Eiji Kido

RIKEN Cluster for Pioneering Research

Overview of the recent results and future developments of the Telescope Array experiment

Outline

- Latest results of the Telescope Array (TA) experiment
  - Energy spectrum
  - Anisotropy
  - Mass composition
- Current status and future developments of the TAx4 experiment
- Summary

Telescope Array Collaboration

R.U. Abbasi[1,2], M. Abe[3], T. Abu-Zayyad[1,2], M. Allen[2], Y. Arai[4], R. Arimura[4], E. Barcikowski[2], J.W. Belz[2], D.R. Bergman[2], S.A. Blake[2], I. Buckland[2], R. Cady[2], B.G. Cheon[5], J. Chiba[6], M. Chikawa[7], T. Fujii[8], K. Fujisue[7], K. Fujita[4], R. Fujiwara[4], M. Fukushima[7], R. Fukushima[4], G. Furlich[2], R. Gonzalez[2], W. Hanlon[2], M. Hayashi[9], N. Hayashida[10], K. Hibino[10], R. Higuchi[7], K. Honda[11], D. Ikeda[10], T. Inadomi[12], N. Inoue[3], T. Ishii[11], H. Ito[13], D. Ivanov[2], H. Iwakura[12], A. Iwasaki[4], H.M. Jeong[14], S. Jeong[14], C.C.H. Jui[2], K. Kadota[15], F. Kakimoto[10], O. Kalashev[16], K. Kasahara[17], S. Kasami[18], H. Kawai[19], S. Kawakami[4], S. Kawana[3], K. Kawata[7], I. Kharuk[16], E. Kido[13], H.B. Kim[5], J.H. Kim[2], J.H. Kim[2], M.H. Kim[14], S.W. Kim[14], Y. Kimura[4], S. Kishigami[4], Y. Kubota[12], S. Kurisu[12], V. Kuzmin[16], M. Kuznetsov[16,20], Y.J. Kwon[21], K.H. Lee[14], B. Lubsandorzhiev[16], J.P. Lundquist[2,22], K. Machida[11], H. Matsumiya[4], T. Matsuyama[4], J.N. Matthews[2], R. Mayta[4], M. Minamino[4], K. Mukai[11], I. Myers[2], S. Nagataki[13], K. Nakai[4], R. Nakamura[12], T. Nakamura[23], T. Nakamura[12], Y. Nakamura[12], A. Nakazawa[12], T. Nonaka[7], H. Oda[4], S. Ogio[4,24], M. Ohnishi[7], H. Ohoka[7], Y. Oku[18], T. Okuda[25], Y. Omura[4], M. Ono[13], R. Onogi[4], A. Oshima[4], S. Ozawa[26], I.H. Park[14], M. Potts[2], M.S. Pshirkov[16,27], J. Remington[2], D.C. Rodriguez[2], G.I. Rubtsov[16], D. Ryu[28], H. Sagawa[7], R. Sahara[4], Y. Saito[12], N. Sakaki[7], T. Sako[7], N. Sakurai[4], K. Sano[12], K. Sato[4], T. Seki[12], K. Sekino[7], P.D. Shah[2], Y. Shibasaki[12], F. Shibata[11], N. Shibata[18], T. Shibata[7], H. Shimodaira[7], B.K. Shin[28], H.S. Shin[7], D. Shinto[18], J.D. Smith[2], P. Sokolsky[2], N. Sone[12], B.T. Stokes[2], T.A. Stroman[2], T. Suzawa[3], Y. Takagi[4], Y. Takahashi[4], M. Takamura[6], M. Takeda[7], R. Takeishi[7], A. Taketa[29], M. Takita[7], Y. Tameda[18], H. Tanaka[4], K. Tanaka[30], M. Tanaka[31], Y. Tanoue[4], S.B. Thomas[2], G.B. Thomson[2], P. Tinyakov[16,20], I. Tkachev[16], H. Tokuno[32], T. Tomida[12], S. Troitsky[16], R. Tsuda[4], Y. Tsunesada[4,24], Y. Uchihori[33], S. Udo[10], T. Uehama[12], F. Urban[34], T. Wong[2], K. Yada[7], M. Yamamoto[12], K. Yamazaki[10], J. Yang[35], K. Yashiro[6], F. Yoshida[18], Y. Yoshioka[12], Y. Zhezher[7,16], and Z. Zundel[2]

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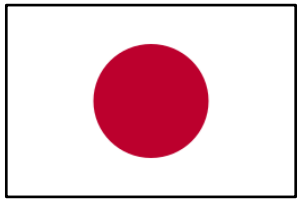
161 members , 35 institutes, 7 countries

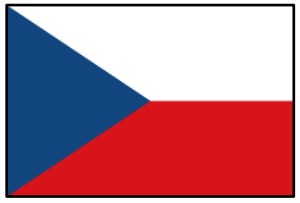

USA

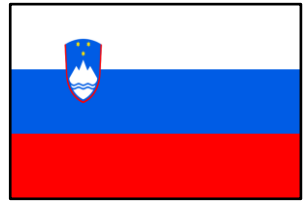

Japan


Korea


Russia


Belgium


Czech Republic


Slovenia

TA detectors

FD station

MDFD

TALE
SD array

SD array

Latitude 39.30° N
Longitude 112.91° W
Height: 1382 m

CLF

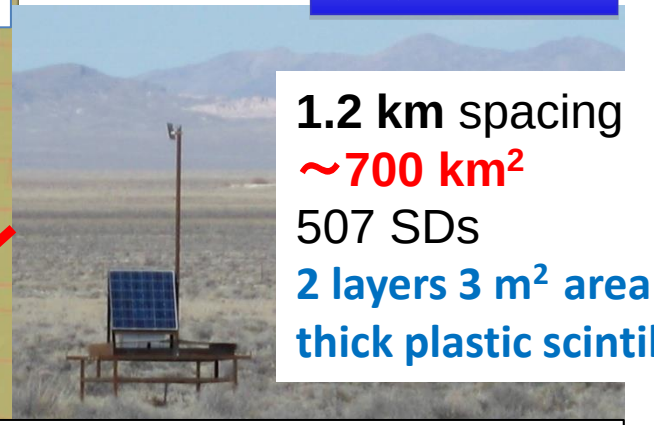
LRFD

28km

BRFD

Full operation from May **2008**
Utah, USA

Surface Detector (SD)



1.2 km spacing
～700 km²
507 SDs
2 layers 3 m² area 1.2 cm thick plastic scintillators

- **Largest cosmic-ray observatory in the northern hemisphere**
- **Hybrid observation by SD and FD**

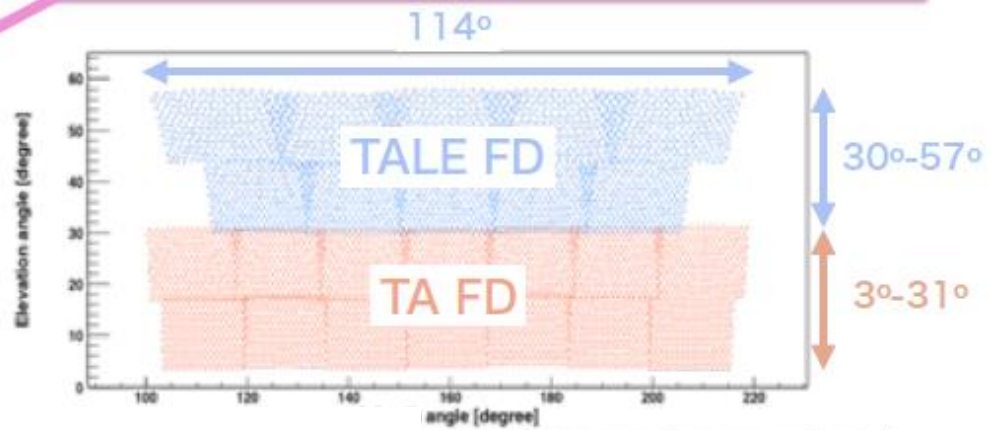
Fluorescence Detector (FD) station

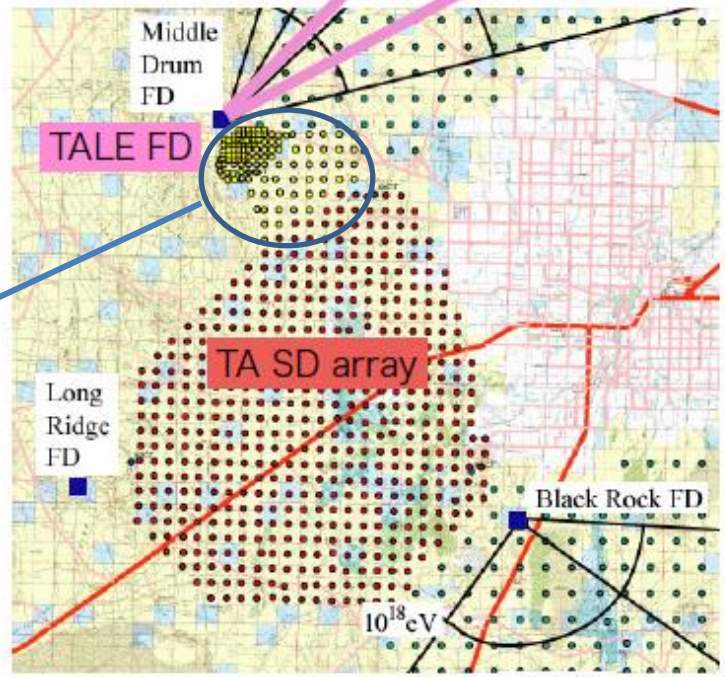
12 telescopes

TALE (Telescope Array Low energy Extension)

Located in TA MD site
10 FDs in the TALE station
Elevation: 30°-57° (higher elevation than MD)
Azimuthal: 114°

Refurbished HiRes telescopes & electronics
Mirror: same as TA FD (MD)
Elec.: 10 MHz 8bit FADC

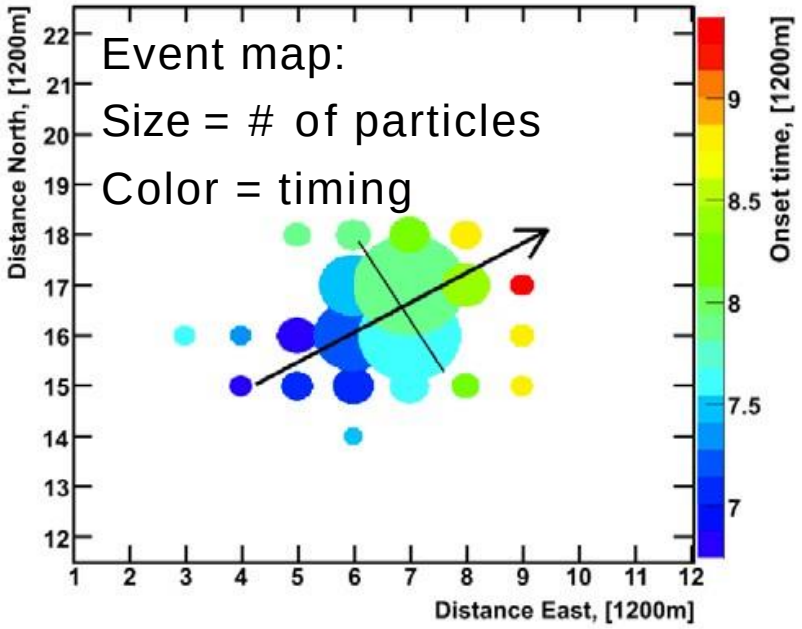


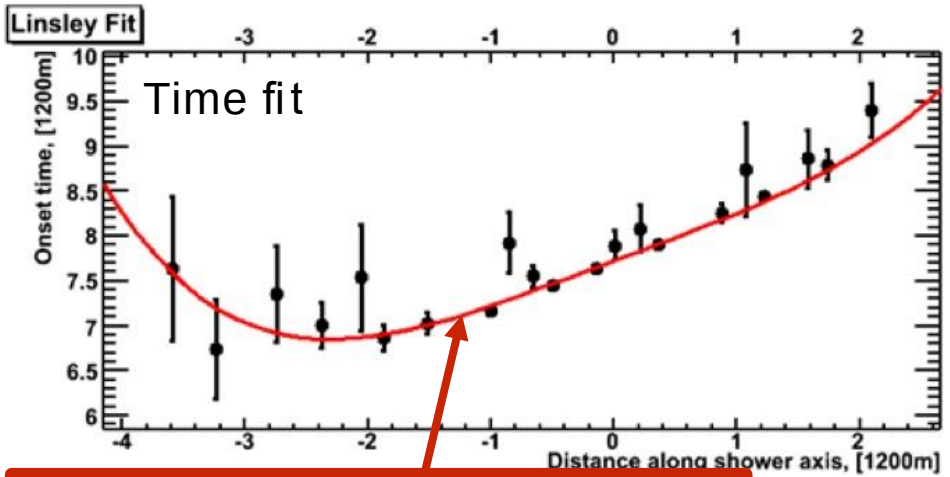


TALE
80 SDs

TALE FD was
installed in Nov. 2012
Operation since Sep. 2013
Hybrid trigger: Sep. 2018

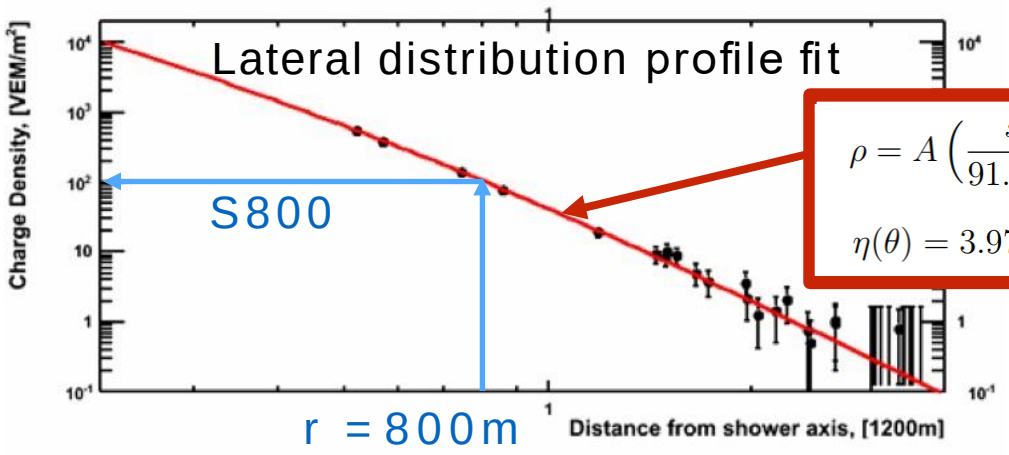
Event reconstructions with SDs





$$\tau = a\left(1-\frac{l}{12\times10^{3}\mathrm{m}}\right)^{1.05}\left(1.0+\frac{s}{30\mathrm{m}}\right)^{1.35}\rho^{-0.5}$$

Modified empirical formula in AGASA



Timing -> shower geometry

$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1+\frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1+\left[\frac{s}{1000\mathrm{m}}\right]^{2}\right)^{-0.6}$$

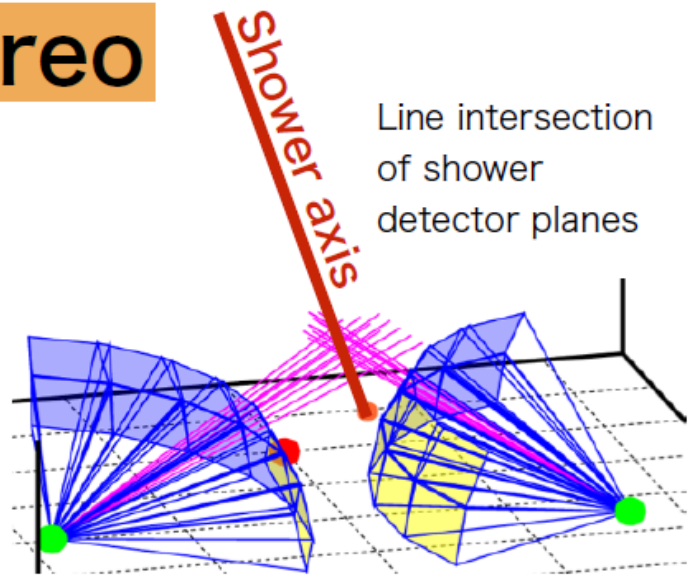
$$\eta(\theta) = 3.97 - 1.79\left[\sec(\theta)-1\right]$$

Empirical formula used by AGASA

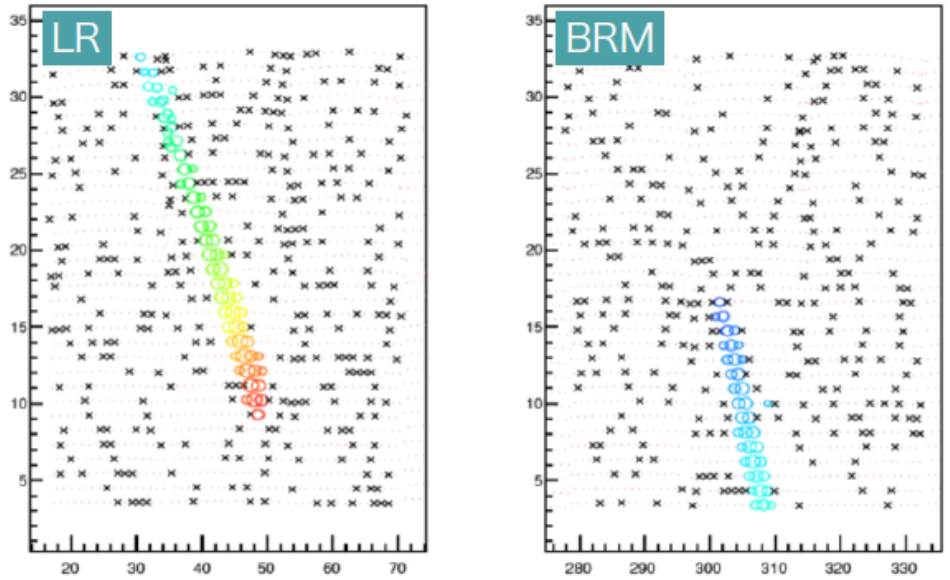
S800 -> primary energy

Event reconstructions with FDs

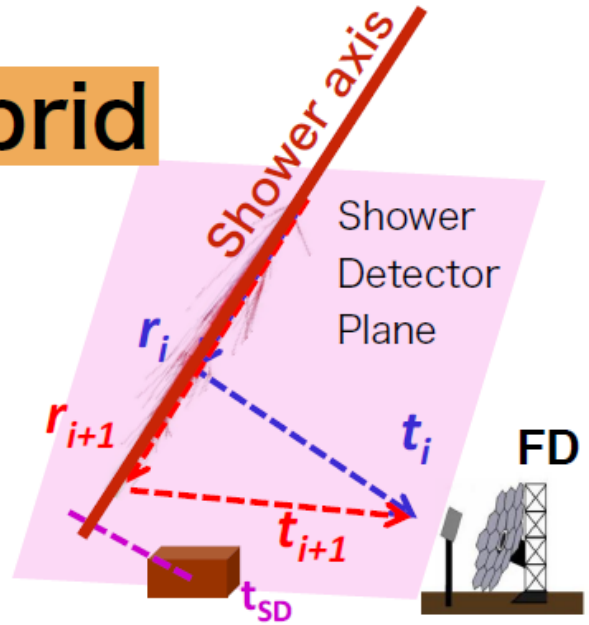
Stereo



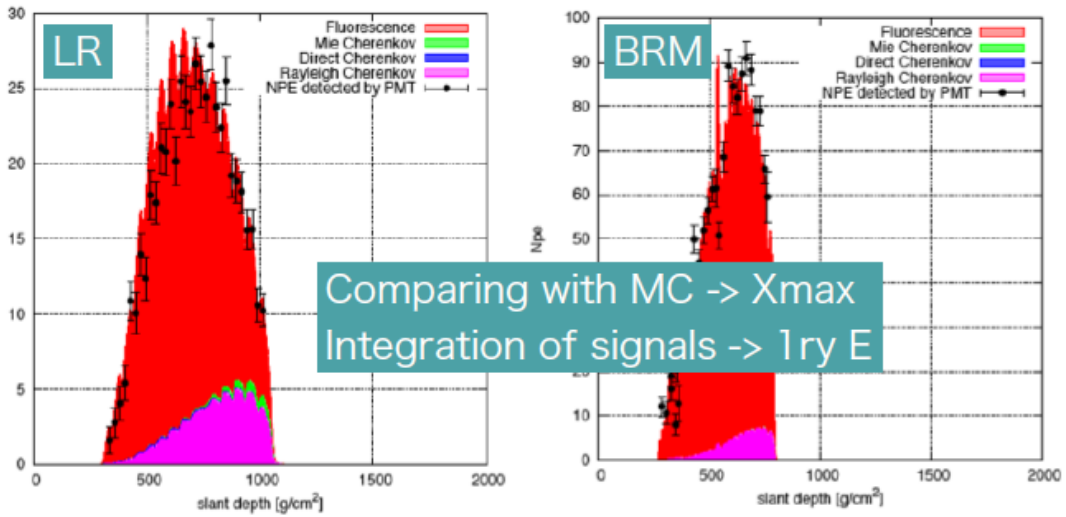
observed images



Hybrid



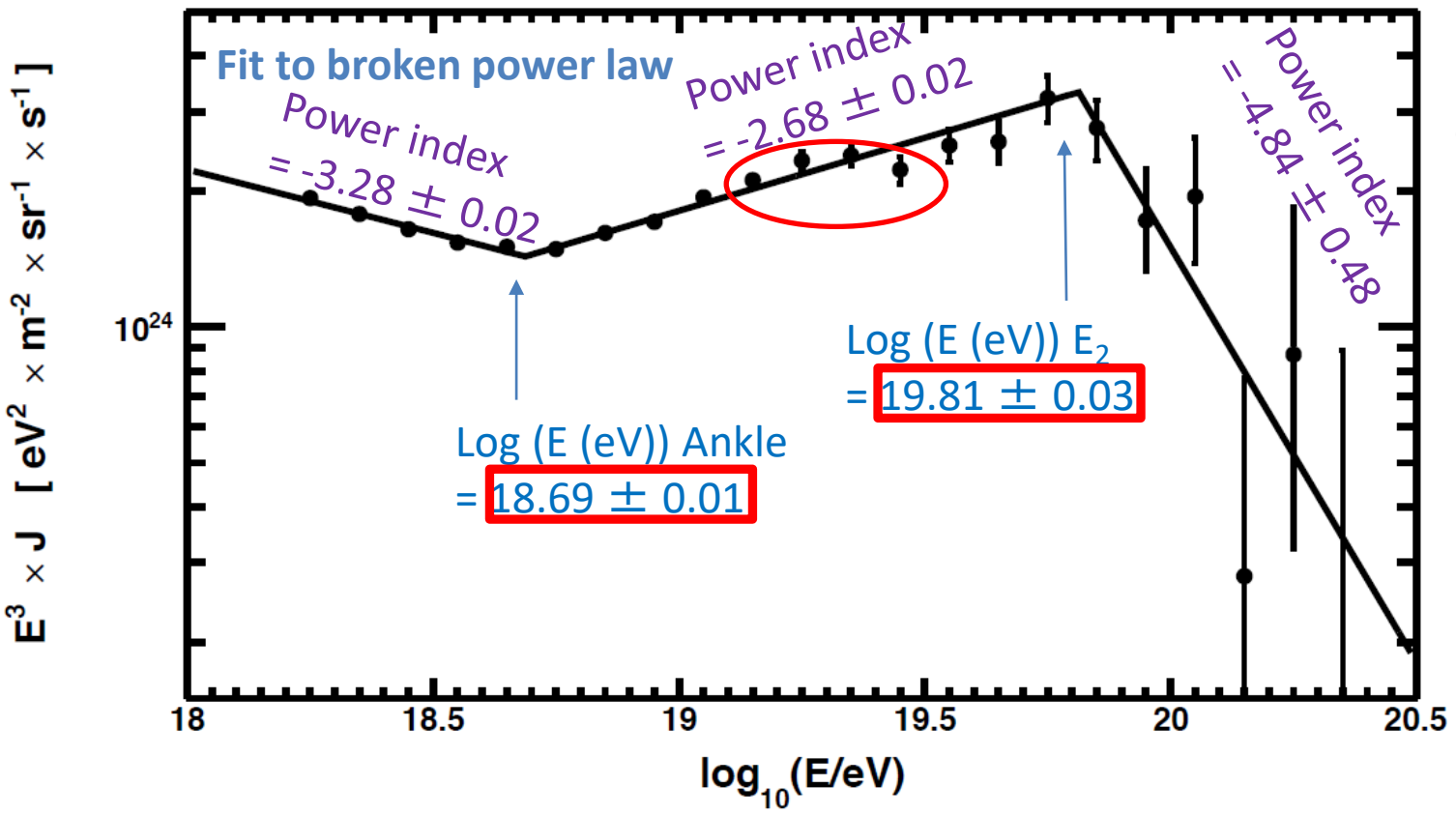
reconstructed shower profiles

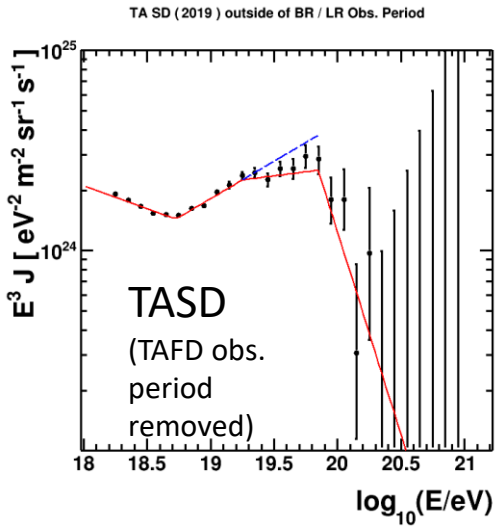


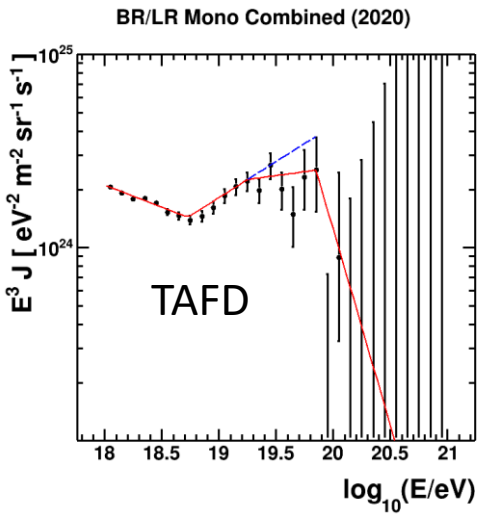
Energy spectra

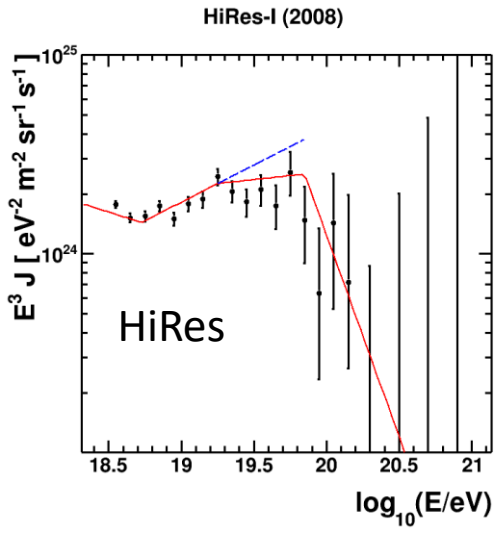
D. Ivanov

TA SD 11 years data





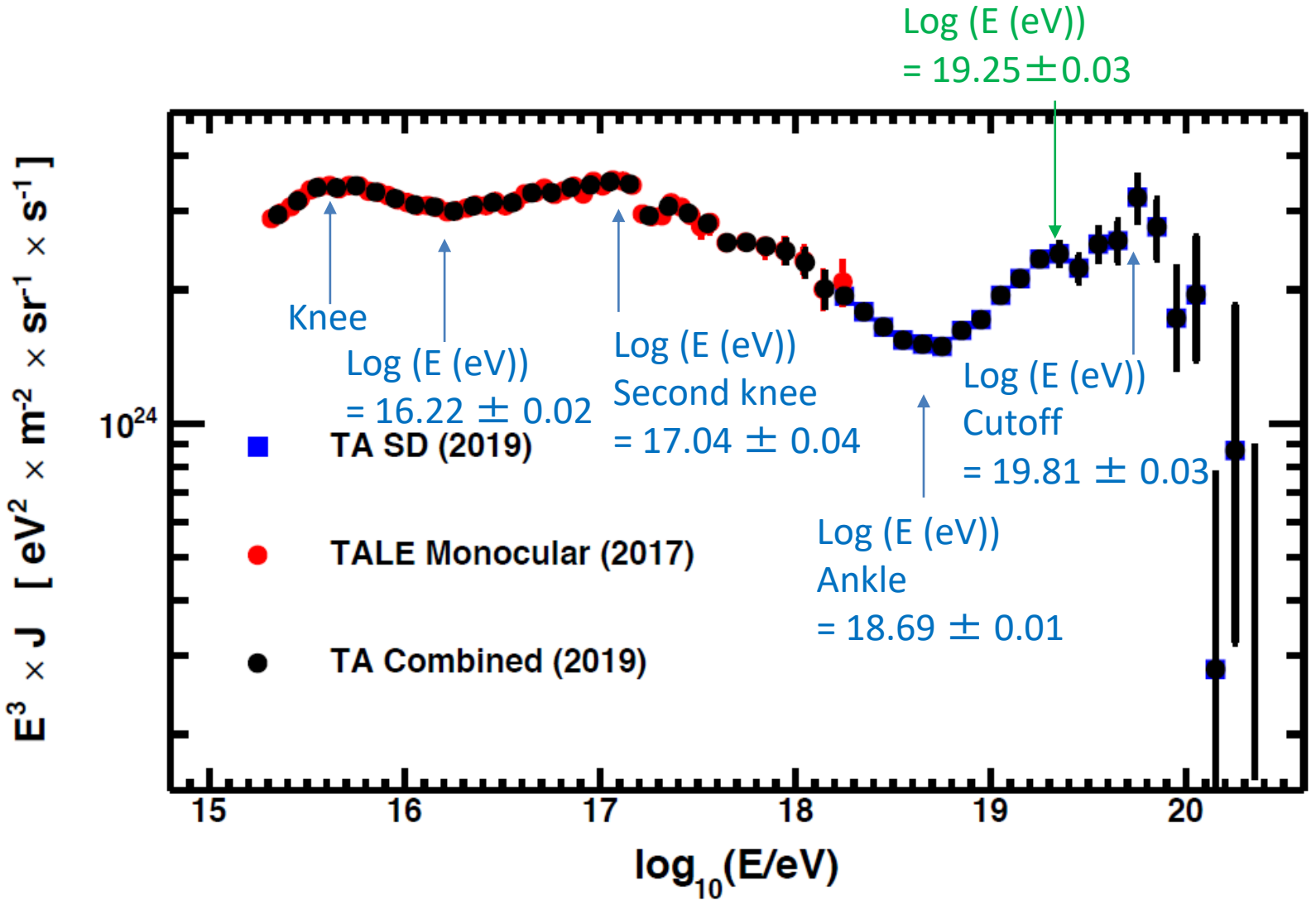




Auger found a new break at 1.3×10^{19} eV.
A break at $10^{19.25 \pm 0.03}$ eV was obtained in 5.3σ by combining TA SD, FD, and HiRes data.

Combined energy spectrum of TA SD with TALE FD Mono.

D. Ivanov

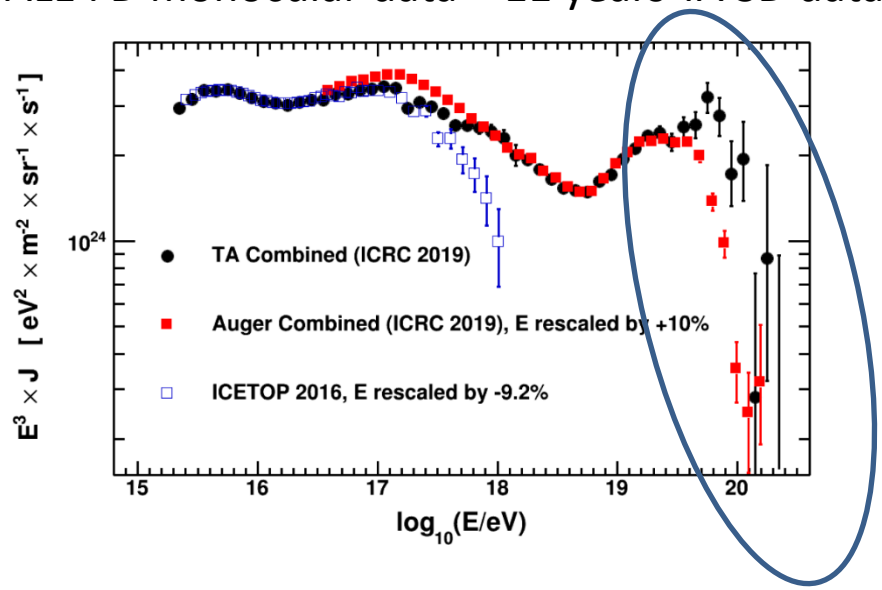


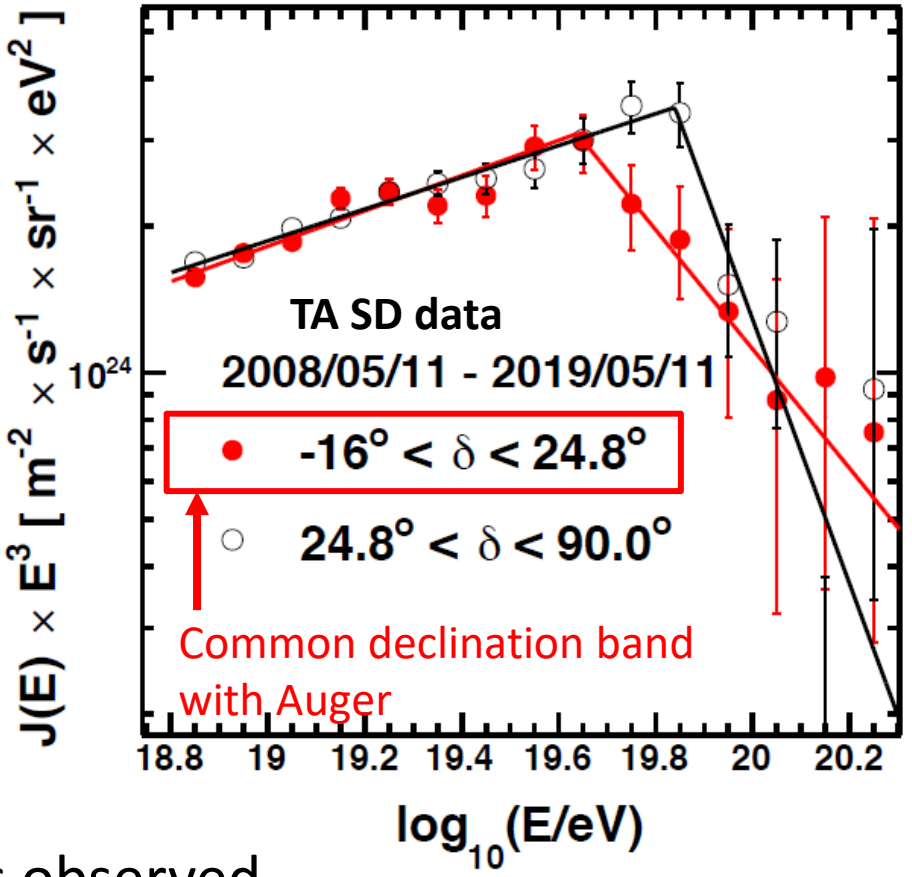
Combined TA spectrum using
22 months TALE FD monocular data +
11 years TA SD data

Declination dependence of the energy spectrum

D. Ivanov

22 months TALE FD monocular data + 11 years TA SD data





- Implication of cutoff energies was observed
  - log(E/eV) = 19.64 ± 0.04 lower declination band (-16° - 24.8 °)
  - log(E/eV) = 19.84 ± 0.02 higher declination band (24.8 ° - 90 °)
- Significance of the cutoff energies ~ **4.3σ**

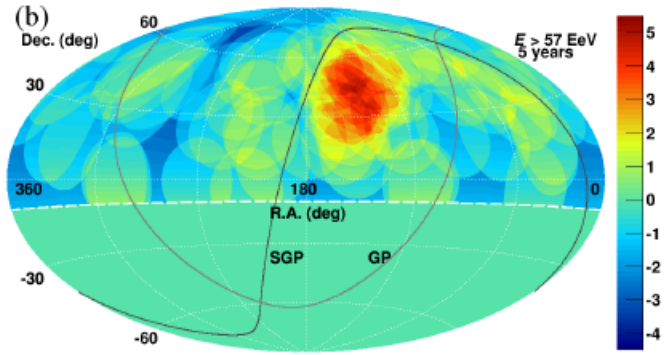
E > 57 EeV TA hotspot

J.H. Kim

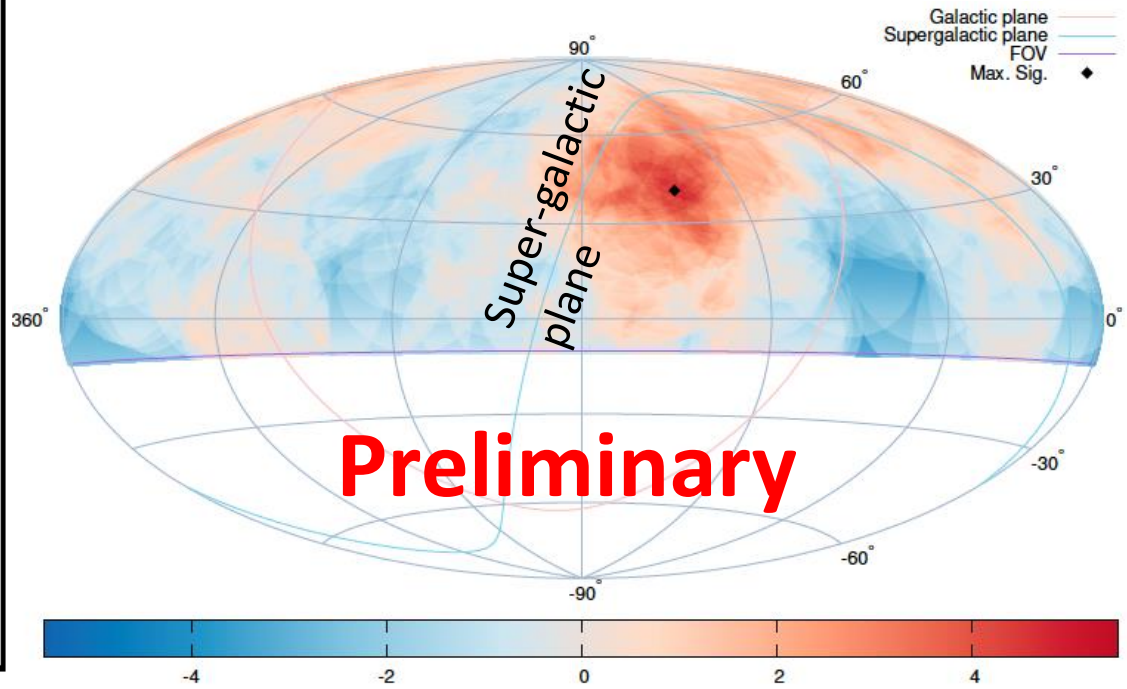
TA SD 12 years data

Original hotspot reported in 2014, from 5 years of data

Ap. J., 790, L21(2014)
E > 57 EeV (Observed 72 events)
20° over-sampling circle
19 events fall in "Hotspot" centered at (146.7°, 43.2°)
(Expected = 4.5 events)
local significance 5.1σ, post trial significance 3.4σ



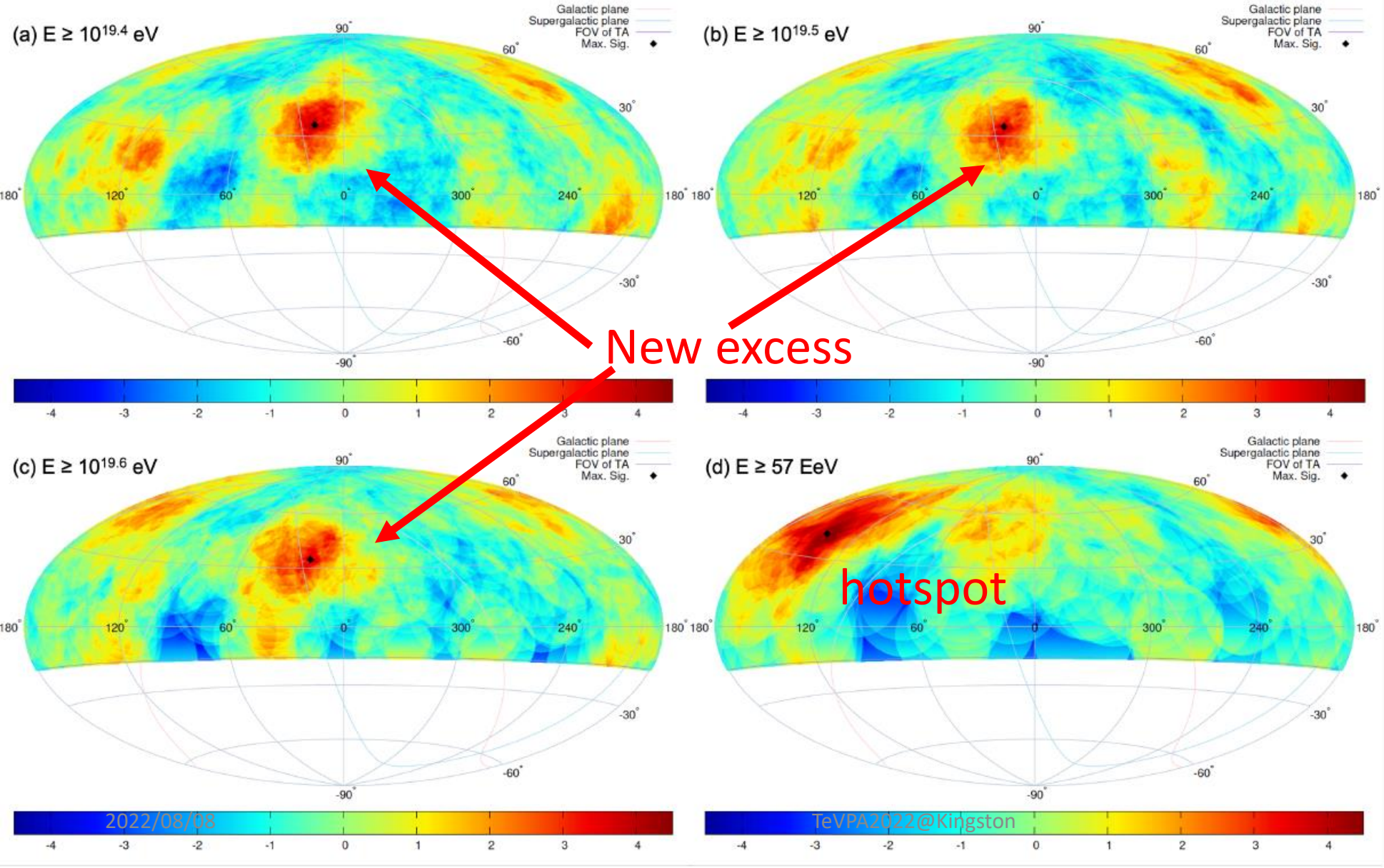
Significance map from isotropy expectation



Equatorial coordinate

- 179 evetns E > 5.7×10^{19} eV
- Maximum local significance: 5.1σ (144.0°, 40.5°)
  - Observed: 40 events
  - Expectation from isotropy: 14.6 events
- **Post-trial probability: $P(S_{MC} > 5.1\sigma) = 6.8 \times 10^{-4}$ → 3.2σ**

E > $10^{19.4}$ eV excess in the arrival directions



arXiv: 2110.14827

Excess was observed at lower energies than TA hotspot

Significance of the excess

For E ≥ $10^{19.4}$, **3.6σ**

For E ≥ $10^{19.5}$ eV, **3.6σ**

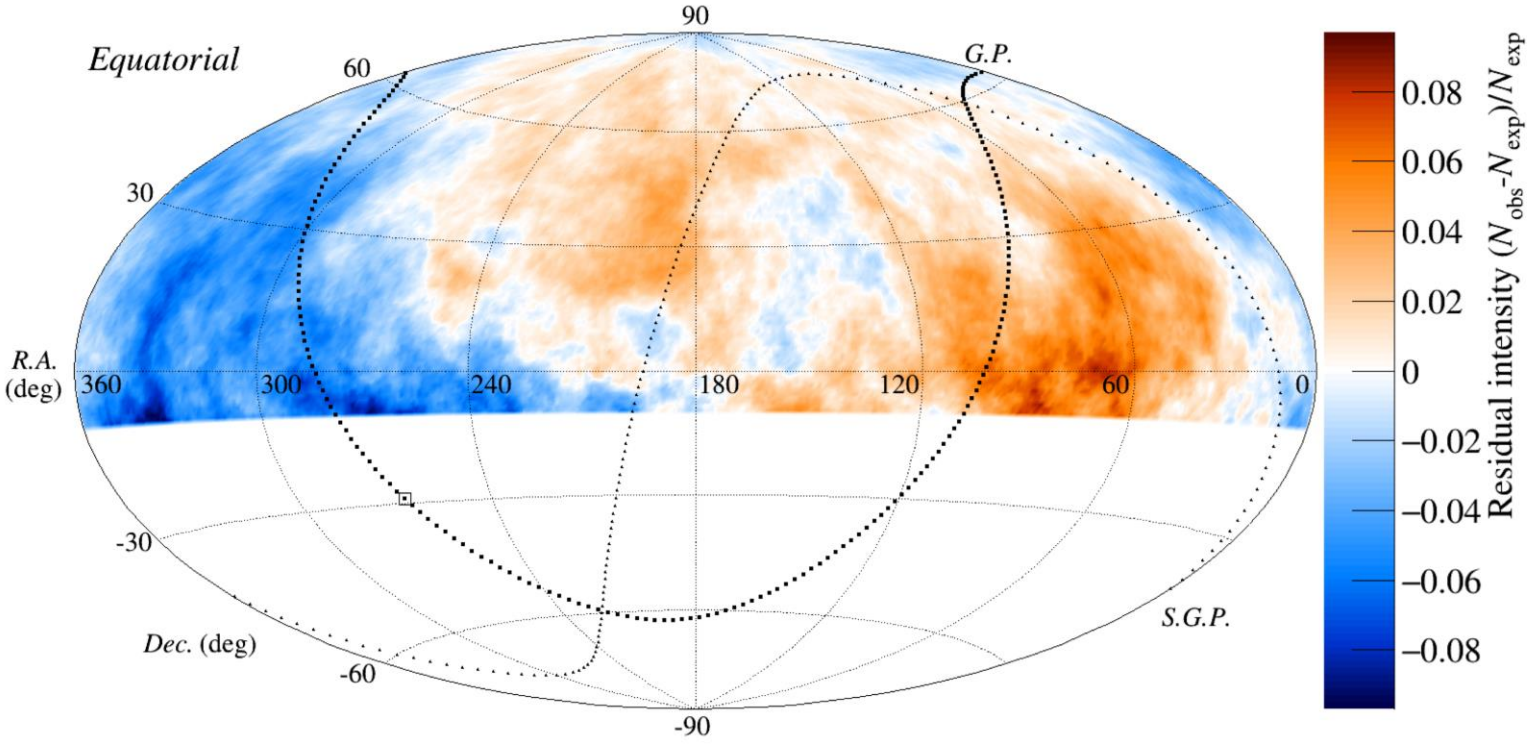
For E ≥ $10^{19.6}$ eV, **3.4σ**

(20 degrees oversampling radius)

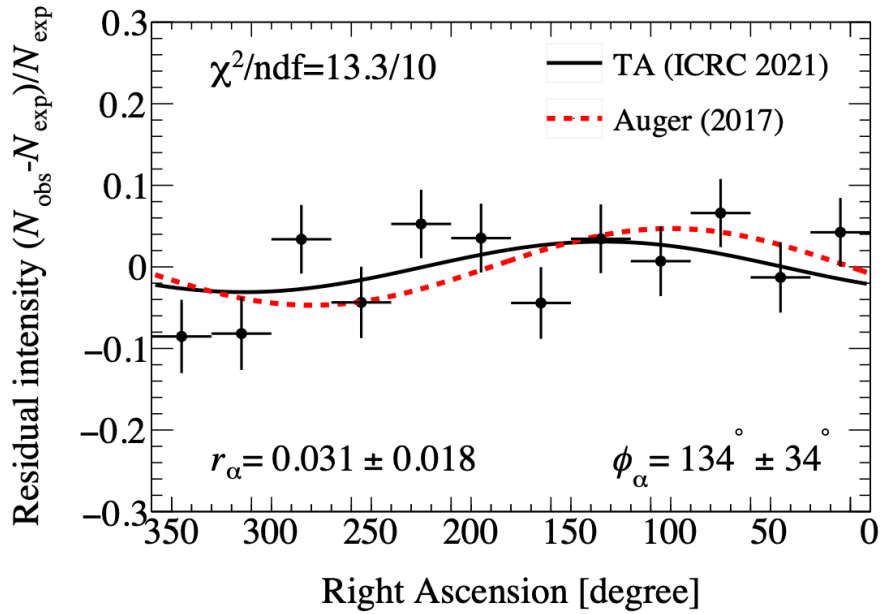
11 years TA SD data

E > 8.8 EeV search for the dipole anisotropy

T. Fujii



Sky map of residual intensity between TA data and an isotropic distribution for E > 8.8 EeV (energy cut corresponds to E > 8 EeV used by Auger).

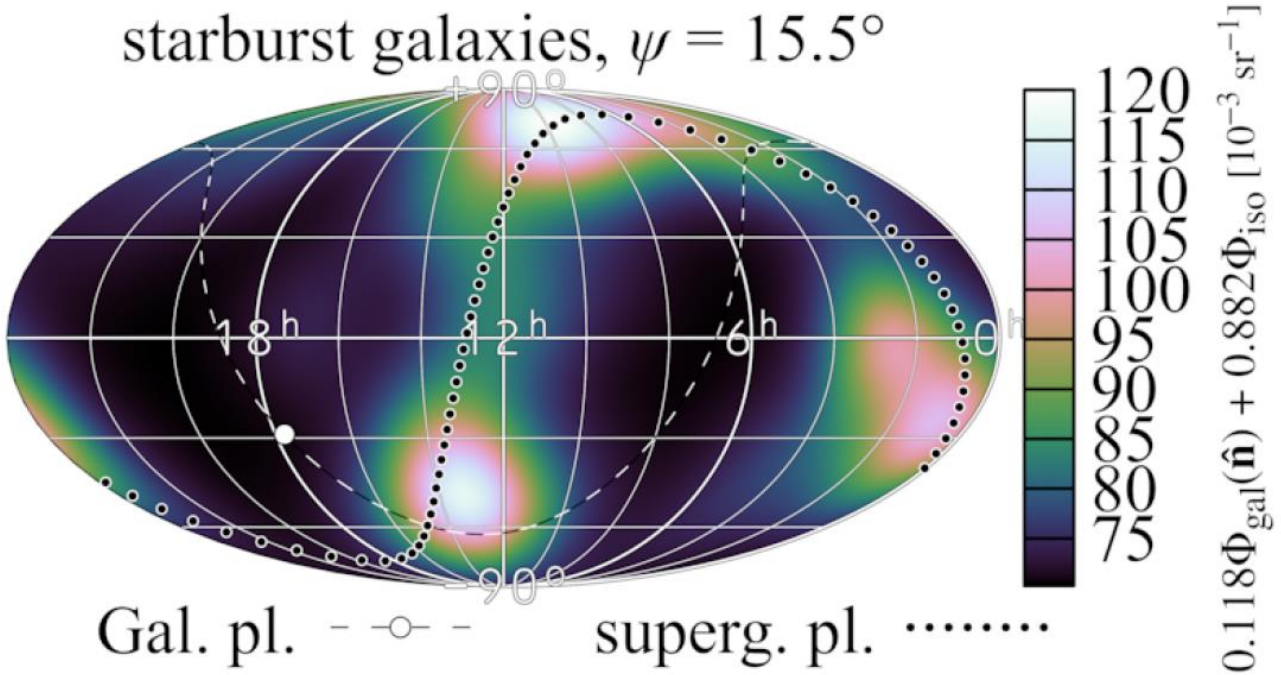


TASD 12-yr result : $r_\alpha \simeq 3.1\%; \phi_\alpha \simeq 134^\circ$
Auger 2017 result : $r_\alpha \simeq 4.7\%; \phi_\alpha \simeq 100^\circ$

Auger discovered a dipole anisotropy for E > 8 EeV at more than 5σ significance.

Correlation of arrival directions with astrophysical sources searched by the Auger and TA anisotropy working group

A. di Matteo



Equatorial coordinate

- Auger: E > 38 EeV
- TA: E > 49 EeV
- Correlations with a sample of nearby starburst galaxies and 2MRS catalog galaxies.
- Angular scales and energy thresholds were scanned.
- Post-trial significance of the correlation with **starburst galaxies** is estimated to be **4.2σ**.

Rescale of energies

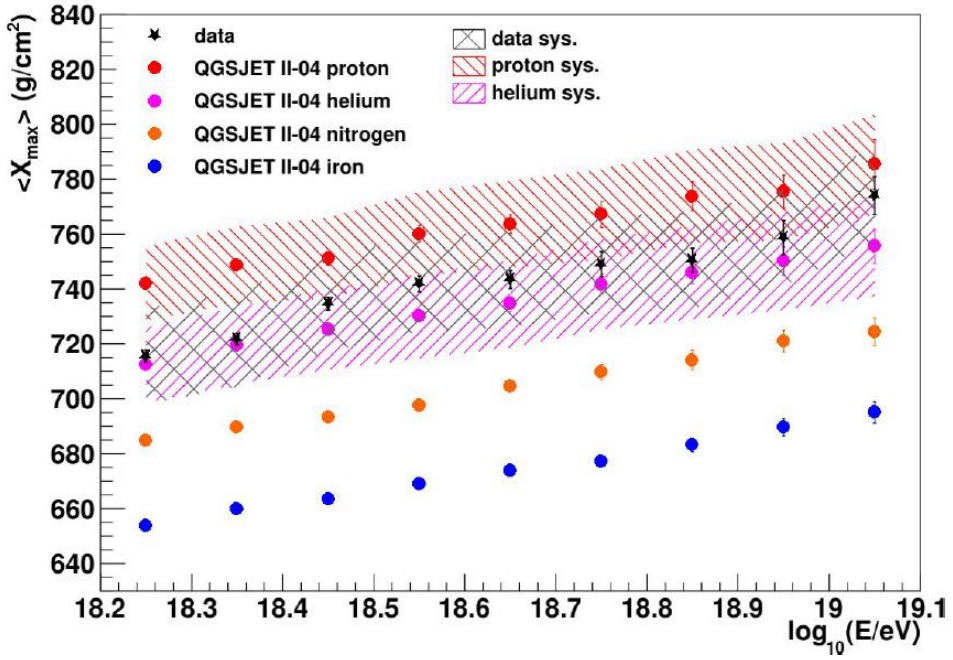
$$E_{\rm TA} \mapsto E_{\rm Auger} = 8.57\ (E_{\rm TA}/10\ {\rm EeV})^{0.937}\ {\rm EeV}$$

Measurement of mass composition with TA SD and FD in hybrid mode

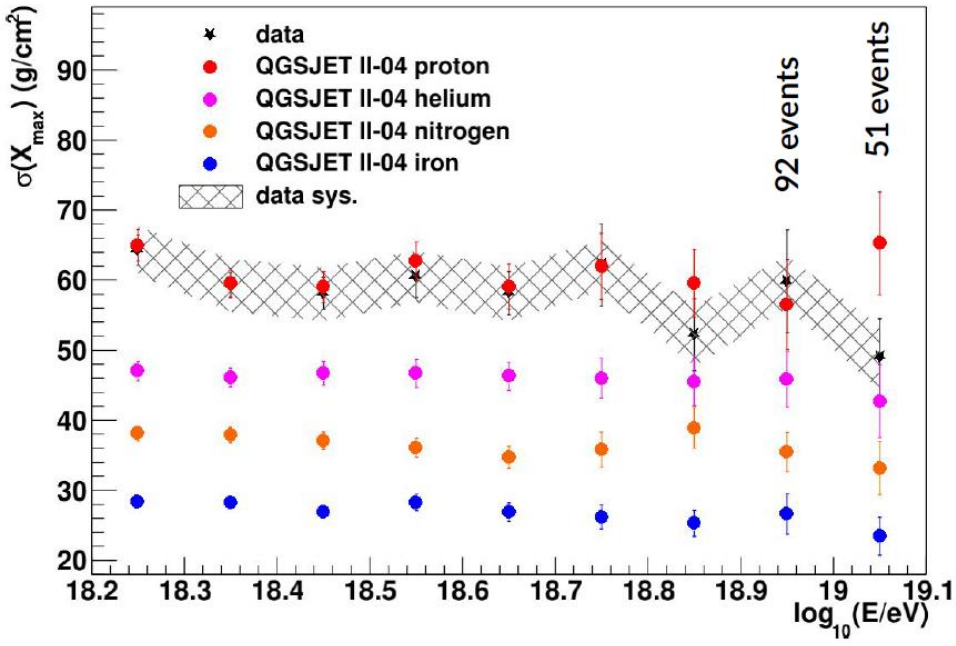
W. Hanlon

10 years TA SD and FD hybrid data

Mean Xmax



σ (Xmax)

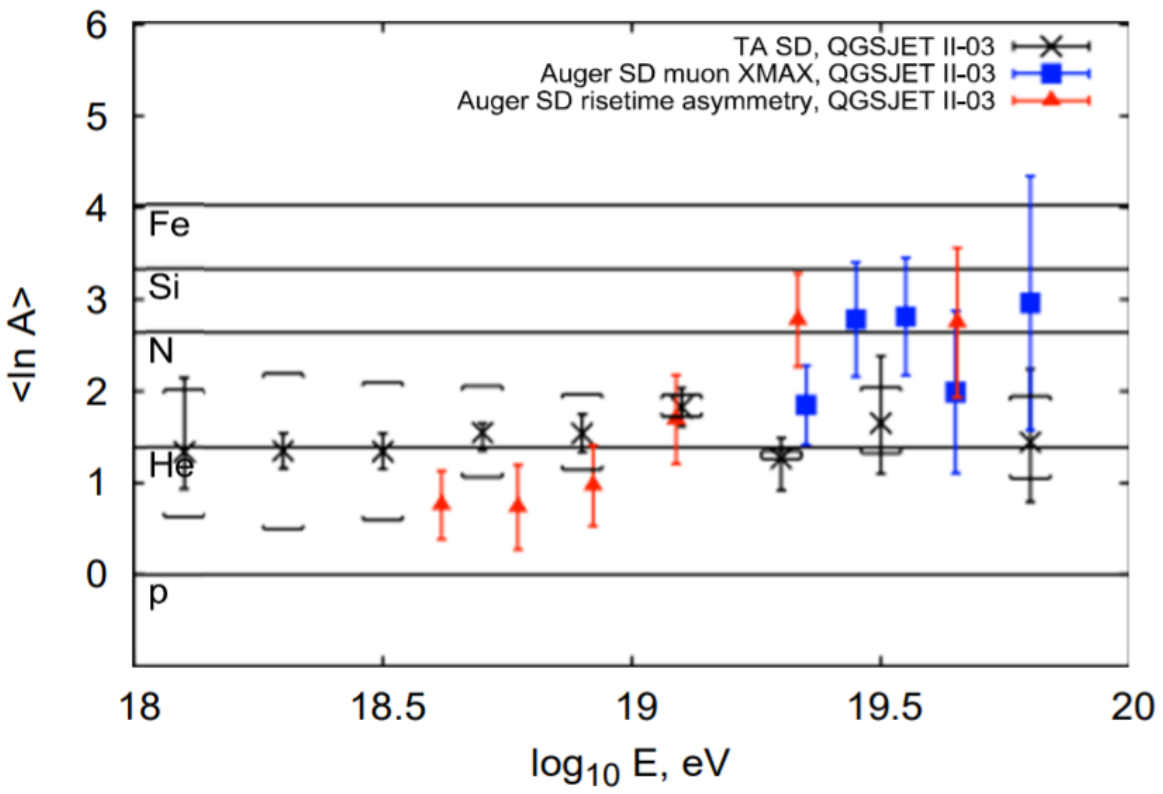


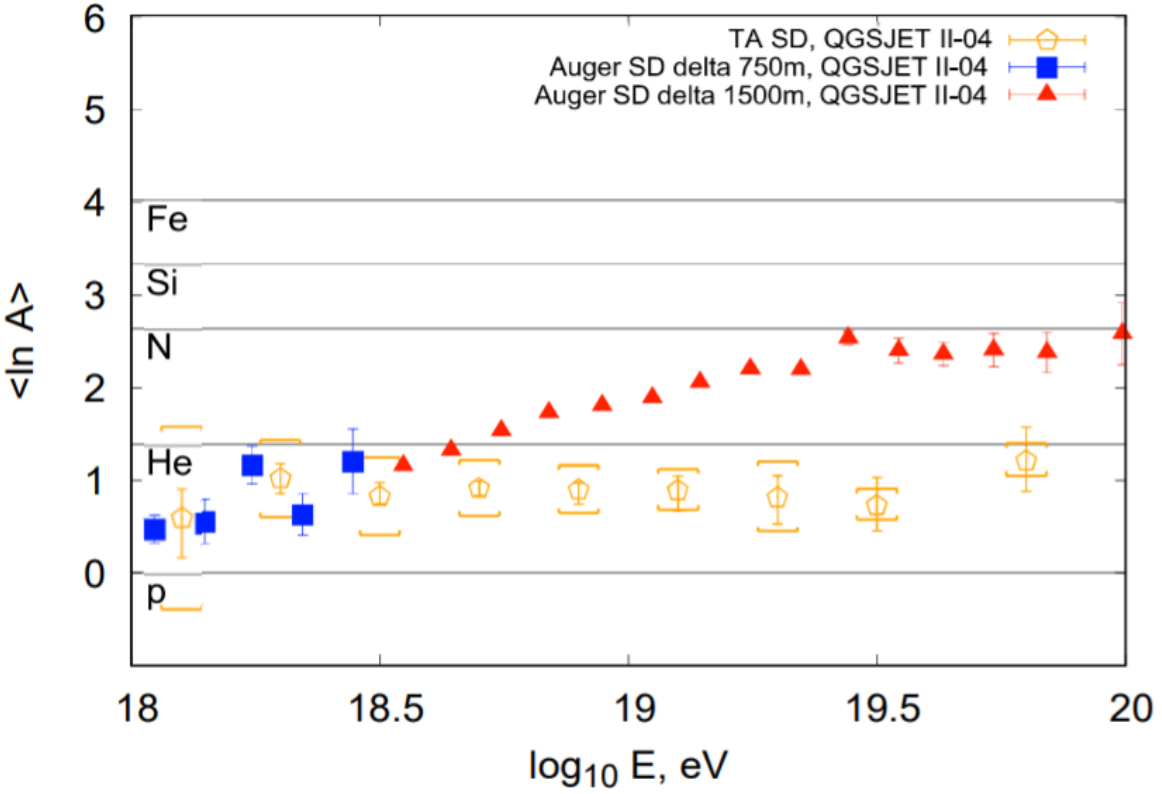
- Energy Range: $10^{18.2}$ eV – $10^{19.1}$ eV
- 3560 events after the quality cuts
- Systematic uncertainty of <Xmax>: ± 17 g/cm^2
- QGSjetII-04 interaction model was compared with the data
  → agreement with light composition
- More events are needed to study highest energies

Measurement of mass composition with TA SDs

Machine learning technique based on BDT and 16 composition-sensitive observables with 12 years of TA SD data.

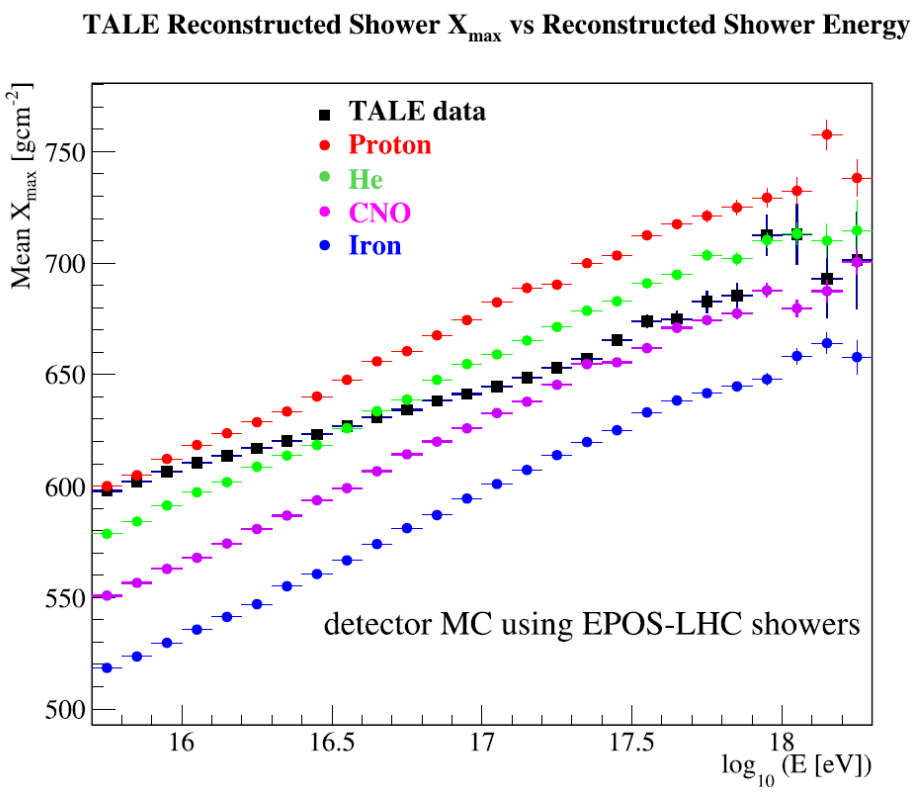
Y. Zhezher

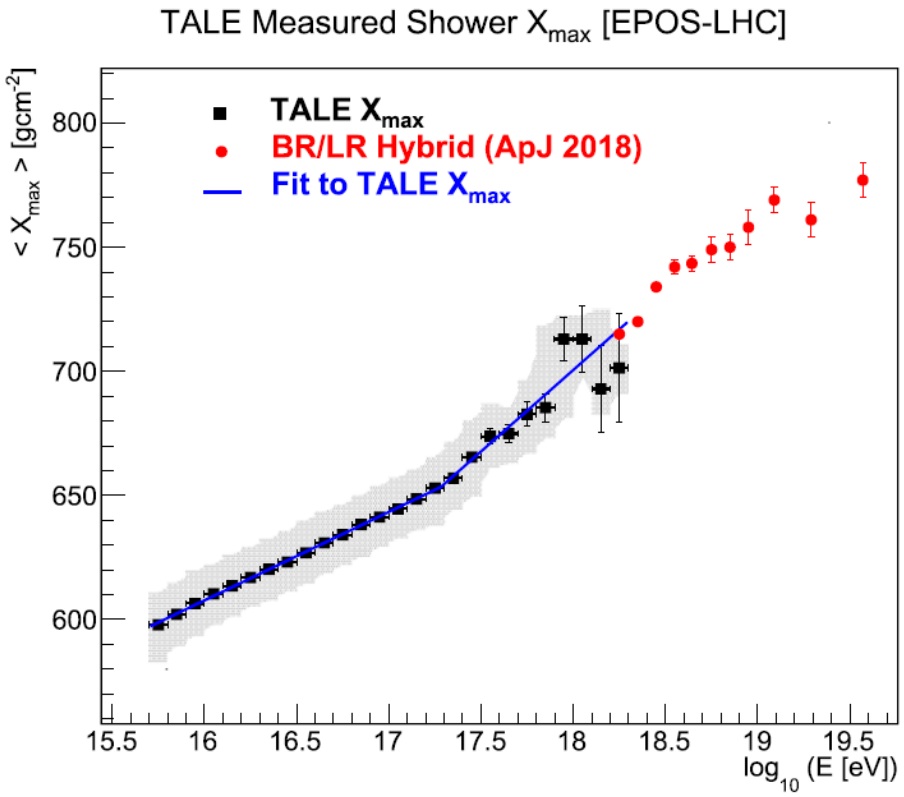




Measurement of mass composition with TALE FD in monocular mode

ApJ 909 178 (2021)

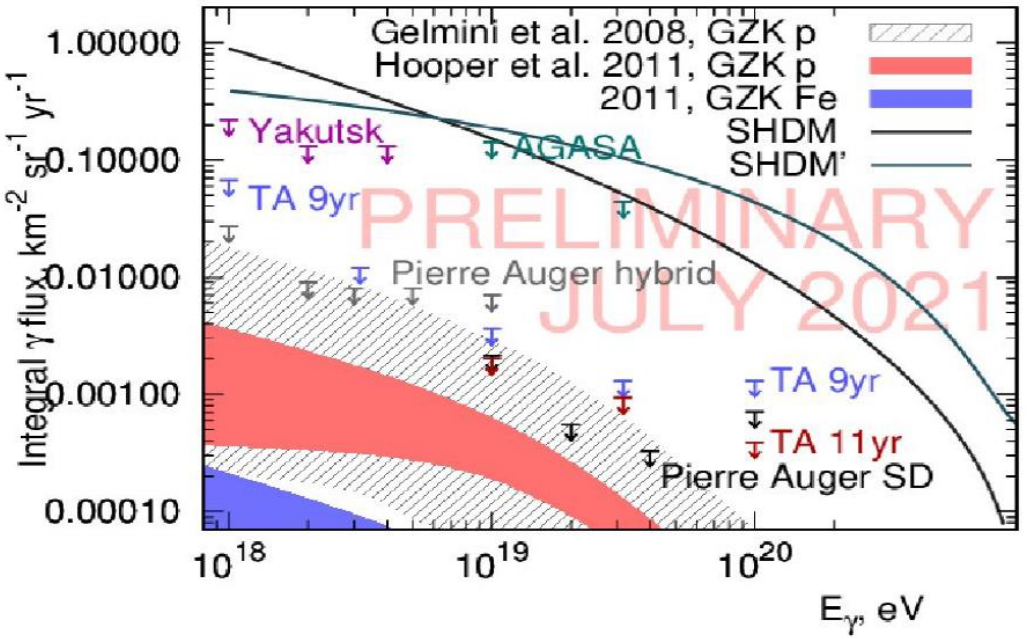




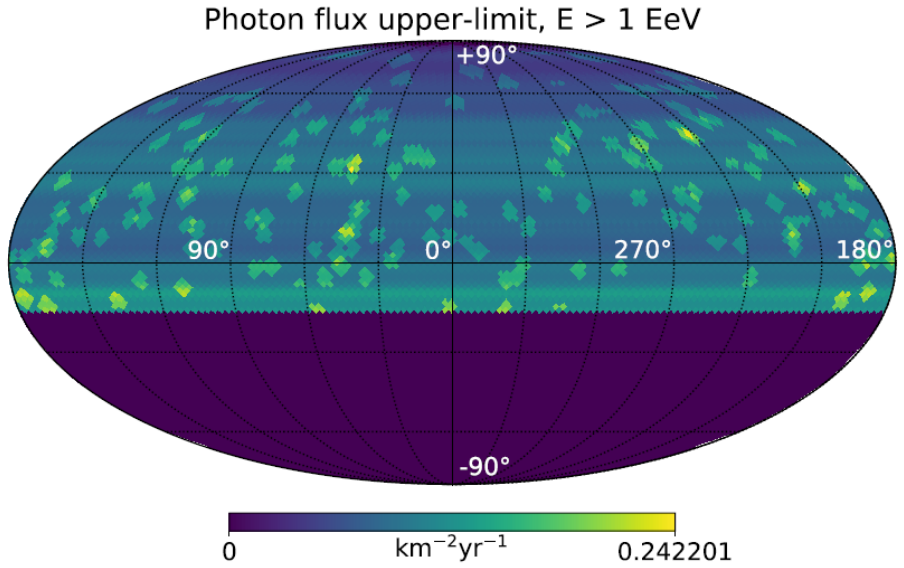
- Jun. 2014 – Nov. 2018 TALE FD mono data
- Energy Range: $10^{15.8}$ eV – $10^{18.3}$ eV
- Break point log (E/eV) = $17.291 \pm 0.060 + 0.077 - 0.084$ (EPOS LHC)

Upper limits of UHE photons

Astropart. Phys. ***110****, 8 (2019)*
updated in 2021.

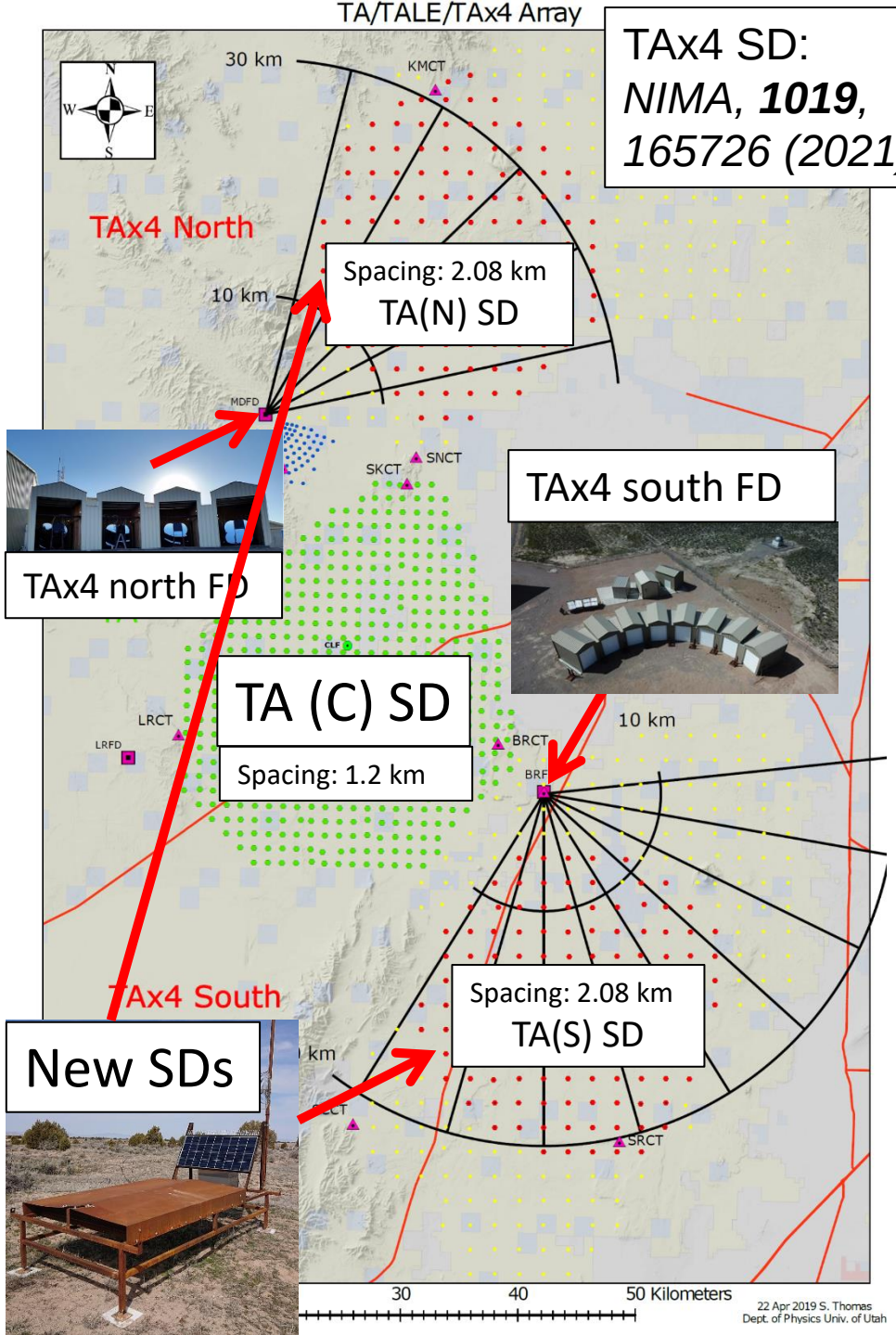


MNRAS, ***492****, 3984 (2020)*



- UHE photons were not detected.
- Left: the updated upper limit on GZK photons with 11-years TA SD data
- Right: upper limit for directions in the field of view with 9-years TA SD data

The TAx4 experiment



To examine the implications of anisotropy at the highest energies obtained by TA, TAx4 was developed to accelerate the pace of data collection at the highest energies.

500 new SDs with **2.08 km** spacing (TASD: 1.2 km spacing)

New SDs and TA SDs cover

4 × TA SD detection area (~2800 km^2)

More than half of the new SDs (**257 SDs**) were deployed in 2019.

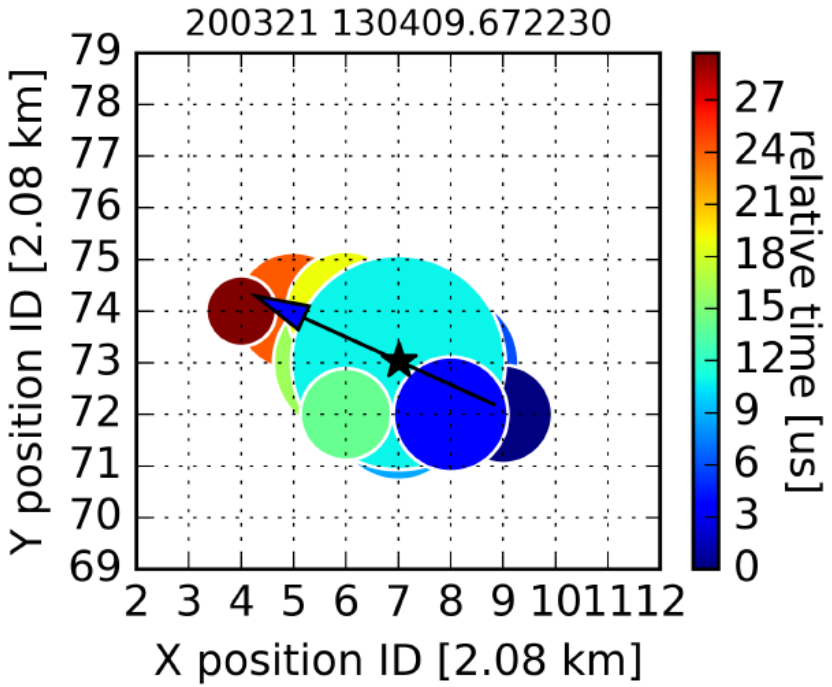
Deployed SDs are running stably from 2019 Nov.

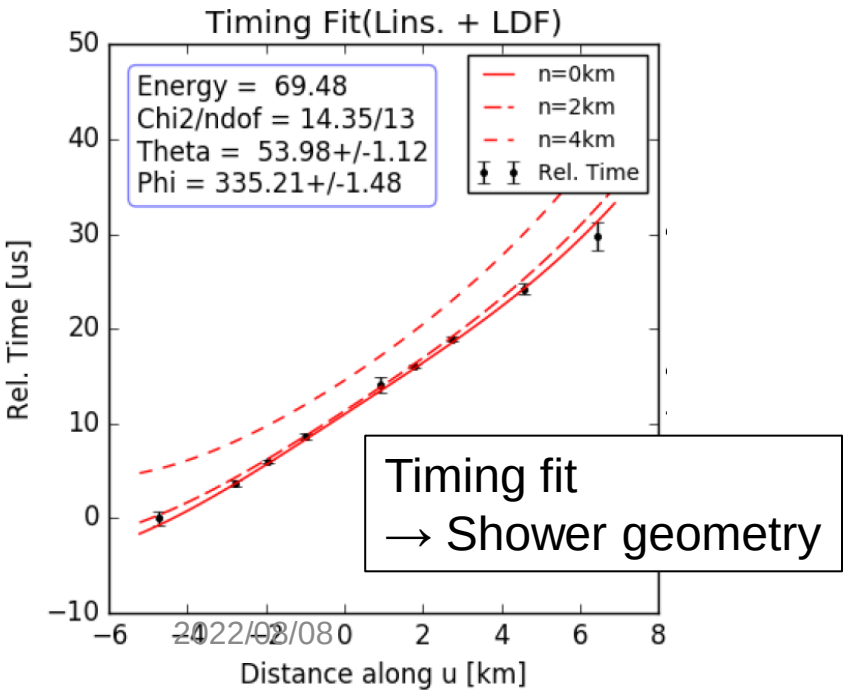
2 new Fluorescence Detector (FD) stations (4+8 HiRes Telescopes)

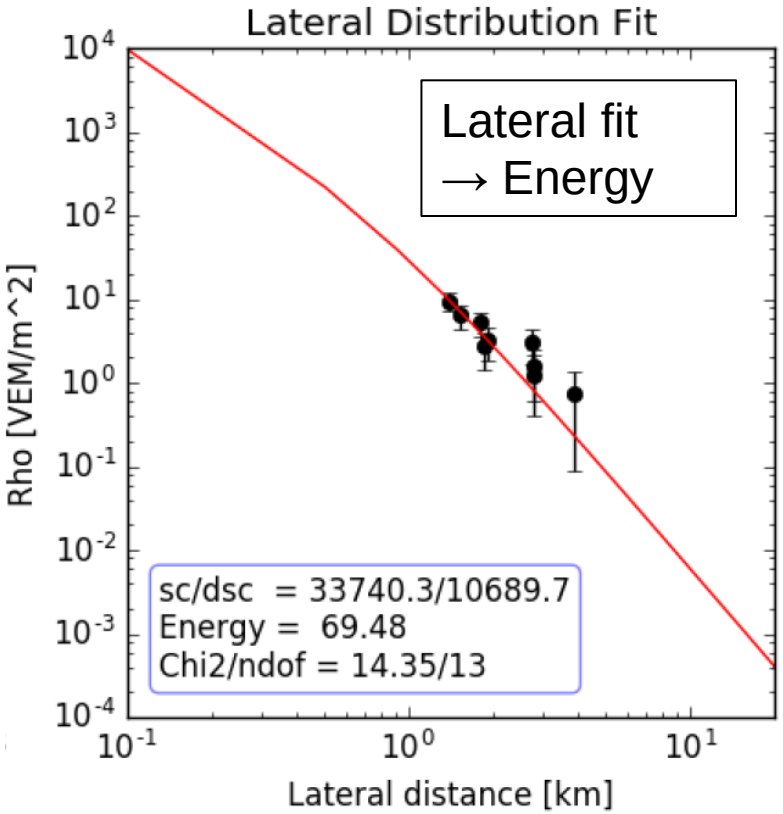
FD(north): stable run from 2018 Jun.

FD(south): stable run from 2020 Sep.

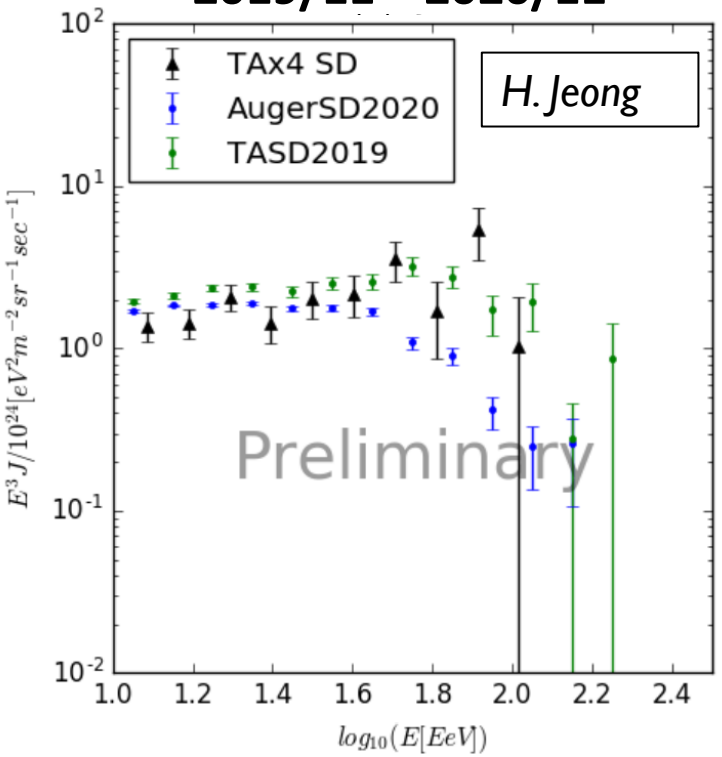
Analysis with new SDs (2.08km spacing, 257 SDs)



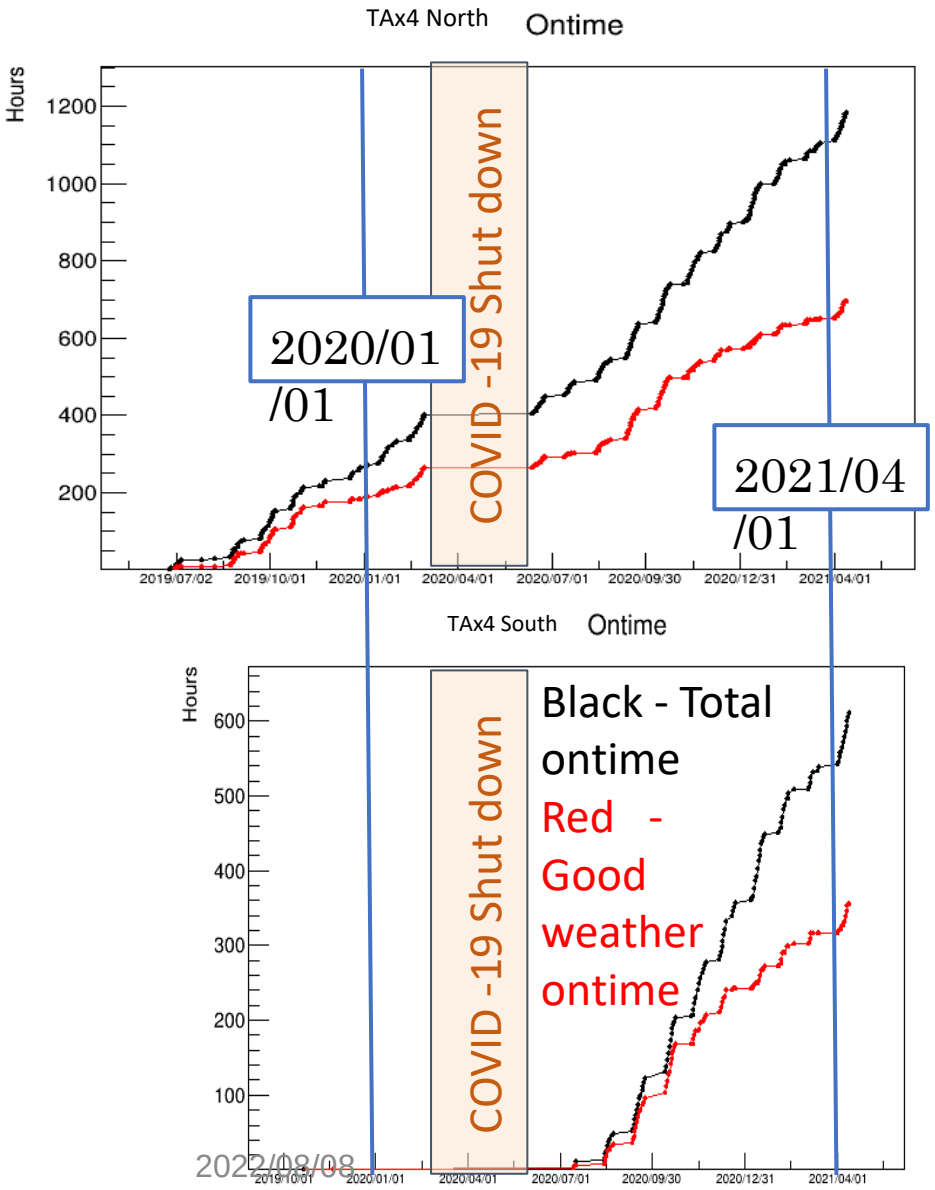




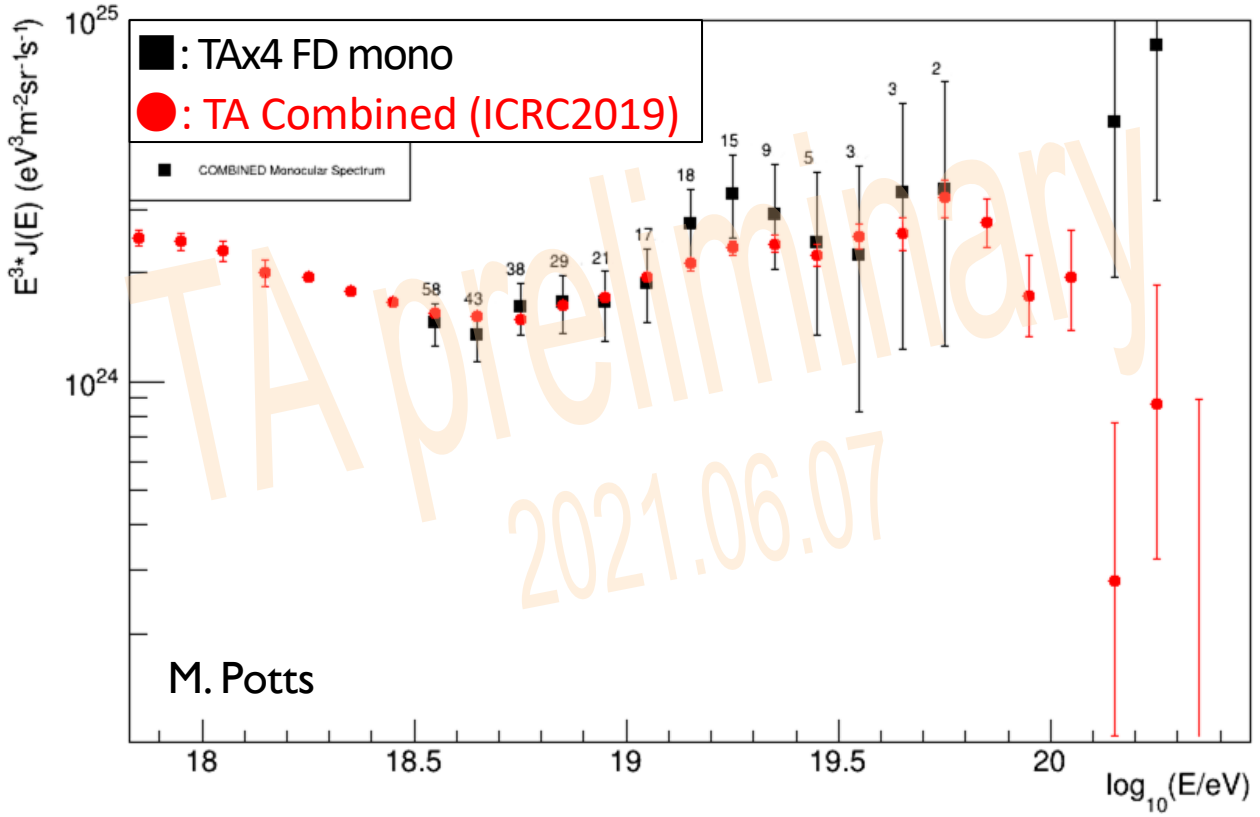
TAx4 SD 1 year data
2019/11 – 2020/11



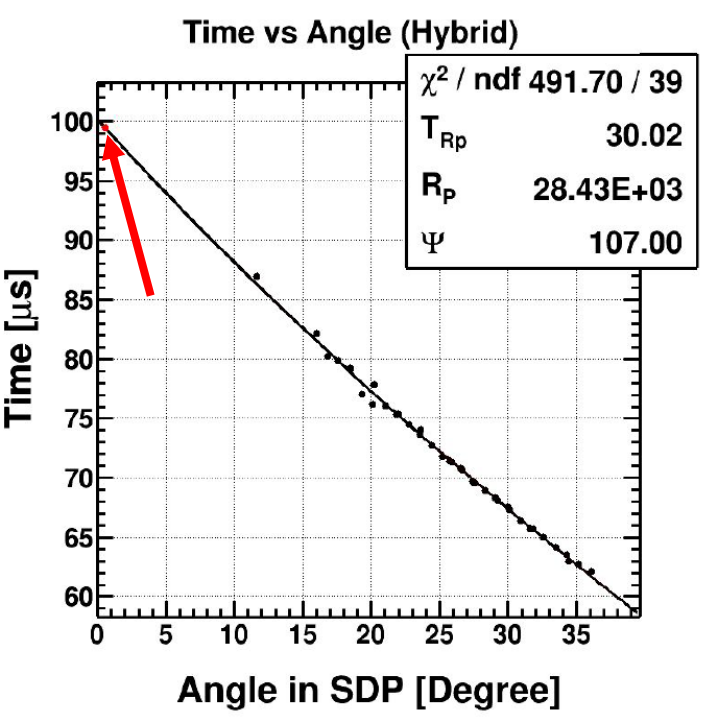
Monocular energy spectrum with new FDs

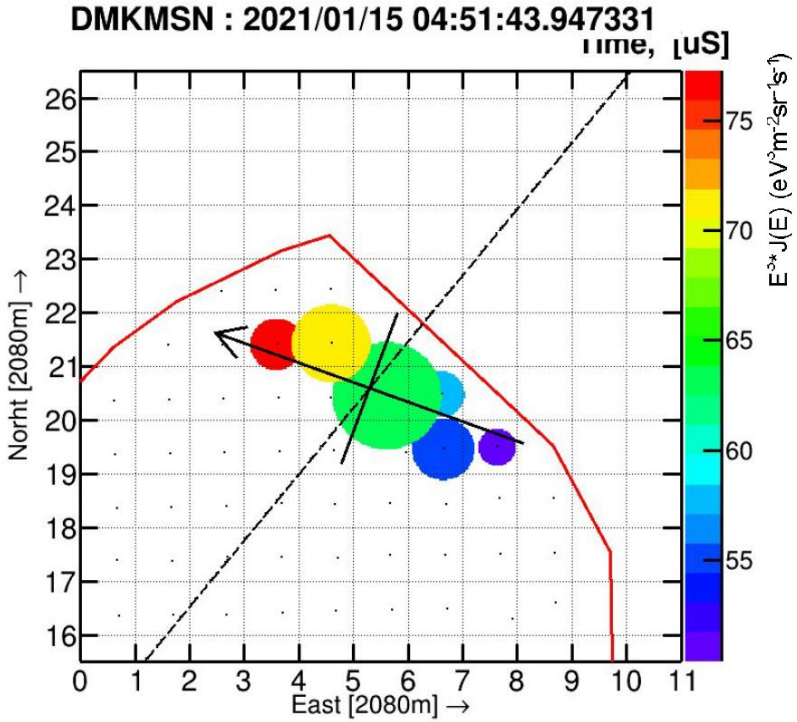


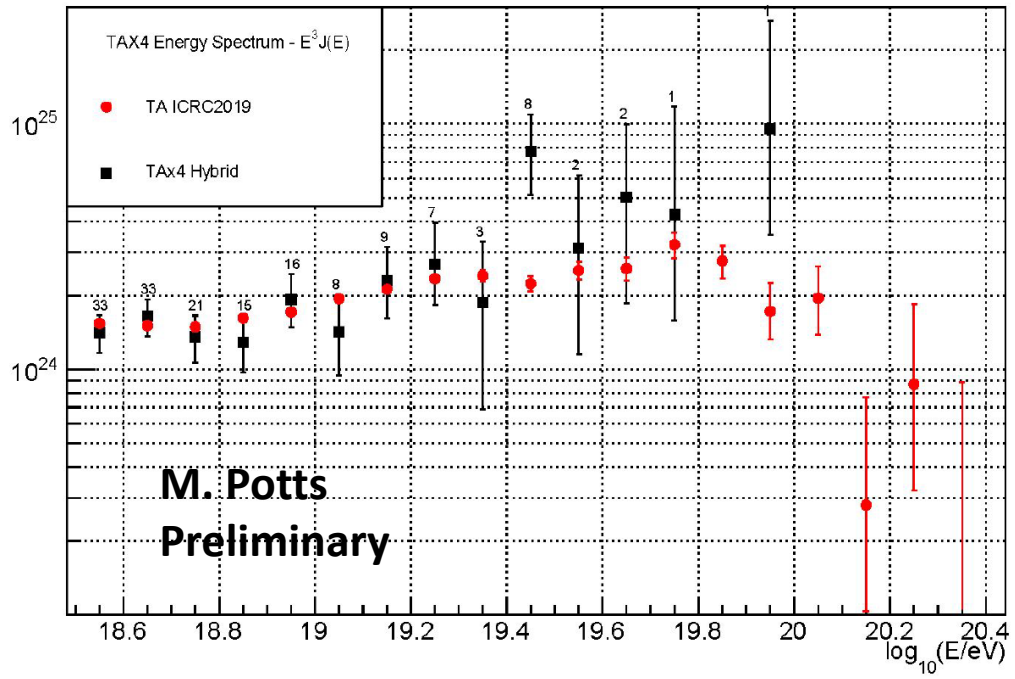
- 2019/06/26 – 2021/04/14
- Energy resolution: ~20%
- Zenith angle resolution: ~3°
- All geometrical parameters get a reasonable agreement with MC simulations.



Hybrid energy spectrum with new SDs and FDs





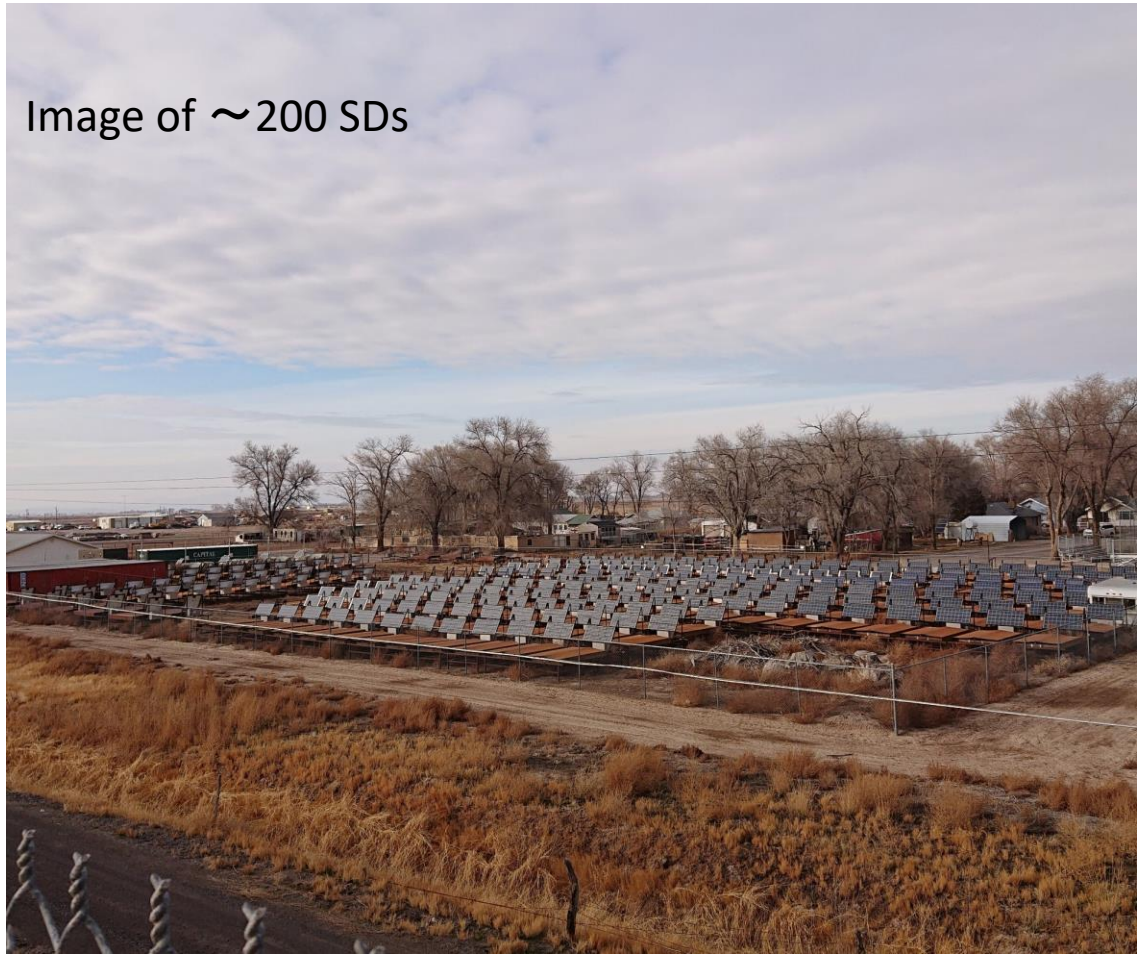


TAx4 SD trigger condition: ～30% efficiency at around 10 EeV

→ **Hybrid triggers** have been stably operated from **June 2020**.
FDs send the trigger timing to the communication towers of the SDs within +/- 128 usec time window.

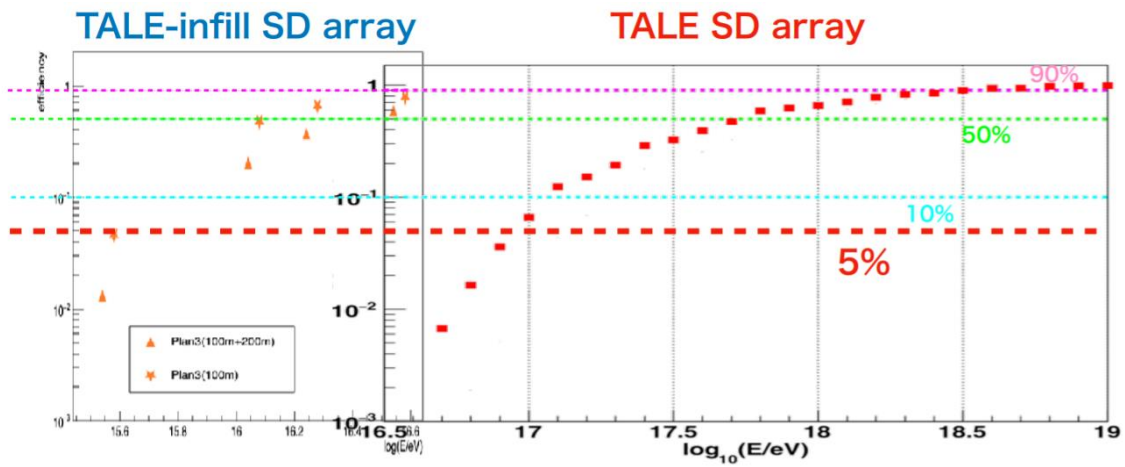
→ **～3 × TA SDFD equivalent number of events** (E > 10 EeV) expected from the full TAx4

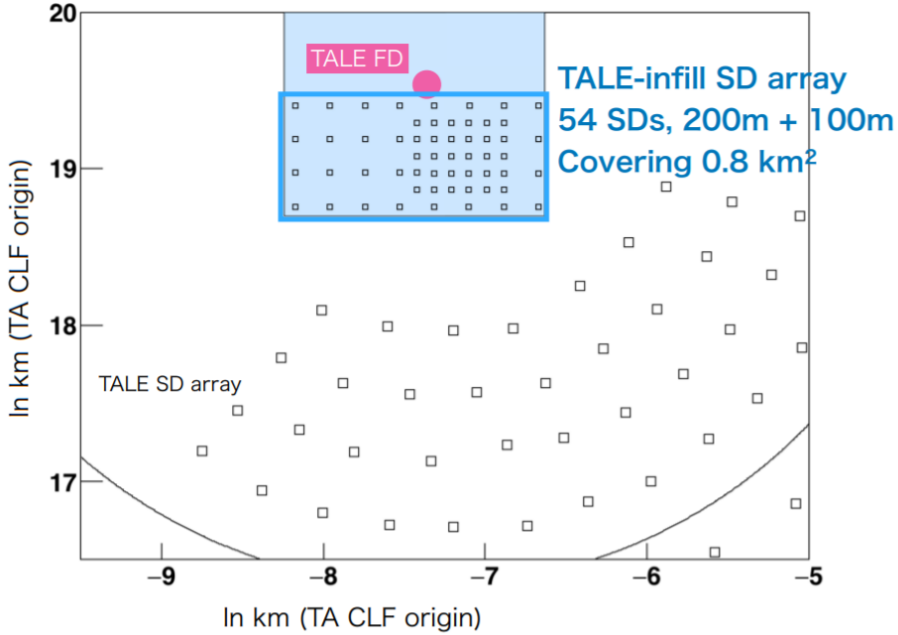
Future prospects: the TAx4 experiment



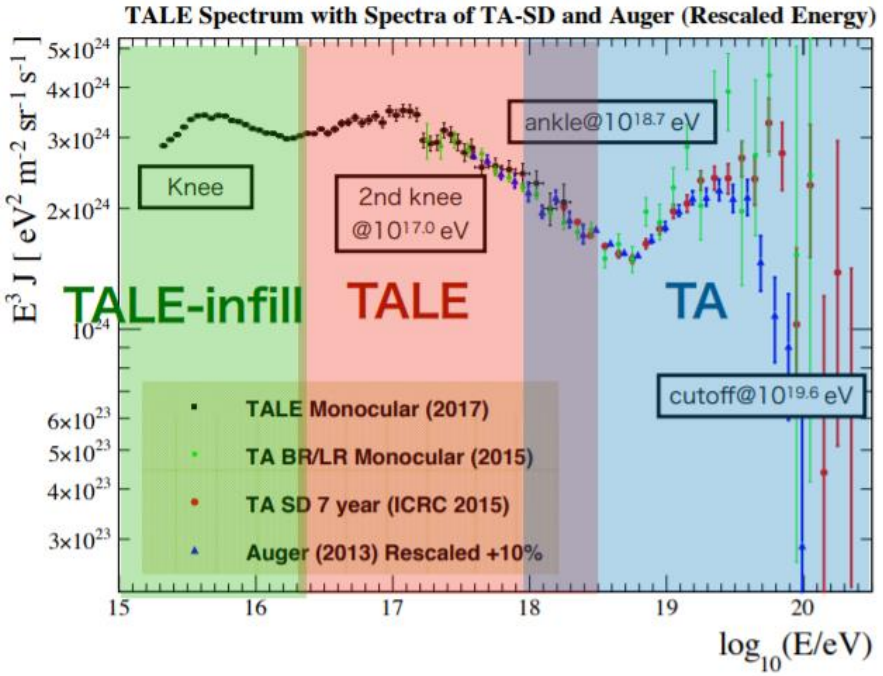
- We plan to deploy the remaining 250 SDs to realize the full TAx4 coverage in 2023-2024.
- We are investigating the analyses of anisotropies and compositions with new detectors.

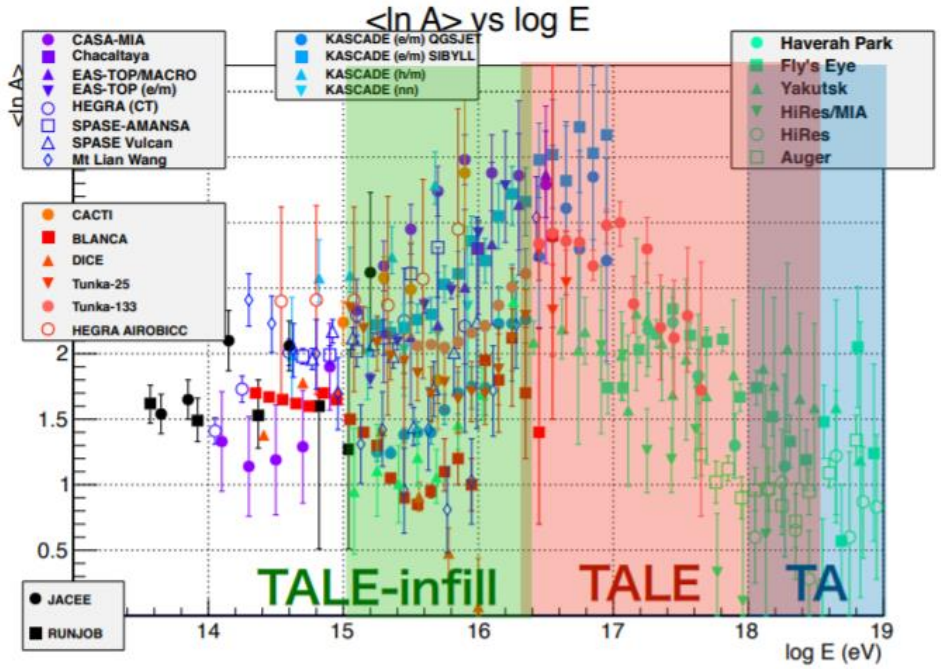
Extension of TALE SD: TALE-infill





Ap. J., 865, 74(2018), arXiv: 1803.01288





S. Ogio

54 SDs will be deployed this winter.

Summary

- The TA experiment continue to observe UHECRs from 2008 with the largest detection area in the northern hemisphere.
- Arrival directions
  - **3.2σ** hotspot with E > **57** EeV was obtained using TASD 12 years data
  - **3.5σ** excess with E > $\mathbf{10^{19.4}}$eV was obtained using TASD 11 years data
  - Correlation with a sample of **Starburst Galaxies** at **4.2σ** confidence level obtained by the Auger and TA working group.
- Energy Spectrum
  - Declination dependence was claimed at **4.3σ** in the energy spectrum using TASD 11 years data
- Mass composition
  - TA SD and FD hybrid: consistent with light composition with 18.2 < log (E/eV) < 19.1. More events at the highest energies are needed.
  - TA SD: Analysis was conducted for 18.0 < log (E/eV). More events at the highest energies are also needed.
  - TALE FD mono.: Xmax results were obtained with log (E/eV) > 15.3.
  - Upper limits of photons are being updated.
- **Implications of anisotropy are being updated by the TA experiment.**
- Plan of the detectors of the TAx4 experiment:
  - **500 new** SDs with **2.08 km** spacing + TA SDs (1.2 km spacing) → Coverage of **4 × TA SDs ～2800 km^2**
  - **2 new** Fluorescence Detector (FD) stations (4+8 Telescopes)
- **257 new SDs** were deployed in 2019. The SDs are running stably since Nov. 2019.
- **New FDs were completed.** New north FD is running stably since Jun. 2018. New south FD is running stably since Sep. 2020.
- The extension of the SDs to the full coverage of TAx4 is scheduled for 2023 and 2024.
- Preliminary energy spectra were measured with new SDs, FDs, and SD FD hybrid.
- Anisotropies and compositions will be analyzed using the data obtained with new detectors.