Recent Results of the Telescope Array Experiment

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Outline

- Telescope Array Experiment
- TA Results
  - Spectrum
  - Composition
  - Anisotropy
- The Future
- Conclusions

Telescope Array Collaboration

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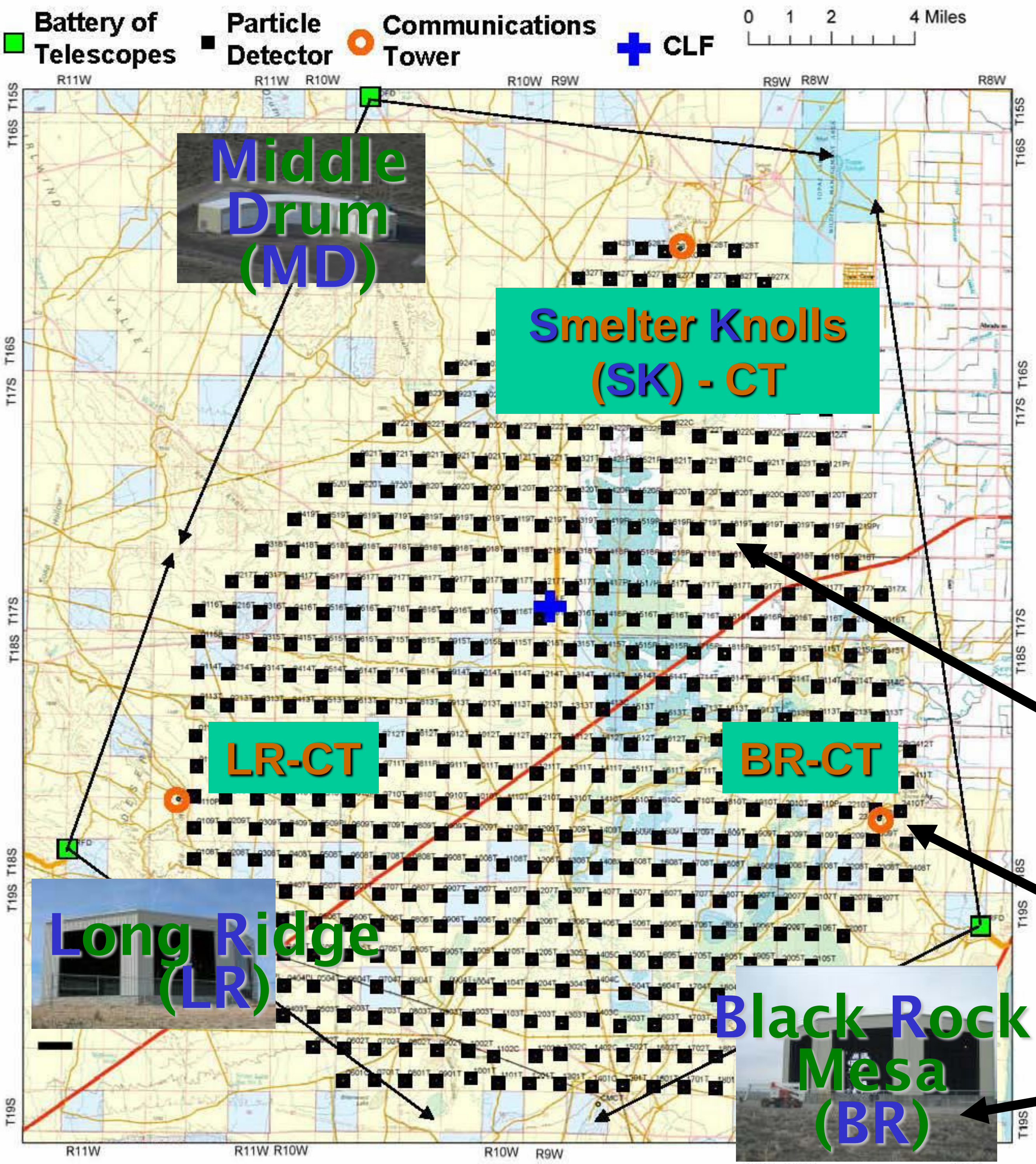
USA, Japan, Korea, Russia, Belgium



Telescope Array(TA)

Hybrid detector

Millard County, UT
39.3° N , 112.9° W,
Alt. 1400m
~880g/cm^2

507 Surface Detector (SD) counters, 1.2km apart, cover 680km^2

3 Communication Towers (CT):
BR,LR,SK

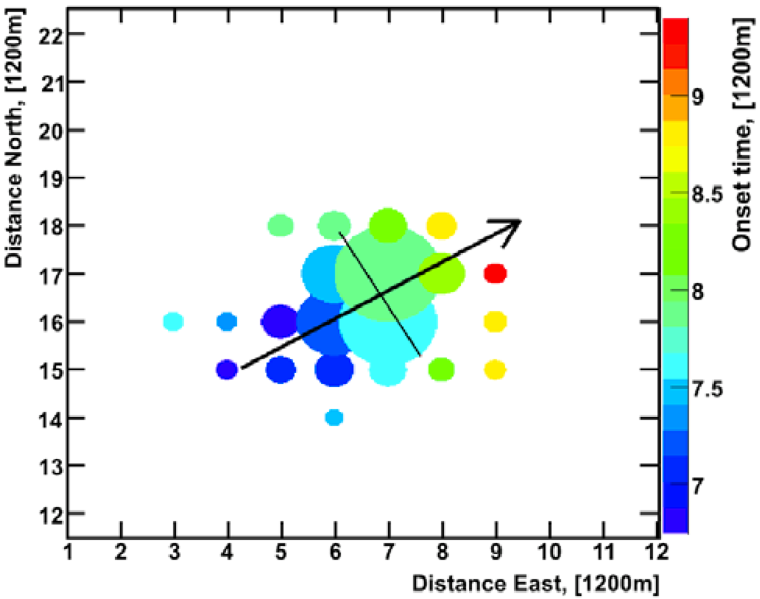
3 Fluorescence Detectors (FD):
BR,LR,MD

TA Surface Detector

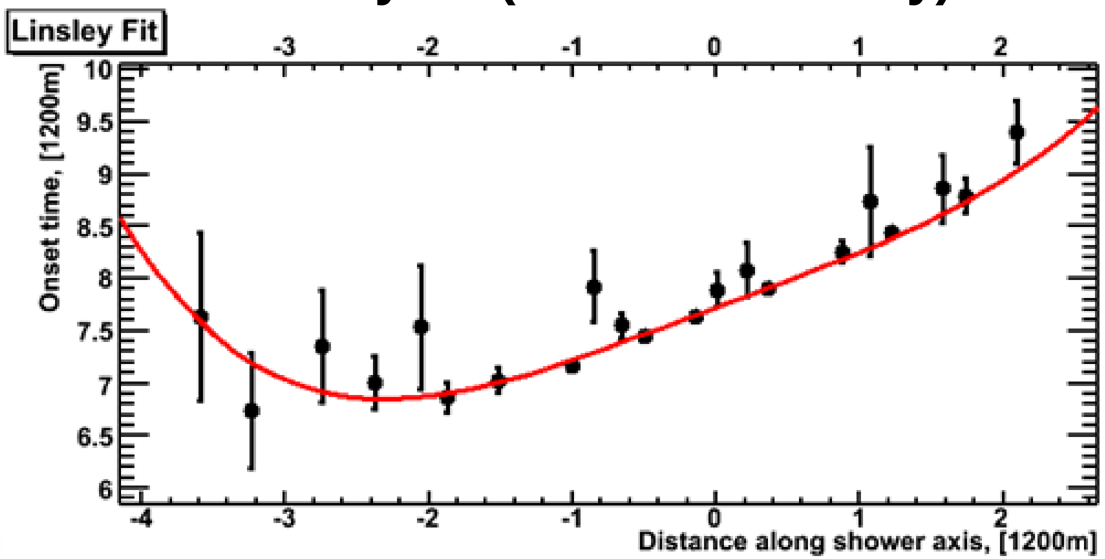
- Scintillation counters, area = 3 m^2.
- Powered by solar cells; radio readout.
- In operation since March, 2008.
- Self-calibration using single muons.

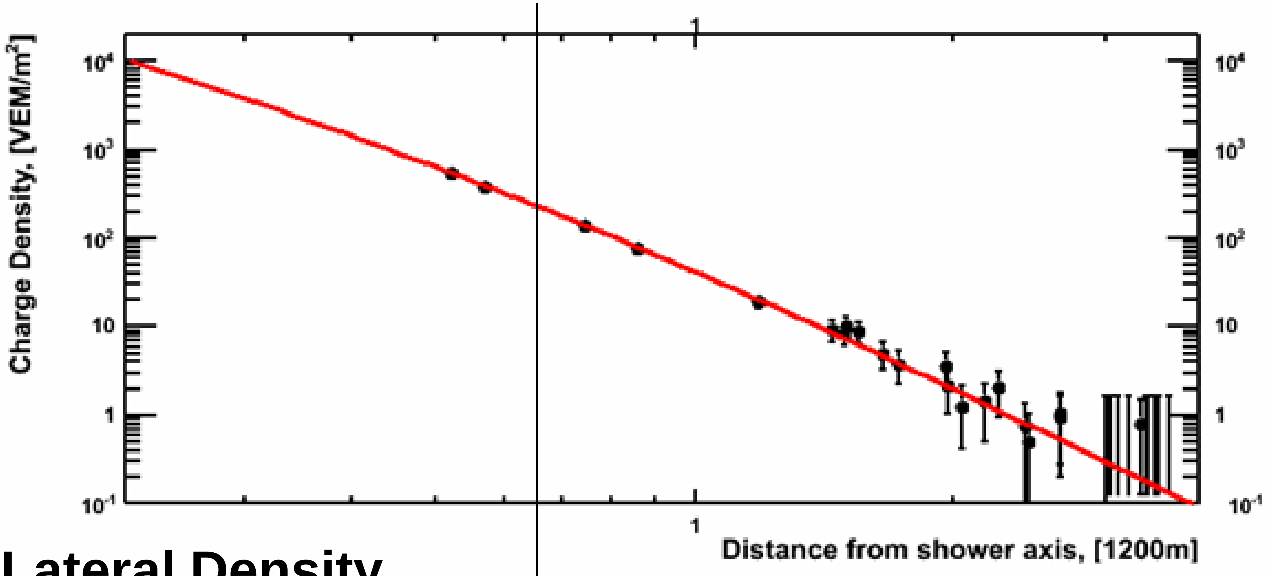
Typical surface detector event

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



Geometry Fit (modified Linsley)





Fit with AGASA LDF

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

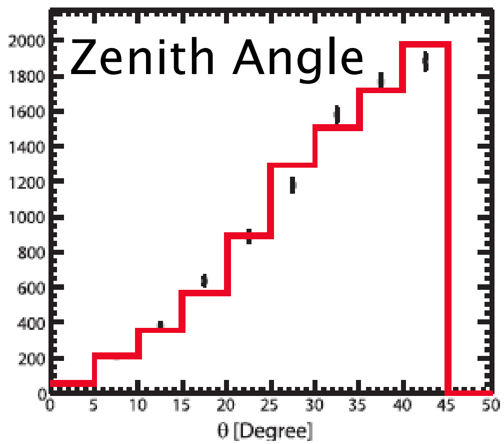
$$\eta = (3.97 \pm 0.13) - (1.79 \pm 0.62)(\sec\theta - 1)$$

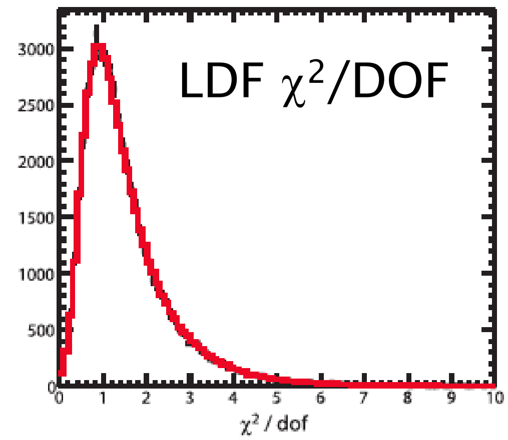
- S(800): Primary Energy
- Zenith attenuation by MC (not by CIC).

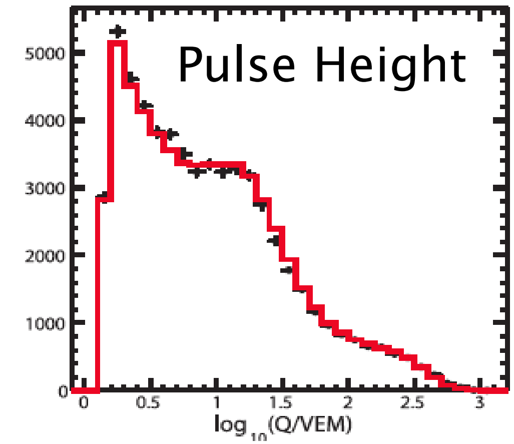
Lateral Density Distribution Fit

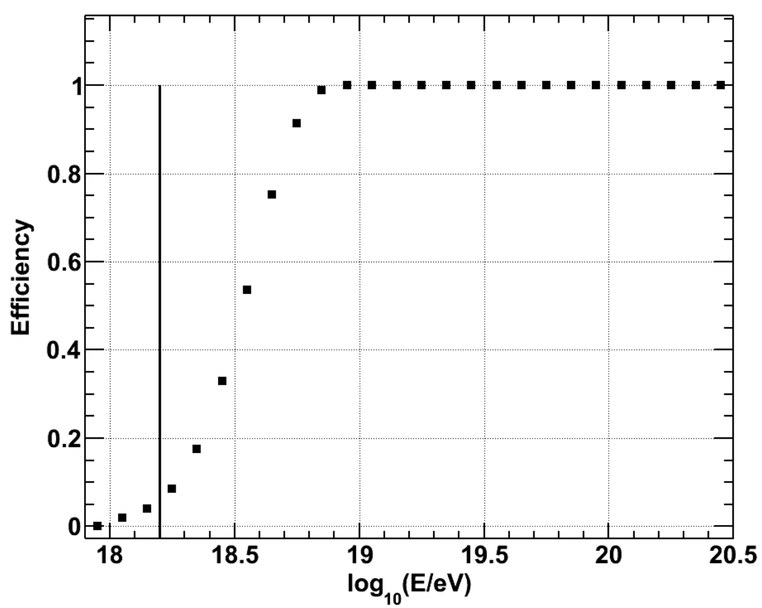
r = 800m

SD Data/MC Comparisons





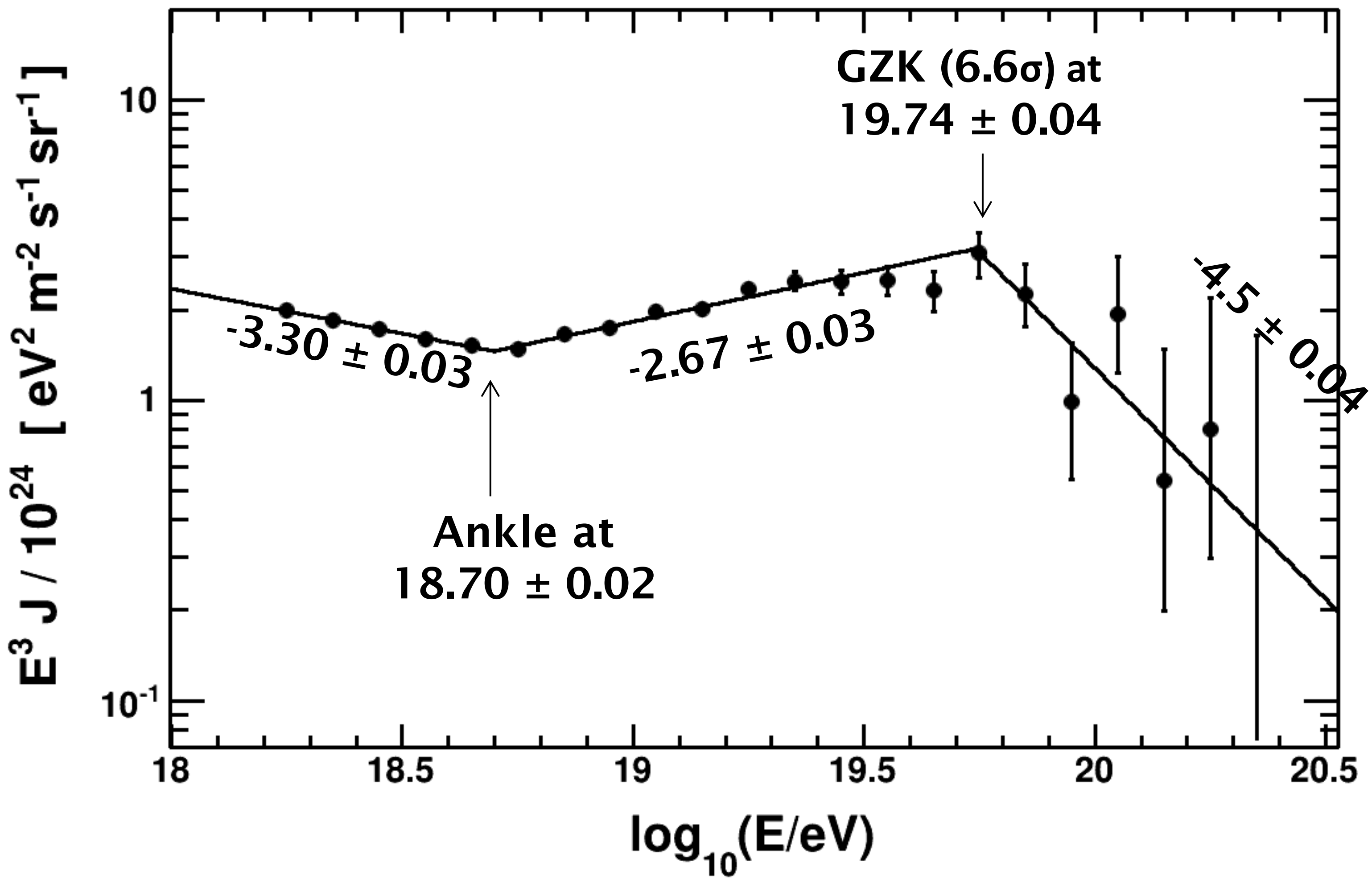




Detailed detector simulation and DATA/MC comparisons are done in all TA analyses.

Understand down to 8% efficiency

SD Spectrum



GZK (6.6σ) at
19.74 ± 0.04
-3.30 ± 0.03
-2.67 ± 0.03
-4.5 ± 0.04
Ankle at
18.70 ± 0.02
E^3 J / 10^{24} [eV^2 m^{-2} s^{-1} sr^{-1}]
log_{10}(E/eV)
10
1
10^{-1}
18
18.5
19
19.5
20
20.5

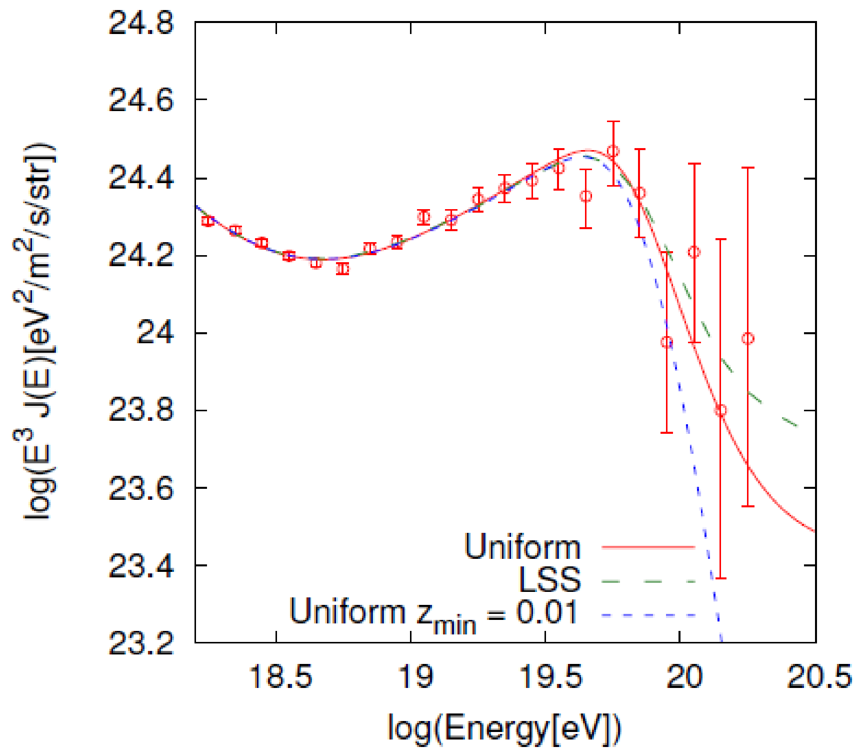
Fit spectrum to energy-loss model

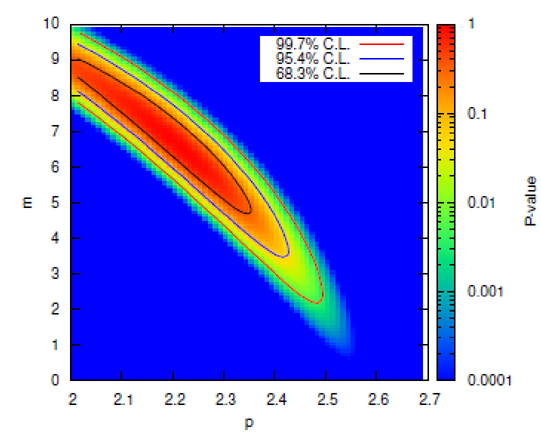
Inputs:

1. Protonic composition.
2. Pion photoproduction and e+e- pair production on CMBR.
2. Hubble expansion.

Fitting parameters:

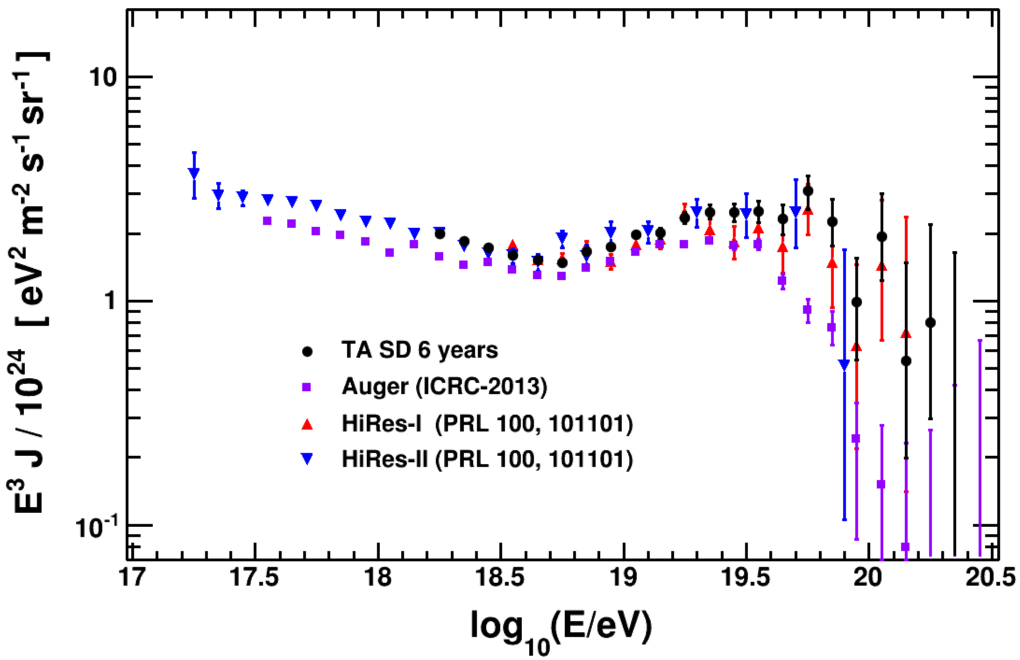
1. Power law at the source, E^{-p}
2. Evolution of the sources, $(1+z)^{m}$



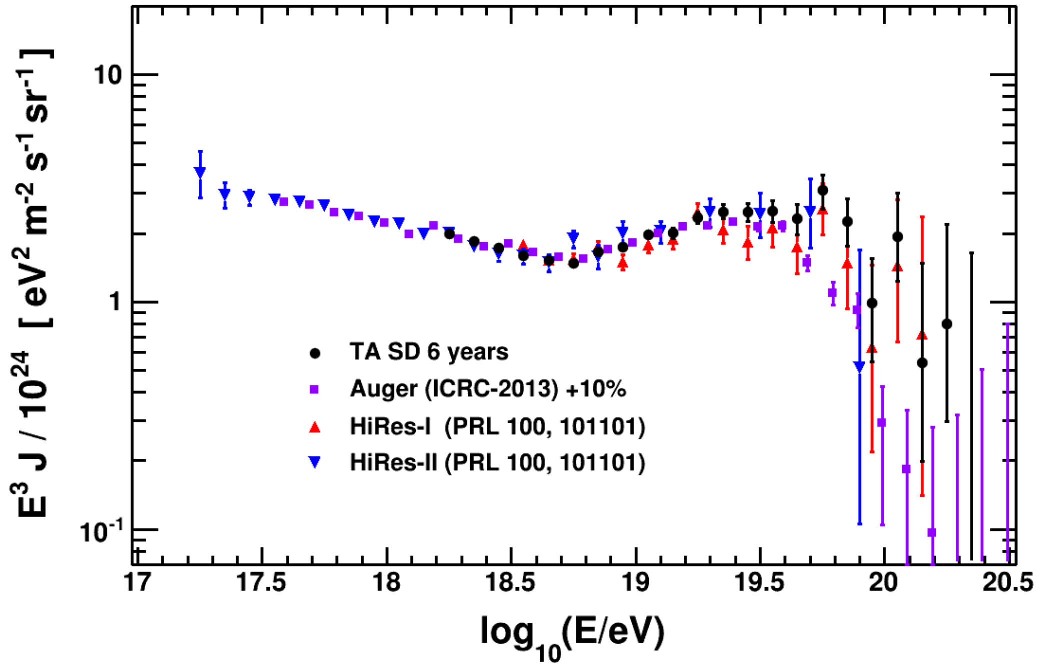


TA, HiRes, and Auger Spectra

as published



10% energy shift



Difference above $10^{19.3}$ eV.

Spectrum WG at UHECR2014 did not find an instrumental cause of the difference.

TA Low Energy Extension (TALE)

- Study the 10^{16} and 10^{17} eV decades with a hybrid detector.
  - End of the rigidity-dependent cutoff that starts with the knee (at 3×10^{15} eV).
  - The second knee
  - The galactic-extragalactic transition
- High energy physics measurements:
  - σ(p-air) and σ(p-p) from LHC energy (10^{17}) to 10^{19} eV.
- Need to observe from 3×10^{16} eV to 3×10^{20} eV all in one experiment. That is TA and TALE.

TALE FD

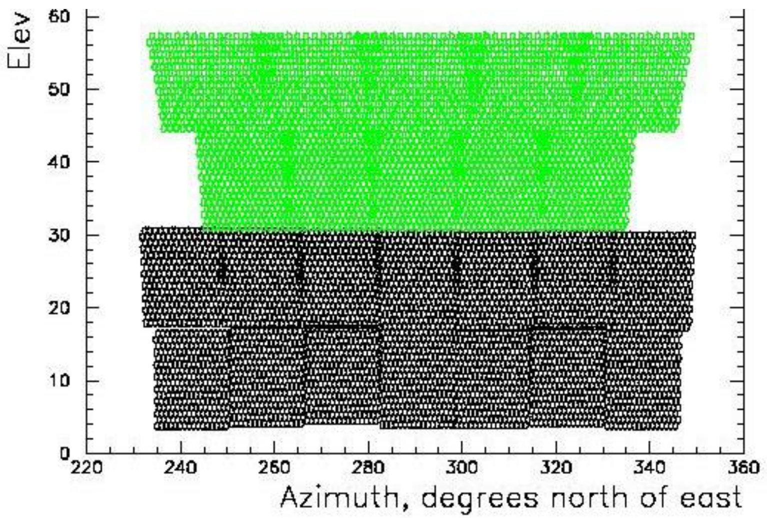
Add 10 telescopes at the Middle Drum site, looking from 31°-59° in elevation.

Operate in conjunction with the TA Middle Drum FD.

$10^{16.5} < E < 10^{20.5}$ eV

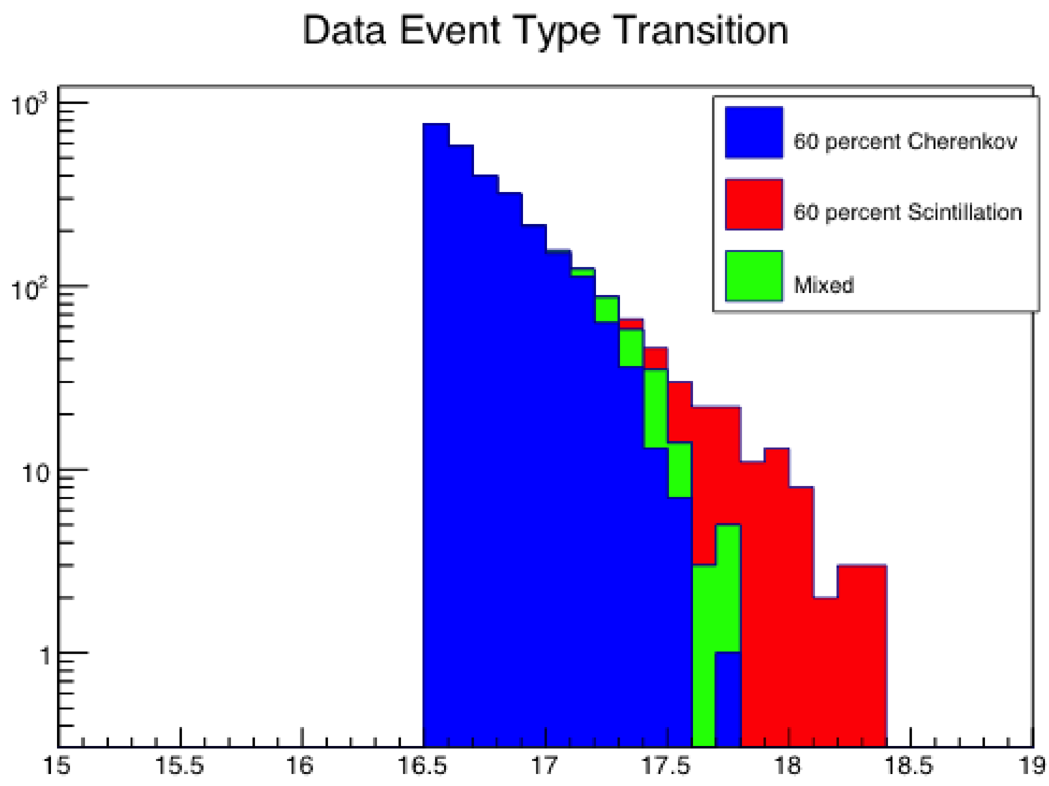
together

TALE telescopes



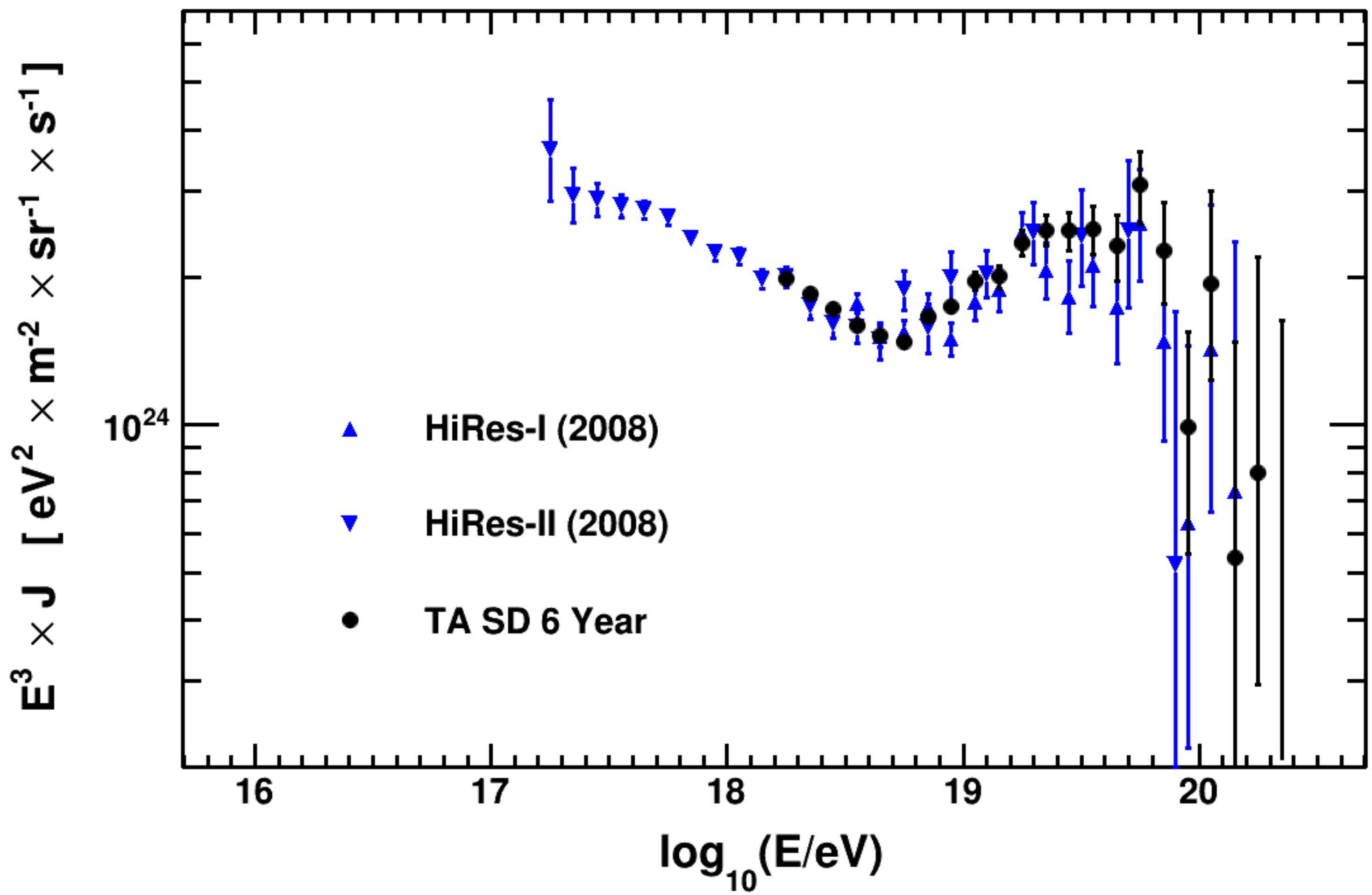
TA MD telescopes

TALE Cherenkov vs. Fluorescence

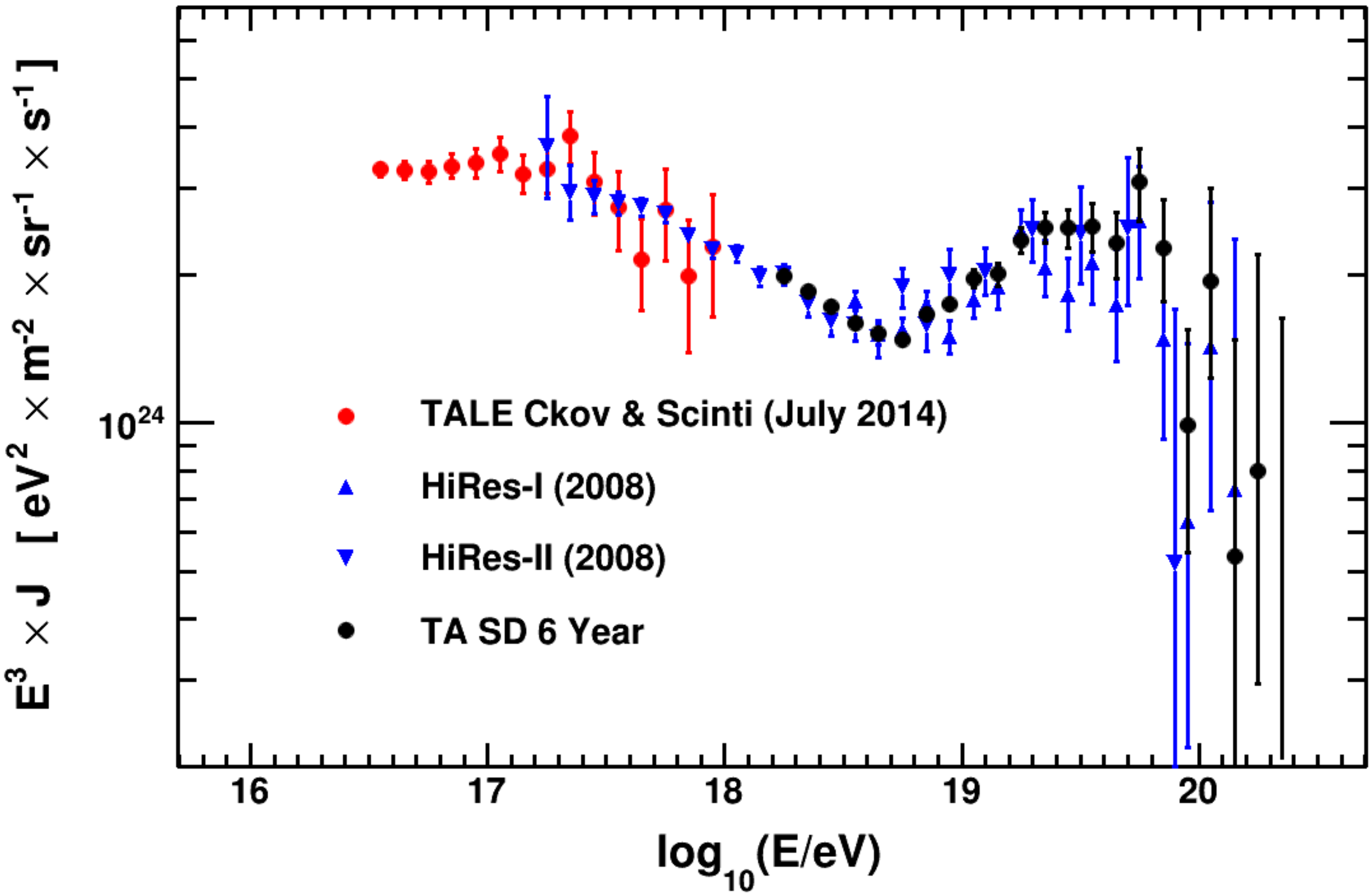


Unexpected result: many Cherenkov events are seen as tracks (most land ~0.5 km from FD).
Use profile constrained reconstruction.
Cherenkov light is bright ➔ can go lower in energy than expected.

TA SD and HiRes Spectra

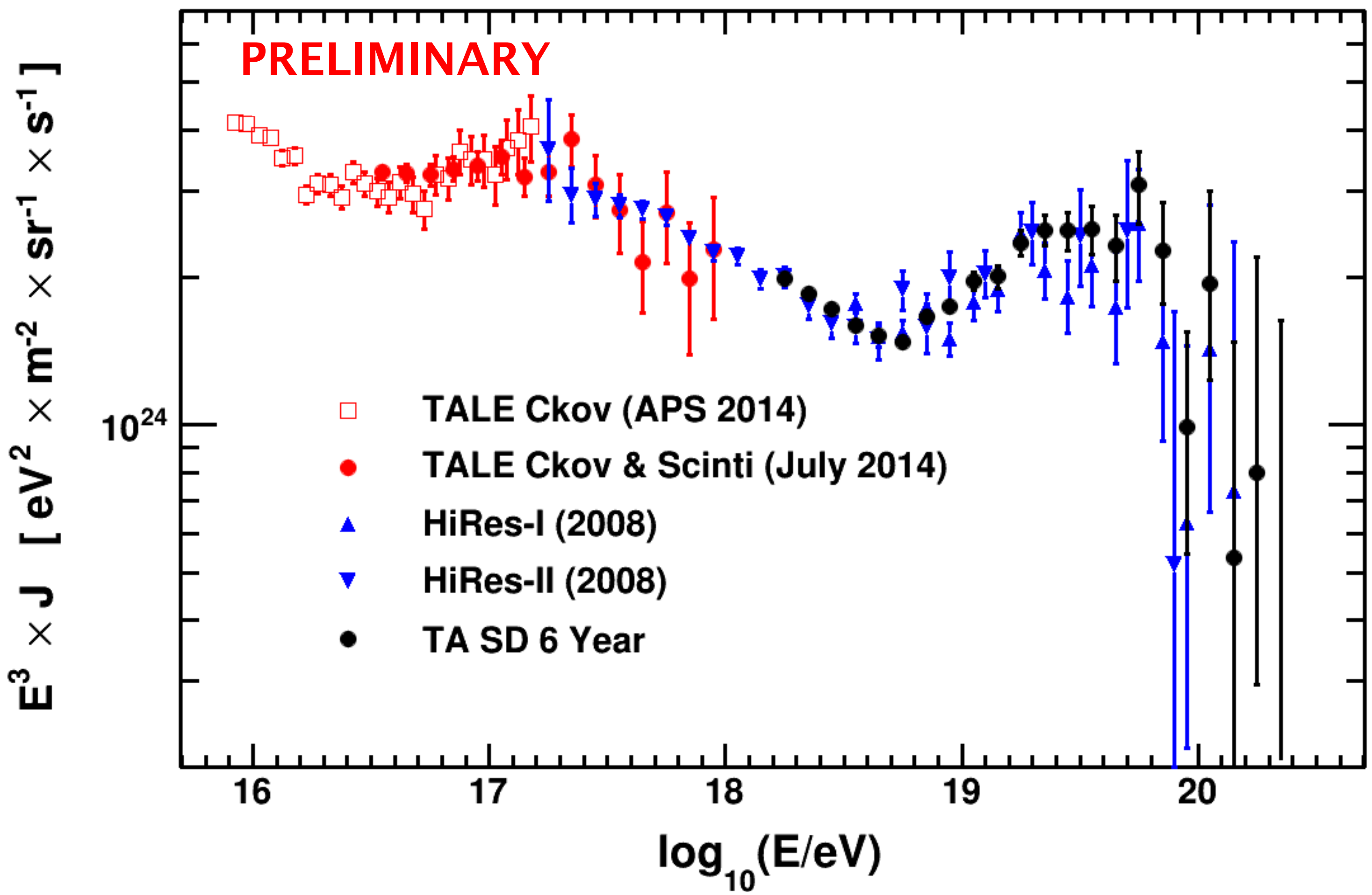


TALE, TA, HiRes spectra:
Mixed Cherenkov and fluorescence,
The Second Knee Appears



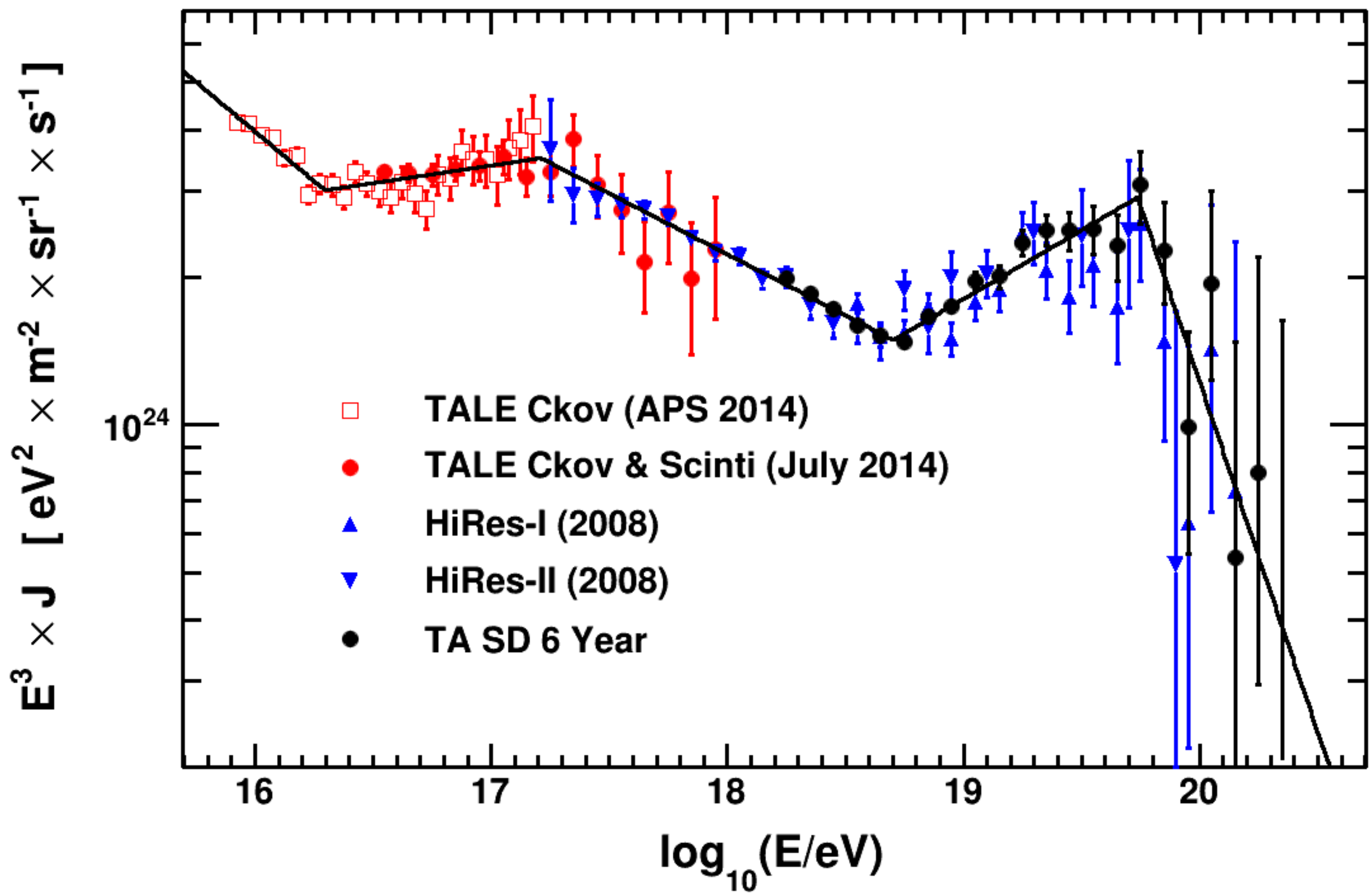
First TALE data, Sept. – Dec., 2013

Add the pure Cherenkov Spectrum: **Hardening in 10^{16} eV Region**



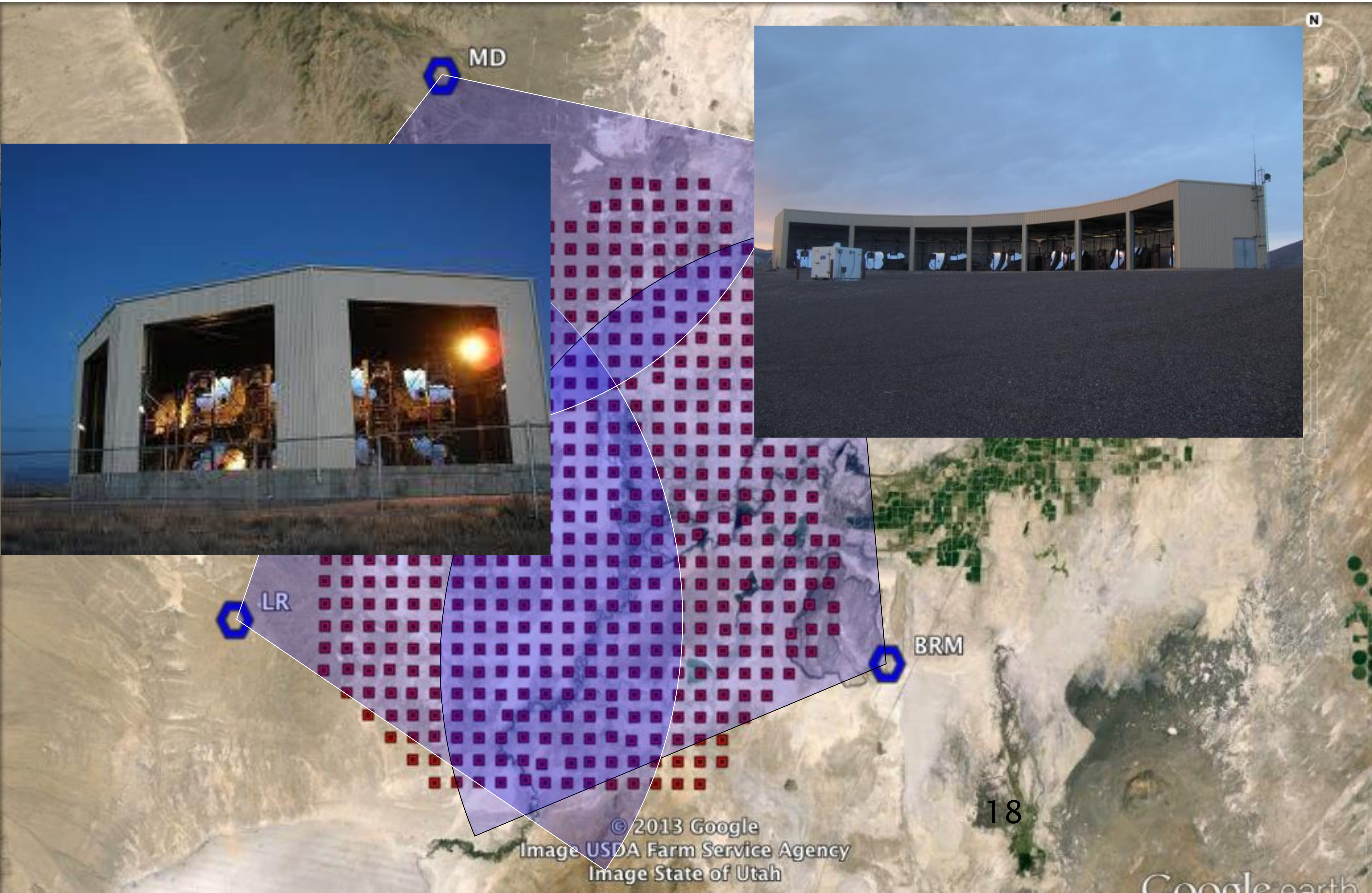
Spectrum covering 4.4 decades in energy

Spectrum fit to Broken Power Law

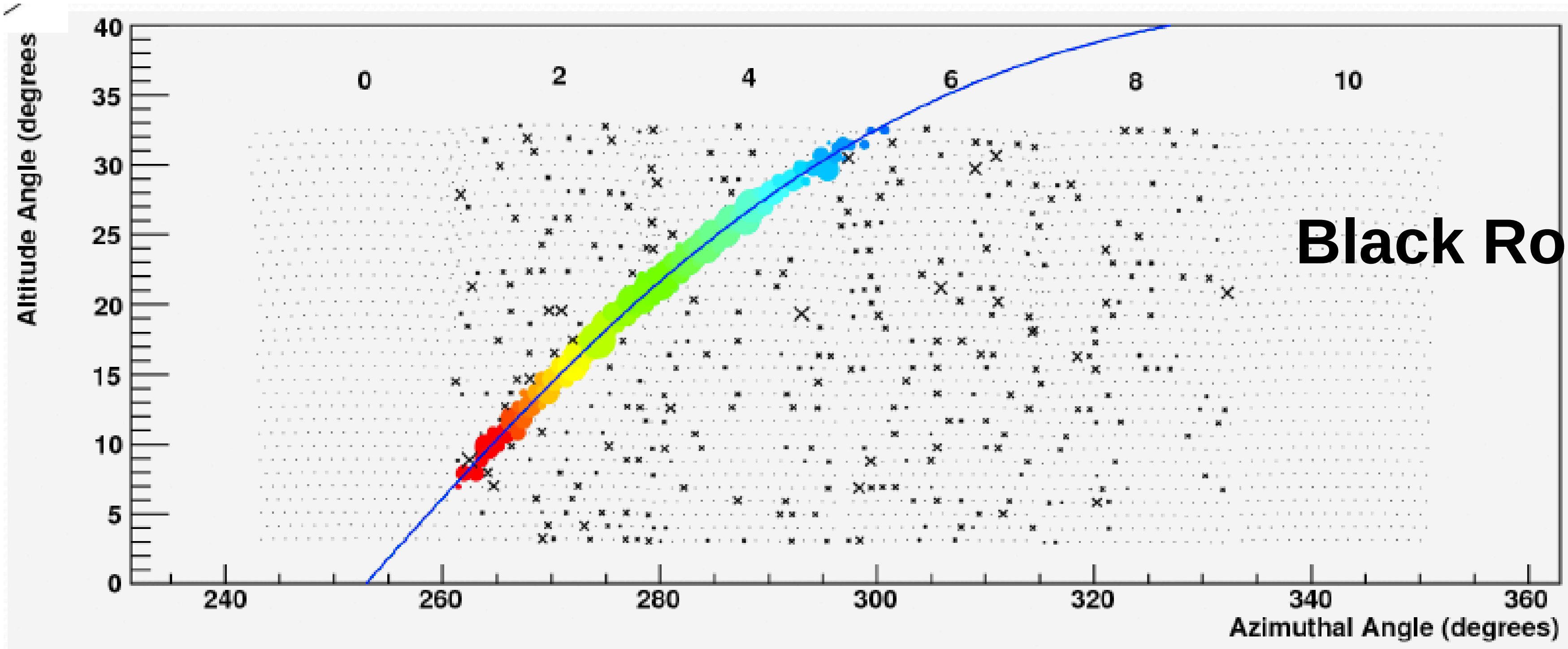


Spectrum covering 4.4 decades in energy, showing 4 spectral features

TA Fluorescence Detector (**FD**)

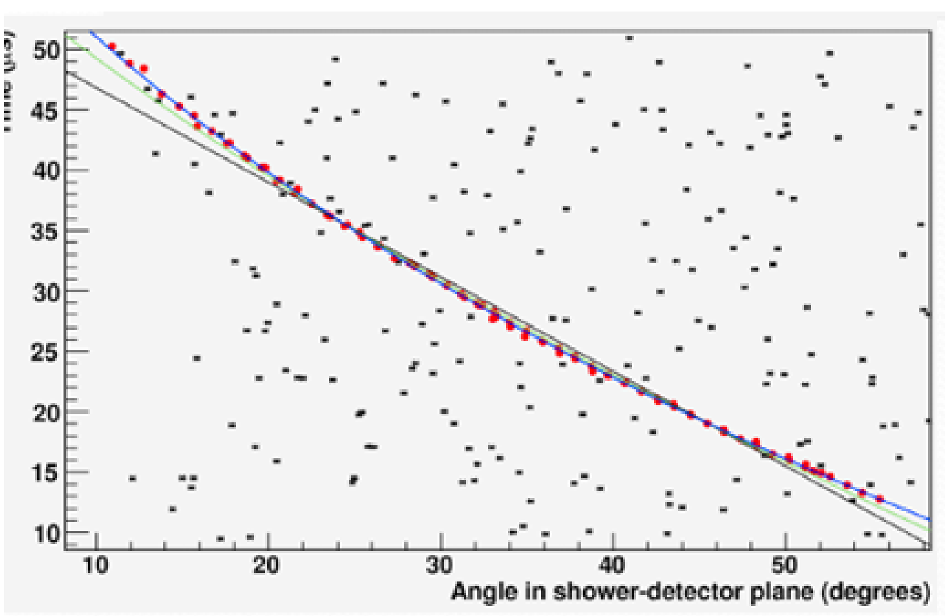


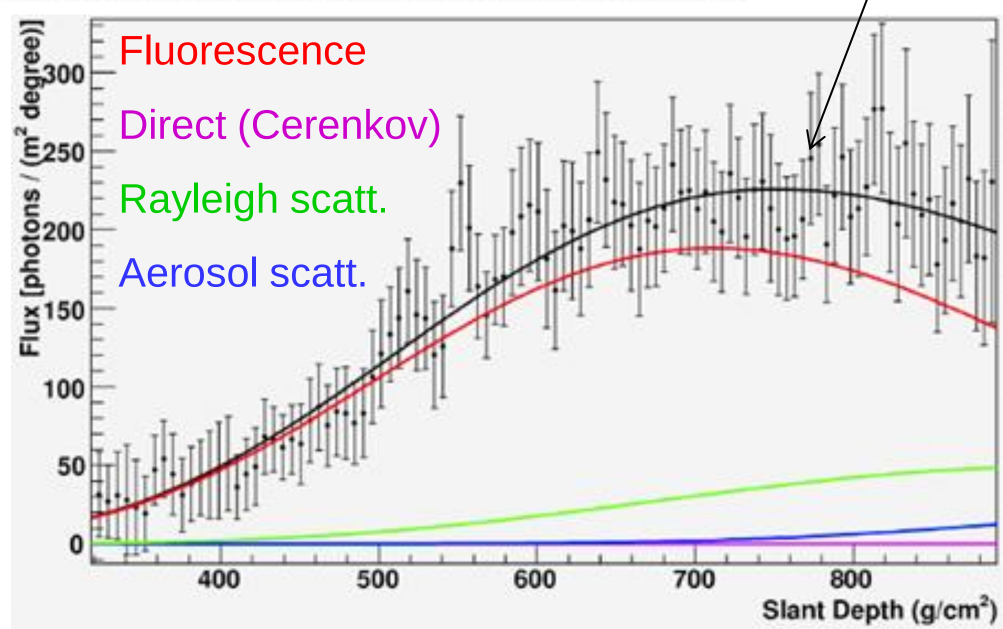
Fluorescence Analysis



Black Rock Mesa

Xmax



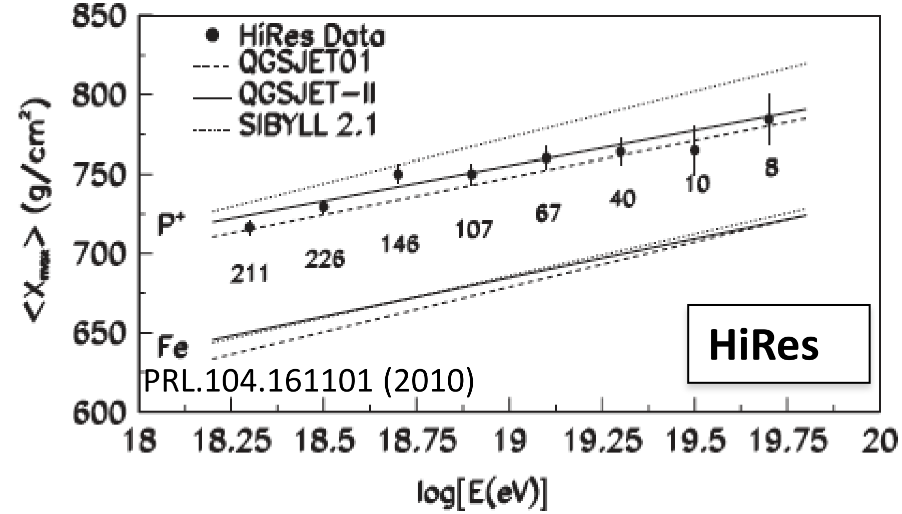


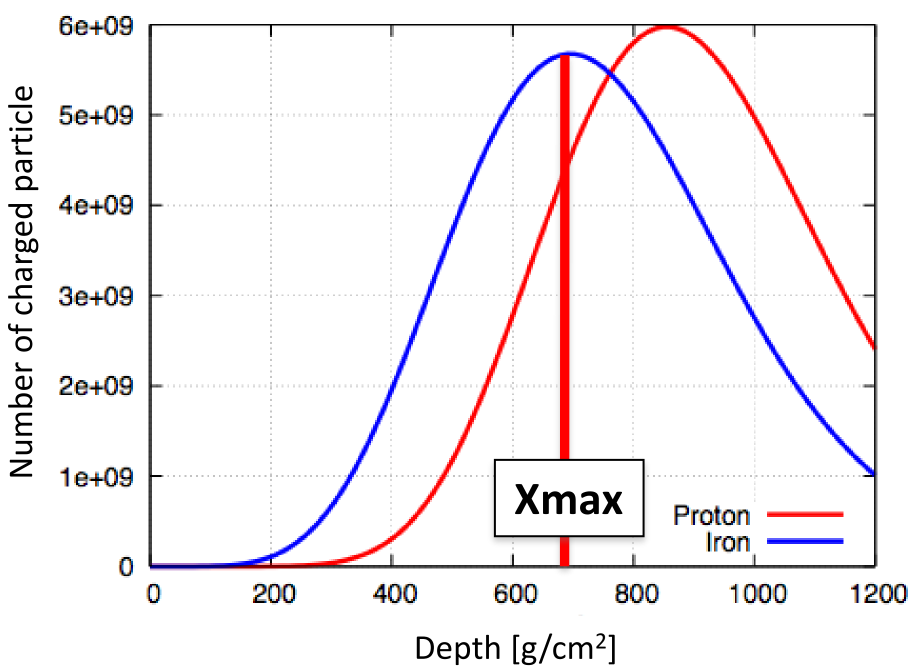
Time fit

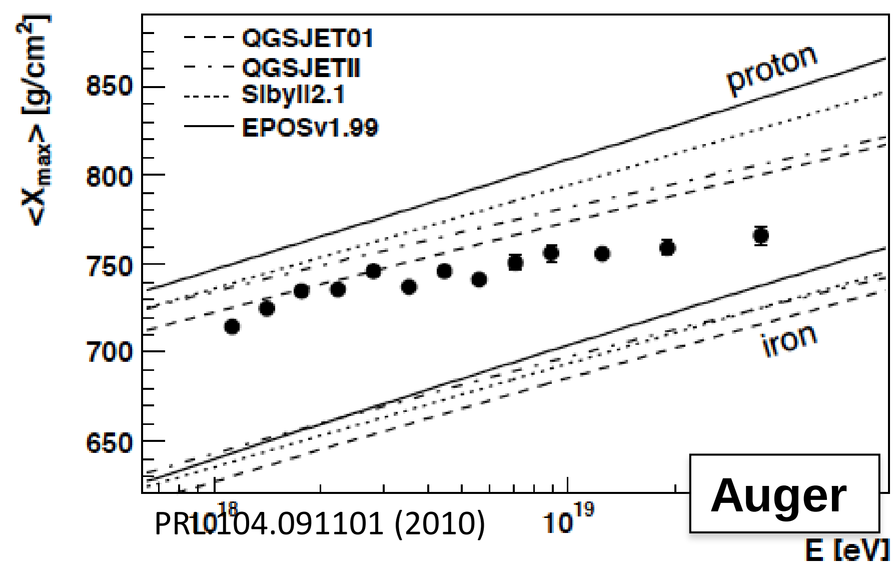
Profile fit

Composition from Xmax - HiRes and Auger

- **Shower longitudinal development depends on primary particle type.**
- **FD observes shower development directly.**
- **Xmax is the most efficient parameter for determining primary particle type.**

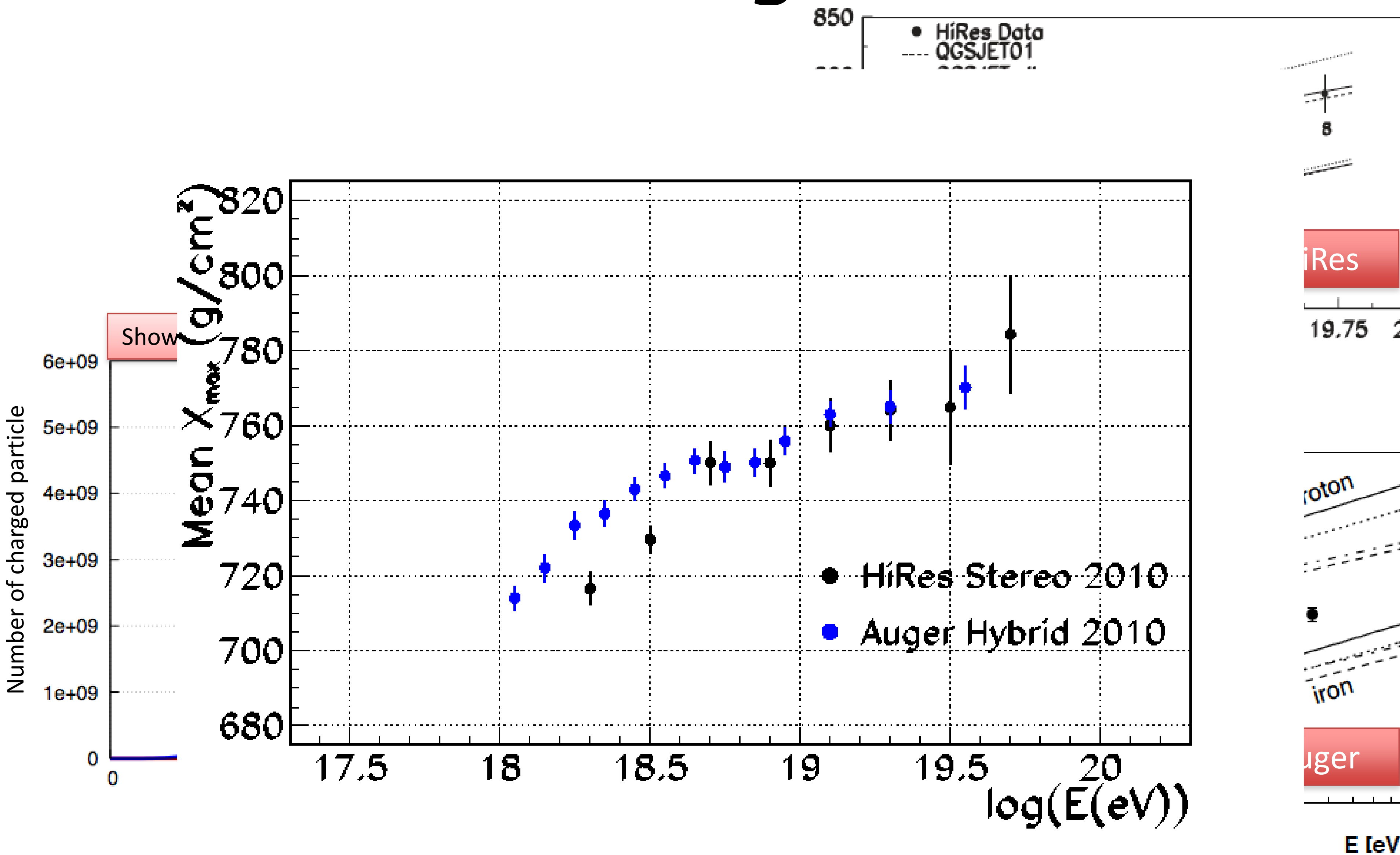






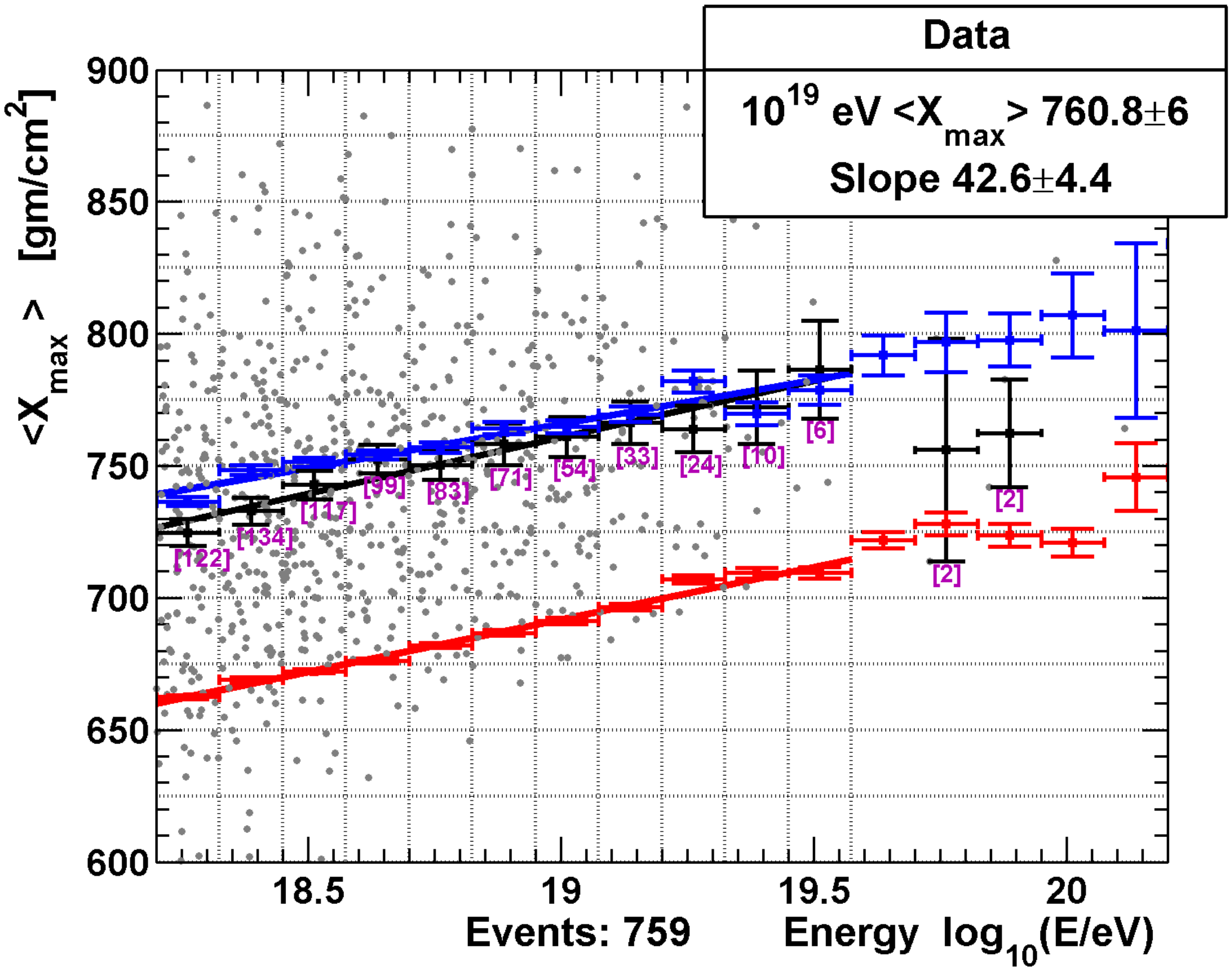
Difference above $10^{18.5}$ eV

Composition from Xmax - HiRes and Auger



No Difference in HiRes and Auger data above $10^{18.5}$ eV …

Composition from Xmax – TA Middle Drum Hybrid



Data
QGSJET-II.3 Proton
QGSJET-II.3 Iron

TA always uses full detector simulation and applies same quality cuts to the MC as to the data

Consistent with QGSJet-II.3 protons

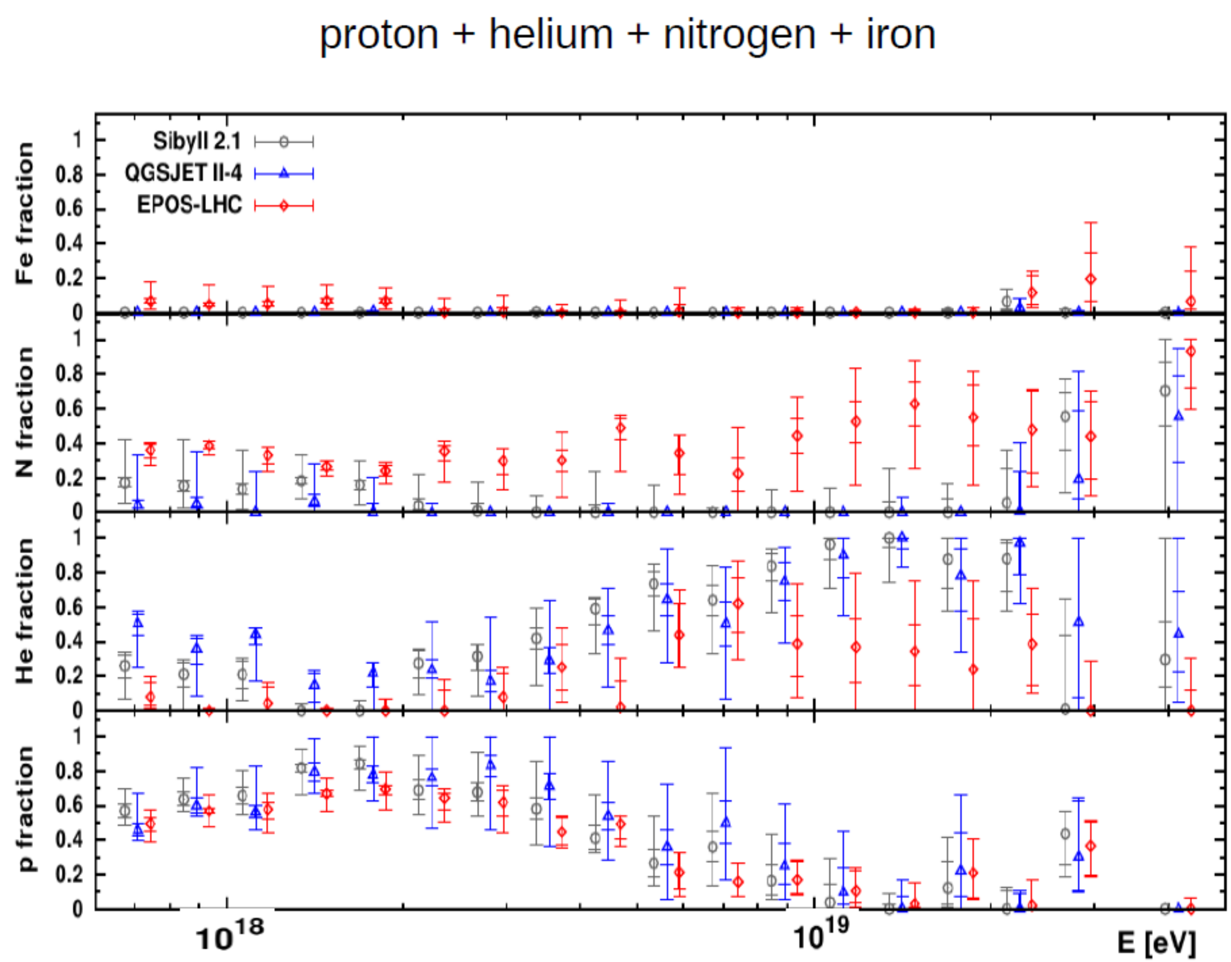
Poor statistics beyond $10^{19.5}$ eV

Auger Xmax Results

- Latest Auger Xmax paper.
- Performed fits to <Xmax> and RMS(Xmax) using 3 models.

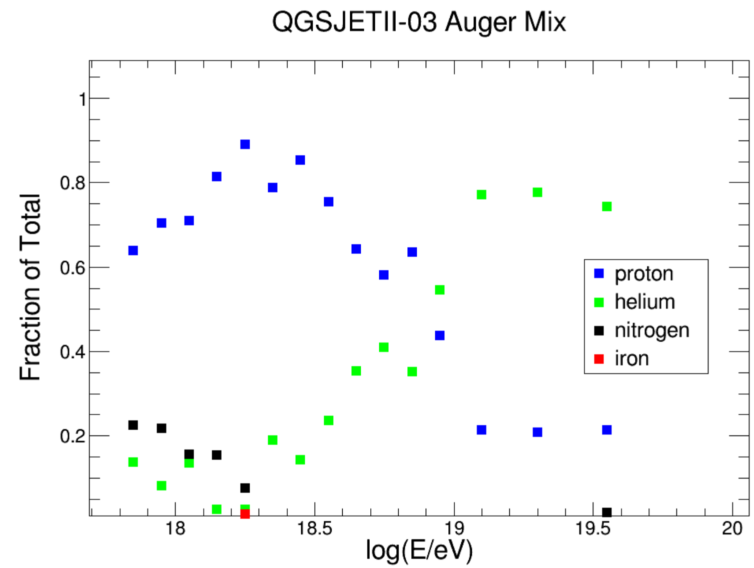
<u>3 comments:</u>

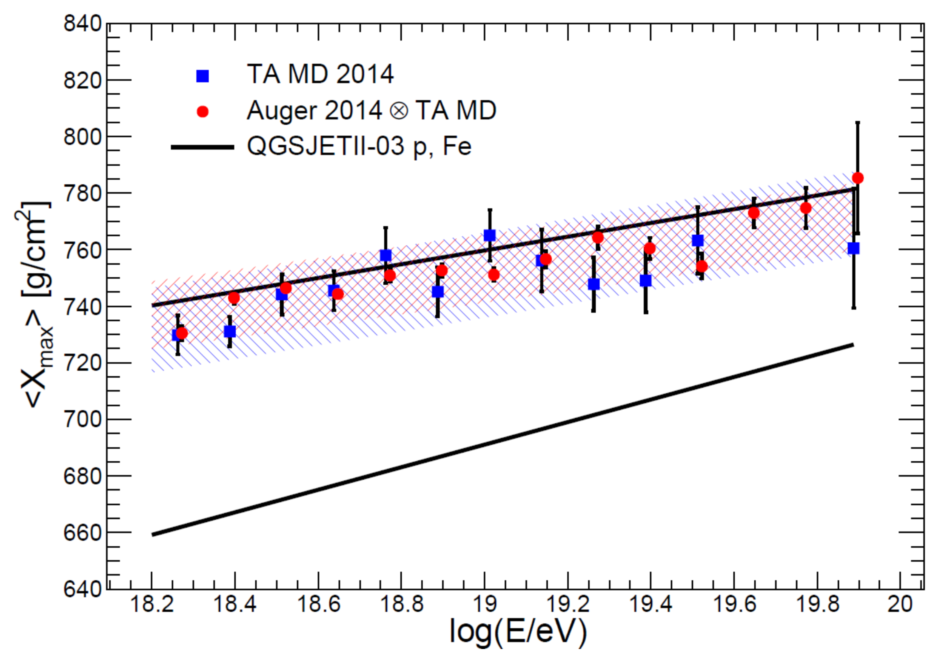
- No iron appears.
- No rigidity-dependent sequence is present.
- Test of models?
  - He above $10^{19.1}$ eV

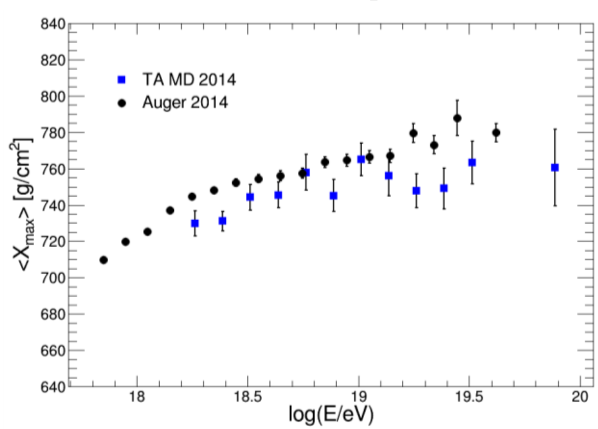


TA-PAO Composition WG at UHECR2014

- PAO fit their Xmax data to a mix of QGSJet II-3 H, He, N, and Fe.
- TA simulated the result using our MC and analysis programs.
- Result: TA data statistics can not yet differentiate between Auger mix and QGSJet II-3 protons.



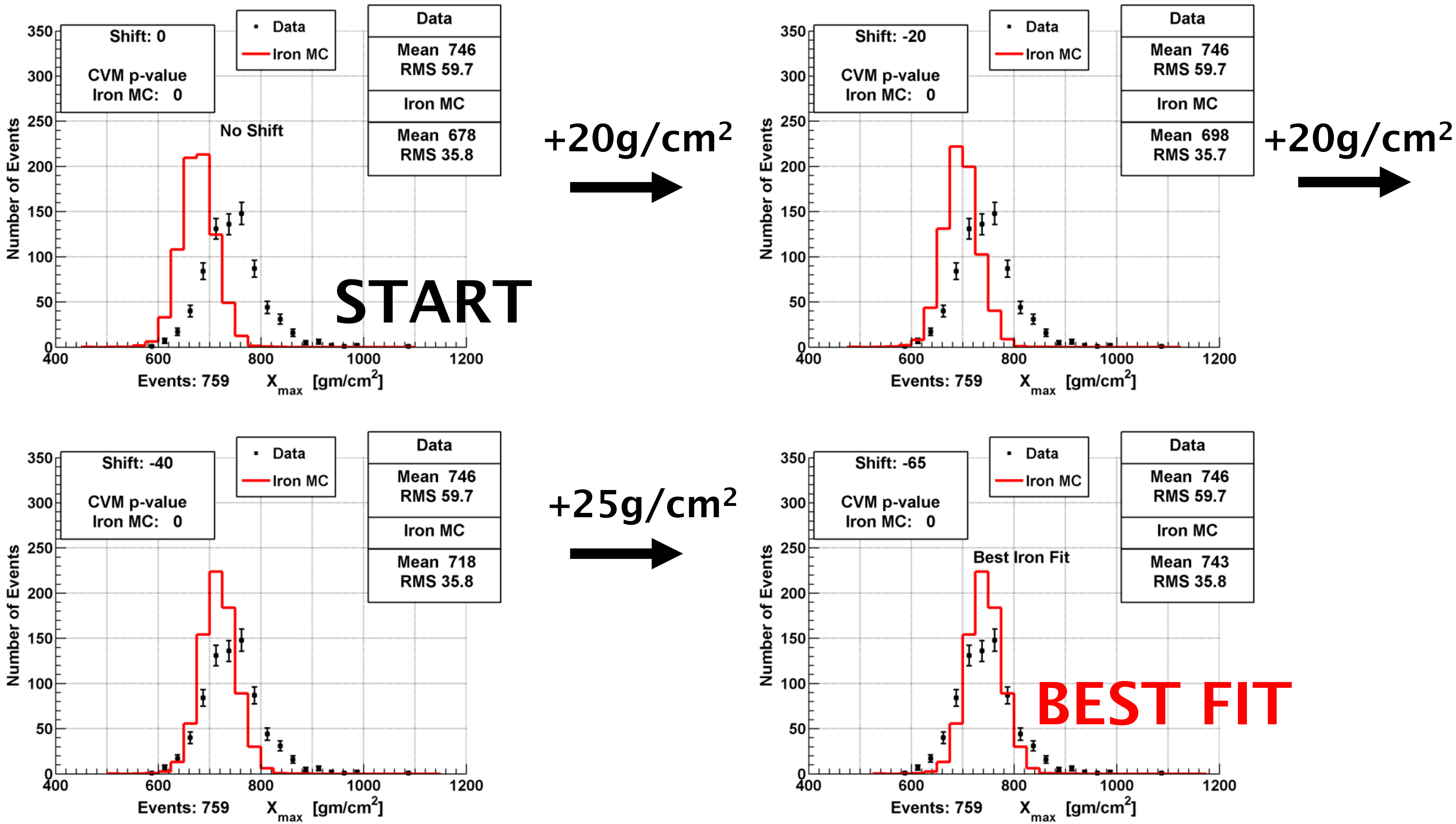




New Method of using Xmax

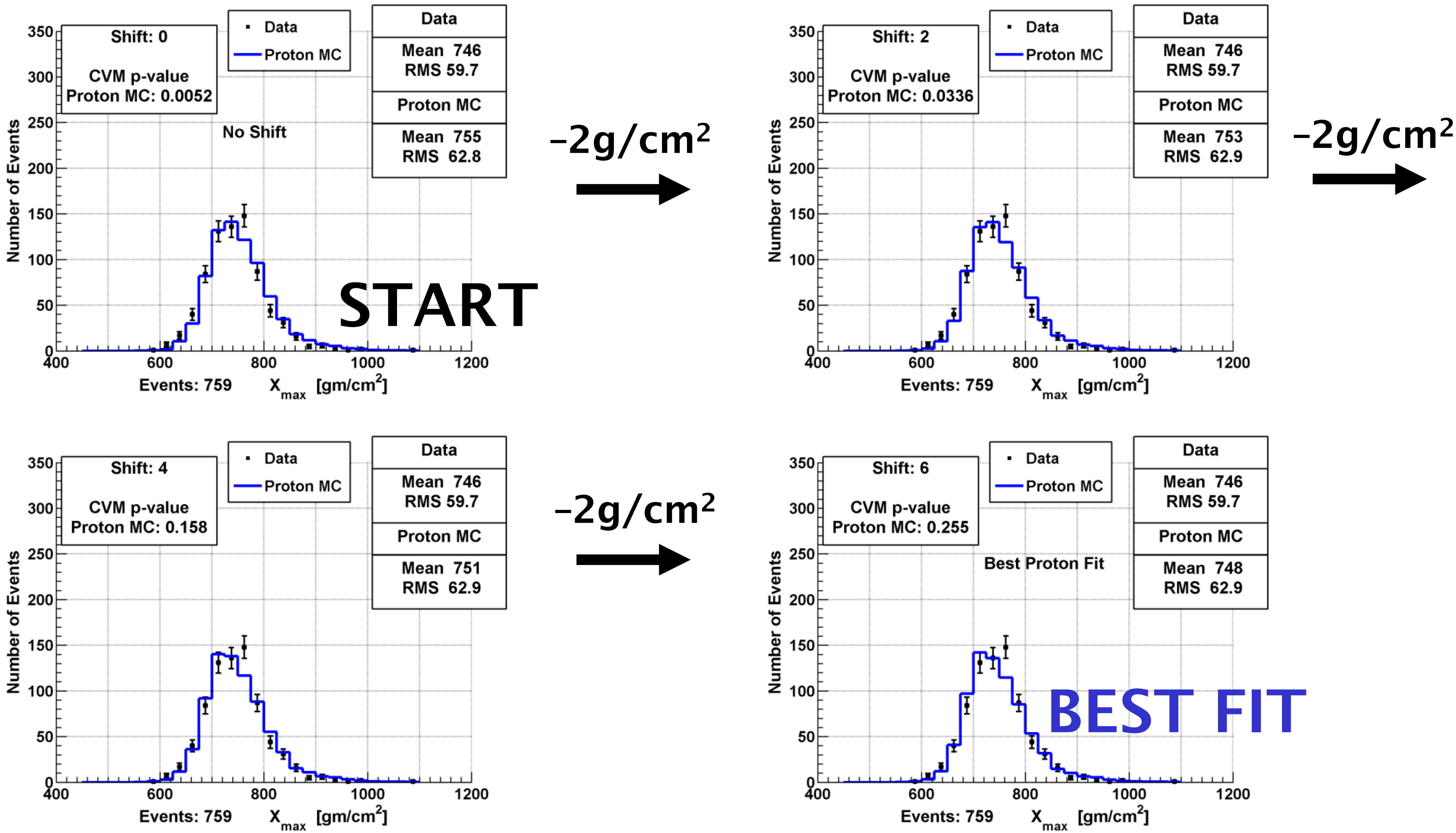
- Traditionally, cosmic ray experiments use 1st and 2nd moments of Xmax distributions…
- But small event counts near the tails cause large fluctuations in these quantities which lead to biased results!
- **--> Need to use full Xmax distributions rather than just their moments**
- **Approach: Shift proton and iron MC distributions until they match the data best, and quantify the compatibilities with a statistical test.**

Shift for QGSJET-II.3 iron MC



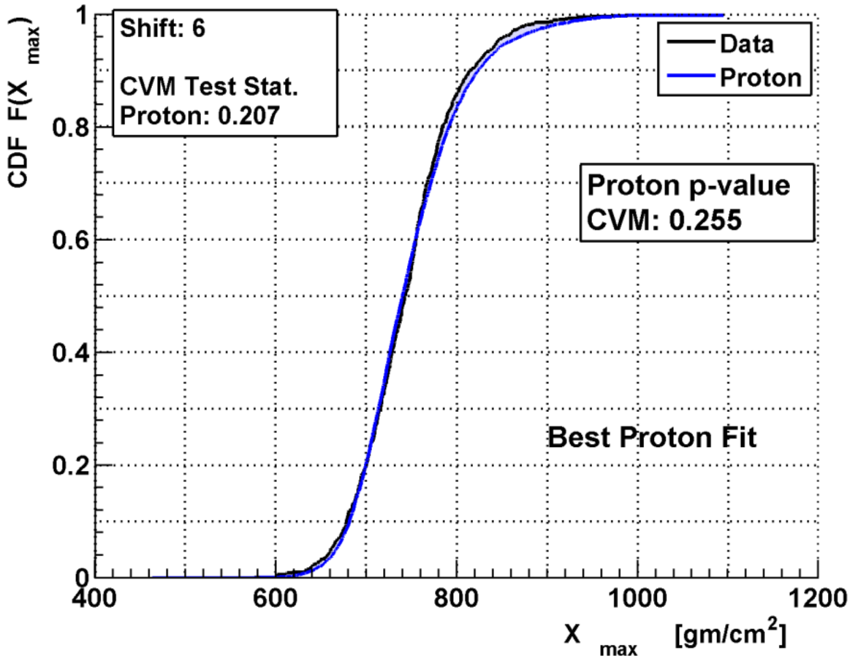
Best fit for QGSJET-II.3 iron obtained after shifting the MC by 65 g/cm^2 to the right

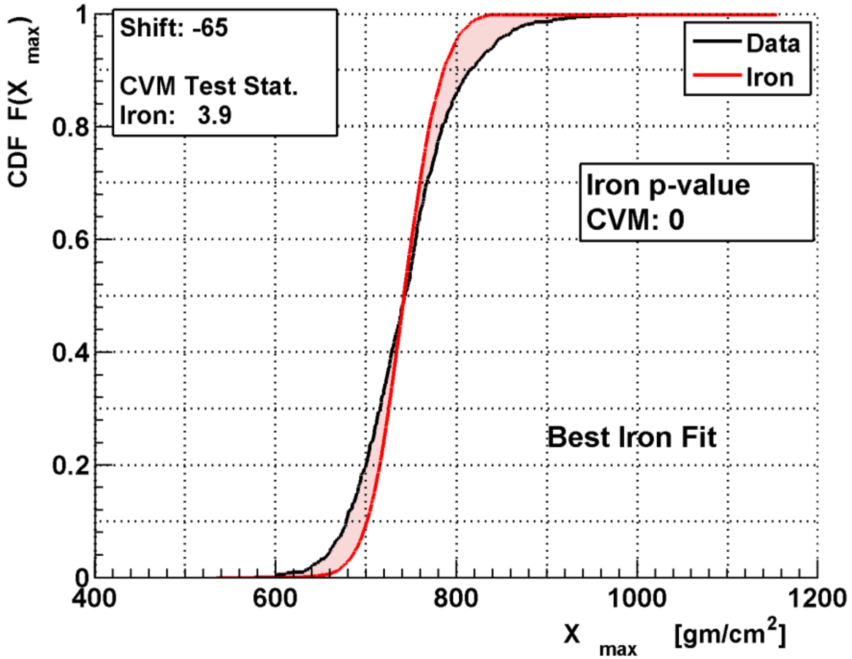
Shift for QGSJET-II.3 proton



Best fit for QGSJET-II.3 proton obtained after shifting the MC by 6 g/cm² to the left

Statistical Test Used



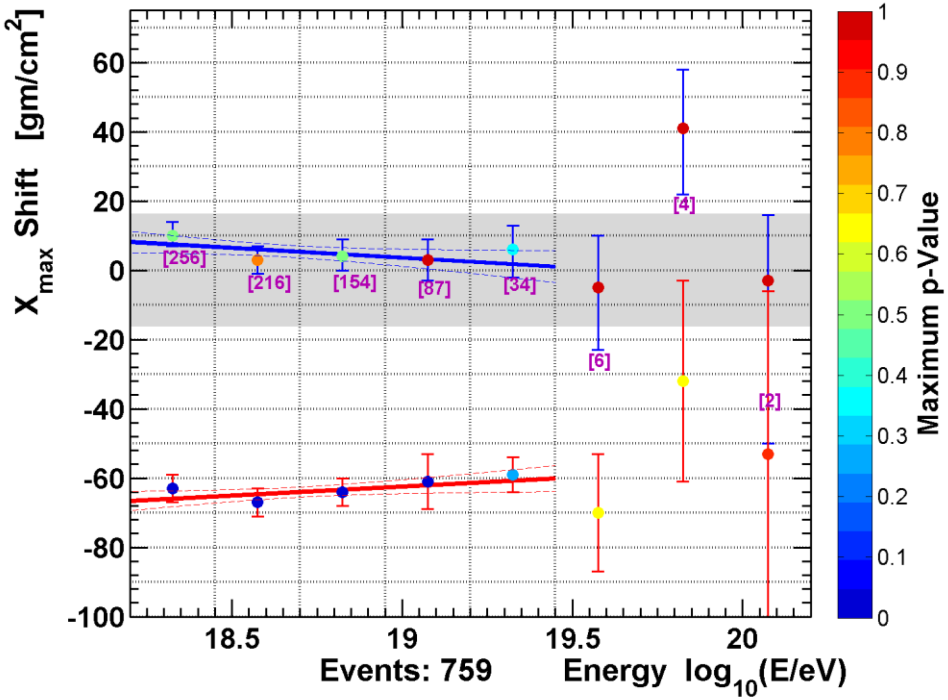


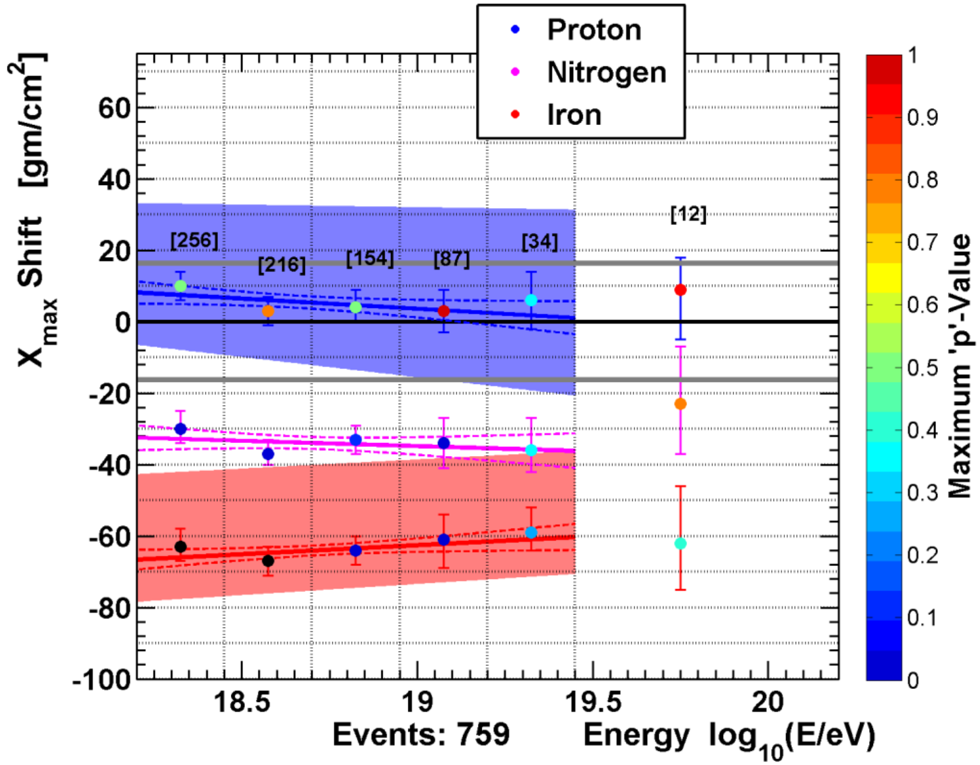
Cramer-Von Mises (**CVM**) test:
-No binning required
-Uses square of differences
-Captures well global and local properties of the distributions: more sensitive at the tails than Kolmogorov-Smirnov test

$$\omega^2 = \int_{-\infty}^{\infty} [F_n(x) - F^*(x)]^2 \, \mathrm{d}F^*(x)$$

$$T = n\omega^2 = \frac{1}{12n} + \sum_{i=1}^{n} \left[\frac{2i-1}{2n} - F(x_i) \right]^2 .$$

TA Composition Results





- **TA is consistent with a light composition below $10^{19.5}$ eV.**

- **TA data exclude Fe, using all QGSJet, Sibyll, and EPOS models. N disfavored.**

Anisotropy: TA “Hotspot”

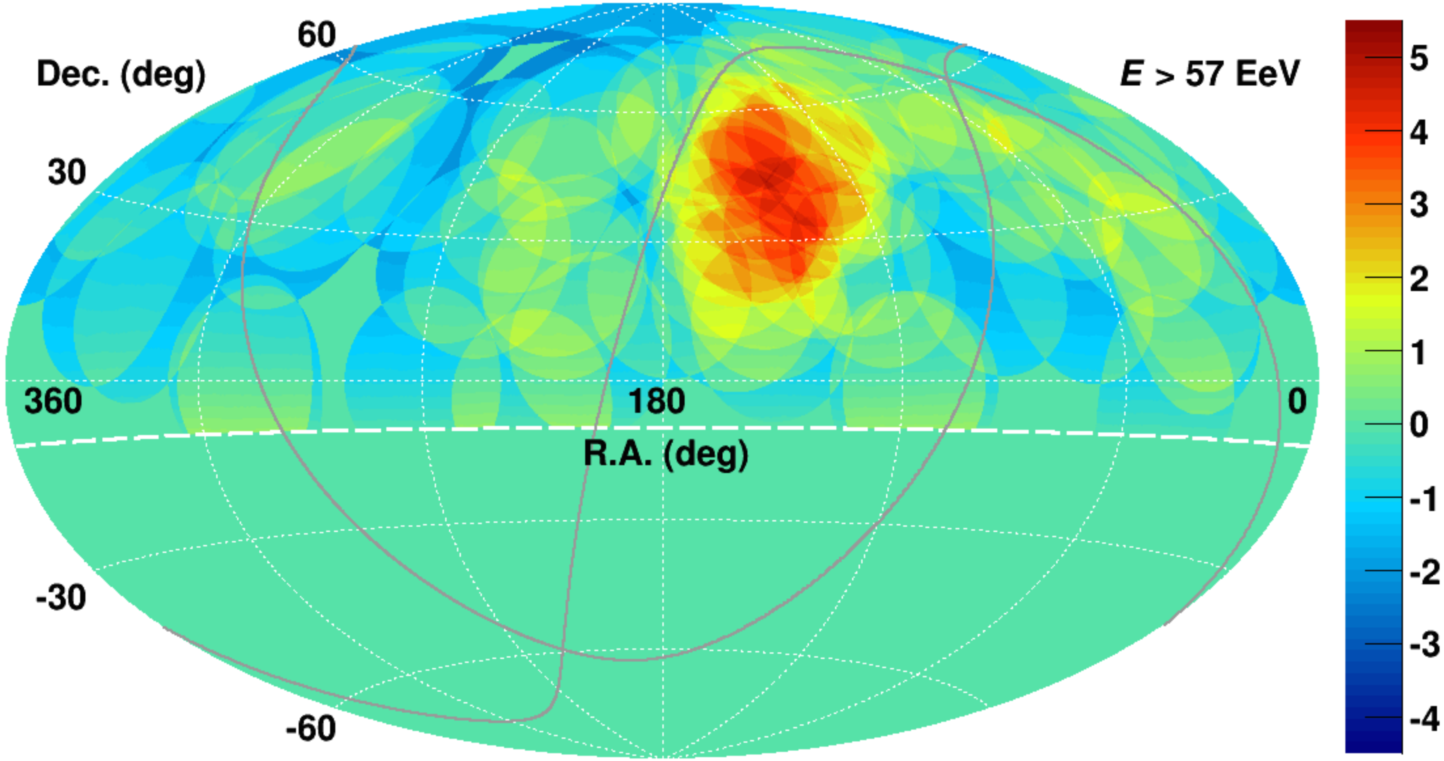
There is a cluster of just south of the supergalactic plane, “the hotspot”. Plot uses oversampling, r = 20˚.

5-year SD data: 72 ev. > 57 EeV, 19 corr. (expect 4.5)

26% of events in 6% of sky.

Li-Ma significance = 5.1σ

Chance probability = 3.4σ



Ap.J. **790**, L21 (2014)

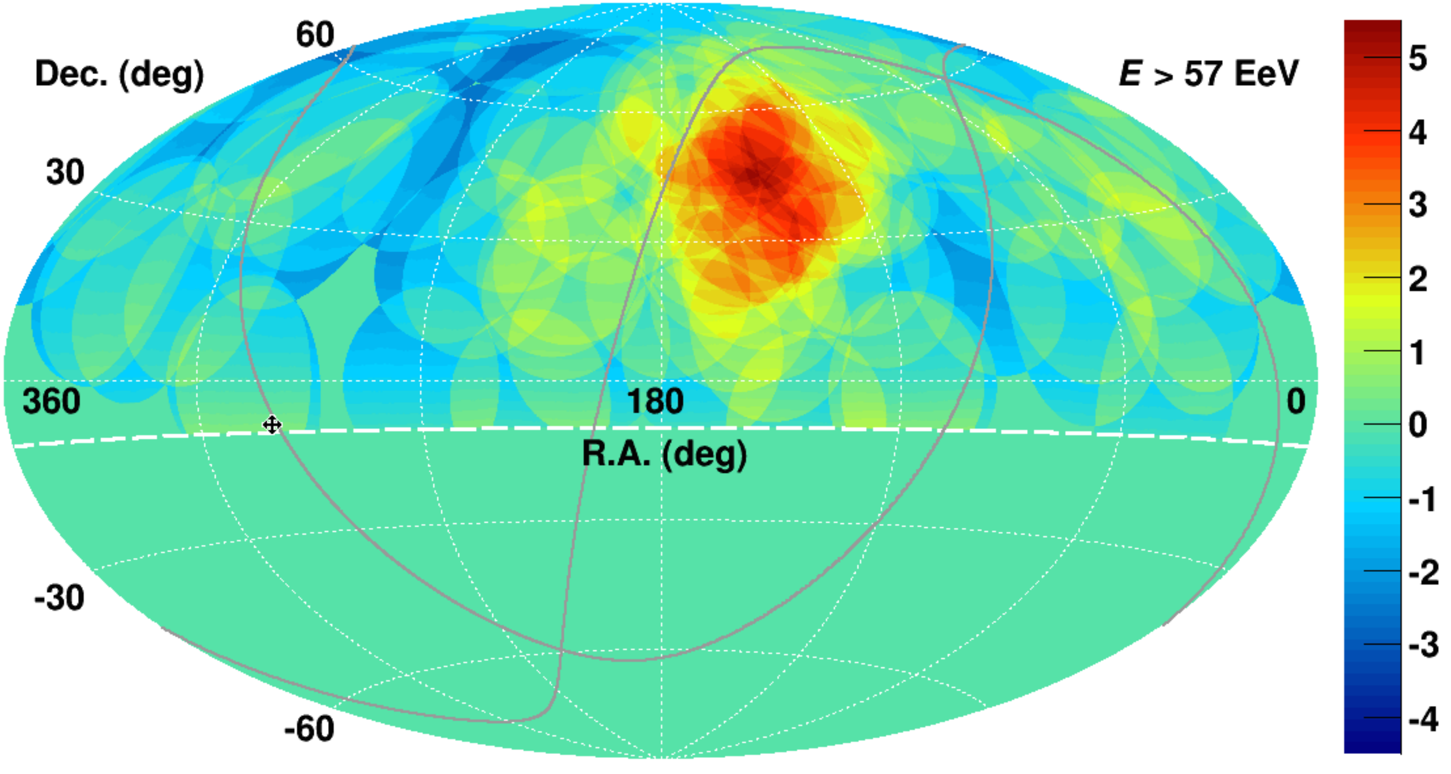
Hotspot, 6-years of SD Data

6th year: 15 further events, 4 in hotspot (27%)

Li-Ma significance = 5.5σ

Chance probability = 4.0σ

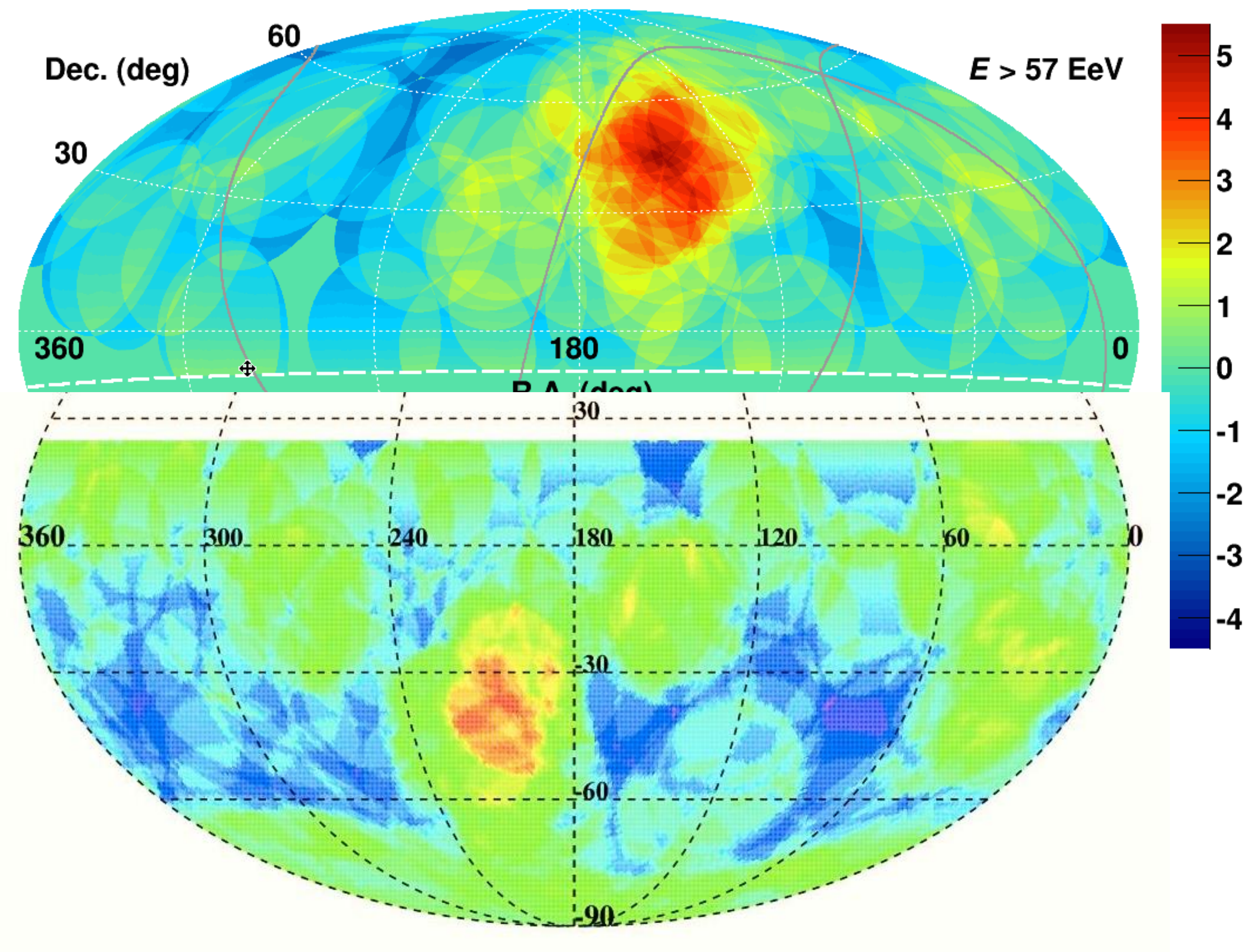
Take-home message: 3½ σ ➔ just over 4 σ



Significance map; equatorial coordinates, 2008/05/11-2014/05/11

Auger "Warm Spot"*

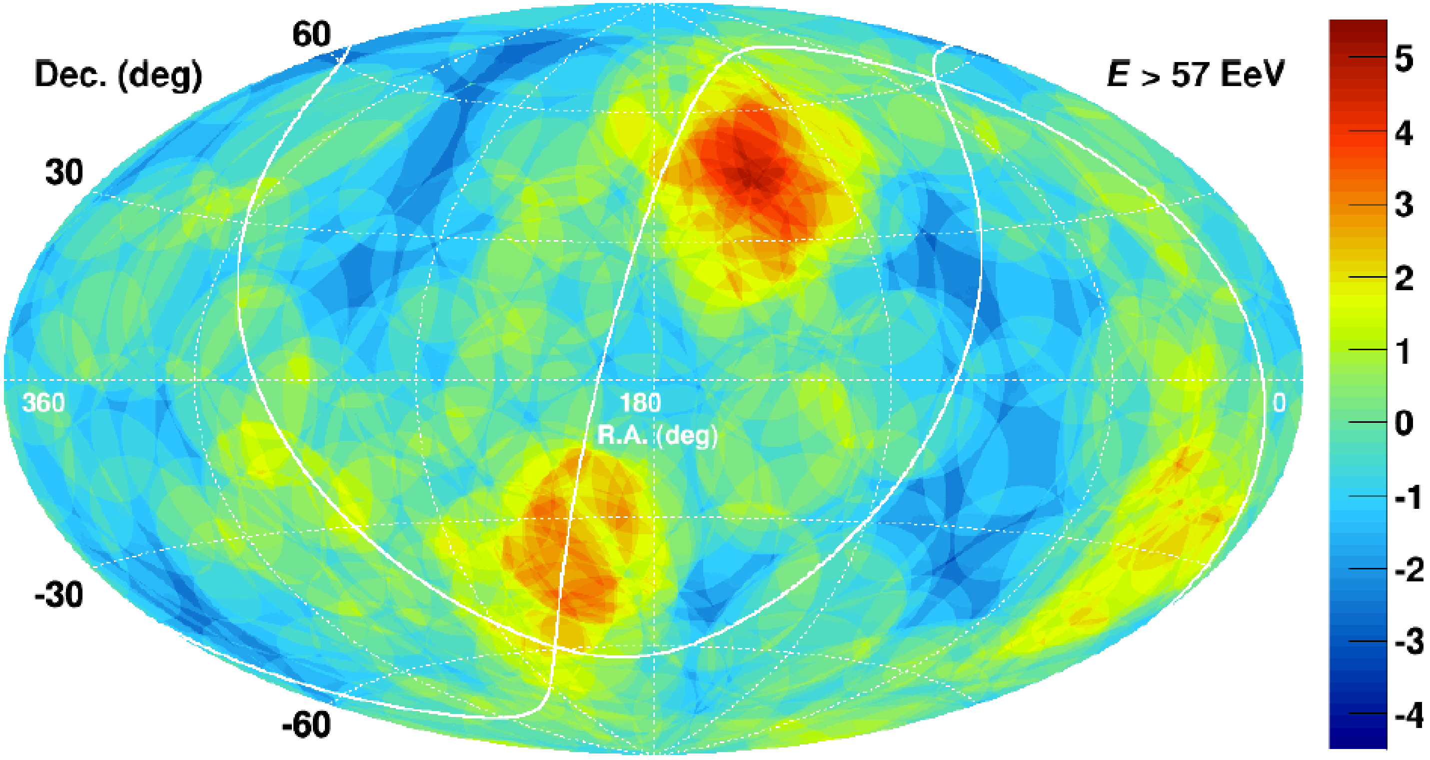
PAO sees cluster of events near CEN-A: 3.1σ



* K.-H. Kampert

Attempt at full-sky coverage

- E > 57EeV
- r = 20˚



TAx4 Project

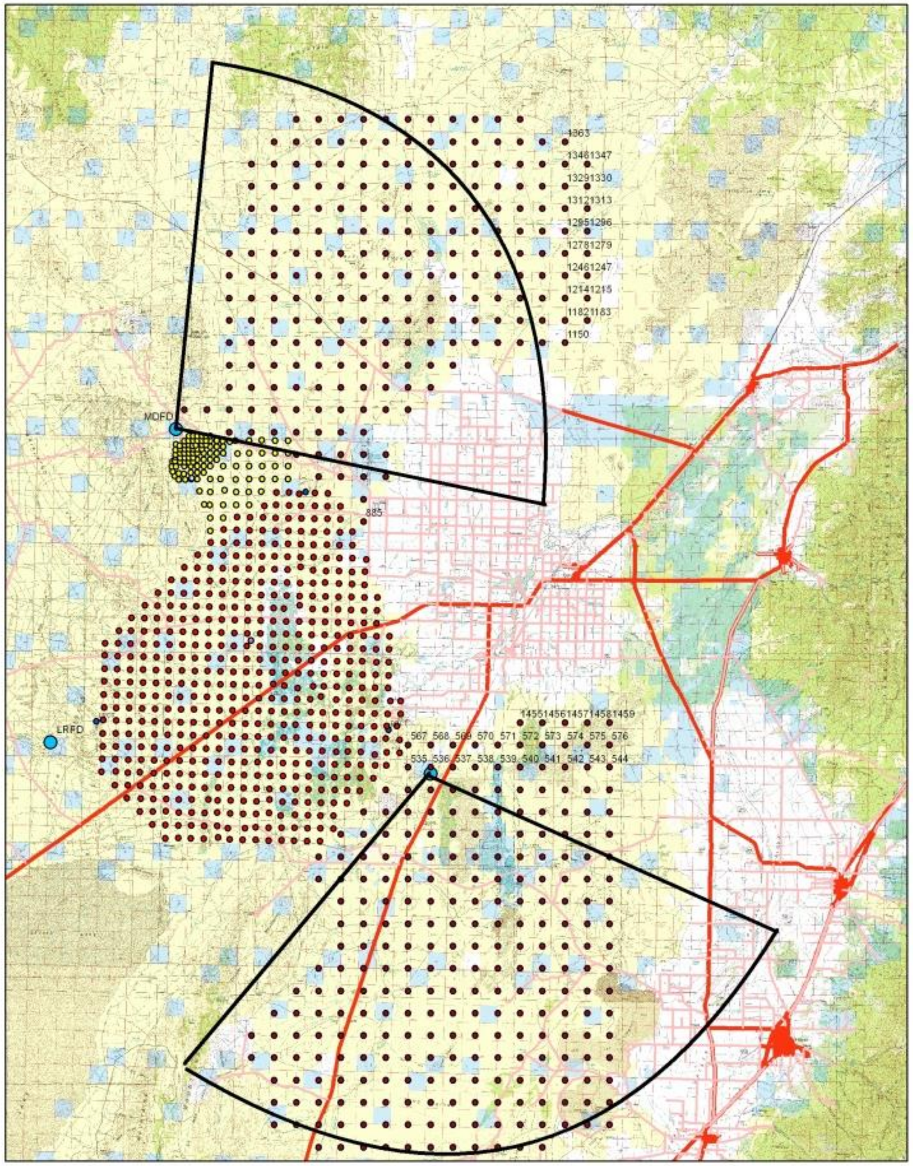
Fourfold increase in size of TA SD.

- Add 500 SD counters, at 2.08 km spacing.
- Add 2 FD sites, 28 telescopes

Get 21 TA-years by 2020: look for structure within hotspot.

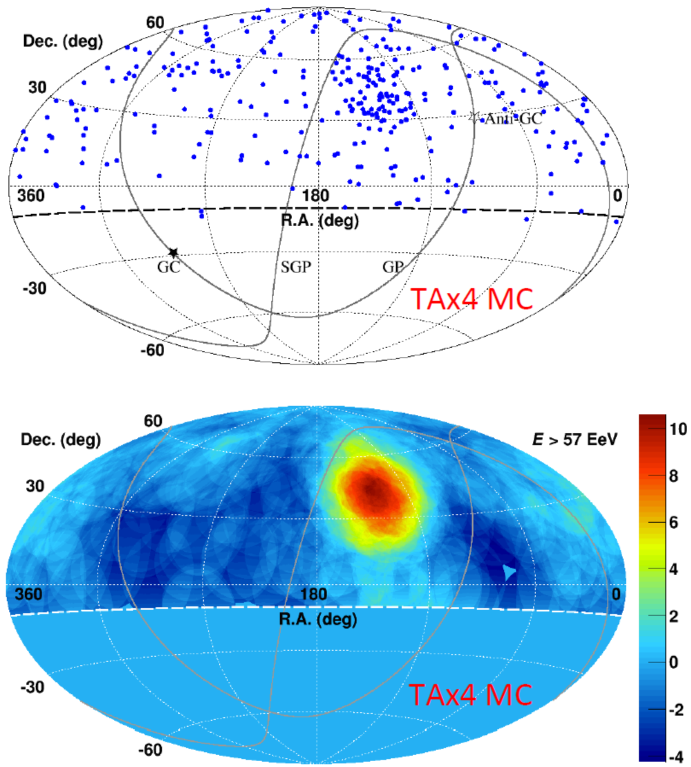
Proposals:

- SD = Japan (**successful!**)
- FD = U.S. (October, 2015)



21 TA-years of SD Data by 2020

(1) One Hotspot

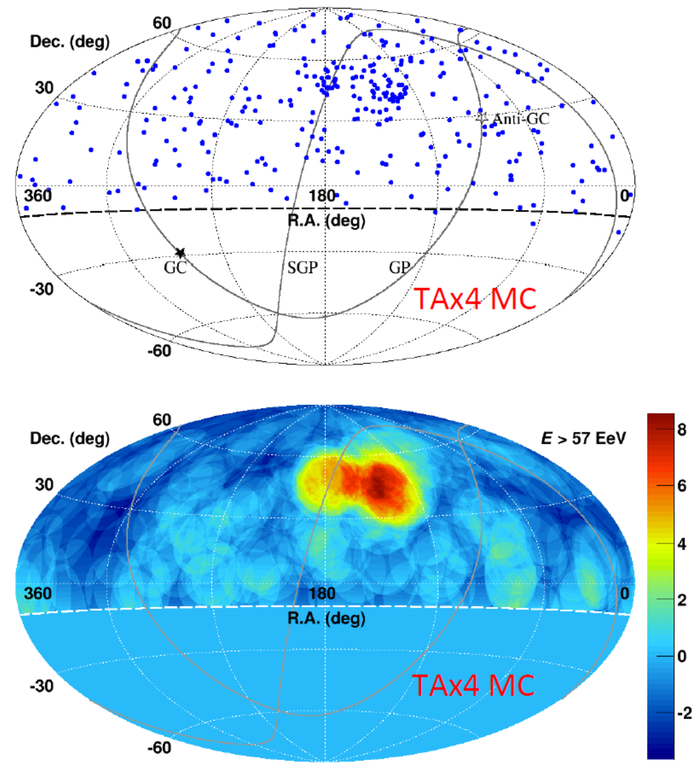


Hotspot Signal
80-18.9=61events
(RA, Dec)=(145°,45°)
Gaussian σ=10°

Isotropic B.G.
305-61=244events

Oversampling
20° radius circle

(2) Double Hotspot



Hotspot Signal
Total 61 events
1. 41events
(RA, Dec)=(145°,40°)
Gaussian σ=10°
2. 20events
(RA, Dec)=(175°,40°)
Gaussian σ=5°

Isotropic B.G.
305-61=244events

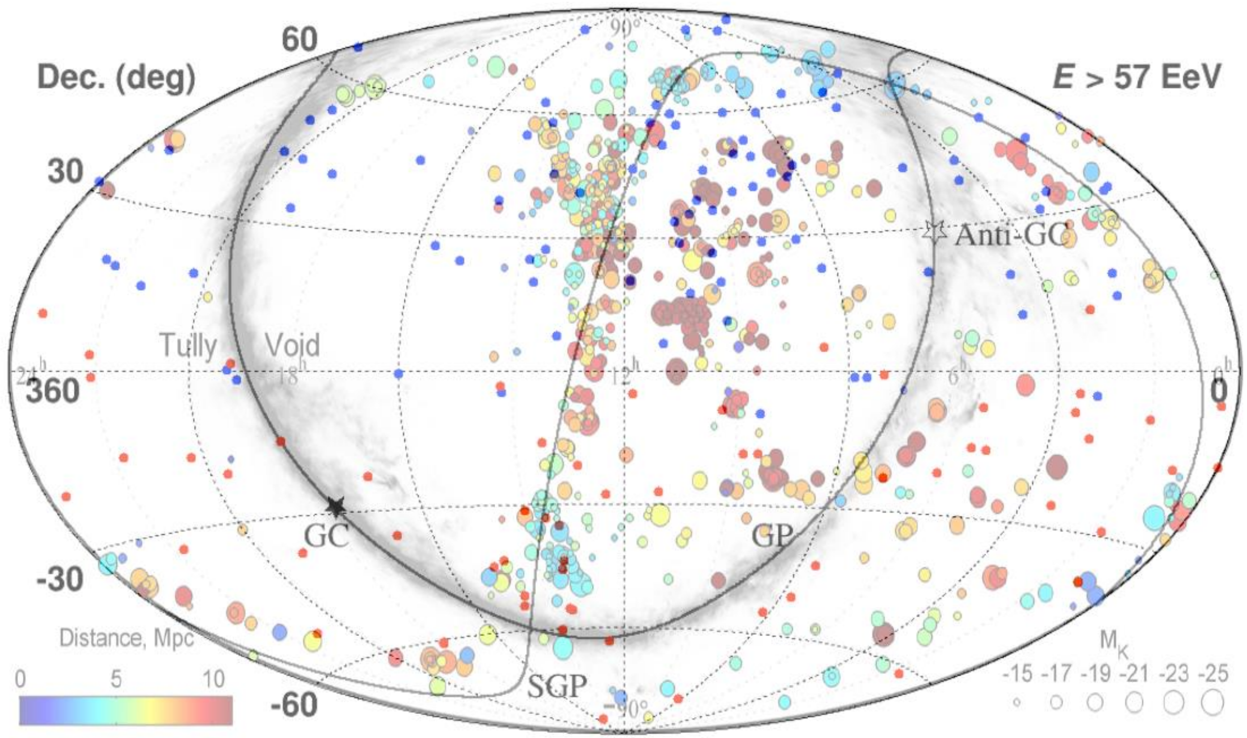
Oversampling
15° radius circle

Clarify the nature of the hotspot!

Conclusions

- TA is a LARGE experiment which has important results and excellent control of systematic uncertainties.
- **TA/TALE spectrum covers 4.4 decades in energy, and sees 4 spectral features.**
- TA composition and spectrum results are consistent with light composition below $10^{19.5}$ eV; statistics still low at higher energies. **TA data exclude Fe.**
- **TA sees 4σ evidence for anisotropy in the northern hemisphere.**
- Build TAx4 to see what is in the hotspot.

Filament in the Local Large Scale Structure of the Universe

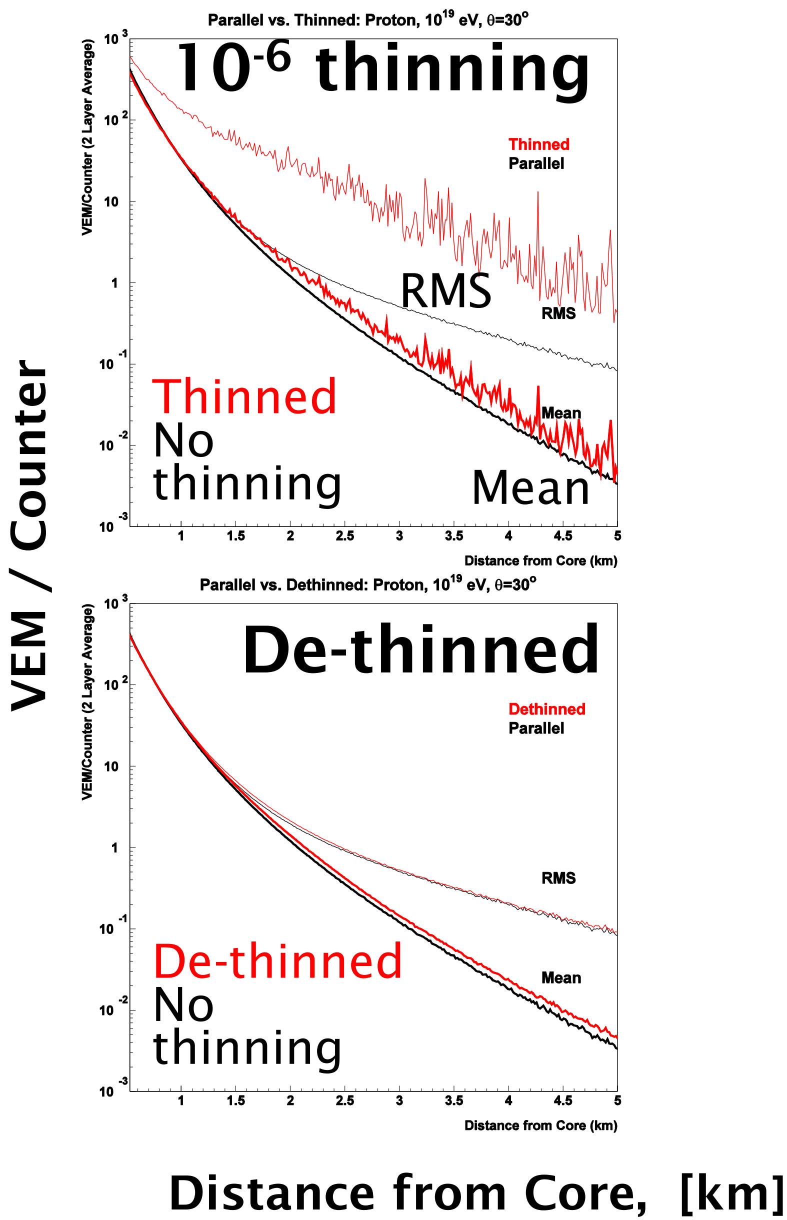


r < 11 Mpc

Blue dots: TA events

Red dots: Auger events

How to Use CORSIKA Events in Simulation of SD



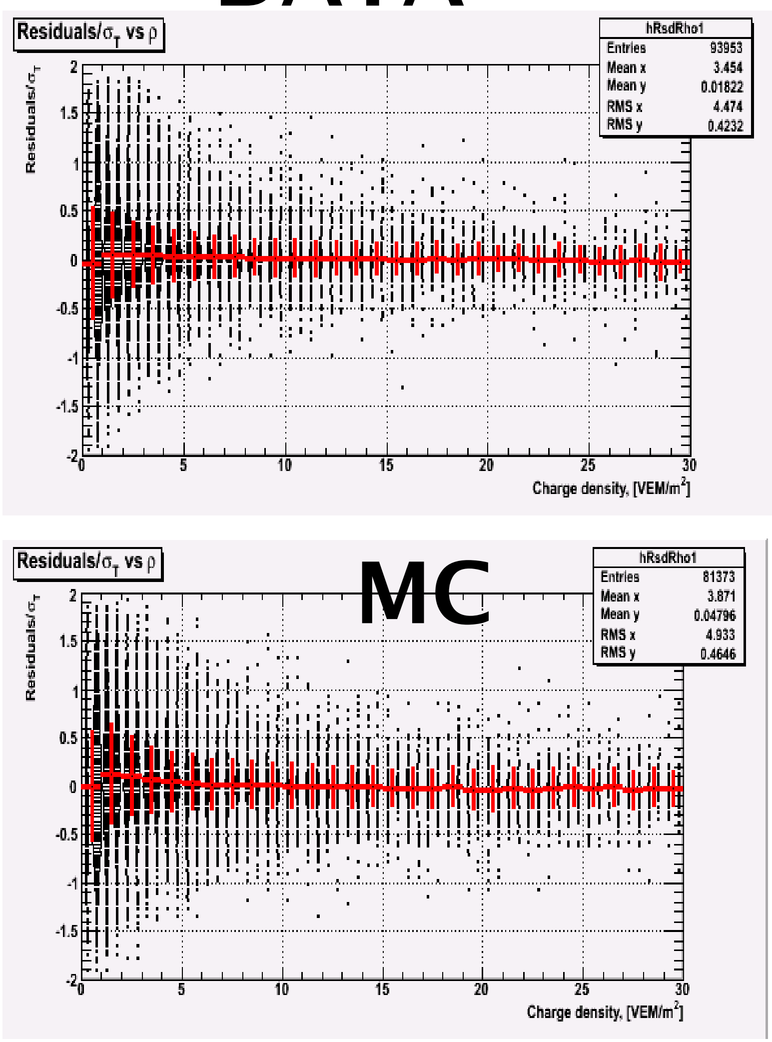
Use 10^{-6} – thinned CORSIKA QGSJET-II proton showers that are de-thinned in order to restore information in the tail of the shower.

De-thinning procedure is validated by comparing results with un-thinned CORSIKA showers, obtained by running CORSIKA in parallel

We fully simulate the SD response, including actual FADC traces

SD Time Fit Residuals

DATA



MC

Time fit residual over sigma

Counter signal, [VEM/m^2]

Fitting procedures are derived solely from the data

Same analysis is applied to MC

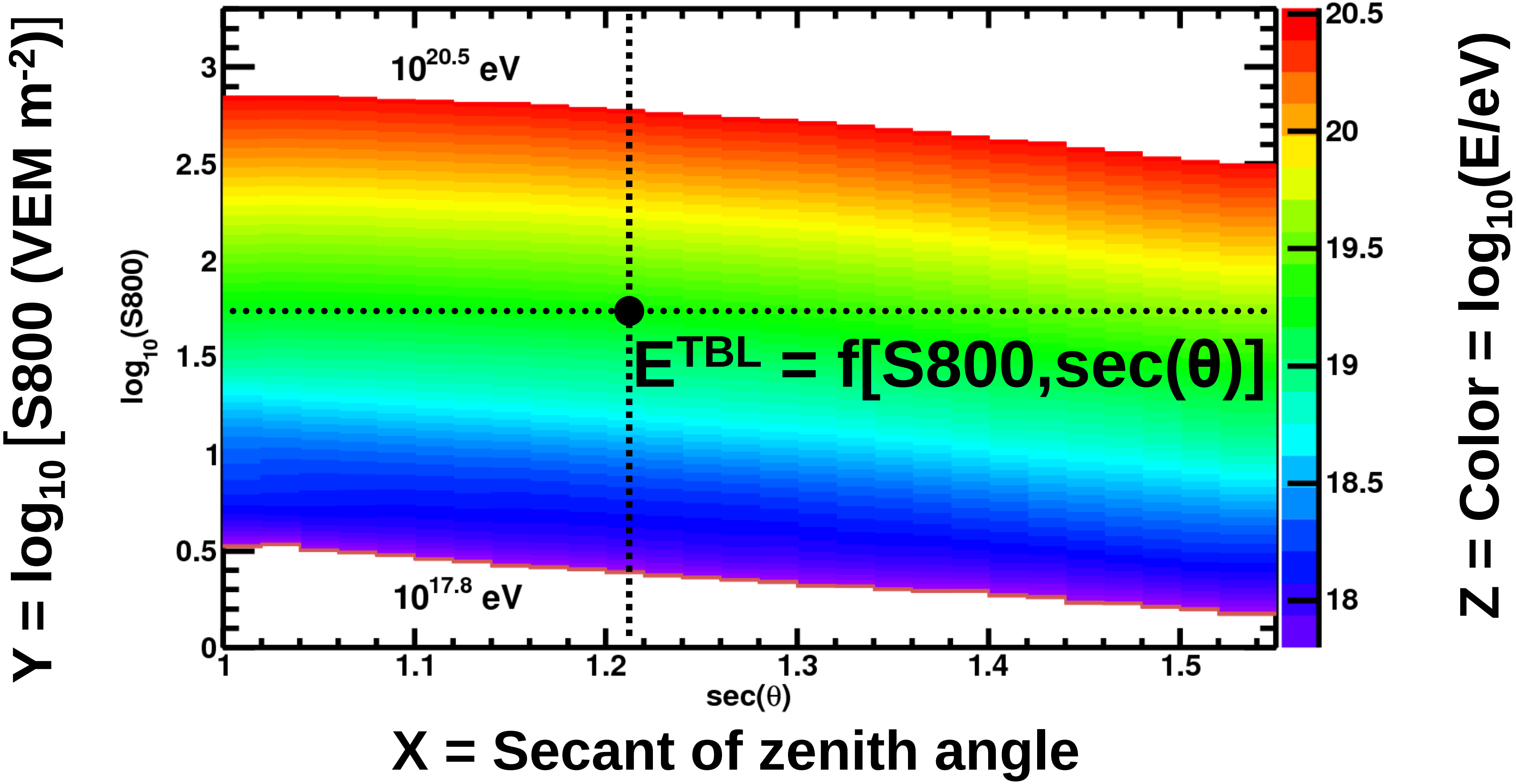
Fit results are compared between data and MC

MC fits the same way as the data.

Consistency for both time fits and LDF fits.

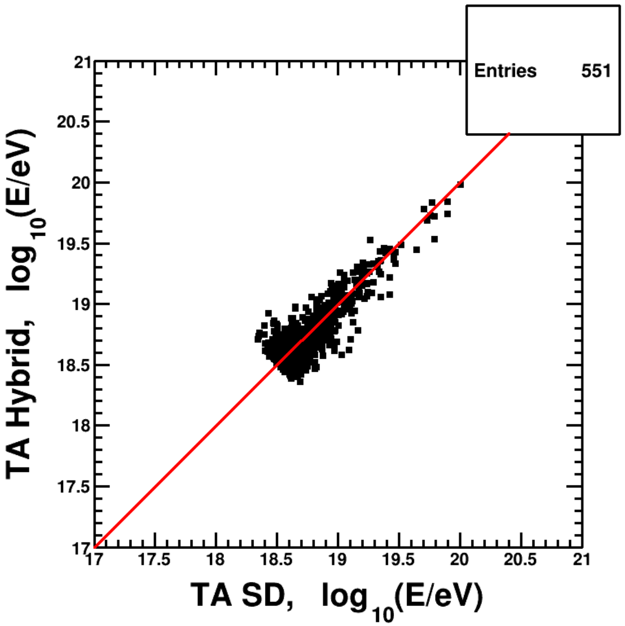
Corsika/QGSJet-II and data have same lateral distributions!

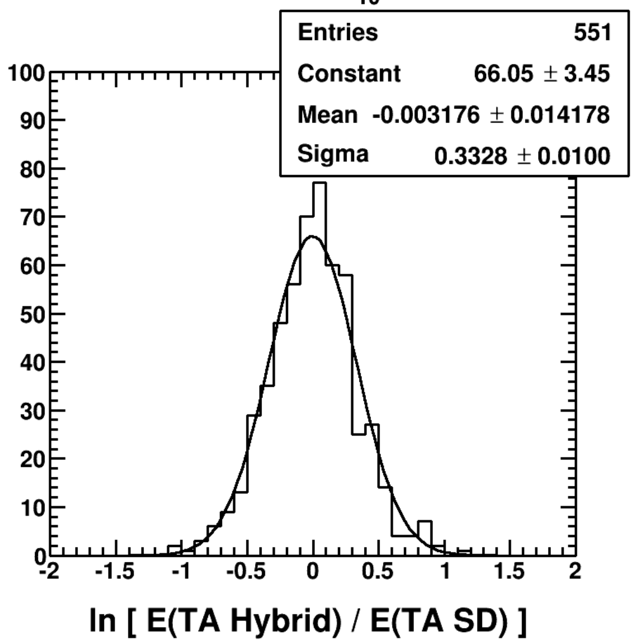
SD Energy 1/2



- A look-up table made from the Monte-Carlo
- Event energy (E^{TBL}) = function of *reconstructed* S800 and sec(θ)
- Energy reconstruction ←→ interpolation between S800 vs sec(θ) contours of constant values of E^{TBL}
- The overall energy scale locked to the fluorescence detector

SD Energy 2/2: Energy Scale Set to FD





- Energy scale locked to the FD to reduce the systematic due to the model
- Use events well reconstructed separately by SD and FD in hybrid mode:
  - SD ∩ [BR U LR U MD Hybrid]
  - $E^{FINAL} = E^{TBL} / 1.27$
- TOP figure: E^{FINAL} vs E^{FD} scatter plot
- BOTTOM figure: histogram of E^{FINAL} / E^{FD} ratio
- 2008/05/11-2013/05/04