High-Energy Astroparticle Observation in Japan - History and Future -

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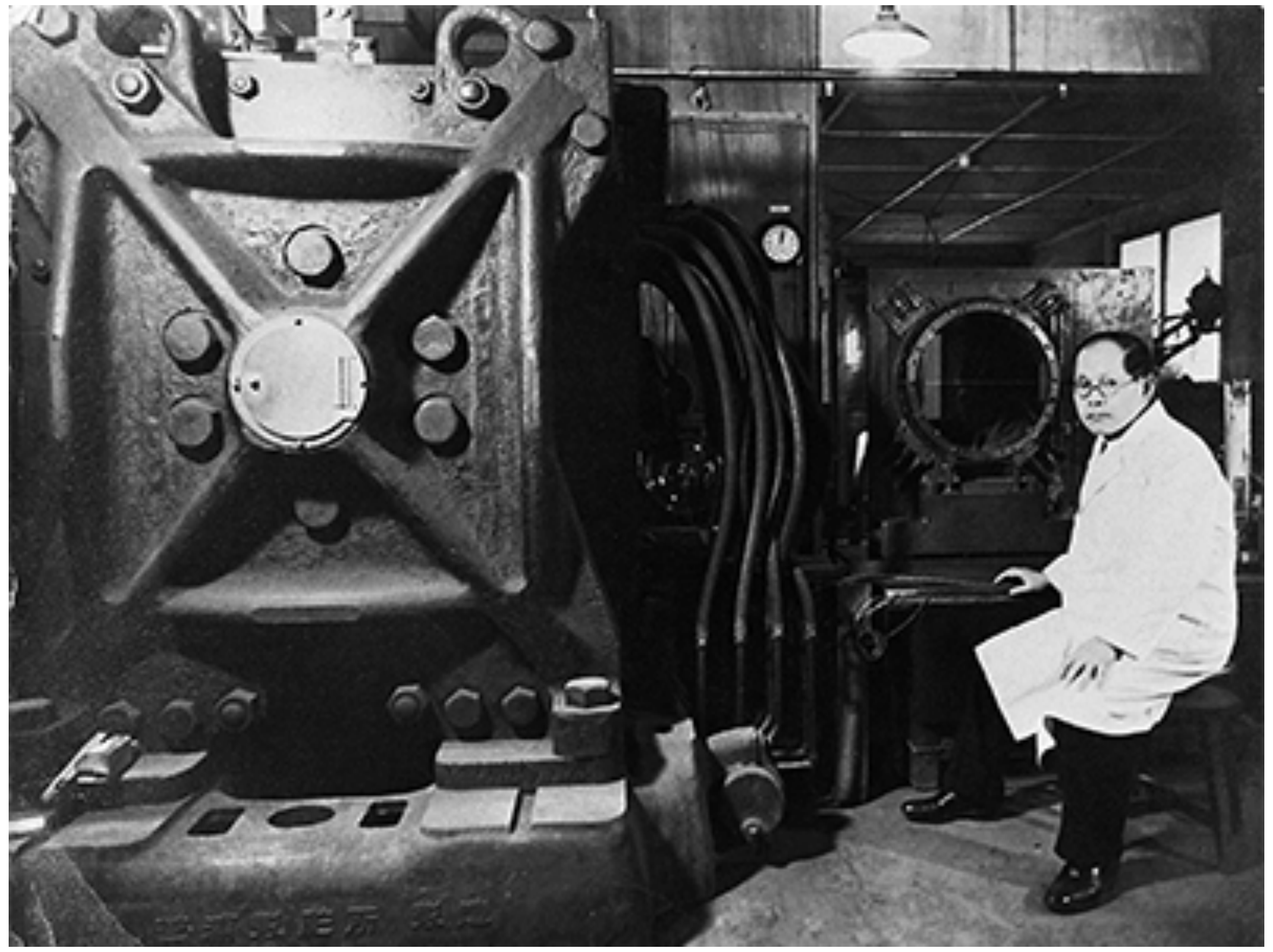
CosPa Meeting, October 27, 2025

Beginning of cosmic ray research in Japan (1931)

- **Yoshio Nishina** started cosmic ray research (and nuclear physics) at RIKEN from 1931
  - First observation of high energy cosmic rays by the large cloud chamber at underground tunnel in Japan
  - Imported "Copenhagen spirits" of Niels Bohr
  - Mentored a lot of Nobel laureates

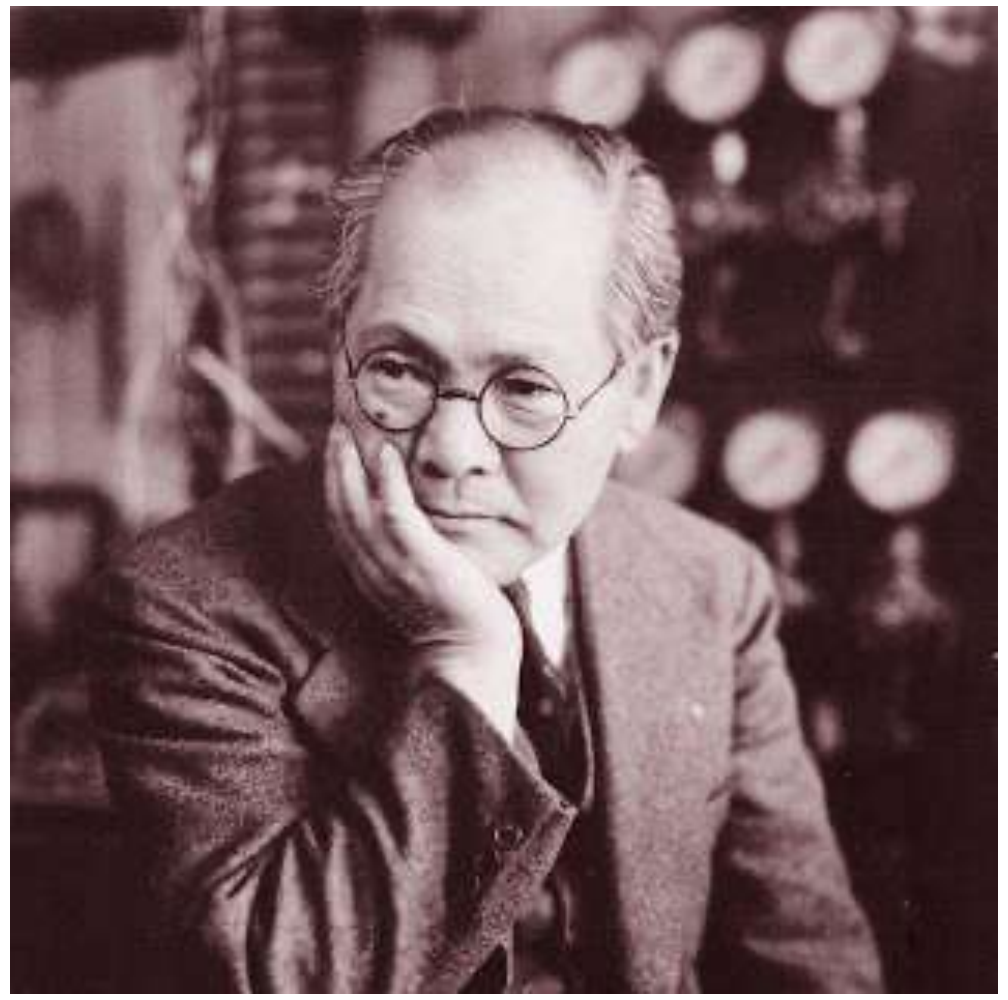


世界最大のウィルソン霧箱

https://www.nishina-mf.or.jp/digitalmemorial_4/

清水トンネル内での宇宙線観測

Nishina



https://www.nishina-mf.or.jp/wp/wp-content/uploads/2020/10/Lecture6.pdf

Sakata → **Kobayashi, Maskawa**

Yukawa  **Tomonaga** Kobayashi

Measurement of the mesotron (muon) mass

On the Nature of Cosmic-Ray Particles

Y. Nishina, M. Takeuchi, and T. Ichimiya
Institute of Physical and Chemical Research, Tokyo

(Received August 28, 1937)

Phys. Rev. 52, 9 (1937), **Received Aug. 28, Published Dec 1st**

to lie between 7.3 and 8.1 cm. According to the range-energy curve for the proton given by Livingston and Bethe[2] we calculate the mass of the particle by using the above values of $H\rho$ and range and obtain

$$M_m = (170 \pm 9)m, \qquad (1)$$

where m is the mass of the electron.

as was given by Bhabha,[4] where E is the initial energy of the particle, $\eta = (1 - v^2/c^2)^{\frac{1}{2}}$, and c is the velocity of light. If we do this and use the above data of the new measurements, we obtain

$$M_m = (180 \pm 20)m, \qquad (4)$$

which is in better agreement with the value (1).

J.C. Street and E.C. Stevenson, Phys. Rev. 52, 1003 (1937),
Received Oct. 6th, Published Nov. 1st

as the velocity squared, the rest mass of the particle in question is found to be approximately 130 times the rest mass of the electron. Because of uncertainty in the ion count this determination has a probable error of some 25 percent. In any case it does not seem possible to explain

On the Mass of the Mesotron

Since we published[1] the results of mass determination of the mesotron, the existence of which had theoretically been foreseen by Yukawa, we have been continuing the same experiments with the Wilson cloud chamber.

During last September we obtained a photograph shown in Fig. 1. A lead bar 5 cm thick was mounted in the middle

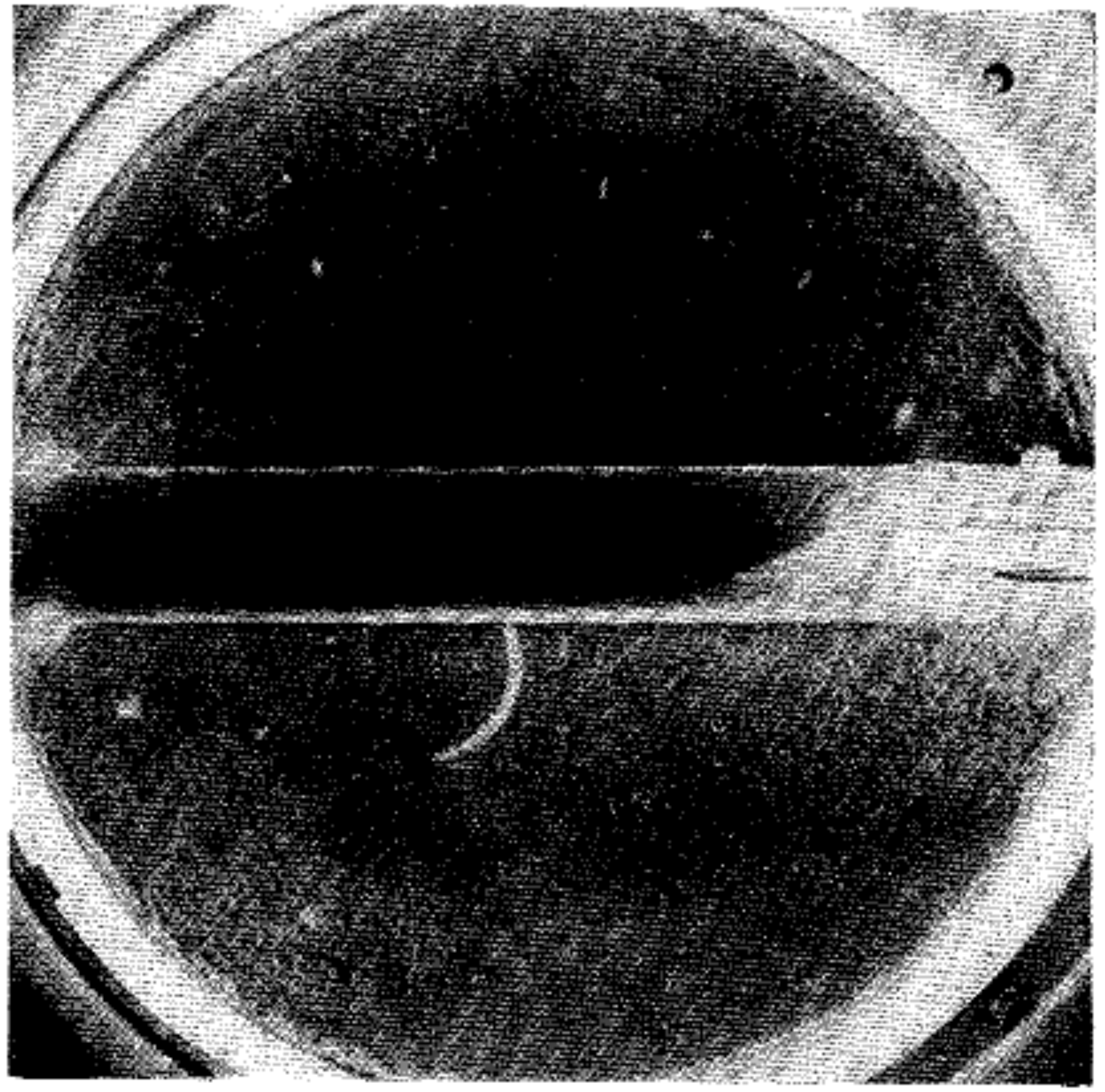


FIG. 1. Wilson track of a mesotron. $H = 12{,}600$ oersteds. $H\rho \approx 3.88 \times 10^4$ oersted·cm. Observed range = 6.15 cm.

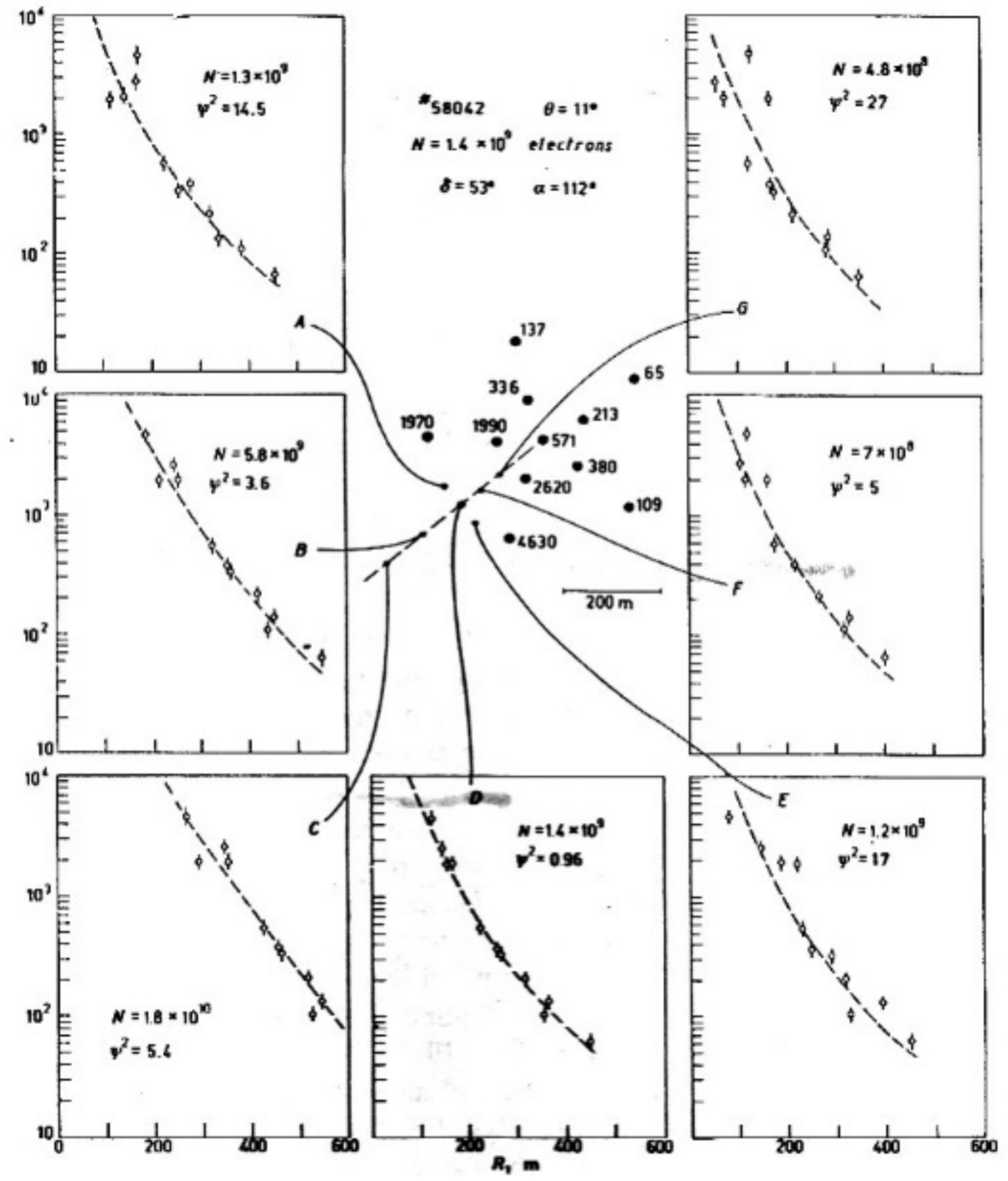

Extensive air showers
Surface detector array
Scintillator, Water-Cherenkov, Radio
Fluorescence detector
X_{max} observation for mass composition

Beginning of air shower observation in Japan (1956)

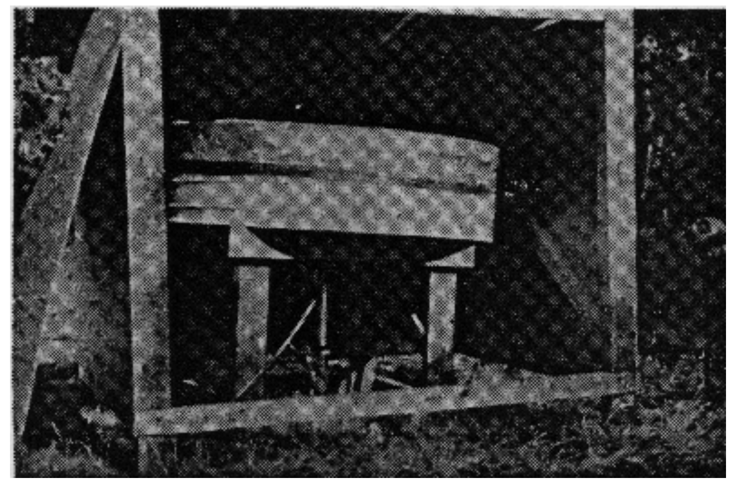
- **Minoru Oda** learned air shower observation using surface detector array at USA (1953)
  - Agassiz air shower detector
    - Liquid toluene scintillators, but **burned in the forest**
    - Switched to use plastic scintillators
- Minoru Oda imported this technique, and constructed surface detector array in Japan (1956)
  - **First measurement of *Nμ* vs *Ne***
    - Start gamma-ray observations

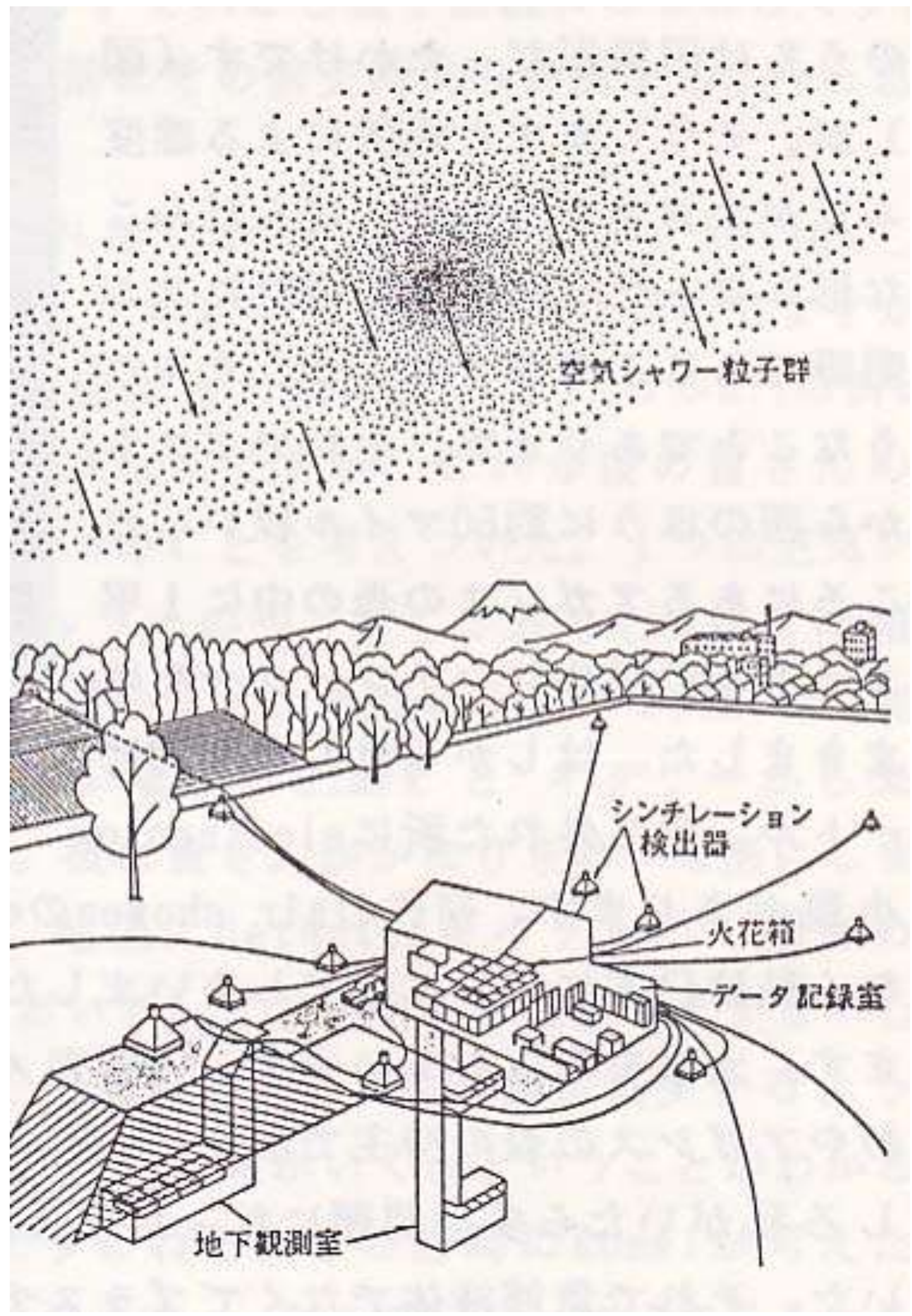
Oda

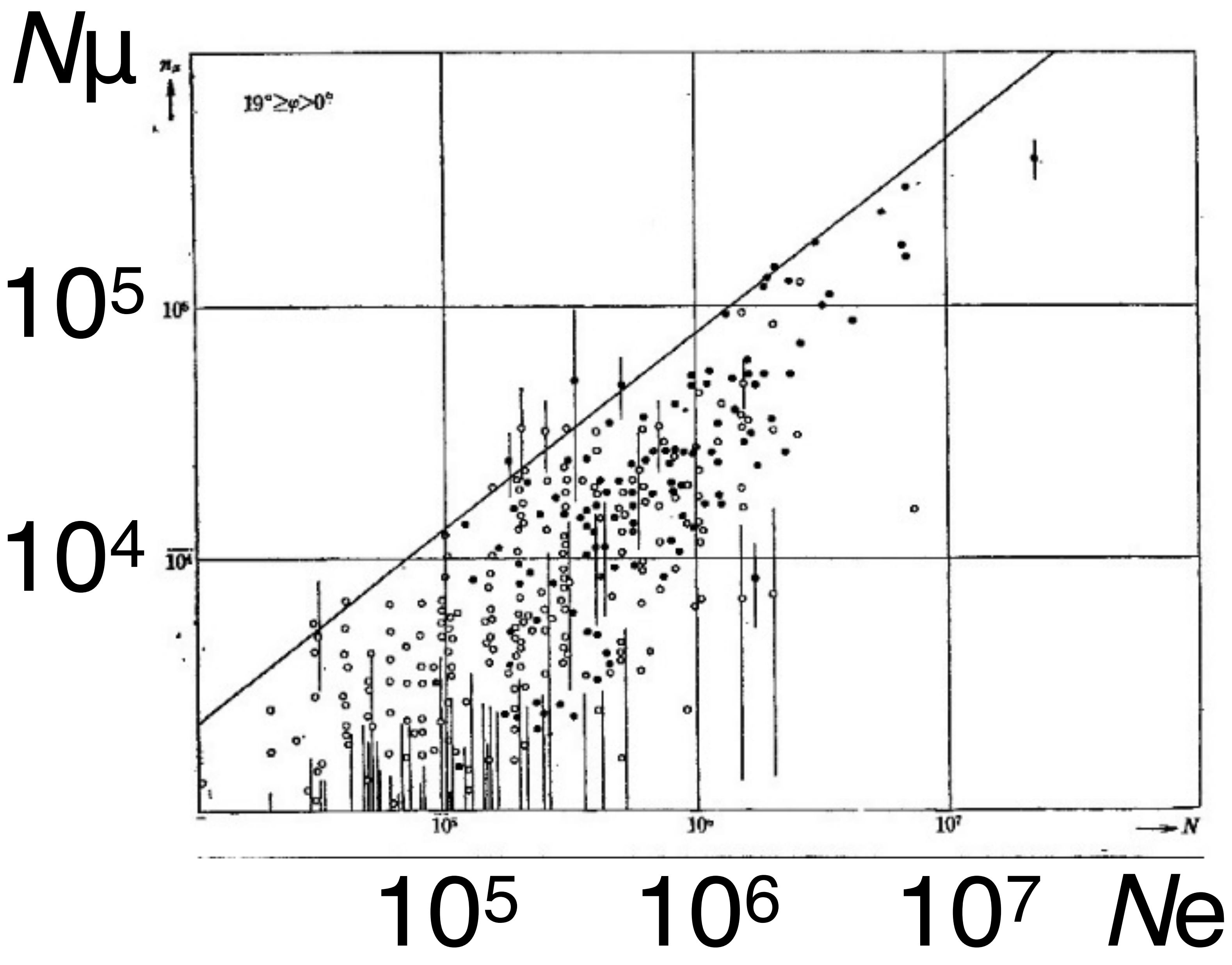
https://www2.nhk.or.jp/archives/articles/?id=D0009250466_00000



5 EeV





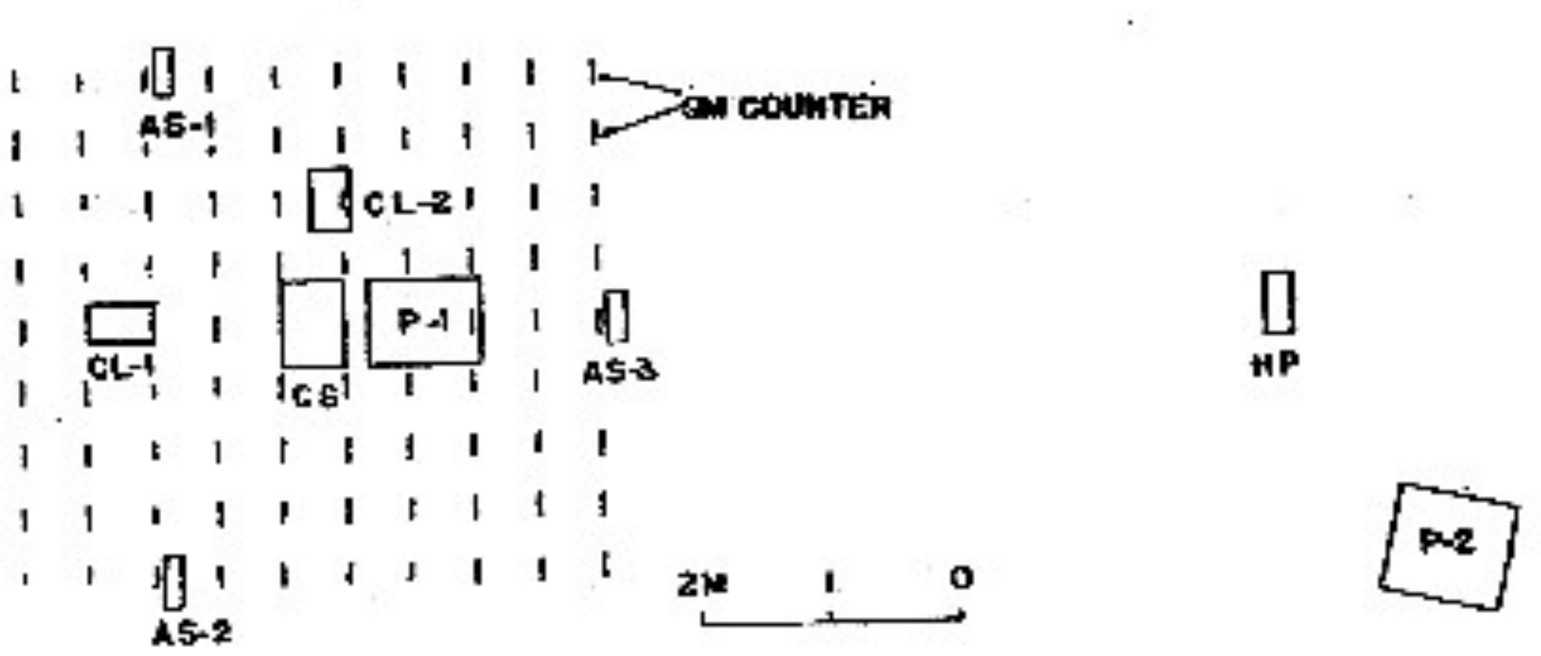


「空気シャワー観測による宇宙線研究の歴史」永野元彦

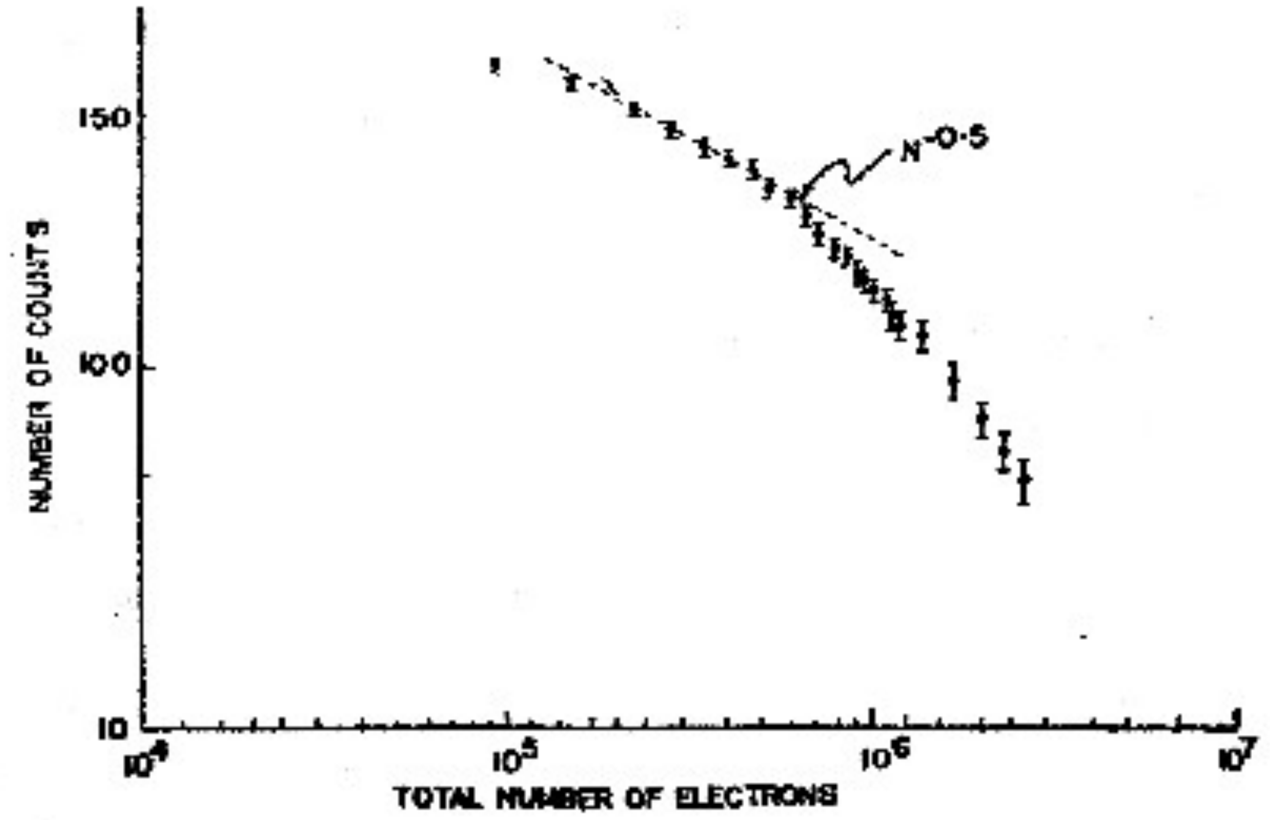
Beginning of air shower array at high altitude

- Constructed a air shower array at **Morikura mountain** in Japan (1957)
- **Koichi Suga** started observation with **Bolivian Air Shower Joint Experiment, BASJE** (1962)
  - Observation of **gamma-ray** air showers at high altitude

Norikura mountain

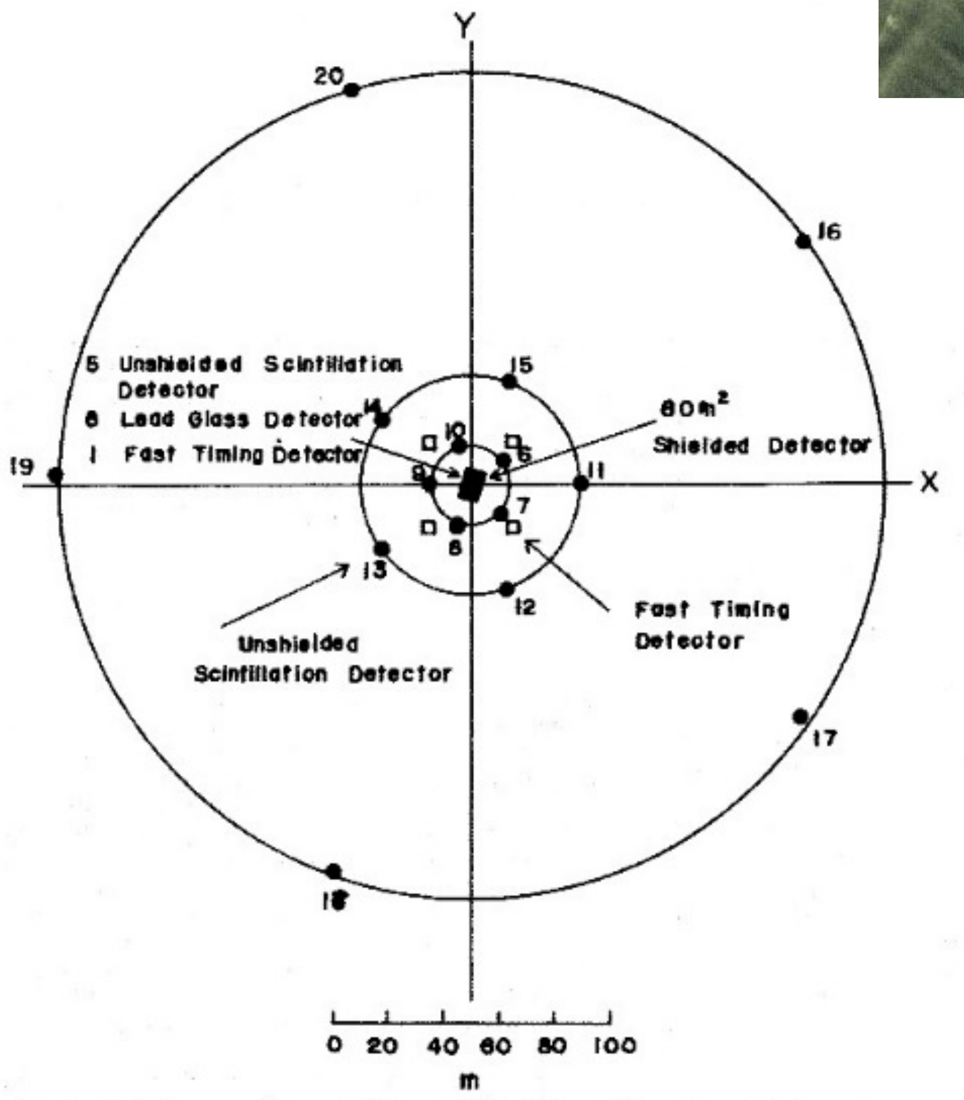


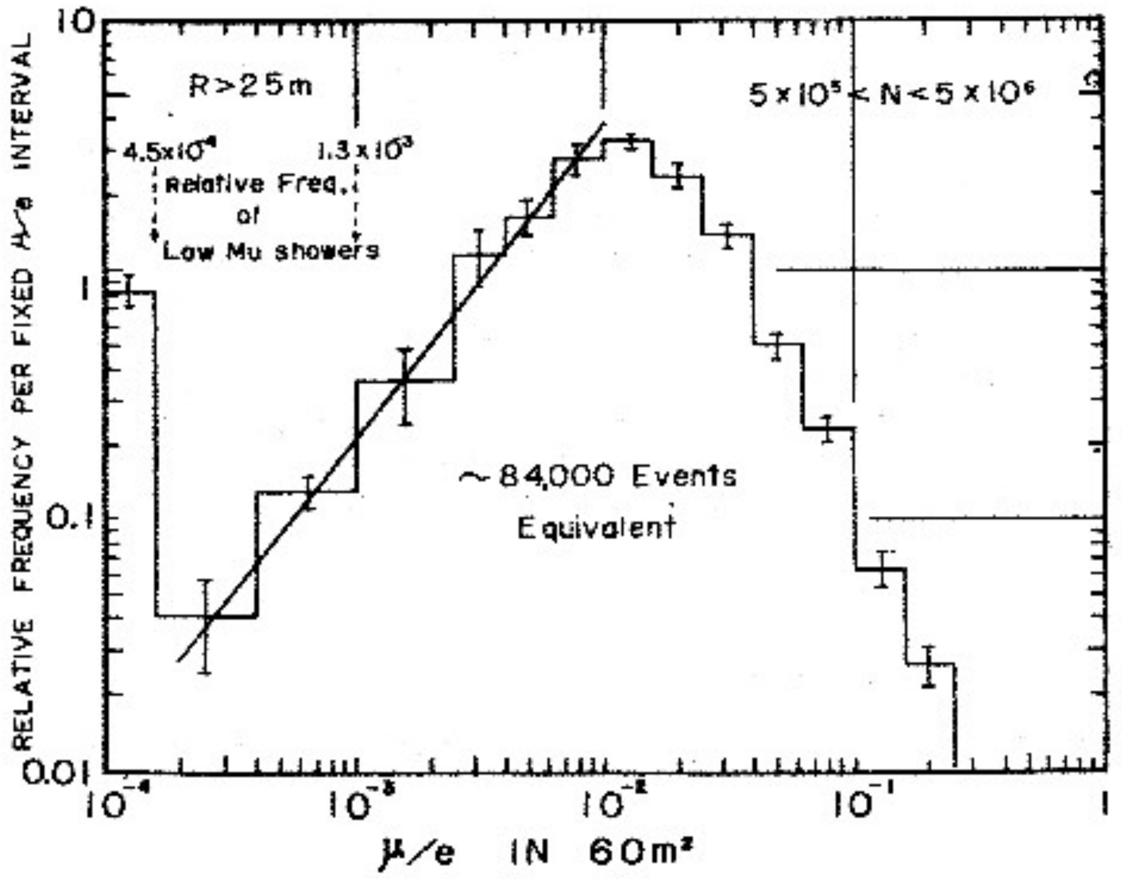
Knee?

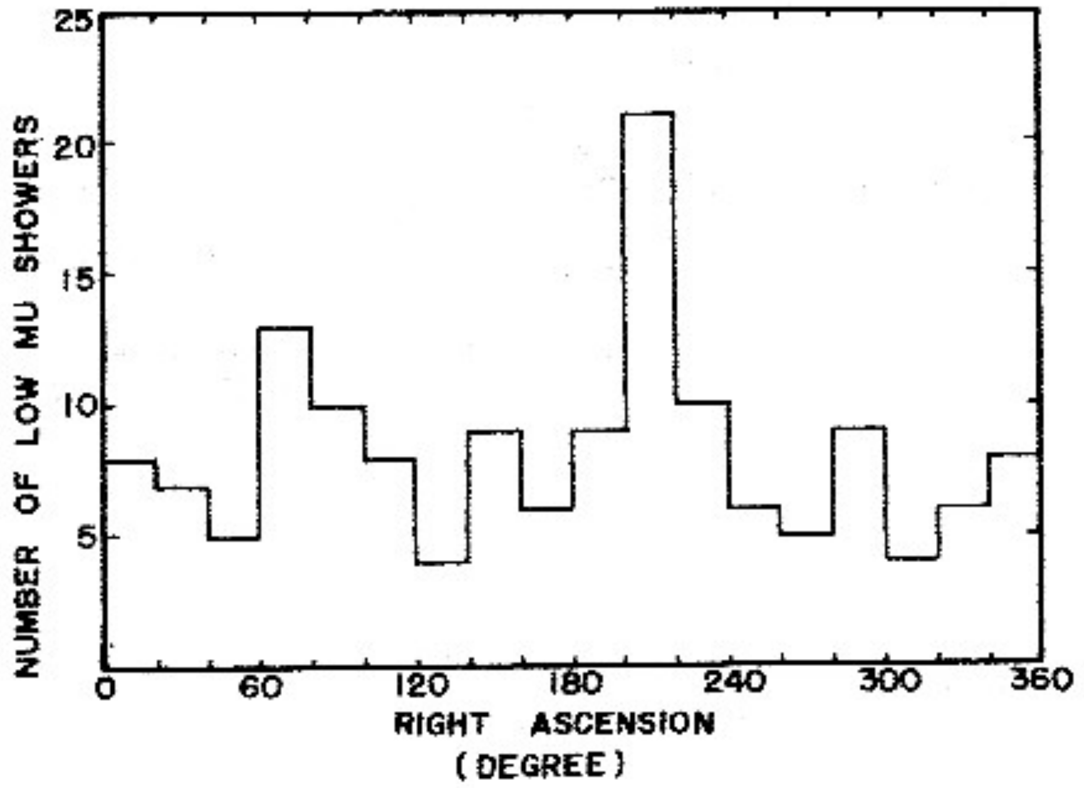


Suga

BASJE





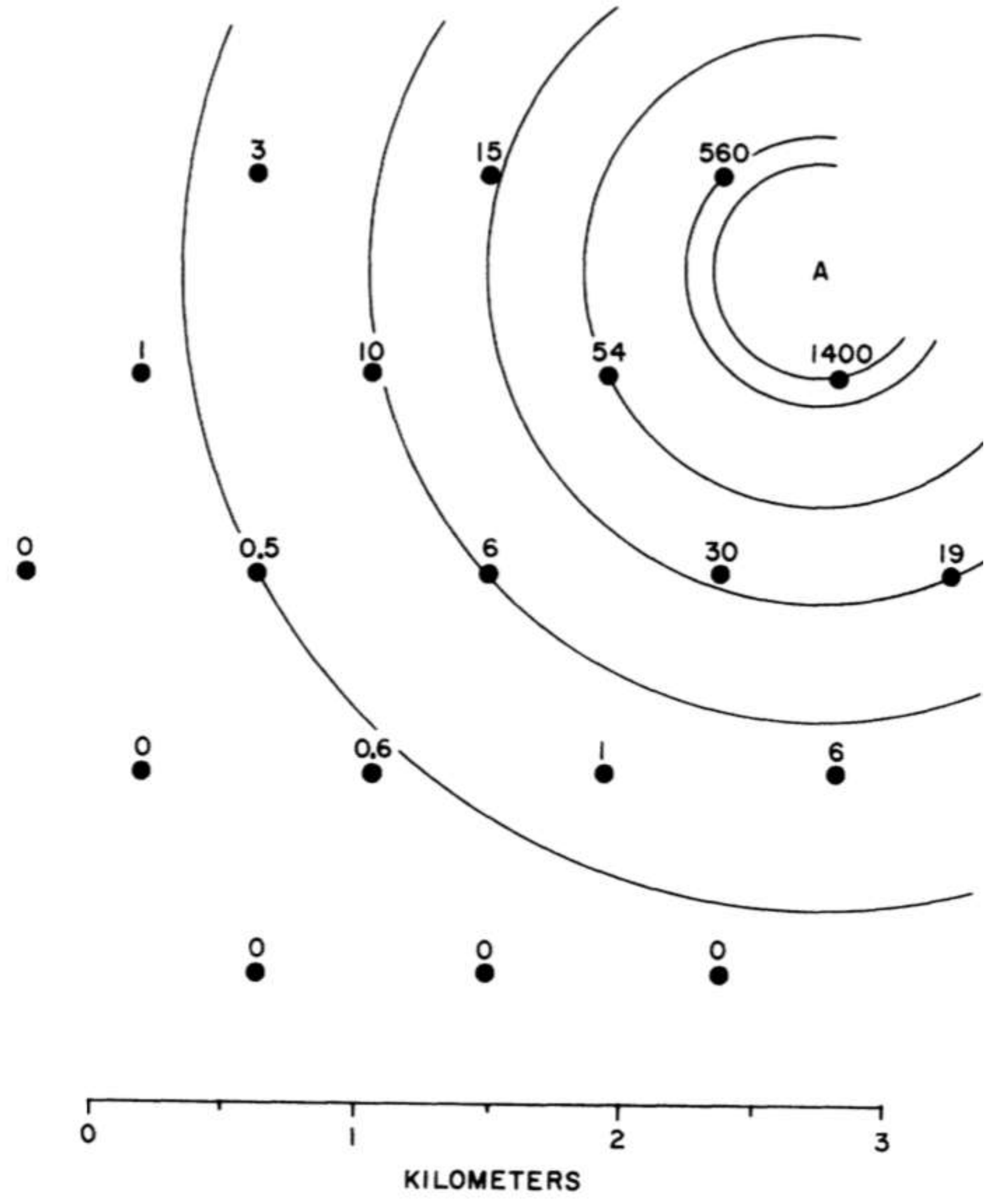


Gamma-ray excess?

「空気シャワー観測による宇宙線研究の歴史」永野元彦

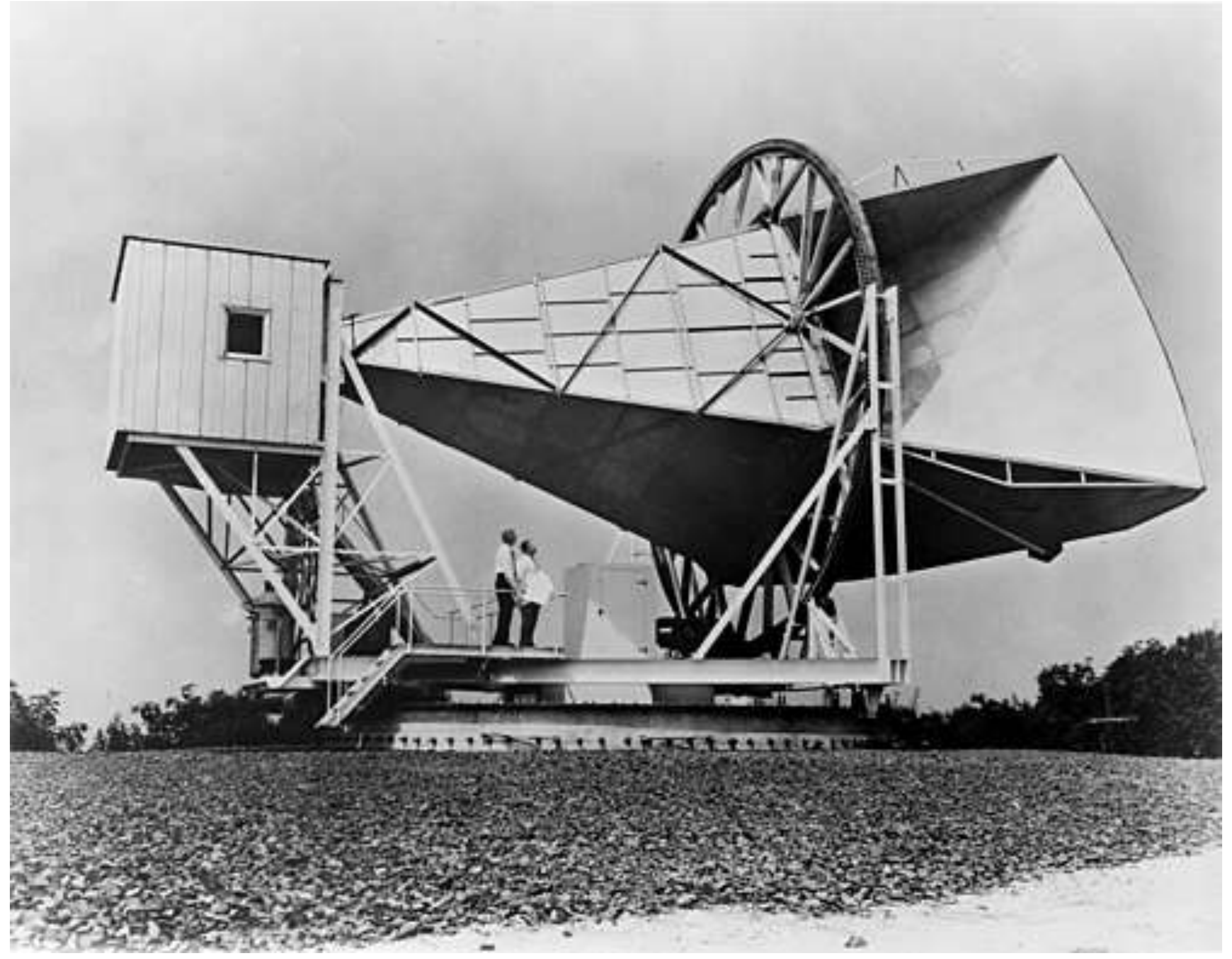
Beginning of 100 EeV (10^{20} eV) detection

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)

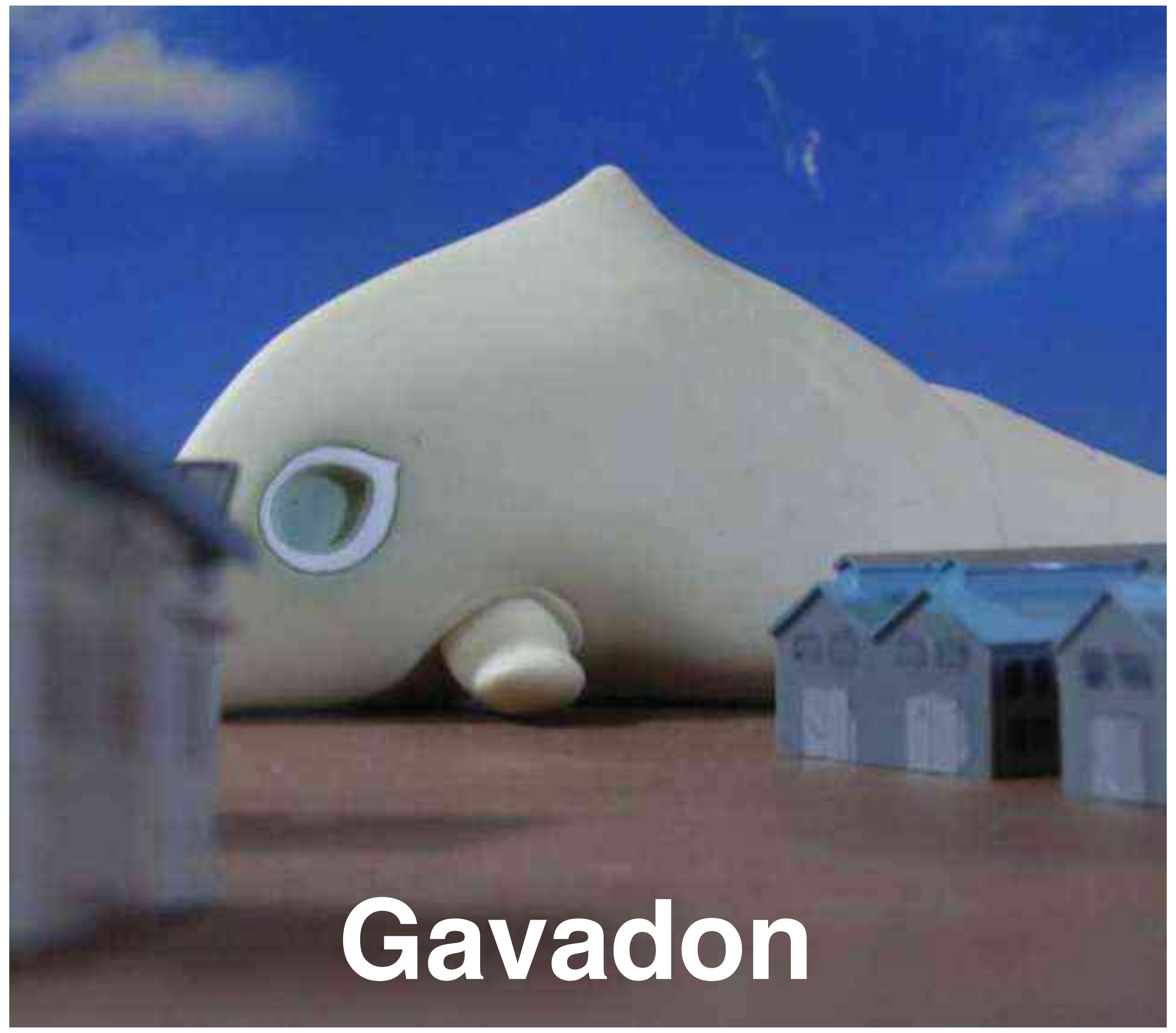
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi^{0} \quad {}^{A}_{Z}N + \gamma_{\mathrm{CMB}} \rightarrow {}^{A-1}_{Z-1}N' + p$$

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

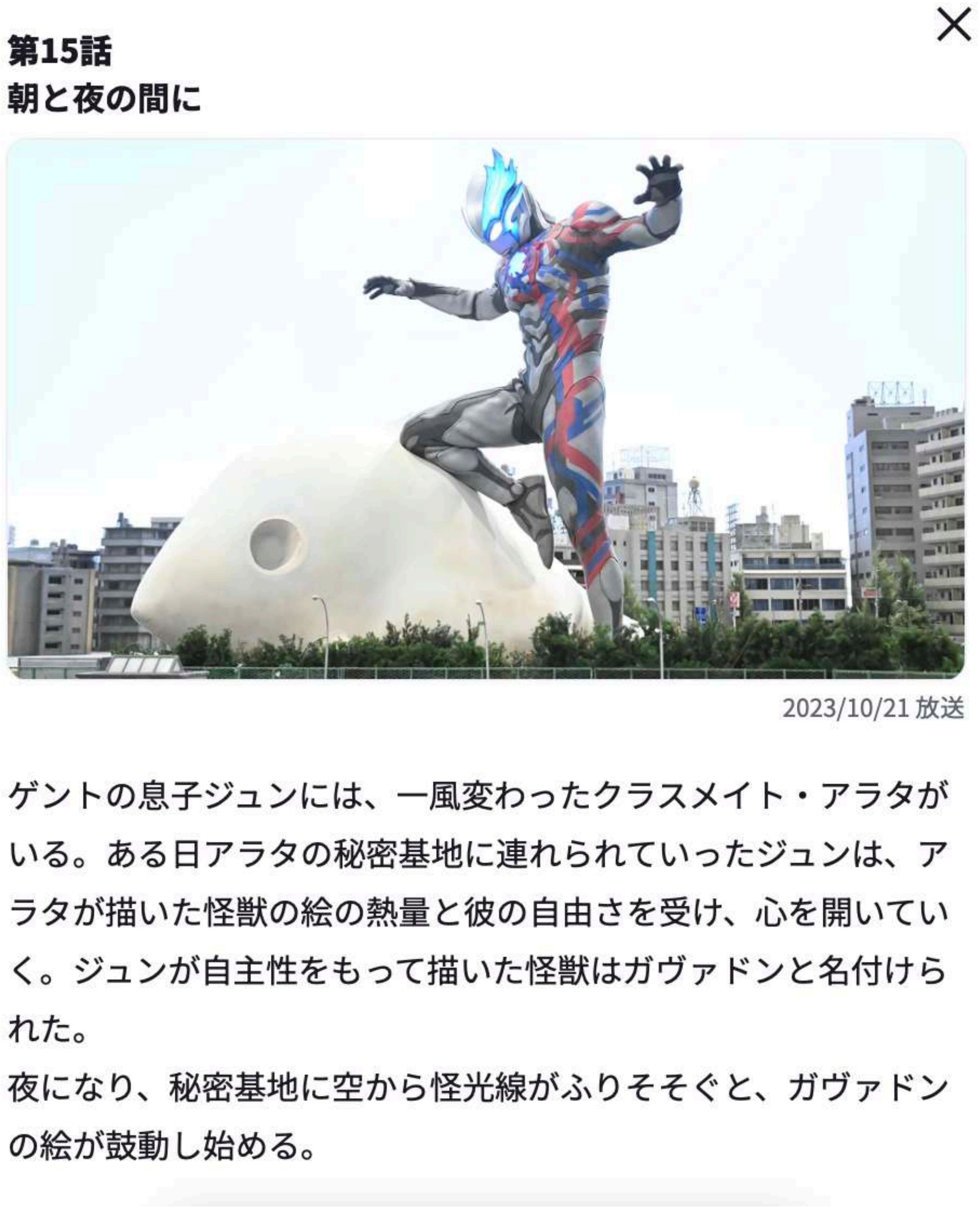
G.T. Zatsepin and V.A. Kuzmin, “Upper limit of the spectrum of cosmic rays”. *JETP Lett.* 4 (1966), 78–80

Cosmic rays became popular among citizens? (1960s)

Ultraman (1966)
"*Feared* cosmic rays"



Remake version of
Ultraman blazar (2023)


第15話
朝と夜の間に

2023/10/21 放送

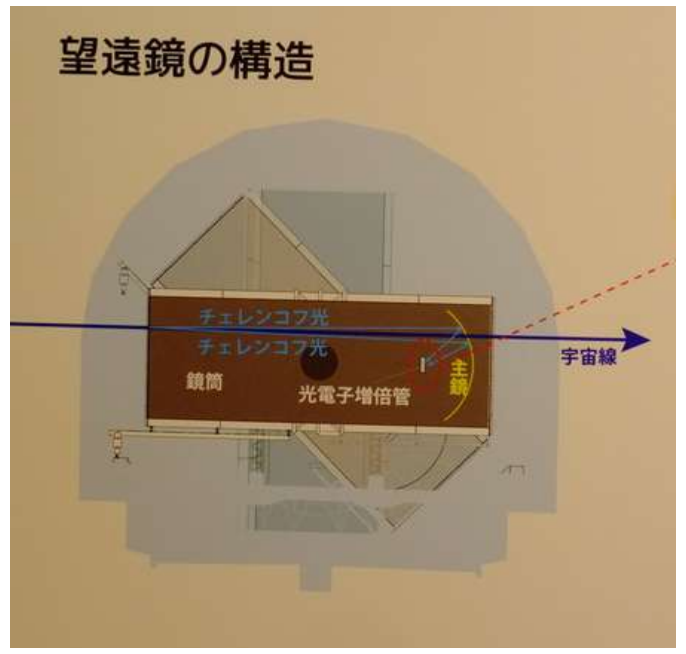
ゲントの息子ジュンには、一風変わったクラスメイト・アラタがいる。ある日アラタの秘密基地に連れられていったジュンは、アラタが描いた怪獣の絵の熱量と彼の自由さを受け、心を開いていく。ジュンが自主性をもって描いた怪獣はガヴァドンと名付けられた。
夜になり、秘密基地に空から怪光線がふりそそぐと、ガヴァドンの絵が鼓動し始める。

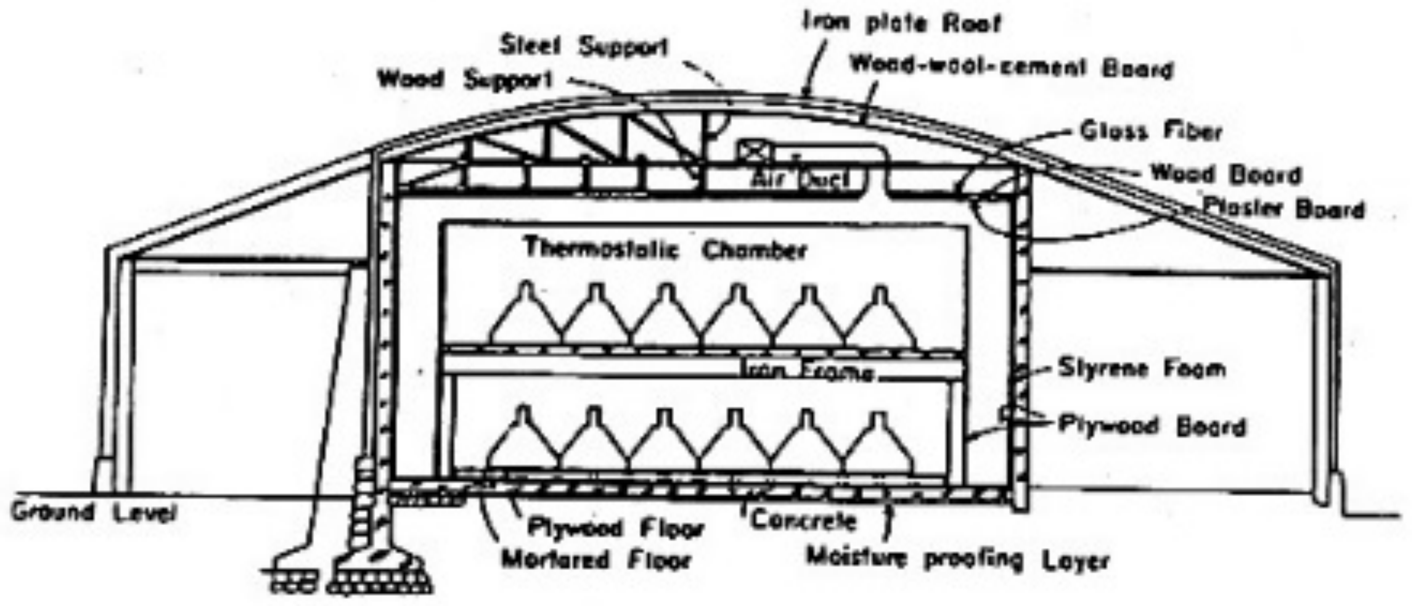
https://m-78.jp/videoworks/ultraman-blazar/

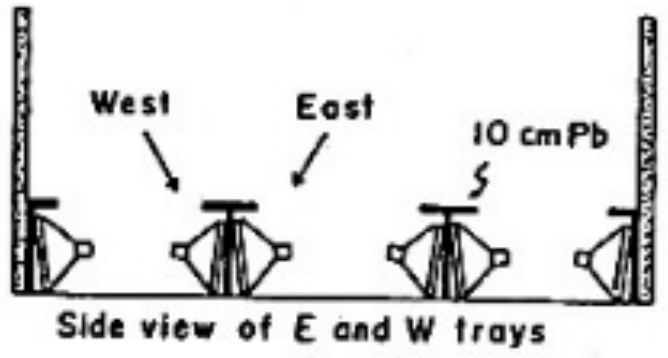
Gavadon in my office

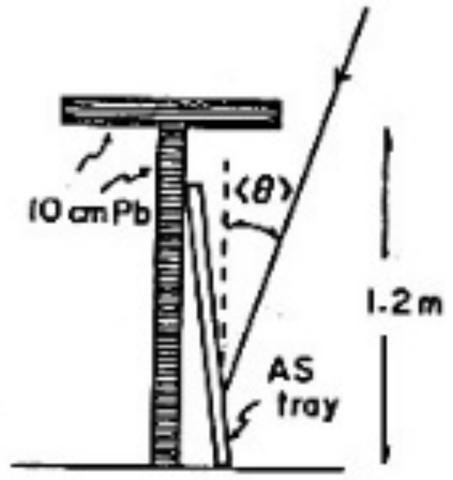
Beginning of cosmic ray anisotropy studies

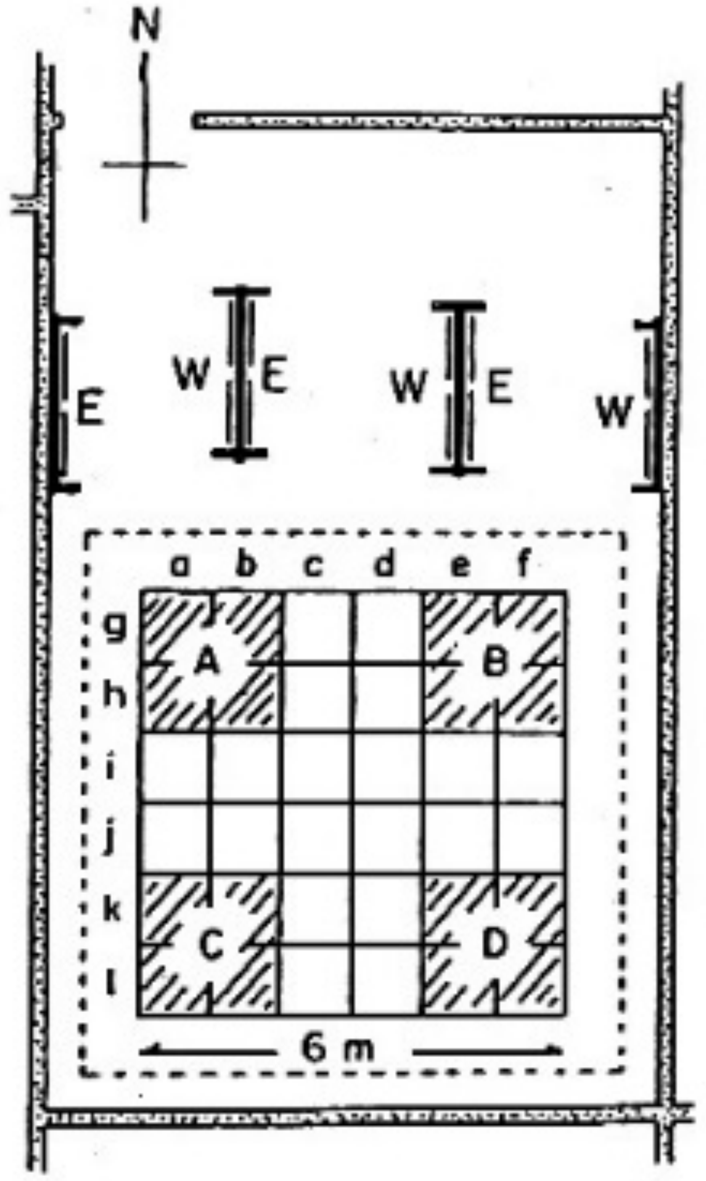
Sekido





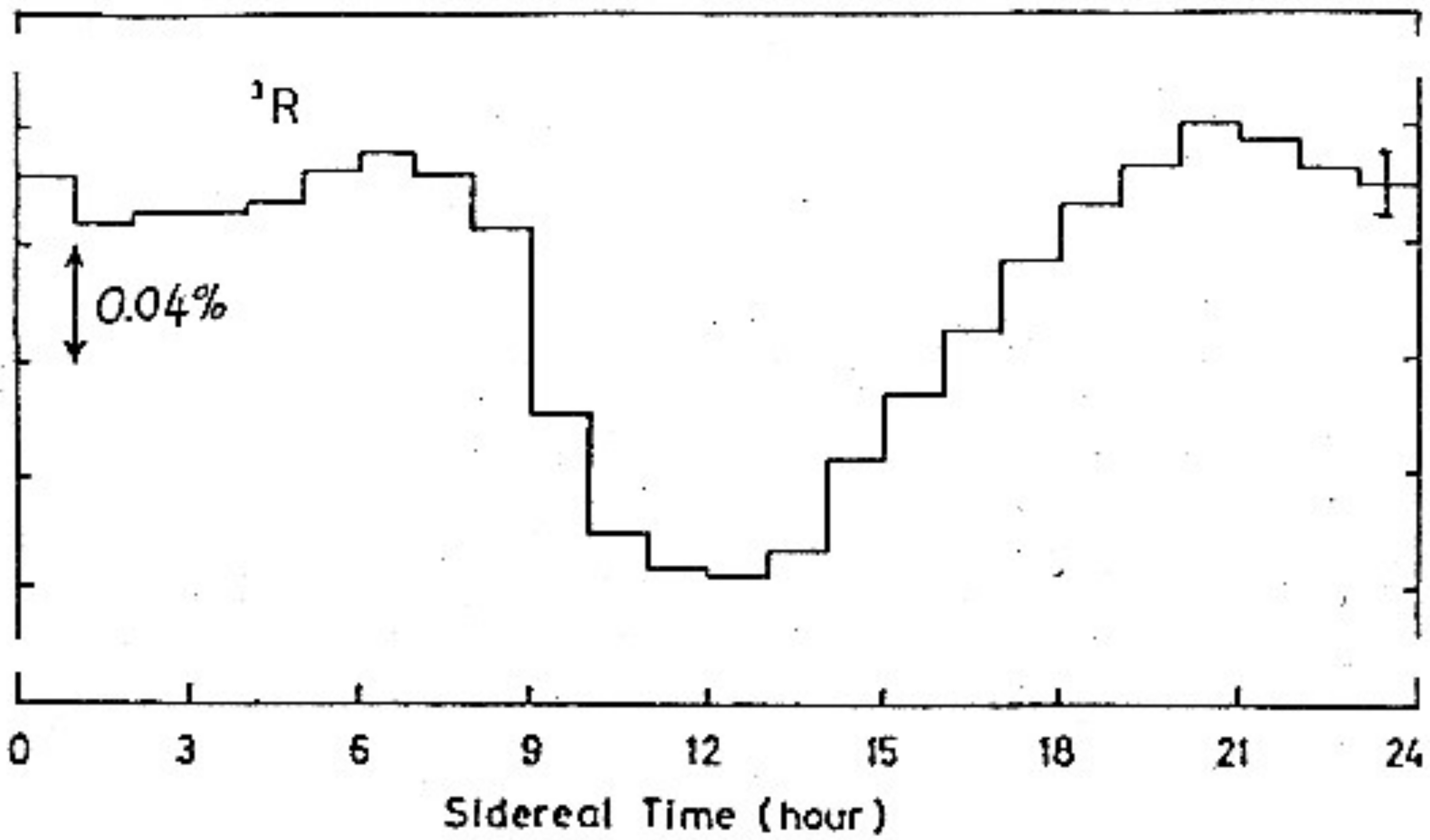






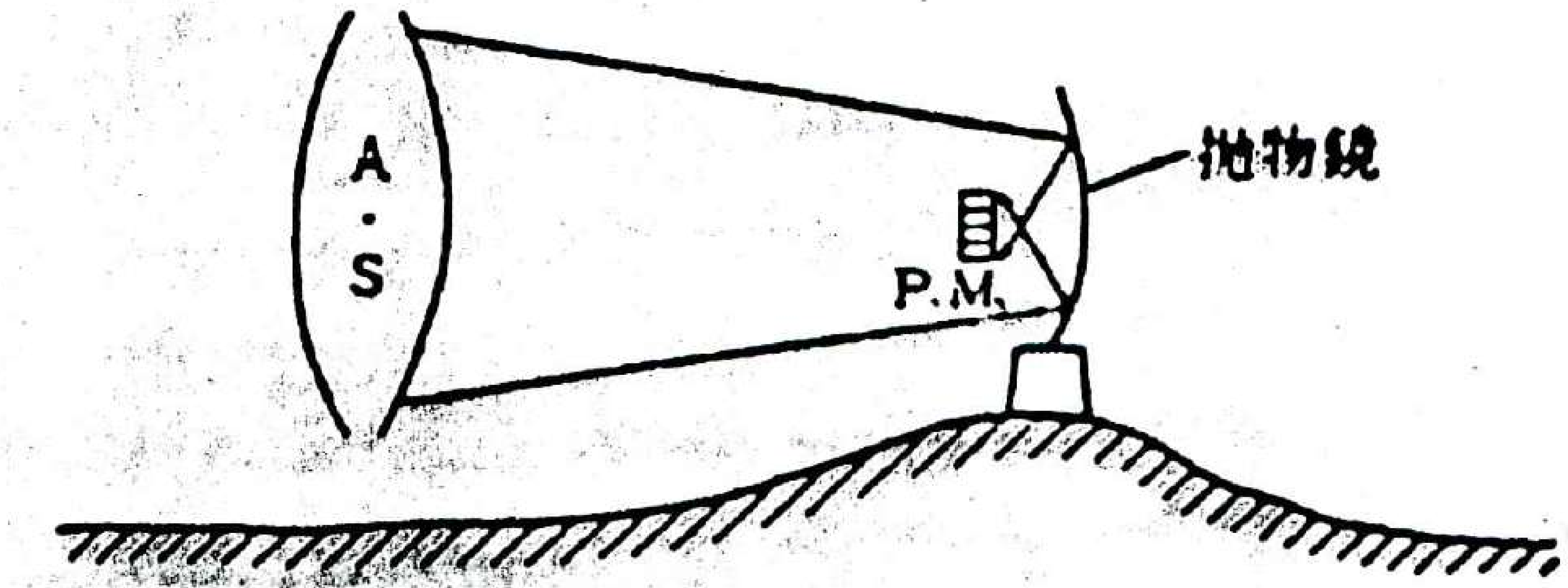
空気シャワーの種類	平均エネルギー (P_m)
^3E, ^3W : Directional AS (ac+ad+ae+af) (E;W)	$\approx 2 \times 10^{13}$ eV
^3F : ABC+BCD+CDA+DAB	1.5×10^{13} eV
^4F : ABCD	2×10^{13} eV
^{36}F : (1, 2, 3, ……, 35, 36)	2×10^{14} eV

Sidereal time anisotropy >20 TeV



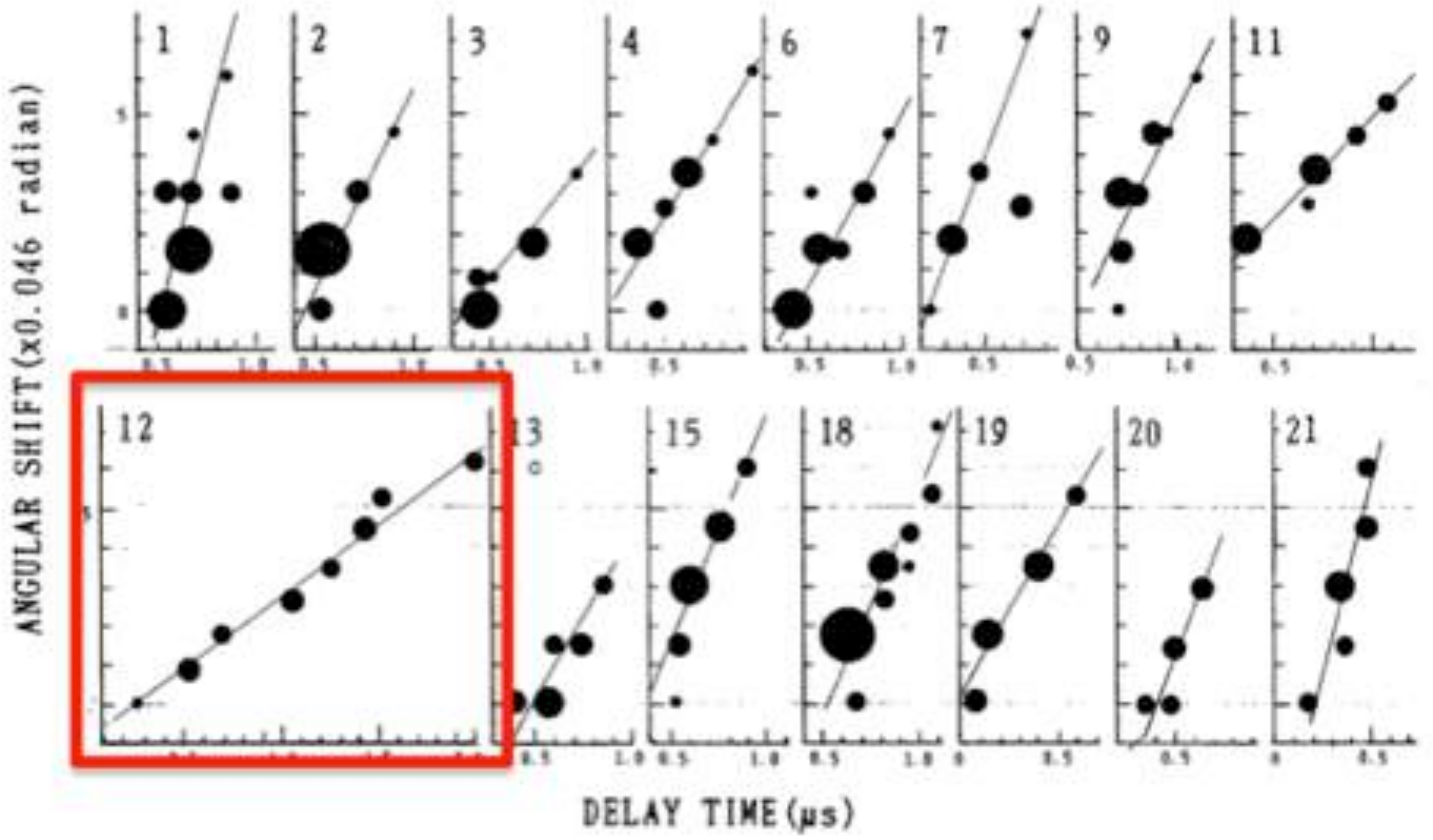
https://www.num.nagoya-u.ac.jp/english/exhibitions/spot/20230726.html

Beginning of fluorescence detector (1969)

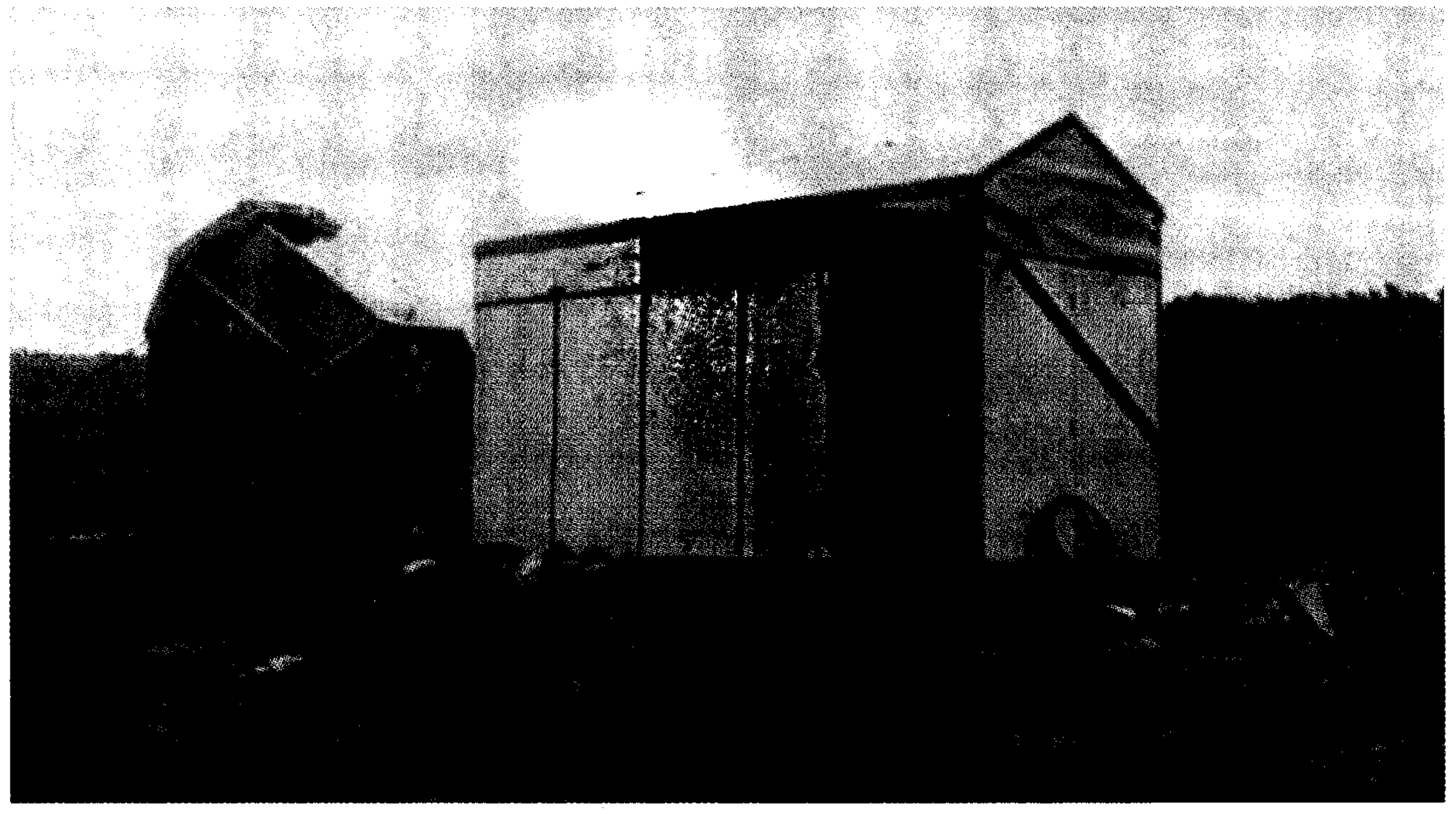


第3図 1958年乗鞍シンポジウムで話されたシャワー・カーブ測定の提案

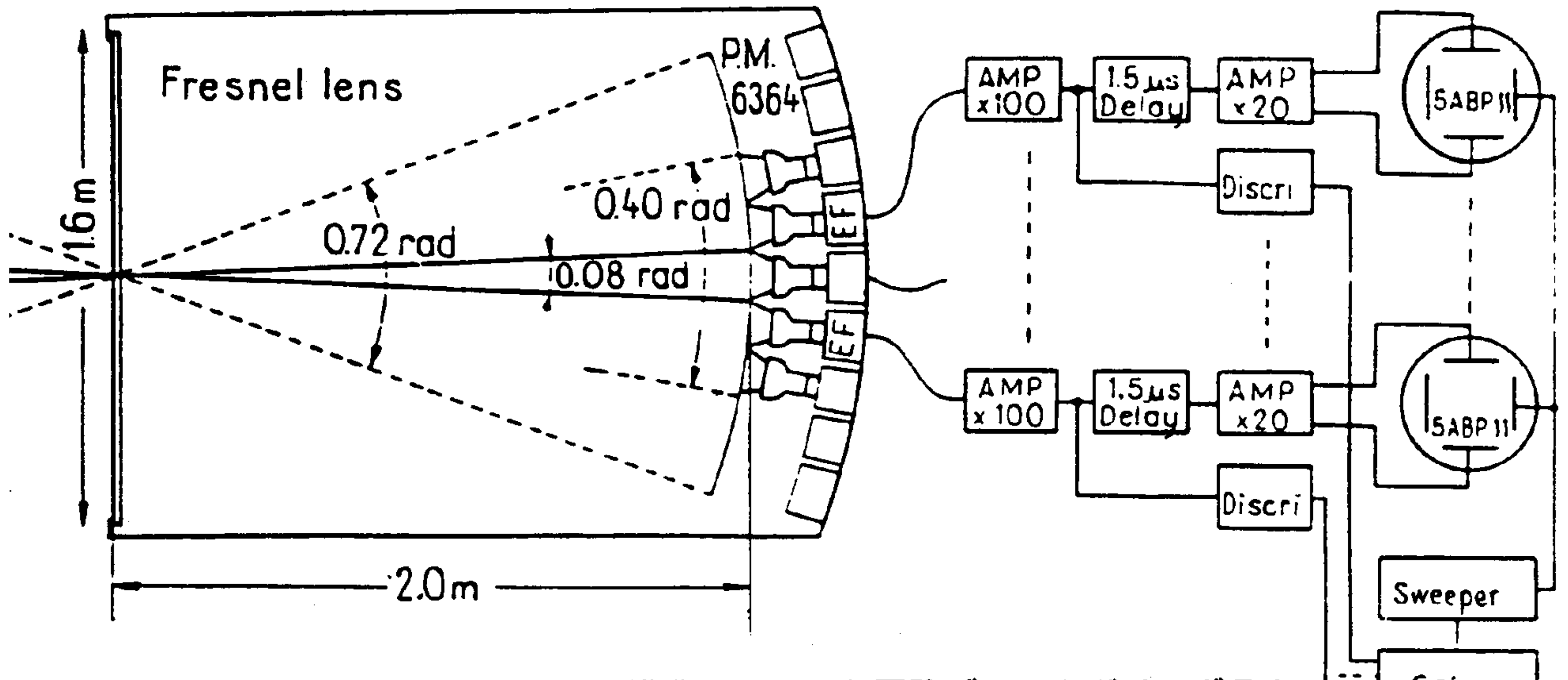
- Proposed by K. Suga and M. Oda (1958), also by Greisen and Chudakov at the same time
- First detection by Fresnel lens and 55 PMTs, TOKYO-1 (**1969**)



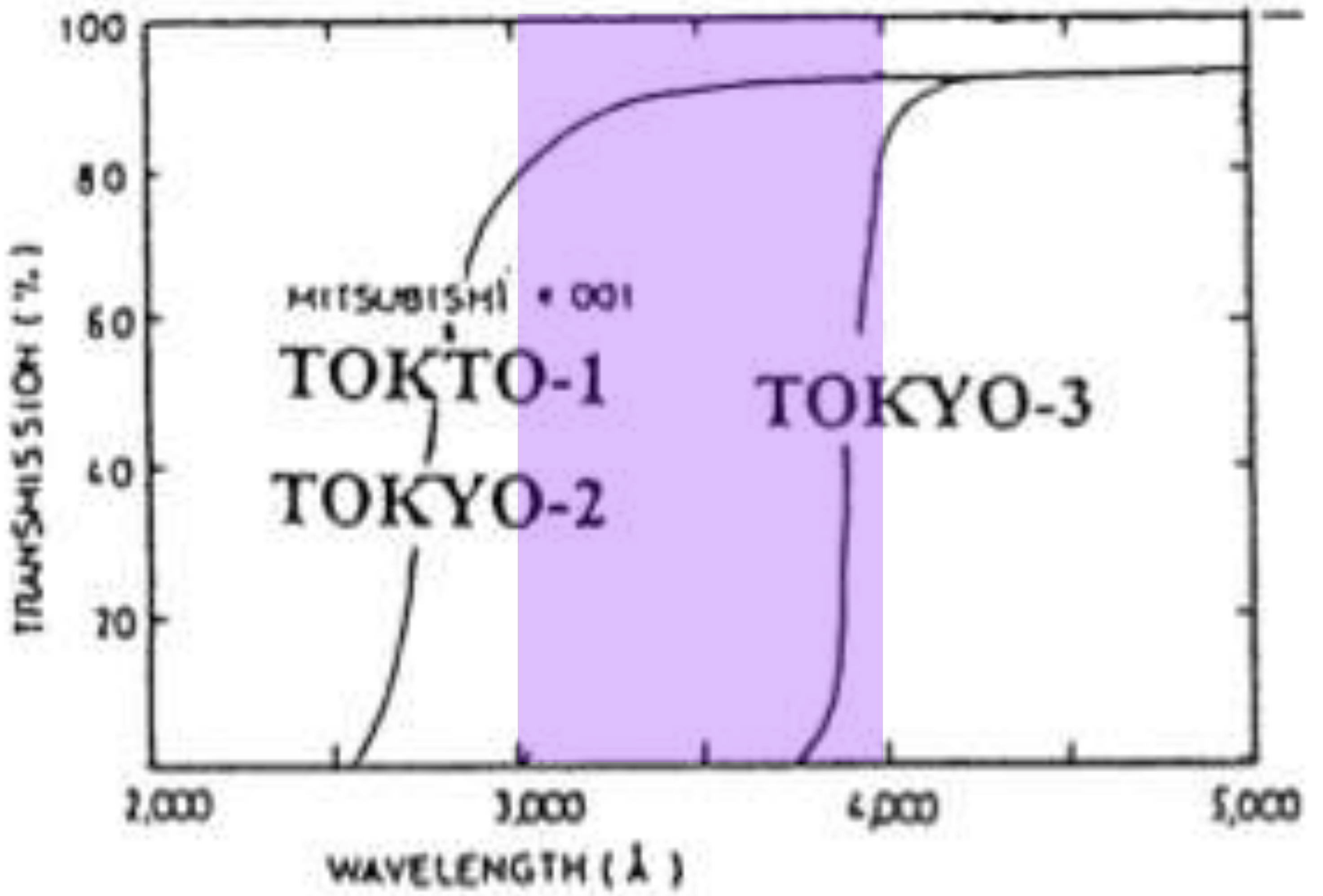
$5{\times}10^{18}$ eV, 680 g/cm^2 analyzed by B. Dawson, arXiv:1112.5686 (2011)



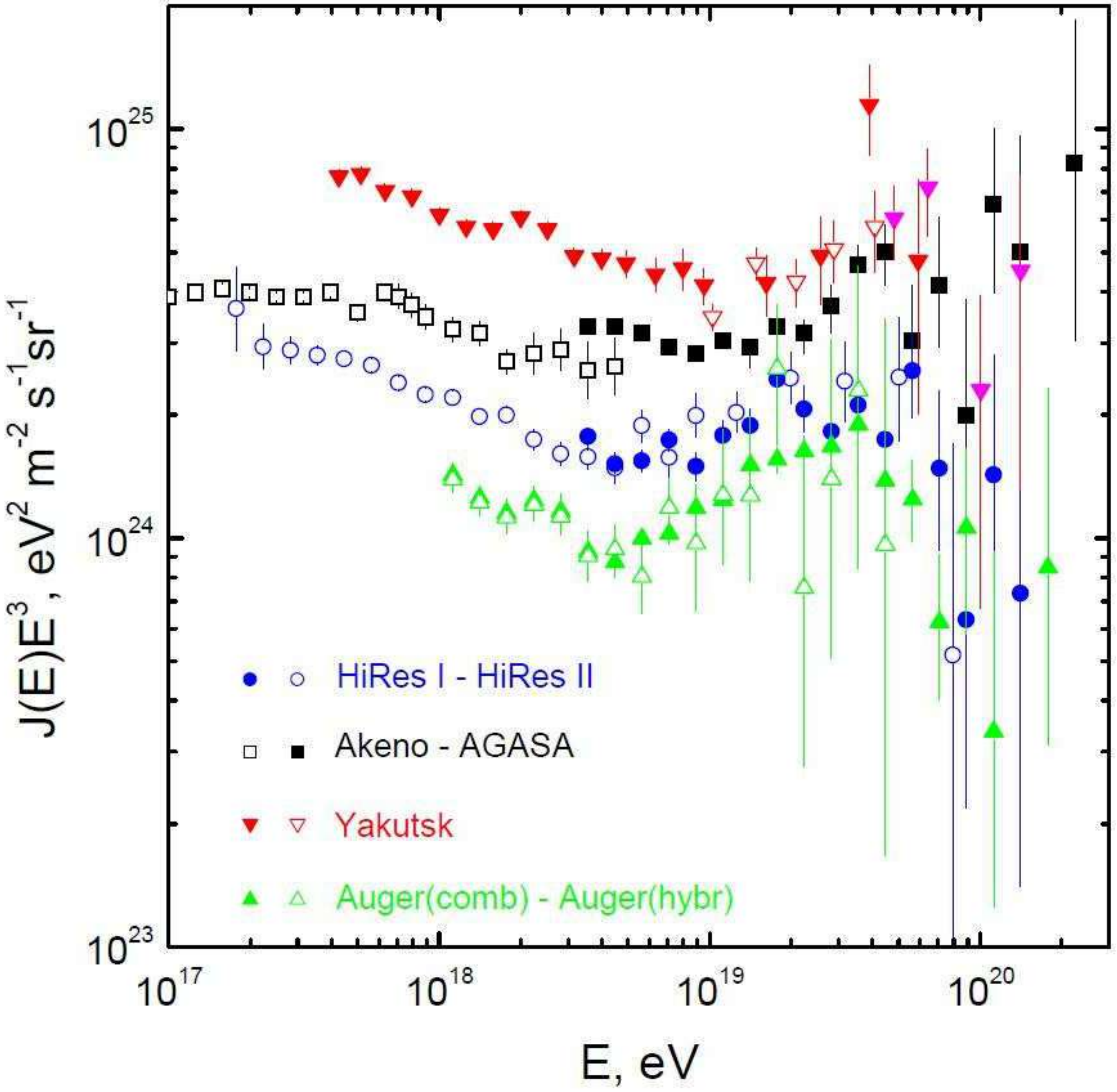
第8図 TOKYO−1の設置写真

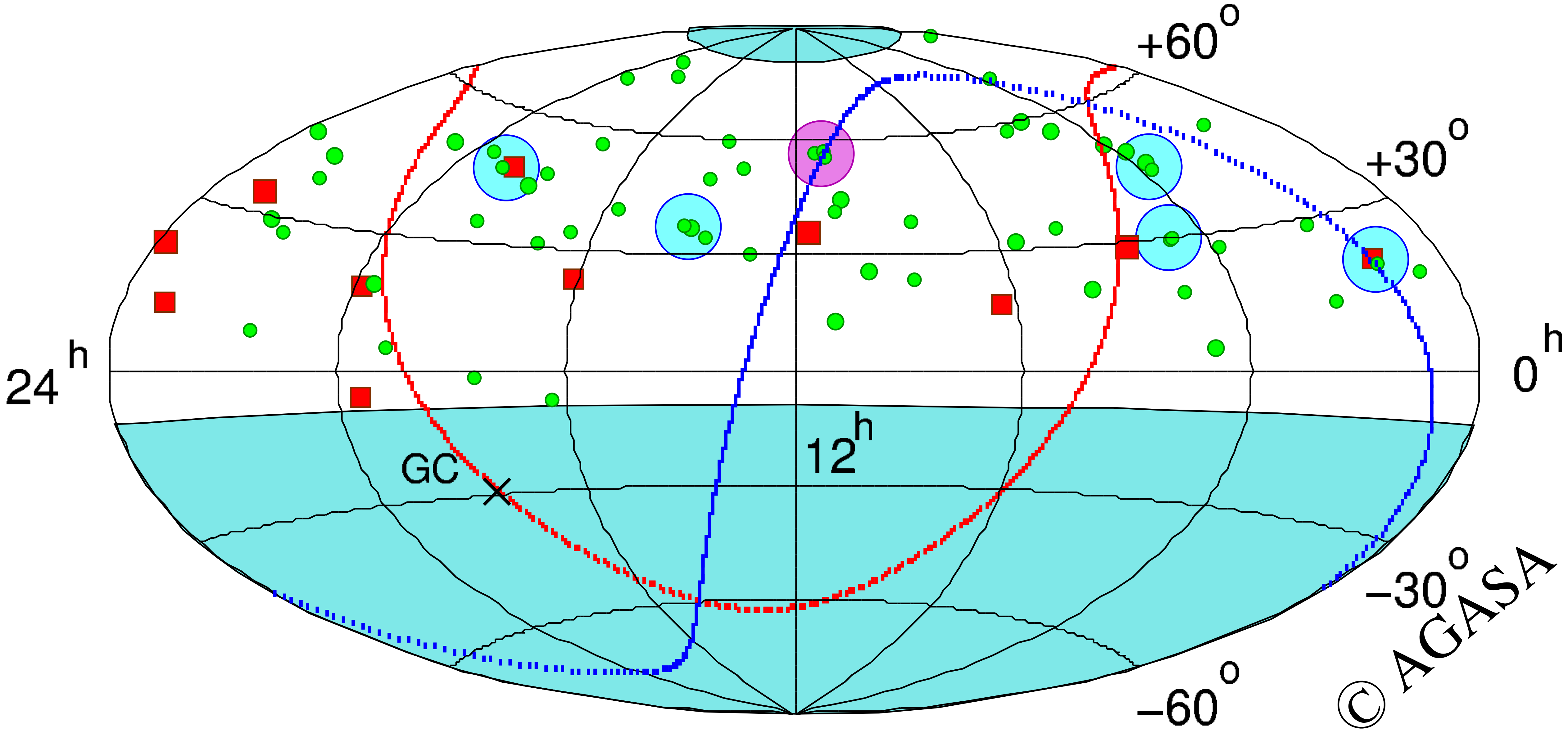


第7図 TOKYO-1の構造スケッチと回路ブロックダイアグラム



Akeno (1 km²) → AGASA (100 km²)

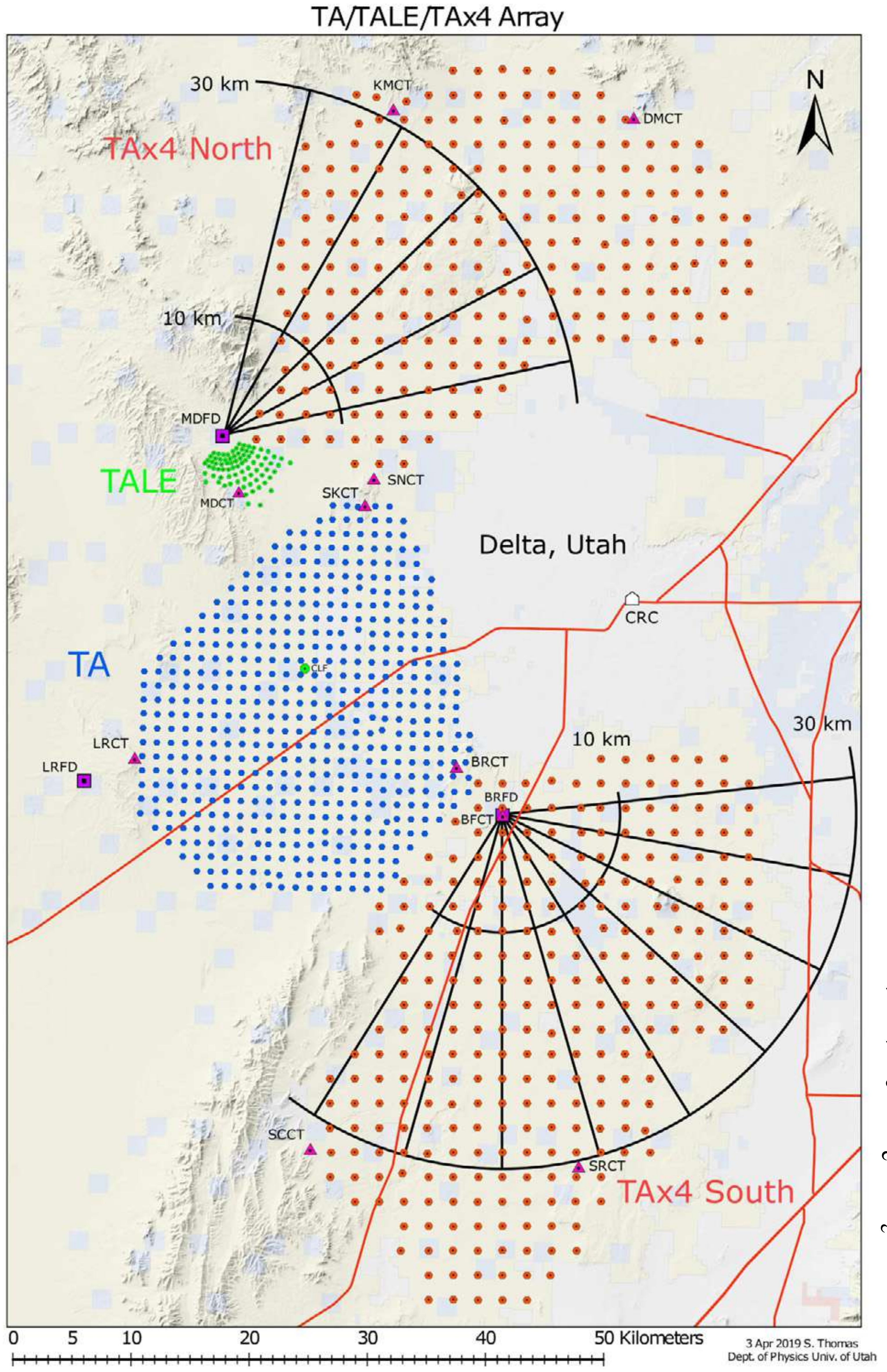




M. Takeda et al., ApJ 522, 225 (1999)

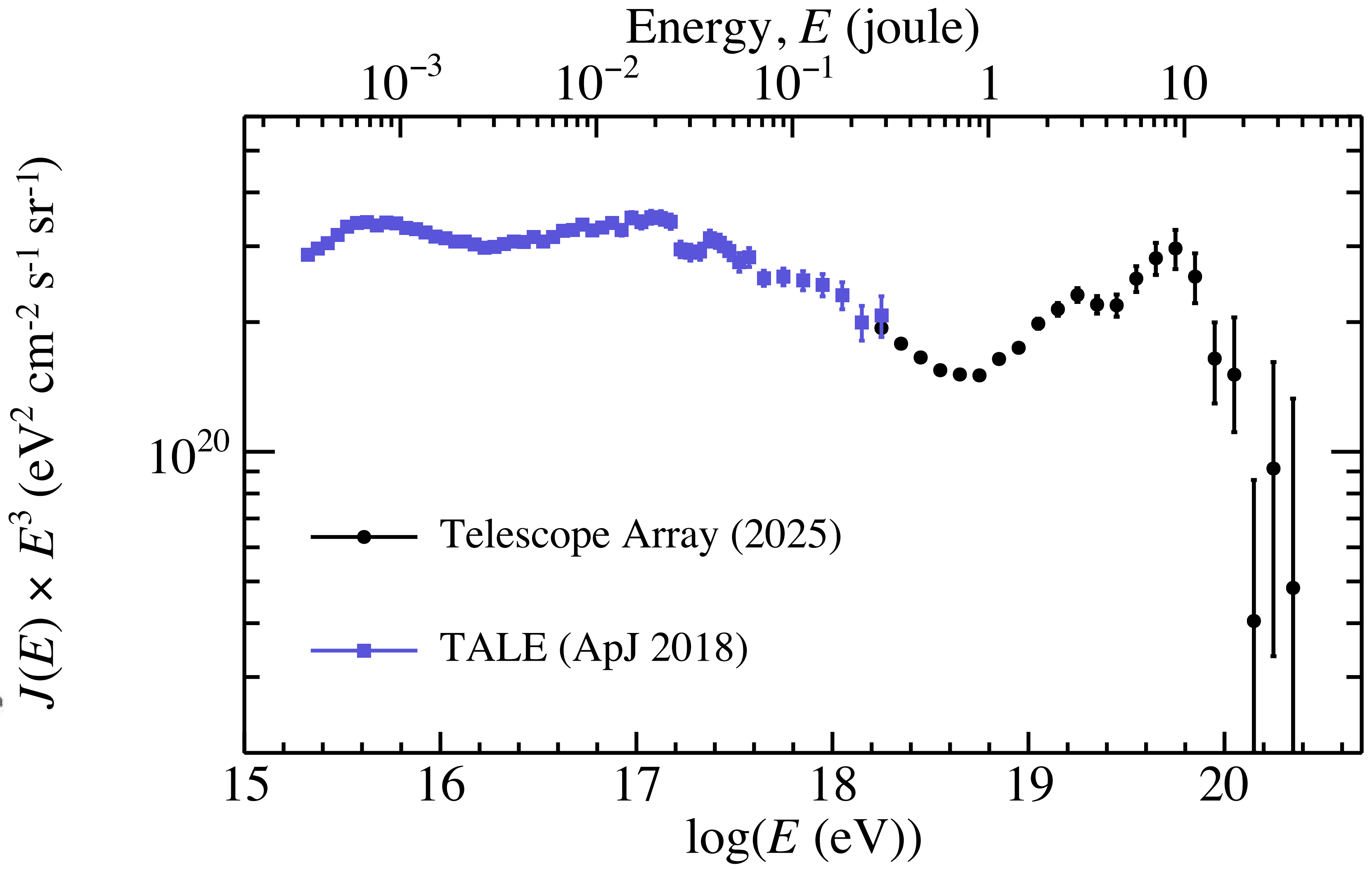
N. Hayashida, et al., Phys. Rev. Lett. 73, 3491 (1994)

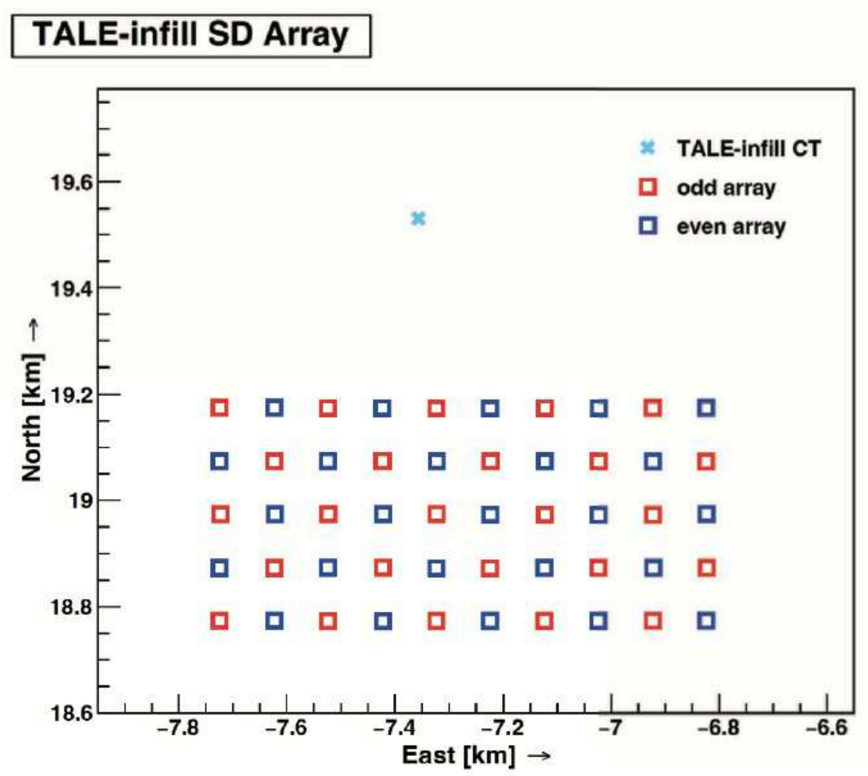
Telescope Array experiment (700 km²) → TAx4 (2800 km²)

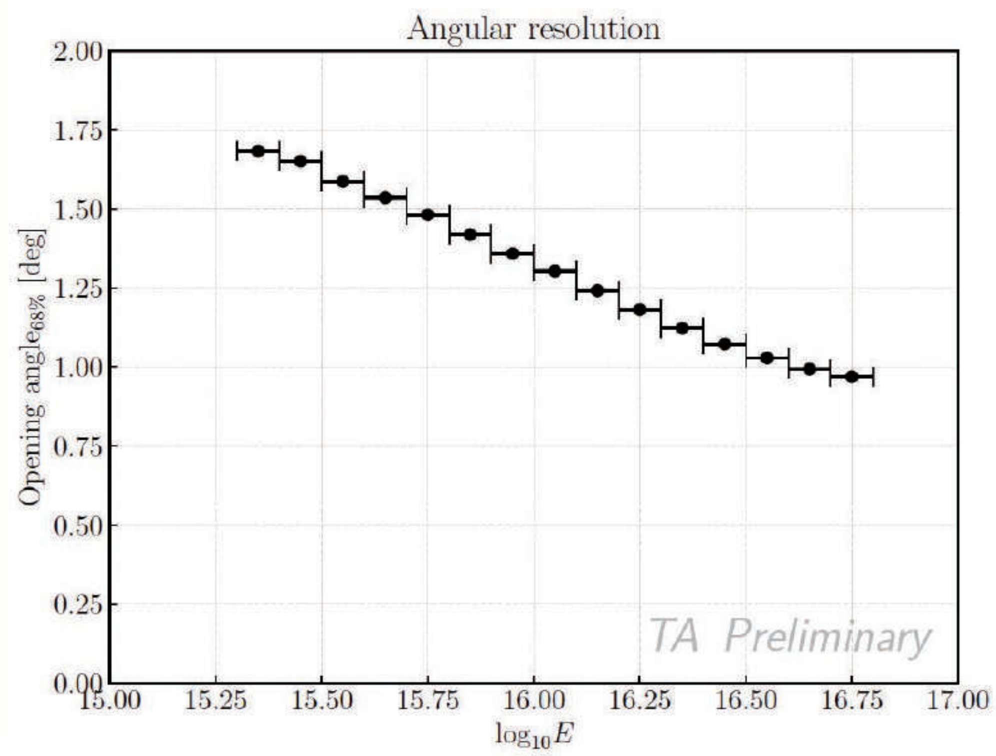


TA Collab., NIM-A 1019 (2021) 165726

- **Largest cosmic-ray observatory in northern hemisphere**, located at Utah USA
  - Hybrid observation with surface detector array and fluorescence detector with effective area of TA (700 km²) → TAx4 (2800 km²)
- Dense array, TALE/TALE-infill for low energies to cover 3 PeV ~ 300 EeV (5 order of magnitudes)





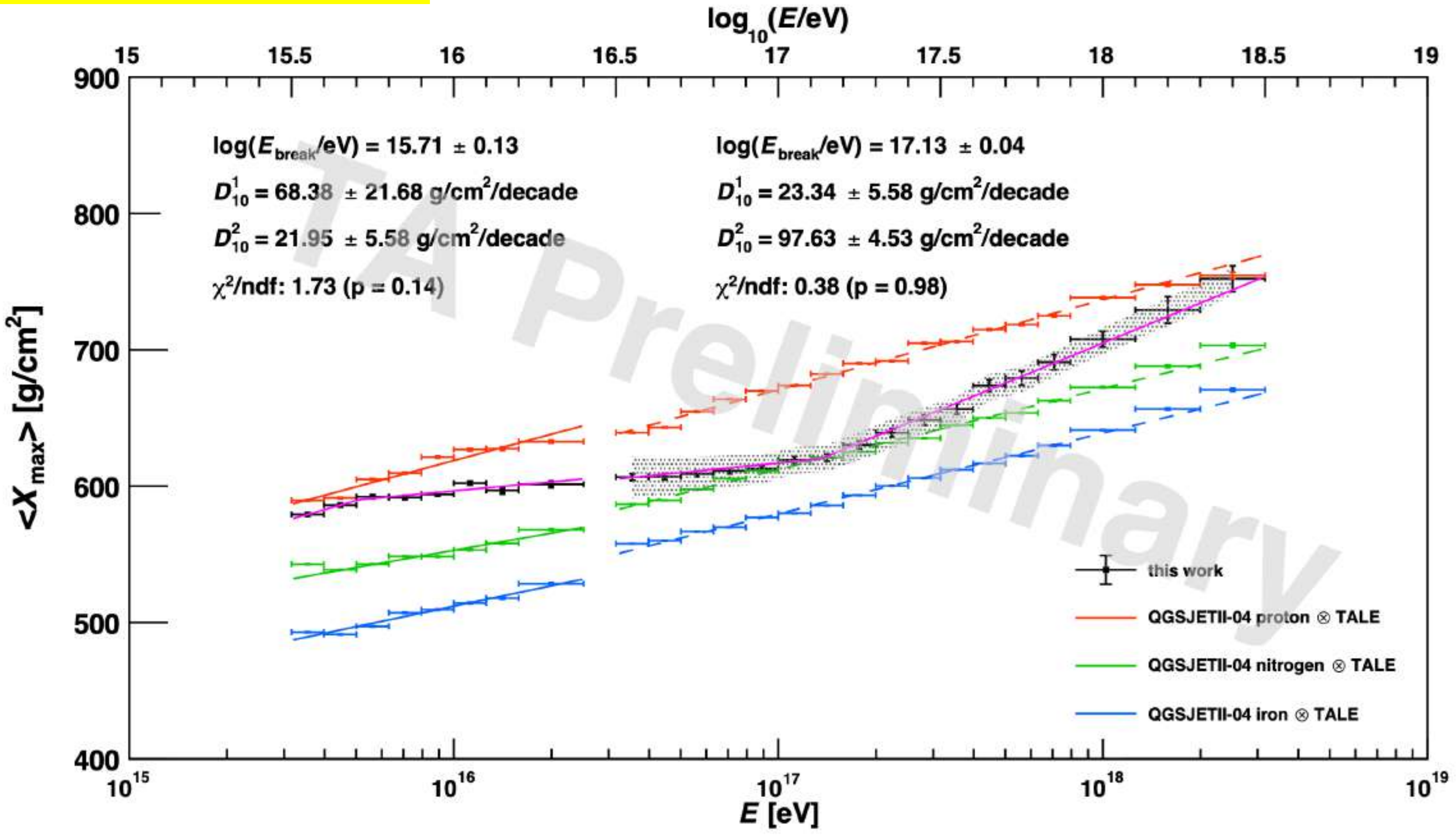


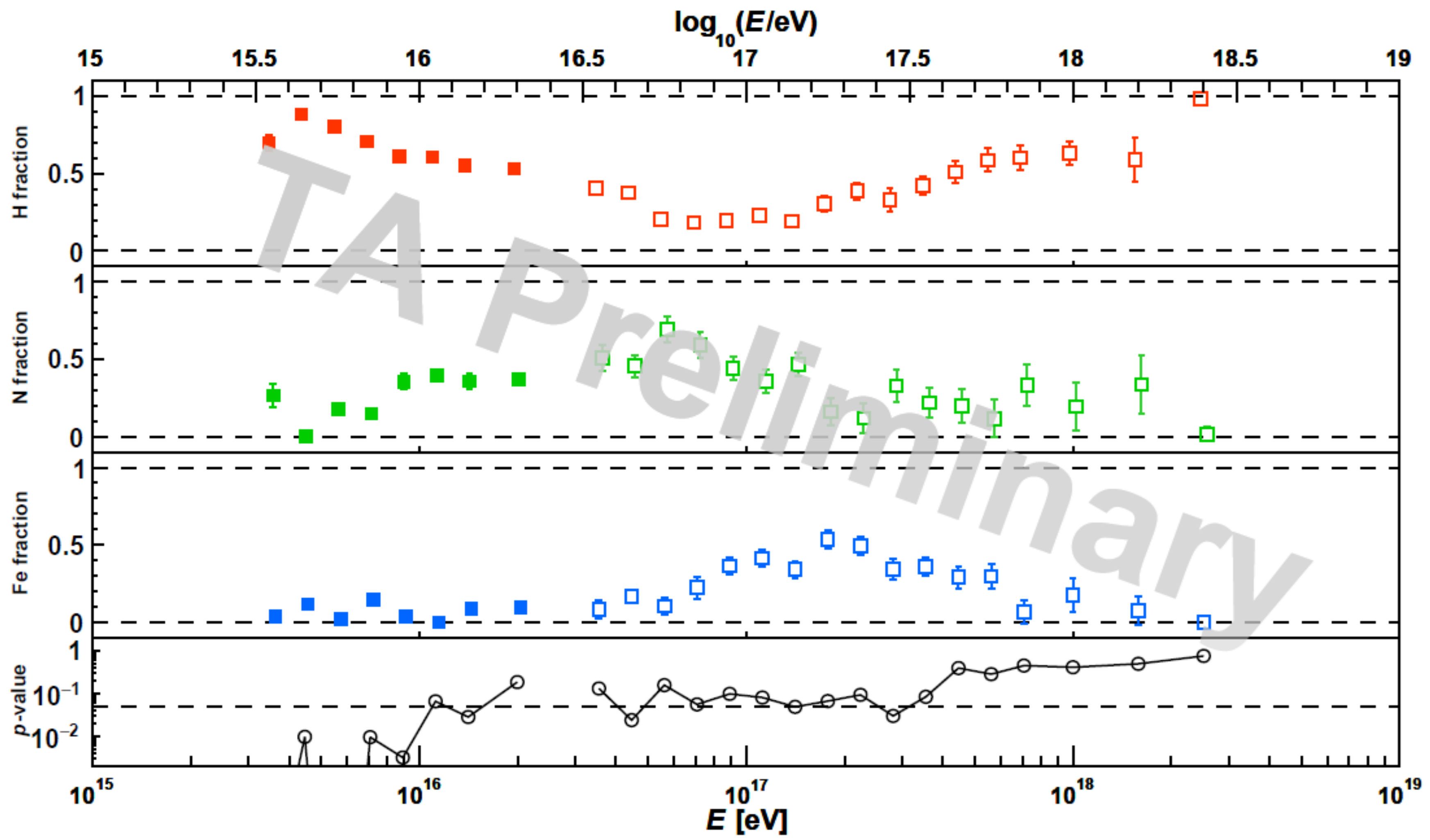
50 SDs with 100 m spacing (0.36 km²)

TALE/TALE-infill hybrid X_{max} analysis

Highlight talk at ICRC 2025, E. Kido

K. Fujita,
CRI poster 1157, PO-1

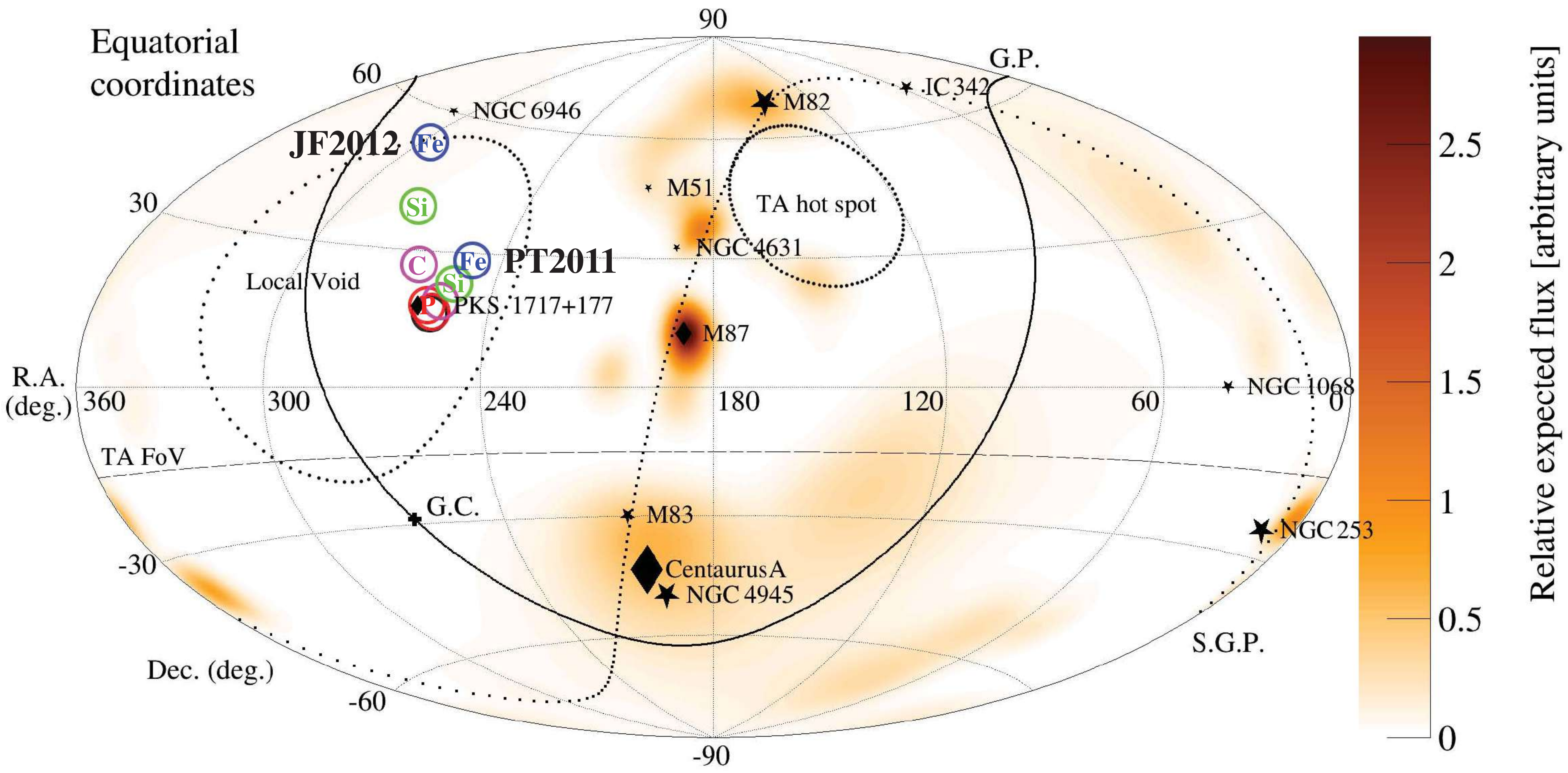




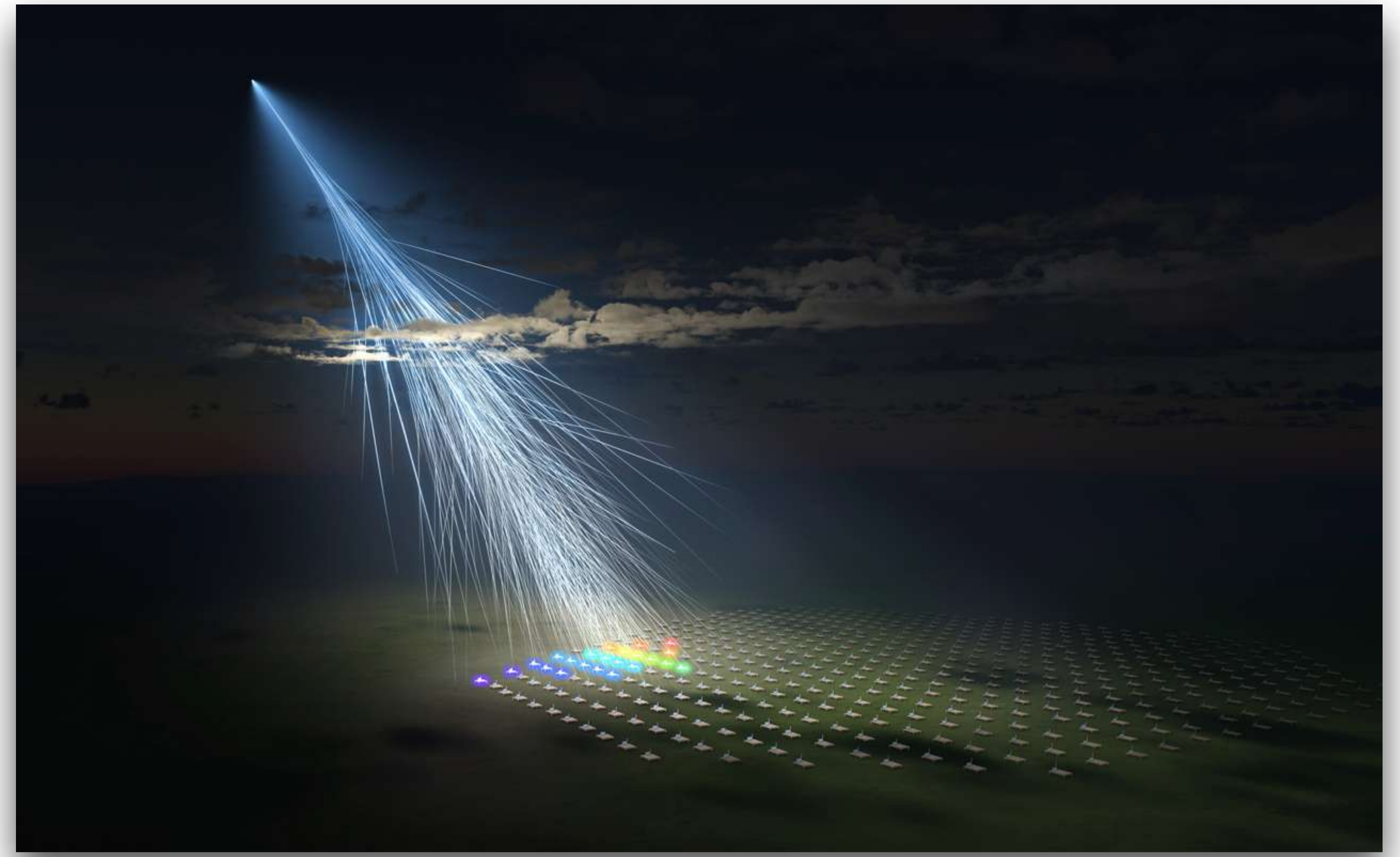
- Breaks in the $\langle X_{max} \rangle$ coincide with the knee and second knee.
- X_{max} distribution fits show a transition from light to heavy composition, peaking near $10^{17.2}$ eV.
- Further studies with He nuclei, and interaction model EPOS-LHC-R and QGSJET-III are ongoing.

Extremely energetic particle, dubbed "Amaterasu particle"

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



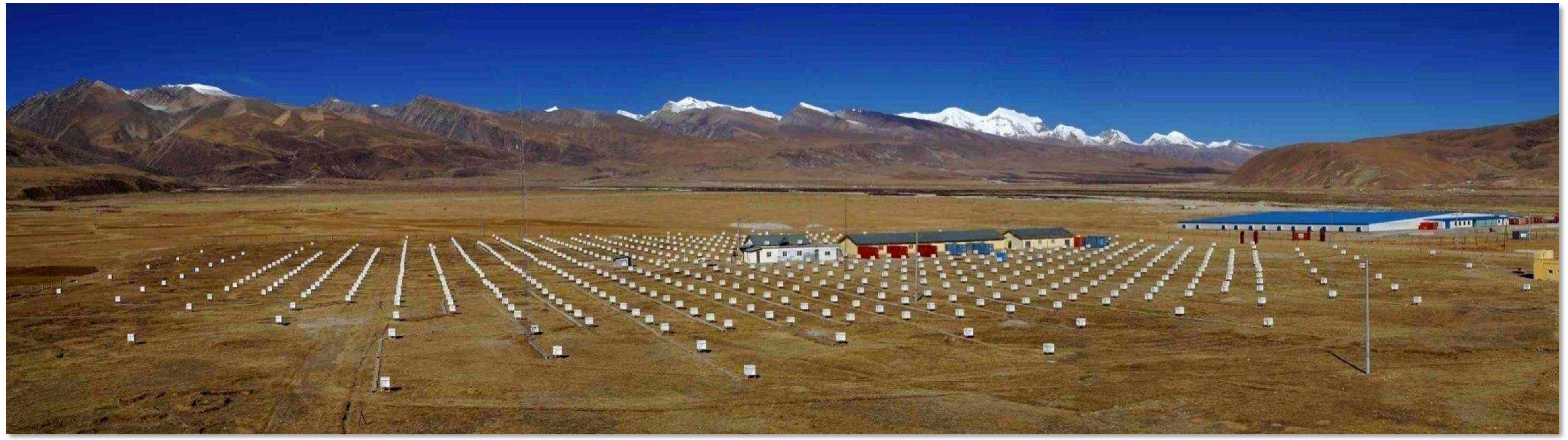
Telescope Array Collaboration, Science 382, 903 (2023)



- **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]

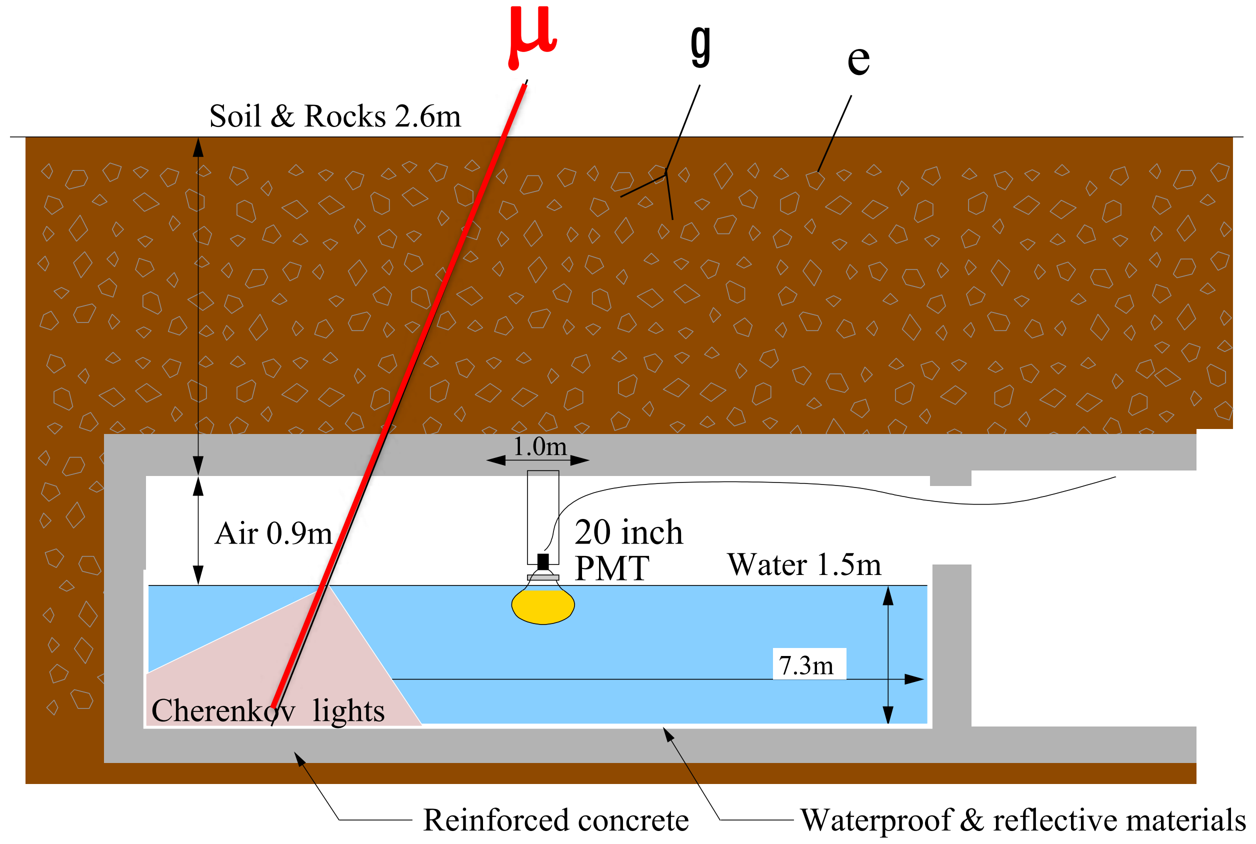
Tibet ASγ experiment (0.0657 km²)

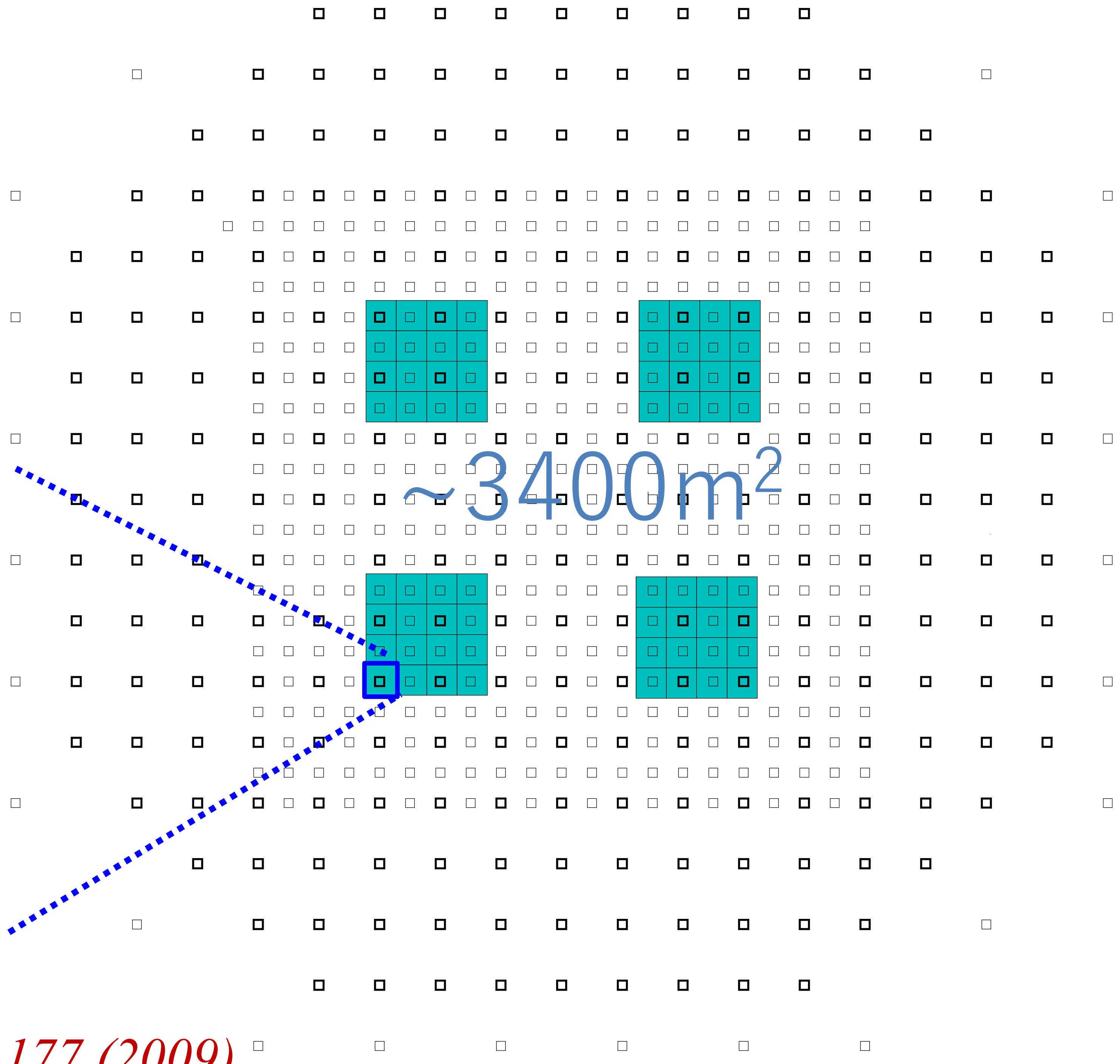
Highlight talk at ICRC 2023, M. Takita



65,700 m²

- ✓ 2.4m underground (~515g/cm² ~9X_0)
- ✓ 4 pools, 16 units / pool
- ✓ 7.35m × 7.35m × 1.5m deep (water)
- ✓ 20" Φ PMT (HAMAMATSU R3600)
- ✓ Concrete pools + white Tyvek sheets



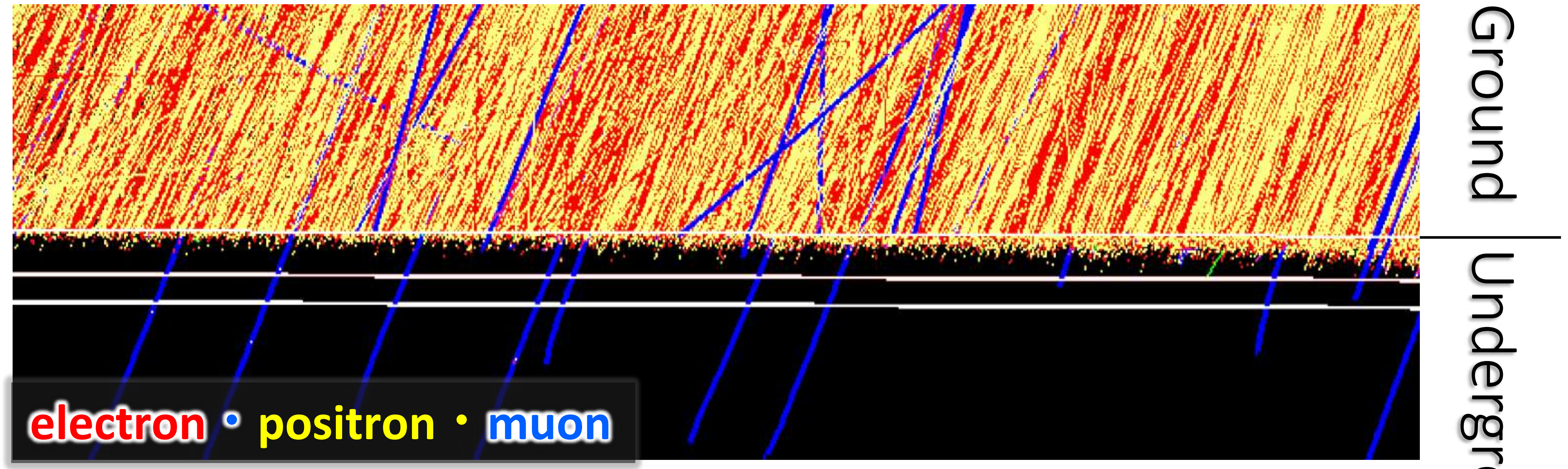


Basic idea: T. K. Sako+, Astropart. Phys. 32, 177 (2009)

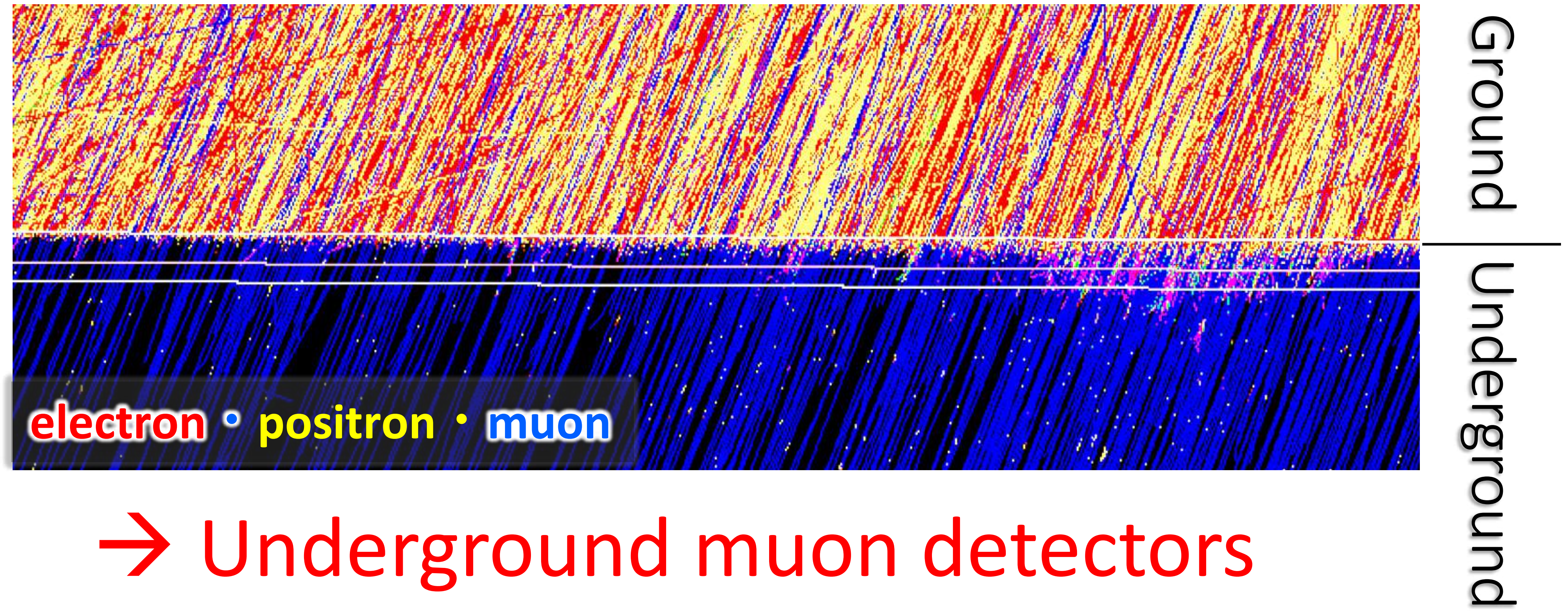
γ-ray → poor muons

Muons can penetrate underground

0.2PeV γ-ray



0.2PeV Cosmic ray (Noise)

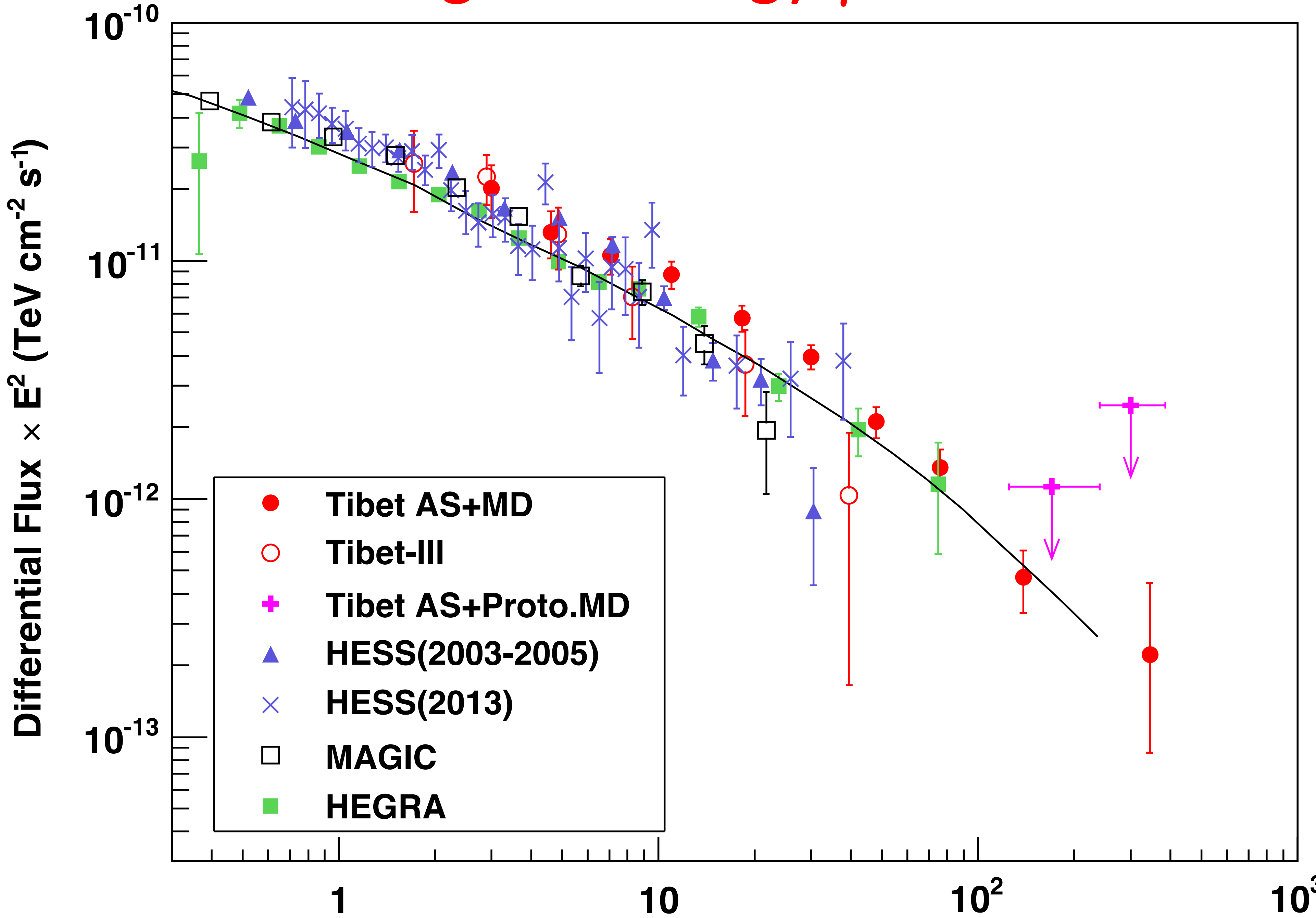


→ Underground muon detectors

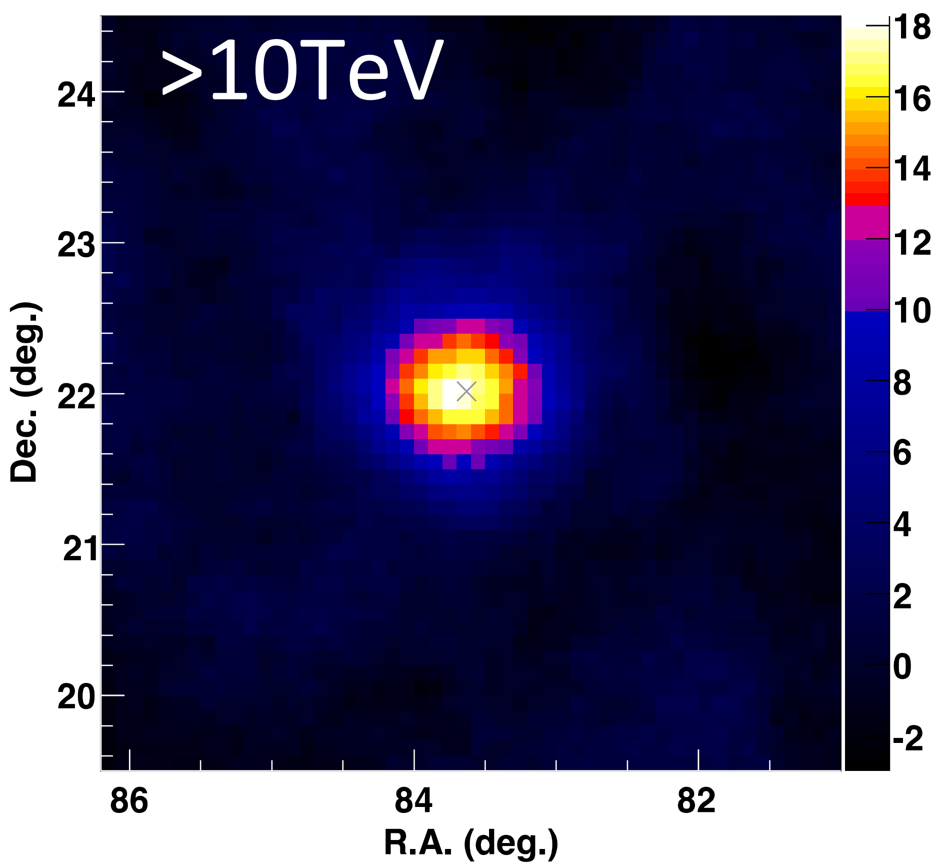
Results from Tibet ASγ experiment

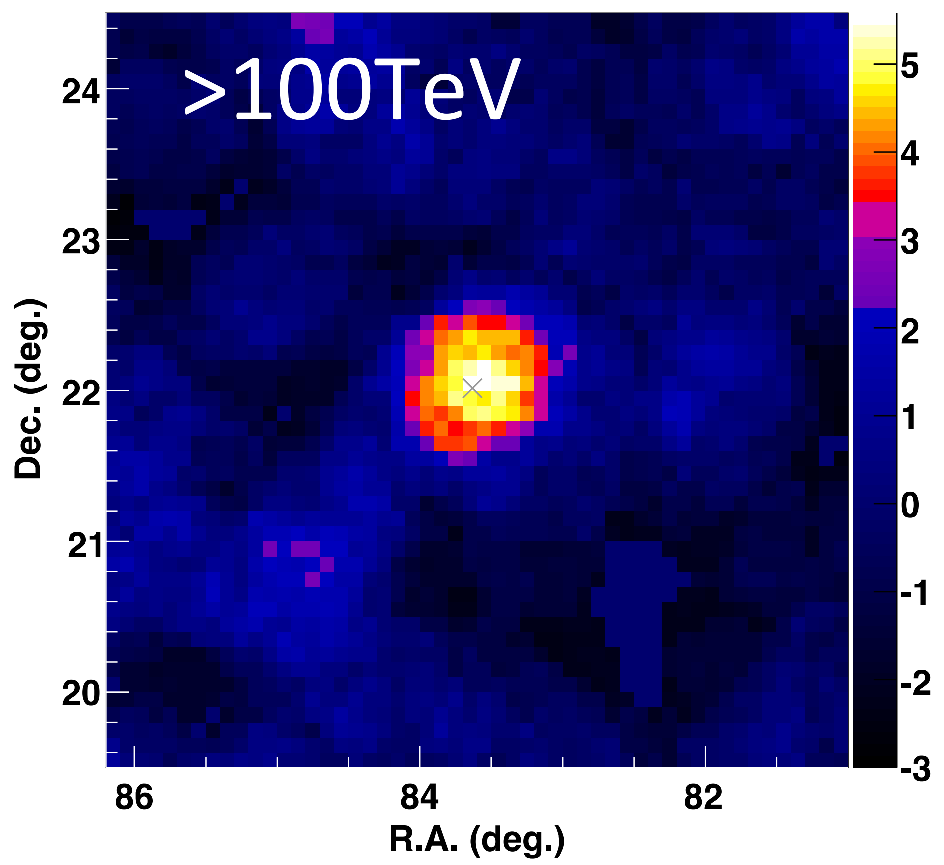
Crab

The highest energy γ ~450 TeV



Amenomori et al., PRL (2019)



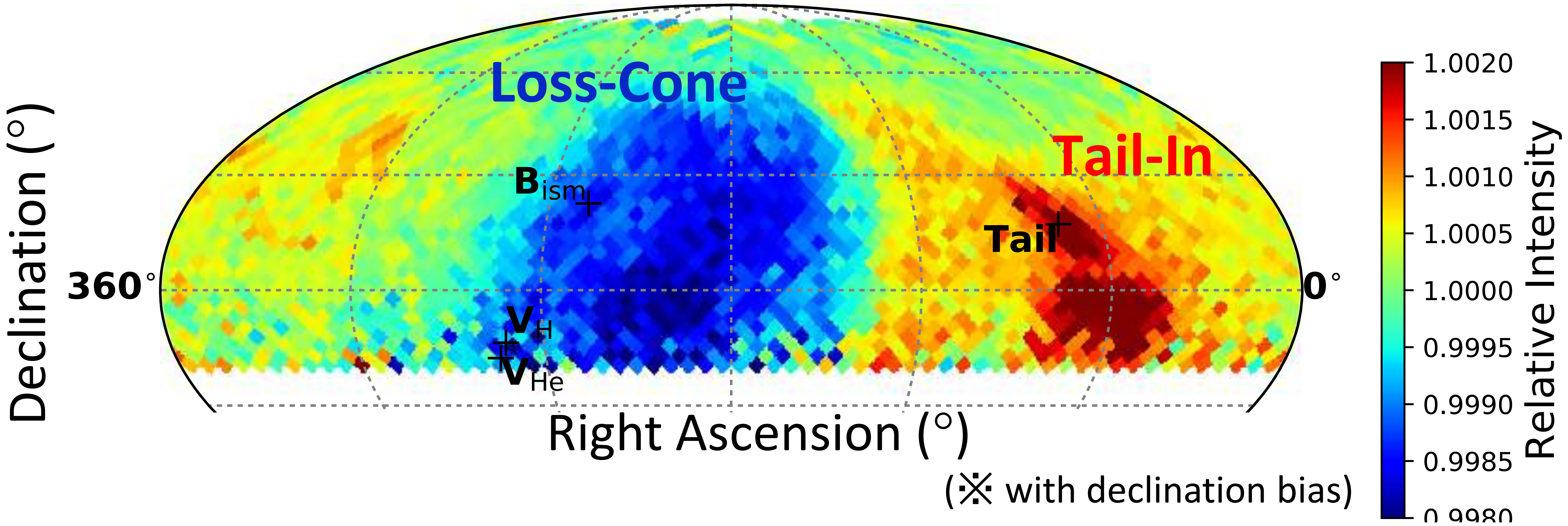


Highlight talk at ICRC 2023, M. Takita

Anisotropy at TeV energies

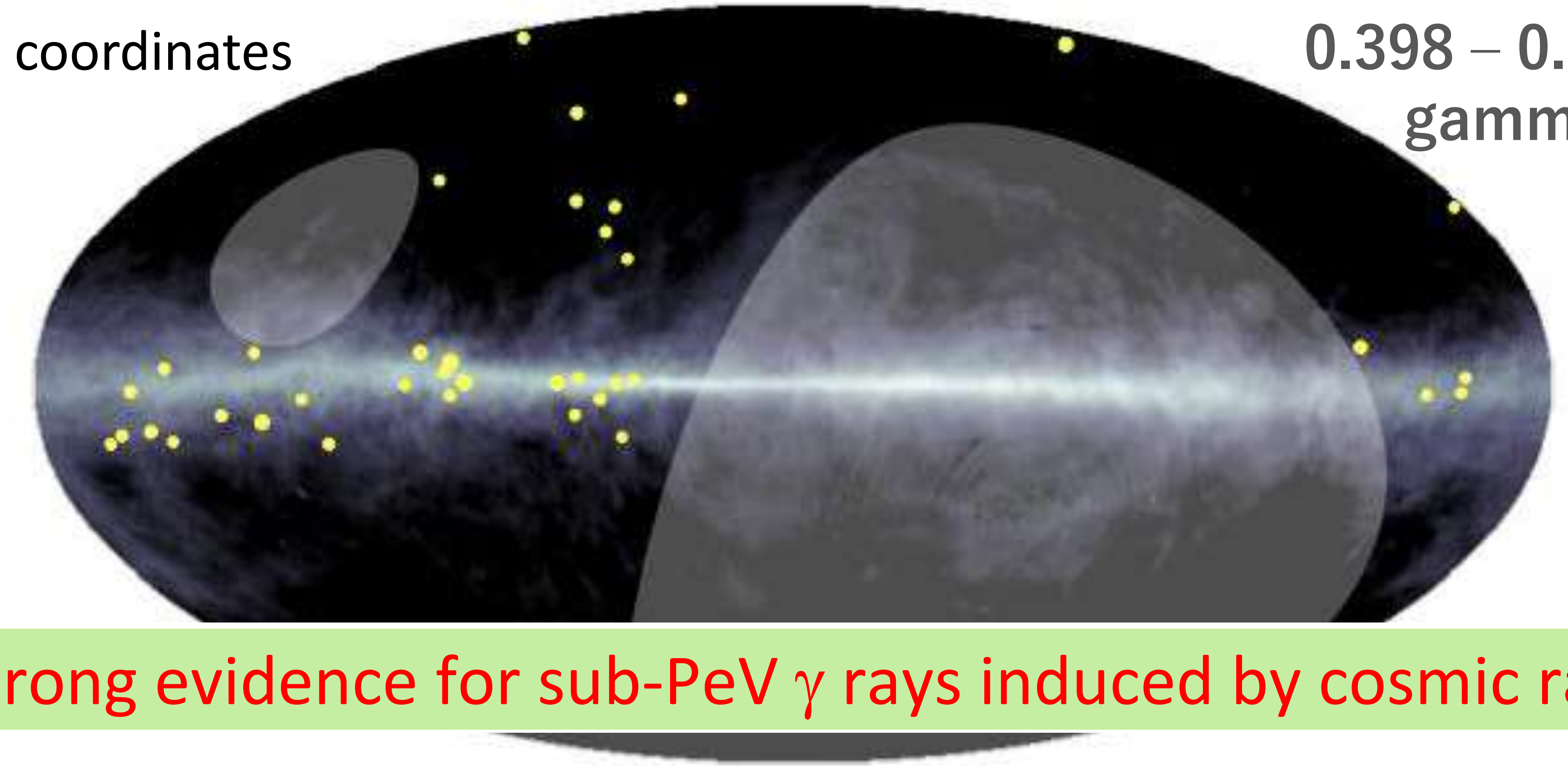
From SH7-04 Talk by Takashi K. Sako

Tibet III, Nov 1999 - May 2010



Galactic coordinates

0.398 – 0.957 PeV gamma rays

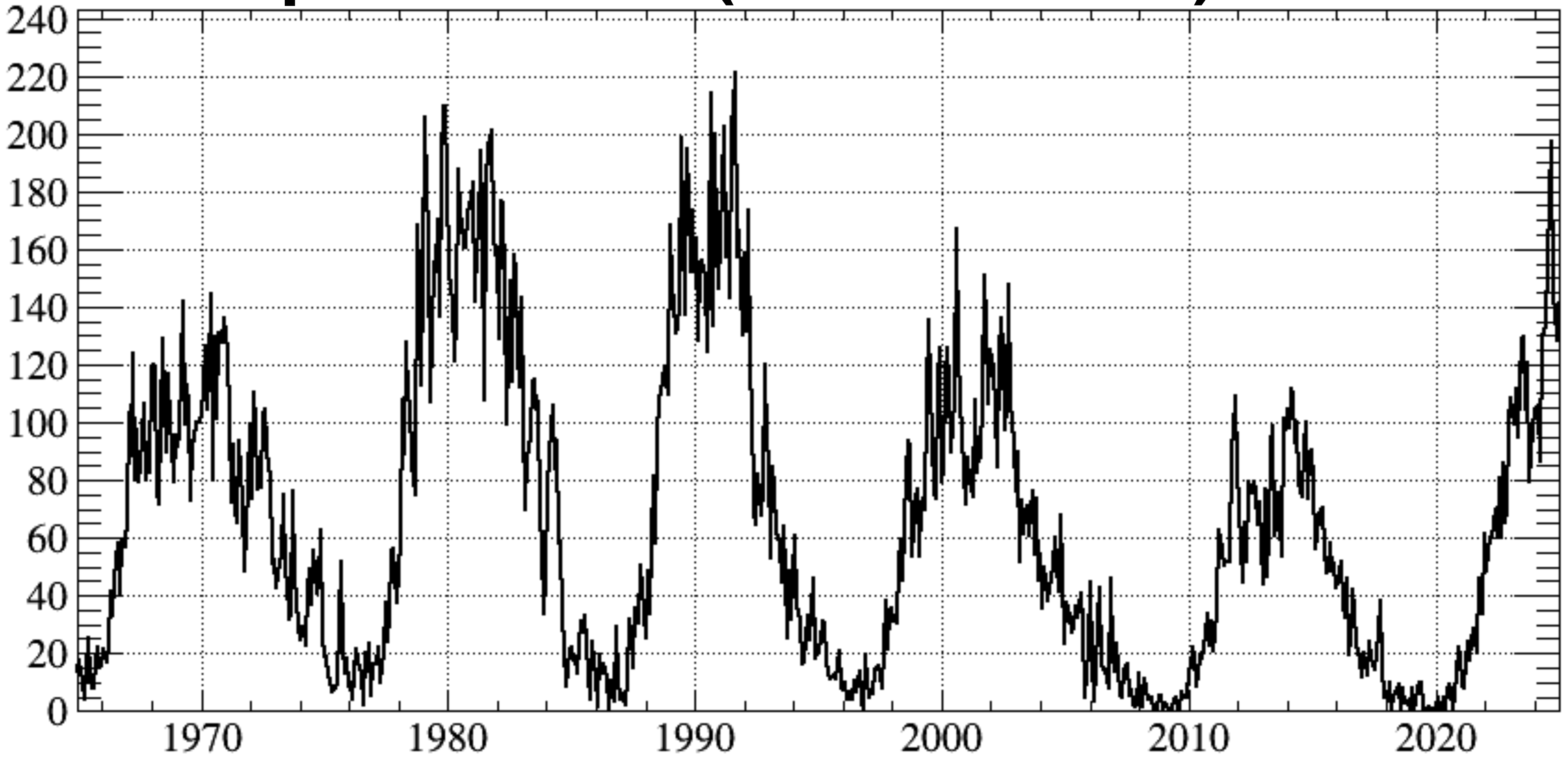


Strong evidence for sub-PeV γ rays induced by cosmic rays

Amenomori+., PRL 126, 141101,(2021)

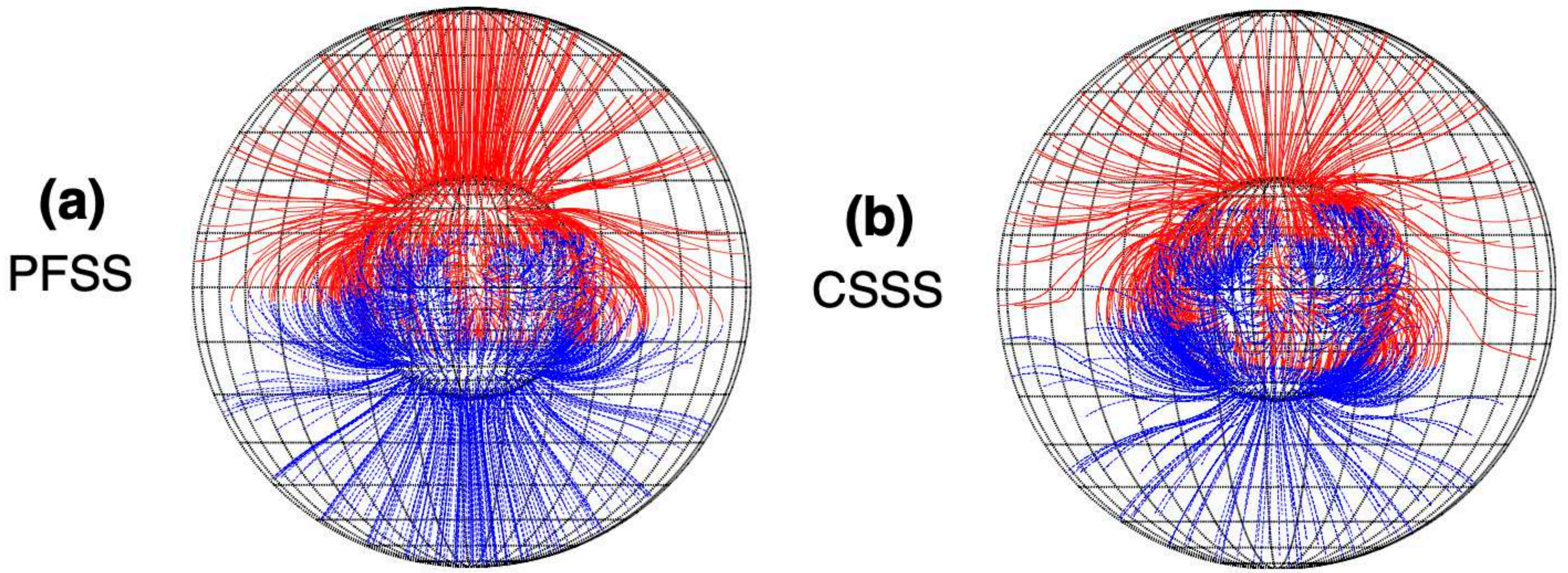
Sun shadow to clarify its magnetic field

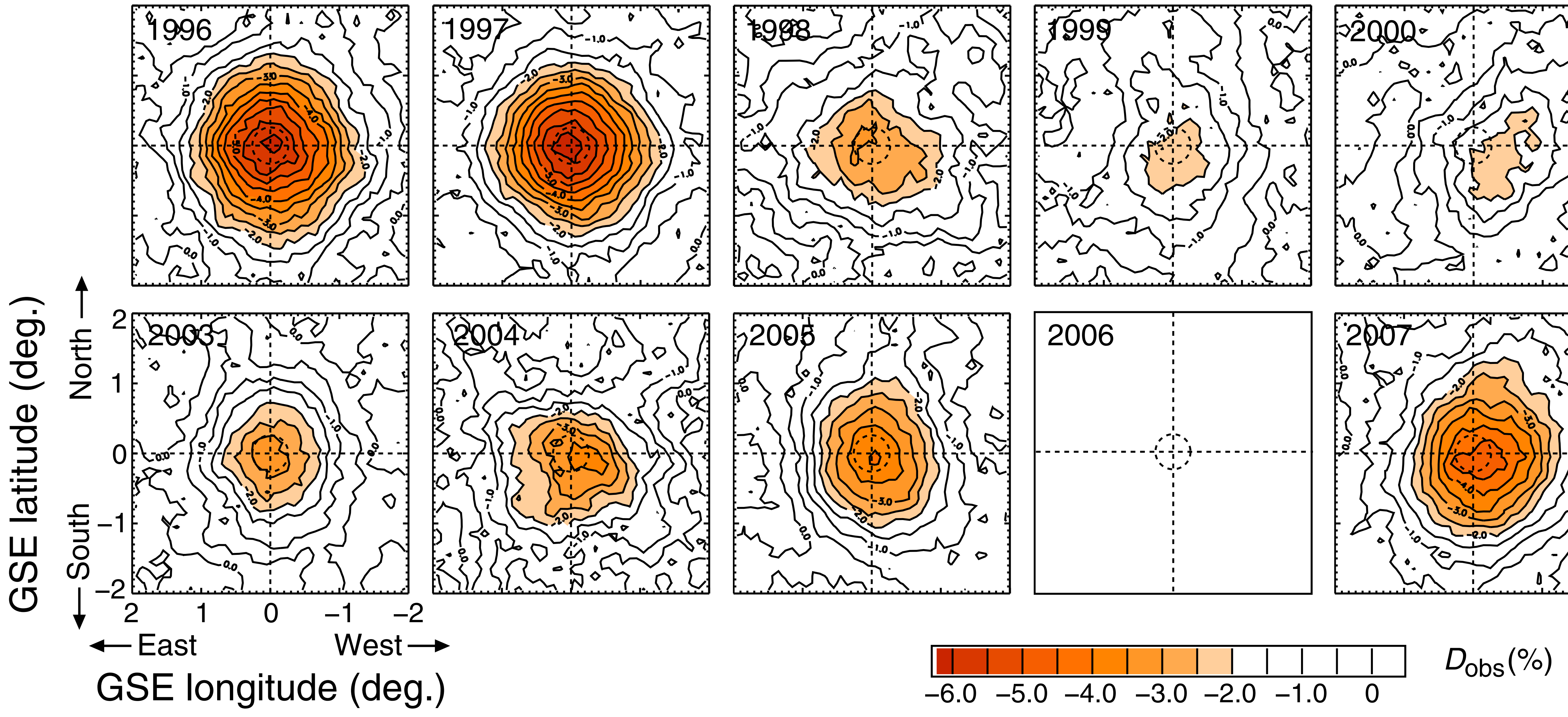
Sun spot number (NAOJ/Mitaka)

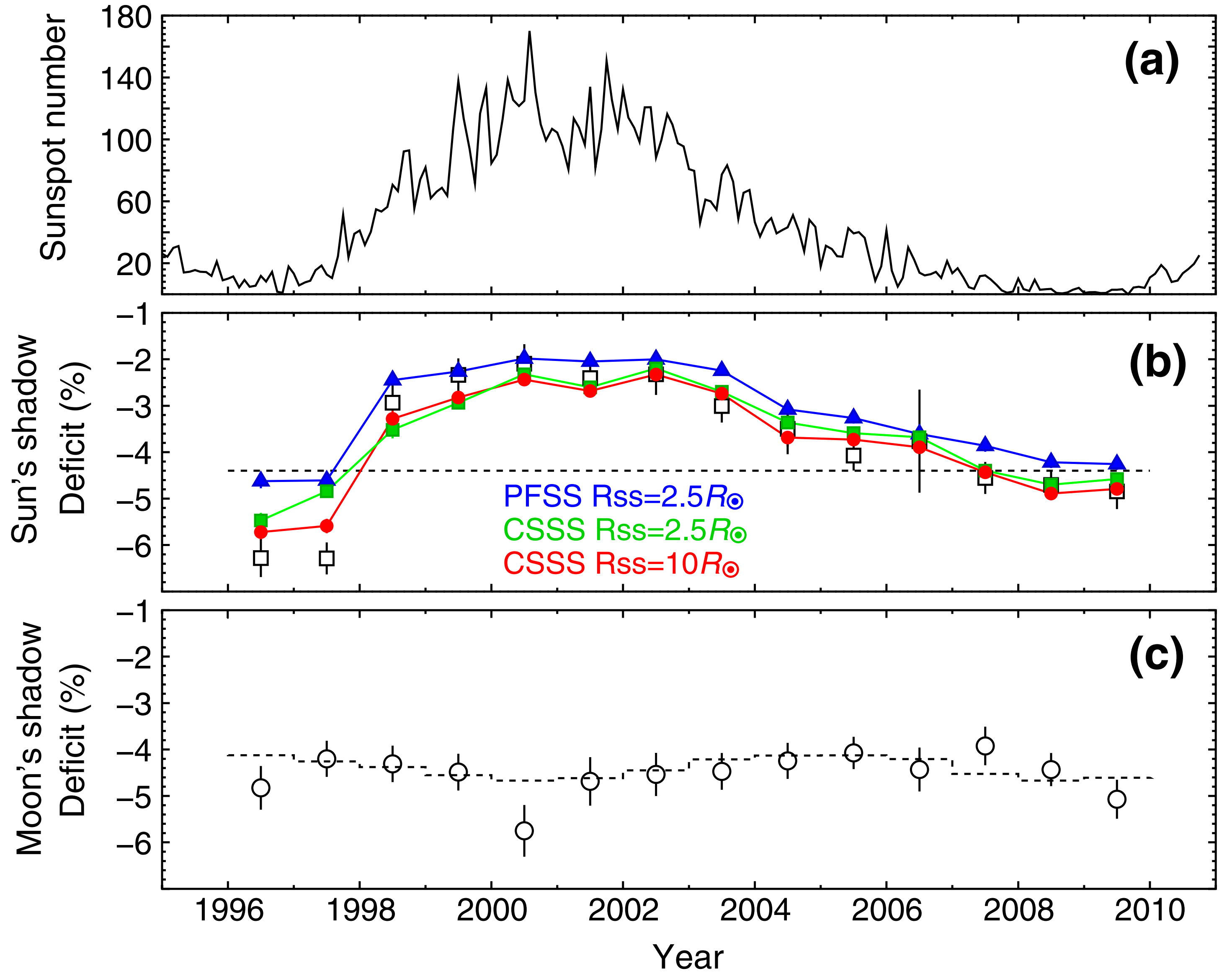


Tibet ASγ collaboration, PRL 111, 011101 (2013)

Magnetic field models



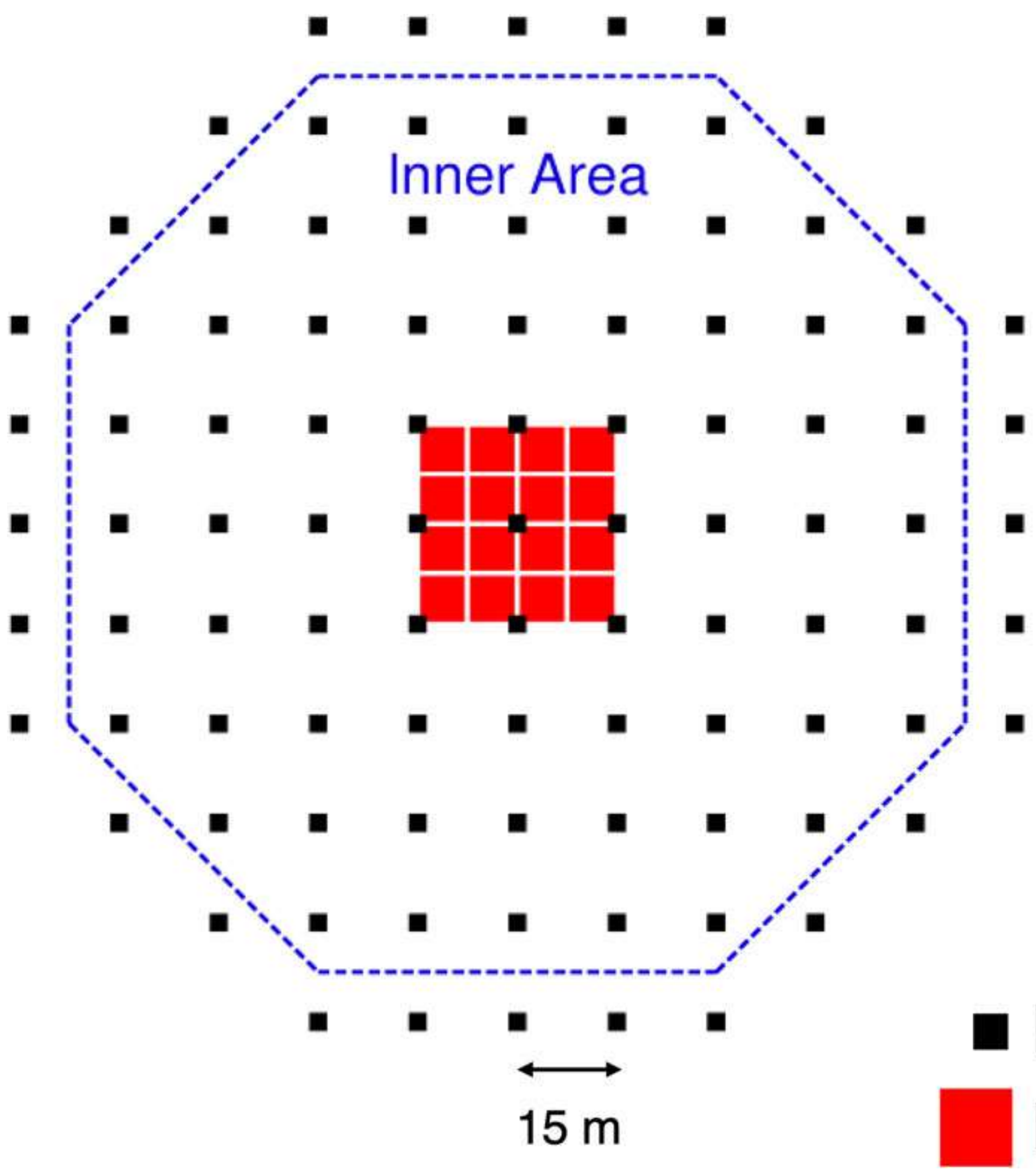




PeVatron search in southern hemisphere

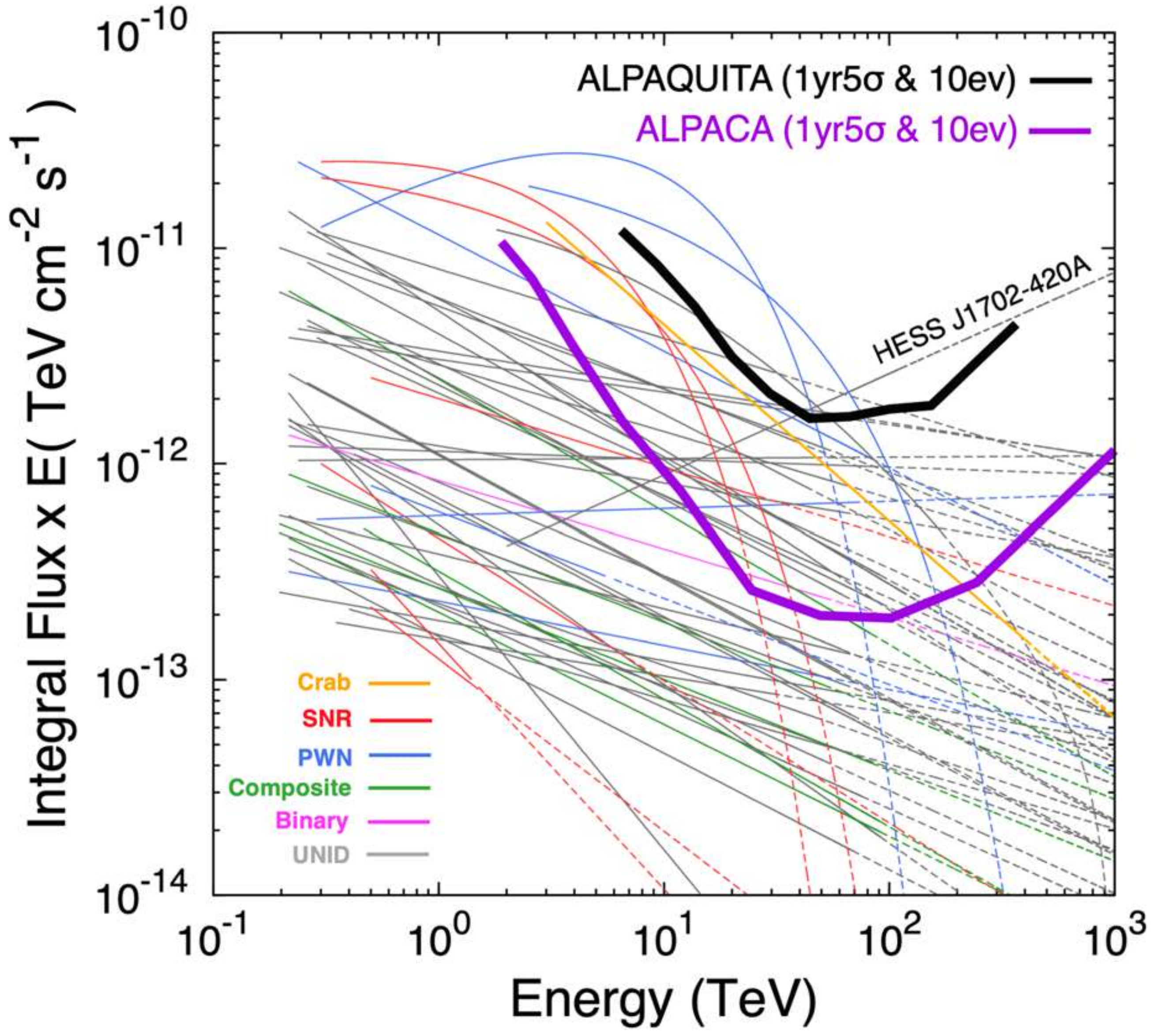
T. Sako, K. Kawata in ICRC 2025

ALPAQUITA



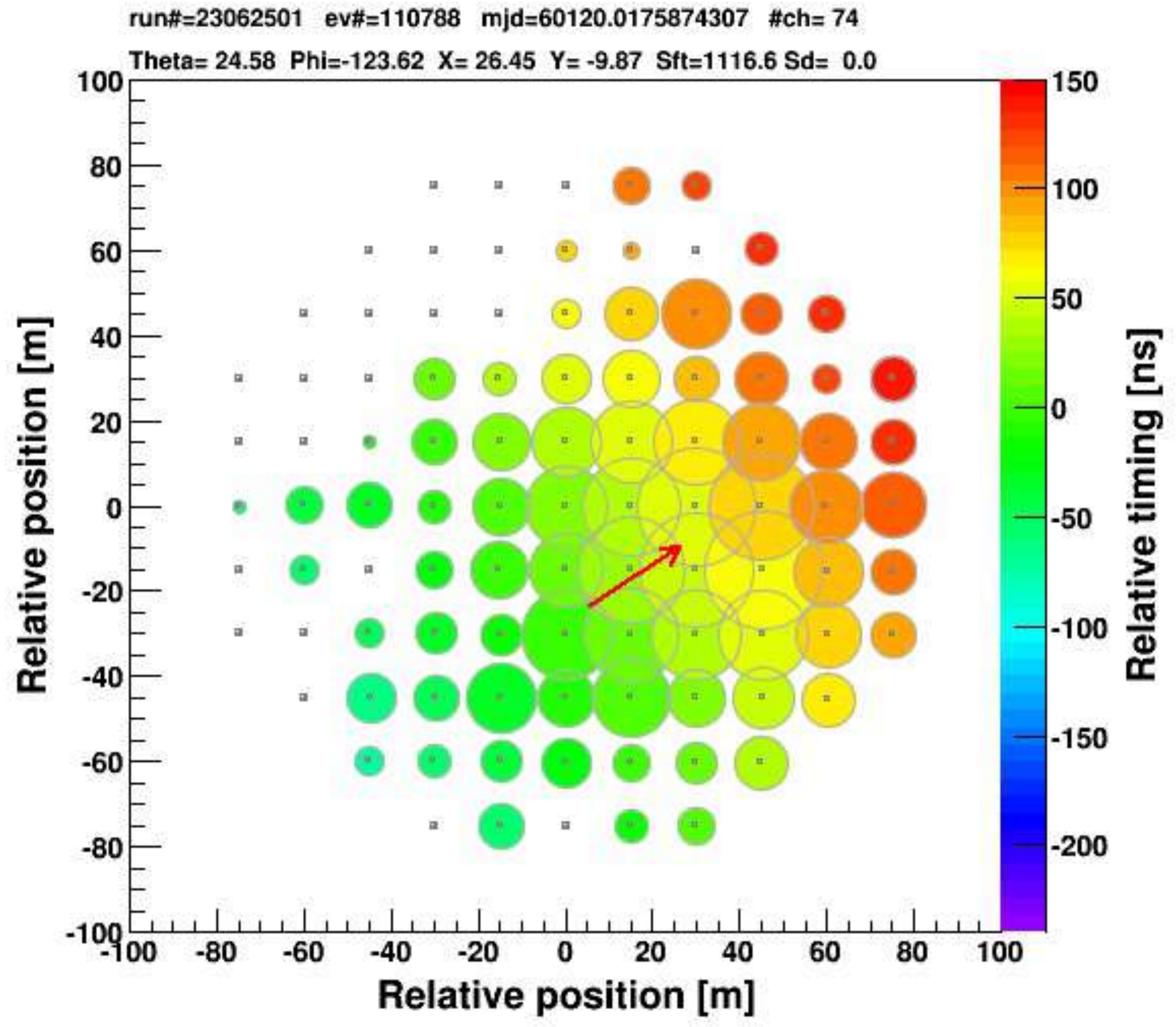
■ Plastic scintillators (1 m^2)

MD cells (56 m^2)



S. Kato et al., Experimental Astronomy 52, 85–107 (2021)

- Stable observation with ALPAQUITA (0.018 km^2)
  - 97 x 1 m^2 scintillators with 15 m spacing



Air Shower Trigger Condition：

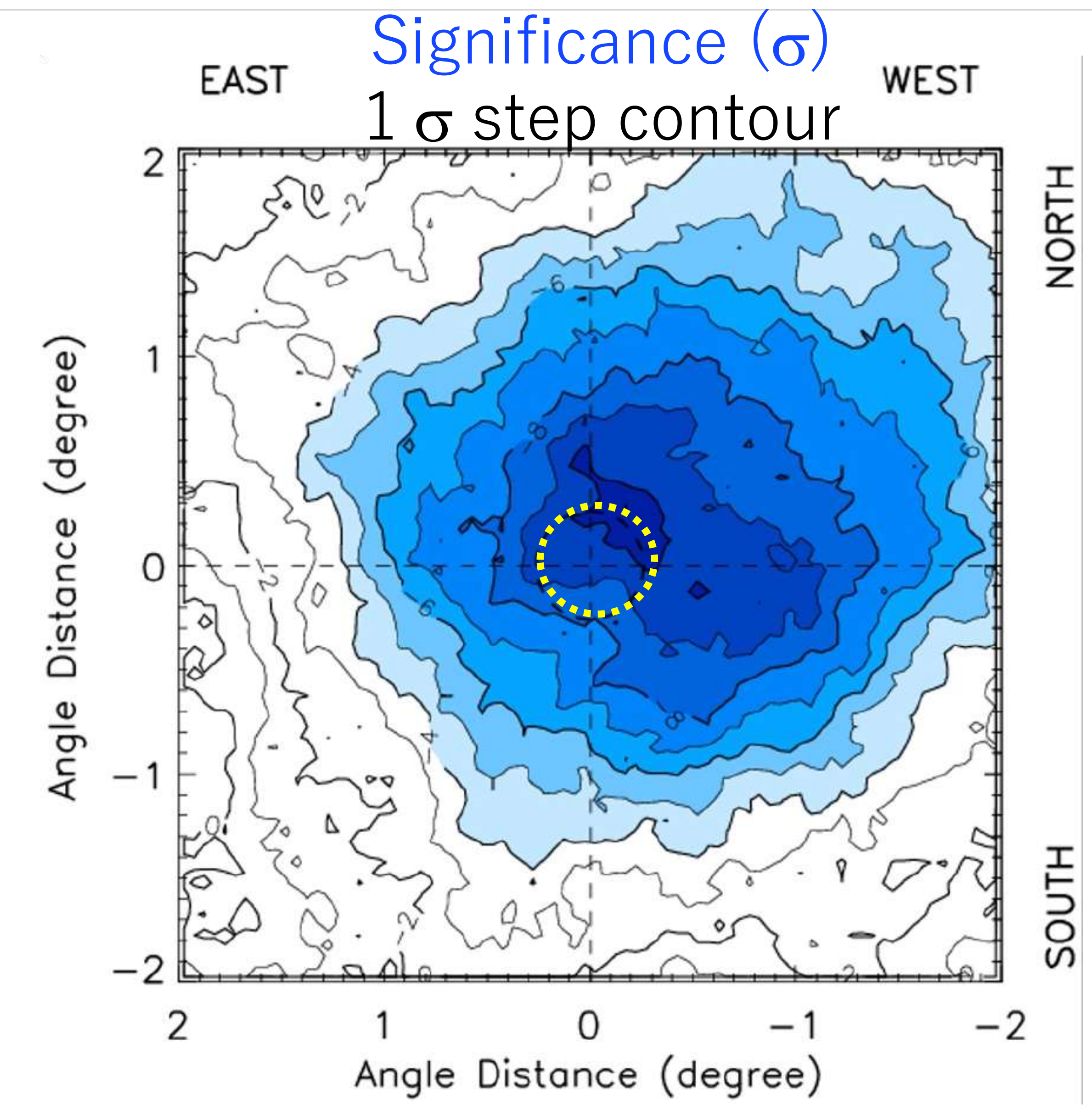
Any 4 detectors with >0.6 particles within 600ns

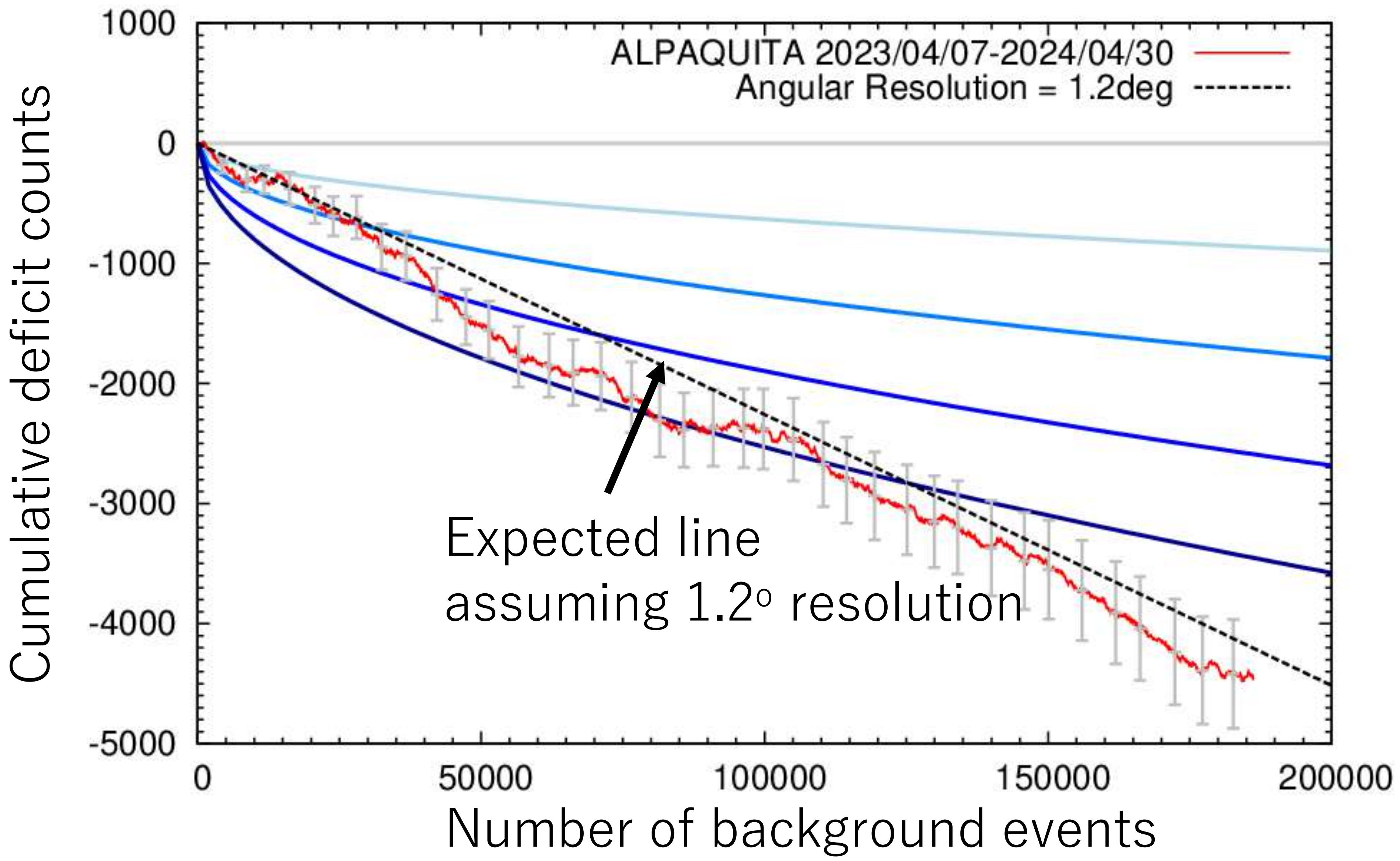
→ Air shower trigger rate ~280Hz

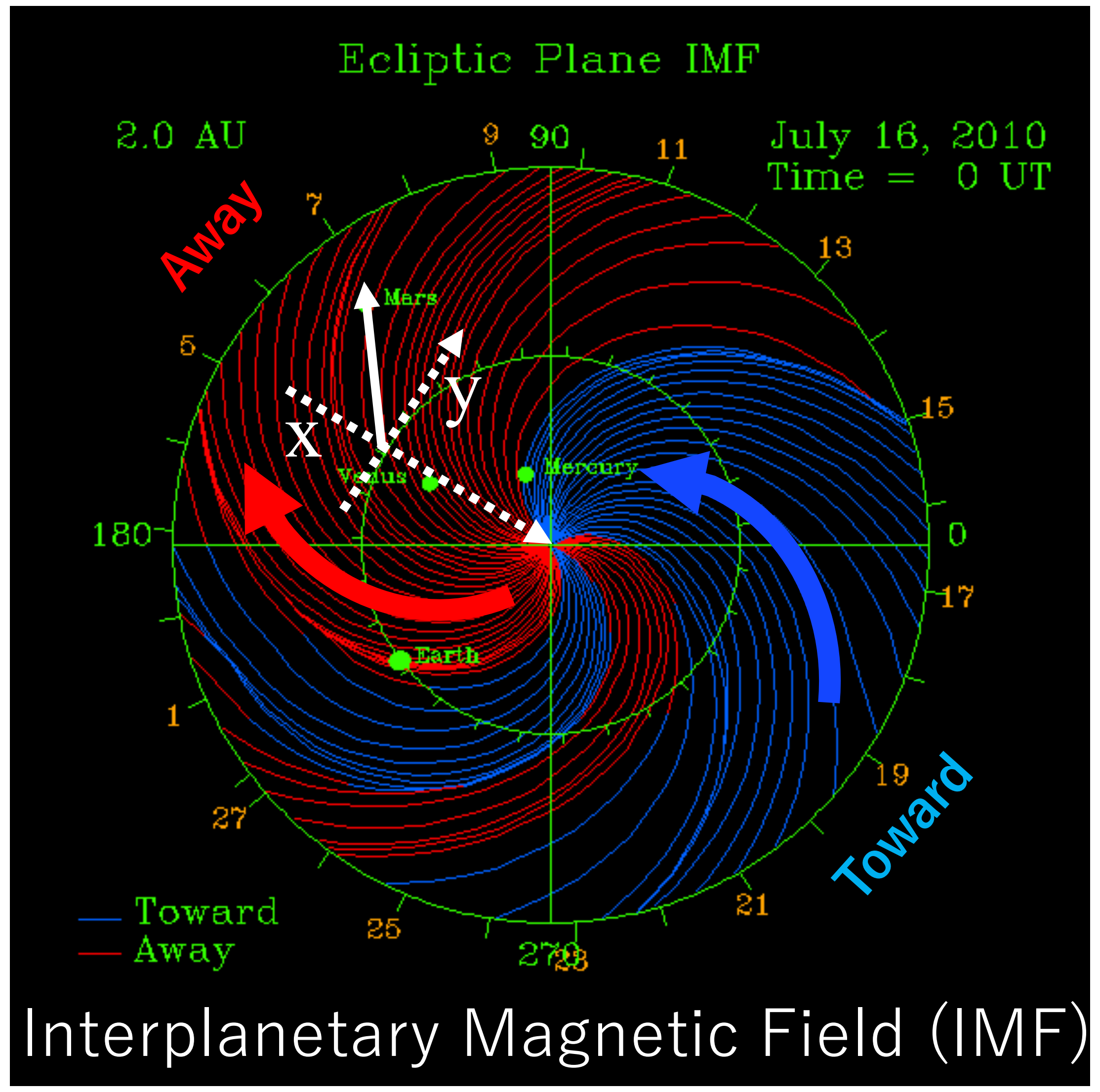
Cosmic-ray mode energy ~7 TeV

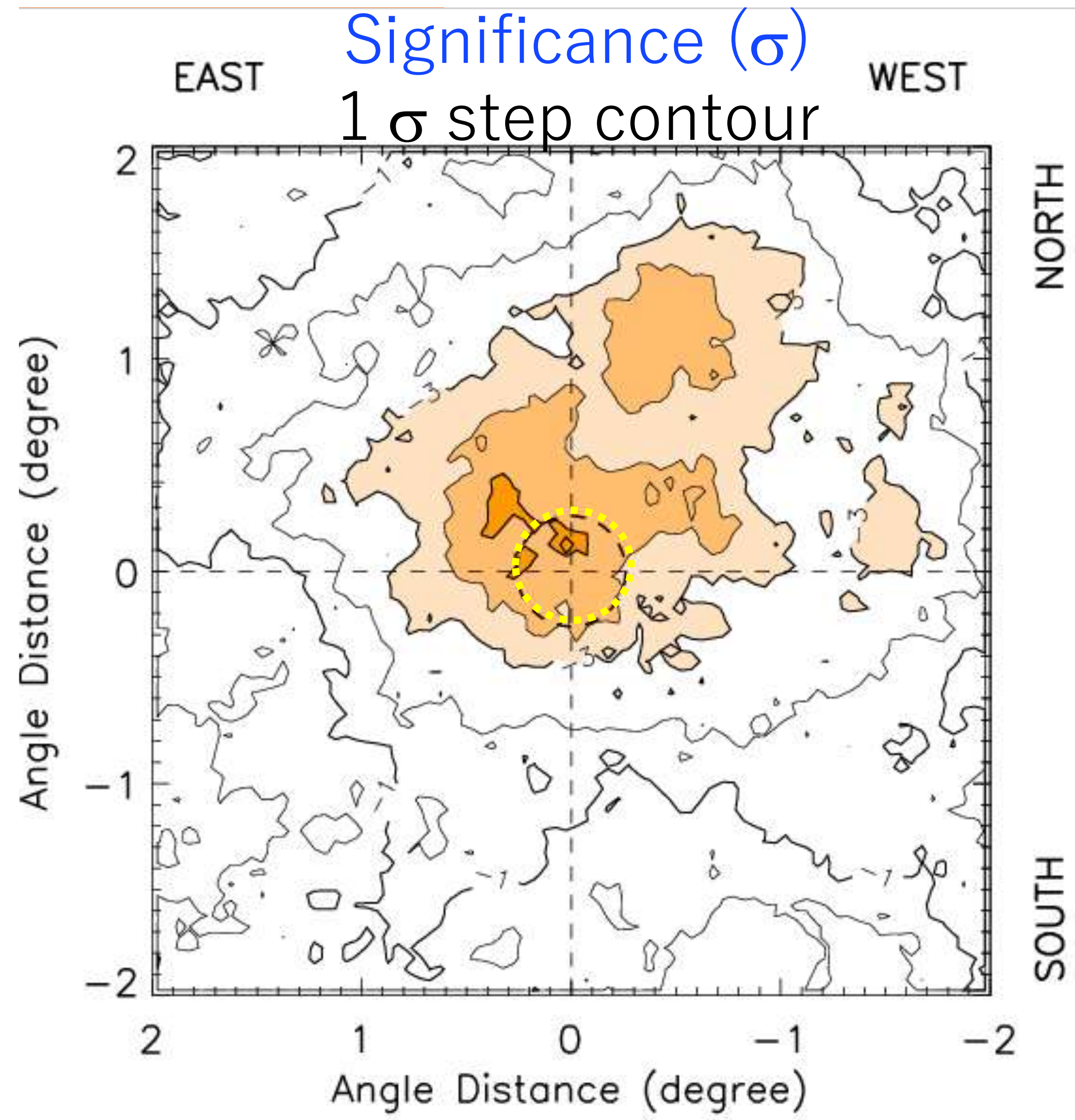
Sun and moon shadow results with ALPAQUITA

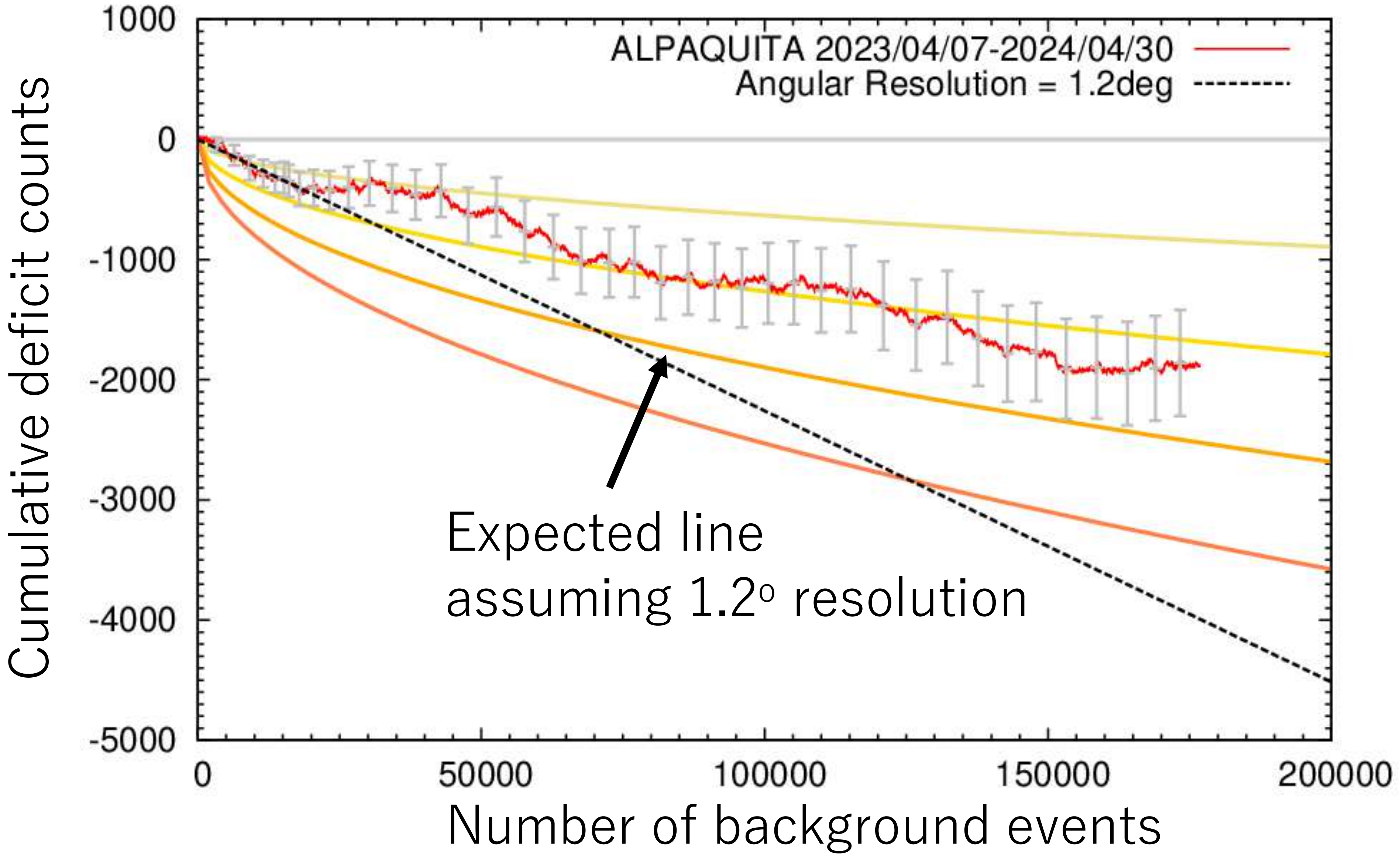
K. Kawata in ICRC 2025

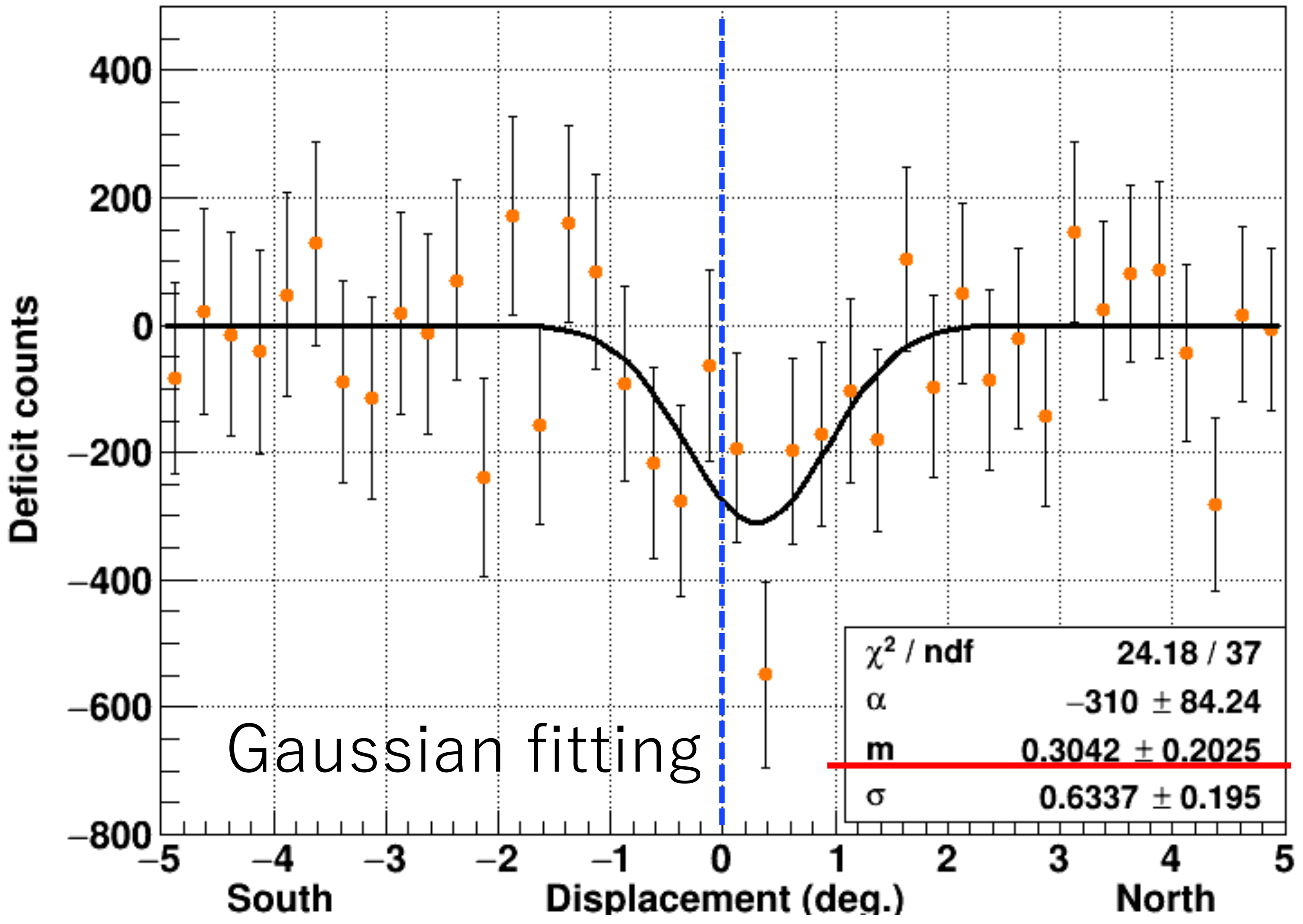












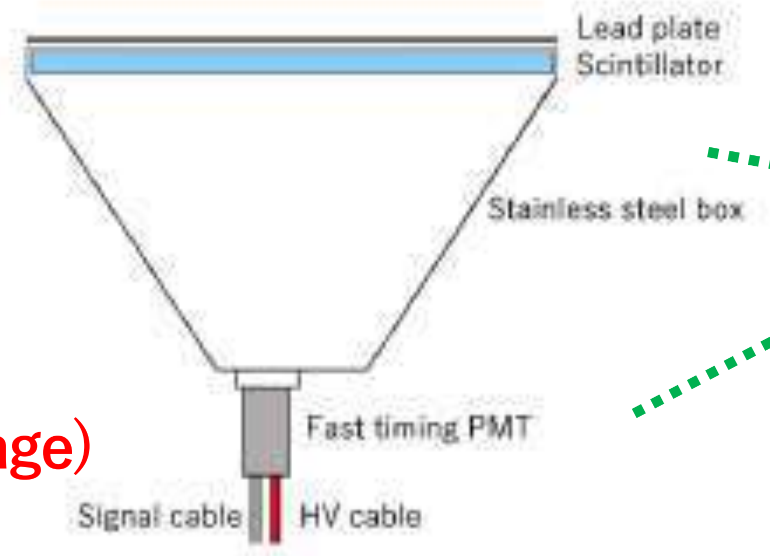
0.3° shift (1.5σ) expected from IMF

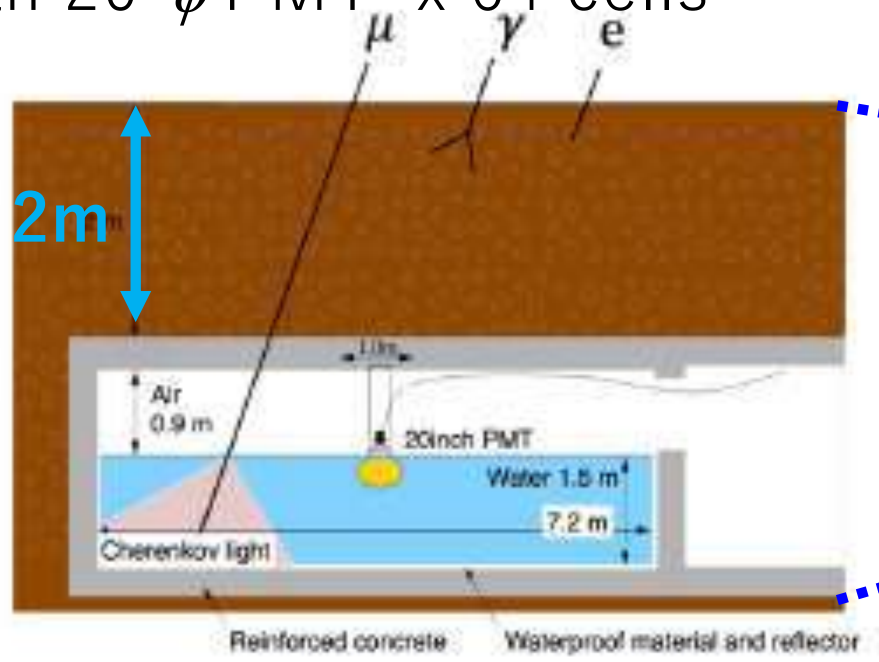
Future: ALPACA and Mega ALPACA

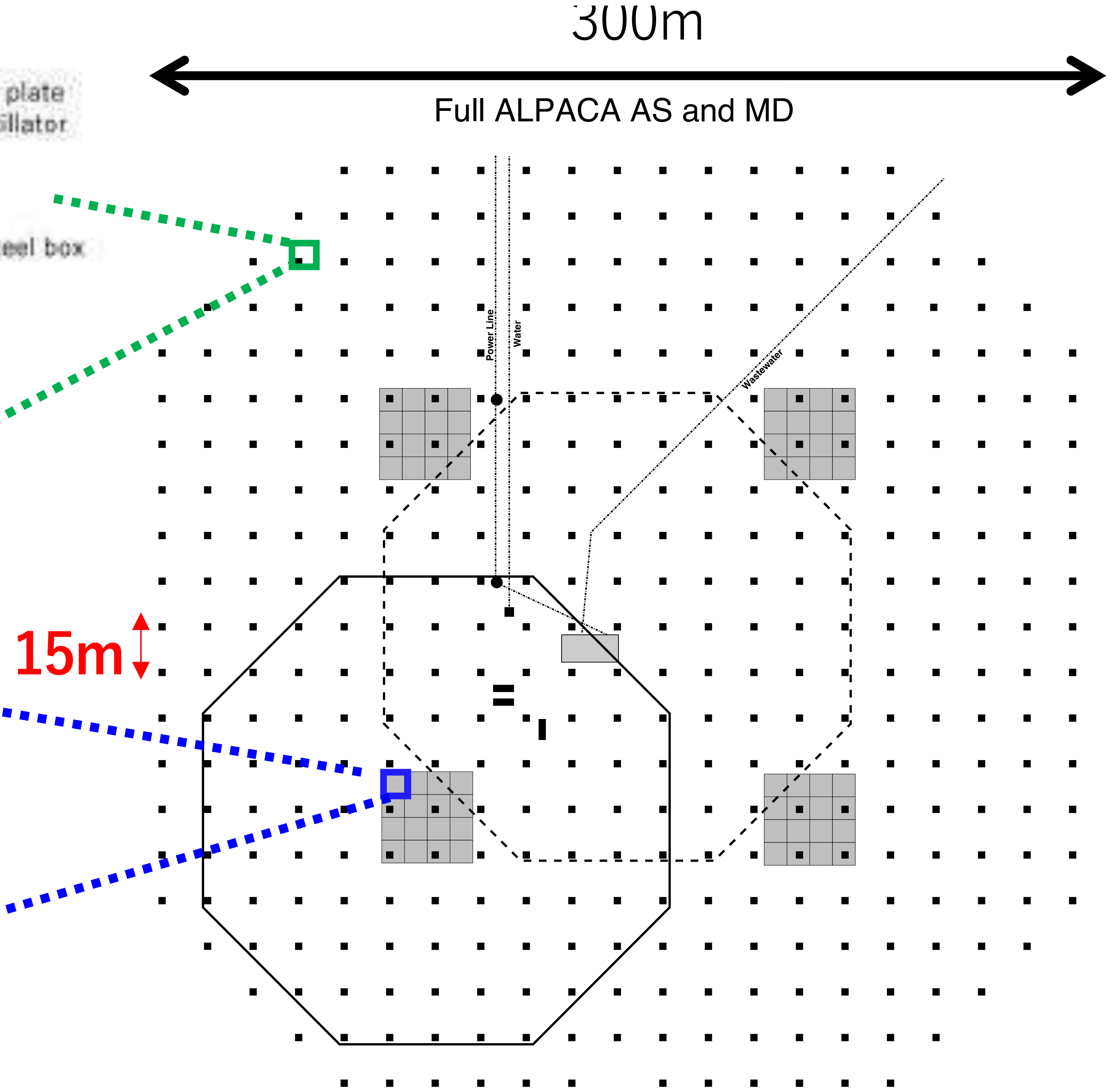
T. Sako in ICRC 2025

1. Array coverage 82,800m^2
   = 401 x 1m^2 plastic scintillators

2. Underground water Cherenkov muon detector (MD) 3600m^2
   Soil over 2m (~16X_0) **(4.3% coverage)**
   = 58m^2 with 20”ϕPMT x 64 cells

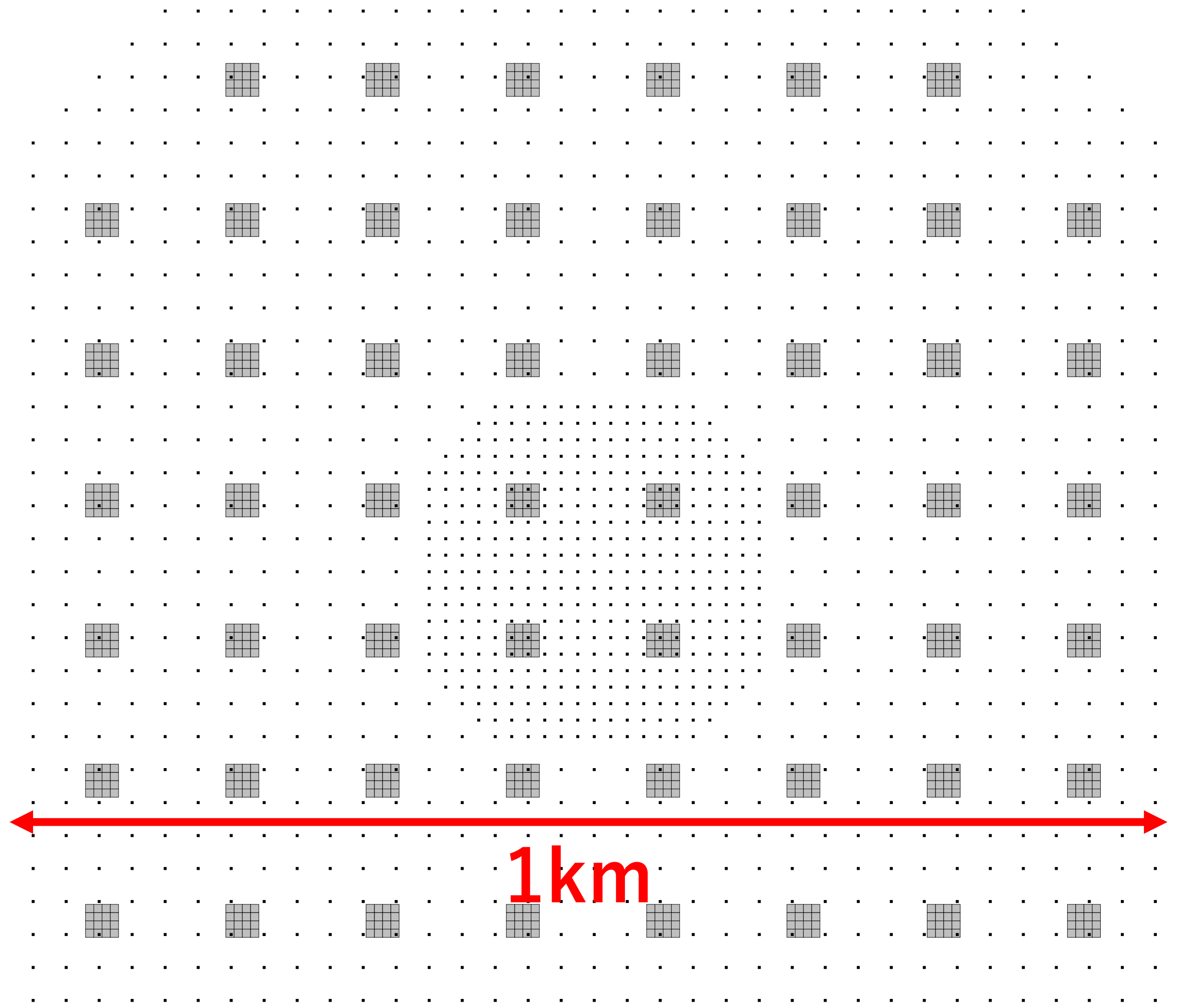




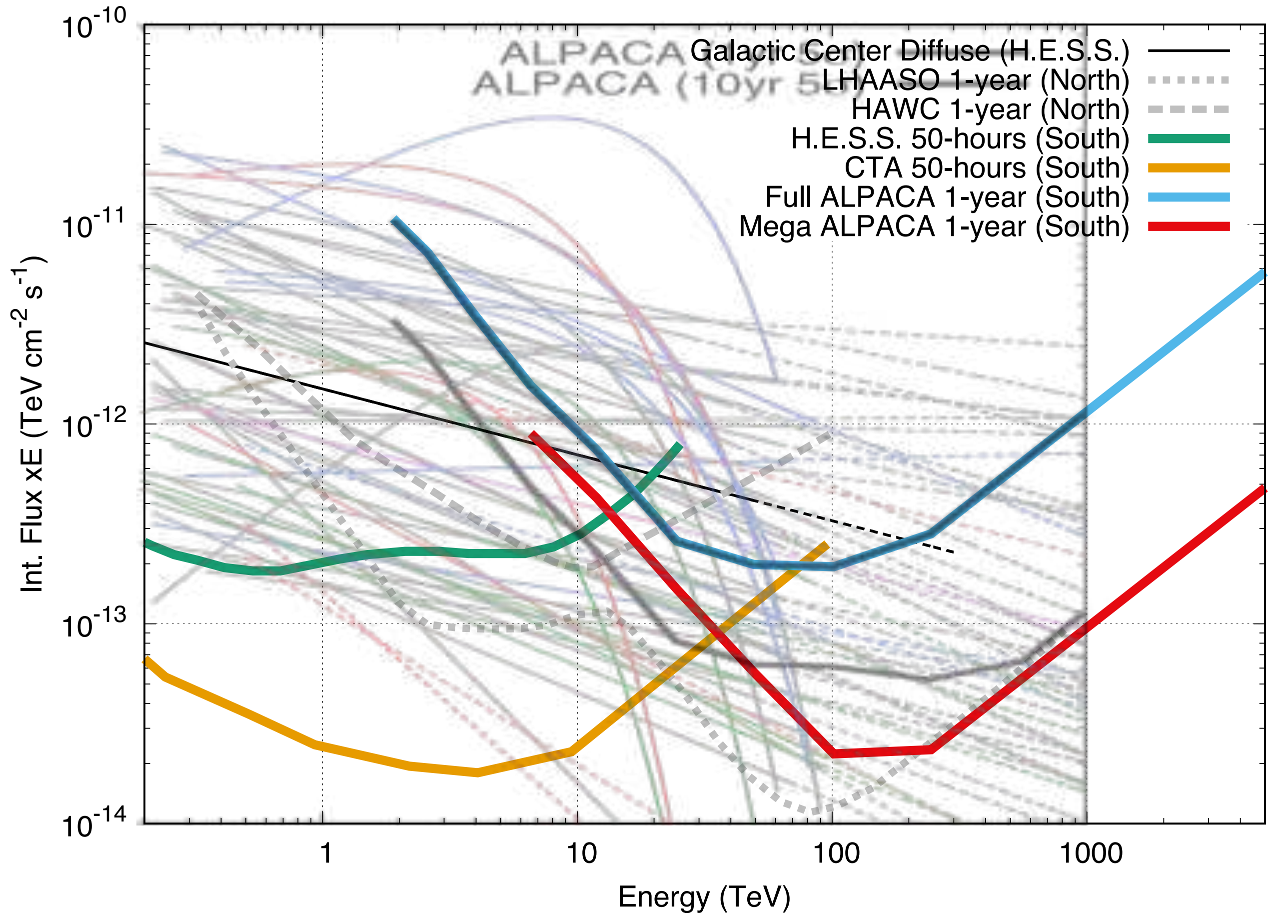


ALPAQUITA x 4 = ALPACA

ALPACA x 12 = Mega ALPACA



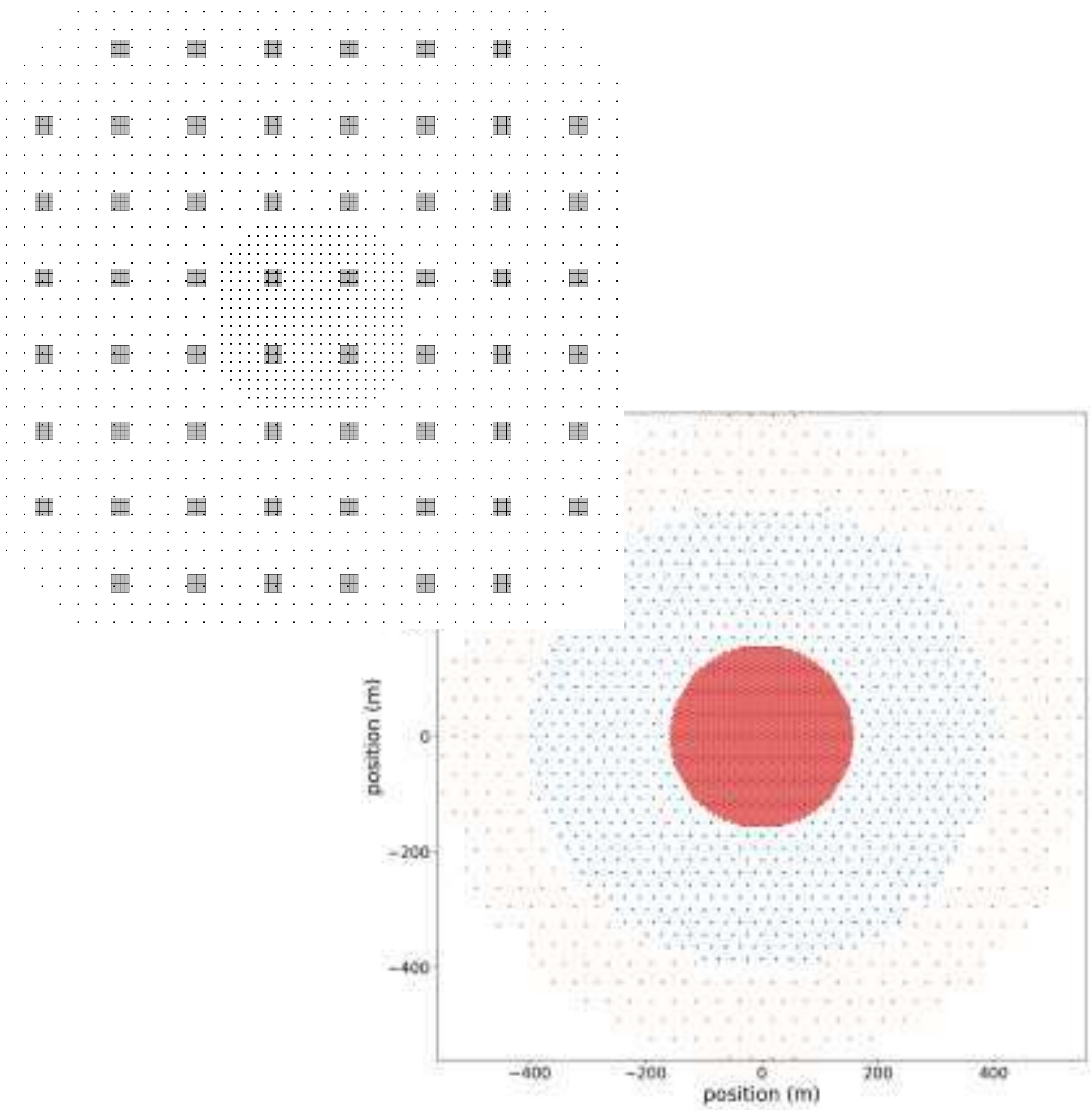
ALPACA Collaboration, PoS(ICRC2023)632



Where is the highest energy accelerator in our Galaxy?

Mega ALPACA and SWGO

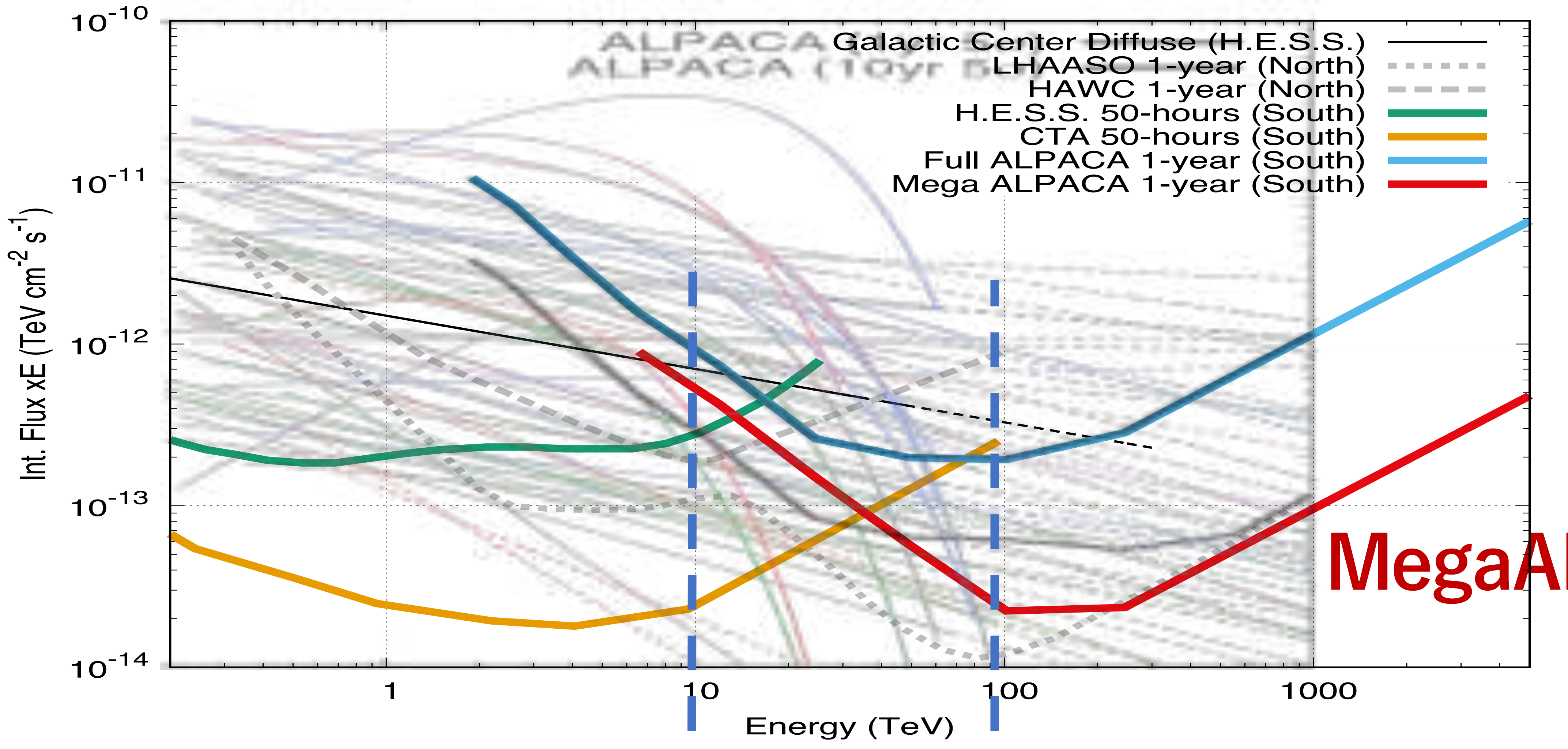
T. Sako in ICRC 2025



Lukas Nellen, UHECR2024

ALPACA Collaboration, PoS(ICRC2023)632

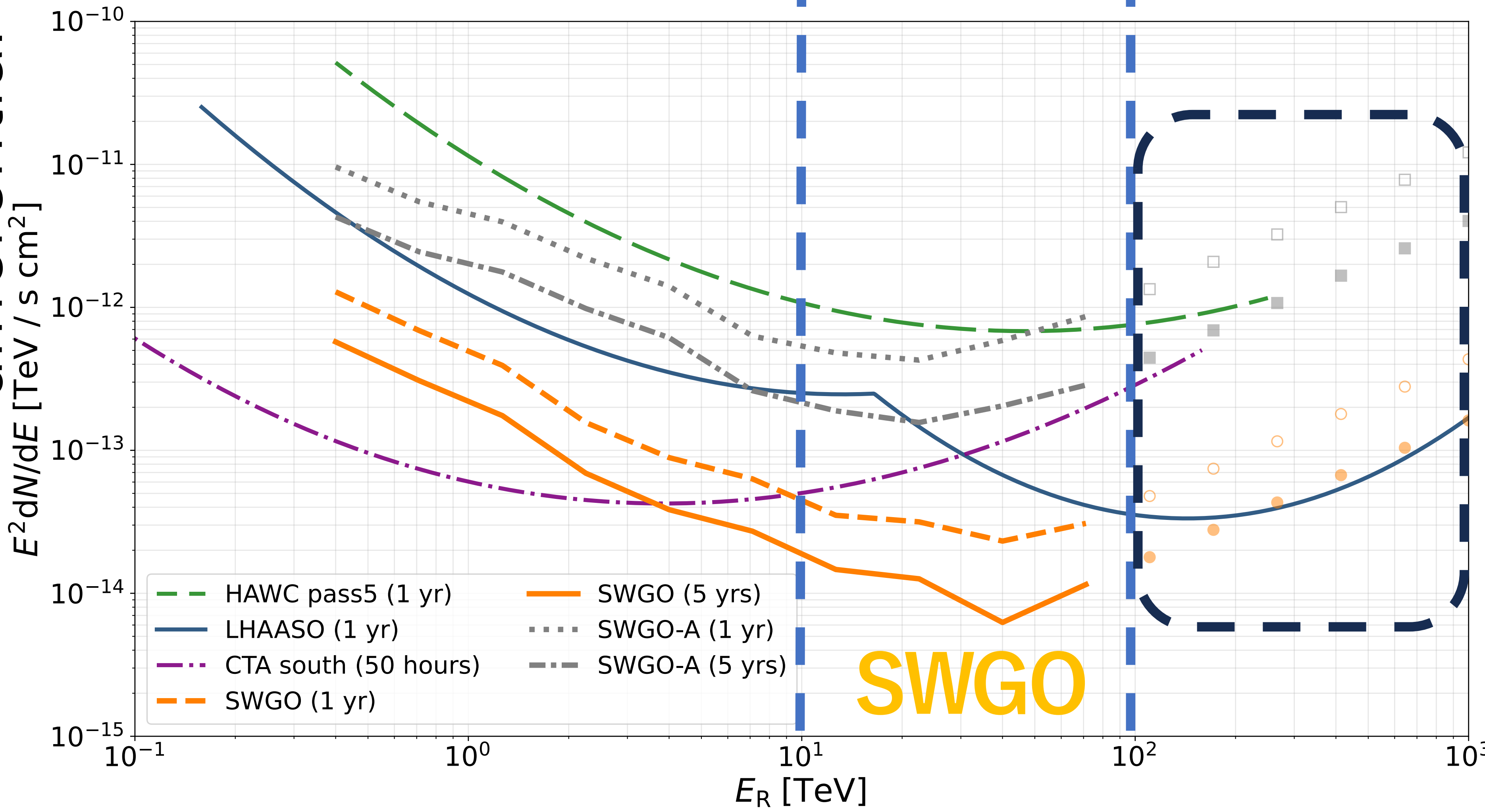
integral



10TeV

100TeV

differential

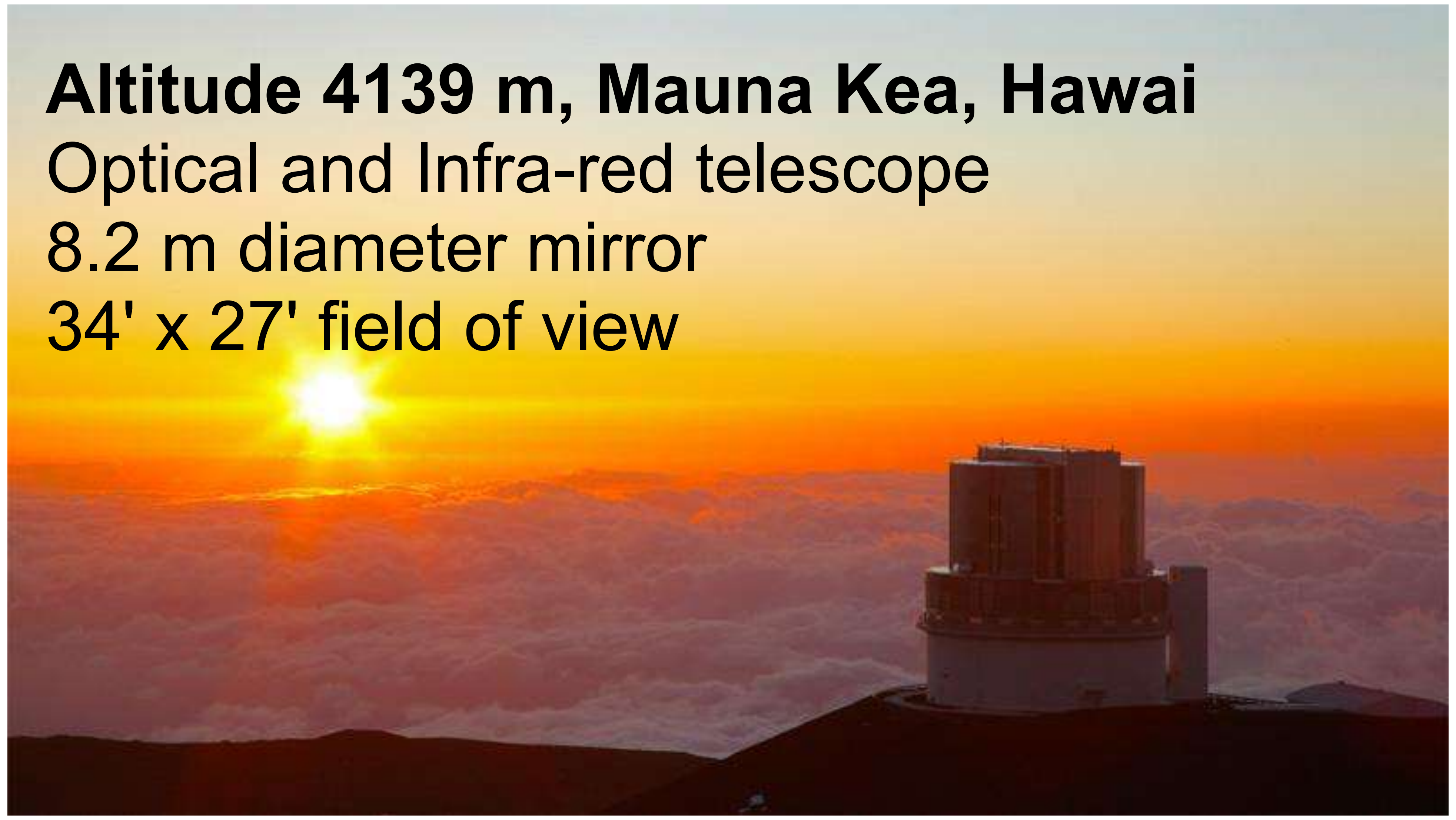


in optimization

SWGO Collaboration, arXiv:2506.01786

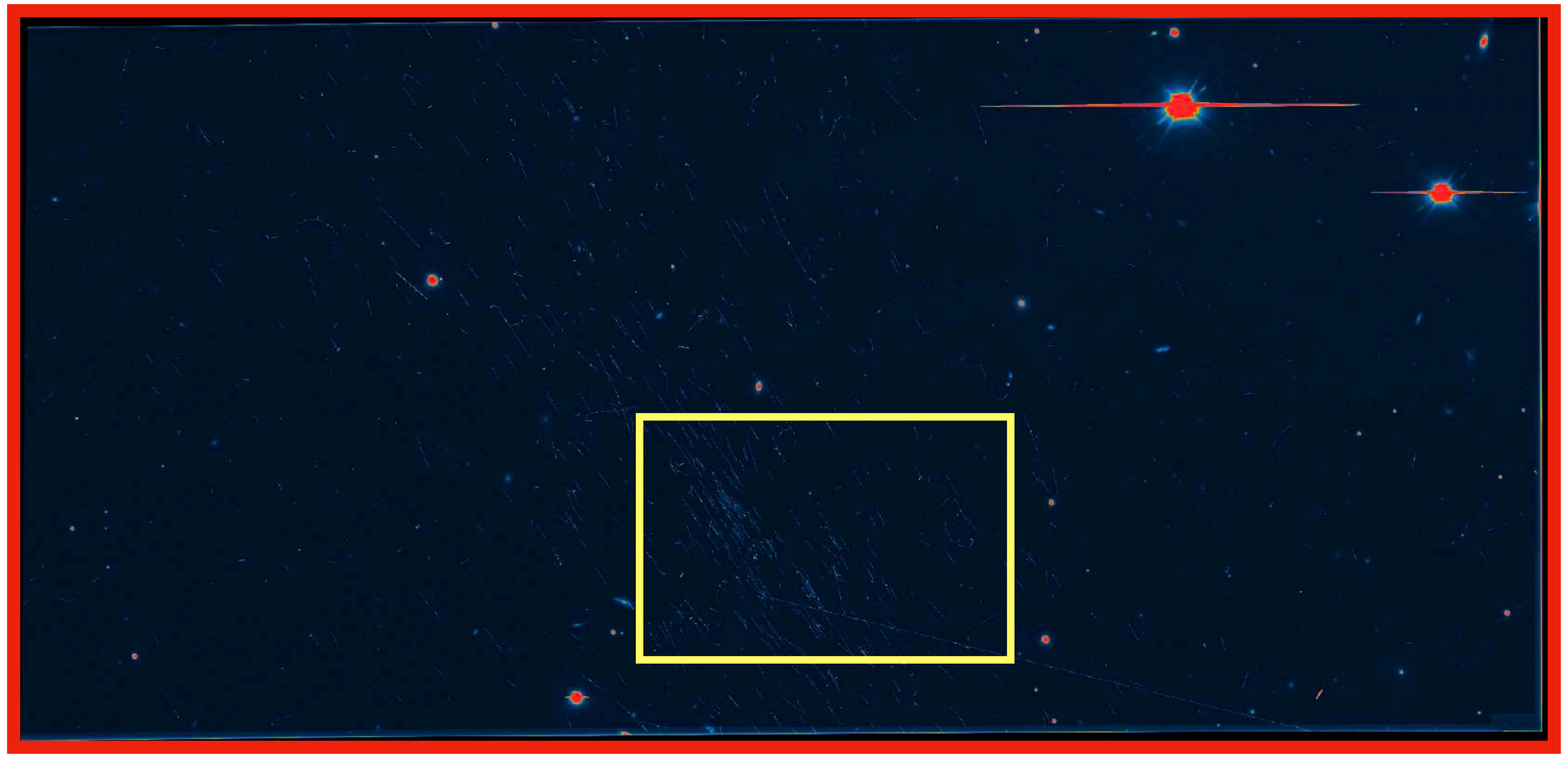
Subaru Hyper Supreme-Cam as "cosmic ray detector"

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



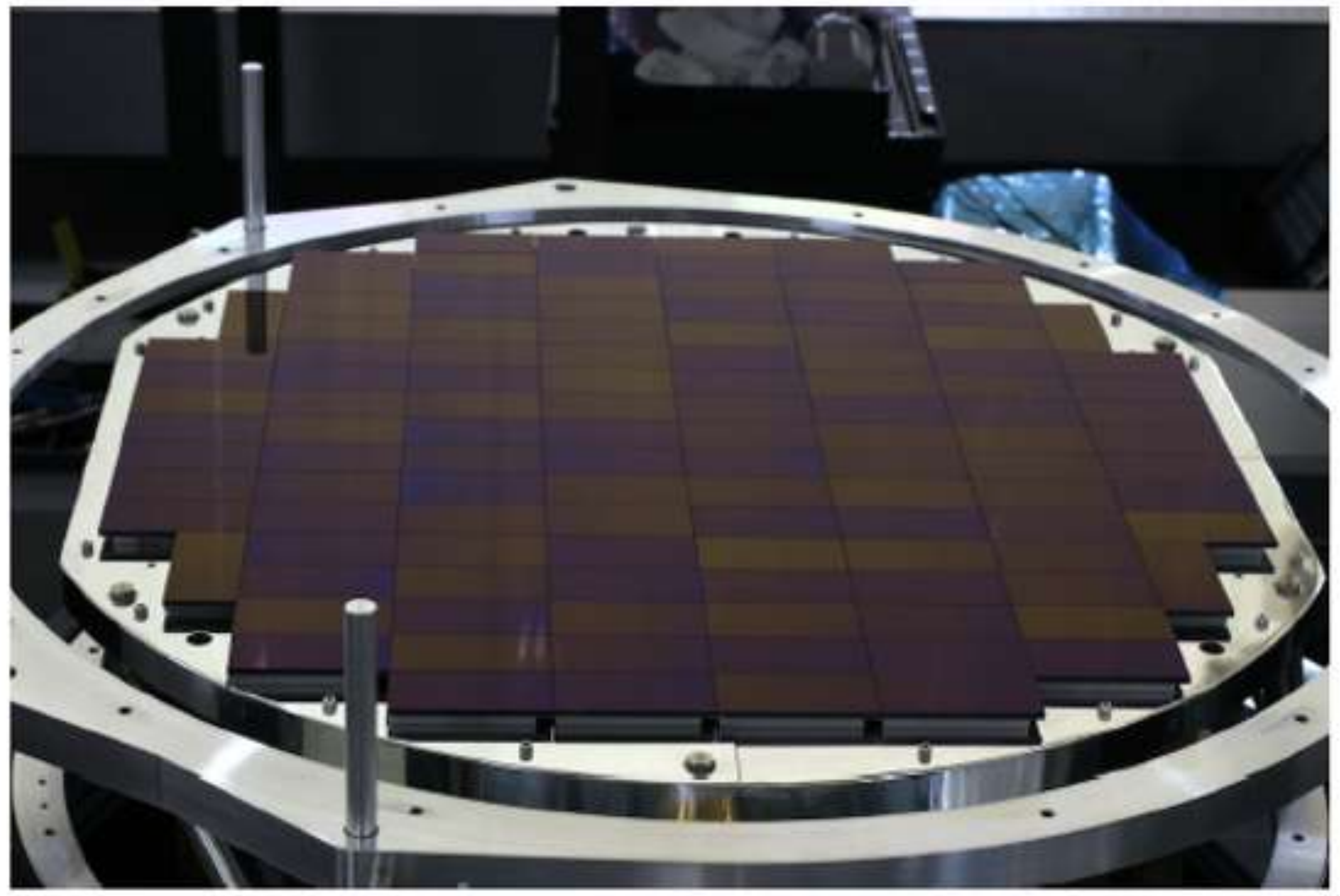
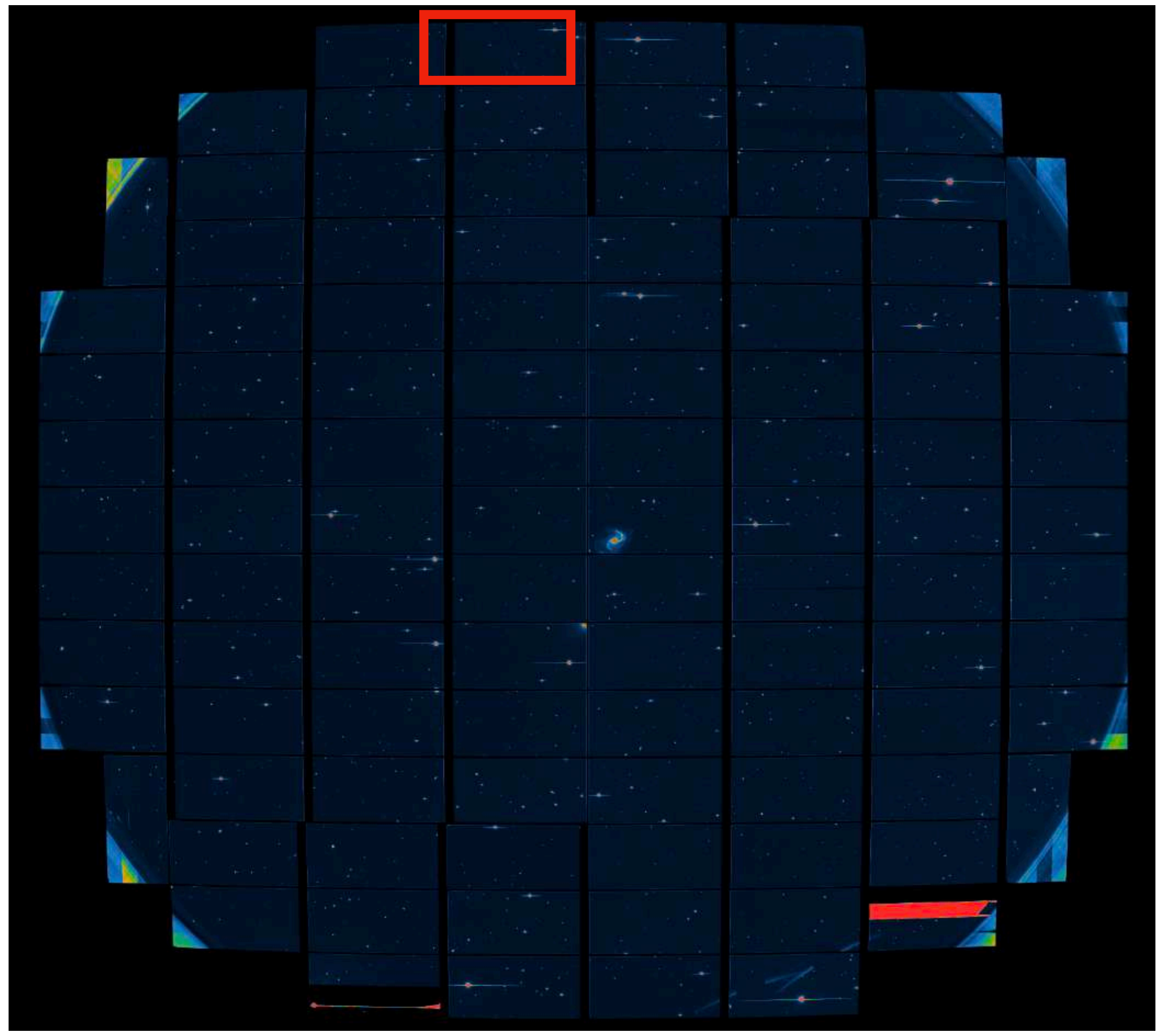


Image credit: https://subarutelescope.org



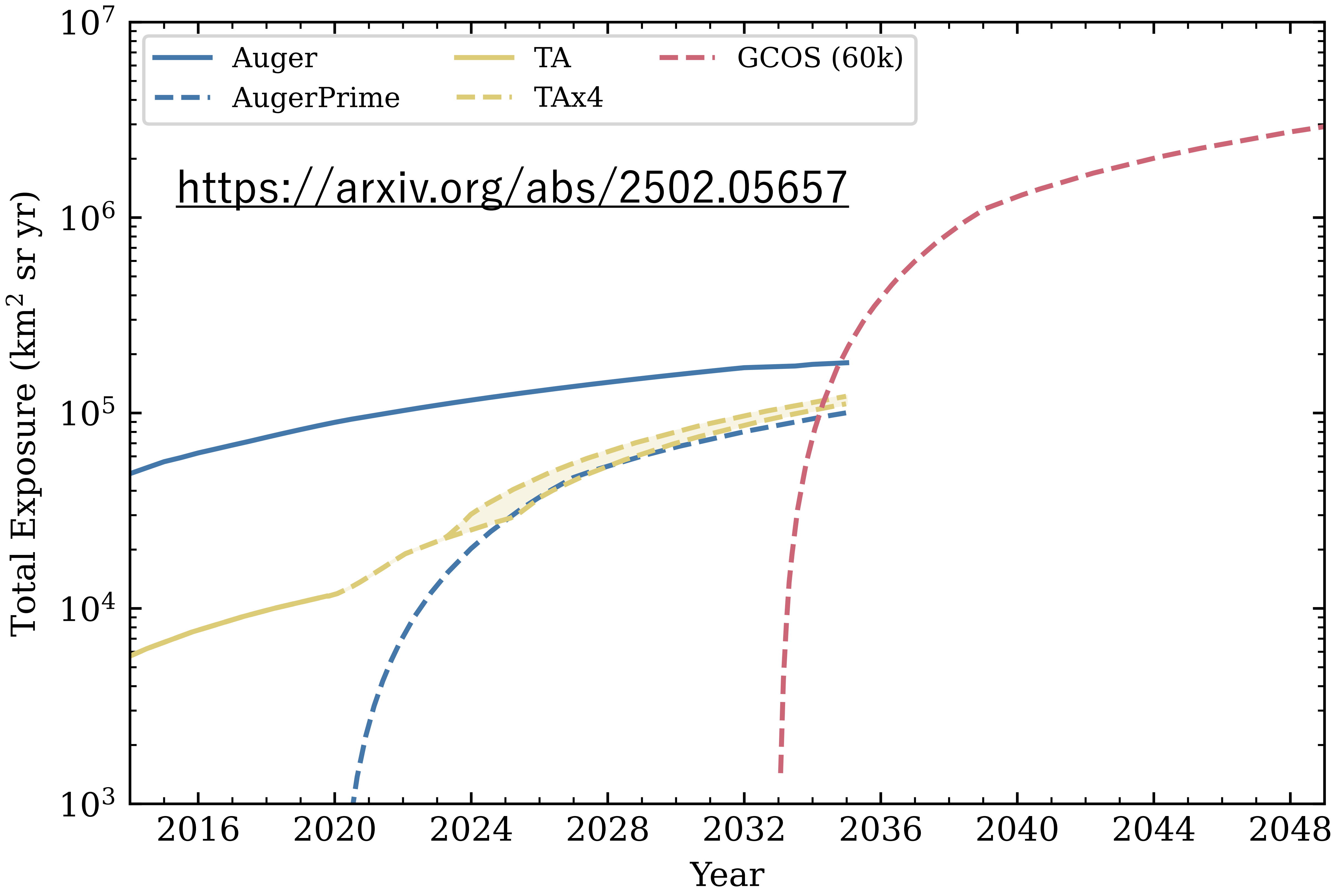
S. Kawanomoto, M. Koike, TF et al., Scientific Reports 13:16091 (2023)

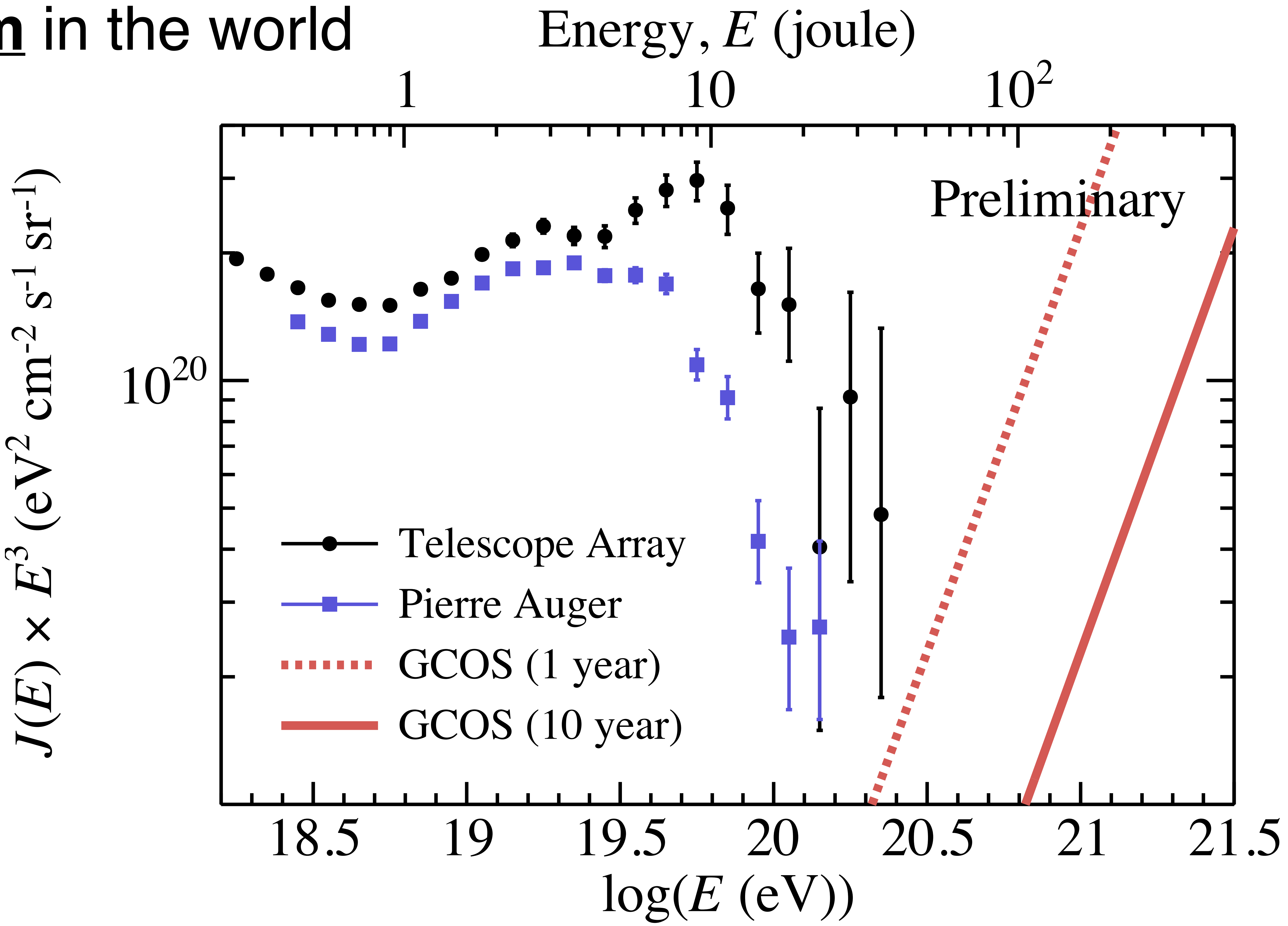
Future: The Global Cosmic Ray Observatory

TA×4×20 ~ 60,000 km^2

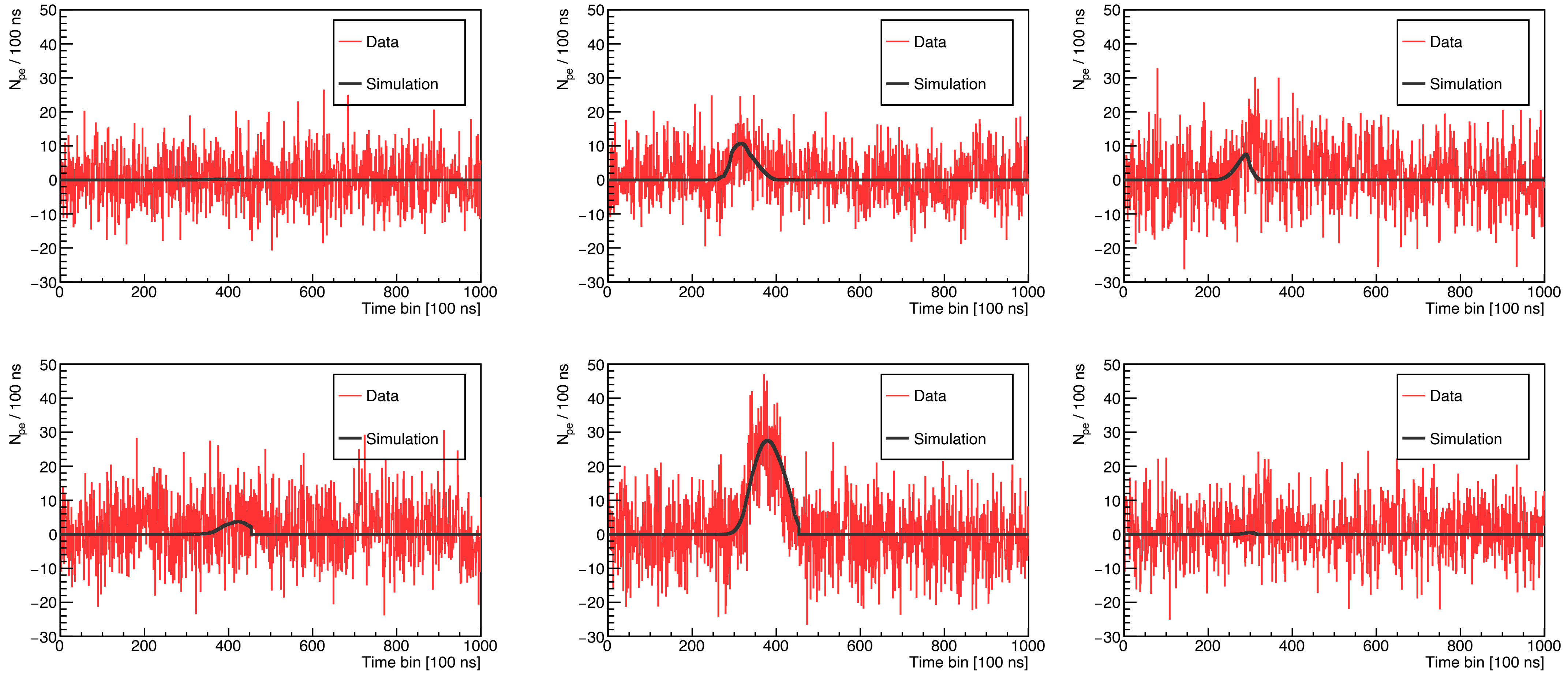
Science of the Global Cosmic Ray Observatory

- **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

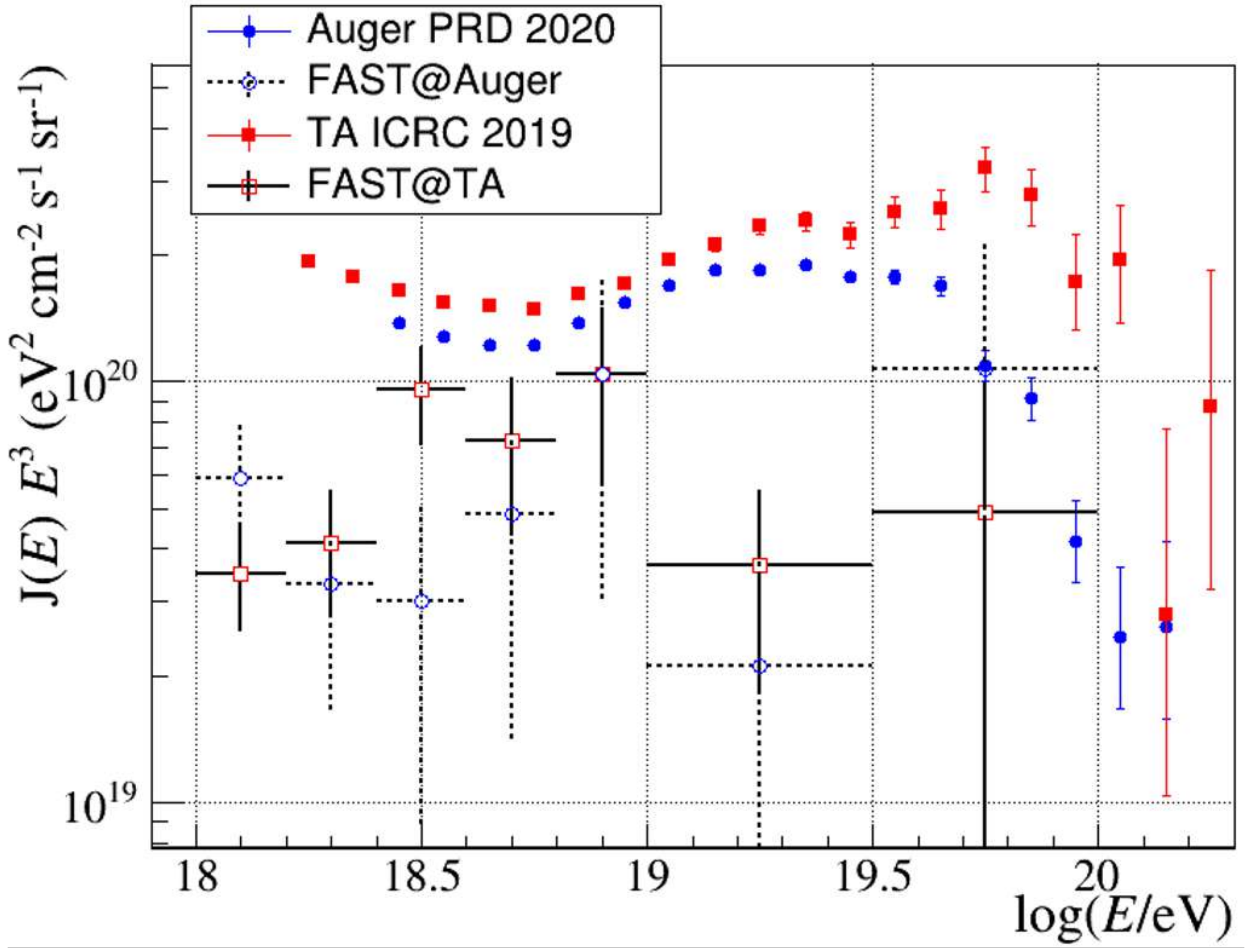


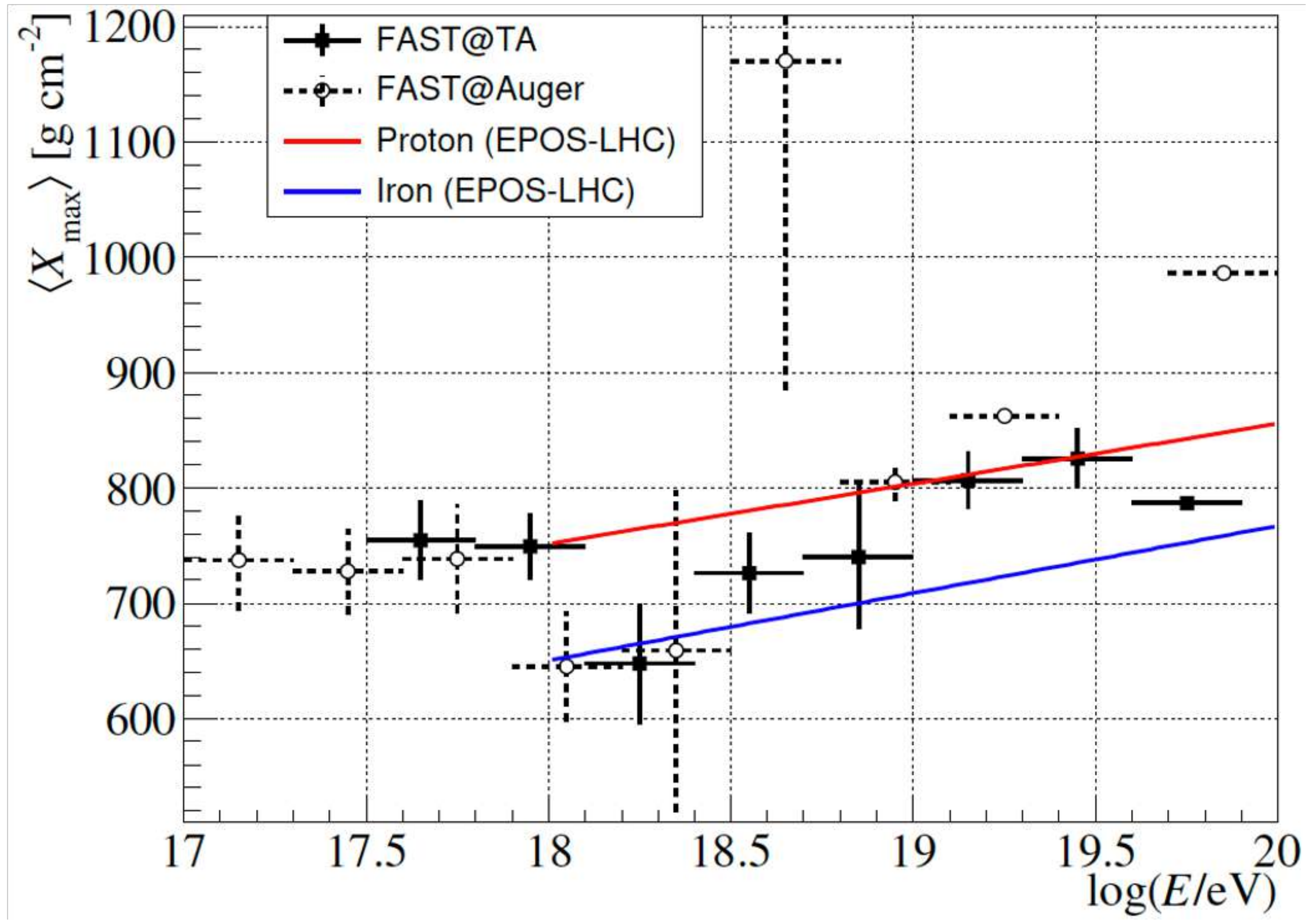


Development of low-cost fluorescence detector



- 3 telescopes at TA, 2 telescopes at Auger
  - DAQ with external triggers
- **Calorimetric energy determination** and **mass composition with X_{max}**
- **Cross calibration between Auger and TA**





https://www.omu.ac.jp/sci/uhelab/thesis.html

Summary and future

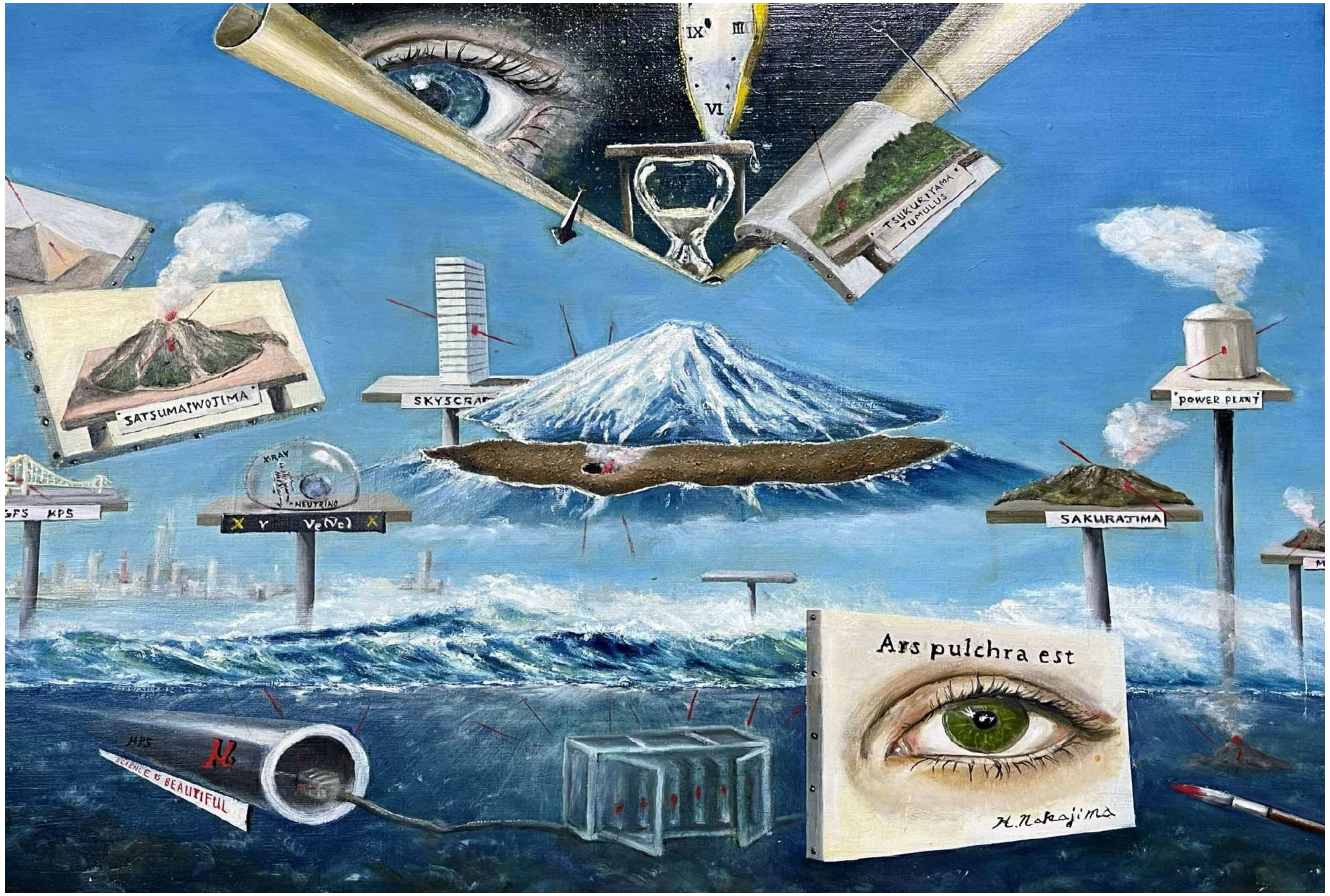
- **>90-year history of cosmic ray research in Japan**
- Endeavor to clarify origin and nature of the most energetic particles from the Galactic and extra-galactic sources
  - Galactic PeVatron search with Tibet ASγ experiment and ALPACA, extra-galactic cosmic rays research with Telescope Array experiment and its upgrades
- Start the stable observations using ALPAQUITA, TAx4, TALE/TALE-infill
- Encourage a further world-wide collaboration for future: Mega ALPACA, GCOS

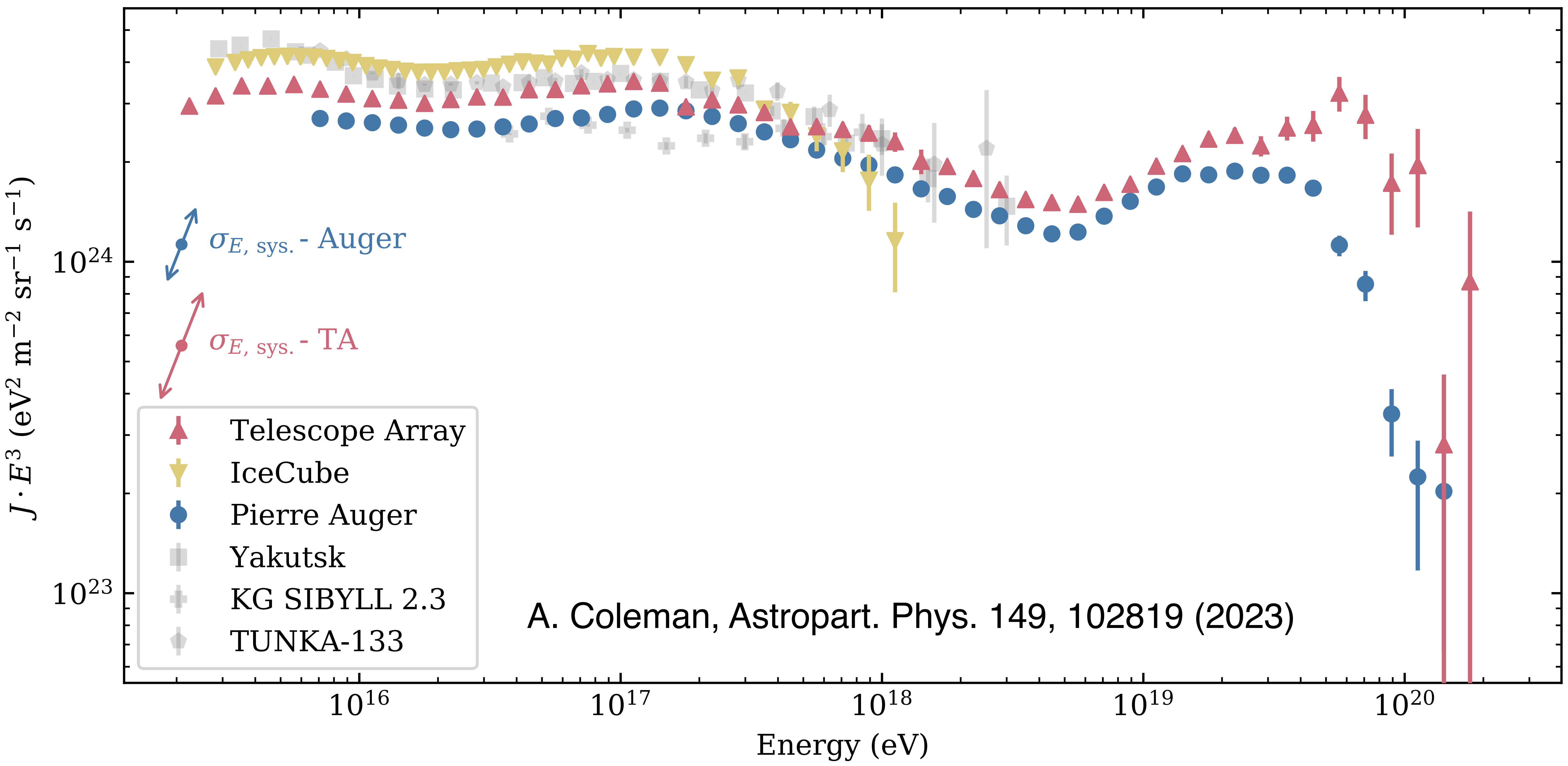
Backup

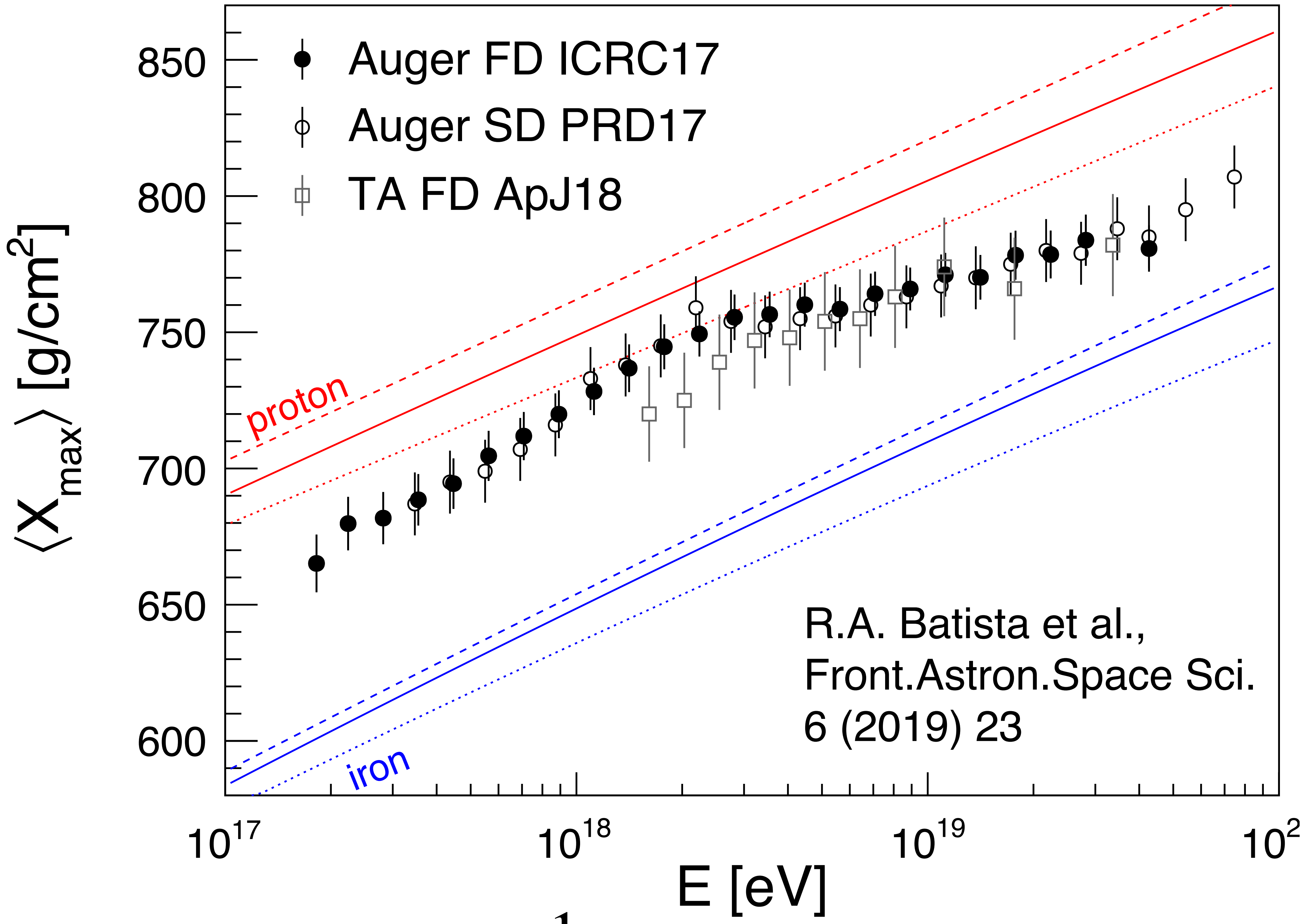
Art of cosmic ray (Hiroshi Nakajima, Japan)

← Amaterasu particle

↓ Muon tomography

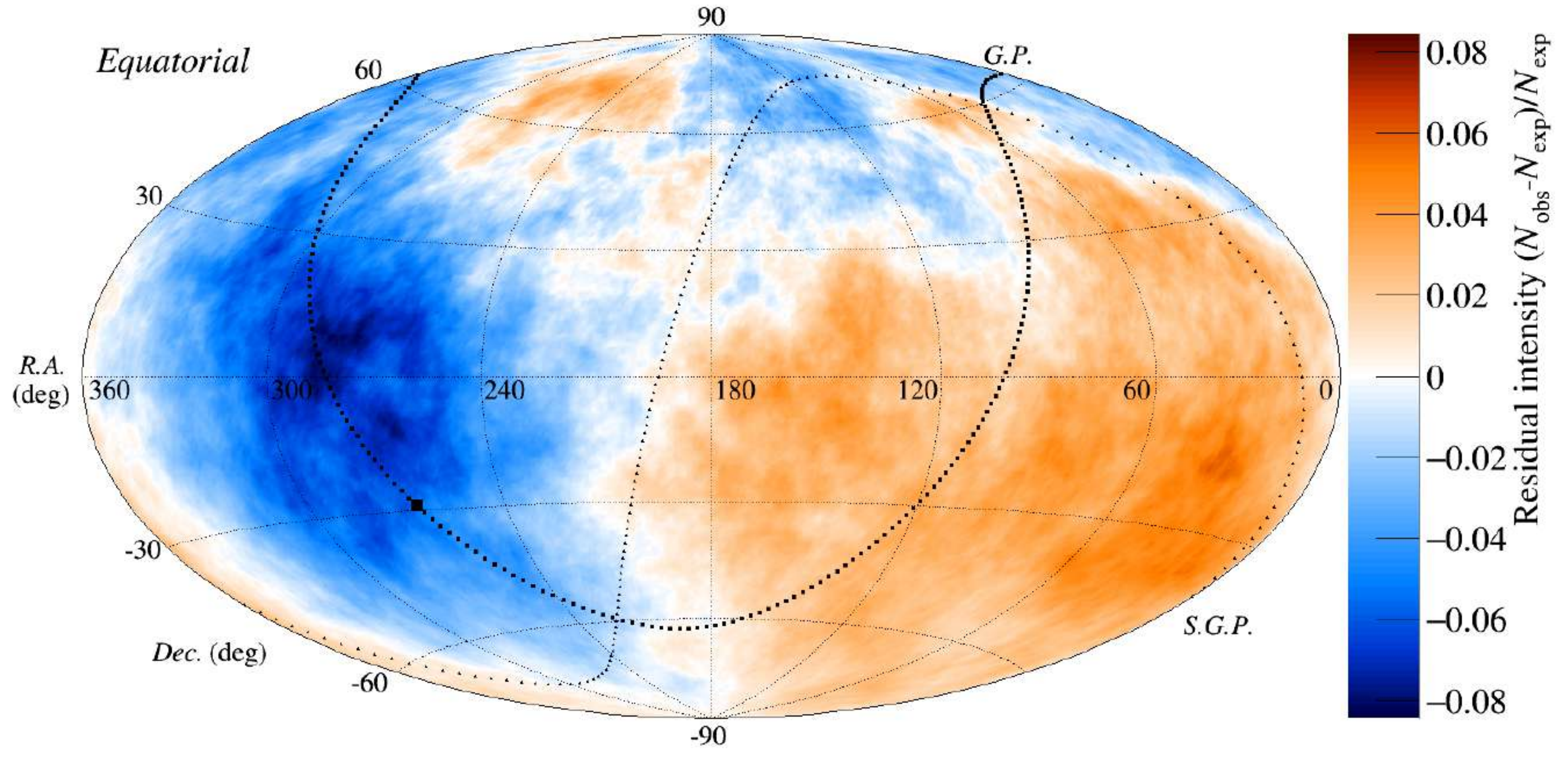




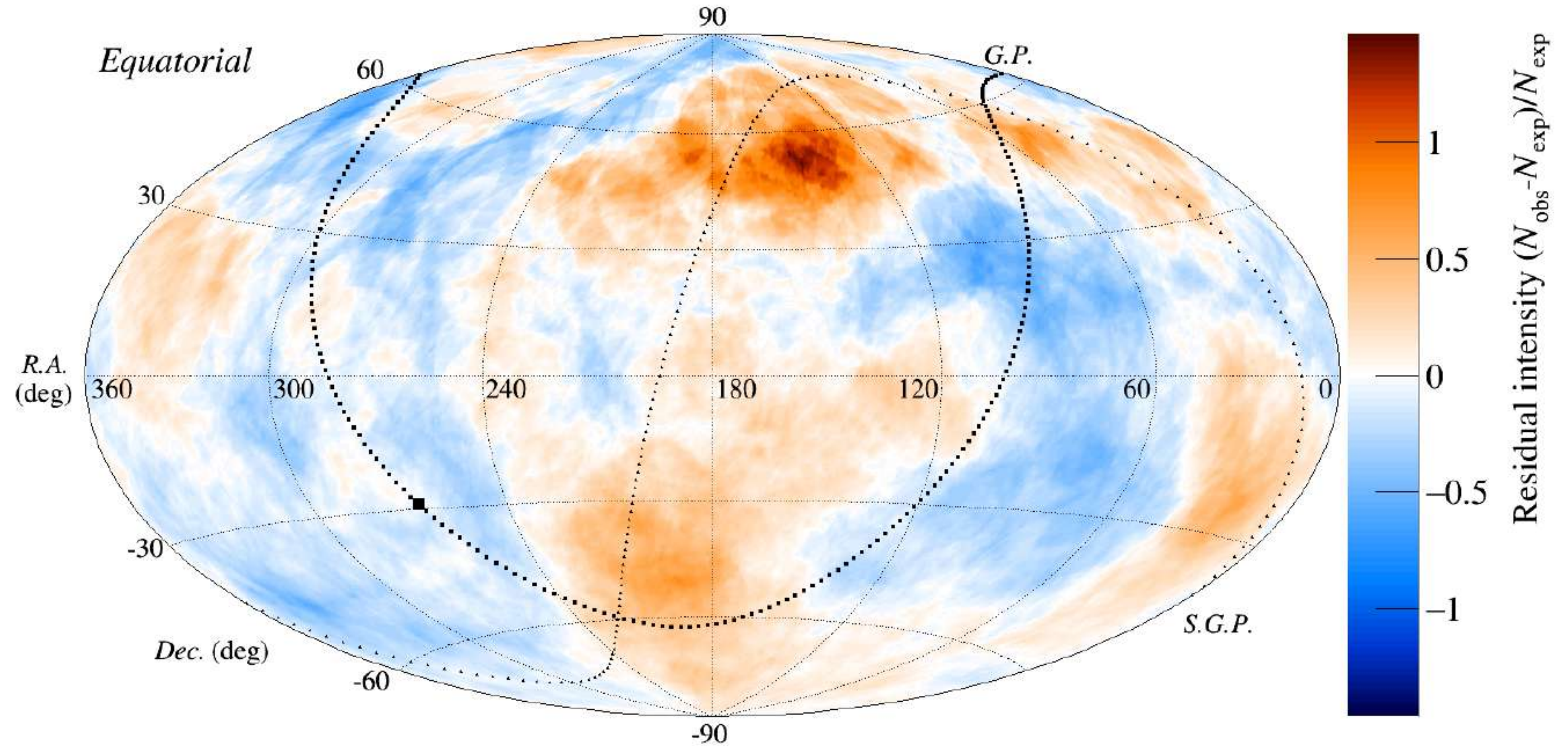


Latest results

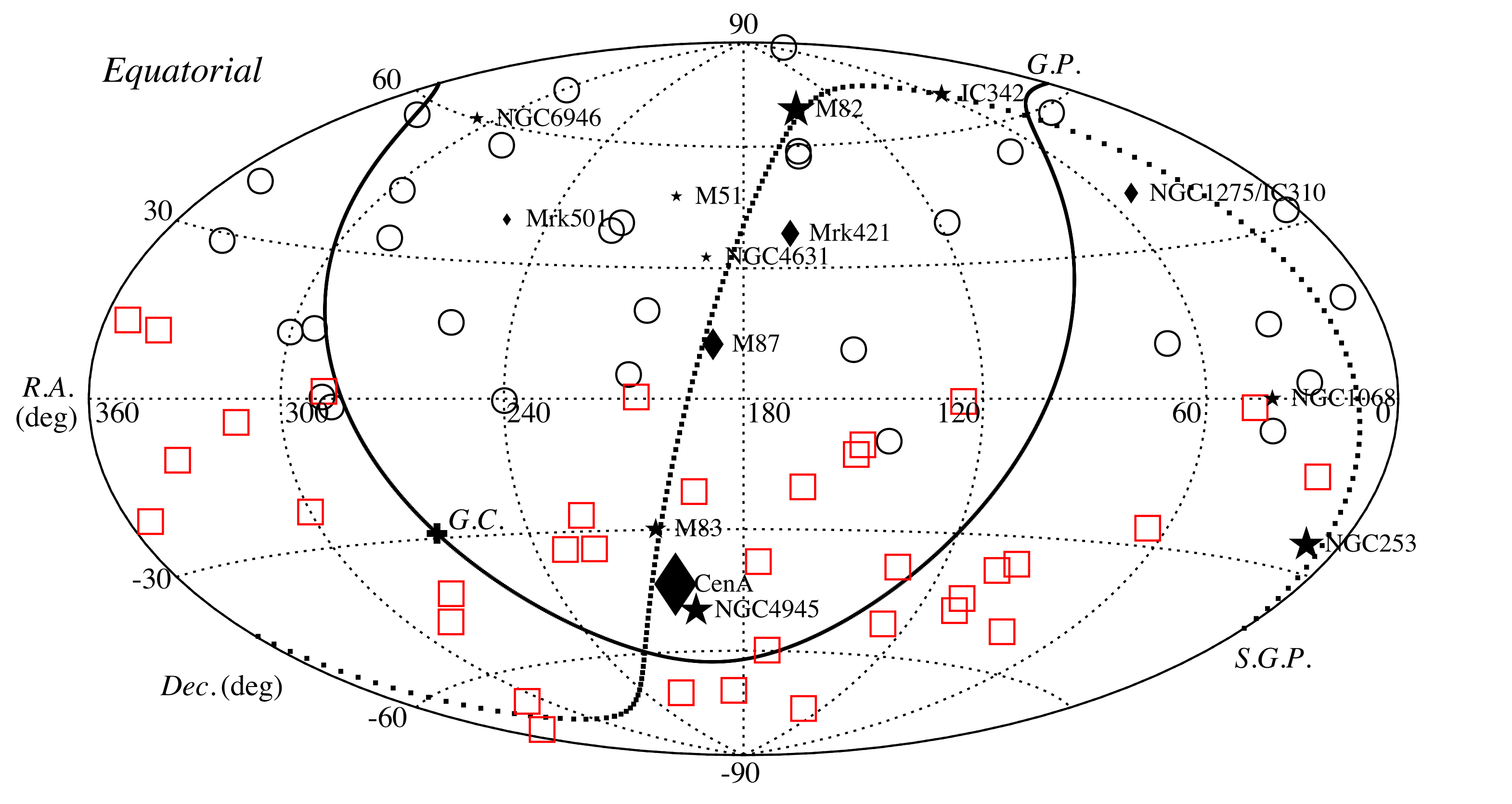
$$\theta \sim 10^\circ Z \left(\frac{E}{10\,\mathrm{EeV}} \right)^{-1}$$



Ankle ($E > 10$ EeV)



Cutoff ($E > 50$ EeV)

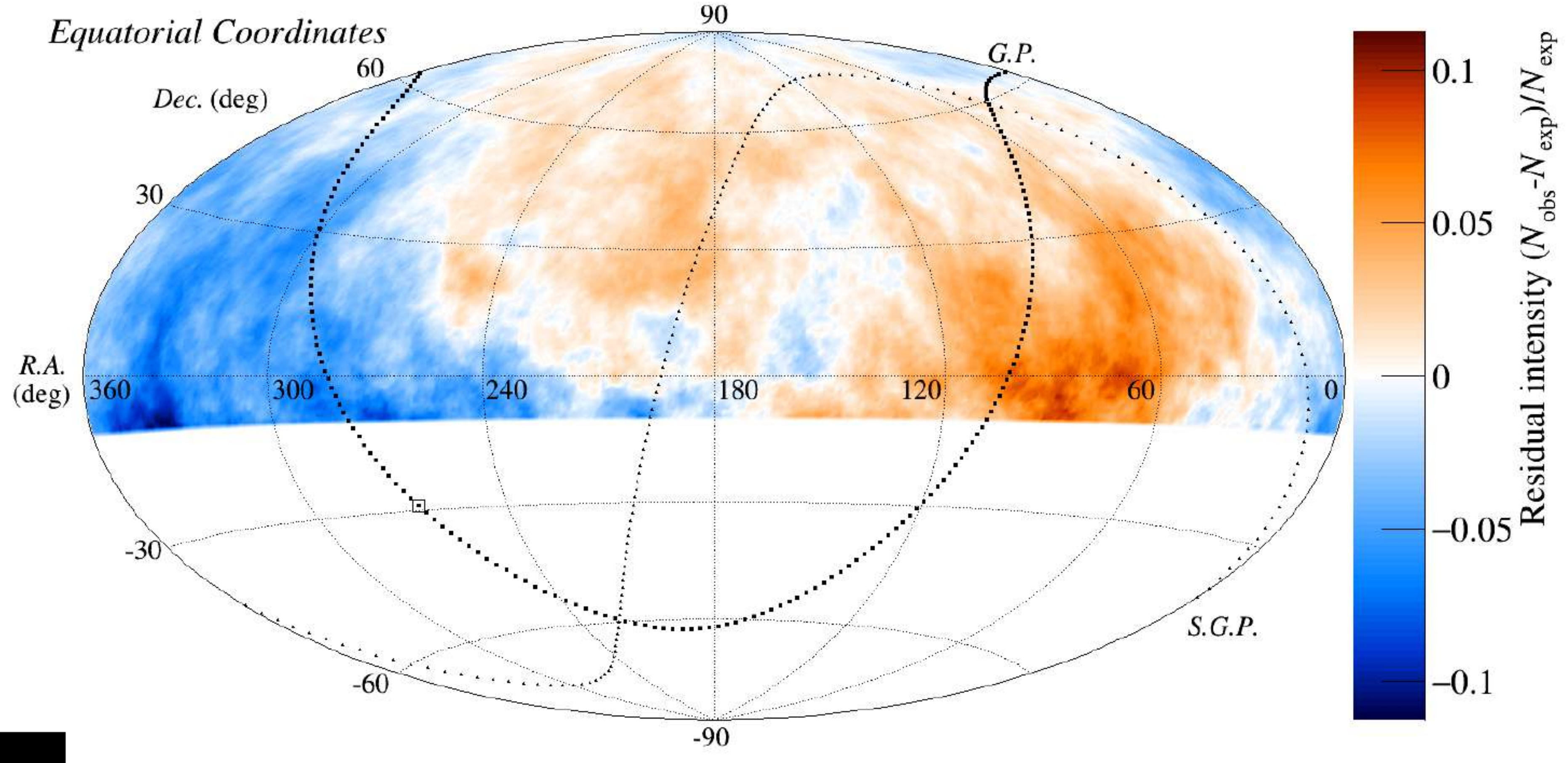


Beyond-cutoff ($E > 100$ EeV)

Anisotropy of UHECRs (>10 EeV)

Northern TA ApJL, 898:L28 (2020)

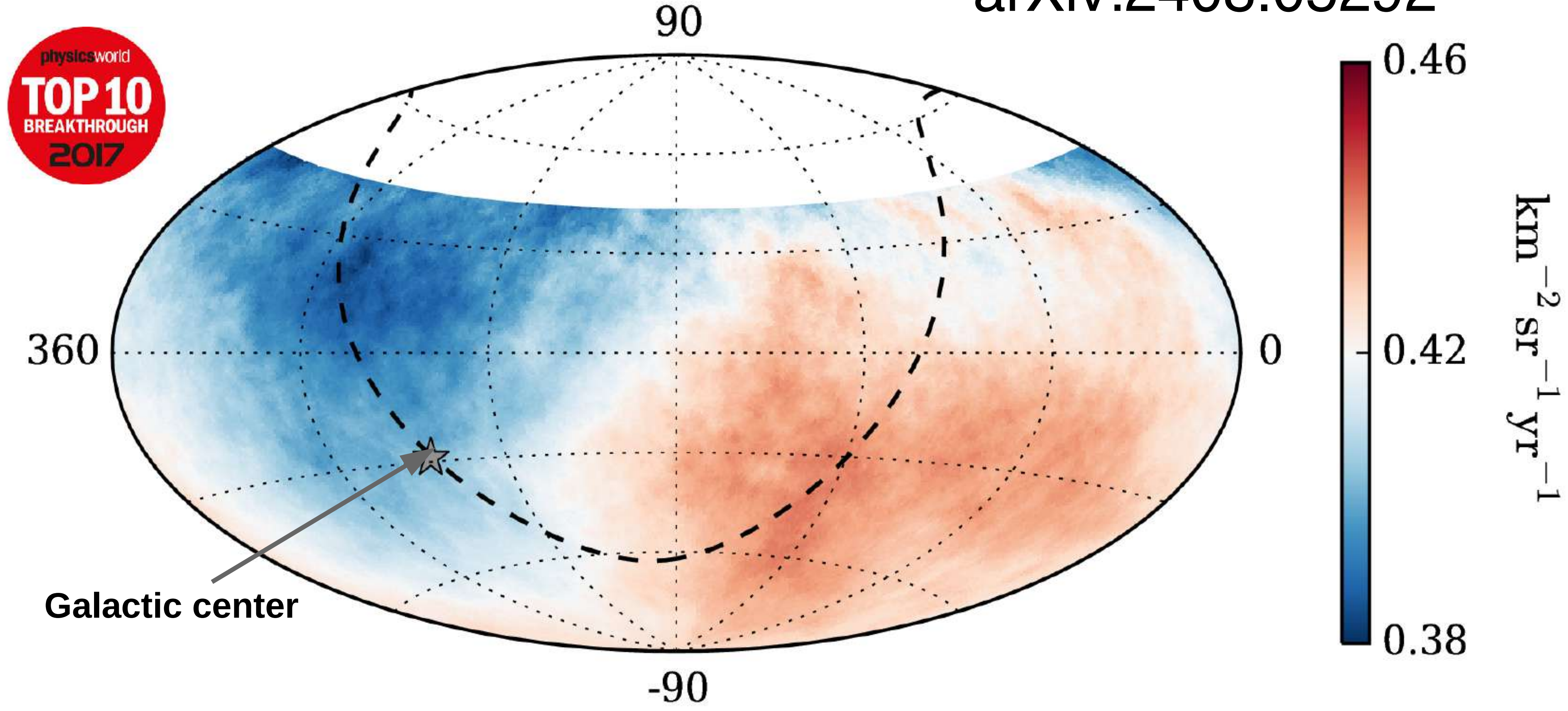
E_{TA}> 8.8 EeV



Southern Auger Science 357, 1266 (2017)

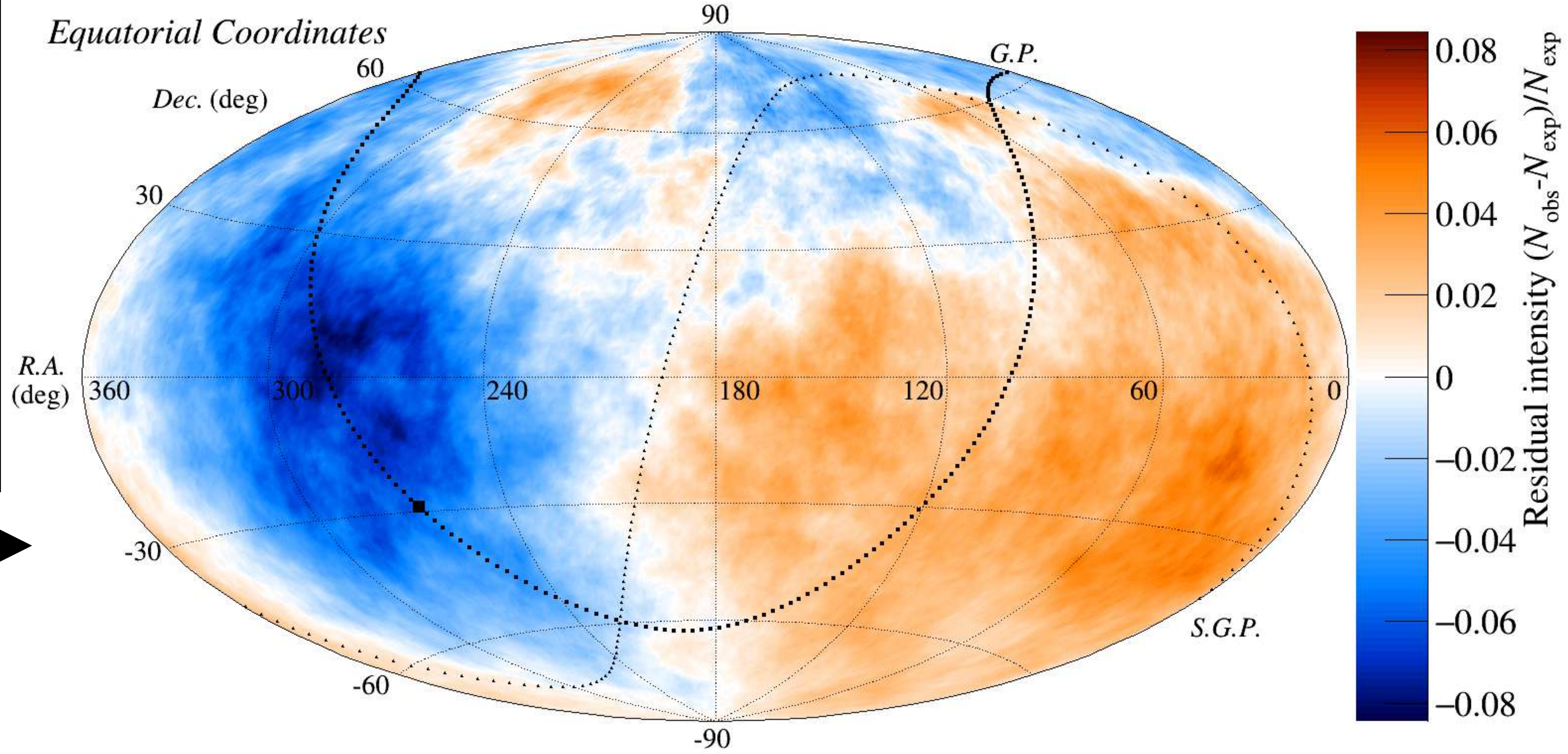
E_{Auger}> 8 EeV

6.9σ using19-years data
arXiv:2408.05292



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

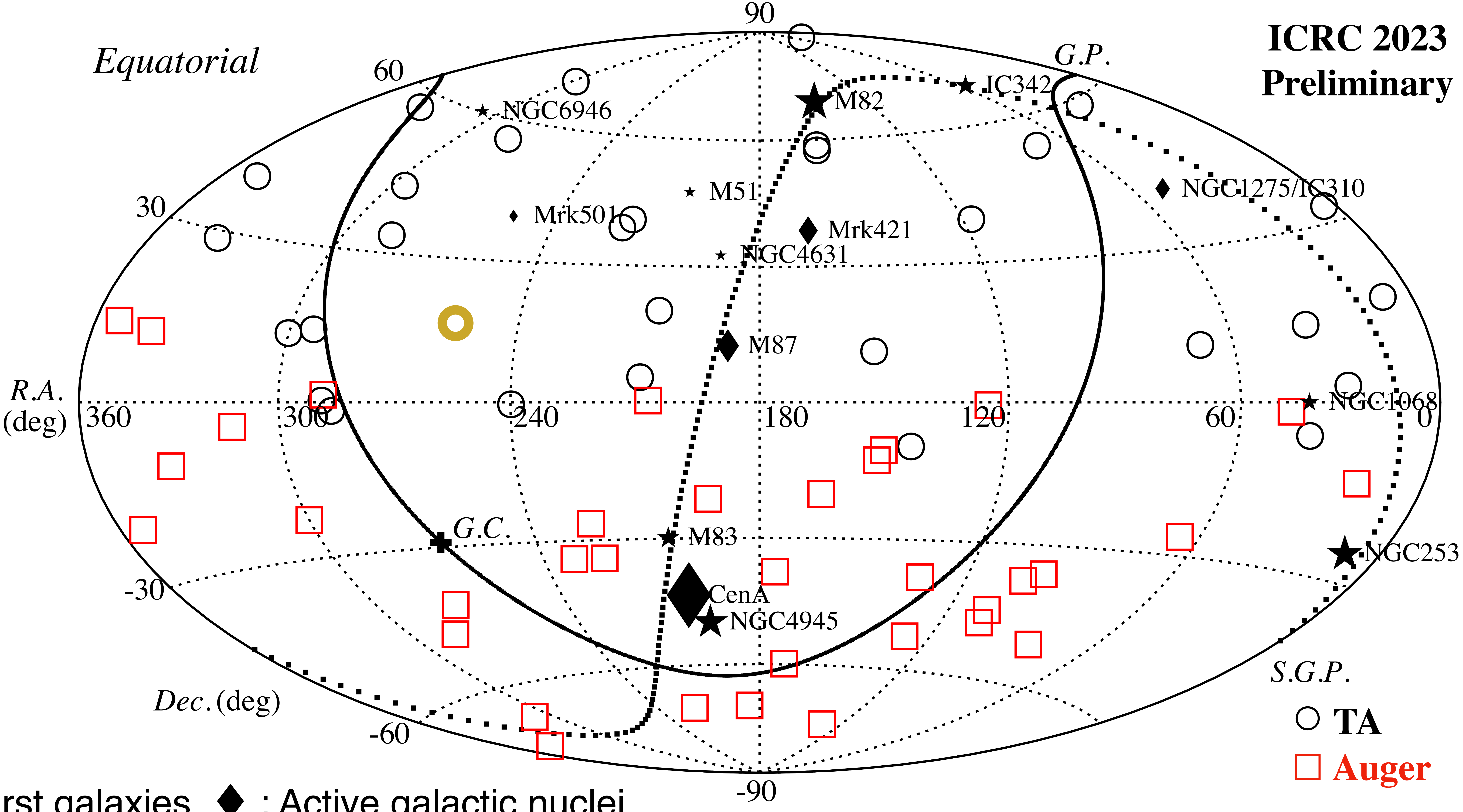
Cutoff (E_{TA}>52.3 EeV E_{Auger}>40 EeV), ~**1000 events**

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

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

>100 EeV skymap

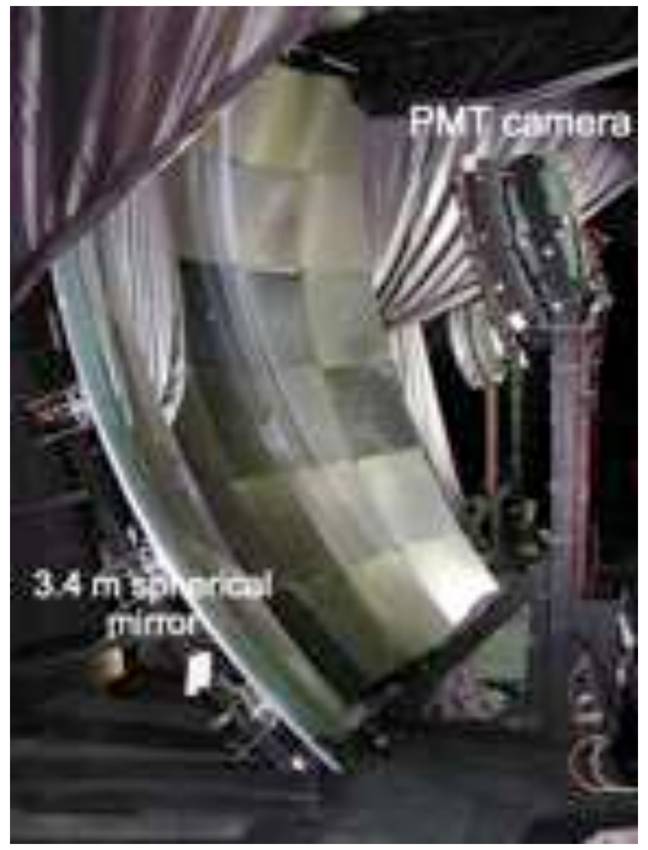
T. Fujii, PoS (ICRC2023) 031 (2023)

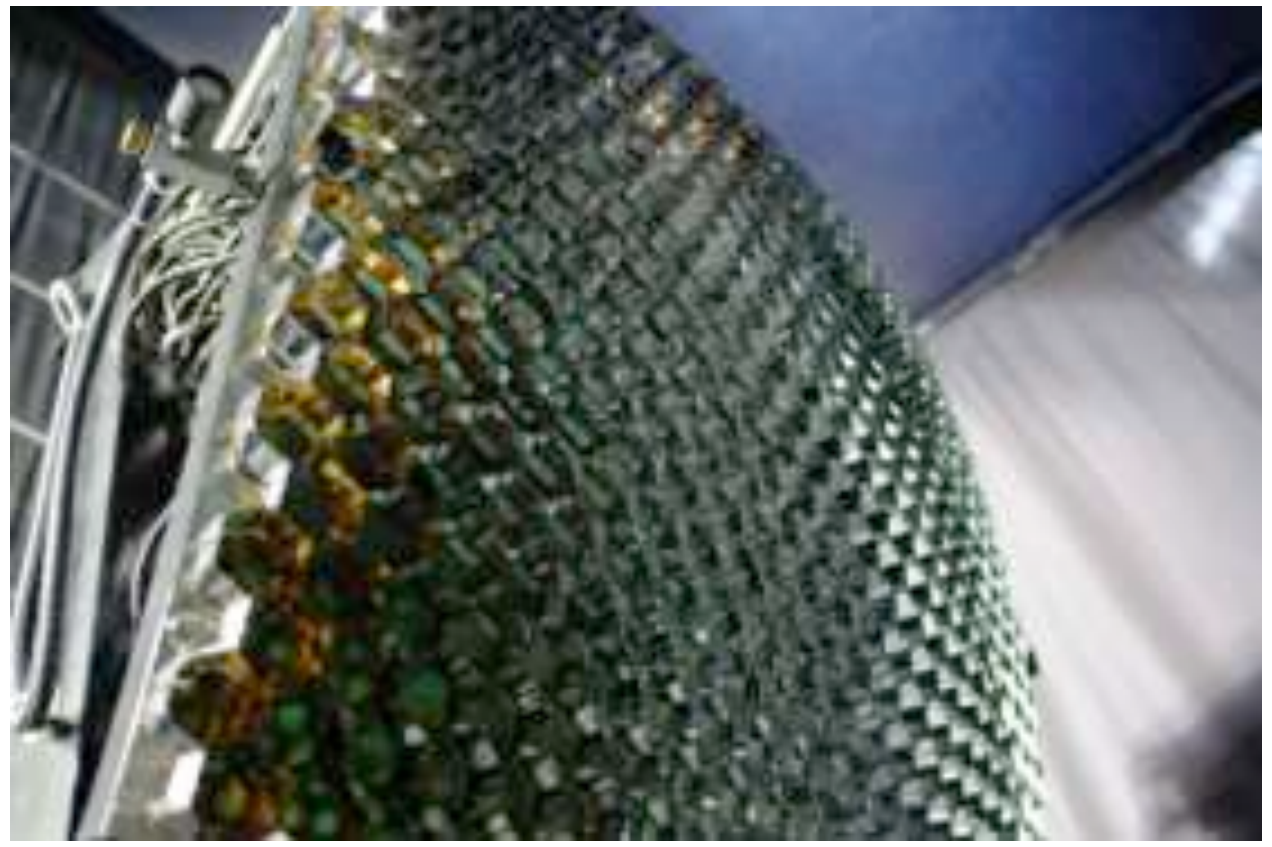


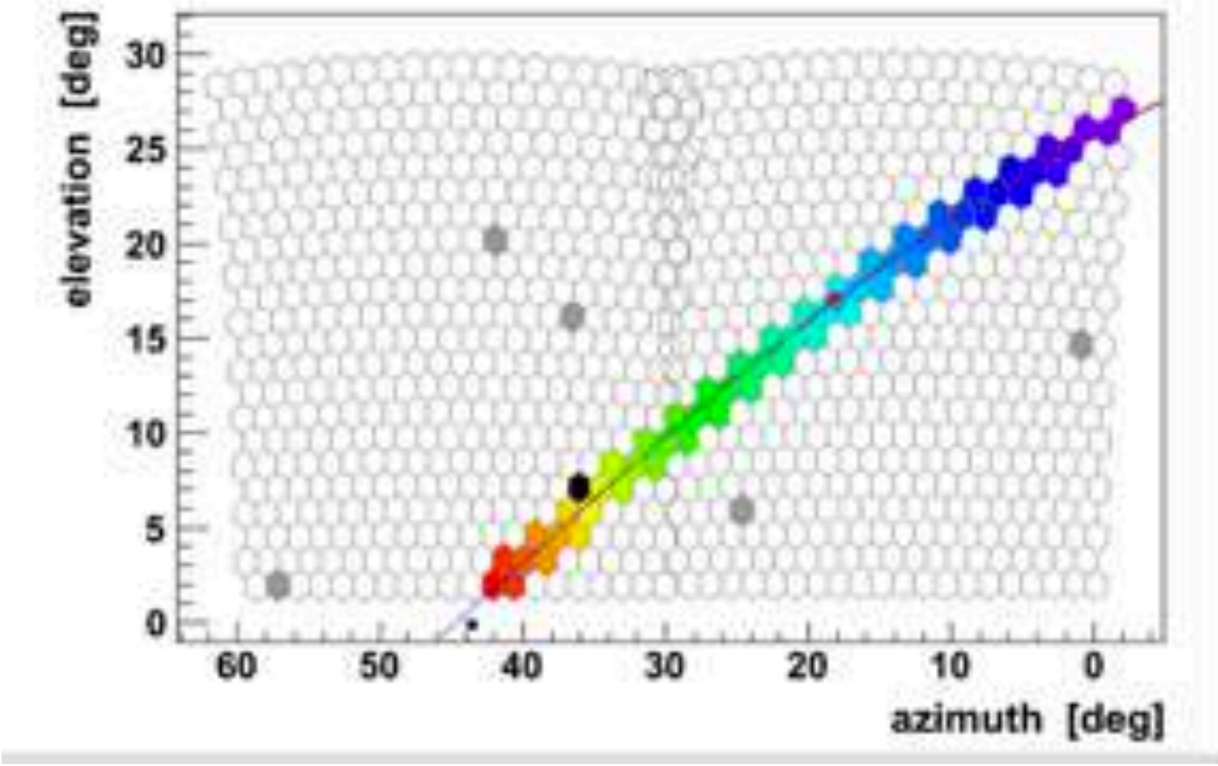
★ : Starburst galaxies ♦ : Active galactic nuclei

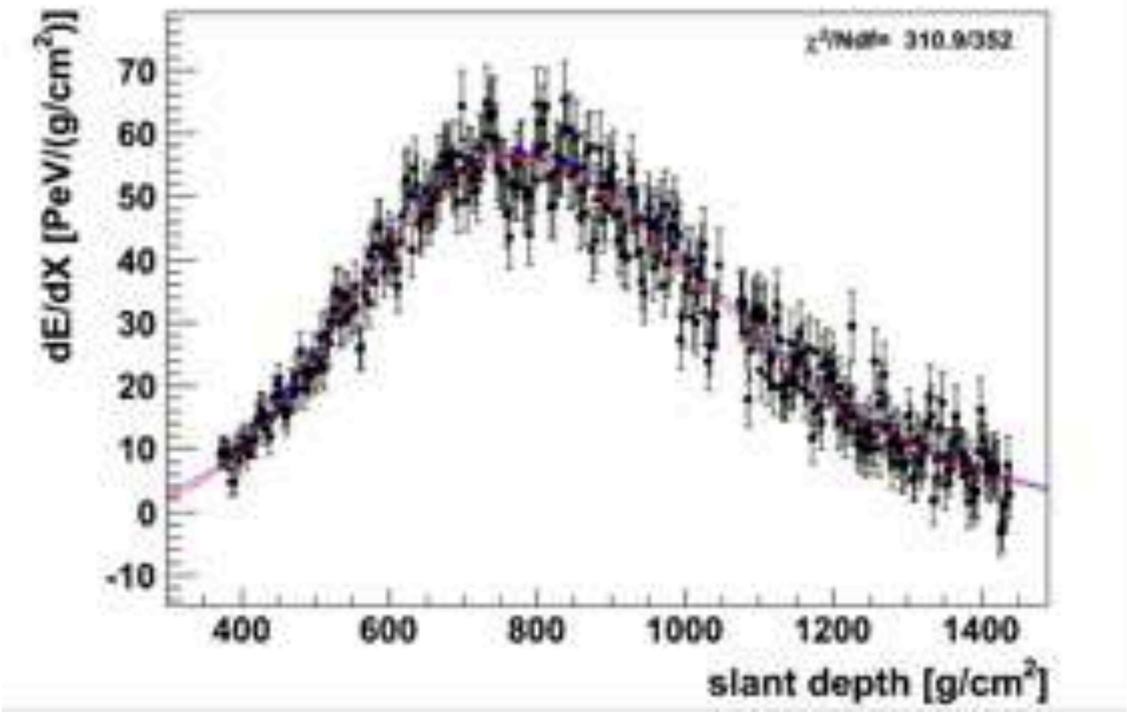
>100 EeV of TA 15-years and Auger 17-years

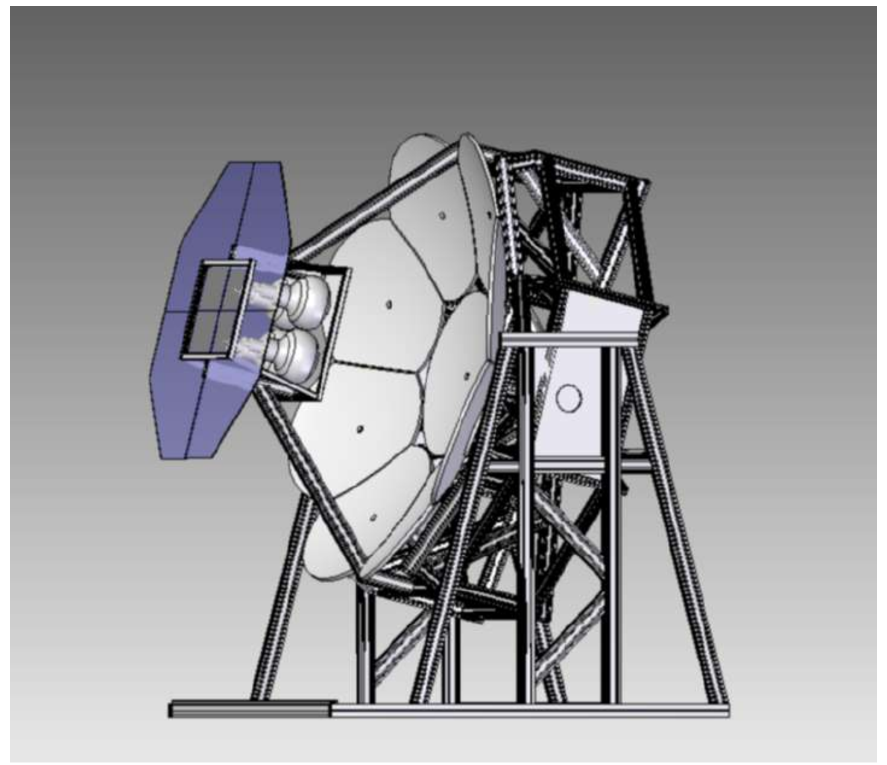
No obvious clustering appeared

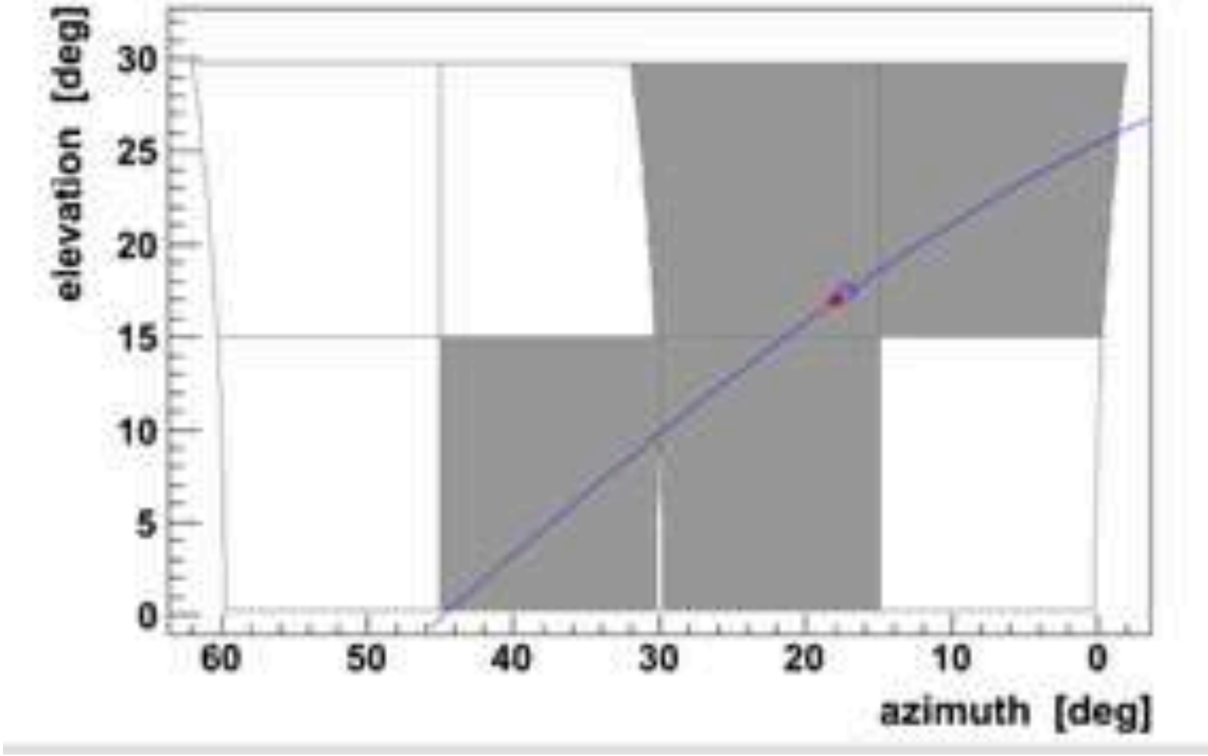

PMT camera
3.4 m spherical mirror

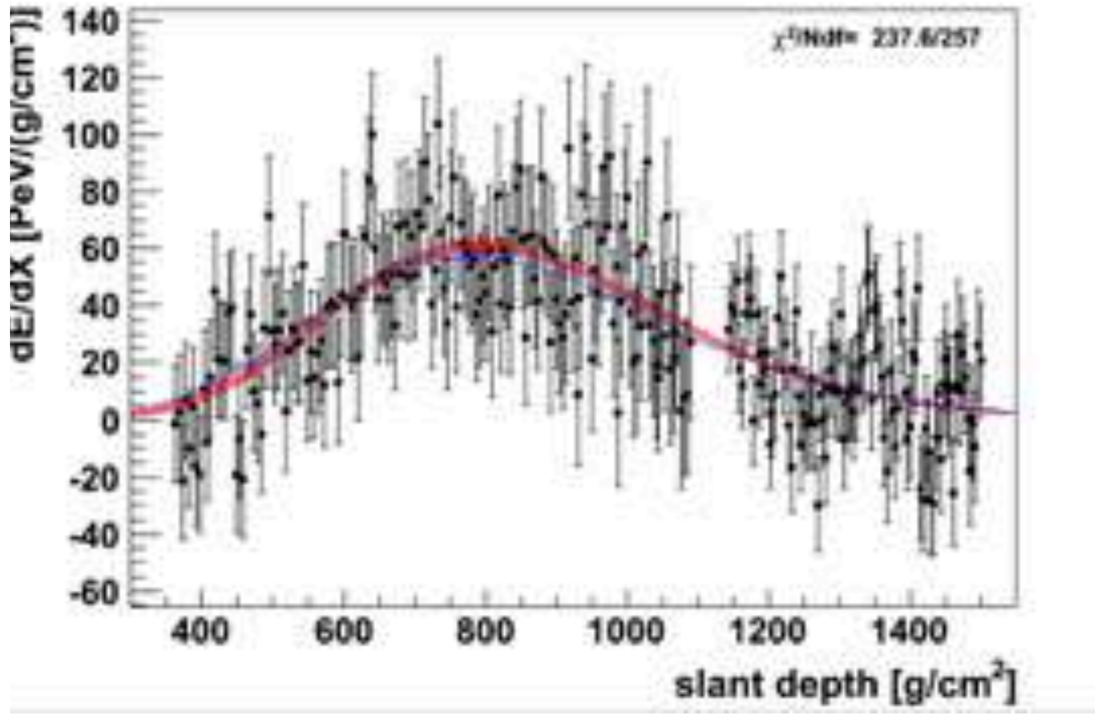


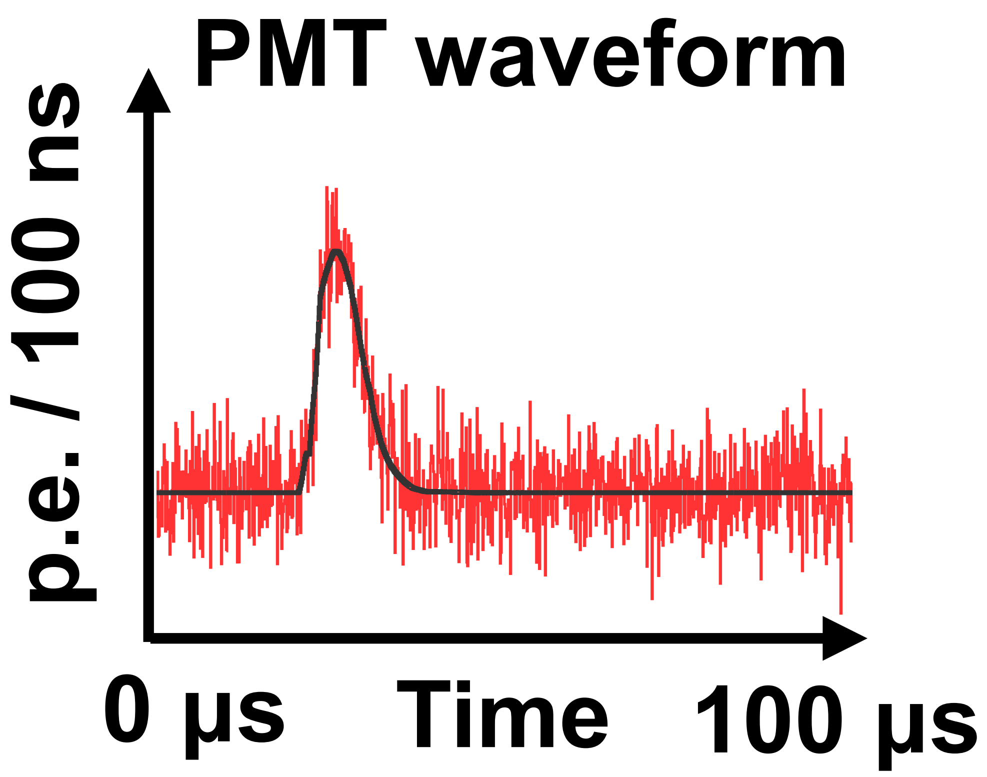

elevation [deg]
azimuth [deg]

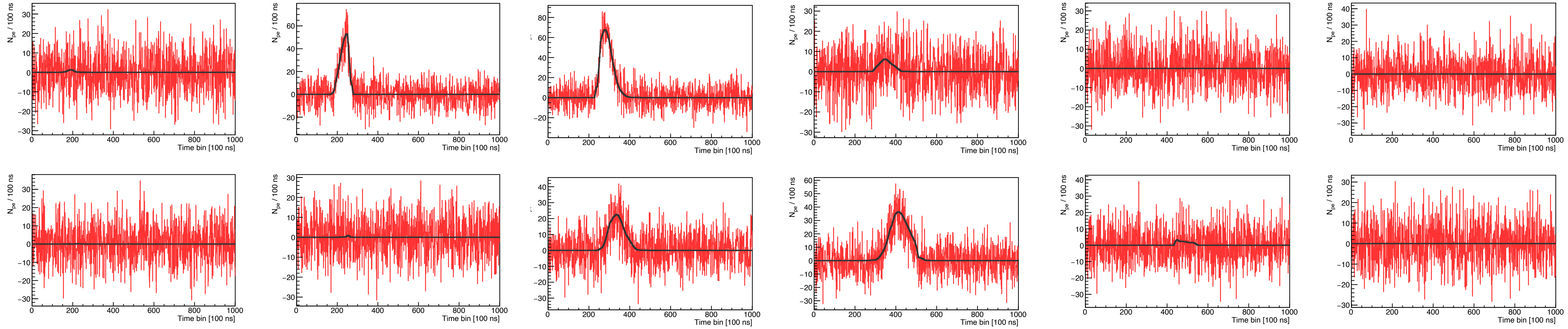

χ^2/Ndf= 310.9/352
dE/dX [PeV/(g/cm^2)]
slant depth [g/cm^2]

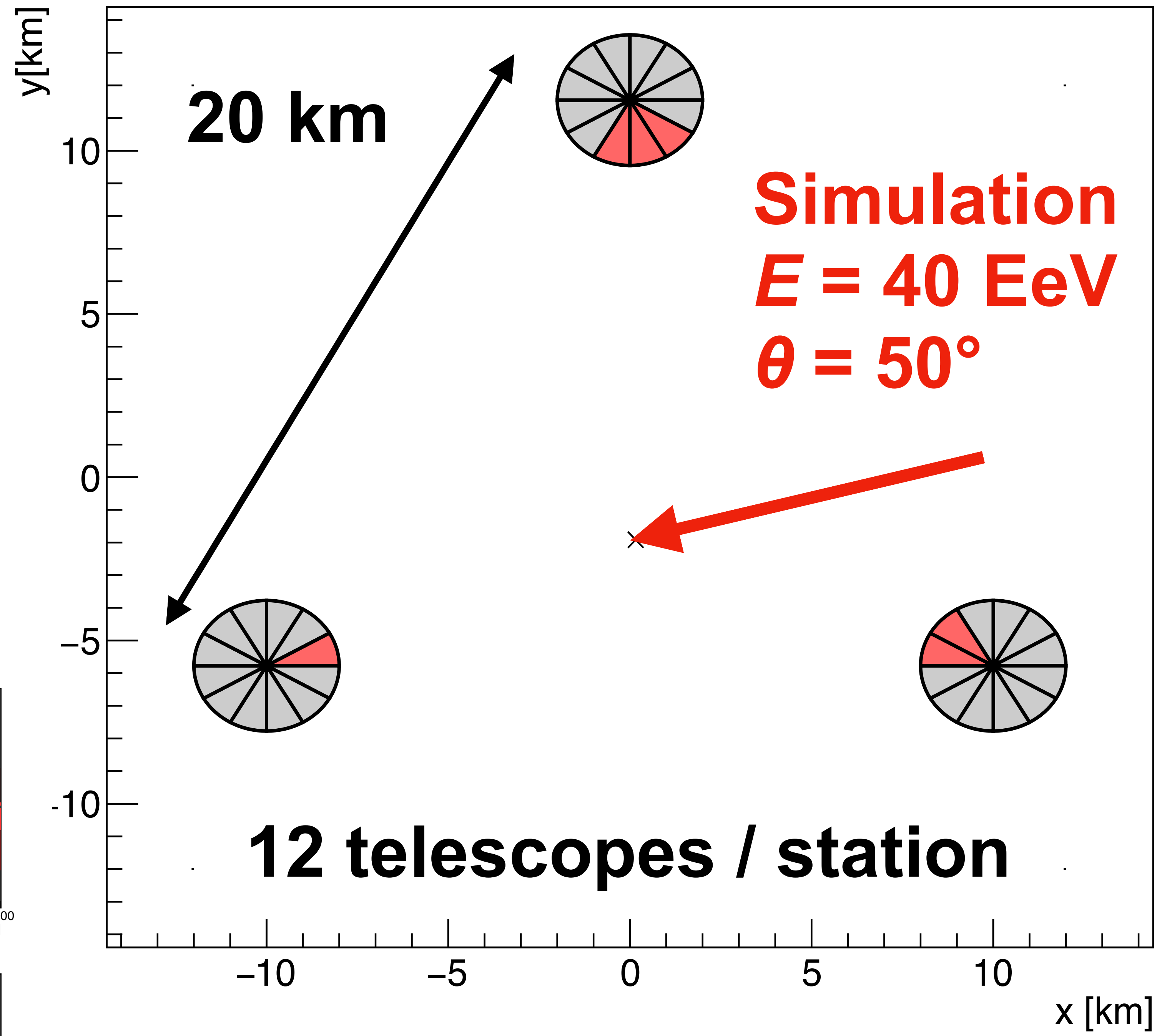



elevation [deg]
azimuth [deg]


χ^2/Ndf= 237.6/257
dE/dX [PeV/(g/cm^2)]
slant depth [g/cm^2]

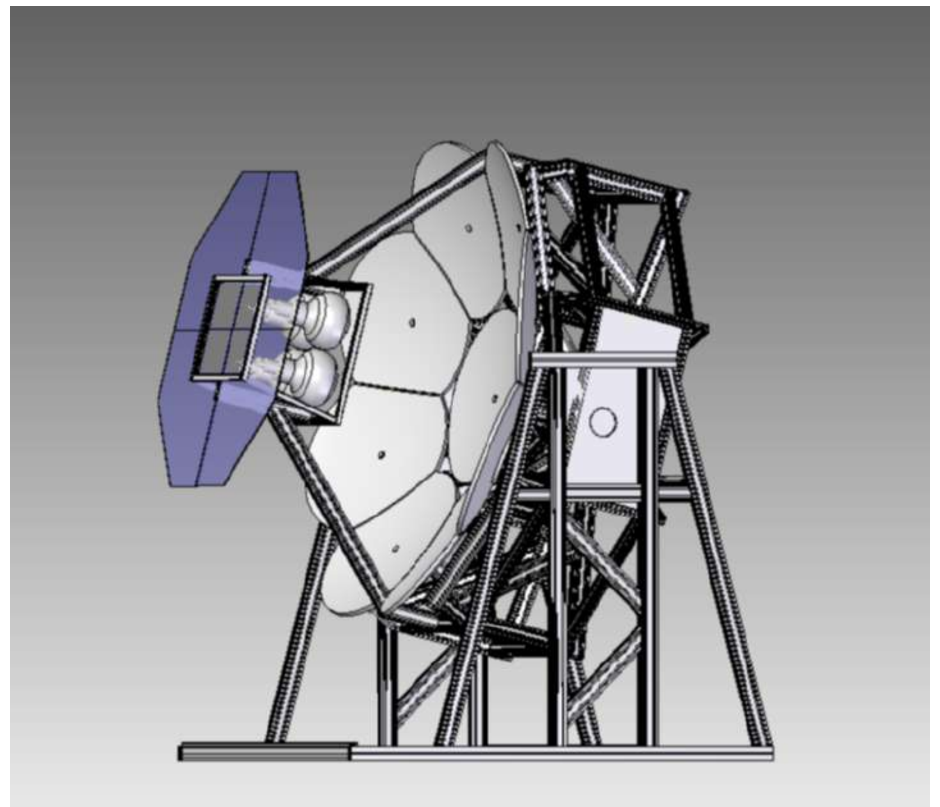






500 stations

→ 150,000 km²



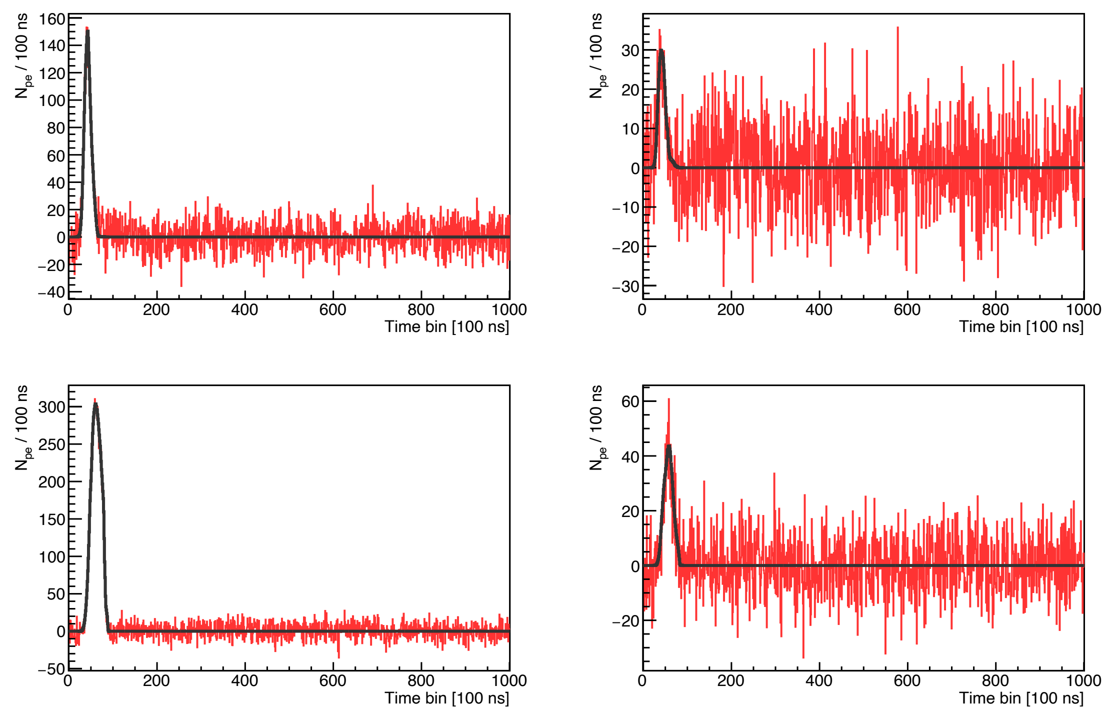
FAST telescope

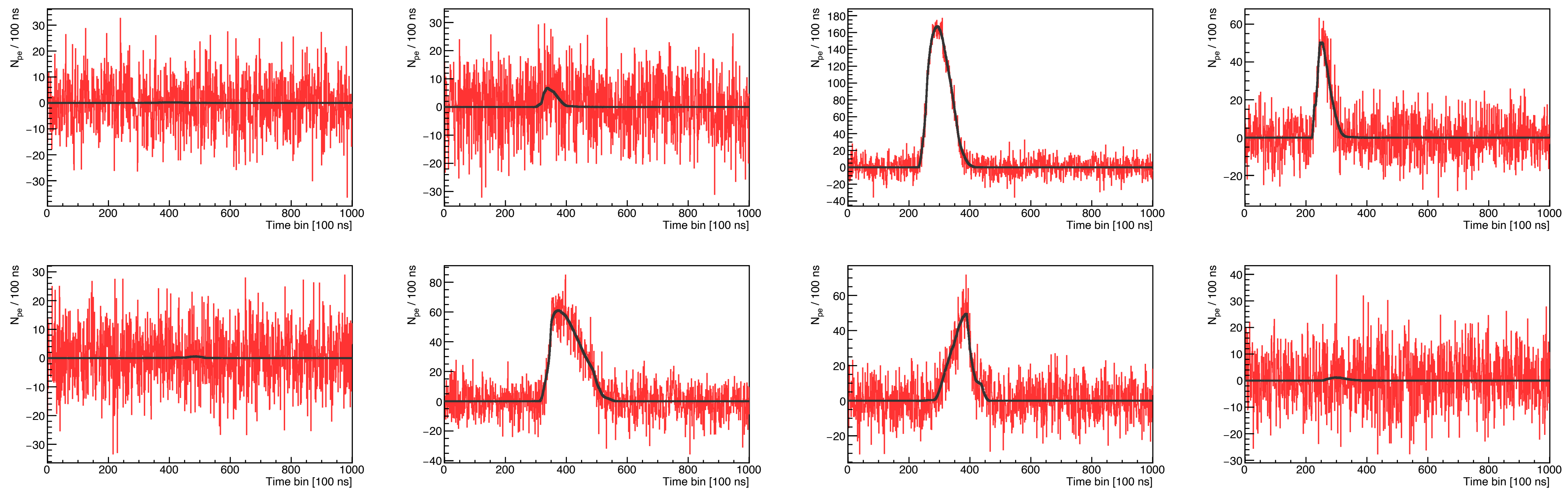
4 PMTs (20 cm diameter)

1 m² aperture (UV filter)

Segmented mirror

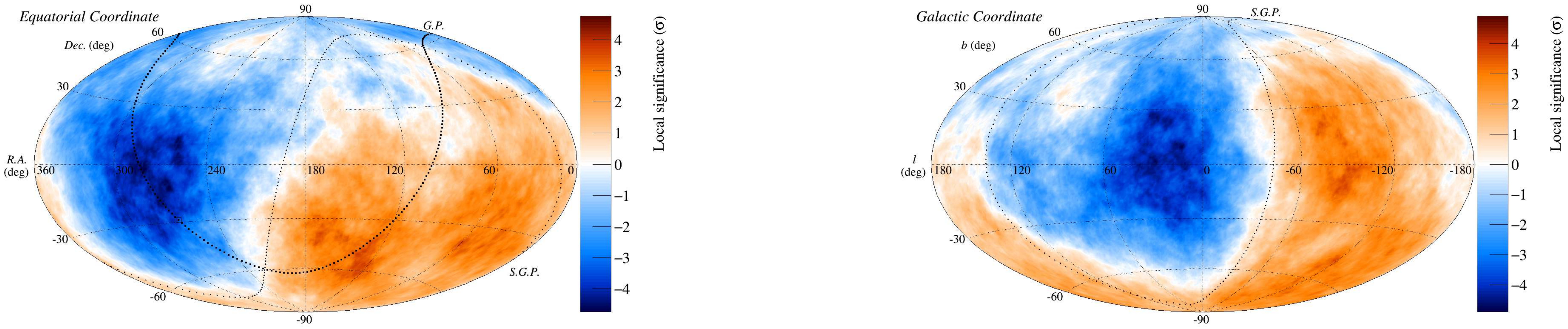
in 1.6 m diameter



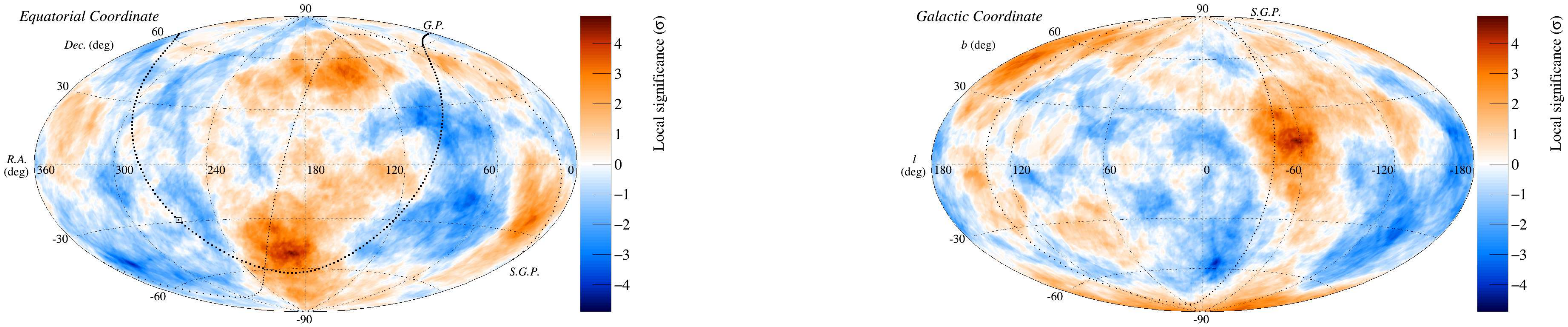


UHECR full-sky by TA and Auger

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

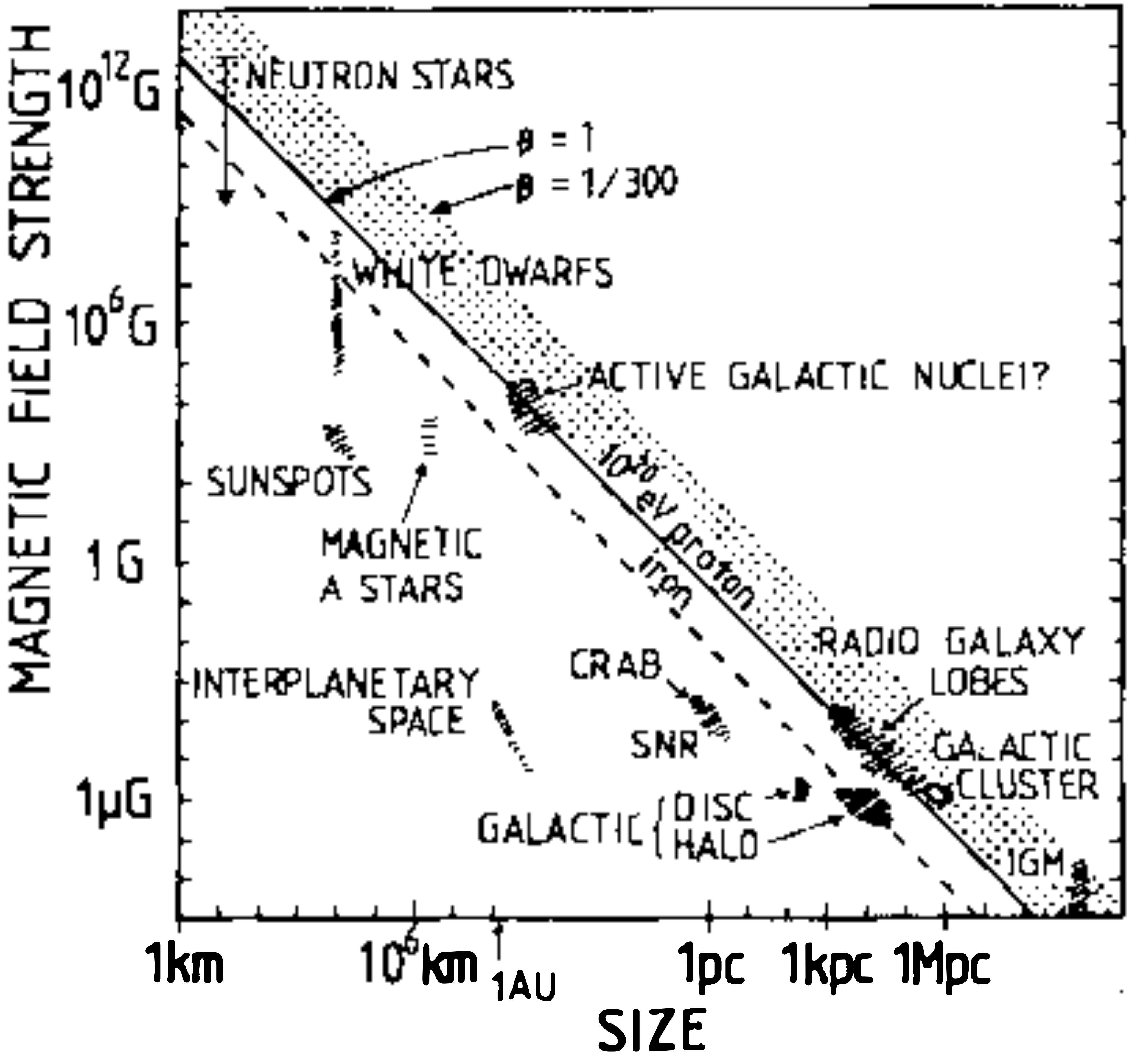


Suppression (E_{TA}>52.3 EeV E_{Auger}>40 EeV) 20° circle



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

Hillas diagram



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

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

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

Deflection angle in Milky way

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

Time delay in Milky way

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

TALE & TA spectra