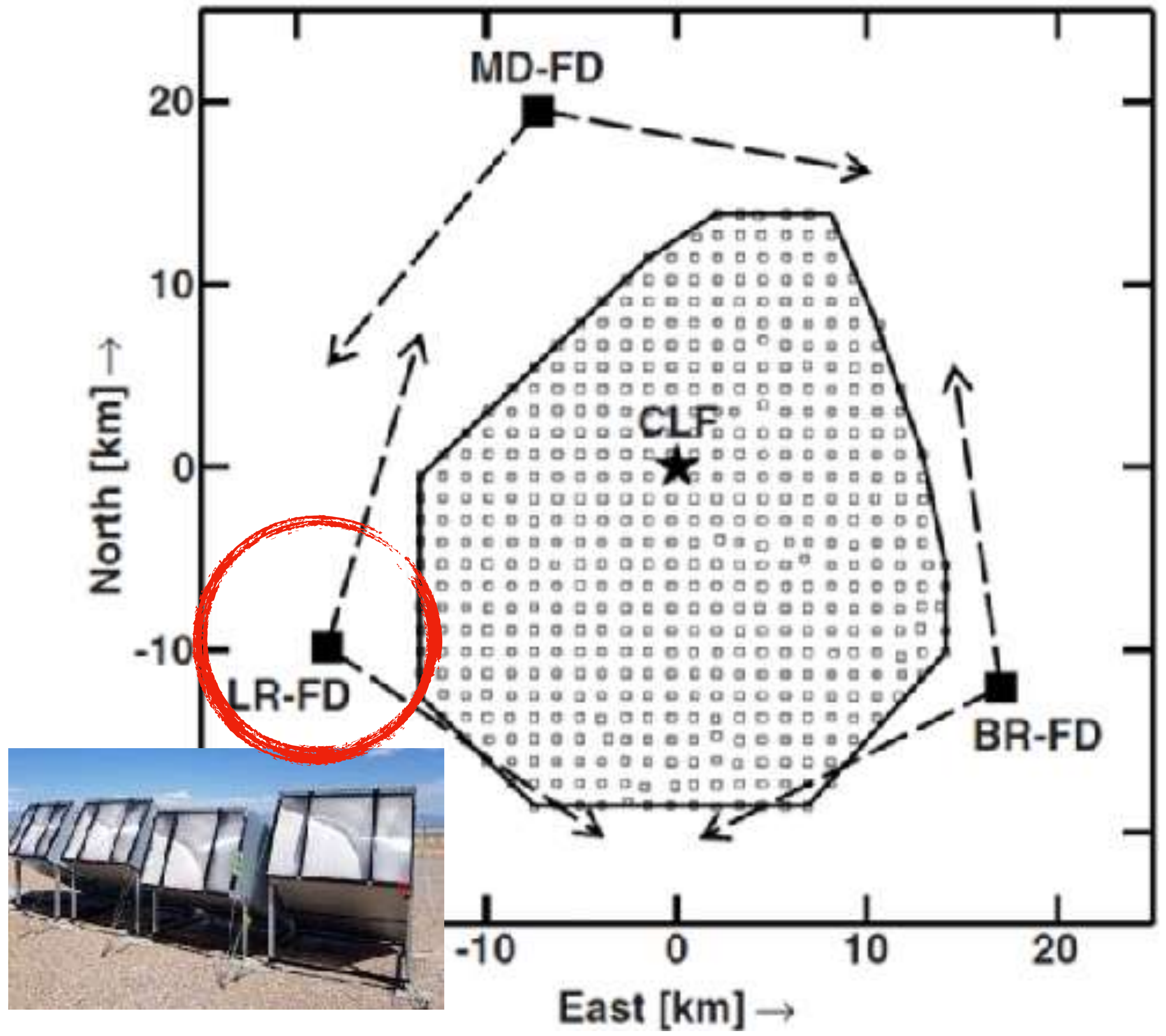
I. Maris et al., GCOS 2025

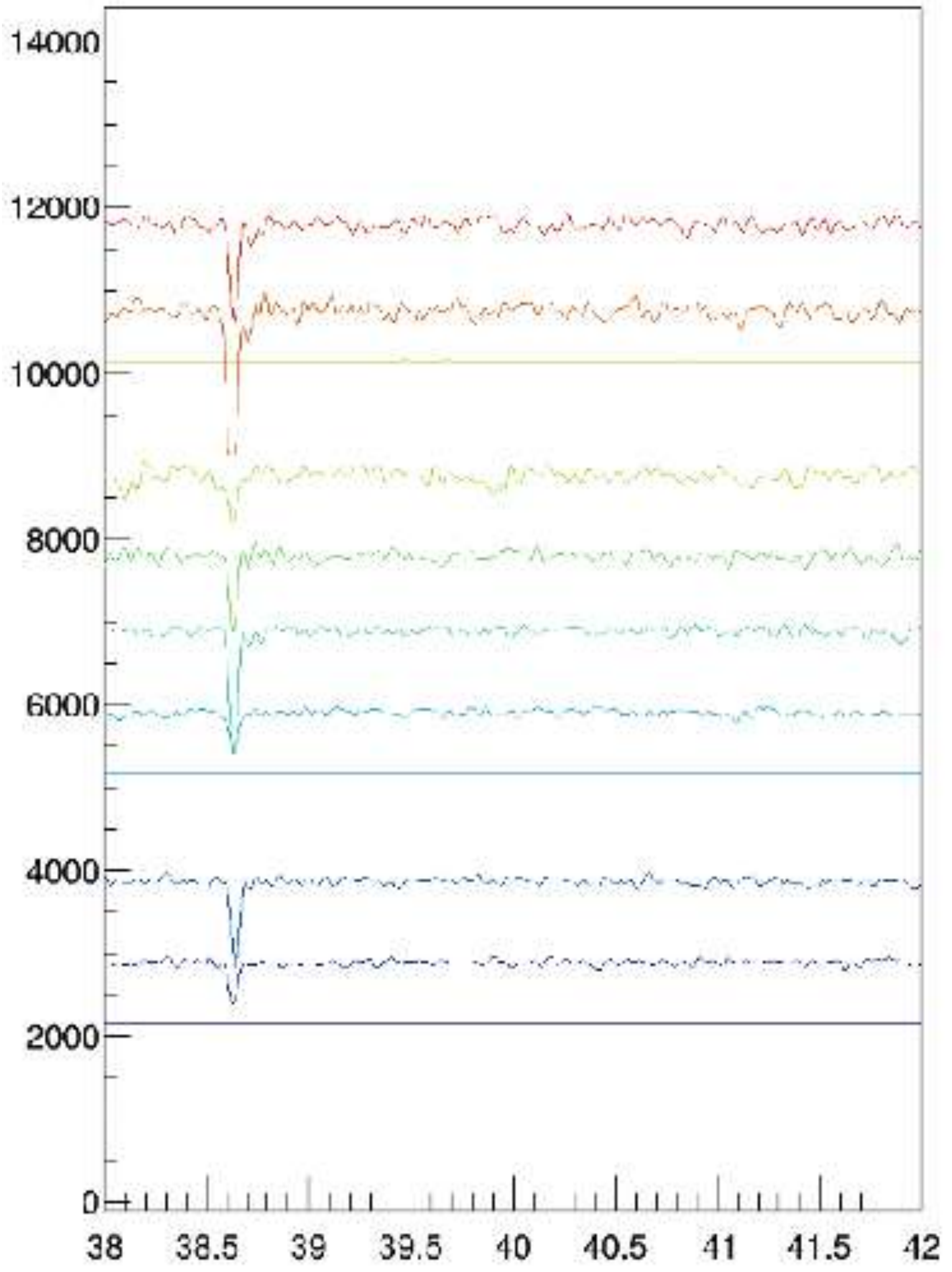
Detector development platform at Akeno observatory

- **9 scintillators and 1 layered water-Cherenkov detector to be installed**

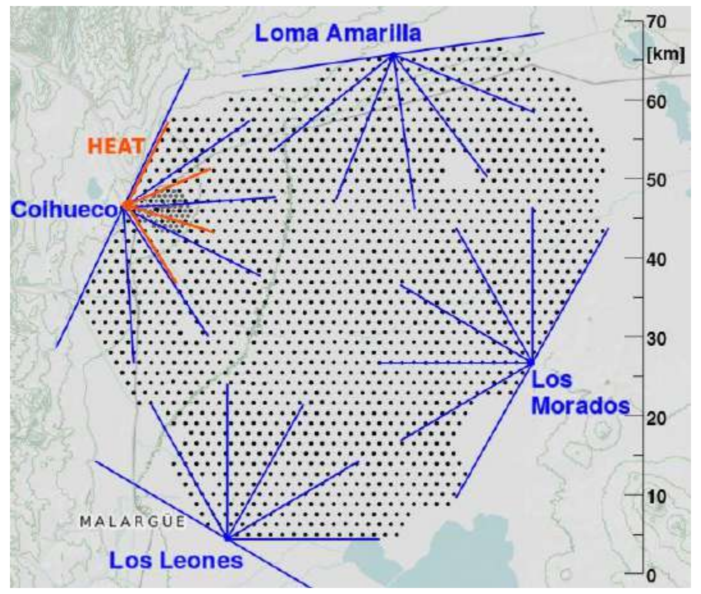


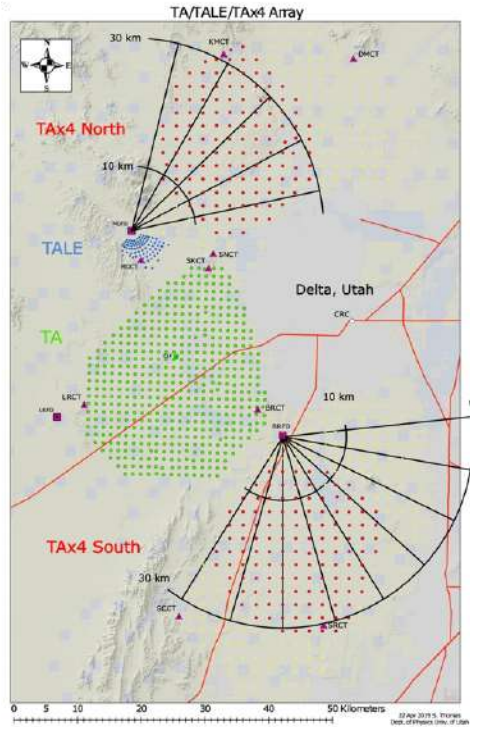
GCOS FD developments: CRAFFT/FAST

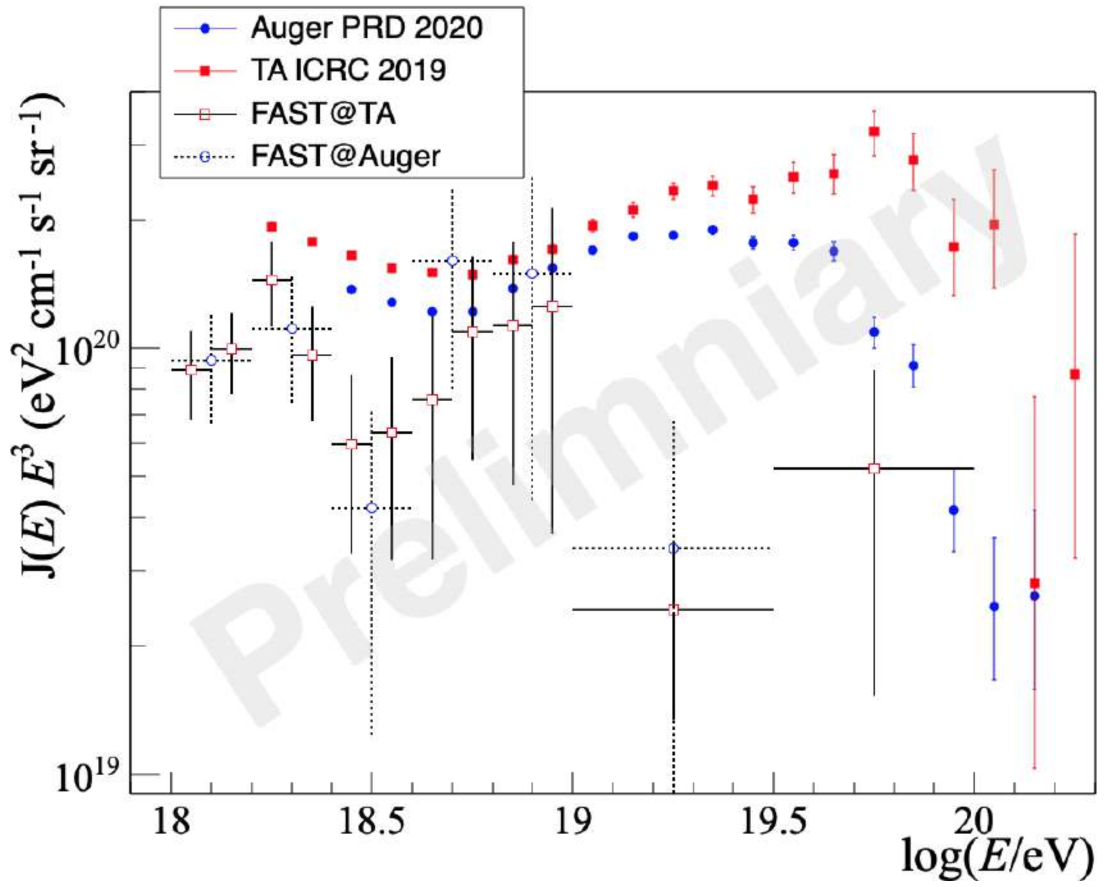


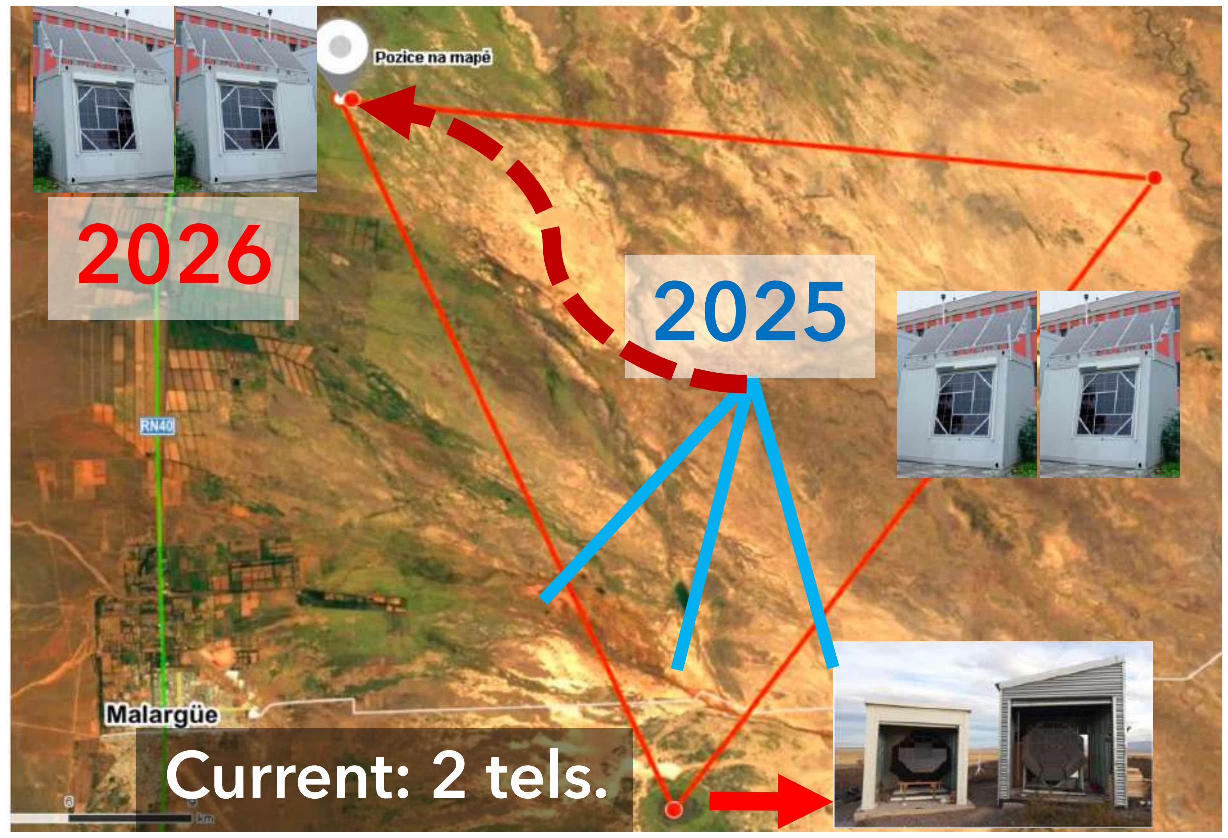


Y. Tameda et al., PoS (ICRC2025) 411







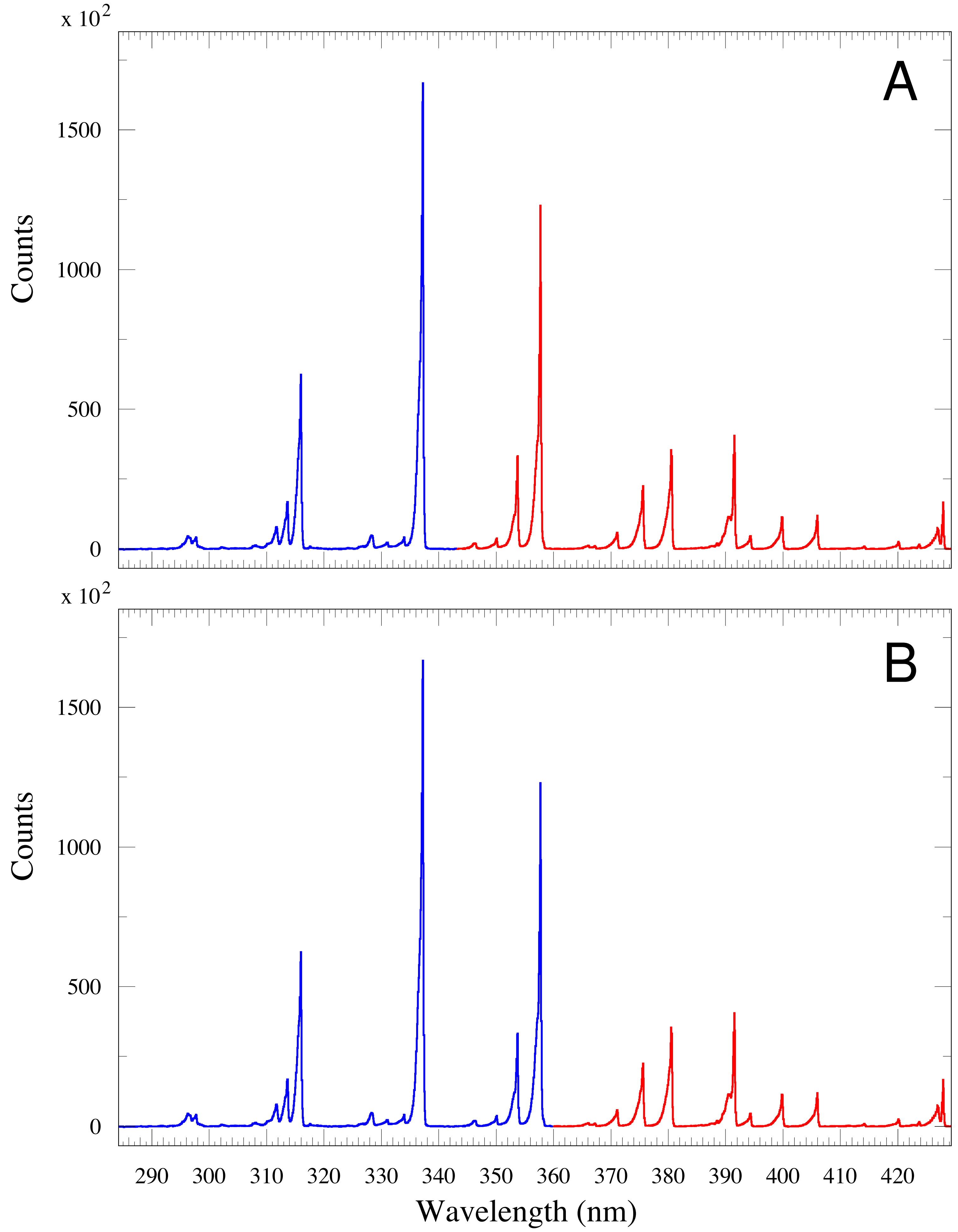


S. Sakurai et al., PoS (ICRC2025) 380

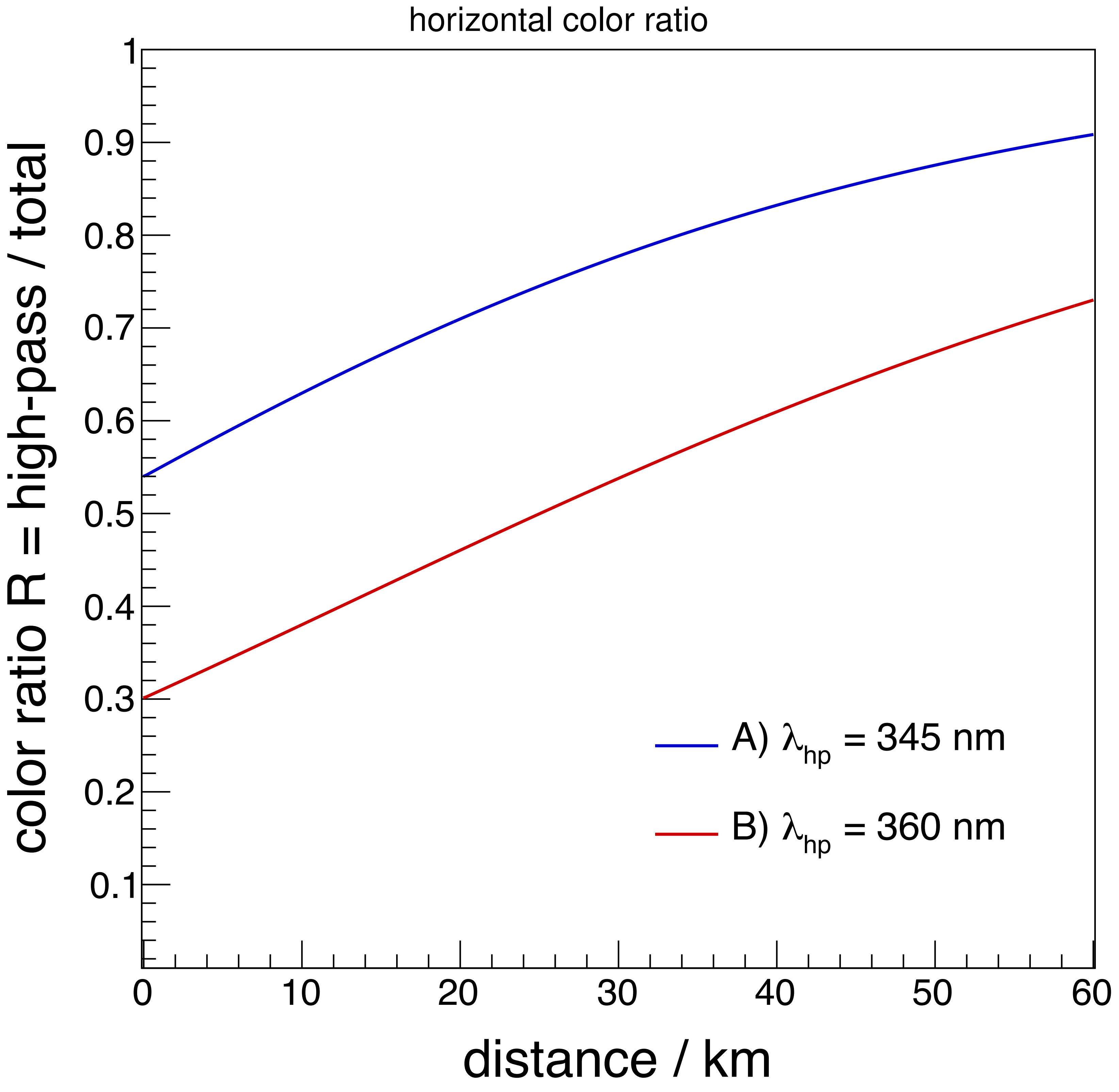
New idea: "Chromatic" Fluorescence detection

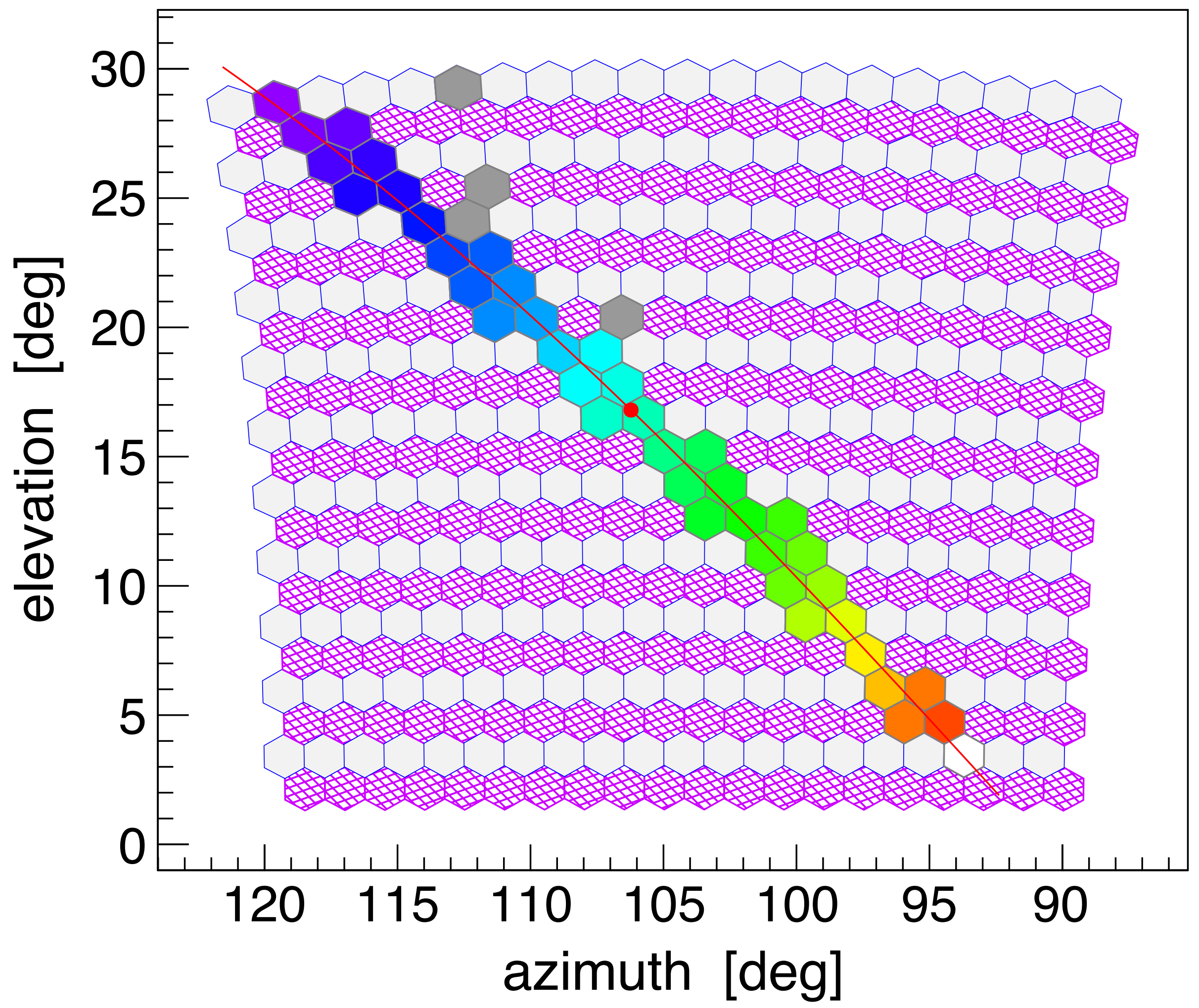
M. Unger (KIT)

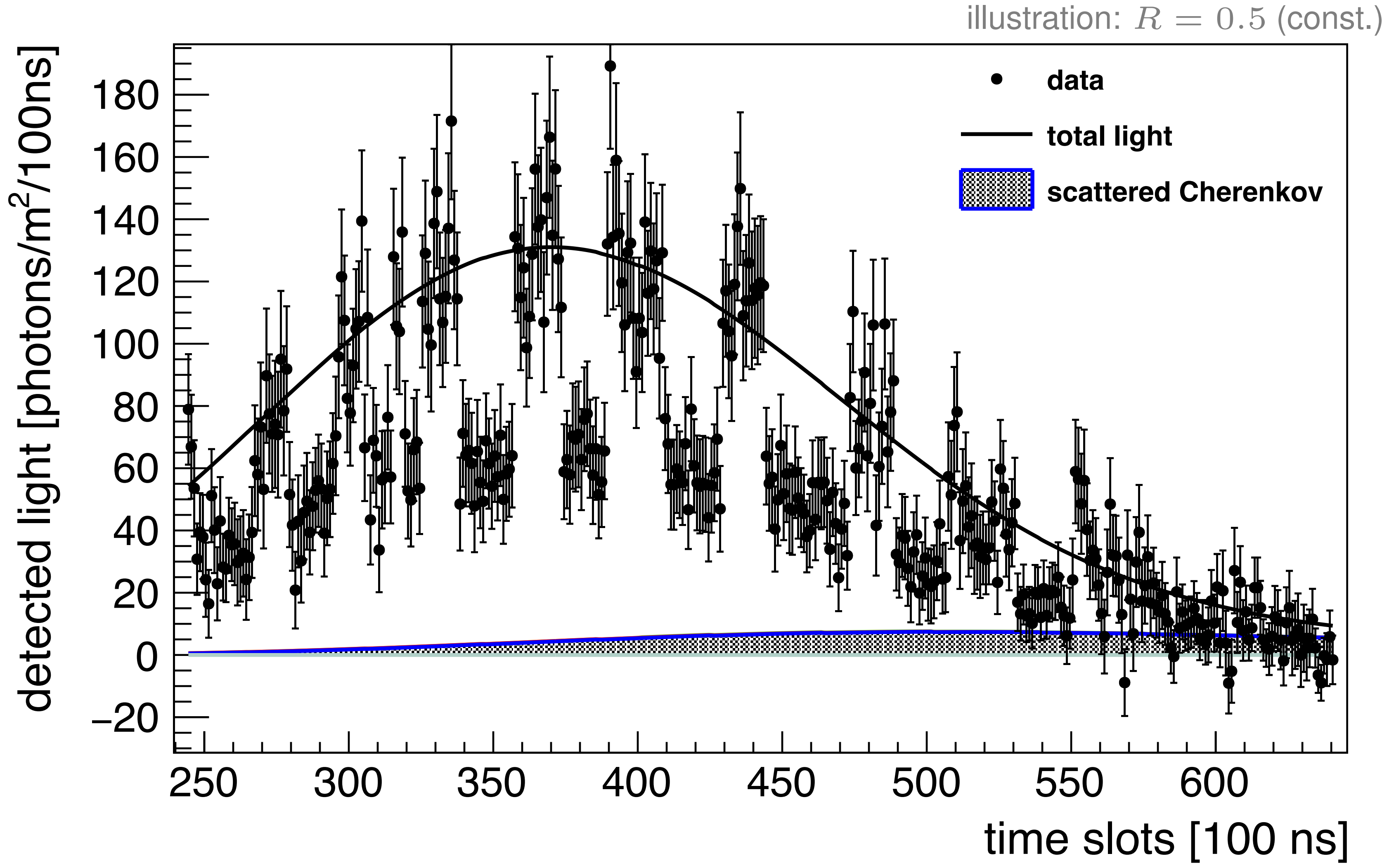
fluorescence spectrum (AIRFLY 2007)



Chromatic Fluorescence Detection



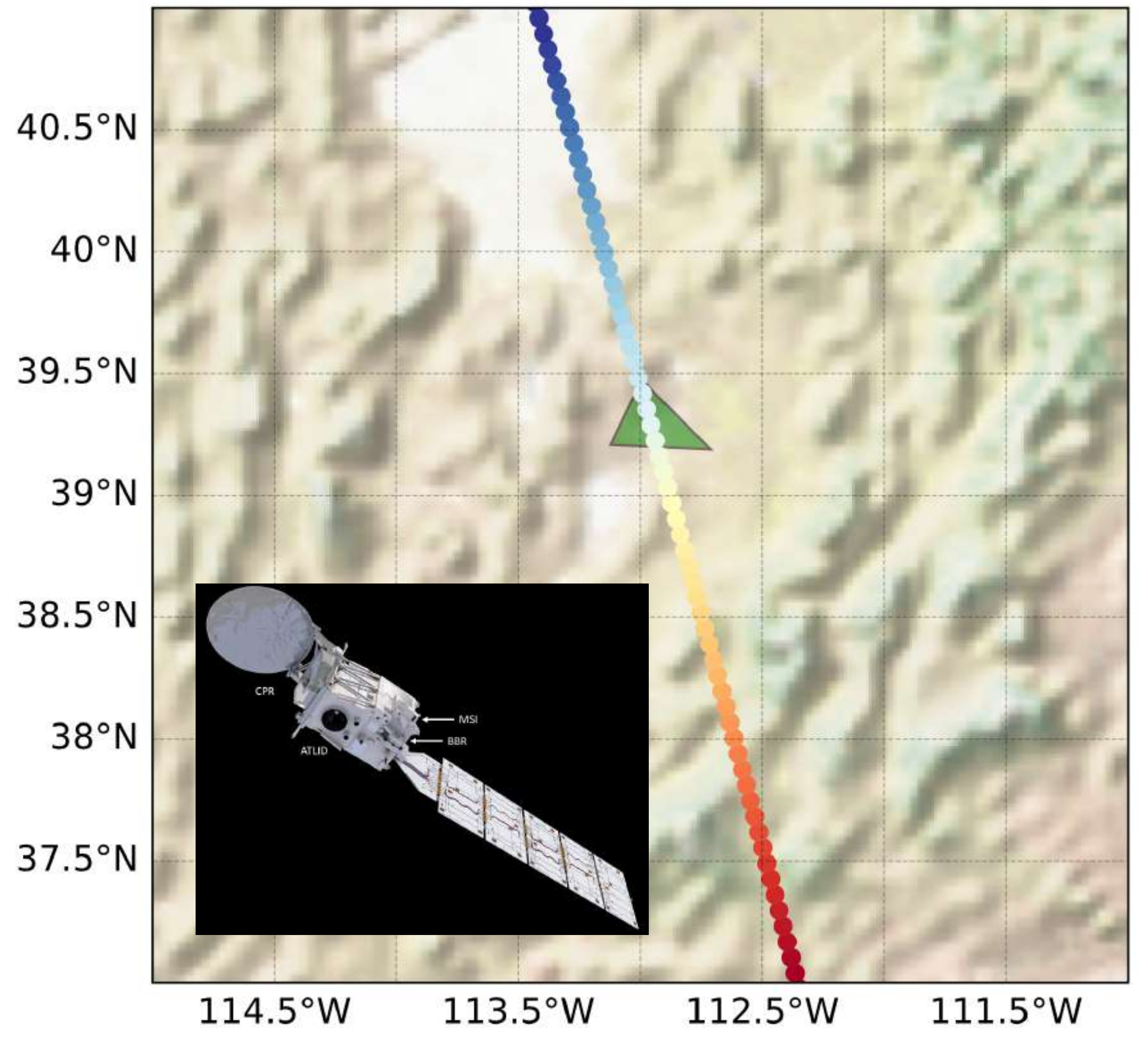


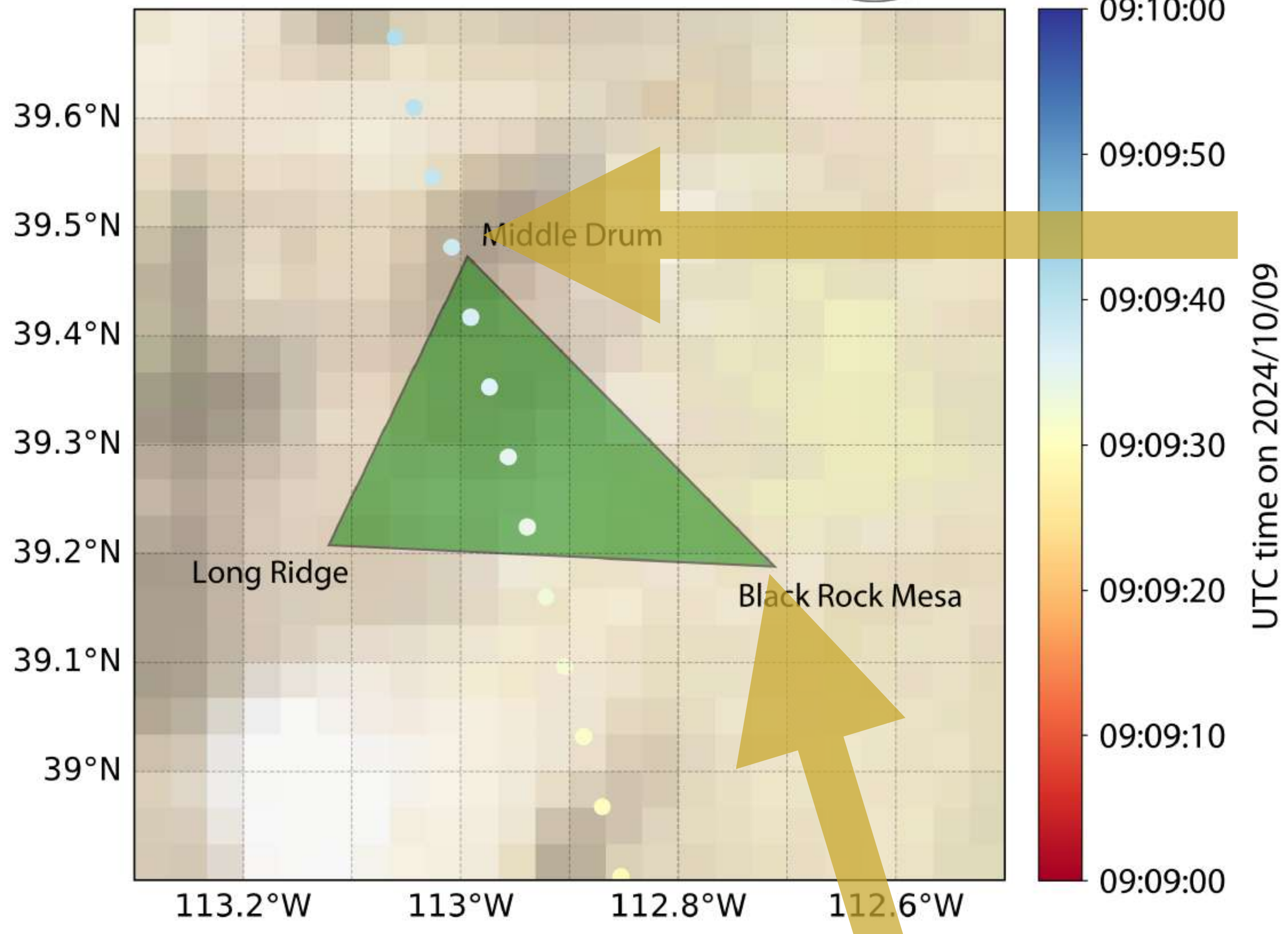


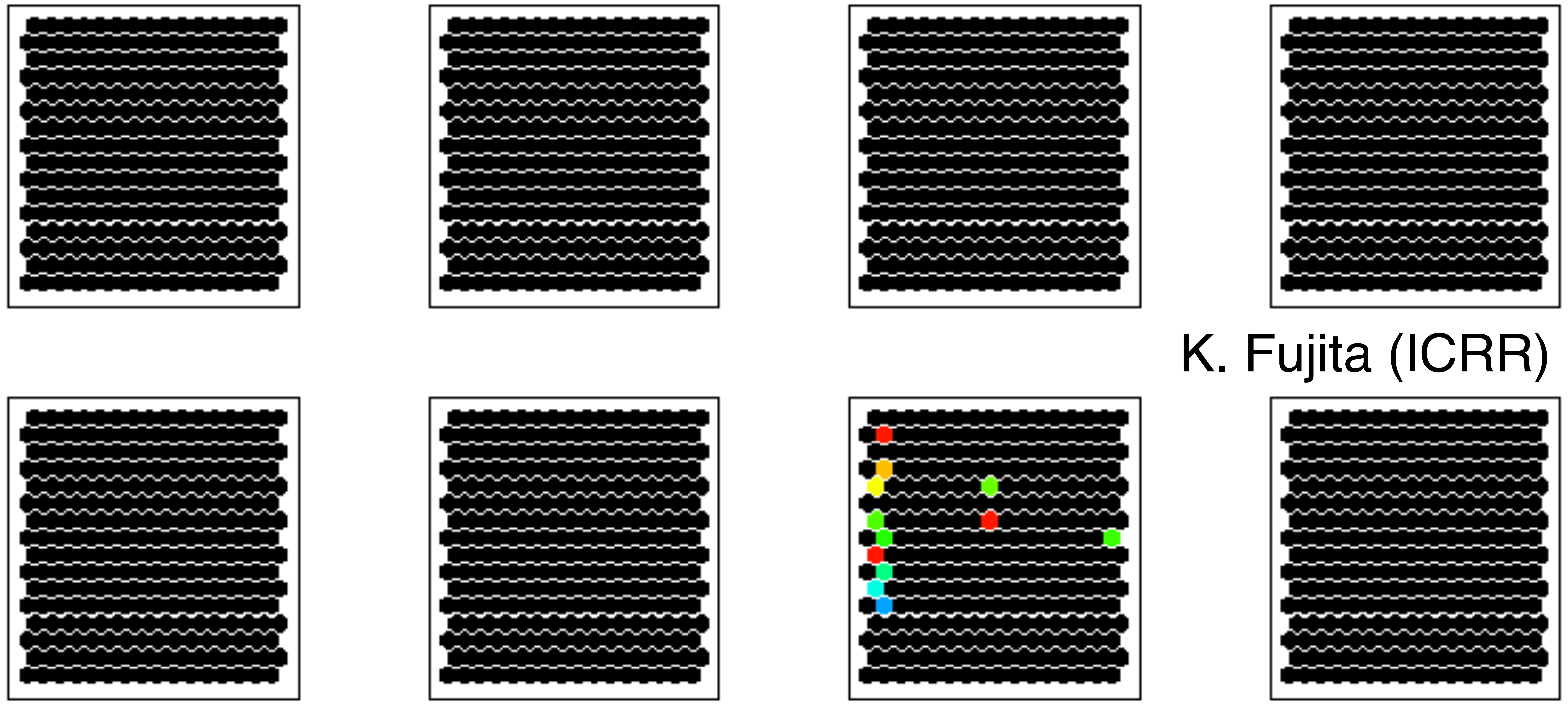
Color ratio = distance toward shower axis → better resolution even in monocular mode

Intersection with Earth science as "global light source"

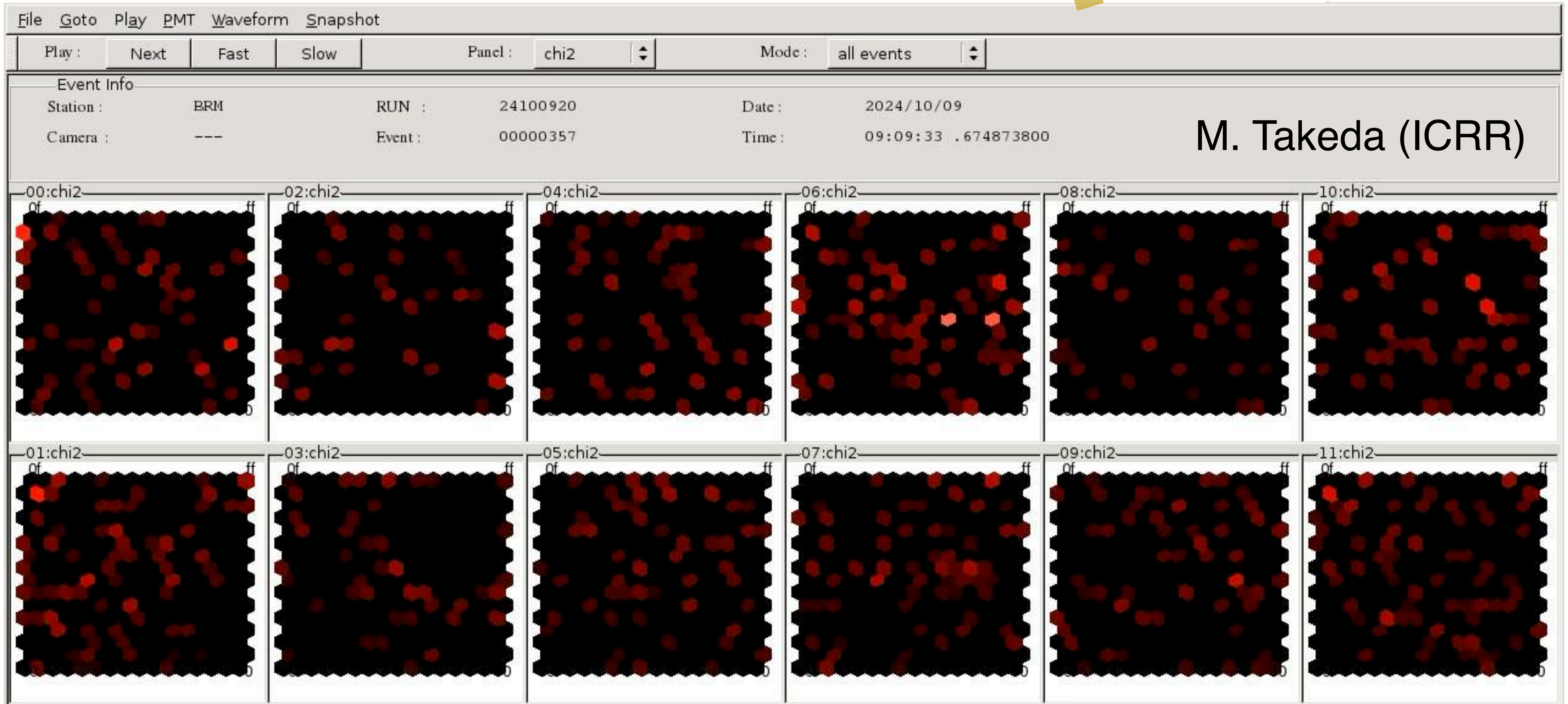
TA overpass on 9 October 2024







K. Fujita (ICRR)

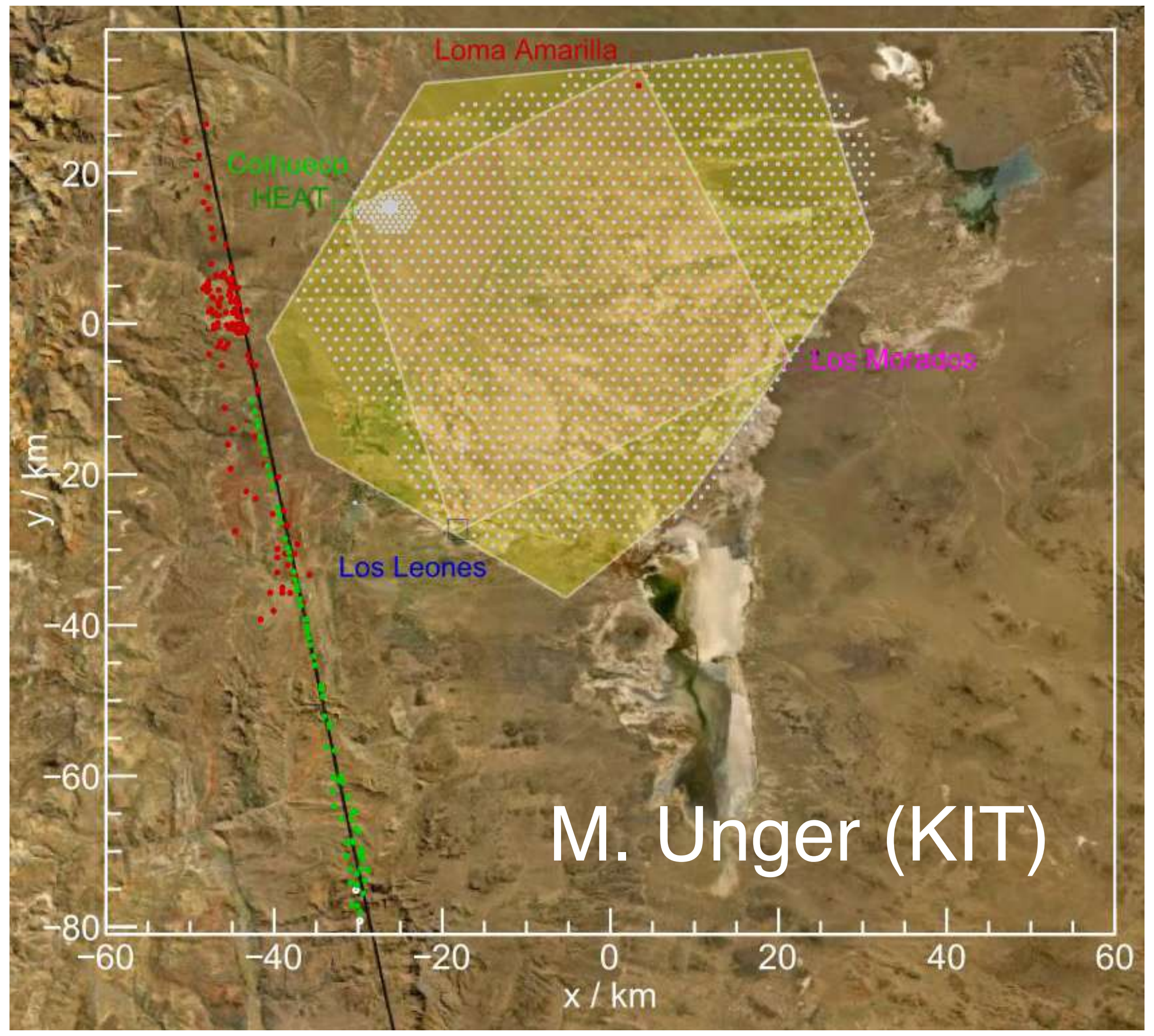


M. Takeda (ICRR)

Auger overpass on 29 October 2024

PIERRE AUGER OBSERVATORY

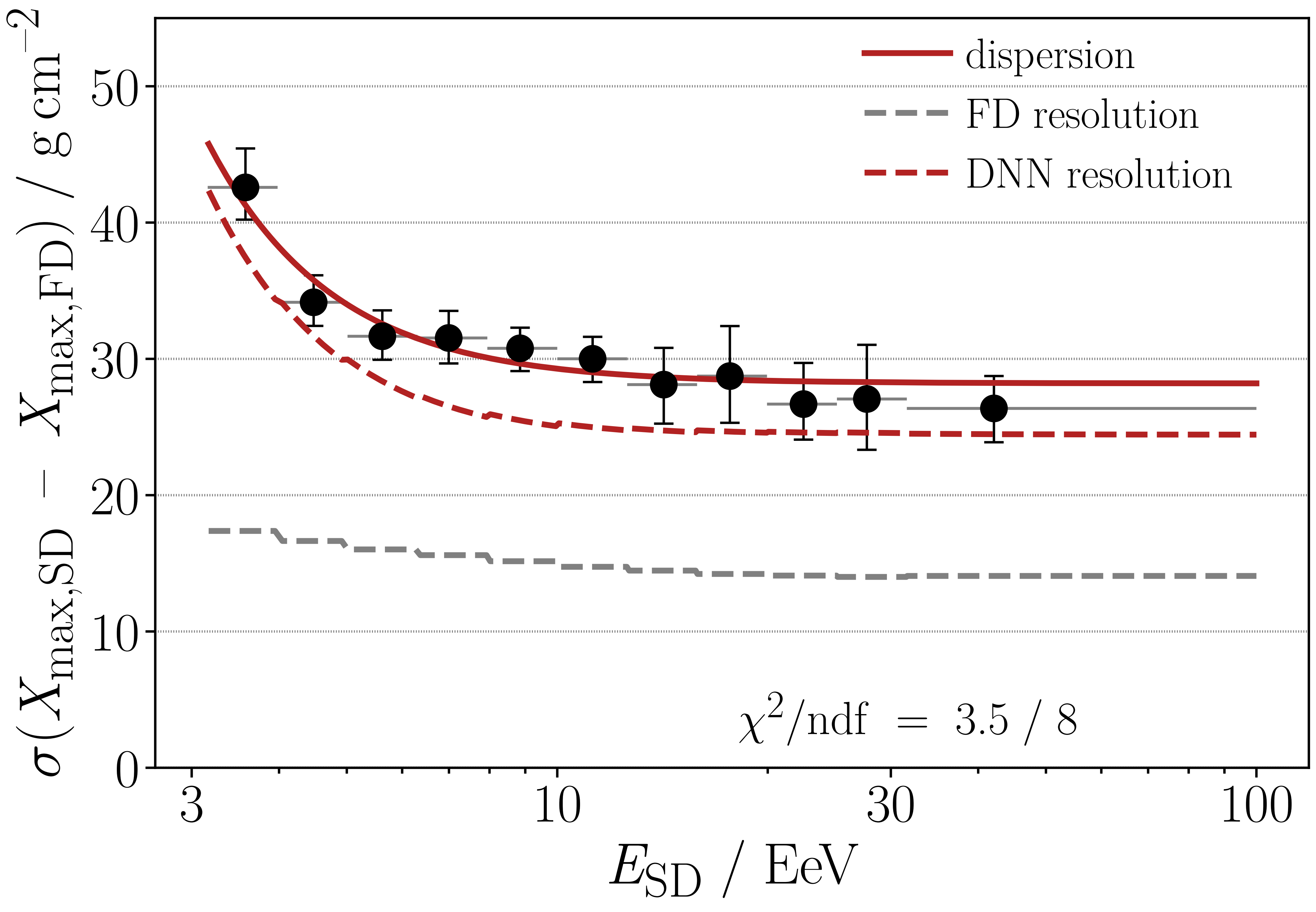
EarthCARE team: O. Lux and O. Reitebuch (DLR)

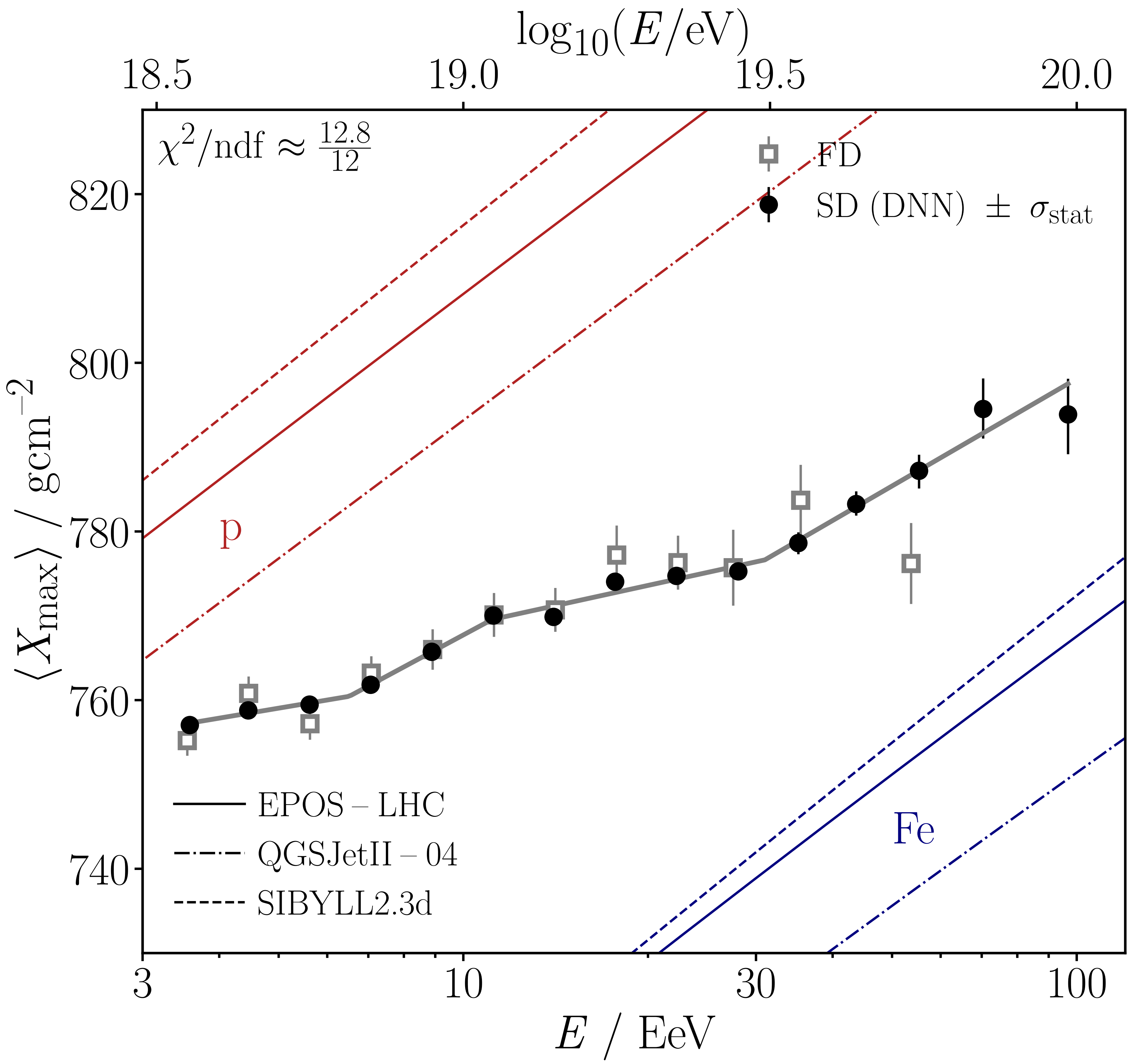


M. Unger (KIT)

Importance of machine learning for GCOS

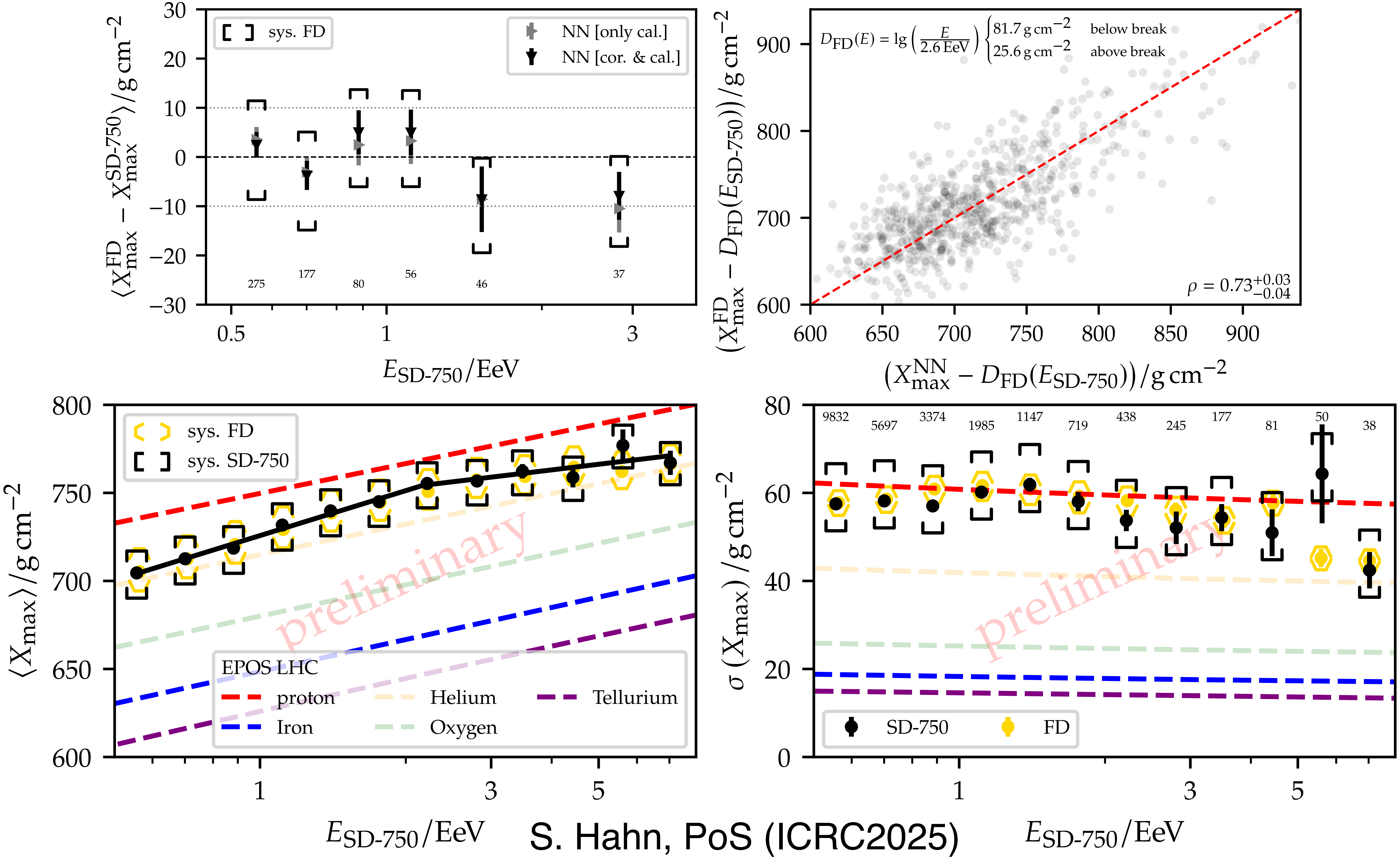
- Machine learning will be capable to **"Event-by-event"** mass(-group) of primary cosmic rays
    - Optimization of detector design from feedbacks of machine learning





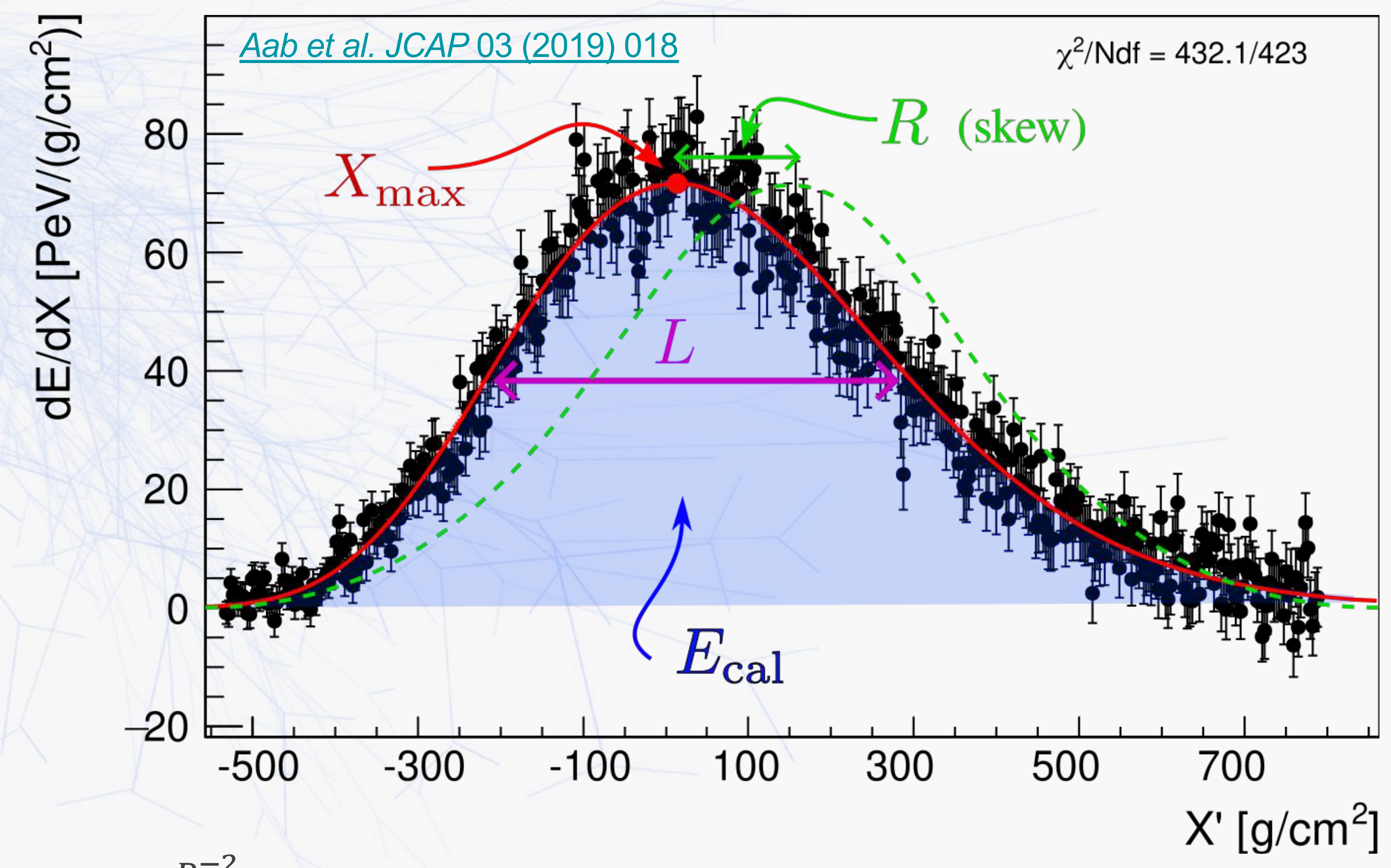
Pierre Auger Collab. PRD 111, 022003 (2025), See details in Jonas's talk

Auger Infill SD + machine learning



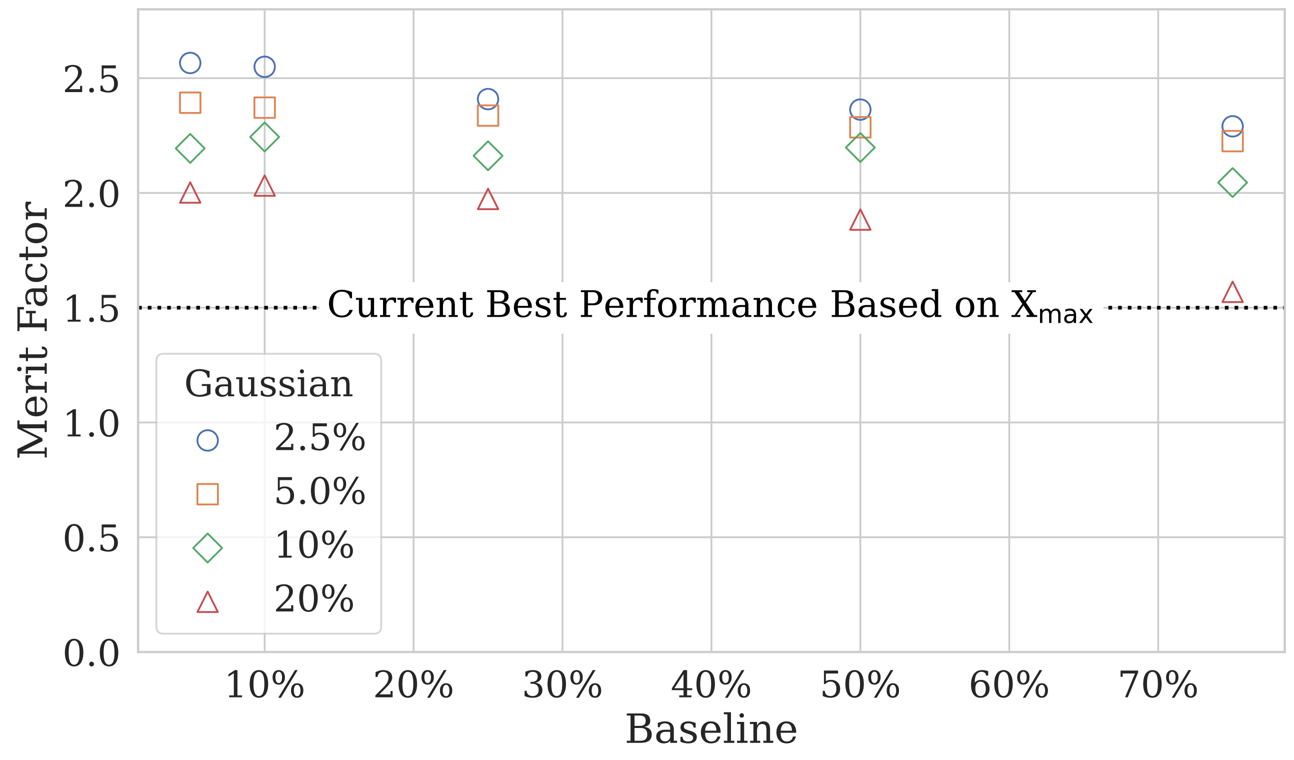
S. Hahn, PoS (ICRC2025)

FD shower profile + machine learning

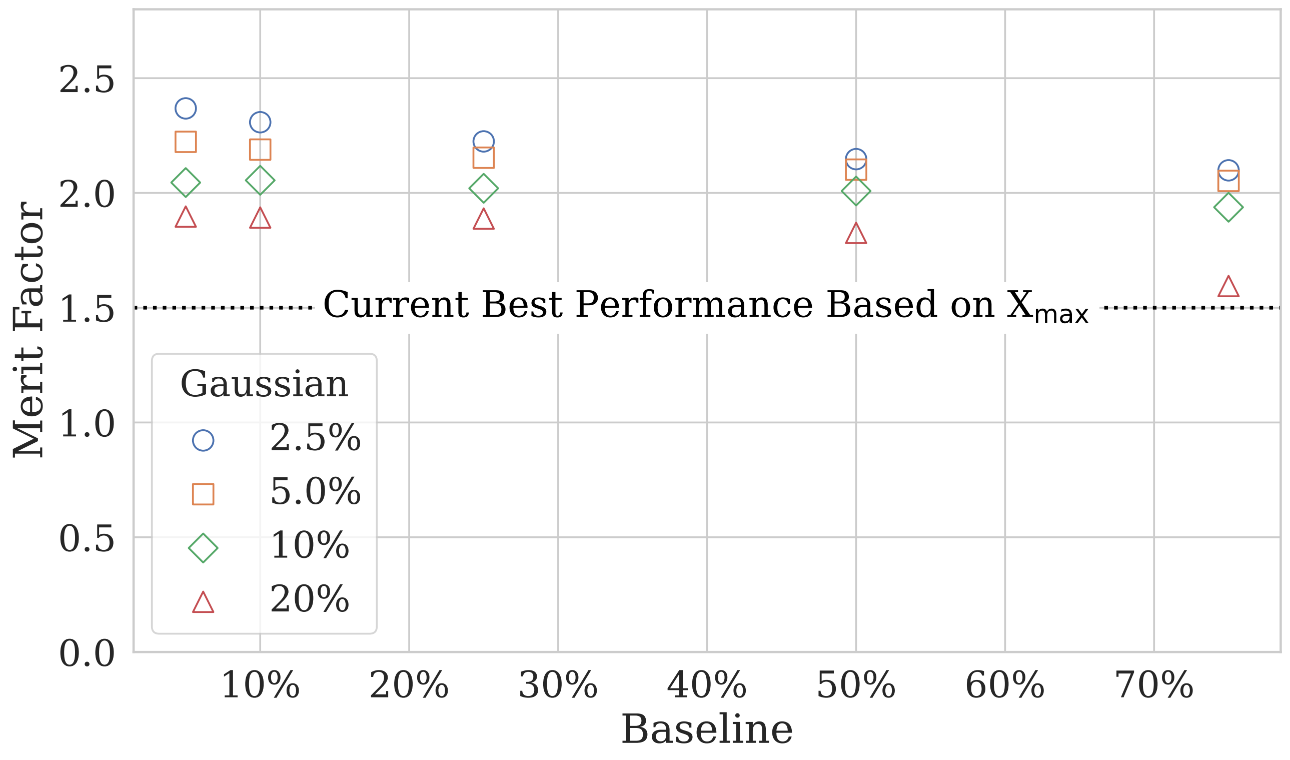


$$\frac{dE}{dX'} = \left(1 + \frac{R\,X'}{L}\right)^{R^{-2}} exp\left(-\frac{X'}{R\,L}\right) \quad \text{where} \quad X' = X - X_{\max},\, R = \sqrt{\lambda/|X_0'|},\, \text{L} = \sqrt{\lambda\,|X_0'|}$$

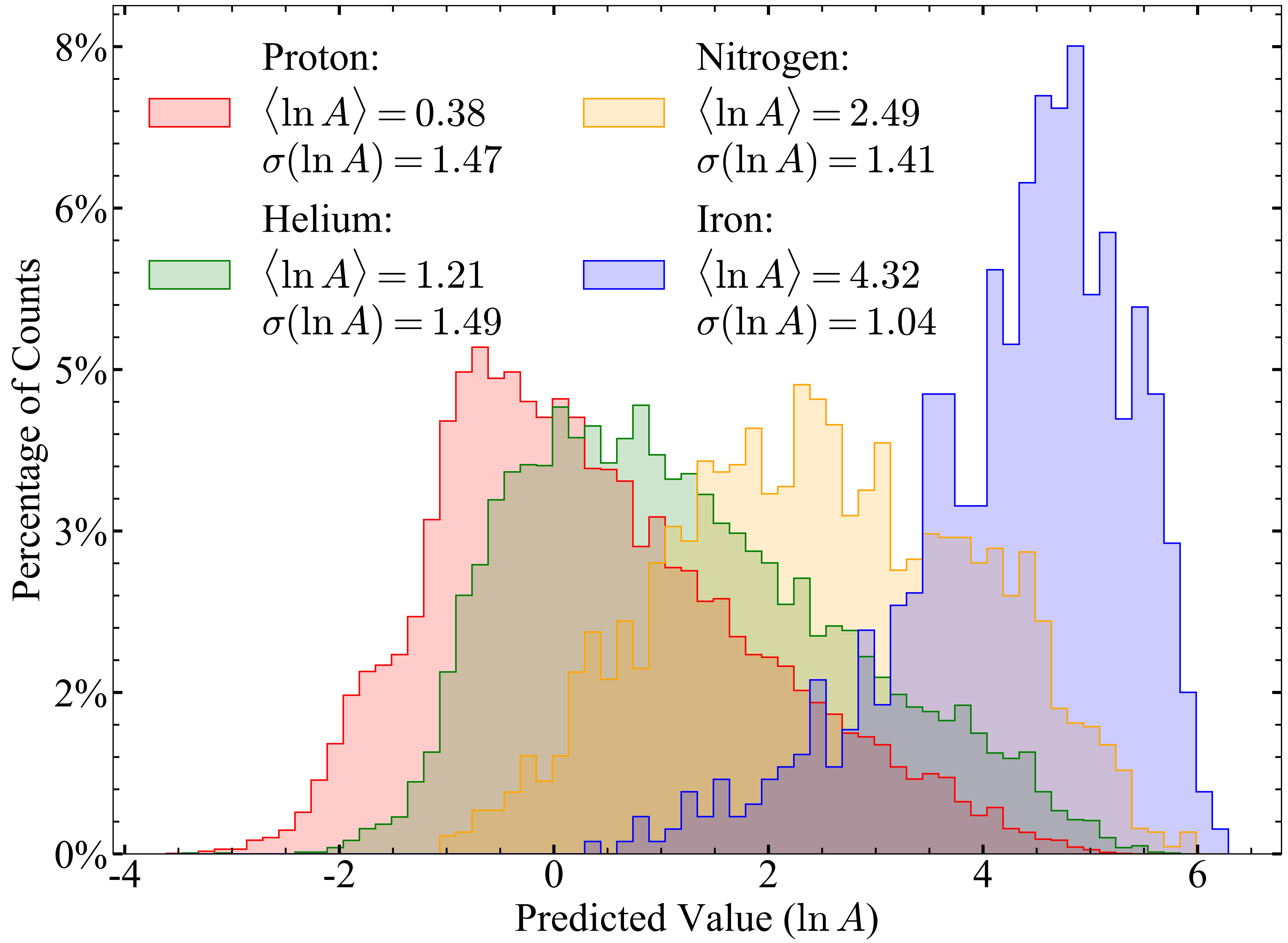
E. Mayotte, GCOS 2025



(a) Peak performance on EPOS data



(b) Cross-validation on Sibyll data



$$\text{MeritFactor} = \frac{\langle \ln(A) \rangle_{\rm Fe} - \langle \ln(A) \rangle_{\rm p}}{\sigma(\ln(A))_{\rm p} \oplus \sigma(\ln(A))_{\rm Fe}}$$

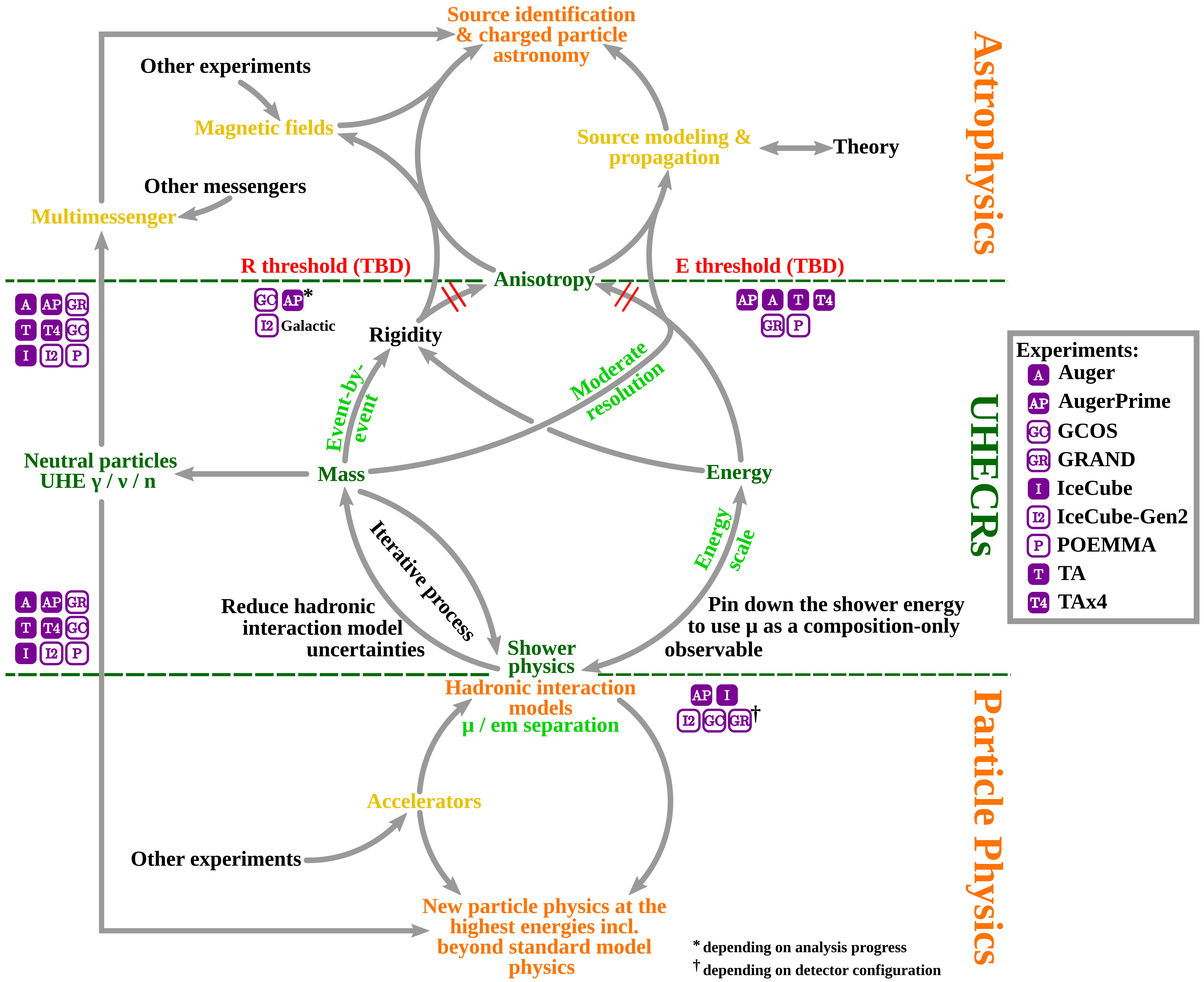
Z. Wang et al., arXiv: 2508.13933 submitted to JCAP

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**
  - Constrain a detailed structure of the Galactic magnetic field
  - Detect 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
- **Machine learning is important for GCOS to enhance primary mass sensitivity**

Backup

Strong connections to astrophysics and particle physics



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

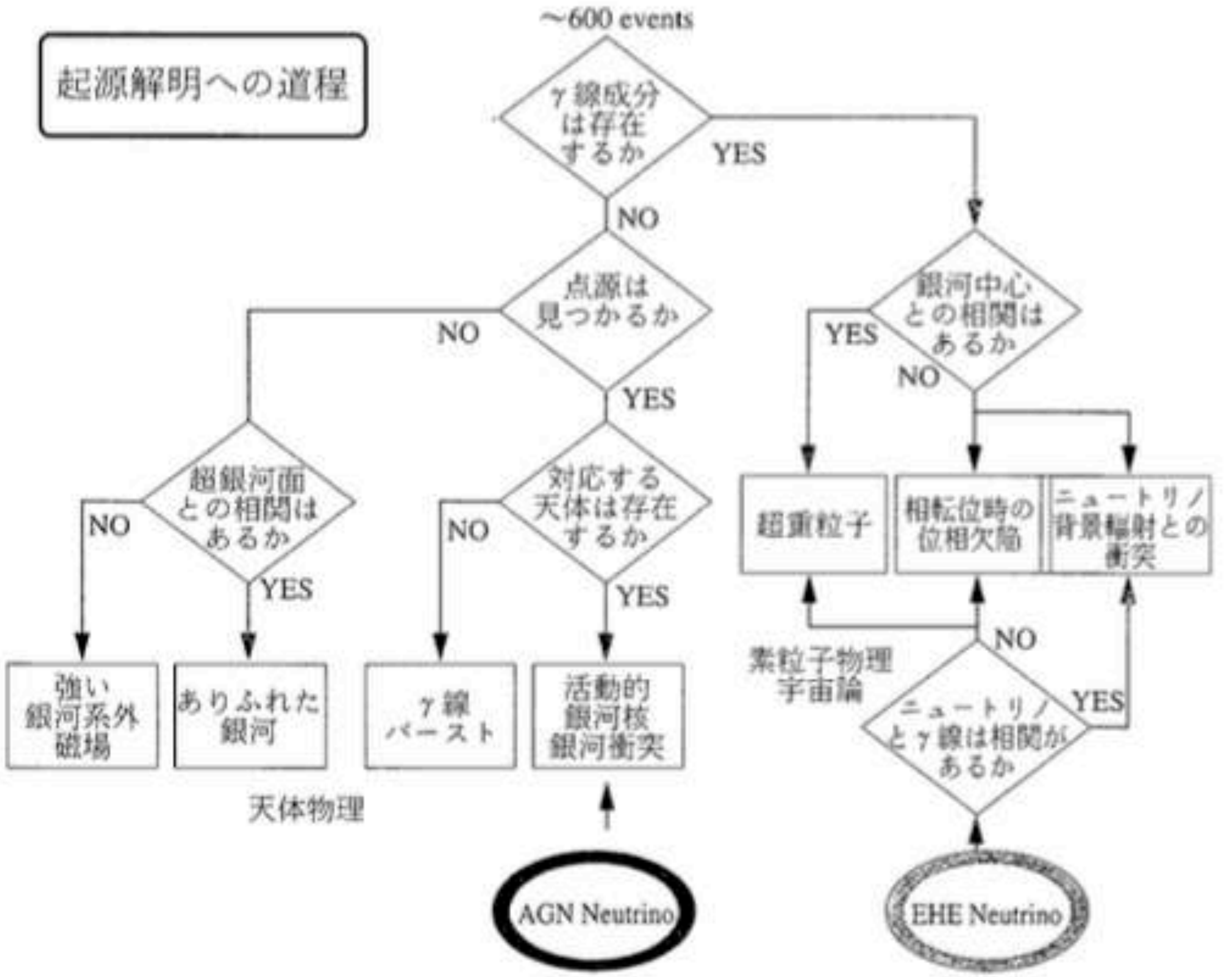
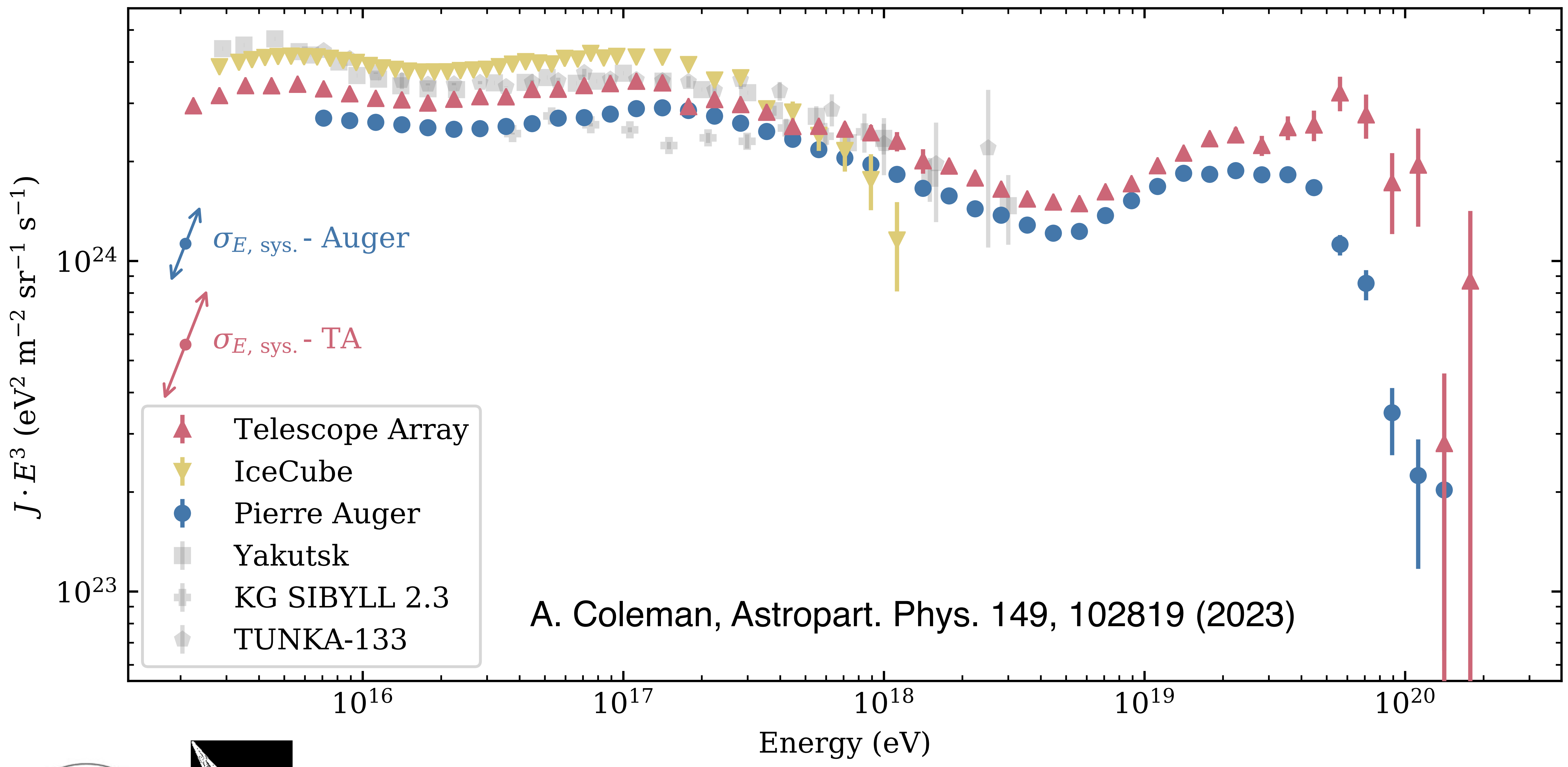
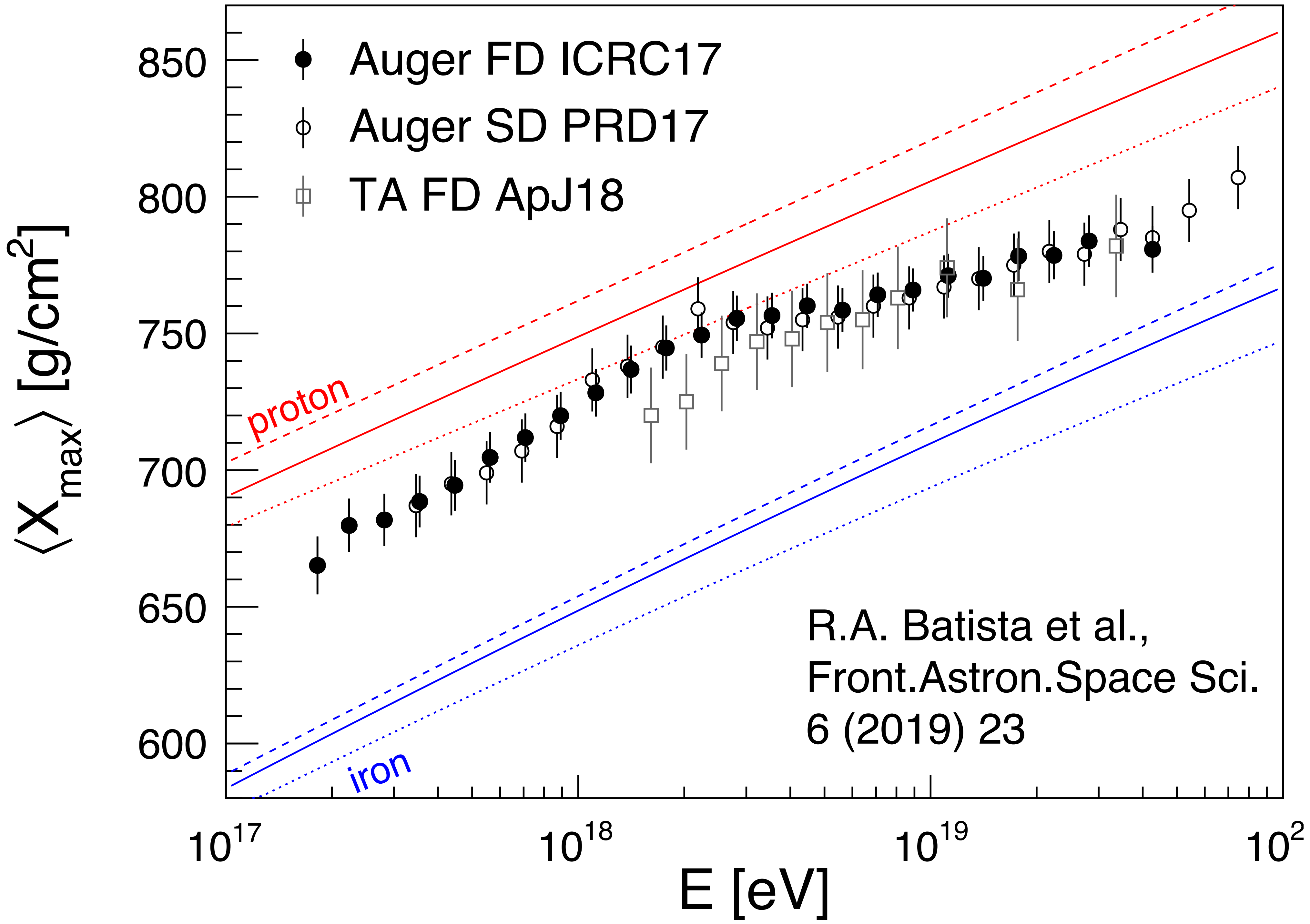


図10　宇宙からくる超高エネルギー粒子放射の起源を観測によって解明する道筋を示した．到来方向分布や既知の天体との相関，ガンマ線やニュートリノ成分の検出によって，提案されている様々なモデルの真偽を確かめることができる．

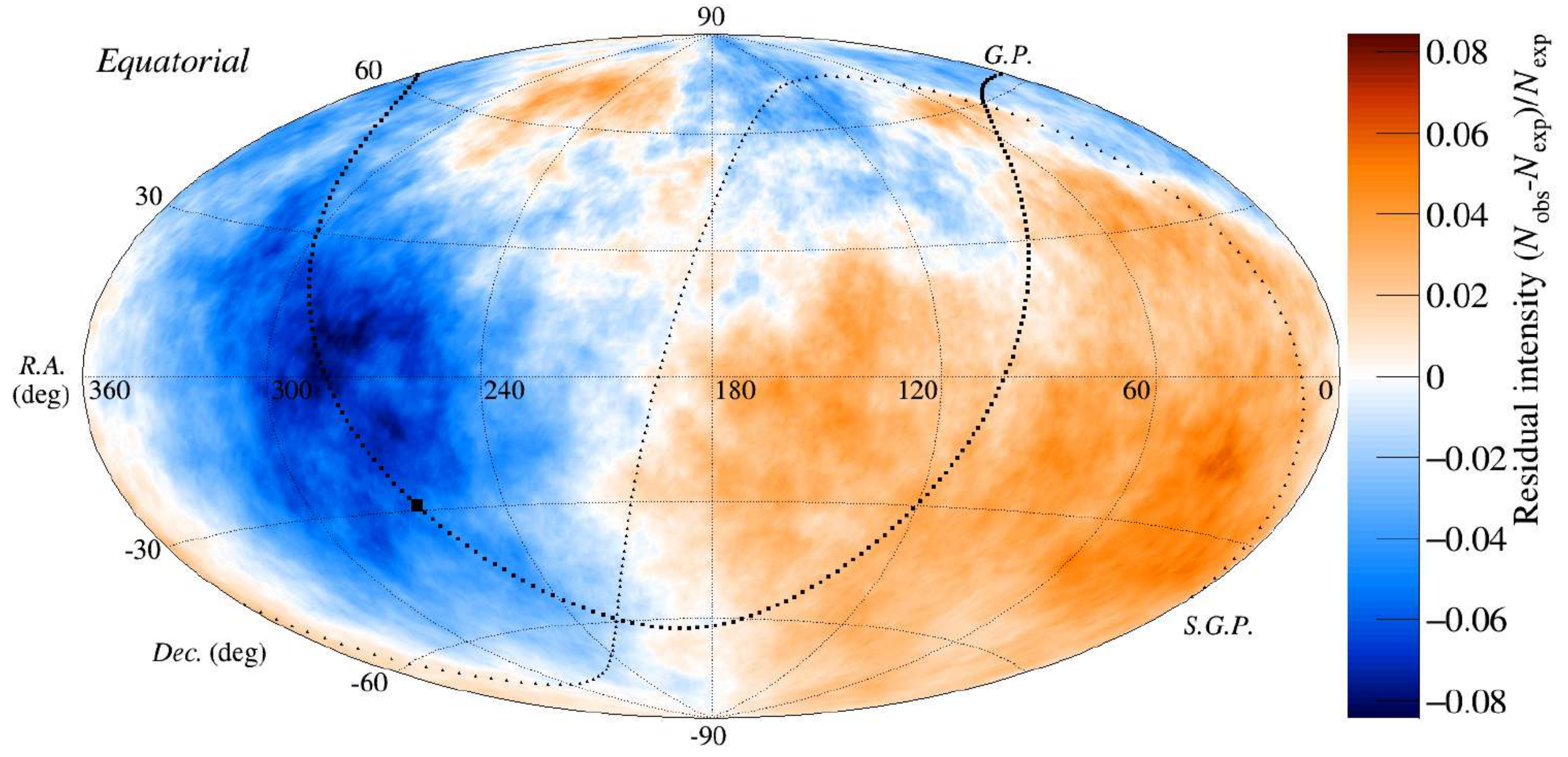
物理学会誌 2000年 福島・吉田



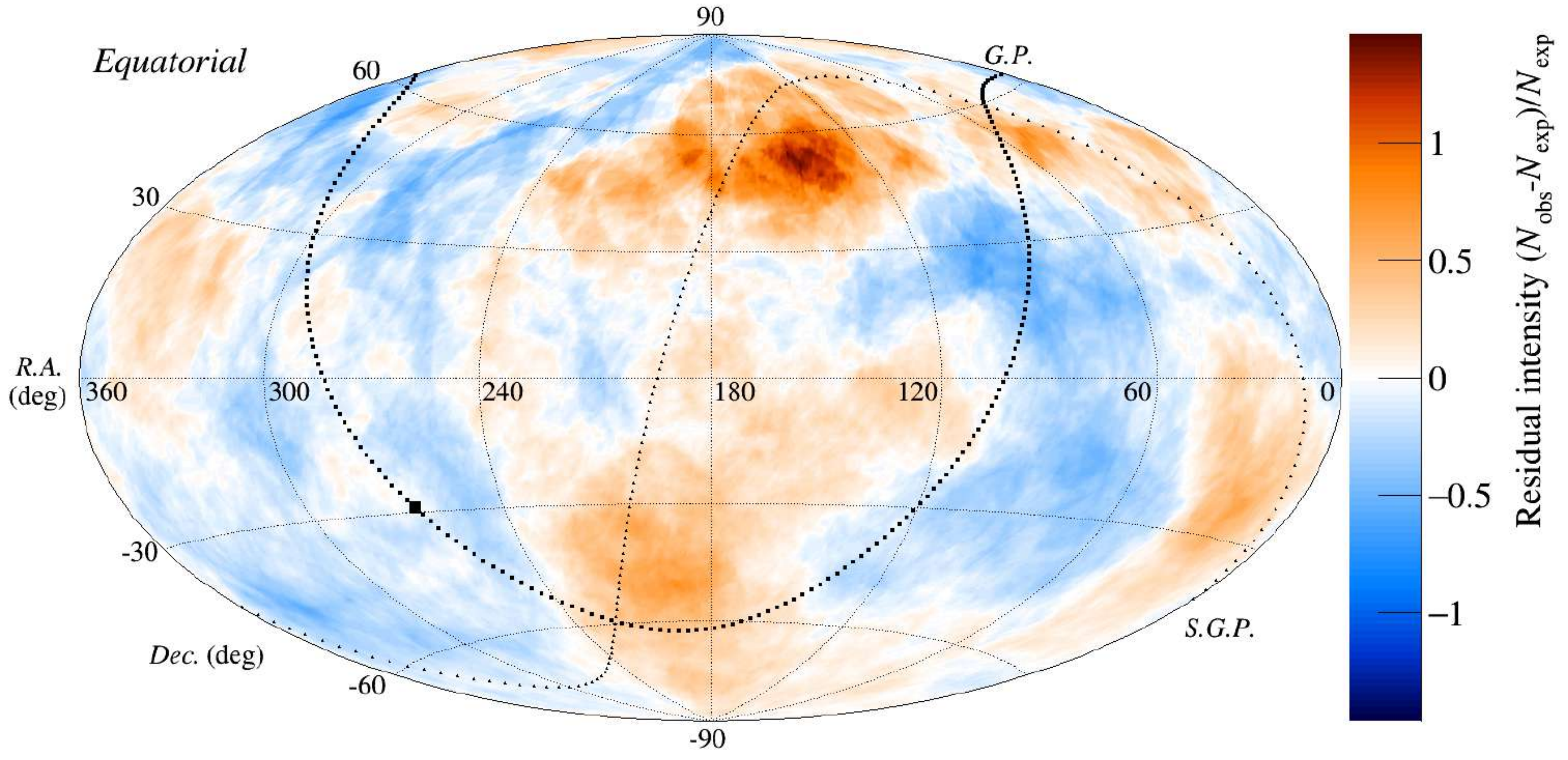


Latest results

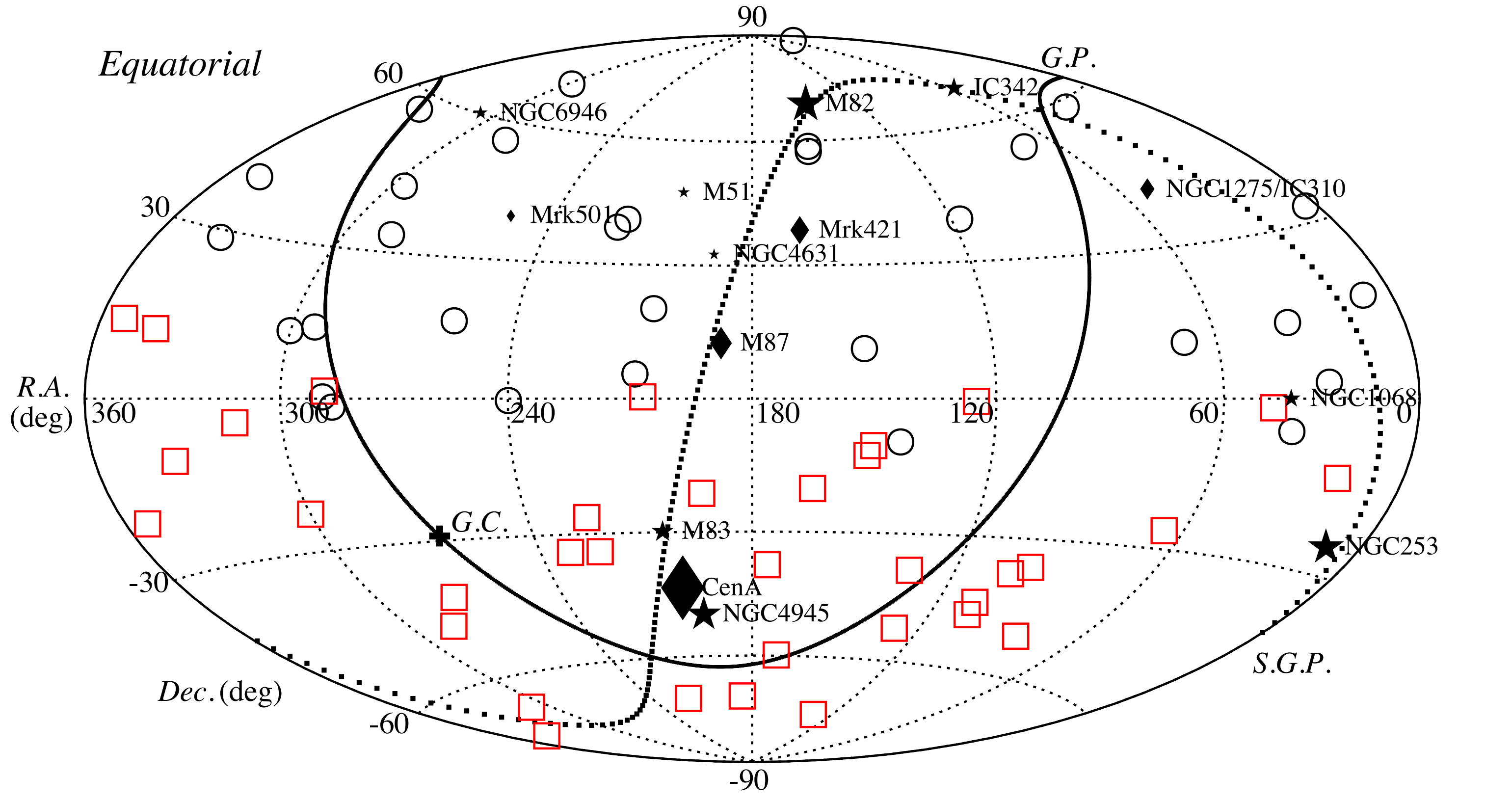
$$\theta \sim 10^\circ Z \left(\frac{E}{10\,\mathrm{EeV}}\right)^{-1} \qquad t_{\mathrm{delay}} \sim 100\, Z^2 \left(\frac{E}{10\,\mathrm{EeV}}\right)^{-2} \mathrm{yr}$$



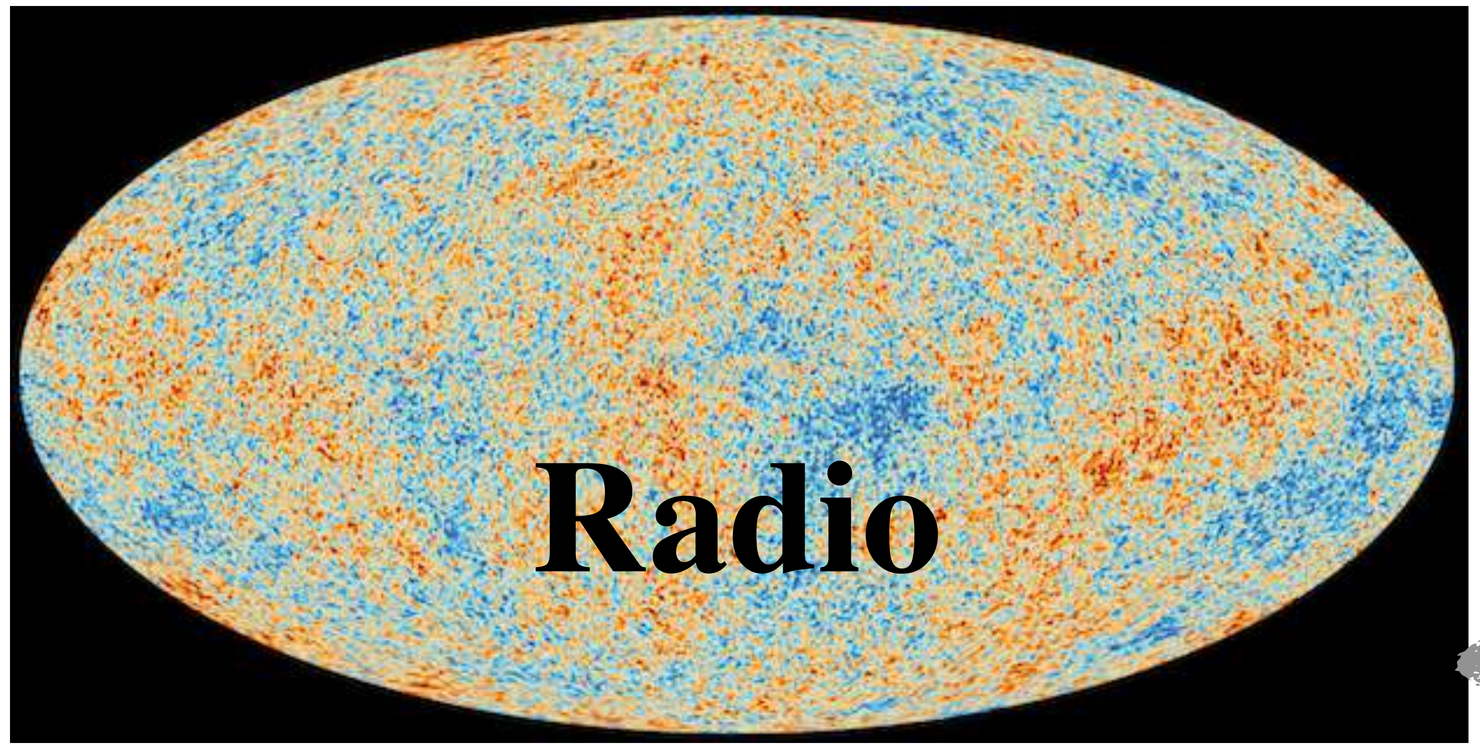
Ankle ($E > 10$ EeV)



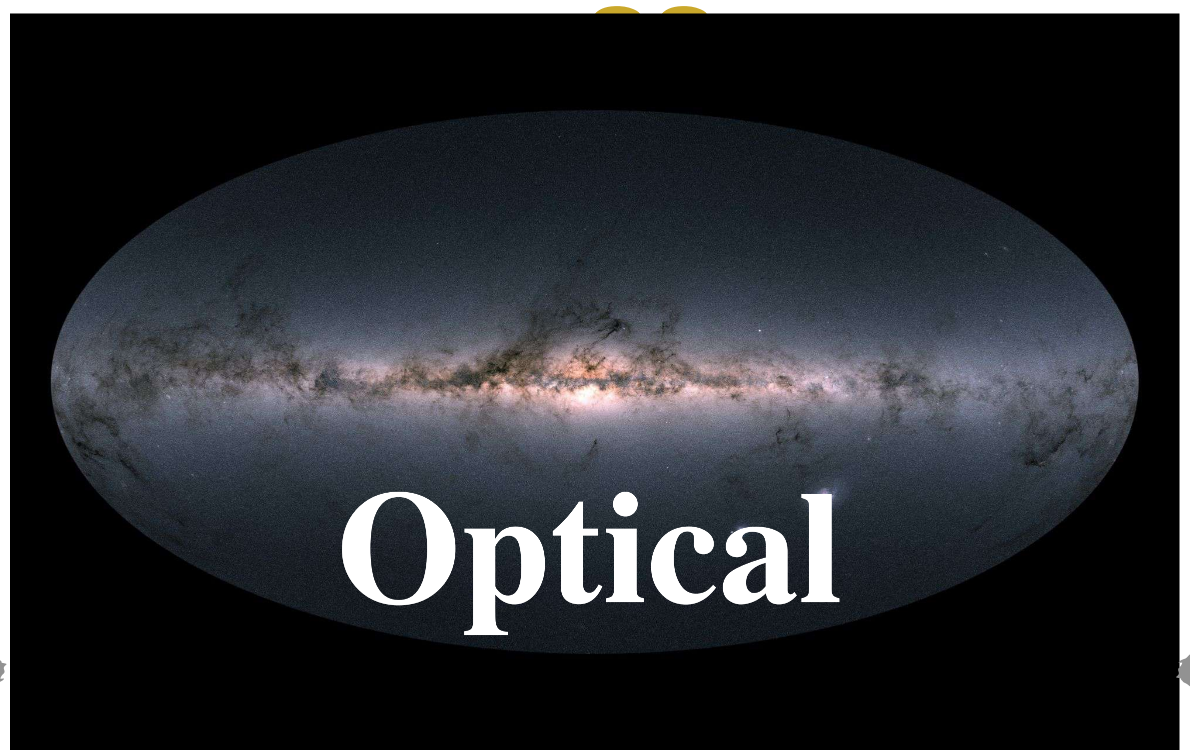
Cutoff ($E > 50$ EeV)



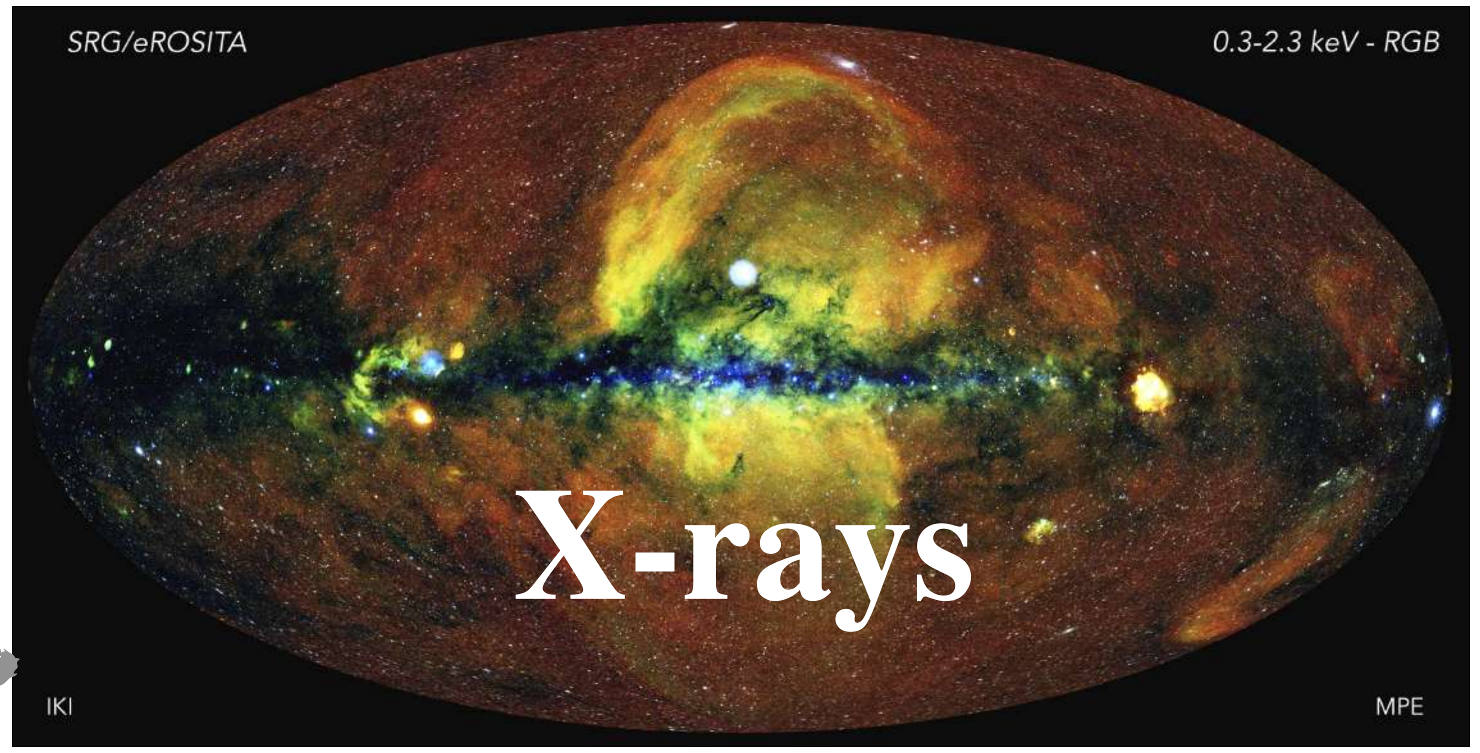
Beyond-cutoff ($E > 100$ EeV)



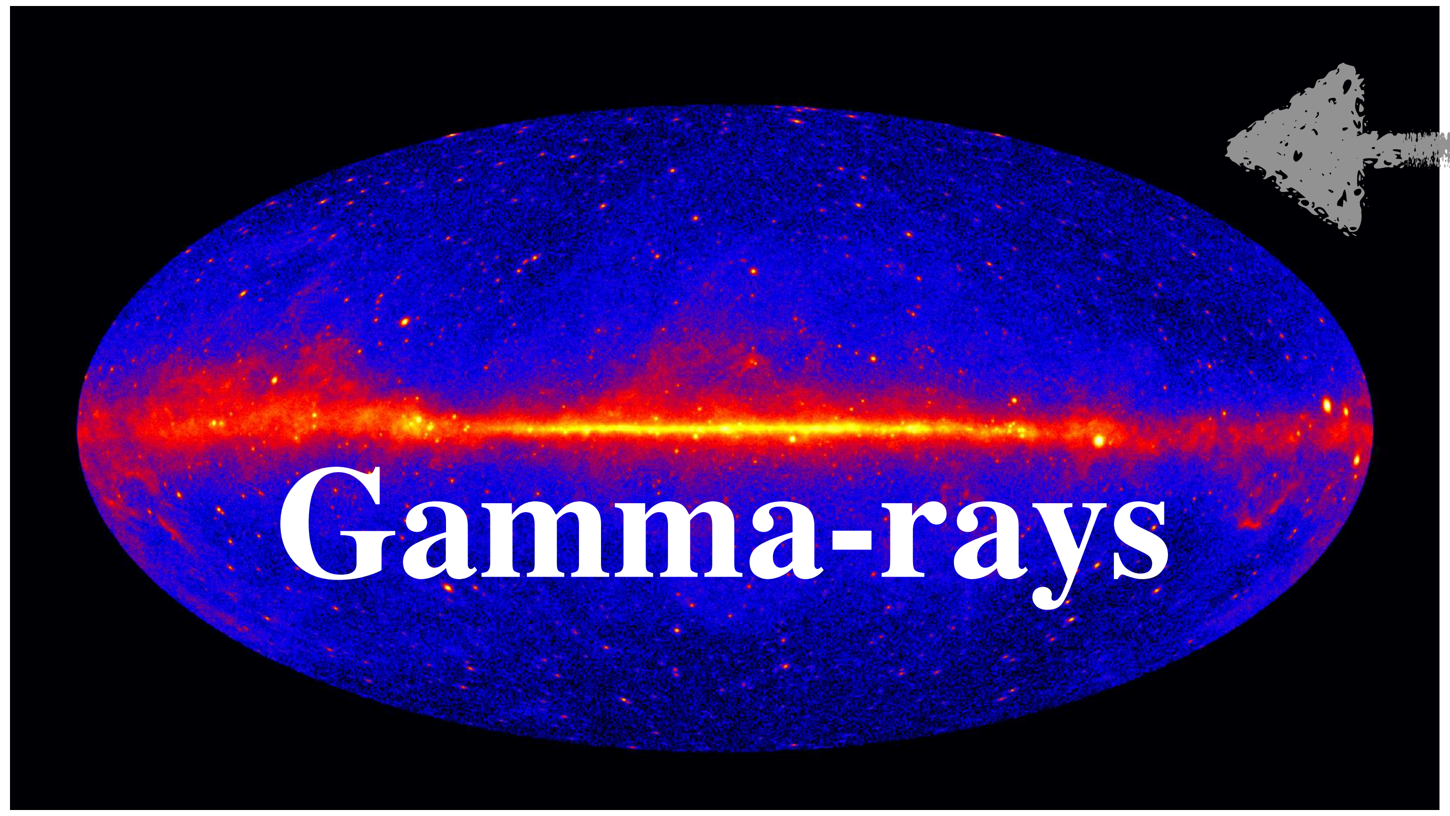
Planck Collaboration



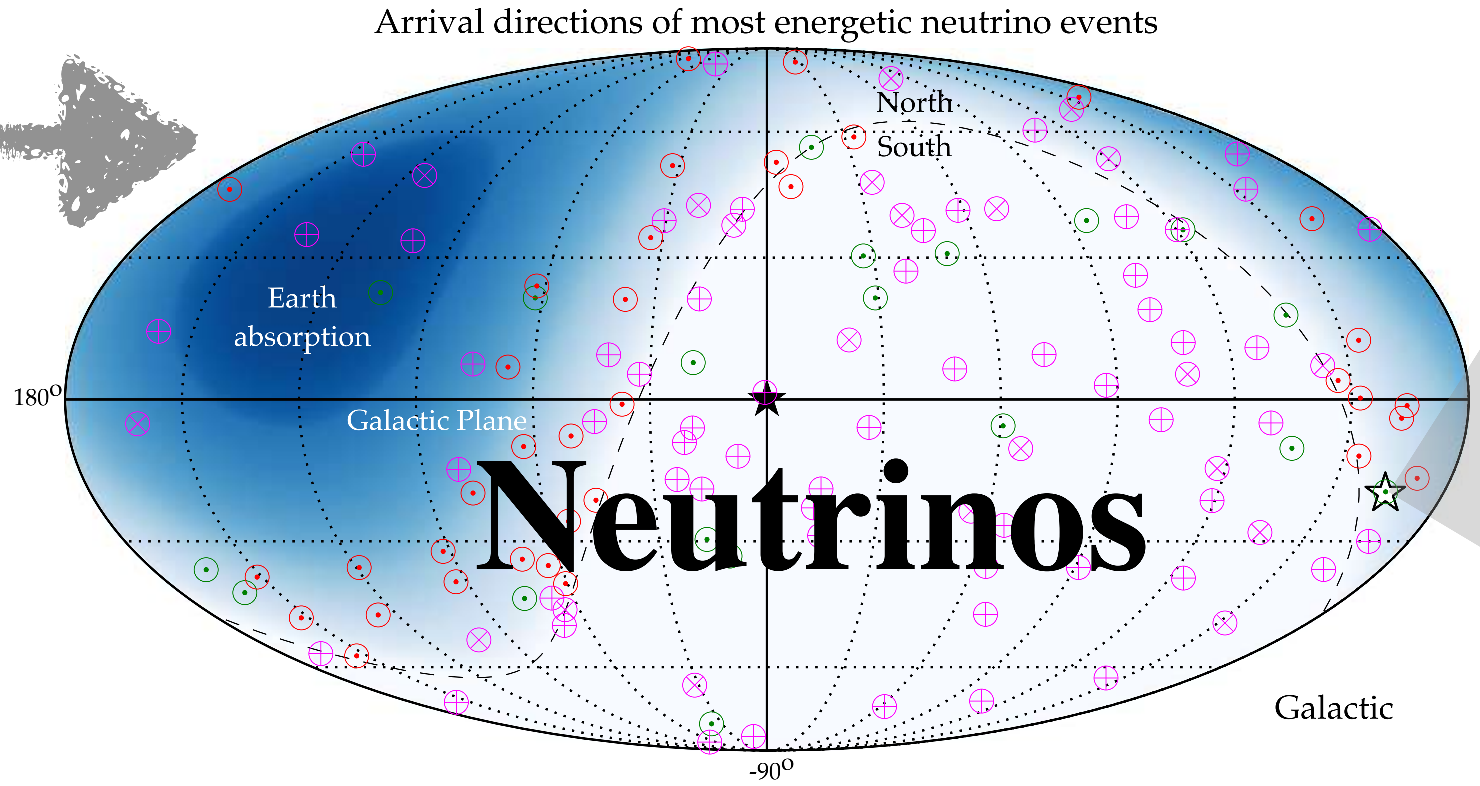
GAIA Collaboration

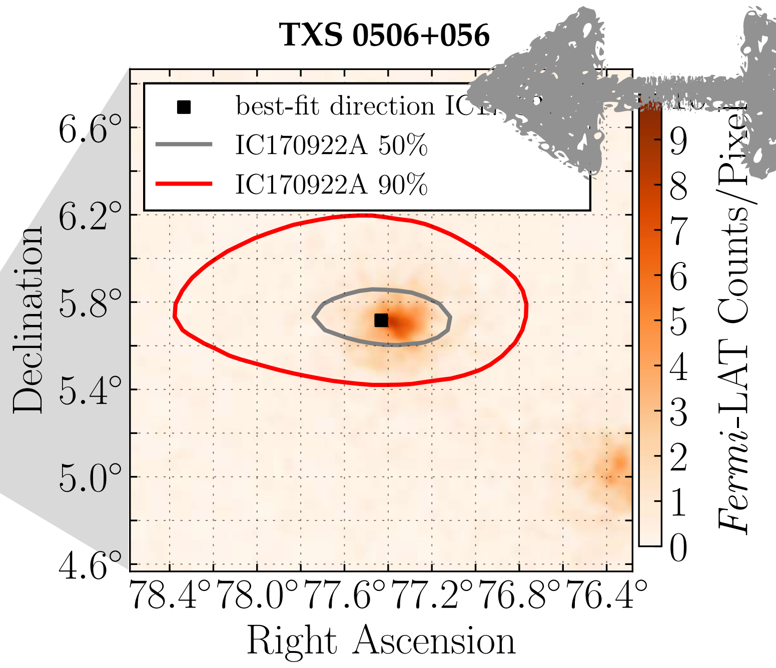


eROSITA Collaboration

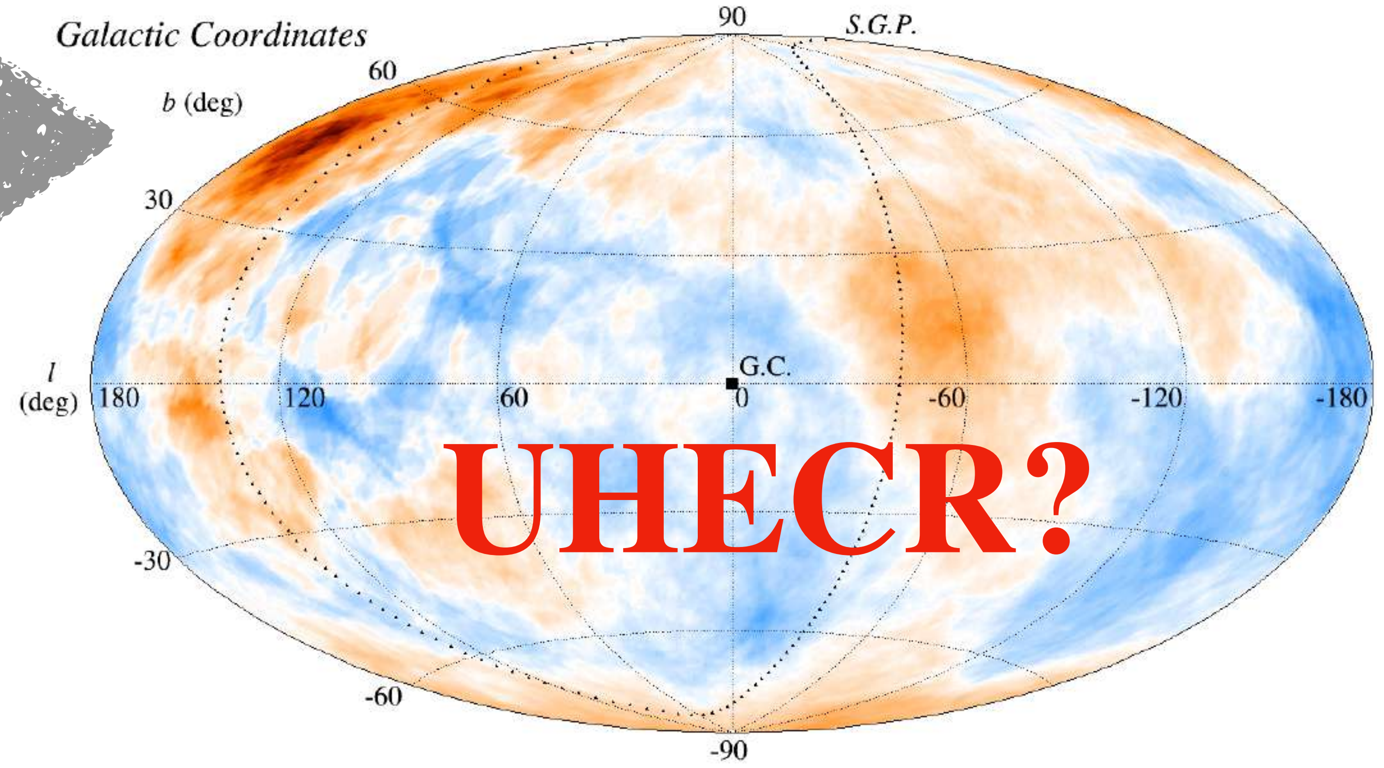


Fermi Collaboration





IceCube Collaboration



Pierre Auger and Telescope Array Collaborations

Energy spectrum

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

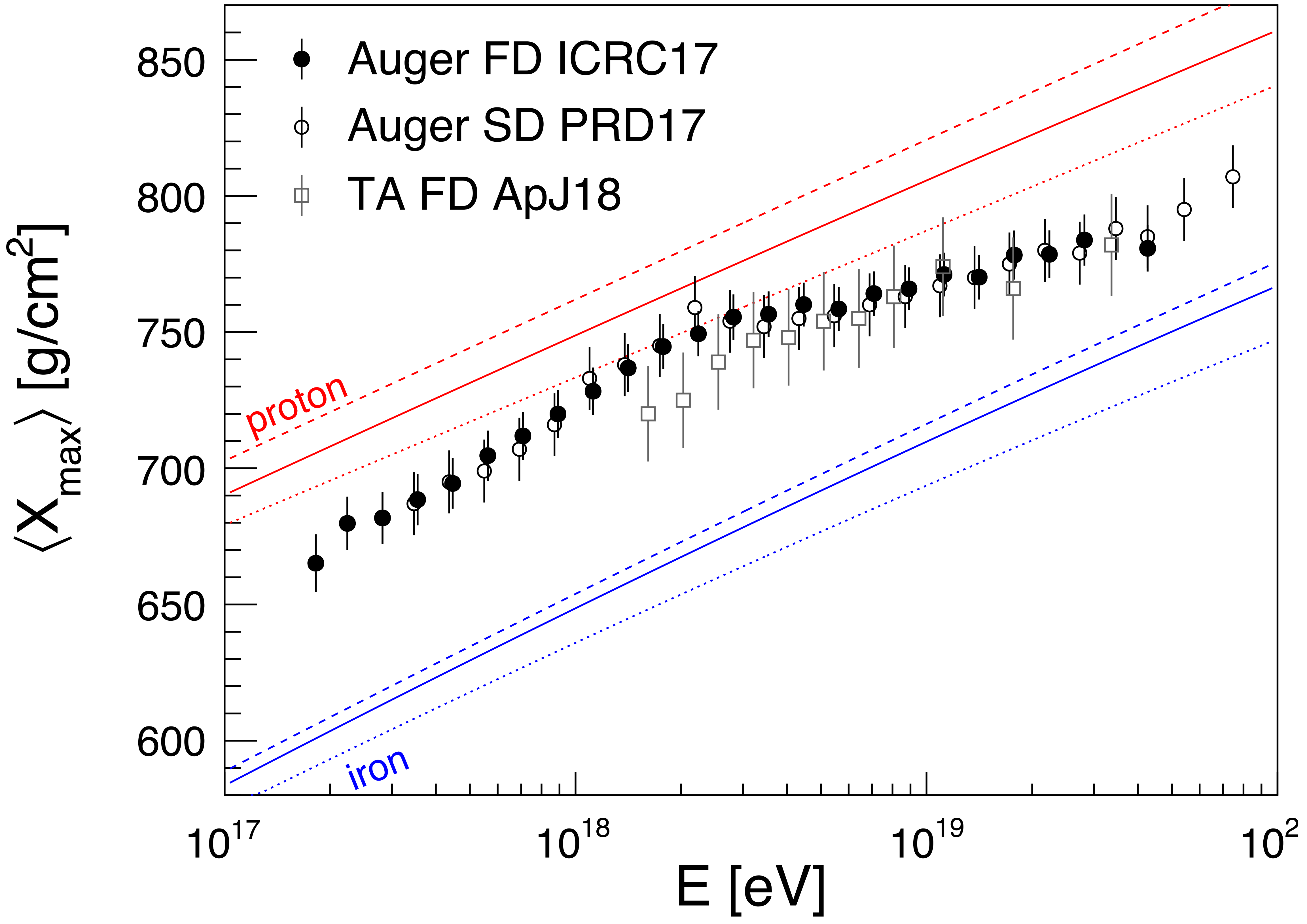
A. Coleman et al., Astropart. Phys. 149, 102819 (2023)

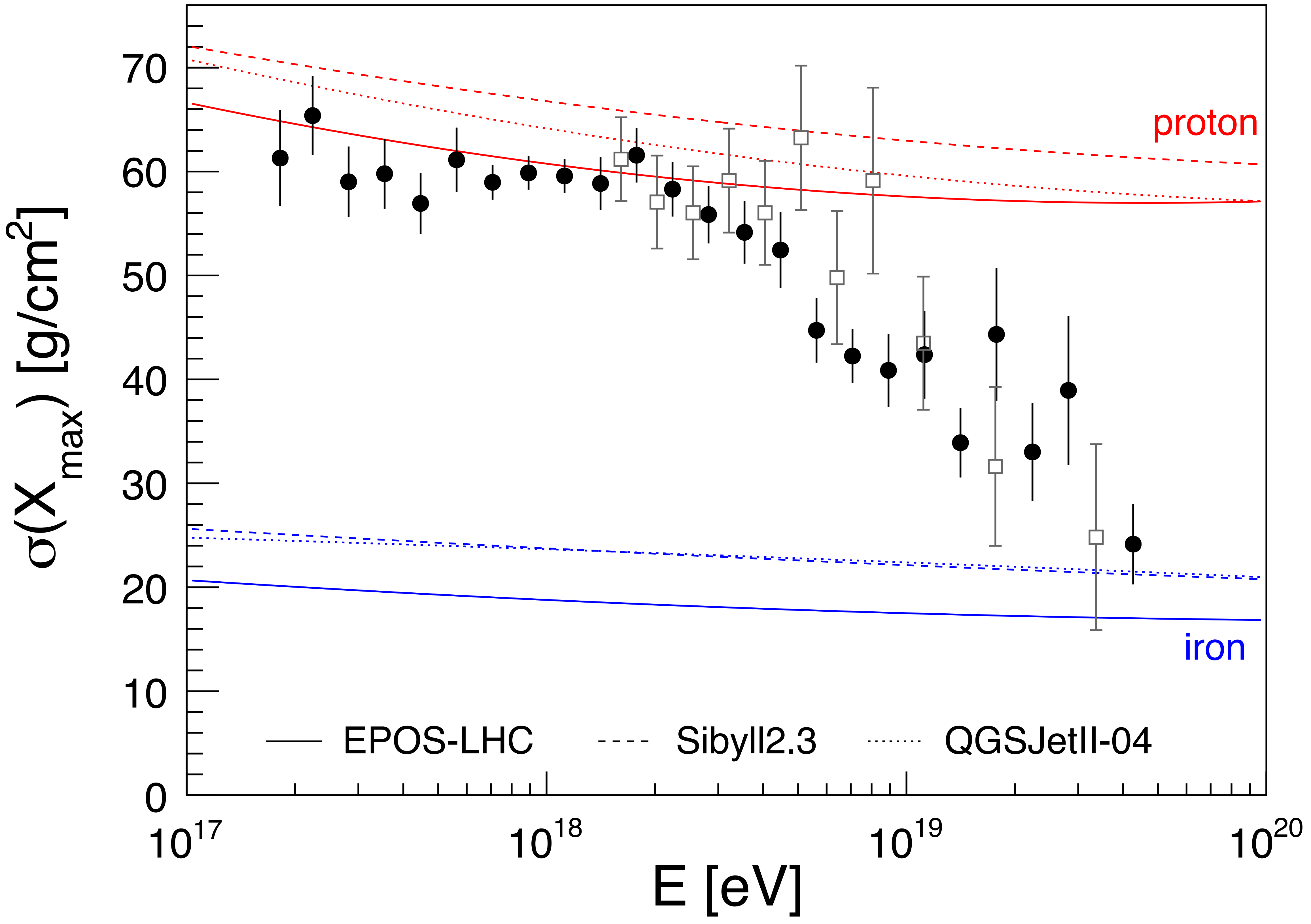
Mass composition

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

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

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





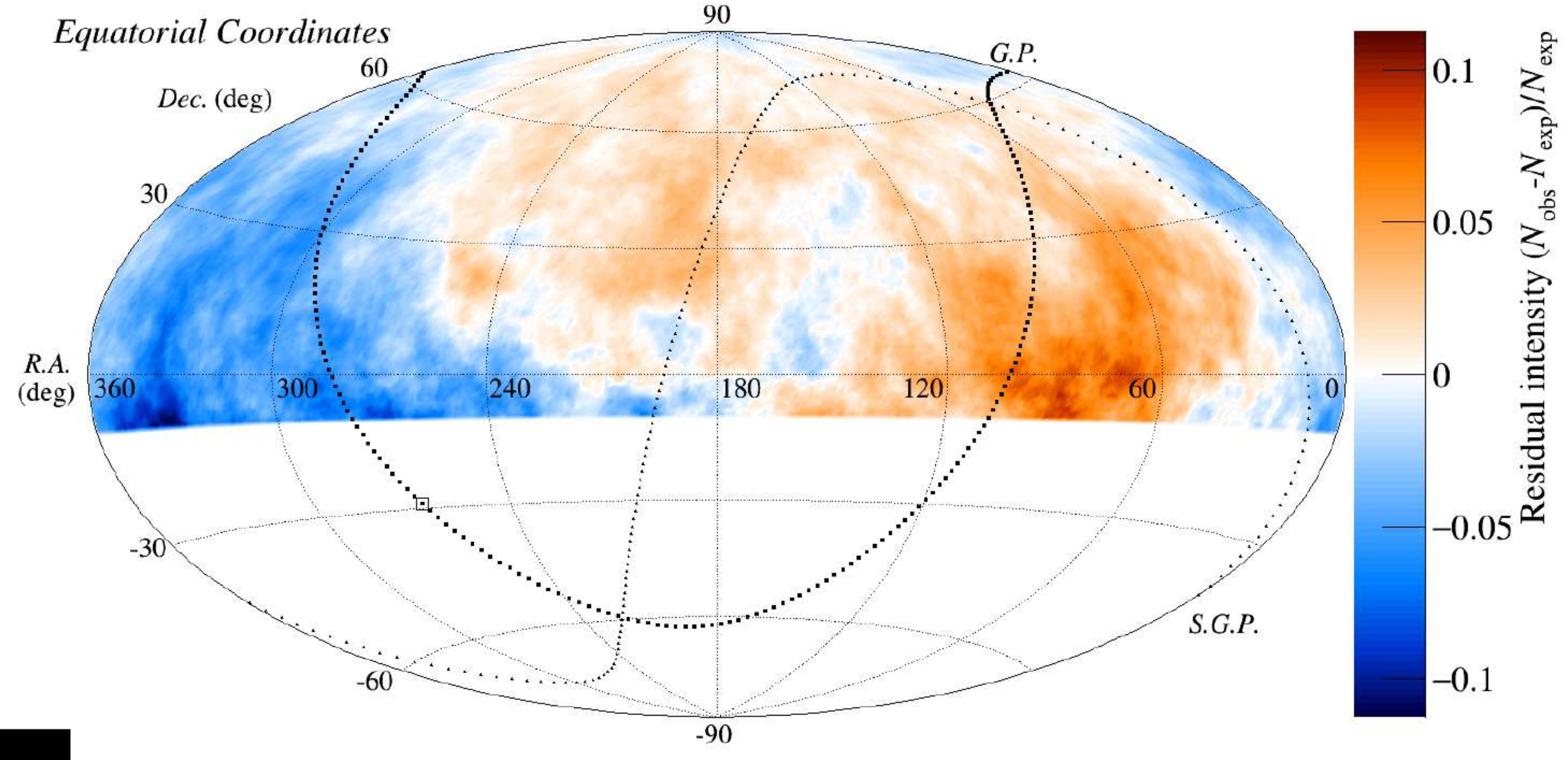
Gradually increase to the heavier composition above 3 EeV

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

Anisotropy of UHECRs (10 EeV)

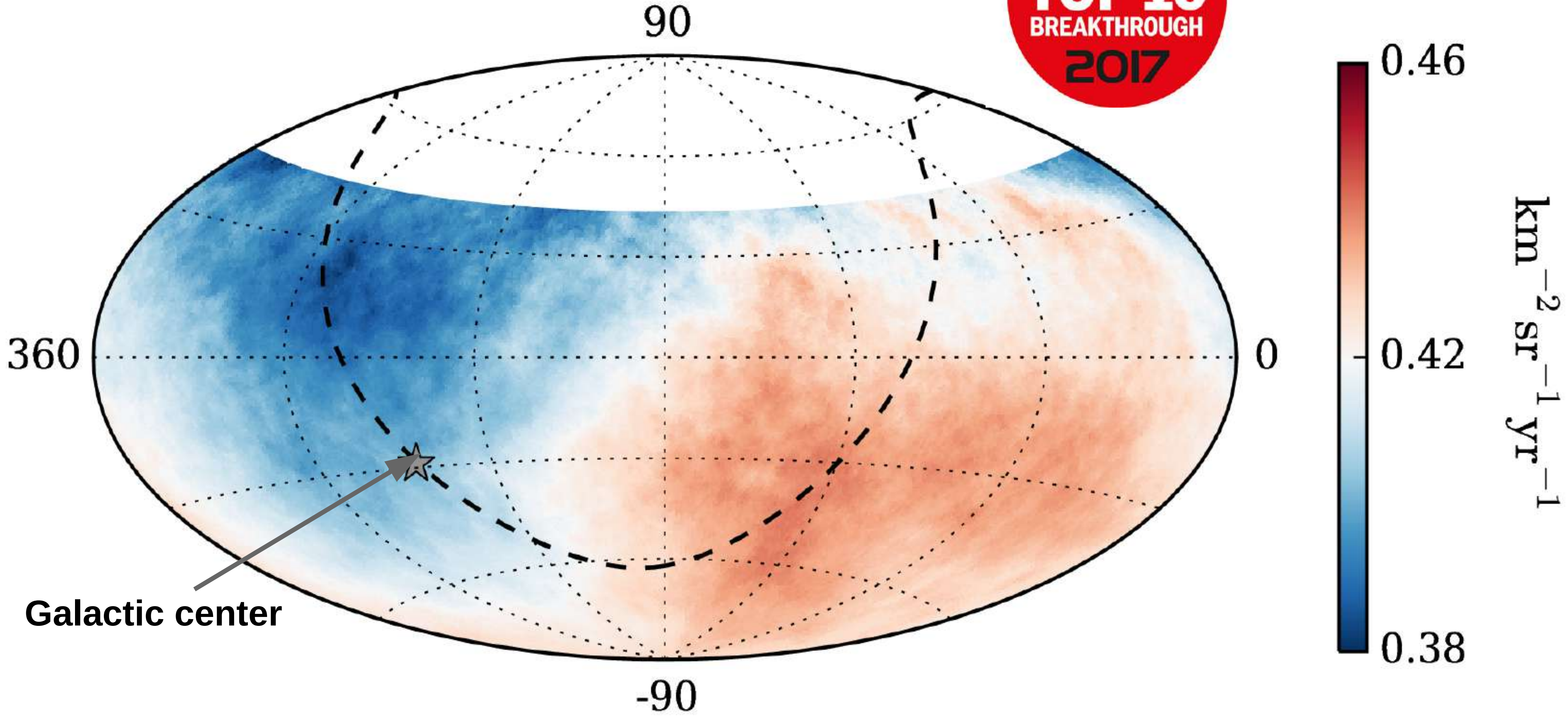
Northern TA ApJL, 898:L28 (2020)

E_{TA}> 8.8 EeV



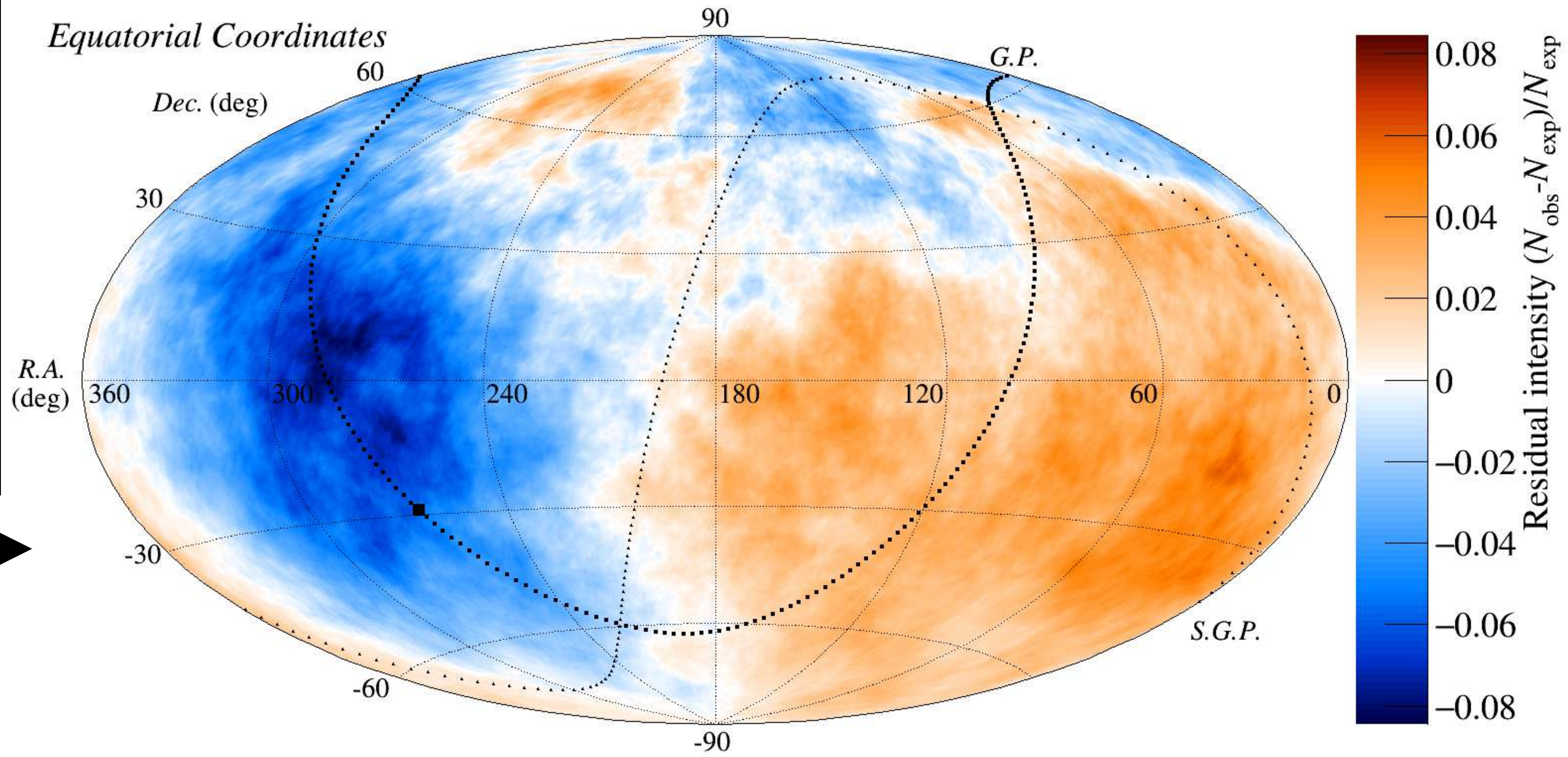
Southern Auger Science 357, 1266 (2017)

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**

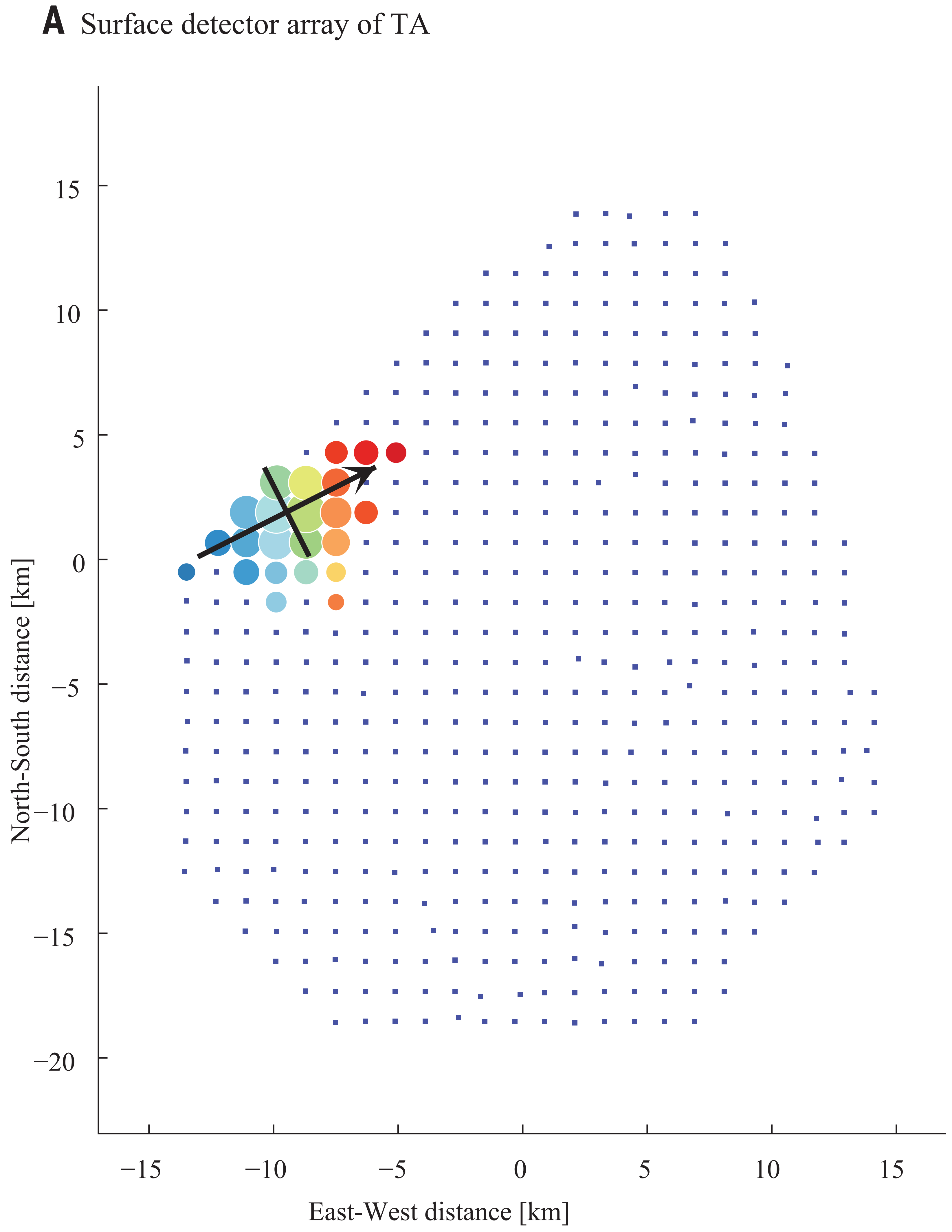
T. Fujii et al., PoS (ICRC2021) 291 (2020)

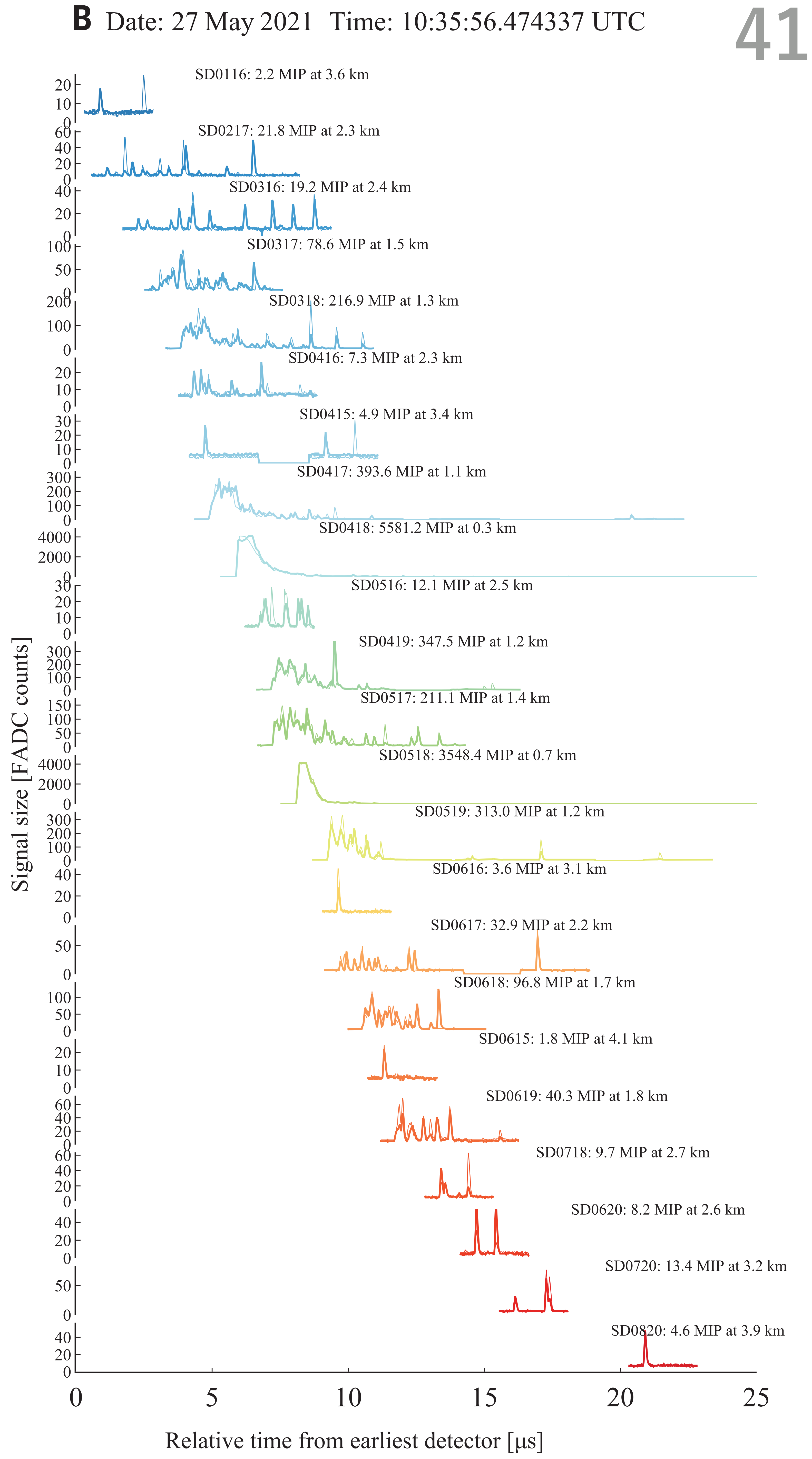
- Intriguing **intermediate-scale anisotropies** (~20 degrees) such as **hot/warm spots**
  - No excess from Virgo cluster, dubbed "***Virgo scandal***"
- **Isotropic distributions of UHECRs than our (optimistic) expectation**

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





Telescope Array Collaboration, Science 382, 903 (2023)

Multi-messenger synergies

L. Lu, PoS(ICRC2023)1188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