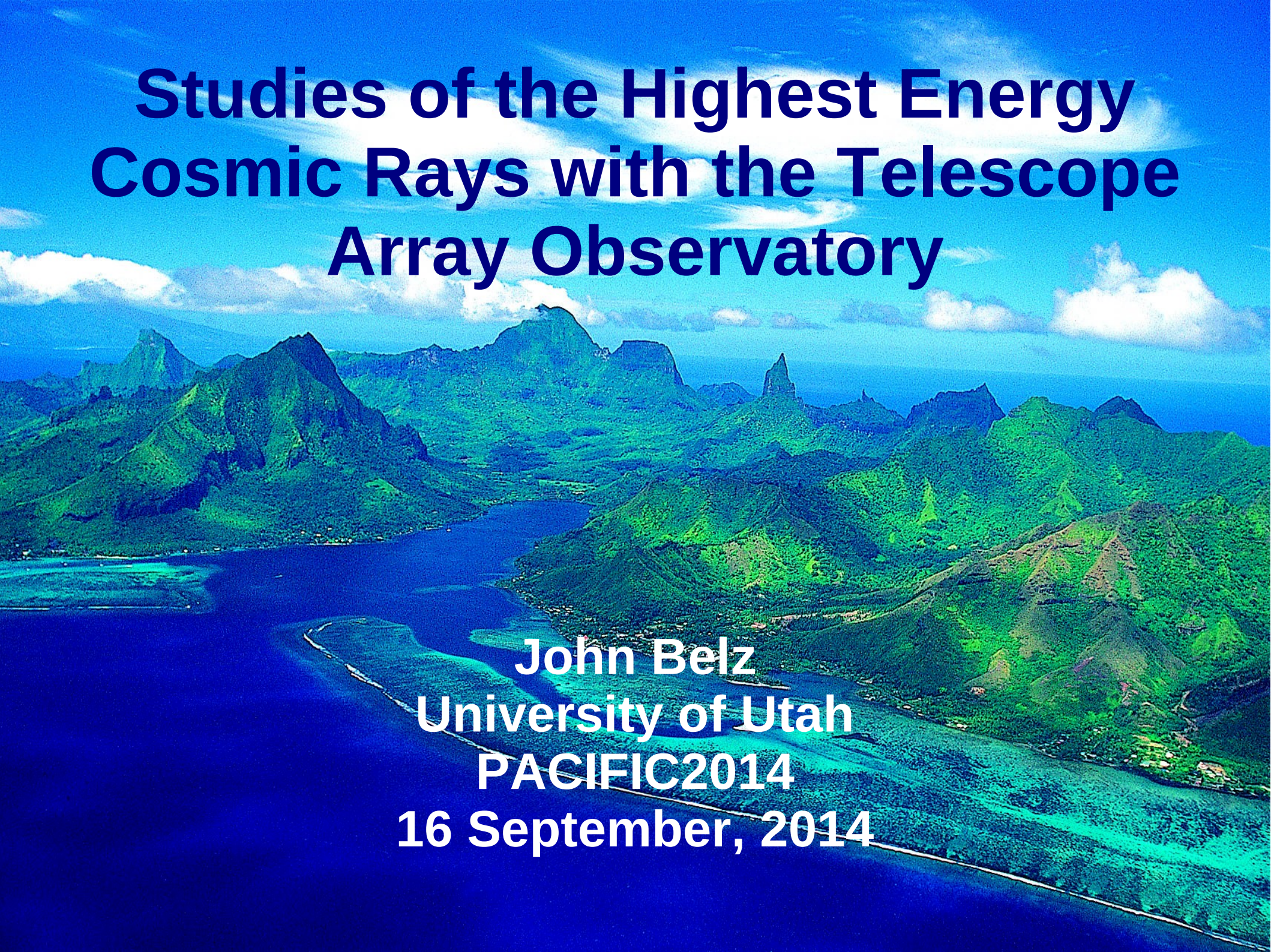

Studies of the Highest Energy Cosmic Rays with the Telescope Array Observatory

John Belz
University of Utah
PACIFIC2014
16 September, 2014

The Telescope Array Collaboration

RU Abbasi[a], M Abe[b], T Abu-Zayyad[a], M Allen[a], R Anderson[a], R Azuma[c], E Barcikowski[a], J.W. Belz[a], DR Bergman[a], SA Blake[a], R Cady[a], MJ Chae[d], BG Cheon[e], J Chiba[f], M Chikawa[g], WR Cho[h], T Fujii[i], M Fukushima[i,j], T Goto[k], W Hanlon[a], Y Hayashi[k], N Hayashida[l], K Hibino[l], K Honda[m], D Ikeda[i], N Inoue[b], T Ishii[m], R Ishimori[c], H Ito[n], D Ivanov[a], CCH Jui[a], K Kadota[o], F Kakimoto[c] , O Kalashev[p], K Kasahara[q], H Kawai[r], S Kawakami[k], S Kawana[b], S Kawata[i], E Kido[i], HB Kim[e], JH Kim[a], JH Kim[e], S Kitamura[c], Y Kitamura[c], V Kuzmin[p], YJ Kwon[h], J Lan[a], SI Lim[d], JP Lundquist[a], K Machida[m], K Martens[j], T Matsuda[s], T Matsuyama[k], JN Matthews[a], M Minamino[k], Y Mukai[m], I Myers[a], K Nagasawa[b], S Nagataki[n], T Nakamura[t], T Nonaka[i] , T Nozato[g] , S Ogio[k], J Ogura[c], M Ohnishi[i], H Ohoka[i], K Oki[i], T Okuda[u], M Ono[n], A Oshima[k], S Ozawa[q], IH Park[v], MS Pshirkov[w], DC Rodriguez[a], G Rubtsov[p], D Ryu[x], H Sagawa[i], N. Sakurai[k], AL Sampson[a], LM Scott[y], PD Shah[a], F Shibata[m], T Shibata[i], H Shimodaira[i], BK Shin[e], JD Smith[a], P Sokolsky[a], RW Springer[a], BT Stokes[a], SR Stratton[a,y], T Stroman[a], S Suzawa[b], Y Takamura[f], M Takeda[i], A. Taketa[z], M Takita[i], Y Tameda[l], H Tanaka[k], K Tanaka[aa], M Tanaka[s], SB Thomas[a], GB Thomson[a], P Tinyakov[p,w], I Tkachev[p], H Tokuno[c], T Tomida[ab], S Troitsky[p], Y Tsunesada[c], K Tsutsumi[c], Y Uchihori[ac], S Udo[l], F Urban[w], G Vasiloff[a], T Wong[a], R Yamane[k], H Yamaoka[s], K Yamazaki[k], J Yang[d], K Yashiro[f], Y Yoneda[k], S Yoshida[r], H Yoshii[ad], R Zollinger[a], Z Zundel[a]

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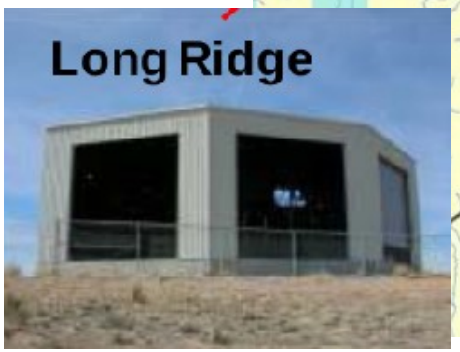
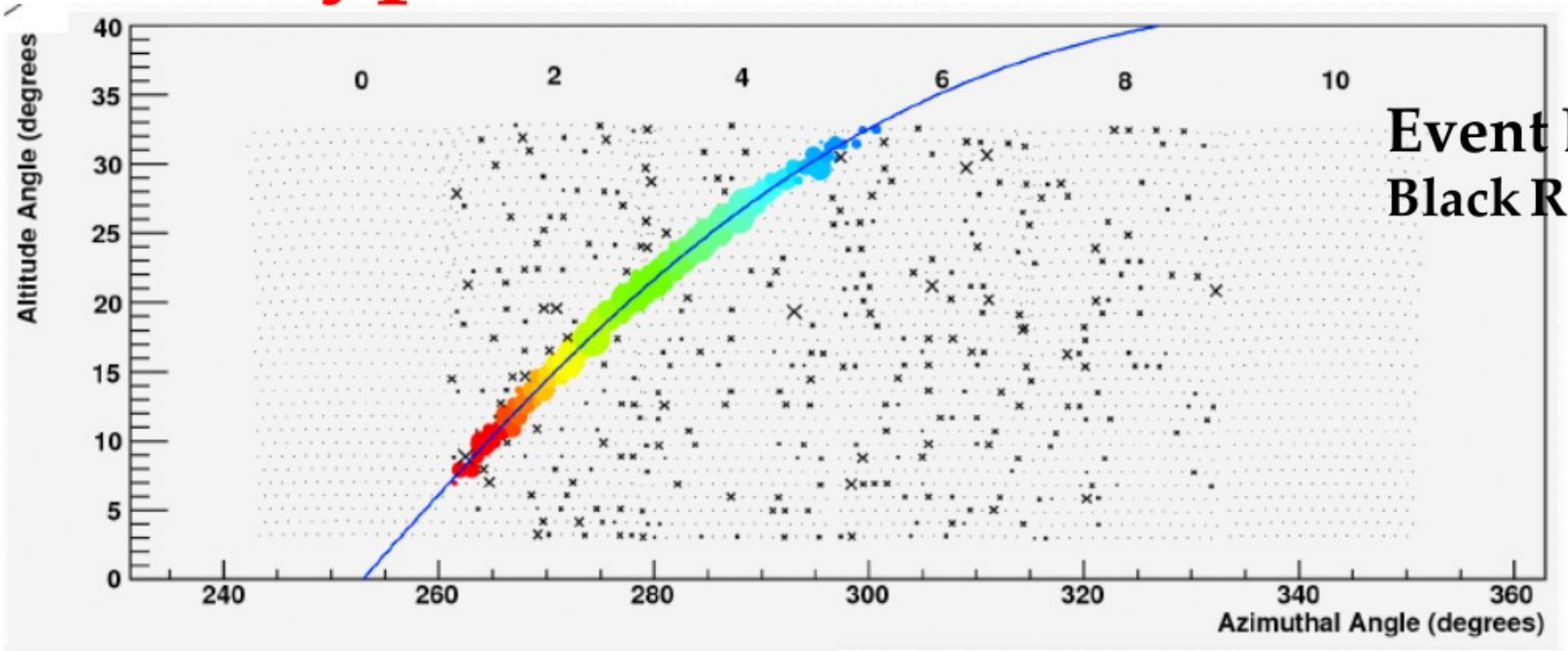
The TA Observatory

- **3 fluorescence detectors (FD's)**
  - **120° azimuth, 3°-31° elevation**
  - **Overlook SD array**
  - **Full shower reconstruction**
  - **10% duty cycle**

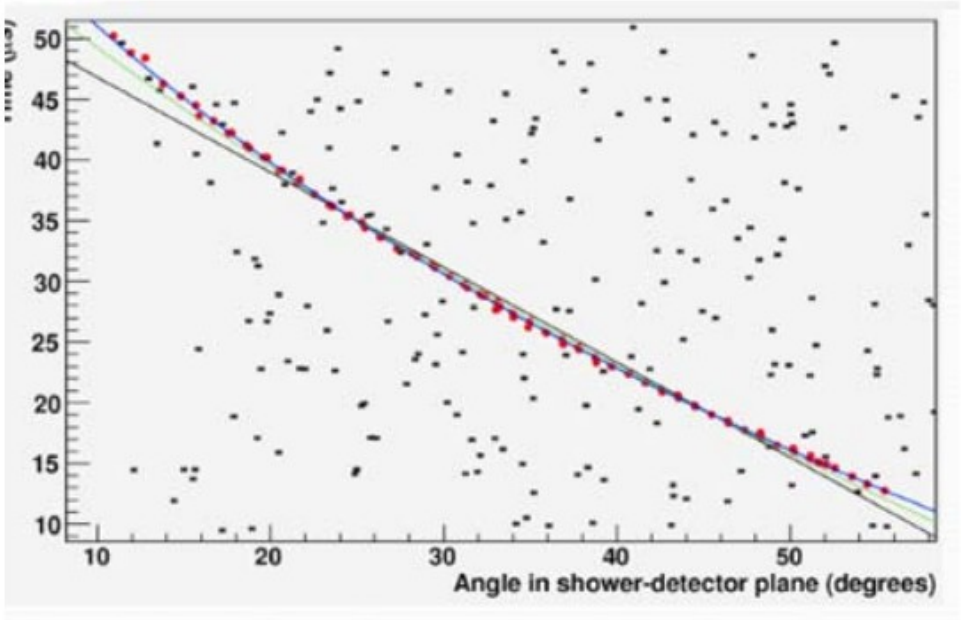


Middle Drum
Long Ridge
U.S. Highway 6 & 50
Hinckley
Delta
Black Rock Mesa
Telescope Array Locations
General Reference Map
N
0 3,000 6,000
Meters
Lakes
Town Boundaries
State Land
Private Land
BLM Land
Military Airspace: Sevier B
Department of Geography
University of Utah
April 2004

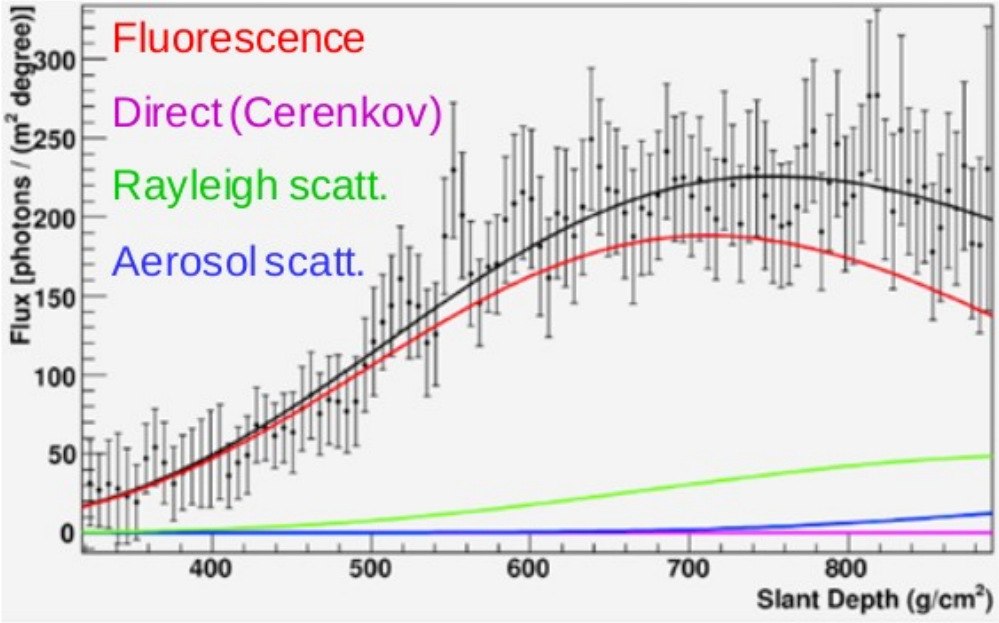
Typical Fluorescence Event



Event Display
Black Rock Mesa



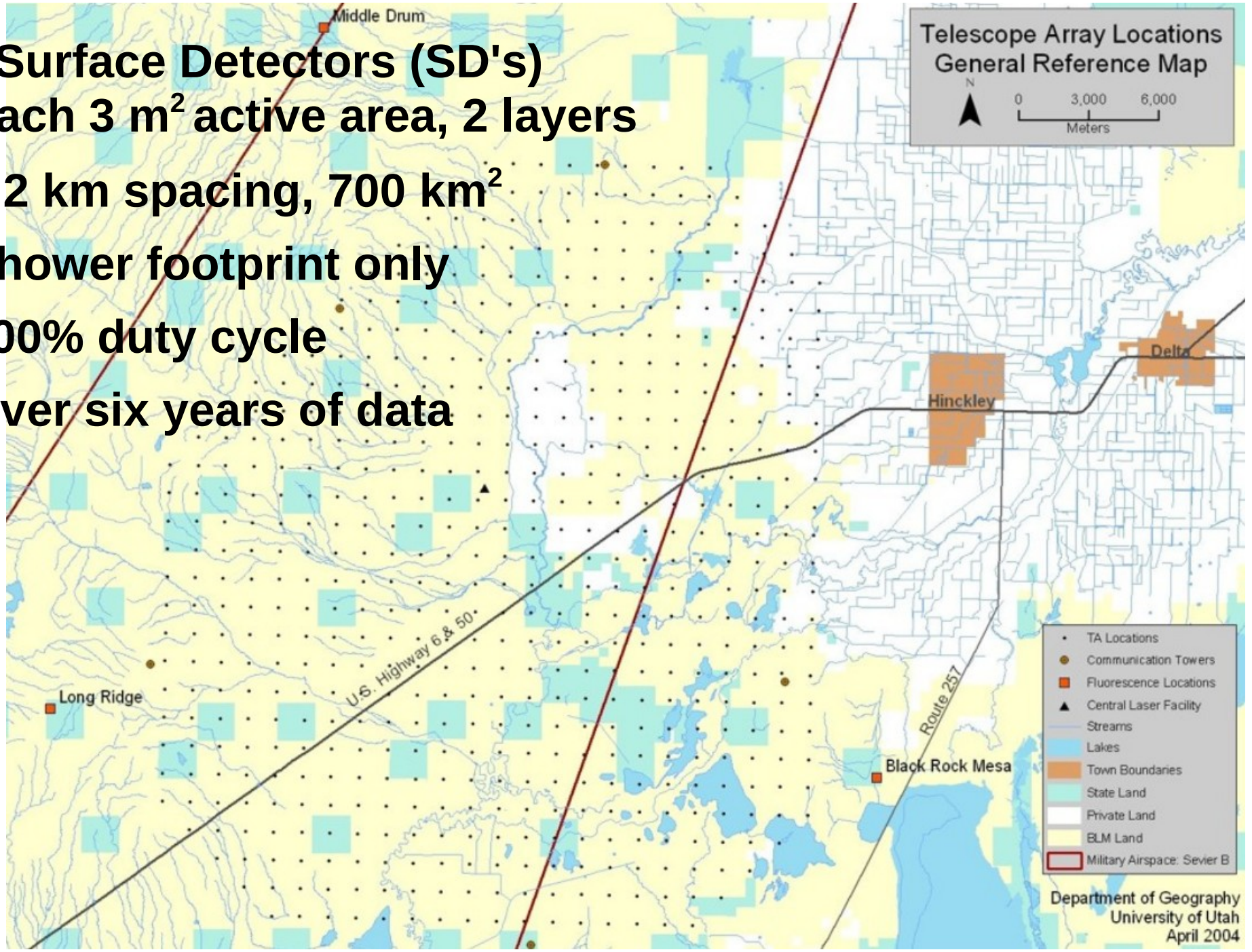
Monocular timing fit (time vs angle)



Reconstructed Shower Profile

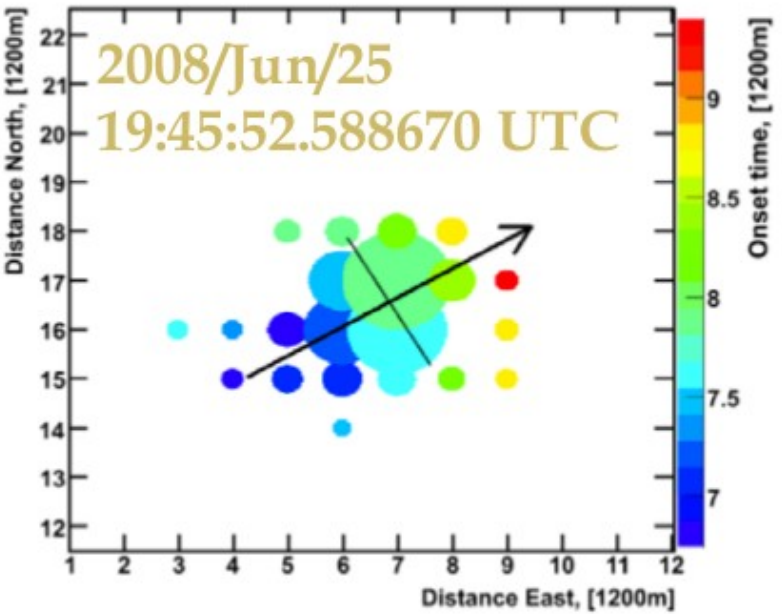
The TA Observatory

- **507 Surface Detectors (SD's)**
  - **Each 3 m^2 active area, 2 layers**
  - **1.2 km spacing, 700 km^2**
  - **Shower footprint only**
  - **100% duty cycle**
  - **Over six years of data**

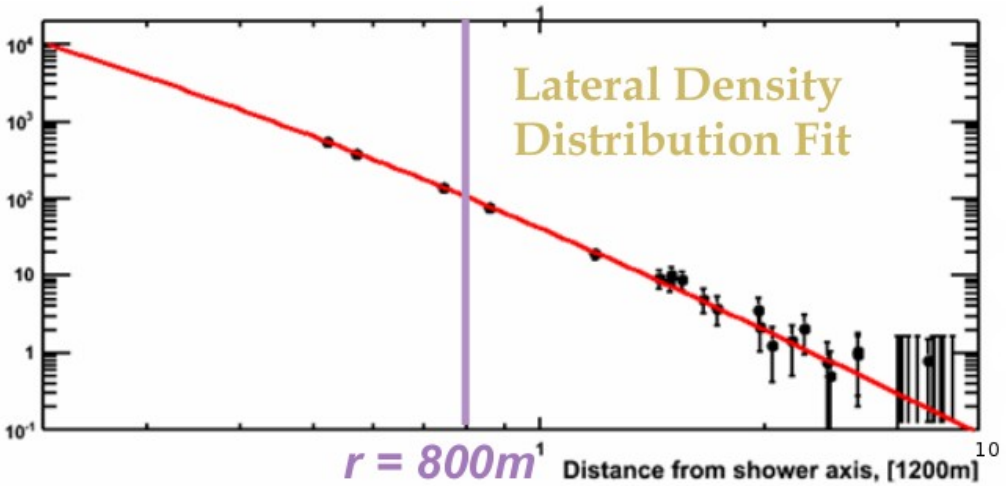


Surface Detector Reconstruction

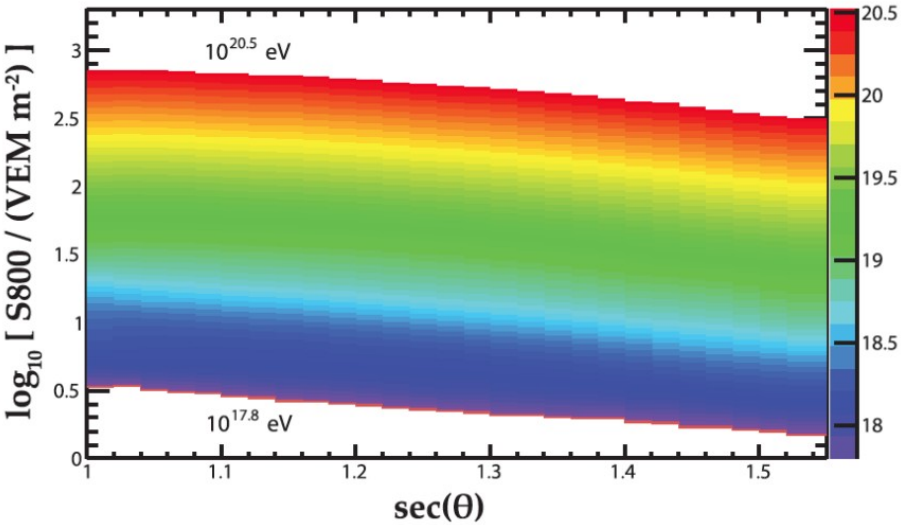
Individual SD



Shower Geometry from Timing



Determine flux 800 m from core



1st Energy Estimate from lookup table

UHE Cosmic Ray Spectrum

SD Data (6 Yrs: 20080511-20140511, 5400 km^2 str yr)

Broken Power Law Fit

$\gamma_1 = -3.298 \pm 0.029$

$\gamma_2 = -2.673 \pm 0.028$

Log(E_GZK/eV) = 19.74 +/- 0.038

$\gamma_3 = -4.539 \pm 0.441$

Significance of GZK Effect:

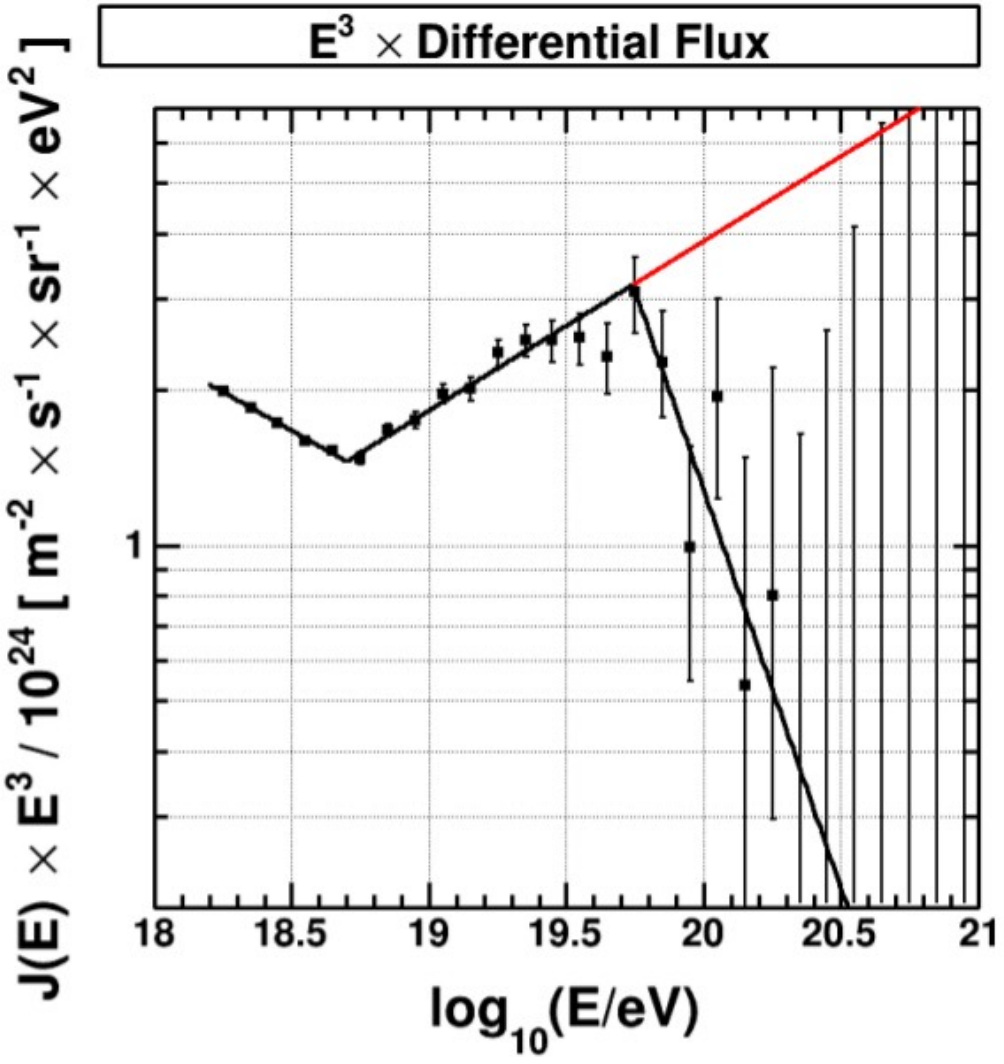
Integrate log10(E/eV) = 19.8 to 21.0

N_{exp} = 85.9 N_{obs} = 32

GZK $_{\text{Chance Prob}}$ = 2.248e-11 = 6.59σ

Berezinsky $E_{1/2}$:

Log(E/eV) = 19.73 +/- 0.042

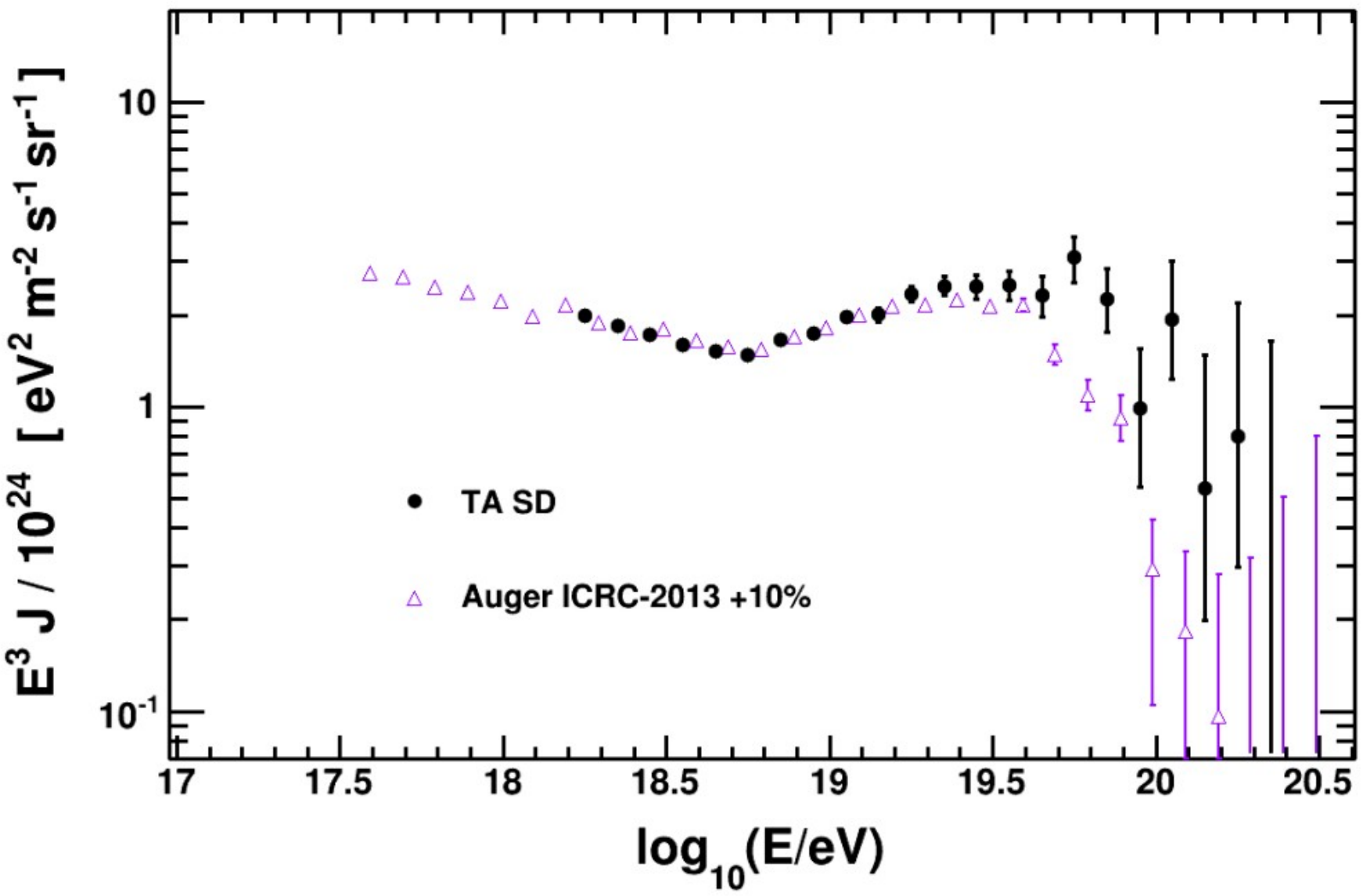


Break significance = 6.59σ

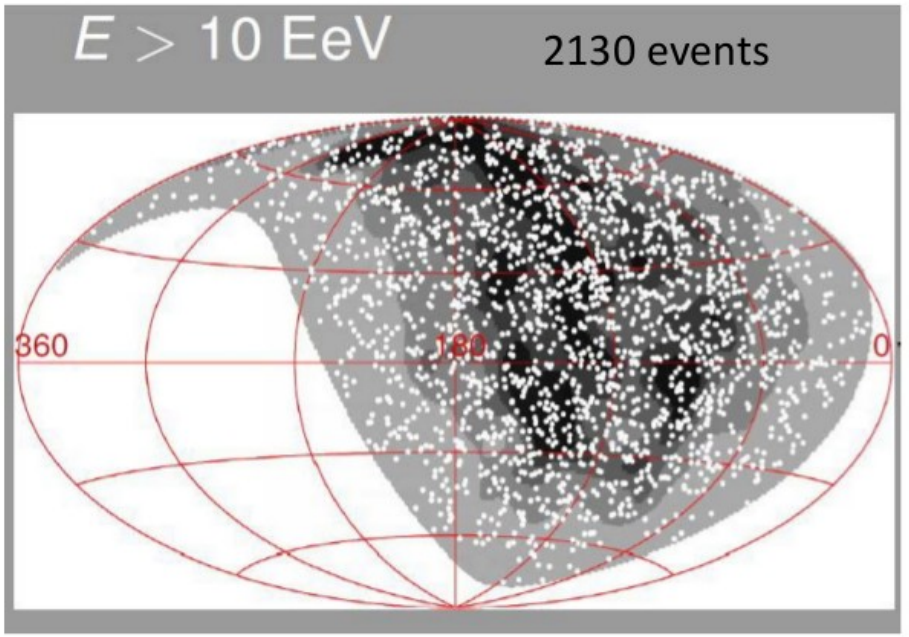
CR Spectrum

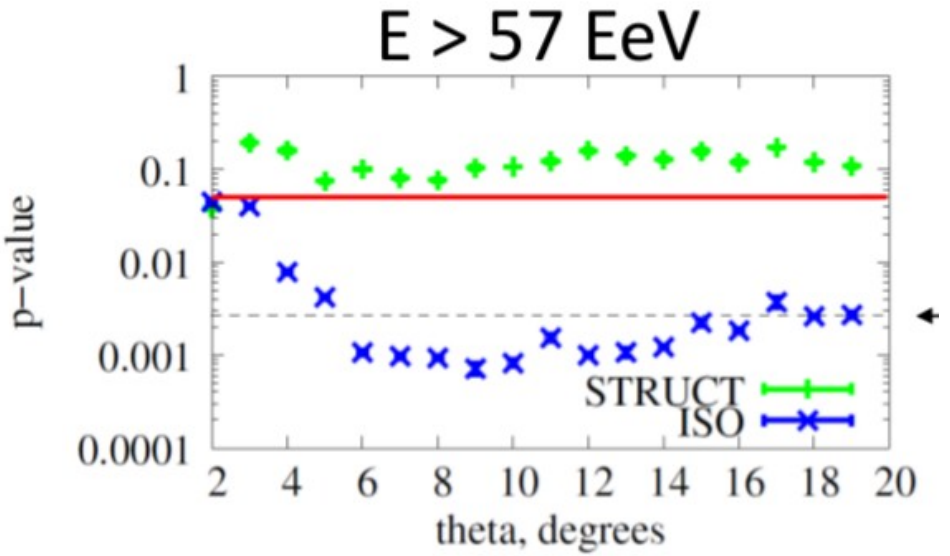
SD Data (6 Yrs: 20080511-20140511)

Comparison with Auger: ICRC 2013 + 10%

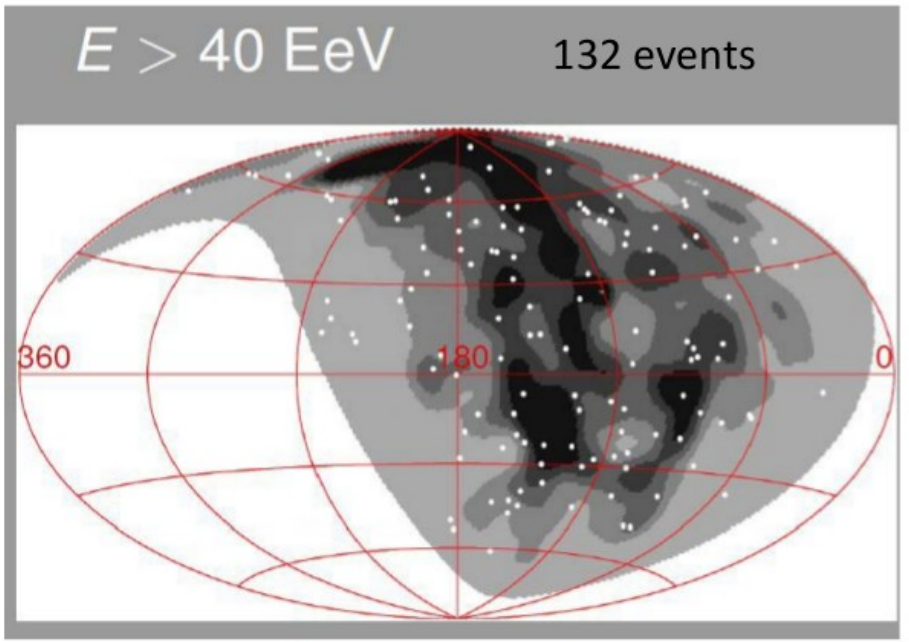


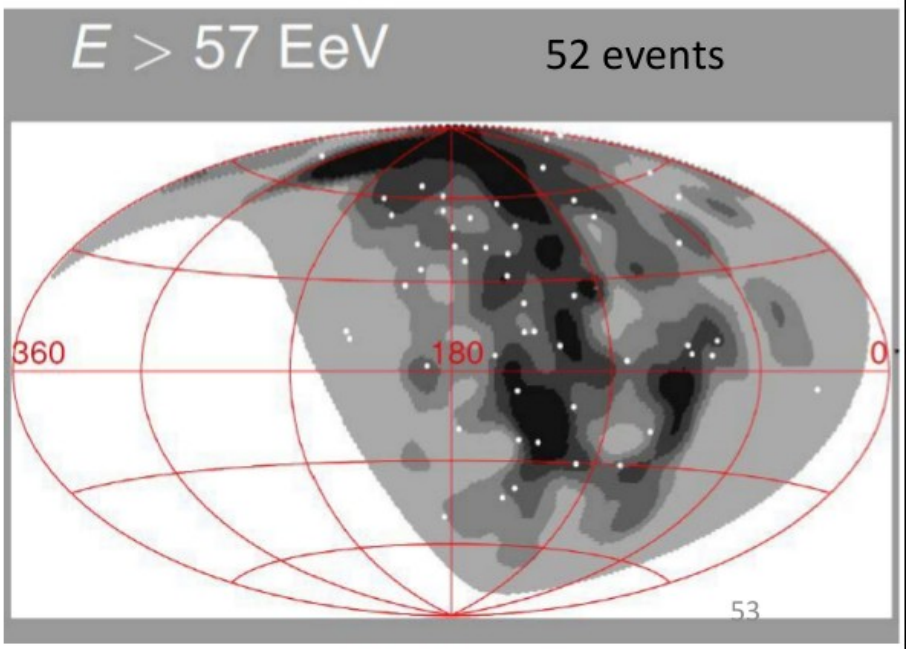
Search for Arrival Direction Anisotropy



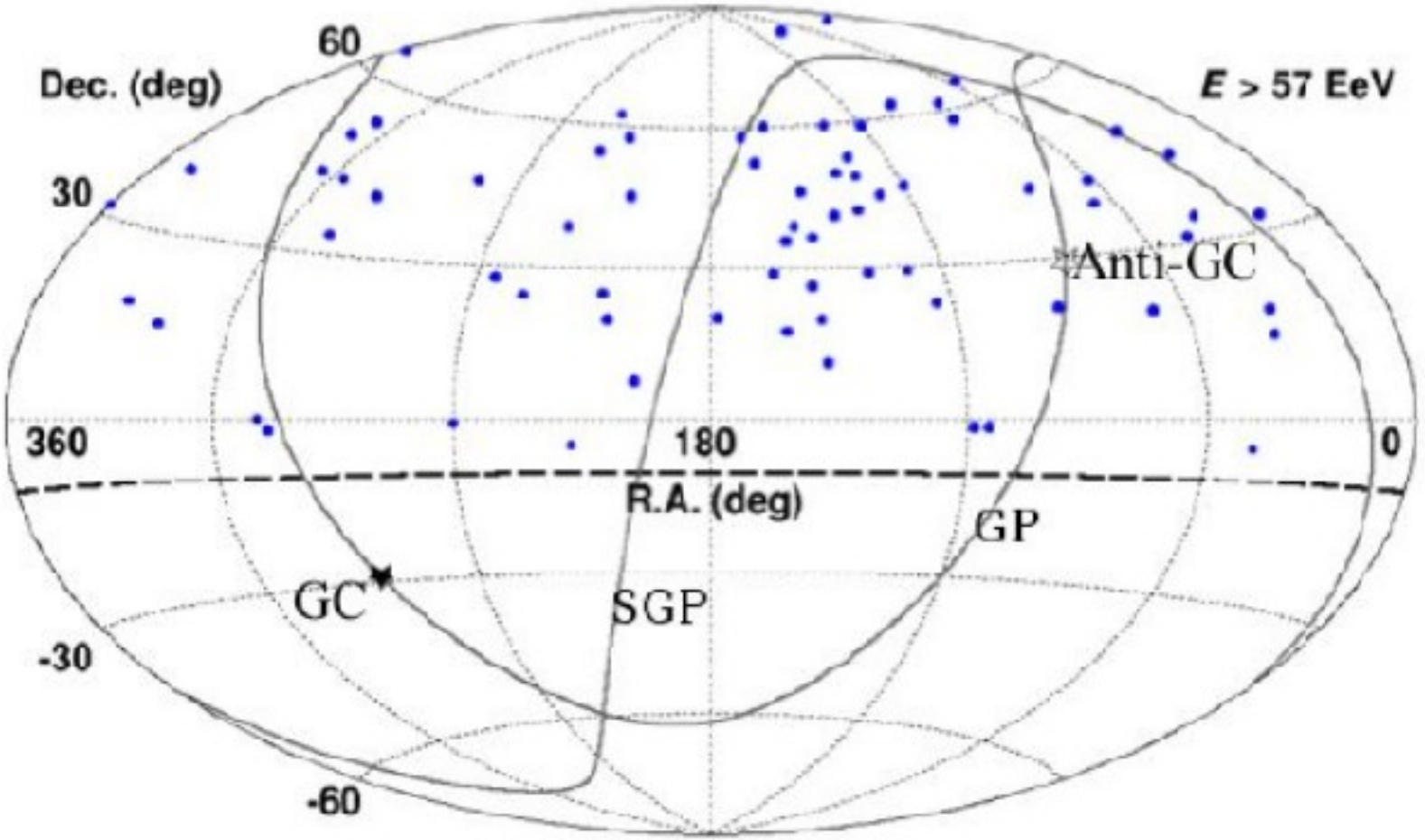


ApJ, 2013



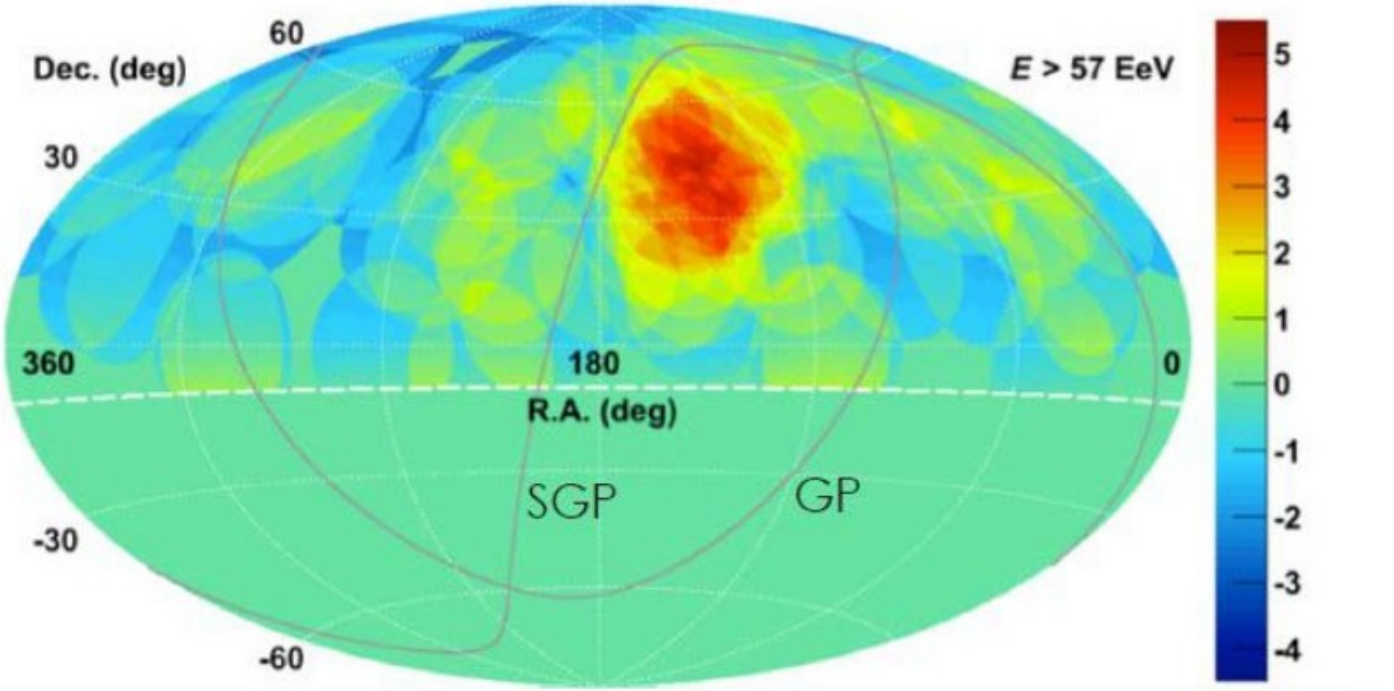


TASD 5-Year Skymap, E > 57 EeV



Hotspot

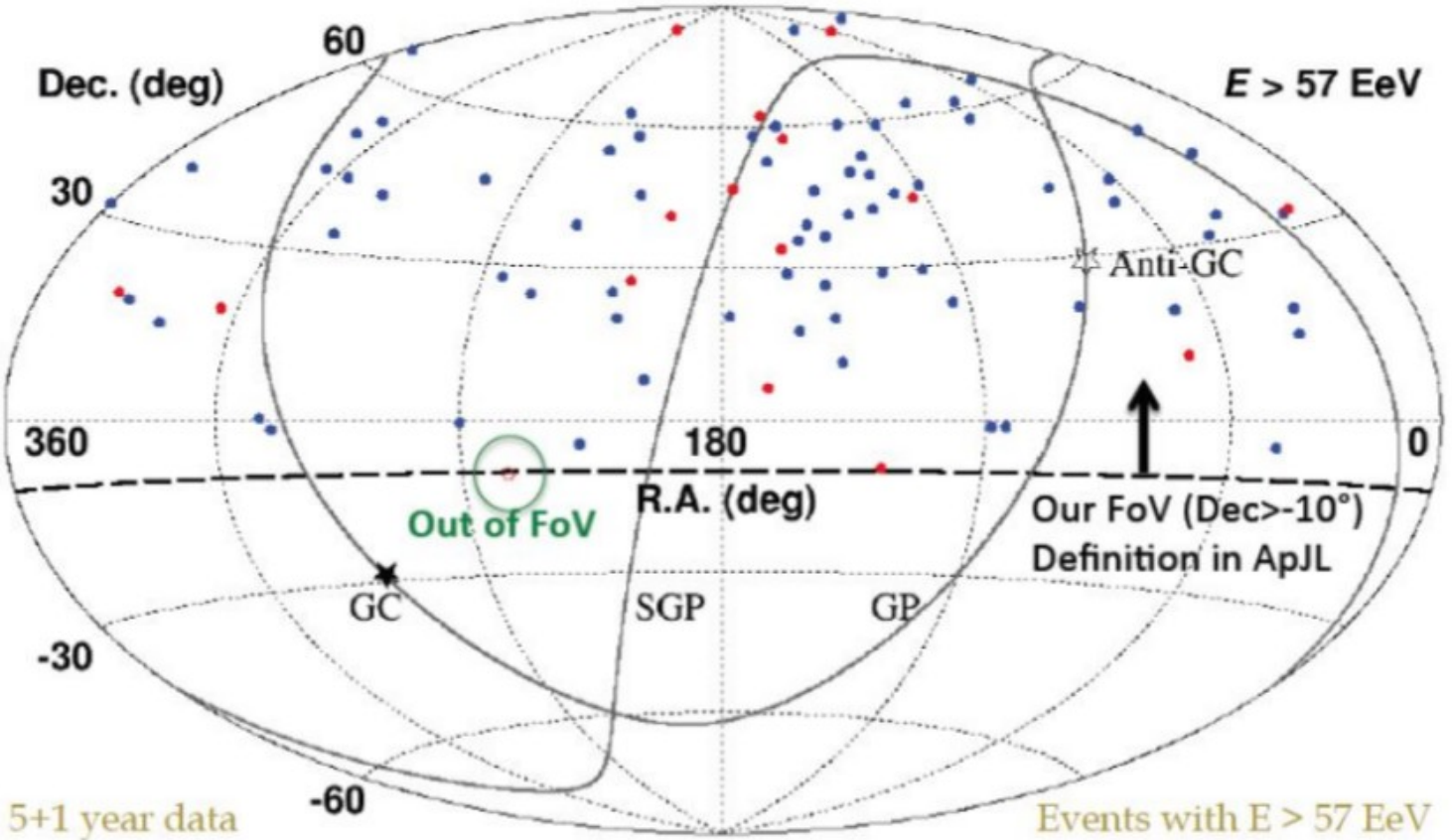
5-year data



- Over-sampling with 20° radius circle
- 19 events found at R.A.=146.7°, Dec. = 43.2° with isotropic BG of 4.5 events (5.1σ by Li-Ma)
- Chance probability from Isotropic sky is 3.7×10^{-4} (3.4 σ)

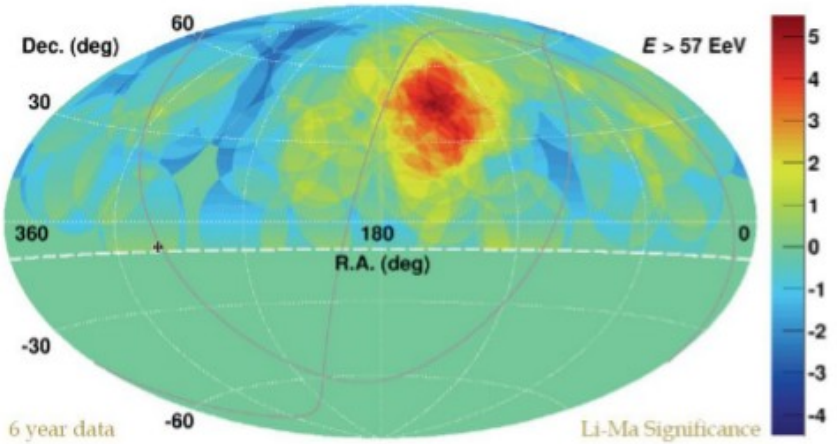
  i.e. we generated 100k sets of isotropic 72 events, analyzed the same way as data, and counted how often we have 5.1σ enhancement, anywhere in TA's FoV with any size of r=15, 20,… 35°.

ApJ:790:L21(2014),
arXiv:1404:5890



+1 year

in red



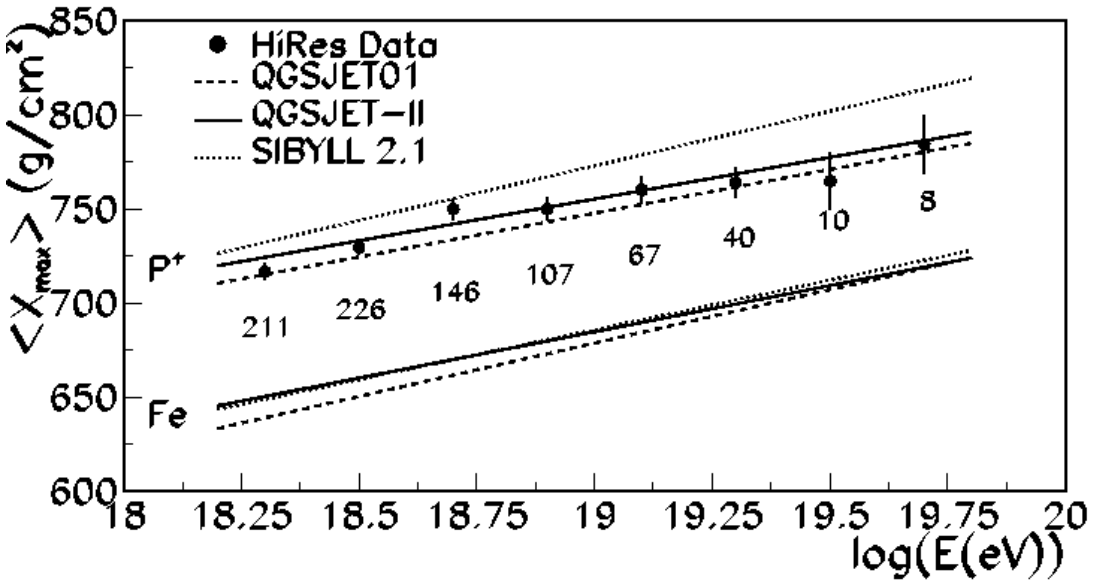
- 6th year: 15 further events, 4 in hotspot.
- Li-Ma significance = 5.5 σ
- Chance probability = 4.3 σ

  (4.0 σ with r-scan)
- **Take-home message:**

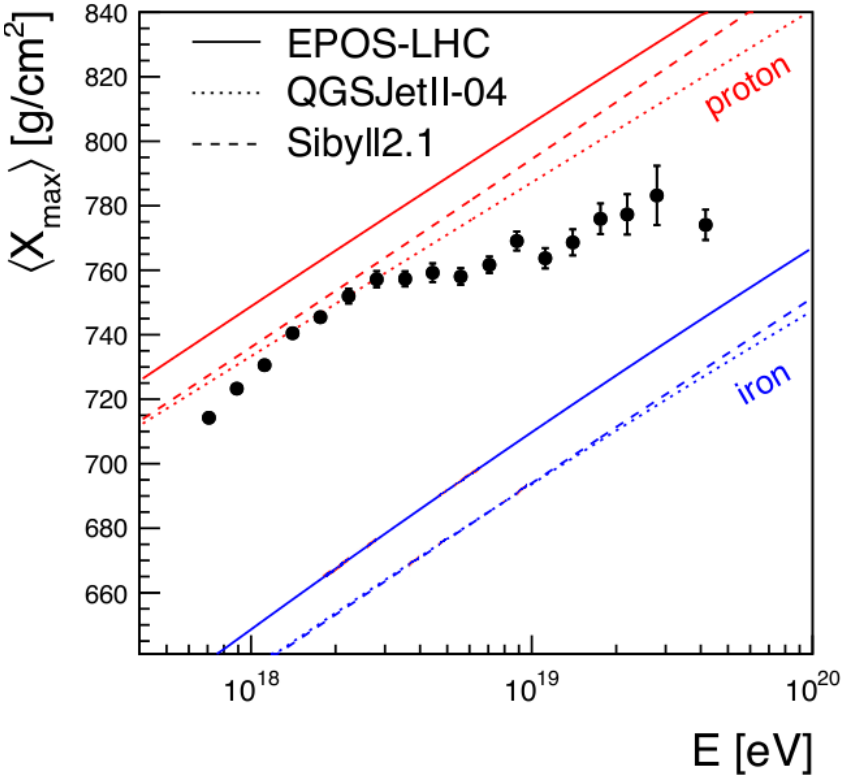
  3½ σ ➔ just over 4 σ

G.Thomson, ECRS 2014

UHECR Composition via Depth of Shower Maximum X_{max}



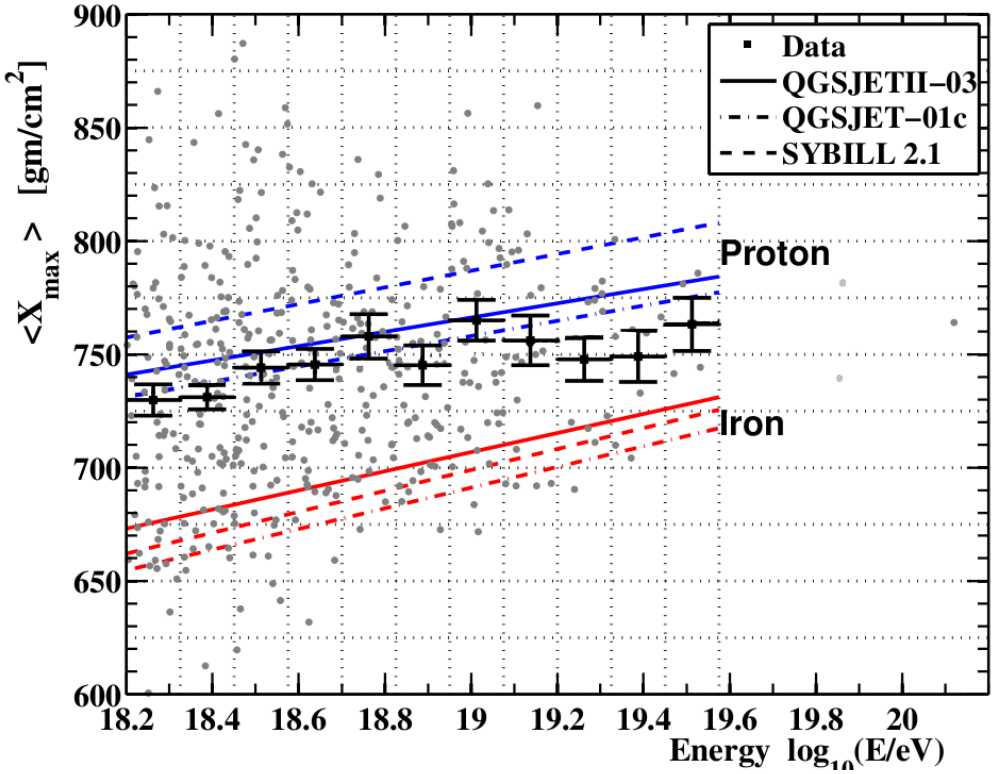
HiRes stereo, PRL 104 (2010)

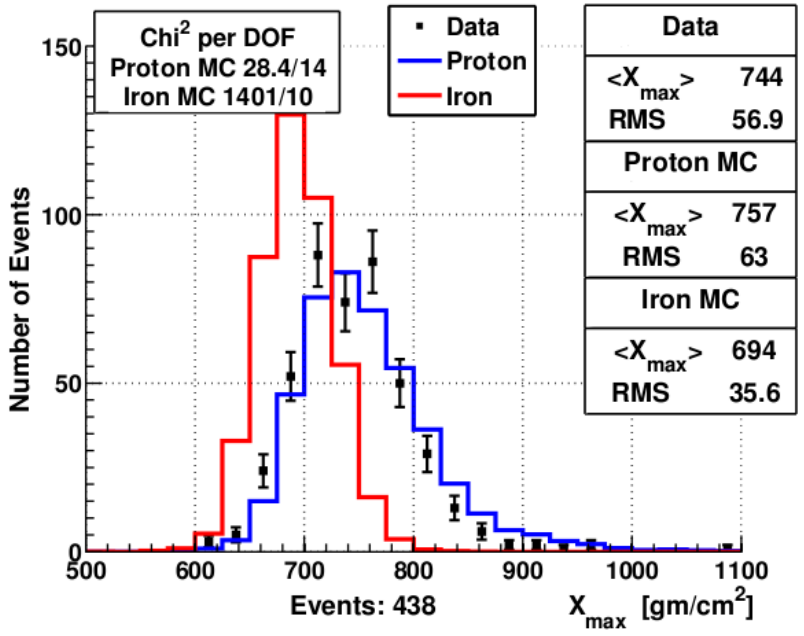


PAO hybrid, 2013 ICRC

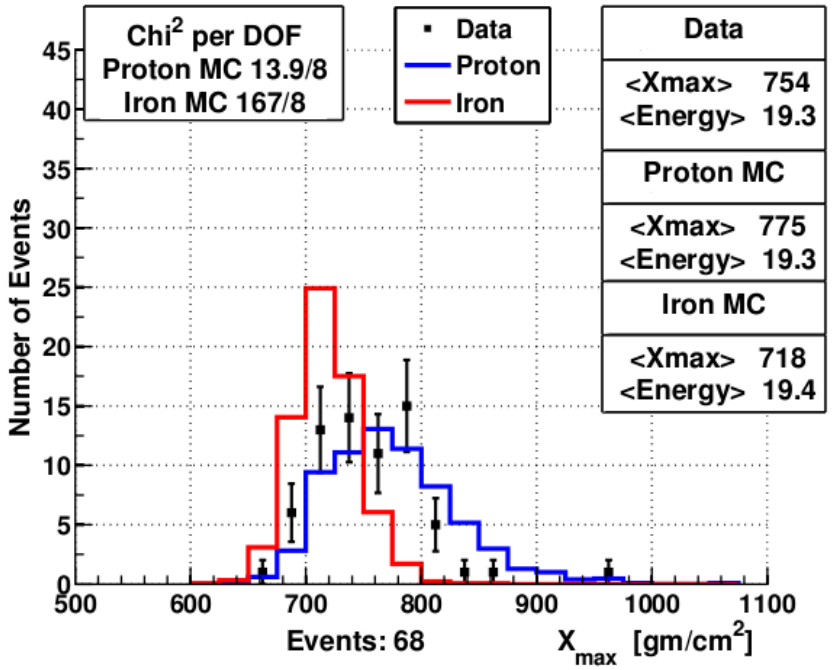
Hybrid Composition

- Middle Drum (ref HiRes) fluorescence detector, in *hybrid* mode.
- Light composition
- Paper in review, *APP*





$\log_{10}$ E(eV) > 18.2



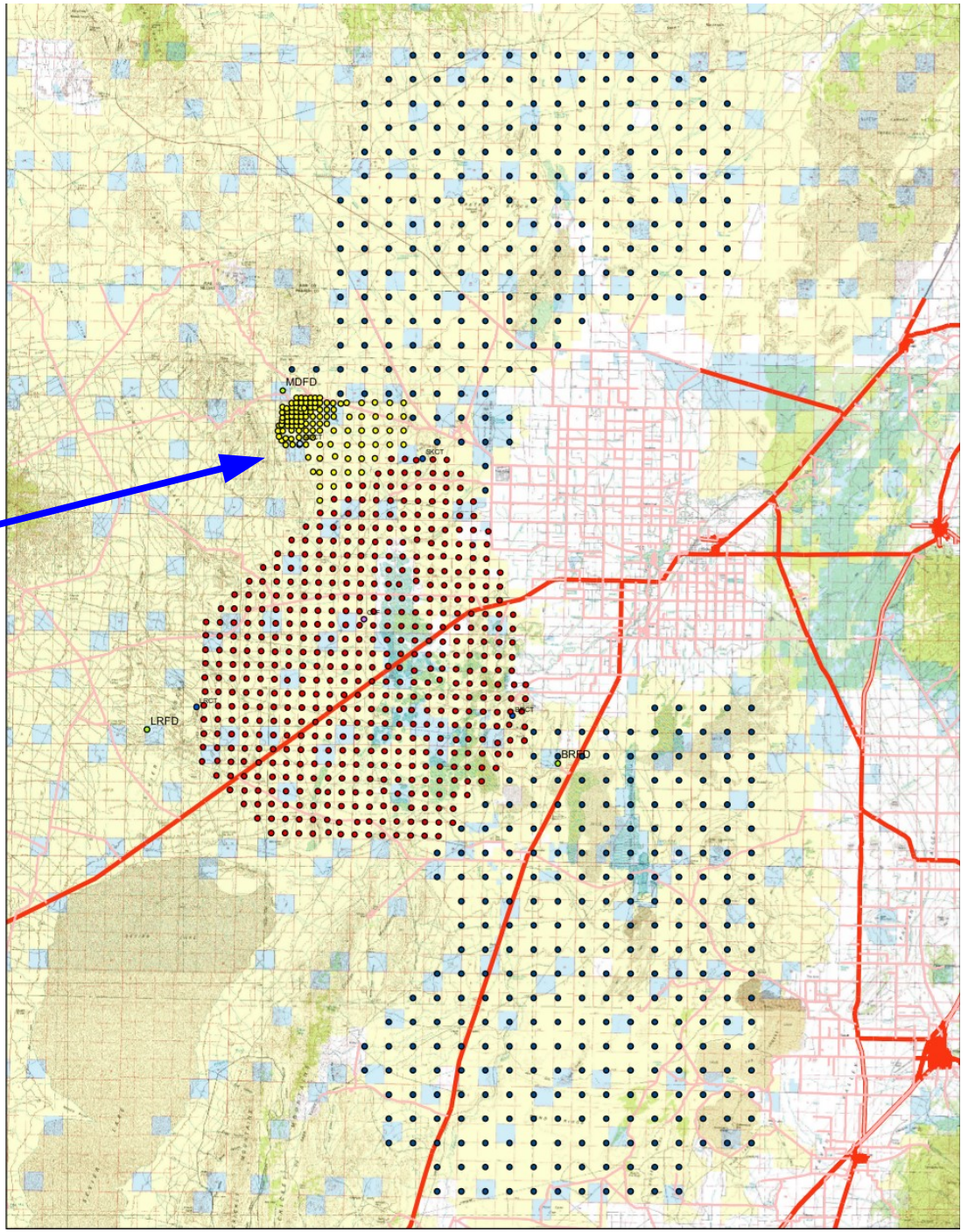
$\log_{10}$ E(eV) > 19.0

Upgrades and Affiliated Experiments

- TALE – Low-Energy Extension
- NICHE – Non-Imaging Cherenkov Array
- TA × 4 – Anisotropy engine to map the hotspot
- Electron Light Source
- TARA – EAS detection by bistatic radar
- TA/LMA – Novel use for a cosmic ray detector

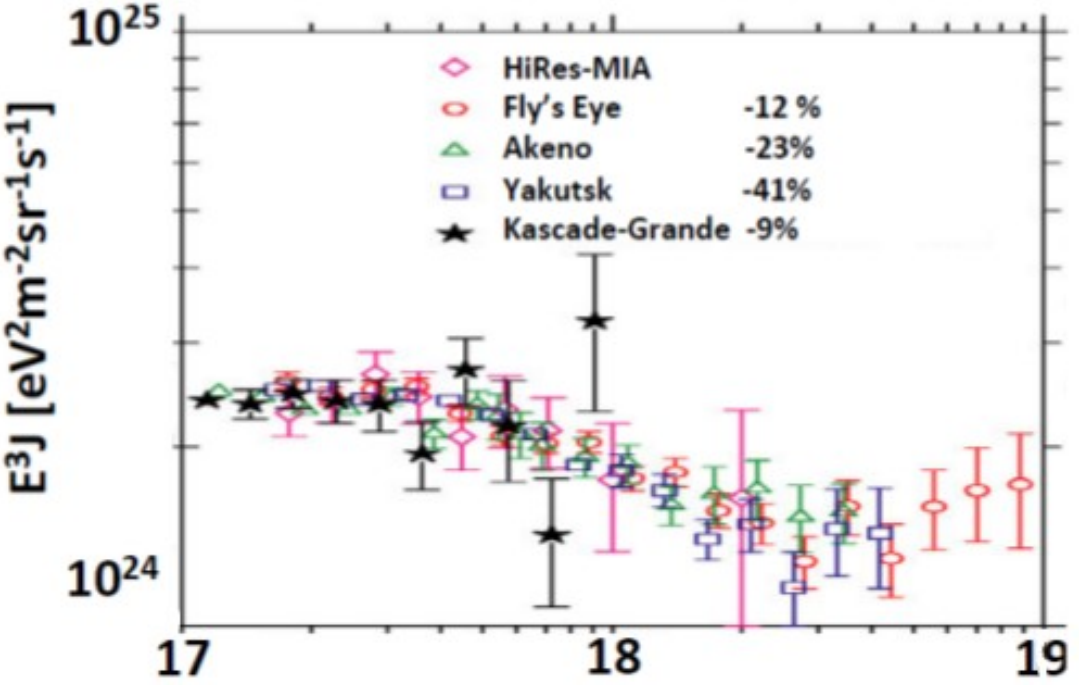
TA Upgrades

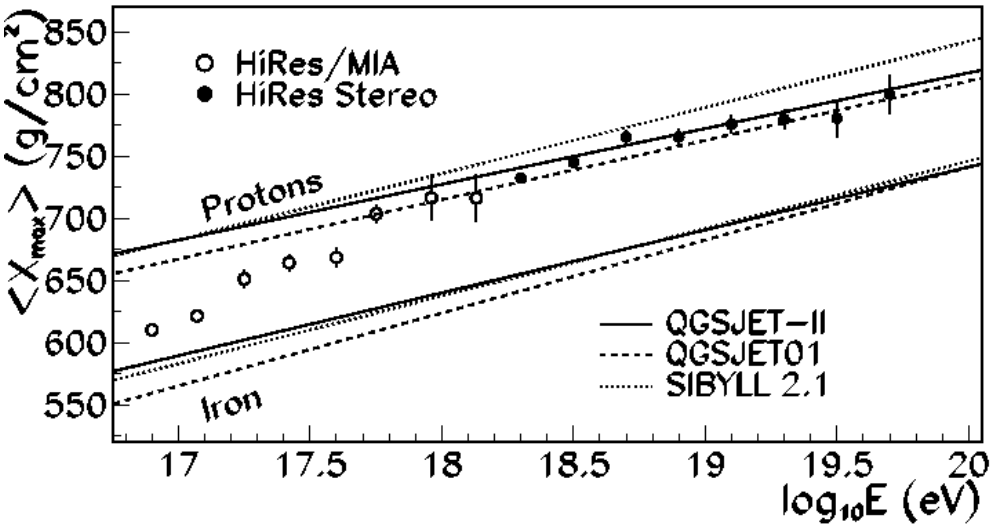
- Low-energy extension; TALE
- NICHE



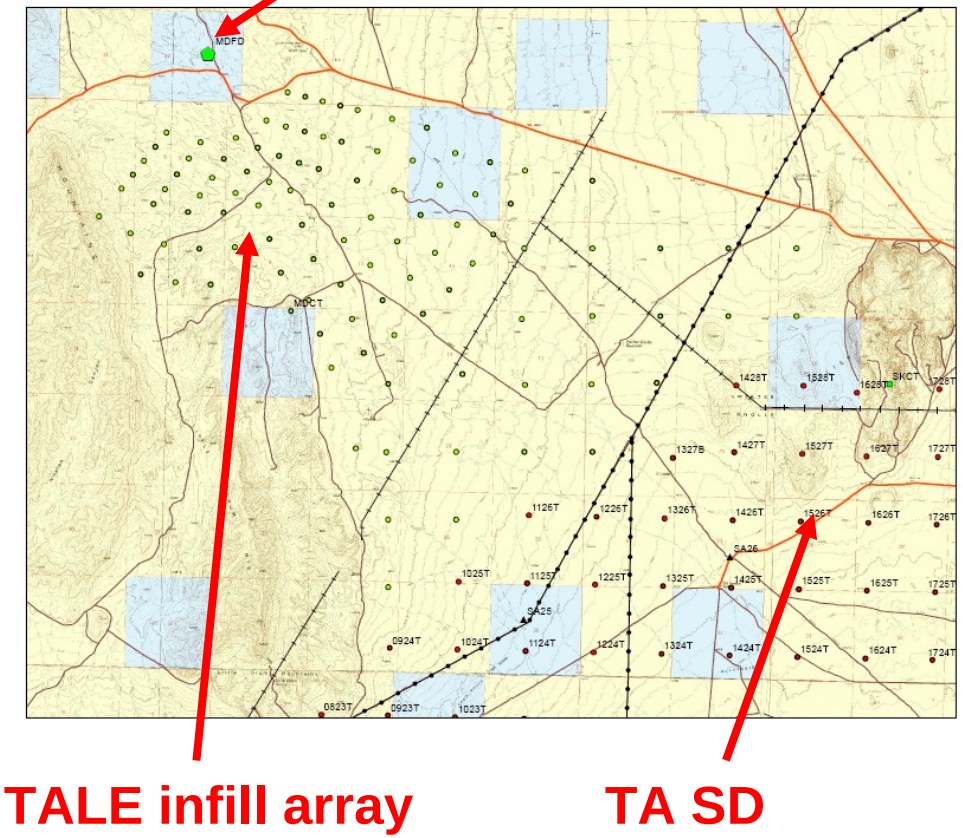
TA Low Energy Extension (TALE)

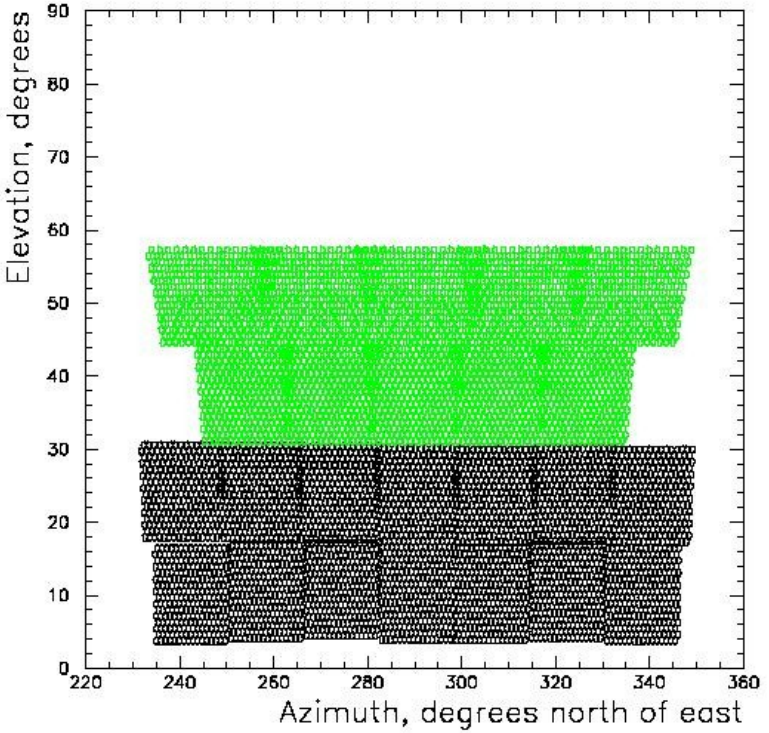
- Study 10^{16} and 10^{17} eV decades in hybrid
- Astrophysics
  - End of “knee”
  - Second knee
  - Galactic-Extragalactic Transition
- High-energy physics: Cross-section measurements overlapping LHC





TALE Detectors are being deployed.

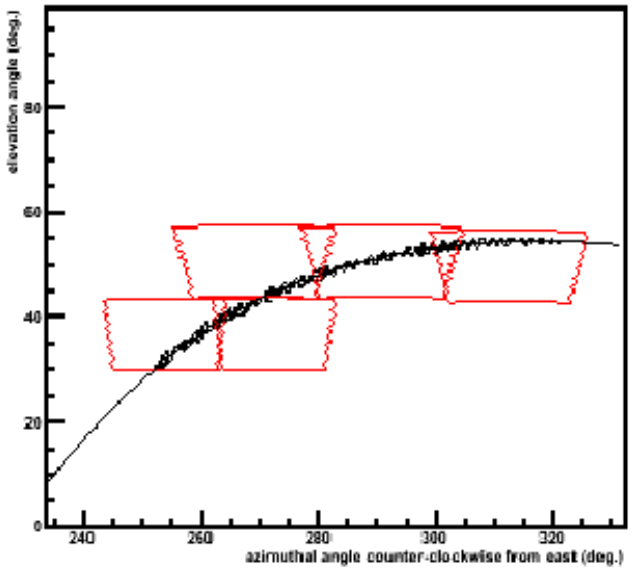


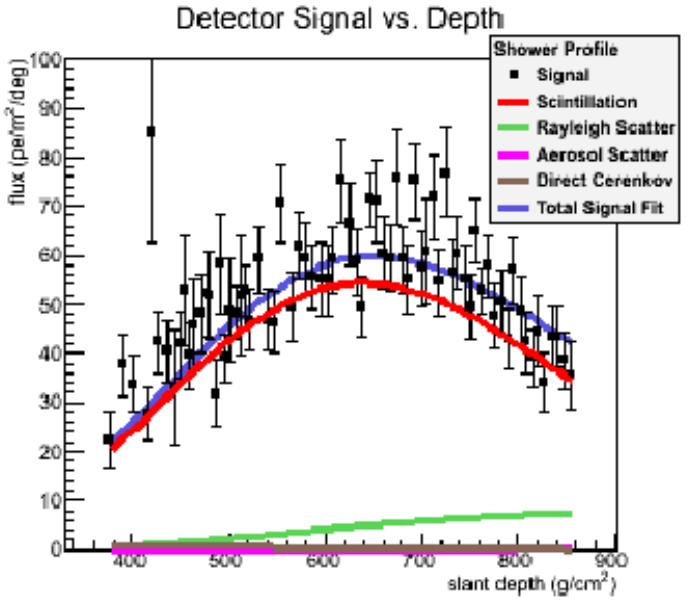


TALE mirrors

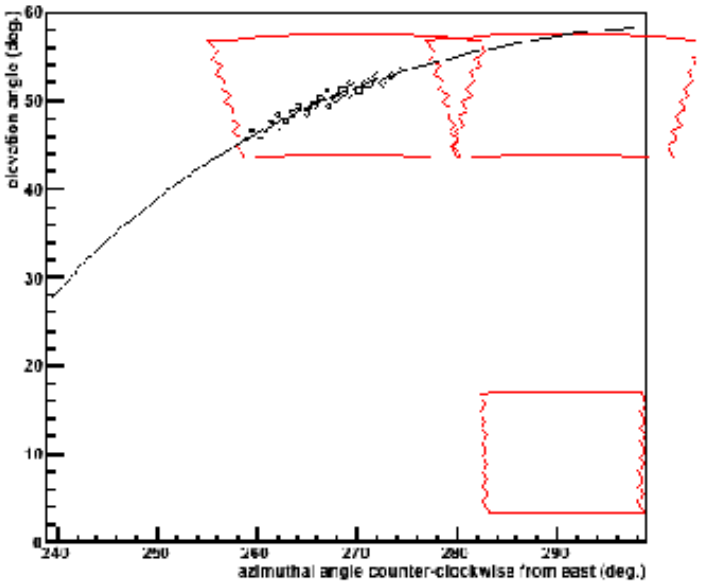
TA mirrors

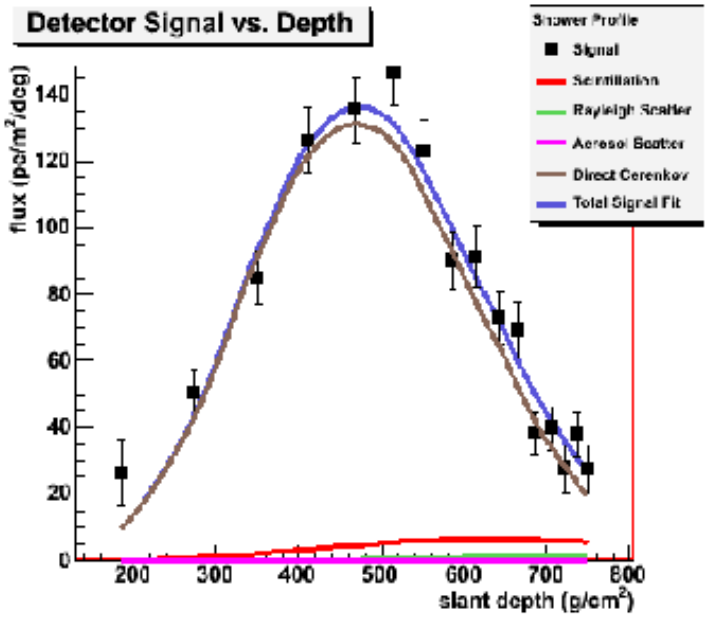
TALE: Cherenkov Events





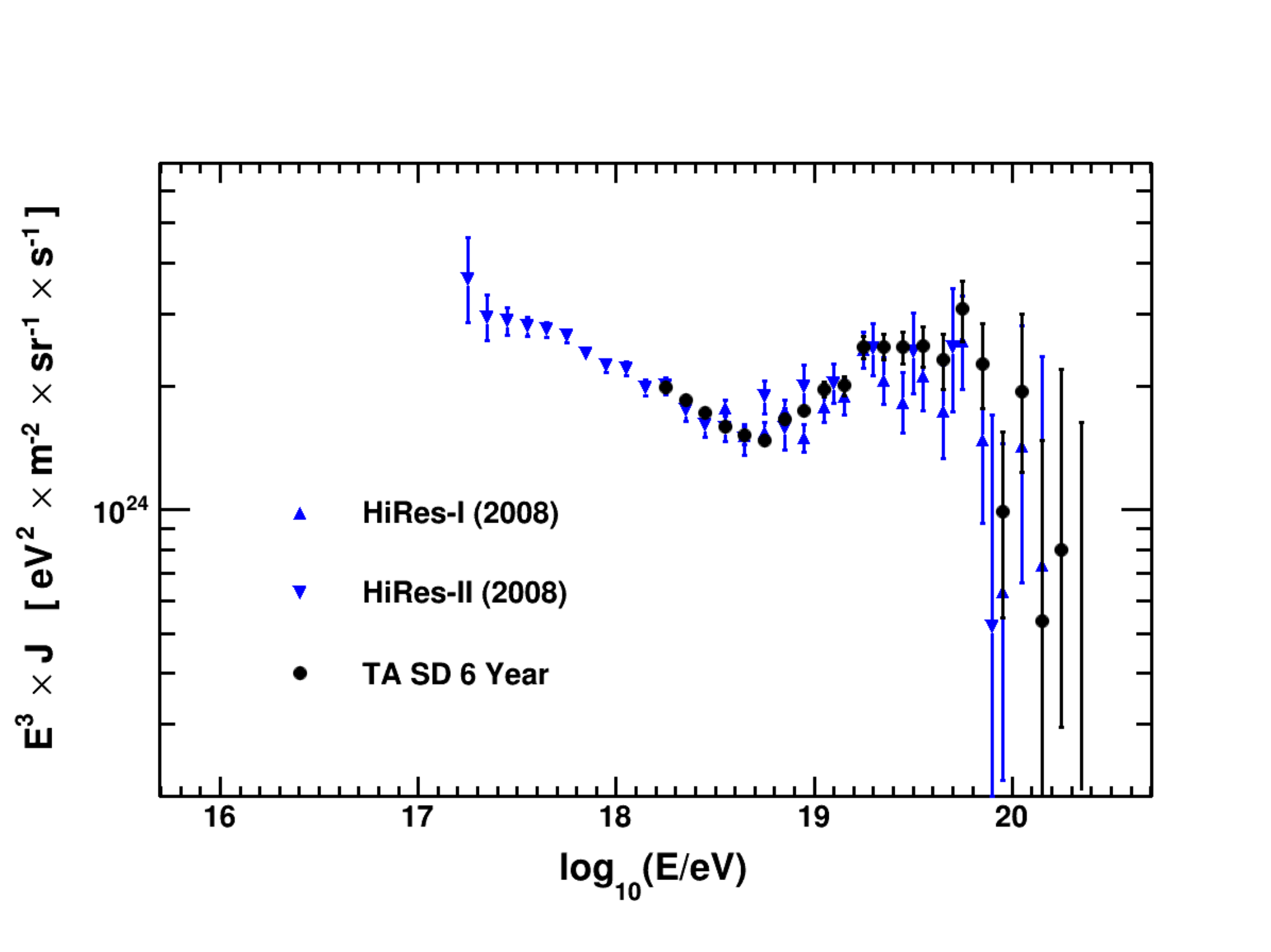
TALE fluorescence event: 0.5 EeV

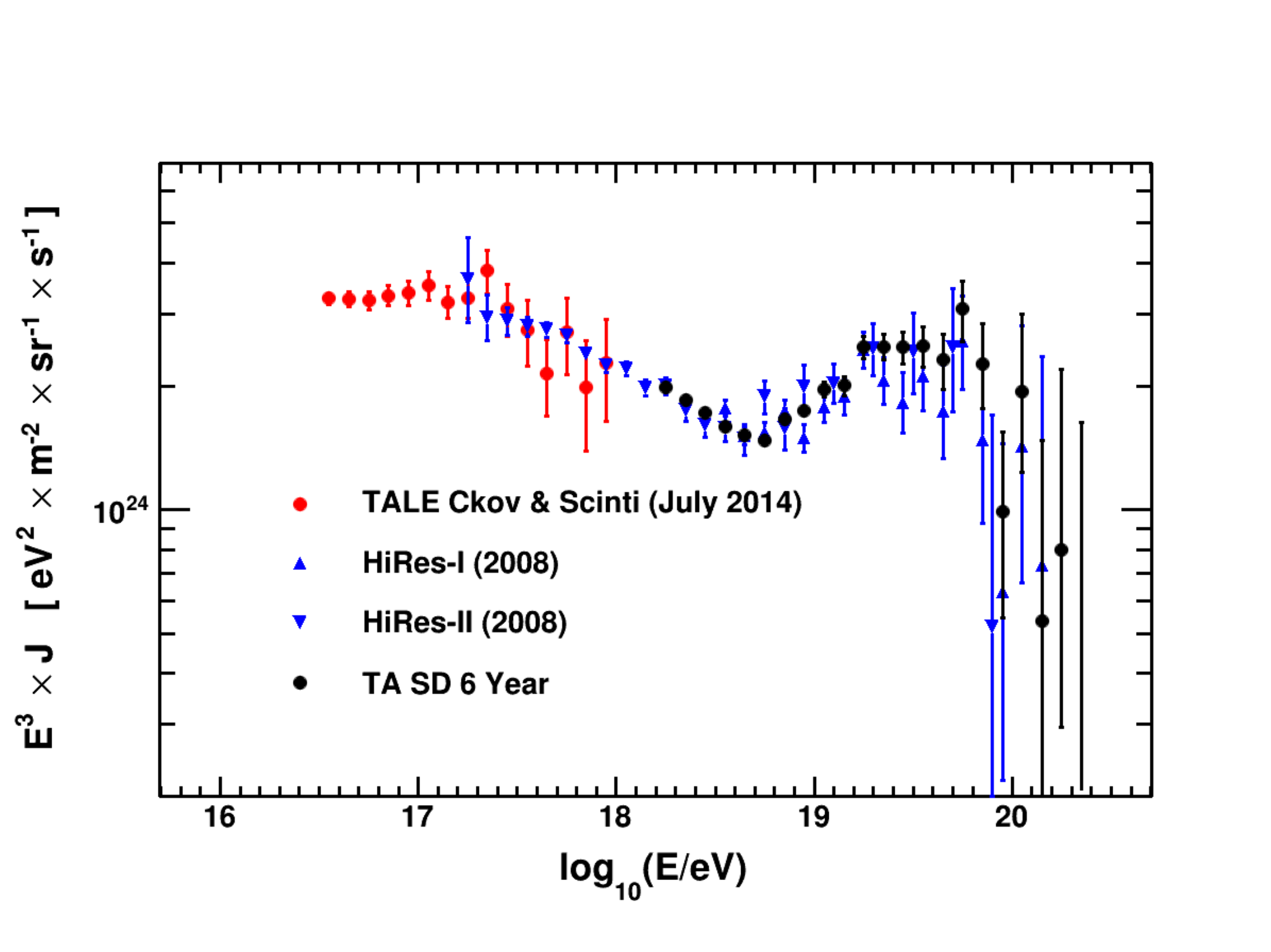


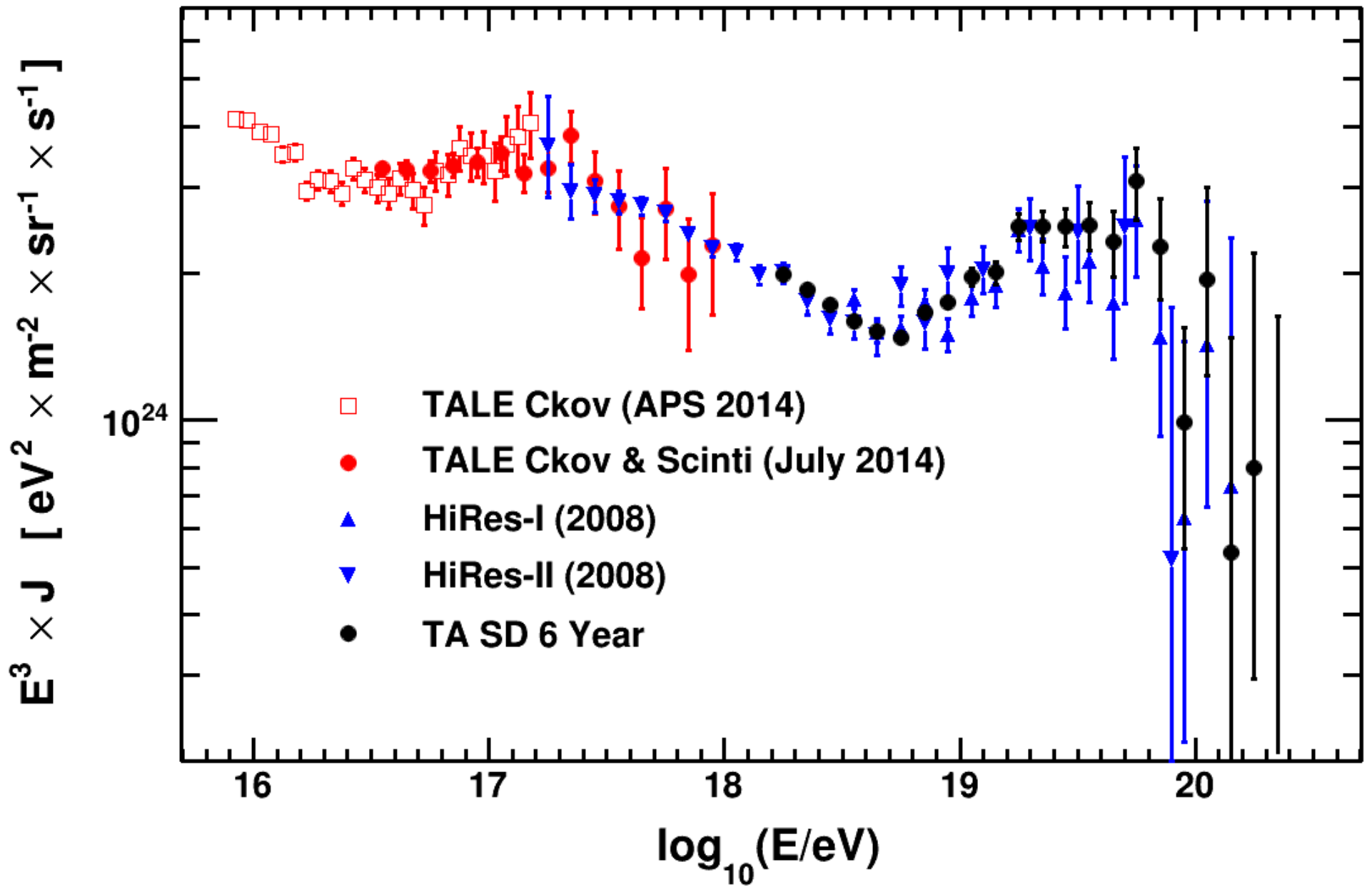


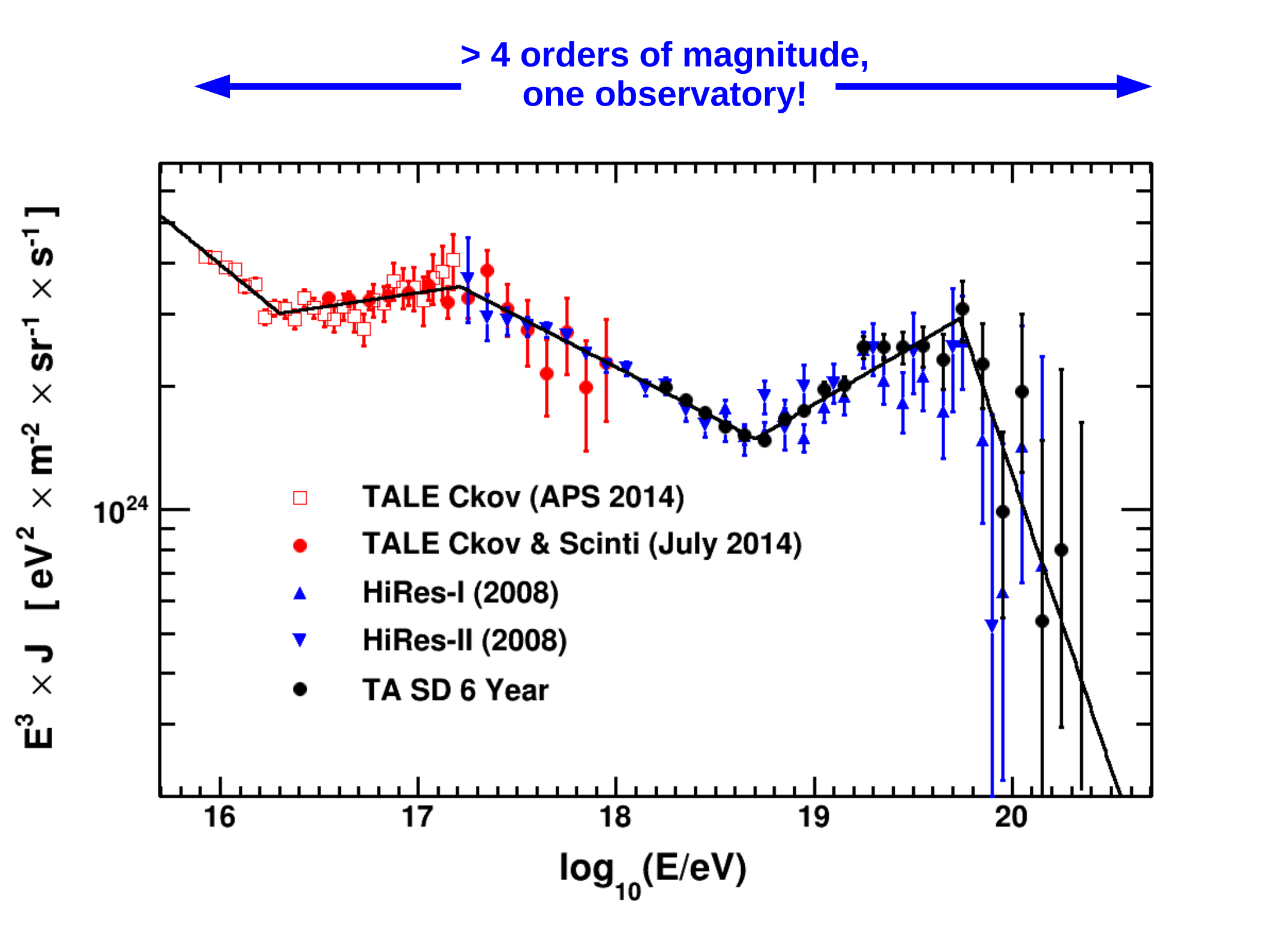
TALE Cherenkov event: 9 PeV

T. Abu- Zayyad


$E^3 \times J$ [$eV^2 \times m^{-2} \times sr^{-1} \times s^{-1}$]
10^{24}
HiRes-I (2008)
HiRes-II (2008)
TA SD 6 Year
16
17
18
19
20
$\log_{10}(E/eV)$

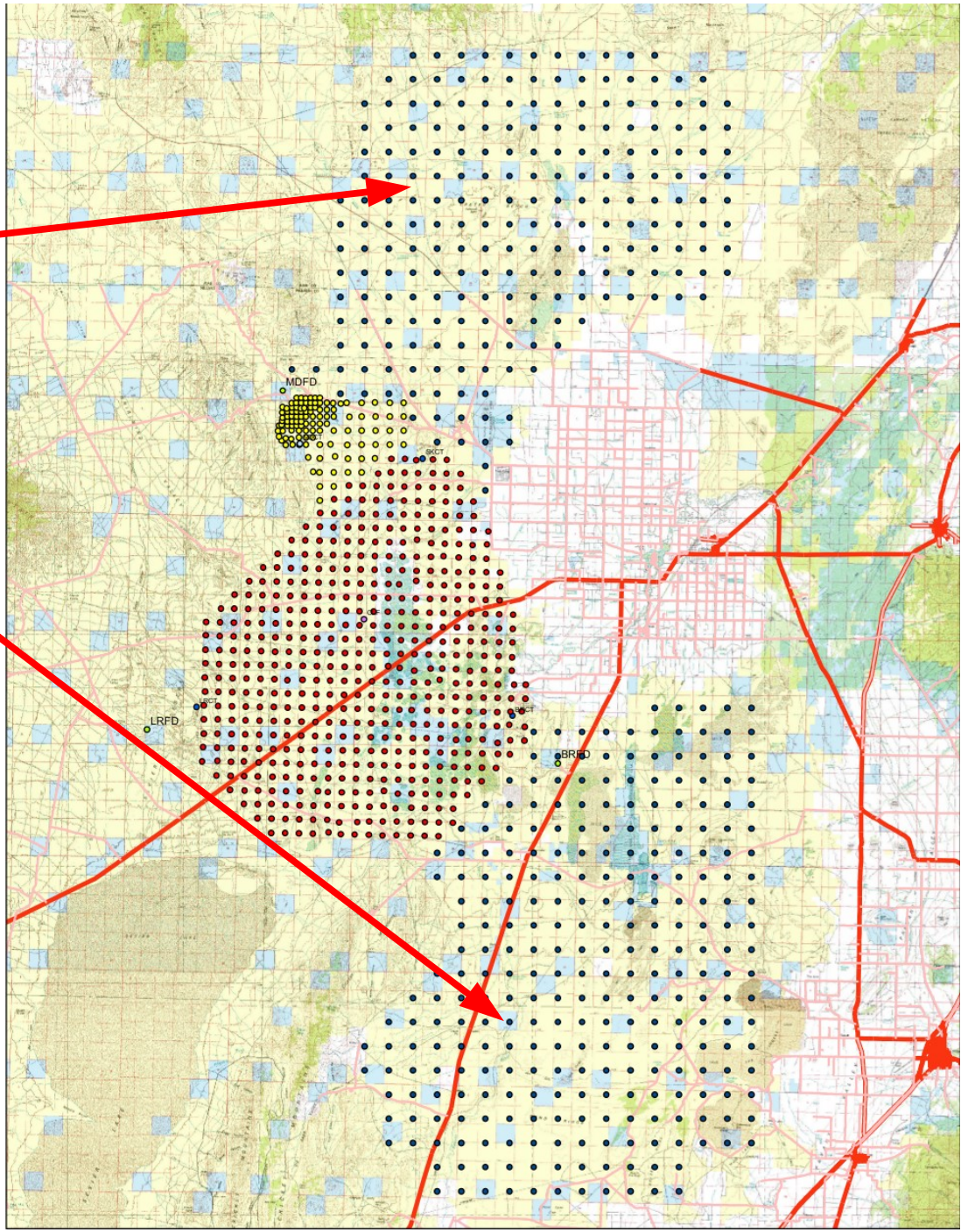

$E^3 \times J$ [$eV^2 \times m^{-2} \times sr^{-1} \times s^{-1}$]
10^{24}
TALE Ckov & Scinti (July 2014)
HiRes-I (2008)
HiRes-II (2008)
TA SD 6 Year
16
17
18
19
20
$\log_{10}(E/eV)$


$E^3 \times J$ [$eV^2 \times m^{-2} \times sr^{-1} \times s^{-1}$]
10^{24}
TALE Ckov (APS 2014)
TALE Ckov & Scinti (July 2014)
HiRes-I (2008)
HiRes-II (2008)
TA SD 6 Year
16
17
18
19
20
$\log_{10}(E/eV)$

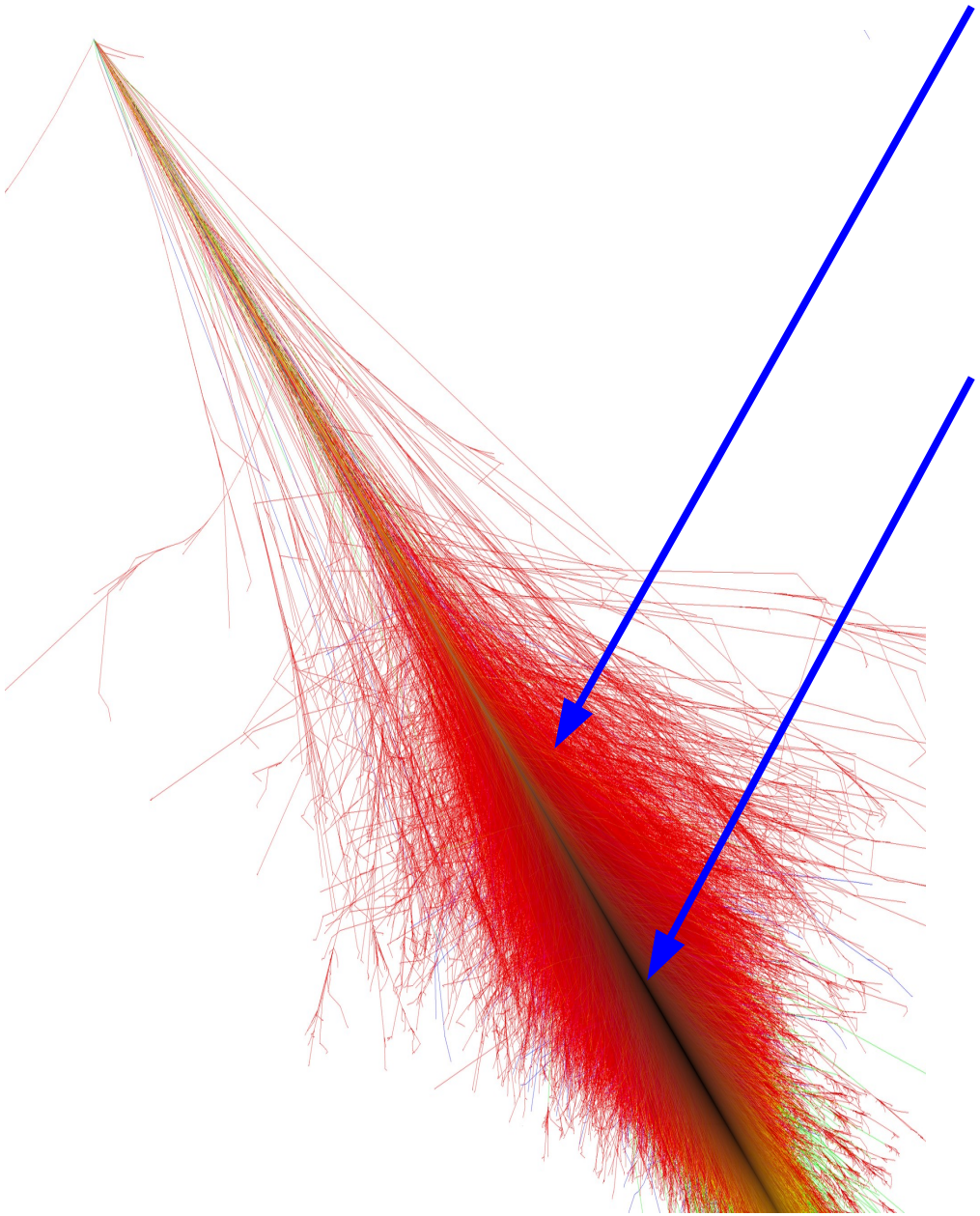

> 4 orders of magnitude,
one observatory!
E^3 × J [eV^2 × m^-2 × sr^-1 × s^-1]
10^24
TALE Ckov (APS 2014)
TALE Ckov & Scinti (July 2014)
HiRes-I (2008)
HiRes-II (2008)
TA SD 6 Year
16
17
18
19
20
log10(E/eV)

TA Upgrades

- TA x 4
- 3,000 km^2
  - 500 SD's, 2 km spacing
  - 1 new FD (HiRes refurbished)
- Proposals submitted NSF, Japan
- Anisotropy: 20 TA-SD years by 2019



TARA: What is the EAS radar cross-section?



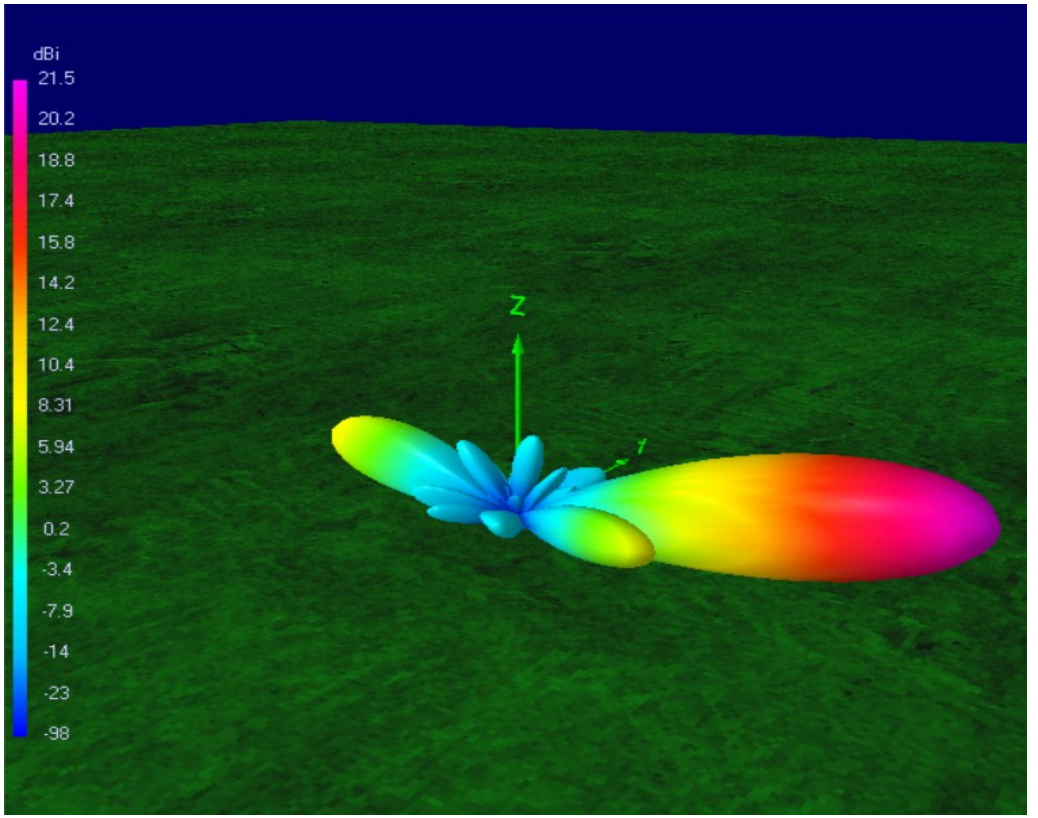
- 80 year old question!
- Underdense Region
  - Most of shower
  - $\sigma = (\text{Thomson x } N_e)$
- Overdense Region: ionization density exceeds critical density (plasma frequency = sounding frequency)
  - Relatively small (few cm?)
  - like macroscopic conductor

$$\omega_p = \left(\frac{n_e e^2}{m_e \varepsilon_0} \right)^{\frac{1}{2}}$$

- Collisional Damping?

TARA

- 40 kW analog TV transmitter (54.1 MHz, Channel 2)
- High-gain antenna (8 MW ERP)
- 250 MS/s smart receiver



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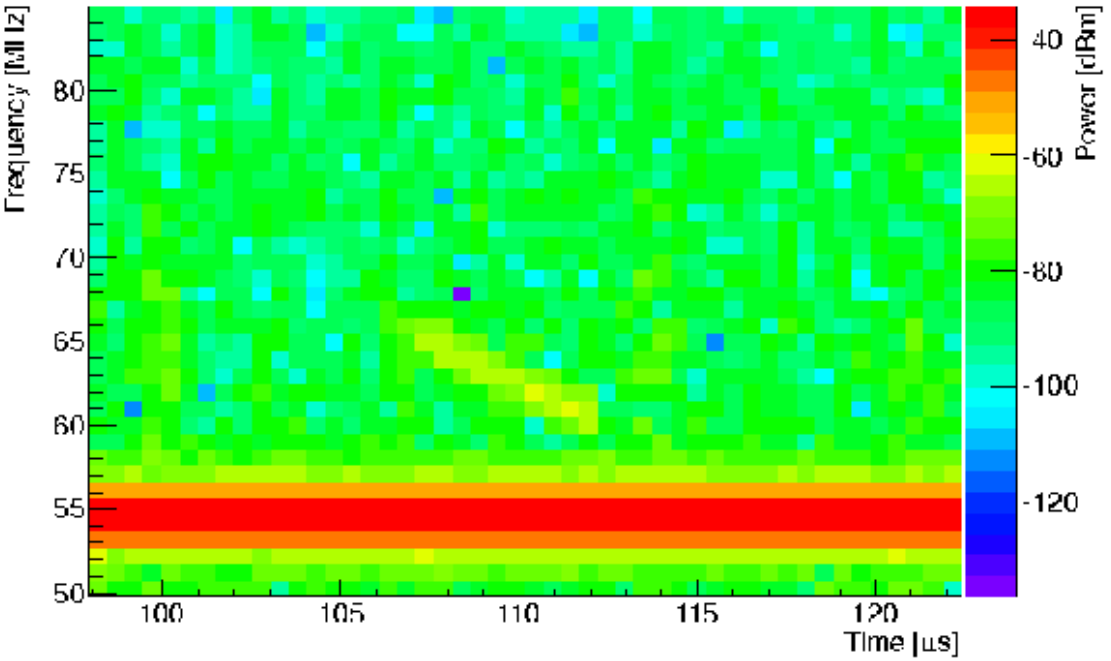
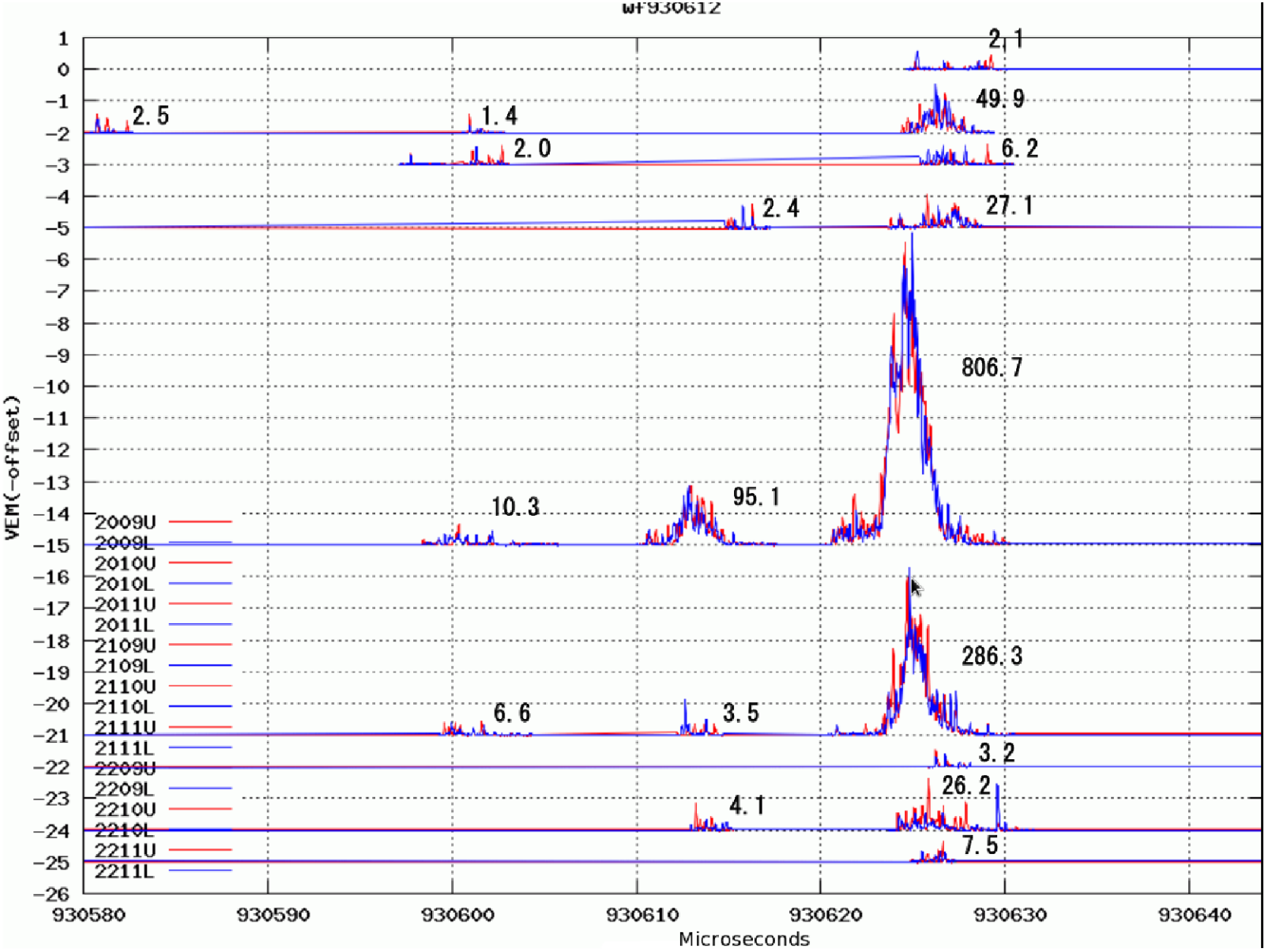


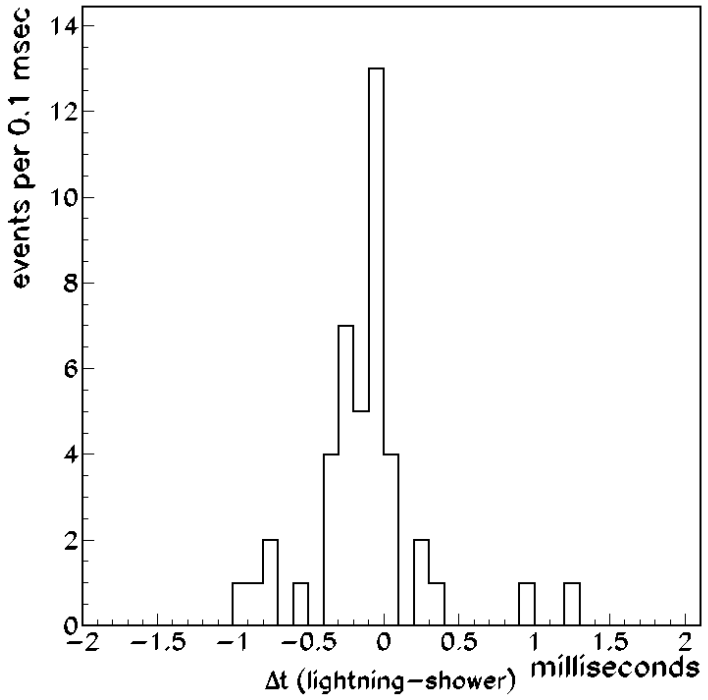
Trigger calibration “event”

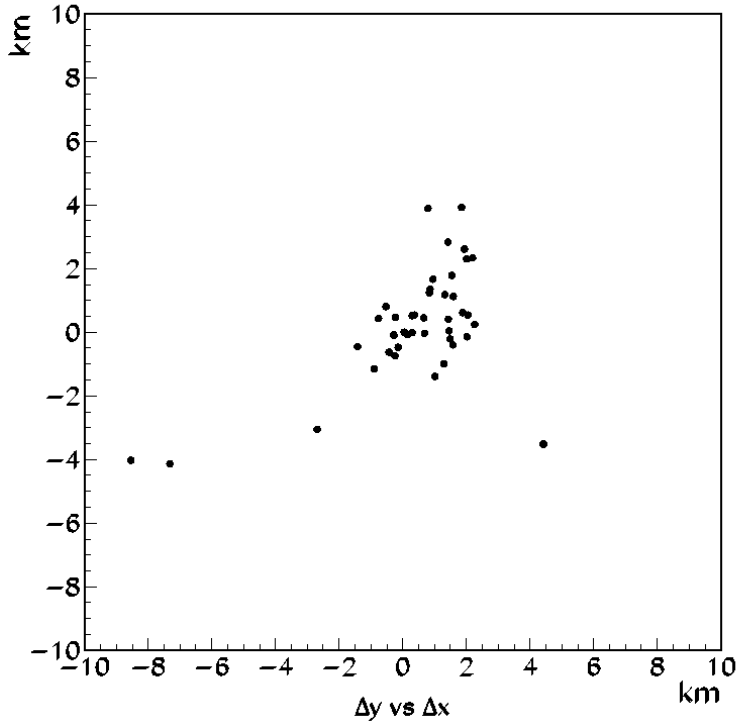
Novel Discovery: TA “Burst” Events

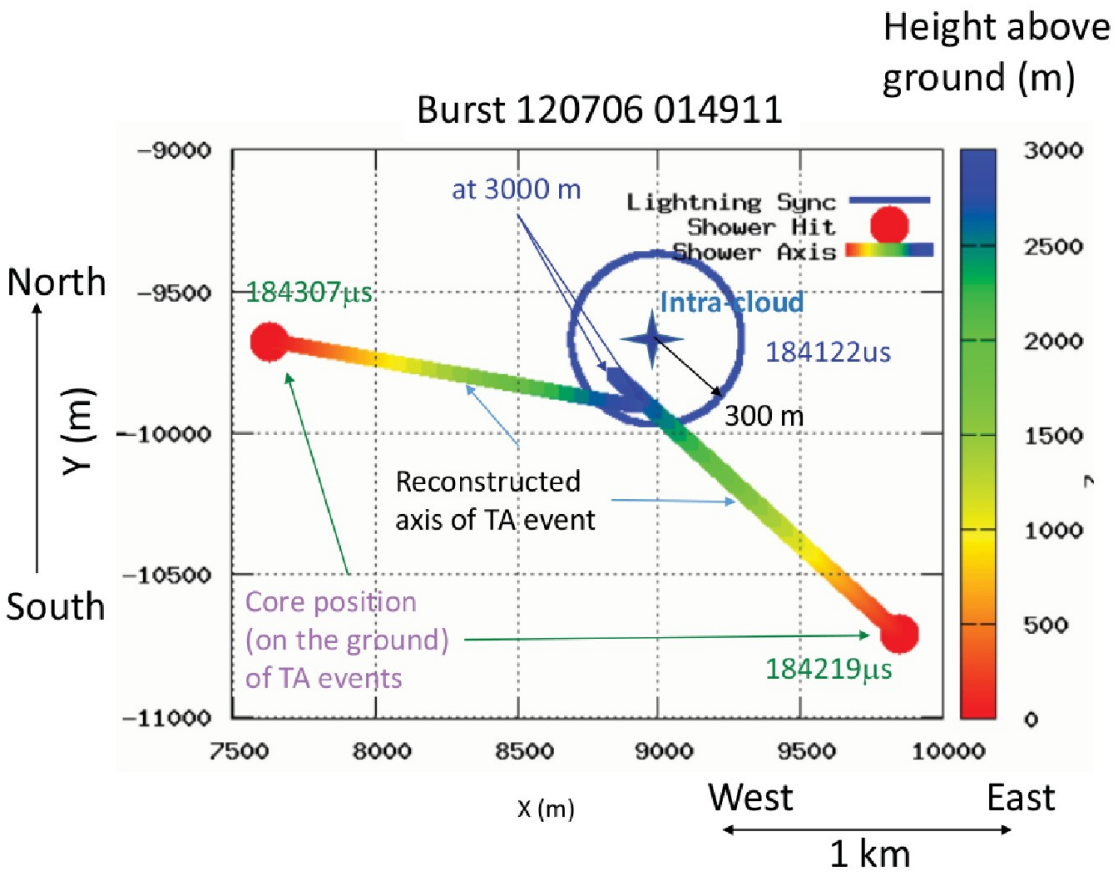


T. Okuda

“Burst Events” and National Lightning Detector Network







Reconstructable!

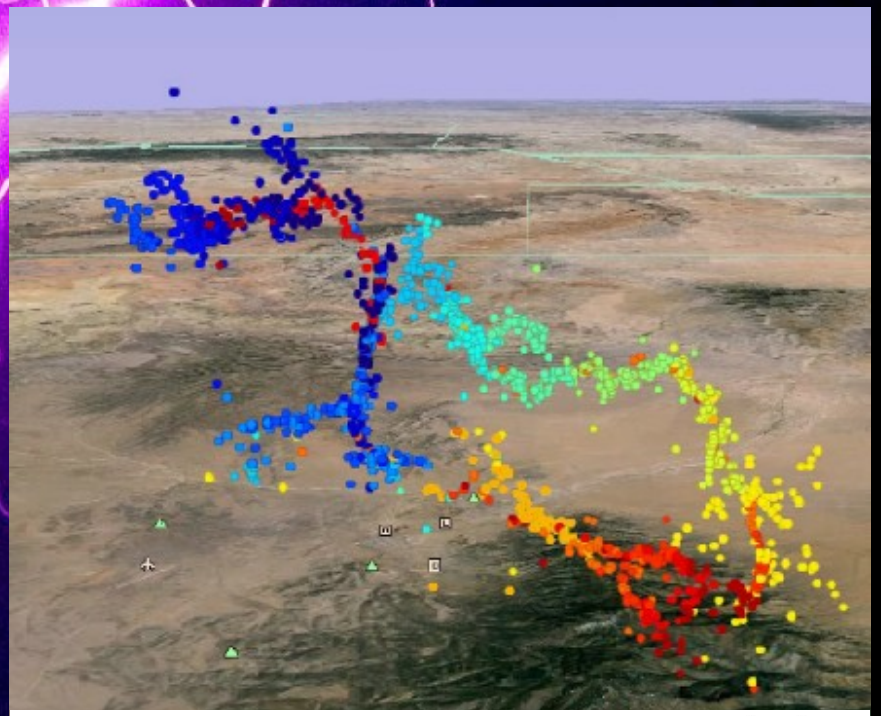
Lightning Mapping at Telescope Array

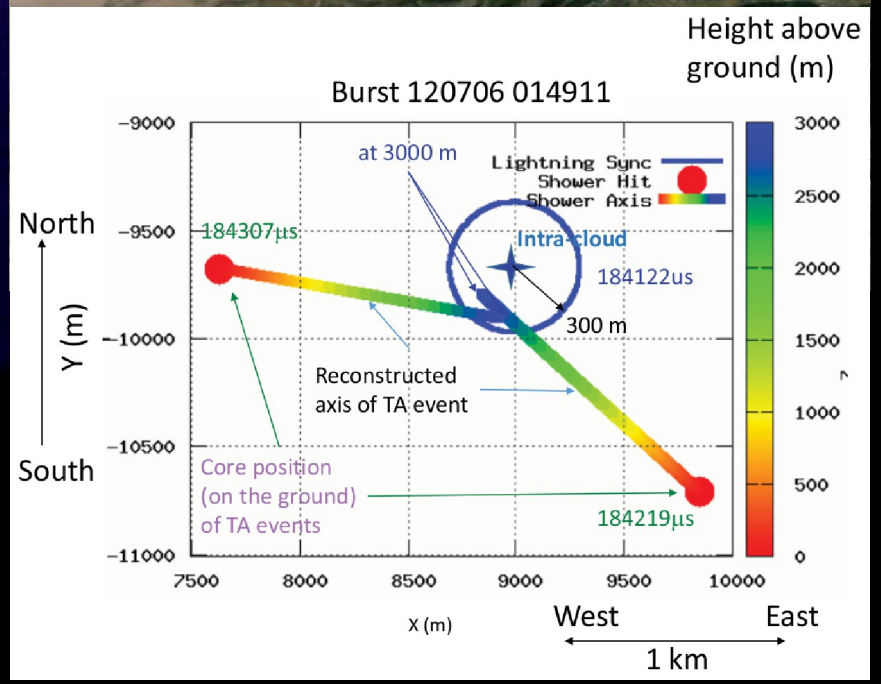
NM Tech, BNL, and the TA Collaboration

VHF Lightning Detector

+

TA Surface Detector



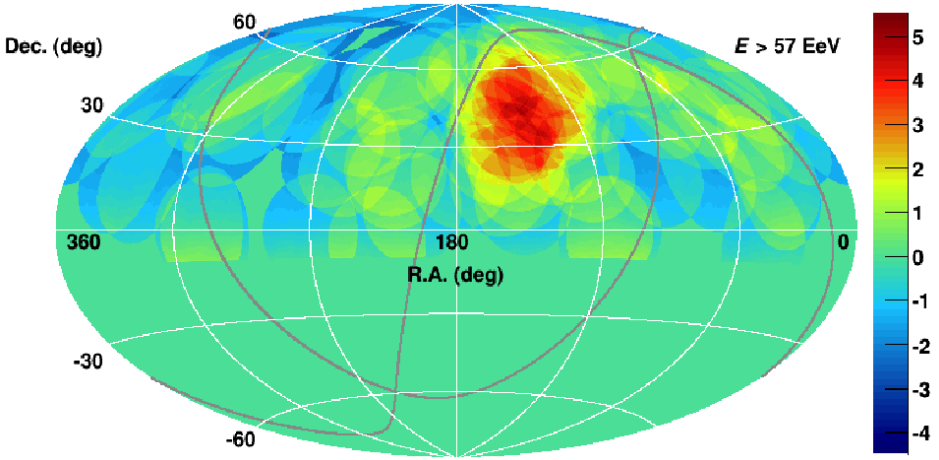


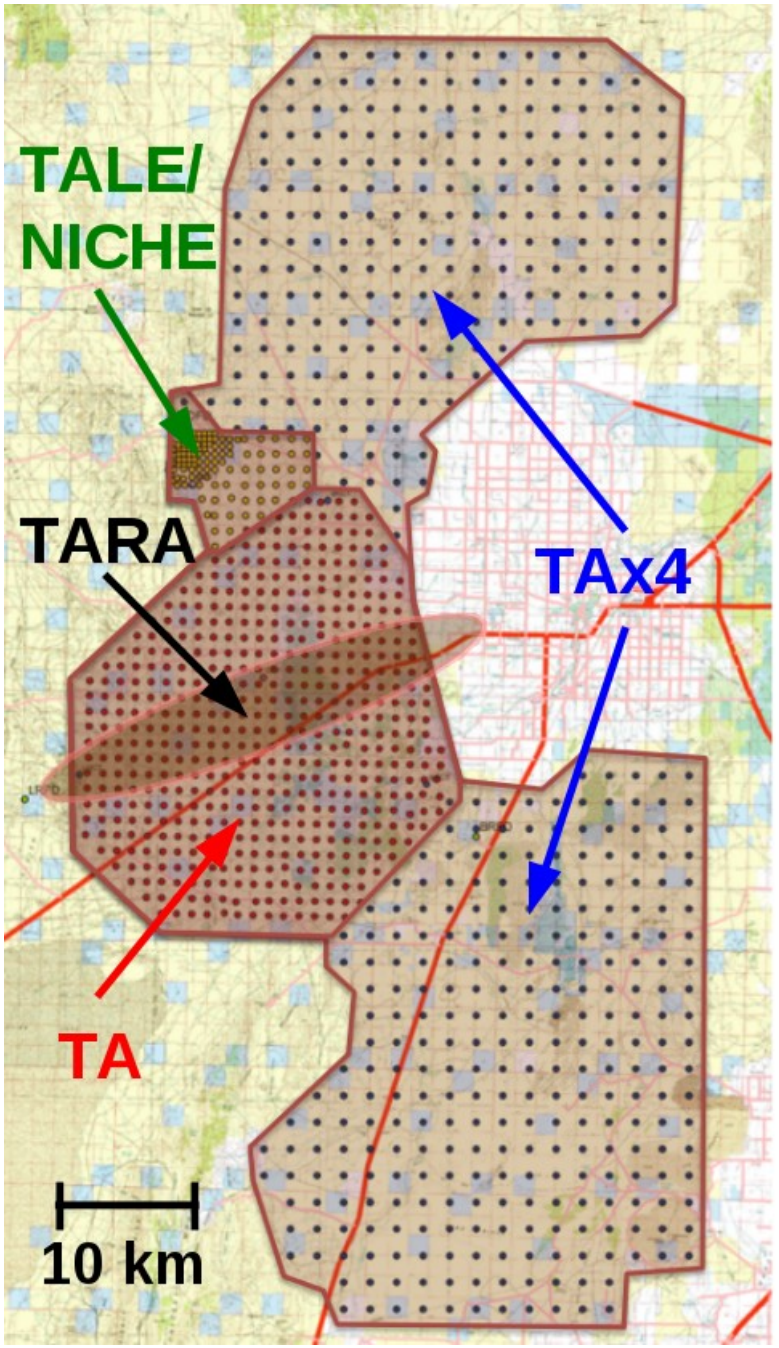
Lightning produces keV-MeV gamma showers
TA (uniquely) can reconstruct these showers
Also: Can cosmic rays initiate lightning?

3D Reconstruction of Gamma Showers and lightning strike

Conclusions

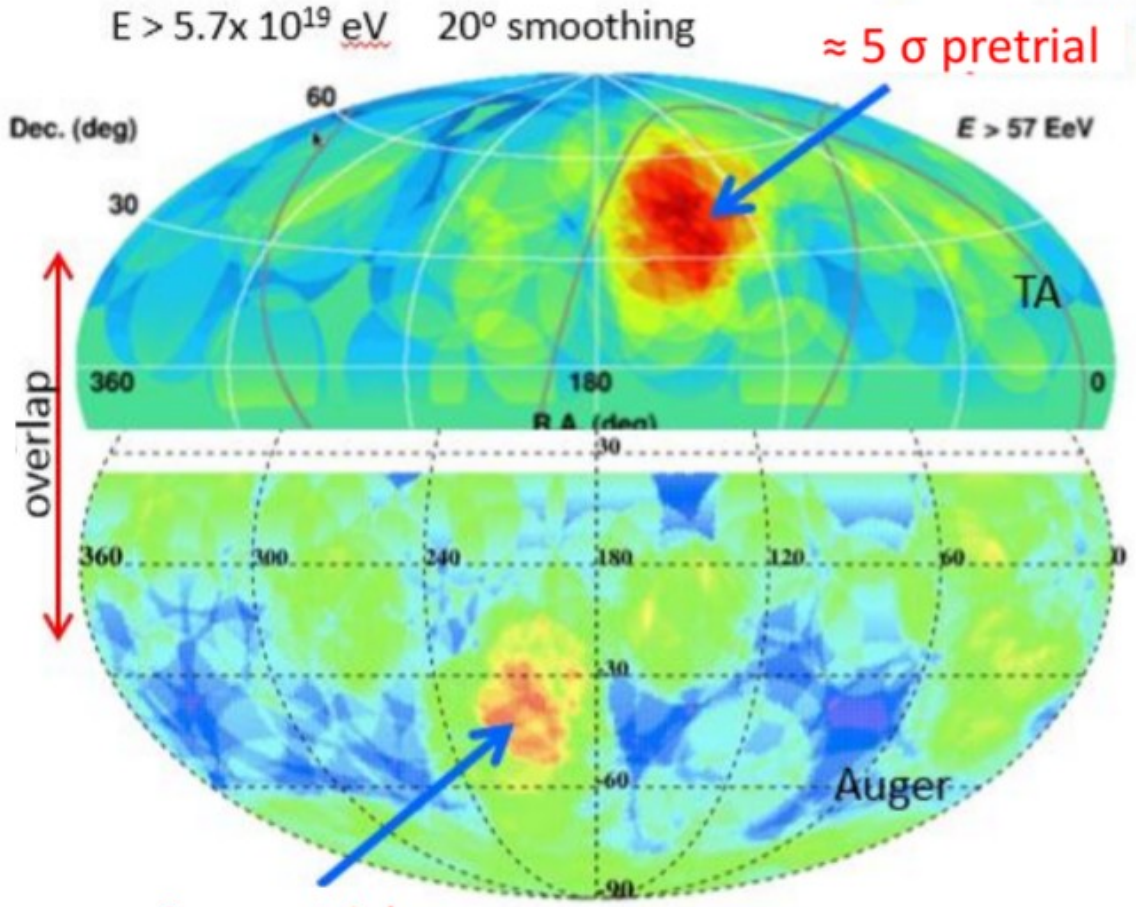
- TA energy spectrum now spans four orders of magnitude. (Just above the “knee” to GZK feature.
- TA sees evidence for anisotropy in the Northern Hemisphere
- Composition measured via X_{max} appears light, mostly protonic.
- Rich program of affiliated experiments



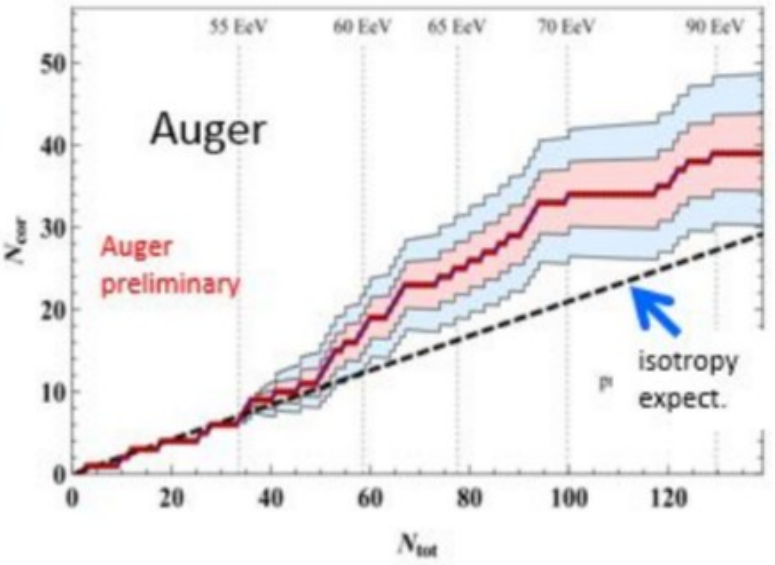


Origin of UHE Cosmic Rays?

Evidence for Comic Ray Anisotropy above 5.7x 10^{19} eV in the North and South - Still statistically limited – but it will be clear in a few years



# of events correlating with AGN, ordered in energy (integral plot)



A. Olinto, P5 Presentation 12/3/13
Cosmic Particles Overview of Opportunities