The latest results of the Telescope Array experiment

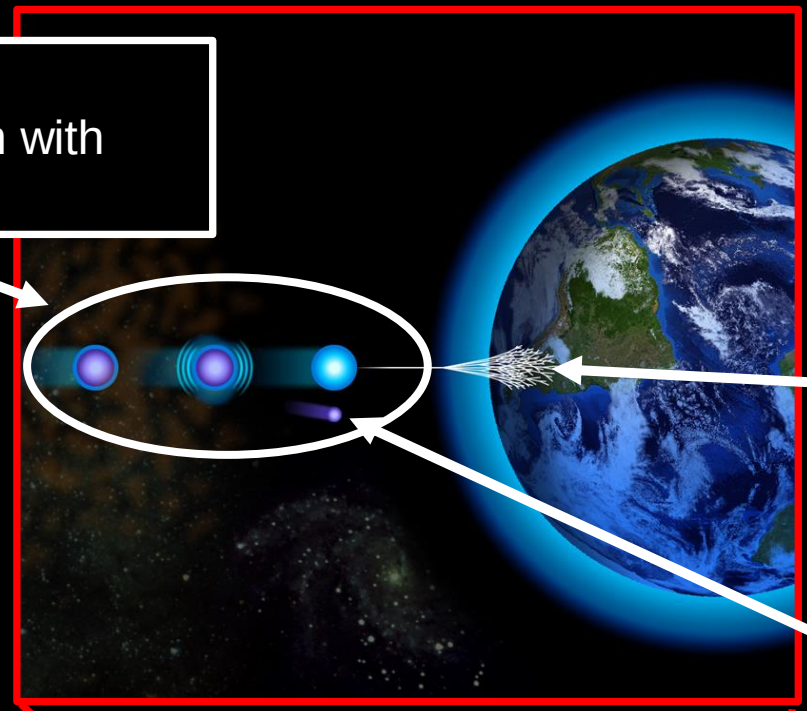
E. Kido for the Telescope Array Collaboration

ABBL, RIKEN

Outline

- Detection of ultra-high energy cosmic rays (UHECRs)
- Overview of the Telescope Array (TA) experiment
  - TA detectors
  - Extension to the TALE (lower energies) and TAx4 experiment (higher energies)
- Latest results of the TA experiment
  - Energy spectrum
  - Anisotropies in arrival directions
  - Mass composition
- Summary

Schematic view of the UHECR propagation



Cosmic-ray nuclei:
photo-nuclear reaction with
background photons

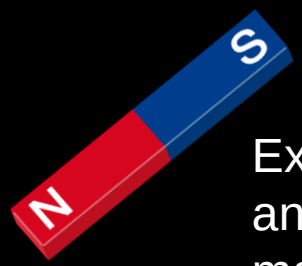
Air shower in the atmosphere

Cosmic-ray protons:
photo-pion production
with background photons
→ secondary neutrinos
and gamma-rays

Unknown origins of
cosmic rays

Cosmic Rays
(charged particles)

Magnetic deflection
∝ Z/E **(1/Rigidity)**

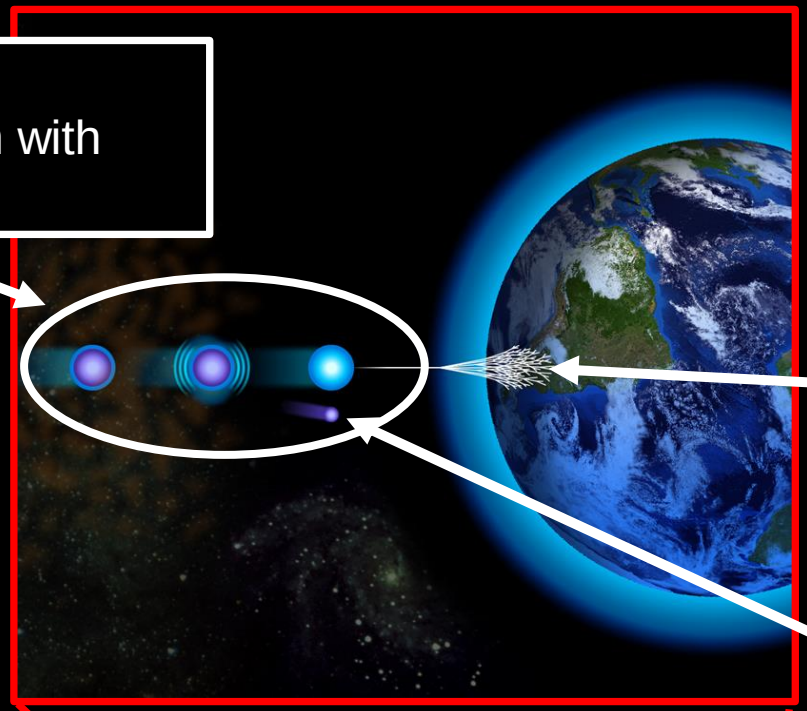


Extragalactic
and Galactic
magnetic fields

UHECR:
E > 1 EeV
(1 EeV = 10^{18} eV)

Schematic view of the UHECR propagation

Cosmic-ray nuclei:
photo-nuclear reaction with
background photons



Air shower in the atmosphere

Cosmic-ray protons:
photo-pion production
with background photons
→ secondary neutrinos
and gamma-rays

Unknown origins of
cosmic rays

Magnetic deflection
∝ **Z/E (1/Rigidity)**

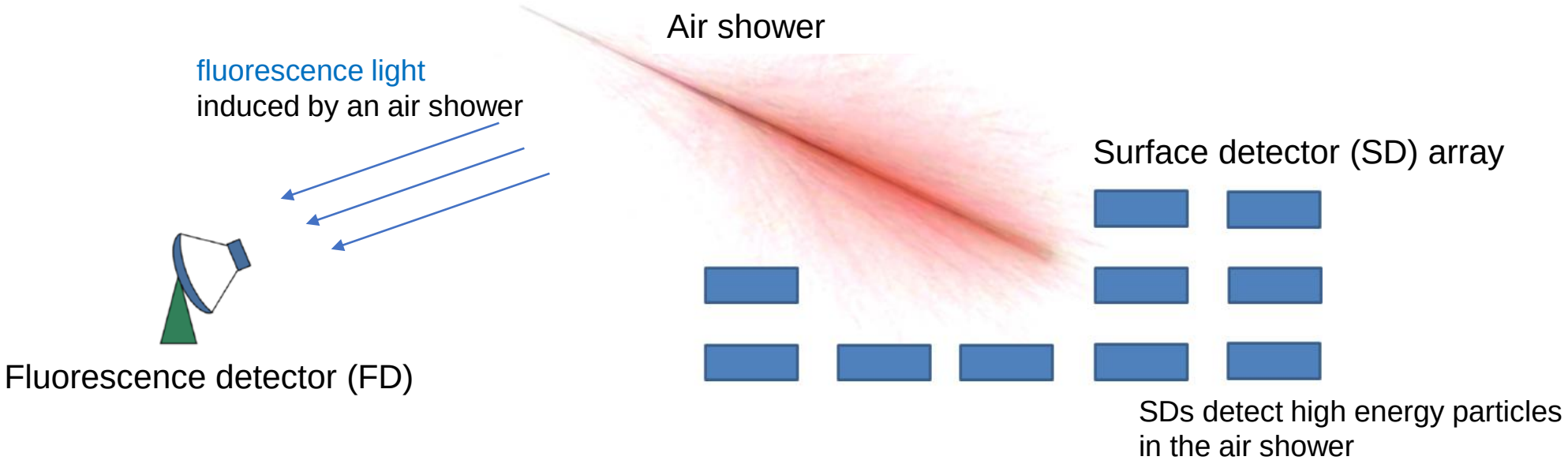
Cosmic Rays
(charged particles)

Cosmic-rays with high E
if Z is fixed
→ small magnetic deflections
& short mean free path
→ **origins of cosmic rays**
clarified with the arrival directions?

magnetic fields

UHECR:
E > 1 EeV
(1 EeV = 10^{18} eV)

Detection of air showers



- UHECRs: **small** number of events (∼10^{-3} $km^{-2}yr^{-1}$ $E > 10^{20}$ eV) → indirect measurements with air showers for huge detection area
- **More than 1000 km^2** detection area was realized by the Pierre Auger observatory (∼3000 km^2) and the Telescope Array experiment (∼1750 km^2).
- SD array: duty cycle∼100% → **anisotropies in arrival directions** and **energy spectrum** with high statistics (∼FDx10)
- FD: measure longitudinal development of air showers → provide **mass composition** with X_{max} (slant depth of the shower maximum)
  → **absolute energy scale** of UHECRs with calorimetric measurement of fluorescence lights

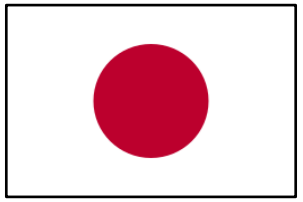
Telescope Array Collaboration

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]

[1] Loyola University Chicago [2] University of Utah [3] Saitama University [4] Osaka City University [5] Hanyang University [6] Tokyo University of Science [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 Instit. for Quantum and Radiological Science and Technology [34] CEICO, Institute of Physics, Czech Academy of Sciences [35] Ewha Womans University

32 institutions, 145 collaborators


USA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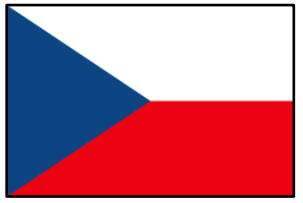
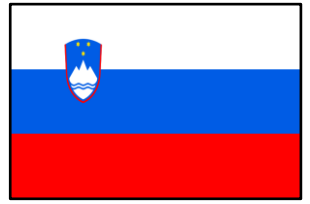
Korea


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

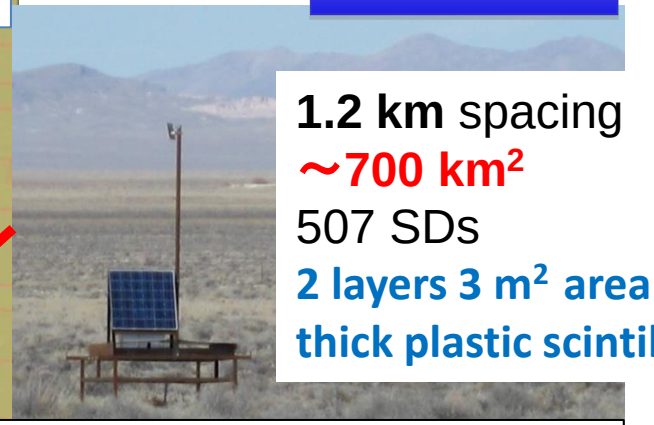
CLF

LRFD

28km

BRFD

Surface Detector
(SD)



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

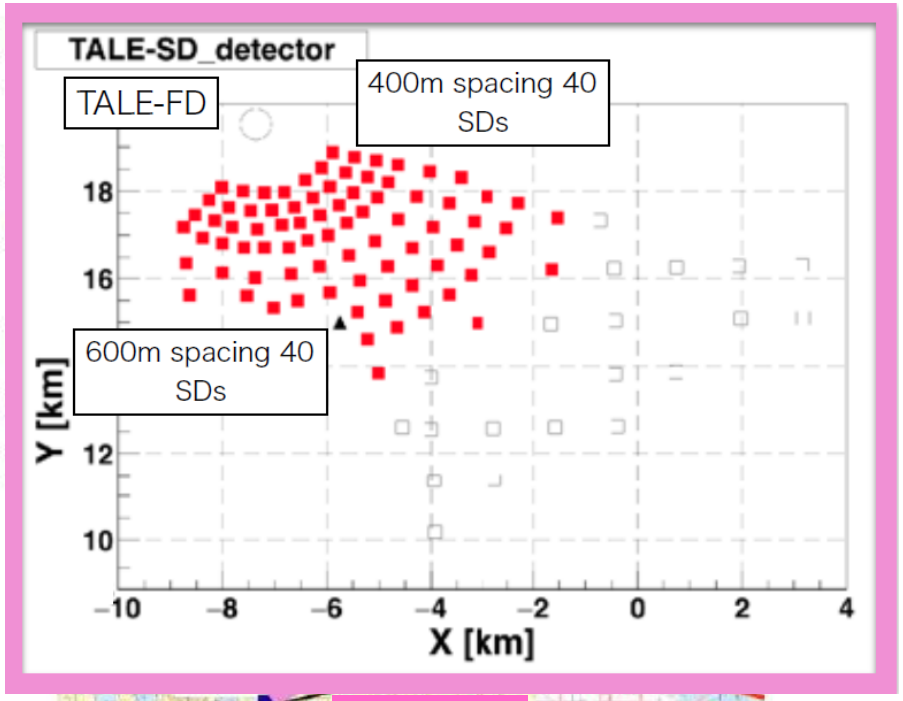
- **Largest cosmic-ray observatory in the northern hemisphere**
- **Hybrid observation by SD and FD**

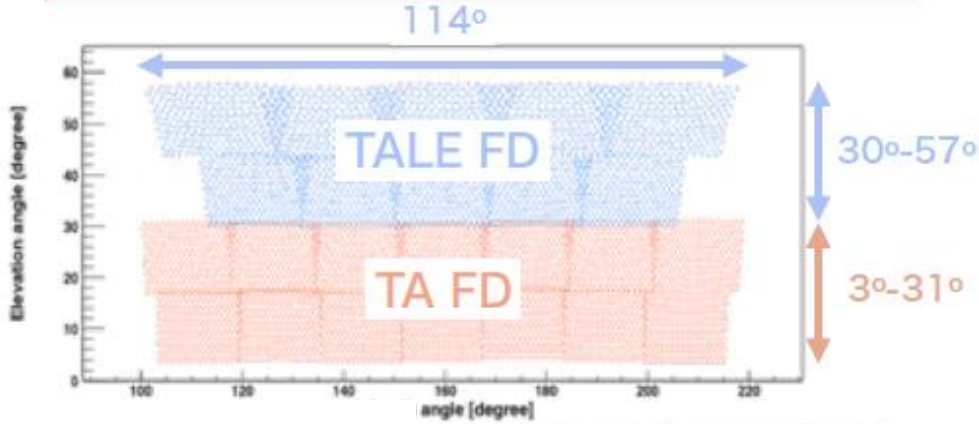
Fluorescence Detector
(FD) station

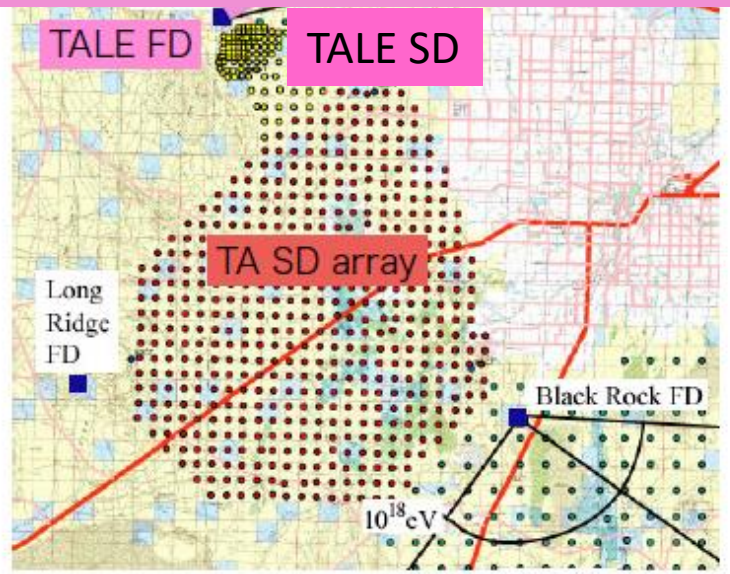
12 telescopes

Full operation since May **2008** @ Utah, USA

TALE (TA Low-energy Extension) Detectors







TALE FD was installed in Nov. 2012

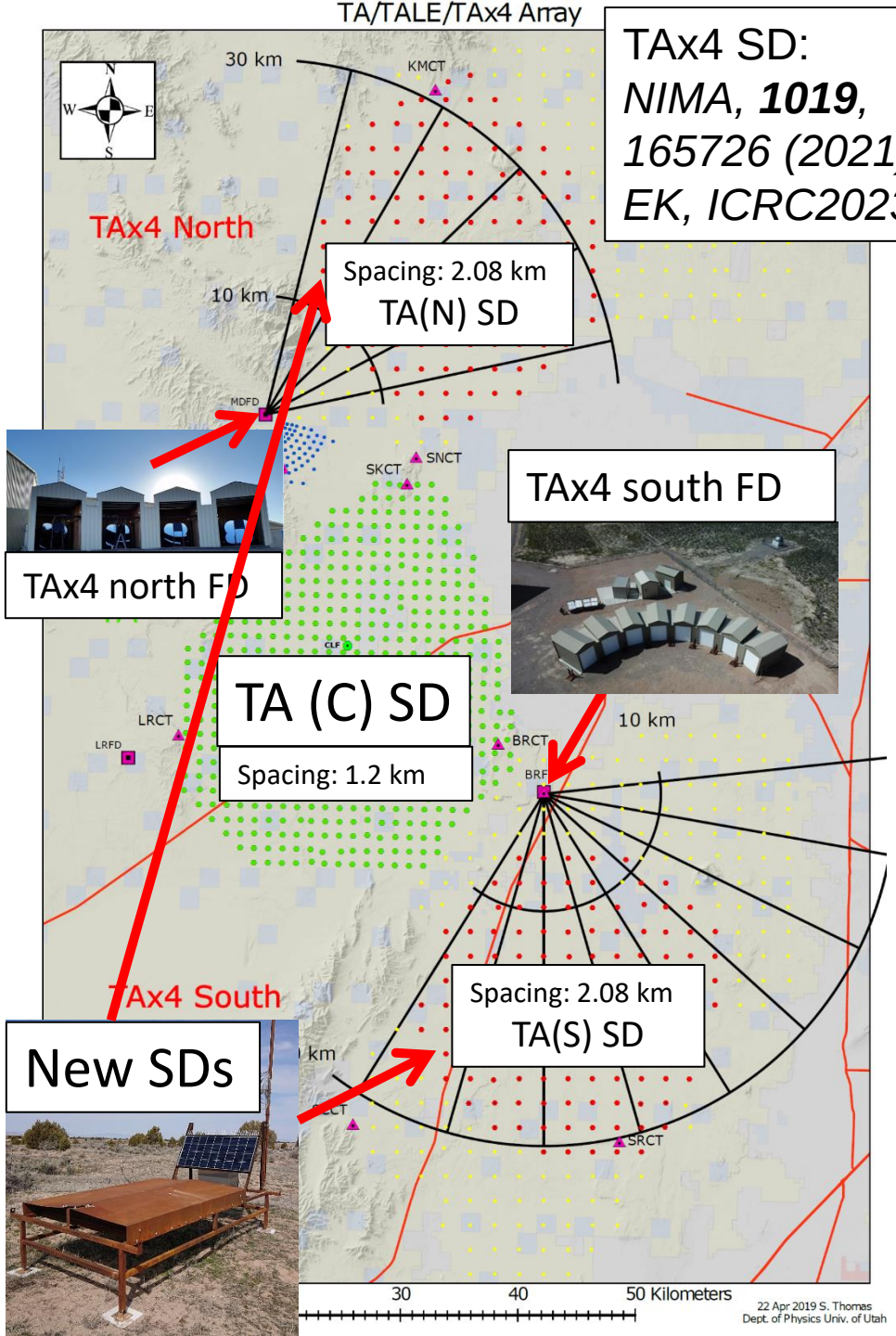
Operation since Sep. 2013

Hybrid trigger: Sep. 2018

- **Extension for cosmic rays with lower energies**
- **Dense SD array (spacing: 400 m and 600 m)**
- **FD for higher elevation angles**
- **Hybrid observation by SD and FD**

The TAx4 experiment

TAx4 SD:
*NIMA, **1019**, 165726 (2021)*
EK, ICRC2023



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 Nov. 2019.

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

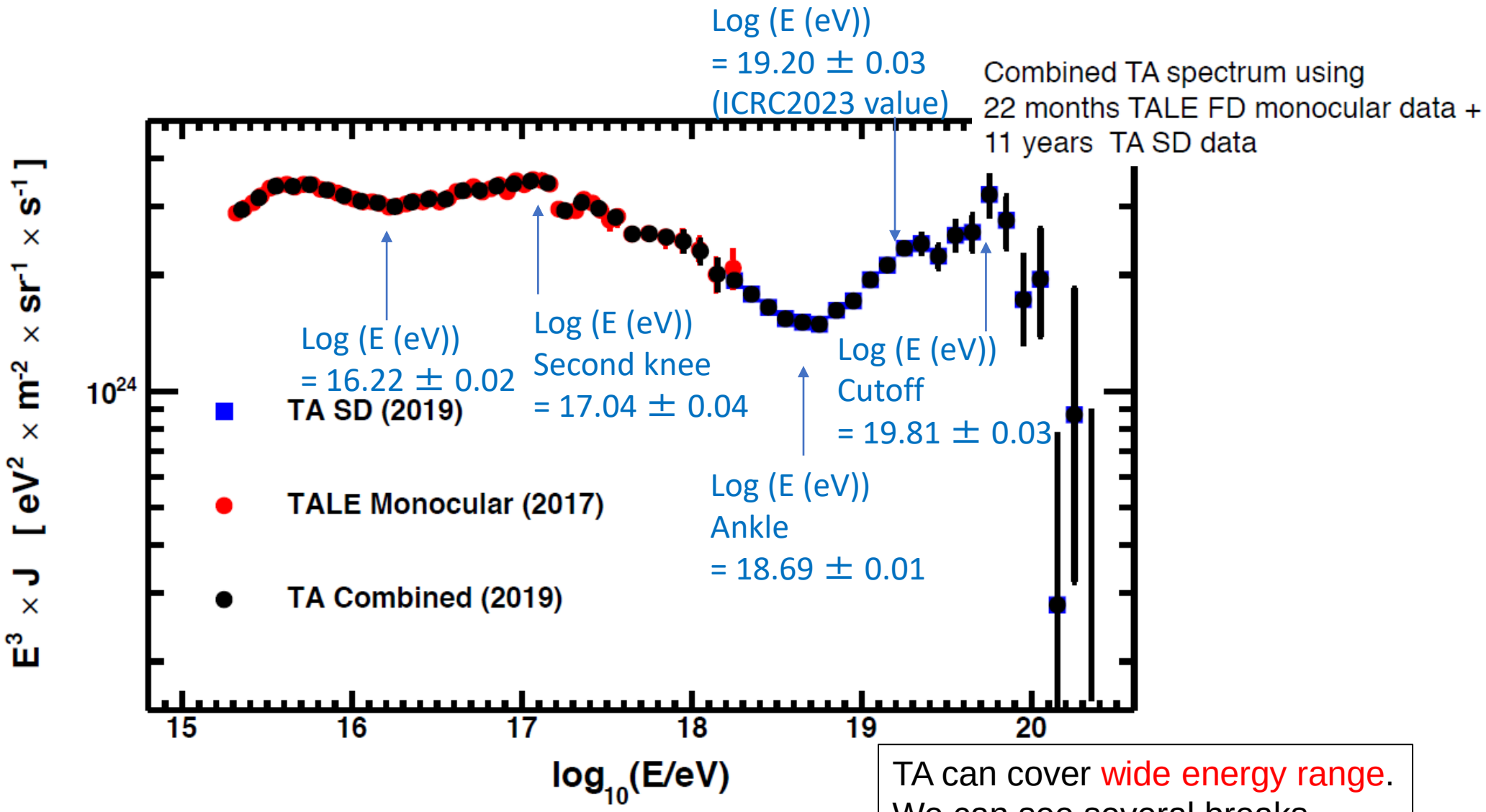
FD(north): stable run since Jun. 2018.

FD(south): stable run since Sep. 2020.

- **Extension for cosmic rays with higher energies**
- **Sparse SD array (spacing: 2.08 km)**
- **Two new FD stations**
- **Hybrid observation by SD and FD**

TA SD + TALE FD combined energy spectrum

D. Ivanov, ICRC2019

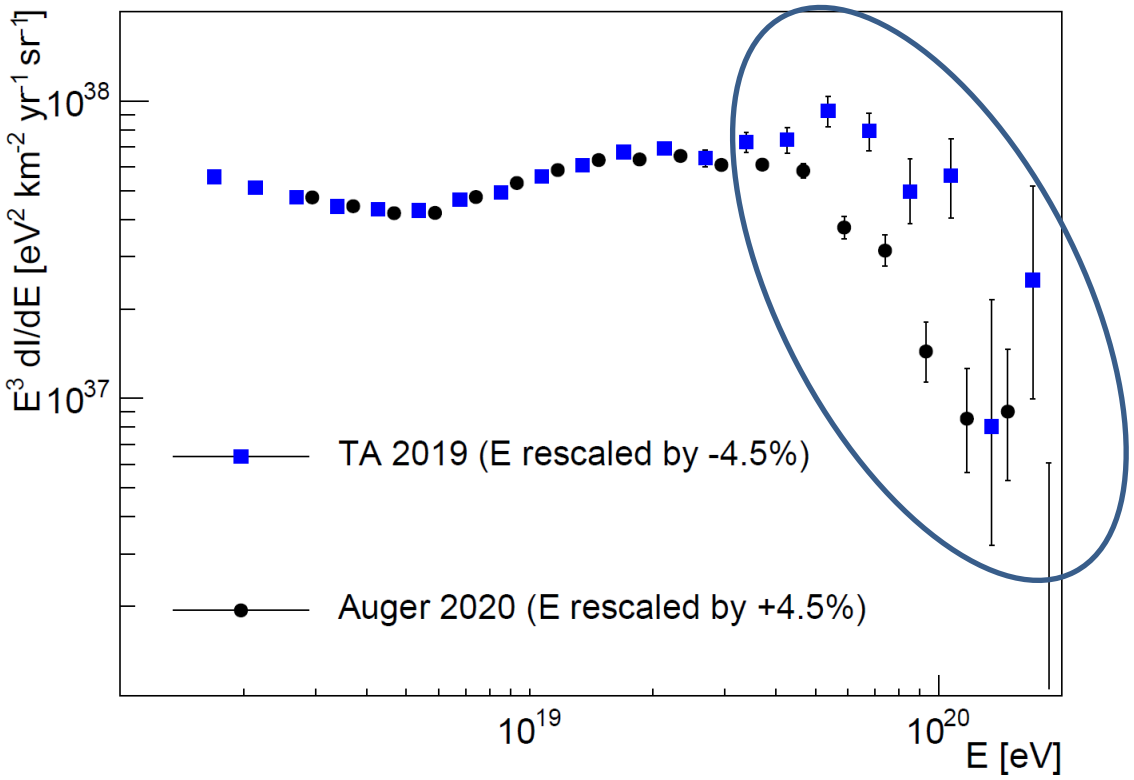


TA can cover wide energy range.
We can see several breaks
in the energy spectrum.

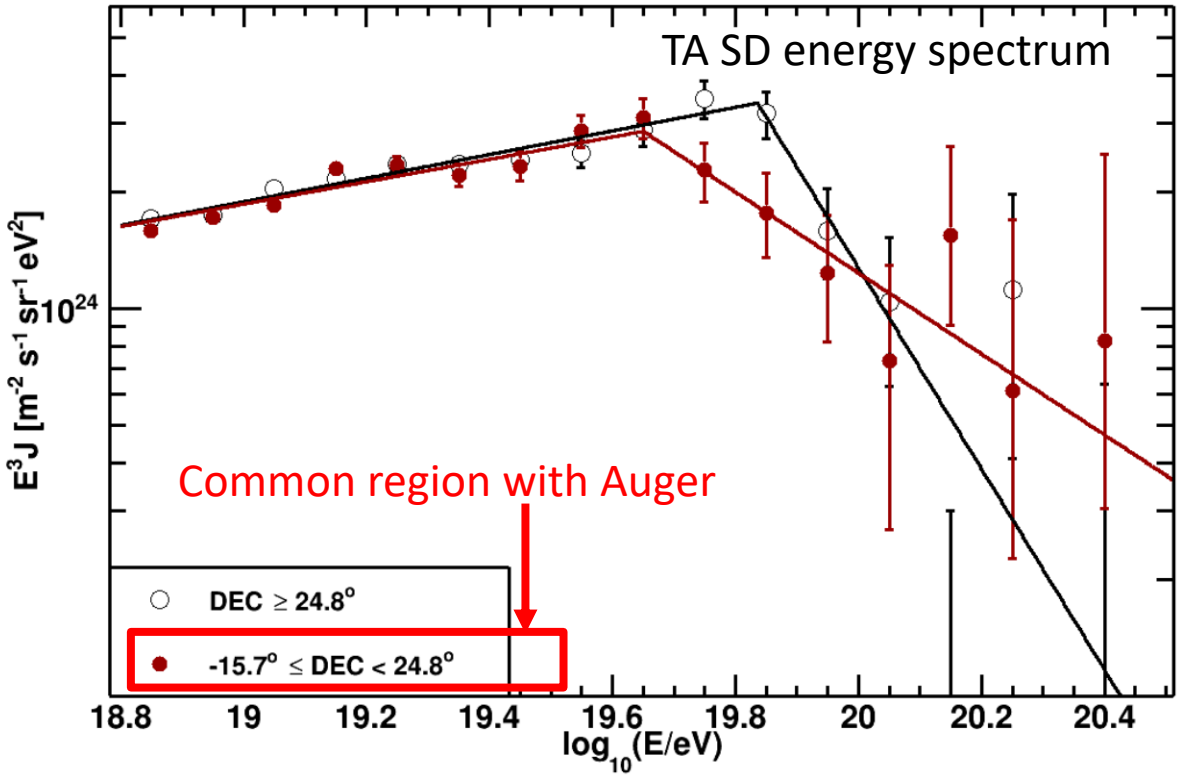
Declination dependence of TA SD energy spectrum

Y. Tsunesada, ICRC2023

Auger+TA spectrum working group



J.H. Kim, ICRC2023



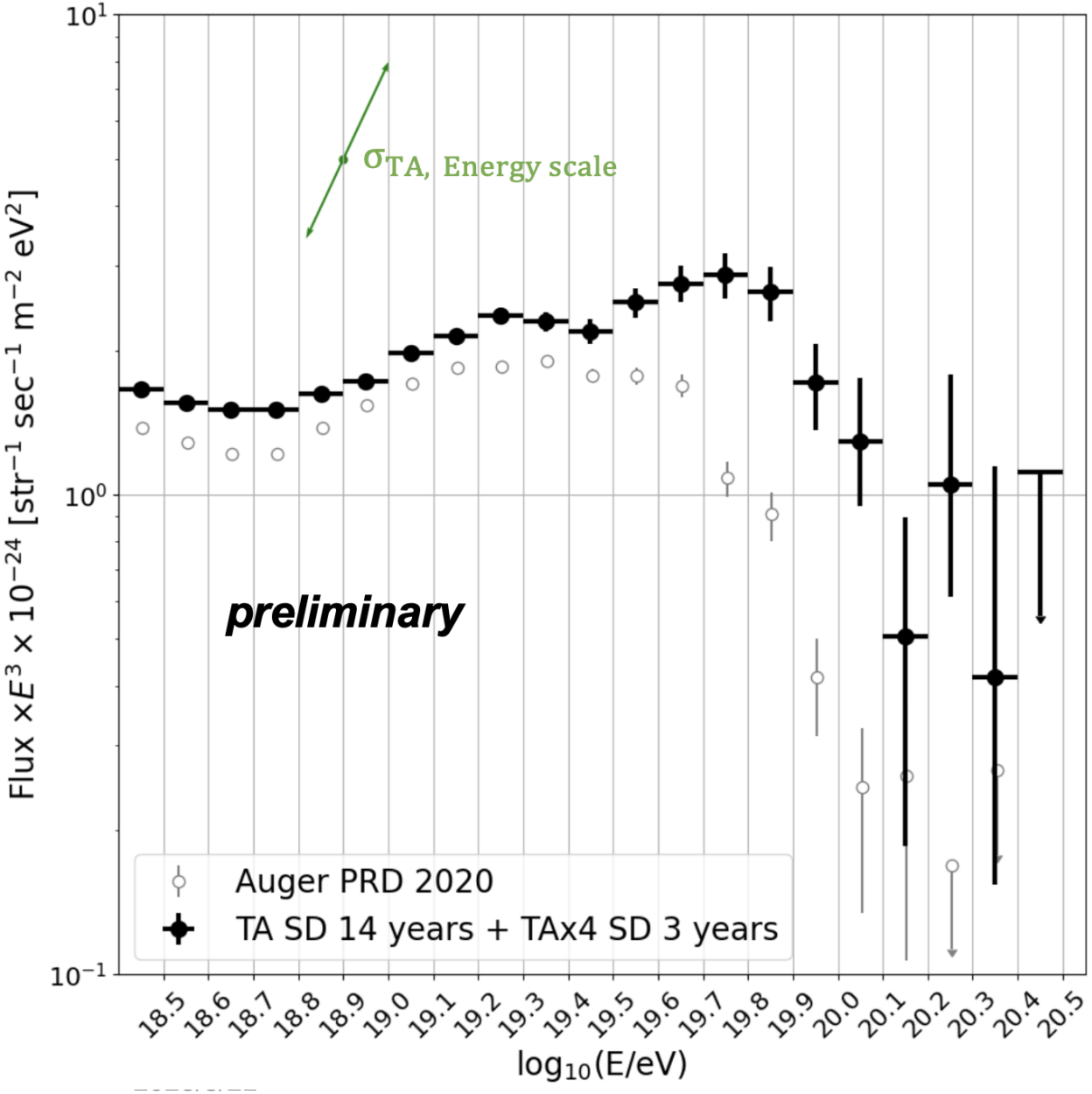
- Difference of the cutoff energies of energy spectra
  - log(E/eV) = 19.65 ± 0.03 for lower dec. band (-16° - 24.8°)
  - log(E/eV) = 19.84 ± 0.02 for higher dec. band (24.8° - 90°)
- The global significance of the difference was estimated to be **4.4σ**

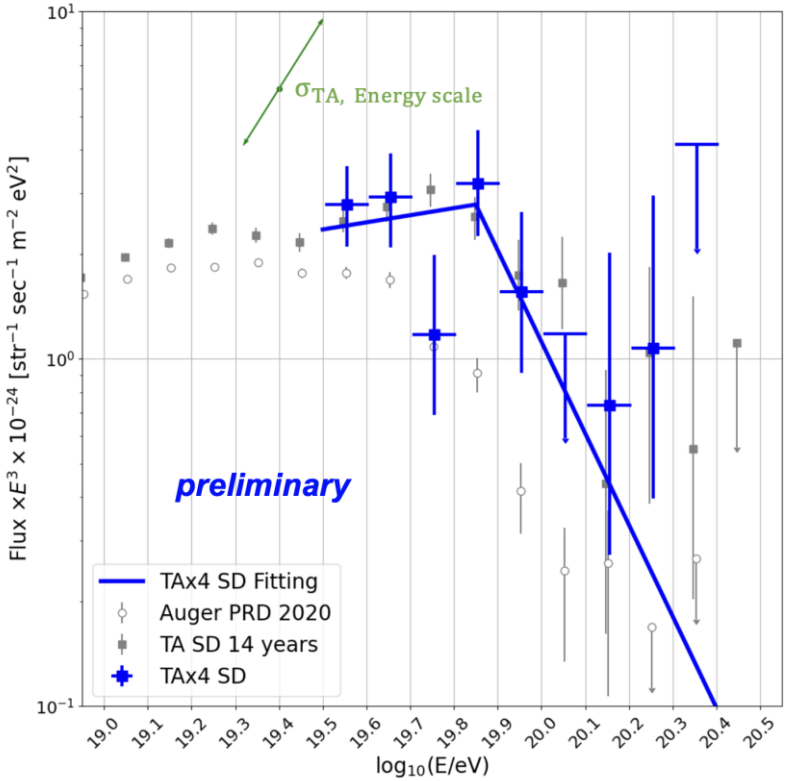
K. Fujisue, ICRC2023

TA + TAx4 SD combined energy spectrum

TA SD: data was collected over 14 years
TAx4 newly deployed SD:
$E > 10^{19.5}$ eV, data was collected over 3 years

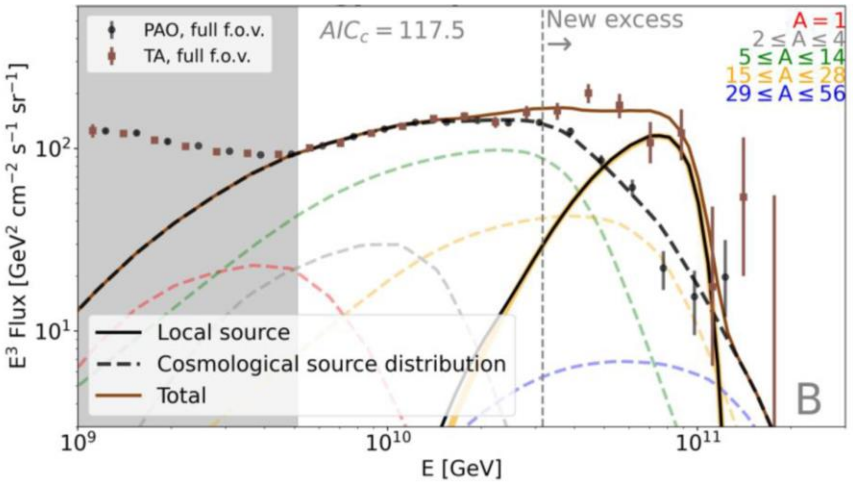
The energy spectrum obtained using newly deployed SDs is compatible with the TA SD energy spectrum.



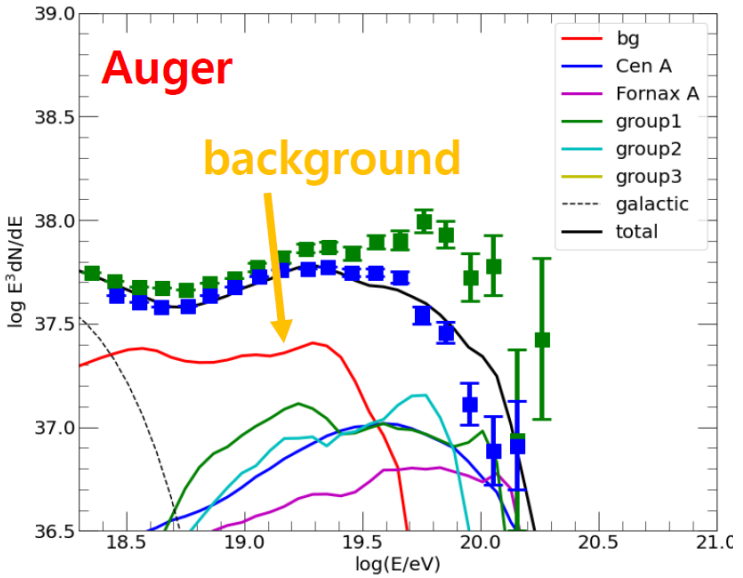


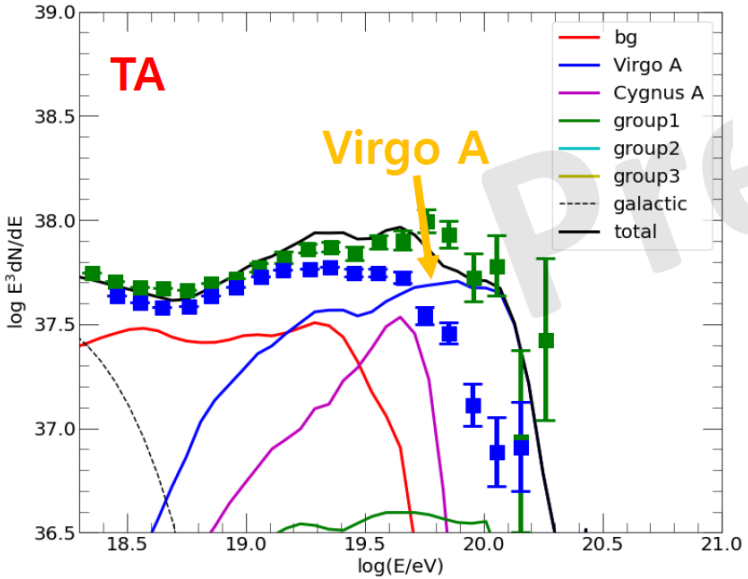
Astrophysical interpretation of the declination dependence

P. Plotko, ICRC2023



D. Ryu et al., ICRC2023

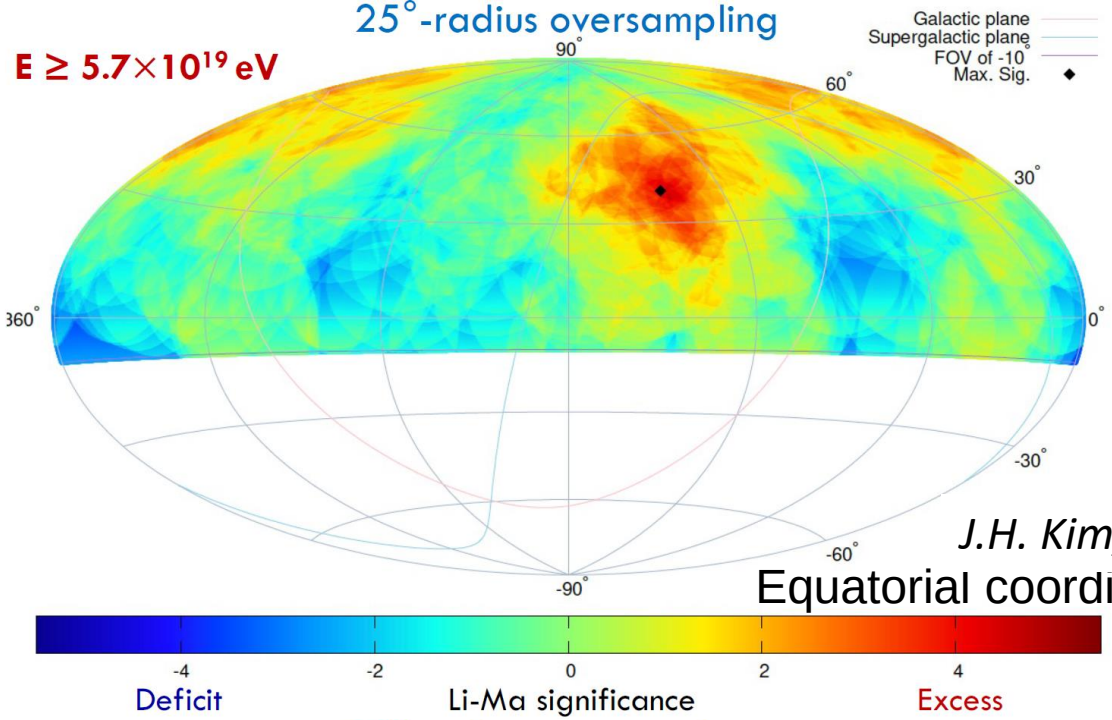




Some astrophysical interpretations were provided by some theorists.

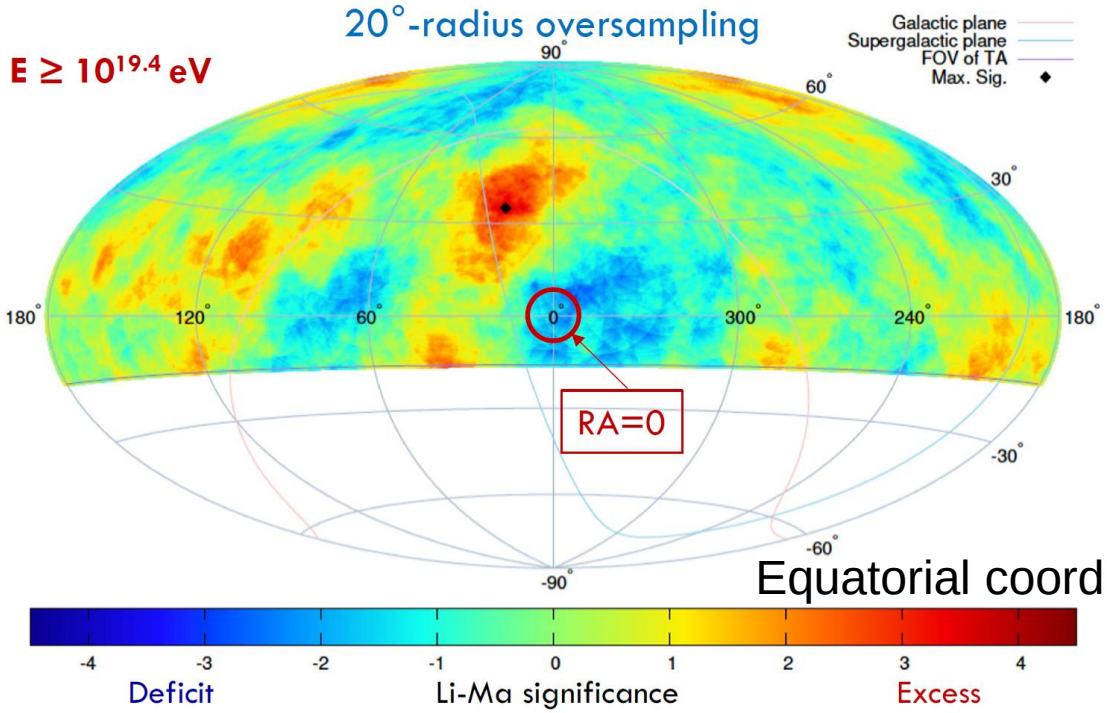
- Local source in the northern hemisphere?
- Local radio galaxies?

Intermediate-scale anisotropy: Hotspot and a PPSC excess



J.H. Kim, ICRC2023

Equatorial coordinate



Equatorial coordinate

Analysis method (*ApJ 790, L21 (2014)*):

- Oversample number of UHECR events within a fixed radius circle from each arrival direction.
- Evaluate Li-Ma significance from isotropy expectation.
- The TA SD data collected over 15 years was used.

Hotspot (E > 57 EeV):

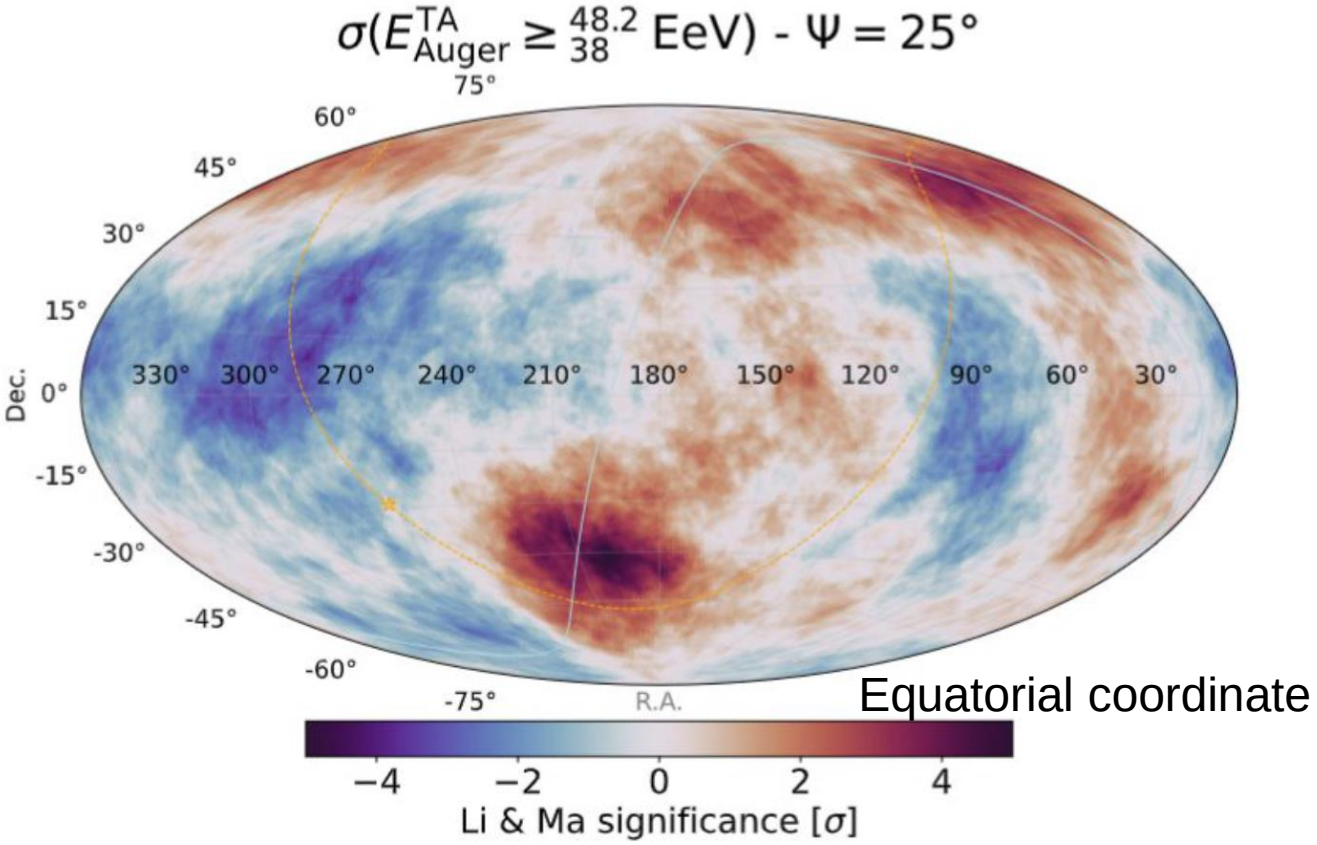
- 216 events
- max. local significance: 4.8σ at (144.0°, 40.5°)
- global significance: **2.8σ**

The Perseus-Pisces super cluster (PPSC) excess ($E > 10^{19.4}$ eV) (arXiv: 2110.14827):

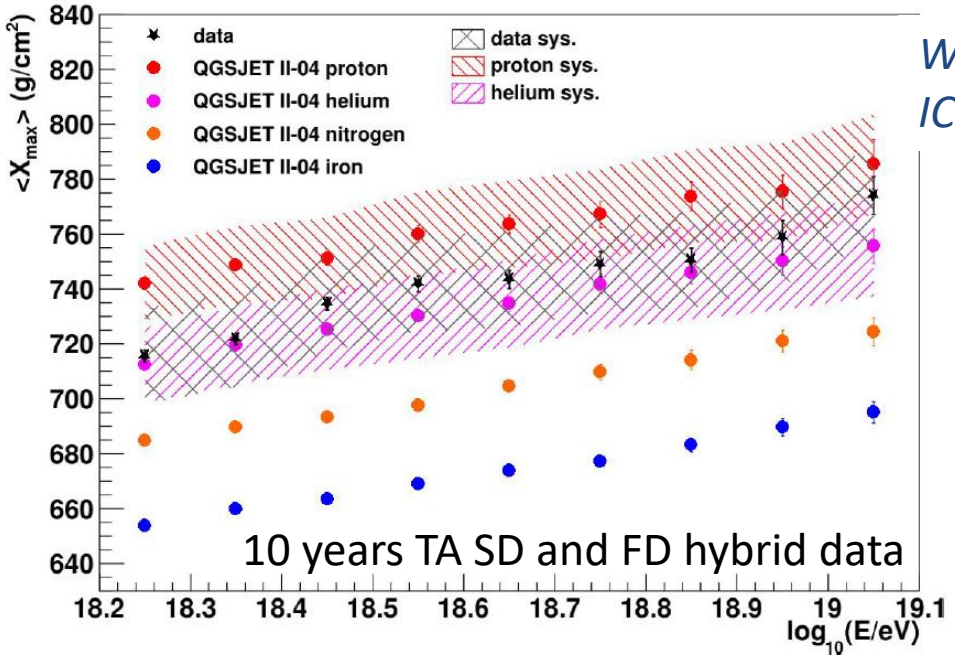
- 1125 events
- max. local significance: 4.0σ at (17.9°, 35.2°)
- significance: **3.3σ**

Correlation study with catalog galaxies by the Auger+TA anisotropy working group

L. Caccianga, ICRC2023



- Correlations of arrival directions of UHECRs with expected flux calculated using a sample of nearby starburst galaxies and using nearby all types of galaxies in 2MASS catalog.
- Post-trial significance of the correlation with **starburst galaxies** is estimated to be **∼4.6σ**.
- Auger: E > 38 EeV
- TA: E > 48.2 EeV
- Cross calibration of energies was conducted in the common declination band between Auger and TA.
- Angular scales and energy thresholds were scanned.
- Ongoing updates of the two observatories, AugerPrime and TAx4 will improve the results in the future.

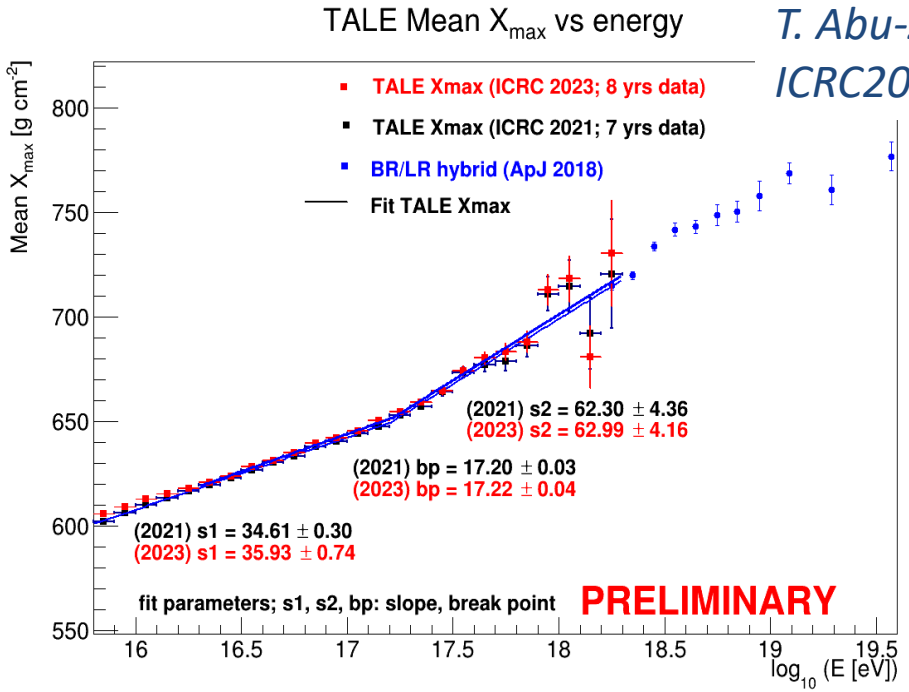


W. Hanlon, ICRC2019

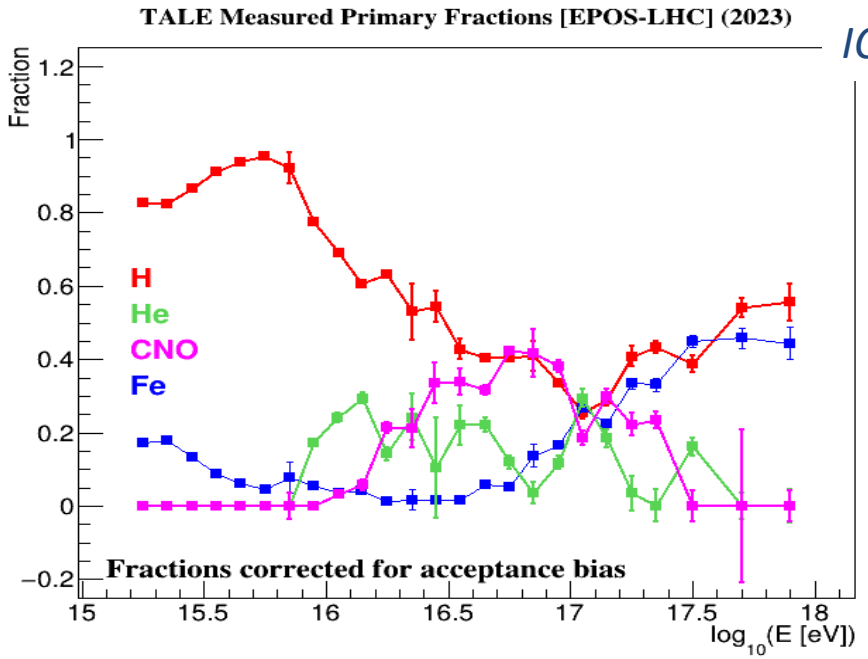
Mass composition

Observed X_{max} are compared with air shower simulations using hadron interaction models.

- Light-heavy-light transition in 10^{15} eV – 10^{18} eV and a break at ~$10^{17.2}$ eV in mean X_{max} were obtained with a TALE FD monocular analysis.
- TA SD and FD hybrid: consistent with light composition with 18.2 < log (E/eV) < 19.1. More events are needed for E > 10^{19} eV.



T. Abu-Zayyad, ICRC2023



T. Abu-Zayyad, ICRC2023

Summary

Thank you for your attention!

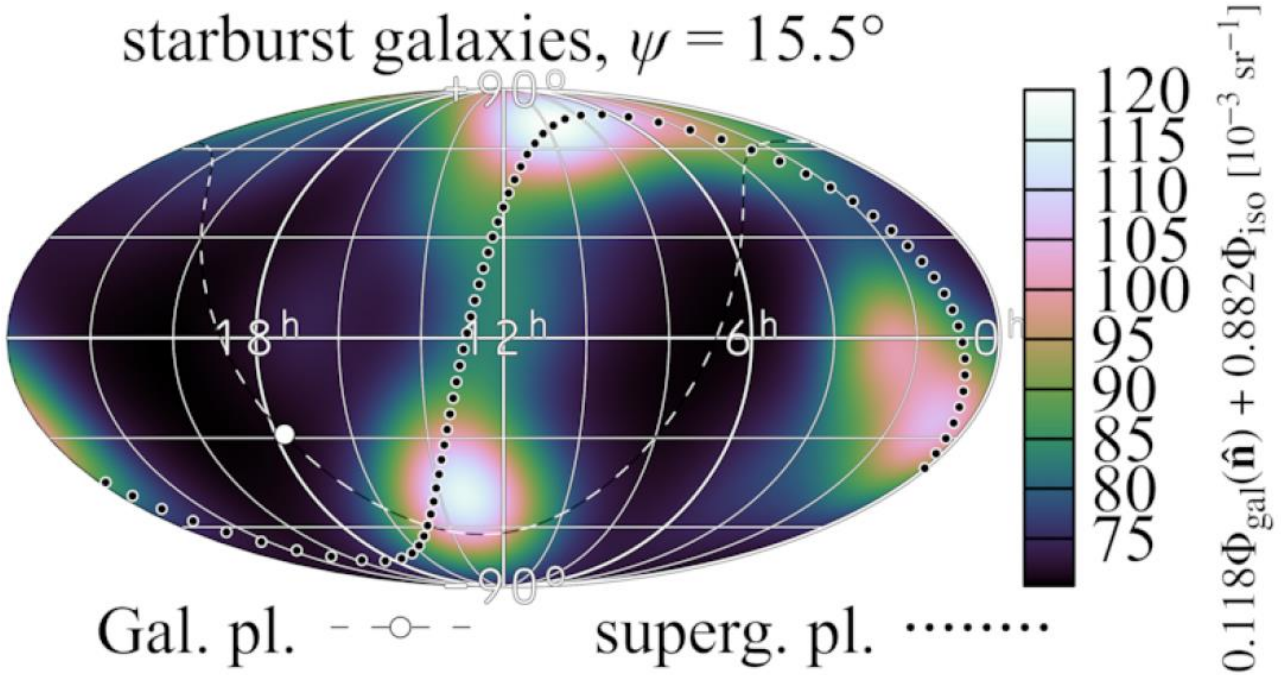
- TA detectors
  - TA: FDs and SDs are fully operated since May 2008.
  - TALE: FDs are operated since Sep. 2013. FD and SD hybrid triggers are operated since Sep. 2018.
  - TAx4: 257 new SDs (out of 500) and two new FDs were completed. North FD station stably runs since Jun. 2018, and south FD stably runs since Sep. 2020. SD stably runs since Nov. 2019.

- Energy spectrum
  - Declination dependence (arXiv: 1801.07820) of the cutoff energies: **4.4σ**
  - Energy spectrum obtained with new TAx4 SDs shows similar energy spectrum to the TA SDs.
- Anisotropies in arrival directions
  - Hotspot (E > 57 EeV) (*ApJ 790, L21 (2014)*): **2.8σ**
  - An excess around the Perseus-Pisces super cluster (PPSC) (E > $10^{19.4}$ eV) (arXiv: 2110.14827): **3.3σ**
  - Correlation with nearby starburst galaxies (Auger+TA working group): **∼4.6σ**

  We will analyze the data obtained with **new TAx4 SDs** to search for **anisotropies** at the highest energies.
- Mass composition
  - Light-heavy-light transition in 10^{15} eV – 10^{18} eV and a break at ∼$10^{17.2}$ eV in mean X_{max} were obtained with the TALE FDs.
  - TA SD and FD hybrid: consistent with light composition with 18.2 < log (E/eV) < 19.1. More events are needed for E > 10^{19} eV.
- Results on the UHECRs were mainly shown in this presentation due to the limitation of time.

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

A. di Matteo, ICRC2021



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

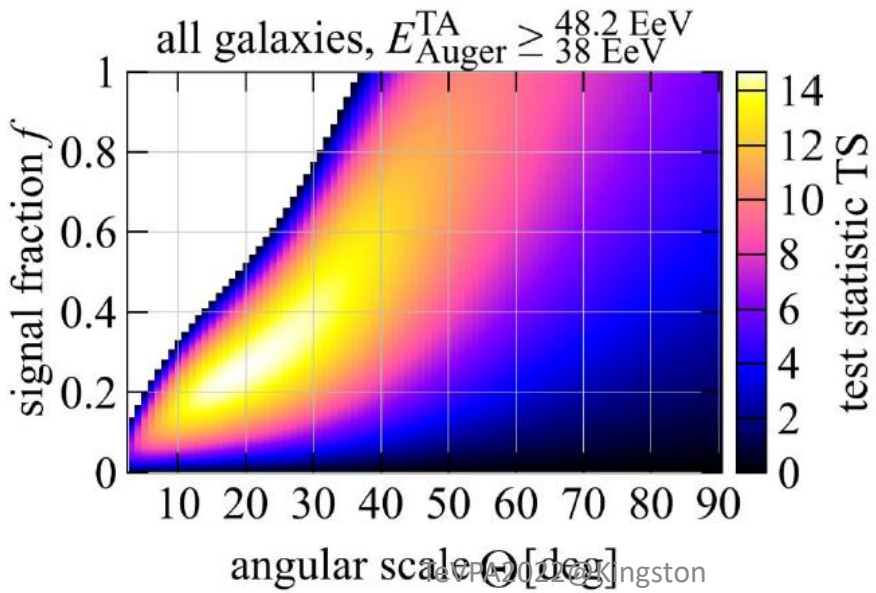
$$E_{\rm TA} \mapsto E_{\rm Auger} = 8.57\ (E_{\rm TA}/10\ {\rm EeV})^{0.937}\ {\rm EeV}$$

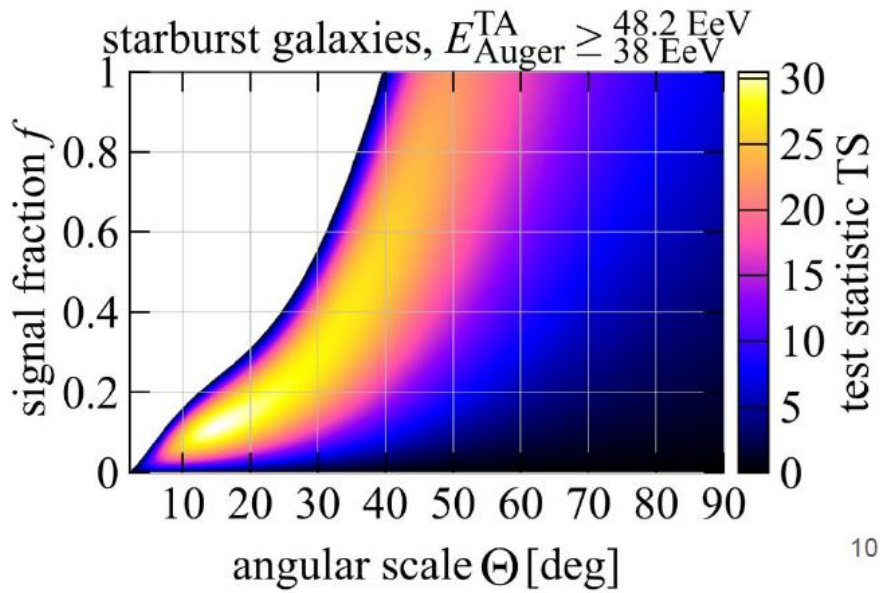
Likelihood analysis using catalogs

L. Caccianga, ICRC2023

Catalog	E_{Auger} threshold	E_{TA} threshold	Θ	f	TS	post-trial significance
All Galaxies	38 [40]	48.2 [51]	18.7 [29]	24.8 [41]	14.7 [14.3]	2.8σ [2.7σ]
Starburst Galaxies	38 [38]	48.2 [49]	15.4 [15.1]	11.7 [12.1]	30.5 [31.1]	4.6σ [4.7σ]

[previous results as presented at UHECR2022]

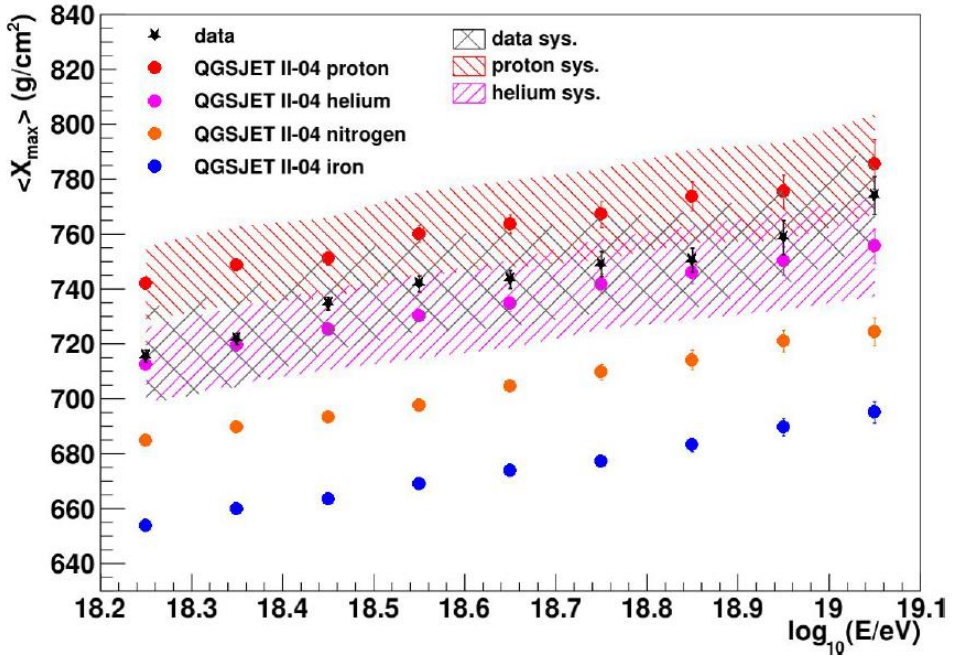




Composition Analysis with TA SDFD Hybrid Xmax

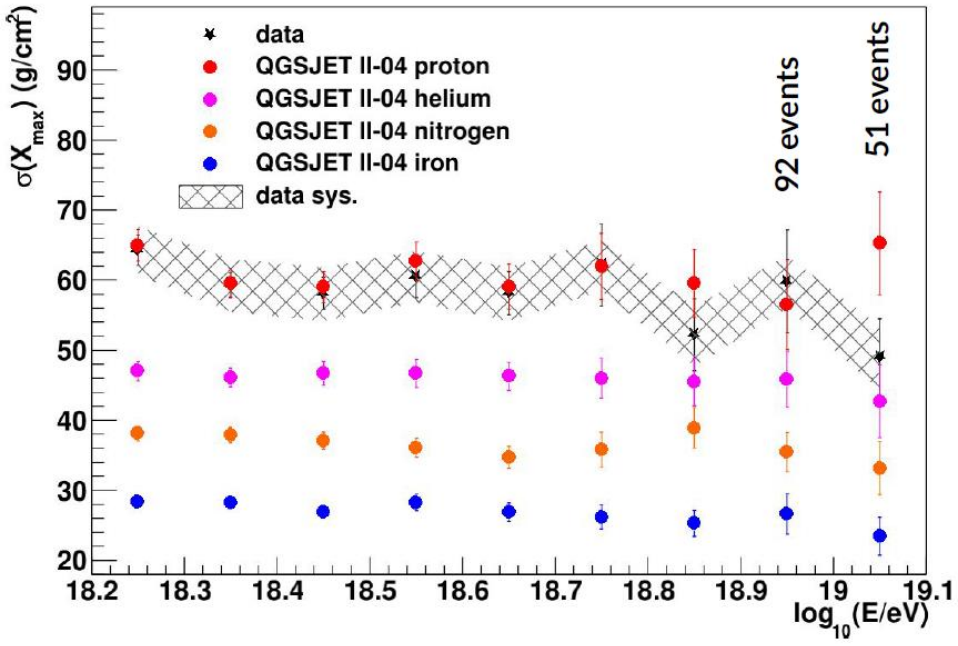
W. Hanlon, ICRC2019

Mean Xmax



10 years SD and FD hybrid data

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