# The 100-year endeavor for detecting the highest energy cosmic rays

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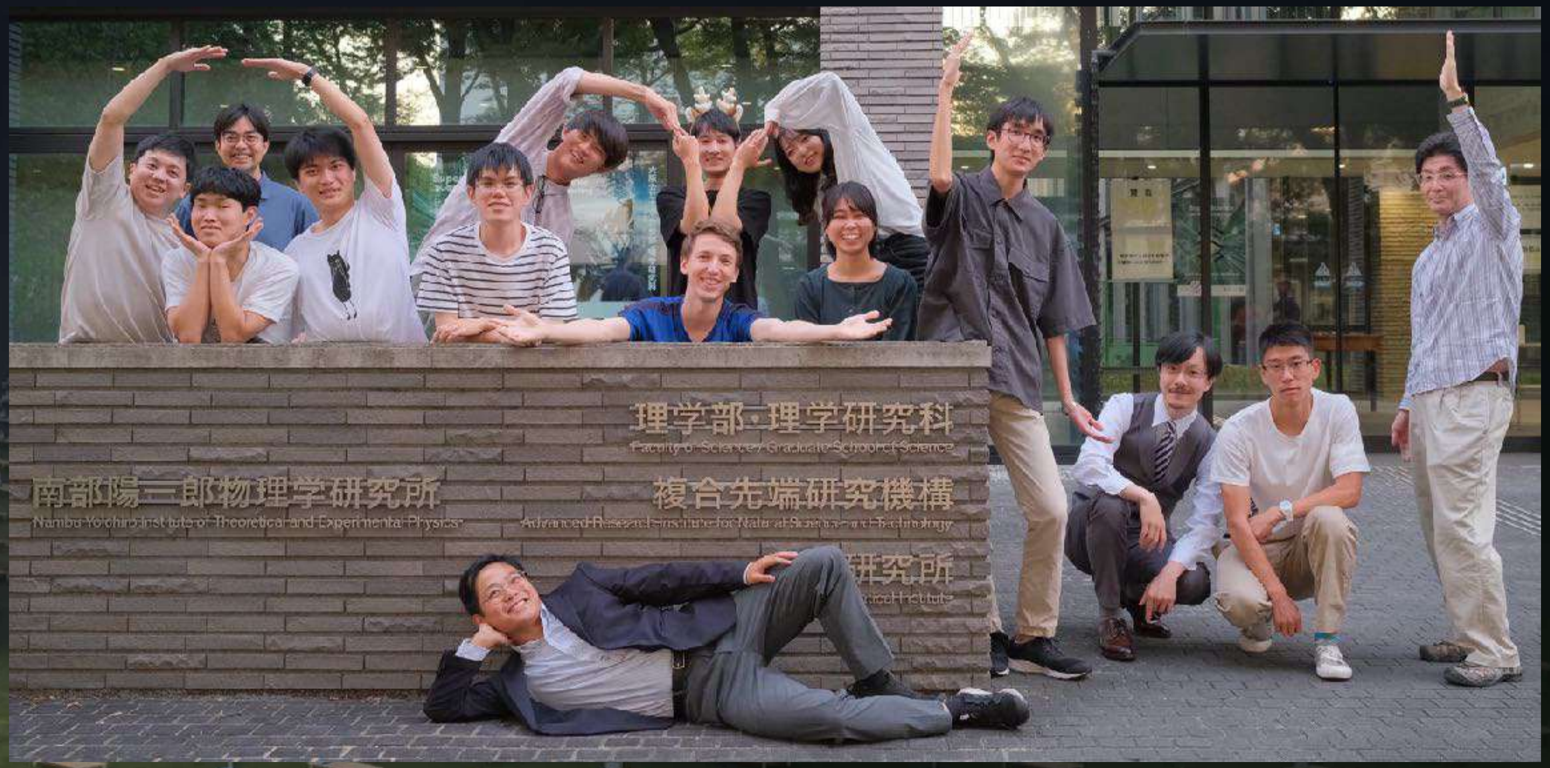
TeVPA 2024, August 26 2024



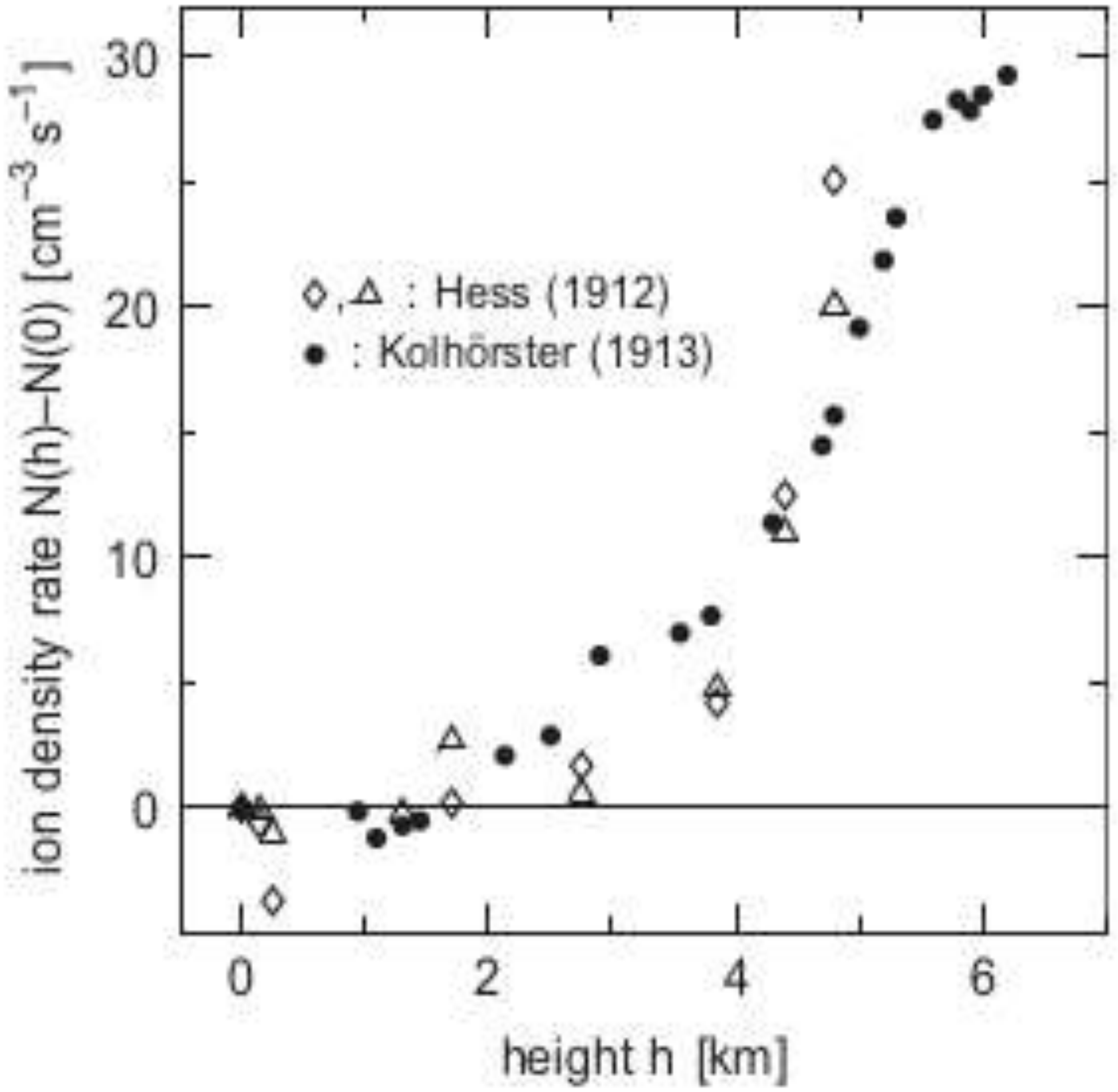
# What are cosmic rays?

- 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**

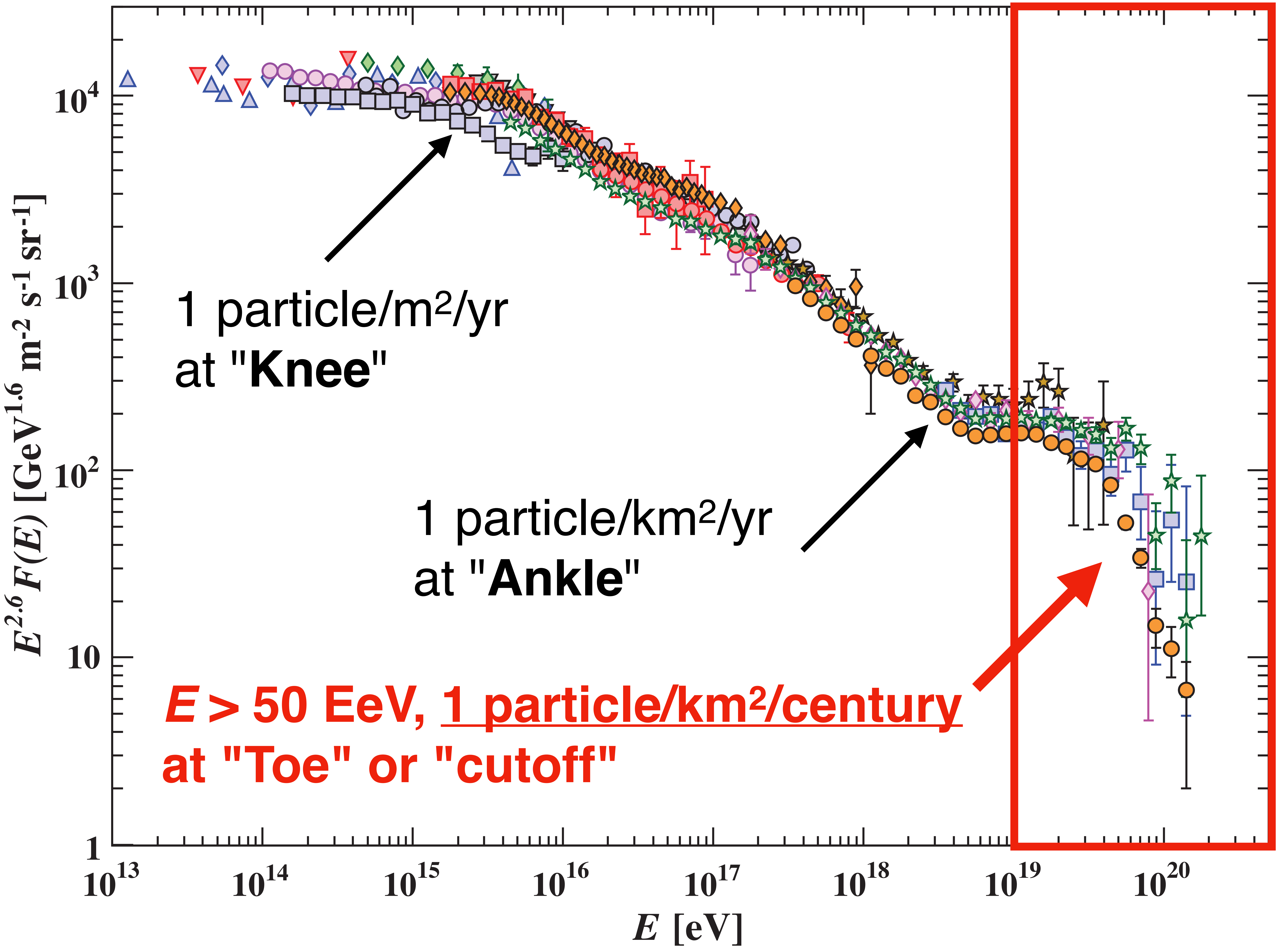



W. Kolhörster, Phys. Z. 14, 1153 (1913)

**9300 m**

# Energy spectrum of cosmic rays

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




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

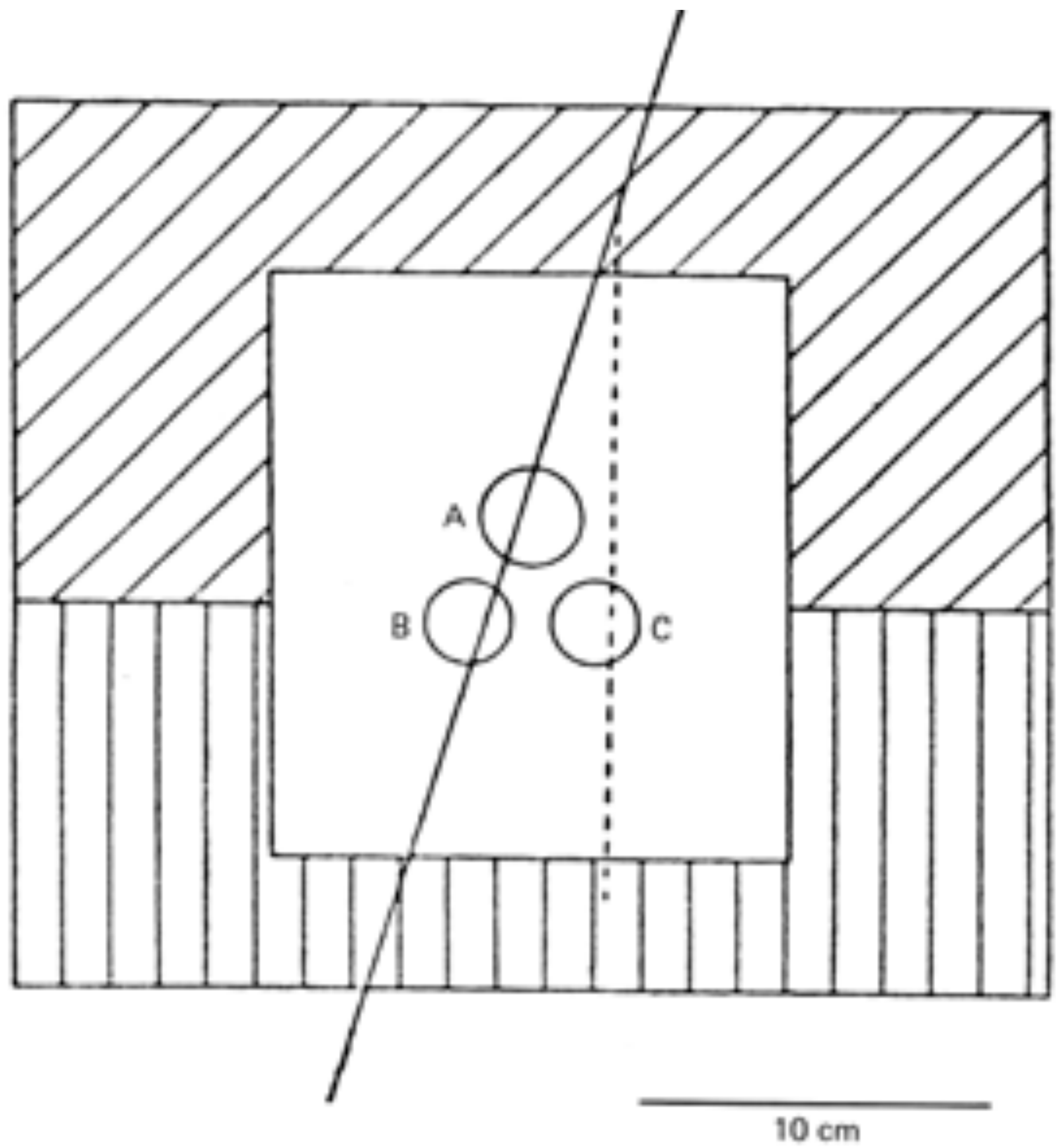
Particle Data Group, Phys.Rev.D, 98, 030001 (2018)

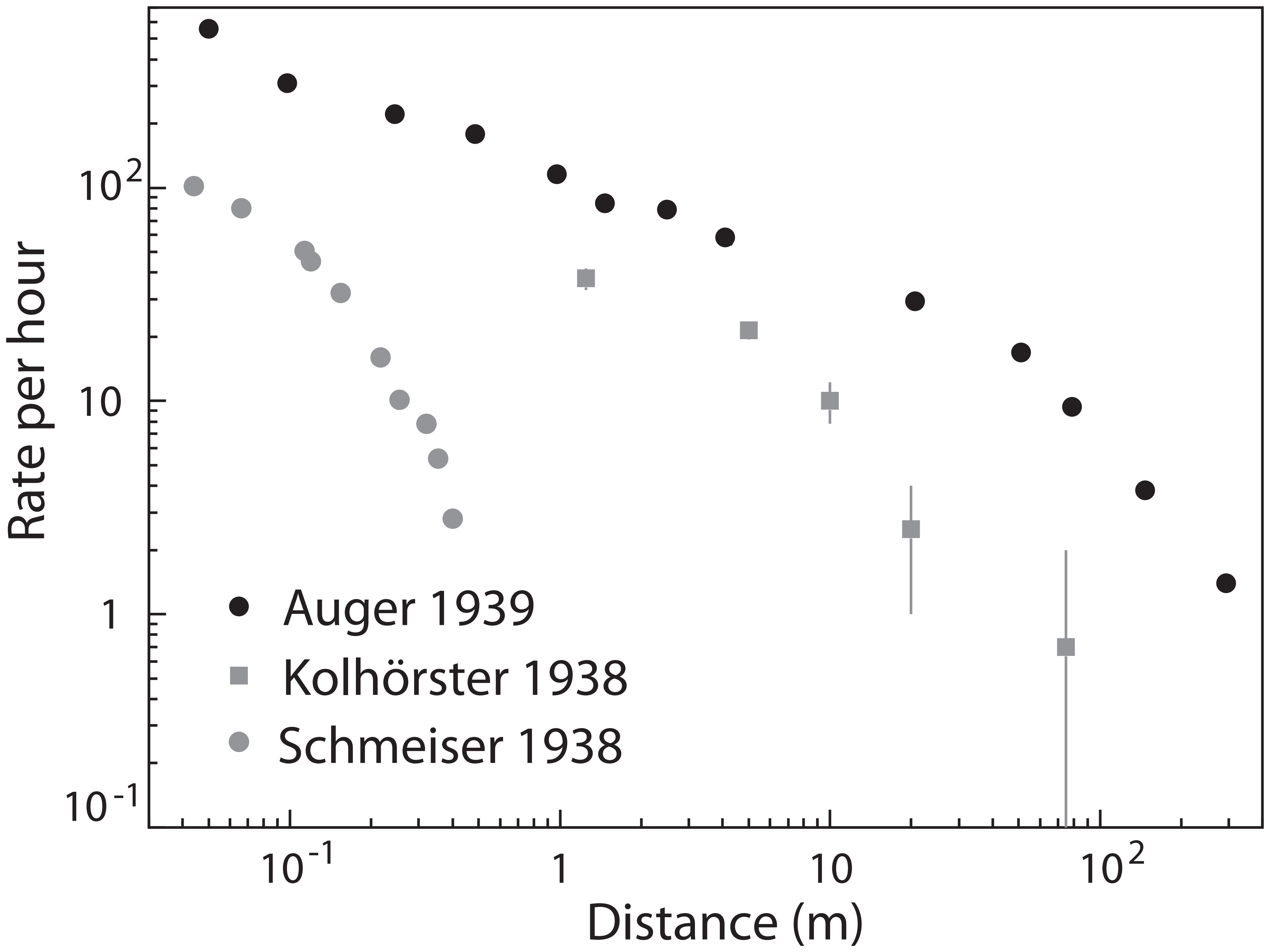
- Measurements of cosmic rays from **$10^9$ eV** to **$10^{20}$ eV**
  - **Origins are still largely unknown**
- **The most energetic particles in the universe**
  - **Only ~$10^{13}$ eV** by the Earth's largest particle accelerator
- **Extremely infrequent**
  - A huge effective area, ~1000 km²
  - Long term observation in decades

# 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)

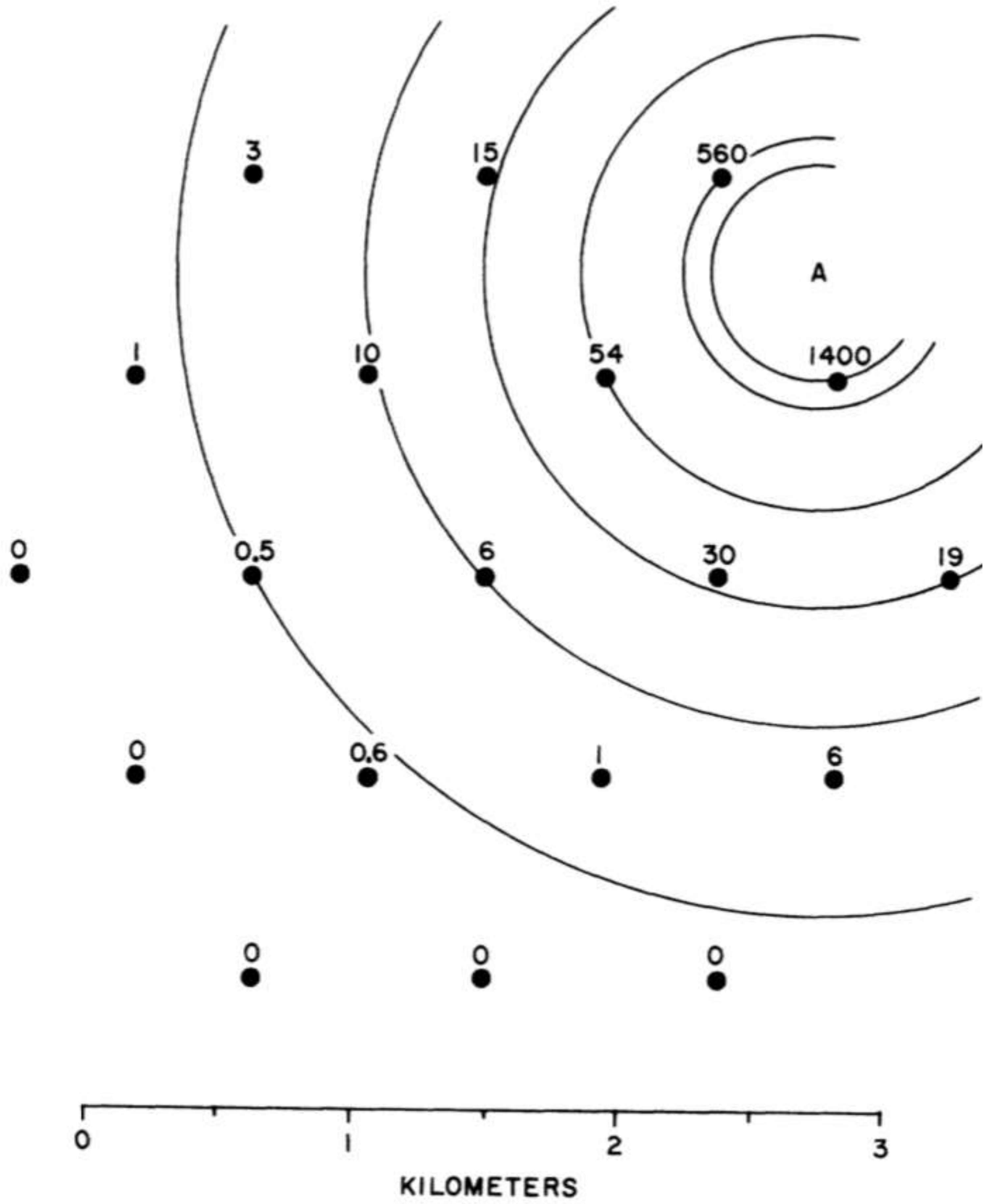



K.H. Kampert, A.A. Watson, Eur. Phys. J. H 37, 359–412 (2012)

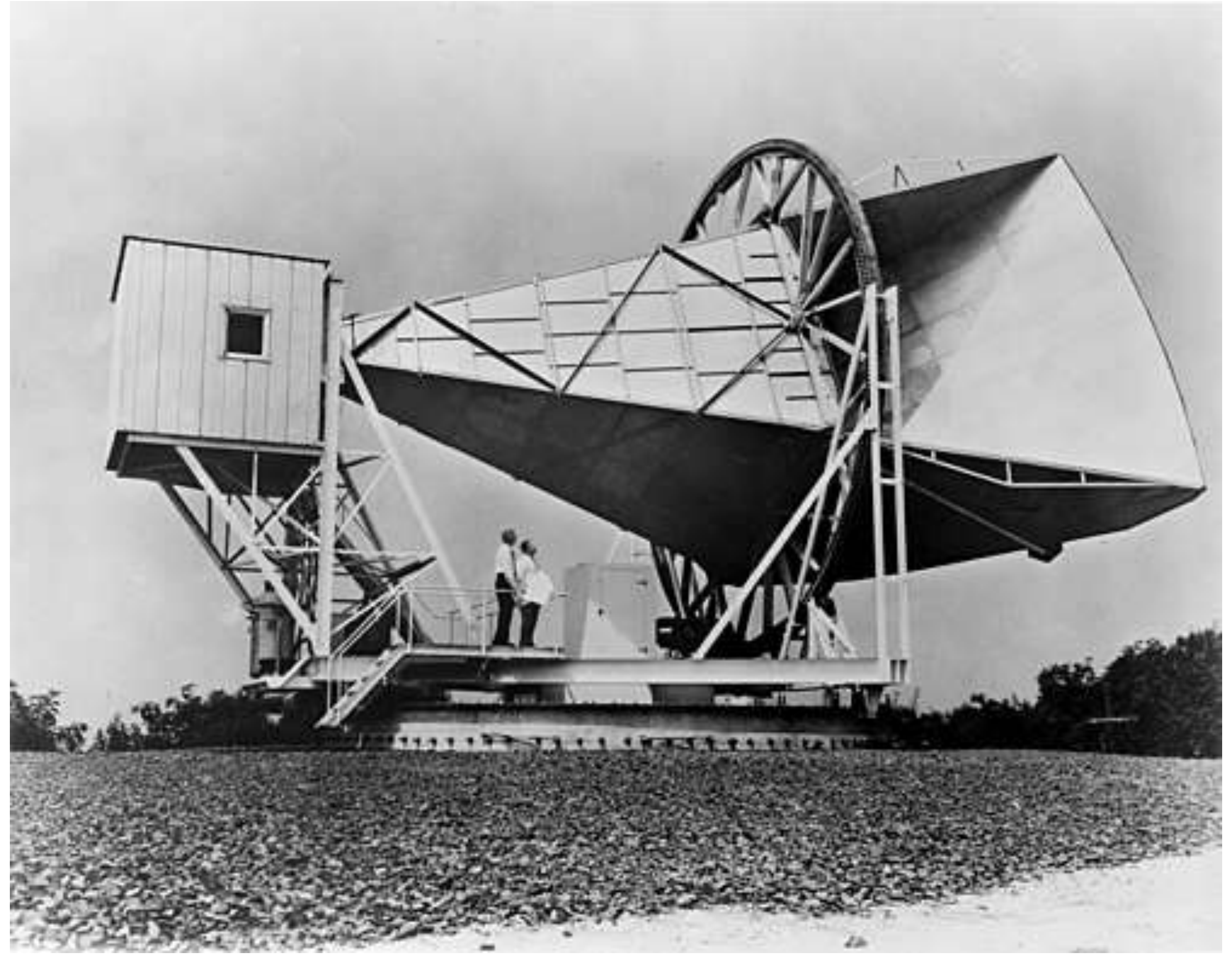
# The beginning of 100 EeV ($10^{20}$ eV) detection

## 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)

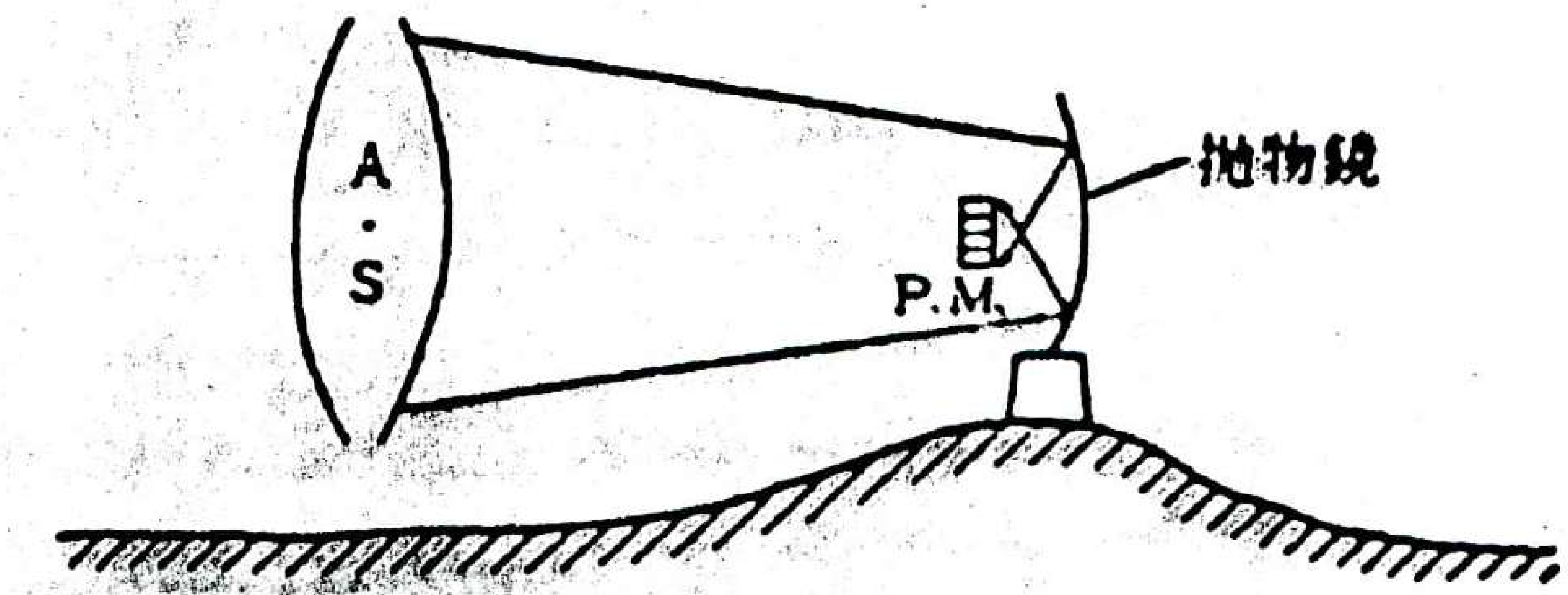
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

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

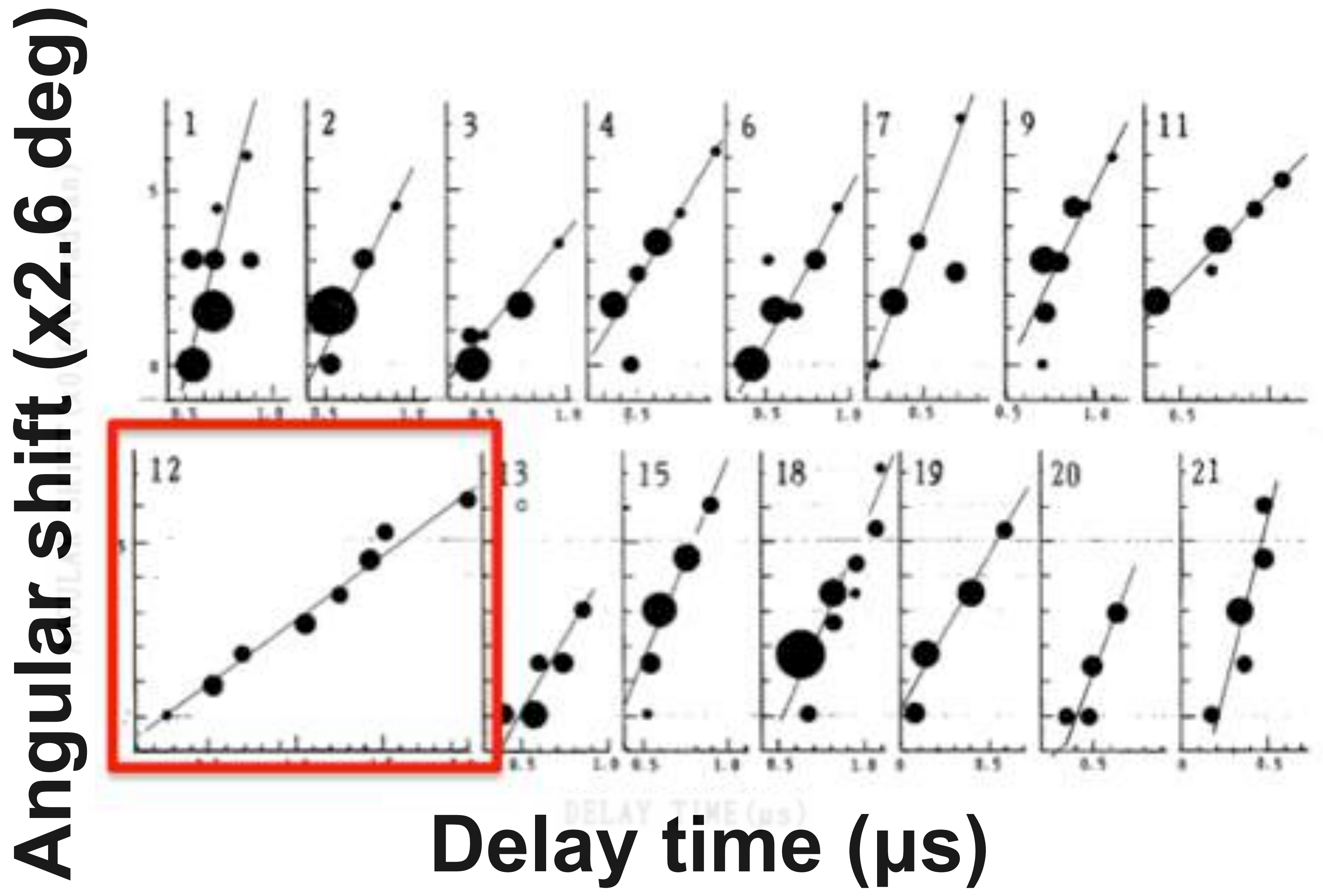

How to detect extremely infrequent UHECRs?
Extensive air showers
Surface detector array
Fluorescence detector
© Osaka Metropolitan University/Kyoto University/Ryuunosuke Takeshige

# History of fluorescence detector

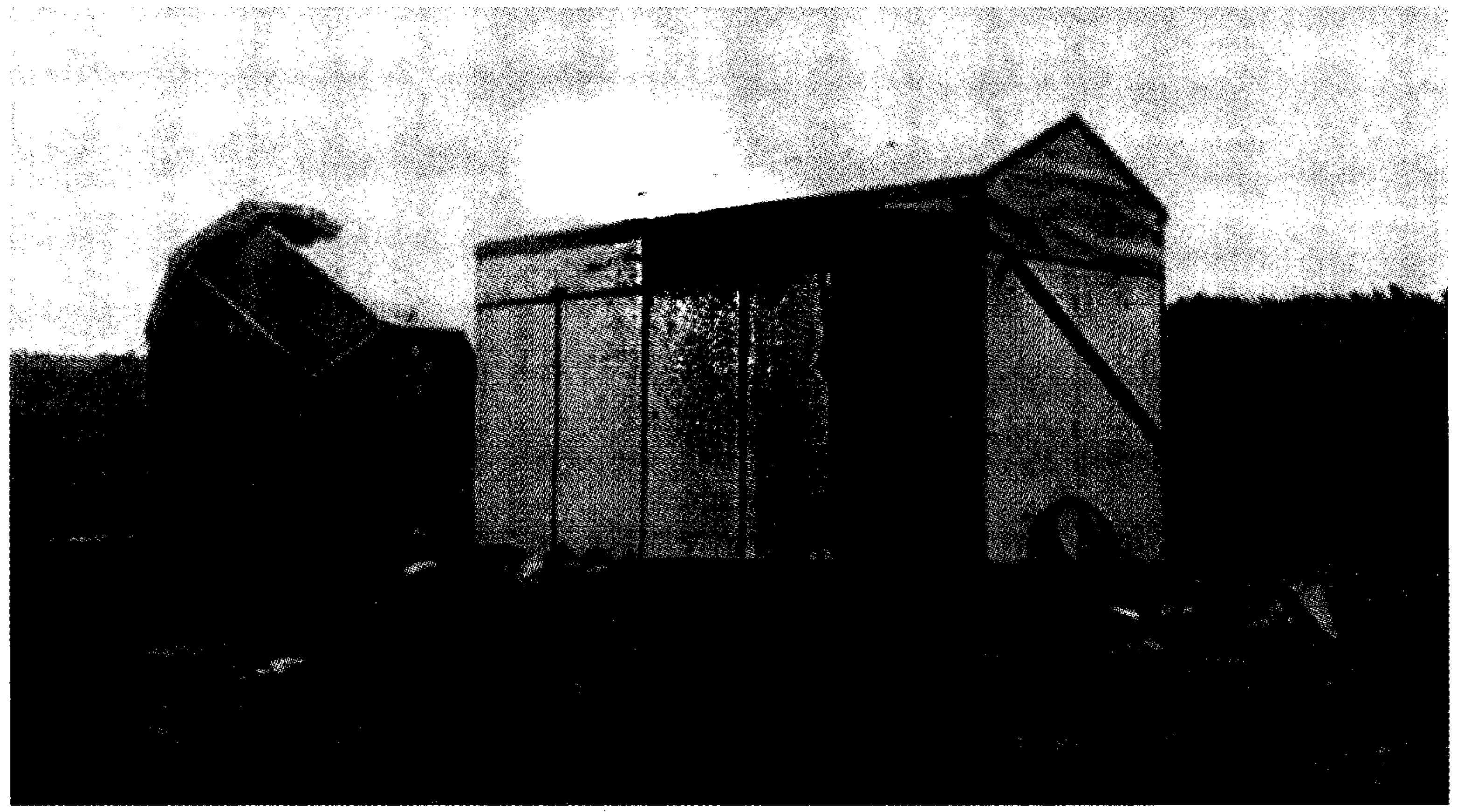



第3図 1958年乗鞍シンポジウムで話されたシャワー・カーブ測定の提案

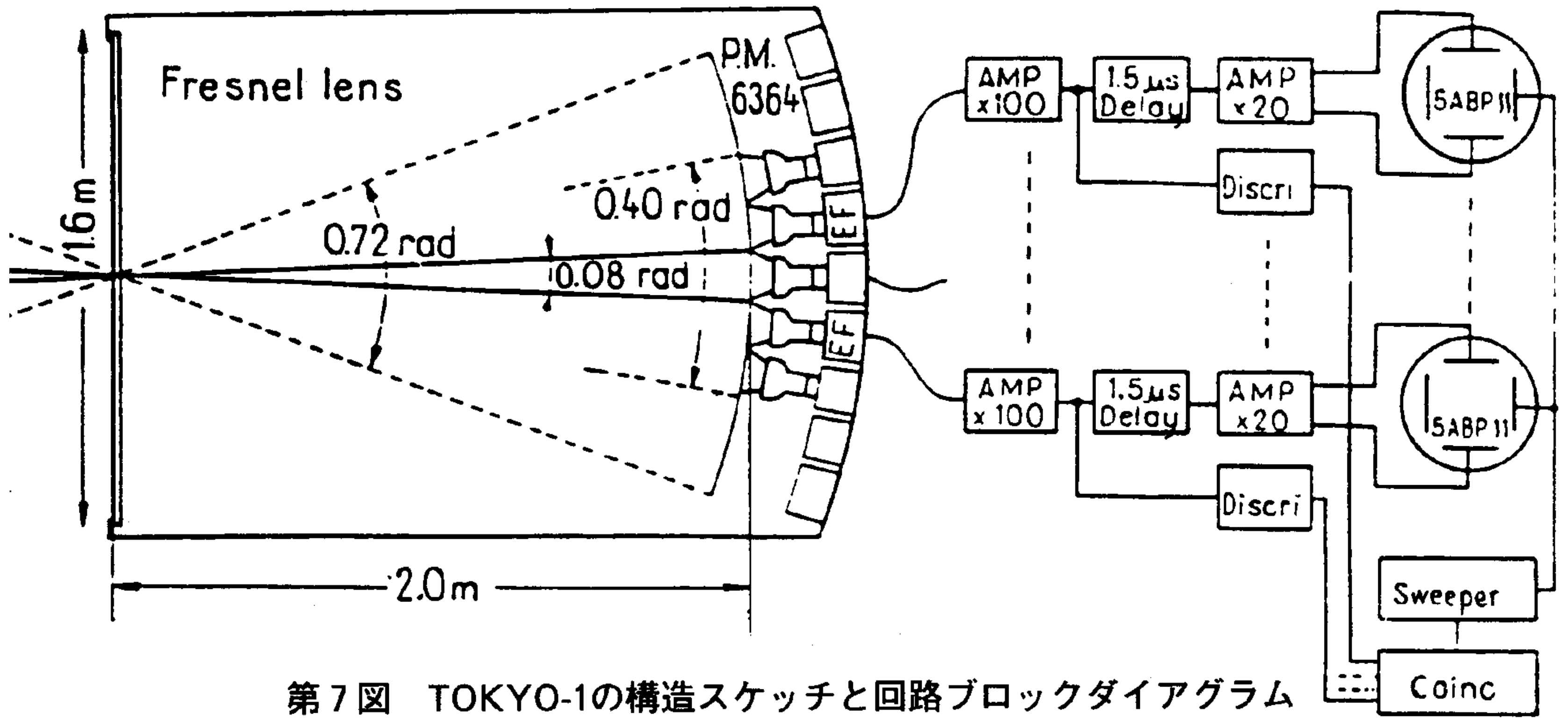
- Proposed by K. Suga and M. Oda (1958), also by Greisen and Chudakov at the same time
- First detection by Fresnel lens and 55 PMTs, TOKYO-1 (**1969**)



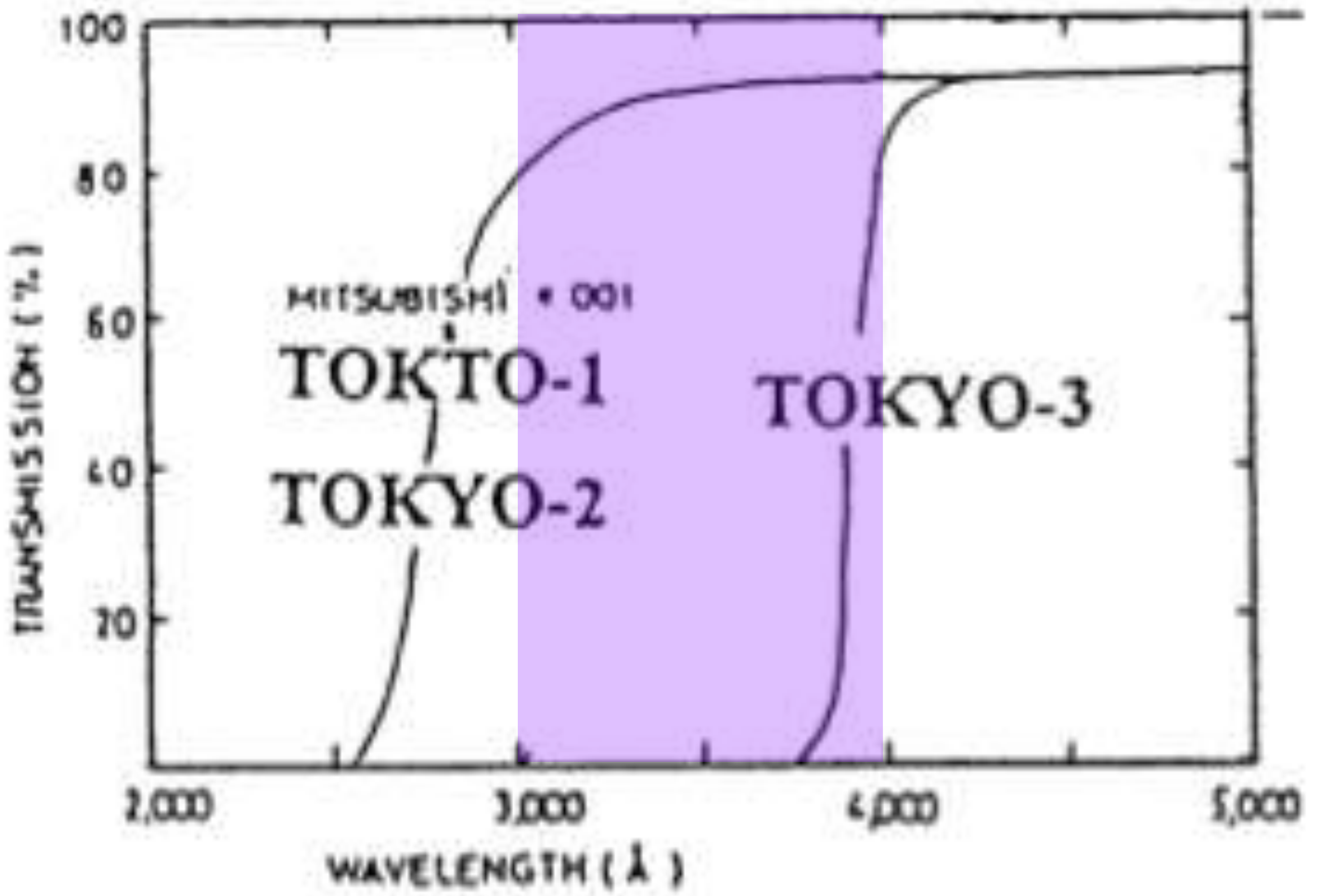

**$5\times10^{18}$ eV, 680 g/cm$^2$** analyzed by B. Dawson, arXiv:1112.5686 (2011)



第8図 TOKYO−1の設置写真

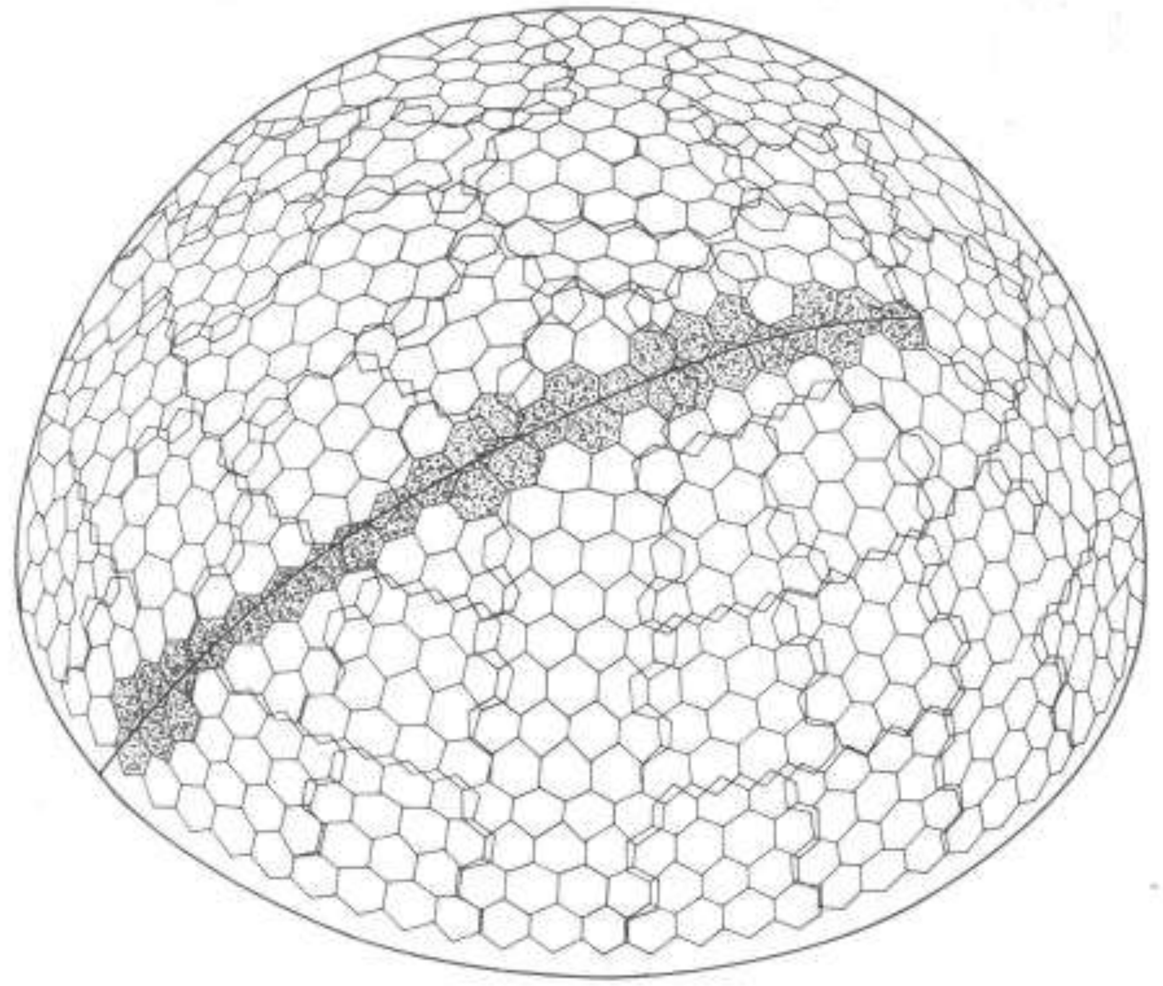



第7図 TOKYO-1の構造スケッチと回路ブロックダイアグラム




参考文献: 大気の蛍光観測による宇宙線実験の始まり 棚橋五郎

# The Universe's most energetic particle

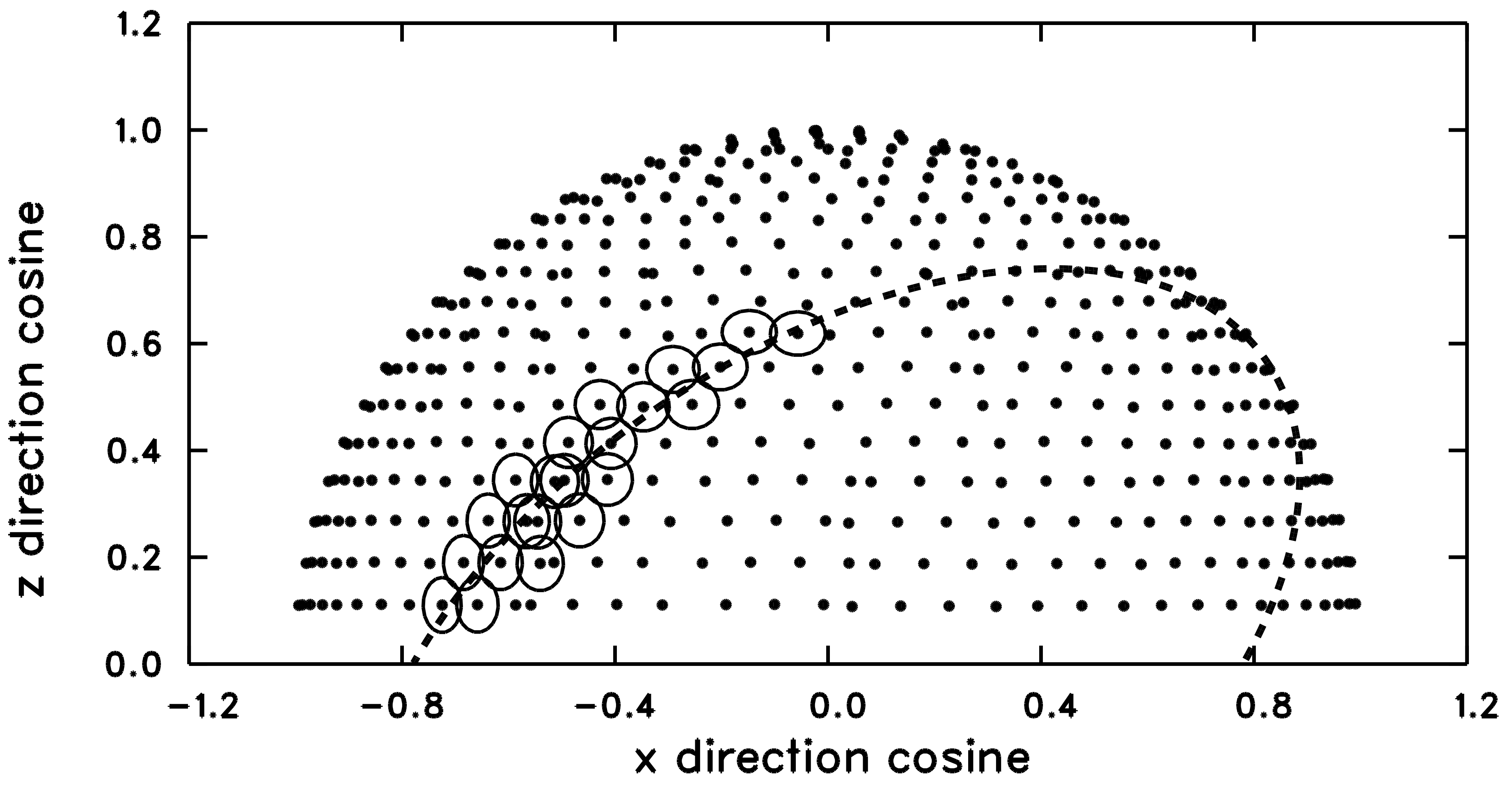


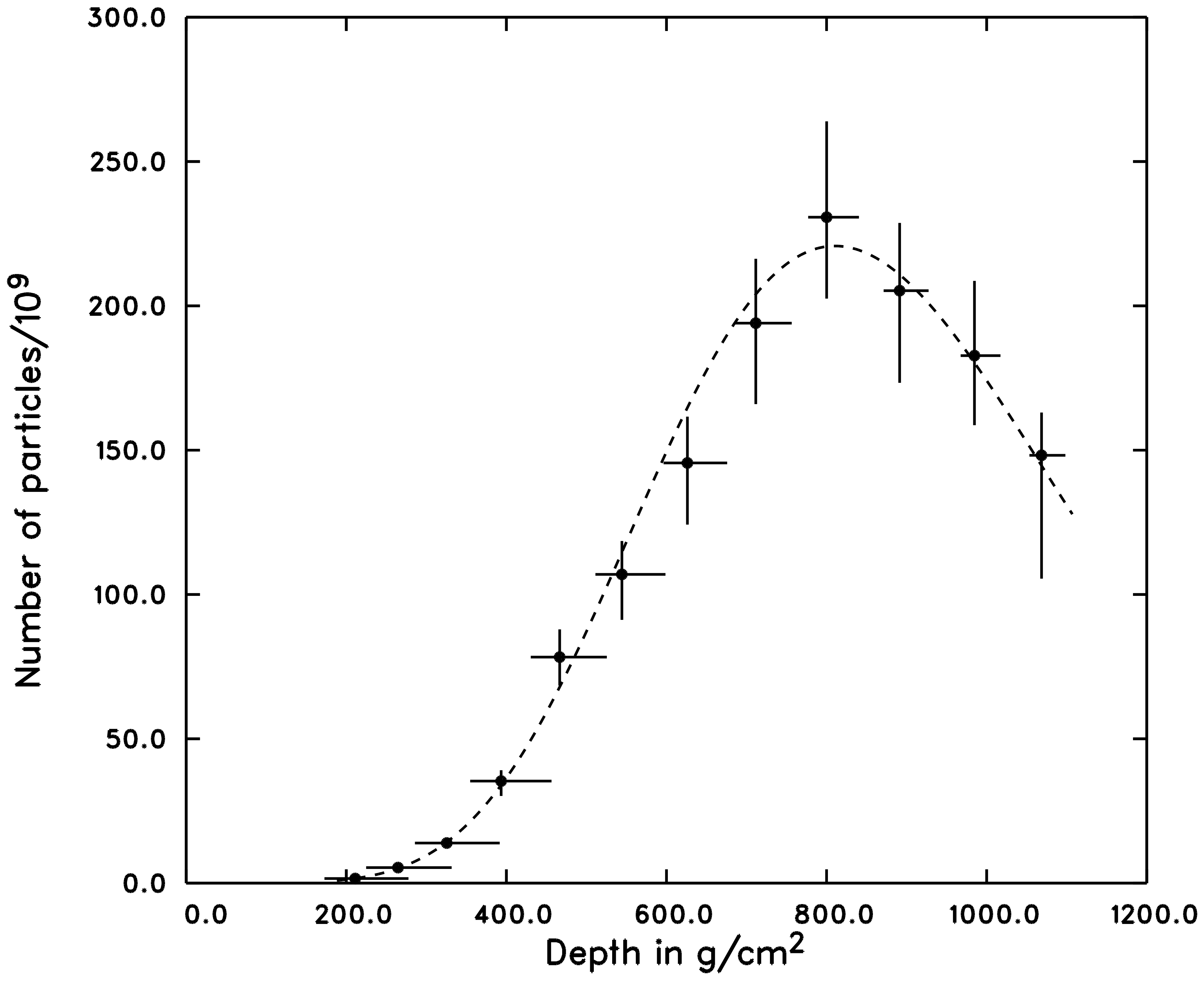
**Fly's Eye (Utah, USA)**
Construction started from **1976**, after a confirmation of fluorescence signal at Volcano Ranch Array

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

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

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

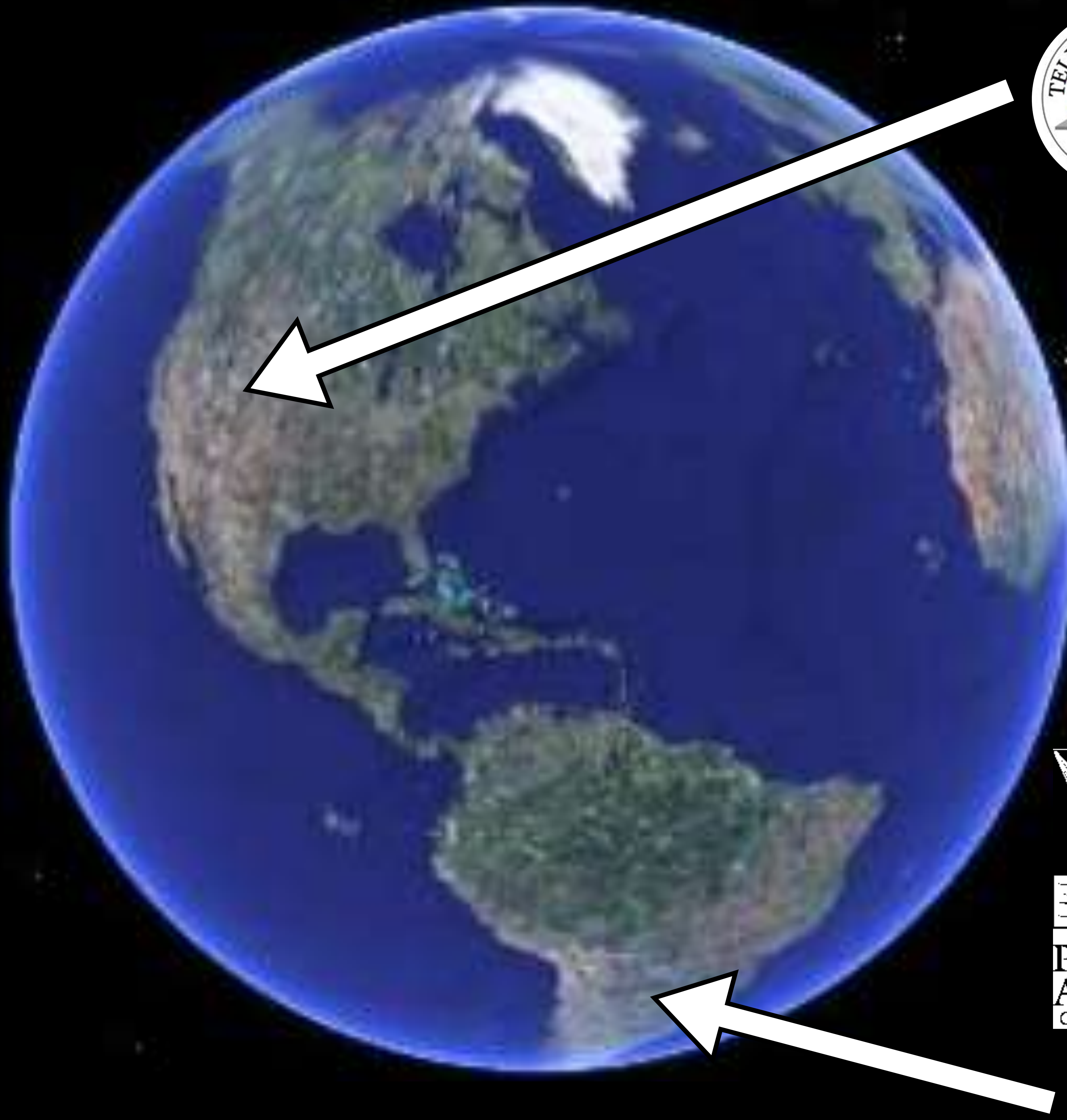



(R.A., Dec.) = (85.2°, 48.0°)
D.J. Bird et al., ApJ 441 (1995) 144

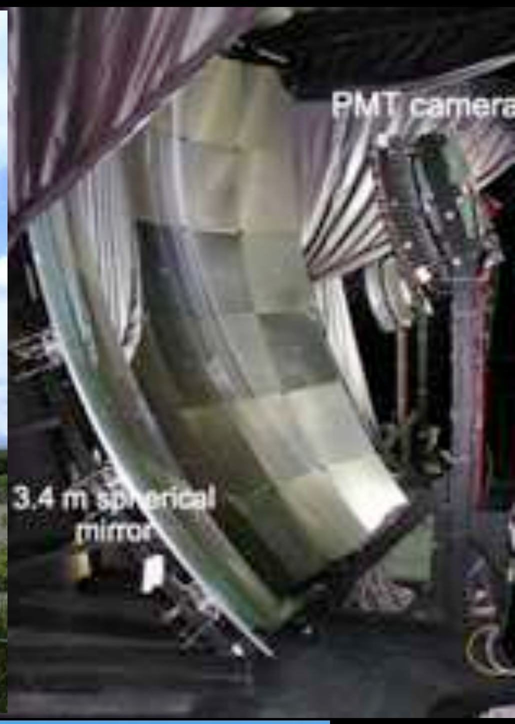
Start the High Resolution Fly's Eye (HiRes-1) from 1994.

# Latest UHECR observatories



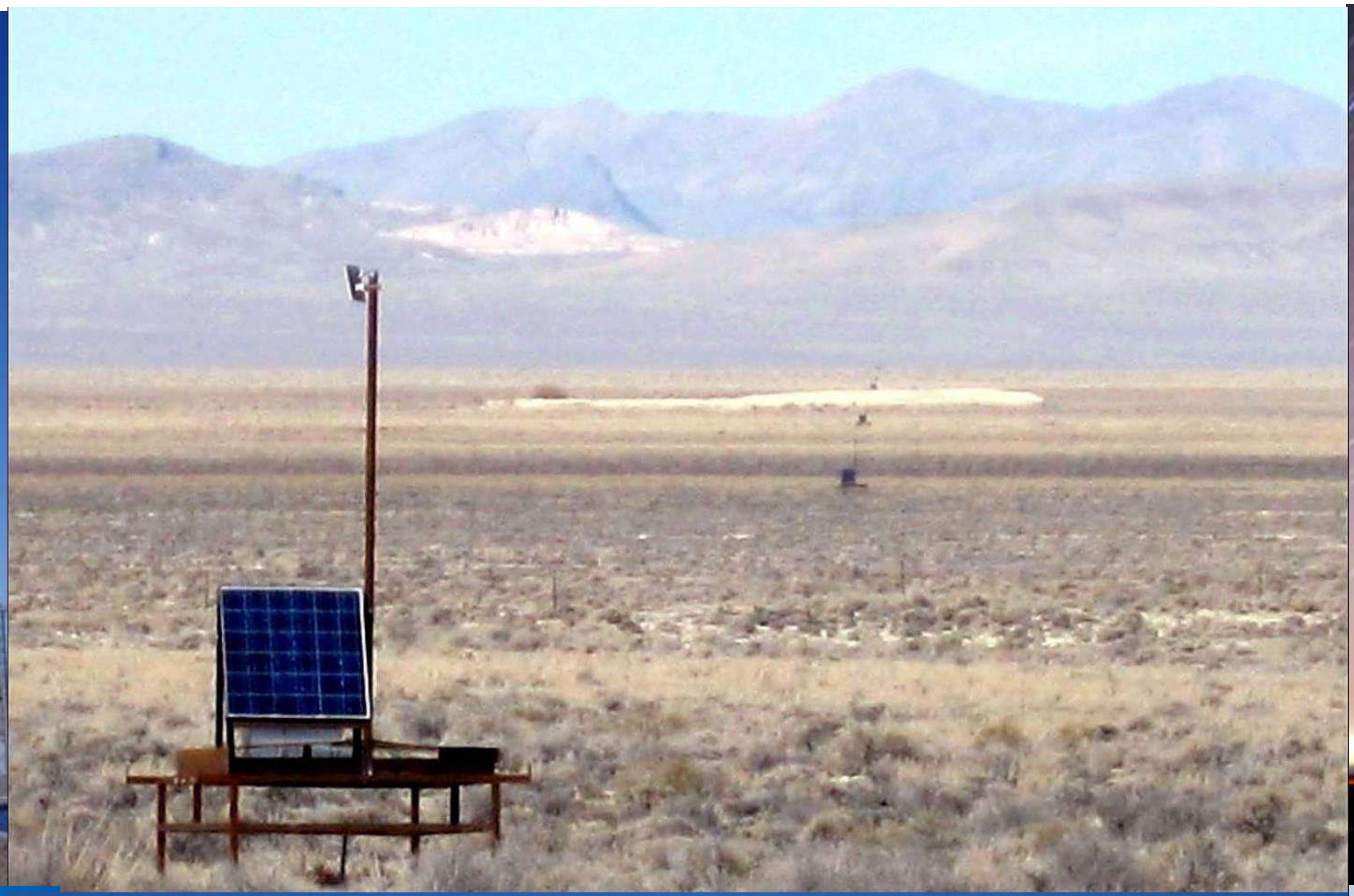
Google Earth

- **Telescope Array Experiment (TA)**
  - Utah, USA
  - 2008~, **700 km²**
    - **TA×4 → 3000 km²**
- **Pierre Auger Observatory (Auger)**
  - Malargüe, Argentina
  - 2004~, **3000 km²**
    - **AugerPrime** upgrade scintillator + small PMT + radio + buried muon detector + high speed electronics




# Pierre Auger Observatory @Malargüe, Argentina


# Telescope Array experiment @Utah, USA

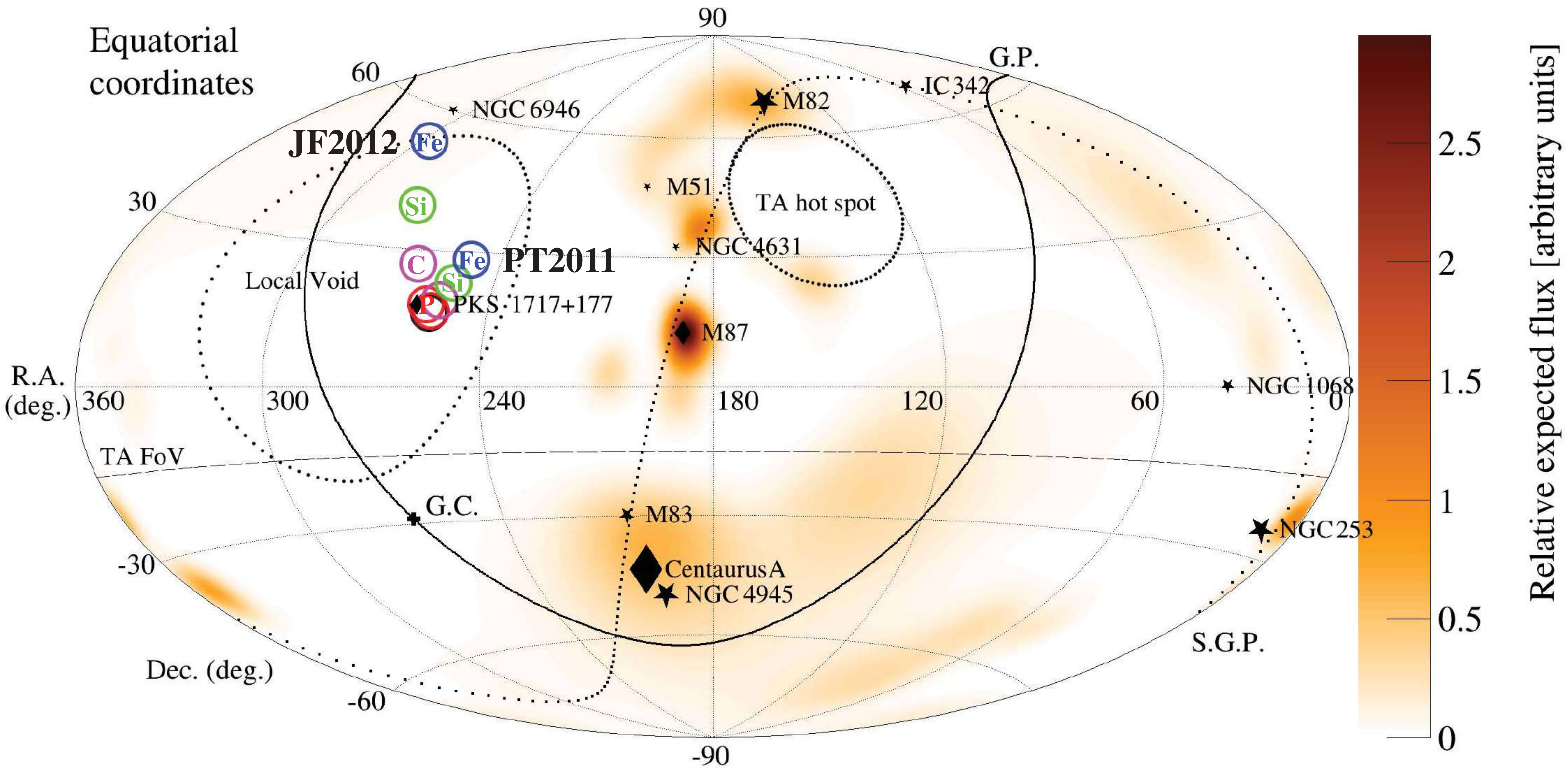




2021 May 27, 04:35:56 AM
Detection of "Amaterasu" particle
© Toshihiro Fujii, L-INSIGHT, Kyoto University and Ryuunosuke Takeshige
Telescope Array Collaboration, Science 382, 903 (2023)

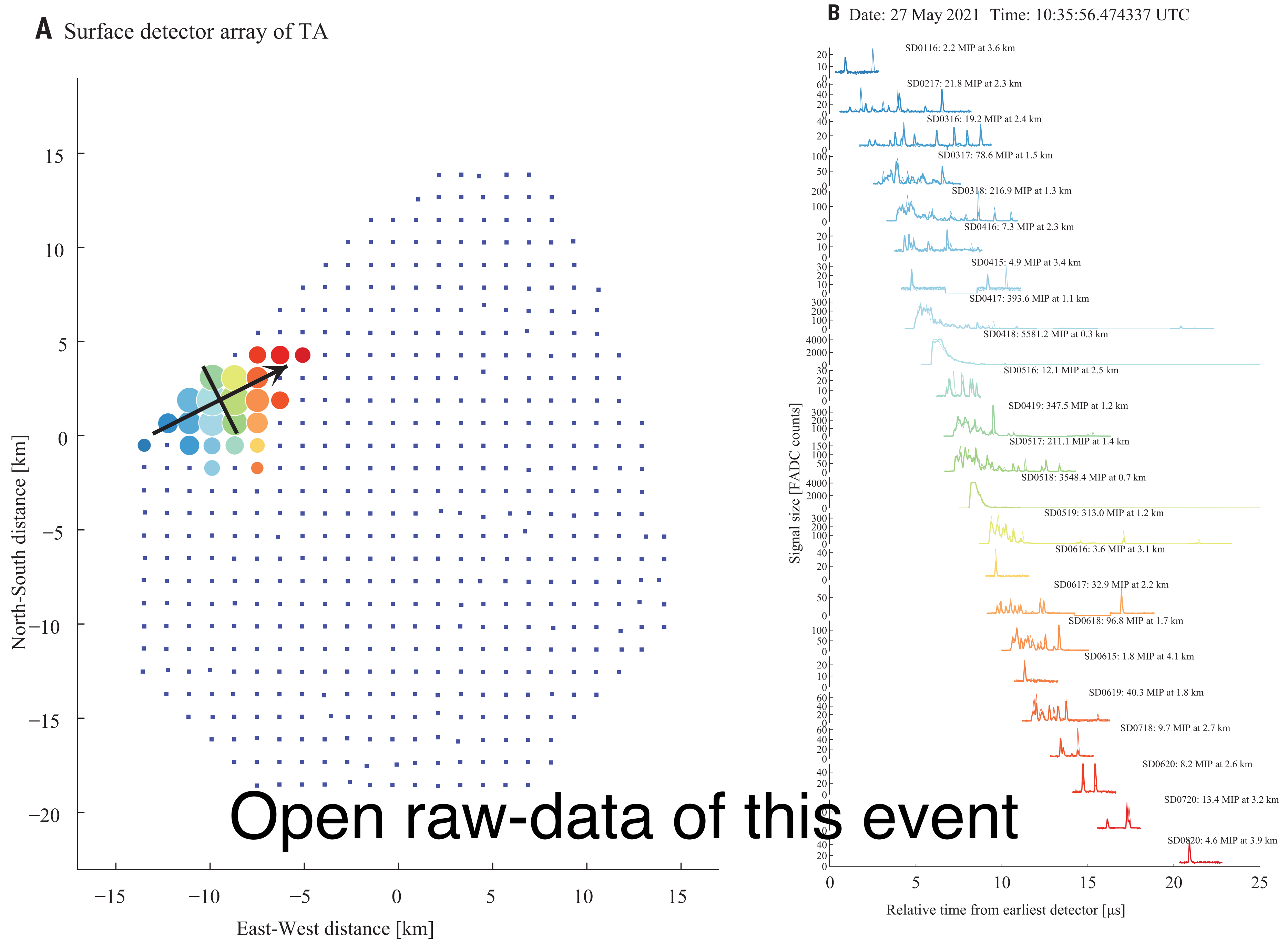
| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 20210527 | 001716.635727 | 5.737 | -8.895 | 9.98 | 22.48 | 168.53 | 0.587 | 0.00 | 2.06 |
| 20210527 | 005753.524148 | 7.988 | 1.748 | 10.51 | 38.09 | 155.29 | 0.277 | 0.00 | 3.14 |
| 20210527 | 012459.385602 | -5.703 | -9.588 | 6.59 | 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 |
| 20210527 | 150126.752502 | 8.285 | 2.897 | 3.52 | 40.84 | 76.01 | 0.411 | 0.00 | 1.07 |

# Arrival direction of Amaterasu particle

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

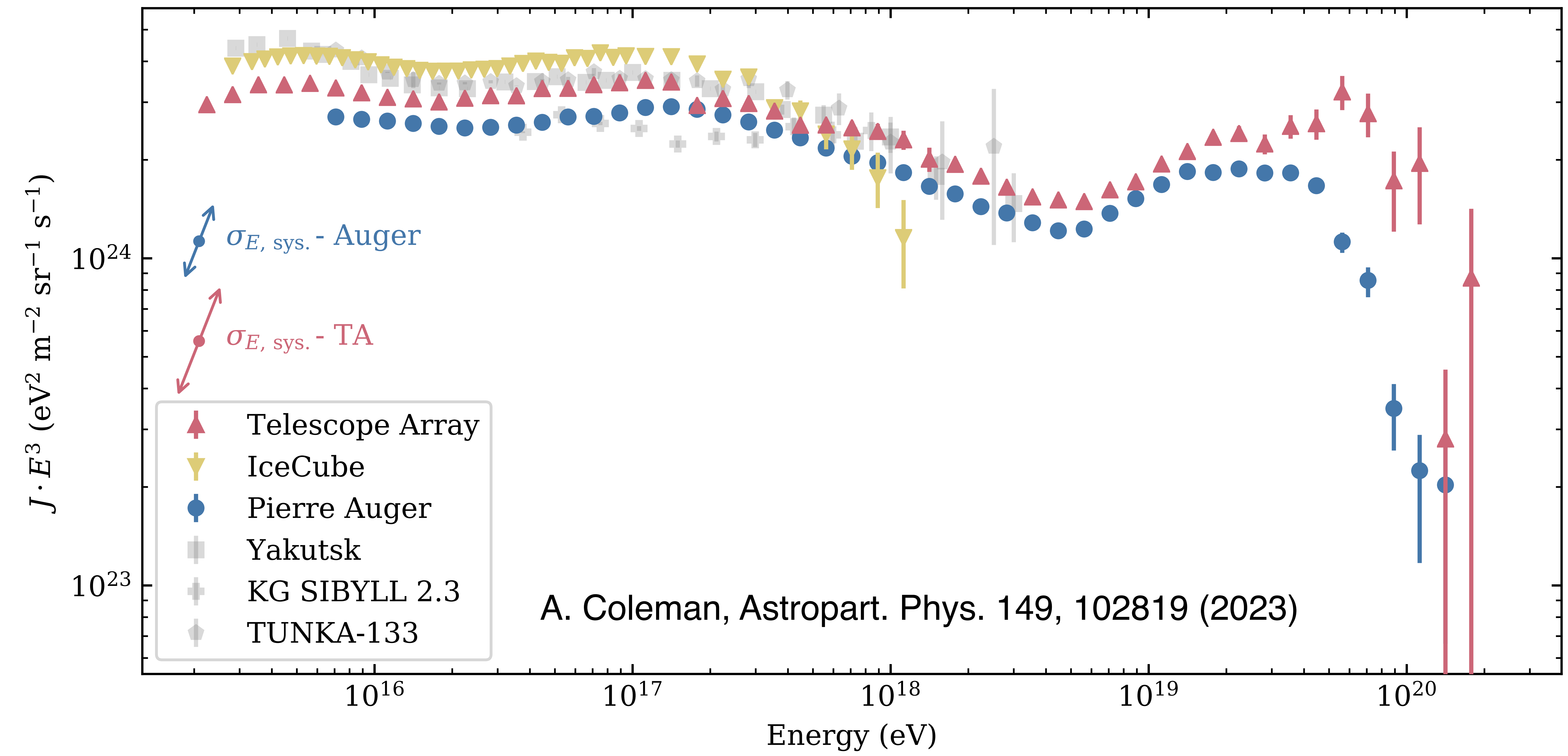


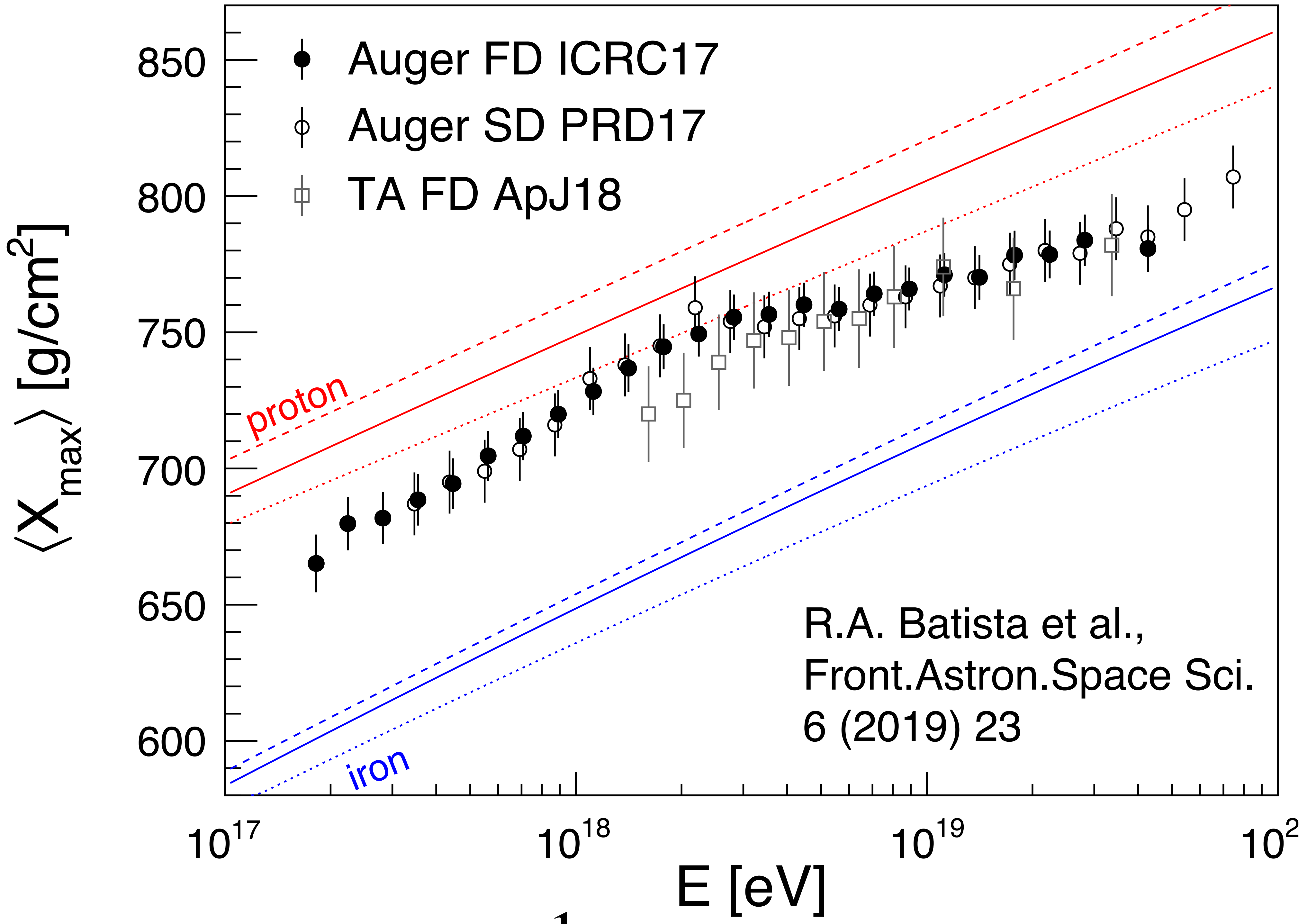

Telescope Array Collaboration, Science 382, 903 (2023)




Open raw-data of this event

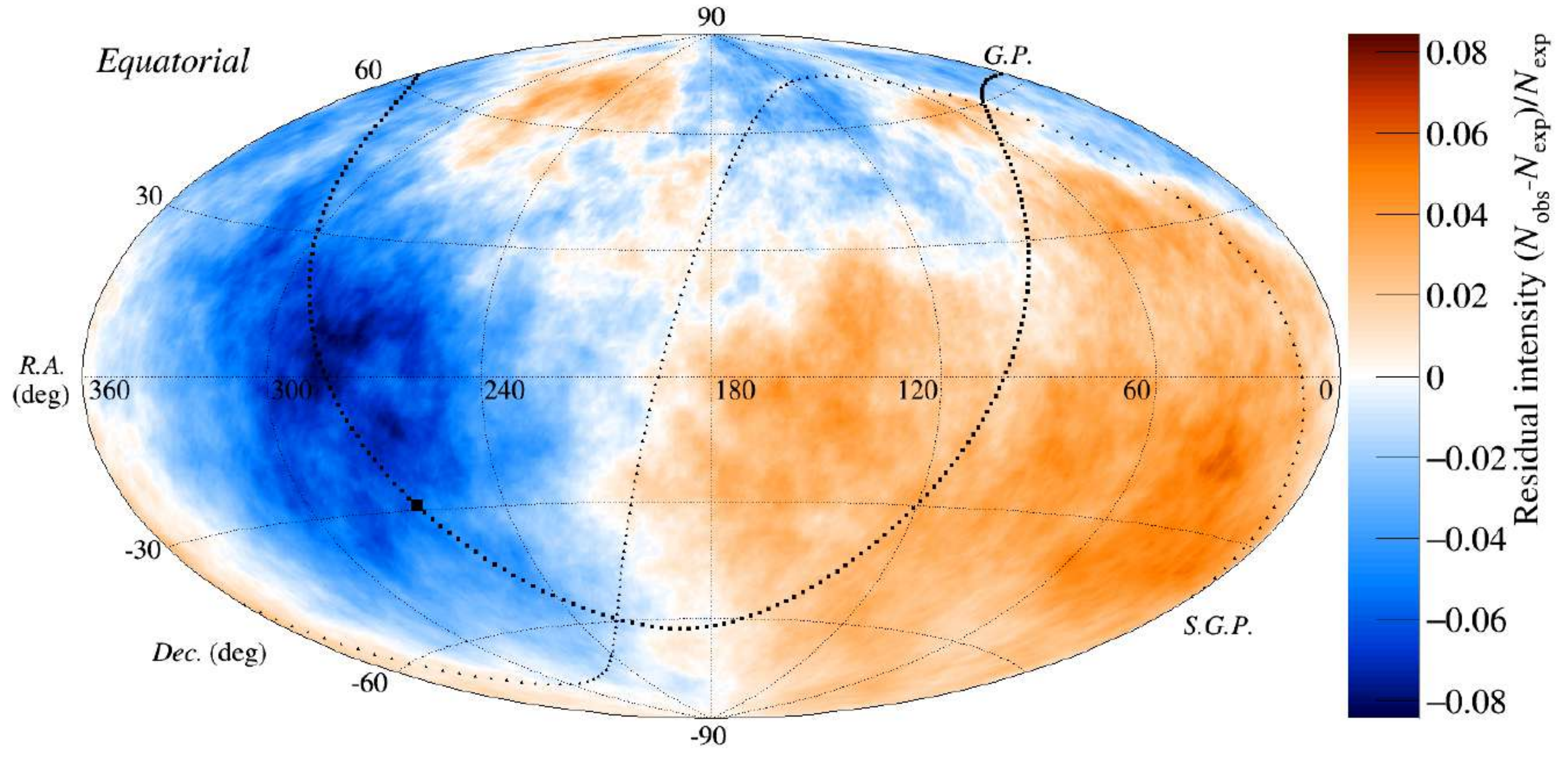
- **Possible source region** (Unger and Farrar, arXiv:2312.13273)
- **Monopole** (Frampton, arXiv:2403.12322)
- **Binary neutron star merger** (Farrar, arXiv:2405.12004)
- **Ultra-heavy** composition like Te or Pt (Zhang+, arXiv:2405.17409)



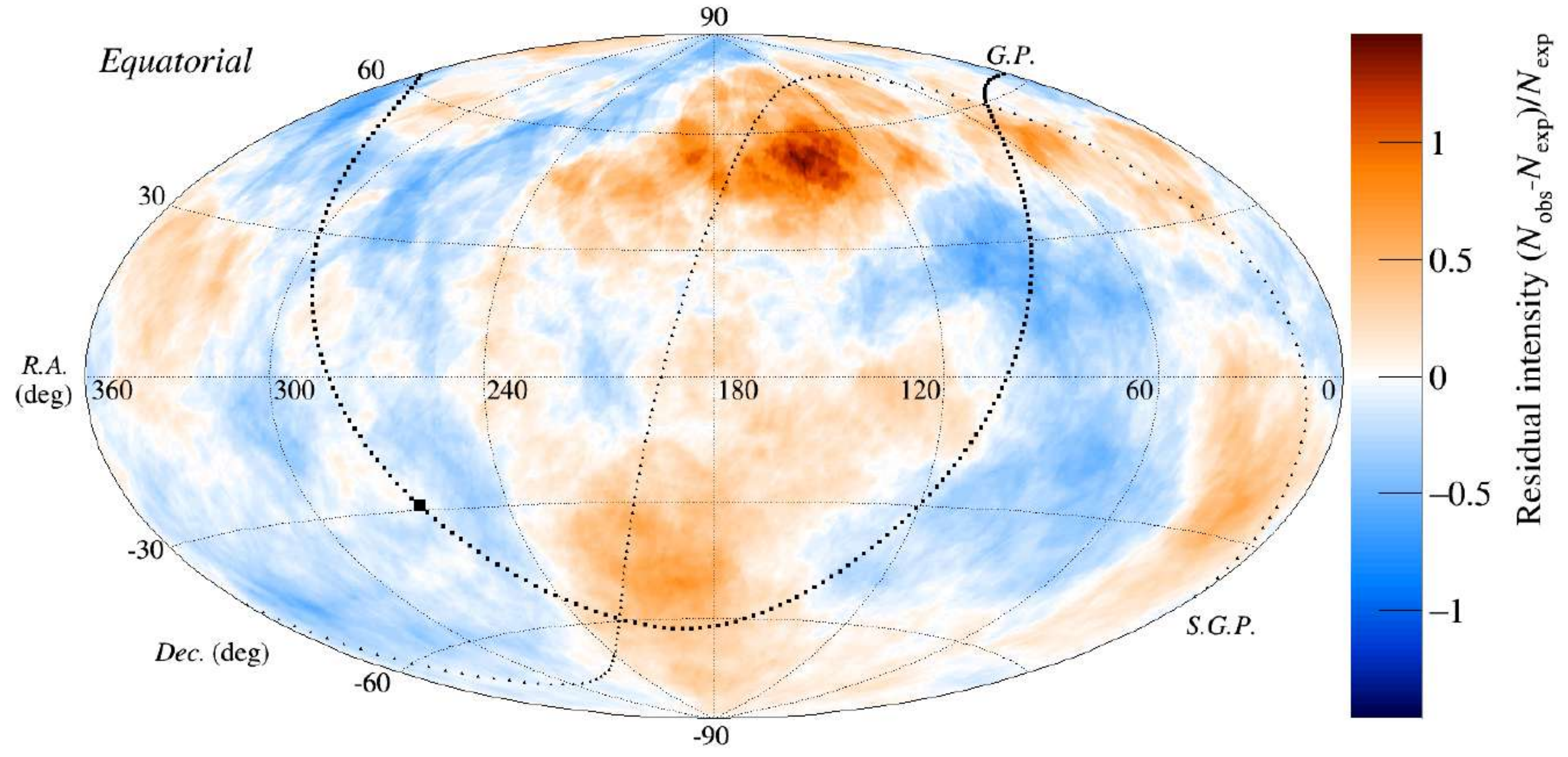




# Latest results

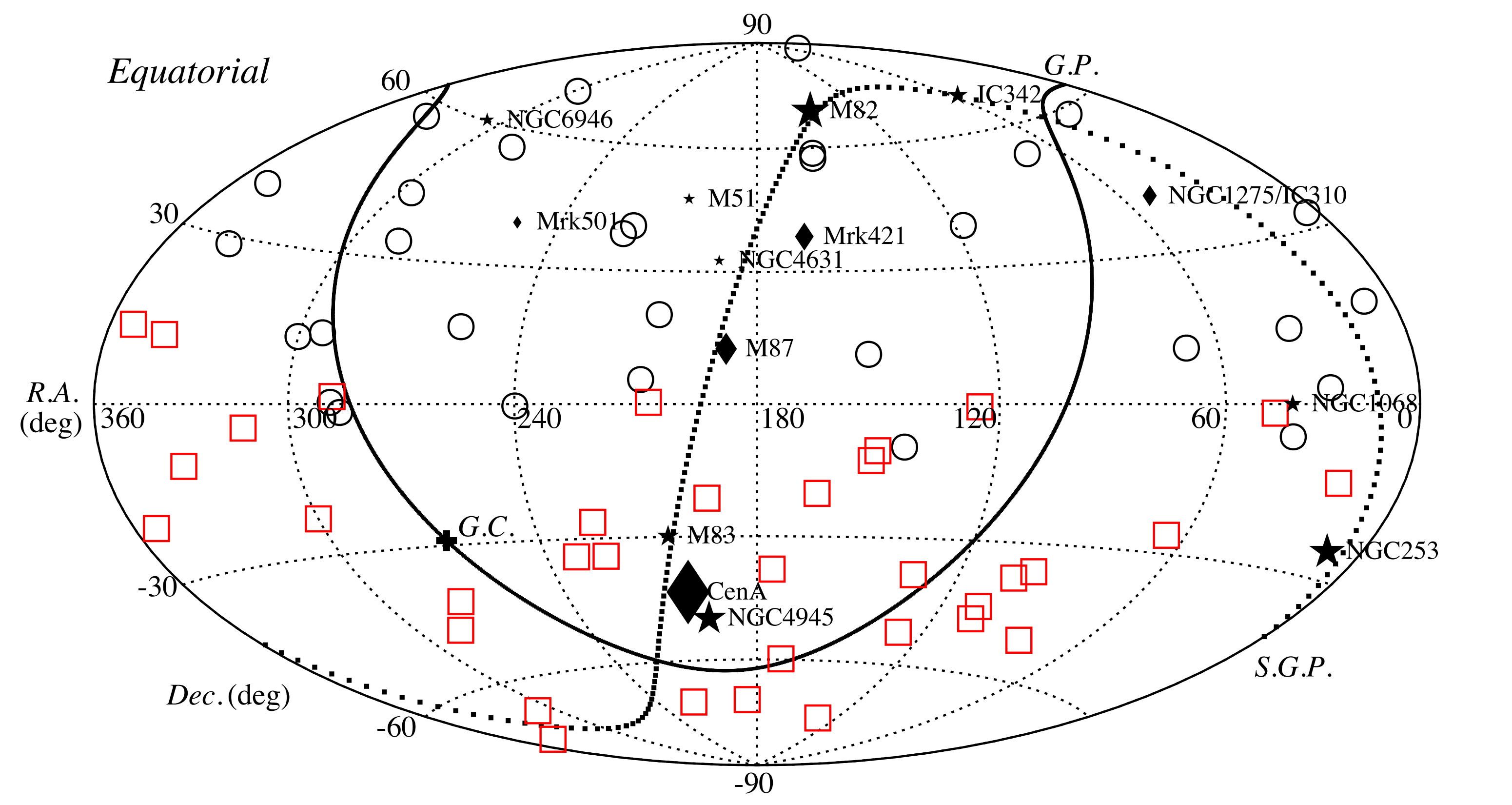
$$\theta \sim 10^{\circ} Z \left( \frac{E}{10\,\mathrm{EeV}} \right)^{-1}$$




Ankle ($E > 10$ EeV)




Cutoff ($E > 50$ EeV)



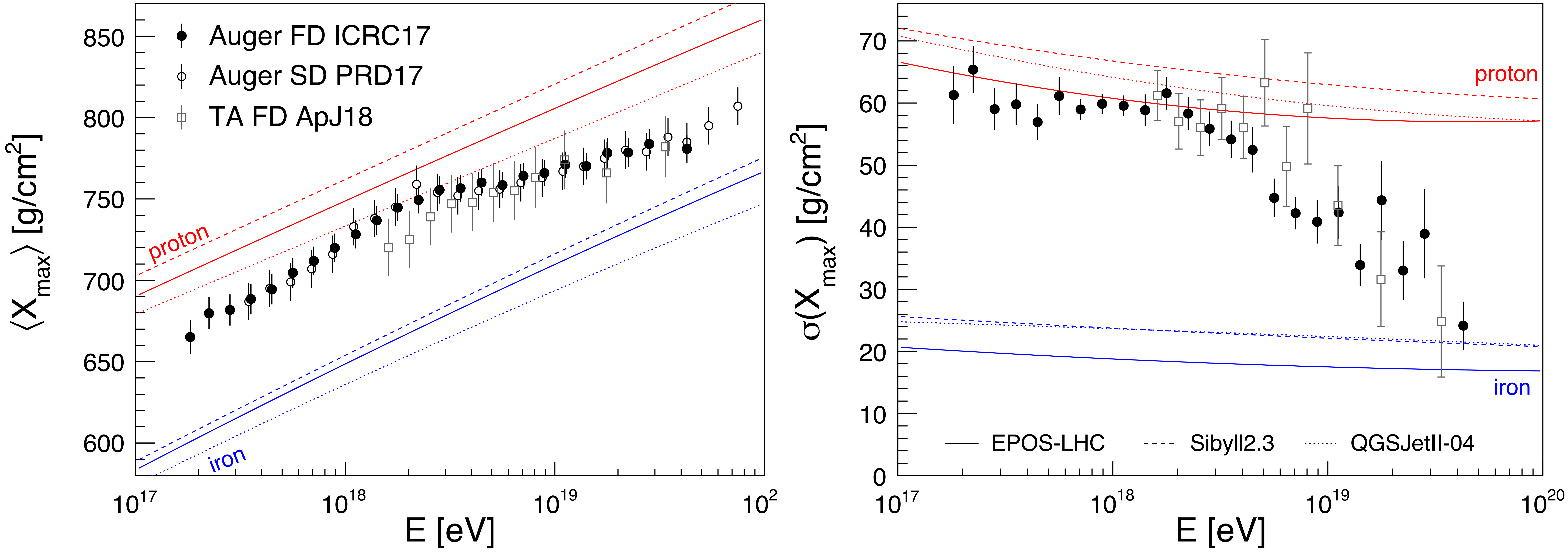

Beyond-cutoff ($E > 100$ EeV)

# Energy spectrum


- Firmly confirmed the spectrum cutoff above 50 EeV
  - No detection above 300 EeV
- **Tension of the spectra at highest energies?**

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

# Mass composition




**Gradually increase to the heavier composition above 3 EeV**

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

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

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

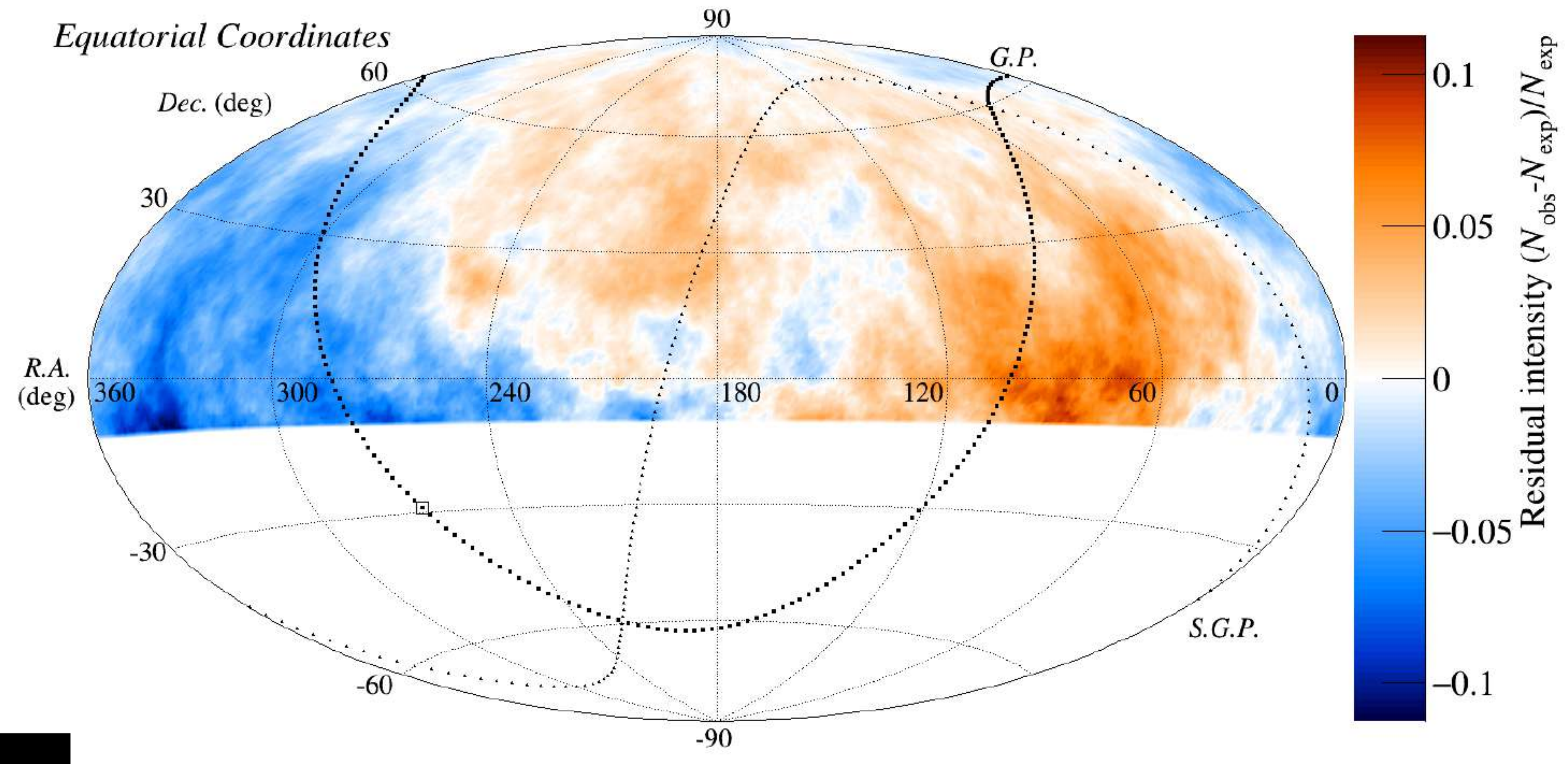
**TA reported a heavy composition above 100 EeV from isotropy**

Telescope Array Collaboration, PRL 133, 041001 (2024)

# Anisotropy of UHECRs (>10 EeV)

## Northern TA ApJL, 898:L28 (2020)

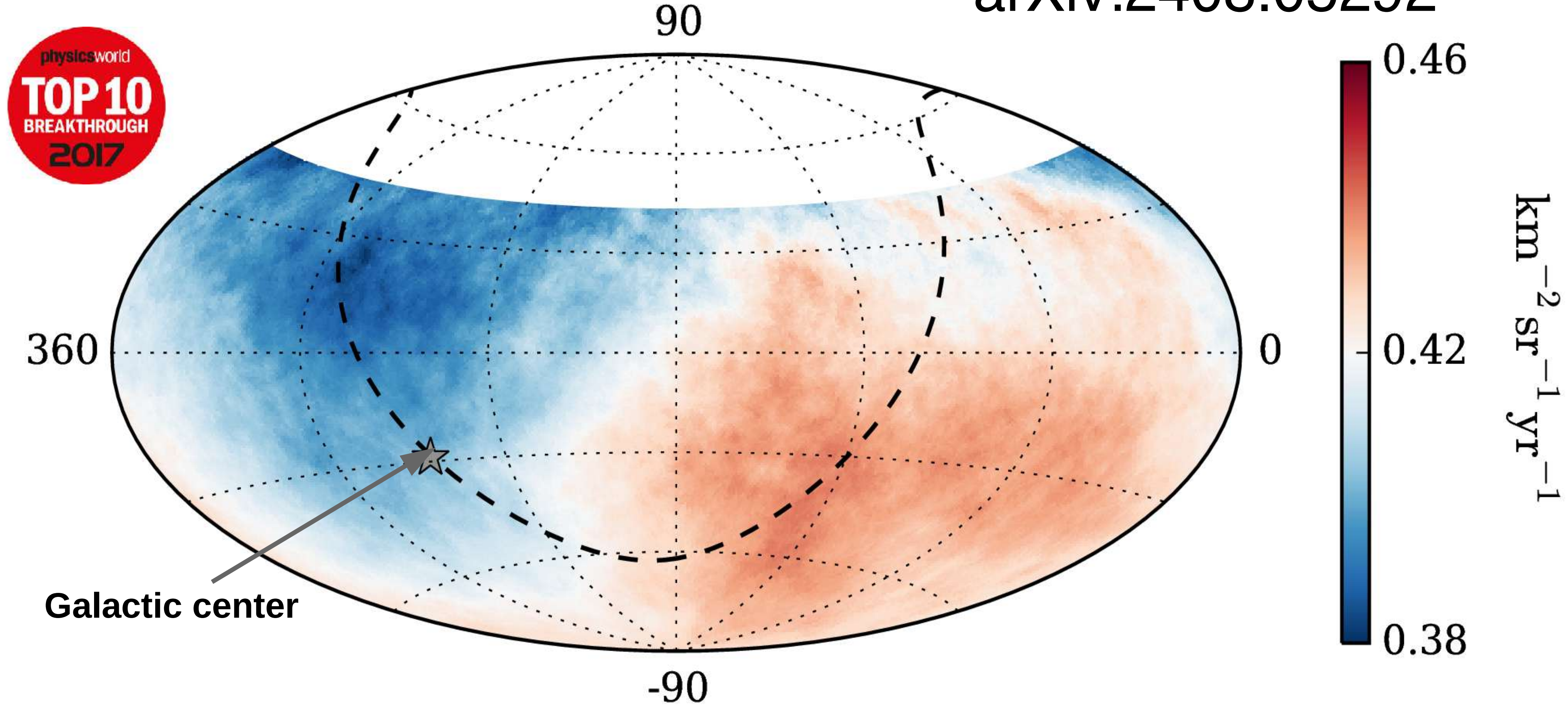
$E_{TA}$> 8.8 EeV




## Southern Auger Science 357, 1266 (2017)

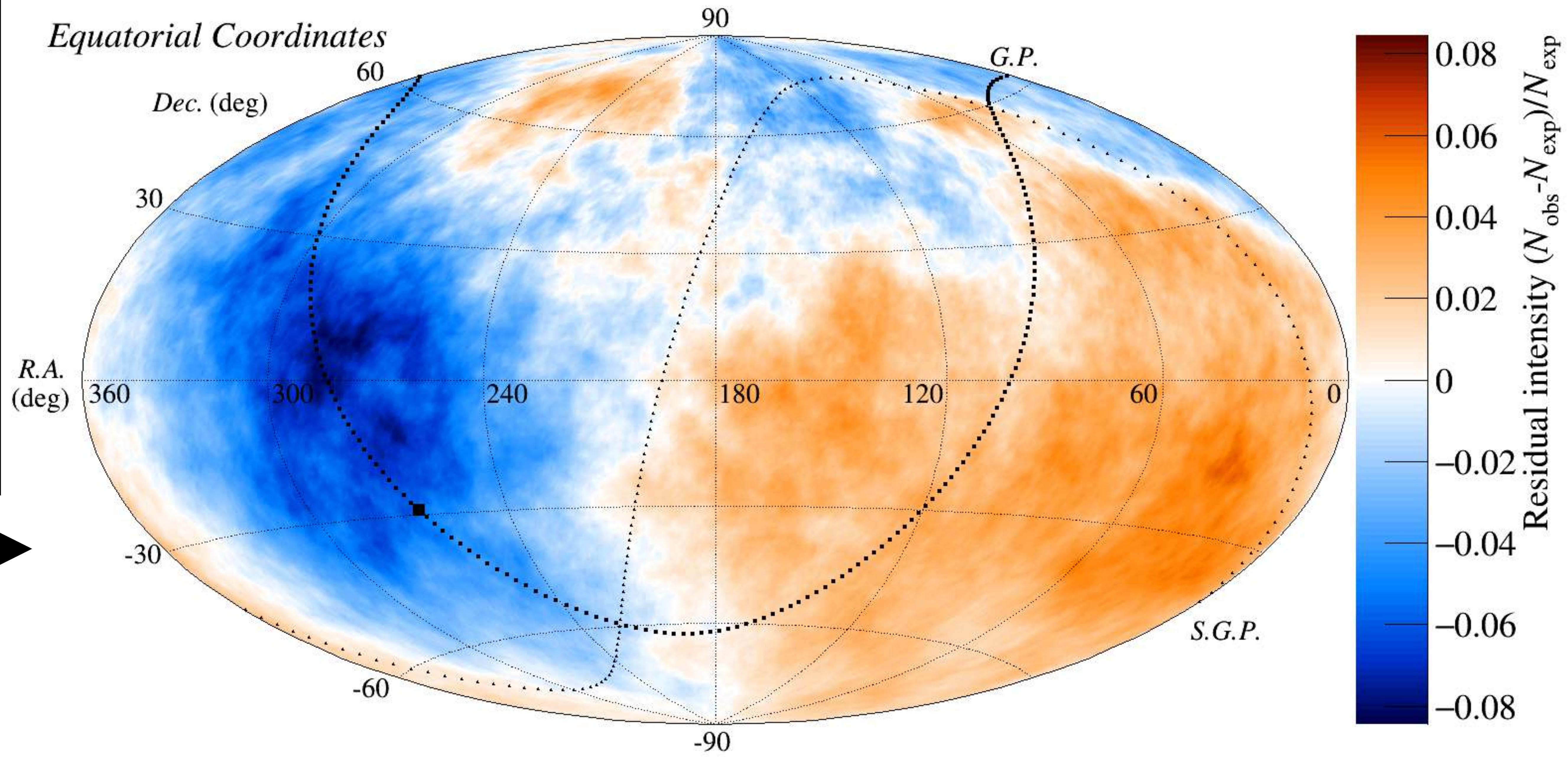
$E_{Auger}$> 8 EeV

**6.9σ** using19-years data
arXiv:2408.05292



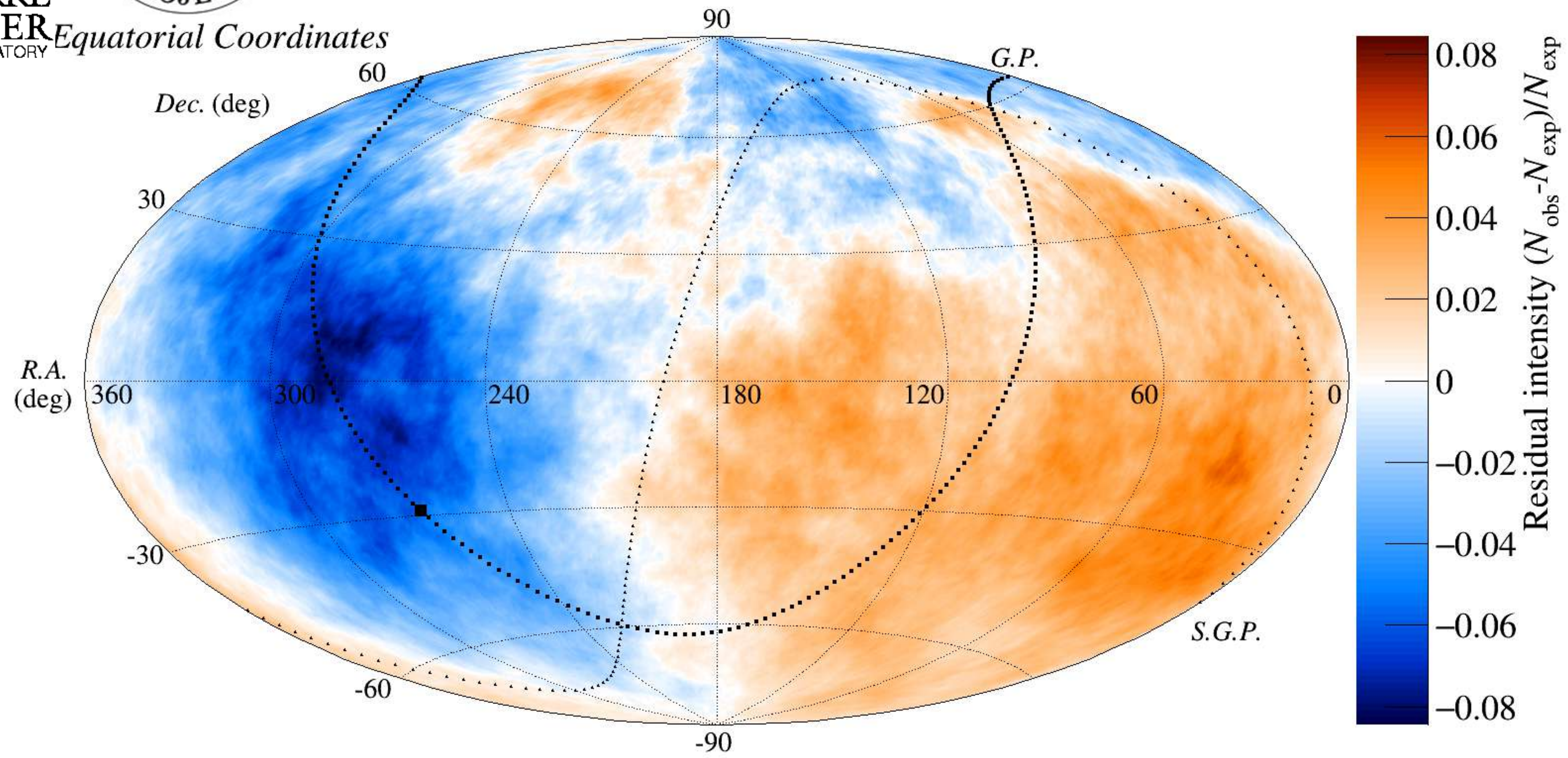

- **Significant (> 5σ) large-scale anisotropy** observed by Pierre Auger Observatory
  - 125 degrees away from Galactic Center
  - **Supporting the extragalactic origins**

**Joint analysis**

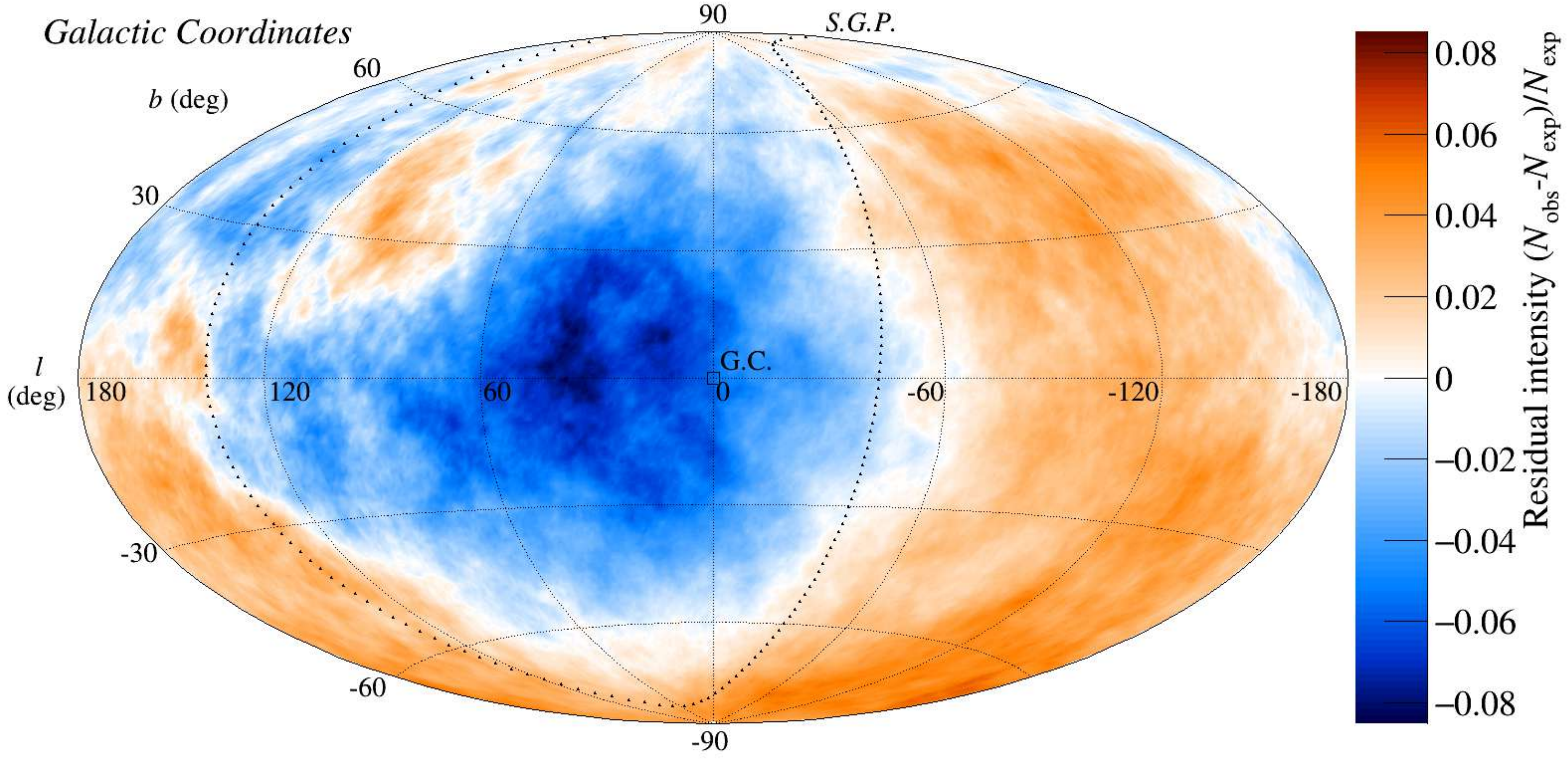



Ankle ($E_{TA}$>10 EeV, $E_{Auger}$> 8.86 EeV)

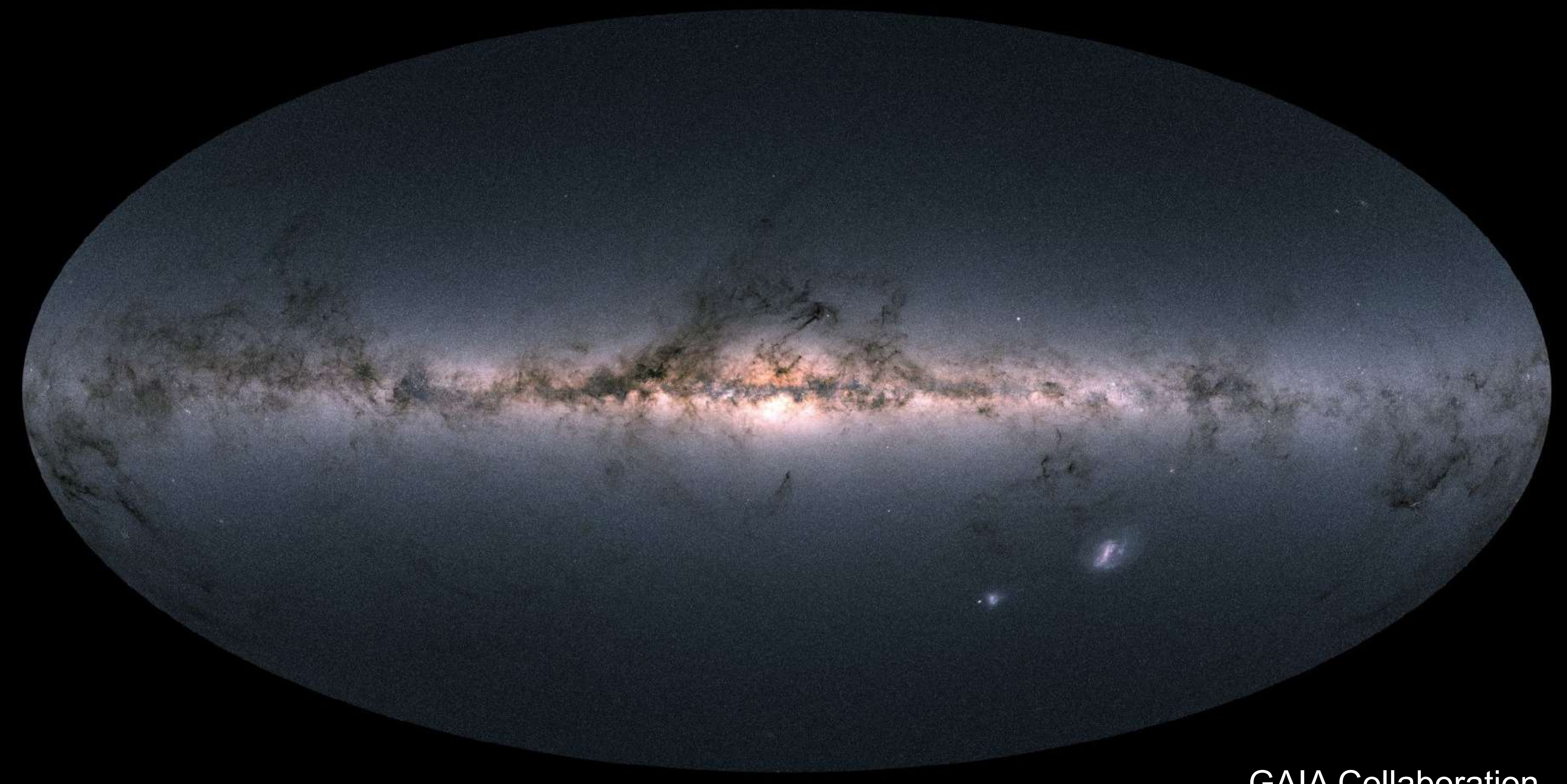
# >10 EeV skymap




**Converted to ⬇ Galactic coordinates**



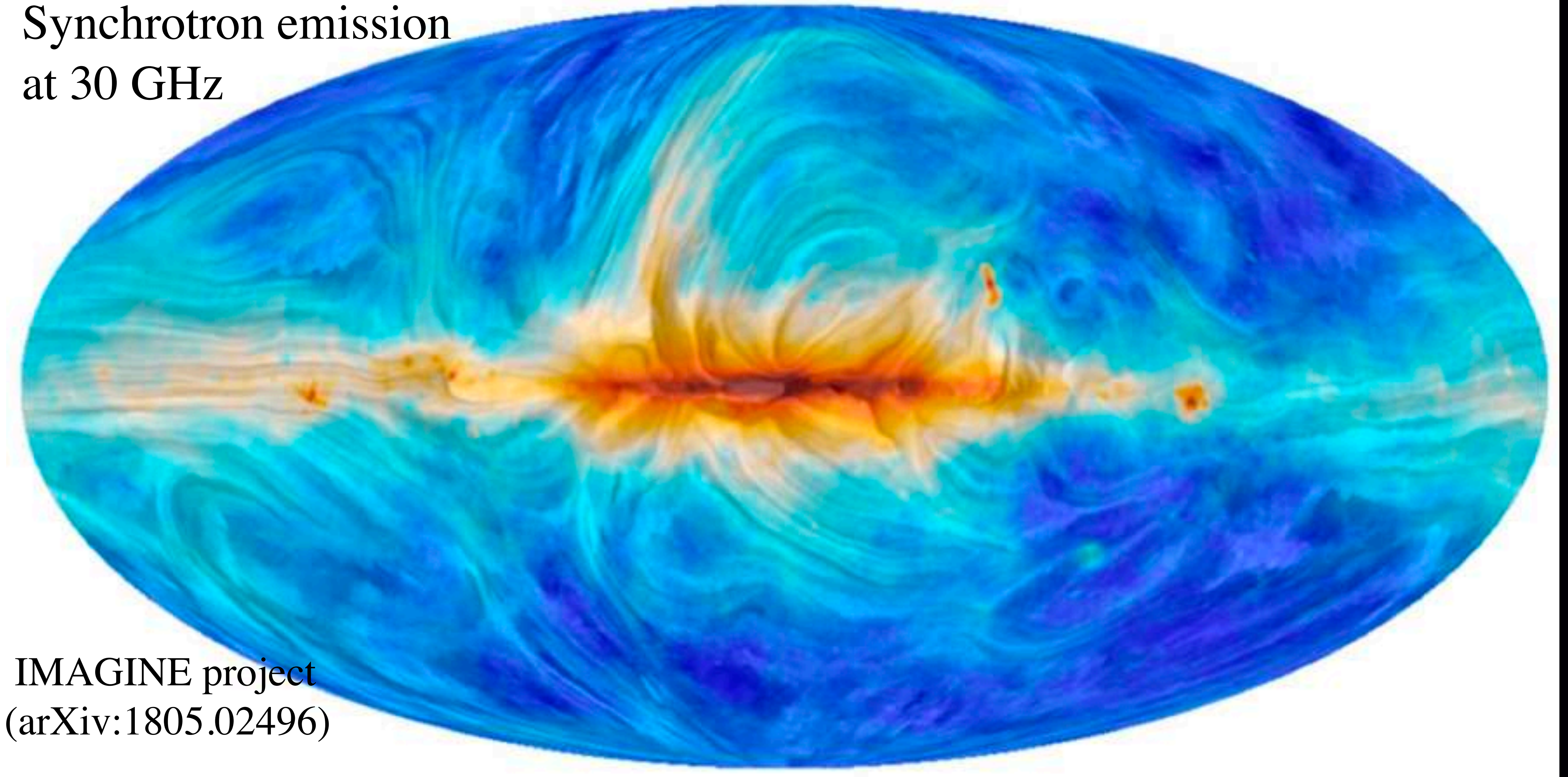

T. Fujii, PoS (ICRC2021) 402 (2021)



GAIA Collaboration

# "Deciphering" magnetic fields

Synchrotron emission at 30 GHz

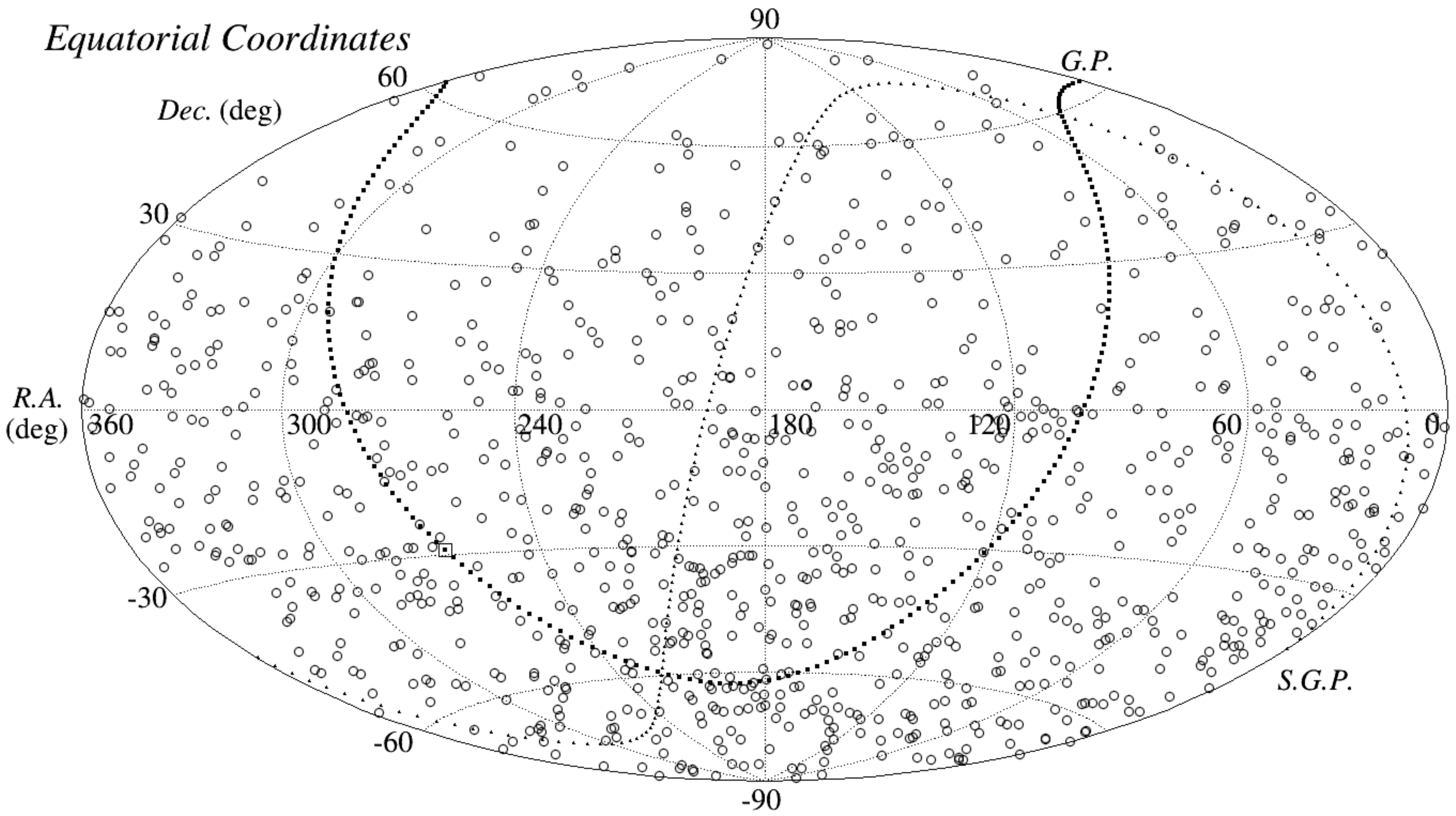


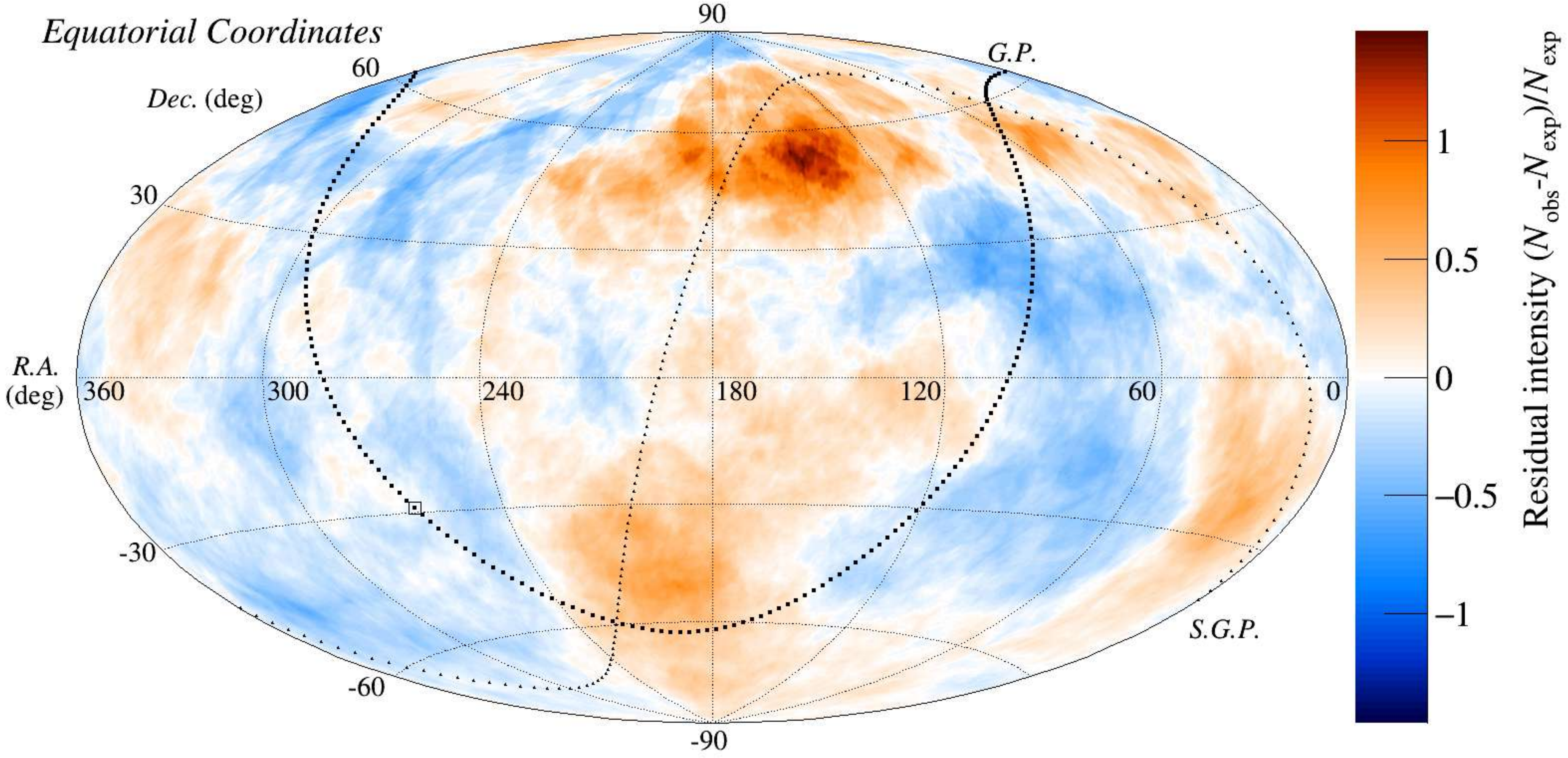
IMAGINE project (arXiv:1805.02496)

# >50 EeV skymap

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

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

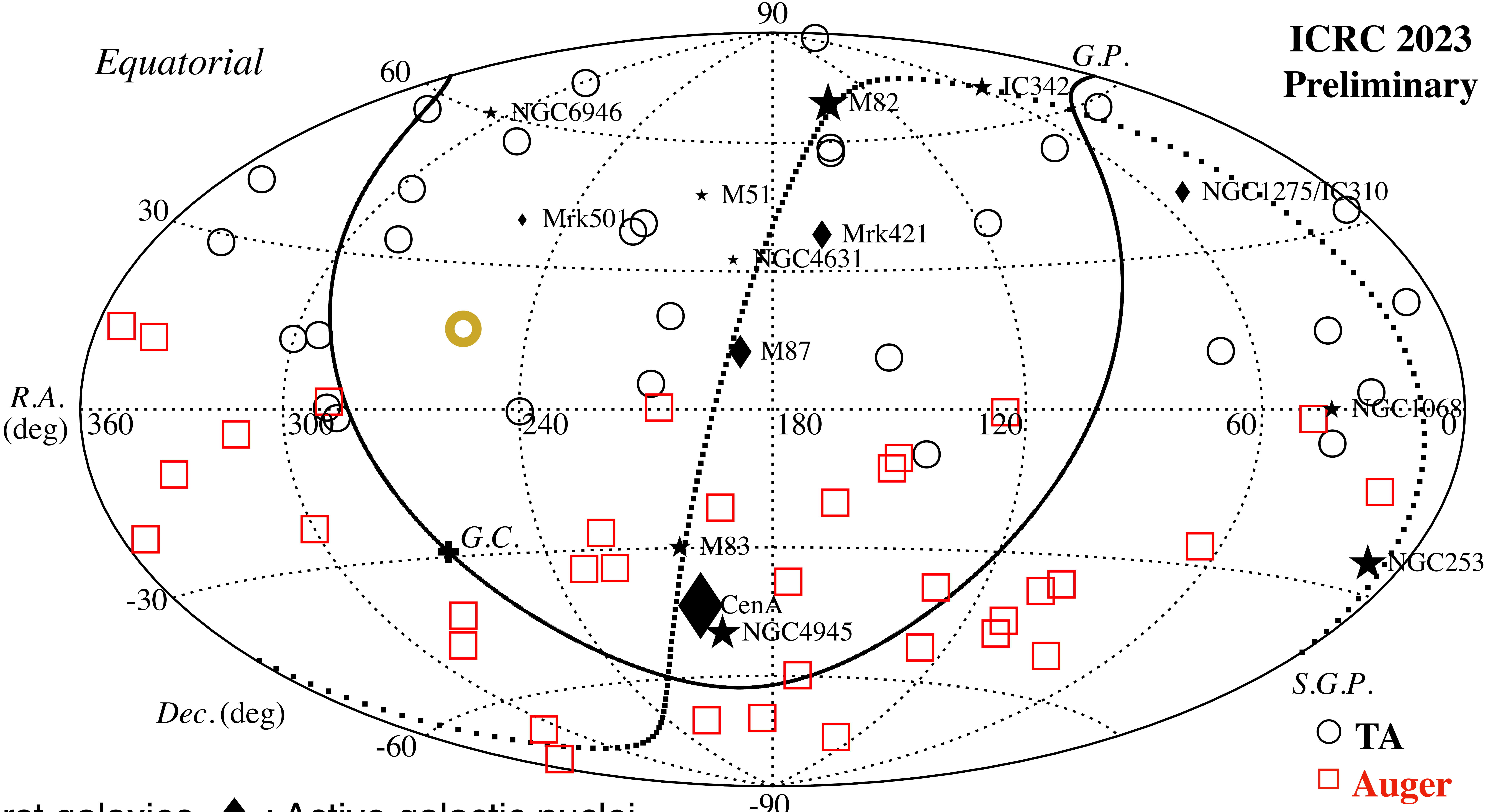



- Intriguing **intermediate-scale anisotropies** (~20 degrees) such as **hot/warm spots**
  - No excess from M87 of Virgo cluster, dubbed "***Virgo scandal***"
- **Isotropic distributions of UHECRs than our (optimistic) expectation**

# >100 EeV skymap

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

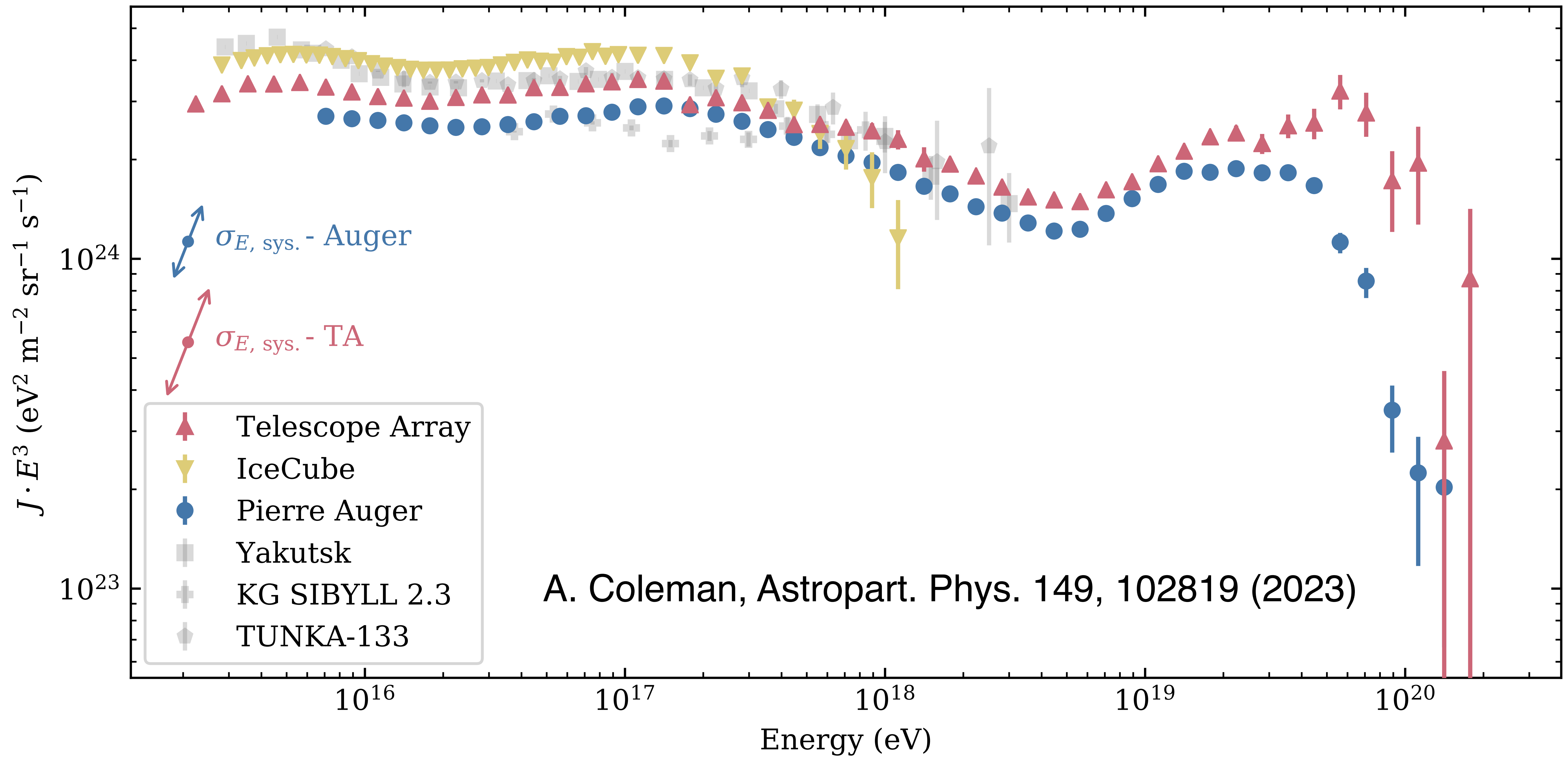


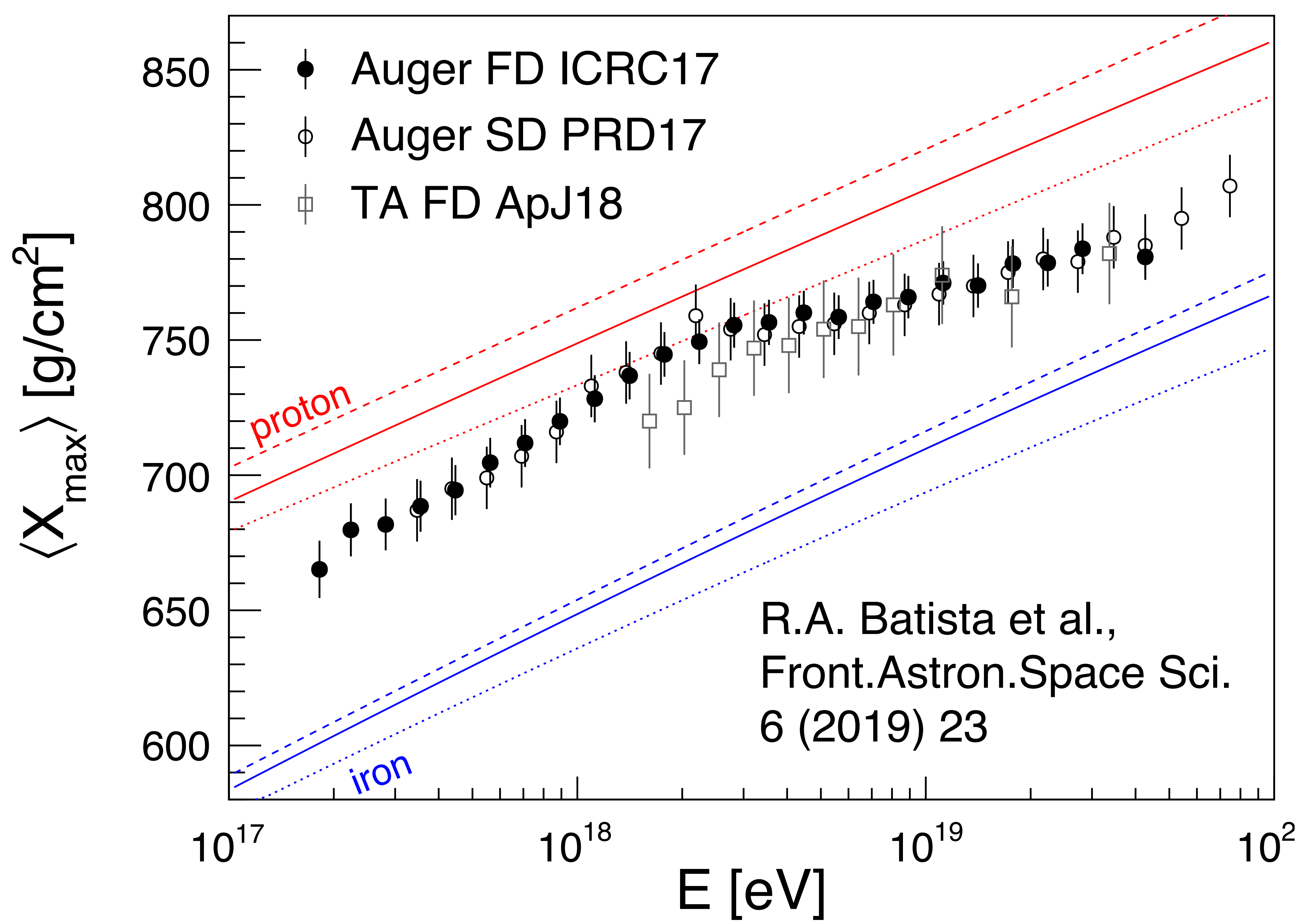

★ : Starburst galaxies ♦ : Active galactic nuclei

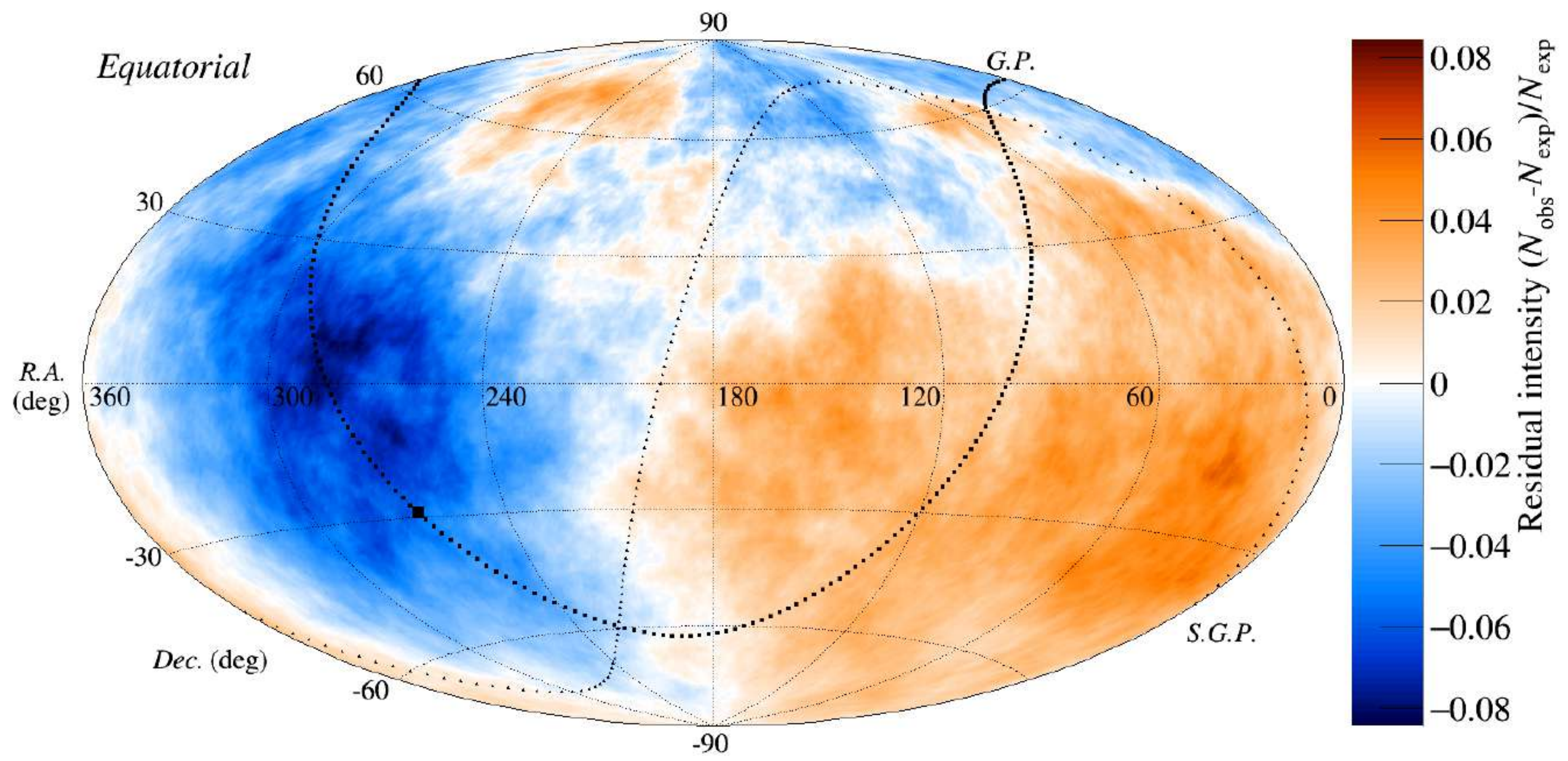
>100 EeV of TA 15-years and Auger 17-years

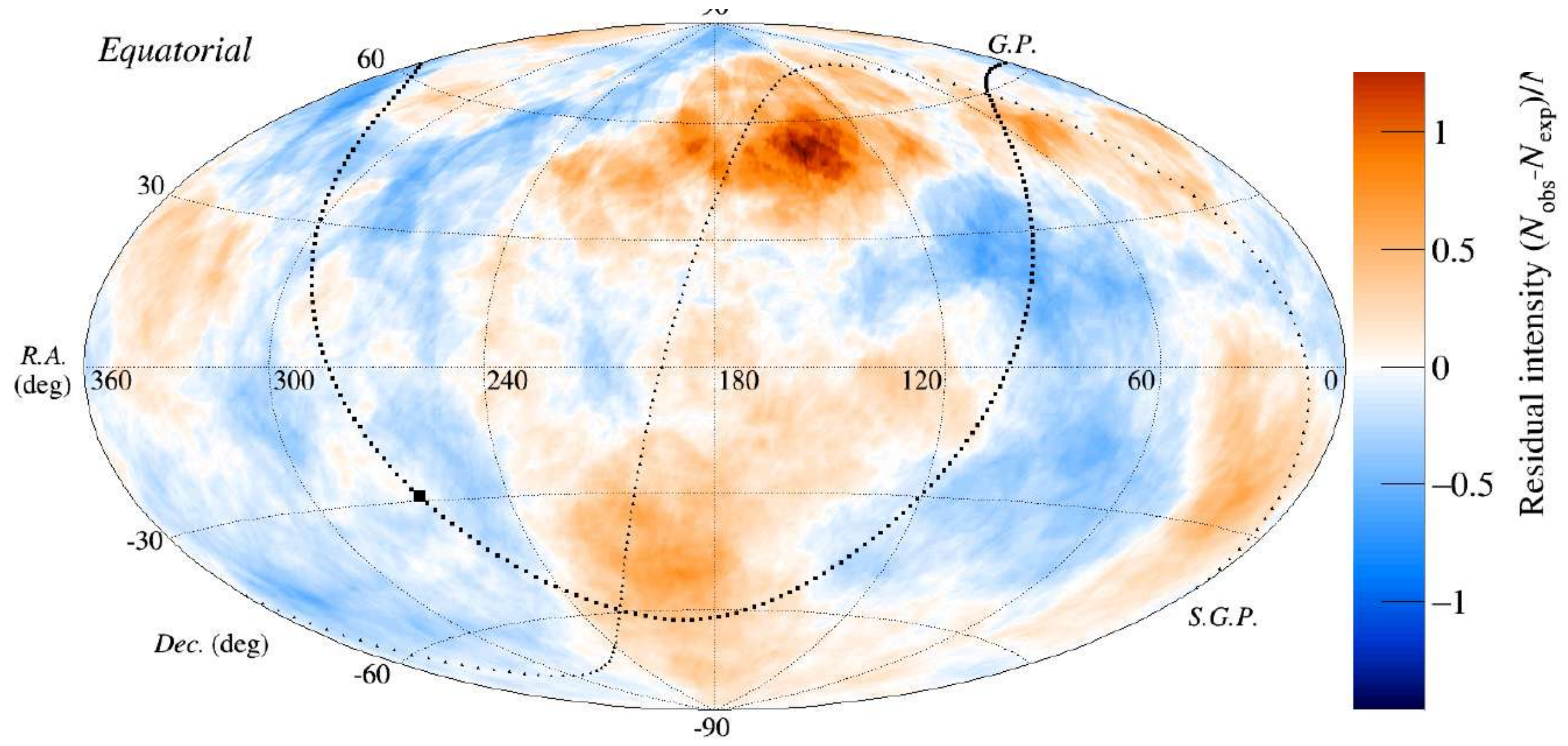
**No obvious clustering appeared**

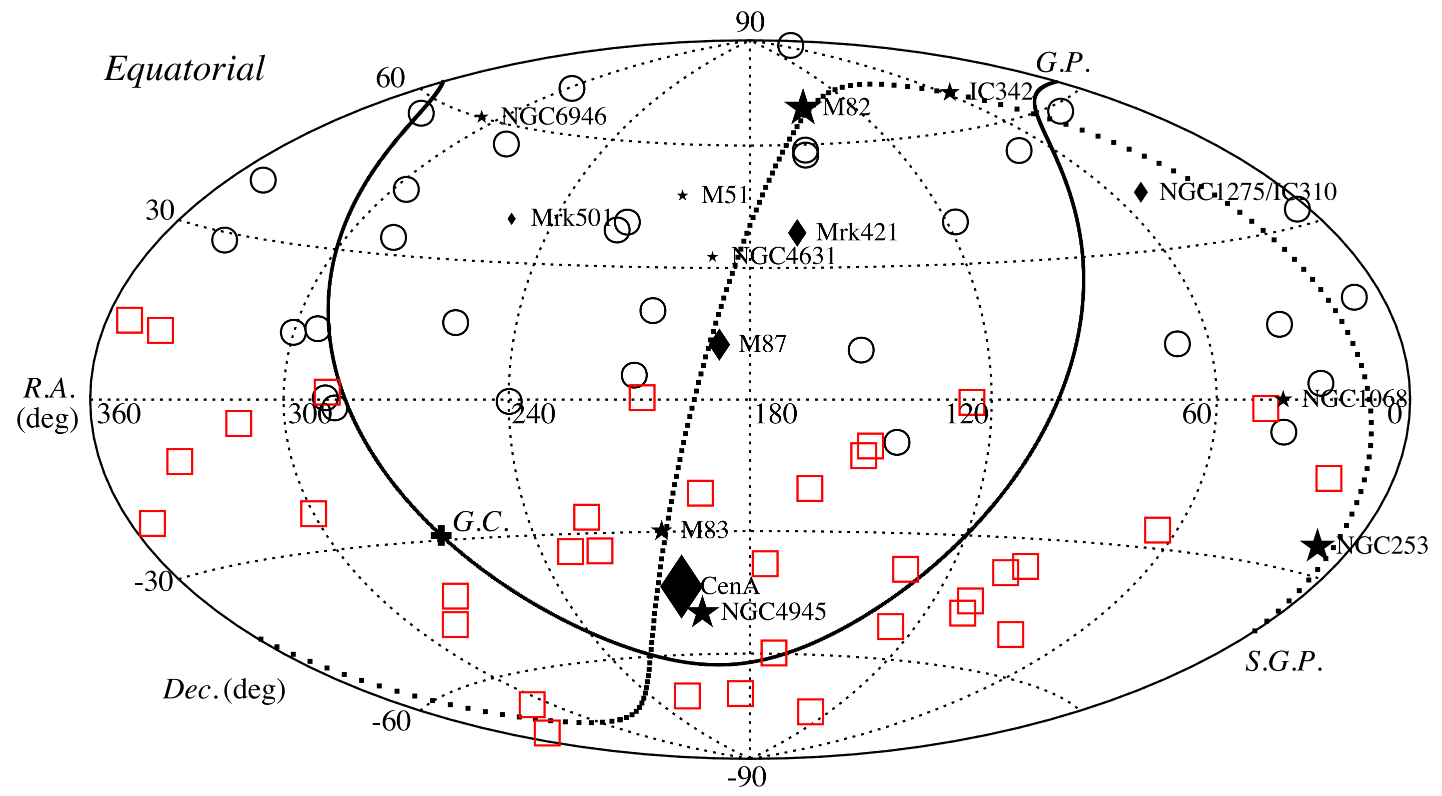
# Summary and future perspective



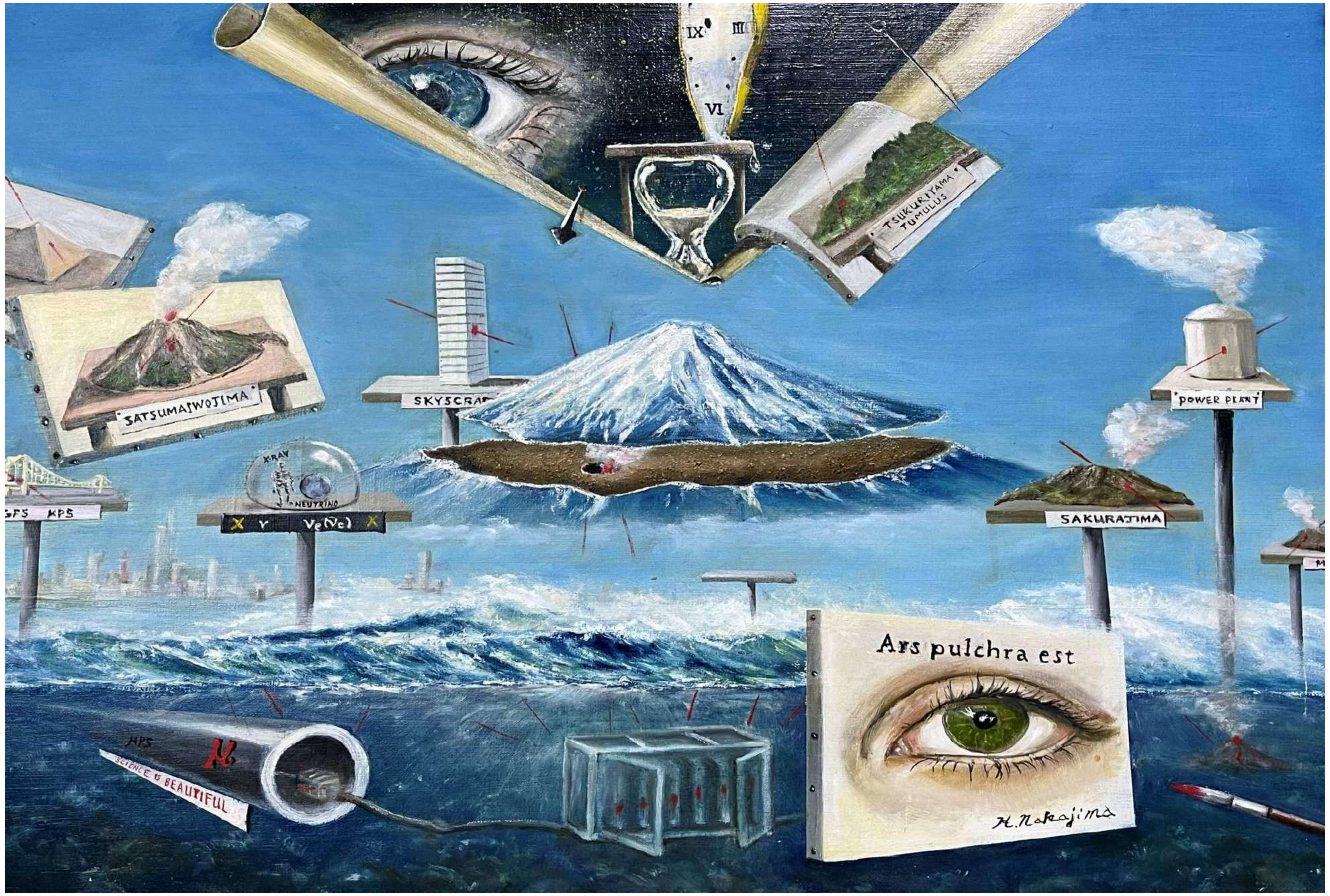




After over-100-year endeavor for detecting cosmic rays,
**origins of UHECRs are still inconclusive...😅** ***We need future observatories!*** 😁

# Art of cosmic ray (Hiroshi Nakajima, Japan)


← Amaterasu particle

↓ Muon tomography



# Backup

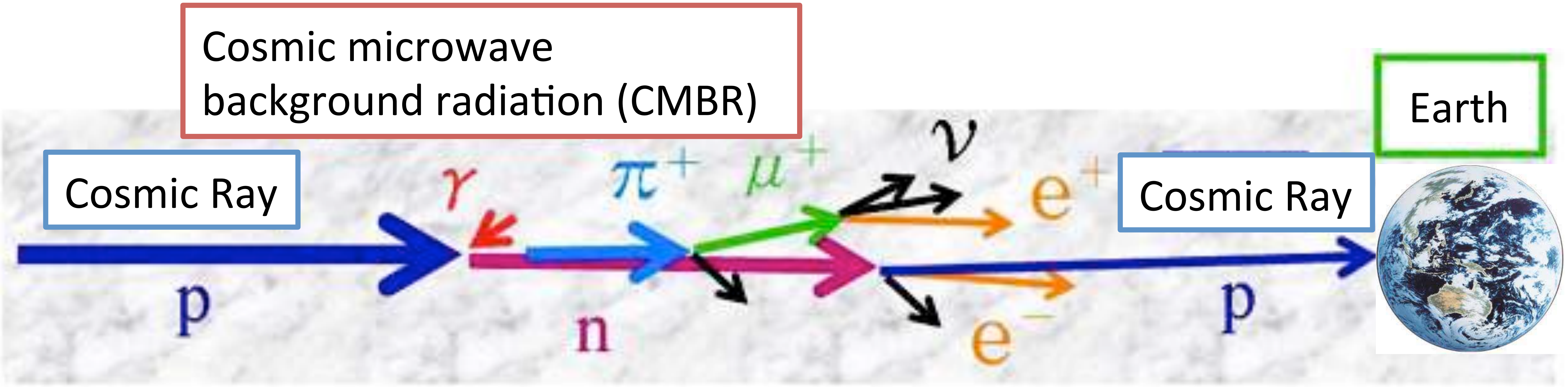
# UHECRs as a high energy pioneer

- Pros
  - The most energetic particle in the Universe, **~3.2x10$^{20}$ eV (=320 EeV)**
    - **√s ~ 800 TeV** (ref. √s ~ 14 TeV at the Earth's largest accelerator)
      - to make a light bulb flash during **only 1 second**
  - **Possible directional correlations** toward nearby powerful astronomical objects as next generation astronomy
  - Pioneering search for new physics at an unprecedented energies for accelerators
- Cons
  - **Extremely infrequent**: **1 particle/km$^2$/century (>50 EeV)**
    - Challenging to detect UHECRs
  - Manage a lot of systematic uncertainties

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

# Greisen–Zatsepin–Kuzmin (GZK) Cutoff

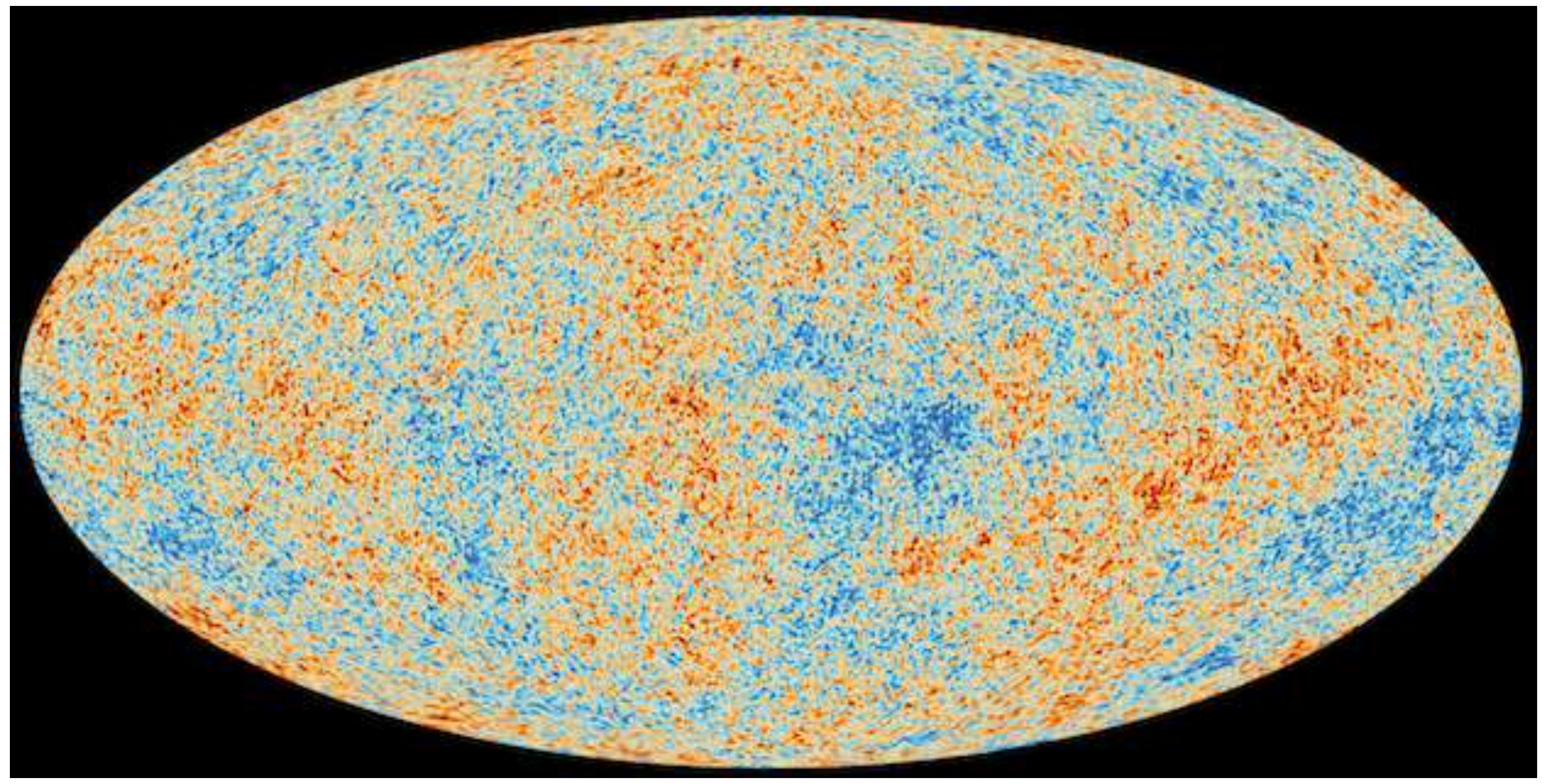





- Interaction between >50 EeV proton and CMB via pion production
  - Heaver nuclei also interact via photo-disintegration
    - Mean free path: **50-100 Mpc (cosmological neighborhood)**
  - **Cutoff feature of energy spectrum above 50 EeV**
    - **The universe's largest-scale interaction between the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

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

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



Planck Collaboration

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

# Less deflection by Galactic magnetic fields

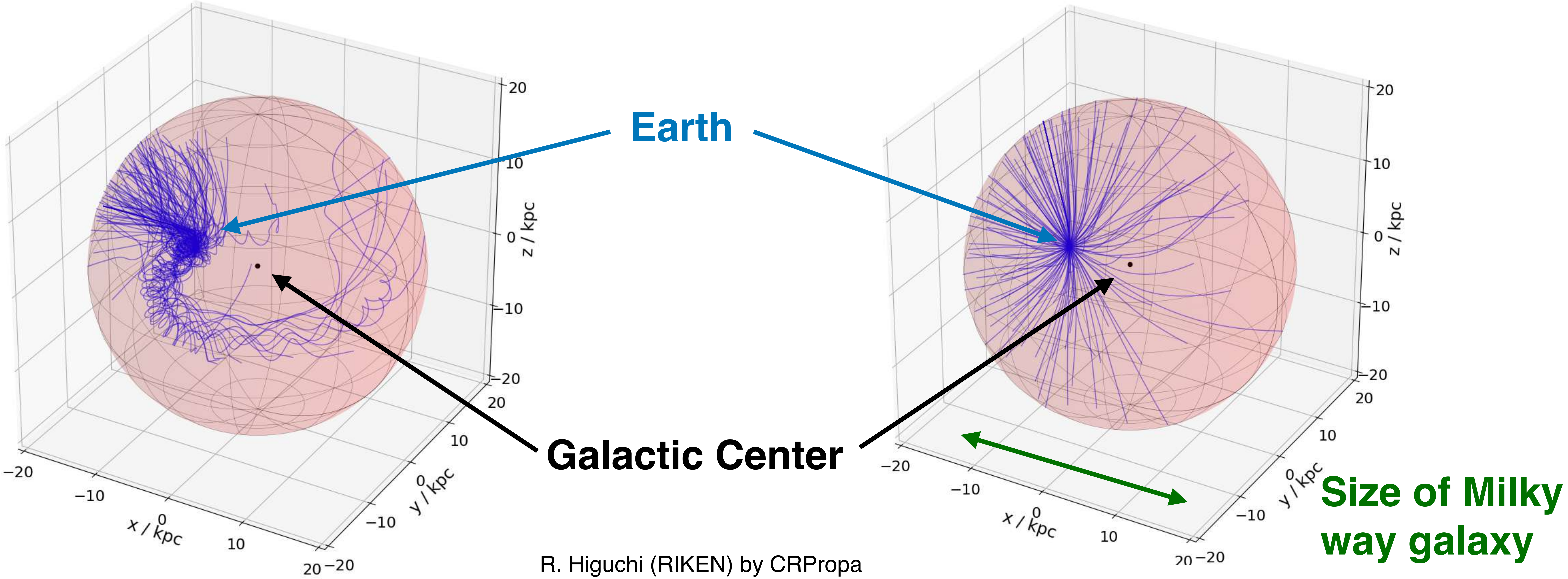
**Deflection angle in Milky Way**

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

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)




R. Higuchi (RIKEN) by CRPropa

# Source candidates and next-generation astronomy



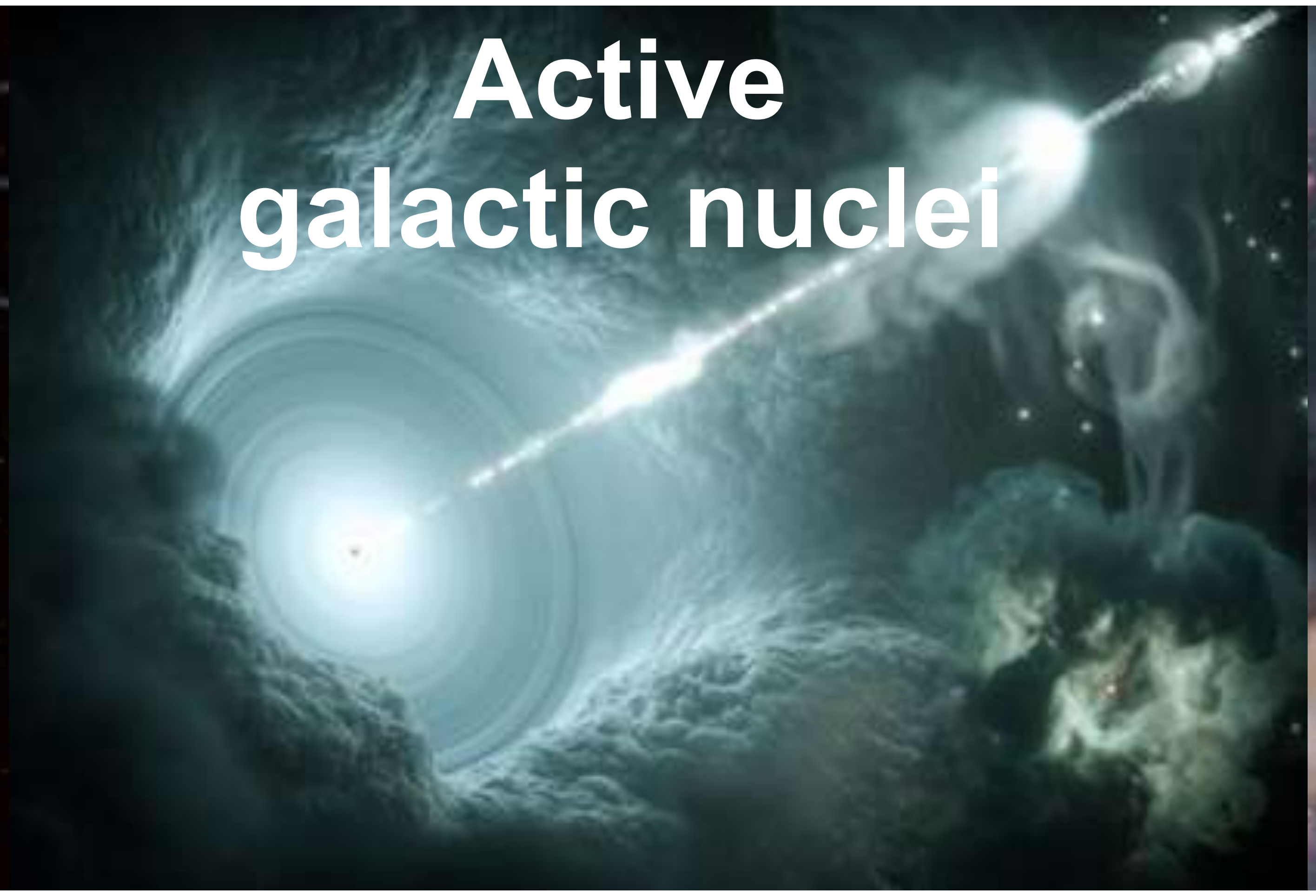
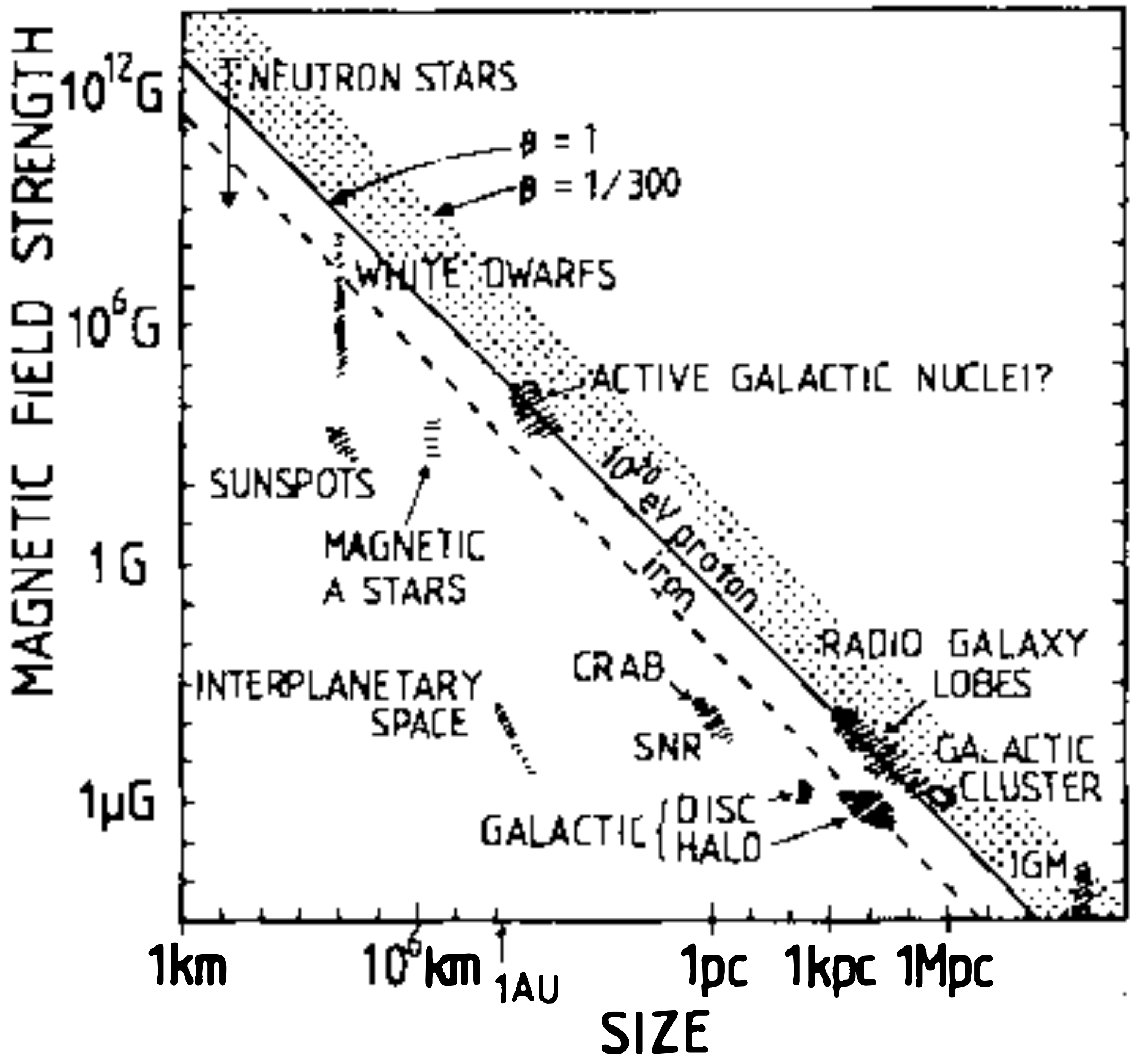




Image credits: Max Plank Inst./RIKEN/DESY/Science Comm

**... or "New physics"**




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

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

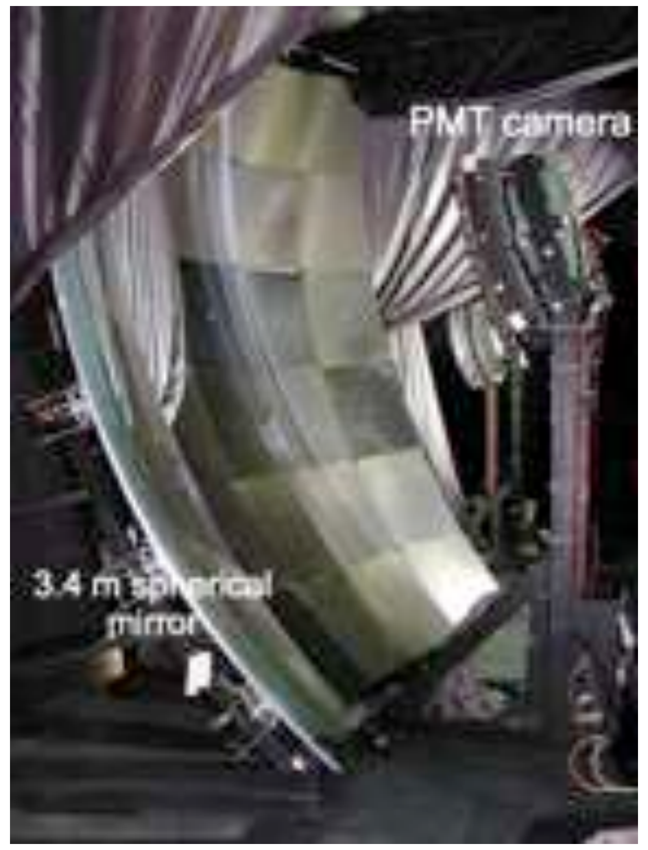
- **Limitation of nearby sources** due to GZK cutoff
- **Less deflections** of Galactic/extragalactic magnetic fields
  - Directionally correlations between **UHECRs** and nearby **inhomogeneous sources** to identify their origins
- **A next-generation "astronomy" using charged particles**

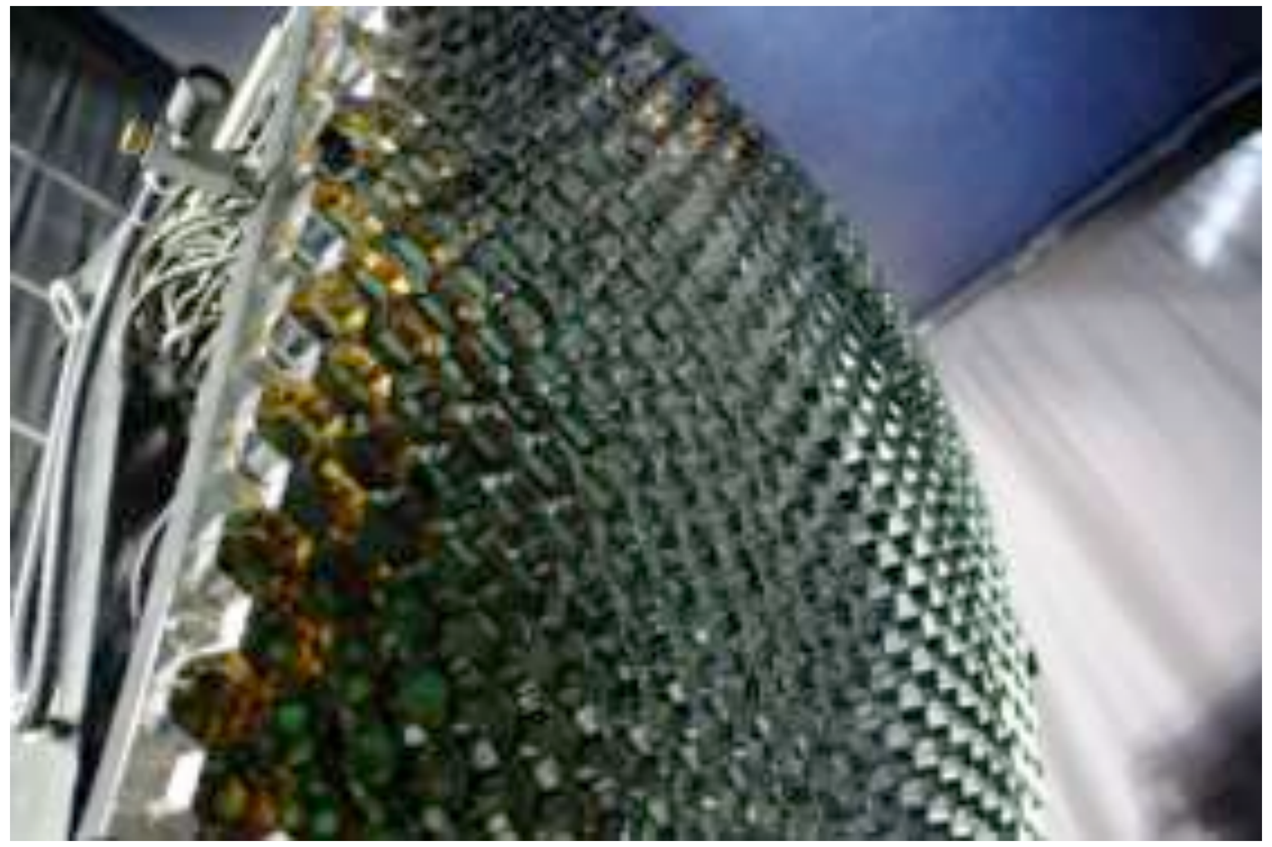
# "Charged particle astronomy" using ultra-high-energy cosmic rays (UHECRs)

# FAST: Fluorescence detector Array of Single-pixel Telescopes

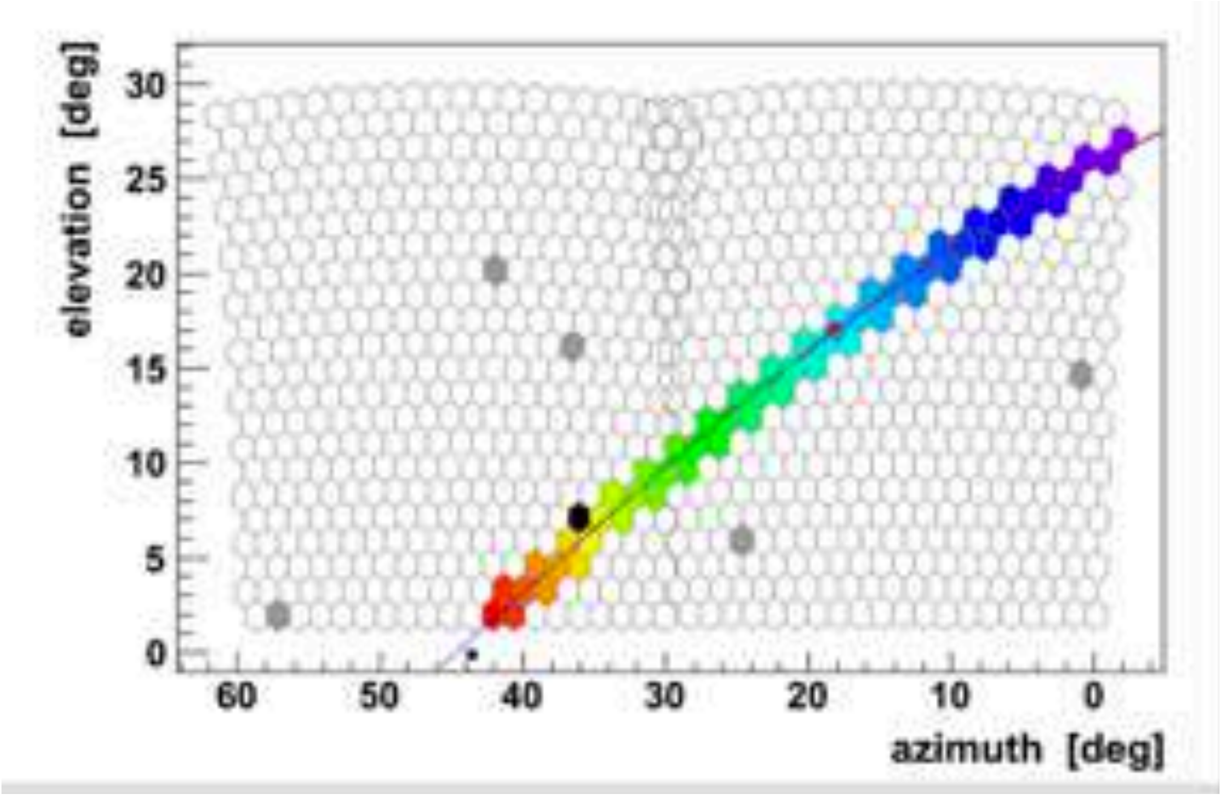
- **Target : > $10^{19.5}$ eV, ultrahigh-energy cosmic rays, neutrino and gamma rays**
  - Huge target volume (10x Auger or TAx4) ⇒ Fluorescence detector array

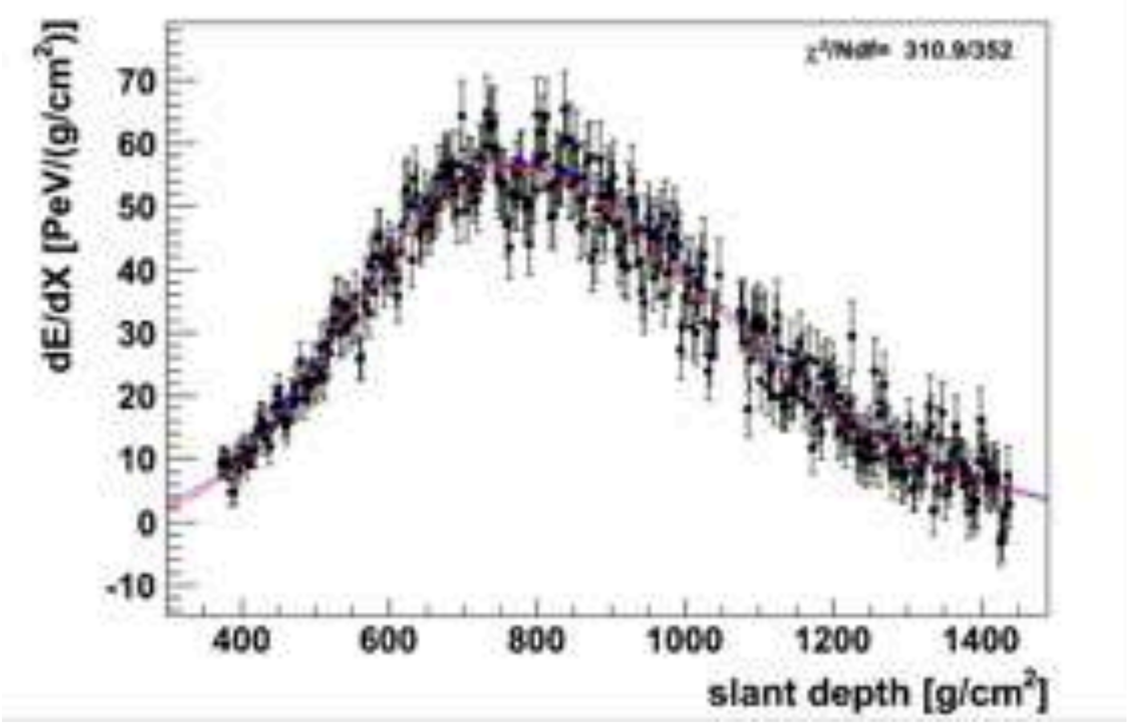
Fine pixelated camera



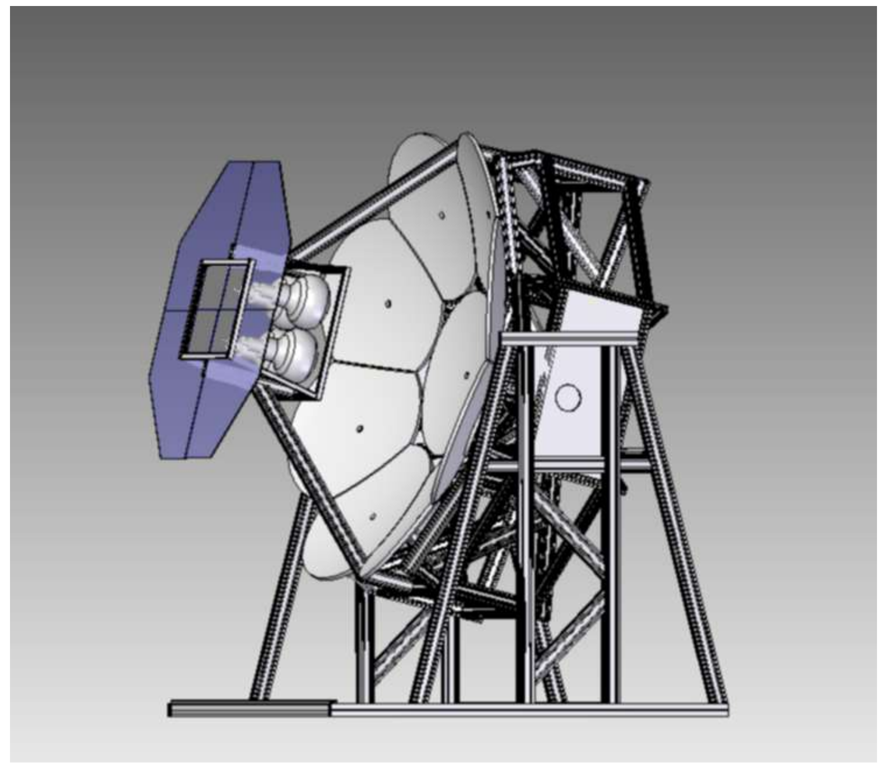



**Too expensive to cover a huge area**

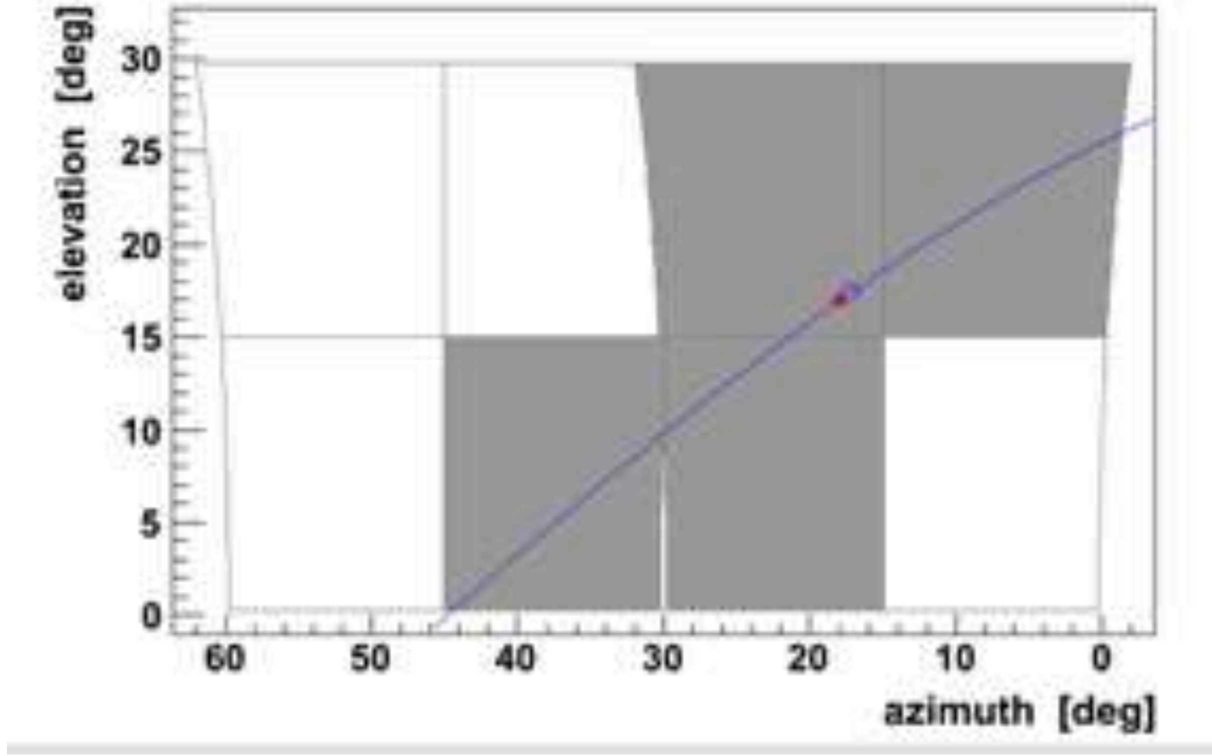


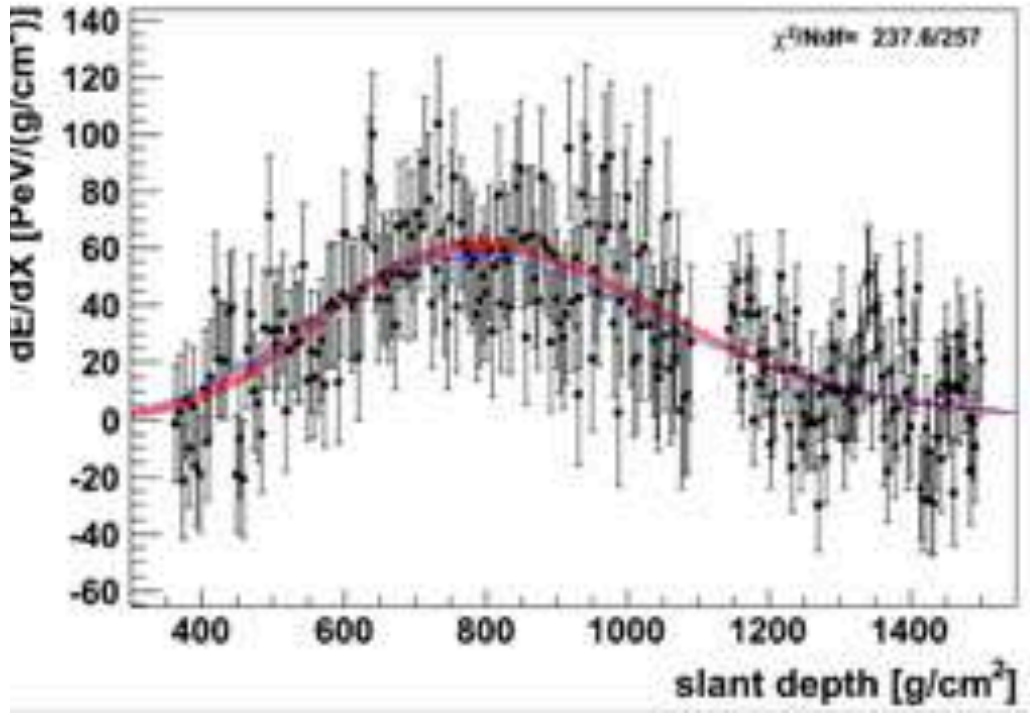




Smaller optics and single or few pixels

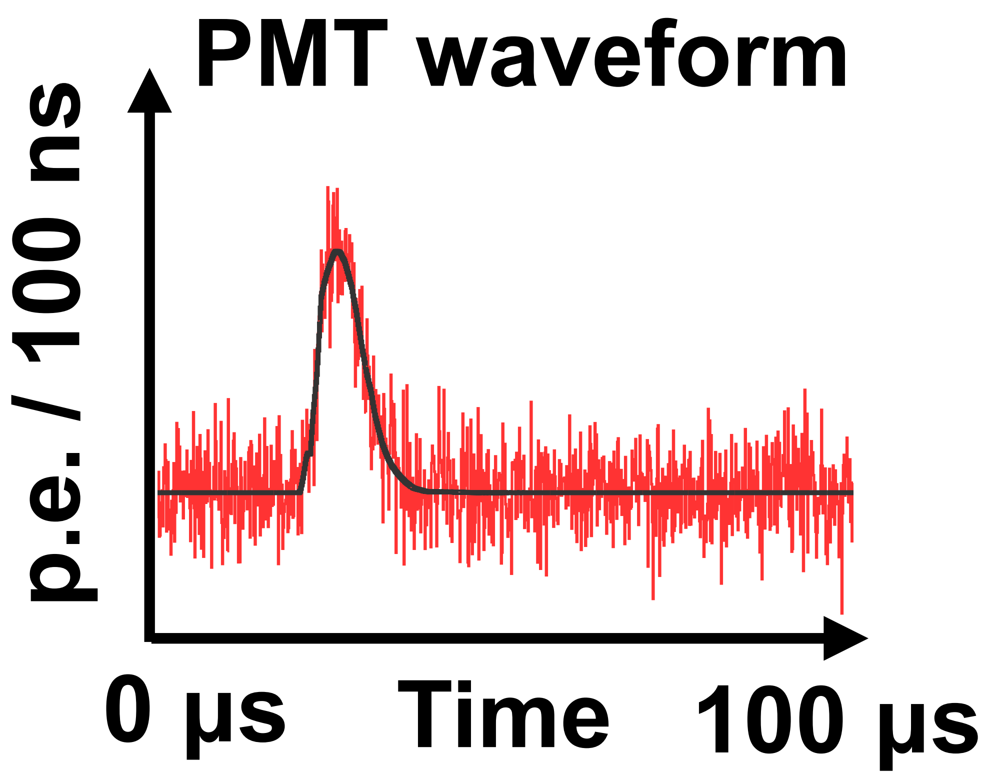


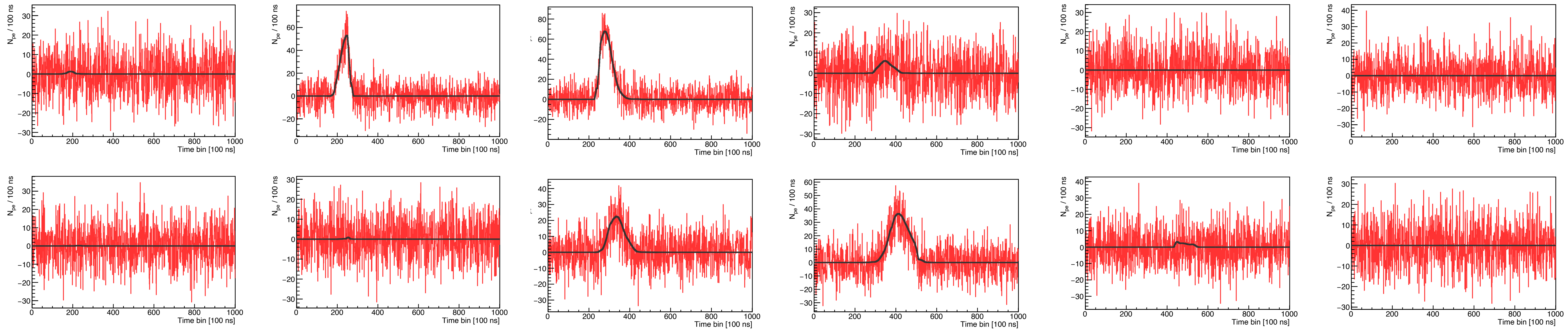
**Low-cost and simplified telescope**

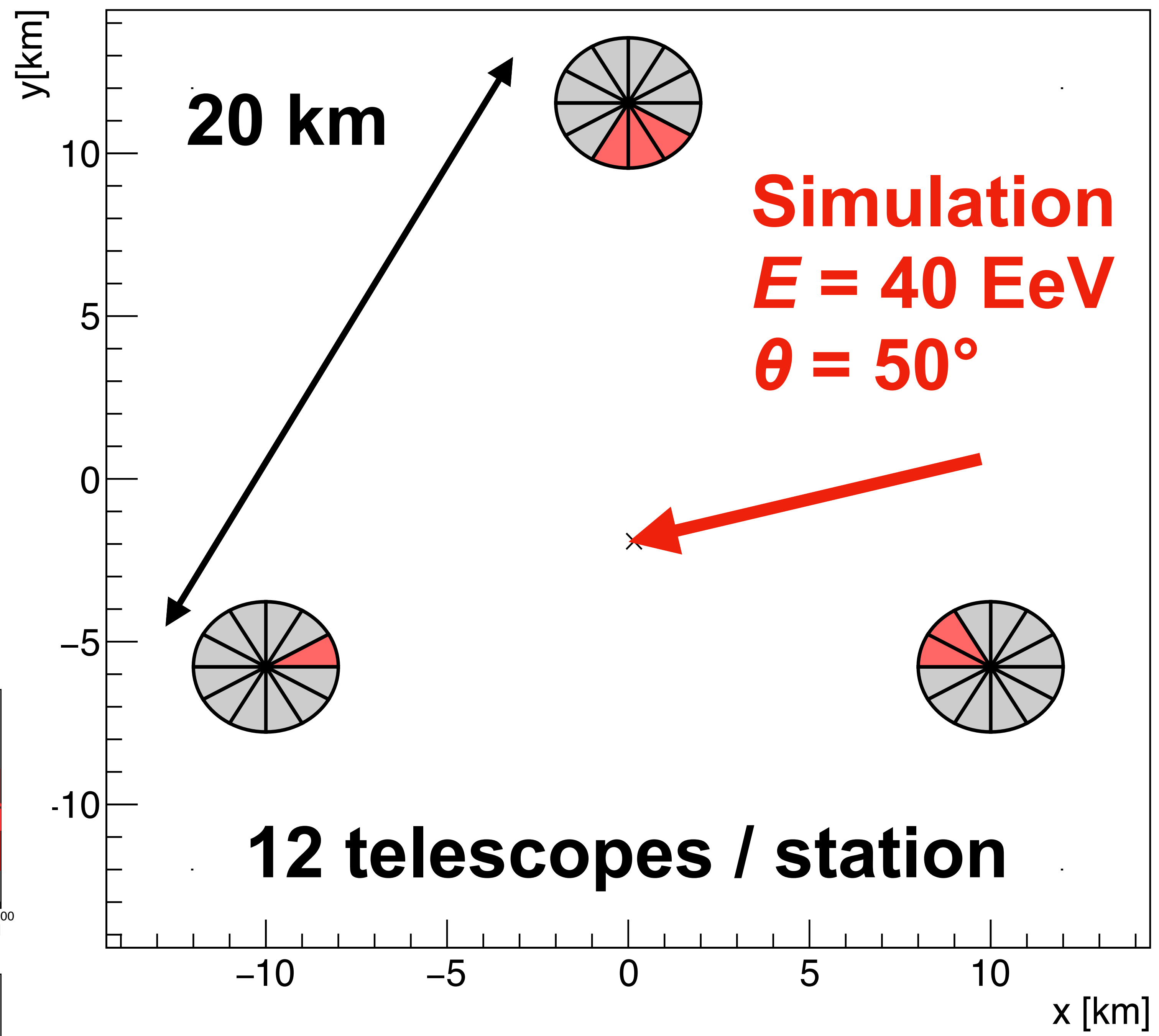


# Fluorescence detector Array of Single-pixel Telescopes

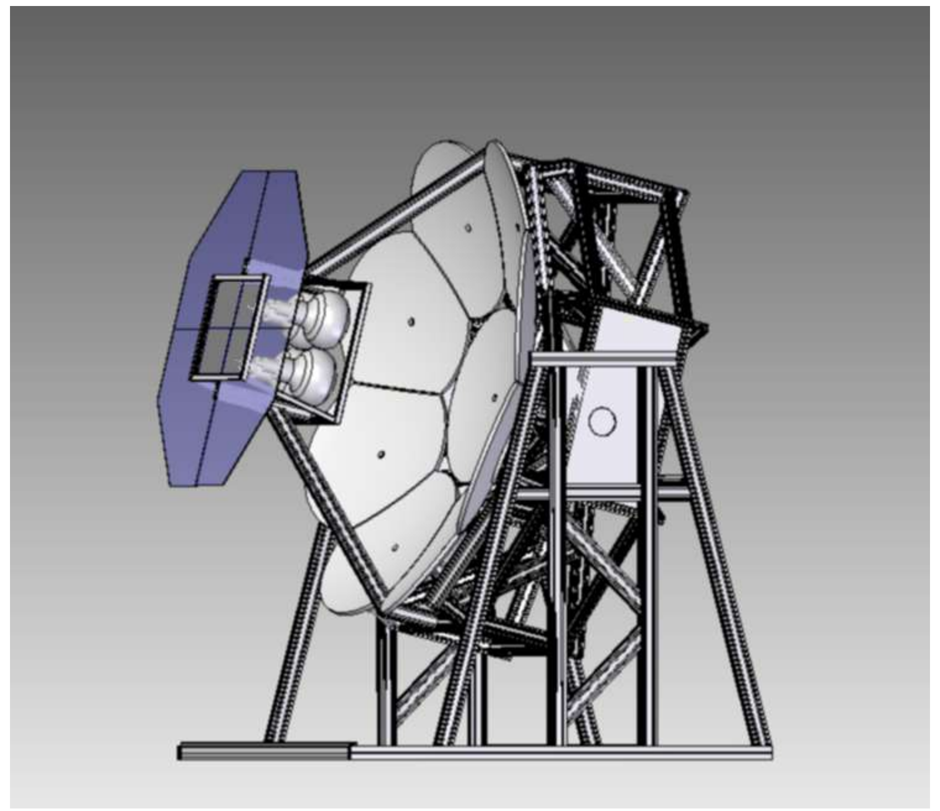





500 stations

→ <u>150,000 km²</u>



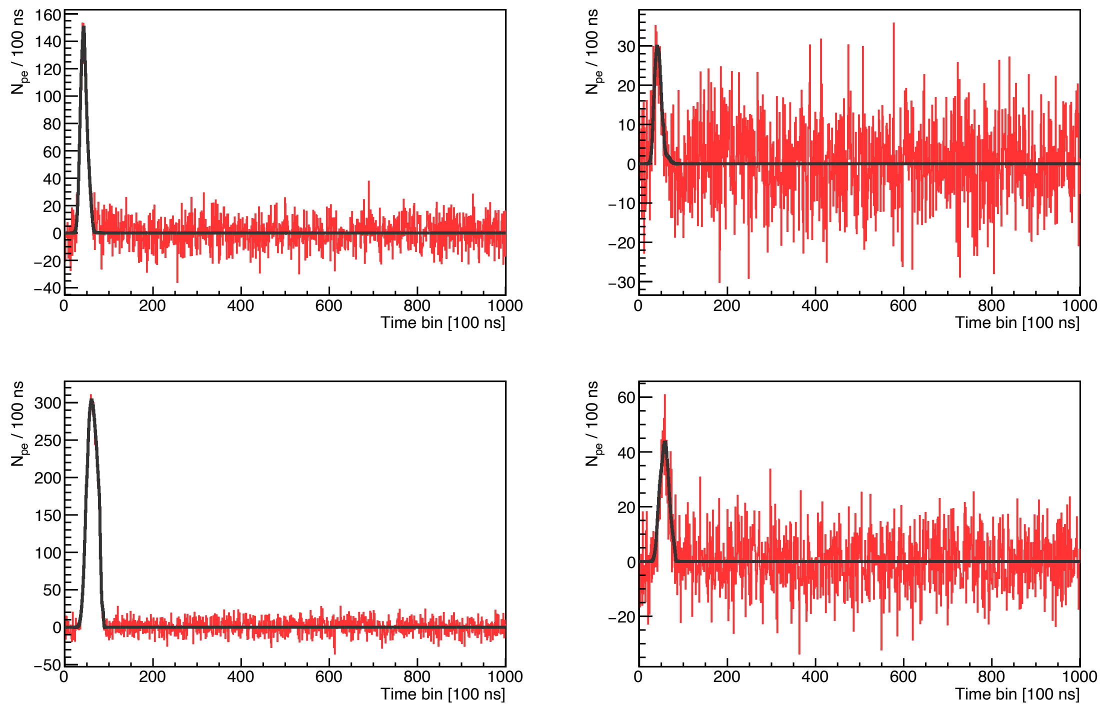
**<u>FAST telescope</u>**

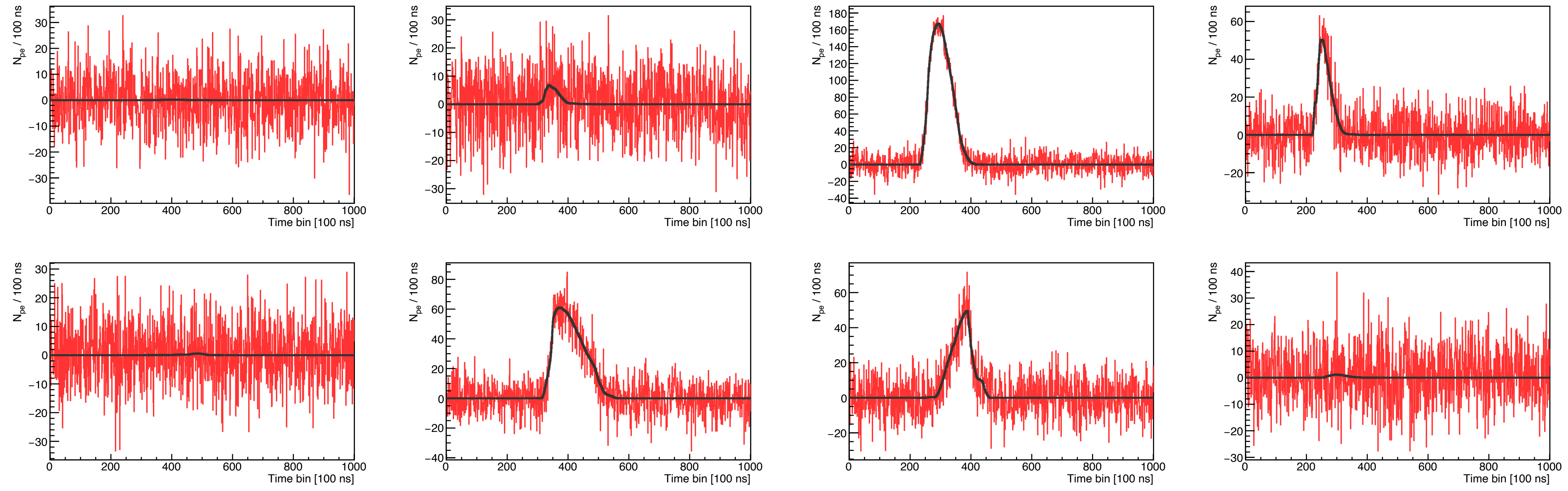
4 PMTs (20 cm diameter)

1 m$^2$ aperture (UV filter)

Segmented mirror

in 1.6 m diameter

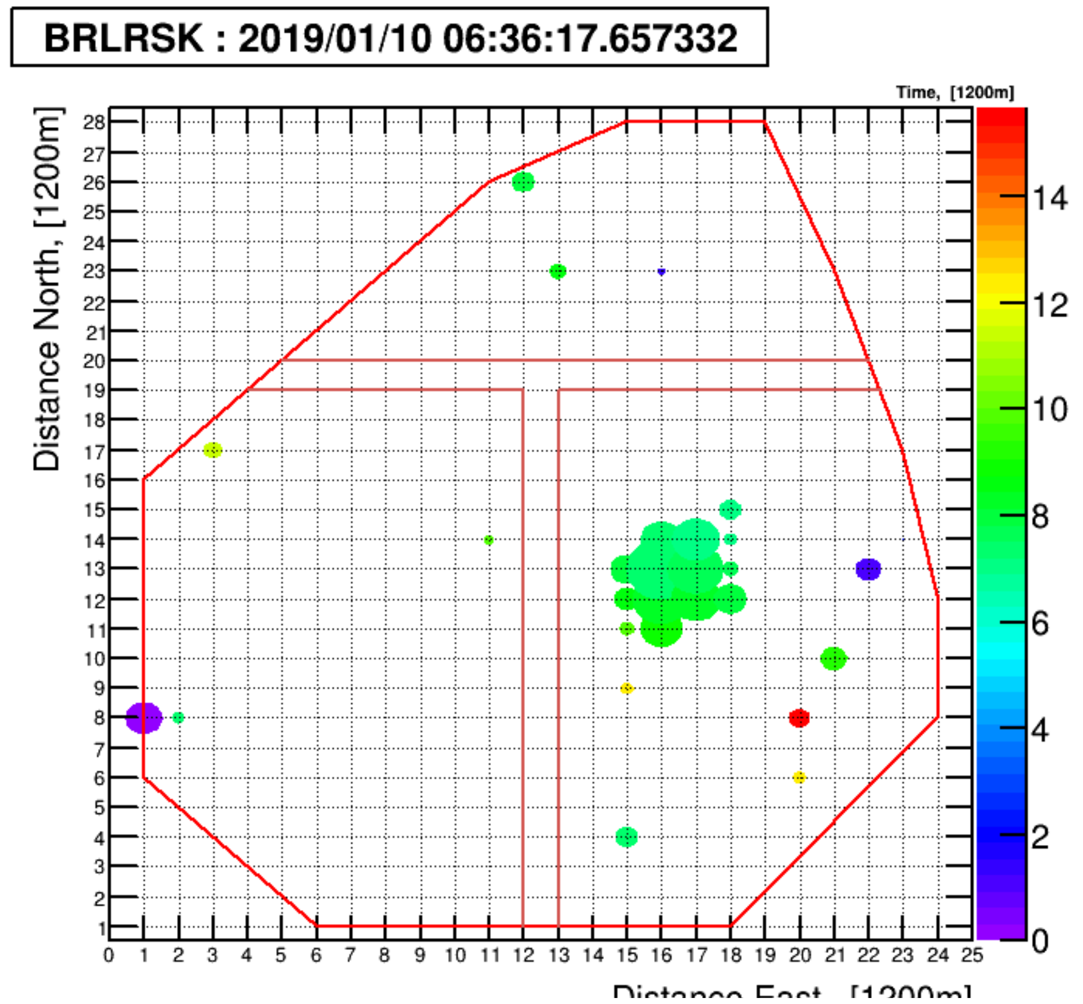


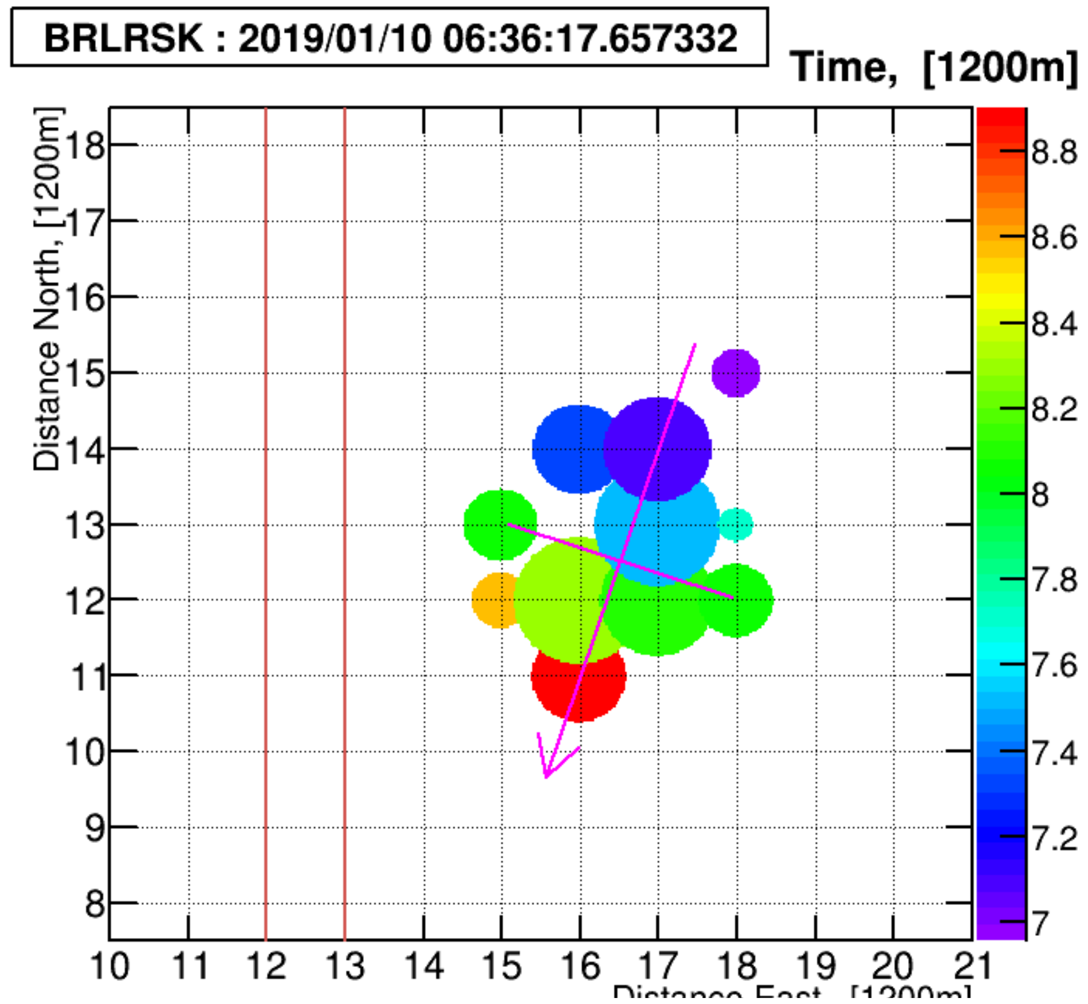


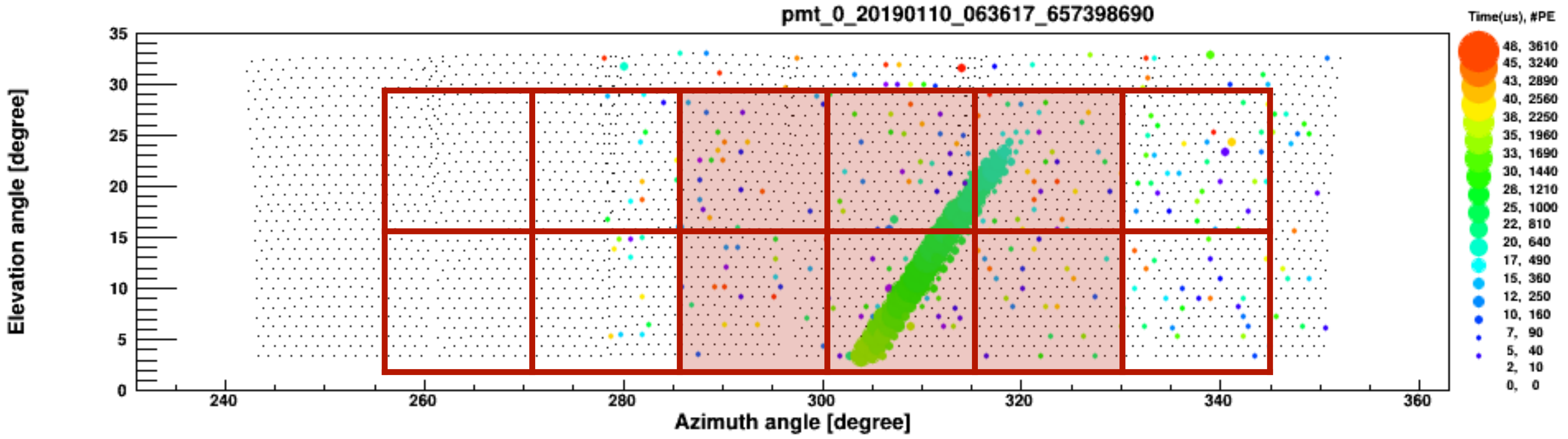
# UHECR detections

Fluorescence detector Array of Single-pixel Telescopes

## TA result




**TA SD (Preliminary)**

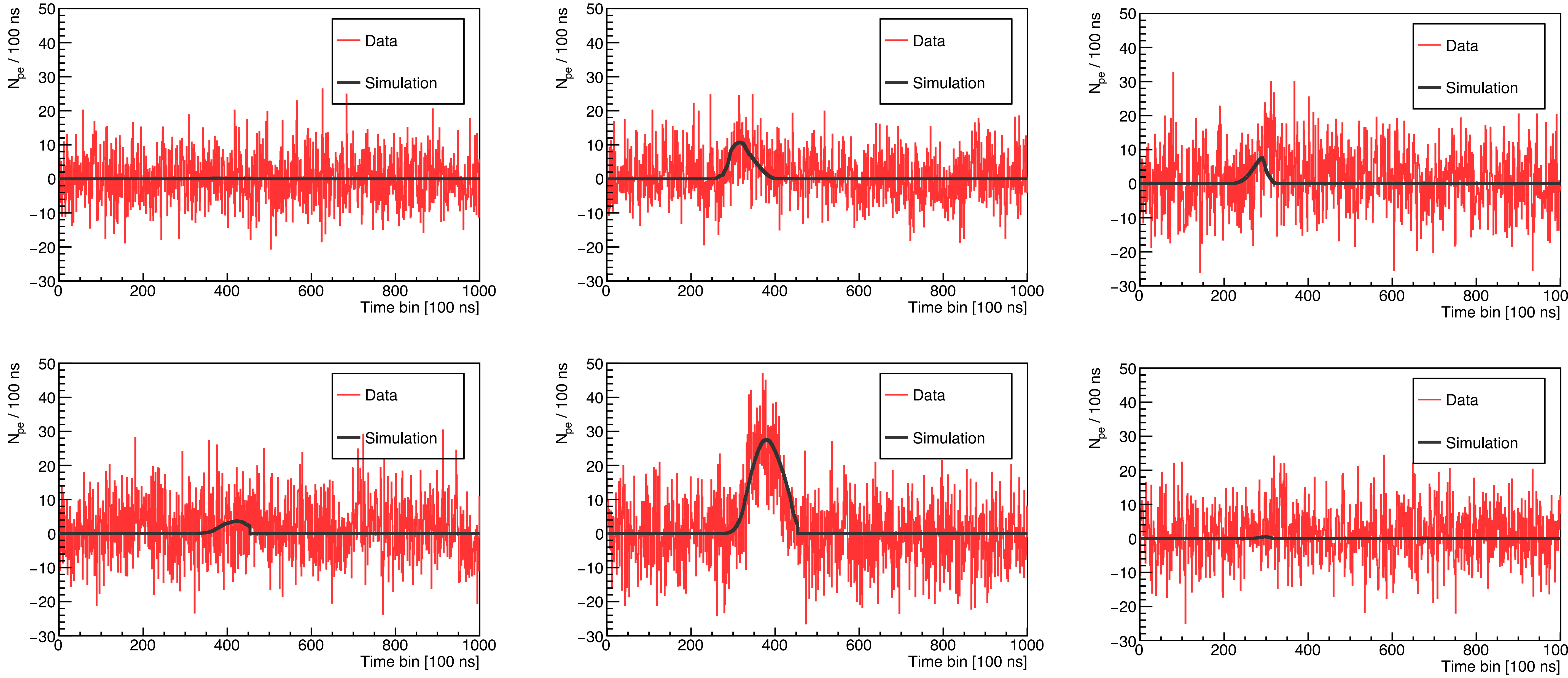
| Zenith | Azimuth | Core(X) | Core(Y) | Energy |
|---|---|---|---|---|
| 36.2 deg | 18.0 deg | 5.0 km | -4.5 km | 15.8 EeV |

**TA FD (Preliminary)**

| Zenith | Azimuth | Core(X) | Core(Y) | Energy |
|---|---|---|---|---|
| 33.2 deg | 35.8 deg | 6.1 km | -5.3 km | 20.0 EeV |

Fluorescence detector Array of Single-pixel Telescopes

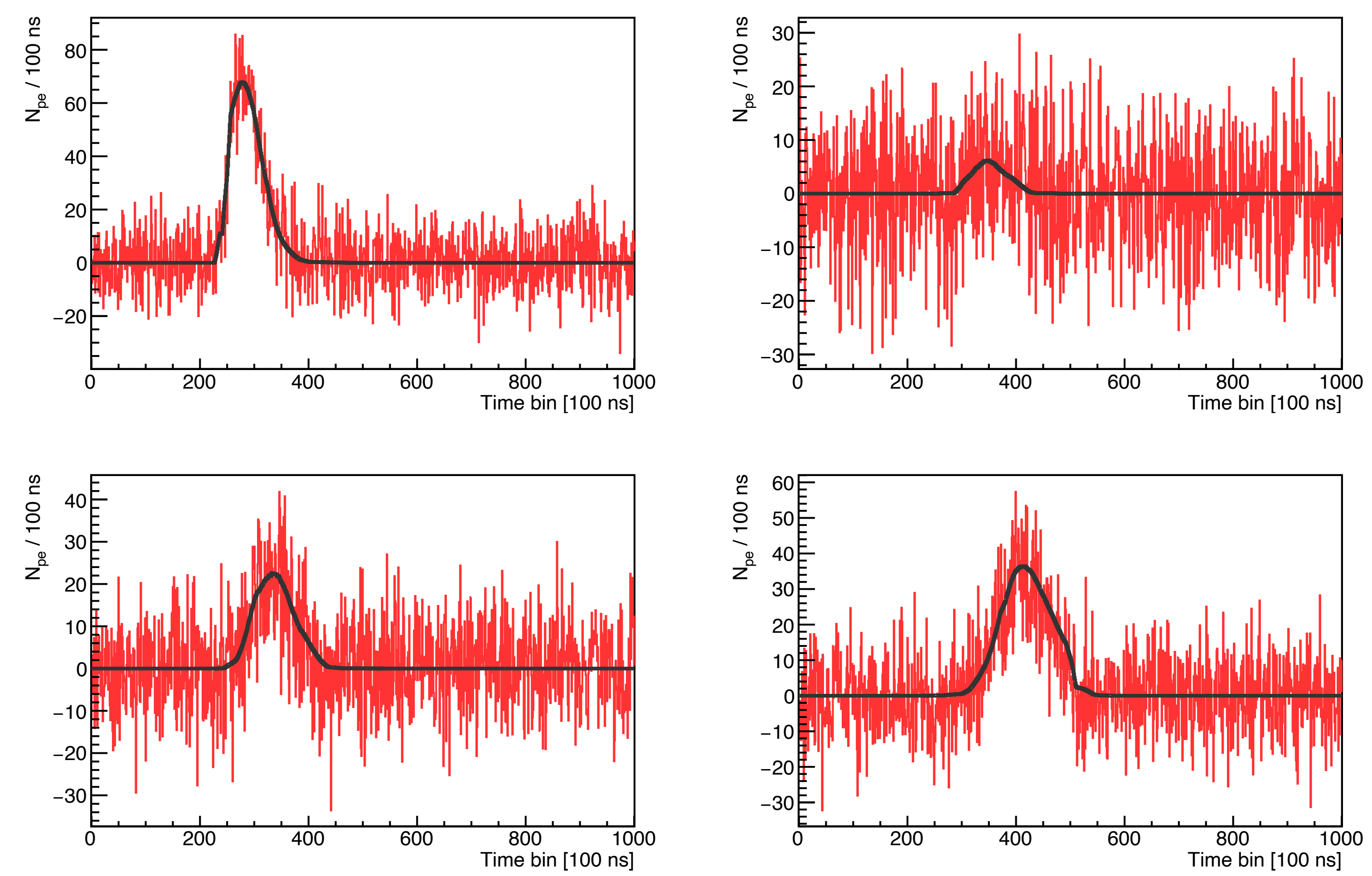
## FAST result

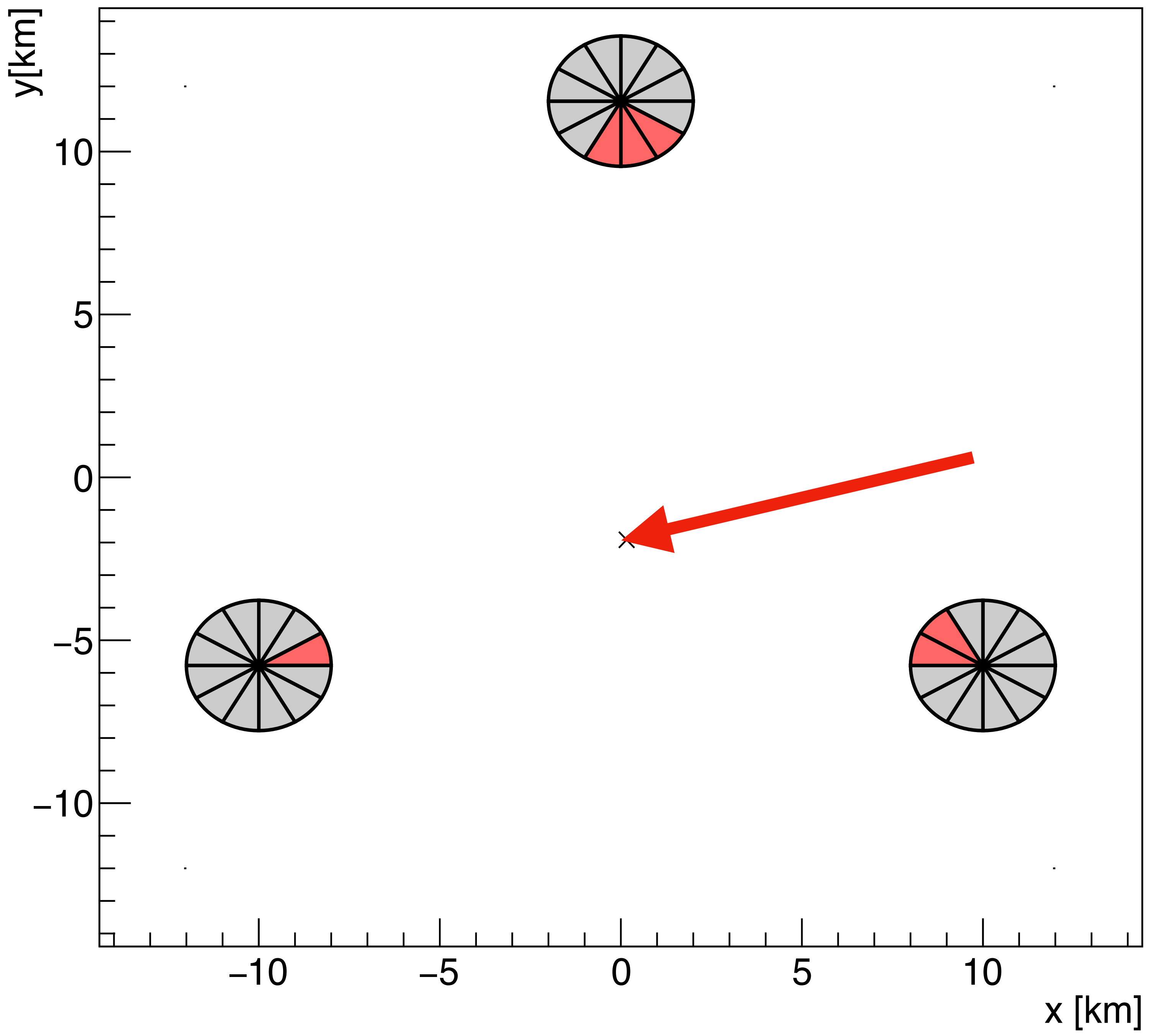




**FAST top-down reconstruction (Preliminary)**

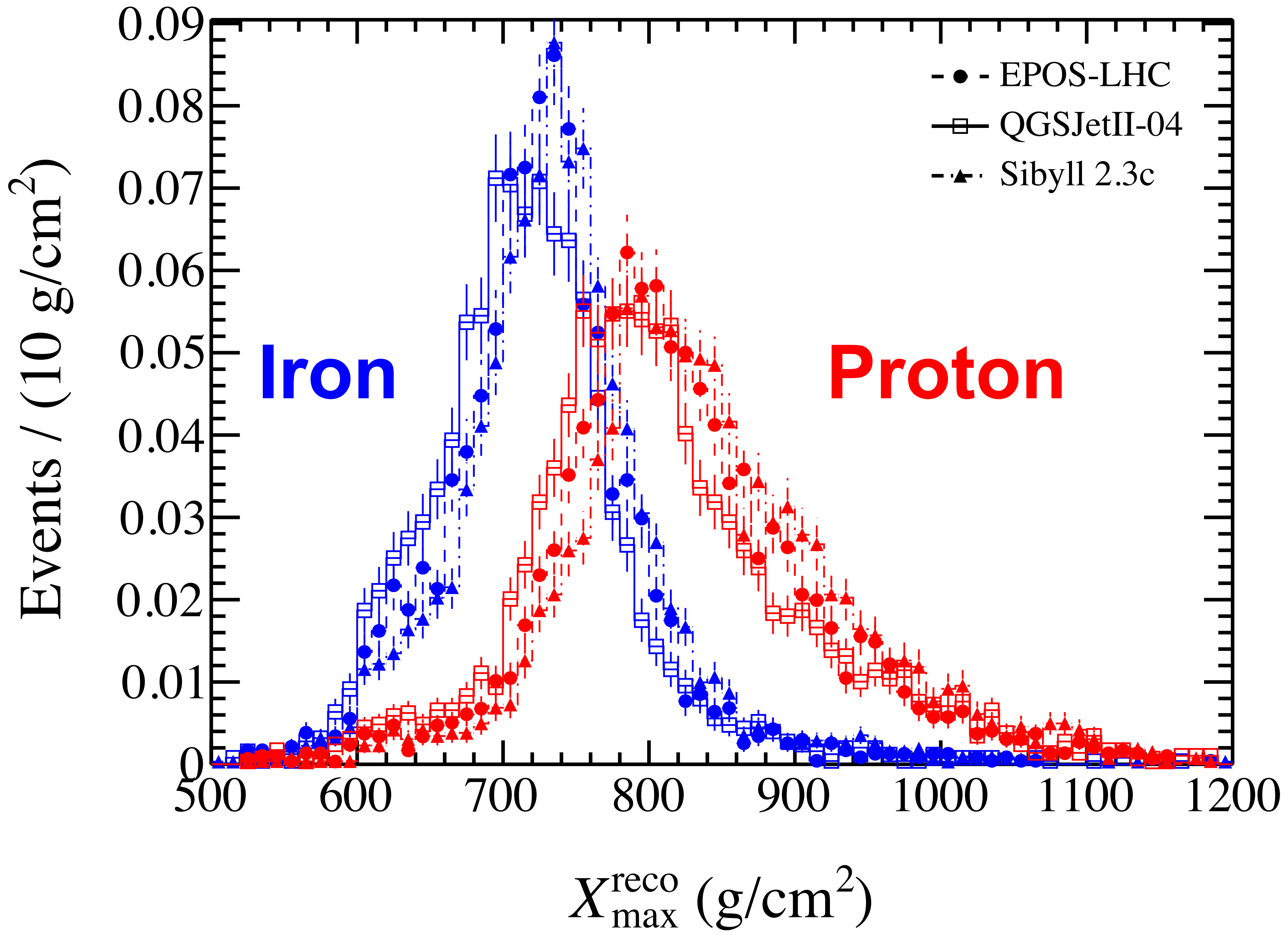
| Zenith | Azimuth | Core(X) | Core(Y) | Xmax | Energy |
|---|---|---|---|---|---|
| 33.9 deg | 19.3 deg | 4.6 km | -4.7 km | 808 g/cm$^2$ | 18.8 EeV |

# Performance studies with FAST

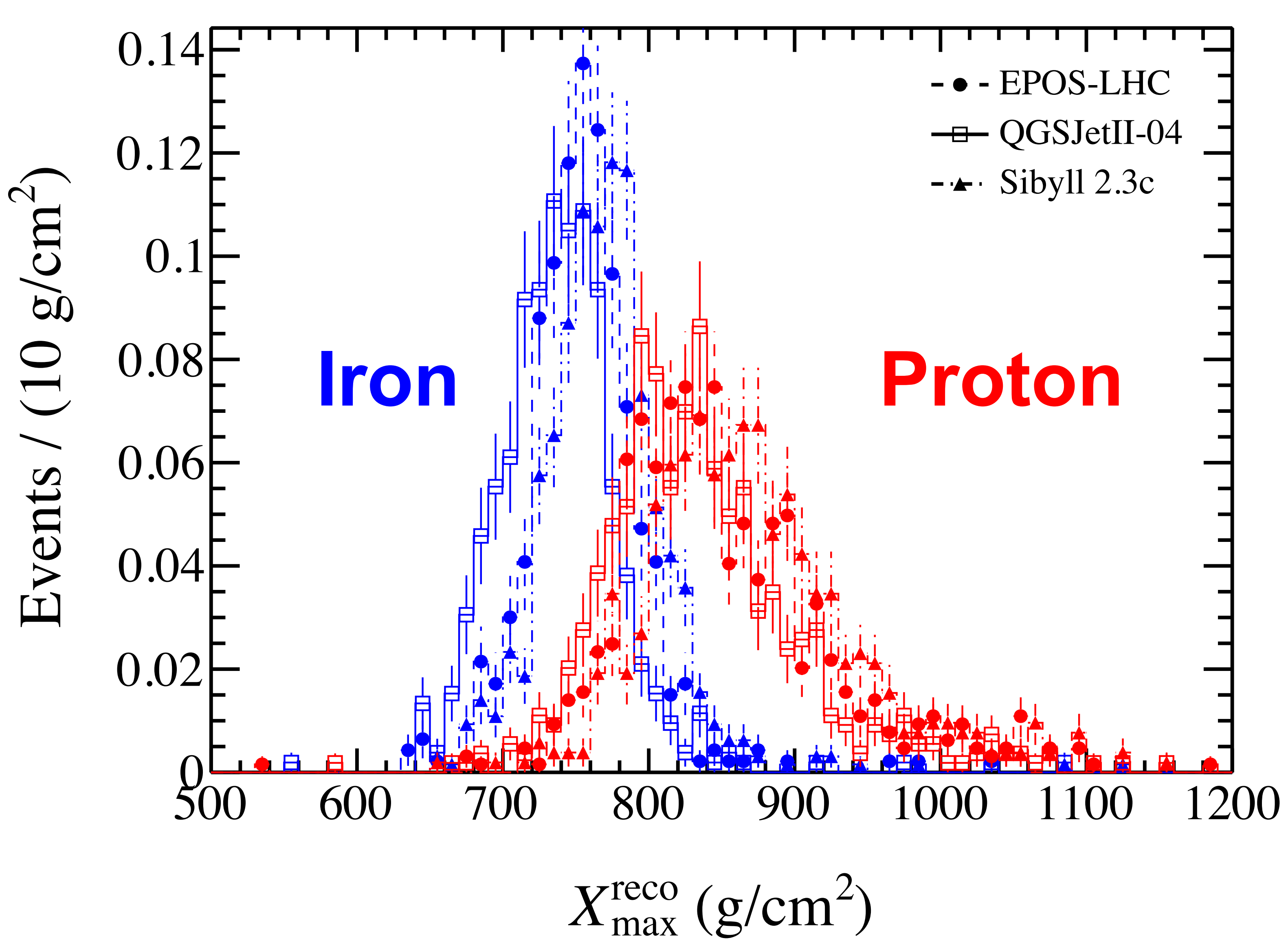


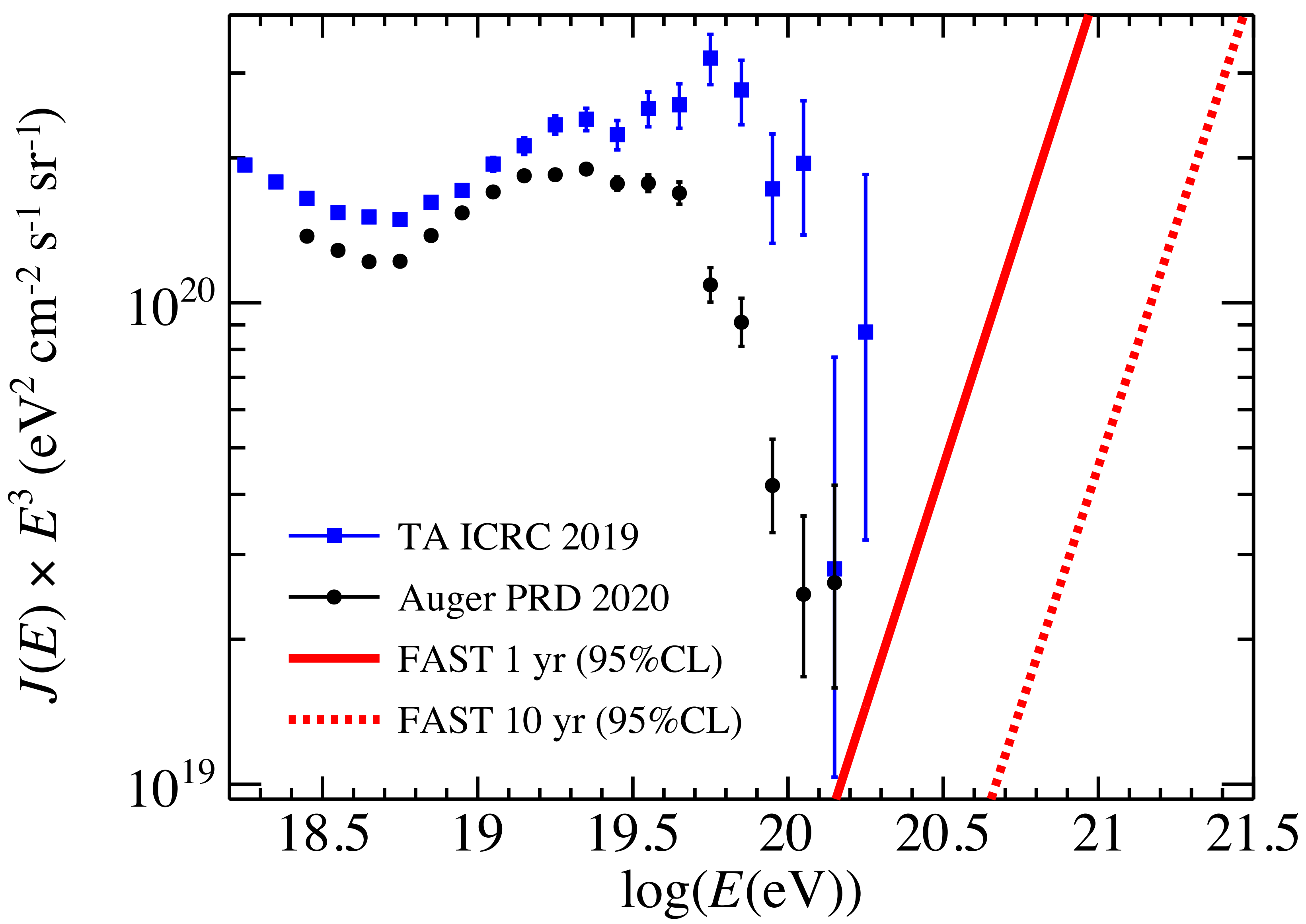

10 - 20 EeV




70 - 80 EeV

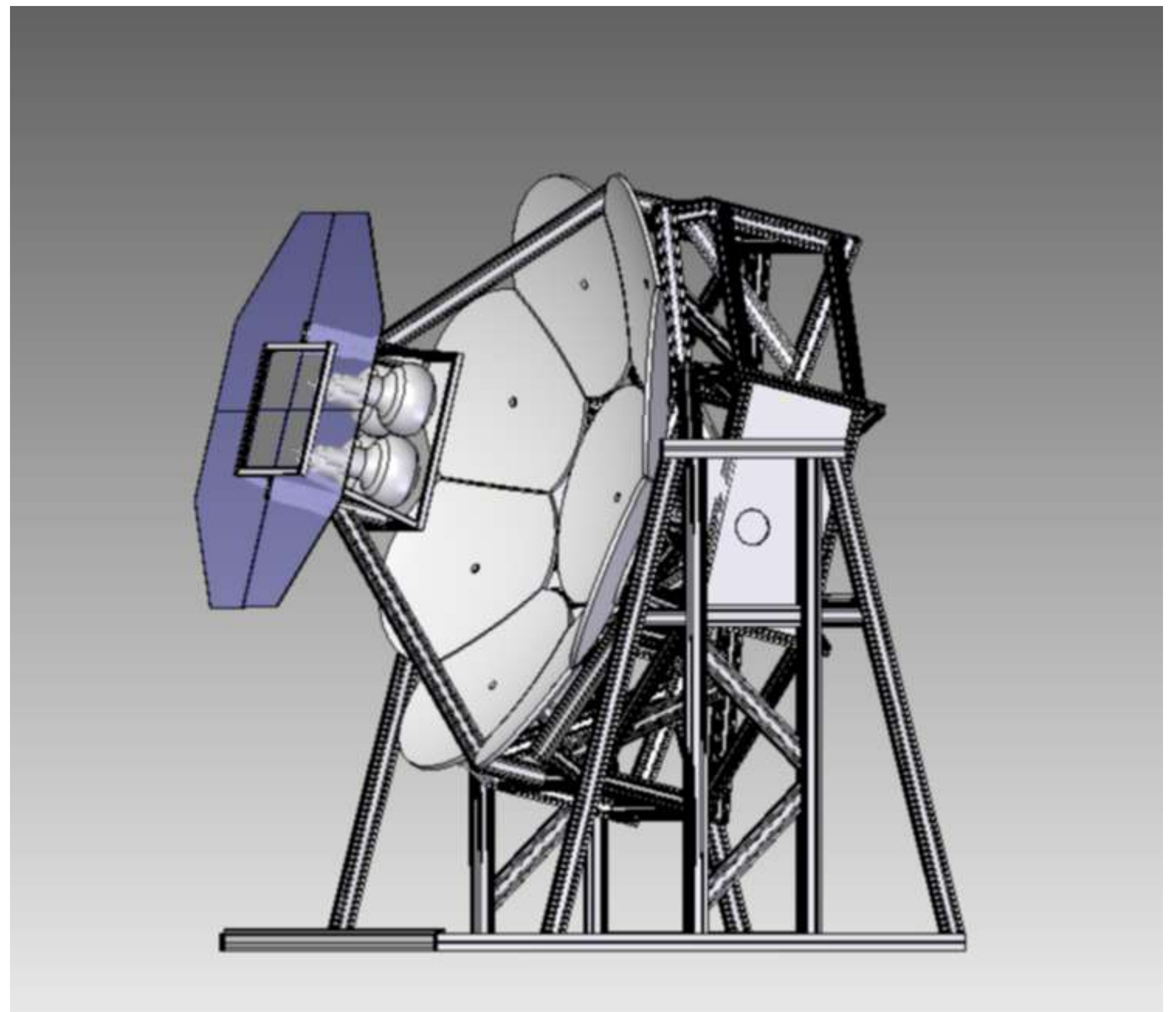



- Preliminary resolution at 40 EeV
  - Arrival direction: 4.2 degrees
  - **Energy: 8%, $X_{max}$: 30 g/cm²**
- Expected sensitivity with a "full-size" FAST array (500 stations to cover **150,000 km²**)
  - **Hunting the Universe's most energetic particles**



# Detector developments for next-generation observatories

## Low-cost, easily deployable



## Fluorescence detector Array of Single-pixel Telescopes (FAST) https://www.fast-project.org



## Global Cosmic ray Observatory (GCOS)

# Multi-messenger synergies

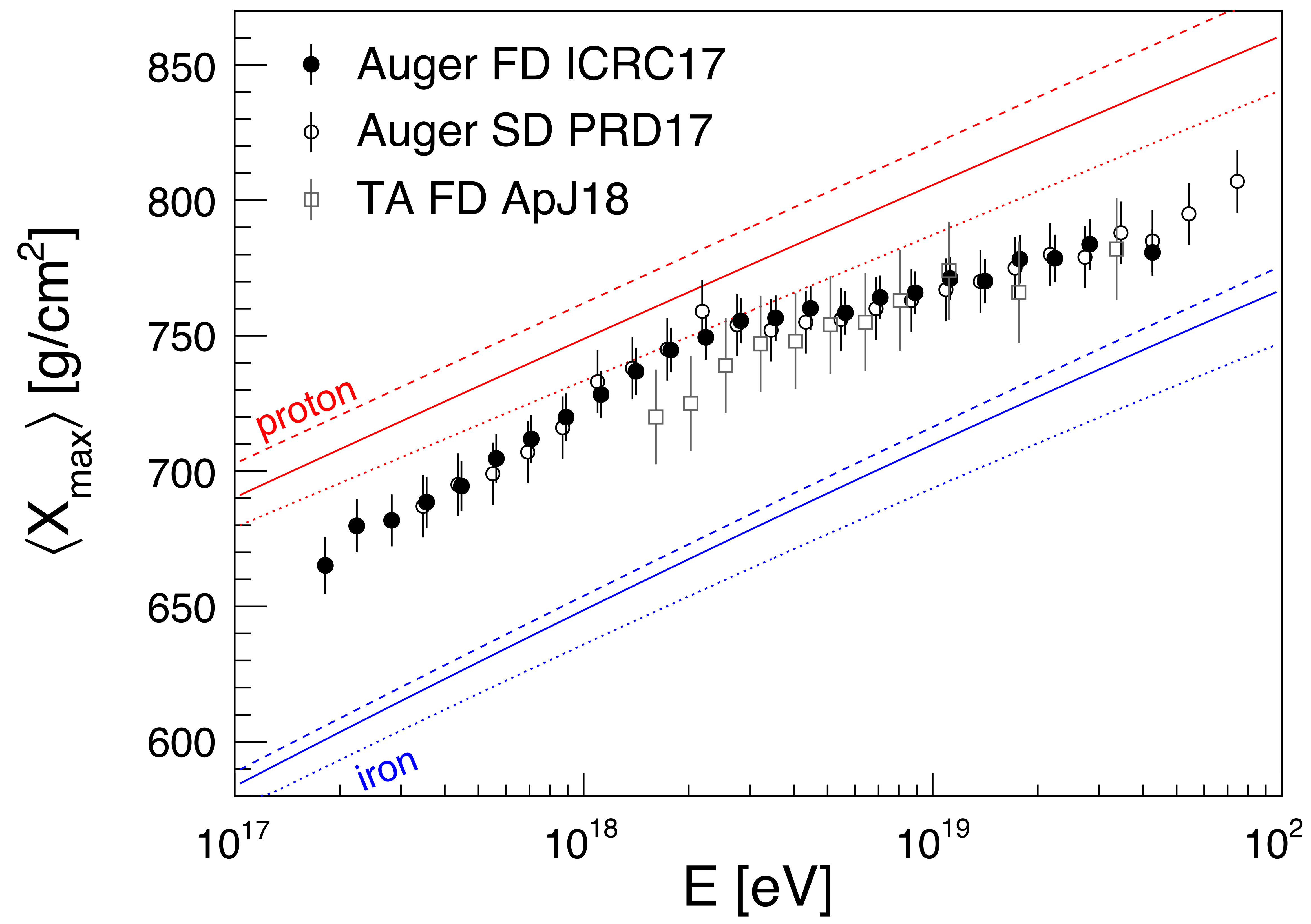

L. Lu, PoS(ICRC2023)1188

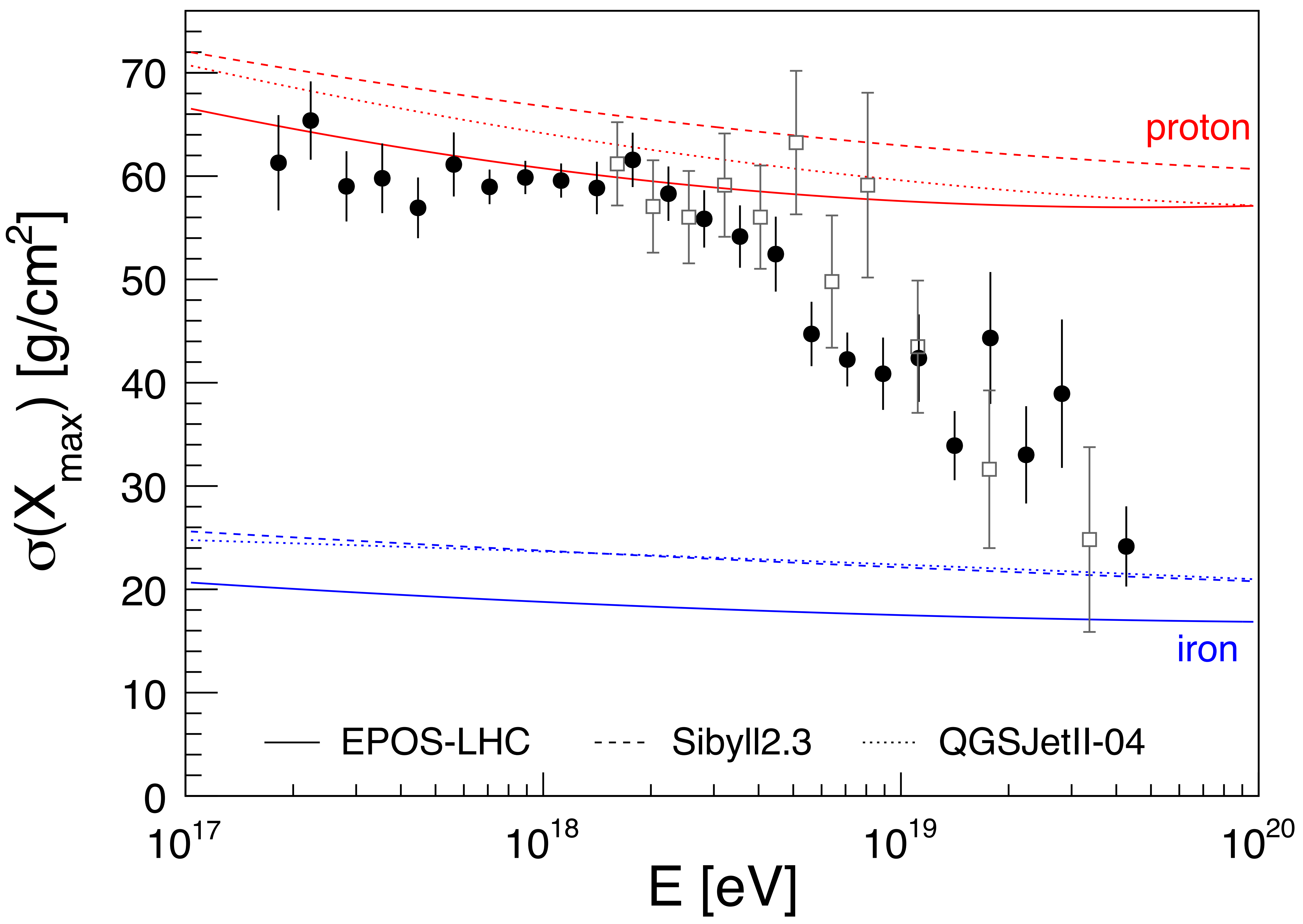
# Energy spectra of TA and Auger

# Mass composition

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

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



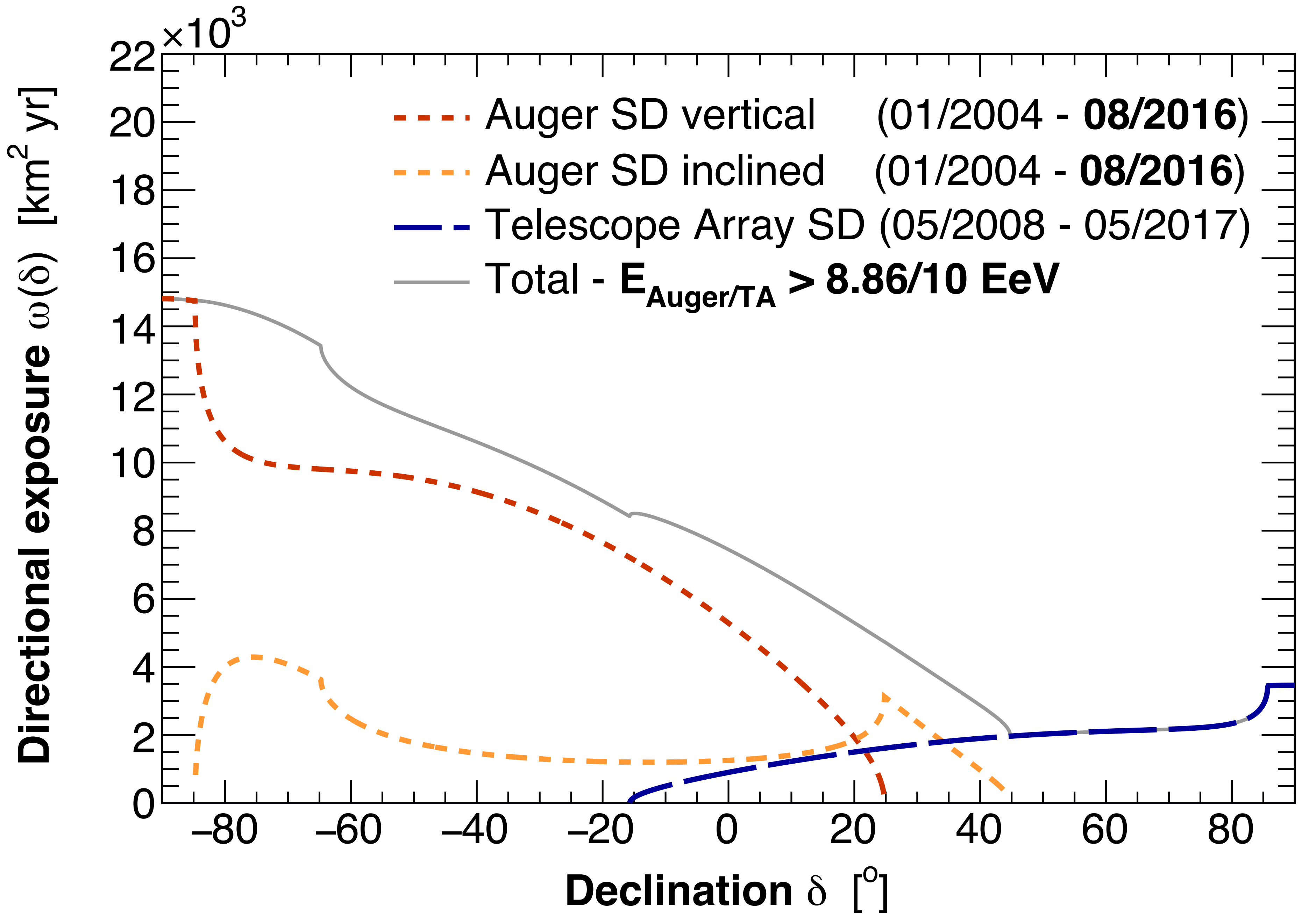




**Gradually increase to the heavier composition above 3 EeV**

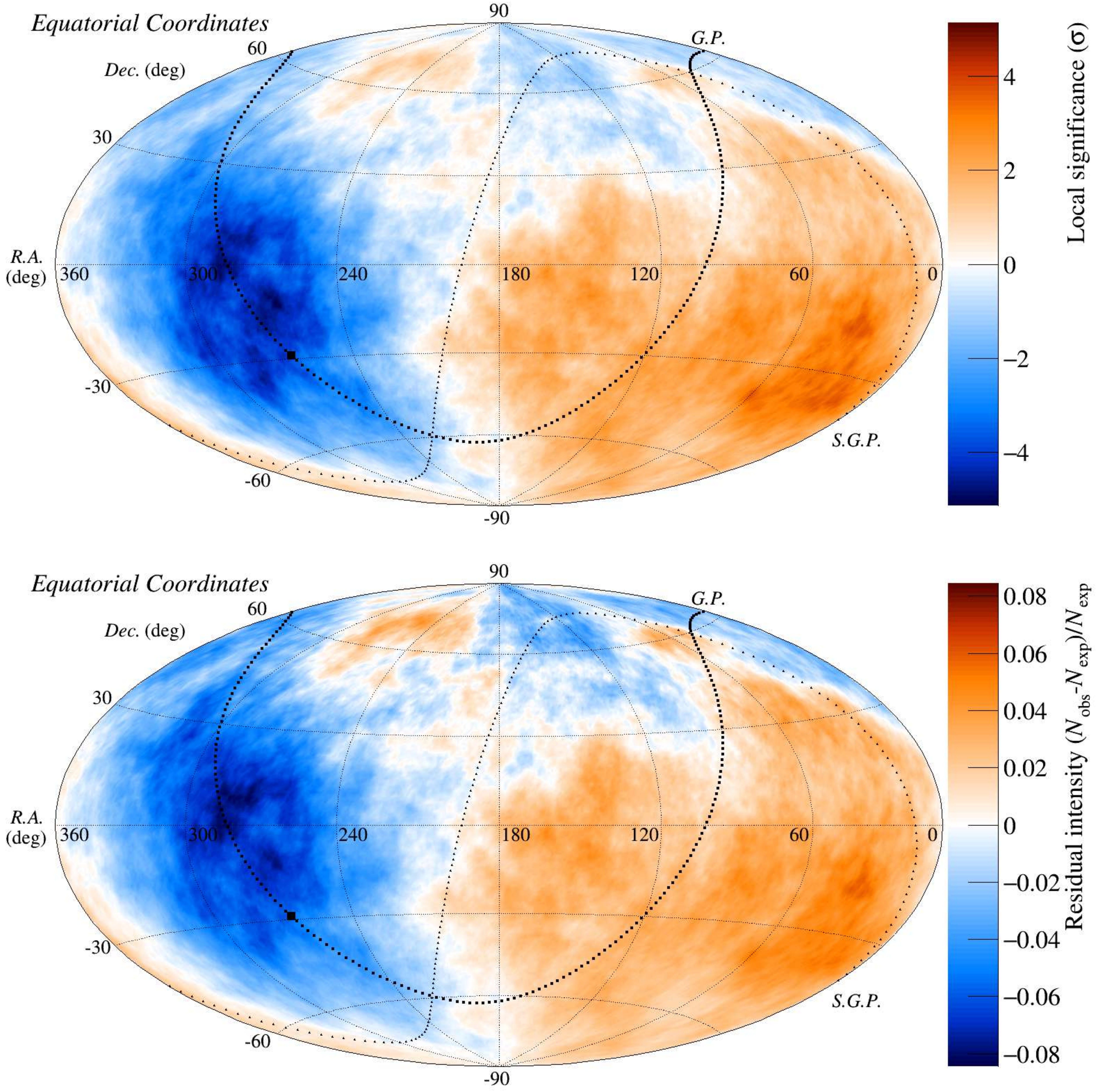
R.A. Batista et al., Front.Astron.Space Sci. 6 (2019) 23

# Auger and TA joint analysis for all-sky survey

- Energy calibration at common declination band



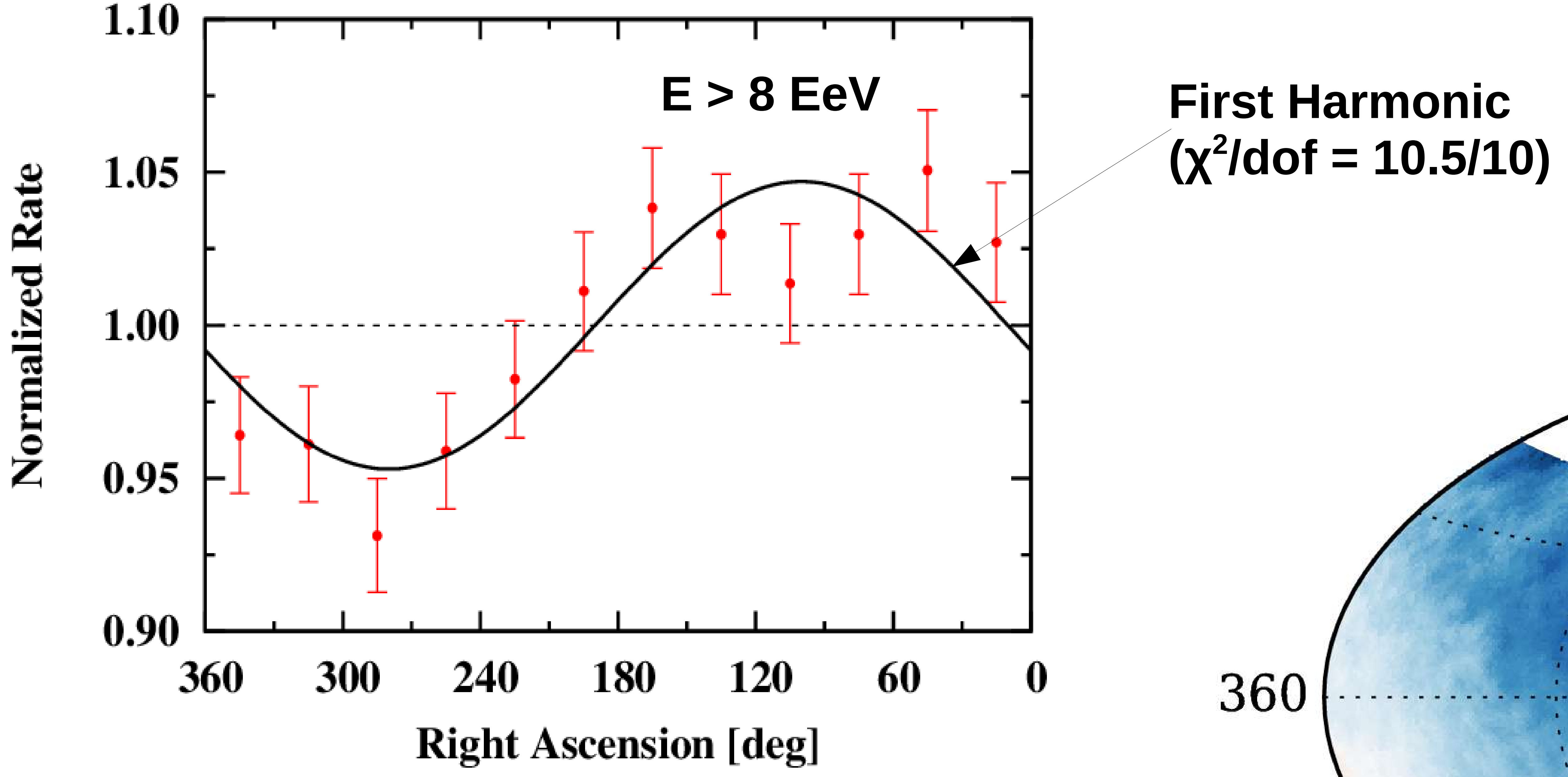

**Auger/TA = 8.86/10 EeV**




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

# Observation of dipole structure above 8 EeV

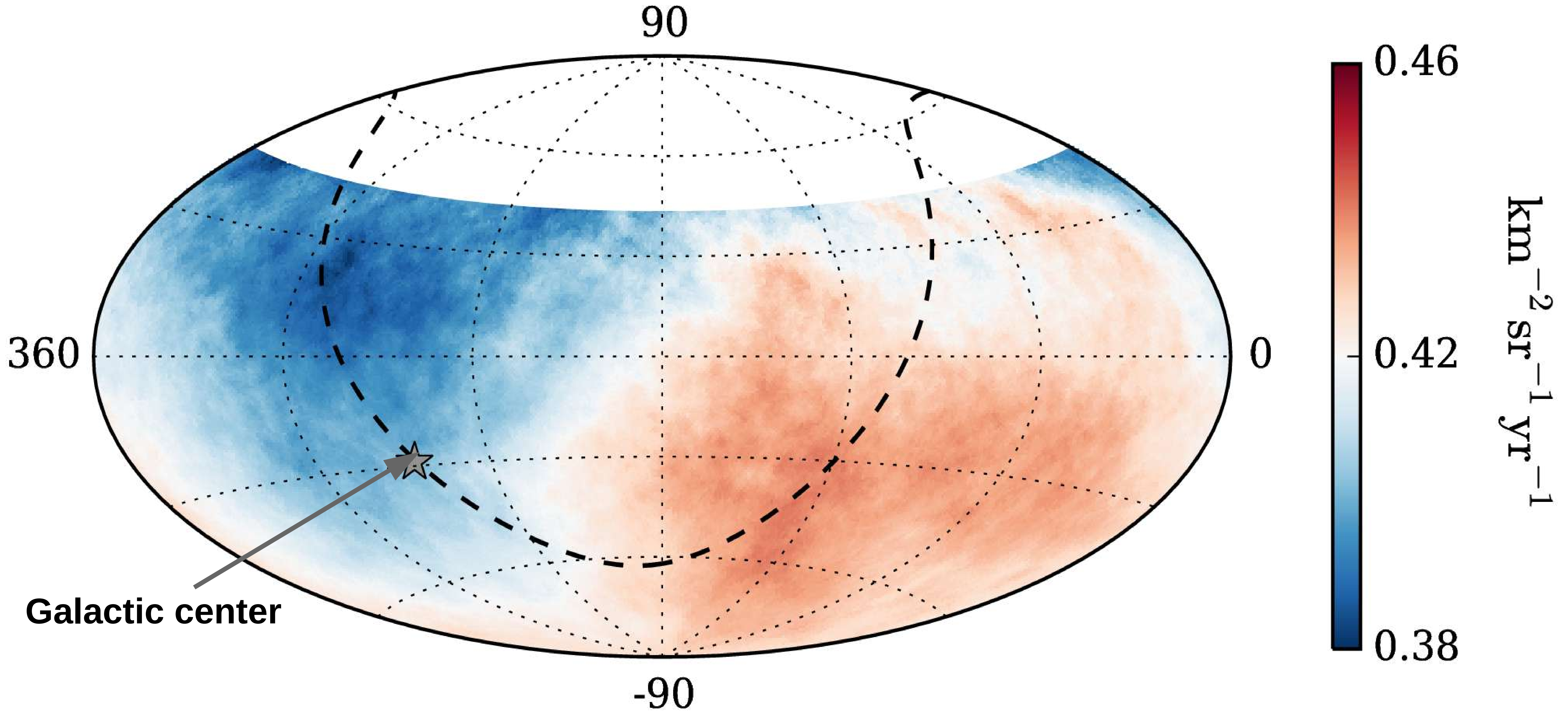
1 January 2004 - 31 August 2016, ~12 years




Harmonic analysis in right ascension $\alpha$

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

significant modulation at $5.2\sigma$ ($5.6\sigma$ before penalization for energy bins explored)




Pierre Auger Collaboration. Science 357, 1266 (2017)

# Energy dependence on the dipole amplitude

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

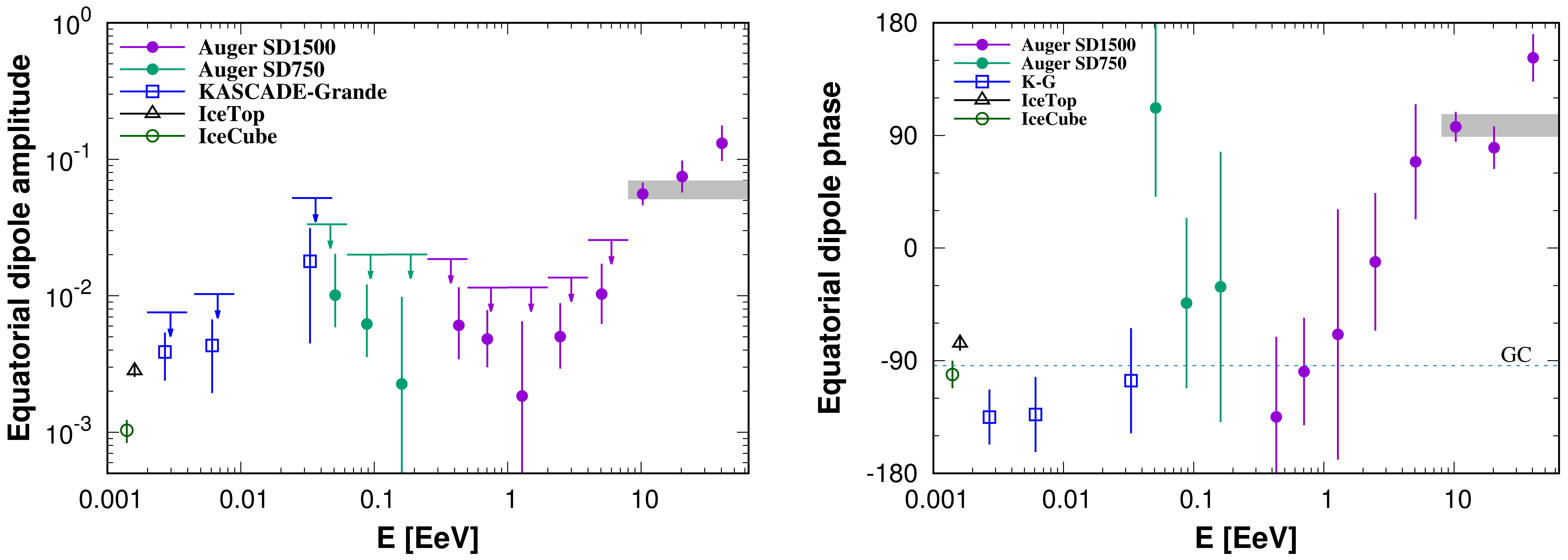



**Figure 1.** Reconstructed equatorial dipole amplitude (left) and phase (right). The upper limits at 99% CL are shown for all the energy bins in which the measured amplitude has a chance probability greater than 1%. The gray bands indicate the amplitude and phase for the energy bin $E \geqslant 8$ EeV.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

Pierre Auger Collaboration, ApJ 891, 142 (2020)

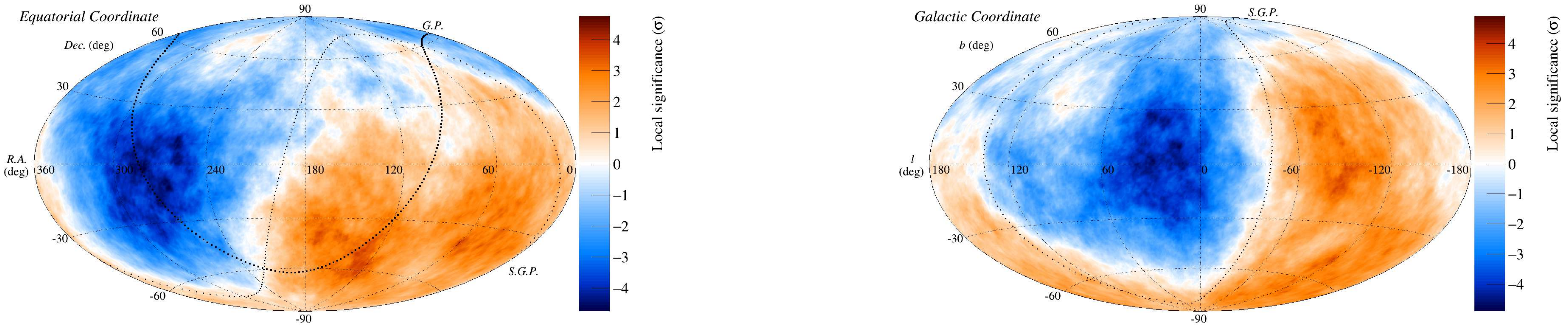
# Multi-wavelength observation at NGC6946


No significant emissions at hard X-ray and gamma-ray

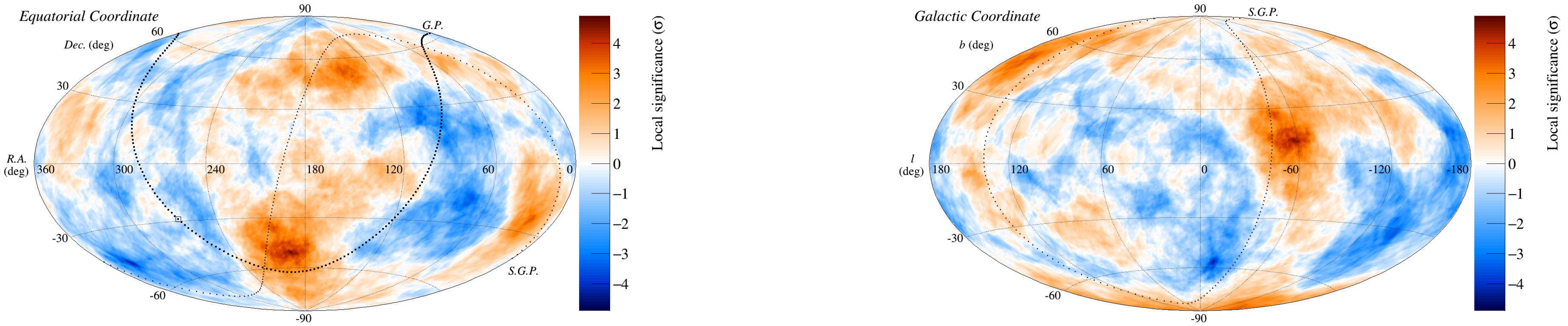
\https://sky.esa.int/?target=308.71805%2060.15367778&hips=DSS2+color&fov=0.4038209968608235&cooframe=J2000&sci=true&lang=en

# UHECR full-sky by TA and Auger

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



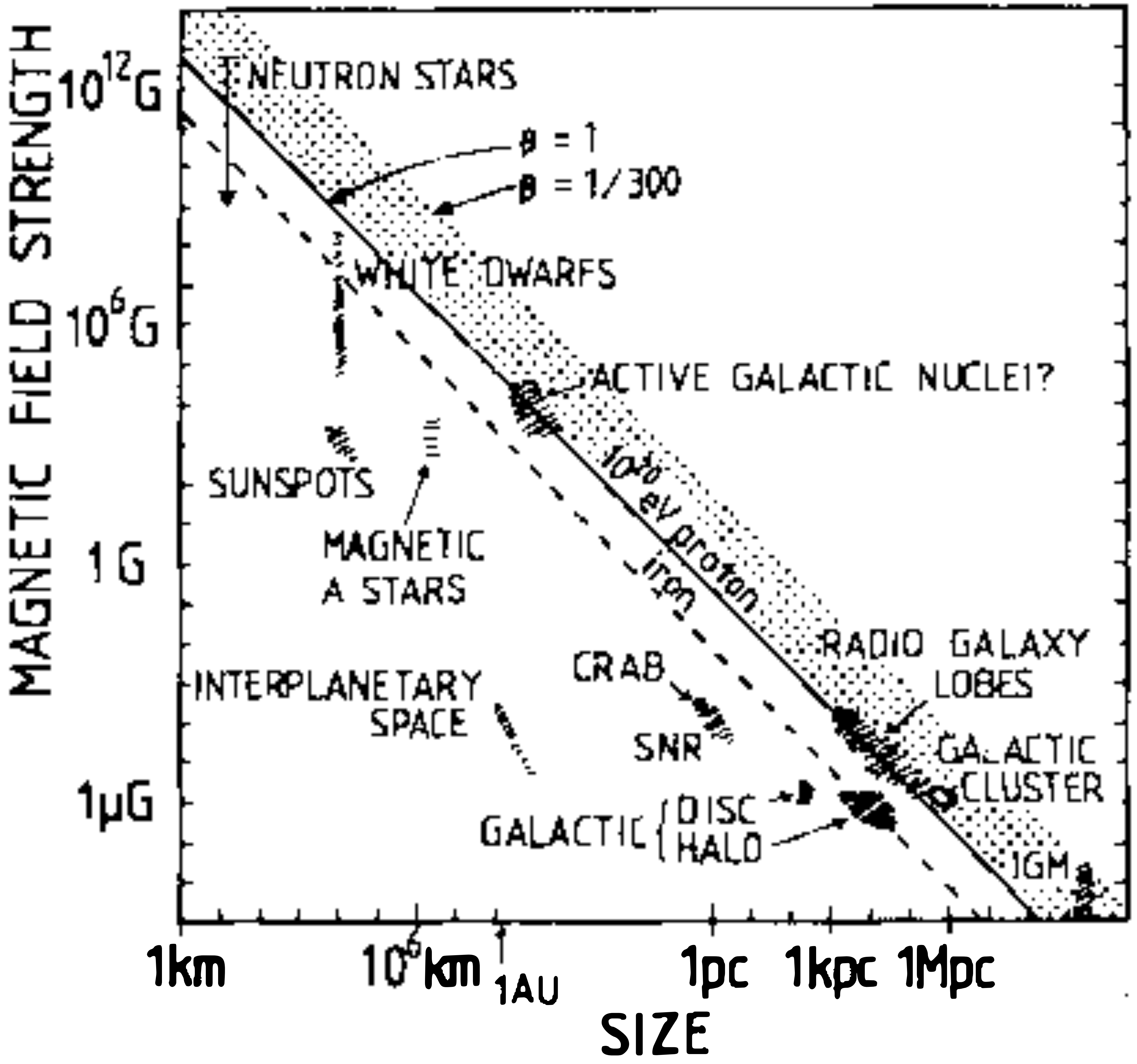

Suppression ($E_{TA}$>52.3 EeV $E_{Auger}$>40 EeV) 20° circle




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

# Overeview

## Hillas diagram




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

$$\left(\frac{E_{\rm max}}{10\,{\rm EeV}}\right) \leq Z\left(\frac{B}{1\,\mu{\rm G}}\right)\left(\frac{R}{10\,{\rm kpc}}\right)$$

$$= Z\left(\frac{B}{10\,{\rm mG}}\right)\left(\frac{R}{1\,{\rm pc}}\right)$$

## Deflection angle in Milky way

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

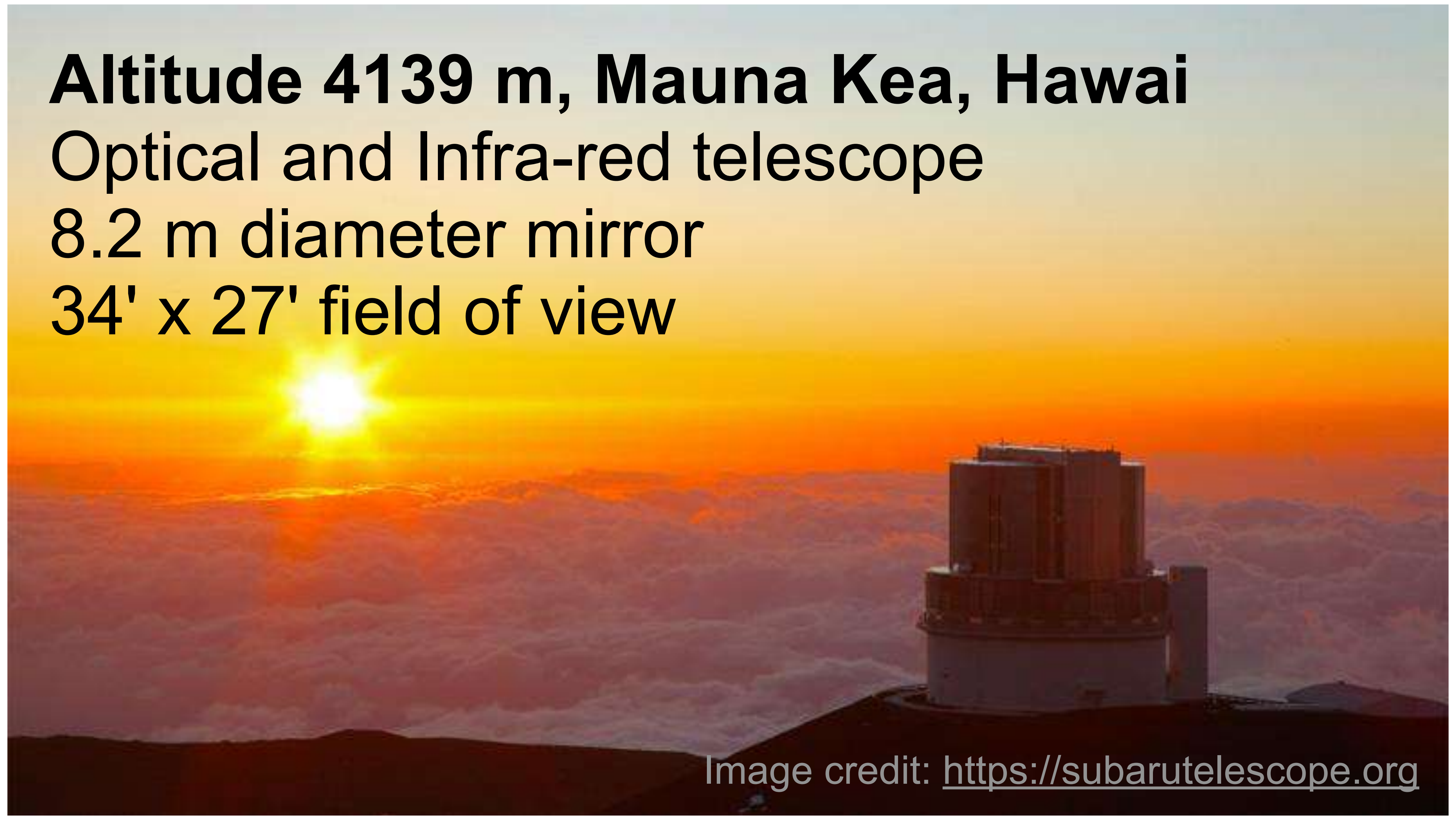
## Time delay in Milky way

$$t \sim 100\,{\rm yr}\left(\frac{R}{10\,{\rm kpc}}\right) Z^2 \left(\frac{E}{10\,{\rm EeV}}\right)^{-2}$$

# A new "lens" for visualizing extensive air showers

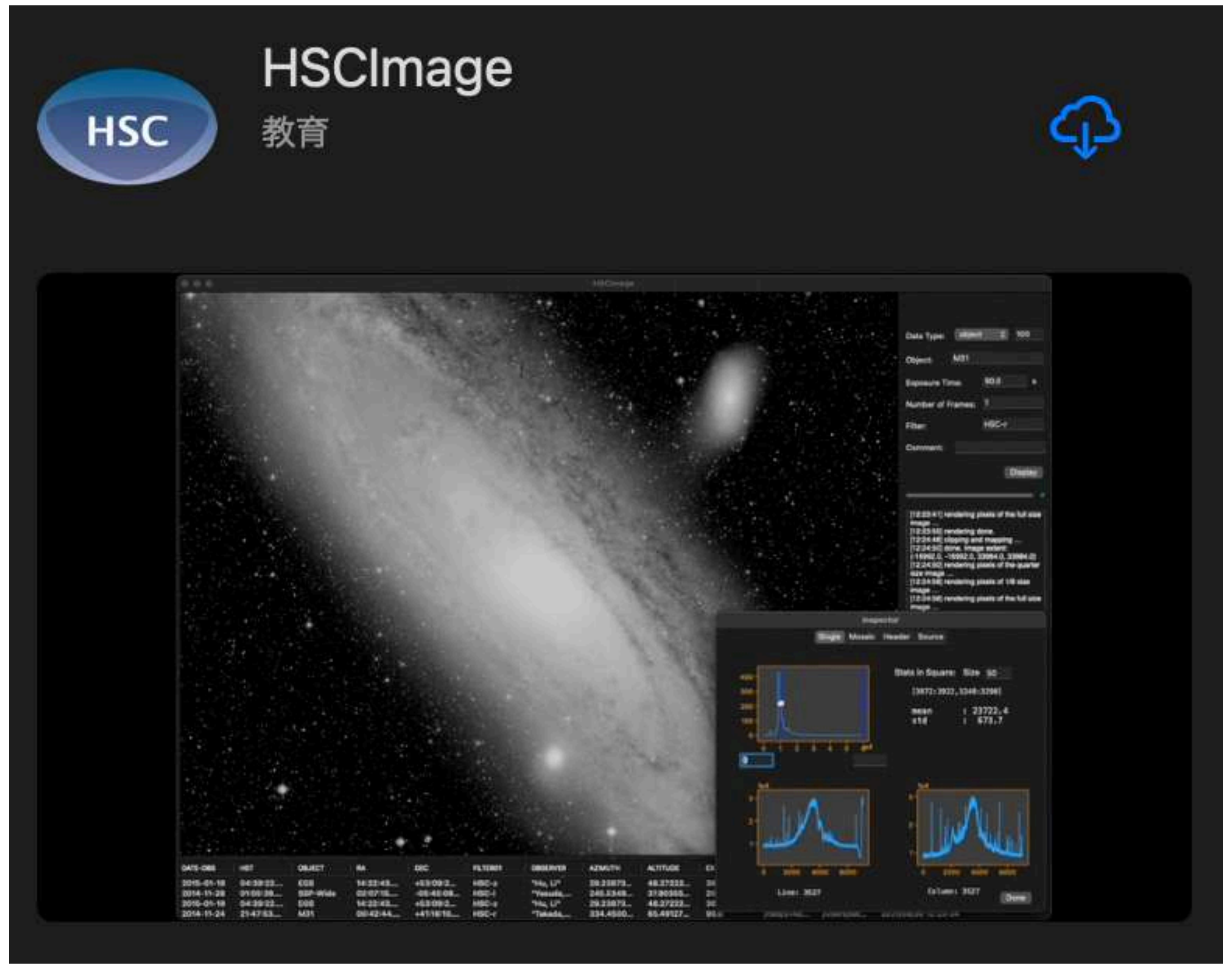
**Directly penetrating Subaru HSC CCDs**

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

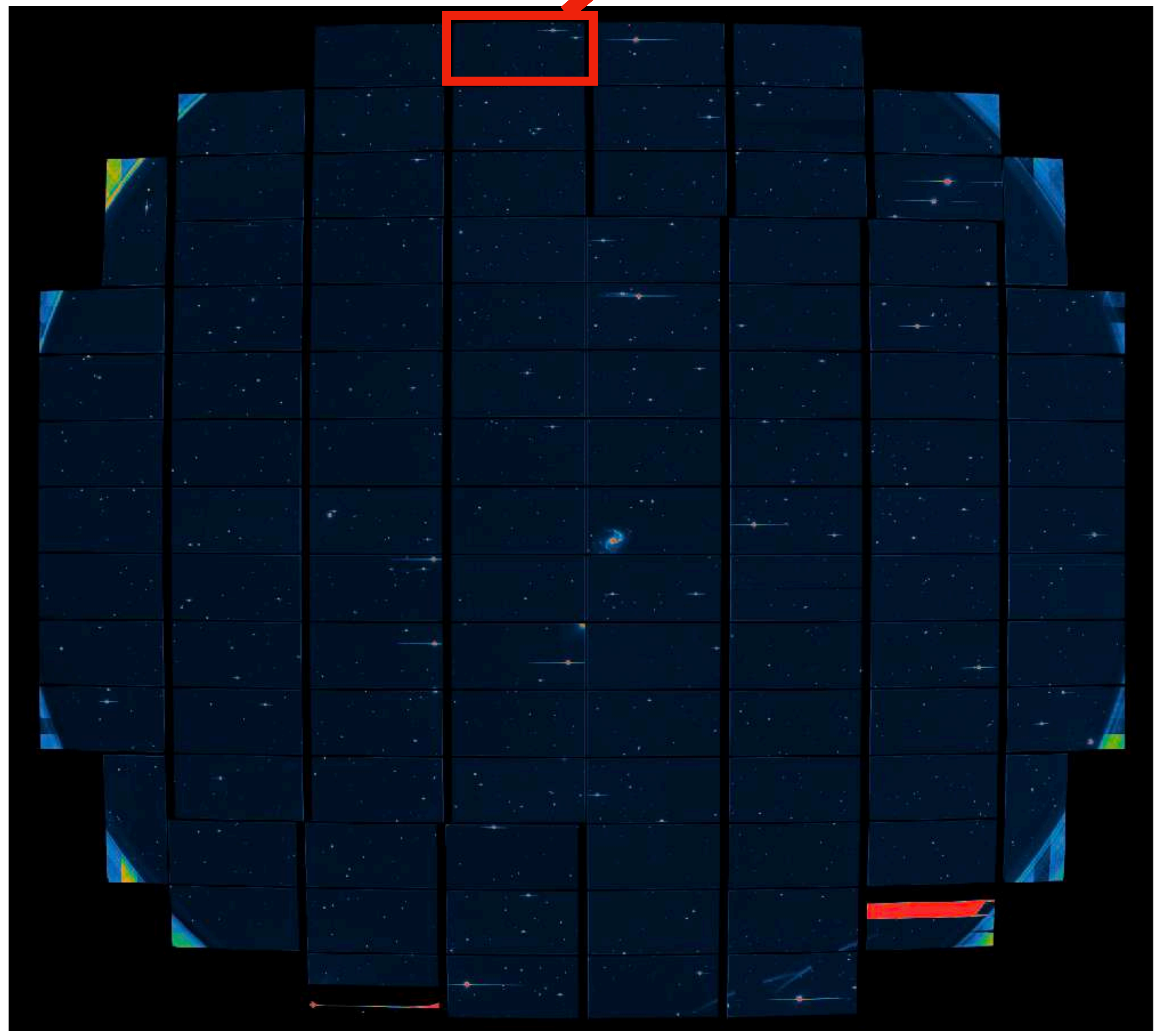


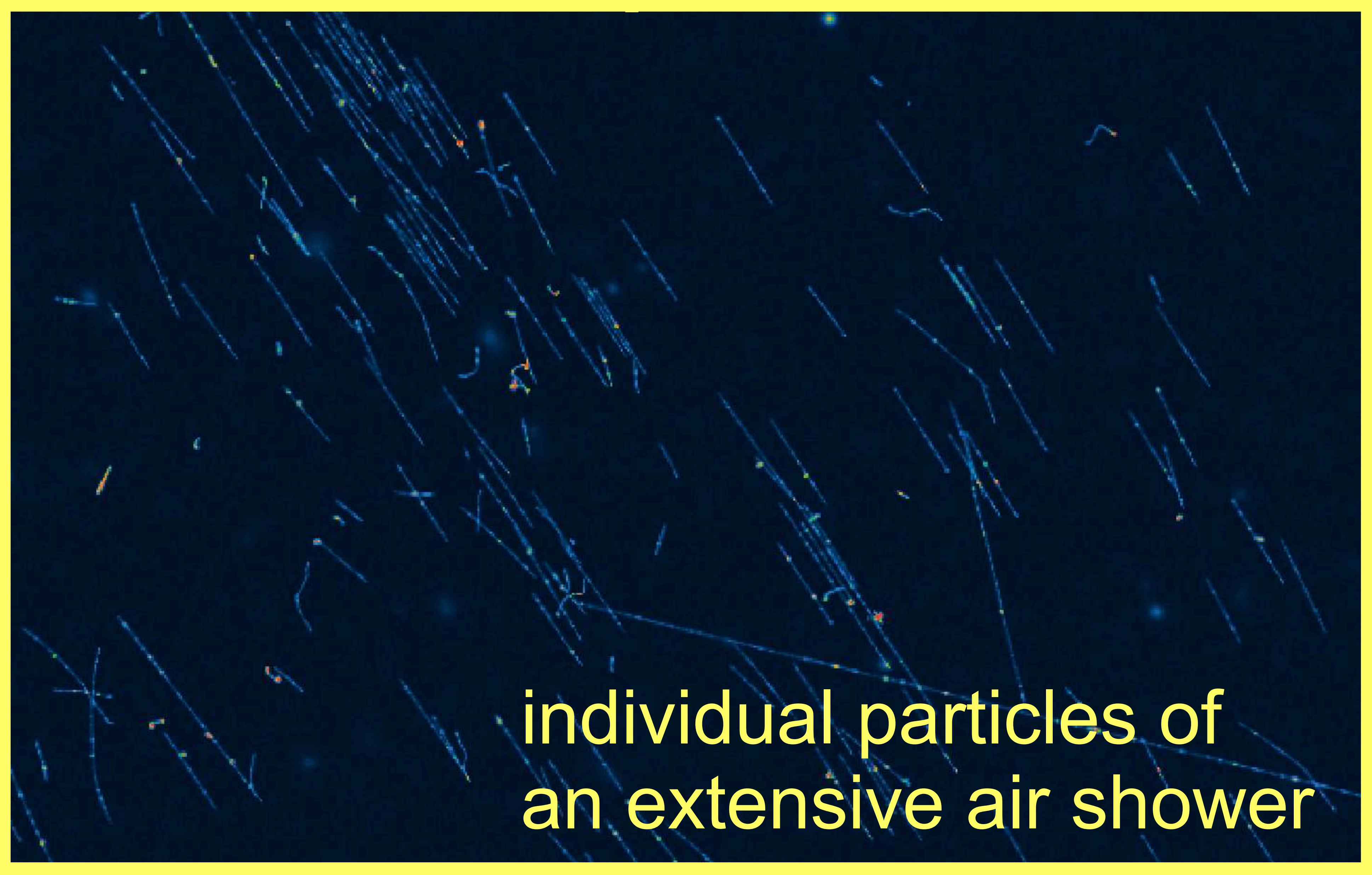

CCD size
30 mm x 60 mm
0.2 mm thickness
150 sec. exposure

116 CCDs

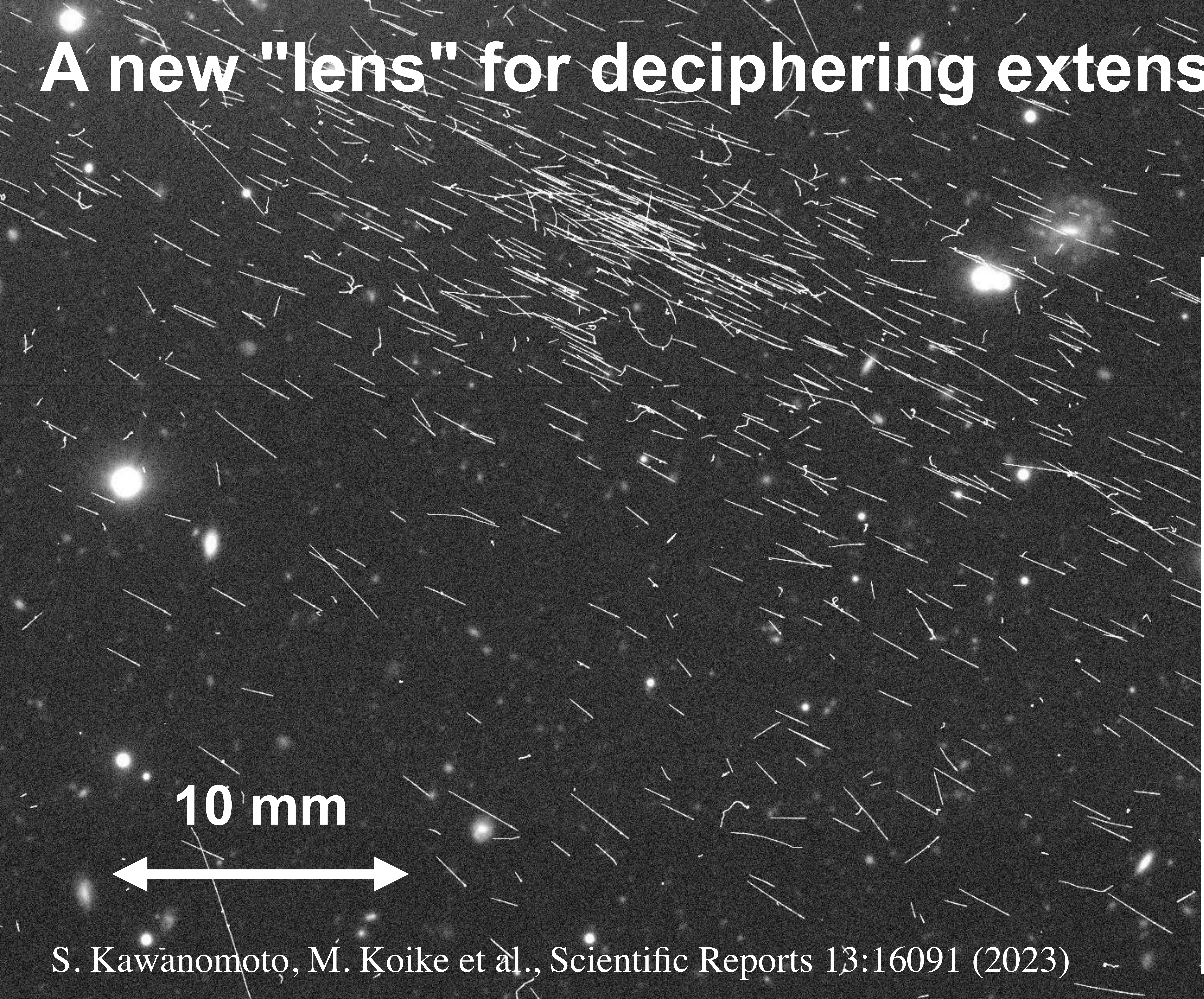



**App Store (Mac)**

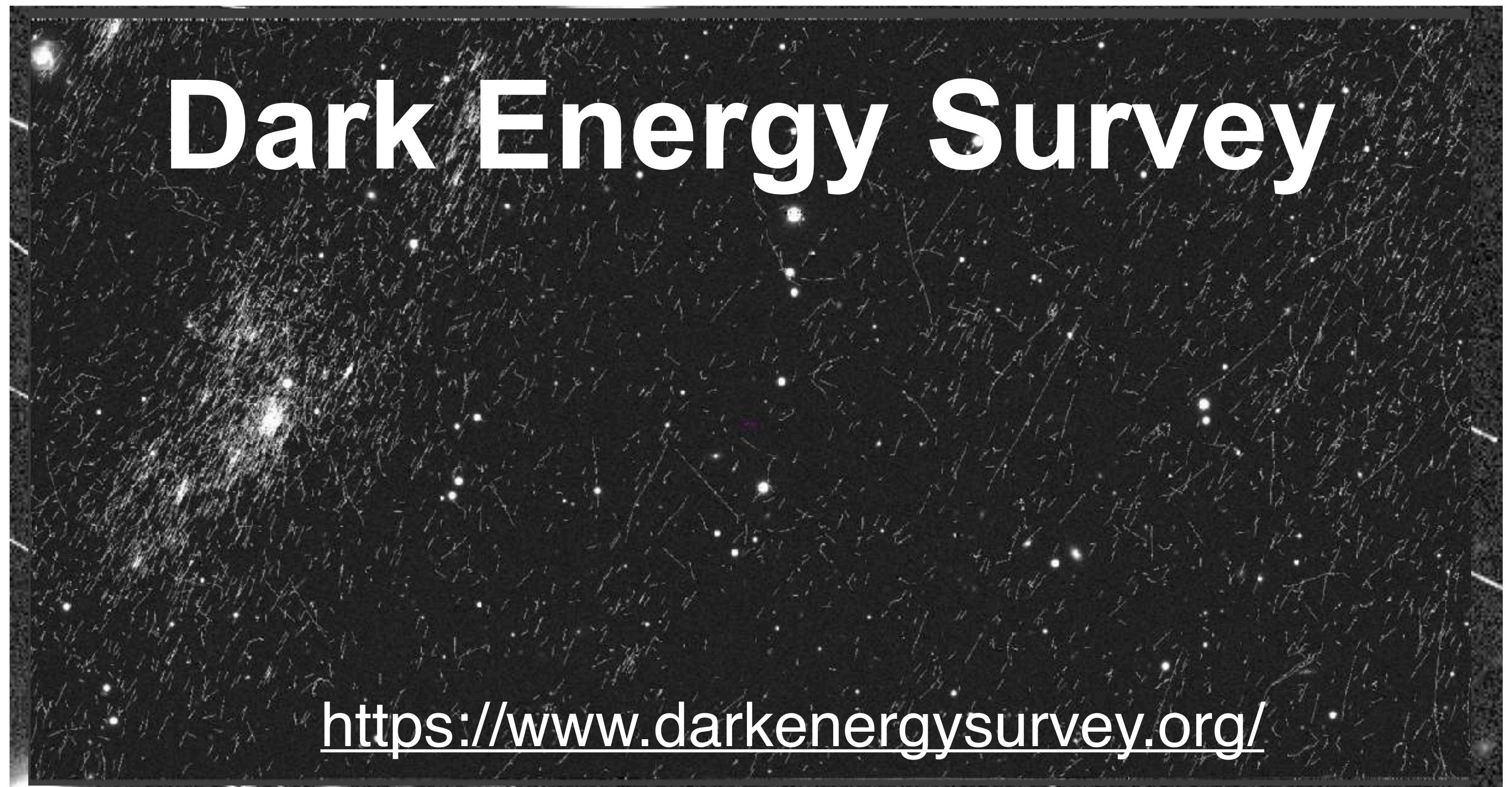


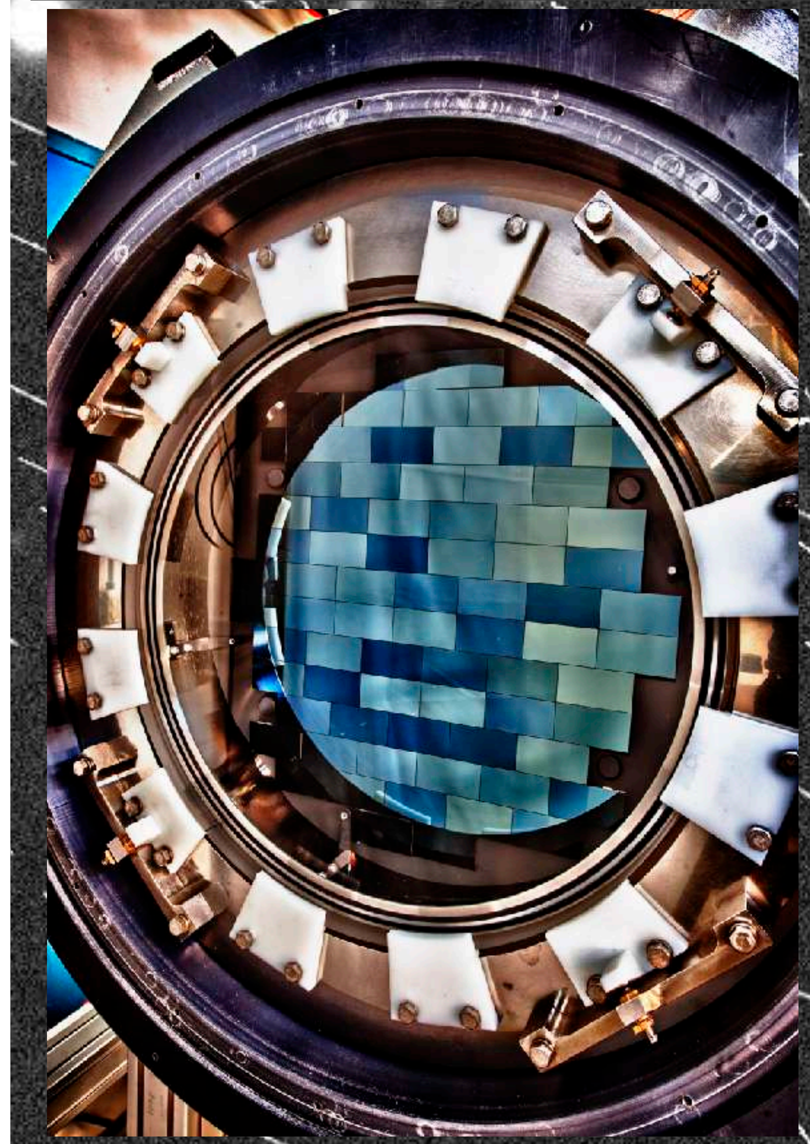


# A new "lens" for deciphering extensive air showers

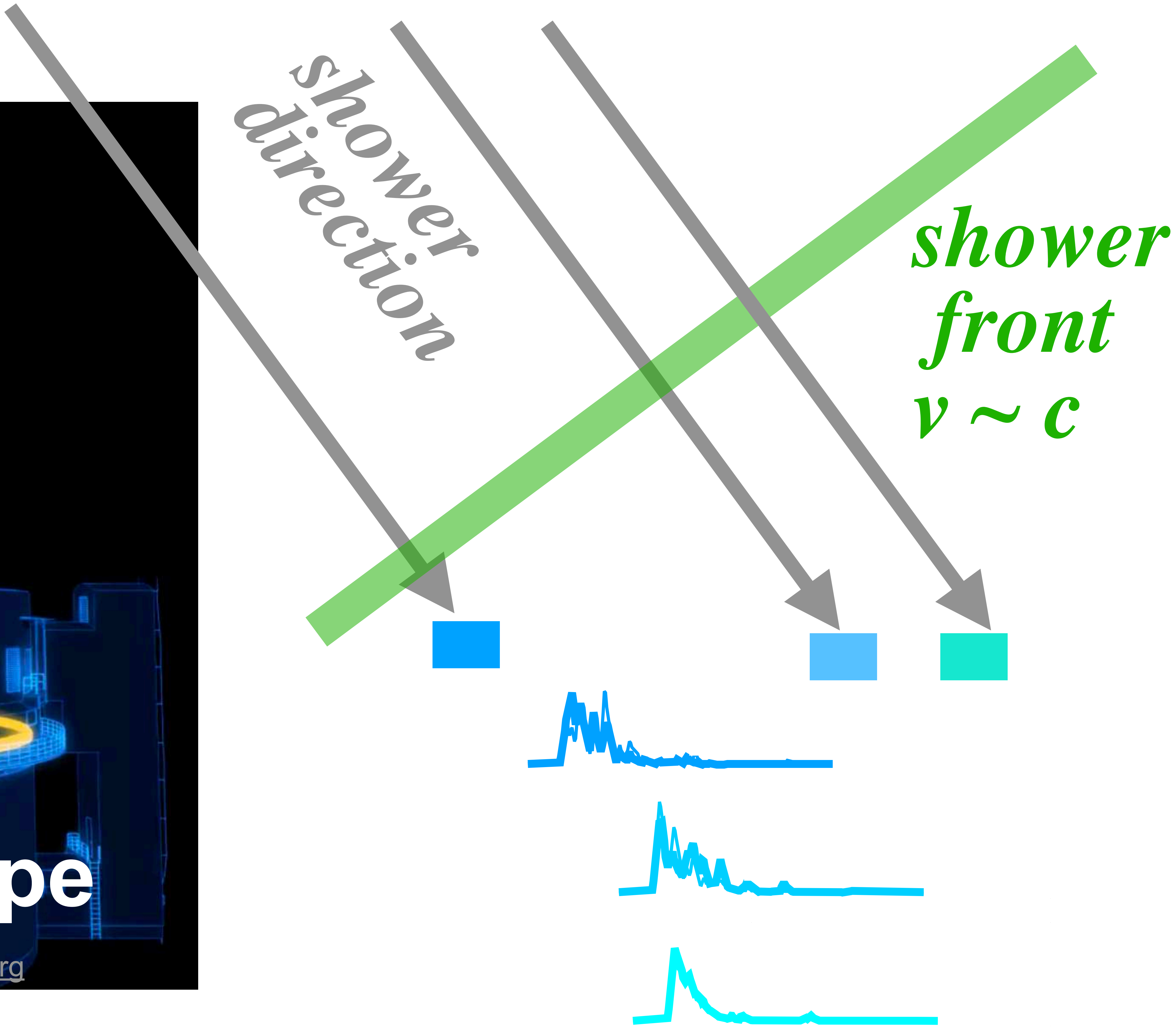



S. Kawanomoto, M. Koike et al., Scientific Reports 13:16091 (2023)



# Air-shower Lensing Observatory at High Altitude (ALOHA)

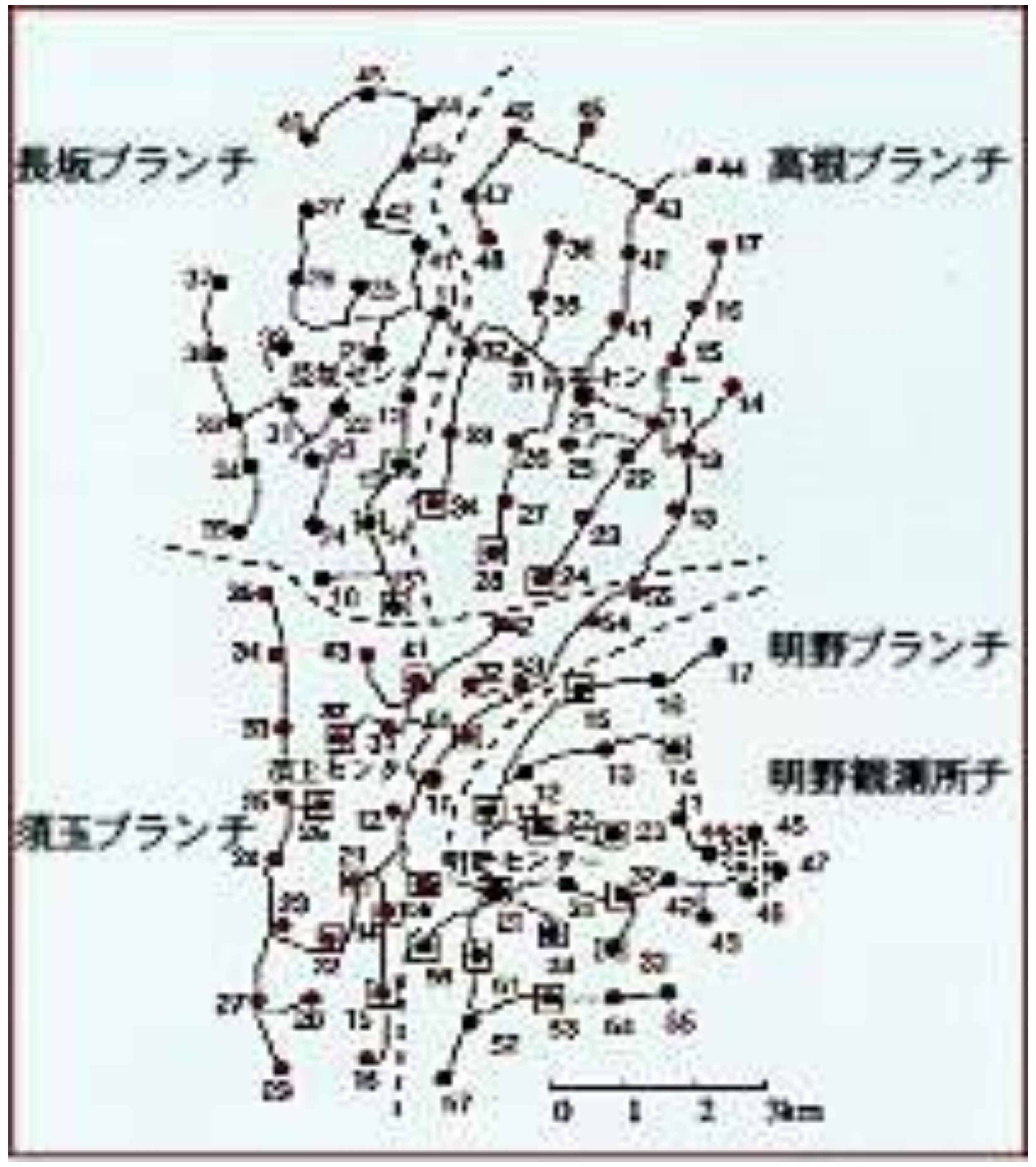

**prototype scintillator @OMU**

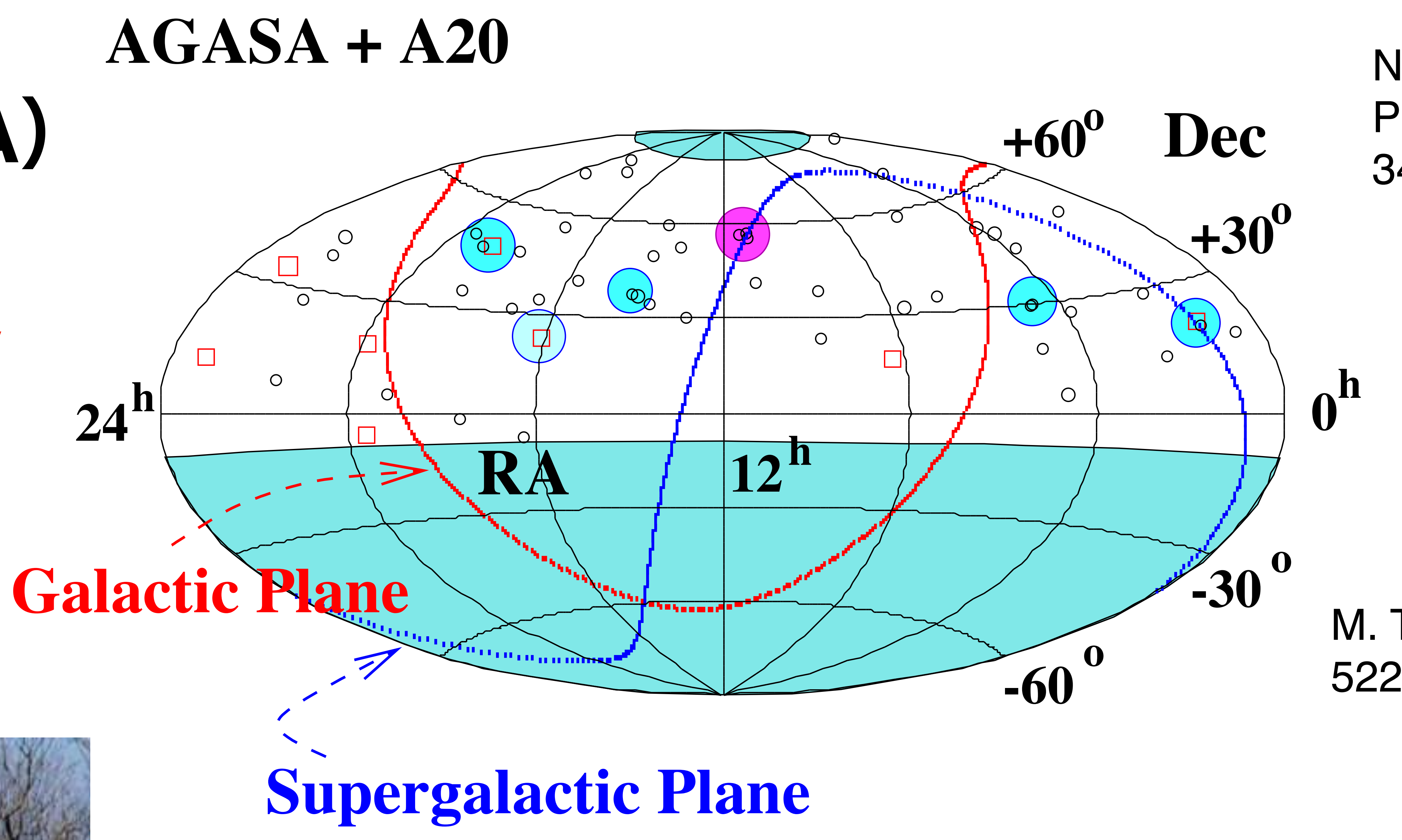
- Possible installation of surface detector array at **ventilation room** of Subaru Telescope
  - **4 plastic scintillators with 20 m spacing**, providing a unique detection combining with Subaru telescope and cosmic ray detectors, like a "**lens**" of extensive air shower

# Extremely energetic particles detected 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**



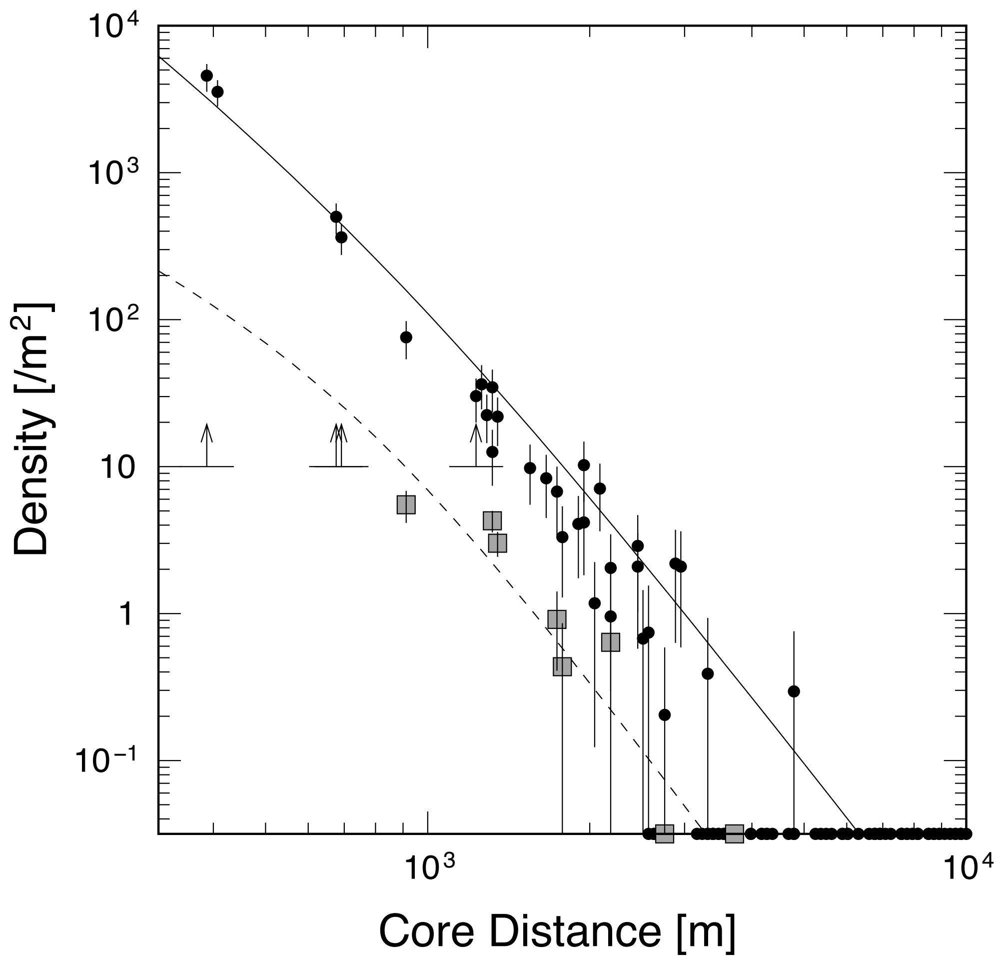



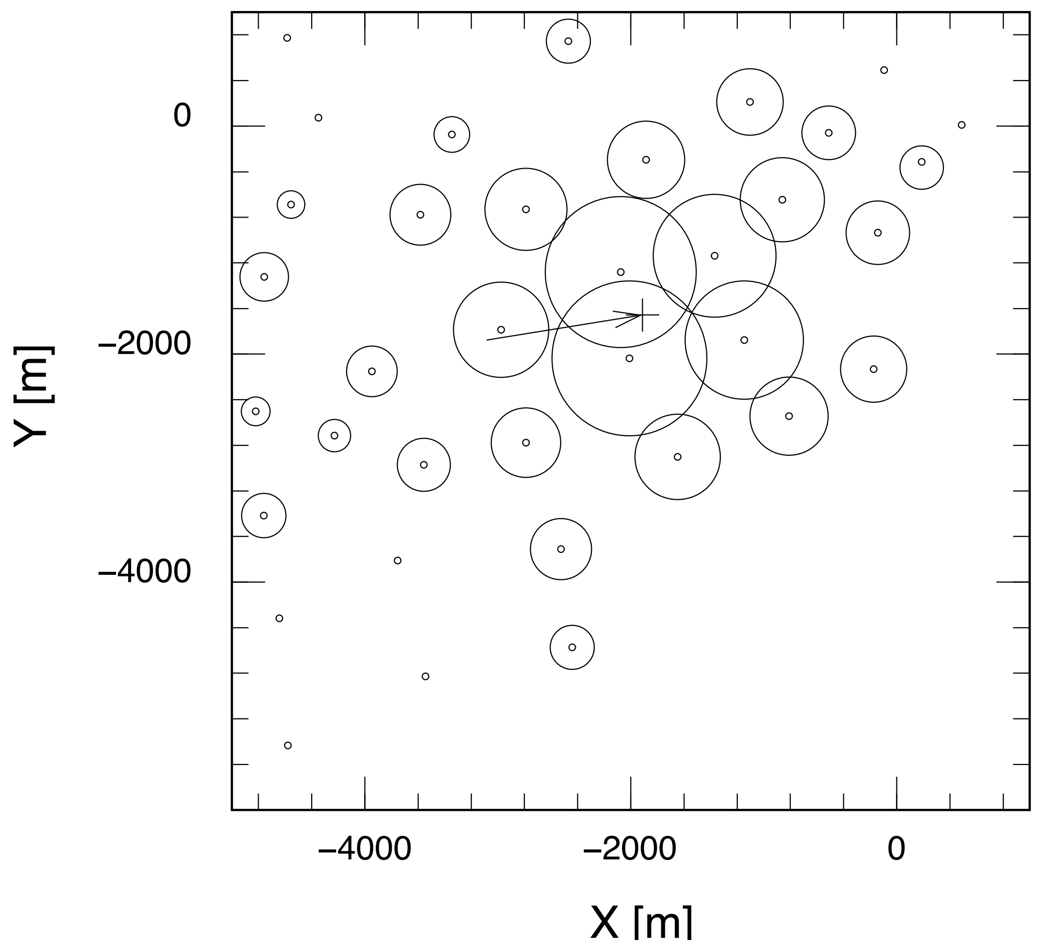

N. Hayashida, et al., Phys. Rev. Lett. 73, 3491 (1994)

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

***E* ~ 280 EeV on May 10, 2001**

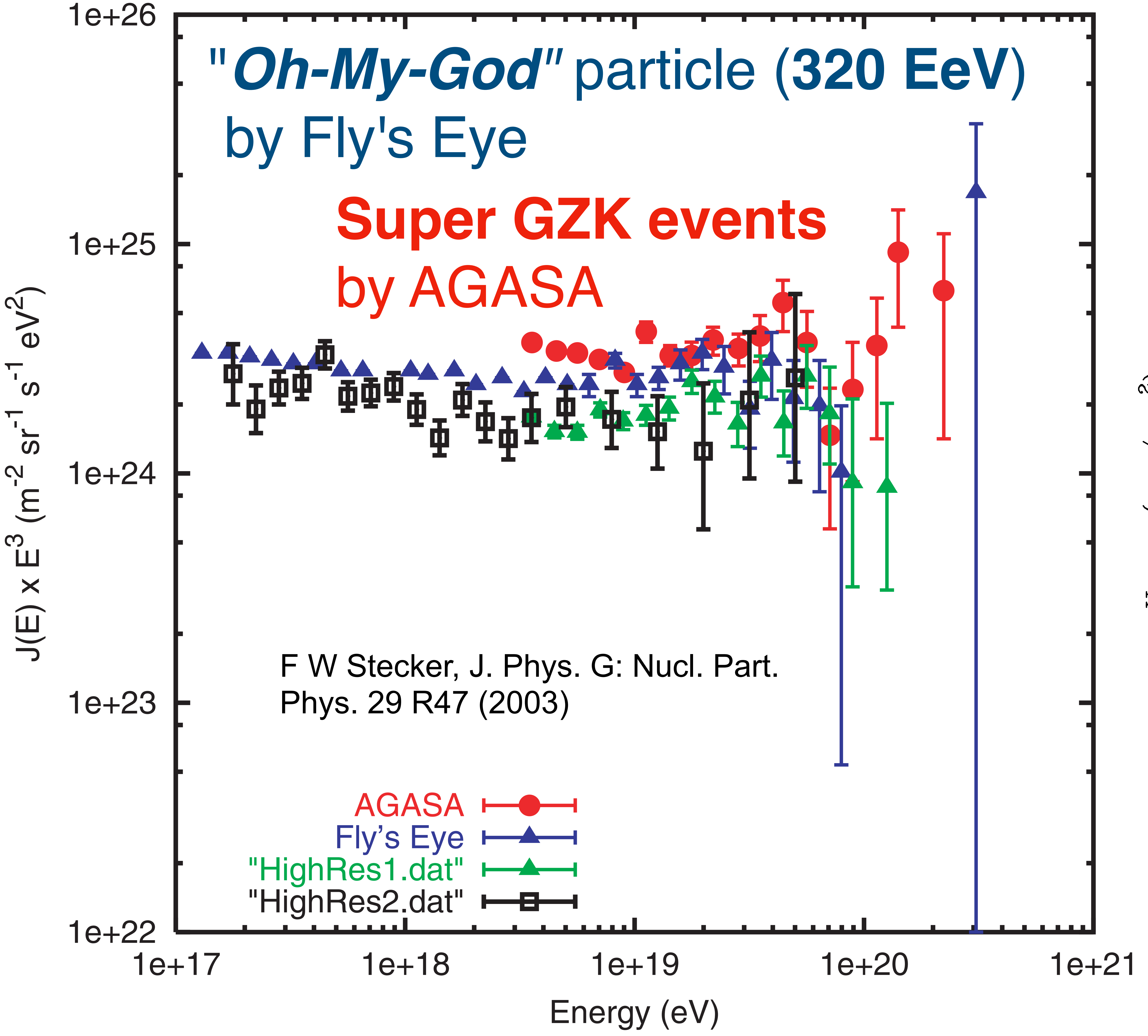
N. Sakaki et al., Proceedings of ICRC 2001: 337



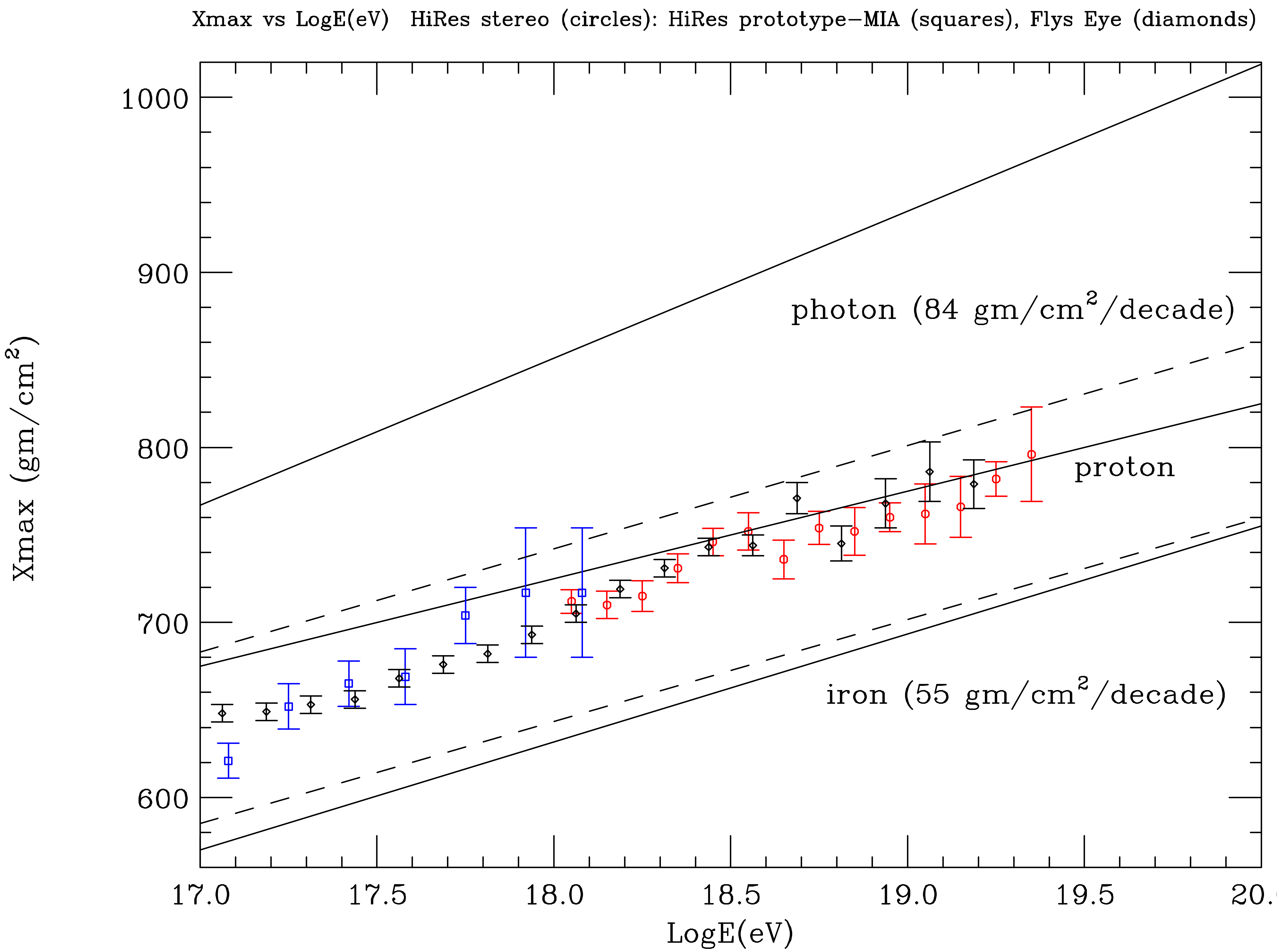



# UHECR results in 2000s

## No GZK cutoff in spectrum?




## Proton dominated composition at highest energies?




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

# Work as "physicist" in desert