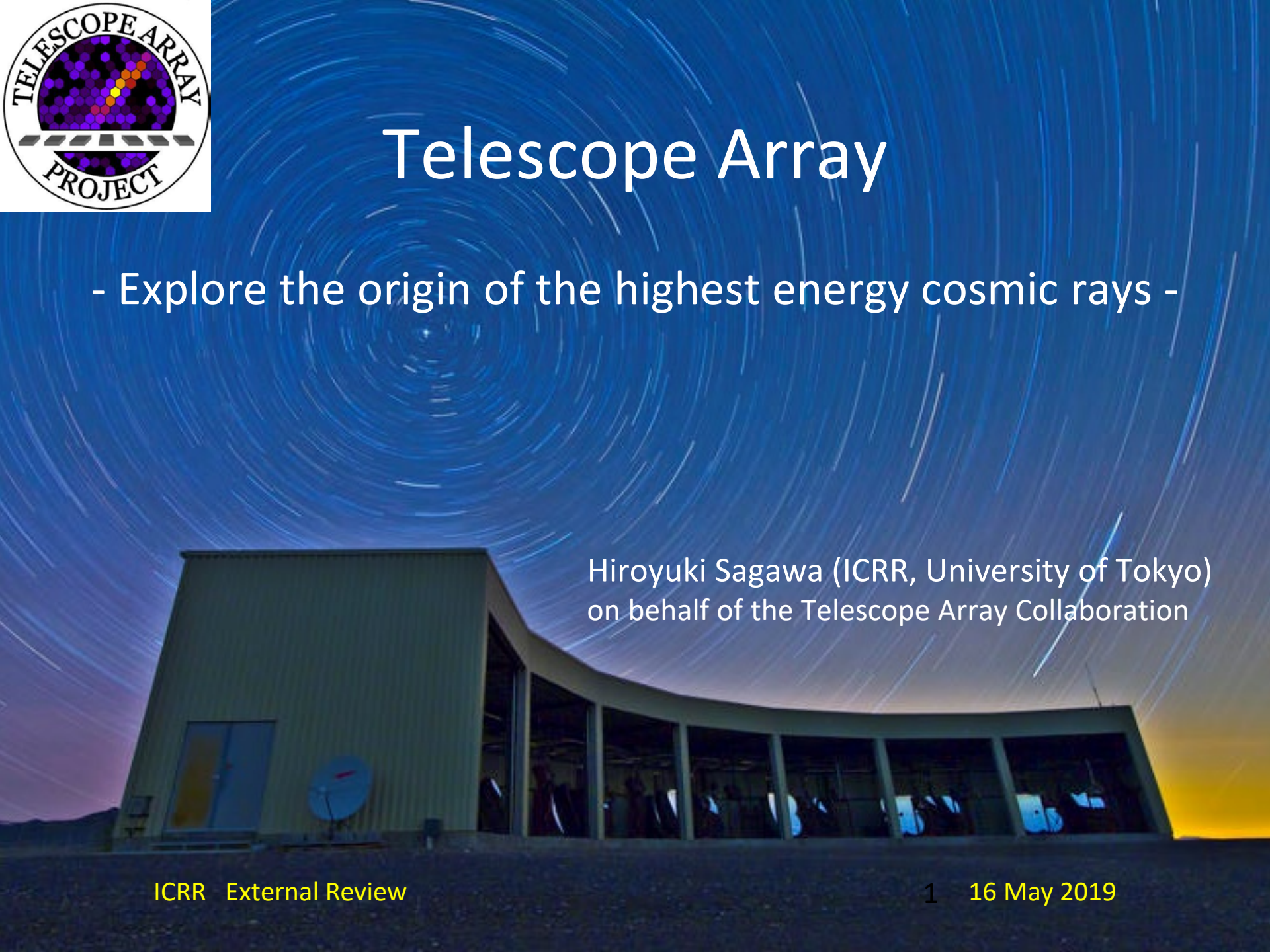


Telescope Array

- Explore the origin of the highest energy cosmic rays -

Hiroyuki Sagawa (ICRR, University of Tokyo)
on behalf of the Telescope Array Collaboration

Outline

- Introduction
- Telescope Array (TA) results
  - Energy spectrum
  - Composition
  - Anisotropy
- TA extension
  - TAx4
  - TALE

TA detector

3 com. towers

Middle Drum (MD)

~30 km

Long Ridge (LR)

Utah
39°N
1400 m asl

Surface Detector (SD)

507 plastic scintillator SDs

1.2 km spacing

~700 km²

Fluorescence Detector(FD)

3 stations

38 telescopes

Hybrid observation since 2008

TA Collaboration

6 countries (Japan, USA, Korea, Russia, Belgium, Czech)

R.U. Abbasi[1], M. Abe[2], T. Abu-Zayyad[1], M. Allen[1], R. Azuma[3], E. Barcikowski[1], J.W. Belz[1], D.R. Bergman[1], S.A. Blake[1], R. Cady[1], B.G. Cheon[4], J. Chiba[5], M. Chikawa[6], A. Di Matteo[7], T. Fujii[1], K. Fujita[9], M. Fukushima[8,10], G. Furlich[1], T. Goto[9], W. Hanlon[1], M. Hayashi[11], Y. Hayashi[9], N. Hayashida[12], K. Hibino[12], K. Honda[13], D. Ikeda[8], N. Inoue[2], T. Ishii[13], R. Ishimori[3], H. Ito[14], D. Ivanov[1], H.M. Jeong[15], S. Jeong[15], C.C.H. Jui[1], K. Kadota[16], F. Kakimoto[3], O. Kalashev[17], K. Kasahara[18], H. Kawai[19], S. Kawakami[9], S. Kawana[2], K. Kawata[8], E. Kido[8], H.B. Kim[4], J.H. Kim[1], J.H. Kim[20], S. Kishigami[9], S. Kitamura[3], Y. Kitamura[3], V. Kuzmin[17], M. Kuznetsov[17], Y.J. Kwon[21], K.H. Lee[15], B. Lubsandorzhiev[17], J.P. Lundquist[1], K. Machida[13], K. Martens[10], T. Matsuyama[19], J.N. Matthews[1], R. Mayta[9], M. Minamino[9], K. Mukai[13], I. Myers[1], K. Nagasawa[2], S. Nagataki[14], R. Nakamura[22], T. Nakamura[23], T. Nonaka[8], H. Oda[9], S. Ogio[9], J. Ogura[3], M. Ohnishi[8], H. Ohoka[8], T. Okuda[24], Y. Omura[9], M. Ono[14], R. Onogi[9], A. Oshima[9], S. Ozawa[18], I.H. Park[15], M.S. Pshirkov[17,25], J. Remington[1], D.C. Rodriguez[1], G. Rubtsov[17], D. Ryu[20], H. Sagawa[8], R. Sahara[9], K. Saito[8], Y. Saito[22], N. Sakaki[8], N. Sakurai[9], L.M. Scott[26], T. Seki[22], K. Sekino[8], P.D. Shah[1], F. Shibata[13], T. Shibata[8], H. Shimodaira[8], B.K. Shin[9], H.S. Shin[8], J.D. Smith[1], P. Sokolsky[1], B.T. Stokes[1], S.R. Stratton[1,26], T.A. Stroman[1], T. Suzawa[2], Y. Takagi[9], Y. Takahashi[9], M. Takamura[5], M. Takeda[8], R. Takeishi[15], A. Taketa[27], M. Takita[8], Y. Tameda[28], H. Tanaka[9], K. Tanaka[29], M. Tanaka[30], S.B. Thomas[1], G.B. Thomson[1], P. Tinyakov[7,17], I. Tkachev[17], H. Tokuno[3], T. Tomida[22], S. Troitsky[17], Y. Tsunesada[9], K. Tsutsumi[3], Y. Uchihori[31], S. Udo[12], F. Urban[32], T. Wong[1], M. Yamamoto[22], R. Yamane[9], H. Yamaoka[30], K. Yamazaki[12], J. Yang[33], K. Yashiro[5], Y. Yoneda[9], S. Yoshida[19], H. Yoshii[34], Y. Zhezher[17], and Z. Zundel[1]

[1]High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA, [2]The Graduate School of Science and Engineering, Saitama University, Saitama, Saitama, Japan, [3]Graduate School of Science and Engineering, Tokyo Institute of Technology, Meguro, Tokyo, Japan, [4]Department of Physics and The Research Institute of Natural Science, Hanyang University, Seongdong-gu, Seoul, Korea, [5]Department of Physics, Tokyo University of Science, Noda, Chiba, Japan, [6]Department of Physics, Kindai University, Higashi Osaka, Osaka, Japan, [7]Service de Physique Th´eorique, Universit´e Libre de Bruxelles, Brussels, Belgium, [8]Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan, [9]Graduate School of Science, Osaka City University, Osaka, Osaka, Japan, [10]Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, the University of Tokyo, Kashiwa, Chiba, Japan, [11]Information Engineering Graduate School of Science and Technology, Shinshu University, Nagano, Nagano, Japan, [12]Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan, [13]Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, Yamanashi, Japan, [14]Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama, Japan, [15]Department of Physics, Sungkyunkwan University, Jang-an-gu, Suwon, Korea, [16]Department of Physics, Tokyo City University, Setagaya-ku, Tokyo, Japan, [17]Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia, [18]Advanced Research Institute for Science and Engineering, Waseda University, Shinjuku-ku, Tokyo, Japan, [19]Department of Physics, Chiba University, Chiba, Chiba, Japan, [20]Department of Physics, School of Natural Sciences, Ulsan National Institute of Science and Technology, UNIST-gil, Ulsan, Korea, [21]Department of Physics, Yonsei University, Seodaemun-gu, Seoul, Korea, [22]Academic Assembly School of Science and Technology Institute of Engineering, Shinshu University, Nagano, Nagano, Japan, [23]Faculty of Science, Kochi University, Kochi, Kochi, Japan, [24]Department of Physical Sciences, Ritsumeikan University, Kusatsu, Shiga, Japan, [25]Sternberg Astronomical Institute, Moscow M.V. Lomonosov State University, Moscow, Russia, [26]Department of Physics and Astronomy, Rutgers University – The State University of New Jersey, Piscataway, New Jersey, USA, [27]Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, Japan, [28]Department of Engineering Science, Faculty of Engineering, Osaka Electro-Communication University, Neyagawa-shi, Osaka, Japan, [29]Graduate School of Information Sciences, Hiroshima City University, Hiroshima, Hiroshima, Japan, [30]Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki, Japan, [31]National Institute of Radiological Science, Chiba, Chiba, Japan, [32]CEICO, Institute of Physics, Czech Academy of Sciences Prague, Czech Republic, [33]Department of Physics and Institute for the Early Universe, Ewha Womans University, Seodaaemun-gu, Seoul, Korea, [34]Department of Physics, Ehime University, Matsuyama, Ehime, Japan

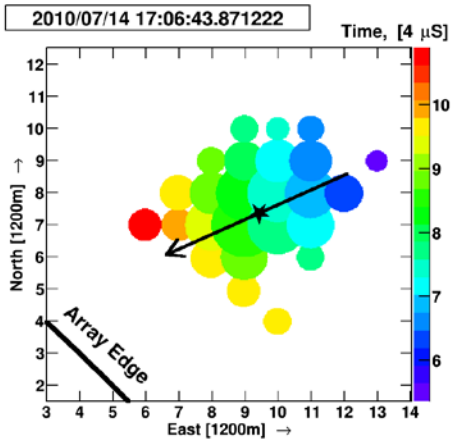
~130 researchers

34 institutes

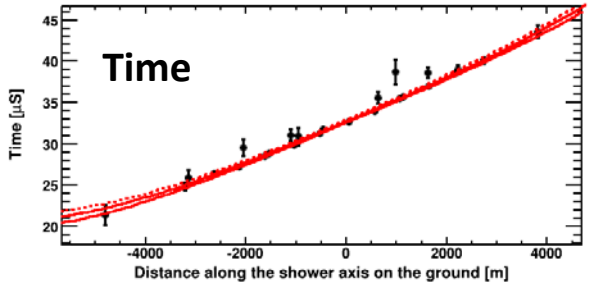
Energy Spectrum Results

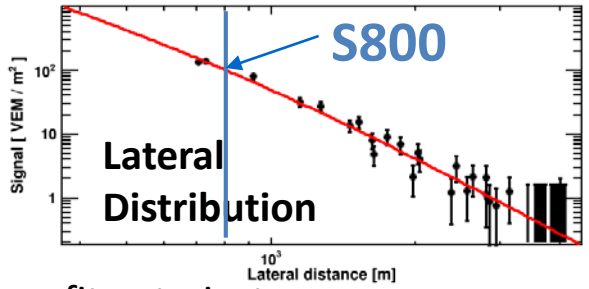
SD Event Reconstruction

1) SD footprint example



2) reconstruction

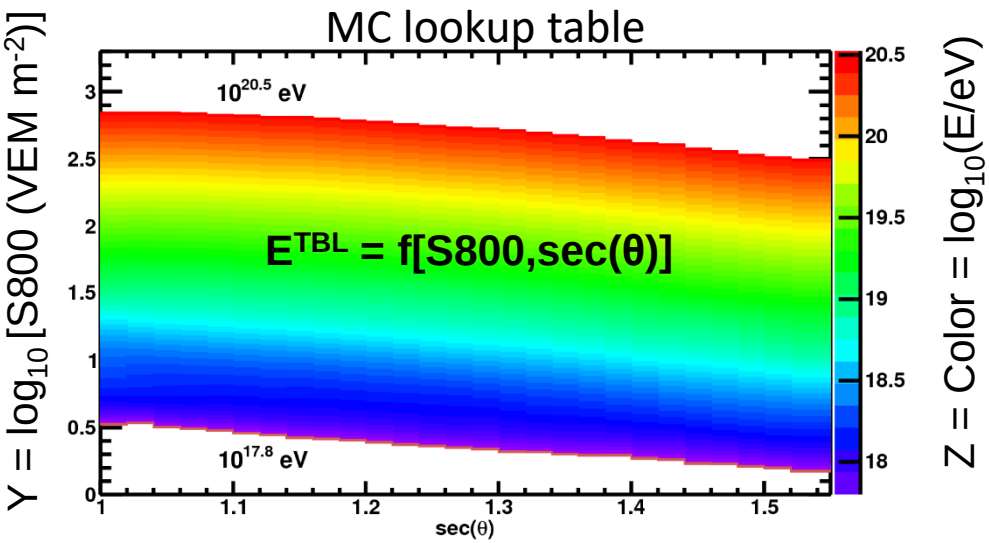




Time fit -> trajectory

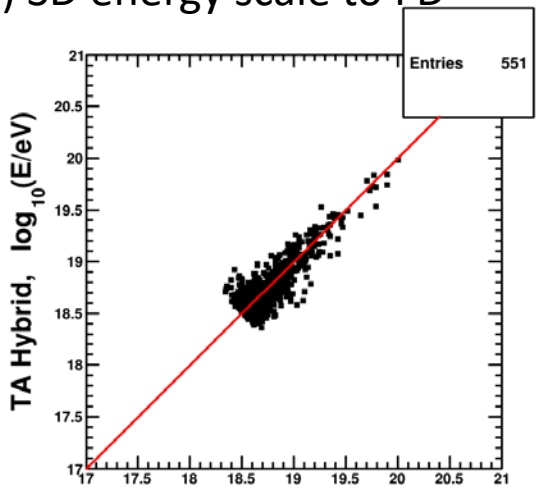
Counter signal lateral distrib. fit -> S800

3) First energy estimation



X = Secant of zenith angle

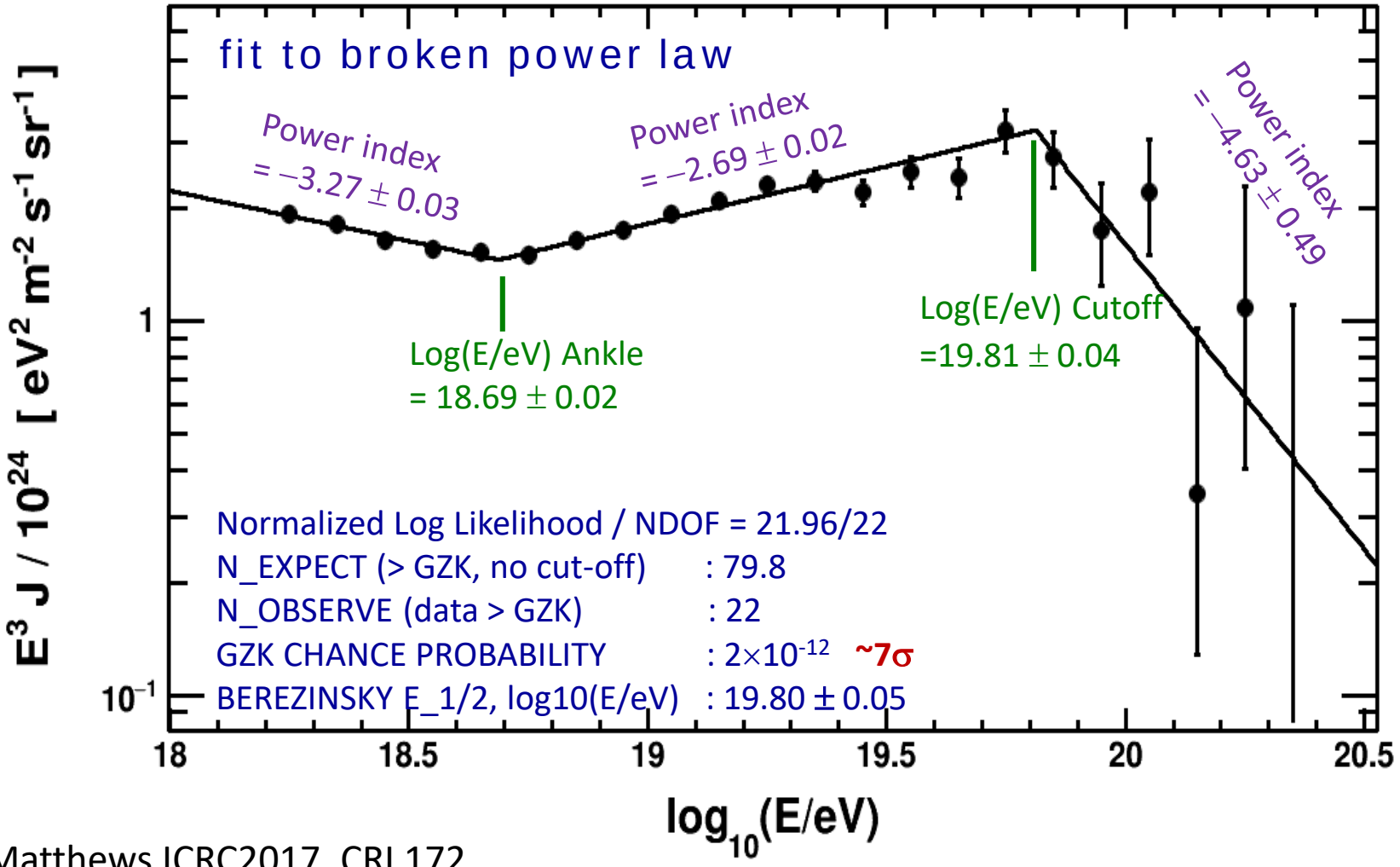
4) SD energy scale to FD



$E^{FINAL} = E^{TABL} / 1.27$

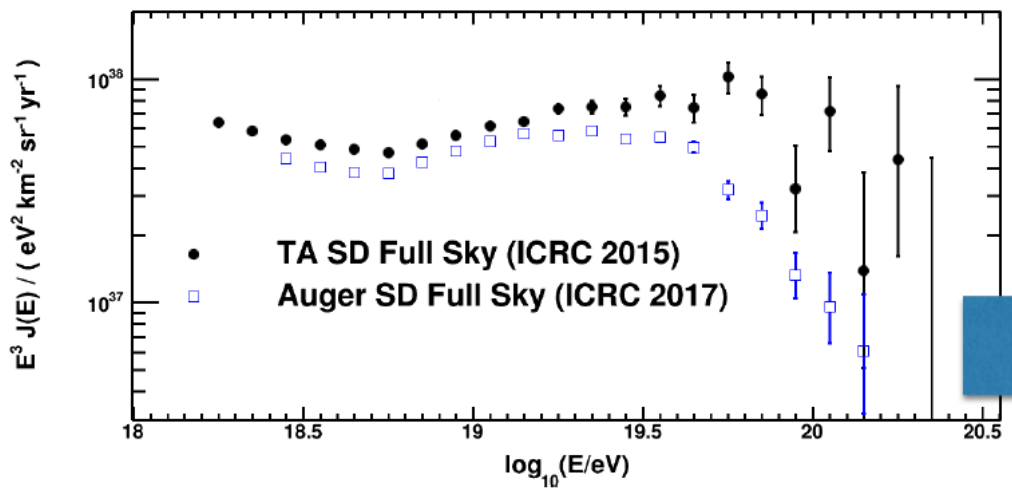
TA SD Spectrum (9 years data)

ICRC2017



J. Matthews ICRC2017, CRI 172

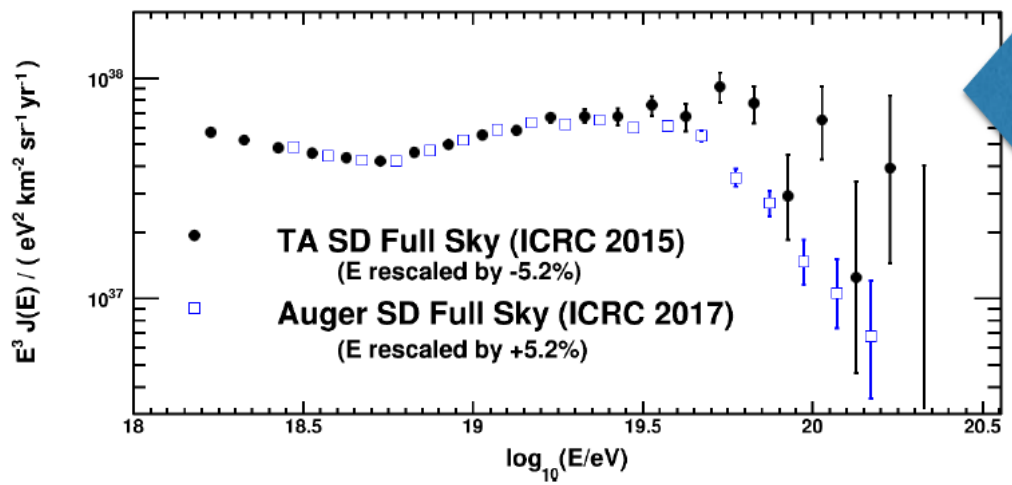
TA & Auger Spectra

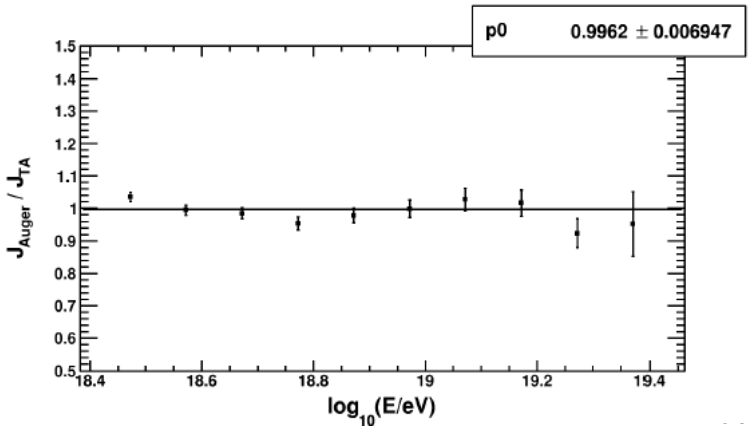


Ivanov ICRC2017, CRI231
(Auger/TA spectrum WG)

10% energy shift well within stated 14%(Auger) and 21%(TA) energy scale systematic uncertainties

- Auger energies raised by 5.2% and
- TA energies lowered by 5.2%



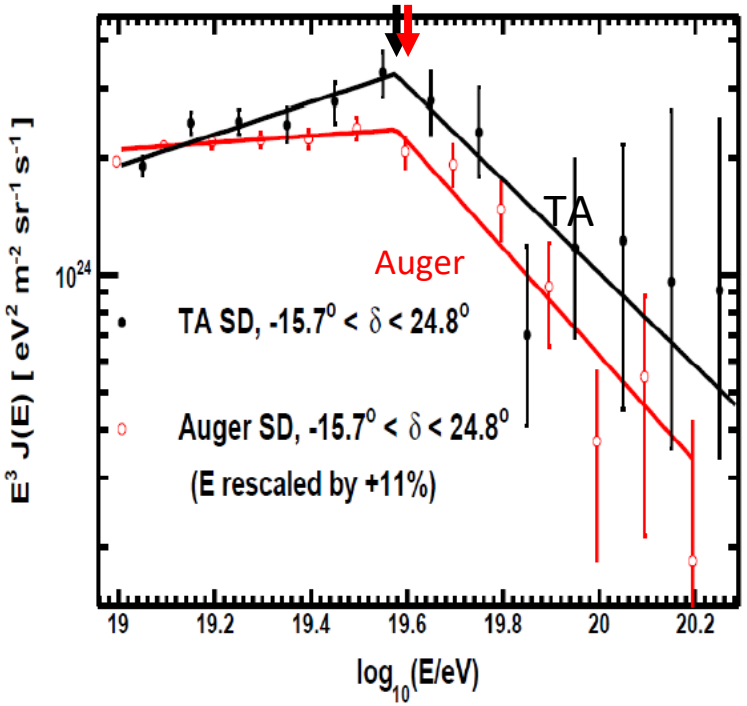


The fluxes by two experiments well overlap below $10^{19.4}$ eV

Declination dependence of breaks

submitted to ApJ, arXiv:1801.07820

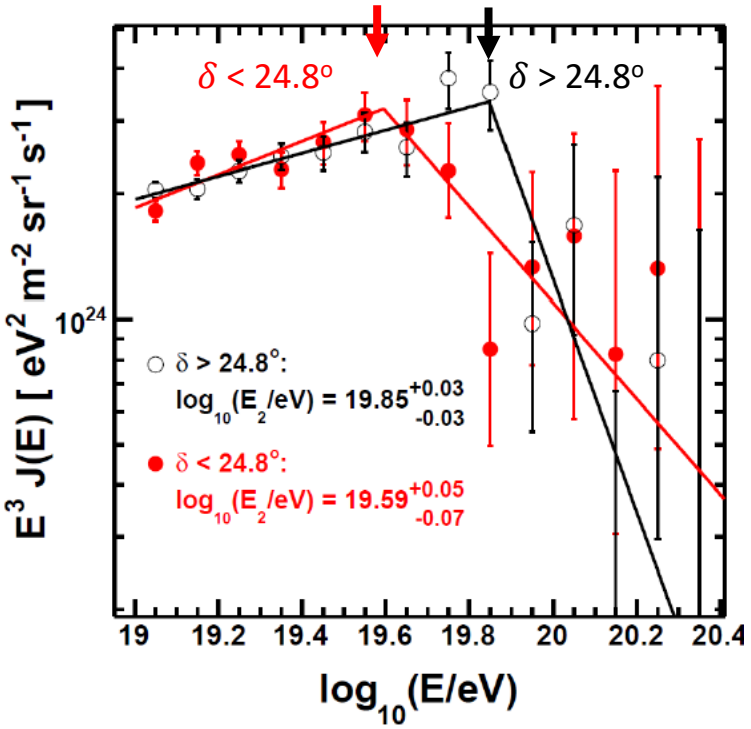
TA, Auger common declination band
-15.7° < declination δ < 24.8°



Energy spectra of TA and Auger in the common declination band. They agree at about 0.5σ level

Break points are the same

TA only



Energy spectra of TA above and below δ=24.8° They disagree at 4σ level

Global Significance 3.5 σ

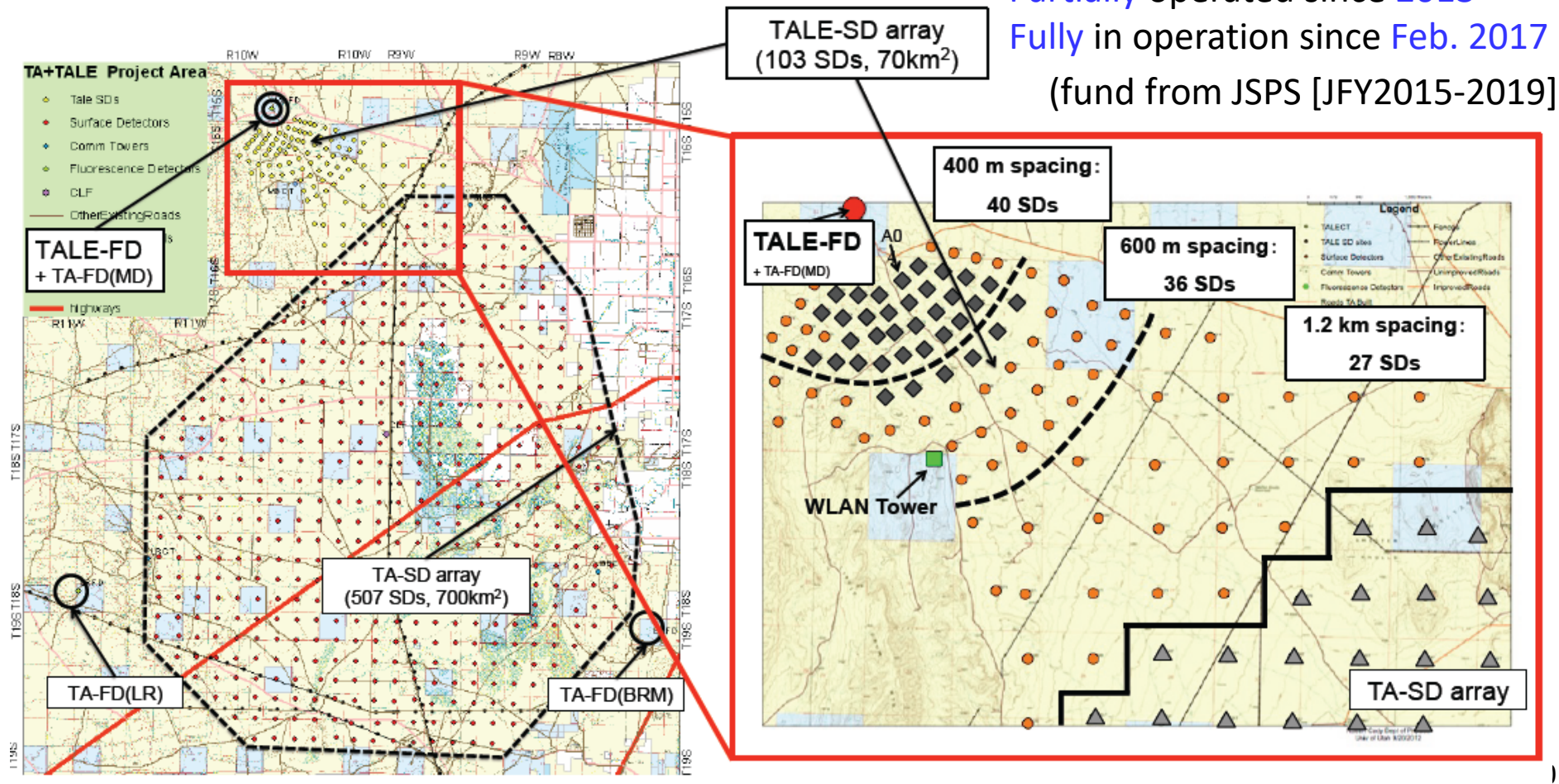
TA Low Energy Extension (TALE)

Galactic to Extra-Galactic Transition

10 new telescopes to look higher in the sky (31-59^{o}) to see shower development to much lower energies
In operation since 2013

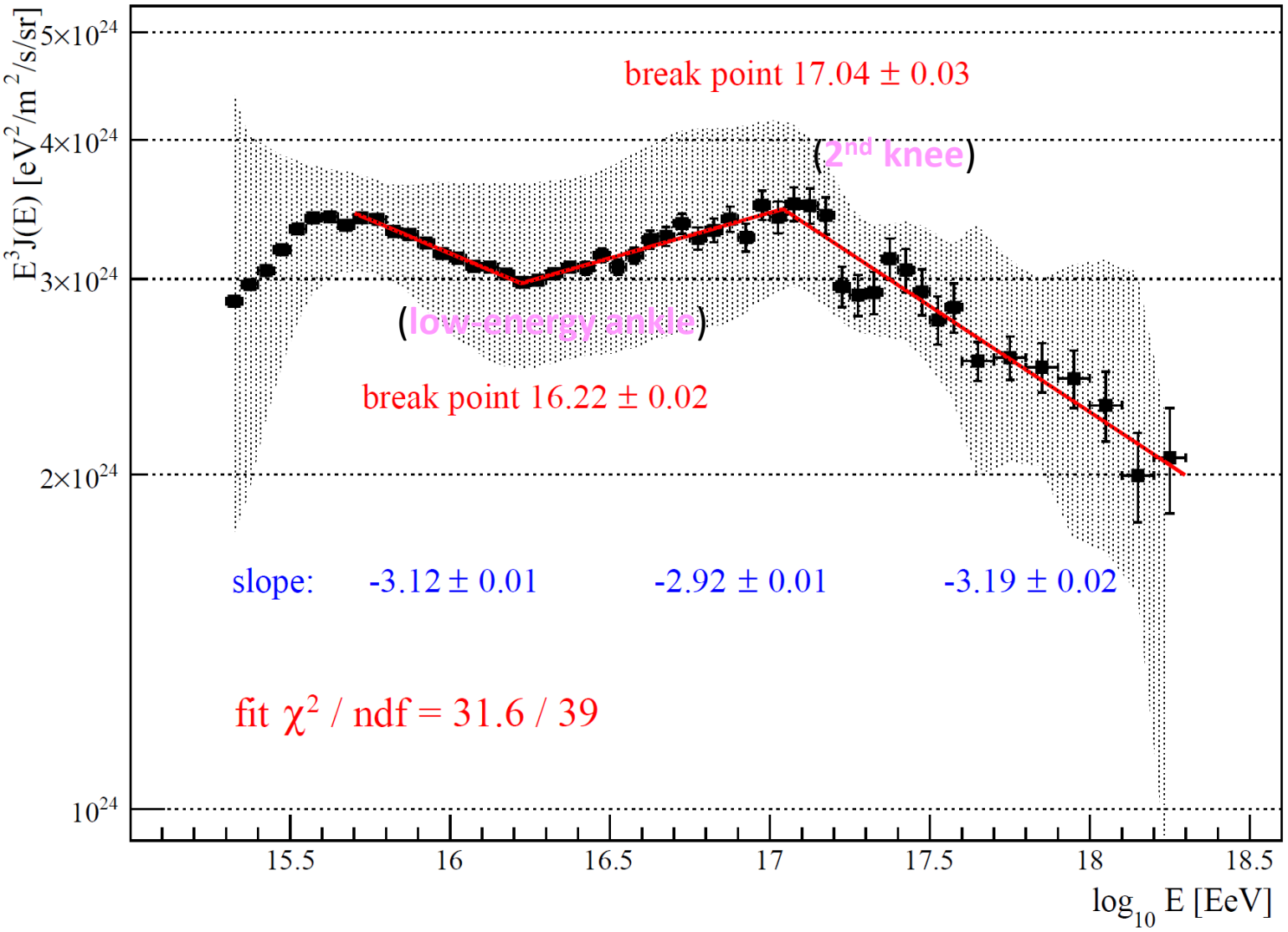
Graded infill surface detector array - more densely packed surface detectors (lower energy threshold)
Partially operated since 2013
Fully in operation since Feb. 2017

(fund from JSPS [JFY2015-2019])



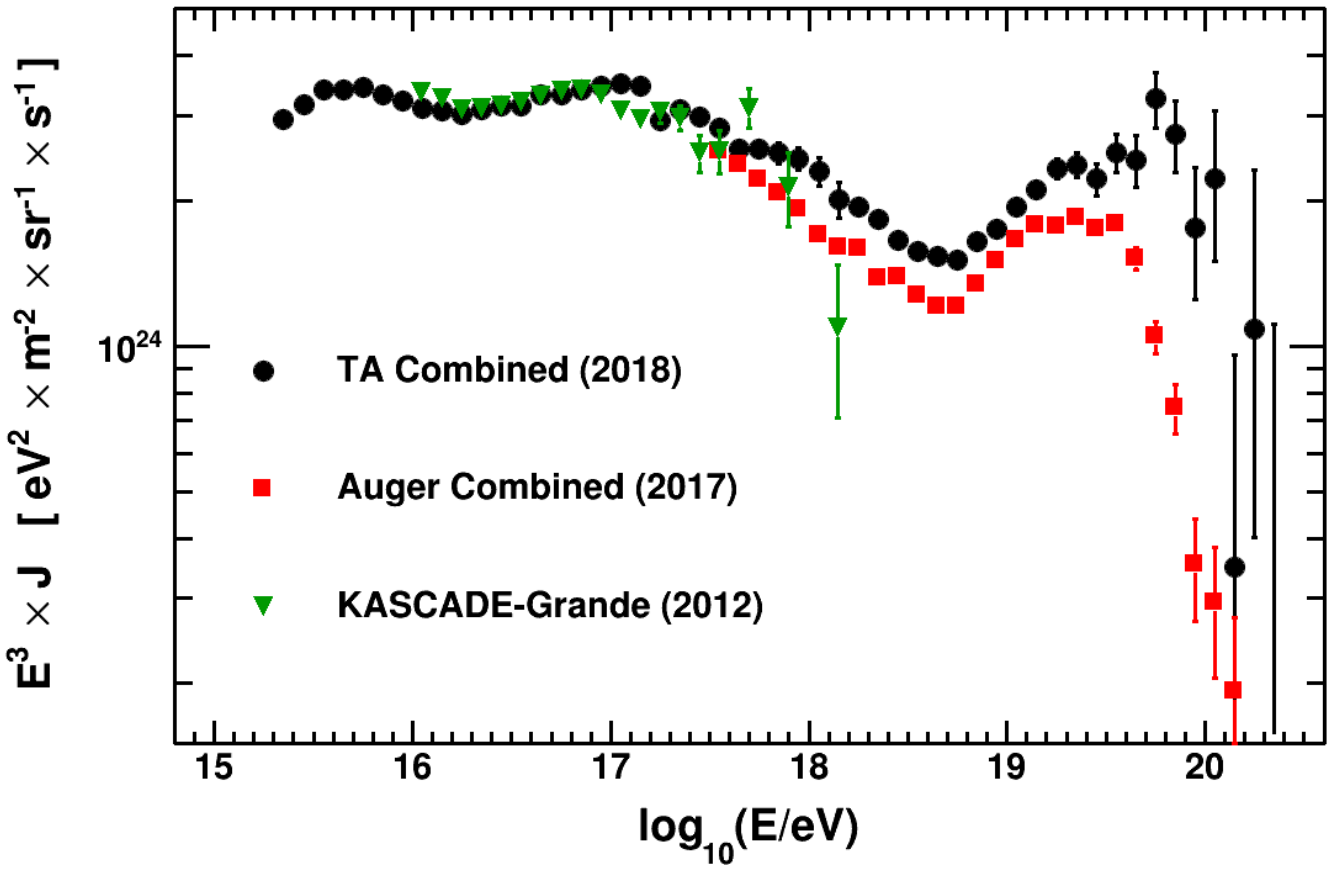
TALE FD Spectrum

R.U. Abbasi et al., ApJ 865:74, 2018

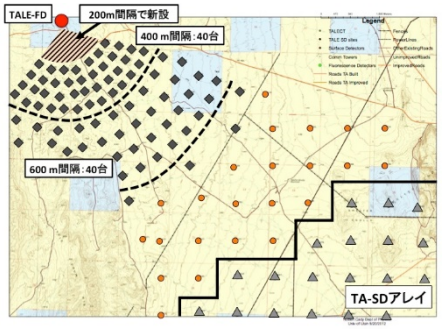


TA combined, Auger, KASCADE-Grande

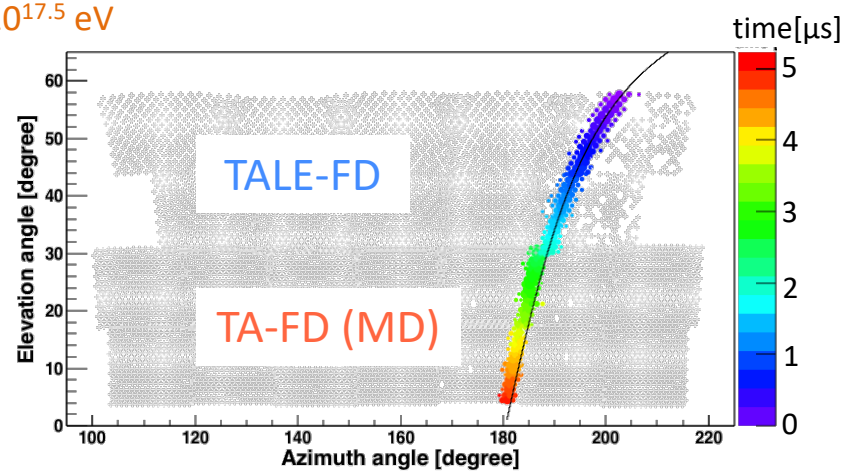
D. Ivanov, UHECR2018

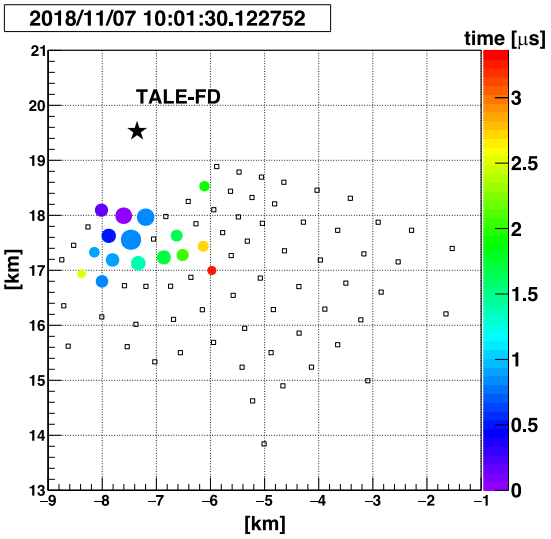


TALE hybrid event example



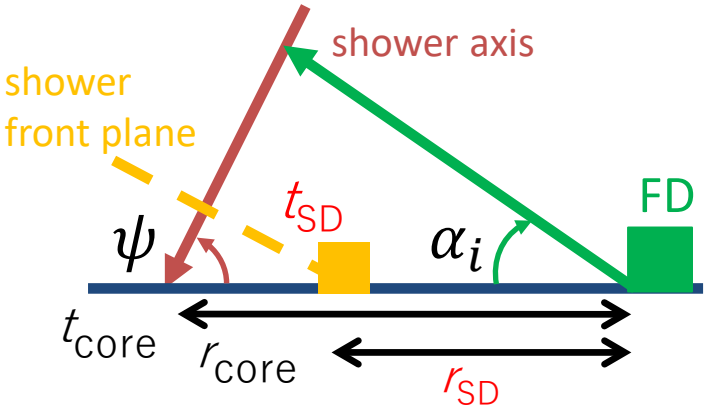
$E_{FD} > 10^{17.5}$ eV

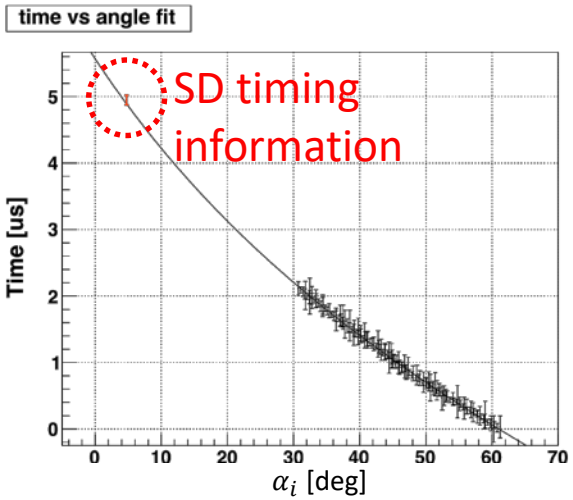




Hybrid event reconstruction

SD for better Xmax measurement





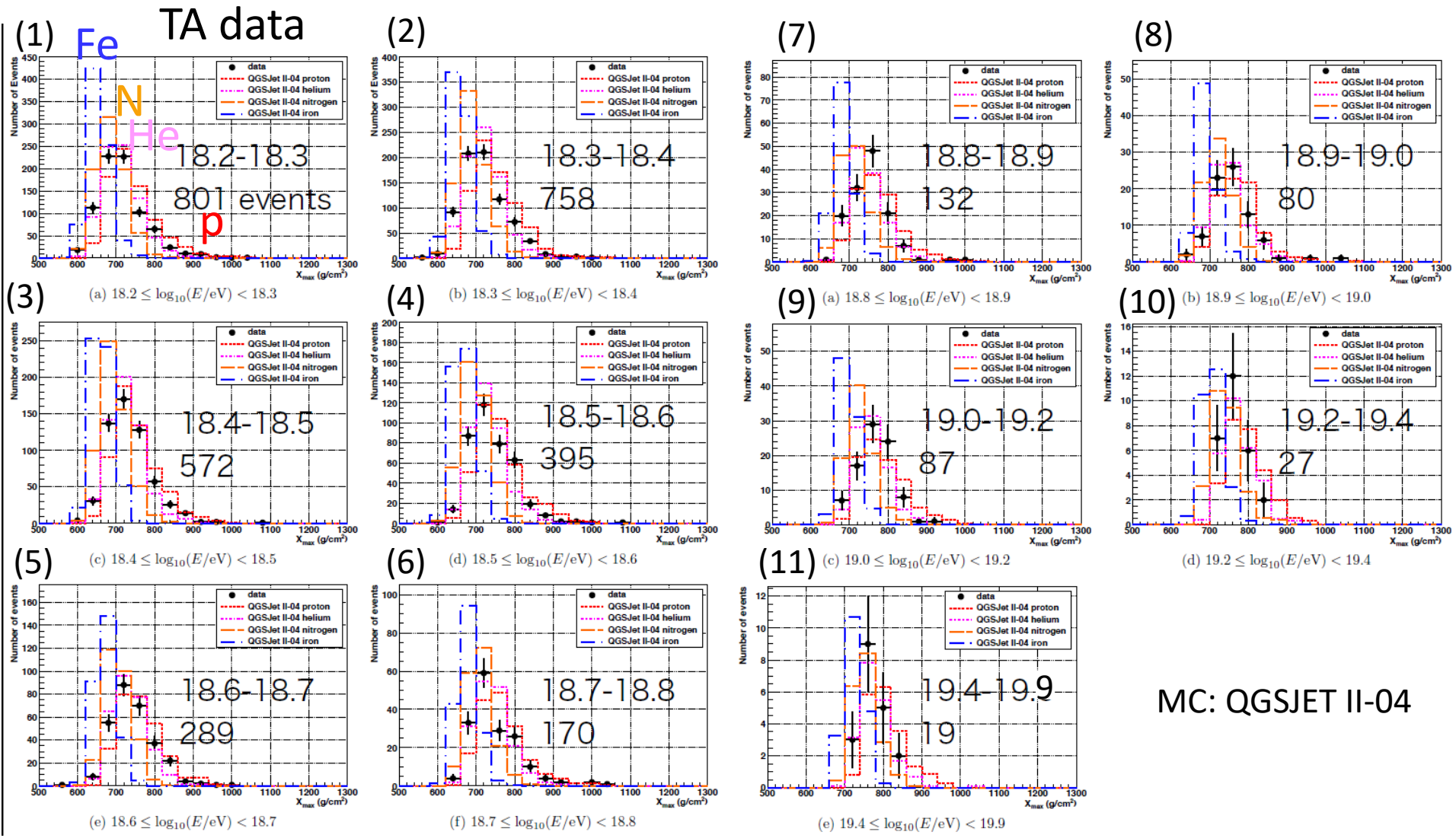
Zen.[deg]	Azi.[deg]
23.6	-33.5
CoreX[km]	CoreY[km]
7.33	17.63
Xmax[g/cm^2]	E[eV]
823	$10^{17.94}$

Composition Results

Xmax Distributions for different energies

Shower maxima data over 8.5 years
using hybrid events (two southern FDs with the SDs)

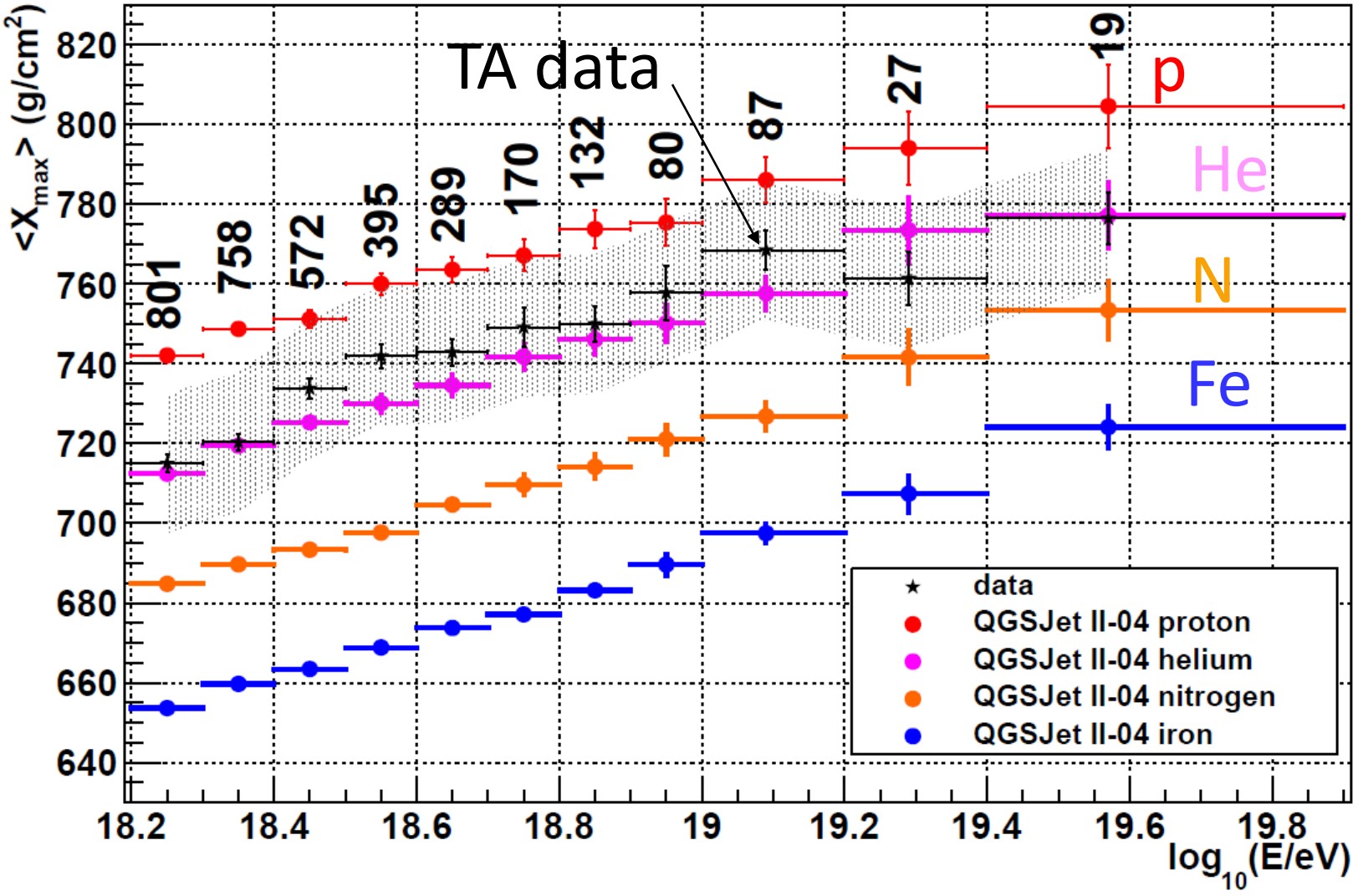
R.U. Abbasi et al., Ap. J., 858, 76 (2018)



MC: QGSJET II-04

<Xmax> vs logE

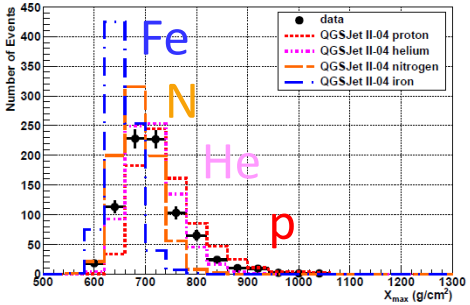
R.U. Abbasi et al., Ap. J., 858, 76 (2018)



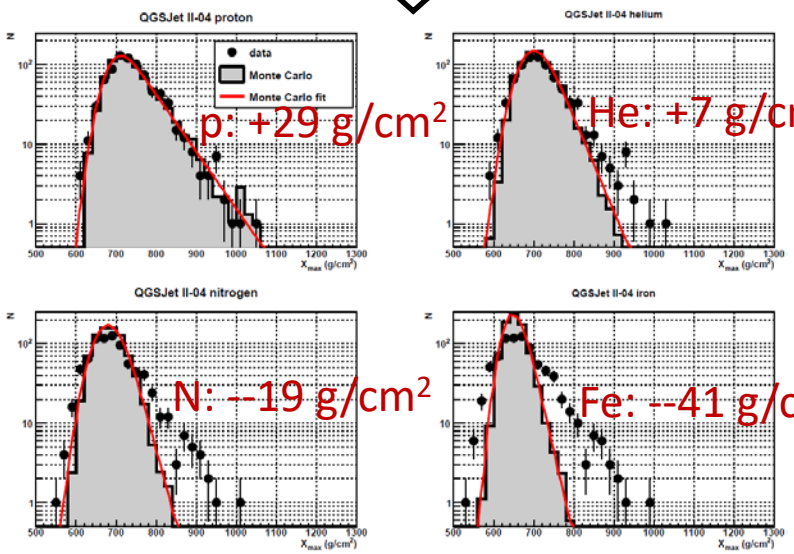
Xmax Shape analysis

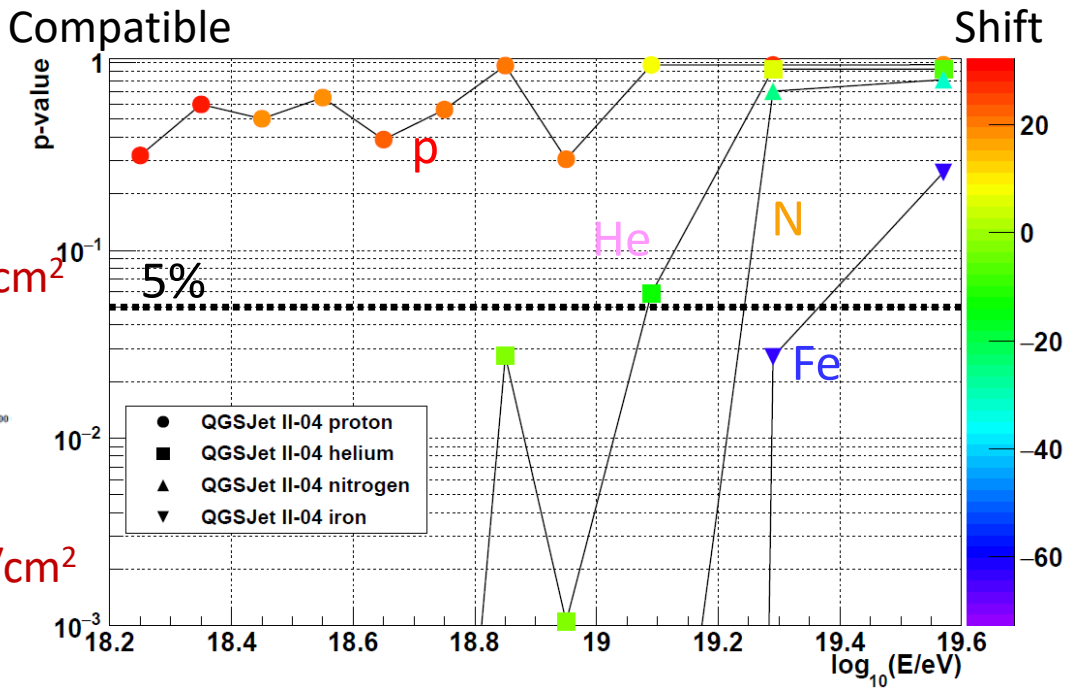
$18.2 \leq \log_{10}(E/\mathrm{eV}) < 18.3$

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



Color indicates the amount of shift in Xmax applied to data for best fit to MC (in g/cm^2)





- max. log$L$ derived p rejects (at 95% C.L.) all species except H (E<$10^{19.0}$eV)
- max. log$L$ derived p FAILS to reject (at 95% C.L.) any species (E>$10^{19.2}$eV)

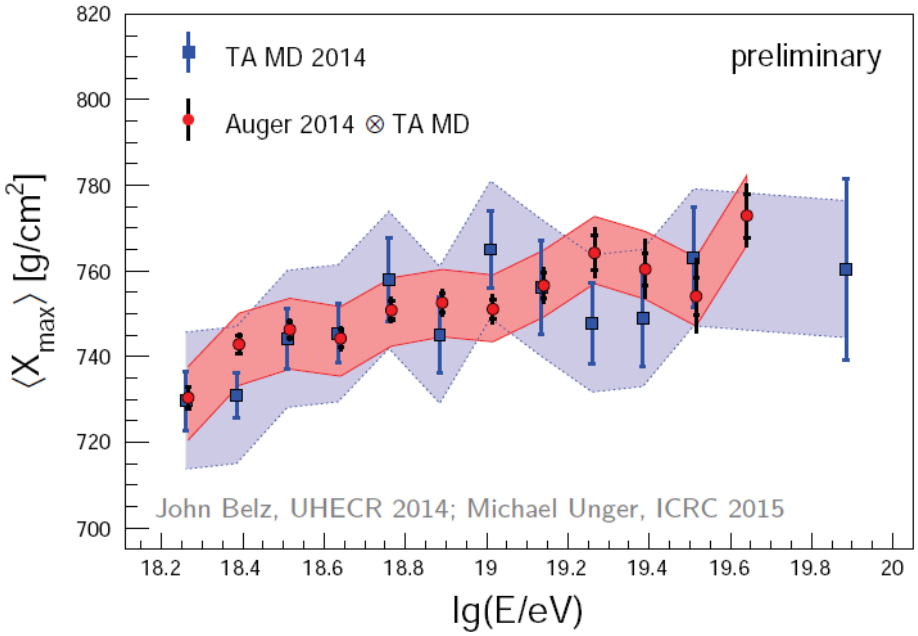
<Xmax>: Auger vs TA measurements

by Auger&TA Working Group

- Auger and TA data cannot compare directly due to different approach of data analysis
- Indirect comparison
  - **Auger⊗TA**: (Auger mix composition model) x (TA simulation/reconstruction/analysis) ⟷ TA result (compare)
    - This simulates TA acceptance and biases

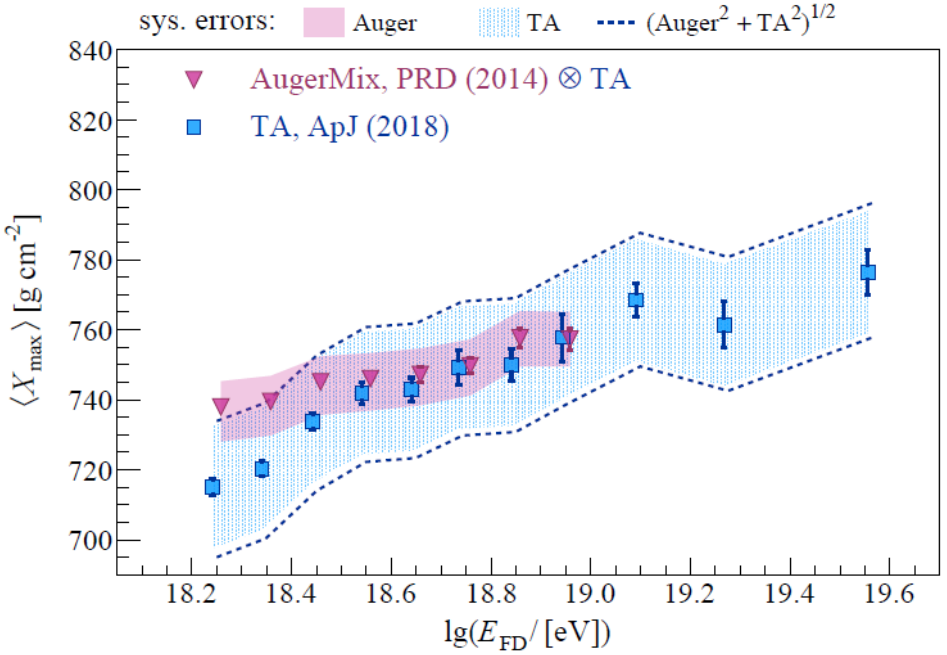
TA Middle Drum

[ApP 64 (2015) 49]



TA Black Rock Mesa/Long Ridge

[ApJ 858 (2018) 76]

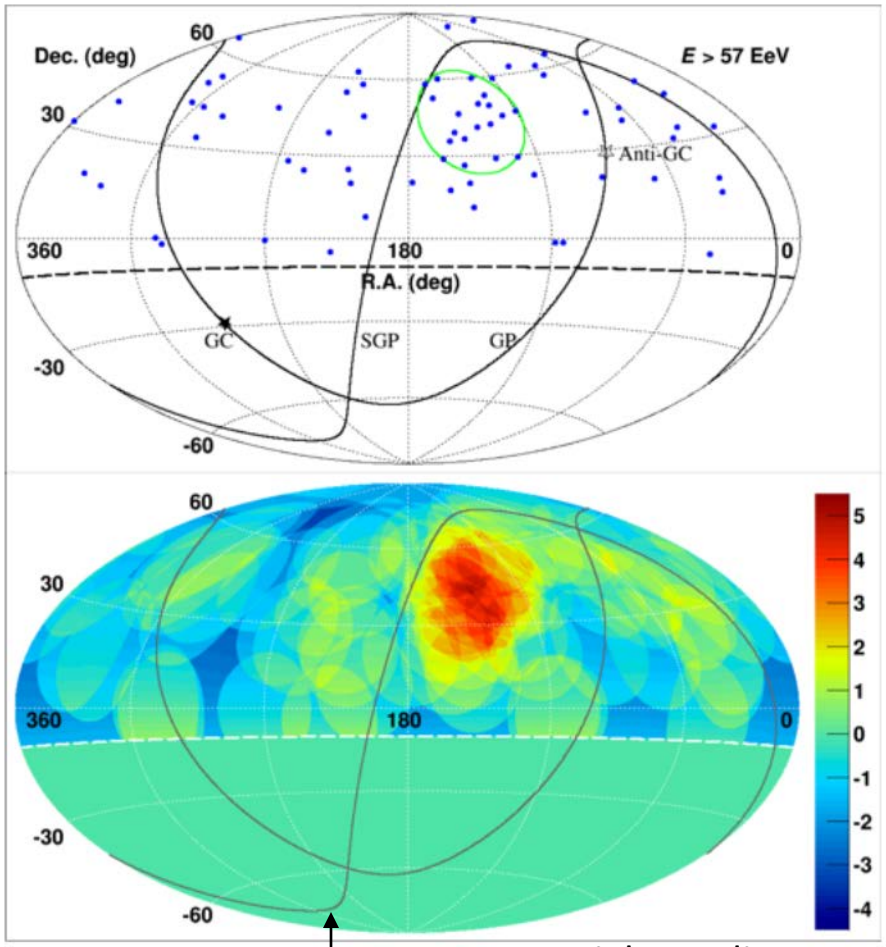


TA agrees with Auger within systematic uncertainty.

Anisotropy Results

Hotspot (5 years)

R.U. Abbasi et al., ApJL 790, L21, 2014



Equatorial coordinates

SuperGalactic Plane (SGP)

- 5-year by the TA SD
- 72 events with E > 57 EeV
- Non = 19, Nbg = 4.49
- Local significance 5.1σ

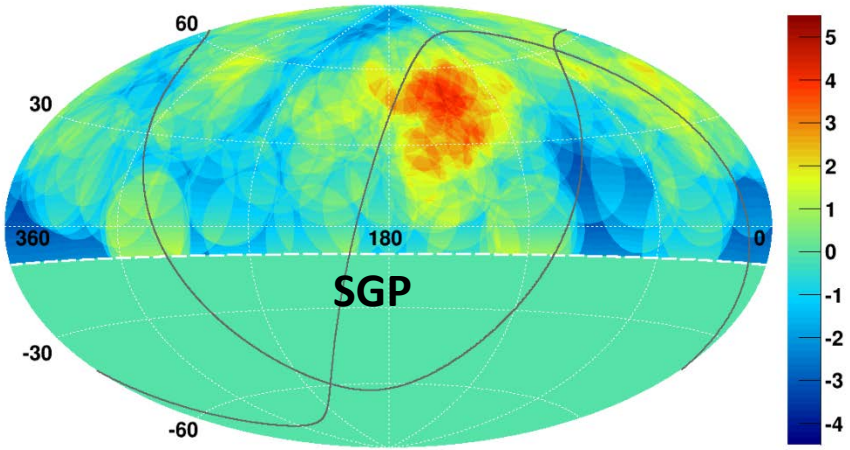
- Assume 5 search window radii (15°, 20°, 25°, 30°, 35°)
- Global significance 3.5σ

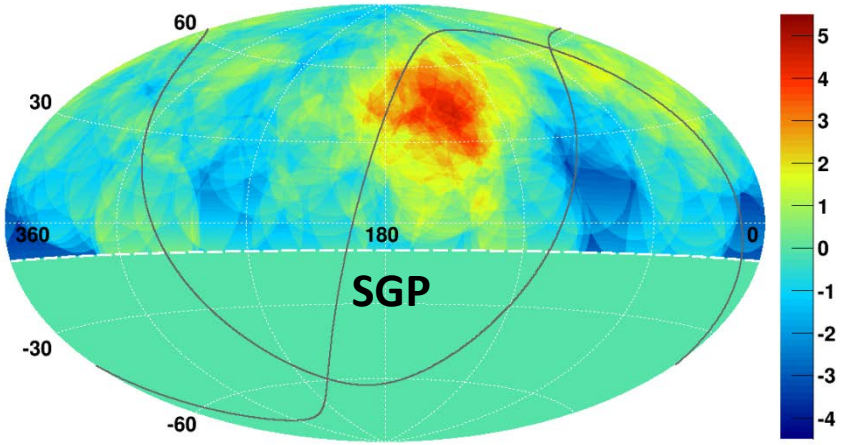
Hotspot center shifted from SGP by ~19°

Hot Spot update (2018)

Kawata, UHECR2018

157 events above 5.7×10^{19} eV for 10 years



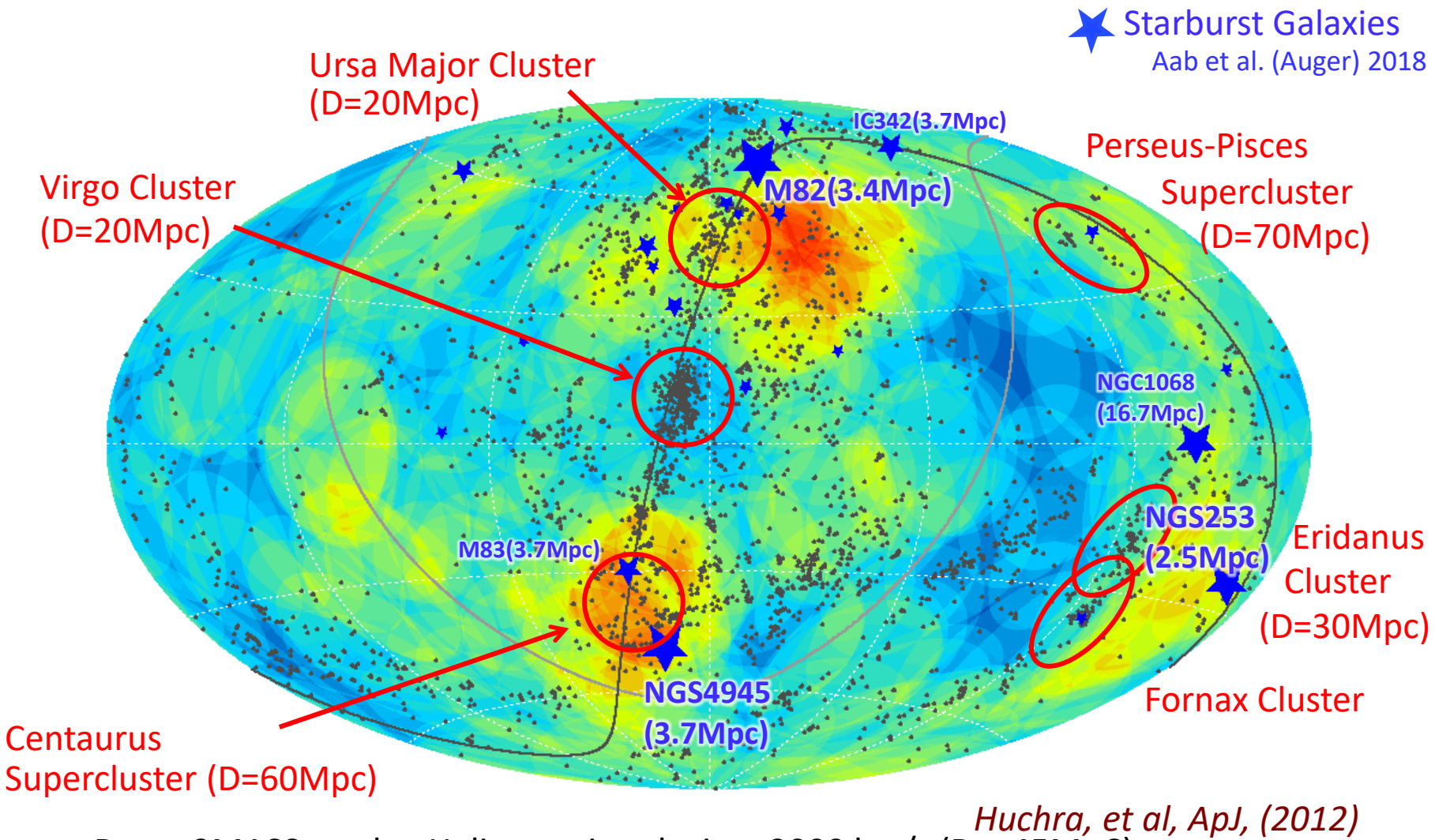


Equatorial coordinates

- With original 20° oversampling
- Hotspot looks larger than originally thought
- Scan over 15°, 20°, 25°, 30°, 35°

- With 25° oversampling
- Max post-trial significance of ~3σ

Nearby Galaxy Clusters



Huchra, et al, ApJ, (2012)

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

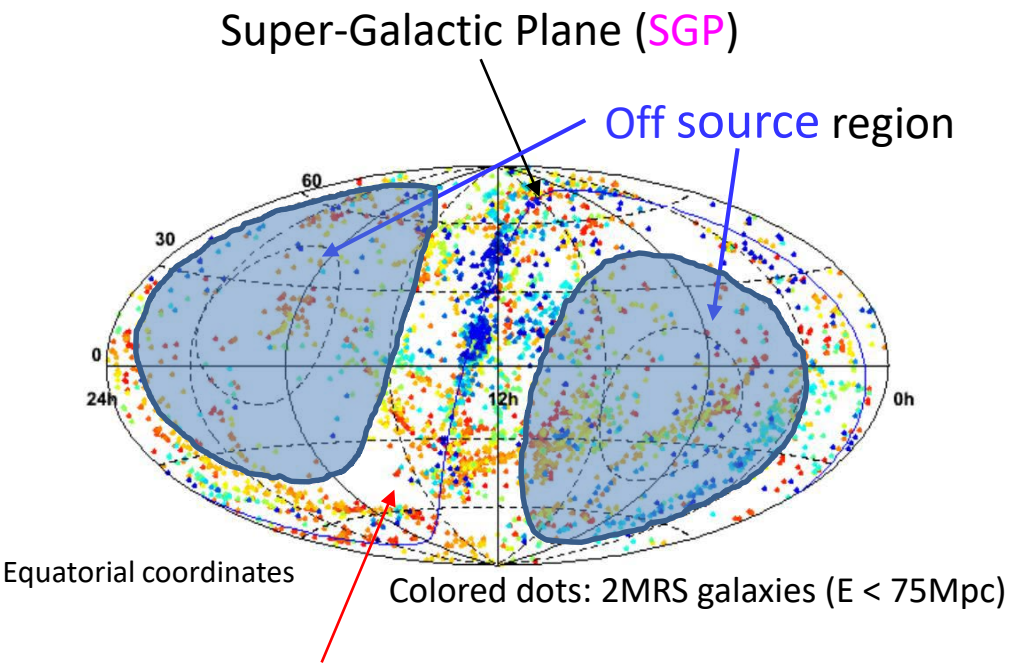
TA hotspot is found near the Ursa Major Cluster

TA & PAO see no excess in the direction of Virgo

Spectral Anisotropy

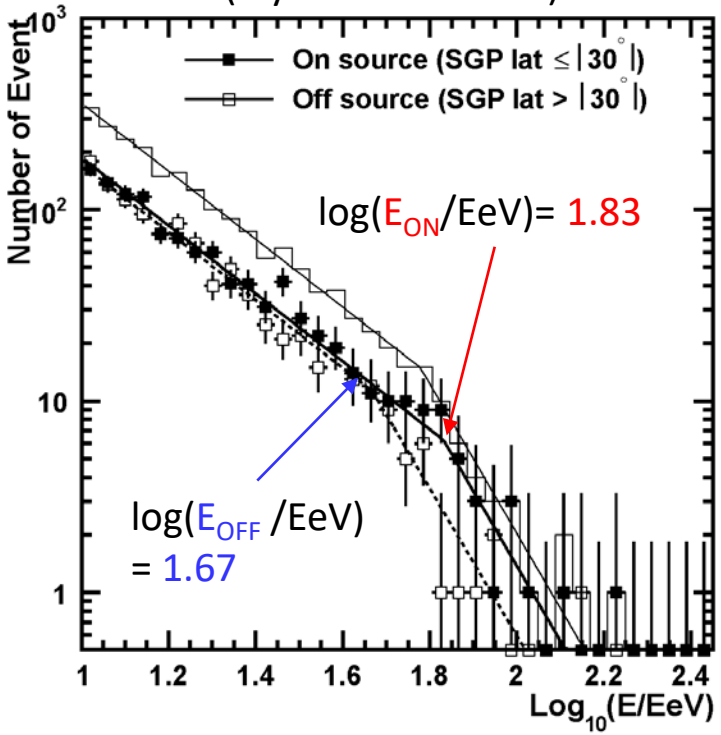
(from the point of regions with more/less nearby objects)

submitted to PRL, arXiv:1707.04967



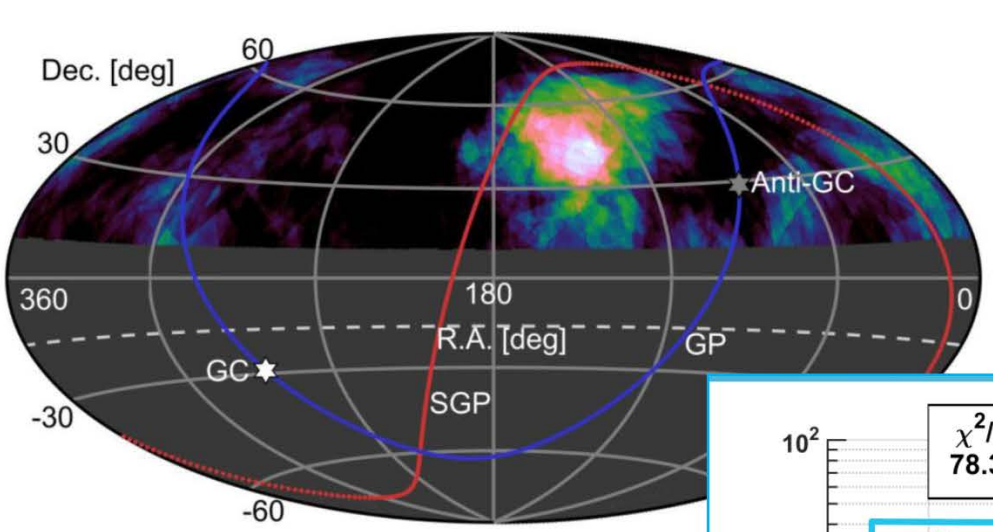
TA energy distributions

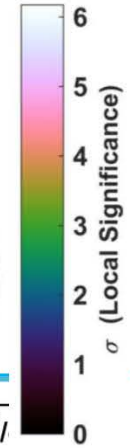
(5 years of SD data)



E_{ON} and E_{OFF}: 3.2σ difference

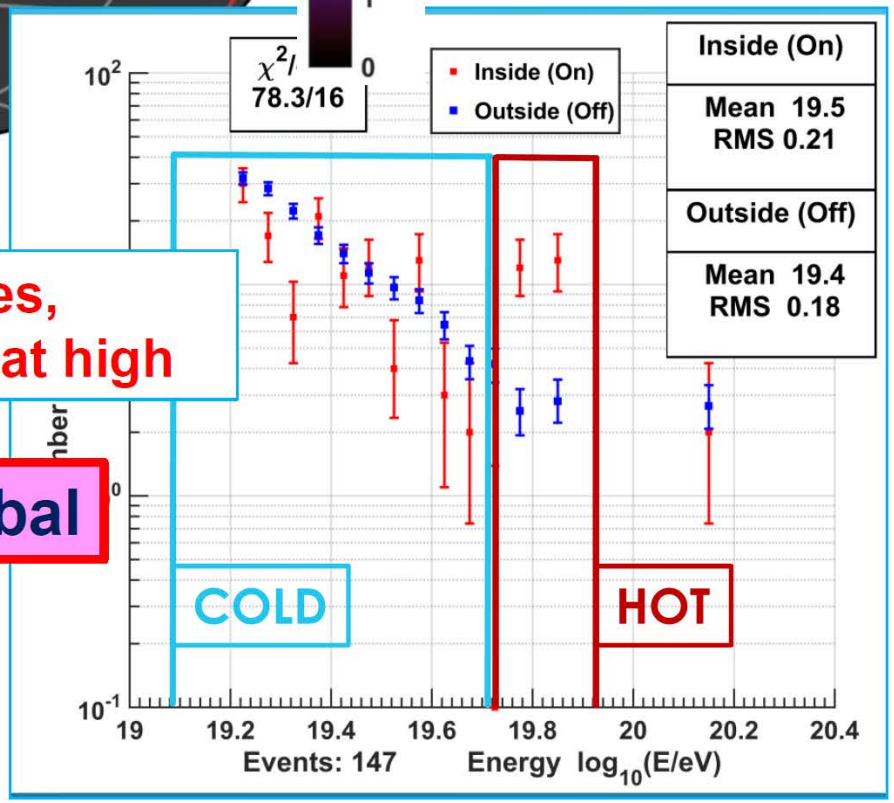
Spectral anisotropy (cold/hot spot)





$E \geq 10^{19.2}$ eV

r = 28.43°

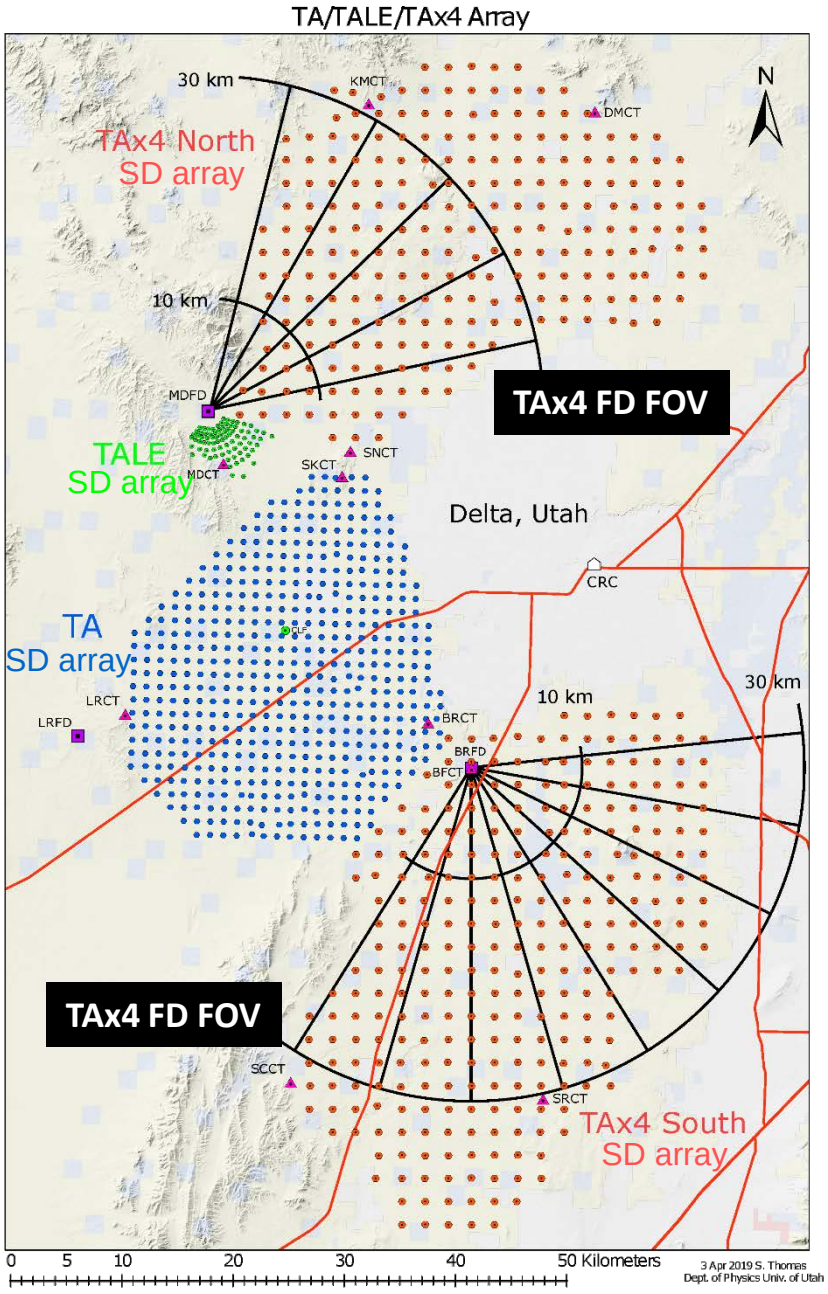


"cold spot" at lower energies, same place as the hot spot at high

3.7σ global

R.U. Abbasi et al., ApJ 862:91, 2018

TAx4

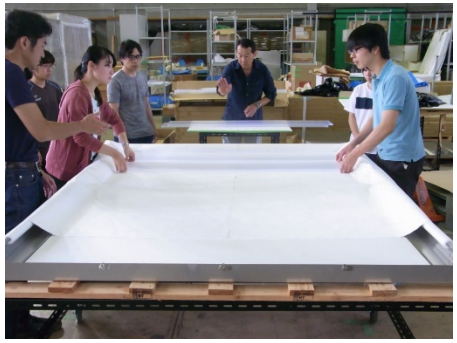


- quadruple TA to accelerate data collection speed
  - Surface detector(~3000 km^2)
    - 500 scintillator SDs with 2.1 km spacing
    - Fund from JSPS (JFY2015-2019) +KRF(2017-)
    - Deployed 257 SDs in 2019
  - Fluorescence detector
    - Xmax meas. & SD energy check
    - 2 FD stations (HiRes-II telescopes)
      - First light at the northern station
      - The southern station: under construction
    - Fund from NSF (2016 -)

TAx4 SD

- Assembly of scintillator counters
  - 260 counters (230 in Japan, 30 in Korea*)

*: fund from KRF



Akeno Observatory

Some modifications (fiber layout, PMT[ET -> HP], new WLAN modem and DAQ etc.)

- Final assembly in CRC**

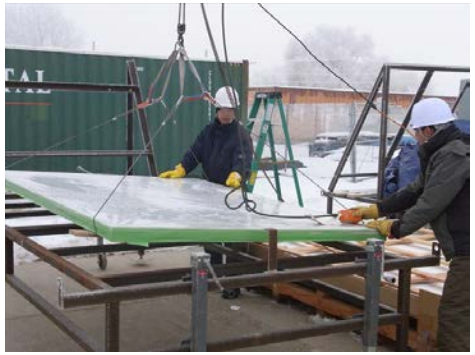


Photo at CRC in Jan. 2019

CRC** = Cosmic Ray Center in Delta City
near TA site

TAx4 SD

- Permission of the deployment by BLM*: delayed
  - EA (Environmental Assessment) approval in 2019.02 due to
    - related surveys (animals, plants, remains, landownership) etc.
    - another 1 mon. delay by US government shutdown in 2018.12-2019.01

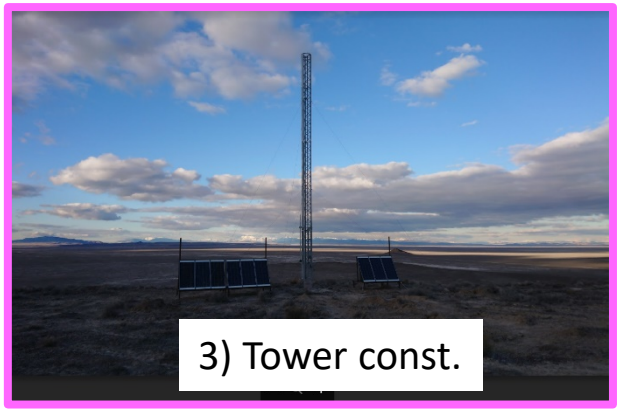
BLM* = Bureau of Land Management

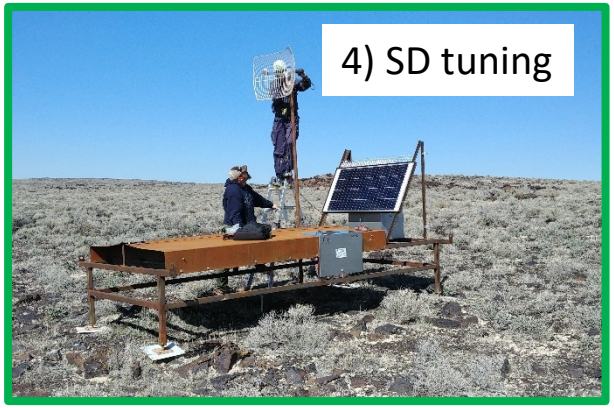
- Deployment work by helicopter in Feb and Mar of 2019 (~1.5 months)
  - Bird habitation period (Mar – Aug)
    - Helicopter work is not allowed
    - But a special permission this March

TAx4 SD

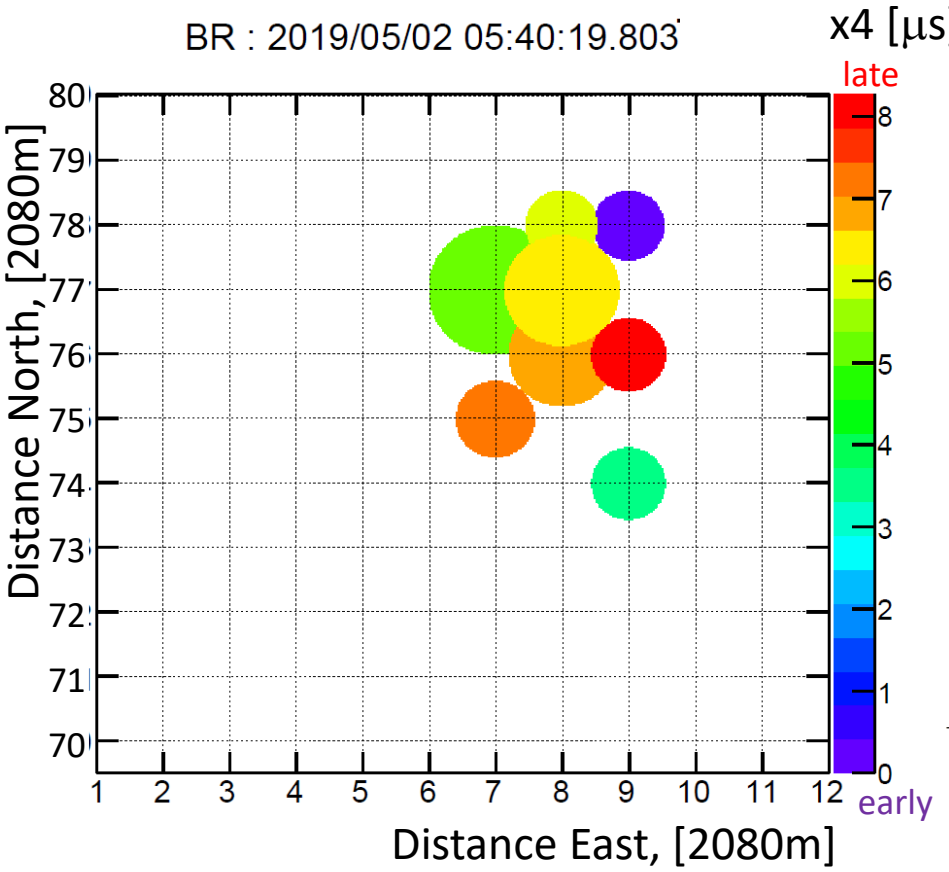
		February, 2019																March, 2019																			
		12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
1	SD (CRC to SAs*)																																										
2	SD deploy. by helicopter																																										
3	Tower construction																																										
4	SD tuning by helicopter																																										

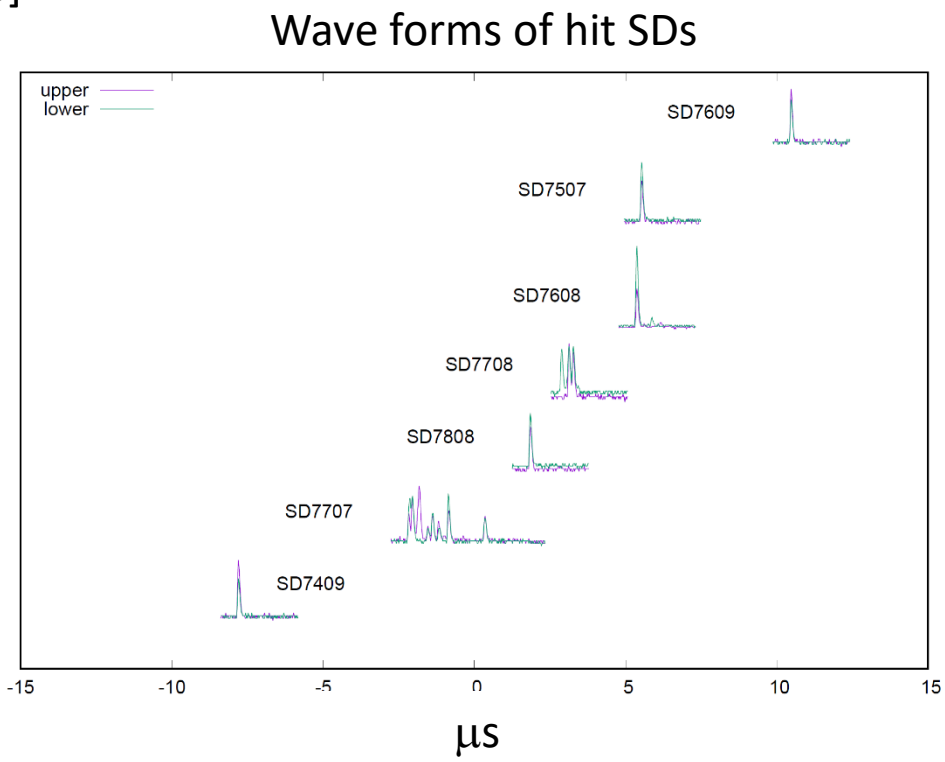
SA* = Staging Area





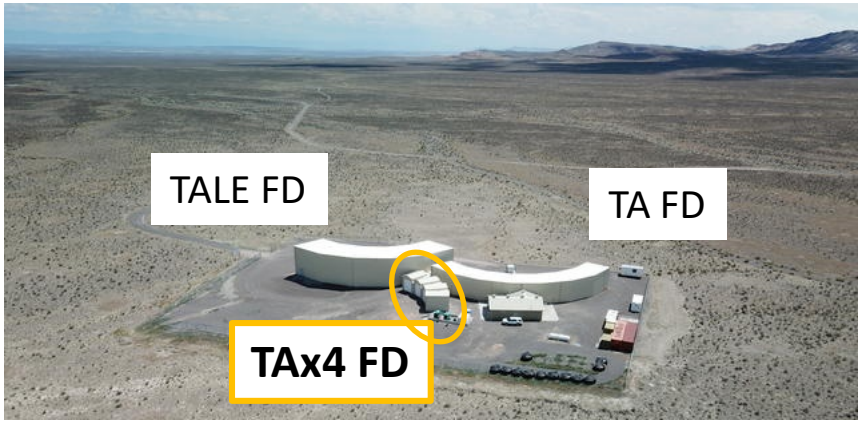
TAx4 SD event example



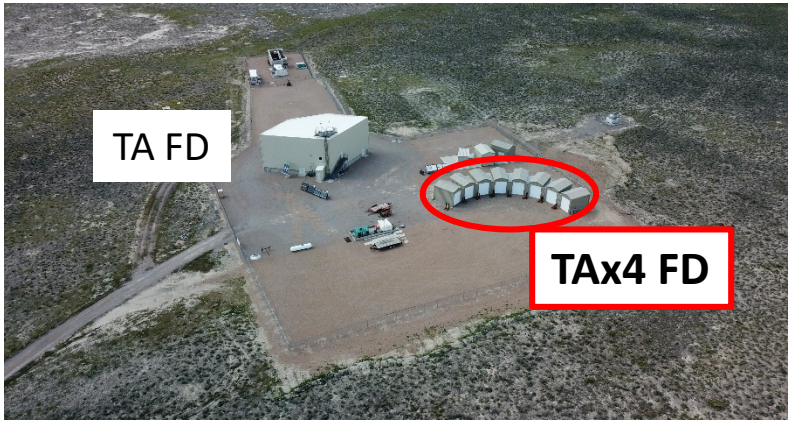


TAx4 FD

- MD site: in operation since Feb. 2018~



- BRM site: under construction



Plan to be commissioning by the end of June, 2019

TAx4

- Resume fine tuning for deployed SDs (ATVs) from June, 2019

- Plan to increase the effective area toward full TAx4 SD
- Full TAx4 in 10 years gives ~50 years of TA SD data adding previous TA data
  - This can give discovery level for the current aniso. hints (~2σ)
  - Even with the current ~2.5 times TA SD in 5 years (TA SD 23.5 years),
    - 5σ or beyond expected for the current evidences (3σ or beyond) of anisotropy

Summary

- TA SD/FD and TALE FD energy spectrum shows spectral features ($10^{15.4}$ eV < E < over 10^{20} eV)
  - cutoff ($10^{19.81}$ eV), ankle ($10^{18.69}$ eV)
  - 2nd knee ($10^{16.22}$ eV) and low-energy ankle ($10^{17.04}$ eV)
- TA Xmax: compatible with light composition (E > ~$10^{18.2}$ eV)
  - Need more statistics for E > 10^{19} eV
- We are seeing evidences of anisotropy (~3σ)
- TA and Auger Working Group worked very well to understand the initially-claimed differences

- TAx4 (SD+FD) has partially started
- Full TALE SD was deployed and is in operation.

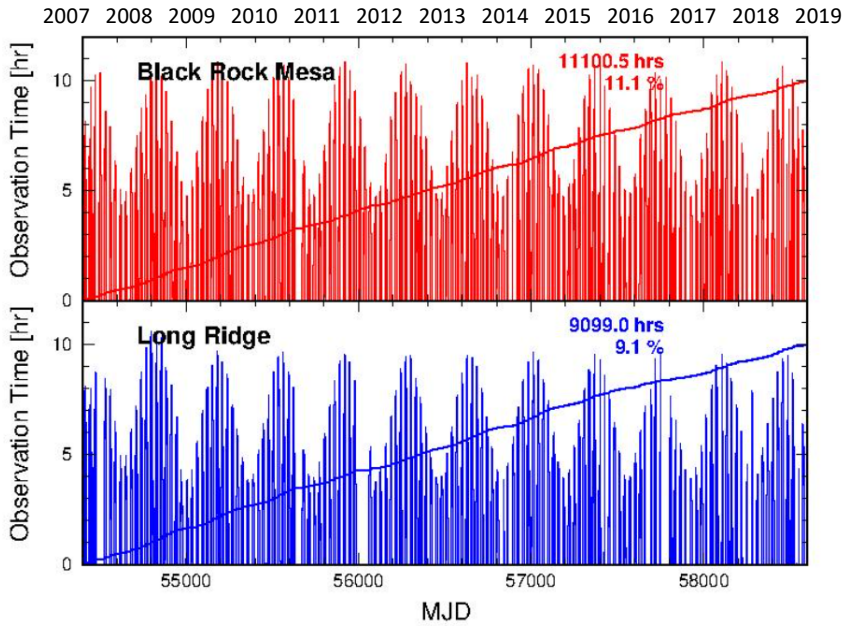
END

Observation time

FD

BR

LR

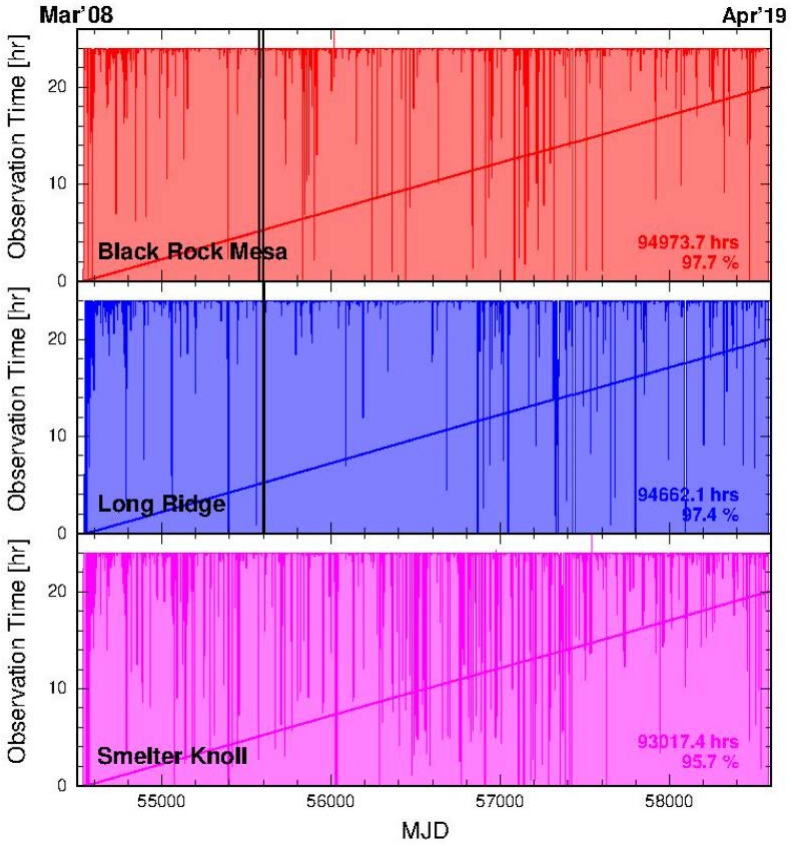


SD

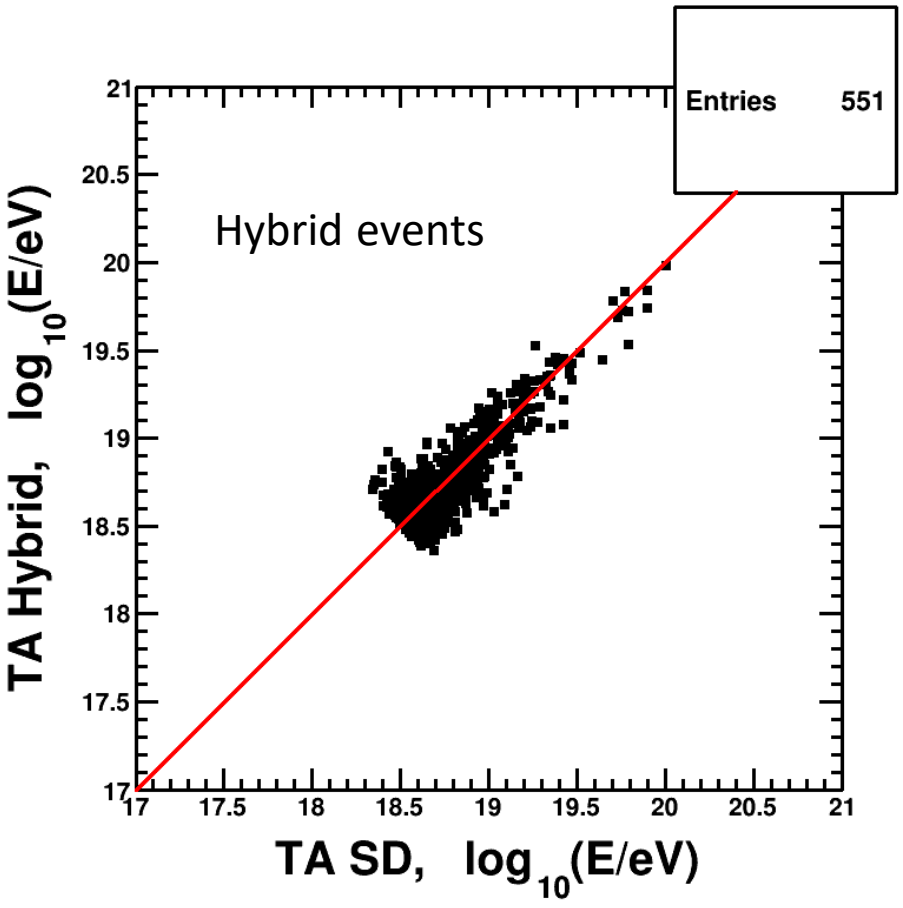
BR

LR

SK

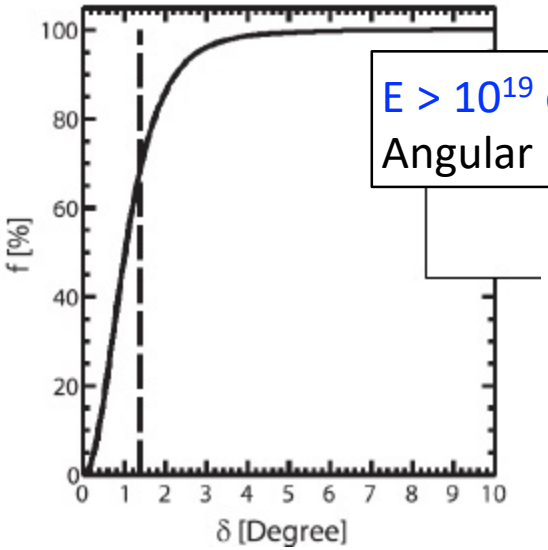


Energy Scale Check and Resolution

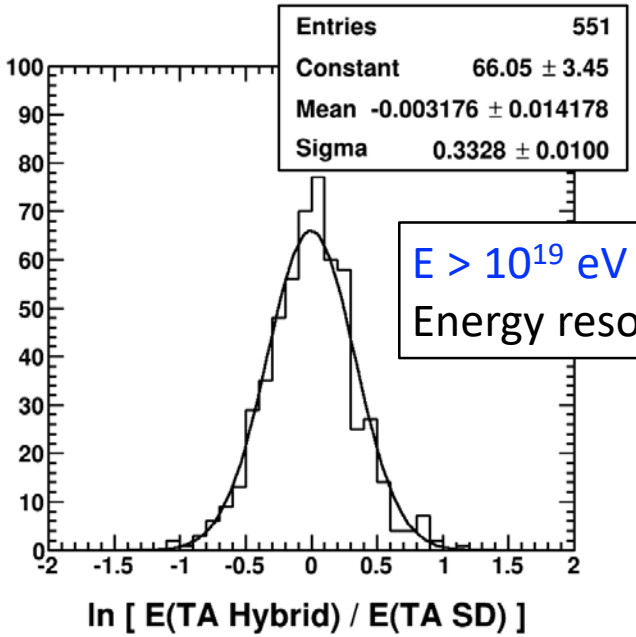


(SD scaled to FD energy: calorimetric)

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



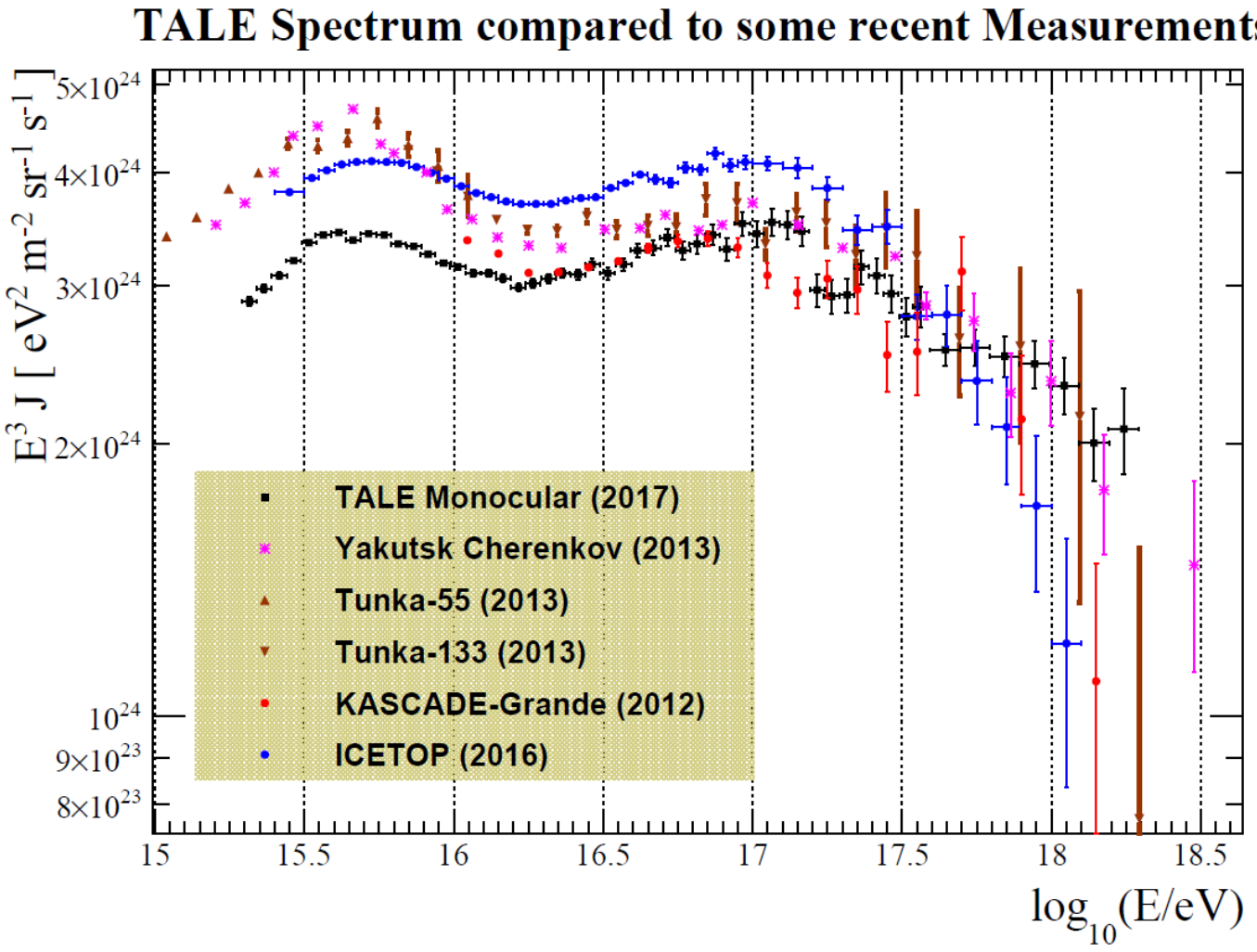
$E > 10^{19}$ eV
Angular resolution = 1.4°



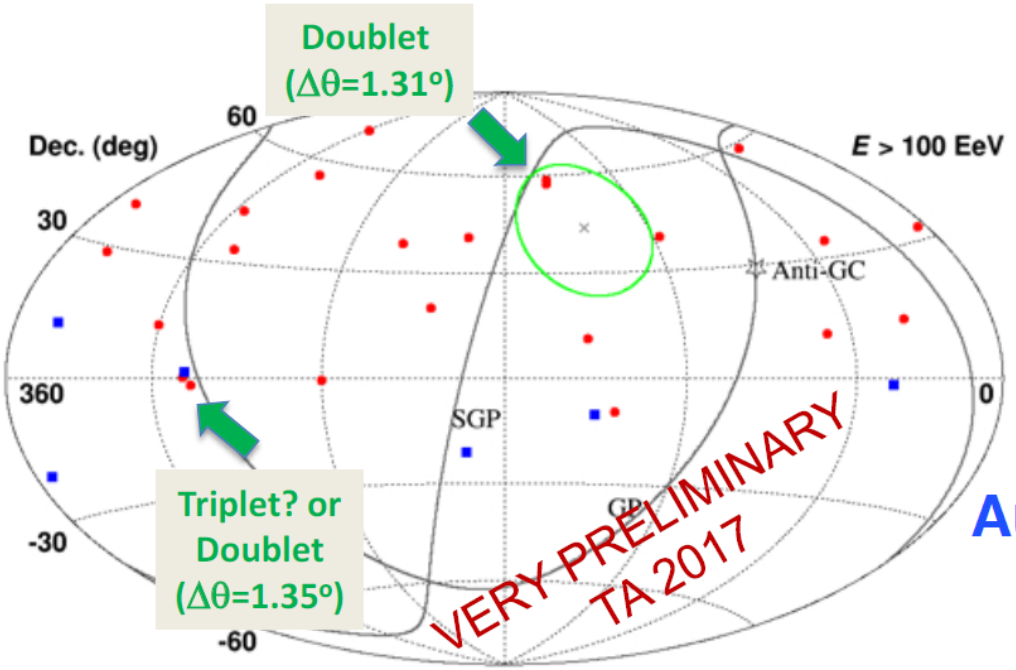
$E > 10^{19}$ eV
Energy resolution < 20%

Comparison with other measurements

C. Jui, SuGAR2018



Cluster events with E > 100 EeV



No correction for
E scale difference
b/w TA and PAO !

TA 9 years (23 events)

Auger 6 years (6 events)

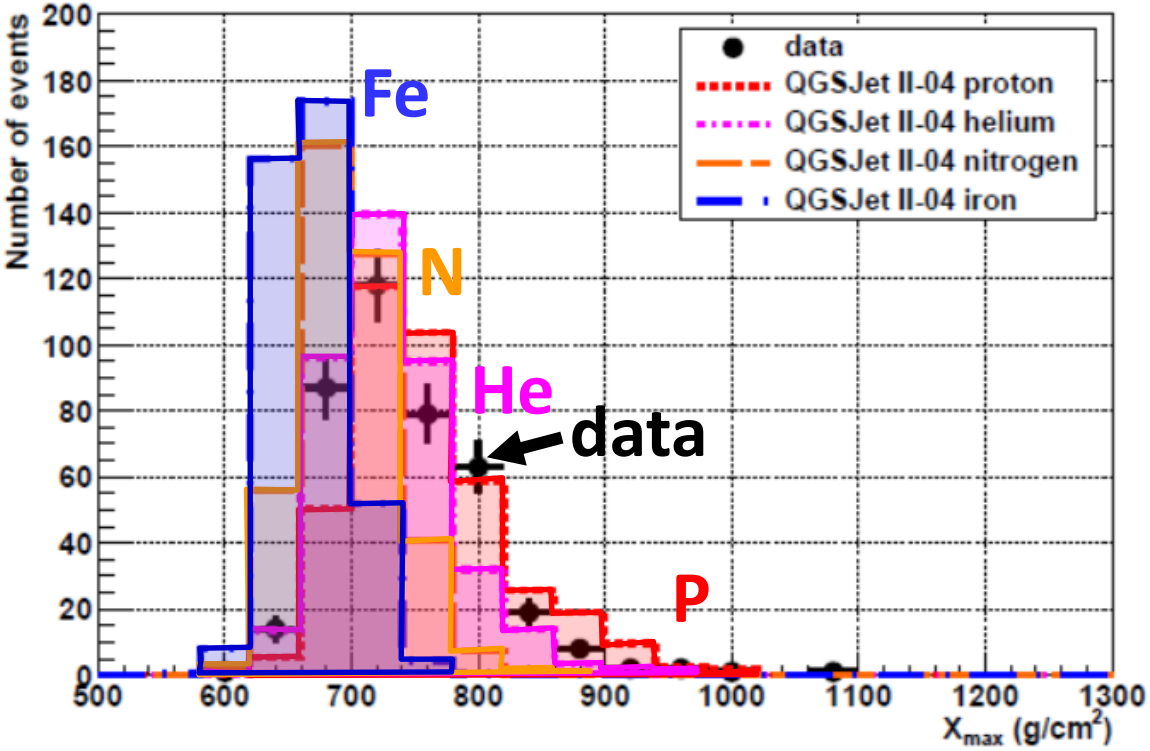
2 doublets above 100 EeV.

→ the probability to have ≥2 doublets at $\leq\sqrt{2}$ deg is

P = 0.30% (2.8σ)

Xmax distributions

R.U. Abbasi et al., ApJ, 858 :76 (27pp), 2018



(d) $18.5 \leq \log_{10}(E/\mathrm{eV}) < 18.6$

Comparison to MC

σ(Xmax) vs <Xmax>

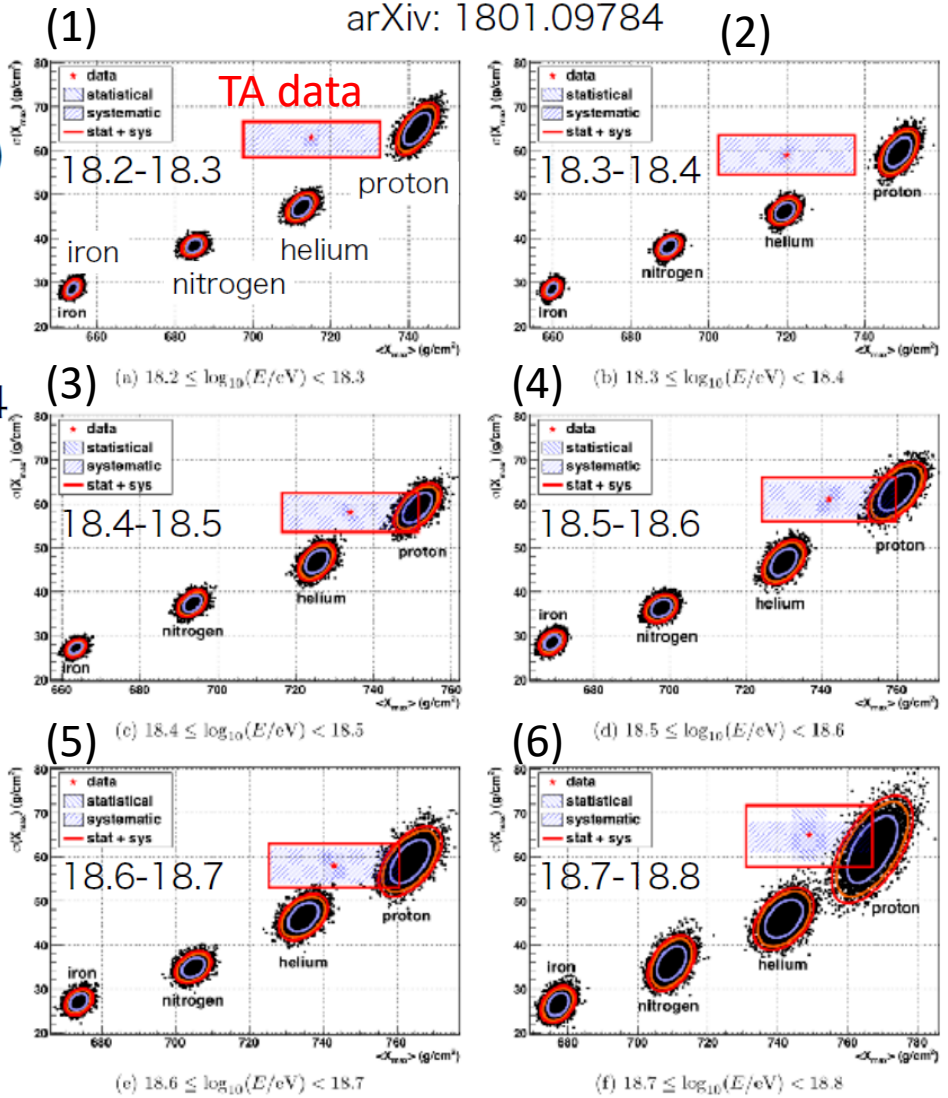
Ap. J., 858, 76(2018)
arXiv: 1801.09784

Compare Data and MC using both <X_{max}> and width of distribution(σ_{Xmax})

- Data : rectangles
- MC: contours

  Repeating 5,000 sets of MCs (Each set = the same # of events, 4 primary types)

In lower energies, log E < 18.8, allowing 10-20g/cm^2 shifts, Data points looks like "proton".



Systematic uncertaiinty

<Xmax> : 17.4g/cm^2

σ_{Xmax} : 21.2g/cm^2

Comparison to MC

σ(Xmax) vs <Xmax>

Ap. J., 858, 76(2018)
arXiv: 1801.09784

Compare Data and MC using both <X_{max}> and σ_{Xmax}

- Data : rectangles
- MC: contours

  Repeating 5,000 sets of MCs (Each set = the same # of events, 4 primary types)

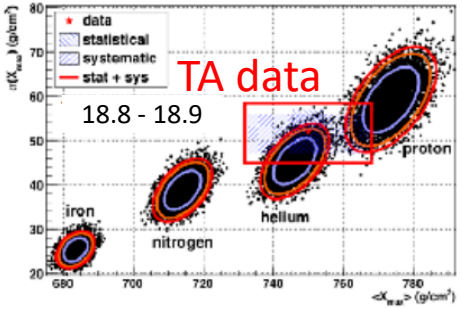
In higher energies, log E > 18.8, data points looks like heavier primary than "proton", and there are significant overlaps between contours of different primaries because of small statistics.

Systematic uncertaiinty

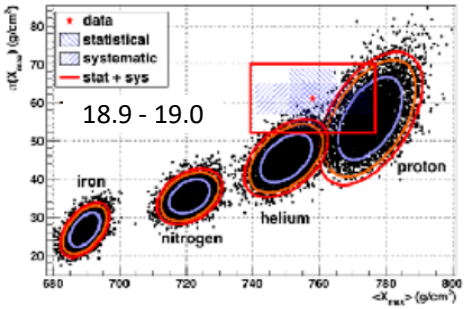
<Xmax> : 17.4g/cm^2

σ_{Xmax} : 21.2g/cm^2

(7)



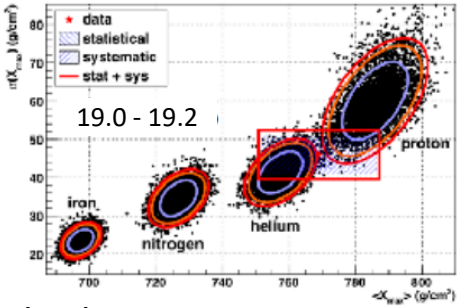
(8)

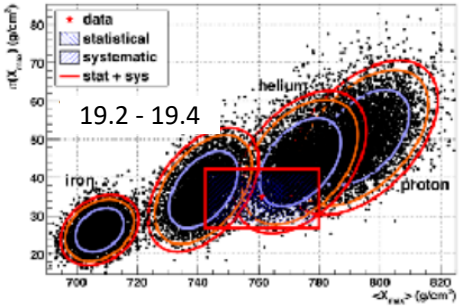


(a) $18.8 \leq \log_{10}(E/\mathrm{eV}) < 18.9$

(b) $18.9 \leq \log_{10}(E/\mathrm{eV}) < 19.0$

(9)

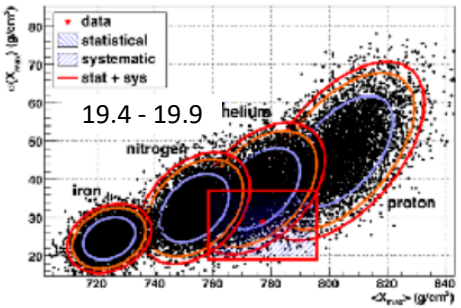




(c) $19.0 \leq \log_{10}(E/\mathrm{eV}) < 19.2$

(d) $19.2 \leq \log_{10}(E/\mathrm{eV}) < 19.4$

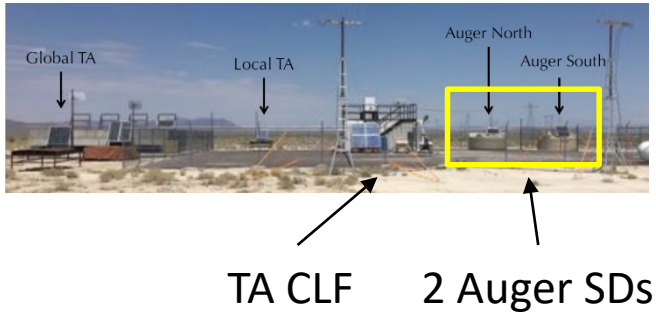
(11)



(e) $19.4 \leq \log_{10}(E/\mathrm{eV}) < 19.9$

Other researches

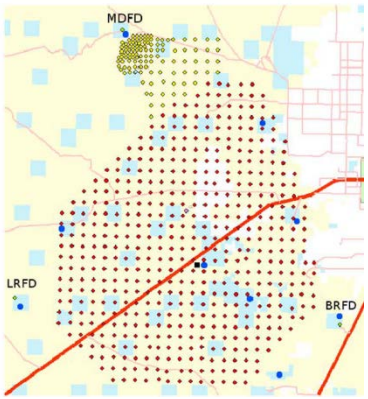
- Auger SD@TA
  - Problem: μ deficit in AS MC
  - Phase I: station-level comparisons at TA CLF

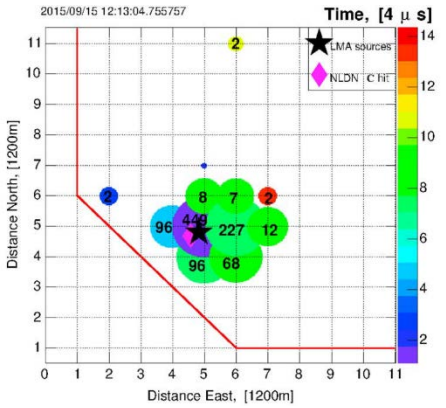


- EUSO-TA
  - JEM-EUSO prototype
  - Co vents

- TALMA (TA Lightning Mapping Array)
  - Coincidence with TA SD events

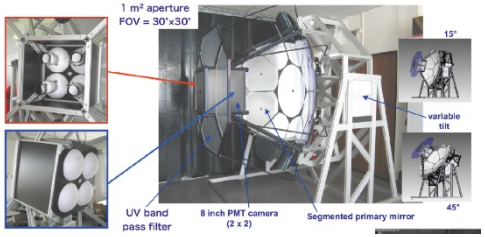
9 antennas in TA





- FD for large ground array
  (aiming low cost)

FAST
4-eye reflection mirror



CRAFFT
Mono-eye Fresnel lens