Recent Results from the Telescope Array Experiment

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Telescope Array Collaboration

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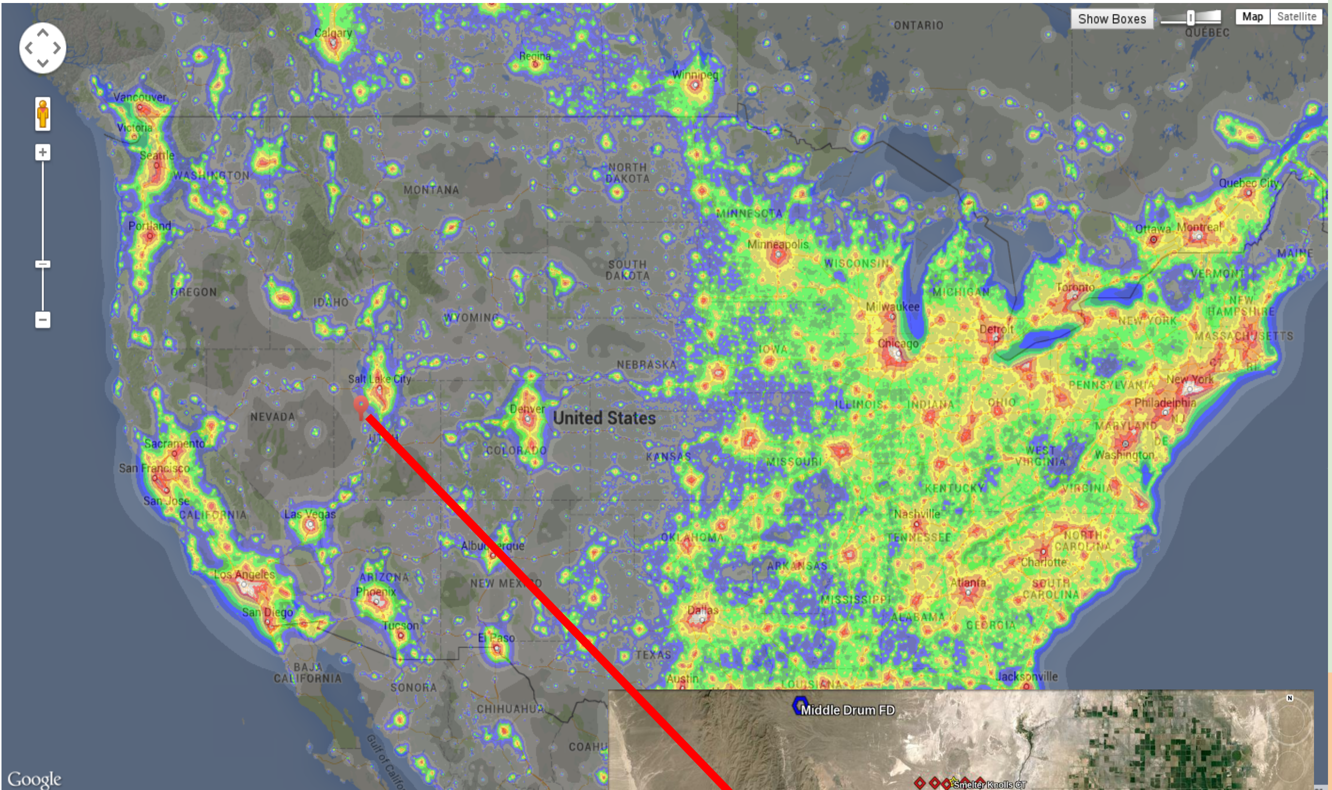
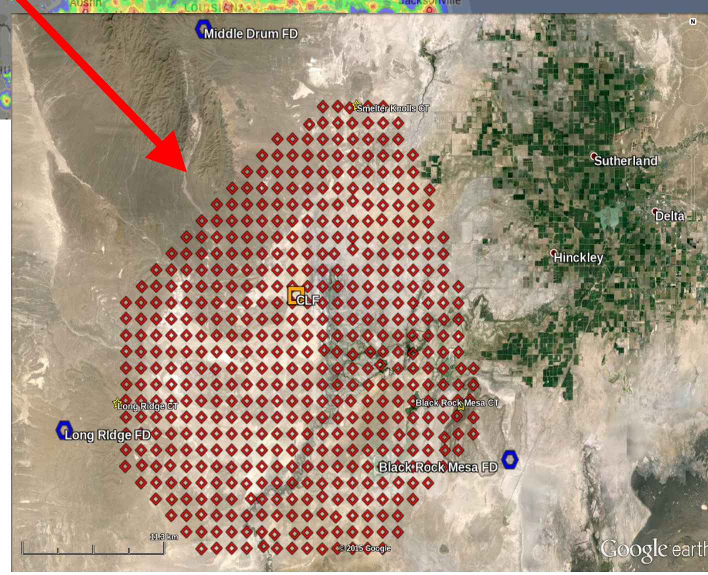
USA, Japan, Korea, Russia, Belgium

Telescope Array Observatory



U.S. Light Pollution Map



Largest cosmic ray observatory in the Northern hemisphere.

~700 km^2 → ≲ *land* area of New York City.

Millard County, Utah
39.30° N
112.91° W
1550 m ASL

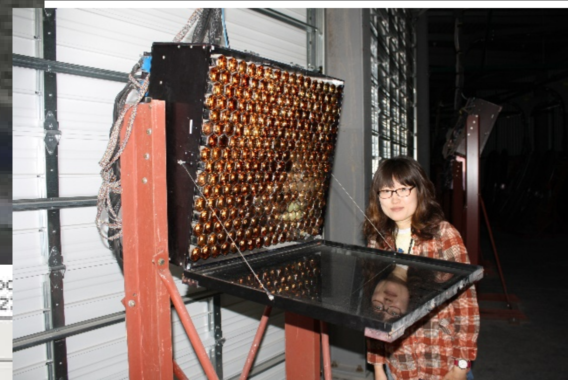
~800 g/cm^2 vertical depth

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) - operational as of 2008.

TA Fluorescence Detectors

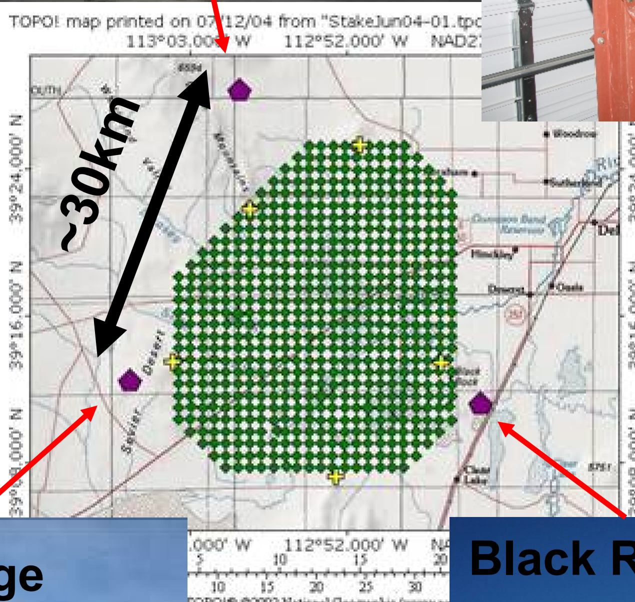
Middle Drum

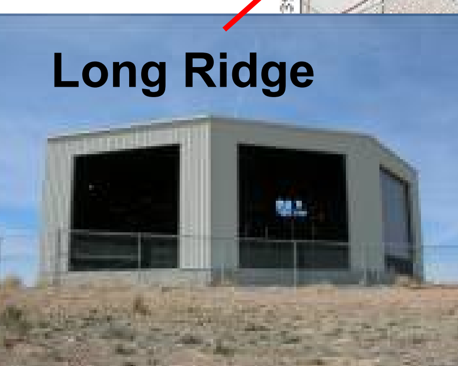
14 telescopes @ station
256 PMTs/camera

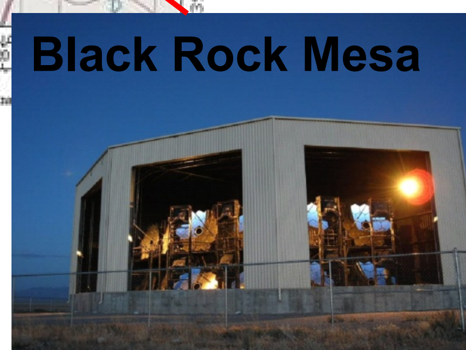


$5.2\ m^2$

Reutilized from HiRes-I

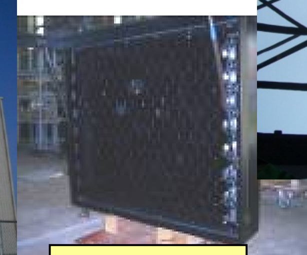






New Telescopes

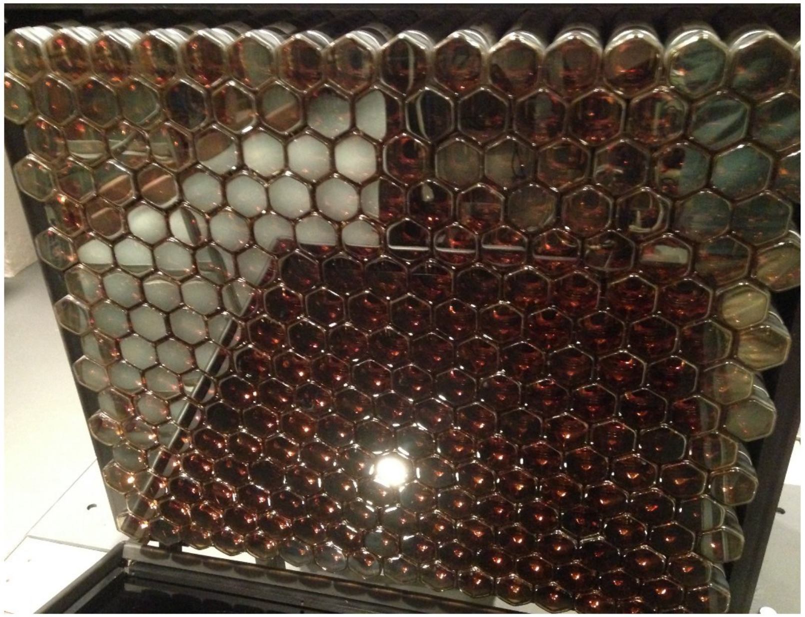
12 telescopes/station
256 PMTs/camera



$\sim 1\ m^2$

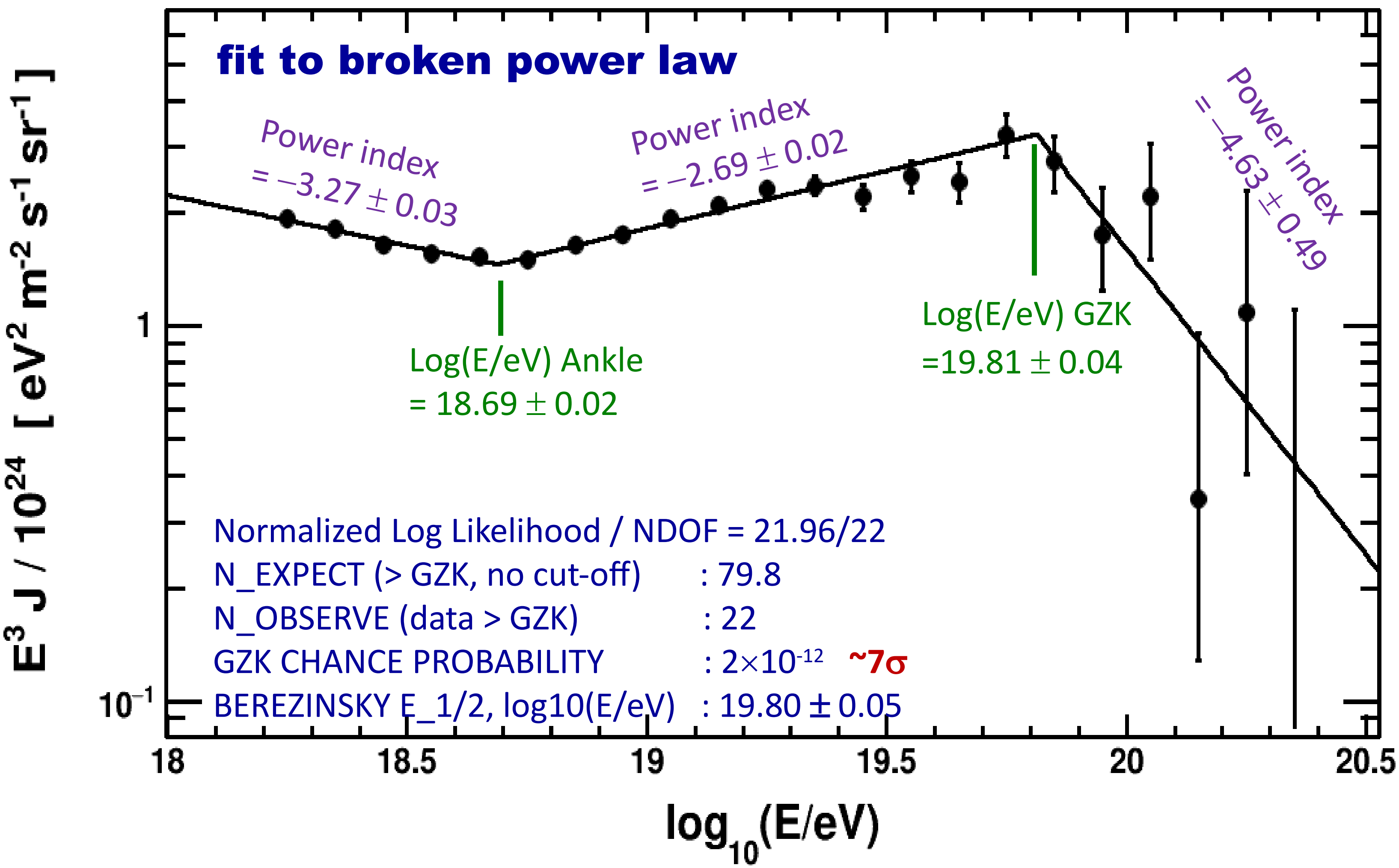
$6.8\ m^2$

TALE FD Telescopes / Camera

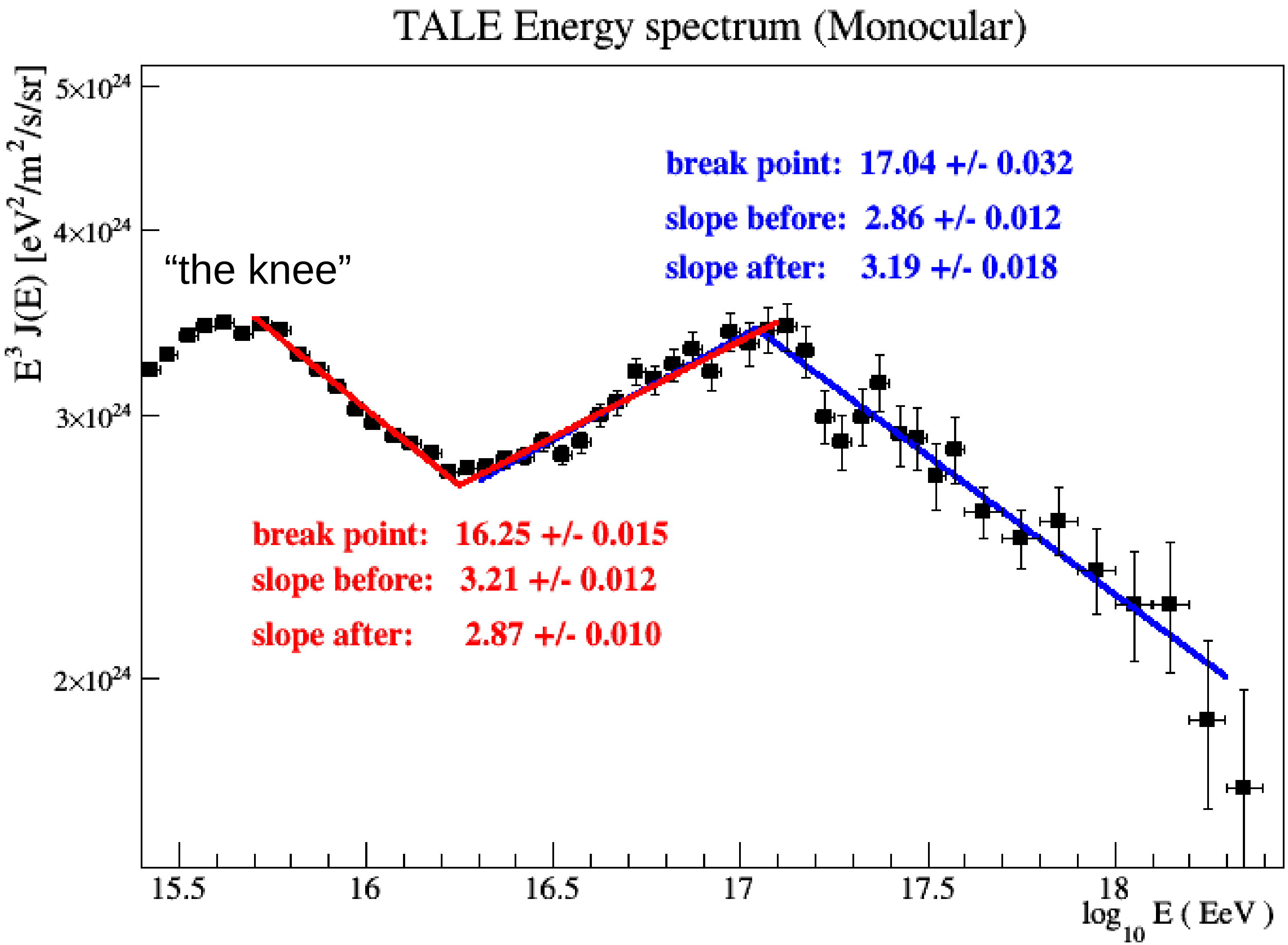


Telescope Array Energy Spectrum Results

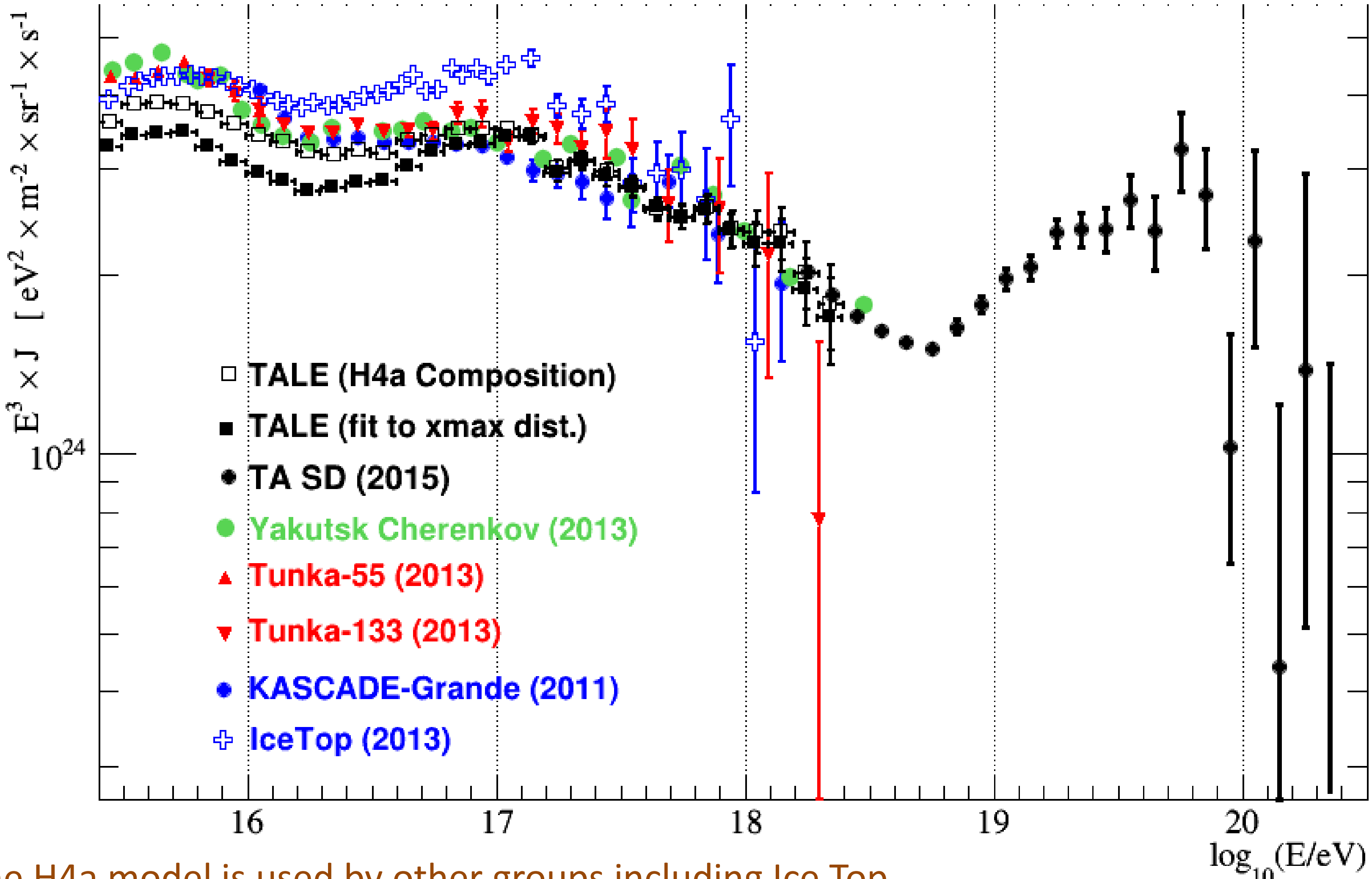
TA SD Spectrum (9 yrs data)



Low Energy Extension Spectrum



Comparison with other Measurements

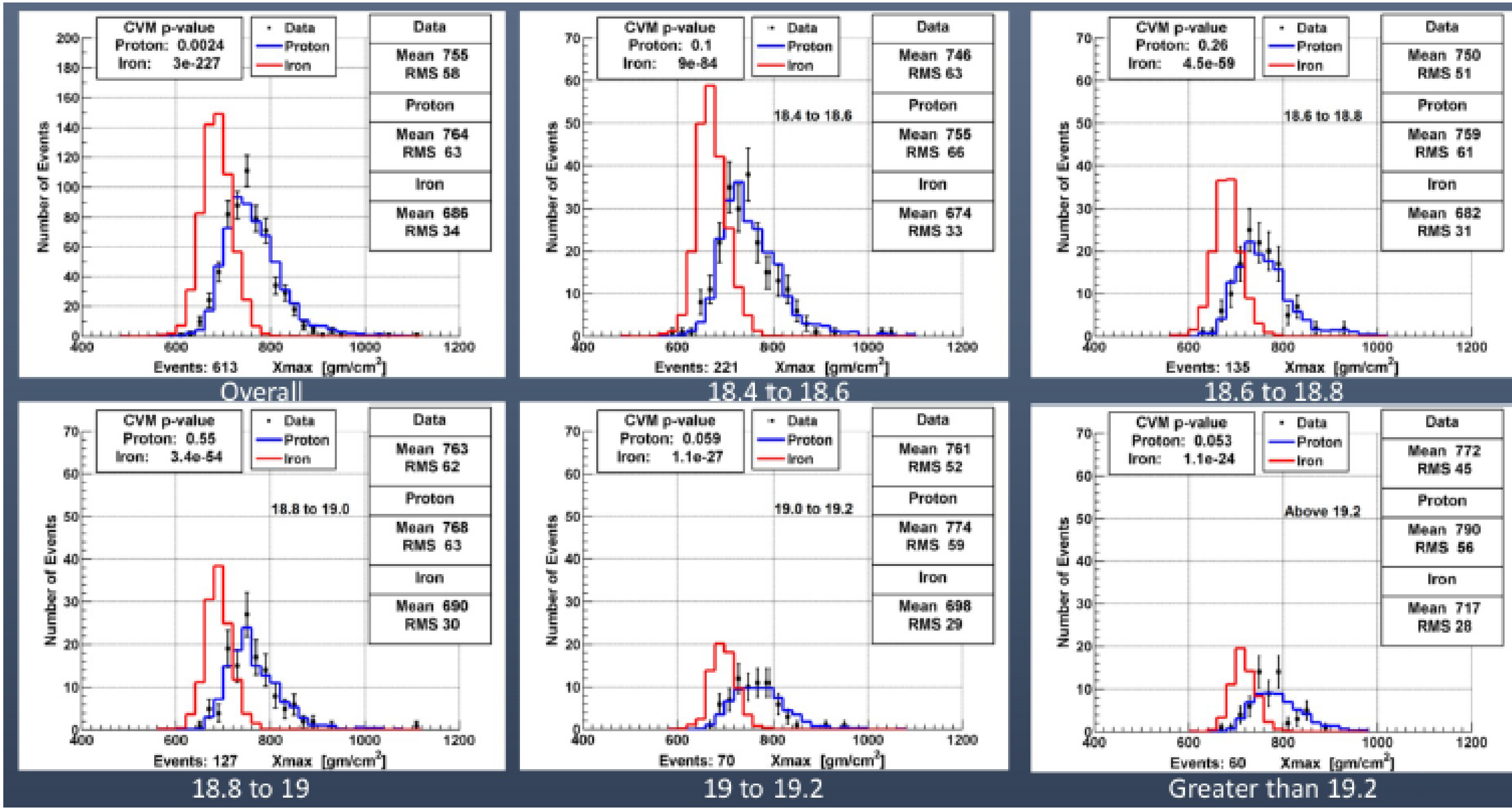


The H4a model is used by other groups including Ice Top. Comparison of the flux using H4a model & TALE Xmax fits checks the systematic error due to uncertainty of the true composition.

Telescope Array Composition Results

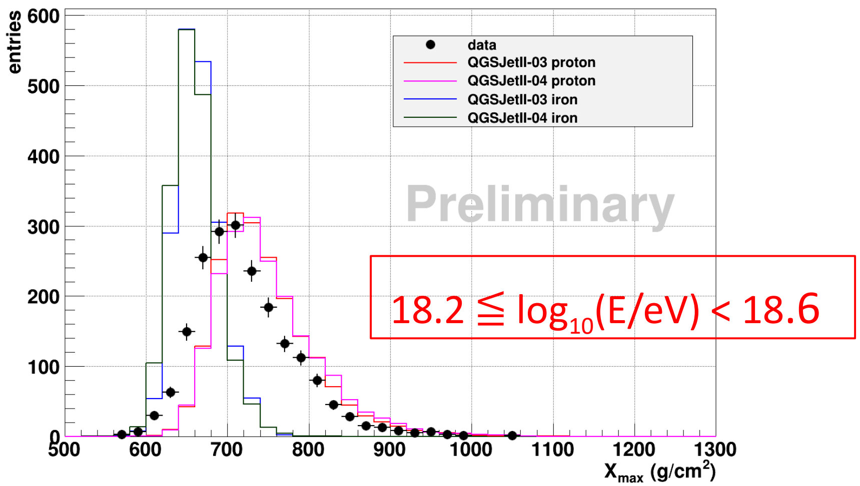
- Use hybrid or stereo to constrain geometry and know X_{max}
- Stereo also provides a redundant measurement of X_{max}

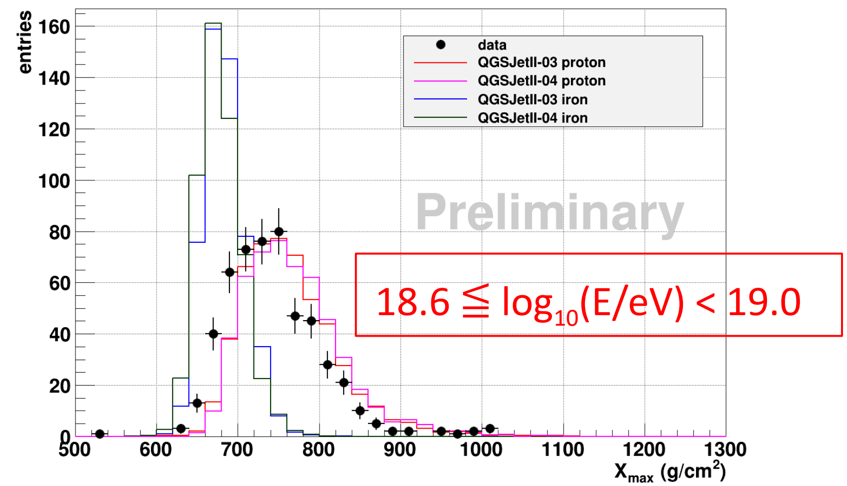
Hybrid X_{max} Measurement (MD)

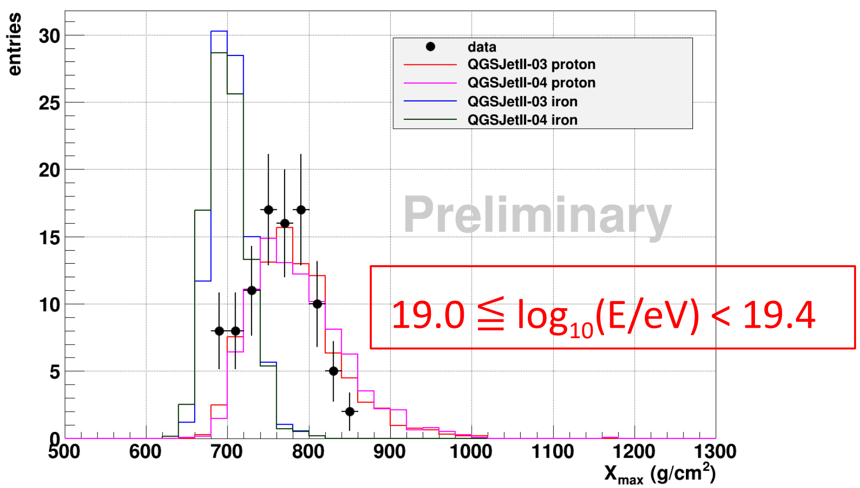


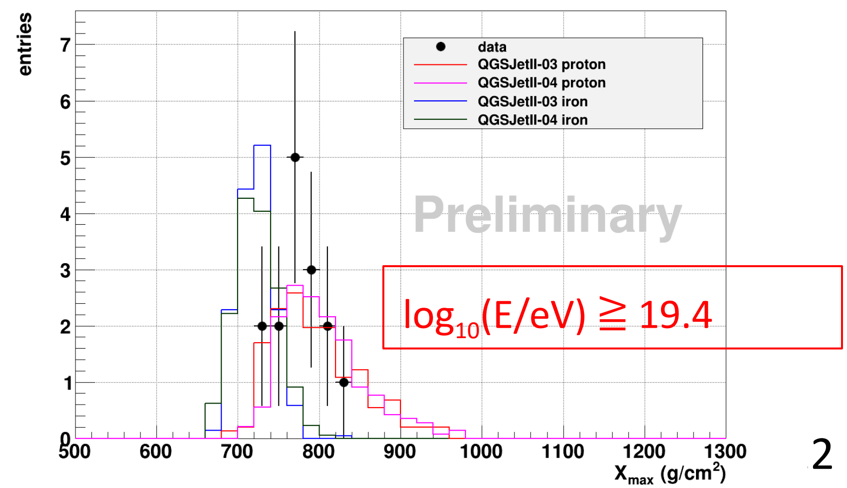
Xmax Data comparison to QGSjet II-03 **proton** and **iron** models

Hybrid TA Composition – (BR/LR)









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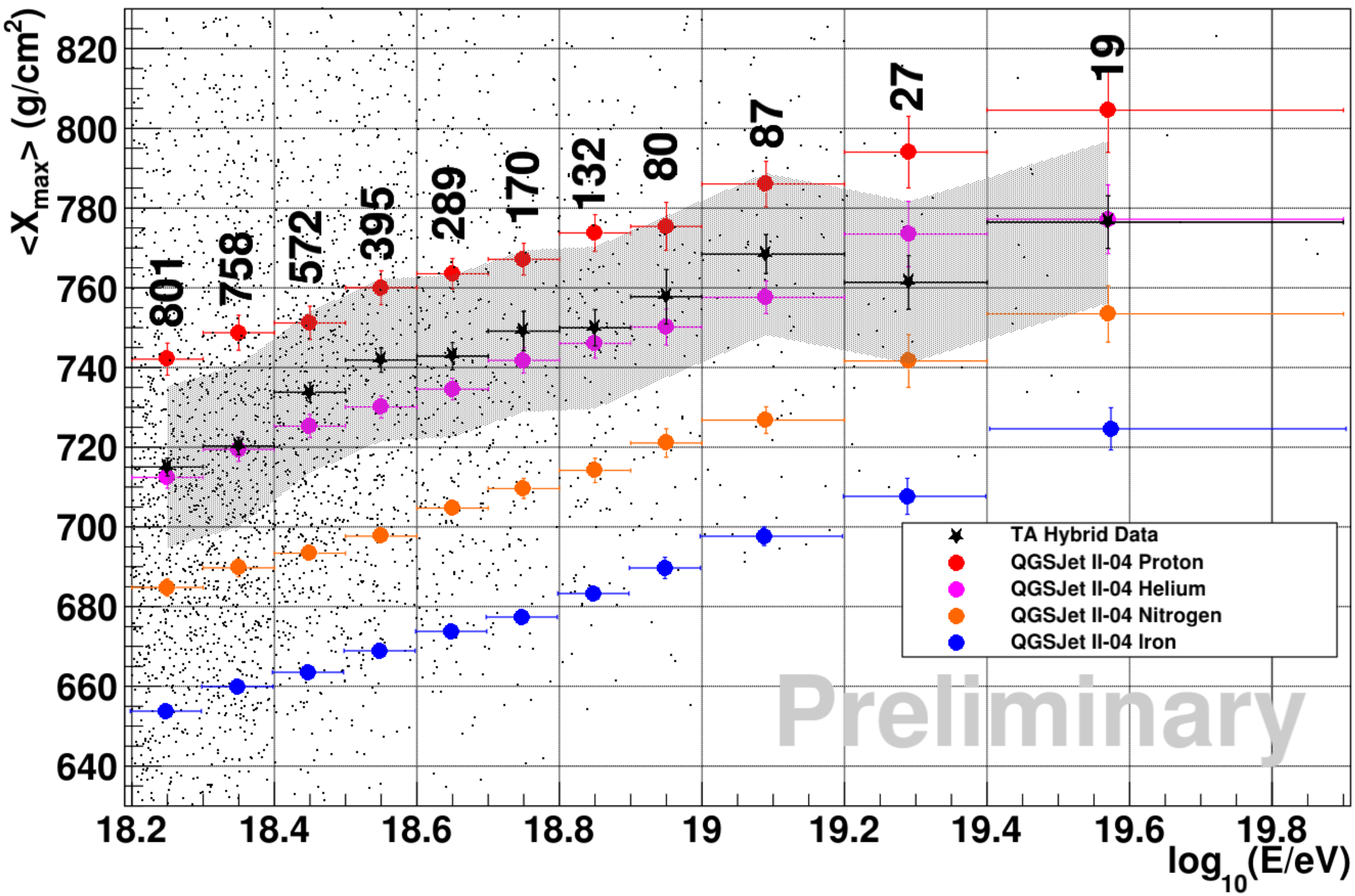
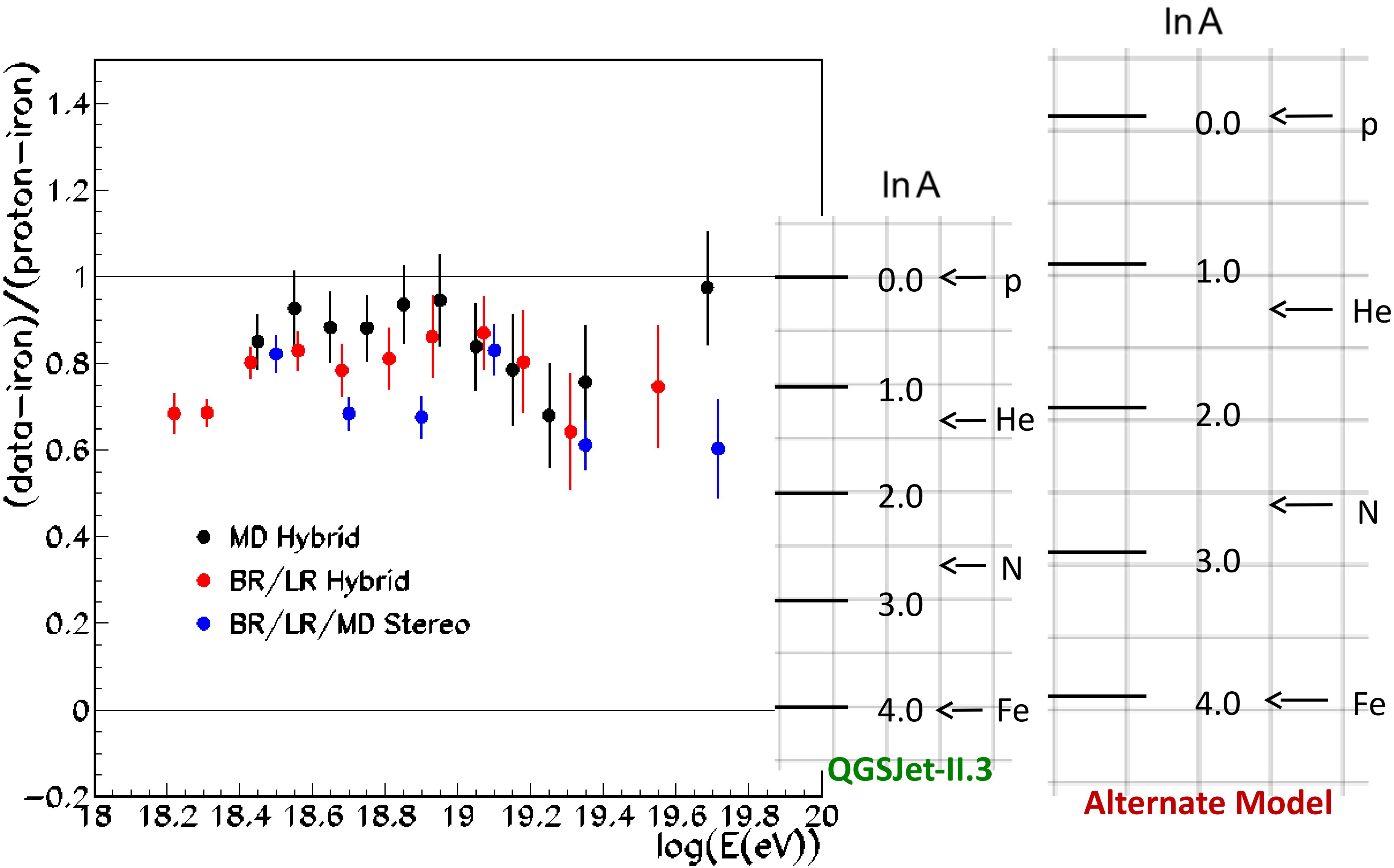
BR/LR Hybrid Composition



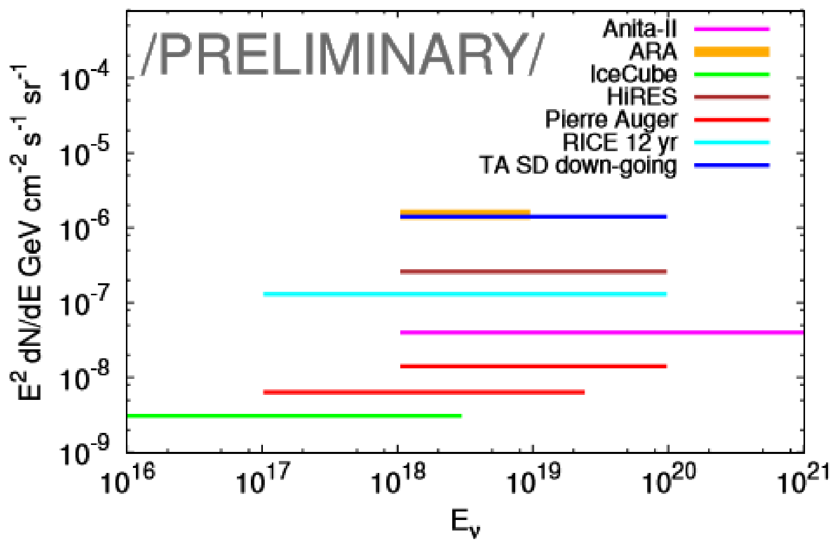
TA data compared to QGSJet-II.3



Neutrino Search

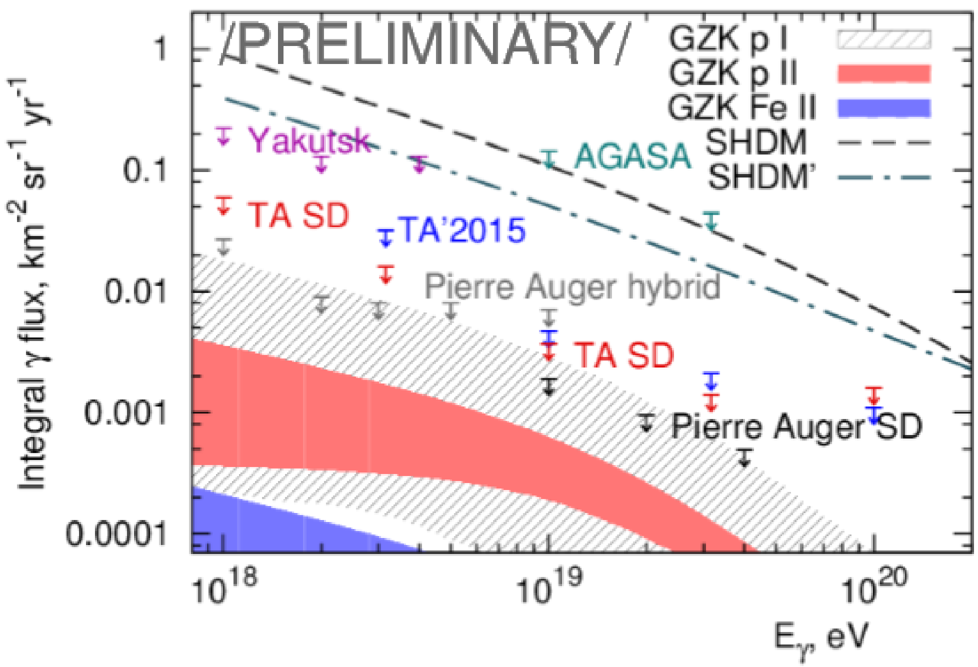
Results

- 0 neutrino candidates after cuts, $\bar{n}_\nu < 2.44$ (90% C.L.)
- **Exposure:**
  - Geometric exposure for $\theta \in (45^\circ, 90^\circ)$: $8042\,\mathrm{km^2\,sr\,yr}$
  - probability to interact in the atmosphere: 1.4×10^{-5}
  - trigger, reconstruction and quality cuts efficiency $\sim 7\%$
  - ξ cut efficiency: $\sim 24\%$
  - total exposure (all flavors): $A = 1.9 \times 10^{-3}\,\mathrm{km^2\,sr\,yr}$
- Single flavor diffuse neutrino flux limit for $E > 10^{18}$ eV:
  $E^2 f_\nu < 1.4 \times 10^{-6}\,\mathrm{GeV\,cm^{-2}s^{-1}sr^{-1}}$ (90% C.L.)



Results: photon flux limits

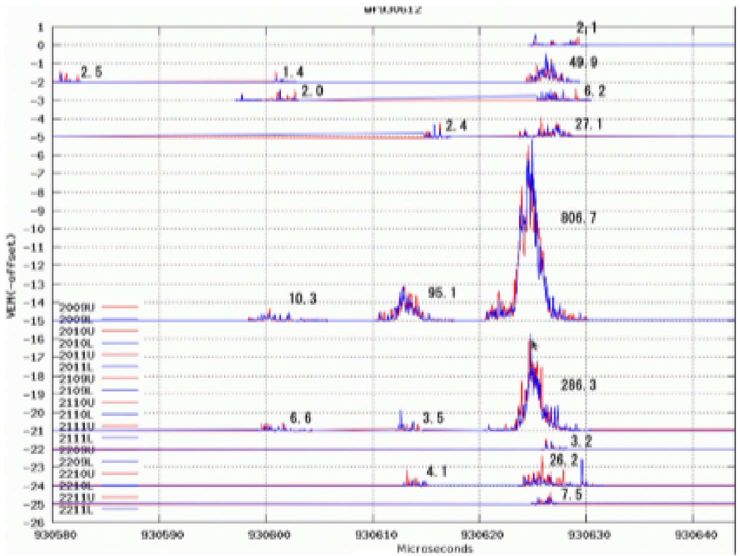
E_0, eV	$10^{18.0}$	$10^{18.5}$	$10^{19.0}$	$10^{19.5}$	$10^{20.0}$
γ candidates	~~1~~ 0	~~1~~ 0	~~4~~ 0	~~4~~ 0	~~4~~ 2
$\bar{n} <$	3.09	3.09	3.09	3.09	6.72
A_{eff}	53	192	846	2138	4317
$F_\gamma <$	0.059	0.016	0.0037	0.0014	0.0016

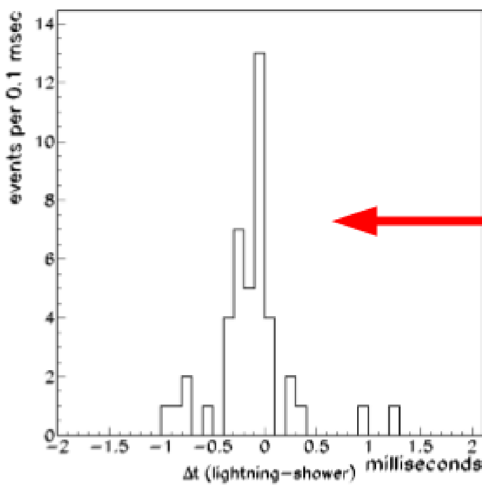


models from J. Alvarez-Muniz et al. EPJ Web Conf. ***53****, 01009 (2013)*

Lightning Detection

Plot: T. Okuda





TA Observation: "Burst" Events

- 5 year data (2008-2013)
- 10 surface detector bursts seen
  - 3 or more SD triggers, Δt < 1 msec
  - Occasional Δt ~ 10 μsec
- "Normal" SD trigger rate < 0.01 Hz. *These cannot be cosmic ray air showers*.
- Found to have close time/space coincidence with *U.S. National Lightning Detection Network* (NLDN) activity.
- Abbasi et al. *Phys. Lett.* **A 381** (2017).

2. Lightning Detection at Telescope Array

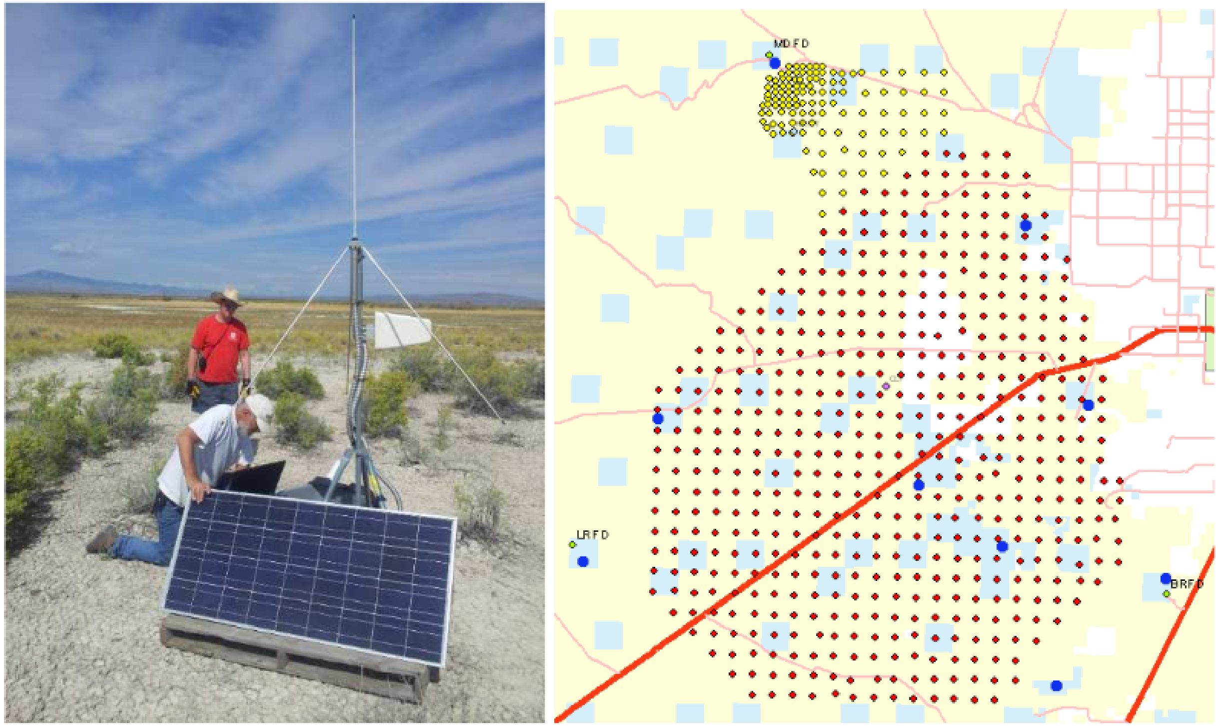


Figure 1: *Left:* W. Hanlon (Utah) and W. Rison (New Mexico Tech) installing VHF Lightning Mapping Array detector at TA site. *Right:* Map of Telescope Array observatory, showing 1.2 km grid of surface detectors (red circles), TALE surface detectors (yellow circles), fluorescence detector locations (green circles) and LMA detectors (blue circles).

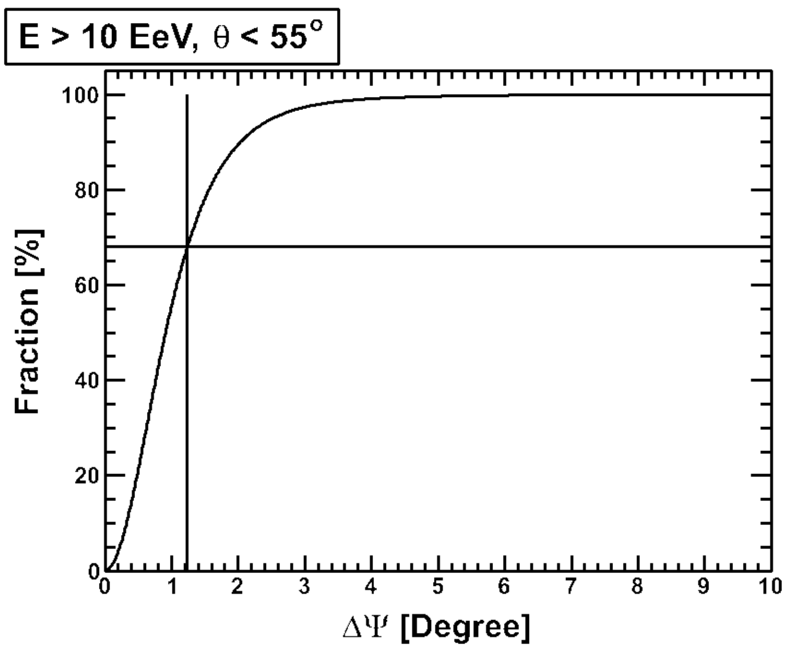
5. Conclusion

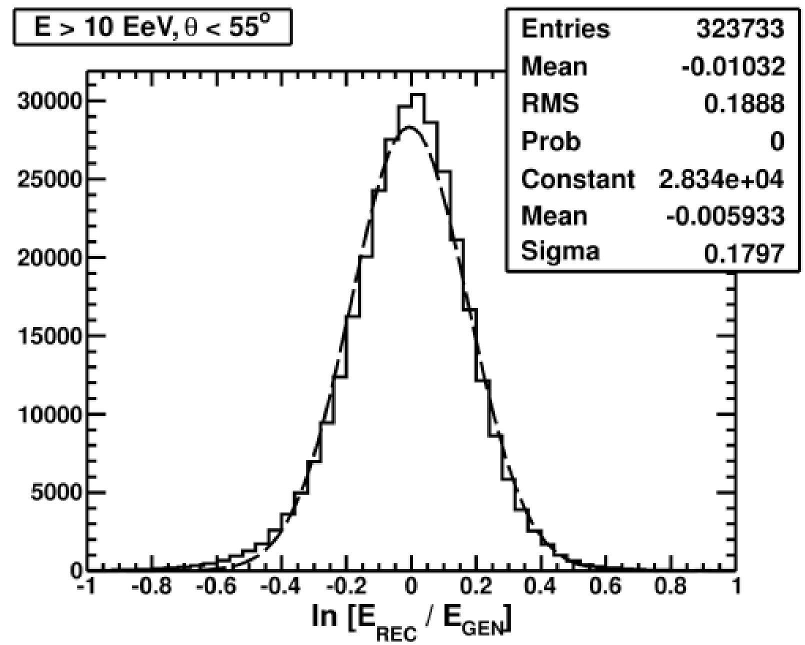
Altogether the Telescope Array observatory has detected approximately 20 burst events in eight years of observation. In about half of these events, the surface detector observations are supplemented with lightning detector data. Measurements to date appear to be consistent with these bursts arising from downward TGFs originating in negative downward lightning leaders. In this case, these events comprise the majority of the world's downward TGF sample and establish the TA/LMA combination as a major emergent facility for high-energy atmospheric research.

Telescope Array Anisotropy Results

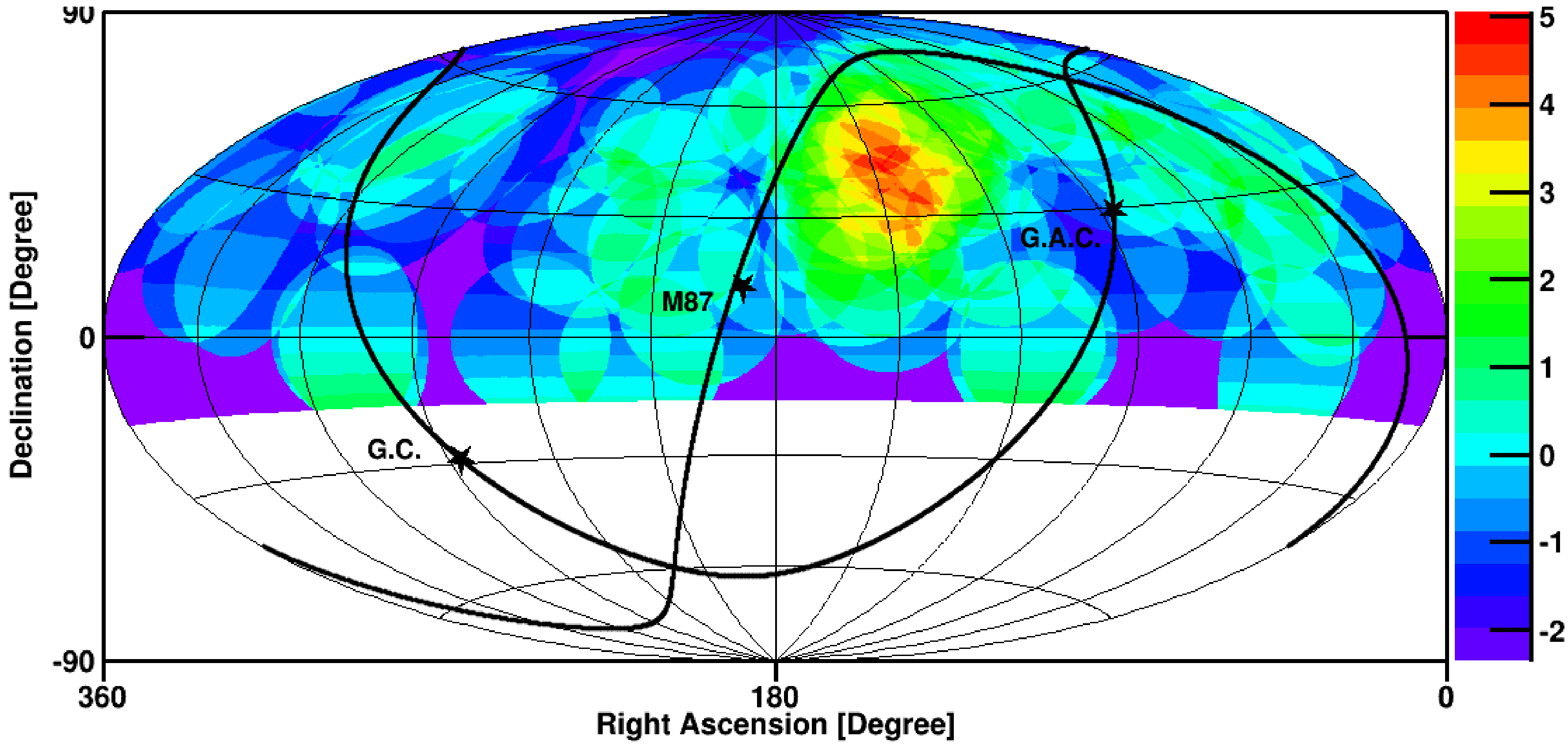
Anisotropy Analysis

- SD data full 9 years
- Zenith angle up to 55°, loose border cut
- Geometrical acceptance; exposure 8600 km^2 yr sr
- Angular resolution: better than 1.5°
- Energy resolution: 20%



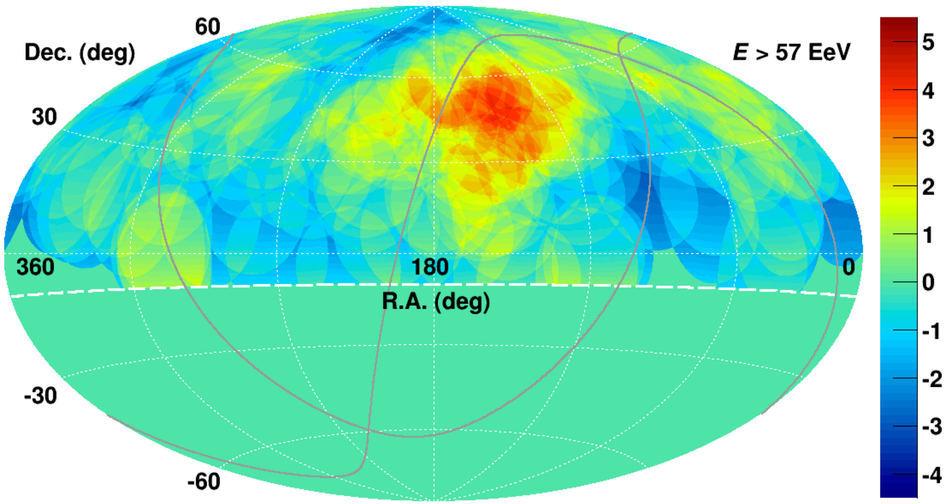


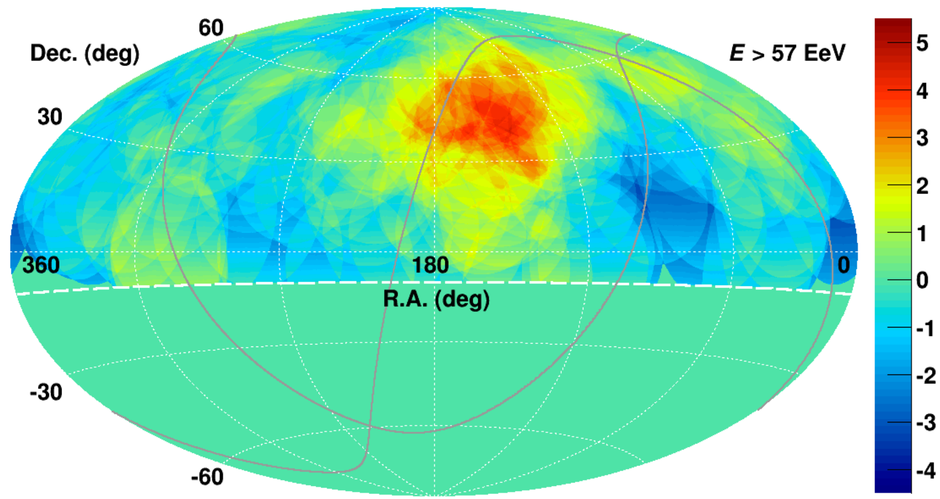
Published Hotspot (5yr data)



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: ~5σ Estimate ~3.4 chance probablity

Hotspot with 9 years data



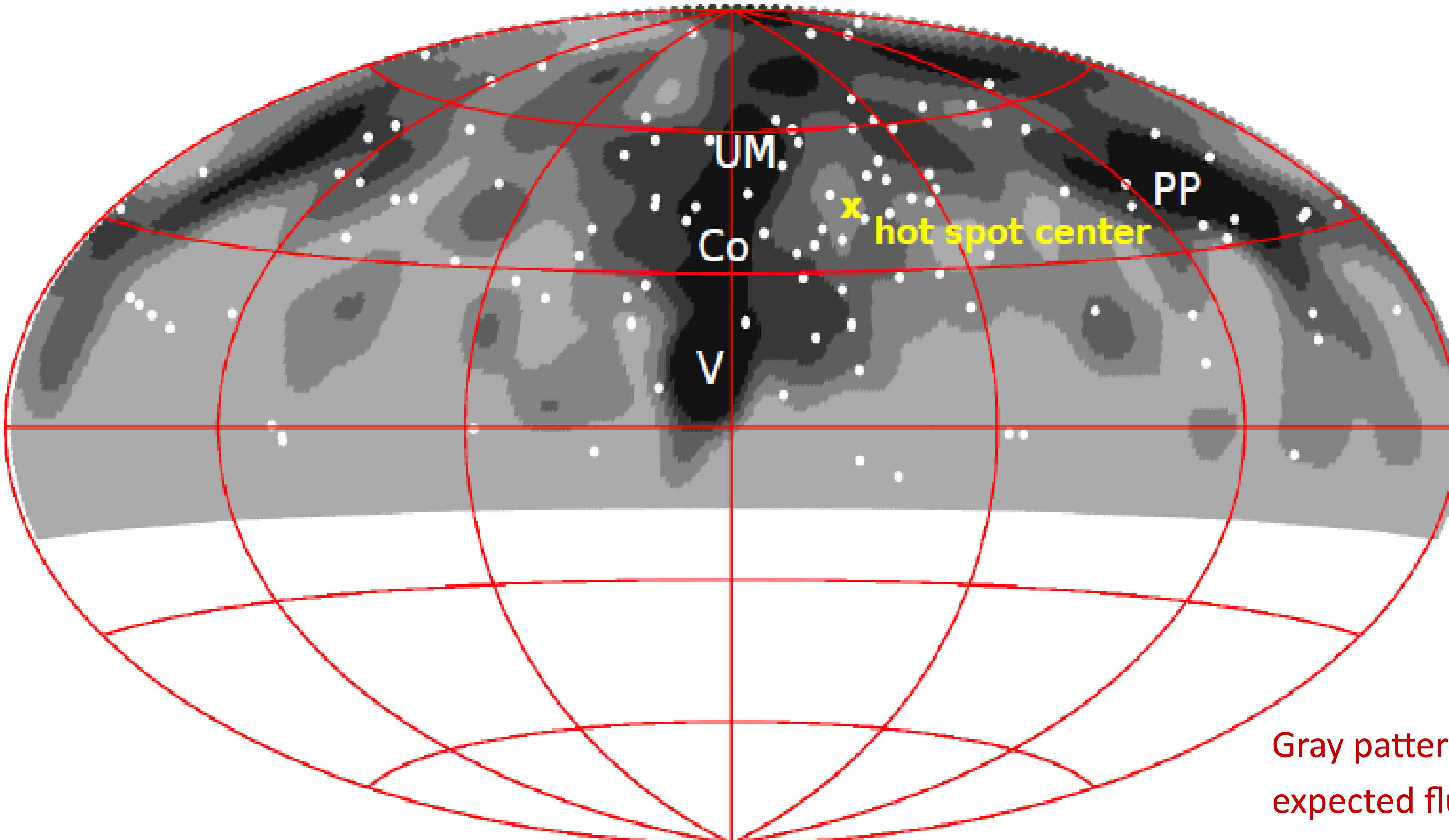


With original 20° oversampling, spot looks larger…. Thus, scan over 15°, 20°, 25°, 30°, & 35°

With 25° oversampling, significance maximum 3σ

Binsize	15		20		25		30		35	
	Local	Global	Local	Global	Local	Global	Local	Global	Local	Global
Year 5	5.12	3.14	5.43	3.55	5.16	3.19	4.82	2.73	4.33	2.05
Year 7	4.92	2.84	5.37	3.44	5.65	3.80	5.37	3.44	5.03	2.99
Year 9	4.42	2.06	4.72	2.50	5.06	2.96	5.01	2.91	4.66	2.41

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)

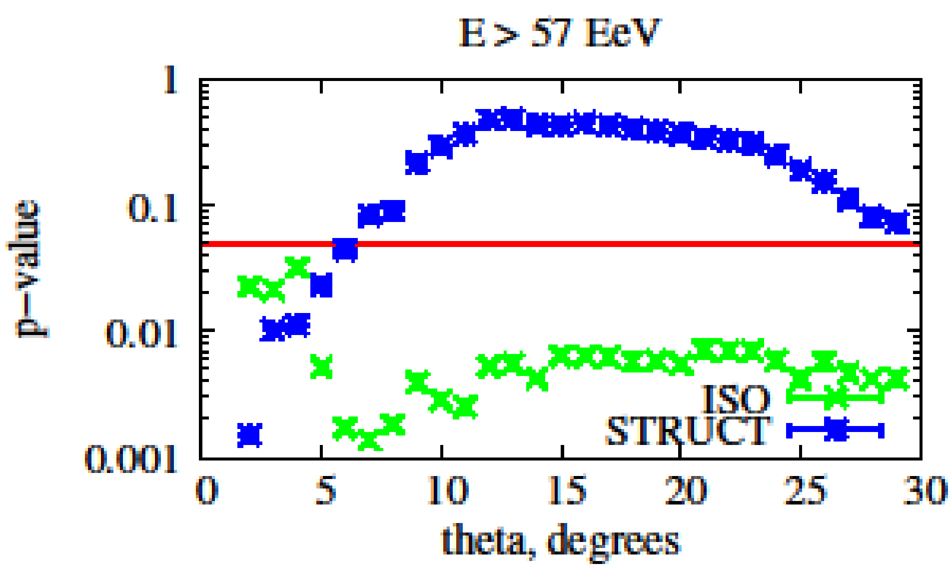
LSS Correlation (continued)

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

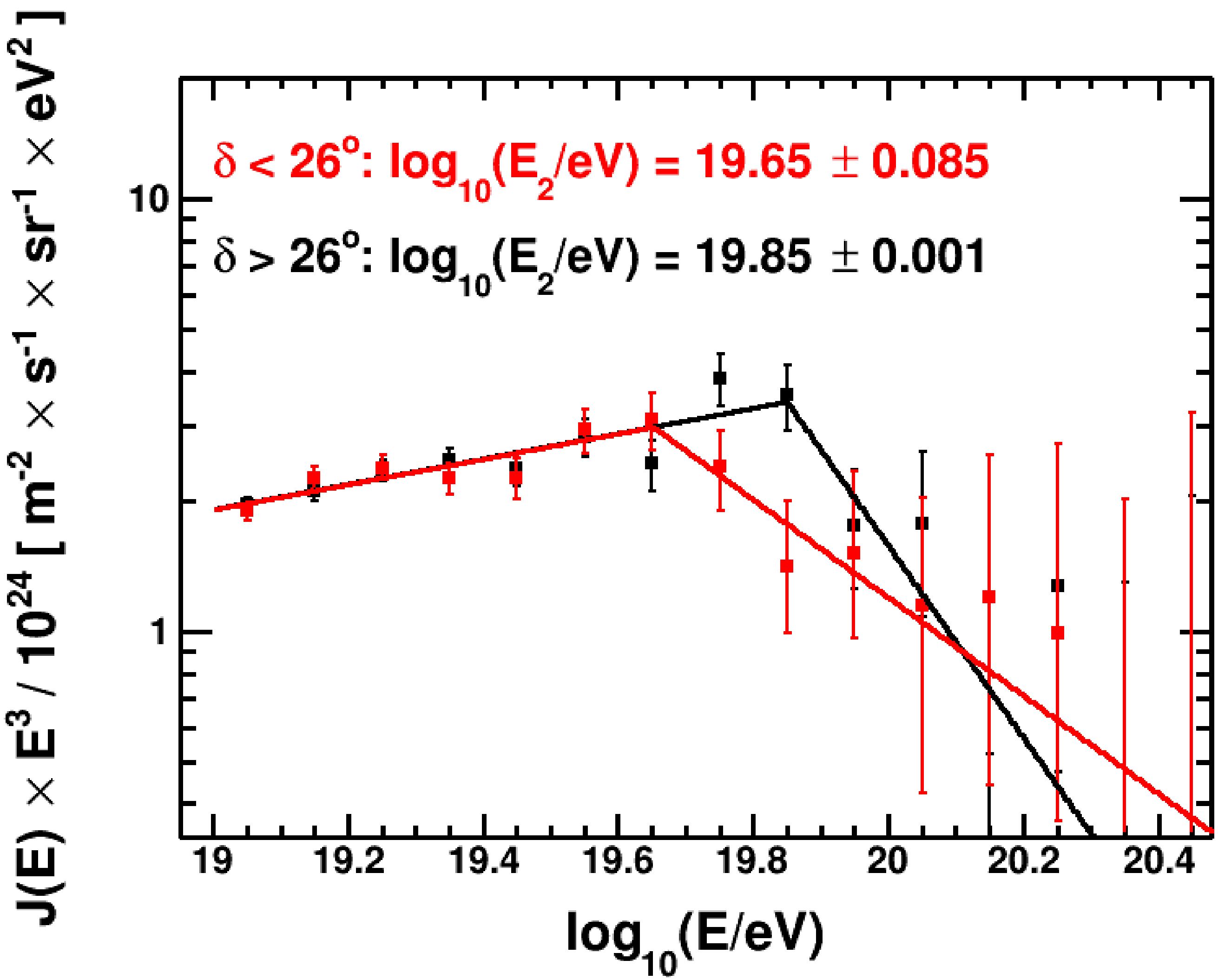
CORRELATION WITH LSS



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

Smearing Angle in degrees

Declination Dependence of SD Spectrum



- Position of 2nd break point moves with declination $10^{19.85}$ to $10^{19.6}$ eV
  ~3.9 sigma effect

The Future of Telescope Array

TALE SD Array and NICHE

TAx4 Project

TA SD (~3000 km²): Quadruple area

Approved in Japan 2015

500 scintillator SDs

2.08 km spacing

3 yrs construction, first 173 SDs have arrived in Utah for final assembly, next 77 SD to be prepared at Akeno Obs. (U.Tokyo) 2017-08 and shipped to Utah

2 FD stations (12 HiRes Telescopes)

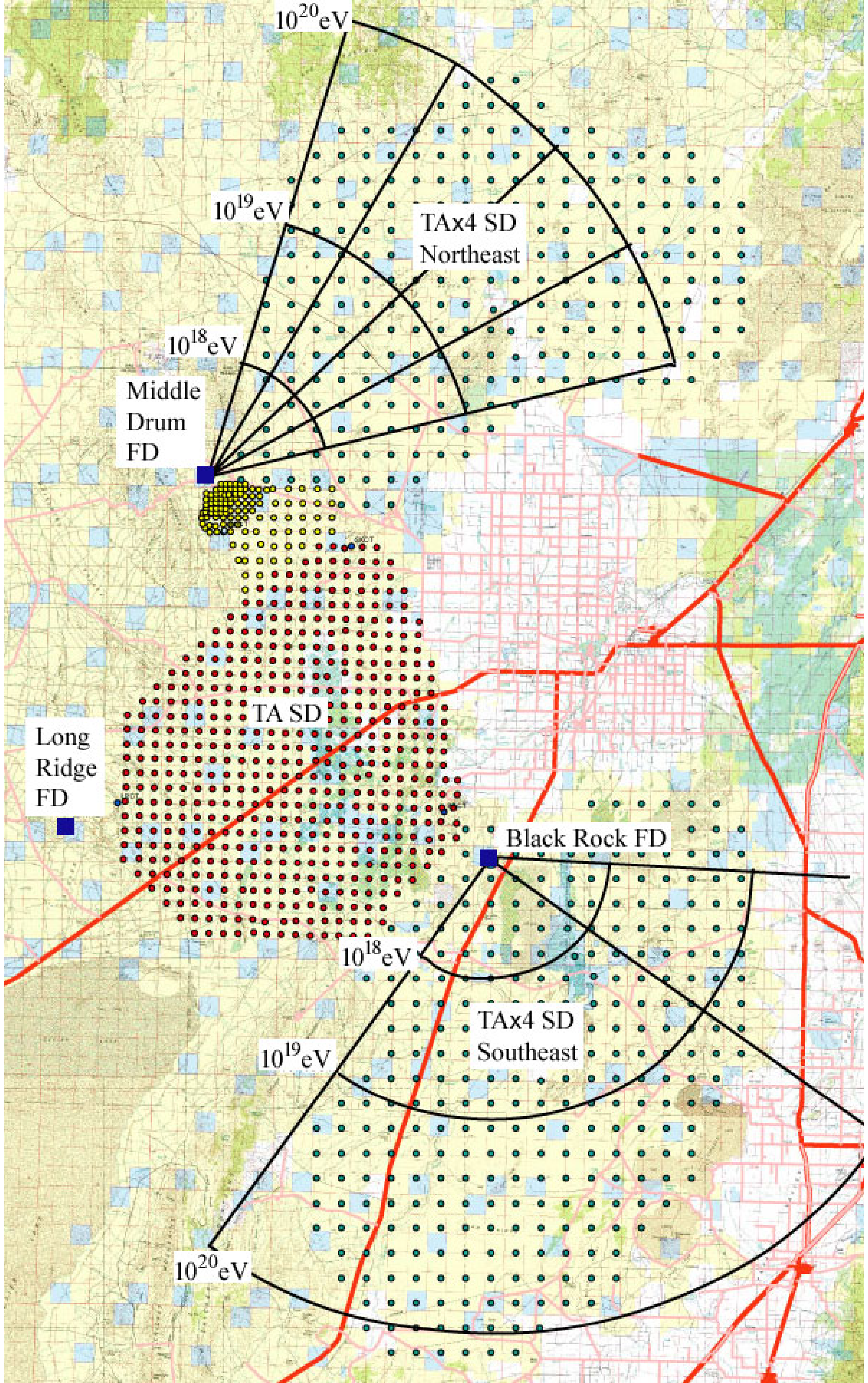
Approved US NSF 2016

Telescopes/electronics being prepared at Univ. Utah

Site construction underway at the northern station.

Get 19 TA-equiv years of SD data by 2020

Get 16.3 (current) TA years of hybrid data



Summary

- Telescope Array 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 above the CR ankle (~6×10^{18} eV).
- We have reported a hot spot seen in the direction of Ursa Major (3σ significance). It now appears larger than we originally thought.
- TA Low Energy Extension (TALE) FD has been taking data (with an engineering SD array) and has extended the energy reach below ~$10^{15.5}$ eV
- Full TALE SD was recently deployed and 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**

Backup Slides

Condensed Version (with some omissions) of Highlights from The Telescope Array

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for the Telescope Array Collaboration

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35^{th} ICRC Busan, S. Korea 17 July 2017

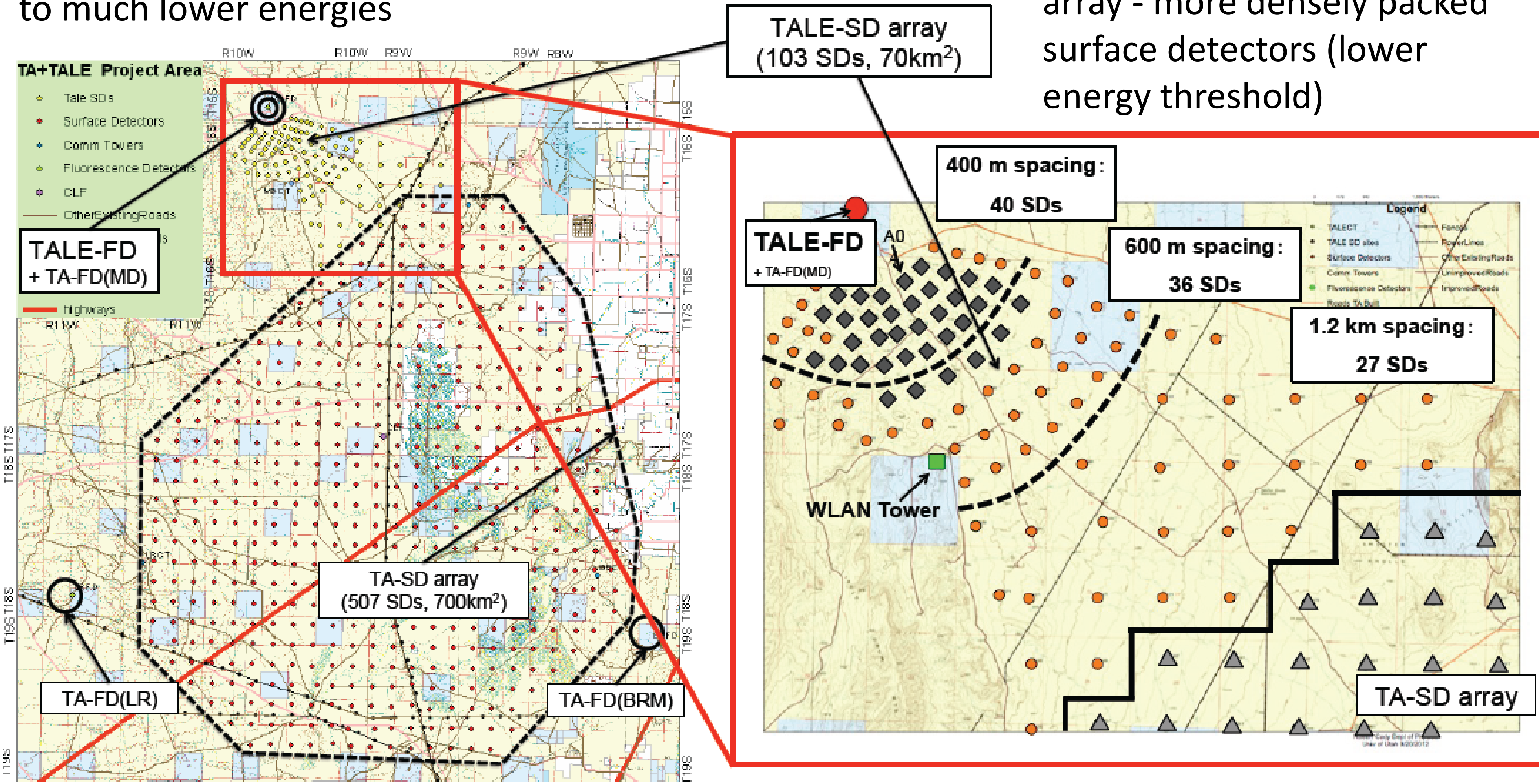
Experiment Present and Future

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)



TAx4

Plans submitted to public lands management and site procurement under negotiation

About 2/3 of SD sites visited in June and staked for follow-up surveys. (*eg* for cultural resources, *etc*) About 2500 km covered over 10 days by 4 teams on ATVs. Resume staking by helicopter this fall (2017) for areas where ATVs are not permitted.

Clarify the details of the Hotspot

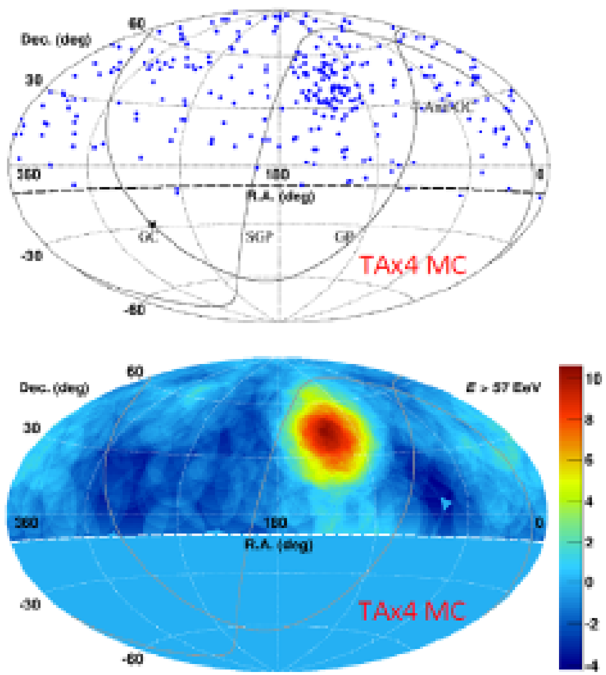
Simulated 19 TA-equiv yrs data

(1) One Hotspot

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

<u>Isotropic B.G.</u>
305-61=244events

Oversampling
20° radius circle



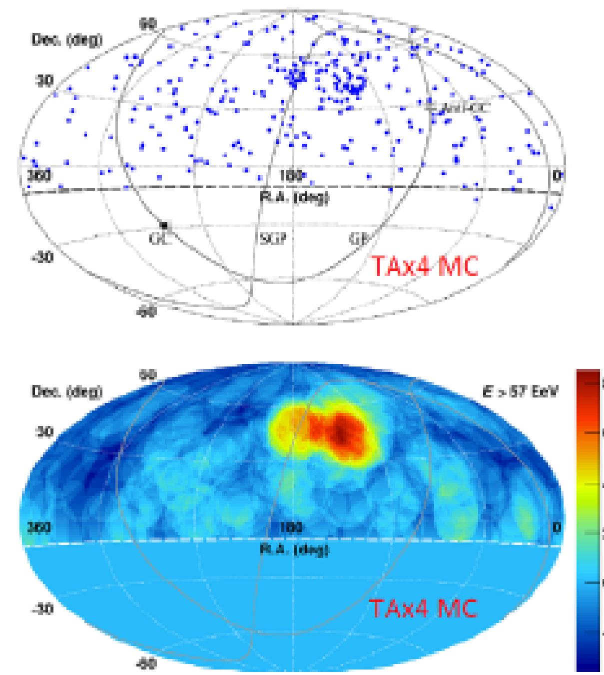
Single Source

(2) Double Hotspot

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

<u>Isotropic B.G.</u>
305-61=244events

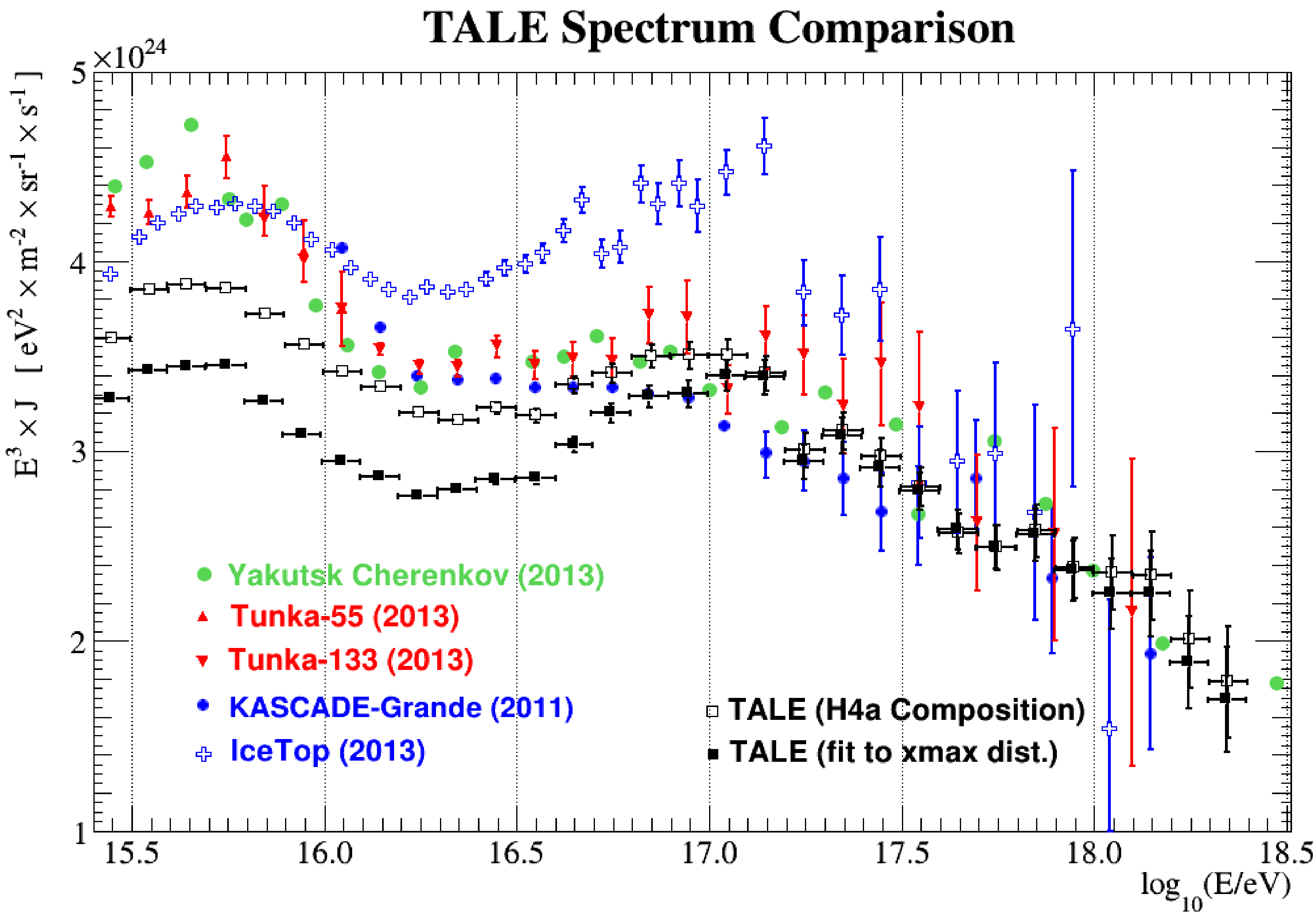
Oversampling
15° radius circle



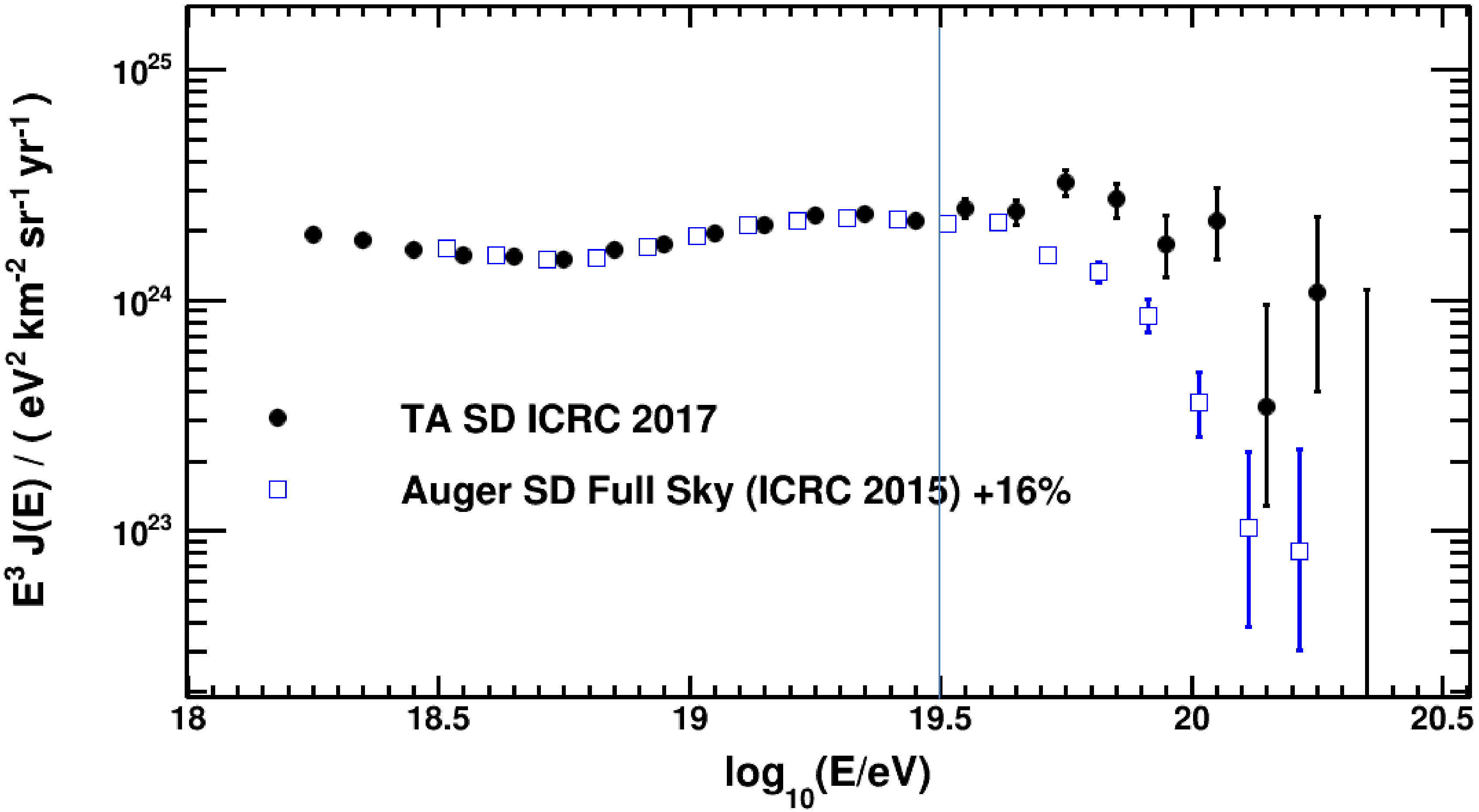
Two Separated Sources

Energy Spectrum & Others

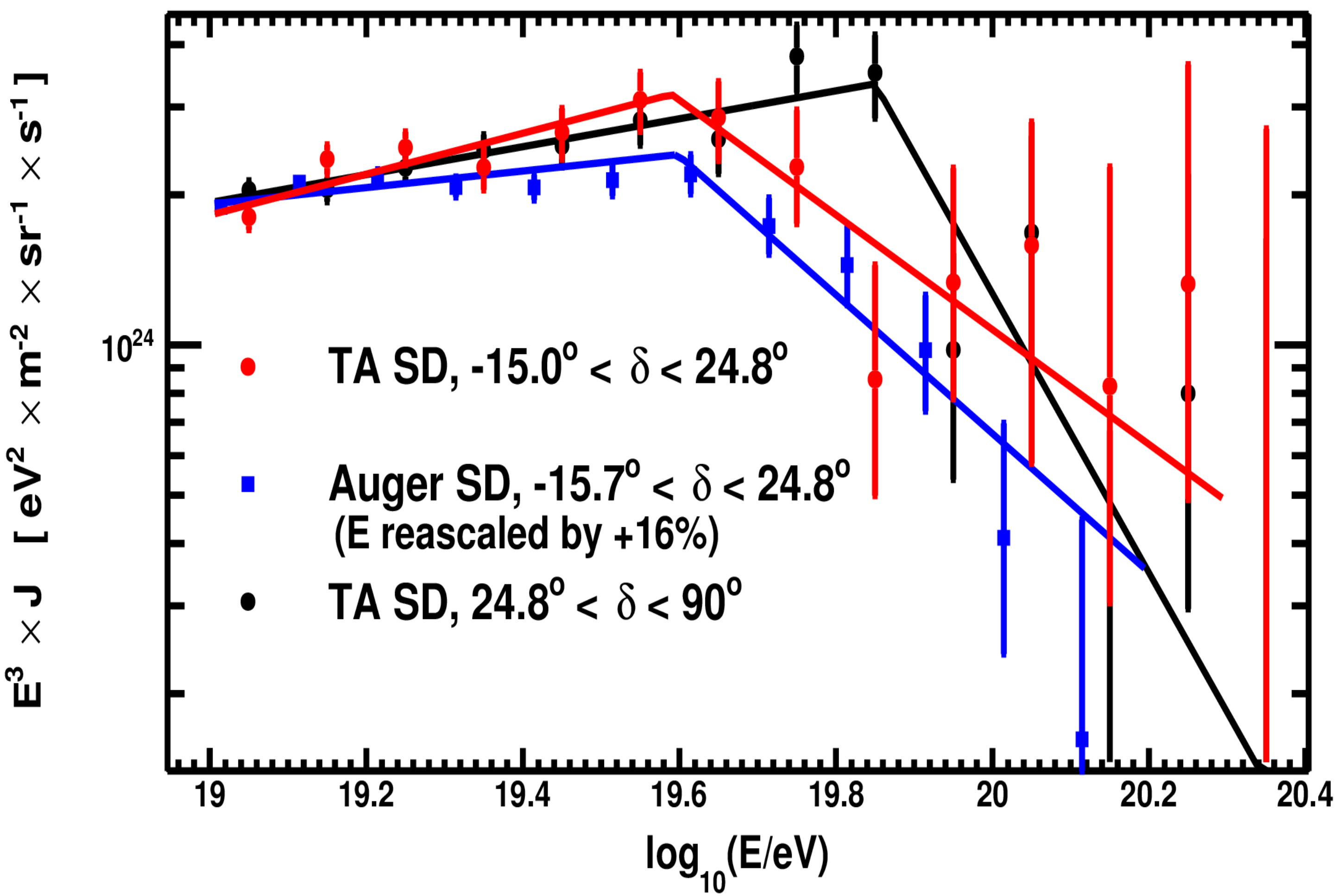
Comparison with other Measurements



Telescope Array & Pierre Auger (+16%) Spectra

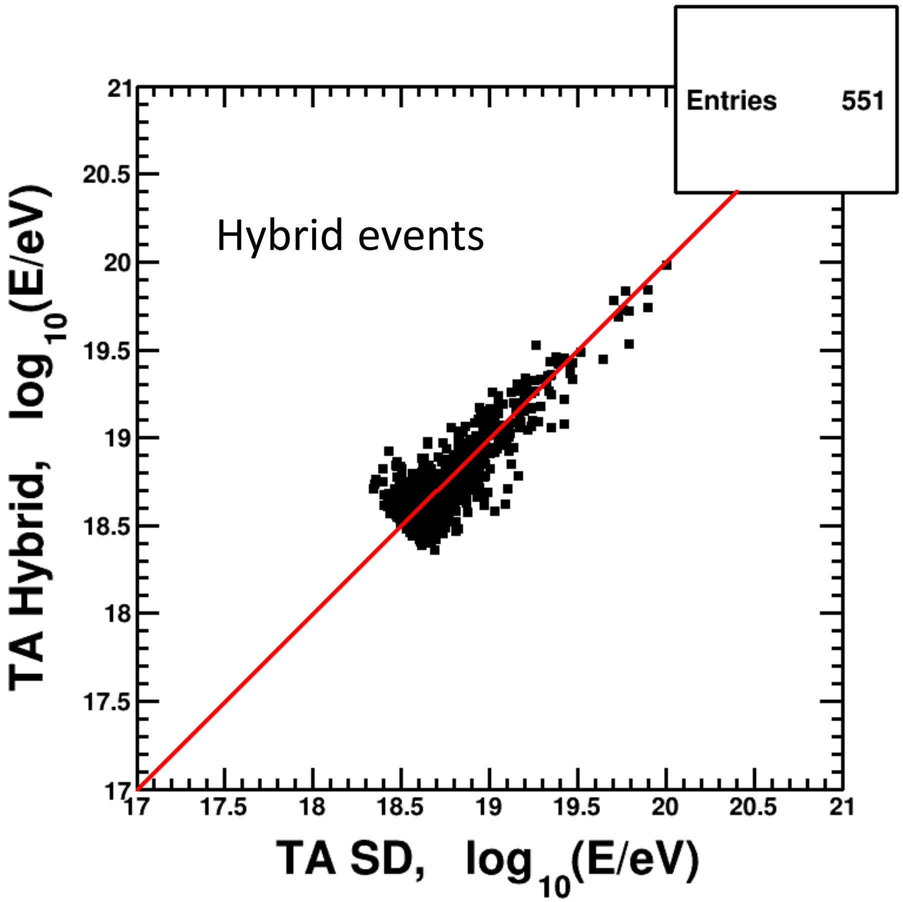


Declination Dependence of SD Spectrum



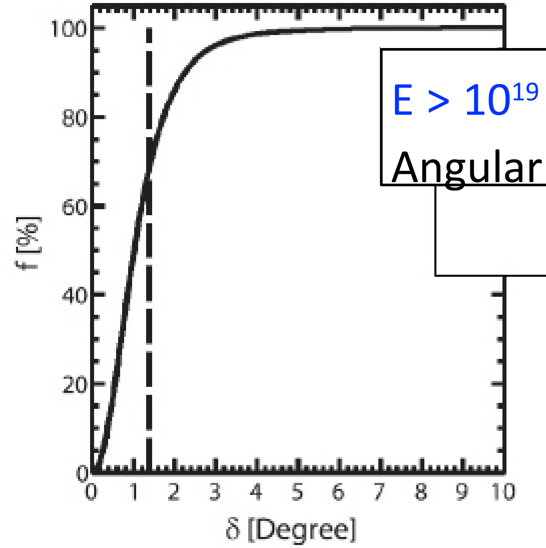
- Better spectral agreement between Telescope Array and Auger in the common declination band

Energy Scale Check and Resolution

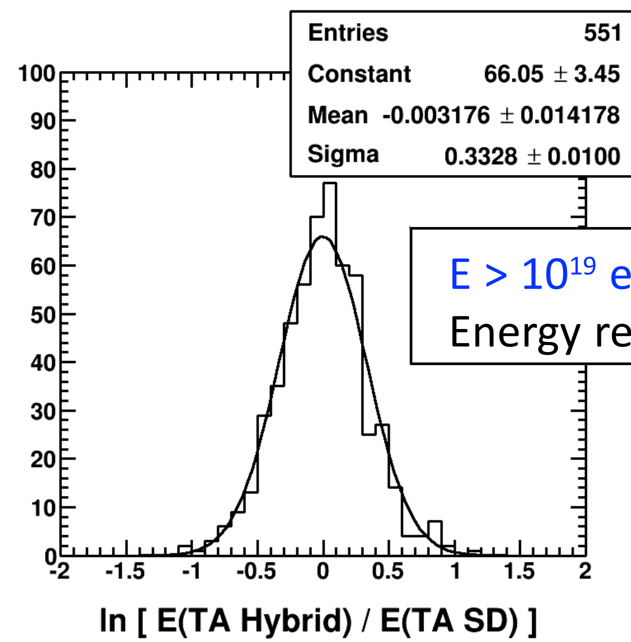


(SD scaled to FD energy: calorimetric)

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



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

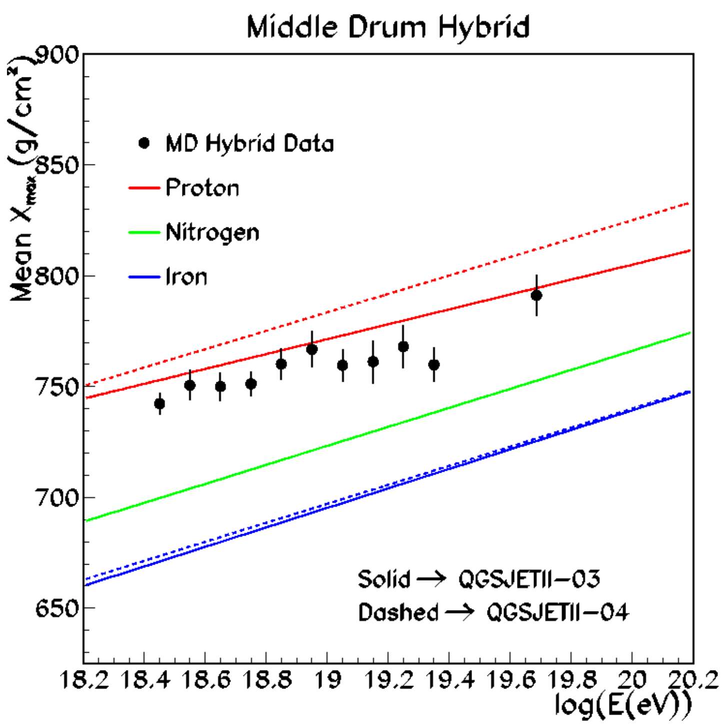


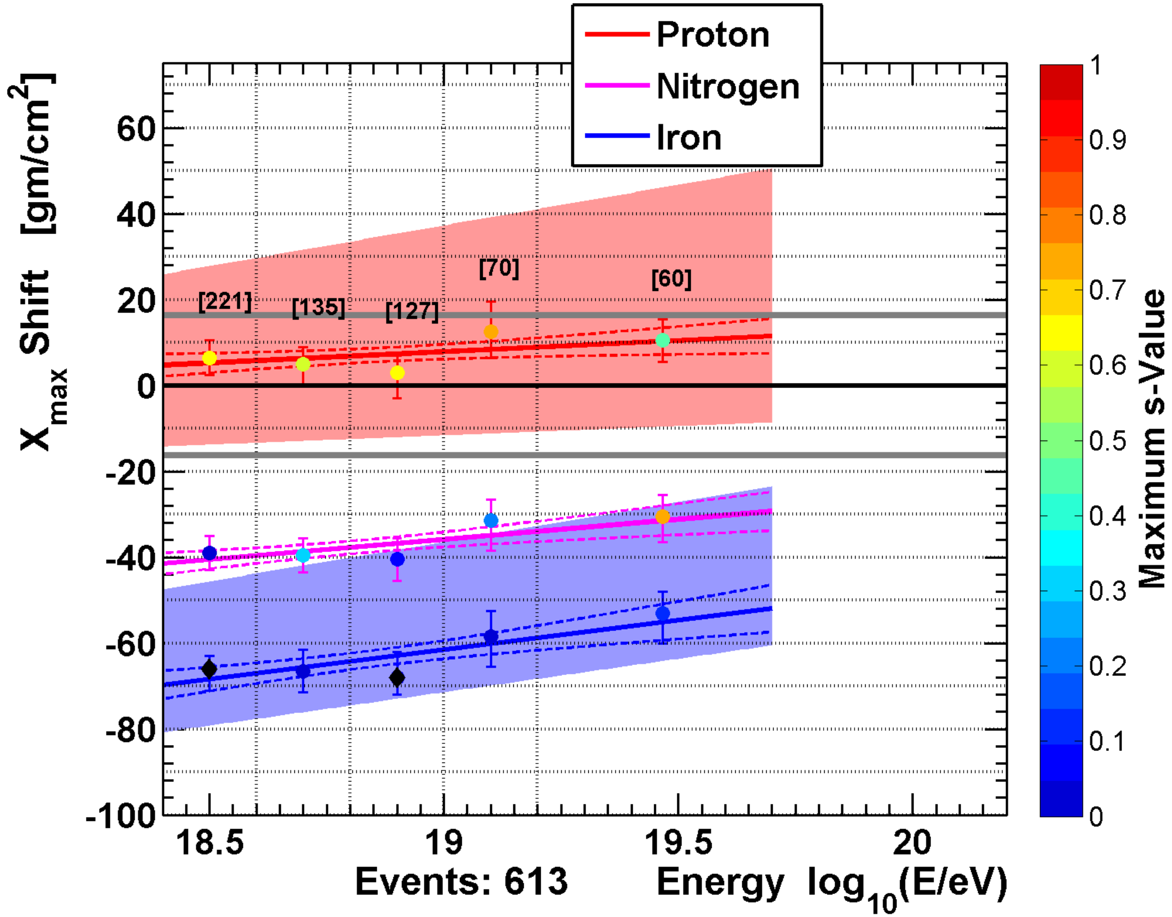
E > 10^{19} eV
Energy resolution < 20%

Composition

MD Hybrid

Elongation:
<Xmax> vs log(E) plot





"Shift Plot"

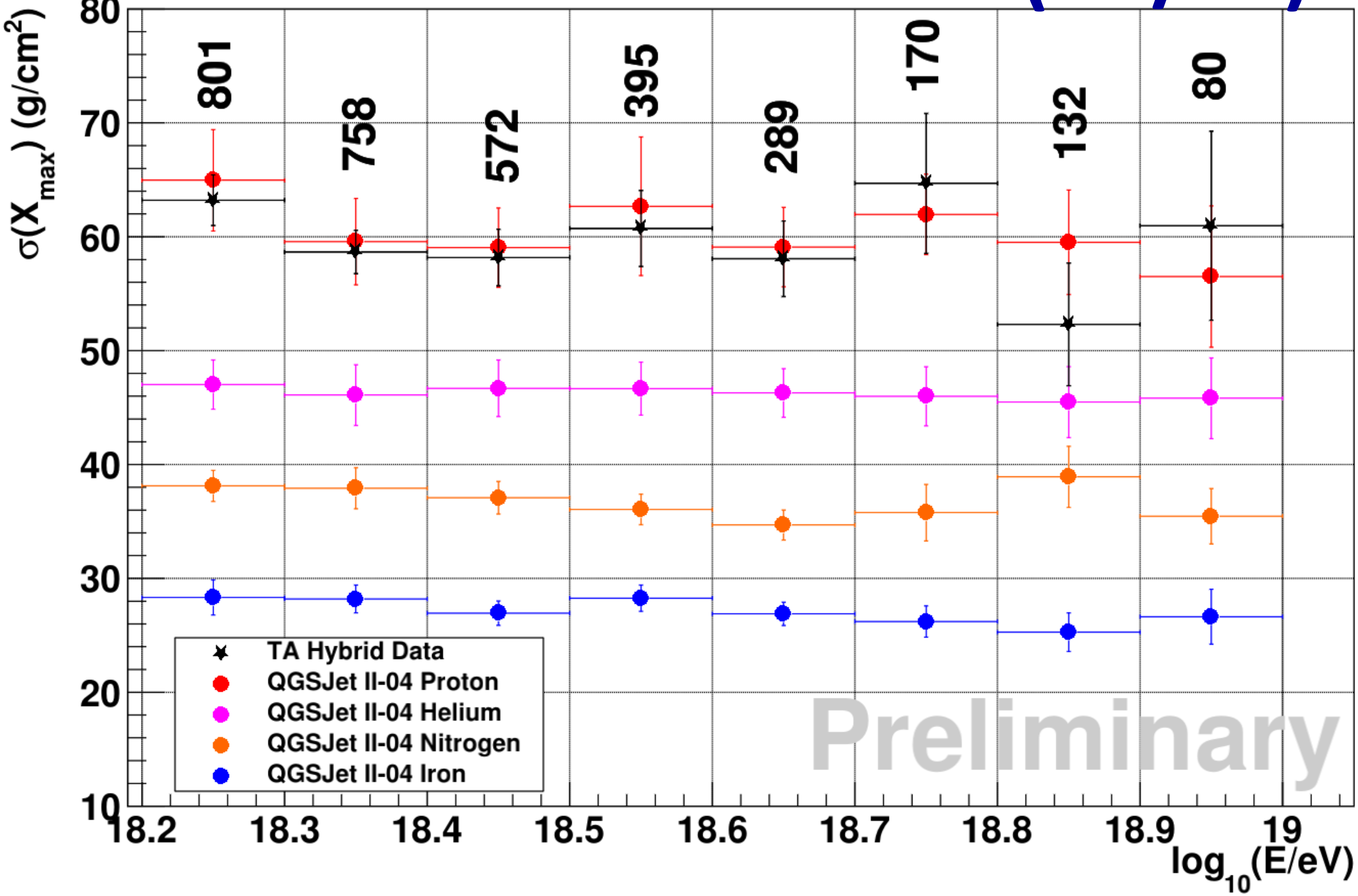
Plot ΔX_{max} required to maximize data/MC agreement (QGSJETII-03).

Standard statistical test on shifted distribution (points)

Pink, blue bands for other hadronic models

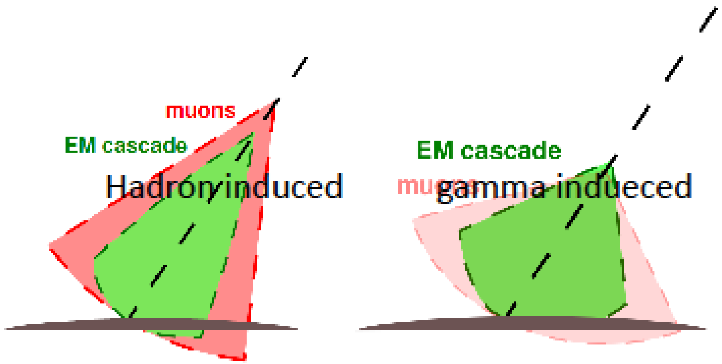
16 g/cm^2 systematic uncertainty

Xmax distribution widths (BR/LR)

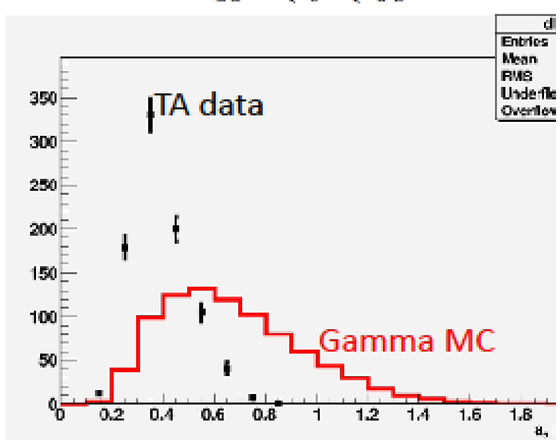


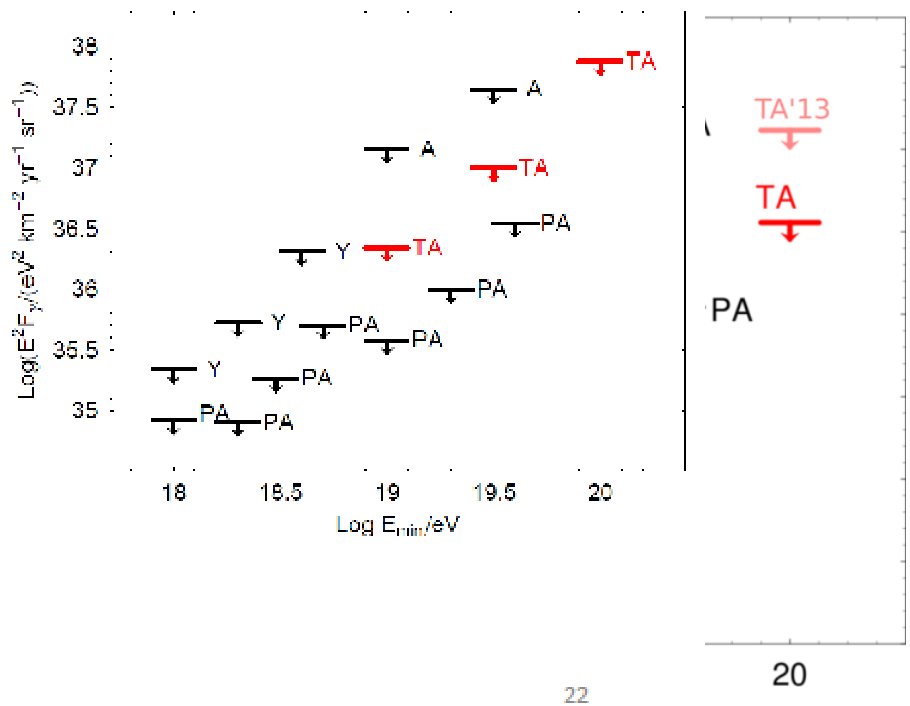
Photon search

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 .



$45° < \theta < 60°$



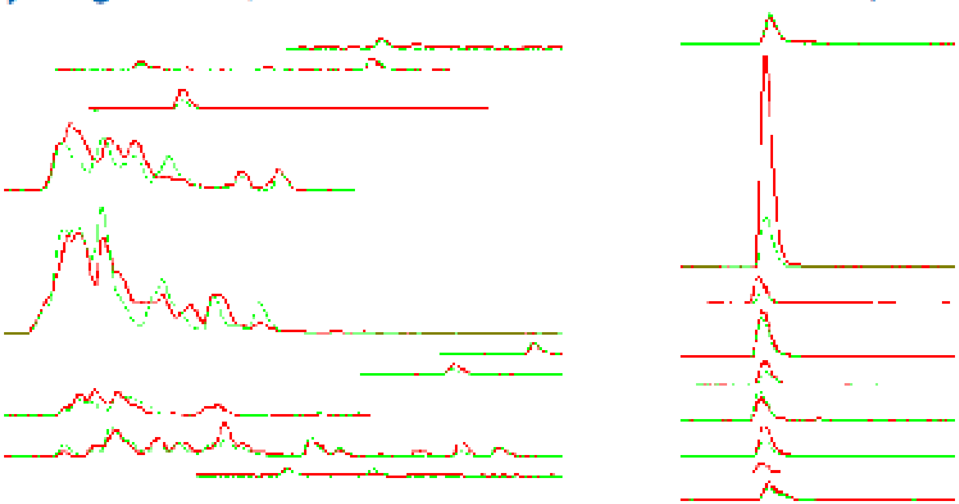


Neutrino search

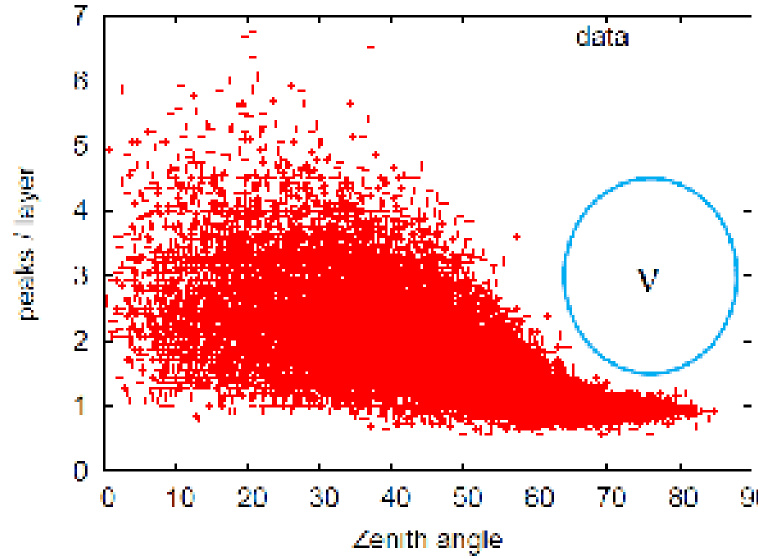
G. Rubtsov, oral 149

- Neutrino produces very inclined young shower

young shower, $\theta = 19.5^{\circ}$ **old shower,** 78.3°



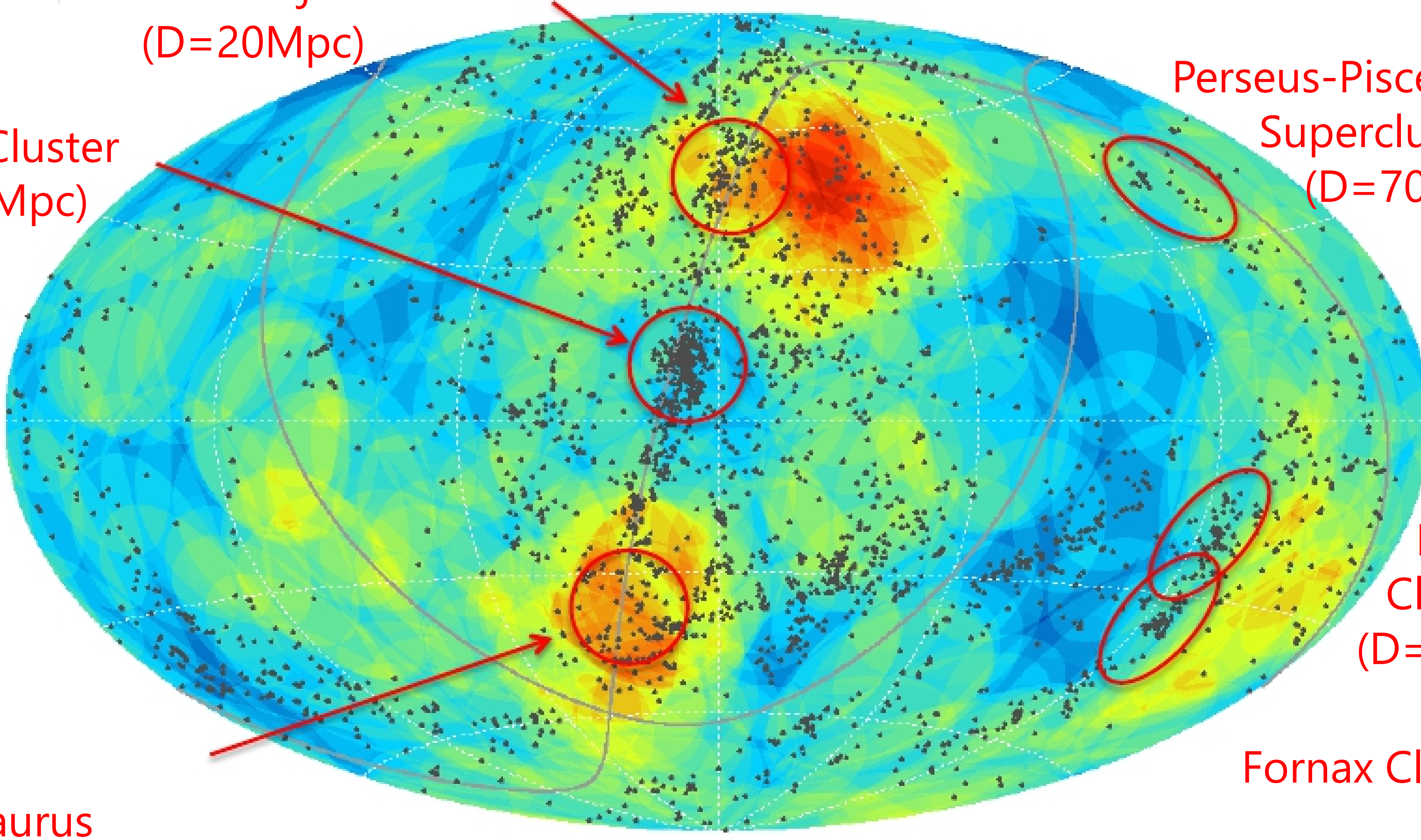
long, indented wafeforms one peak



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

Anisotropy

Nearby Galaxy Clusters



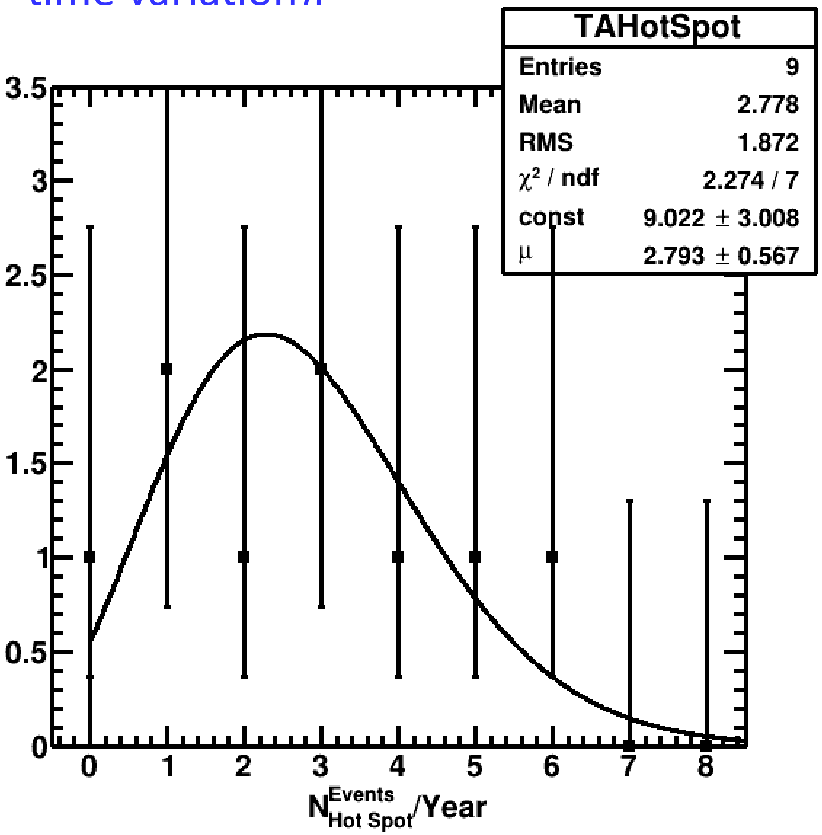
Huchra, et al, ApJ, (2012)

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

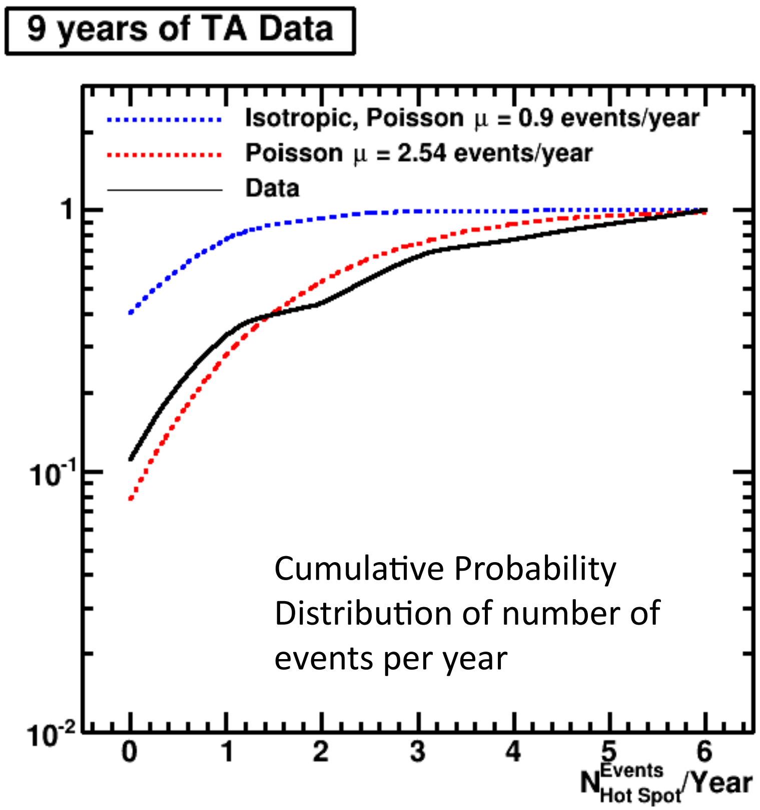
TA hotspot is found near the Ursa Major Cluster

Consistent with Fluctuation

K.S. Test shows data is consistent with fluctuation for hotspot (Poisson: average = 2.78 per year, no time variation).



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

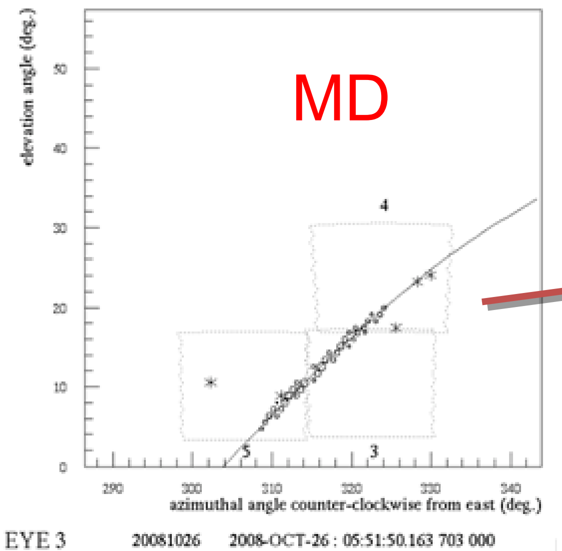


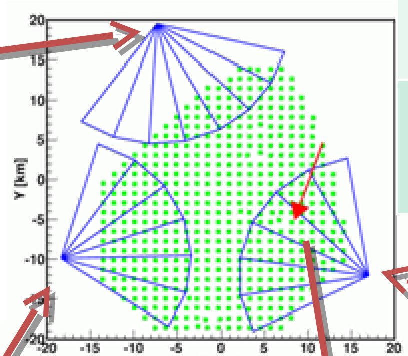
Some Example Events

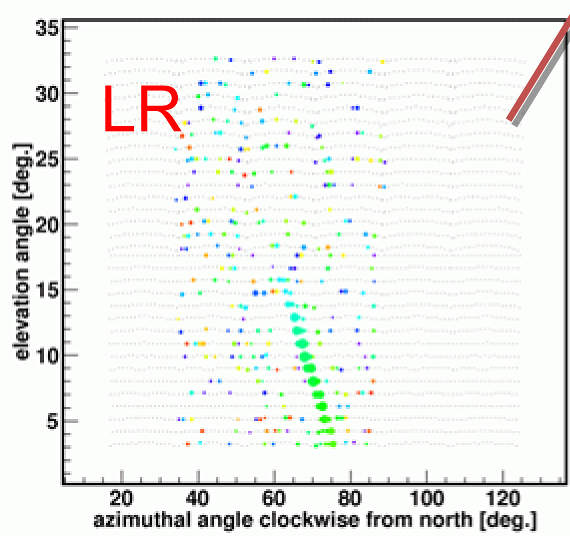
Example Event

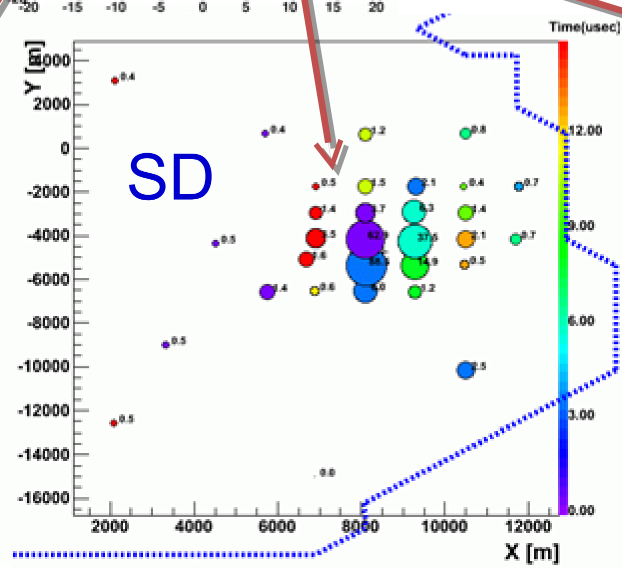
	θ [°]	ϕ [°]	x[km]	y[km]
MD mono	**51.43**	**73.76**	**7.83**	**-3.10**
BR mono	**51.50**	**77.09**	**7.67**	**-4.14**
Stereo BR&LR	**50.21**	**71.30**	**8.55**	**-4.88**

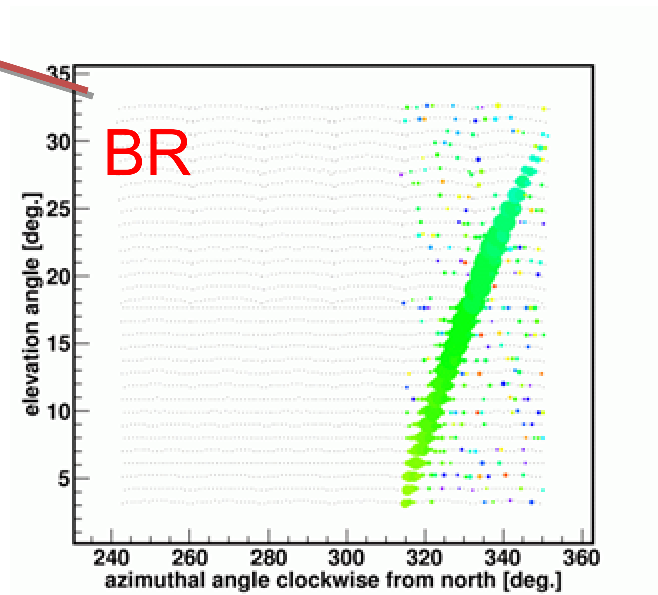
Event from 2008-10-26



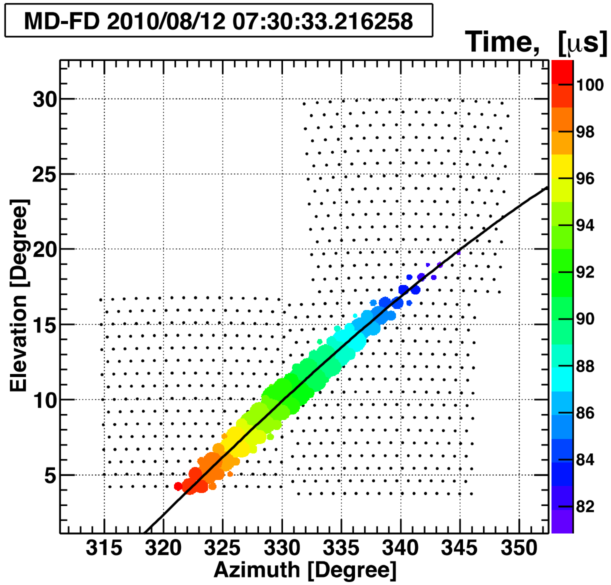


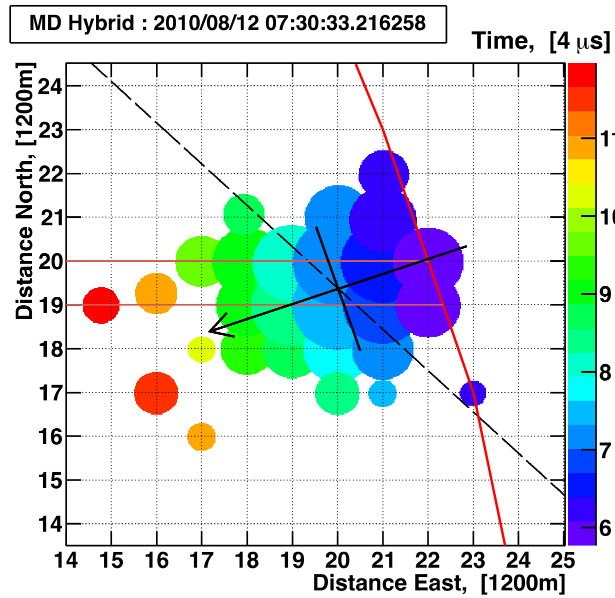


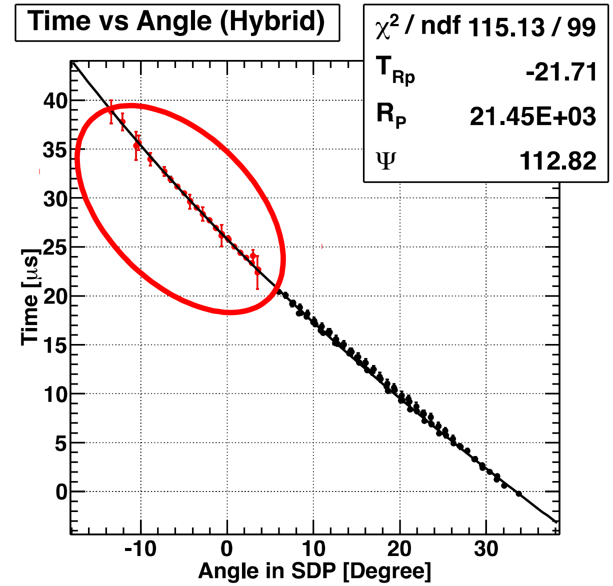


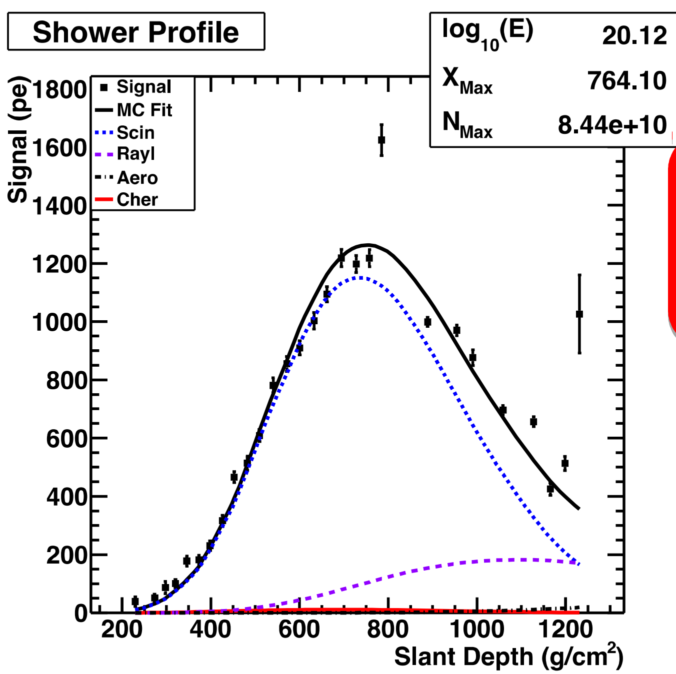


High Energy Hybrid Event







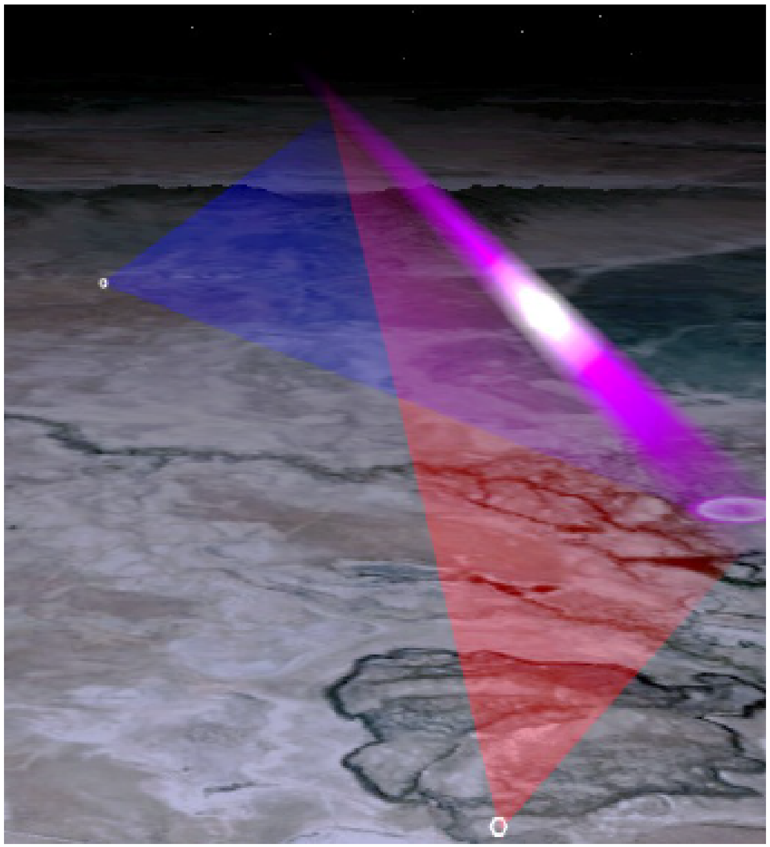


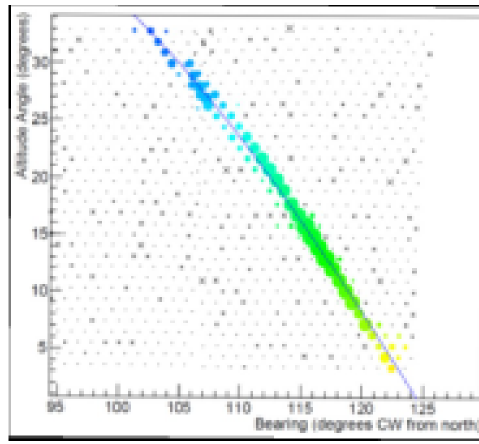
Energy: 1.3 × 10^{20} eV

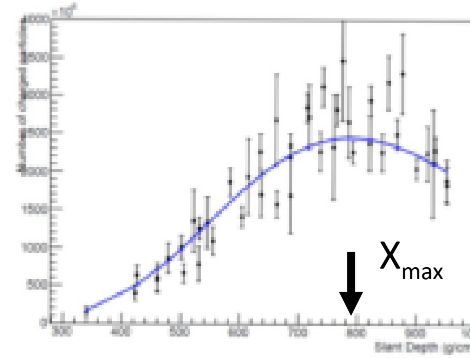
Zenith Angle: 55.7°

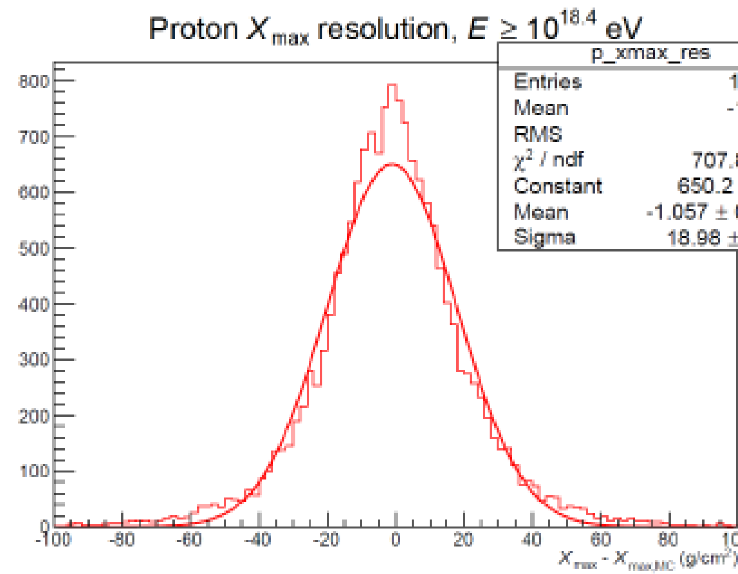
Surface array constrains geometry fit via extra timing & core information

Stereo Observation









Intersect shower planes to get more precise geometry