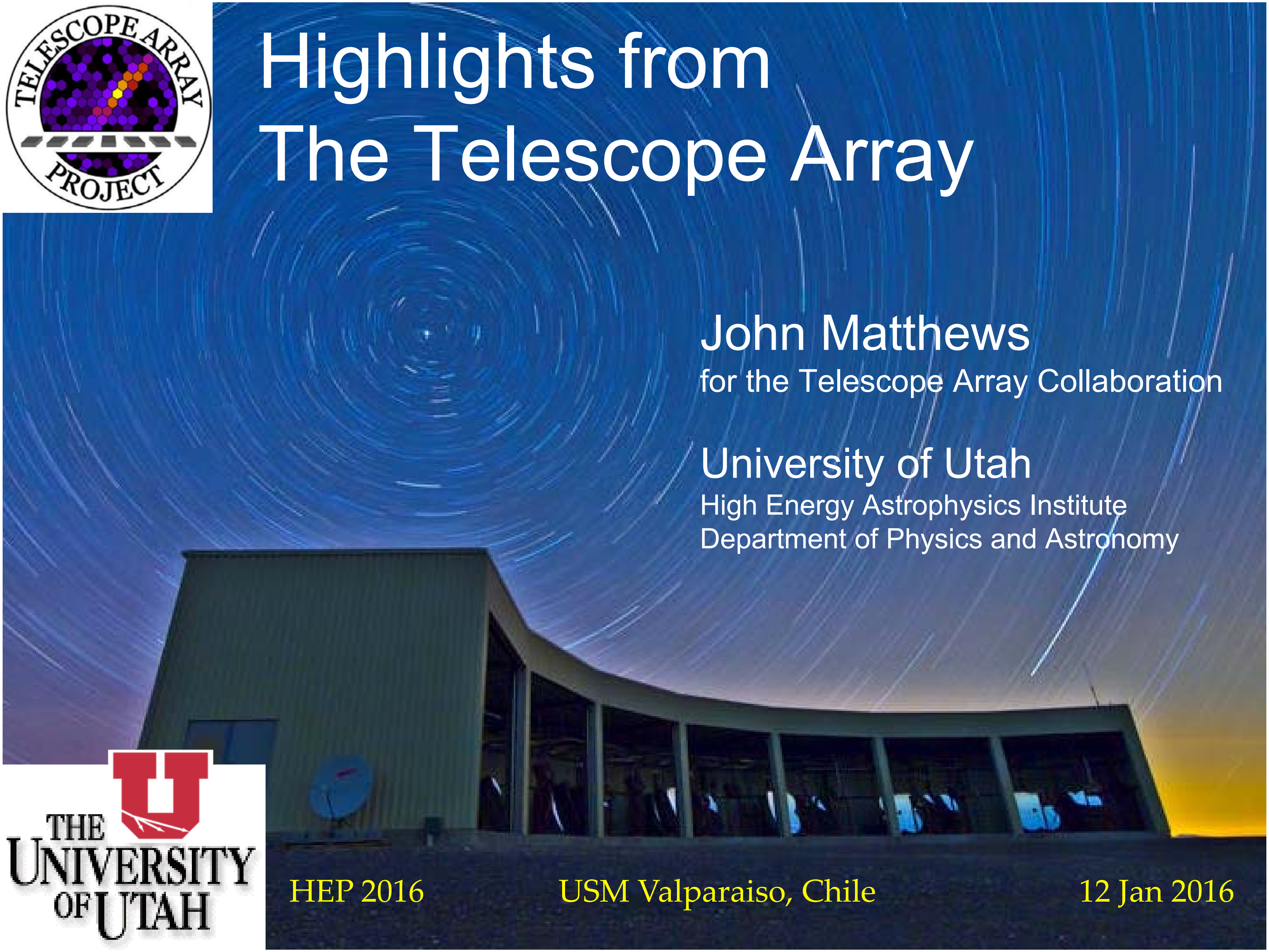
Highlights from The Telescope Array



John Matthews
for the Telescope Array Collaboration

University of Utah
High Energy Astrophysics Institute
Department of Physics and Astronomy

HEP 2016 USM Valparaiso, Chile 12 Jan 2016

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 …. Esp 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, 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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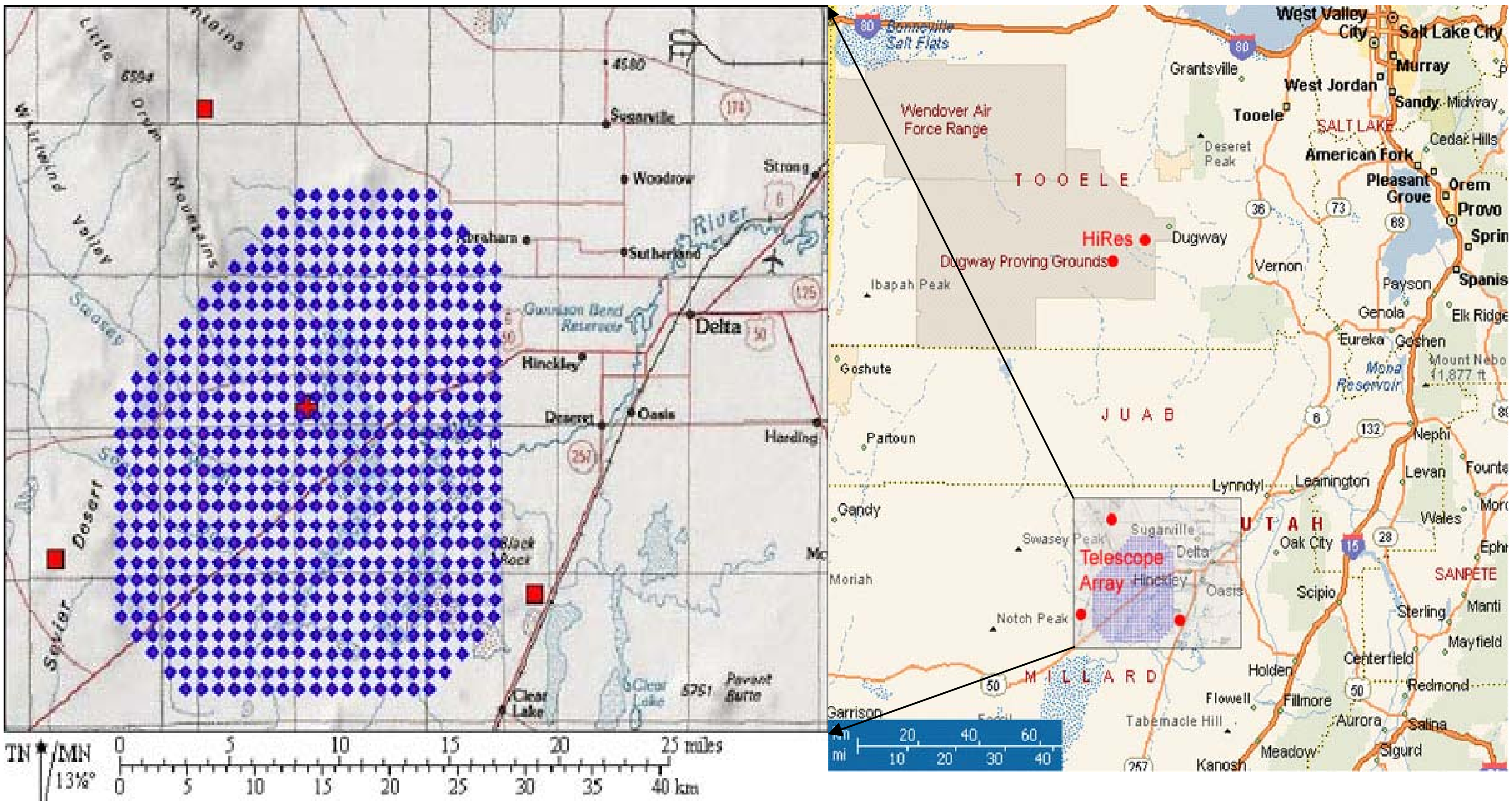
USA, Japan, Korea, Russia, Belgium

Telescope Array



Lat. 39.30°N, Long. 112.91°W (~700 km^2)
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.

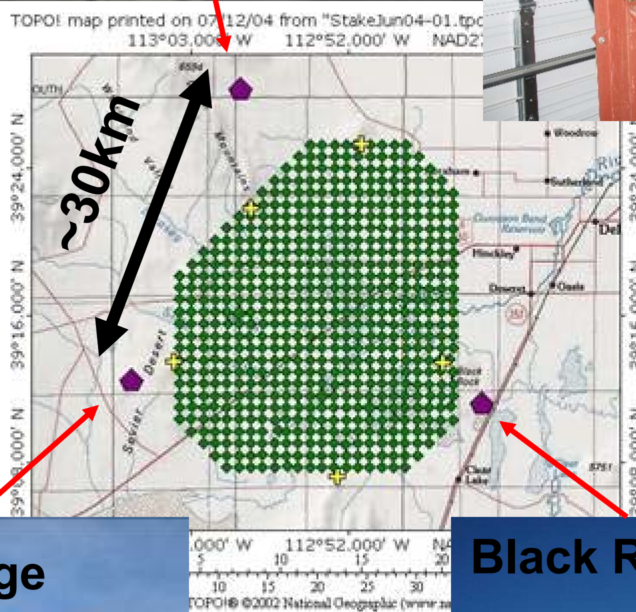
TA Fluorescence Detectors

Middle Drum

14 telescopes @ station
256 PMTs/camera

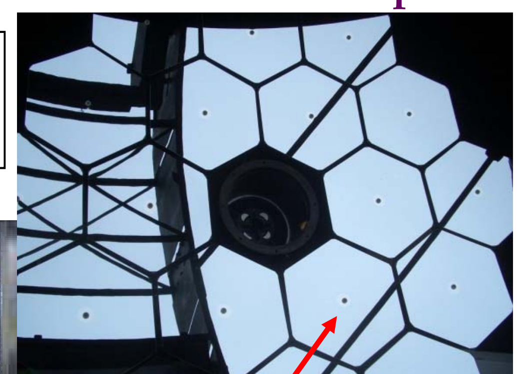
5.2 m²

Reutilized from HiRes-I



New Telescopes

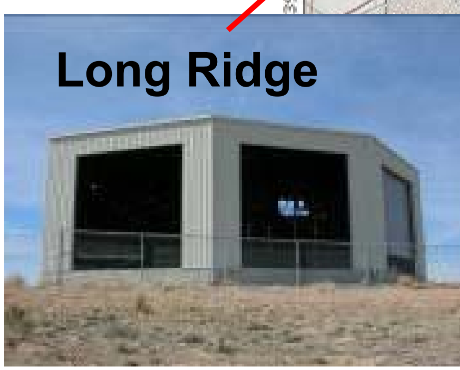
12 telescopes/station
256 PMTs/camera



6.8 m²

~1 m²

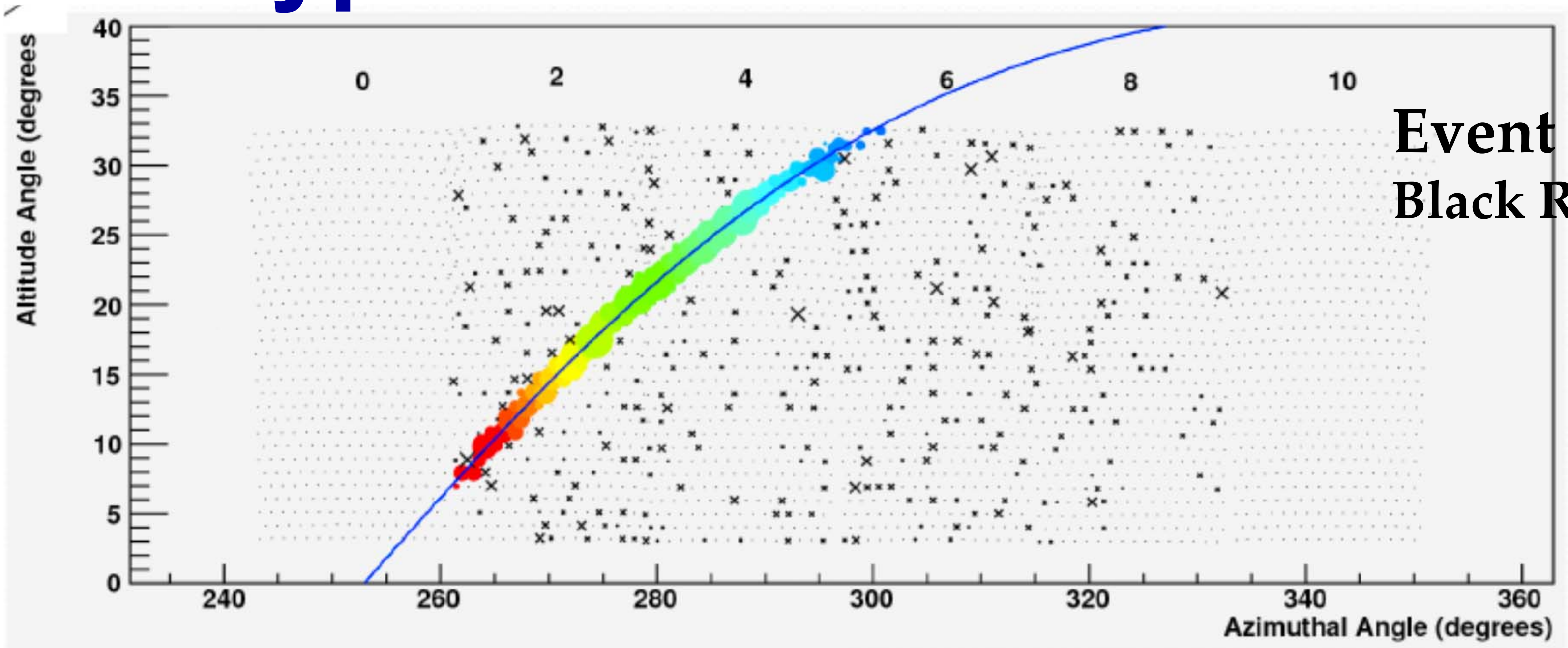
Long Ridge

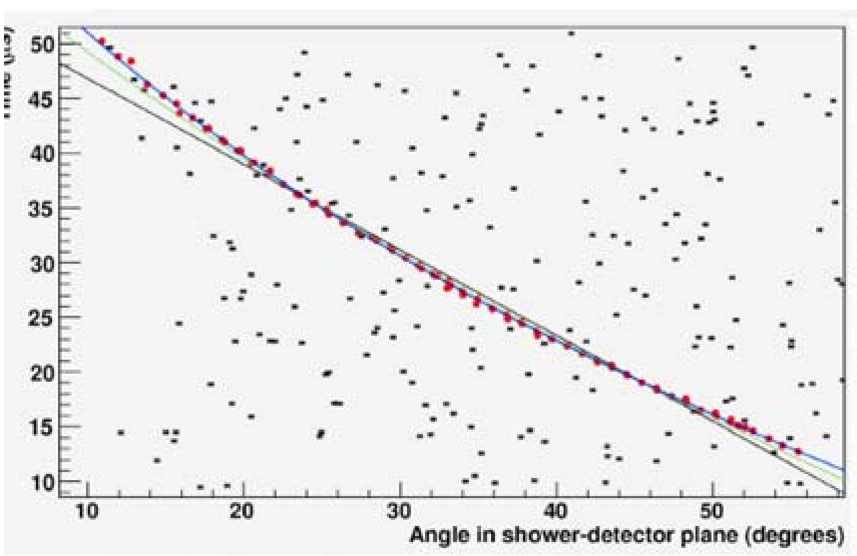


Black Rock Mesa

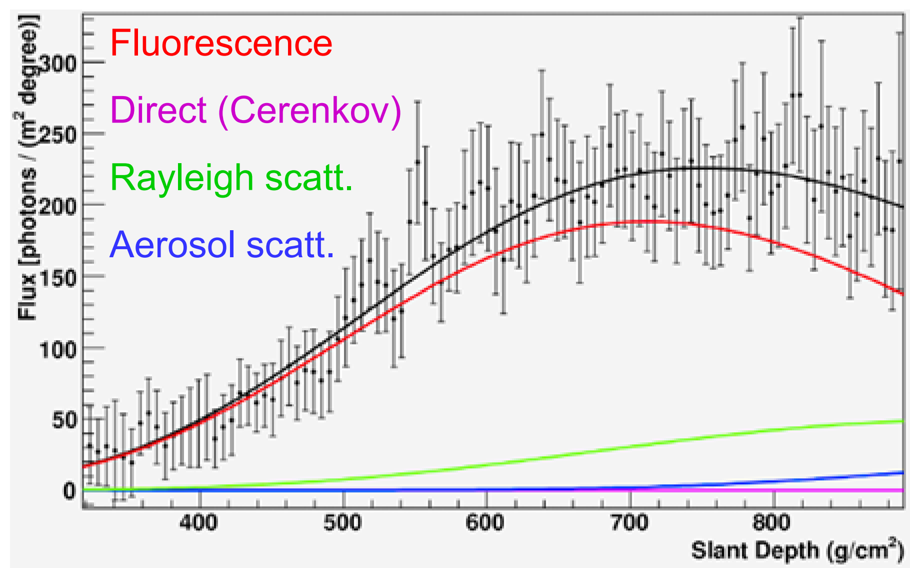
raiso, Chile

Typical Fluorescence Event





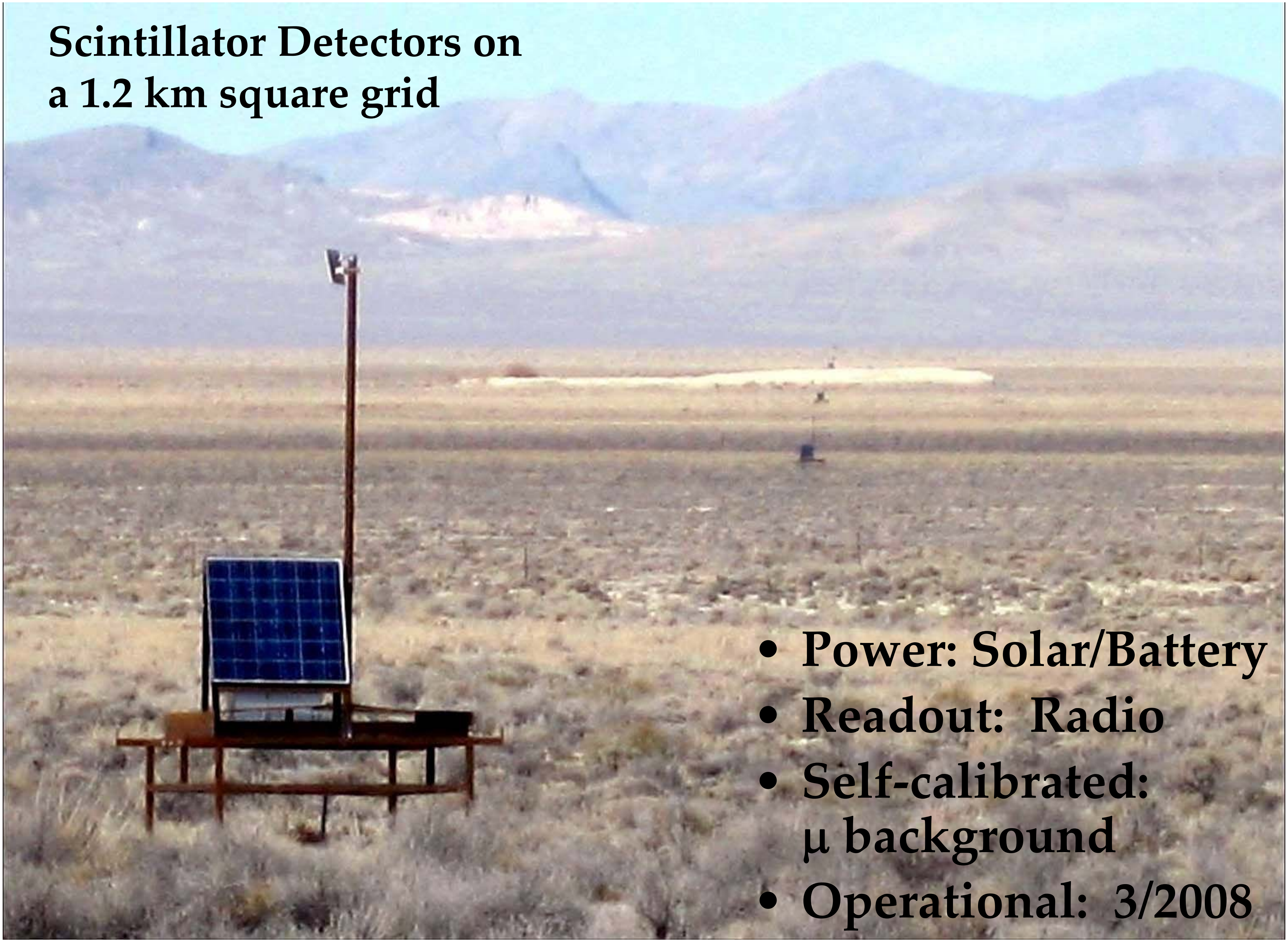
Monocular timing fit (time vs angle)



Reconstructed Shower Profile

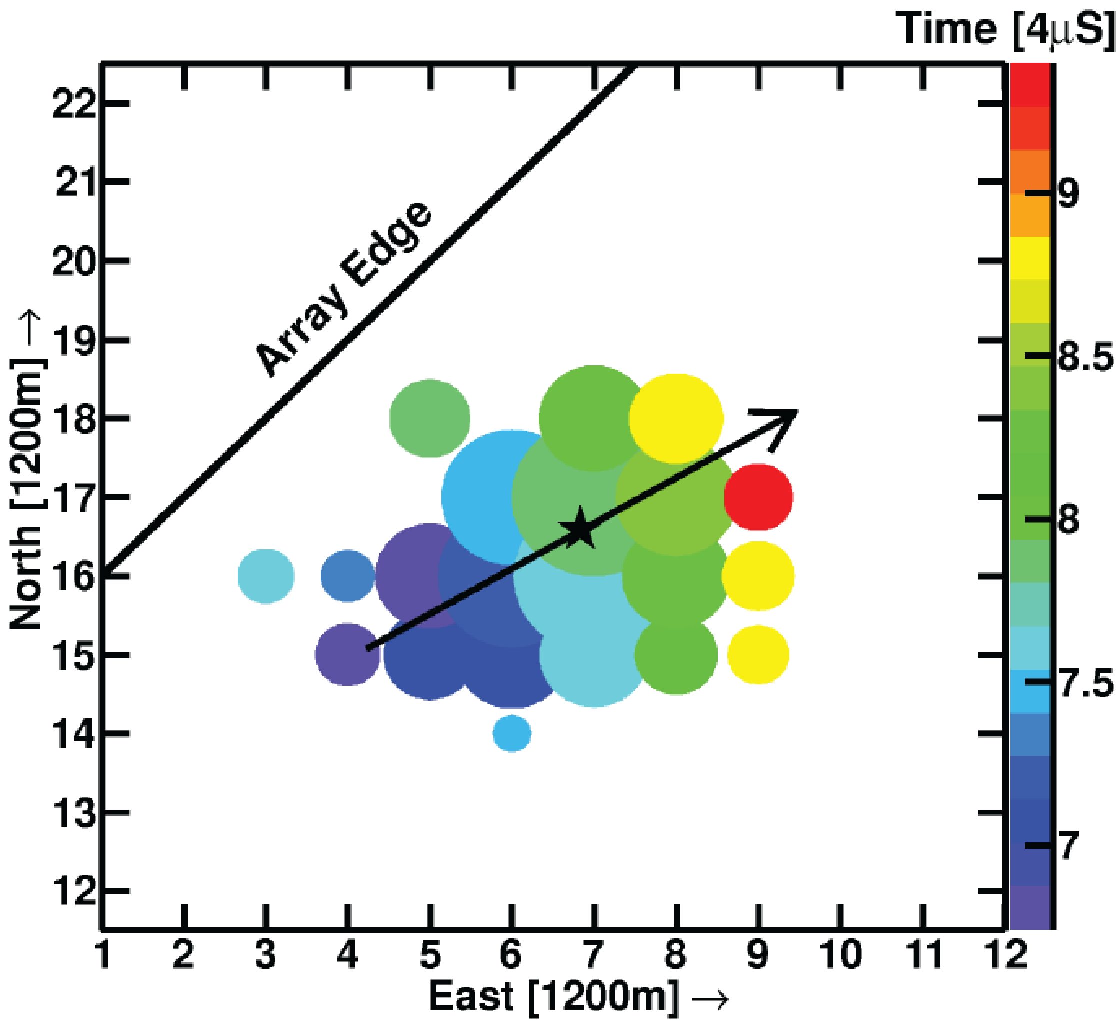
Scintillator Surface Detectors

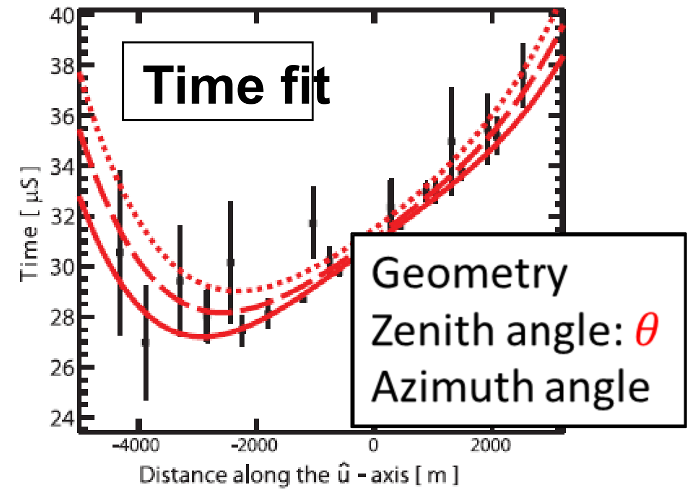
2 layers scintillator
1.25 cm thick, $3m^2$ area
Optical fibers to PMTs

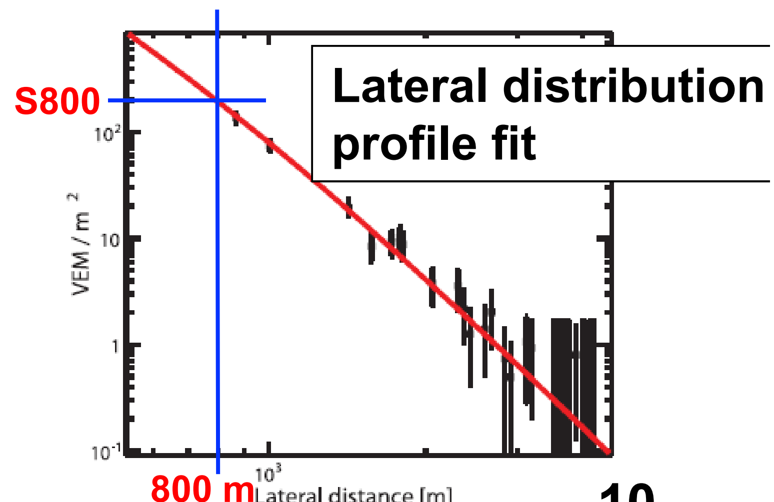

Scintillator Detectors on
a 1.2 km square grid
• Power: Solar/Battery
• Readout: Radio
• Self-calibrated:
μ background
• Operational: 3/2008

TA shower analysis with SD

An SD hit map of a typical high energy event







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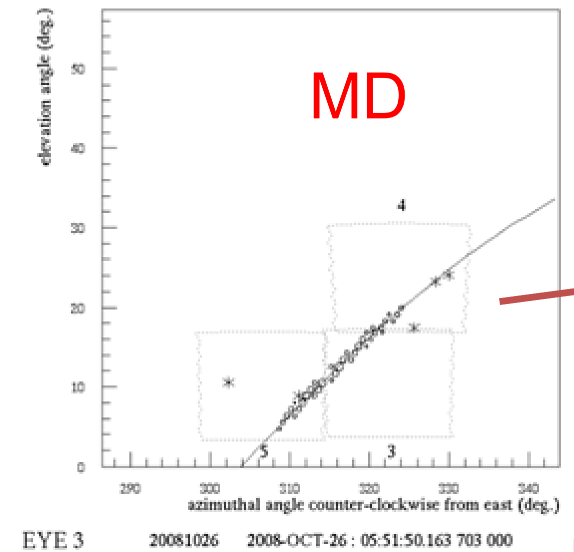
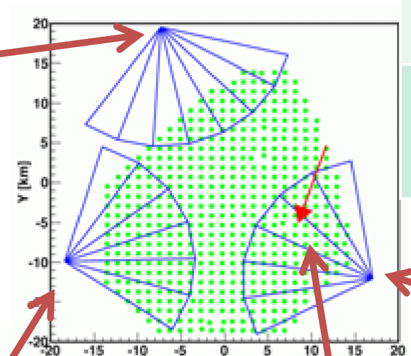
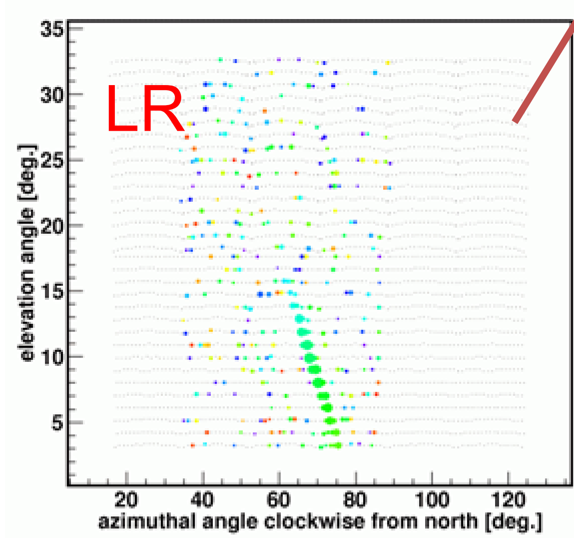
Example Event

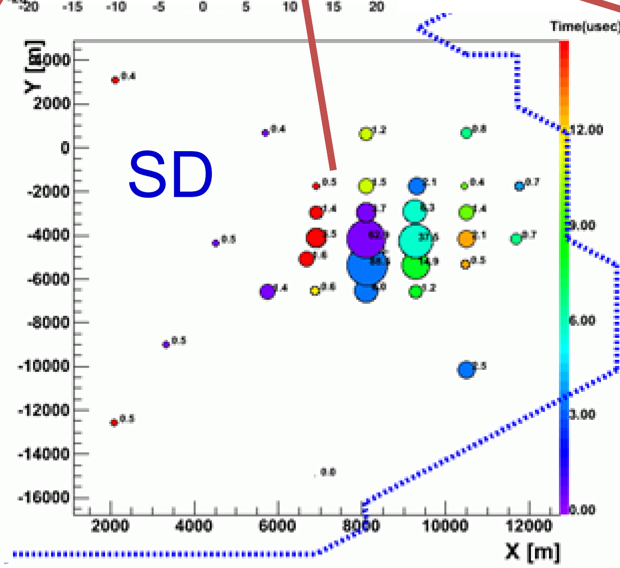
	θ [°]	ϕ [°]	x[km]	y[km]
MD mono	**51.43**	**73.76**	**7.83**	**-3.10**
BR mono	**51.50**	**77.09**	**7.67**	**-4.14**
Stereo BR&LR	**50.21**	**71.30**	**8.55**	**-4.88**

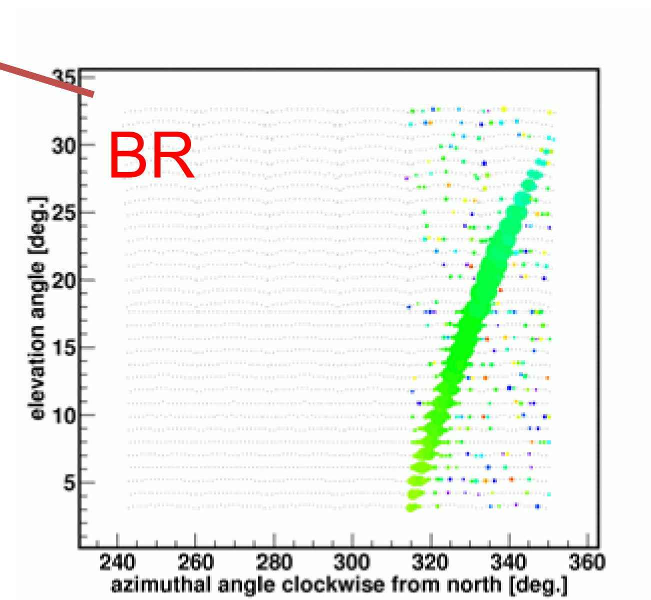
Event from 2008-10-26





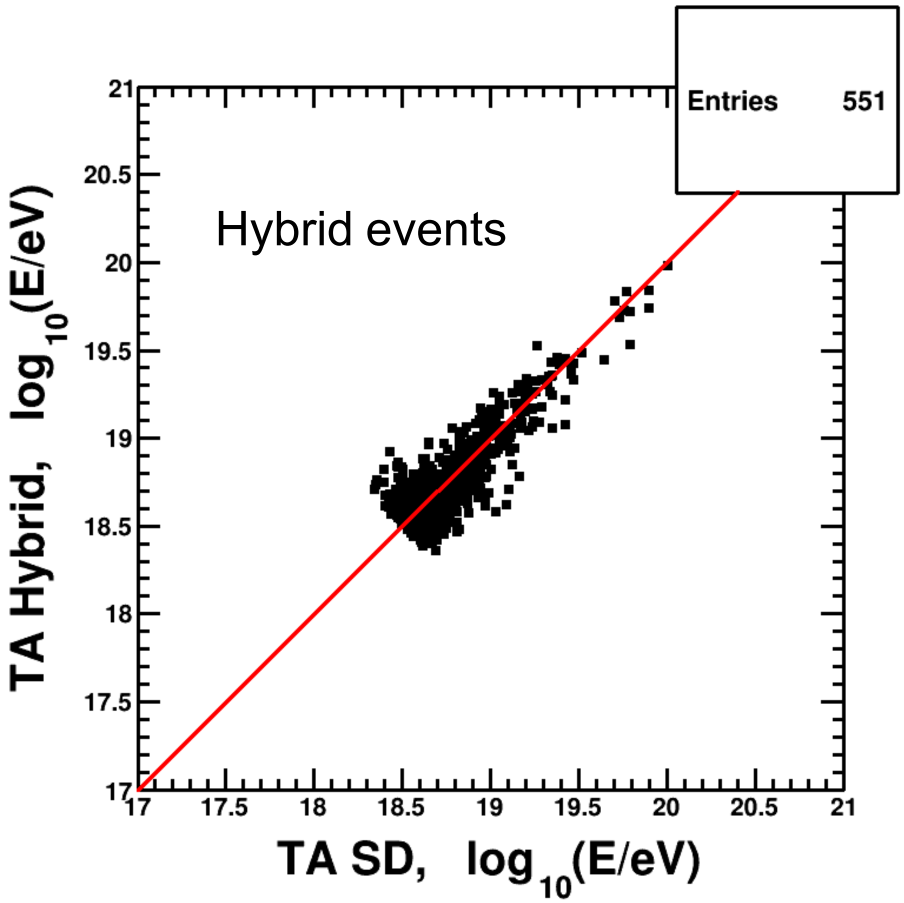






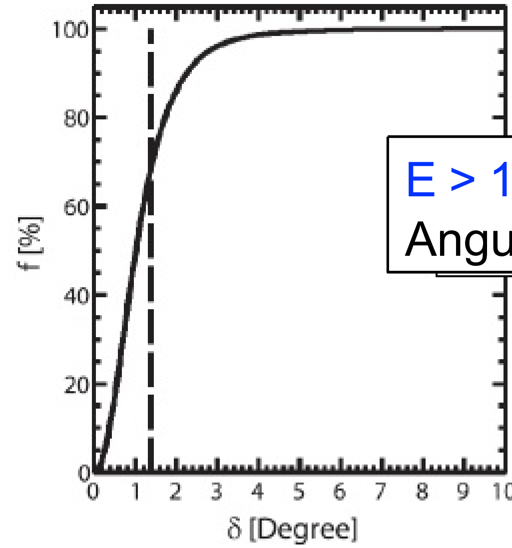
TA Energy Spectrum Results

Energy Scale Check and Resolution



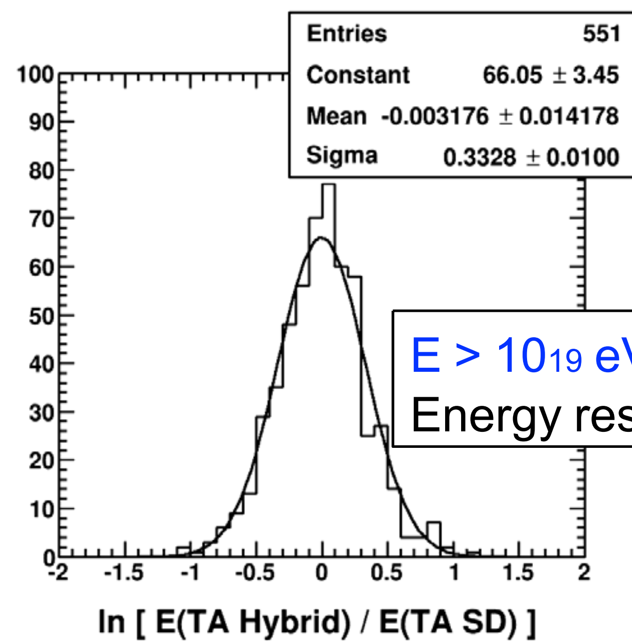
(SD scaled to FD energy: calorimetric)

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



$E > 10^{19}$ eV

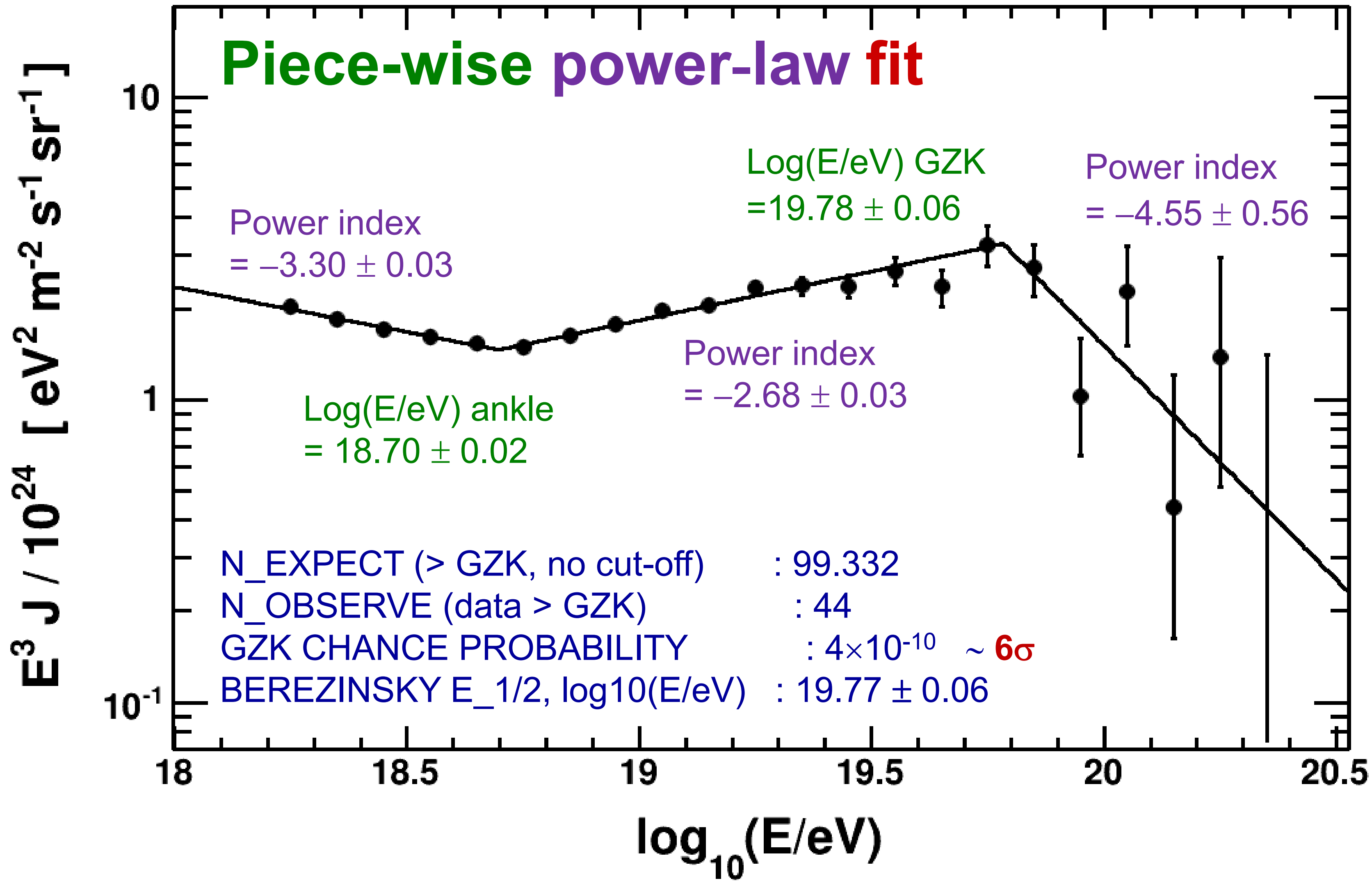
Angular resolution = 1.4^{o}



$E > 10^{19}$ eV

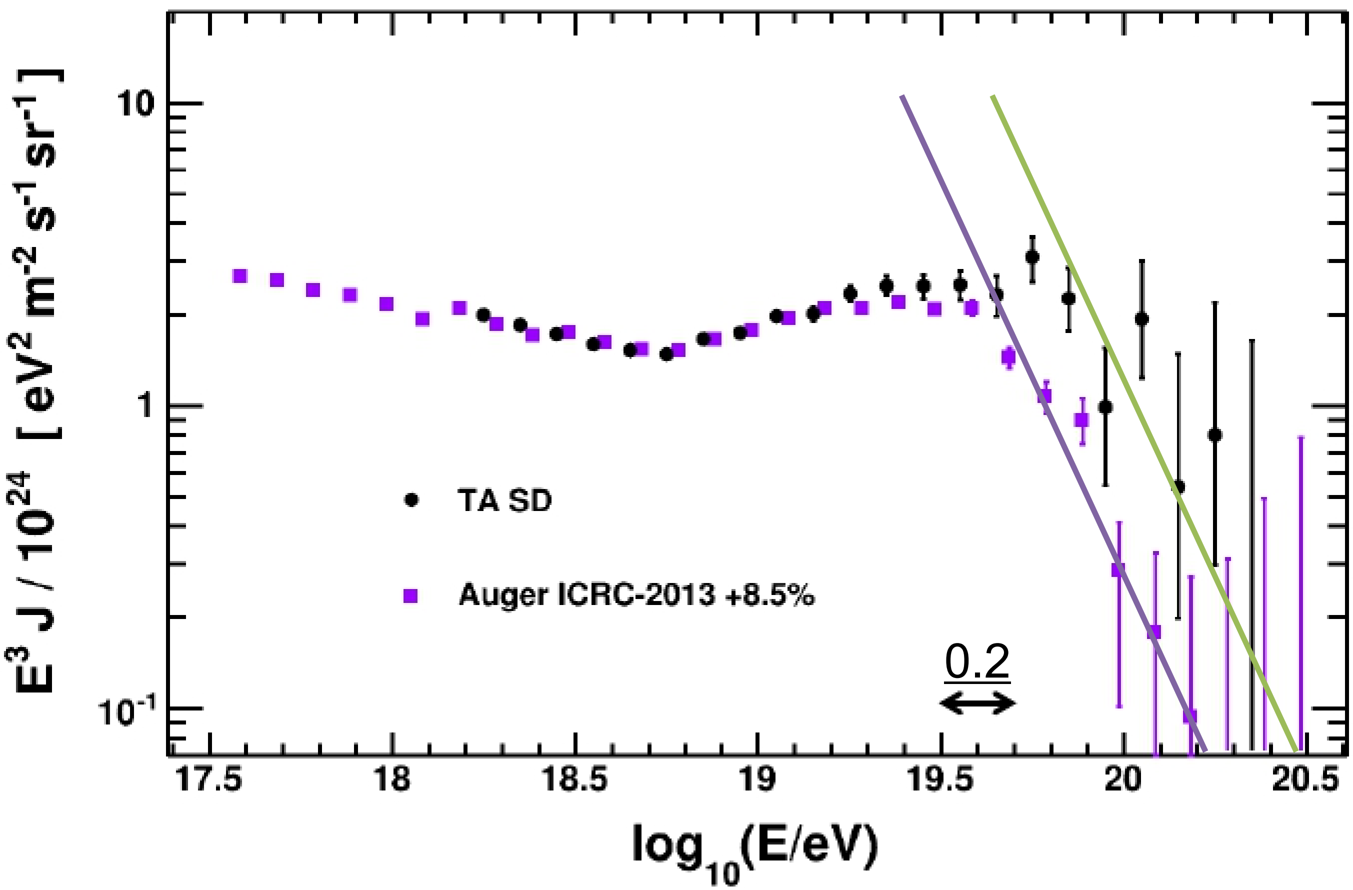
Energy resolution < 20%

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



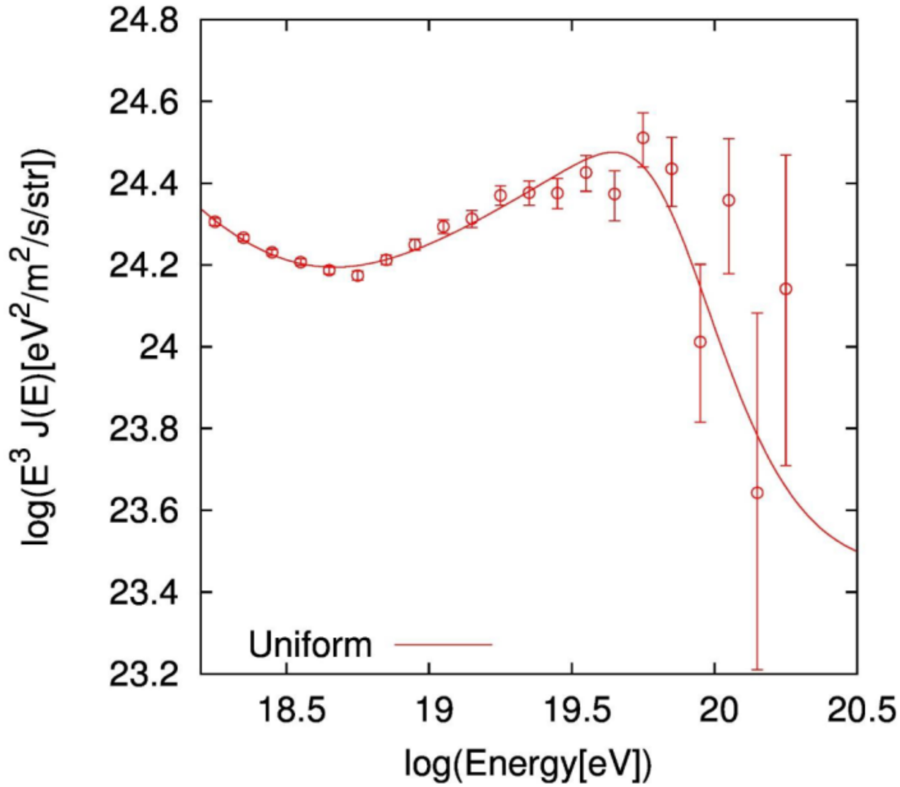
Fitting the UHE Spectrum with TA

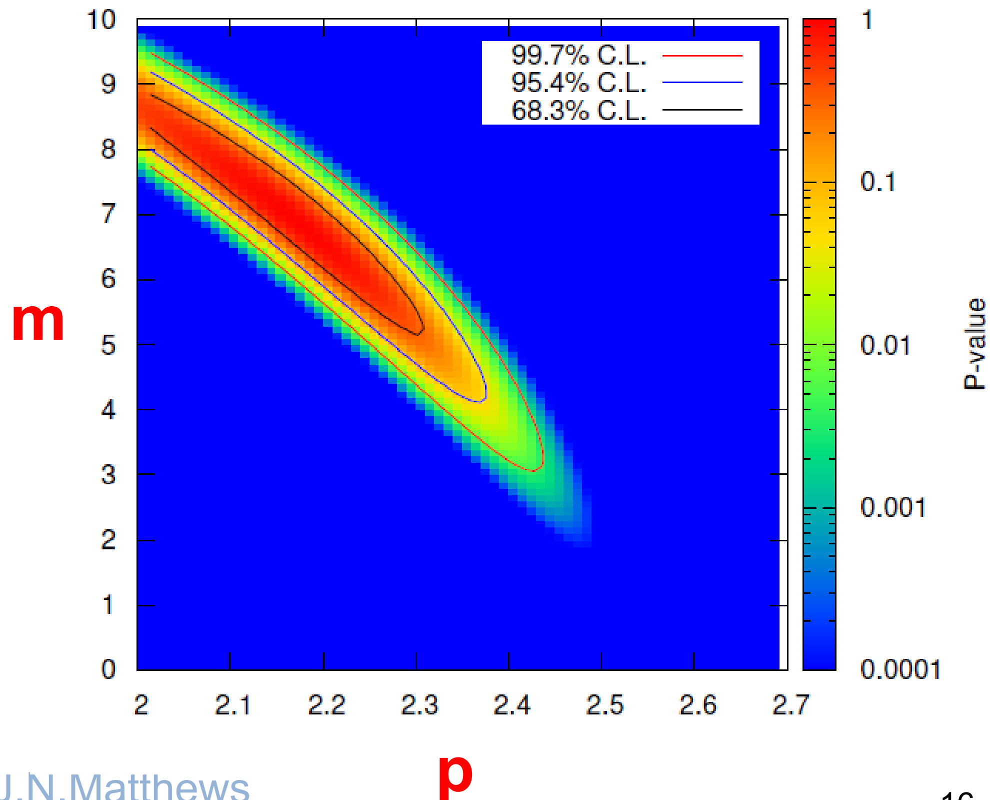
Fitting parameters:

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

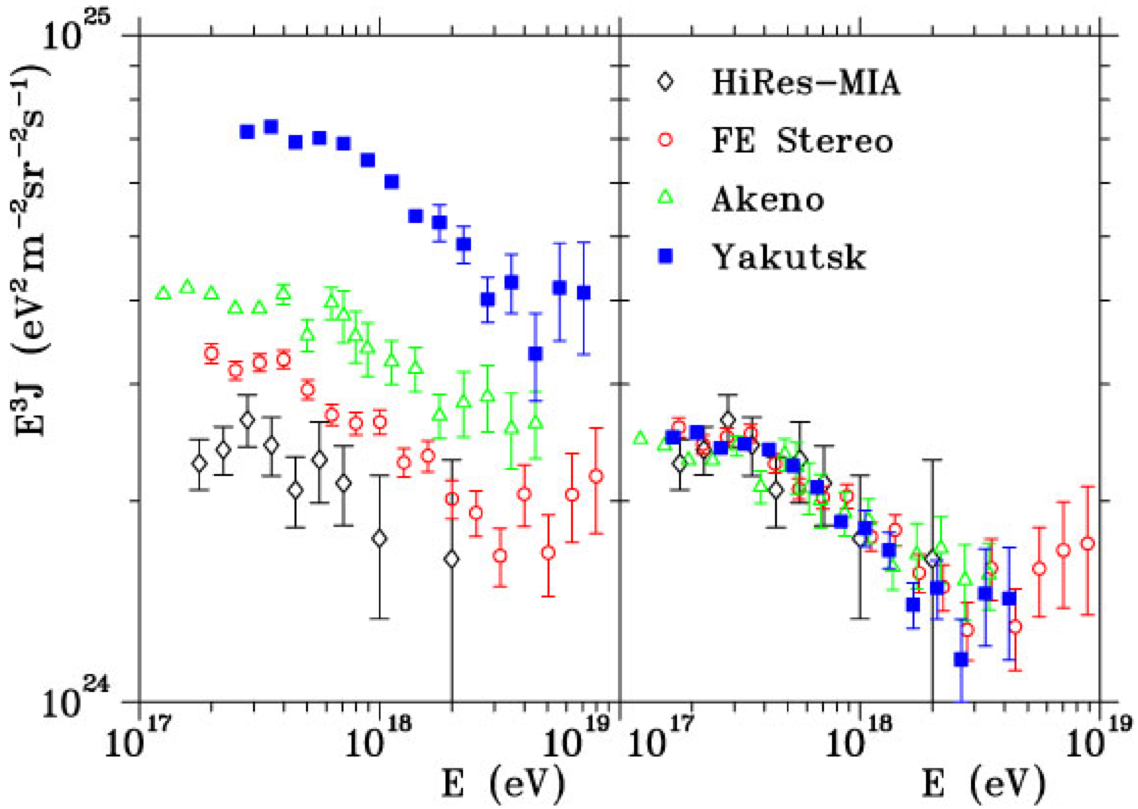
Evolution of the sources, $(1+z)^{m}$

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





Galactic to Extra-Galactic Transition

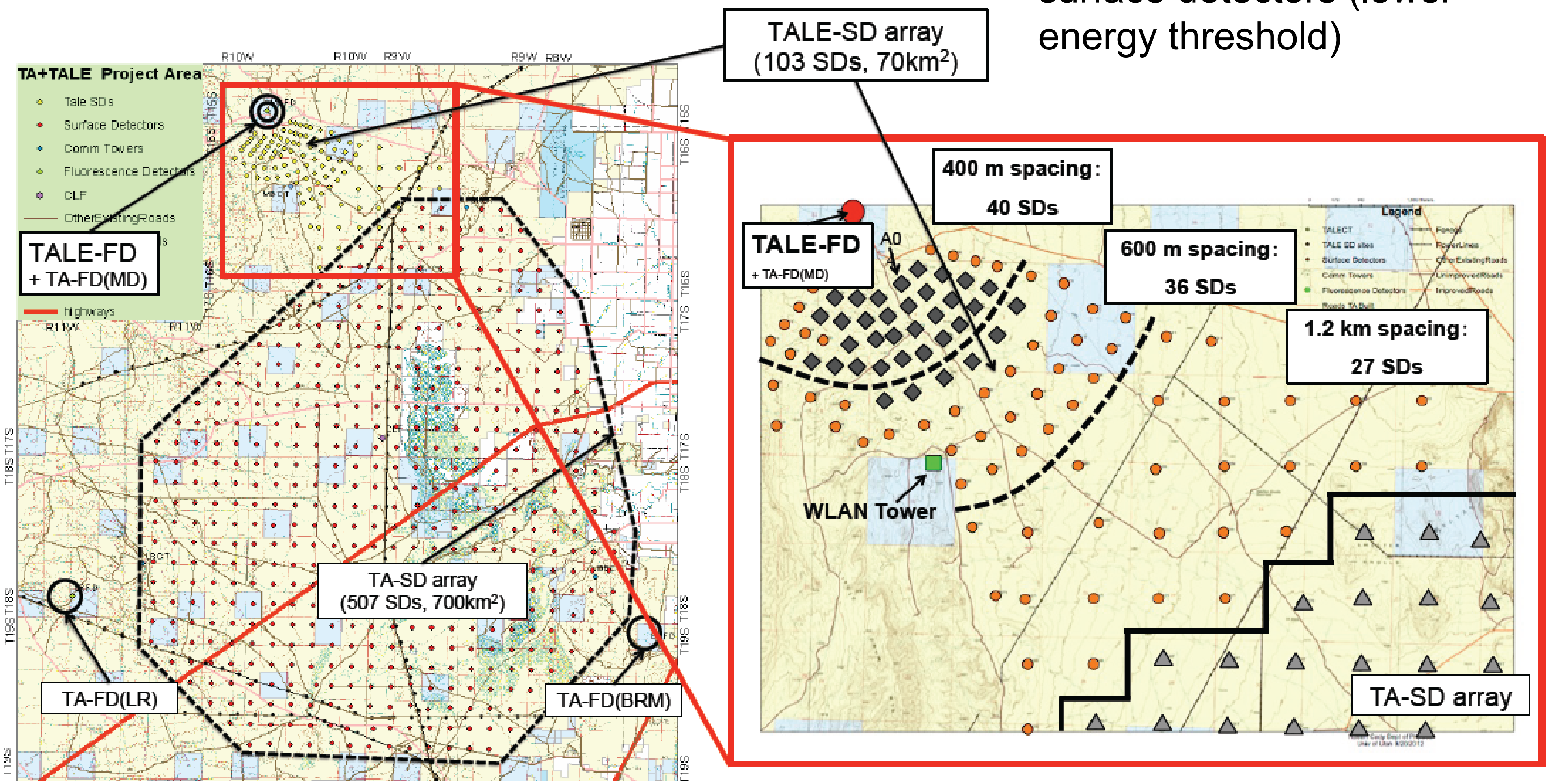


- Previous suspected structure
- Unknown energy scale
- Tie down the energy scale and simultaneously measure spectrum and composition

TA Low Energy Extension (TALE)

10 new telescopes to look higher in the sky (31-59°) to see shower development to much lower energies

Infill surface detector array of more densely packed surface detectors (lower energy threshold)

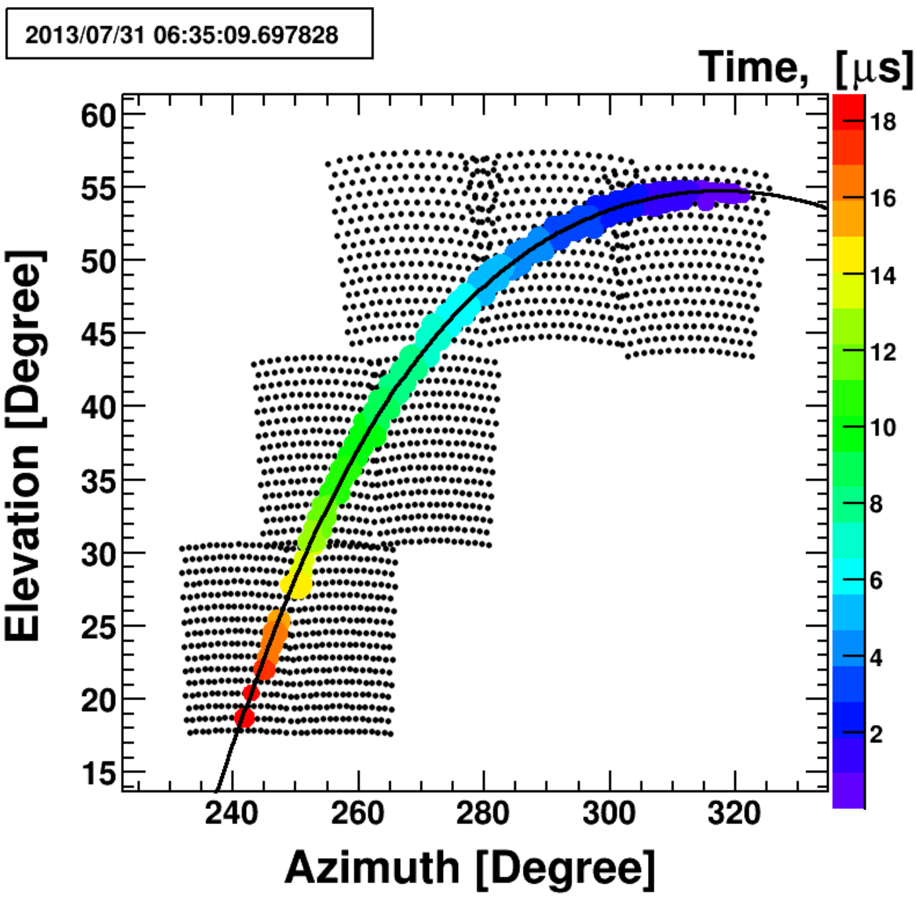


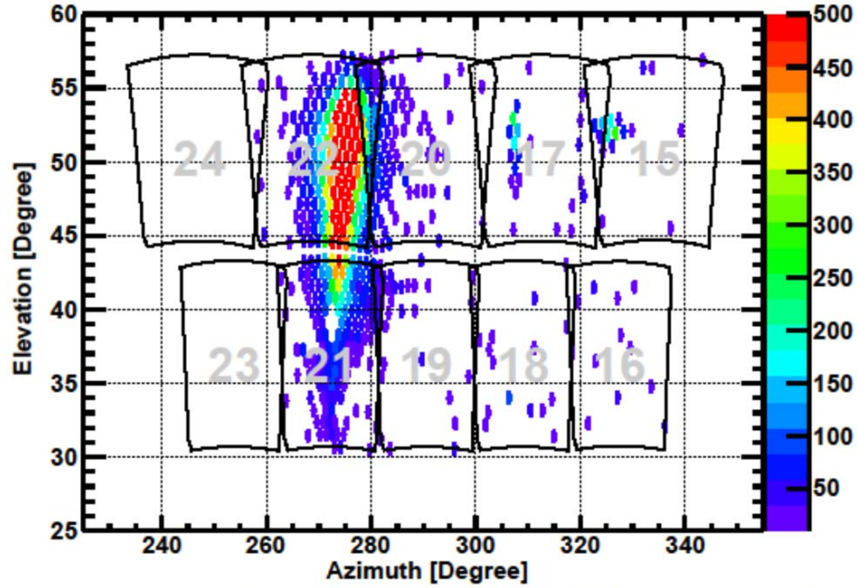
All 10 Telescopes installed and in operation since fall 2013

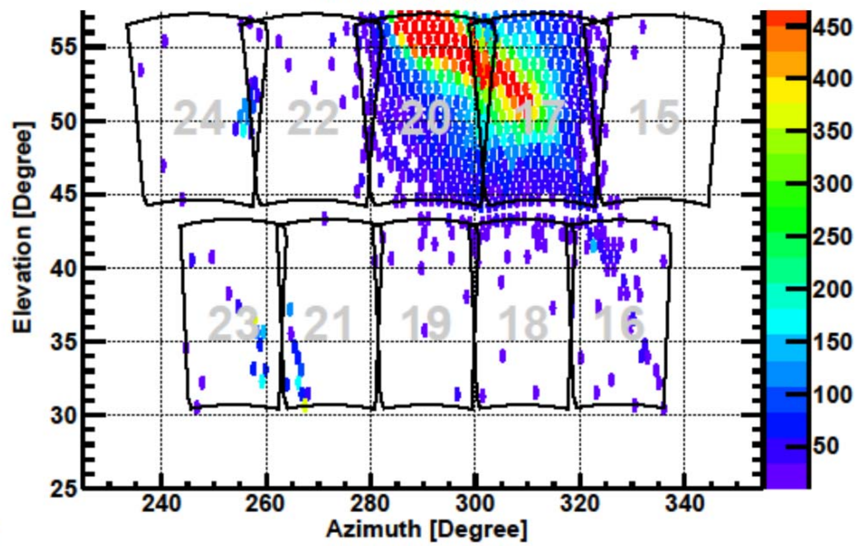
Test array of 16 scintillation surface detectors in operation

TALE SD infill array recently funded from Japan!

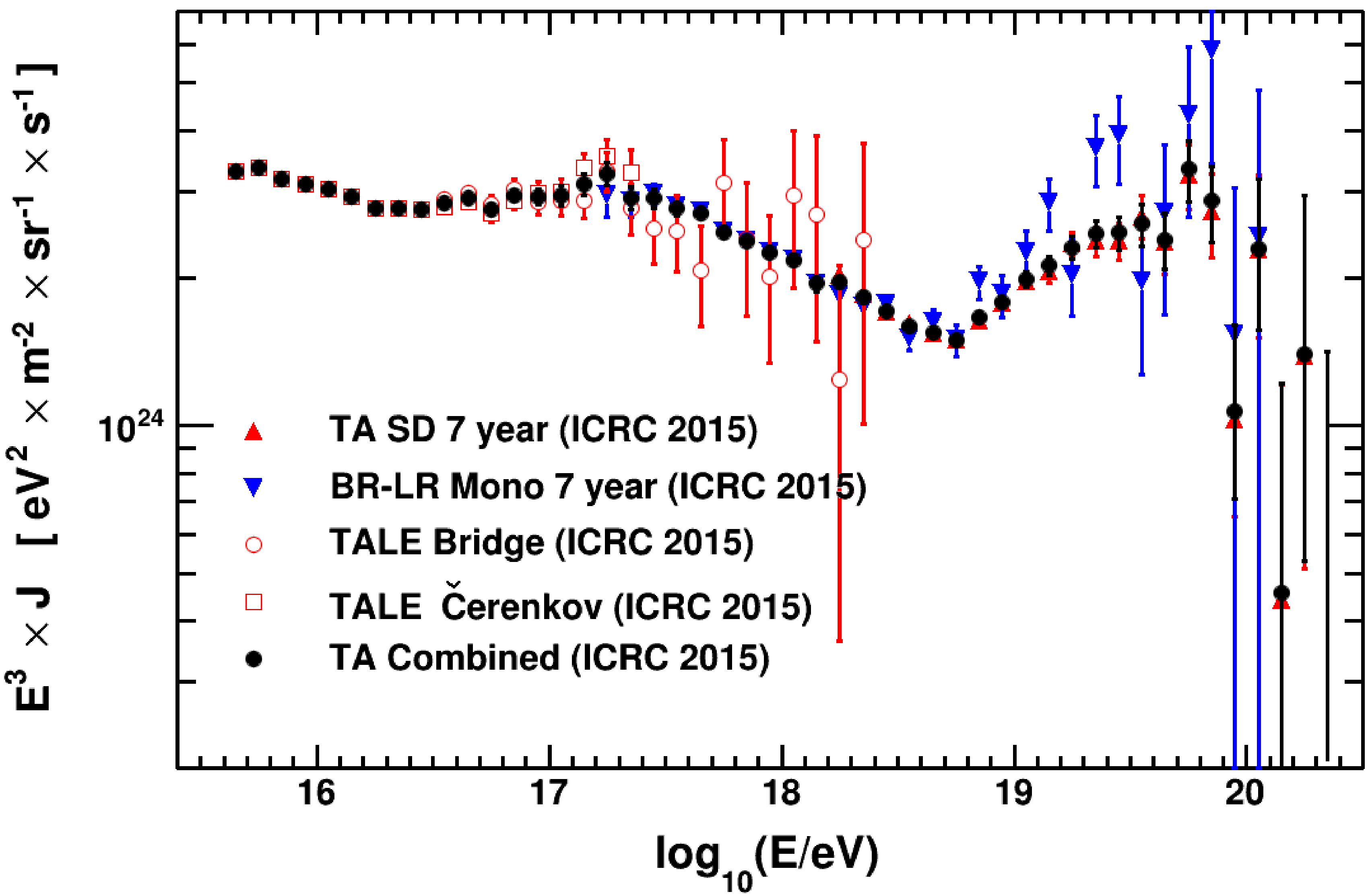
Nearby Events with Cerenkov



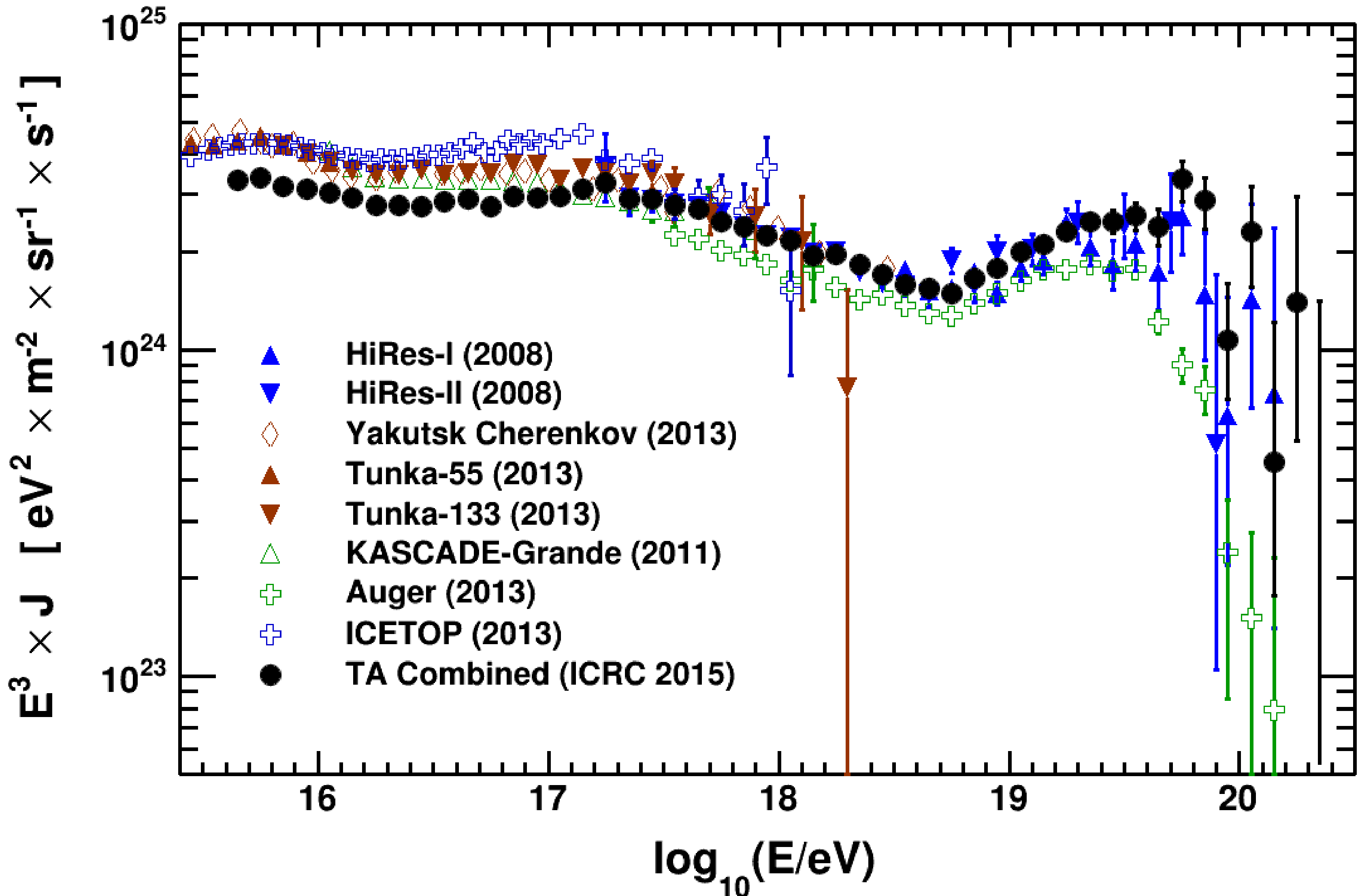




Combined TA Energy Spectrum



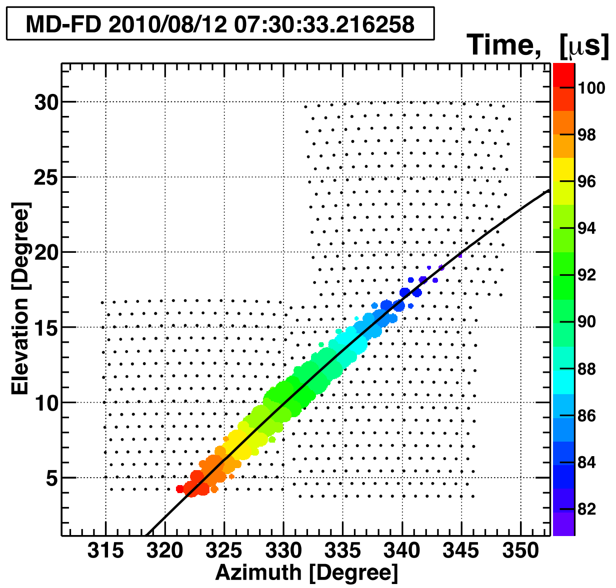
Comparison with other

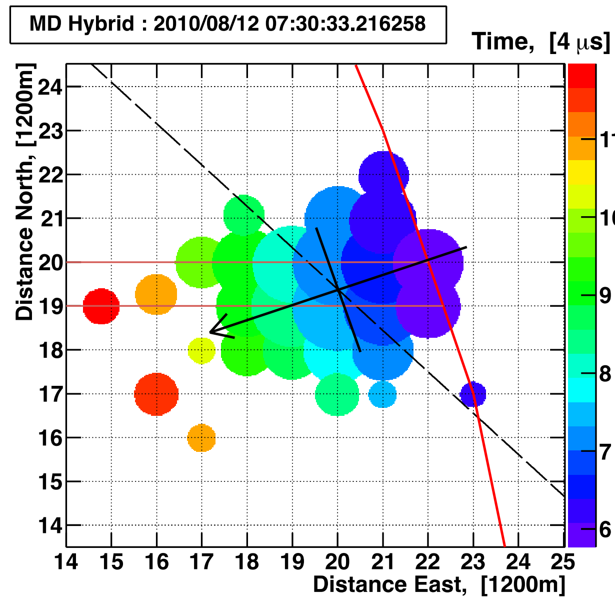


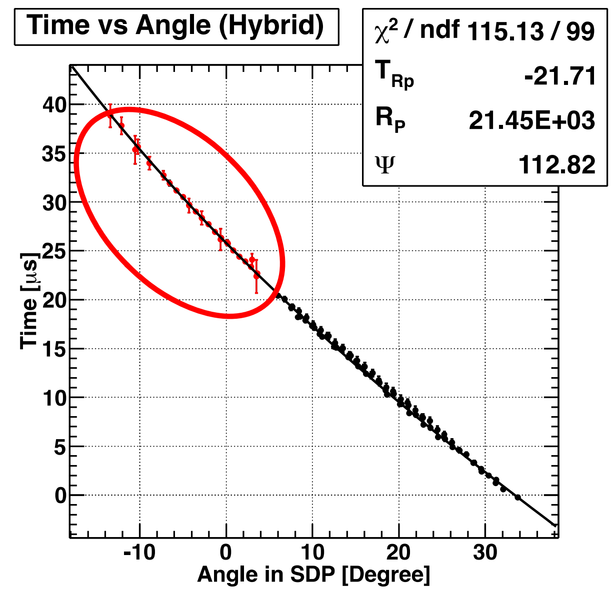
TA Composition Results

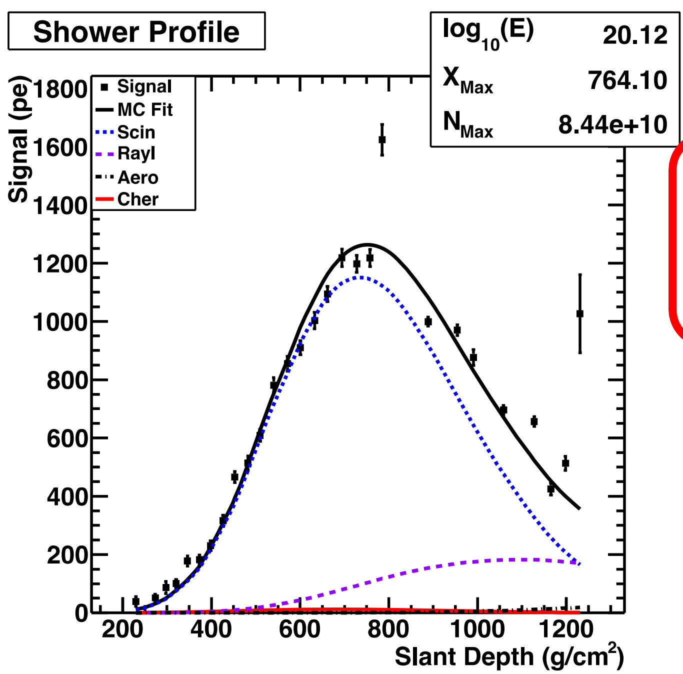
- Use hybrid or stereo to constrain geometry and know X_{max}
- Stereo also provides a redundant measurement of X_{max}

High Energy Hybrid Event







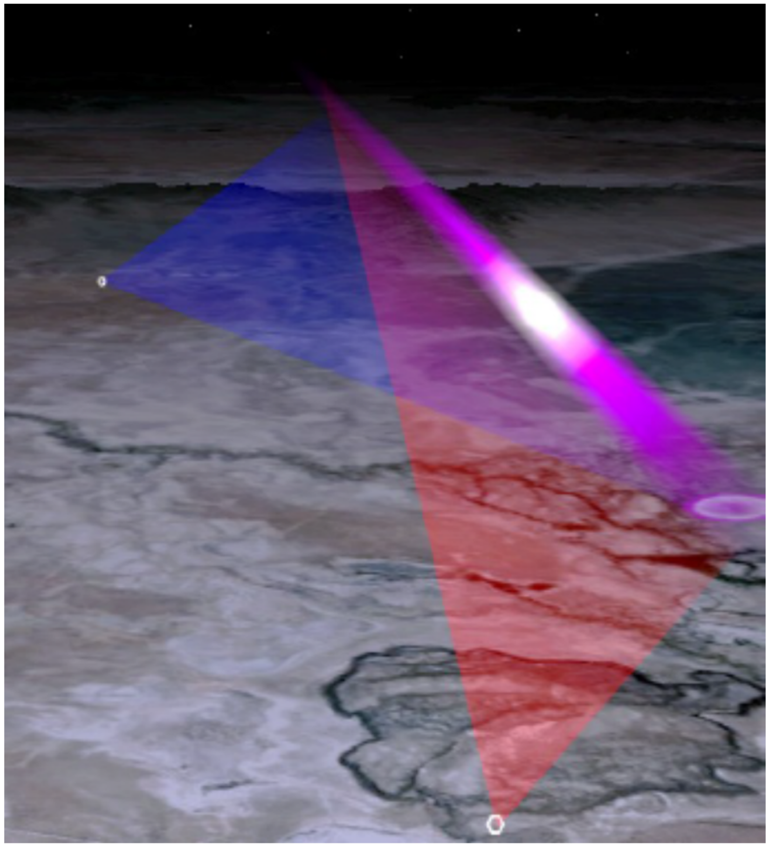


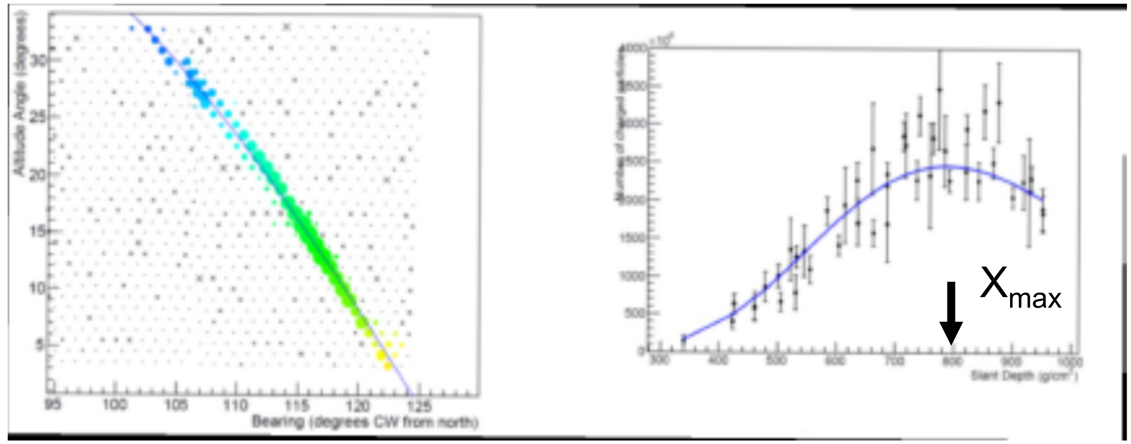
Energy: 1.3×10^{20} eV

Zenith Angle: 55.7°

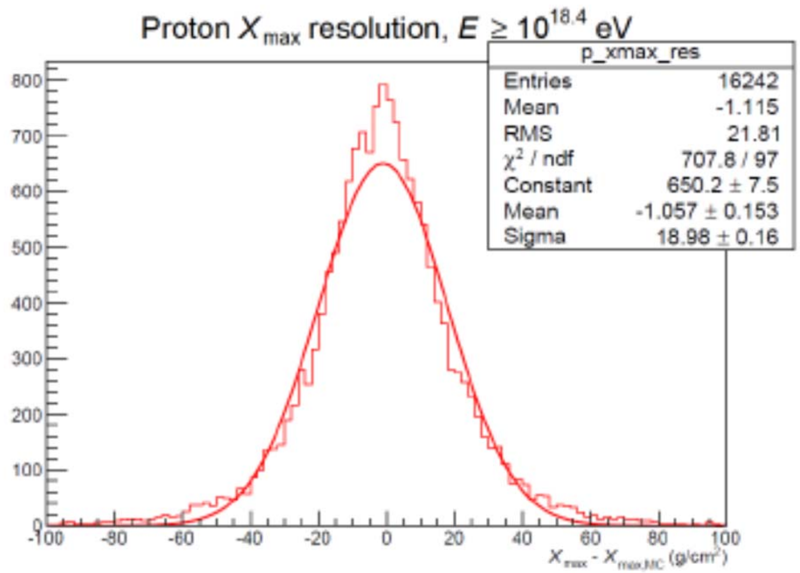
Surface array constrains geometry fit via extra timing & core information

Stereo Observation



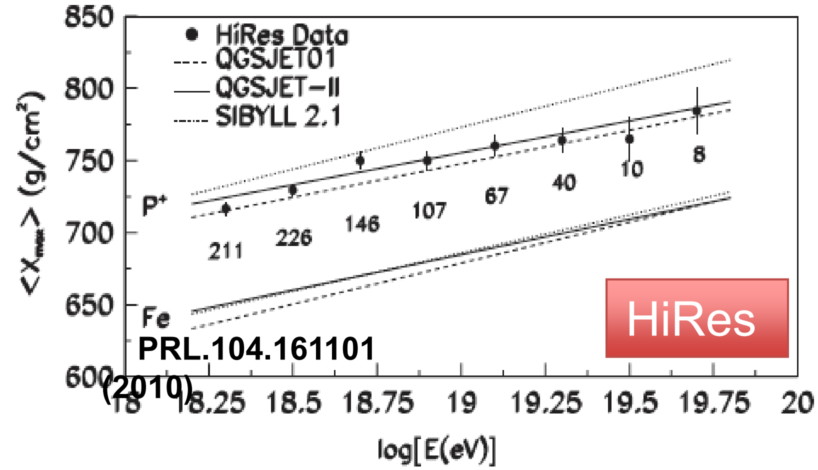


Intersect shower planes to get more precise geometry

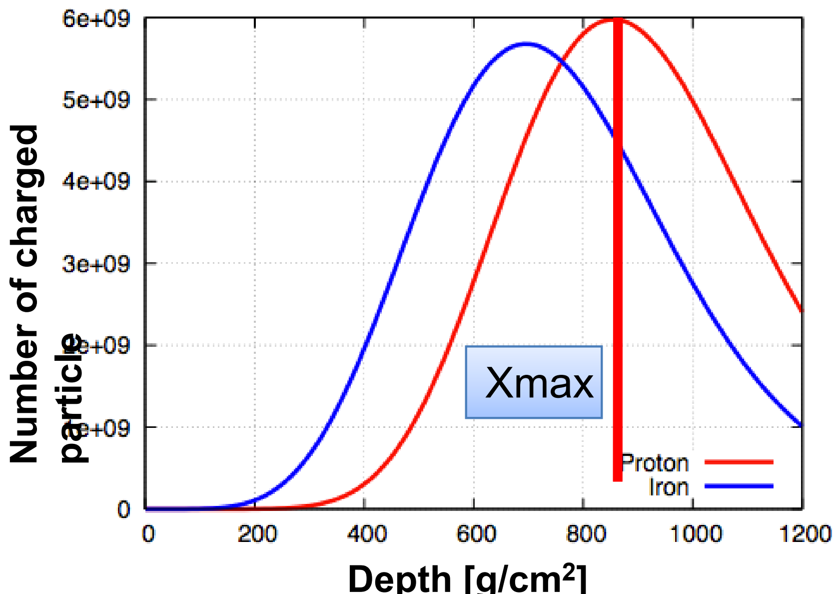


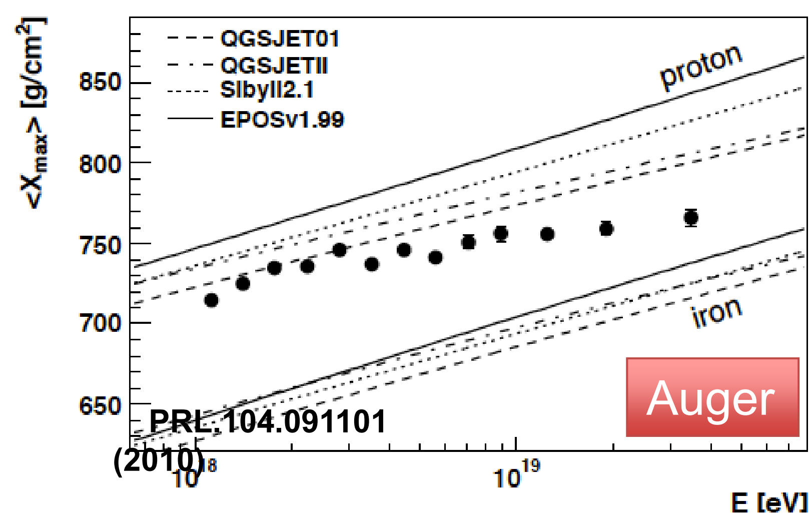
Xmax Technique

- 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

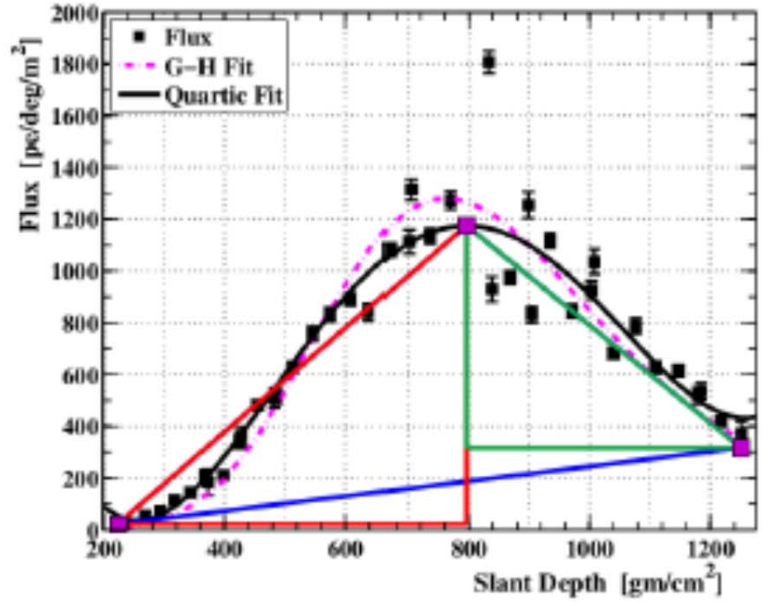


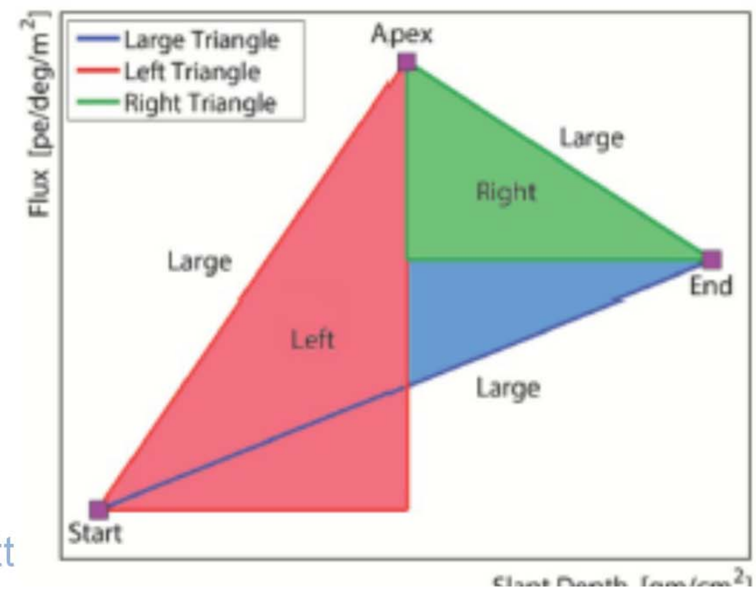


Hybrid Observation

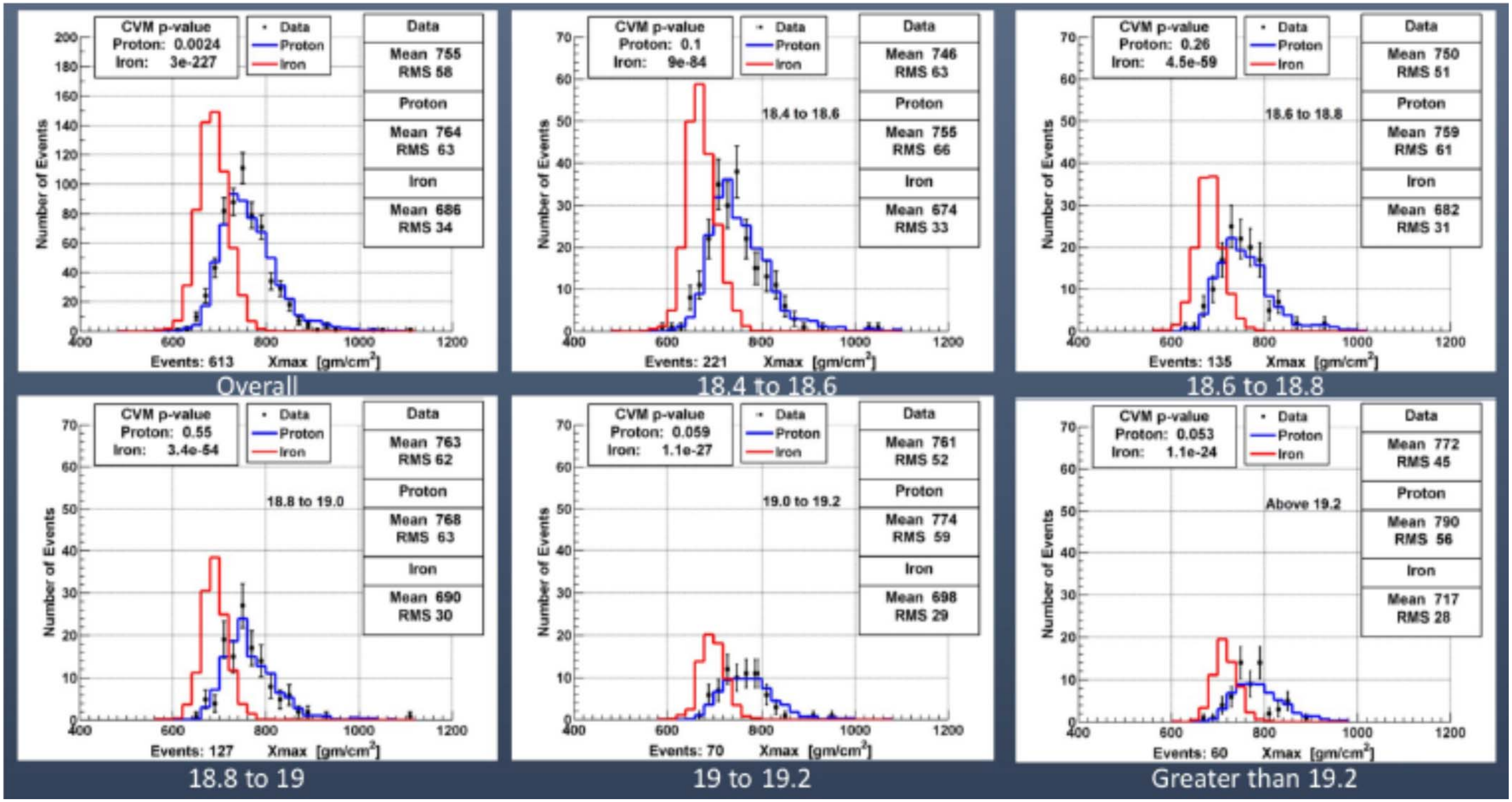
- Astropart. Phys. 64 49 (2014). 4 yrs, 297 Events > $10^{18.4}$ eV
- Cuts based on pattern recognition technique to improve resolutions s ≤ 25 g/cm^2, all energies.
- Update:

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





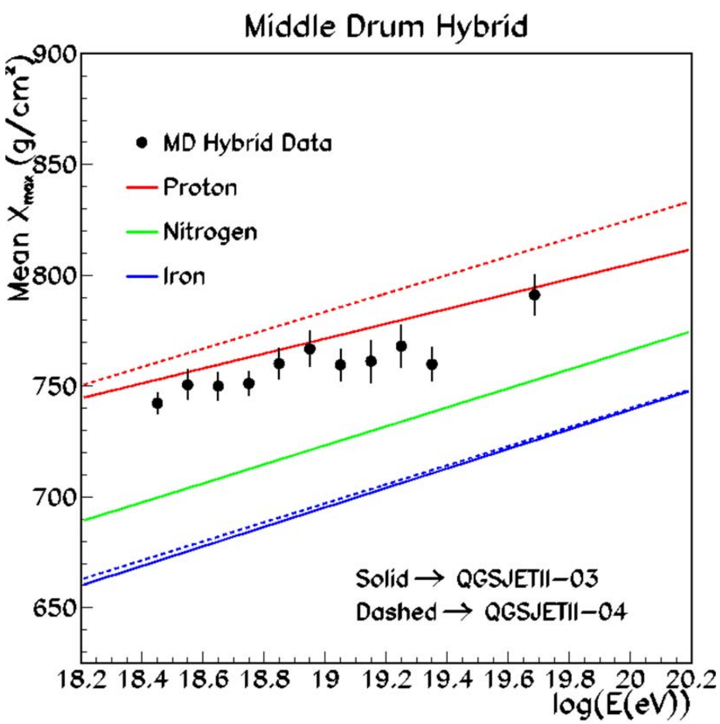
Hybrid X_{max} Measurement

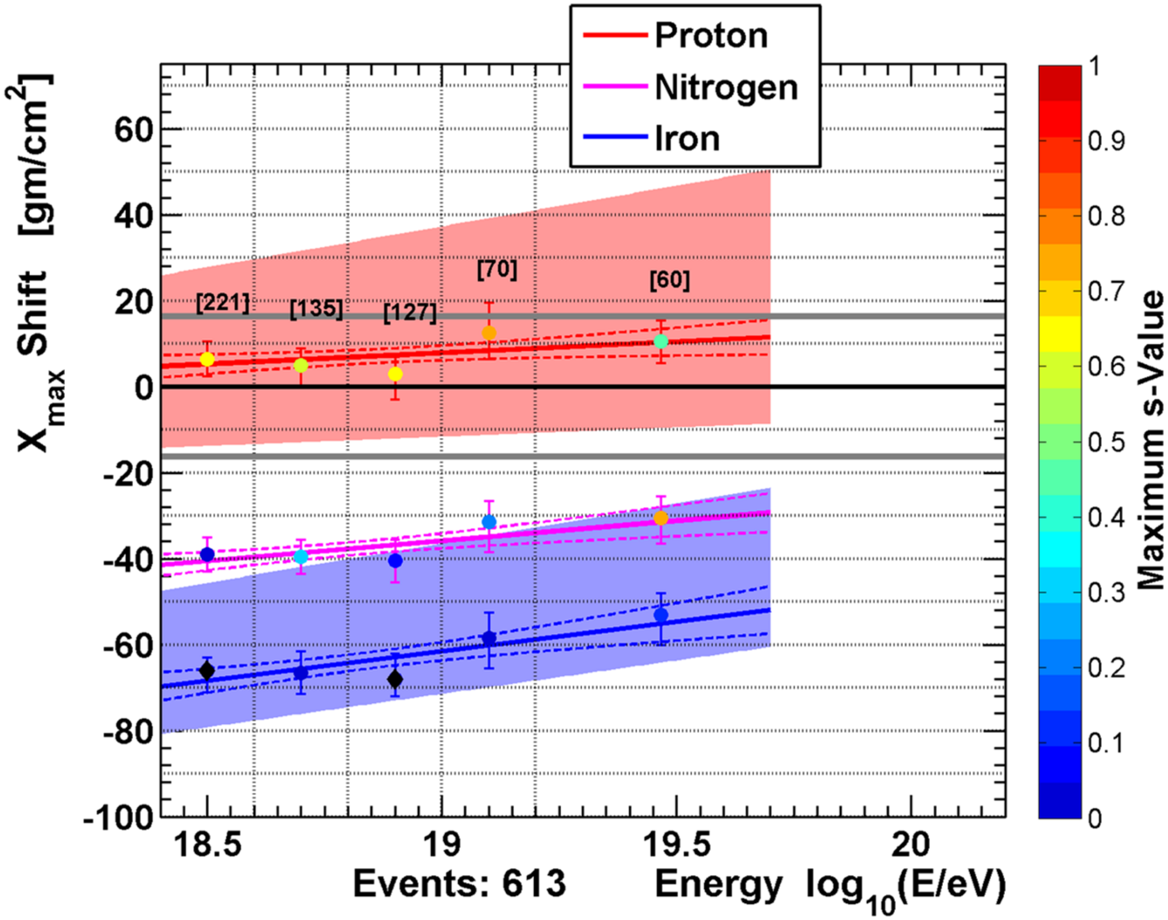


Xmax Data comparison to QGSjet II-03 **proton** and **iron** models

MD Hybrid

Elongation:
<Xmax> vs log(E) plot





"Shift Plot"

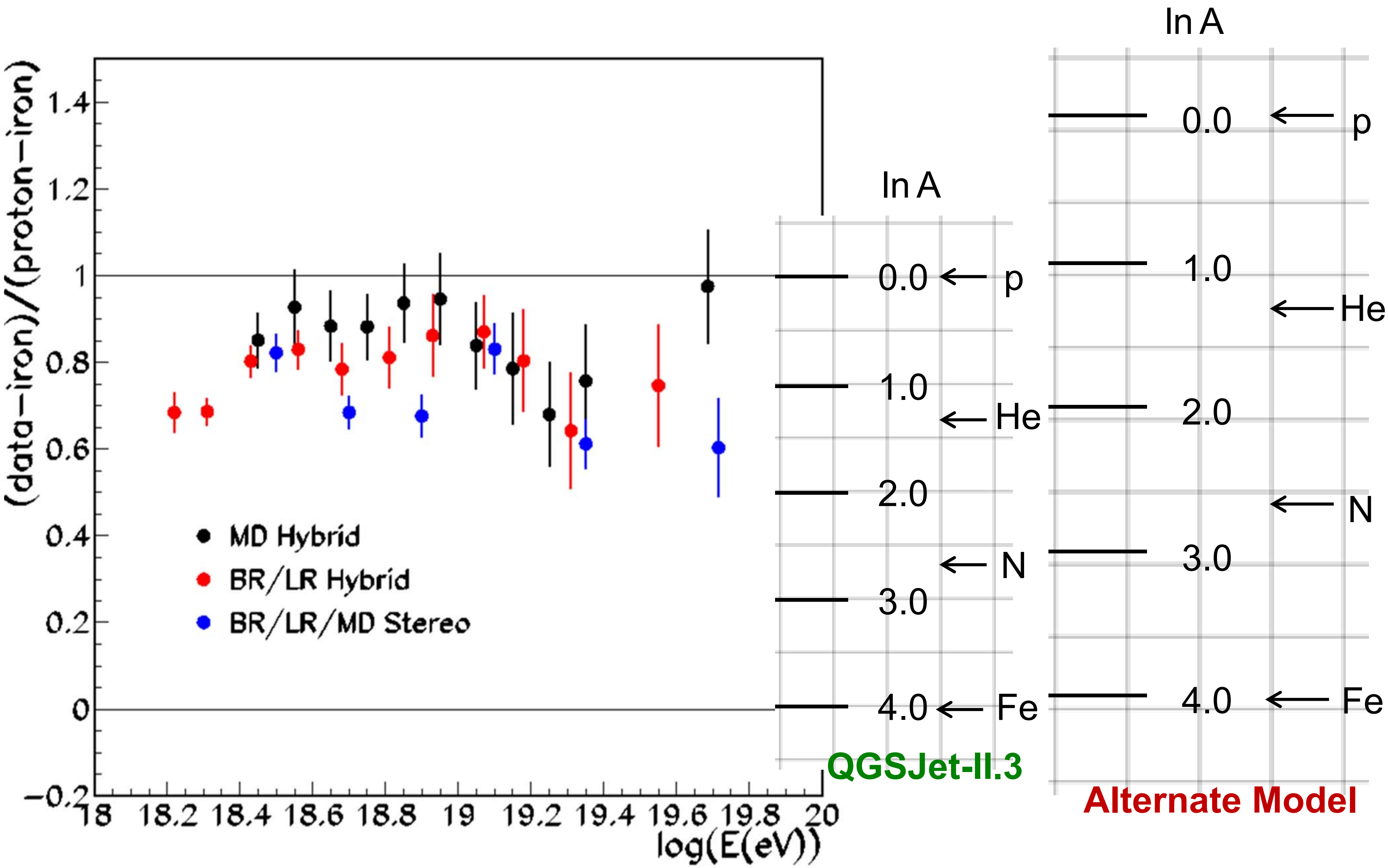
Plot ΔX_{max} required to maximize data/MC agreement (QGSJETII-03).

Standard statistical test on shifted distribution (points)

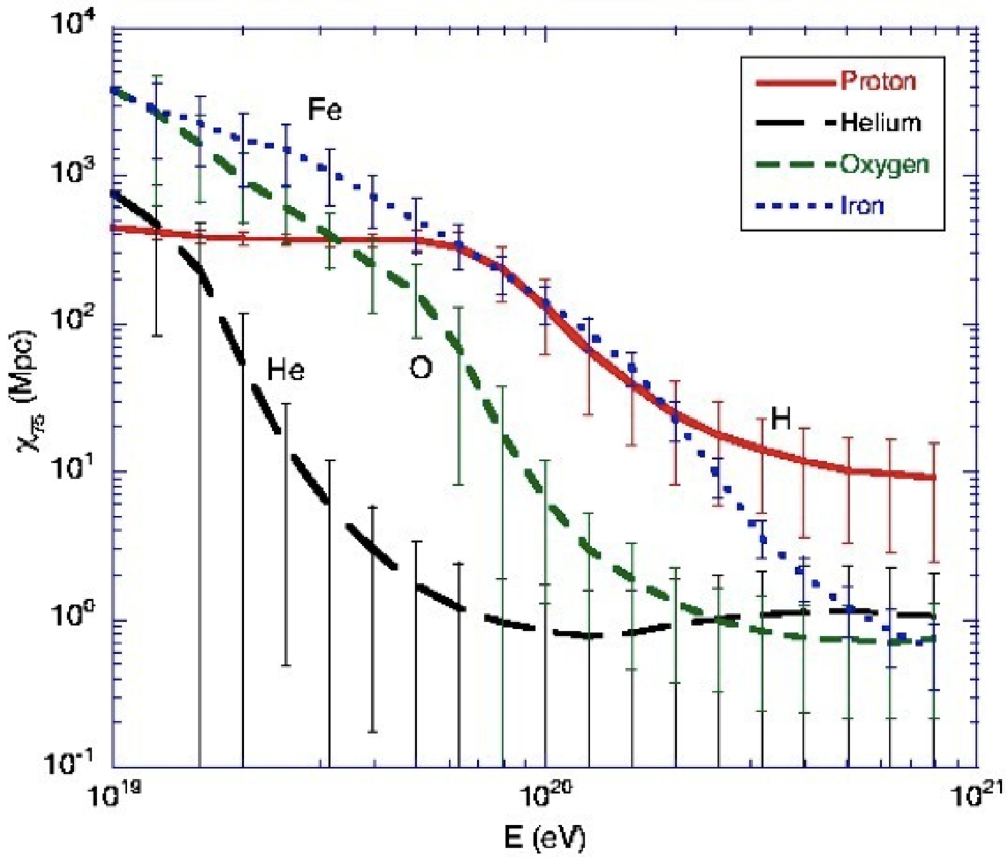
Pink, blue bands for other hadronic models

16 g/cm^2 systematic uncertainty

TA data compared to QGSJet-II.3

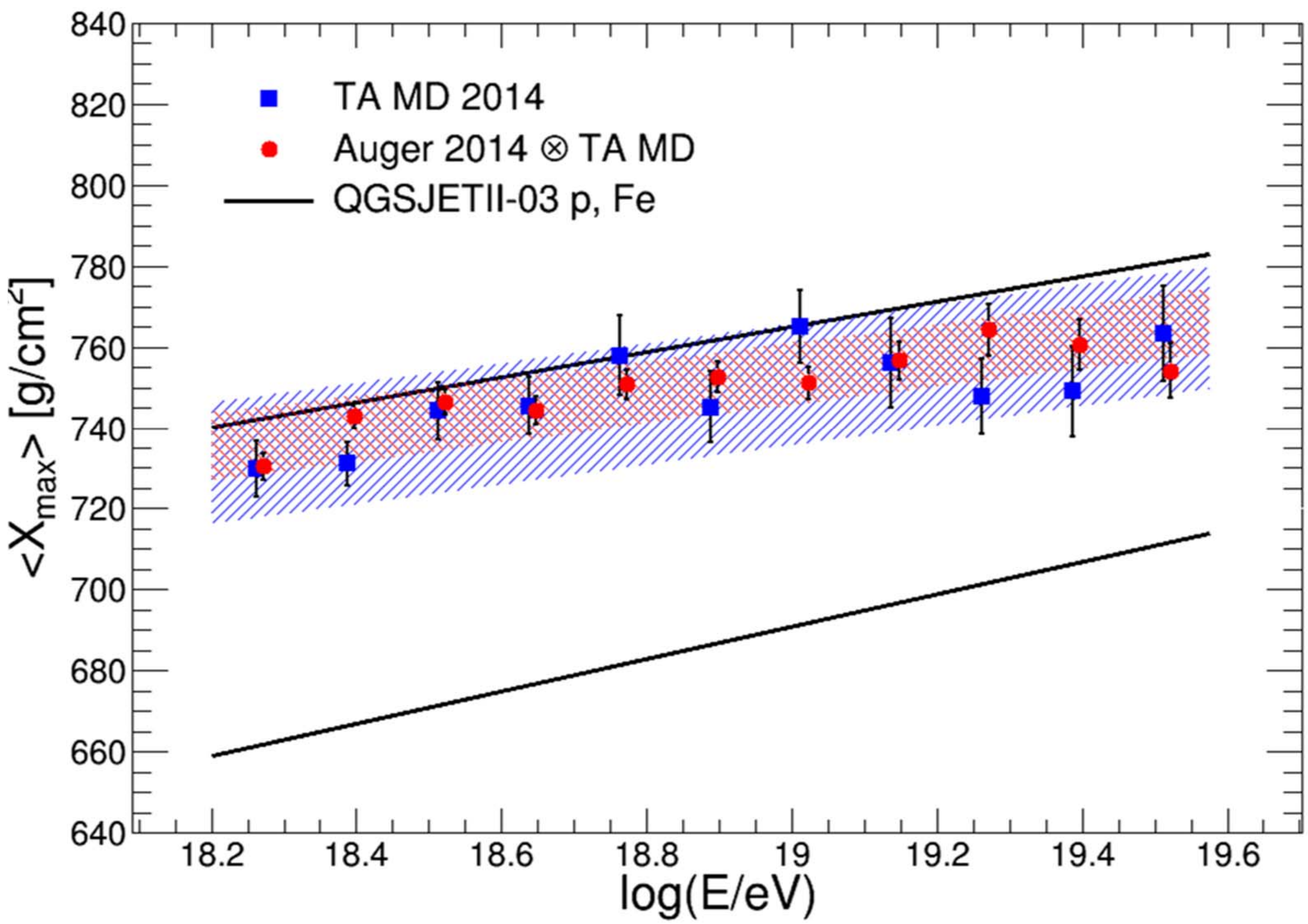


Astrophysically p and He are very different



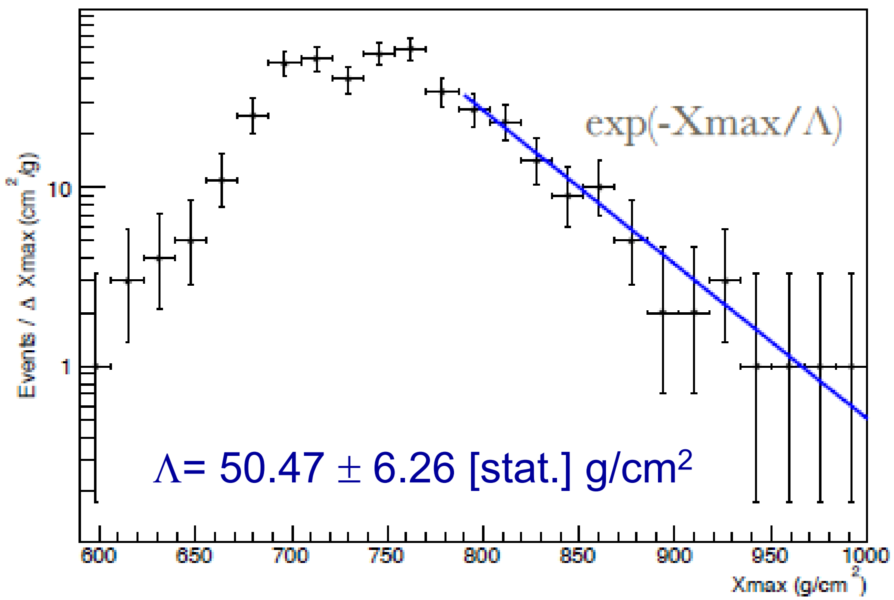
Interaction lengths of p,He,O and Fe

Meta-analysis: Composition WG

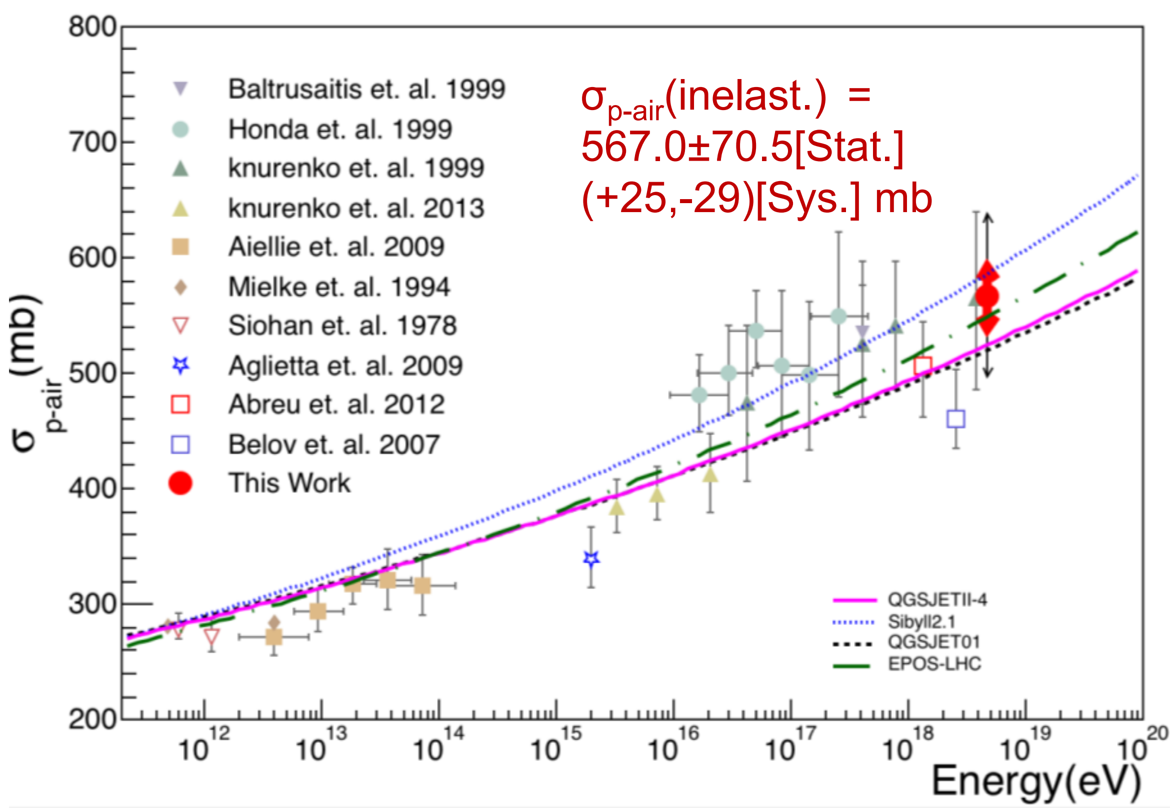


TA data cannot distinguish between mix and QGSJETII-3 protons at this level of systematic uncertainty.

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)

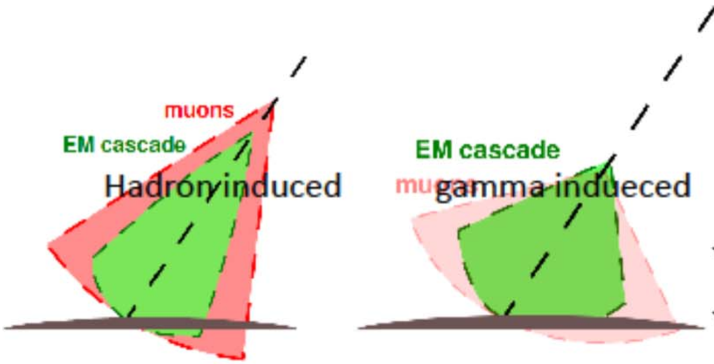


Systematic source	Systematic (mb)
Model Dependence	±17
20%Helium	+18
Gamma<1%*	– 23
Total	(+25,-29)

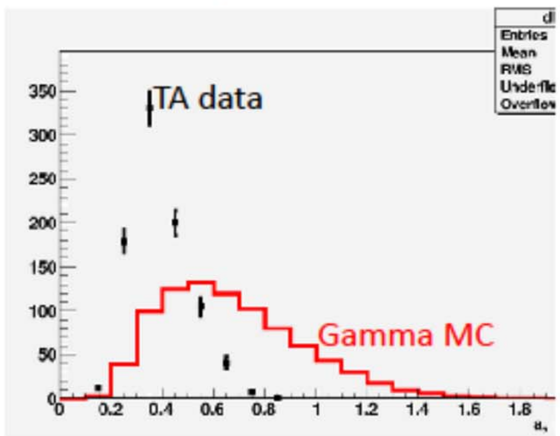
R. Abbasi et. al. (TA collaboration) Accepted for publication by Phys. Rev. D. **Aug 2, 2015**

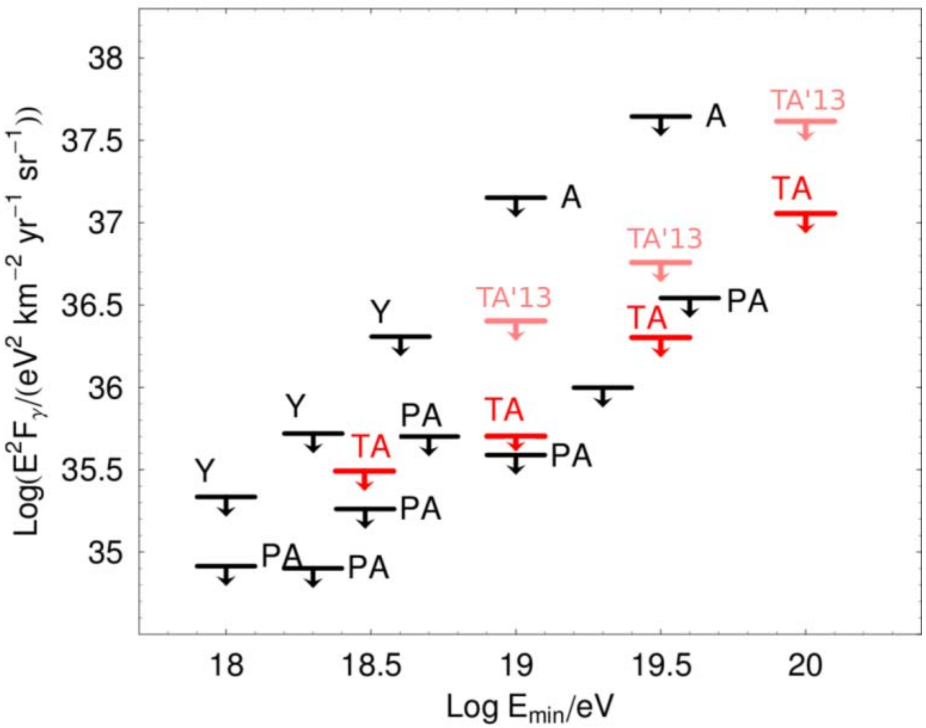
Photon search

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 .



$45° < \theta < 60°$

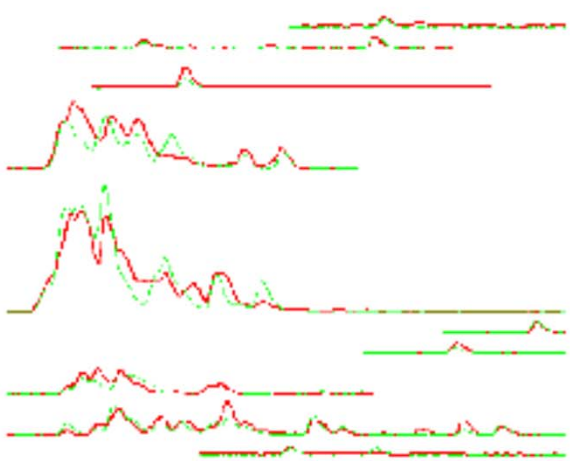




Neutrino search

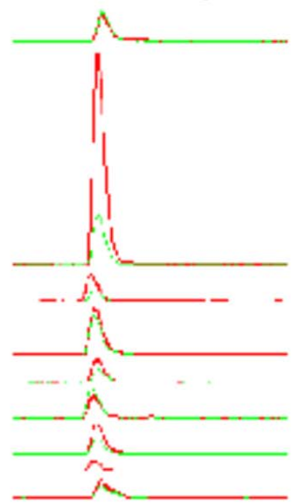
- Neutrino produces very inclined young shower

young shower, $\theta = 19.5°$

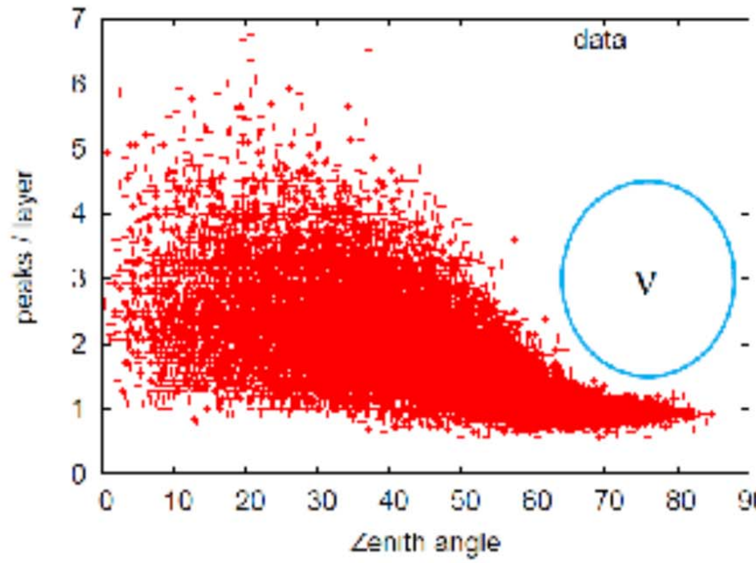


long, indented wafeforms

old shower, 78.3°



one peak

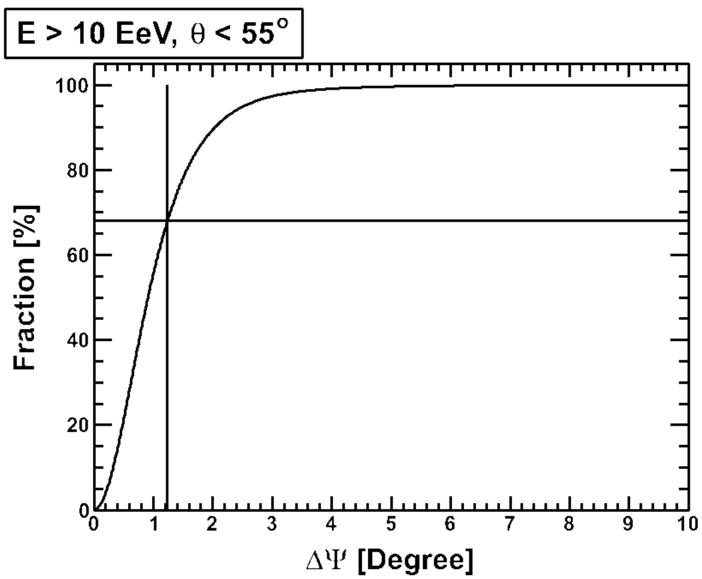


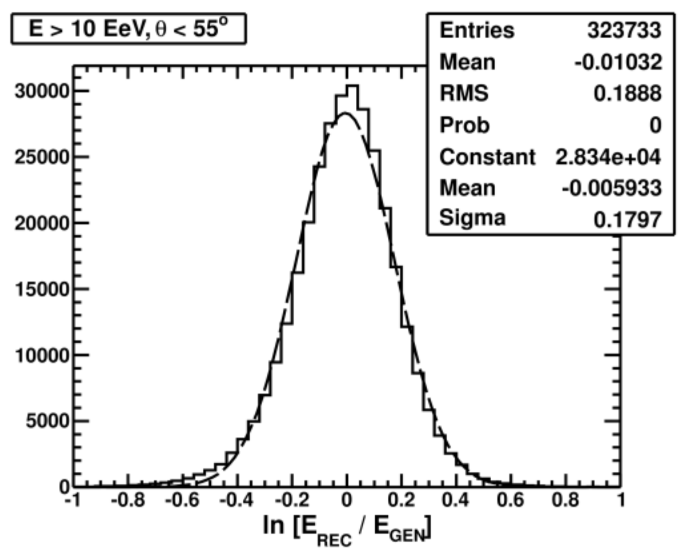
No young inclined showers in the dataset → no neutrino candidates.

TA Anisotropy Results

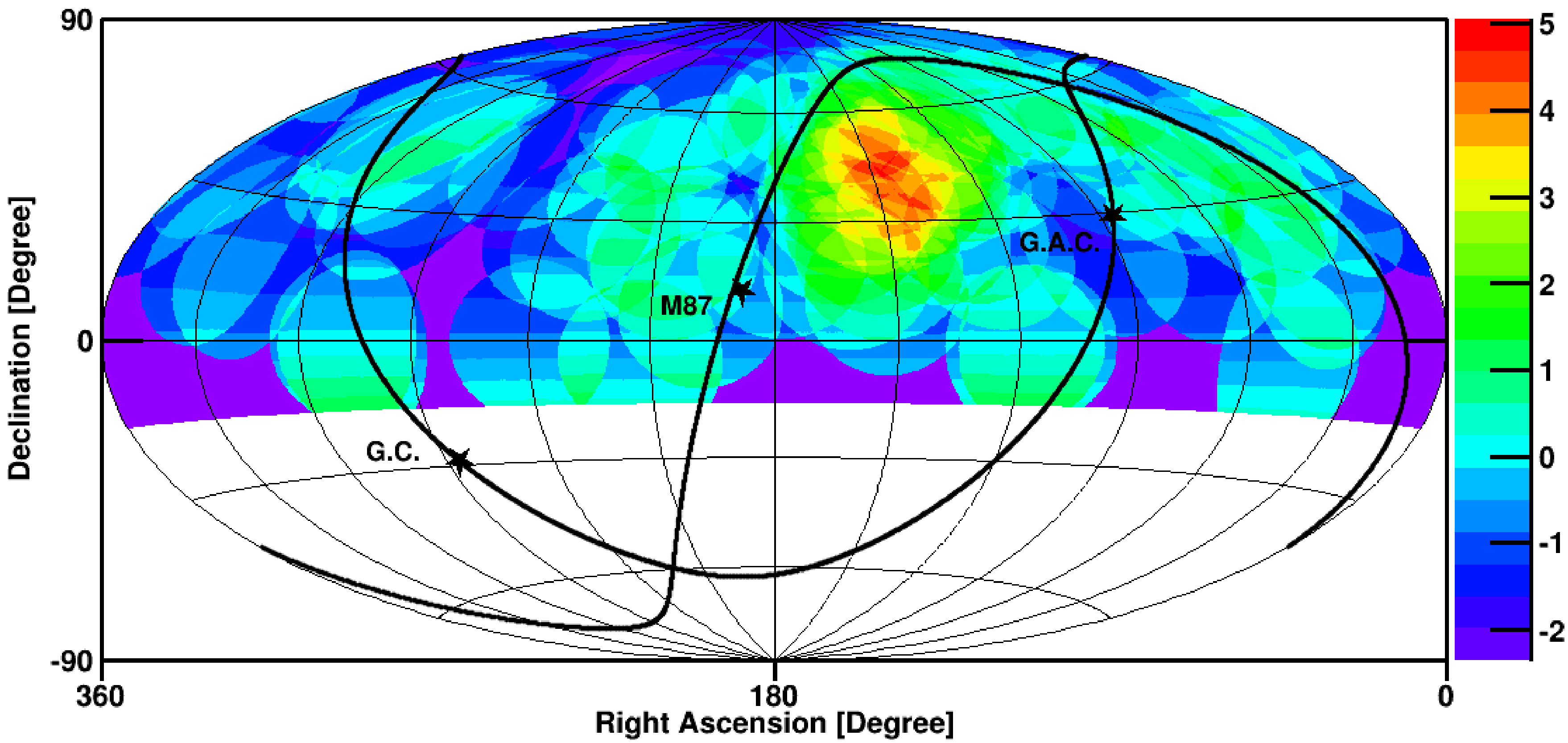
Anisotropy Analysis

- 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)

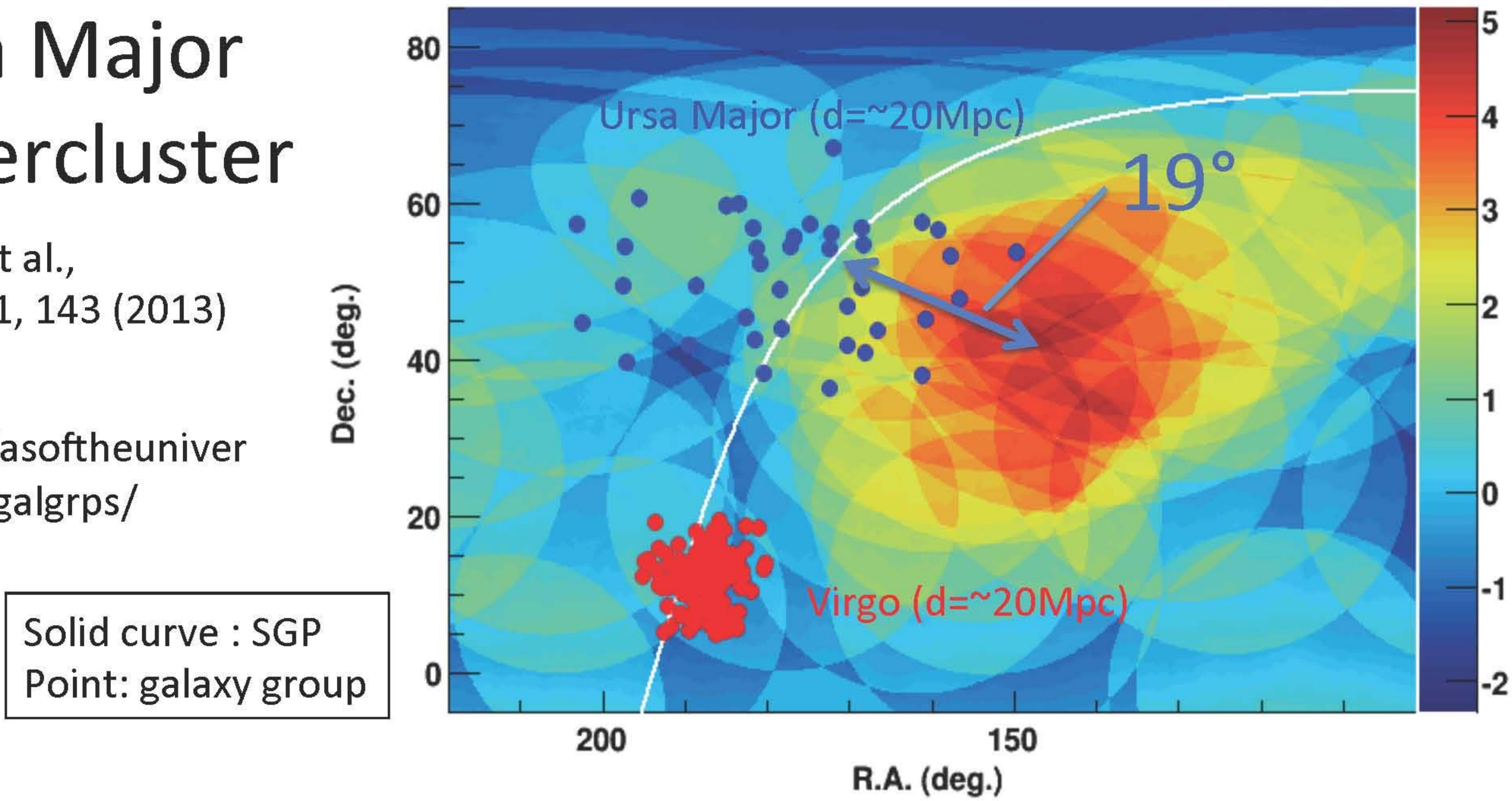


E>5.7x10^{19} eV (72 events)
Aitoff projection in Equatorial Coordinates
Events over-sampled using 20° circles
19/72 events fall in hotspot (RA,dec) ~ (146.7°,43.2°)
4.5 events expected (26% of events in 6% of the area)
LiMa significance: 5.2σ Estimate 3.4σ chance probablity

Ursa Major Supercluster

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

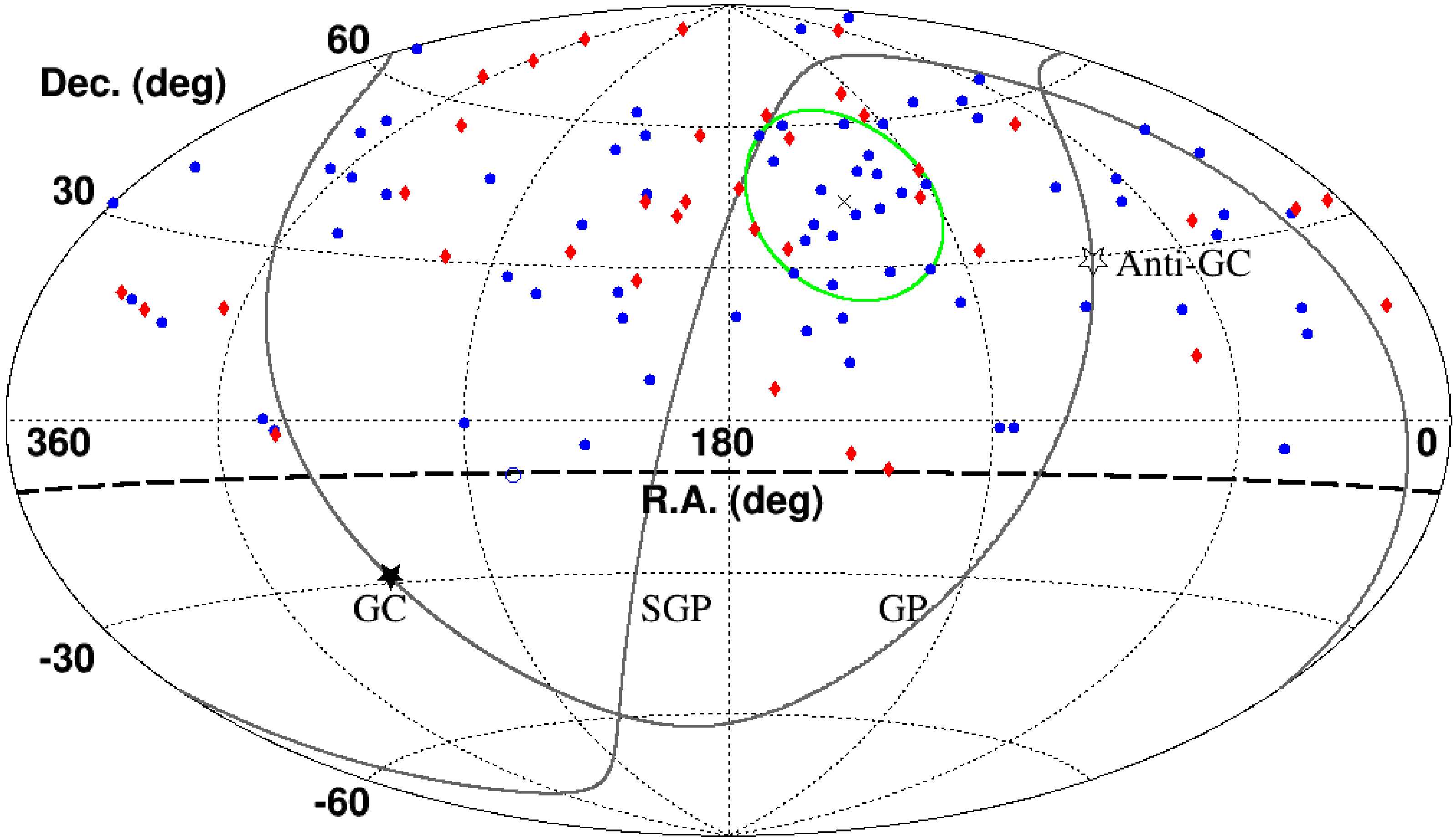
http://www.atlasoftheuniverse.com/galgrps/vir.html



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 ?

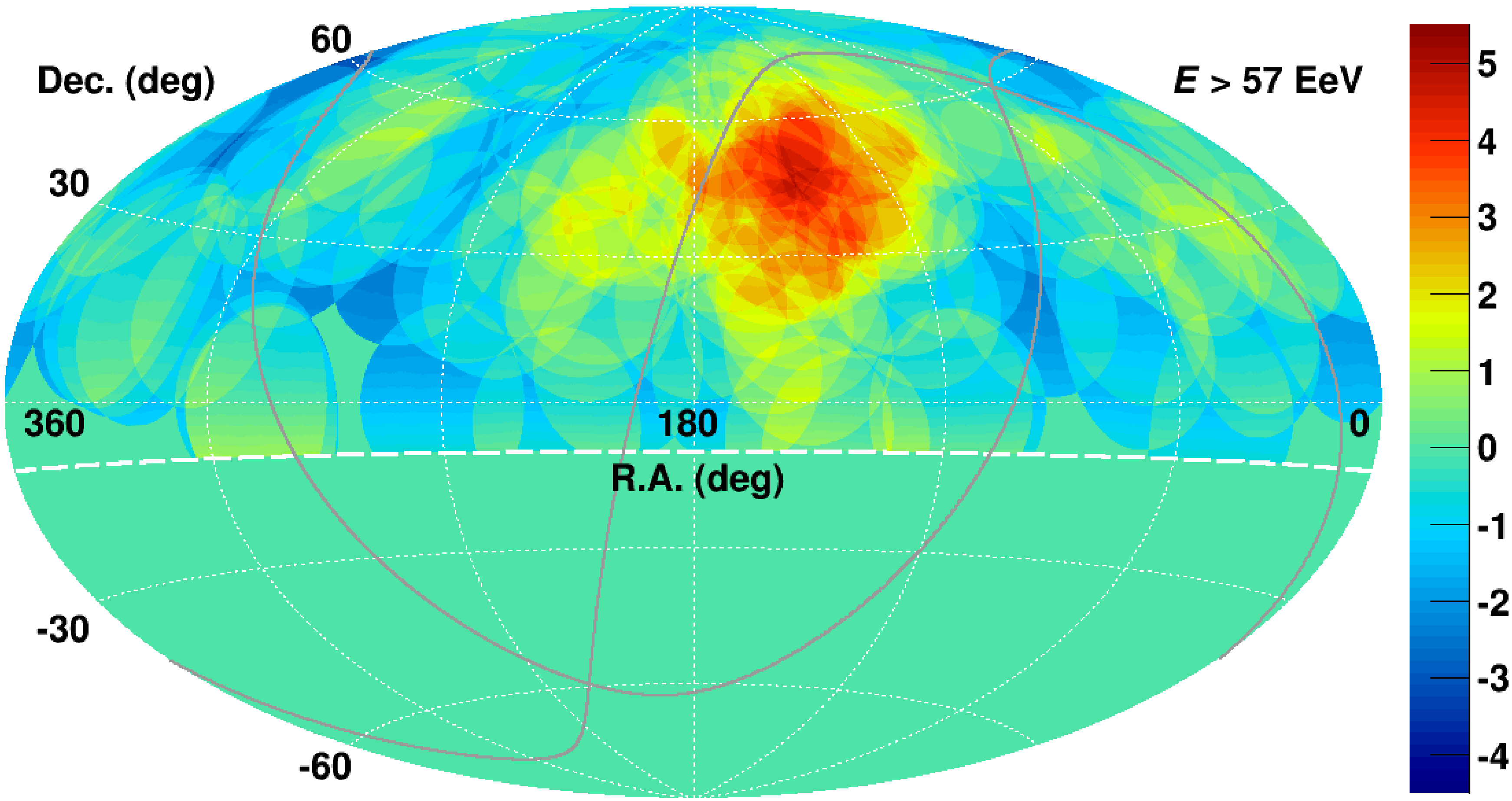
Hot Spot update: 7 years



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

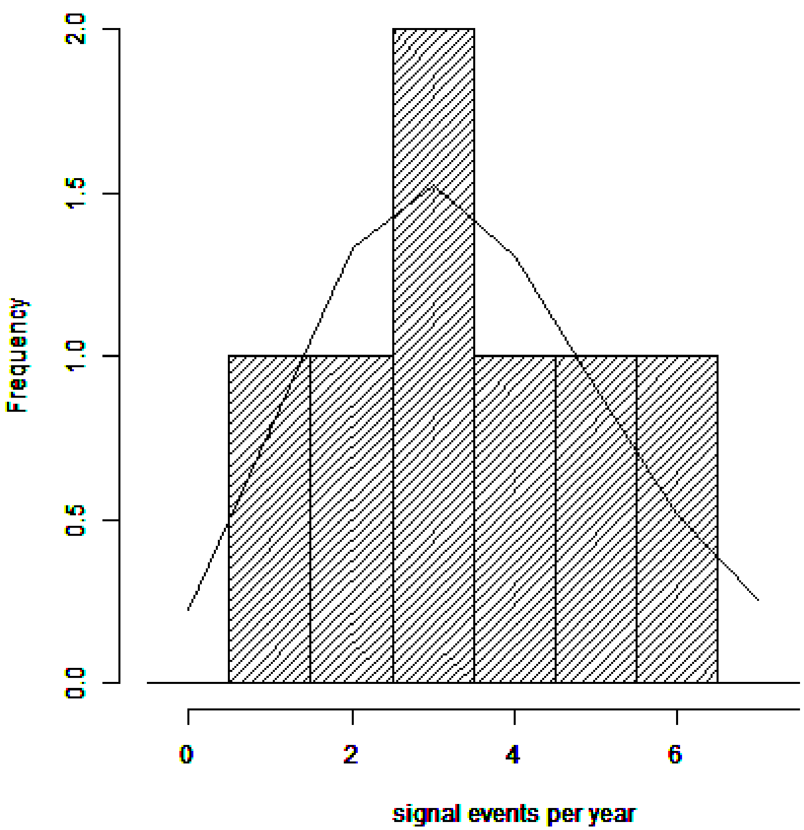


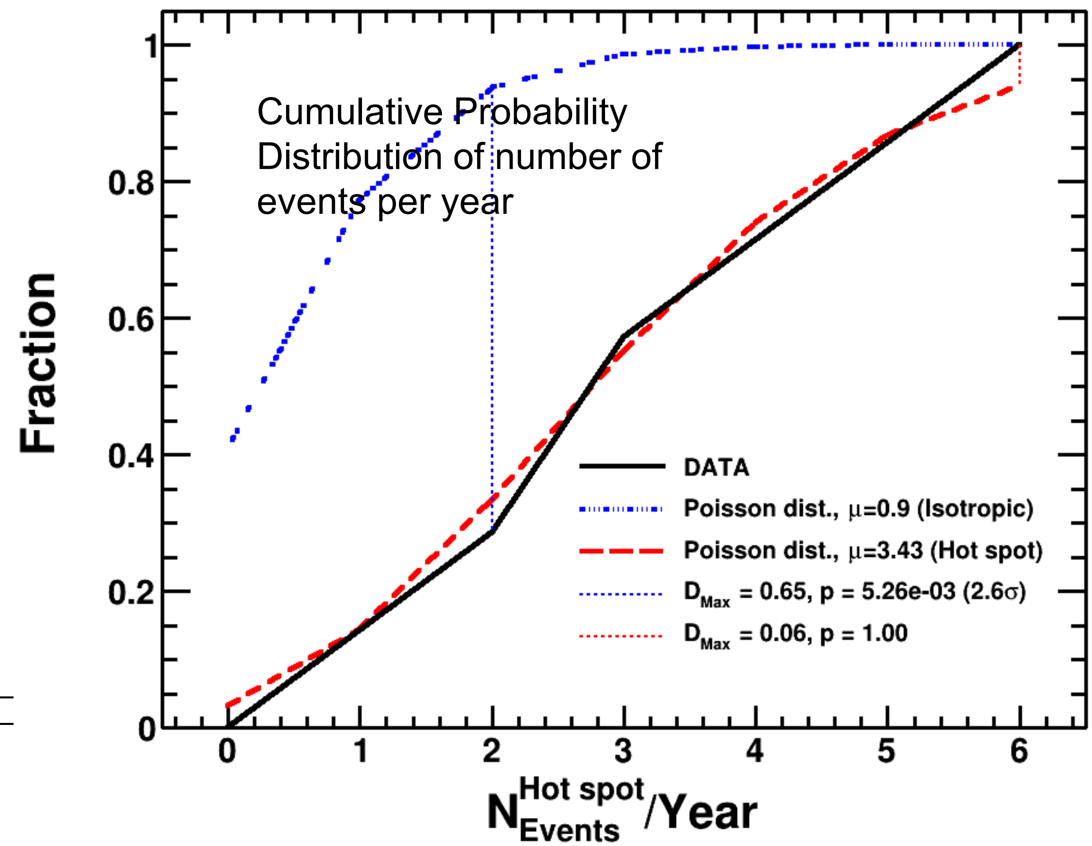
Max significance **5.1**σ (N_{SIG} = 24, N_{BG}=6.88) for 7 years
Centered at R.A=148.4°, Dec.=44.5° (shifted from SGP by 17°)
Global Excess Chance Probability: 3.7×10^{-4} : 3.4σ (~ same as first 5 years)

Consistent with Fluctuation

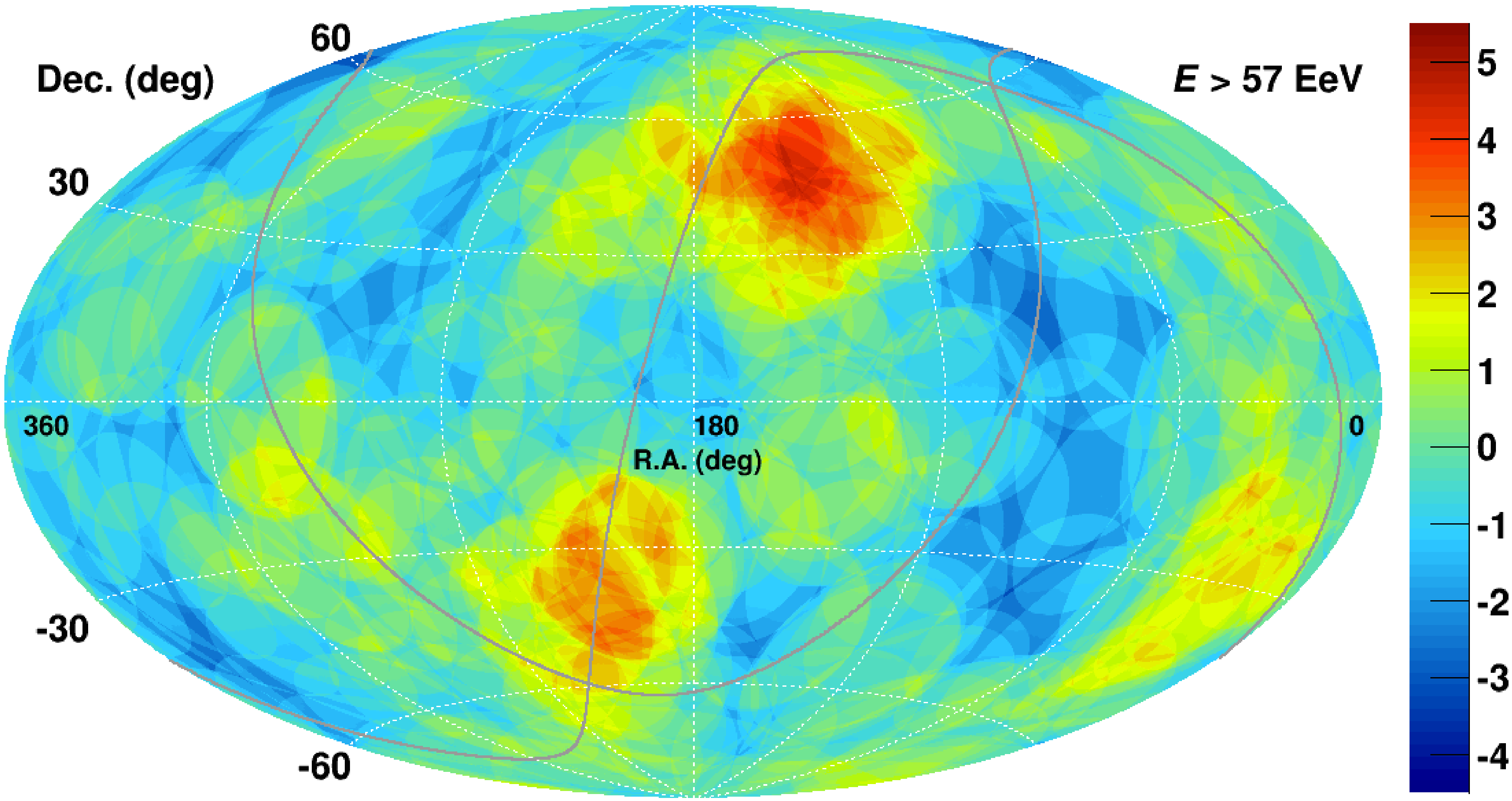
K.S. Test shows data is consistent with fluctuation for hotspot (Poisson: average = 3.43 per year, no time variation),

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





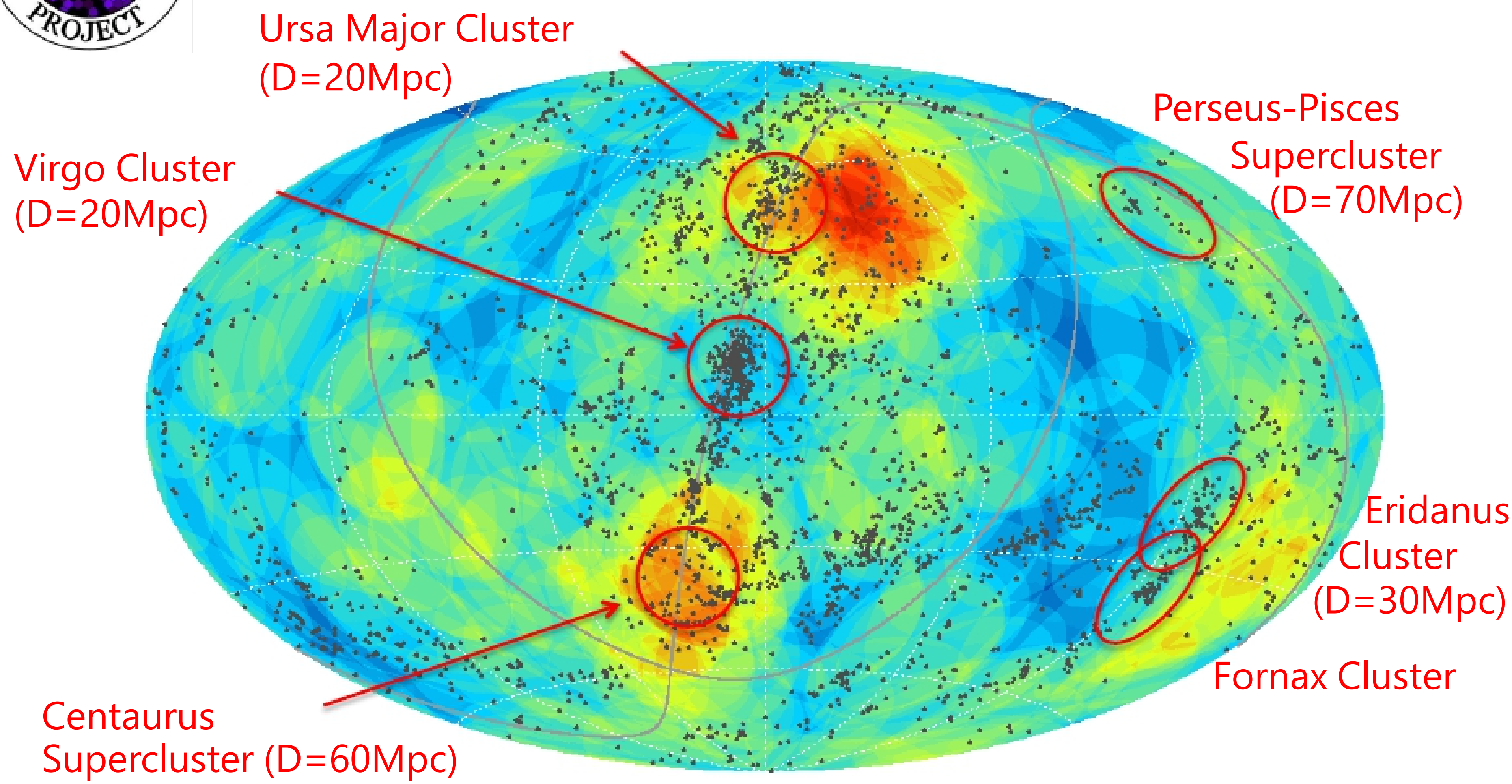
TA + PAO All Sky



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



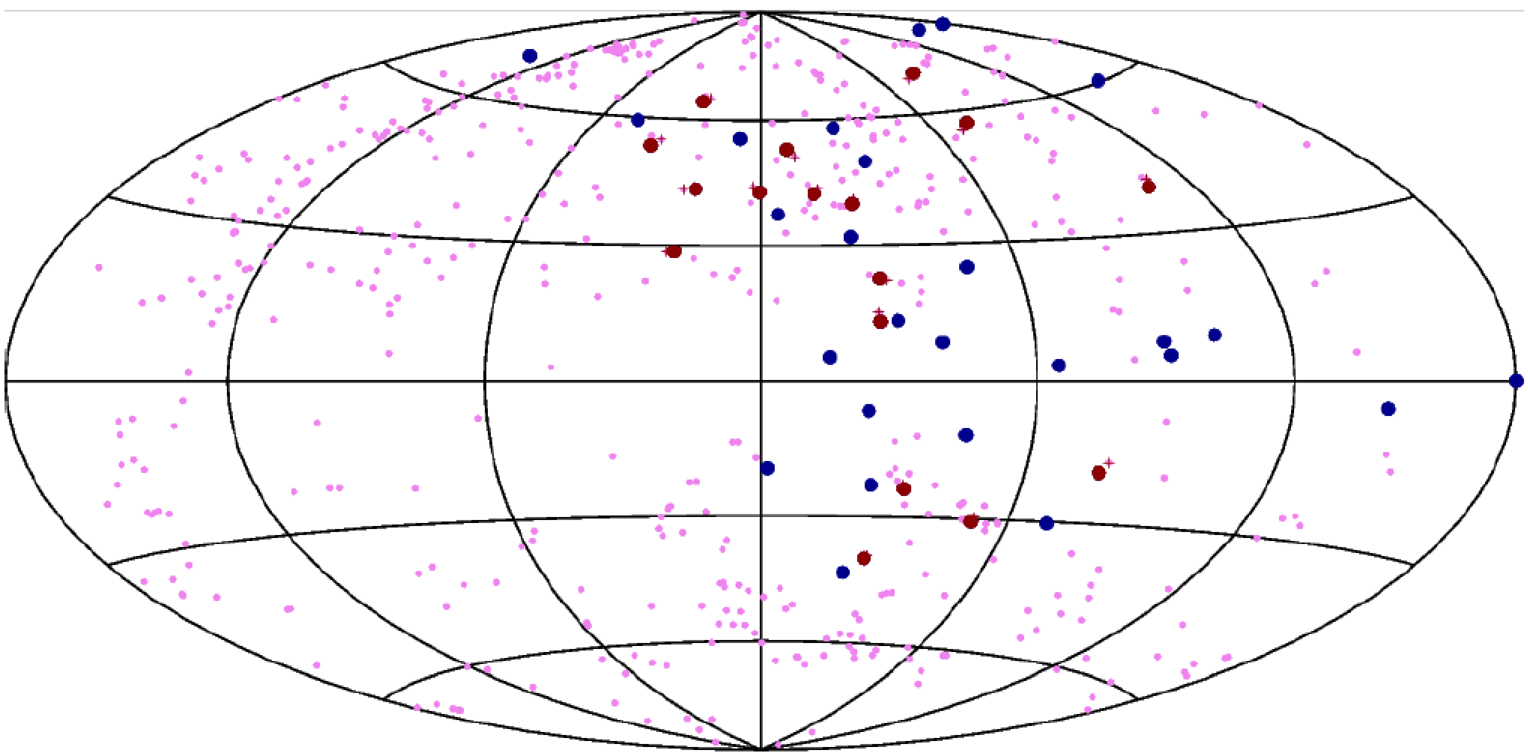
Huchra, et al, ApJ, (2012)

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.

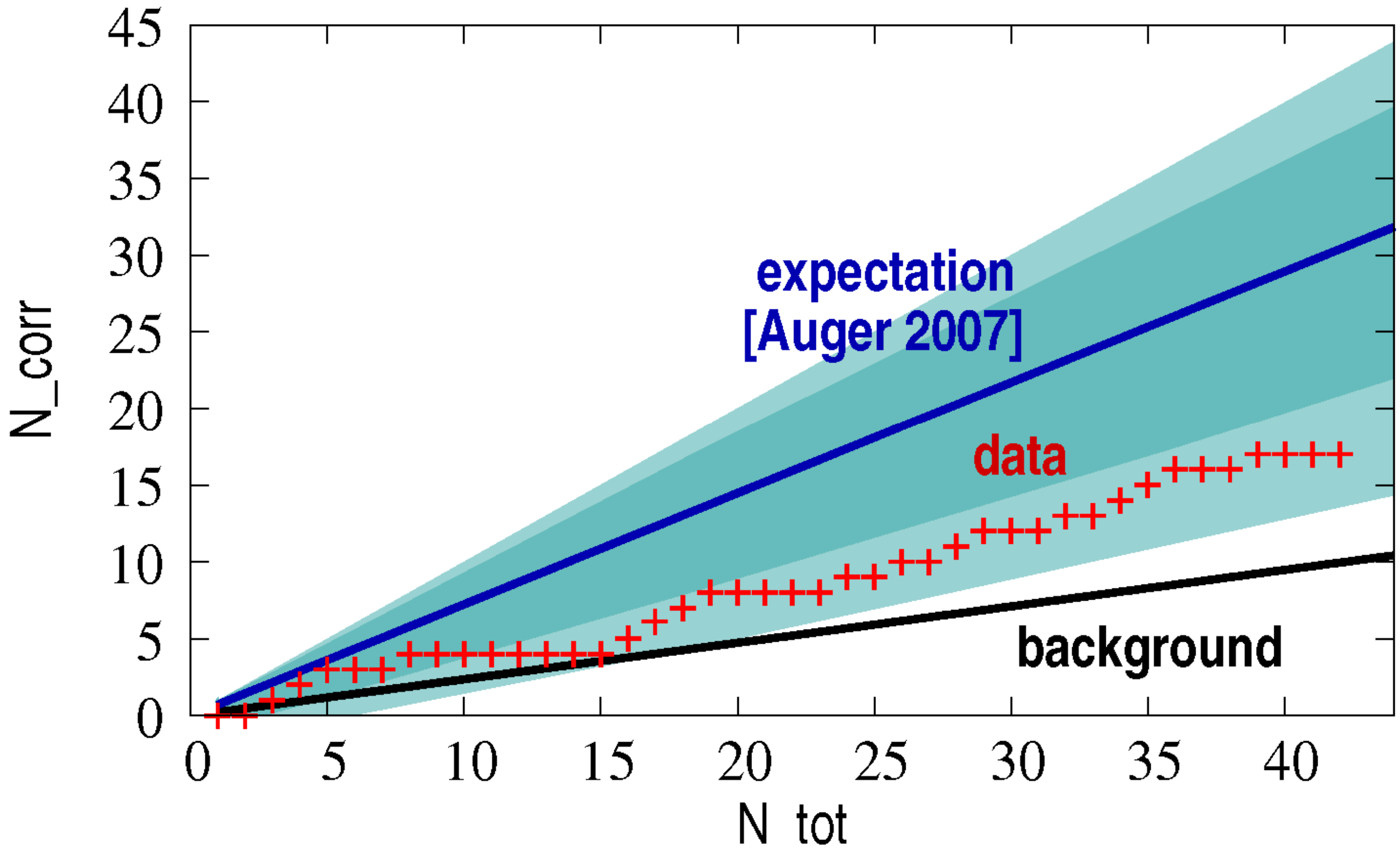
Test Correlations with AGNs

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

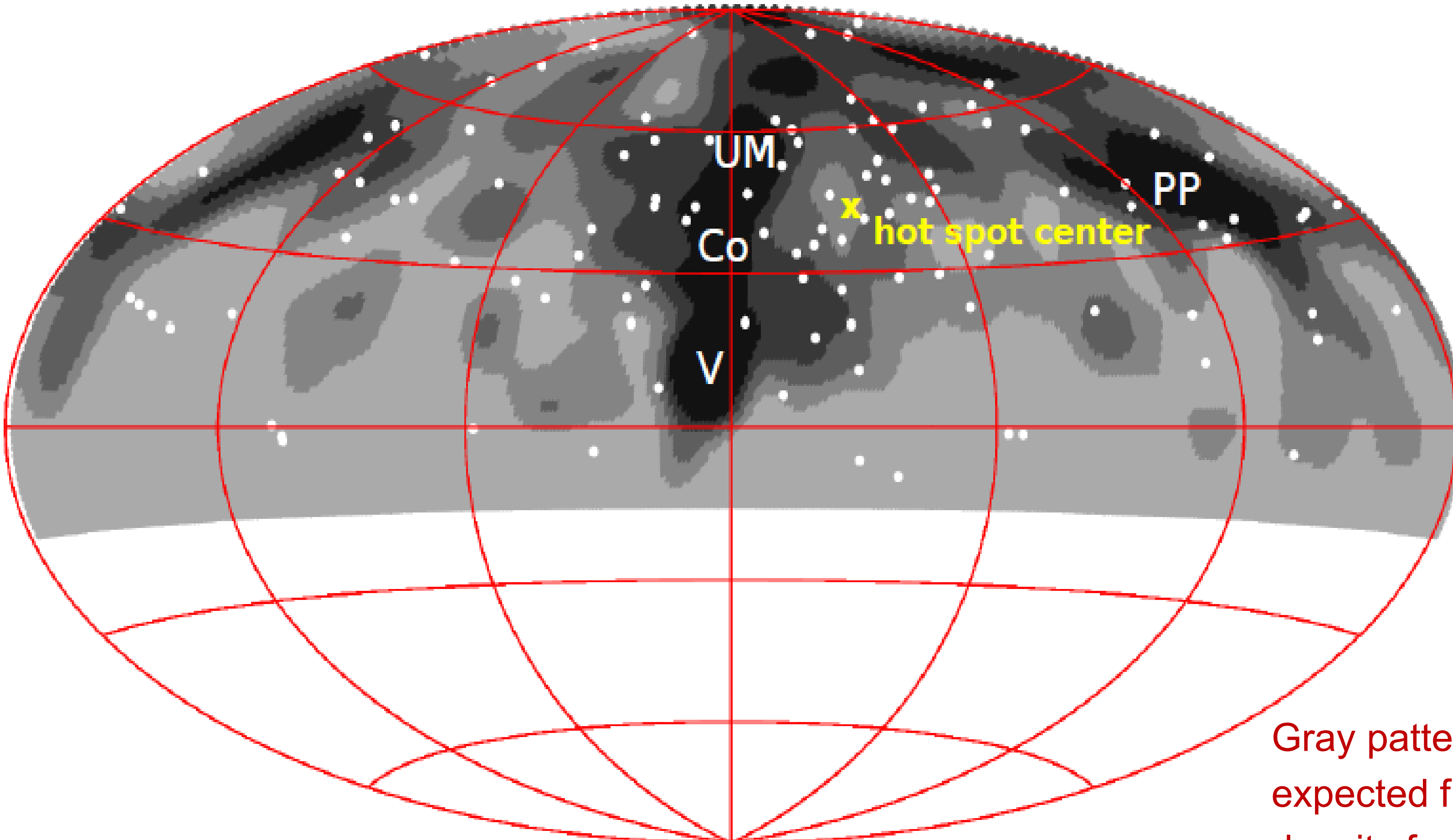


Correlations with AGNs

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



Correlation with Large-Scale Structure (LSS)

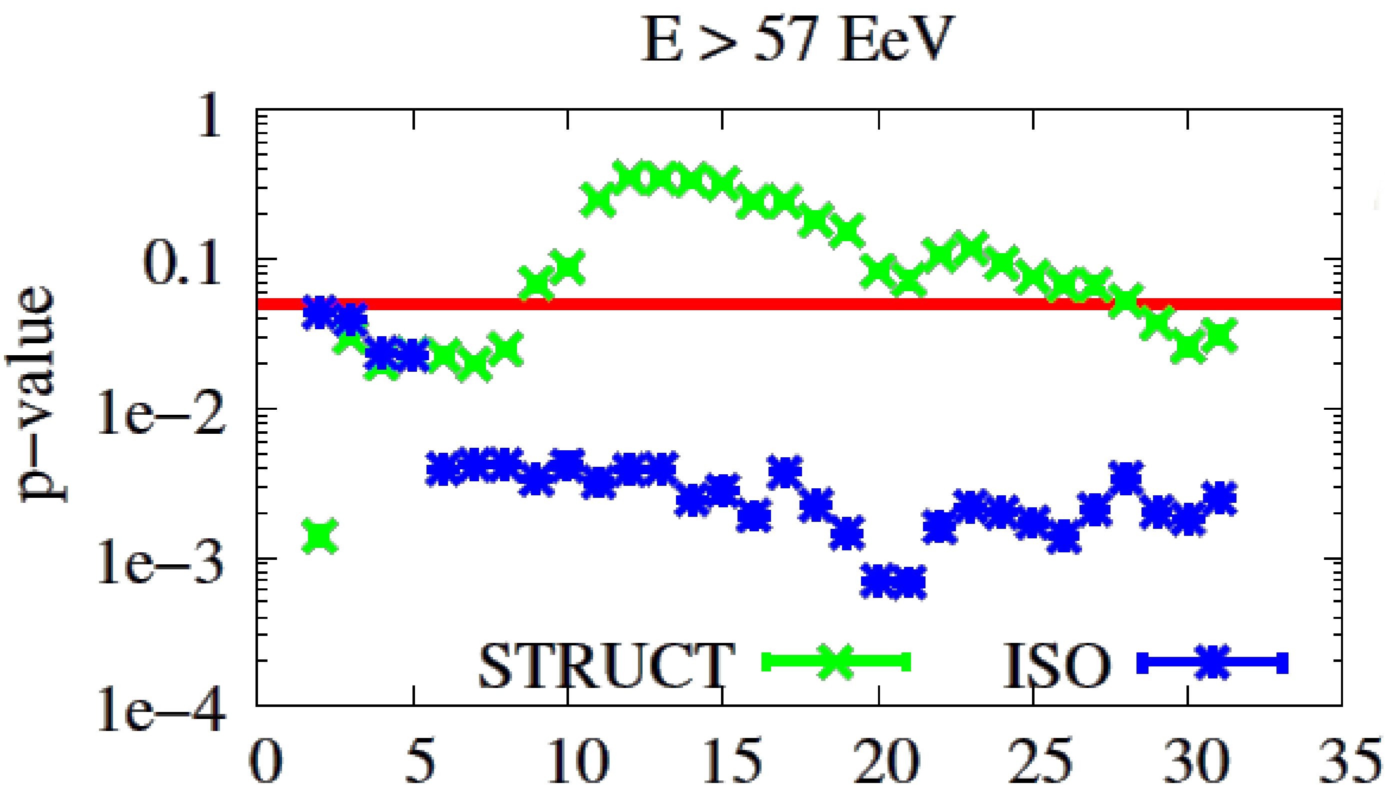


Equatorial coordinates. Darker color represents larger flux.
UM — Ursa Major; Co — Coma; V — Virgo; PP — Perseus-Pisces

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

LSS Correlation (continued)

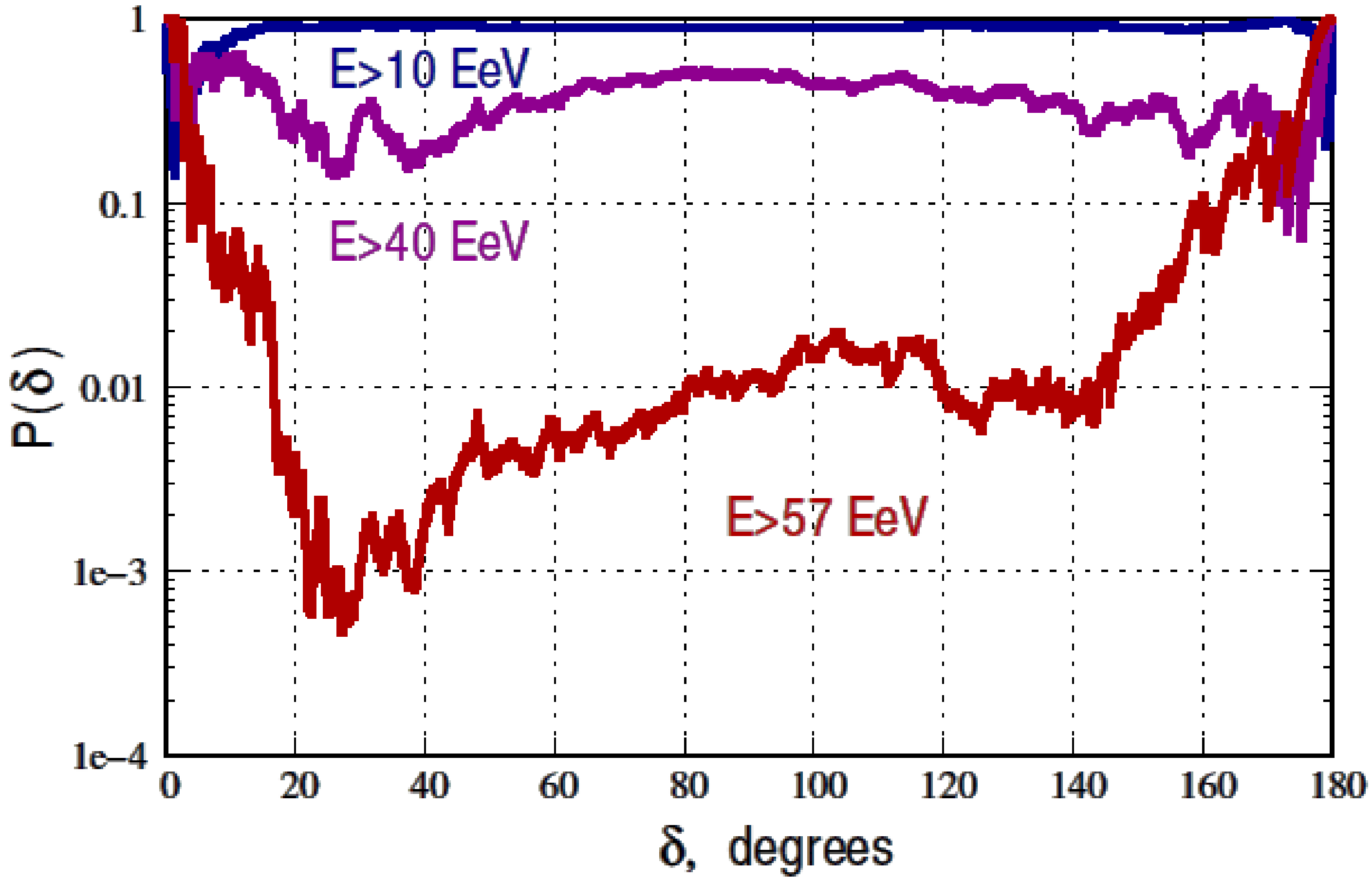
1D Kolmogorov-Smirnov p values comparing expected flux distribution (gray map from previous page) vs. simulation:
Marginally Incompatible with isotropic source simulation
Compatible with LSS source simulation



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 4/2015

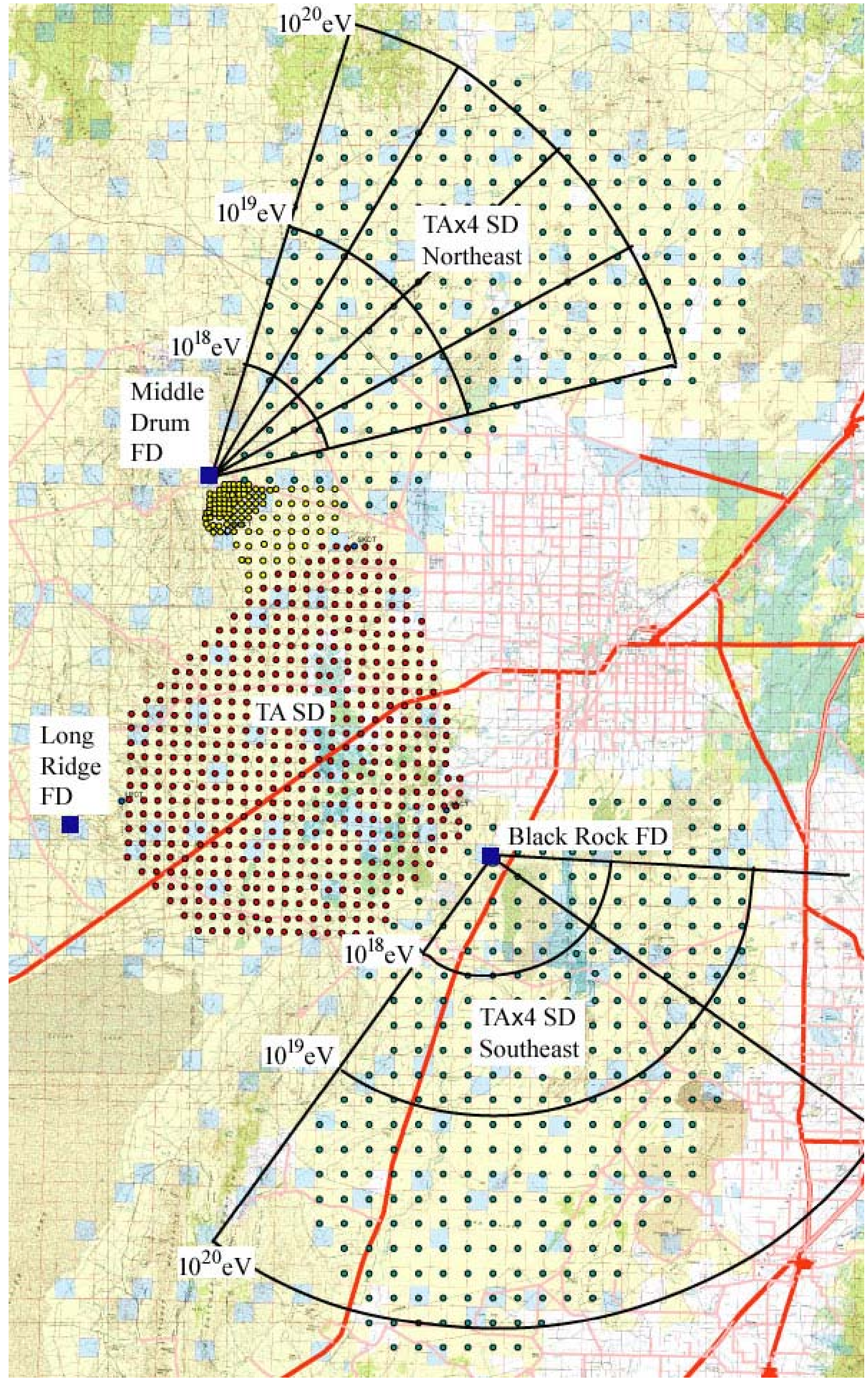
3 yrs construction, first 100 SDs arrive in Utah Spring ‘16

2 FD stations (12 HiRes Telescopes) proposed to US NSF

Submitted in US in 10/2015

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

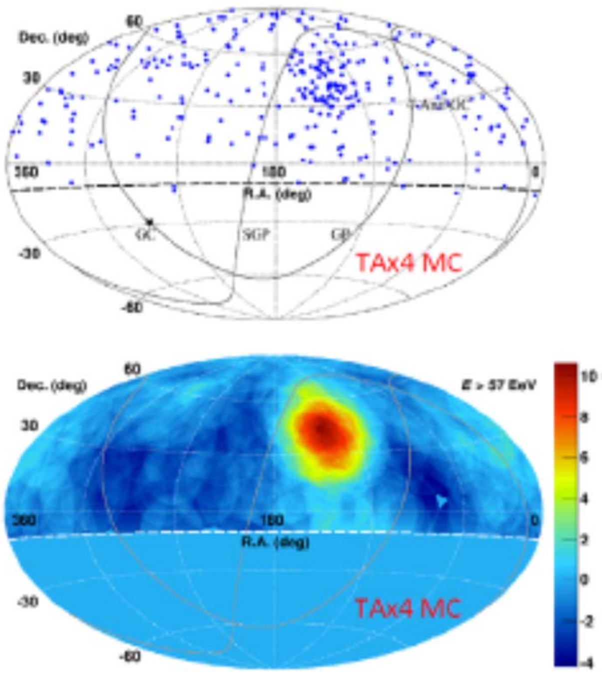
Simulated 19 TA-equiv yrs data

(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

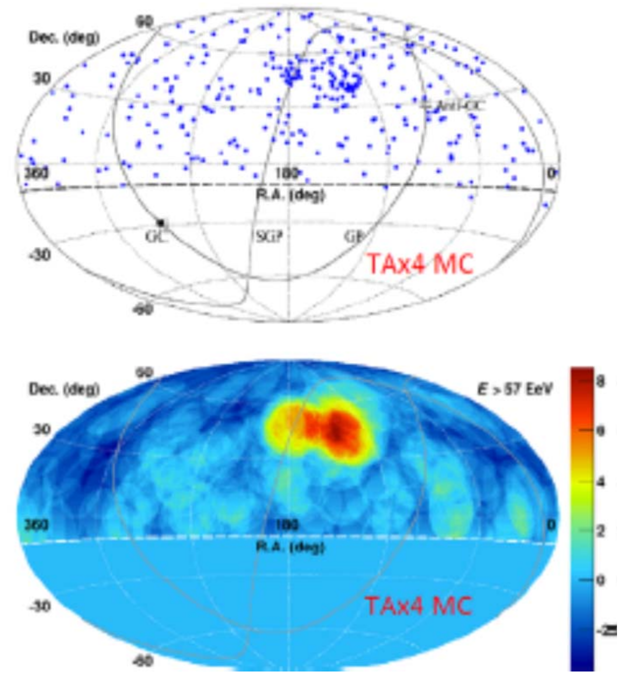


(2) Double Hotspot

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



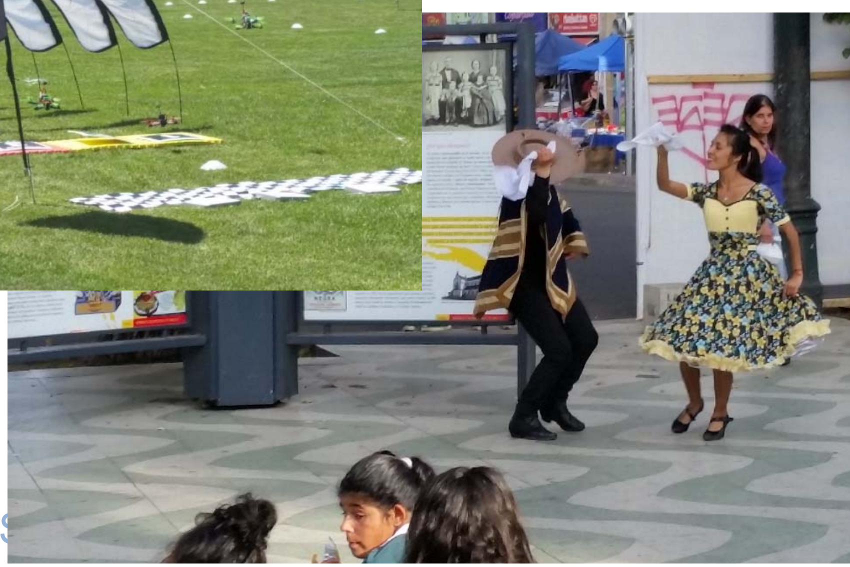
Single Source | **Two Separated Sources**

Summary

- TA has measured the energy spectrum, composition and arrival direction of UHE cosmic rays
- *New:* TA Low Energy Extension (TALE) is coming on line. TALE surface detector array has recently been funded by Gov't of Japan.
- TA and TALE have measured energy spectrum between 6×10^{15} eV to over 10^{20} eV with a single cross-calibrated set of detectors and have observed spectral features
- The spectrum and composition of UHE cosmic rays measured by TA remain compatible with a single light component at above the ankle ($\sim6\times10^{18}$ eV).
- We have reported a hot spot seen in the direction of Ursa Major with 3.4σ significance
- **Much more data are needed! – and coming….TAx4**

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 > 5σ
- PAO – Cerenkov water + fluorescence > 20σ
- TA – Plastic Scintillator + fluorescence > 6σ
- 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?


(C) Oscar Larsson

EUSO-TA

2013: Installation, building, lenses
2014: for Auger/Fast tests
2015:

February/March

- Detector installation
- Focusing, initial calibration
- Initial CLF and CSOM laser observations

May

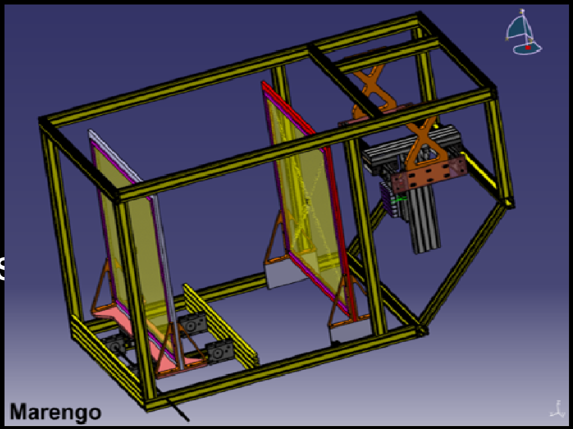
- Cosmic ray observations – one UHECR detected
- CLF and CSOM laser observations
- Flat screen and LED calibration

September

- Cosmic ray observations – analysis ongoing
- CLF and CSOM laser observations

October

- Cosmic ray observations – analysis ongoing
- Internal trigger tests on the balloon PDM board – success triggering on laser
- CLF and CSOM laser observations



November

- Cosmic ray observations
- CLF laser observations