

Cosmic Ray in the Northern Hemisphere: Results from the Telescope Array Experiment

Charlie Jui

University of Utah

DPF, Brown University

Aug. 11, 2011





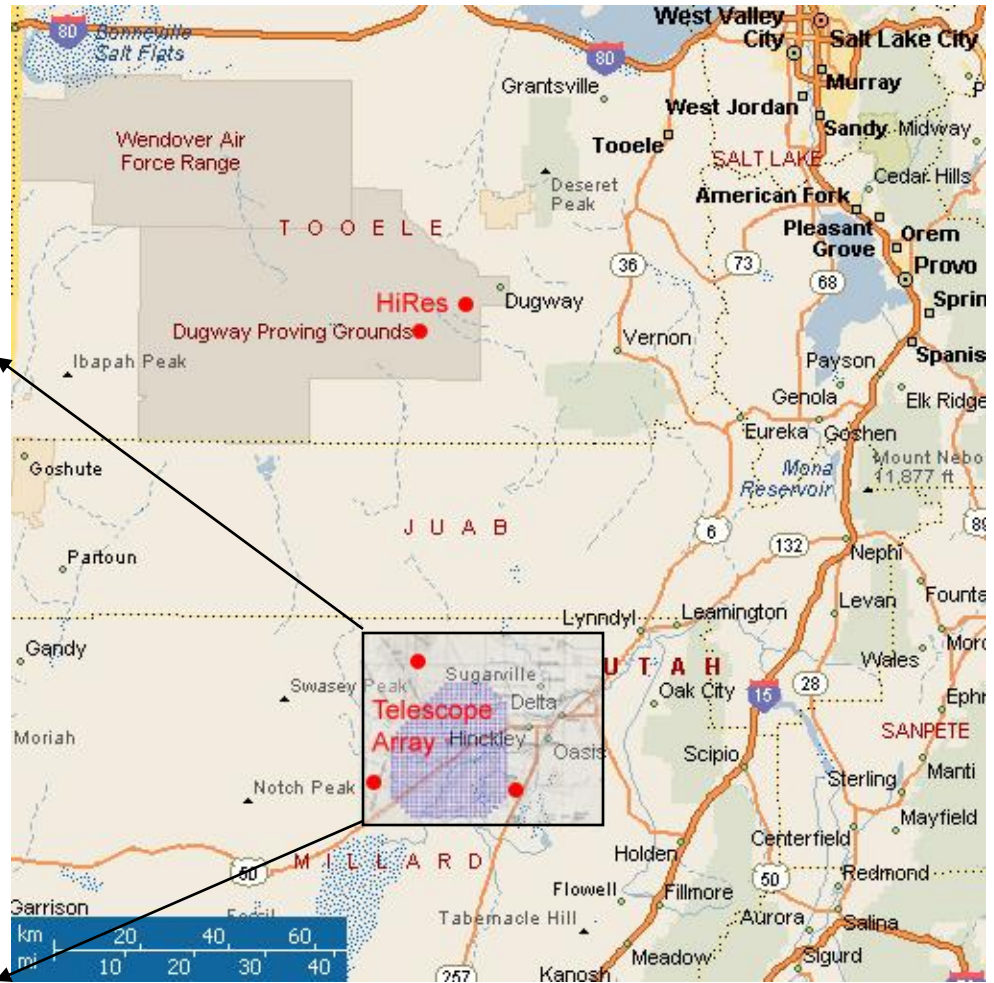
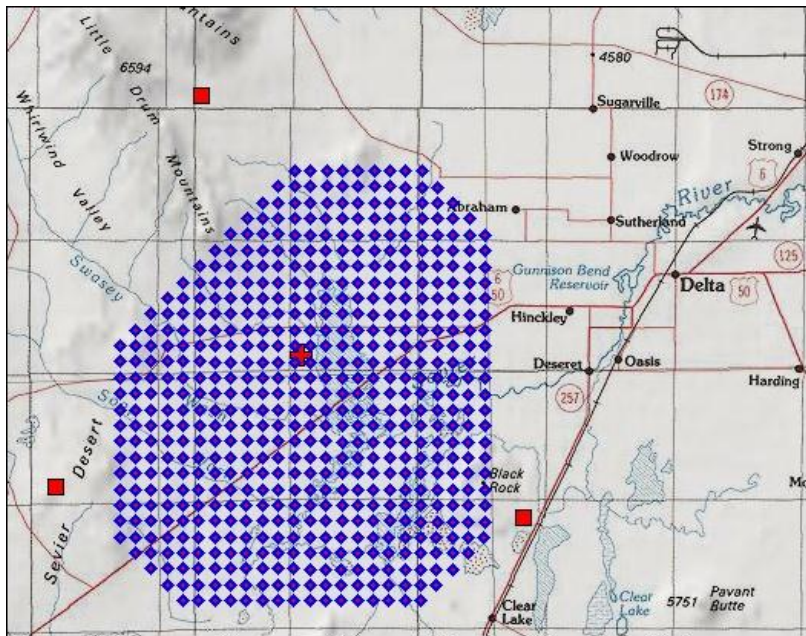
Telescope Array Collaboration

T Abu-Zayyad¹, R Aida², M Allen¹, R Azuma³, E Barcikowski¹, JW Belz¹, T Benno⁴, DR Bergman¹, SA Blake¹, O Brusova¹, R Cady¹, BG Cheon⁶, J Chiba⁷, M Chikawa⁴, EJ Cho⁶, LS Cho⁸, WR Cho⁸, F Cohen⁹, K Doura⁴, C Ebeling¹, H Fujii¹⁰, T Fujii¹¹, T Fukuda³, M Fukushima^{9,22}, D Gorbunov¹², W Hanlon¹, K Hayashi³, Y Hayashi¹¹, N Hayashida⁹, K Hibino¹³, K Hiyama⁹, K Honda², G Hughes⁵, T Iguchi³, D Ikeda⁹, K Ikuta², SJJ Innemee⁵, N Inoue¹⁴, T Ishii², R Ishimori³, D Ivanov⁵, S Iwamoto², CCH Jui¹, K Kadota¹⁵, F Kakimoto³, O Kalashev¹², T Kanbe², H Kang¹⁶, K Kasahara¹⁷, H Kawai¹⁸, S Kawakami¹¹, S Kawana¹⁴, E Kido⁹, BG Kim¹⁹, HB Kim⁶, JH Kim⁶, JH Kim²⁰, A Kitsugi⁹, K Kobayashi⁷, H Koers²¹, Y Kondo⁹, V Kuzmin¹², YJ Kwon⁸, JH Lim¹⁶, SI Lim¹⁹, S Machida³, K Martens²², J Martineau¹, T Matsuda¹⁰, T Matsuyama¹¹, JN Matthews¹, M Minamino¹¹, K Miyata⁷, H Miyauchi¹¹, Y Murano³, T Nakamura²³, SW Nam¹⁹, T Nonaka⁹, S Ogio¹¹, M Ohnishi⁹, H Ohoka⁹, T Okuda¹¹, A Oshima¹¹, S Ozawa¹⁷, IH Park¹⁹, D Rodriguez¹, SY Roh²⁰, G Rubtsov¹², D Ryu²⁰, H Sagawa⁹, N Sakurai⁹, LM Scott⁵, PD Shah¹, T Shibata⁹, H Shimodaira⁹, BK Shin⁶, JD Smith¹, P Sokolsky¹, TJ Sonley¹, RW Springer¹, BT Stokes¹, TA Stroman¹, SR Stratton⁵, S Suzuki¹⁰, Y Takahashi⁹, M Takeda⁹, A Taketa⁹, M Takita⁹, Y Tameda³, H Tanaka¹¹, K Tanaka²⁴, M Tanaka¹⁰, JR Thomas¹, SB Thomas¹, GB Thomson¹, P Tinyakov^{12,21}, I Tkachev¹², H Tokuno⁹, T Tomida², R Torii⁹, S Troitsky¹², Y Tsunesada³, Y Tsuyuguchi², Y Uchihori²⁵, S Udo¹³, H Ukai², B Van Klaveren¹, Y Wada¹⁴, M Wood¹, T Yamakawa⁹, Y Yamakawa⁹, H Yamaoka¹⁰, J Yang¹⁹, S Yoshida¹⁸, H Yoshii²⁶, Z Zundel¹

¹University of Utah, ²University of Yamanashi, ³Tokyo Institute of Technology, ⁴Kinki University,
⁵Rutgers University, ⁶Hanyang University, ⁷Tokyo University of Science, ⁸Yonsei University,
⁹Institute for Cosmic Ray Research, University of Tokyo, ¹⁰Institute of Particle and Nuclear Studies, KEK,
¹¹Osaka City University, ¹²Institute for Nuclear Research of the Russian Academy of Sciences,
¹³Kanagawa University, ¹⁴Saitama University, ¹⁵Tokyo City University, ¹⁶Pusan National University,
¹⁷Waseda University, ¹⁸Chiba University ¹⁹Ewha Womans University, ²⁰Chungnam National University,
²¹University Libre de Bruxelles, ²²University of Tokyo, ²³Kochi University, ²⁴Hiroshima City University,
²⁵National Institute of Radiological Science, Japan, ²⁶Ehime University

Telescope Array Experiment

- TA is a ultrahigh energy ($>10^{17}$ eV) cosmic ray observatory located in the West Desert of Utah: largest in the northern hemisphere



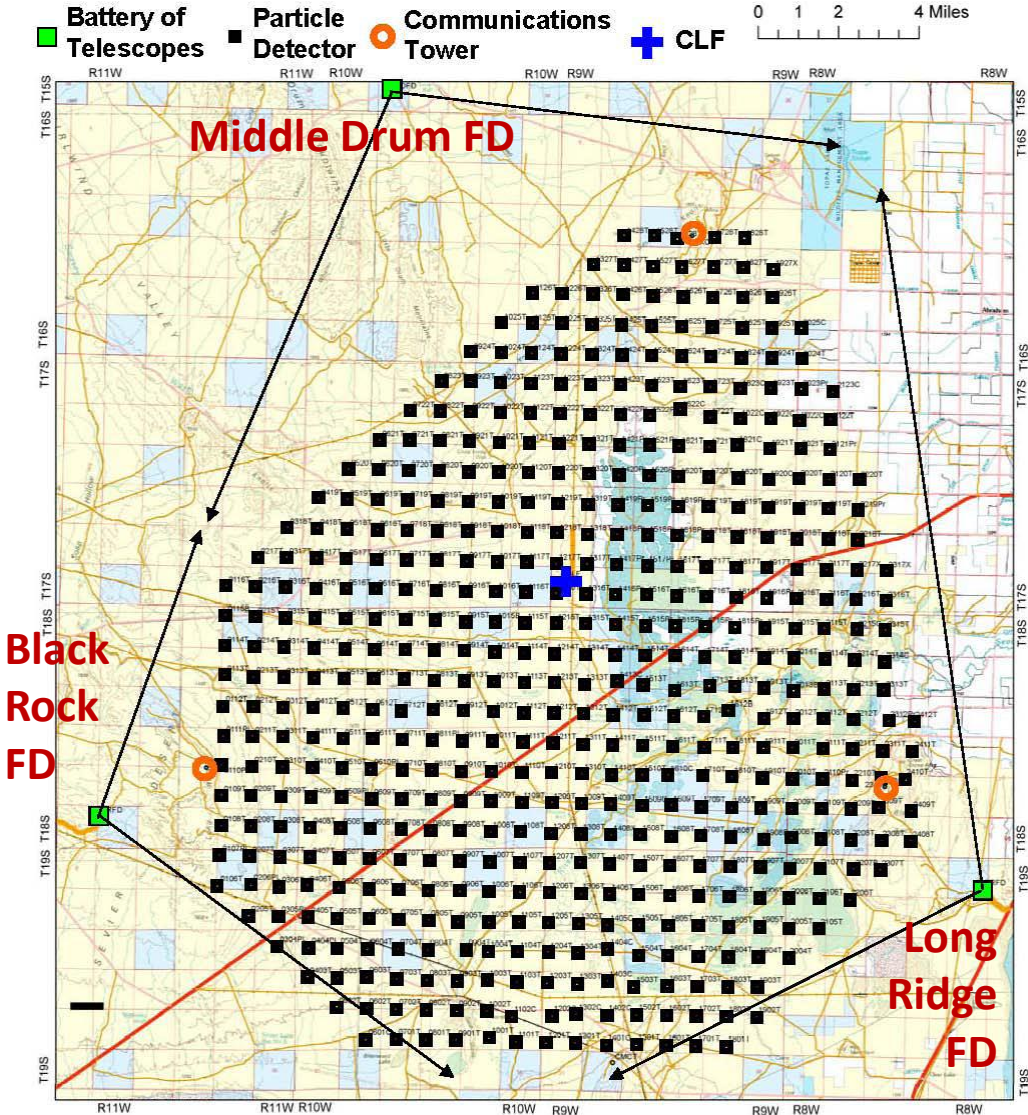
Outline

1. Introduction to Telescope Array
2. TA Data Analysis
3. Energy Spectrum Results
4. Composition Results
5. Anisotropy Results

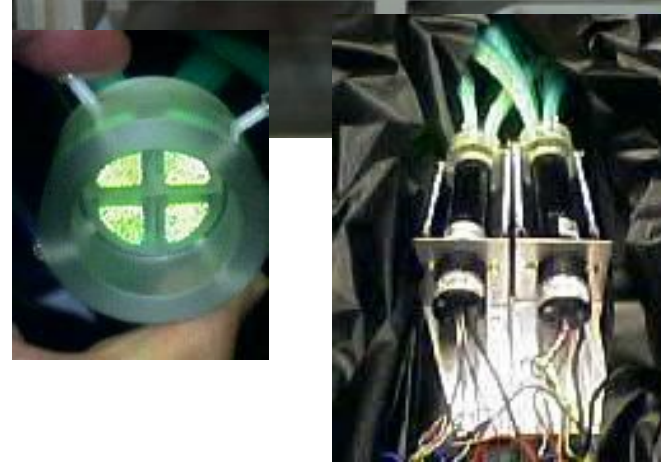
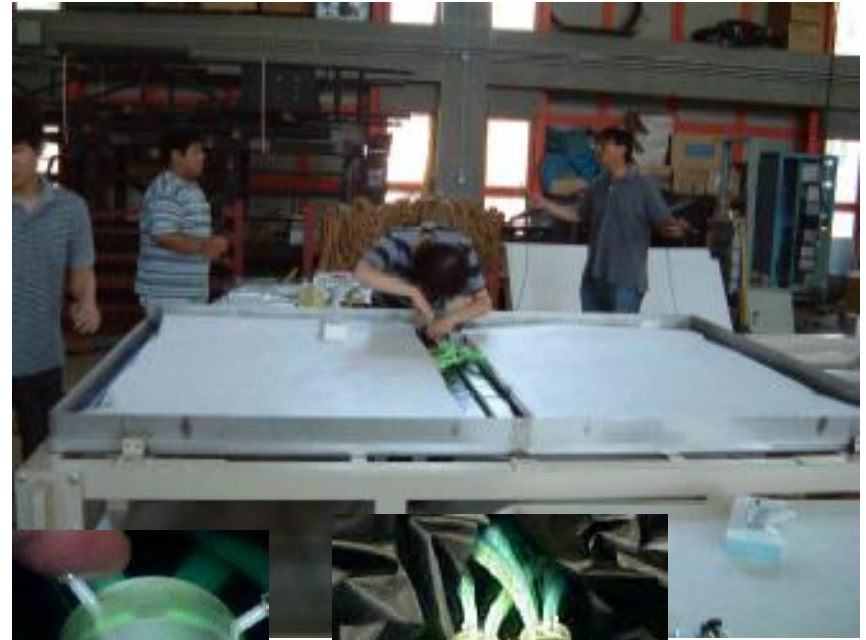
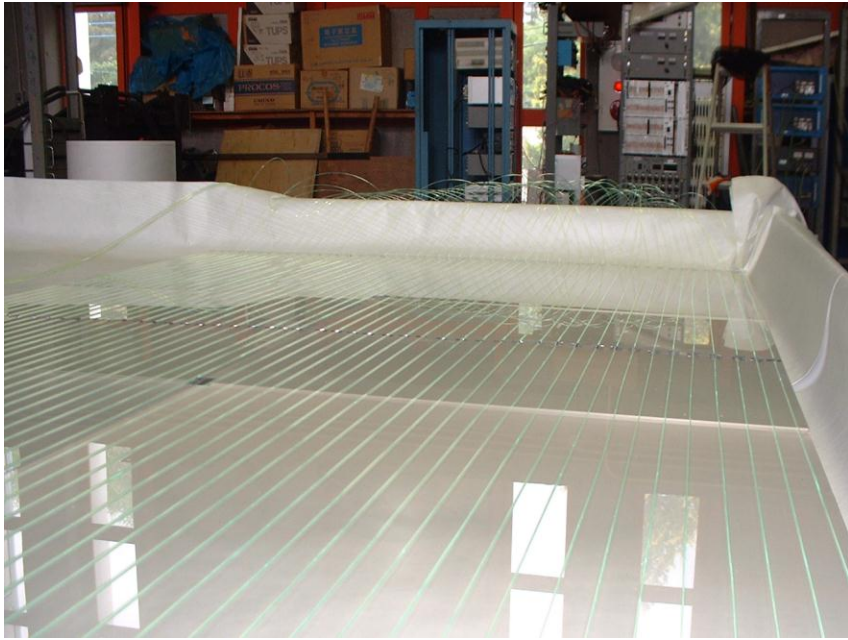
TA Detectors

TA is a hybrid experiment

- 507 scintillation counters surface detector (SD)
 - Covers 730 km².
- 3 fluorescence detector (FD) stations
 - Located at the corners of the SD array

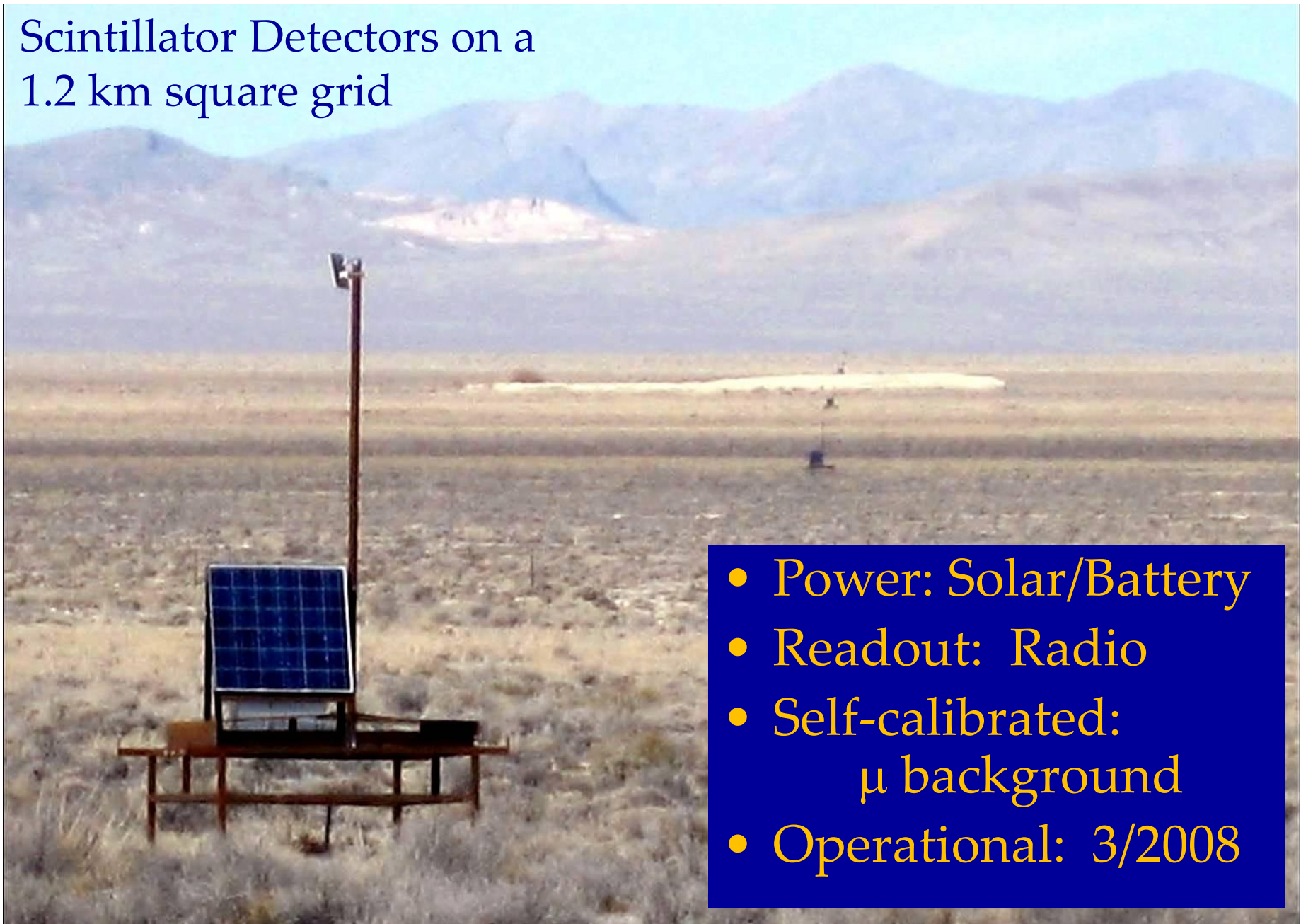


Scintillation Counters



Pre-assembled in Japan, Final Assby/testing in Delta: 2 layers, 1.25 cm scintillator, 3m² area

Scintillator Detectors on a 1.2 km square grid



- Power: Solar/Battery
- Readout: Radio
- Self-calibrated:
 μ background
- Operational: 3/2008

TA Fluorescence Detectors

Refurbished
from HiRes-I

Middle Drum

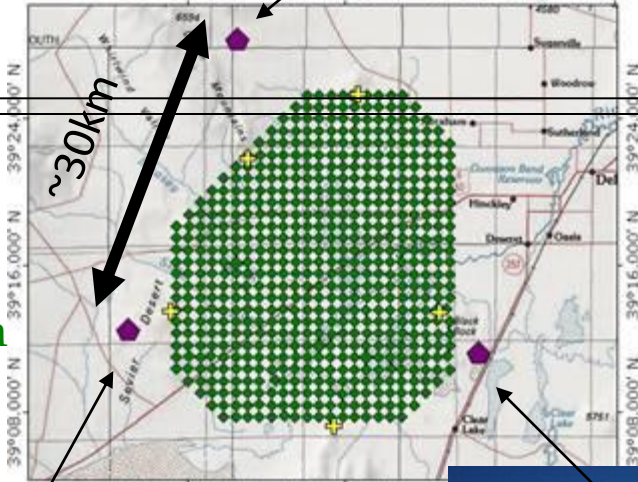
14 telescopes@station
256 PMTs/camera

Observations
since ~10/2007



5.2 m²

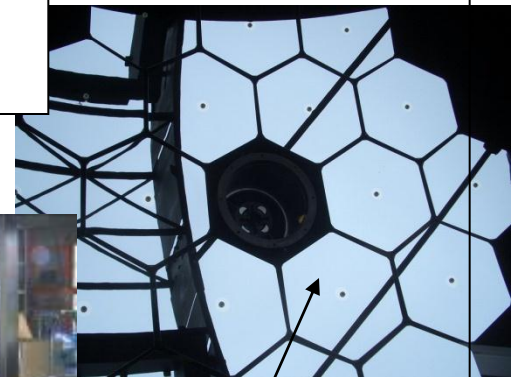
TOPOI map printed on 07/12/04 from "StakeJun04-01.tpo" and "Untitled.tpg"



New FDs

Observation
since ~11/2007

12 telescopes/station
256 PMTs/camera
Hamamatsu R9508
FOV~15x18deg



6.8 m²

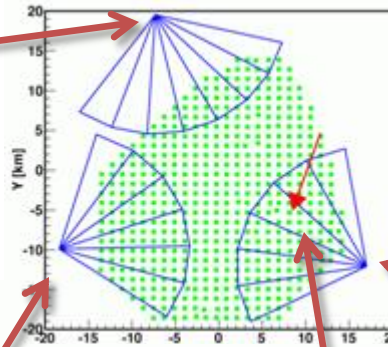
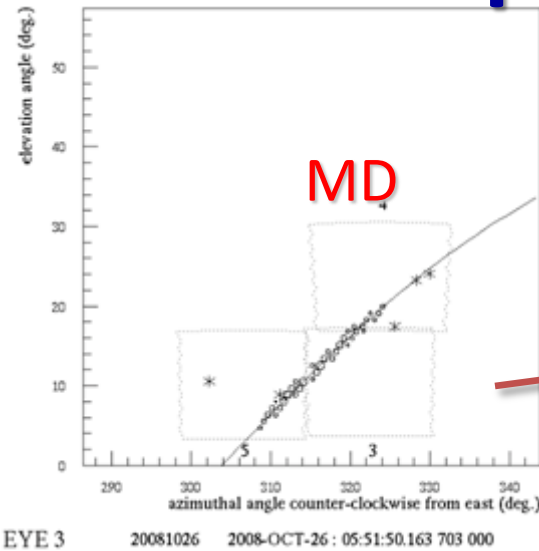
Long Ridge

Observation
since ~6/2007

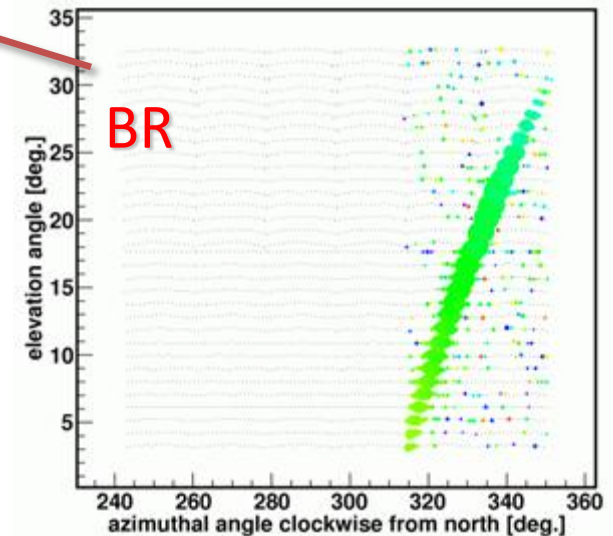
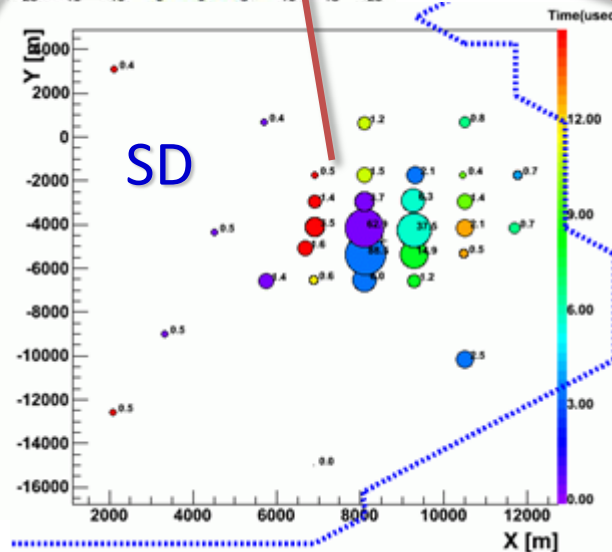
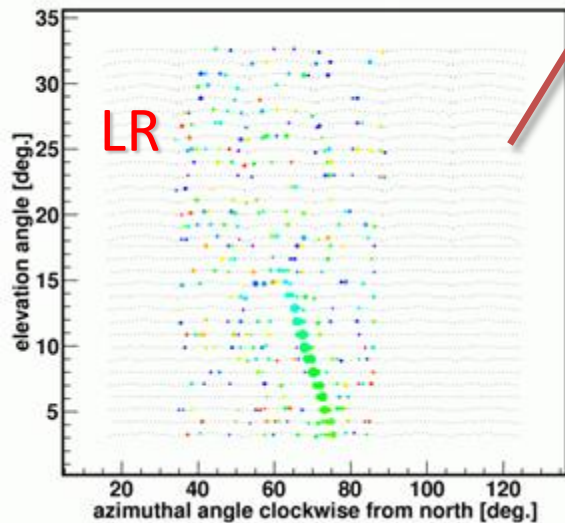
Black Rock Mesa

~1 m²

Example Event from 2008-10-26

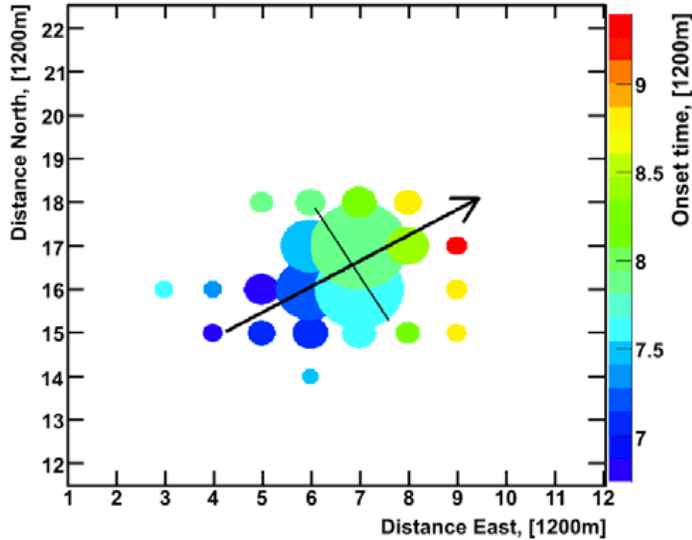


	θ [°]	ϕ [°]	x[km]	y[km]
MD mono	51.43	73.76	7.83	-3.10
BR mono	51.50	77.09	7.67	-4.14
Stereo BR&LR	50.21	71.30	8.55	-4.88

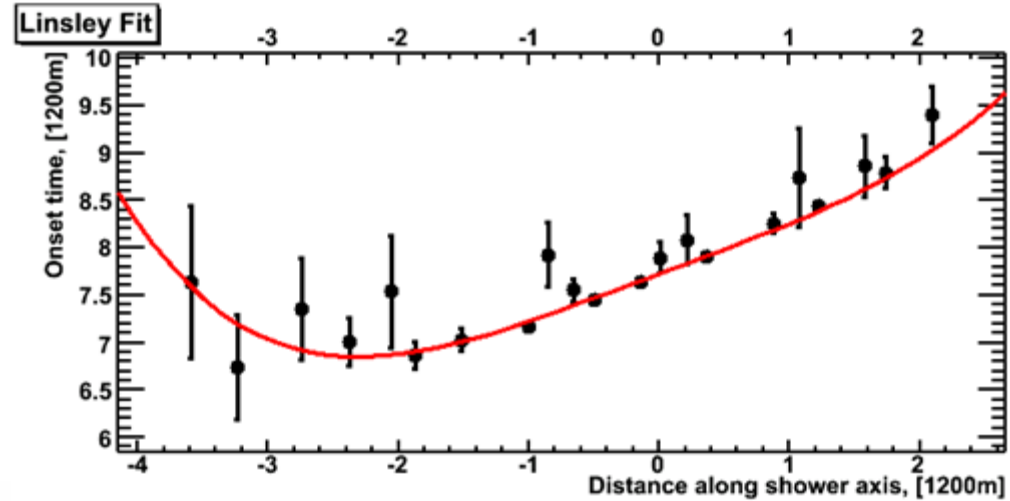


Analyzing SD Event

2008/Jun/25 - 19:45:52.588670 UTC



Geometry Fit (modified Linsley)

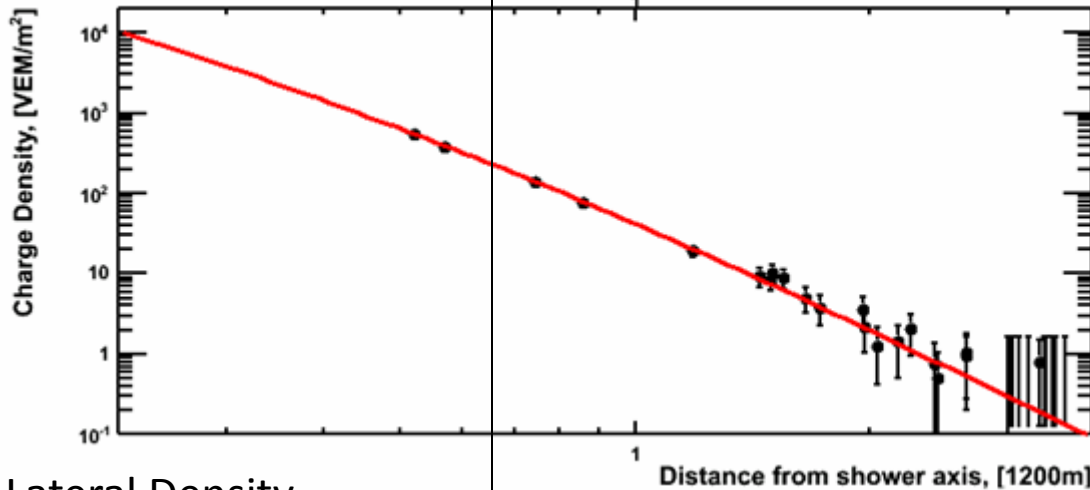


Fit with AGASA LDF

$$\rho(r) \propto \left(\frac{r}{R_M}\right)^{-1.2} \left(1 + \frac{r}{R_M}\right)^{-(\eta-1.2)} \left\{1 + \left(\frac{r}{1000}\right)^2\right\}^{-0.6}$$

$$\eta = (3.97 \pm 0.13) - (1.79 \pm 0.62) (\sec \theta - 1)$$

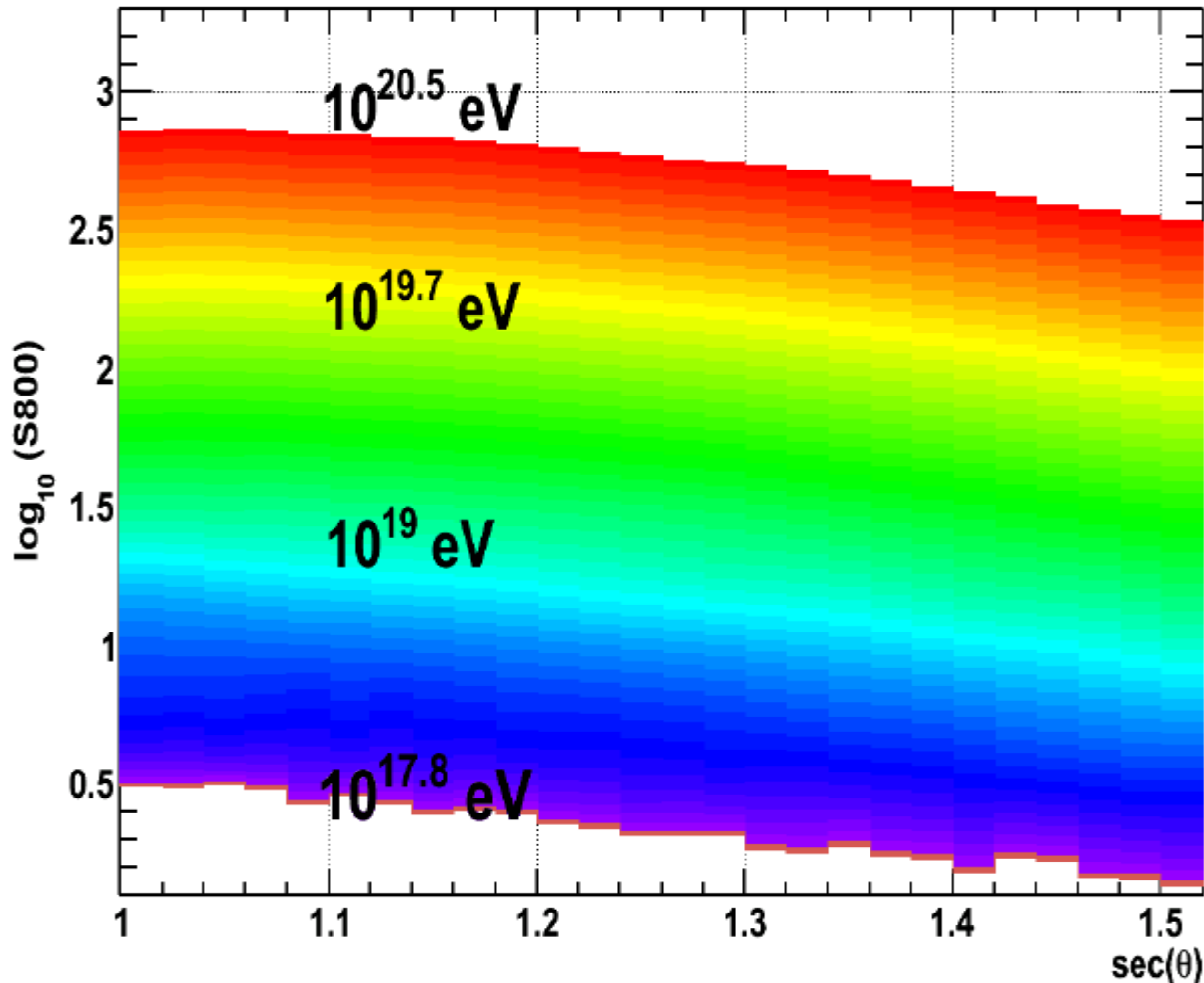
- S(800): Primary Energy
- Zenith attenuation by MC



Lateral Density Distribution Fit

$r = 800m$

Surface Array Energy Measurement

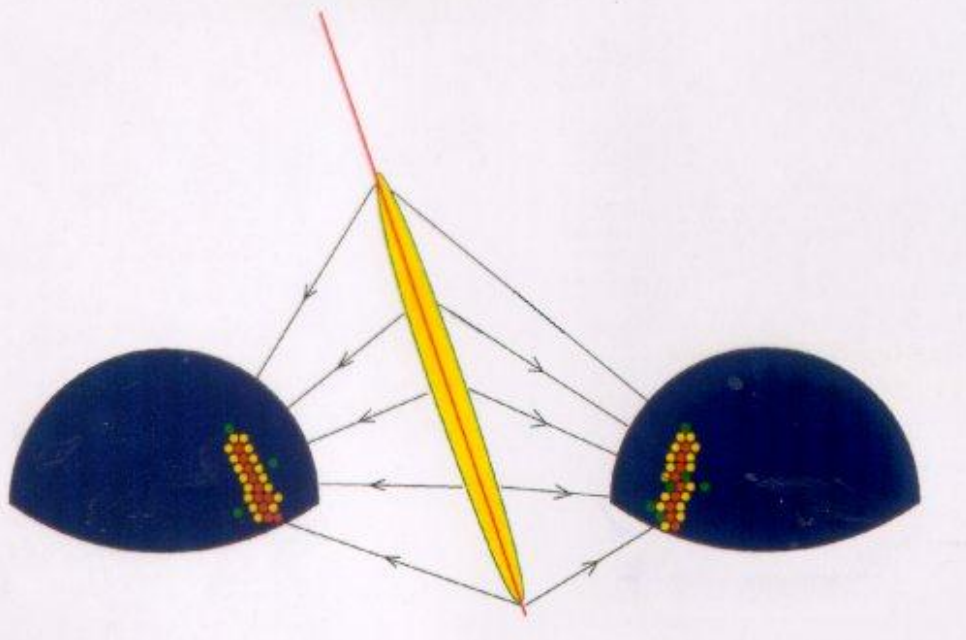


- Energy table is constructed using the MC (CORSIKA)
- Determination of event energy by interpolating between S800 vs. $\sec(\theta)$ lines
- Uses novel “de-thinning” of CORSIKA (paper draft in internal review)

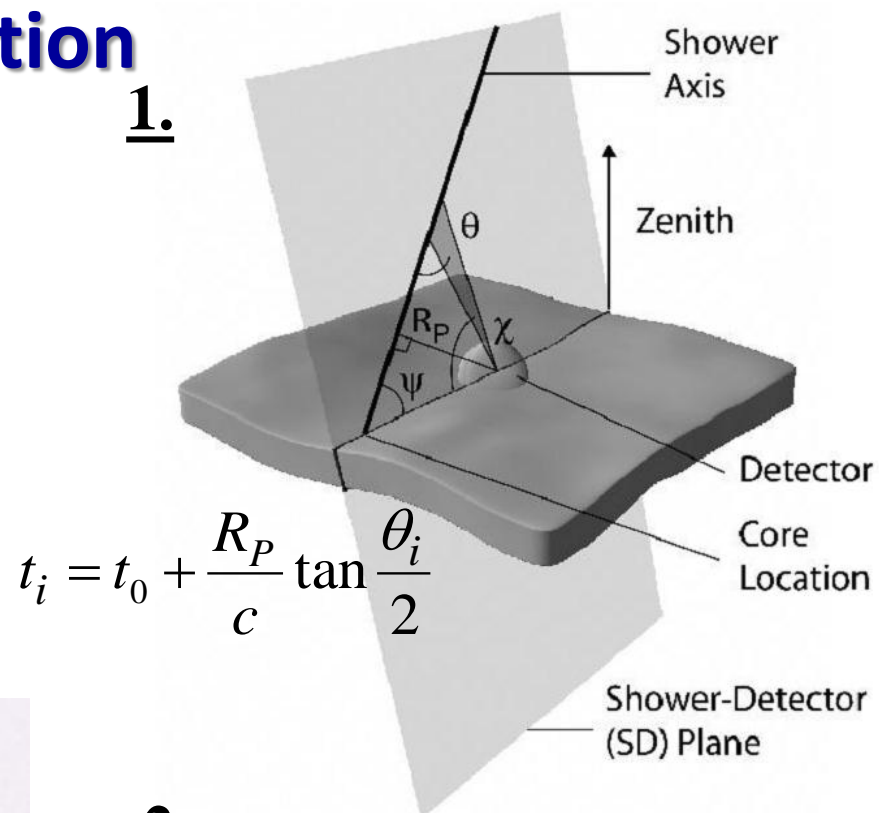
FD Geometrical Reconstruction

The trajectory of the EAS can be determined in one of two ways:

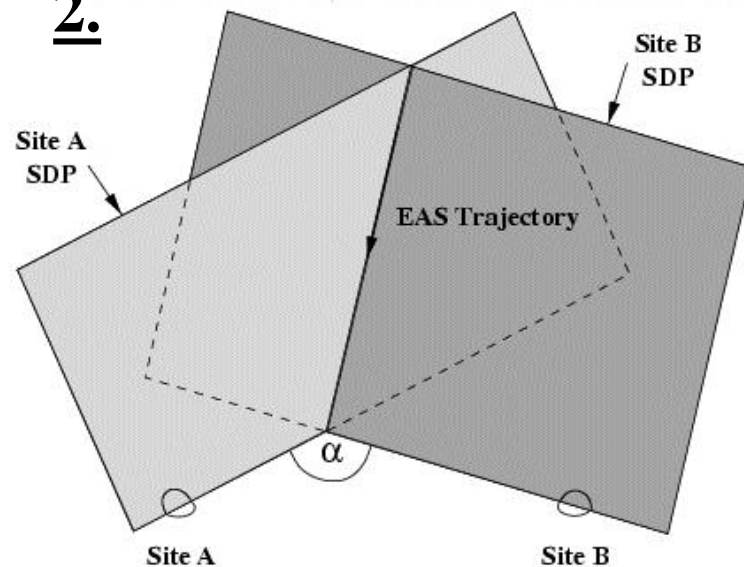
1. Monocular reconstruction using the arrival time of light signal at the detector.
2. By intersecting the shower-detector planes (SDP) seen from the two detector sites.



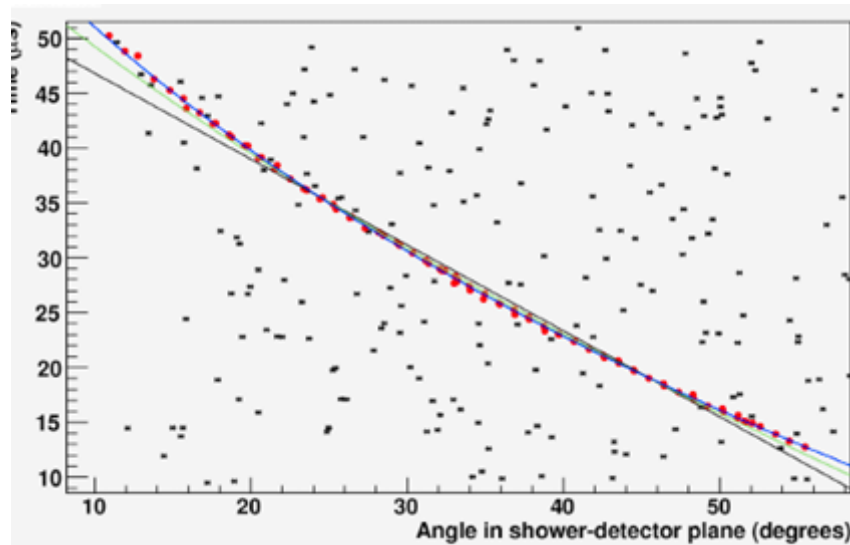
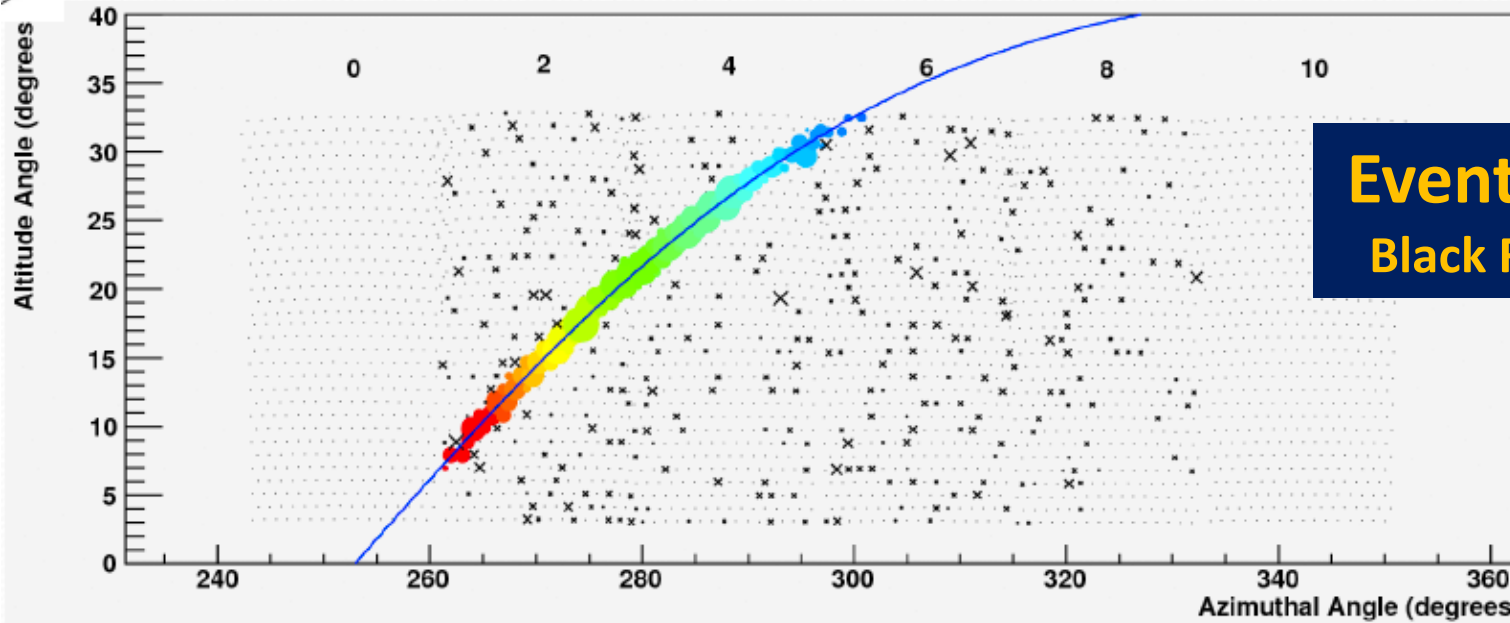
1.



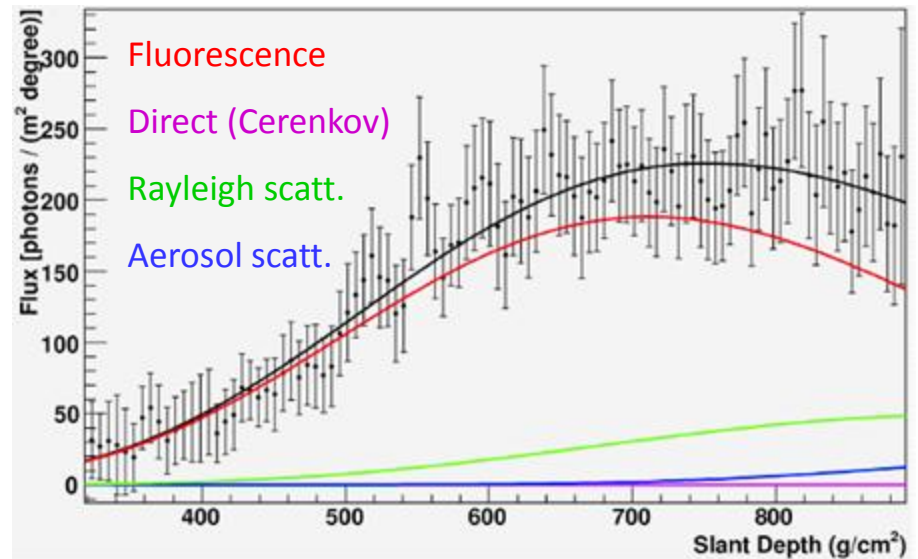
2.



Measurement of a fluorescence Event

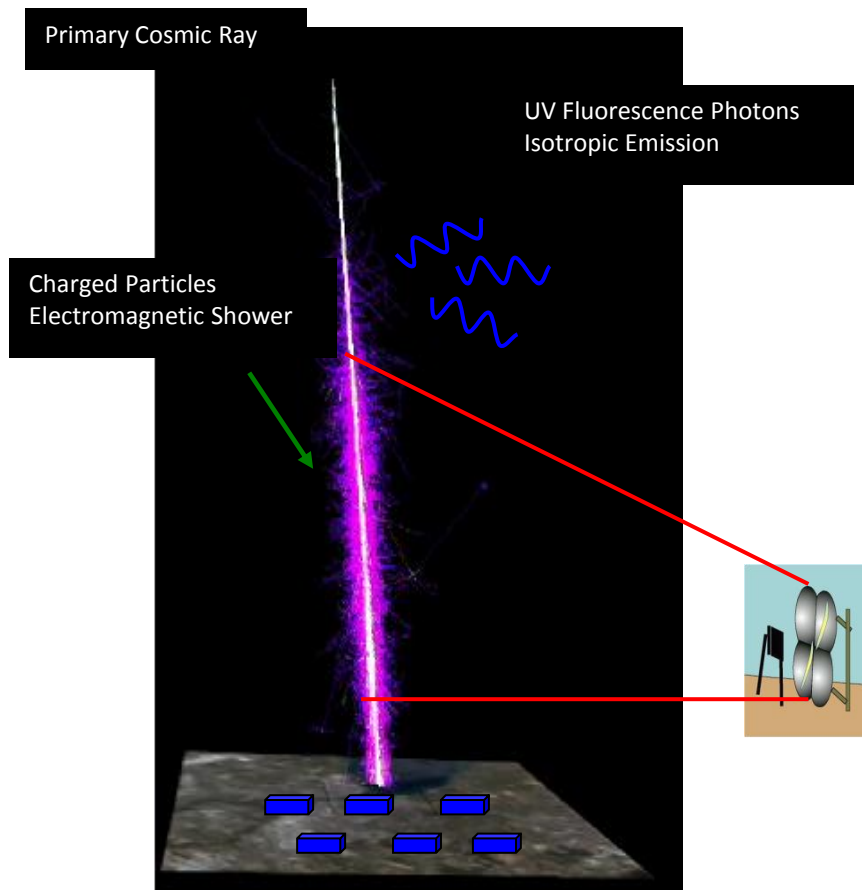


Monocular timing fit



Reconstructed Shower Profile

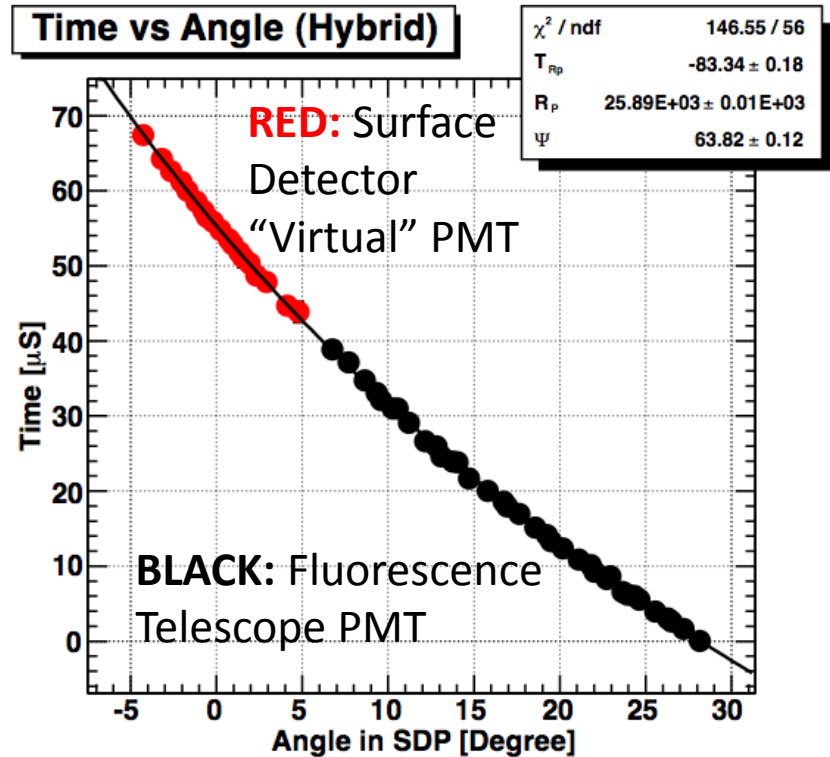
Hybrid Reconstruction



FD mono has $\sim 5^\circ$ ang. resolution

Adding SD $\rightarrow \sim 0.5^\circ$ resolution.

(Stereo FD resolution $\sim 0.5^\circ$)

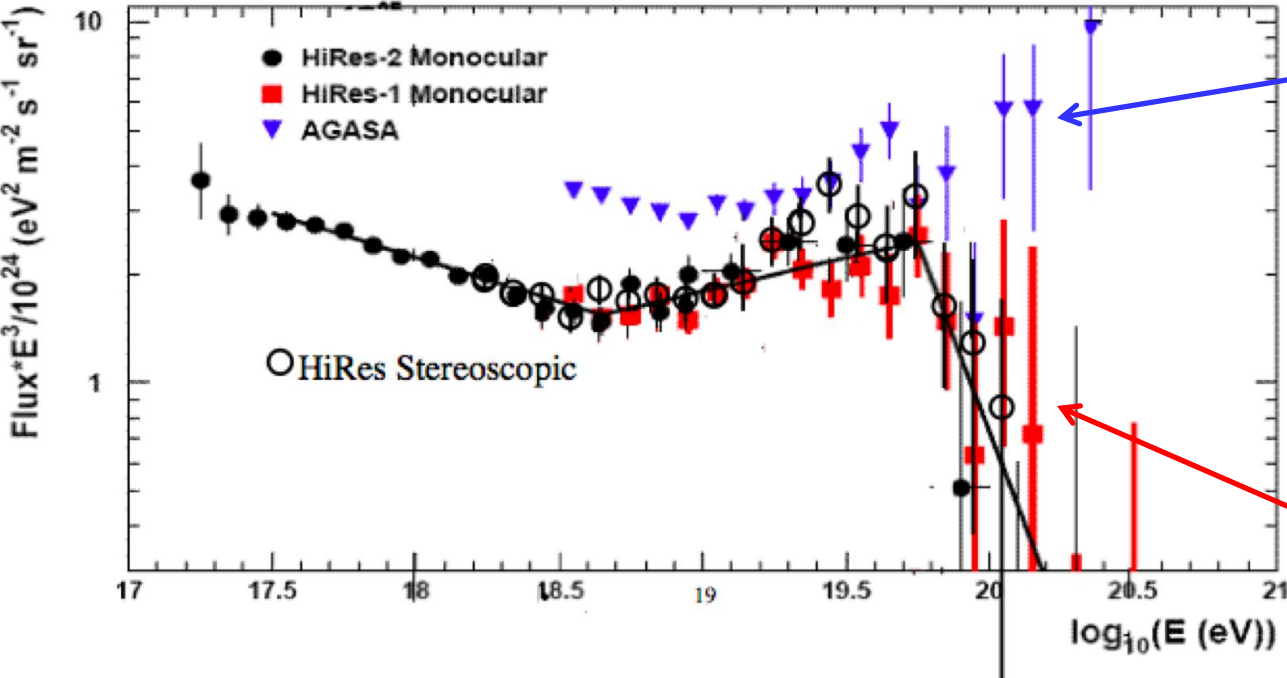


3. Hybrid reconstruction:

Incorporating timing information of SD into FD geometry fit

Energy Spectrum of UHE CR

- The TA Collaboration was in part a merger of the High Resolution Fly's Eye (HiRes) and the Akeno Giant Air Shower Array (AGASA)
- AGASA and HiRes disagreed over the observation of the GZK Suppression @ $\sim 10^{19.8}$ eV: proton+ CMBR $\gamma \rightarrow \Delta \rightarrow \dots$



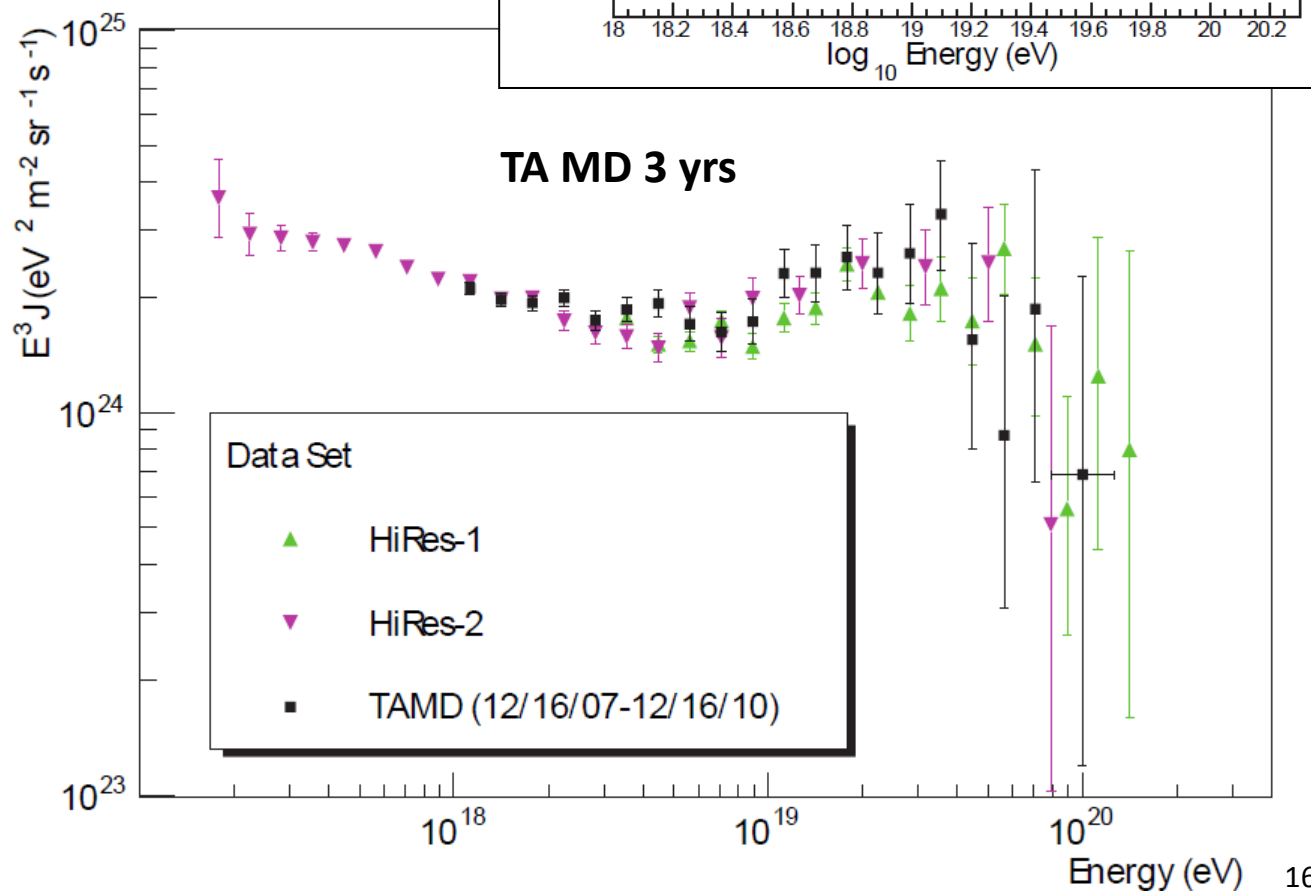
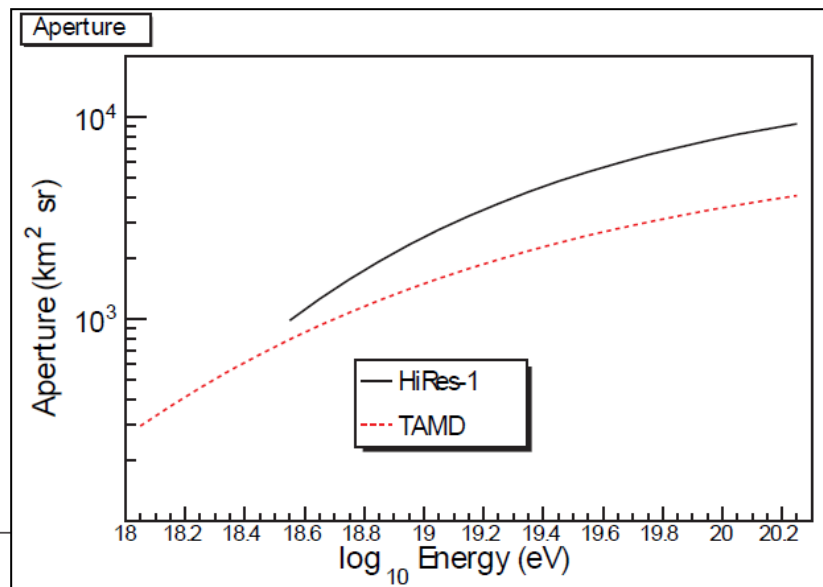
AGASA: continuing spectrum seen

Differential flux multiplied by E^3 To highlight the subtle features in a steeply falling spectrum

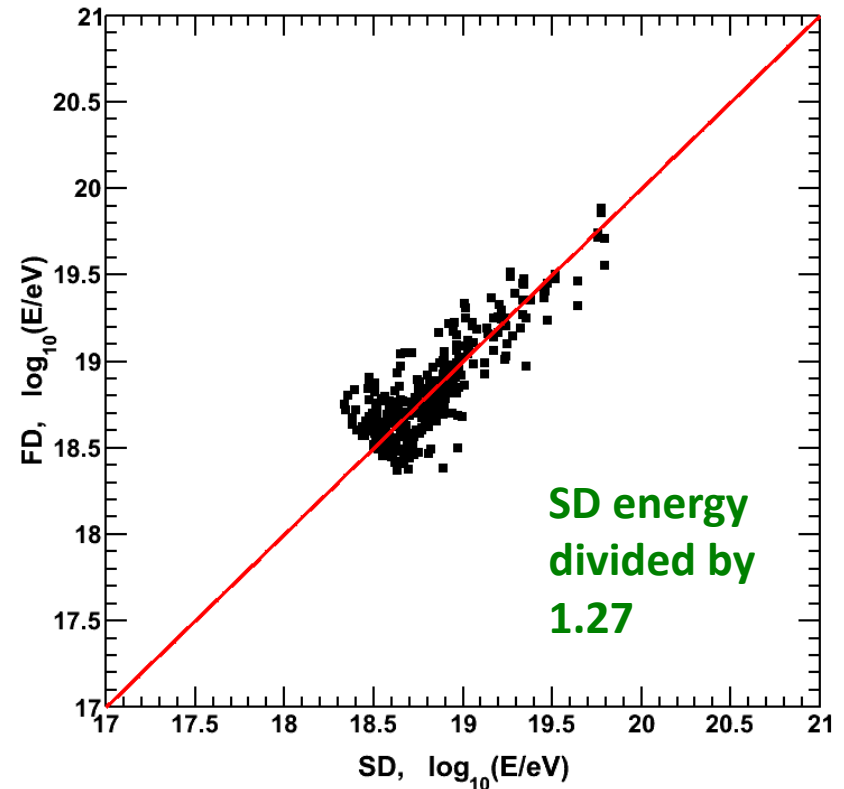
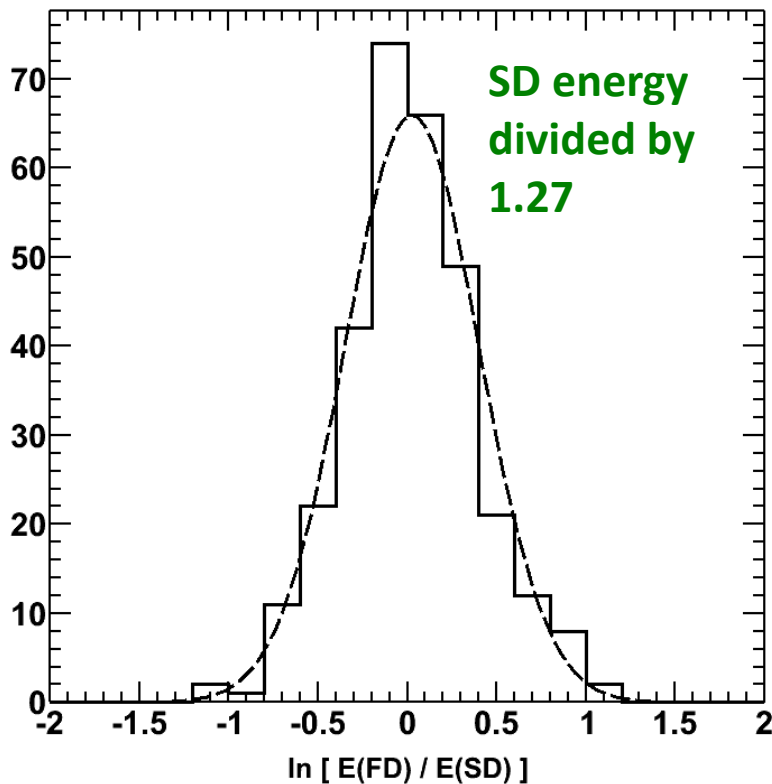
HiRes: GZK suppression At 5σ significance

TA Middle Drum FD

- TA Middle Drum (northern) FD site is instrumented with 14 refurbished telescopes from HiRes
- HiRes : 1 layer of telescopes: $< 17^\circ$ in elevation, all azimuths
- MD: two layers : $< 31^\circ$, 110° azimuth
- Same MC and reconstruction code for aperture calculation and spectrum as HiRes.
- 3 yrs = 1/3 exposure of HiRes
- **Same spectrum!** (paper draft in internal review)



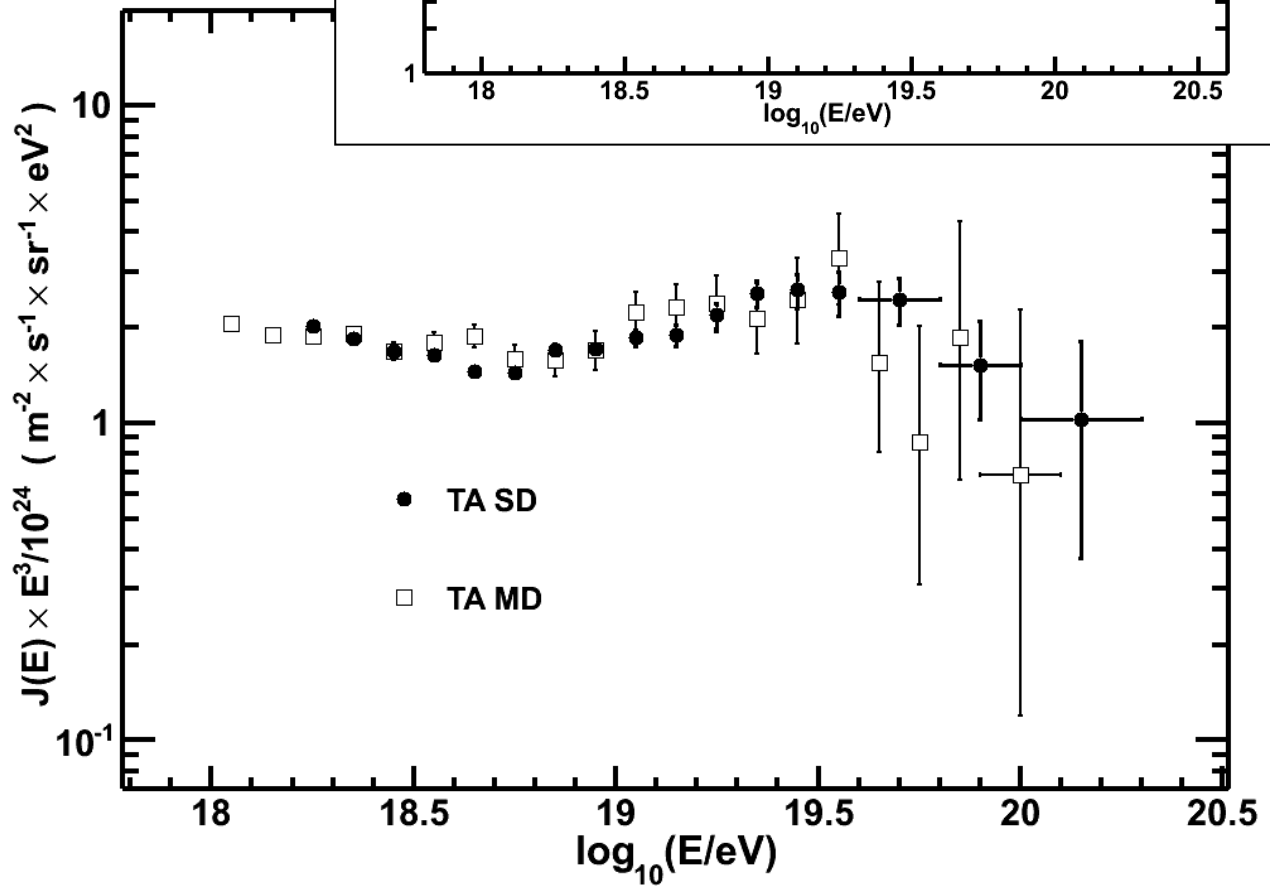
Transfer of HiRes energy scale



- Agreement between the TA MD and HiRes spectra (taken with the same telescopes) \rightarrow Common fluorescence energy scale for TA
- Hybrid events $> 10^{18.5}$ eV: SD energy scale (CORSIKA) 27% higher than the FD: adopt single (linear) scaling factor of 1.27

SD spectrum

- Using SD data from 2008/05/11-2011/04/25
- Only the energy is rescaled down by a factor of 1.27 (determined from hybrid events)
- 3 yrs of data represents about $2 \times$ AGASA exposure
- Resulting SD spectrum is in excellent agreement with the MD FD result
- **SD consistent with GZK Cut-off**



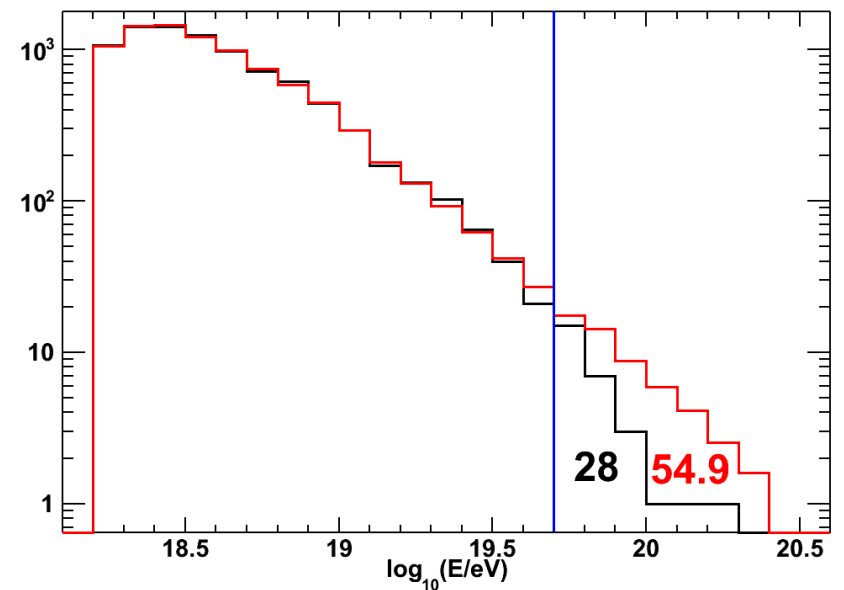
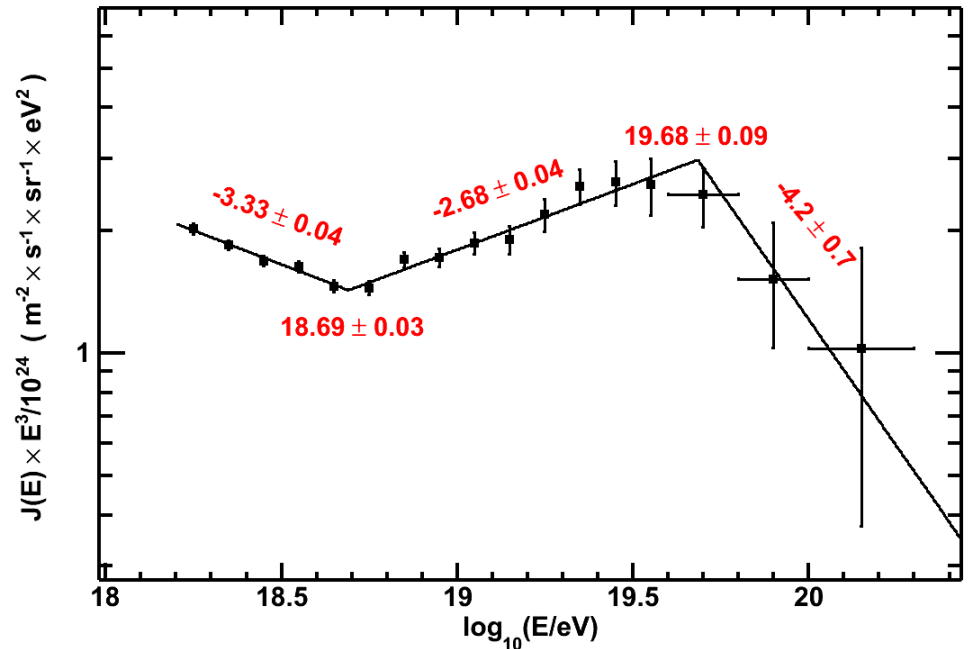
GZK significance

- Broken power law fits show breaks consistent with ankle and GZK cut-off as observed by HiRes (**GZK at 19.7 ± 0.1**)
- Assuming continuing power law beyond cut-off: Expect events; observe 28 events

$$\text{PROB} = \sum_{i=0}^{28} \text{Poisson}(\mu = 54.9; i) = 4.75 \times 10^{-5}$$

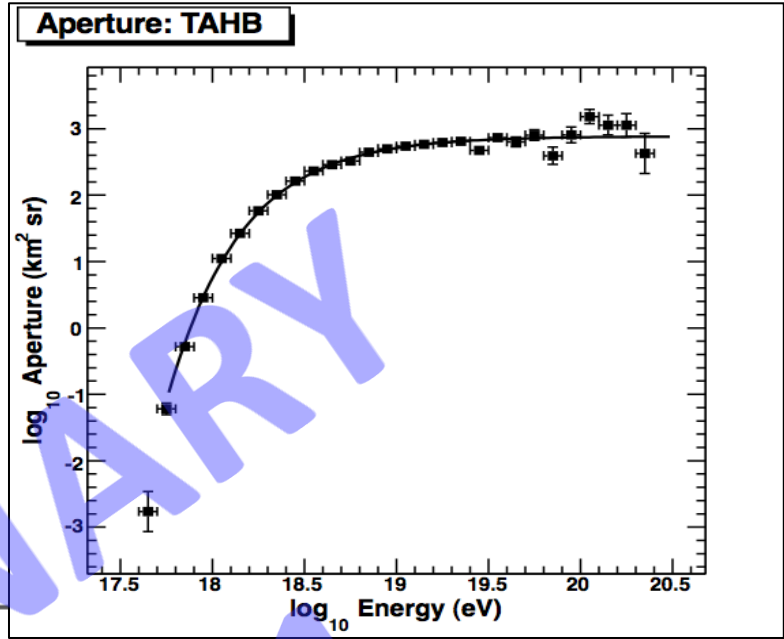
(3.9 σ)

(Paper draft in internal review)

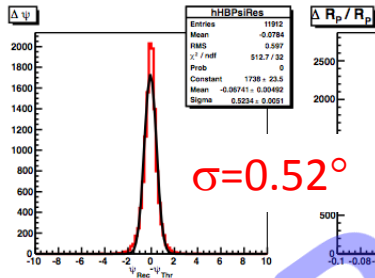


Hybrid Results: MD

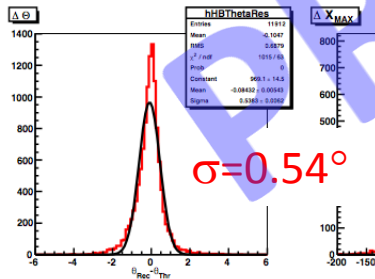
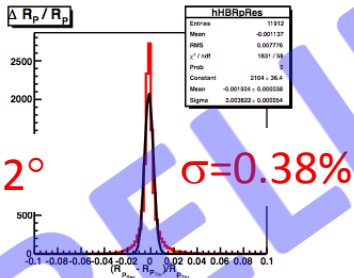
- Using hybrid events from MD site : energy spectrum in good agreement with SD spectrum
- Same FD MC and reconstruction code as HiRes but with hybrid geometry



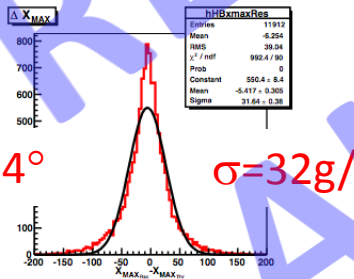
Ψ angle



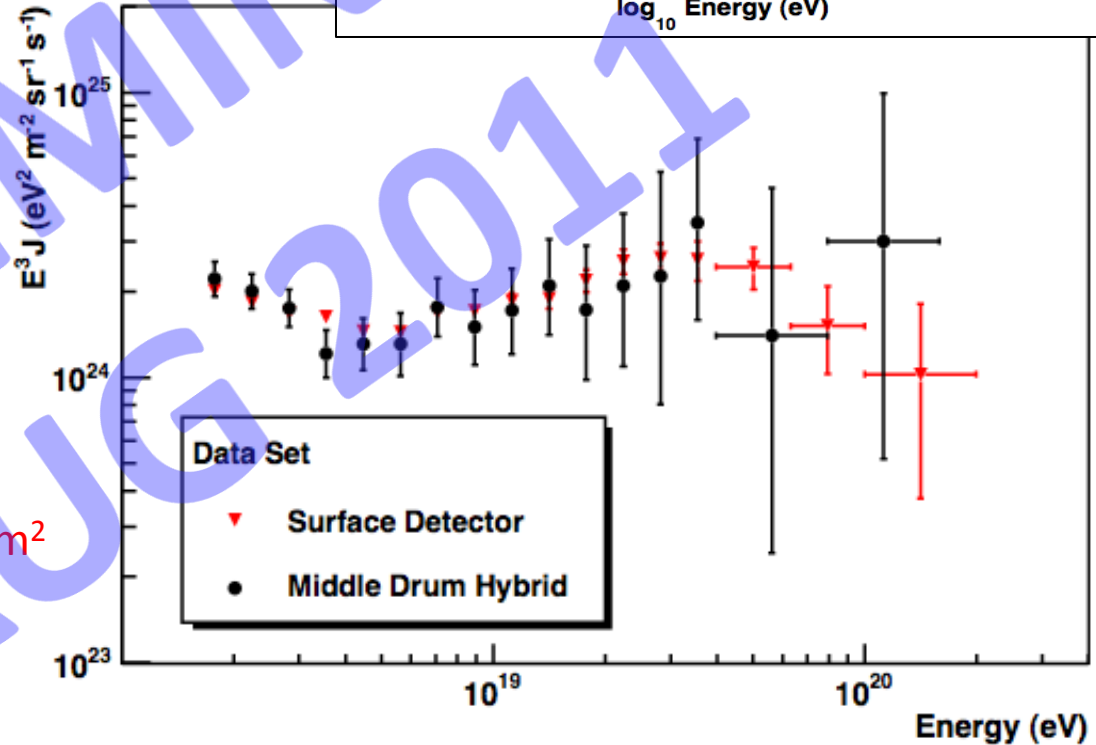
R_p



Zenith

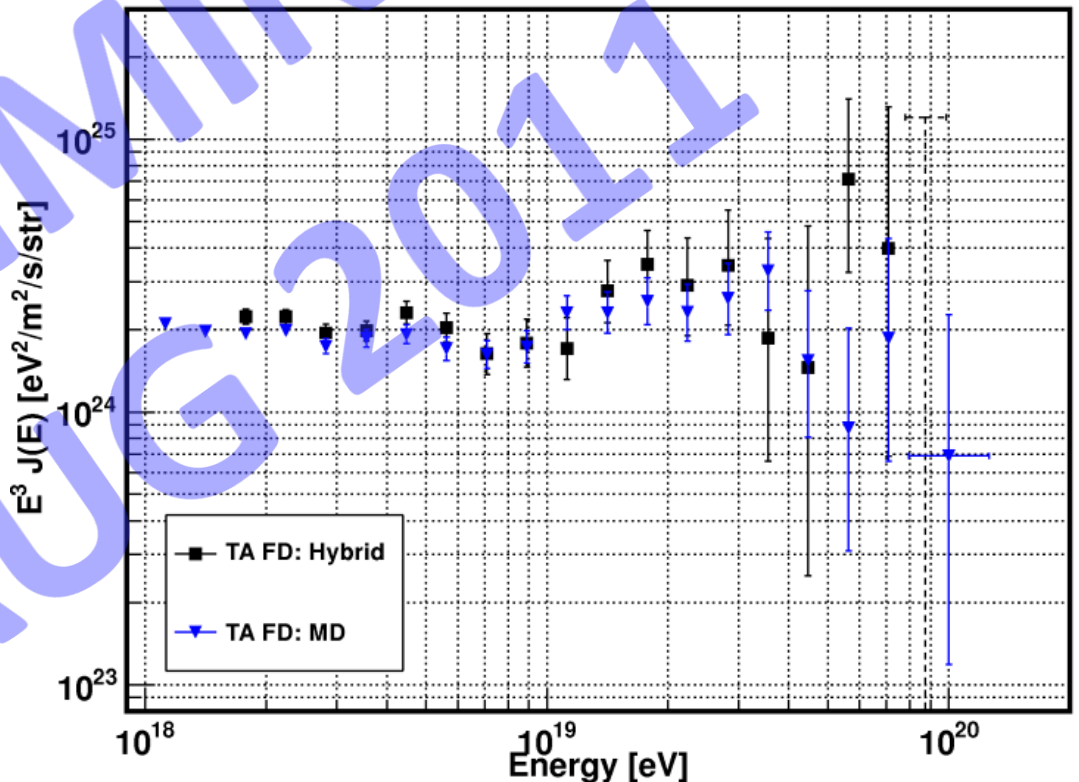
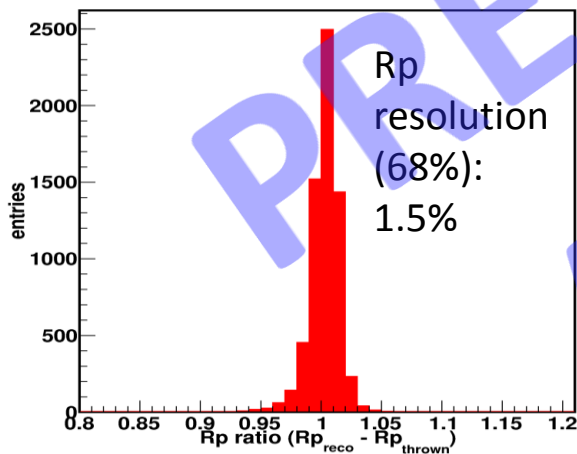
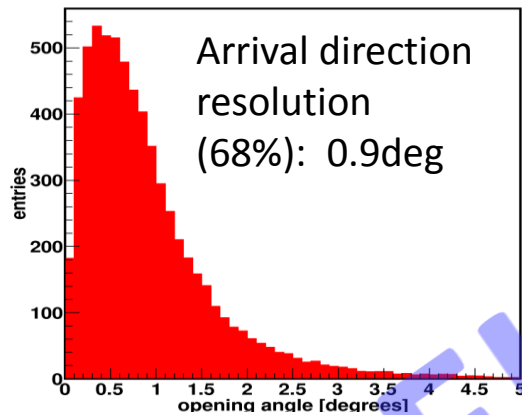
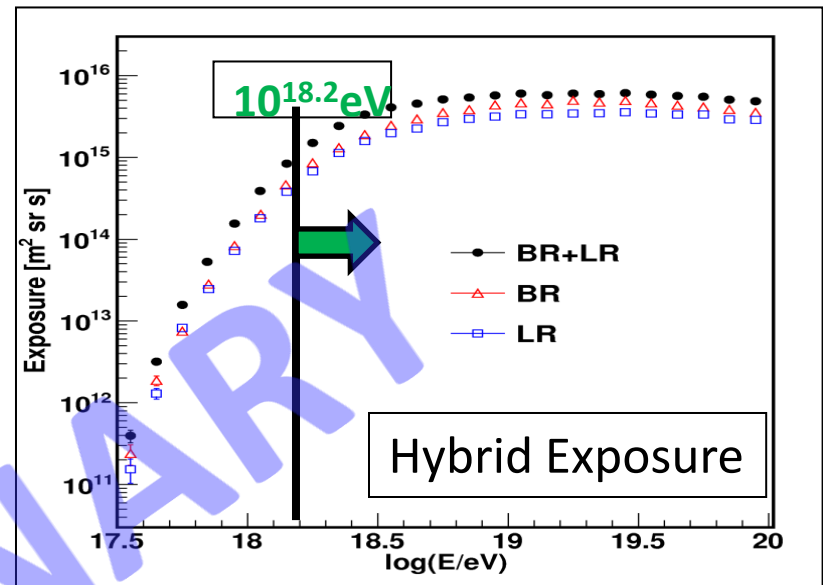


X_{max}



Hybrid Results: BR+LR

- BR+LR have large overlap:
- Combined hybrid spectrum **consistent with the others**
 - Overlaid with MD FD here



Composition Study: Xmax

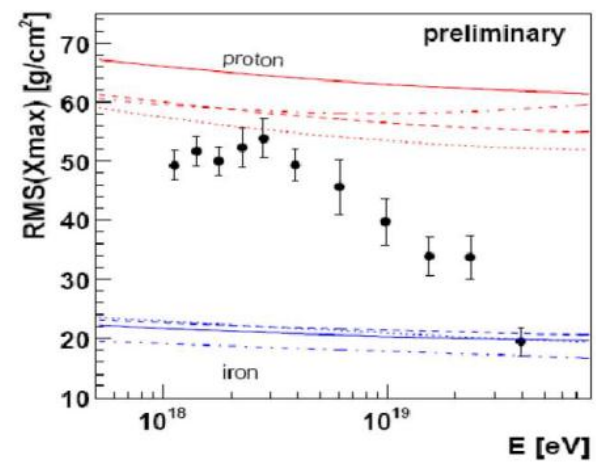
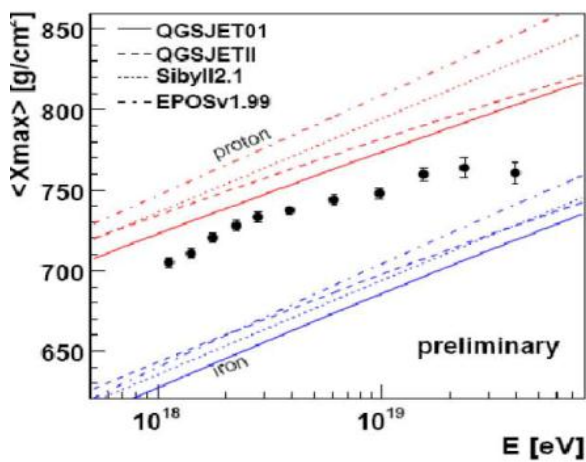
Controversy?

Collider Blog

Mar 3, 2010

<http://muon.wordpress.com/2010/03/03/highest-energy-cosmics-rays-are-iron-nuclei/>

The composition of the highest energy cosmic rays, those with energies on the order of tens of EeV (= 10^6 TeV), **appears to include a significant number of iron nuclei** – a result that I find truly astonishing. I learned about this from a nice post at [DiAx's Rake...](#)



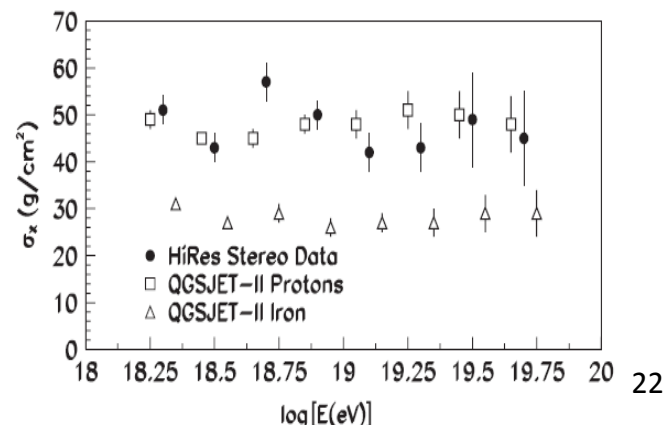
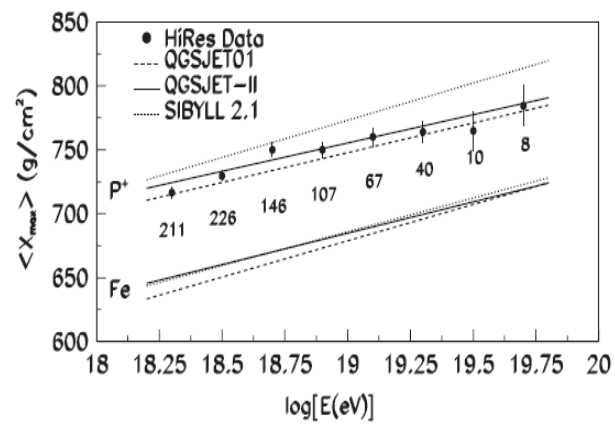
AUGER: Phys.Rev.Lett.104:091101,2010

Suggests shift to heavier composition at higher energies:

But the $\langle X_{max} \rangle$ and RMS(X_{max}) are inconsistent w.r.t a simple two-component model

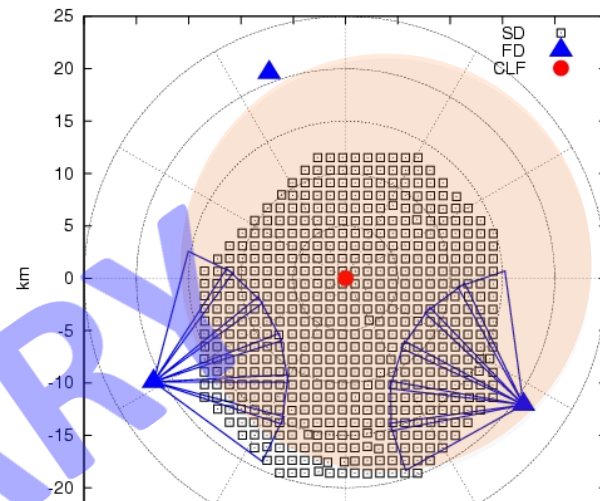
HiRes: Phys.Rev.Lett.104:161101,2010 (with X_{max} data suppl.)

Completely consistent with predominately light (protons) composition

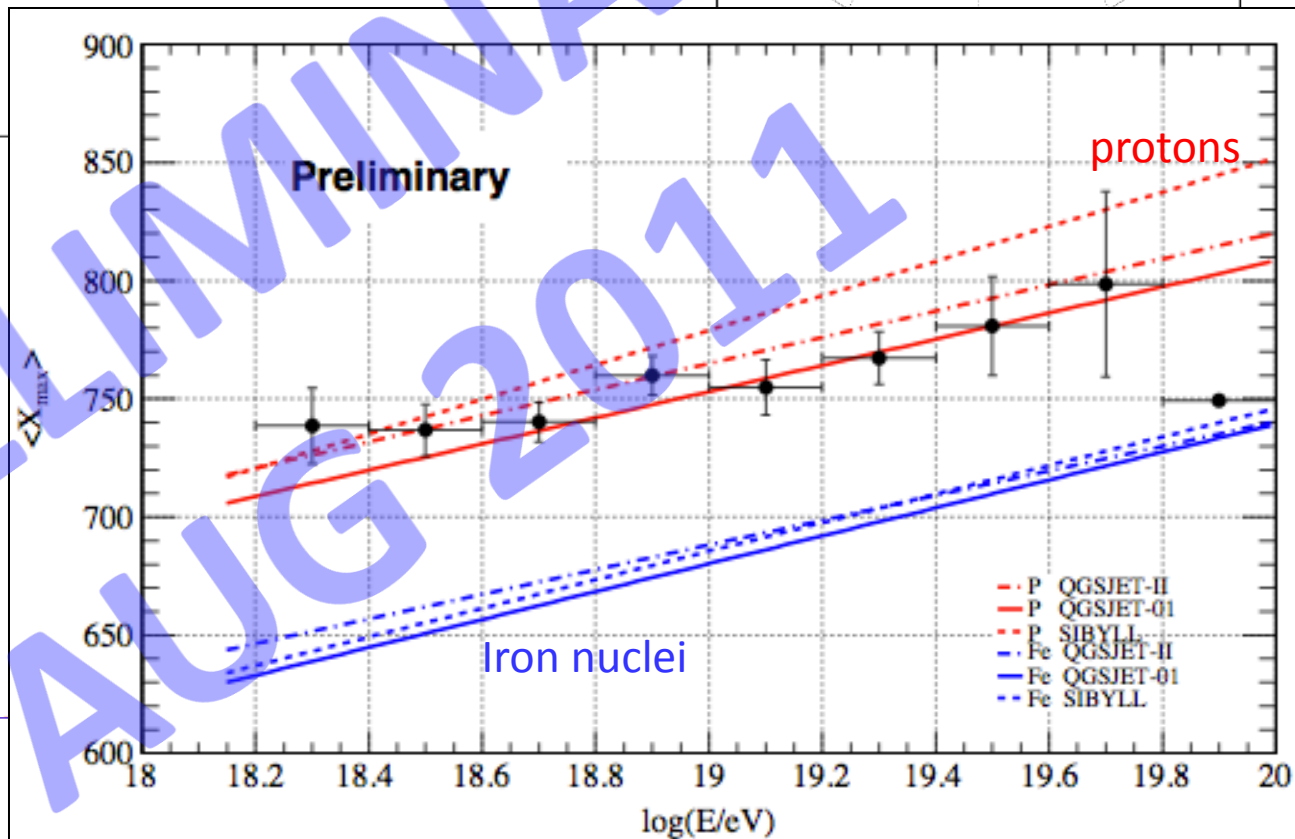
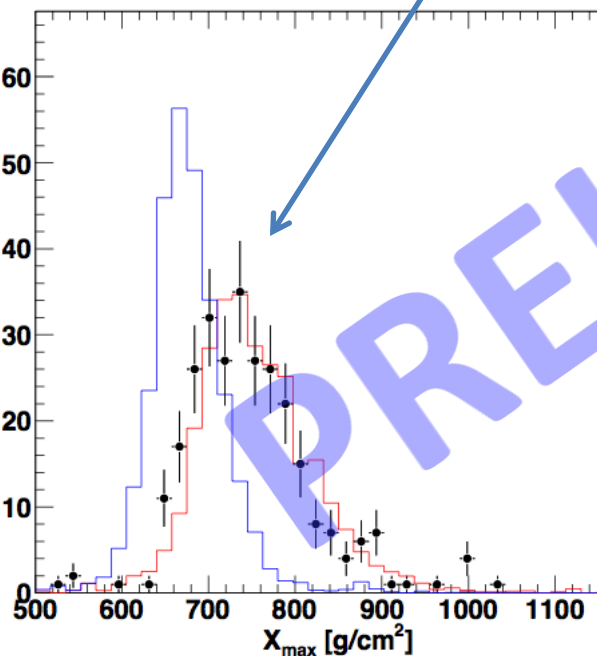


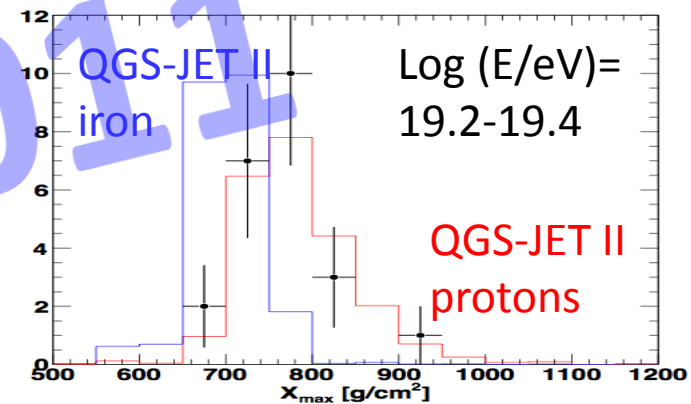
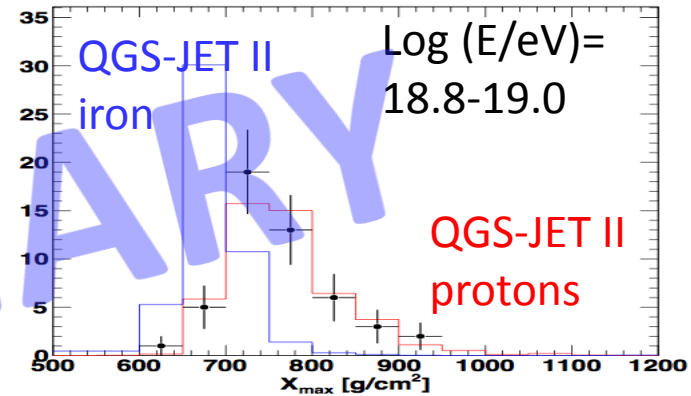
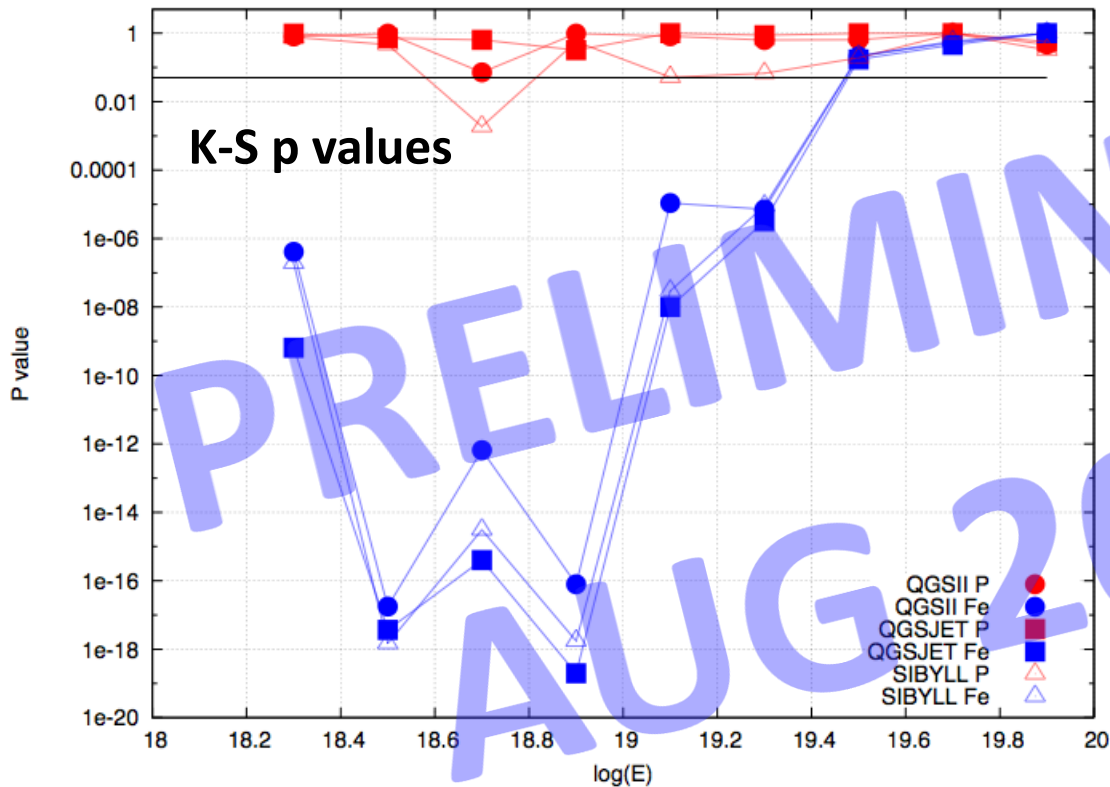
TA preliminary result from BR+LR stereo events

- First $\langle X_{\max} \rangle$ results consistent with predominately proton composition
- Over all distribution and shape also matches proton better than iron.



QGSJET-II





- In 0.2 logE bins data distribution also agrees better with protons
- K-S test favors protons (line at $p=0.05$) up to $10^{19.3}$ eV
 - Low statistics at $10^{19.4}$ eV and above (~ 2.5 years of data)

- **Coming soon**

- **Xmax width analysis**
- **Hybrid Xmax analysis**

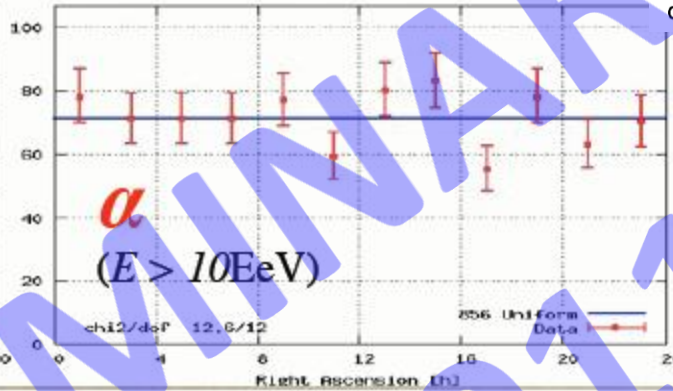
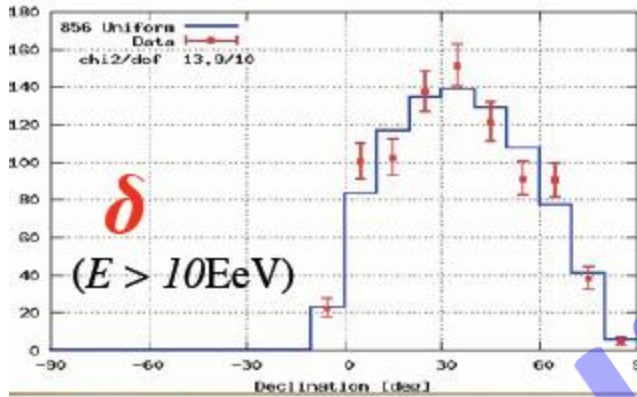
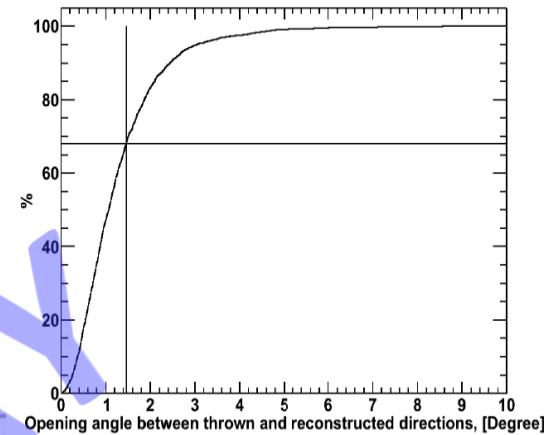
- **Future**

- **Pushing analysis up to the GZK cut-off with more events**

Anisotropy?

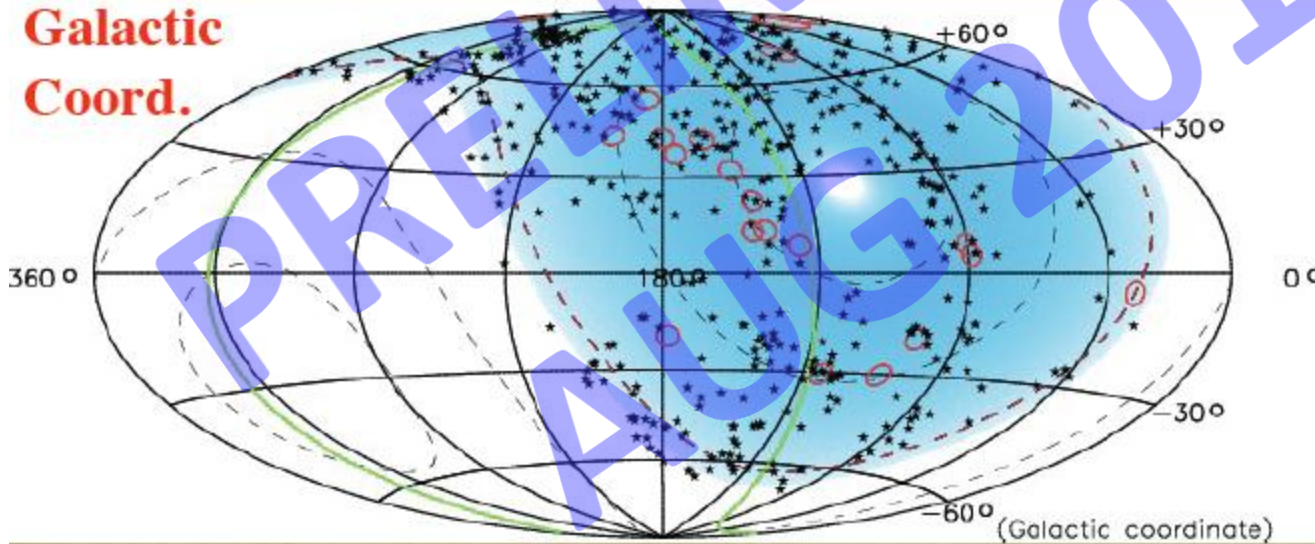
- 3 yrs of SD Events :
 - 856 events $> 10^{19}$ eV;
 - 49 events $> 4.0 \times 10^{19}$ eV

Angular resolution
 $\sim 1.5^\circ$ at $> 10^{19}$ eV



- Dec and RA distribution consistent with isotropy

Galactic Coord.



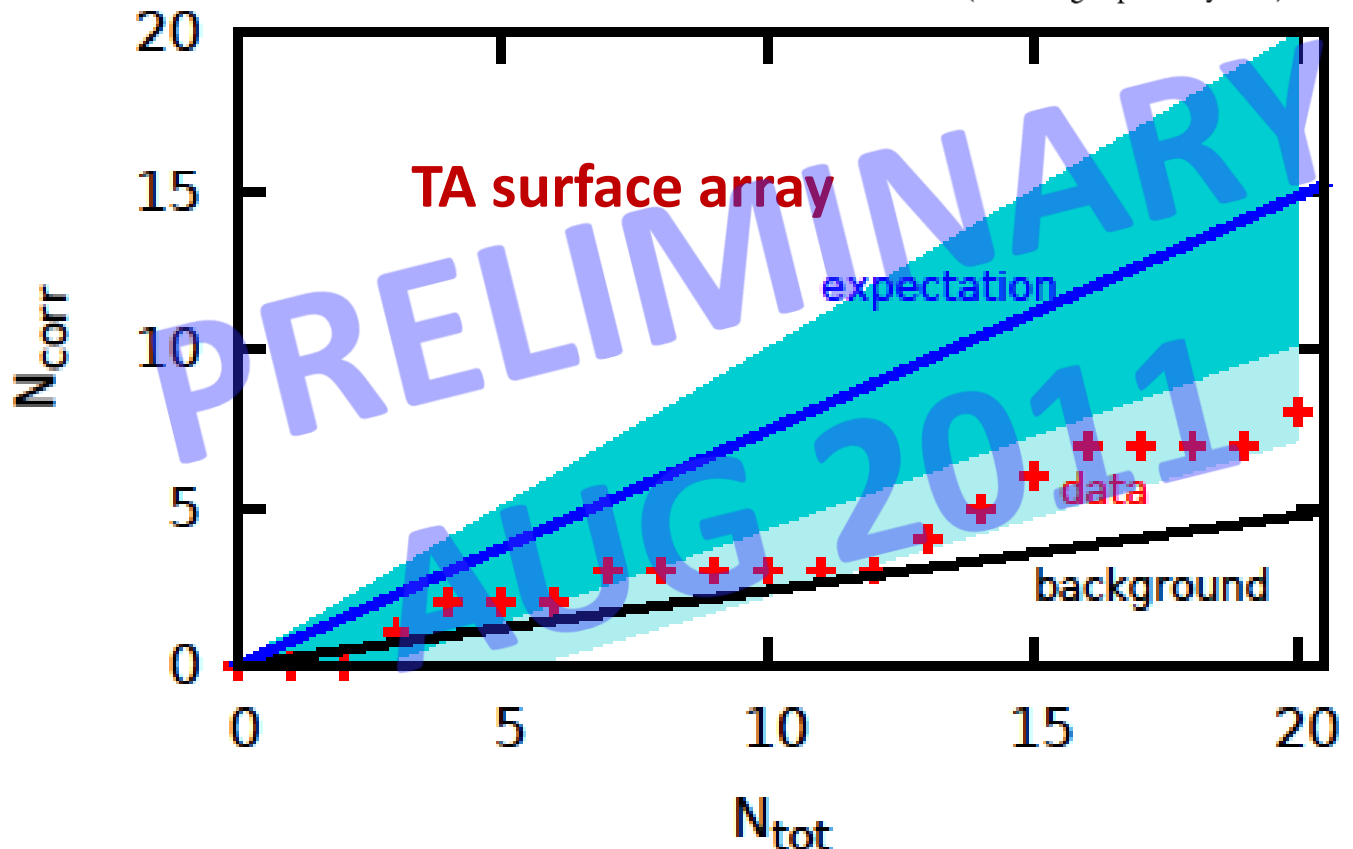
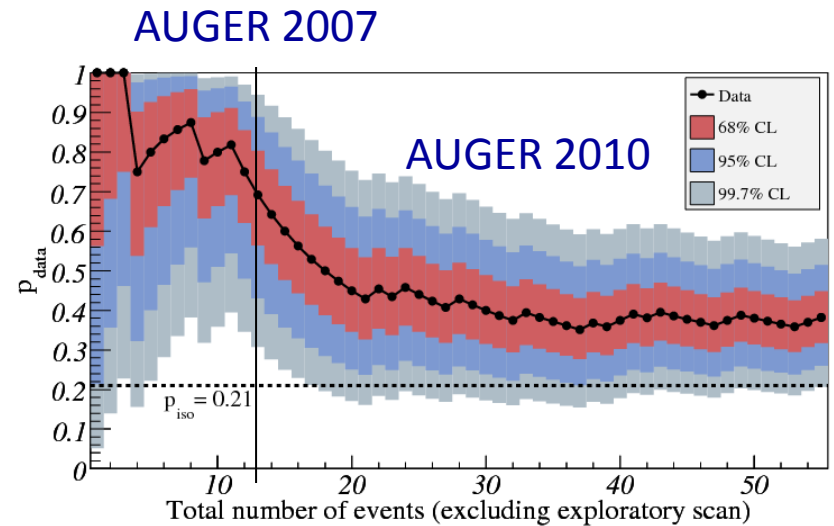
20 events
 $> 5.7 \times 10^{19}$ eV

★ AGN

○ TA SD event with 3.1 circle

AGN correlation?

- Using AUGER hypothesis (2007): 3.1° , $E > 5.7 \times 10^{19}$ eV correlated with AGN $z < 0.018$ (8/13 correlated)
- Expect: $\sim 15/20$, observe 8/20, vs. isotropic background: 5/20 \rightarrow $p_{\text{iso}} = 0.25$
- Updated AUGER (2010): 21/55 consistent with current TA result
- TA excess is however only 3 of 5 expected
- More TA data to come!



Conclusions

- Telescope Array has been observing UHE cosmic rays in the Northern Hemisphere for ~3 years
- Energy spectrum consistent with HiRes results (GZK cut-off + ankle structure)
 - *****TA surface scintillator array consistent with GZK cut-off**
- Preliminary $\langle X_{\max} \rangle$ composition result from stereo data **consistent with light (proton) composition**
 - X_{\max} width and hybrid results to follow soon
- TA SD data **consistent with isotropy**
 - But AUGER 2010 AGN correlation consistent with TA
- More data and results to come in the next few years
- Low Energy Extension (TALE) to begin construction in 2011
- RADAR detection of UHE cosmic rays at TA (a la **MARIACHI**) funded and underway (generating lots of RF interference!)