Searching for the Universe's most energetic particles

Toshihiro Fujii toshi@omu.ac.jp
Osaka Metropolitan University (OMU)
Nambu Yoichiro Institute of Theoretical and Experimental Physics (NITEP)

20th Anniversary of the KICP Celebration
June 6-8, 2024

OMU Osaka Metropolitan University

NITEP Nambu Yoichiro Institute of Theoretical and Experimental Physics

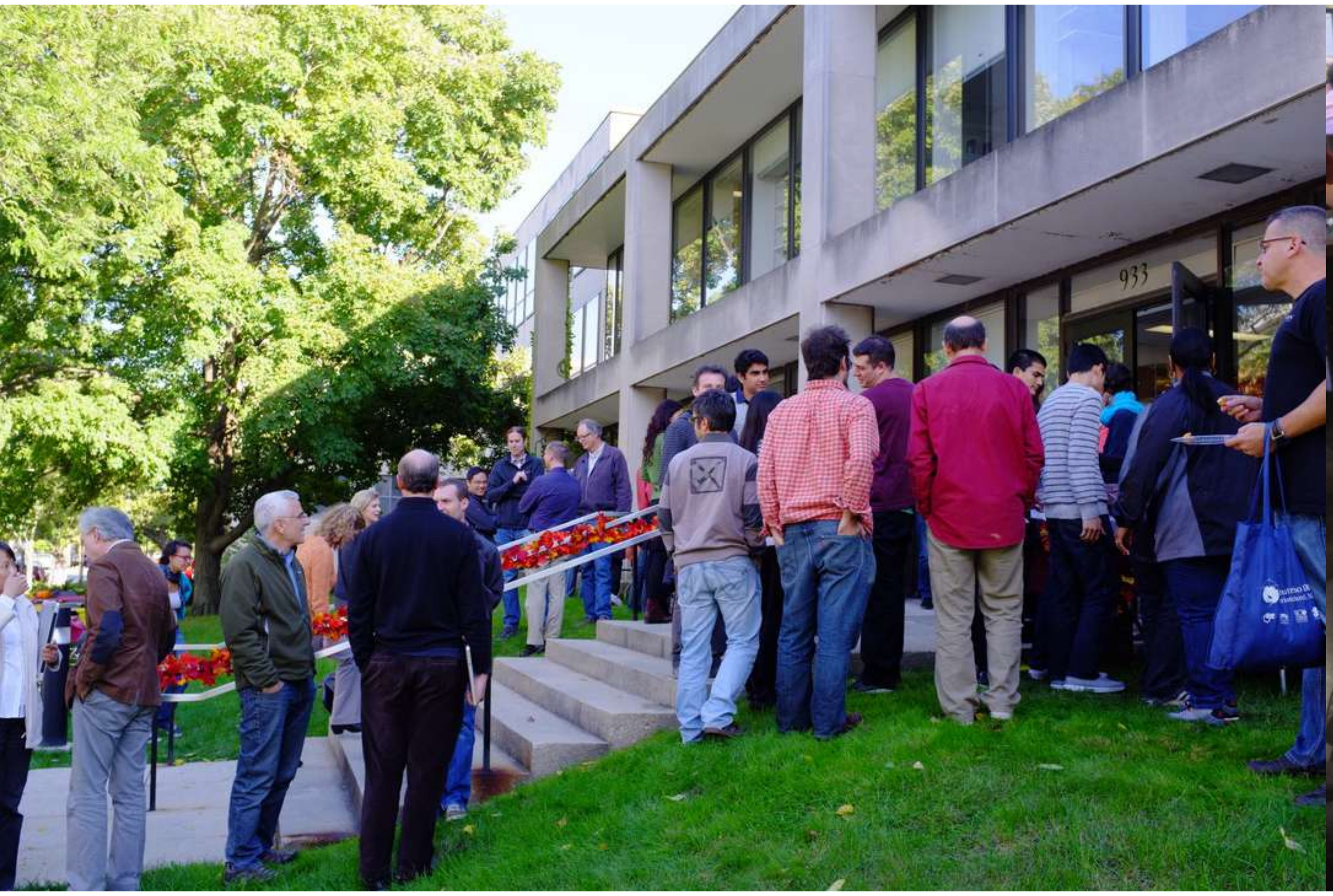
Congratulations on KICP 20th years anniversary!!

- I was in KICP from 2013 to 2016, working with Paolo and Angela about cosmic rays
  - Millions of memories with fantastic colleagues!!
- Congratulations on 20-years "birthday" of KICP
  - おめでとうございます (Omedetou gozaimasu)

Taken from video message for wedding of my friend (scientist)

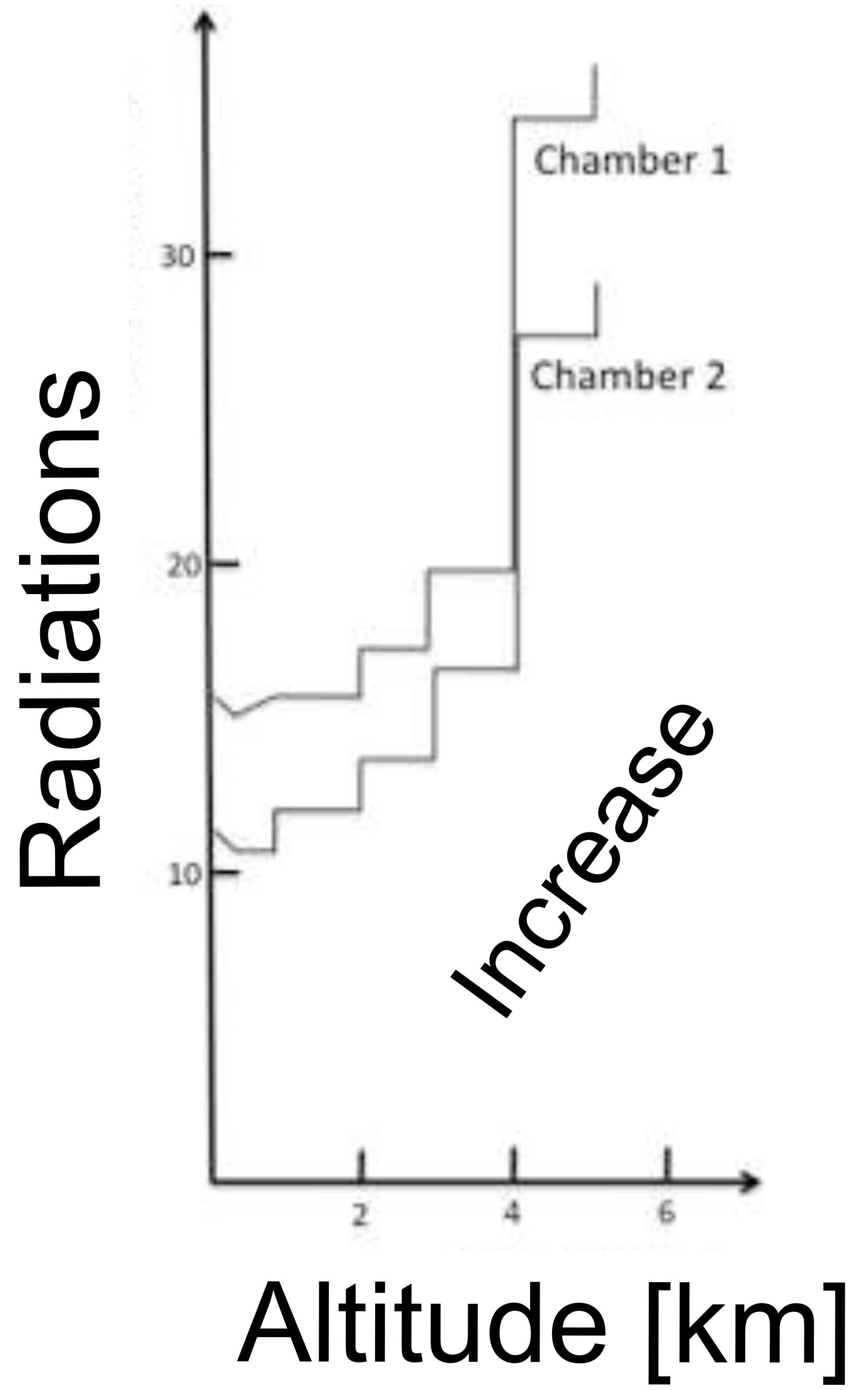
More memories




Birthday of cosmic rays (Aug. 7th 1912)

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



https://www.sciencedirect.com/journal/astroparticle-physics/vol/53/suppl/C

Grandson of V. F. Hess

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

5350 m

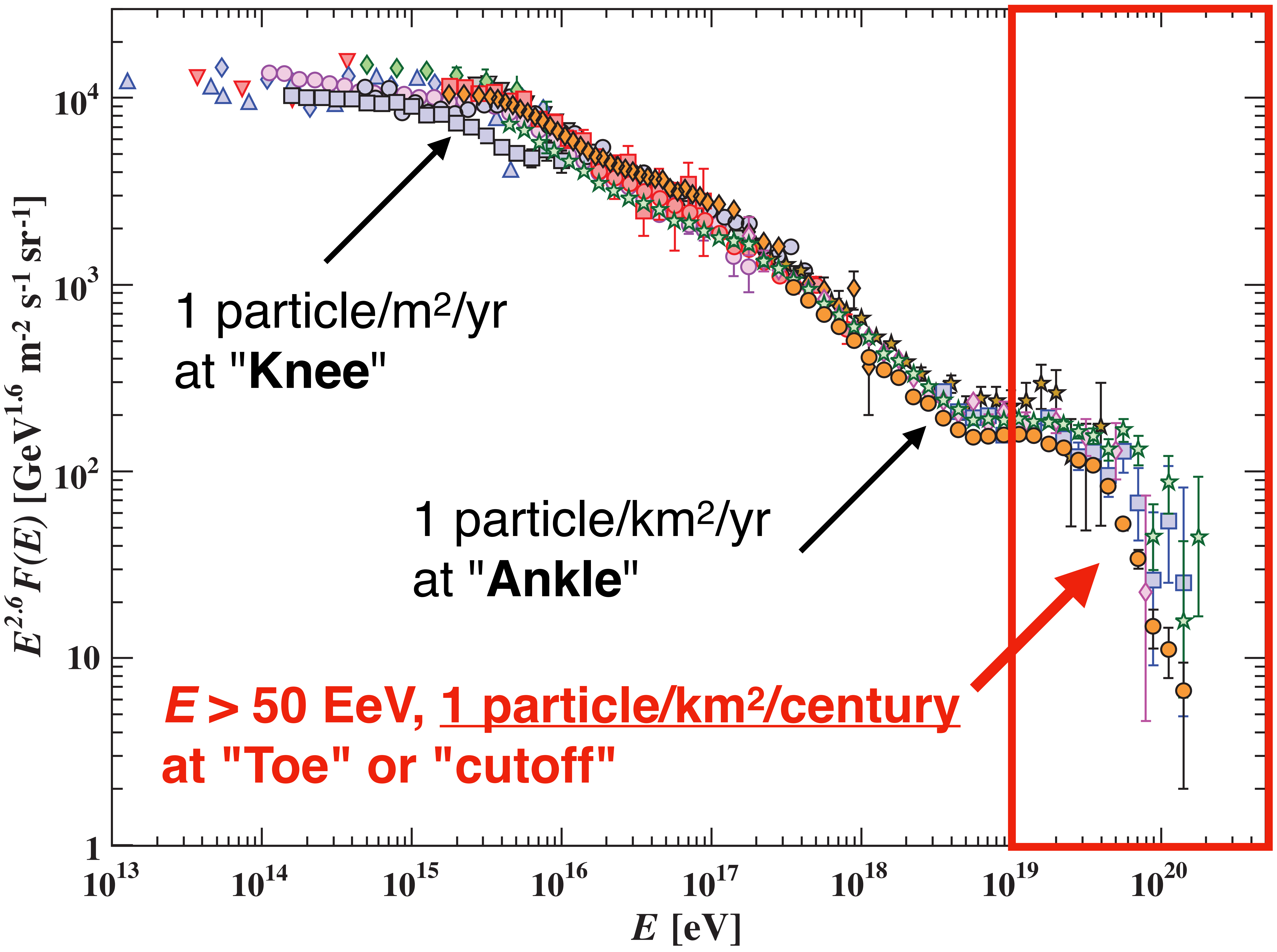
W. Kolhörster, Physikalische Zeitschrift 14 (1913) 1153–1156.

6300 m, 9300 m (1914)


Aug. 7th, 2012
James W. Cronin
Dietrich Müller
Toshihiro Fujii

Energy spectrum of cosmic rays

$E^{2.6}$ J(E)



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

1 Exa-electron-volts (EeV) = 10^{18} eV Particle Data Group, Phys.Rev.D, 98, 030001 (2018)

Emerging "Charged particle astronomy" with Ultra-High-Energy Cosmic Rays (UHECRs)

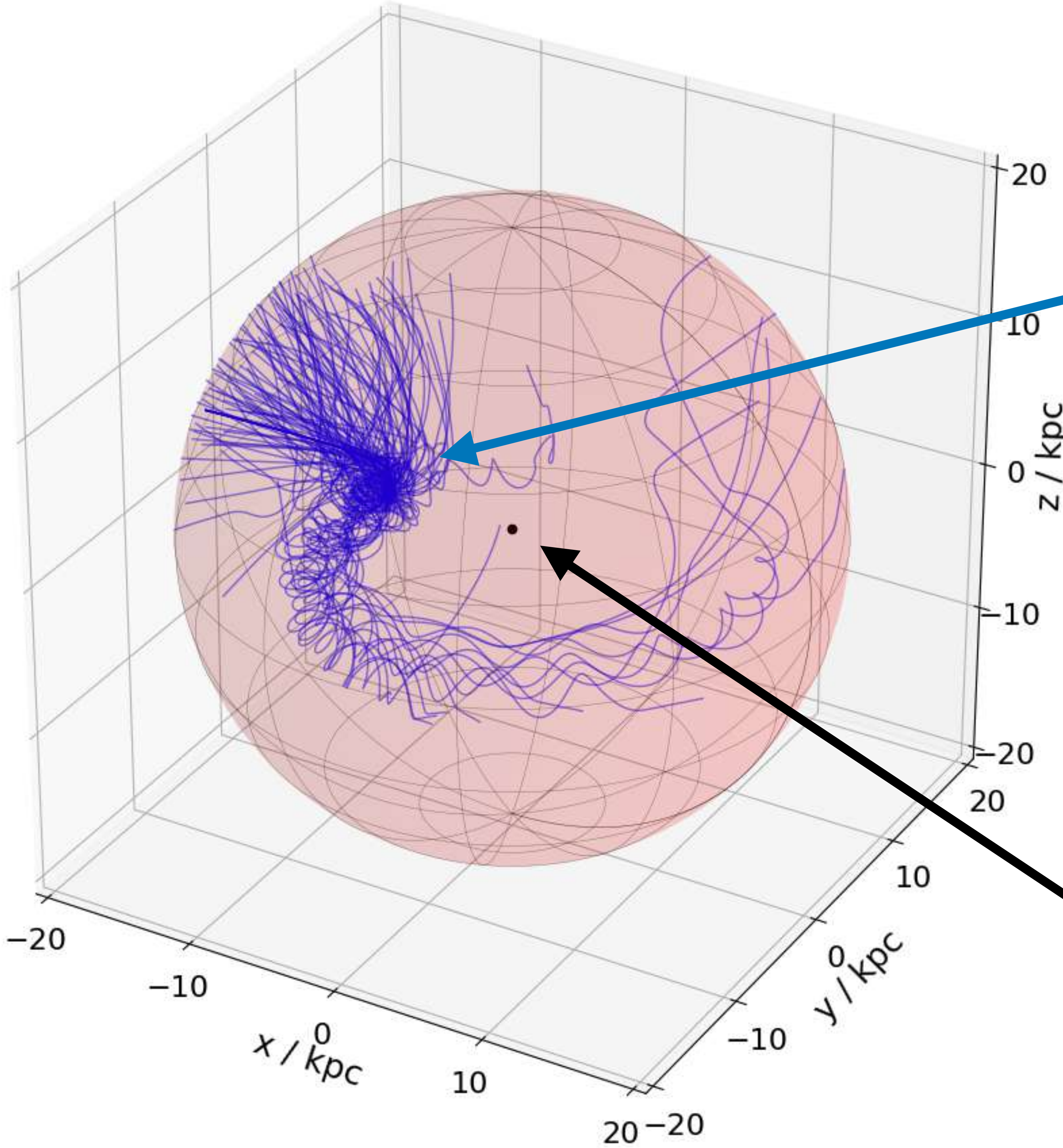
Less deflection by Galactic magnetic fields

Deflection angle in Milky Way

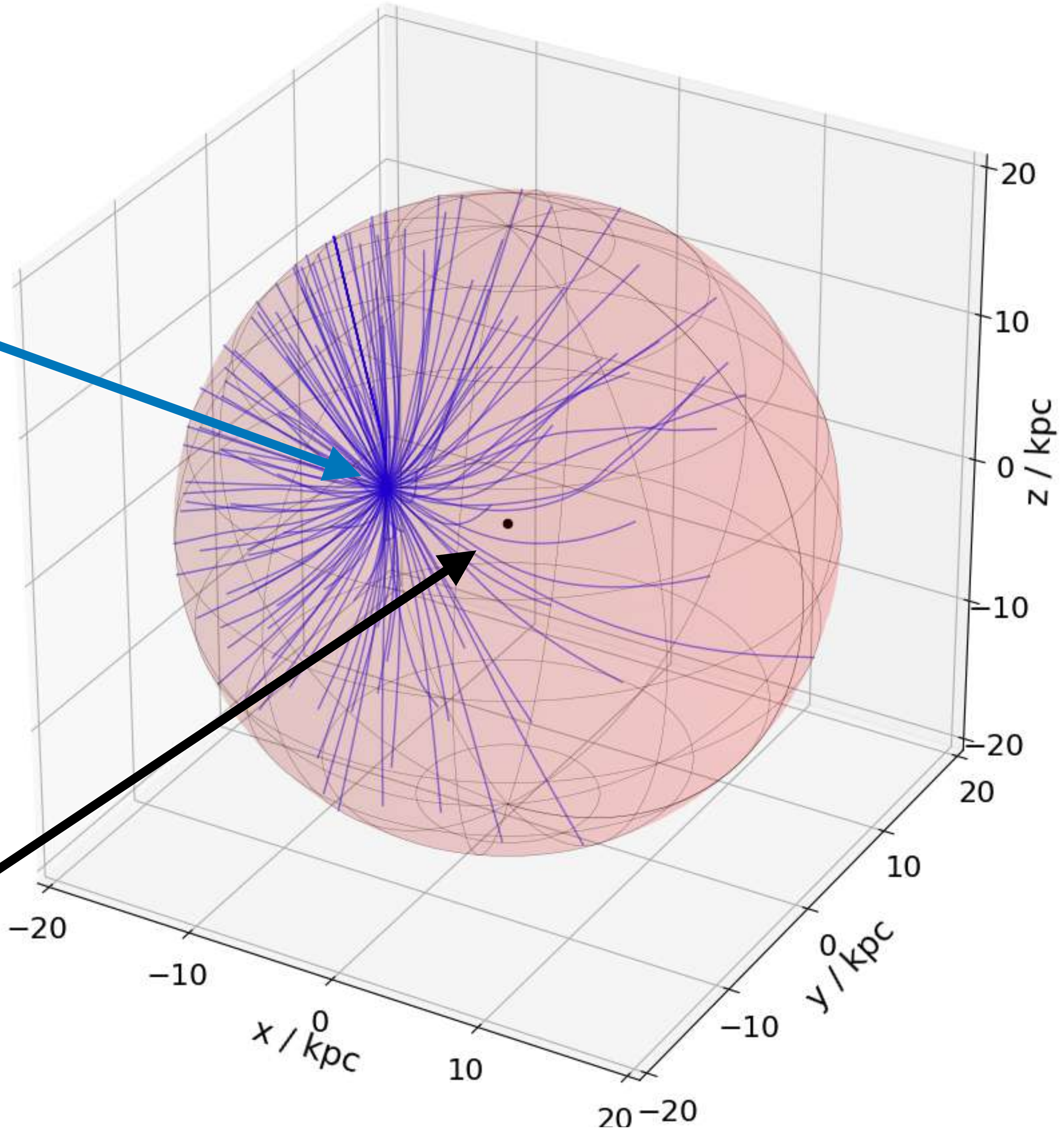
$$\theta \sim 10^\circ Z \left(\frac{E}{10\,\mathrm{EeV}} \right)^{-1}$$

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

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



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

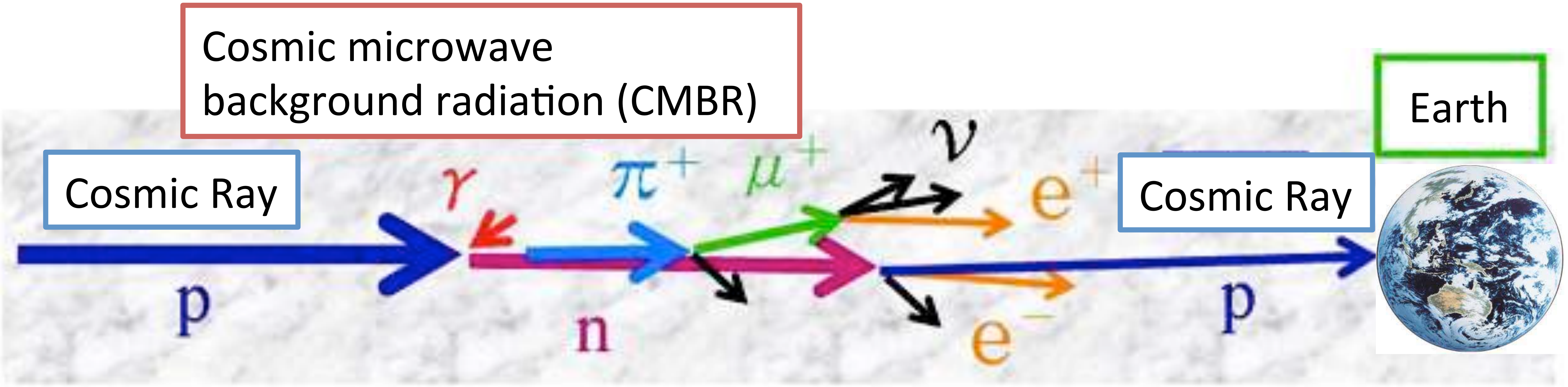


Earth

Galactic Center

R. Higuchi (RIKEN) by CRPropa

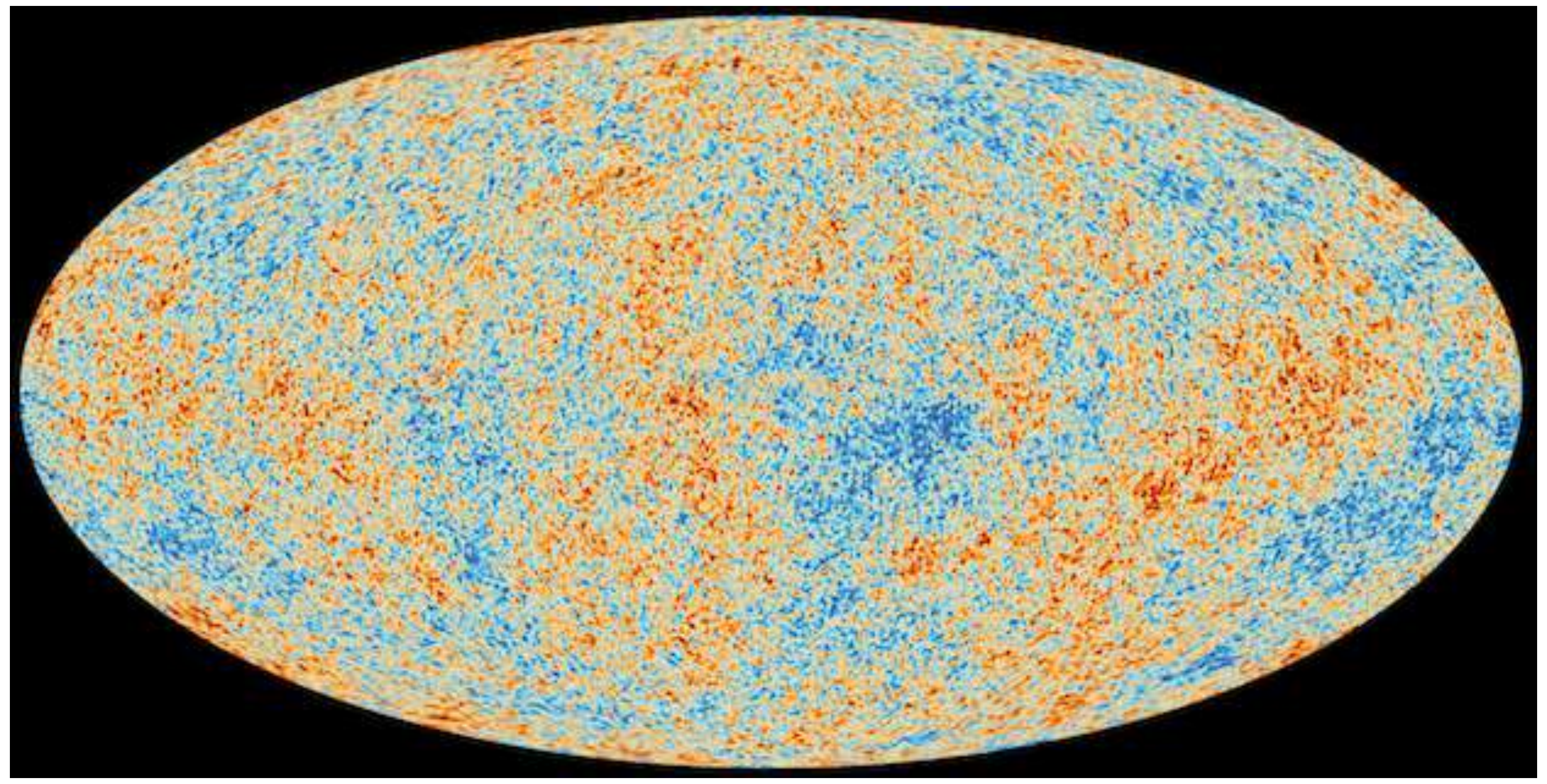
Greisen–Zatsepin–Kuzmin (GZK) Cutoff



- Interaction between >50 EeV proton and 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 interaction between the <u>most energetic particles</u> and the <u>oldest photons</u>**

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

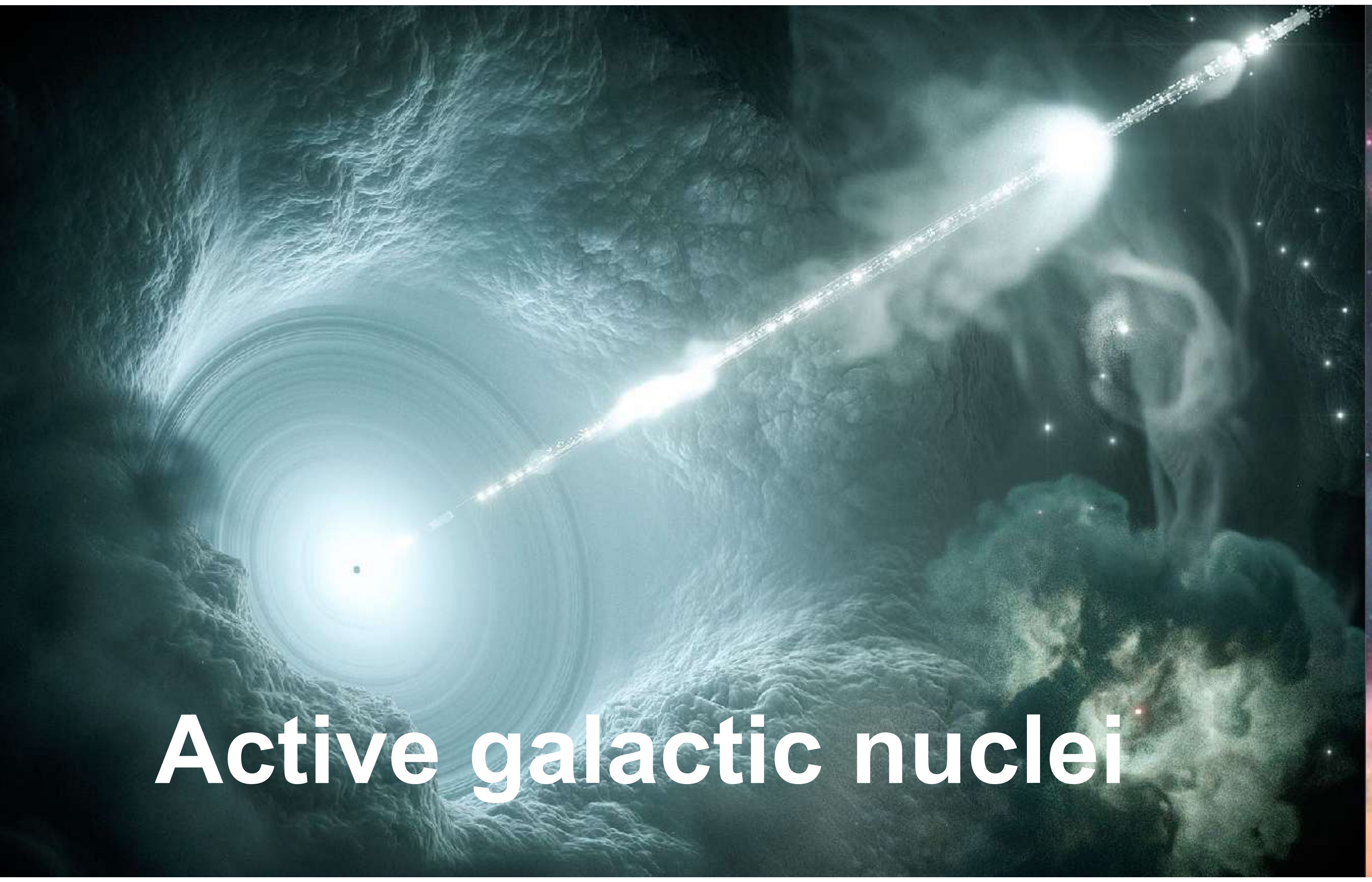
$$^{A}_{Z}N + \gamma_{\mathrm{CMB}} \rightarrow {}^{A-1}_{Z-1}N' + p$$



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 and UHECR "astronomy"



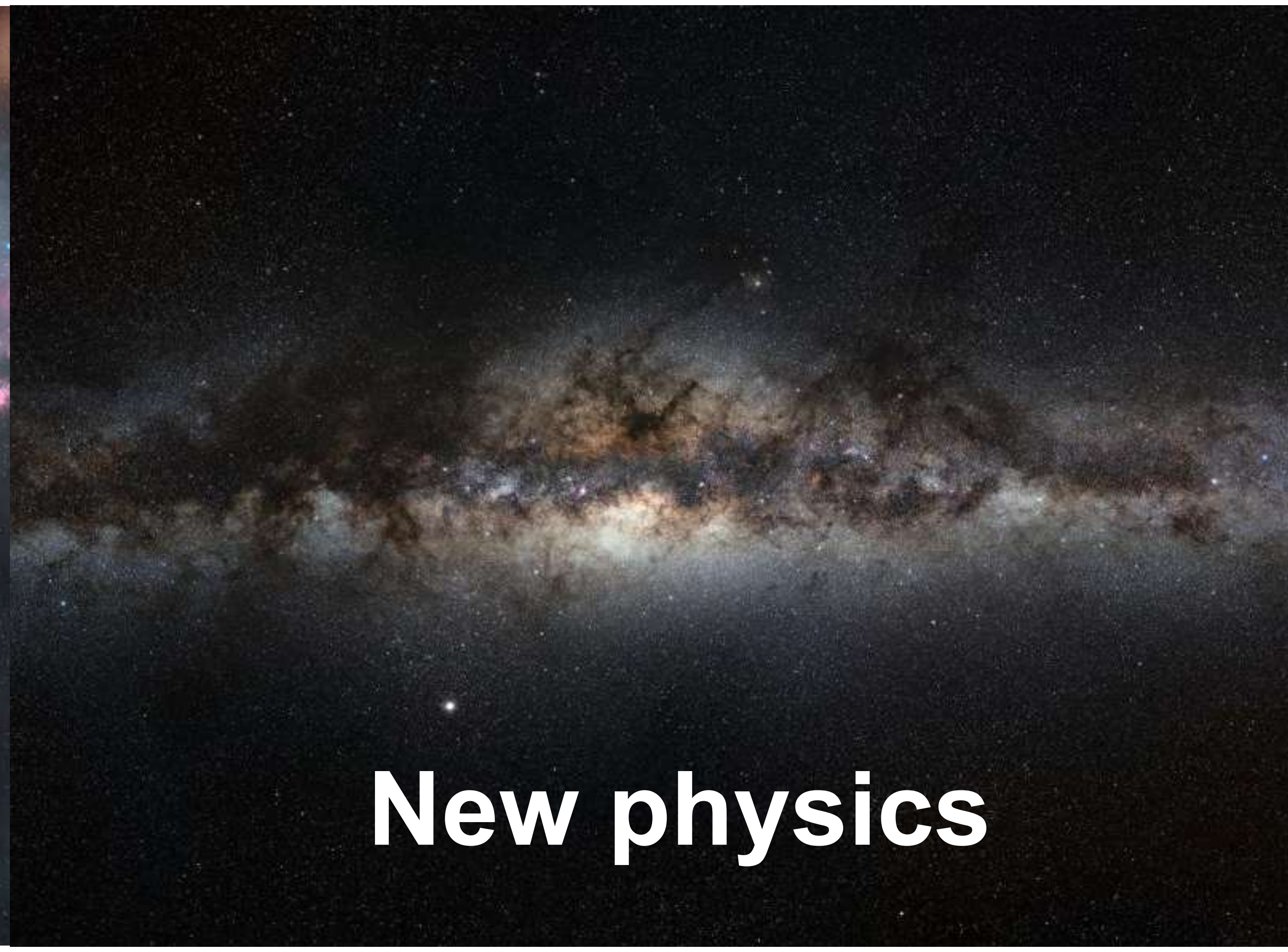
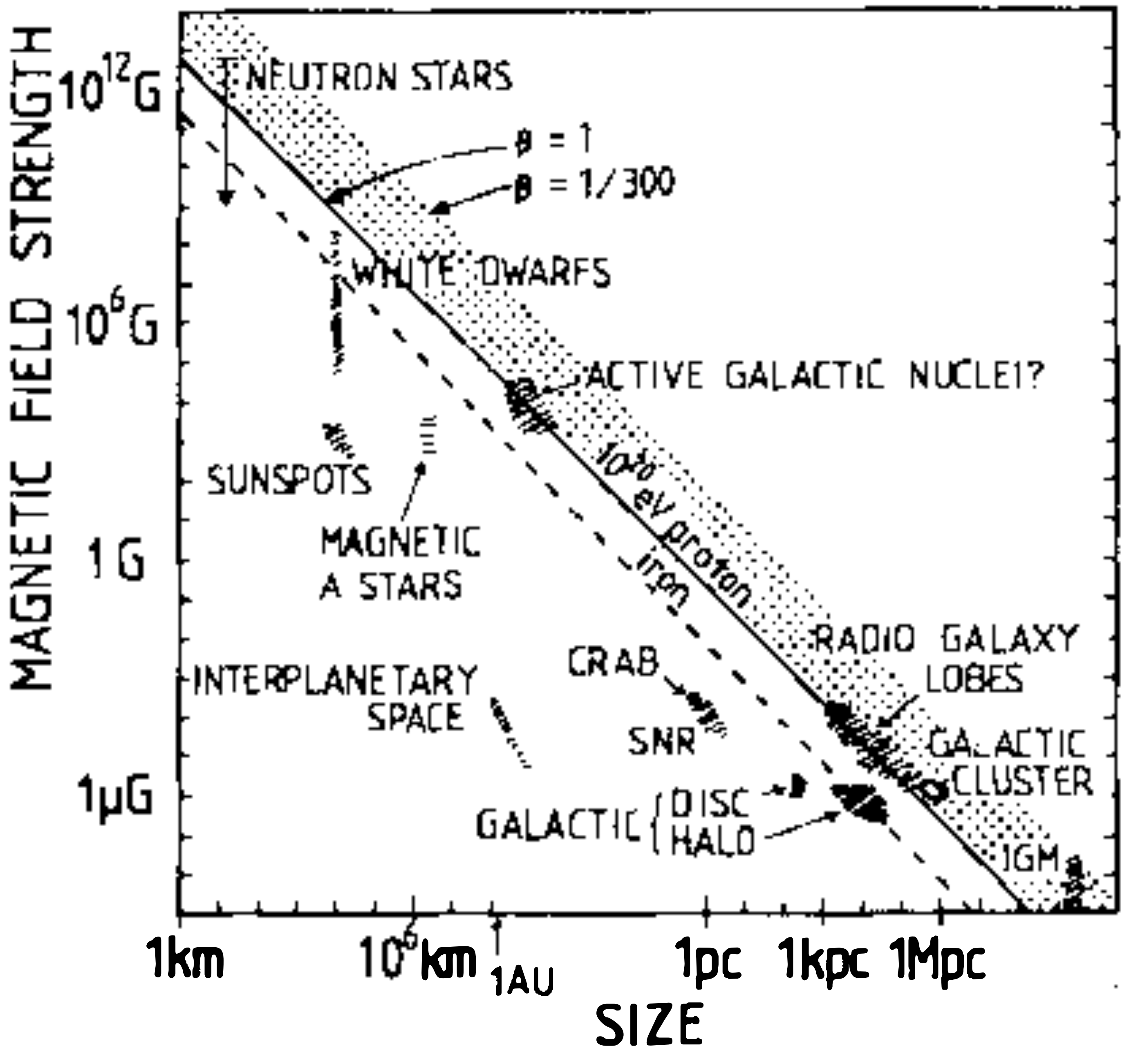


Image credits: DESY, Science Comm. Space News, NASA



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

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

"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**

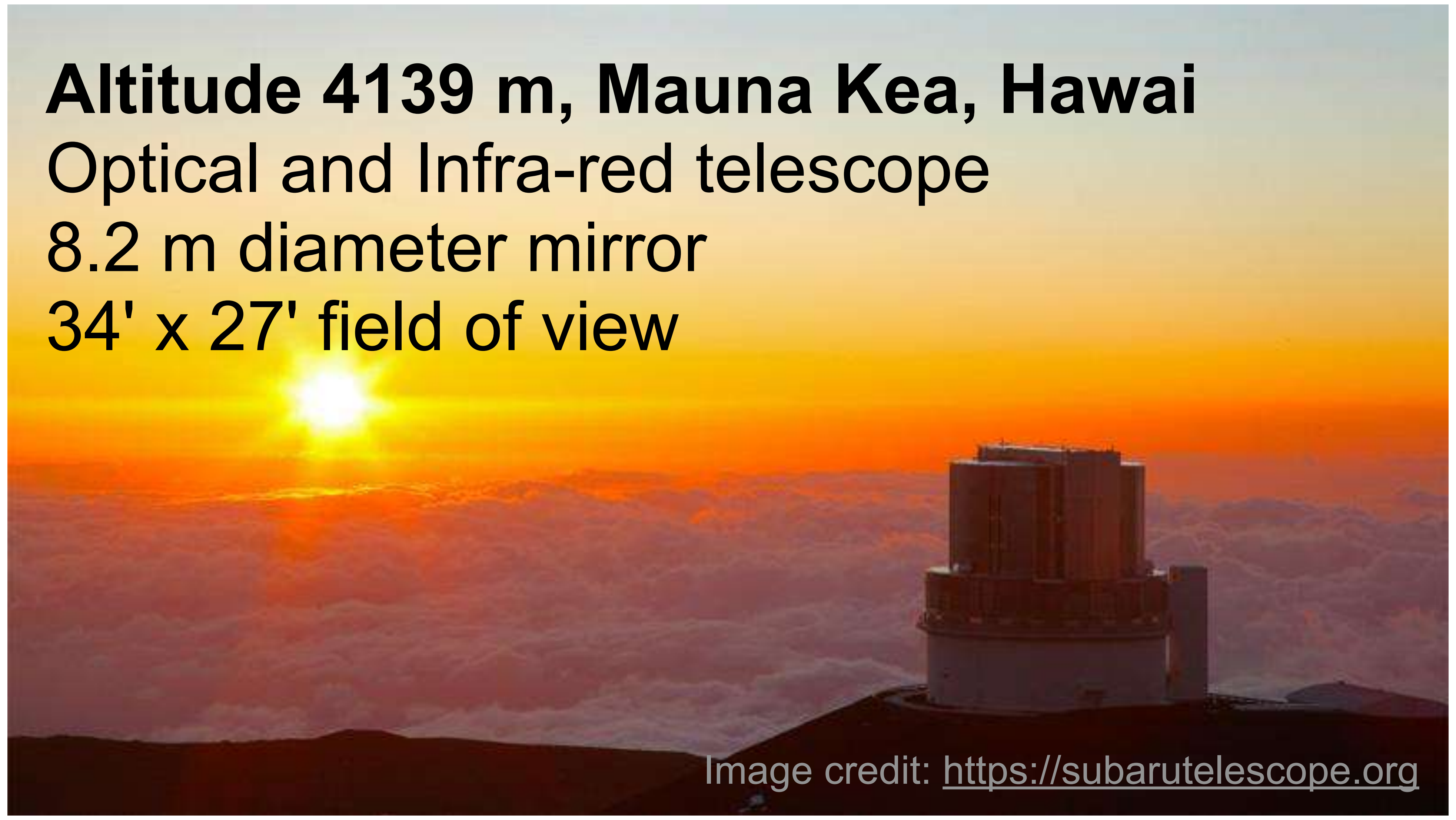
How to detect extremely infrequent UHECRs?

→ **Extensive Air Showers**

Unexpectedly "Seeing" the extensive air showers by Subaru HSC

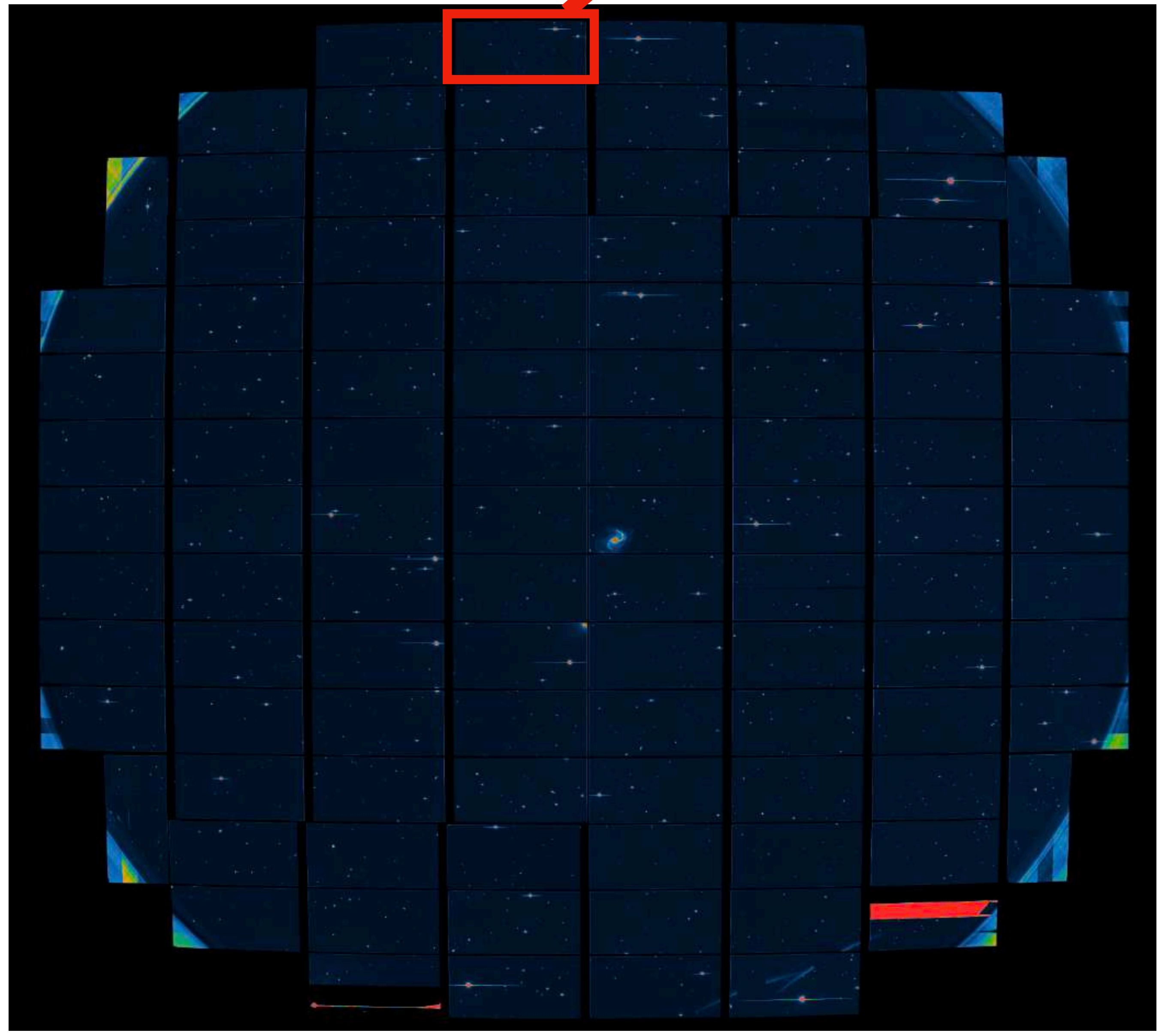
S. Kawanomoto, T.Fujii et al., Scientific Reports 13:16091 (2023)

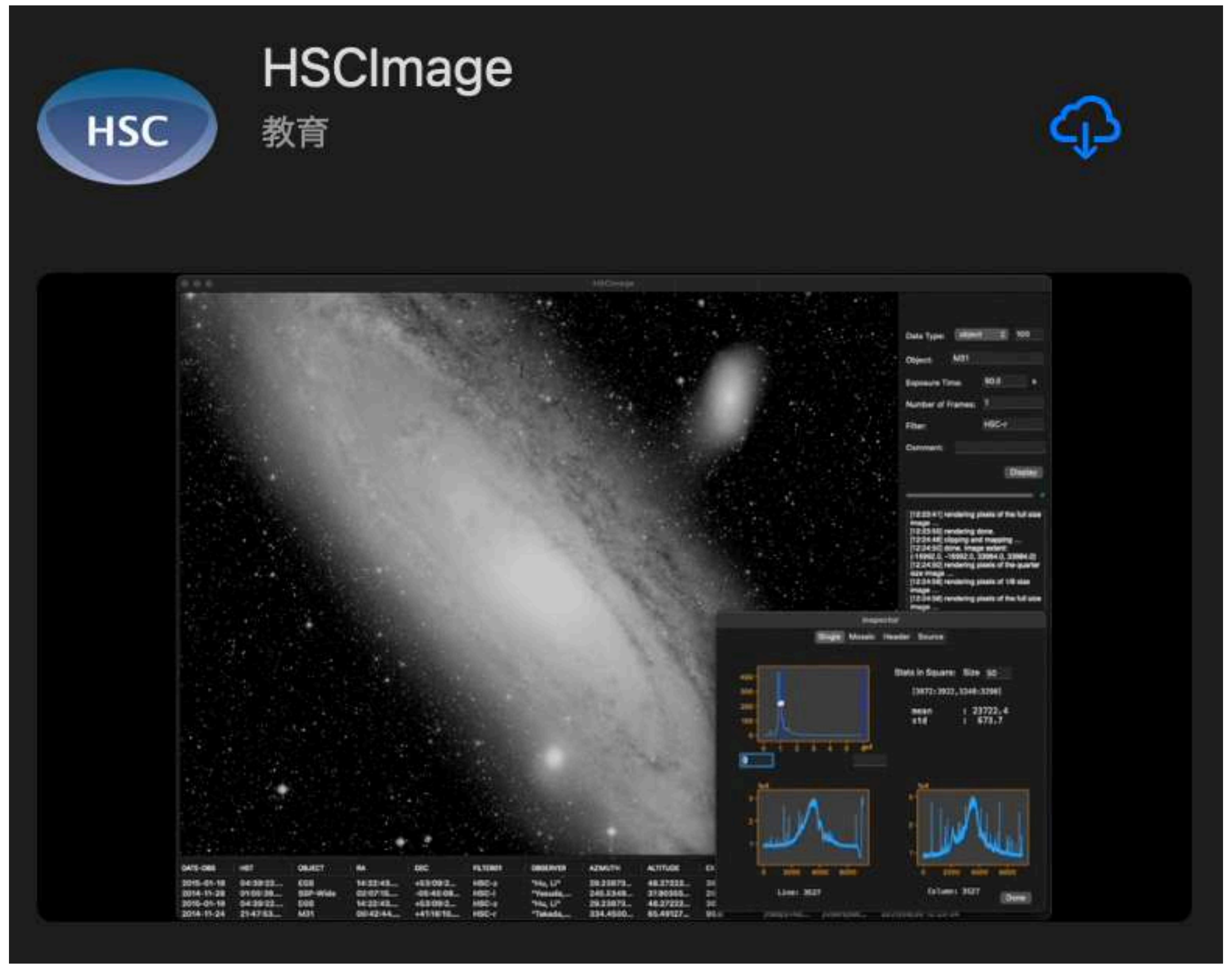
Direct detection of Subaru HSC CCDs



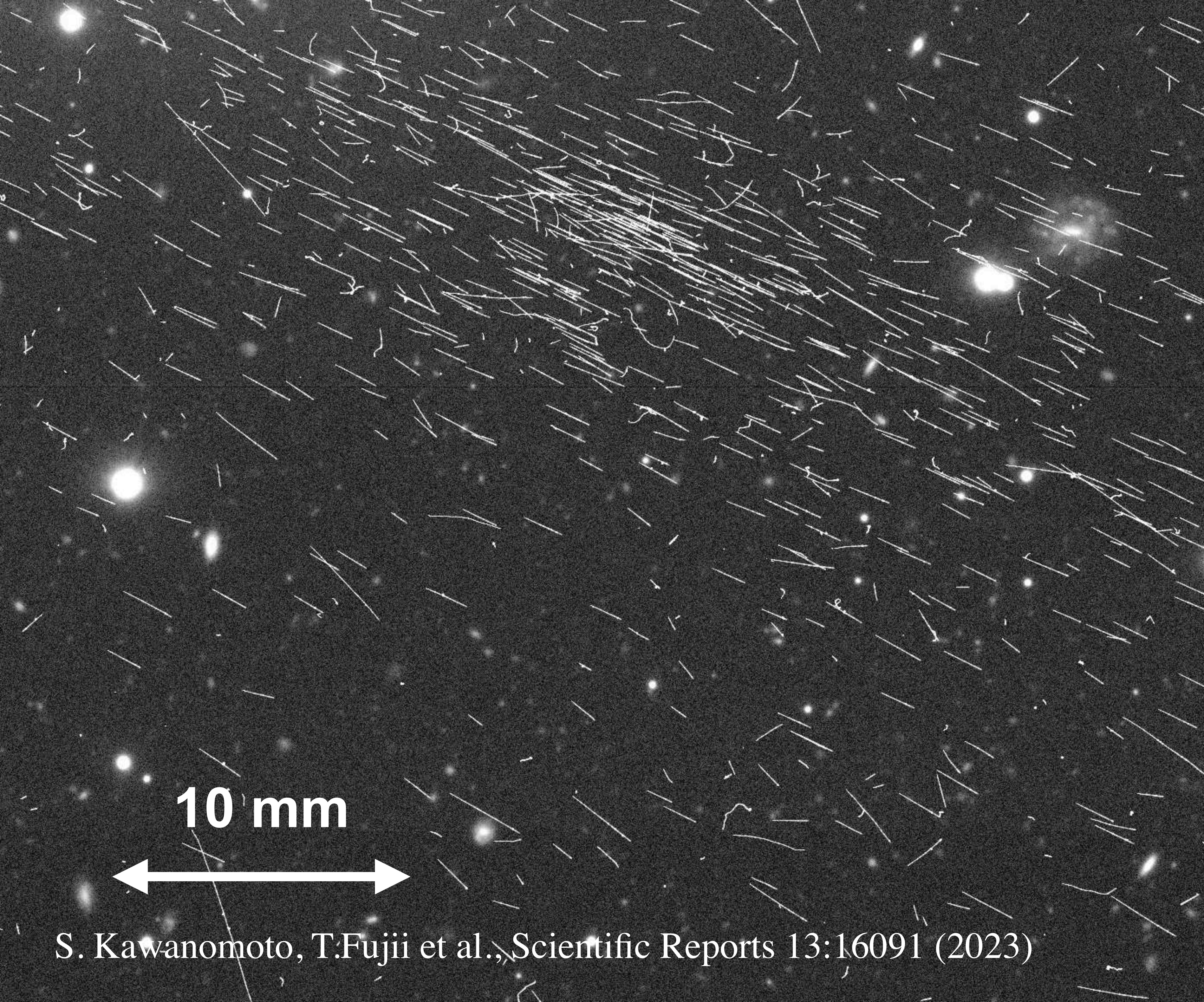
CCD size
30 mm x 60 mm
0.2 mm thickness
150 sec. exposure

116 CCDs

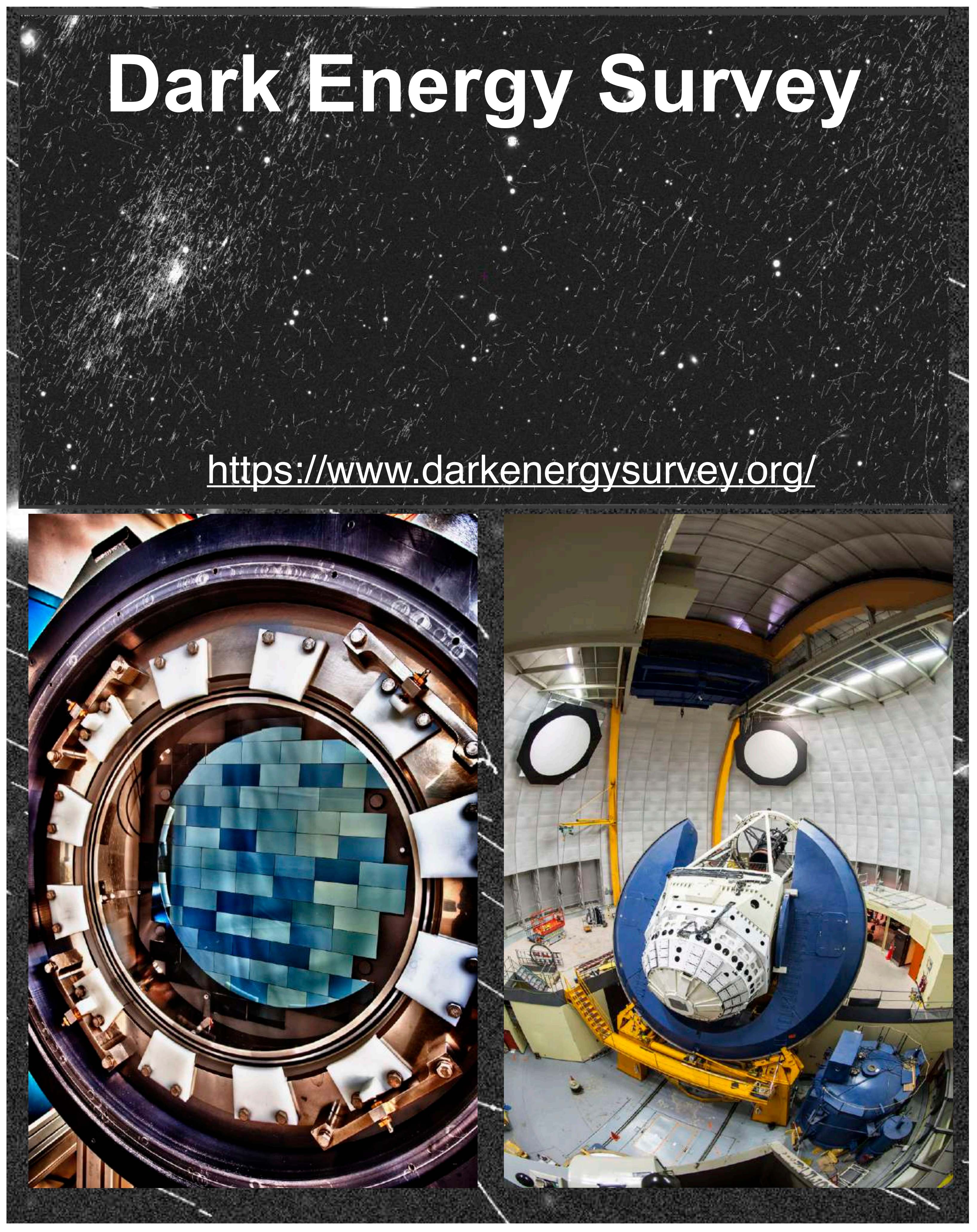




App Store (Mac)

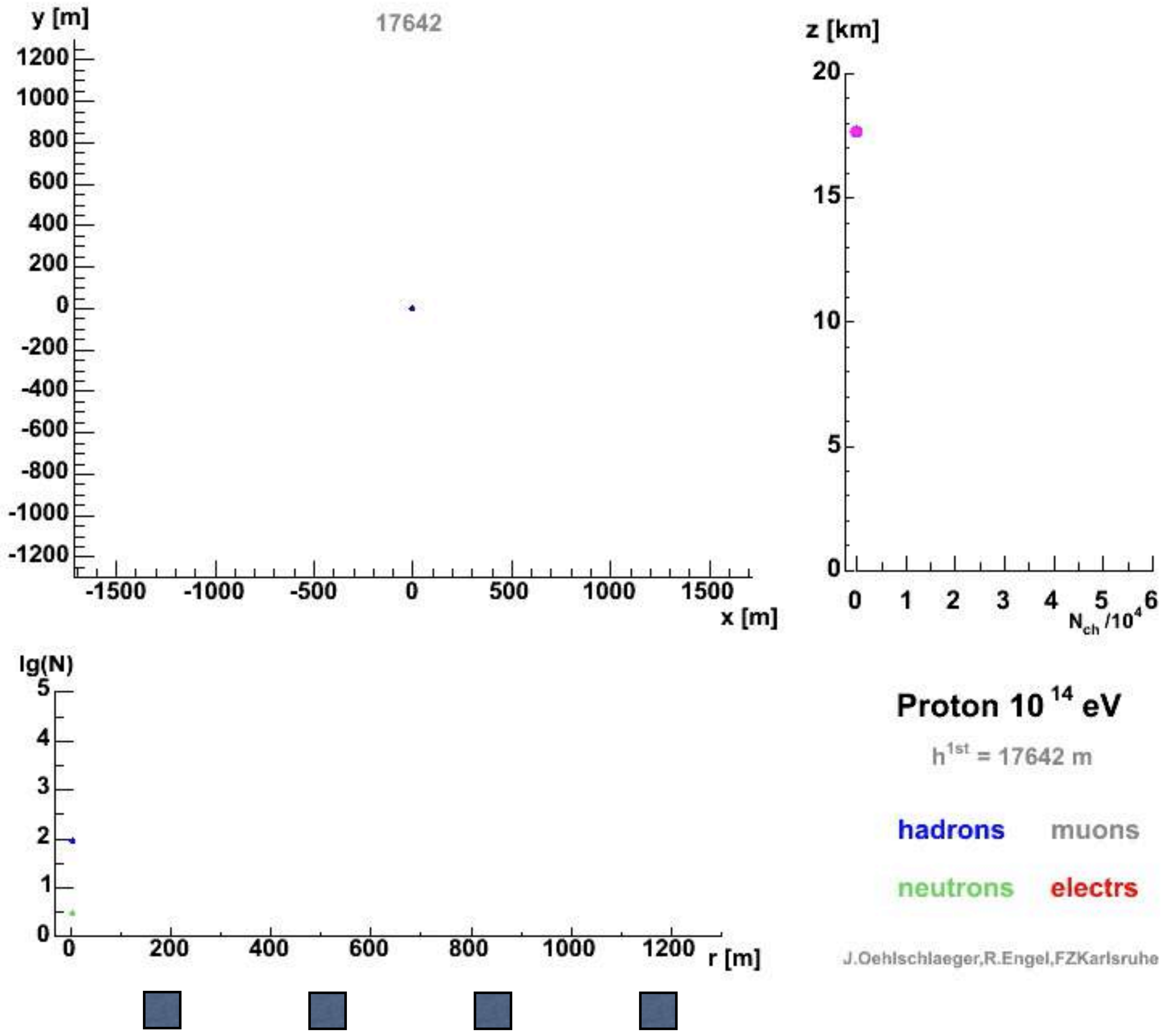


S. Kawanomoto, T.Fujii et al., Scientific Reports 13:16091 (2023)



How to detect extremely infrequent UHECRs?

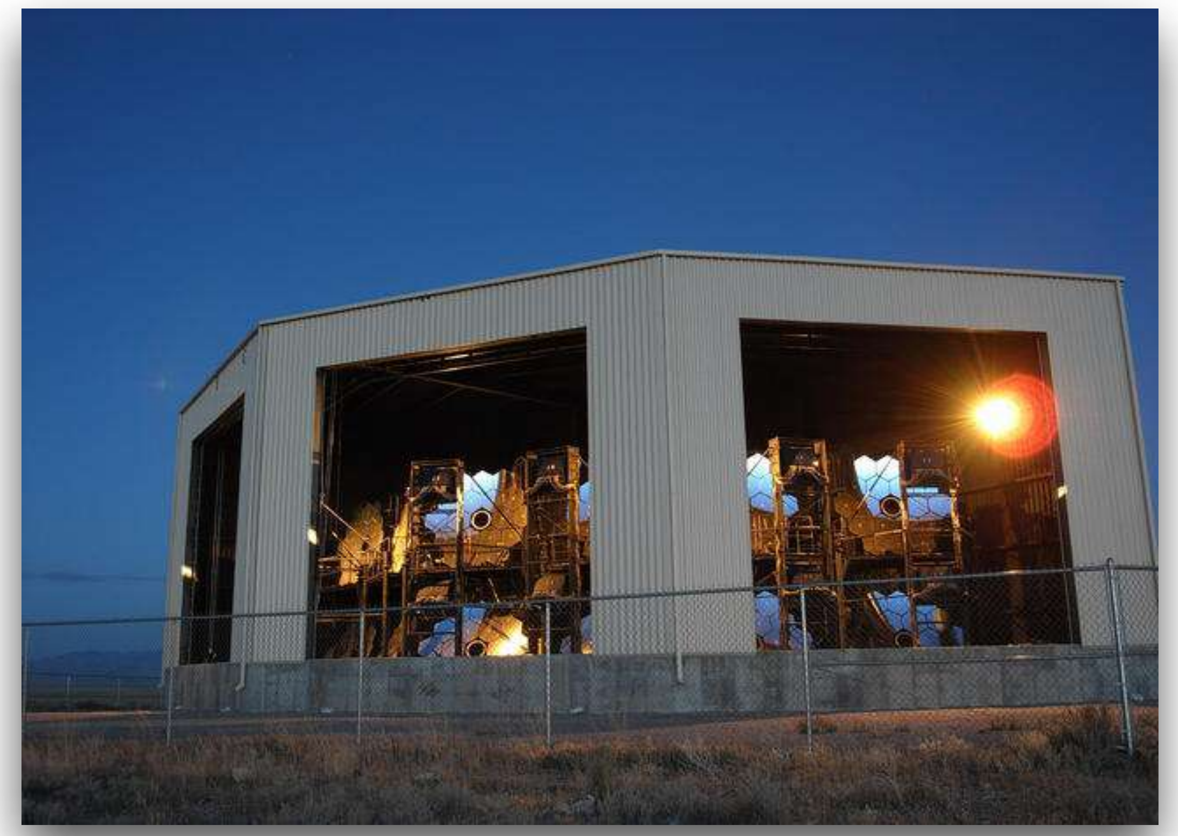
Observing extensive air showers and mass composition

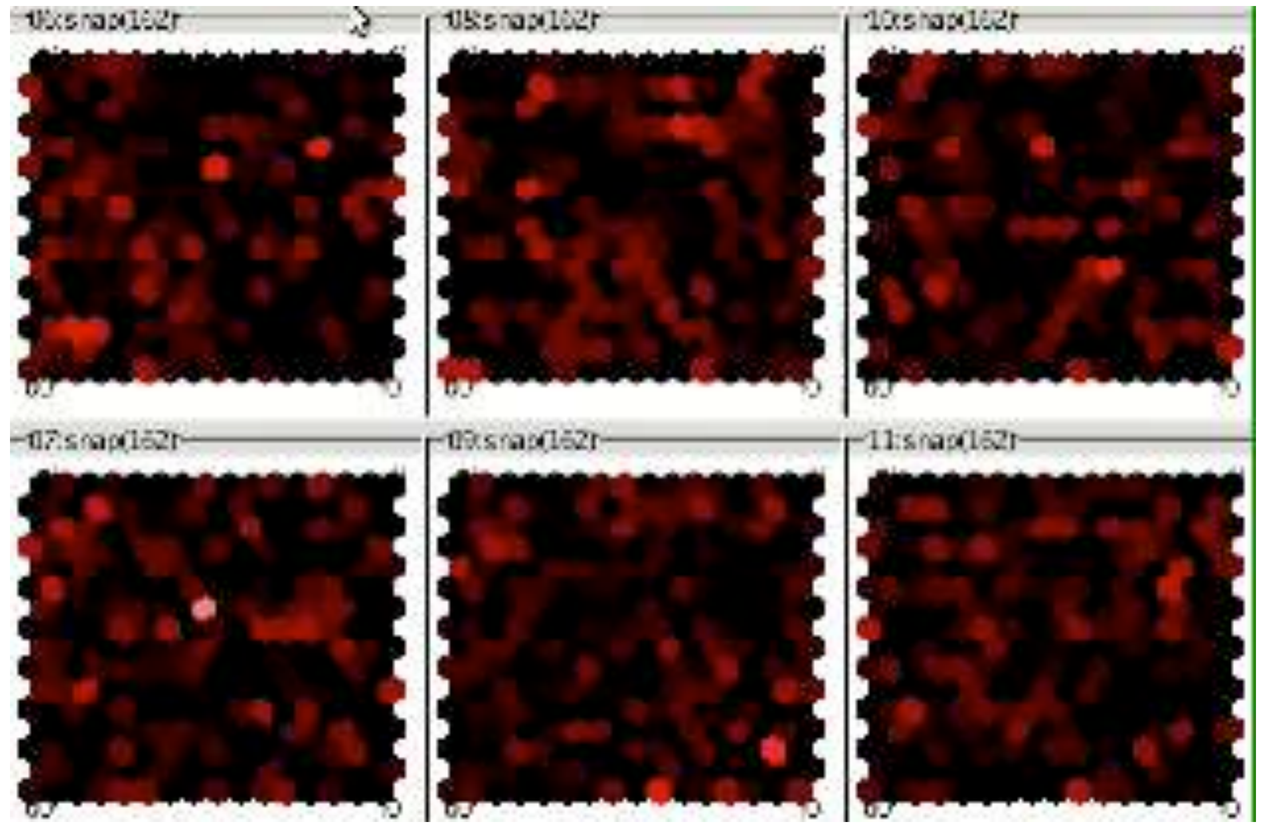


Surface detector array (SD)

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

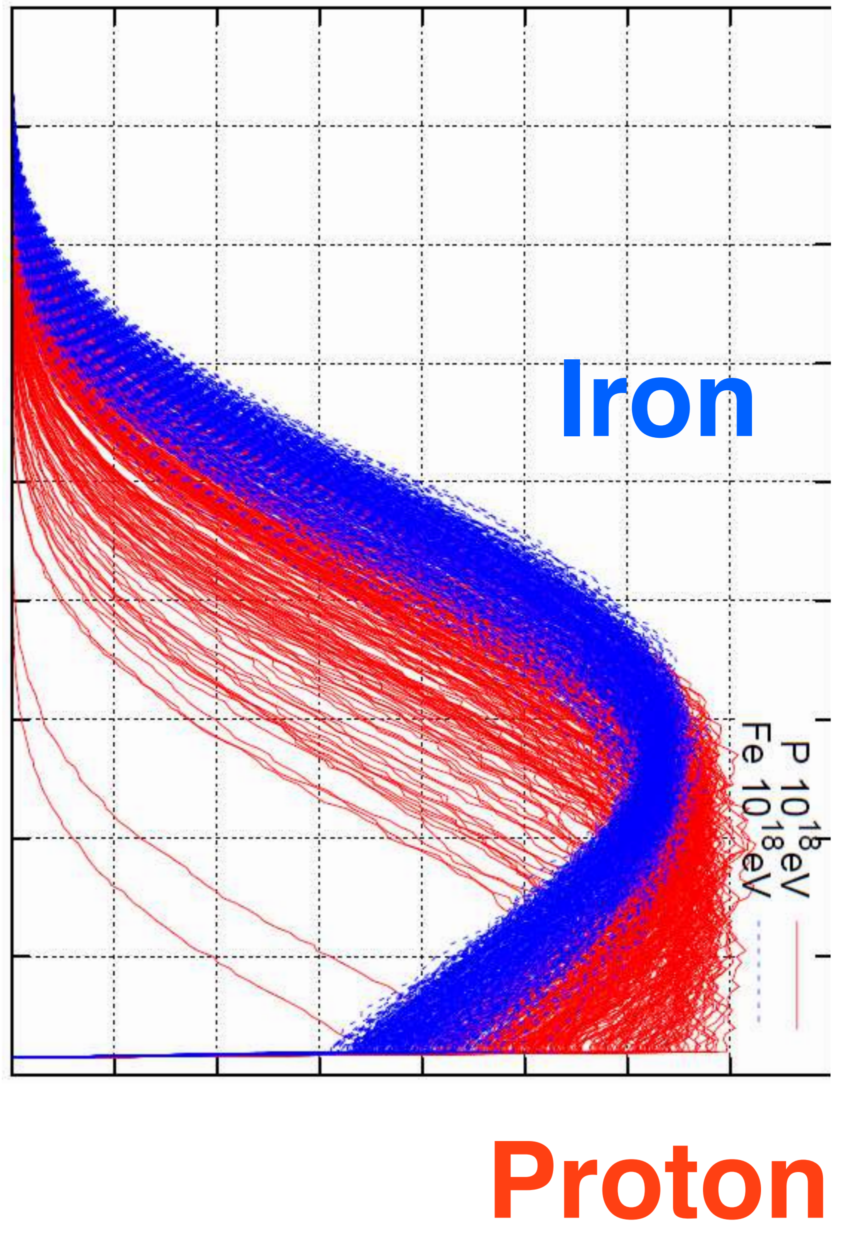
Fluorescence detector (FD)

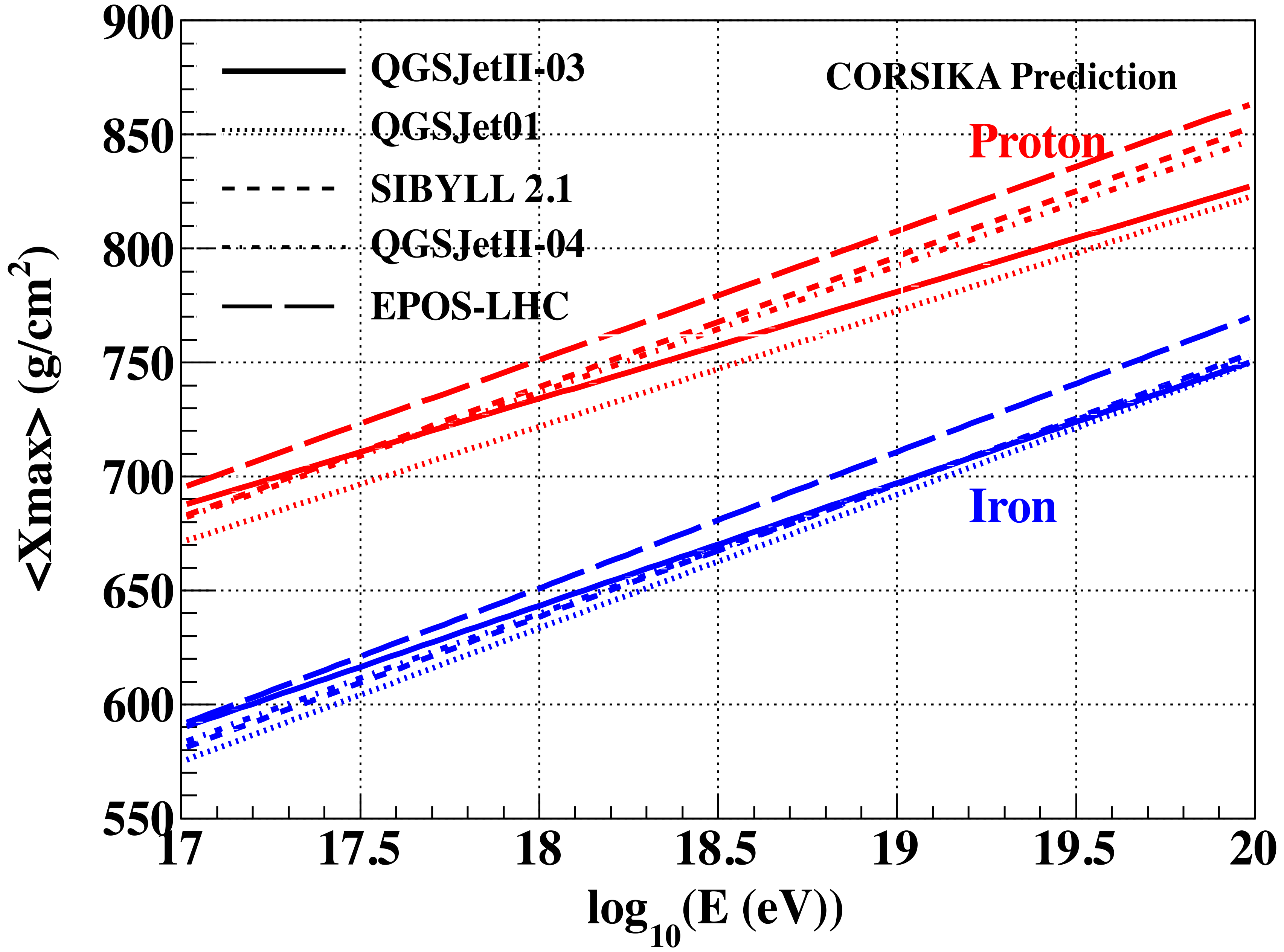




X_{max} measurements for **mass composition (Z)**

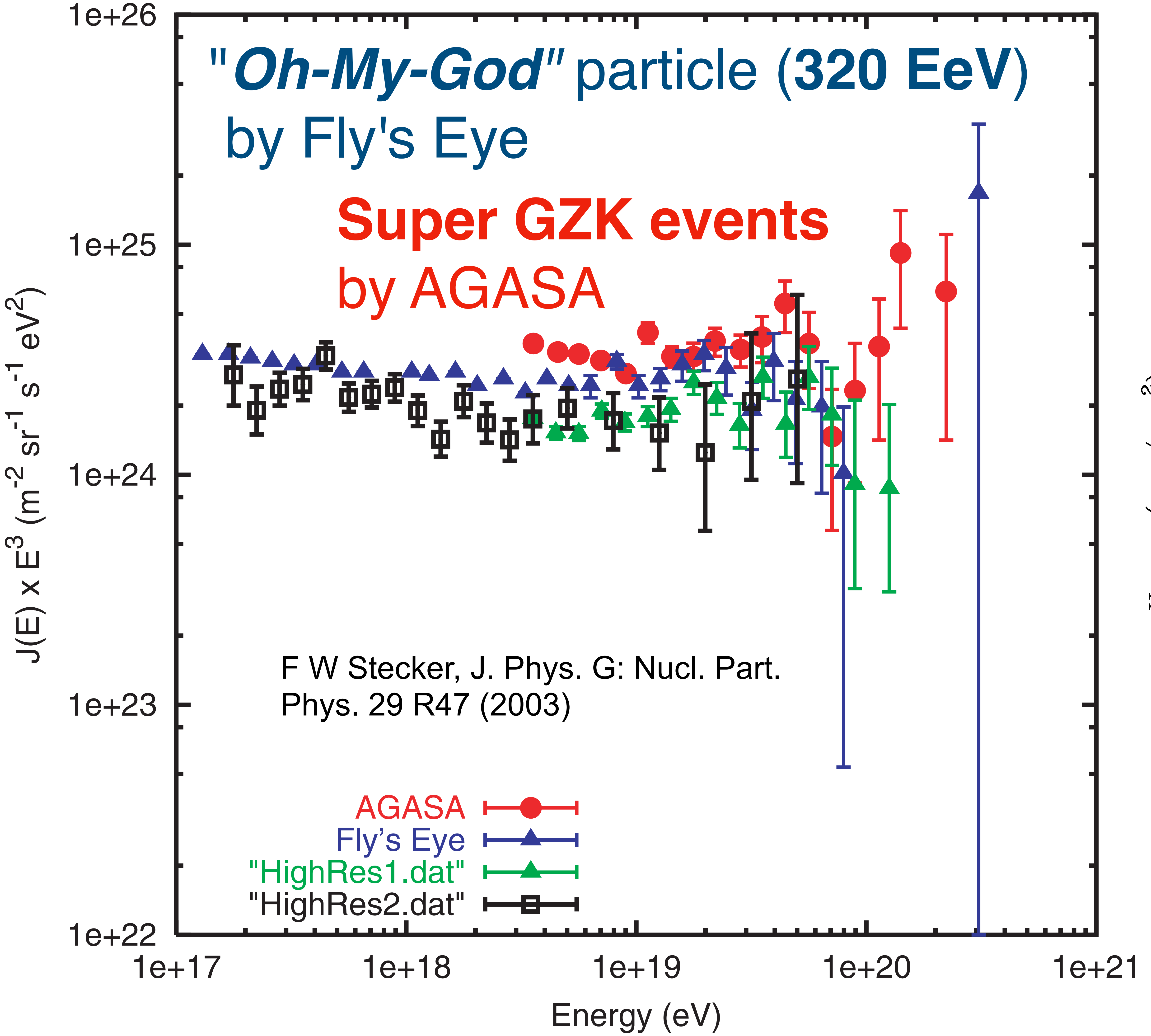
$$X_{max}^{A} \propto \ln \frac{E_0}{A}$$



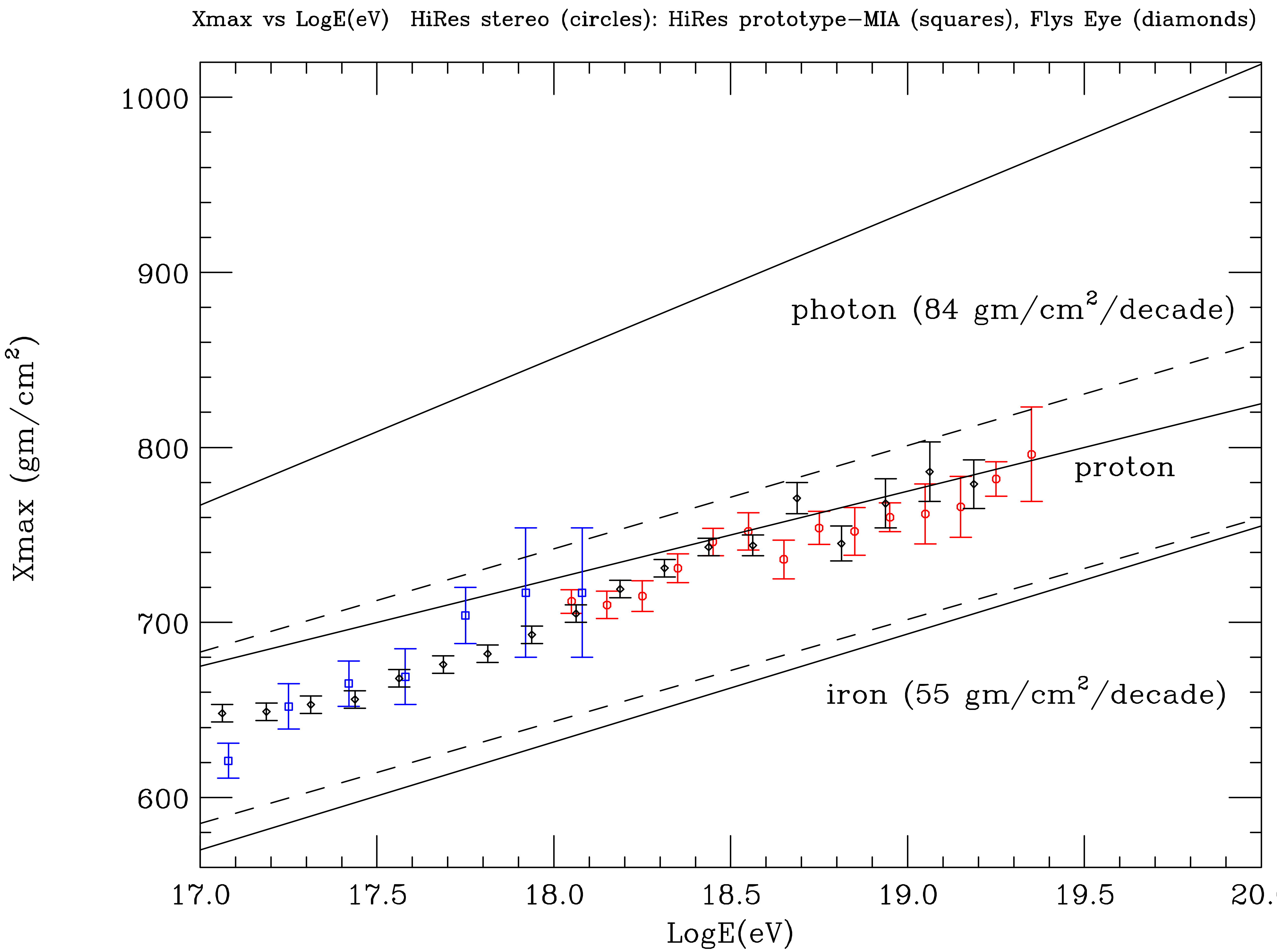


UHECR results 20 years ago (when KICP was founded)

No GZK cutoff in spectrum?



Proton dominated composition at highest energies?



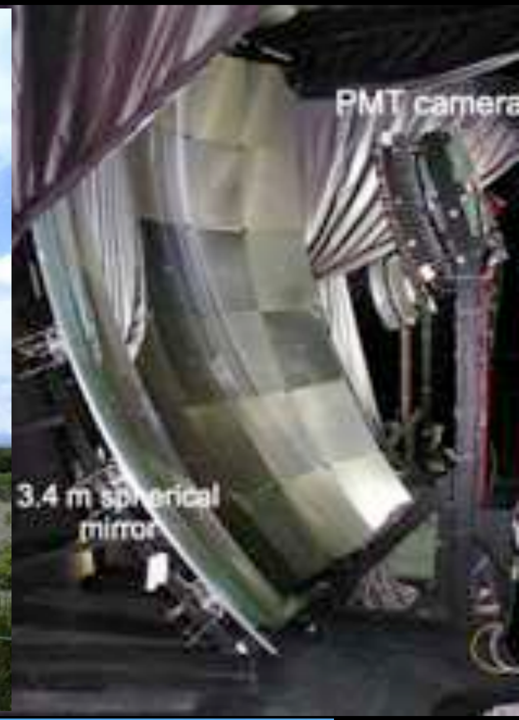
J. Cronin, Nucl.Phys.Proc.Suppl. 138:465 (2005)

Latest UHECR observatories

Google Earth

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

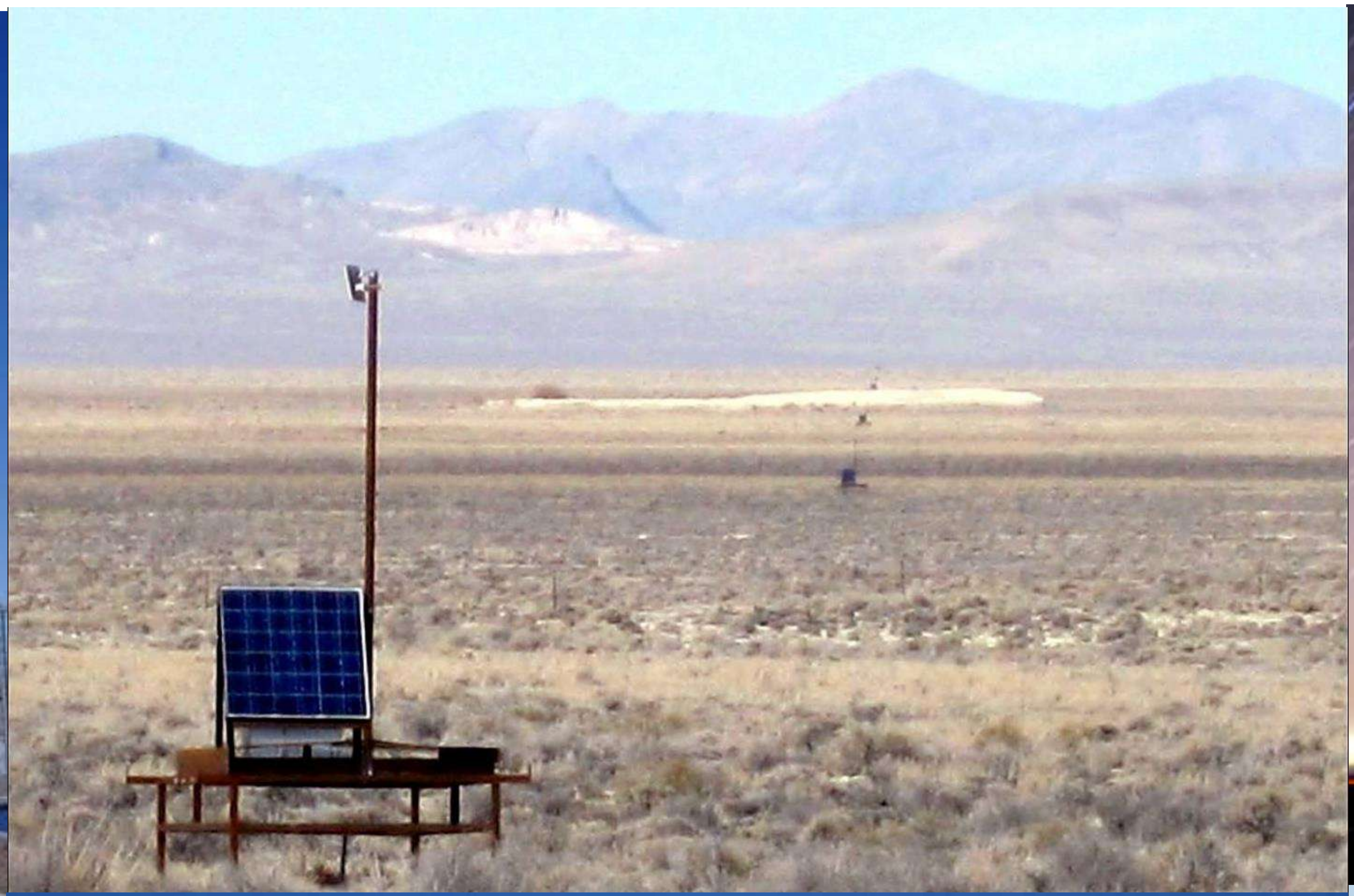
- **Pierre Auger Observatory (Auger)**
  - Malargüe, Argentina
  - 2004~, 3000 km²
    - **AugerPrime** upgrade scintillator + radio + buried muon detector



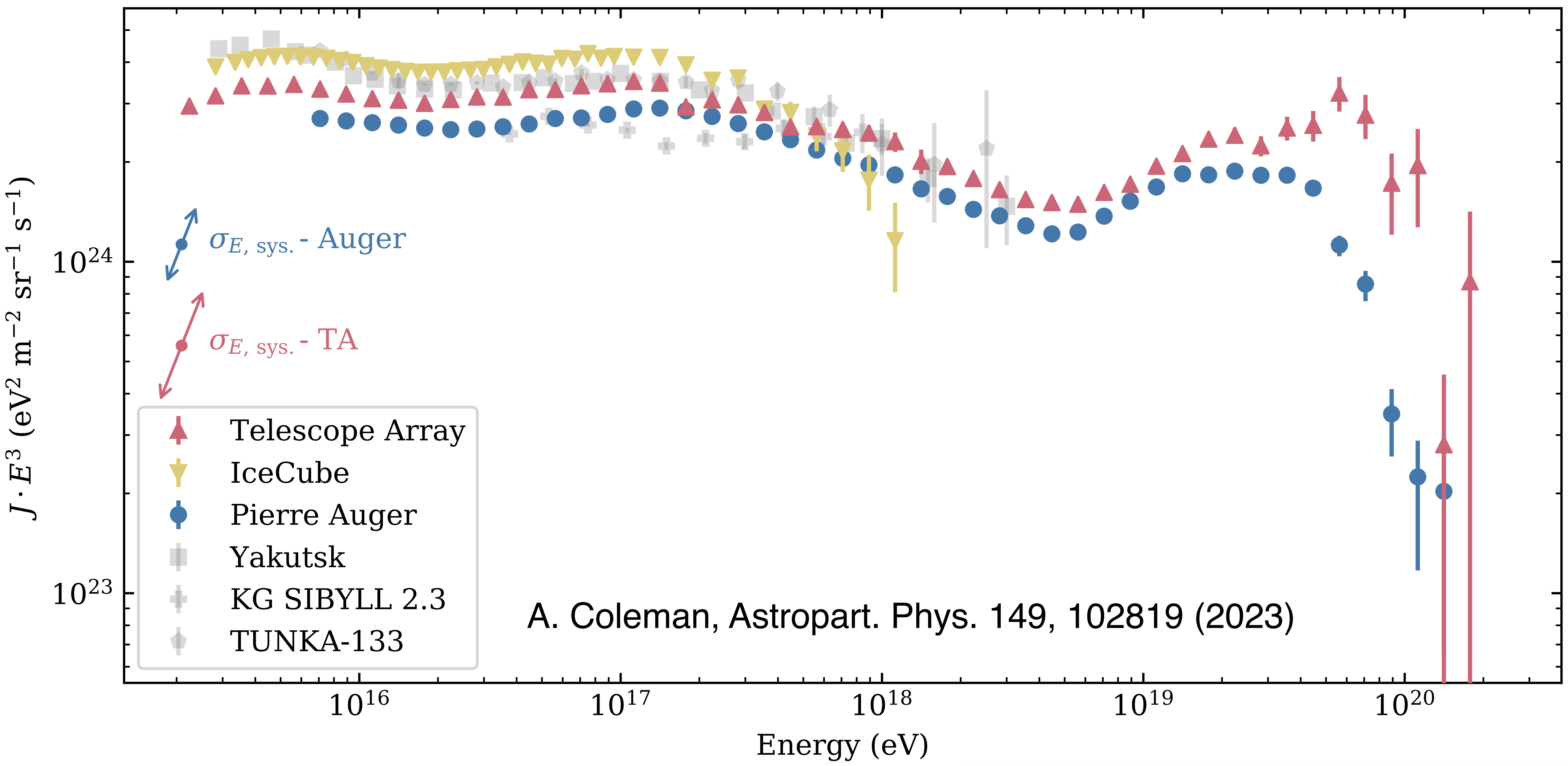
PIERRE AUGER OBSERVATORY

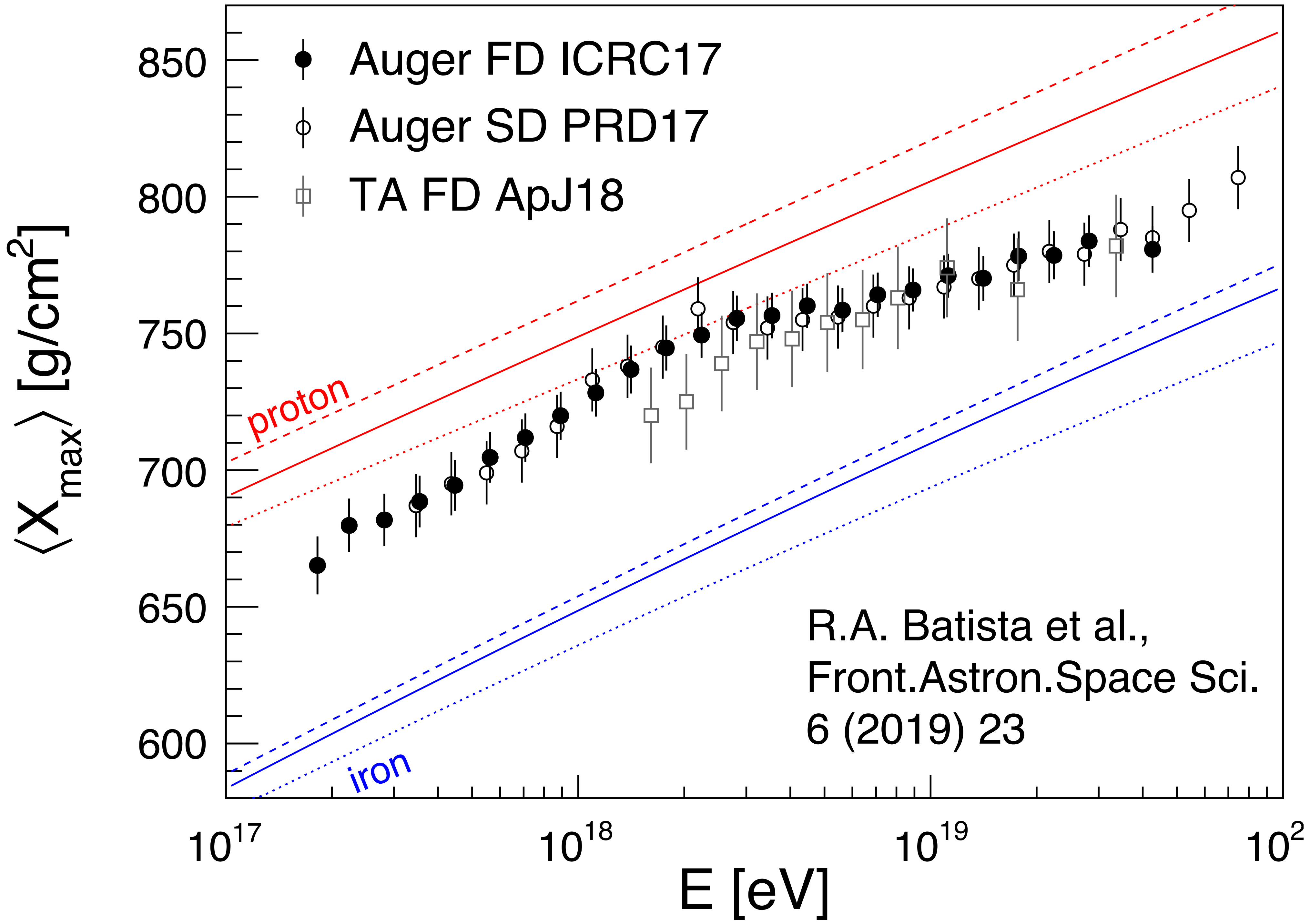
Pierre Auger Observatory @Mendoza, Argentina

Telescope Array experiment @Utah

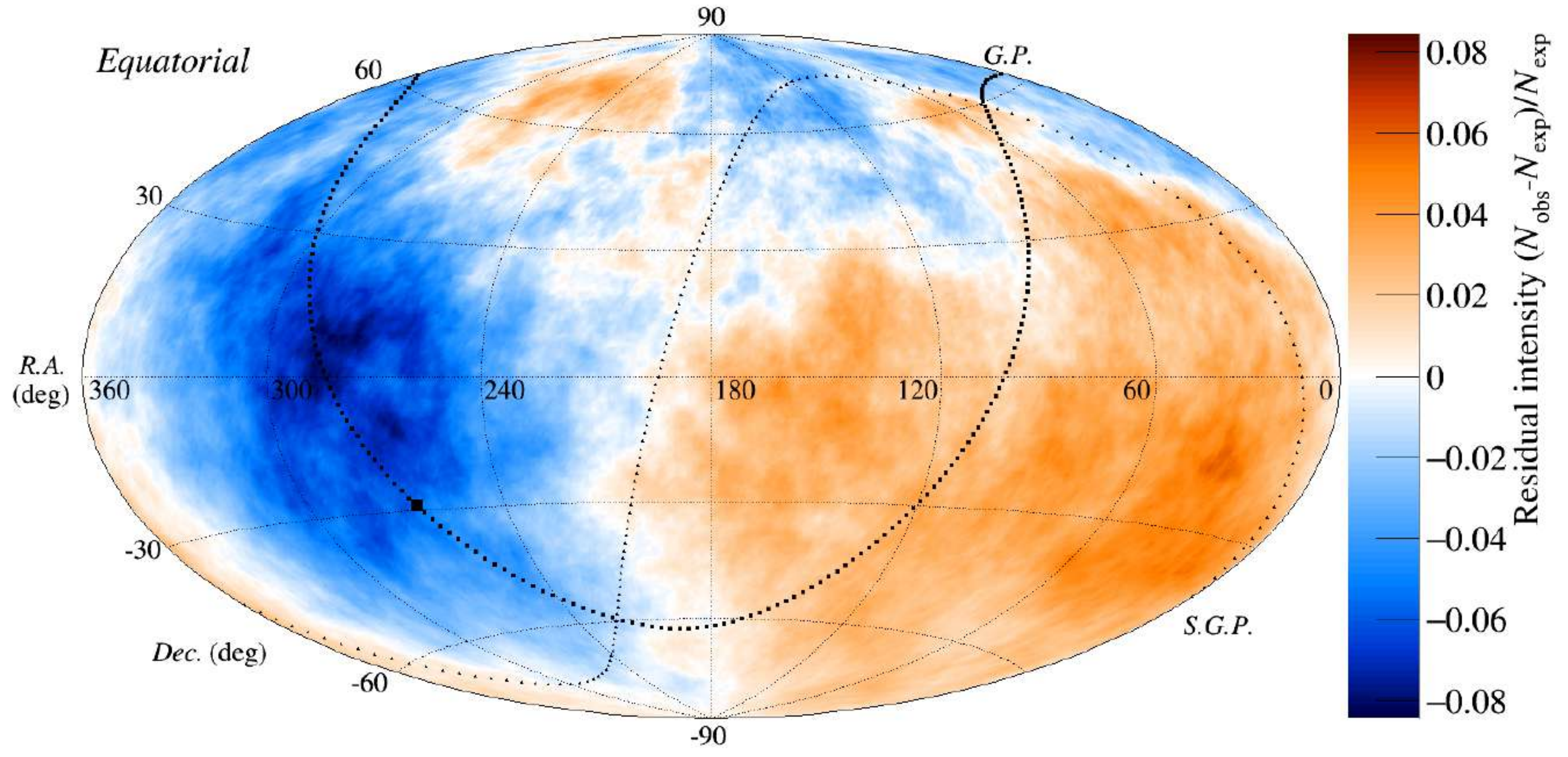


Credit: Telescope Array Collaboration, H. Oshima

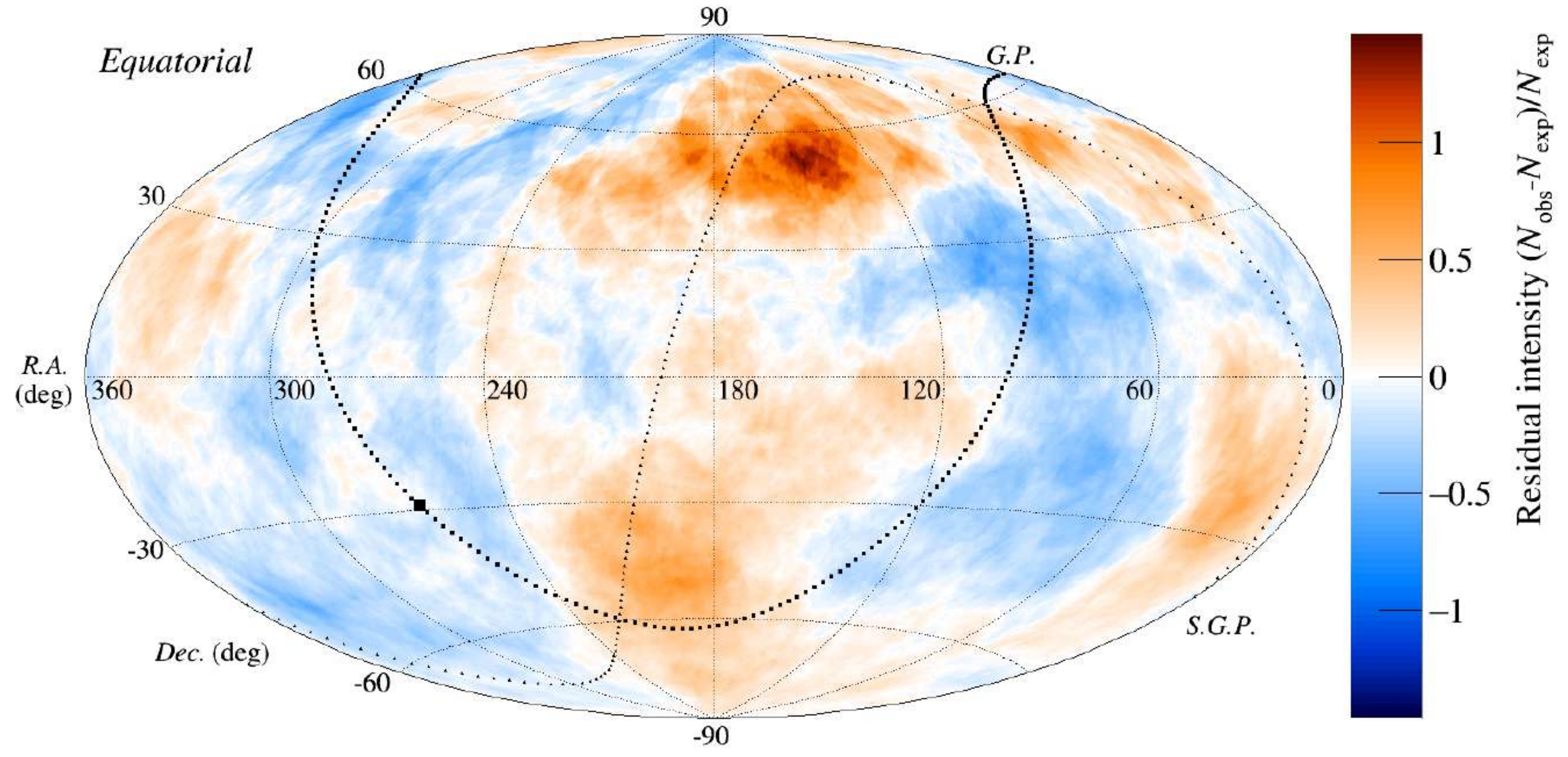




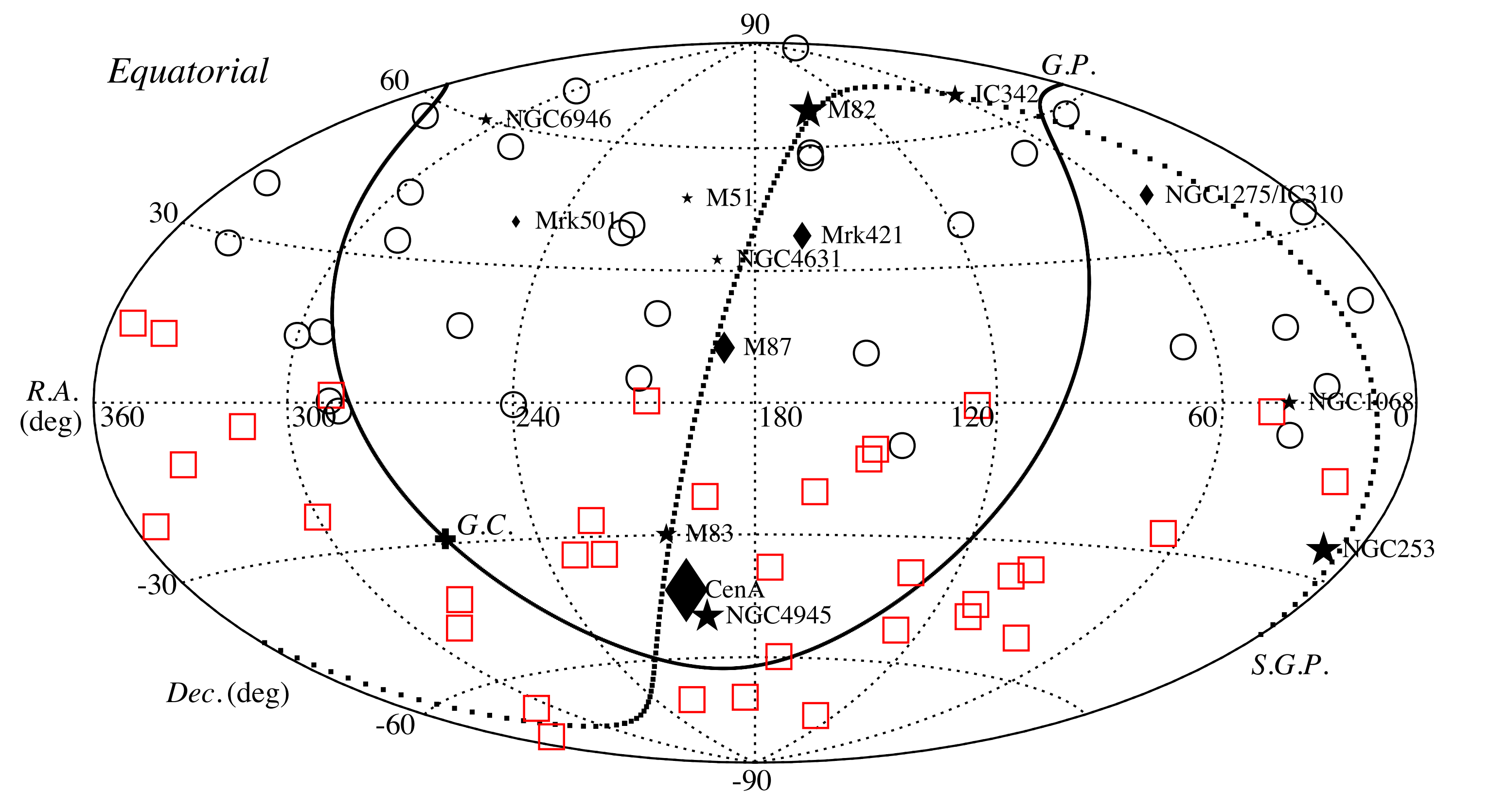
Latest results



Ankle ($E > 10$ EeV)



Cutoff ($E > 50$ EeV)



Beyond-cutoff ($E > 100$ EeV)

Energy spectrum

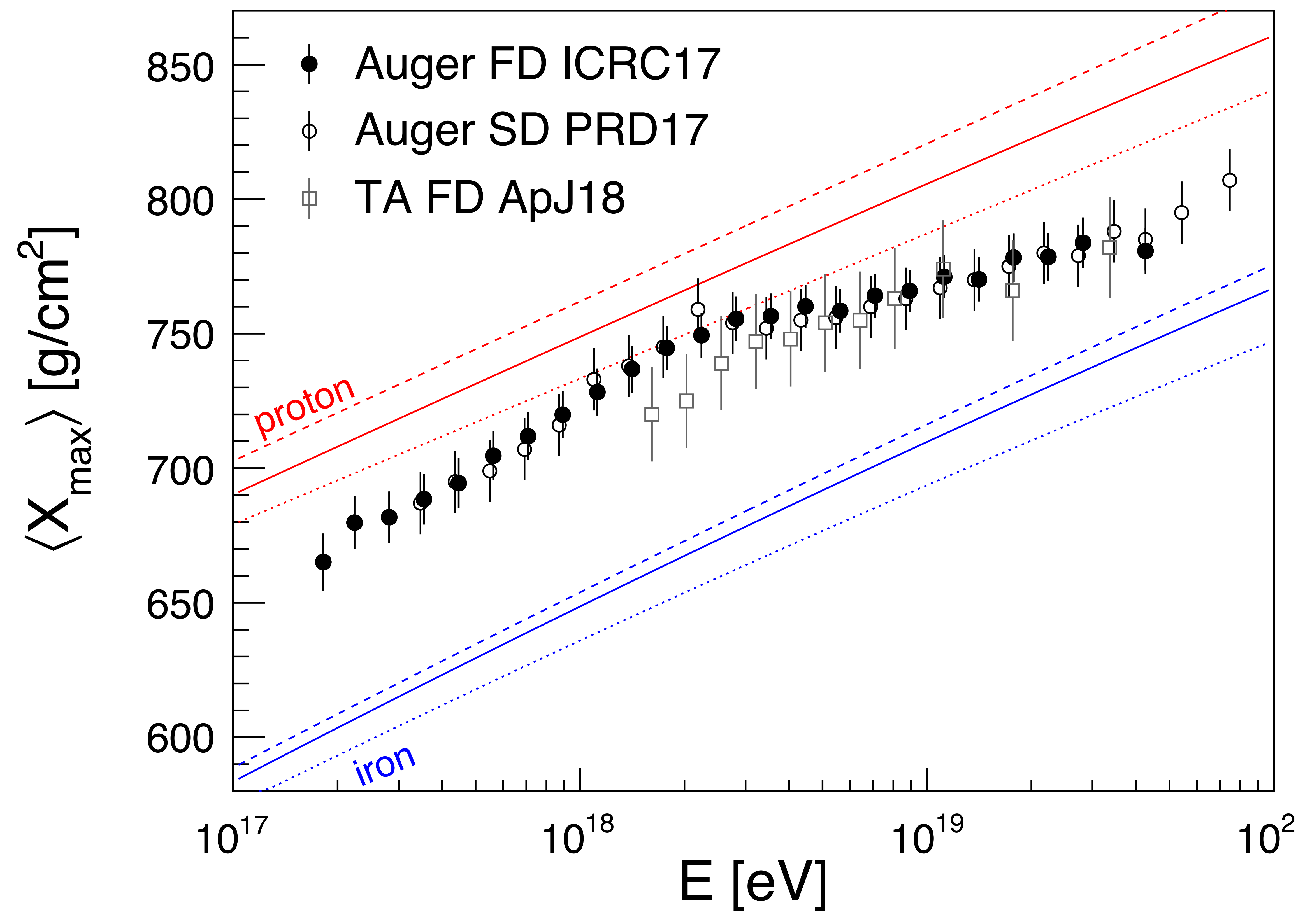
- Firmly confirmed the spectrum cutoff above 50 EeV
- No detection above 300 EeV

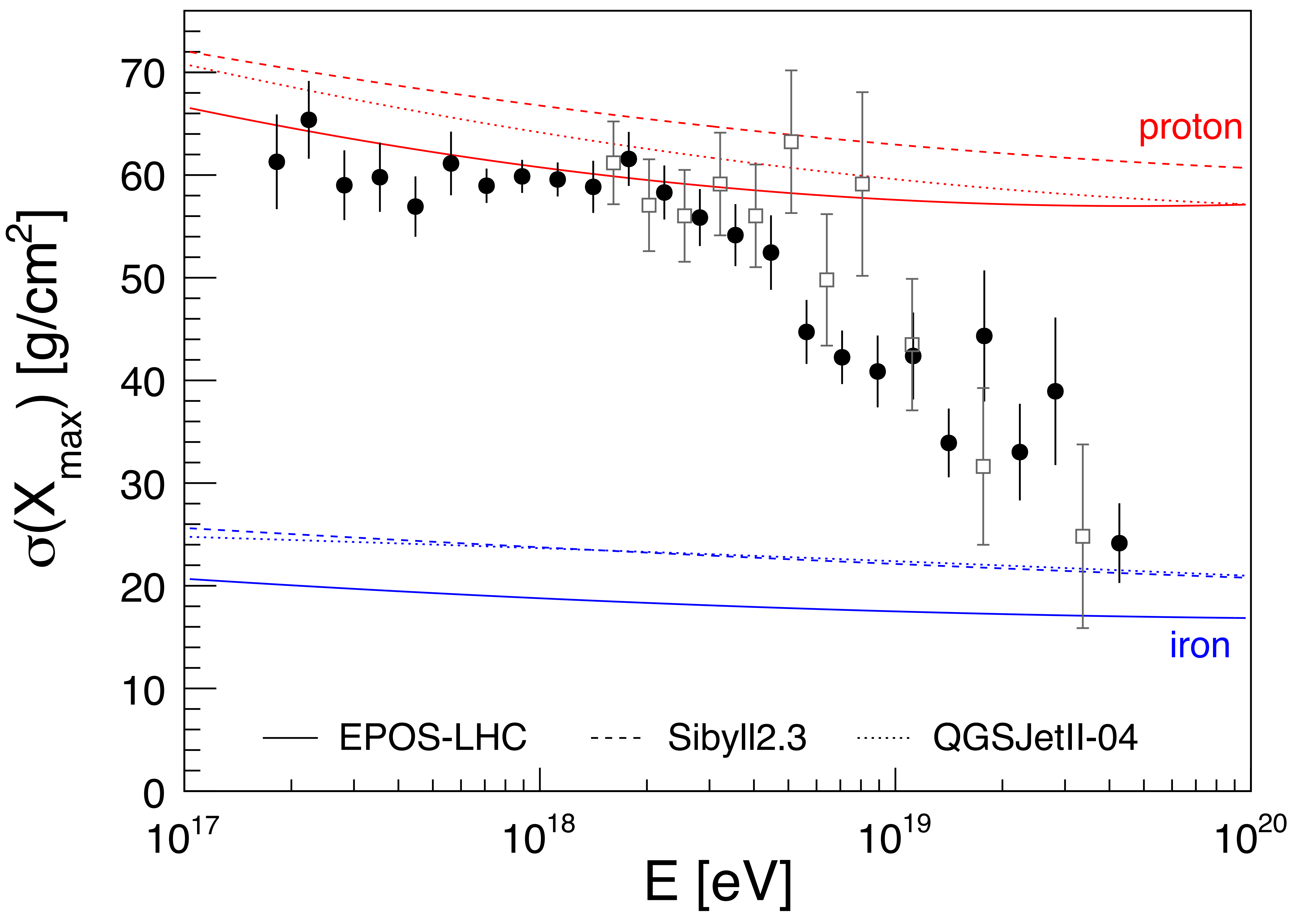
A. Coleman et al., Astropart. Phys. 149, 102819 (2023)

Mass composition

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

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





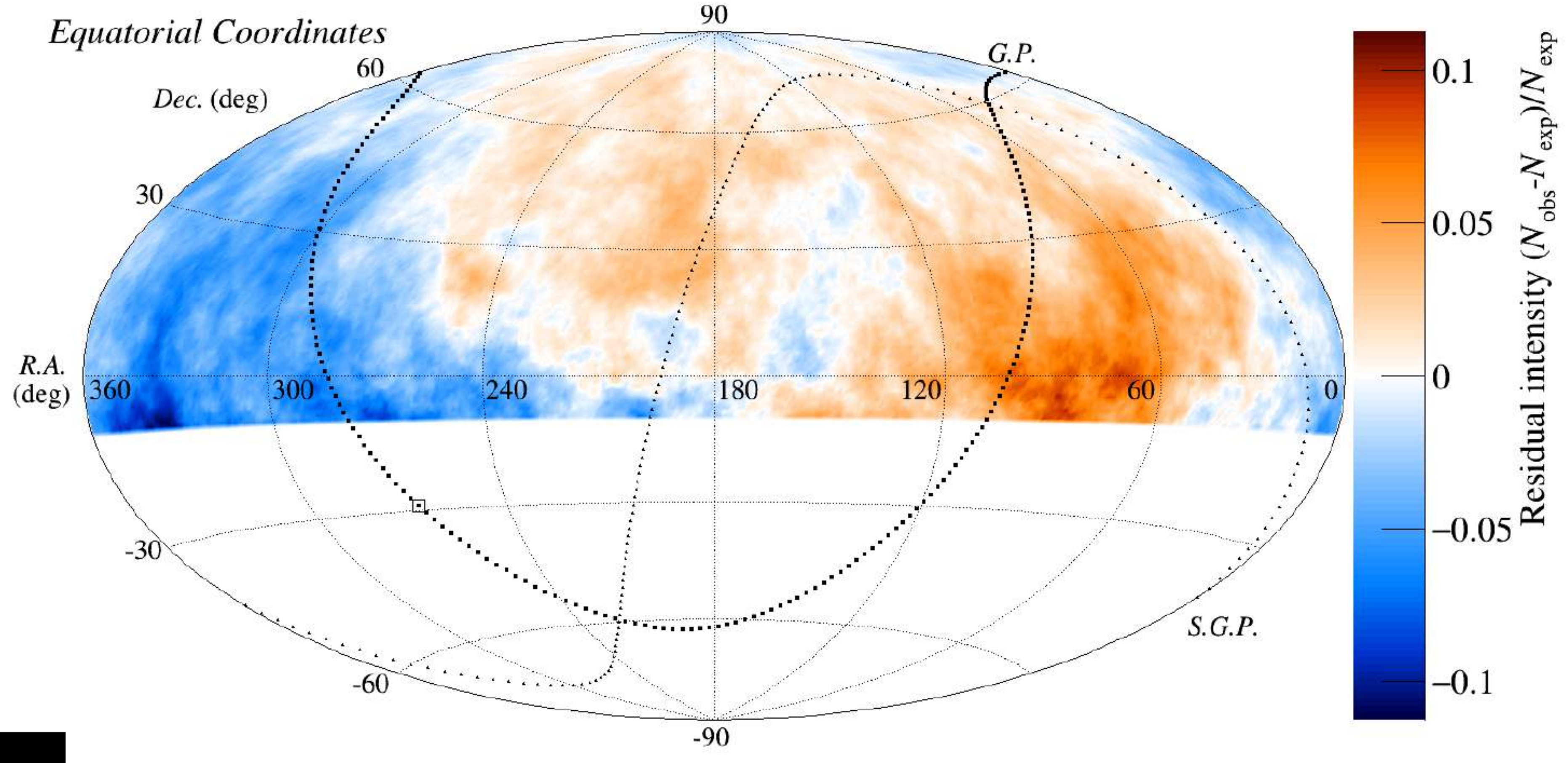
Gradually increase to the heavier composition above 3 EeV

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

Anisotropy of UHECRs (10 EeV)

Northern TA ApJL, 898:L28 (2020)

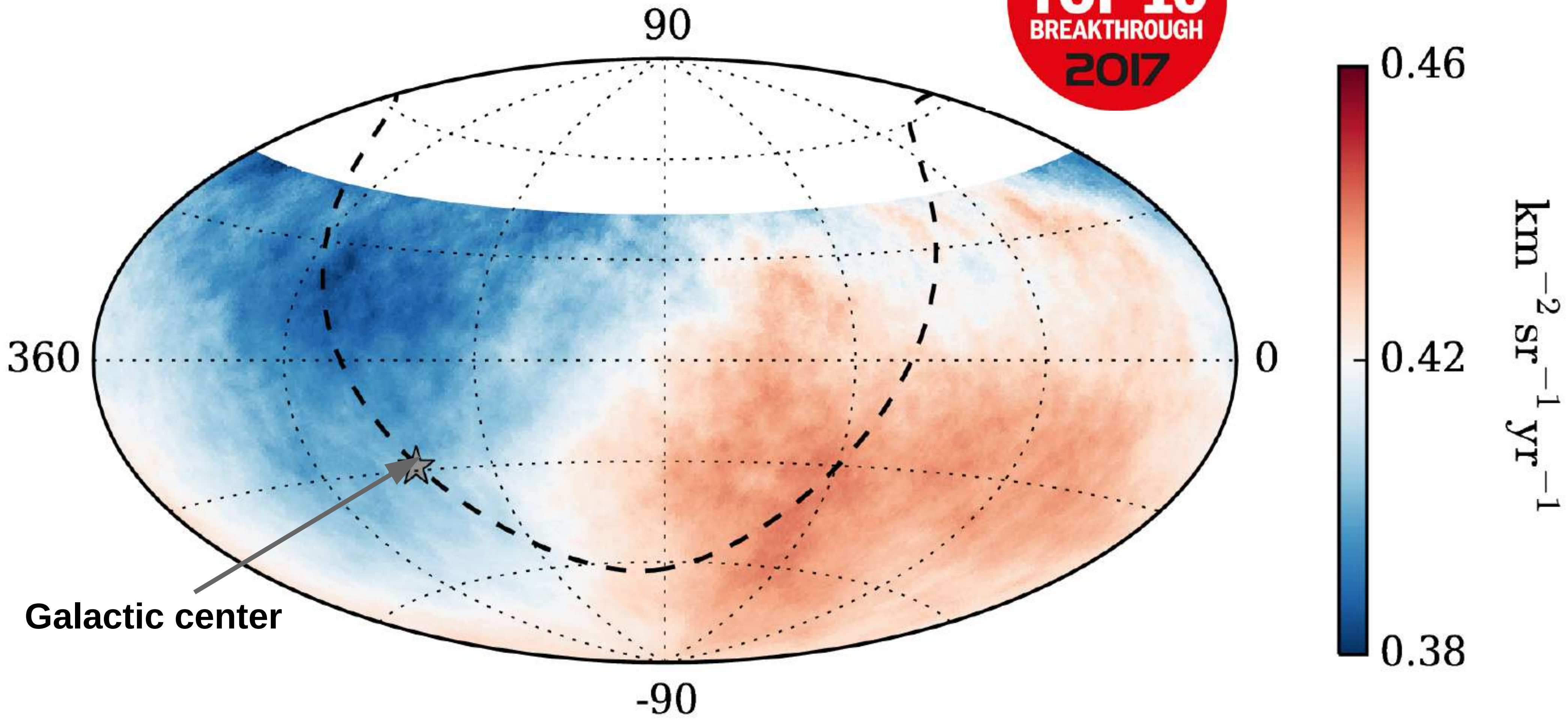
E_{TA}> 8.8 EeV



Southern Auger Science 357, 1266 (2017)

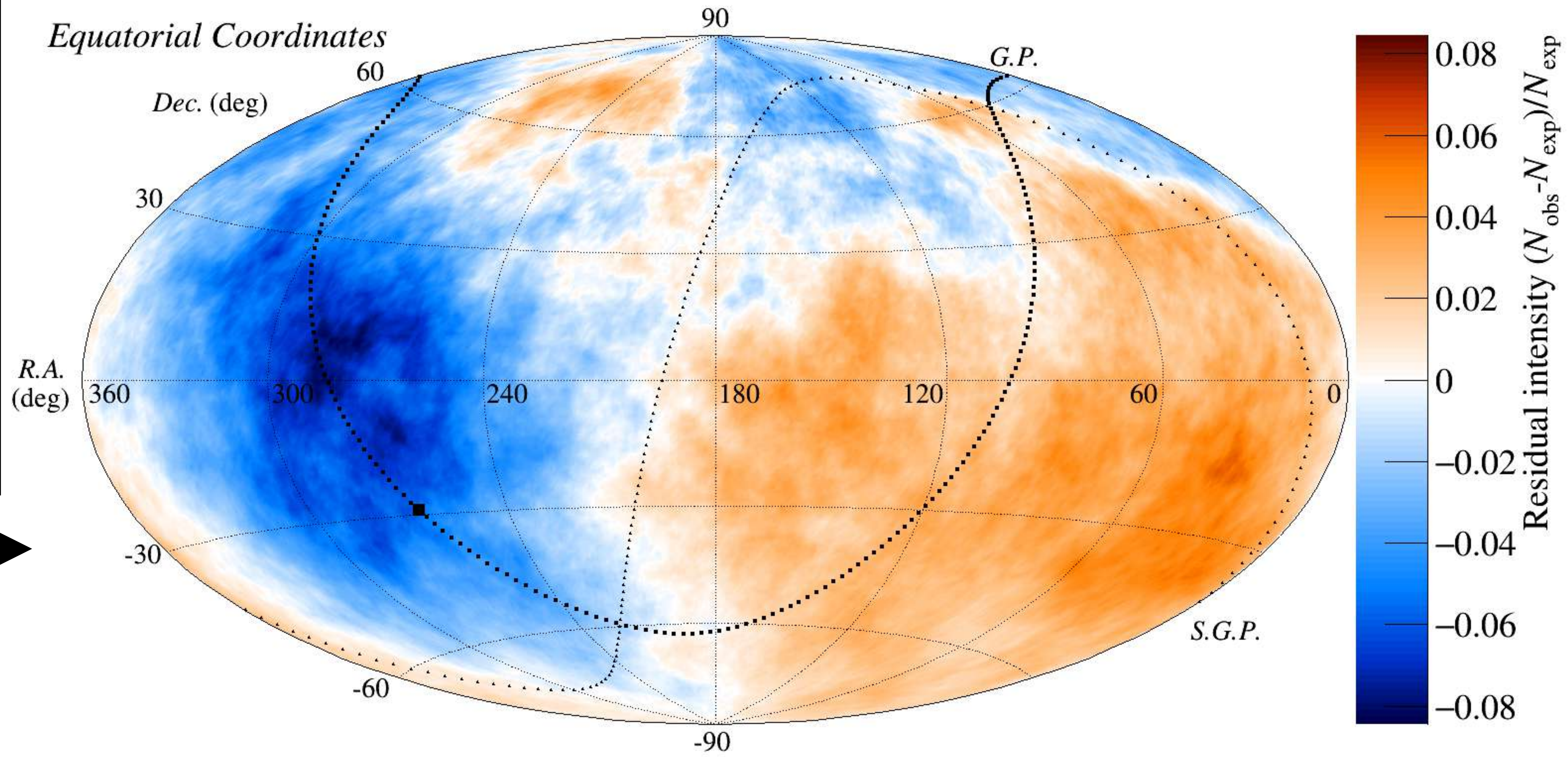
E_{Auger}> 8 EeV

physicsworld TOP 10 BREAKTHROUGH 2017



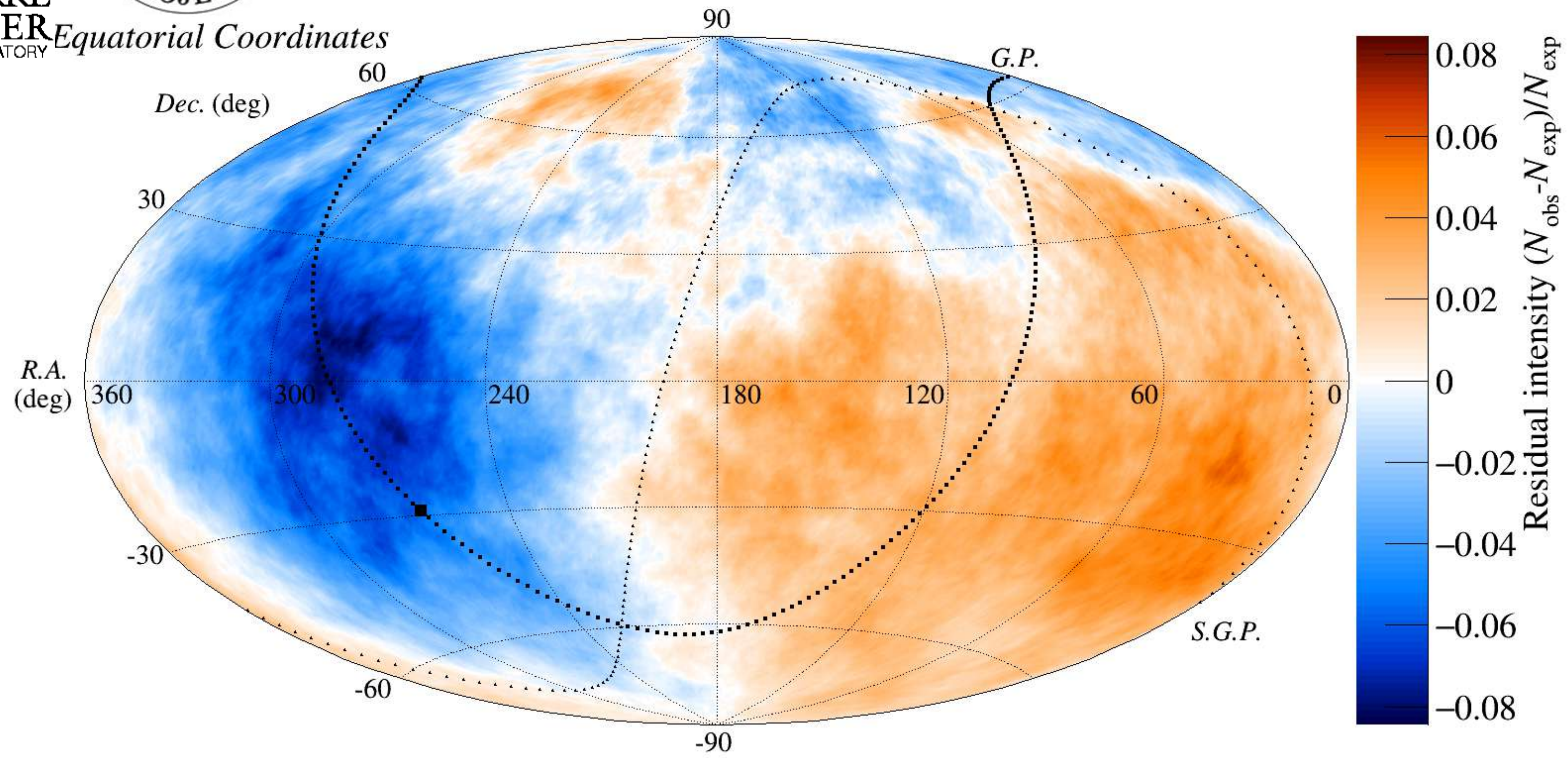
Joint analysis

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

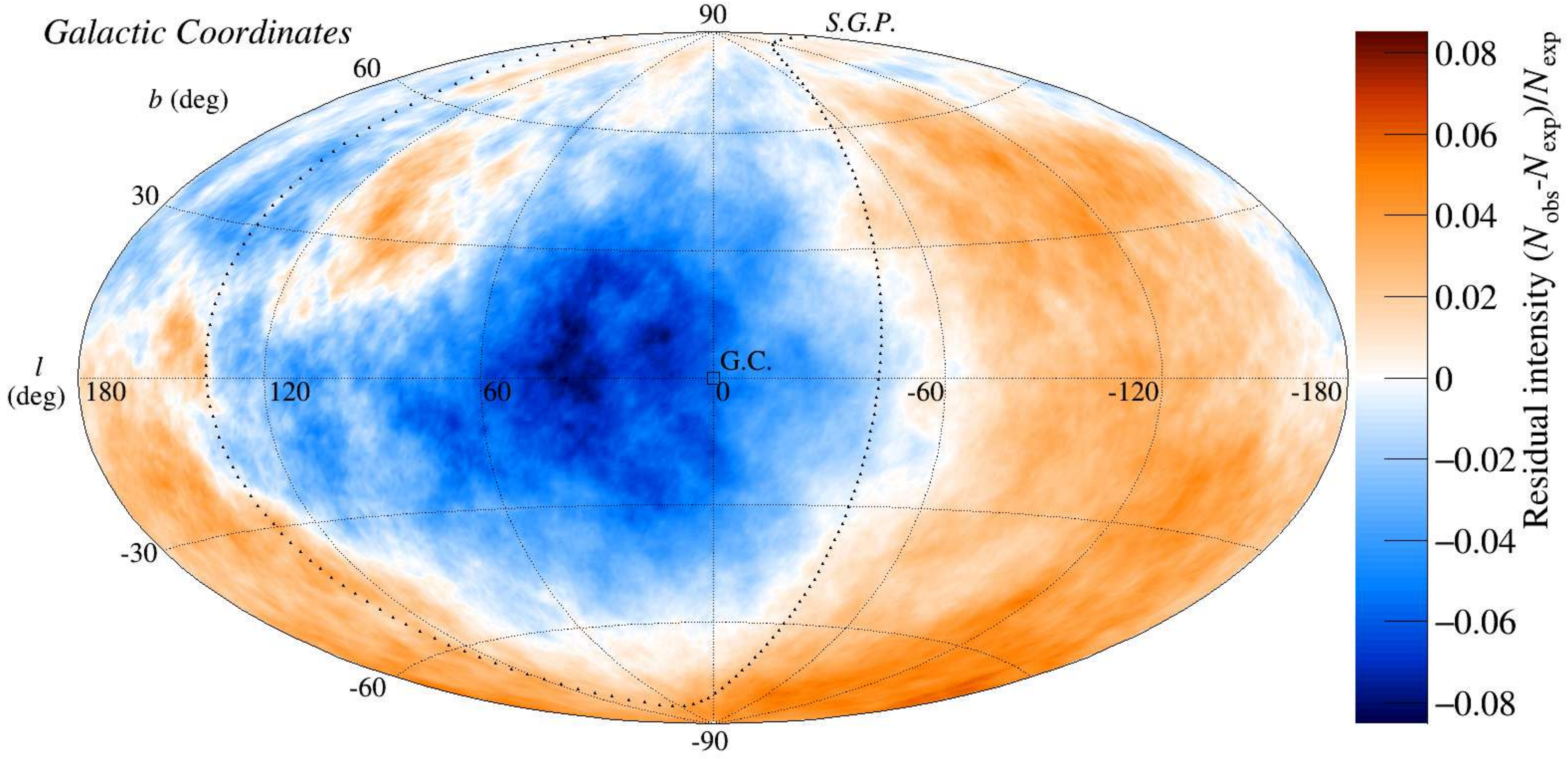


Ankle (E_{TA}>10 EeV, E_{Auger}> 8.86 EeV)

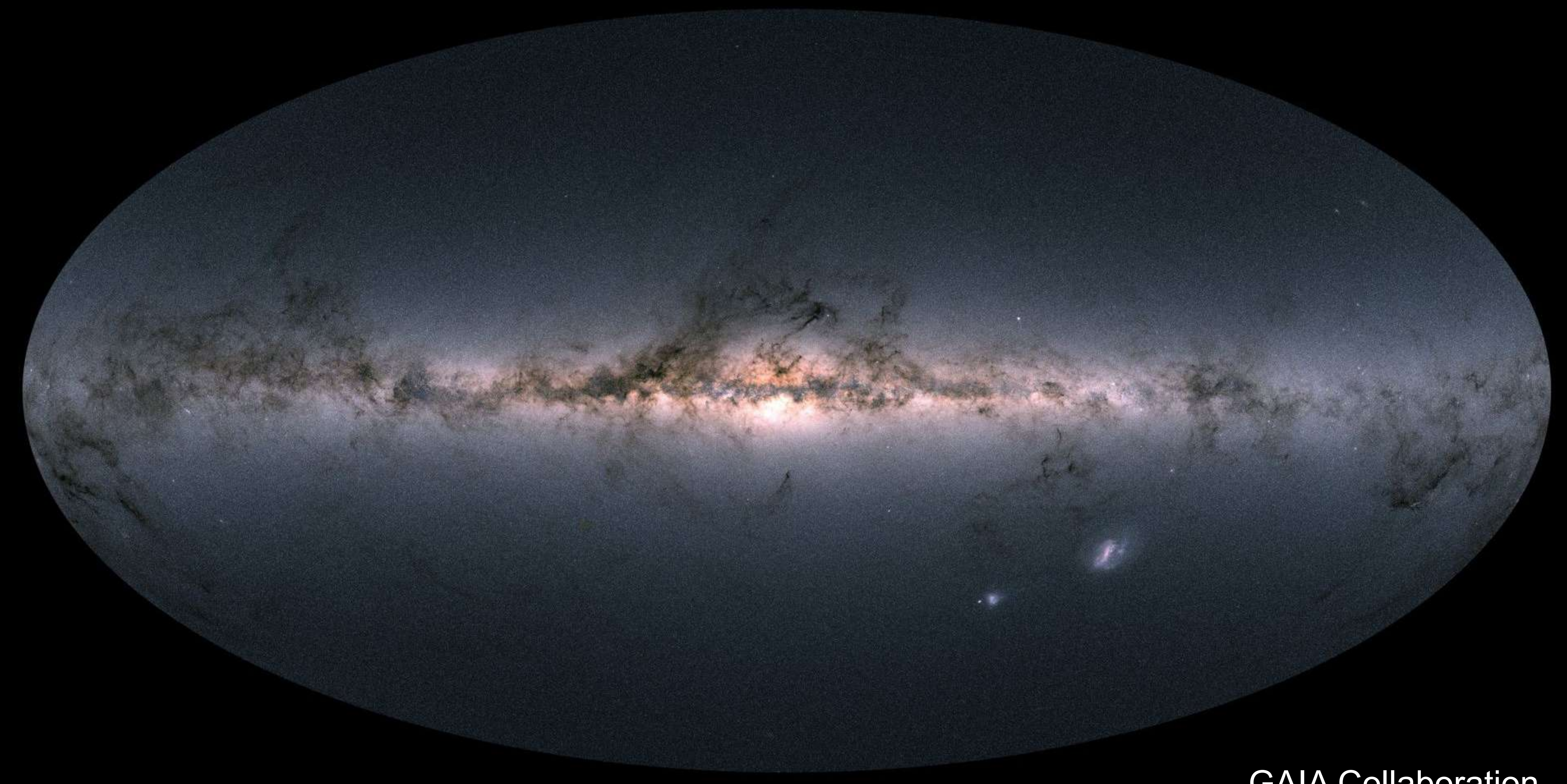
10 EeV skymap



Converted to **Galactic coordinates**

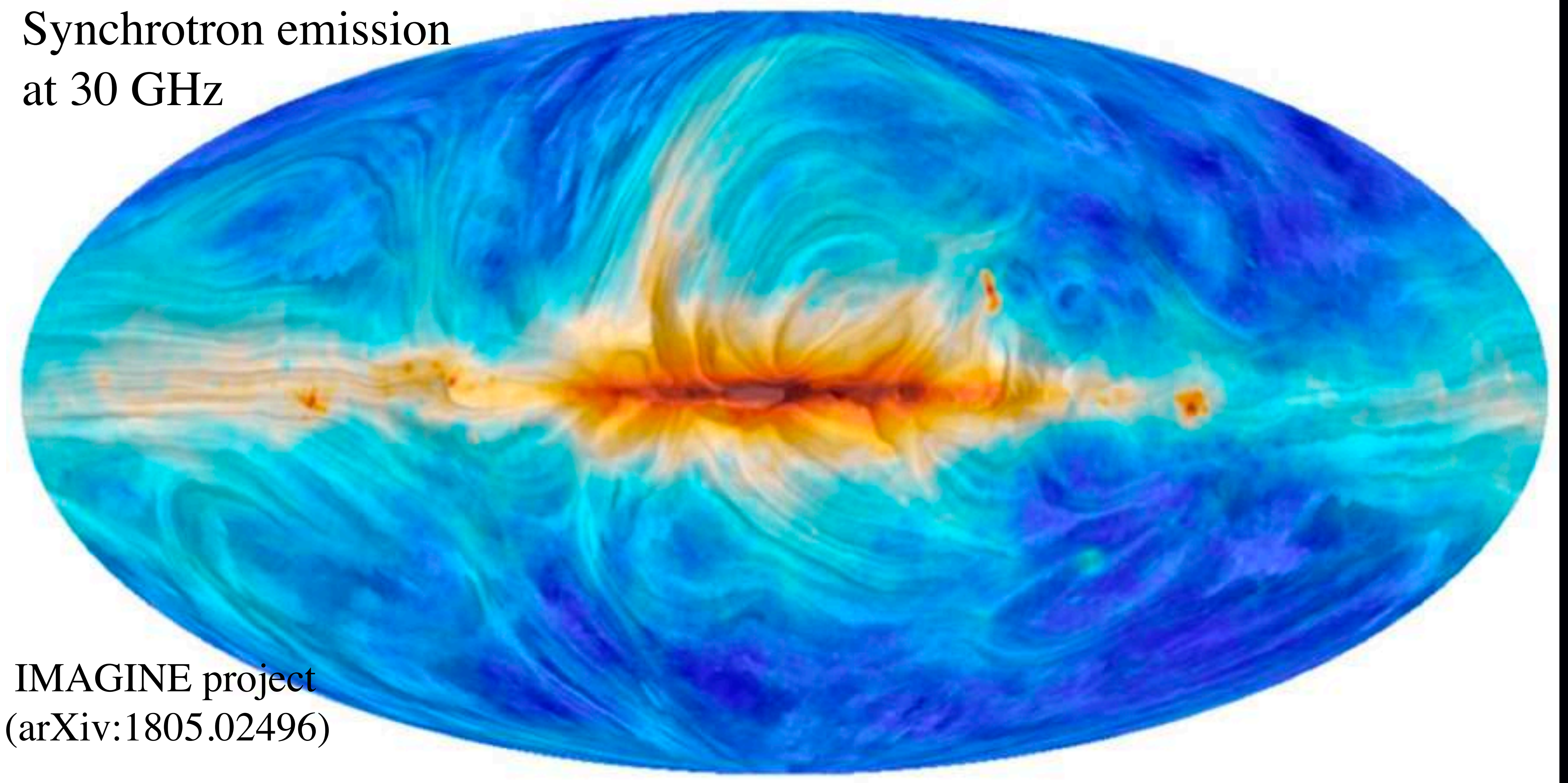


T. Fujii, PoS (ICRC2021) 402 (2021)



"Deciphering" magnetic fields

Synchrotron emission at 30 GHz

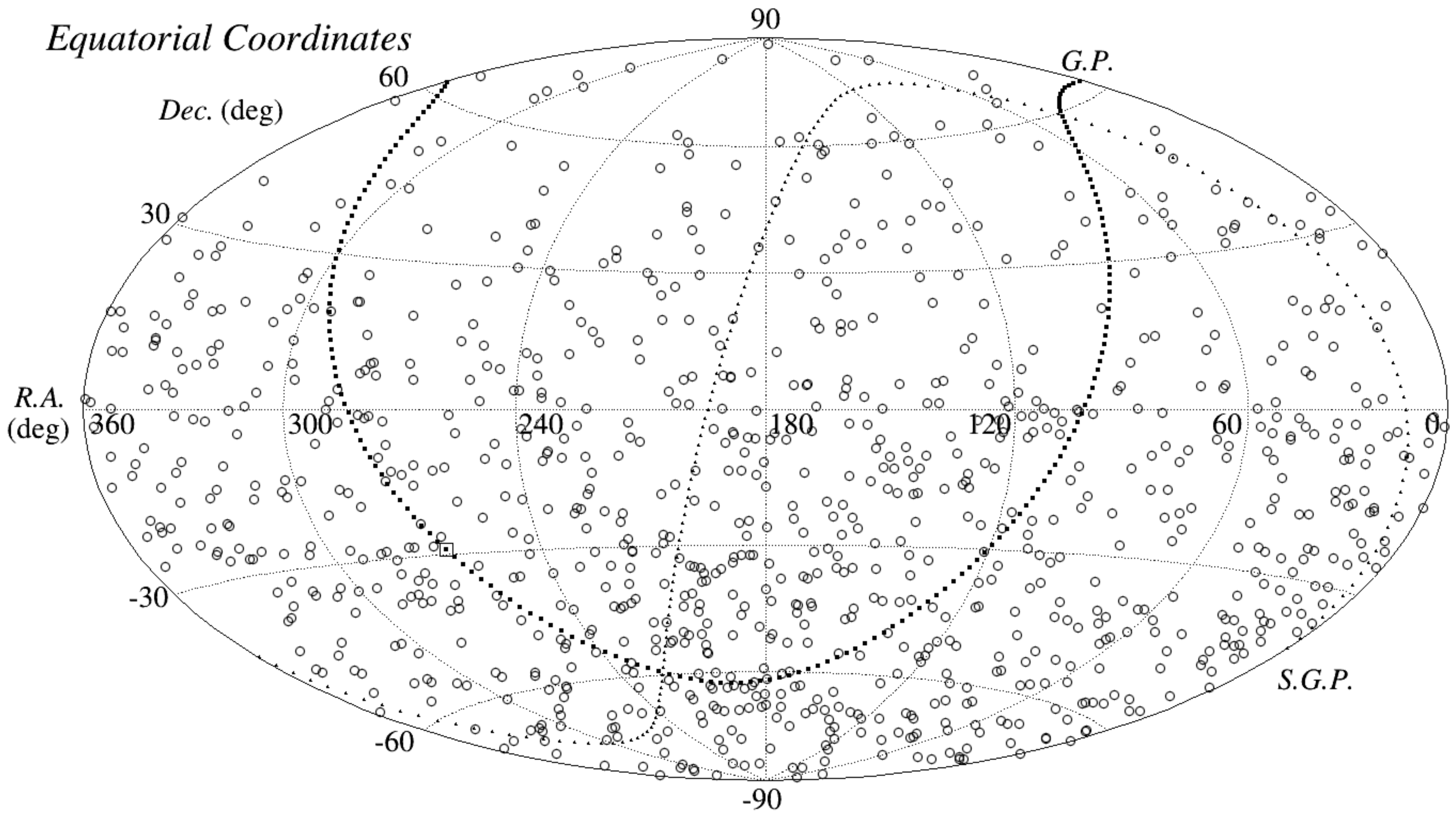


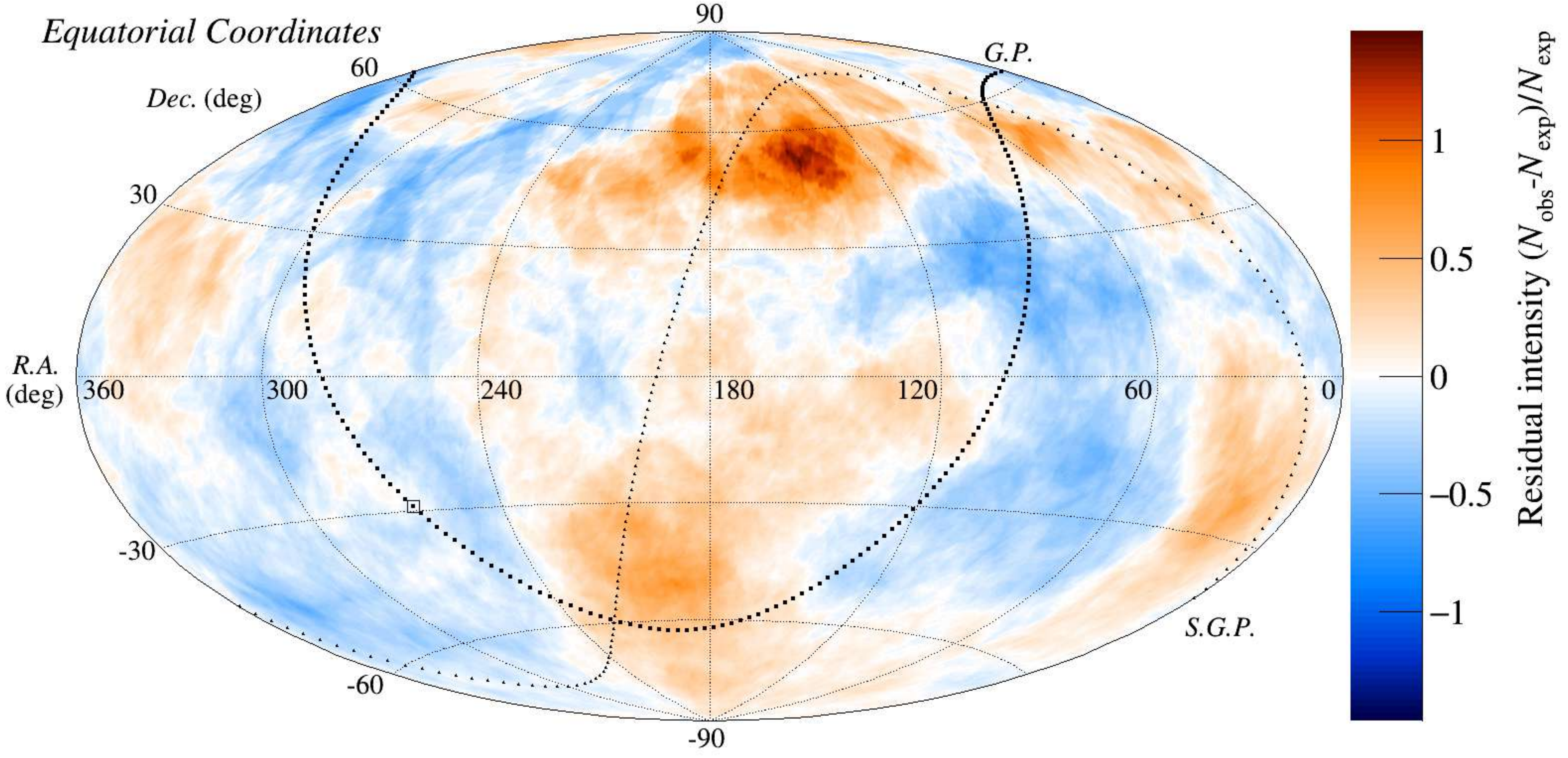
IMAGINE project (arXiv:1805.02496)

50 EeV skymap

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

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

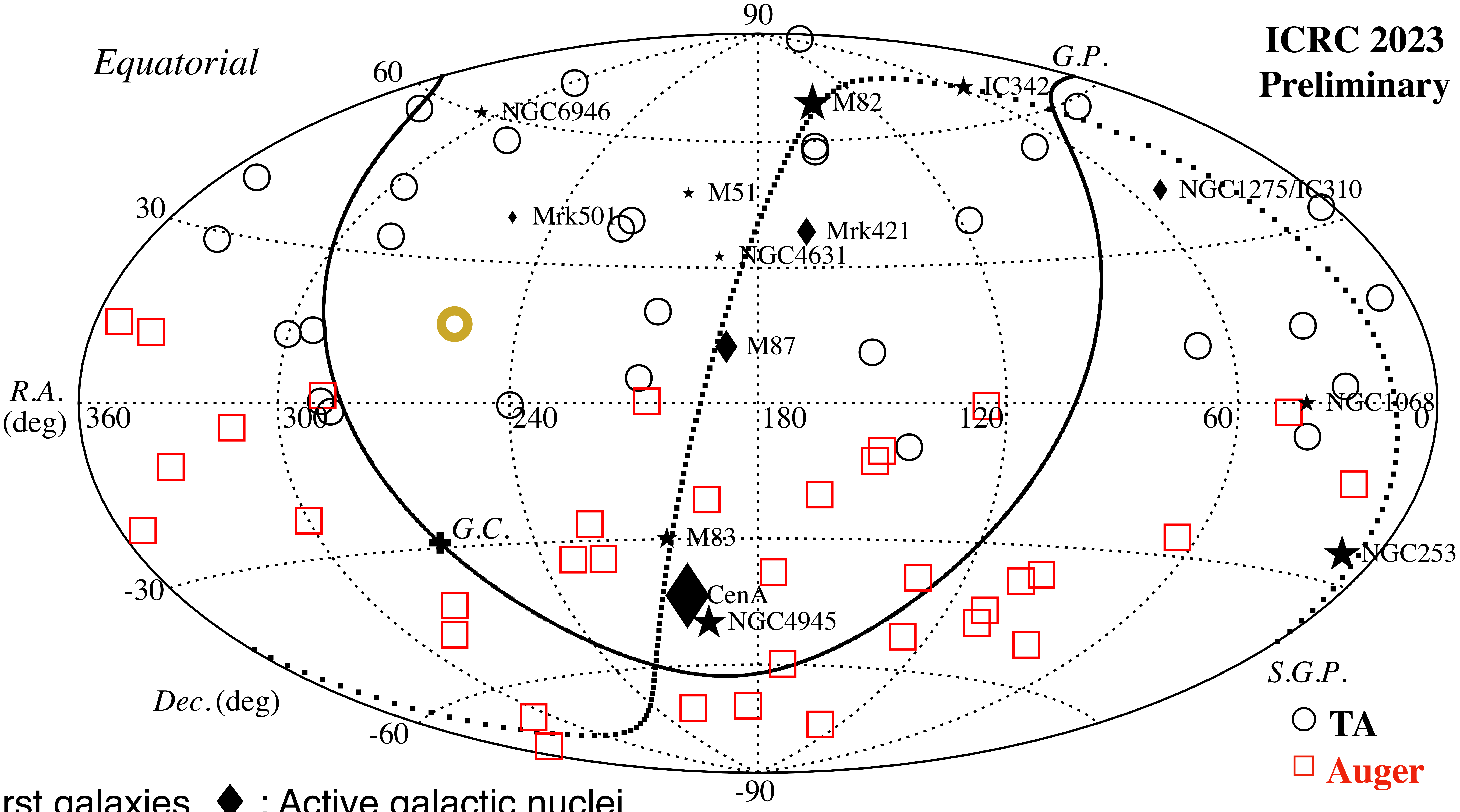




- Intriguing **intermediate-scale anisotropies** (~20 degrees) such as **hot/warm spots**
  - No excess from Virgo cluster, dubbed "***Virgo scandal***"
- **Isotropic distributions of UHECRs than our (optimistic) expectation**

100 EeV skymap

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



★ : Starburst galaxies ♦ : Active galactic nuclei

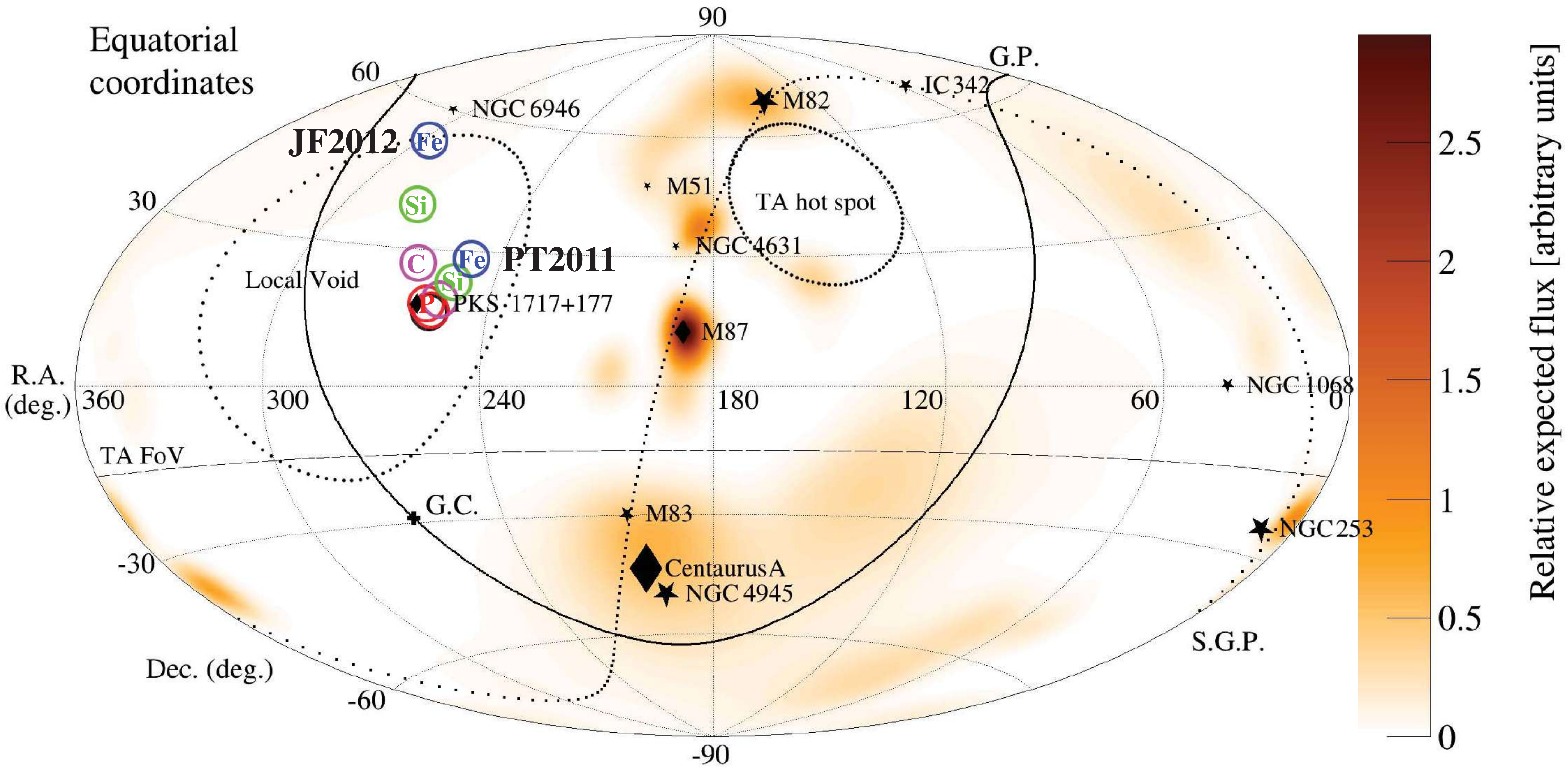
>100 EeV of TA 15-years and Auger 17-years

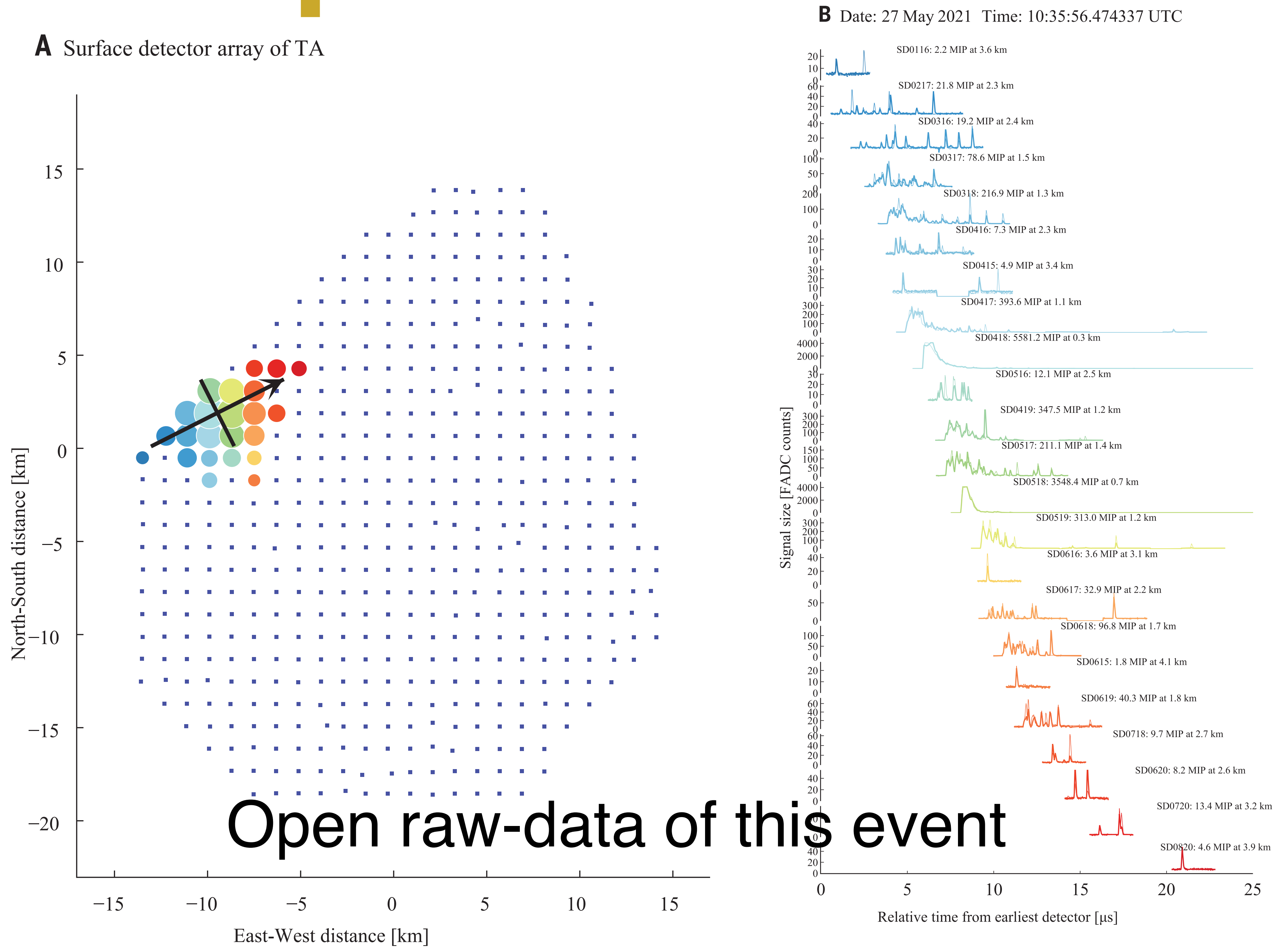
No obvious clustering appeared


2021 May 27, 04:35:56 AM
Detection of **"Amaterasu" particle**
© Toshihiro Fujii, L-INSIGHT, Kyoto University and Ryuunosuke Takeshige
Published in TA Collab. Science 382, 903 (2023)

Arrival direction of Amaterasu particle

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





Open raw-data of this event

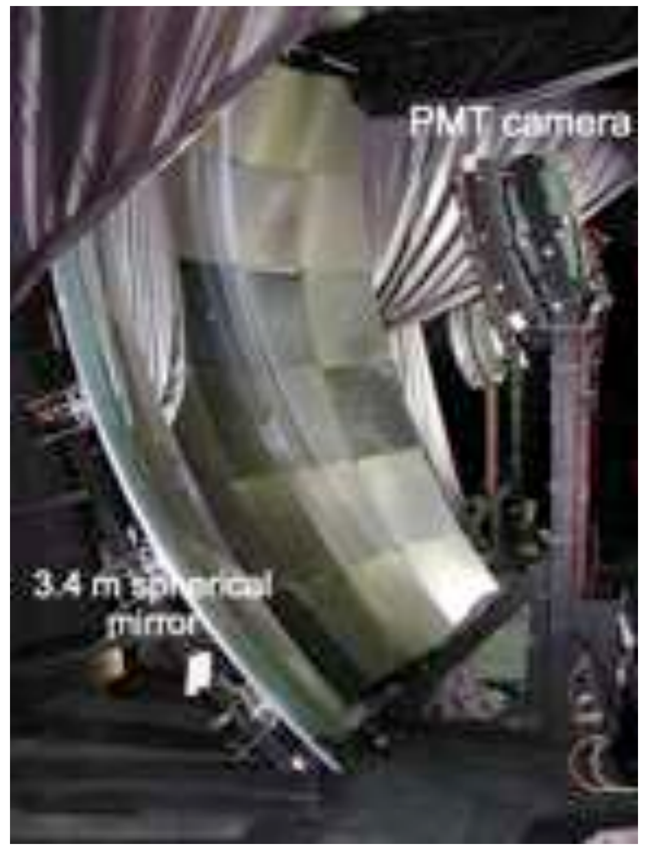
- **Possible source region** (Unger and Farrar, arXiv:2312.13273)
- **Monopole** (Frampton, arXiv:2403.12322)
- **Binary neutron star merger** (Farrar, arXiv:2405.12004)
- **Ultra-heavy** composition like Te or Pt (Zhang+, arXiv:2405.17409)

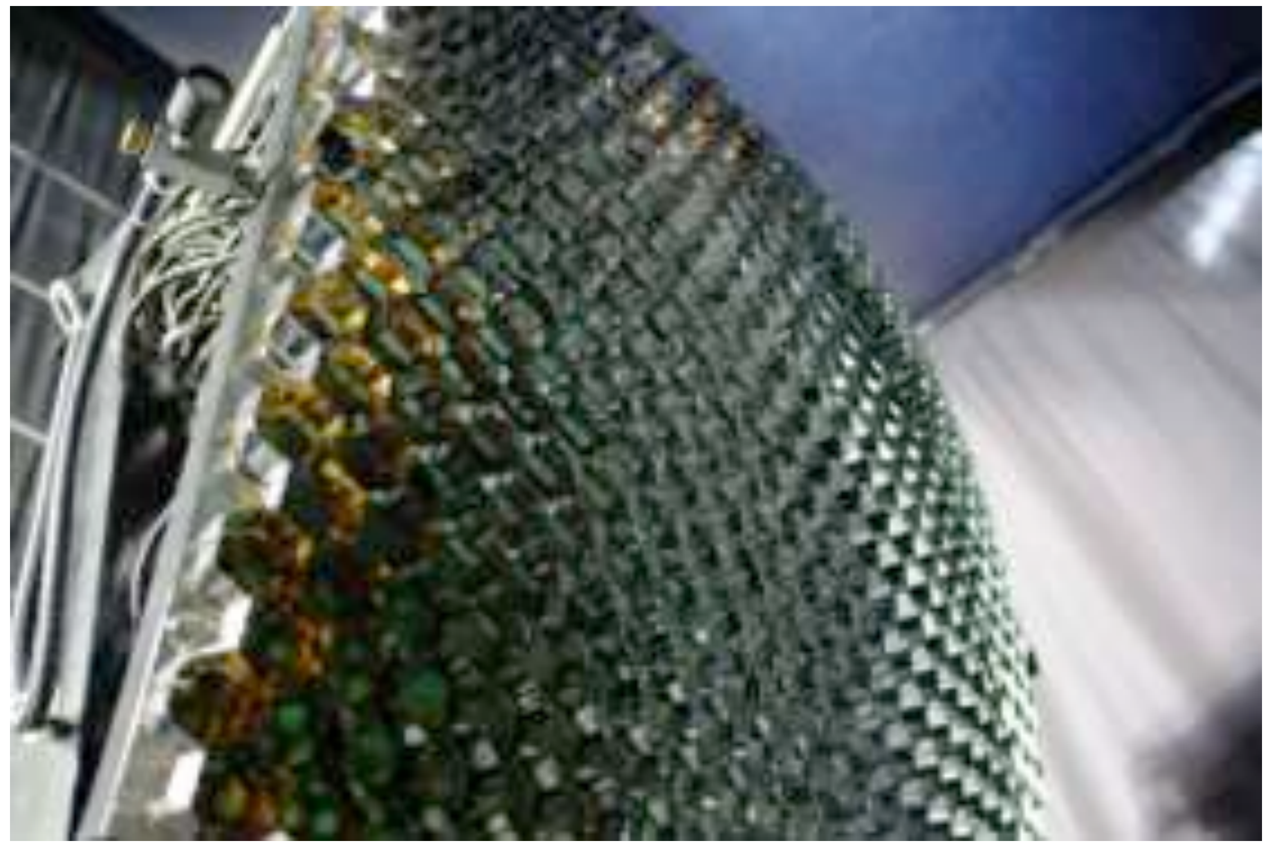
→ **Need more events at the highest energies**

Fluorescence detector Array of Single-pixel Telescopes

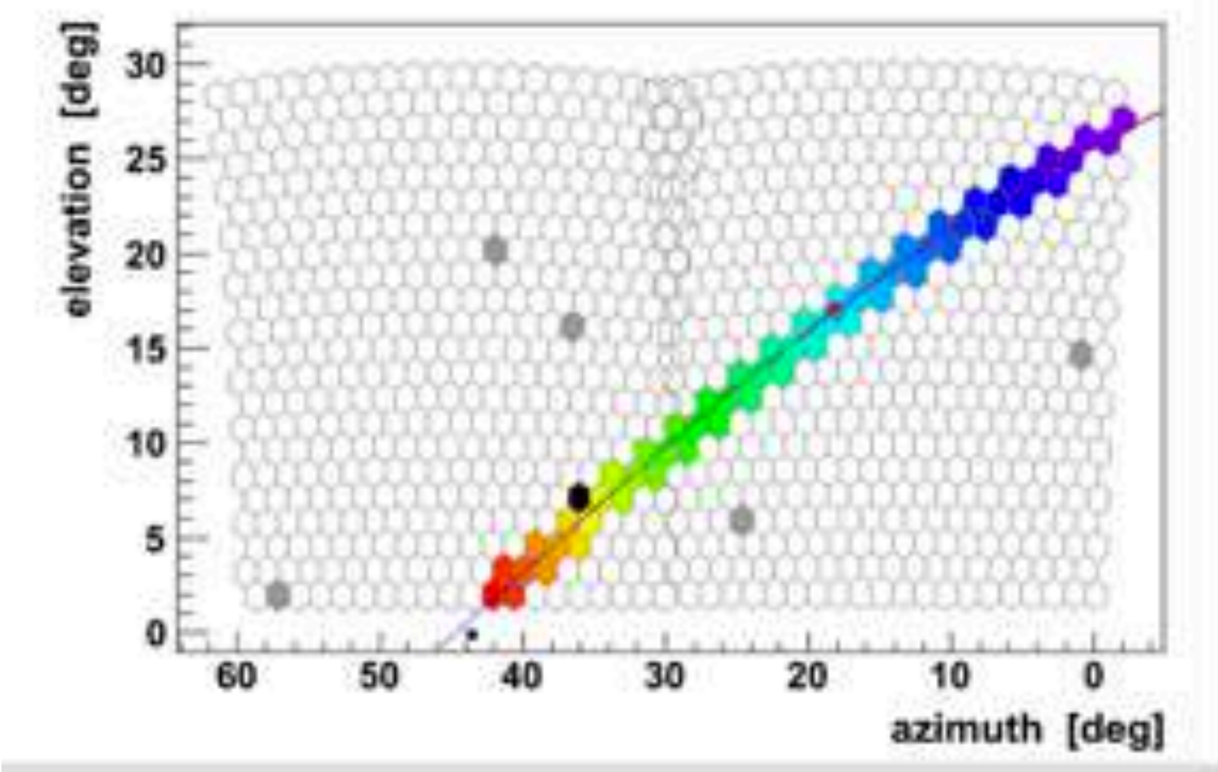
- **Target : > $10^{19.5}$ eV, ultrahigh-energy cosmic rays, neutrino and gamma rays**
  - Huge target volume (10x Auger or TAx4) ⇒ Fluorescence detector array

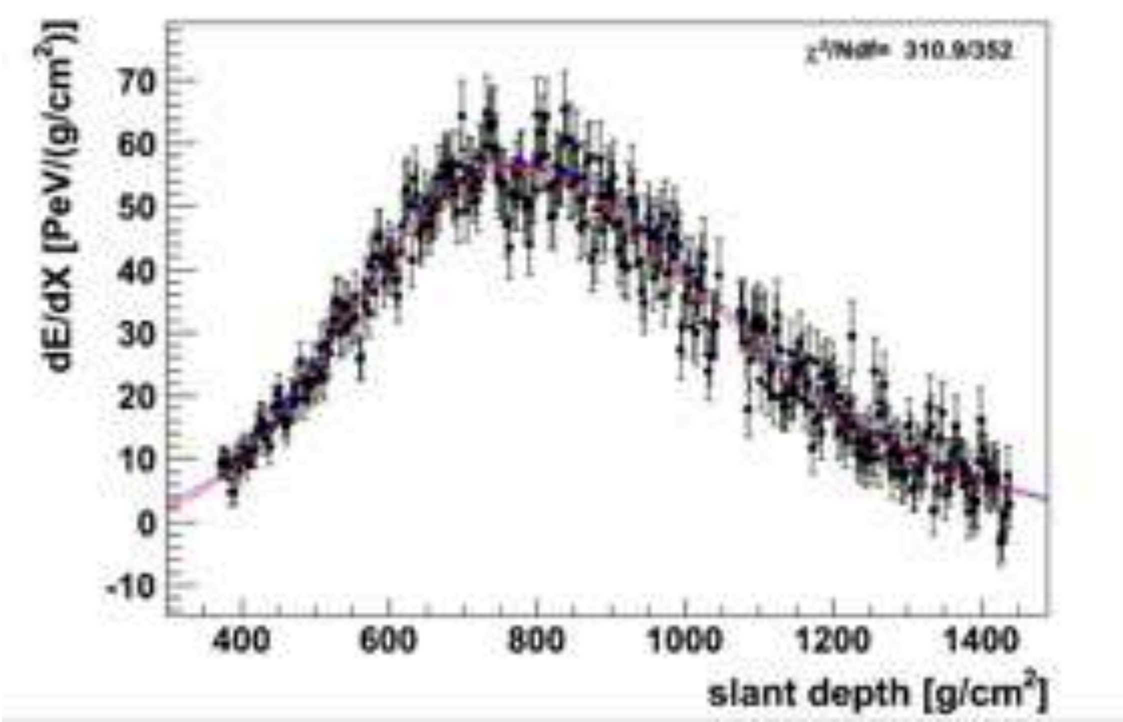
Fine pixelated camera



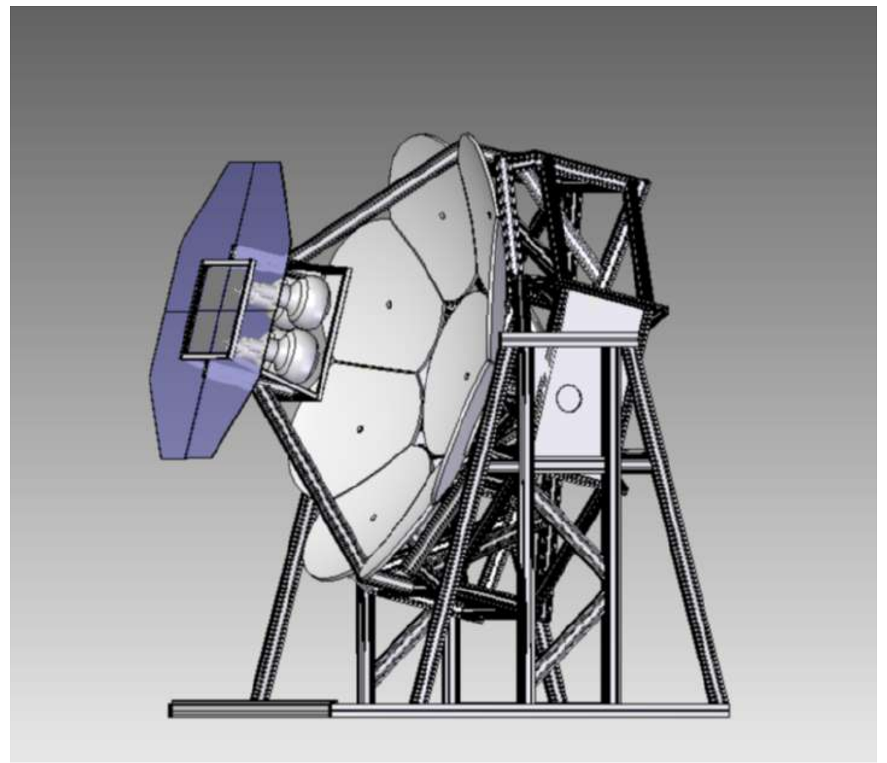


Too expensive to cover a huge area

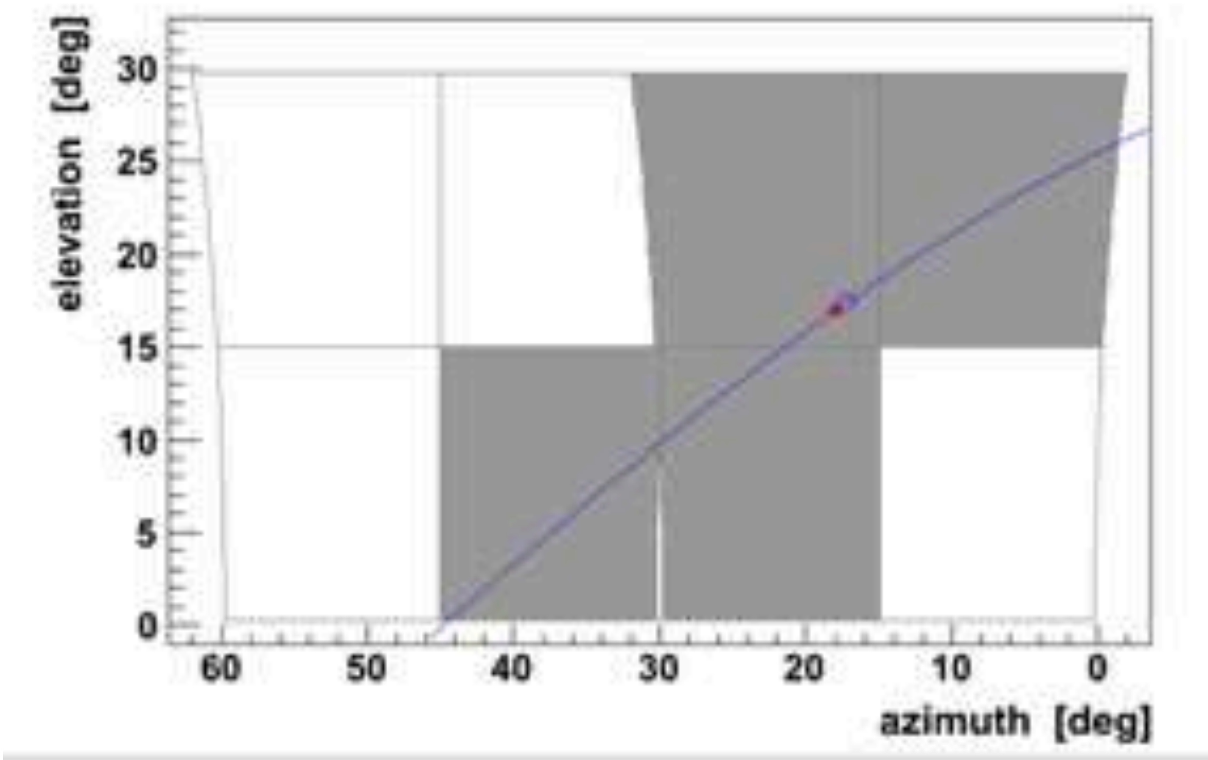


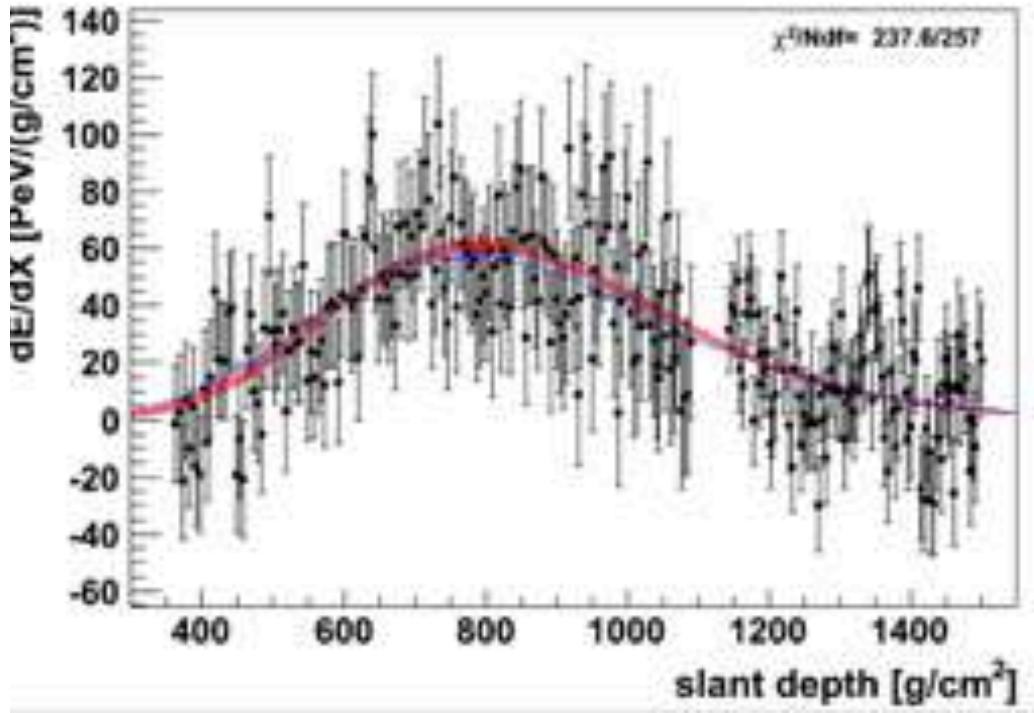


Smaller optics and single or few pixels

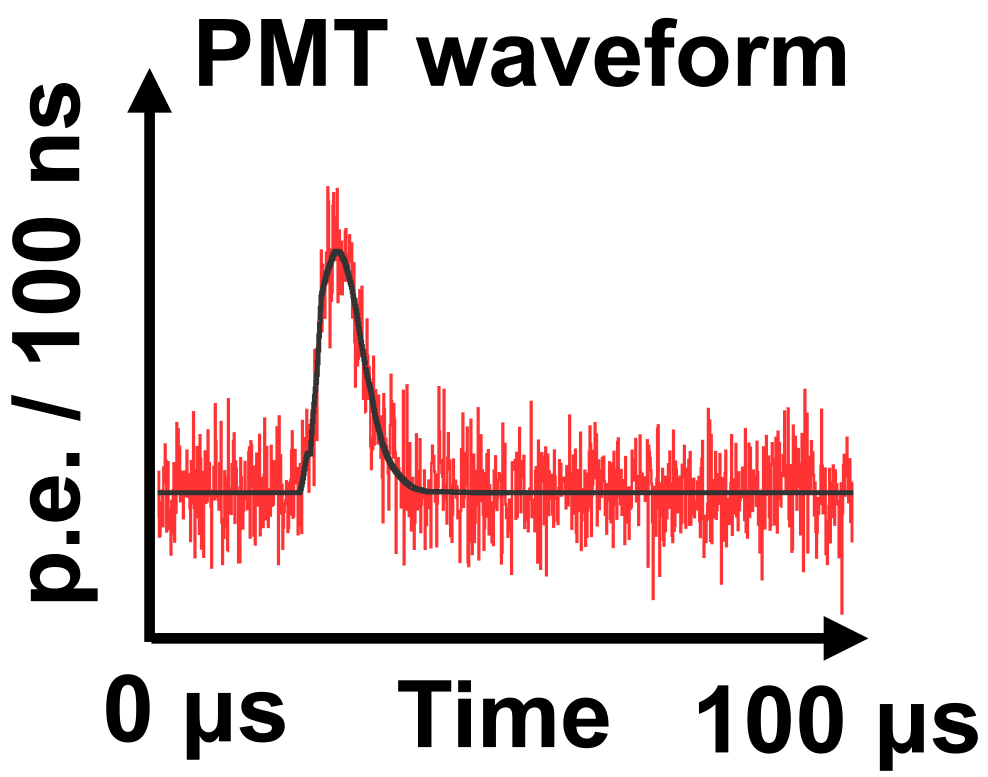


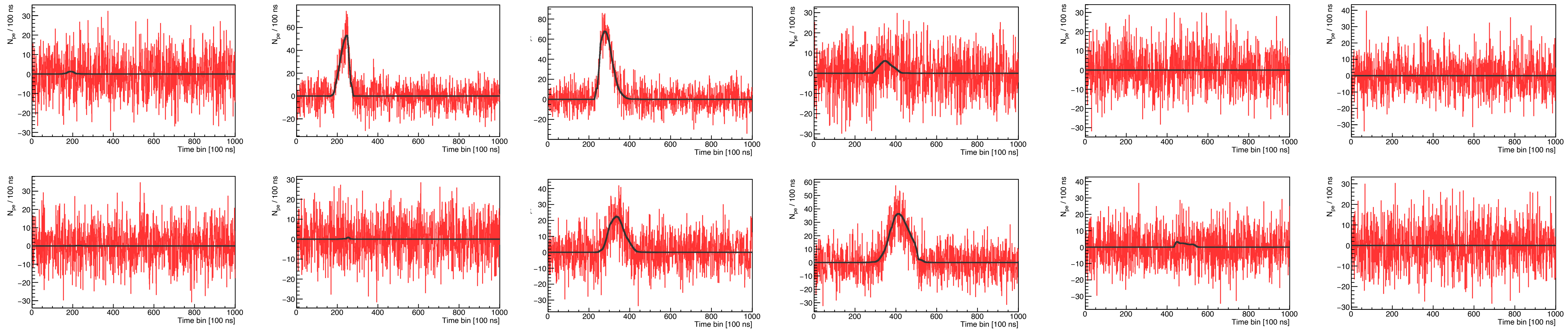
Low-cost and simplified telescope

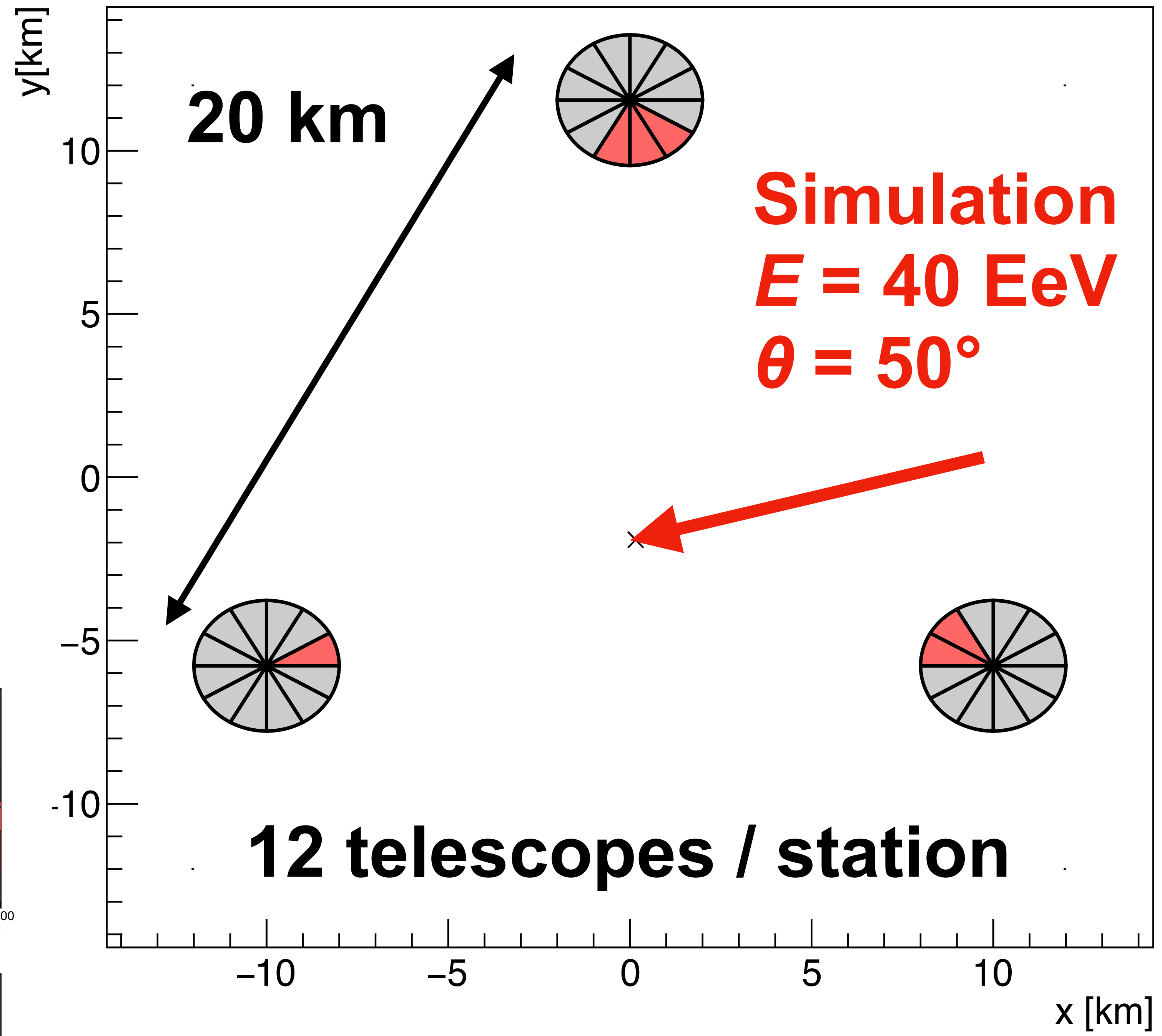




Fluorescence detector Array of Single-pixel Telescopes

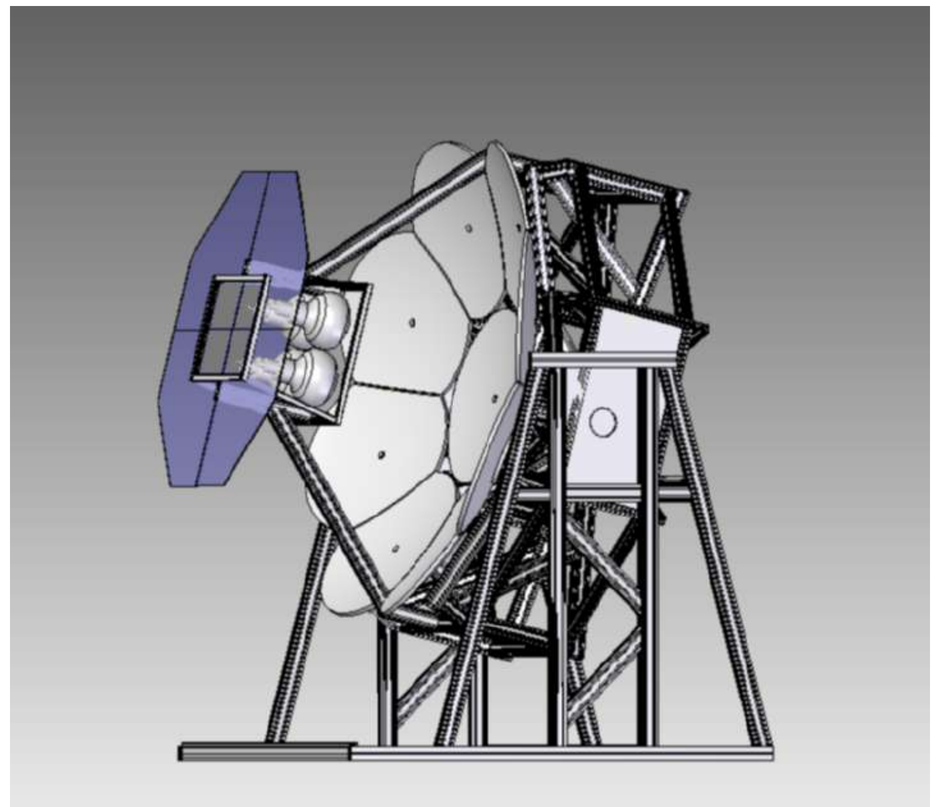






500 stations

→ **<u>150,000 km²</u>**



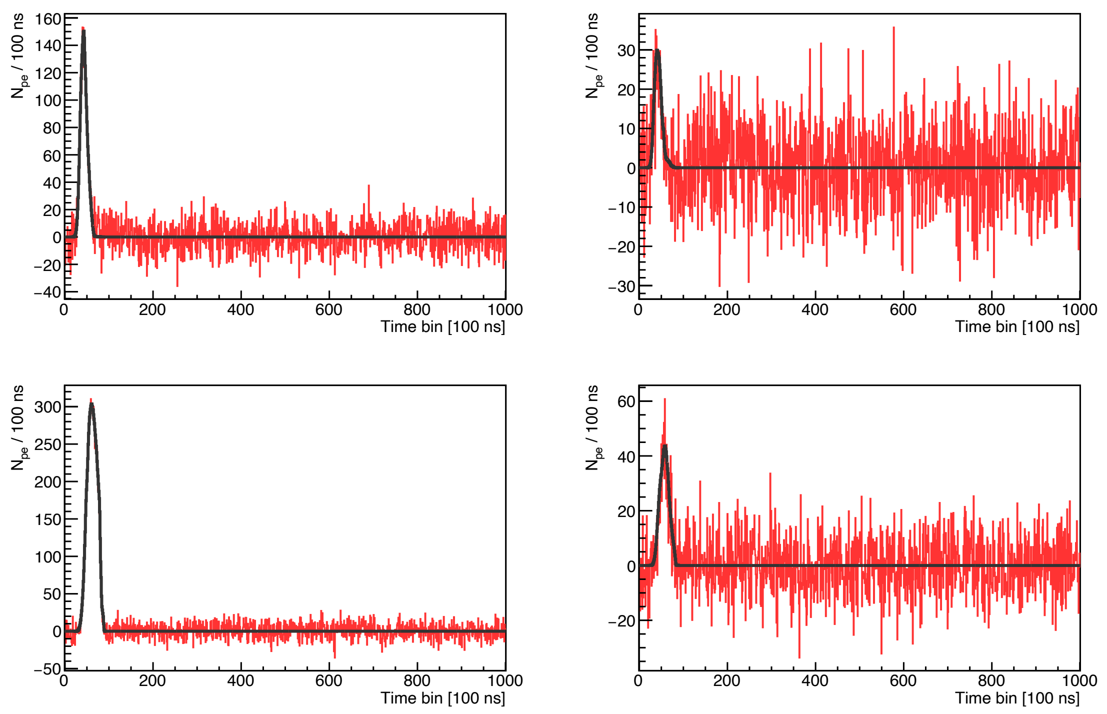
<u>FAST telescope</u>

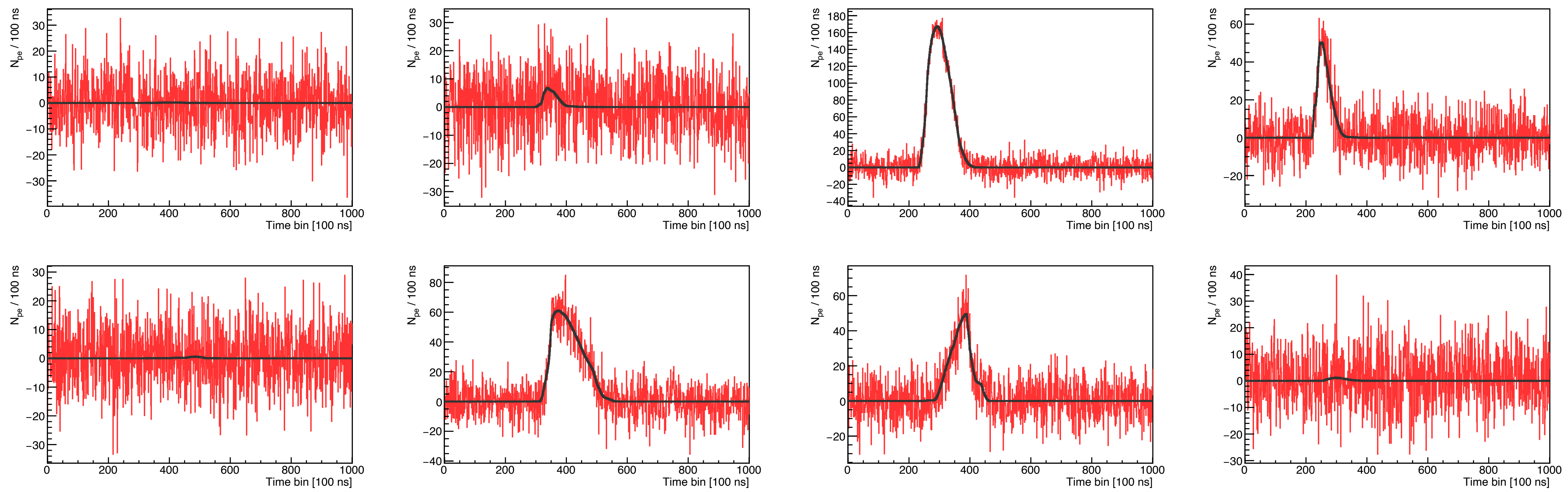
4 PMTs (20 cm diameter)

1 m^2 aperture (UV filter)

Segmented mirror

in 1.6 m diameter





Validations of the FAST concept

Fluorescence detector Array of Single-pixel Telescopes

Feb. 2012

Apr. 2014

Oct. 2016

Sep. 2017

Oct. 2018

@TA

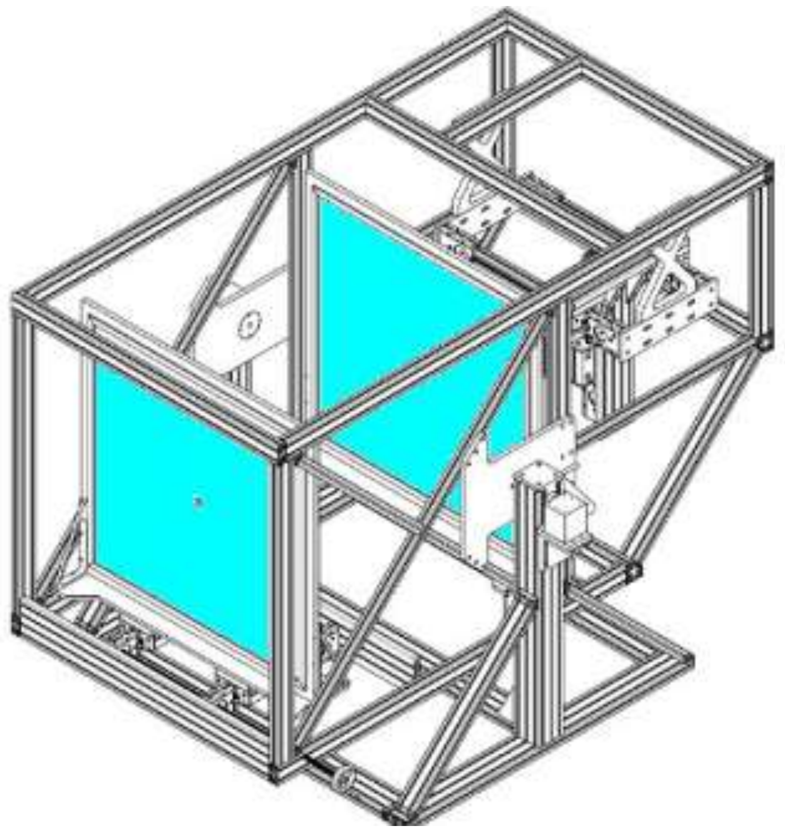
Apr. 2019

Jun. 2022

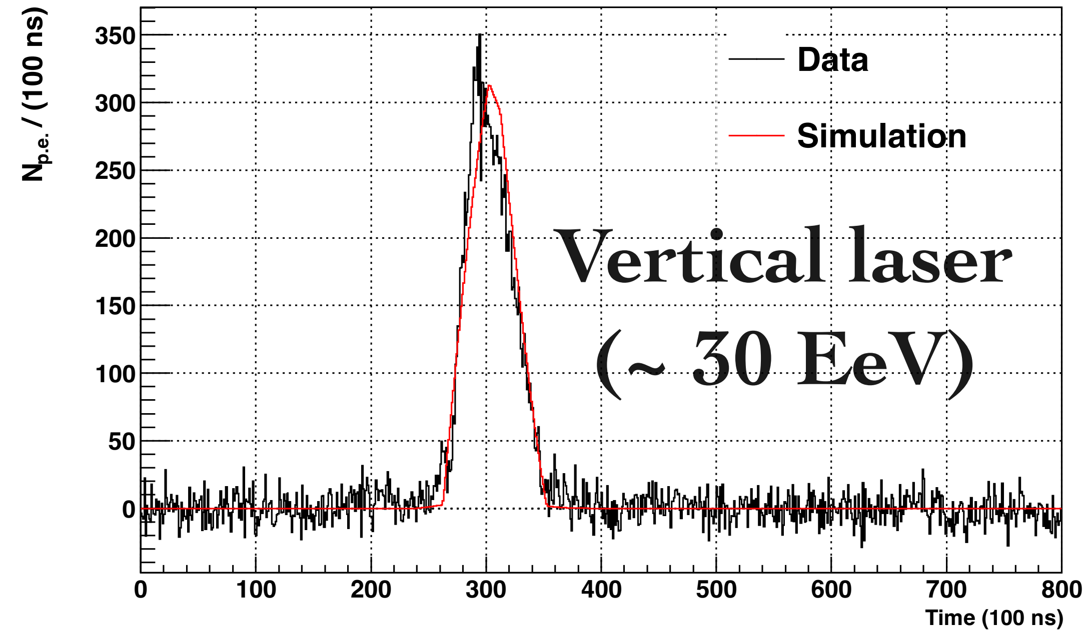
@Auger

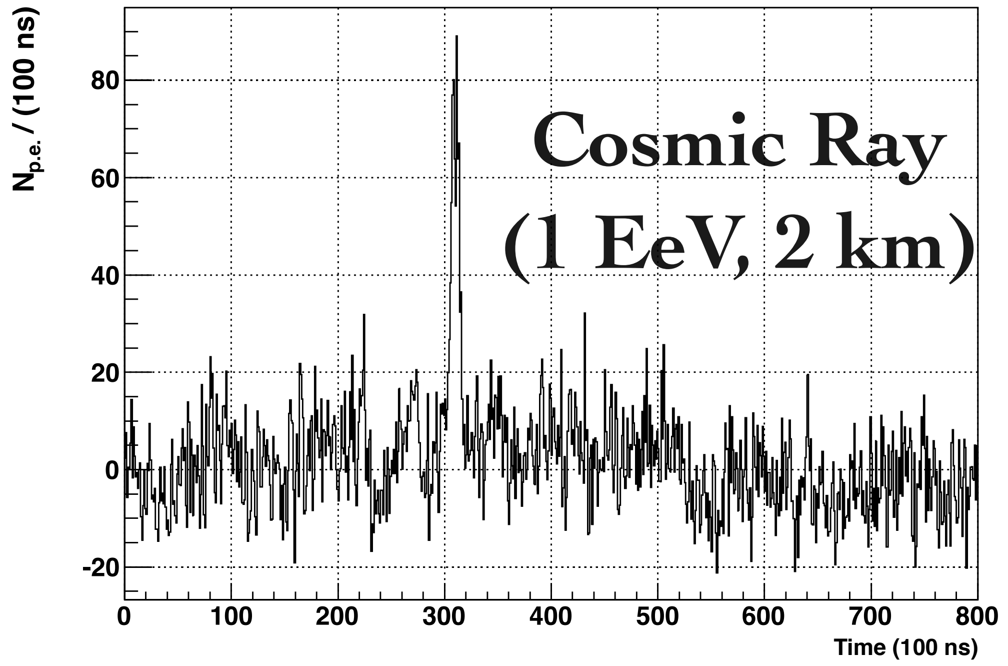
A conceptual design for a large ground array of Fluorescence Detectors

P. Privitera in UHECR 2012



EUSO-TA optics
+
Single-pixel PMT



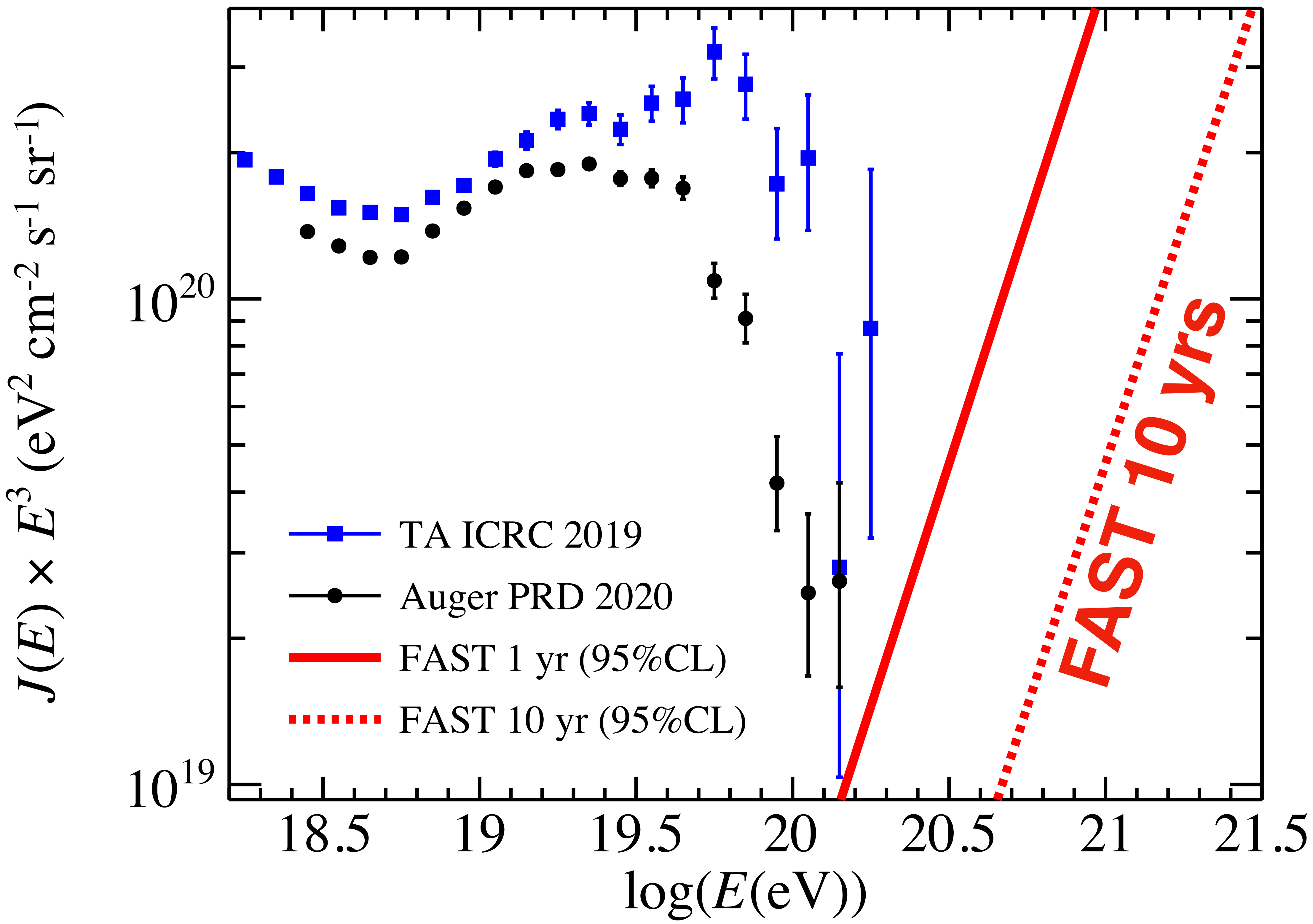


T. Fujii et al., Astroparticle Physics *74* (2016) 64-72

D. Mandat et al., JINST 12, T07001 (2017)

M. Malacari et al., Astroparticle Physics 119 (2020) 102430

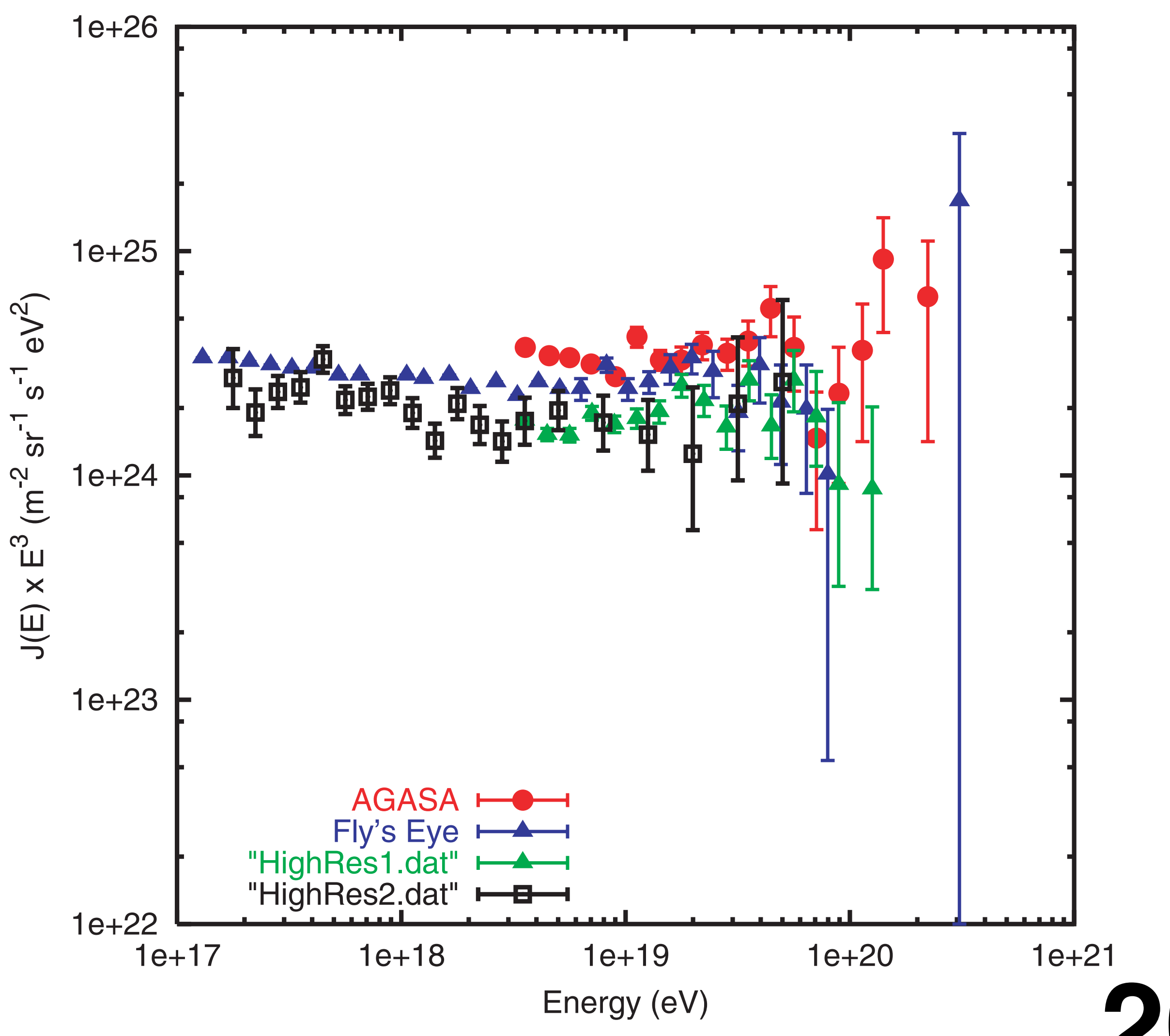
"FAST" installation and scientific goal

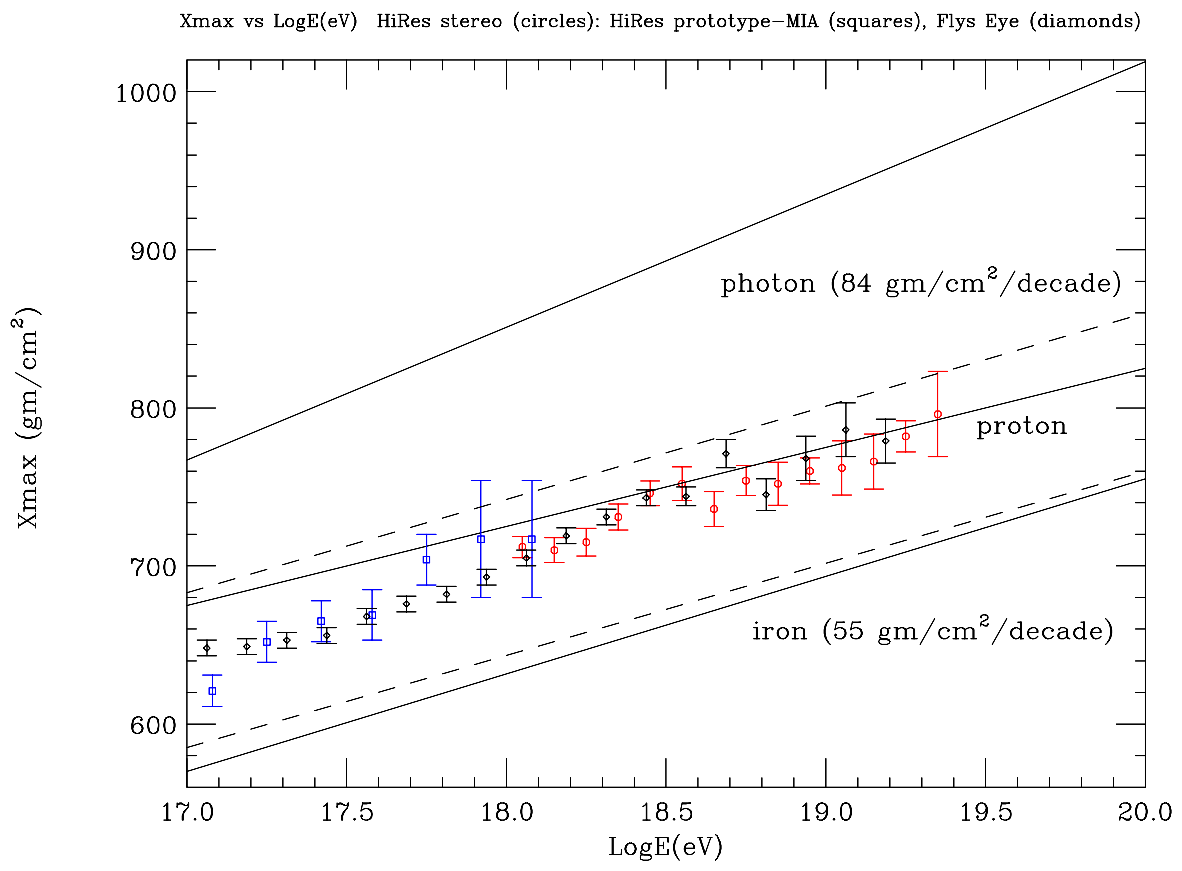


[FAST] 10 × UHECR statistics with X_{max} (mass composition)

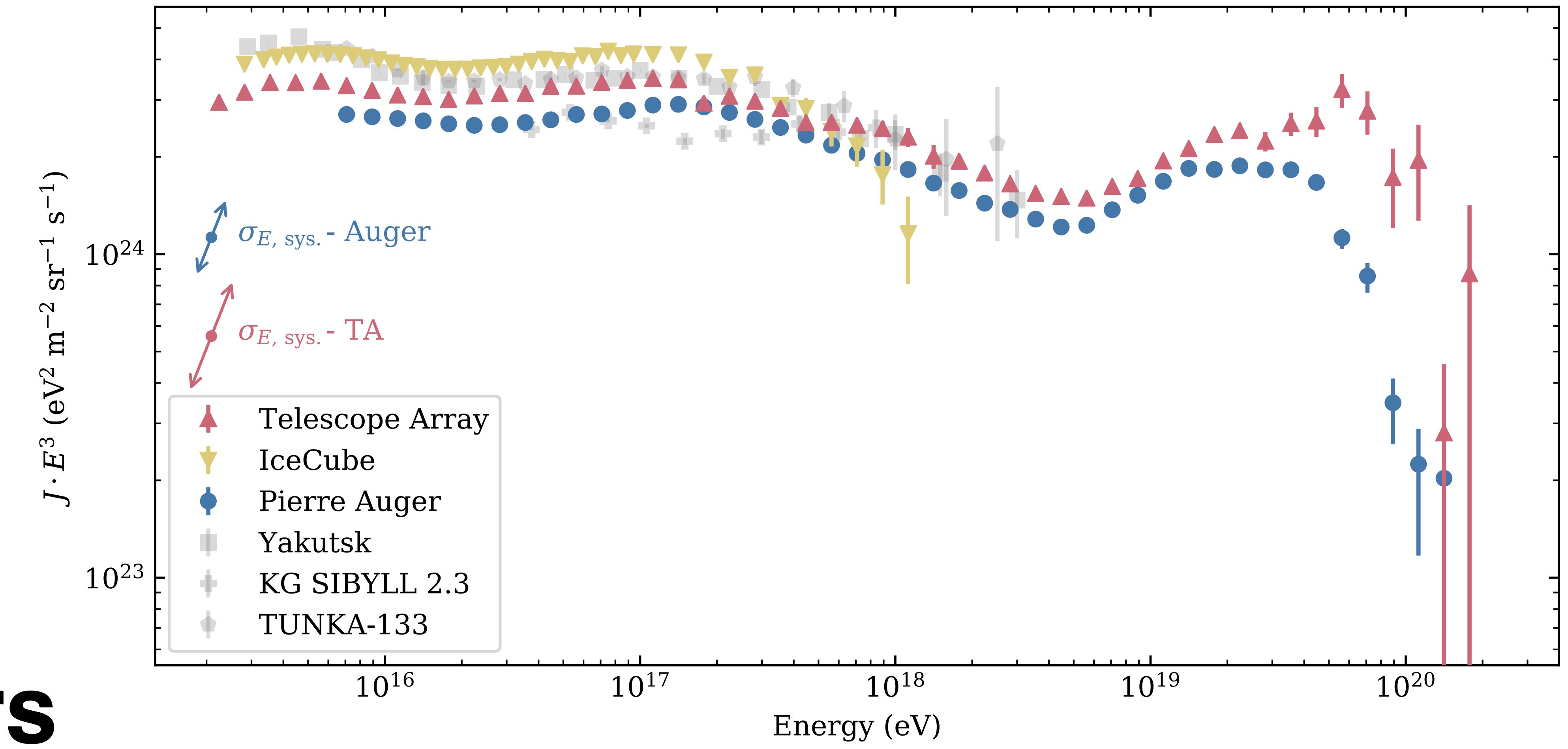
First detection of "ZeV" cosmic ray
Identificcation of UHECR origins

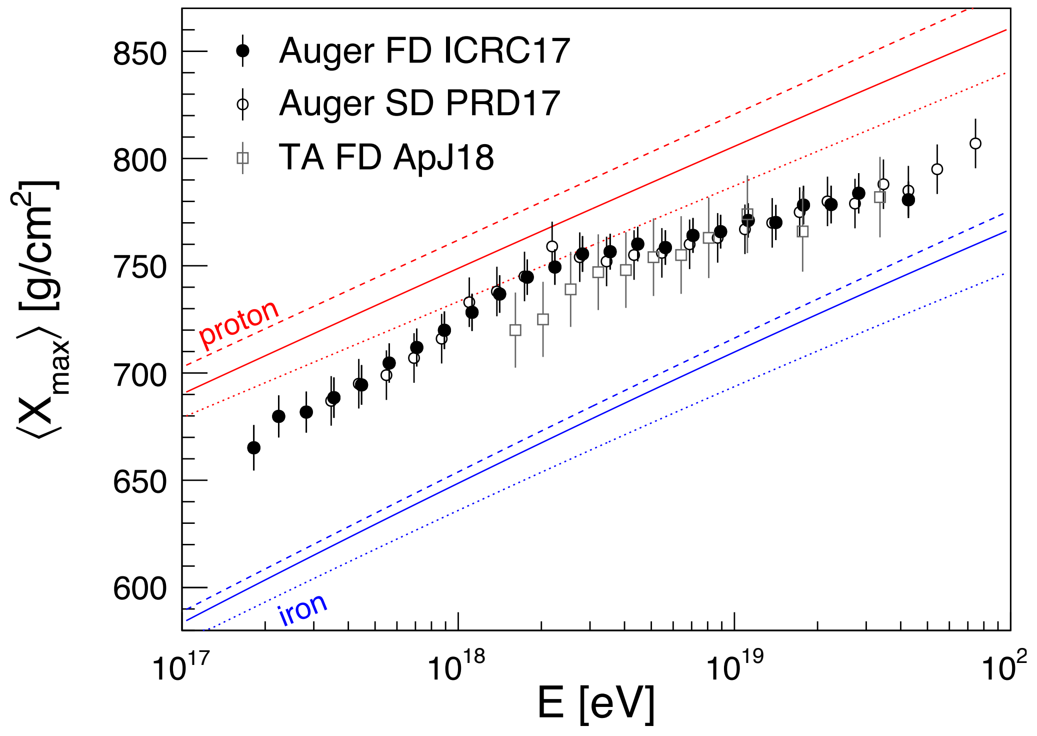
Summary and future perspective

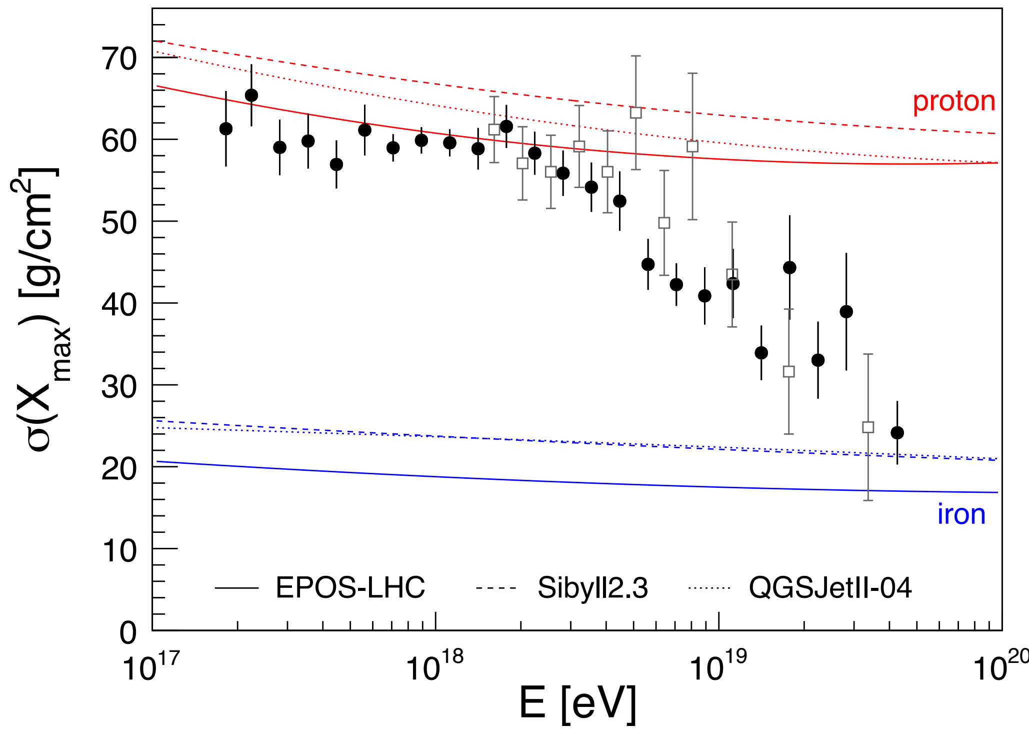


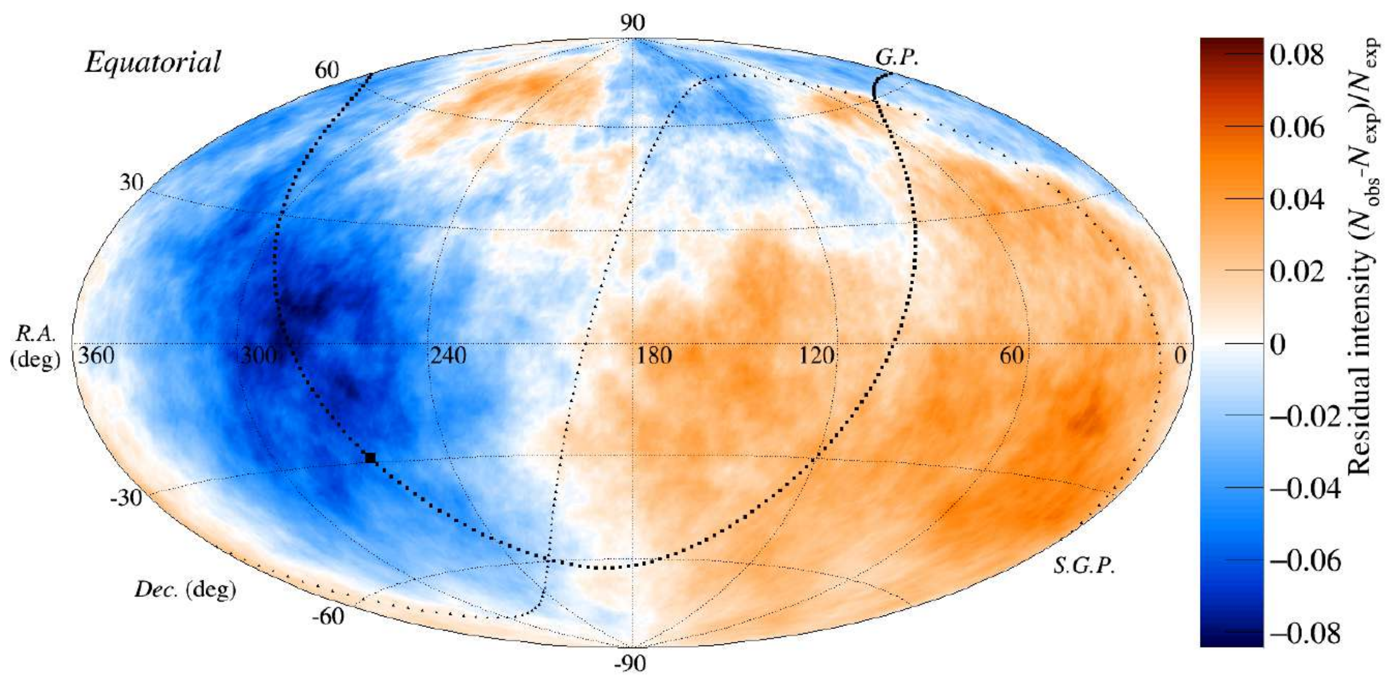


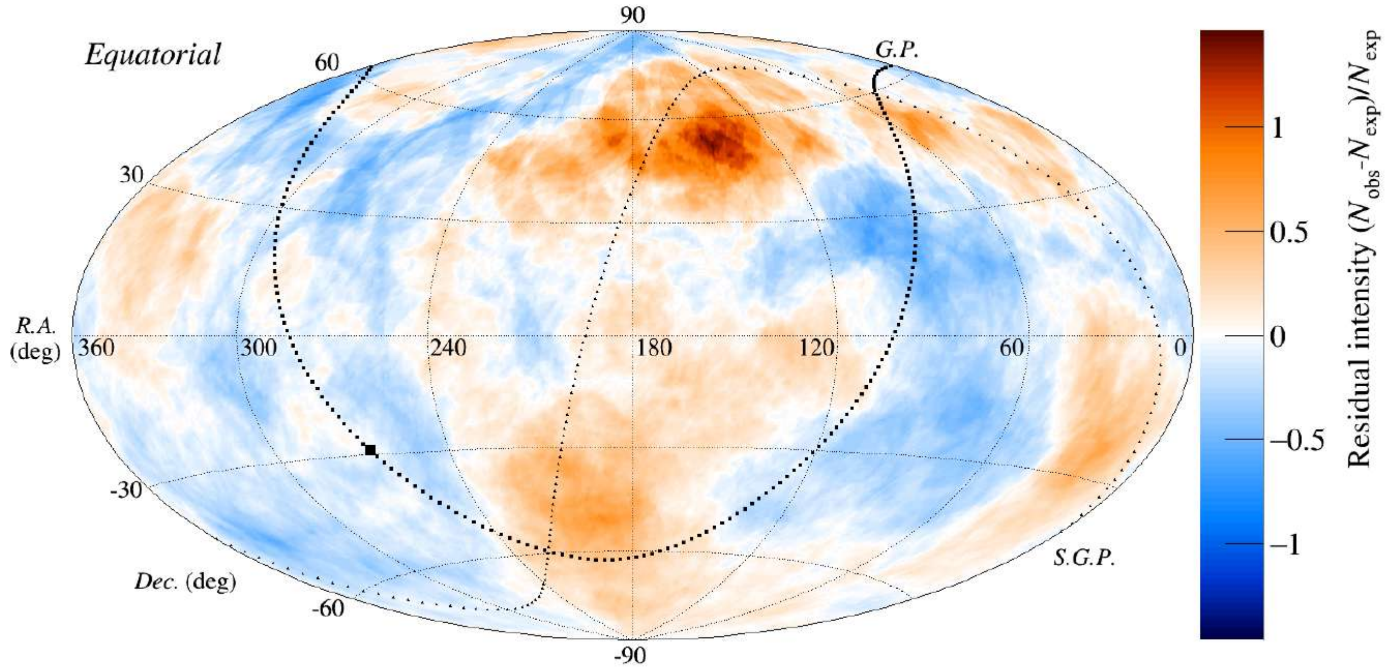
20 years

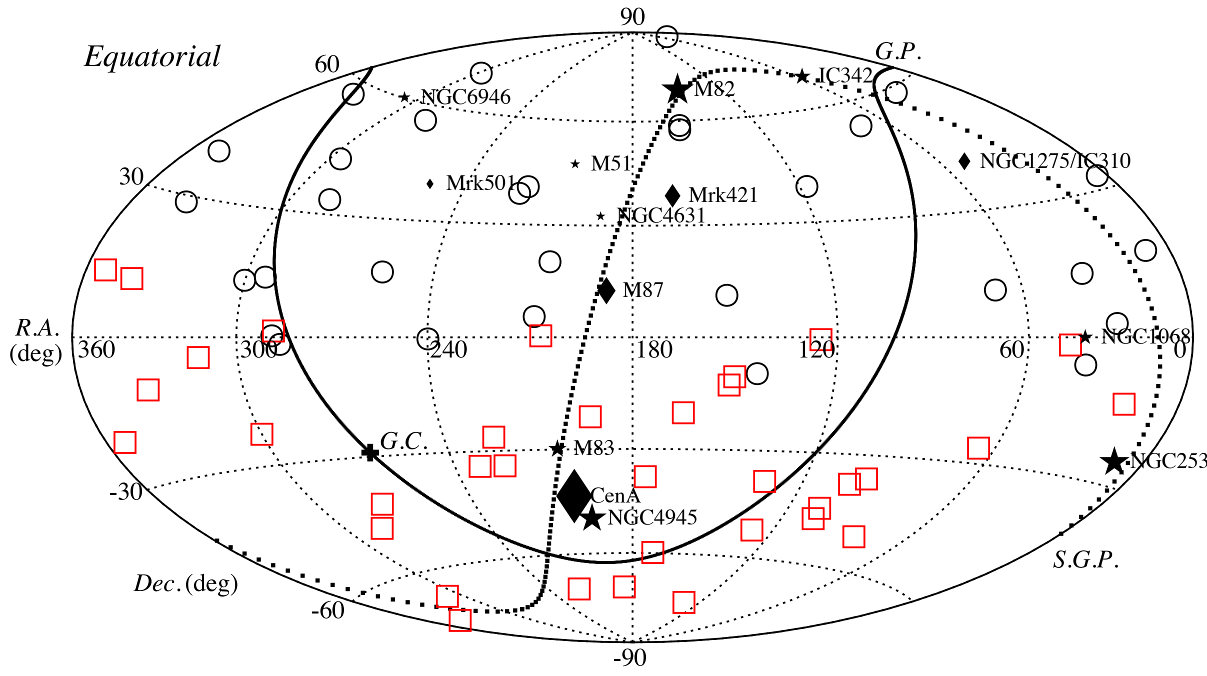


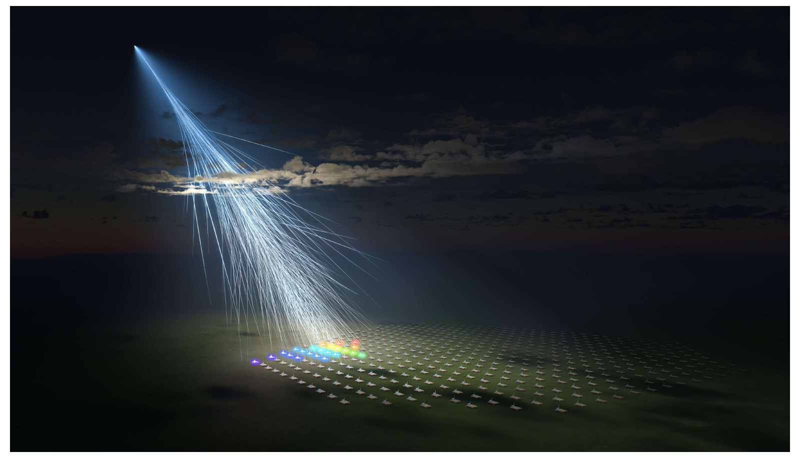










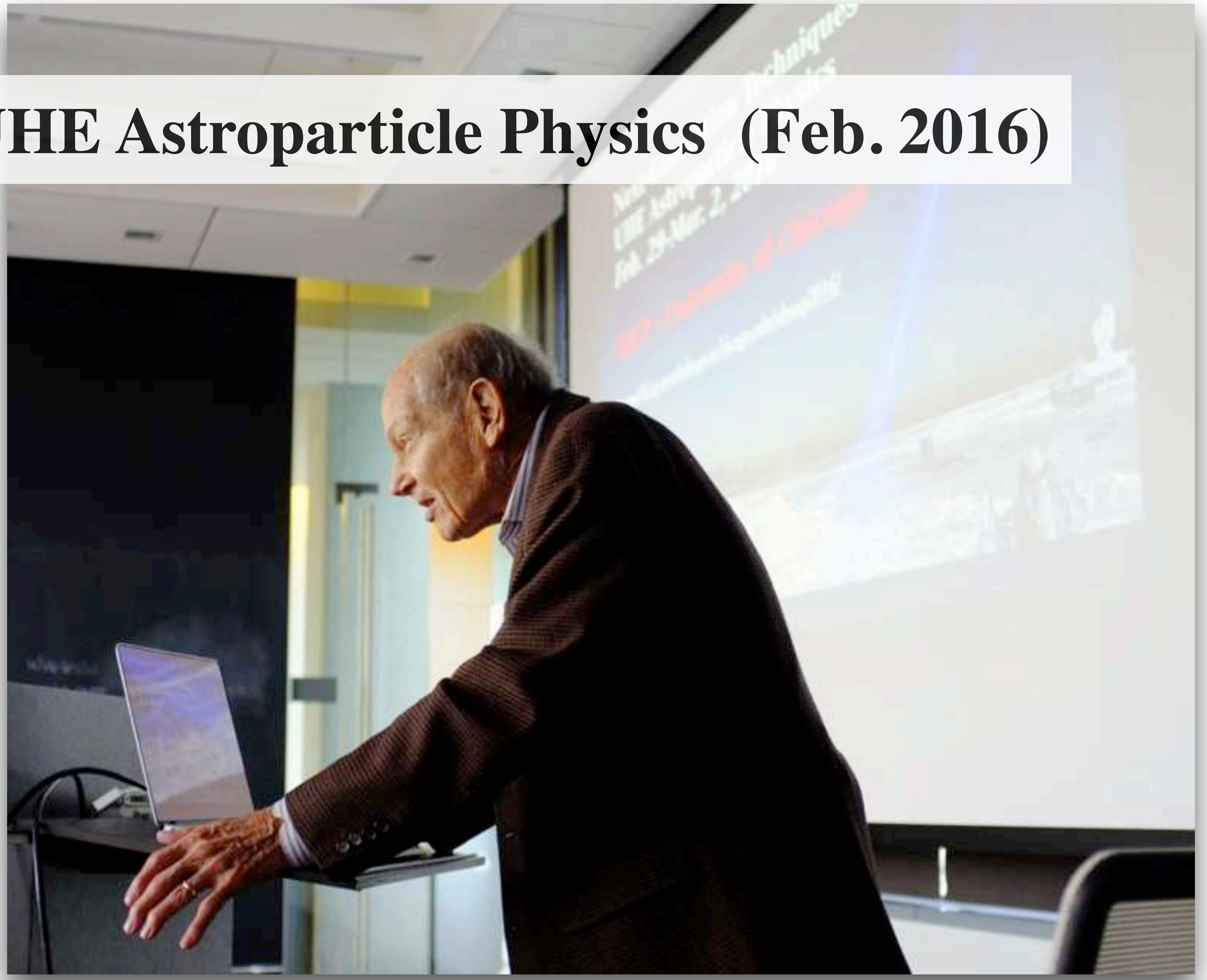


Origins of UHECRs are still inconclusive...

I remind the word from James W. Cronin that "**The greatest pleasure a scientist can experience is to encounter an unexpected discovery.**"

Receiving a baton from Jim

KICP workshop: Next-Generation Technique for UHE Astroparticle Physics (Feb. 2016)



"I hope you can bring the single pixel fluorescence detector to practical application. While most of my colleagues are pleased with the results of Auger, I am disappointed we failed to find sources. Instrumentation like yours may make that possible some day."

James W. Cronin, From email received in March 2016