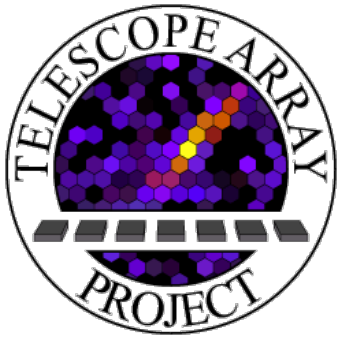
Telescope Array group

Kozo Fujisue
Telescope Array group



Telescope Array Collaboration

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], 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], 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.S. Pshirkov[15,25], J. Remington[3], D.C. Rodriguez[3], C. Rott[3,13], G.I. Rubtsov[15], D. Ryu[26], 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[26], H.S. Shin[6], 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[27], M. Takeda[6], R. Takeishi[6], A. Taketa[28], M. Takita[6], Y. Tameda[17], K. Tanaka[29], M. Tanaka[30], S.B. Thomas[3], G.B. Thomson[3], P. Tinyakov[15,18], I. Tkachev[15], H. Tokuno[31], T. Tomida[2], S. Troitsky[15], R. Tsuda[4], Y. Tsunesada[4,8], S. Udo[10], F. Urban[32], I.A. Vaiman[15], D. Warren[9], T. Wong[3], K. Yamazaki[23], K. Yashiro[27], F. Yoshida[17], Y. Zhezher[6,15], and Z. Zundel[3]

Belgium, Czech Republic, Japan, Korea, Russia, Slovenia, USA

7 countries, 32 institutes

Overview of the Telescope Array (TA) experiment

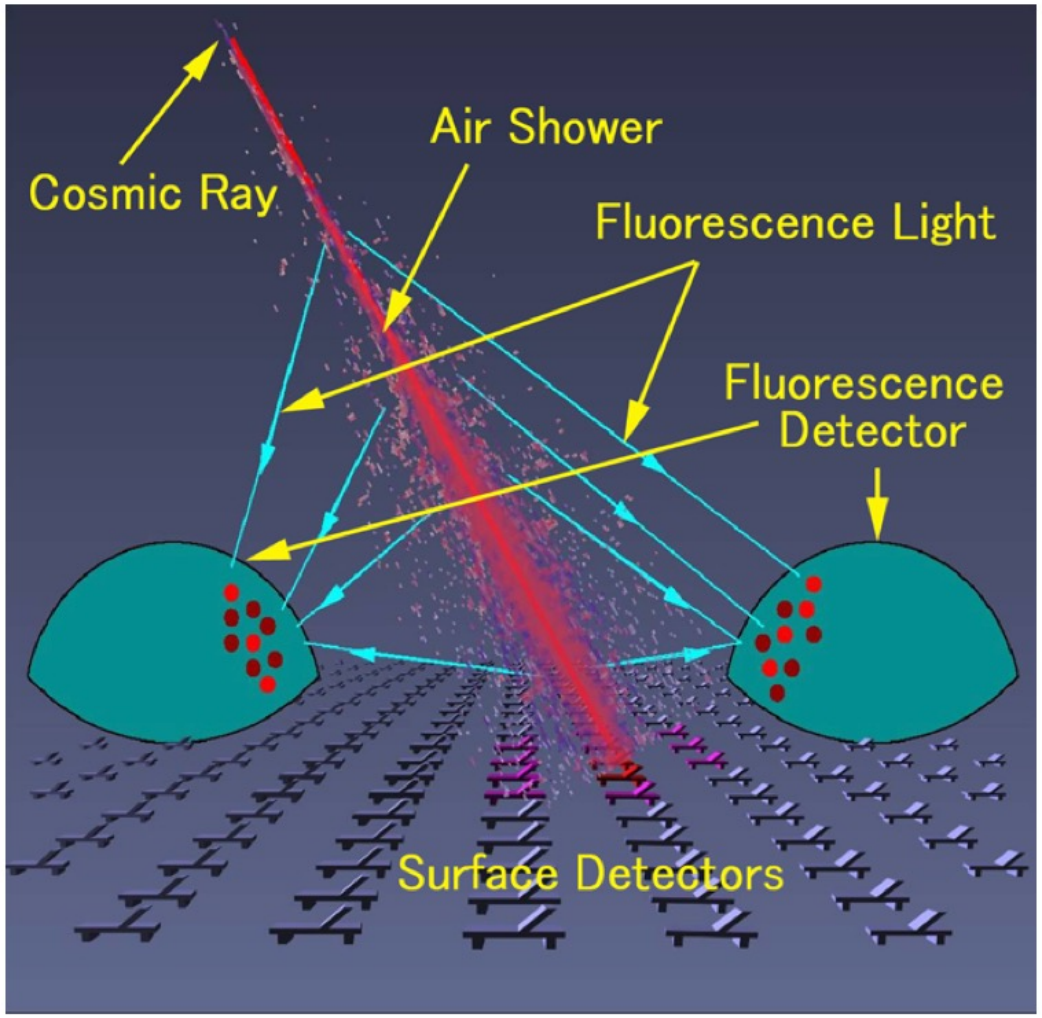
- **Aim**

  Understanding ultra-high energy cosmic rays (UHECRs) by observation
  - Measuring energy, arrival direction, and mass of UHECRs

- **Method**

  Observing cosmic-ray induced air showers with two types of detectors:
  - Surface detectors (**SD**s)
  - Fluorescence detectors (**FD**s)

Overview of the Telescope Array (TA) experiment



SD: measuring the **lateral distribution** of particles in air shower
- pros. ~100% duty cycle
- cons. Not mass sensitive
  Large sys. err. in energy estimation

FD: measuring the **longitudinal development** of air shower
- pros. Mass sensitive, calorimetric obs.
- cons. ~10% duty cycle

SD and FD observations are complementary

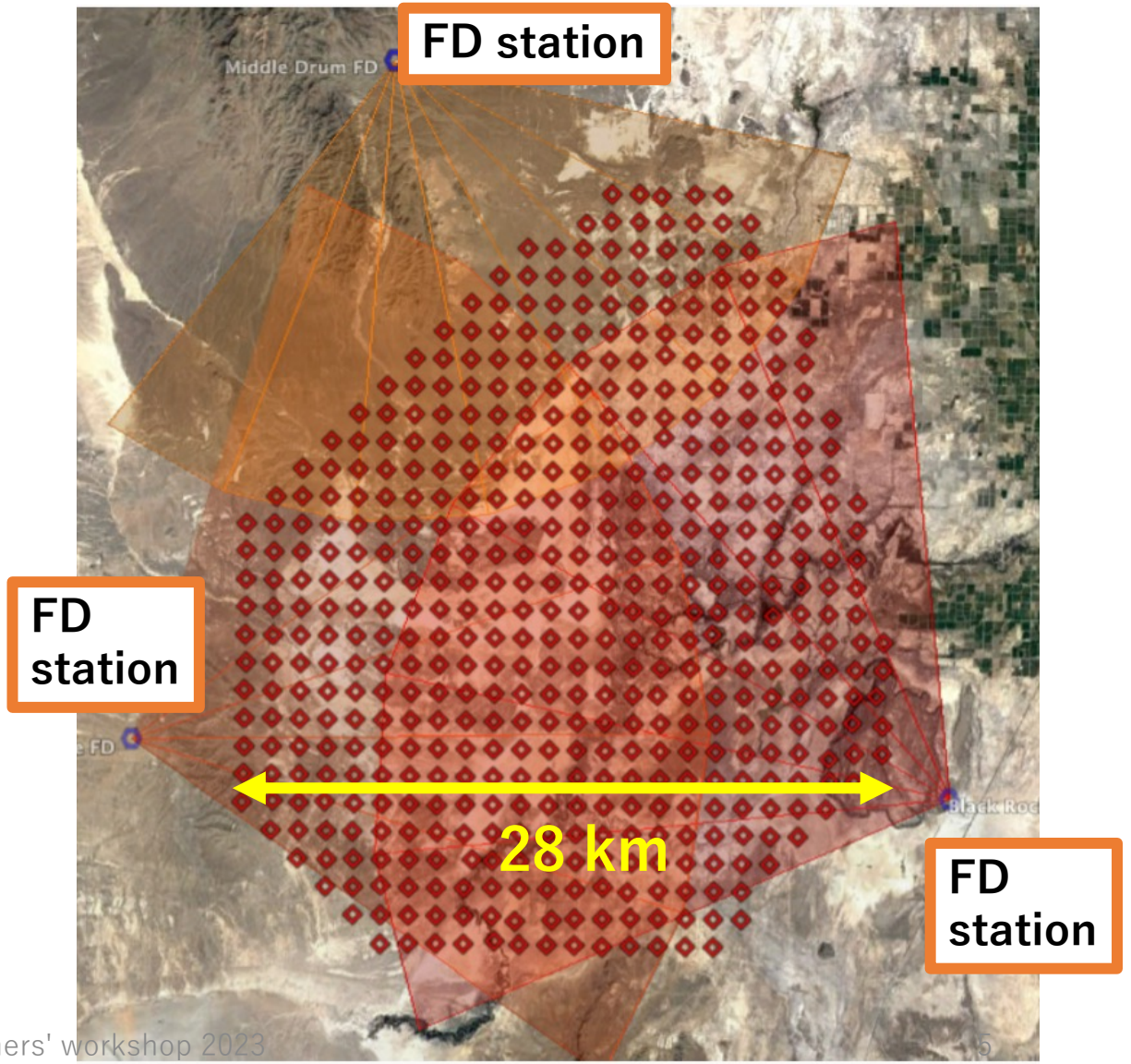
Overview of the Telescope Array (TA) experiment

- Located in Utah, U.S.
  at altitude of 1400 m

- 507 **SD**s (3 $\mathbf{m^2}$ area, 1.2 km spacing)
  covering ~**700 $\mathbf{km^2}$**
  - Largest cosmic-ray observatory
    in the northern hemisphere

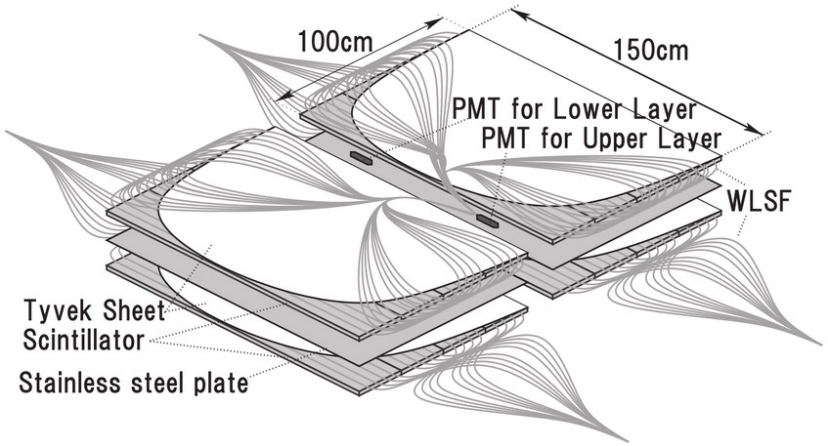
- 3 **FD** stations
  - Looking over SD array for
    hybrid detection

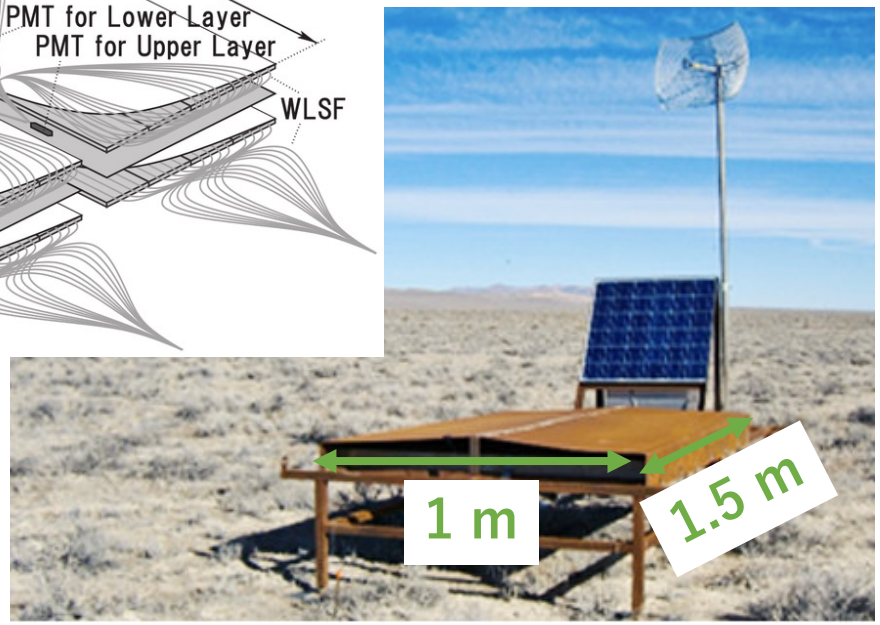
- Started observation in 2008

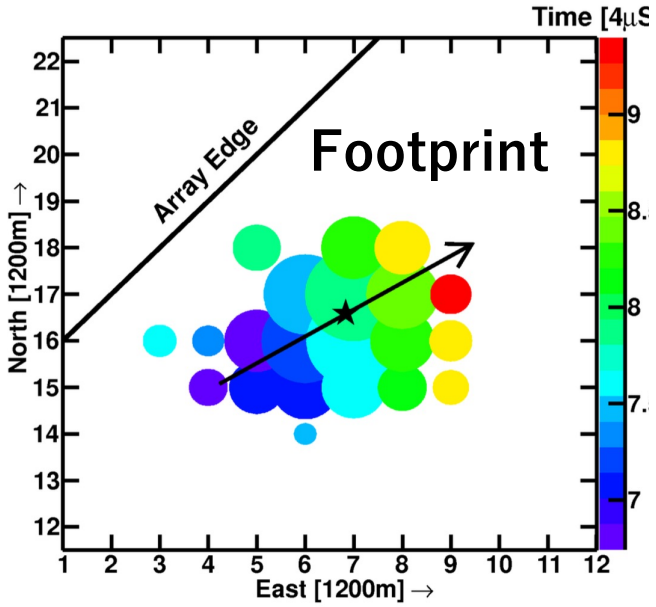


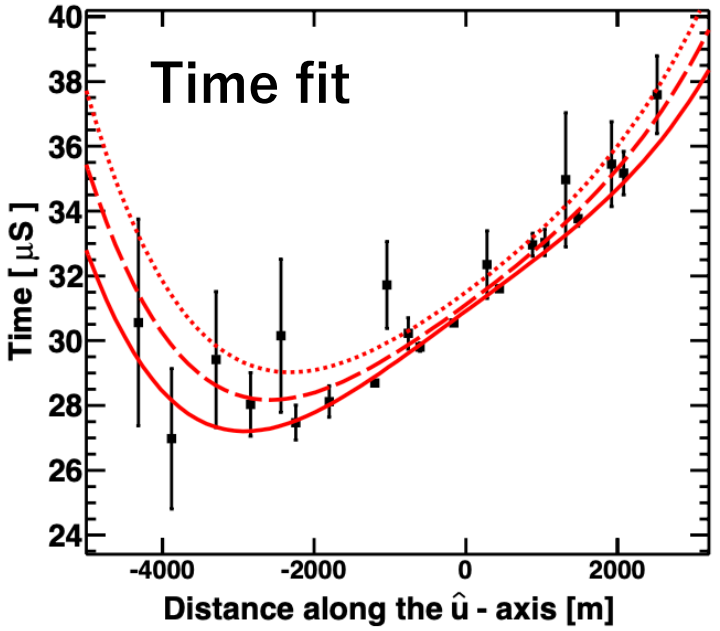
Reconstruction by SD

- 2 layers of plastic scintillators
  (1 m x 1.5 m, thickness: 1.2 cm)
- 12 bit 50 MHz FADC

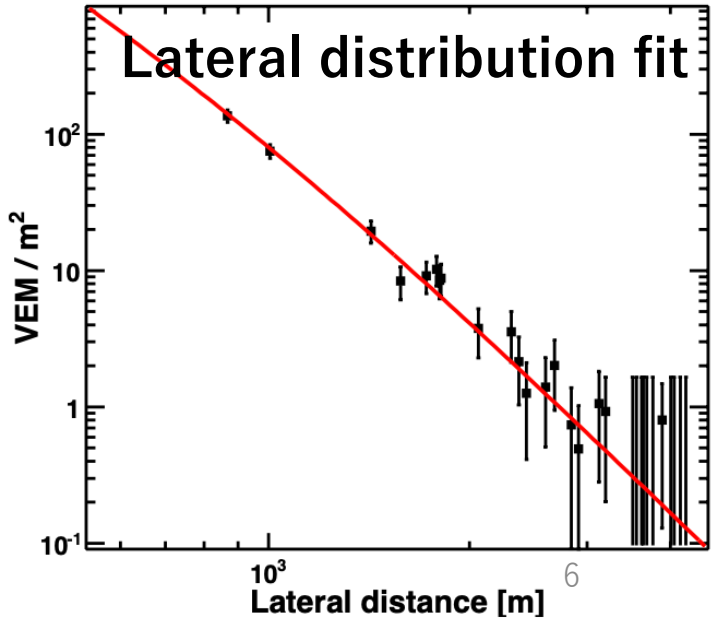








D. Ivanov, doctor thesis (2012)



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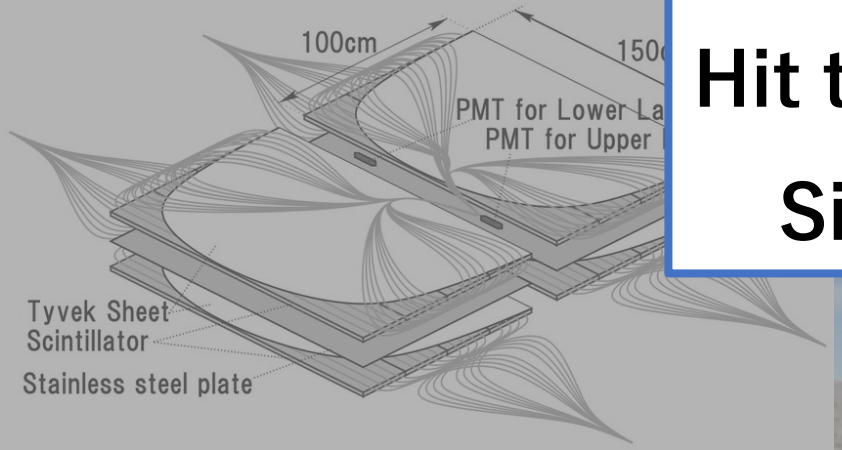
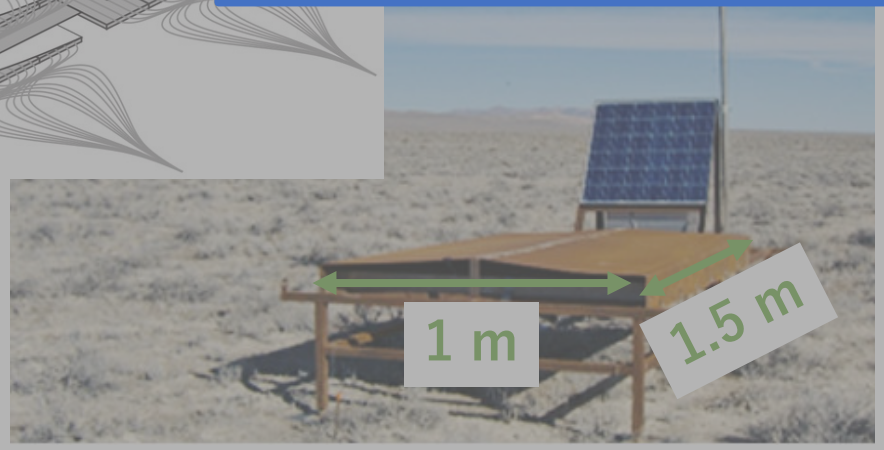
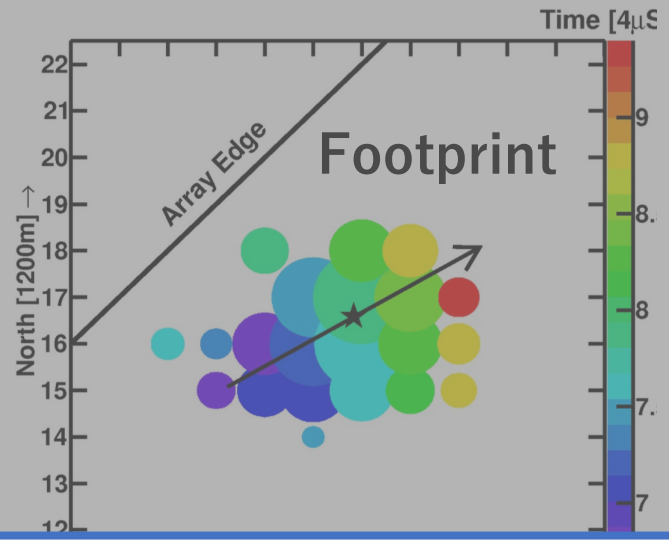
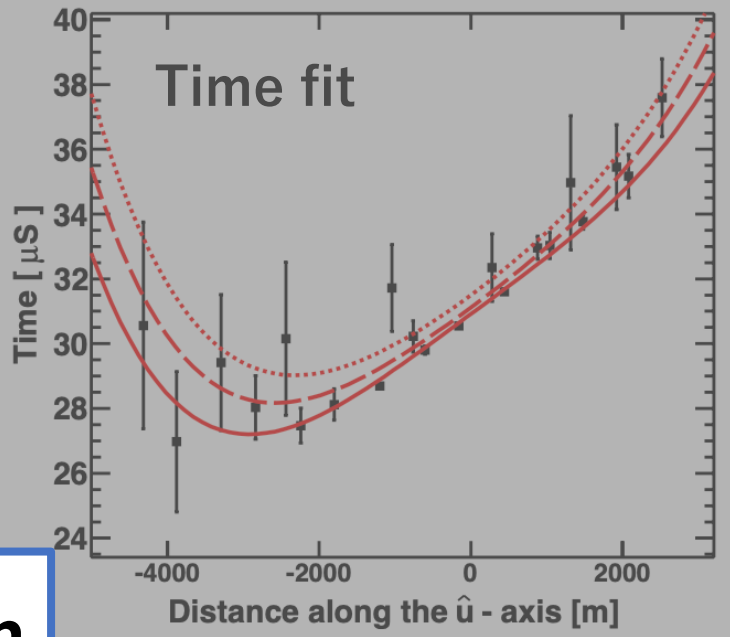




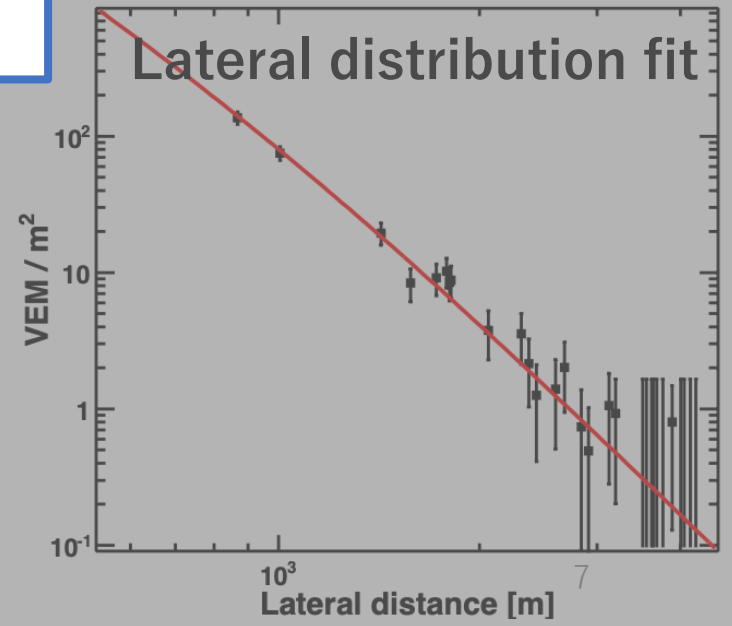




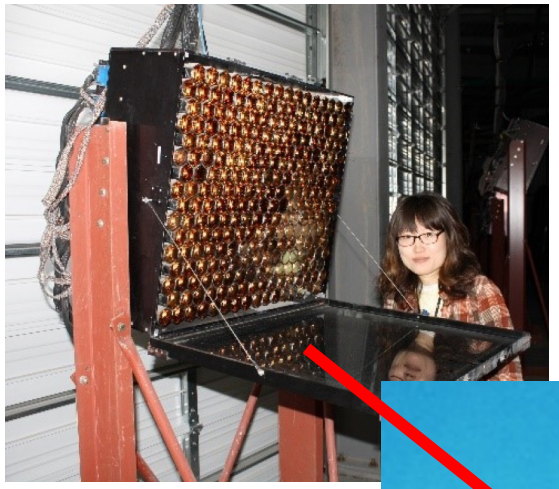
Hit timing → arrival direction

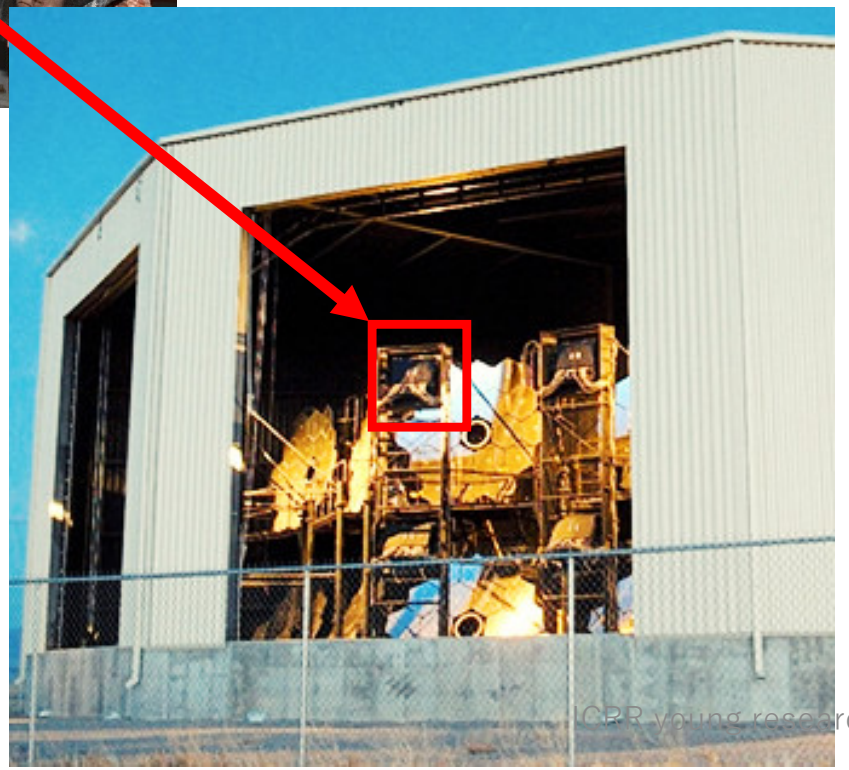
Signal density → energy

D. Ivanov, doctor thesis (2012)

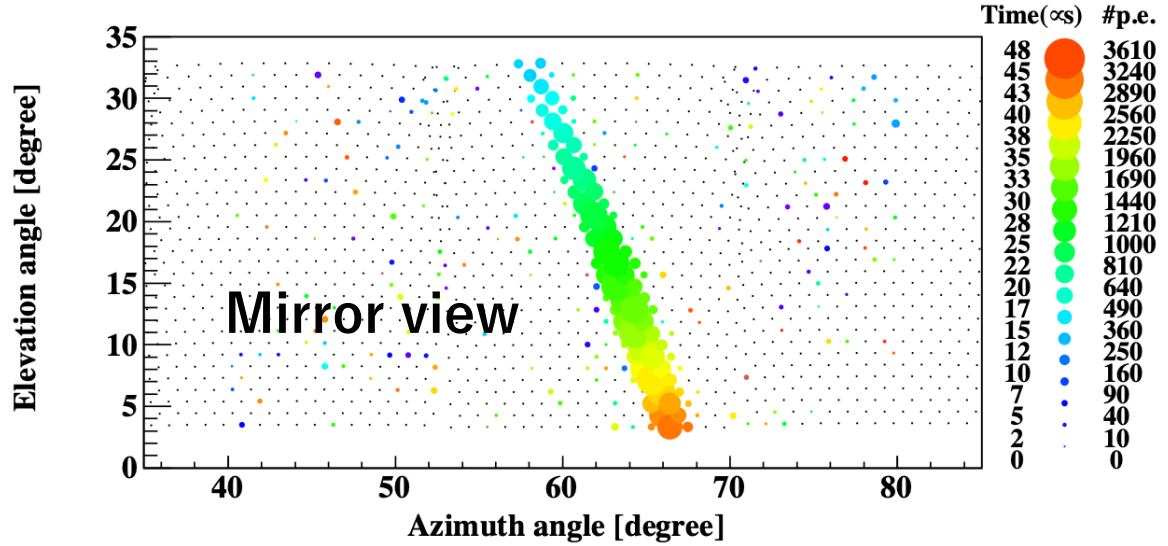


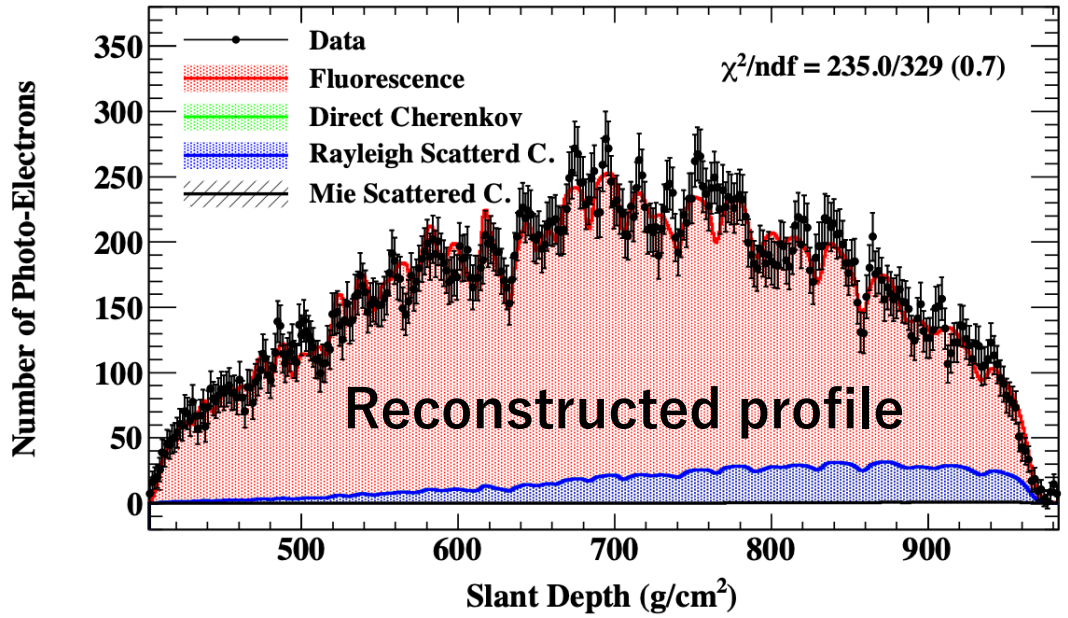
Reconstruction by FD





- **256** PMTs in a camera
- 12—14 telescopes in each station
- Covering 3°– 21° altitude

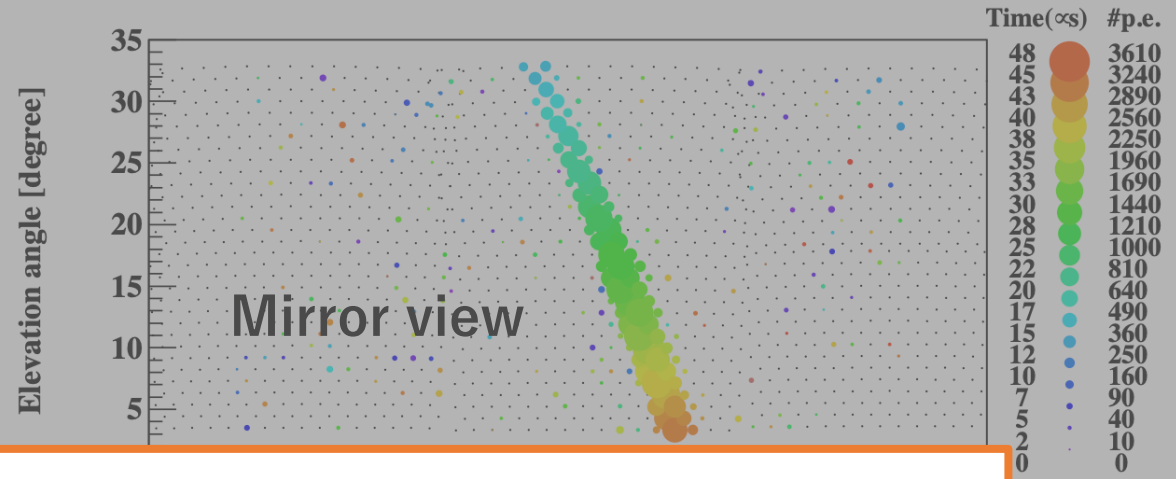




R. U. Abbasi et. al. ApJ, 80, 131-140 (2016)

Reconstruction by FD

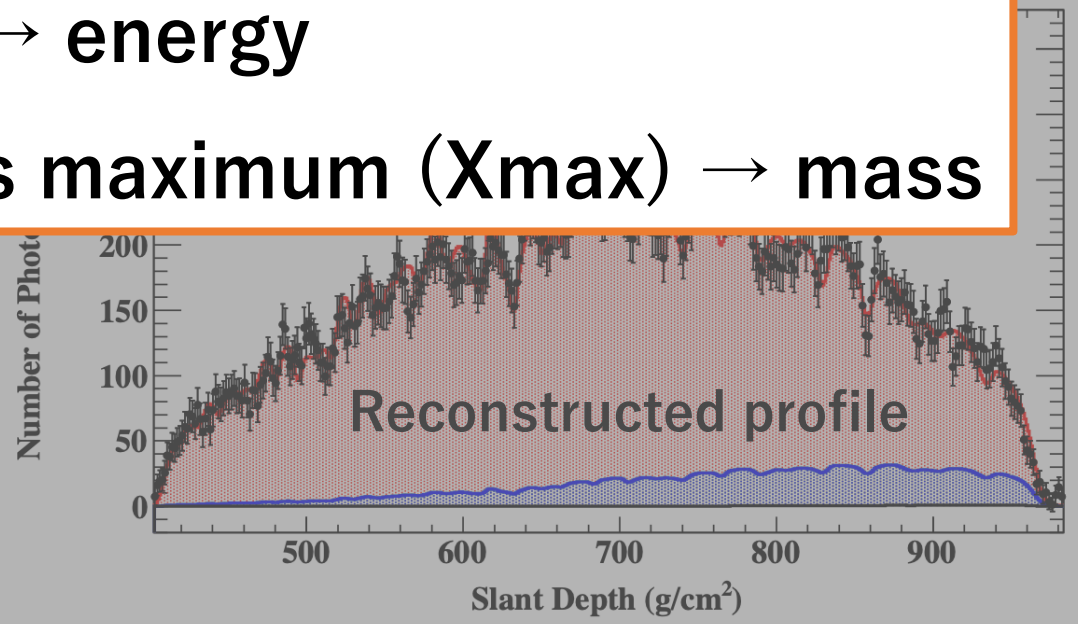
- **256** PMTs in a camera
- 12—14 telescopes in each station
- Covering 3°– 21°



Hit timing & geometry of signals→ arrival direction

Signal size→ energy

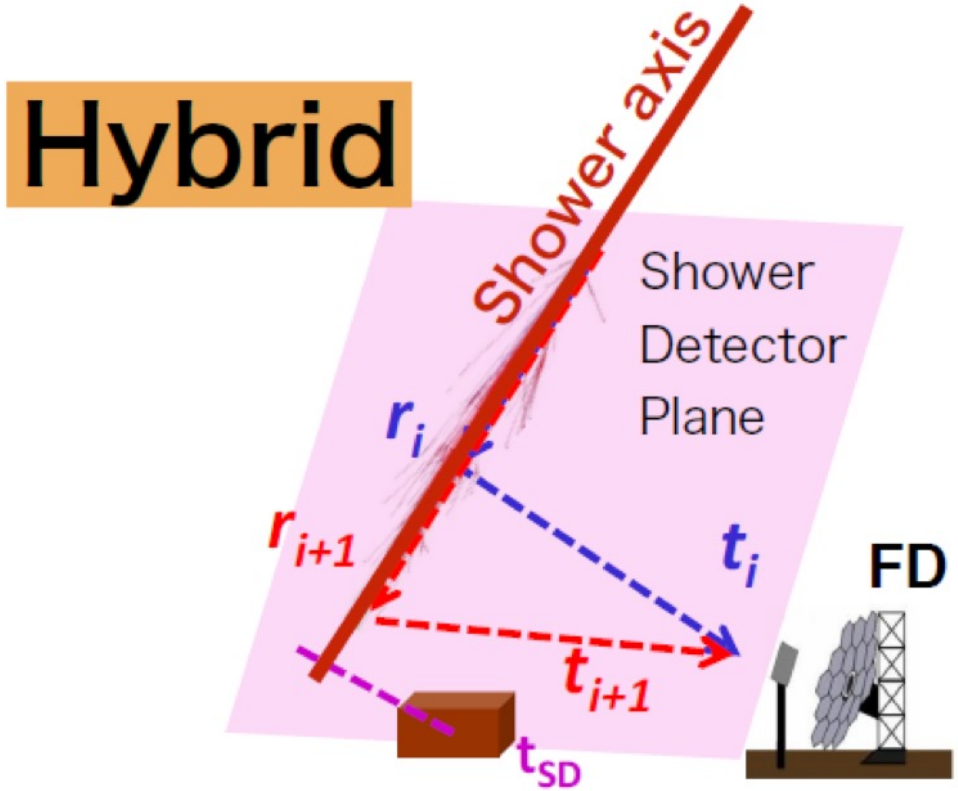
Depth where energy deposit is maximum (Xmax) → mass

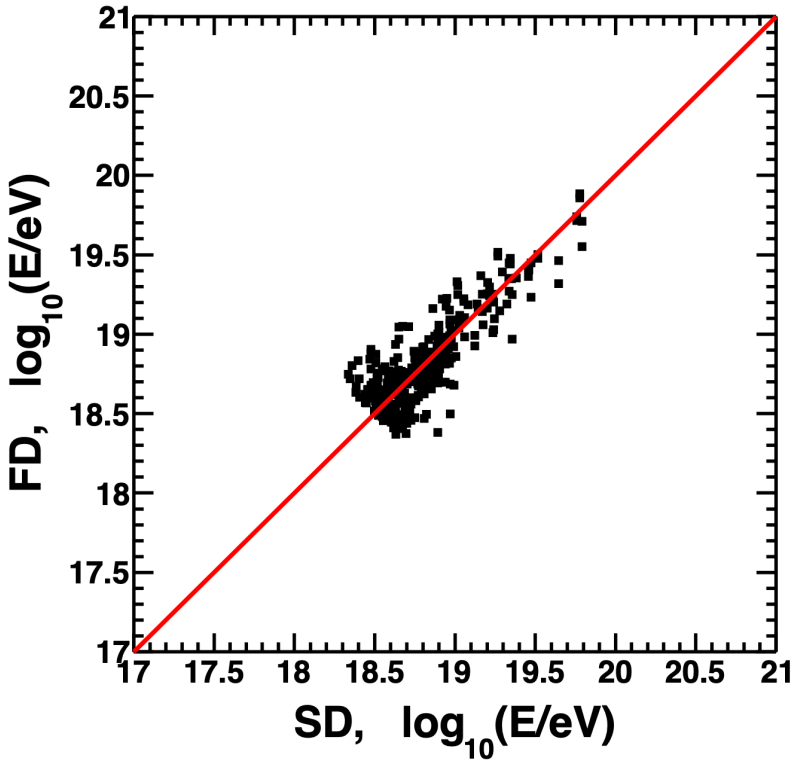


R. U. Abbasi et. al. ApJ, 80, 131-140 (2016)

Hybrid reconstruction

- Simultaneous detection with FD and SD
- Better reconstruction
- Calibrate SD-energy by FD-energy
  - to reduce model dependence of SD energy reconstruction

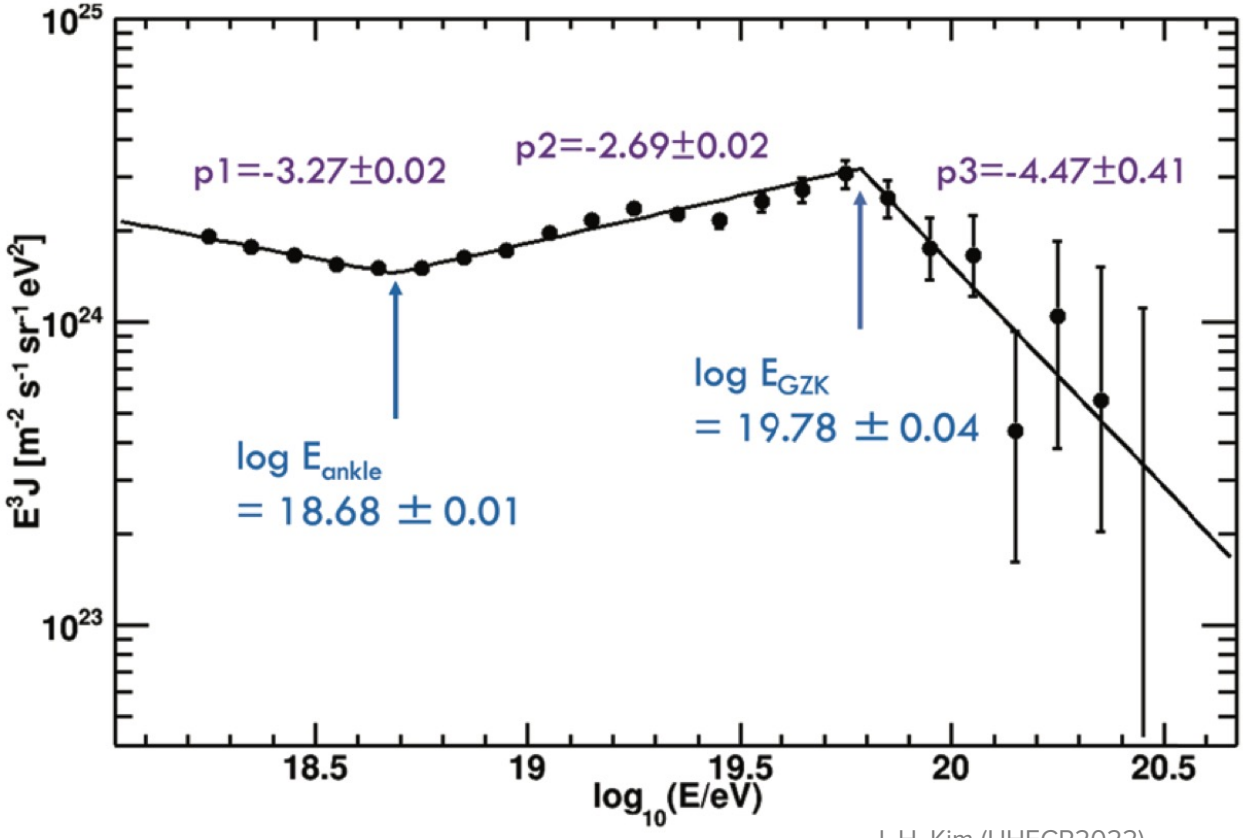




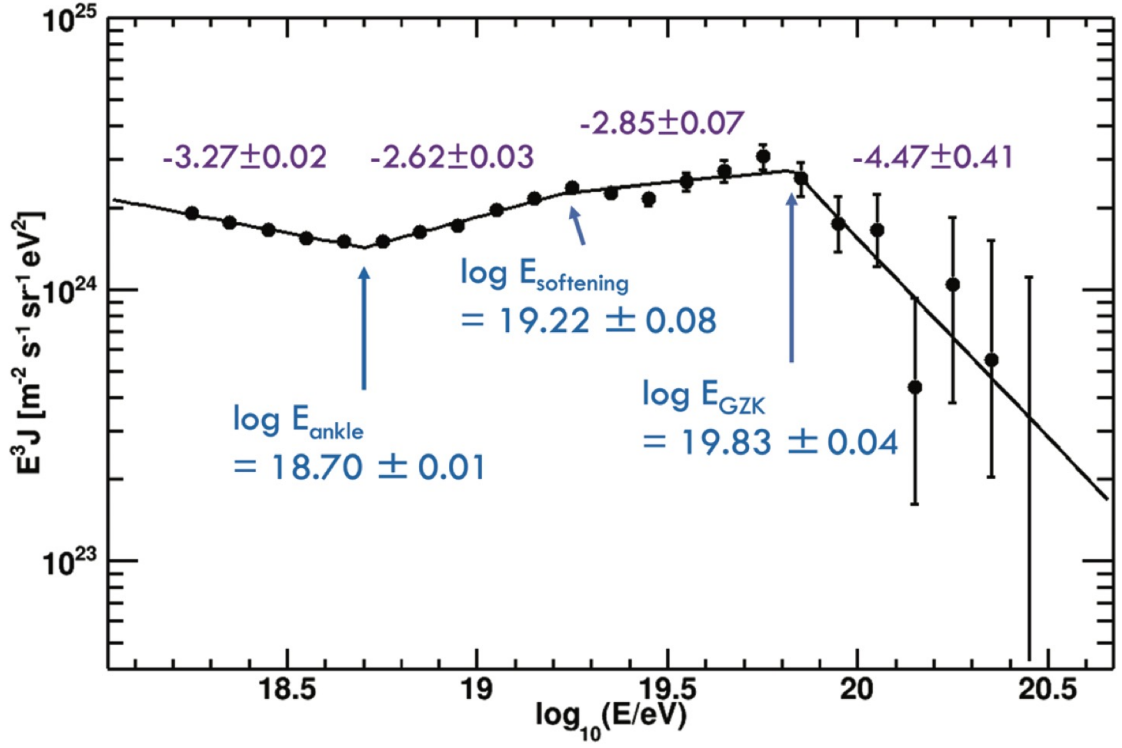
$$E_{SD} = E_{FD}/1.27$$

Energy spectrum

14 years of **TA SD** data
(2008 –2022)



J. H. Kim (UHECR2022)

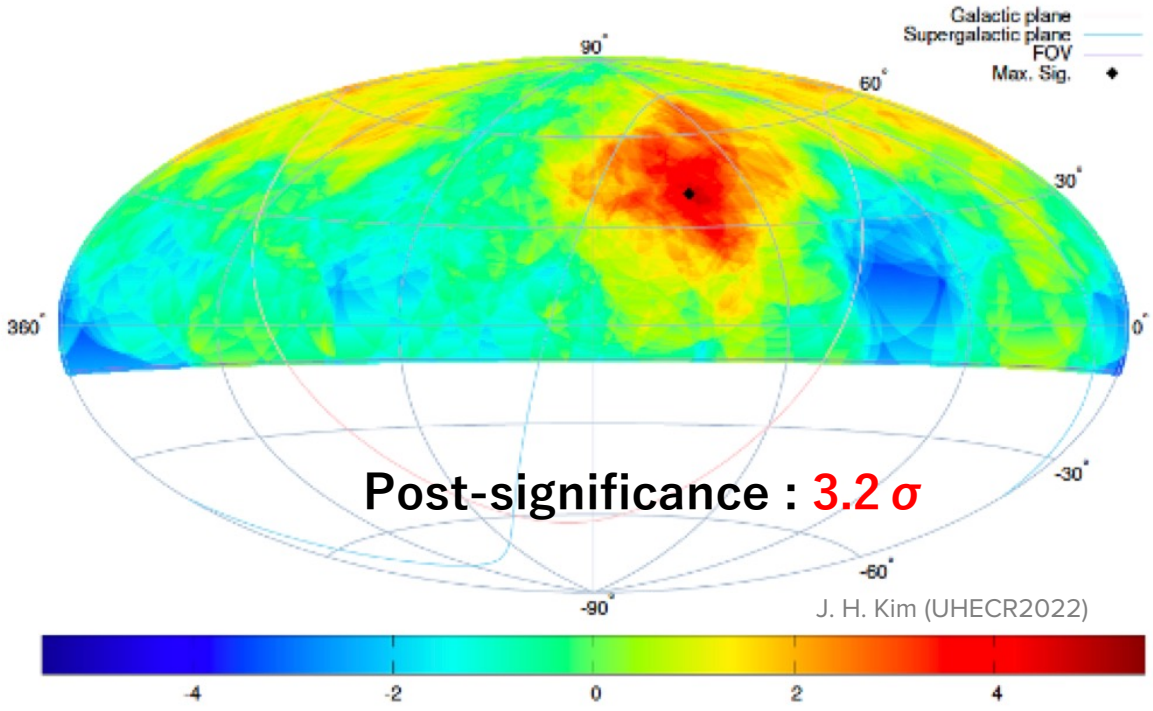


New feature in energy spectrum with a 4.0 σ significance
("shoulder" or "instep")

(Originally observed by Auger)

Pierre Auger Collaboration,
Phys. Rev. Lett. **125**, 121106 (2020)

Anisotropy TA hotspot



14 years of **TA SD** data
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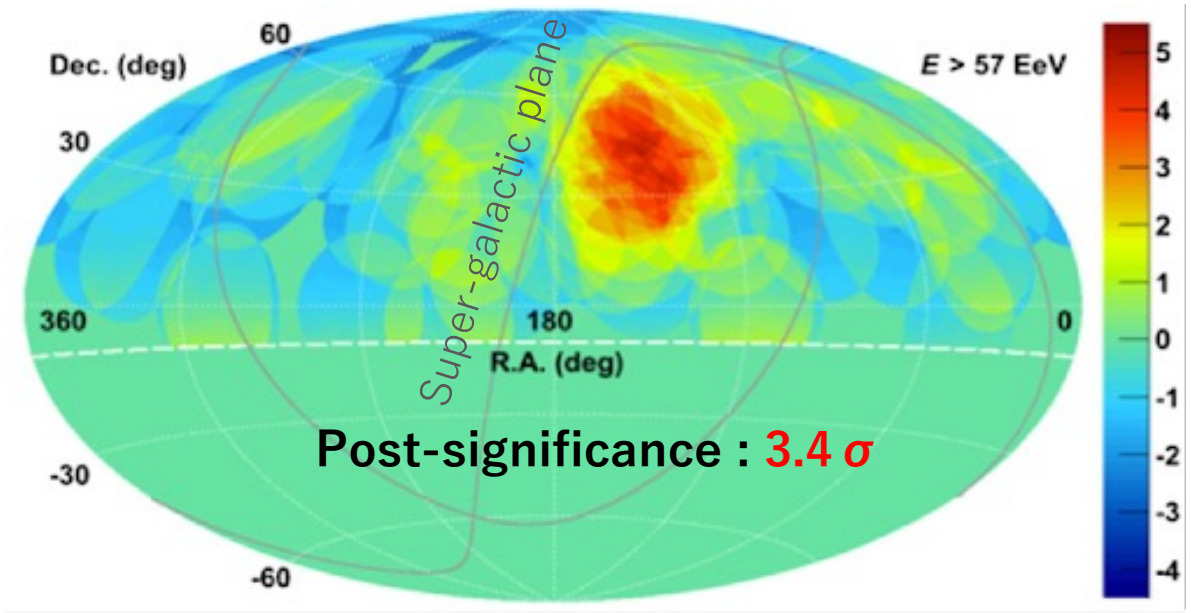
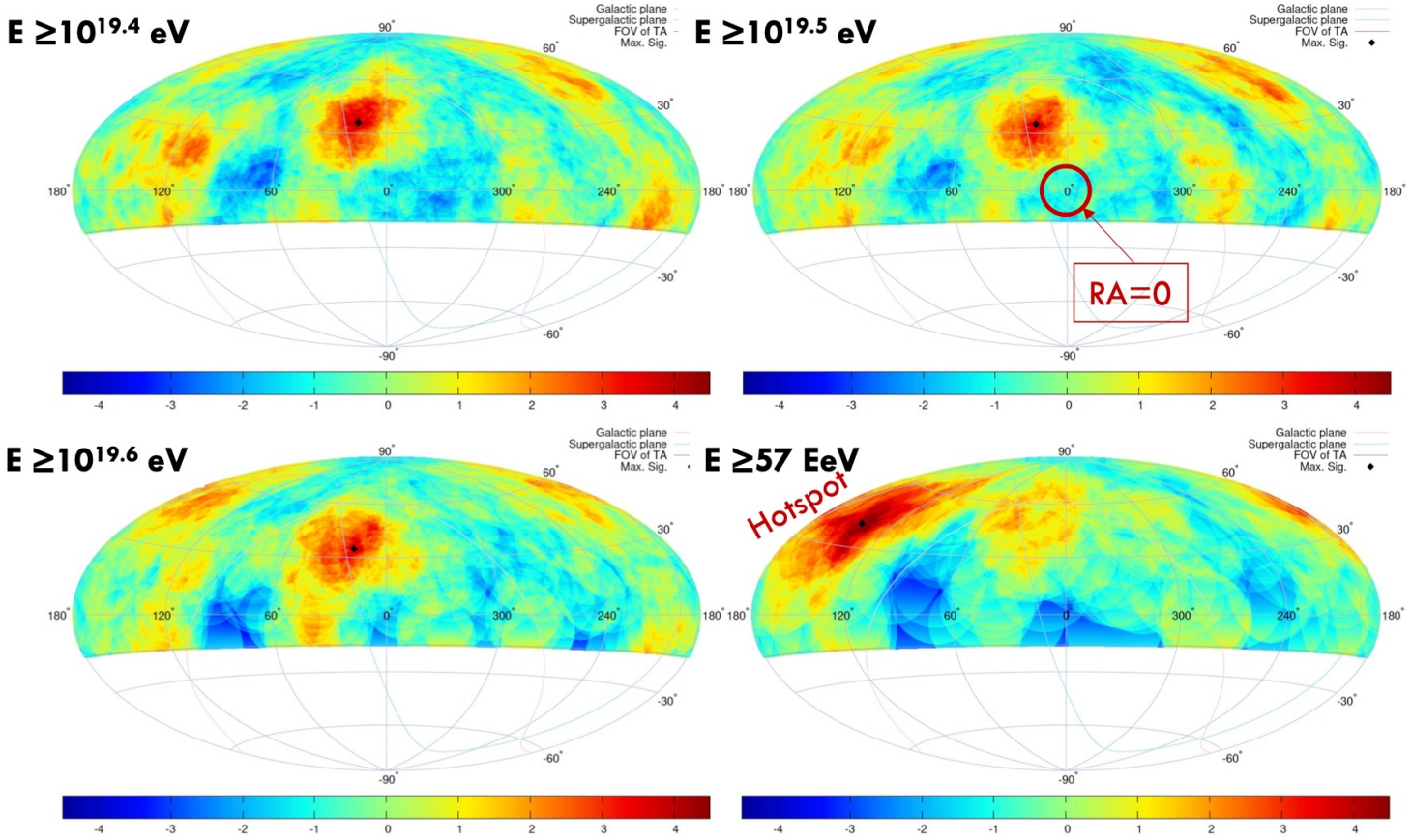


Original hotspot with **5 years** of TA SD data
TA collaboration, *ApJL* **790** L21 (2014)

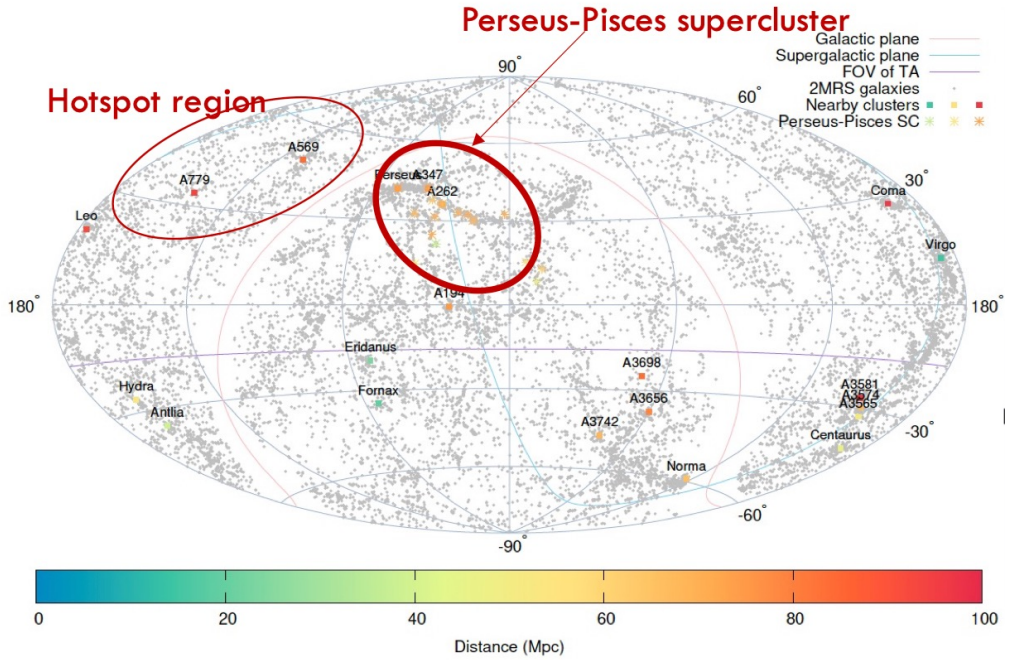
Maximum significance position: (144.0°, 40.5°)

Anisotropy

New intermediate-scale anisotropy



Sky map with nearby galaxies and clusters of galaxies



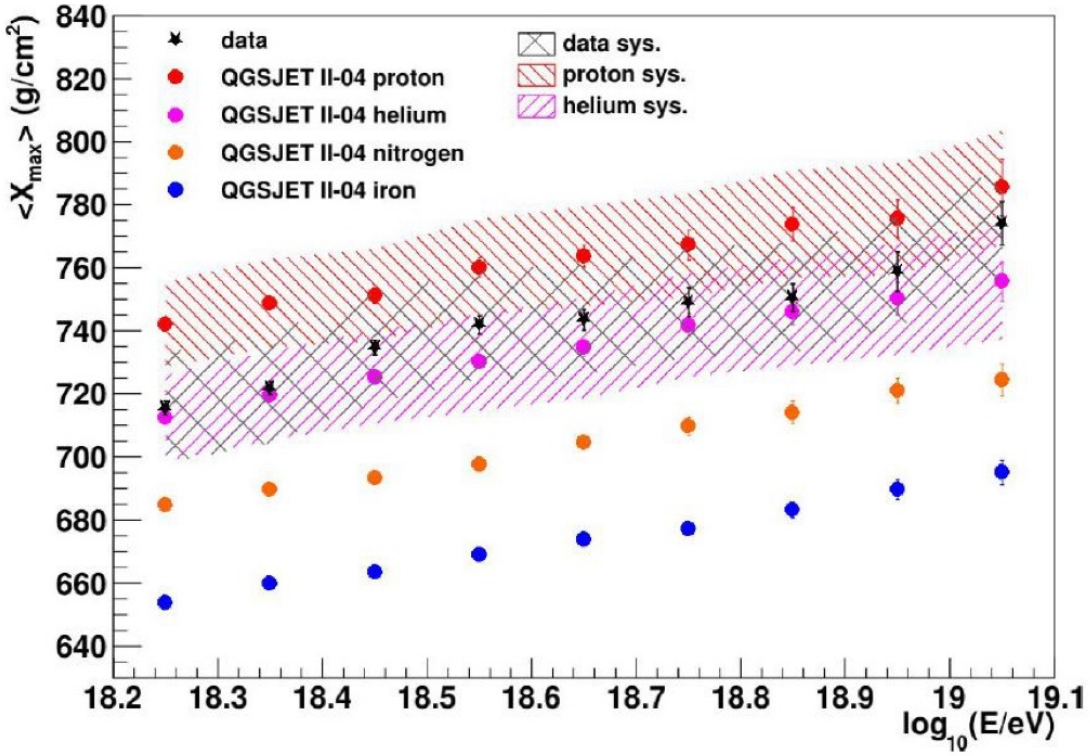
J. H. Kim (UHECR2022)

14 years of **TA SD** data
(2008 –2022)

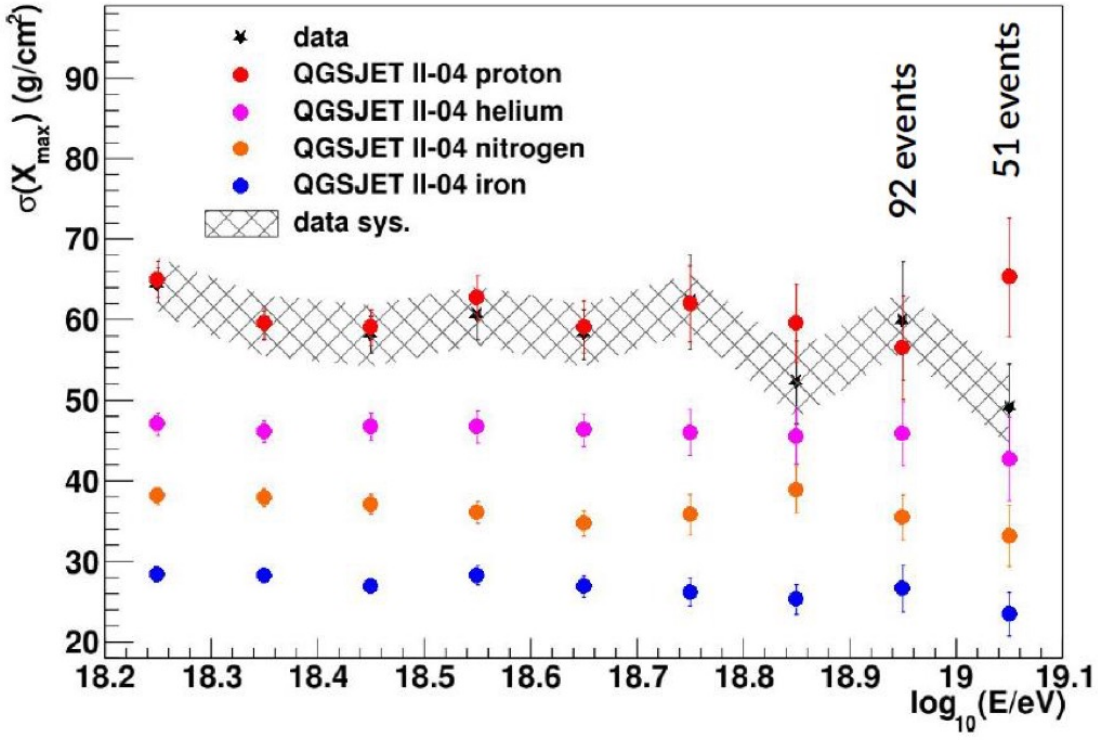
- New excess at lower energy region
  in the direction of **Perseus-Pieces Supercluster**

Composition

<Xmax>



σ (Xmax)



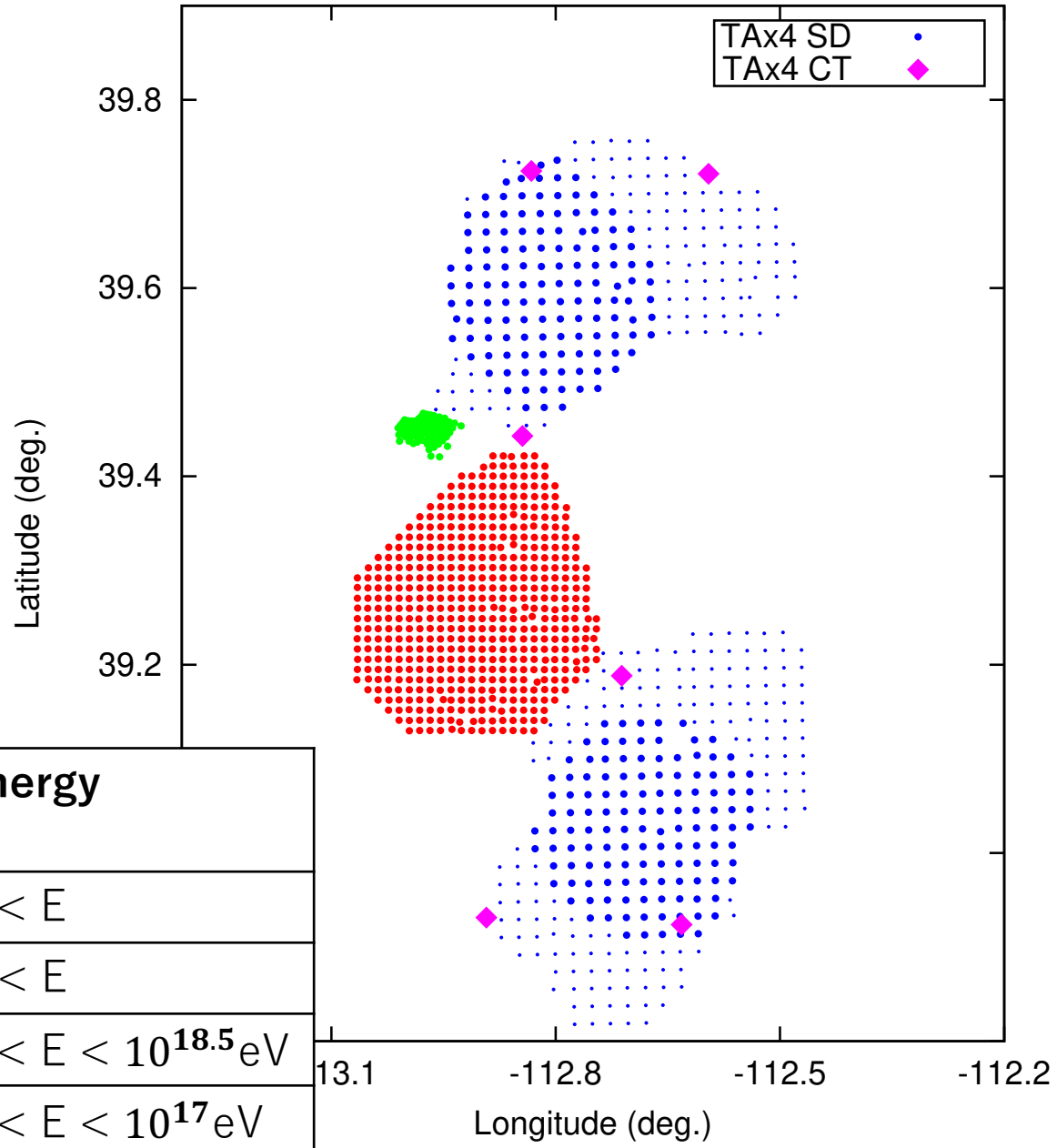
10 years of TA hybrid data: 3560 events after event selection

- Agreement with mixtures of light composition using QGSJET II-04 as a hadronic interaction model in $10^{18.2}\mathrm{eV} - 10^{19.1}\ \mathrm{eV}$

The TA experiment expansion

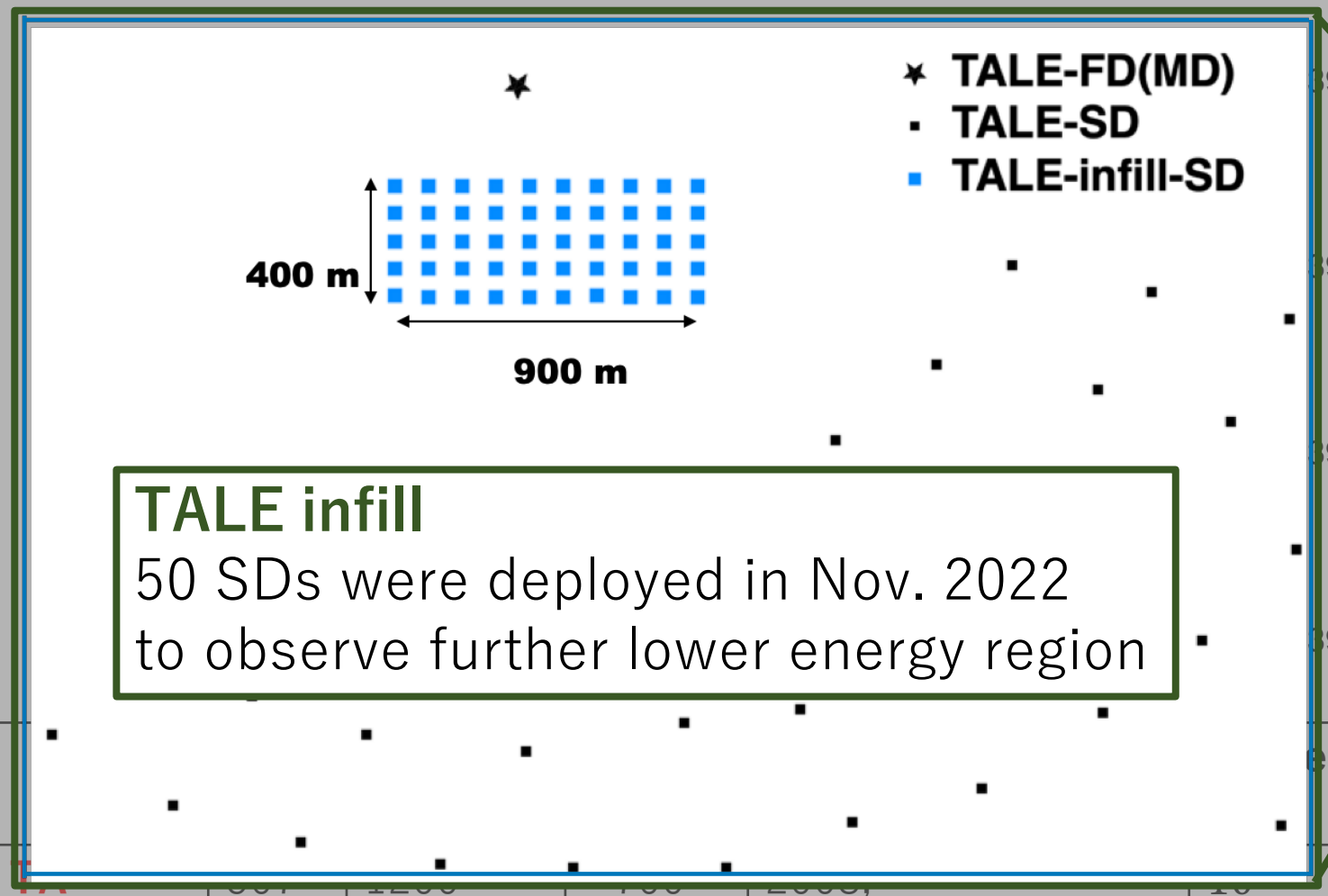
- TA Low energy Extension (**TALE**)
  - Further extension for lower energy (**TALE-infill**) will start observation in near future (this fall/winter)

- **TAx4**: increase the data collection speed for energies greater than 57 EeV
  - Half extension was made in 2019

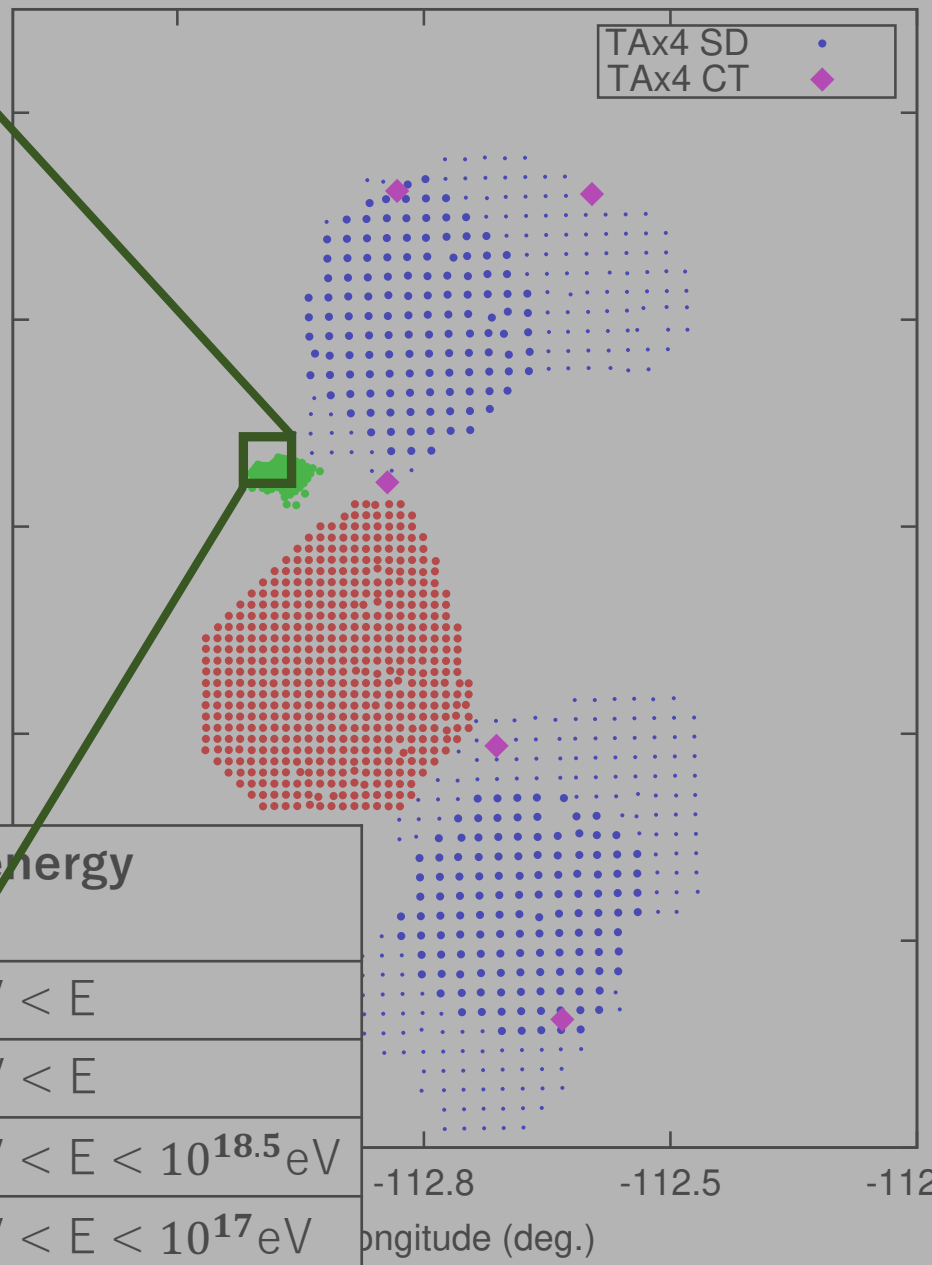


	# of SDs	Spacing [m]	Area [km^2]	Obs. Date (SD)	Target energy
TA	507	1200	~700	2008	10^{18} eV < E
TAx4*	257	2080	~1000	2019	$10^{19.7}$ eV < E
TALE	80	400–600	~20	2017	10^{16} eV < E < $10^{18.5}$eV
TALE infill	50	100	~0.4	(2023)	10^{15} eV < E < 10^{17}eV

* Additionally deployed part, about half of the final plan



TALE infill
50 SDs were deployed in Nov. 2022
to observe further lower energy region



					et energy
TA	507	1200	~700	2008,	$10^{19.7}$ eV < E
TAx4*	257	2080	~1000	2019, 2019(2020)	$10^{19.7}$ eV < E
TALE	80	400–600	~20	2017, 2013	10^{16} eV < E < $10^{18.5}$eV
TALE infill	50	100	~0.4	(2023)	10^{15} eV < E < 10^{17}eV

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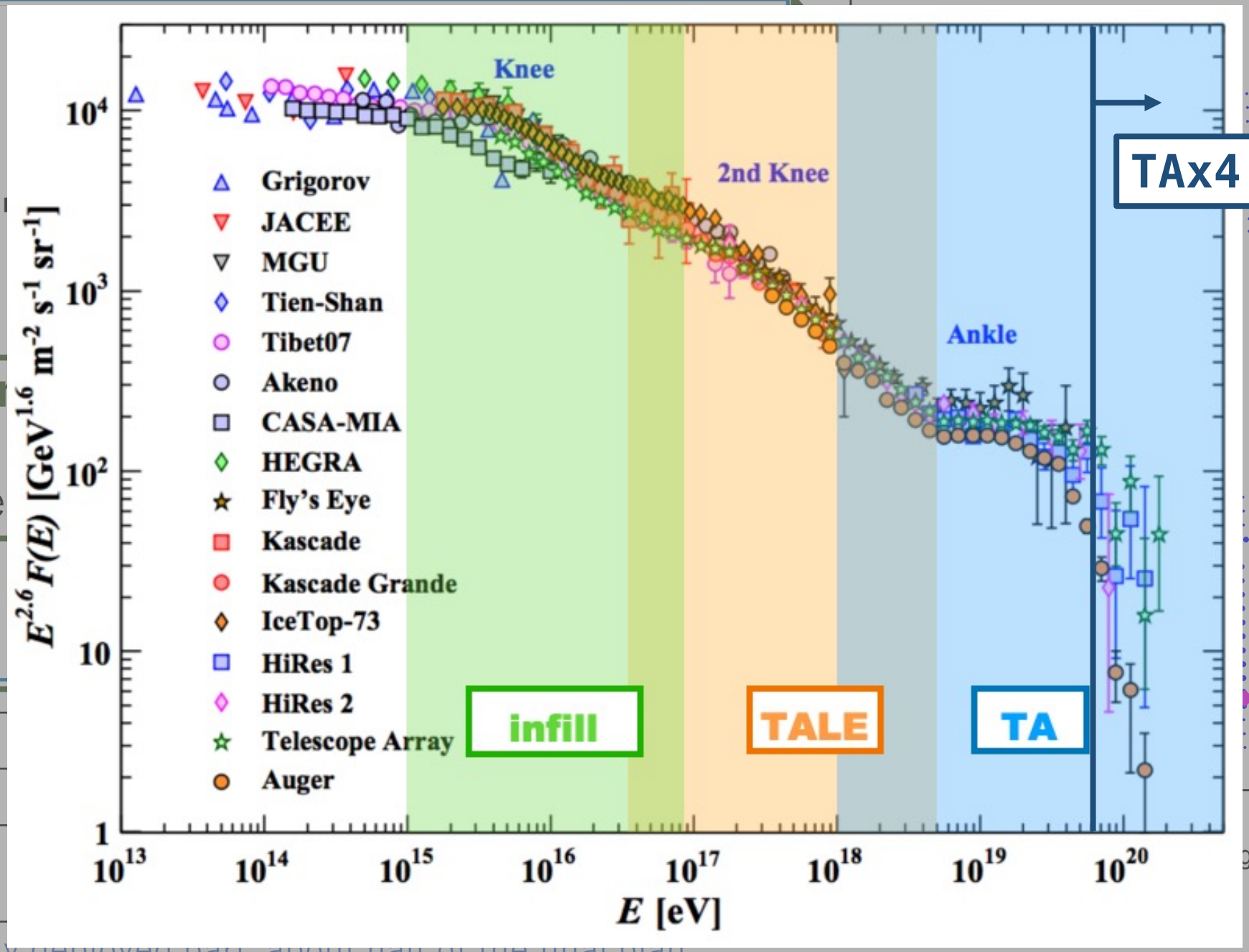
TALE in
50 SDs
to obse

TA	507
TAx4*	257
TALE	80
TALE infill	50



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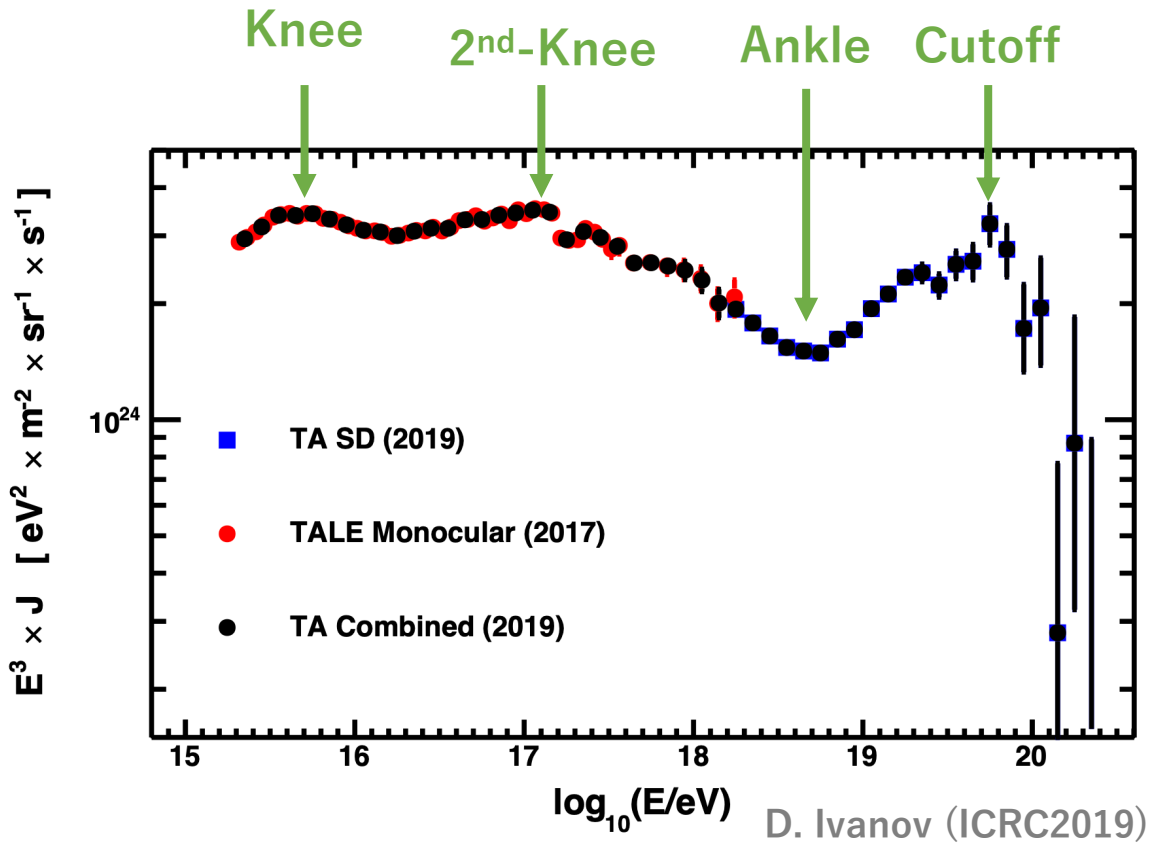
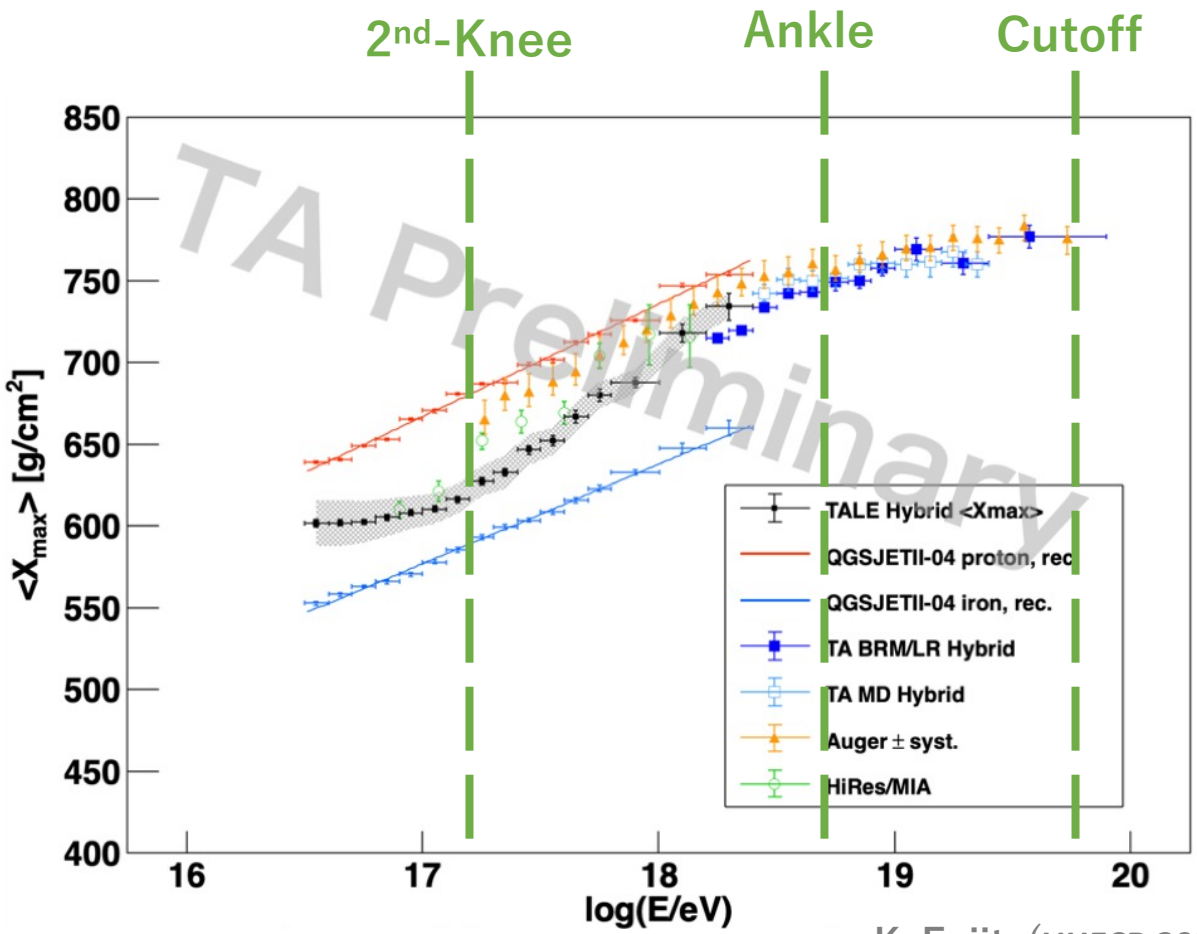
Energy spectrum & composition



D. Ivanov (ICRC2019)

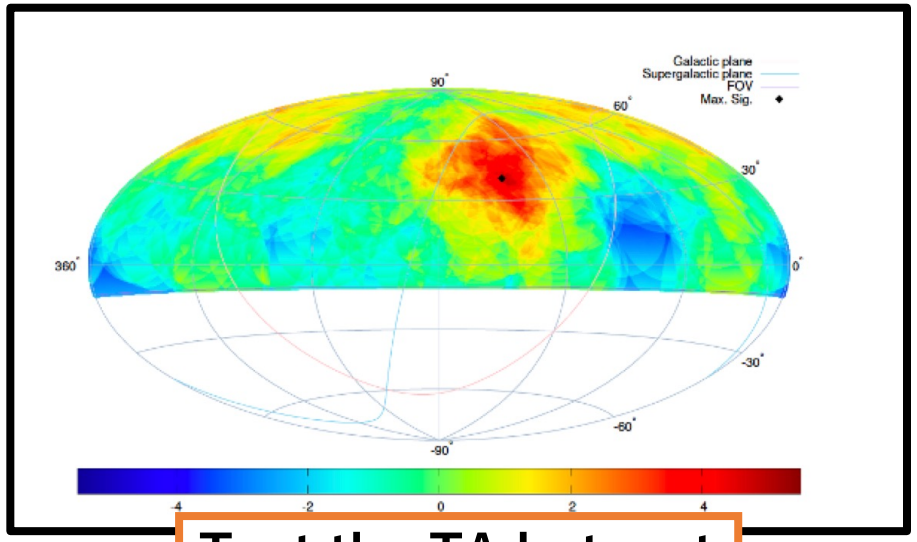
22 months of **TALE FD**
11 years of **TA SD**



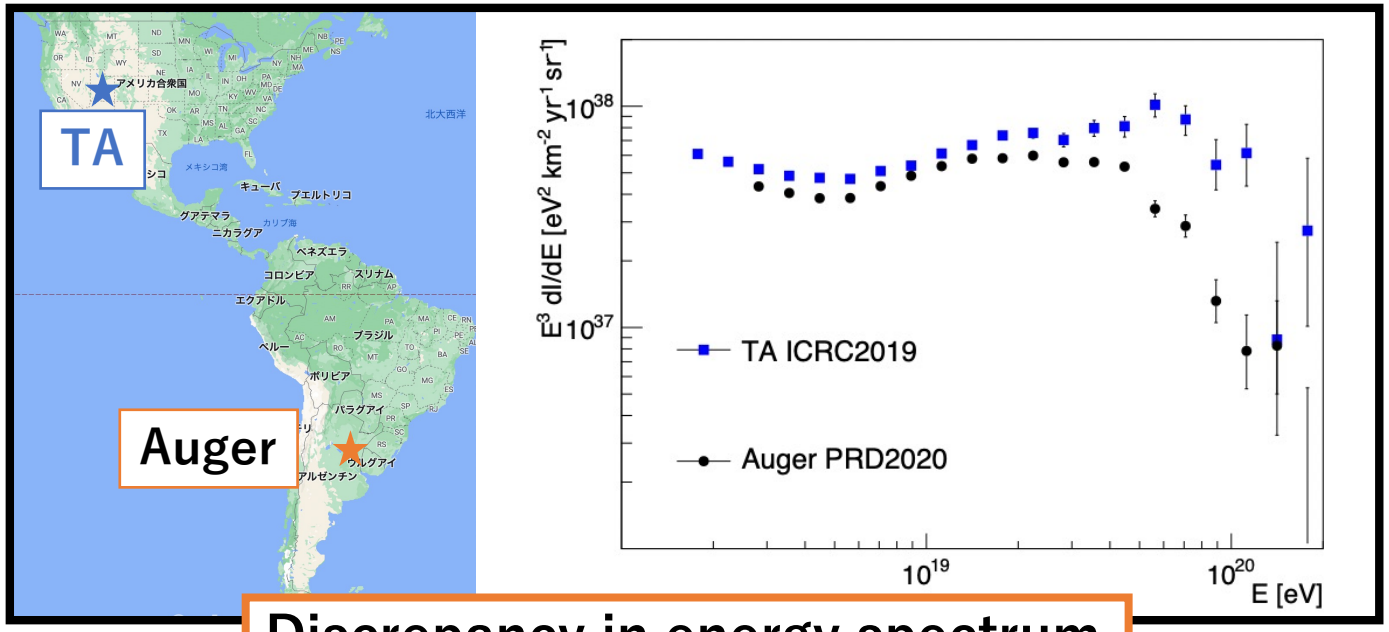
K. Fujita(UHECR 2022)

4 years of **TALE Hybrid**
8.5 years of **TA Hybrid**

TAx4 experiment



Test the TA hotspot



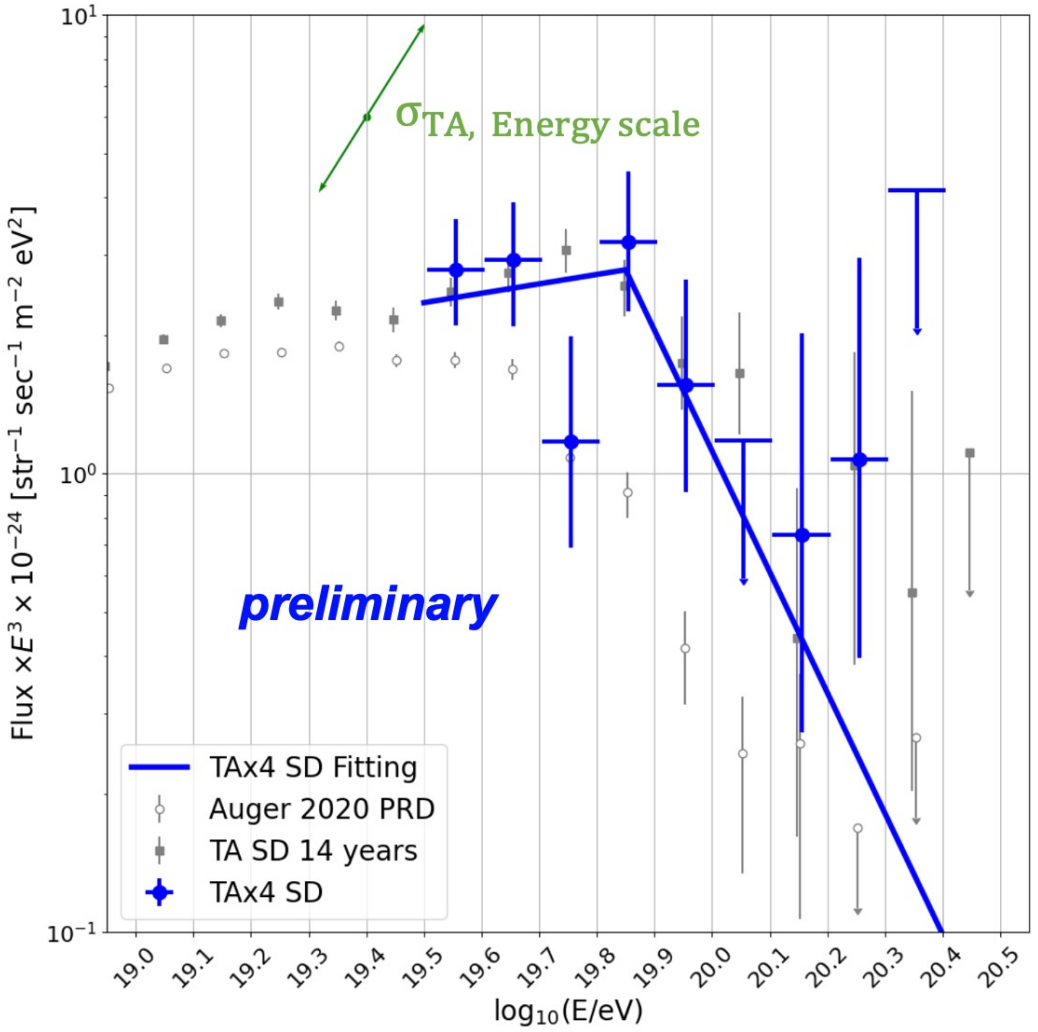
Discrepancy in energy spectrum b/w Auger & TA

Not many highest energy events: ~35 events ($E > 10^{20}$ eV) (TA + Auger)

We need more statistics at the highest energy region

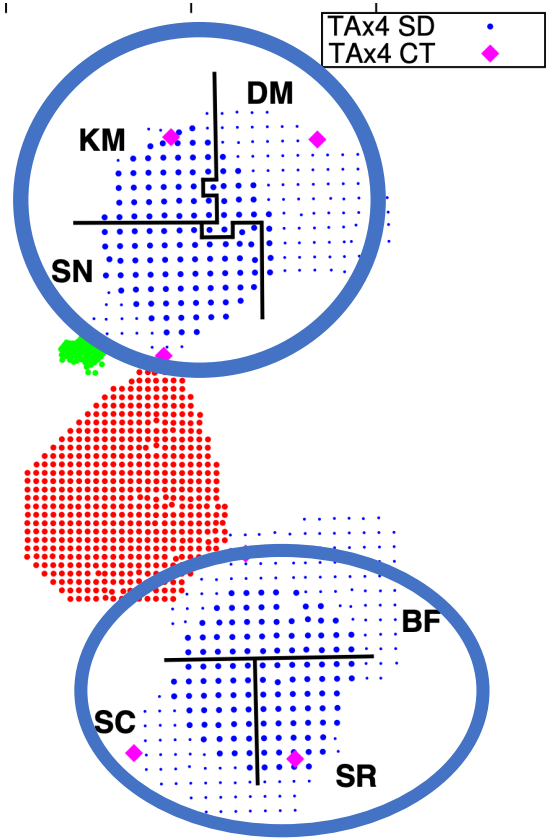
→ TAx4 !

TAx4 experiment



Energy spectrum

- 3 years of TAx4 SD
  - In this period, 6 sub-arrays operated independently
- Consistent with TA SD energy spectrum including cutoff structure



Prospects

- Inter-tower trigger was implemented in Oct. 2022
  → Increasing the aperture
- Data analysis is ongoing

Summary

- The TA experiment observes UHECRs in the Northern Hemisphere
- **Energy spectrum** ($10^{15.5}$ eV—$10^{20.5}$ eV)
  - Some features: Knee, 2nd-Knee, Ankle, Shoulder(Instep), Cutoff
- **Mass composition** ($10^{16.5}$ eV—$10^{19.1}$ eV)
  - Agreement with light composition in $10^{18.2}$ eV—$10^{19.1}$ eV
  - <Xmax> break around 2nd-knee ($\sim 10^{17.1}$ eV)
- **Anisotropy**
  - TA hotspot for E > 57 EeV = $10^{19.76}$ eV: **3.2** σ with 14 years of TA SD data
  - New excess in direction of PPSC for E > $10^{19.4}$ eV

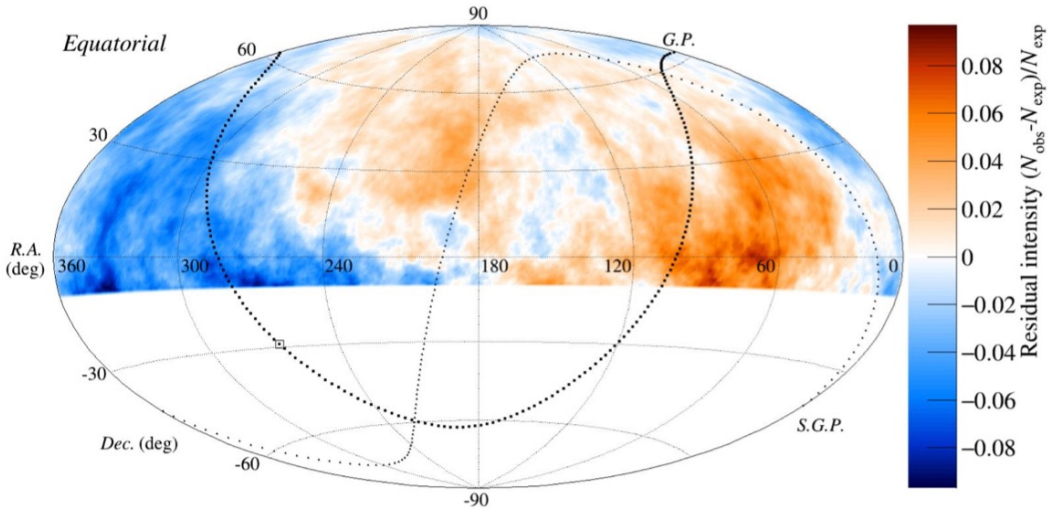
- TALE infill (for 10^{15} eV < E < $10^{16.5}$ eV)
  - It will start observation in near future
- TAx4 (for E > $10^{19.7}$ eV)
  - Energy spectrum is consistent with TA SD energy spectrum

Backup

Anisotropy

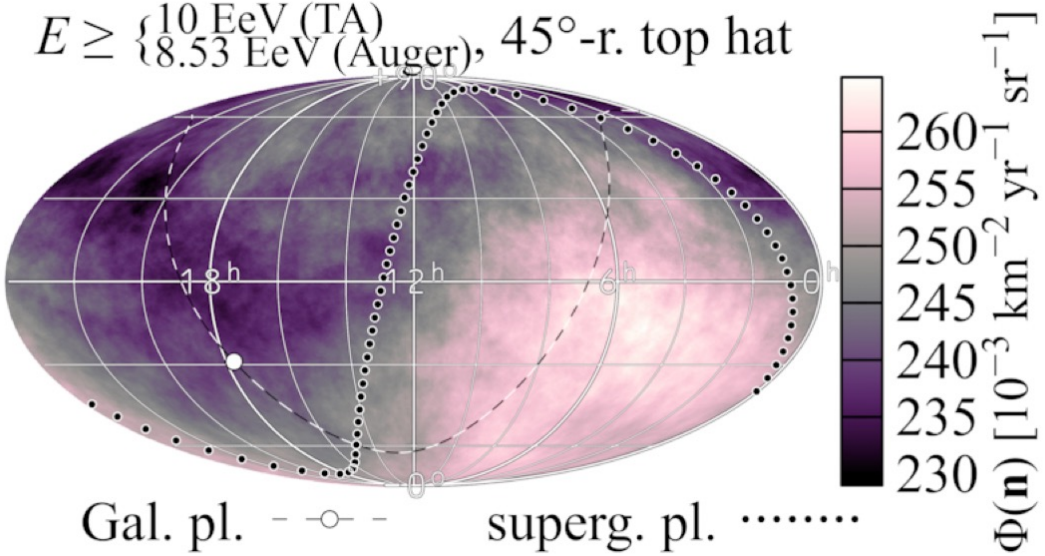
Large-scale anisotropy

TA 14 years: 395 events $E_{TA} \geq 40.5$ EeV
Auger 17 years: 2635 events $E_{Auger} \geq 32$ EeV



TA

R. U. Abbasi et al ApJL 898 L28 (2020)



Auger + TA

A. di Matteo (UHECR2022)

・Dipole analysis
→ UHECRs with E > 10^{19} eV are extra-galactic dominant

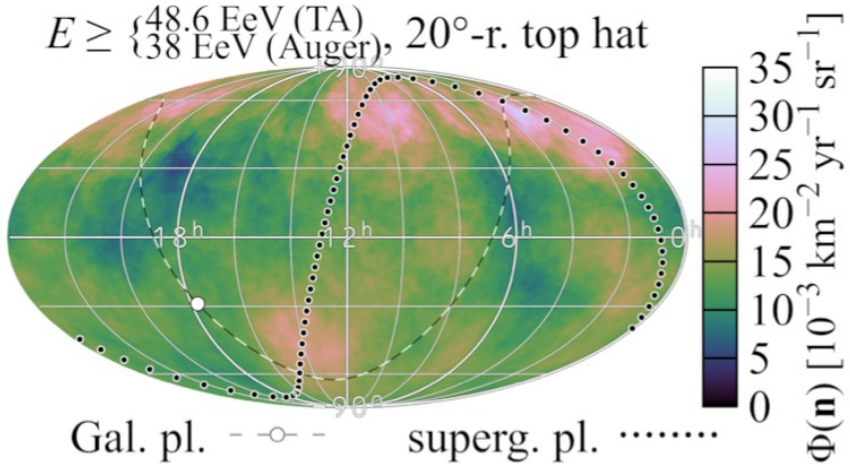
(original paper: *Science* 357 (2017) 6537, 1266-1270)

Anisotropy Correlation with galaxies

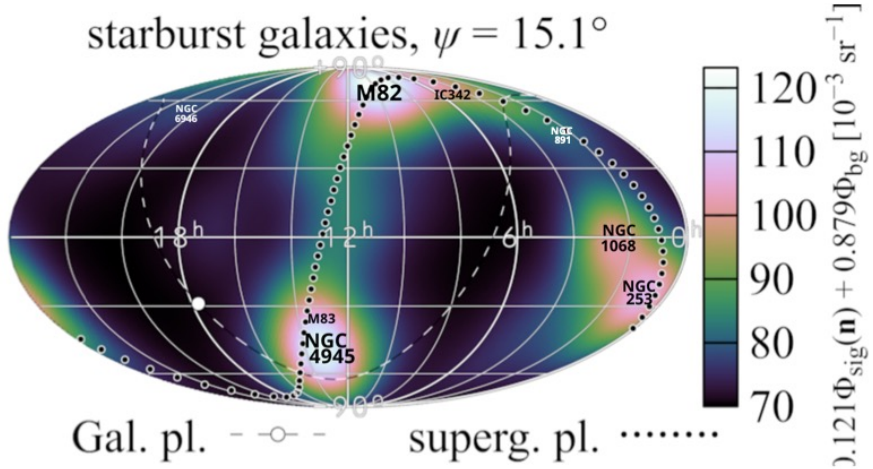
TA 14 years: 395 events $E_{TA} \geq 40.5$ EeV
Auger 17 years: 2635 events $E_{Auger} \geq 32$ EeV

A. di Matteo presentation at UHECR2022

catalogue	$E_{min}^{(Auger)}$	$E_{min}^{(TA)}$	ψ [deg]	f [%]	TS	significance
all galaxies	40 EeV	51 EeV	29^{+11}_{-12}	41^{+29}_{-18}	14.3	$2.7\sigma_{global}$
starburst	38 EeV	49 EeV	$15.1^{+4.6}_{-3.0}$	$12.1^{+4.5}_{-3.1}$	31.1	$4.6\sigma_{global}$

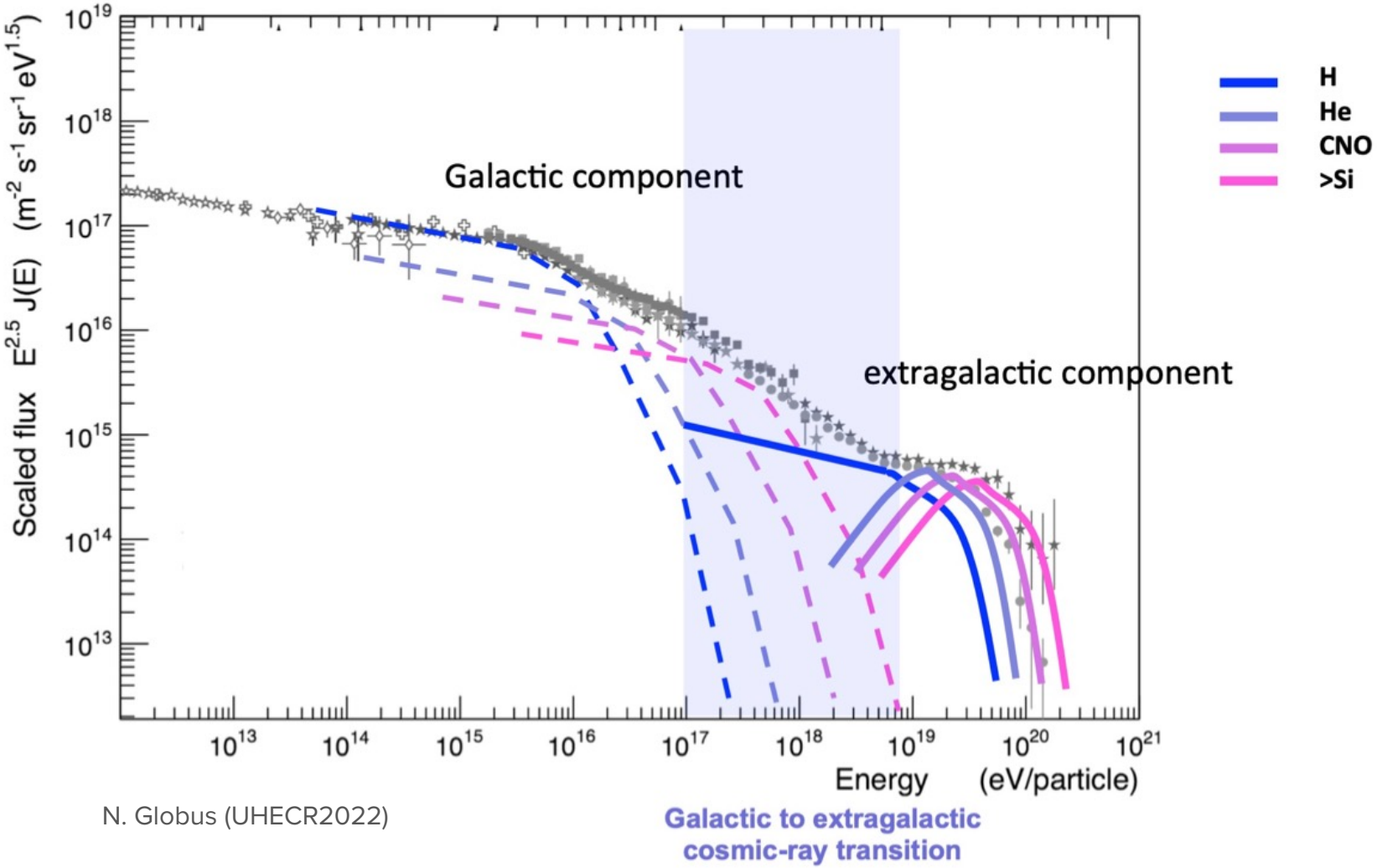


TA-Auger Obs.



Model: starburst galaxy origin

・Best correlation with starburst galaxies
- However, only ~12% can be explained



N. Globus (UHECR2022)