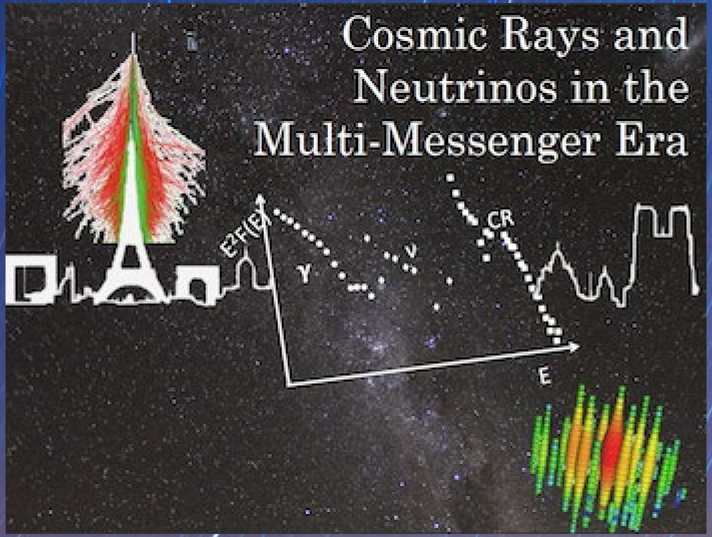
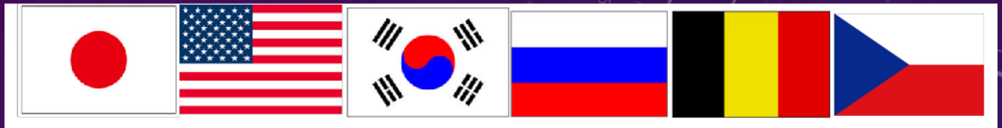
RESULTS FROM THE TELESCOPE ARRAY



John Matthews University of Utah
Telescope Array Collaboration

06 December 2022

TELESCOPE ARRAY COLLABORATION



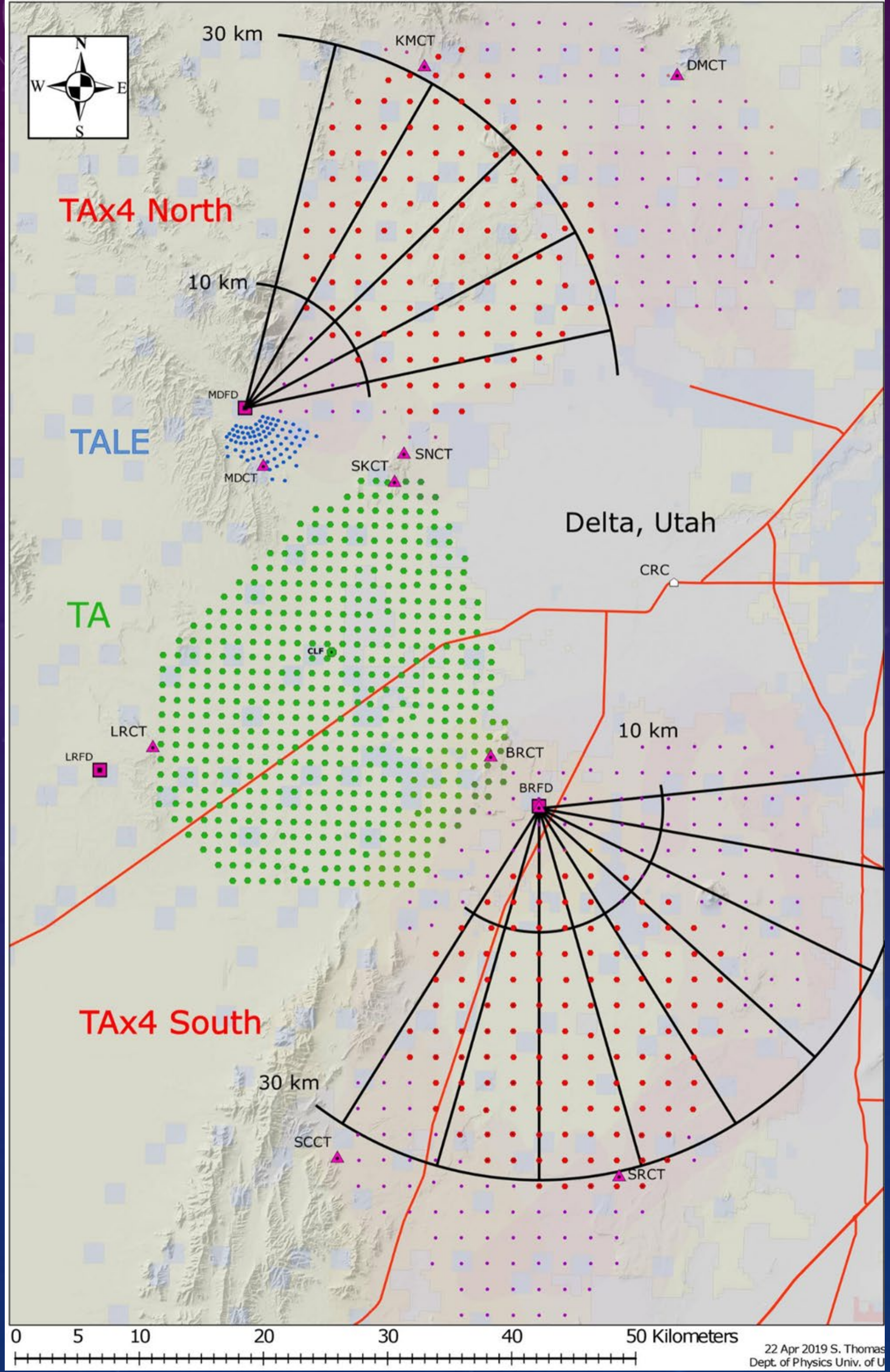
R.U. Abbasi[1,2], M. Abe[3], T. Abu-Zayyad[1,2], M. Allen[2], Y. Arai[4], R. Arimura[4], E. Barcikowski[2], J.W. Belz[2], D.R. Bergman[2], S.A. Blake[2], I. Buckland[2], R. Cady[2], B.G. Cheon[5], J. Chiba[6], M. Chikawa[7], T. Fujii[8], K. Fujisue[7], K. Fujita[4], R. Fujiwara[4], M. Fukushima[7], R. 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

TELESCOPE ARRAY: THE LARGEST COSMIC RAY OBSERVATORY IN THE NORTHERN HEMISPHERE

Telescope Array
Delta, Utah, USA. ~1400 m a.s.l.
Collaborators from HiRes, AGASA and other institutes

TELESCOPE ARRAY



TELESCOPE ARRAY

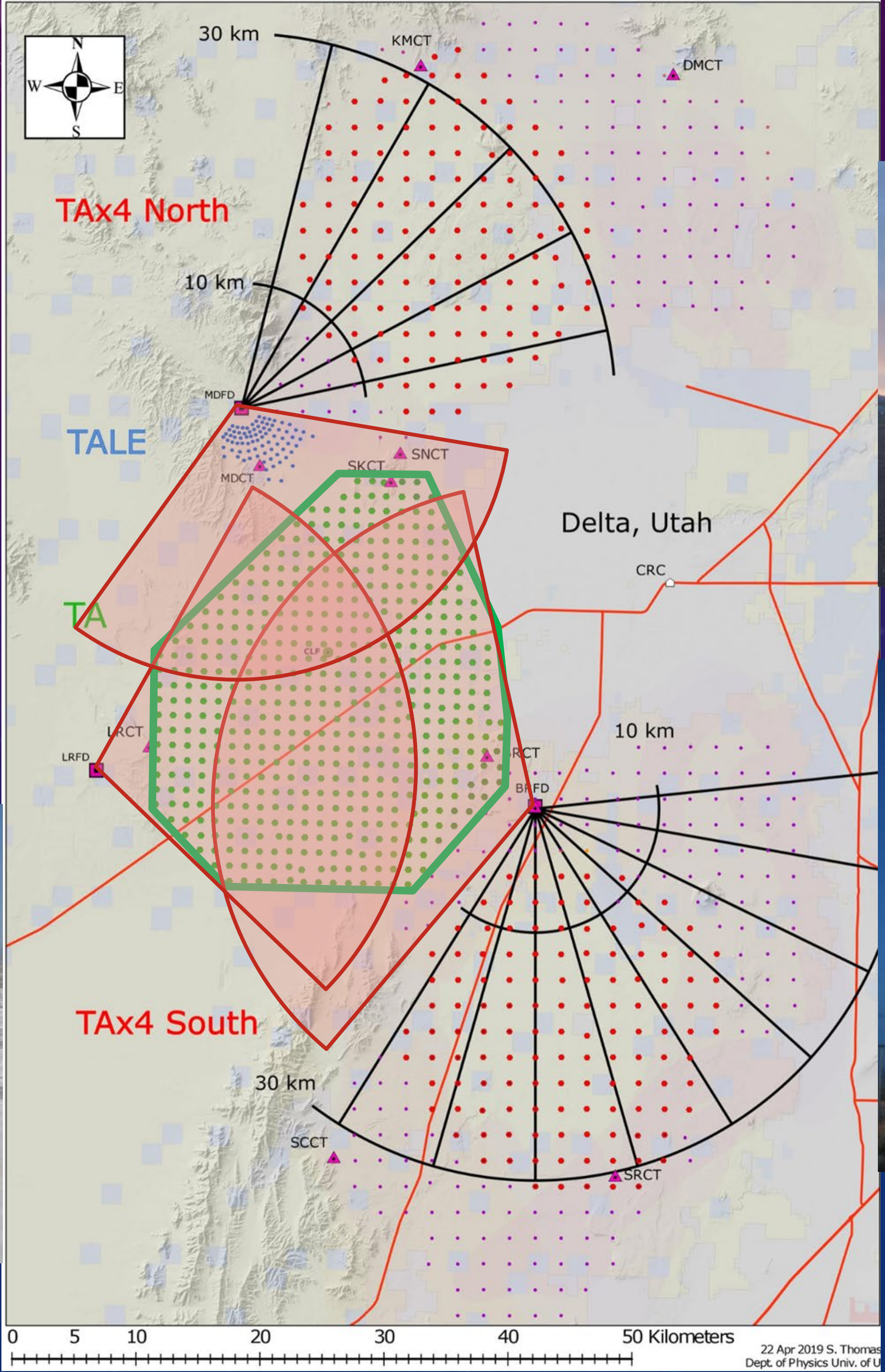
Telescope Array Detectors

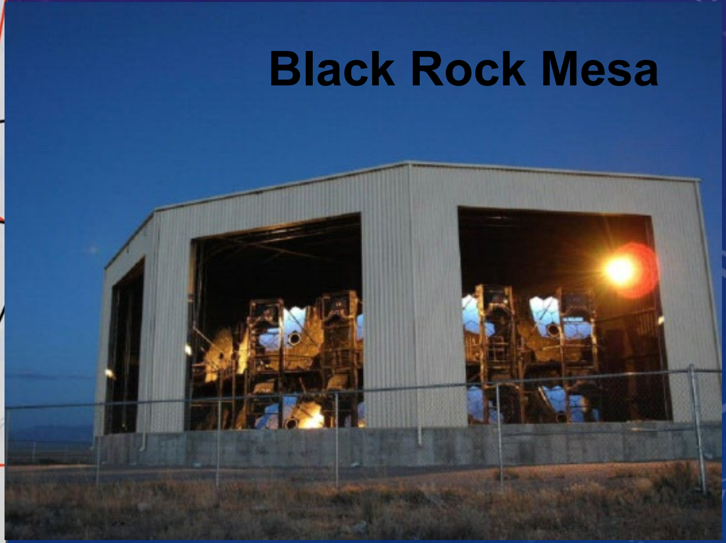
Surface Detector Array (3/2008)

- 507 Scintillator Counters
- 1.2 km spacing
- 3 m^2 area
- ~700 km^2

Fluorescence Telescopes (2007)

- 3 Stations
- 12–14 Telescopes
- 3˚–31˚ elevation
- Cover SD Array





TELESCOPE ARRAY

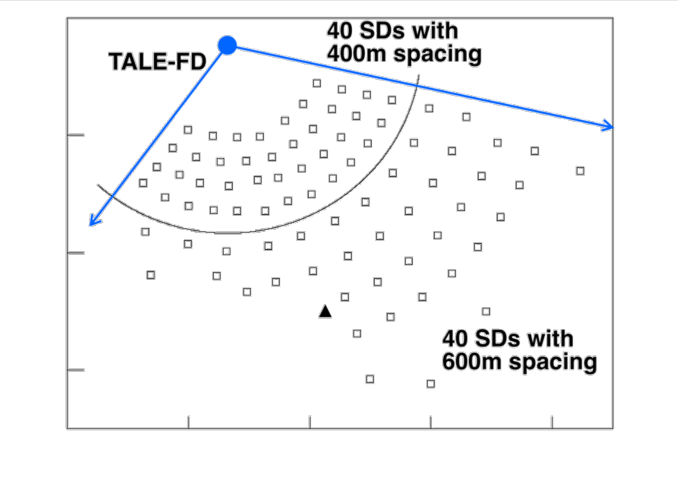
TA Low Energy (TALE)

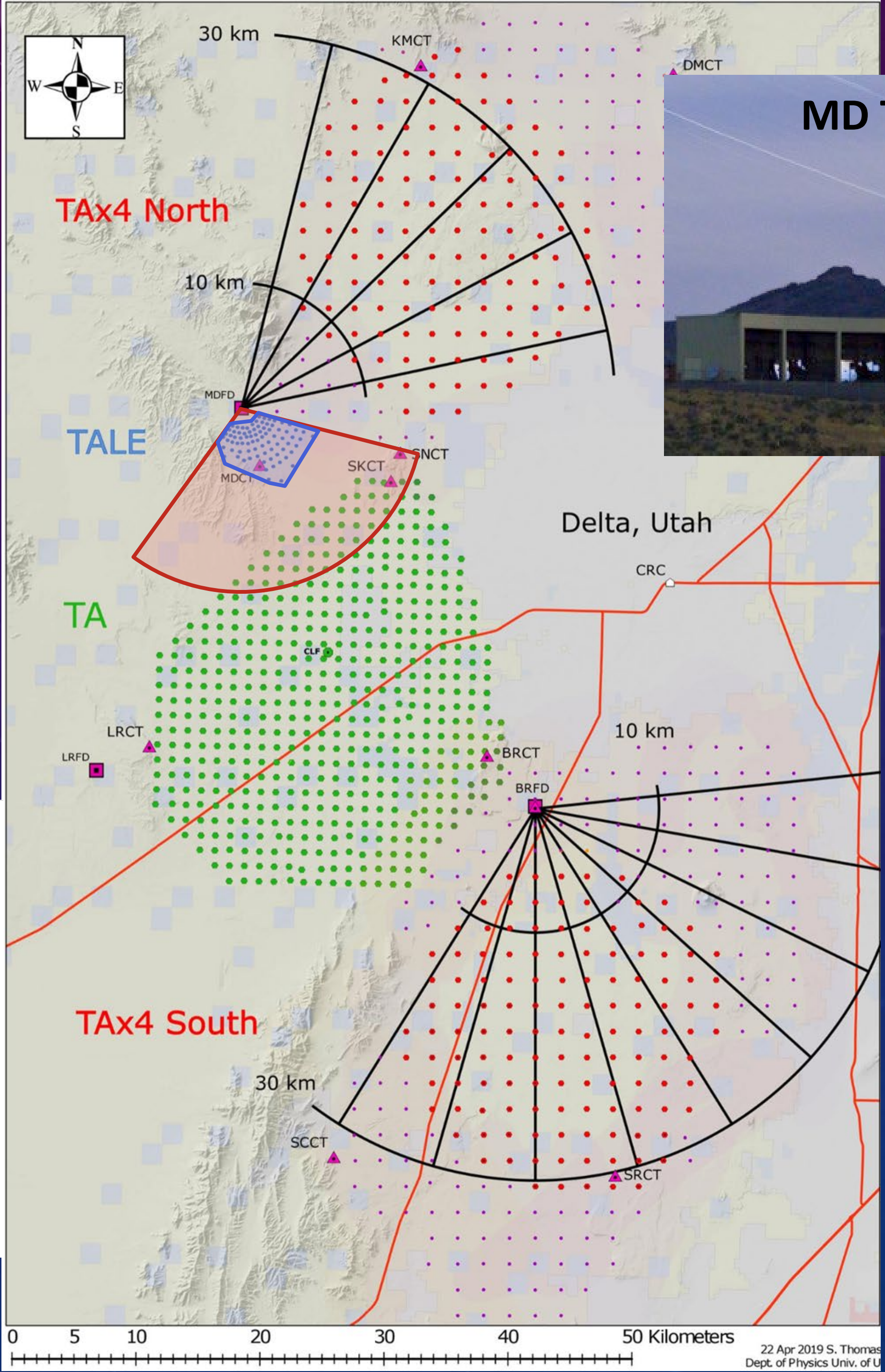
Fluorescence Telescopes

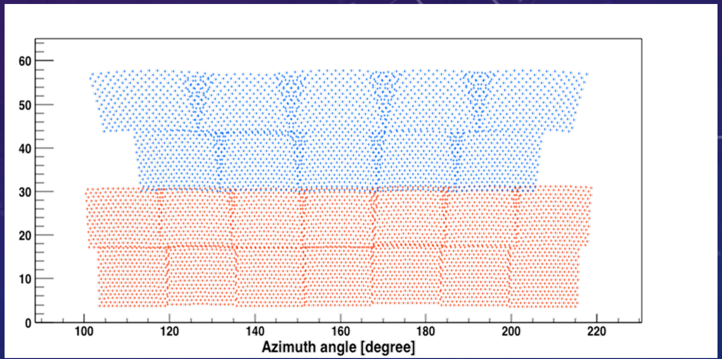
- 10 new telescopes
- 31˚–59˚ elevation
- With main TA 14: 3˚–59˚
- Since 9/2013

Scintillator infill array

- 400 & 600-m spacing
- Same SD design as TA
- Since 3/2018







TELESCOPE ARRAY

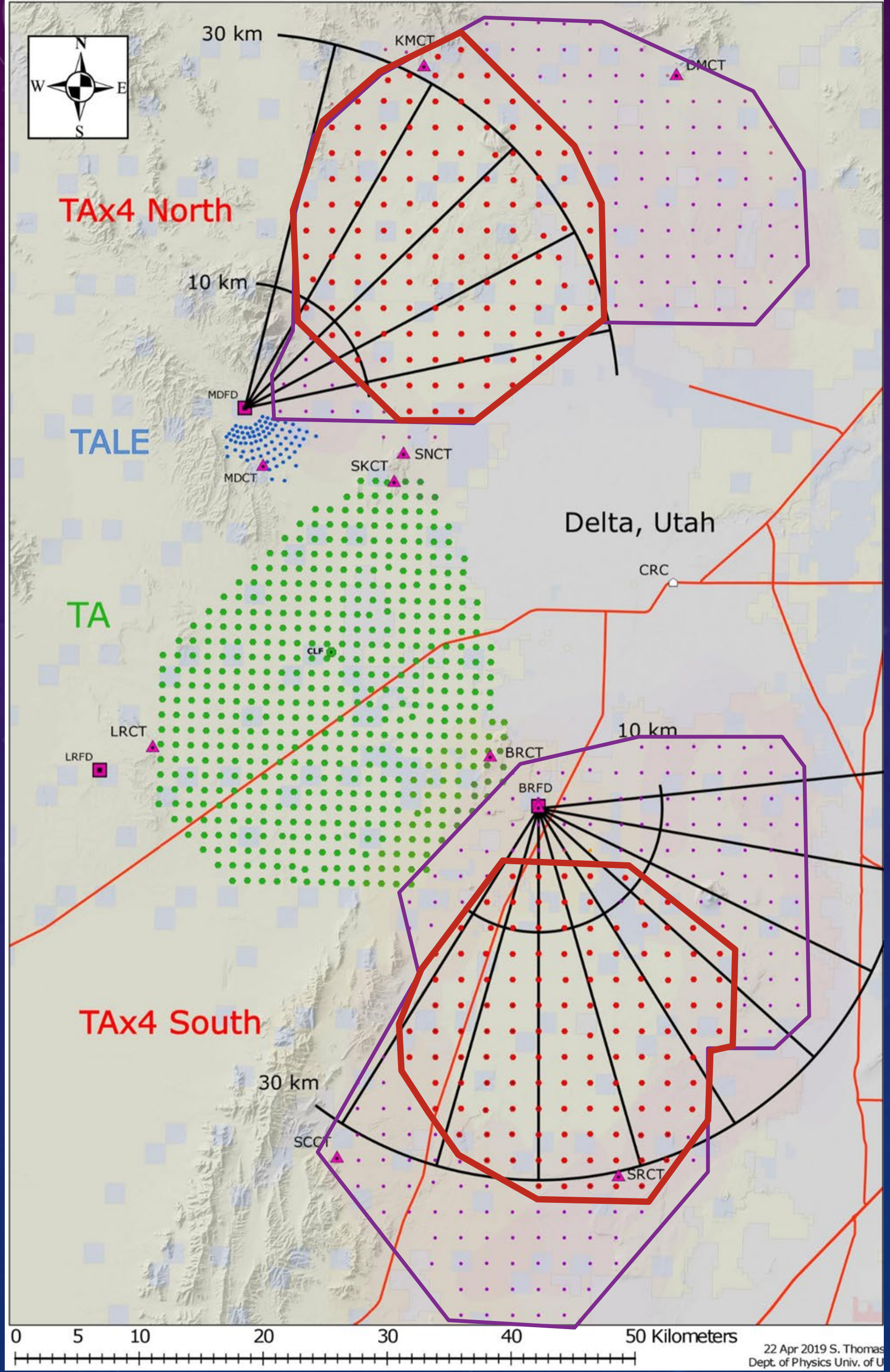
TA x 4

Expanded Surface Array

- 2.08-km spacing
- SDs similar design as TA
- 257 of planned 500 deployed (operational since 11/2019)

Fluorescence Telescopes

- 4 telescopes viewing NE lobe (since 06/2019)
- 8 telescopes viewing SE lobe (since 08/2020)
- 3˚–17˚ elevation

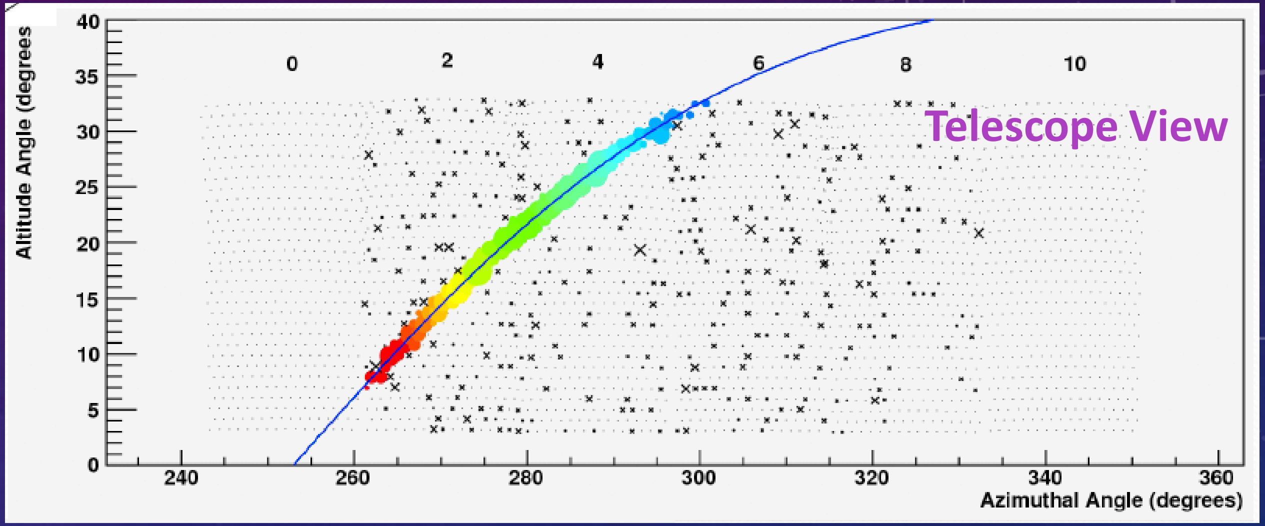


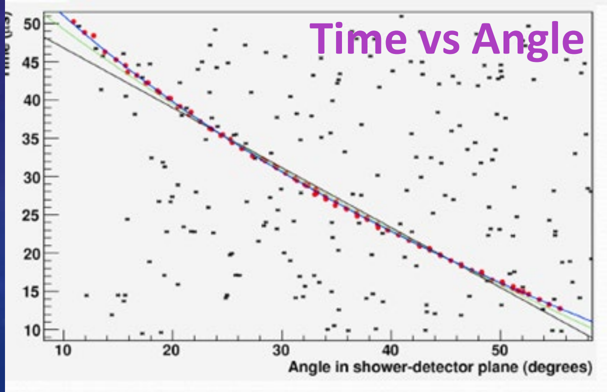
TELESCOPES

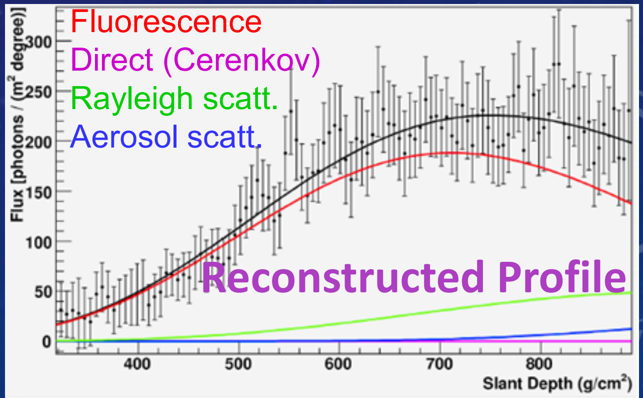
- Segmented mirrors
- 256 hexagonal PMTs/camera
- 1 pixel views ~1^{o} of sky
- UV band-pass filter

EVENT RECONSTRUCTION

- In fluorescence we see the shower sweep across the mirror
- Reconstruct Shower-Detector Plane
- Fit time-vs-angle to get geometry (For hybrid add in SD times giving much more lever arm for fit)
- Reconstruct size of shower vs depth



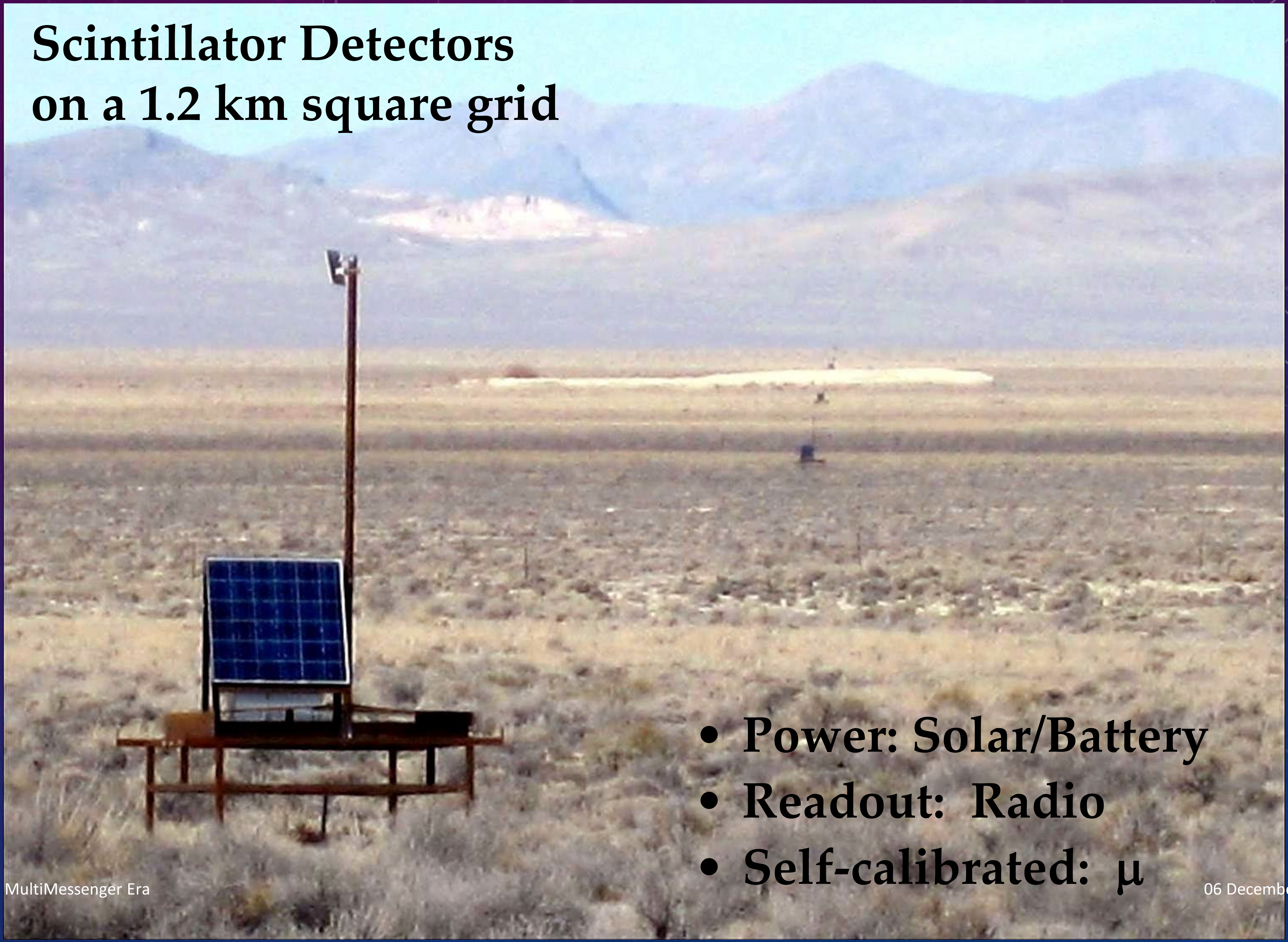




SCINTILLATOR SURFACE DETECTORS

- 2 layers scintillator
- 1.25 cm thick, $3m^2$ area
- Optical fibers to PMTs

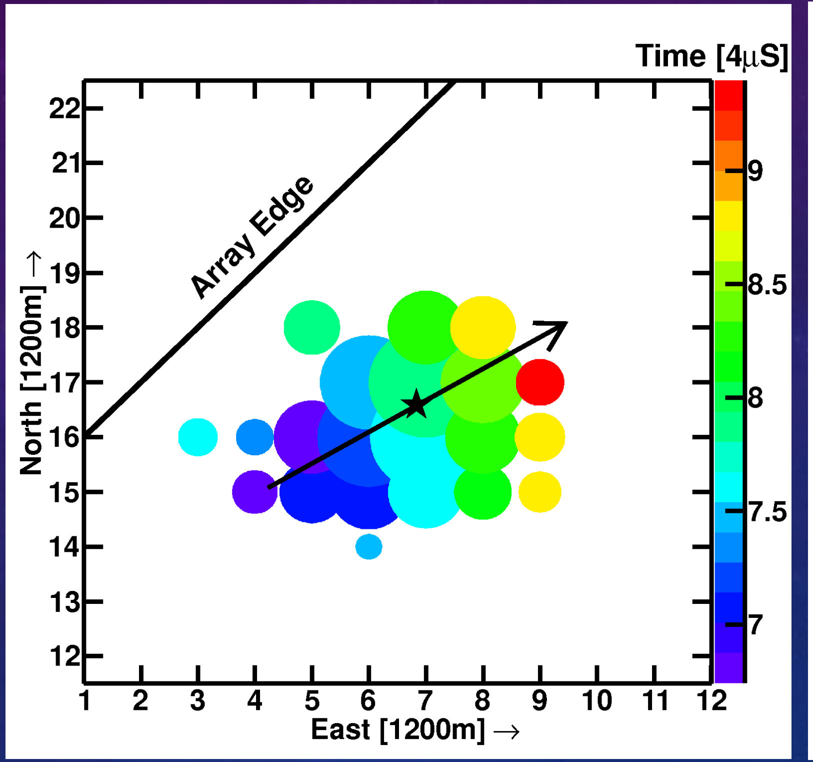
Scintillator Detectors on a 1.2 km square grid

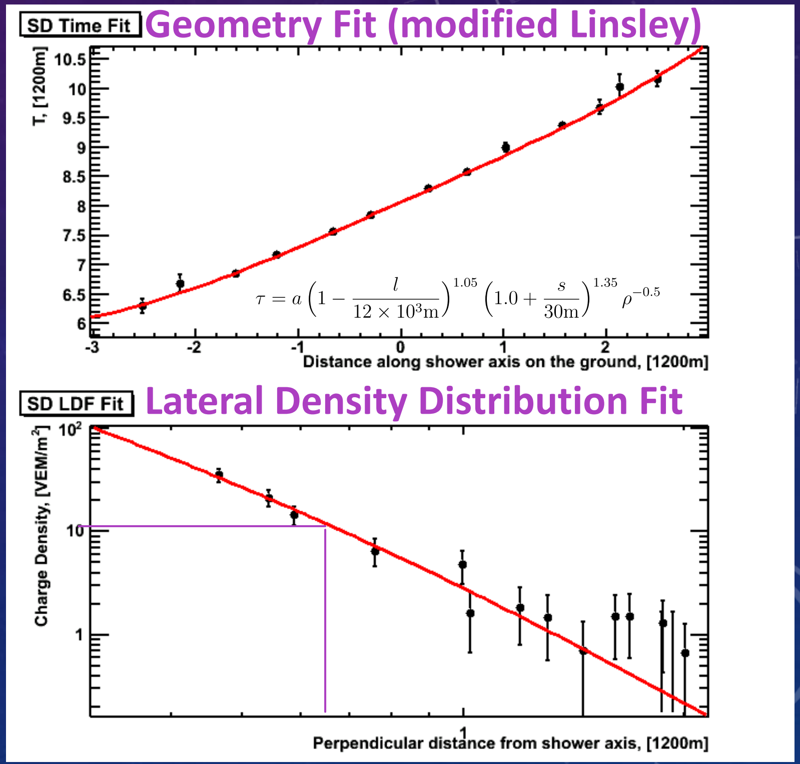


- Power: Solar/Battery
- Readout: Radio
- Self-calibrated: μ

EVENT RECONSTRUCTION

- Use counter location and timing to locate shower core and direction
- Fit counter signal size to find lateral distribution
- S800: Signal size at 800 m is the energy indicator
- Scaled to the calorimetric energy/FD, E/1.27



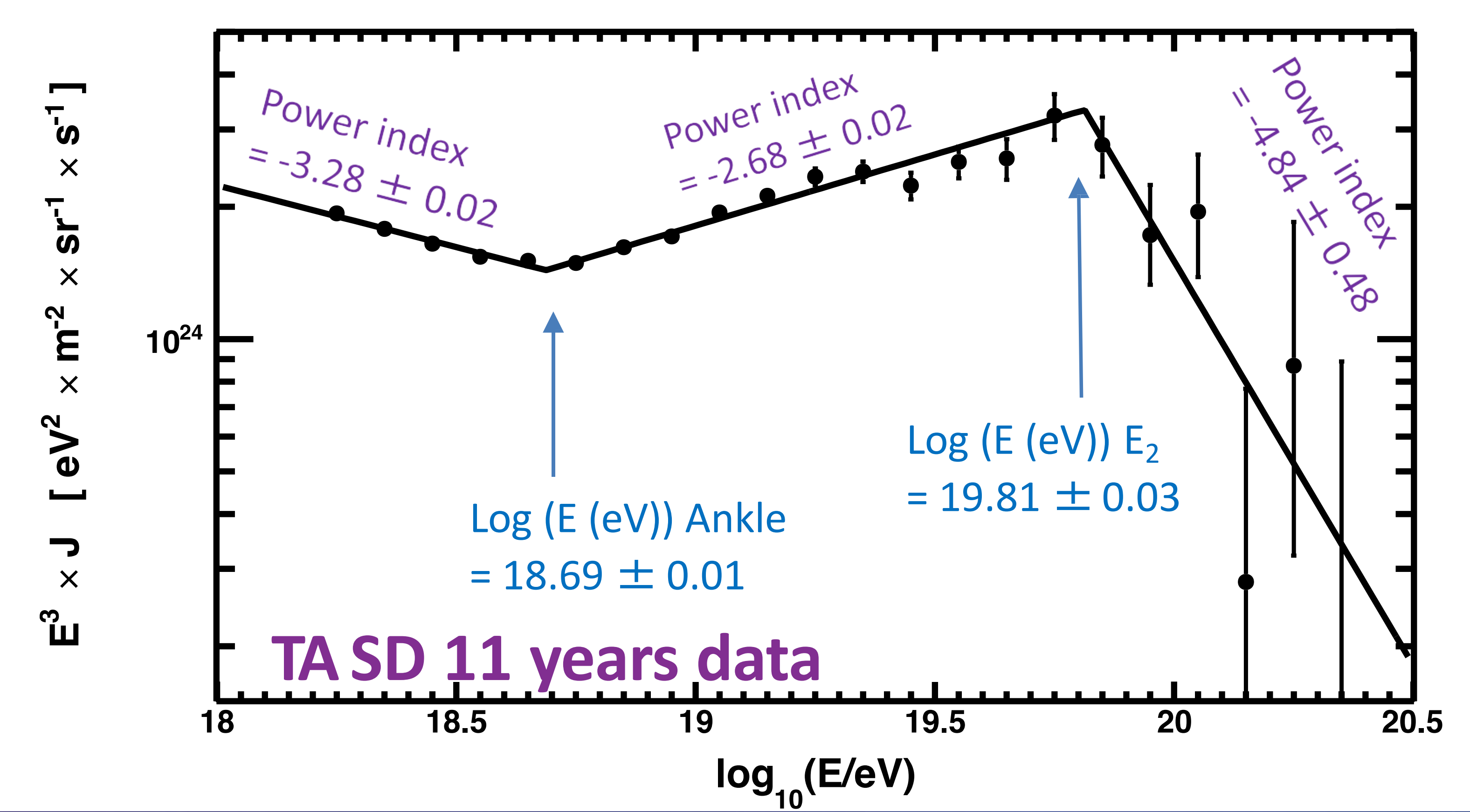


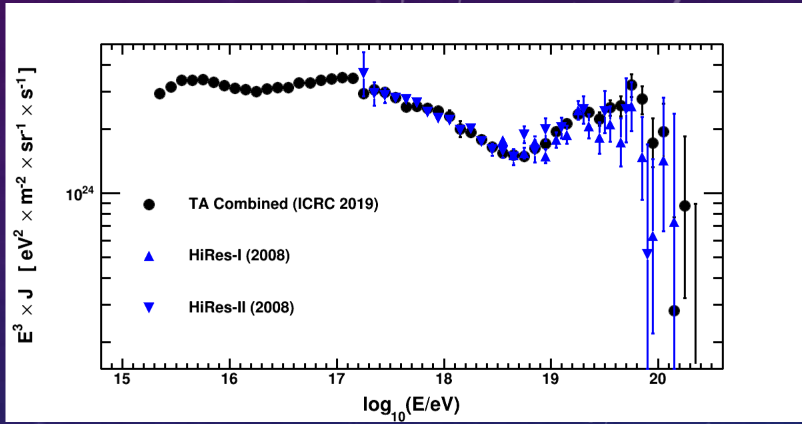
$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1+\frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1+\left[\frac{s}{1000\mathrm{m}}\right]^2\right)^{-0.6}$$

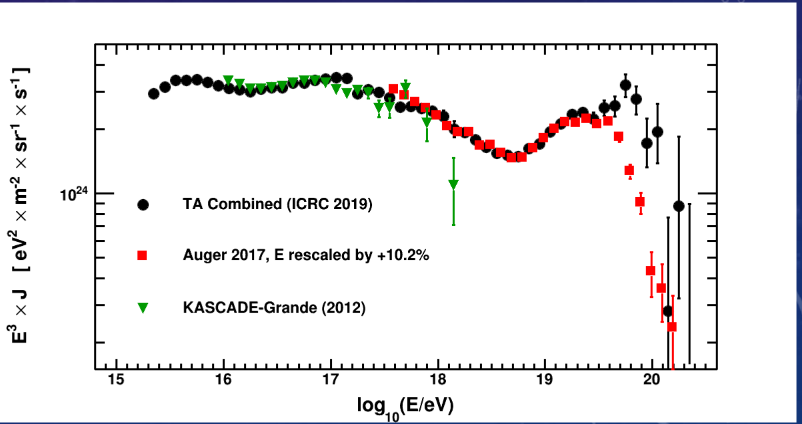
$$\eta(\theta) = 3.97 - 1.79\,[\sec(\theta) - 1]$$

ENERGY SPECTRUM

ENERGY SPECTRUM



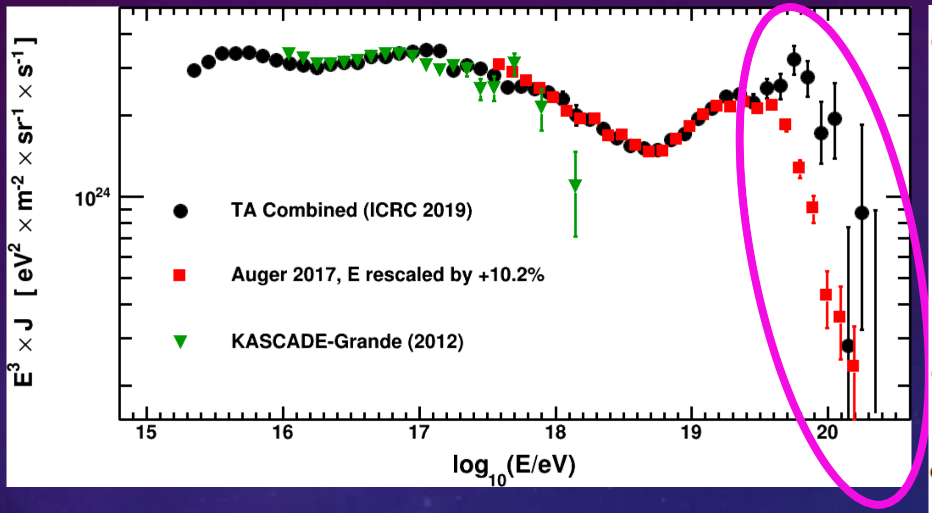


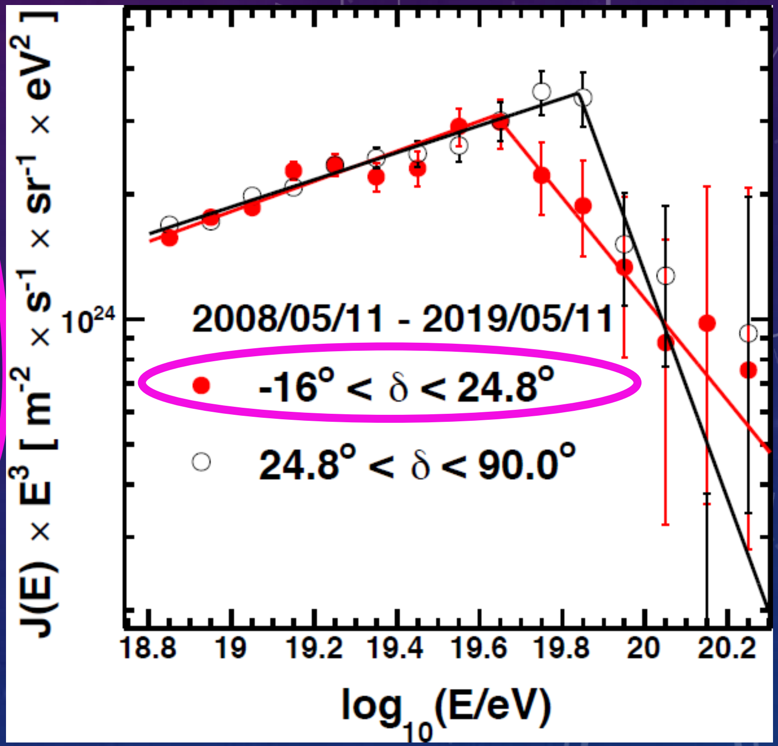


ENERGY SPECTRUM

Declination dependence in the TA SD spectrum

- Difference of the cutoff energies of energy spectra
  - log(E/eV) = **19.64 ± 0.04** 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 is estimated to be **4.3σ**
- Or an Energy Dependent correction (10%/decade E)

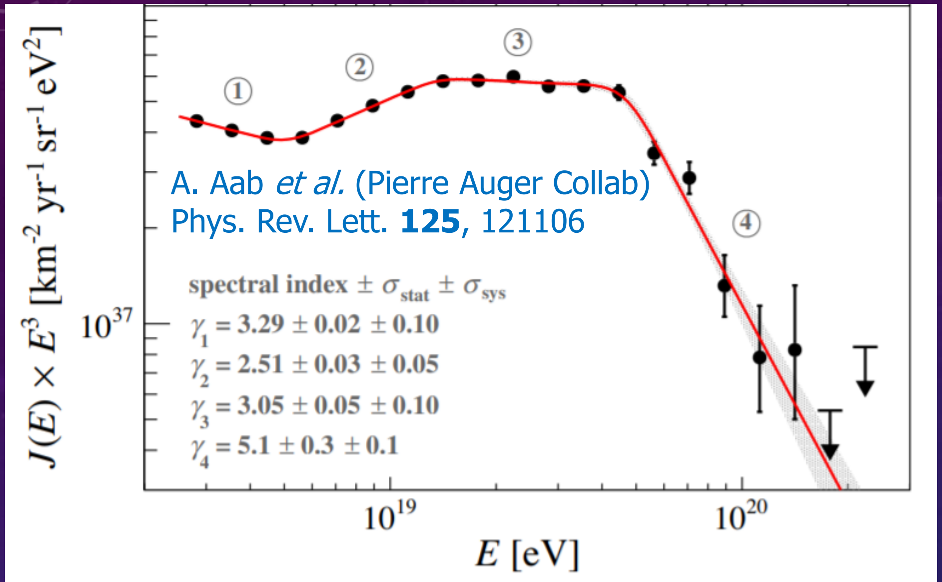




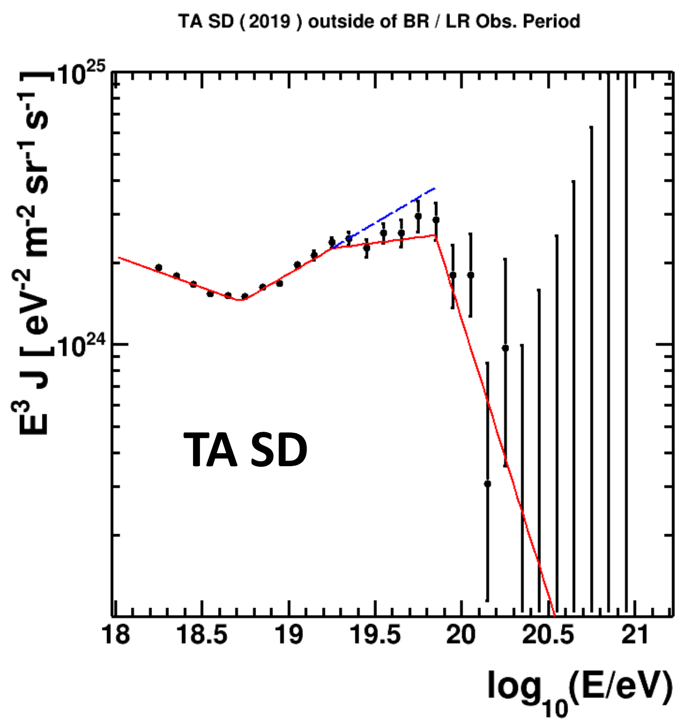
THE INSTEP FEATURE

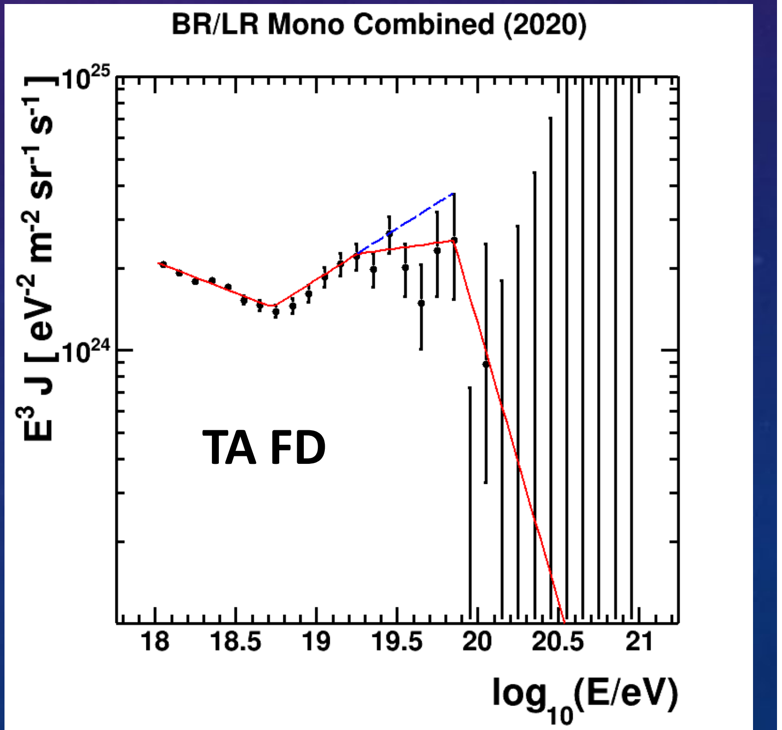
Feature first seen in Auger data

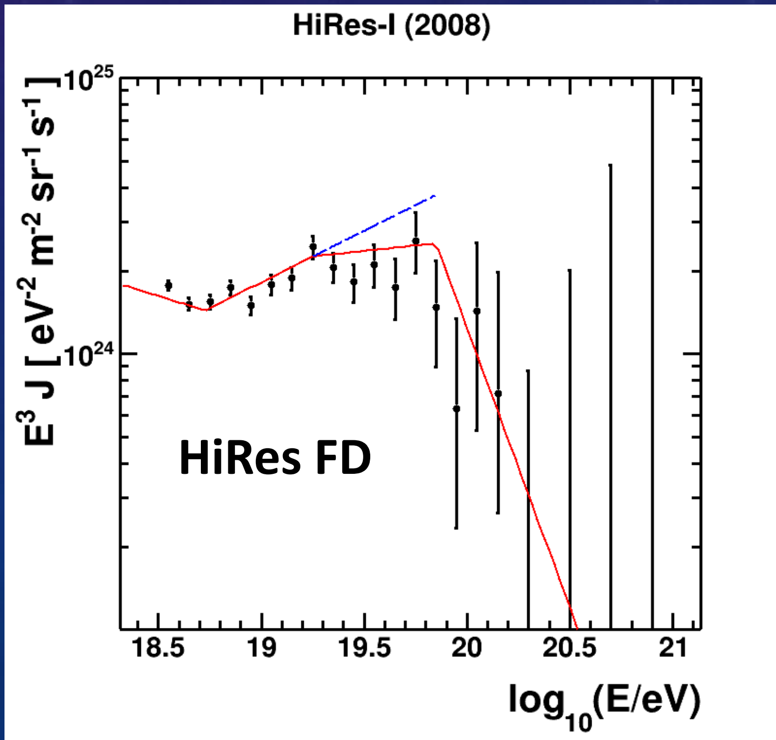
Combined fit of TA SD, TA Monocular, and HiRes data finds the feature with **5.3σ** significance



Parameter	Auger	TA
γ_1	3.29 ± 0.02	3.23 ± 0.01
γ_2	2.51 ± 0.03	2.63 ± 0.02
γ_3	3.05 ± 0.05	2.92 ± 0.06
γ_4	5.1 ± 0.3	5.0 ± 0.4
E_{ankle}/EeV	5.0 ± 0.1	5.4 ± 0.1
E_{instep}/EeV	13 ± 1	18 ± 1
E_{cut}/EeV	46 ± 3	71 ± 3





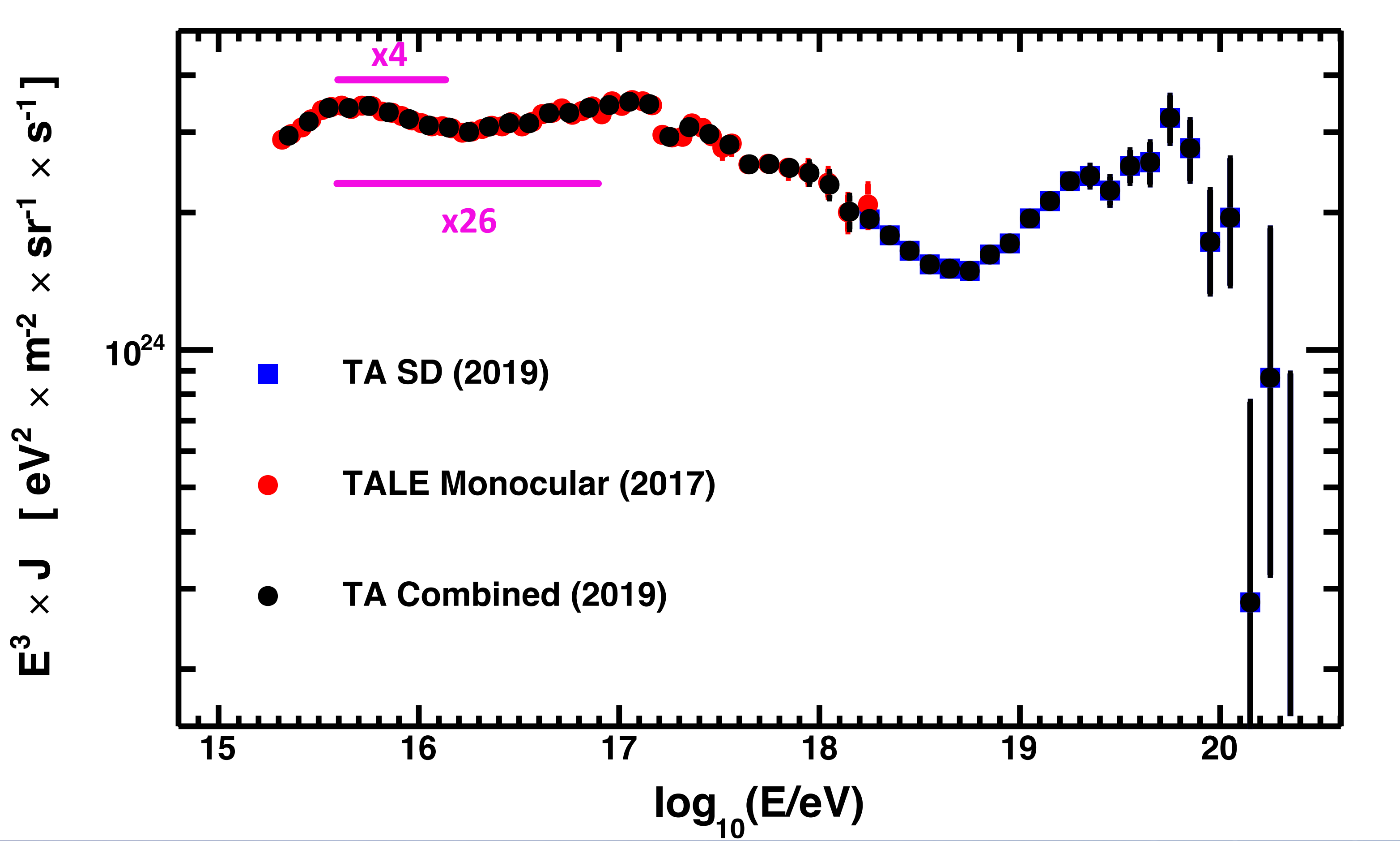


ENERGY SPECTRUM

Combine TA SD spectrum (11 years) with TALE FD monocular (22 months) to get CR spectrum covering 5 orders-of-magnitude

- Knee: $\log_{10}(E/\text{eV}) \sim 15.5$
- LE ankle: $\log_{10}(E/\text{eV}) = 16.22(2)$
- 2nd Knee: $\log_{10}(E/\text{eV}) = 17.04(4)$
- Ankle: $\log_{10}(E/\text{eV}) = 18.69(1)$
- Cutoff: $\log_{10}(E/\text{eV}) = 19.81(3)$

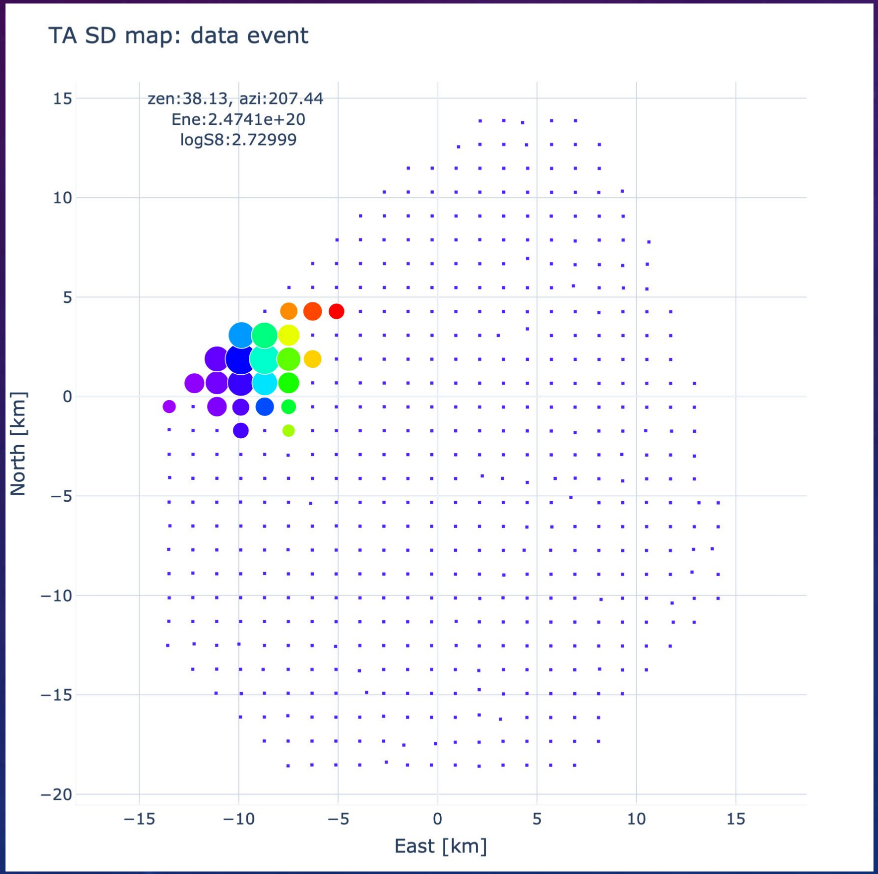
Peter's Cycle? : $10^{15.6} - 10^{17.1}$ eV

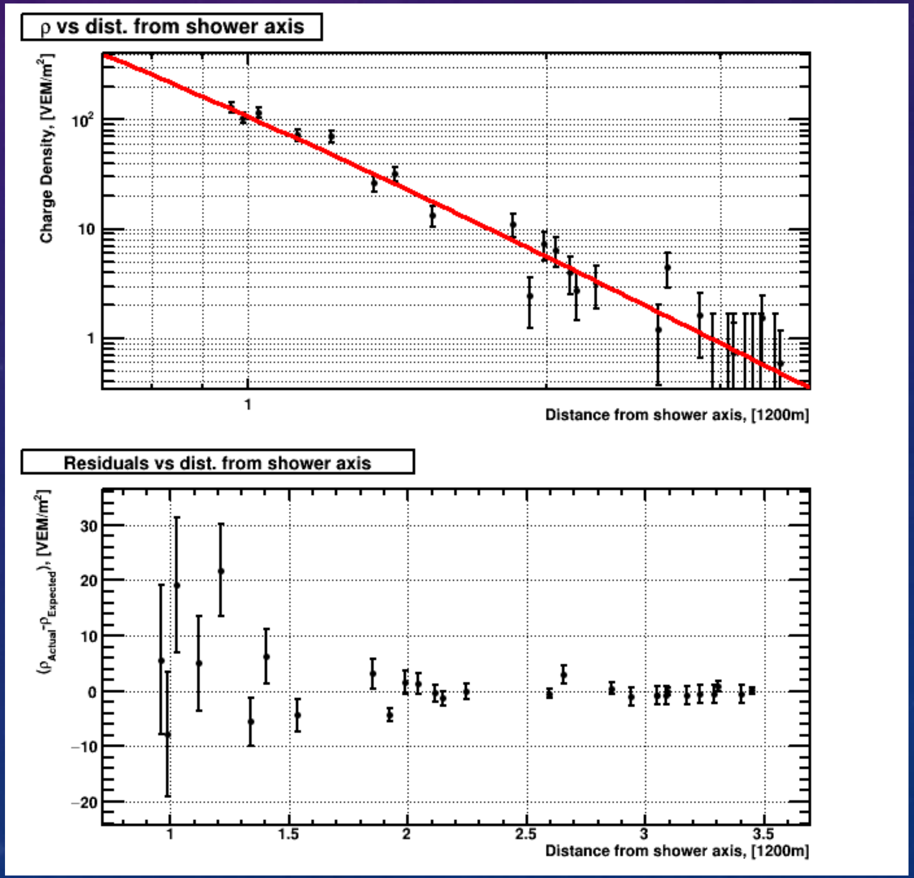


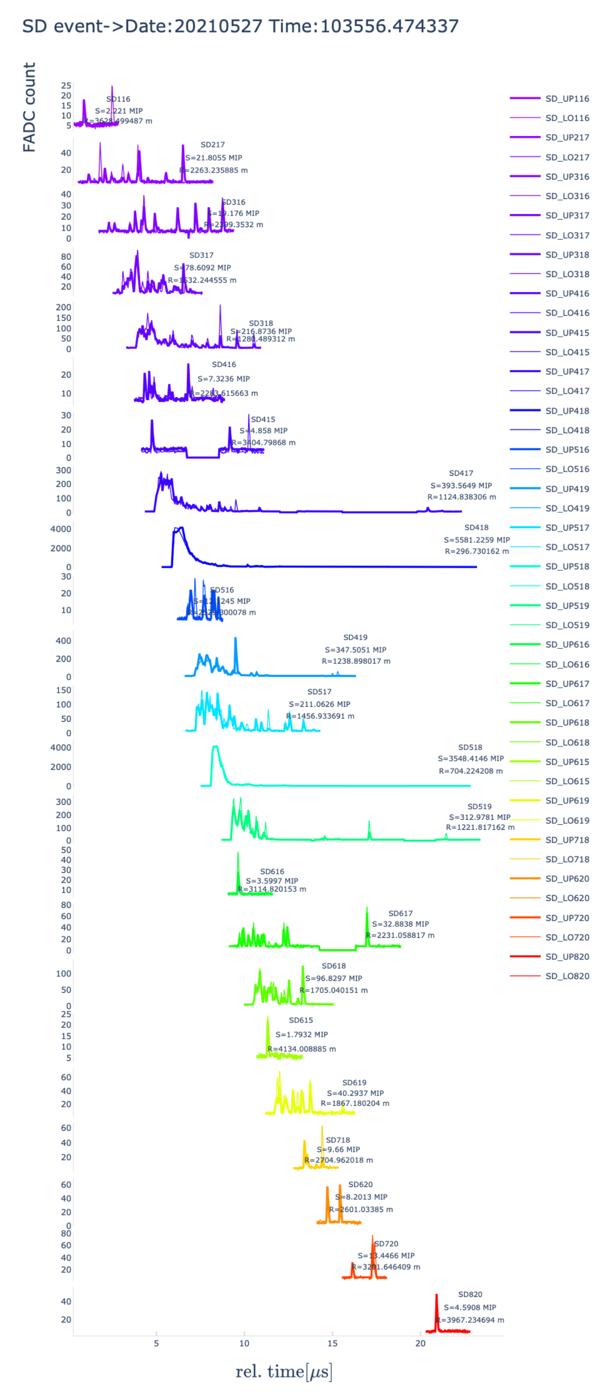
New Highest Event Detected by TA

NEW HIGHEST EVENT DETECTED BY TA

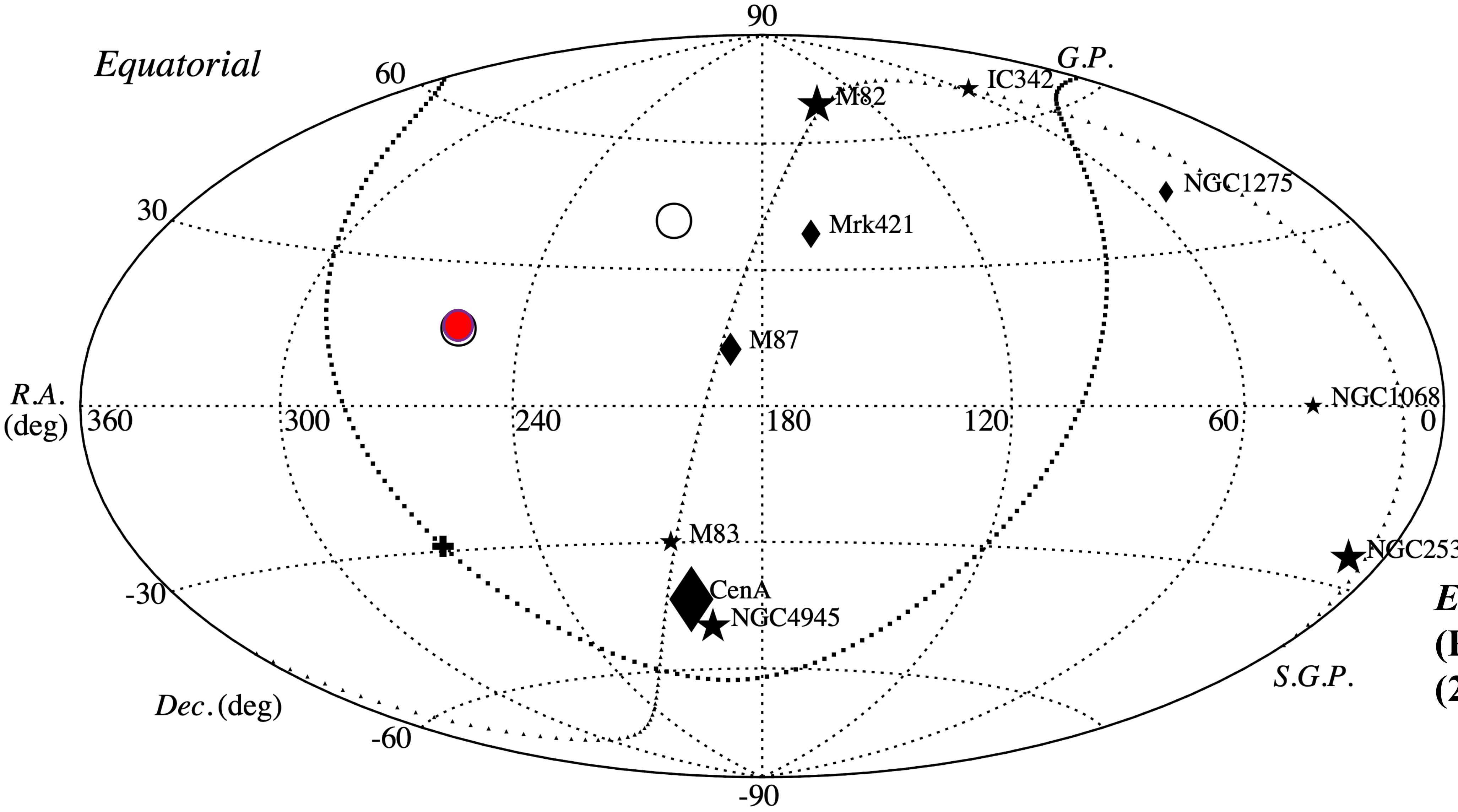
- 2021/05/27 10:35:56.47, No FD observation
  - $E = \mathbf{243.6 \pm 10.7}$ **EeV**, $\theta = 38.6°$, $\varphi = 206.8°$ - **Preliminary**
    - (E = 242.8 EeV with the atmospheric energy correction) - **Preliminary**







DIRECTION IN THE SKY-MAP



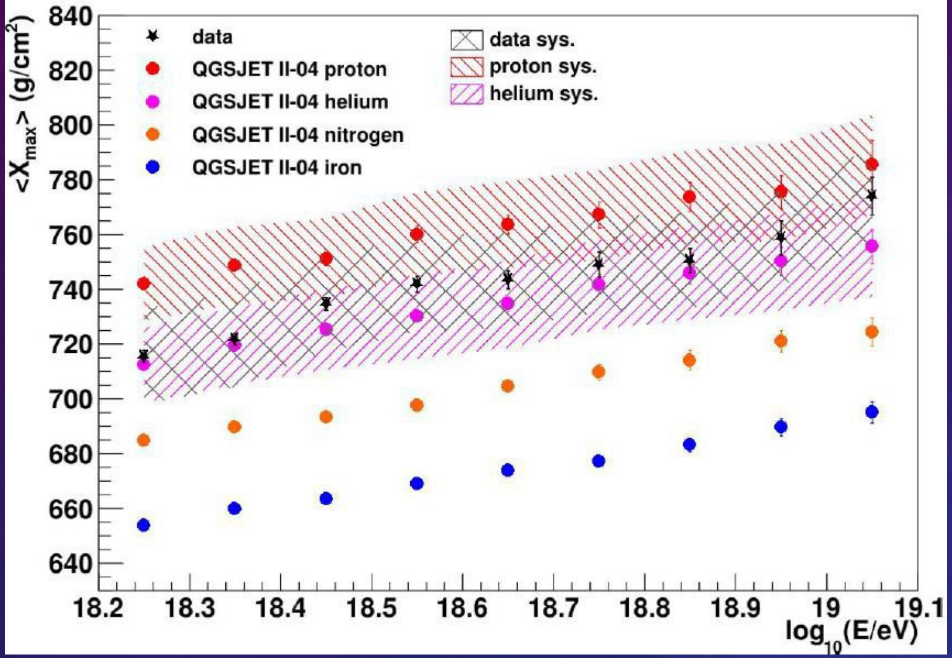
E = 243.6 EeV
(RA, Dec) =
(255.85, 16.08)

CHEMICAL COMPOSITION

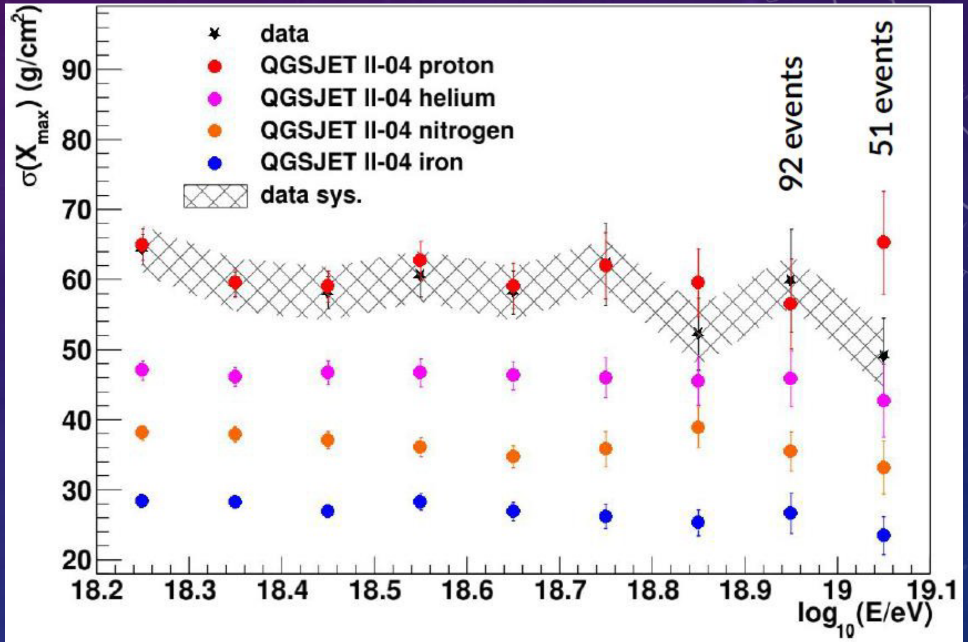
COMPOSITION ANALYSIS WITH TA HYBRID XMAX

10 years SD and FD hybrid data

Mean Xmax

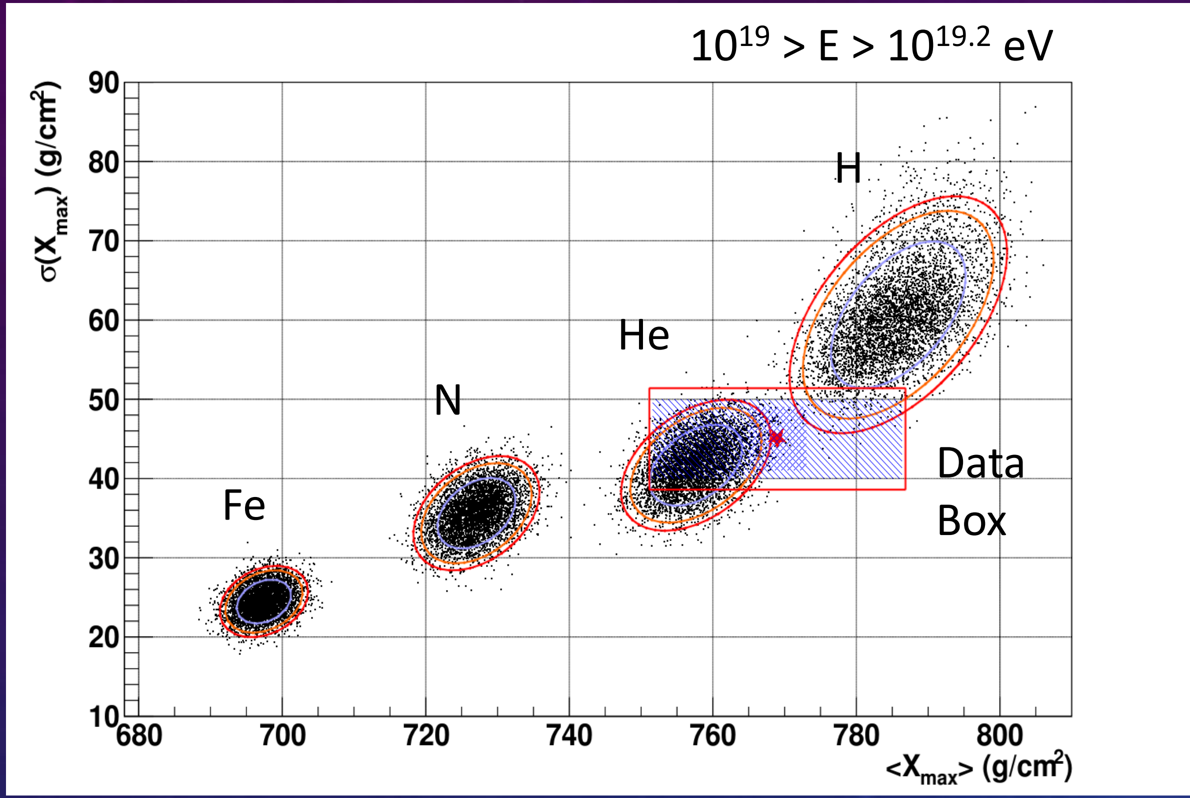


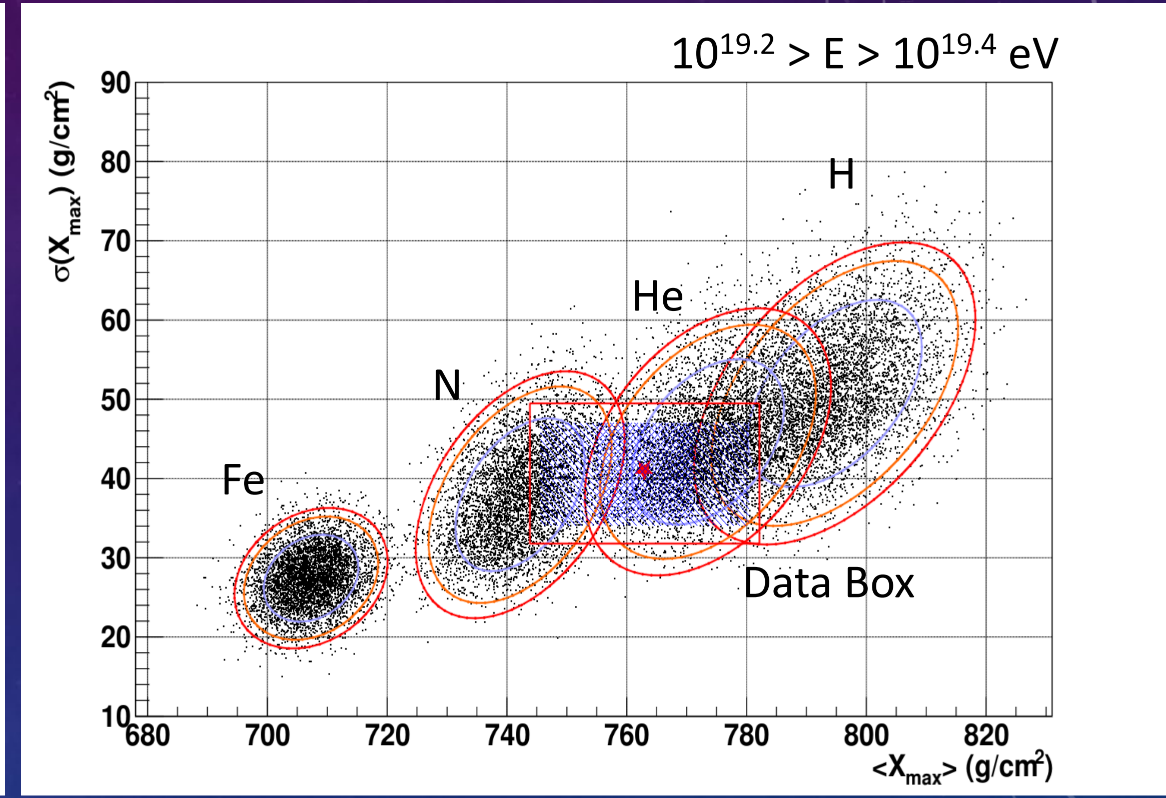
σ (Xmax)



- Energy Range: $10^{18.2}$ eV – $10^{19.1}$ eV
- 3560 events after the quality cuts
- Systematic uncertainty of <Xmax>: ± 17 g/cm²
- QGSjetII-04 interaction model was compared with the data
  → agreement with light composition
- More events are needed to study highest energies
- Also working on more models

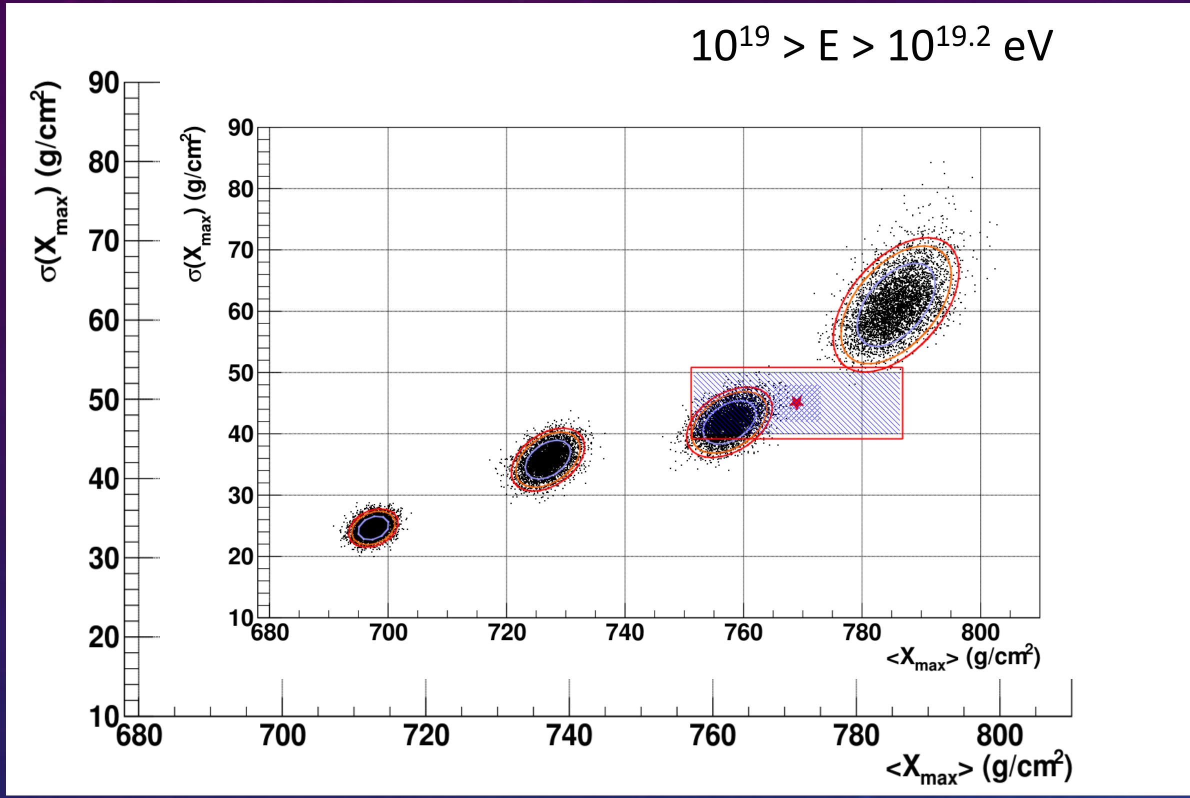
HYBRID COMPOSITION

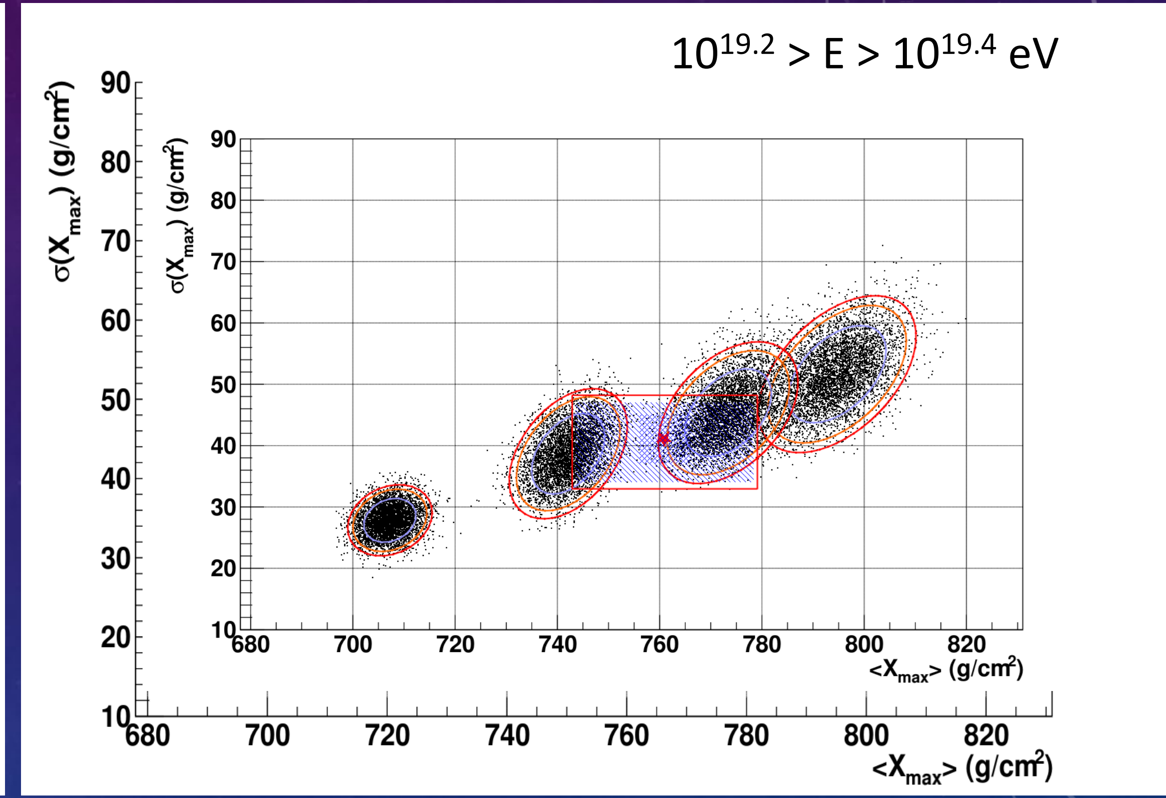




9.5 yrs of data
Adding even 5 years of TAx4 data will significantly improve separation

HYBRID COMPOSITION





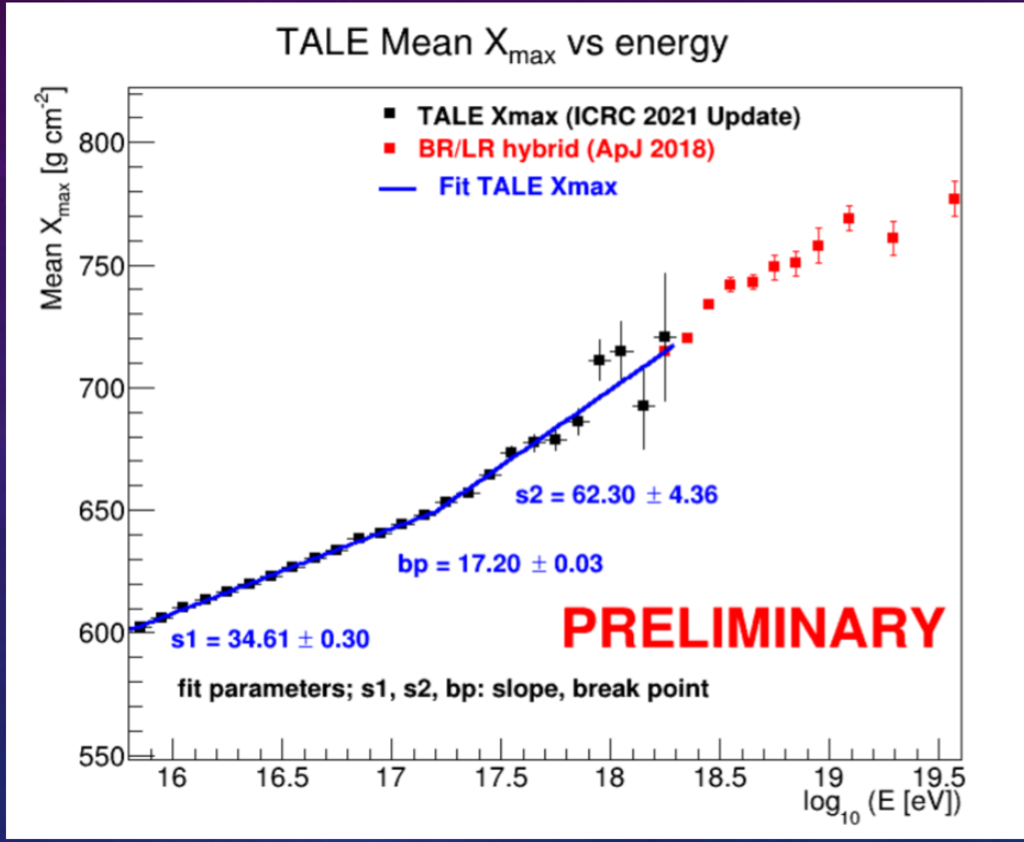
Simulation 9.5 yrs of data + 5 years TAx4 Data

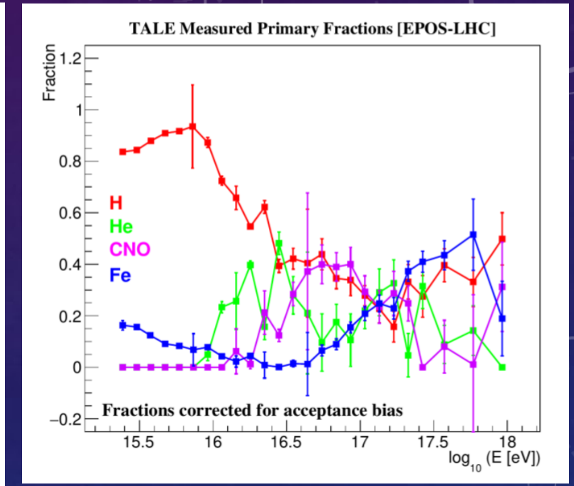
Adding even 5 years of TAx4 data will significantly improve separation

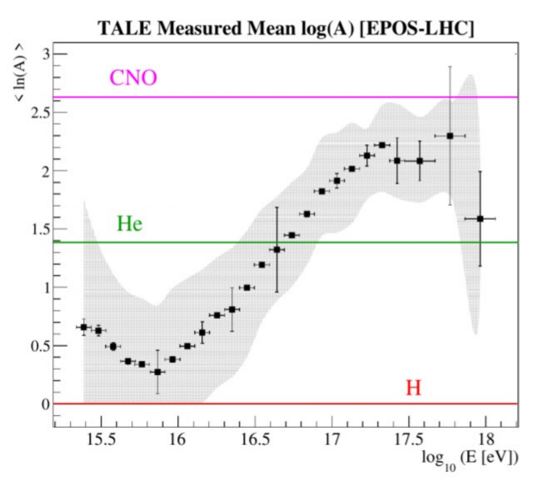
Data box/point shown is not changed but MC spots for elements get smaller due to smaller uncertainties

COMPOSITION

- Detailed measurement of composition from 2 PeV to 2 EeV
  - Using TALE with Cherenkov-light dominated events
  - ApJ 909 (2021)178
- Fit to four species
  - Reduction in protons above the Knee
  - Getting heavier
- Elongation rate fit
  - Break at 160 PeV, 2nd Knee
  - Getting lighter above that

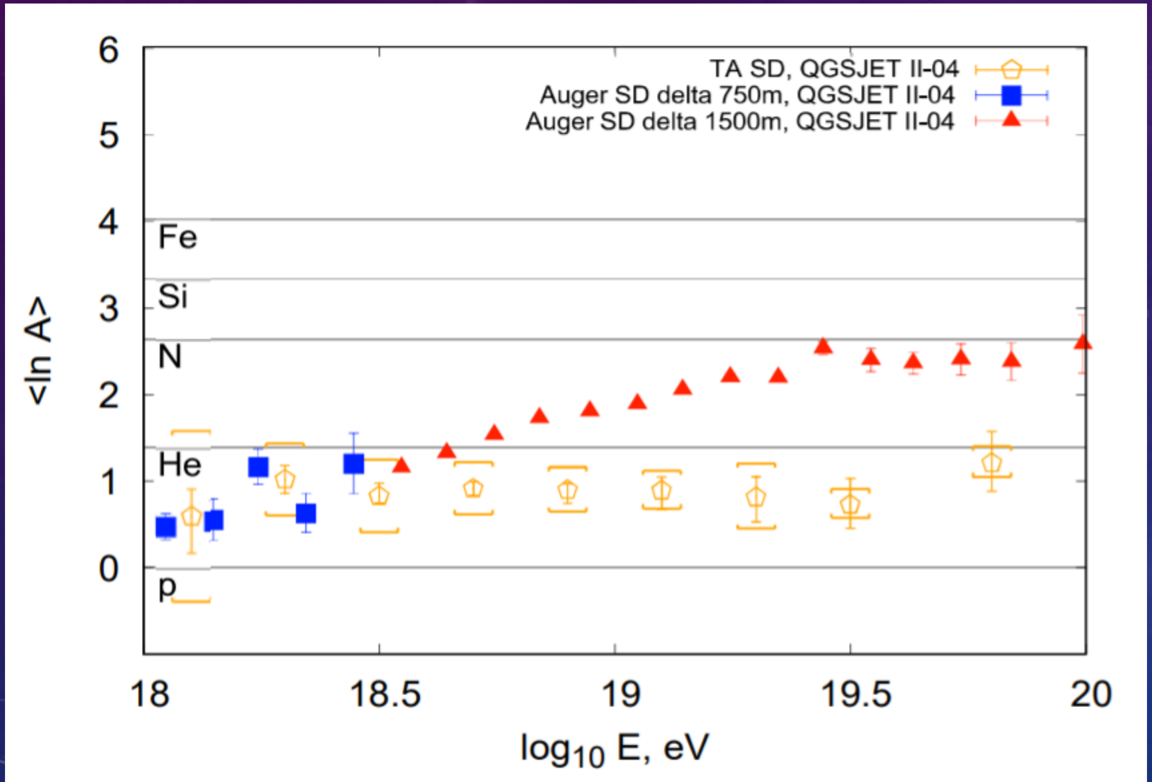


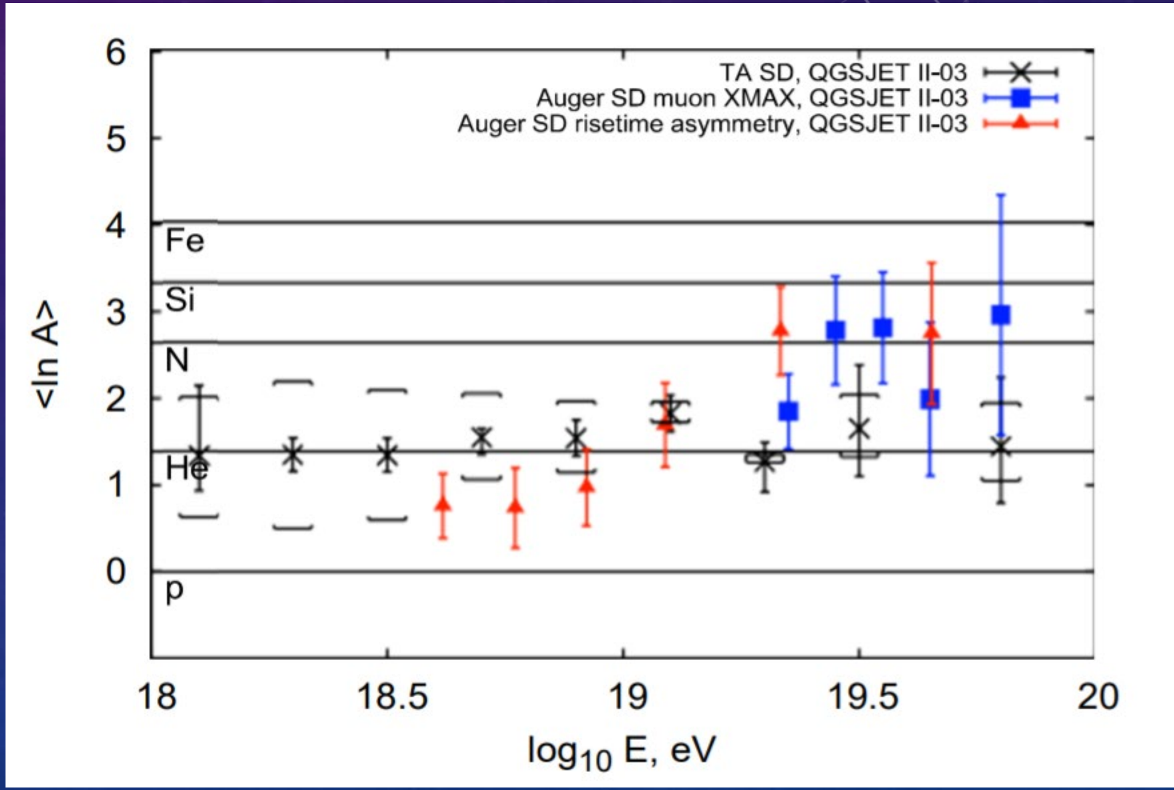




COMPOSITION

- TA SD composition: BDT analysis using 16 composition sensitive signals (12 years: 2008–2020)
  - Find light, unchanging composition above 1 EeV, with two different high-energy interaction models



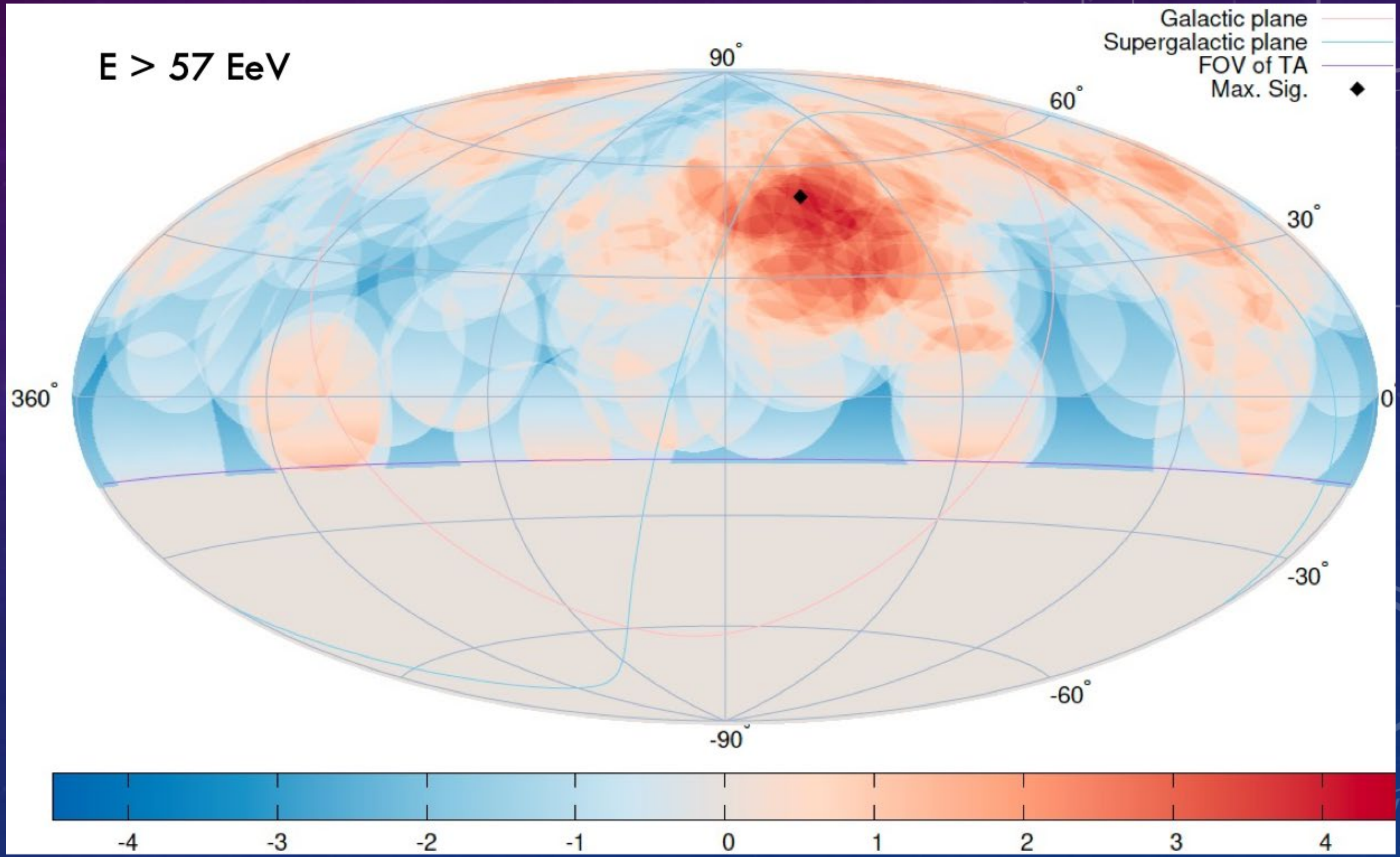


ANISOTROPY STUDY

ANISOTROPY

The TA hot-spot with 12 years of data

- 179 events with *E* > 57 EeV
- 40 events in hot-spot, 25˚ circle, local 4.5σ significance, 3.2σ global



ANISOTROPY

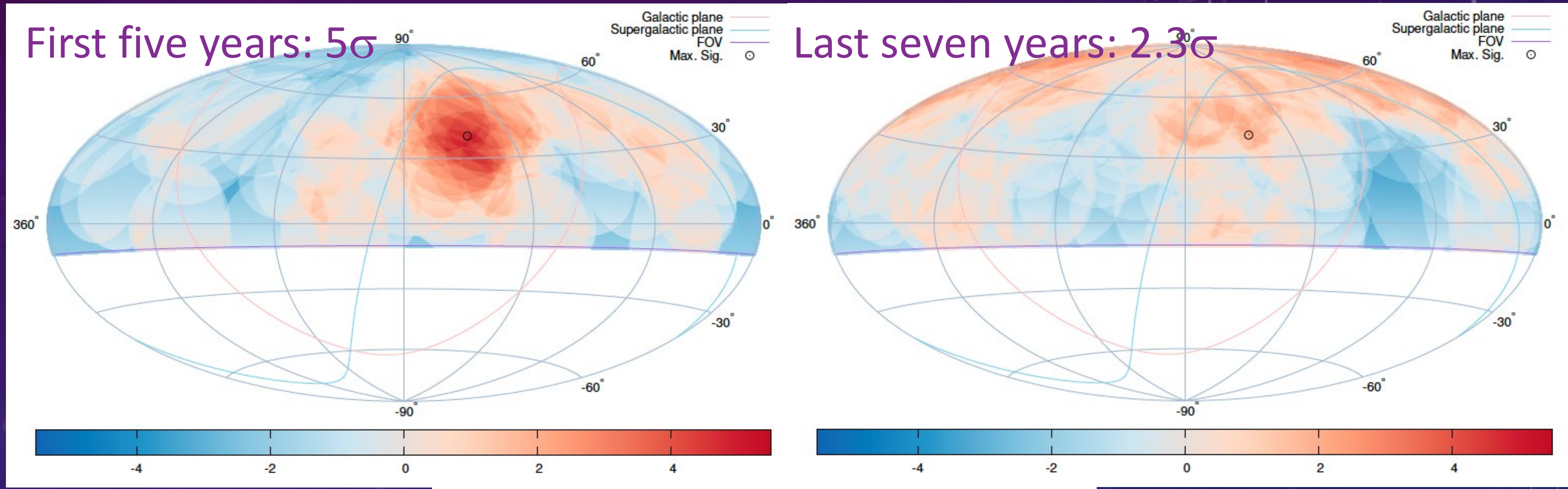
TA Hot Spot announced 2014 in data E>57 EeV (ApJ **790** (2014) L21)

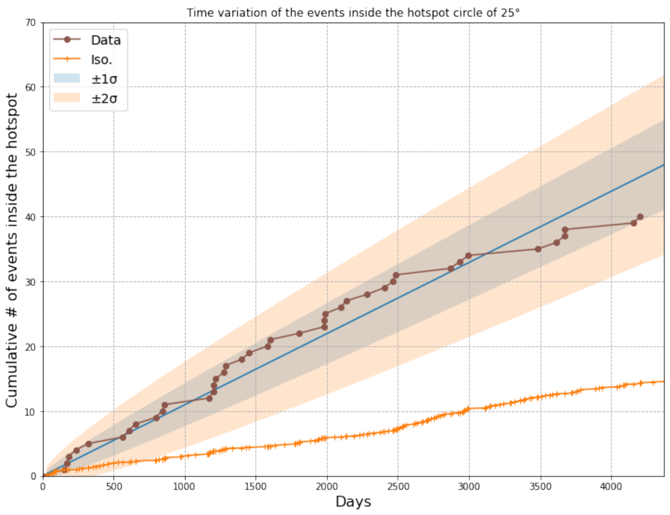
Now with 12 years of data

- 179 events with $E > 57$ EeV
- 40 events in hot-spot, 25˚ circle, local 4.5σ significance, 3.2σ global

The original brightness seems to not be sustained

- Still significantly higher than background
- Growth rate consistent with linear





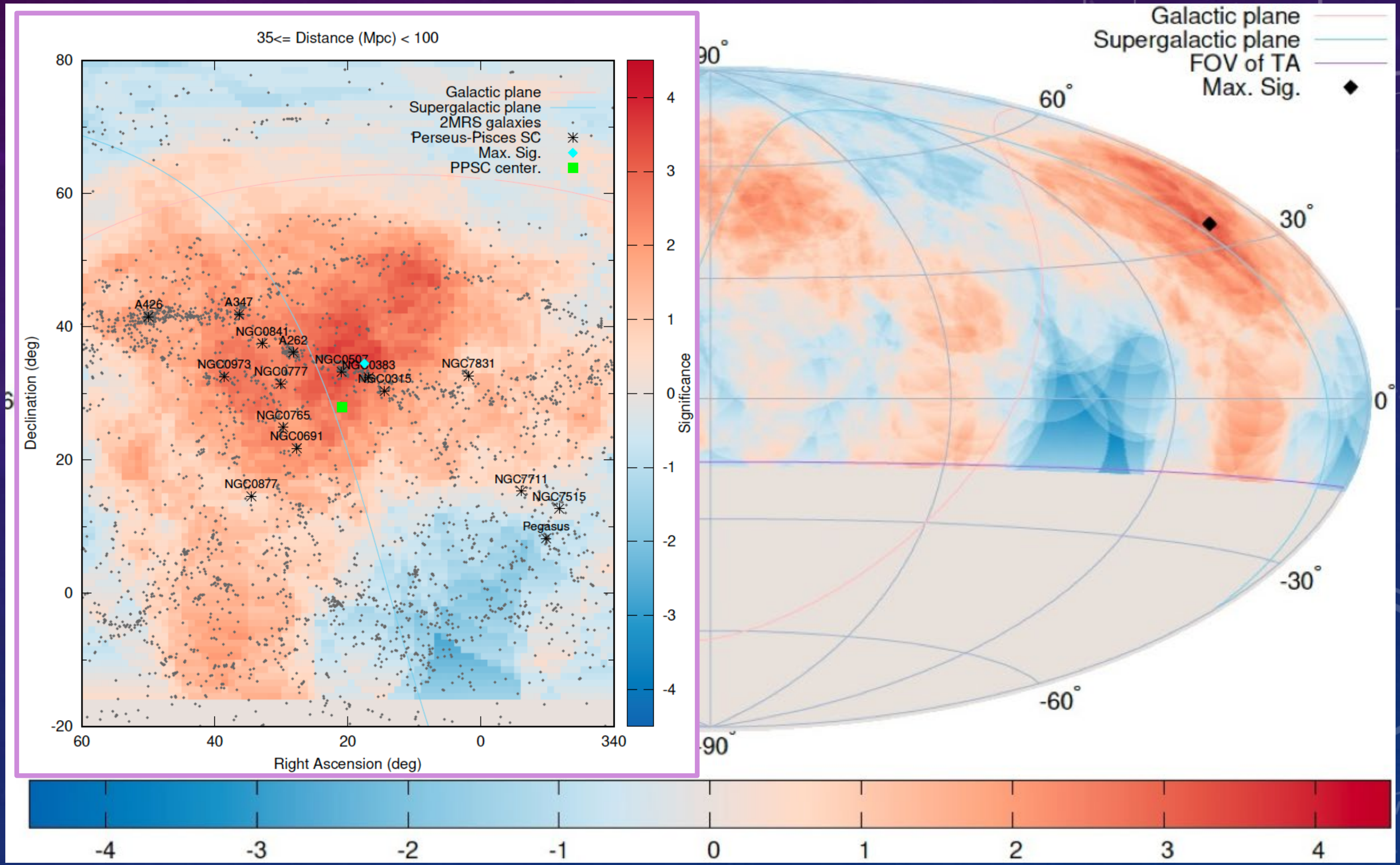
ANISOTROPY

At lower energies (E> 40 EeV) see a new excess

- In the direction of the Perseus-Pisces Supercluster

Significance is still being worked out, will be greater than 3σ and less than 5σ

- Considered these energies motivated by TA-Auger energy spectrum difference
- Have to calculate the penalty factor carefully



SUMMARY – RESULTS FROM TELESCOPE ARRAY

Spectrum

- Spectrum measurements over >5 orders-of-magnitude in energy
- TAx4 has begun to measure and make a contribution to the TA spectrum >10 EeV
- TA finds a significant difference in its own spectra **above and below 25˚ declination** (agrees with Auger in overlapping region)
- Observation of the “instep” feature

High Energy Event Observed

- New high energy event: 2.4×10^{20} eV - Approaching Fly’s Eye (1991 OMG) particle energy: 3.2×10^{20} eV

Composition

- Light-heavy-light pattern in 10^{15} – 10^{18} eV energy range using TALE (w Cherenkov)
- Appears Light and Steady for E> 10^{18} eV

Anisotropy

- Hotspot persists, but significance not increasing very quickly
- New significant excess at slightly lower energy in conjunction with the Perseus-Pisces Supercluster

Future

- Need to Improve statistics especially for Anisotropy and Composition measurements
- Complete TAx4 and take more data!!

Comparison of TA and Auger (+8.5%) Spectra