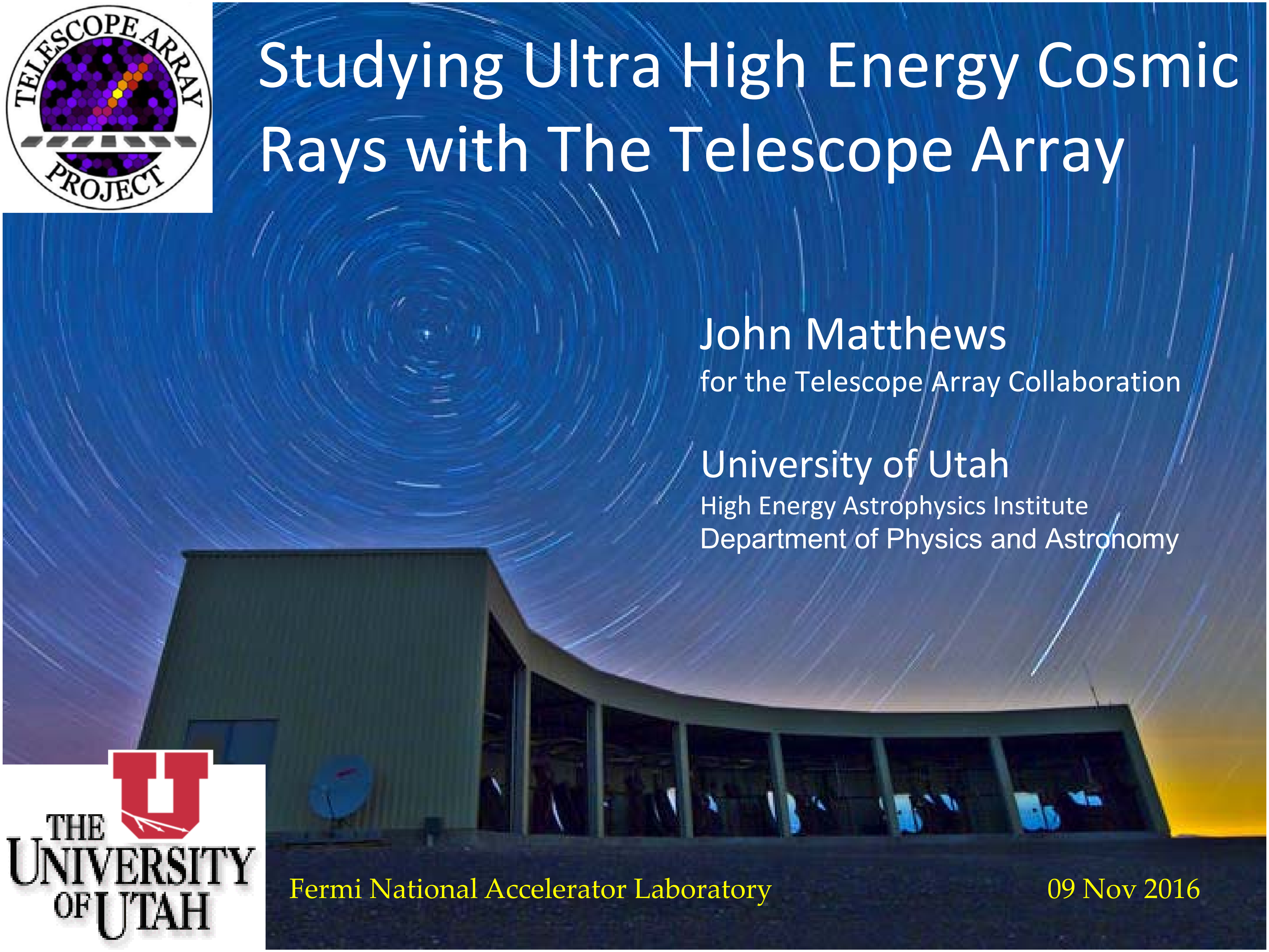

Studying Ultra High Energy Cosmic Rays with The Telescope Array

John Matthews
for the Telescope Array Collaboration

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

Fermi National Accelerator Laboratory

09 Nov 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 …. 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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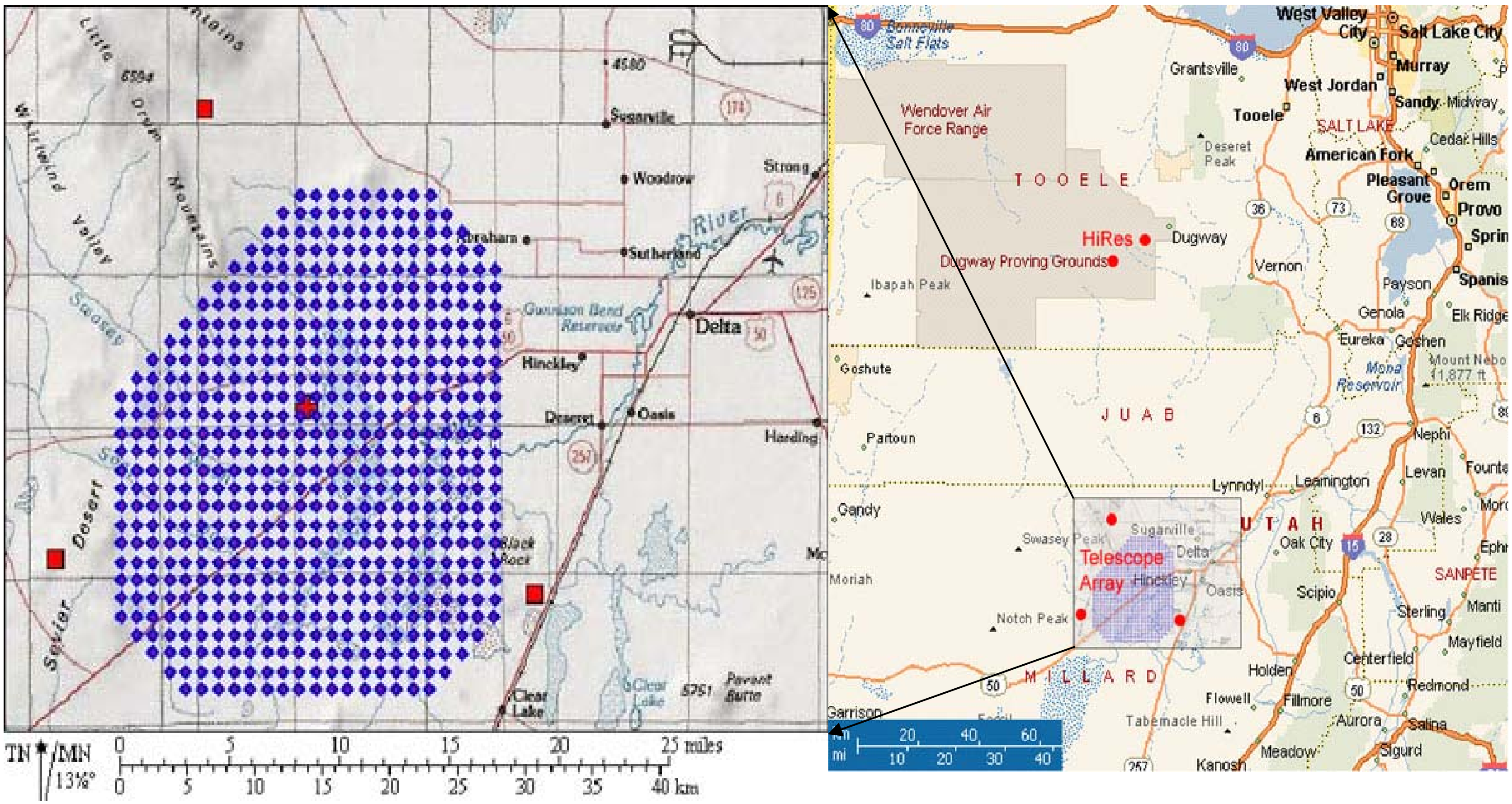
USA, Japan, Korea, Russia, Belgium

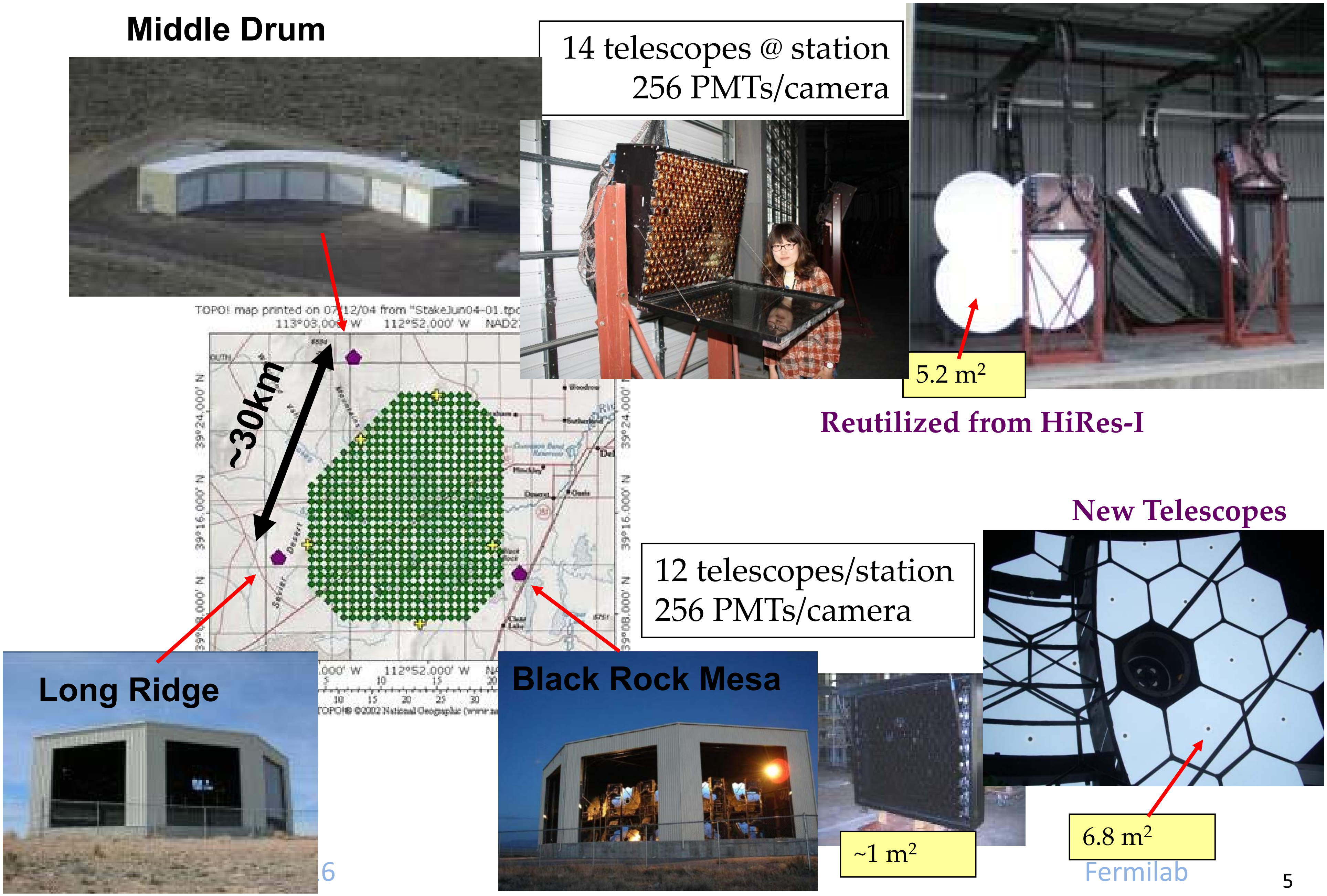
Telescope Array



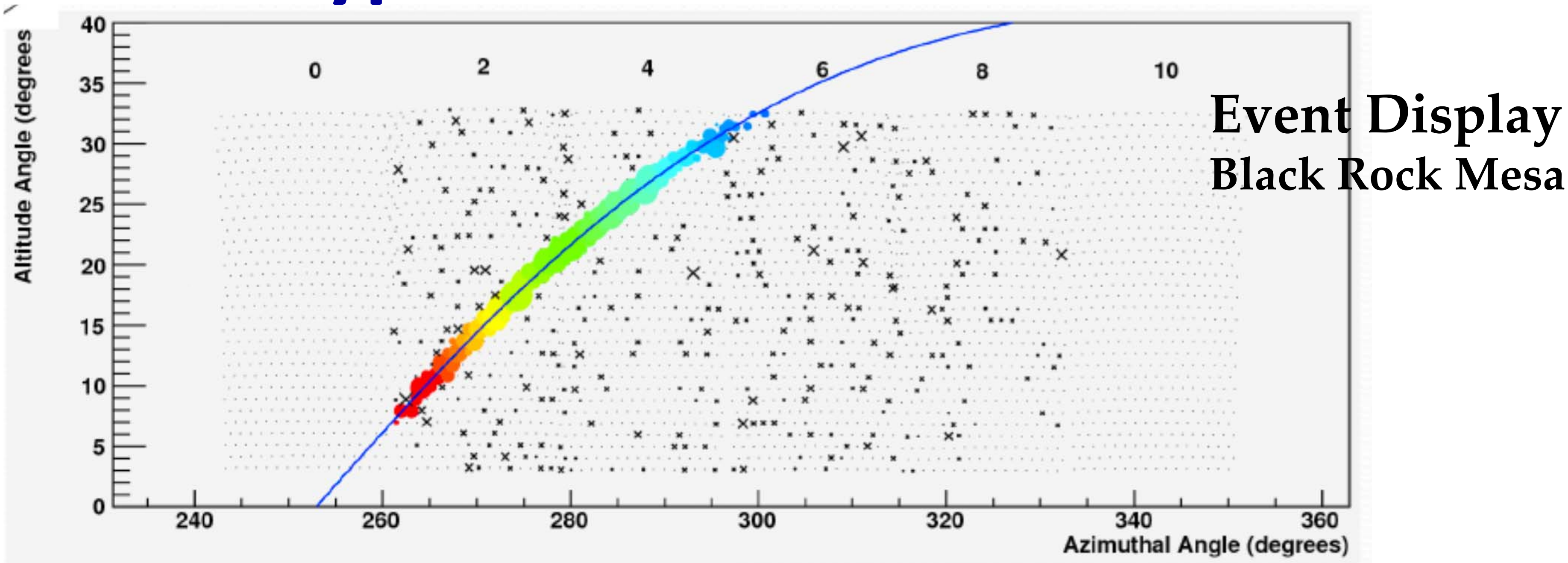
700 km^2:   Lat. 39.30°N, Long. 112.91°W   1550m ASL

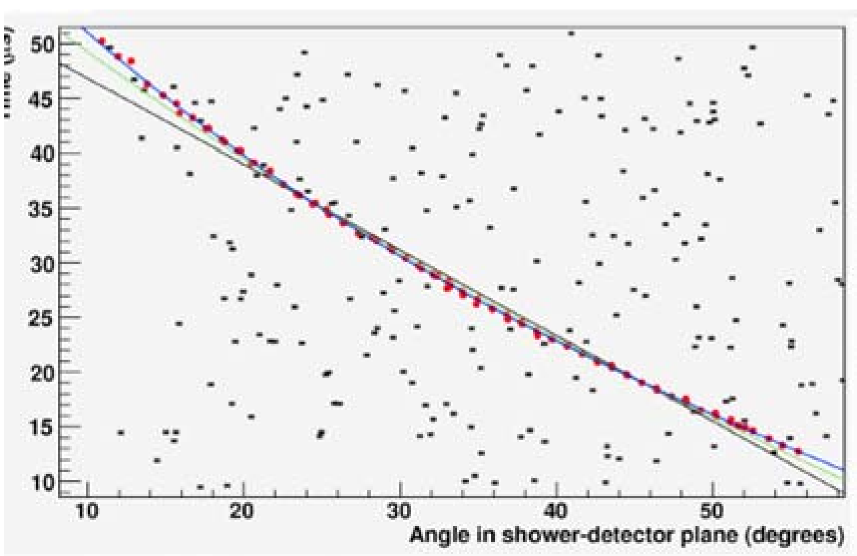
The High Energy component of Telescope Array – 38 fluorescence telescopes (9728 PMTs) at 3 telescope stations overlooking an array of 507 scintillator surface detectors (SD) - complete and operational as of ~1/2008.

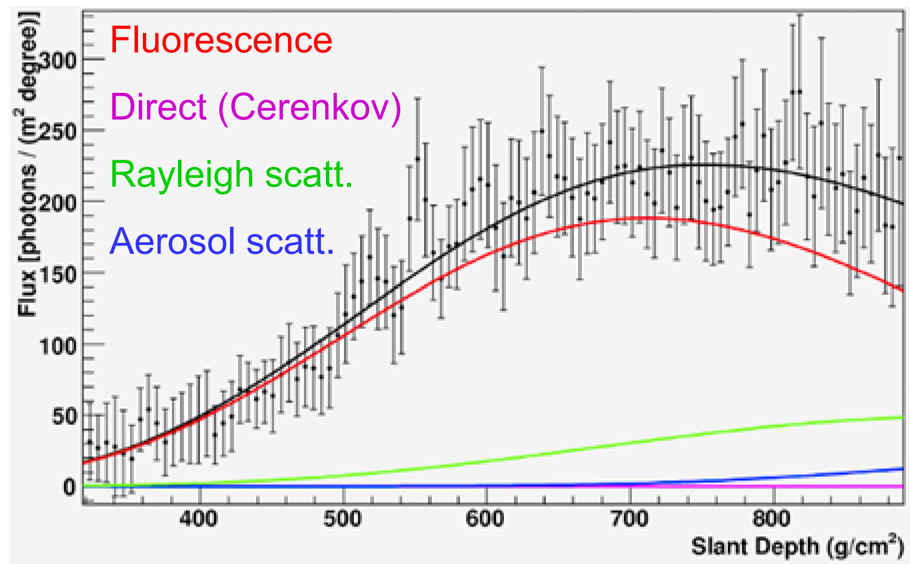
TA Fluorescence Detectors



Typical Fluorescence Event



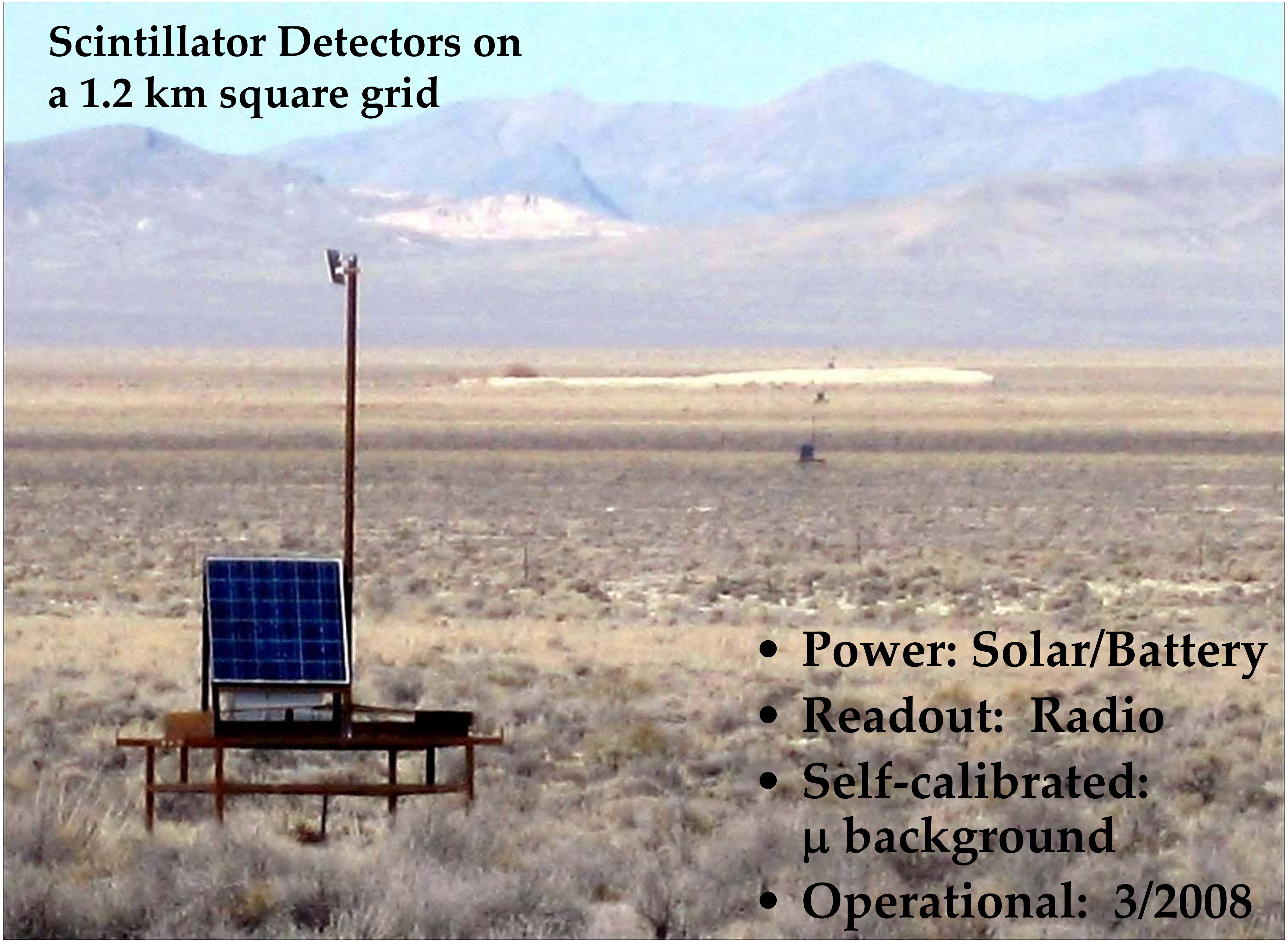




Monocular timing fit (time vs angle) **Reconstructed Shower Profile**

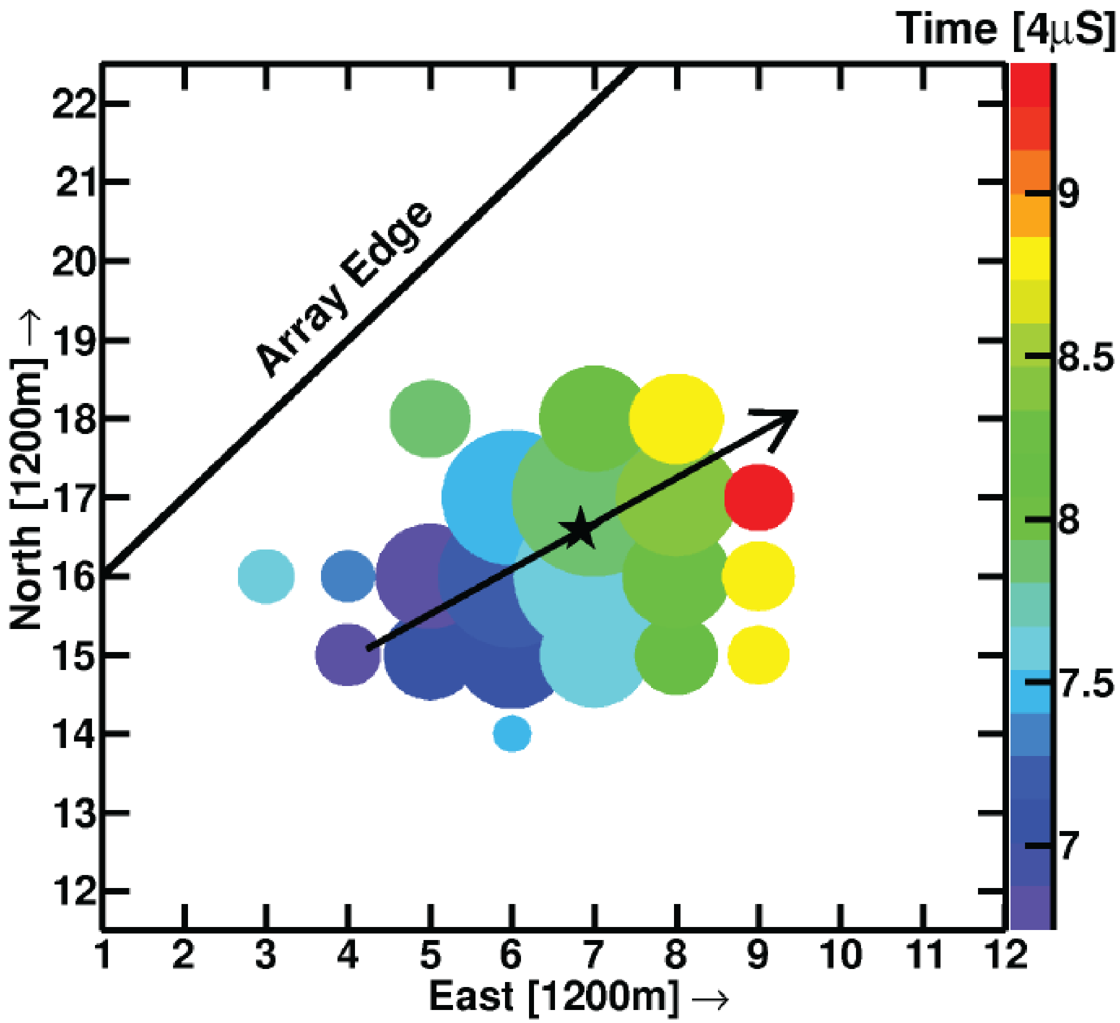
Scintillator Surface Detectors

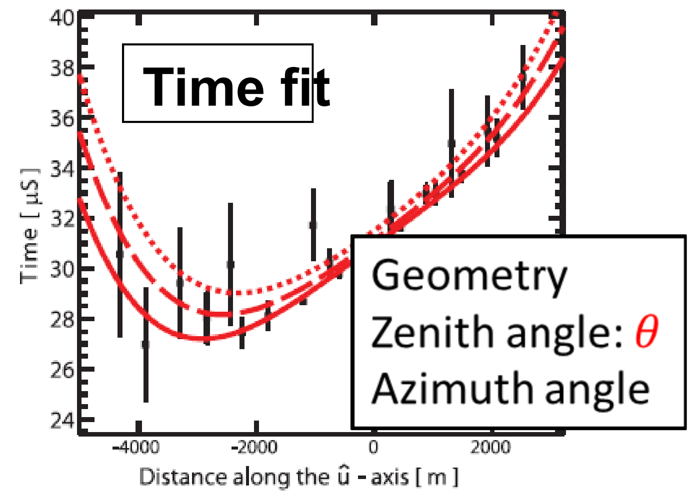
2 layers scintillator
1.25 cm thick, $3m^2$ area
Optical fibers to PMTs

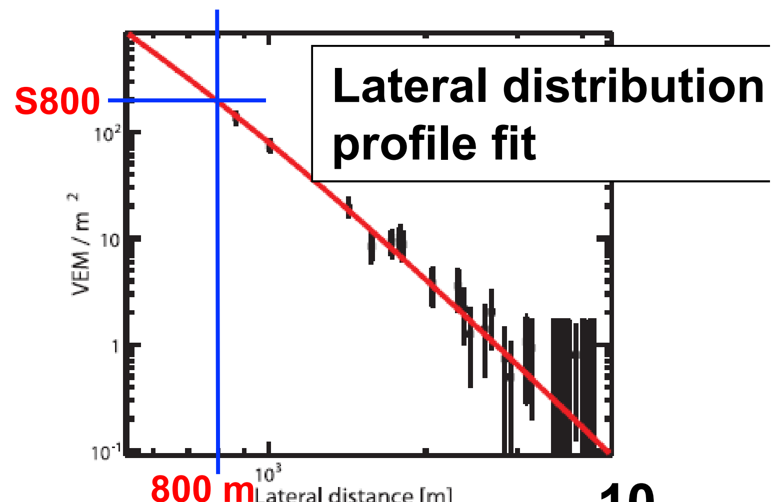

Scintillator Detectors on
a 1.2 km square grid
• Power: Solar/Battery
• Readout: Radio
• Self-calibrated:
μ background
• Operational: 3/2008

TA shower analysis with SD

An SD hit map of a typical high energy event

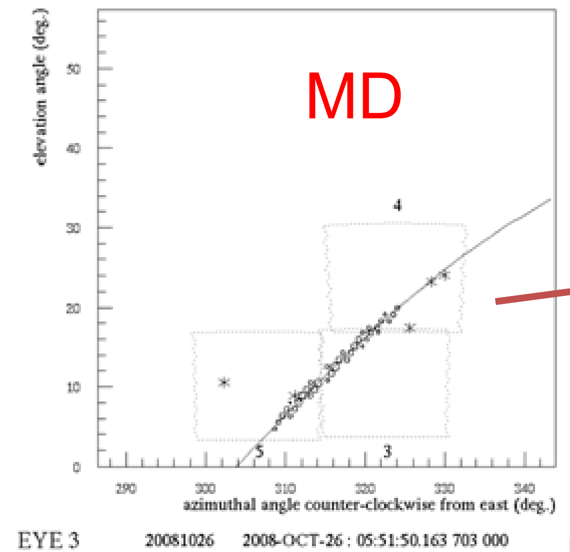






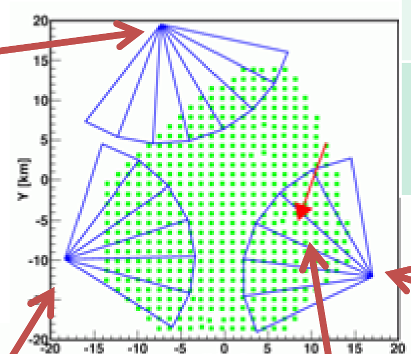
10

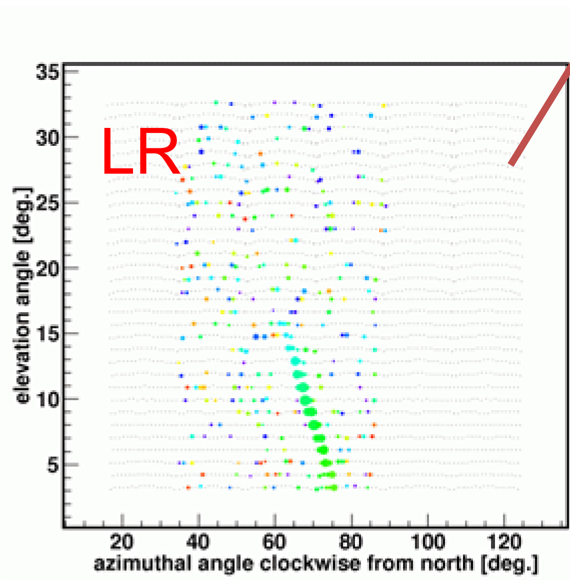
Example Event

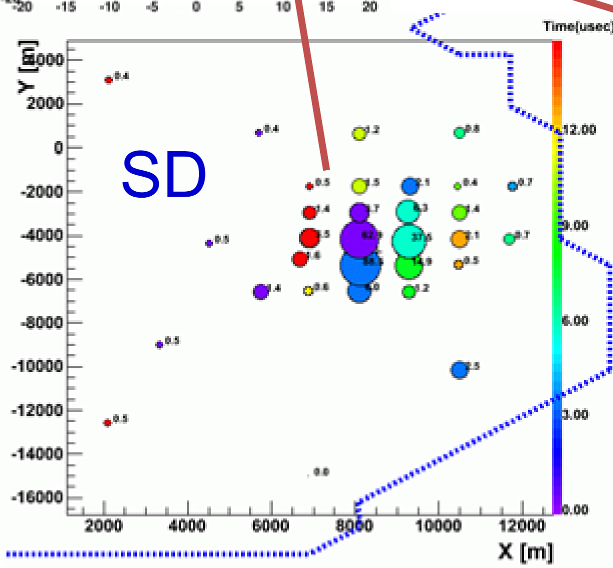


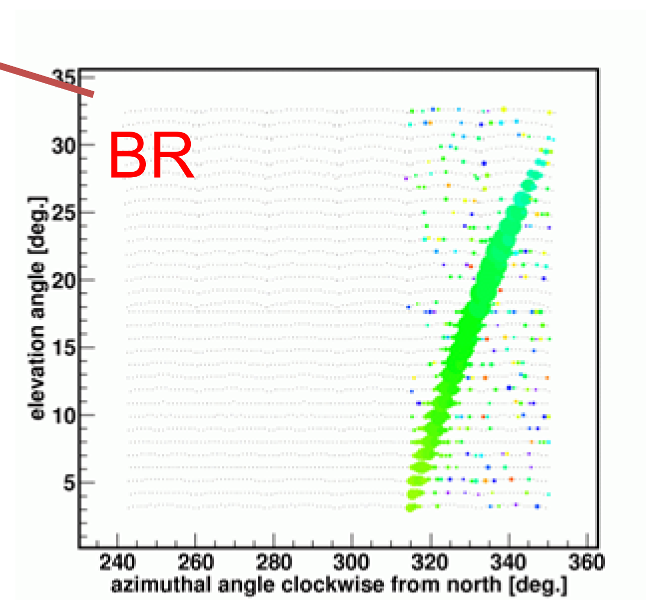
	θ [°]	ϕ [°]	x[km]	y[km]
MD mono	51.43	73.76	7.83	-3.10
BR mono	51.50	77.09	7.67	-4.14
Stereo BR&LR	50.21	71.30	8.55	-4.88

Event from 2008-10-26



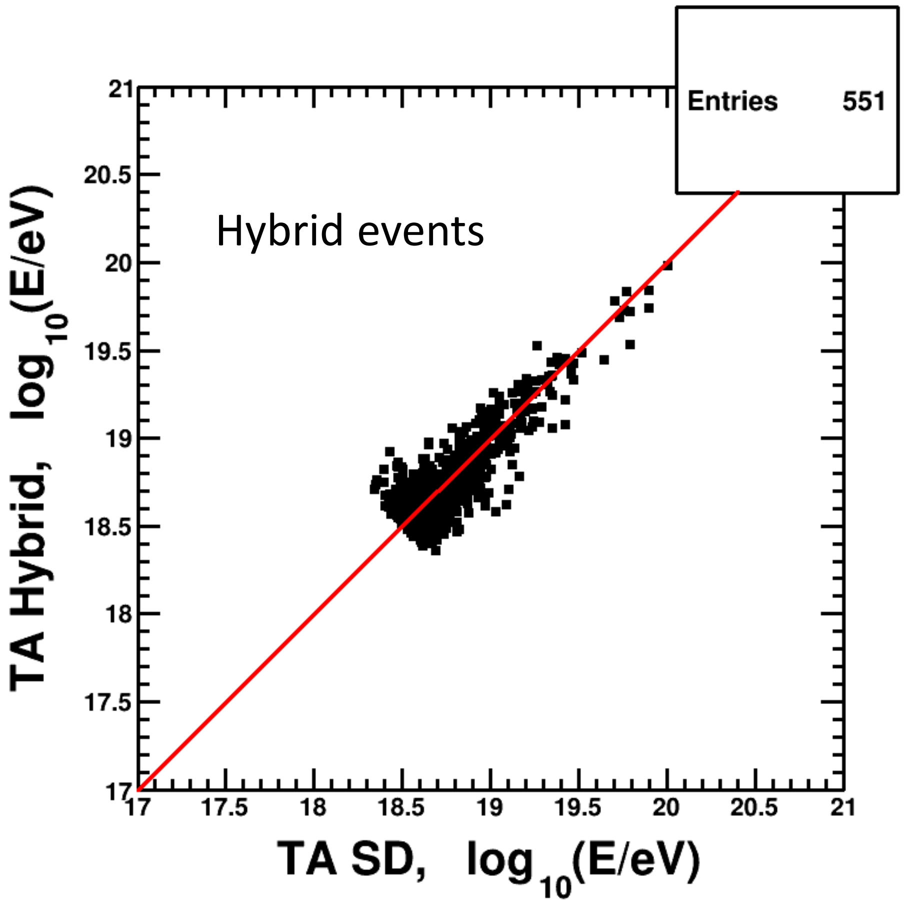


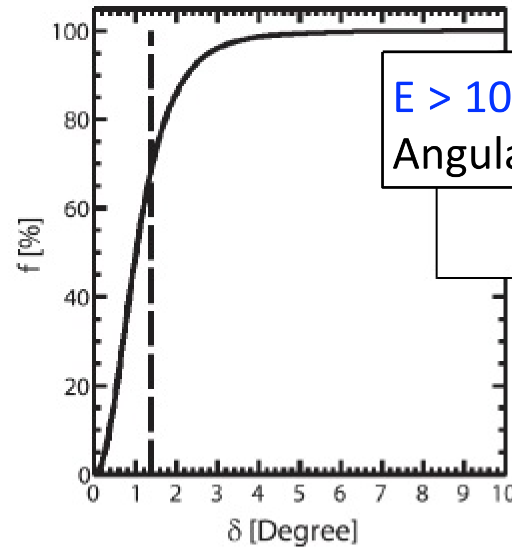




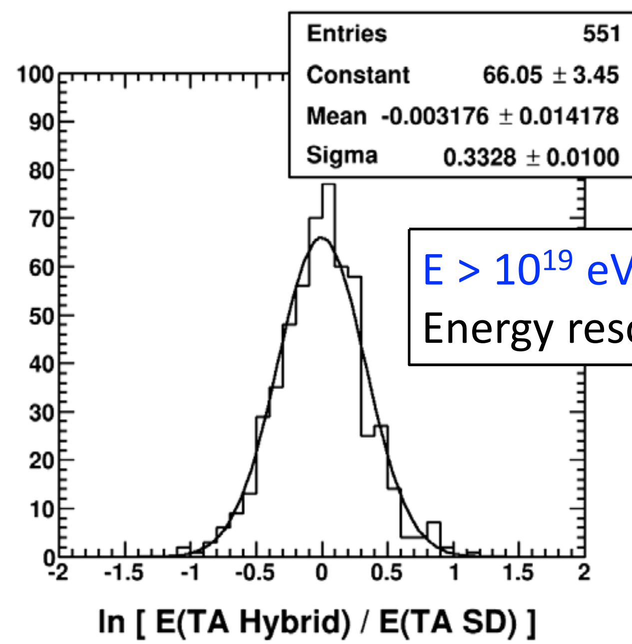
TA Energy Spectrum Results

Energy Scale Check and Resolution





E > 10^{19} eV
Angular resolution = 1.4°

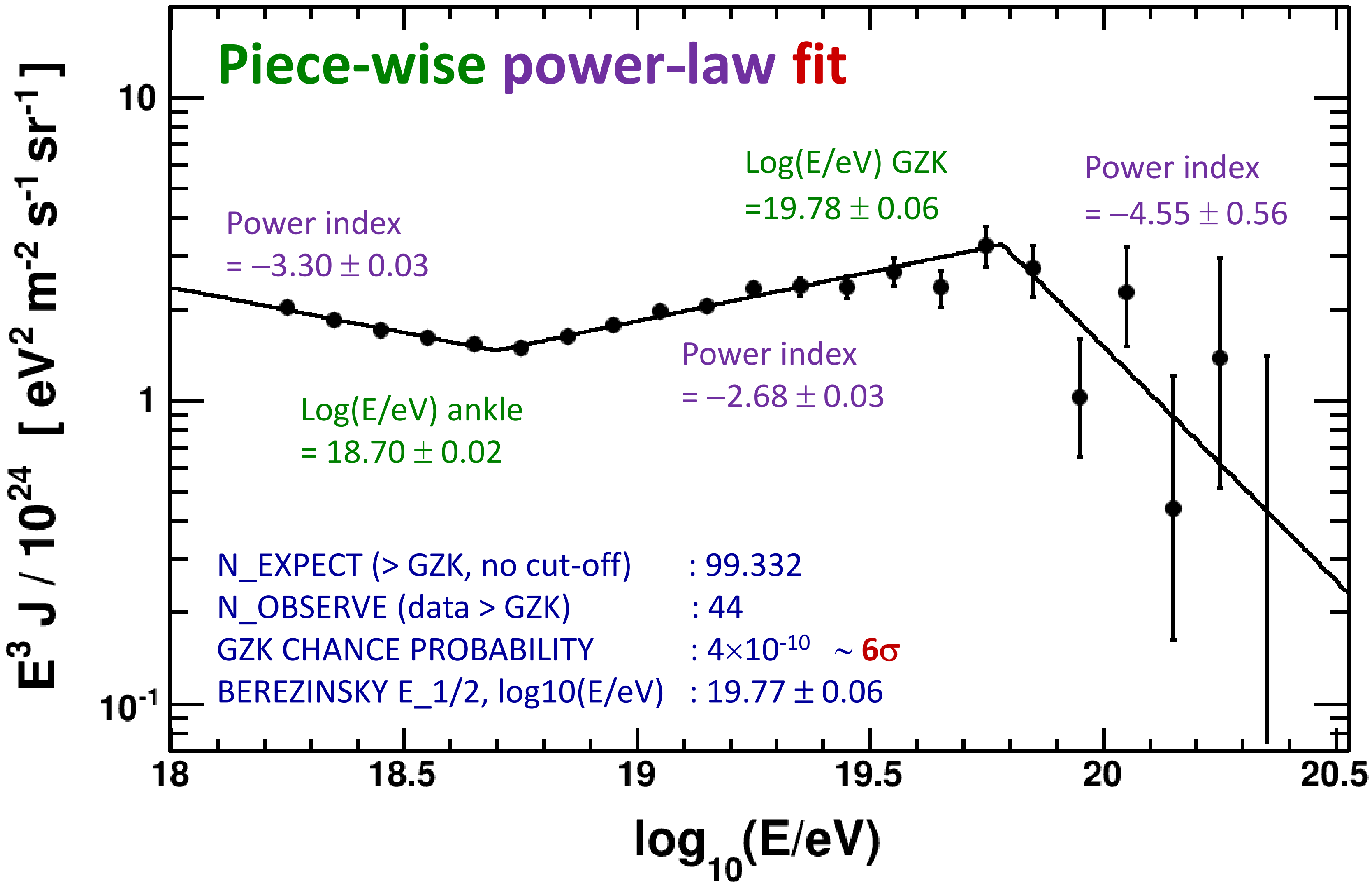


E > 10^{19} eV
Energy resolution < 20%

(SD scaled to FD energy: calorimetric)

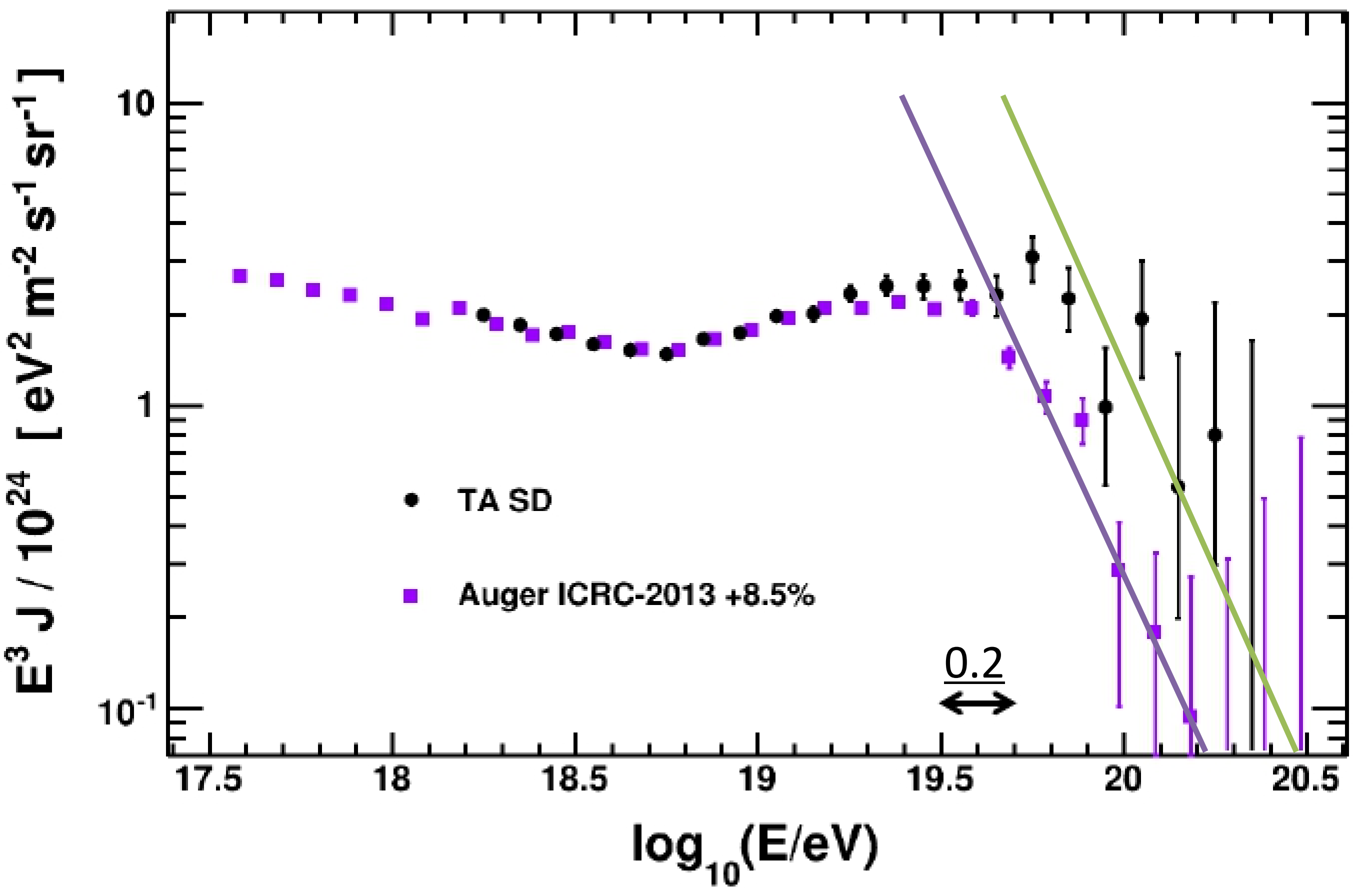
$E_{SD}/1.27 = E_{FD}$

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

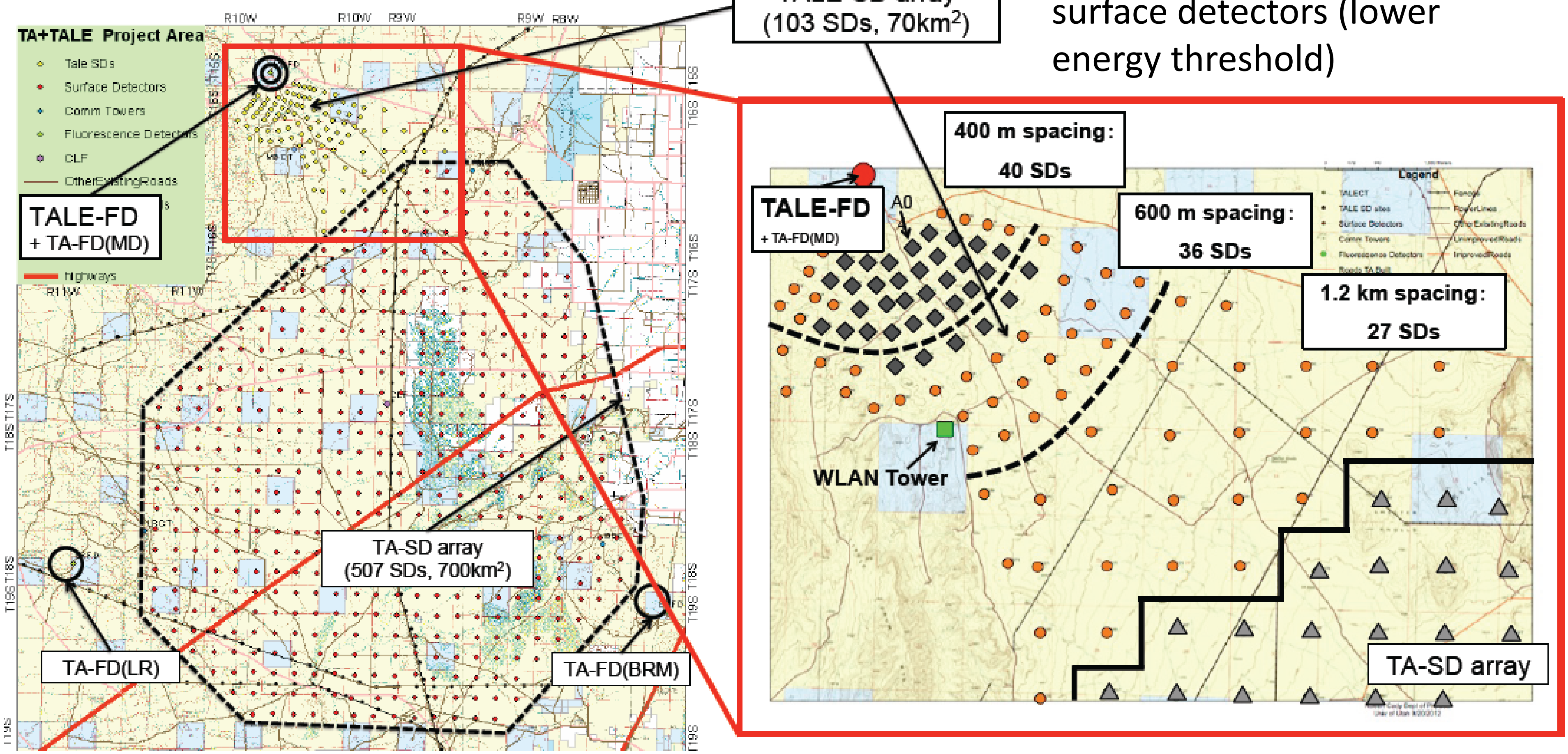


TA Low Energy Extension (TALE)

Galactic to Extra-Galactic Transition

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

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

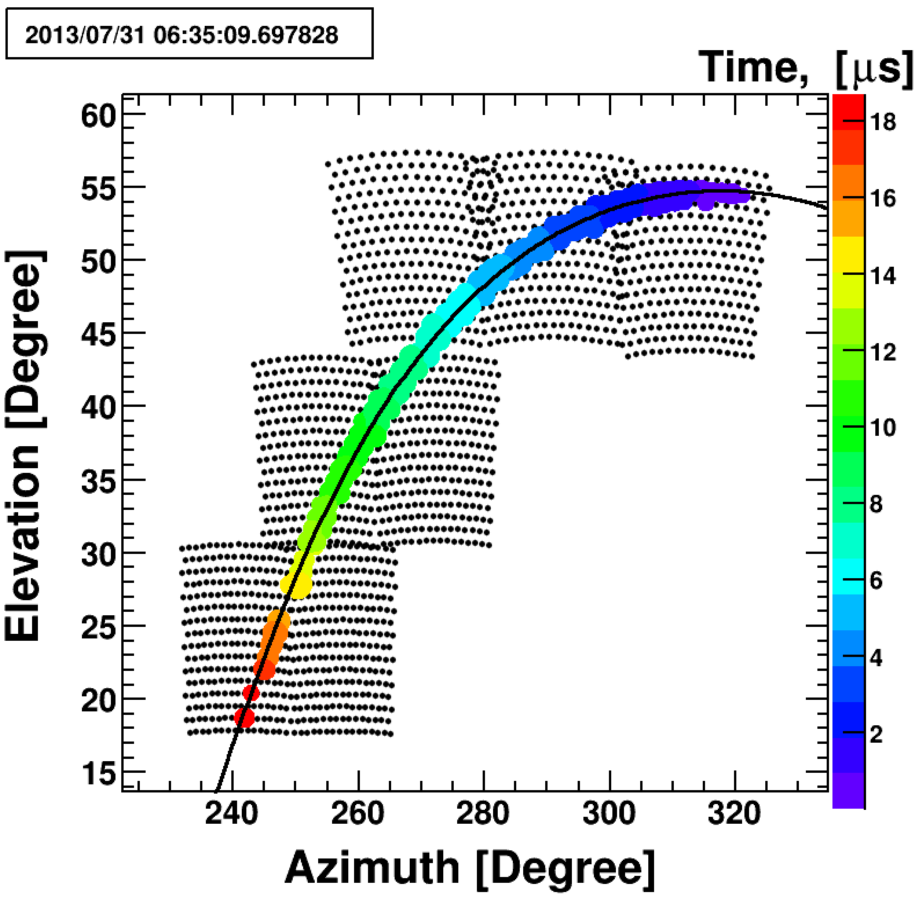


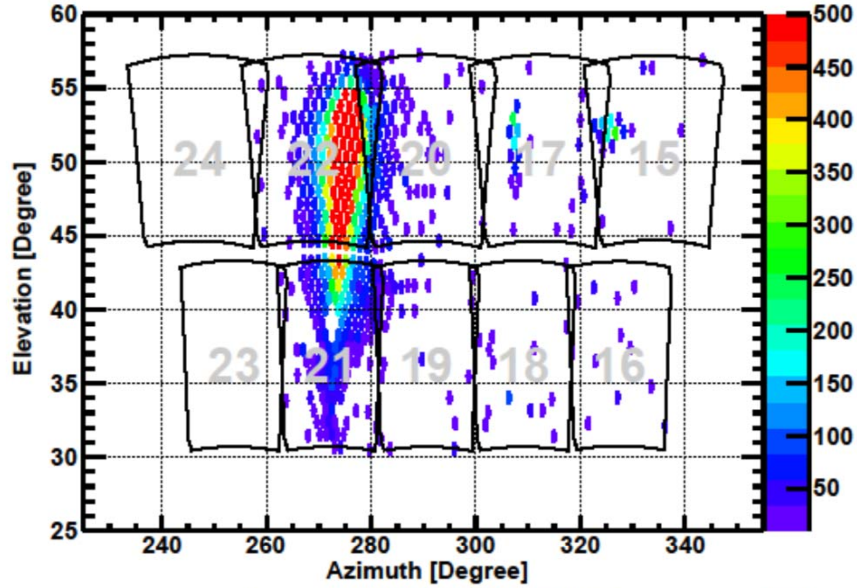
All 10 Telescopes installed and in operation since fall 2013

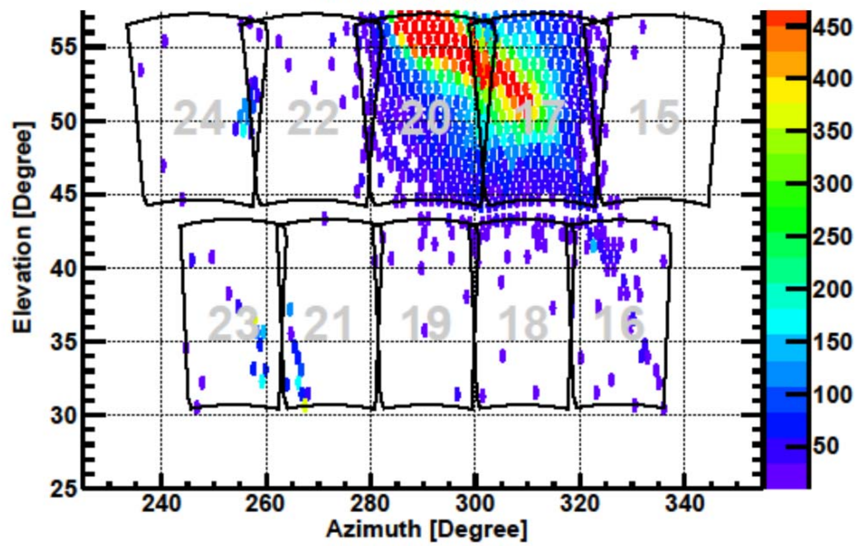
Test array of 16 scintillation surface detectors in operation

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

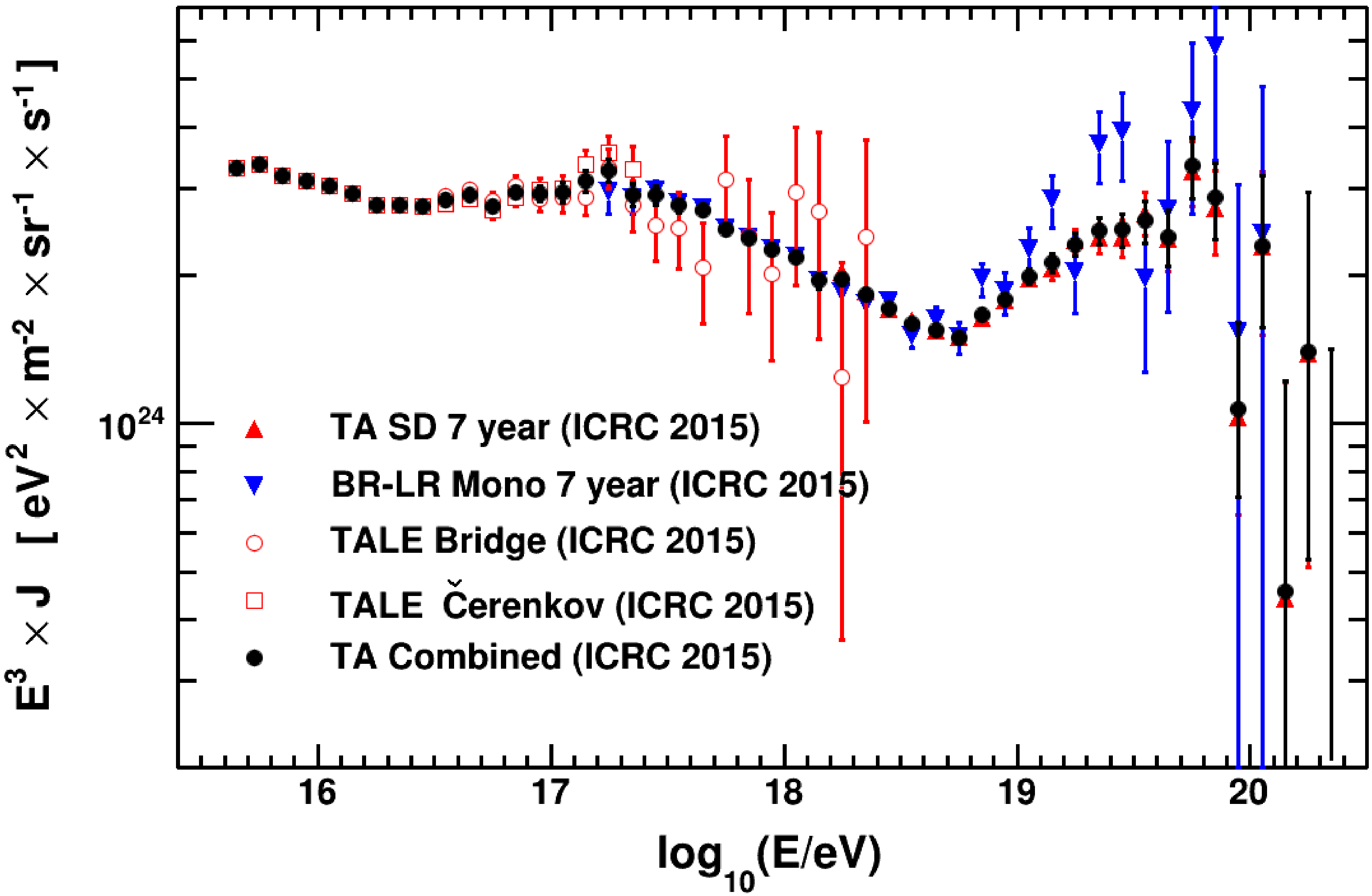
Nearby Events with Cerenkov



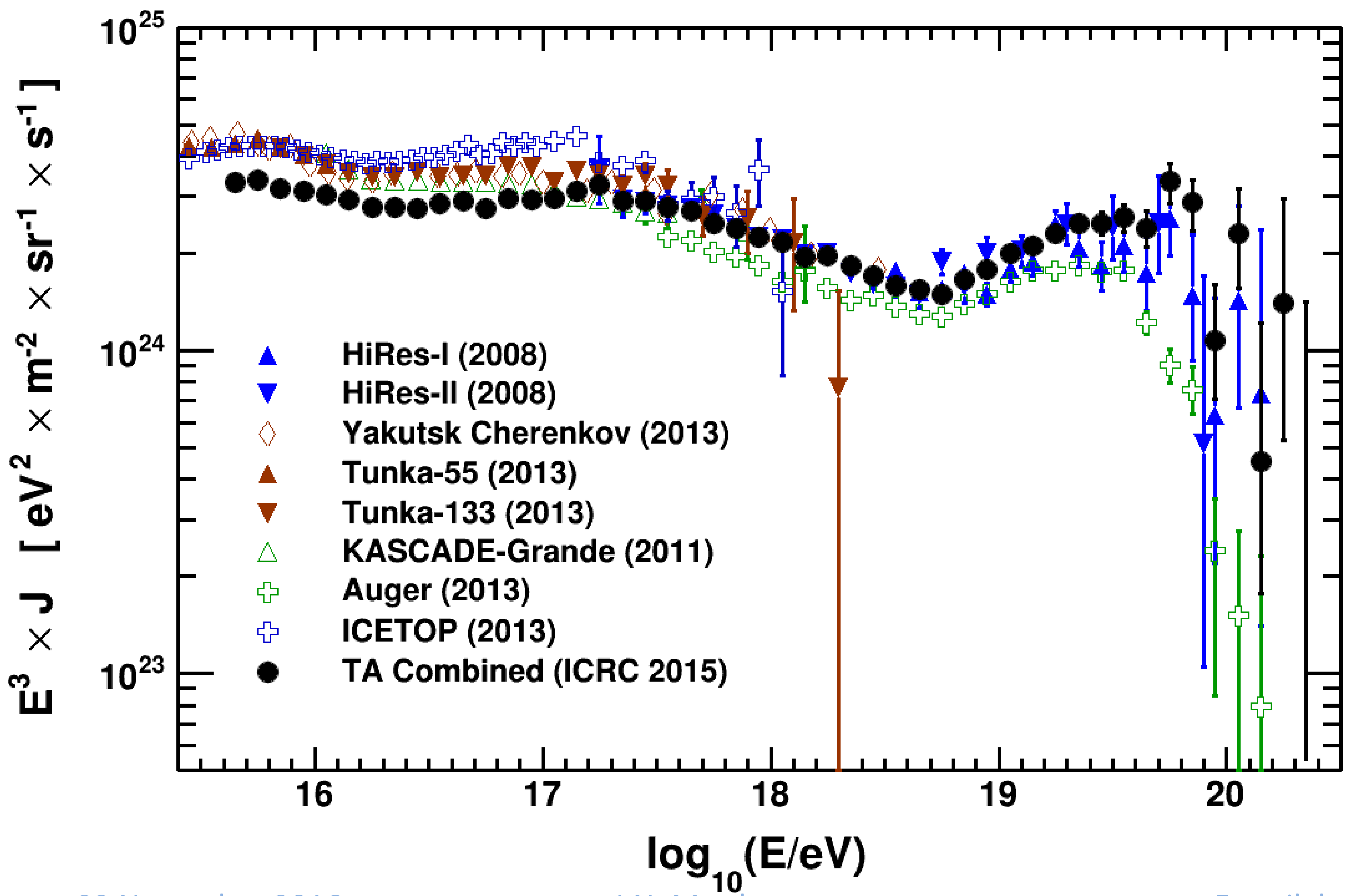




Combined TA Energy Spectrum



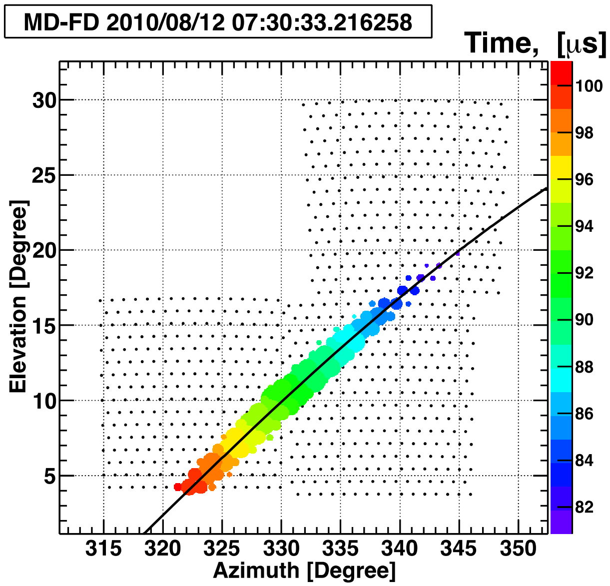
Comparison with other Measurements

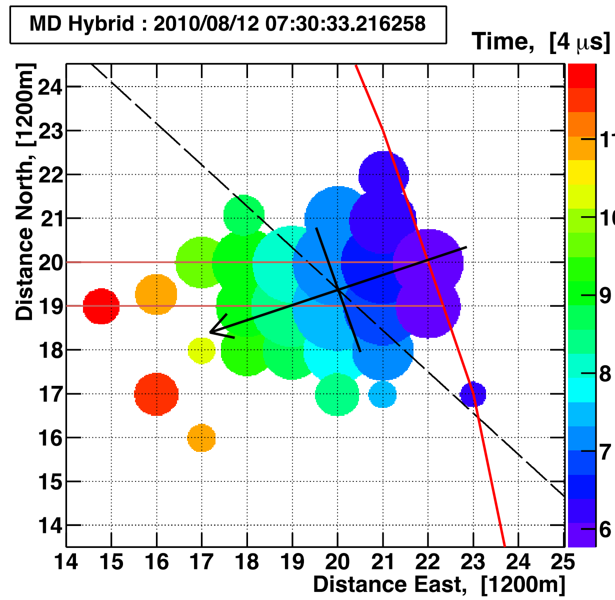


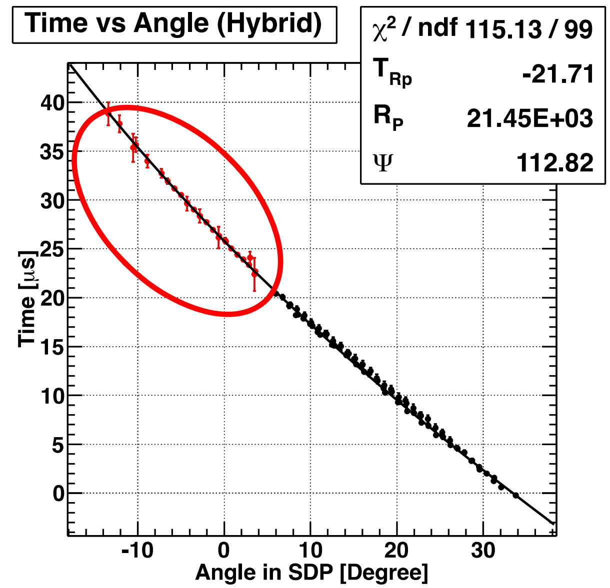
TA Composition Results

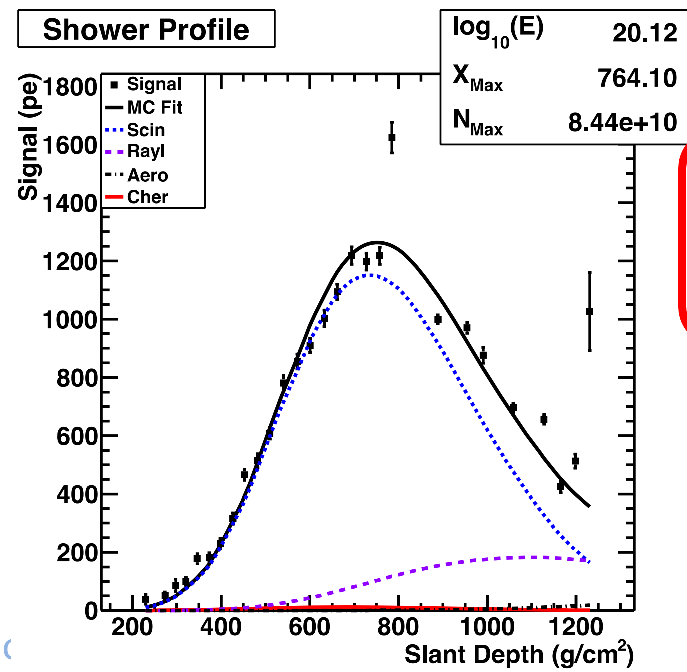
- Use hybrid or stereo to constrain geometry and know X_{max}
- Stereo also provides a redundant measurement of X_{max}

High Energy Hybrid Event







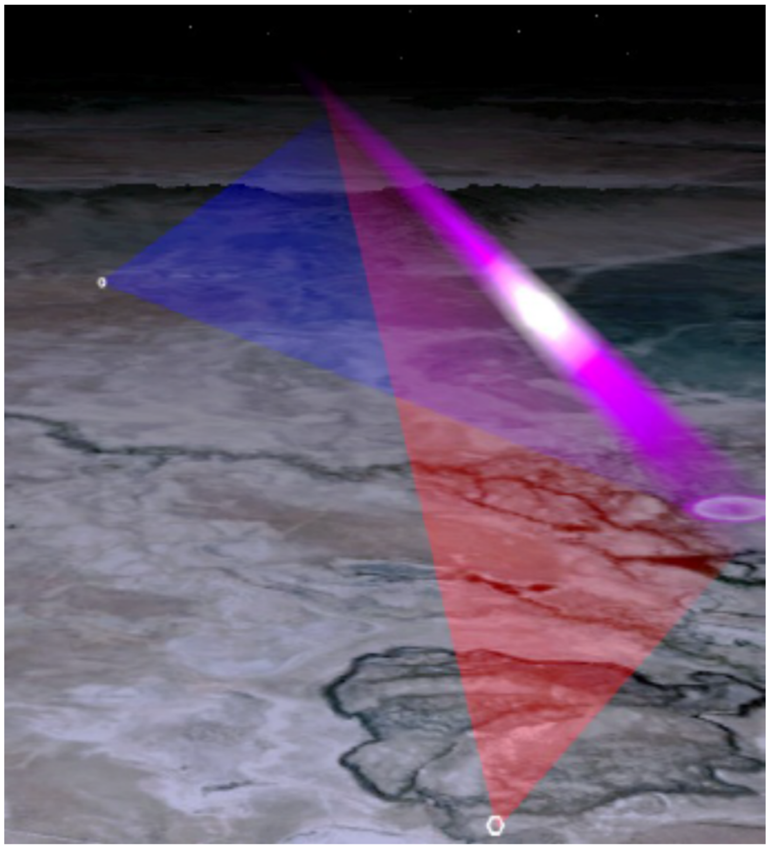


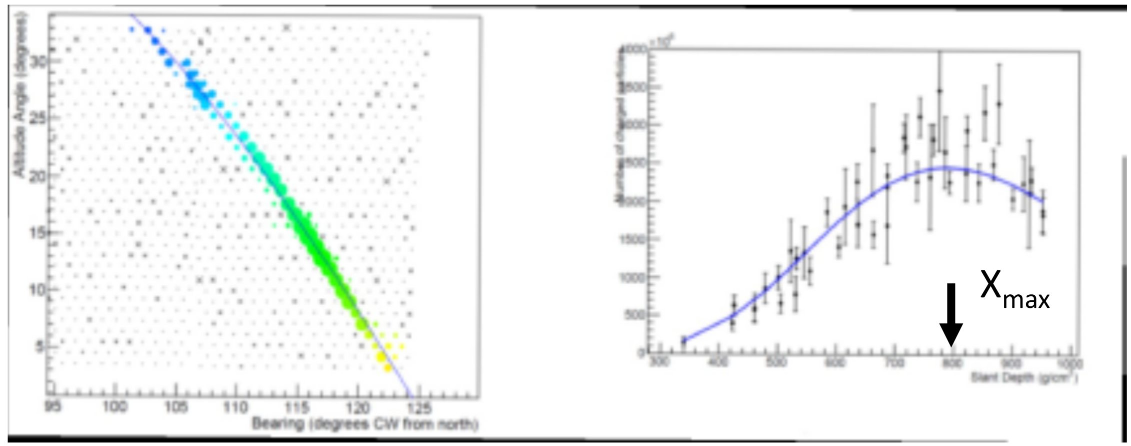
Energy: 1.3 × 10^{20} eV

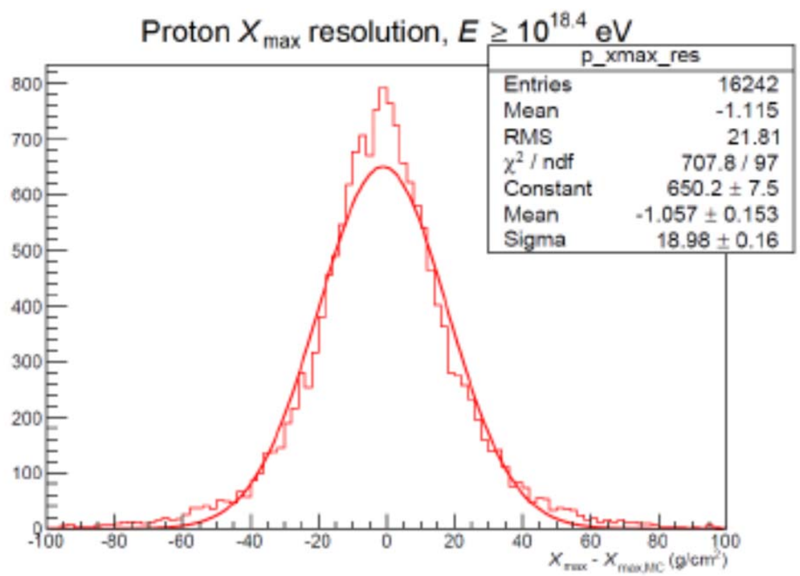
Zenith Angle: 55.7°

Surface array constrains geometry fit via extra timing & core information

Stereo Observation



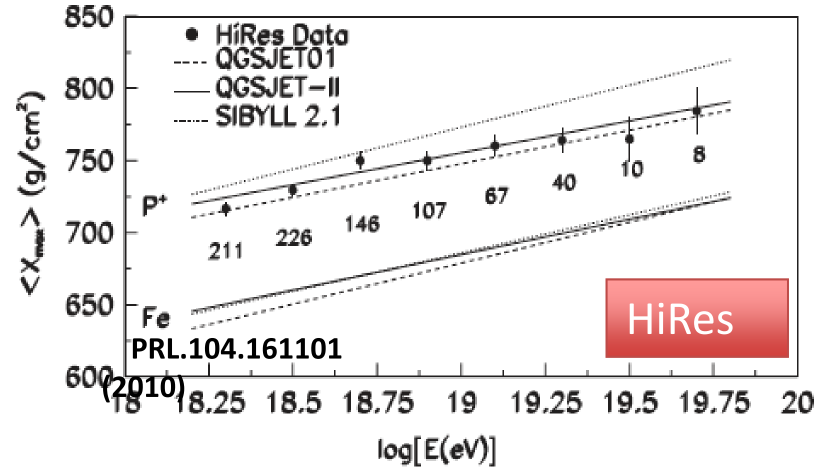




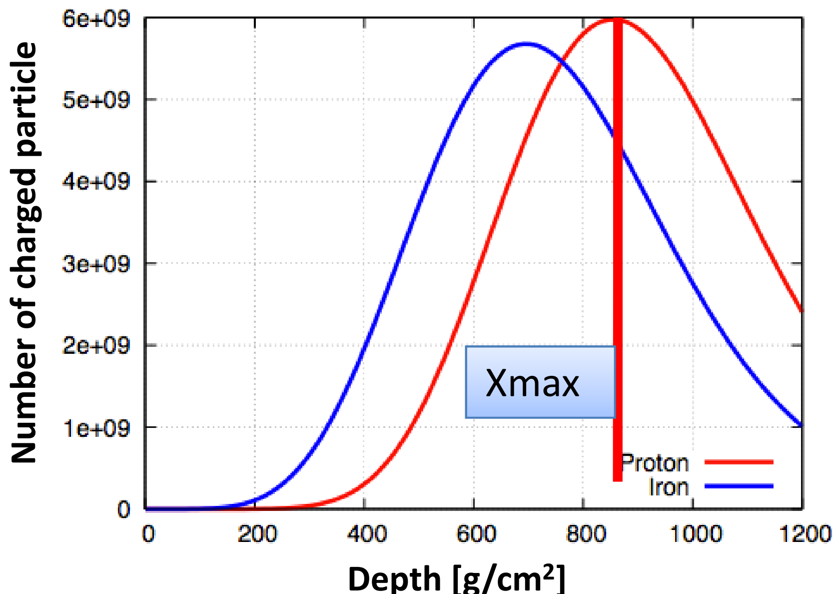
Intersect shower planes to get more precise geometry

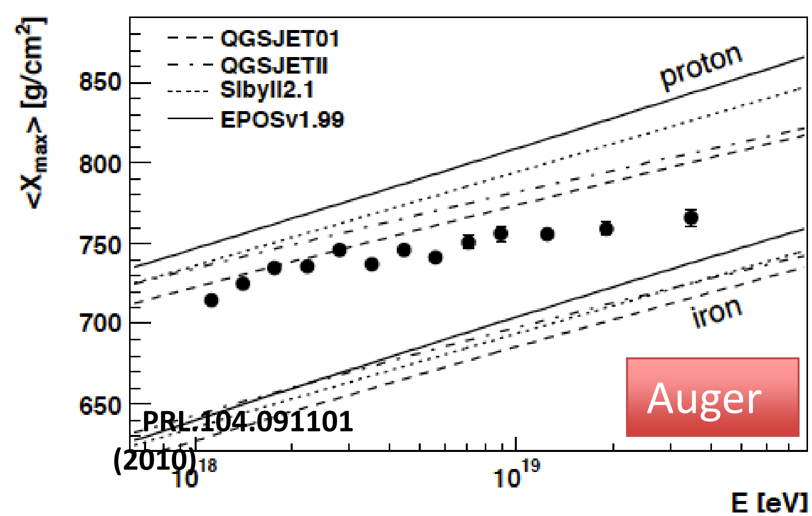
Xmax Technique

- 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

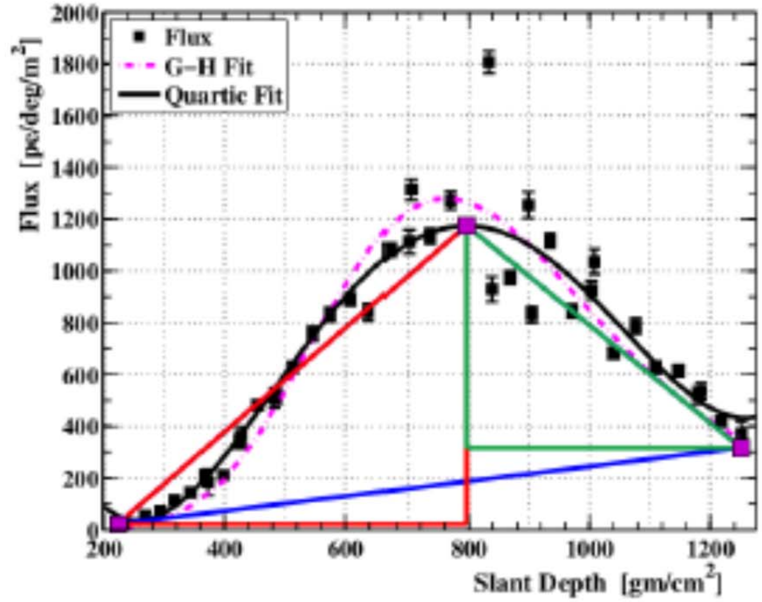


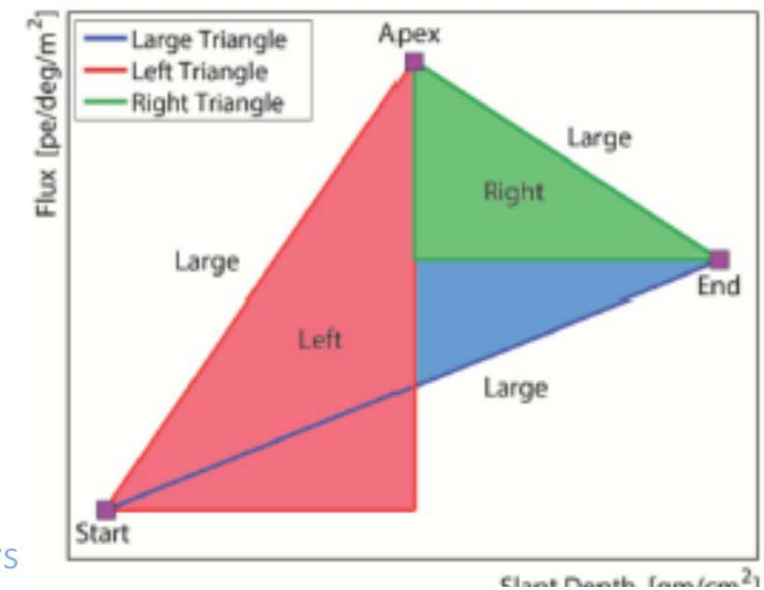


MD Hybrid Observation

● 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.





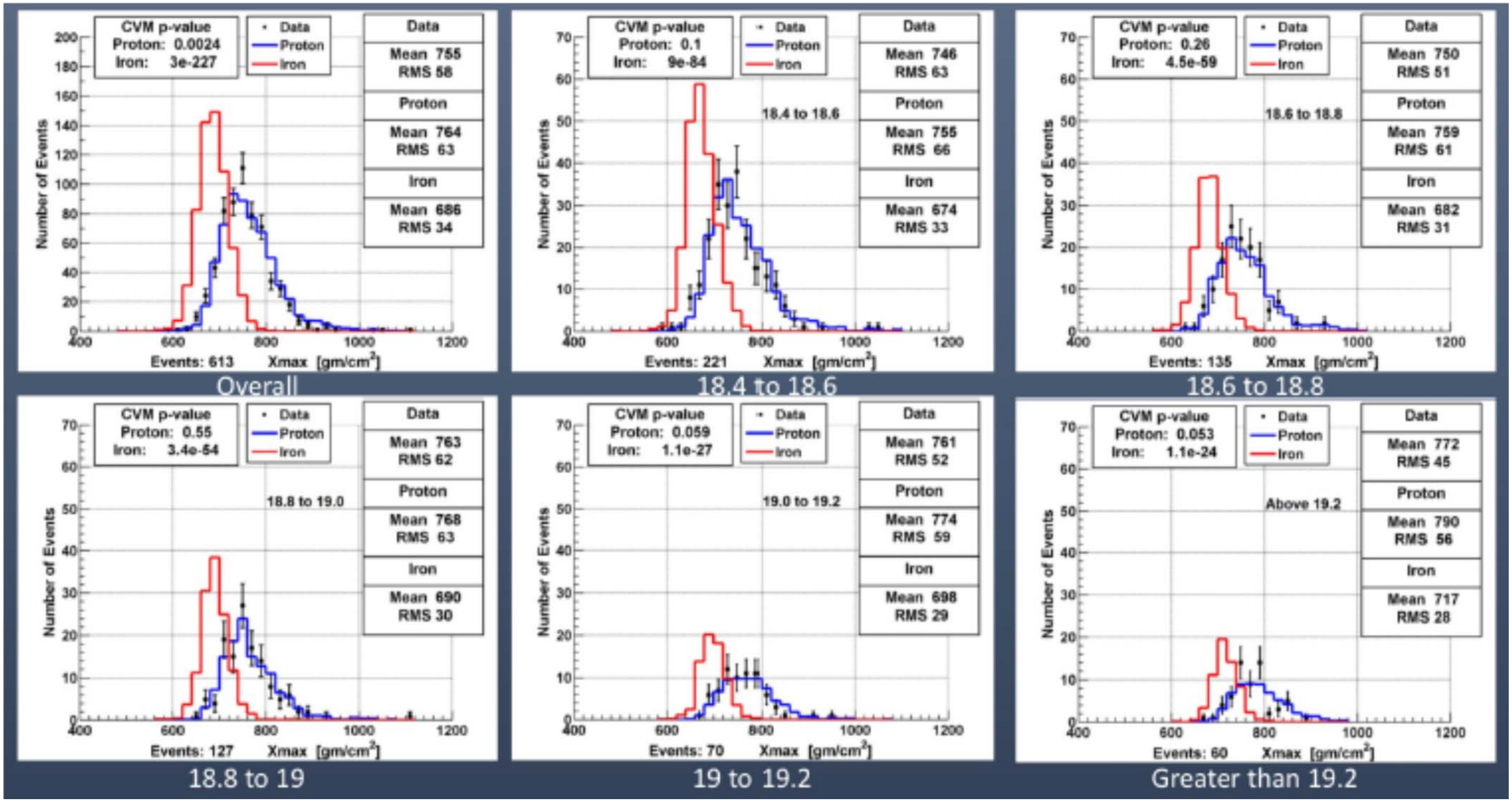
7 years of MD FD hybrid data

623 events [log10(E/eV) > 18.4]

Xmax resolution ~ 22 g/cm^2,
reconstruction bias < 2 g/cm^2

Energy resolution ~ 7%

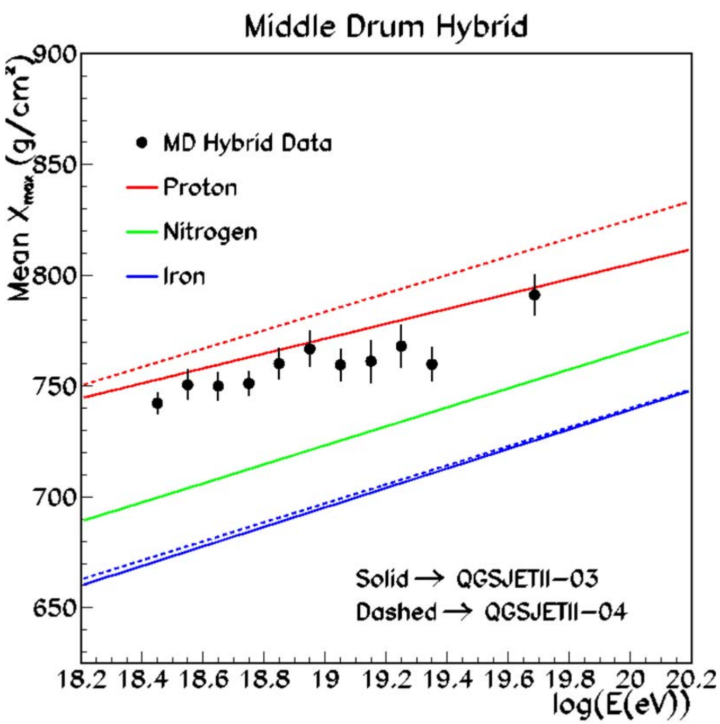
Hybrid X_{max} Measurement

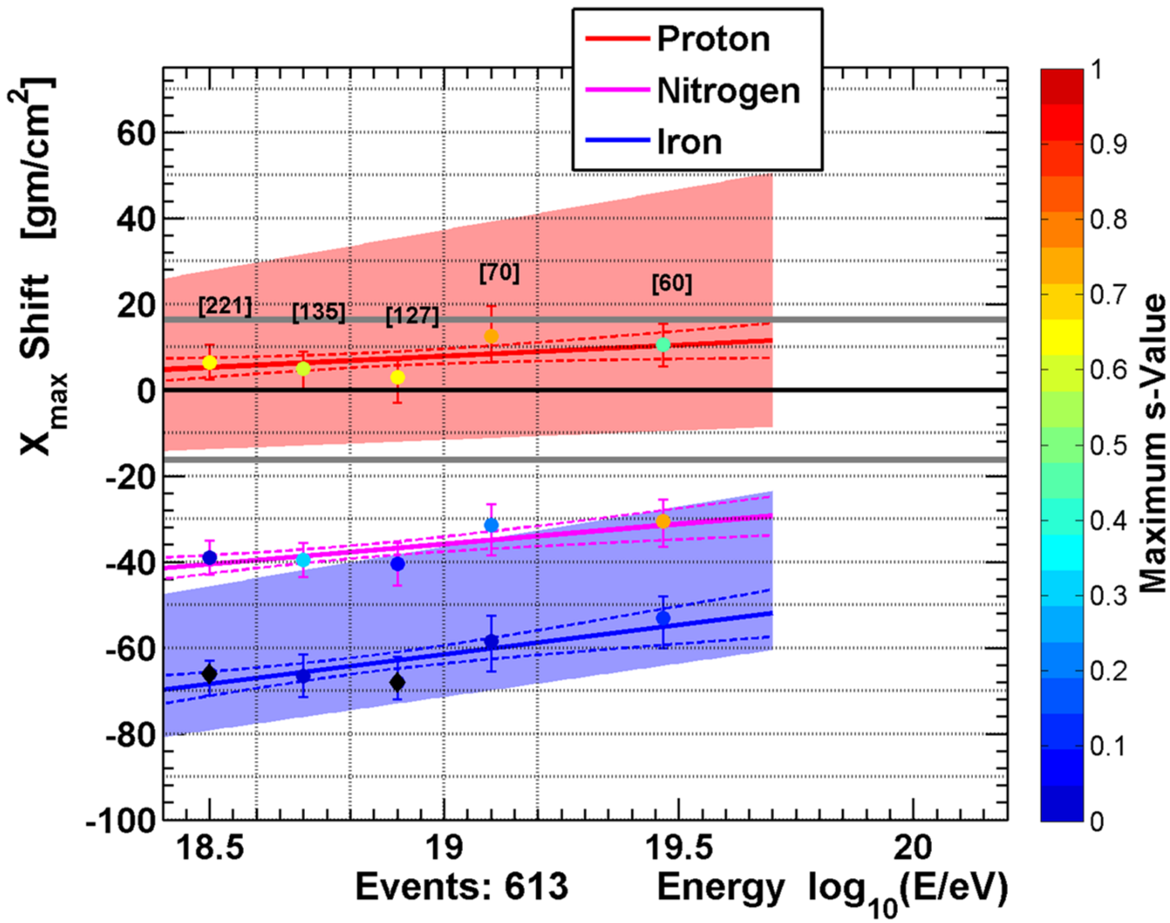


MD Xmax Data comparison to QGSjet II-03 **proton** and **iron** models

MD Hybrid

Elongation:
<Xmax> vs log(E) plot





"Shift Plot"

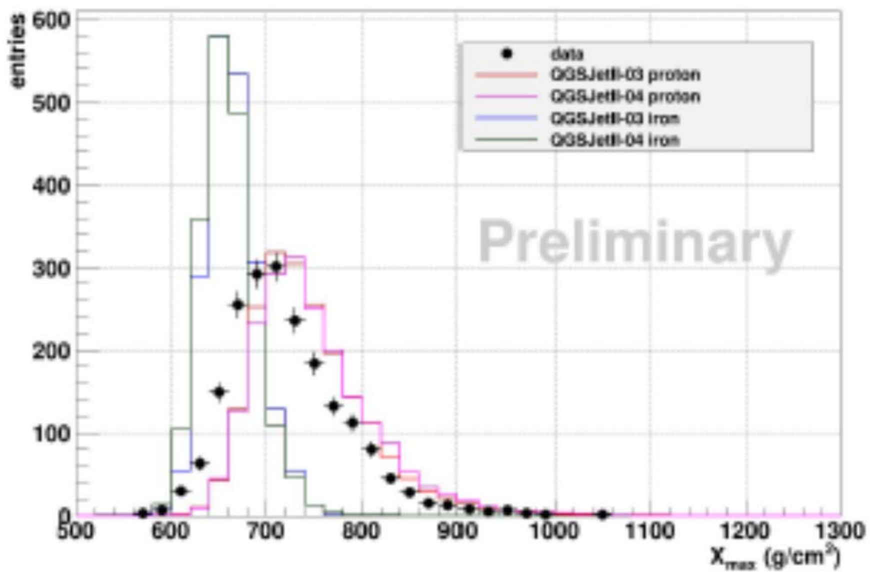
Plot ΔX_{max} required to maximize data/MC agreement (QGSJETII-03).

Standard statistical test on shifted distribution (points)

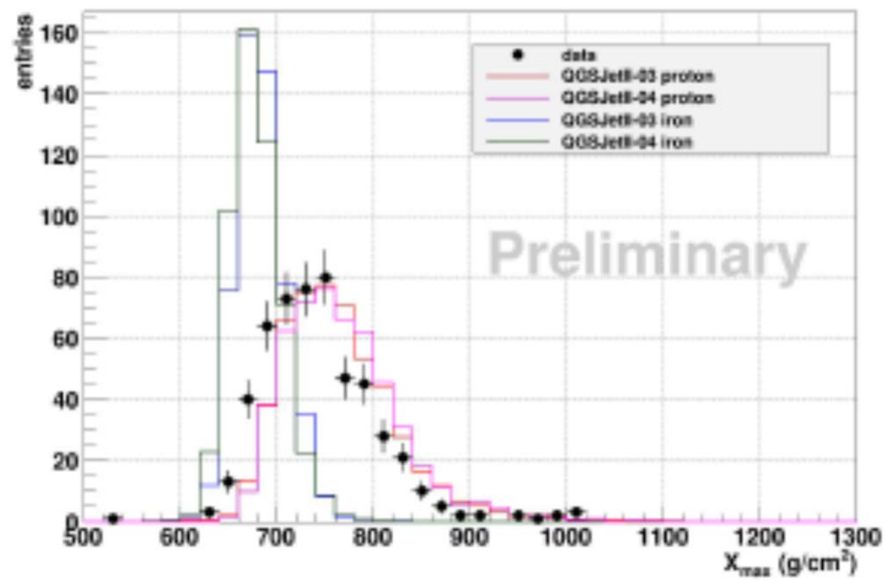
Pink, blue bands for other hadronic models

16 g/cm^2 systematic uncertainty

Hybrid Data/Monte Carlo X_{max}



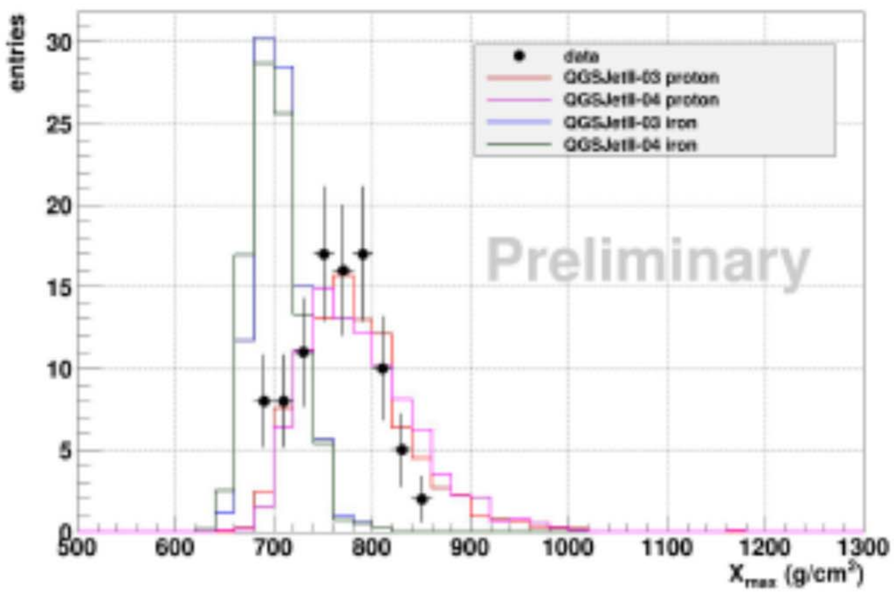
$18.2 < \log_{10}(E/eV) < 18.6$



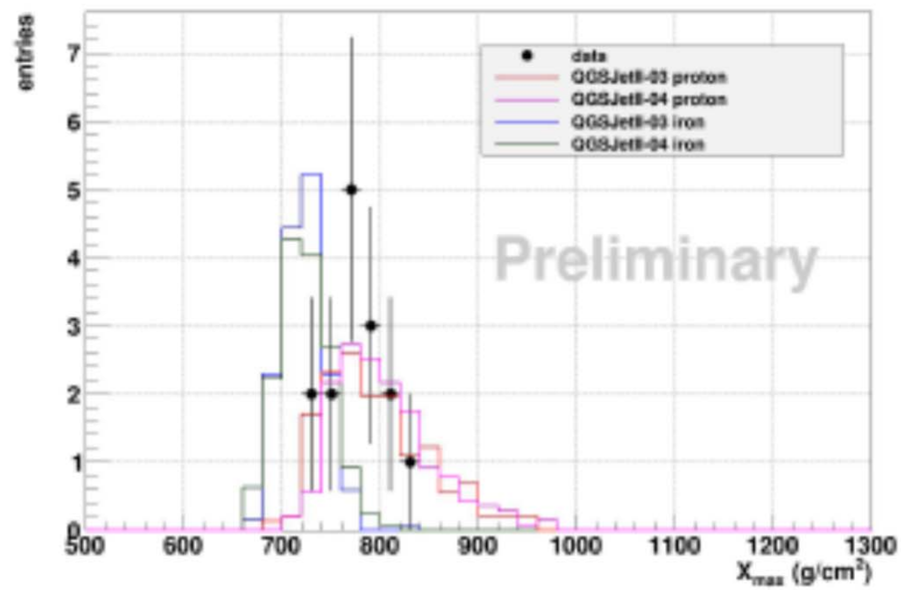
$18.6 < \log_{10}(E/eV) < 19$

28

Hybrid Data/Monte Carlo X_{max}

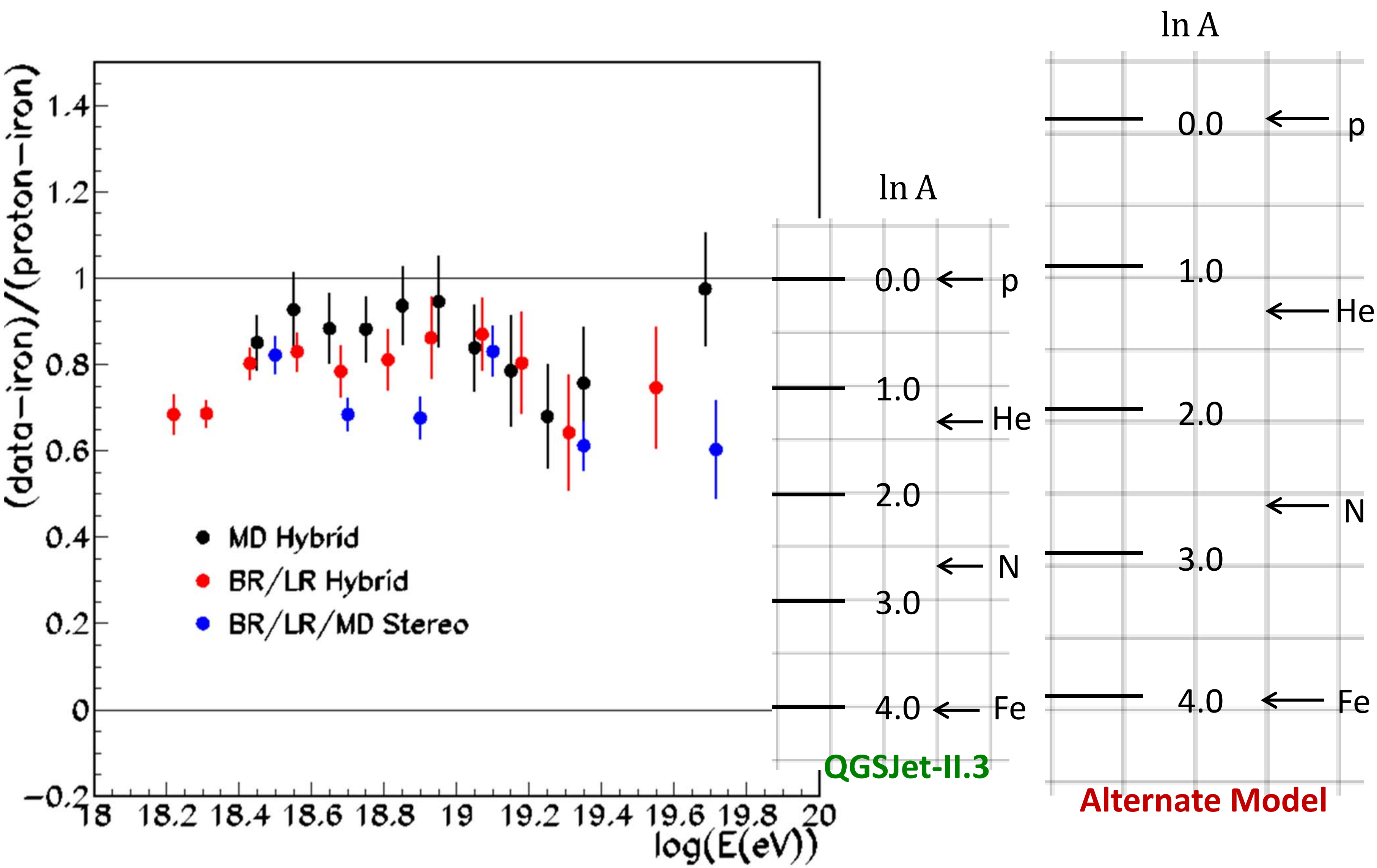


$19 < \log_{10}(E/eV) < 19.4$

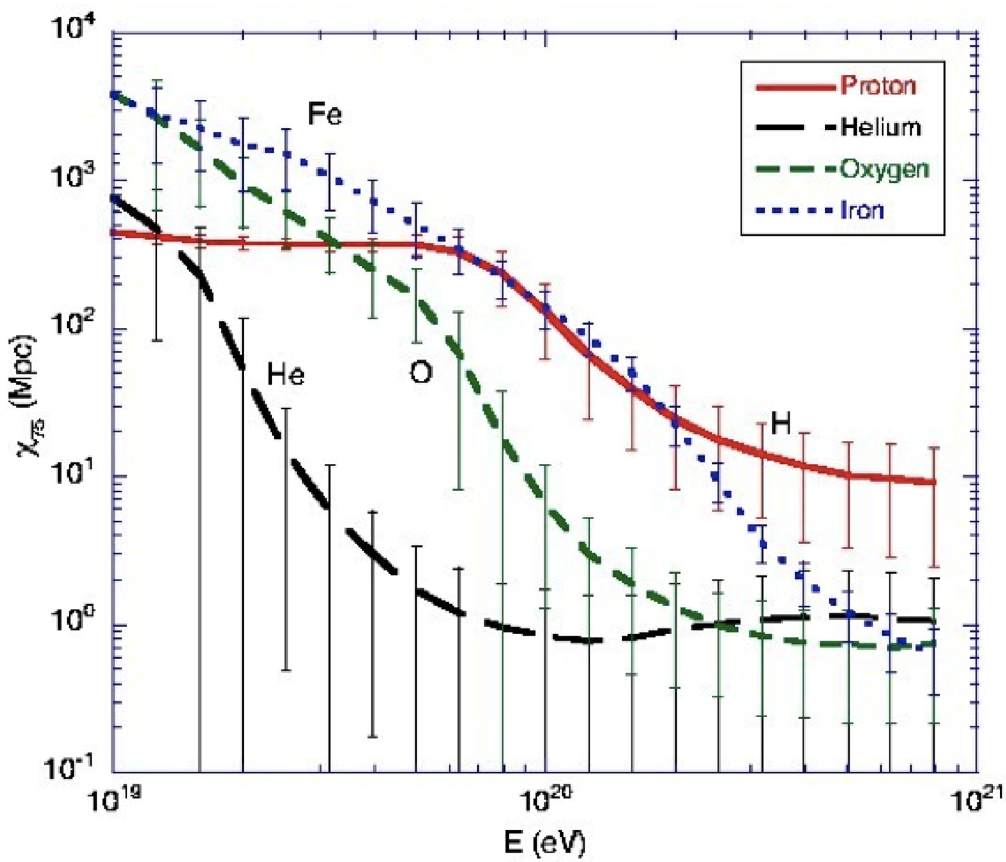


$\log_{10}(E/eV) > 19.4$

TA data compared to QGSJet-II.3

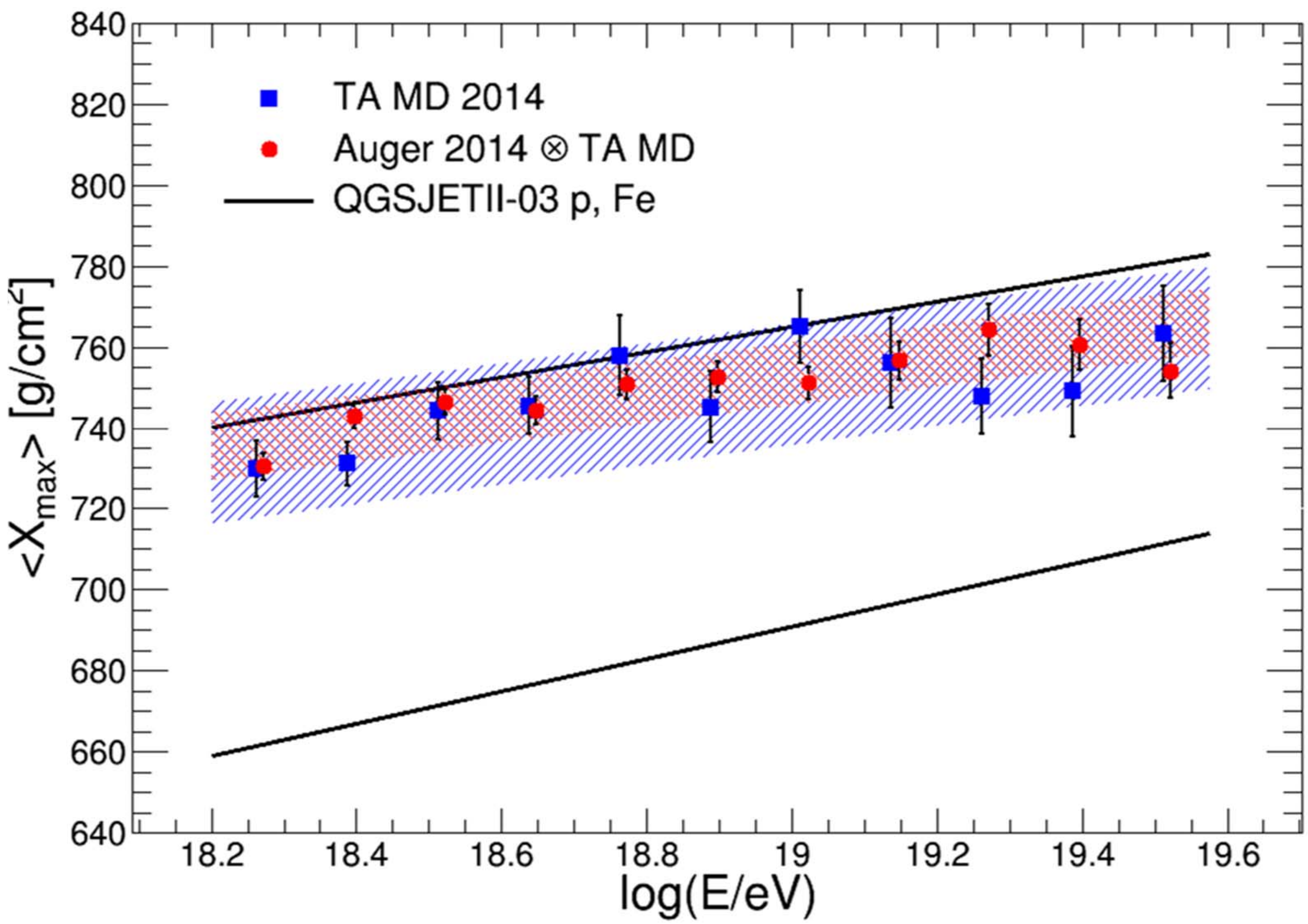


Astrophysically p and He are very different

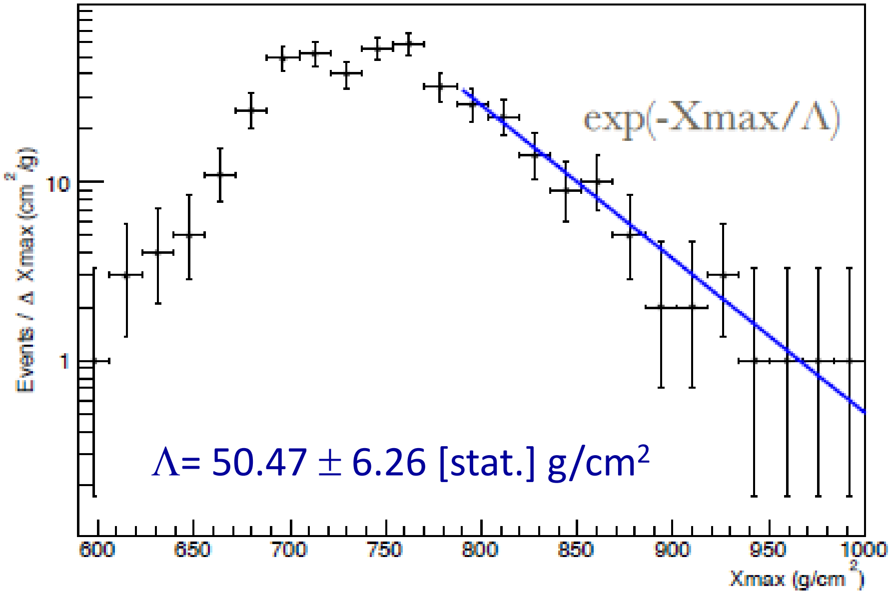


Interaction lengths of p,He,O and Fe

Meta-analysis: Composition WG

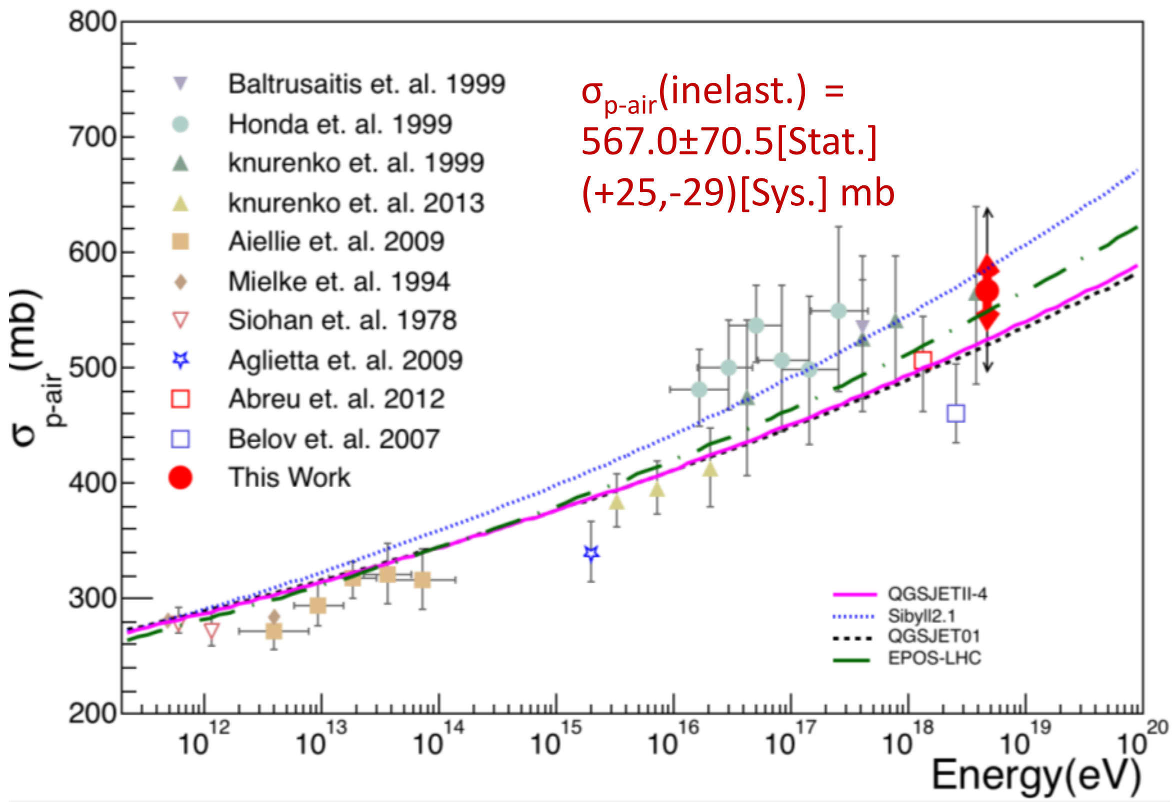


TA data cannot distinguish between mix and QGSJETII-3 protons at this level of systematic uncertainty.



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)

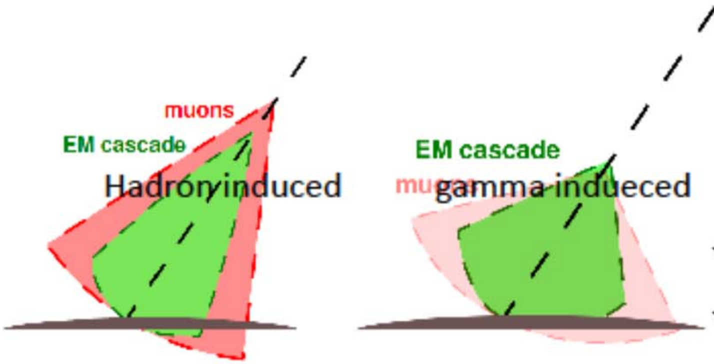


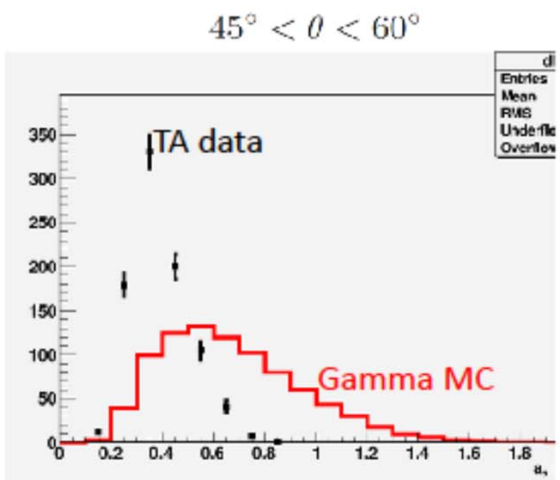
Systematic source	Systematic (mb)
Model Dependence	±17
20%Helium	+18
Gamma<1%*	– 23
Total	(+25,-29)

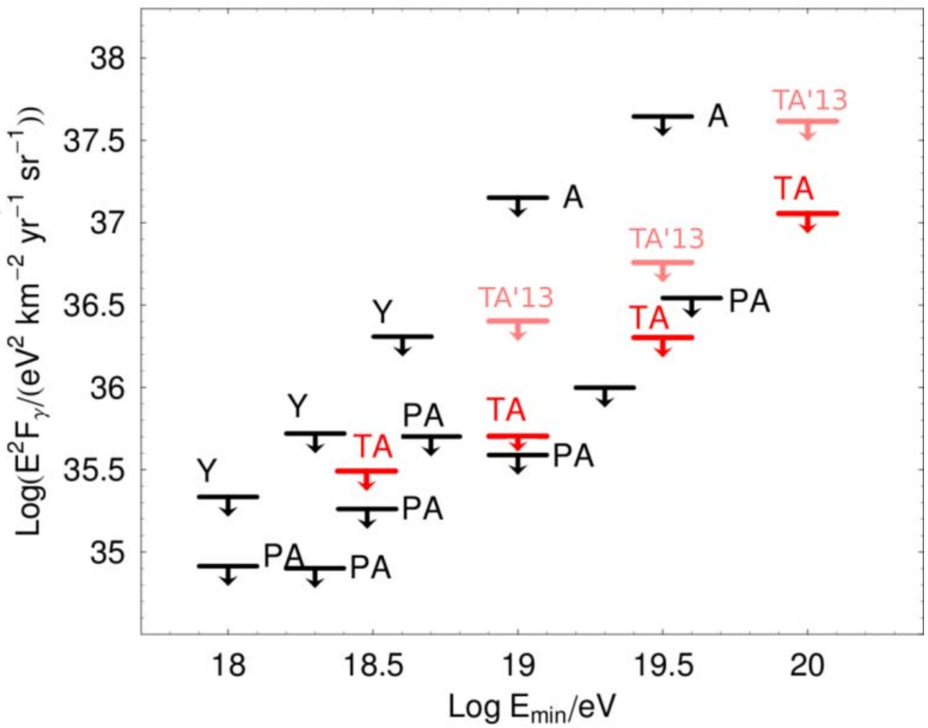
R. Abbasi et. al. (TA collaboration) Accepted for publication by Phys. Rev. D. **Aug 2, 2015**

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 .



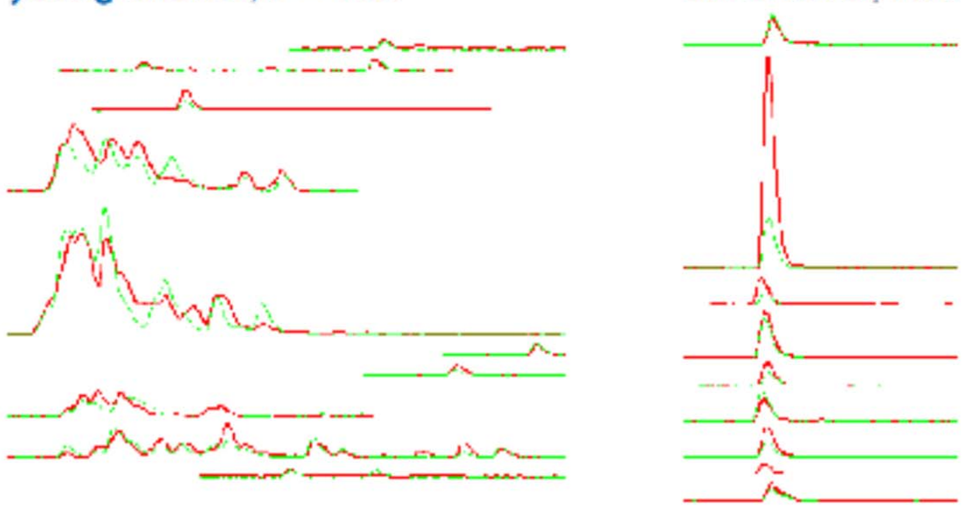




Neutrino search

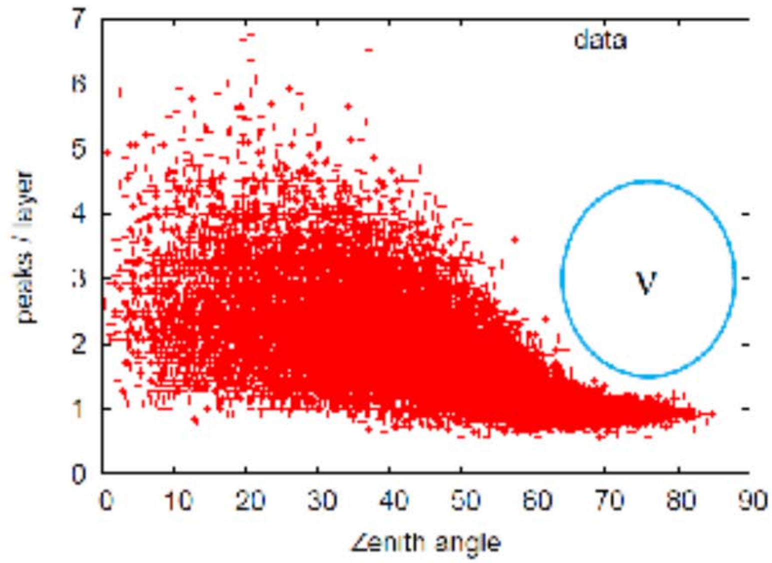
- Neutrino produces very inclined young shower

young shower, $\theta = 19.5°$ **old shower, 78.3°**



long, indented wafeforms

one peak

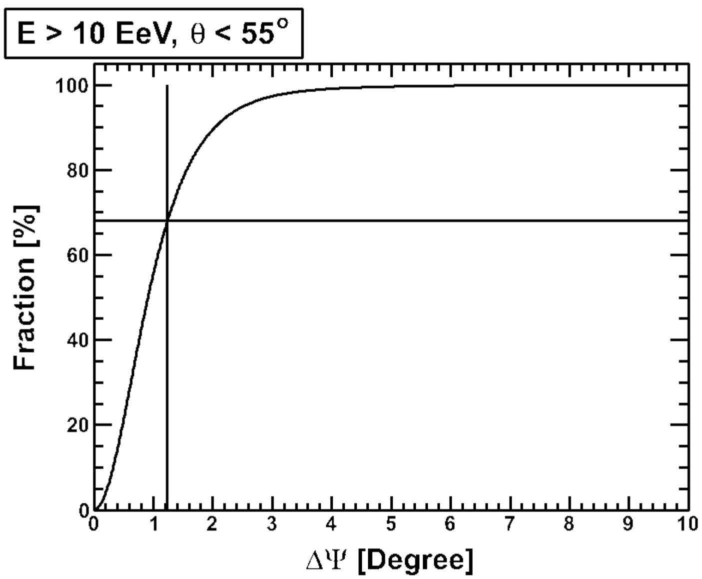


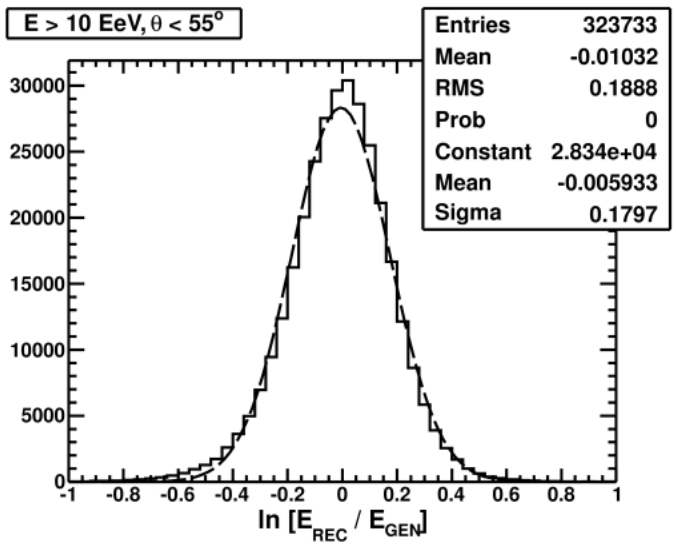
No young inclined showers in the dataset
→ no neutrino candidates.

TA Anisotropy Results

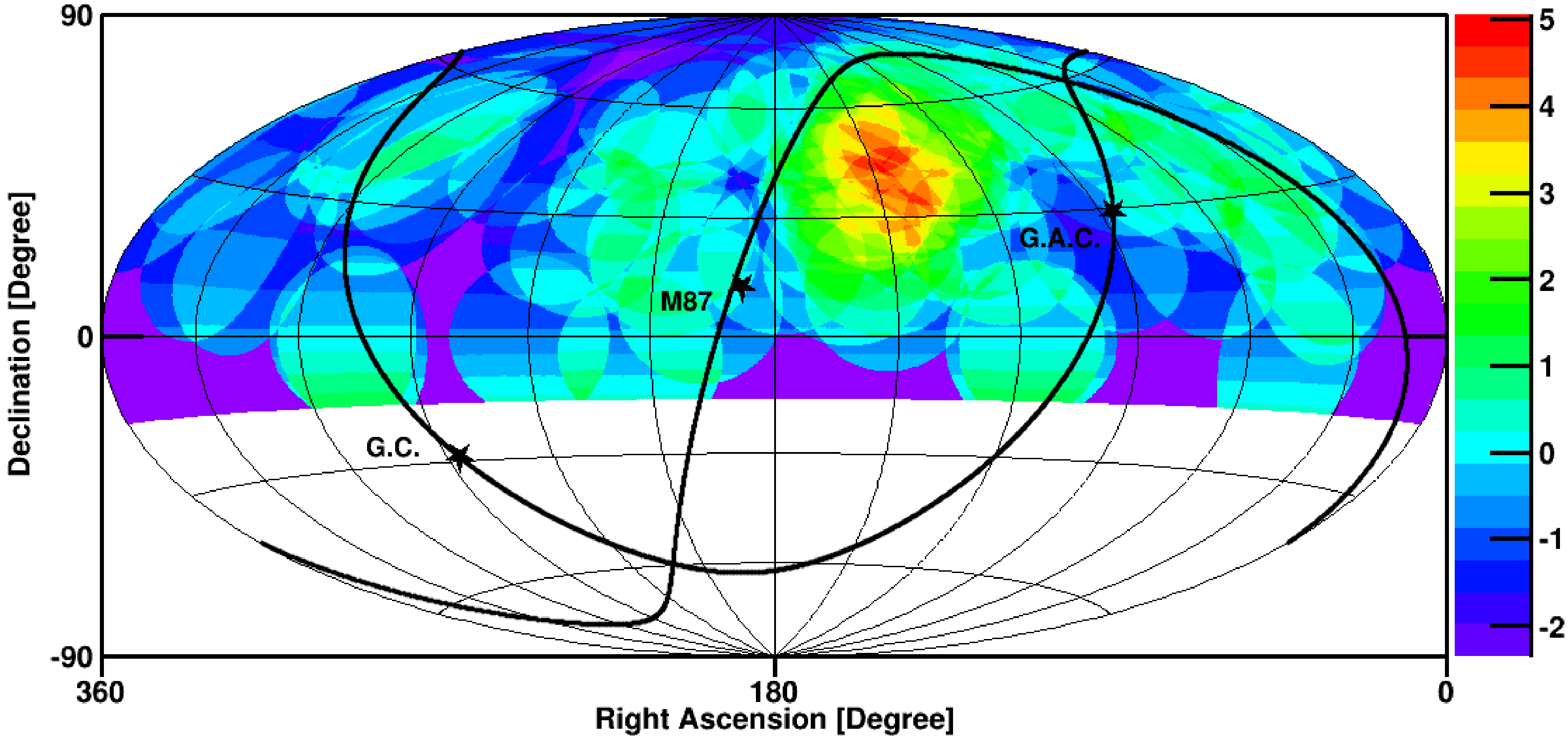
Anisotropy Analysis

- 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%



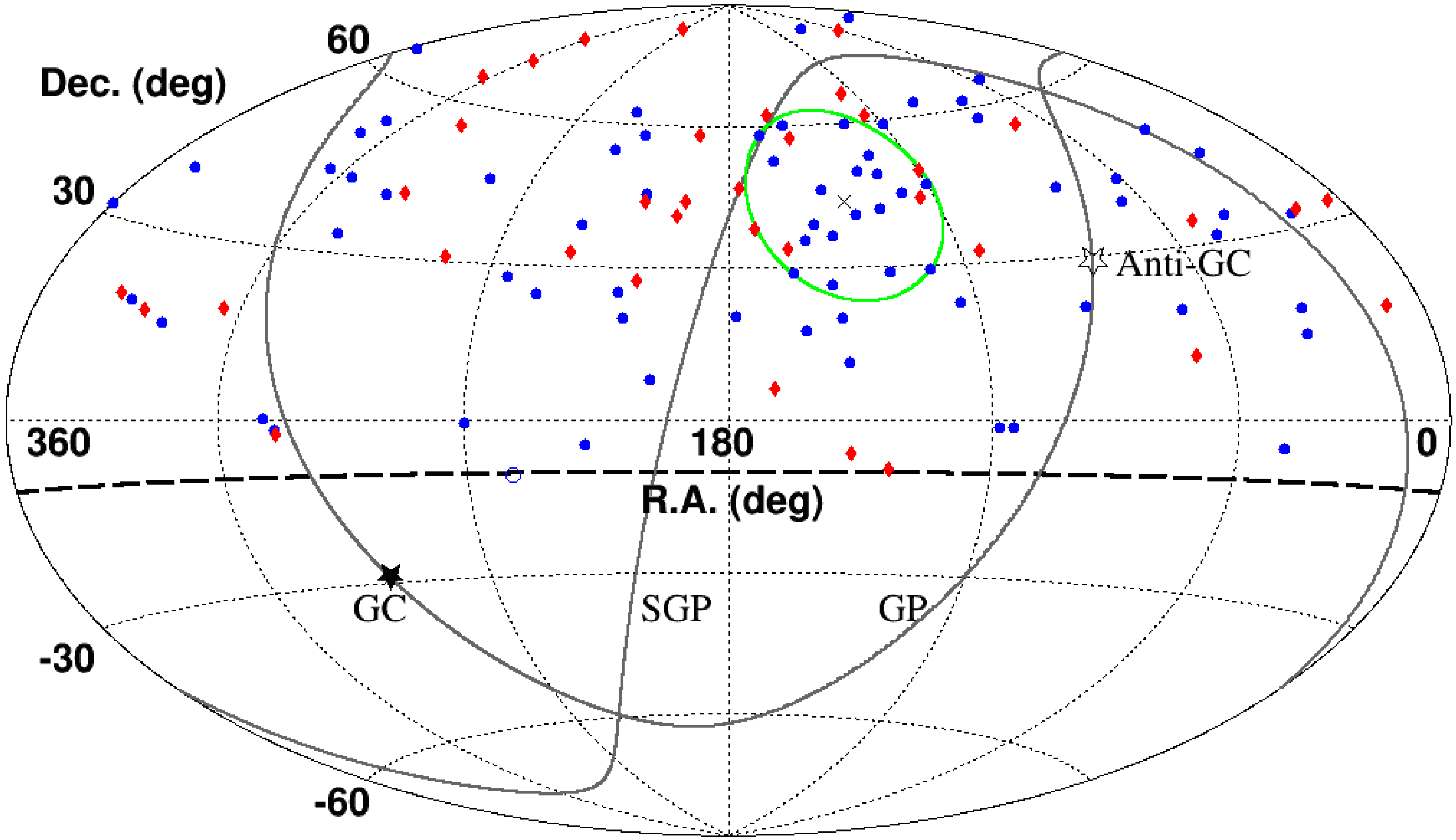


Published Hotspot (5yr data)



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

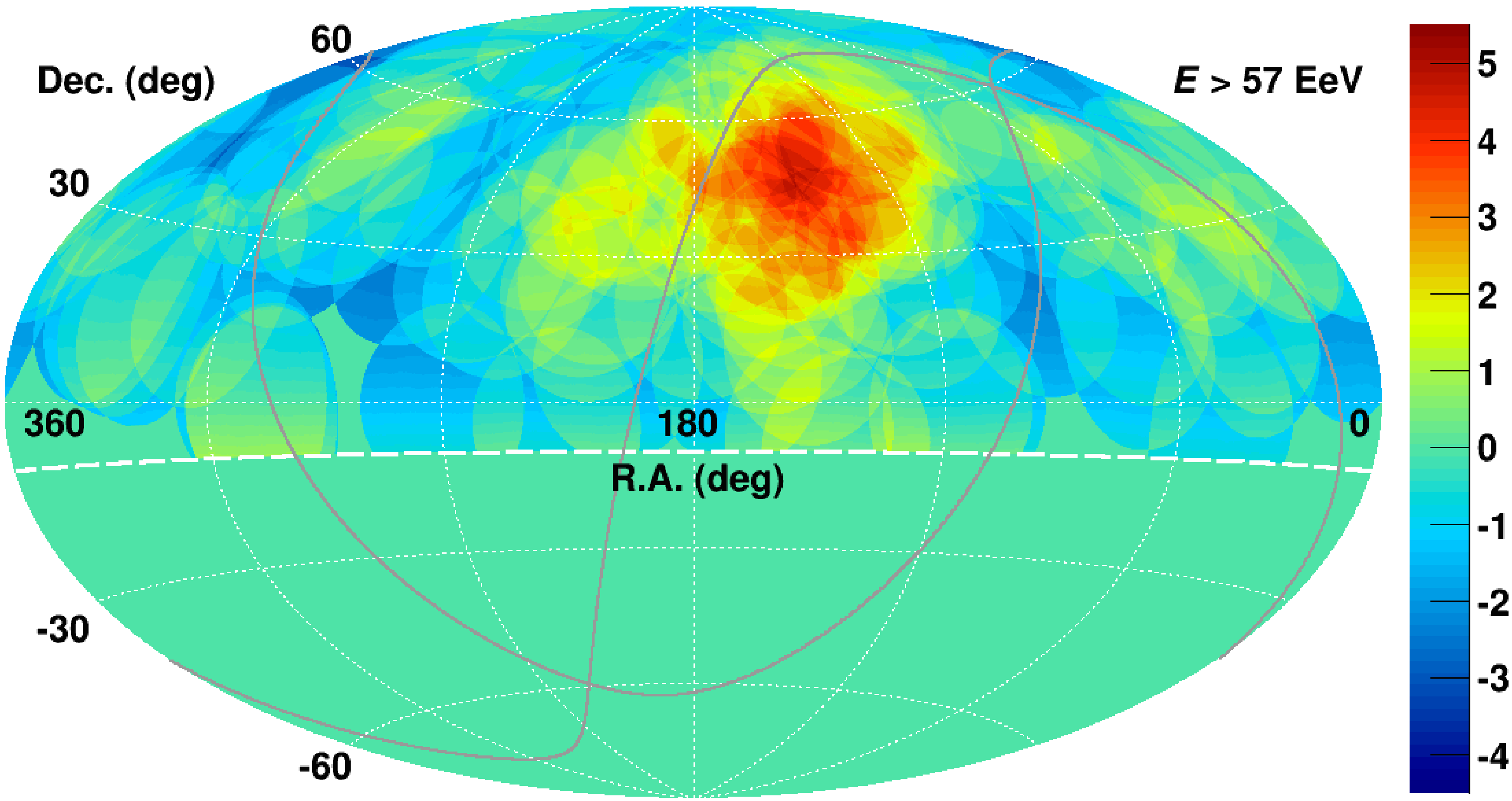
Hot Spot update: 7 years



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

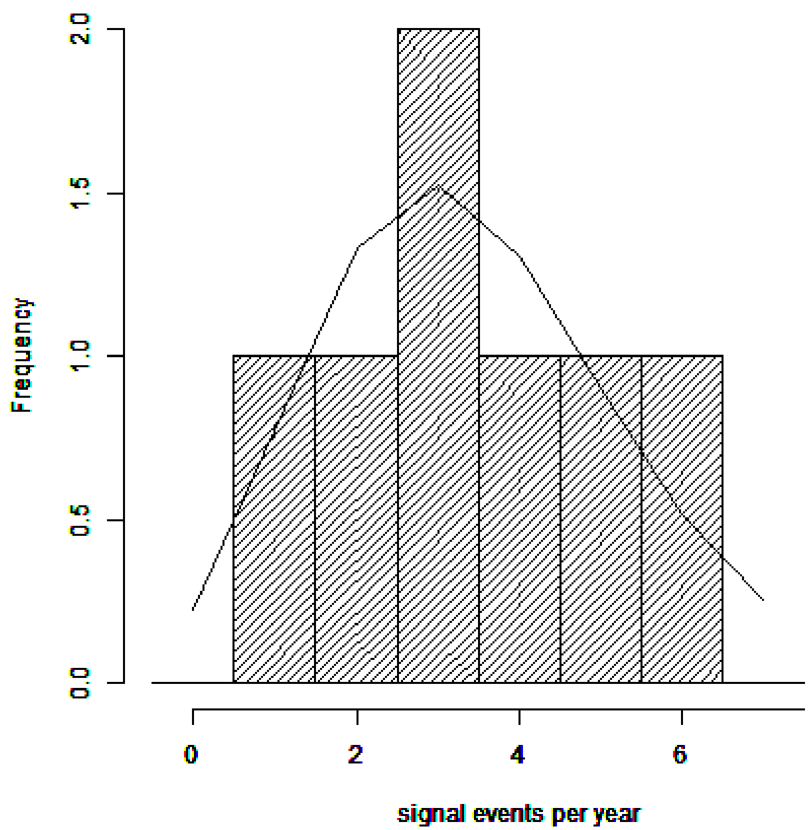


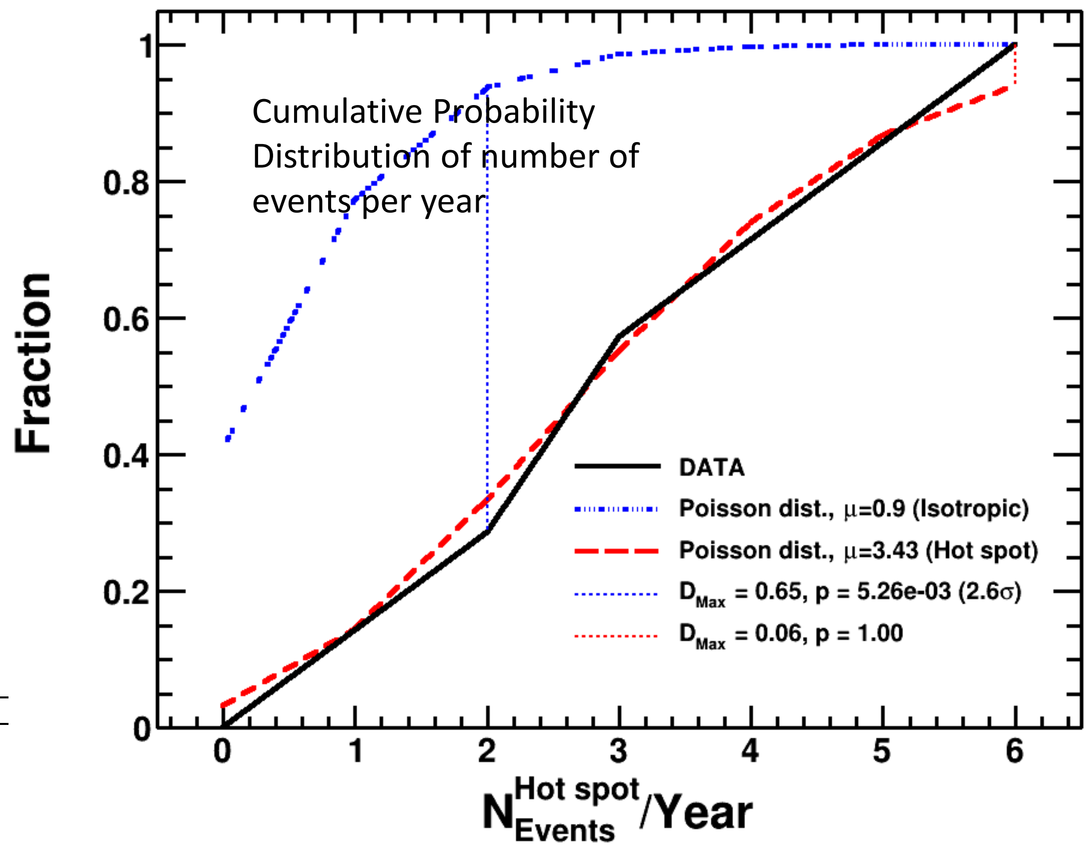
Max significance **5.1**σ (N_{SIG} = 24, N_{BG}=6.88) for 7 years
Centered at R.A=148.4°, Dec.=44.5° (shifted from SGP by 17°)
Global Excess Chance Probability: 3.7×10^{-4} : 3.4σ (~ same as first 5 years)

Consistent with Fluctuation

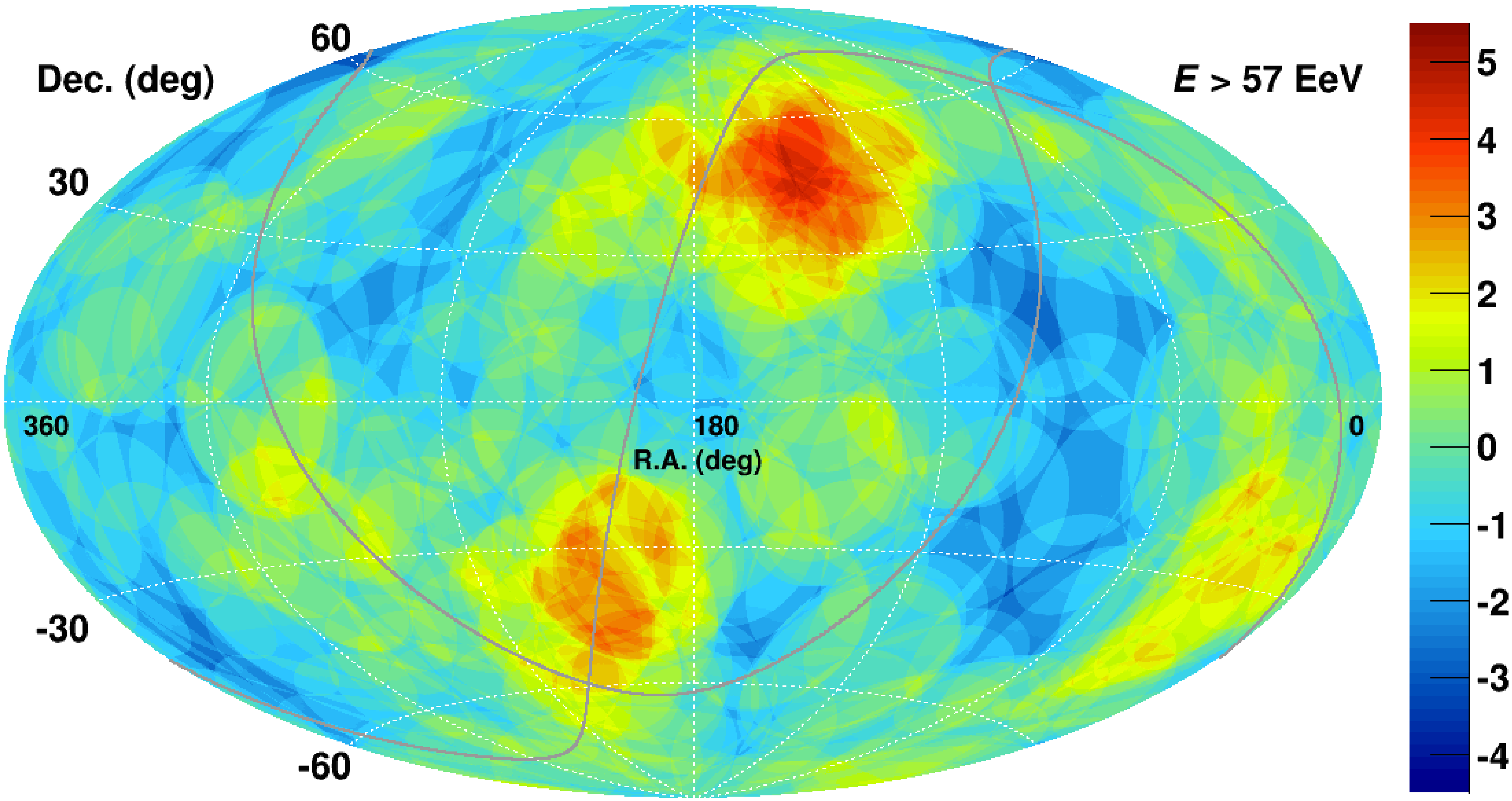
K.S. Test shows data is consistent with fluctuation for hotspot (Poisson: average = 3.43 per year, no time variation),

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 !!

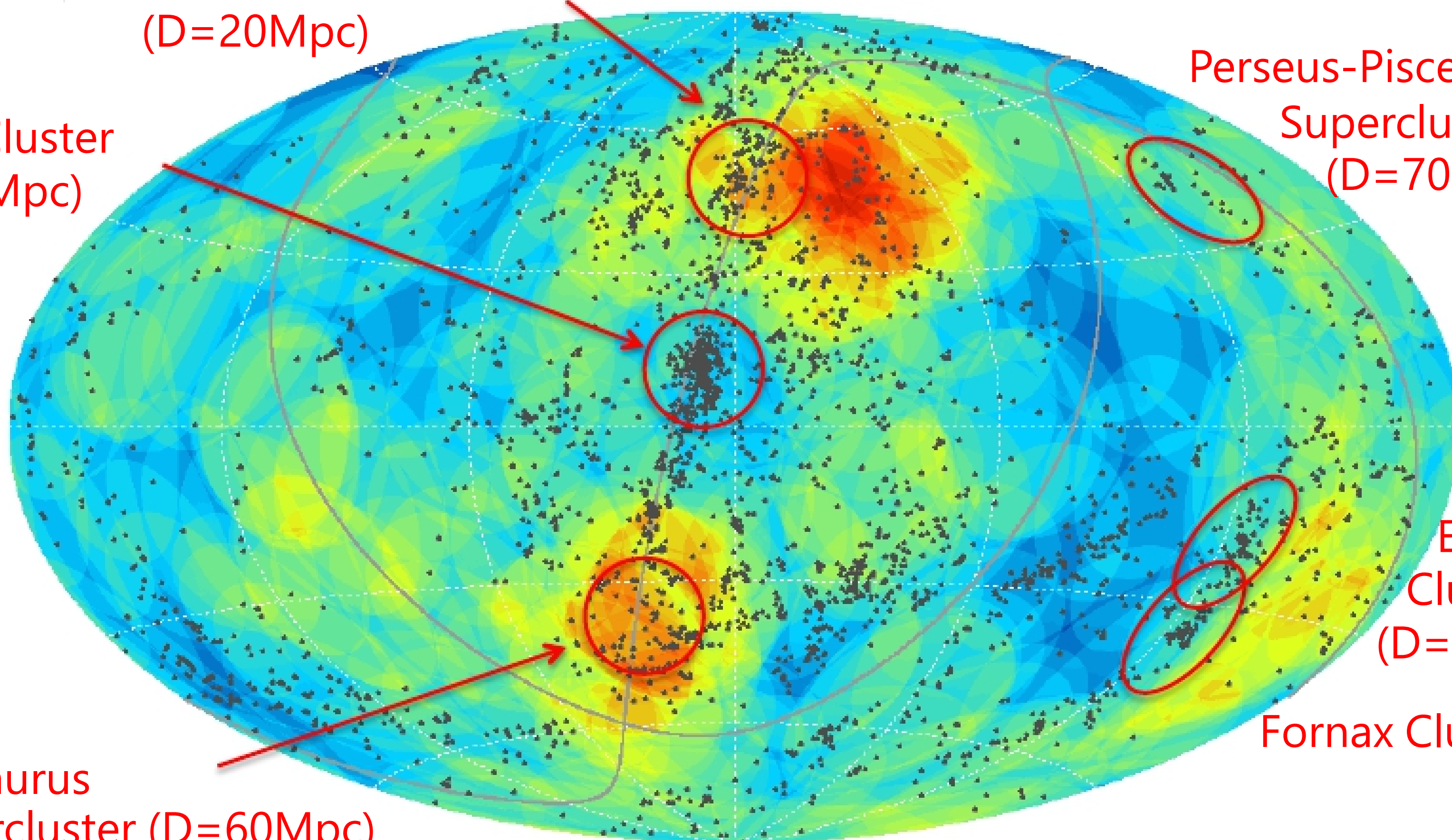
TA : 7 years 109 events (>57EeV)

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

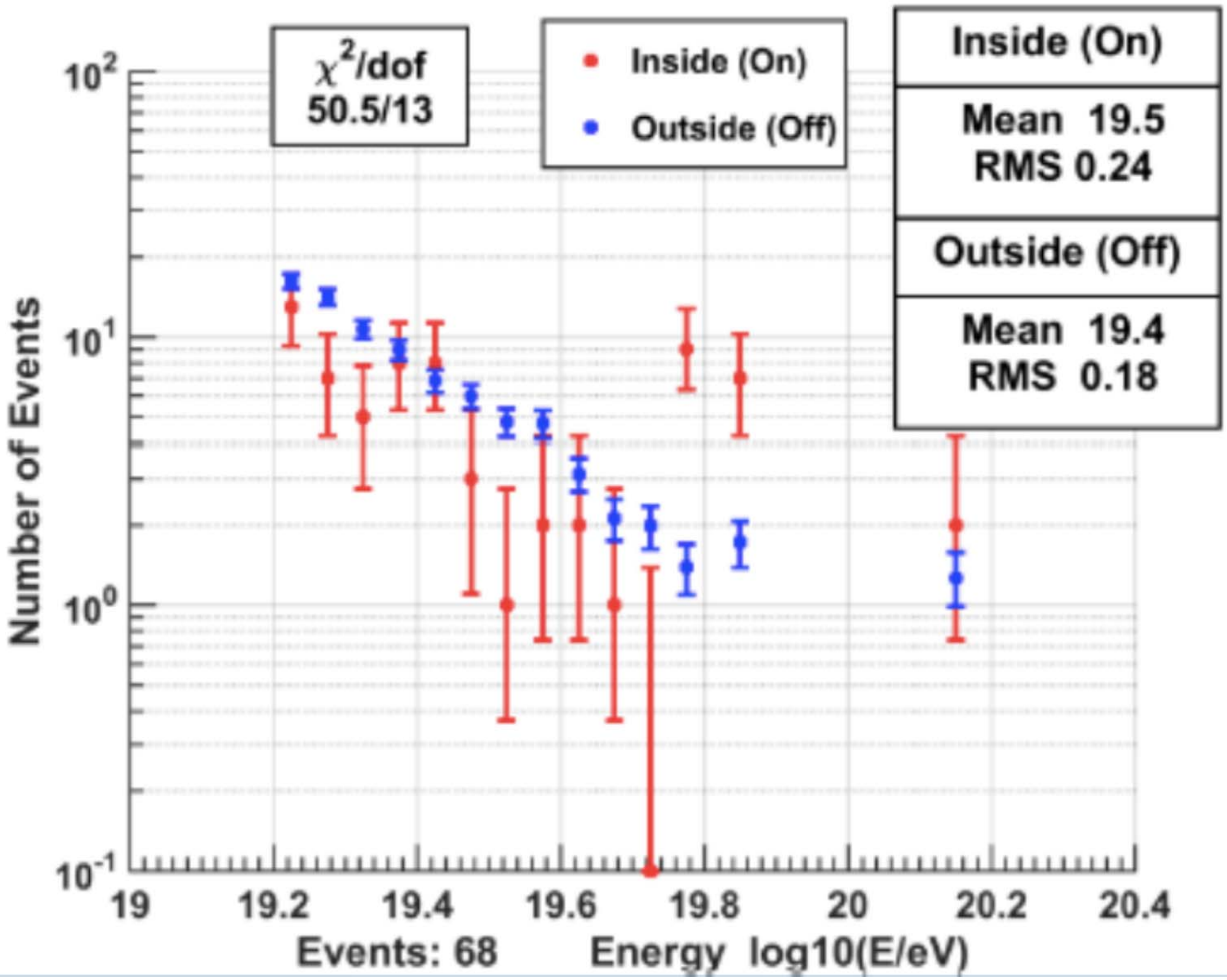


Huchra, et al, ApJ, (2012)

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

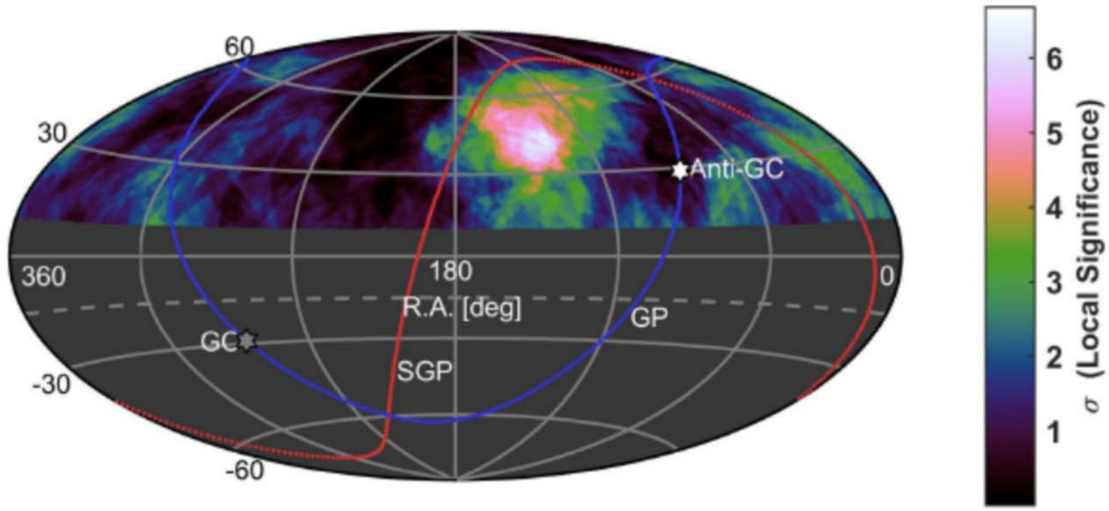
TA hotspot is found near the Ursa Major Cluster
TA & PAO see no excess in the direction of Virgo.

Anisotropy in the Energy Spectrum

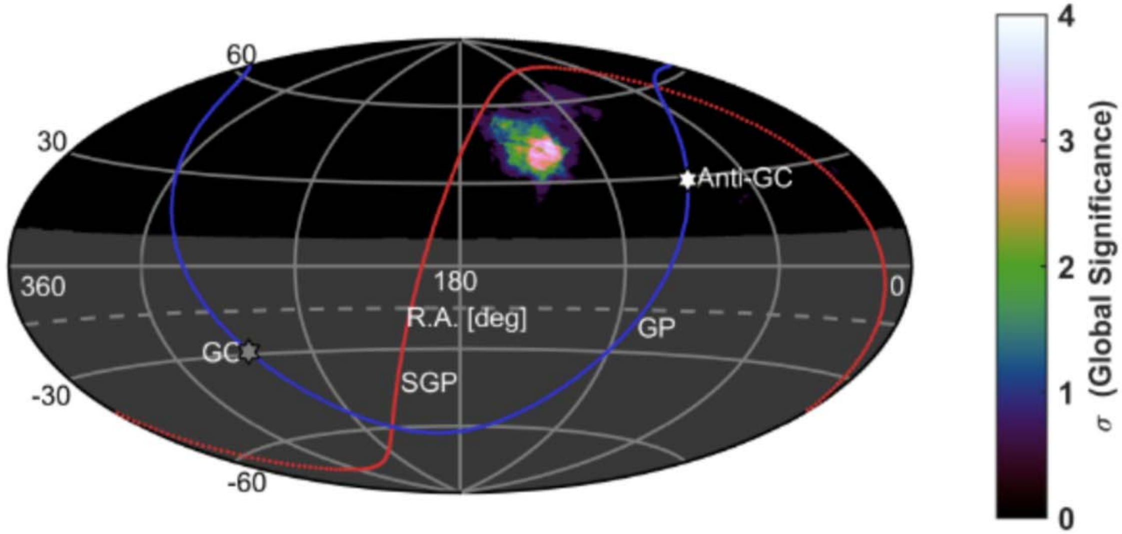


Spectral differences “on” and “off” of the Hot Spot

Anisotropy in Energy Spectrum

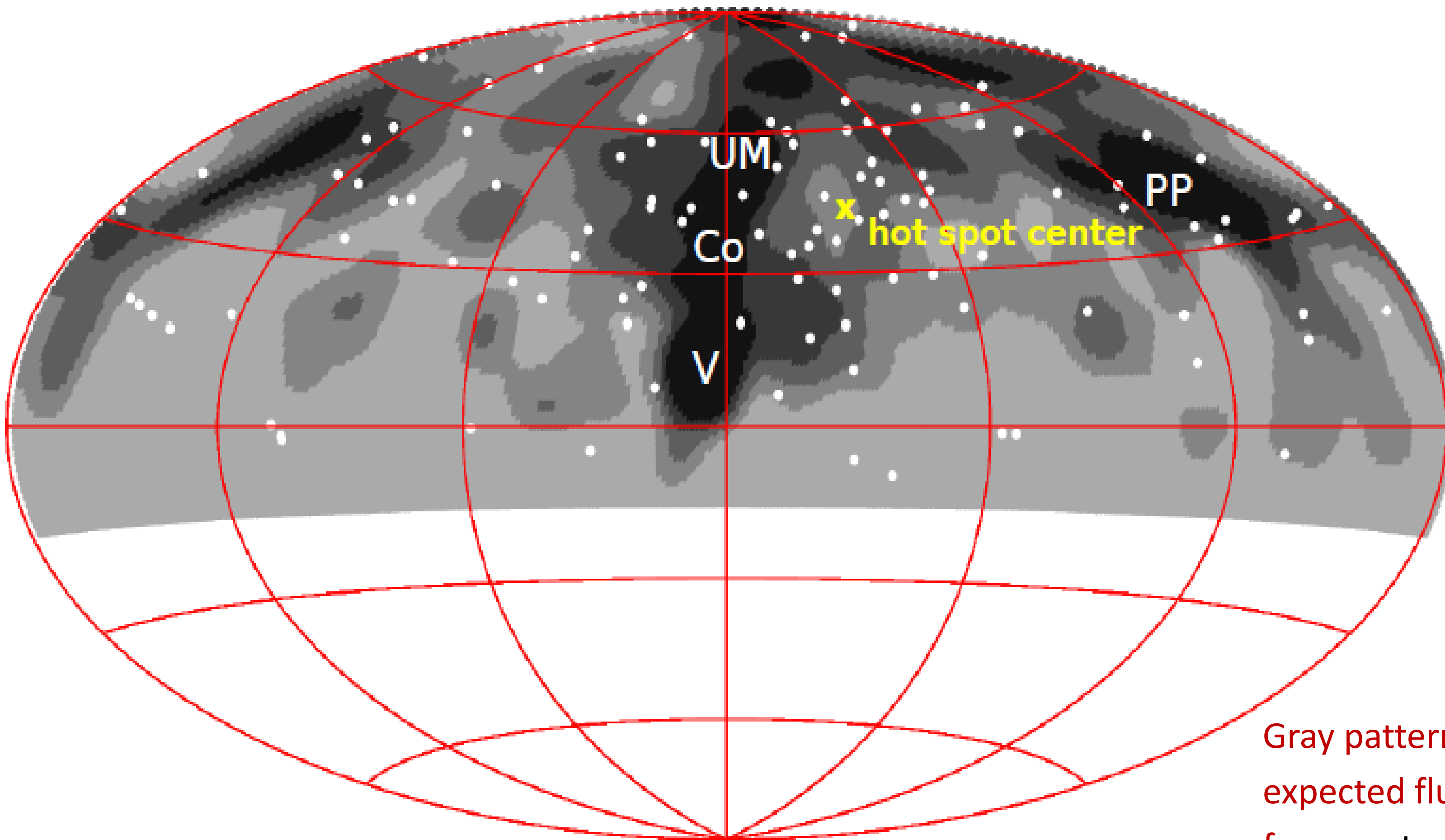


Local: 6.7σ



Global: ~4σ

Correlation with Large-Scale Structure (LSS)



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

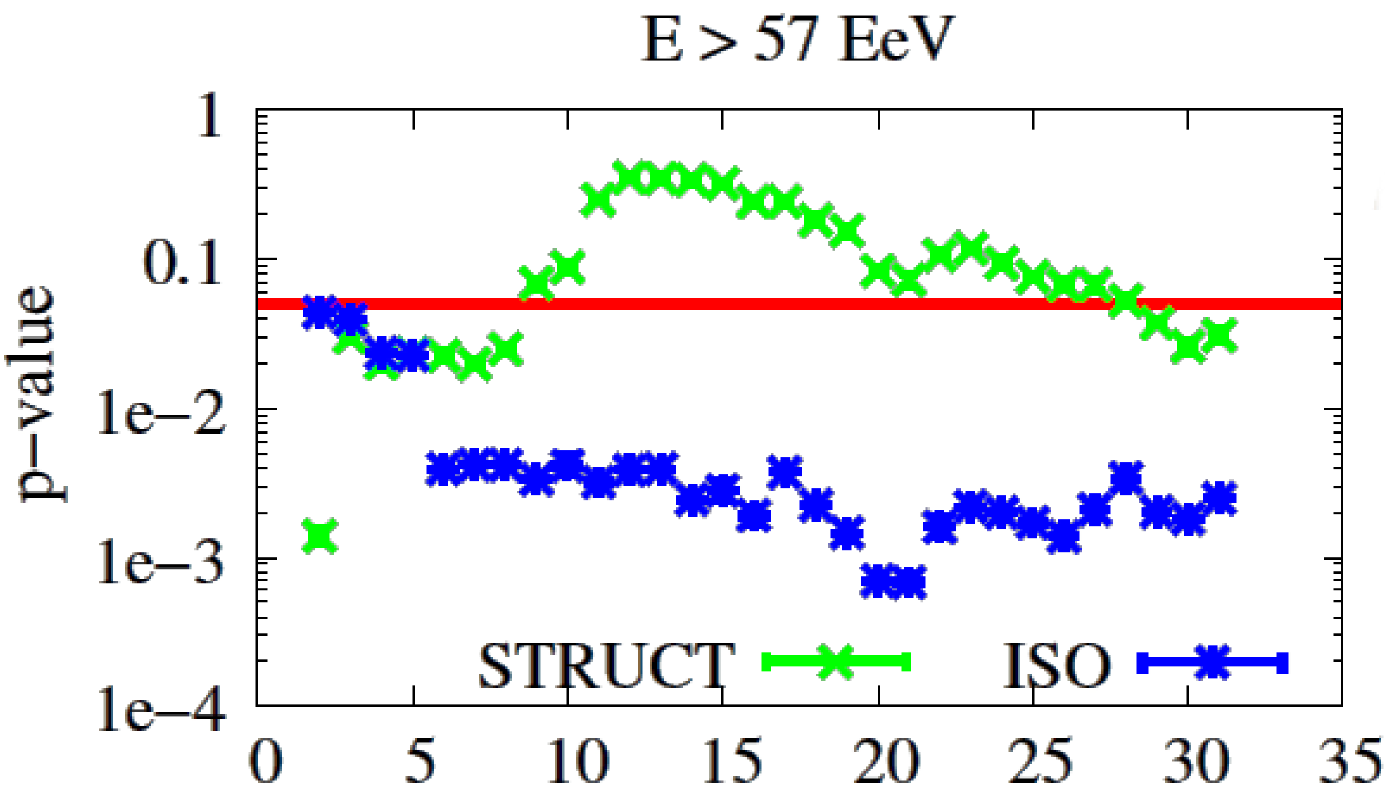
Gray patterns: expected flux density from proton (E=57 EeV) LSS 2MASS Galaxy Redshift catalog (XSCz)

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

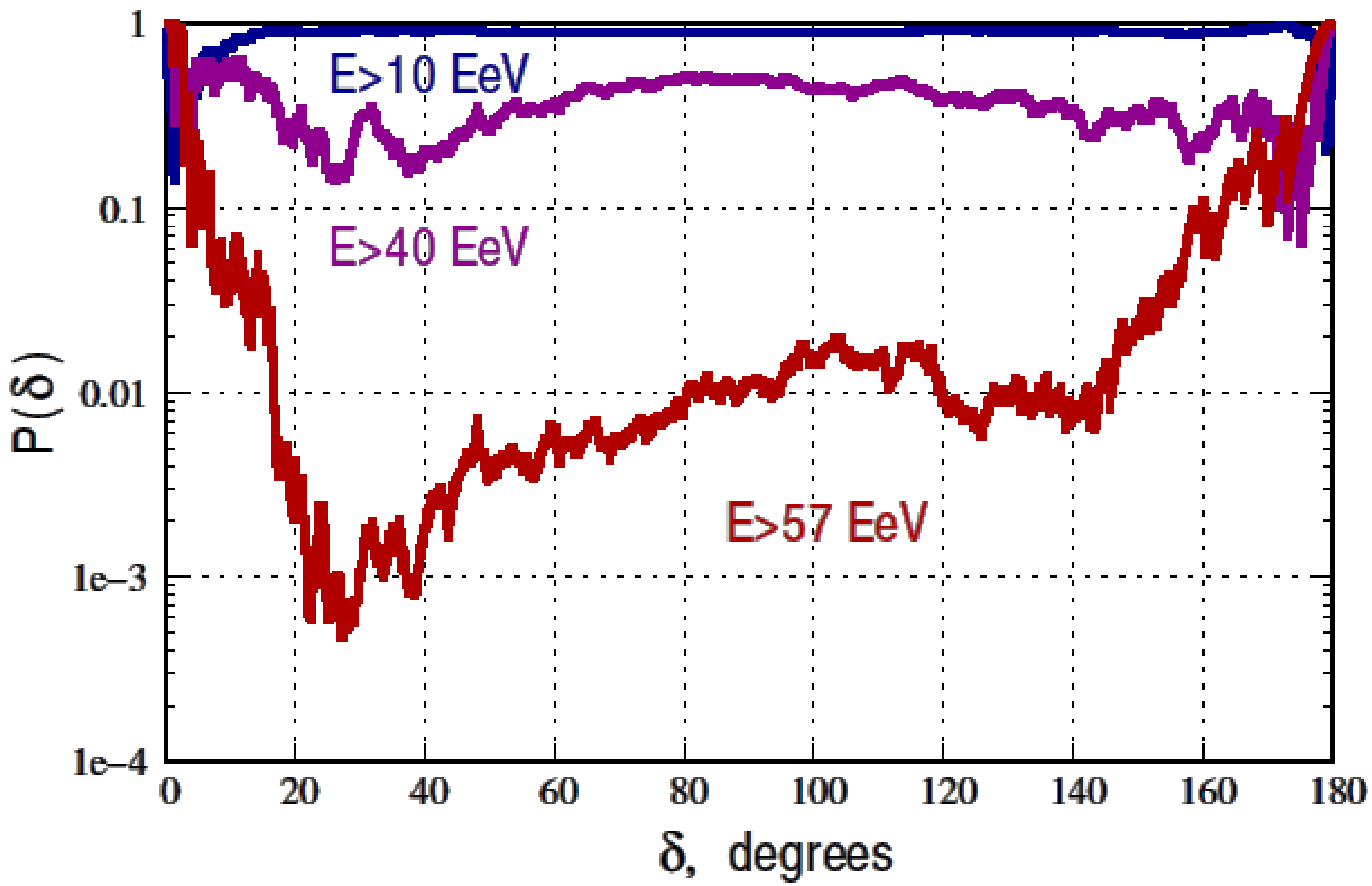
Compatible with LSS source simulation



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:

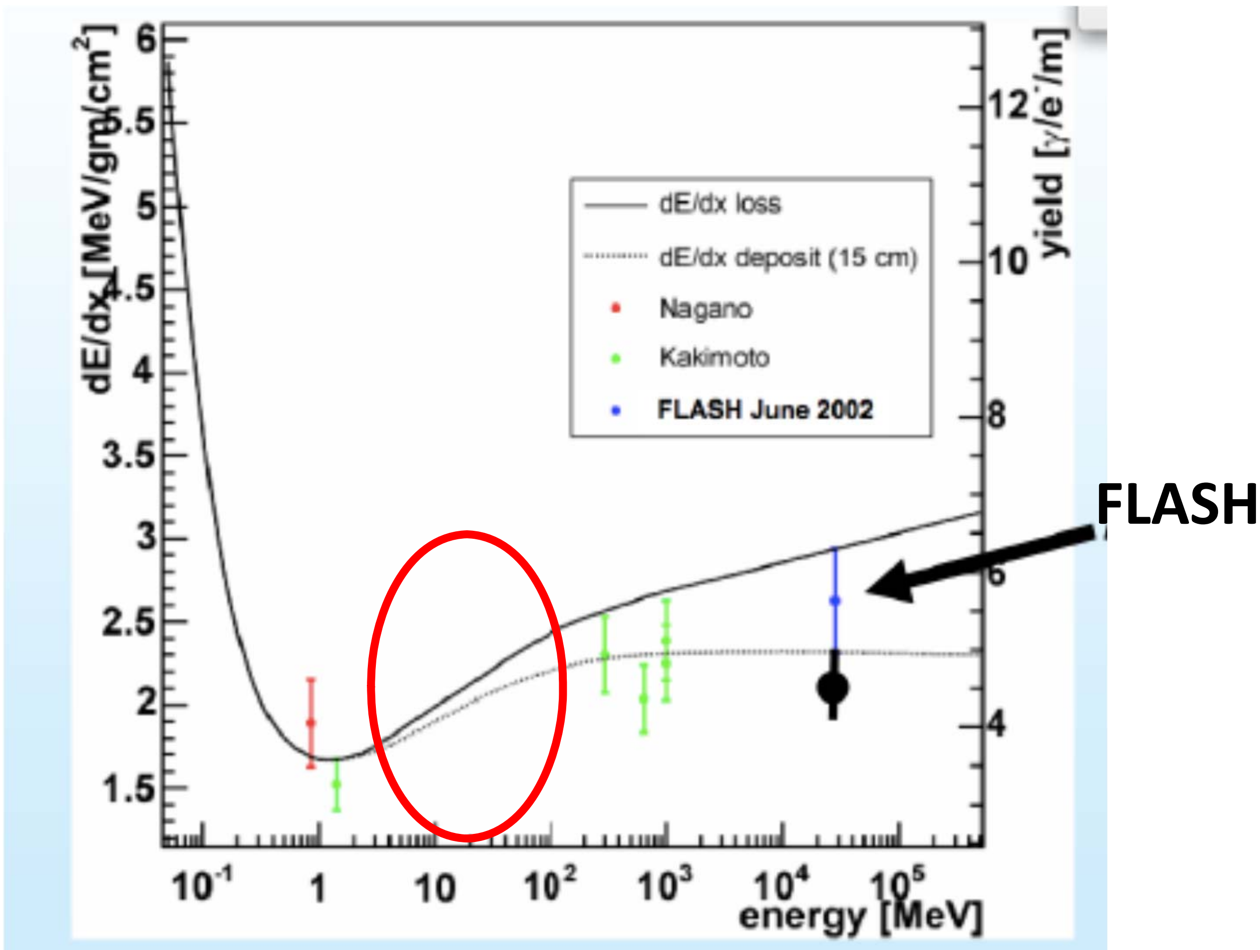
1. Count number of pairs of events at in the bin at separation δ
2. Chance Probability is given by the fraction of isotropic MC sets (with equal statistics) with as many or more than the number of pairs seen in data

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

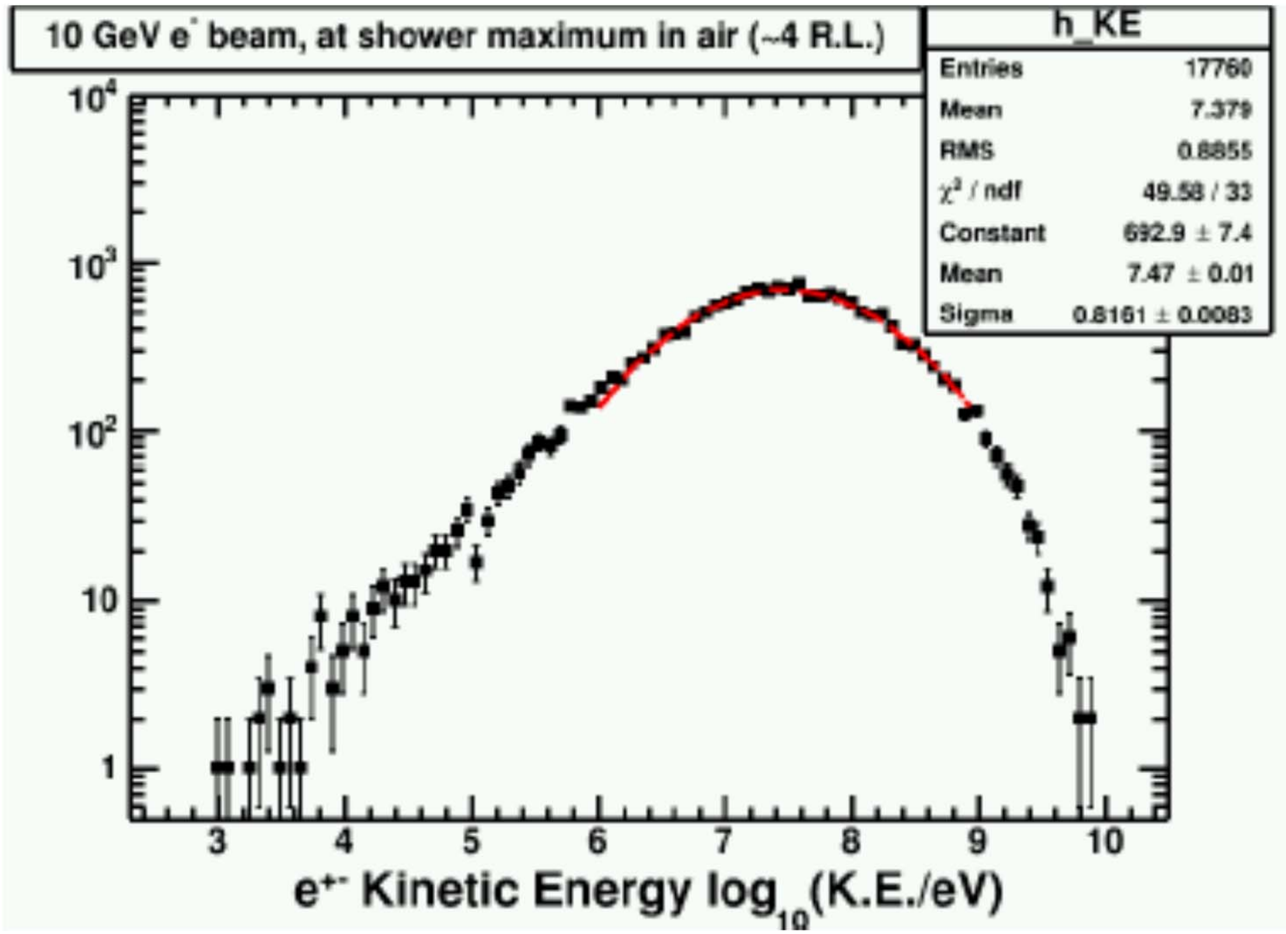
In Related News:

- Discussion of energy scale revealed outstanding issues including missing energy and energy dependence of the fluorescence yield
- Previous FLASH thin target: high energy (28.5 GeV) and thin sampling chamber (1.7cm): 30% missing energy
- FLASH thick target: relative measurement (shower profile), no absolute measurement
- AirFly: 120 GeV beam in Nitrogen, relies on 337nm, two other experiments to get from N to air
- MacFly: measured relative yield as a function of radiation length of Cu target using 50 GeV low intensity slow spill proton beam. Measured relative yield. Absolute yield had large systematic errors (+/- 23%)

Shower max energy range not well covered by experiments



10 GeV Air Shower MC



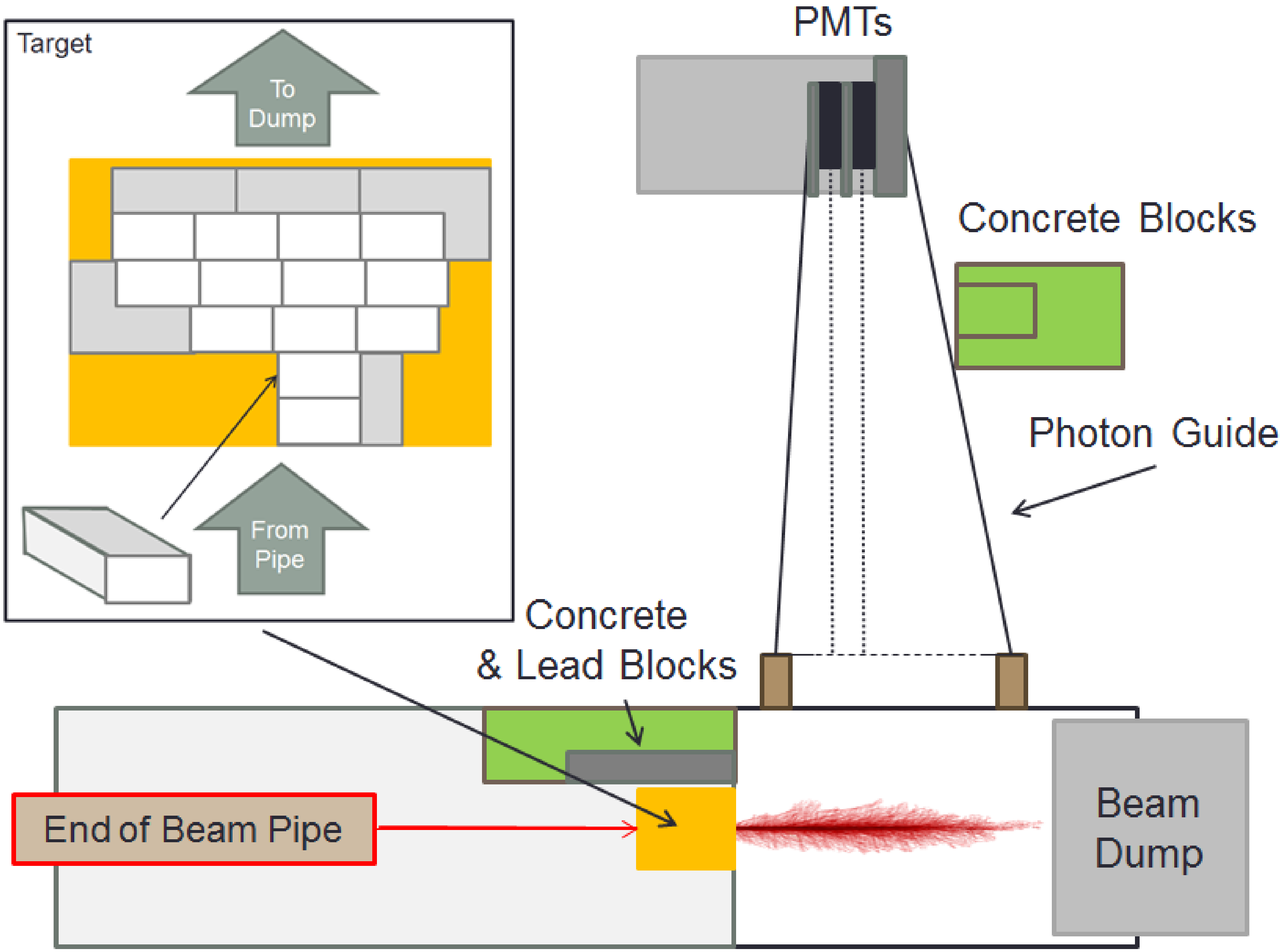
E_{ave} = 23.9 MeV, FWHM: 2-250 MeV

Revisit Fluorescence Yield

Basic idea of SLAC T-542: sFLASH

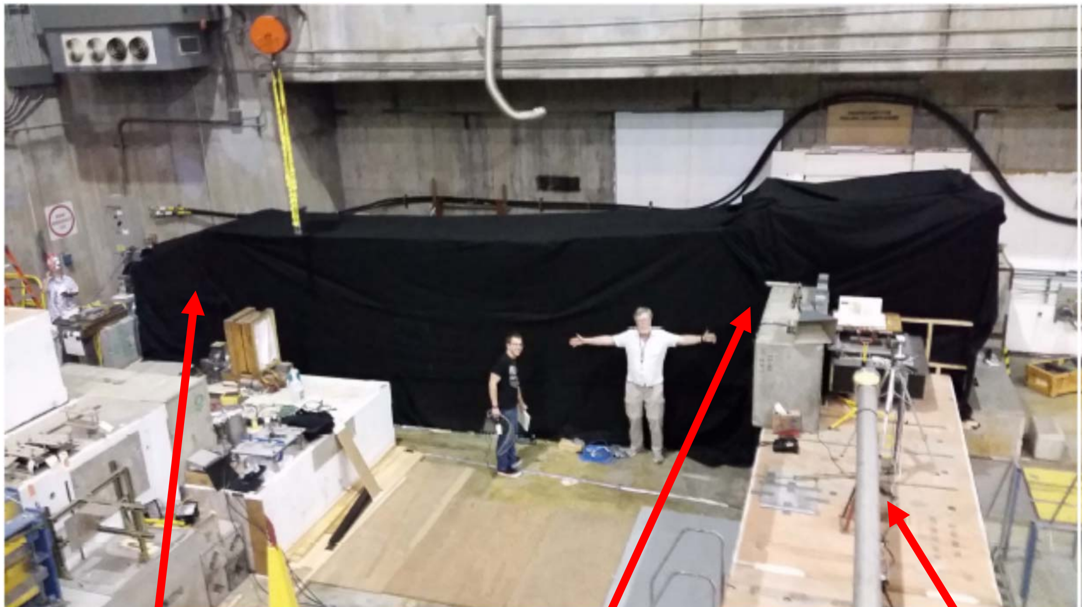
- Deposit E_{EM} ~10^{18} eV (10^{9} e in a pico-second bunch @ 10-15 GeV) into air-equivalent material (Alumina). Shower develops in 0 – 3 r.l. of Alumina (Al_2O_3)
- Measure the air fluorescence photons after the shower exits into air (3 m of air to beam dump) – Particle energies similar to those around shower maximum
- Fluorescence yield of 10^{18} eV electromagnetic shower near shower maximum in air

sFLASH Experiment Setup

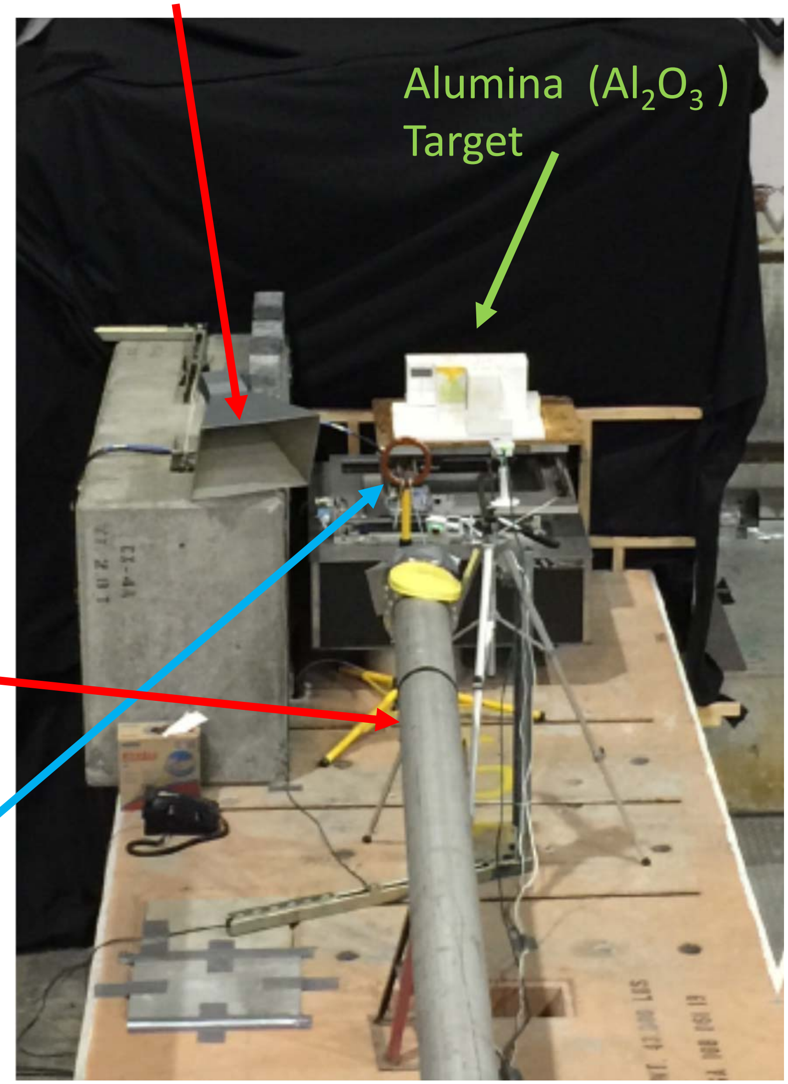


sFLASH In Real Life:

End Station A at SLAC



S-band Horn Antenna



Beam Pipe

PMTs

Window (1x1.2m)
& Shutter

ICT: Integrating
Charge Transformer

sFLASH

- Picosecond beam pulses at SLAC means very large signals are possible. ESA geometry allows shower to develop in meters of air (corrections for delta rays minimized compared to thin chambers)
- Proof of concept in July
- Short run in Sept.
- Improved design to control FOV
- Add shielding (scattering from beam dump) greatly improved S/N (3->30)
- Currently calibrating and looking at data
- First pass puts us in the ball park, now need to beat down the error bars
- Goal is <10% uncertainty in absolute yield

The Future of TA

TA×4 Project

<u>**Quadruple** TA SD (~3000 km^2)</u>

500 scintillator SDs

2.08 km spacing

Approved in Japan 2015

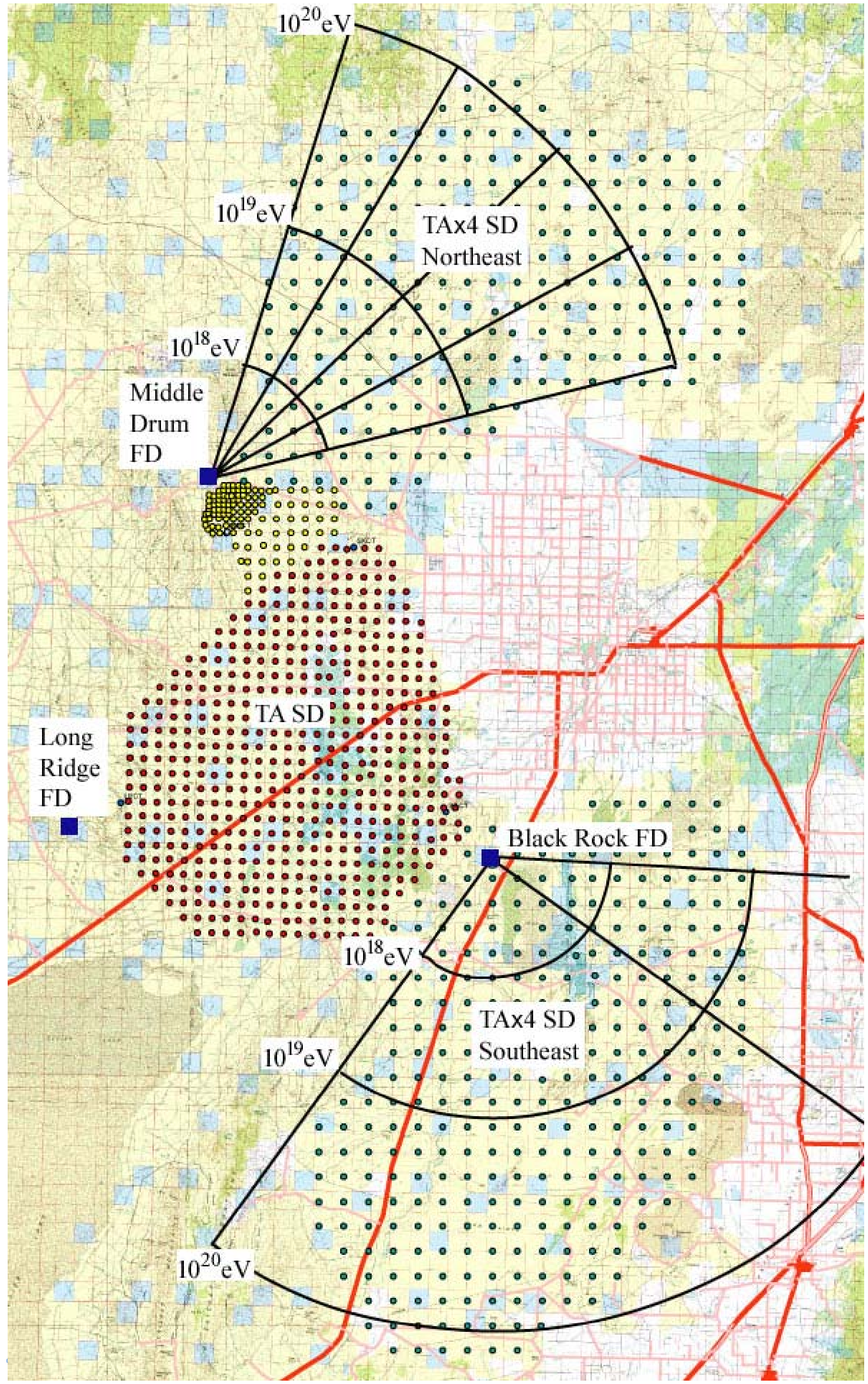
3 yrs construction, first 100 SDs have arrived in Utah (2016-05), second shipment is being preparred

<u>2 FD stations (12 HiRes Telescopes)</u>

<u>Funding approved US summer 2016</u>

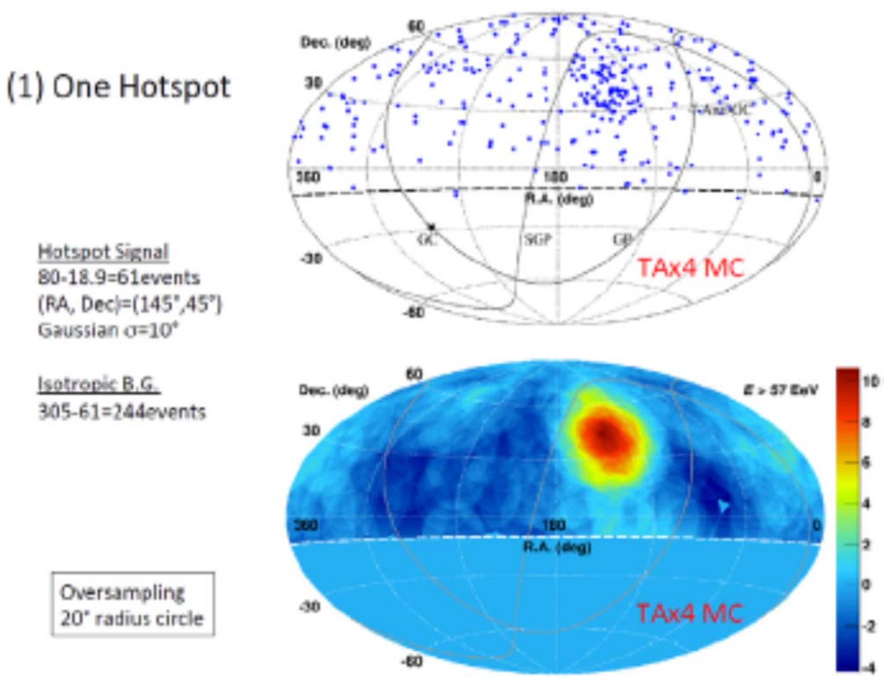
<u>**Get 19 TA-equiv years of SD data by 2020**</u>

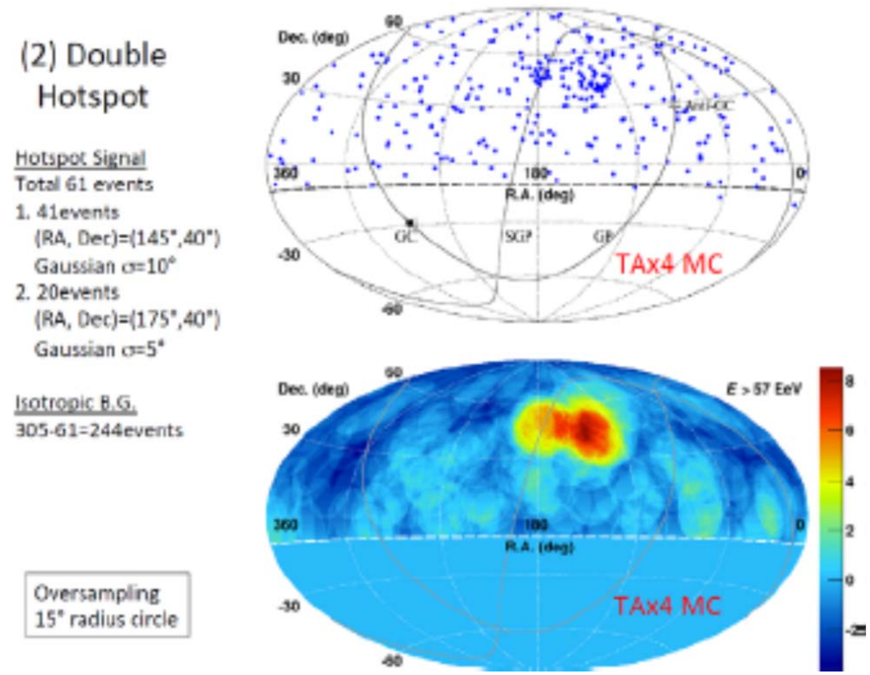
Get 16.3 (current) TA years of hybrid data



Clarify the details of the Hotspot

Simulated 19 TA-equiv yrs data



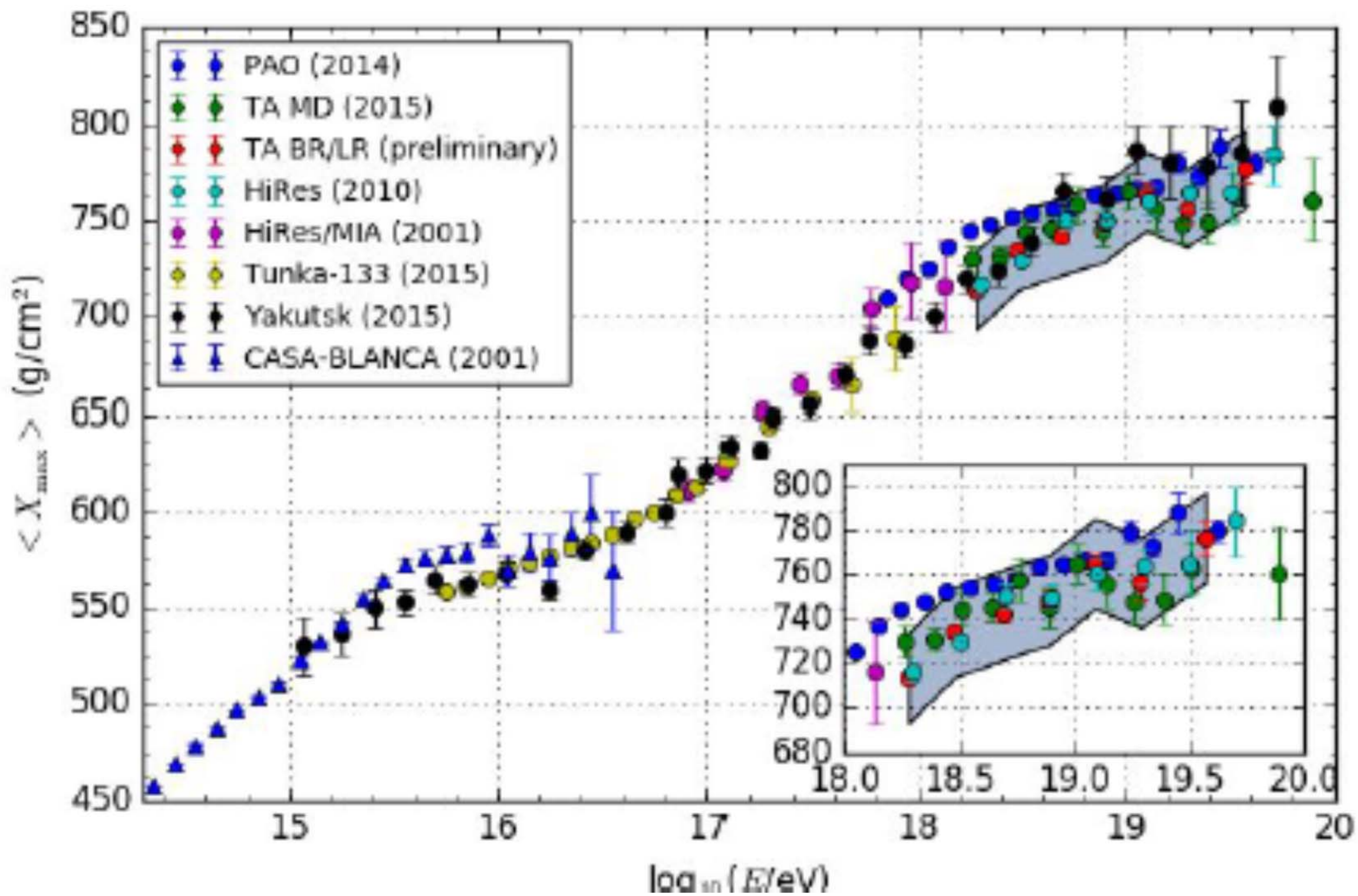


Single Source

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 light component at above the ankle (~6×10^{18} eV).
- We have reported a hot spot seen in the direction of Ursa Major
- Hints of anisotropy are beginning to emerge, but nothing conclusive
- ***New:*** TA Low Energy Extension (TALE) is coming on line.
- 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
- **Much more data are needed! – coming soon TAx4**

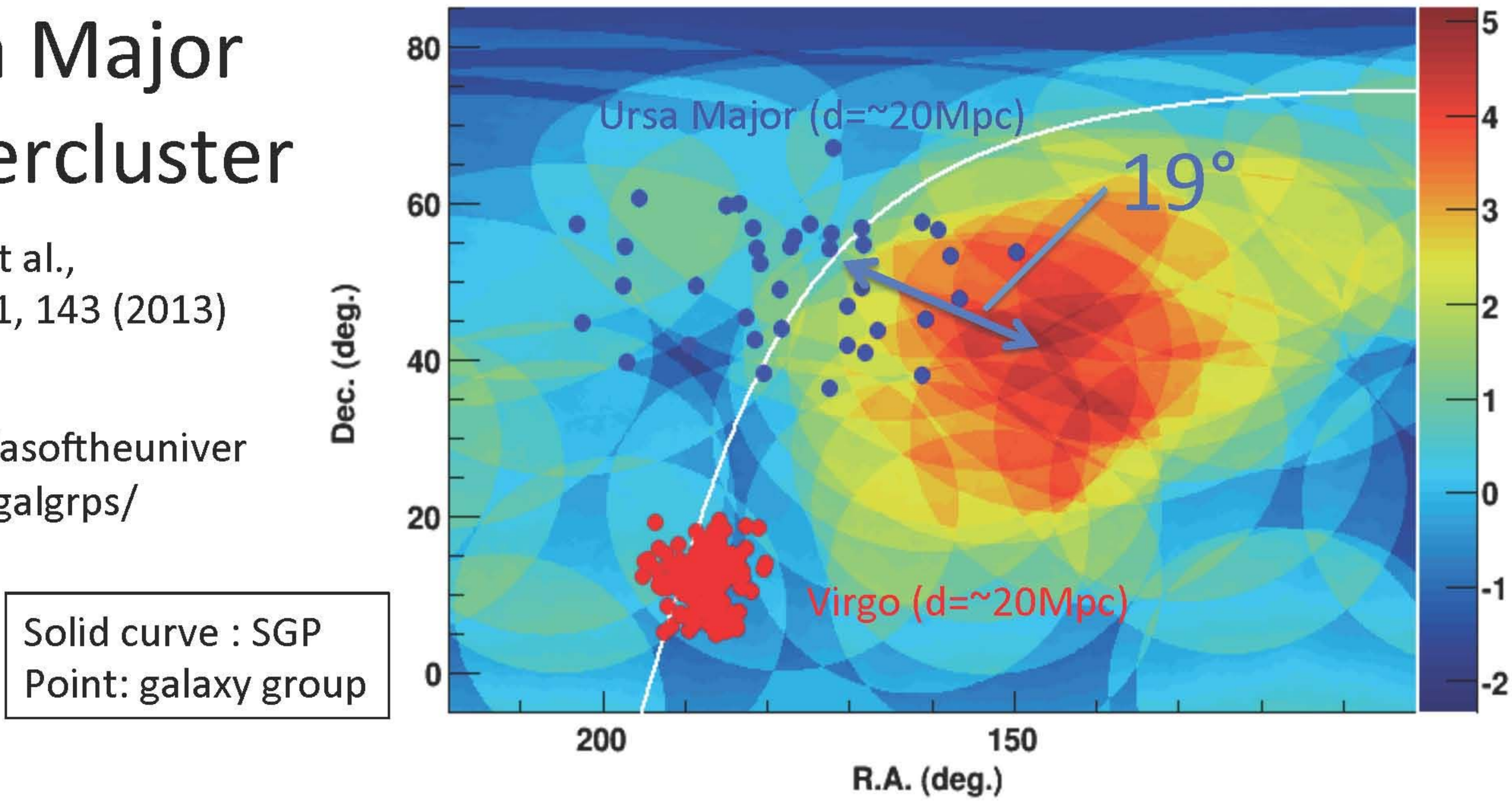


A deeper understanding of the Xmax systematics will help close the gap in the measurements at the highest energies

Ursa Major Supercluster

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

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



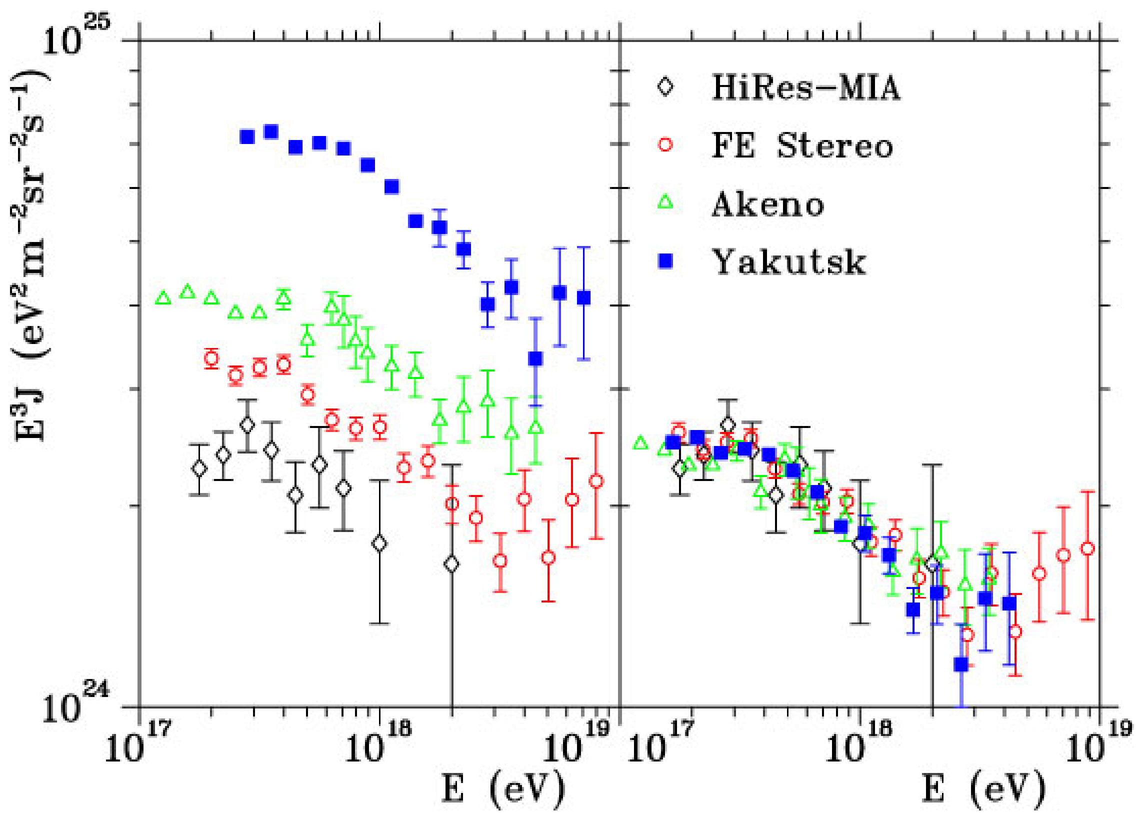
The angular distance between the hotspot center and the supergalactic plane is estimated to be 19◦. The Ursa Major supercluster is extended by more than ±10◦ from the supergalactic plane. We therefore cannot rule out some relationship between the hotspot and this supercluster.

Mrk421? Filament to local cluster ?

Comparison to Previous Attempts

- Previous incarnation a thick target for FLASH measured relative air fluorescence as a function of rad. Length with 28 GeV electron beam. No absolute measurement. Shower measured in small air gap, 2.5 cm thick chamber
- MacFly measured relative yield as a function of radiation length of Cu target using 50 GeV low intensity slow spill proton beam. Measured relative yield. Absolute yield had large systematic errors (+/- 23%)
- Picosecond beam pulses at SLAC means very large signals are possible. ESA geometry allows shower to develop in meters of air (corrections for delta rays minimized compared to thin chambers)

Galactic to Extra-Galactic Transition



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