Recent Results and Prospects of Ultra-high-energy Cosmic Rays

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(Institute for Cosmic Ray Research, the University of Tokyo)
for Telescope Array Collaboration

Joint Colloquium@NTU

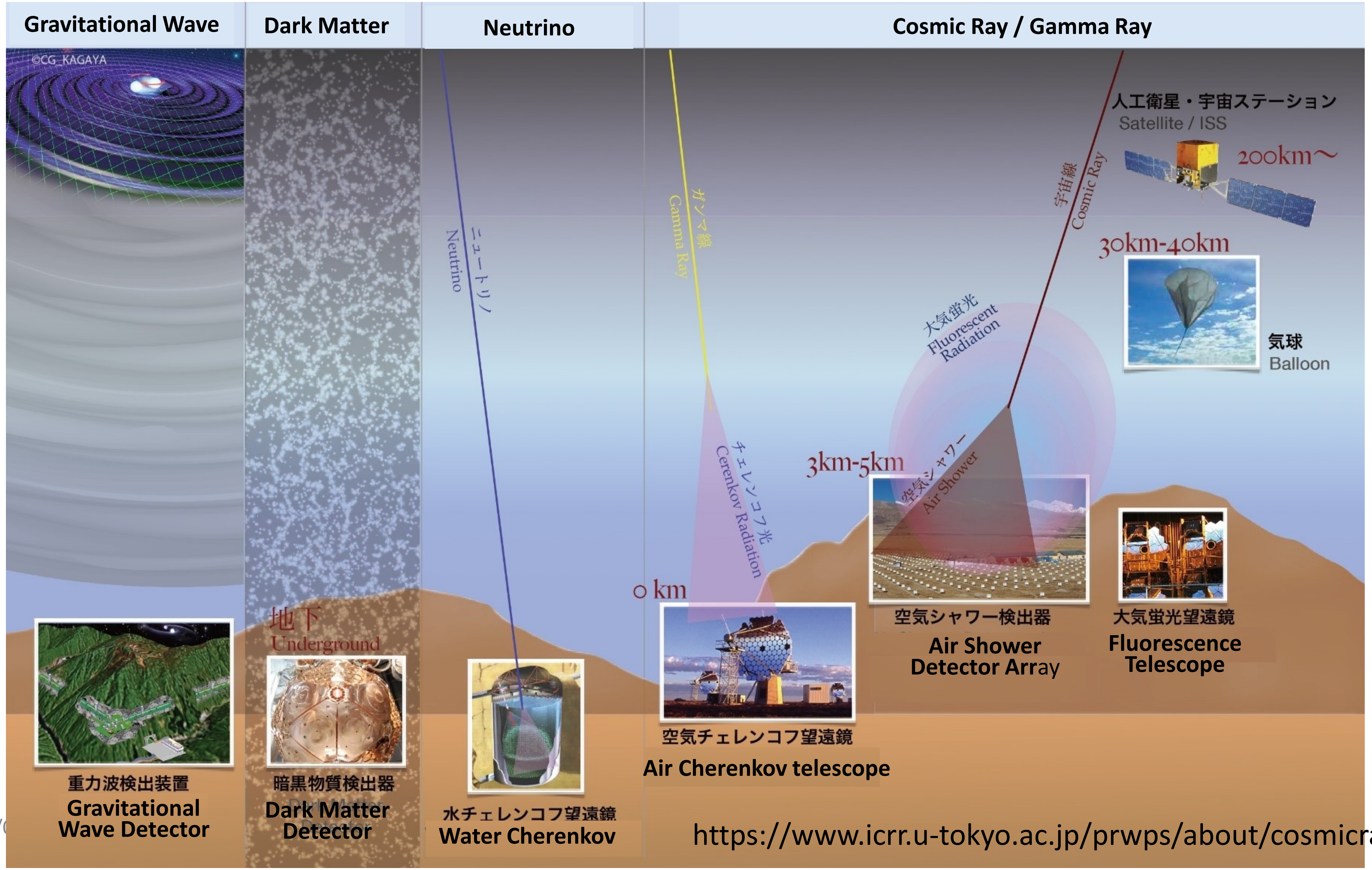
Outline

- Introduction
  - ICRR
  - Ultra-High-Energy Cosmic Rays
  - TA (Telescope Array) and TALE (TA Low-energy Extension)
- Results
  - Energy Spectrum
  - Composition
  - Anisotropy
- TA 4-times expansion: TAx4
- Joint research and prospects

Cosmic Rays

- High-energy particles traveling through the Universe
- Main components: protons; others: nuclei and electrons
- Almost isotropically arriving to the Earth (~0.1%)

Cosmic rays in a broad sense



https://www.icrr.u-tokyo.ac.jp/prwps/about/cosmicray.html

Institute for Cosmic Ray Research (ICRR)

- Place
  - Kashiwa campus of the University of Tokyo
- Research subjects
  - Research of cosmic rays
  - Research using cosmic rays
    - Astroparticle physics, elementary particle physics
- Staffs and graduate students (as of May 1, 2022)
  - Staffs: 164
  - Graduate students: 57

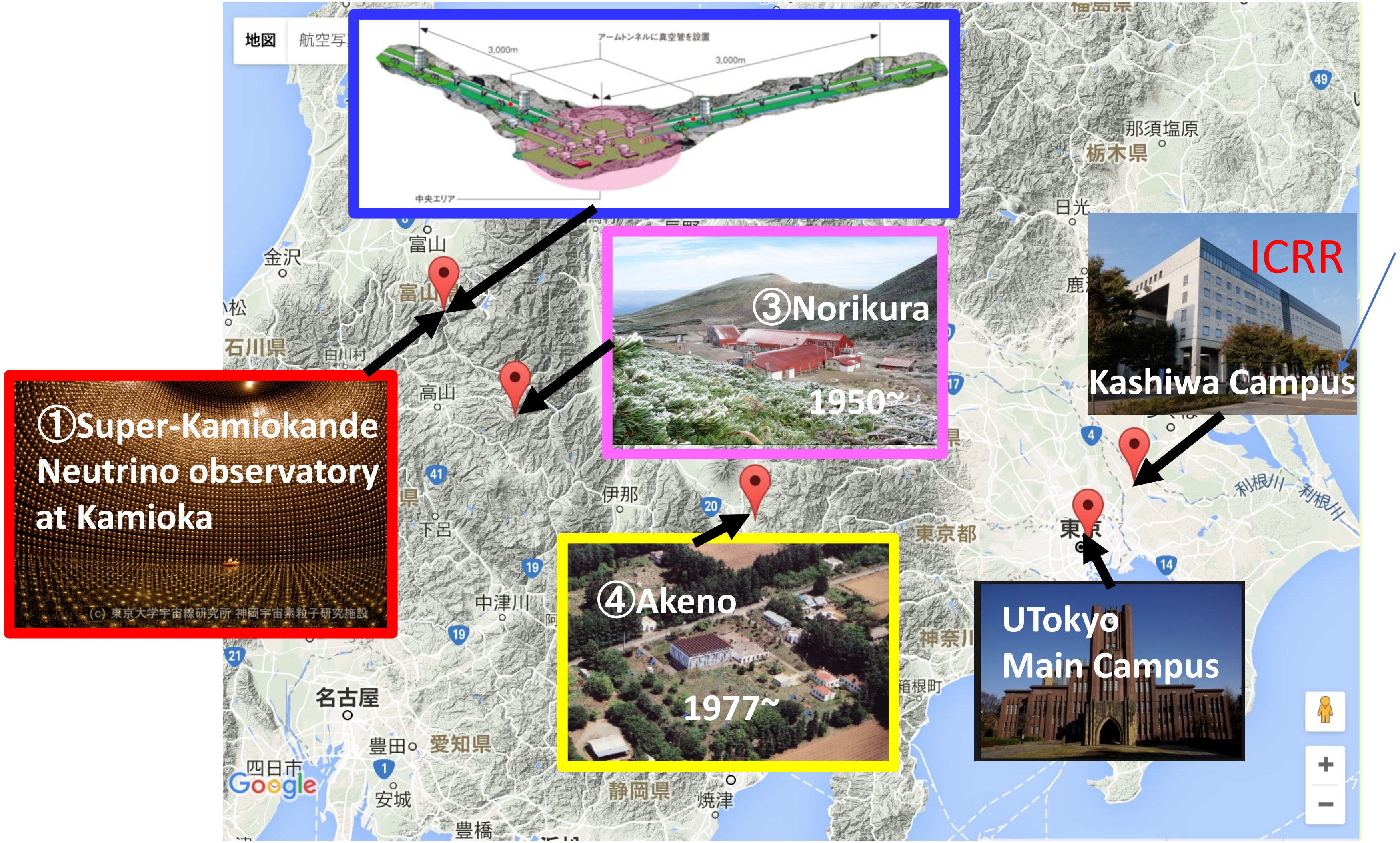
Institute for Cosmic Ray Research (ICRR)

- Current director (Apr. 2022 -)
- Prof. Masayuki Nakahata

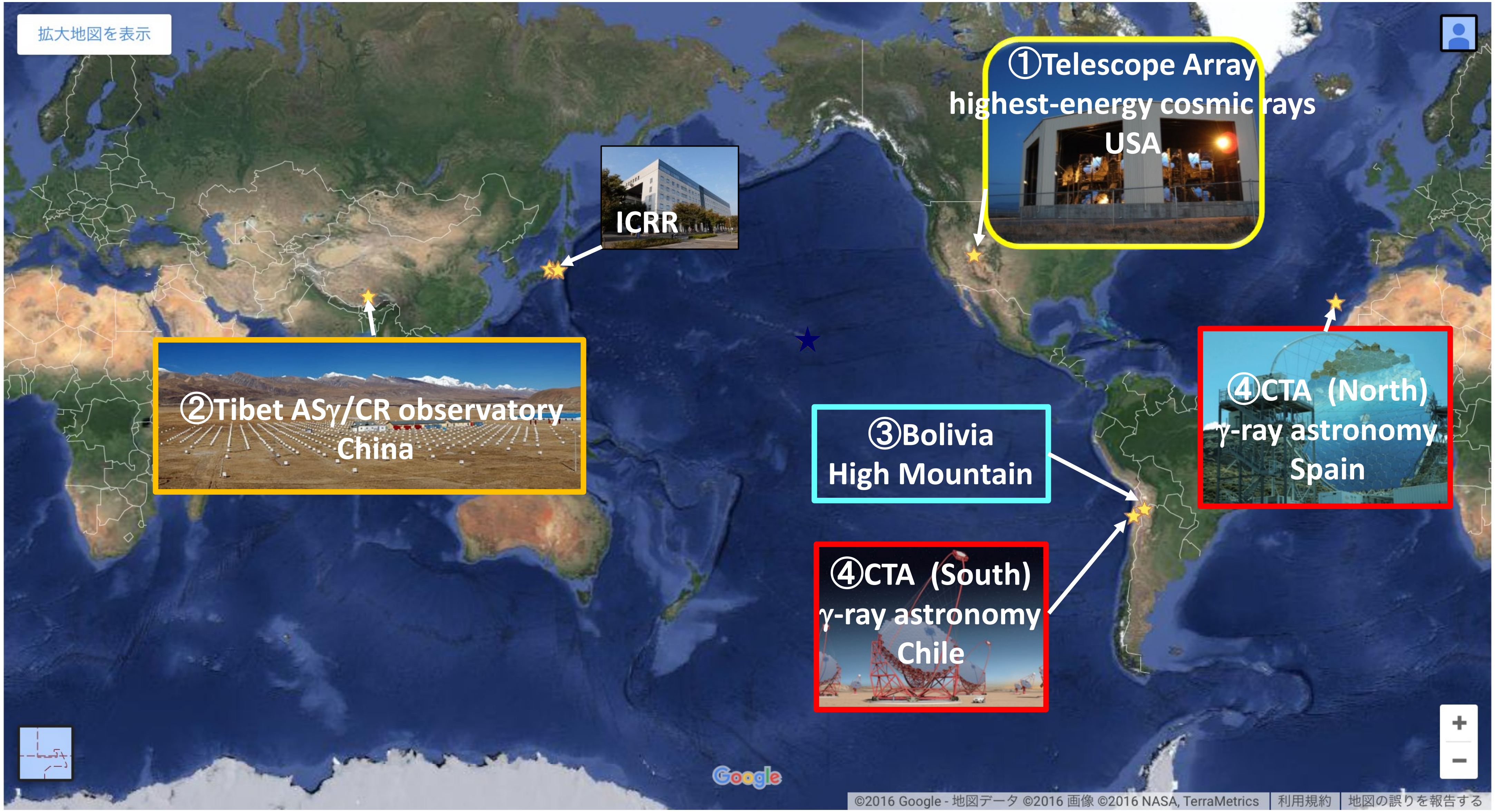
- Former director (Apr. 2008 – Mar. 2022)
- Prof. Takaaki Kajita
  - Nobel laureate in Physics 2015
  - Former president of Science Council of Japan

Facilities inside Japan: 4 observatories

②KAGRA (gravitational wave observatory) at Kamioka

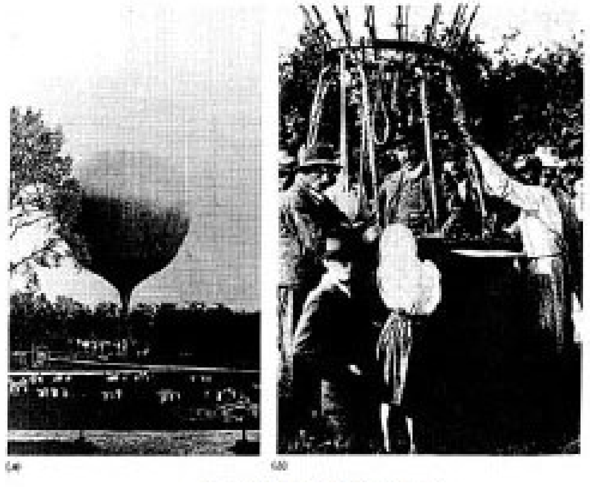


Observational cores outside JAPAN: 4 sites

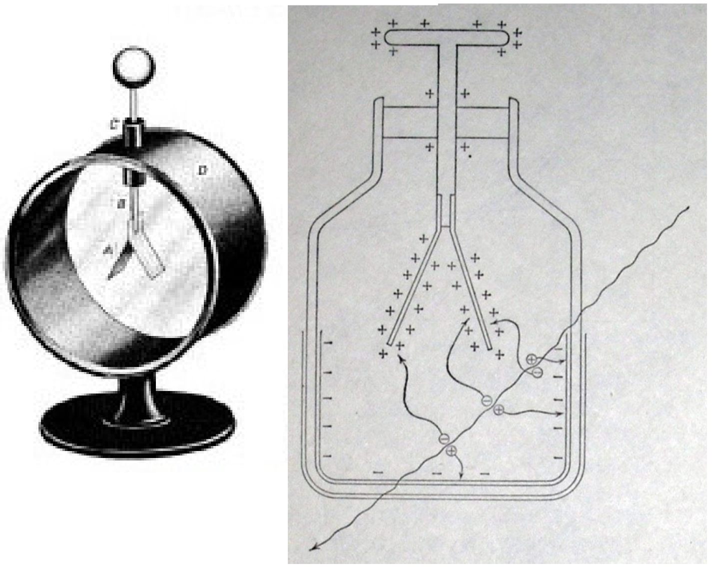


Discovery of cosmic rays

- V.F. Hess discovered cosmic rays in 1912
- Nobel Prize in 1936



Balloon



electroscope

After discovery of cosmic rays

- 1930s ~ 1940s: Discovery of elementary particles using cosmic rays
  - Positrons, muons, pions, …

- 1938: Discovery of extensive air showers
  - Pierre Auger recorded showers of secondary particles by the interactions between primary high-energy cosmic rays and nuclei in the atmosphere

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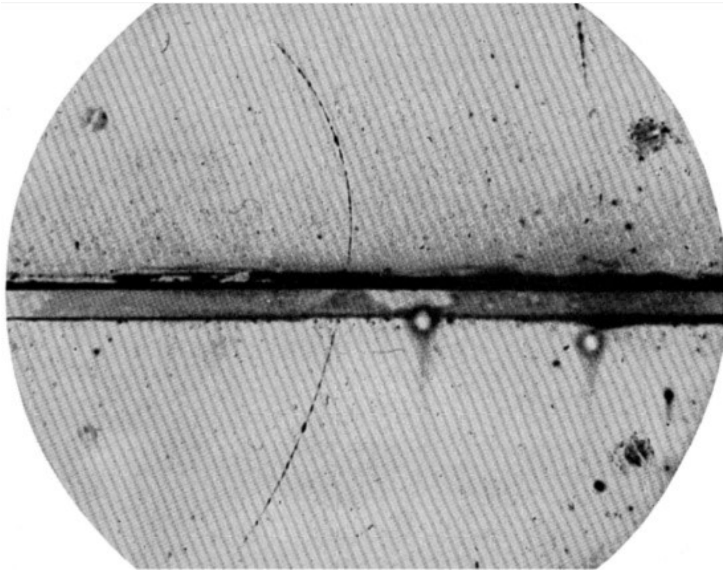
Discovery of positrons with a cloud chamber



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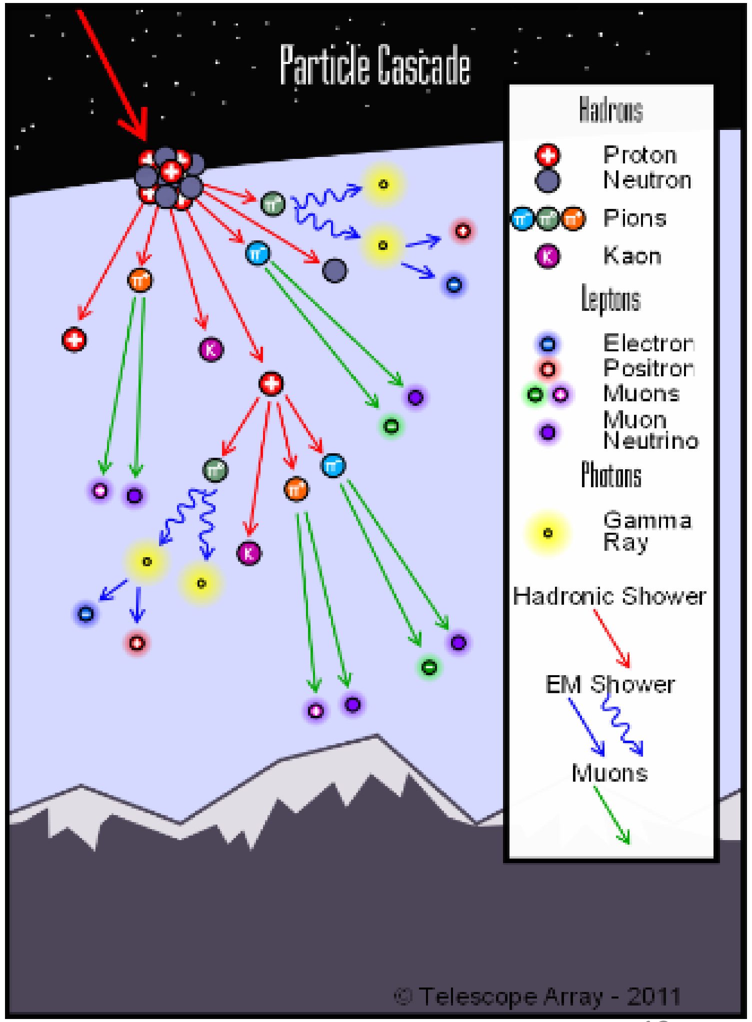
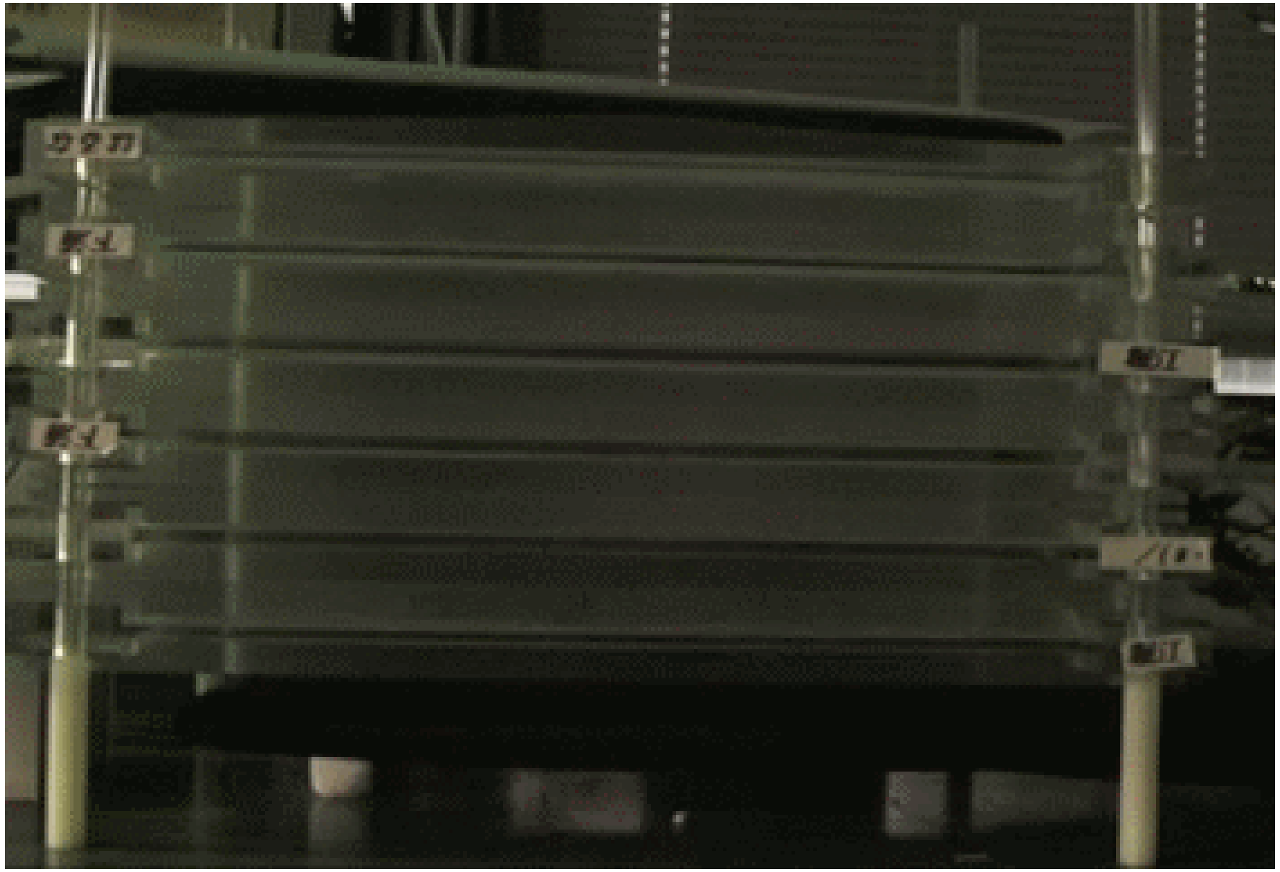
Air shower image



Cosmic rays are constantly falling to the earth



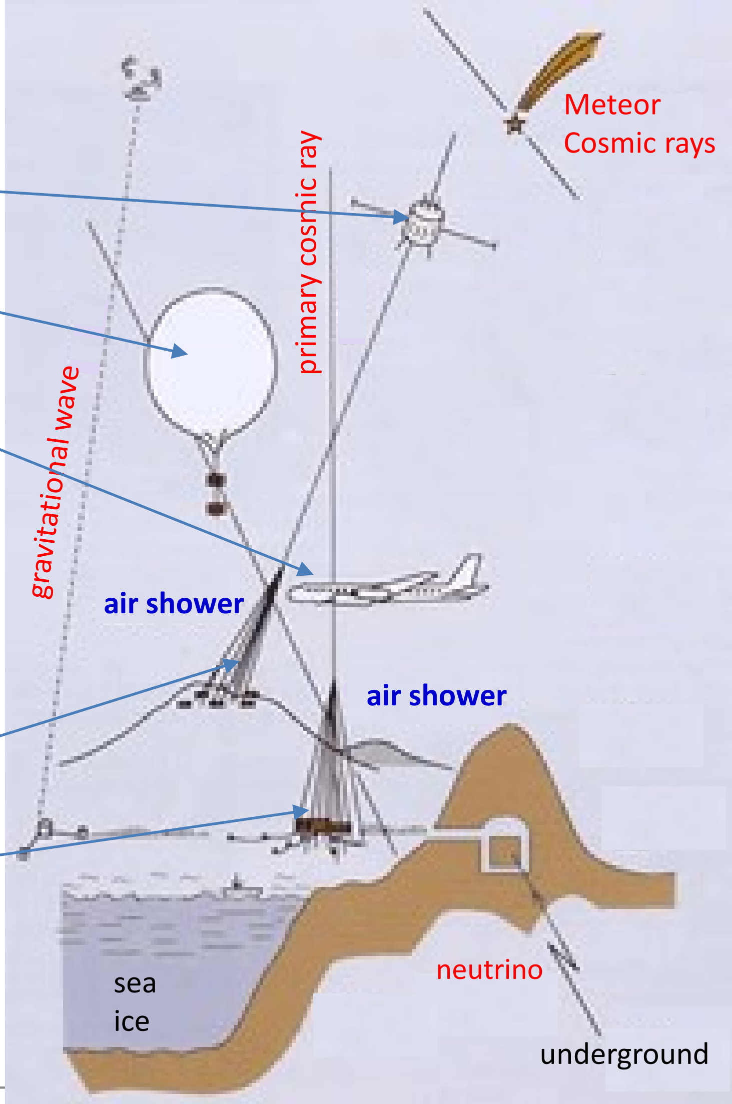
2nd summer challenge at KEK
(detection of secondary cosmic rays with a spark chamber)

Observation of cosmic rays

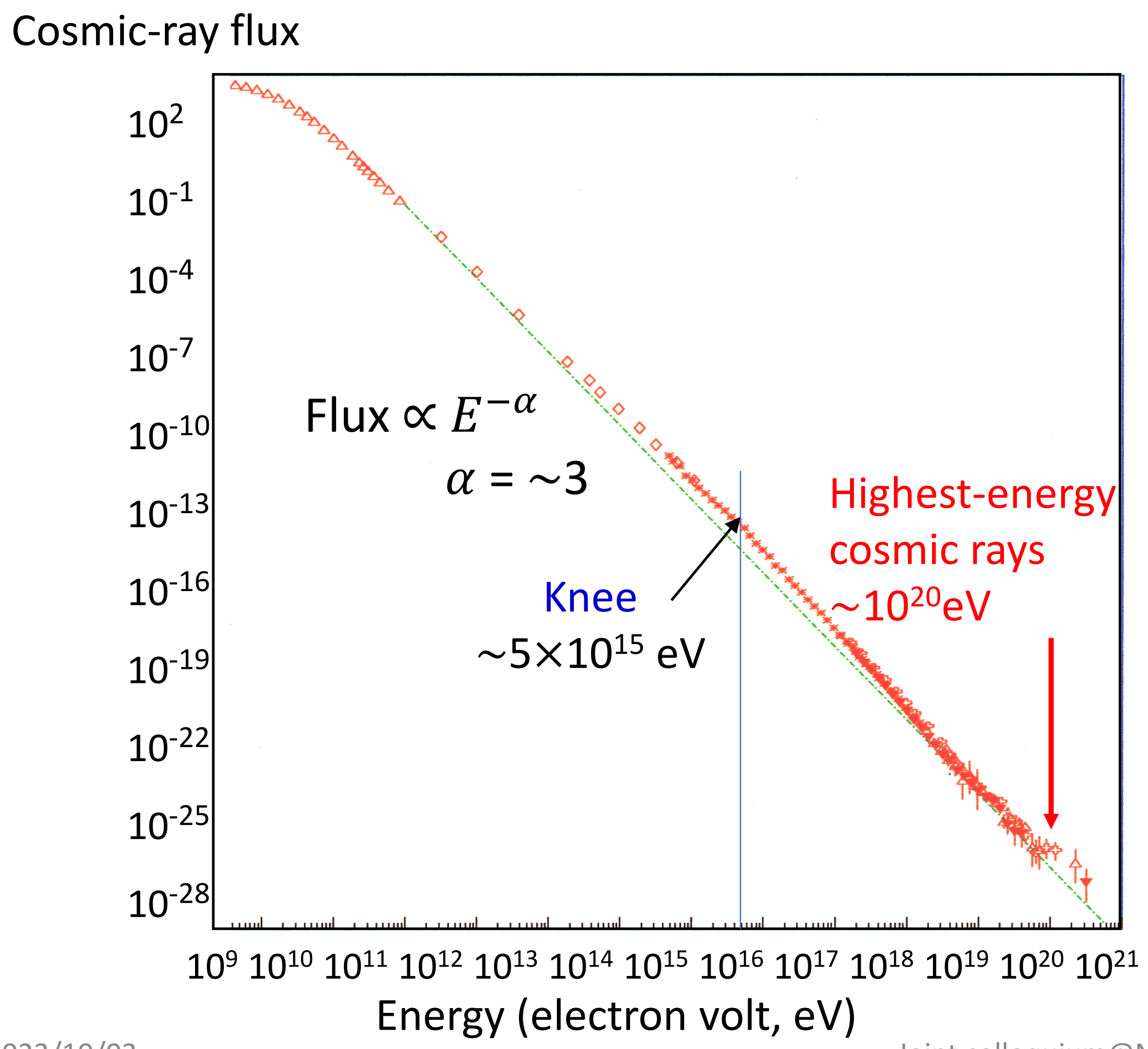
- Primary cosmic rays
  - Satellite
  - Balloon (30~40km)
  - Airplane (10~20km)

$\lesssim 10^{14}$ eV

- Secondary cosmic rays
  - Radiation produced by primary cosmic rays when they enter the atmosphere
  - High mountain (3~5km)
  - Ground (~0km)
  - Underground
  - deep sea, ice



Energy spectrum of cosmic rays

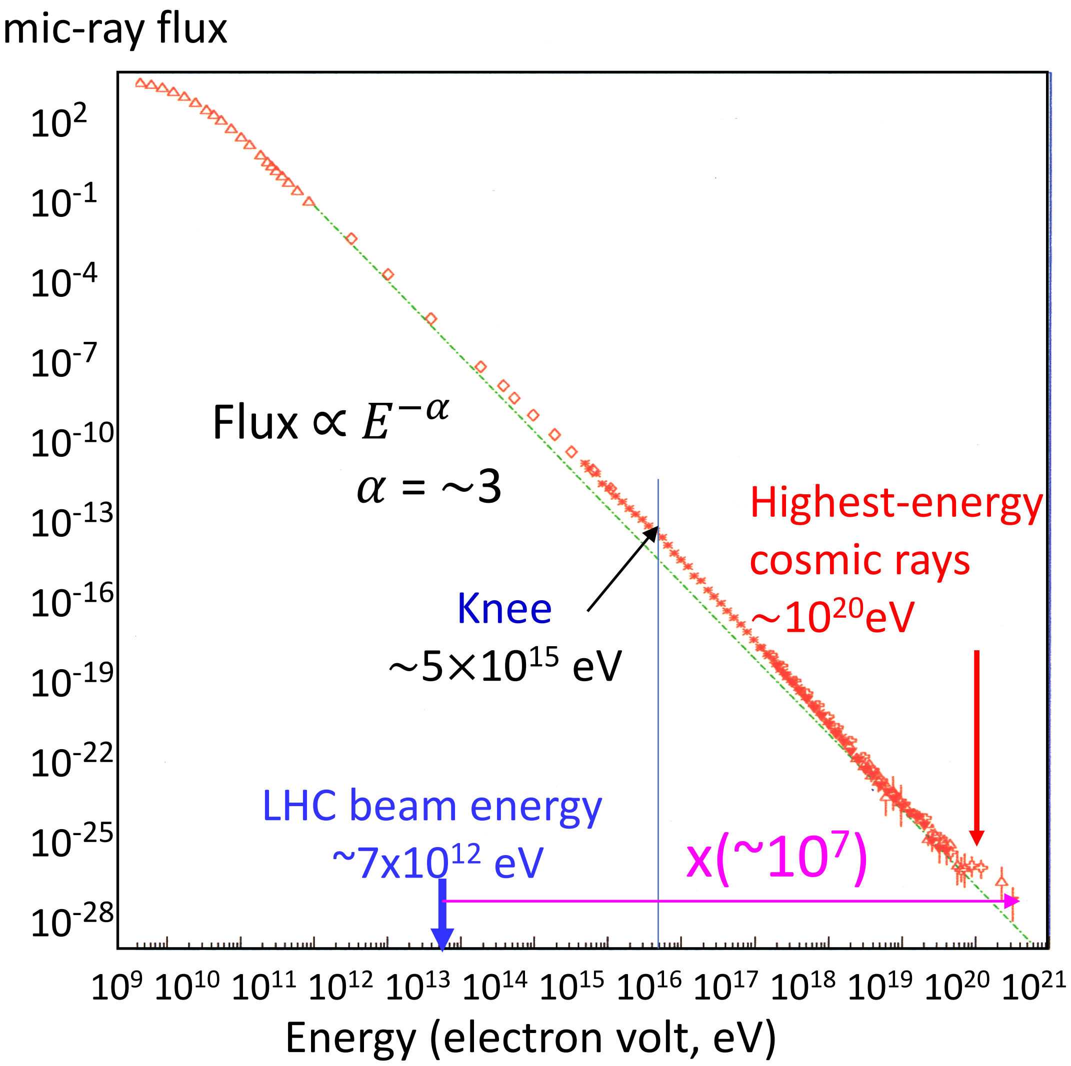


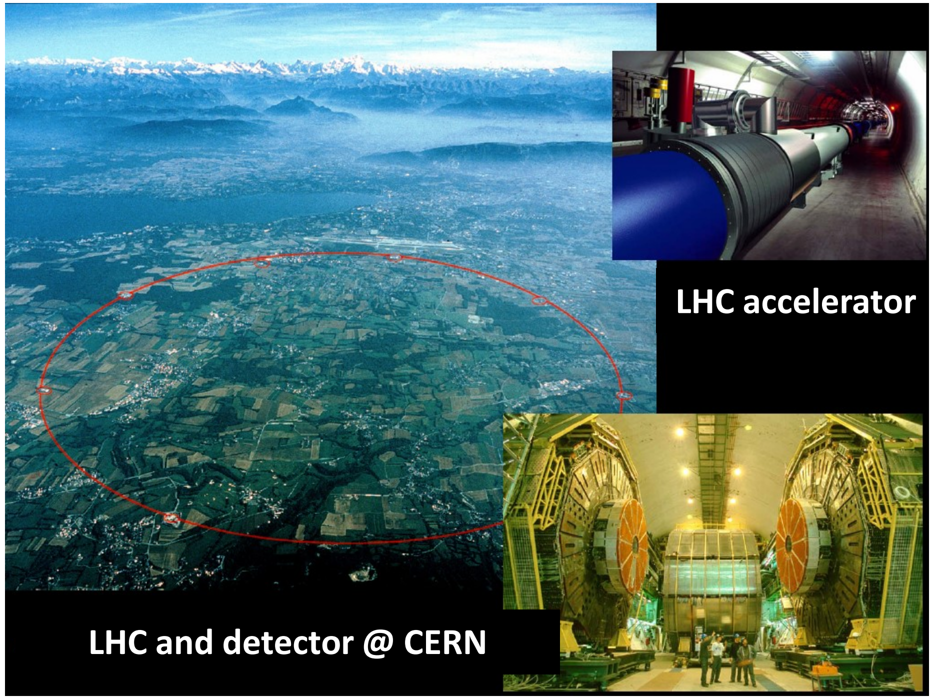
① What is the maximum?

② What are the most powerful accelerators generating cosmic rays of 10^{20} eV?

③ What types of particles?

Energy spectrum of cosmic rays



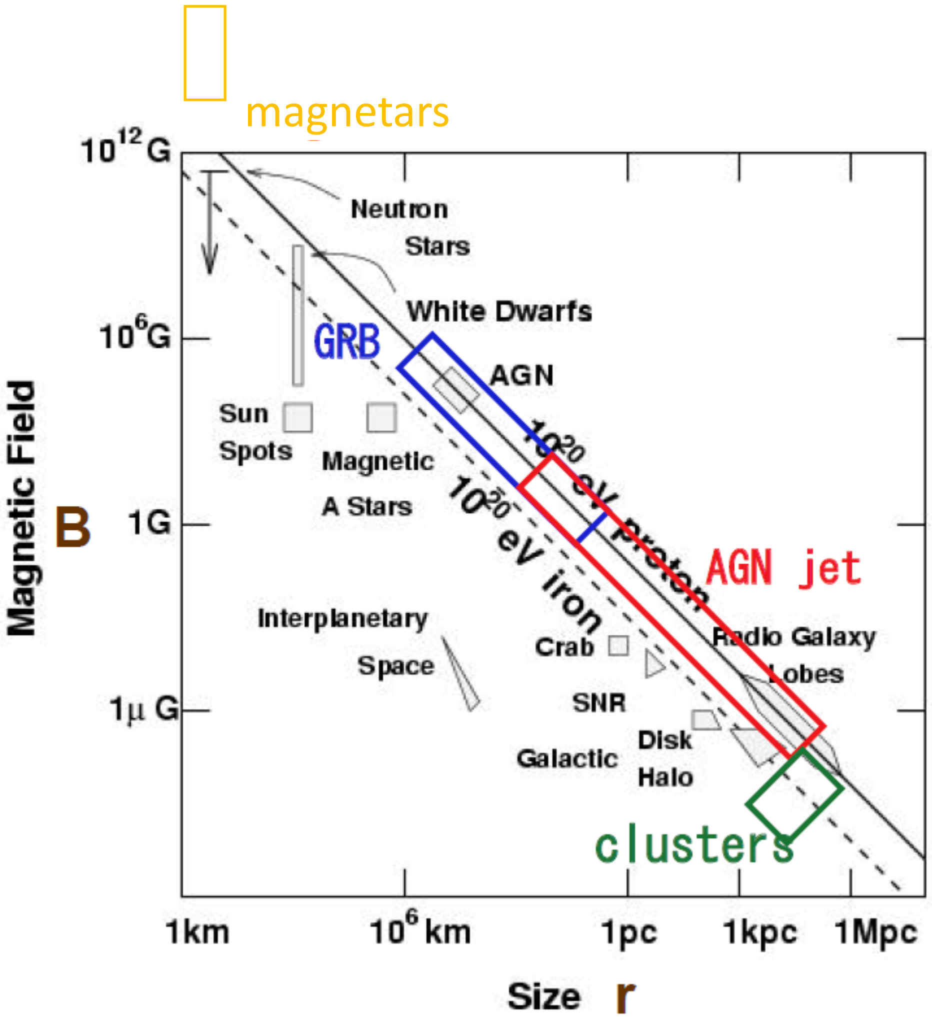


Rate@10^{20} eV

$<$1 particle/100km^2/year

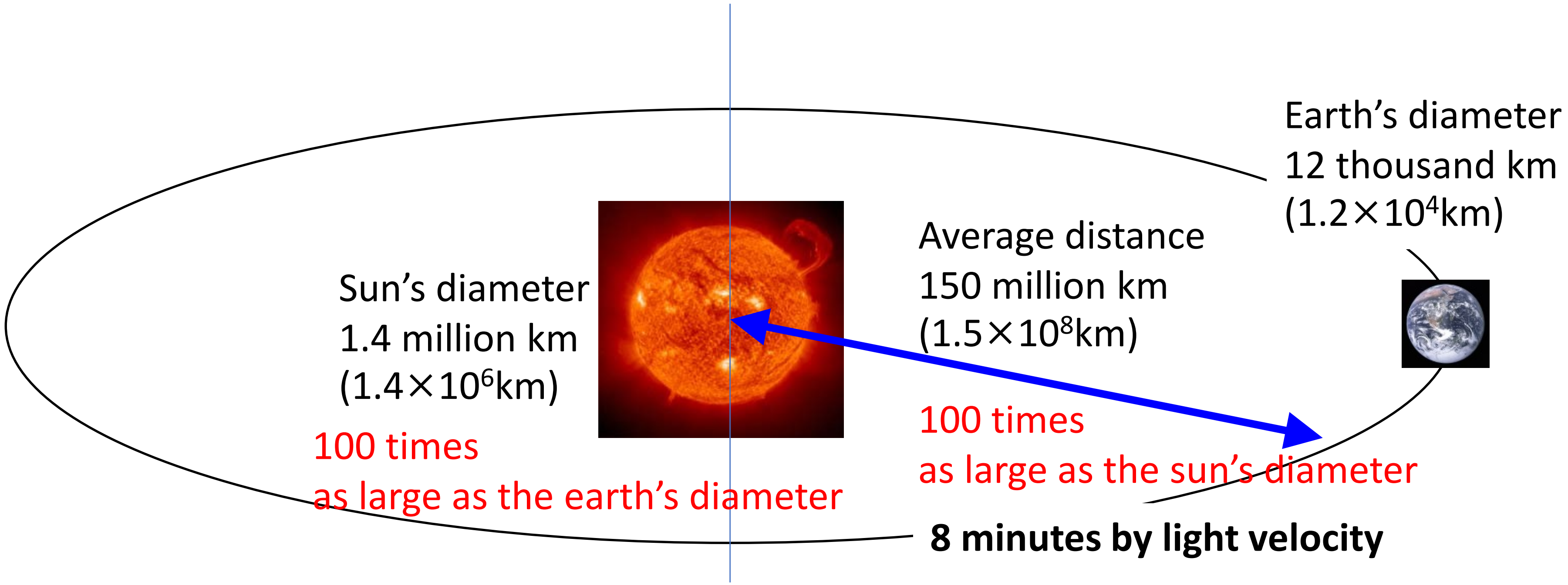
We need a huge detector!

Astrophysical cosmic-ray accelerators as source candidates



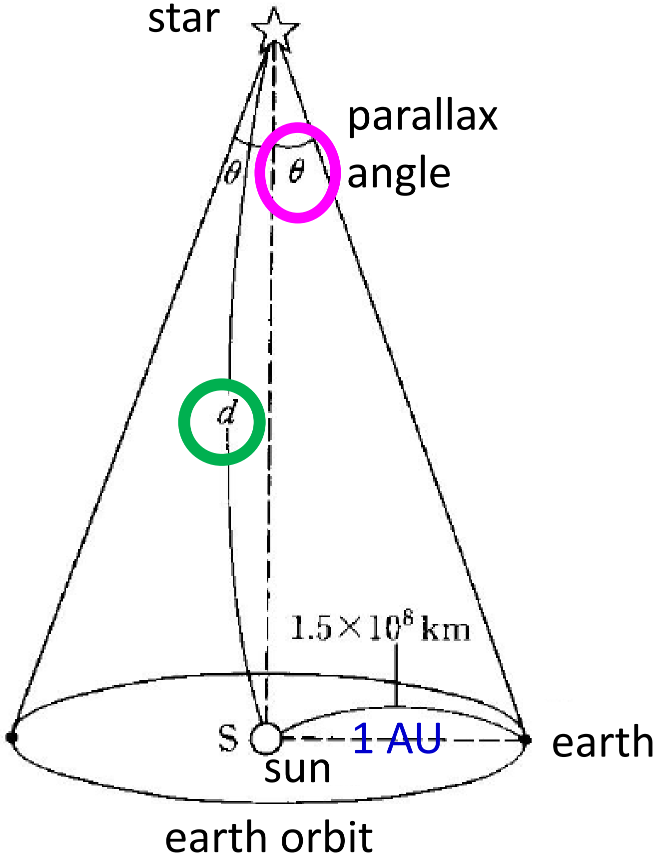
Hillas condition E < e B r β

Distance between the sun and the earth



Light velocity
(3×10^5km/s)

Astronomical Unit (AU)

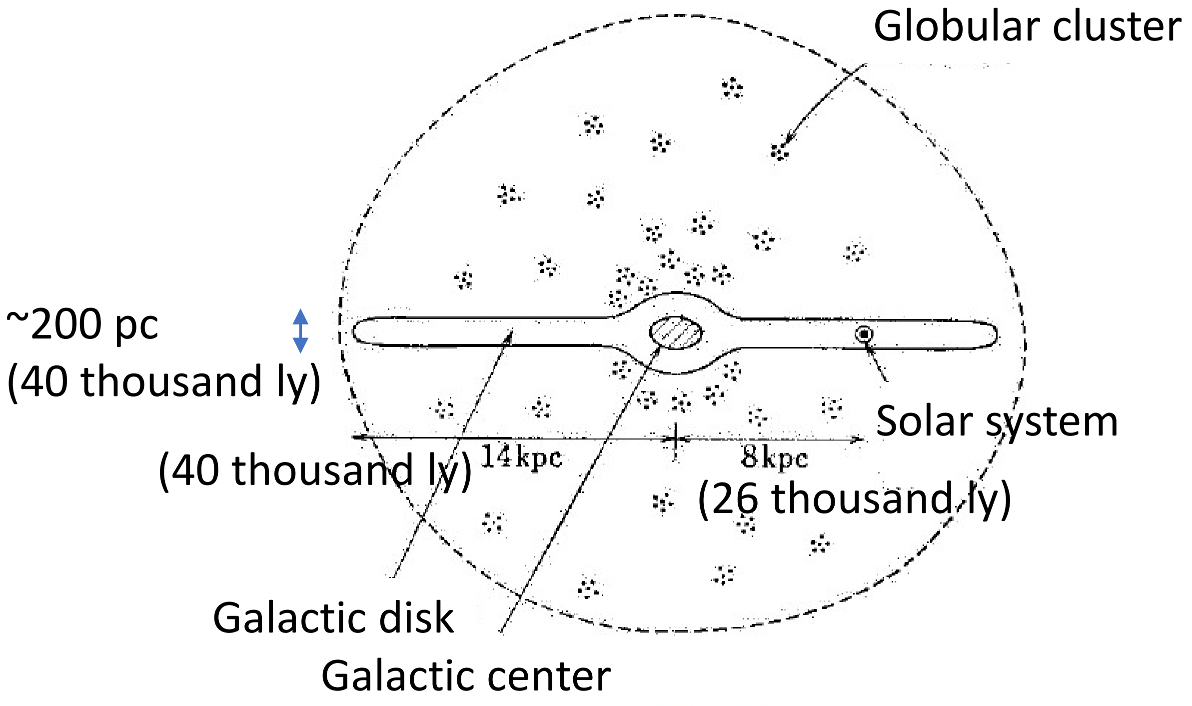


annual parallax

- 1 light year = the distance that light travels in one year = $(3.0 \times 10^{10}$cm/sec$) \times (3.16 \times 10^{7}sec)$ = 9.46×10^{12}km
- 1 AU (Astronomical Unit) = average distance between the sun and the earth = 1.50×10^{8} km
- 1 pc (parsec) : the distance for which annual parallax is 1" = 1 AU/1" = 3.09×10^{13} km
  - 1 pc = 3.26 light years

the Milky way (the Galaxy)

- Galaxy that includes our solar system



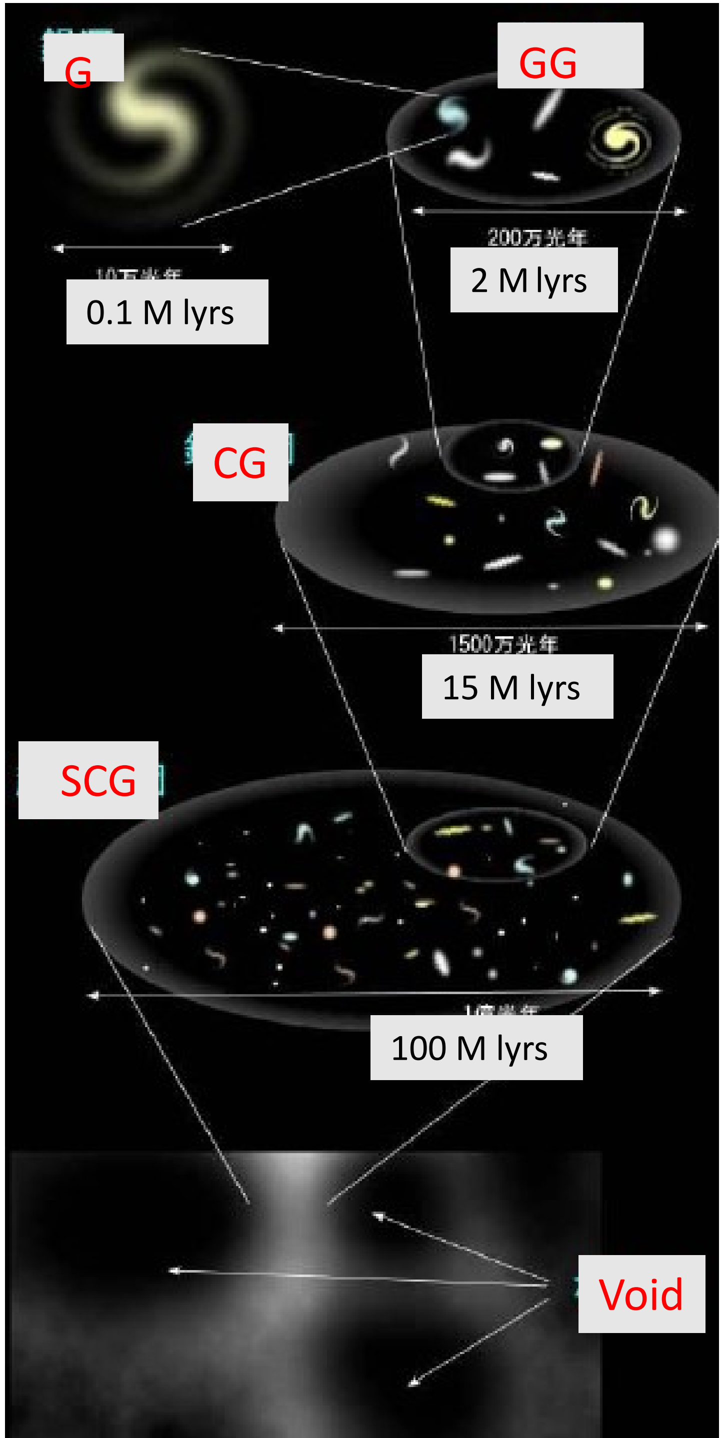
Our galaxy

1pc = 3.26 ly

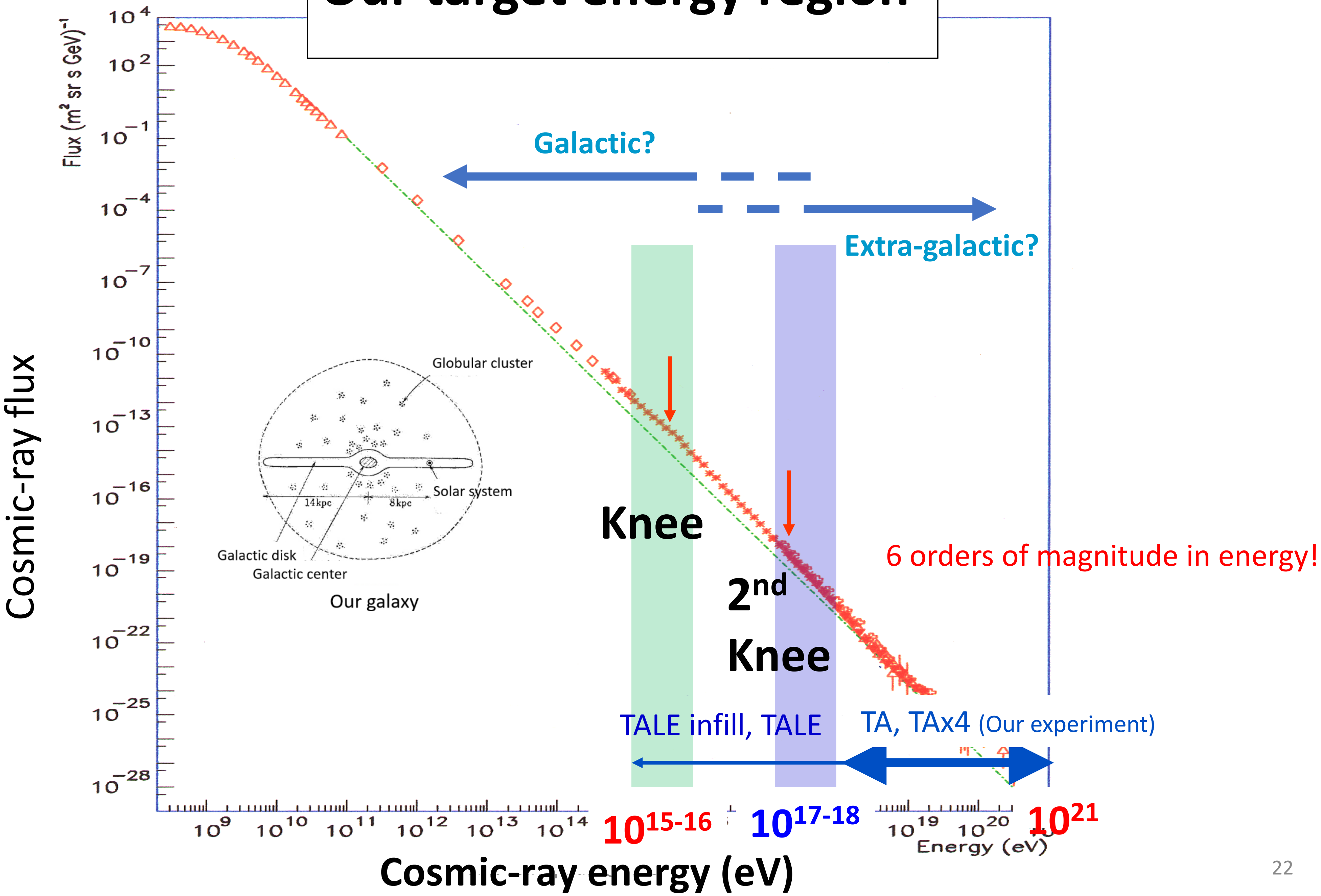
ly= light year

Astronomical distance

- galaxy (G)
- Galaxy Group (GG)
  - 3~some ten galaxies
- Cluster of Galaxies (CG)
  - some~some ten GGs
- Super Cluster of Galaxies (SCG)
  - multiple CGs
- Large scale structure of the universe (LSS)
  - SCGs+Voids



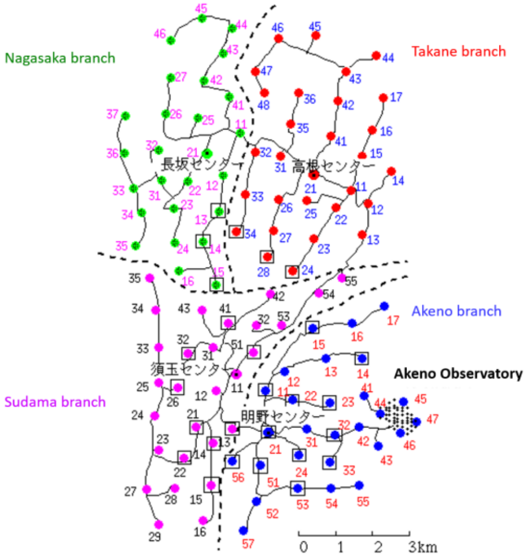
Our target energy region



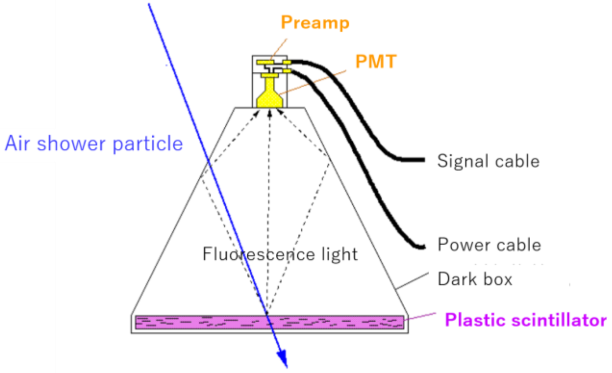
Ultra-High Energy Cosmic Ray Observatories

AGASA and HiRes (1990s – 2000s)

- AGASA (Akeno Giant Air Shower Array)
  - Akeno in Japan
  - 100 scintillator detectors (SD)
  - 100 km^2



Array layout

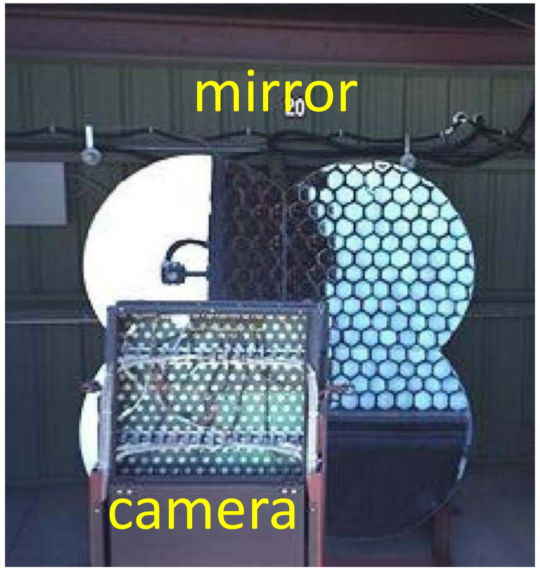


Plastic scintillator detector

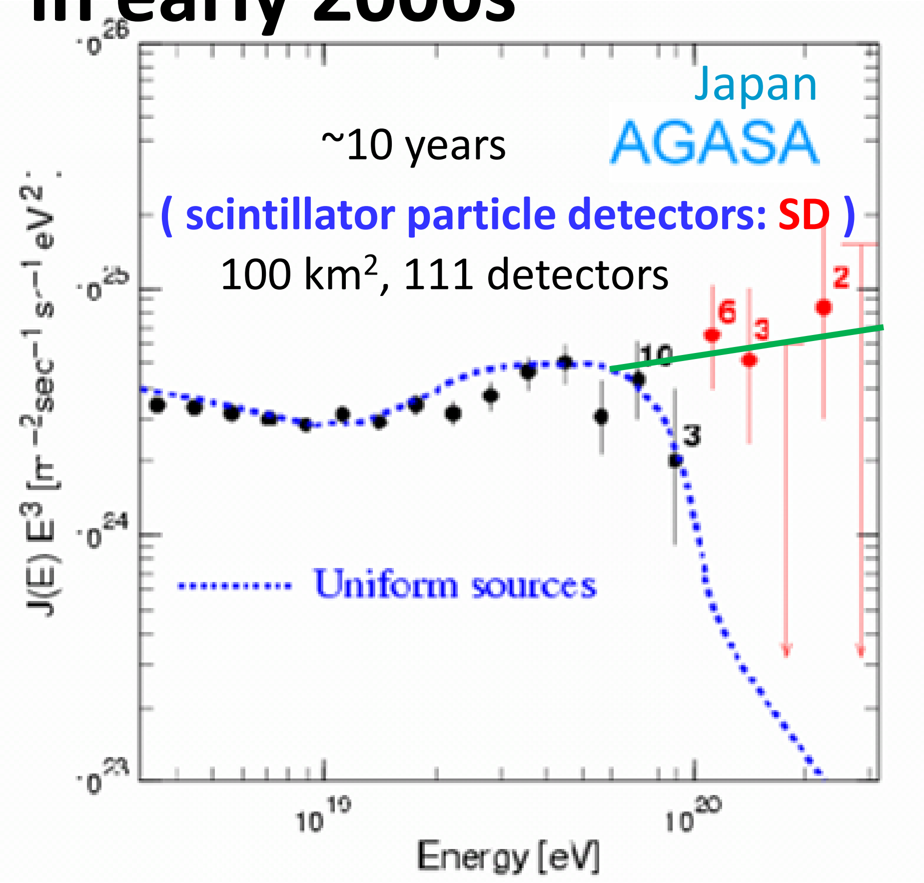
- HiRes (High Resolution Fly's Eyes)
  - Utah, USA
  - Stereoscopic fluorescence telescopes (FD)

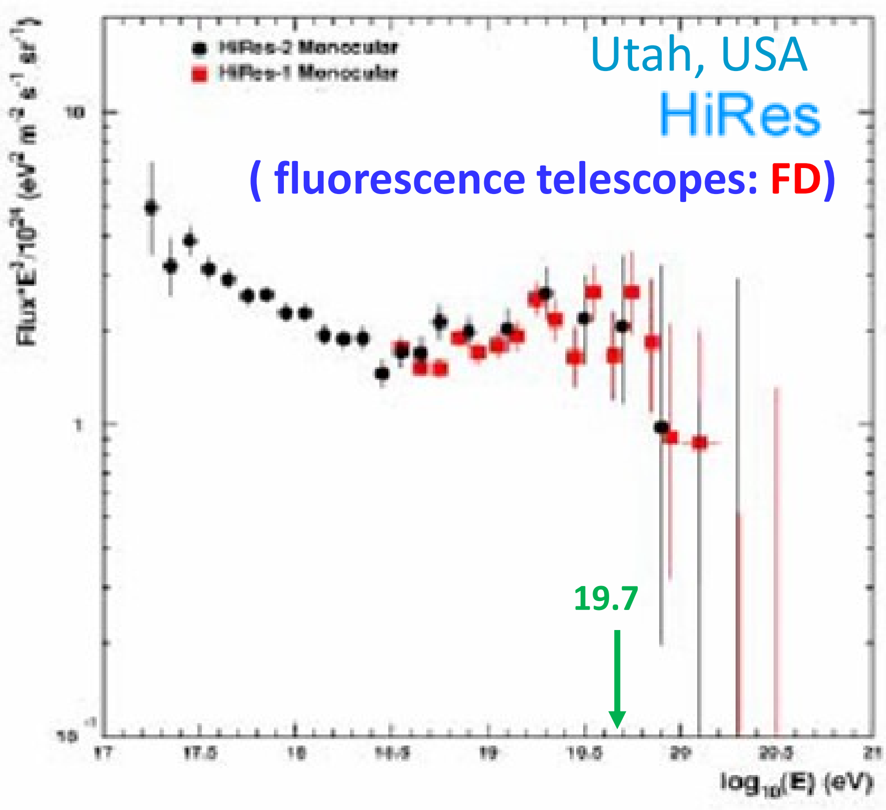
HiRes-1

HiRes-2



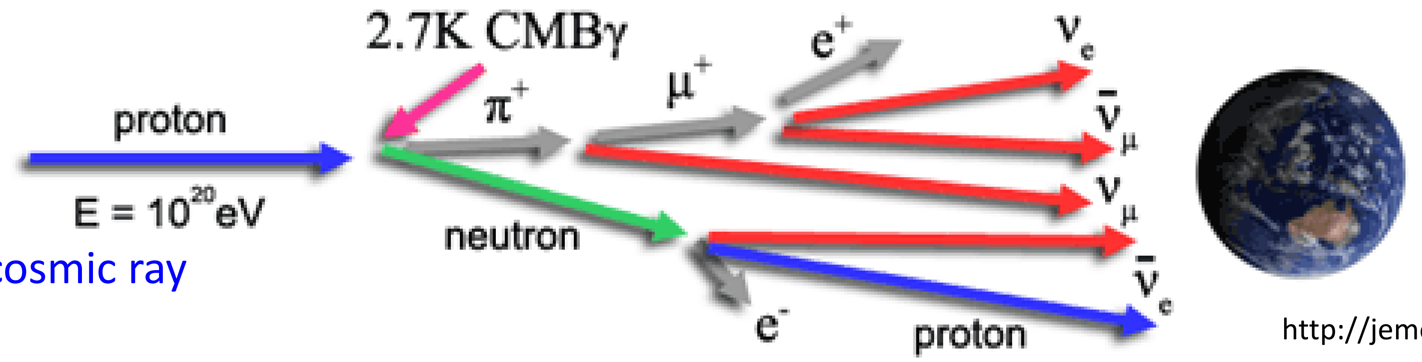
Energy spectra of extremely high energy cosmic rays in early 2000s





GZK cutoff

- 1964 Discovery of CMB radiation
- Greizen, Zatsepin and Kuzmin proposed in 1966
  - According to special theory of relativity,
  - (proton) cosmic rays with ~10^{20} eV coming beyond ~50 Mpc (160 Million light years) cannot arrive at the earth by the energy loss due to the interaction with CMB photon (GZK horizon)



Highest-E cosmic ray

http://jemeuso.riken.jp

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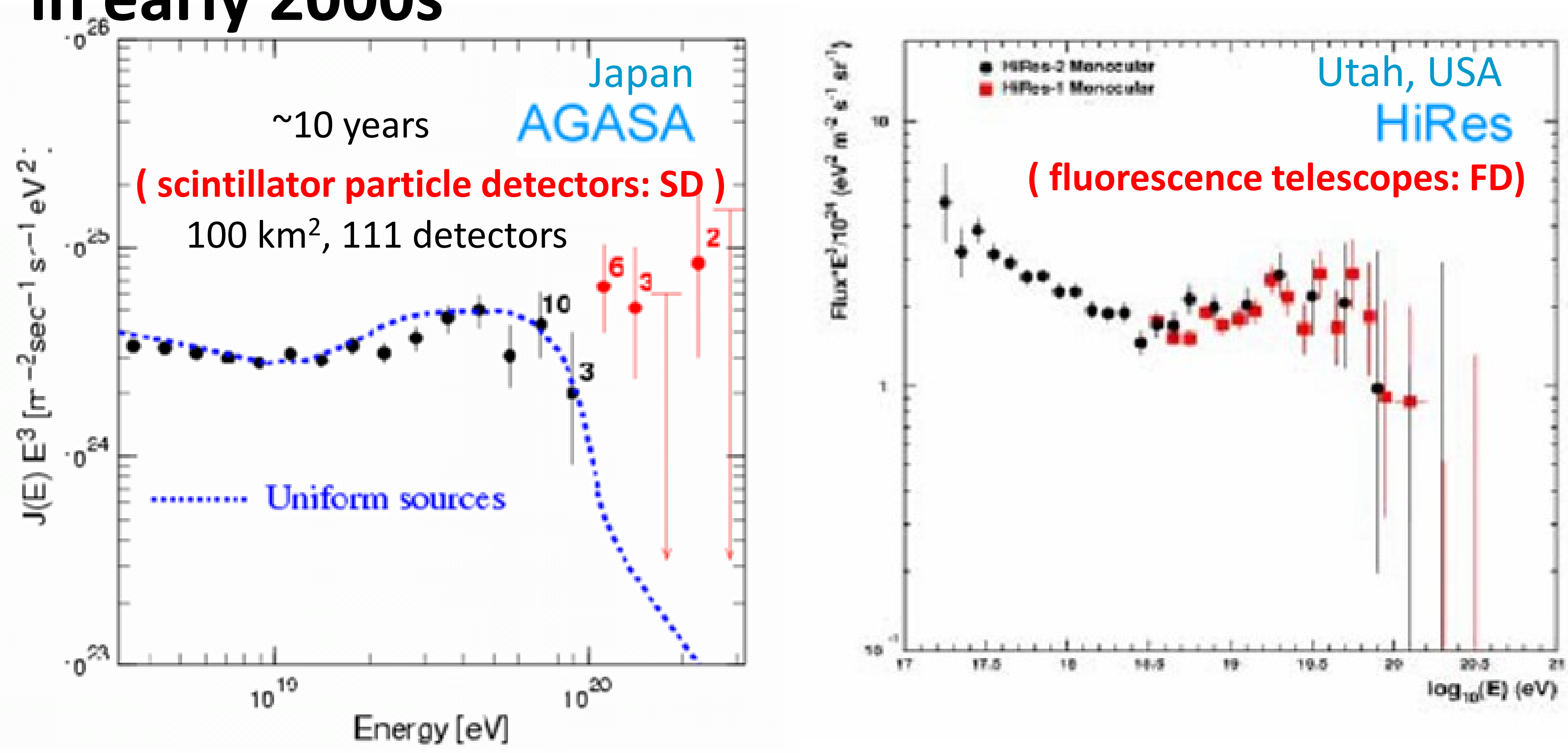
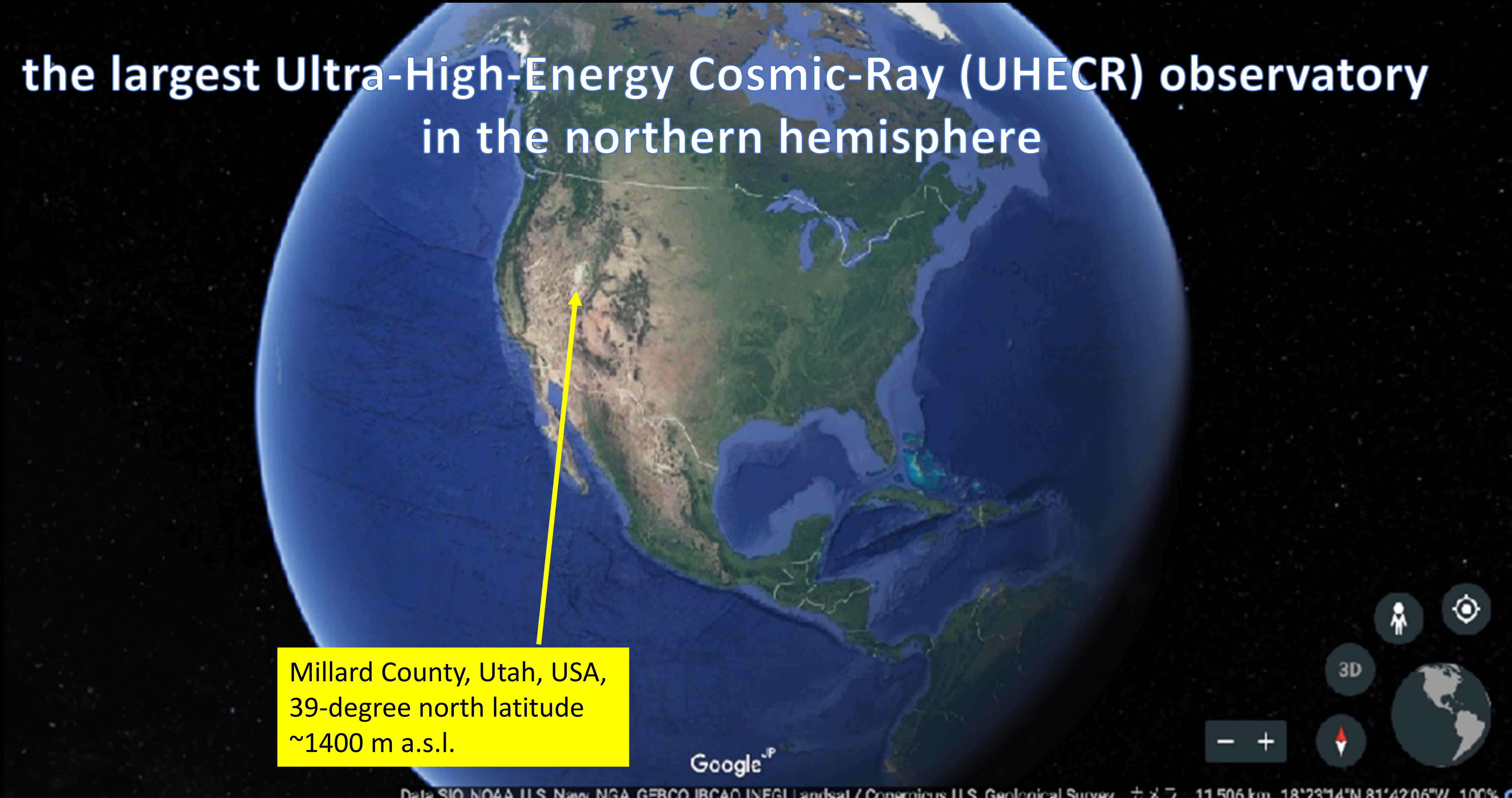


Is the difference due to statistics? Or detector difference (SD or FD)?

Next generation observatory => Verify whether the GZK cutoff exists or not with SD and FD

Telescope Array

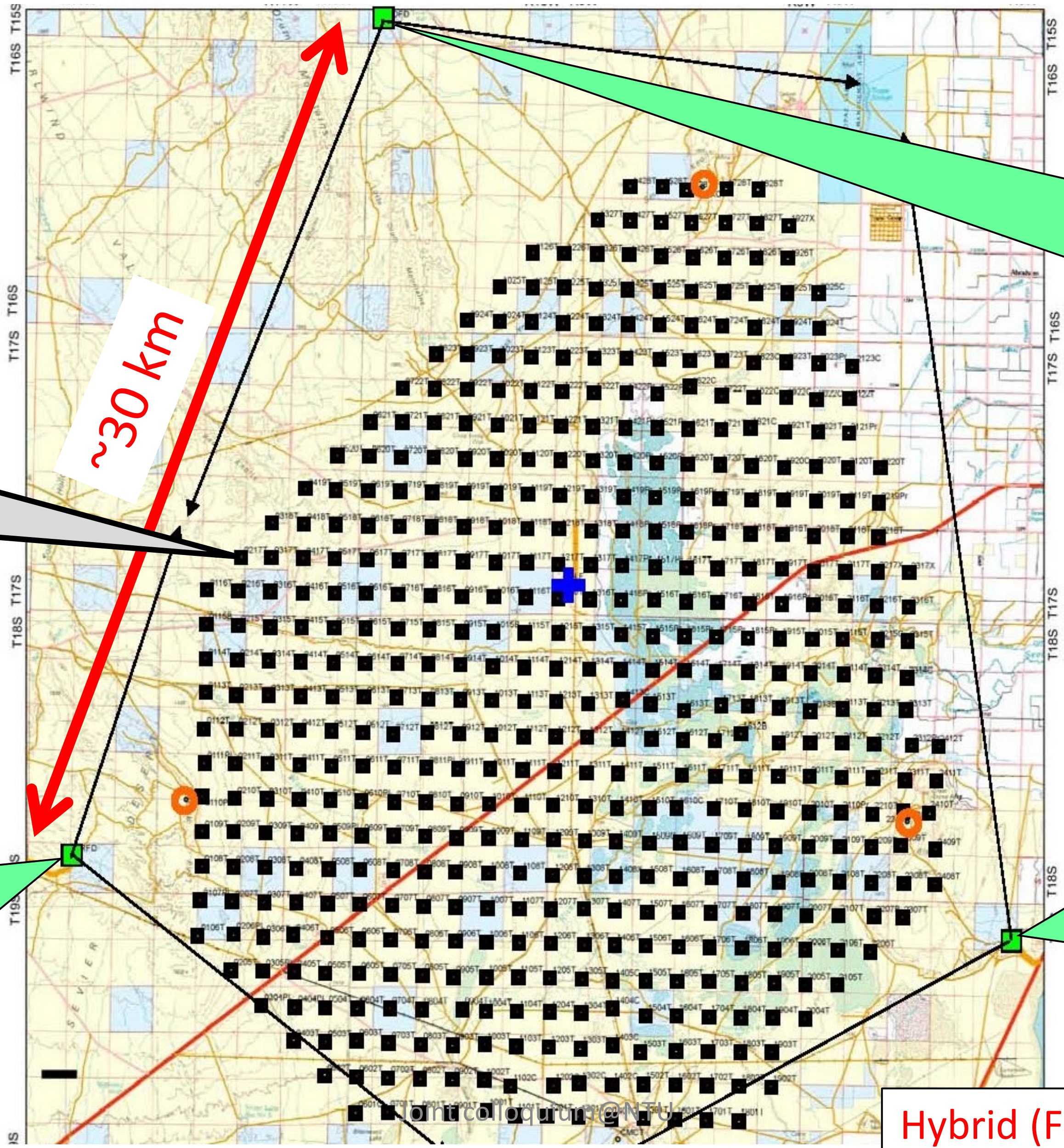
the largest Ultra-High-Energy Cosmic-Ray (UHECR) observatory in the northern hemisphere



Telescope Array (TA) detector

Surface detector (SD)

507 SDs
3m² plastic scintillator
1.2 km spacing
~700 km²



Fluorescence telescope（FD）

3 FD stations
Totally 38 telescopes

Middle Drum (MD)

14 telescopes

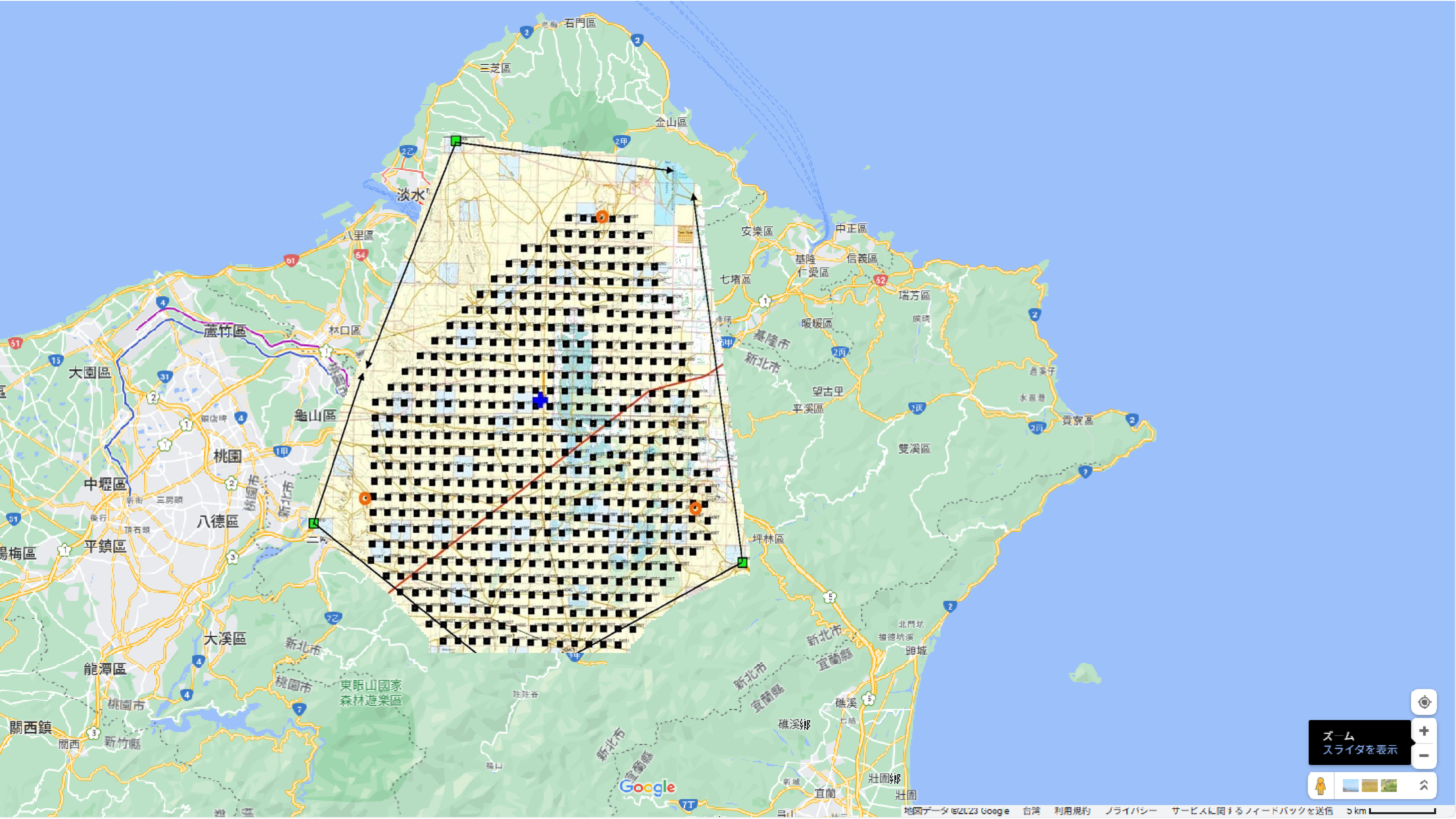
Black Rock Mesa (BR)

12 telescopes

Long Ridge (LR)

12 telescopes

Hybrid (FD/SD) observation started in 2008

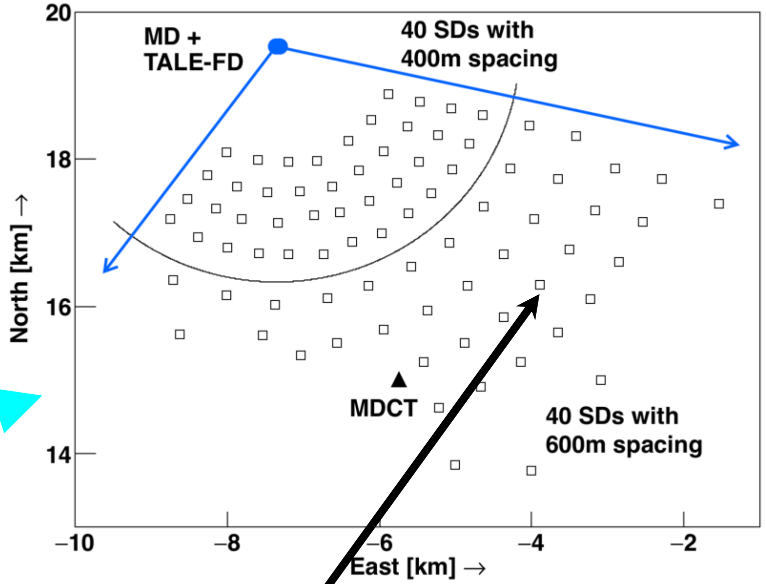


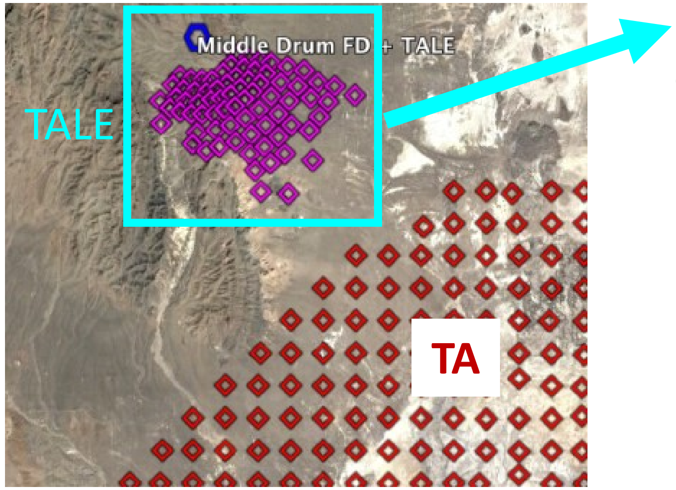
石門區
三芝區
金山區
淡水
八里區
安樂區
中正區
基隆
信義區
仁愛區
七堵區
瑞芳區
暖暖區
蘆竹區
林口區
大園區
基隆市
新北市
平溪區
雙溪區
貢寮區
龜山區
桃園
中壢區
八德區
平鎮區
坪林區
大溪區
桃園市
東眼山國家
森林遊樂區
龍潭區
關西鎮
新竹縣
宜蘭縣
礁溪
礁溪鄉
頭城
壯圍鄉
宜蘭
Google
ズーム
スライダを表示
地図データ ©2023 Google
台湾
利用規約
プライバシー
サービスに関するフィードバックを送信
5 km

TALE (TA Low-energy Extension)

- **Main aim: study on the transition from galactic to extra-galactic cosmic rays**
- Low energy CRs-induced shower
  - Not so bright, higher $X_{\max}$ (shower maximum depth)
    → high elevation telescope
  - compact shower size
    → dense SD array
- Low energy target: E > 10^{16} eV
- Constructed in north part of TA site
- Same concept as TA detector
  - 10 Fluorescence Telescopes
  - 80 Surface Detectors, 20 km^2
- Operation: FD since Sep. 2013

  SD since Nov. 2017





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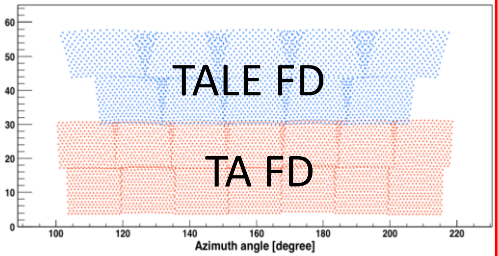

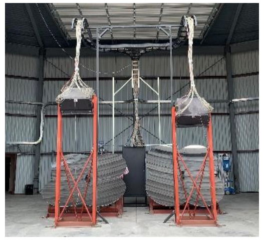

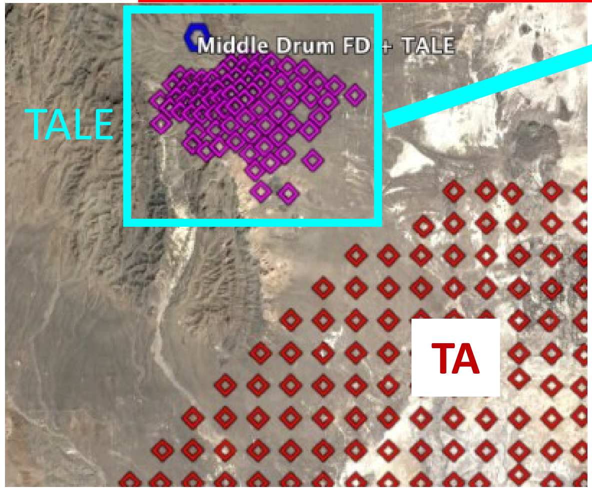

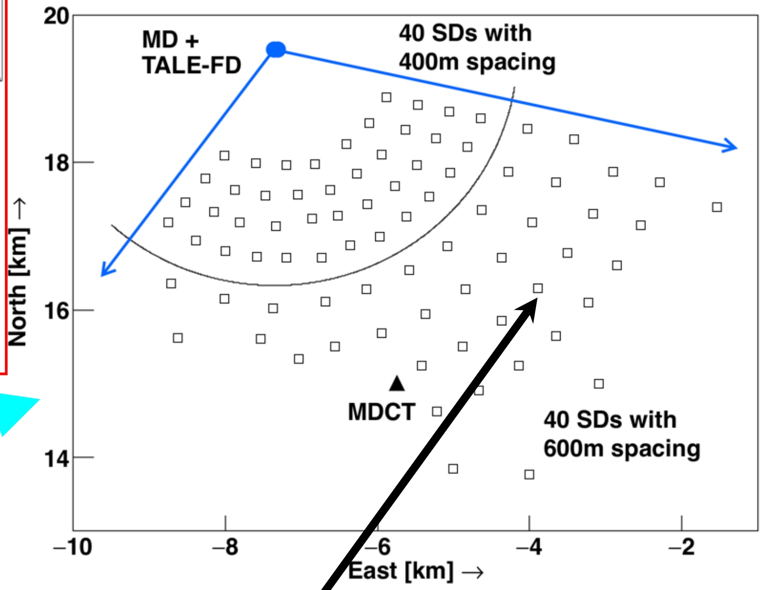

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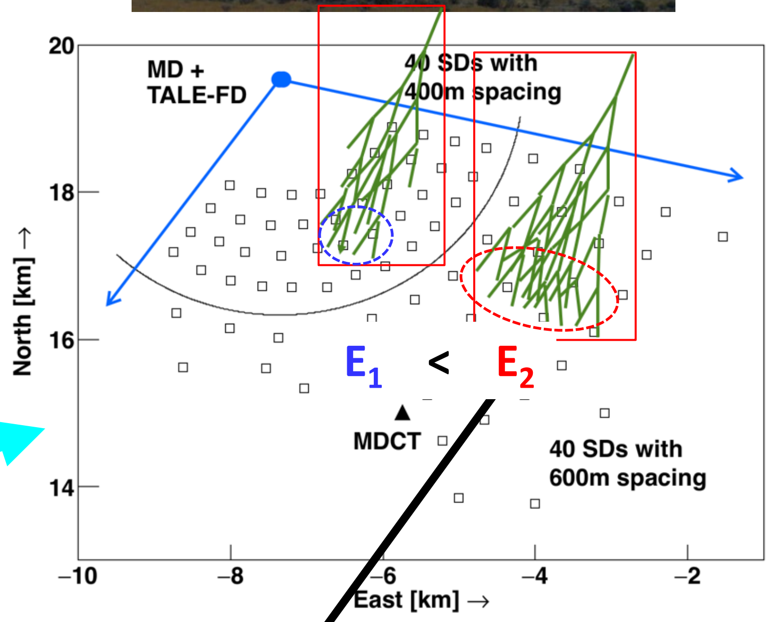

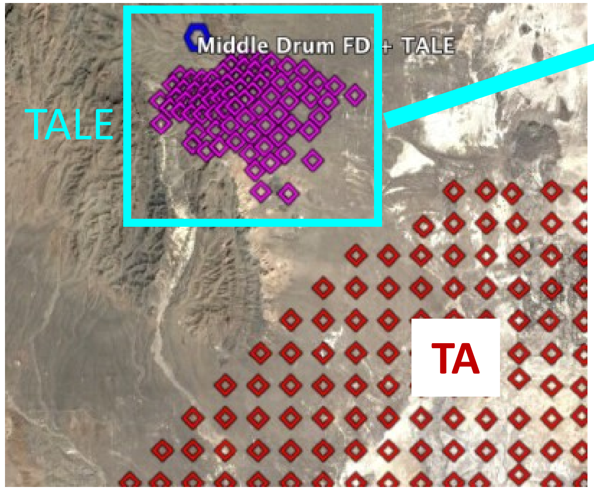

Telescope Array Collaboration

150 collaborators

R.U. Abbasi[1], Y. Abe[2], T. Abu-Zayyad[1,3], M. Allen[3], Y. Arai[4], R. Arimura[4], E. Barcikowski[3], J.W. Belz[3], D.R. Bergman[3], S.A. Blake[3], I. Buckland[3], B.G. Cheon[5], M. Chikawa[6], A. Fedynitch[6,7], T. Fujii[4,8], K. Fujisue[6], K. Fujita[6], R. Fujiwara[4], M. Fukushima[6], G. Furlich[3], Z. Gerber[3], N. Globus[9], W. Hanlon[3], N. Hayashida[10], H. He[9], R. Hibi[2], K. Hibino[10], R. Higuchi[9], K. Honda[11], D. Ikeda[10], N. Inoue[12], T. Ishii[11], H. Ito[9], D. Ivanov[3], A. Iwasaki[4], H.M. Jeong[13], S. Jeong[13], C.C.H. Jui[3], K. Kadota[14], F. Kakimoto[10], O. Kalashev[15], K. Kasahara[16], S. Kasami[17], Y. Kawachi[4], S. Kawakami[4], K. Kawata[6], I. Kharuk[15], E. Kido[9], H.B. Kim[5], J.H. Kim[3], J.H. Kim[3], S.W. Kim[13], Y. Kimura[4], I. Komae[4], K. Komori[17], Y. Kusumori[17], M. Kuznetsov[15,18], Y.J. Kwon[19], K.H. Lee[5], M.J. Lee[13], B. Lubsandorzhiev[15], J.P. Lundquist[3,20], T. Matsuyama[4], J.A. Matthews[3], J.N. Matthews[3], R. Mayta[4], K. Miyashita[2], K. Mizuno[2], M. Mori[17], M. Murakami[17], I. Myers[3], S. Nagataki[9], M. Nakahara[4], K. Nakai[4], T. Nakamura[21], E. Nishio[17], T. Nonaka[6], S. Ogio[6], H. Ohoka[6], N. Okazaki[6], Y. Oku[17], T. Okuda[22], Y. Omura[4], M. Onishi[6], M. Ono[9], A. Oshima[23], H. Oshima[6], S. Ozawa[24], I.H. Park[13], K.Y. Park[5], M. Potts[3], M. Przybylak[25], M.S. Pshirkov[15,26], J. Remington[3], D.C. Rodriguez[3], C. Rott[3,13], G.I. Rubtsov[15], D. Ryu[27], H. Sagawa[6], R. Saito[2], N. Sakaki[6], T. Sako[6], N. Sakurai[4], D. Sato[2], K. Sato[4], S. Sato[17], K. Sekino[6], P.D. Shah[3], N. Shibata[17], T. Shibata[6], J. Shikita[4], H. Shimodaira[6], B.K. Shin[27], H.S. Shin[4,8], K. Shinozaki[25], D. Shinto[17], J.D. Smith[3], P. Sokolsky[3], B.T. Stokes[3], T.A. Stroman[3], Y. Takagi[17], K. Takahashi[6], M. Takamura[28], M. Takeda[6], R. Takeishi[6], A. Taketa[29], M. Takita[6], Y. Tameda[17], K. Tanaka[30], M. Tanaka[31], S.B. Thomas[3], G.B. Thomson[3], P. Tinyakov[15,18], I. Tkachev[15], H. Tokuno[32], T. Tomida[2], S. Troitsky[15], R. Tsuda[4], Y. Tsunesada[4,8], S. Udo[10], F. Urban[33], I.A. Vaiman[15], M. Vr´abel[25], D. Warren[9], T. Wong[3], K. Yamazaki[23], K. Yashiro[28], F. Yoshida[17], Y. Zhezher[6,15], and Z. Zundel[3]

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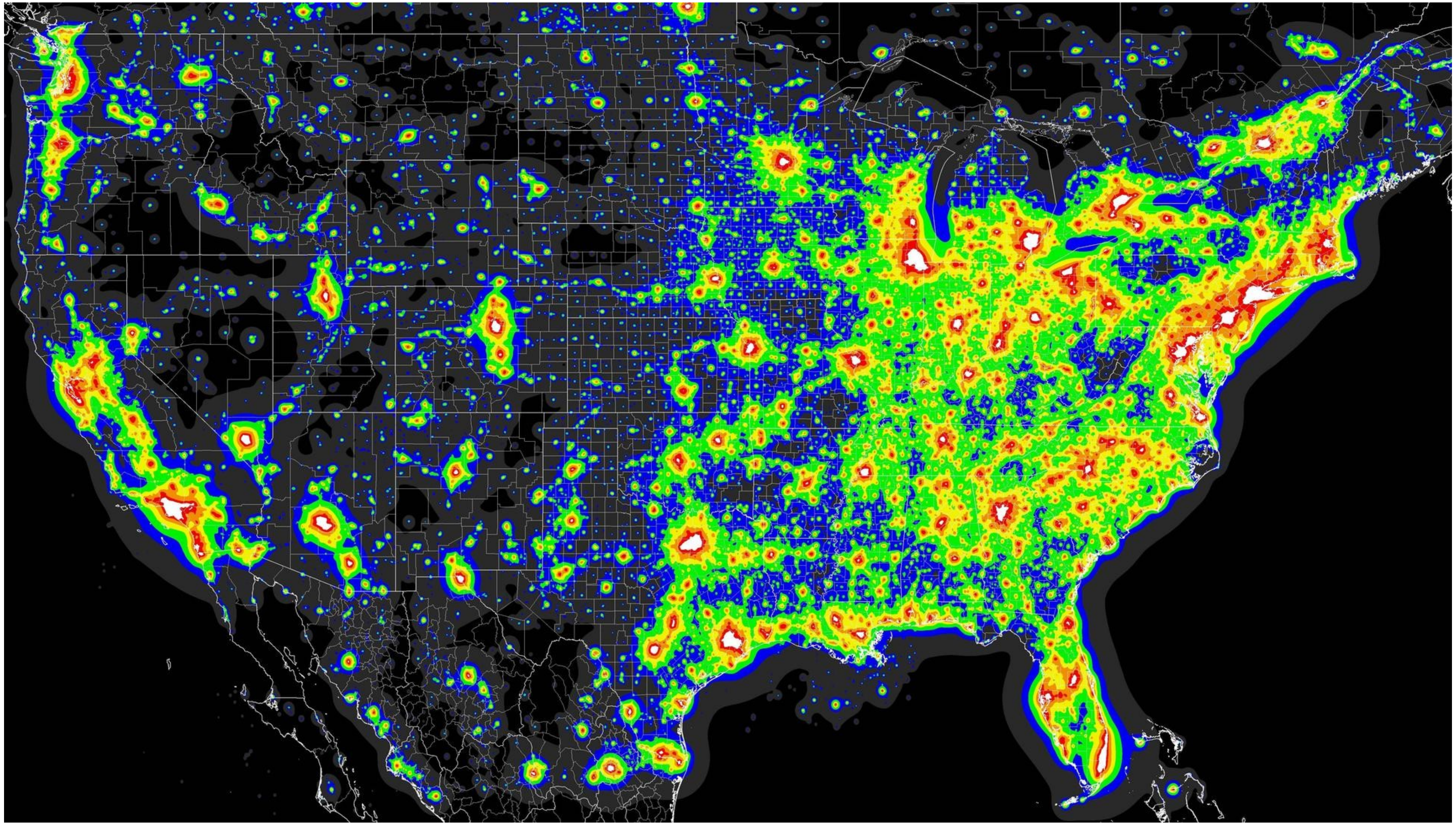
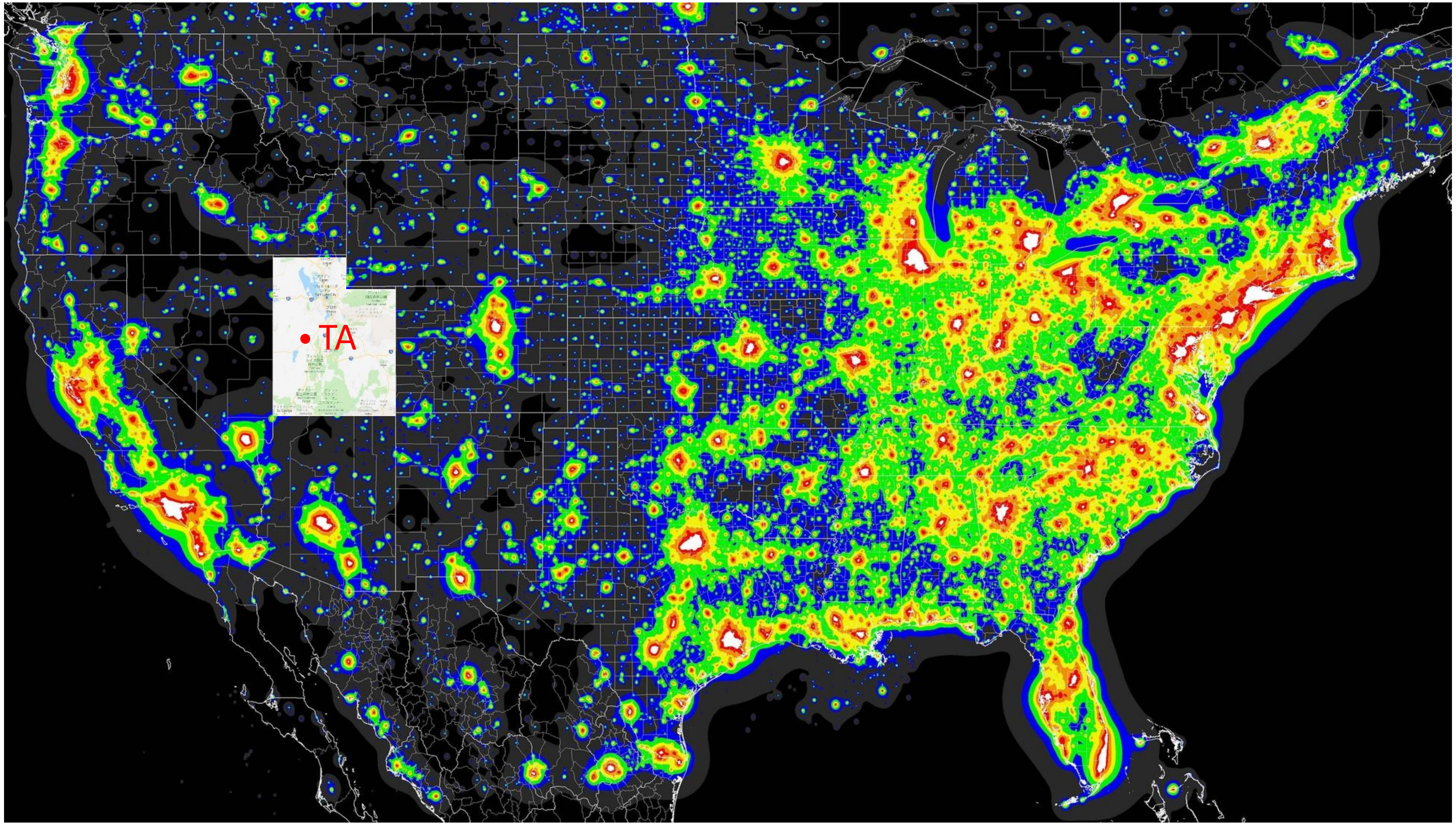
33 univ./institutes

US light polution map



http://i.imgur.com/aOPFB.jpg

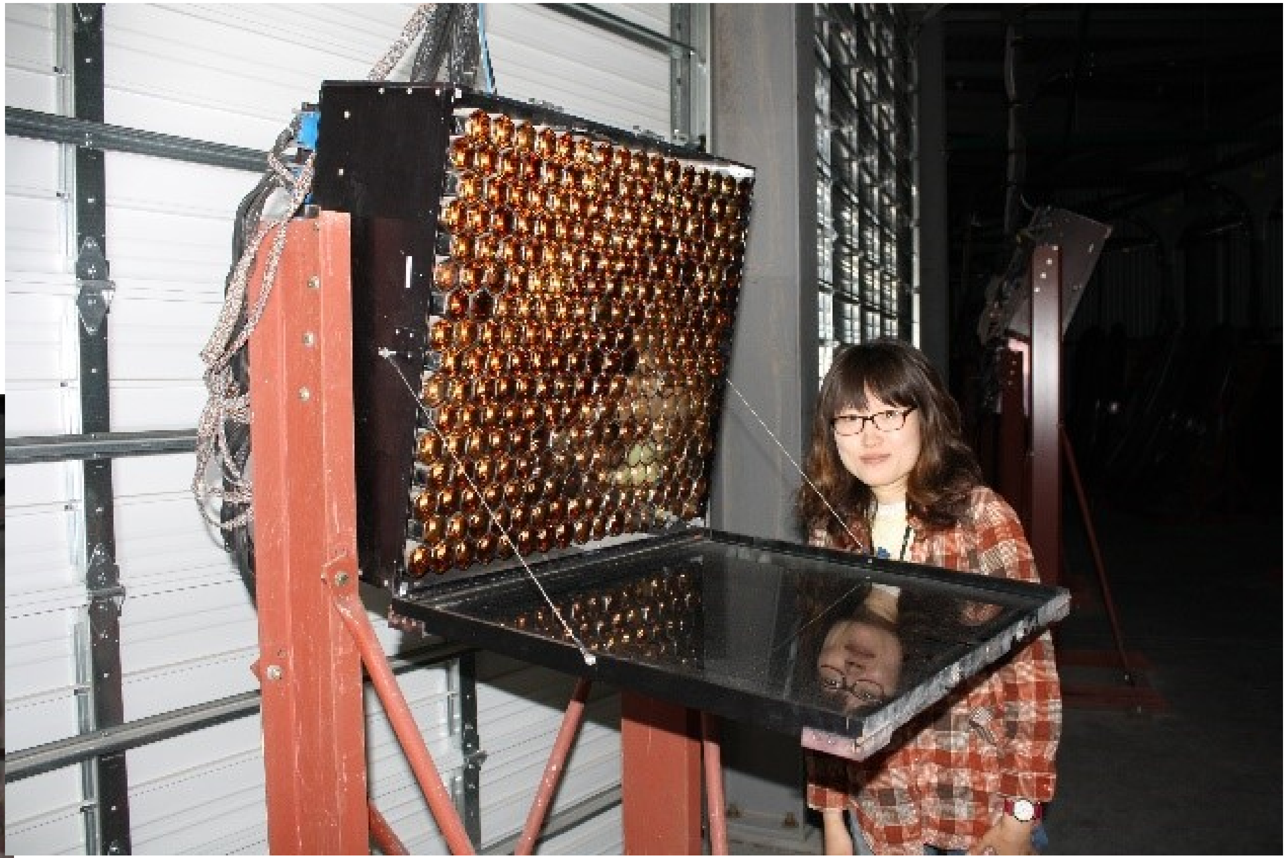
US light polution map



http://i.imgur.com/aOPFB.jpg

Telescopes

Refurbished HiRes telescope installed at TA MD FD

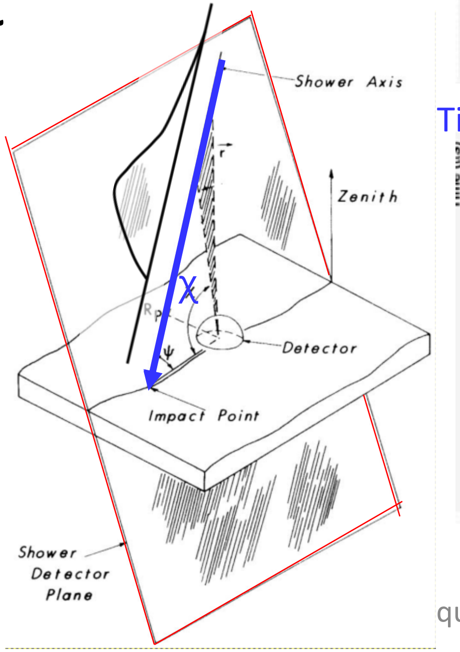


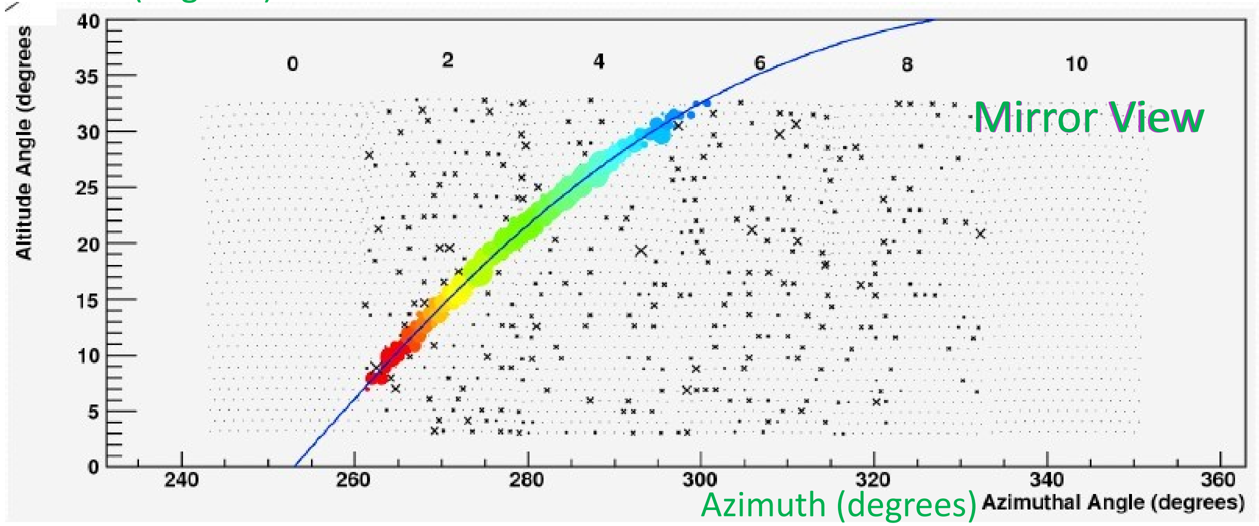
- Segmented mirrors
- 256 hexagonal PMTs/camera
- 1 pixel views ~1^{o} of sky
- UV band-pass filter

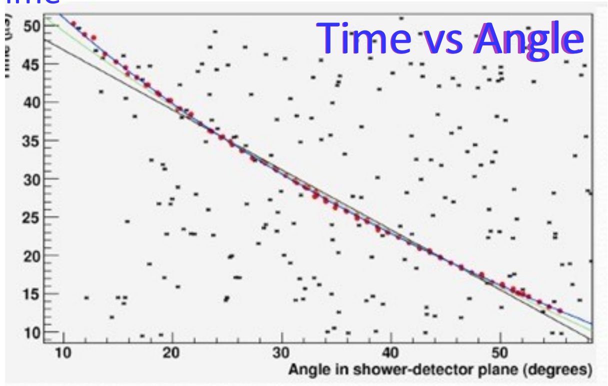
Clear, moonless nights ==> ~10% duty cycle

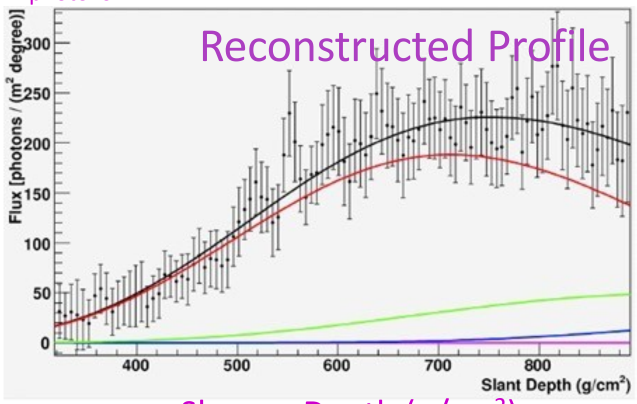
FD Event Reconstruction

- For FD, we see the shower sweep across the mirror
- Reconstruct Shower-Detector Plane
- Fit time-vs-angle to get
  - geometry (add in SD times for hybrid, giving much more lever arm for fit)
- Reconstruct shower size vs depth

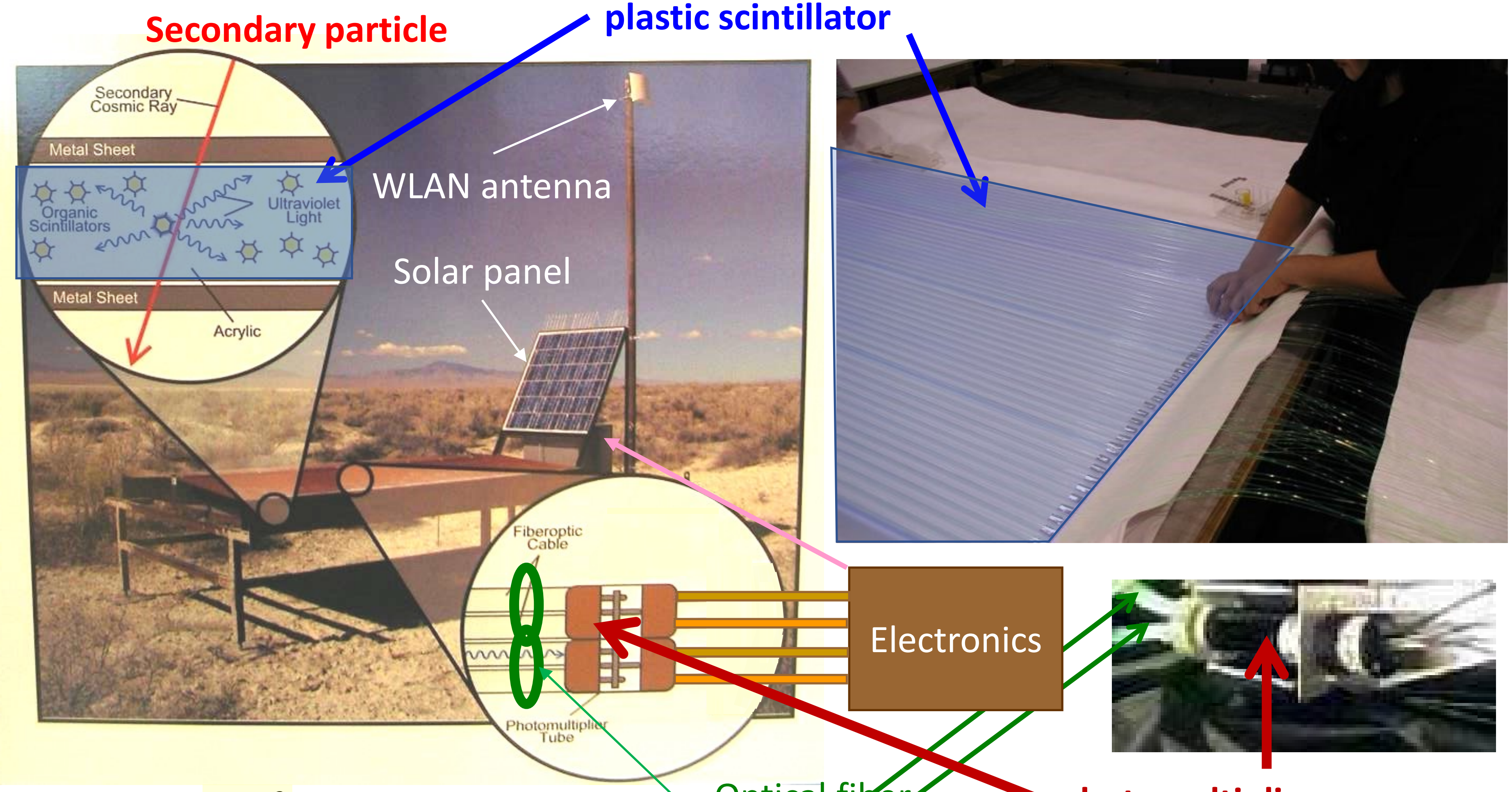








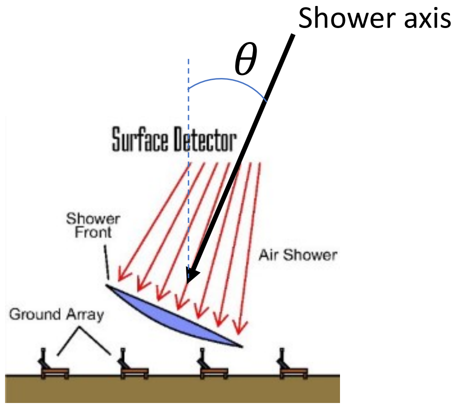
Scintillator detector (SD)



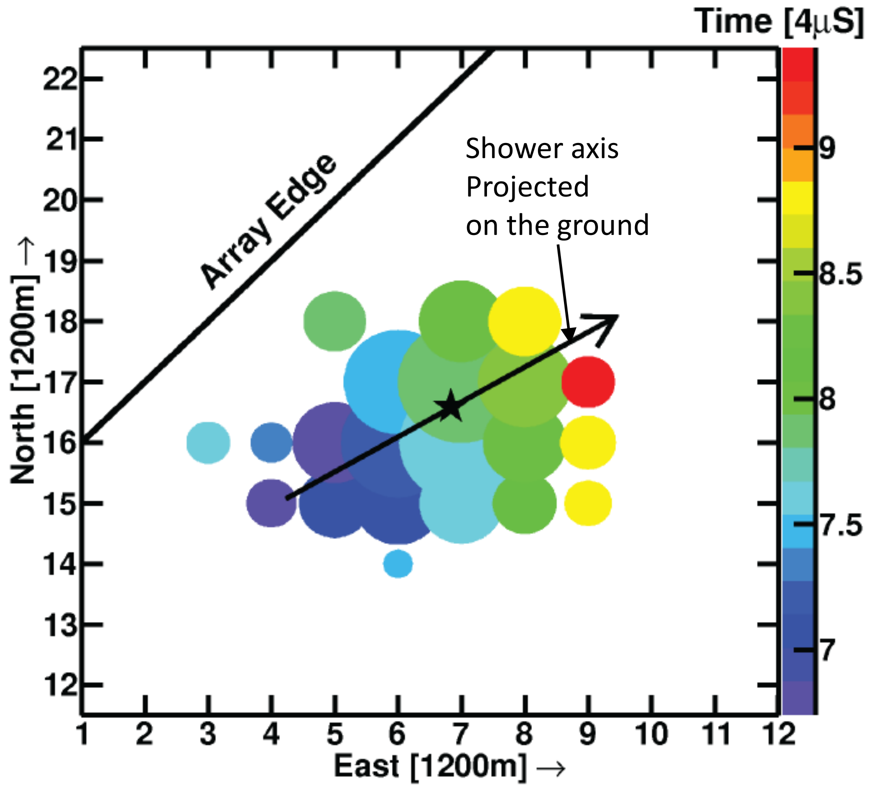
Scintillator: 3 m^2 x two layers
each layer 1.2 cm thickness

SD duty cycle is ~100%

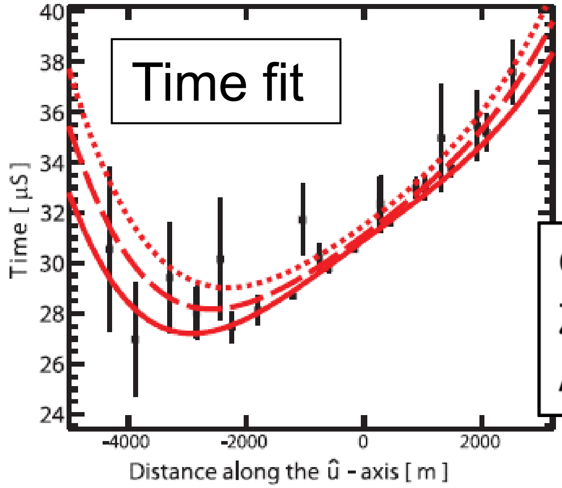
TA shower analysis with SD



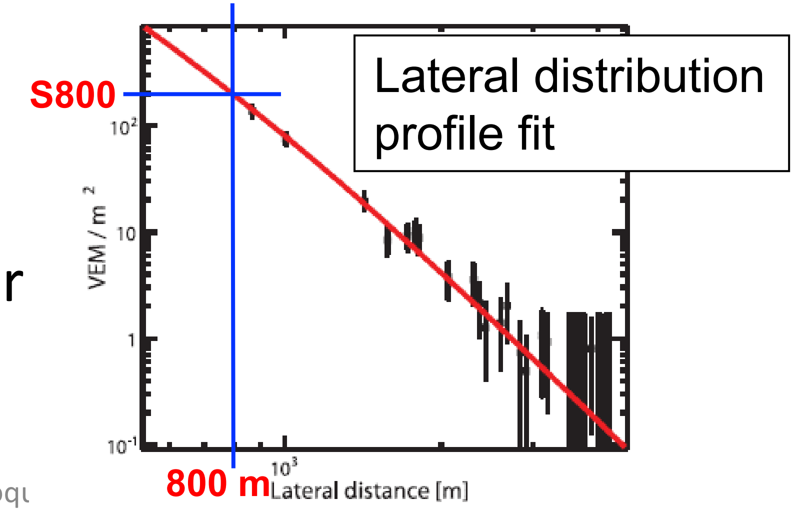
An SD hit map of a typical event



Use S800 as an energy estimator



Geometry
Zenith angle: θ
Azimuth angle

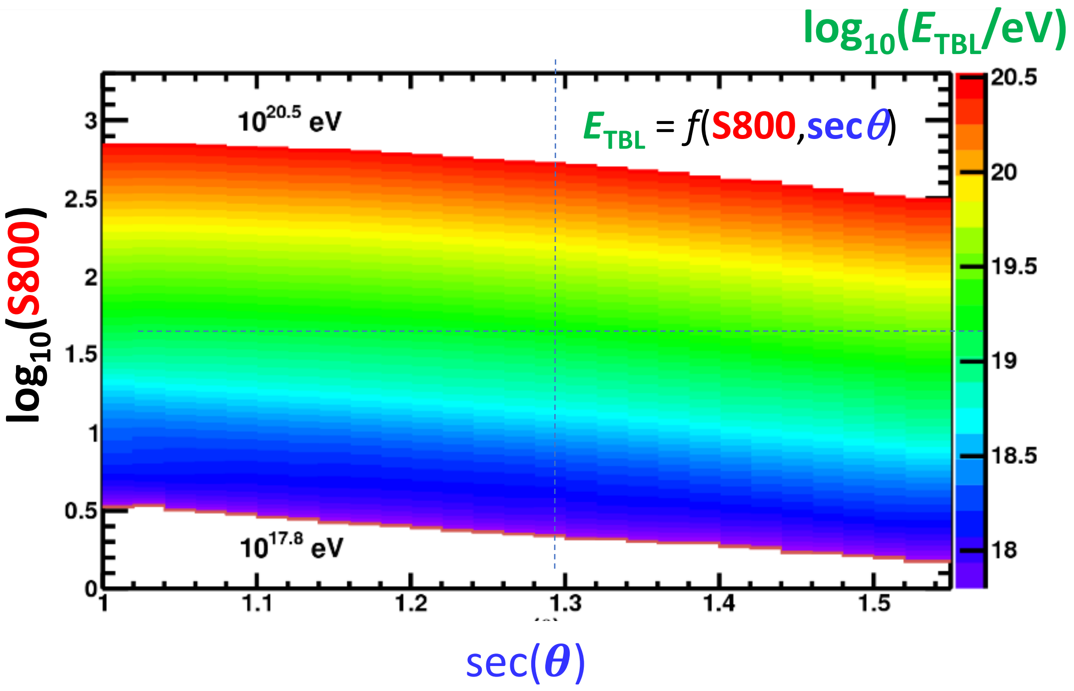


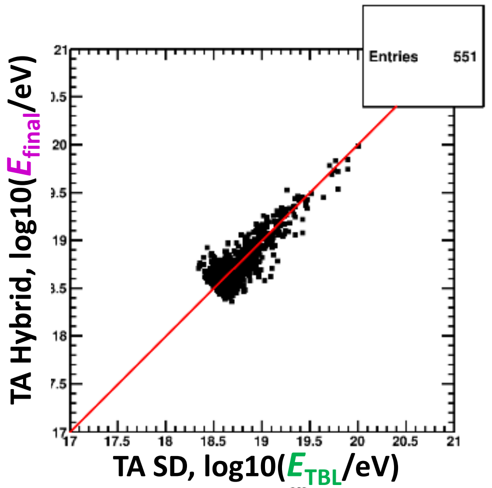
SD Event Reconstruction

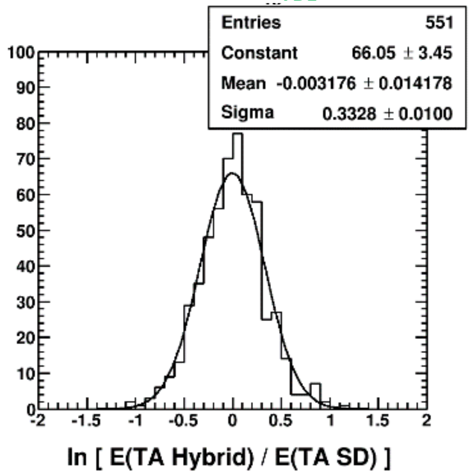
Signal size at 800 m, **S800**, is the energy indicator

Use **S800** and zenith angle (**secθ**) to look up energy E_{TBL} (from the table from CORSIKA air-shower MC simulation)

Hybrid fluorescence provides energy scale: $E_{final} = E_{TBL}/1.27$







Staking at the site in Utah

Piling to confirm and decide SD positions
ATV* riders : ran, lost the way and stacked

*: not allowed to drive vehicles off-road under BLM** direction

**: Bureau of Land Management

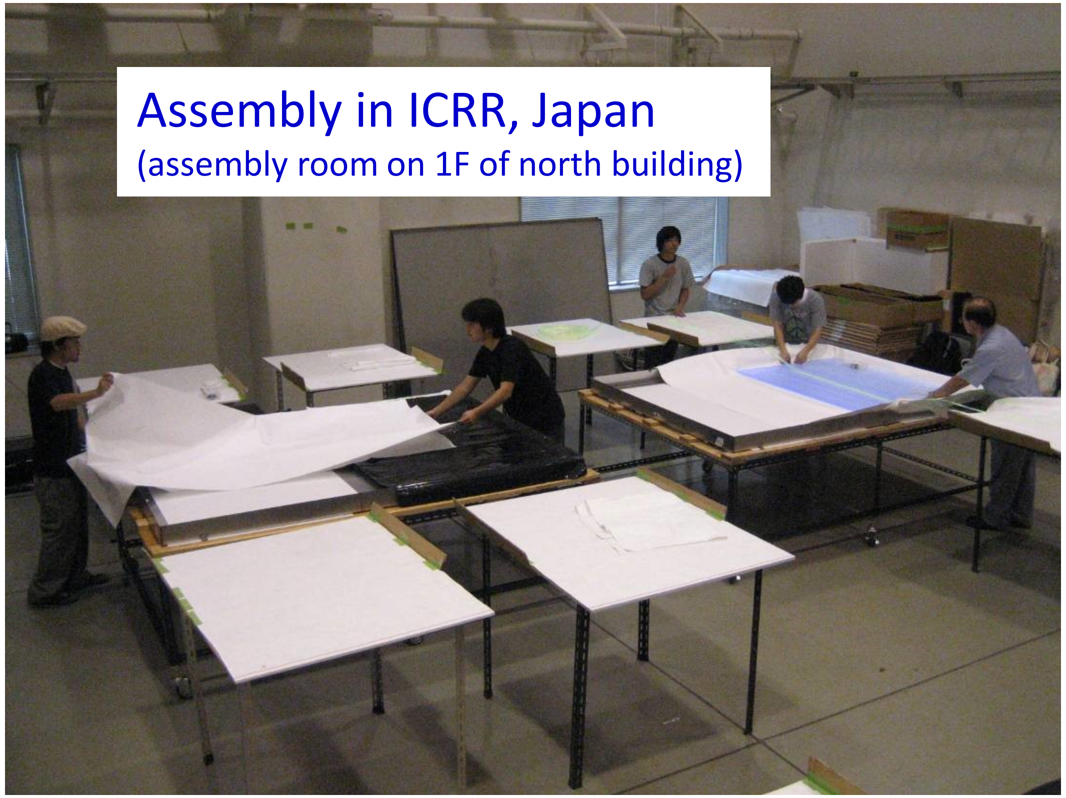
ATVs were permitted by BLM for this work

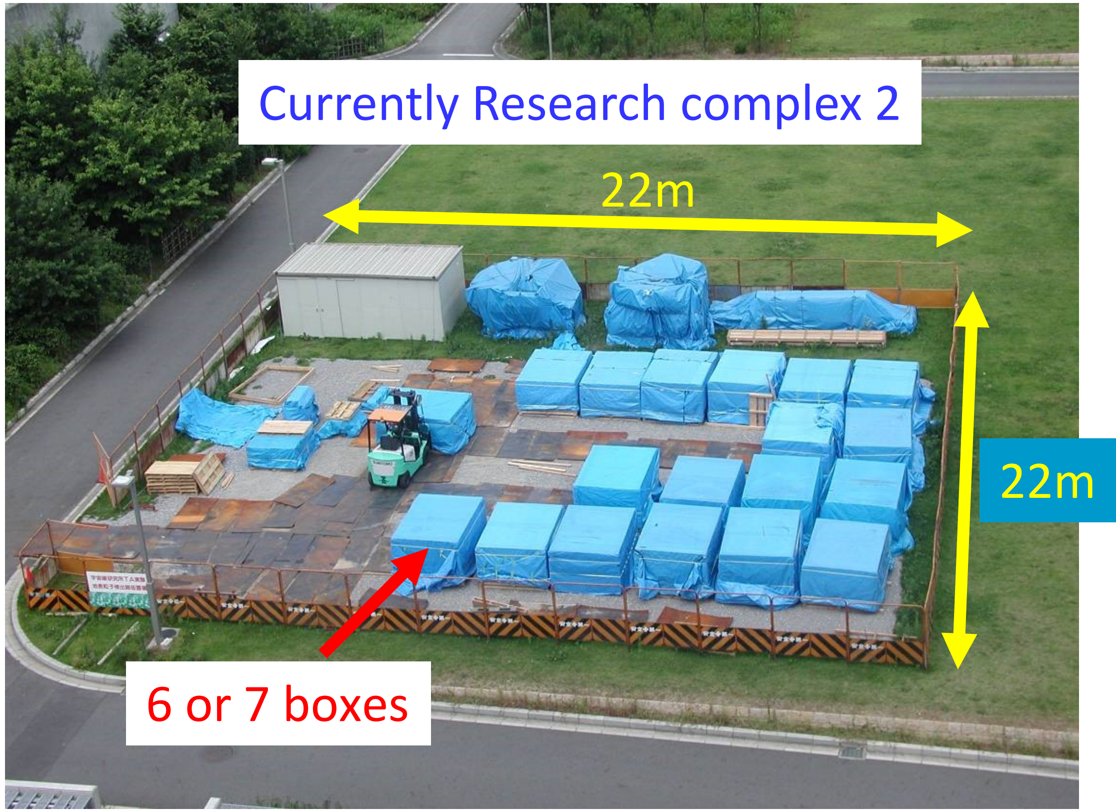
Jun 15~25, 2004

Staking work

Assembly of scintillation detectors

- Started mass production in May, 2005

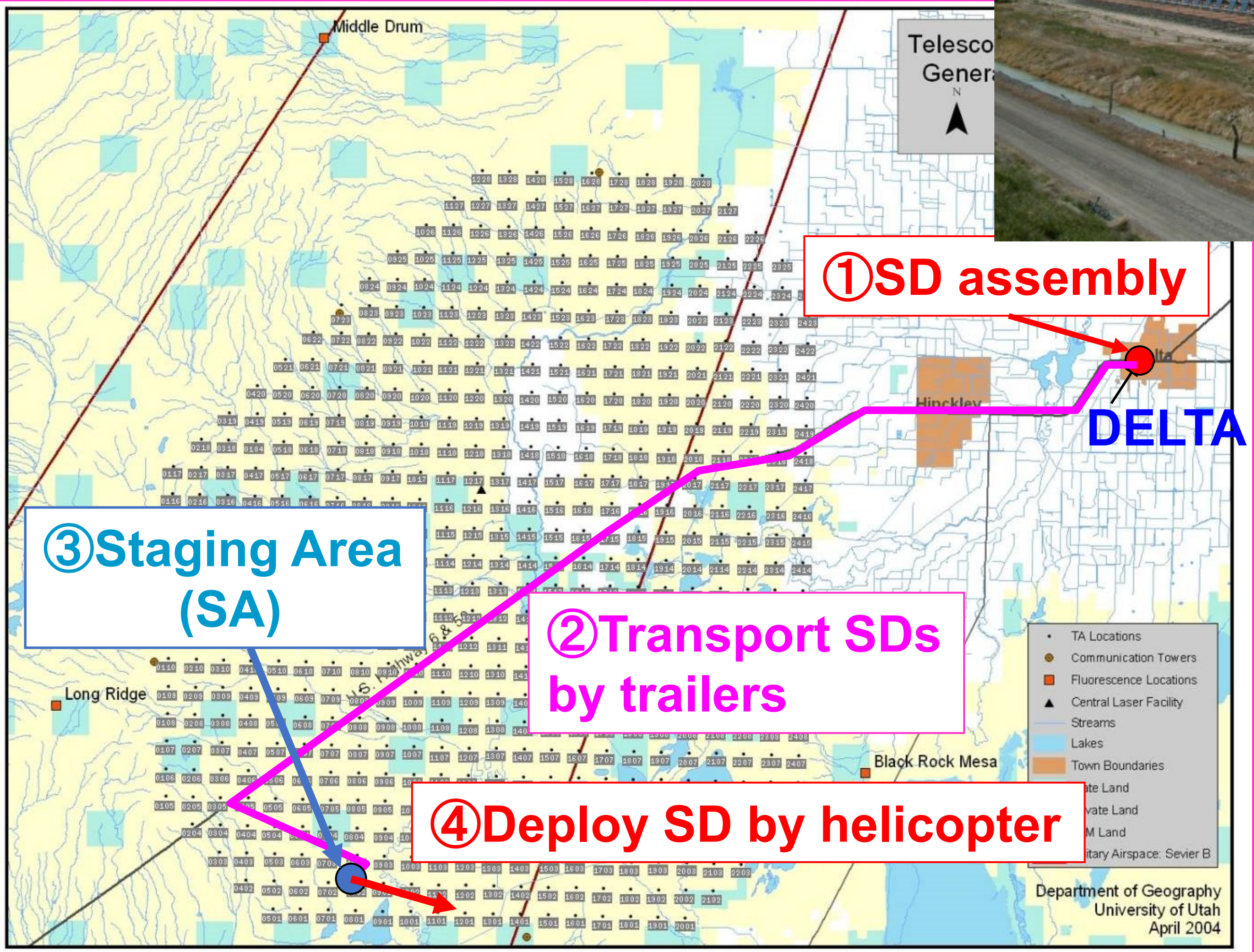




- **Completion of assembly (518 SDs) in Oct 2006**

SD assembly and deployment in Utah

④ deployment by helicopter

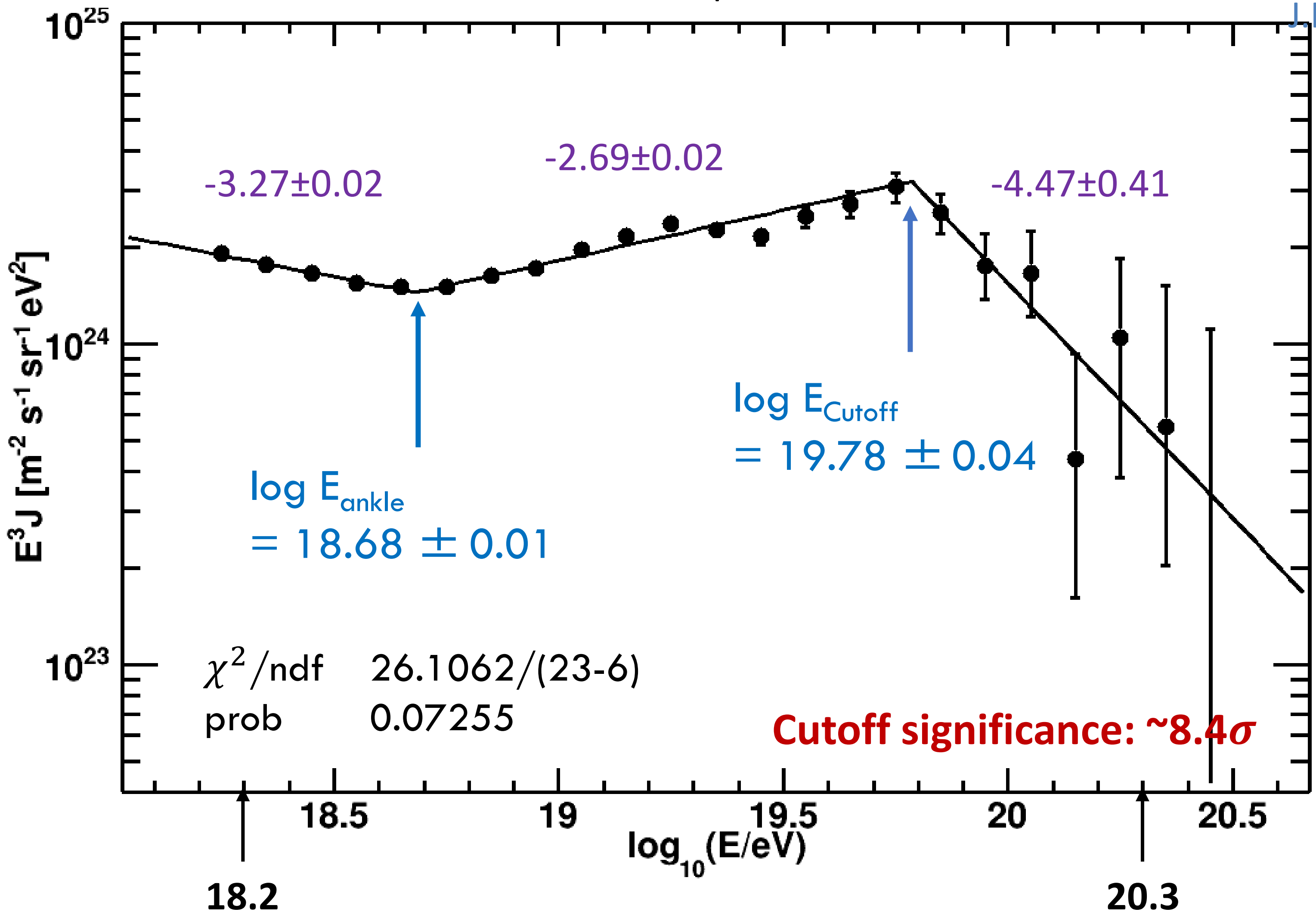


Energy spectrum

TA SD energy spectrum (14 years)

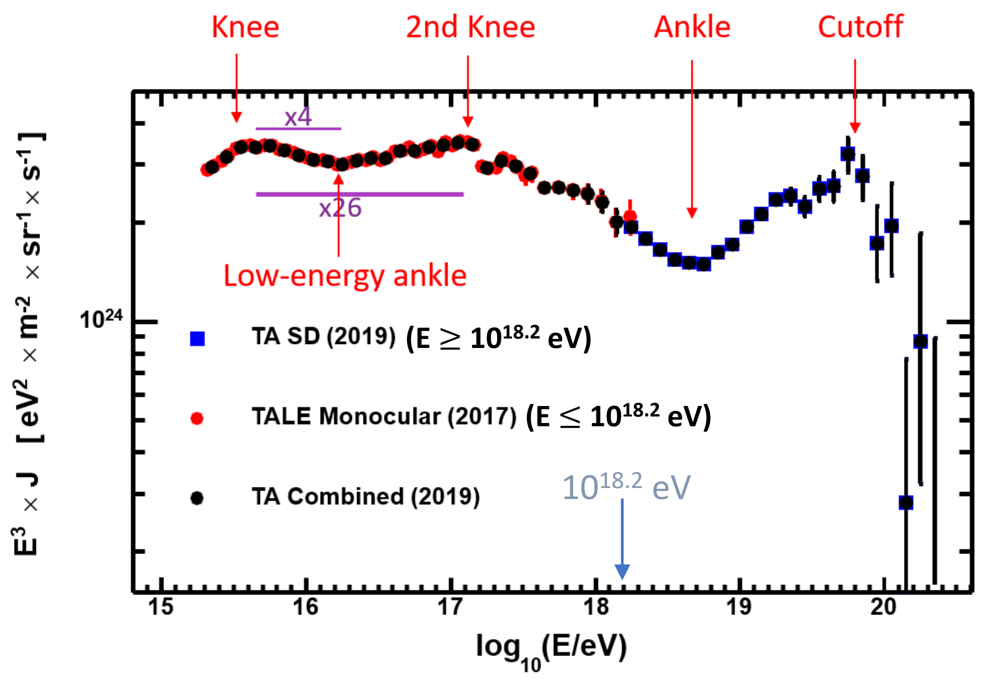
Observation periods: 2008-05-11 to 2022-05-10

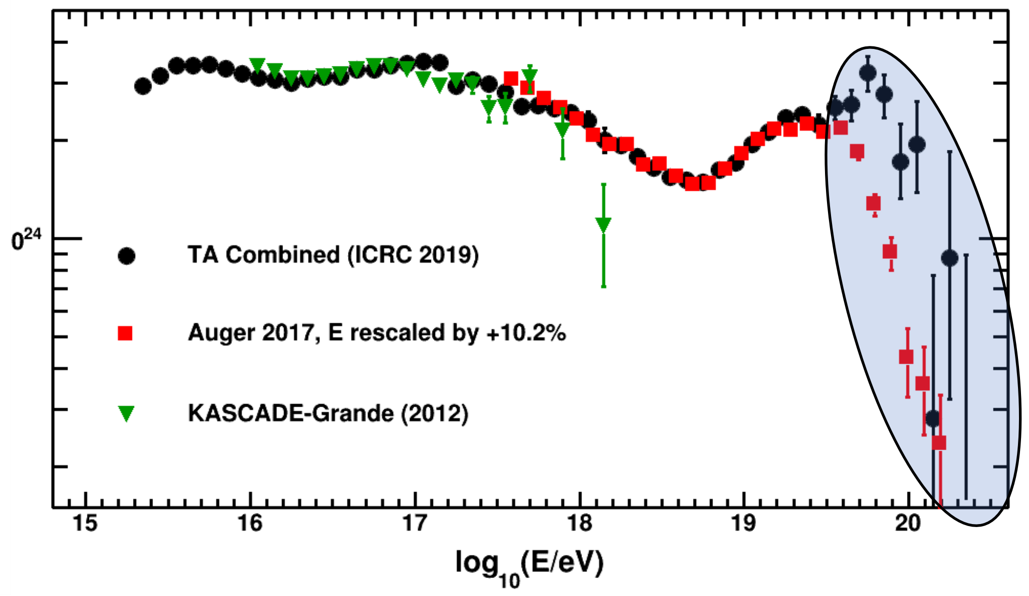
J.H. Kim, ICRC2023



Combined Energy Spectrum

TA SD spectrum (11 yrs.) with TALE FD monocular (22 mos.)

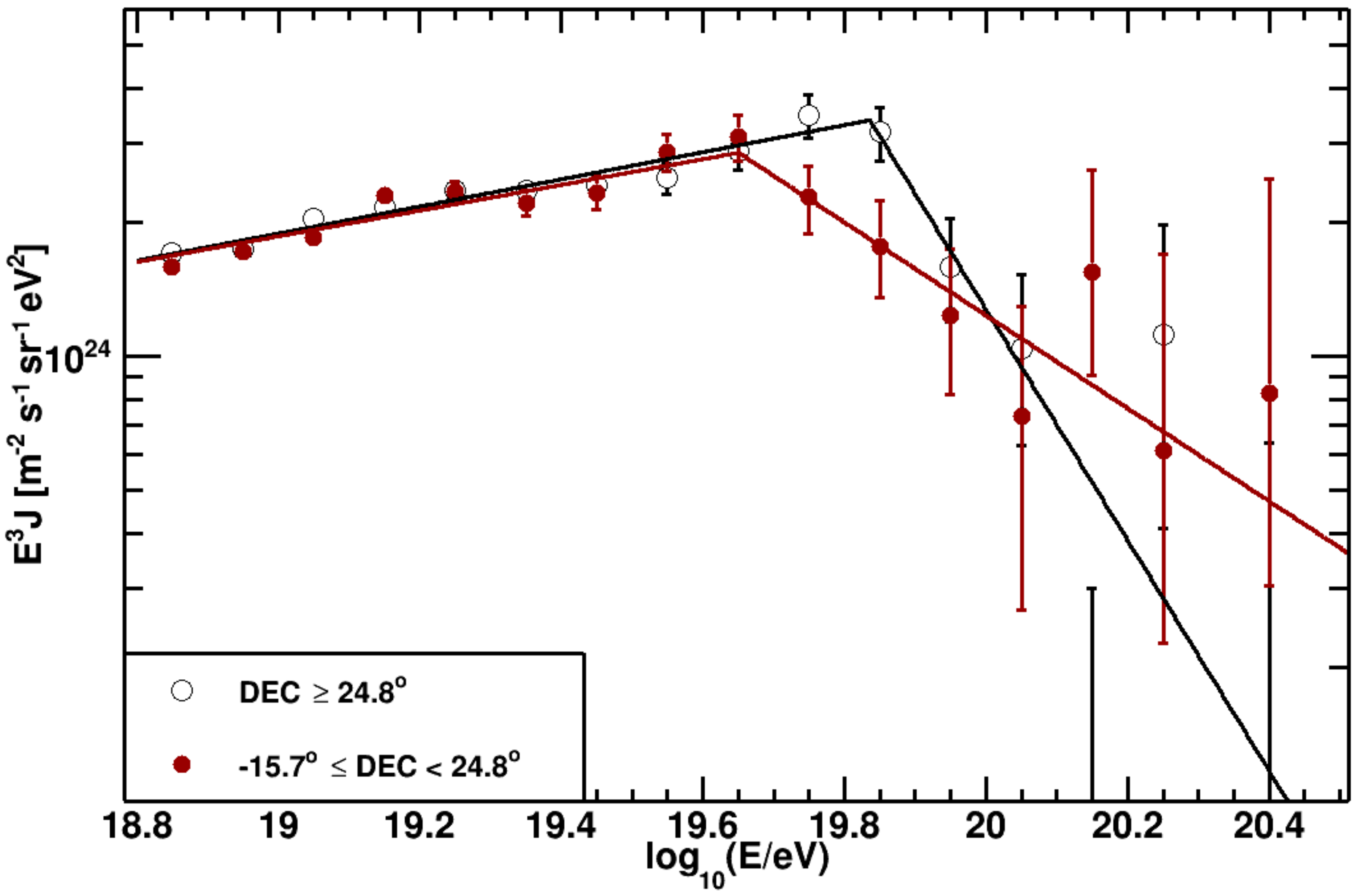




CR spectrum covering 5 orders-of-magnitude

Declination Dependence in the TA SD Spectrum

J.H.Kim ICRC2023



- Differences in the cutoff energies

  - log(E/eV)=**19.84 ±0.02**

  for higher declination (24.8°–90°)

  - log(E/eV)=**19.65 ±0.03**

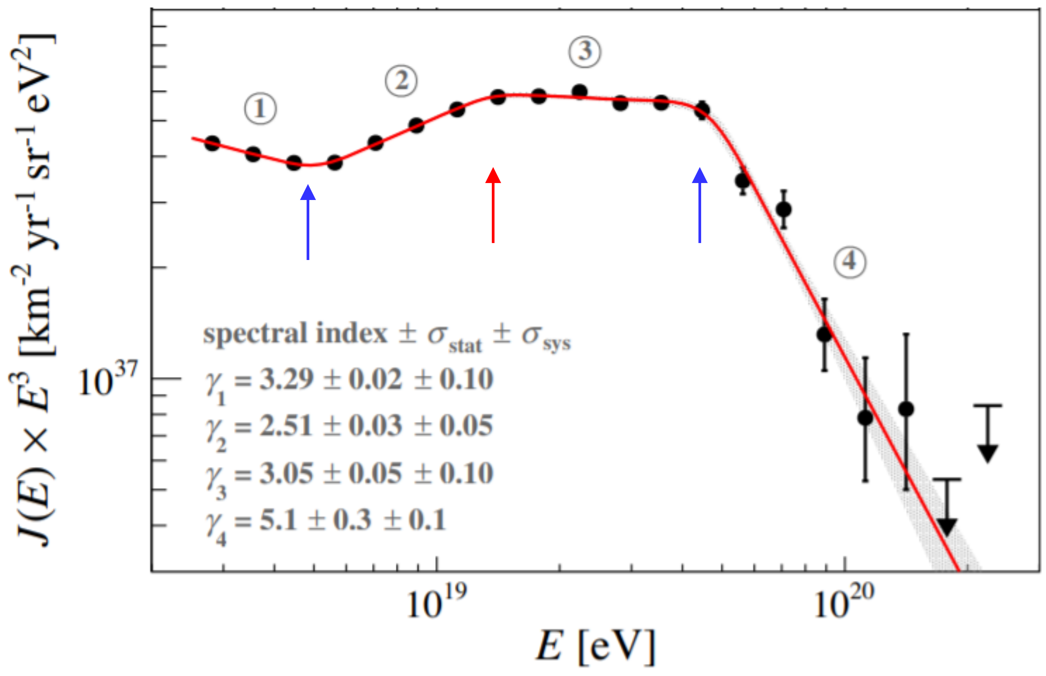
  for lower declination (-16°–24.8°)

- The local significance is **4.8σ.**
- The global significance of the difference is estimated to be ***4.4σ.***
- No instrumental causes were found. This difference implies it is astrophysical in nature.

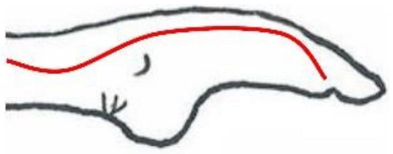
“*Shoulder*” **feature** of the energy spectrum

A. Aab *et al.* (The Pierre Auger Collaboration)
Phys. Rev. Lett. **125**, 121106 (2020)

Pierre Auger found a spectrum hardening in 10^{19} – $10^{19.5}$ eV range



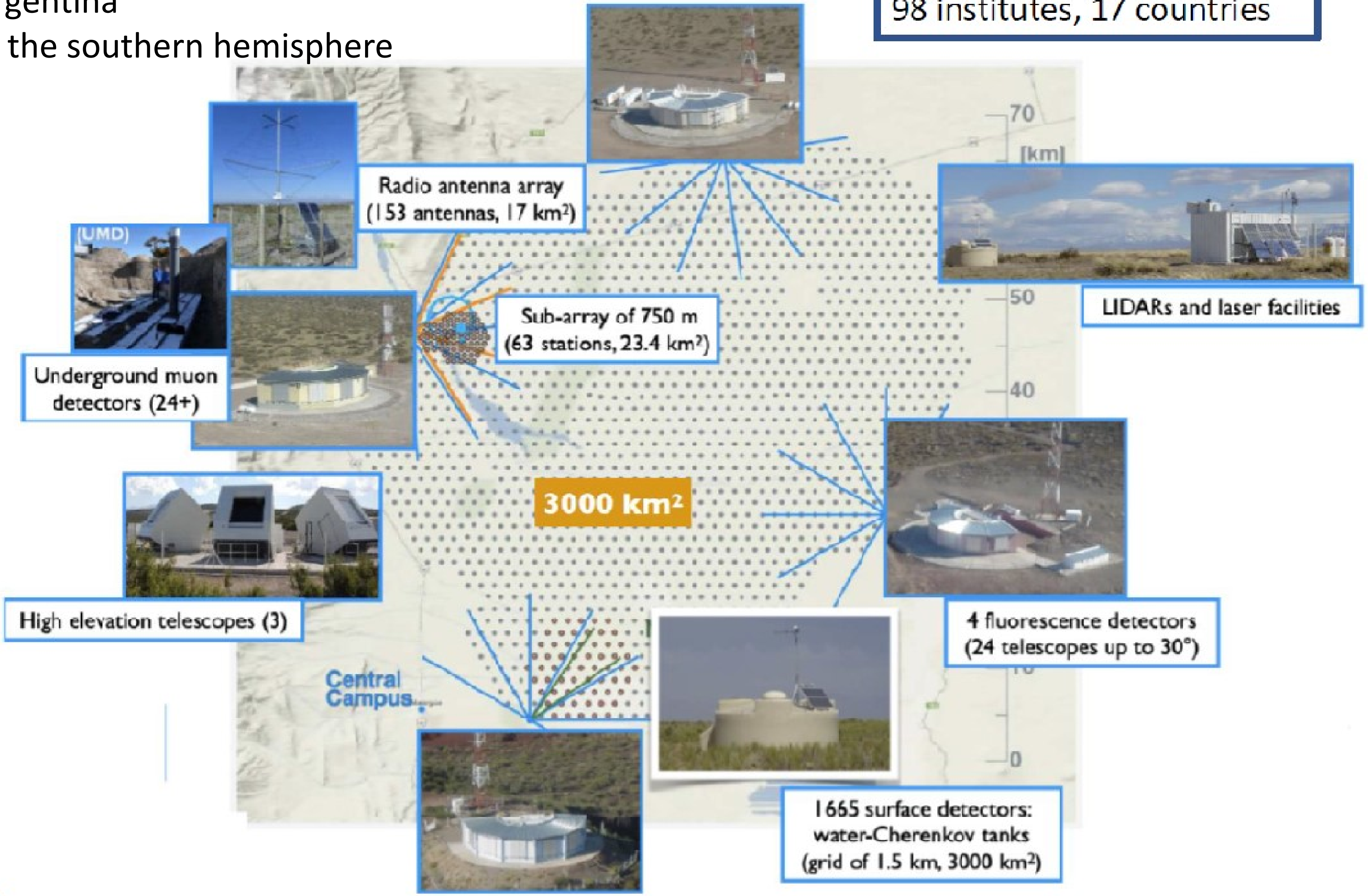
“instep”



Pierre Auger Observatory

Argentina
in the southern hemisphere

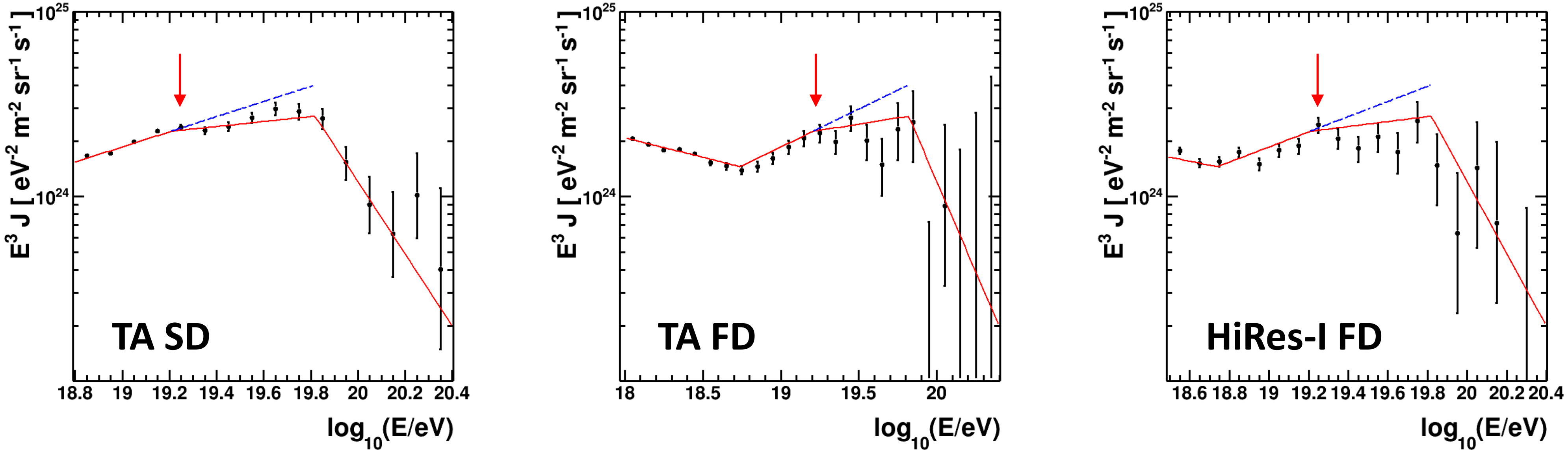
More than 400 members,
98 institutes, 17 countries



Phase 1 : data taking from 2004 on (from 2008 with the full array in operation):
✓ Over 120, 000 km^2 sr yr for anisotropy studies
✓ Over 90, 000 km^2 sr yr for spectrum studies

Phase 2 : the AugerPrime upgrade Data taking from 2023 to 2030...
✓ + 40, 000 km^2 sr yr
✓ Multi-hybrid events : FD, SD, SSD, RD, UMD

TA SD: Spectral Feature in 10^{19}–$10^{19.5}$ eV



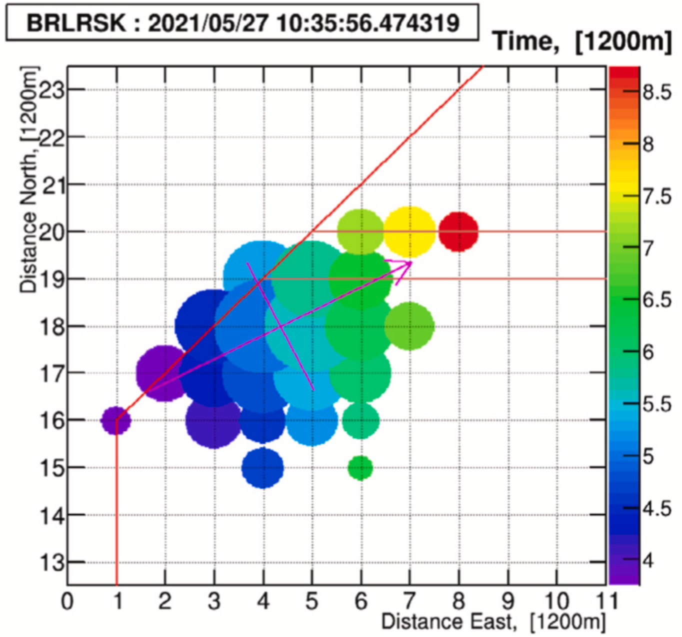
Fit parameter	HiRes—TA	Auger (PRD 2020)
p_1	-3.21 ± 0.01 (stat)	-3.29 ± 0.02 (stat)
p_2	-2.59 ± 0.01 (stat)	-2.51 ± 0.03 (stat)
p_3	-2.87 ± 0.03 (stat)	-3.05 ± 0.05 (stat)
p_4	-5.0 ± 0.3 (stat)	-5.1 ± 0.3 (stat)
$\log_{10}[E_{ANKLE}/eV]$	18.74 ± 0.01 (stat)	18.70 ± 0.01 (stat)
$\log_{10}[E_{SHOULDER}/eV]$	19.20 ± 0.03 (stat)	19.11 ± 0.03 (stat)
$\log_{10}[E_{GZK}/eV]$	19.82 ± 0.02 (stat)	19.66 ± 0.03 (stat)

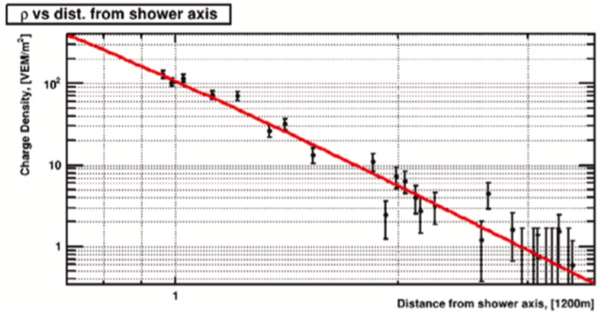
- Auger found a new spectral feature in 10^{19}–$10^{19.5}$ eV.
  (*instep/shoulder* feature)
- We observed the same softening feature in the northern hemisphere at $10^{19.20\pm0.03}$ eV with a 6.5σ significance.
- TA and Auger agree within 1.2σ.

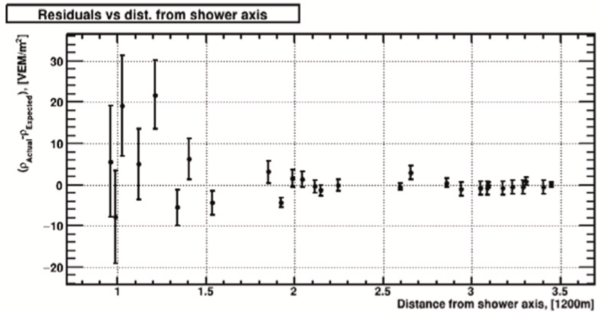
Highest Energy Event by a Surface Detector Array

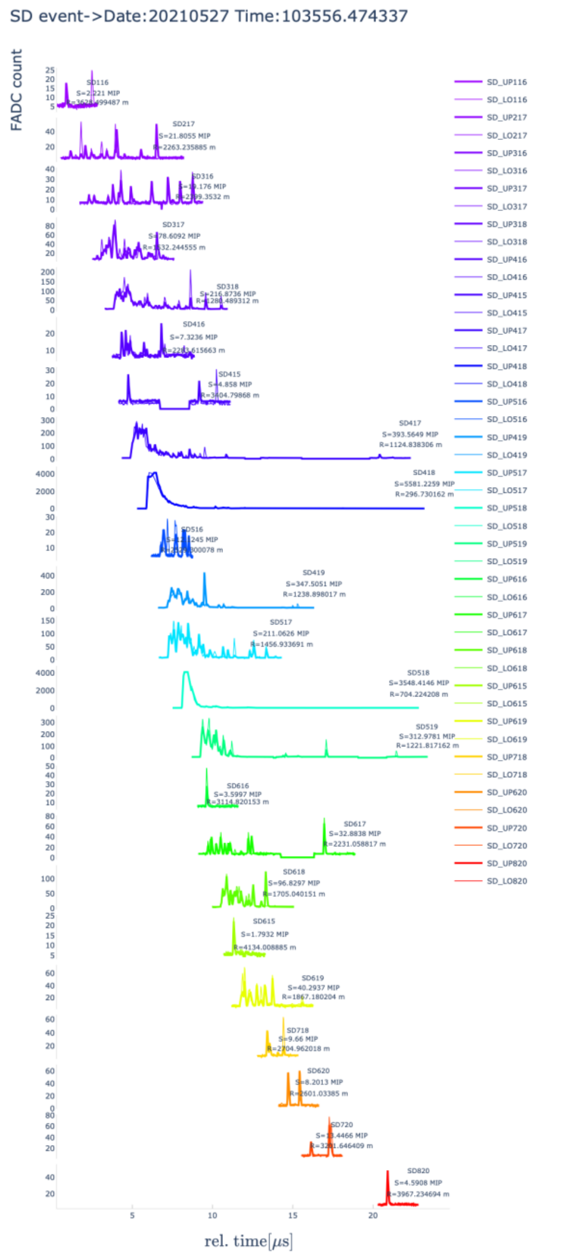
- Observed with TA SD at 10:35:56 on 27 May 2021 (UTC)
  - No FD observation
- ***E* = 244 ± 29(stat.) ± 51(syst.) EeV**, zenith angle ϑ = 38.6°

Ref.
Oh-my-God particle
3.2x10^{20} eV by Fly's Eye in 1991







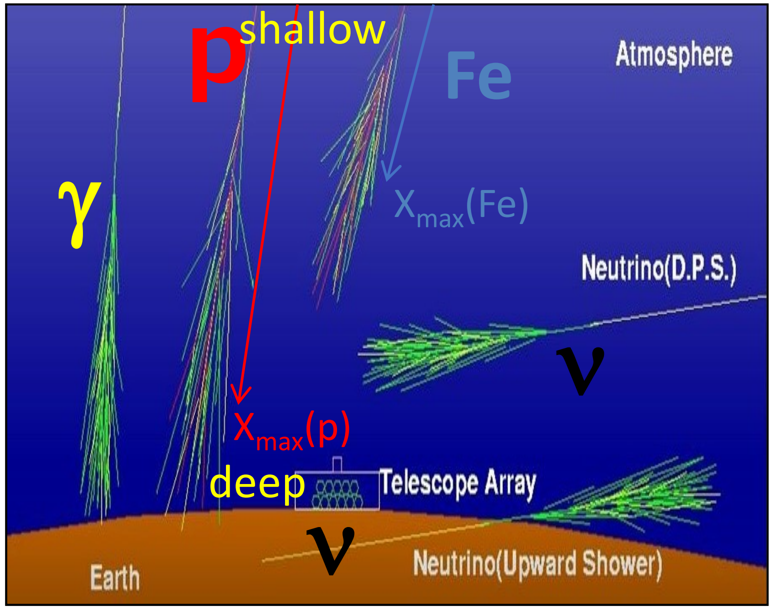


Composition

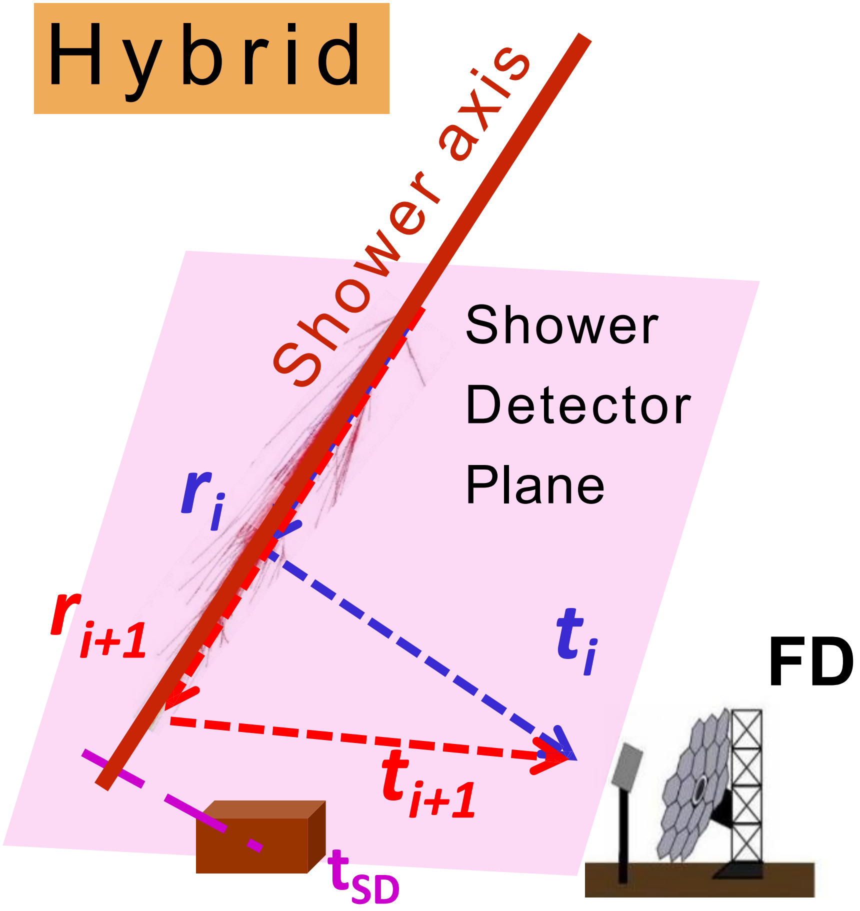
Interaction in the air

The UHECR shower profile depends on the type of particle.

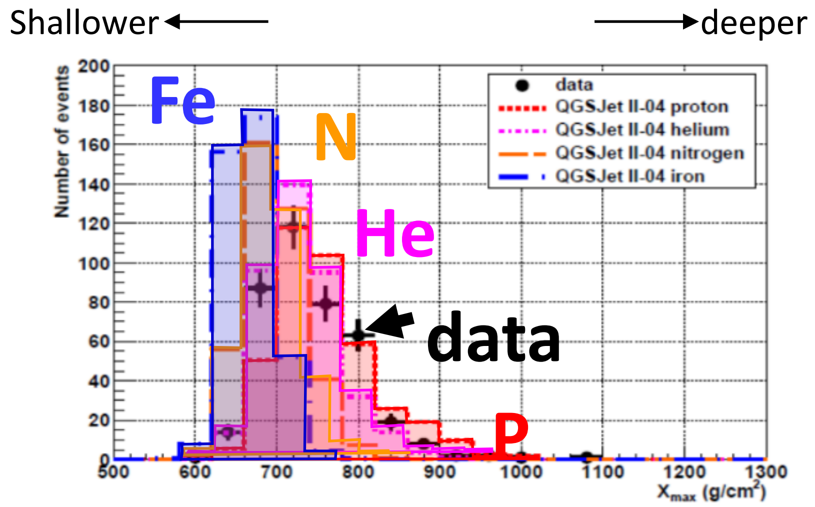
- A: mass number of incident nucleus
- Nuclear radius: r
  - $r \propto A^{1/3}$
- Cross section: σ
  - $\sigma \propto A^{2/3}$
- Mean free path: λ
  - $\lambda \propto A^{-2/3}$
- Interaction depth vs. heavy nuclei
  - Shallower for heavier composition



TA hybrid composition



R.U. Abbasi et al., Ap. J., 858, 76 (2018)



$10^{18.5}$ eV < E < $10^{18.6}$ eV

consistent with light composition

Better reconstruction with the SD timing information

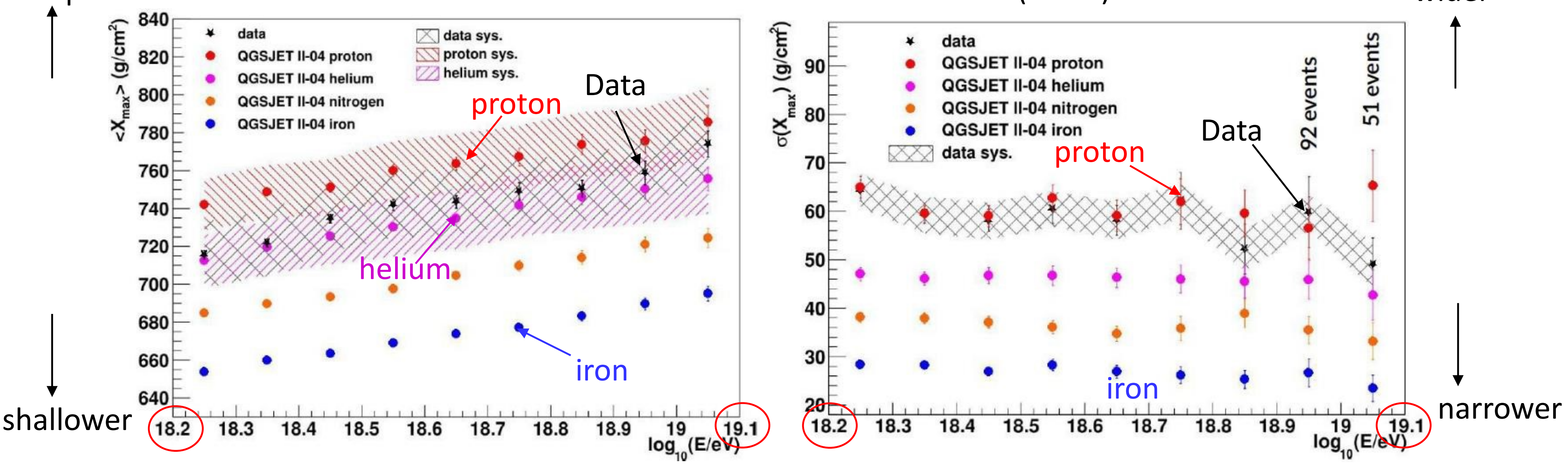
Composition Analysis with TA Hybrid Xmax

10 years SD and FD hybrid data

W.Hanlon, ICRC2019

Mean Xmax

σ (Xmax): Xmax width



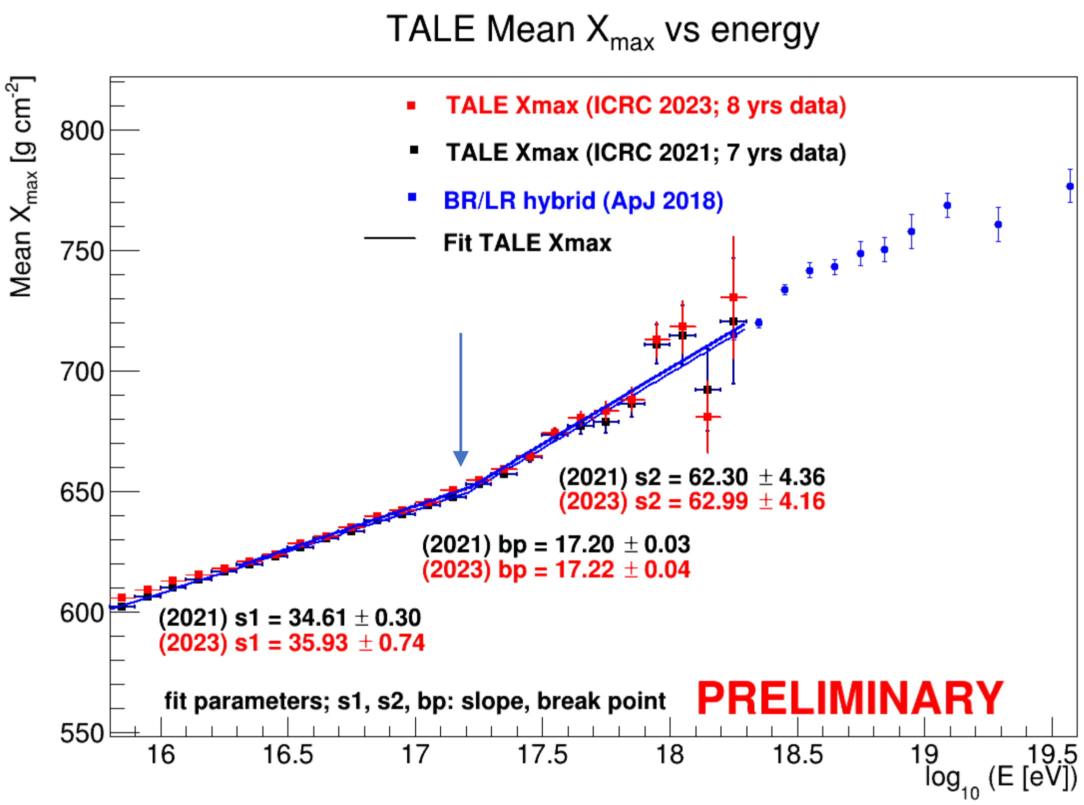
- Energy Range: $10^{18.2}$ eV – $10^{19.1}$ eV
- 3560 events after the quality cuts
- Systematic uncertainty of <Xmax>: ± 17 g/cm^2
- QGSjetII-04 interaction model was compared with the data

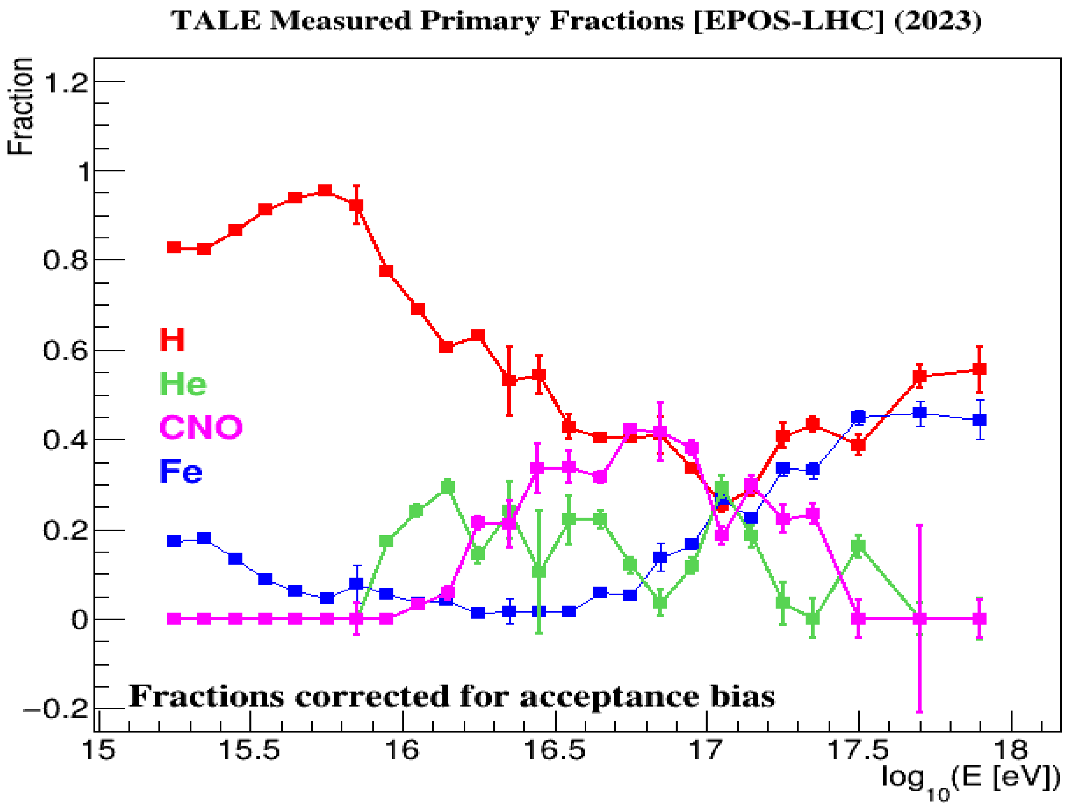
  agreement with light composition
- More events are needed to study highest energies

TALE monocular FD Xmax

- Eight-year TALE FD monocular data set (Jun. 2014–Aug. 2022)

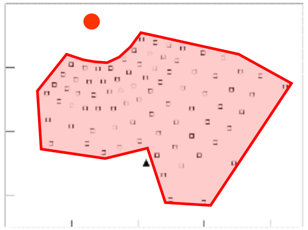
T. Abu-Zayyard, ICRC2023





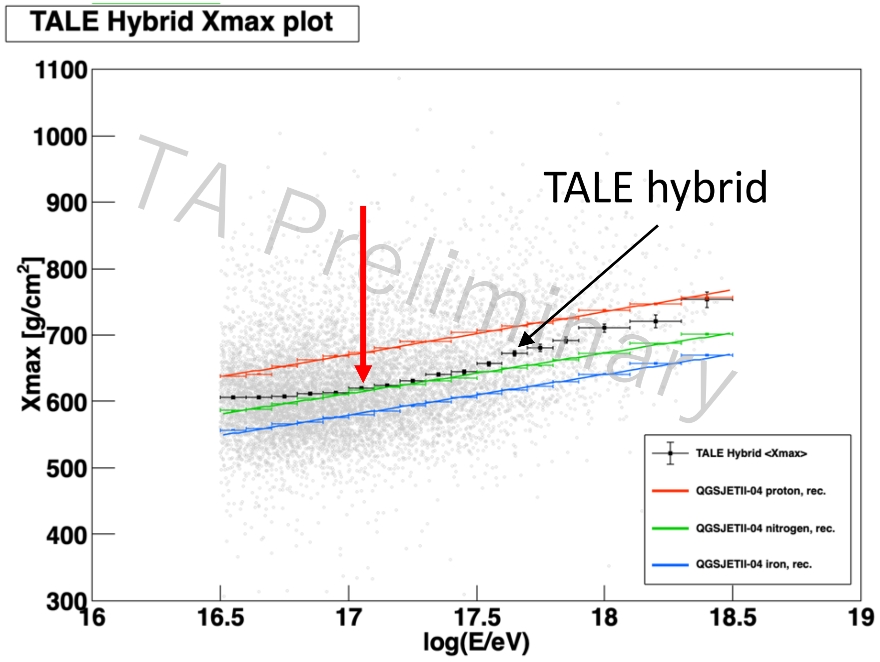
- A break in the elongation rate at energy $10^{17.22\pm0.04}$ eV (2nd knee).
- Light-heavy-light pattern in 10^{15}–10^{18} eV.

TALE Hybrid Composition

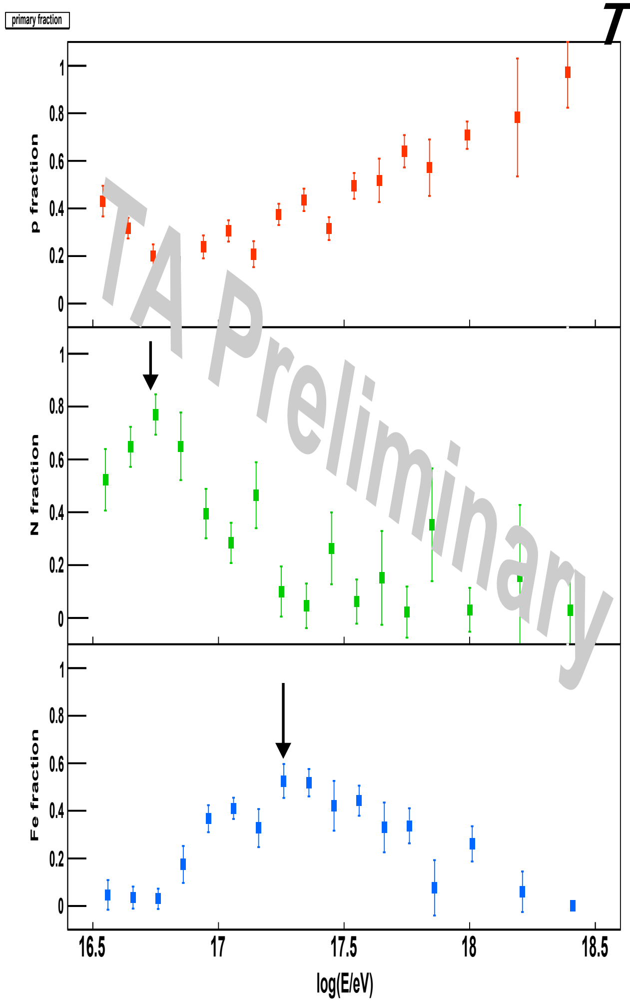


Five-year TALE hybrid data (Nov. 2017 – Mar. 2023)

K. Fujita, ICRC2023



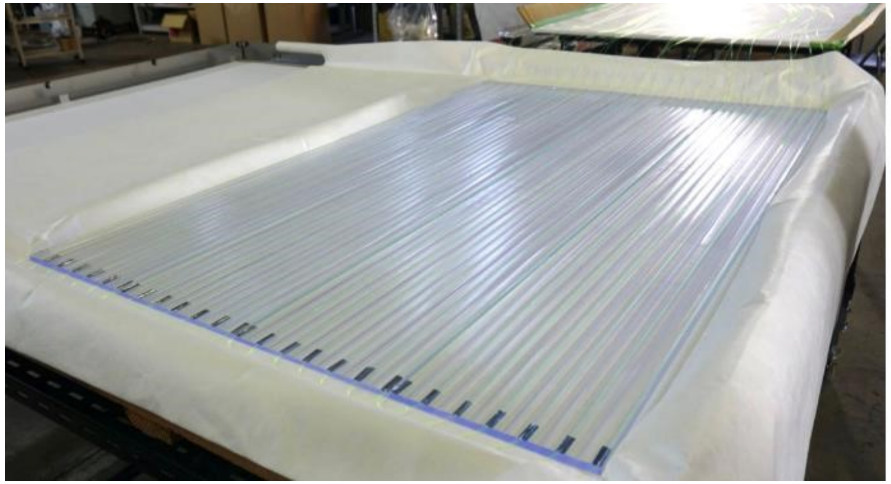
$\langle X_{\max} \rangle$ and $\sigma(X_{\max})$ along with predictions of QGSJetII-04 proton, iron, nitrogen

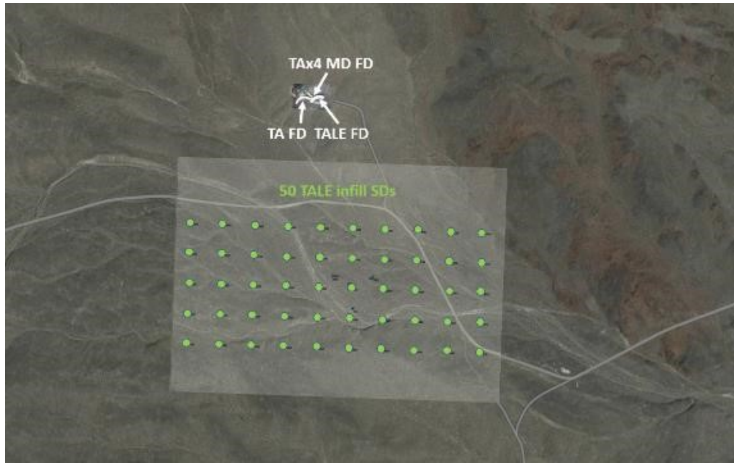


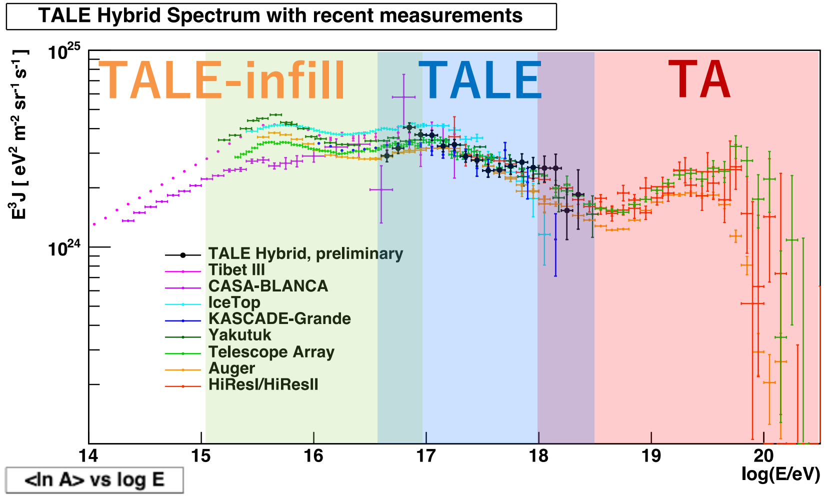
- proton/nitrogen/iron fraction by *TFractionFitter*
  - low proton fraction at low energies
  - nitrogen break: ~ $10^{16.7}$ eV
  - iron break: ~ $10^{17.3}$ eV

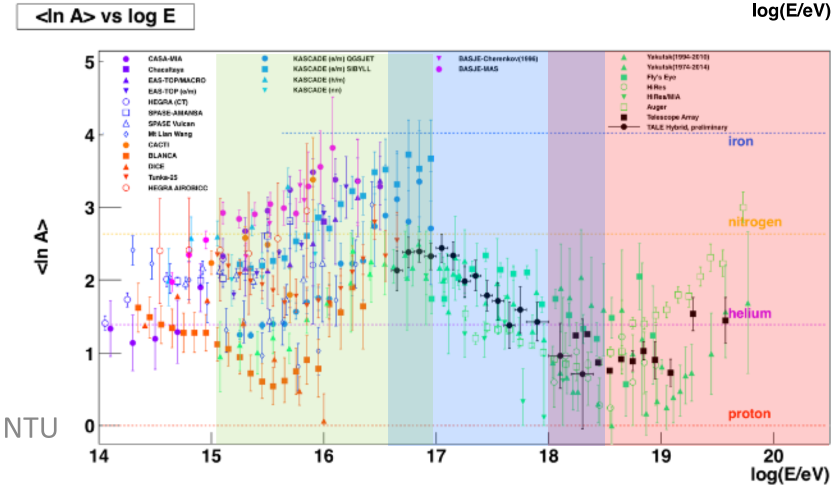
TALE-infill SD

- Further low energy extension with Hybrid mode
    - 50 SDs with 100m spacing
- Target energy: E > 10^{15} eV ($10^{16.5}$ eV for TALE hybrid)
- SD counter assembly in Oct. 2021
    - same design as TALE/TAx4 SD





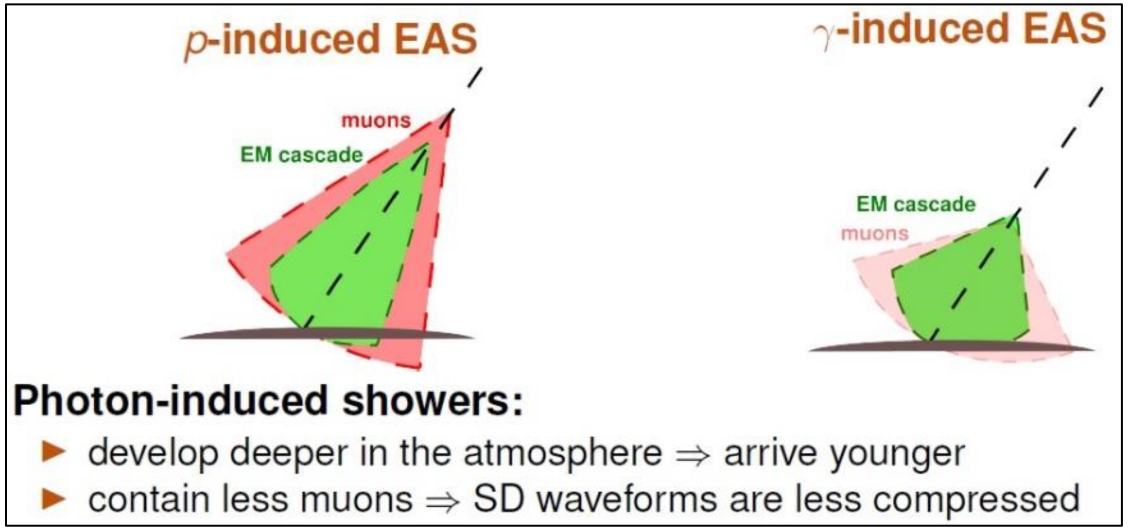


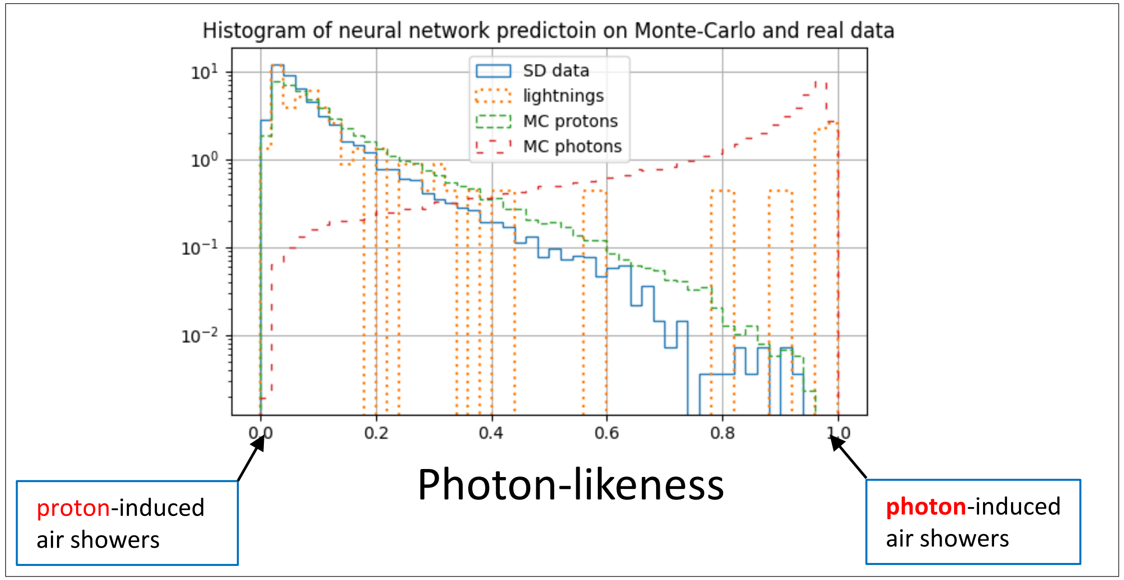


- SDs deployed on Nov. 15, 2022

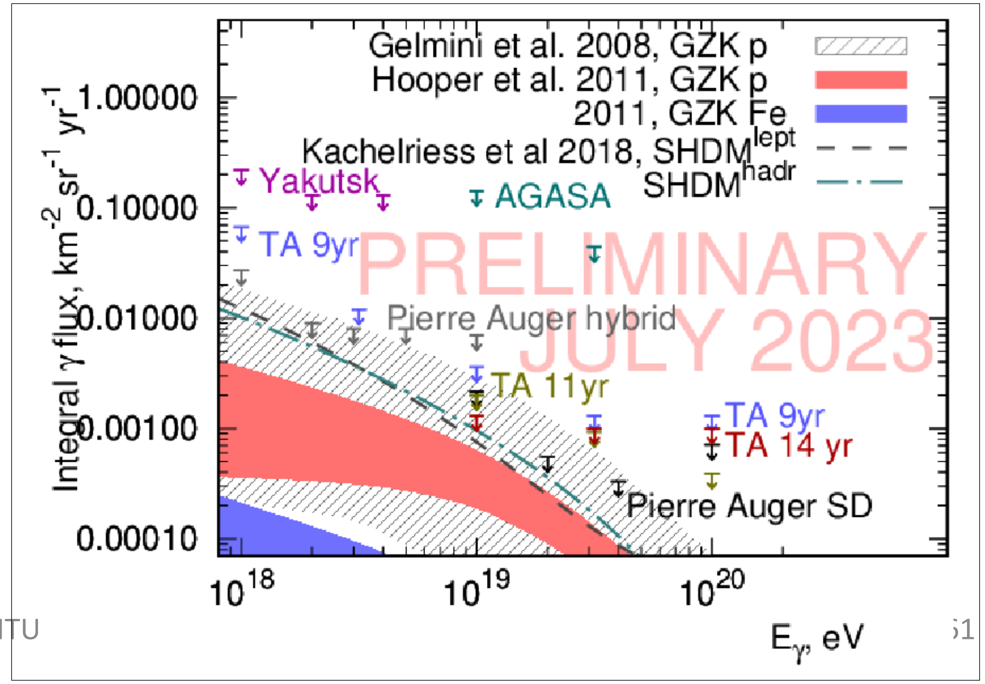
UHE photon search for 14-year TA SD data

I. Kharuk, ICRC2023





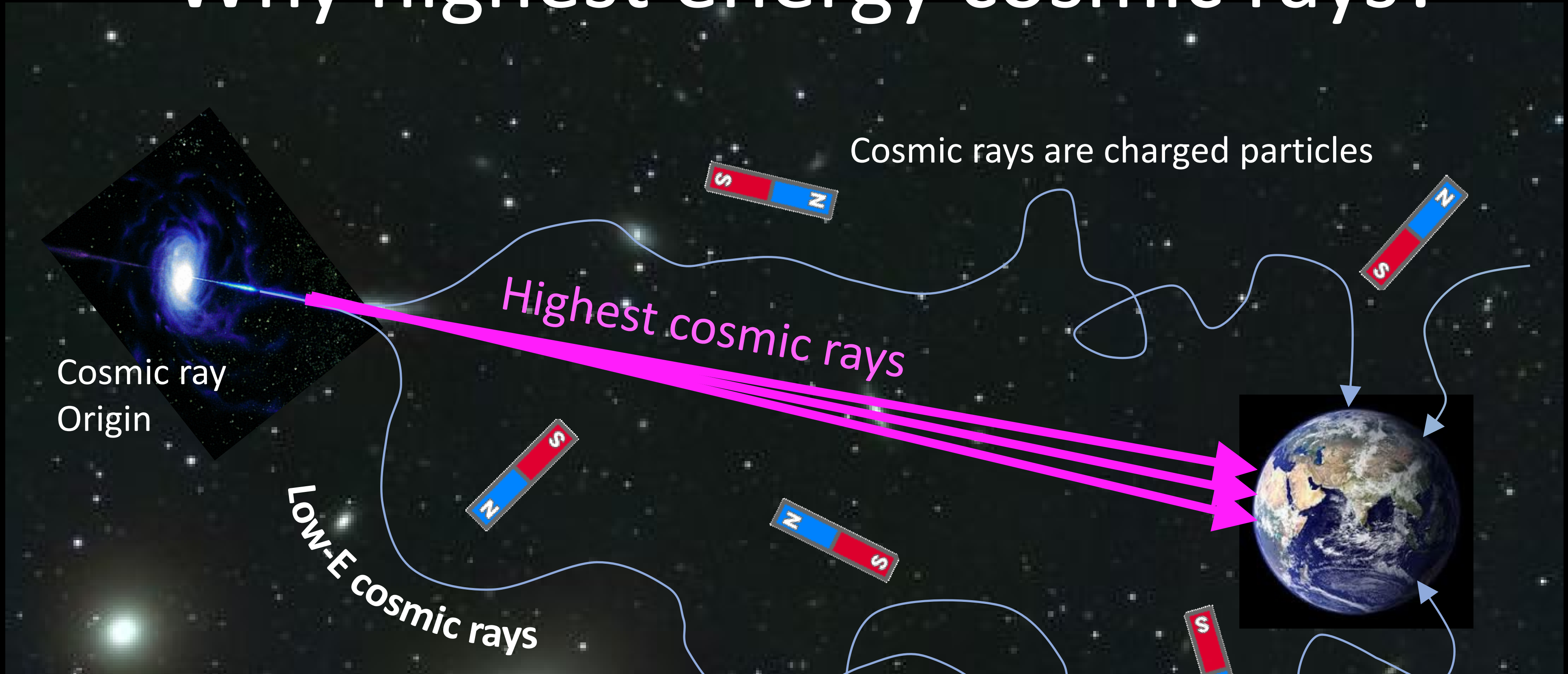
After all cuts



- Neural network trained to classify proton and photon
- using SD signals (waveforms)
  → one output parameter **photon-likeness**
- No excess was found in photon-likeness distributions → photon flux upper limits

Anisotropy

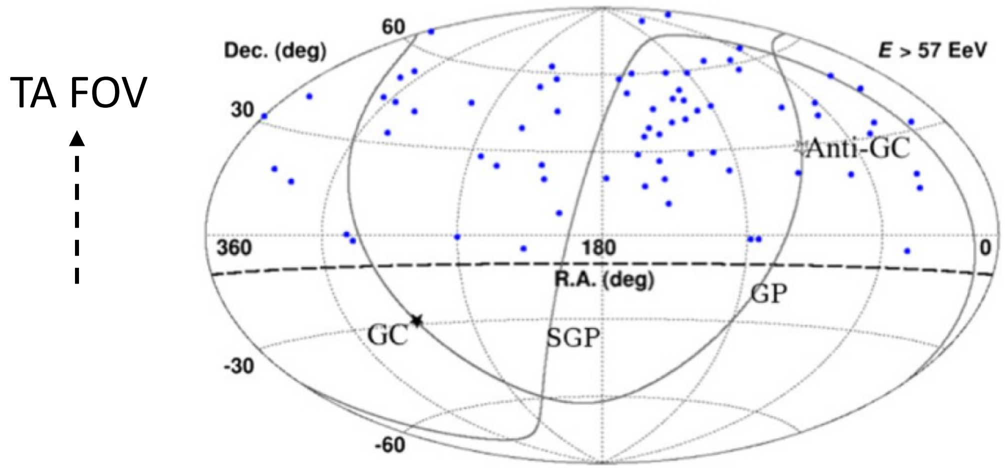
Why highest energy cosmic rays?



- Low energy cosmic rays
  → bend by the magnetic field
  → Isotropy at the Earth
- Highest energy cosmic rays
  → Almost go straight against magnetic field
  → Possible to find cosmic-ray hotspot

TA Hot Spot (5years)

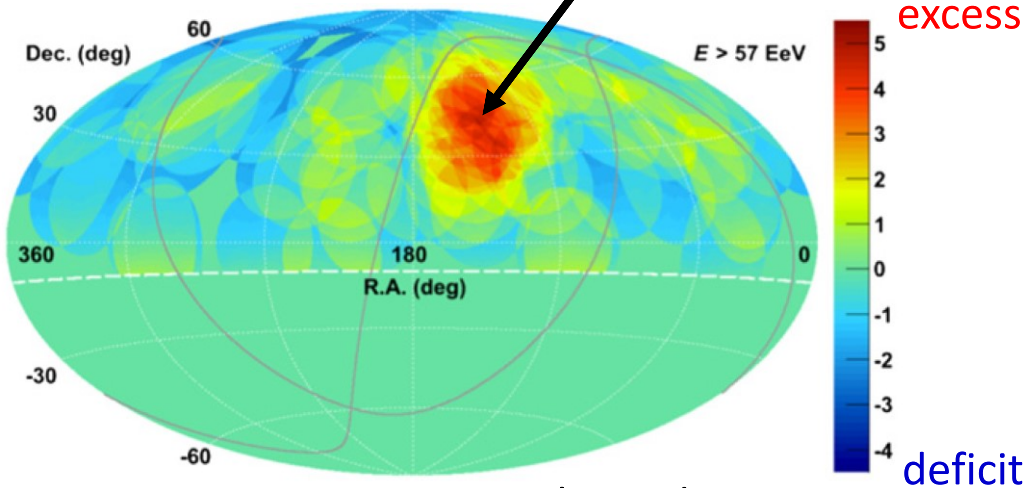
- 72 events (E > 5.7x10^{19} eV [57 EeV])



Equatorial coordinates

- Oversampling using 20° radius circles

- Maximum pretrial significance of 5.1σ at (R.A.=146.7°, decl.=43.2°)

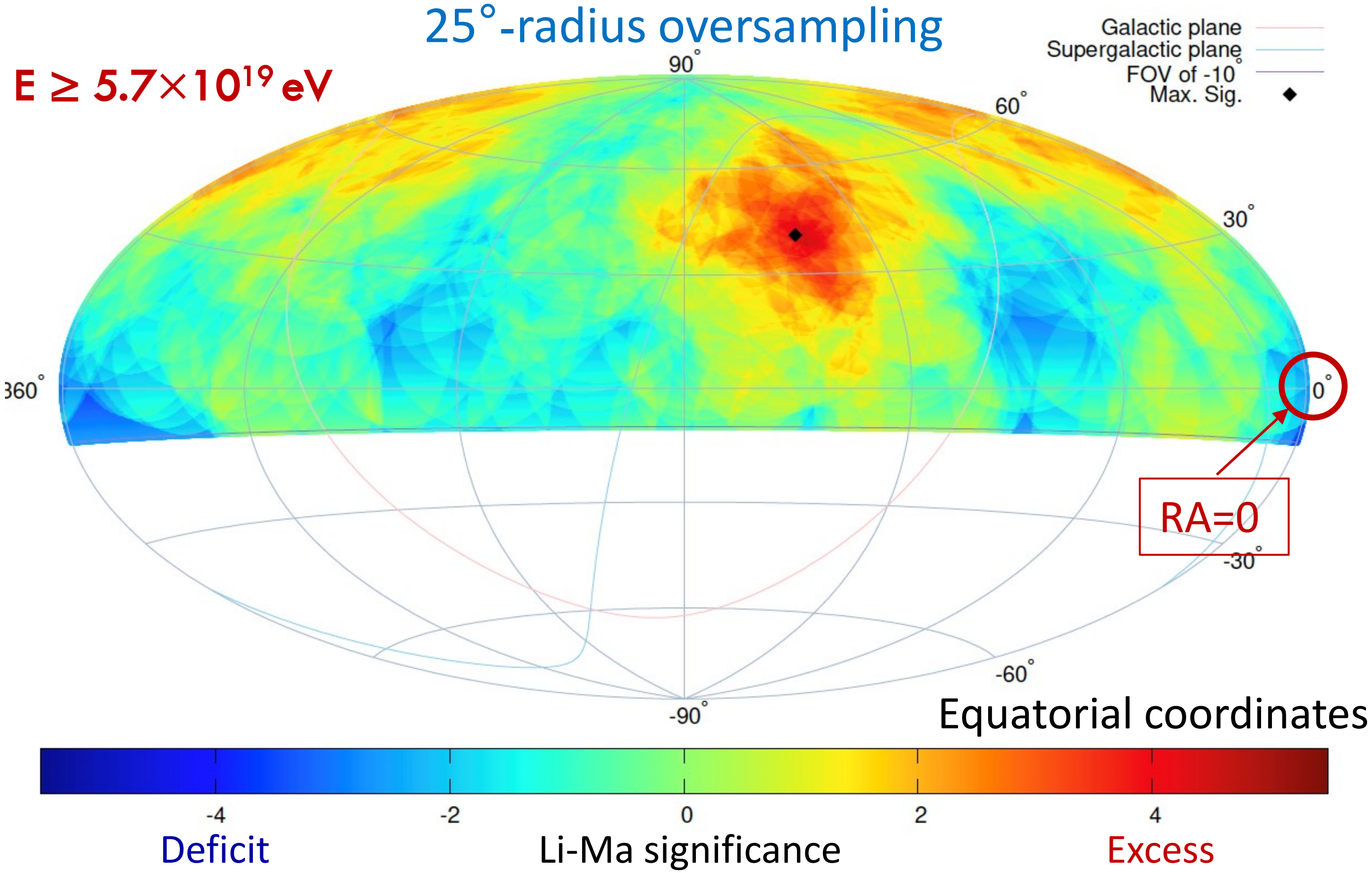


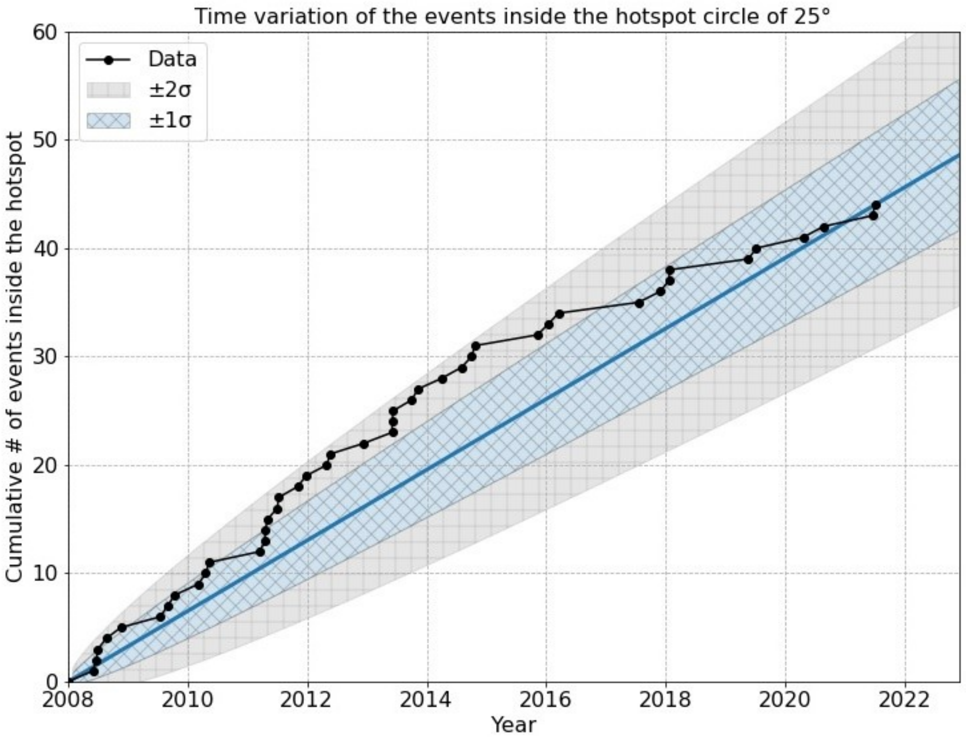
Equatorial coordinates

- 40 events observed, 14.6 events expected
- Chance prob. = 3.7 × 10^{-4} (3.4σ)

Hot spot update (15 years)

J.H. Kim, ICRC2023





- 216 events
- Max local sig.: **4.8σ** at (144.0°, 40.5°)
  - 44 events observed (18.0 events expected as background)
- Post-trial prob.: $P(S_{\rm MC} > 4.8\sigma) = 2.7 \times 10^{-3}$ → **2.8σ**

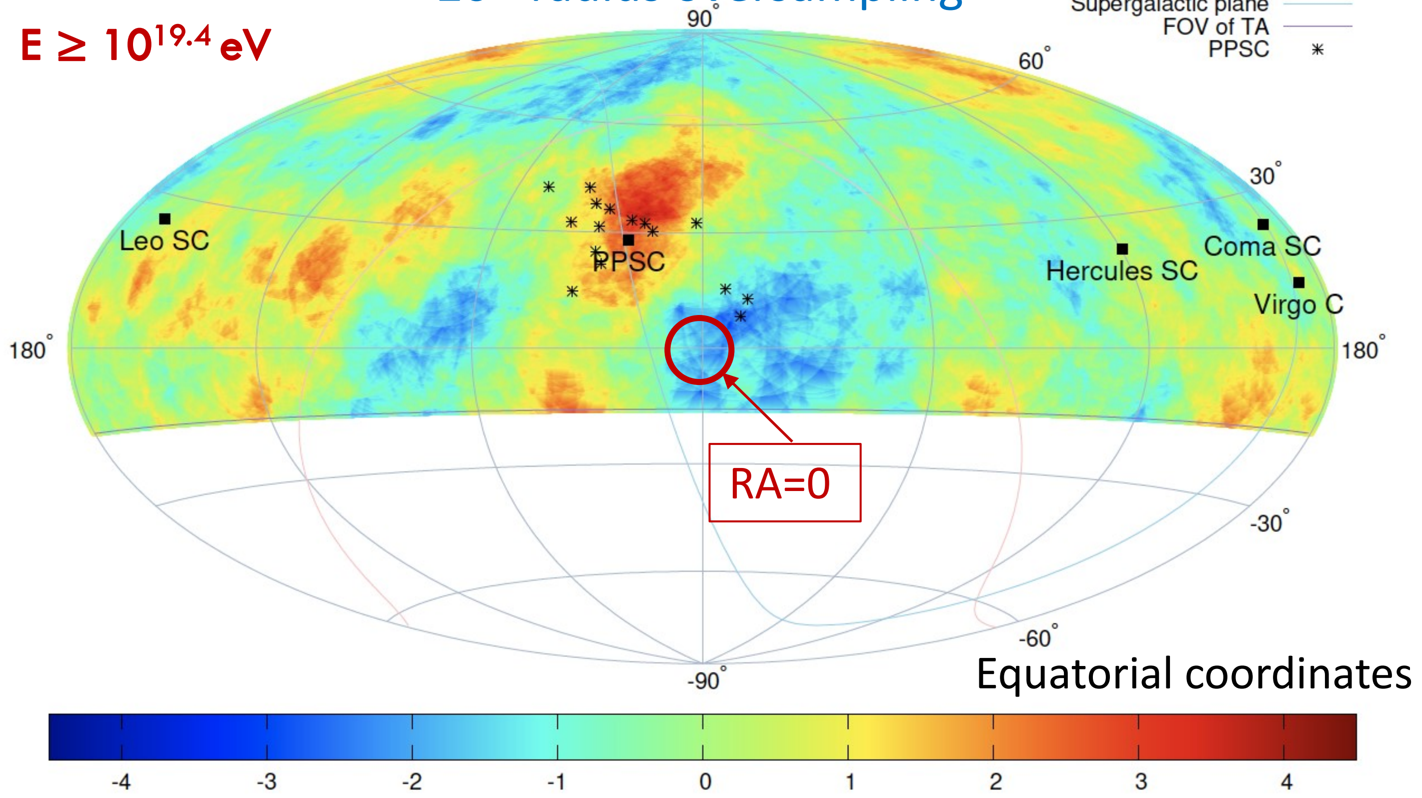
- The increase rate of the events inside the hotspot circle is **consistent with the linear increase within ~2σ.**

Anisotropy at slightly lower energy thresholds

20°-radius oversampling

ICRC2023

$E \geq 10^{19.4}$ eV

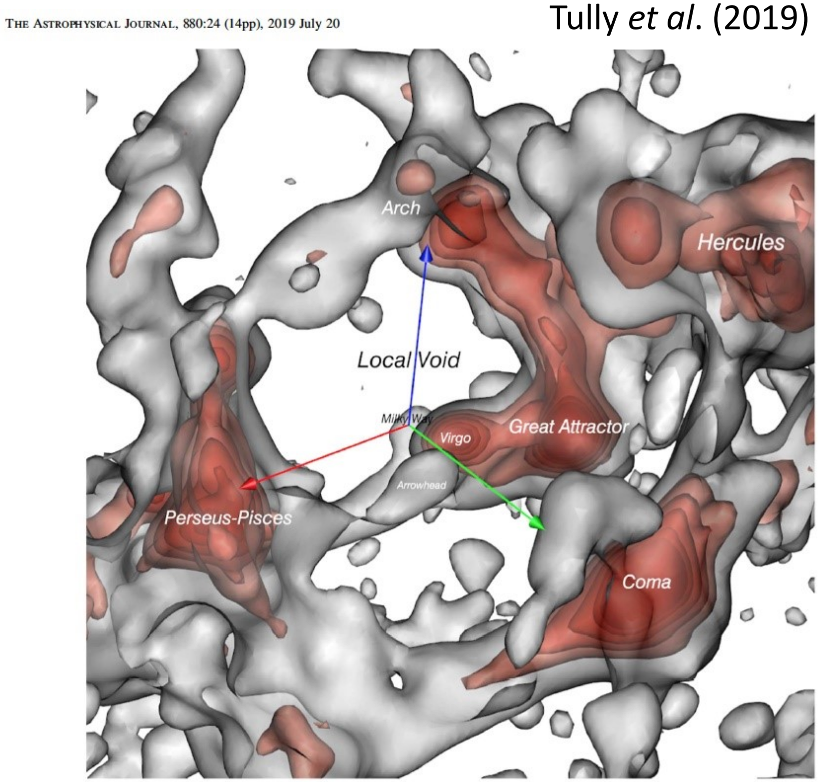


Equatorial coordinates

Deficit   Li-Ma significance   Excess

- 1125 events (15-year TA SD data)
- Max local significance: **4.0σ** at (17.9°, 35.2°)

Tully *et al*. (2019)

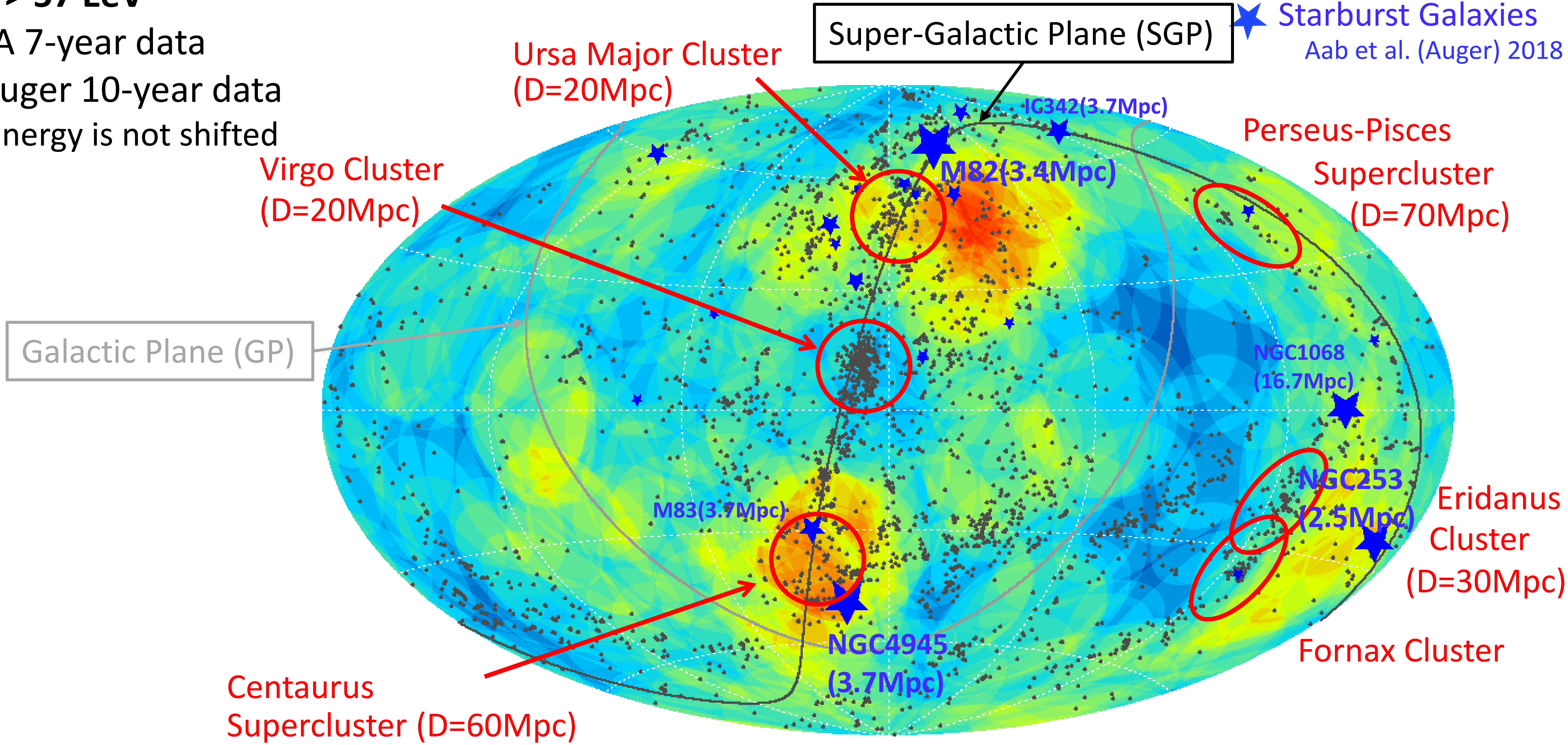


A new excess in slightly lower energy events in the direction of **the Perseus-Pisces supercluster** has been identified. The chance probability of having an excess as close to the PPSC as the data is estimate:

$$(S_{mc} \geq 4.0\sigma)\ \&\ (\theta_{mc} \leq 7.7°) \rightarrow \mathbf{3.3\sigma.}$$

Excesses and Nearby Galaxy Clusters

E > 57 EeV
TA 7-year data
Auger 10-year data
energy is not shifted



Huchra, et al, ApJ, (2012)

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

TA hotspot is found near the Ursa Major Cluster or M82
Excesses (red and yellow) are seen along or near SGP

TAx4

- Aim

Quadruple TA

↓

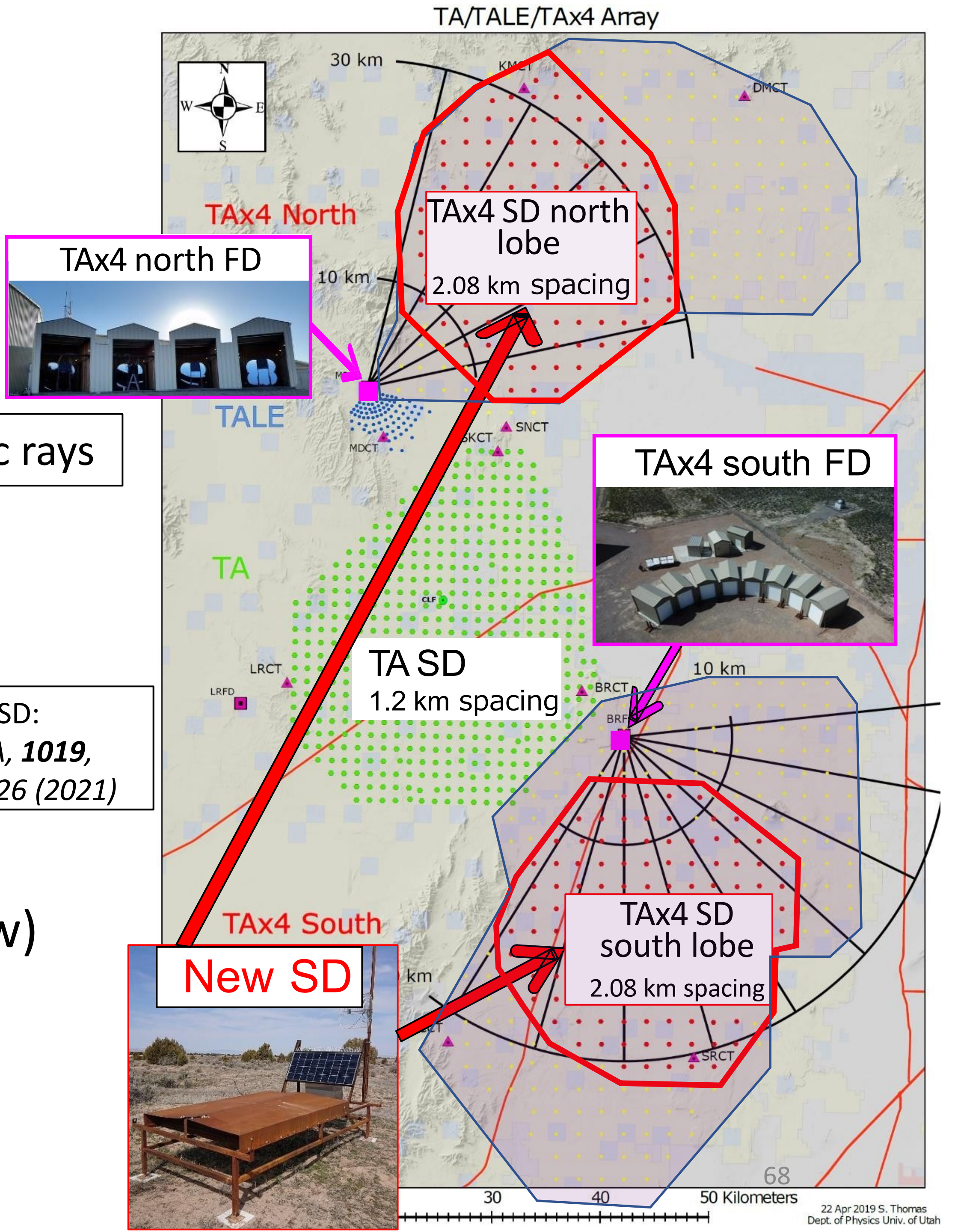
Increase the pace of collection of highest energy cosmic rays

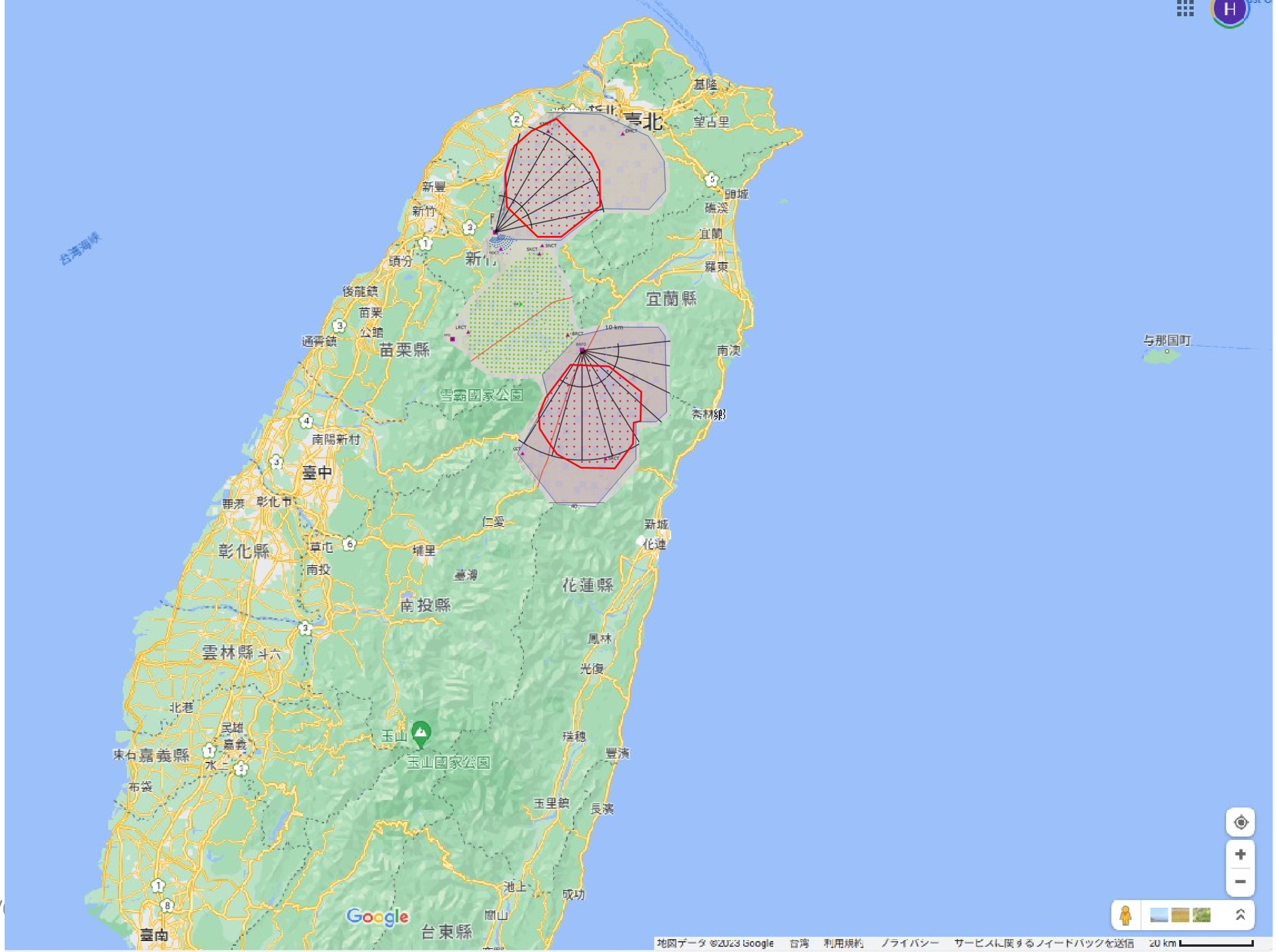
↓

Confirm the evidence of anisotropy by TA

- TAx4 SD
  - Deploy 500 new SDs with 2.08 km spacing
  - 4 times～2800 km^2 (TA SD + new SD)
  - Deployed **257** new SDs in 2019 (~2.5 times now)
- TAx4 FD stations at two FD sites
  - (4+8) HiRes FD refurbished

TAx4 SD:
NIMA, ***1019***, *165726 (2021)*

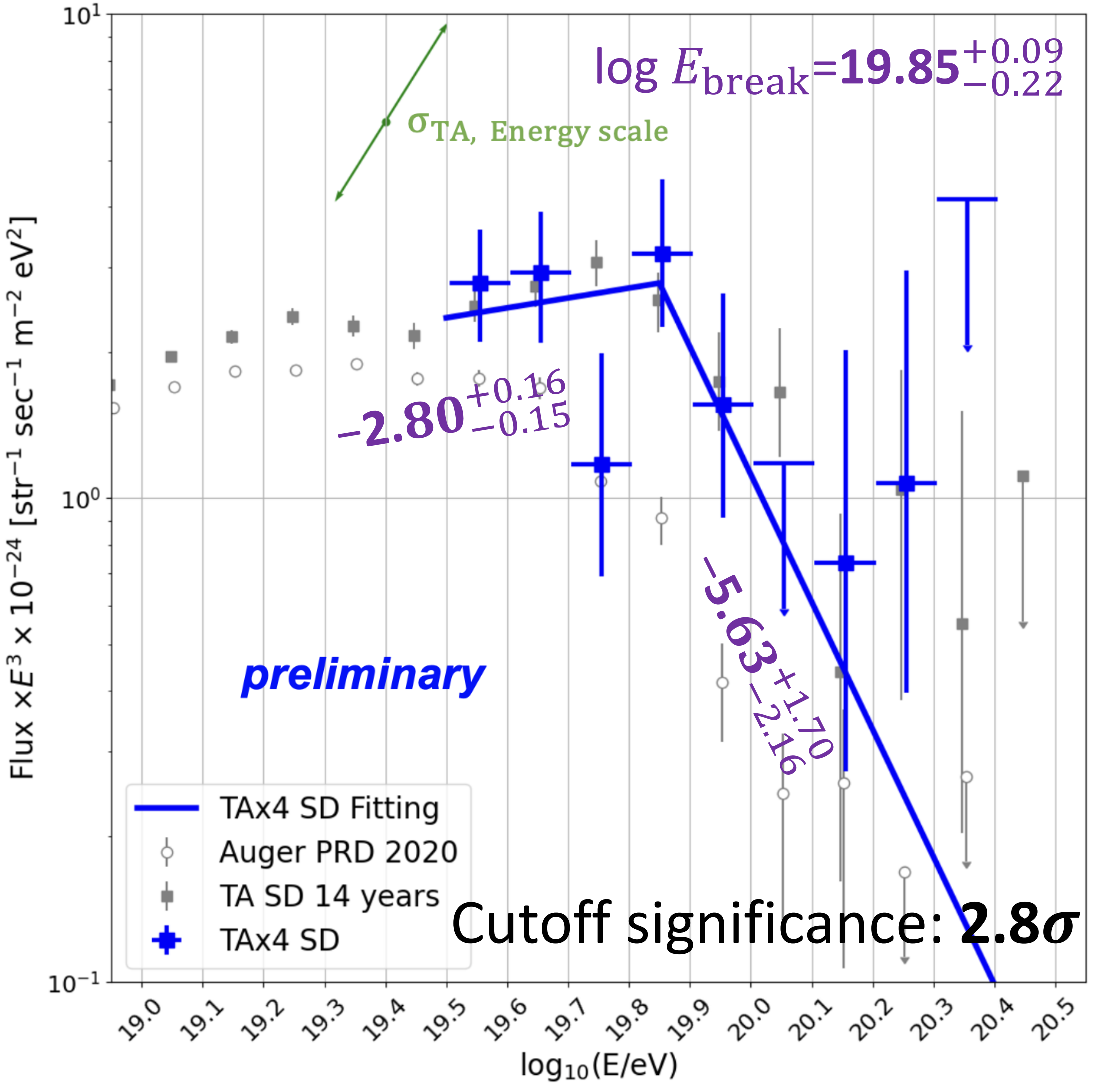



基隆
台北
望古里
新豊
新竹
頭分
後龍鎮
苗栗
公館
通霄鎮
苗栗縣
宜蘭
羅東
宜蘭縣
南澳
雪霸国家公園
与那国町
南陽新村
臺中
彰化市
彰化縣
草屯
南投
埔里
仁愛
新城
花蓮
花蓮縣
南投縣
鳳林
光復
雲林縣
北港
民雄
嘉義
嘉義縣
布袋
玉山
玉山国家公園
瑞穂
豊濱
玉里鎮
長濱
池上
成功
台東縣
臺南
Google
地図データ ©2023 Google
20 km

TAx4 SD using 3-year data

K. Fujisue, ICRC2023

Consistent with TA SD measurements



Consistent with TA SD spectrum

Prospects: Summary of TA anisotropy study

- TA found some evidences for anisotropy

Topics	E_{th} (EeV) [10^{18} eV]	years	Post-trial significance (σ)
TA hotspot	57 EeV	15	2.8
A new excess to Perseus-Pisces Supercluster	$10^{19.4}$ eV	15	3.3
Declination dependence of energy spectrum	$10^{18.8}$ eV	14	4.4

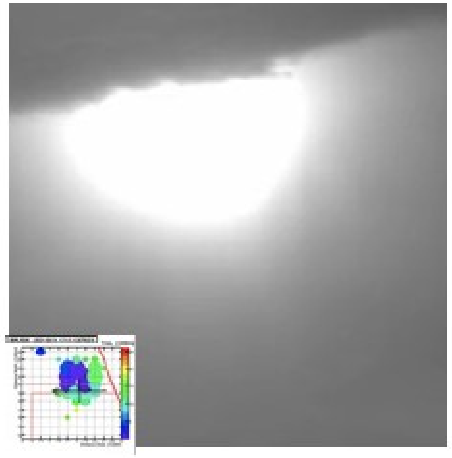
- We will see conclusive results with more data

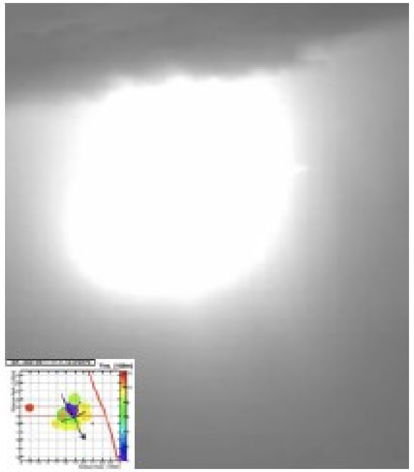
Joint and Interdisciplinary Research

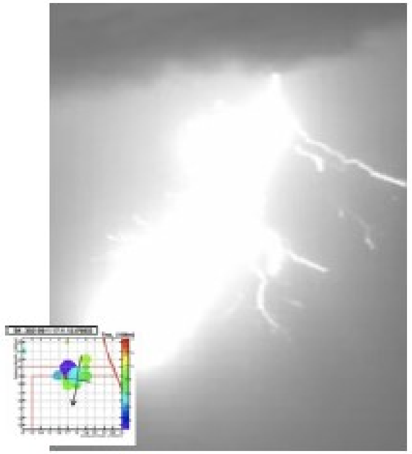
Observation of Terrestrial Gamma-Ray Flashes with TA SD

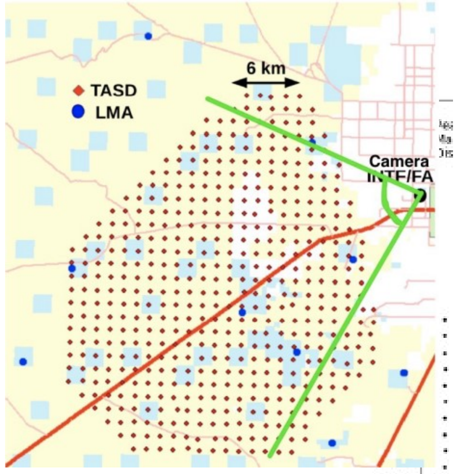
- The Telescope Array is a unique instrument that allows us to study gamma-ray emission from the atmosphere.

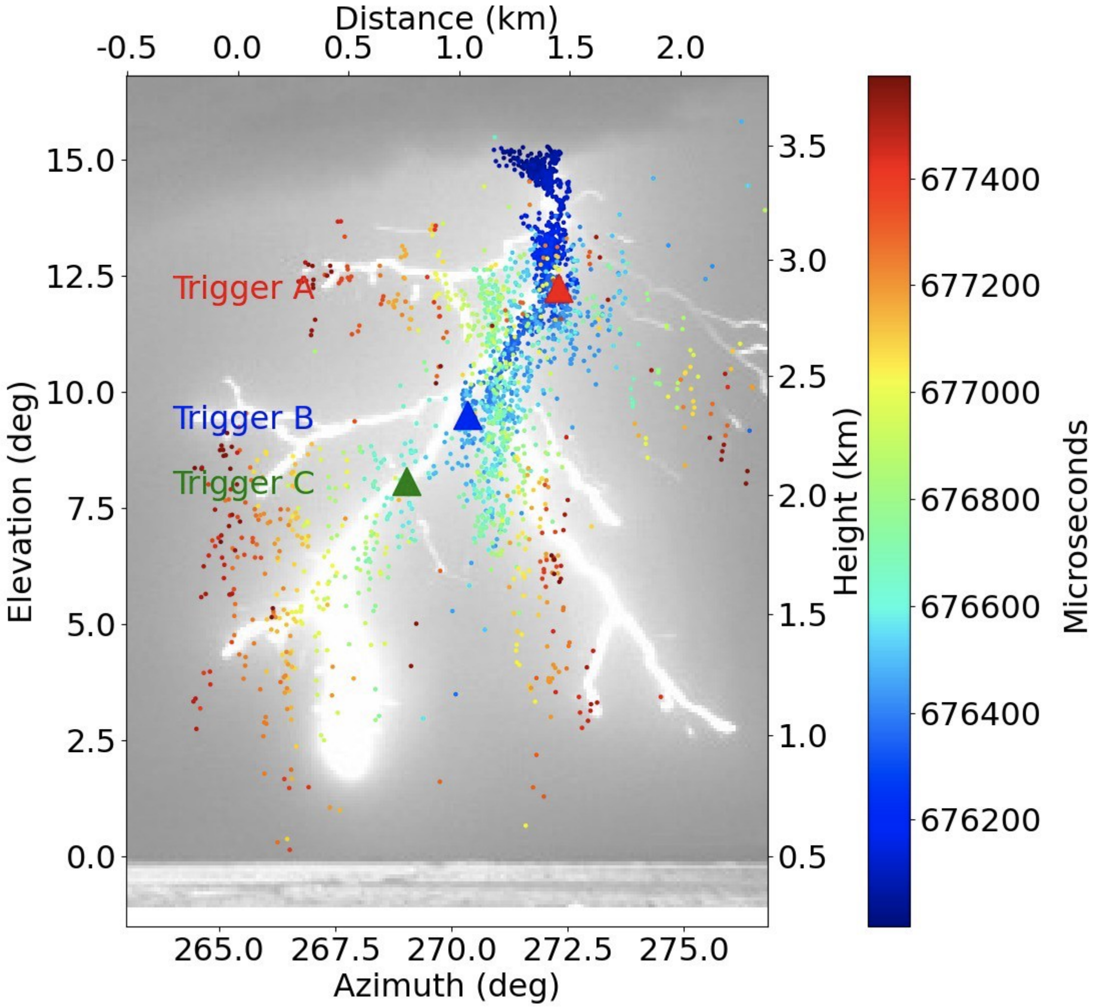
Rasha Abbasi, CRI12-02 Jul. 29



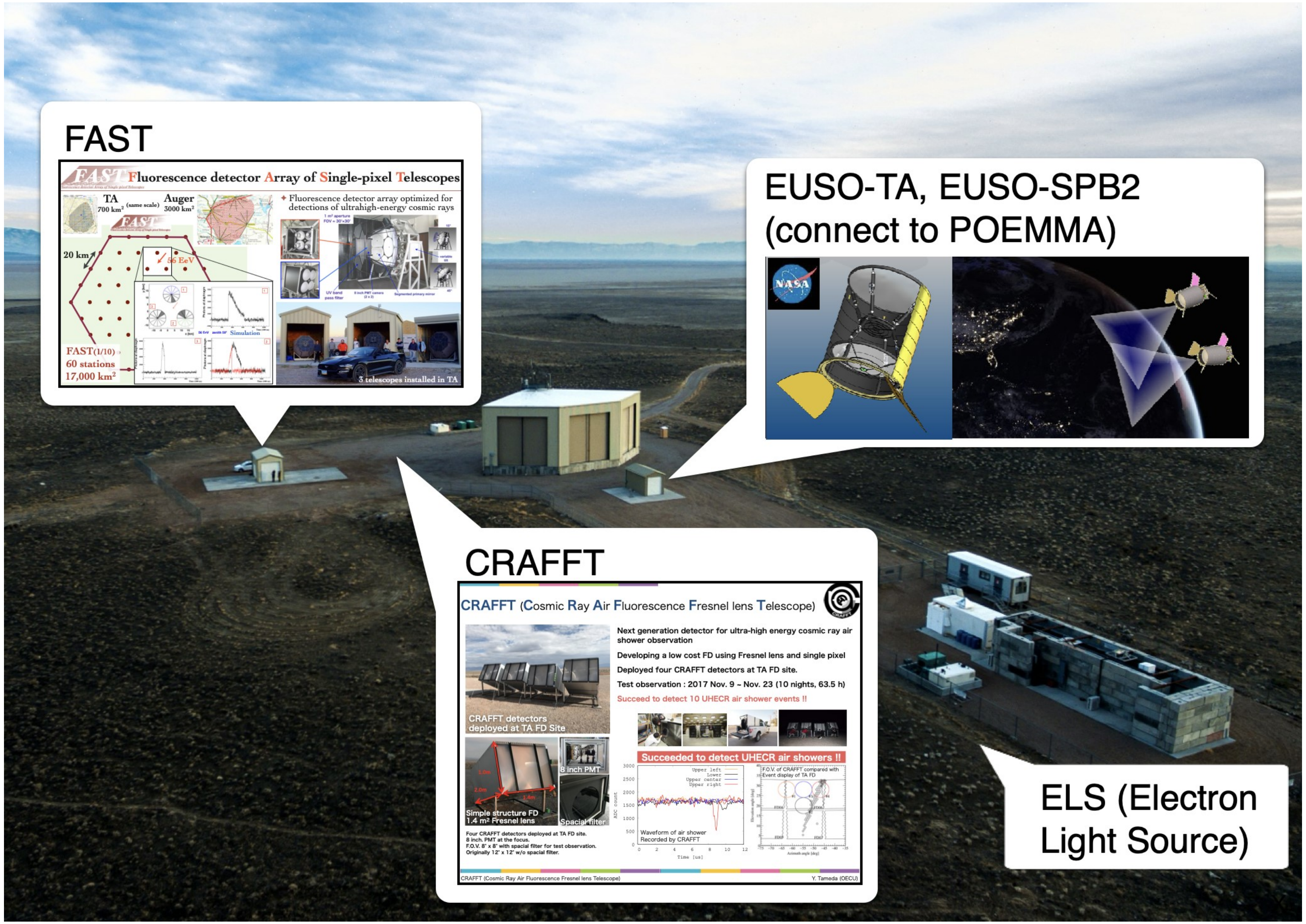








TA site as the test bed for the next-generation observatories



- Cost-effective fluorescence detectors for all-sky UHECR observatory
- Cosmic Ray Air Fluorescence Fresnel lens Telescope (CRAFFT)

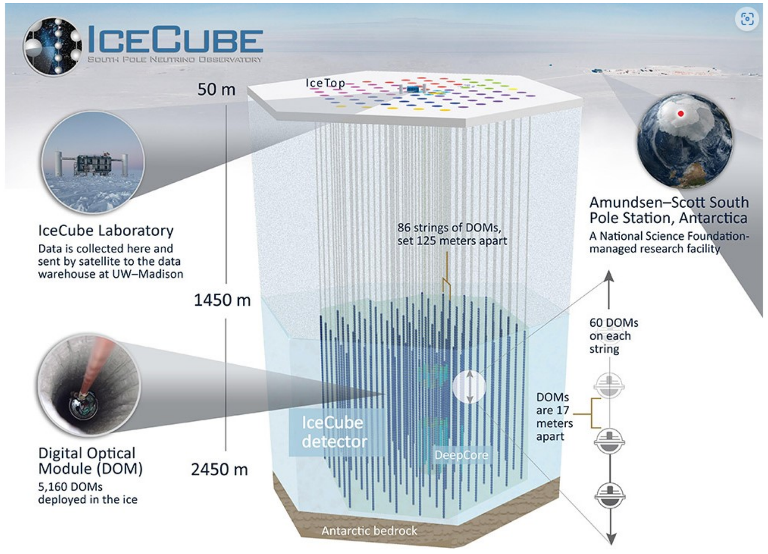
  Yuichiro Tameda, PCRI2-19 Jul. 29
- Fluorescence detector Array of Single-pixel Telescopes (FAST)

  Shunsuke Sakurai, CRI11-04 Jul. 29

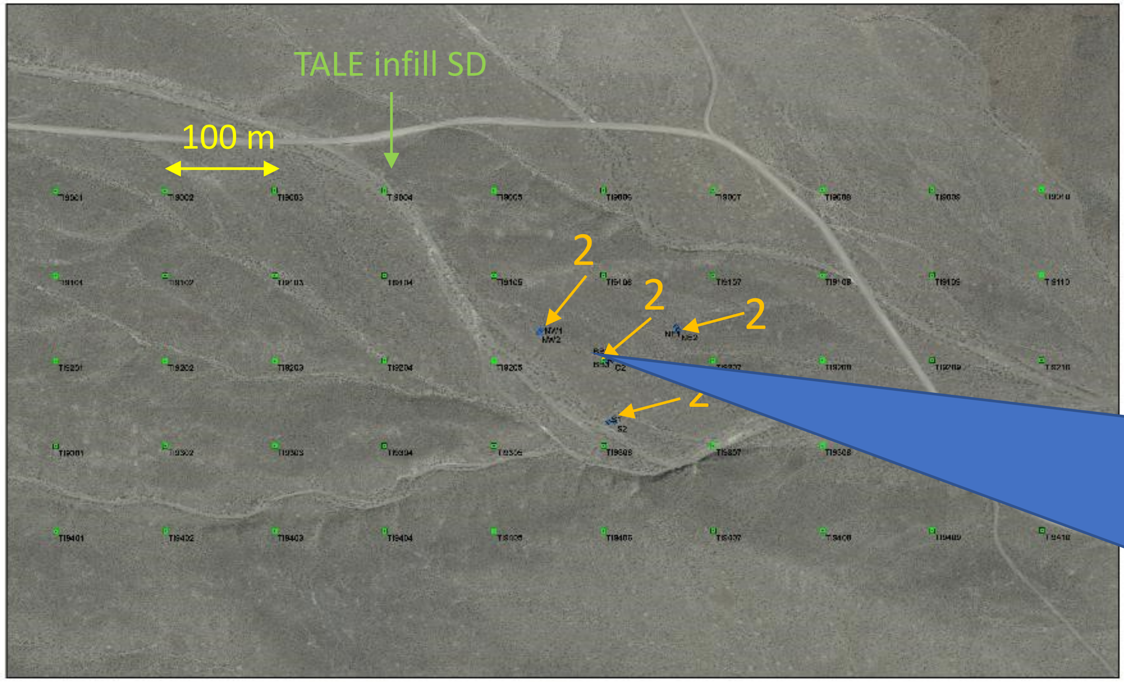
  Fraser Bradfield, PCRI2-46 Jul. 29

IceCube surface detectors

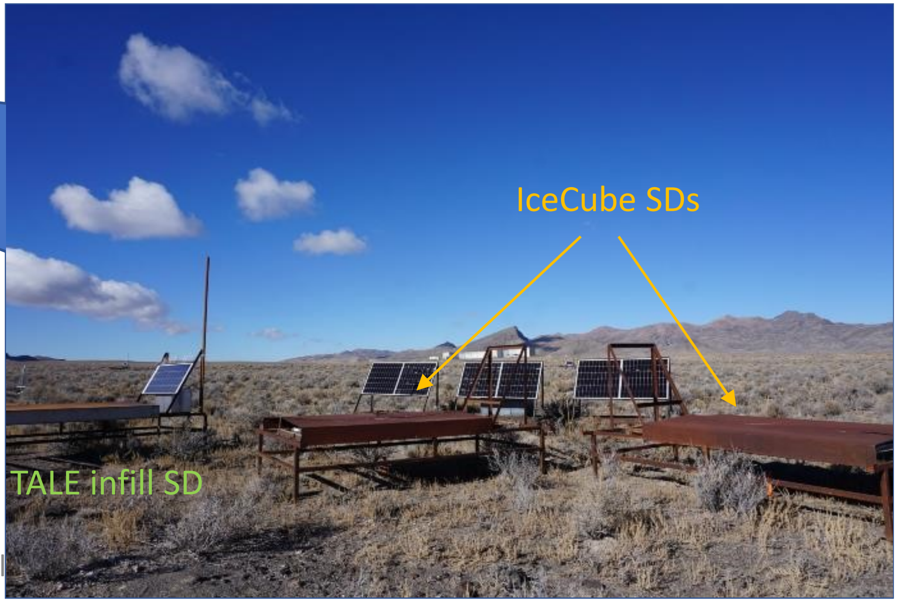
- IceCube is a neutrino observatory located in Antarctica.
- Now IceCube SDs are tested at the TALE infill SD array site for the IceCube upgrade (IceCube Gen2).



TALE infill SD array and IceCube SD array (8 SDs)



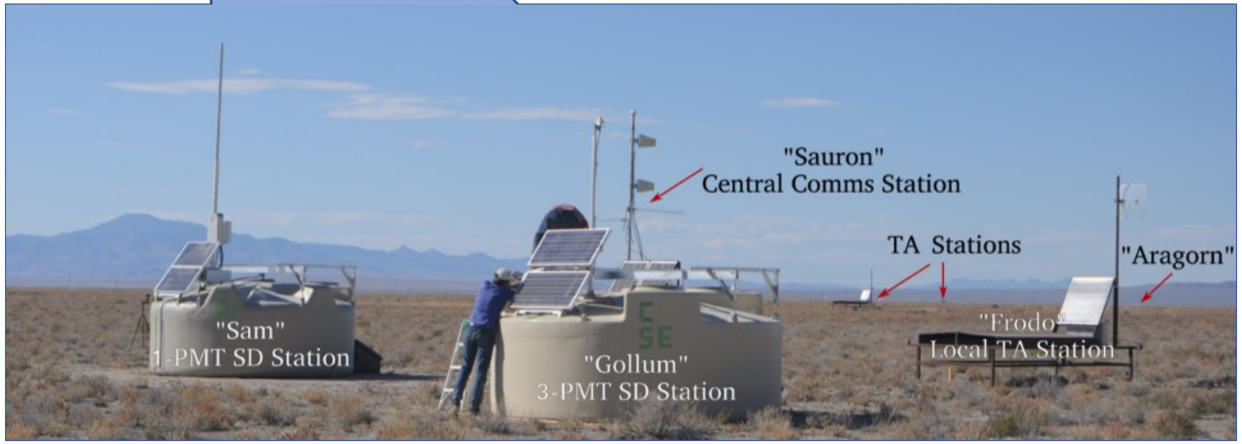
2 IceCube detectors and 1 TALE infill SD (main counter under rusted roof)



Auger SD micro-array in the TA SD array

(from F. Sarazin)

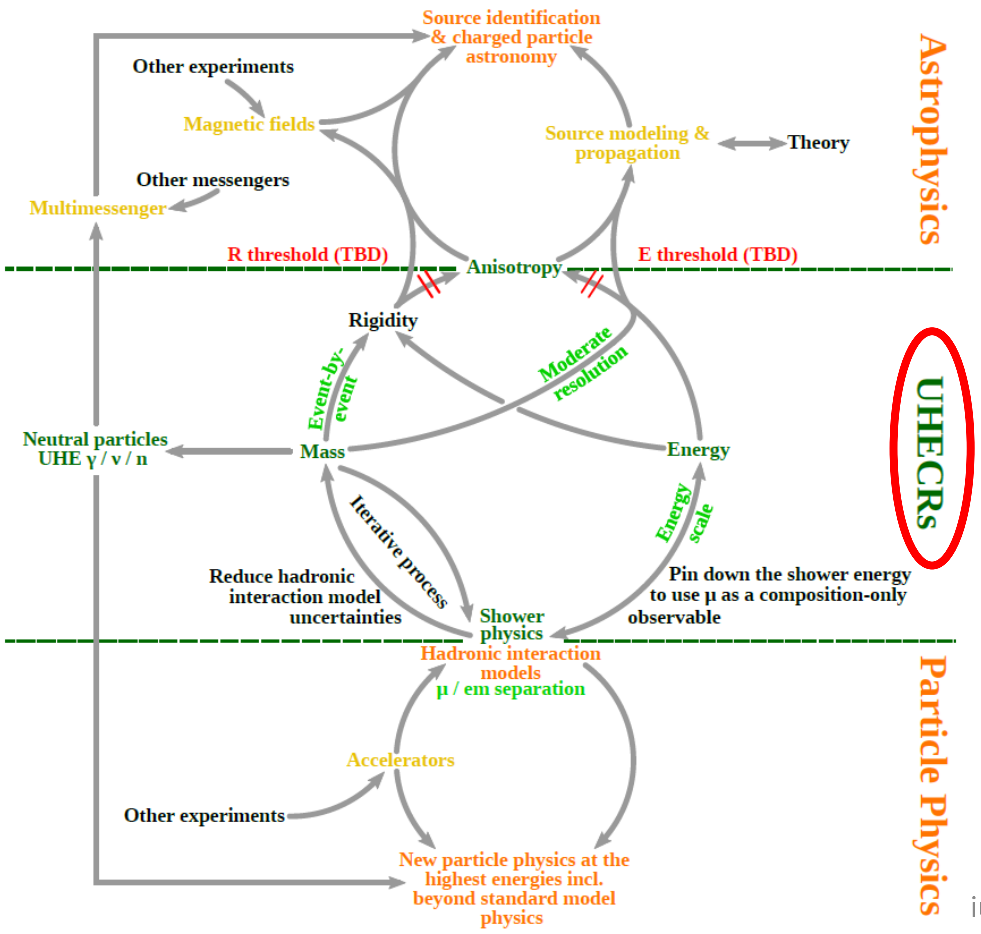
Hexagonal array of 8 Auger SDs in the TA SD square-grid array



2 Auger SDs and TA SDs at the center

UHECRs in the next Decades
Snowmass Whitepaper (arXiv:2205.05845)

- UHECR research connecting with Astrophysics & Particle Physics



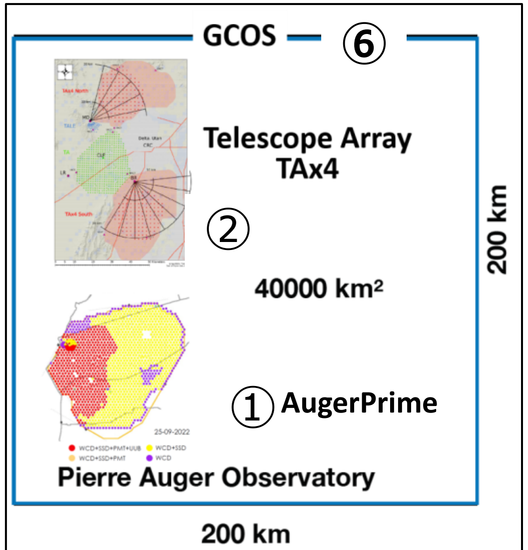
- Connection with Astrophysics
  - Sources of UHECRs
    - Charged particle astronomy
    - Exotic phenomena?
- UHECR: measurements at energy frontier
  - Arrival directions
  - Energy
  - Mass composition
  - Muon
- Connection with Particle Physics
  - Hadronic interaction models
    - UHECR extensive air showers
      - Mass composition
      - Muon deficits in simulations
    - LHC experiments
  - BSM

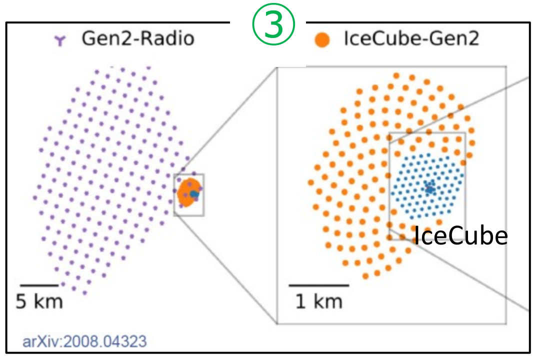
Prospects: Experiments

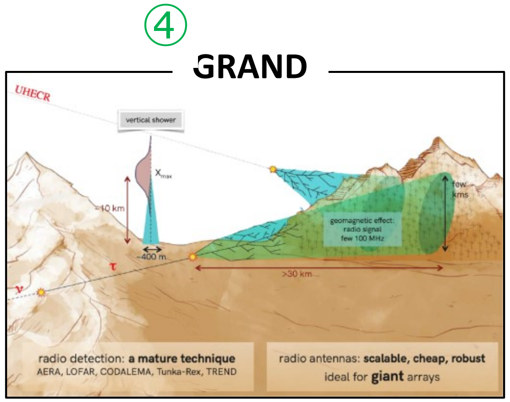
	Experiment	Feature	Cosmic Ray Science*	Timeline
①	Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
②	Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	TAx4 upgrade
③	IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement → IceCube-Gen2 deployment → IceCube-Gen2 operation
④	GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	GRANDProto 300 → GRAND 10k → GRAND 200k multiple sites, step by step
⑤	POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	JEM-EUSO program → POEMMA
⑥	GCOS	Hybrid array with X_{max} + e/μ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{\text{p-Air}}$	GCOS R&D + first site → GCOS further sites

Timeline: 2025, 2030, 2035, 2040

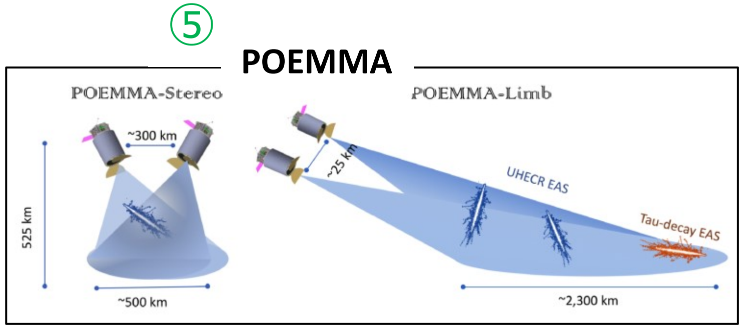
*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.







200,000 km^2 total worldwide



from the space

Summary

- Energy Spectrum: $10^{15.5}$ to $10^{20.5}$ eV (5 decades)
  - Several features (breaks): New feature “shoulder” at ~$10^{19.2}$ eV
- New highest energy event: 2.44×10^{20} eV
- Mass Composition
  - TA hybrid Xmax: compatible with predominantly light elements ($10^{18.2}$ - $10^{19.1}$ eV)
  - TALE FD / TALE hybrid Xmax: break at ~10^{17} eV
- Anisotropy: some evidences
  - Hot spot for E>57 EeV (post-trial): 3.4σ (5 years) –> 2.8σ (15 years)
  - A new excess E > $10^{19.4}$ eV in the direction of Perseus Pisces Supercluster
- Need more data at highest energy region –>TAx4 (now TAx2.5 for SD) in operation!
- Prospects: on-going & planned projects worldwide
  - TAx4, AugerPrime, IceCube/IceCubeGen2, GRAND, GCOS, POEMMA