Osaka Metropolitan University

Telescope Array Experiment: Exploring Extremely High Energy Universe

Cosmic Ray Physics - 宇宙線物理学

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About myself…

- 常定 芳基 TSUNESADA YOSHIKI
- 愛媛県新居浜市出身, 1974年生
- 1993: 東京工業大学 (TokyoTech)
- 2002-2005: 国立天文台研究員
- 2005-2015: 東京工業大学　助教
- 2015-2022: 大阪市立大学　准教授
- 2022 - : 大阪公立大学　教授

- I moved to OCU 2015, and OCU became OMU, 2022.
- TokyoTech has merged with 東京医科歯科大学 to establish 東京科学大学 Institute of Science Tokyo, 2024.

宇宙線？

- 宇宙線：宇宙を飛び交う高エネルギー粒子の総称
  - 高エネルギー： 1 GeV = 10^9eV = 10億eV 以上
  - 粒子：陽子、原子核、電子・陽電子、γ線、ν, etc.
  - 狭義には 1GeV 以上の陽子、原子核のみを指す
- 宇宙線の発見：1912 V. Hess （奧地利->美國）
  - 検電器を気球に載せた
  - 当時から地球内部起源の放射線は既知
  - 高度とともに放射線量は減るかと思われた -> 増加した
  - 放射線は下からではなく上から来ている
  - Nobel prize in 1936.

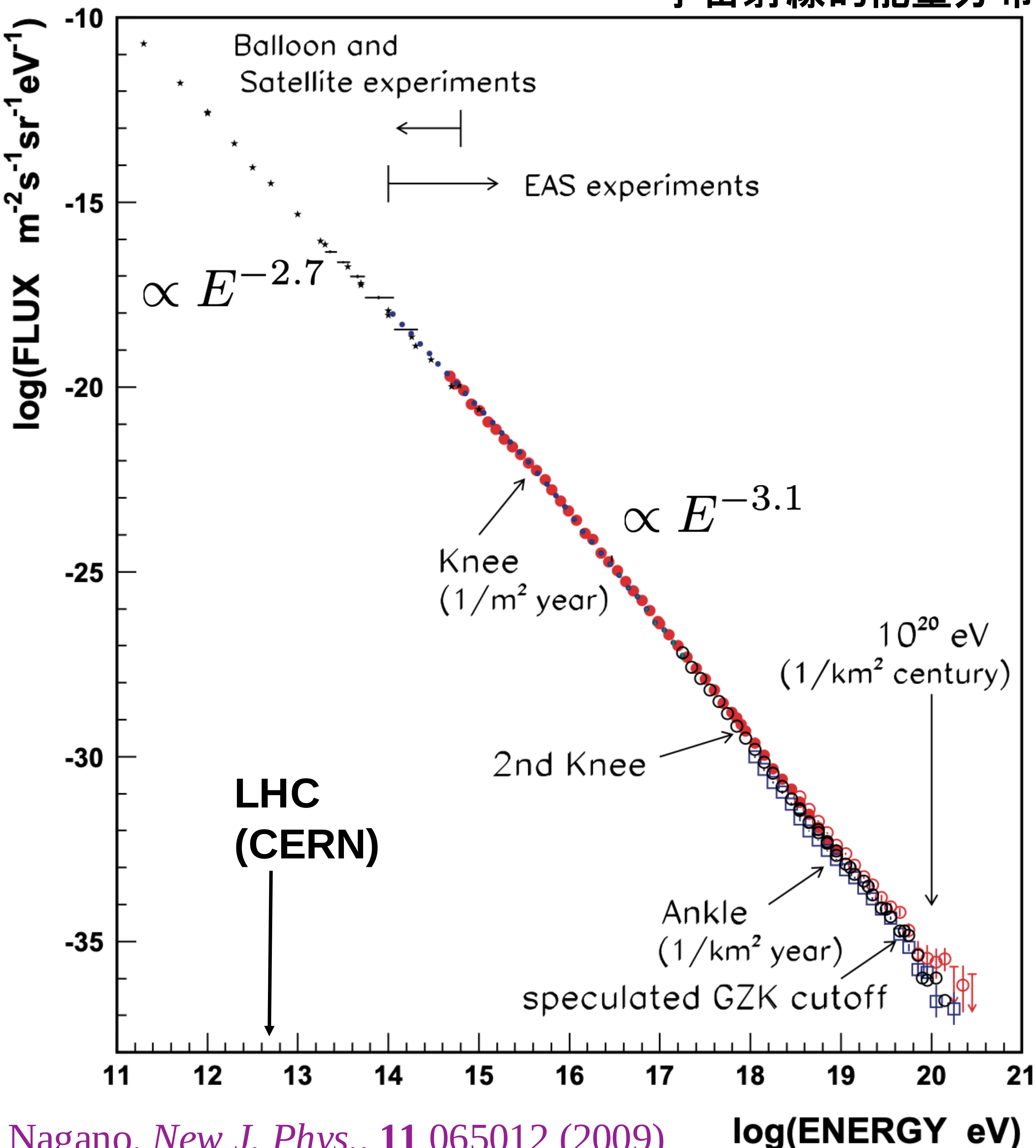
www.nobelprize.org

Cosmic Rays

High-energy, relativistic particles from the universe,
Proton and nucleus, with energies $E > 1\text{GeV}$

Energy Spectrum of Cosmic Rays

宇宙射線的能量分布



M. Nagano, *New J. Phys.*, **11** 065012 (2009)

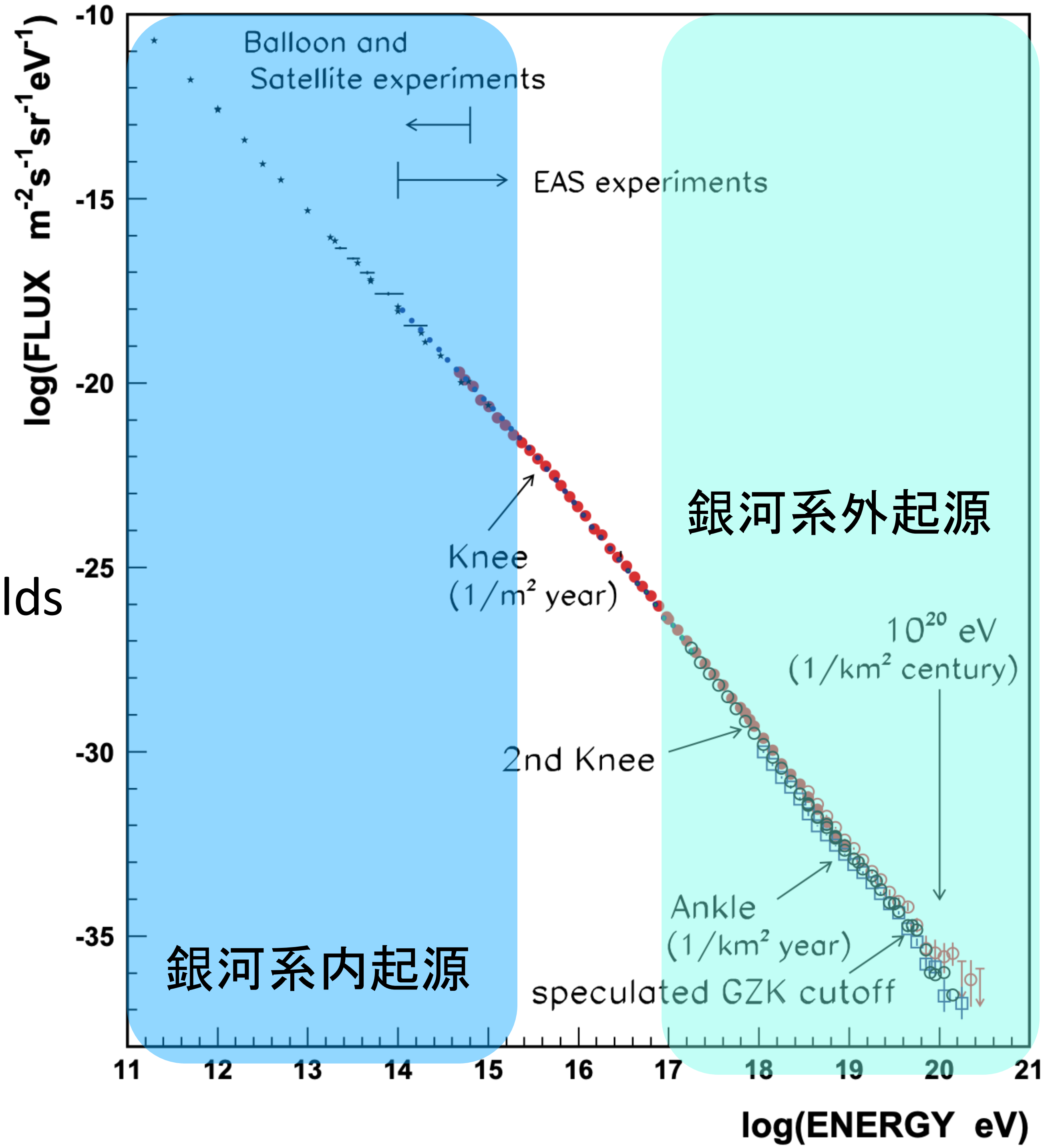
- 10^9 ~ 10^{20} eV
  - 11 order of magnitude = 10^9 eV x 100 billion
- Power-law energy distribution, $E^{-\gamma}$
  - γ ~ 3
  - Non-thermal
  - Very steep – high-energy cosmic rays exist, but their arrival frequency is super low.

Are we safe in such a “cosmic ray sea”?

- **Answer: Yes, you don’t have to worry about it.**
  - It's too late to realize you are in the cosmic ray sea, and panic. You've been exposed to cosmic rays ever since you were born. You don't have to worry about cosmic rays any more.
  - We are designed tough enough: Human being and all other living organism on this planet have evolved in an environment of continuous exposure to cosmic rays.
    - From analysis of meteorites: Cosmic ray intensity didn't change in 10^9 years.
- **即使在听了宇宙射**线的故事后感到不舒服，那也只是心理作用。

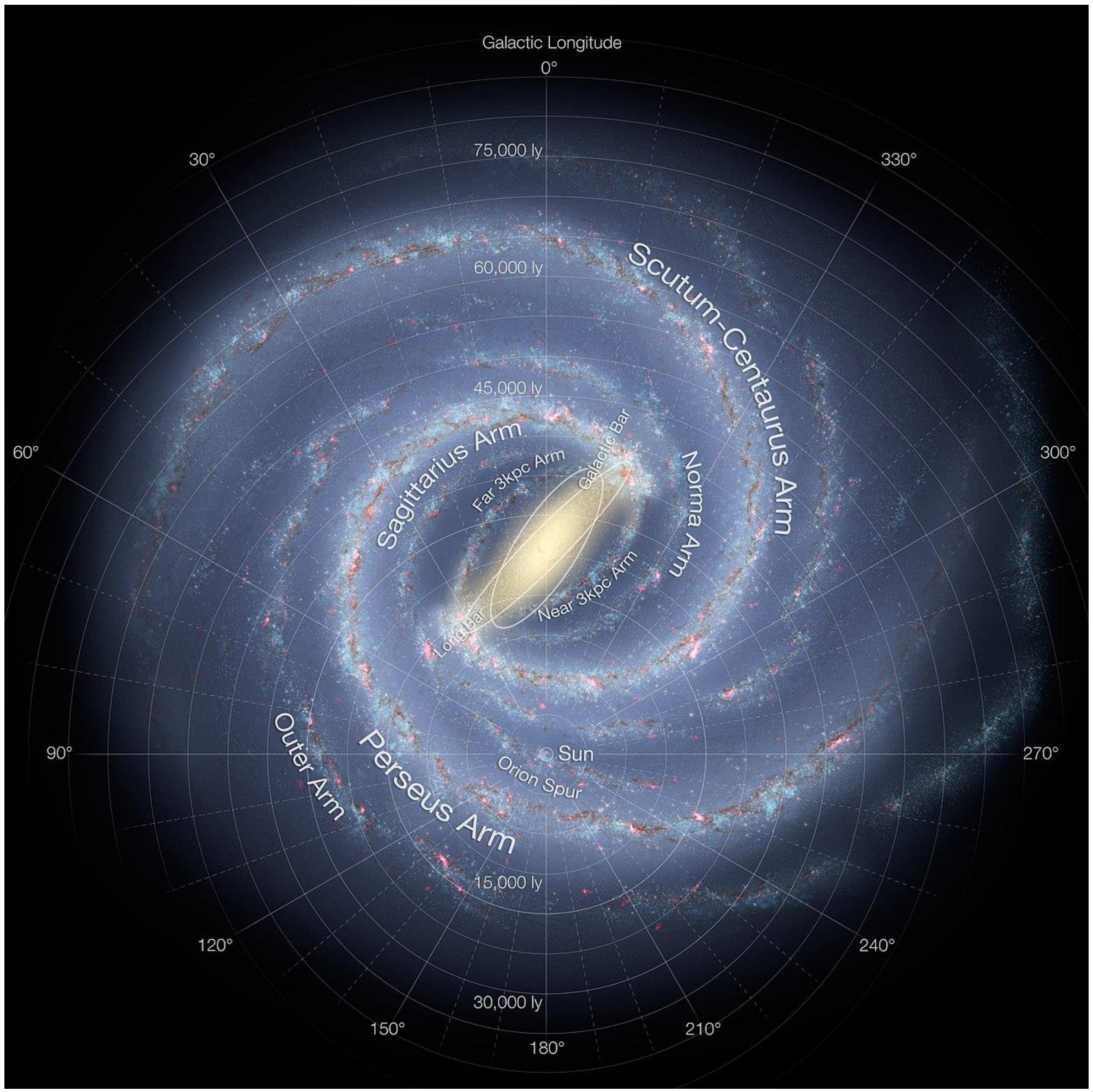
What are cosmic ray sources, where do they come from?

- Unknown.
  - Supernovae and active galaxies are the candidates
- General consensus:
  - Low-energy CRs: Galactic.
  - High-energy CRs: Extragalactic.
    - <-Size of galaxies and magnetic fields



Our Galaxy 銀河系

(the Milky Way)



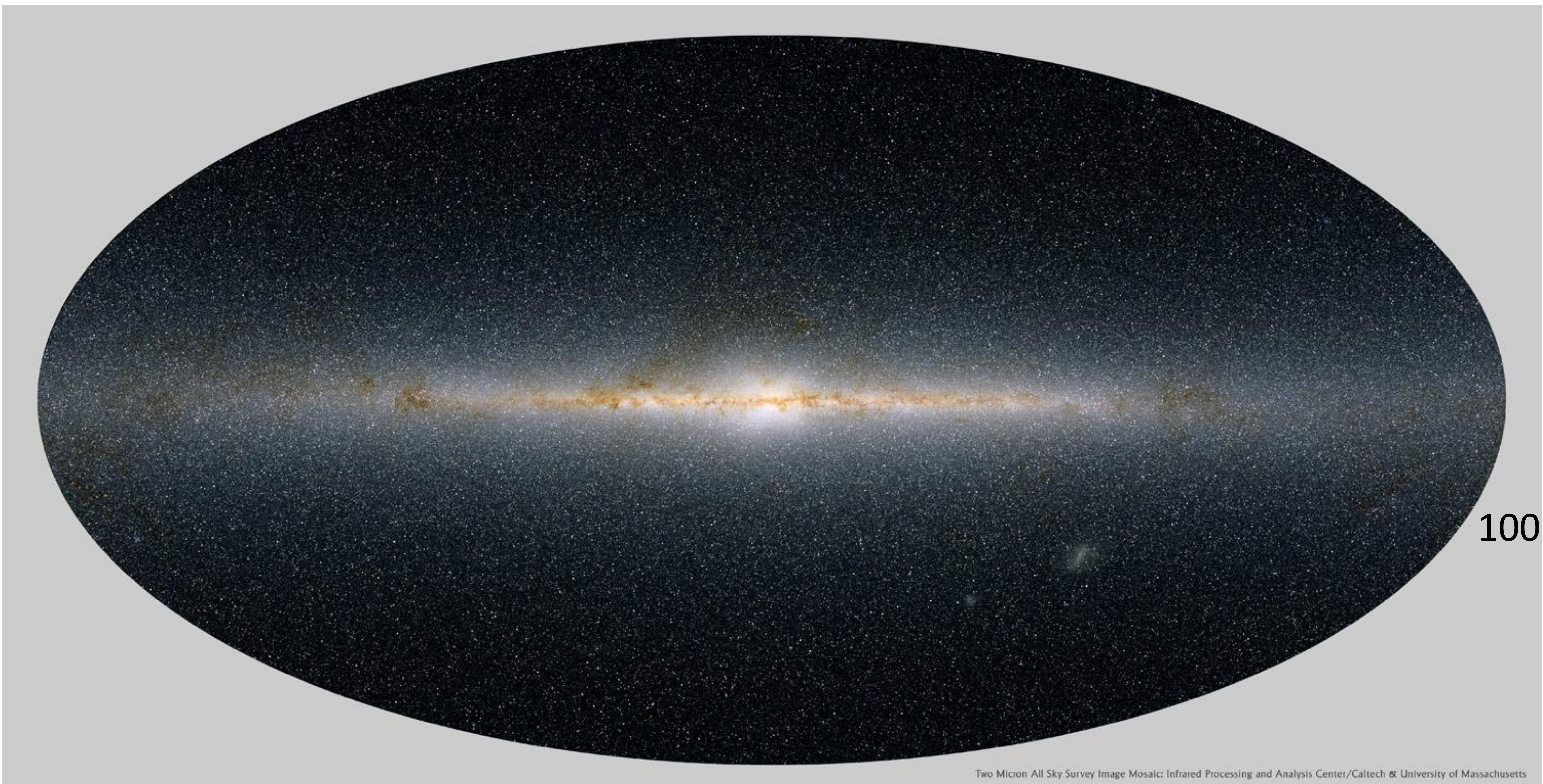
30kpc

- Huge cluster of stars and gasses
- Typical size of a galaxy is 10kpc in radius or diameter

- 1pc = $3x10^{16}$ m = 3.26 ly
- Average distance between stars in the galaxy

Our Galaxy is very thin

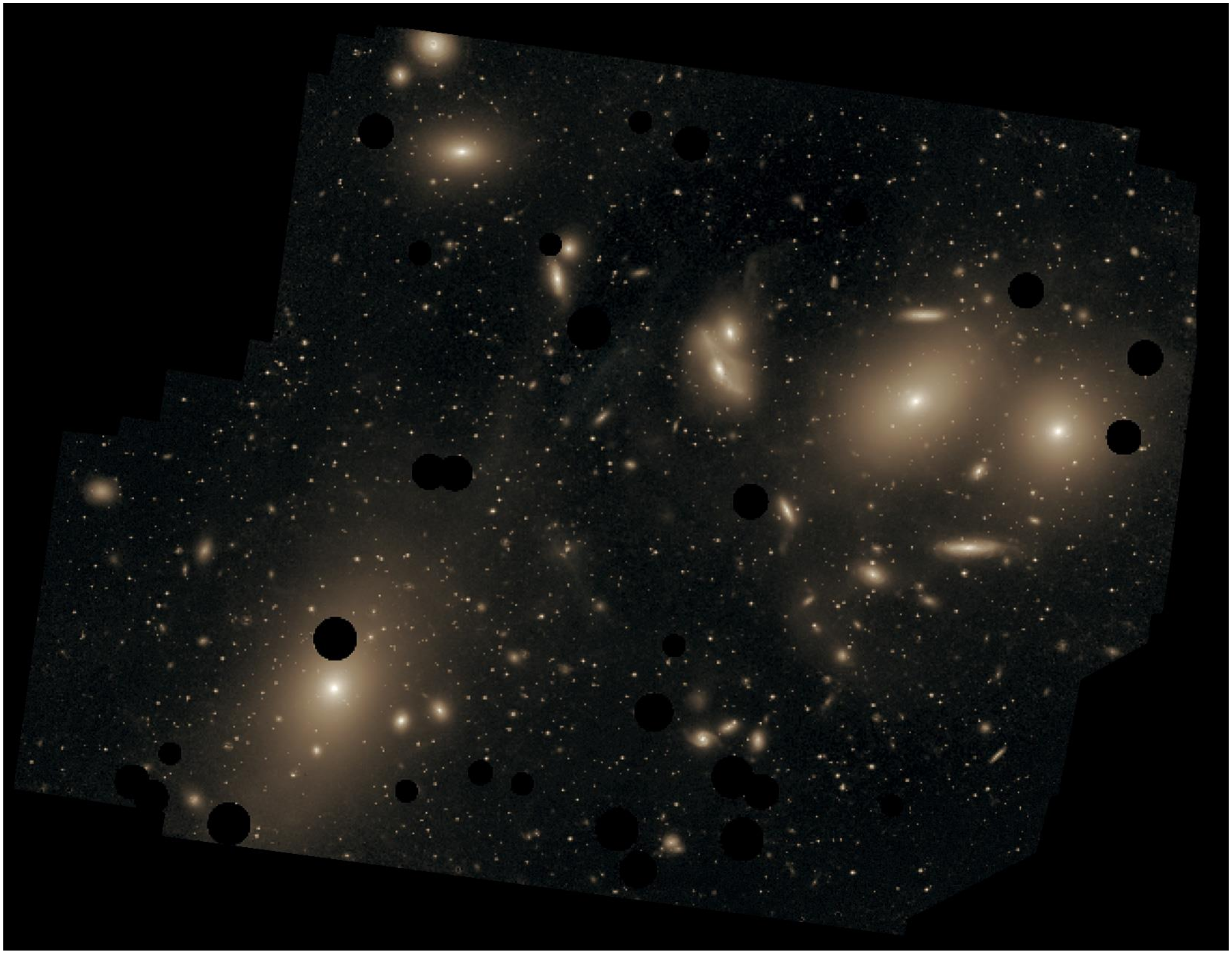
30kpc



100pc

Radius : Thickness = 100 : 1

So many galaxies in the universe



- At least trillion galaxies in the universe
- Typical size of a galaxy is 10kpc
- Average distance between galaxies : 1Mpc

Wherever you go in the universe there is a magnetic field.

- Galactic B field: ~1uG
- Extragalactic B field: ~1nG
- C.f.
  - Geomagnetic field: 0.1G
  - Blackboard magnet: 1000G
  - Very strong magnet: 10^4G = 1T

Cosmic Rays in Galactic B Field (uG)

- Cosmic rays : proton and nuclei : charged particles
- Charged particle in B field gyrates <-- Lorentz force.
- E.g. Gyration radius of a 10^{15}eV cosmic ray in μG

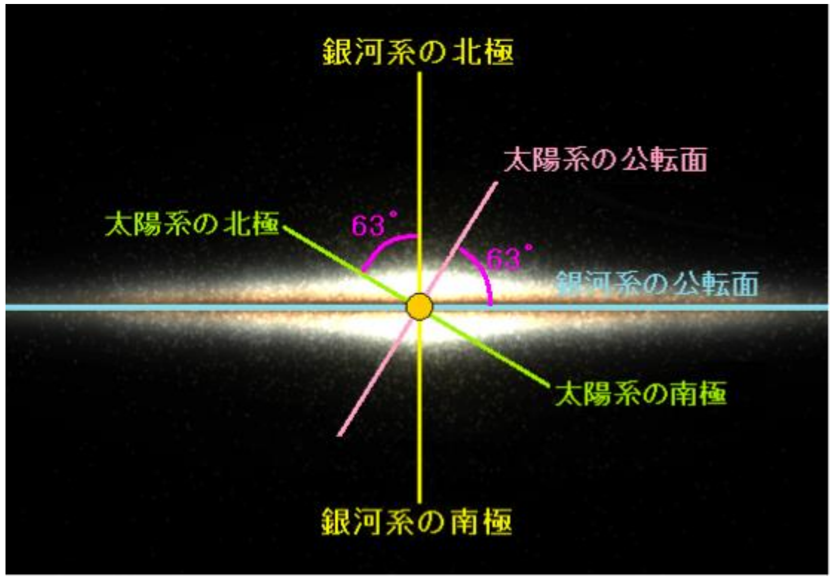
$$R = \frac{E}{eB} \quad = \frac{(10^{15}\mathrm{eV}) \times (1.6 \times 10^{-12}\mathrm{erg/eV})}{(4.8 \times 10^{-10}\mathrm{esu}) \times (10^{-6}\mathrm{G})}$$

$$= 1\mathrm{pc} \left(\frac{E}{10^{15}\mathrm{eV}} \right) \left(\frac{1\mu\mathrm{G}}{B} \right)$$

銀河磁場内の宇宙線

- 銀河系：半径 15kpc, 厚さ 100pc (very very thin!),
- 磁場 1μG

100pc



30kpc

$$R = \frac{E}{eB} = 1\mathrm{pc}\left(\frac{E}{10^{15}\mathrm{eV}}\right)\left(\frac{1\mu\mathrm{G}}{B}\right)$$

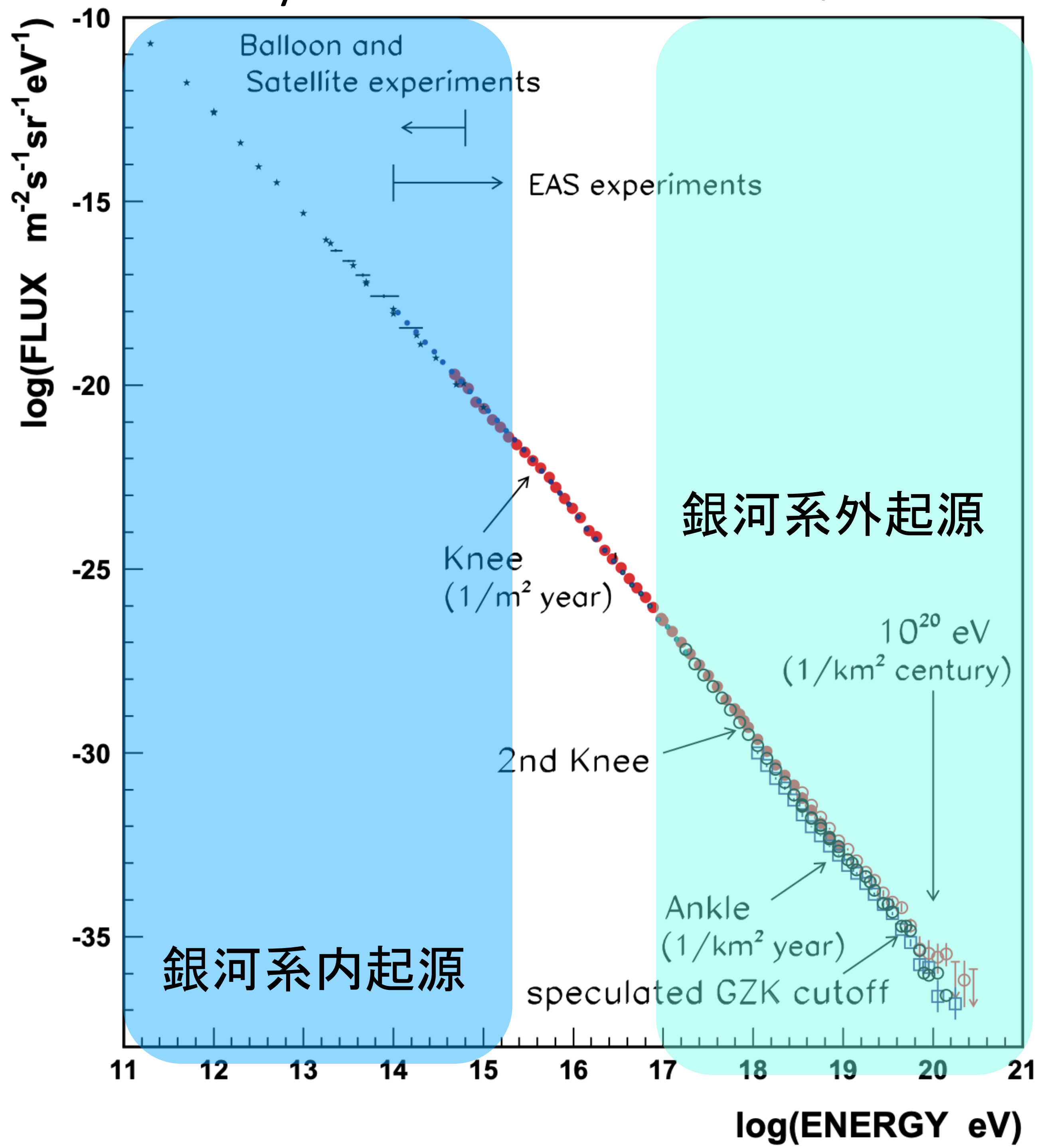
- $E < 10^{15}$eV : Confined in the Galaxy.
  - *R* is much smaller than the thickness of the Galaxy.
  - Magnetic field is turbulent, and trajectory is complicated.
  - Cannot travel long distance. Totally confined in the Galaxy.
  - Do not come from outer galaxies.
- $E > 10^{17}$eV : No more confined in the Galaxy
  - They travel almost straight, ballistic.
  - If cosmic rays of $E > 10^{17}$eV are generated within the Galaxy, they must come from the plane of the Galaxy, but such *anisotropy* has not been observed. Cosmic ray arrival distribution is *isotropic*.

What are cosmic ray sources, where are they?

- Unknown.
- General consensus:
  - Low-energy CRs: Galactic.
  - High-energy CRs: Extragalactic.
  - The boundary is quite uncertain.

Confined in the Galavy

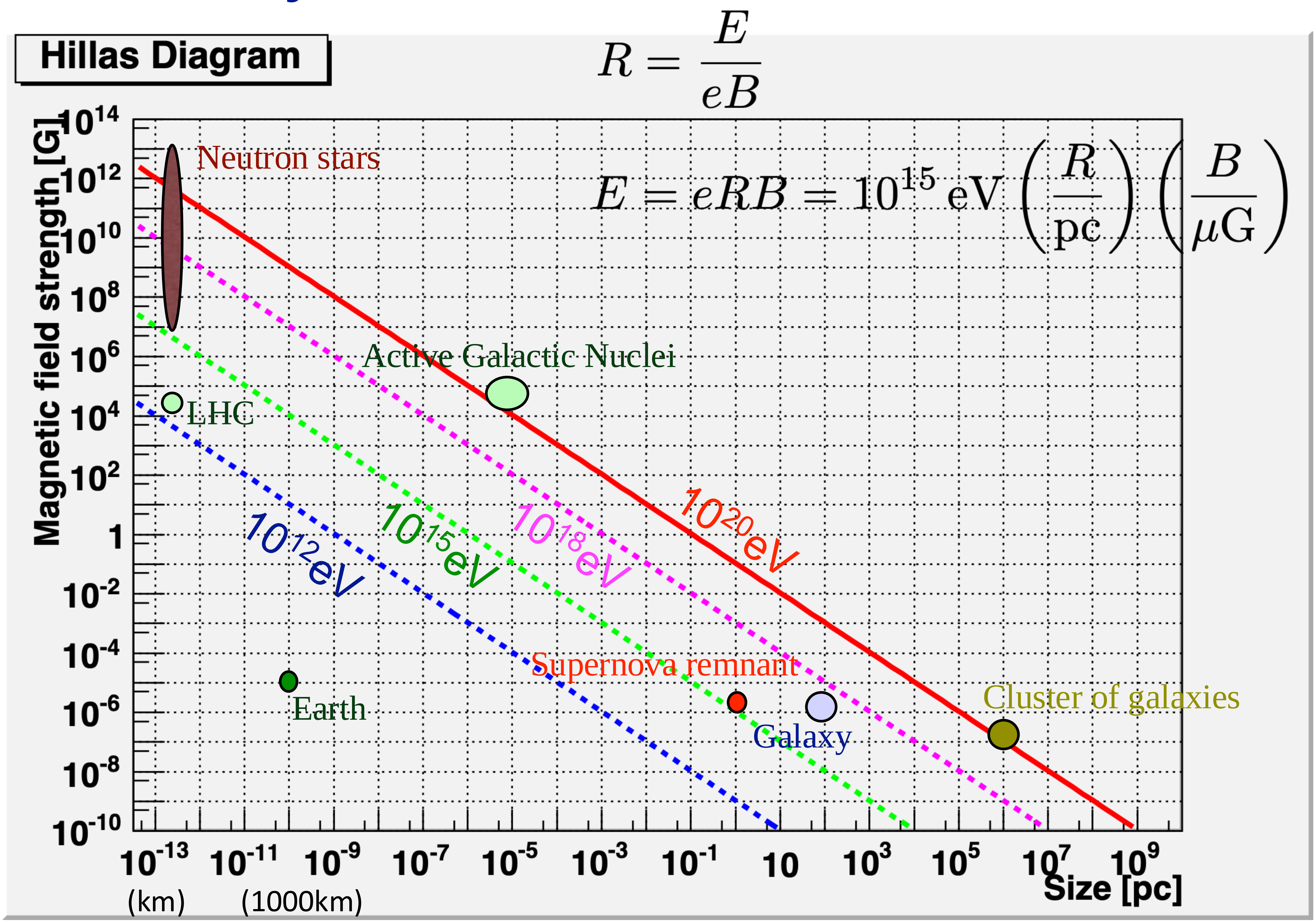
No more confined in the Galavy



10^{20}eV

- 10^{20}eV = 16J   A proton, microscopic particle, has a macroscopic energy
- Dropping 1kg object (10^{26} nucleons) from 1m height yields 10J
  - How a single proton can have 10J?

Necessary condition of CR acceleration



- The universe is vast, anything can happen, but accelerating a particle up to 10^{20} eV is, *ridiculous*, if we think about physics.

History of UHECR Researches

Phys. Rev. Lett., 16, 748 (1966)

END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

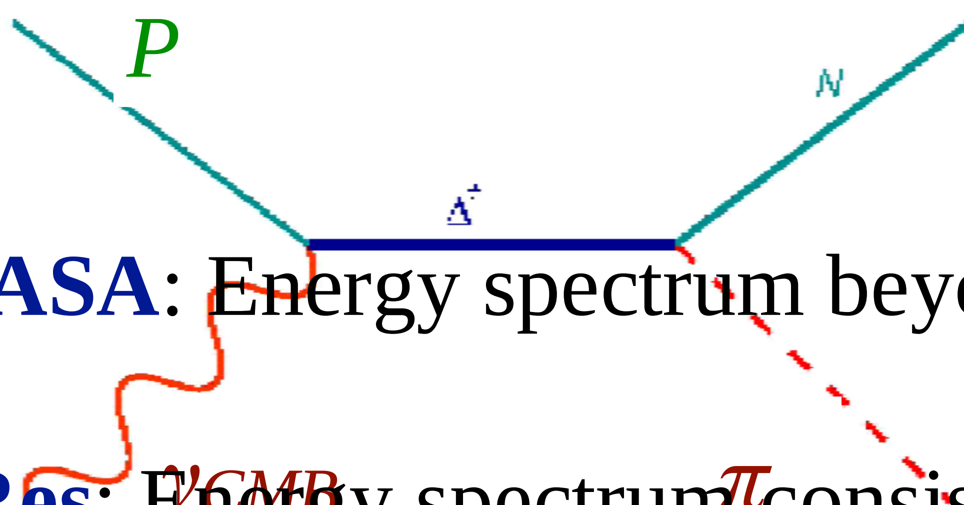
Cornell University, Ithaca, New York

(Received 1 April 1966)

The primary cosmic-ray spectrum has been measured up to an energy of 10^{20} eV,[1] and several groups have described projects under development or in mind[2] to investigate the spectrum further, into the energy range 10^{21}-10^{22} eV. This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.

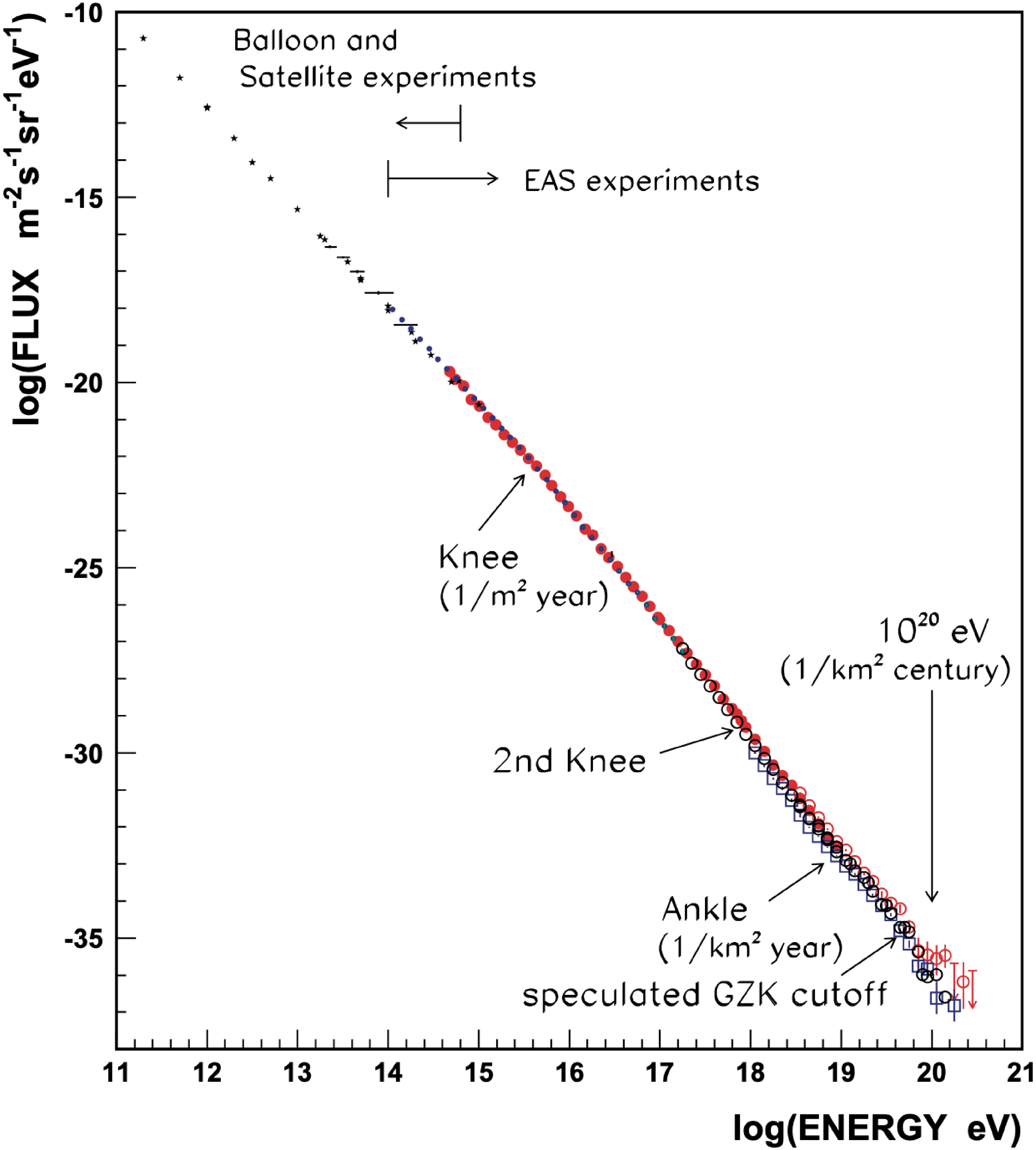
The cause of the catastrophic cutoff is the intense isotropic radiation first detected by Penzias and Wilson[3] at 4080 Mc/sec (7.35 cm) and now confirmed as thermal in character by measurements of Roll and Wilkinson[4] at 3.2 cm wavelength. It is not essential to the present argument that the origin of this radiation conform exactly to the primeval-fireball model outlined by Dicke, Peebles, Roll, and Wilkinson[5]; what matters is only that the radiation exists and pervades the observable universe. The transparency of space at the pertinent wavelengths, and the consistency of intensity observations in numerous directions,

- **19** … ct
- **1991 I**



Multipion production on CMB:
- $E_p > 5 \cdot 10^{19}$ eV
- Mean free path ~10 Mpc
- $\Delta E_p / E_p$ ~ 20%
- Energy attenuation length: R_{GZK} ~ 50 Mpc

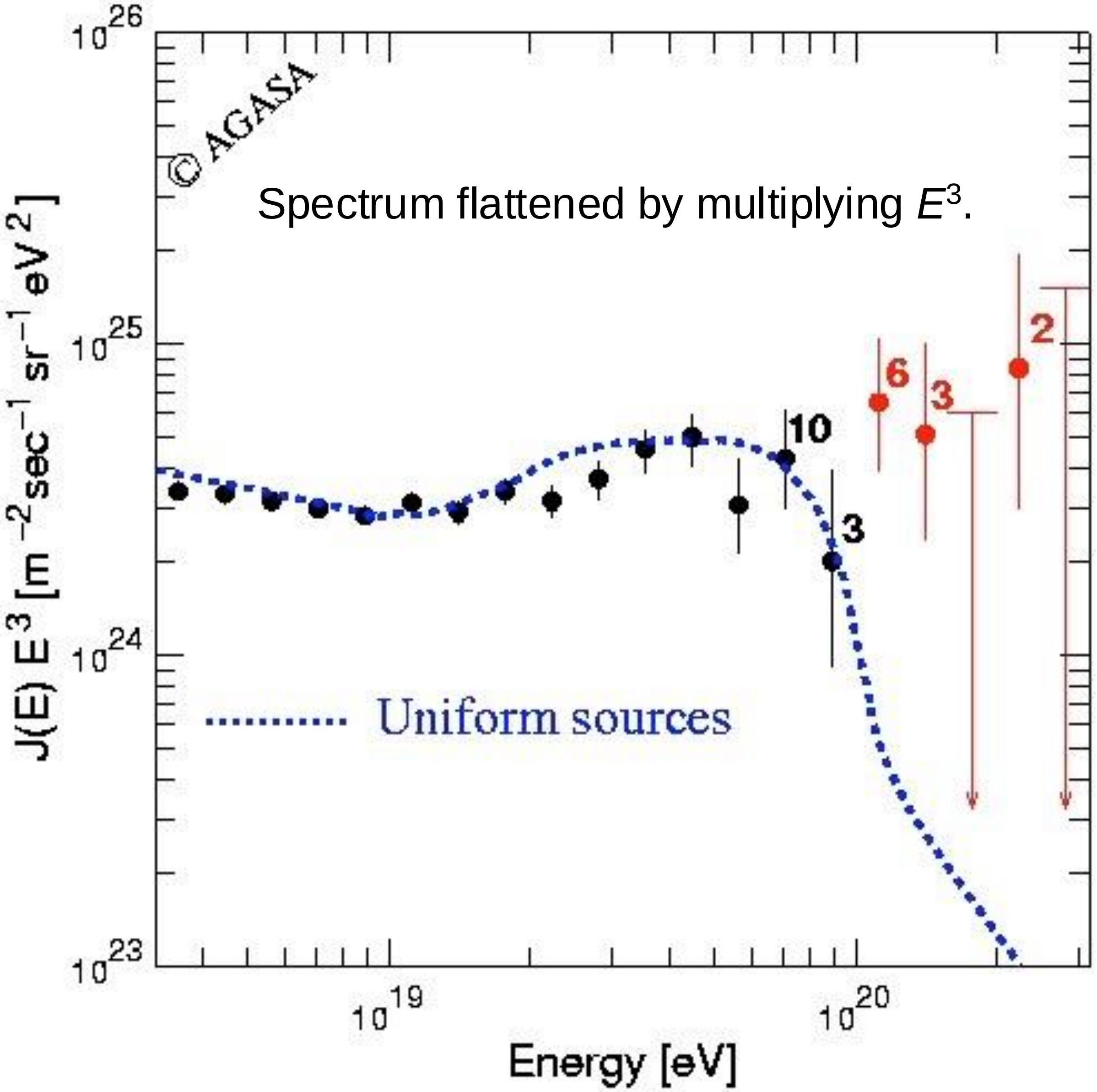
- **1998 AGASA**: Energy spectrum beyond the GZK energy
- **2002 HiRes**: Energy spectrum consistent with the GZK prediction



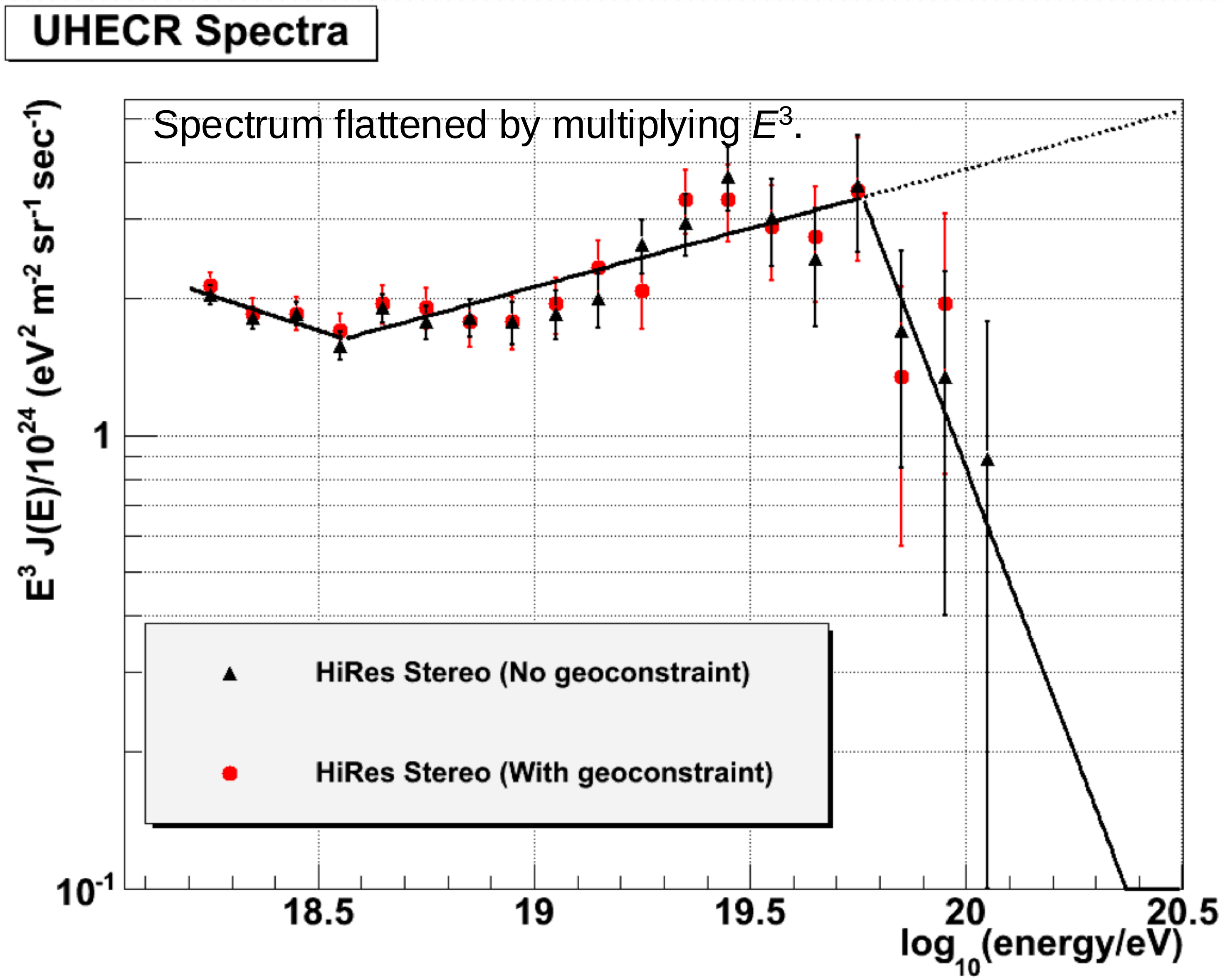
log(FLUX m-2s-1sr-1eV-1)
-10
-15
-20
-25
-30
-35
Balloon and
Satellite experiments
EAS experiments
Knee
(1/m² year)
2nd Knee
10²⁰ eV
(1/km² century)
Ankle
(1/km² year)
speculated GZK cutoff
11
12
13
14
15
16
17
18
19
20
21
log(ENERGY eV)

20th Century Results

AGASA （Japan）
(Akeno Giant Air Shower Array)

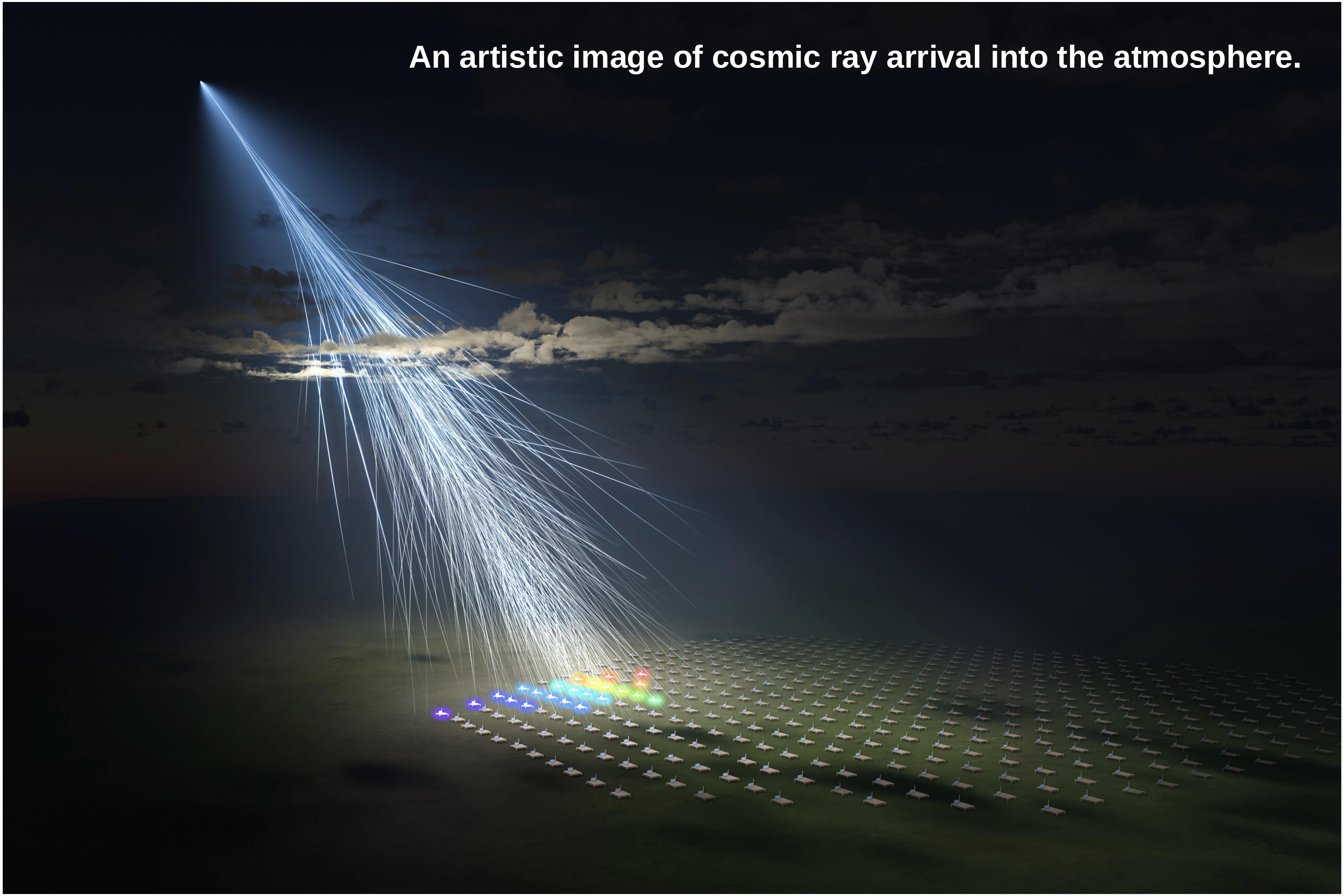


High-Resolution Fly's Eye (HiRes) （US）



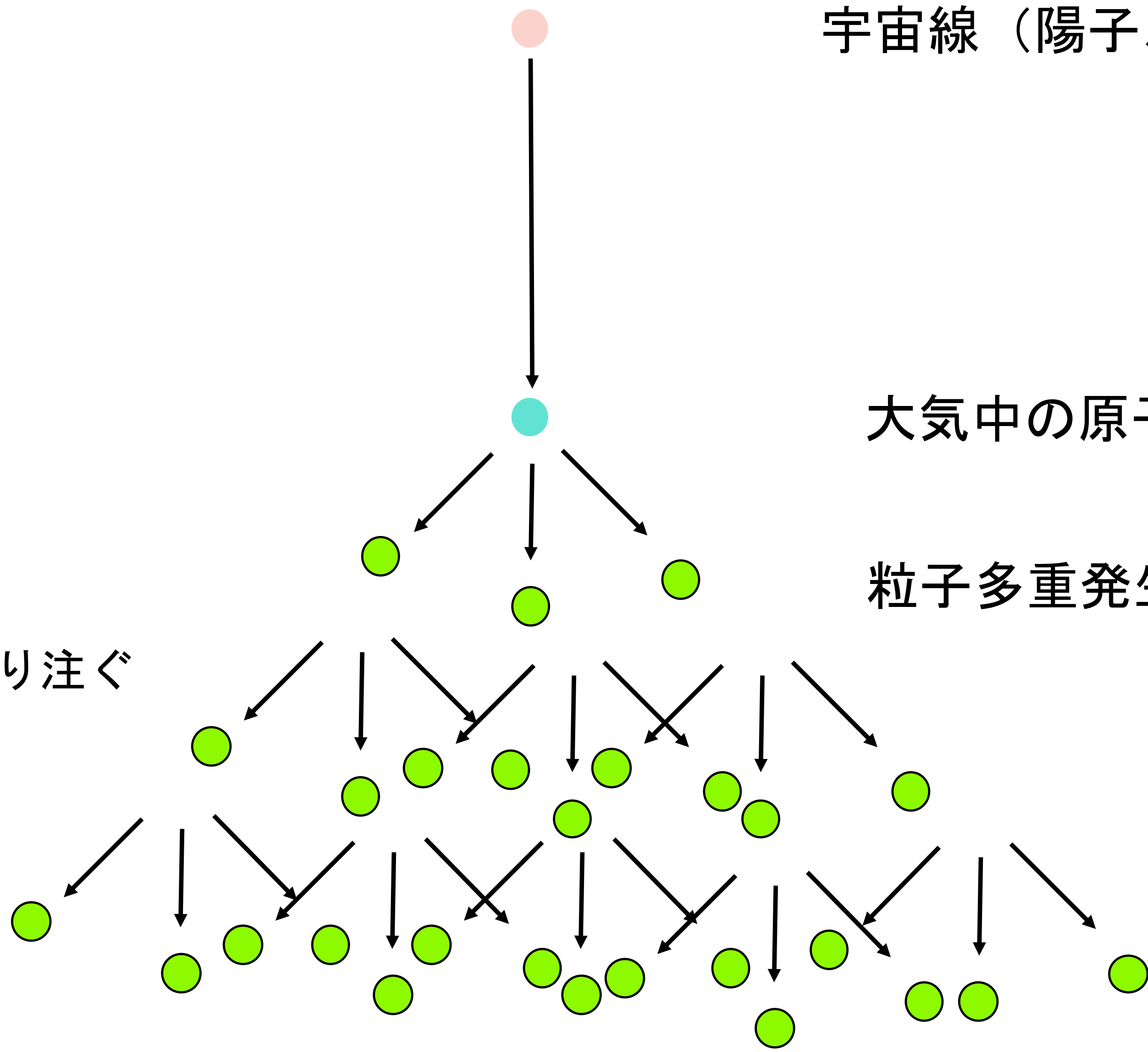
- Difficult to judge which was correct.
- Different techniques used in detection.

How to Detect UHECRs?


An artistic image of cosmic ray arrival into the atmosphere.

Air Shower Phenomenon

宇宙線（陽子、原子核）



大気中の原子核（酸素、窒素）

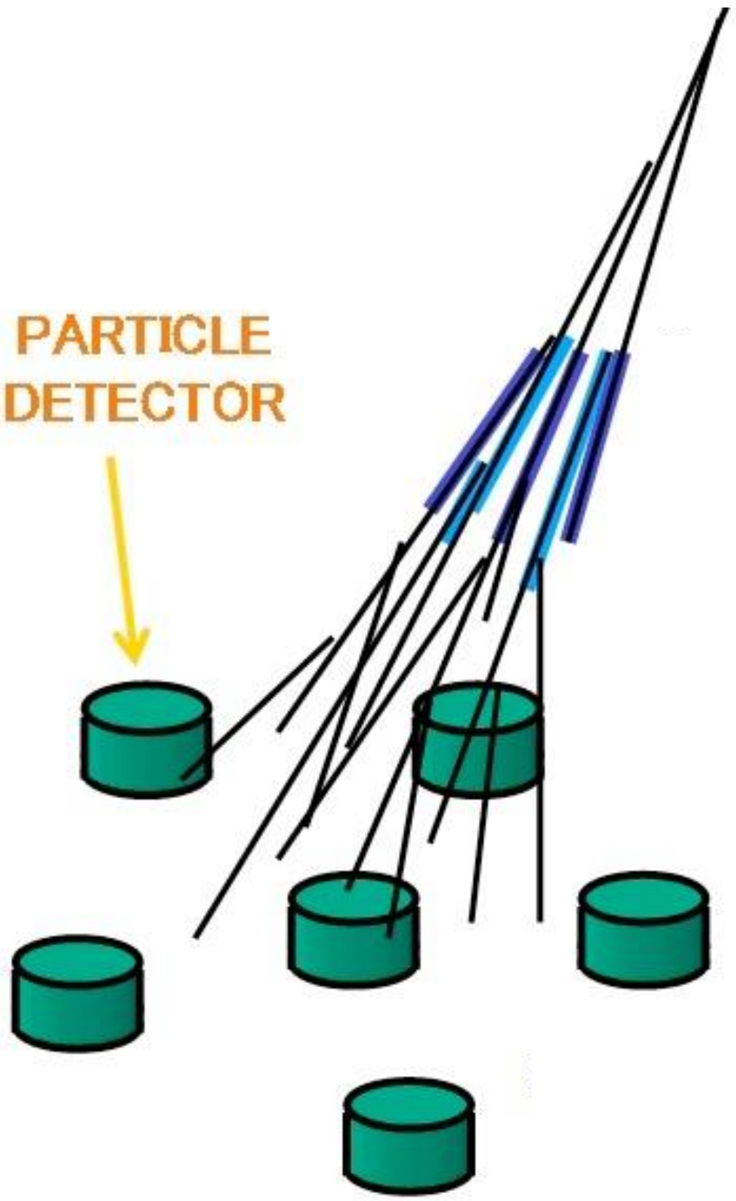
粒子多重発生

元は１個の宇宙線
-> 粒子の大群が降り注ぐ

「空気シャワー」

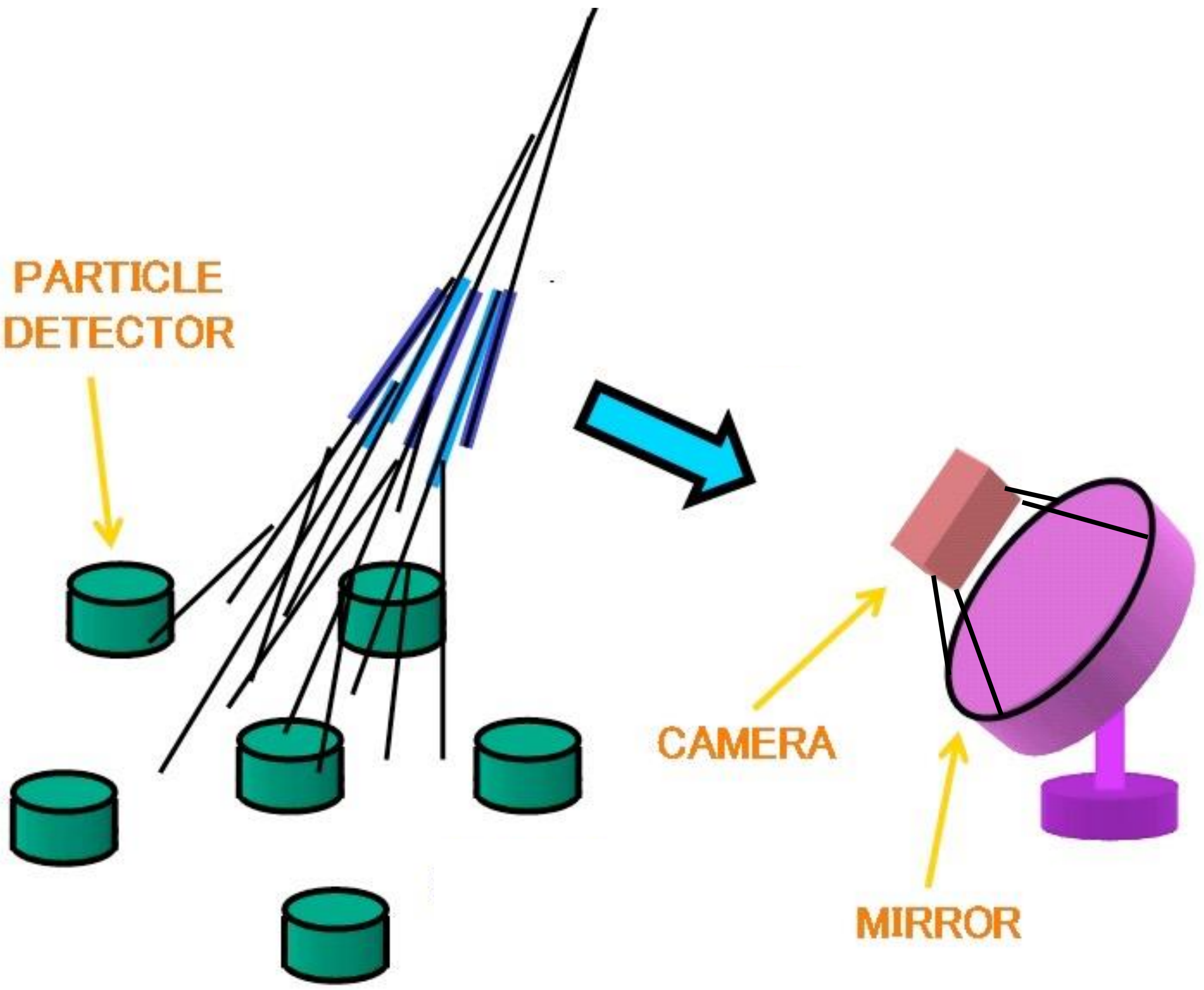
CR Detection
with Surface Detectors (SDs)

- CR in the atmosphere —> Cascade of particle productions -> Air showers.
- Deploy many SDs on the ground
- Traditional, since 1950
- AGASA.



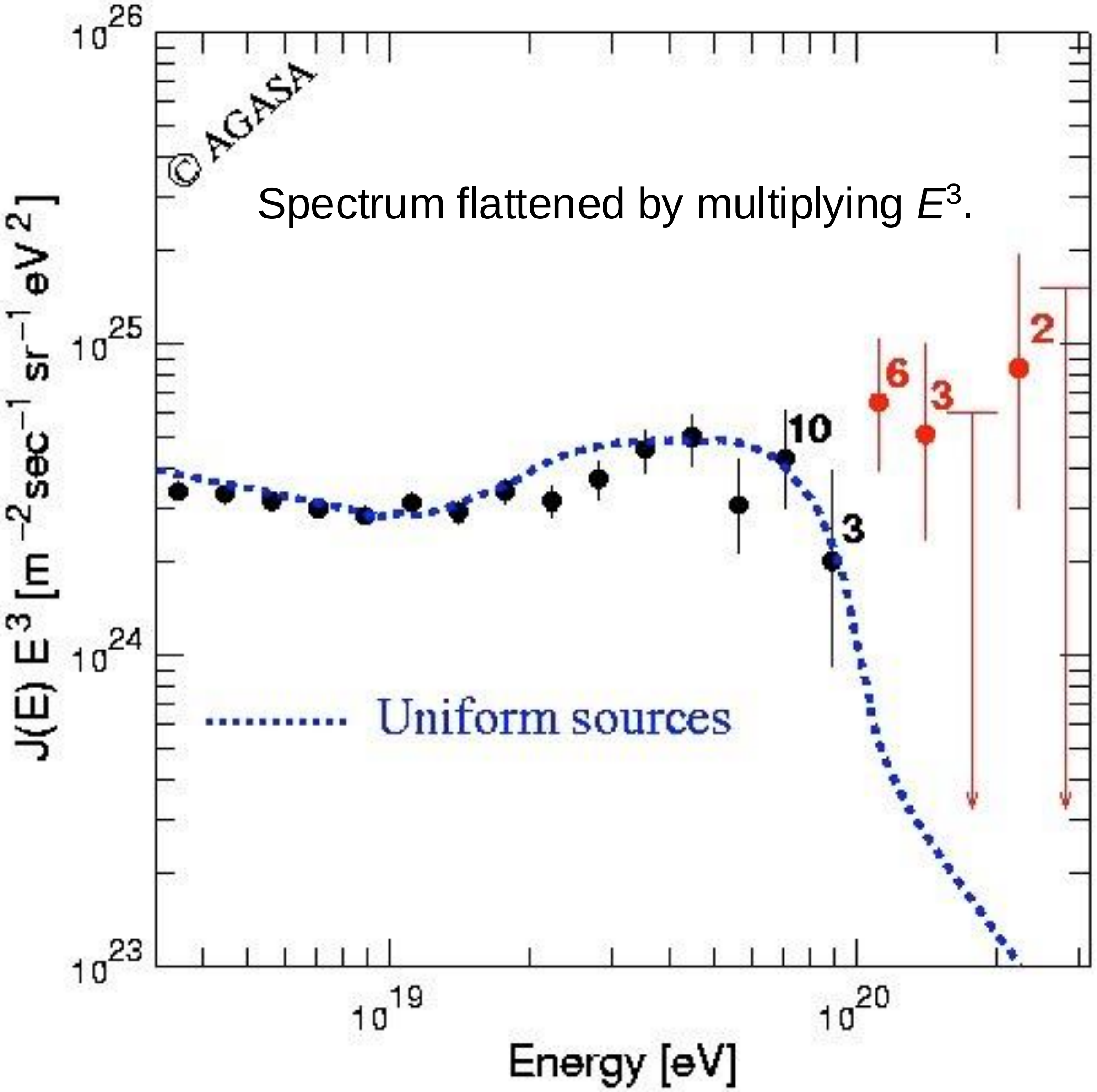
CR Detection with Fluorescence Detectors (FDs)

- UV emission from atmospheric molecules excited by charged particles in an air shower.
- Faint flash of photons are collected by mirrors and detected by highly sensitive photo sensors (photo-multiplier tubes)
- HiRes.



20th Century Results

AGASA （Japan）
(Akeno Giant Air Shower Array)



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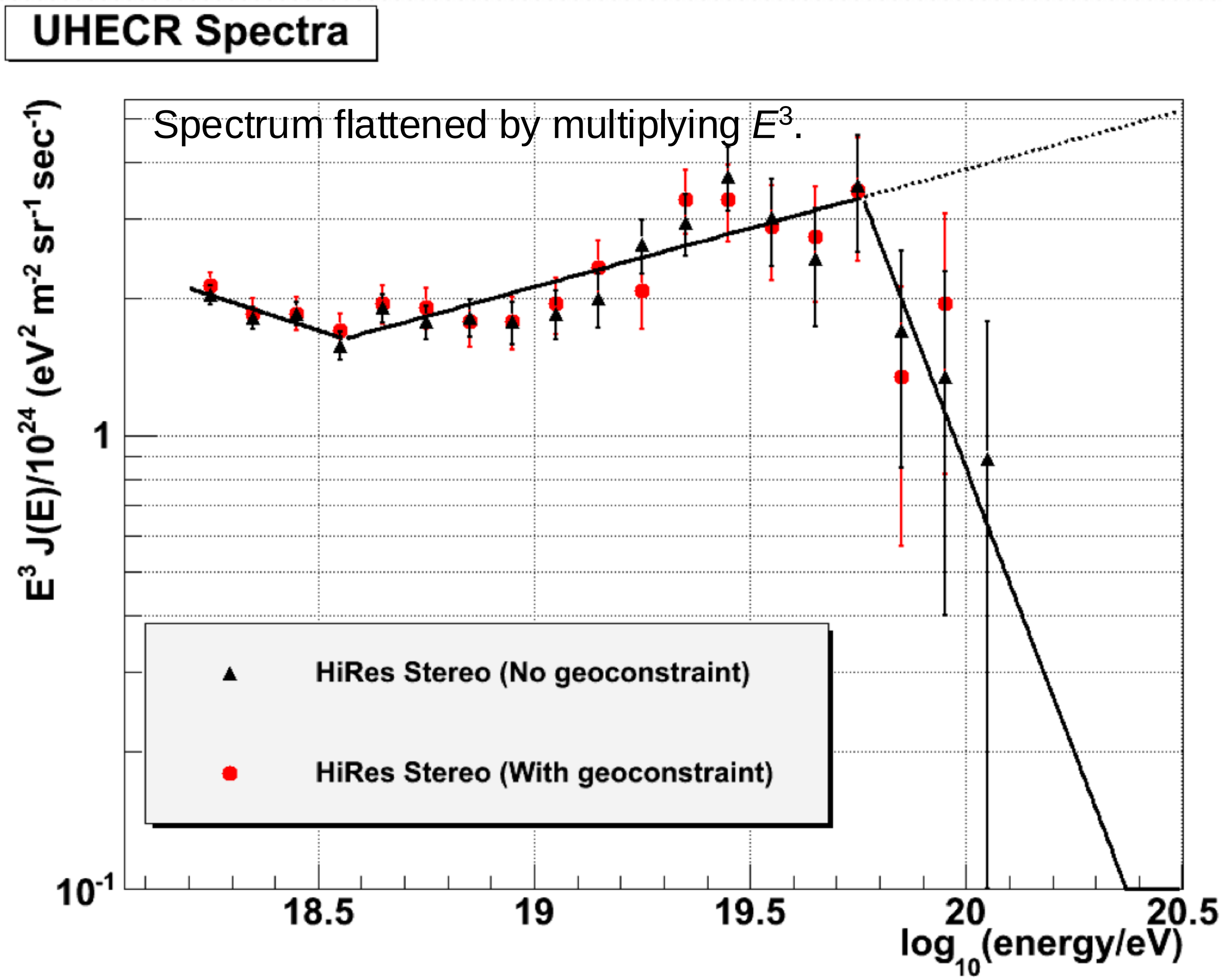


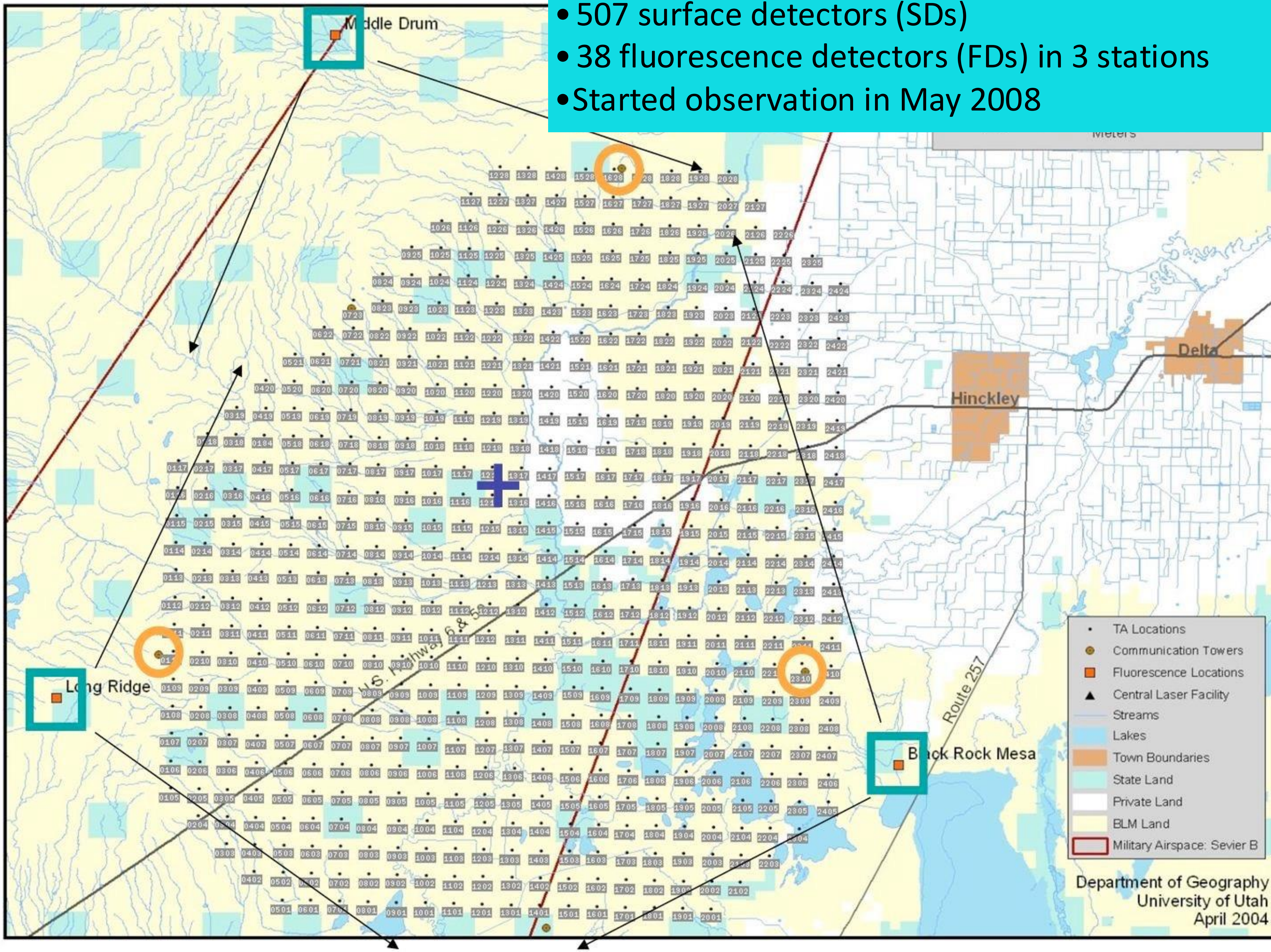
- Difficult to judge which was correct.
- Different techniques used in detection.

Telescope Array (TA)

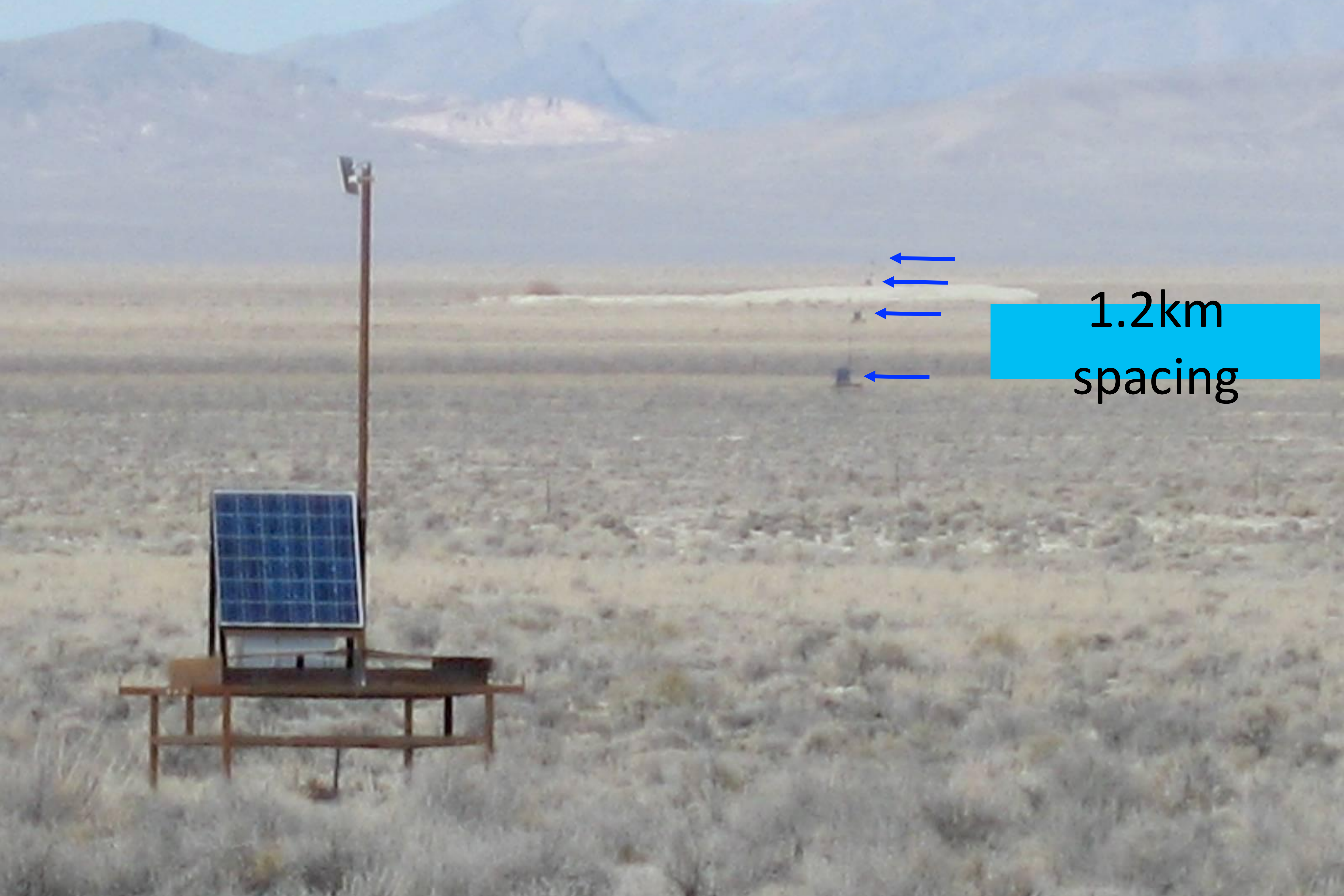
- The largest cosmic ray detector in the northern hemisphere.
  - Constructed in Utah, USA, by Japan, US, and Korea
  - 700km^2 c.f. Lake Biwa (琵琶湖), Singapore.
    - c.f. AGASA - 100km^2
  - International collaboration of Japan, US, Korea, Russia, ~150 researchers.
    - Japanese and American CR researchers united.
    - Reported by a newspaper “呉越同舟”
- Started operation in 2008
- YT serves as a co-PI since 2023.

Telescope Array (TA)

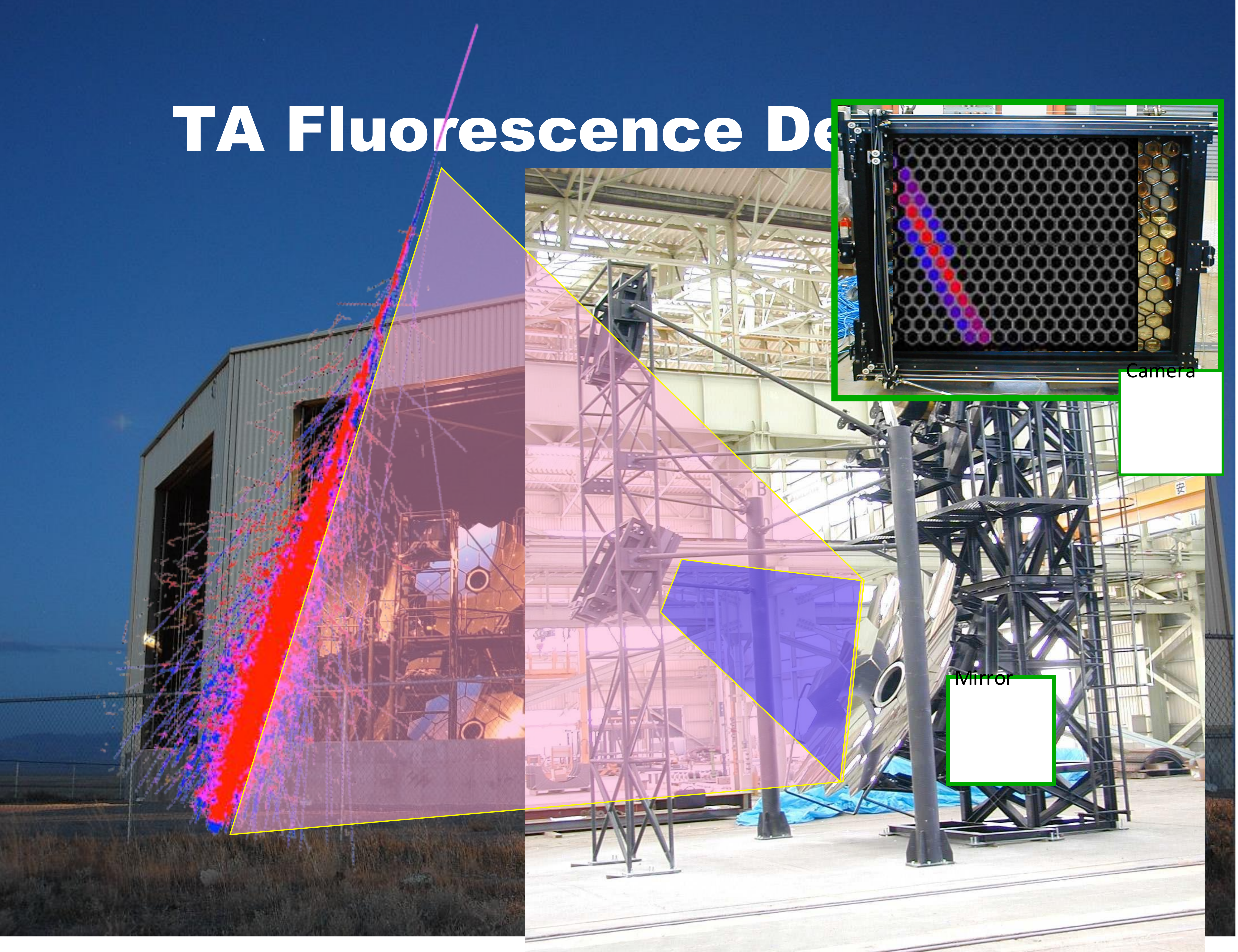
- 507 surface detectors (SDs)
- 38 fluorescence detectors (FDs) in 3 stations
- Started observation in May 2008



TA地表検出器 (SD)

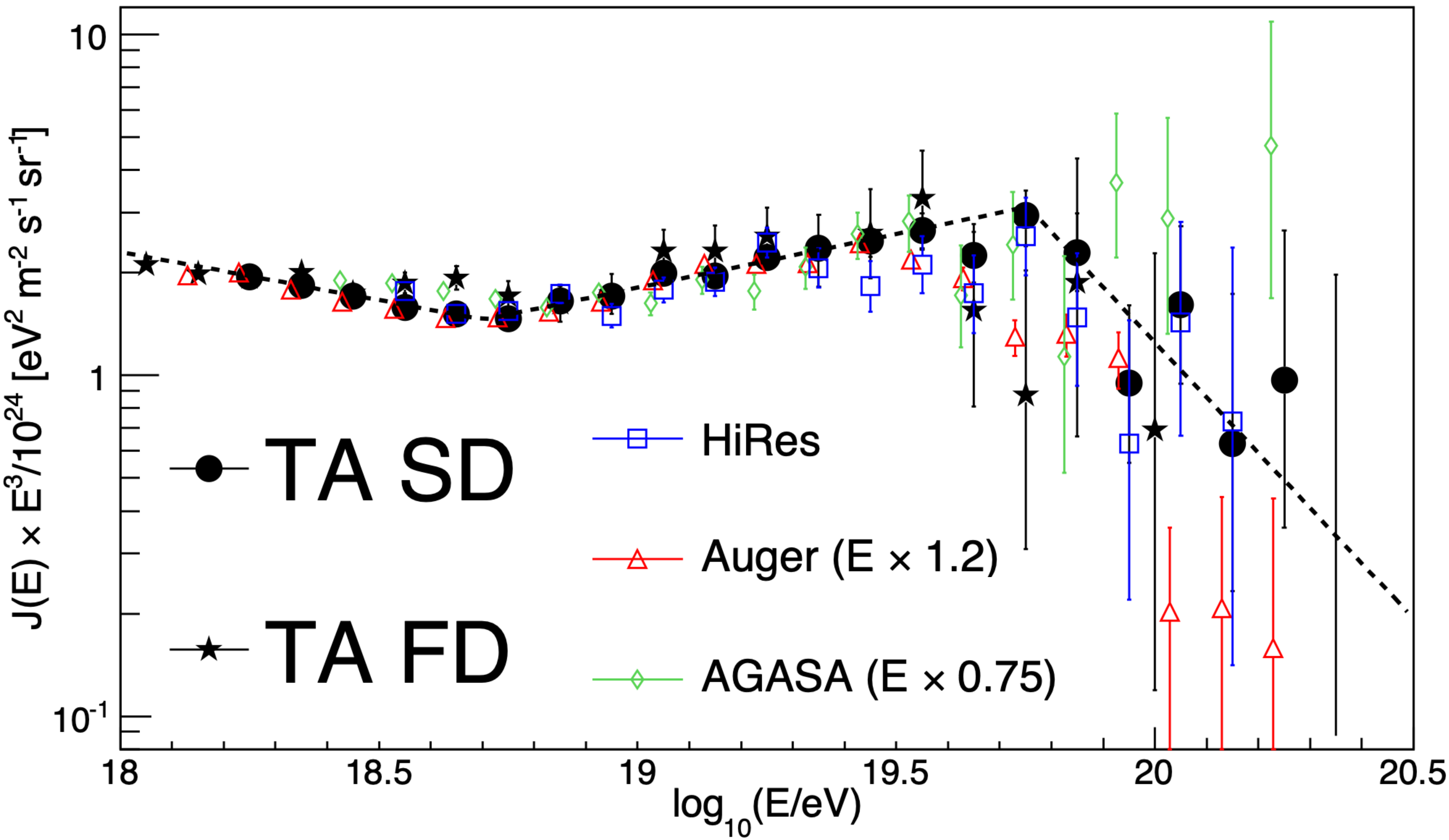


TA Fluorescence De



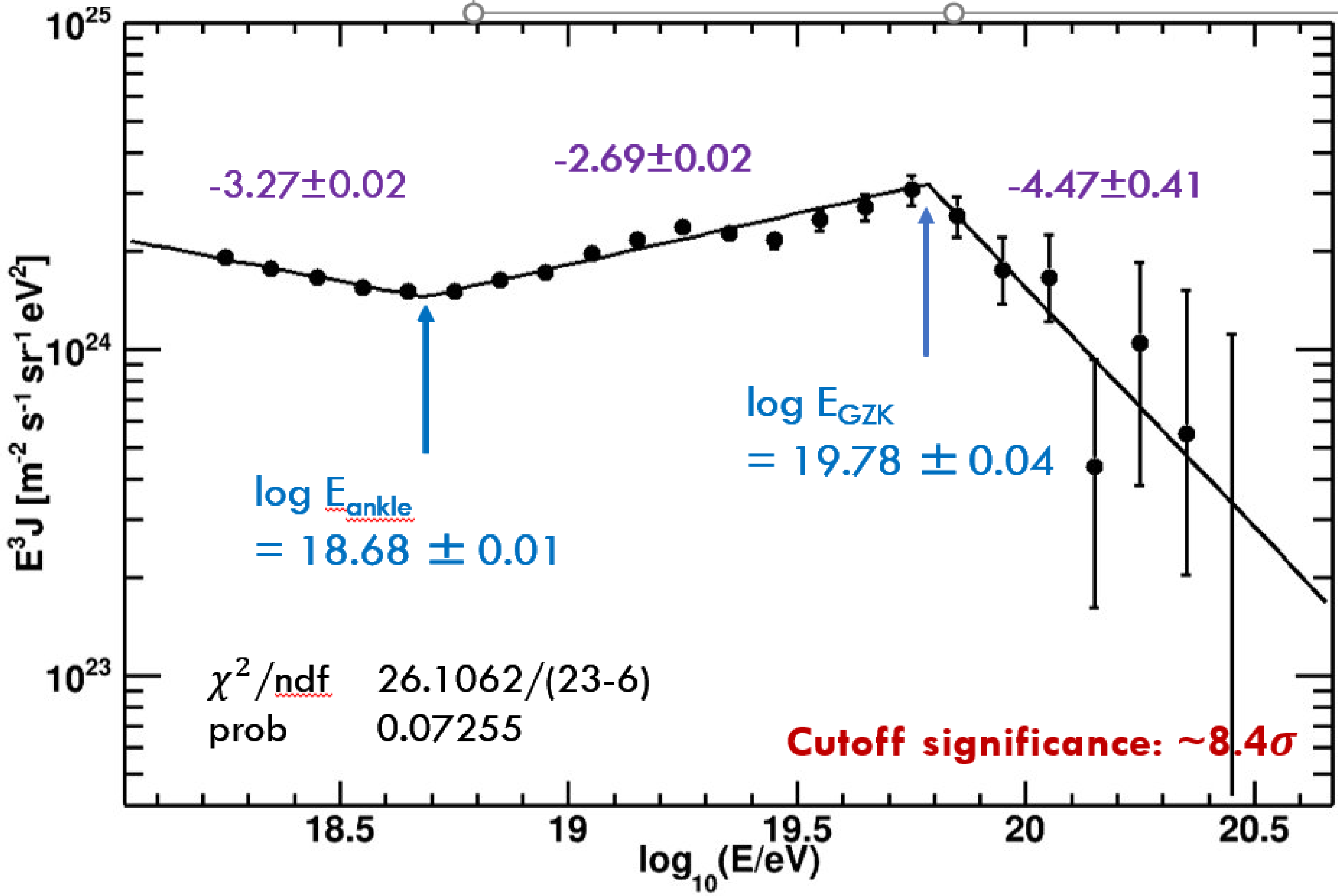
OMU Guys in the desert

TA Result 2011 :
Energy Spectrum of UHECRs

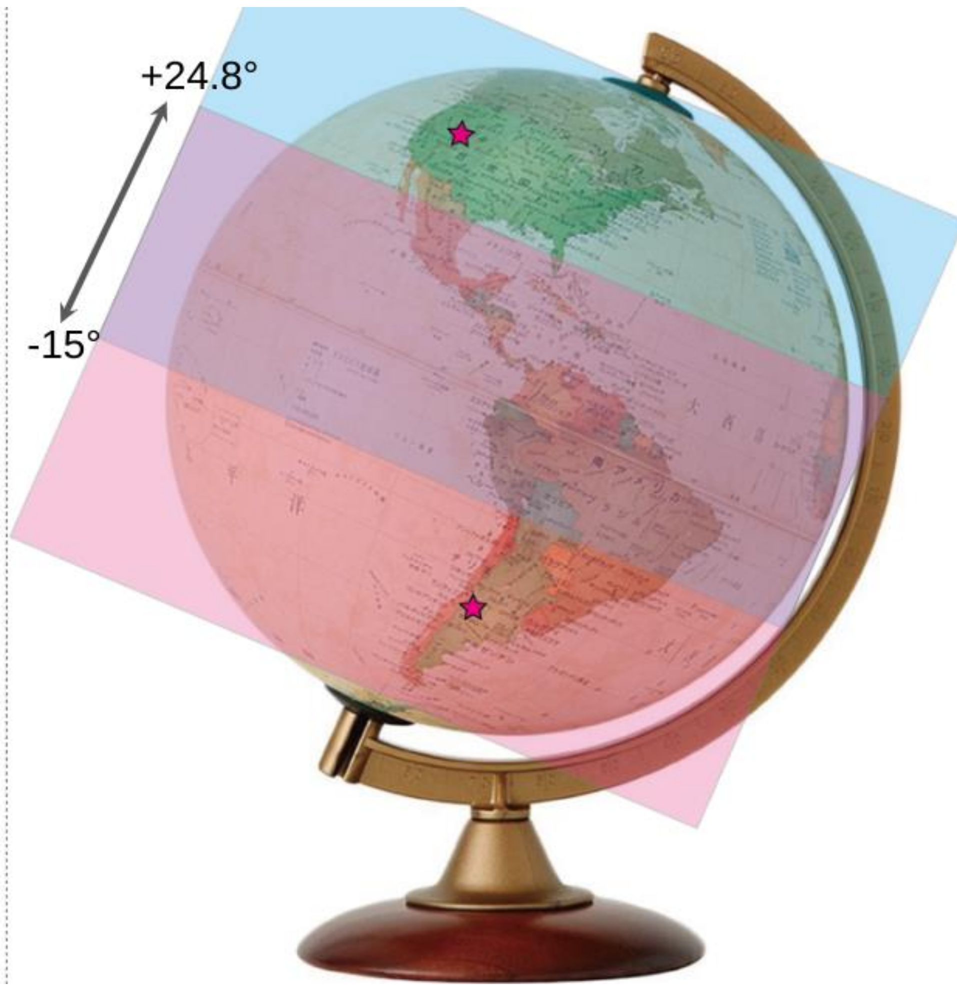


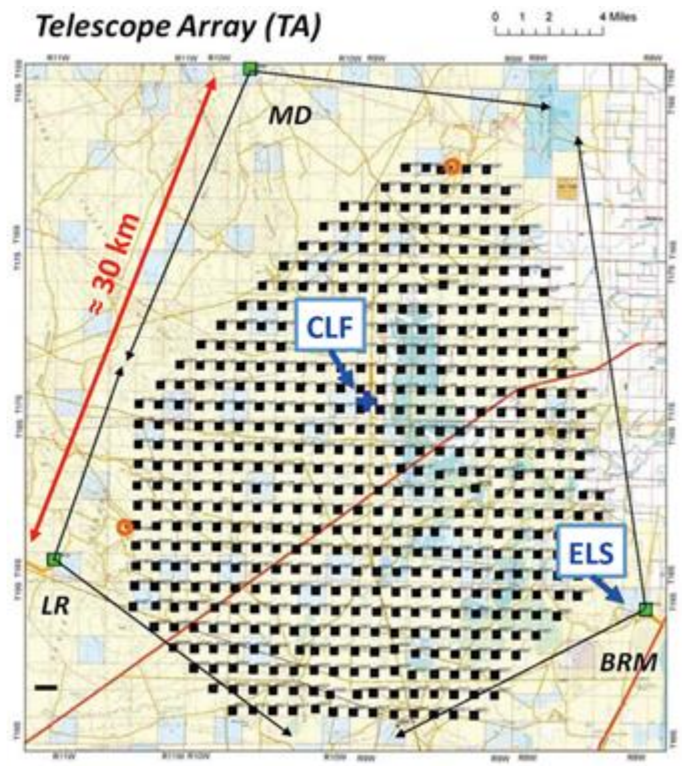
TA SD: Spectral Feature in 14-year Data

Observation periods: 2008-05-11 to 2022-05-10

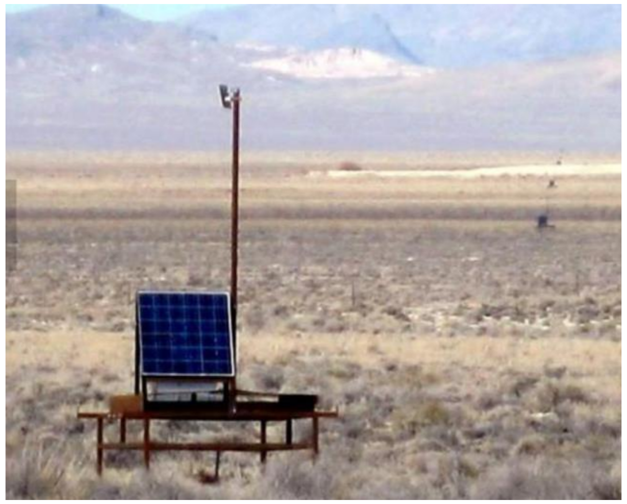


Observations in northern and southern hemispheres

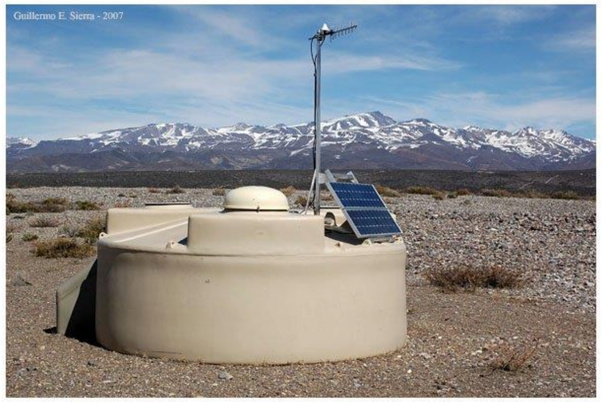


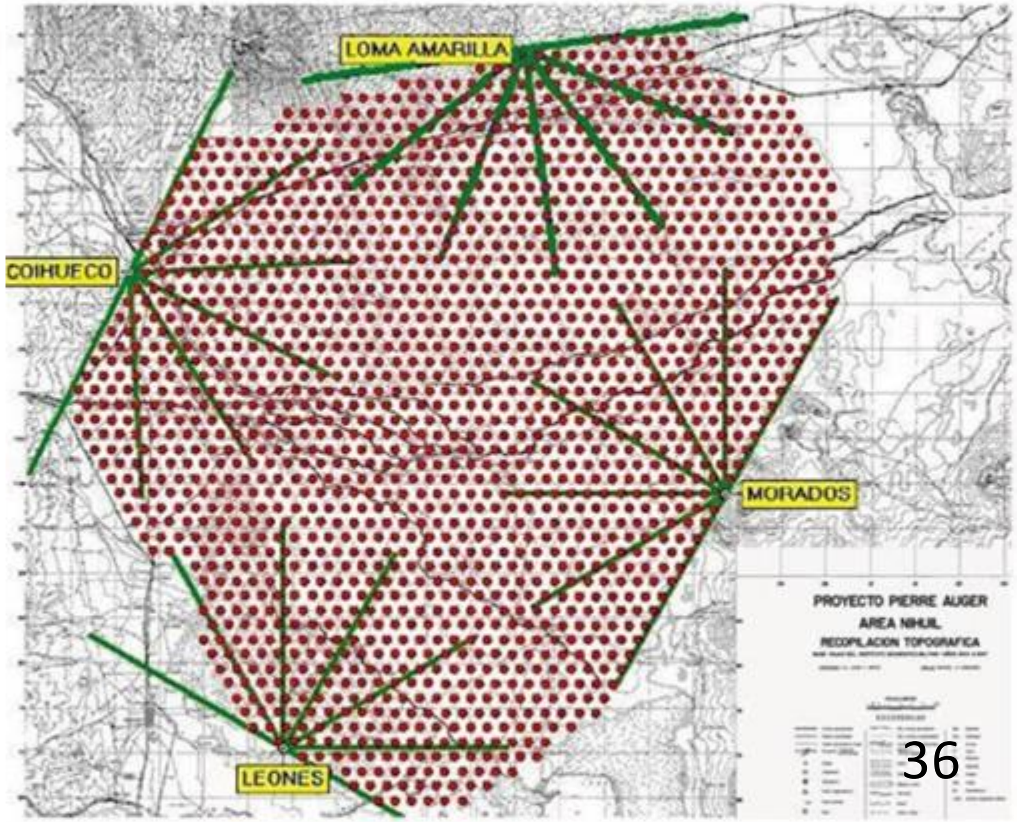


TA
39°N
700km^2

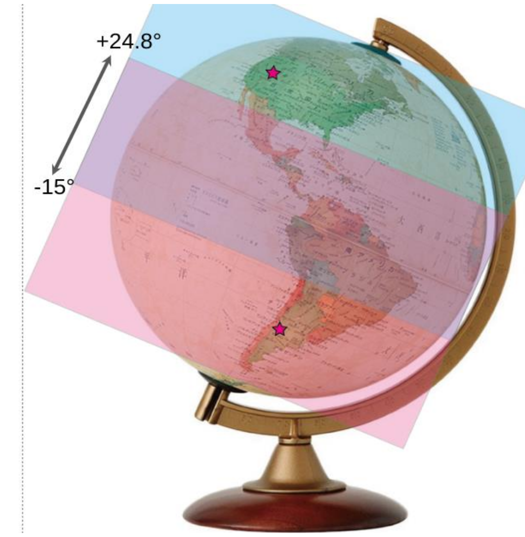


Auger
35°S
3000km^2

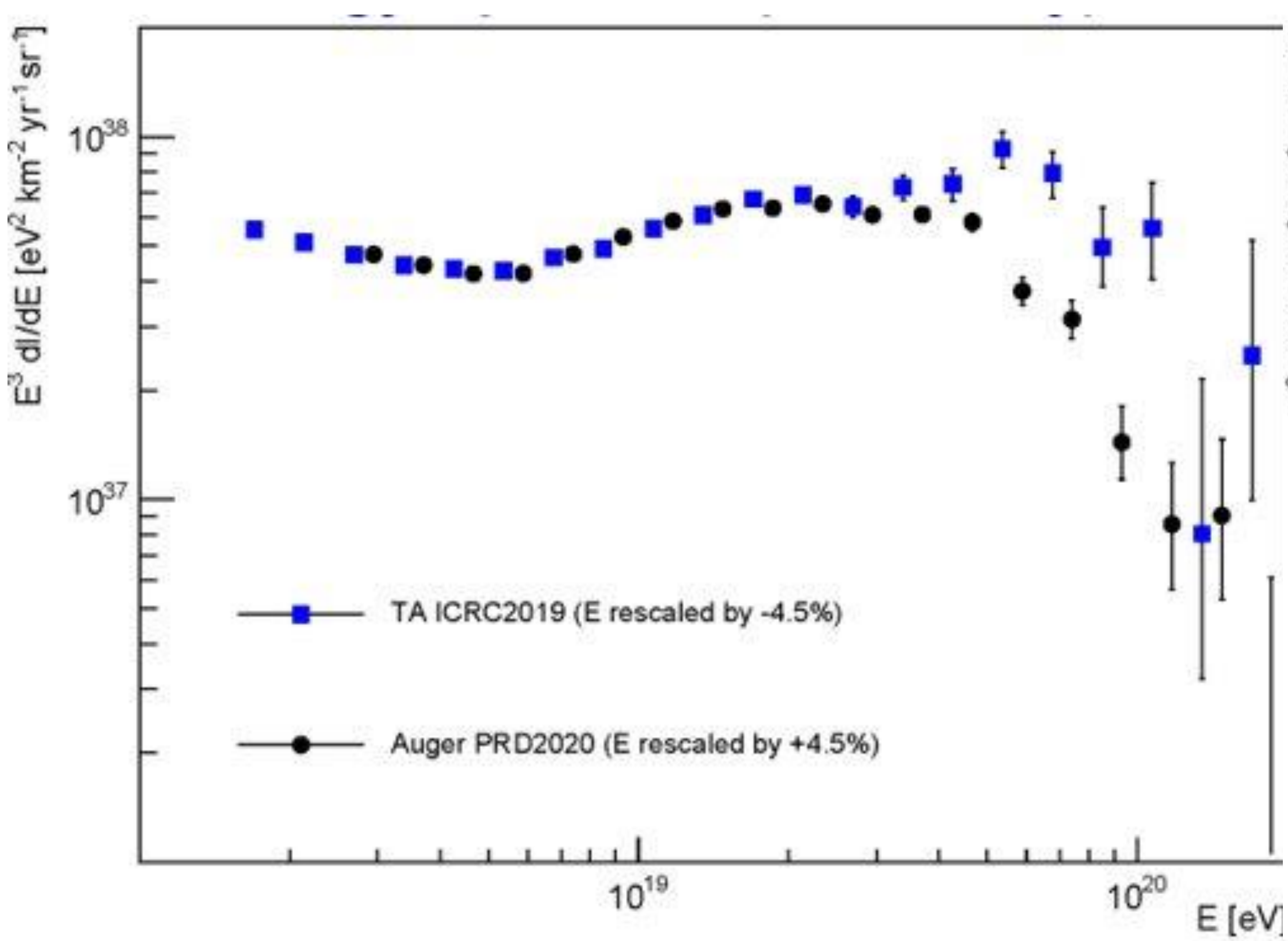




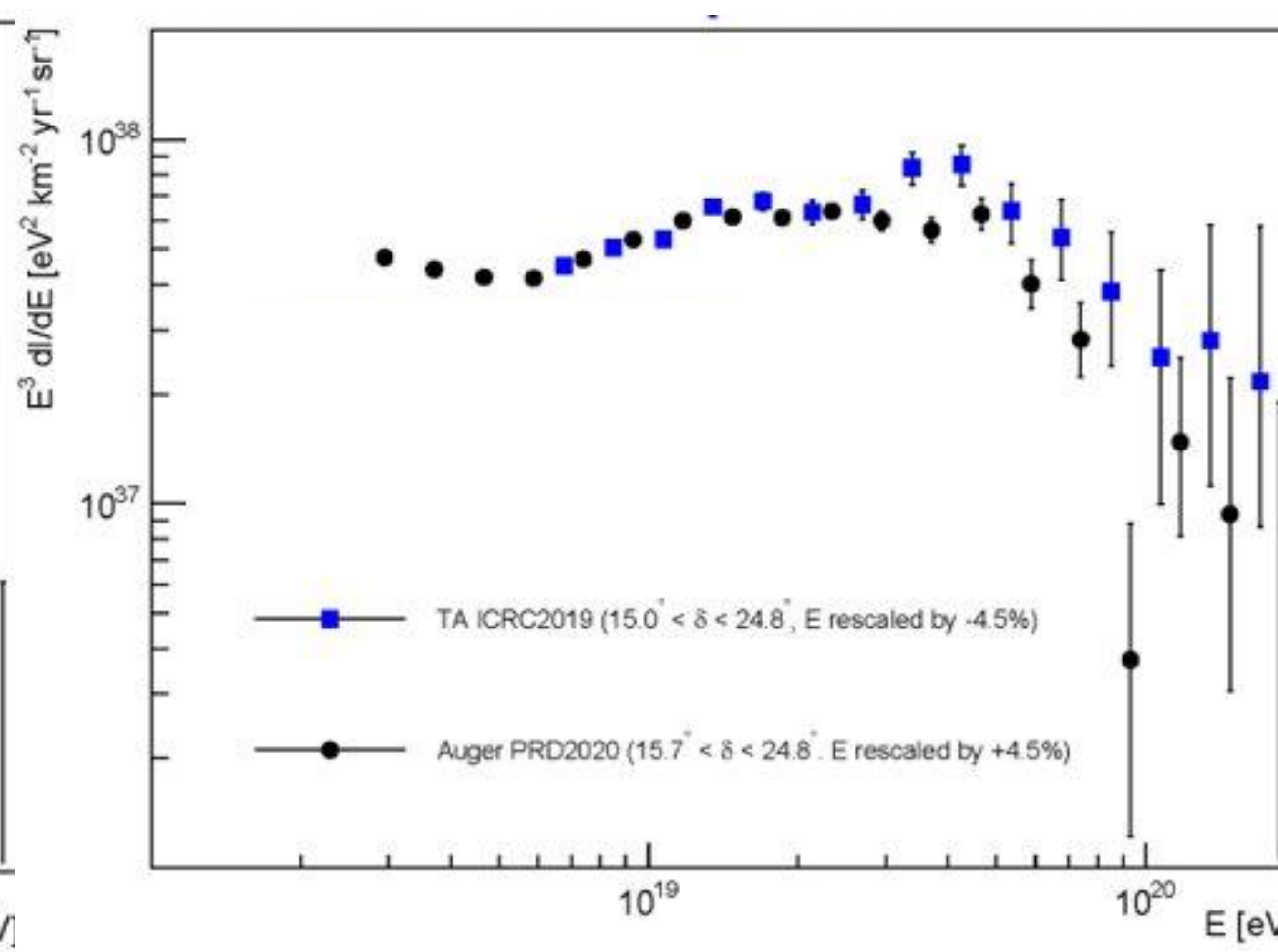
Auger and TA



Whole sky



Common region



- The energy spectra in the common band are in agreement
- North/South difference persists.

Multi-Messenger Observation

- There are many types of "messenger" from the universe
  - EM waves: Radio, optical, UV, X, gamma
  - Cosmic Rays (nuclei)
  - Neutrinos
  - Gravitational waves

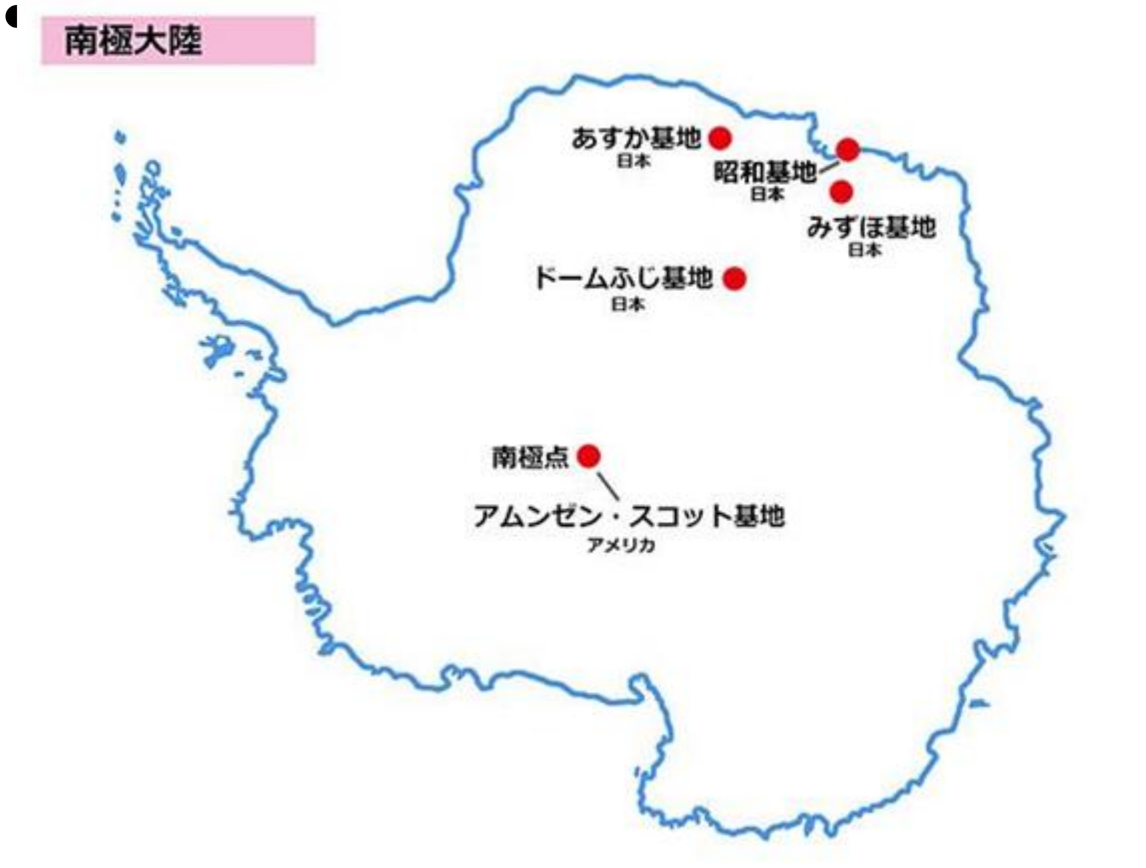
Cosmic Neutrinos

- Generated by Cosmic Ray Interaction

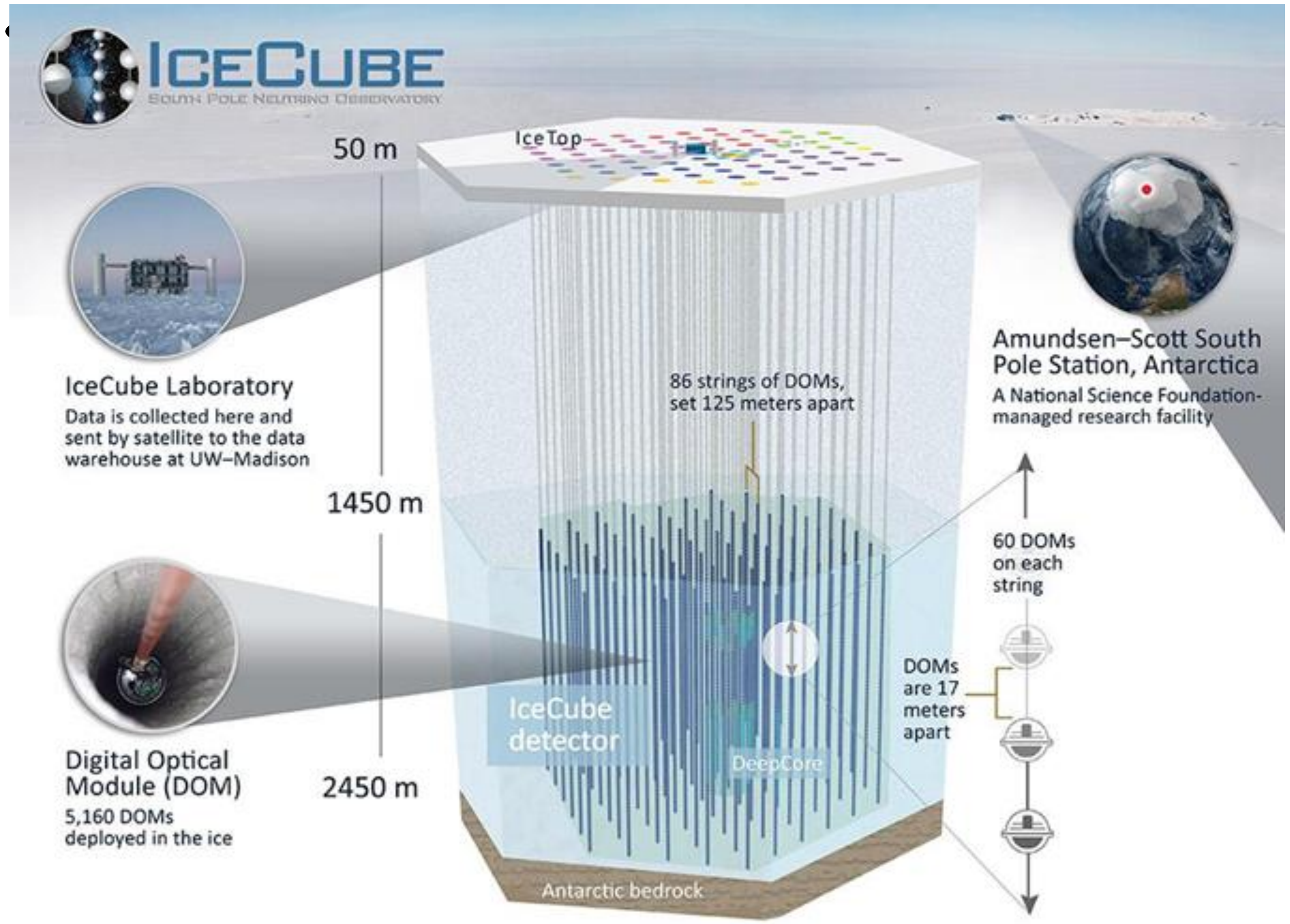
  $P + X \rightarrow \pi^+, \pi^- \rightarrow \mu^+, \mu^- + \nu \rightarrow e^+, e^- + \nu$
- Come straight long distances
- Detection of cosmic neutrino leads to clarify the origin of cosmic rays
- Extremely difficult to detect
  - A huge volume detector needed
  - Kamiokande: an artificial water tank as a neutrino target, 40m
  - IceCube: Use natural ice as a neutrino target, $1km^3$

IceCube: Cosmic Neutrino Detector at the South Pole

- カミオカンデは巨大な水タンク、壁に光センサ
- 南極には氷がいっぱい -> 天然の「氷タンク」！



図提供：千葉大学

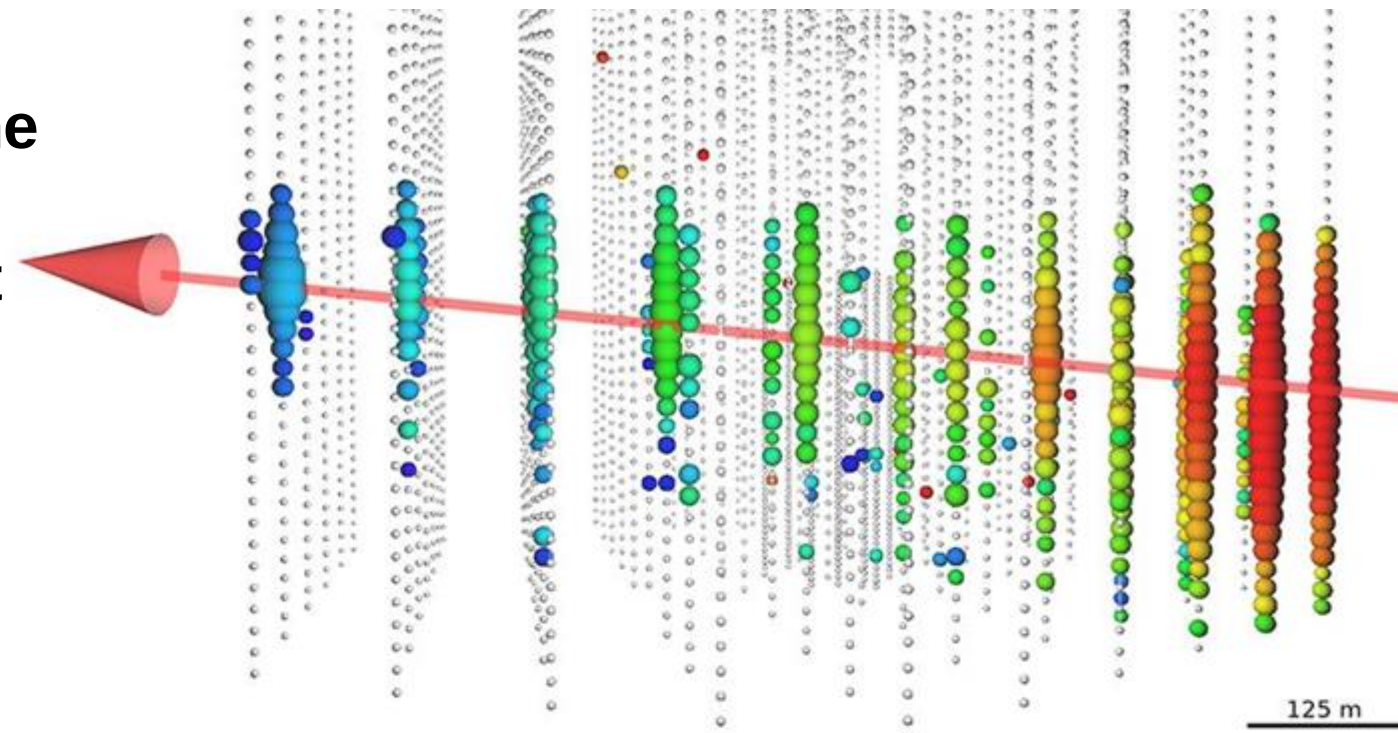


OMU group joined IC3 in 2022.

2017年９月23日

- **IceCube detected 1015 eV event**
- **Gamma-rays were also detected from the same direction at the same time**
- **First high-energy multimessenger event**

IceCube Collaboration, *Science* 361 (2018)



- 白丸：氷中の光センサで、何も検出しなかったもの
- 色のついた丸：光を検出したセンサ
  - 検出した光の量で大きさを変えている
  - 検出した光のタイミングで色を変えている
- 赤の矢印方向にニュートリノ（正確にはニュートリノに蹴とばされたミューオン）が走った

Summary

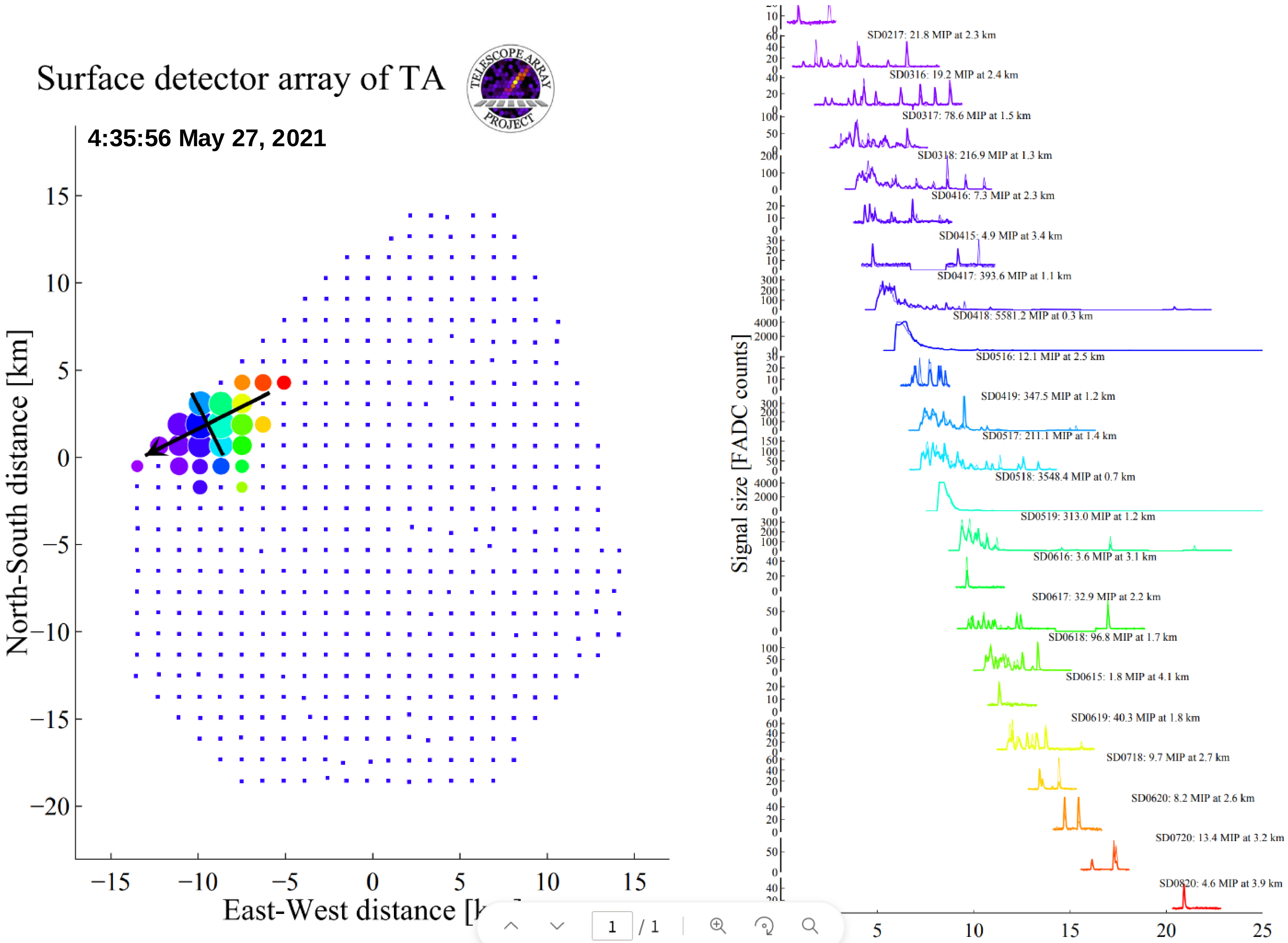
- Cosmic rays are high-energy particles from the universe
  - Low-energy CRs are of Galactic origin
  - High-energy CRs are of extragalactic origin

Summary

- Ultra-high-energy cosmic ray observation ($E > 10^{18}$eV)
  - TA and Auger
  - Nice agreement in the common region
  - North/South difference?
- Future: Multi-messenger approach
  - An Neutrino + Gamma-ray event detected
  - A Gamma-ray + gravitational wave event detected.
  - Waiting Neutrino – Gamma-ray – Gravitational wave – Cosmic ray event

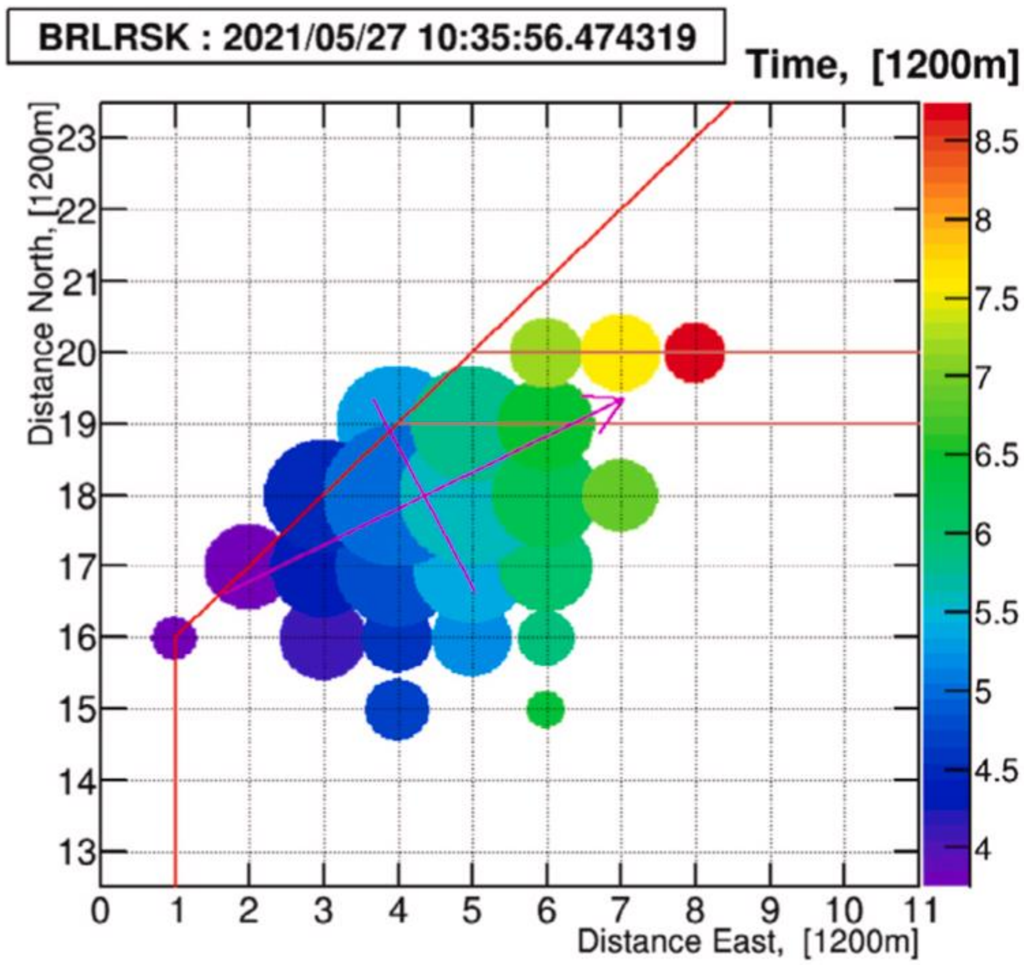
TA Highest Energy Event "Amateras particle"

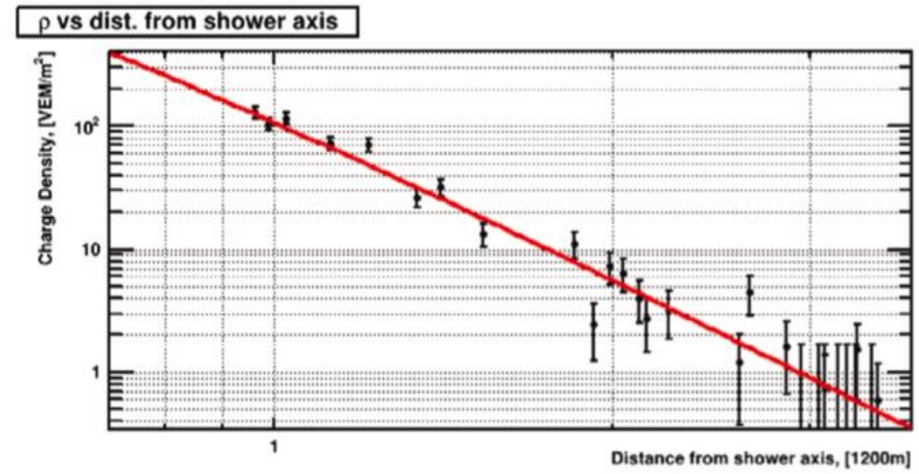
SCIENCE
23 Nov 2023
Vol 382, Issue 6673
pp. 903-907
DOI: 10.1126/science.abo5095

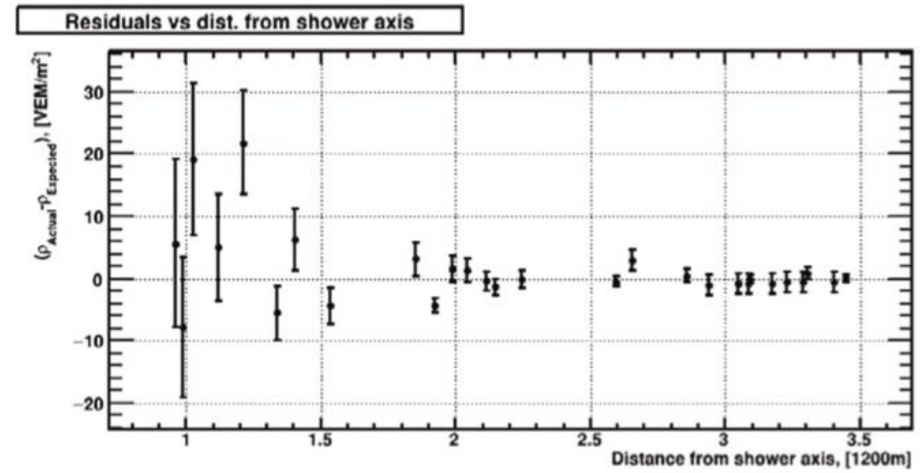


TA highest energy event "Amateras"

- 2021-05-27 10:35:56.47, No FD observation





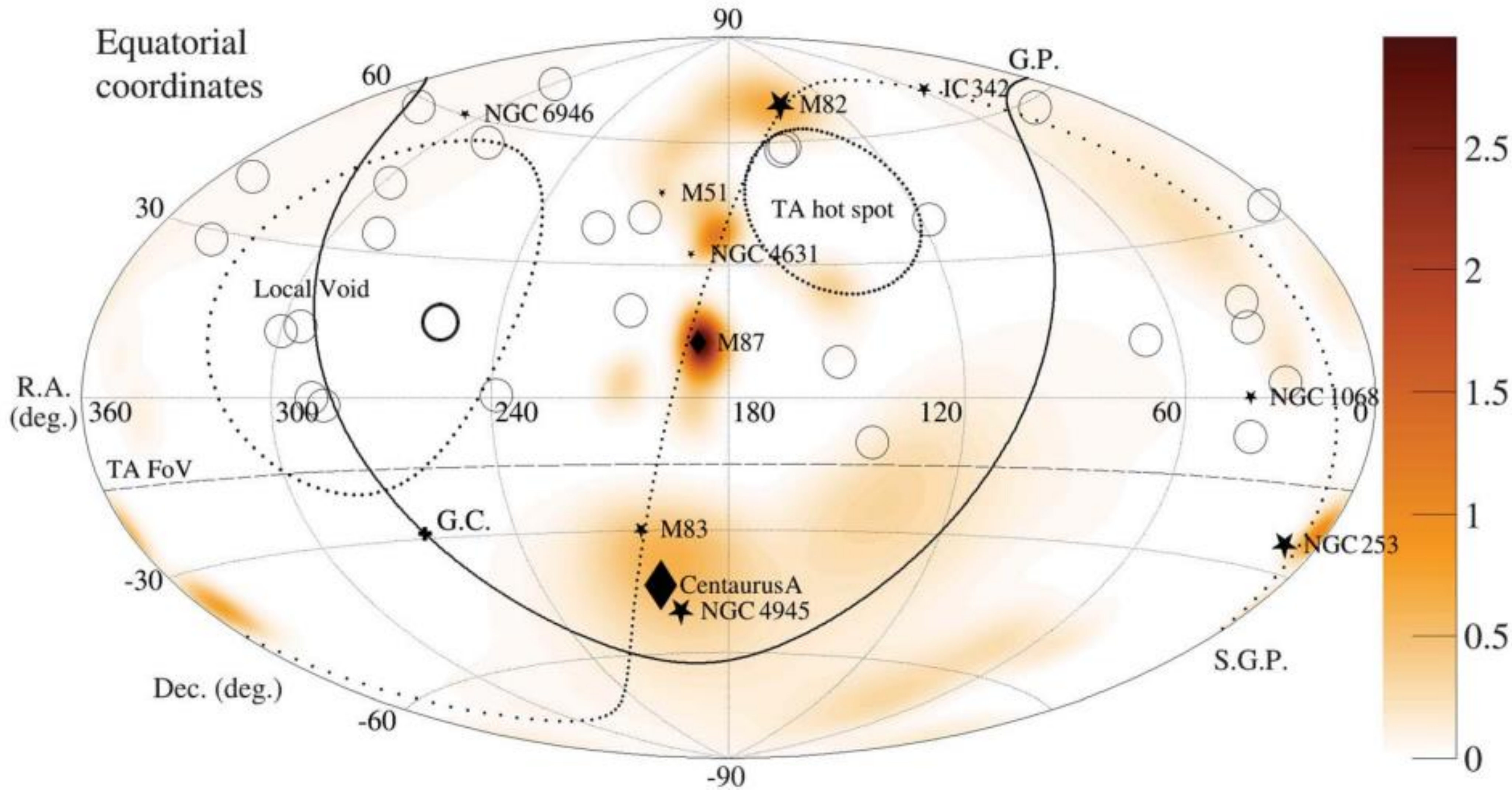


Date (UTC)	Energy (EeV)	S_{800} (m^{-2})	Zenith angle	Azimuth angle	R.A.	Dec.	Directional uncertainty
May 27 2021 10:35:56	244 ± 29(stat.) $^{+51}_{-76}$ (syst.)	530 ± 57	38.6°	206.8°	255.9°	16.1°	0.8°

Amateras is uncorrelated with LSS

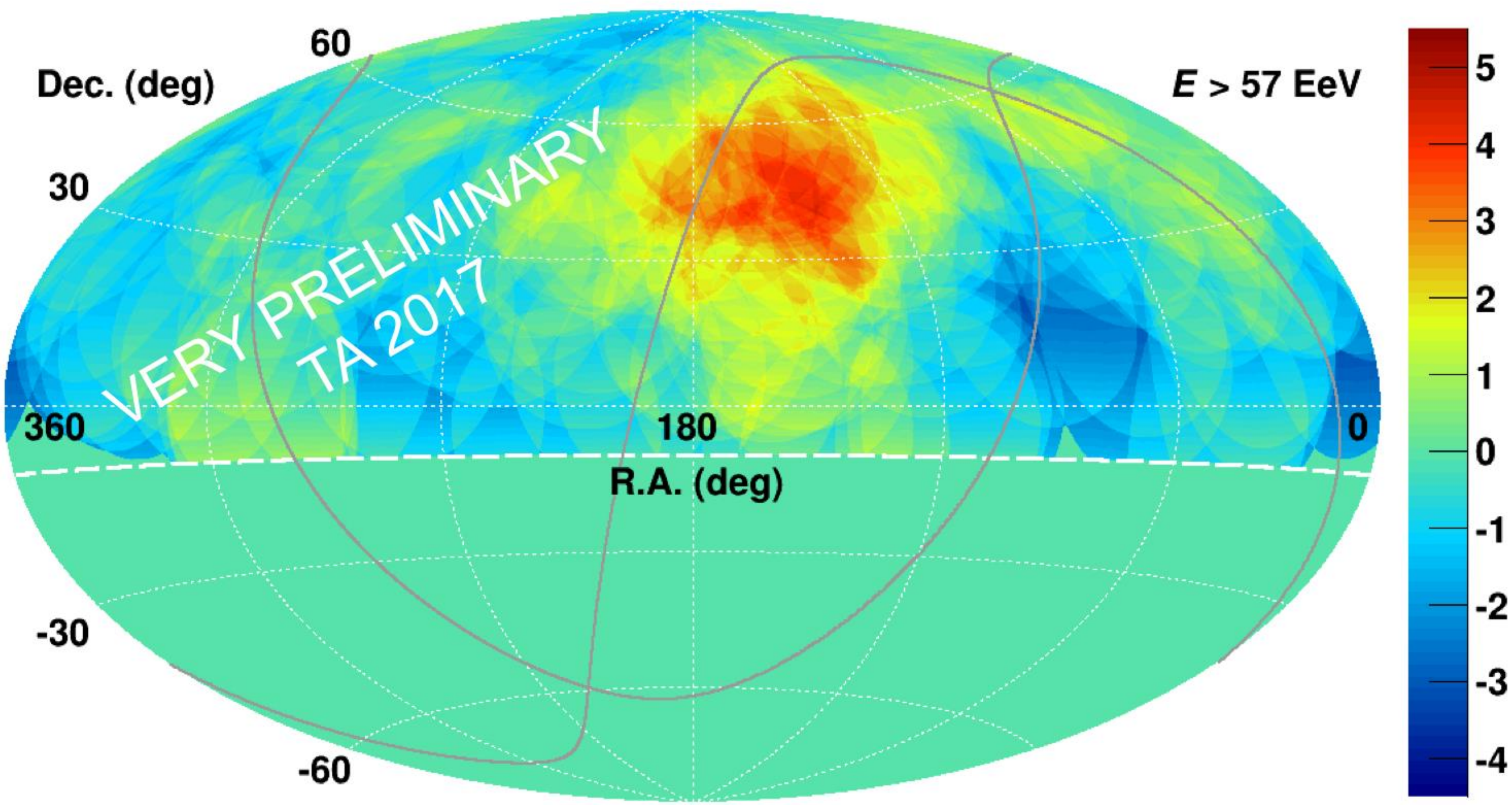
Telescope Array Collaboration, Science 382, 903–907 (2023)

Fig. 3. Arrival directions of all >100-EeV cosmic rays. Empty circles indicate the arrival directions of all cosmic rays observed by TA SD over 13.5 years of operation that had energies >100 EeV. The background and other symbols are the same as in Fig. 2. No clustering around the highest-energy event (thick circle) is evident.



Hint to the UHECR source locations? “Hot Spot”

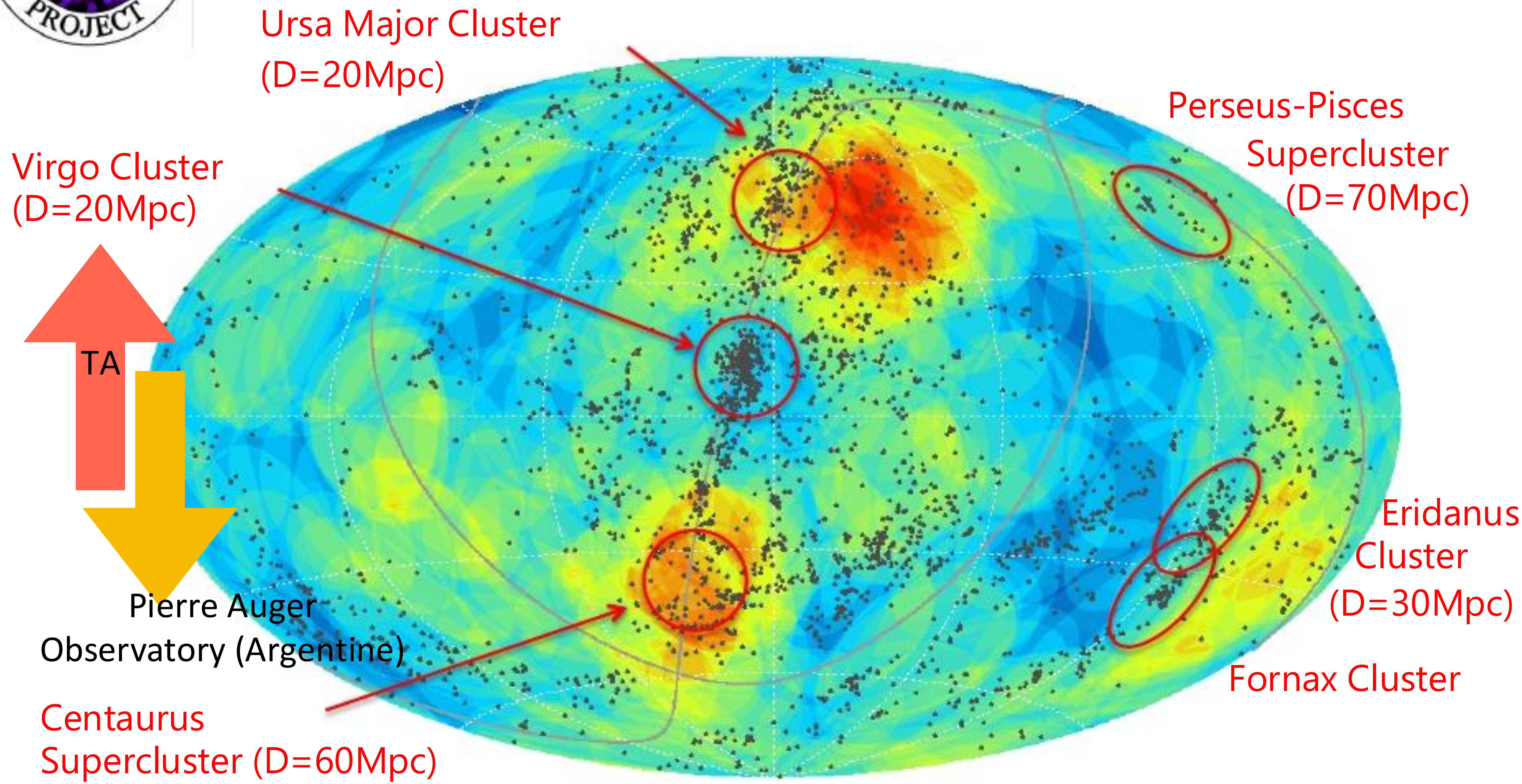
E>57 EeV - Years 1-9 excess map



Total events: 143
Observed: 34
Expected : 13.5

Best circle center: RA=144.3°, Dec=+40.3°
Best circle radius: 25°
Local significance : 5 σ
Global significance : 3 σ

Nearby Galaxy Clusters



Huchra, et al, ApJ, (2012)

Dots : 2MASS catalog Heliocentric velocity <3000 km/s (D<~45MpC)

TA hotspot is found near the Ursa Major Cluster
TA & PAO see no excess in the direction of Virgo.

GZK Prediction: The high-end of cosmic ray energies

- The universe is not transparent: Cosmic Microwave Background (CMB), 400/cm^3, $10^{-4 \sim -3}$ eV
- UHECRs: 10^{18-20}eV -> $\gamma = 10^{9-11}$
  - A CMB photons appears as a high-energy gamma ray of ~100MeV
  - Photo-pion production is possible by UHECR proton + γ_{CMB}, and the UHECR loses its large fraction of energy
  - A steepening is expected at ~5x10^{19}eV - prediction by Greisen, Zatsepin, and Kuzmin - the *GZK cutoff*.

超新星残骸でどこまで加速できるか？

- 爆発の初速度概算

$$E_{\rm SN} = \frac{1}{2}MV^2 \qquad E_{\rm SN} = 10^{51}\,{\rm erg}, M = M_\odot$$

$$V \sim 10^9\,{\rm cm/s}$$

- 銀河系内空間の密度

$$\rho_G \sim 1\,{\rm proton/cc} \sim 10^{-24}\,{\rm g/cm^3}$$

- 掃き広げた星間物質の質量とぶっ飛んだ質量が同程度になるあたりでヘタりはじめる

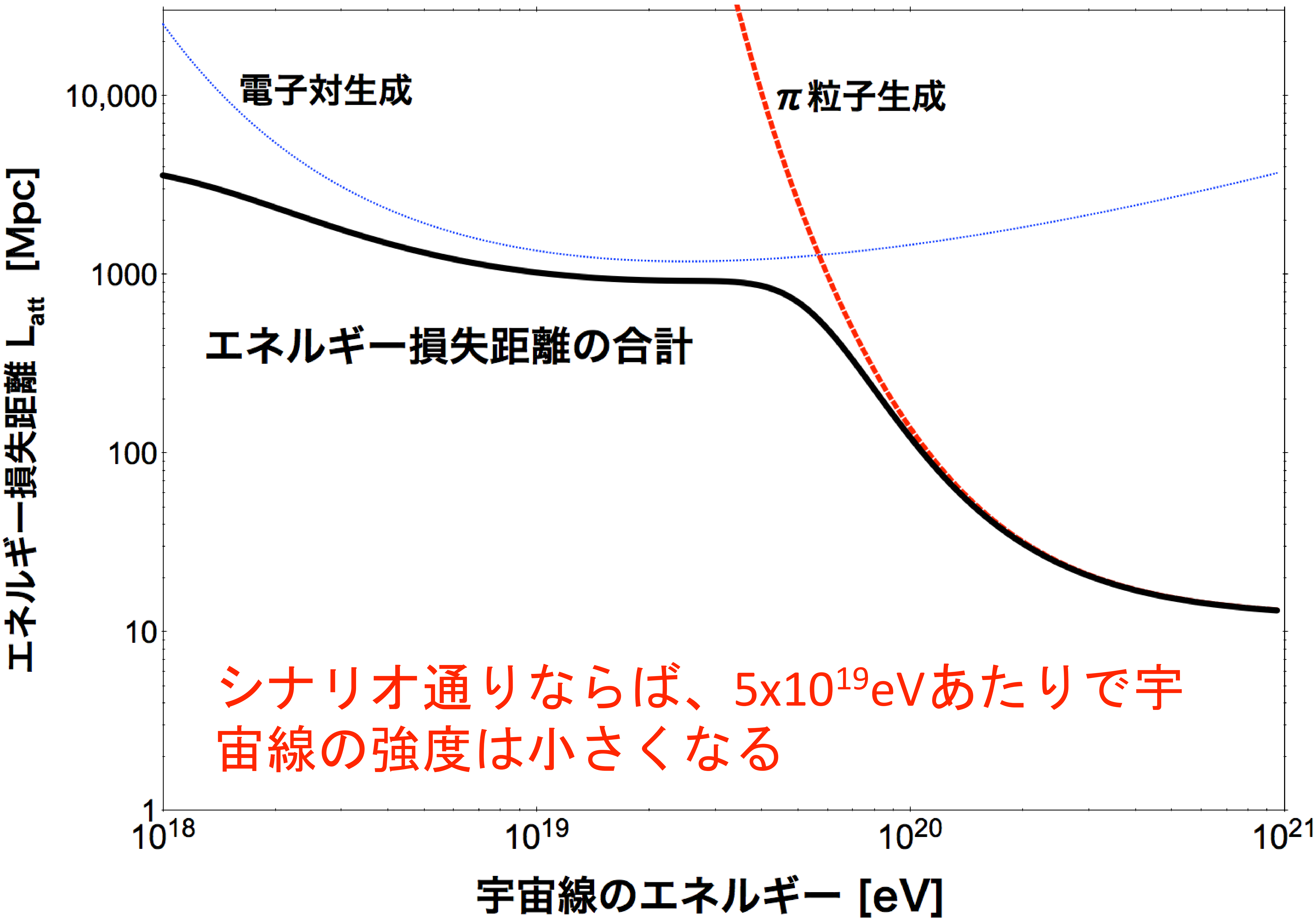
$$M = \frac{4}{3}\pi R^3 \rho \qquad R \sim 5 \times 10^{18}\,{\rm cm}$$

- そうなるまでの時間は

$$\tau = R/V \sim 5 \times 10^9\,{\rm s} \sim 10^{2-3}\,{\rm yr}$$

- 数100年で数pc に広がる。加速が効率的なのはその時間の間。
- あとは磁場だ

宇宙線が走り回れる距離



陽子か原子核か、それは大問題だ

- 宇宙線：陽子、原子核

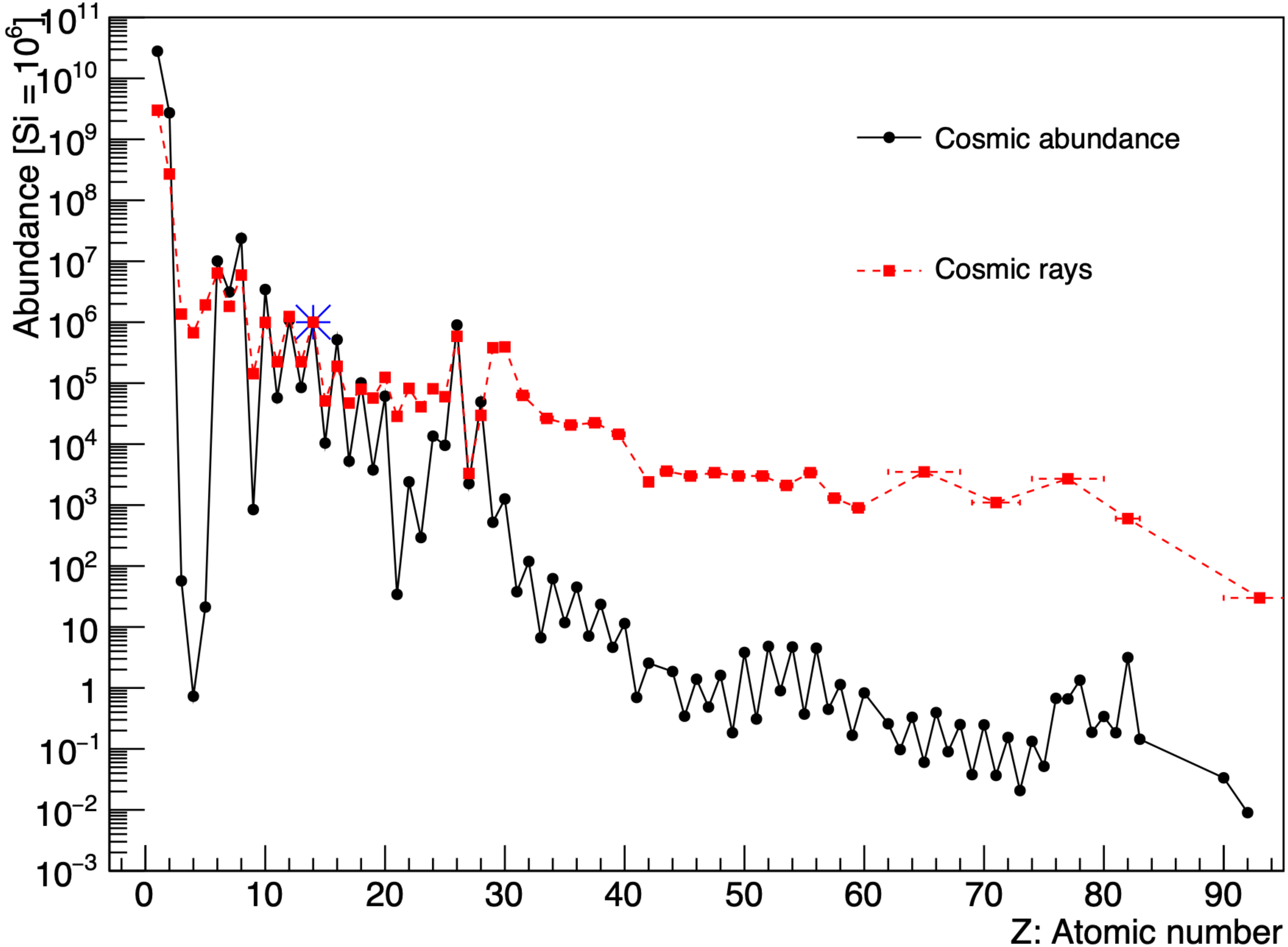
- 宇宙組成 (Cosmic Abundance): これは非常によい精度でわかっている。
  - 陽子 70%、ヘリウム28%、残り2%を他の元素で分け合う

- 宇宙線の組成：（低エネルギーの）宇宙線中では、重い原子核が相対的に多い
  - 元素合成が進んだ天体が起源と考えられている：超新星爆発など
  - 重い原子核（電荷の大きい原子核）ほど加速されやすい

- UHECRs は陽子が主成分と考えられてきた
  - 銀河系外起源（銀河系内には候補天体がない） —- 非常に遠い
  - 重い原子核として生成されても、宇宙空間を伝播する間に壊れる（宇宙背景放射との光破砕反応）
  - では組成を観測に決めるとどうか

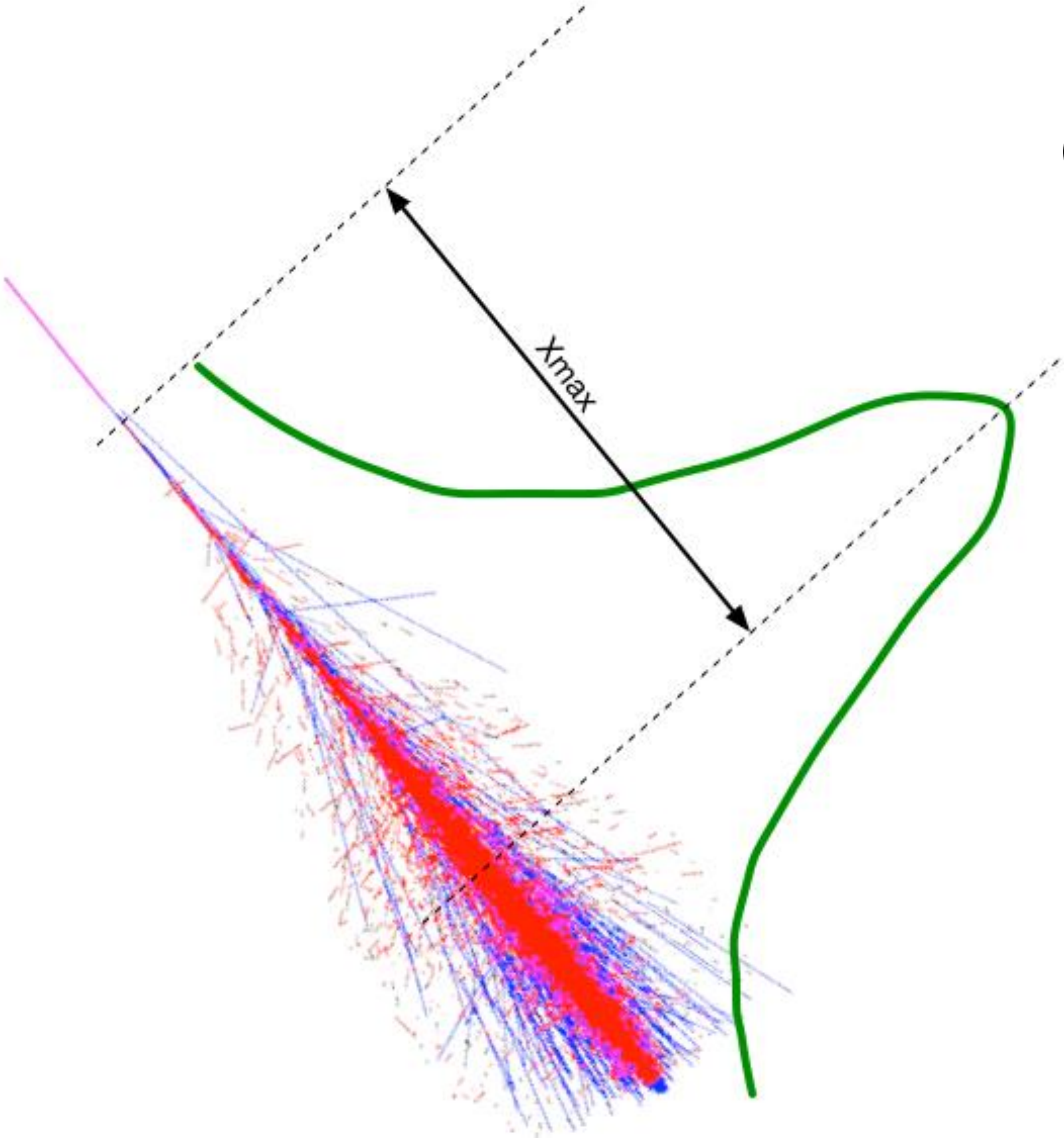
- （空気シャワー実験で原子核種を知ることは難しい）

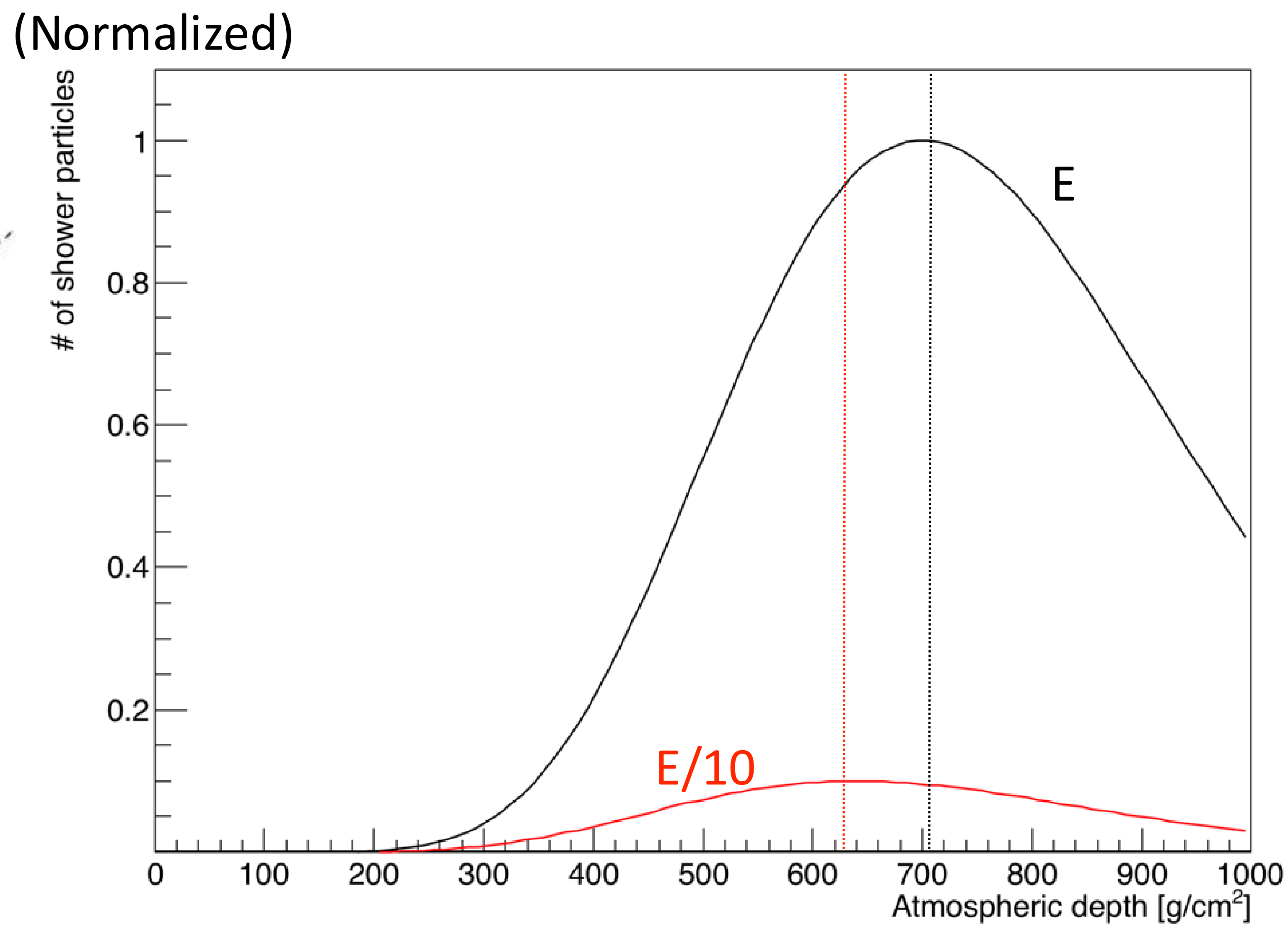
宇宙組成と低エネルギー銀河系宇宙線組成



空気シャワー観測での粒子種決定

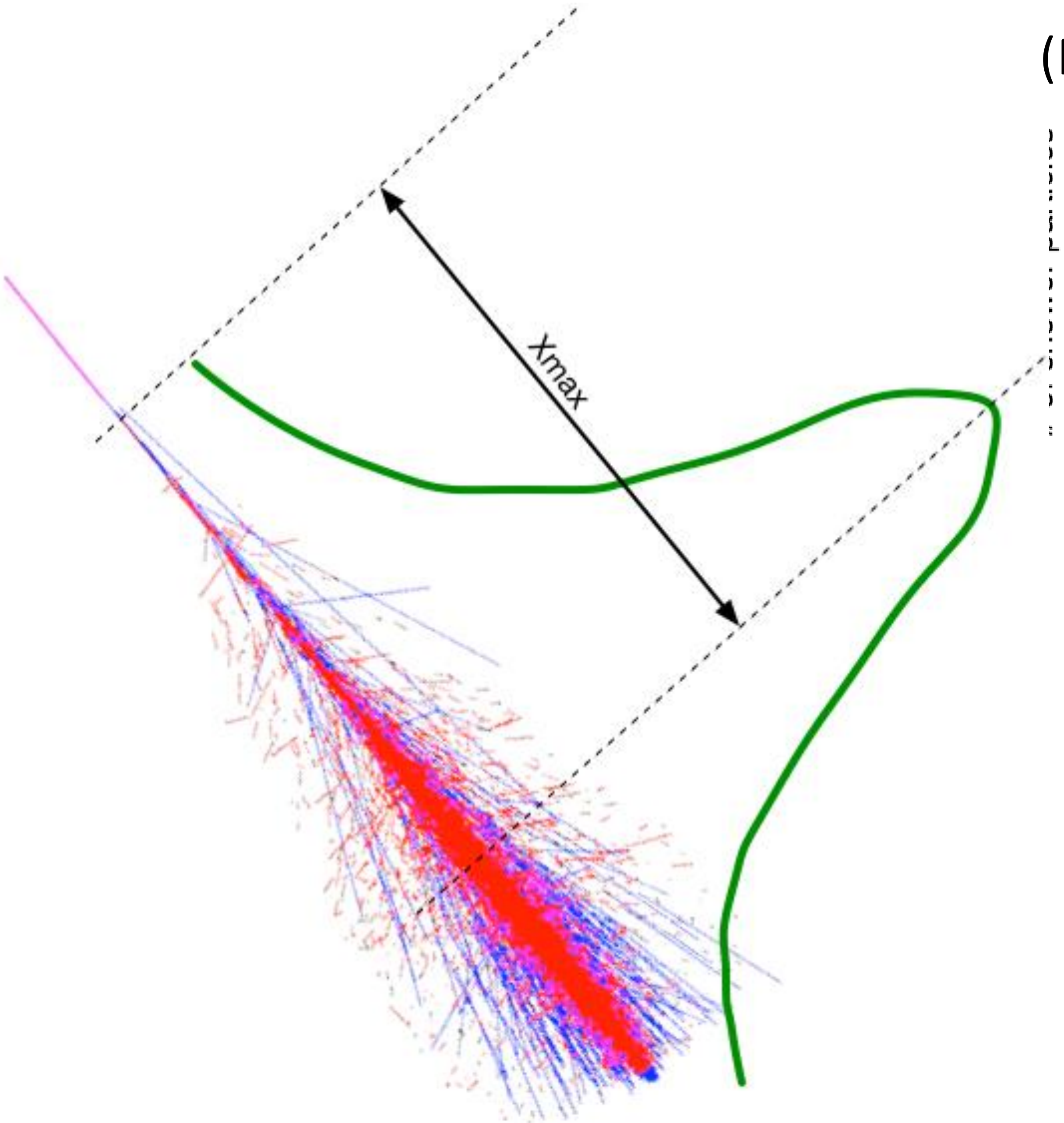
- 空気シャワーの発達が最大になったときの大気深さ Xmax を使う
  - エネルギーが高いほど深く突っ込む -> Xmax は大きくなる

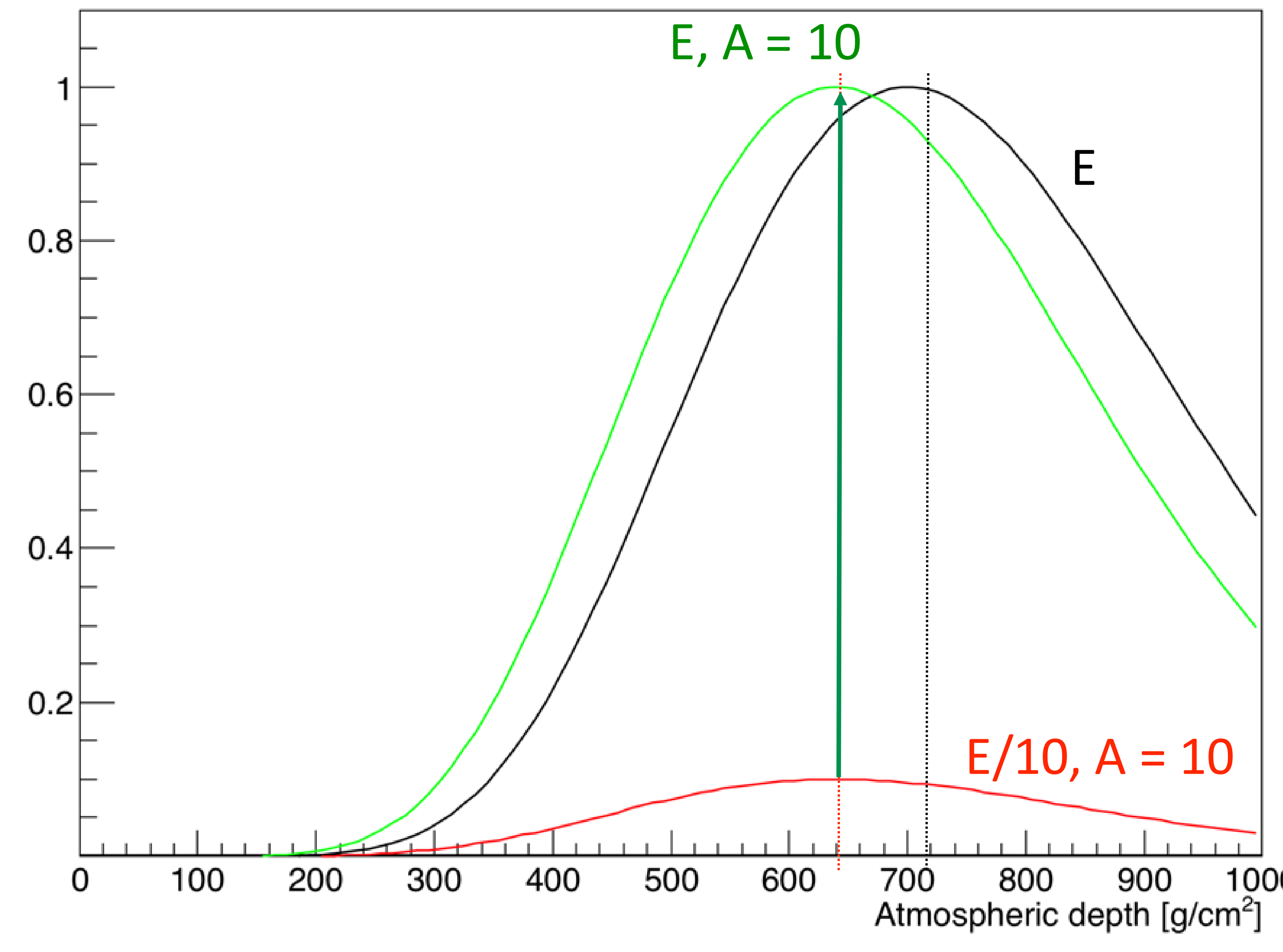




空気シャワー観測での粒子種決定

- 空気シャワーの発達が最大になったときの大気深さ Xmax を使う - FD
  - エネルギーが高いほど深く突っ込む -> Xmax は大きくなる
  - 重い原子核ほど Xmax は小さくなる
    - 相互作用断面積大きい - シャワー発達が早く始まる
    - 核子あたりのエネルギーが小さい -> エネルギーの低いシャワーの重ね合わせ

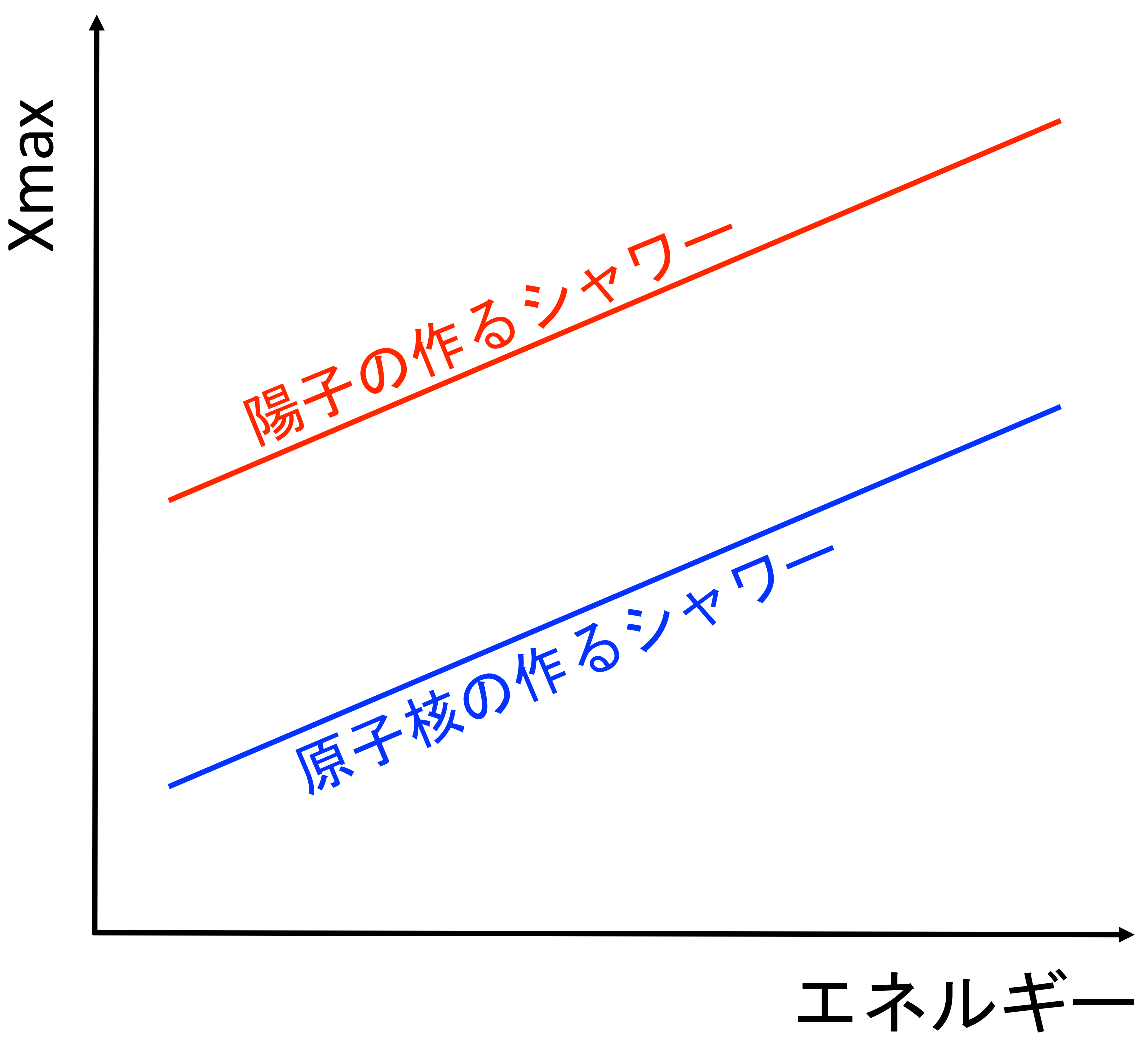


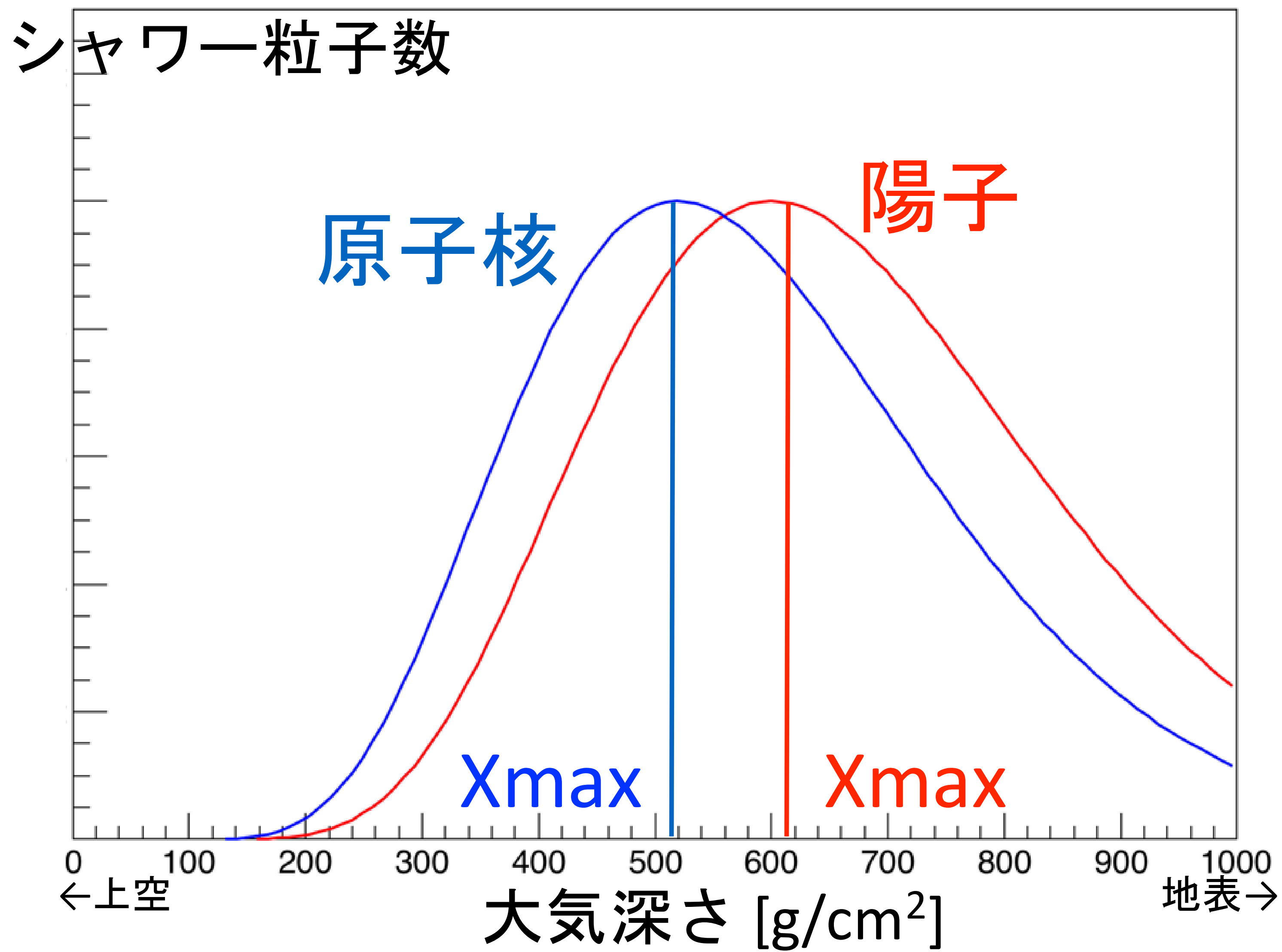


空気シャワー観測での粒子種決定

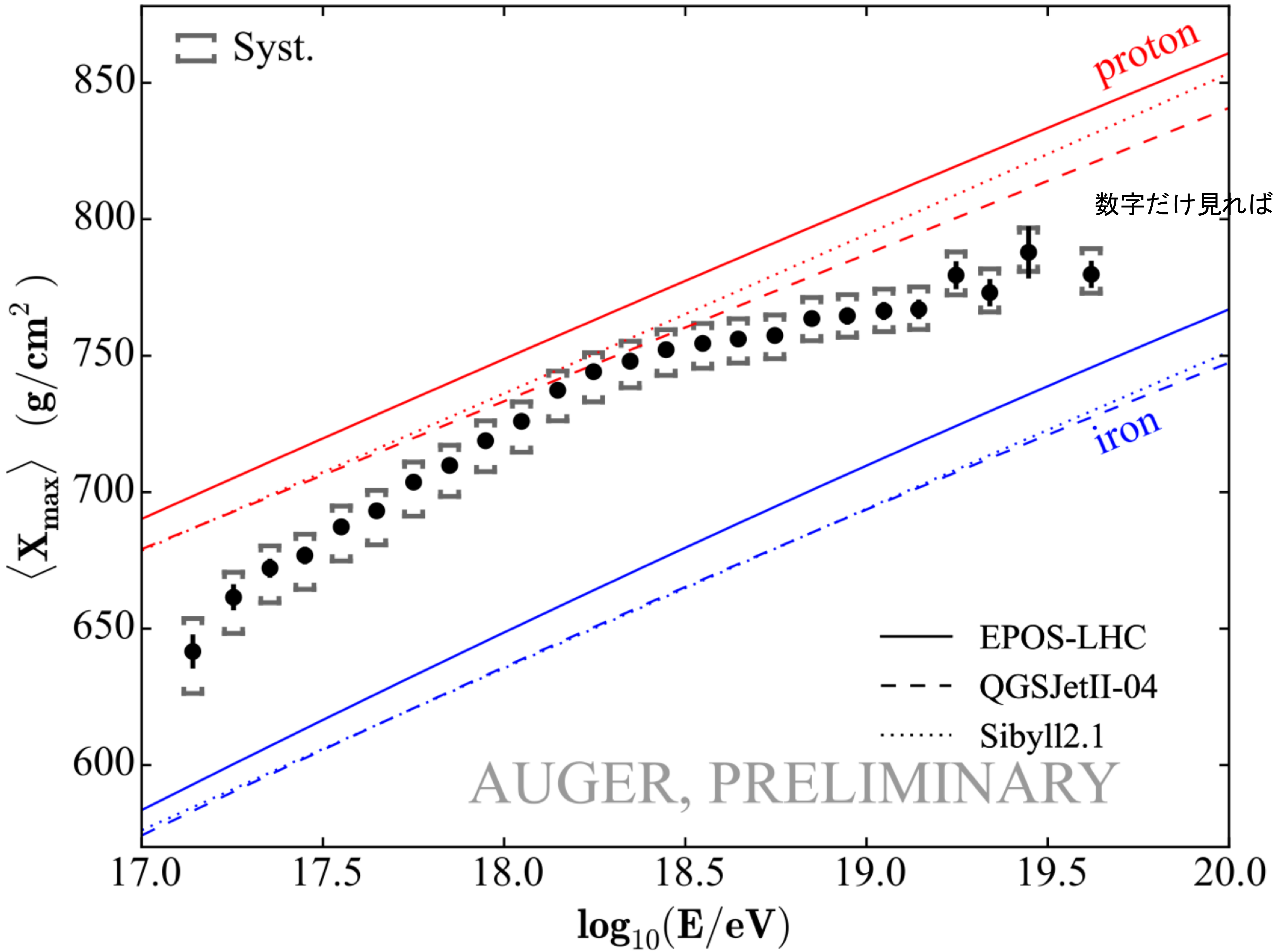
技術的には大変難しい！

- FD観測による「空気シャワーの縦方向発達」を使う
- 重い原子核：同じエネルギーの陽子と比較すると
    - 大きい断面積 -> 大気上空で早くにシャワー発達が始まる
    - 小さい E/A: E/A というエネルギー A 個の重ね合わせ
    - 重い原子核の方が発達と減衰が早い。ぱっと咲いてパッと散る
- シャワー発達が最大になる大気深さを Xmax と呼ぶ
    - 原子核の方がXmaxは小さくなる
    - イベントごとのXmaxのばらつきも小さくなる（原子核シャワーのXmaxはエネルギーの低い陽子シャワーのXmaxの平均）
- 従来の予想：原子核は飛んでくる間にCMBとの相互作用で壊れる -> UHECRs はほぼ陽子では？



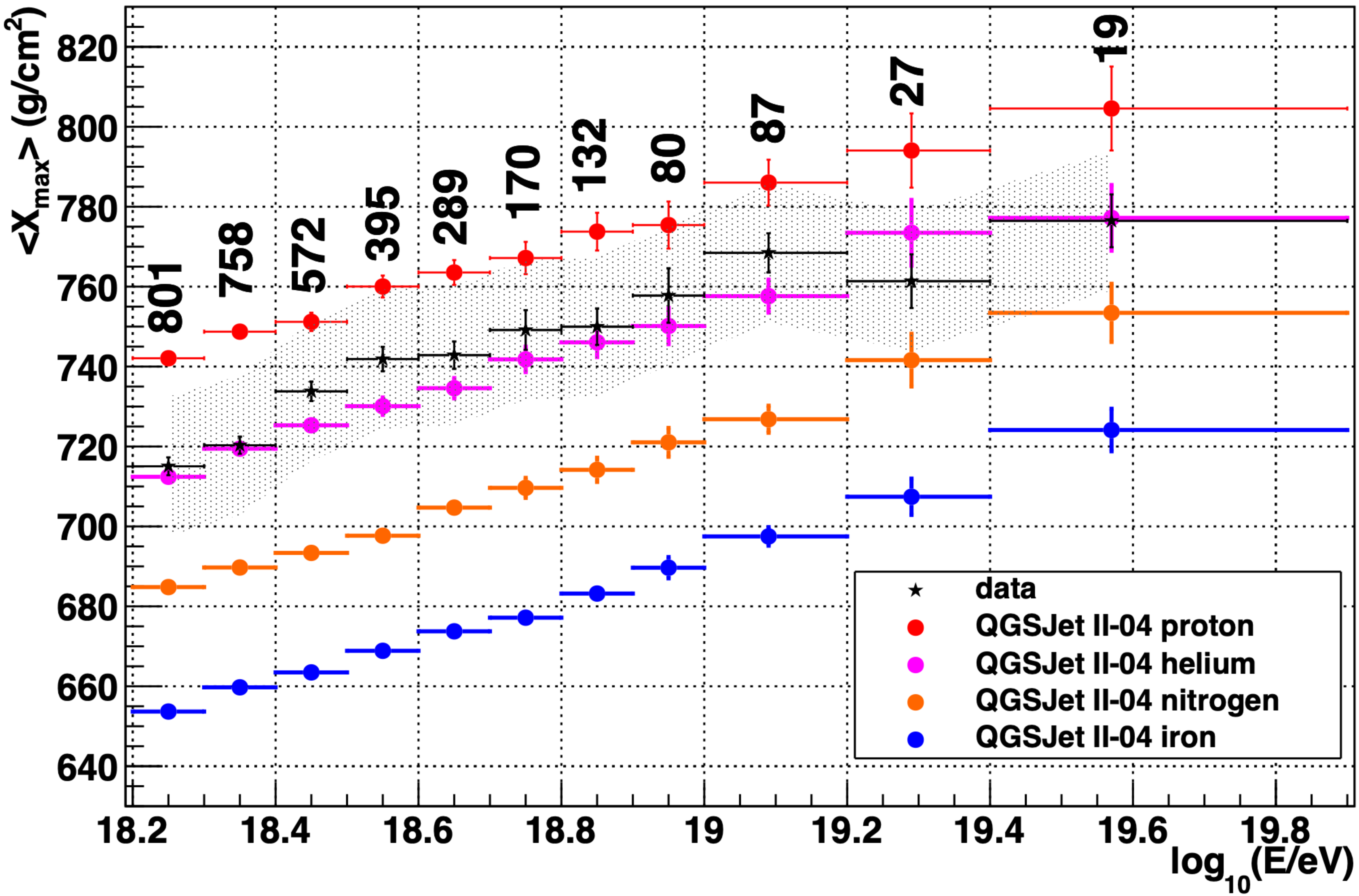


Auger <Xmax>



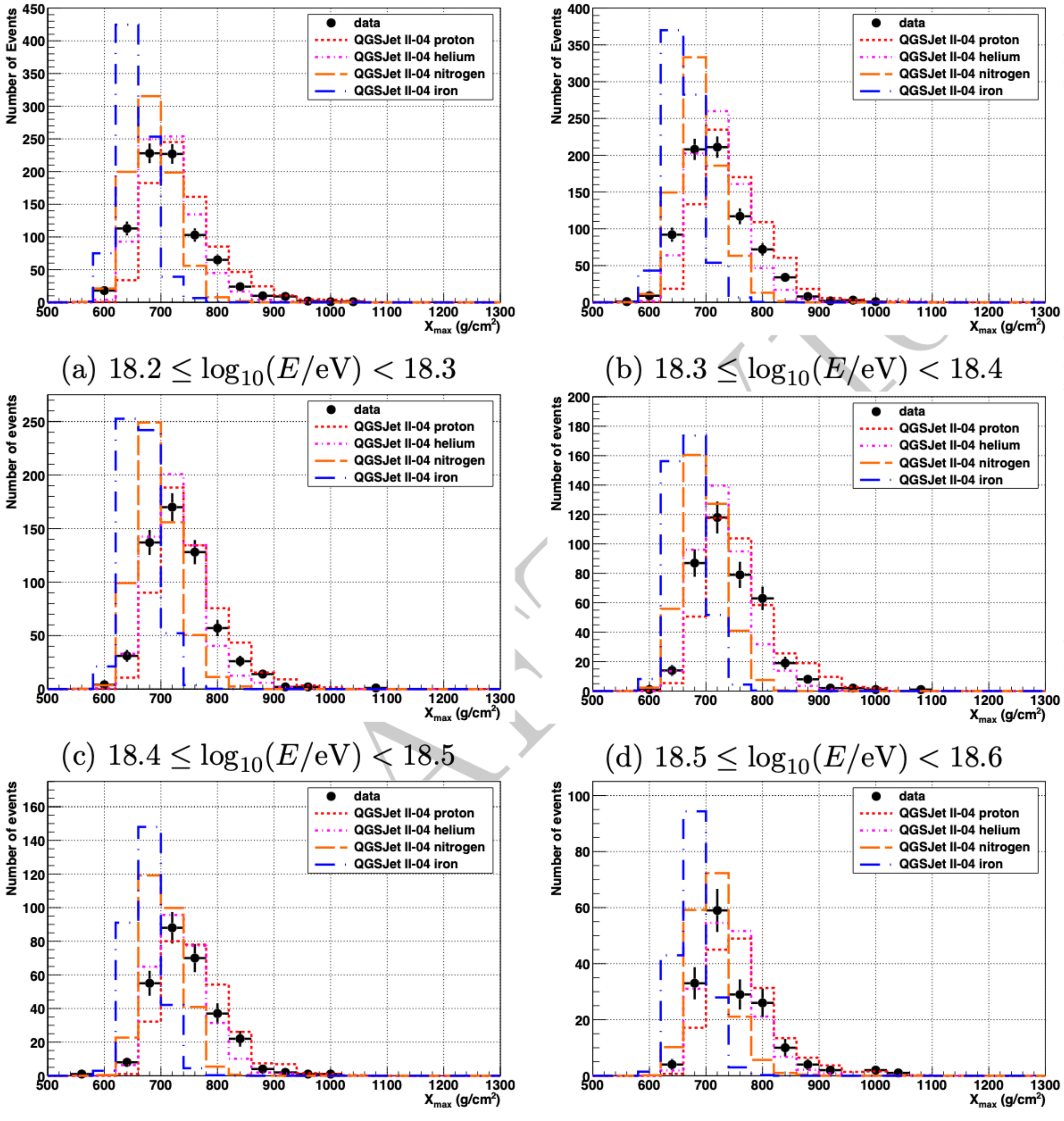
数字だけ見ればＮくらい

TA <Xmax>



$\langle X_{max} \rangle$ (g/cm^2)
820
800
780
760
740
720
700
680
660
640
18.2
18.4
18.6
18.8
19
19.2
19.4
19.6
19.8
$\log_{10}$(E/eV)
801
758
572
395
289
170
132
80
87
27
19
data
QGSJet II-04 proton
QGSJet II-04 helium
QGSJet II-04 nitrogen
QGSJet II-04 iron

TA Xmax 分布



(a) $18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$

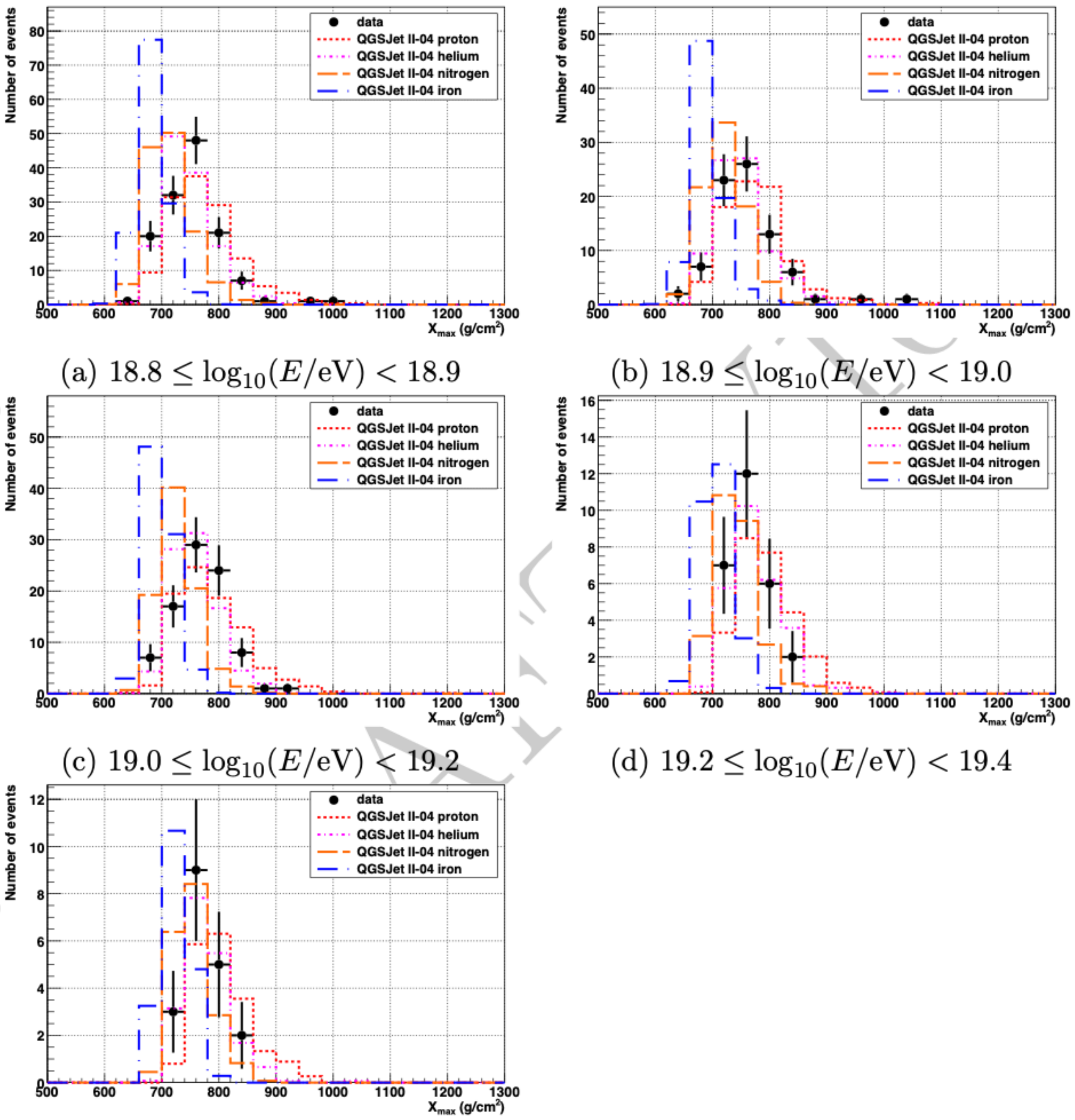
(b) $18.3 \leq \log_{10}(E/\mathrm{eV}) < 18.4$

(c) $18.4 \leq \log_{10}(E/\mathrm{eV}) < 18.5$

(d) $18.5 \leq \log_{10}(E/\mathrm{eV}) < 18.6$

(e) $18.6 \leq \log_{10}(E/\mathrm{eV}) < 18.7$

(f) $18.7 \leq \log_{10}(E/\mathrm{eV}) < 18.8$



(a) $18.8 \leq \log_{10}(E/\mathrm{eV}) < 18.9$

(b) $18.9 \leq \log_{10}(E/\mathrm{eV}) < 19.0$

(c) $19.0 \leq \log_{10}(E/\mathrm{eV}) < 19.2$

(d) $19.2 \leq \log_{10}(E/\mathrm{eV}) < 19.4$

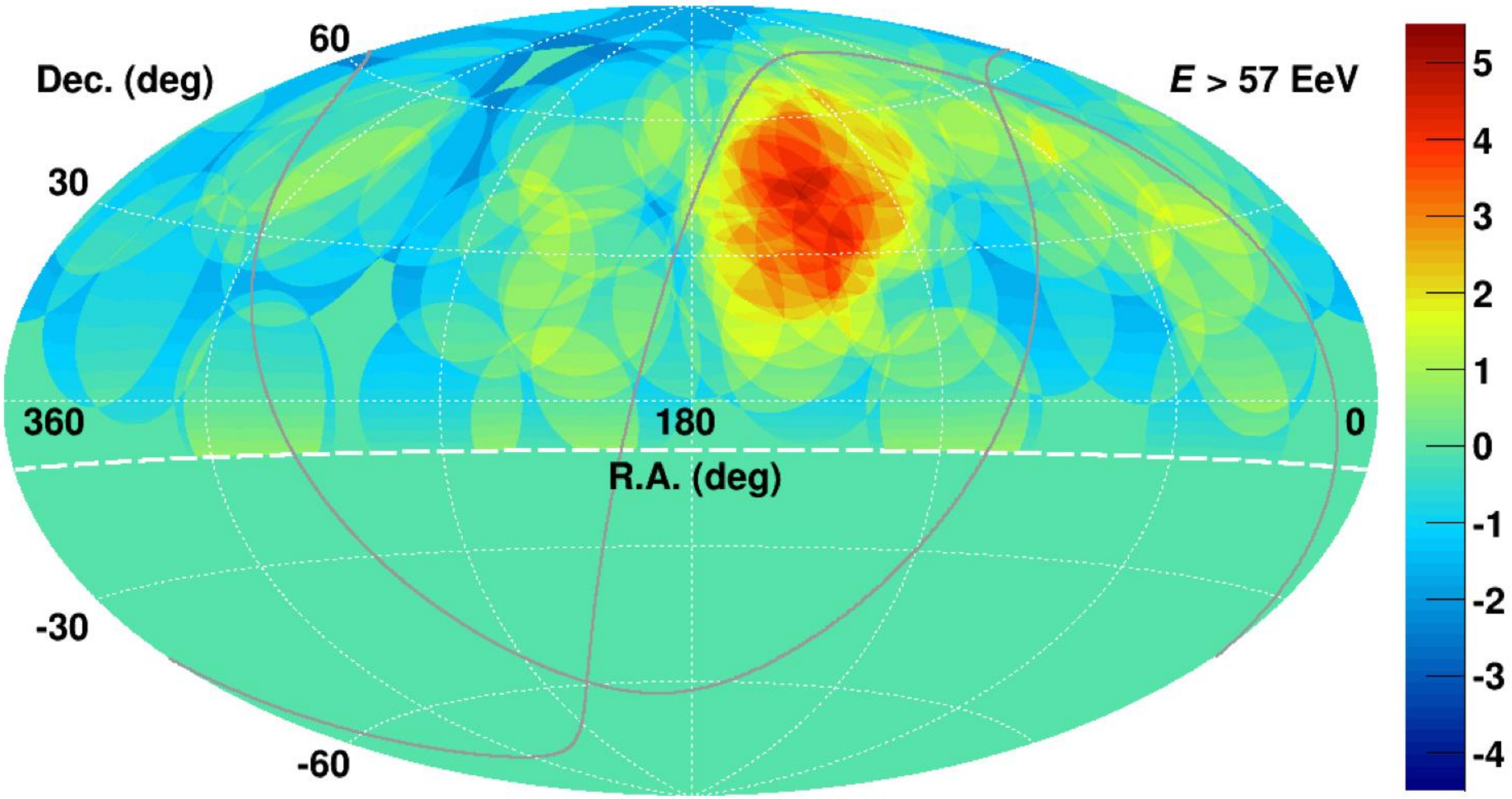
(e) $19.4 \leq \log_{10}(E/\mathrm{eV}) < 19.9$

S. Troitsky, ICRC2017
（解析は川田さん）

Hot spot

E>57 EeV - Years 1-5 excess map

TA 2014



Total events: 72
Observed: 19
Expected : 4.5

Best circle center: RA=146.7°, Dec=+43.2°
Best circle radius: 20°
Local significance : 5 σ
Global significance : 3 σ