# Highlights from The Telescope Array

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# Telescope Array (TA)

- Telescope Array Collaboration was forged by Members of HiRes (High Resolution Fly's Eye) and AGASA
  - Study Ultra High Energy Cosmic Rays (spectrum, composition, anisotropy, …)
  - Understand the differences between AGASA and HiRes …. Especially wrt super-GZK events
  - Study the galactic to extra-galactic transition: measure cosmic rays over the second knee, ankle, and GZK with one cross-calibrated detector
- Current collaboration from the US, Japan, Russia (INR RAS), Korea, and Belgium

# Telescope Array Collaboration

RU Abbasi[1], M Abe[13], T Abu-Zayyad[1], M Allen[1], R Anderson[1], R Azuma[2], E Barcikowski[1], JW Belz[1], DR Bergman[1], SA Blake[1], R Cady[1], MJ Chae[3], BG Cheon[4], J Chiba[5], M Chikawa[6], WR Cho[7], T Fujii[8], M Fukushima[8,9], T Goto[10], W Hanlon[1], Y Hayashi[10], N Hayashida[11], K Hibino[11], K Honda[12],D Ikeda[8], N Inoue[13], T Ishii[12], R Ishimori[2], H Ito[14], D Ivanov[1], CCH Jui[1], K Kadota[16], F Kakimoto[2], O Kalashev[17], K Kasahara[18], H Kawai[19], S Kawakami[10], S Kawana[13], K Kawata[8], E Kido[8], HB Kim[4], JH Kim[1], JH Kim[25], S Kitamura[2], Y Kitamura[2], V Kuzmin[17], YJ Kwon[7], J Lan[1], SI Lim[3], JP Lundquist[1], K Machida[12], K Martens[9], T Matsuda[20], T Matsuyama[10], JN Matthews[1], M Minamino[10], K Mukai[12], I Myers[1], K Nagasawa[13], S Nagataki[14],T Nakamura[21], T Nonaka[8], A Nozato[6], S Ogio[10], J Ogura[2], M Ohnishi[8], H Ohoka[8], K Oki[8], T Okuda[22], M Ono[14], A Oshima[10], S Ozawa[18], IH Park[23], MS Pshirkov[24], DC Rodriguez[1], G Rubtsov[17], D Ryu[25], H Sagawa[8], N Sakurai[10], AL Sampson[1], LM Scott[15], PD Shah[1], F Shibata[12], T Shibata[8], H Shimodaira[8], BK Shin[4], JD Smith[1], P Sokolsky[1], RW Springer[1], BT Stokes[1], SR Stratton[1,15], TA Stroman[1], T Suzawa[13], M Takamura[5], M Takeda[8], R Takeishi[8], A Taketa[26], M Takita[8], Y Tameda[11], H Tanaka[10], K Tanaka[27], M Tanaka[20], SB Thomas[1], GB Thomson[1], P Tinyakov[17,24], I Tkachev[17], H Tokuno[2], T Tomida[28], S Troitsky[17], Y Tsunesada[2], K Tsutsumi[2], Y Uchihori[29], S Udo[11], F Urban[24], G Vasiloff[1], T Wong[1], R Yamane[10], H Yamaoka[20], K Yamazaki[10], J Yang[3], K Yashiro[5], Y Yoneda[10], S Yoshida[19], H Yoshii[30], R Zollinger[1], Z Zundel[1]

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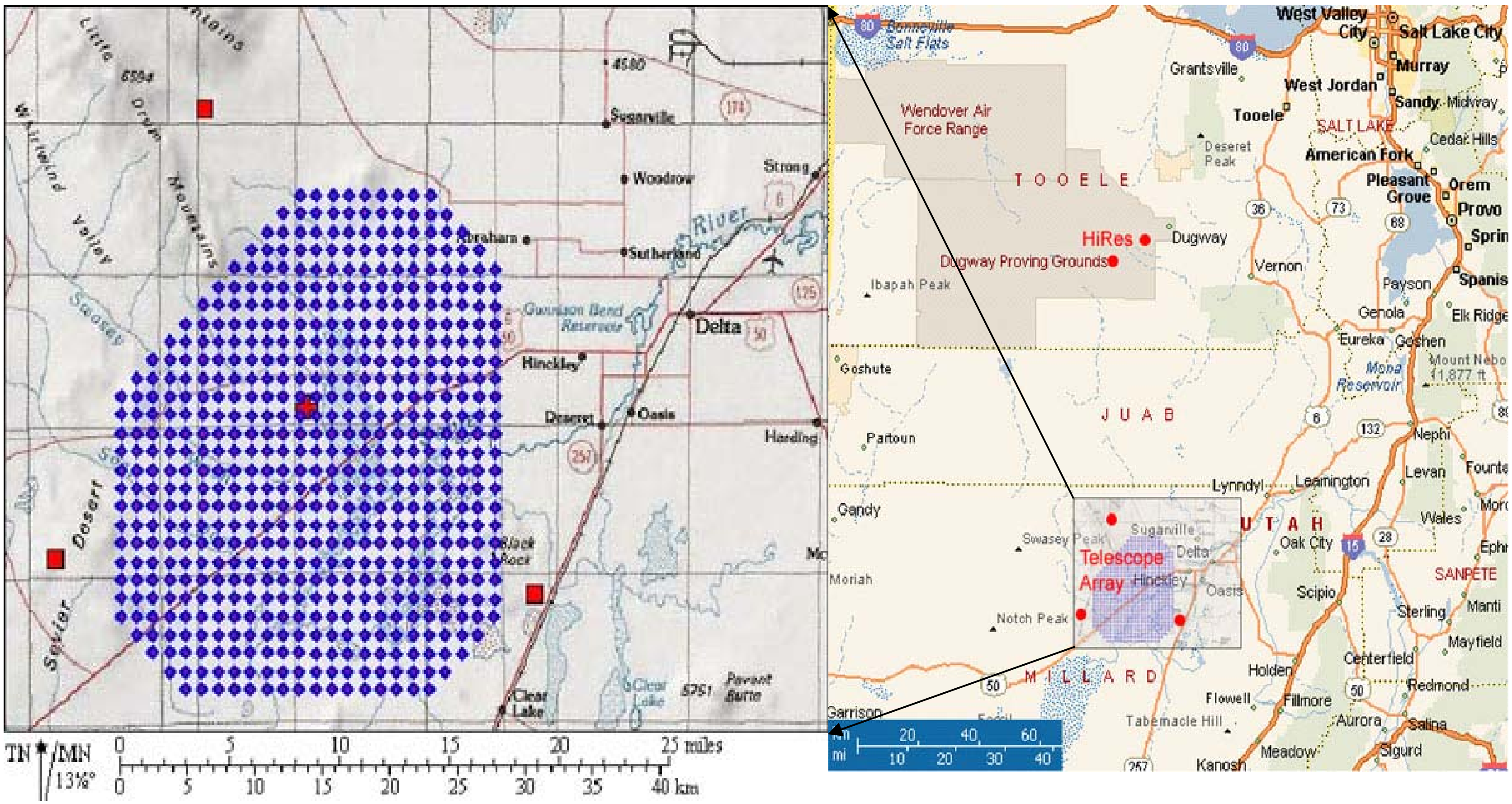
USA, Japan, Korea, Russia, Belgium

# Telescope Array




700 km²: Lat. 39.30°N, Long. 112.91°W 1550m ASL

The High Energy component of Telescope Array – 38 fluorescence telescopes (9728 PMTs) at 3 telescope stations overlooking an array of 507 scintillator surface detectors (SD) - complete and operational as of ~1/2008.

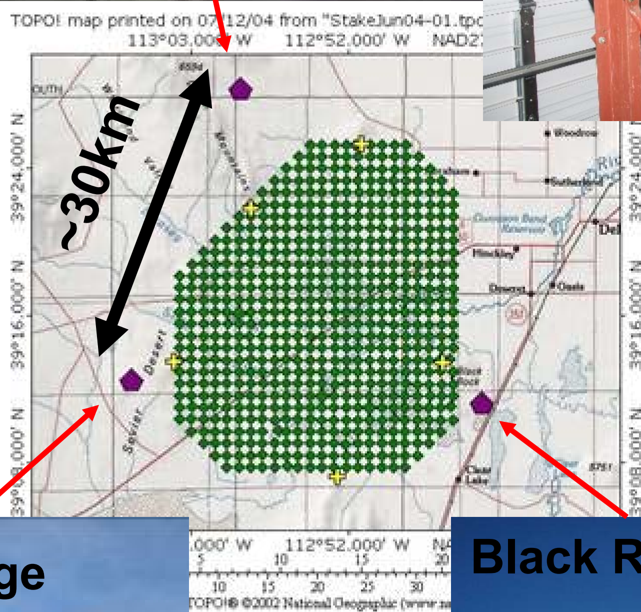
# TA Fluorescence Detectors

Middle Drum

14 telescopes @ station
256 PMTs/camera

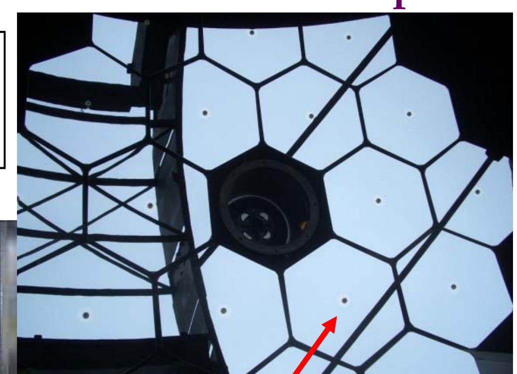
5.2 m$^2$

Reutilized from HiRes-I



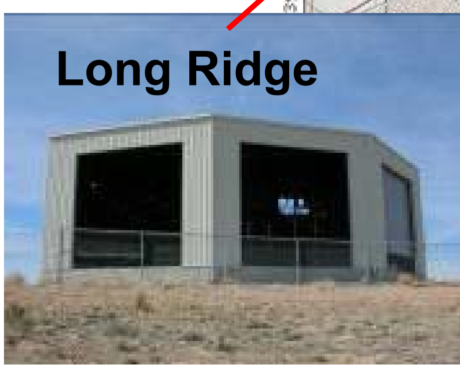

New Telescopes

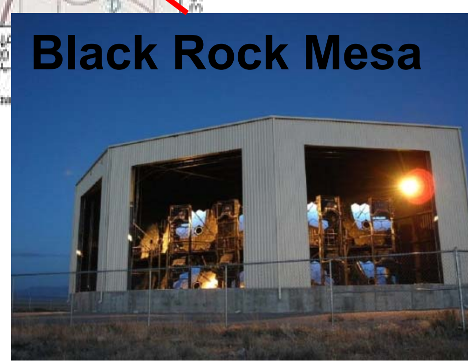
12 telescopes/station
256 PMTs/camera



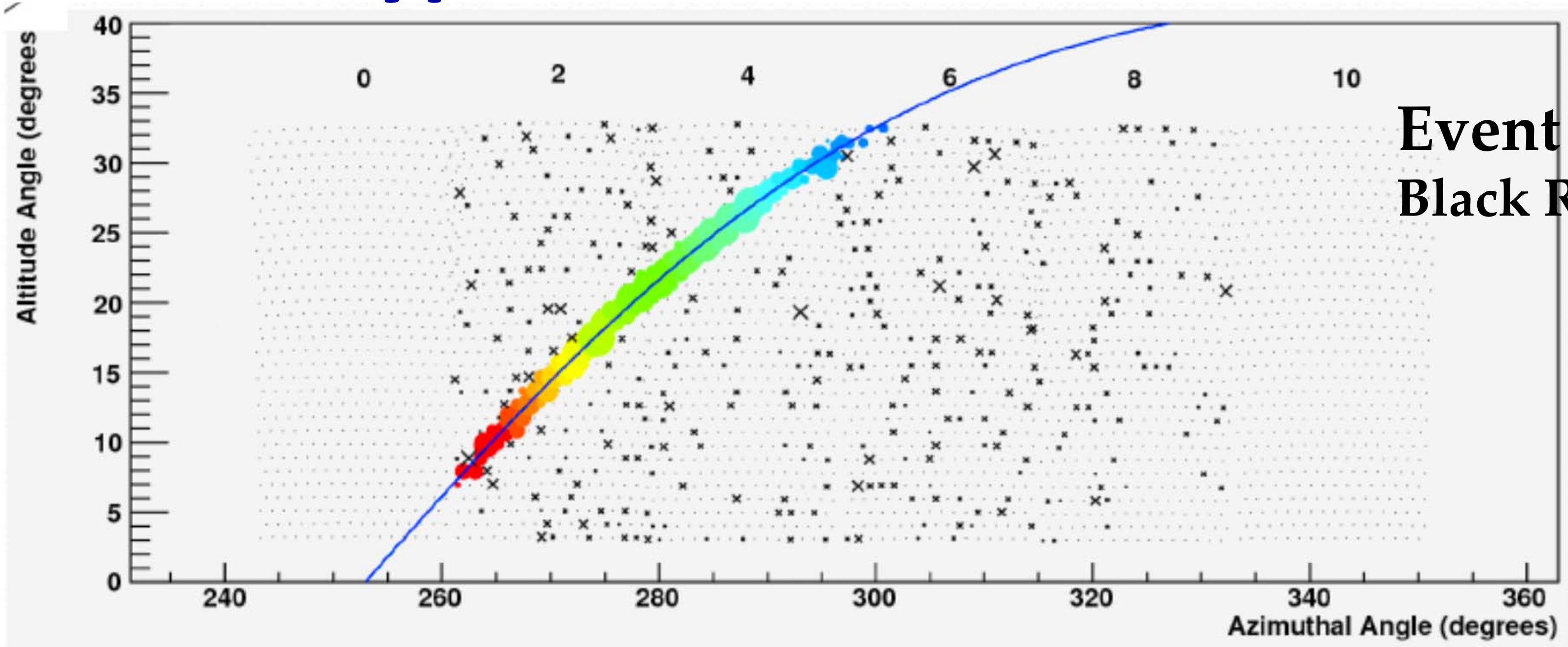
6.8 m$^2$

~1 m$^2$

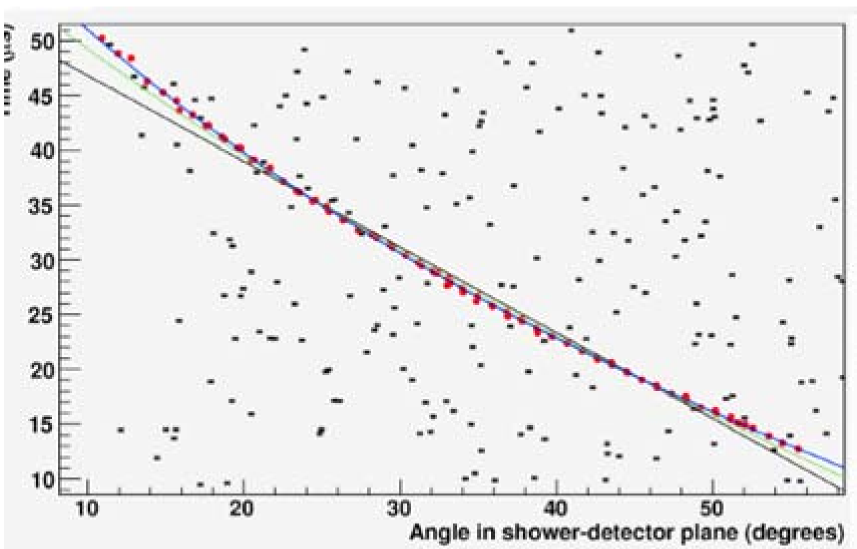


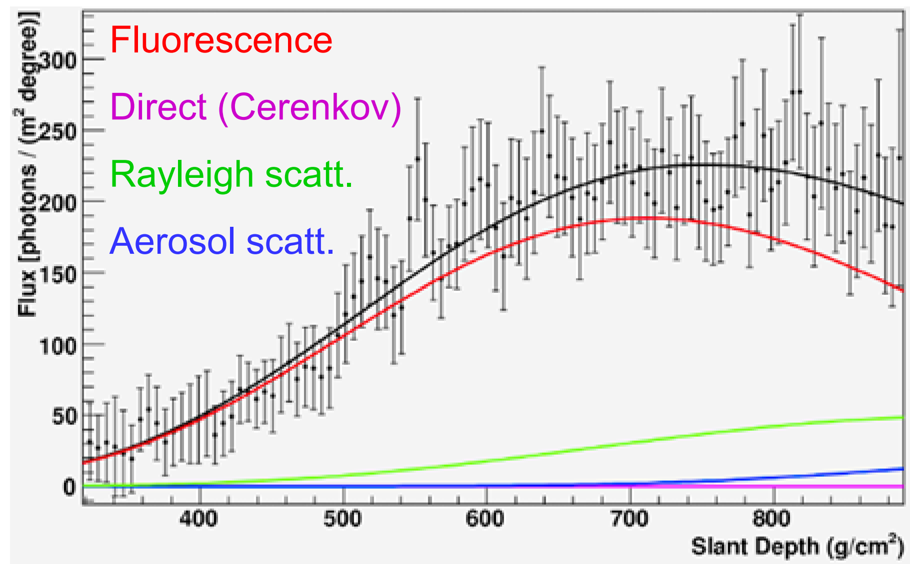



# Typical Fluorescence Event




**Event Display**
**Black Rock Mesa**

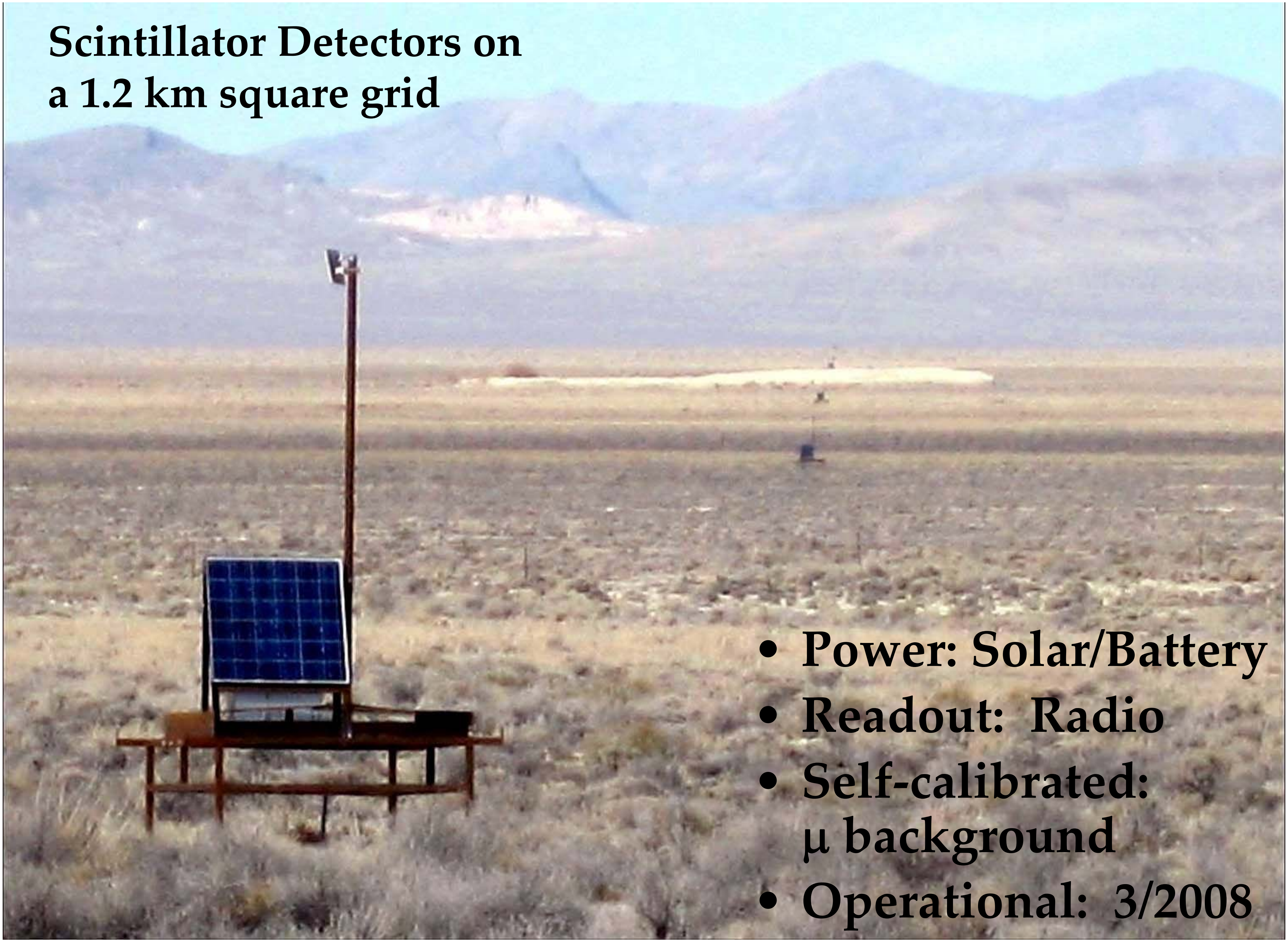



**Monocular timing fit (time vs angle)** **Reconstructed Shower Profile**

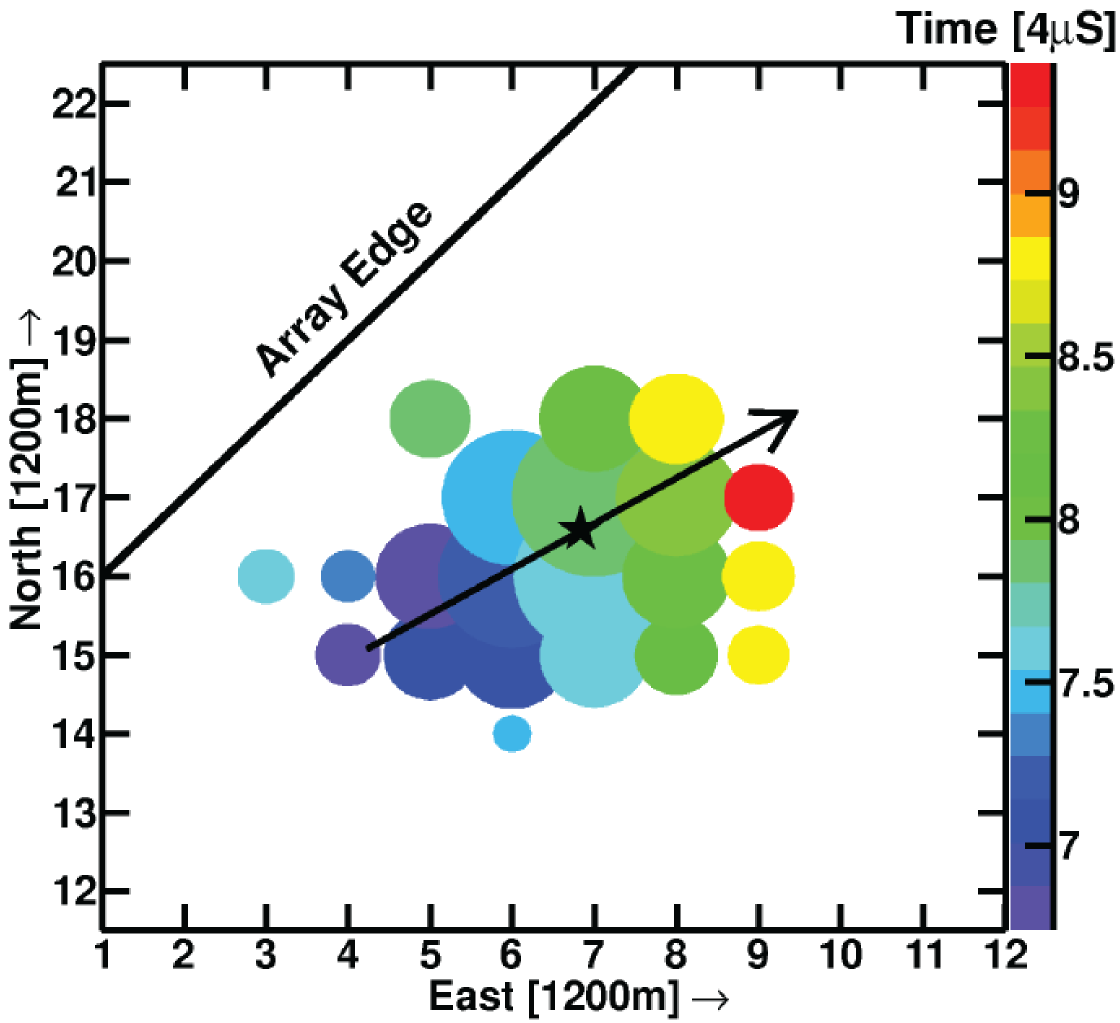
# Scintillator Surface Detectors

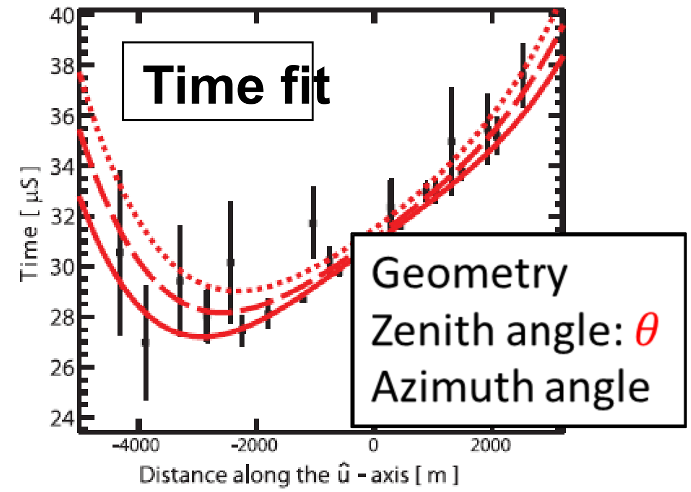
2 layers scintillator
1.25 cm thick, $3\text{m}^2$ area
Optical fibers to PMTs

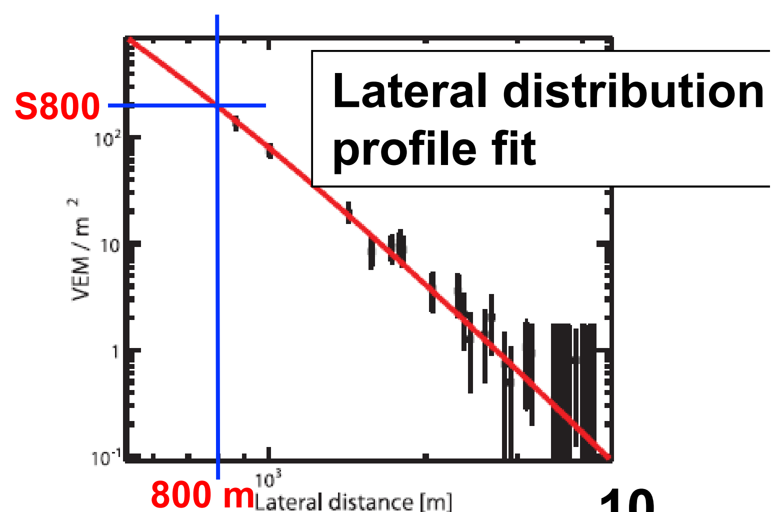

Scintillator Detectors on a 1.2 km square grid
• Power: Solar/Battery
• Readout: Radio
• Self-calibrated: μ background
• Operational: 3/2008

# TA shower analysis with SD

**An SD hit map of a typical high energy event**

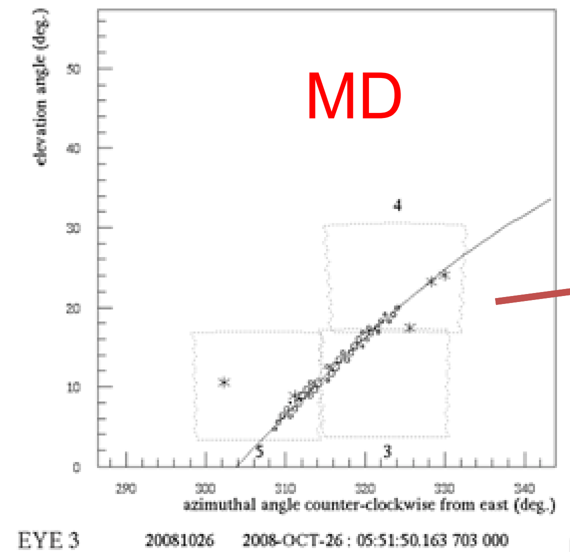


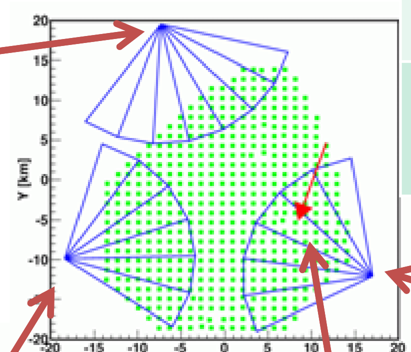

**10**

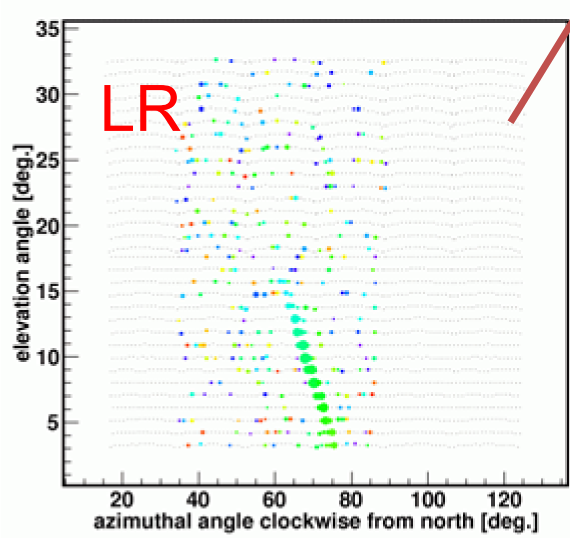
# Example Event

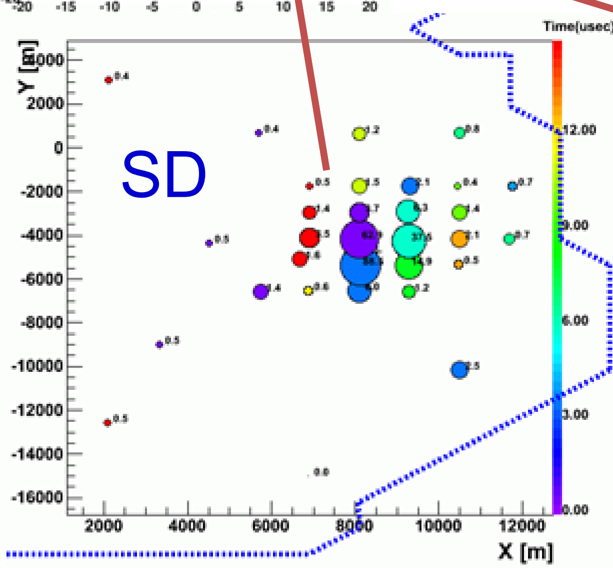


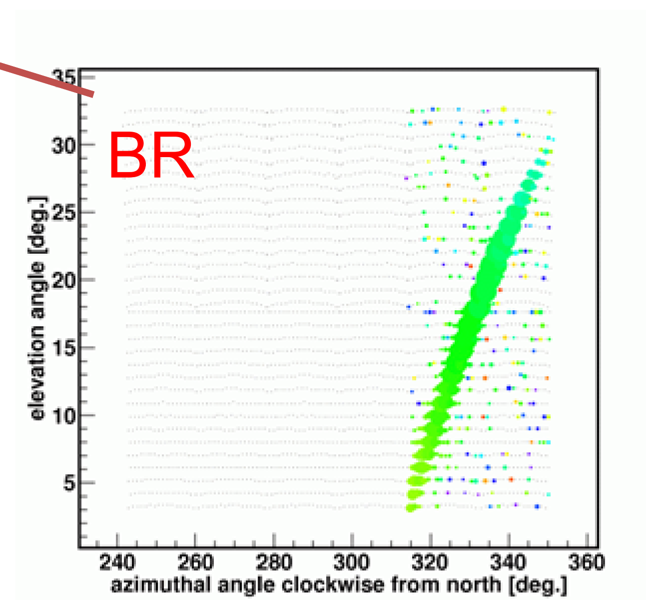

| | $\theta$ [°] | $\phi$ [°] | x[km] | y[km] |
|---|---|---|---|---|
| MD mono | 51.43 | 73.76 | 7.83 | -3.10 |
| BR mono | 51.50 | 77.09 | 7.67 | -4.14 |
| Stereo BR&LR | 50.21 | 71.30 | 8.55 | -4.88 |

Event from 2008-10-26



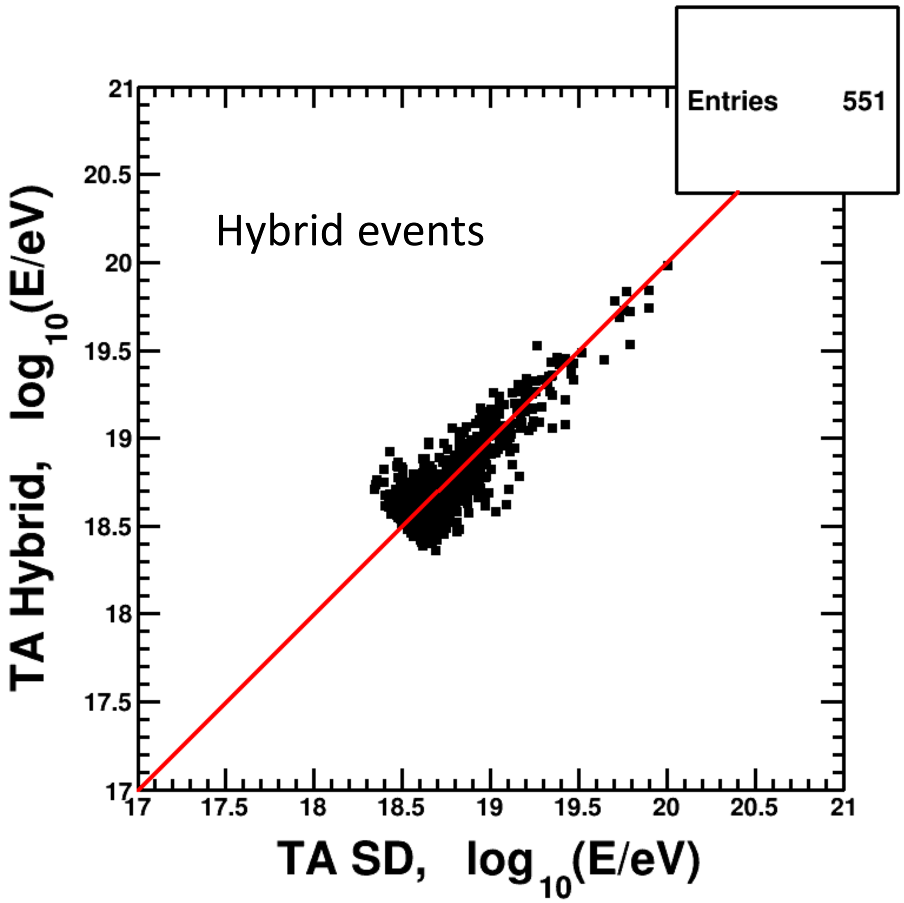



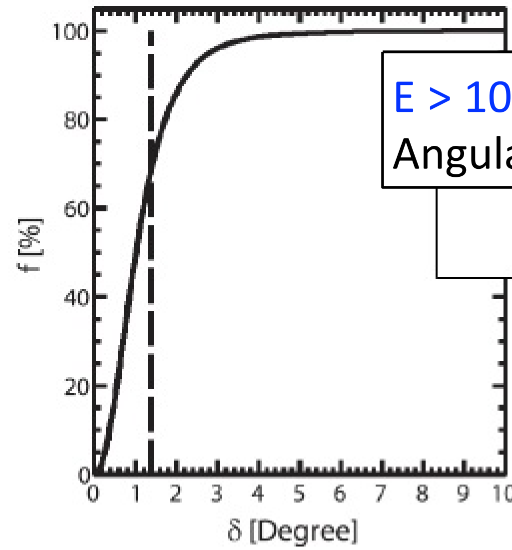
# TA Energy Spectrum Results

# Energy Scale Check and Resolution



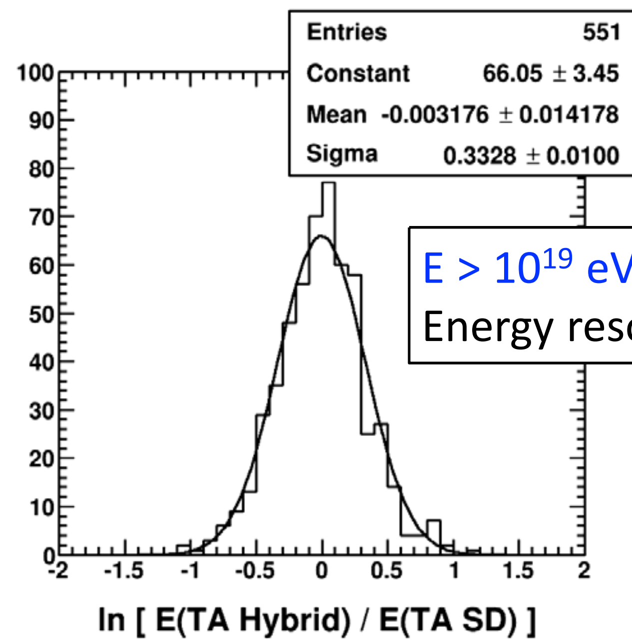

(SD scaled to FD energy: calorimetric)

$E_{SD}/1.27 = E_{FD}$




$E > 10^{19}$ eV

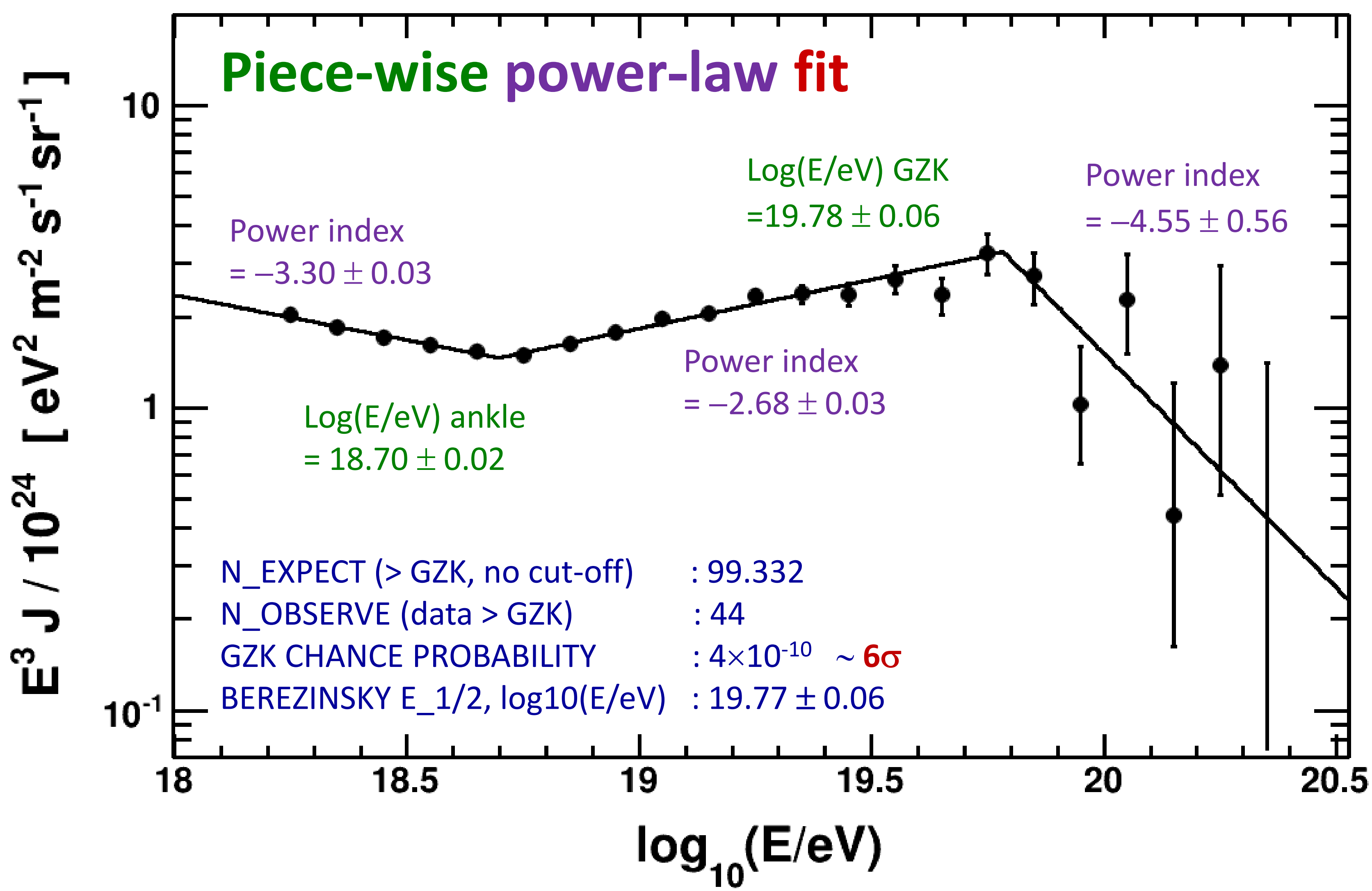
Angular resolution = 1.4°




$E > 10^{19}$ eV

Energy resolution < 20%

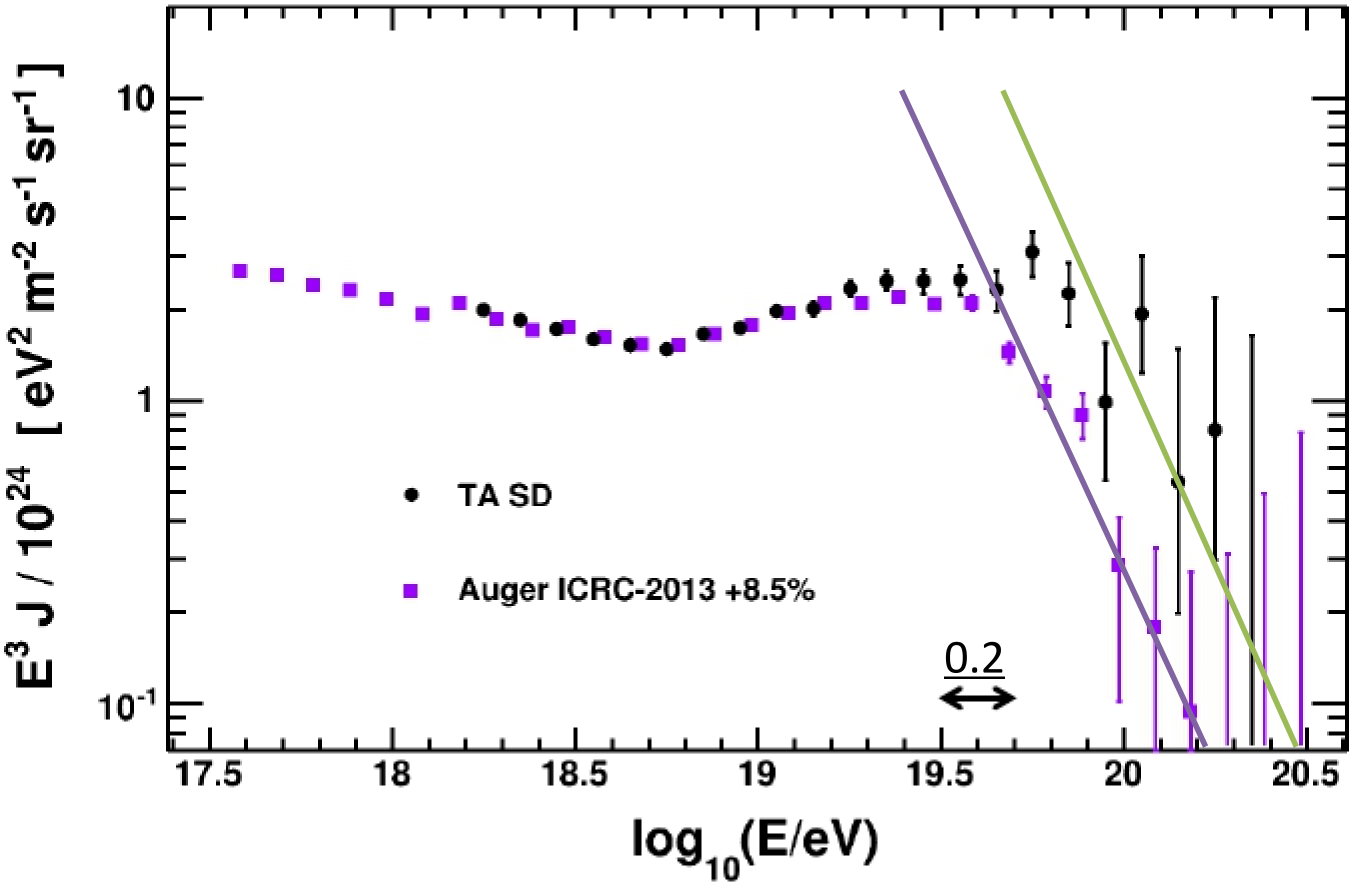
# TA SD Spectrum (7 yrs data)




**Previously Pubilshed:** **4 year TA surface detector spectrum**

Astrophysical Journal Letters 768 L1 (2013)

# Comparison of TA and Auger (+8.5%) Spectra

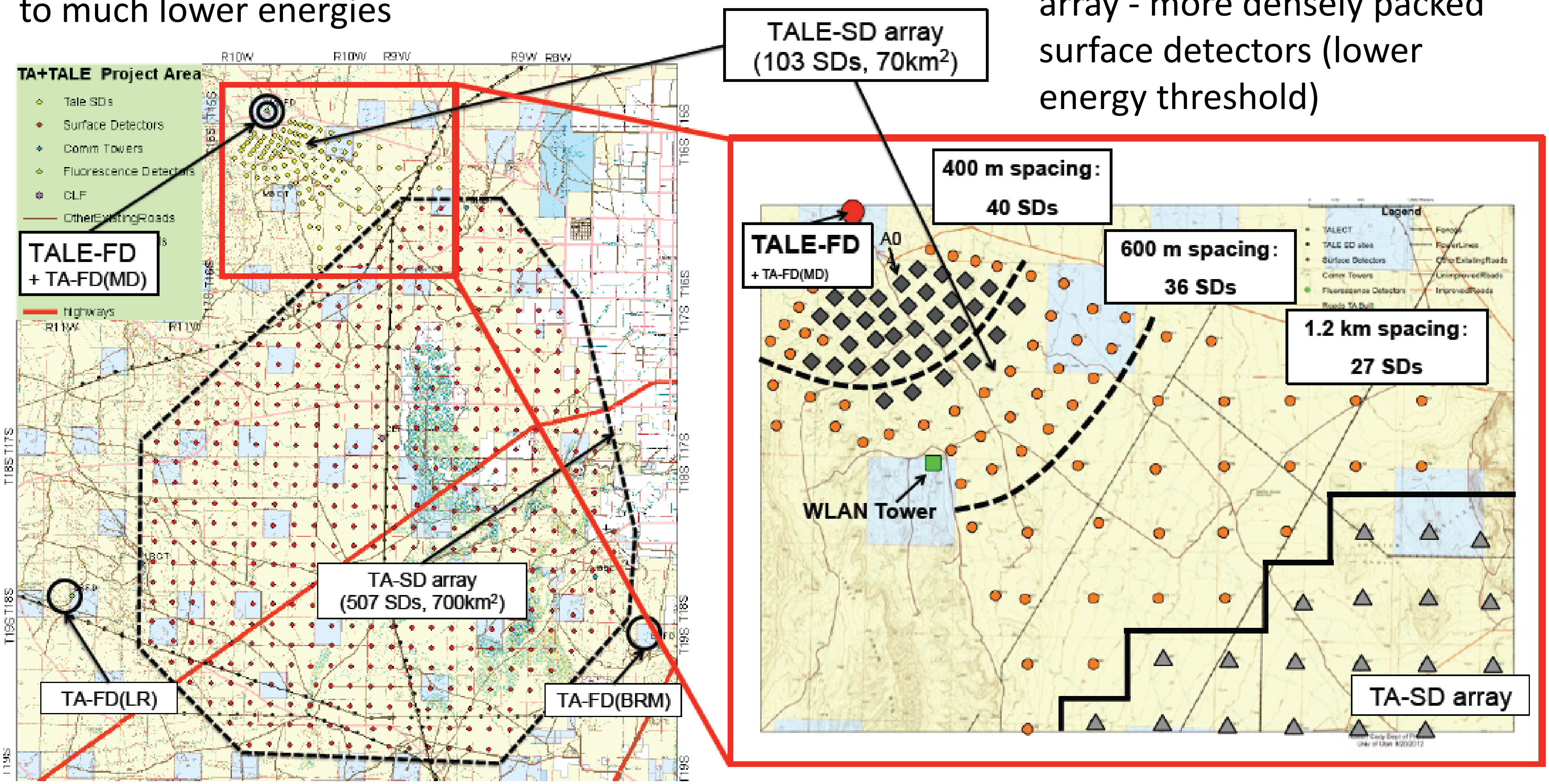


# TA Low Energy Extension (TALE)

## Galactic to Extra-Galactic Transition

10 new telescopes to look higher in the sky (31-59$^{o}$) to see shower development to much lower energies

Graded infill surface detector array - more densely packed surface detectors (lower energy threshold)

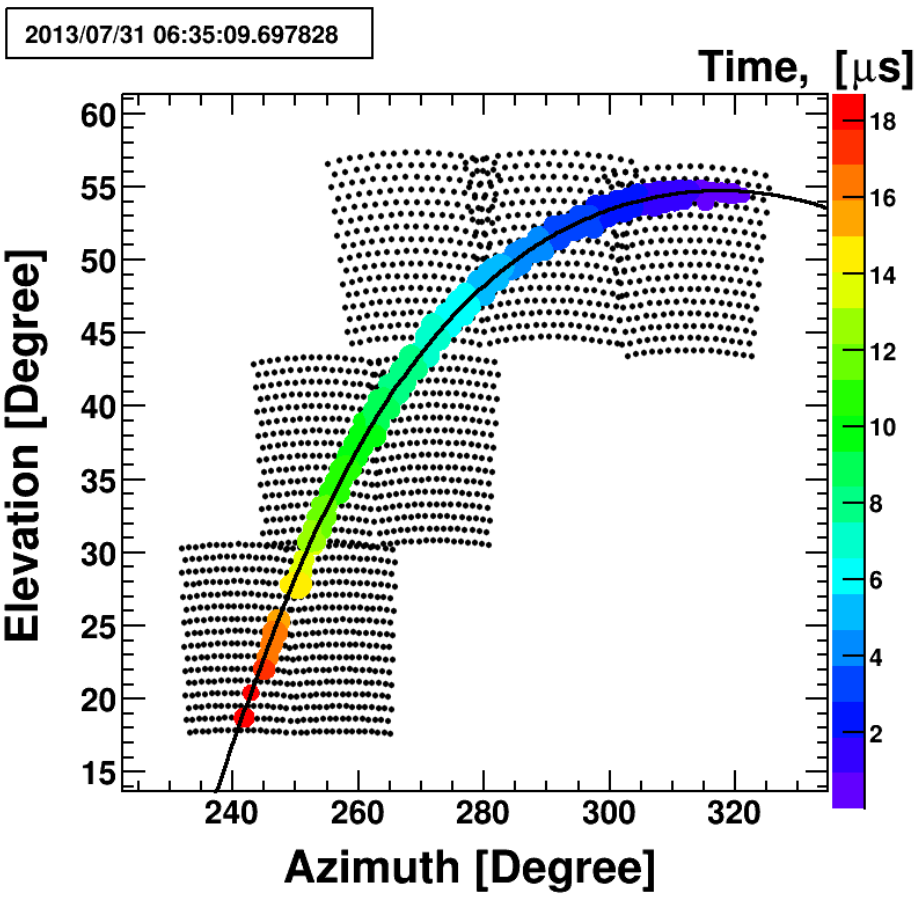


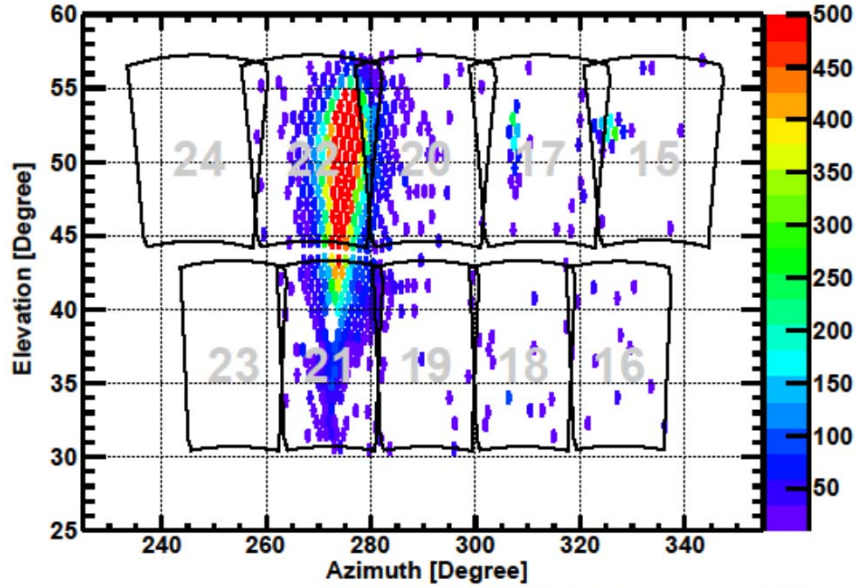

All 10 Telescopes installed and in operation since fall 2013

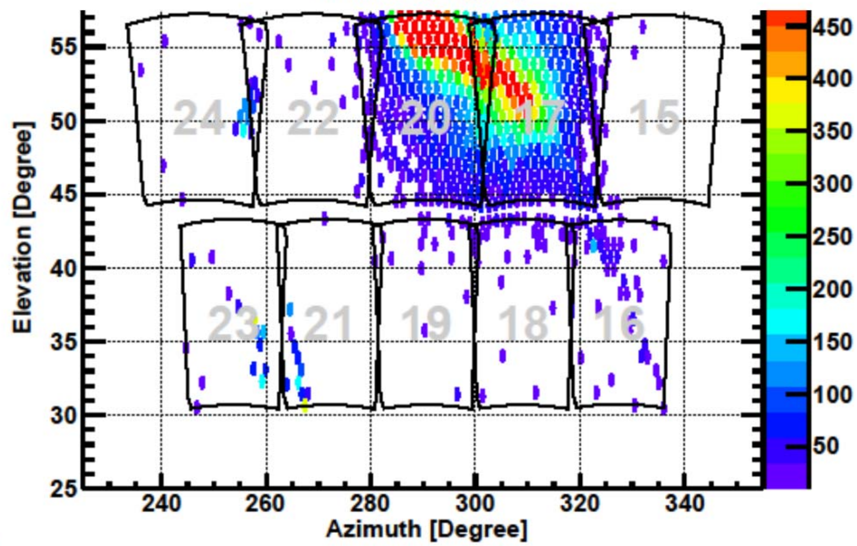
Test array of 16 scintillation surface detectors in operation

**TALE SD infill array recently funded from Japan – deploy to field 2016-17**

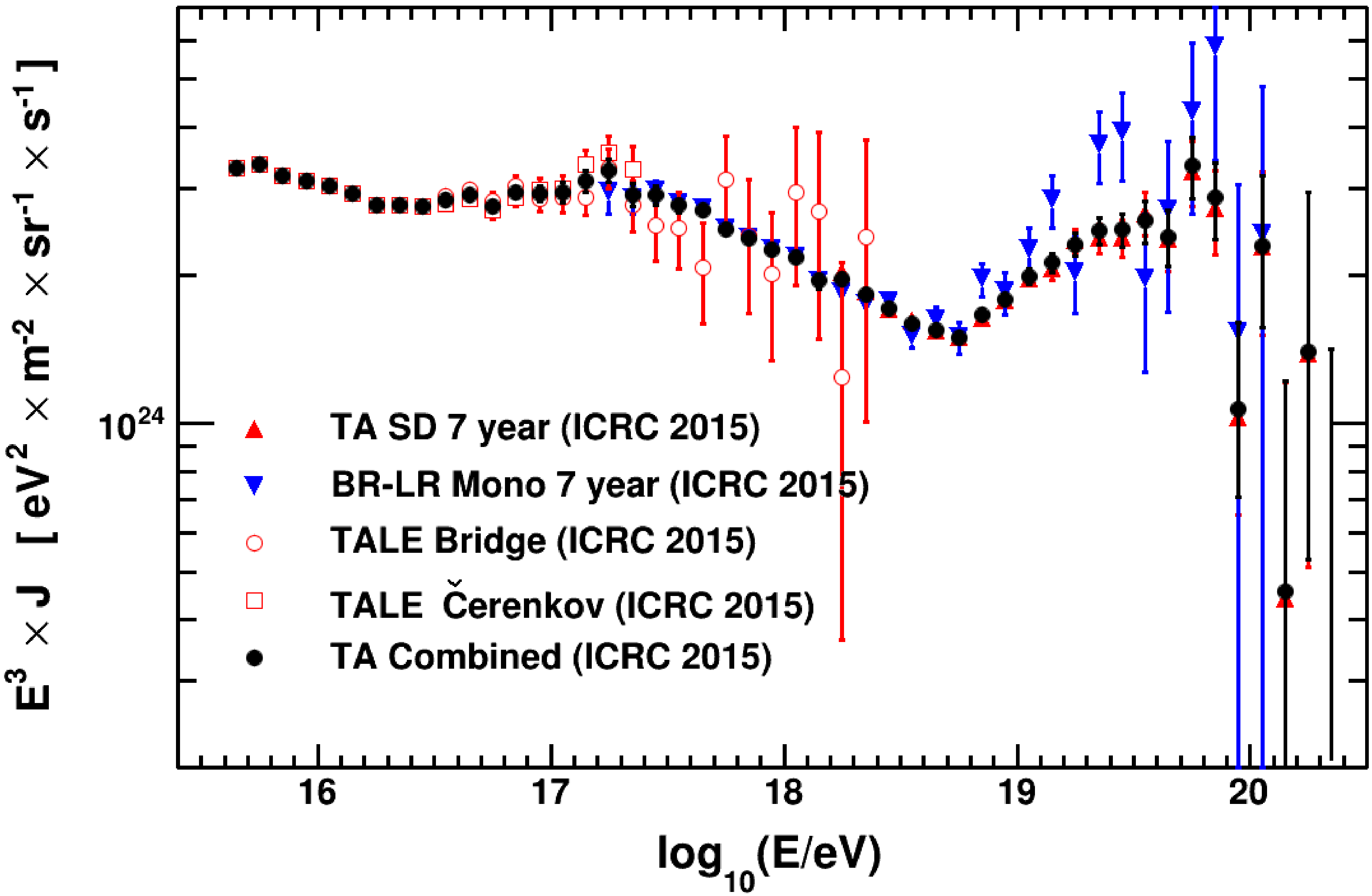
# Nearby Events with Cerenkov



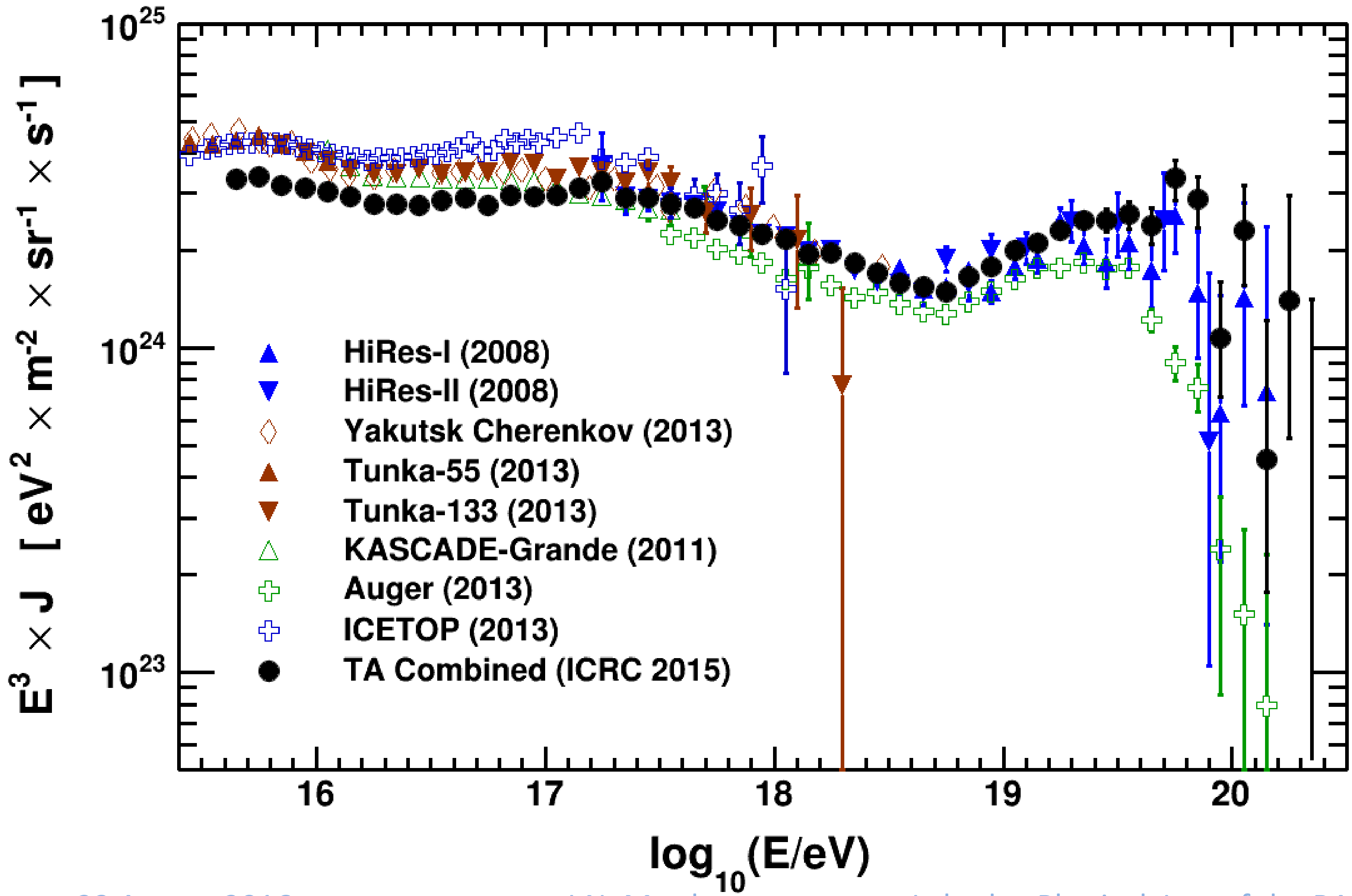



# Combined TA Energy Spectrum



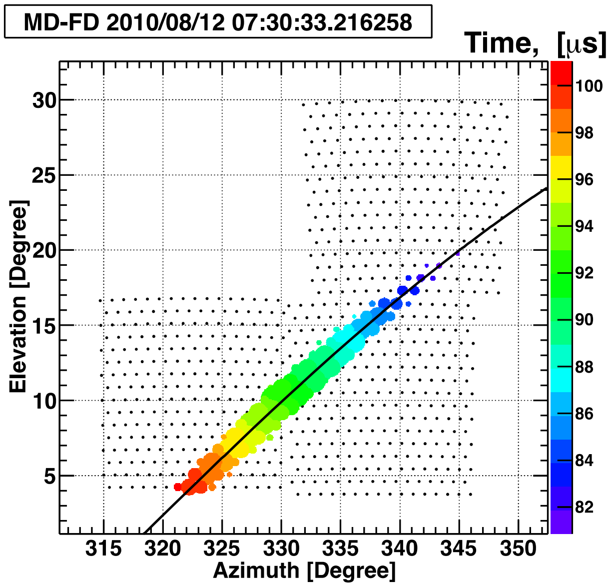
# Comparison with other Measurements

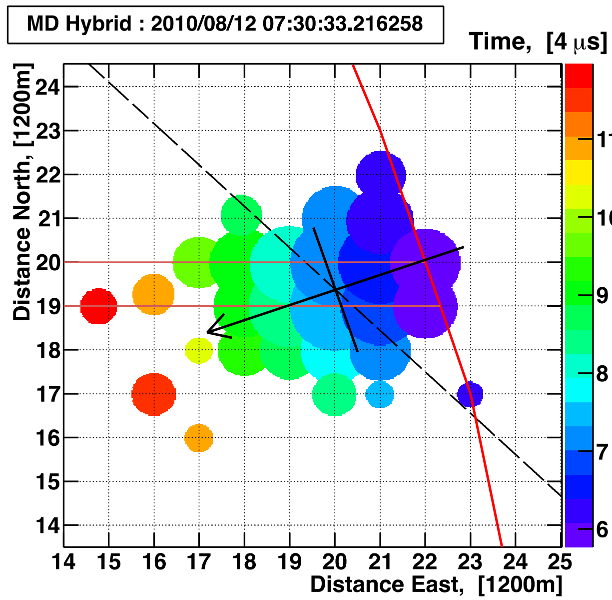


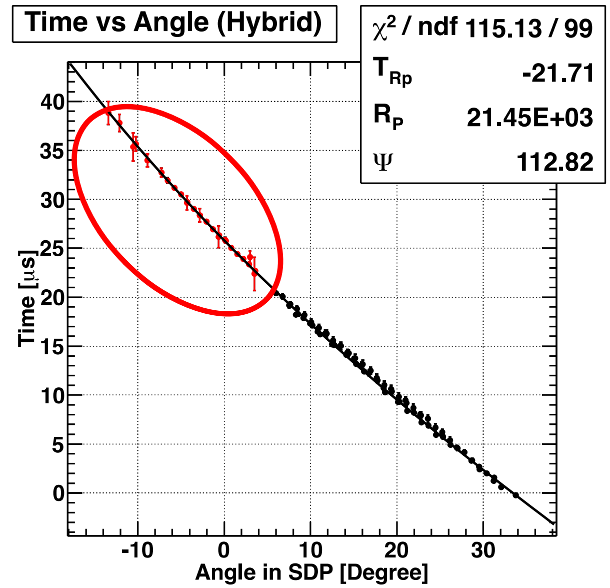
# TA Composition Results

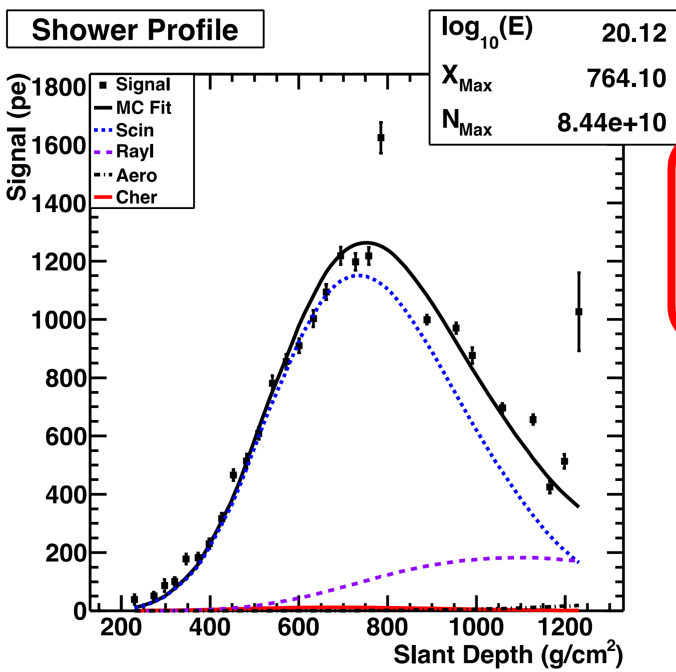
- Use hybrid or stereo to constrain geometry and know $X_{max}$
- Stereo also provides a redundant measurement of $X_{max}$

# High Energy Hybrid Event



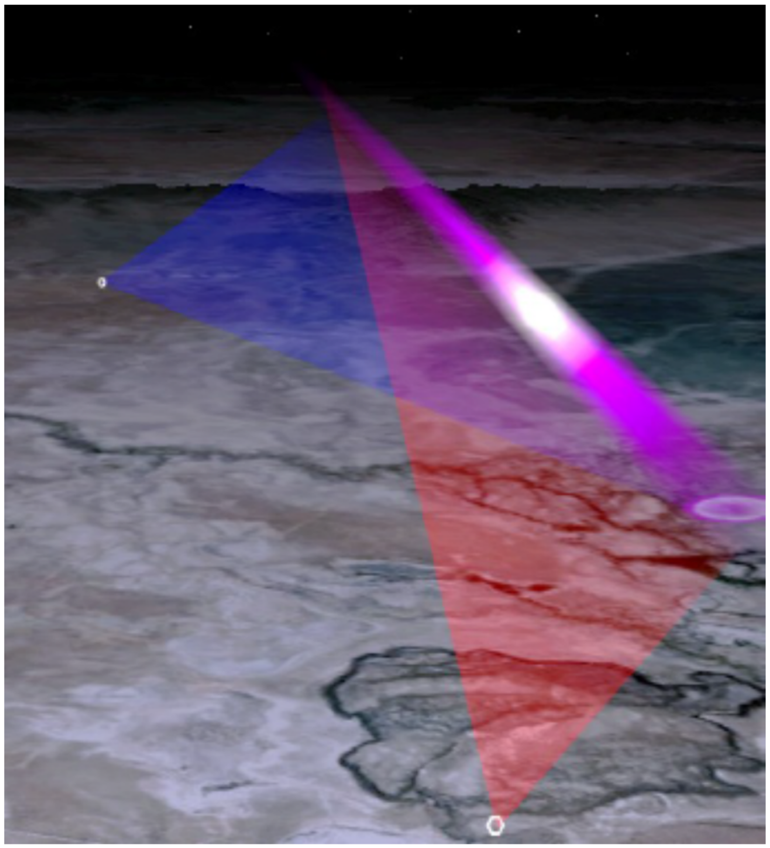



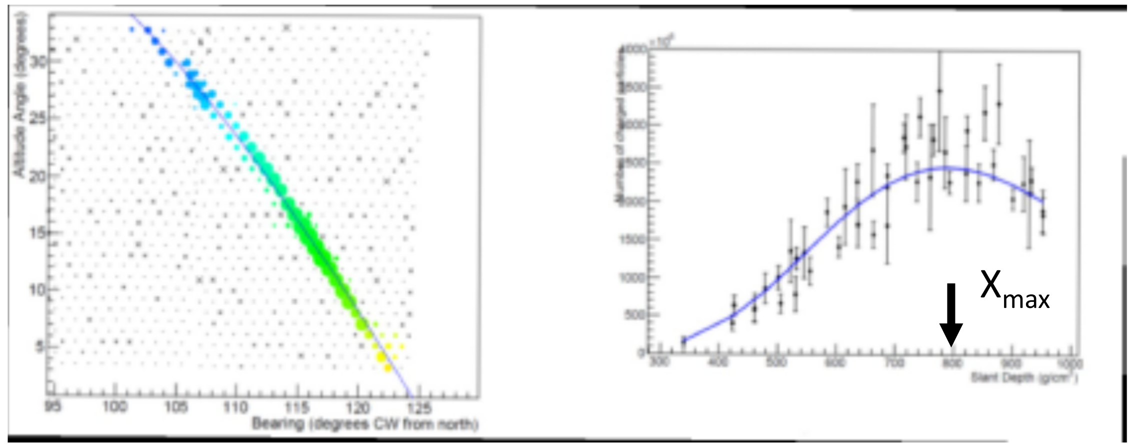

**Energy: $1.3 \times 10^{20}$ eV**

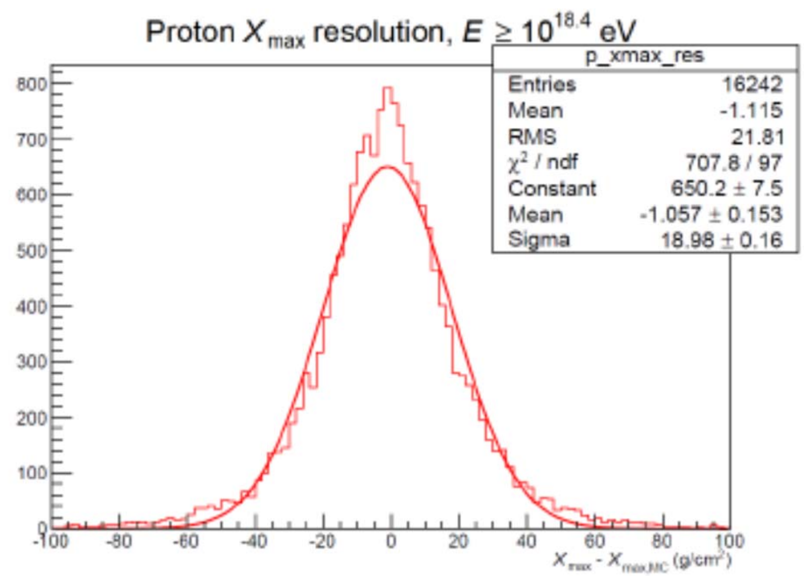
**Zenith Angle: 55.7°**

**Surface array constrains geometry fit via extra timing & core information**

# Stereo Observation



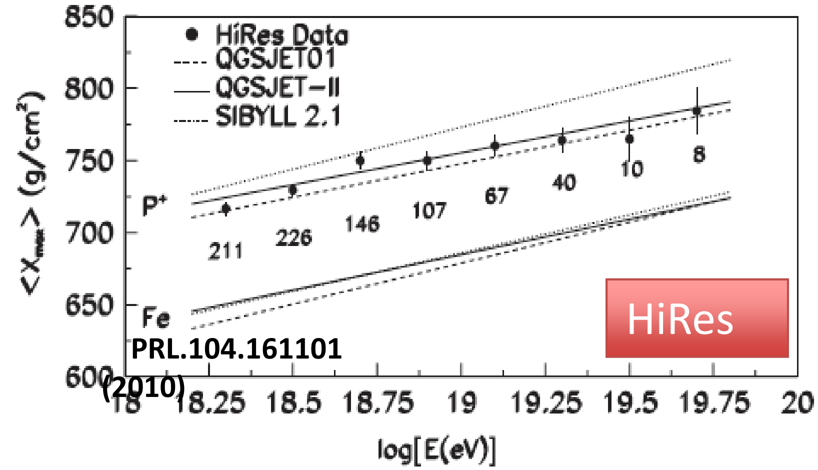


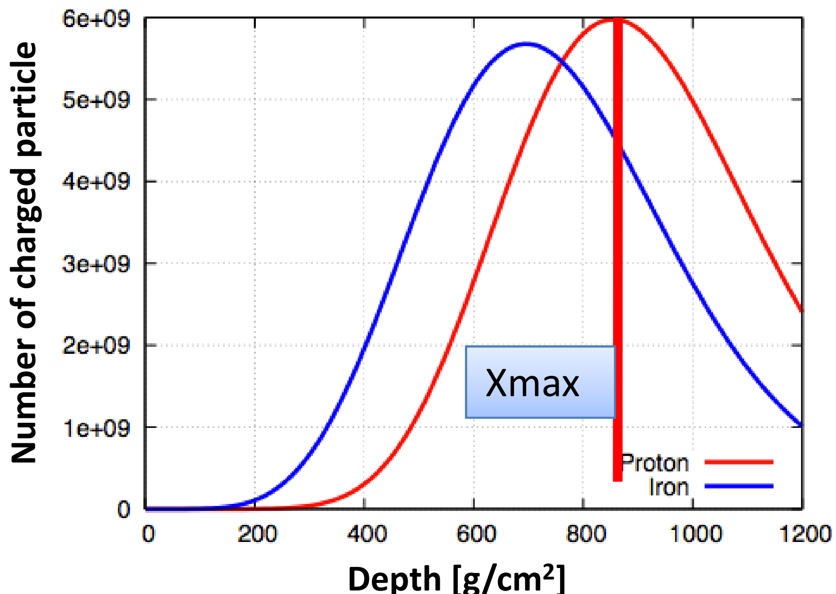

Intersect shower planes to get more precise geometry

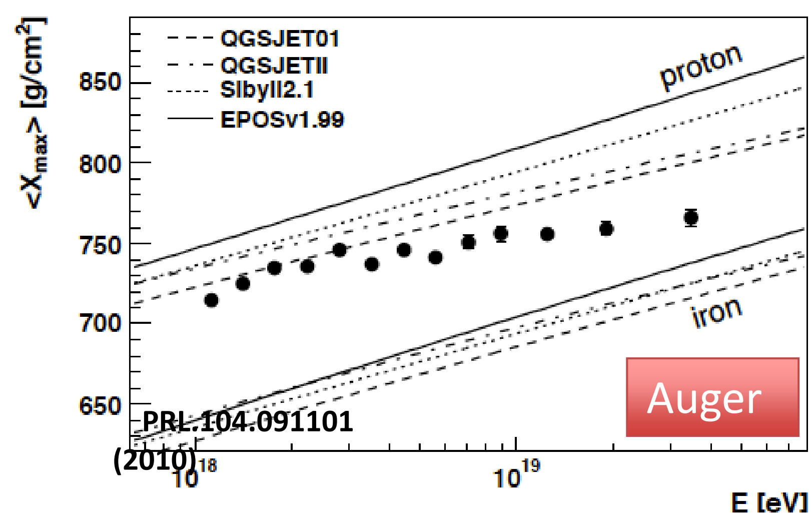
# Xmax Technique

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




Shower longitudinal development

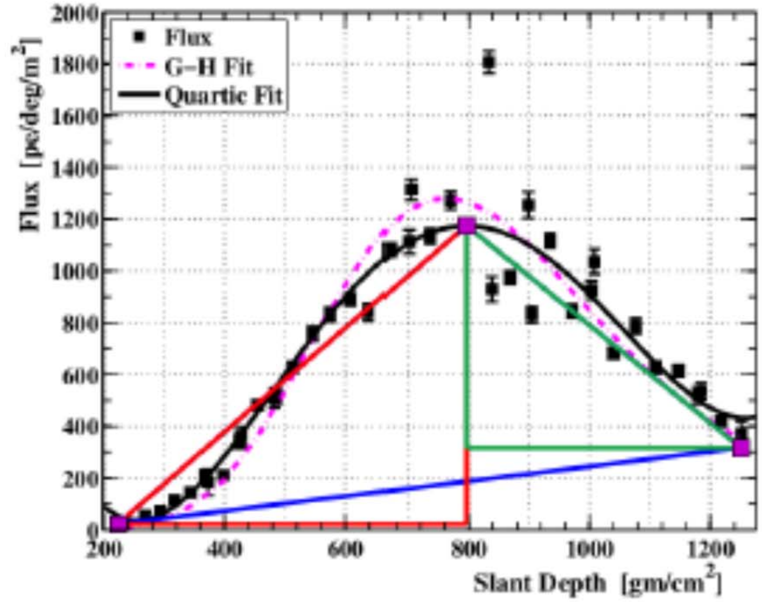


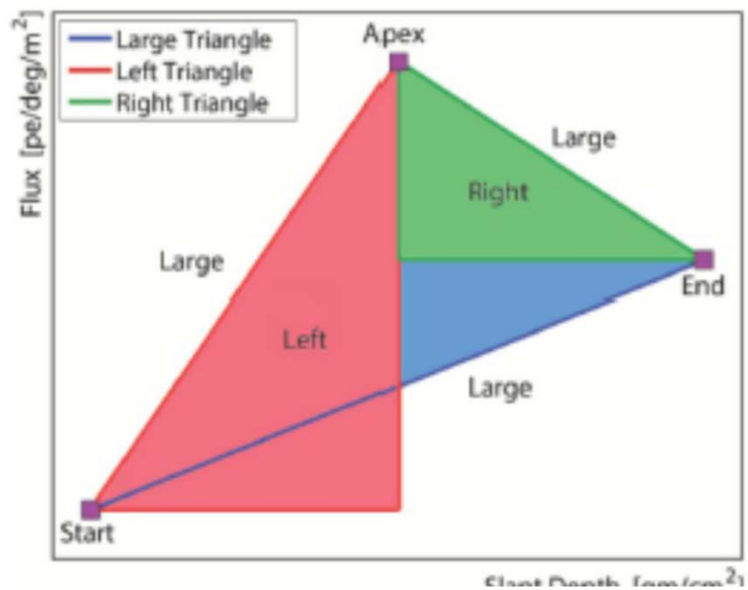



# Hybrid Observation

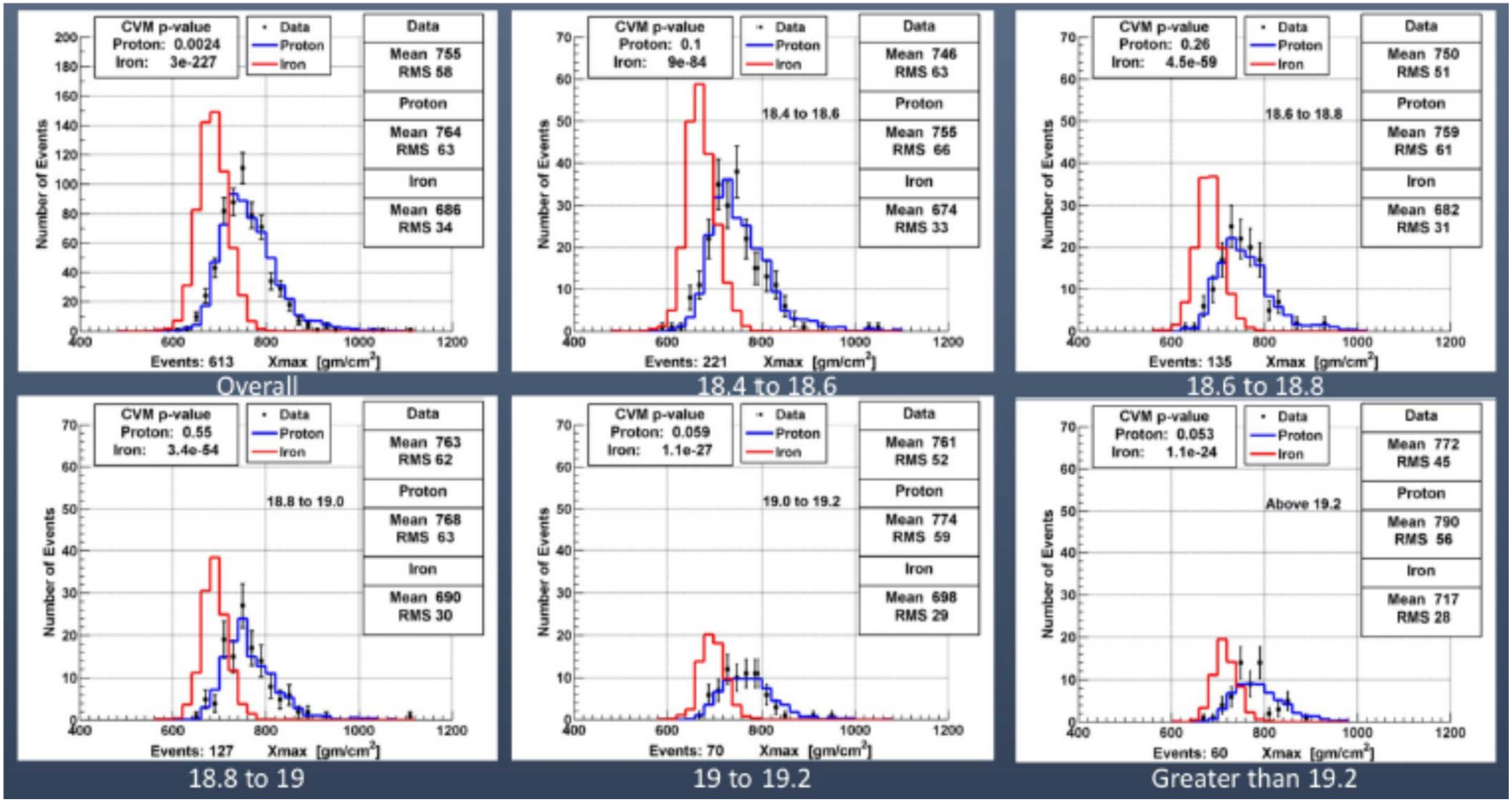
- Astropart. Phys. 64 49 (2014).
4 yrs, 297 Events > $10^{18.4}$ eV
- Cuts based on pattern recognition technique to improve resolutions s ≤ 25 g/cm$^2$, all energies.
- Update:

  7 yr, 613 Events > $10^{18.4}$ eV



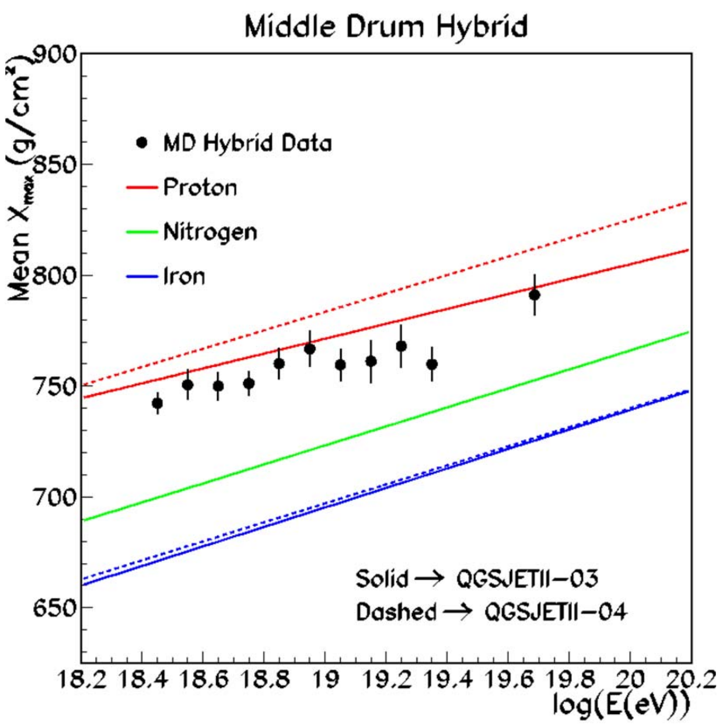
# Hybrid $X_{max}$ Measurement

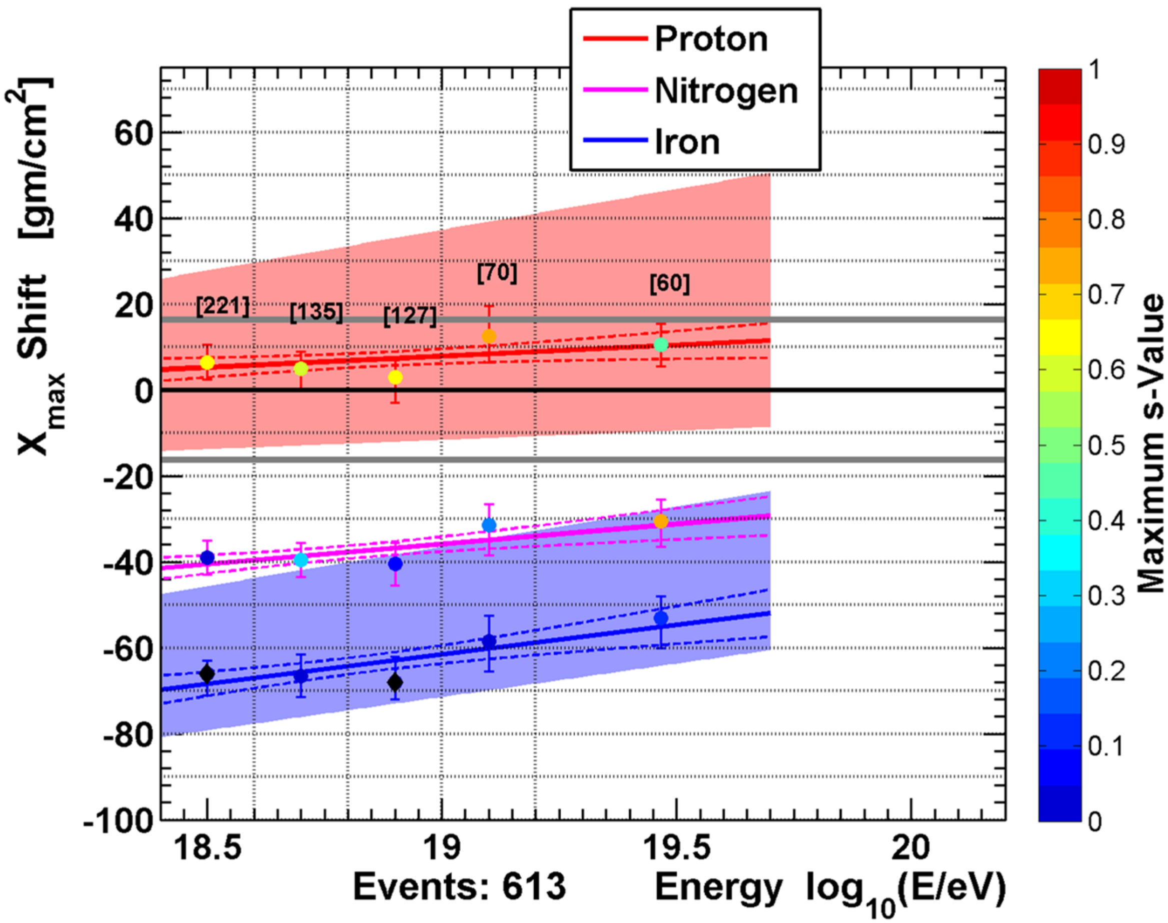



Xmax Data comparison to QGSjet II-03 **proton** and **iron** models

# MD Hybrid

**Elongation:**
**<Xmax> vs log(E) plot**




**"Shift Plot"**

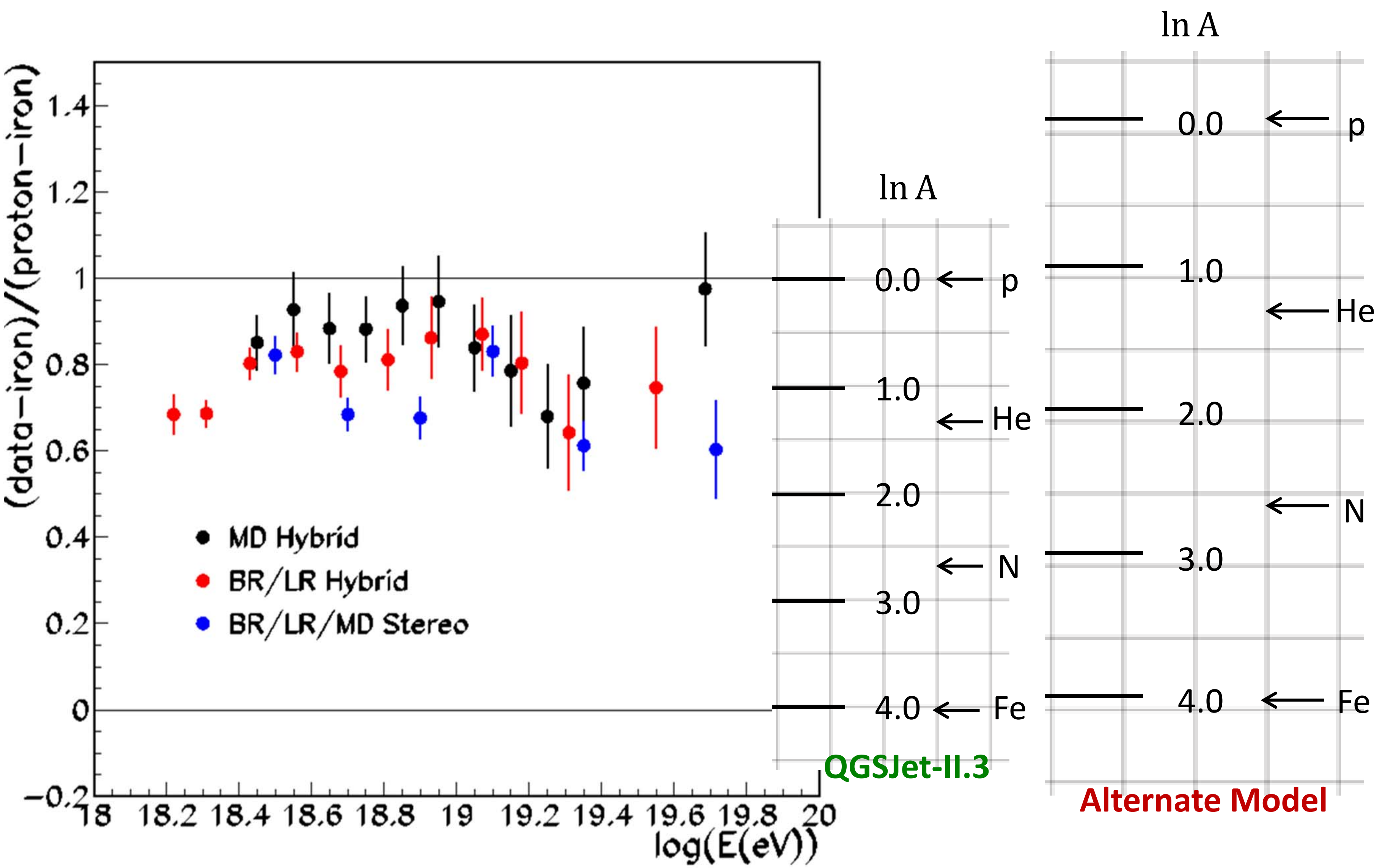
Plot $\Delta X_{max}$ required to maximize data/MC agreement (QGSJETII-03).

Standard statistical test on shifted distribution (points)

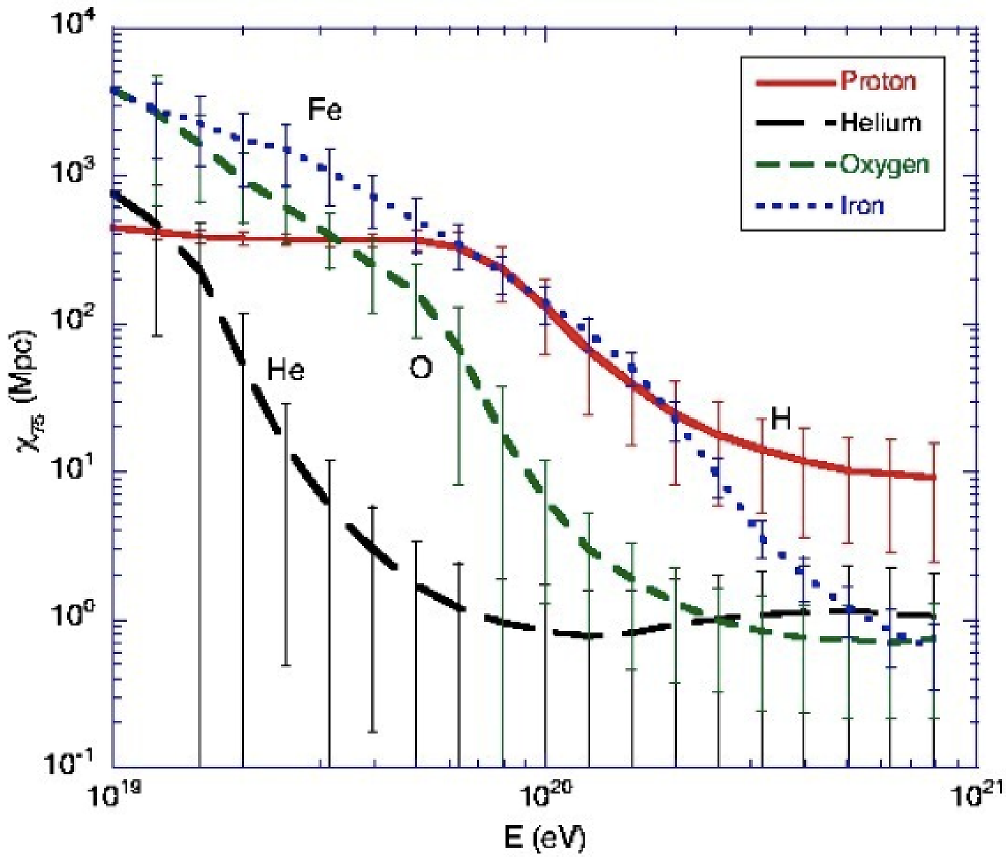
Pink, blue bands for other hadronic models

16 g/cm$^2$ systematic uncertainty

# TA data compared to QGSJet-II.3

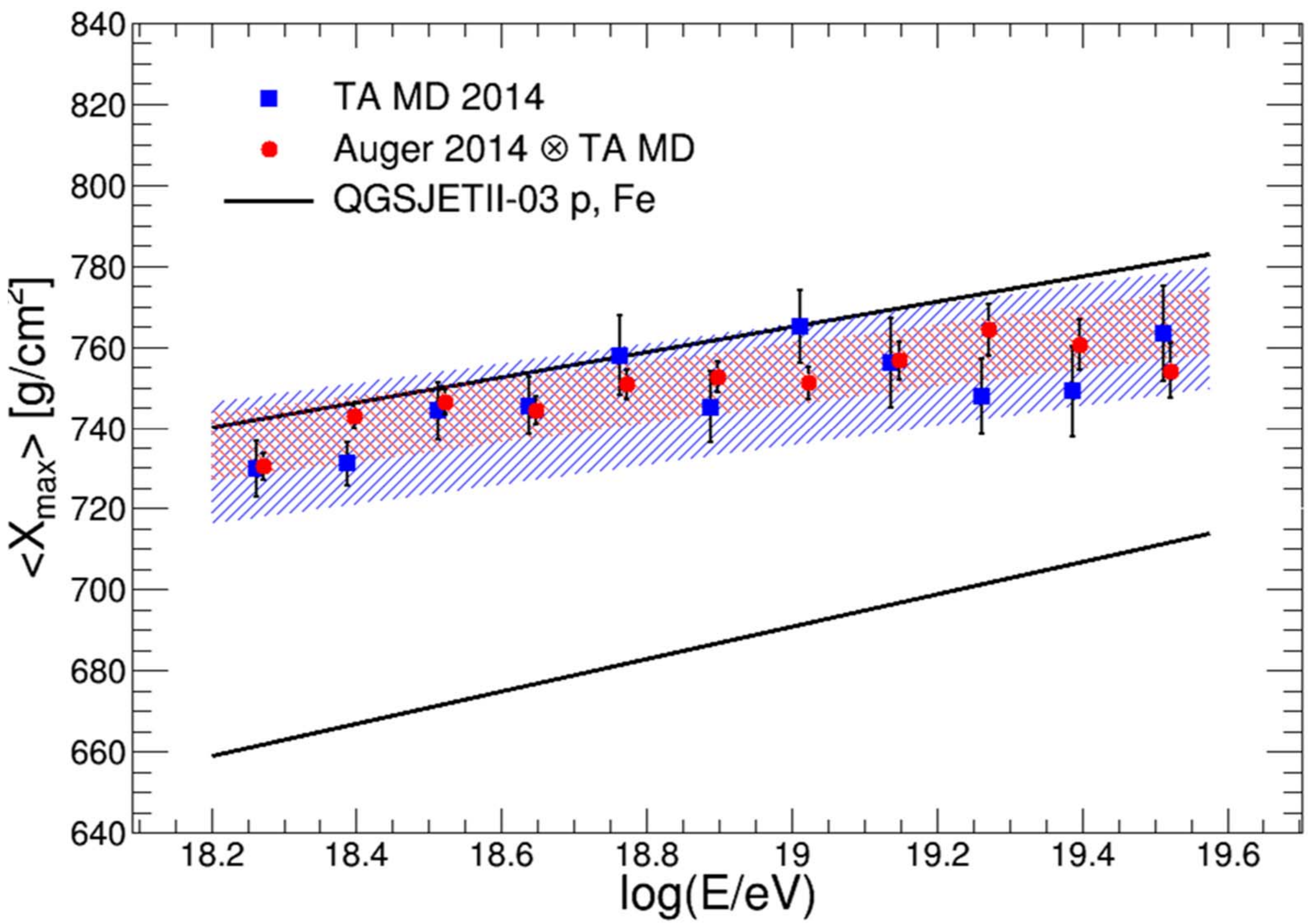


# Astrophysically p and He are very different



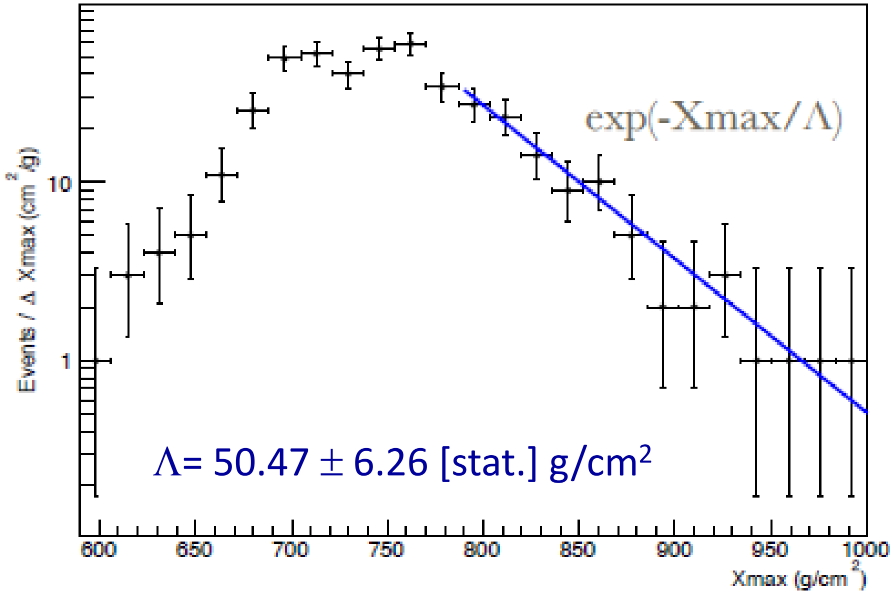

**Interaction lengths of p,He,O and Fe**

# Meta-analysis: Composition WG

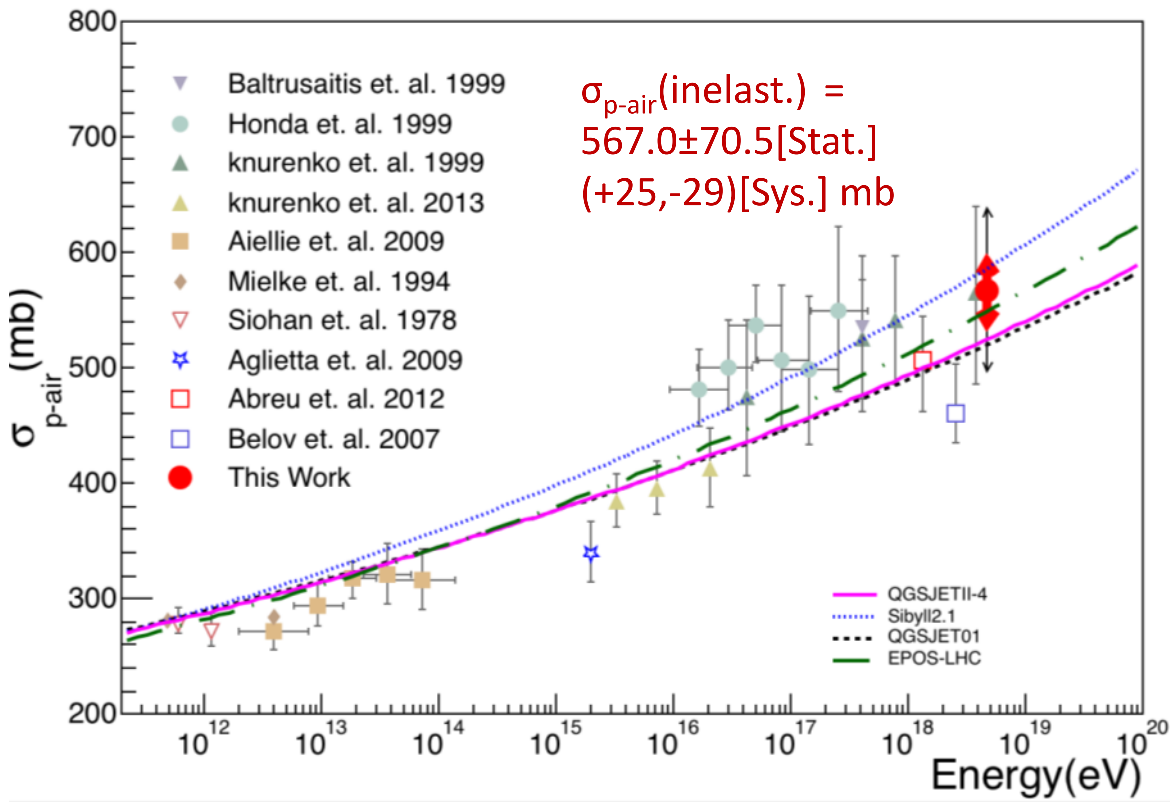



TA data cannot distinguish between mix and QGSJETII-3 protons at this level of systematic uncertainty.

# TA Measurement of $\sigma_{p\text{-}air}$ (inelast.)




- Extract $\sigma_{p\text{-}air}$ from tail of $X_{max}$ distribution
- Estimate $\sigma_{p\text{-}p}$ (Glauber)

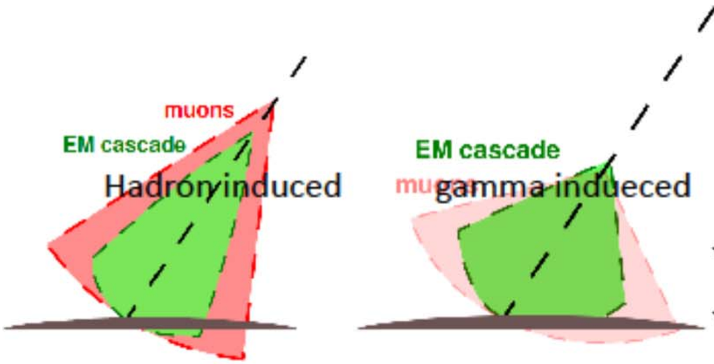



| Systematic source | Systematic (mb) |
|---|---|
| Model Dependence | ±17 |
| 20%Helium | +18 |
| Gamma<1%* | – 23 |
| Total | (+25,-29) |

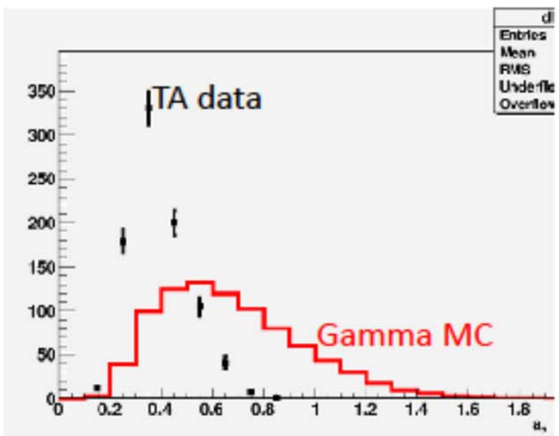
**R. Abbasi et. al.** (TA collaboration) Accepted for publication by Phys. Rev. D. **Aug 2, 2015**

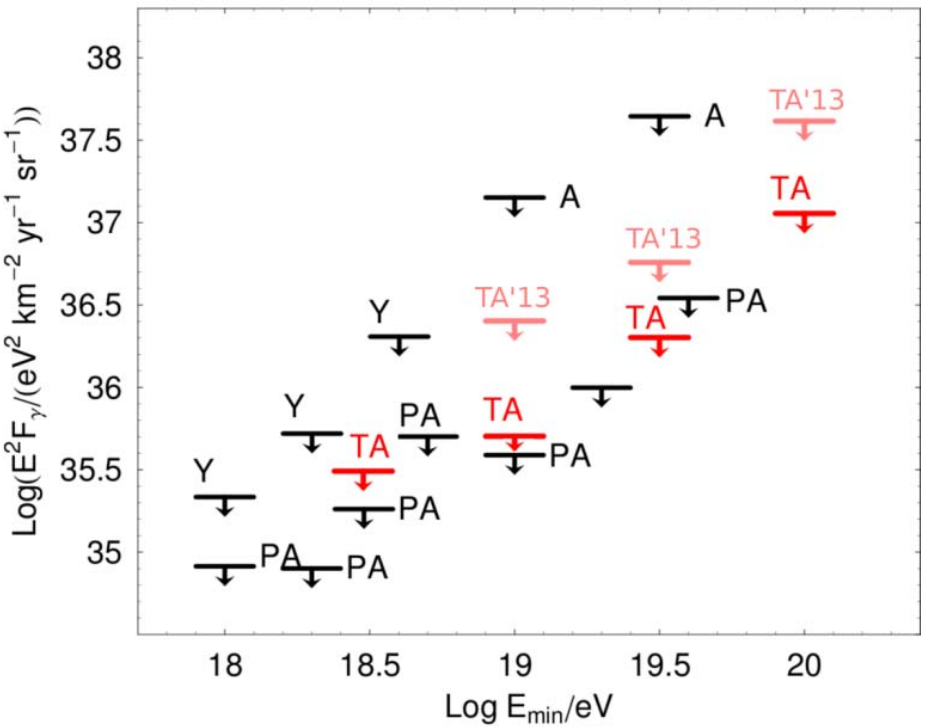
# Photon search

Photon-induced showers:
arrive younger
contain less muons
⇒ multiple SD observables affected:
front curvature, Area-over-peak, # of FADC signal peaks, χ2/d.o.f .



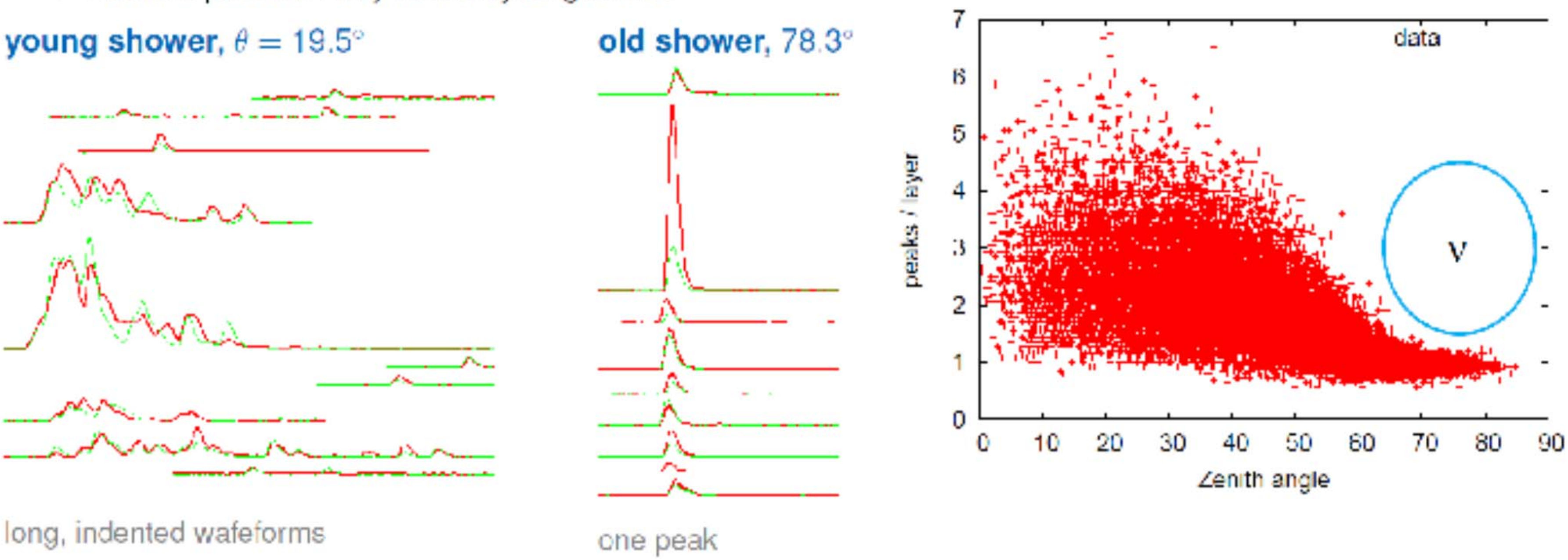

$45° < \theta < 60°$



# Neutrino search

- Neutrino produces very inclined young shower

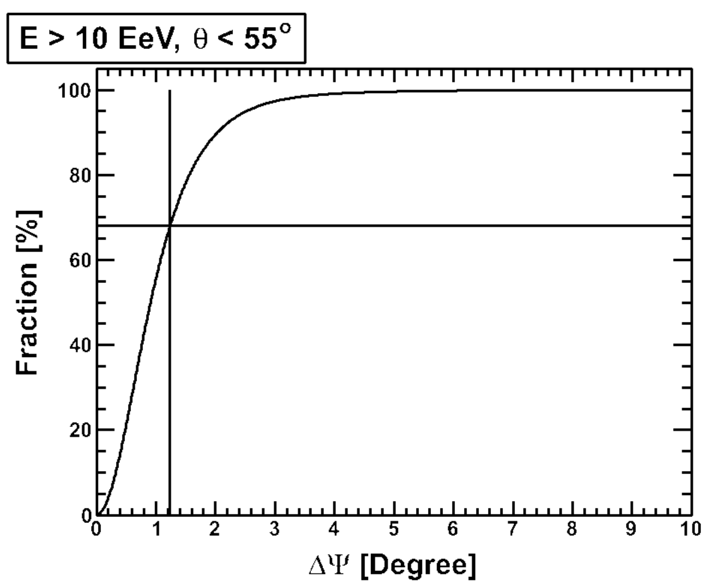


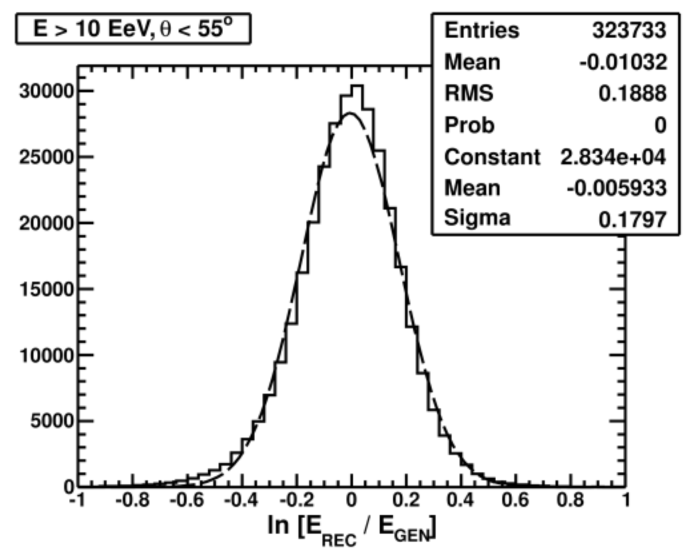

**No young inclined showers in the dataset → no neutrino candidates.**

# TA Anisotropy Results

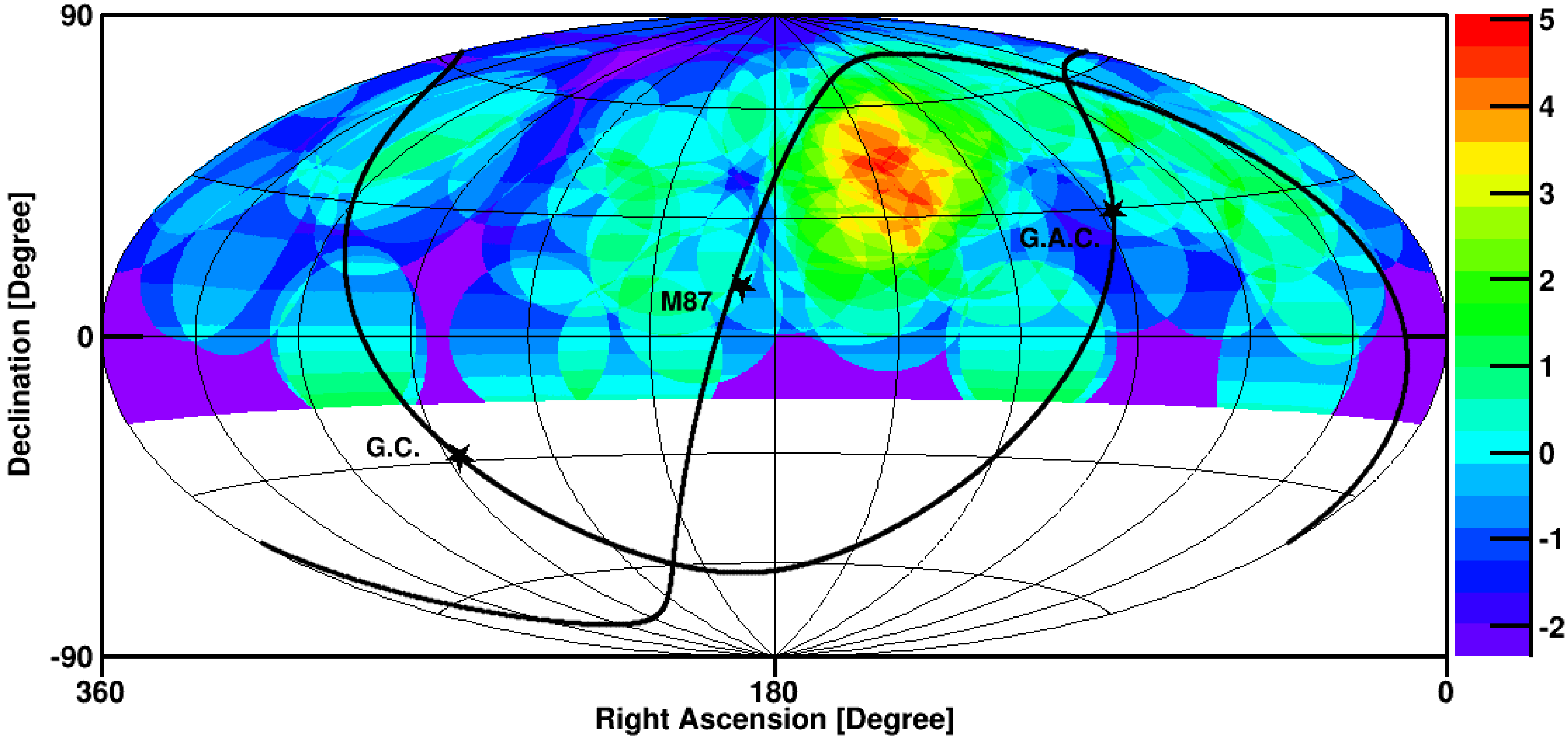
# Anisotropy Analysis

- SD data from period **12.05.2008 — 11.05.2015 (full 7 years)**
- Zenith angle up to 55°, loose border cut
- Geometrical acceptance; exposure 8600 $km^2$ yr sr
- **2996** above **10 EeV**
- **210** above **40 EeV**
- **83** above **57 EeV**
- Angular resolution: better than 1.5°
- Energy resolution: 20%



# Published Hotspot (5yr data)

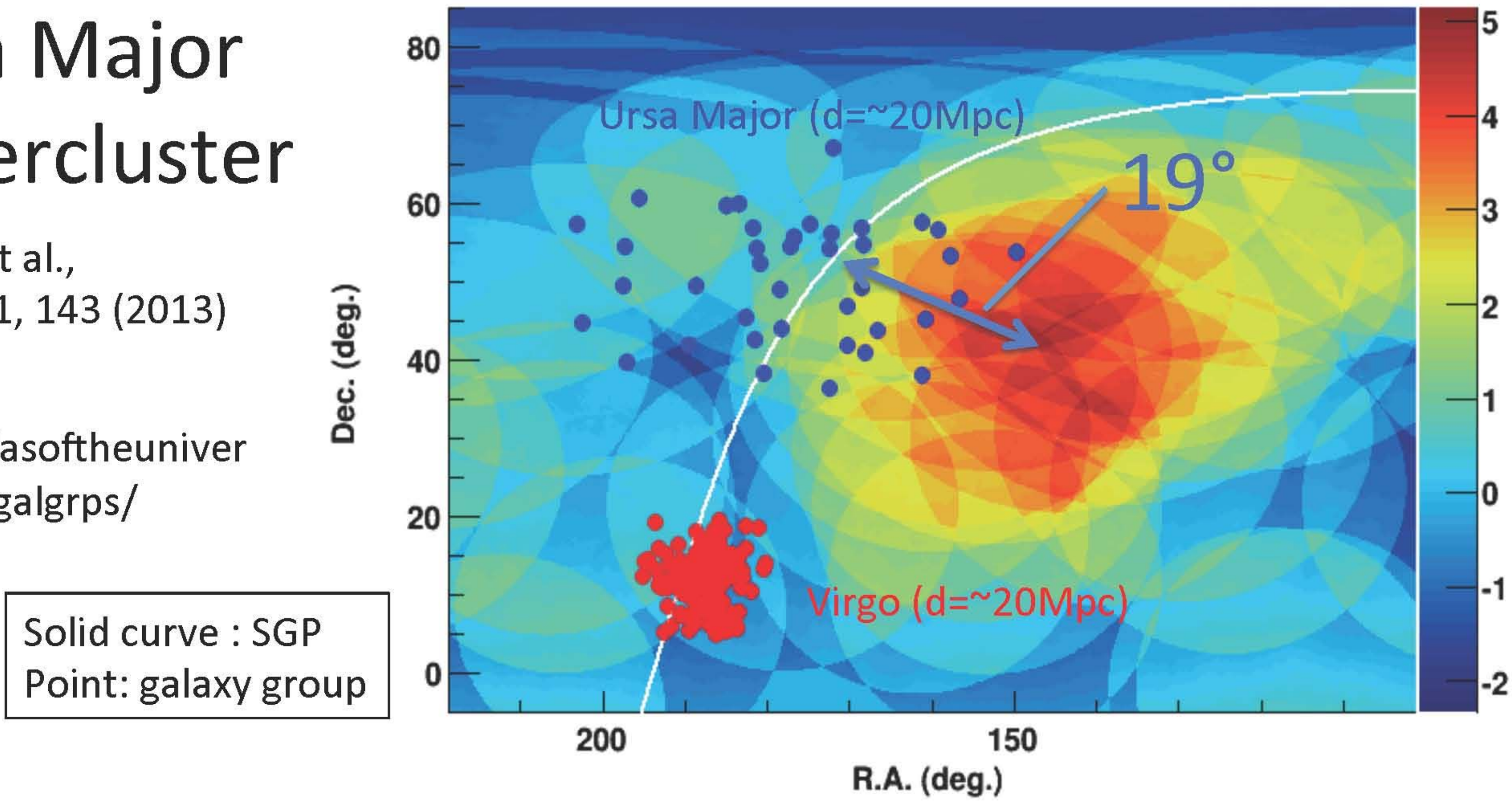



**E>5.7x10$^{19}$ eV (72 events)**
**Aitoff projection in Equatorial Coordinates**
**Events over-sampled using 20° circles**
**19/72 events fall in hotspot (RA,dec) ~ (146.7°,43.2°)**
**4.5 events expected (26% of events in 6% of the area)**
**LiMa significance: 5.2$\sigma$ Estimate 3.4$\sigma$ chance probablity**

# Ursa Major Supercluster

Krause et al.,
A&A, 551, 143 (2013)

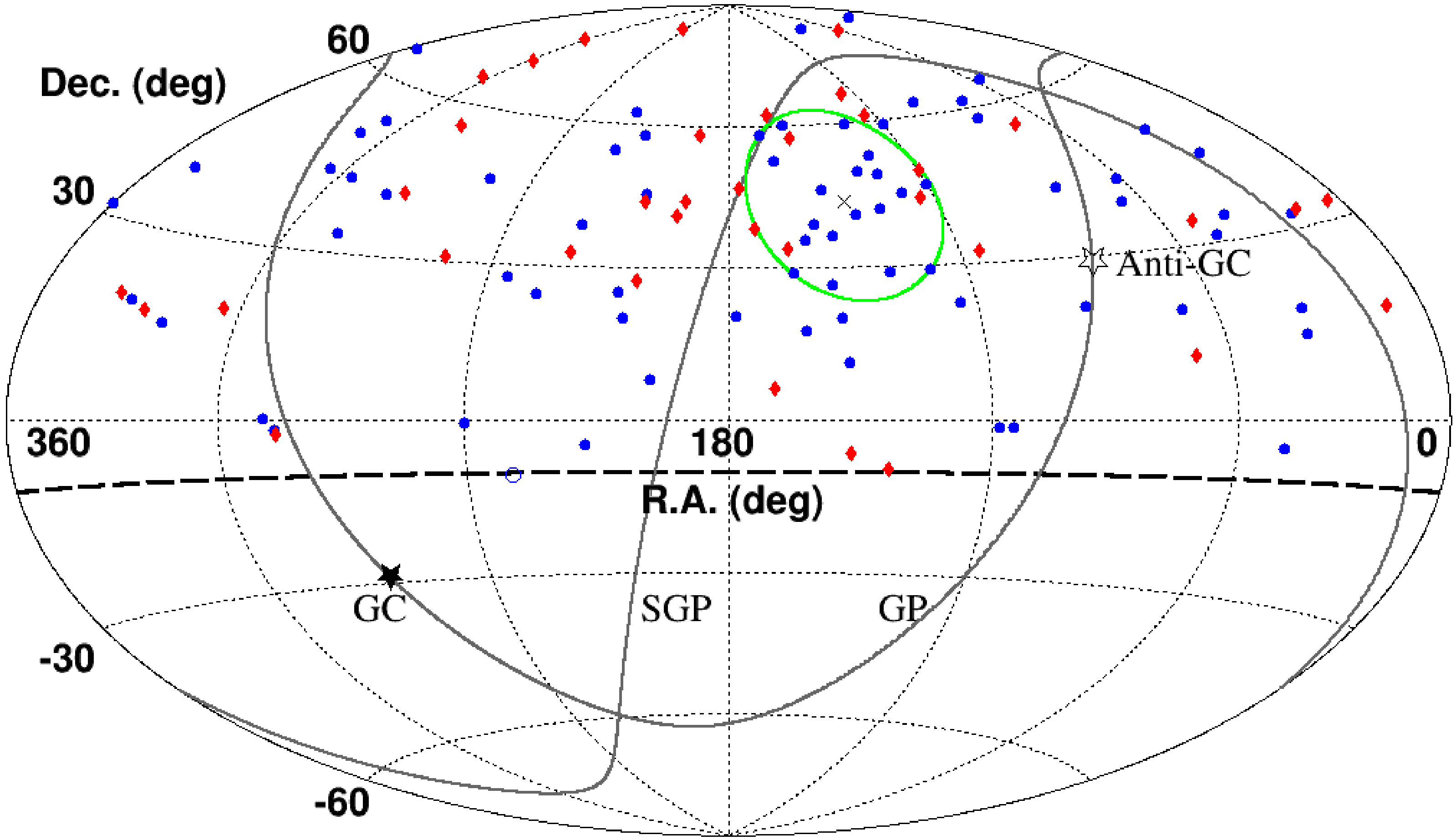
http://www.atlasoftheuniverse.com/galgrps/vir.html




The angular distance between the hotspot center and the supergalactic plane is estimated to be 19◦. The Ursa Major supercluster is extended by more than ±10◦ from the supergalactic plane. We therefore cannot rule out some relationship between the hotspot and this supercluster.

Mrk421? Filament to local cluster ?

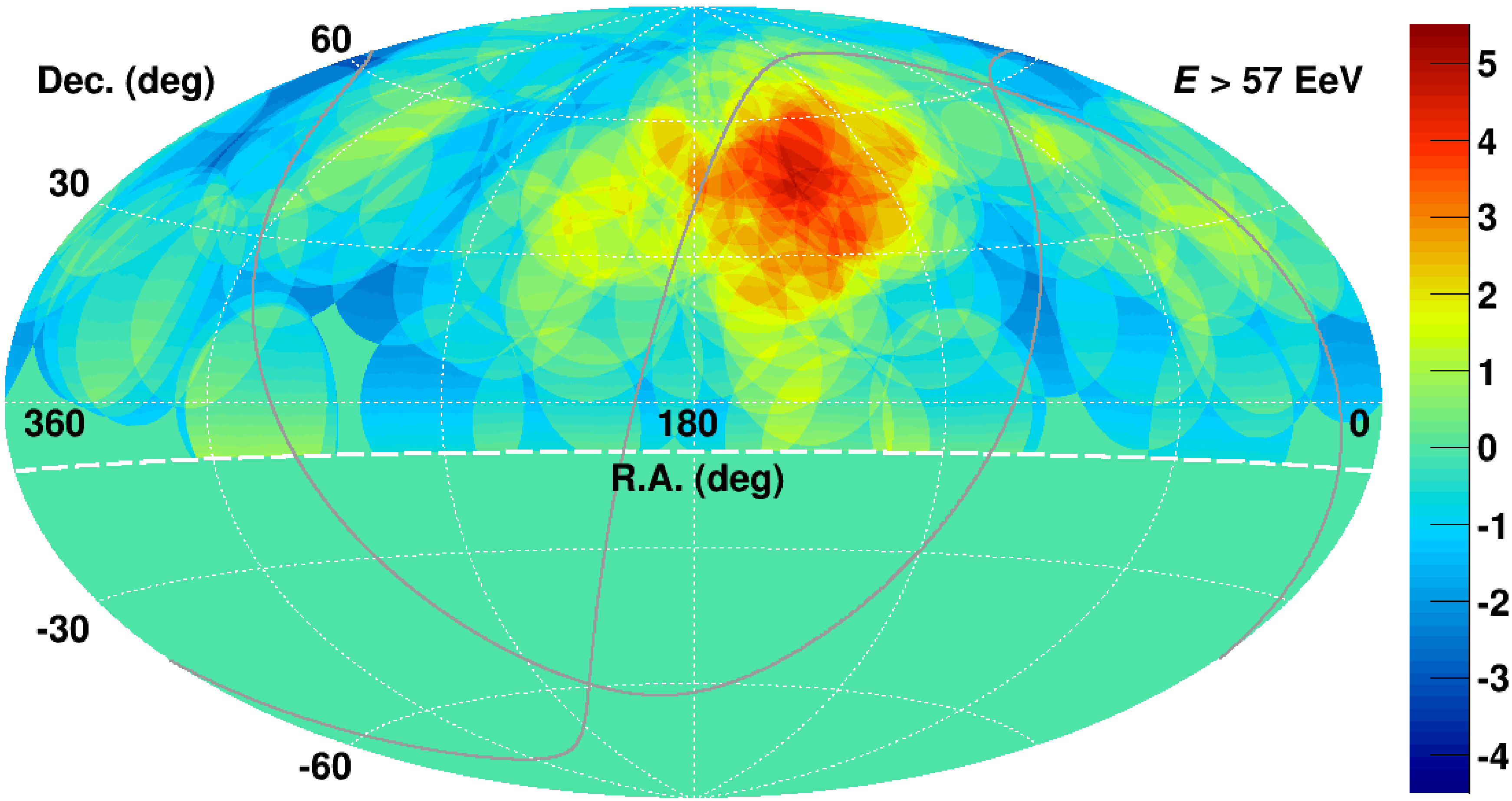
# Hot Spot update: 7 years




First 5-year data (72 events) -- ApJ 790 L21 (2014)
New 2-year data (37 events)
Total (2008 May 11 – 2015 May 11) 109 events

| Period | Total | Signal | B.G. | Chance Prob. |
|---|---|---|---|---|
| 6-th Year | 15 | 3 | 0.94 | 7% |
| 7-th Year | 22 | 1 | 1.37 | 74% |
| 6th + 7th | 37 | 4 | 2.31 | 20% |

# 7 Year Excess Map




Max significance **5.1**σ ($N_{SIG}$ = 24, $N_{BG}$=6.88) for 7 years

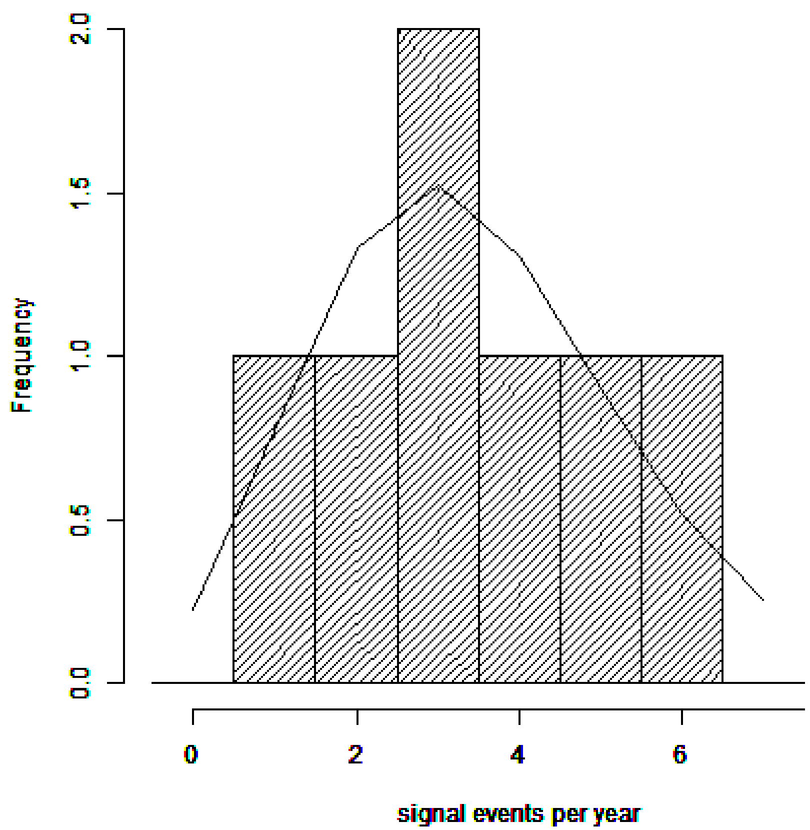
Centered at R.A=148.4°, Dec.=44.5° (shifted from SGP by 17°)

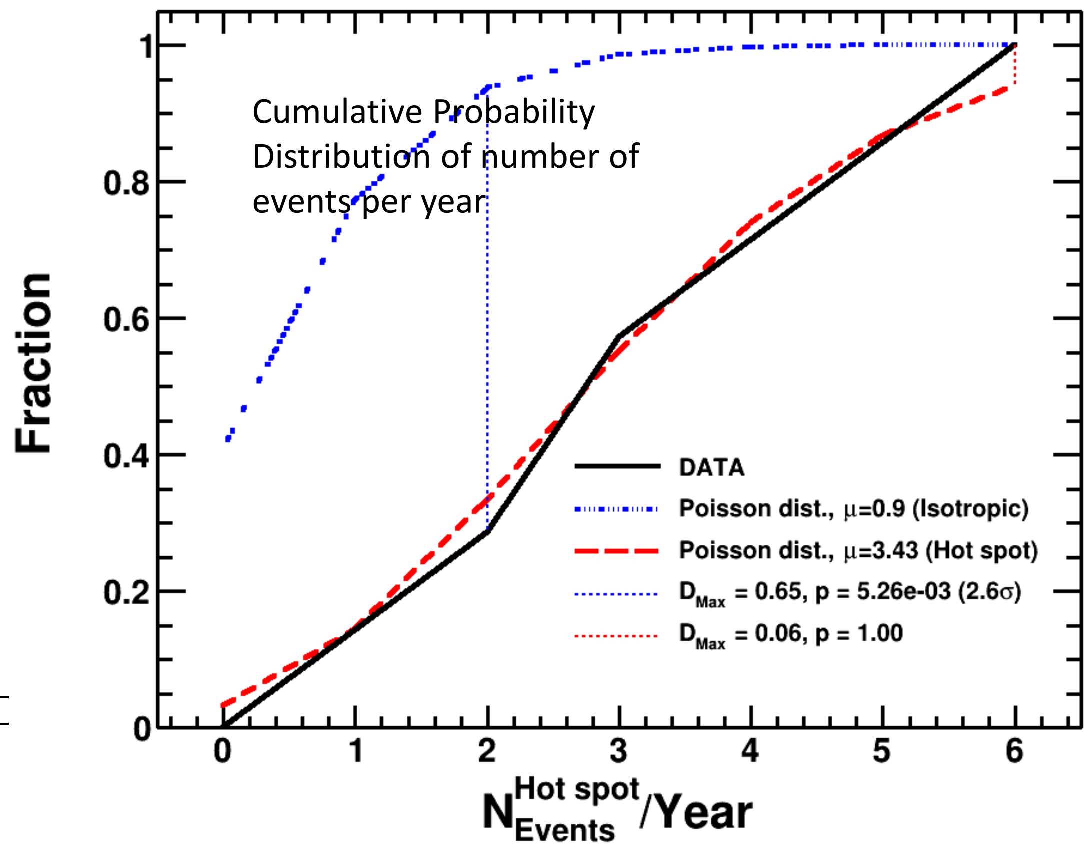
Global Excess Chance Probability: $3.7\times10^{-4}$ : 3.4σ (~ same as first 5 years)

# Consistent with Fluctuation

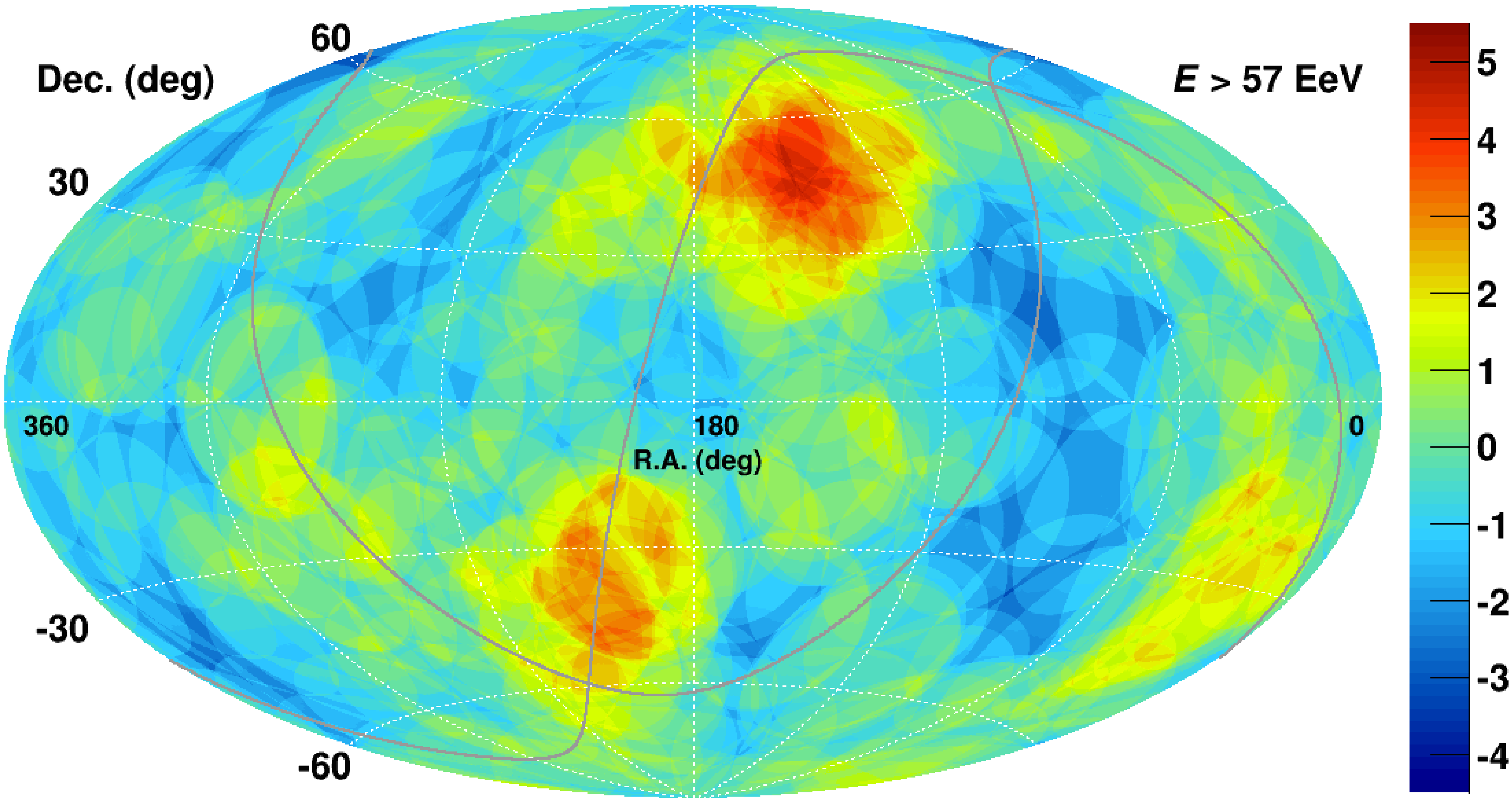
**K.S. Test** shows data is consistent with fluctuation for hotspot (Poisson: average = 3.43 per year, no time variation),

**BUT, inconsistent with chance excess from isotropic distribution (Poisson: average = 0.9 per year) at ~ 2.6σ**



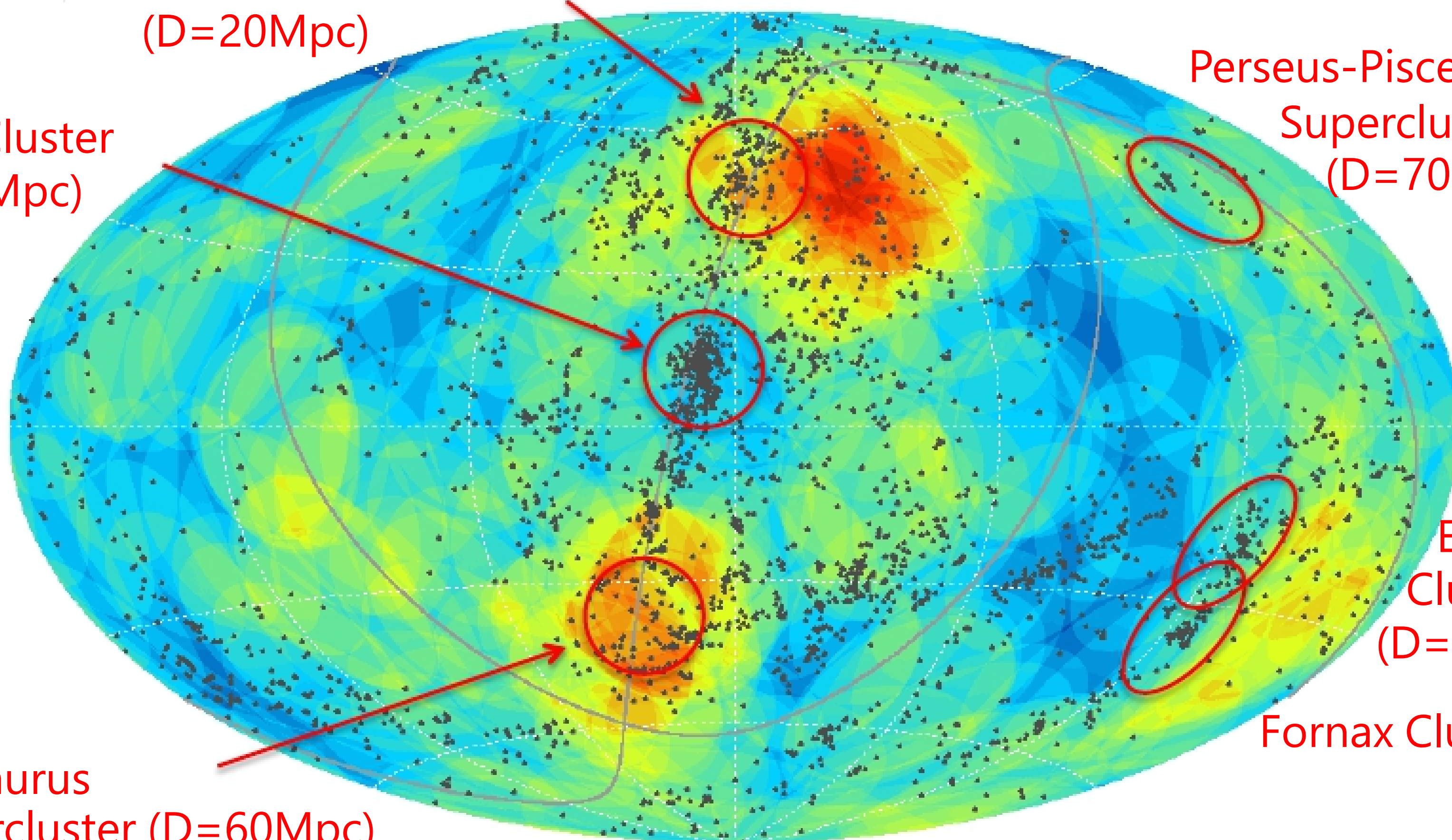
# TA + PAO All Sky




No correction for
Energy scale difference
b/w TA and PAO !!

TA : 7 years 109 events (>57EeV)
PAO : 10 years 157 events (>57EeV)
**Oversampling with 20°-radius circle**
Southern hotspot is seen at Cen A (Pre-trial ~3.6σ)

# Nearby Galaxy Clusters

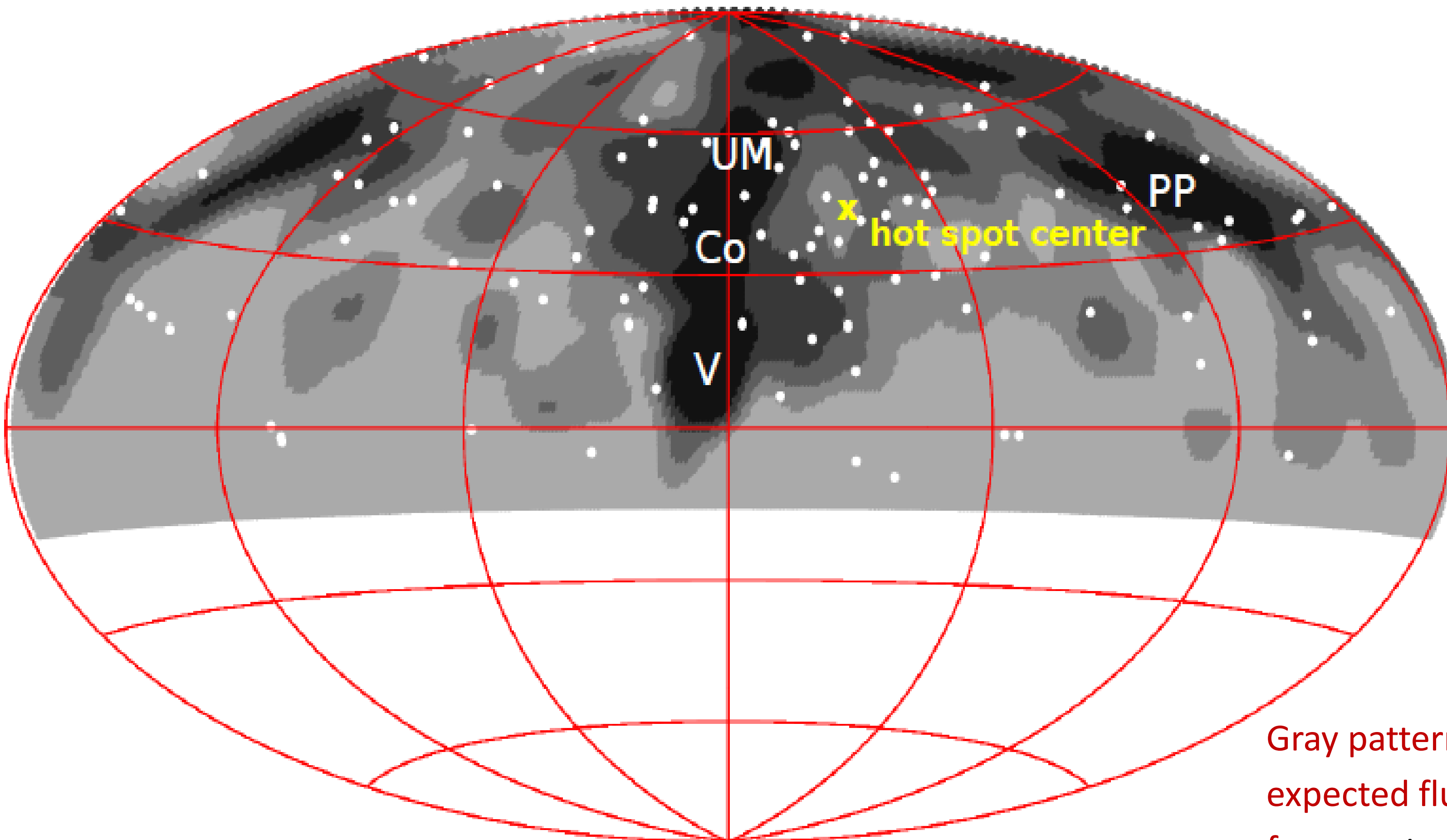



*Huchra, et al, ApJ, (2012)*

Dots : 2MASS catalog Heliocentric velocity <3000 km/s (D<~45MpC)

TA hotspot is found near the Ursa Major Cluster
TA & PAO see no excess in the direction of Virgo.

# Correlation with Large-Scale Structure (LSS)




**Equatorial coordinates. Darker color represents larger flux.**
**UM — Ursa Major; Co — Coma; V — Virgo; PP — Perseus-Pisces**

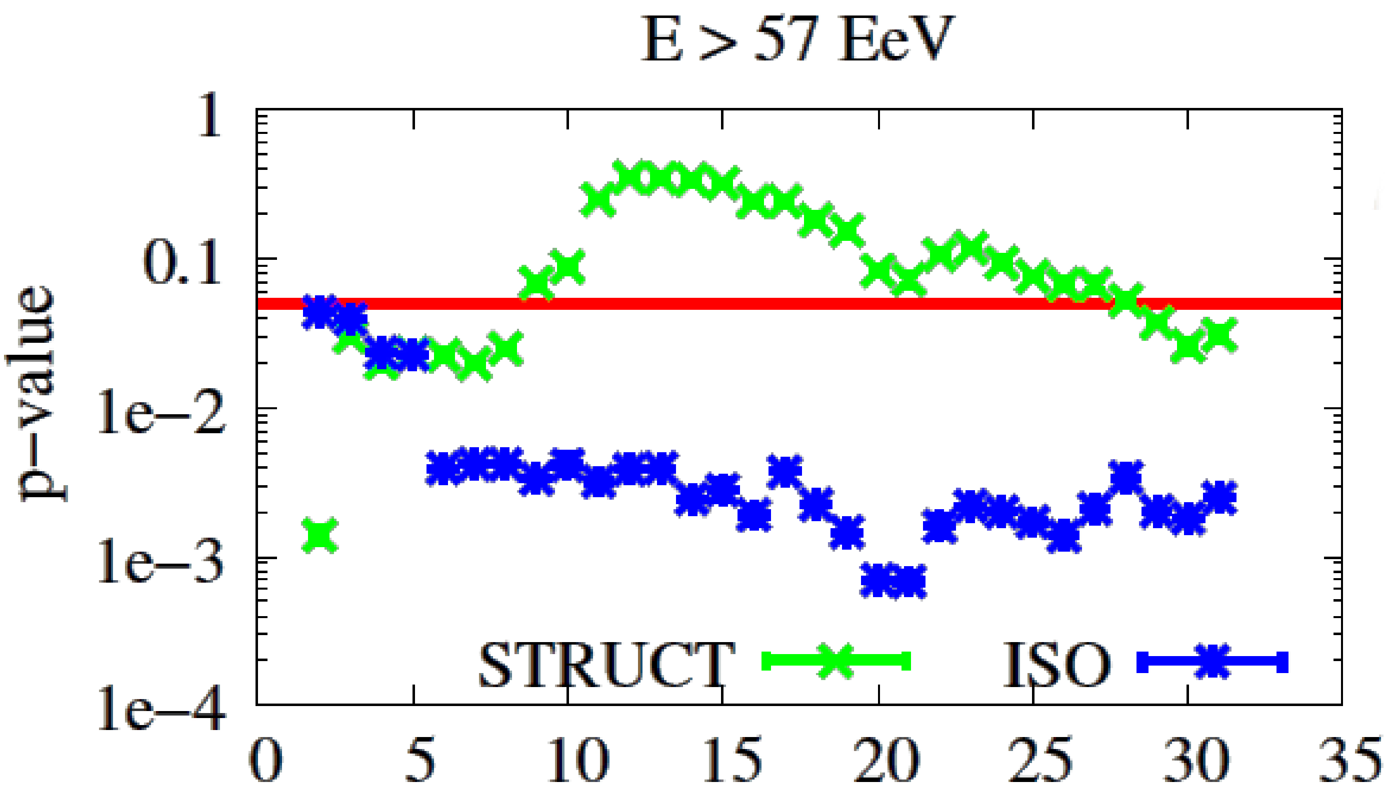
Gray patterns: expected flux density from proton (E=57 EeV) LSS 2MASS Galaxy Redshift catalog (XSCz)

# LSS Correlation (continued)

**1D Kolmogorov-Smirnov p values comparing expected flux distribution (gray map from previous page) vs. simulation:**

**Marginally Incompatible with isotropic source simulation**

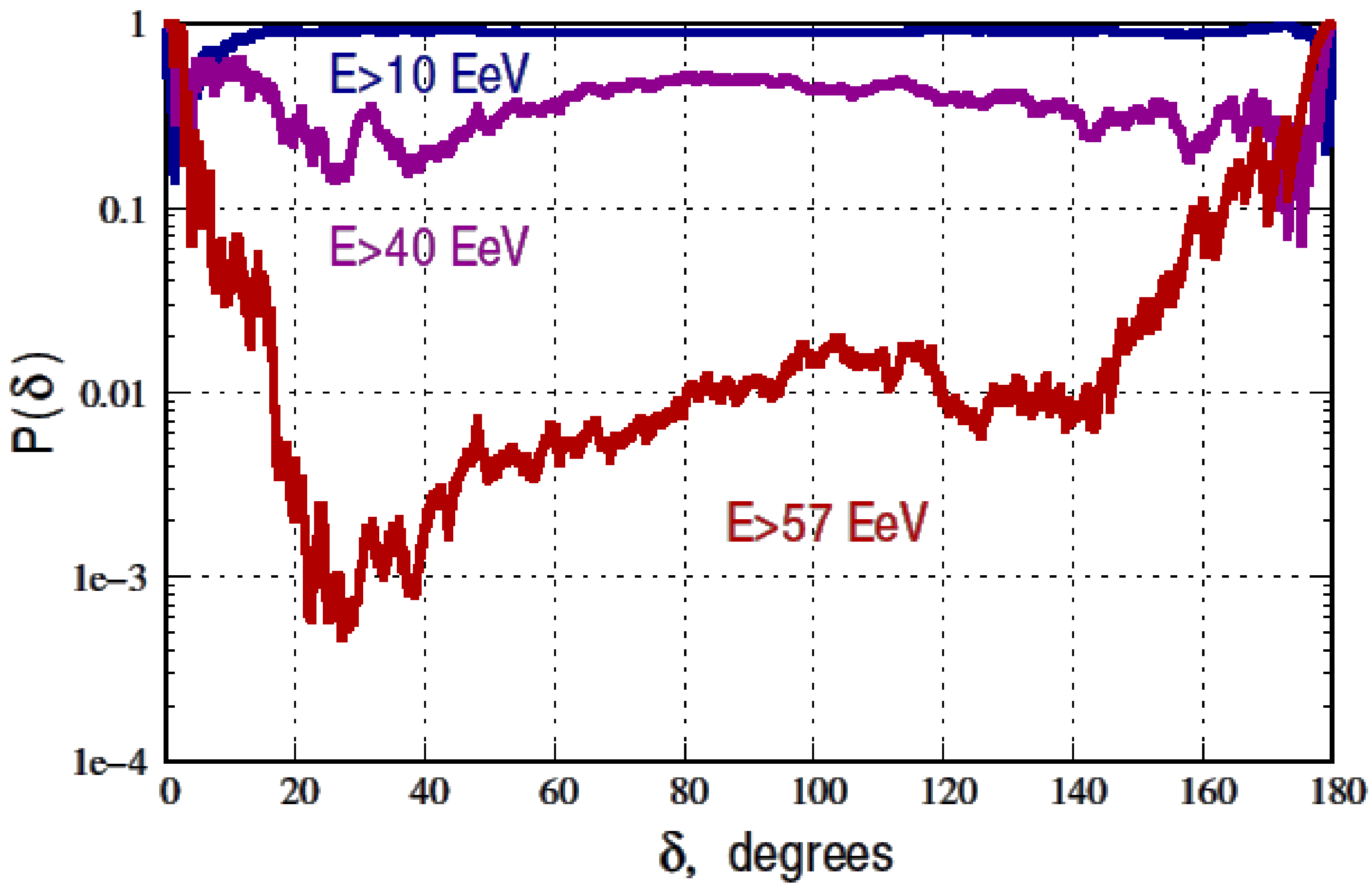
**Compatible with LSS source simulation**




Smearing Angle in degrees

**Cannot distinguish between LSS and isotropic simulations for E>10 EeV and E>40 EeV distributions**

# Autocorrelation




**For each angular bin:**

1. Count number of pairs of events at in the bin at separation δ
2. Chance Probability is given by the fraction of isotropic MC sets (with equal statistics) with as many or more than the number of pairs seen in data

**Compatible with isotropy at E > 10 EeV and E > 40 EeV,**
**Tension with isotropy at E>57 EeV**

# The Future of TA

# TA×4 Project

Quadruple TA SD (~3000 km$^2$)

**500** scintillator SDs

**2.08 km** spacing

Approved in Japan 2015

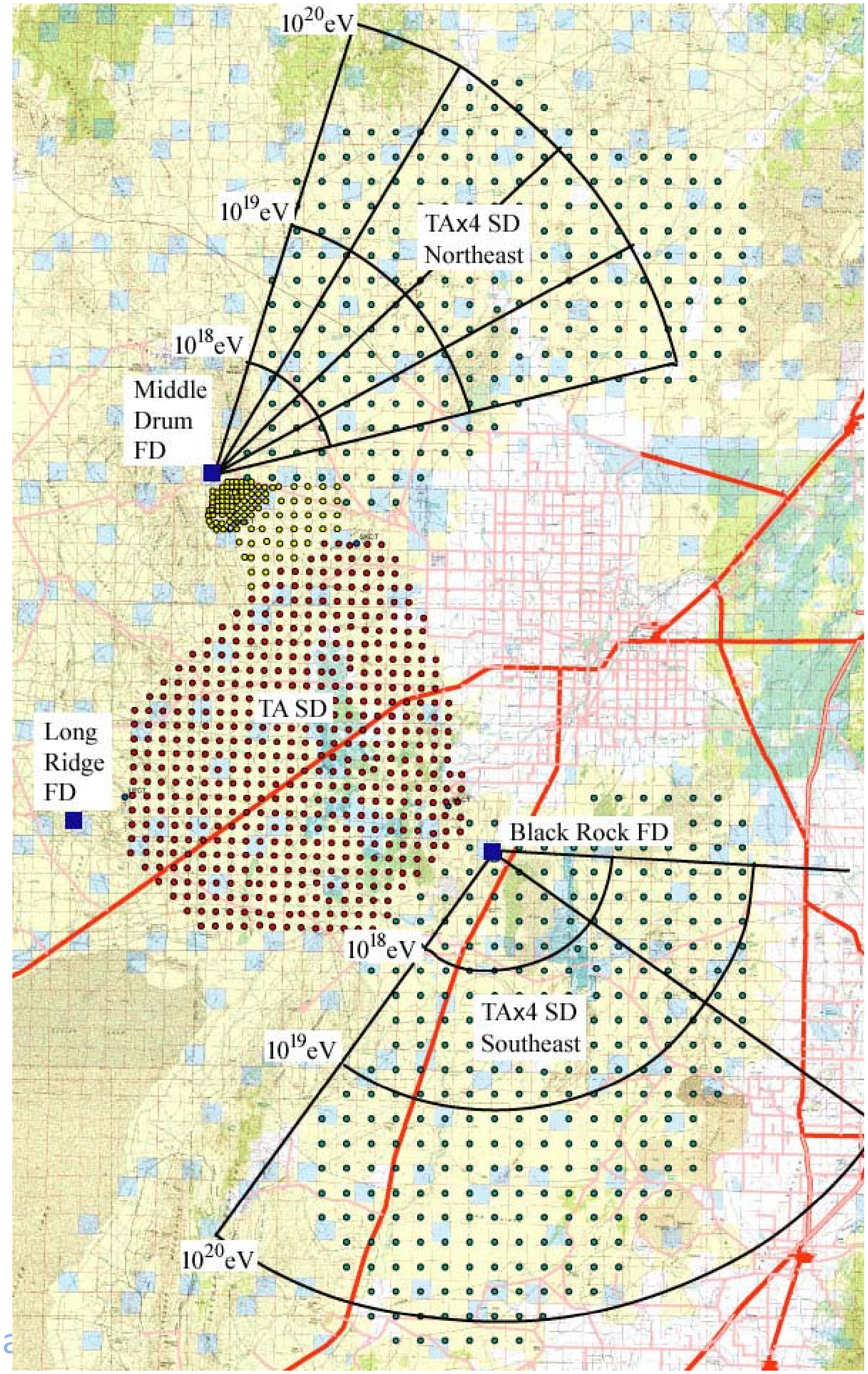
3 yrs construction, first 100 SDs have arrived in Utah (2016-05)

2 FD stations (12 HiRes Telescopes)

Funding approved US summer 2016

**Get 19 TA-equiv years of SD data by 2020**

Get 16.3 (current) TA years of hybrid data



# Clarify the details of the Hotspot

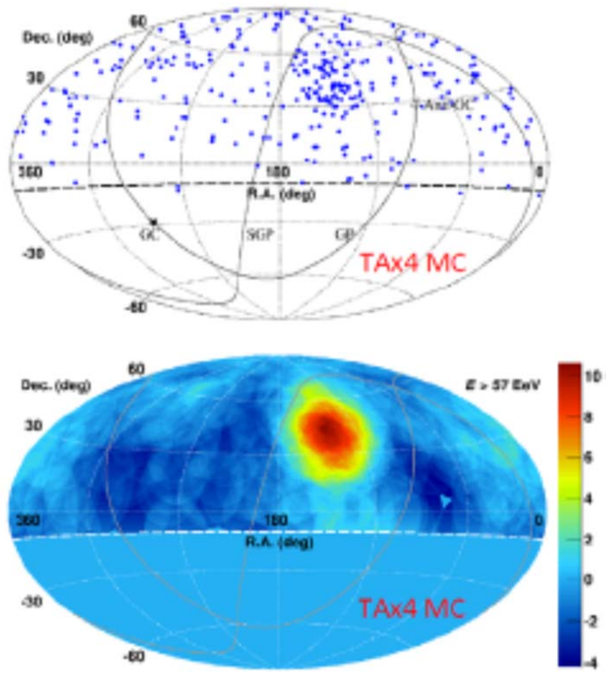
## Simulated 19 TA-equiv yrs data

(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

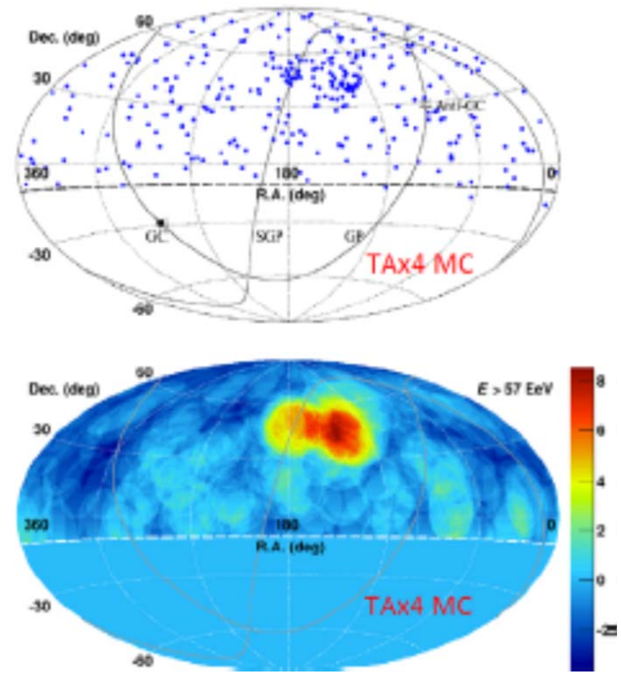



(2) Double Hotspot

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



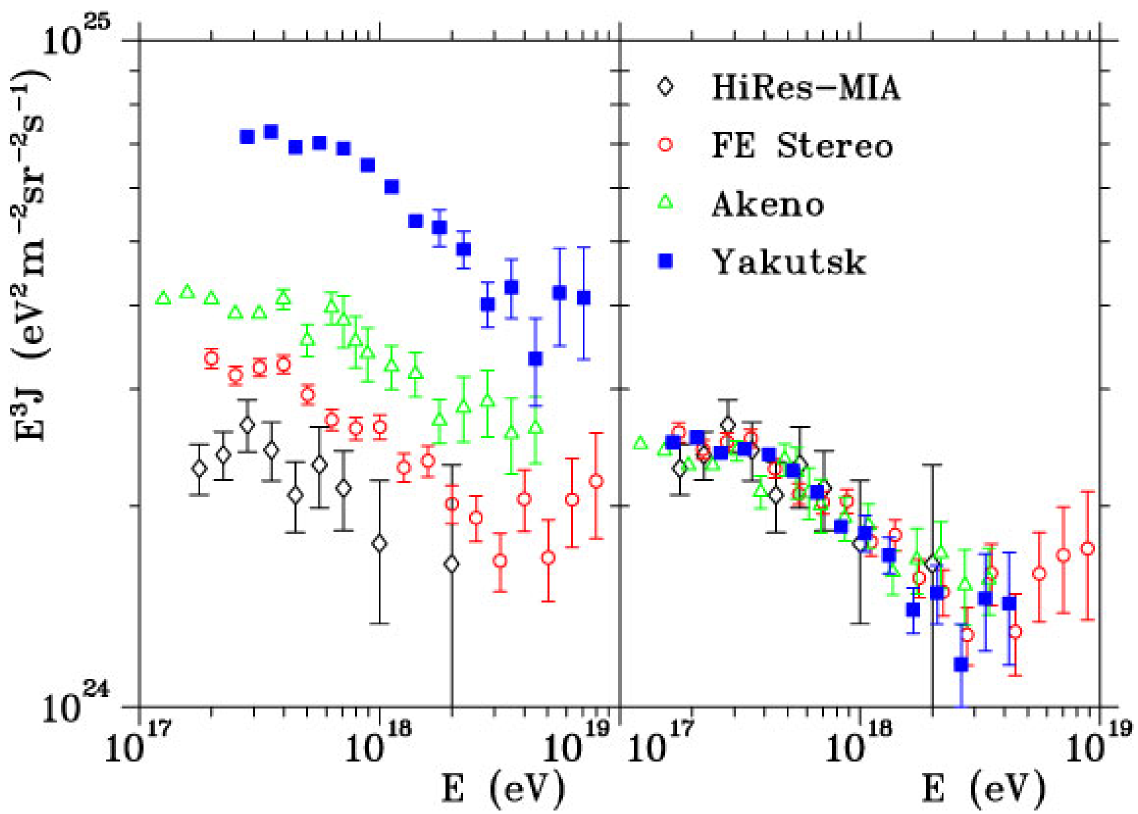

**Single Source**

**Two Separated Sources**

# Summary

- TA has measured the energy spectrum, composition and arrival direction of UHE cosmic rays
- The spectrum and composition of UHE cosmic rays measured by TA remain compatible with a single light component at above the ankle (~$6\times10^{18}$ eV).
- We have reported a hot spot seen in the direction of Ursa Major with $3.4\sigma$ significance
- *New:* TA Low Energy Extension (TALE) is coming on line. TALE surface detector array was funded by the Univ . of Utah and was recently been funded by Gov't of Japan.
- TA and TALE have measured energy spectrum between $6\times10^{15}$ eV to over $10^{20}$ eV with a single cross-calibrated set of detectors and have observed spectral features
- **Much more data are needed! – coming soon TAx4**

# Galactic to Extra-Galactic Transition




- Previous suspected structure
- Unknown energy scale
- Tie down the energy scale and simultaneously measure spectrum and composition

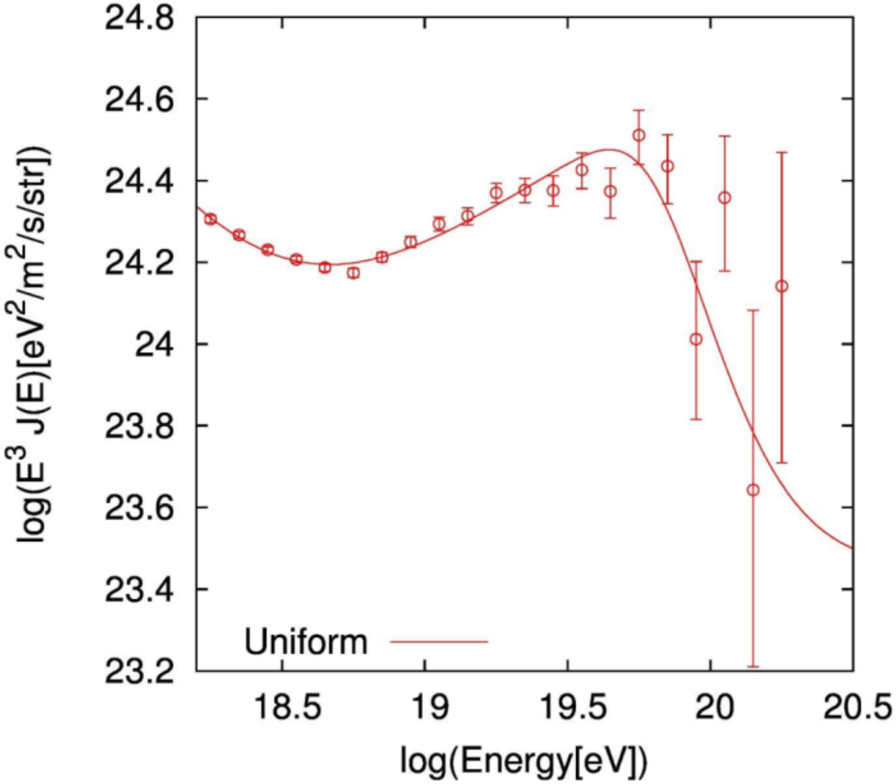
# Fitting the UHE Spectrum with TA

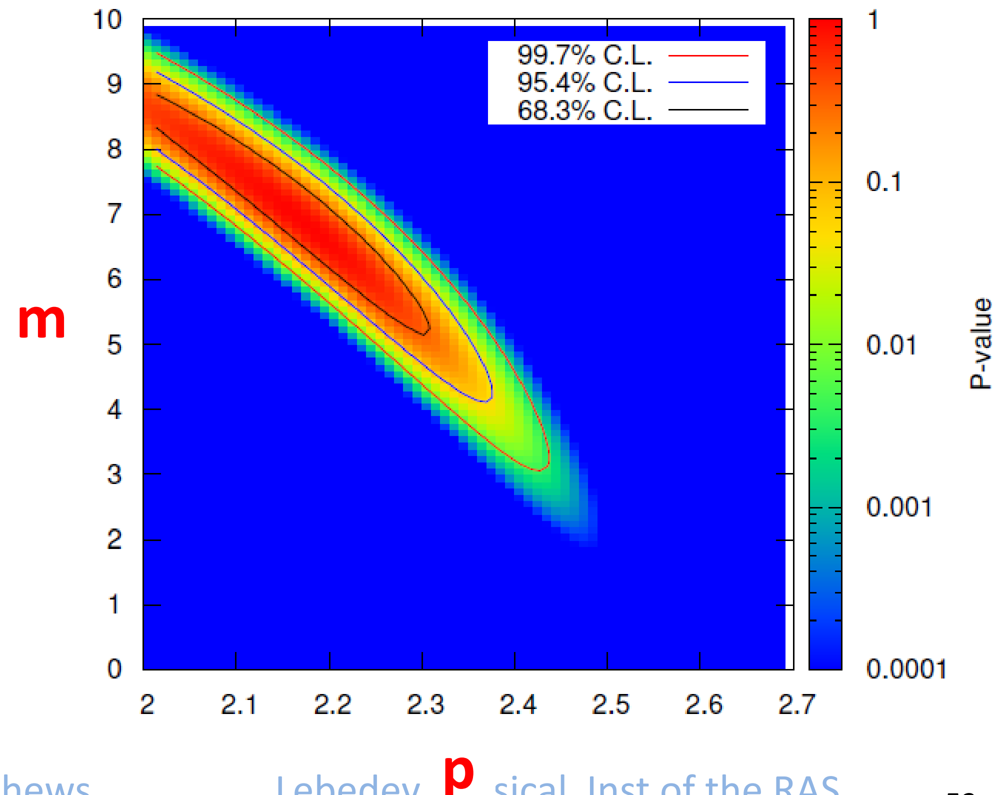
**Fitting parameters:**

Power law at the source, $E^{-p}$

Evolution of the sources, $(1+z)^{m}$

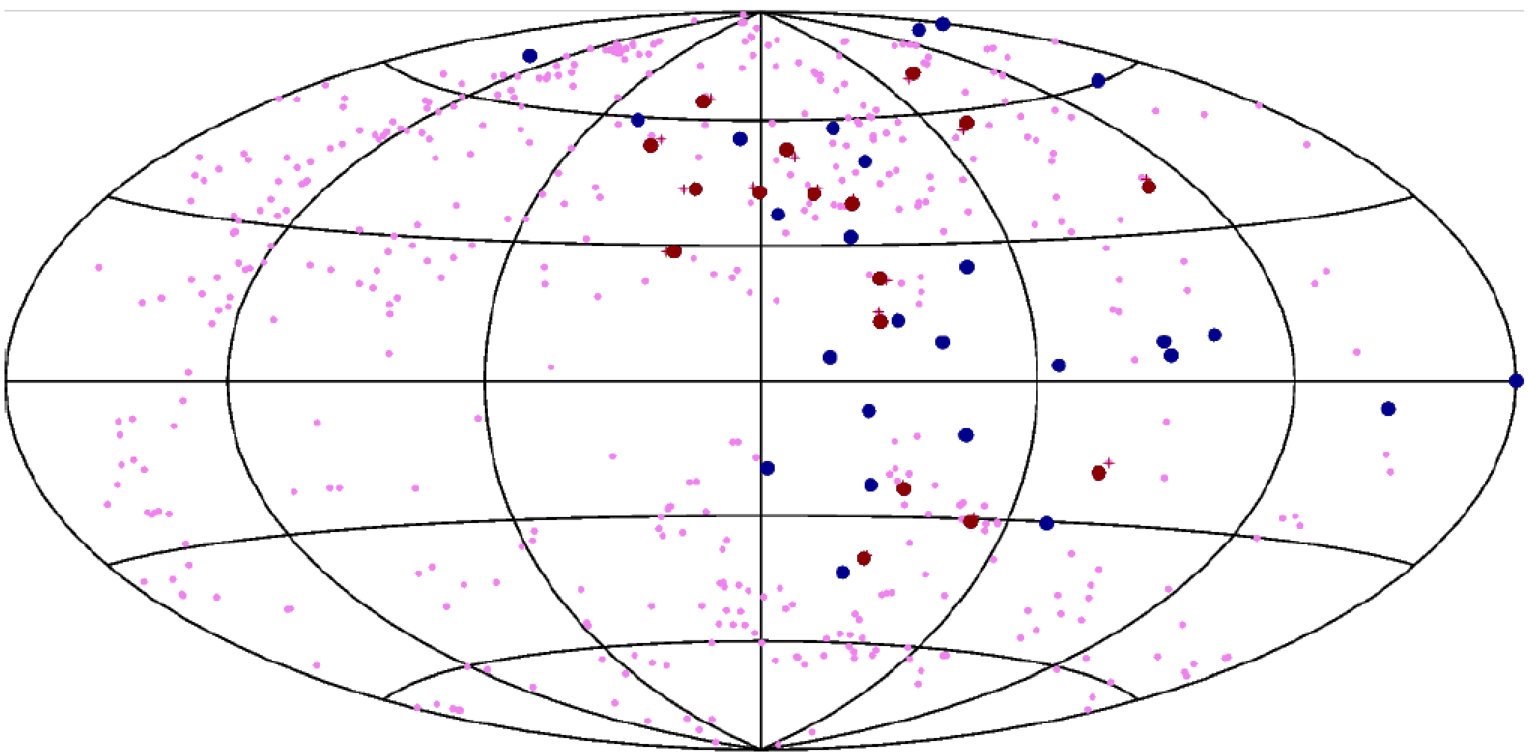
$p = 2.18^{+0.08}_{-0.14}$, $m = 6.8^{+1.6}_{-1.1}$;
(stat. + sys.)



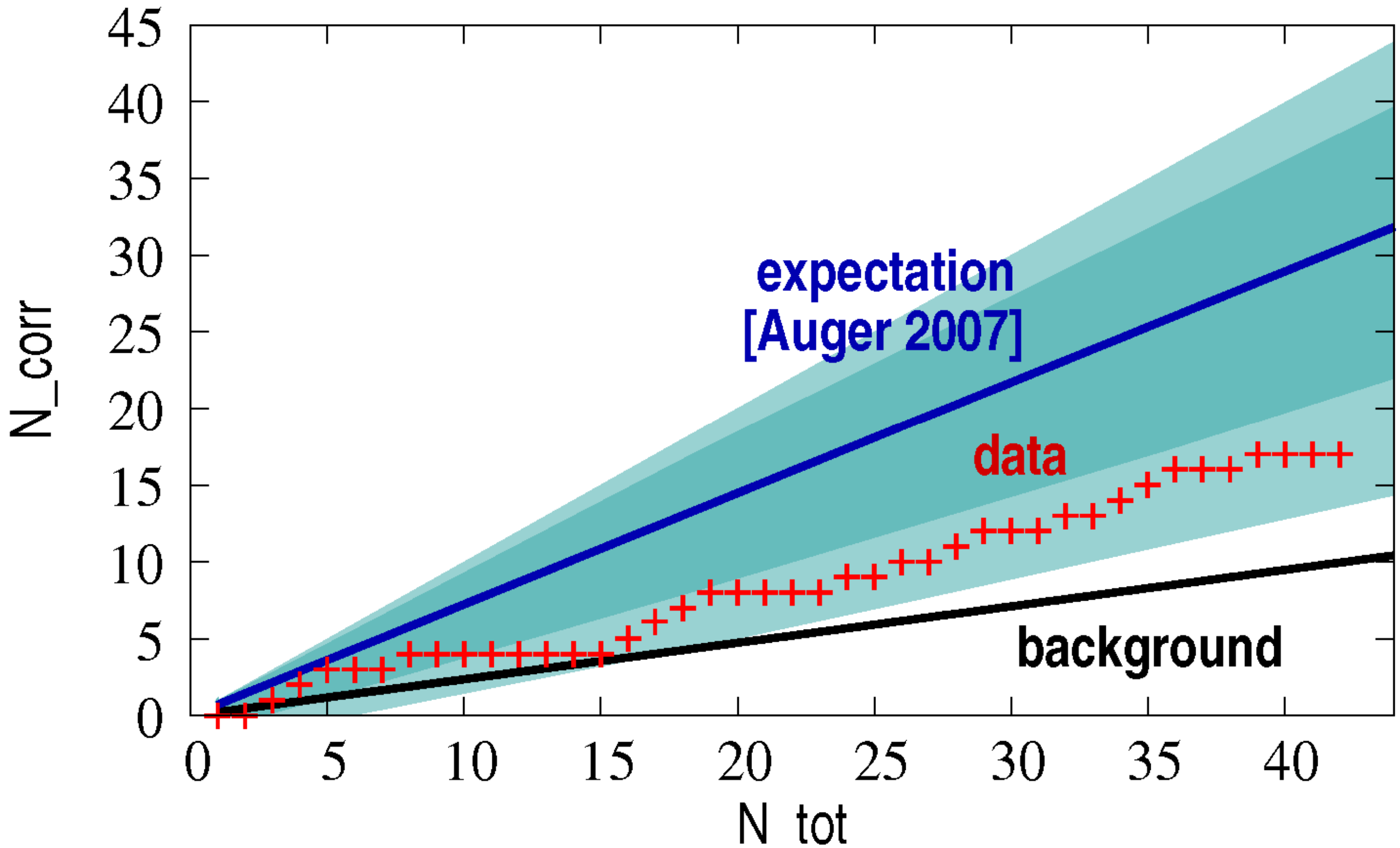
# Test Correlations with AGNs

- 472 AGN from 2006 Veron catalog with $z < 0.018$
- $E > 57$ EeV, zenith angle $< 45^{o}$, $N = 42$ (5 yr)
- Separation angle = $3.1^{o}$



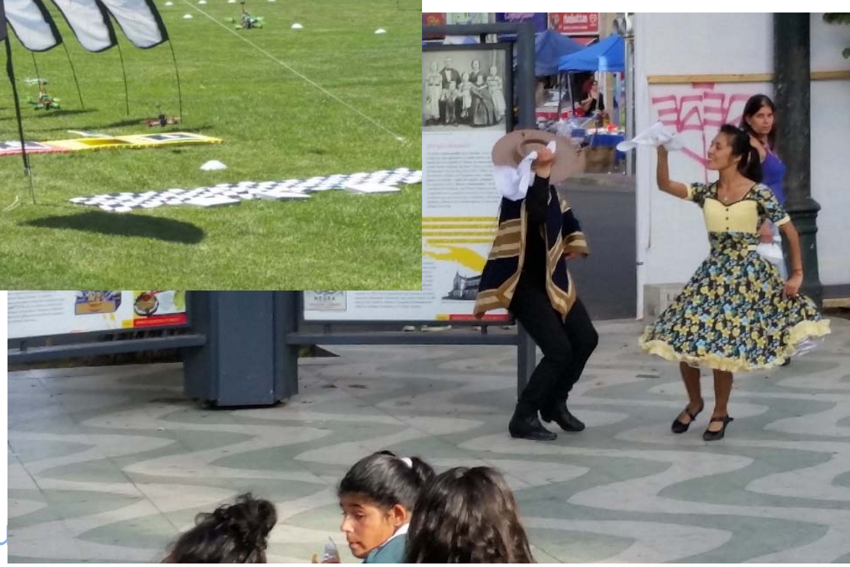
# Correlations with AGNs

**Probability of event overlapping with AGN is $p_o = 0.24$**
**Find 17 events correlate of 42 ⇨ $p = 0.014$**



# Thank you!

- For inviting me to this beautiful venue
- The great food
- The many interesting talks and conversations

# Status of the GZK Cutoff

- Now observed by multiple methods
- HiRes – Fluorescence > $5\sigma$
- PAO – Cerenkov water + fluorescence > $20\sigma$
- TA – Plastic Scintillator + fluorescence > $6\sigma$
- Energy within 20% of eachother – within systematics
- TA SD is 1.27 x higher in energy than FD, explains AGASA normalization (PAO 1.25)
- GZK suppression clearly exists, but is this the only thing happening or is injection spectrum also playing a role?
- What is the composition?