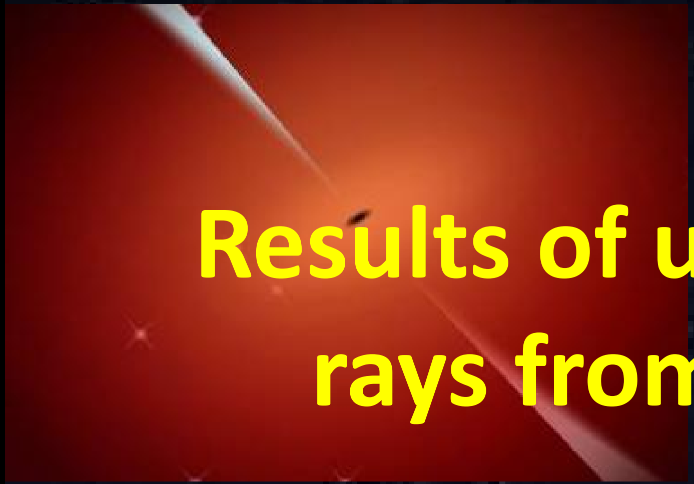


Results of ultra-high energy cosmic rays from the Telescope Array

Hiroyuki Sagawa

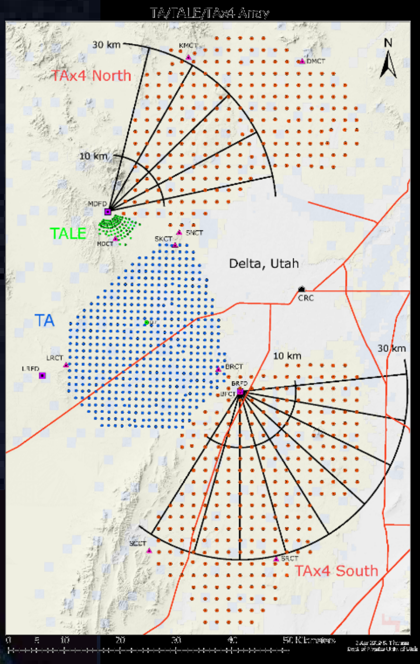
Institute for Cosmic Ray Research

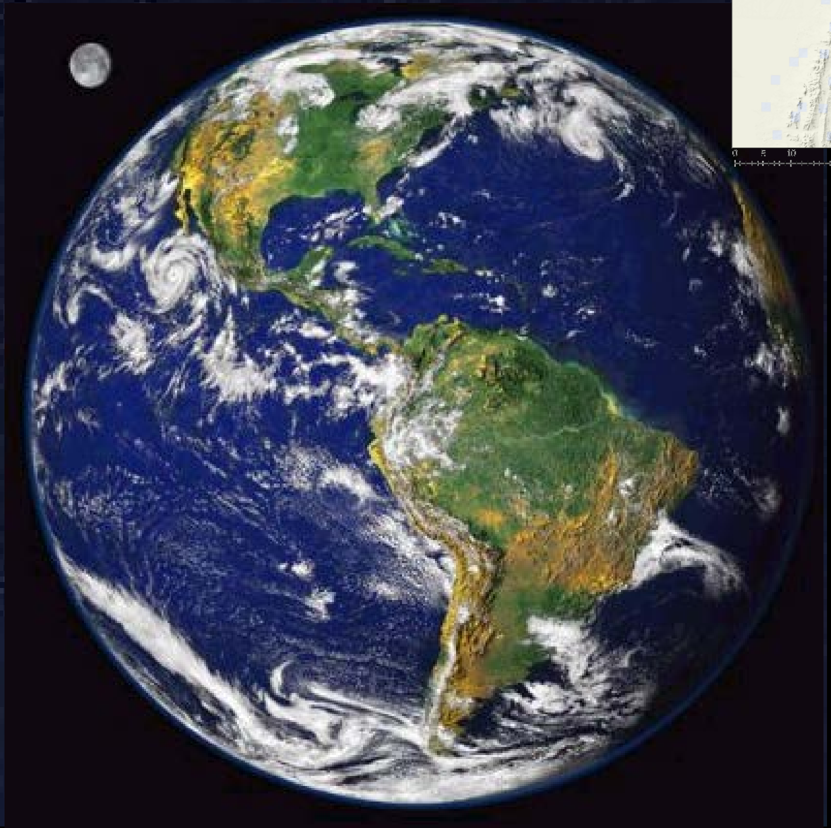
The University of Tokyo

for the Telescope Array Collaboration

BINP, Novosibirsk, Russia

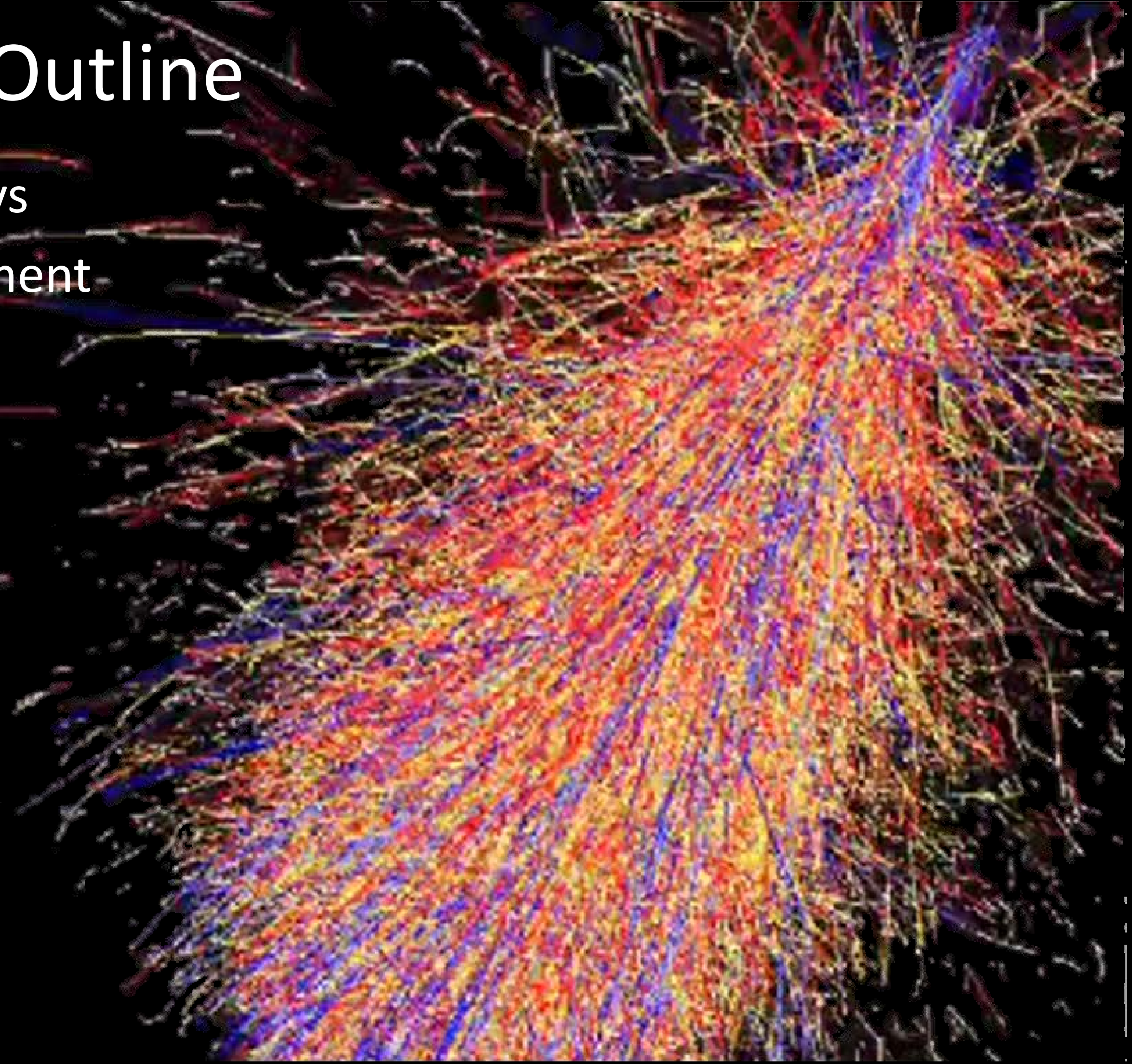
February 24, 2020



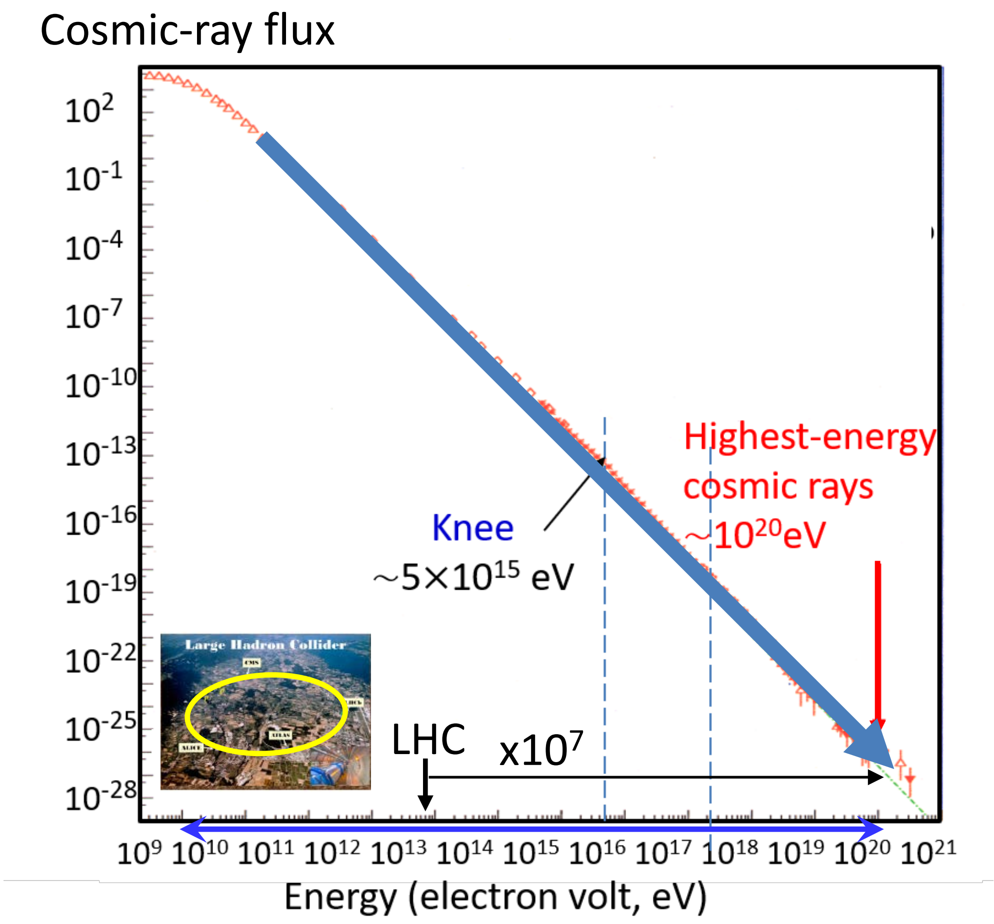


Outline

- Ultra-high energy cosmic rays
- Telescope Array (TA) experiment
- TA results
- TA extension
- Summary

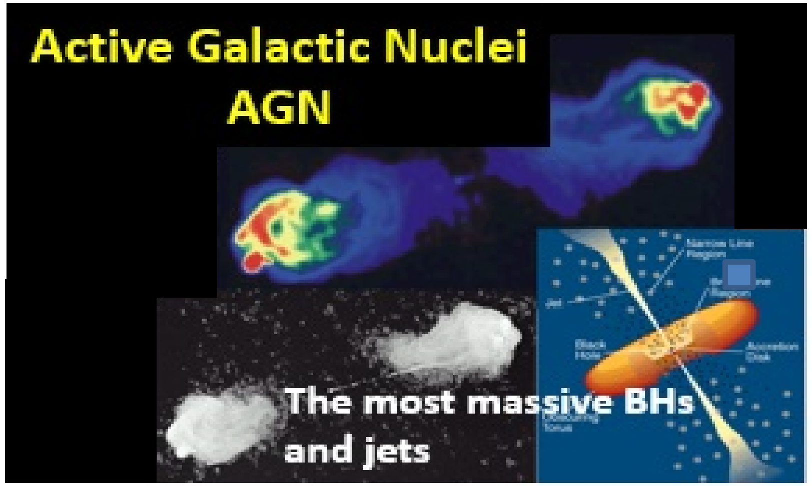


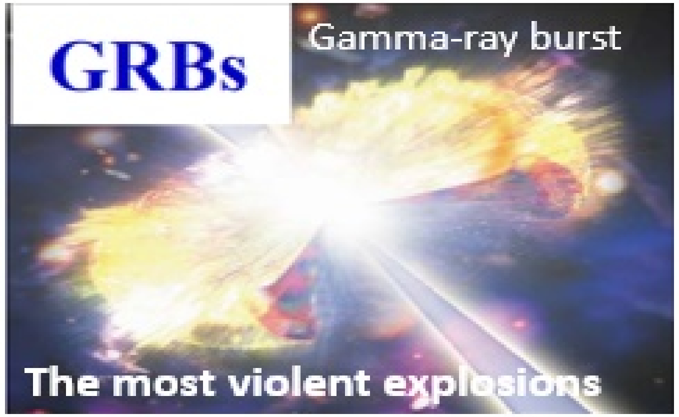
How powerful are Ultra-High-Energy (UHE) cosmic rays?



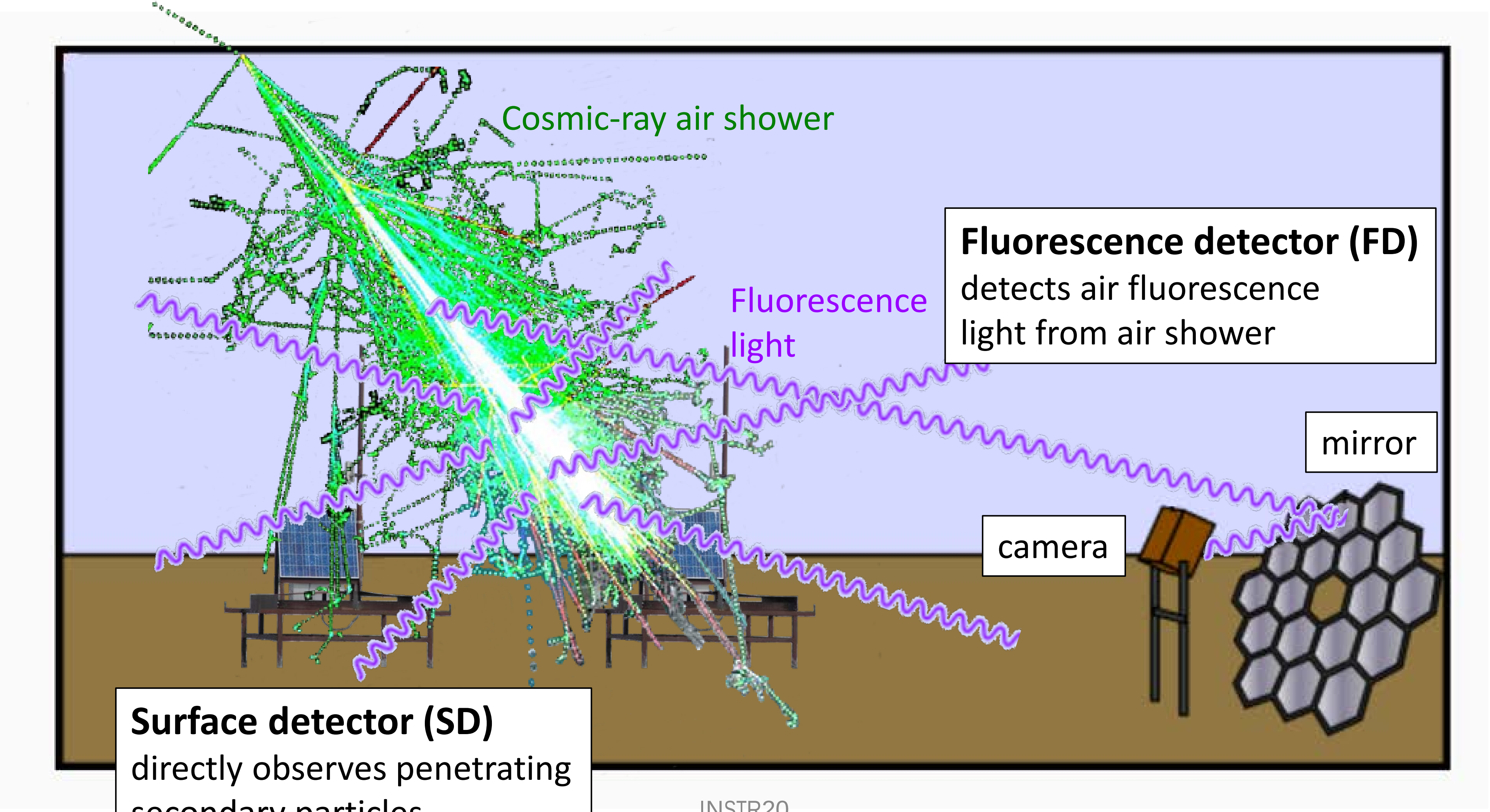
- Cosmic-ray energies range from 10^9 eV to 10^{20} eV
- The most power UHE cosmic rays have over 10^{20} electron volts (eV)
  - 10,000,000 (10^7) times more powerful than the human-made accelerator (LHC)
  - How do cosmic rays gain 10^{20} eV?
- Cosmic-ray flux decreases very rapidly as their energies increase
  - <1 event of 10^{20} eV /100km^2/year
  - Huge detector is necessary!

What are candidates of the strongest cosmic accelerators?





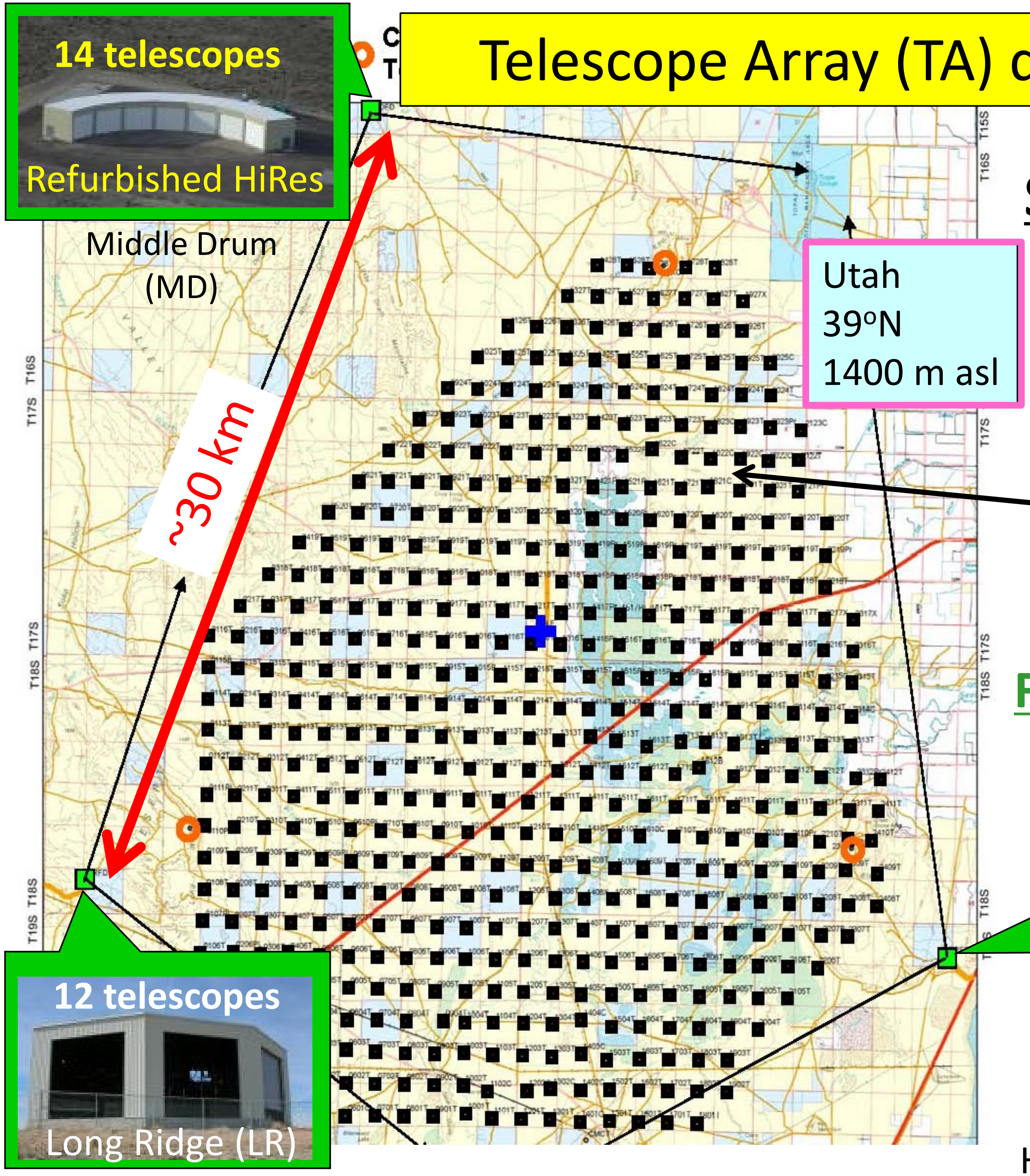
How do we detect UHE cosmic ray air showers?



Fluorescence detector (FD)
detects air fluorescence light from air shower

Surface detector (SD)
directly observes penetrating secondary particles

Telescope Array (TA) detector



Surface Detector (SD)

507 plastic scintillator SDs

1.2 km spacing

∼**700 km²**

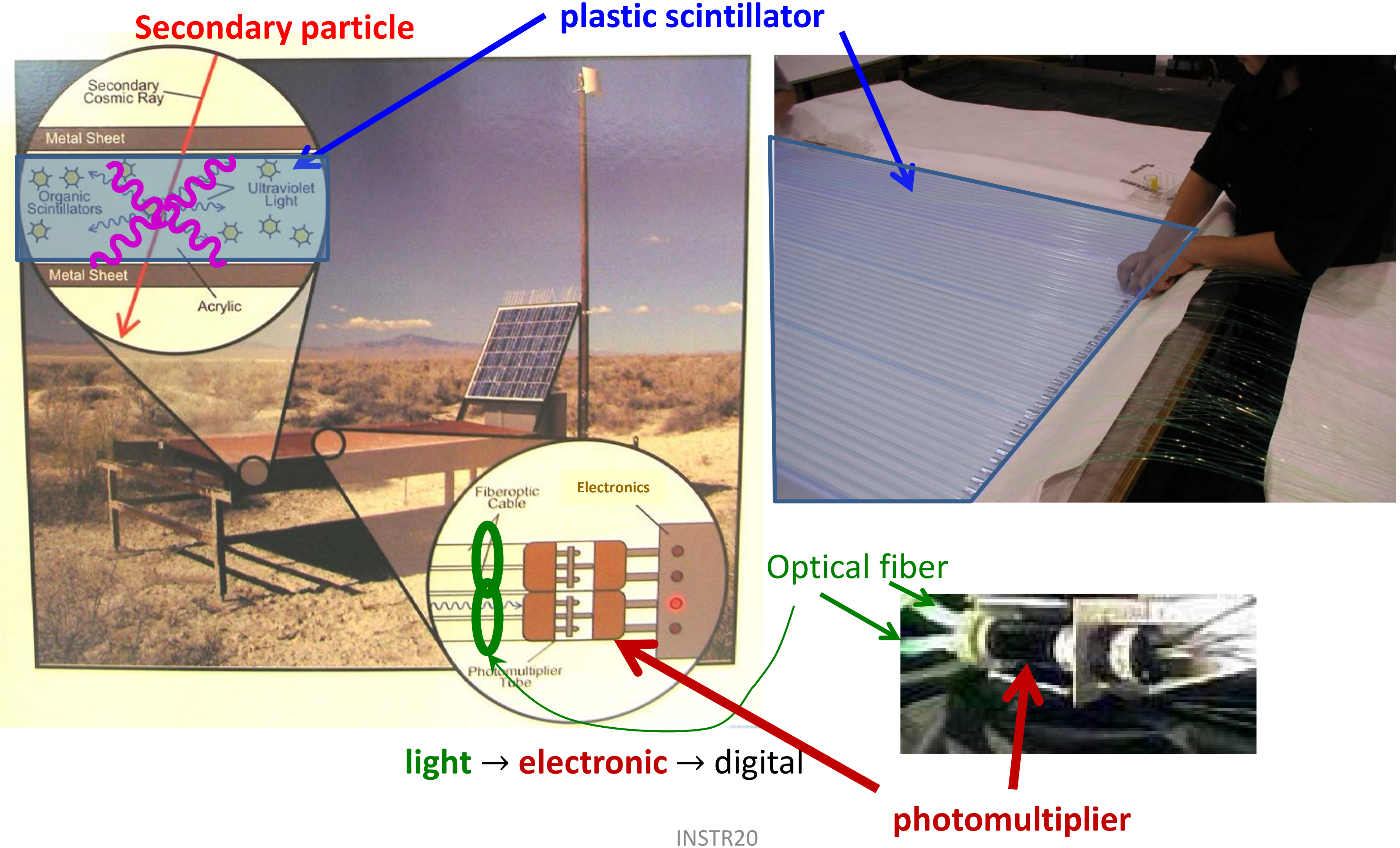
Fluorescence Detector(FD)

3 stations

38 telescopes

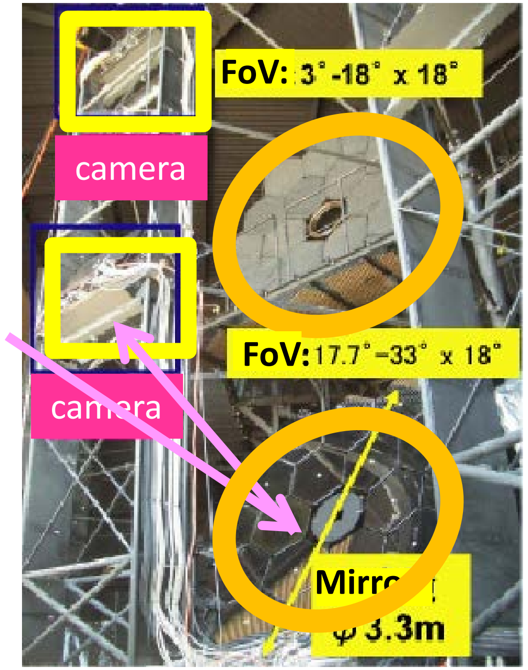
Hybrid observation since 2008

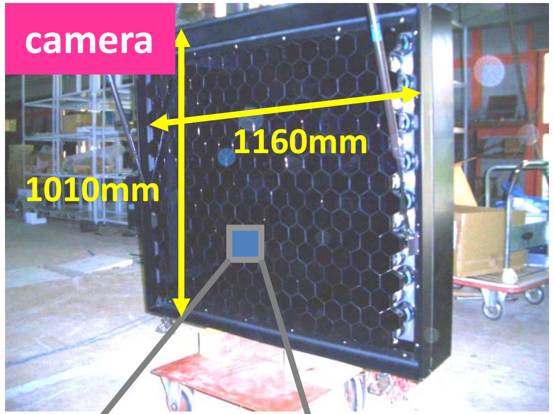
Scintillator detector (SD)



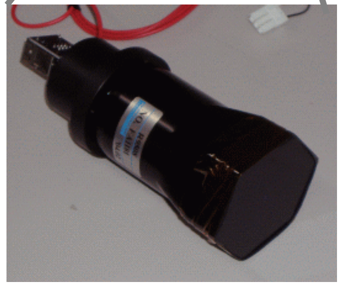
Fluorescence Detector (FD)

Observation with moonless and clear sky: duty cycle ~10%
Three FD stations started observation in Nov., 2007





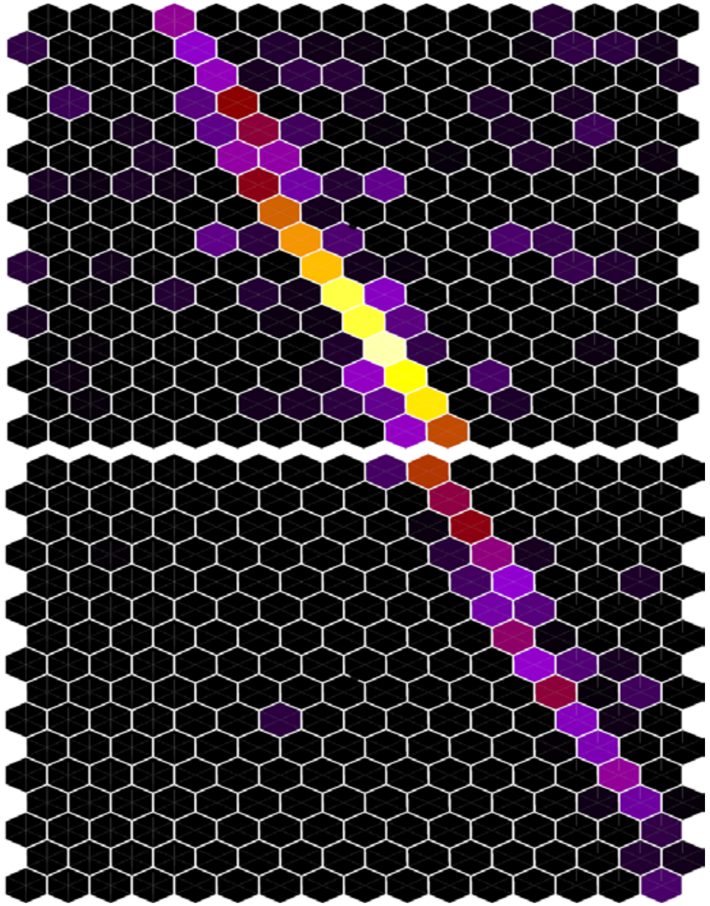
256PMTs



Hexagonal photomultiplier (PMT)

Air shower observed with TA FD

Upper FoV camera



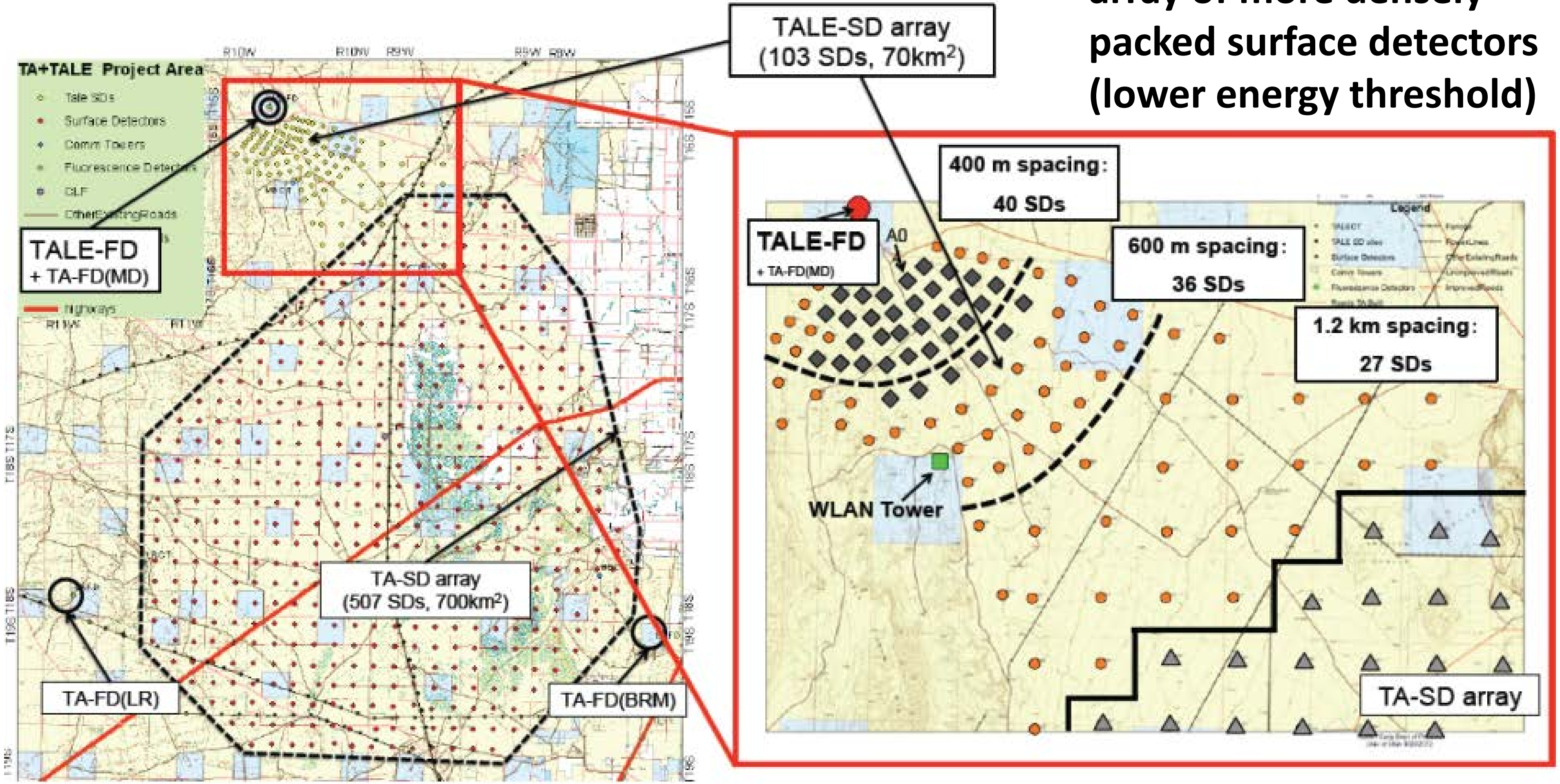
Lower FoV camera

TA Low Energy Extension (TALE)

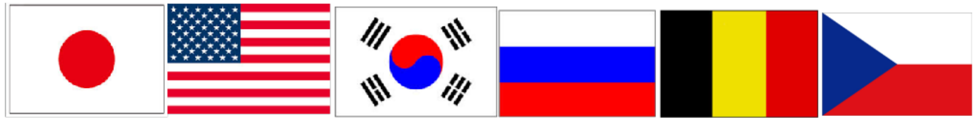
10 new telescopes to look higher in the sky (31-59°) to see shower development to much lower energies

[859- PoS 637] Poster 1 CR Track: CRIN Board #: 148
Presented by Shoichi OGIO on 30 Jul 2015
at 15:30

Infill surface detector array of more densely packed surface detectors (lower energy threshold)



Telescope Array Collaboration



Japan, USA, Korea, Russia, Belgium, Czech

147 collaborators from 36 institutes in 6 countries

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[8], K. Fujita[9], R. Fujiwara[9], M. Fukushima[10,11], G. Furlich[1], W. Hanlon[1], M. Hayashi[12], Y. Hayashi[9], N. Hayashida[13], K. Hibino[13], K. Honda[14], D. Ikeda[15], T. Inadomi[16], N. Inoue[2], T. Ishii[14], R. Ishimori[3], H. Ito[17], D. Ivanov[1], H. Iwakura[16], H.M. Jeong[18], S. Jeong 18 , C.C.H. Jui[1], K. Kadota[19], F. Kakimoto[3], O. Kalashev[20], K. Kasahara[21], S. Kasami[22], H. Kawai[23], S. Kawakami[9], S. Kawana[2], K. Kawata[10], E. Kido[10], H.B. Kim[4], J.H. Kim[1], J.H. Kim[24], S. Kishigami[9], V. Kuzmin[20], M. Kuznetsov[7,20], Y.J. Kwon[25], K.H. Lee[18], B. Lubsandorzhiev[20], J.P. Lundquist[1], K. Machida[14], K. Martens[11], H. Matsumiya[9], T. Matsuyama[9], J.N. Matthews[1], R. Mayta[9], M. Minamino[9], K. Mukai[14], I. Myers[1], S. Nagataki[17], K. Nakai[9], R. Nakamura[16], T. Nakamura[26], Y. Nakamura[16], T. Nonaka[10], H. Oda[9], S. Ogio[9,27], M. Ohnishi[10], H. Ohoka[10], Y. Oku[22], T. Okuda[28], Y. Omura[9], M. Ono[17], R. Onogi[9], A. Oshima[9], S. Ozawa[21], I.H. Park[18], M.S. Pshirkov[20,29], J. Remington[1], D.C. Rodriguez[1], G. Rubtsov[20], D. Ryu[24], H. Sagawa[10], R. Sahara[9], K. Saito[10], Y. Saito[16], N. Sakaki[10], T. Sako[10], N. Sakurai[9], K. Sano[16], L.M. Scott[30], T. Seki[16], K. Sekino[10], P.D. Shah[1], F. Shibata[14], T. Shibata[10], H. Shimodaira[10], B.K. Shin[9], H.S. Shin[10], J.D. Smith[1], P. Sokolsky[1], N. Sone[16], B.T. Stokes[1], S.R. Stratton[1,30], T.A. Stroman[1], T. Suzawa[2], Y. Takagi[9], Y. Takahashi[9], M. Takamura[5], M. Takeda[10], R. Takeishi[18], A. Taketa[15], M. Takita[10], Y. Tameda[22], H. Tanaka[9], K. Tanaka[31], M. Tanaka[32], Y. Tanoue[9], S.B. Thomas[1], G.B. Thomson[1], P. Tinyakov[7,20], I. Tkachev [20], H. Tokuno[3], T. Tomida[16], S. Troitsky[20], Y. Tsunesada[9,27], Y. Uchihori[33], S. Udo[13], T. Uehama[16], F. Urban[34], T. Wong[1], M. Yamamoto[16], H. Yamaoka[32], K. Yamazaki[13], J. Yang[35], K. Yashiro[5], M. Yosei[22], H. Yoshii[36], Y. Nakamura[16], Y. Zhezher[20], Z. Zundel[1]

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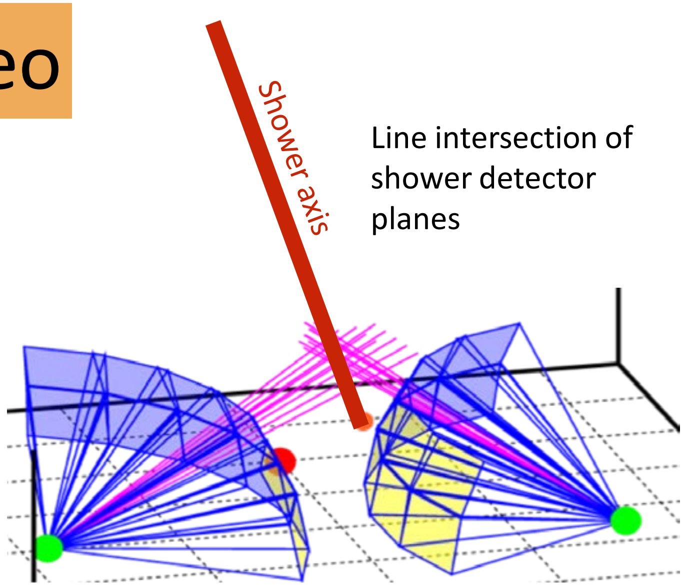
TA results

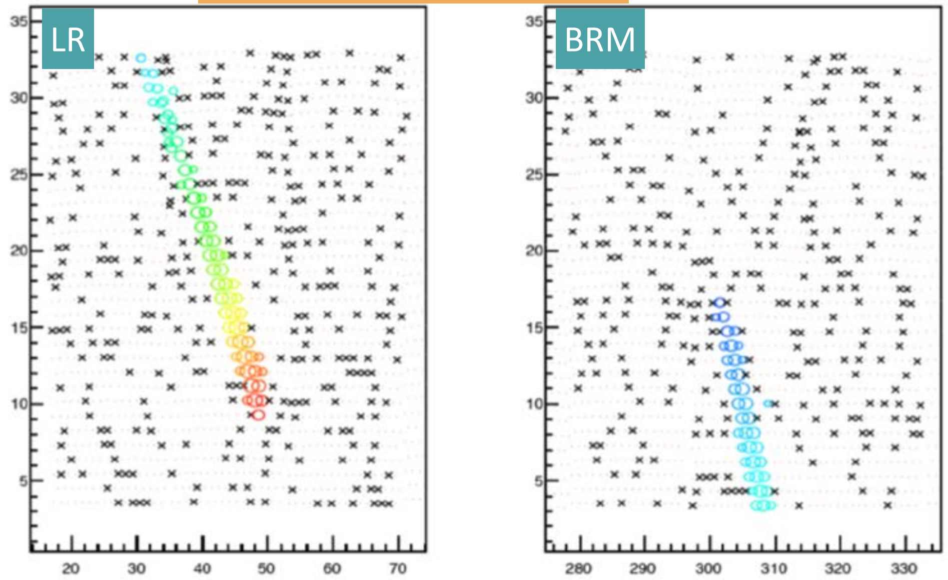
1. Energy spectrum
2. Composition
3. Anisotropy of arrival directions

Shower analysis with FD

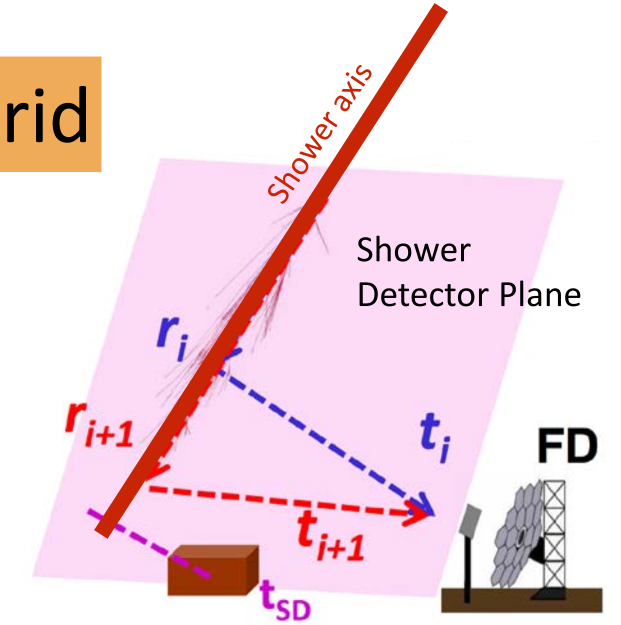
Stereo



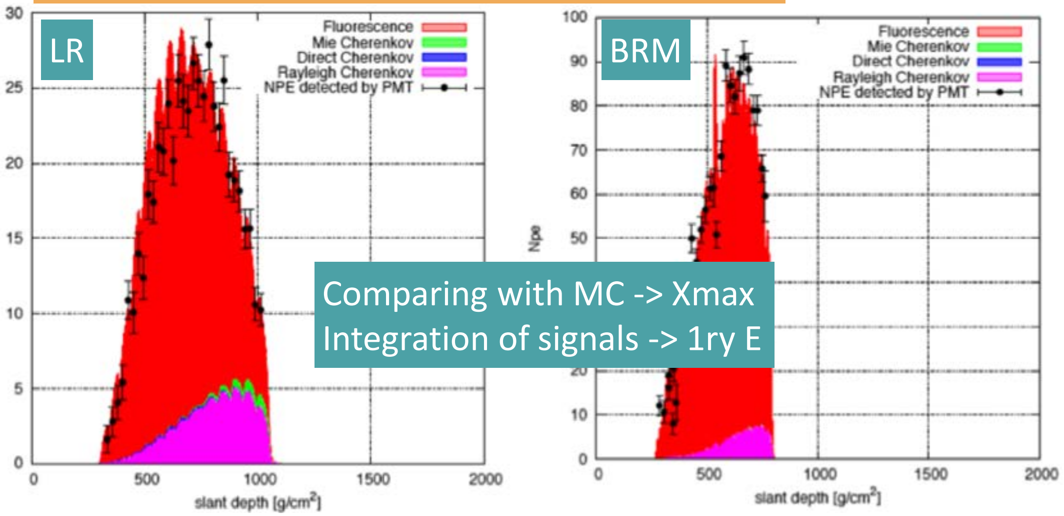
observed images



Hybrid



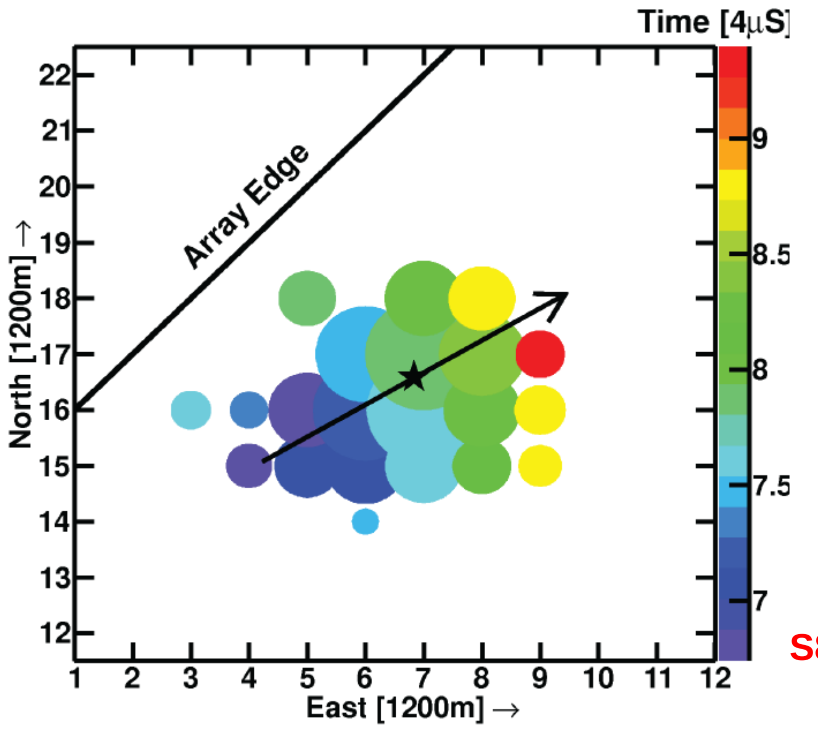
reconstructed shower profiles



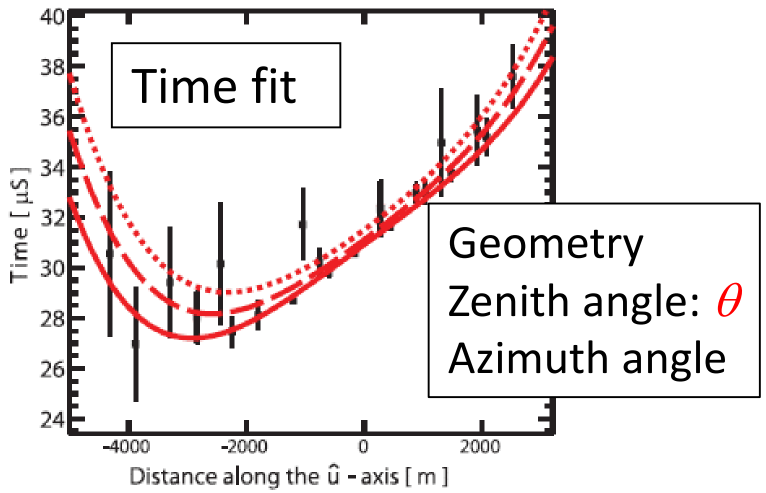
Comparing with MC -> Xmax
Integration of signals -> 1ry E

Shower analysis with SD

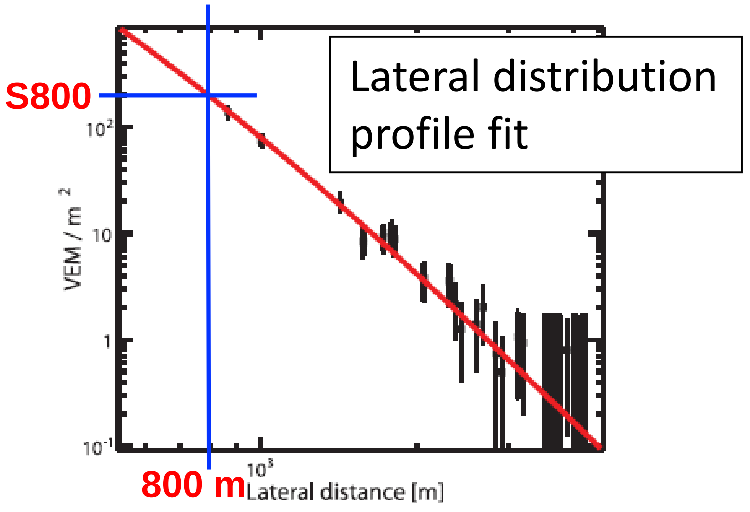
① An SD hit map of a typical event



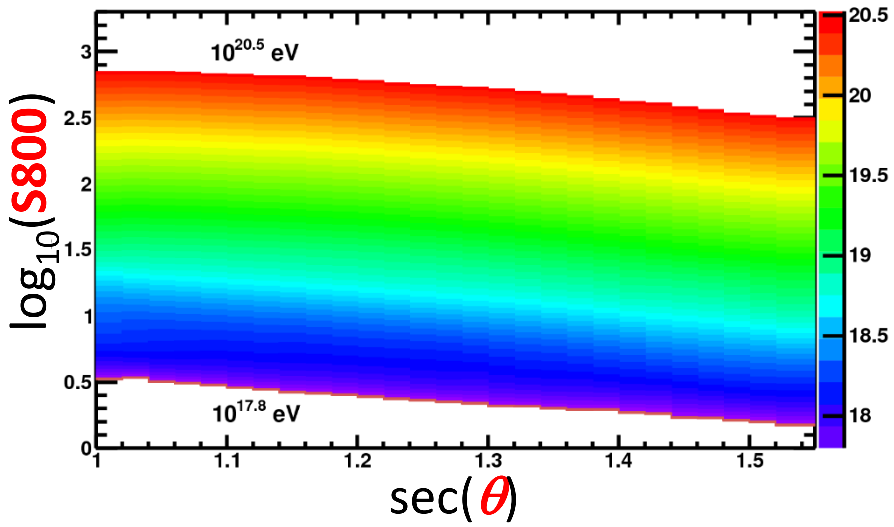
②



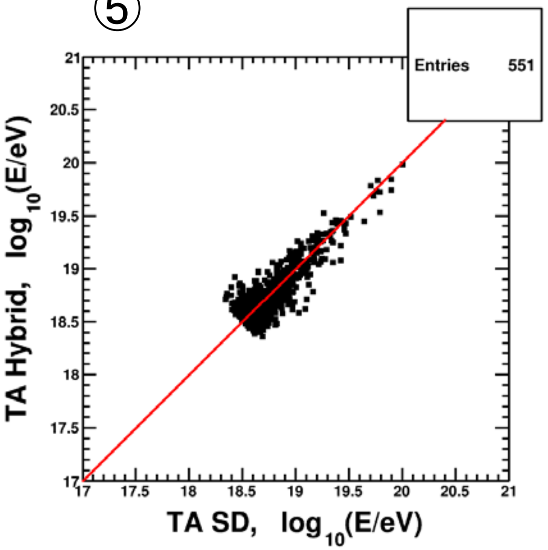
③



④ Energy (E'_{SD}) table from MC



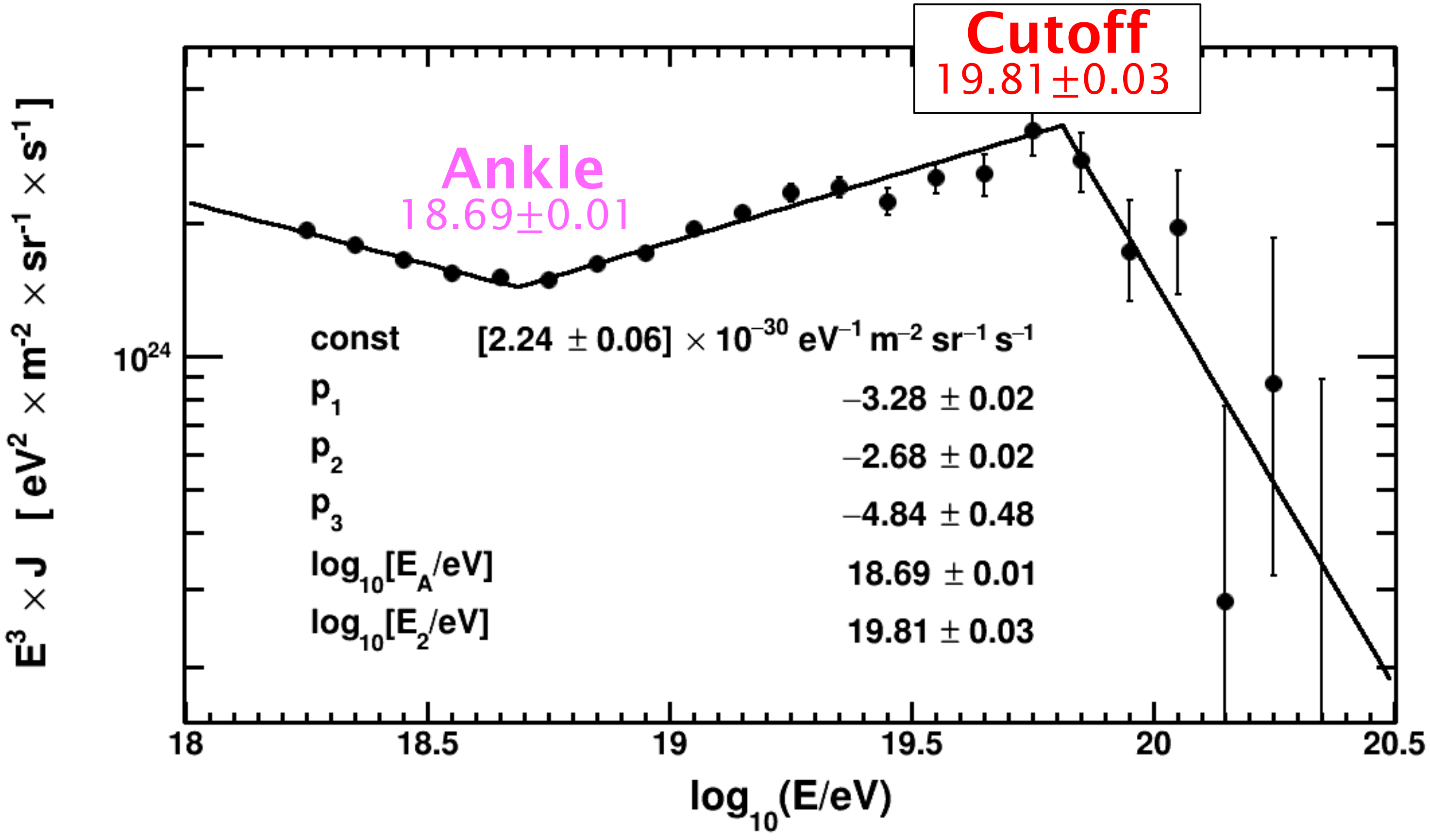
⑤



$E_{SD} = E'_{SD}/1.27$

Energy Spectrum from 11 years of TA SD data
(2008/05/11 – 2019/05/11)

(ICRC 2019)

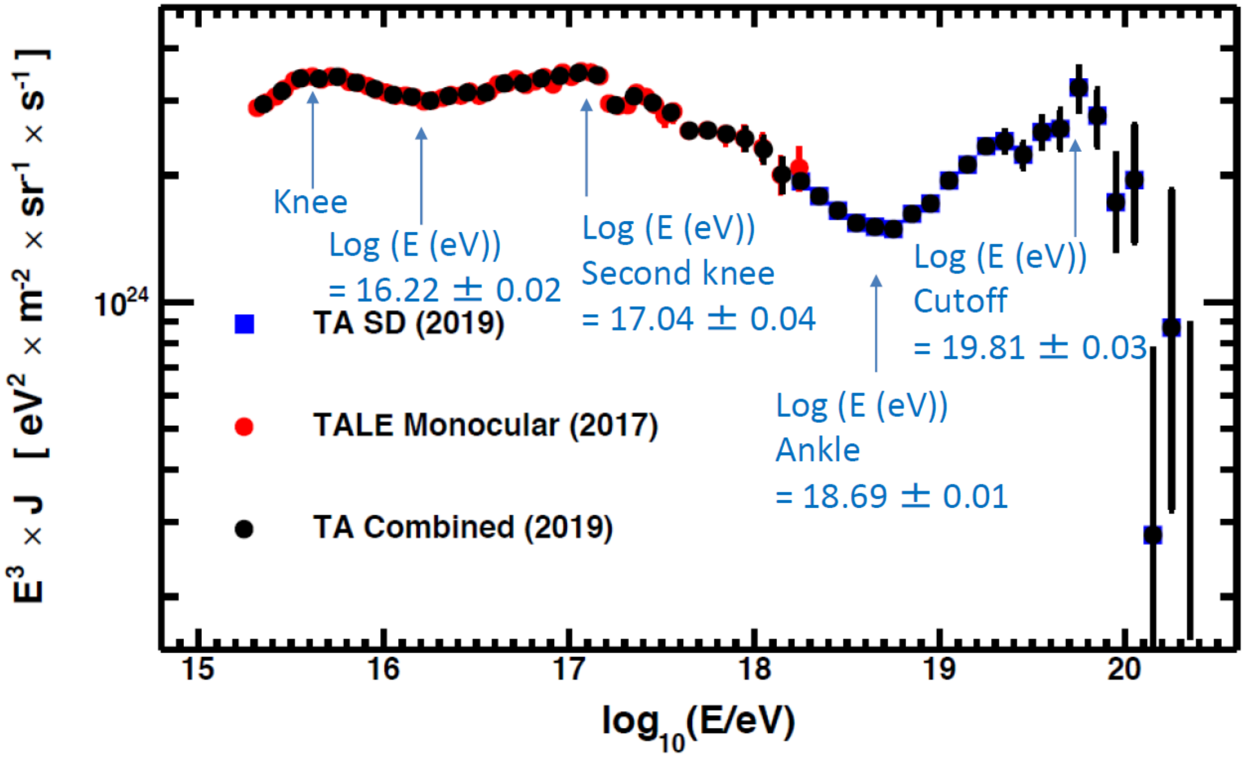


Significance of suppression: 8.6σ

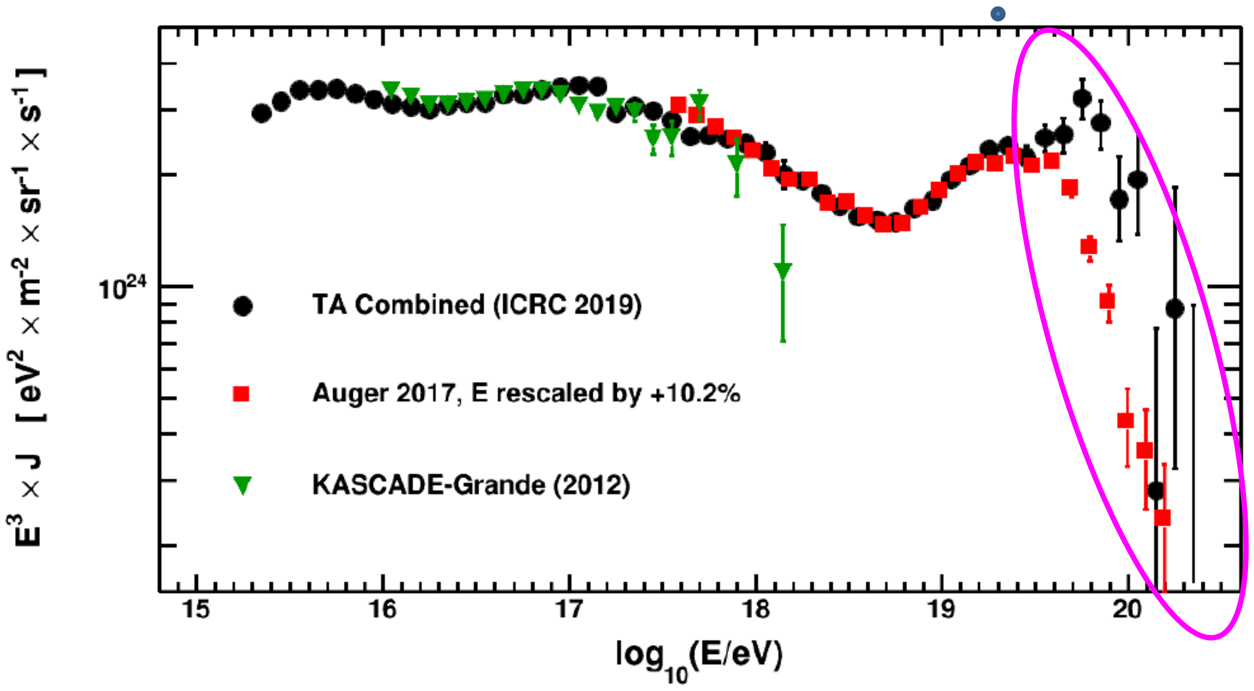
TA Combined Energy Spectrum

D. Ivanov, ICRC2019

TA SD, TALE FD, TA Combined

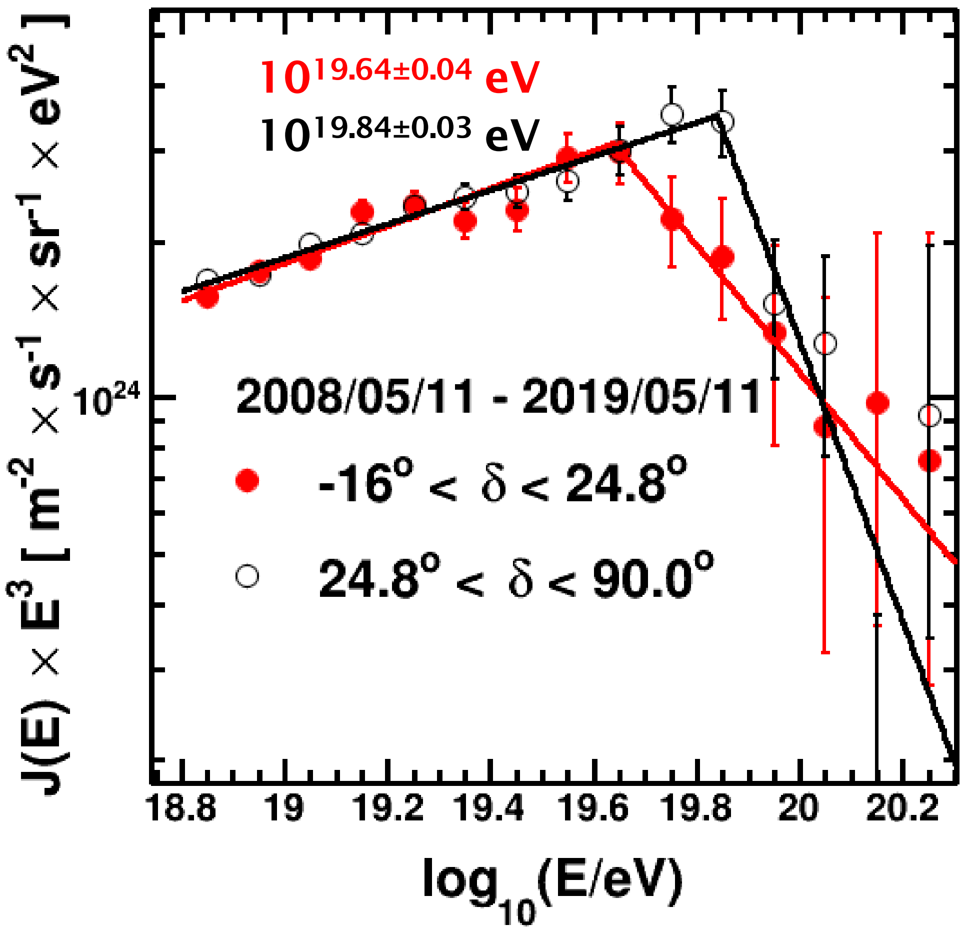


Compare with KASCADE-Grande and Auger



Declination (δ) dependence of energy spectrum

11 years of TA SD data



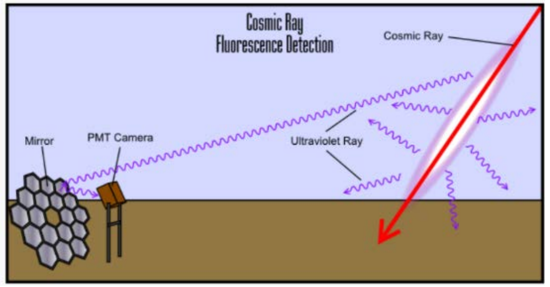
- Cutoff energies in lower and higher TA declination bands are 4.7 σ different
  - **4.3 σ global chance probability of the effect**
- Strong evidence of cosmic ray spectrum declination dependence in the Northern Hemisphere

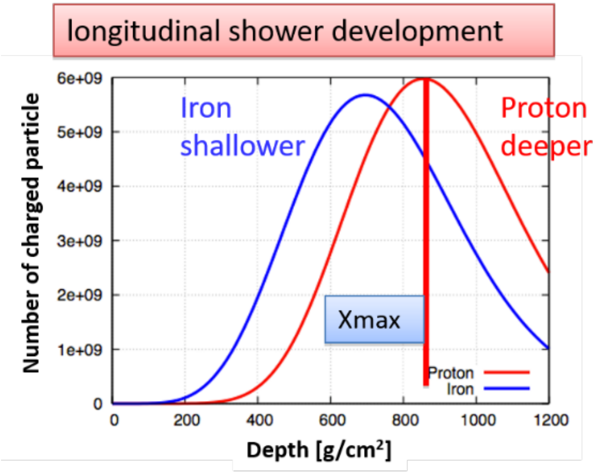
Composition: Xmax

- FD observes longitudinal shower development
- Longitudinal development of cosmic-ray showers depends on primary particle type
- Xmax (shower maximum depth)
  - the most efficient parameter for determining particle type (mass composition)

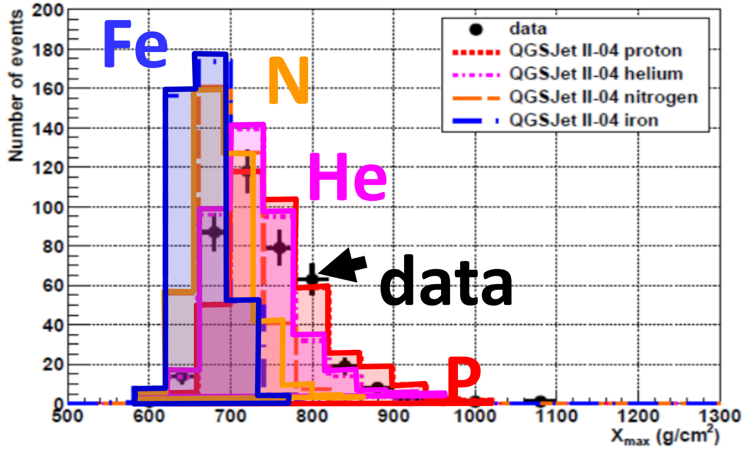
- TA result -

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





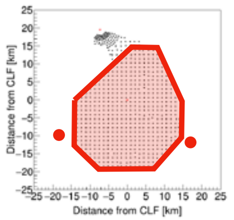
upper sky ground

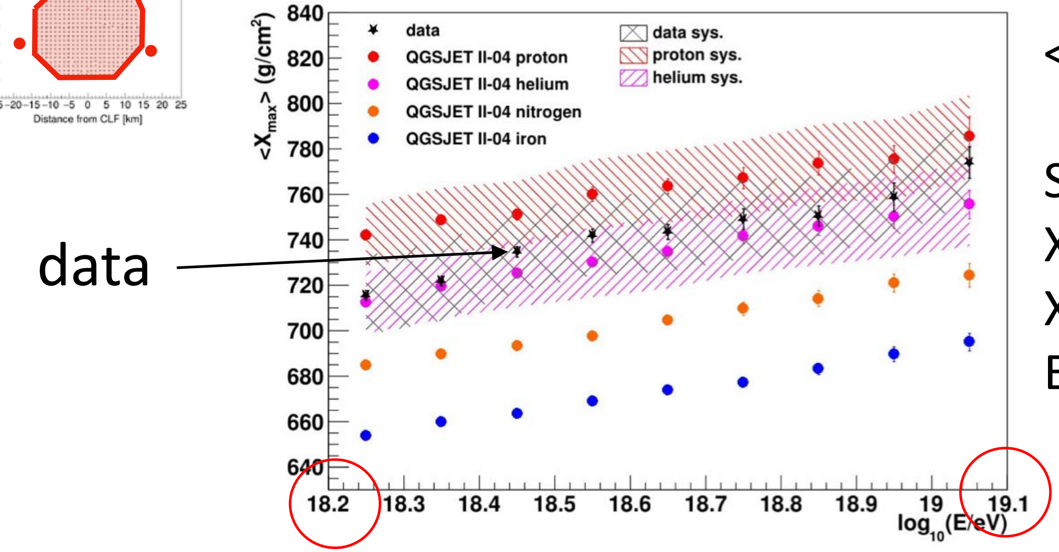


$10^{18.5}$ eV < E < $10^{18.6}$ eV

TA BRM+LR hybrid: <Xmax> and σXmax

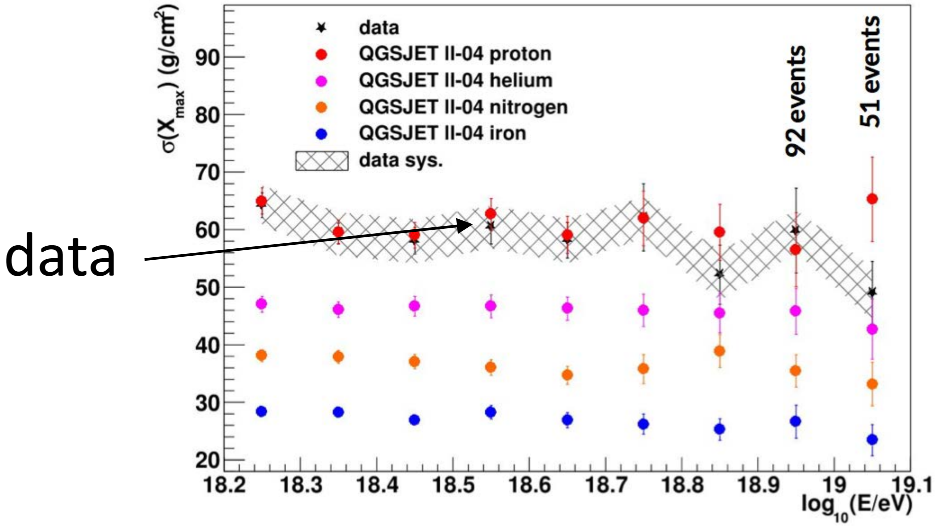
10 years of TA data by W. Hanlon @ICRC2019





< Xmax > **data** with QGSJET II-04 (p, He, N, Fe) models

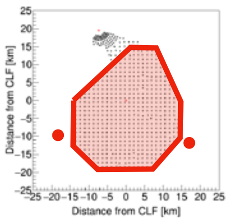
Systematic uncertainty: 17 g/cm^2 (shaded areas)
Xmax bias < 1 g/cm^2
Xmax resolution: 17.2 g/cm^2
Energy resolution: 5.7 %



σXmax **data** with QGSJET II-04 (p, He, N, Fe) models

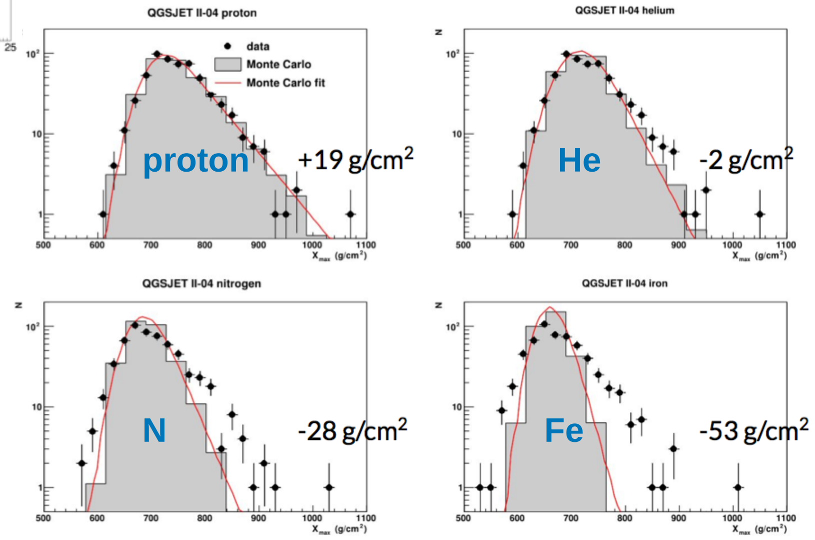
The data are compatible with the protons below 10^{19} eV

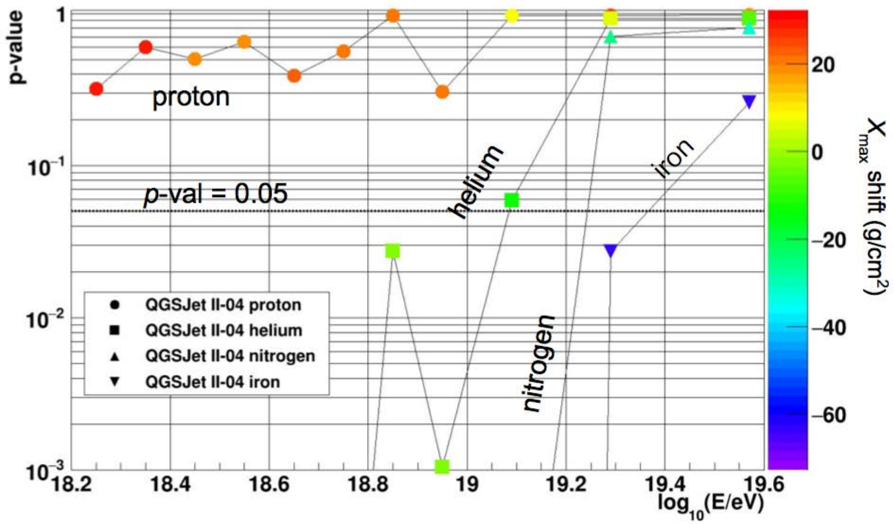
TA BRM+LR hybrid: single element model



Xmax shape check

$18.4 \le \log_{10}(E/eV) < 18.5$





Ap. J., 858, 76(2018)

Compare Xmax shapes of data and single element QGSJET II-04 models by shifting data Xmax distribution

Proton and He agree with the data
N and Fe do not resemble the data.

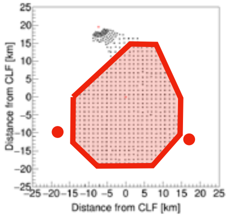
(Xmax systematic uncertainty = 17 g/cm^2)

Data: compatible with proton for all energies

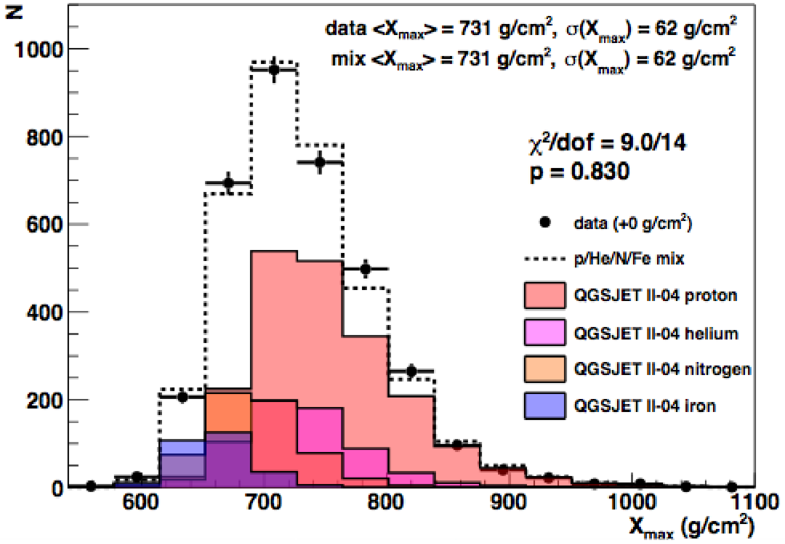
Other components: not compatible in $E < 10^{19}$eV
All single components: compatible in the highest energy bin.
← low statistics (19 events)

TA BRM+LR+SD hybrid: 4 element model

ICRC2019 W. Hanlon

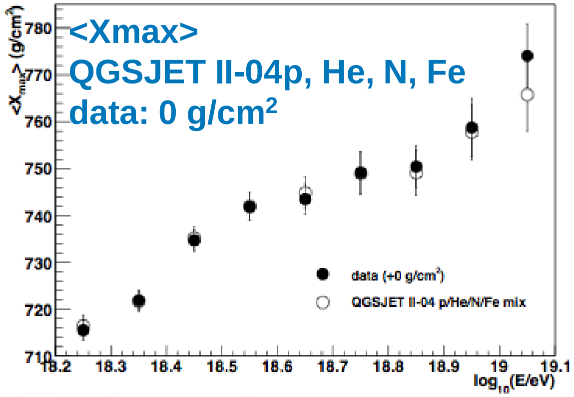


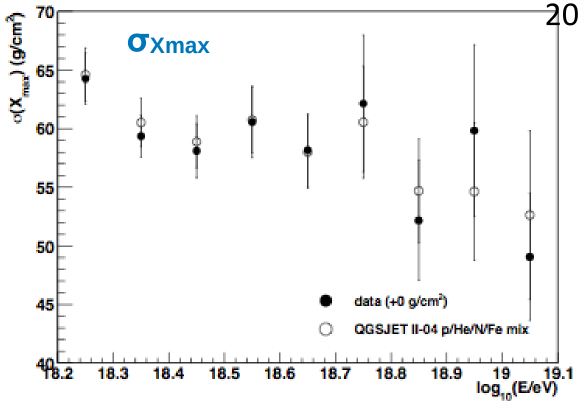
QGSJET II-04 proton, He, N, Fe, data



Compare data and mixed 4-element model

For $10^{18.2}$-$10^{19.1}$ eV,
proton = 57%, He = 18%, N = 17%, Fe = 8%

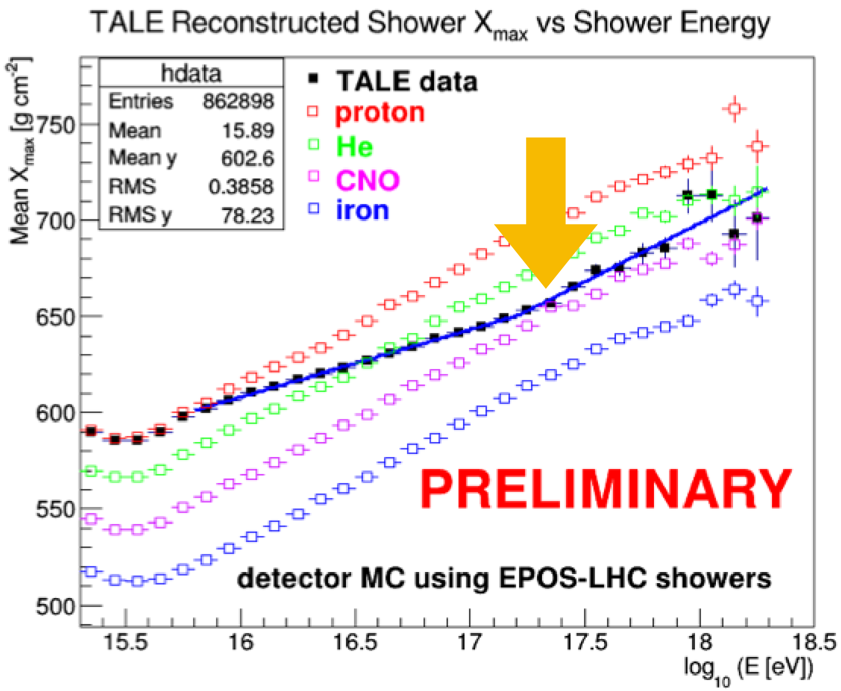


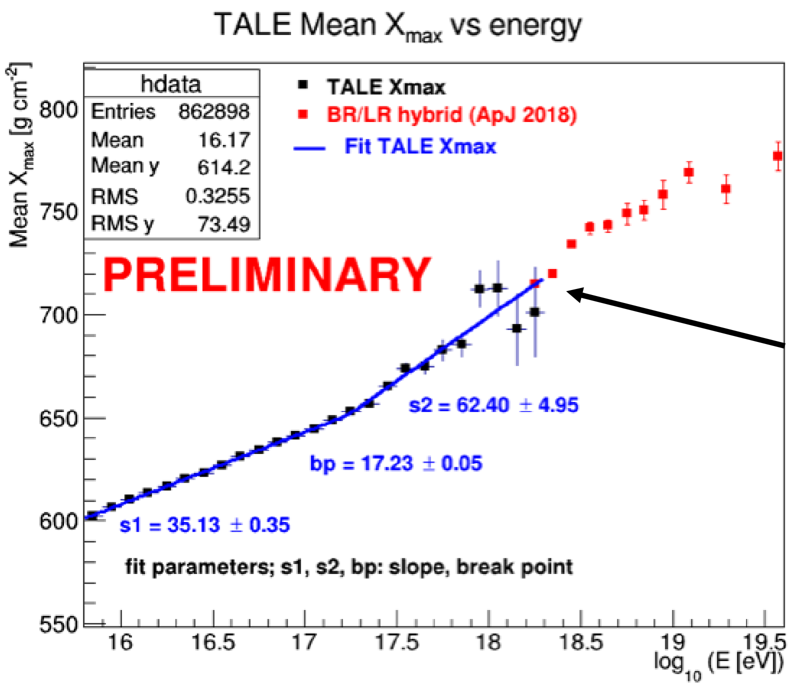


● : the data
○ : mixed 4-element model

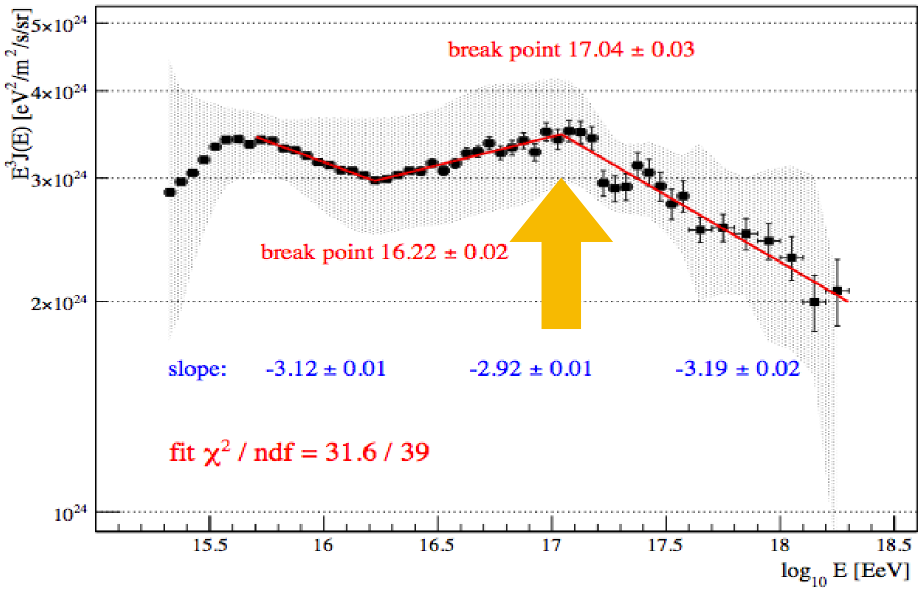
TALE FD Xmax

TALE FD 4 years of data
(Jun. 2014 - Nov. 2018)





Smooth connection to high energy rail

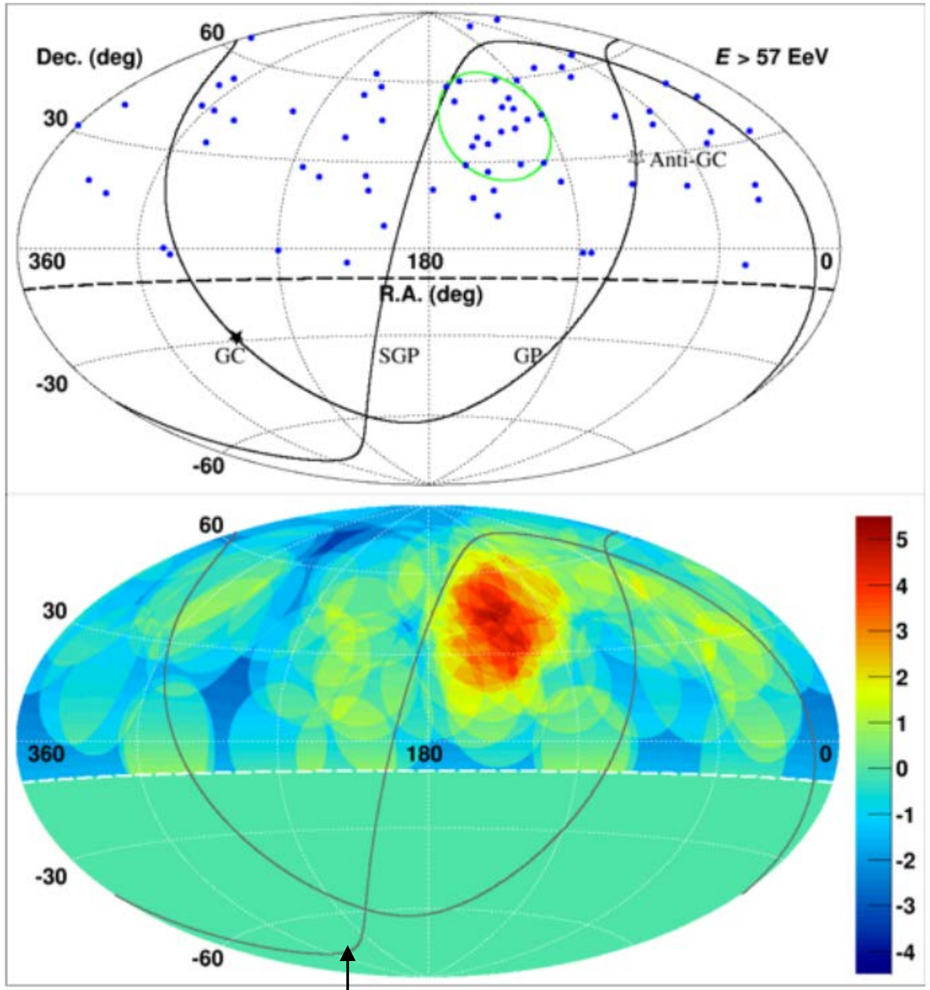


TALE FD monocular spectrum (2 years)

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

Hotspot

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



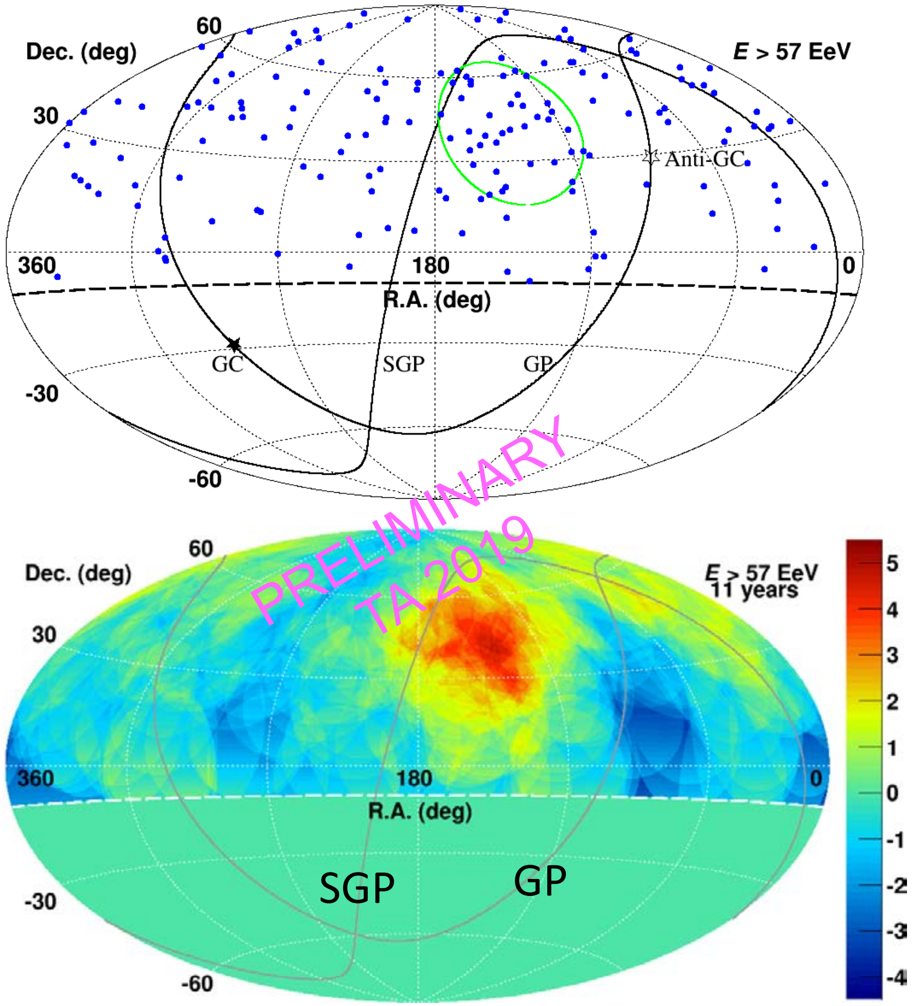
Equatorial coordinates

SuperGalactic Plane (SGP)

- 5-year by the TA SD
- 72 events with E > 57 EeV
- 20-degree radius oversampling
- Maximum pre-trail significance 5.1σ
  - N_{ON} (observ.) = 19, N_{BG} (iso.) = 4.49
  - centered at R.A. = 146.7^{o}, Dec. = 43.2^{o}
- Post-trial significance 3.7x10^{-4} (3.5σ)
  - 5 search window radii (15^{o}, 20^{o}, 25^{o}, 30^{o}, 35^{o}) for chance prob. calculation by MC

Hotspot center shifted from SGP by ~19^{o}

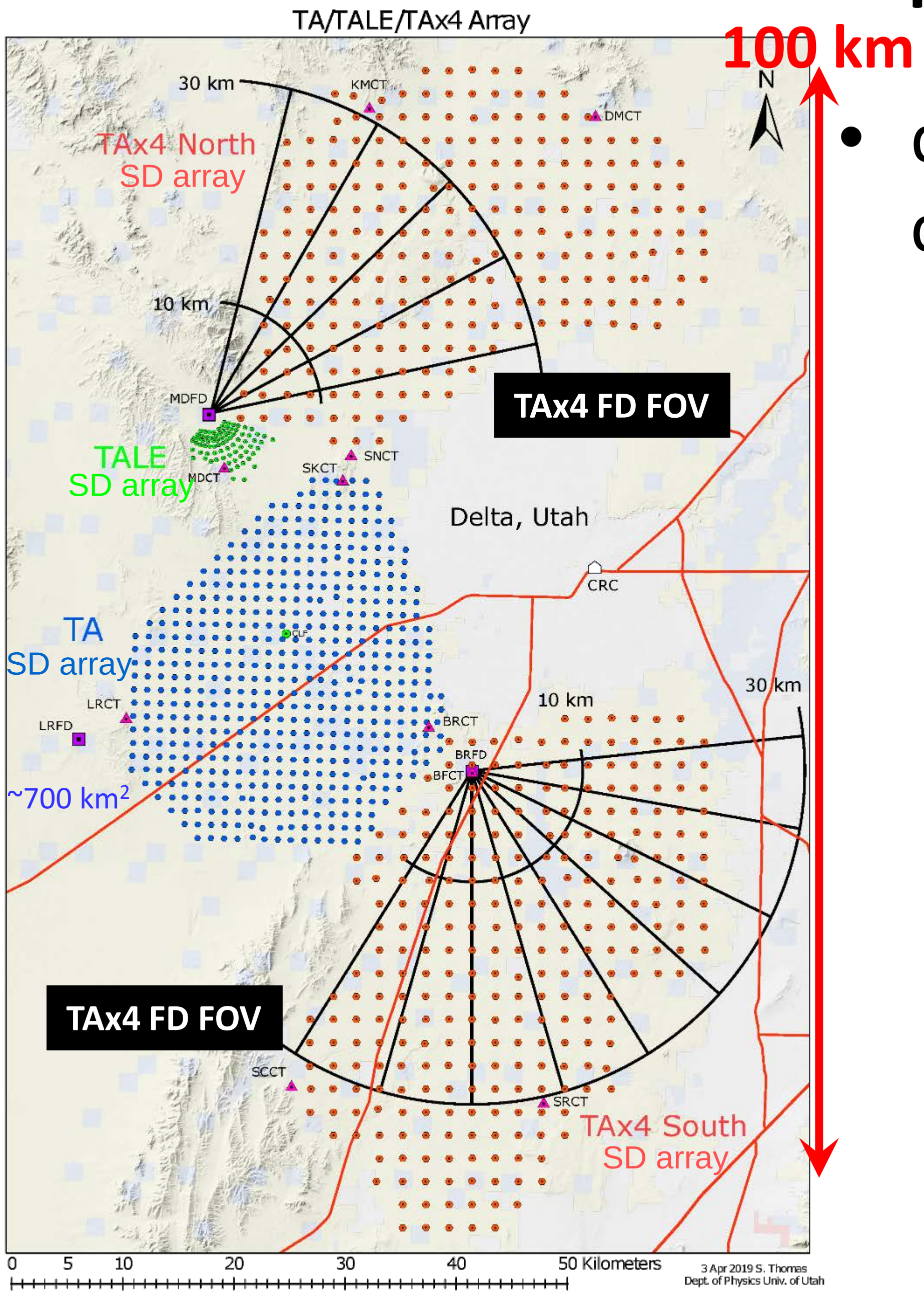
Update of Hotspot



Equatorial coordinates

- 11-year by the TA SD
- 168 events with E > 57 EeV
- Scan with (15°, 20°, 25°, 30°, 35°)
- Maximum with 25° radius
  - Pre-trial significance 5.1σ
  - N_{ON} = 38, N_{BG} = 13.5
  - Centered at RA=144.3°, Dec=+40.3°
- Post-trial significance ~0.2% (2.9σ)
  - 5 search window radii (15°, 20°, 25°, 30°, 35°) for chance prob. calculation by MC

TAx4 project



- quadruple TA to accelerate data collection speed
  - Surface detector(~3000 km^2)
    - Size comparable to Auger
    - 500 scintillator SDs with 2.1 km spacing
  - Fluorescence detector
    - 2 FD stations (HiRes-II telescopes)
    - Xmax meas. & SD energy check

TAx4 SD

Assembly mostly in Japan (or 30 SDs in Korea)

Utah, USA

① Scintillator counter assembly (Japan)

In Utah, USA

② Final assembly @CRC* in Delta in Utah

③ Assembled SDs @CRC

④ Staking (for SD positioning and follow-up surveys)

- finished by ATVs or helicopter in 2017

CRC*: Cosmic Ray Center in Delta

TAx4 SD deployment

- We deployed 257 SDs in Feb. and Mar. of 2019

(half of planned addition)

Now TAx2.5!

(1) SDs from CRC

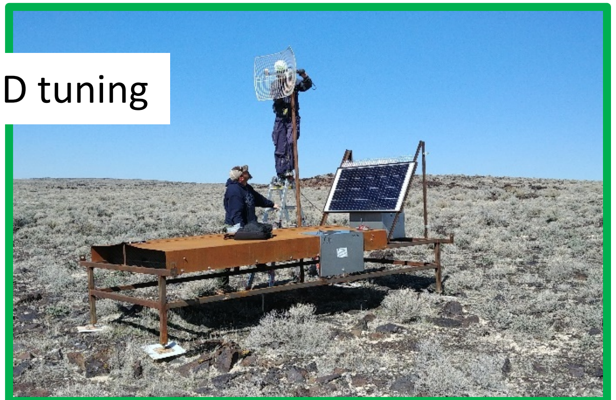
(1) SDs to Staging Area (SA)

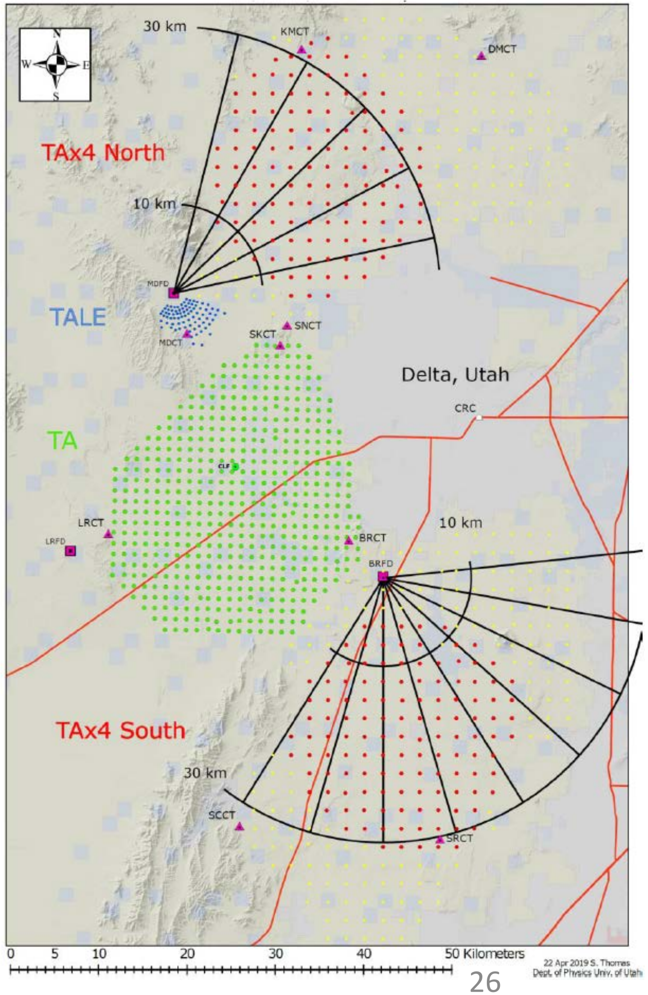
3) Communication Tower const.

2) SD from SA

2) to SD site

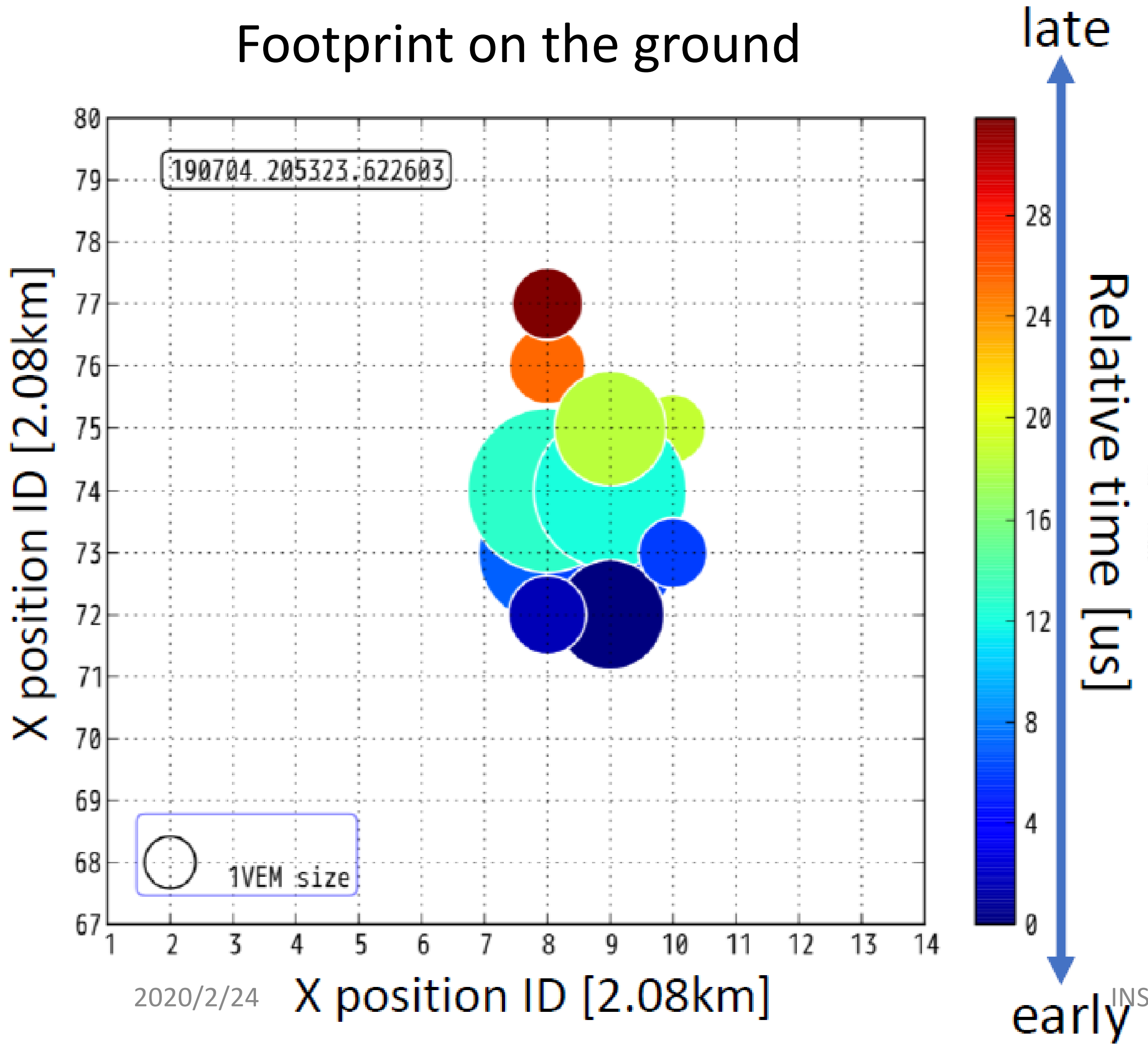
4) SD tuning



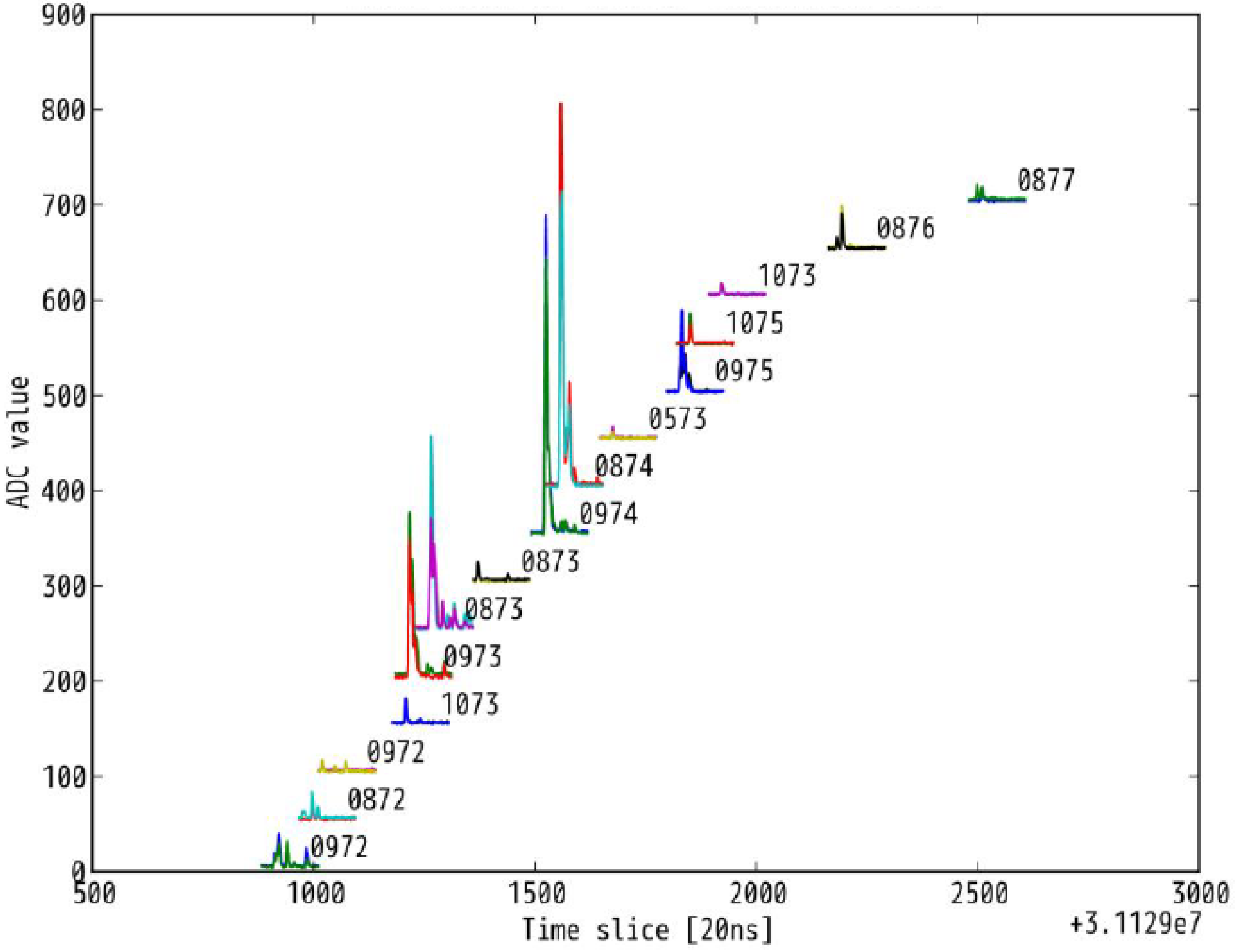


TAx4 SD event example

Footprint on the ground

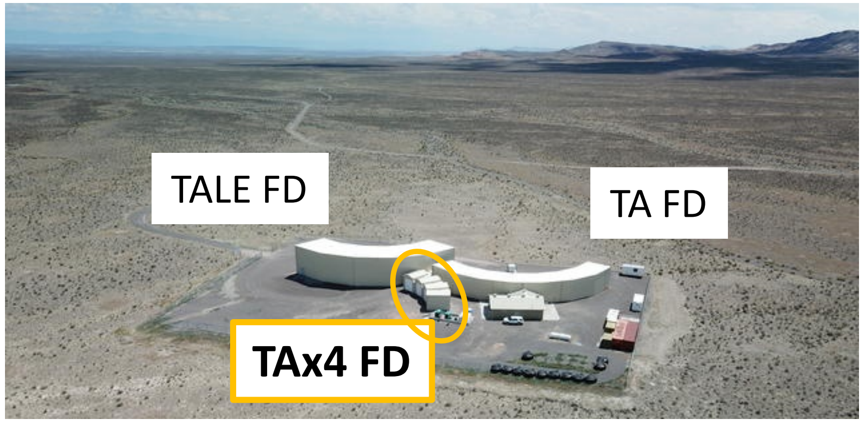


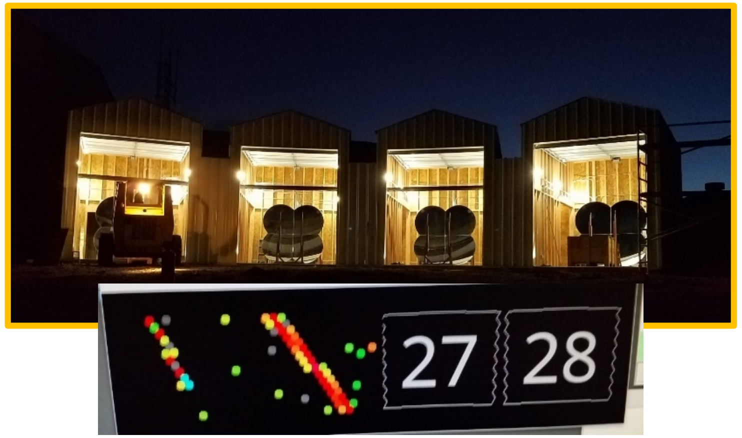
Observed waveforms



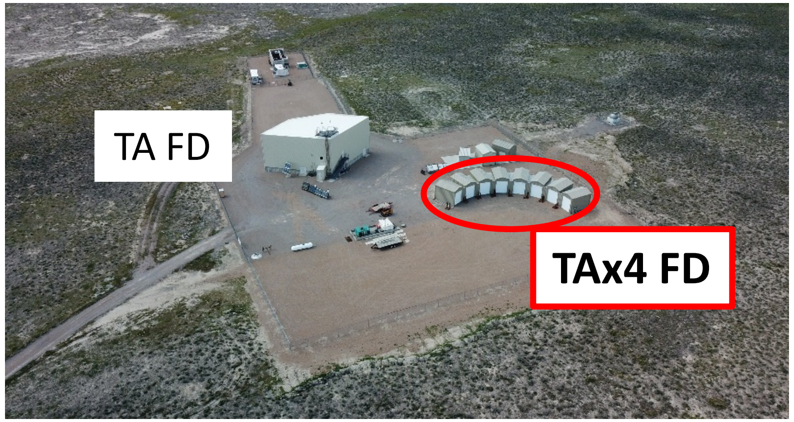
TAx4 FD

- **MD** (northern) site: first light on Feb. 16, 2018





- **BRM** (southern) site: first light on Oct. 22, 2019



Summary

- TA SD/FD and TALE FD energy spectrum shows four spectral features for $10^{15.4}$ eV < E < over 10^{20} eV
- TA Xmax: compatible with light composition (E > ~$10^{18.2}$ eV)
  - Need more statistics for E > 10^{19} eV
- We found evidences of anisotropy

- TAx4 has partially started: TA SD → TAx2.5 now

A New Window into Ultra-High-Energy Cosmic Rays!