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RIKEN Cluster for Pioneering
Research

Latest results and future prospects of the Telescope Array experiment



2022/7/20



COSPAR2022@Athens



Outline

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

Telescope Array Collaboration

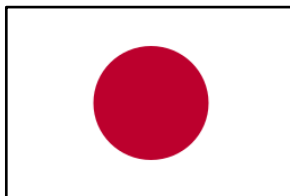
R.U. Abbasi^{1,2}, M. Abe³, T. Abu-Zayyad^{1,2}, M. Allen², Y. Arai⁴, R. Arimura⁴, E. Barcikowski², J.W. Belz², D.R. Bergman², S.A. Blake², I. Buckland², R. Cady², B.G. Cheon⁵, J. Chiba⁶, M. Chikawa⁷, T. Fujii⁸, K. Fujisue⁷, K. Fujita⁴, R. Fujiwara⁴, M. Fukushima⁷, R. Fukushima⁴, G. Furlich², R. Gonzalez², W. Hanlon², M. Hayashi⁹, N. Hayashida¹⁰, K. Hibino¹⁰, R. Higuchi⁷, K. Honda¹¹, D. Ikeda¹⁰, T. Inadomi¹², N. Inoue³, T. Ishii¹¹, H. Ito¹³, D. Ivanov², H. Iwakura¹², A. Iwasaki⁴, H.M. Jeong¹⁴, S. Jeong¹⁴, C.C.H. Jui², K. Kadota¹⁵, F. Kakimoto¹⁰, O. Kalashev¹⁶, K. Kasahara¹⁷, S. Kasami¹⁸, H. Kawai¹⁹, S. Kawakami⁴, S. Kawana³, K. Kawata⁷, I. Kharuk¹⁶, E. Kido¹³, H.B. Kim⁵, J.H. Kim², J.H. Kim², M.H. Kim¹⁴, S.W. Kim¹⁴, Y. Kimura⁴, S. Kishigami⁴, Y. Kubota¹², S. Kurisu¹², V. Kuzmin¹⁶, M. Kuznetsov^{16,20}, Y.J. Kwon²¹, K.H. Lee¹⁴, B. Lubsandorzhiev¹⁶, J.P. Lundquist^{2,22}, K. Machida¹¹, H. Matsumiya⁴, T. Matsuyama⁴, J.N. Matthews², R. Mayta⁴, M. Minamino⁴, K. Mukai¹¹, I. Myers², S. Nagataki¹³, K. Nakai⁴, R. Nakamura¹², T. Nakamura²³, T. Nakamura¹², Y. Nakamura¹², A. Nakazawa¹², T. Nonaka⁷, H. Oda⁴, S. Ogio^{4,24}, M. Ohnishi⁷, H. Ohoka⁷, Y. Oku¹⁸, T. Okuda²⁵, Y. Omura⁴, M. Ono¹³, R. Onogi⁴, A. Oshima⁴, S. Ozawa²⁶, I.H. Park¹⁴, M. Potts², M.S. Pshirkov^{16,27}, J. Remington², D.C. Rodriguez², G.I. Rubtsov¹⁶, D. Ryu²⁸, H. Sagawa⁷, R. Sahara⁴, Y. Saito¹², N. Sakaki⁷, T. Sako⁷, N. Sakurai⁴, K. Sano¹², K. Sato⁴, T. Seki¹², K. Sekino⁷, P.D. Shah², Y. Shibasaki¹², F. Shibata¹¹, N. Shibata¹⁸, T. Shibata⁷, H. Shimodaira⁷, B.K. Shin²⁸, H.S. Shin⁷, D. Shinto¹⁸, J.D. Smith², P. Sokolsky², N. Sone¹², B.T. Stokes², T.A. Stroman², T. Suzawa³, Y. Takagi⁴, Y. Takahashi⁴, M. Takamura⁶, M. Takeda⁷, R. Takeishi⁷, A. Taketa²⁹, M. Takita⁷, Y. Tameda¹⁸, H. Tanaka⁴, K. Tanaka³⁰, M. Tanaka³¹, Y. Tanoue⁴, S.B. Thomas², G.B. Thomson², P. Tinyakov^{16,20}, I. Tkachev¹⁶, H. Tokuno³², T. Tomida¹², S. Troitsky¹⁶, R. Tsuda⁴, Y. Tsunesada^{4,24}, Y. Uchihori³³, S. Udo¹⁰, T. Uehama¹², F. Urban³⁴, T. Wong², K. Yada⁷, M. Yamamoto¹², K. Yamazaki¹⁰, J. Yang³⁵, K. Yashiro⁶, F. Yoshida¹⁸, Y. Yoshioka¹², Y. Zhezher^{7,16}, and Z. Zundel²

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⁷ University of Tokyo (ICRR) ⁸ Kyoto University ⁹ Shinshu University ¹⁰ Kanagawa University ¹¹ University of Yamanashi ¹² Shinshu University (Inst. of Engineering) ¹³ RIKEN ¹⁴ Sungkyunkwan University ¹⁵ Tokyo City University ¹⁶ Institute for Nuclear Research of the Russian Academy of Sciences ¹⁷ Shibaura Institute of Technology ¹⁸ Osaka Electro-Communication University ¹⁹ Chiba University ²⁰ Université Libre de Bruxelles ²¹ Yonsei University ²² University of Nova Gorica ²³ Kochi University ²⁴ Osaka City University (Nambu Yoichiro Institute) ²⁵ Ritsumeikan University ²⁶ National Inst. for Information and Communications Technology, Tokyo ²⁷ Lomonosov Moscow State University ²⁸ Ulsan National Institute of Science and Technology ²⁹ University of Tokyo (Earthquake Inst.) ³⁰ Hiroshima City University ³¹ KEK ³² Tokyo Institute of Technology ³³ National Inst. for Quantum and Radiological Science and Technology ³⁴ CEICO, Institute of Physics, Czech Academy of Sciences ³⁵ Ewha Womans University

161 members , 35 institutes, 7 countries



USA



Japan



Korea



Russia



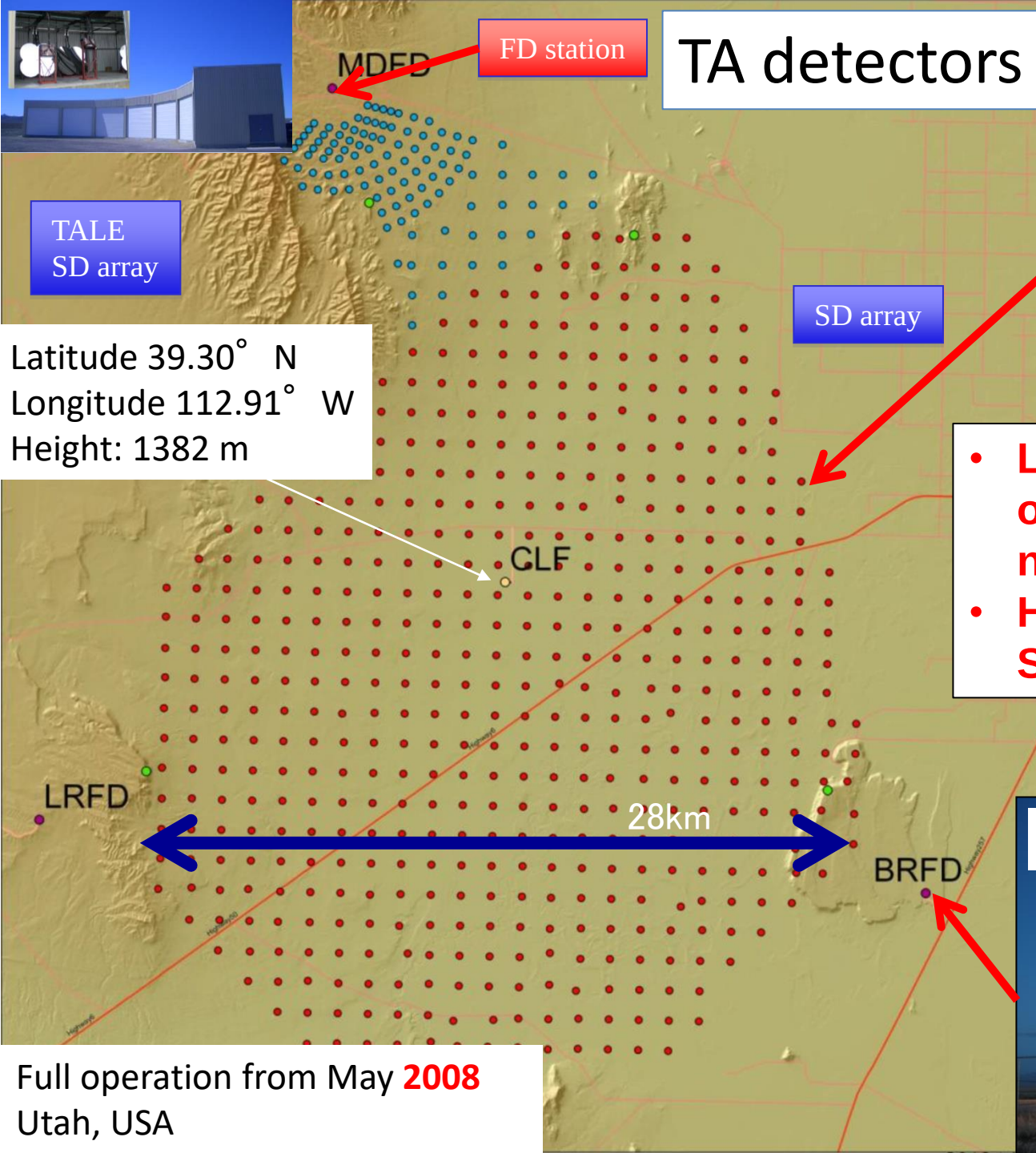
Belgium



Czech Republic



Slovenia



TA detectors

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



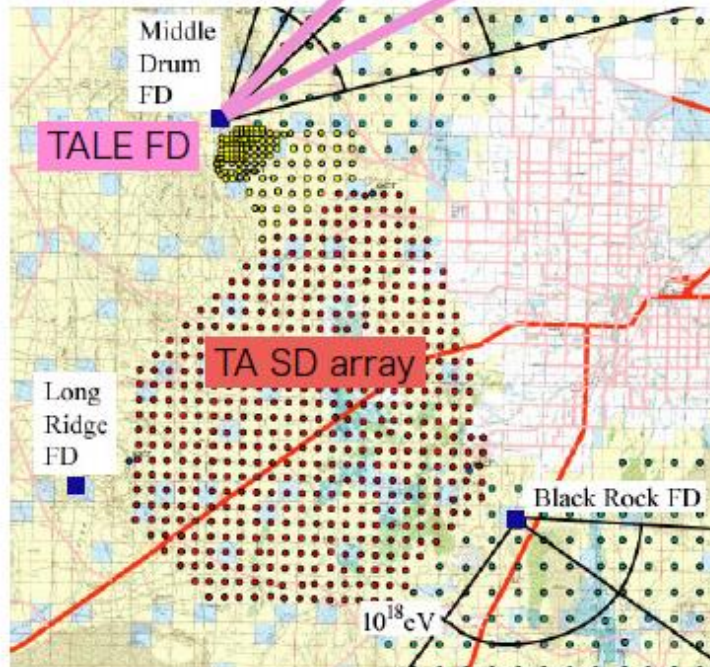
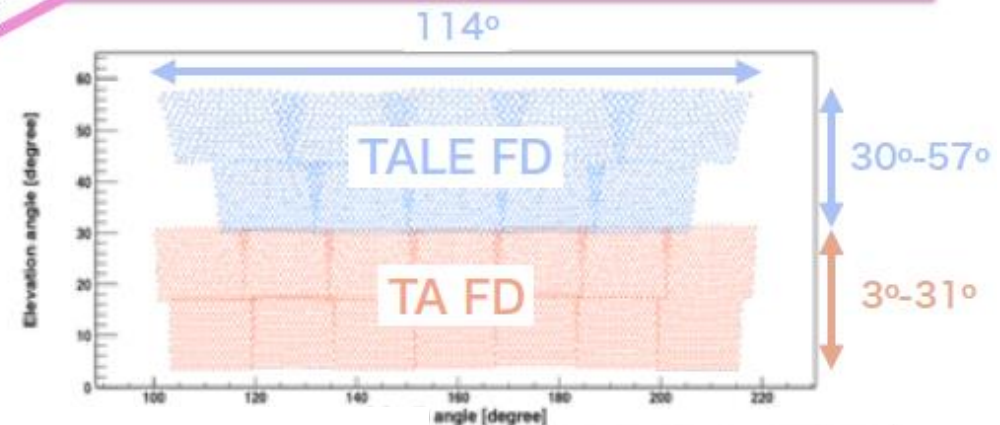
12 telescopes

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

Middle Drum station



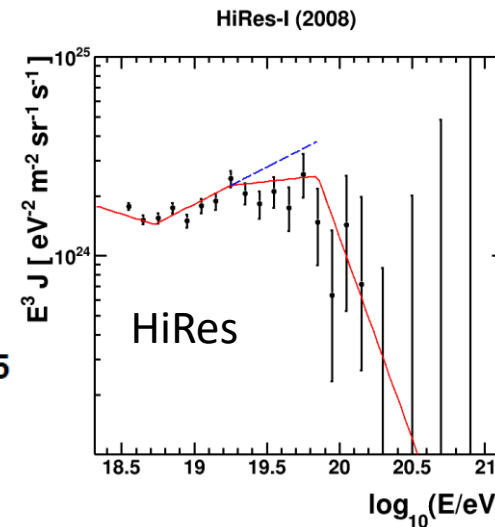
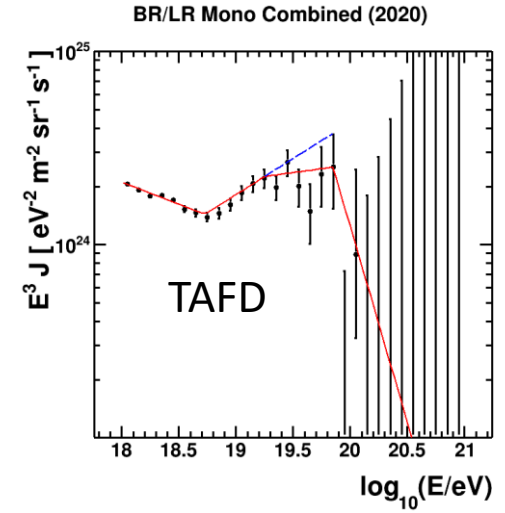
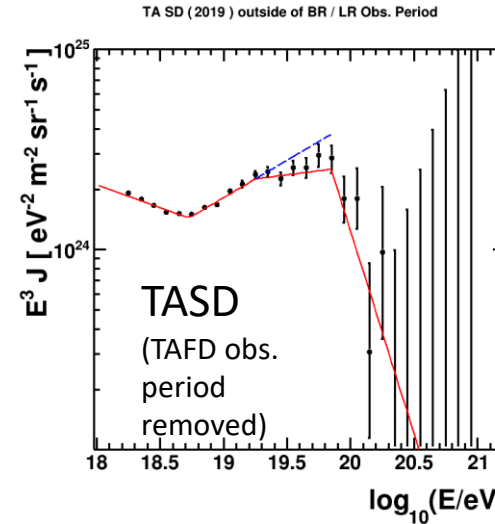
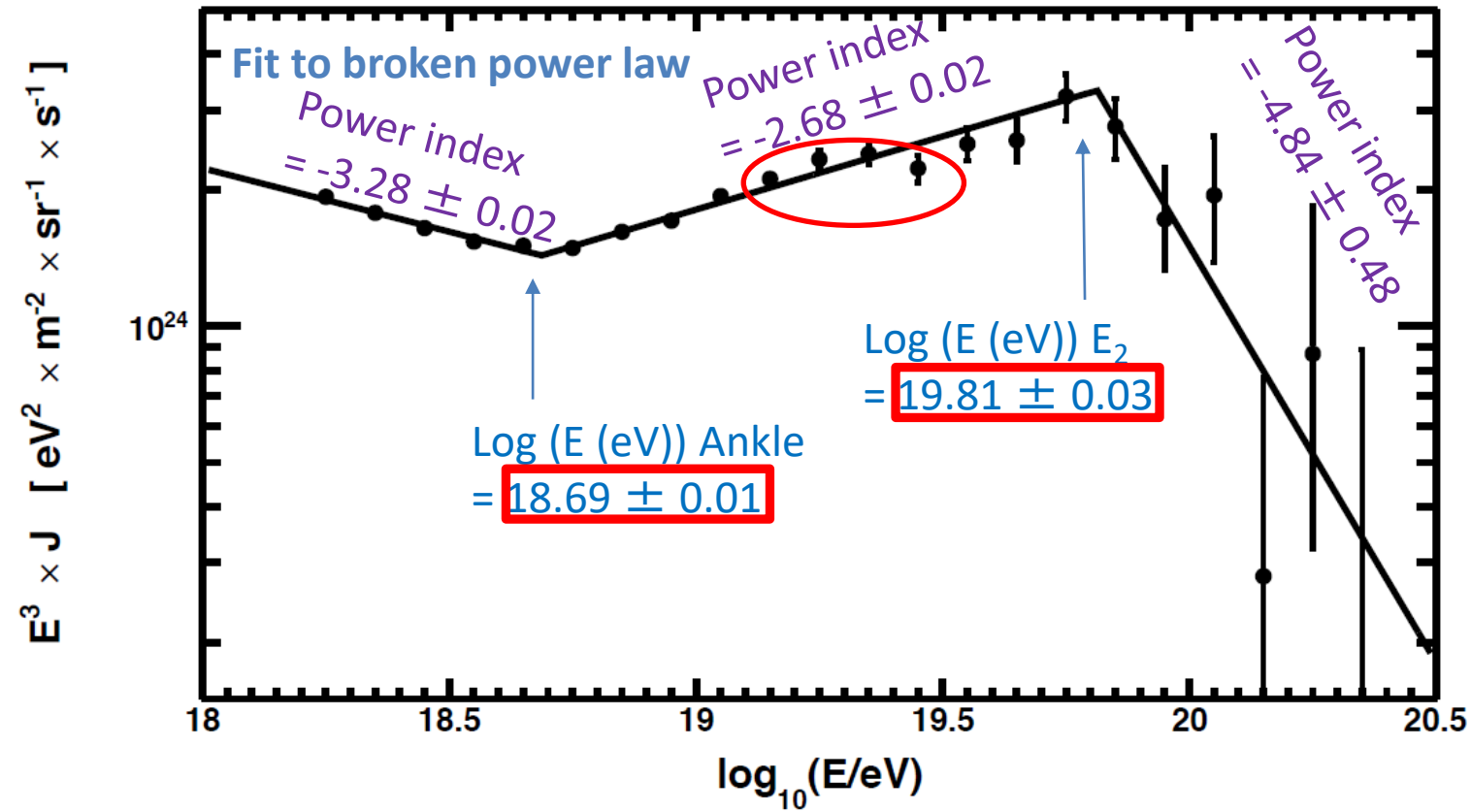
TALE FD was
installed in Nov. 2012
Operation since Sep. 2013
Hybrid trigger: Sep. 2018



Energy spectra

D. Ivanov

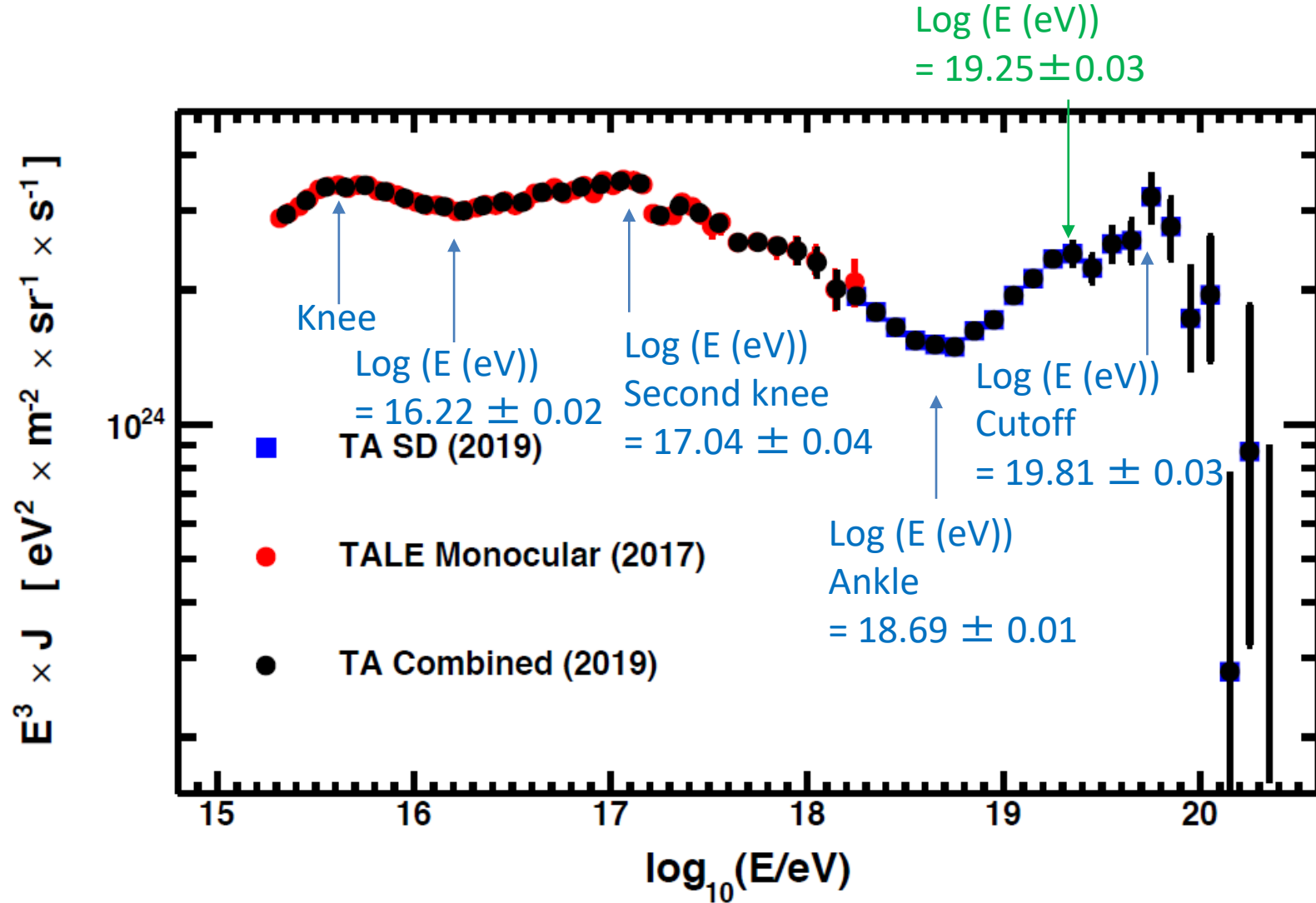
TA SD 11 years data



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

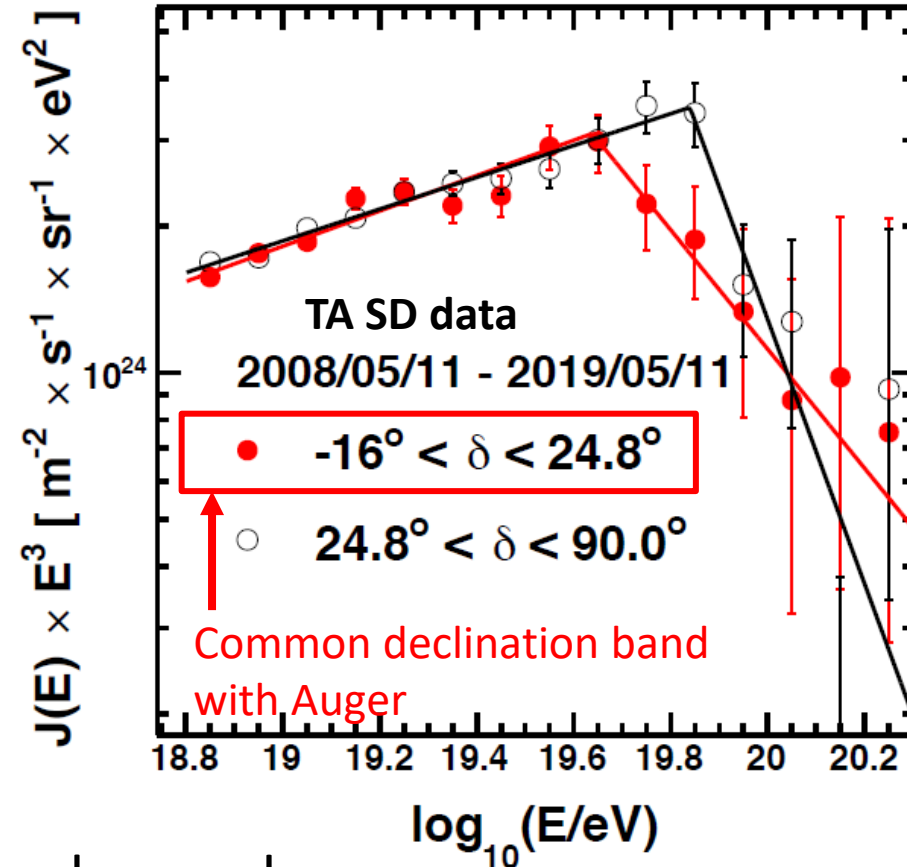
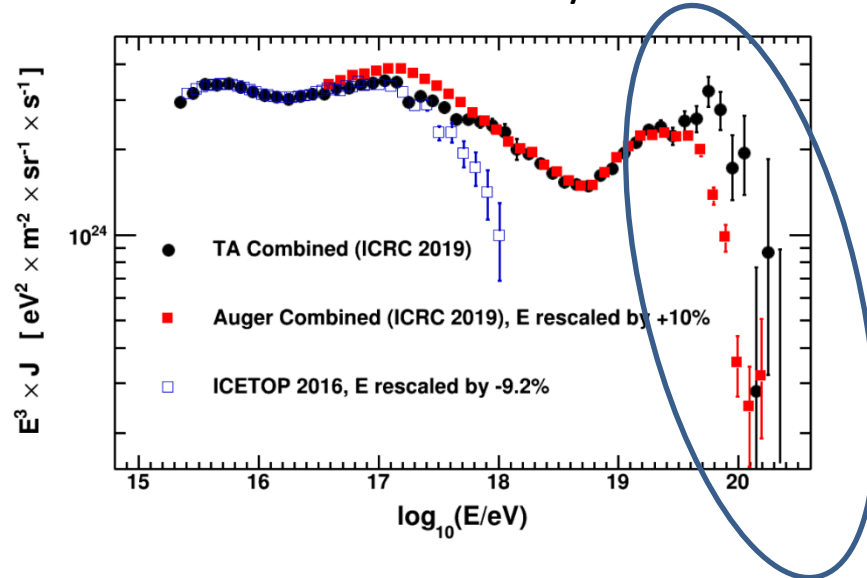


Combined TA spectrum using
22 months TALE FD monocular data +
11 years TA SD data

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
 - $\log(E/\text{eV}) = 19.64 \pm 0.04$ lower declination band ($-16^\circ - 24.8^\circ$)
 - $\log(E/\text{eV}) = 19.84 \pm 0.02$ higher declination band ($24.8^\circ - 90^\circ$)
- Significance of the cutoff energies $\sim 4.3\sigma$

$E > 57$ EeV TA hotspot

J.H. Kim

TA SD 12 years data

Original hotspot reported in 2014,
from 5 years of data

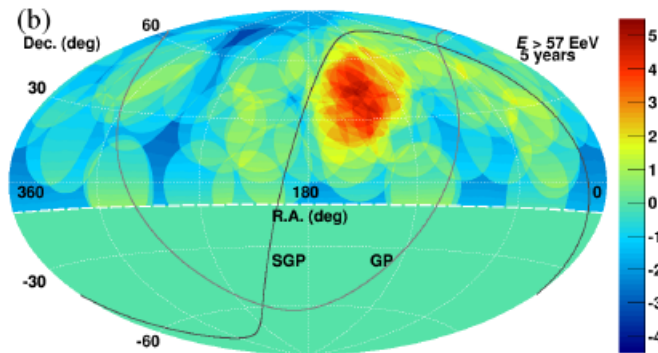
Ap. J., 790, L21(2014)

$E > 57$ EeV (Observed 72 events)

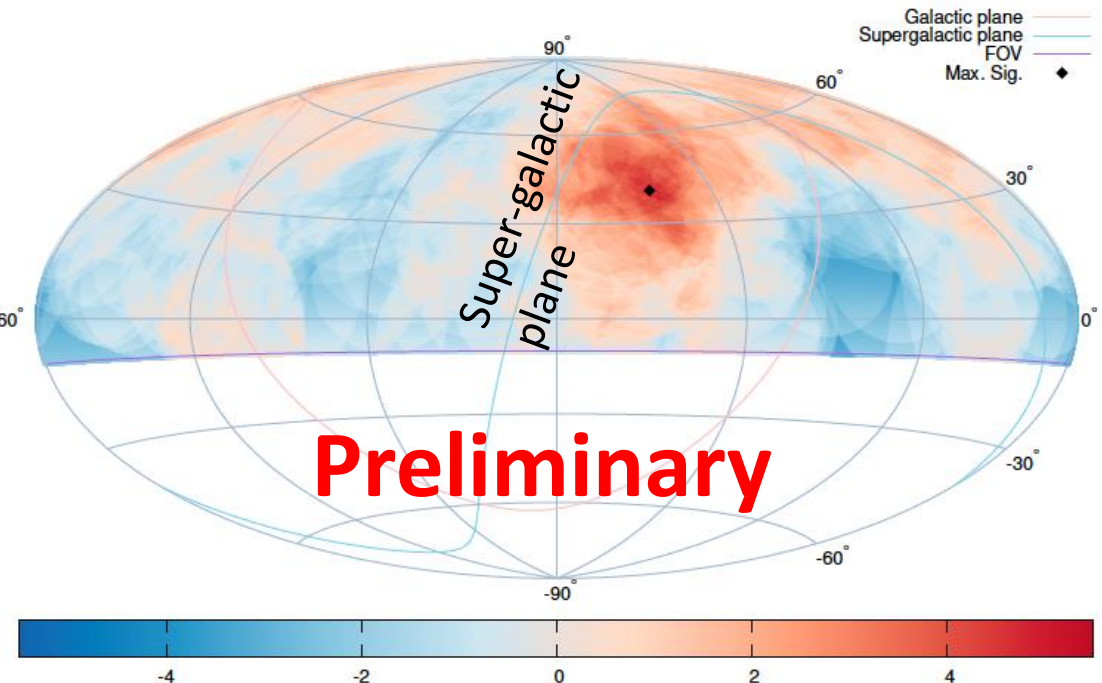
20° over-sampling circle

19 events fall in "Hotspot" centered at $(146.7^\circ, 43.2^\circ)$
(Expected = 4.5 events)

local significance 5.1σ , post trial significance 3.4σ



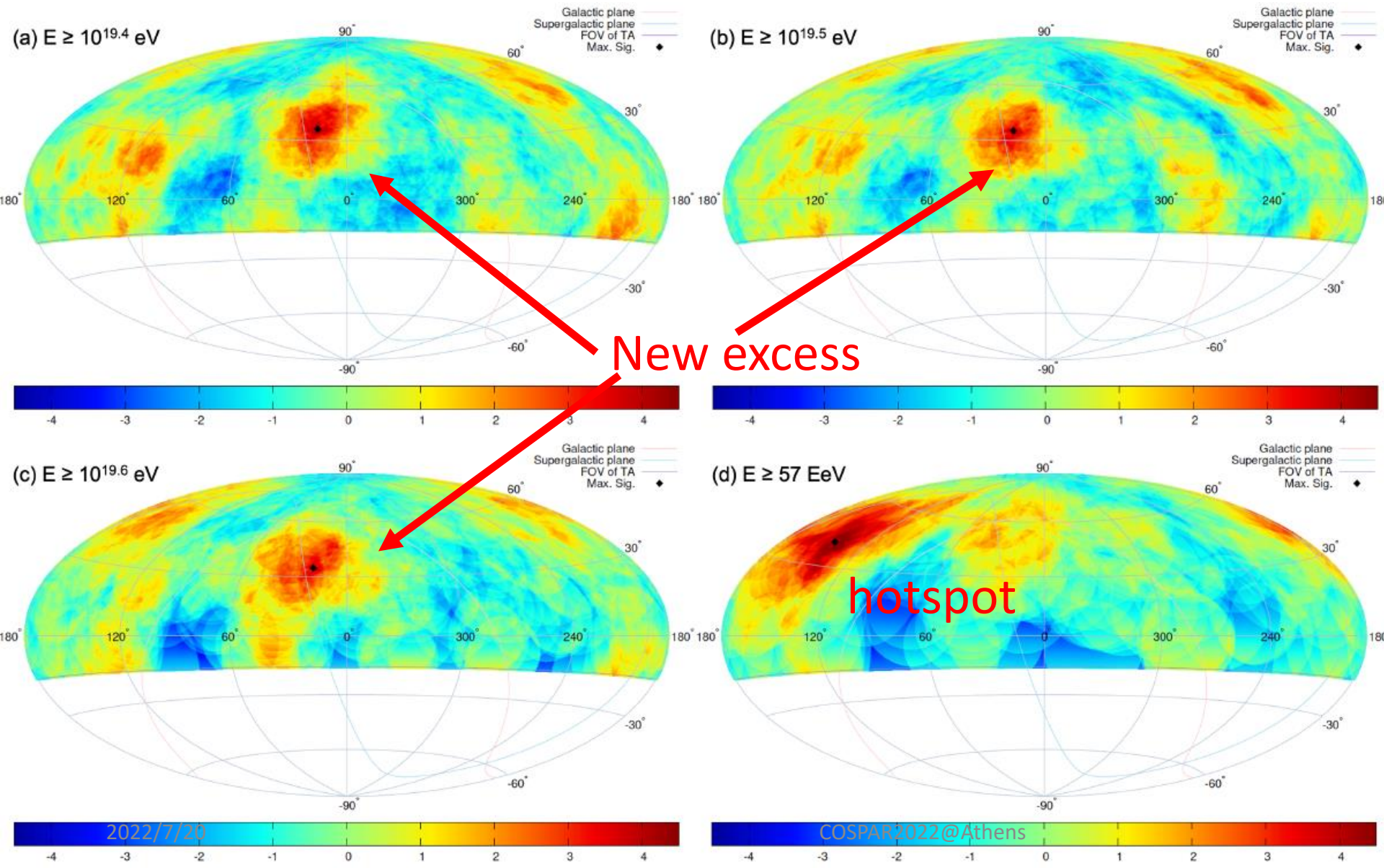
Significance map from isotropy expectation



Equatorial coordinate

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

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



arXiv: 2110.14827

Excess was observed at lower energies than TA hotspot

Significance of the excess

For $E \geq 10^{19.4}$, 3.6σ

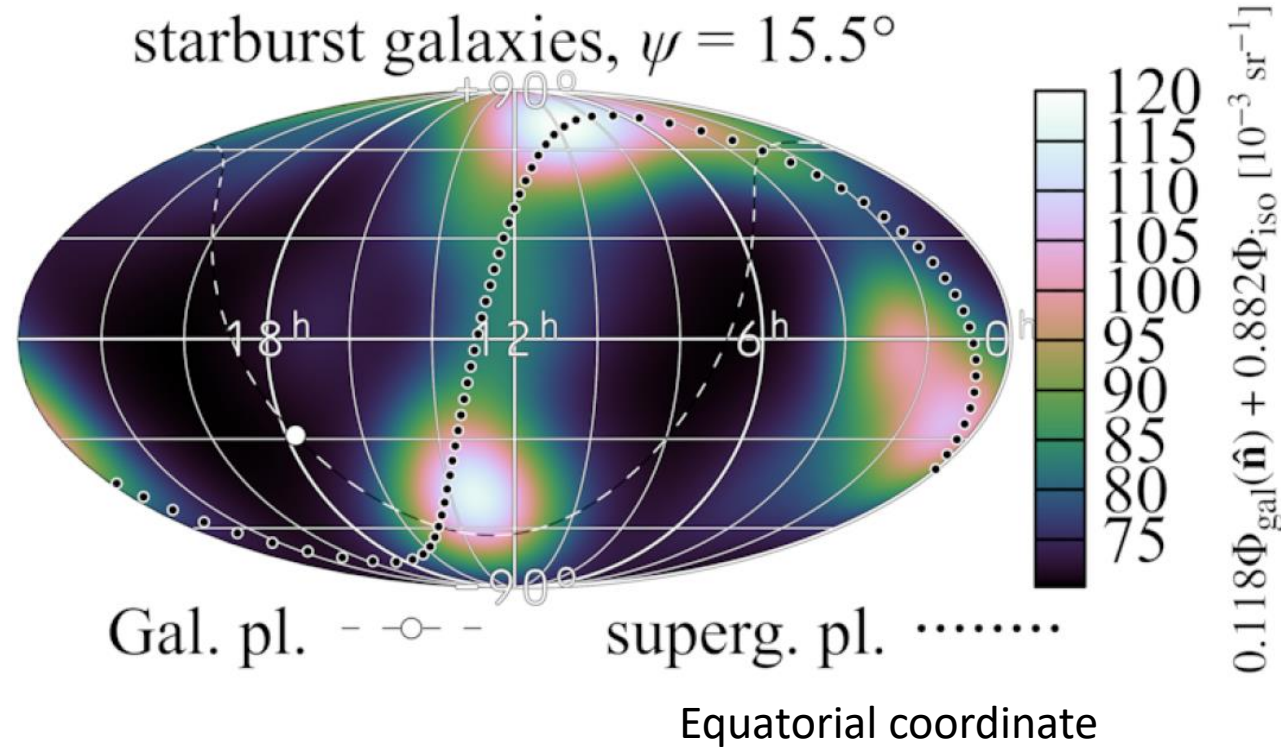
For $E \geq 10^{19.5}$ eV, 3.6σ

For $E \geq 10^{19.6}$ eV, 3.4σ

(20 degrees oversampling radius)
11 years TA SD data

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

A. di Matteo



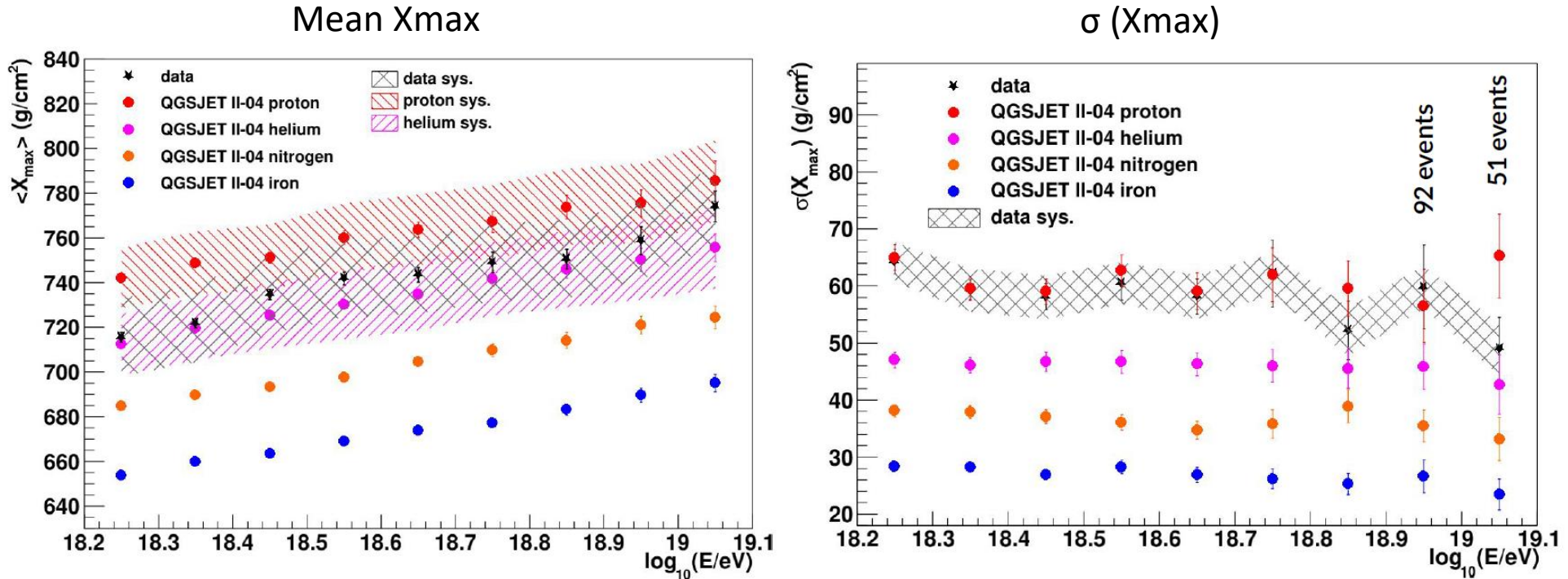
- Auger: $E > 38 \text{ EeV}$
- TA: $E > 49 \text{ EeV}$
- Correlations with a sample of nearby starburst galaxies and 2MRS catalog galaxies.
- Angular scales and energy thresholds were scanned.
- Post-trial significance of the correlation with **starburst galaxies** is estimated to be **4.2σ** .

Rescale of energies

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

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

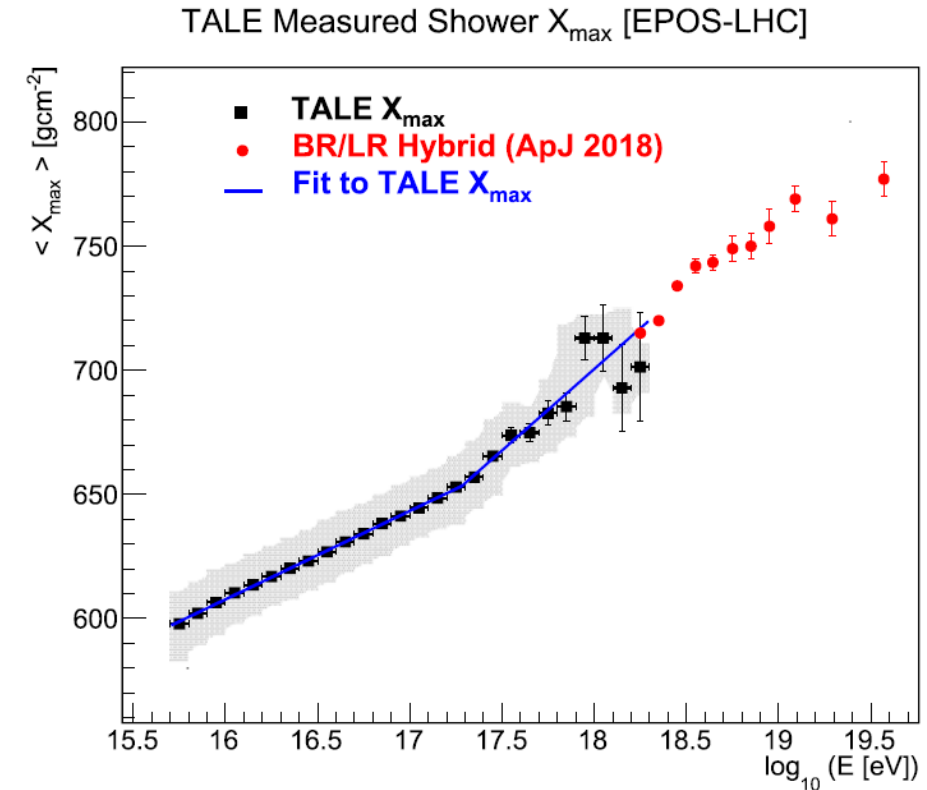
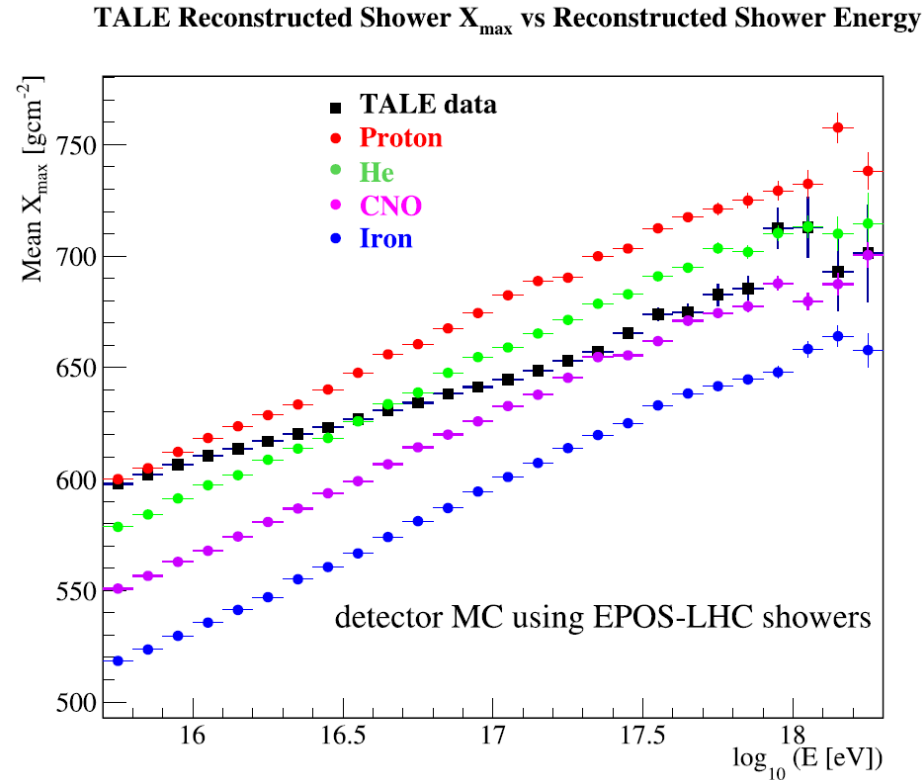
W. Hanlon



- Energy Range: $10^{18.2} \text{ eV} - 10^{19.1} \text{ eV}$
- 3560 events after the quality cuts
- Systematic uncertainty of $\langle X_{\max} \rangle$: $\pm 17 \text{ g/cm}^2$
- 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 TALE FD in monocular mode

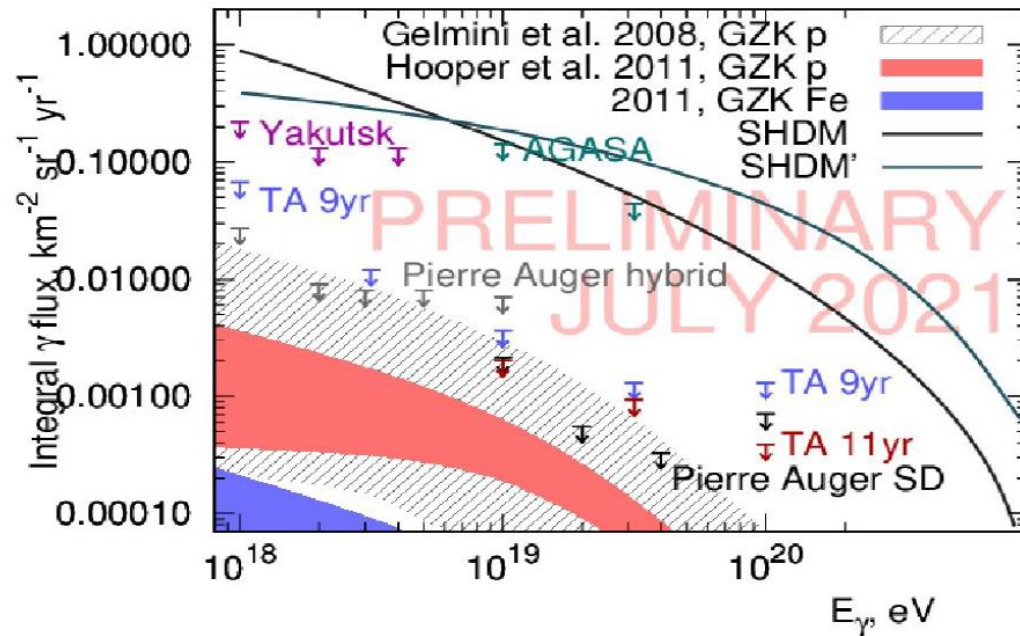
ApJ 909 178 (2021)



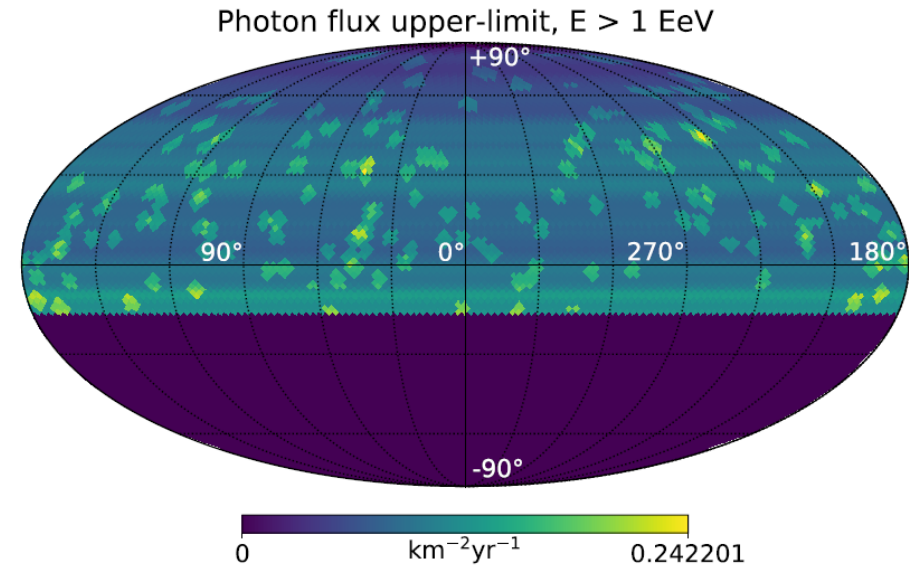
- Jun. 2014 – Nov. 2018 TALE FD mono data
- Energy Range: $10^{15.8} \text{ eV} - 10^{18.3} \text{ eV}$
- Break point $\log (E/\text{eV}) = 17.291 \pm 0.060 + 0.077 - 0.084$ (EPOS LHC)

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

TA/TALE/Tax4 Array

Tax4 SD:
*NIMA, 1019,
165726 (2021)*

30 km

10 km

Spacing: 2.08 km
TA(N) SD

MDFD

SKCT

SNCT

Tax4 north FD

Tax4 south FD

10 km

TA (C) SD

Spacing: 1.2 km

LRFD

LRCT

BRCT

BRF

10 km

Tax4 South

Spacing: 2.08 km
TA(S) SD

1 km

30 40 50 Kilometers

New SDs

22 Apr 2019 S. Thomas
Dept. of Physics Univ. of Utah

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

4 × TA SD detection area (~2800 km²)

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

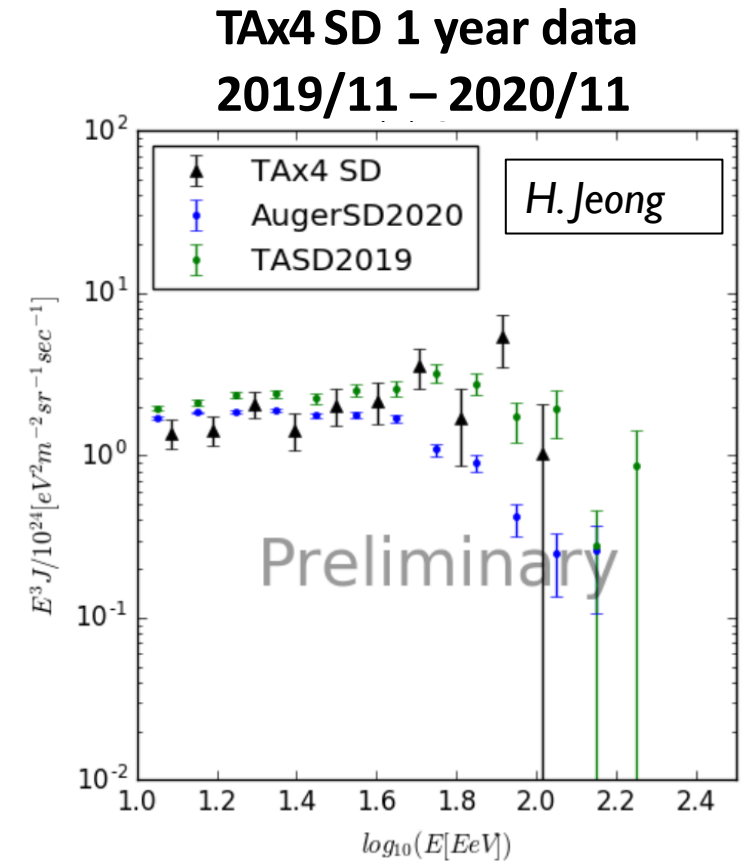
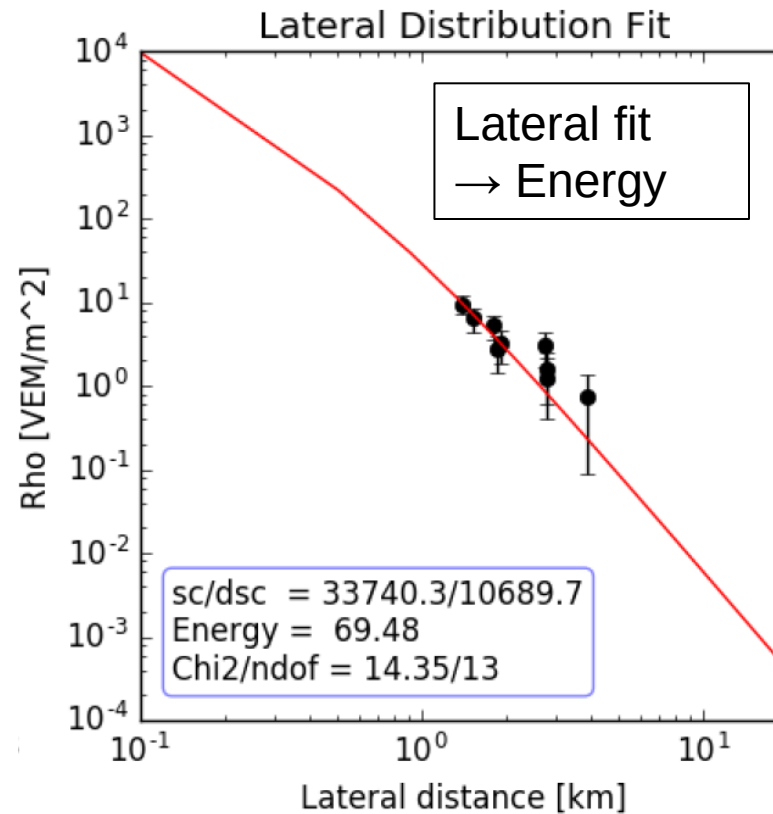
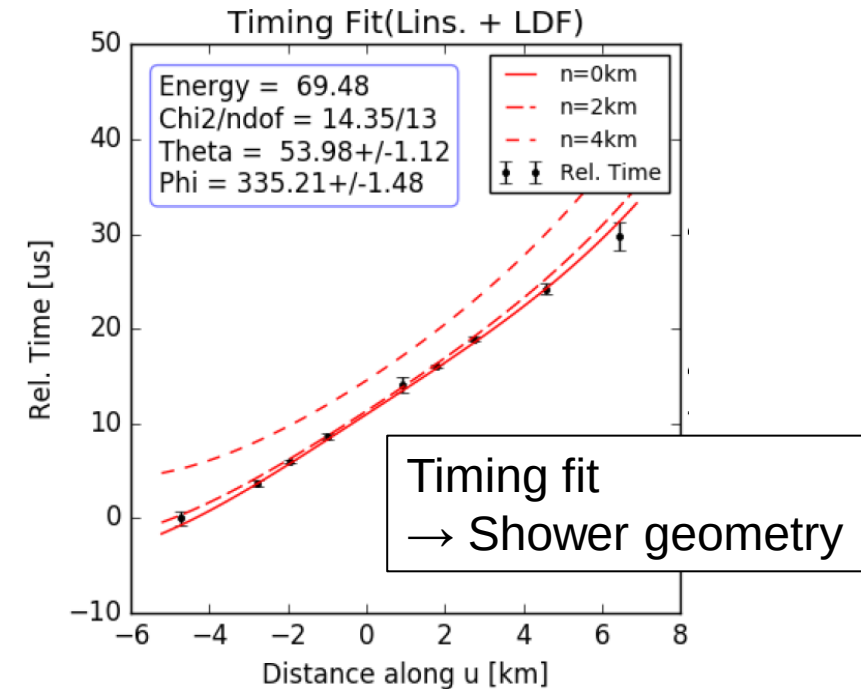
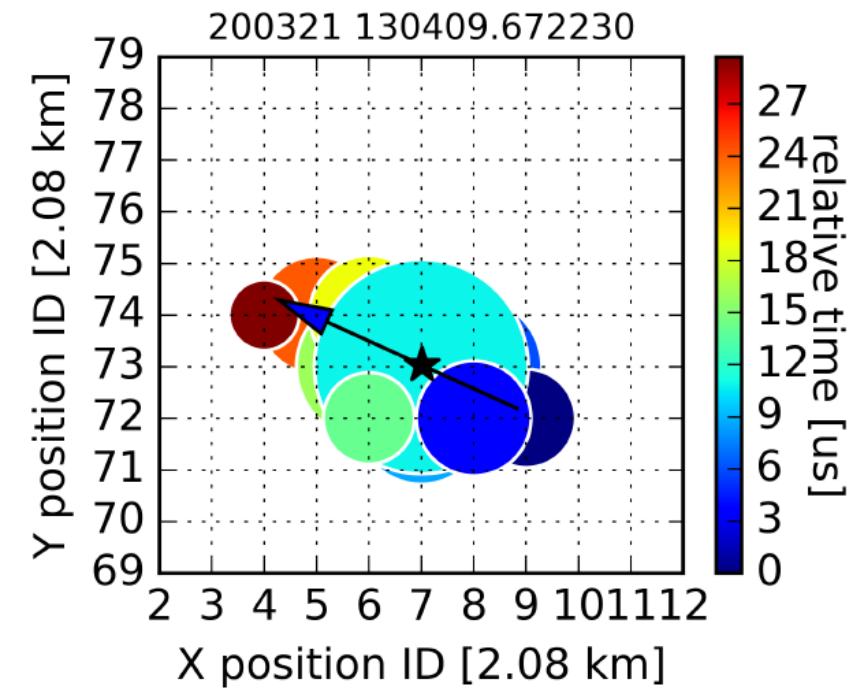
Deployed SDs are running stably from 2019 Nov.

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

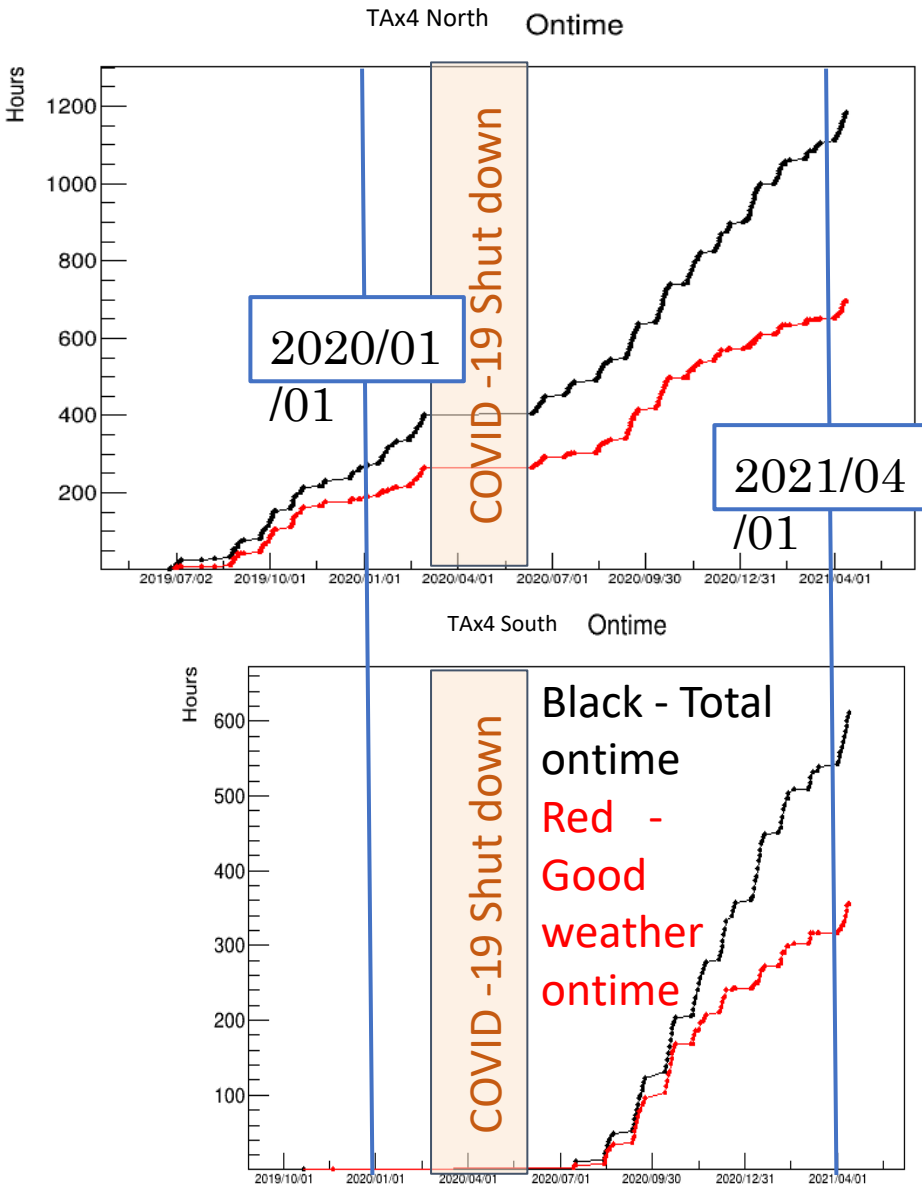
FD(north): stable run from 2018 Jun.

FD(south): stable run from 2020 Sep.

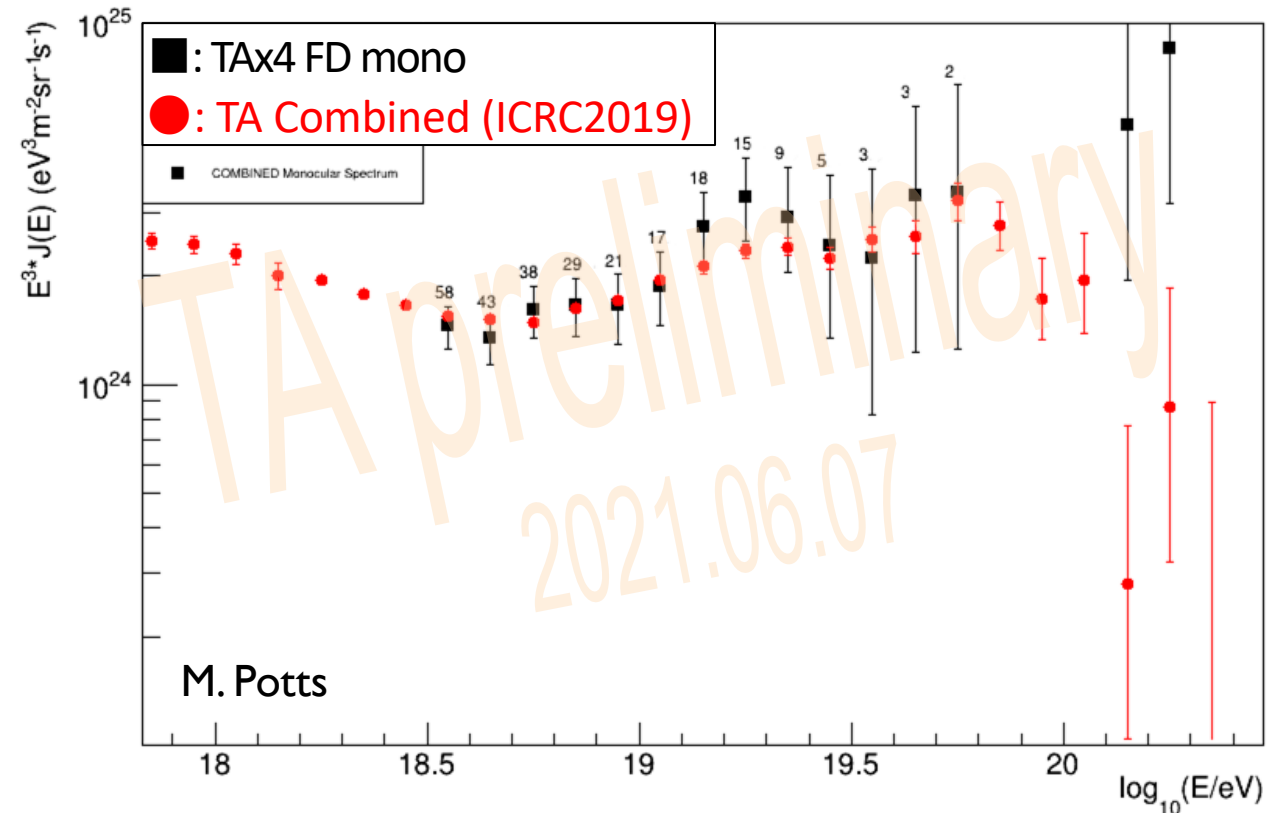
Analysis with new SDs (2.08km spacing, 257 SDs)



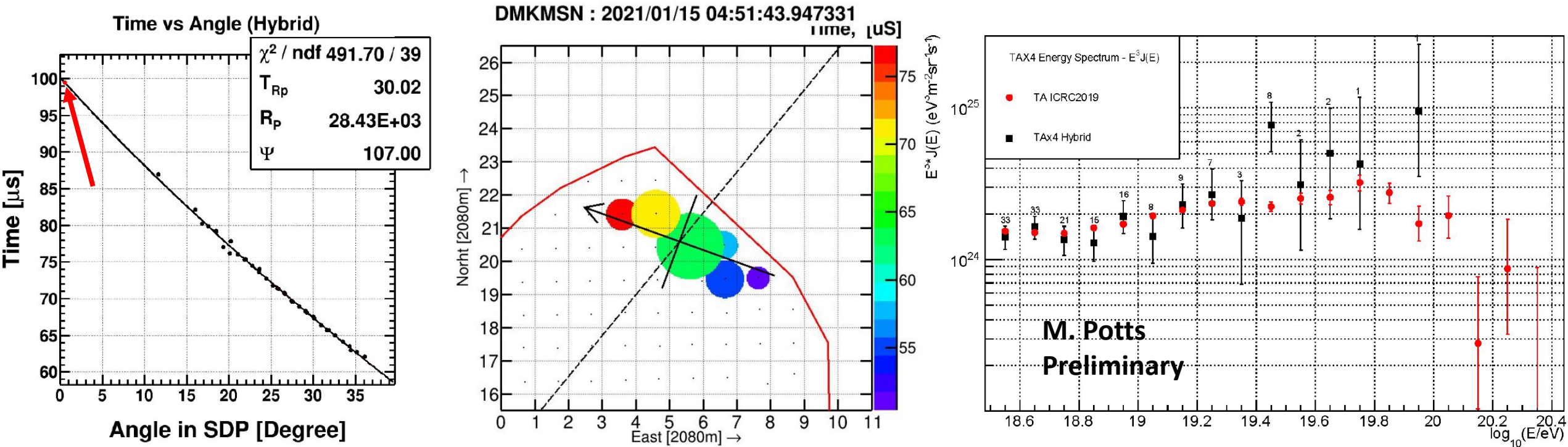
Monocular energy spectrum with new FDs



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



Hybrid energy spectrum with new SDs and FDs



TAX4 SD trigger condition: $\sim 30\%$ efficiency at around 10 EeV

$\rightarrow$ **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.

$\rightarrow$ **$\sim 3 \times$ 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.

Summary

- The TA experiment continue to observe UHECRs from 2008 with [the largest detection area in the northern hemisphere](#).
- Arrival directions
 - **3.2 σ hotspot with $E > 57$ EeV** was obtained using T ASD 12 years data
 - **3.5 σ excess with $E > 10^{19.4}$ eV** was obtained using T ASD 11 years data
 - Correlation with a sample of **Starburst Galaxies** at **4.2 σ** confidence level obtained by the Auger and TA working group.
- Energy Spectrum
 - **Declination dependence** was claimed at **4.3 σ** in the energy spectrum using T ASD 11 years data
- Mass composition
 - TA SD and FD hybrid: consistent [with light composition](#) with $18.2 < \log (E/\text{eV}) < 19.1$. More events at the highest energies are needed.
 - TALE FD mono.: Xmax results were obtained with $\log (E/\text{eV}) > 15.3$.
 - 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 $\sim 2800 \text{ km}^2$**
 - **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.