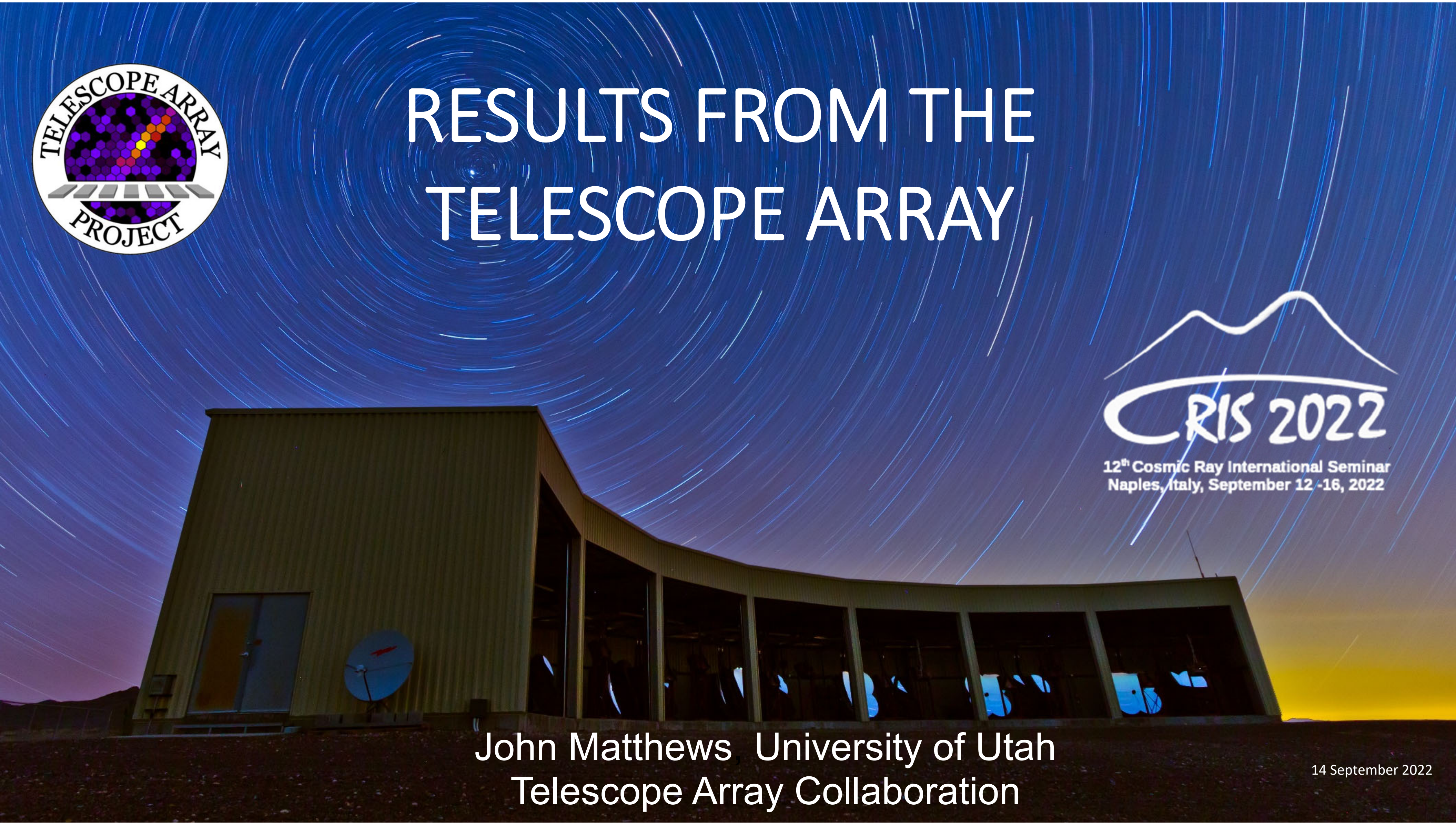
RESULTS FROM THE TELESCOPE ARRAY

John Matthews University of Utah
Telescope Array Collaboration

14 September 2022



TELESCOPE ARRAY COLLABORATION

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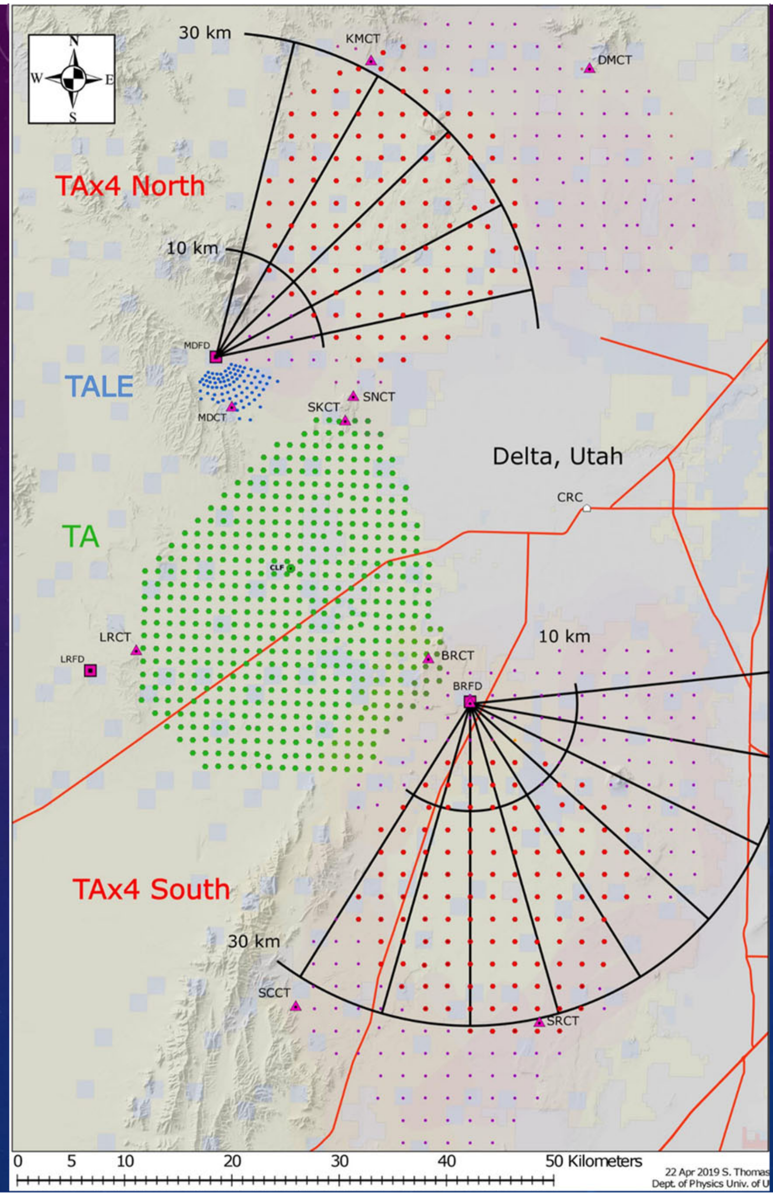
TELESCOPE ARRAY: THE LARGEST COSMIC RAY OBSERVATORY IN THE NORTHERN HEMISPHERE

TELESCOPE ARRAY



TELESCOPE ARRAY

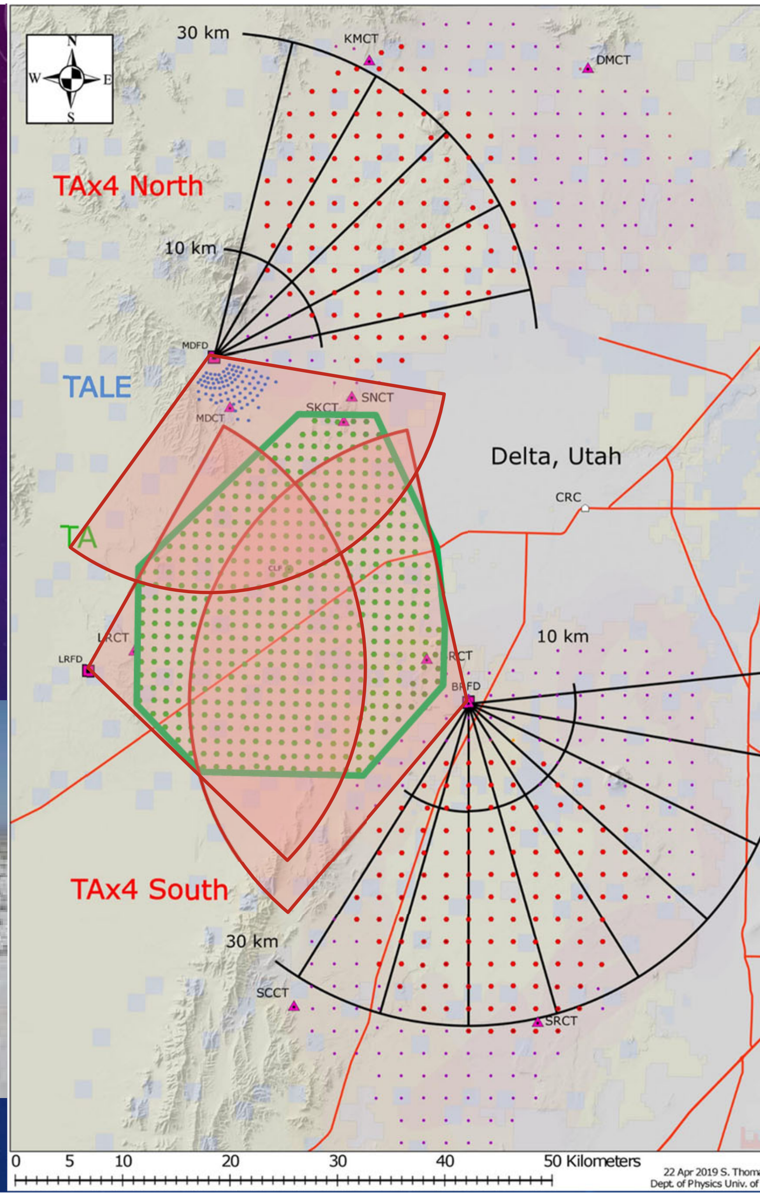
Telescope Array Detectors

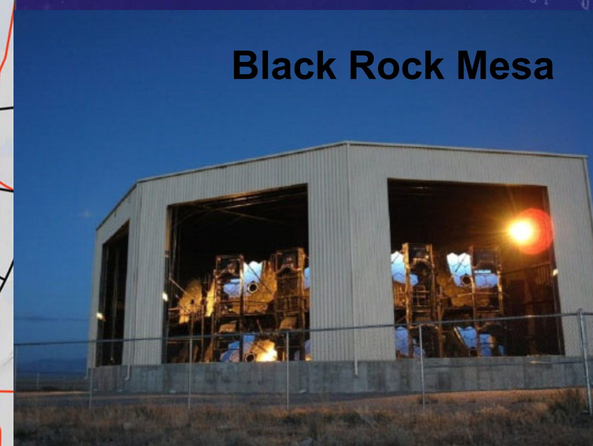
Surface Detector Array (3/2008)

- 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

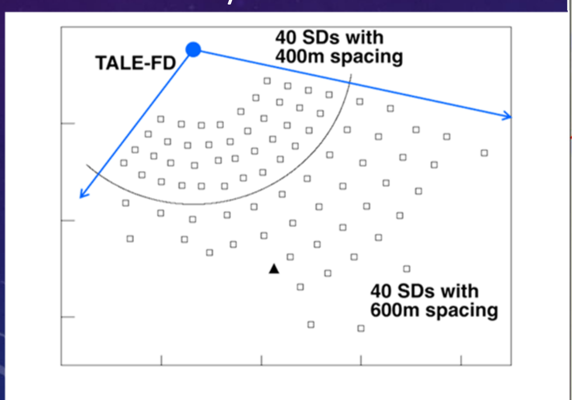
TA Low Energy (TALE)

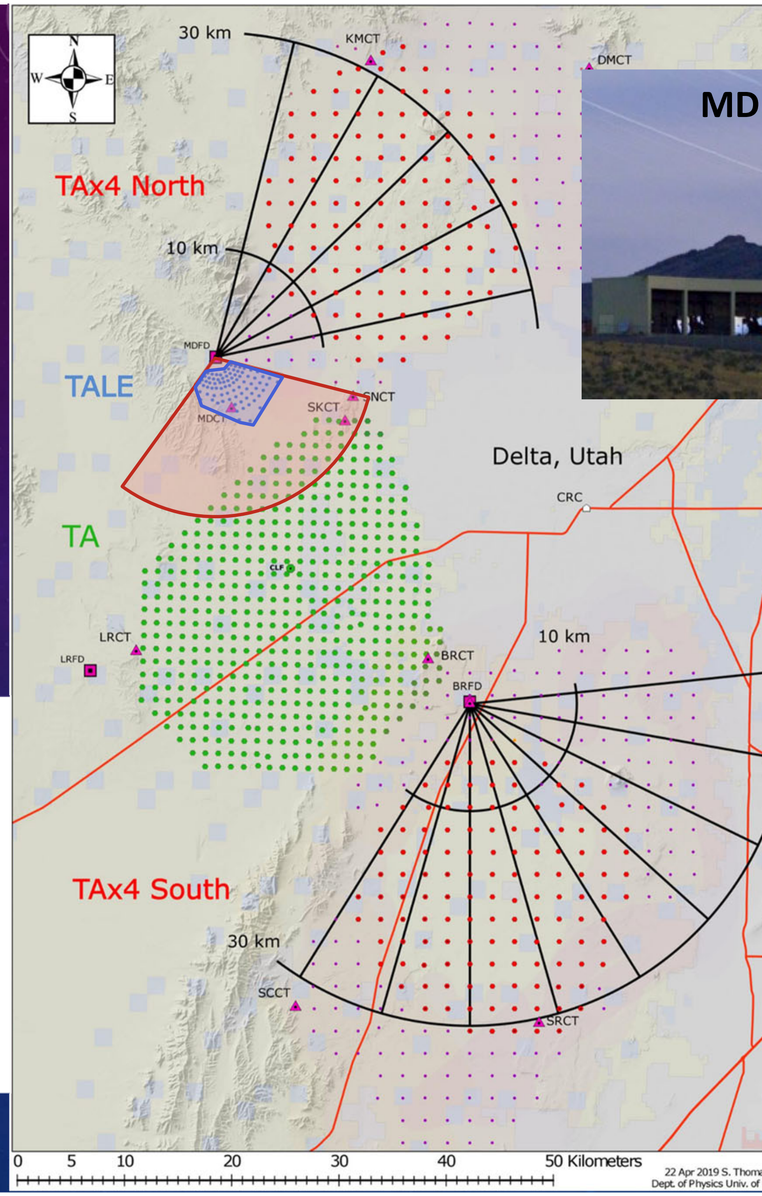
Fluorescence Telescopes

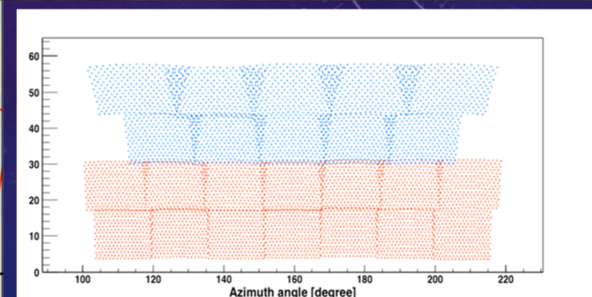
- 10 new telescopes
- 31˚–59˚ elevation
- With main TA 14: 3˚–59˚
- Since 9/2013

Scintillator infill array

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







TELESCOPE ARRAY

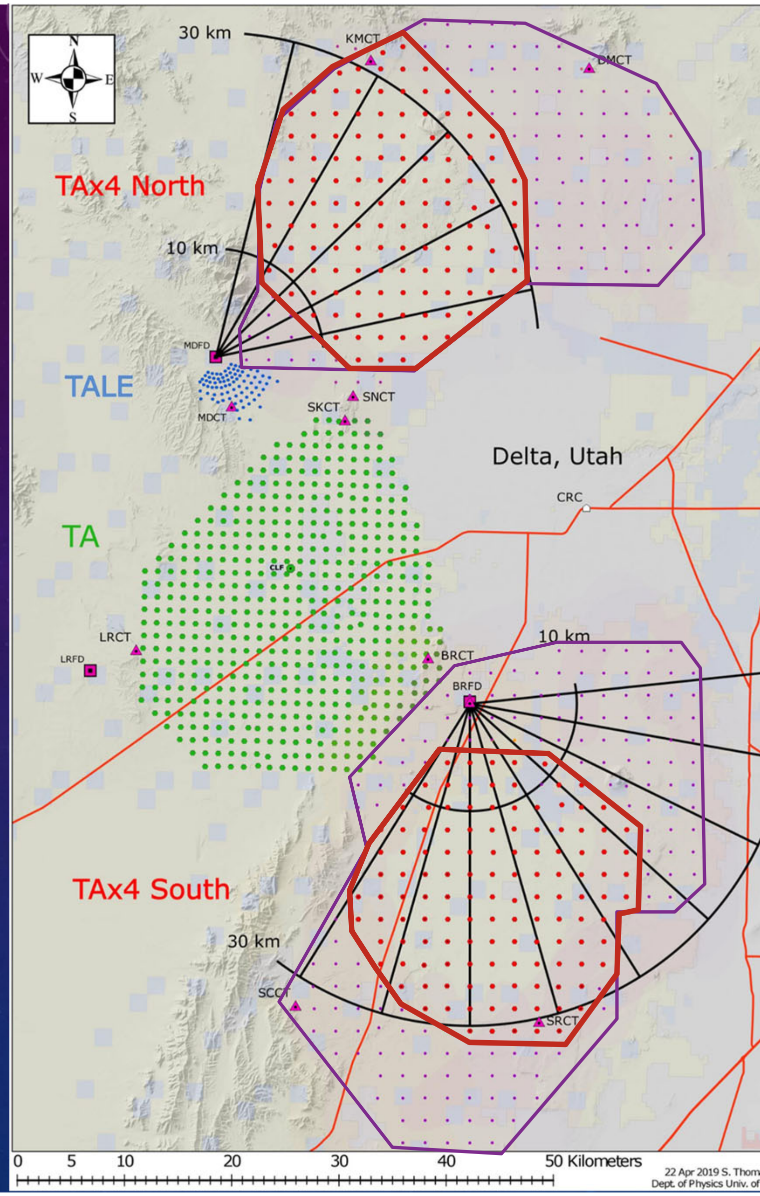
TA x 4

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

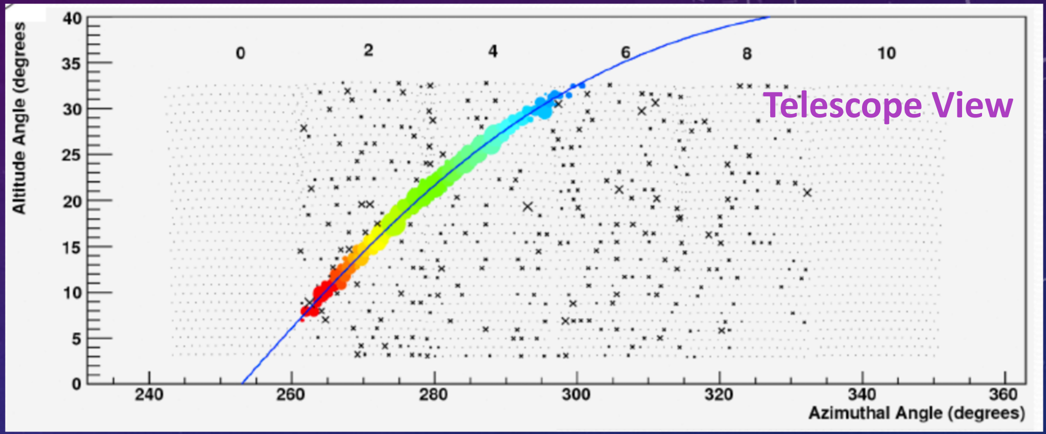


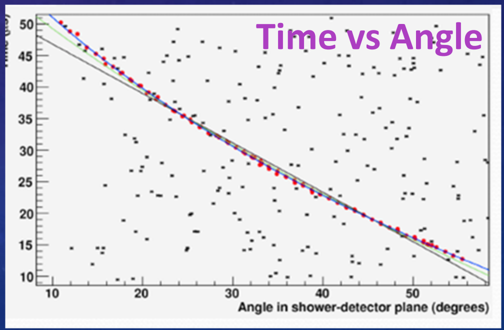
TELESCOPES

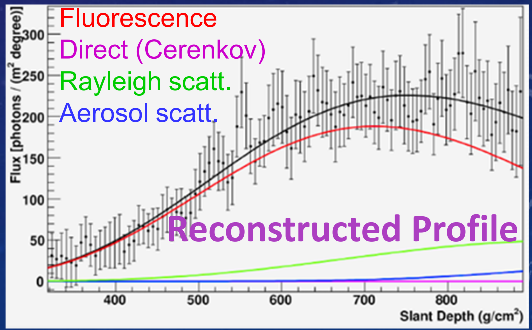
- Segmented mirrors
- 256 hexagonal PMTs/camera
- 1 pixel views ~1° of sky
- UV band-pass filter

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



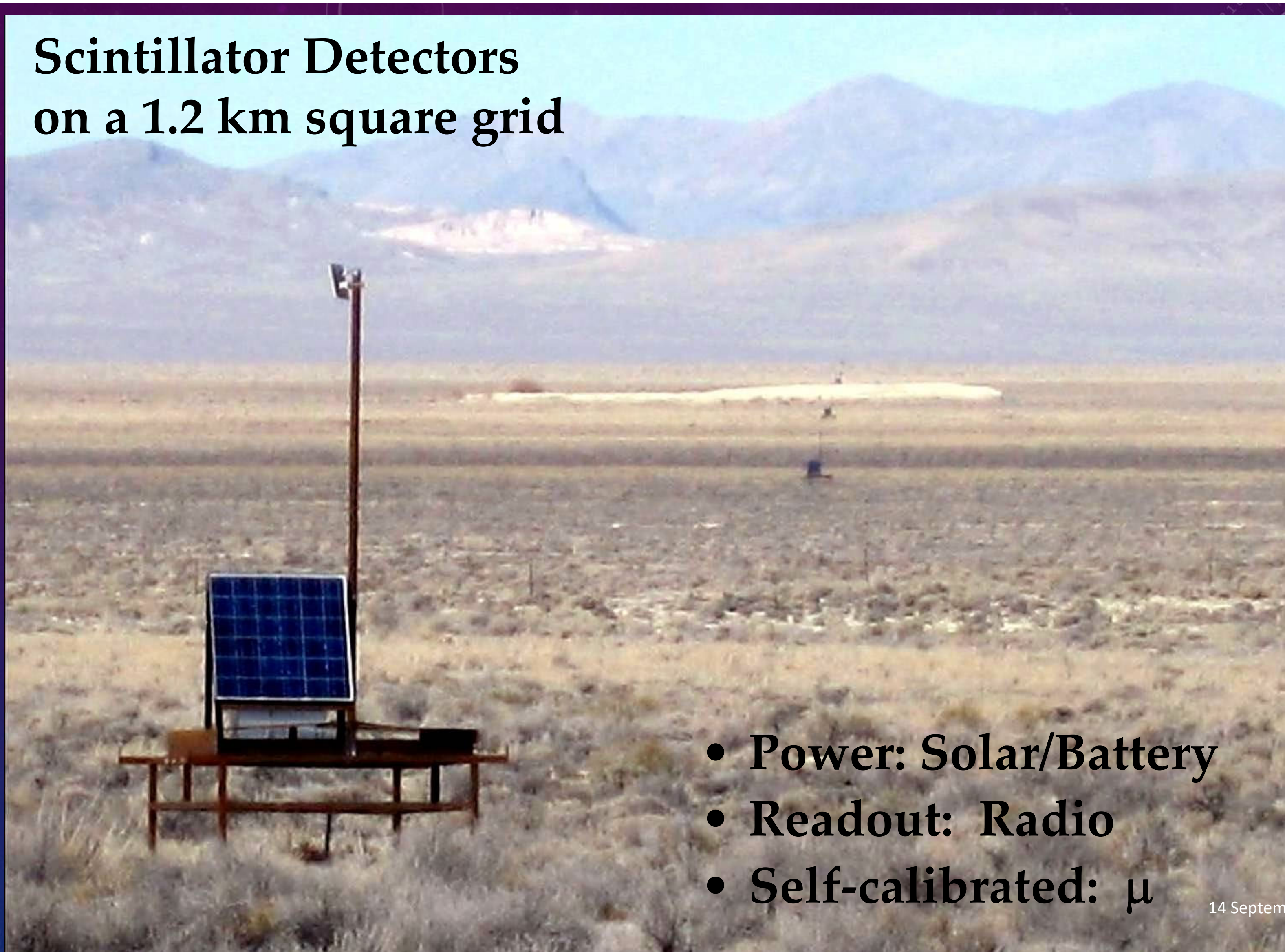




SCINTILLATOR SURFACE DETECTORS

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

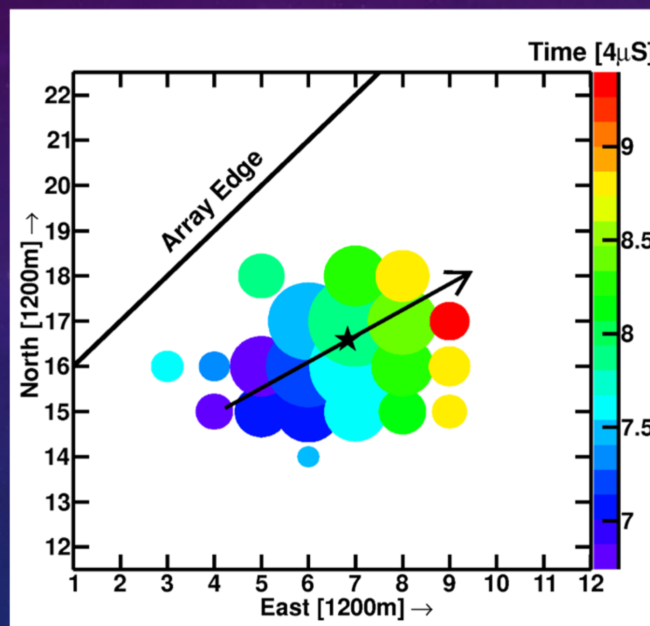
Scintillator Detectors on a 1.2 km square grid

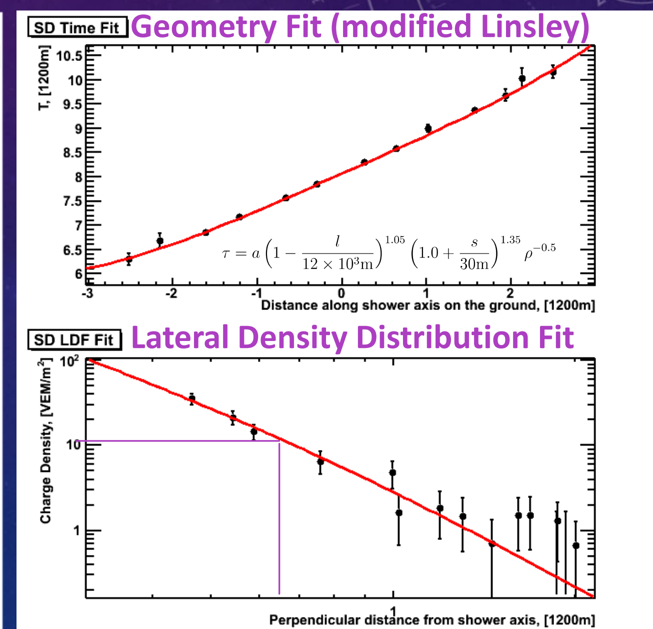


- Power: Solar/Battery
- Readout: Radio
- Self-calibrated: μ

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



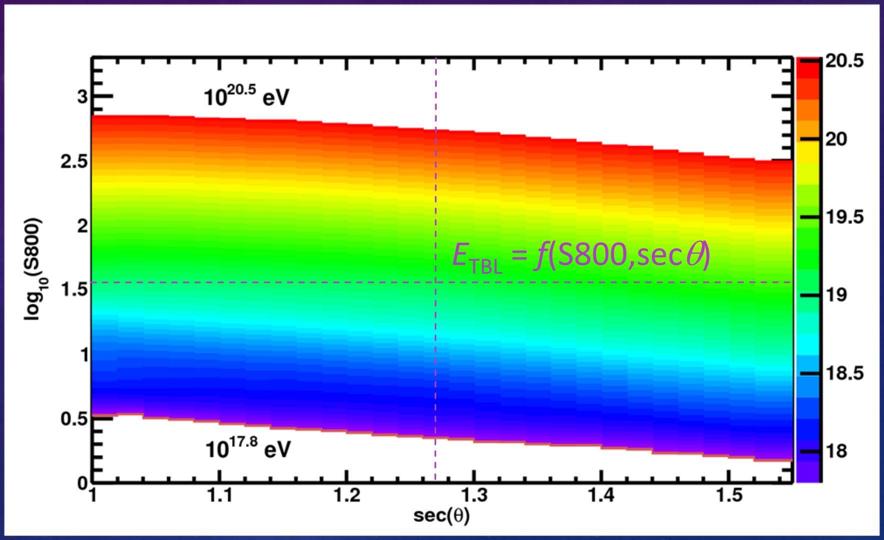


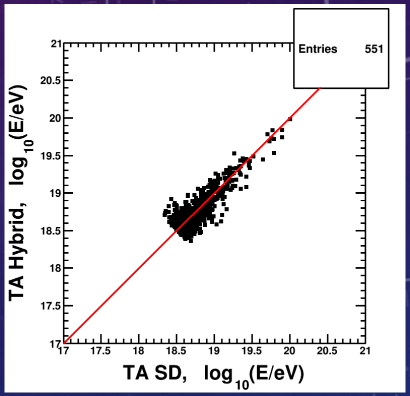
$$\rho = A\left(\frac{s}{91.6\mathrm{m}}\right)^{-1.2}\left(1+\frac{s}{91.6\mathrm{m}}\right)^{-(\eta(\theta)-1.2)}\left(1+\left[\frac{s}{1000\mathrm{m}}\right]^2\right)^{-0.6}$$

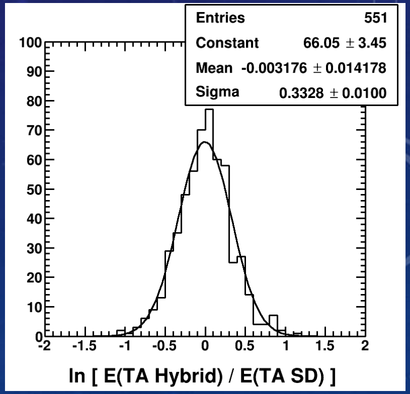
$$\eta(\theta) = 3.97 - 1.79\left[\sec(\theta) - 1\right]$$

EVENT RECONSTRUCTION

- Use counter location and timing to locate shower core and direction
- Fit counter signal size to find lateral distribution
- Signal size at 800 m, S800, is the energy indicator
- Use S800 and zenith angle to look up energy (from CORSIKA-produced table)
- Hybrid fluorescence provides energy scale: $E_{final} = E_{TBL}/1.27$



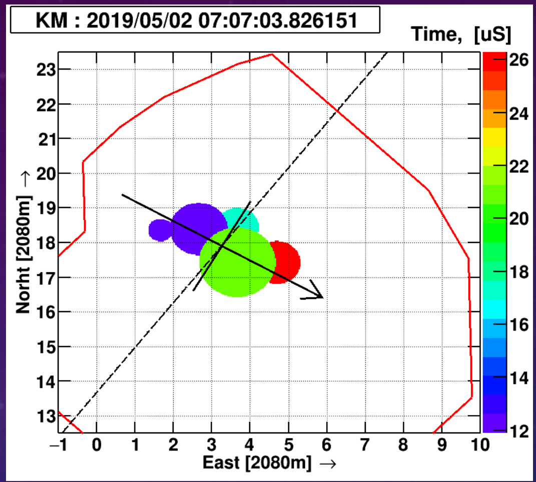


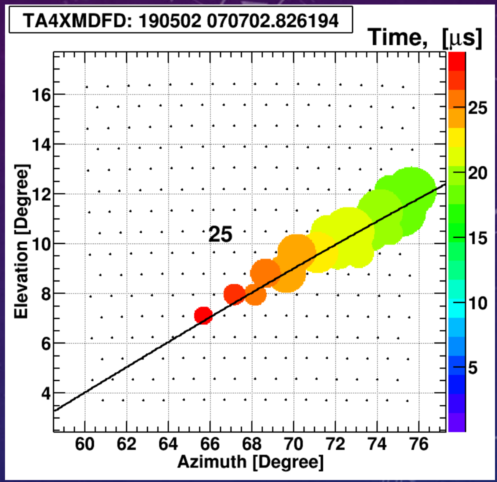


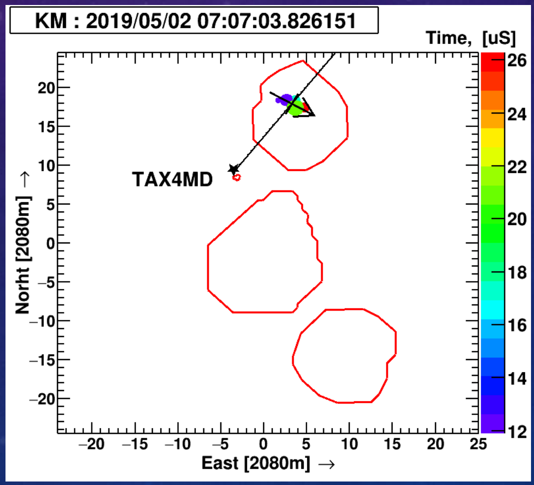
TAX4 HYBRID EXAMPLE EVENT

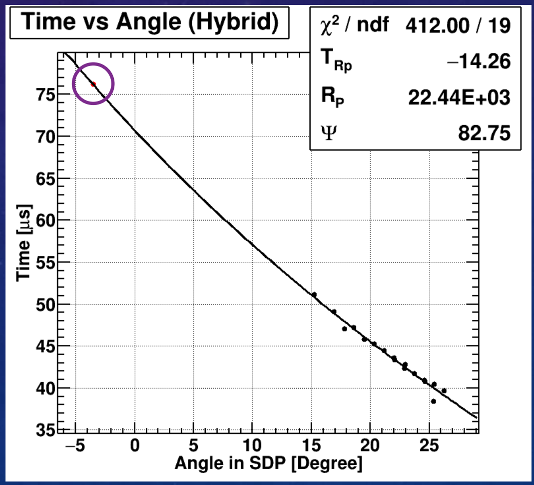
Hybrid Analysis

- Fluorescence Telescope event
- Surface detector event
- Time-matched within 1 ms
- Accurate event geometry
  - SDP-ground intersection
  - Time vs Angle fit with long lever arm



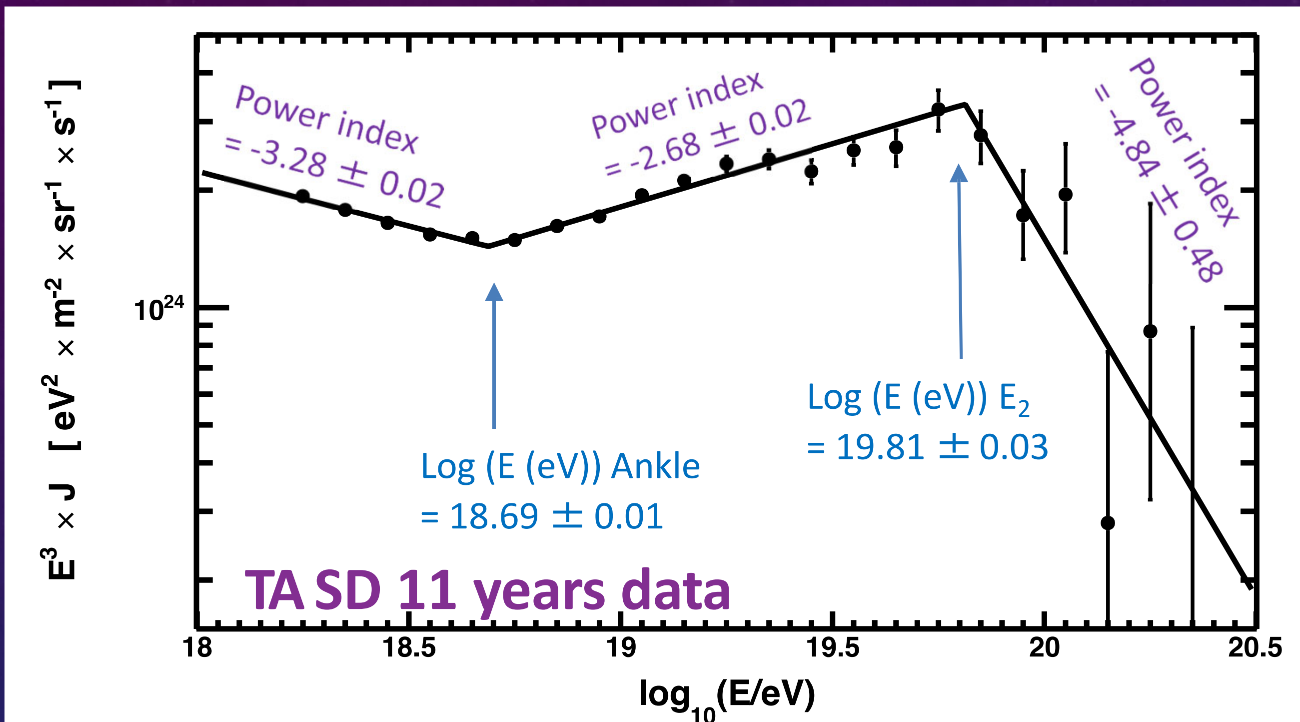


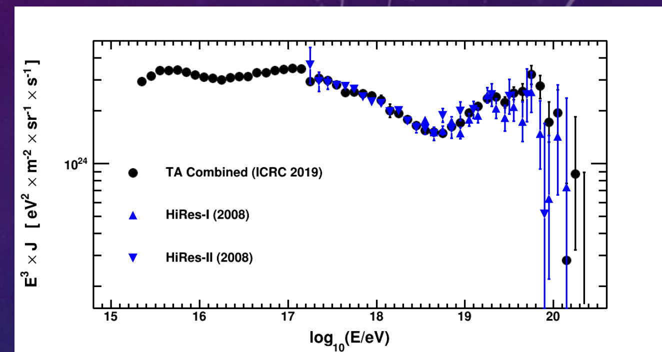


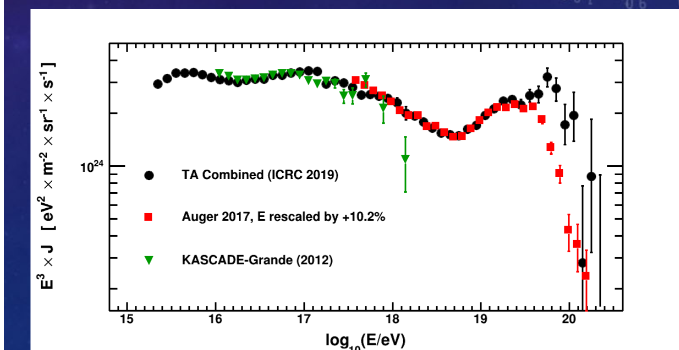


ENERGY SPECTRUM

ENERGY SPECTRUM

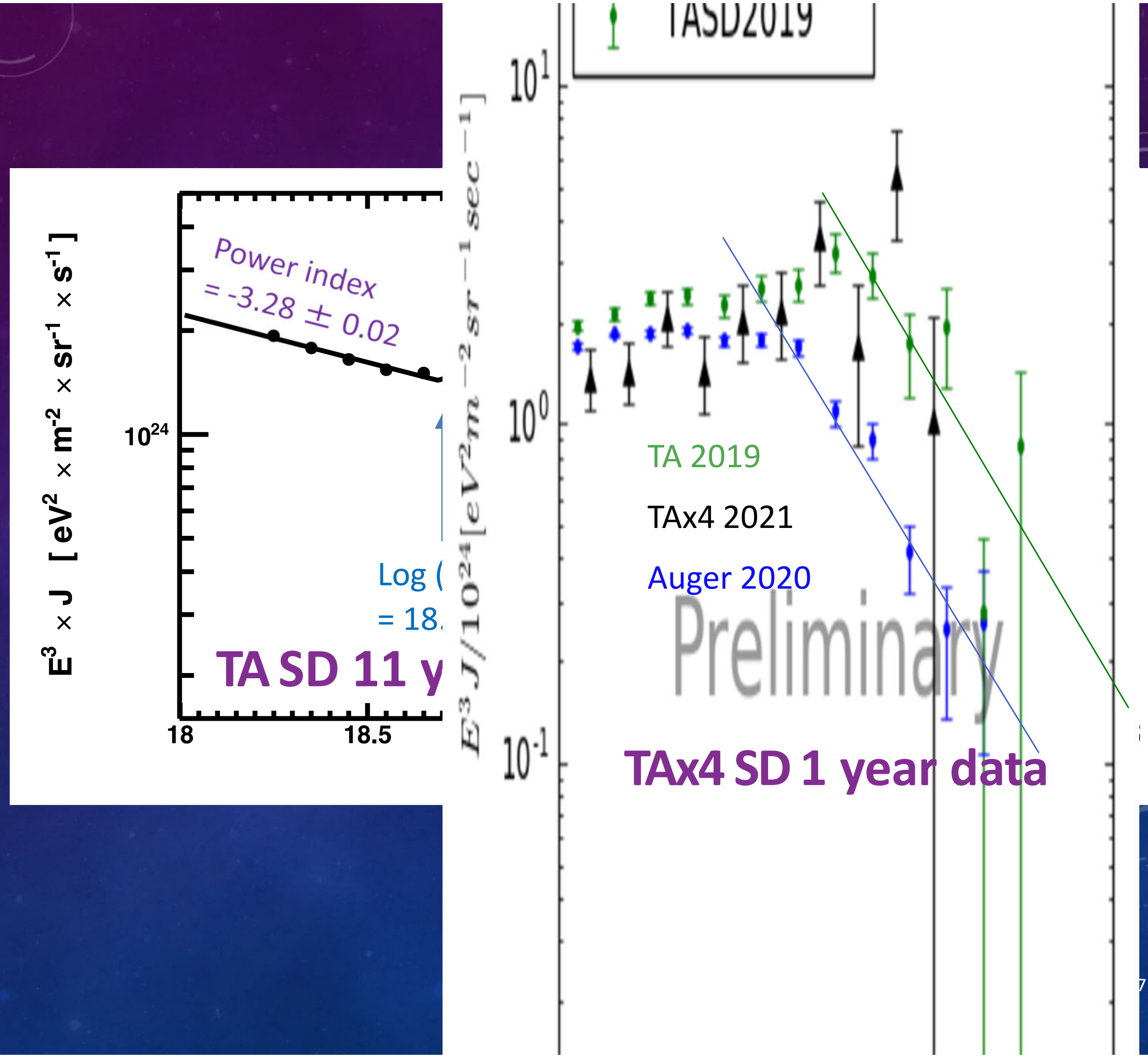






ENERGY SPECTRUM

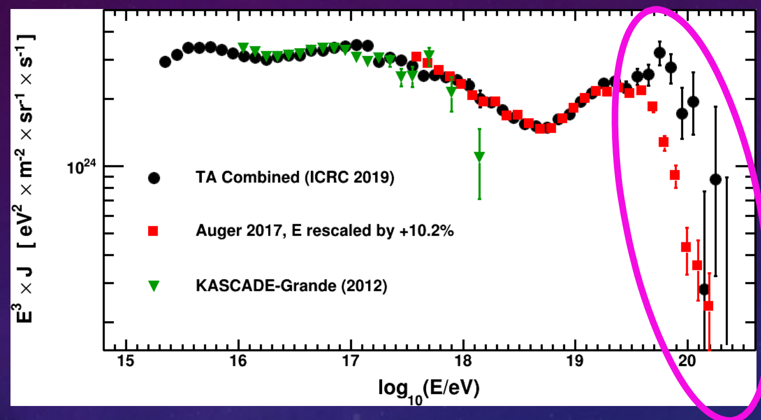
- TA Energy Spectrum
- TAx4 1-year spectrum superimposed
- Auger data (south) appears to drop off ~$10^{19.6}$ eV, Telescope Array (north) sees a higher energy $10^{19.8}$ eV
- 1-year of (half of) the TAx4 expansion, data looks like it supports the higher GZK threshold in north

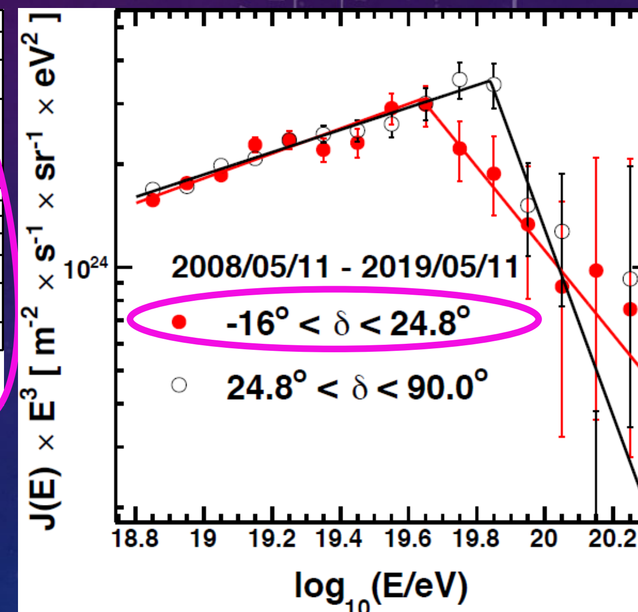


ENERGY SPECTRUM

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)

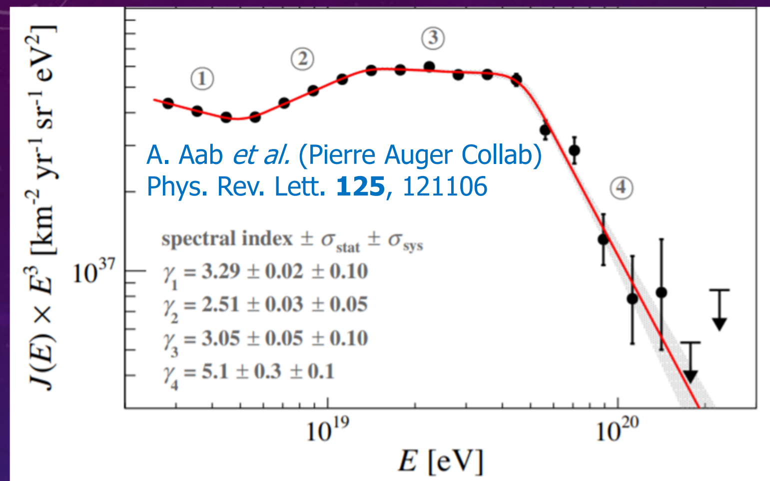




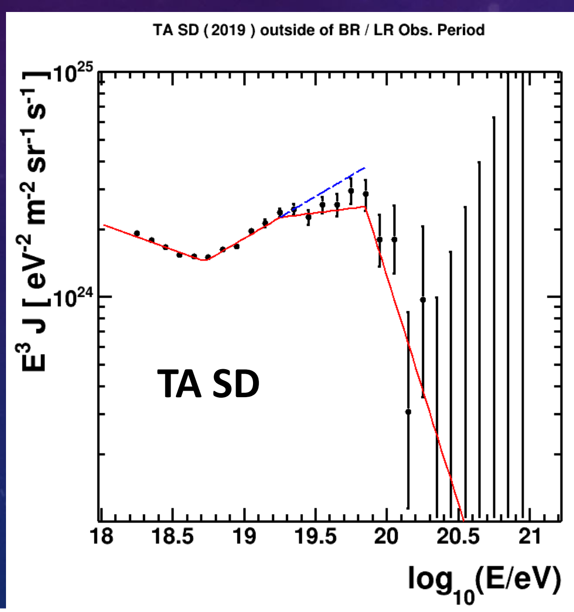
THE INSTEP FEATURE

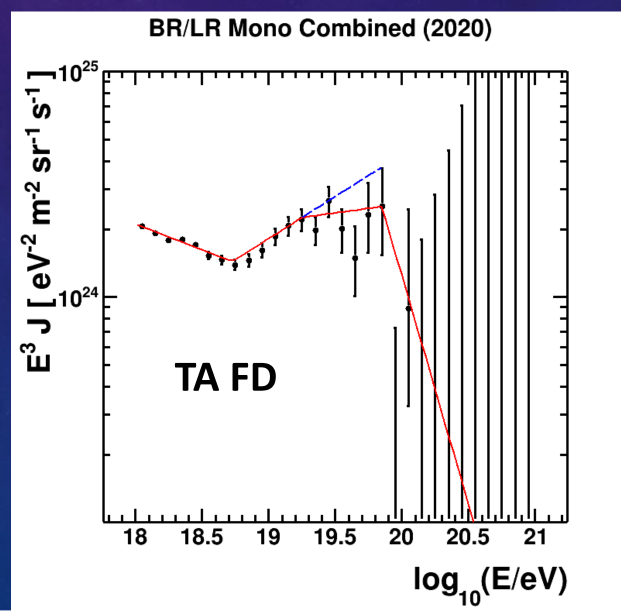
Feature first seen in Auger data

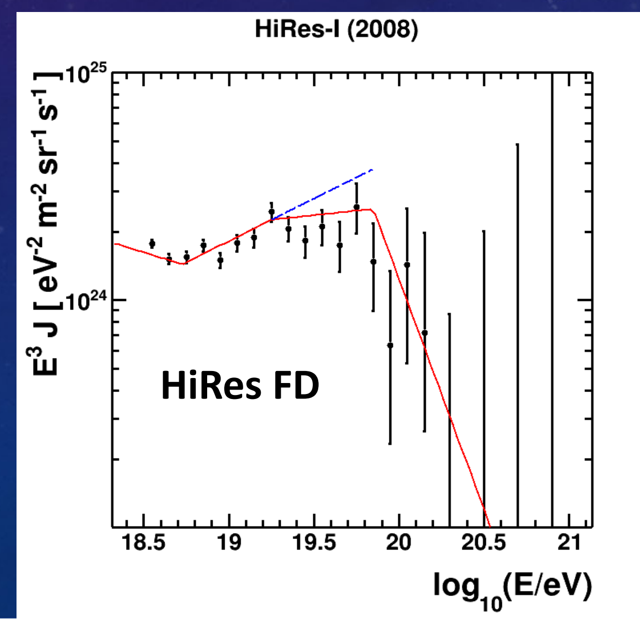
Combined fit of TA SD, TA Monocular, and HiRes data finds the feature with **5.3σ** significance



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





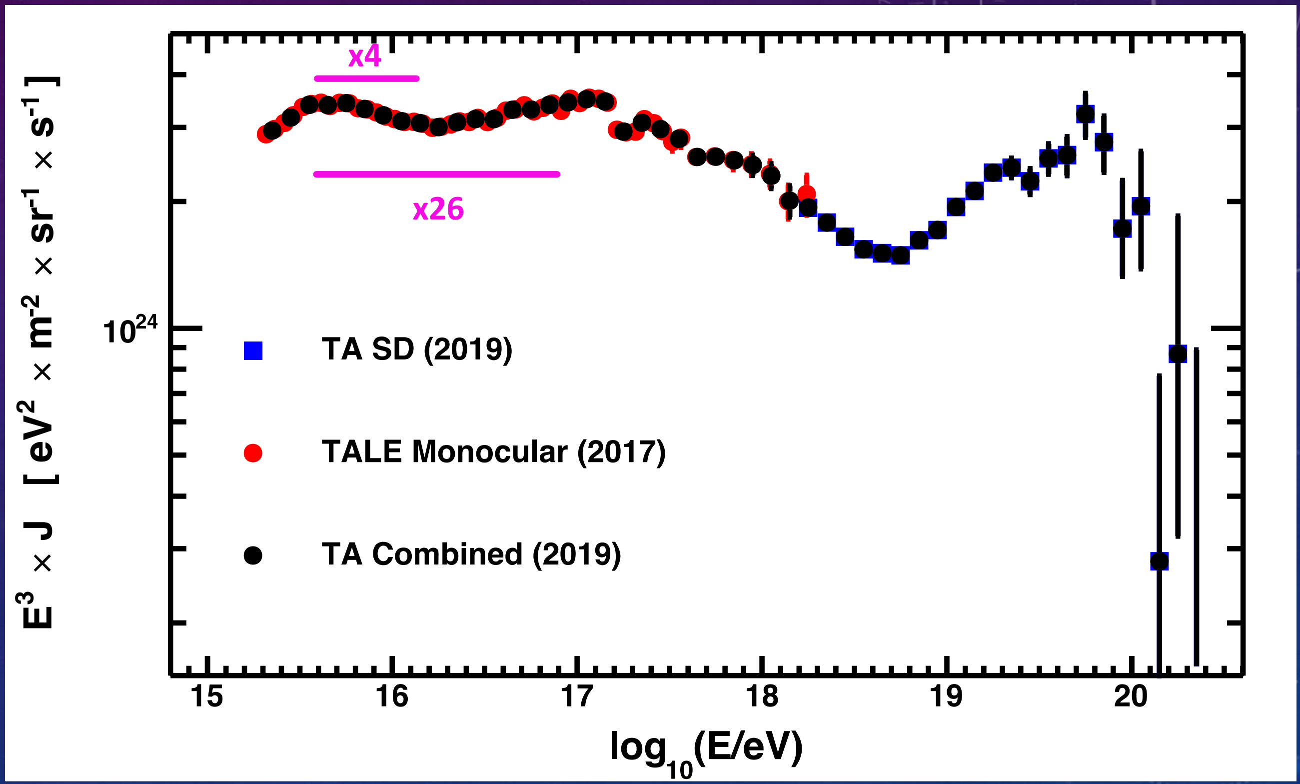


ENERGY SPECTRUM

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

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

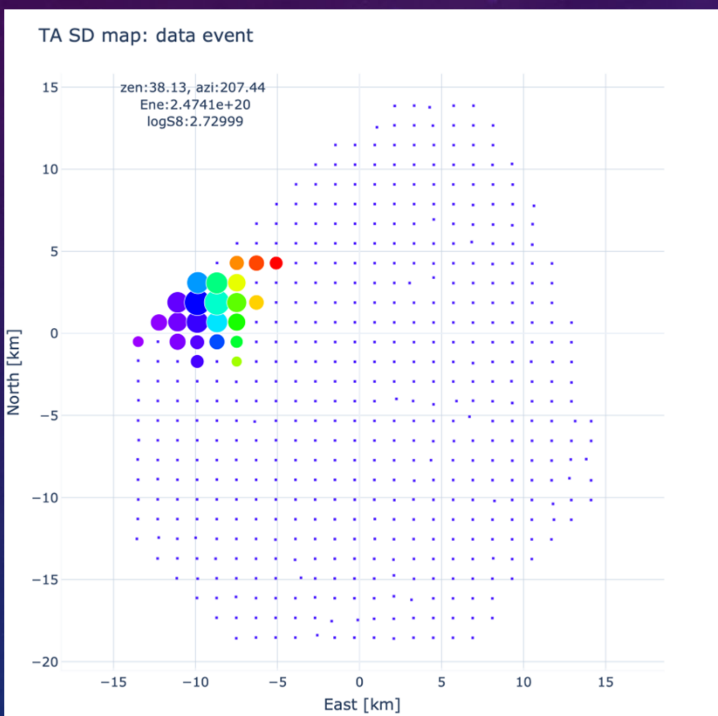
Peter's Cycle? : $10^{15.6} - 10^{17.1}$ eV

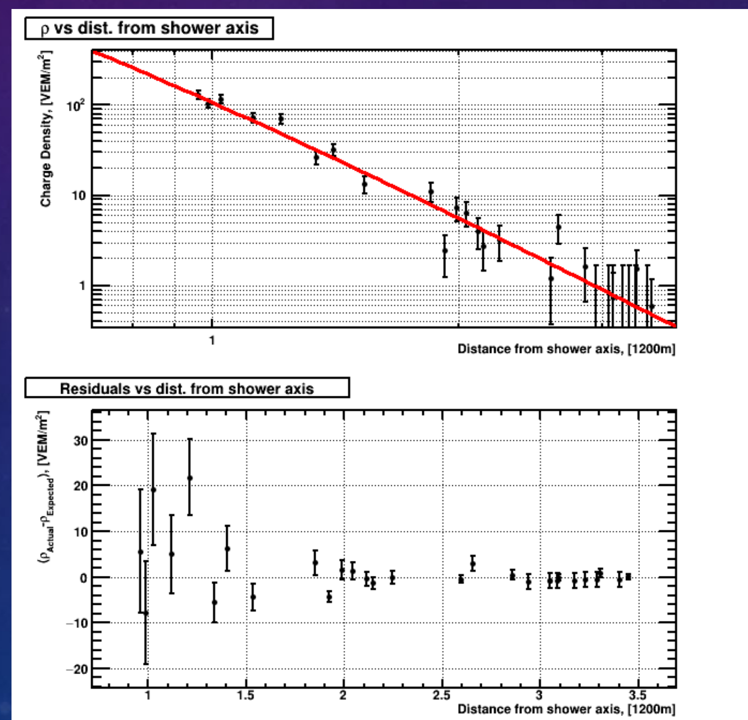


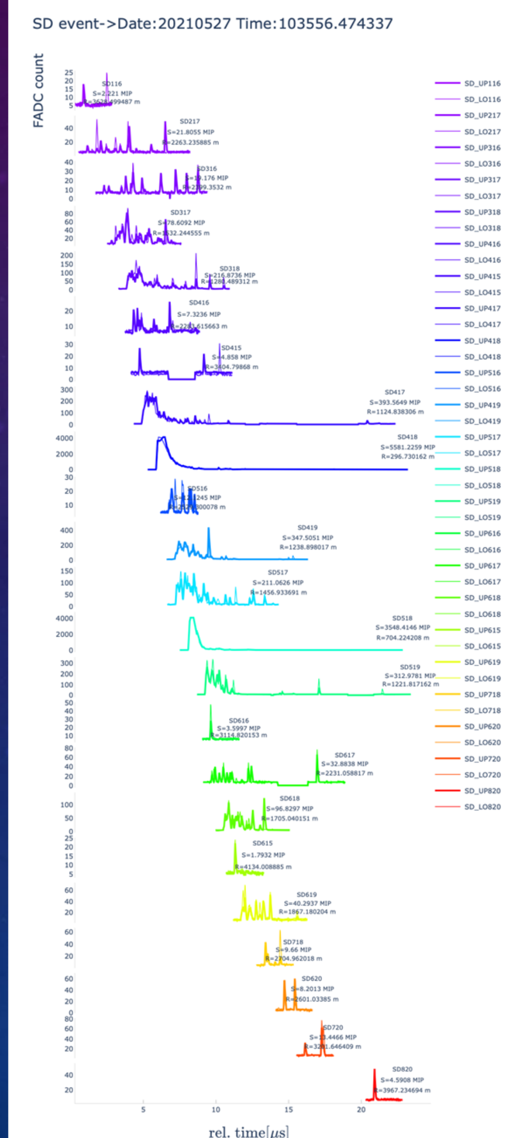
New Highest Event Detected by TA

NEW HIGHEST EVENT DETECTED BY TA

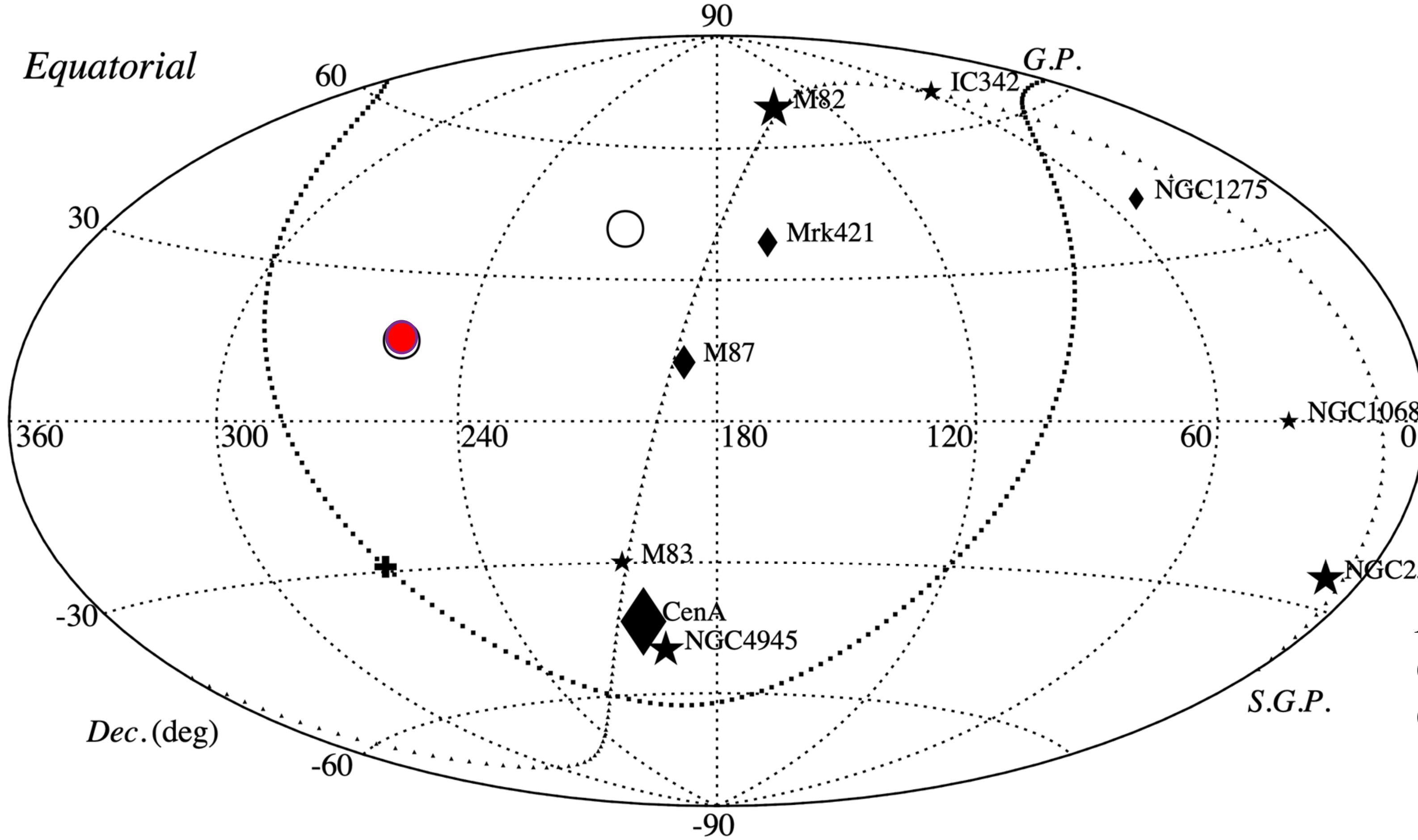
- 2021/05/27 10:35:56.47, No FD observation
  - E = **243.6 ± 10.7 EeV**, $\theta = 38.6°$, $\varphi = 206.8°$ - **Preliminary**
    - (E = 242.8 EeV with the atmospheric energy correction) - **Preliminary**







DIRECTION IN THE SKY-MAP

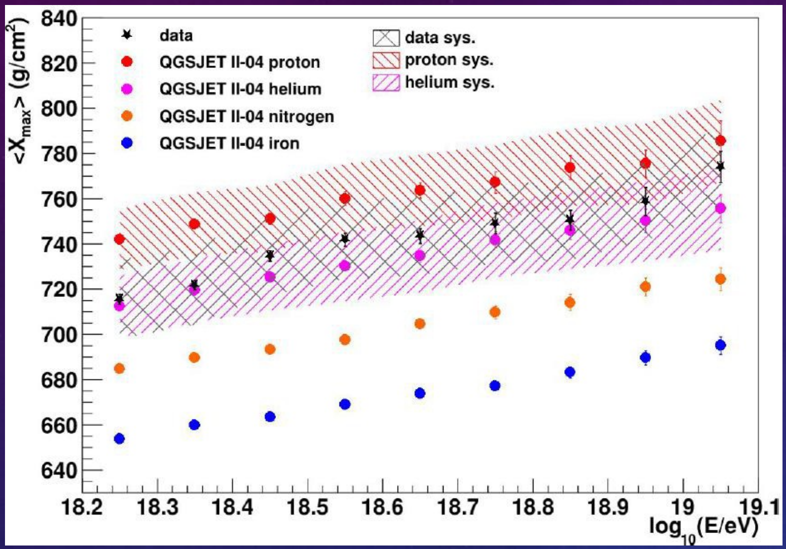


***E* = 243.6 EeV**
(RA, Dec) =
(255.85, 16.08)

CHEMICAL COMPOSITION

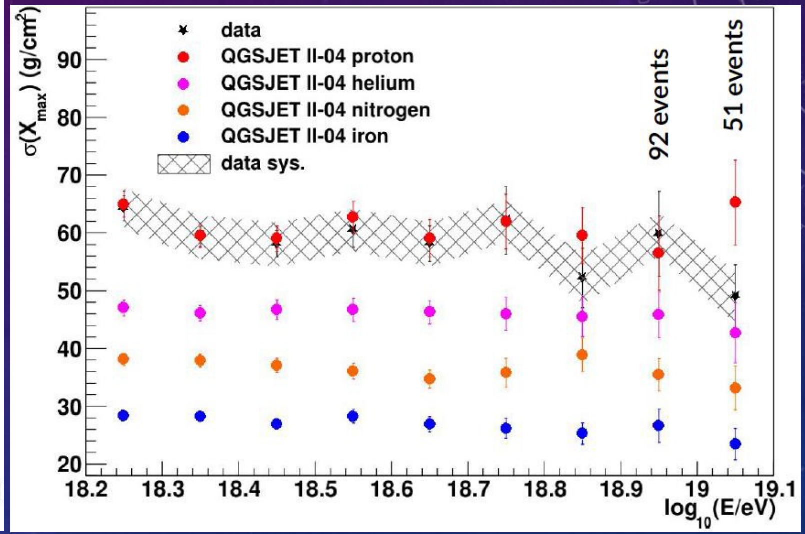
COMPOSITION ANALYSIS WITH TA HYBRID XMAX

Mean Xmax



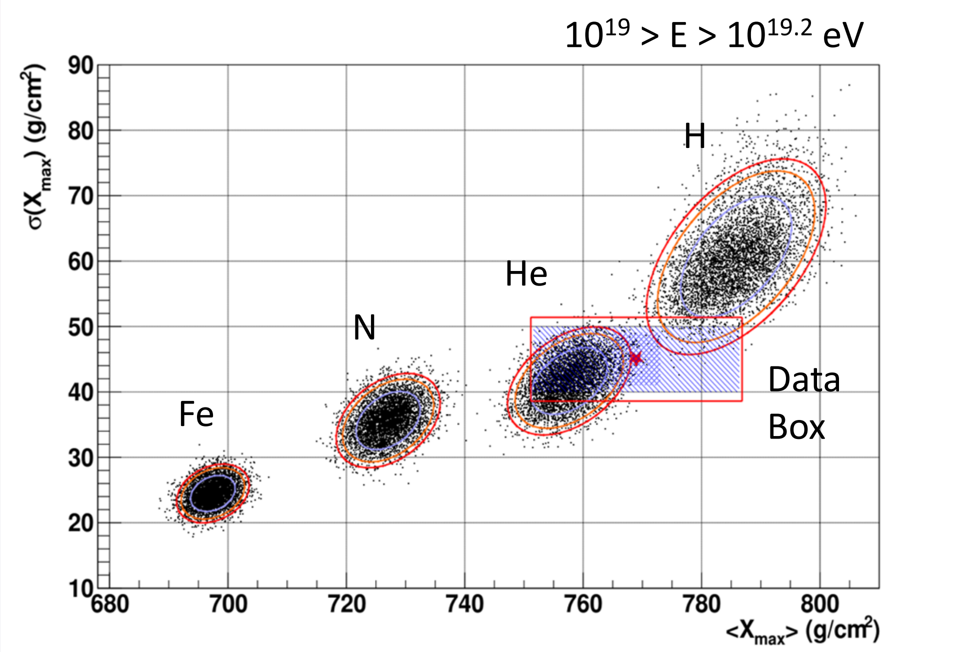
10 years SD and FD hybrid data

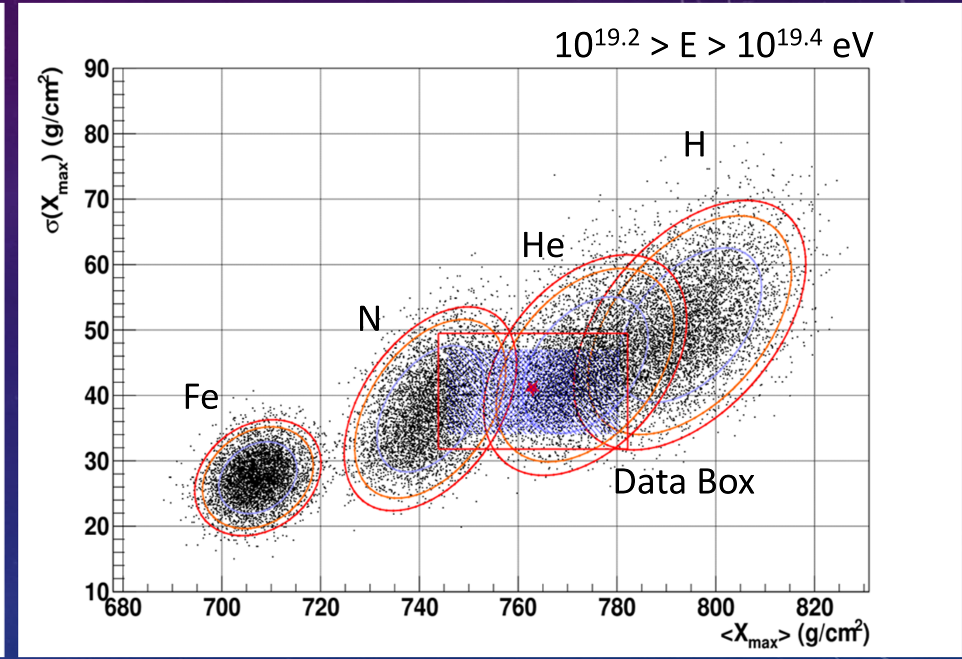
σ (Xmax)



- 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
- Also working on more models

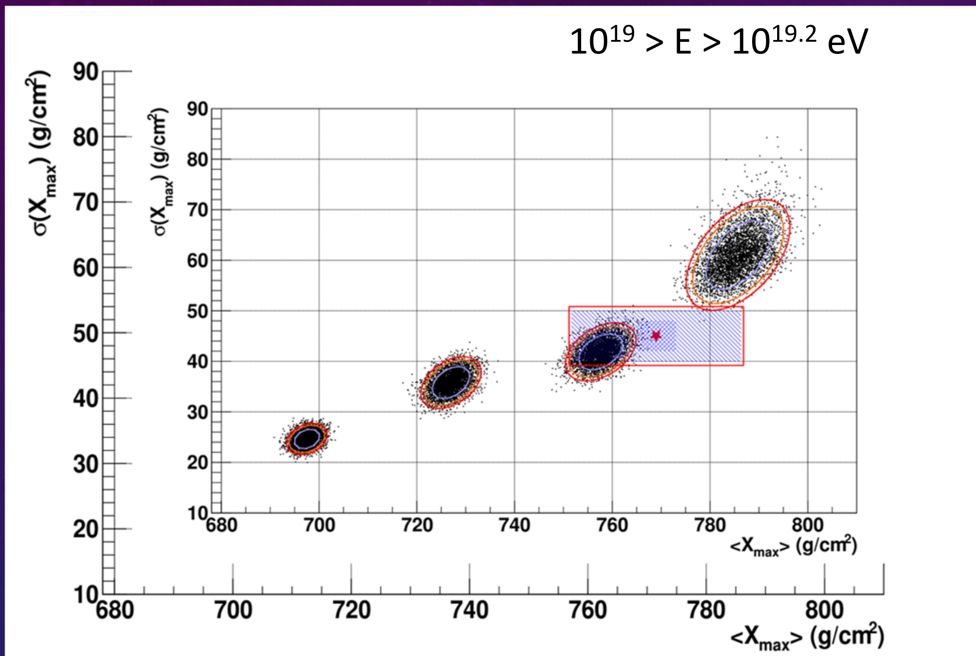
HYBRID COMPOSITION

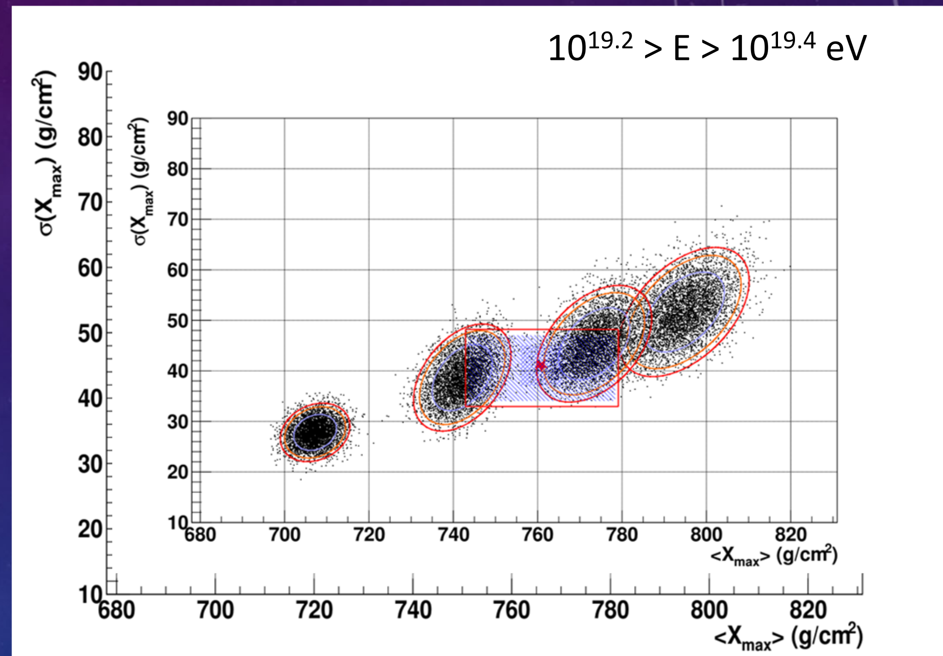




9.5 yrs of data
Adding even 5 years of TAx4 data will significantly improve separation

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

TALE FD XMAX STUDY

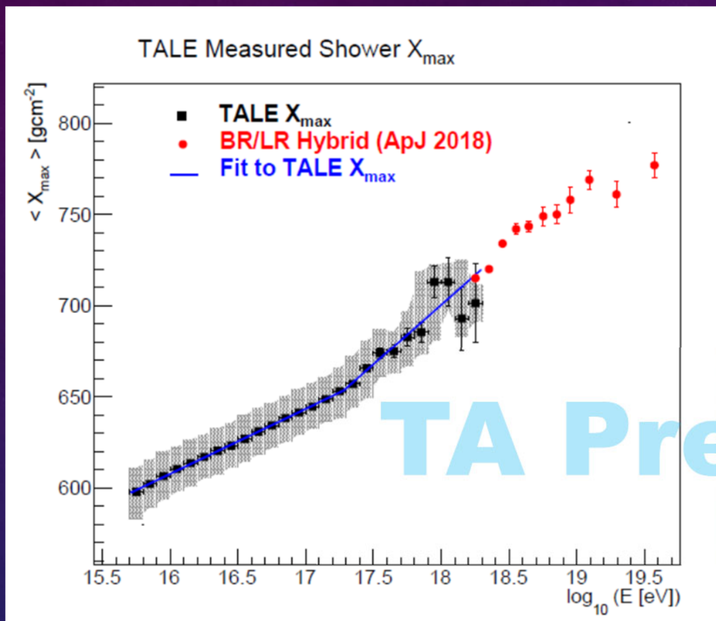


Table 2. Fit parameters to a broken line fit to TALE X_{max} elongation rate. The upper set of measurements are for the EPOS-LHC, the lower set is for QGSJetII-03. Uncertainty reported as $value \pm \sigma_{stat.} + \sigma_{sys.} - \sigma_{sys.}$.

EPOS-LHC	break point	17.291 ±0.060 + 0.077 − 0.084
	slope before	35.863 ±0.294 + 1.481 − 0.536
	slope after	65.413 ±6.655 + 0.000 − 3.269
QGSJet-II-03	break point	17.310 ±0.049 + 0.052 − 0.179
	slope before	35.784 ±0.298 + 1.337 − 0.667
	slope after	70.860 ±6.508 + 0.000 − 11.387

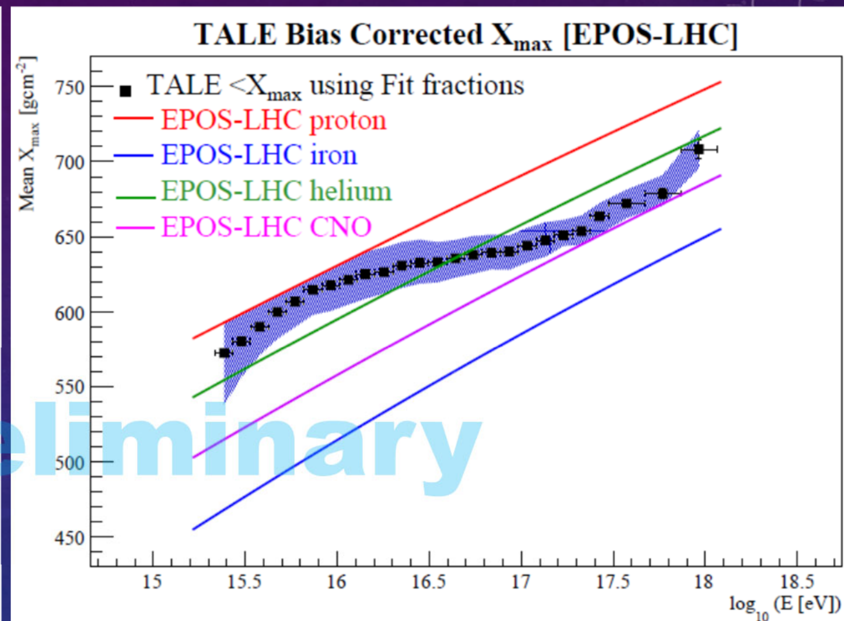
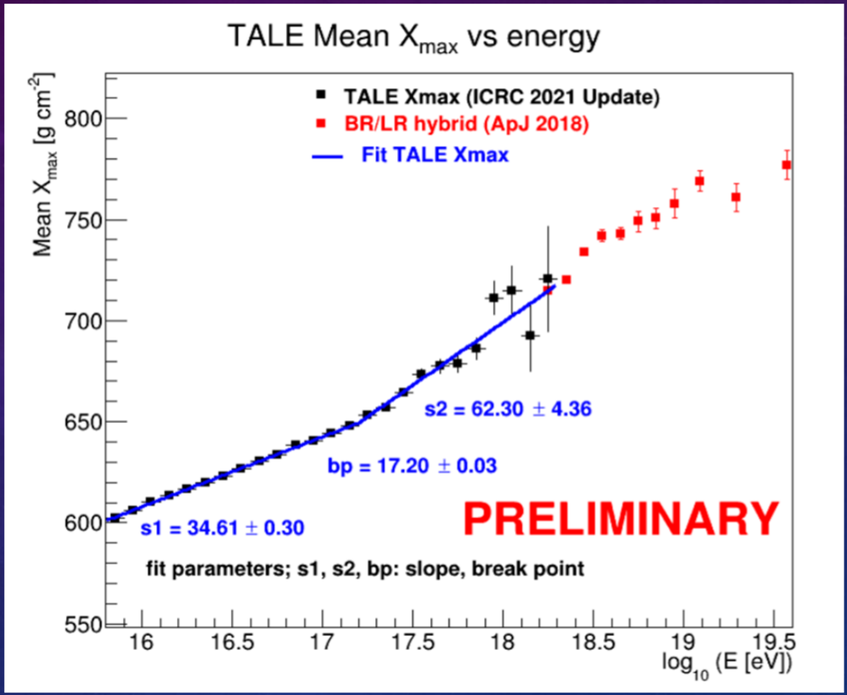
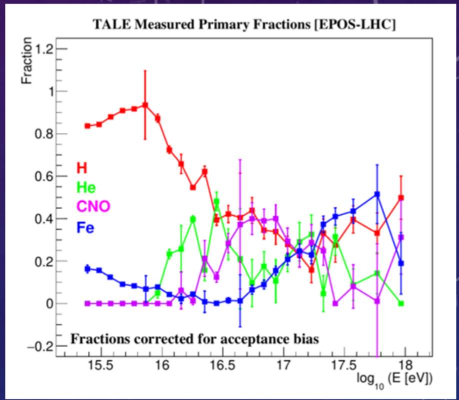


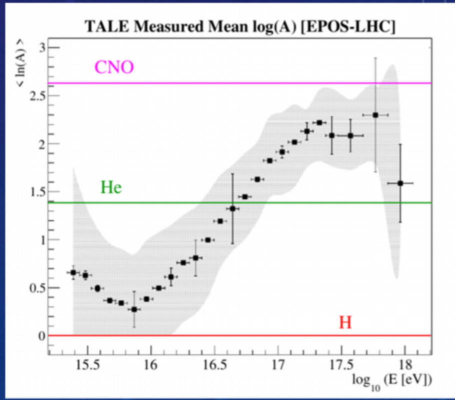
Figure 22. Bias corrected X_{max} using EPOS-LHC fit fractions and the unbiased EPOS-LHC MC prediction for the mean X_{max} of the four primary particles used in the analysis. These results include a first order correction to the detector acceptance bias.

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

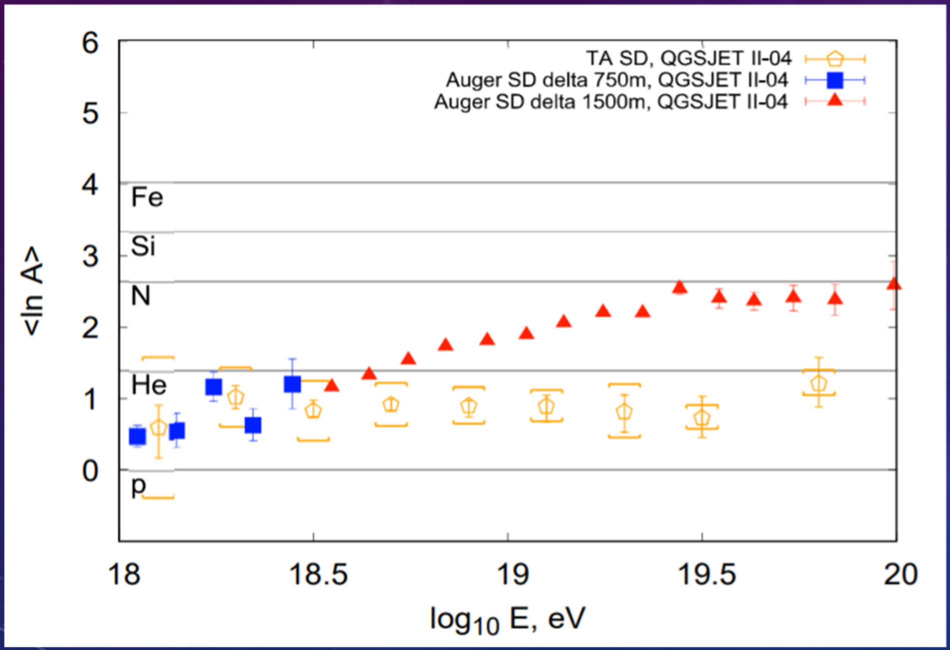


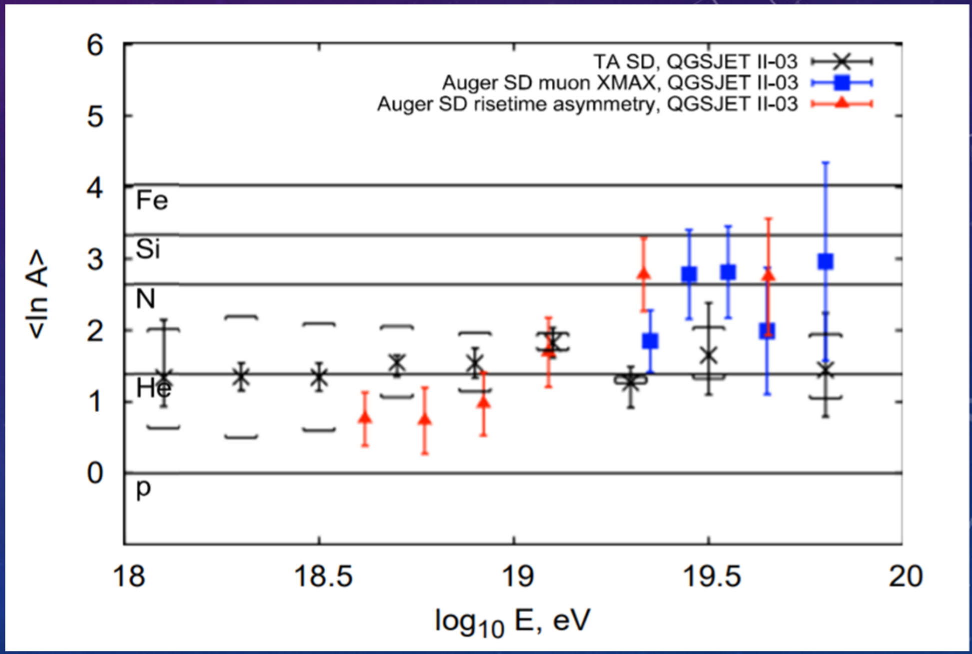




COMPOSITION

- 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





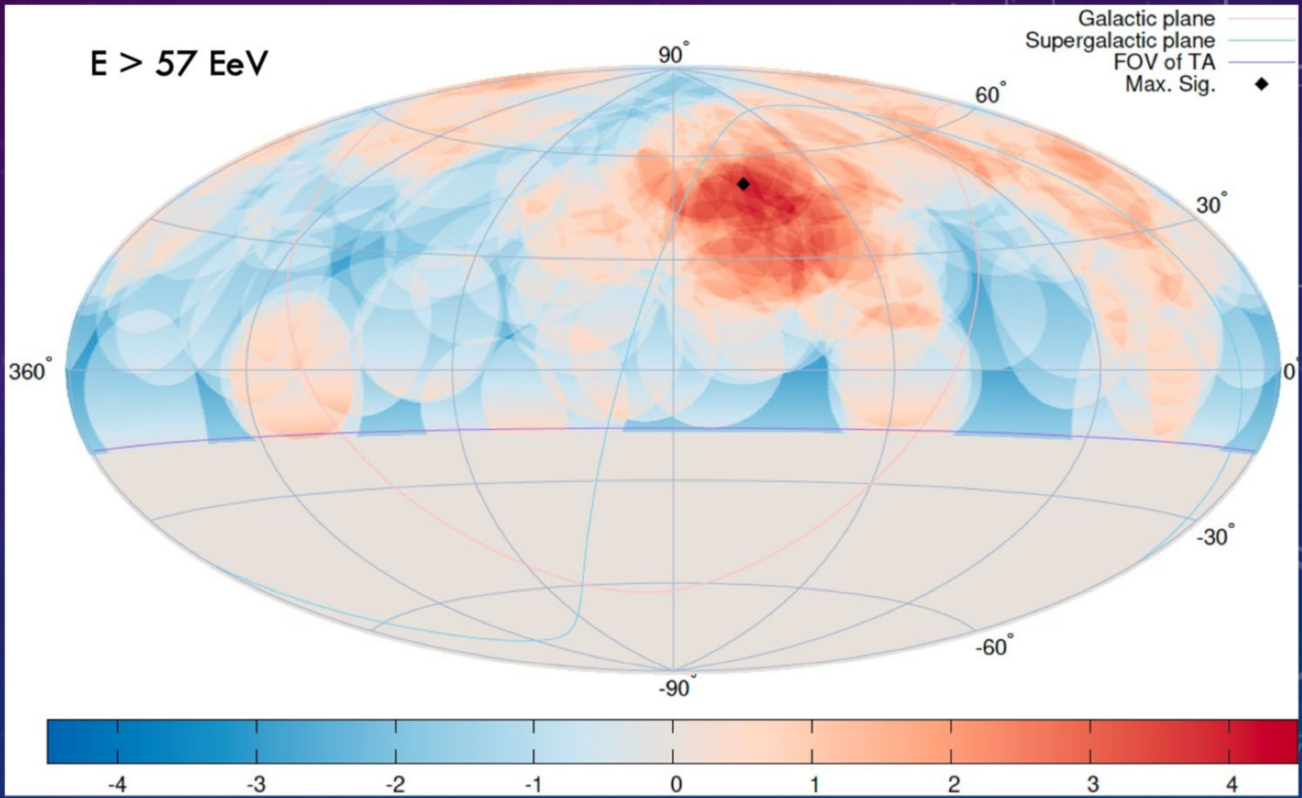
ANISOTROPY STUDY

14 September 2022

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

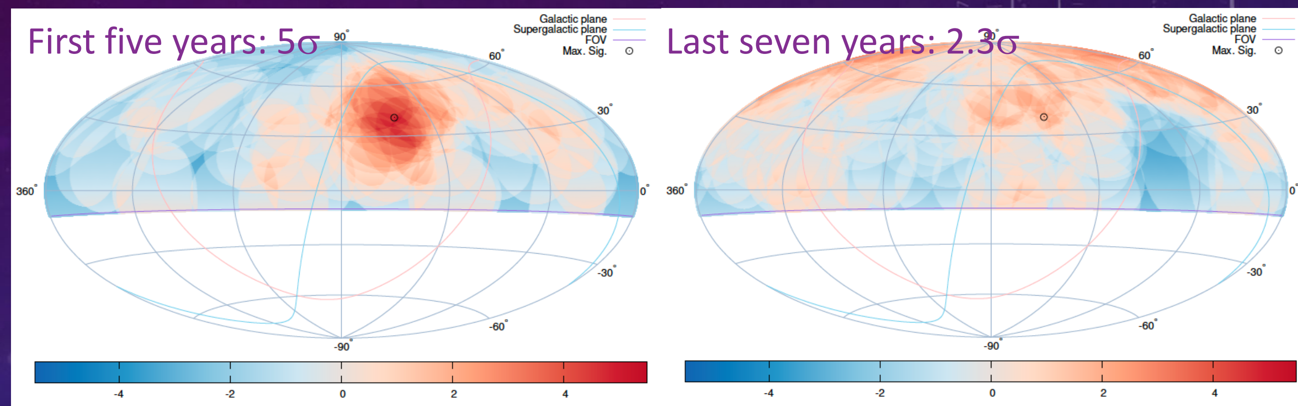
TA Hot Spot announced 2014 in data
E>57 EeV   (ApJ **790** (2014) L21)

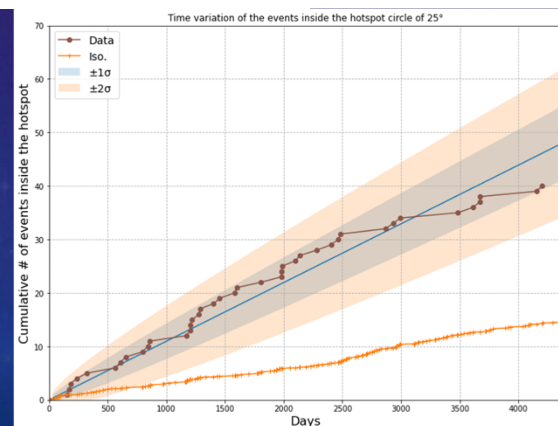
Now with 12 years of data

- 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

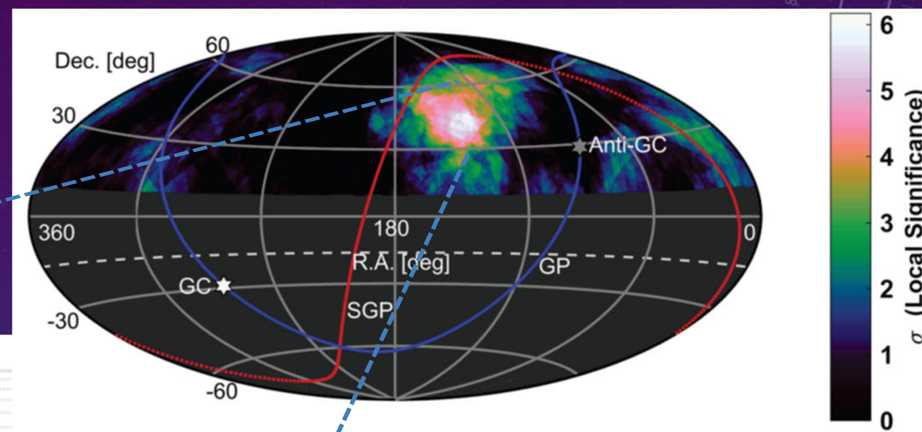


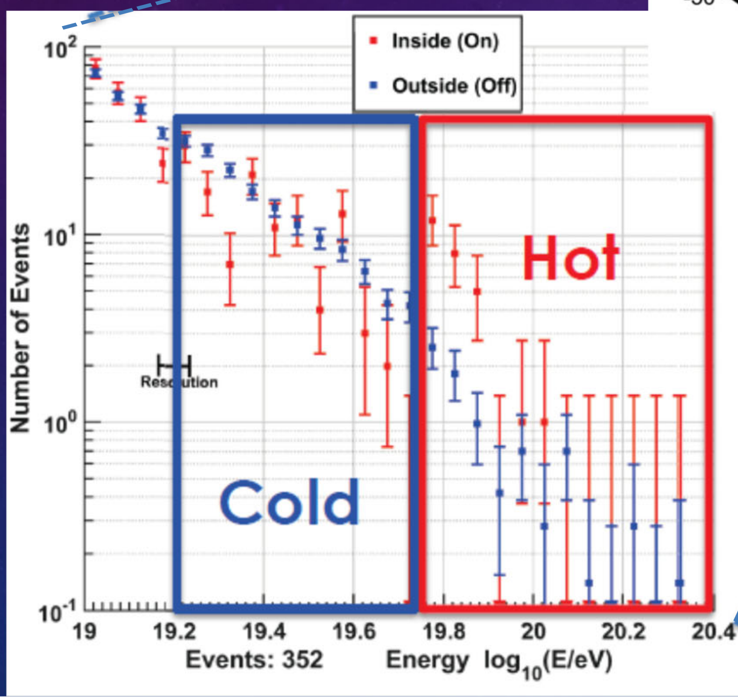


SPECTRAL ANISOTROPY AT HOTSPOT

Abbasi+2018, ApJ, 862, 91

Comparison between
the averaged spectrum and
the directional spectrum



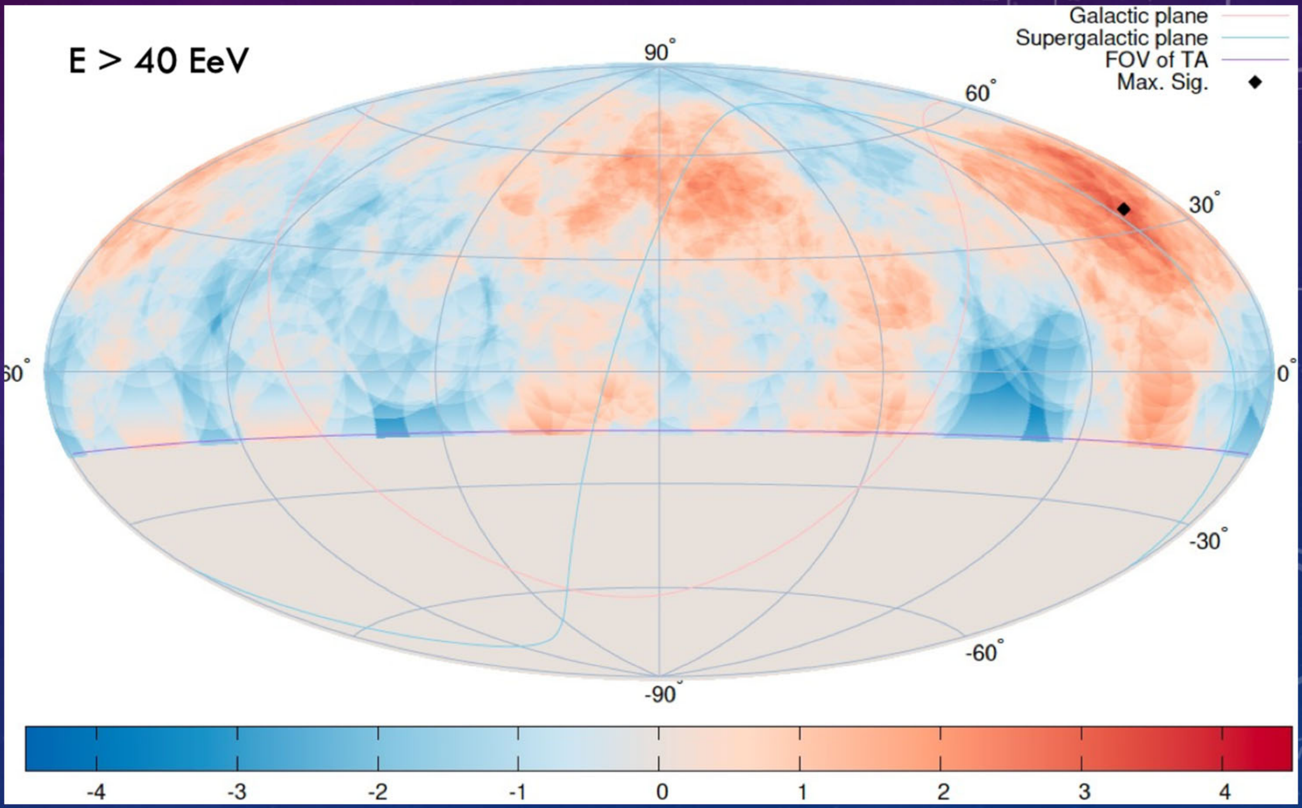


"cold spot" at lower energies,
same place as the hot spot at high

$>10^{19.2}$ eV
3.7σ post-trial significance

ANISOTROPY

At lower energies (above 40 EeV) see a new excess
- In the direction of the Perseus-Pisces Supercluster



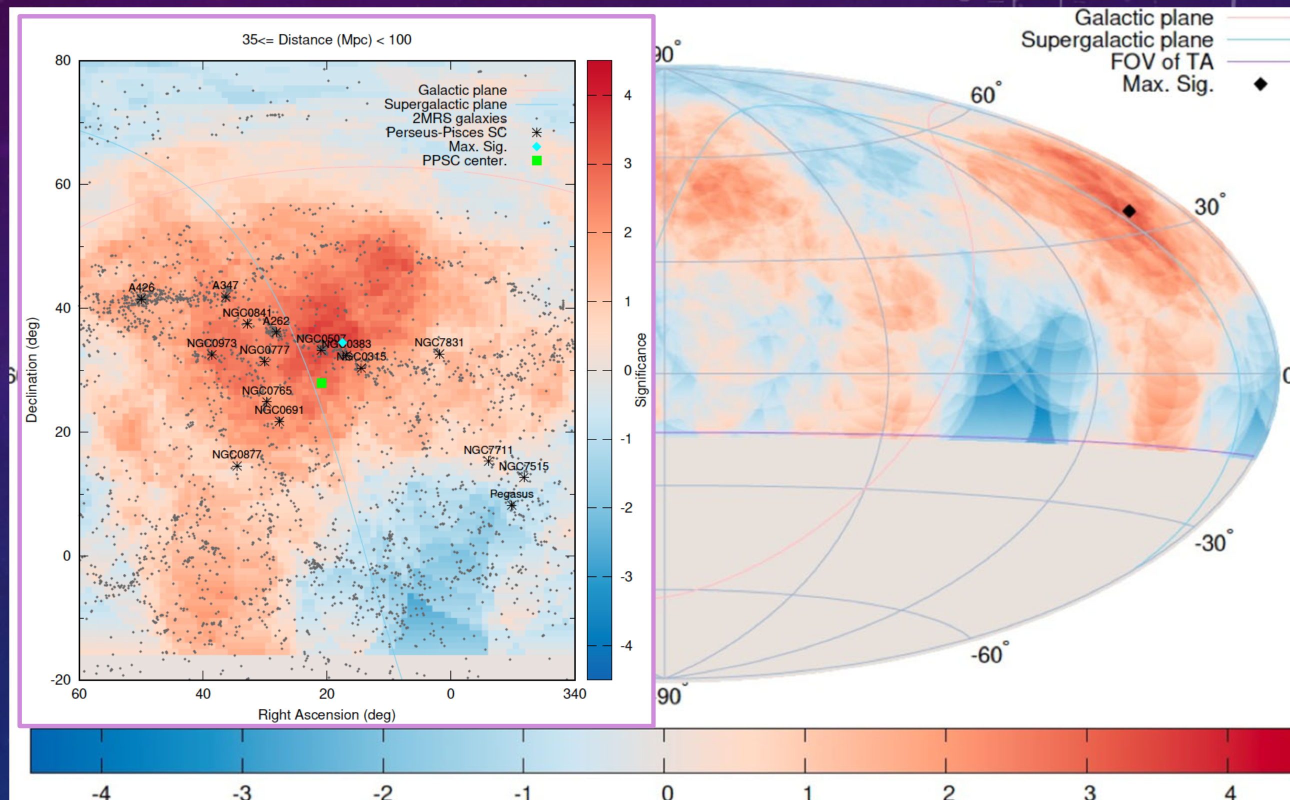
ANISOTROPY

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!!

ANISOTROPY

At energies above 8.8 EeV

- Look for dipole (a la Auger)
- TA 12-yr result :
  $r_\alpha \simeq 3.1\%; \phi_\alpha \simeq 134°$
- Auger 2017 result :
  $r_\alpha \simeq 4.7\%; \phi_\alpha \simeq 100°$