Results from the Telescope Array Experiment

For the Telescope Array Collaboration

Charlie Jui

RICAP 2016, Frascati

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R.U. Abbasi,[1] M. Abe,[2] T. Abu-Zayyad,[1] M. Allen,[1] R. Azuma,[3] E. Barcikowski,[1] J.W. Belz,[1] D.R. Bergman,[1] S.A. Blake,[1] R. Cady,[1] M.J. Chae,[4] B.G. Cheon,[5] J. Chiba,[6] M. Chikawa,[7] W.R. Cho,[8] T. Fujii,[9] M. Fukushima,[9,10] T. Goto,[11] W. Hanlon,[1] Y. Hayashi,[11] N. Hayashida,[12] K. Hibino,[12] K. Honda,[13] D. Ikeda,[9] N. Inoue,[2] T. Ishii,[13] R. Ishimori,[3] H. Ito,[14] D. Ivanov,[1] C.C.H. Jui,[1] K. Kadota,[15] F. Kakimoto,[3] O. Kalashev,[16] K. Kasahara,[17] H. Kawai,[18] S. Kawakami,[11] S. Kawana,[2] K. Kawata,[9] E. Kido,[9] H.B. Kim,[5] J.H. Kim,[1] J.H. Kim,[19] S. Kitamura,[3] Y. Kitamura,[3] V. Kuzmin,[16] Y.J. Kwon,[8] J. Lan,[1] S.I. Lim,[4] J.P. Lundquist,[1] K. Machida,[13] K. Martens,[10] T. Matsuda,[20] T. Matsuyama,[11] J.N. Matthews,[1] M. Minamino,[11] Y. Mukai,[13] I. Myers,[1] K. Nagasawa,[2] S. Nagataki,[14] T. Nakamura,[21] T. Nonaka,[9] A. Nozato,[7] S. Ogio,[11] J. Ogura,[3] M. Ohnishi,[9] H. Ohoka,[9] K. Oki,[9] T. Okuda,[22] M. Ono,[23] A. Oshima,[24] S. Ozawa,[17] I.H. Park,[25] M.S. Pshirkov,[16,26] D.C. Rodriguez,[1] G. Rubtsov,[16] D. Ryu,[19] H. Sagawa,[9] N. Sakurai,[11] L.M. Scott,[27] P.D. Shah,[1] F. Shibata,[13] T. Shibata,[9] H. Shimodaira,[9] B.K. Shin,[5] H.S. Shin,[9] J.D. Smith,[1] P. Sokolsky,[1] R.W. Springer,[1] B.T. Stokes,[1] S.R. Stratton,[1,27] T.A. Stroman,[1] T. Suzawa,[2] M. Takamura,[6] M. Takeda,[9] R. Takeishi,[9] A. Taketa,[28] M. Takita,[9] Y. Tameda,[12] H. Tanaka,[11] K. Tanaka,[29] M. Tanaka,[20] S.B. Thomas,[1] G.B. Thomson,[1] P. Tinyakov,[30,16] I. Tkachev,[16] H. Tokuno,[3] T. Tomida,[31] S. Troitsky,[16] Y. Tsunesada,[3] K. Tsutsumi,[3] Y. Uchihori,[32] S. Udo,[12] F. Urban,[30] G. Vasiloff,[1] T. Wong,[1] R. Yamane,[11] H. Yamaoka,[20] K. Yamazaki,[28] J. Yang,[4] K. Yashiro,[6] Y. Yoneda,[11] S. Yoshida,[18] H. Yoshii,[33] R. Zollinger,[1] and Z. Zundel[1]

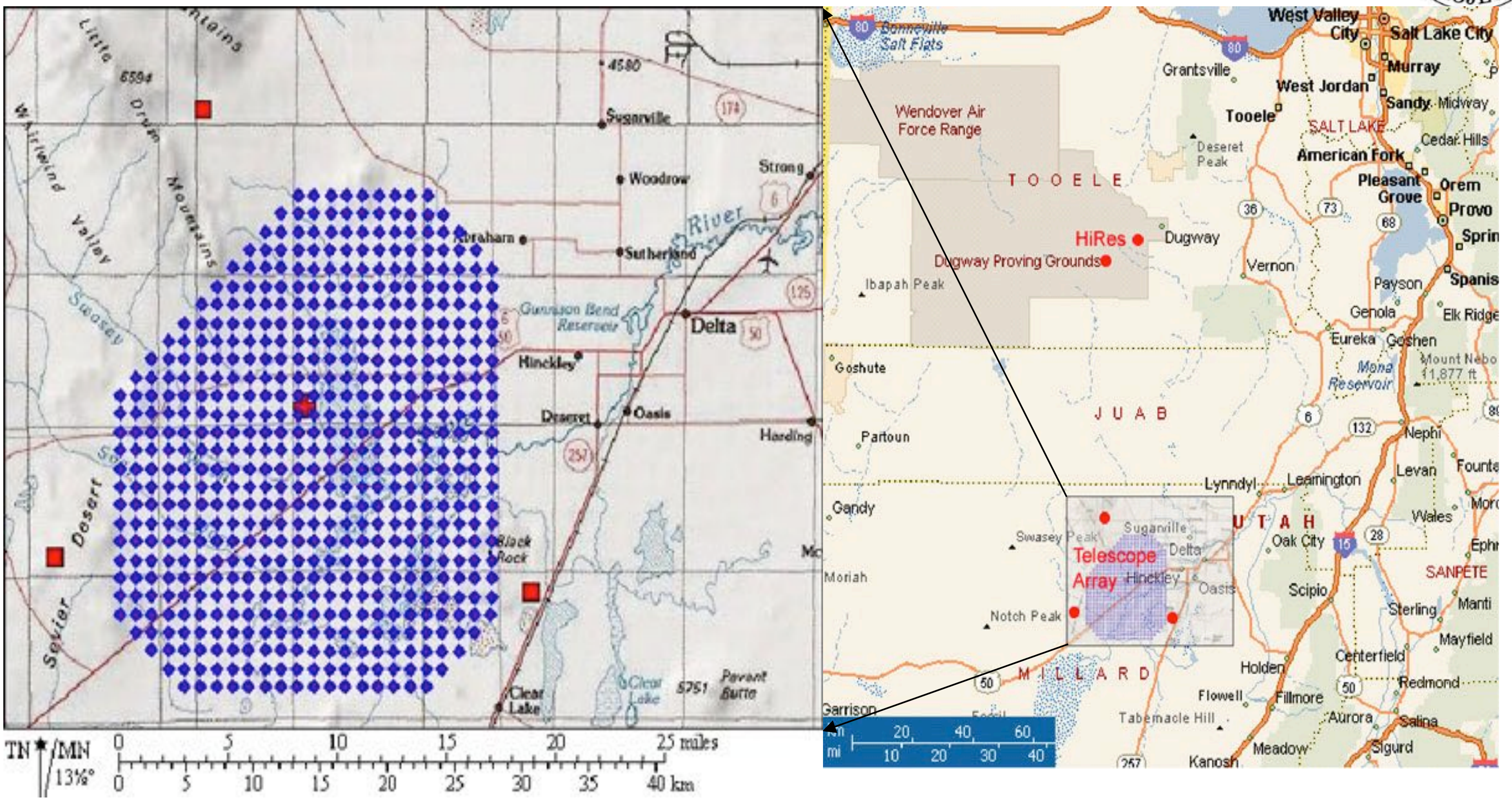
[1] *High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA*
[2] *The Graduate School of Science and Engineering, Saitama University, Saitama, Saitama, Japan*
[3] *Graduate School of Science and Engineering, Tokyo Institute of Technology, Meguro, Tokyo, Japan*
[4] *Department of Physics and Institute for the Early Universe, Ewha Womans University, Seodaaemun-gu, Seoul, Korea*
[5] *Department of Physics and The Research Institute of Natural Science, Hanyang University, Seongdong-gu, Seoul, Korea*
[6] *Department of Physics, Tokyo University of Science, Noda, Chiba, Japan*
[7] *Department of Physics, Kinki University, Higashi Osaka, Osaka, Japan*
[8] *Department of Physics, Yonsei University, Seodaemun-gu, Seoul, Korea*
[9] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan*
[10] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, the University of Tokyo, Kashiwa, Chiba, Japan*
[11] *Graduate School of Science, Osaka City University, Osaka, Osaka, Japan*
[12] *Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan*
[13] *Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, Yamanashi, Japan*
[14] *Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama, Japan*
[15] *Department of Physics, Tokyo City University, Setagaya-ku, Tokyo, Japan*
[16] *Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia*
[17] *Advanced Research Institute for Science and Engineering, Waseda University, Shinjuku-ku, Tokyo, Japan*
[18] *Department of Physics, Chiba University, Chiba, Chiba, Japan*
[19] *Department of Physics, School of Natural Sciences, Ulsan National Institute of Science and Technology, UNIST-gil, Ulsan, Korea*
[20] *Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki, Japan*
[21] *Faculty of Science, Kochi University, Kochi, Kochi, Japan*
[22] *Department of Physical Sciences, Ritsumeikan University, Kusatsu, Shiga, Japan*
[23] *Department of Physics, Kyushu University, Fukuoka, Fukuoka, Japan*
[24] *Engineering Science Laboratory, Chubu University, Kasugai, Aichi, Japan*
[25] *Department of Physics, Sungkyunkwan University, Jang-an-gu, Suwon, Korea*
[26] *Sternberg Astronomical Institute, Moscow M.V. Lomonosov State University, Moscow, Russia*
[27] *Department of Physics and Astronomy, Rutgers University – The State University of New Jersey, Piscataway, New Jersey, USA*
[28] *Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, Japan*
[29] *Graduate School of Information Sciences, Hiroshima City University, Hiroshima, Hiroshima, Japan*
[30] *Service de Physique Théorique, Université Libre de Bruxelles, Brussels, Belgium*
[31] *Department of Computer Science and Engineering, Shinshu University, Nagano, Nagano, Japan*
[32] *National Institute of Radiological Science, Chiba, Chiba, Japan*
[33] *Department of Physics, Ehime University, Matsuyama, Ehime, Japan*

5 nations, 33 institutions, 124 members

Outline

- Introduction to the Telescope Array (TA)
- Energy Spectrum
- Composition
- Anisotropy
- Future of TA

Telescope Array

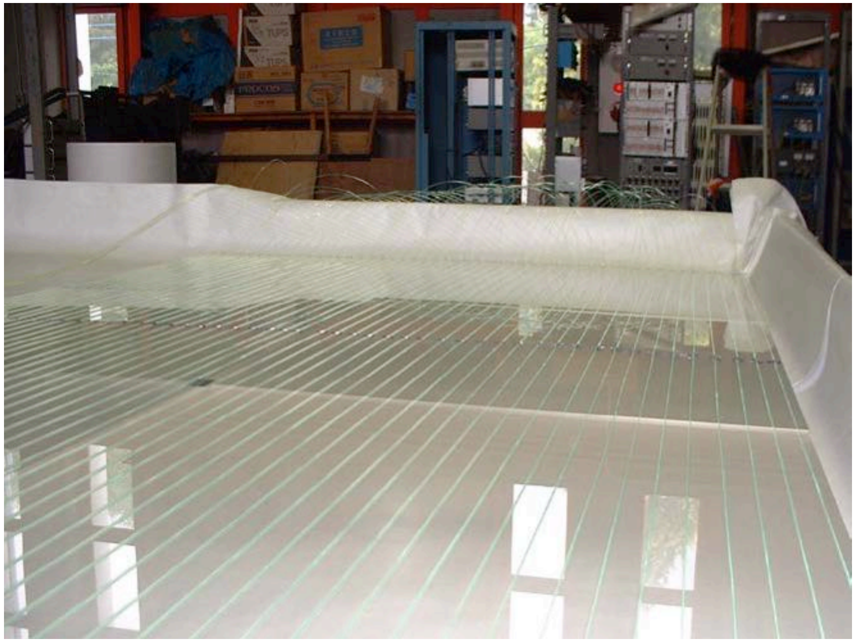


507 scintillation counters surface detector (SD): Area: ~700 km^2.

3 fluorescence detector (FD) stations

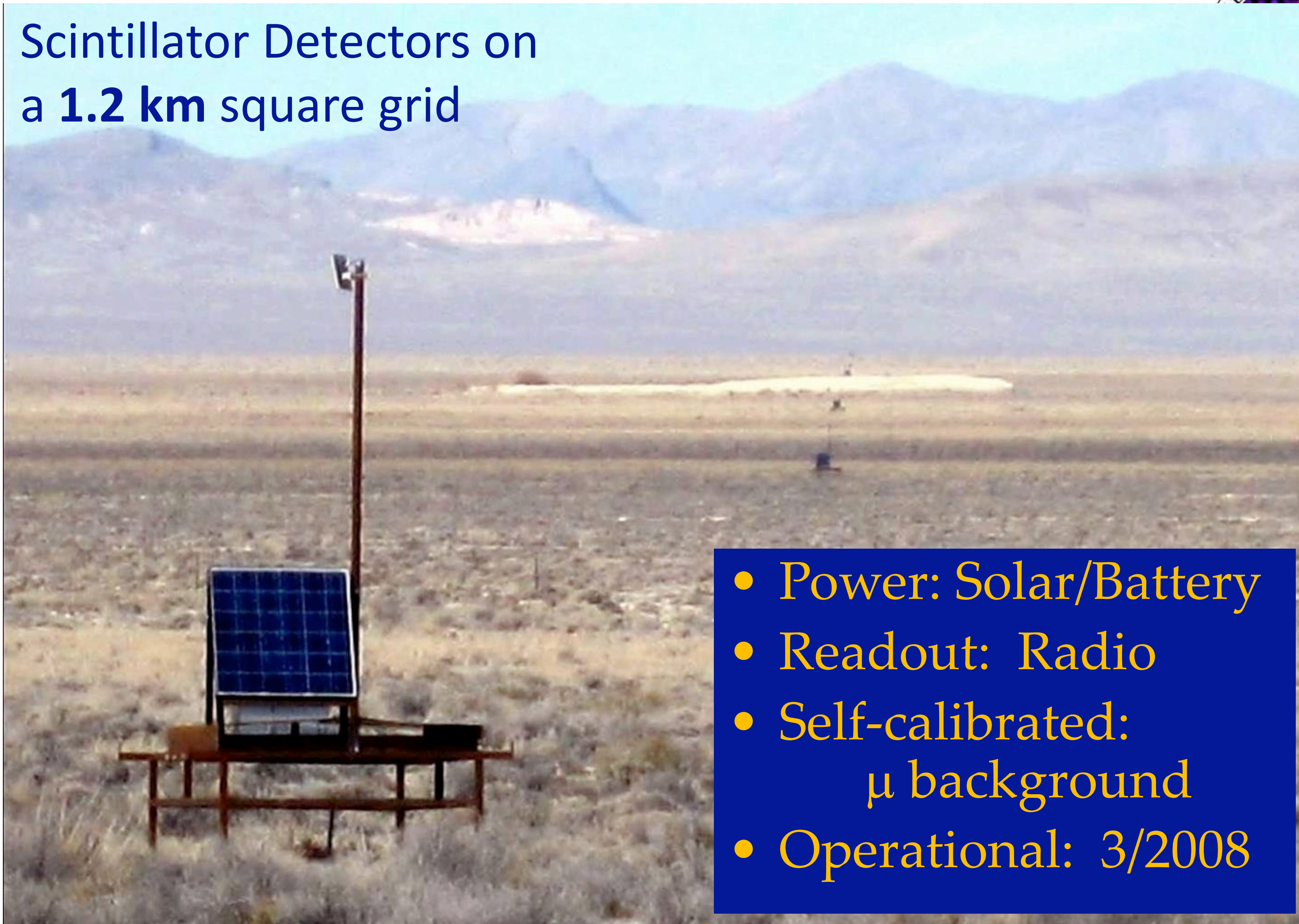
In operation since 2008

Scintillation Counters



Pre-assembled in Japan, Final Assby/testing in Delta: **2 layers**, **1.25 cm** scintillator, **$3m^2$** area

Scintillator Detectors on a **1.2 km** square grid



- Power: Solar/Battery
- Readout: Radio
- Self-calibrated: μ background
- Operational: 3/2008

TA Fluorescence Detectors

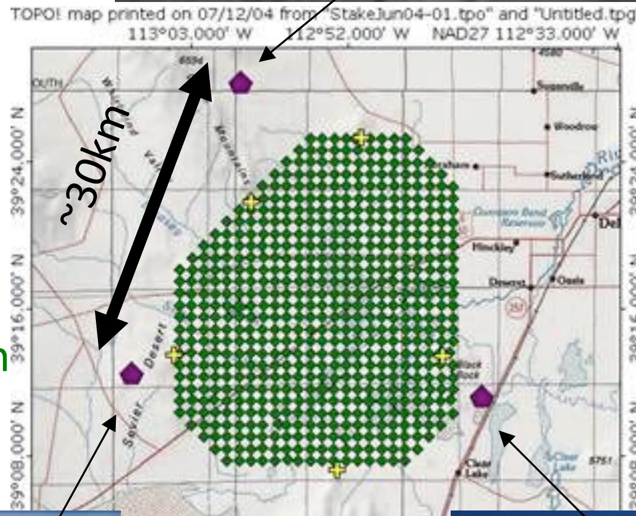
Refurbished from HiRes-I

Observations since ~10/2007

Middle Drum

14 telescopes@station
256 PMTs/camera

5.2 m²



New FDs

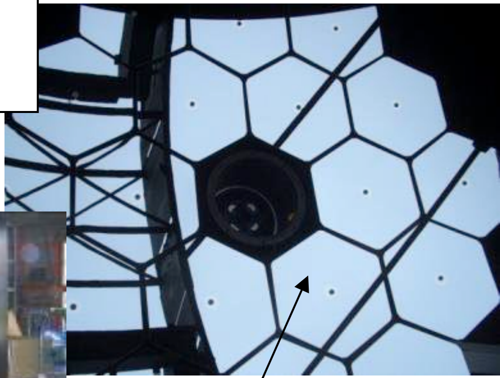
Observation since ~11/2007

12 telescopes/station
256 PMTs/camera
Hamamatsu R9508
FOV~15x18deg

1° pixels

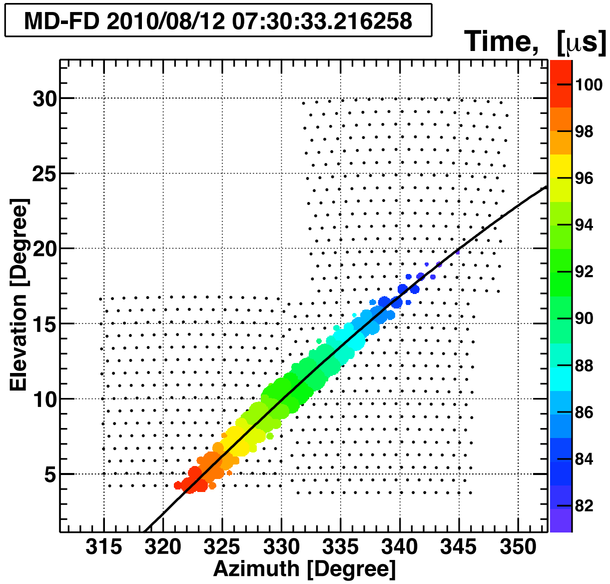
Observation since ~6/2007

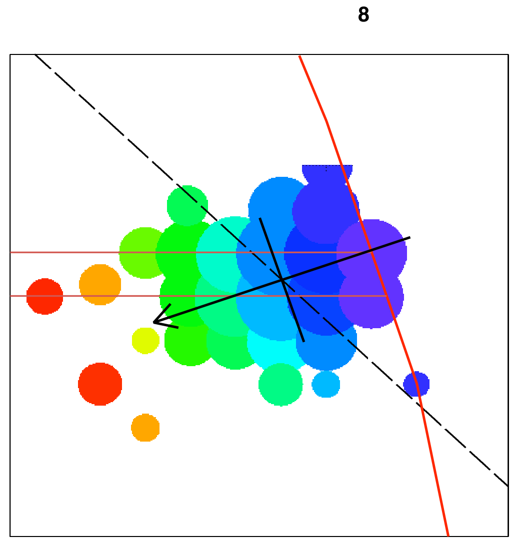
~1 m²

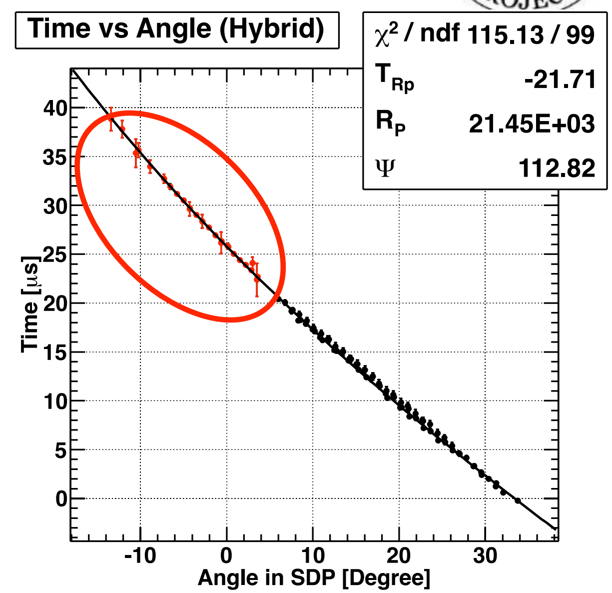


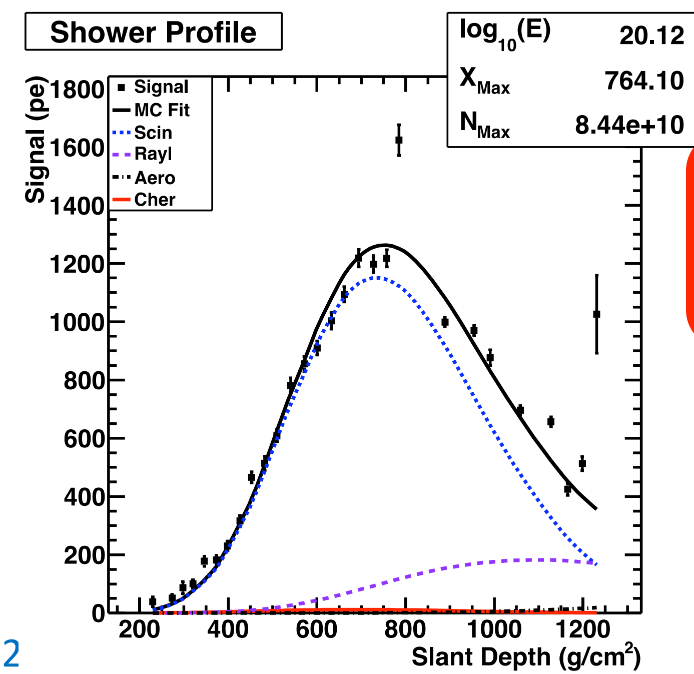
6.8 m²

High Energy Hybrid Event







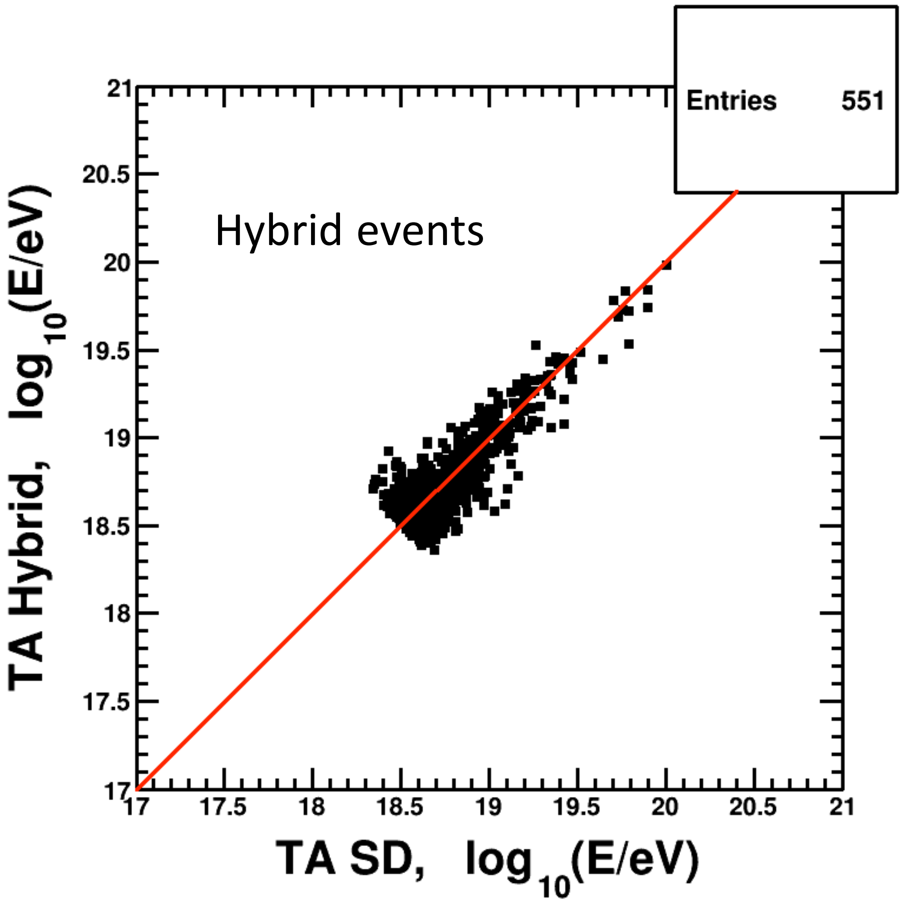


Energy: 1.3×10^{20} eV

Zenith Angle: 55.7°

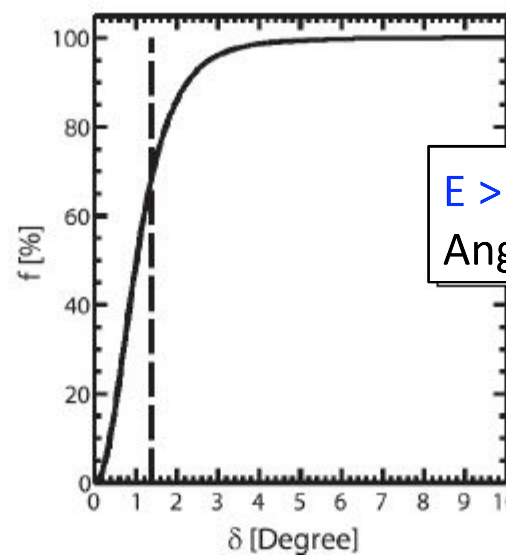
Surface array constrains geometry fit via extra timing & core information

1. Energy Spectrum

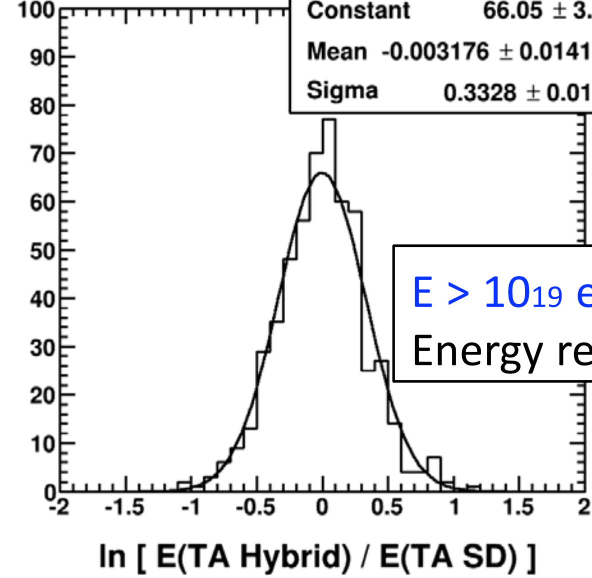


(scaled to FD energy)

$$EE_{ssss} = EE'_{ssss}/1.27$$

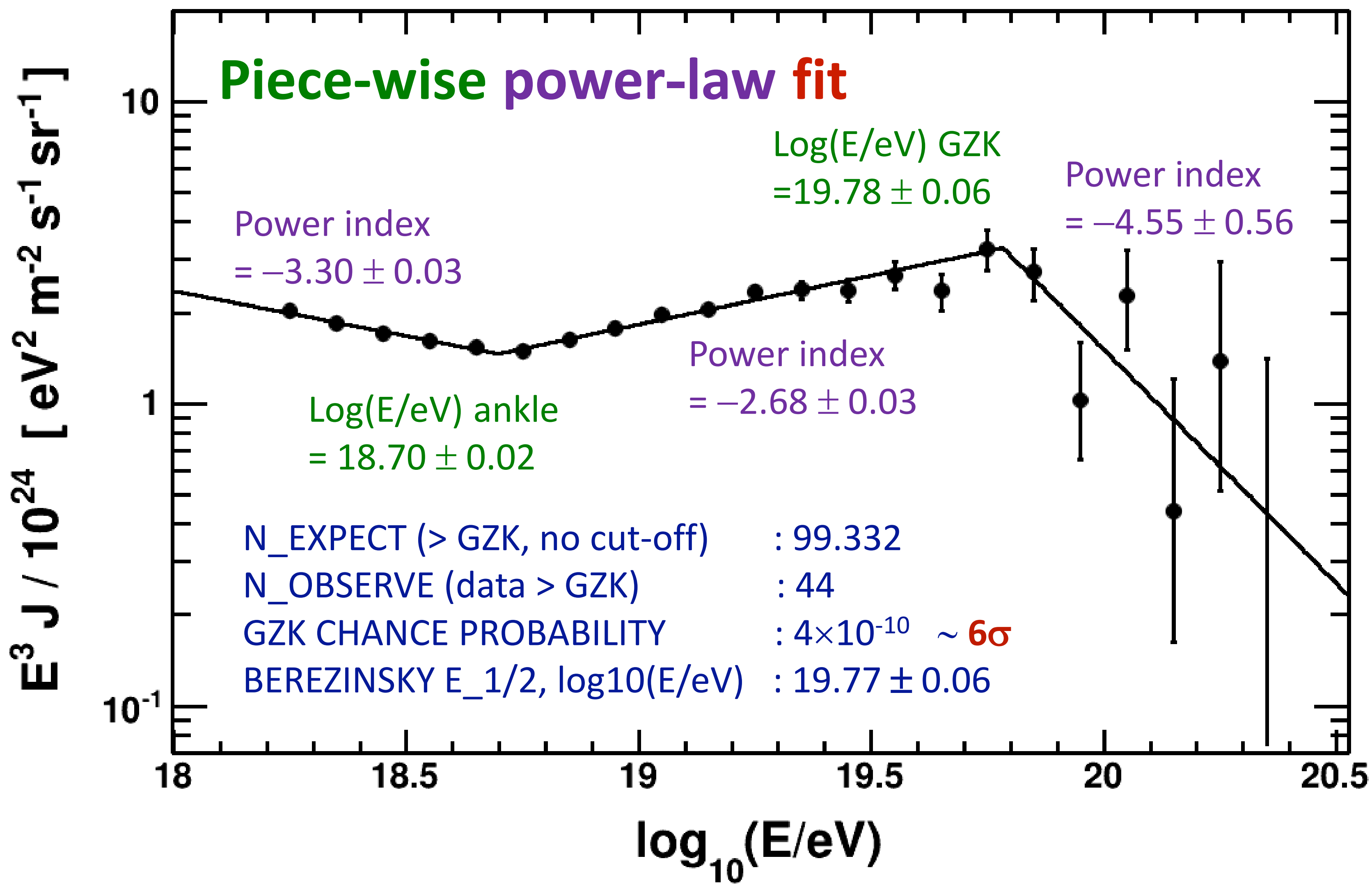


E > 10^{19} eV
Angular resolution = 1.4°



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

TA Surface Detector Energy Spectrum



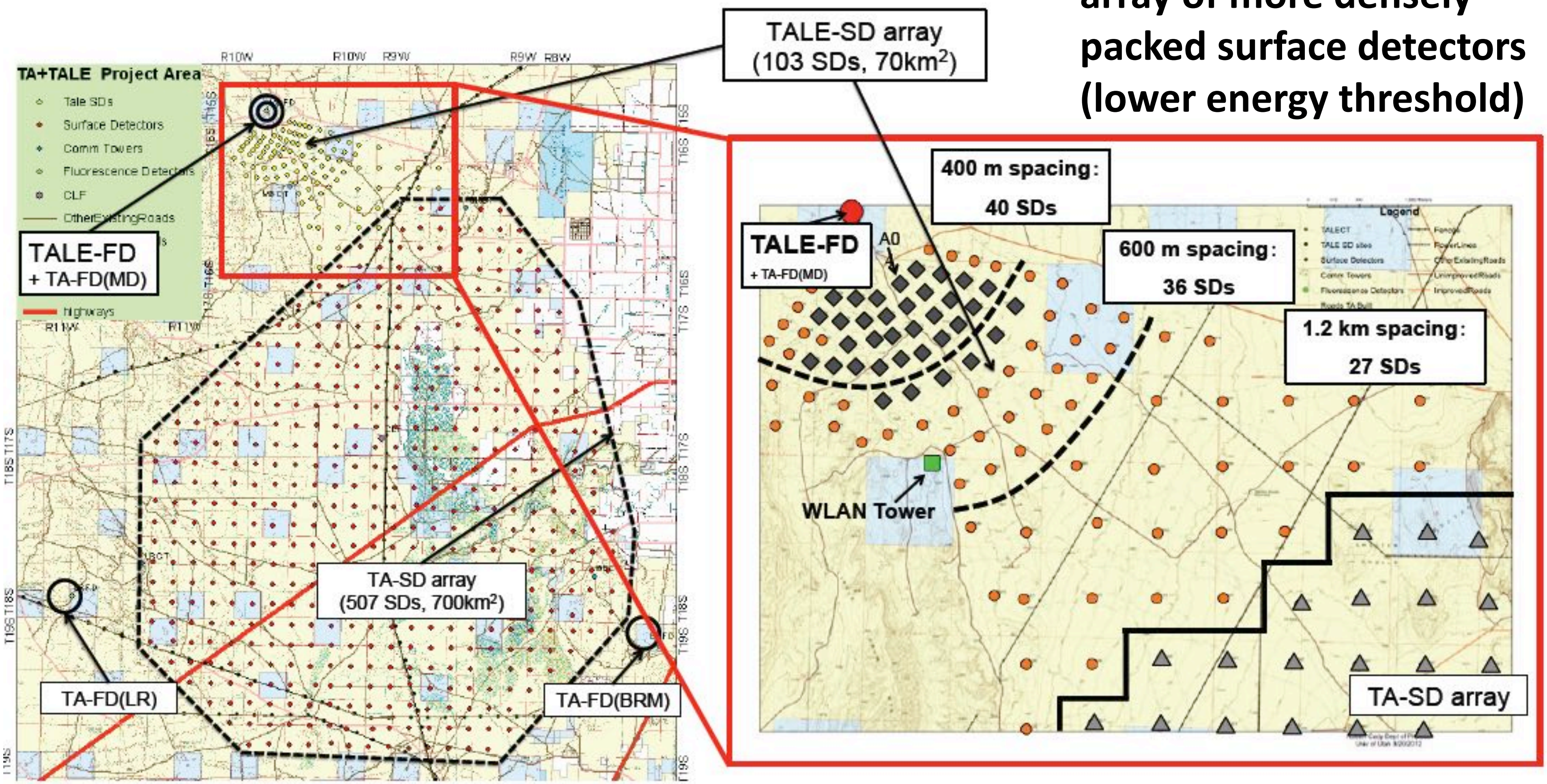
Previously Pubilshed: **4 year TA surface detector spectrum**
Astrophysical Journal Letters 768 L1 (2013)

TA Low Energy Extension (TALE)

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

[859- PoS 637] Poster 1 CR Track: CRIN Board #: 148
Presented by Shoichi OGIO on 30 Jul 2015
at 15:30

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

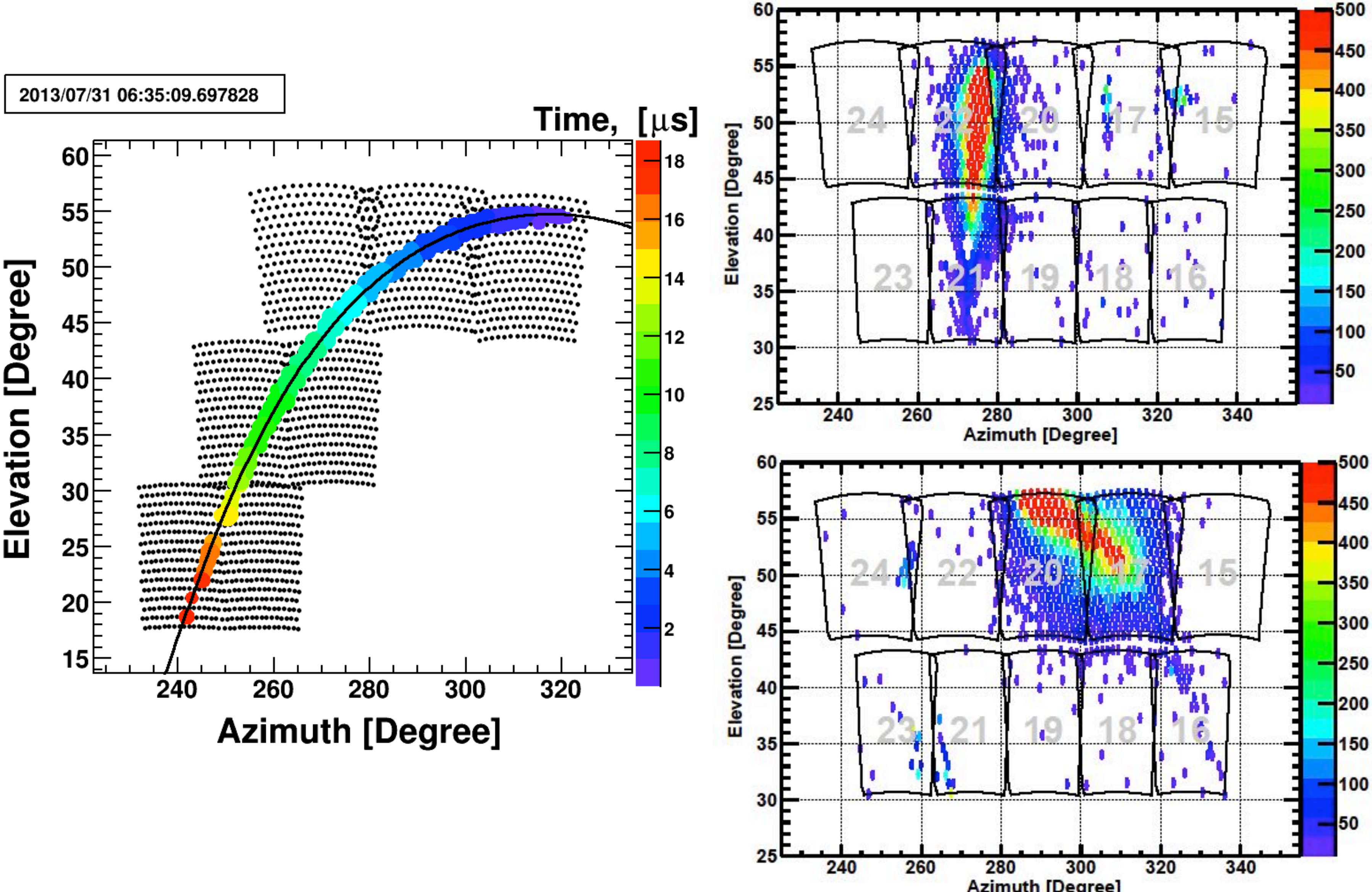


All 10 Telescopes installed and in operation since fall 2013

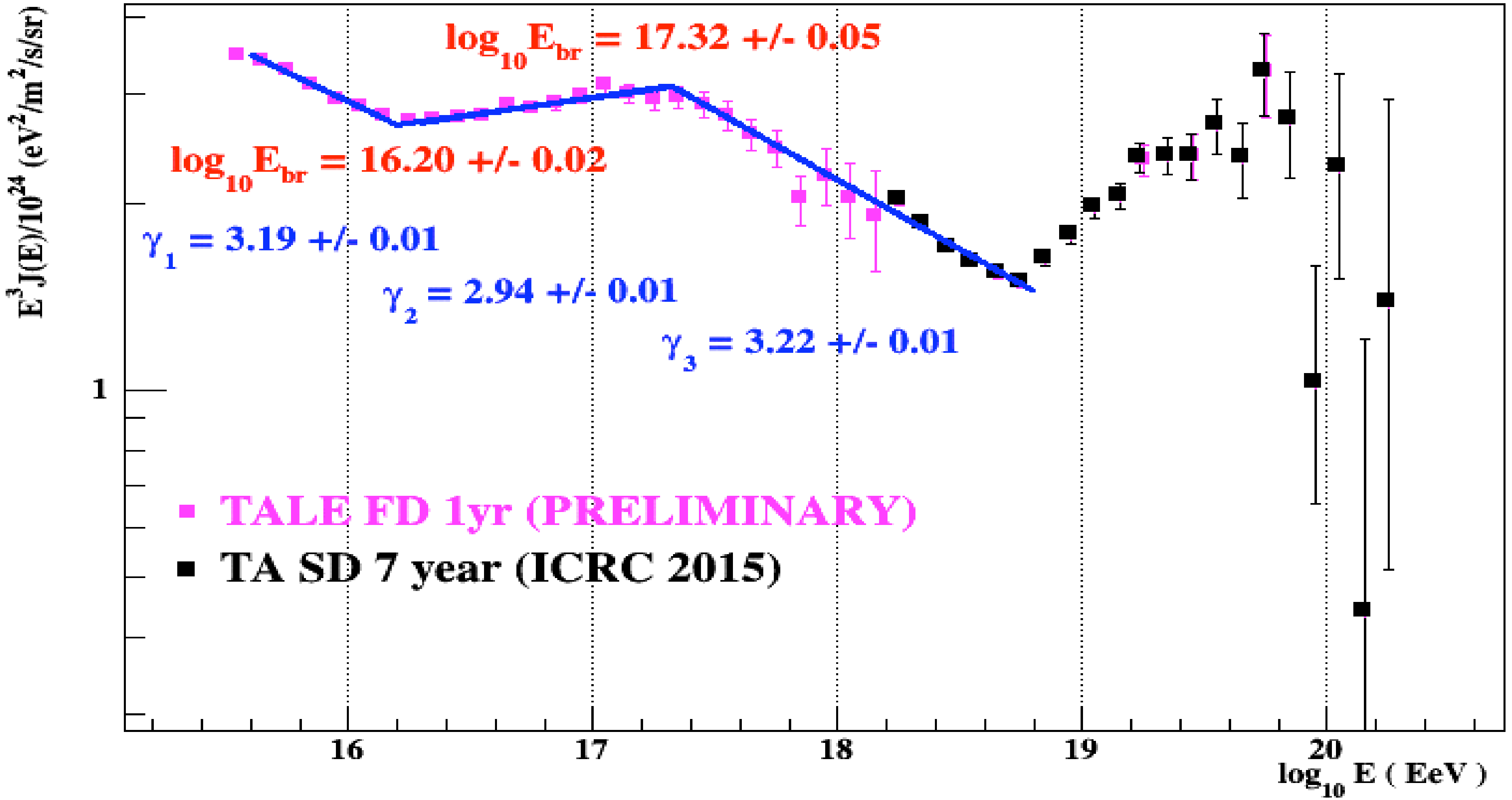
First 35 scintillation surface detectors deployed, 16 are instrumented and operational

64 more TALE SD (now funded in Japan) counters to be installed starting in September 2016

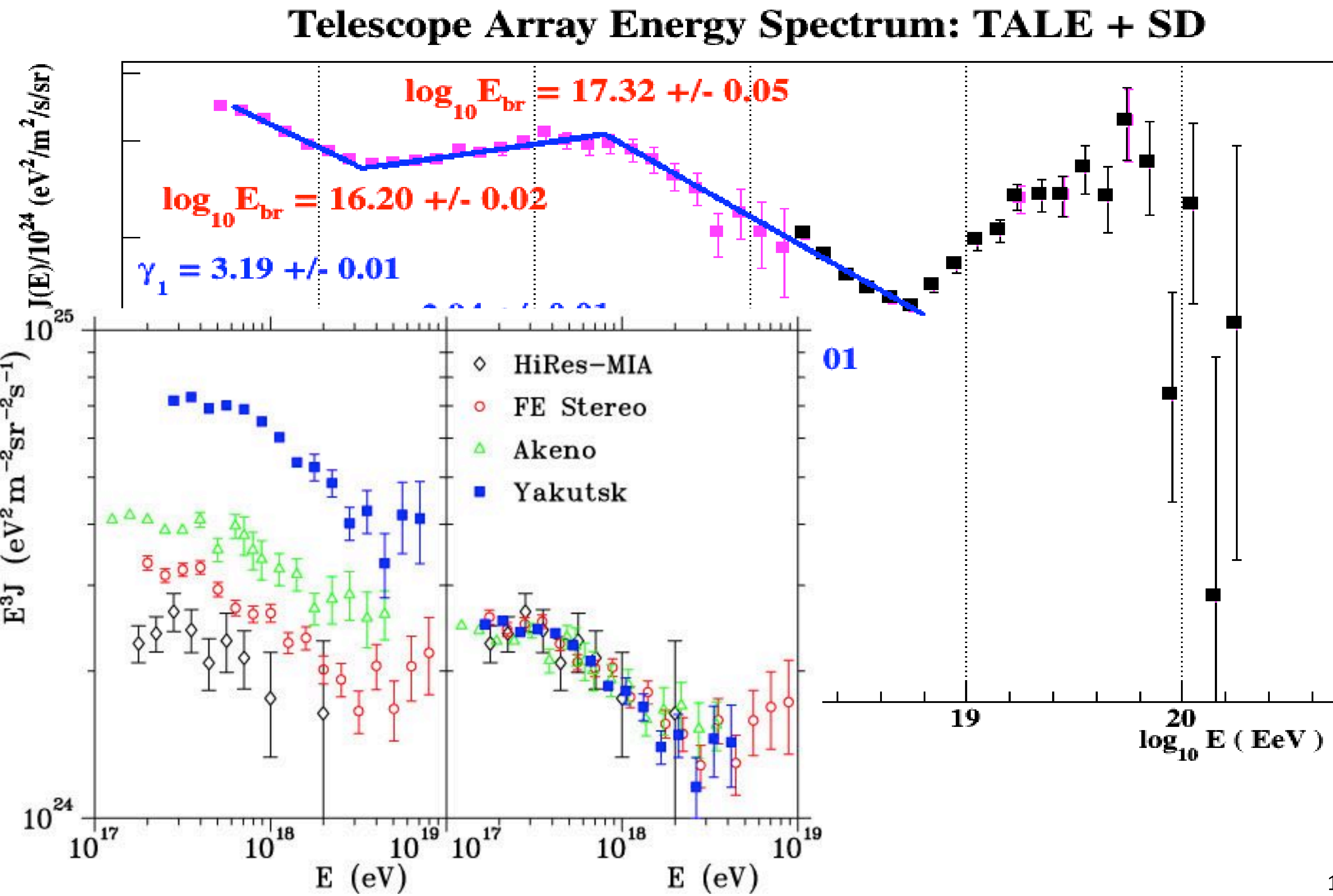
Nearby Events with Cerenkov



Combined TA Energy Spectrum

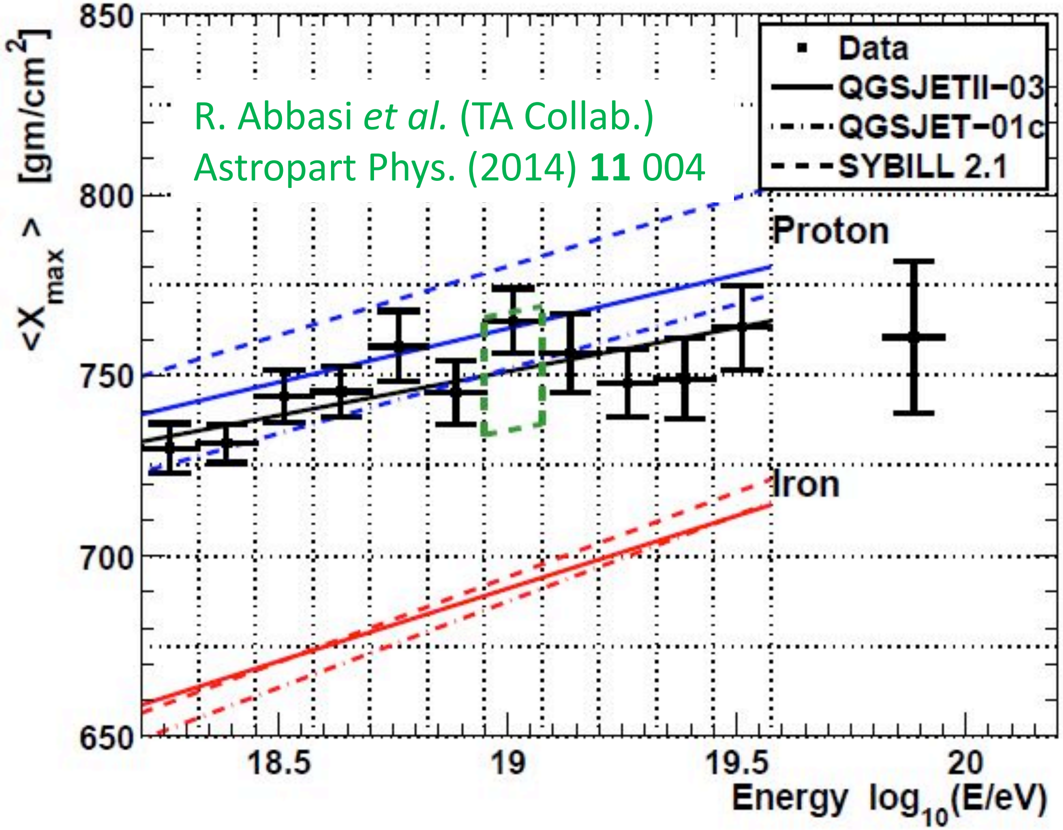


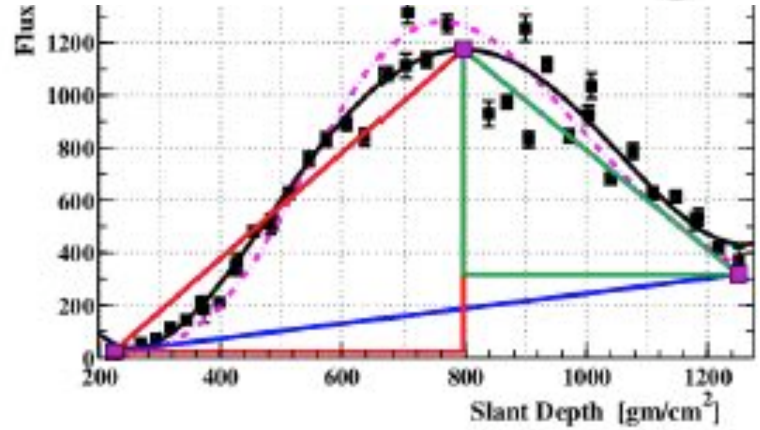
Combined TA Energy Spectrum

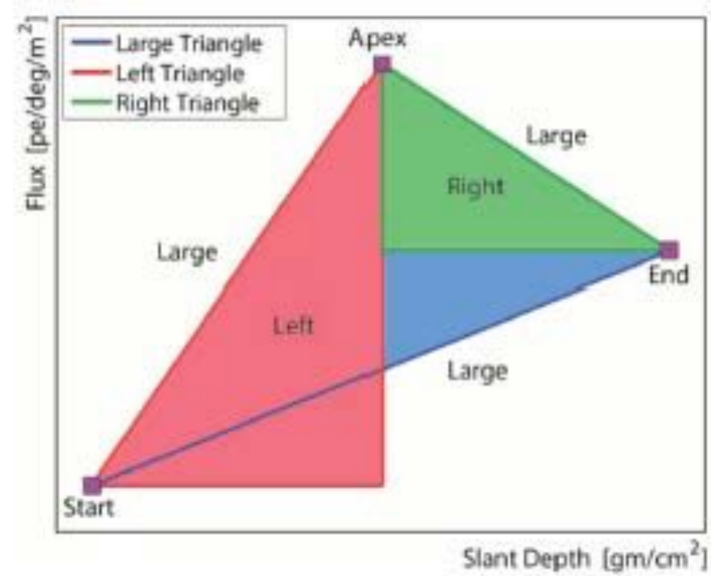


Published Hybrid Composition (MD)

R. Abbasi *et al.* (TA Collab.)
Astropart Phys. (2014) **11** 004



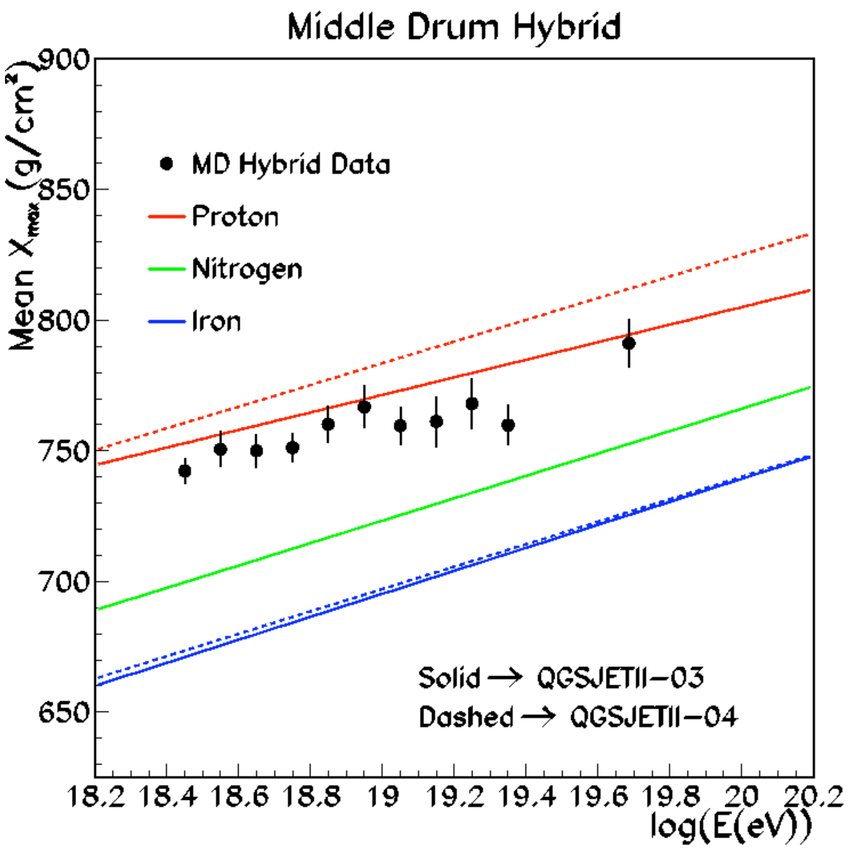




4 yrs, 297 Events > $10^{18.4}$ eV
Cuts based on pattern recognition to improve resolutions $s \le 25$ g/cm^2, all energies.

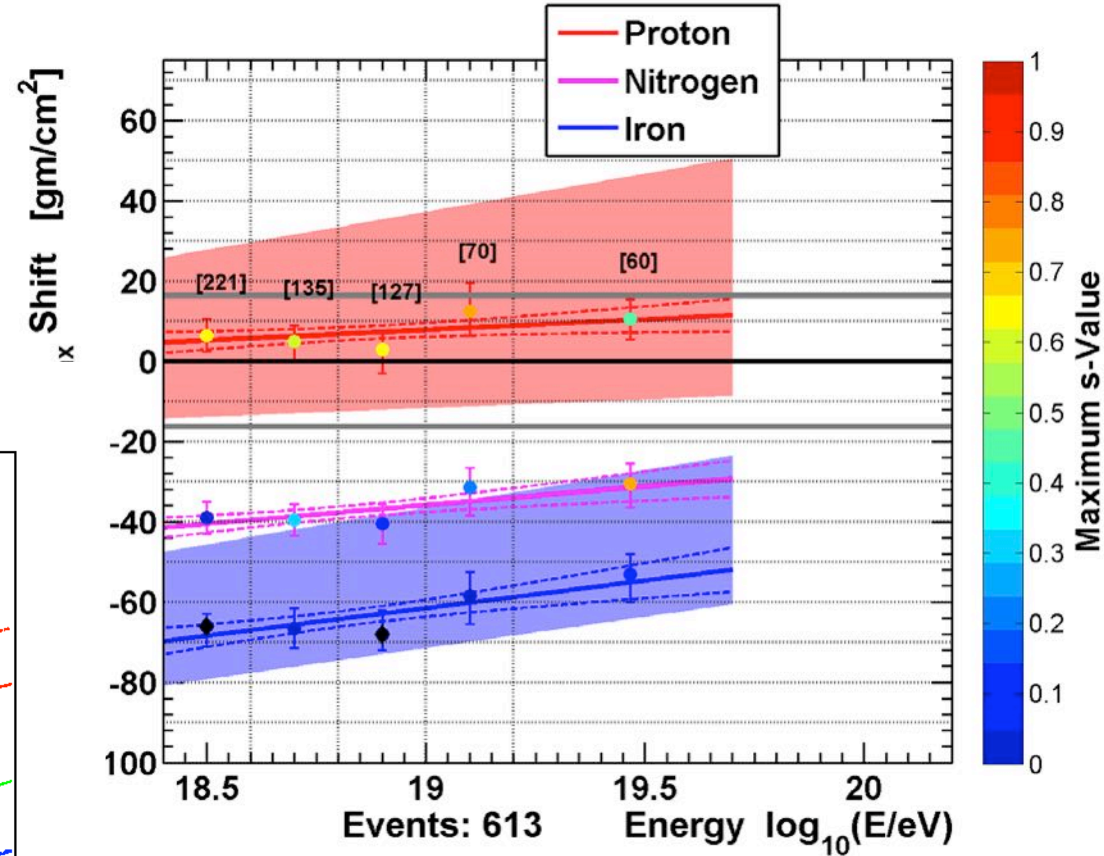
TA MD Hybrid Composition

Left: <Xmax> vs log(E) plot



Update:

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



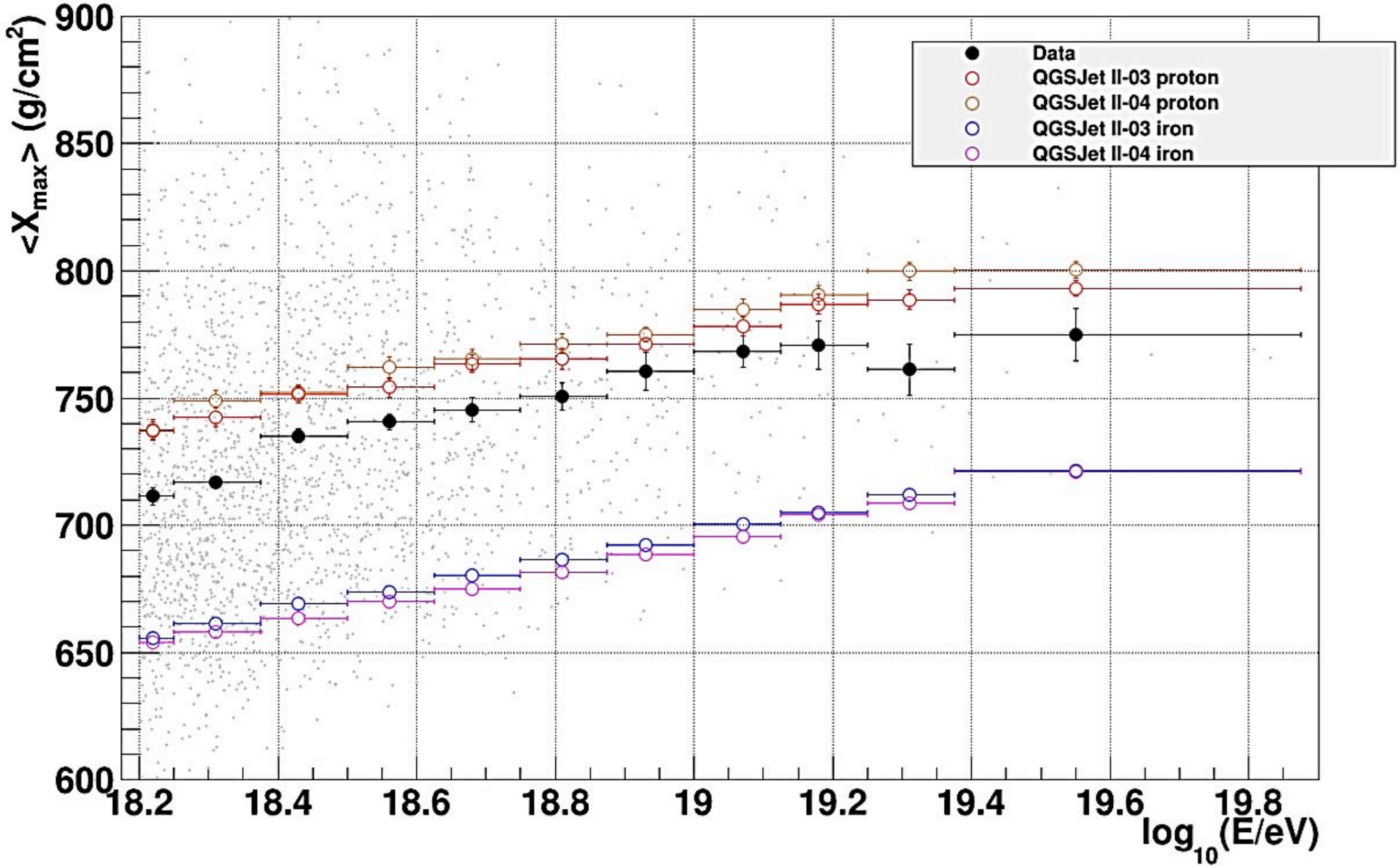
Right: "Shift Plot"

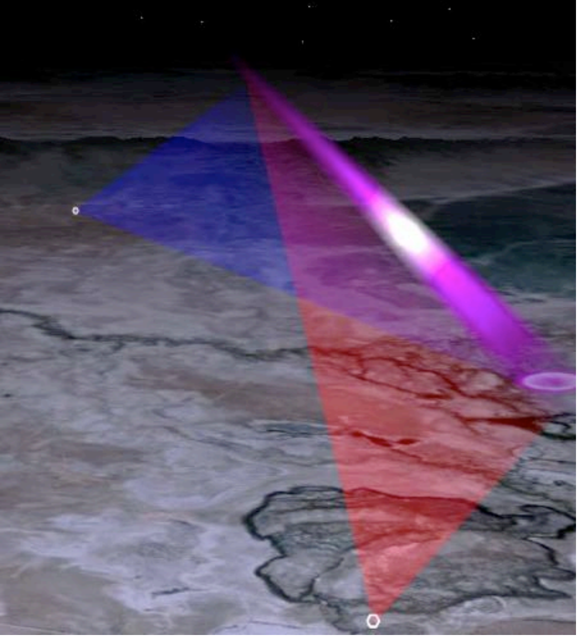
Plot ΔX_{max} required to maximize data/MC agreement (QGSJETII-03).

Standard statistical test on shifted distribution (points) Pink, blue bands for other hadronic models

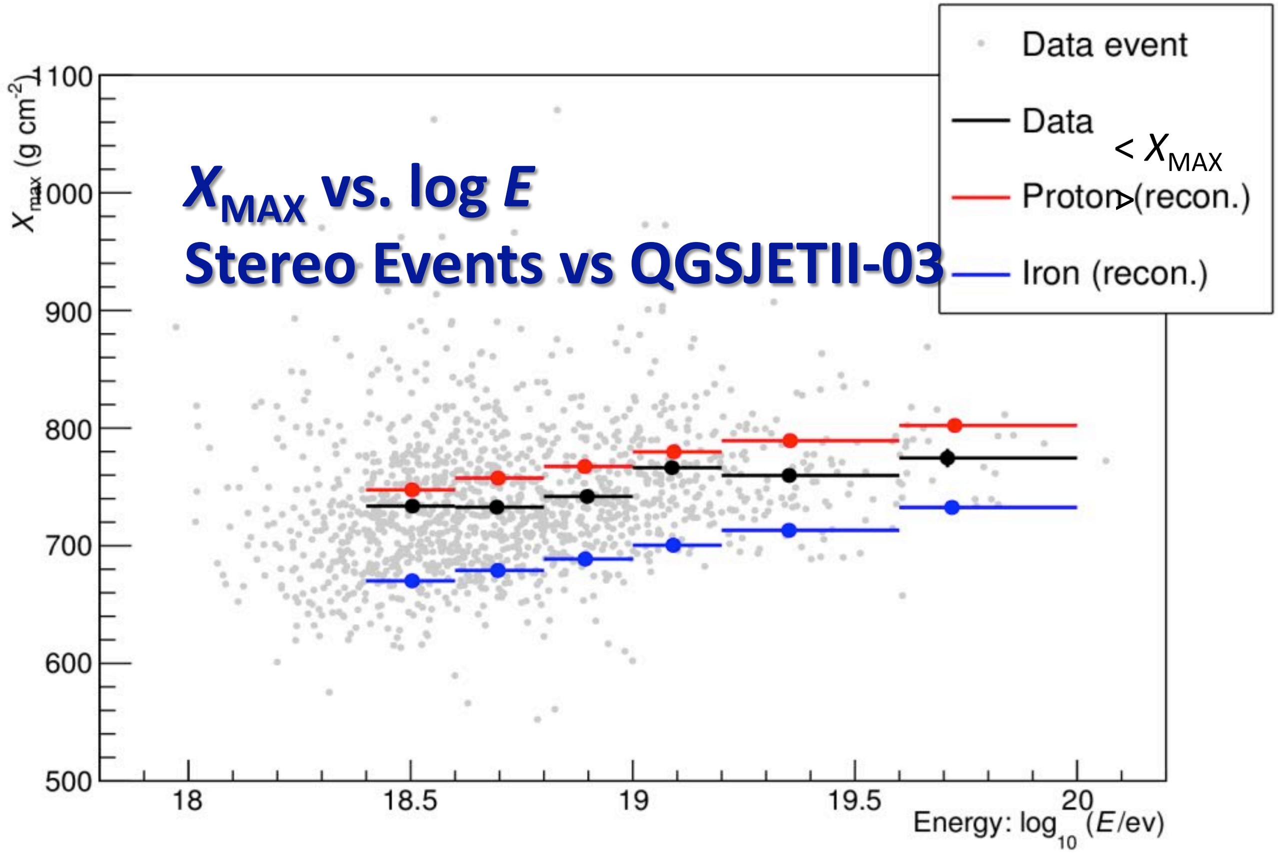
16 g/cm^2 systematic uncertainty

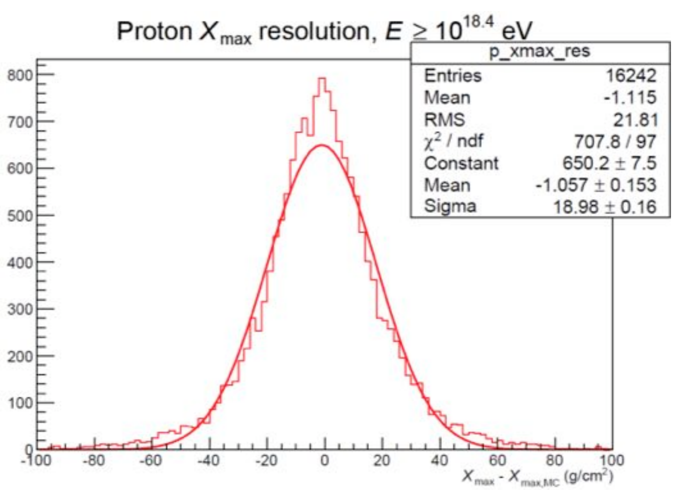
X_{MAX} vs. logE for hybrid events from Black Rock and Long Ridge FD

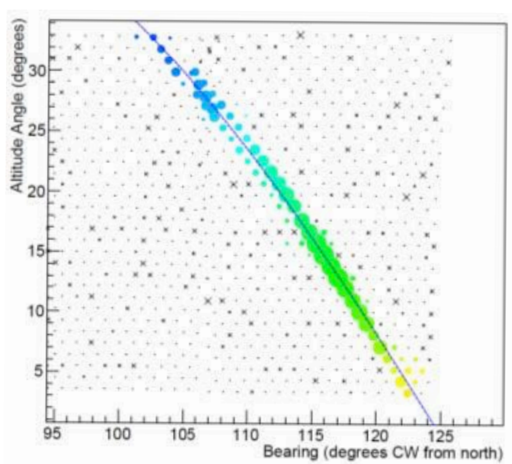


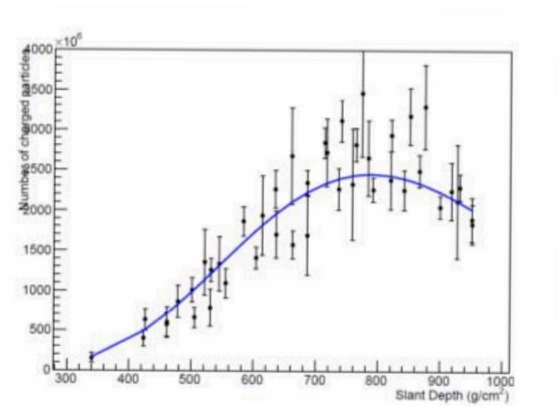


X_{MAX} vs. log E
Stereo Events vs QGSJETII-03

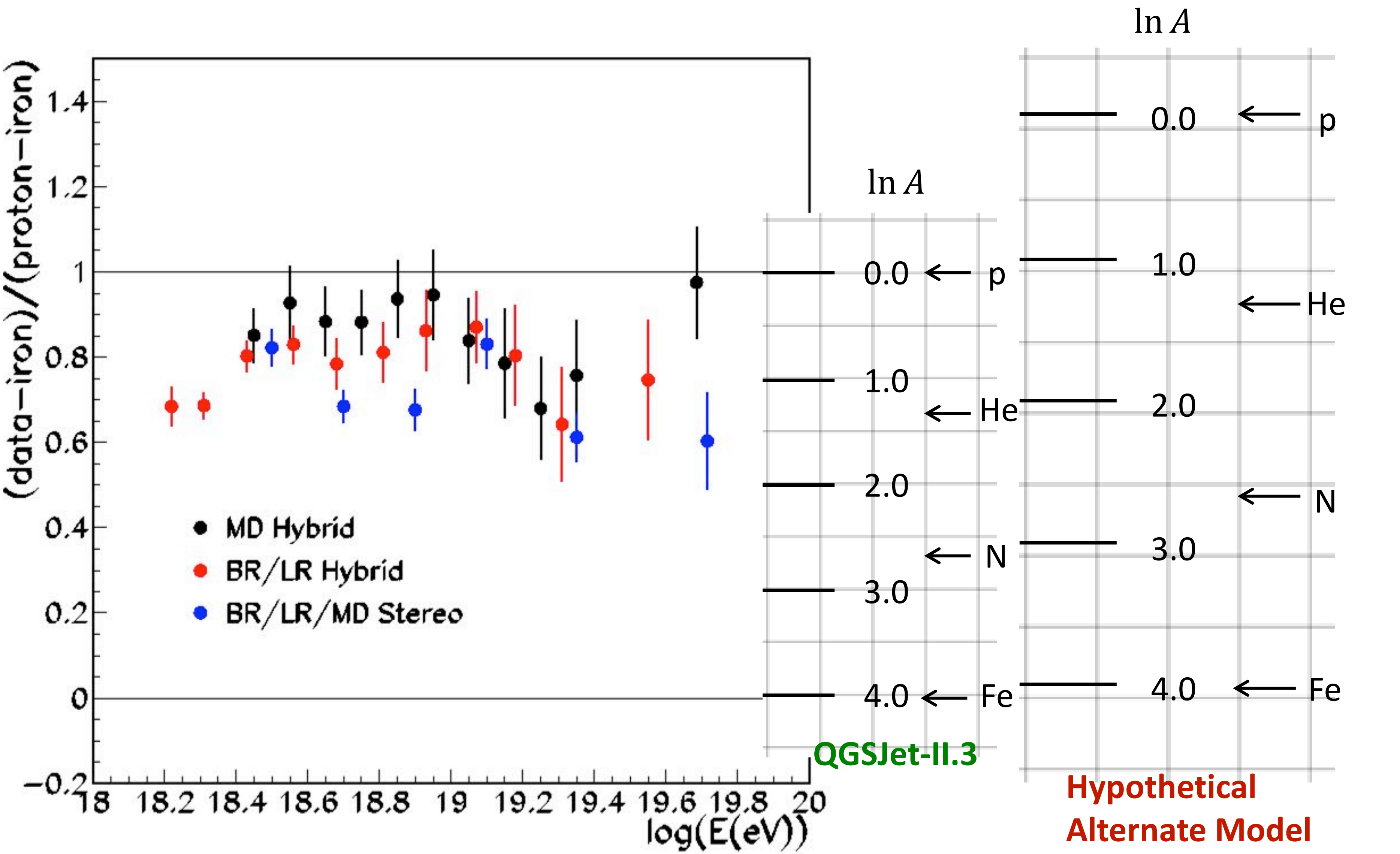




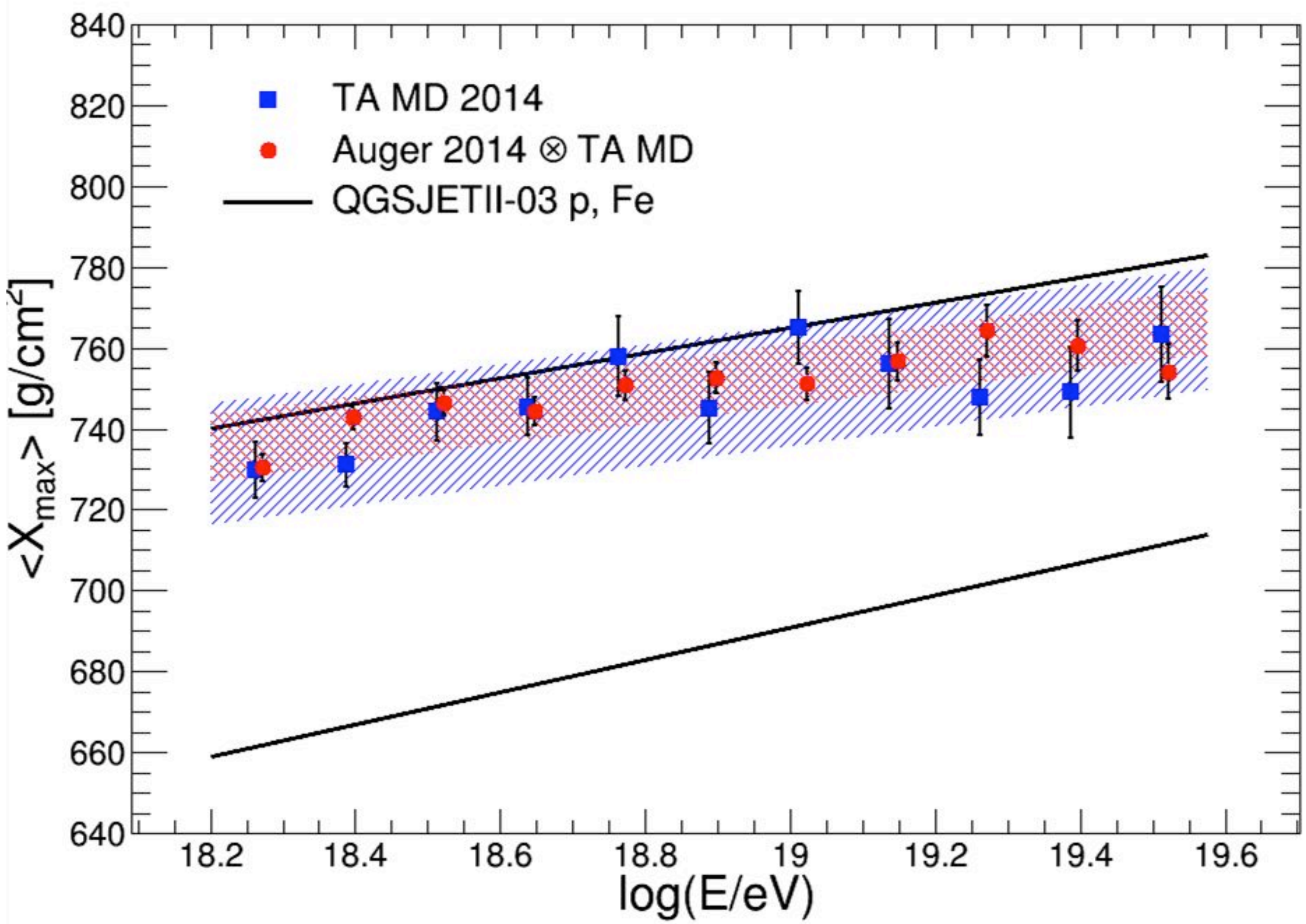




TA data compared to QGSJet-II.3

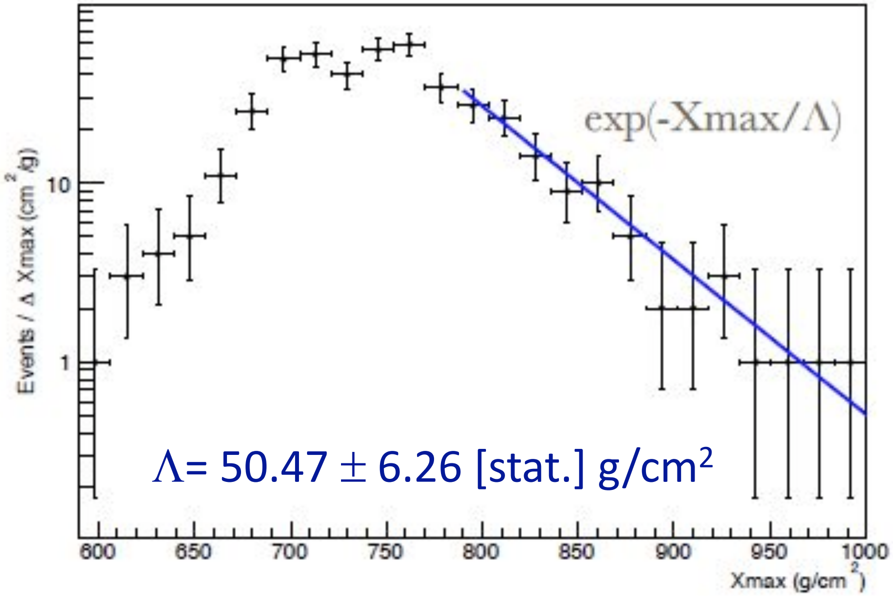


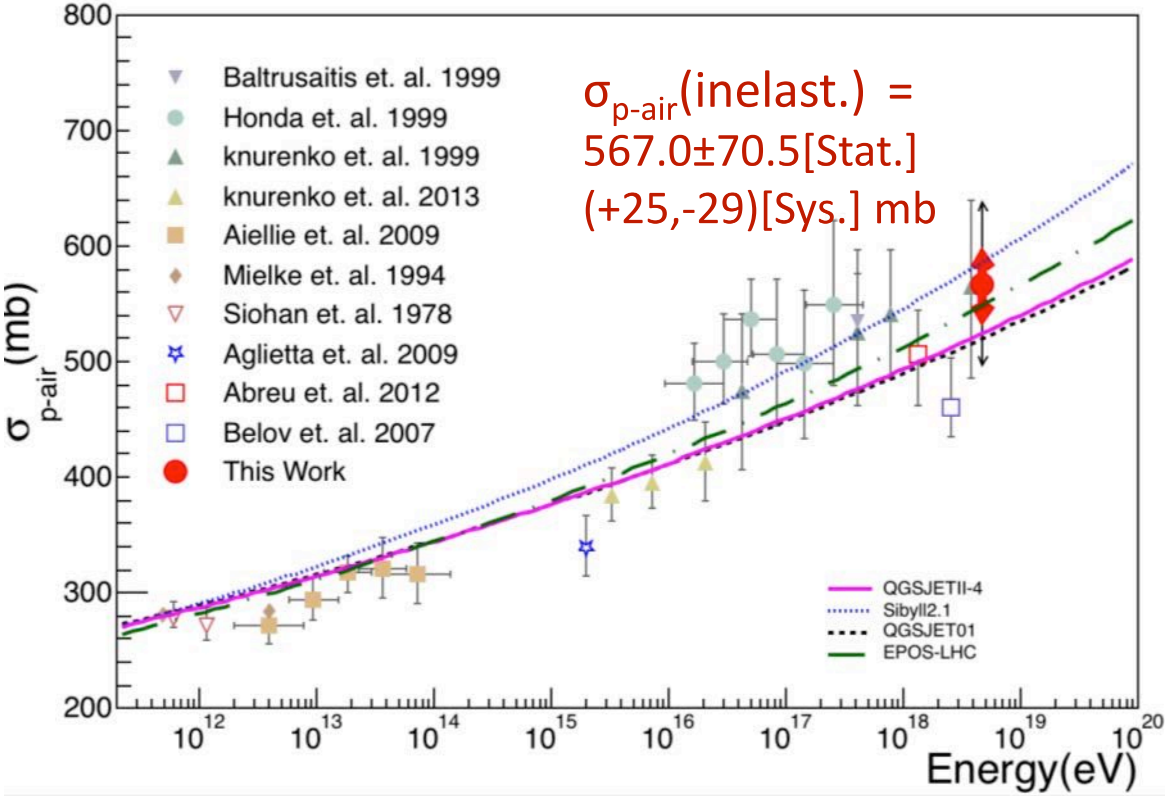
Meta-analysis: Auger-TA Composition Working Group



TA data cannot distinguish between mix and QGSJETII-03 protons at this level of systematic uncertainty.

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



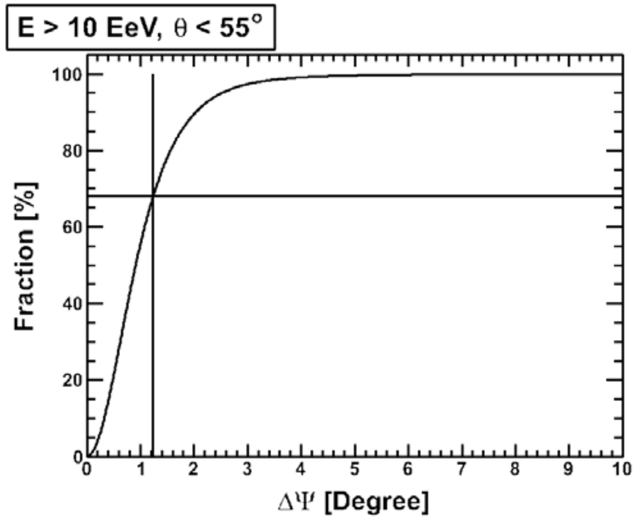


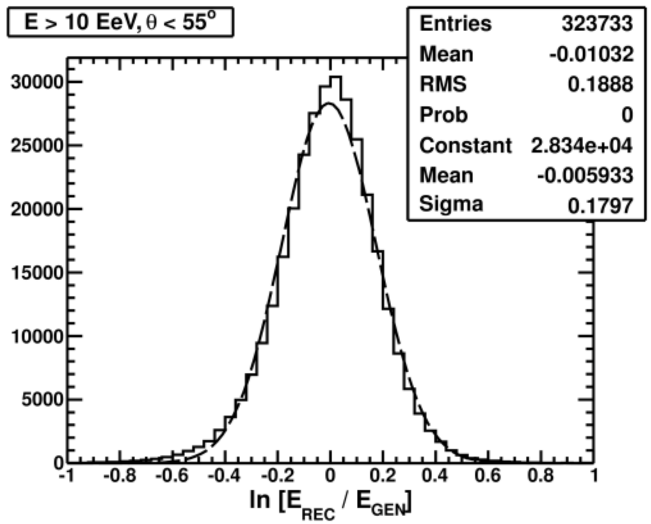
Systematic source	Systematic (mb)
Model Dependence	±17
20%Helium	+18
Gamma<1%*	– 23
Total	(+25,-29)

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

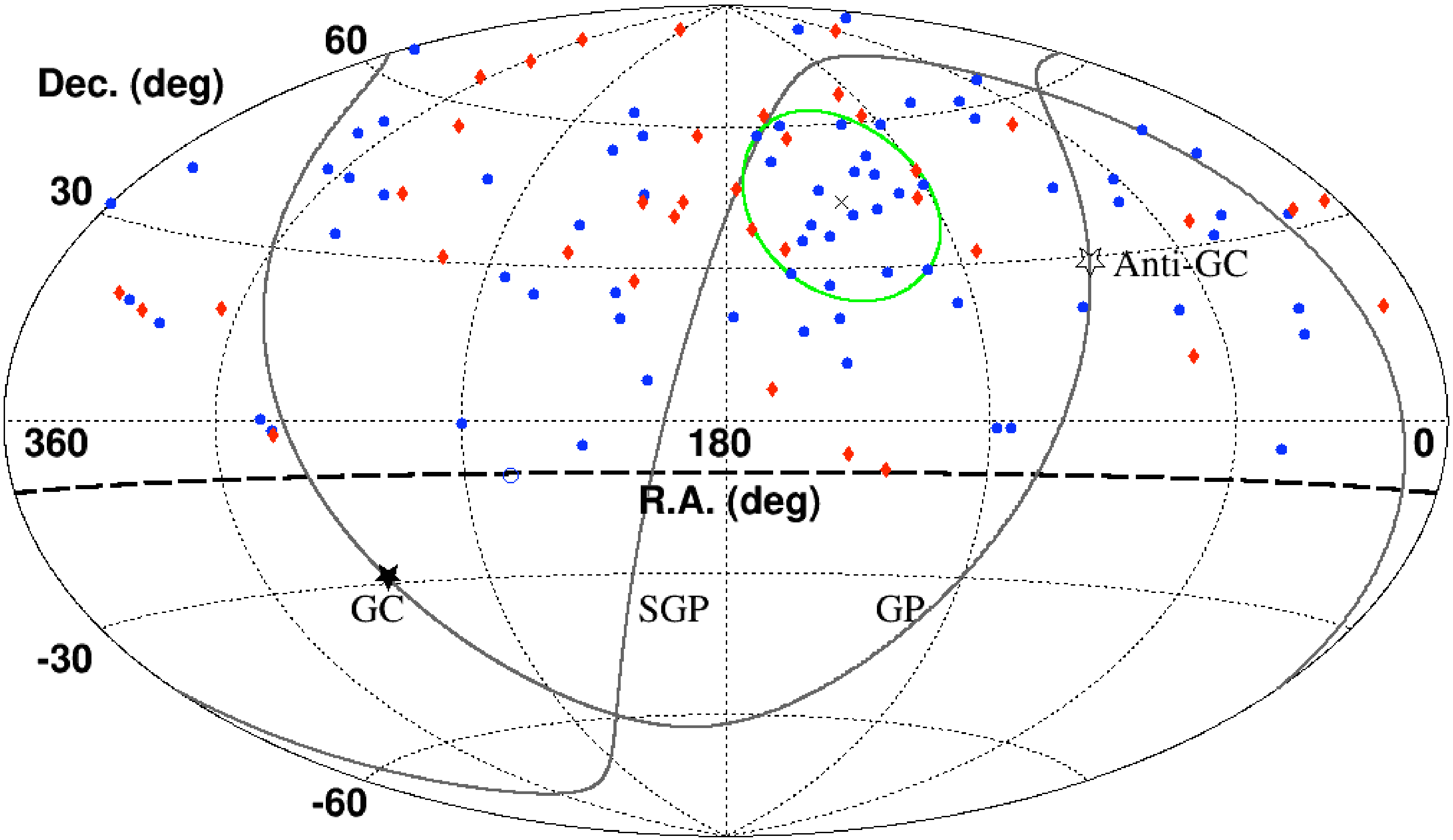
Anisotropy Analysis: ICRC 2015

- 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%





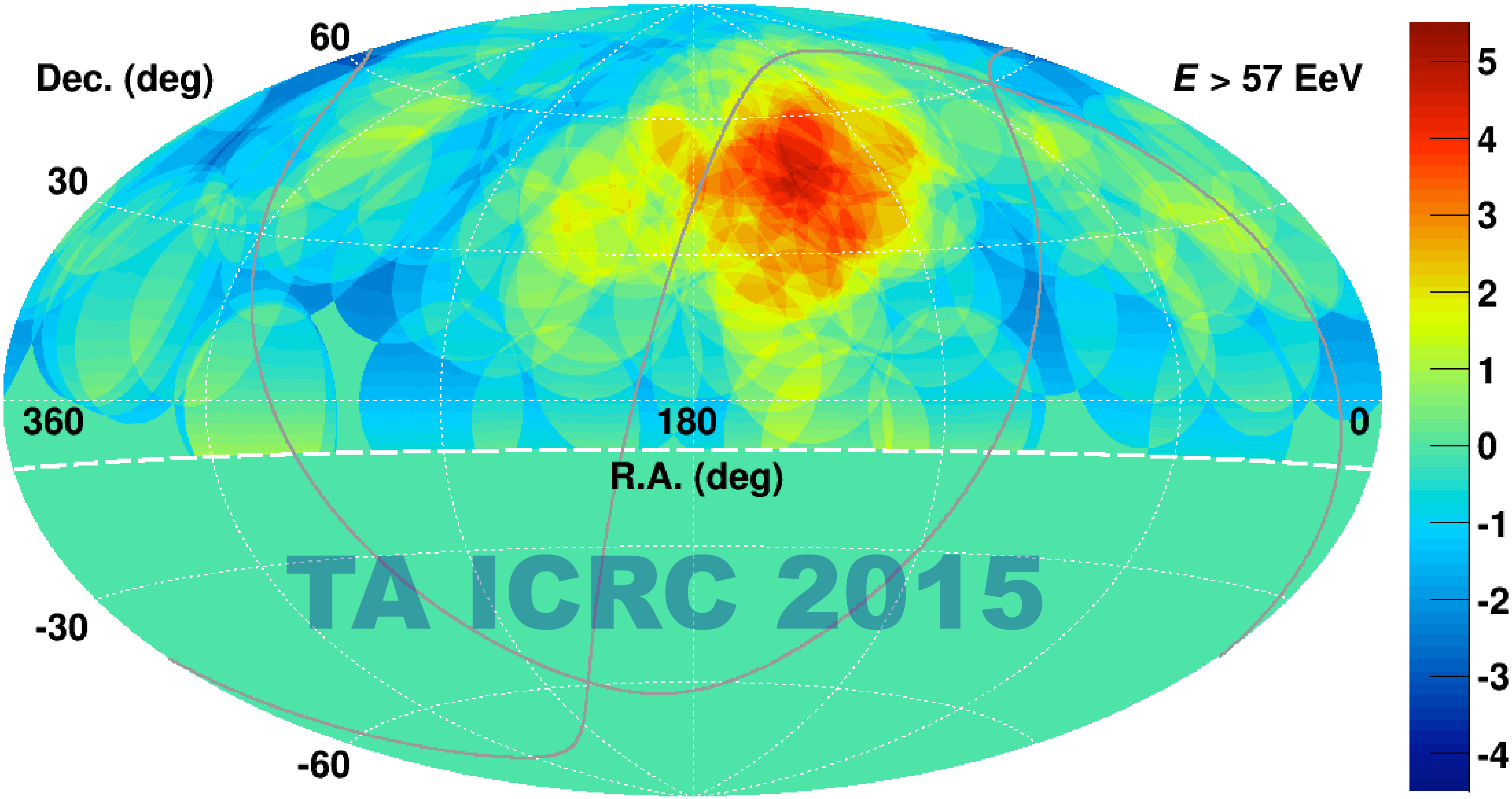
The TA Hot Spot



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%

Excess Map



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

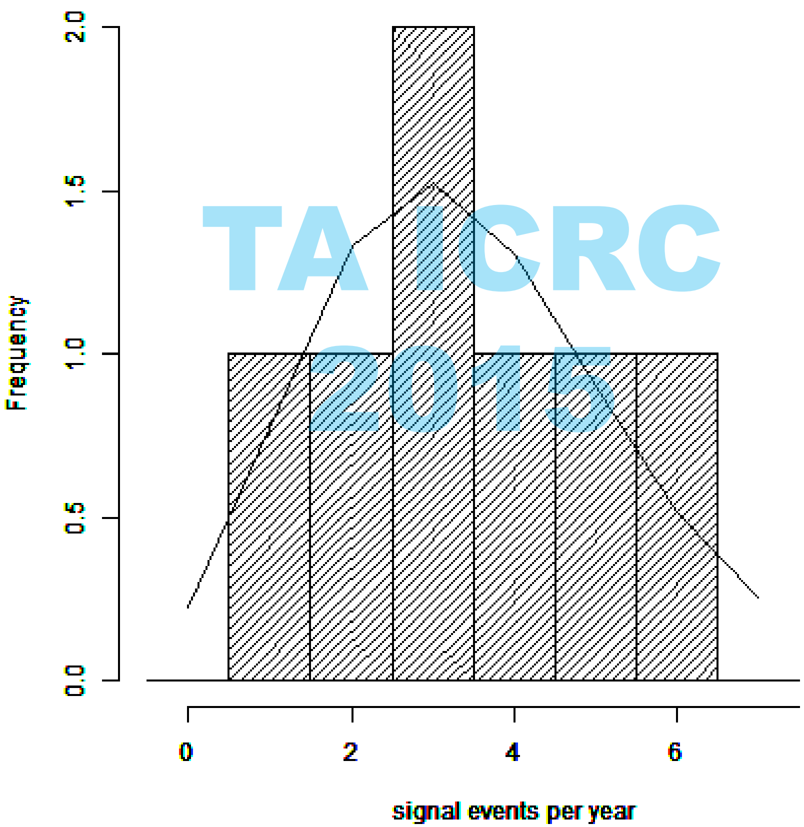
Centered at R.A=148.4°, Dec.=44.5° (shifted from SGP by 17°)

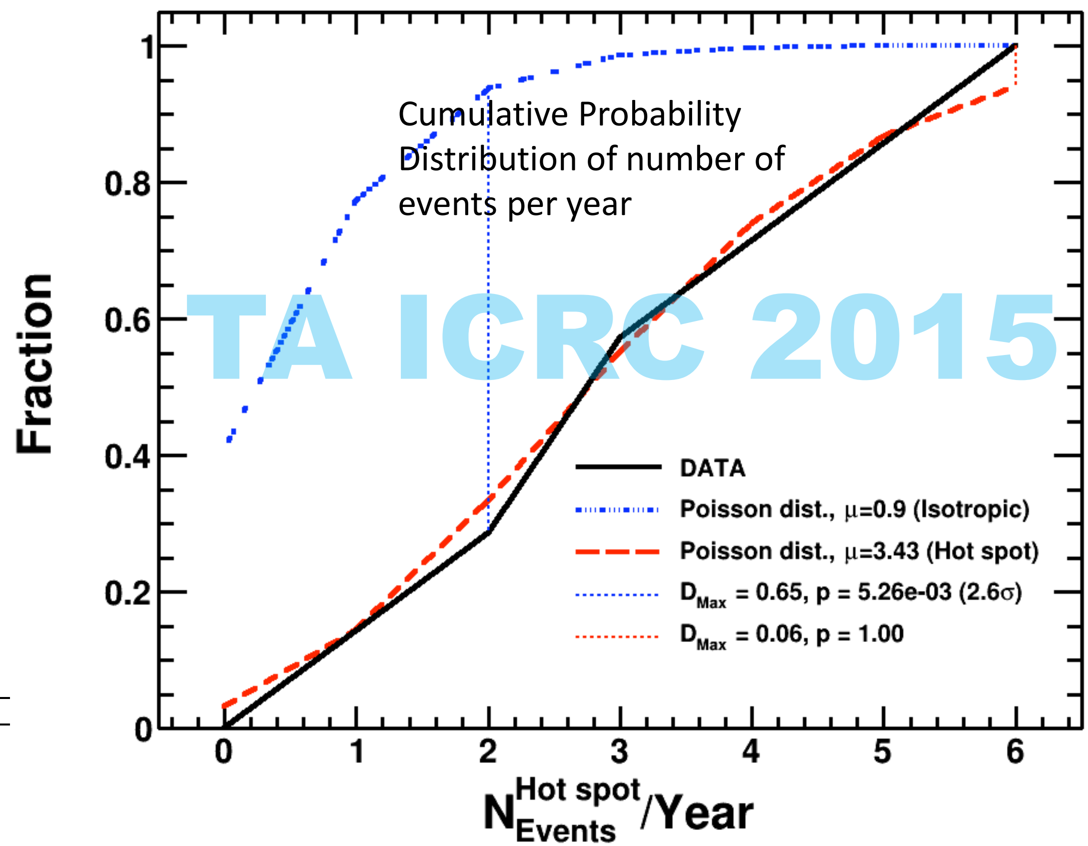
Global Excess Chance Probability: 3.7×10^{-4} : 3.4σ (~ same as first 5 years)

Consistent with Fluctuation

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

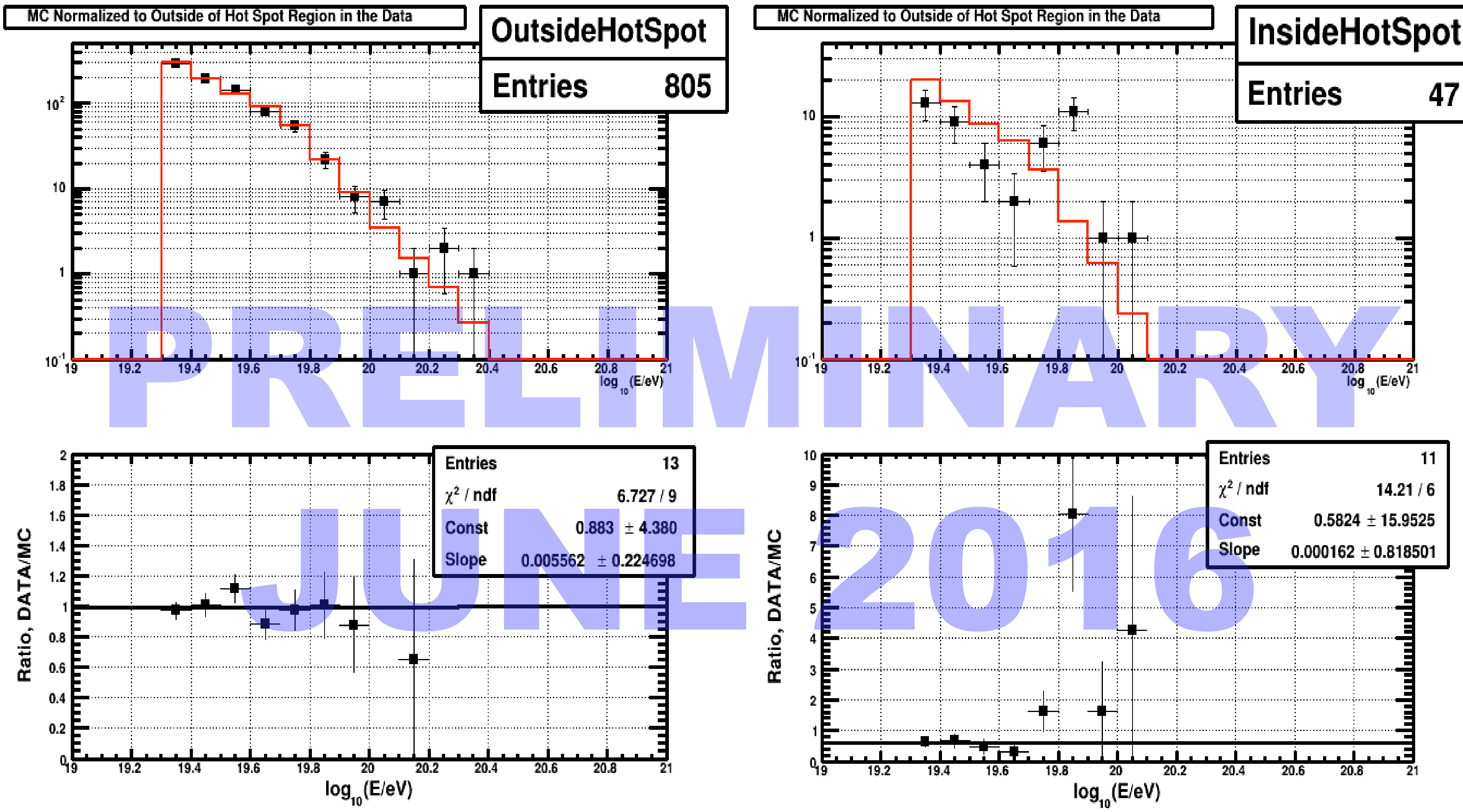
but inconsistent with chance excess from isotropic distribution (Poisson: average = 0.9 per year) at ~ 2.6σ





Energy Spectrum in the hot spot

MC normalized to spectrum outside hot spot region



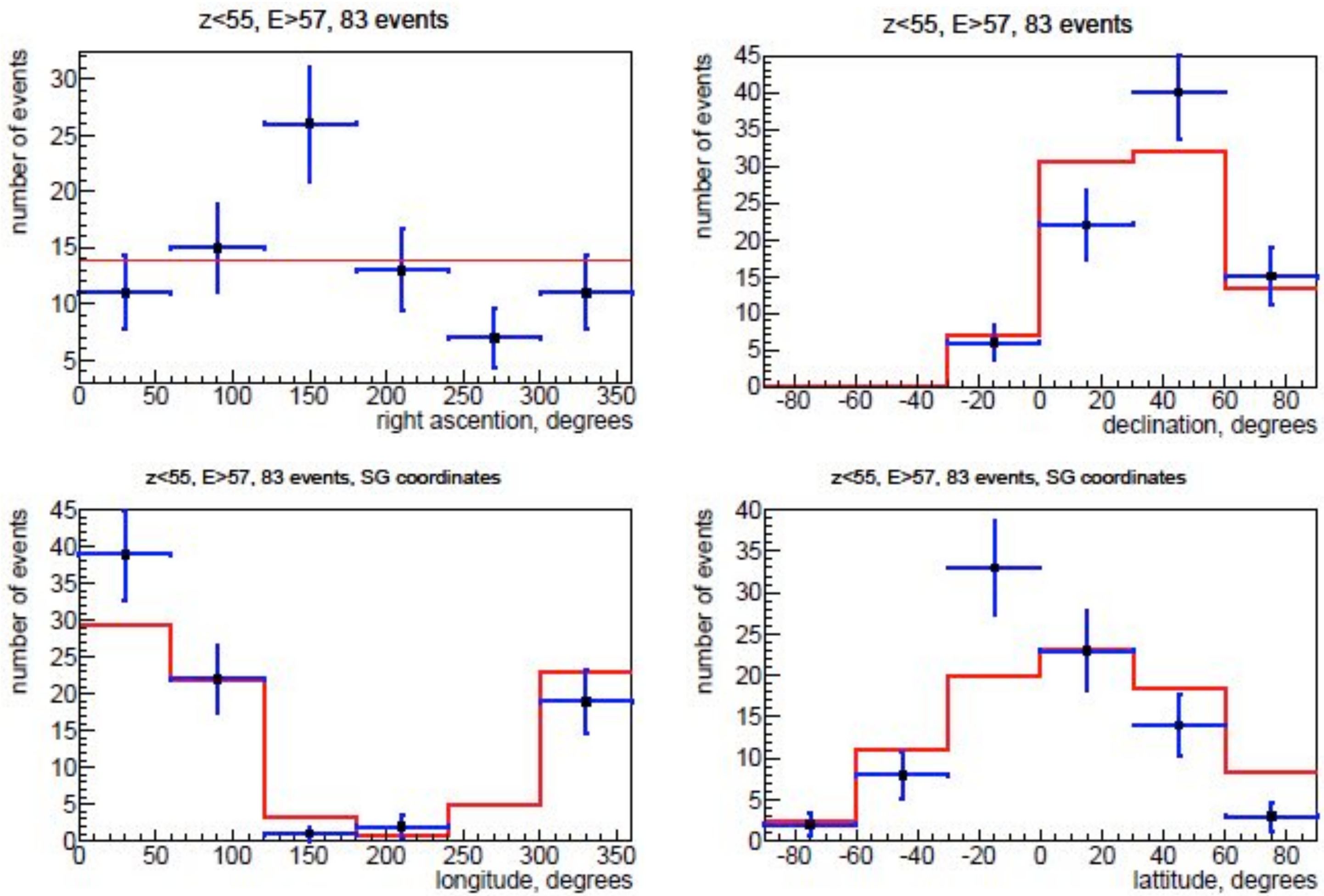
Global Distributions

E > 57 EeV

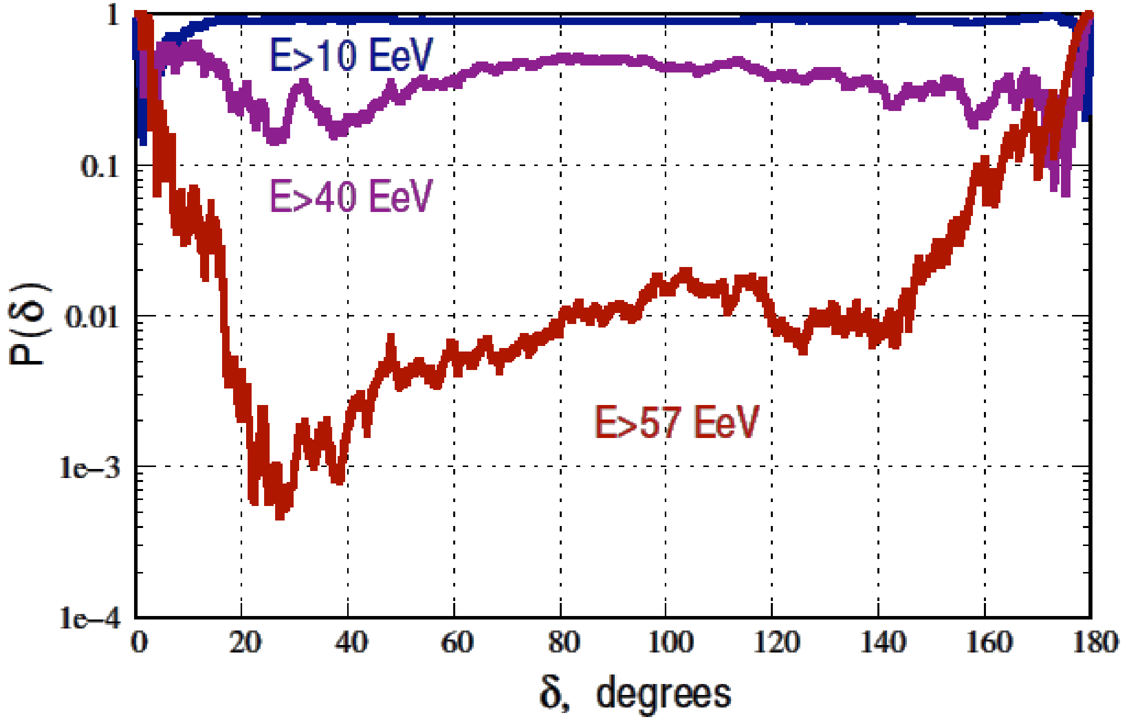
KS p-values

Frame	Long.	Lat.
Equatorial	0.07	0.04
Supergalactic	0.01	0.03

Low energy sets: E > 10 EeV and E > 40 EeV are compatible with isotropy; the smallest KS p-value is 0.12.



Autocorrelation

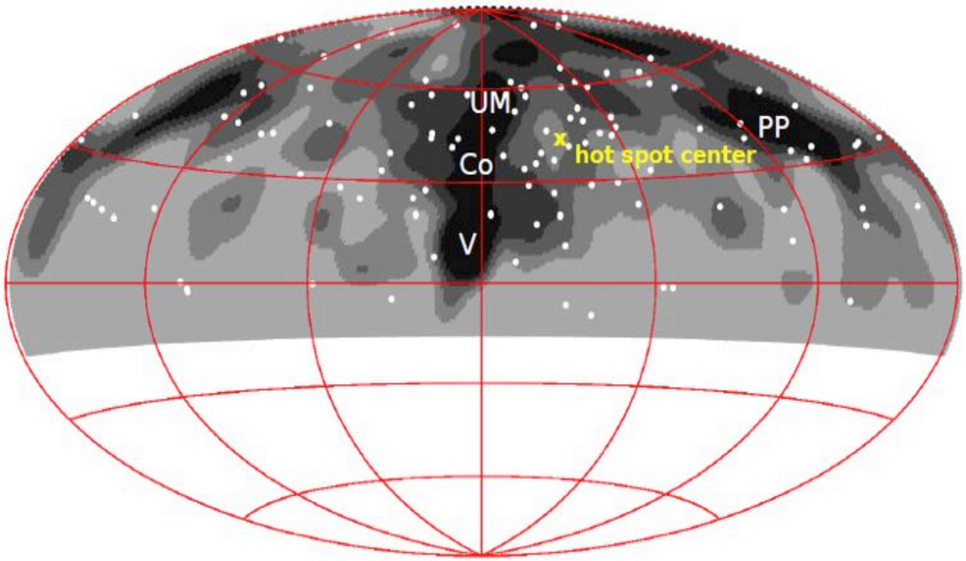


For each angular bin:

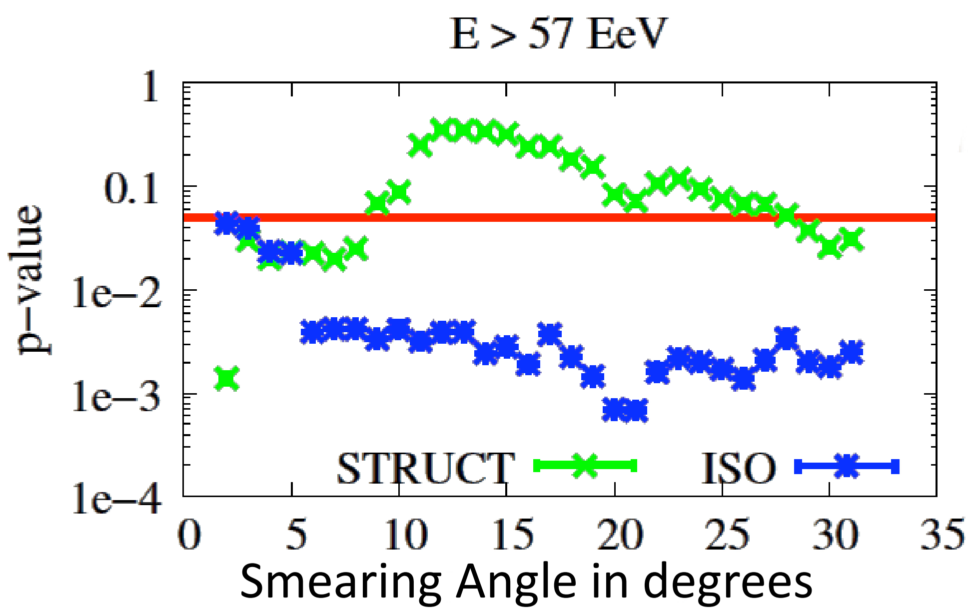
1. Count number of pairs of events at in the bin at separation δ
2. Chance Probability is given by the fraction of isotropic MC sets (with equal statistics) with as many or more than the number of pairs seen in data

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

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)

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

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

TA×4 project

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

- **500** scintillator SDs
- **2.08 km** spacing

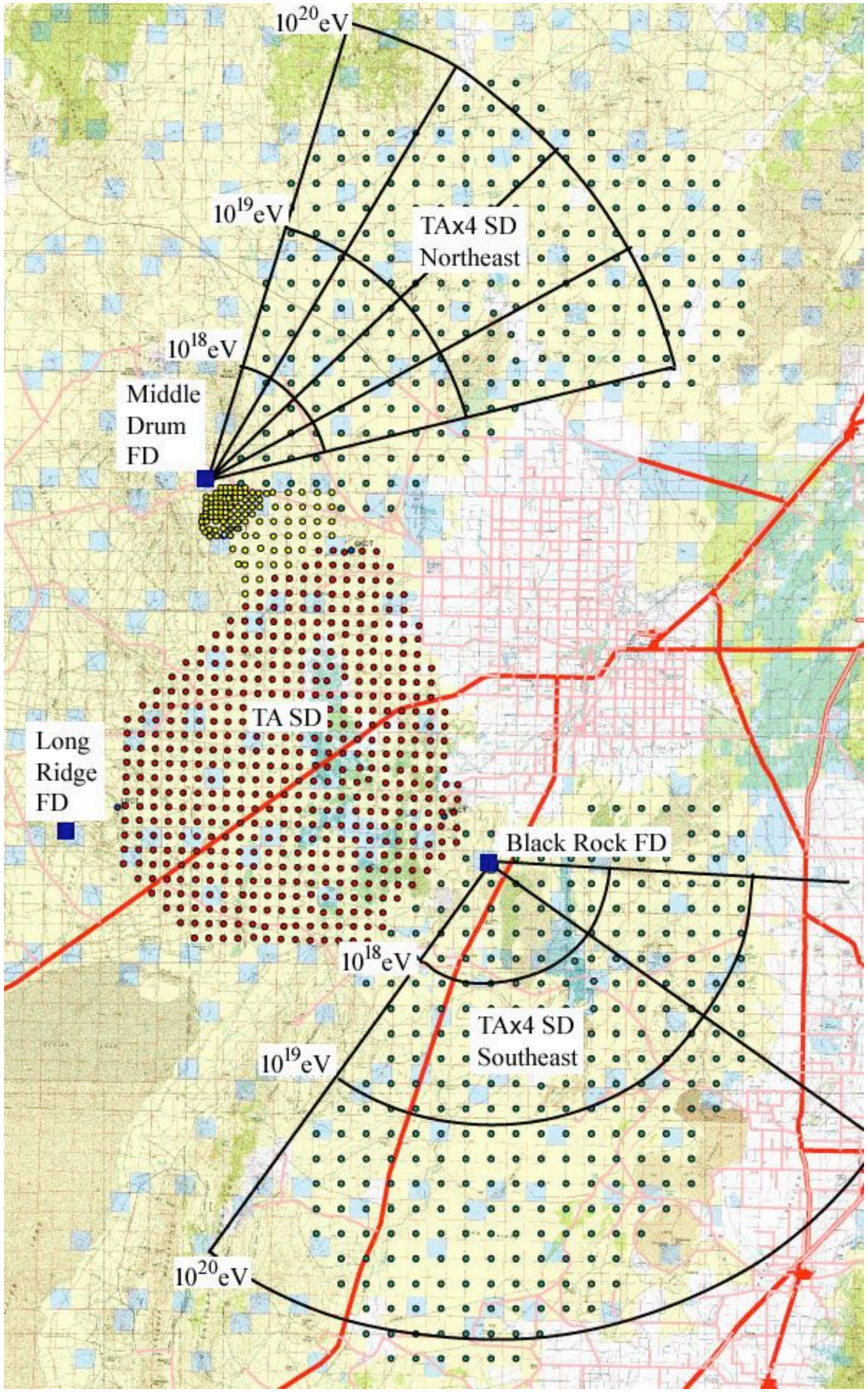
<u>2 additional FD stations</u>

<u>Proposals</u>

- **SD: approved** in Japan
  - April 2015
- **FD: approved by NSF** in U.S
  - June 2016

<u>Collect 19 TA-euivalent years of SD data by 2020</u>

Incl. 16.3 TA-equivalent years of hybrid data



12

Summary

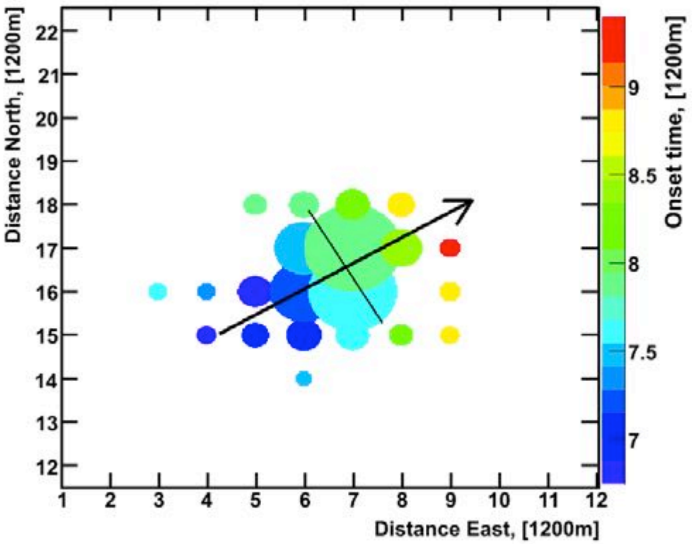
- TA has measured the energy spectrum, composition and arrival direction of UHE cosmic rays
- New TA Low Energy Extension (TALE) is coming on line. TALE surface detector array has now been funded by Gov't of Japan.
- TA and TALE has measured energy spectrum between 6×10^{15} eV to over 10^{20} eV and 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 (~6×10^{18} eV).
- We have seen a hot spot in the direction of Ursa Major with 3.4σ global signficance
- Much more data are needed!
- TAx4 upgrade has been approved for funding both in Japan and in the U.S.

End

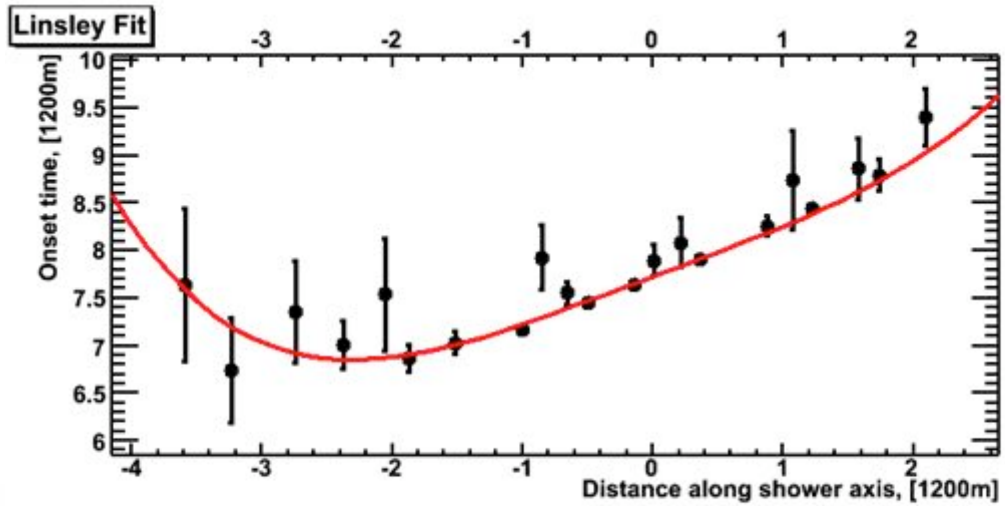
Reserve Slides

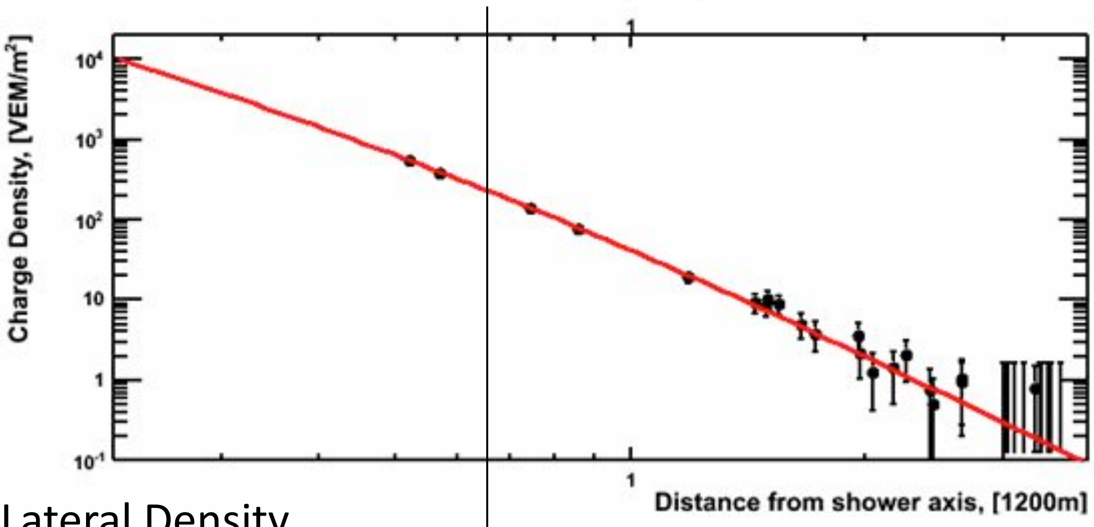
Analyzing SD Event

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



Geometry Fit (modified Linsley)





Lateral Density Distribution Fit

r = 800m

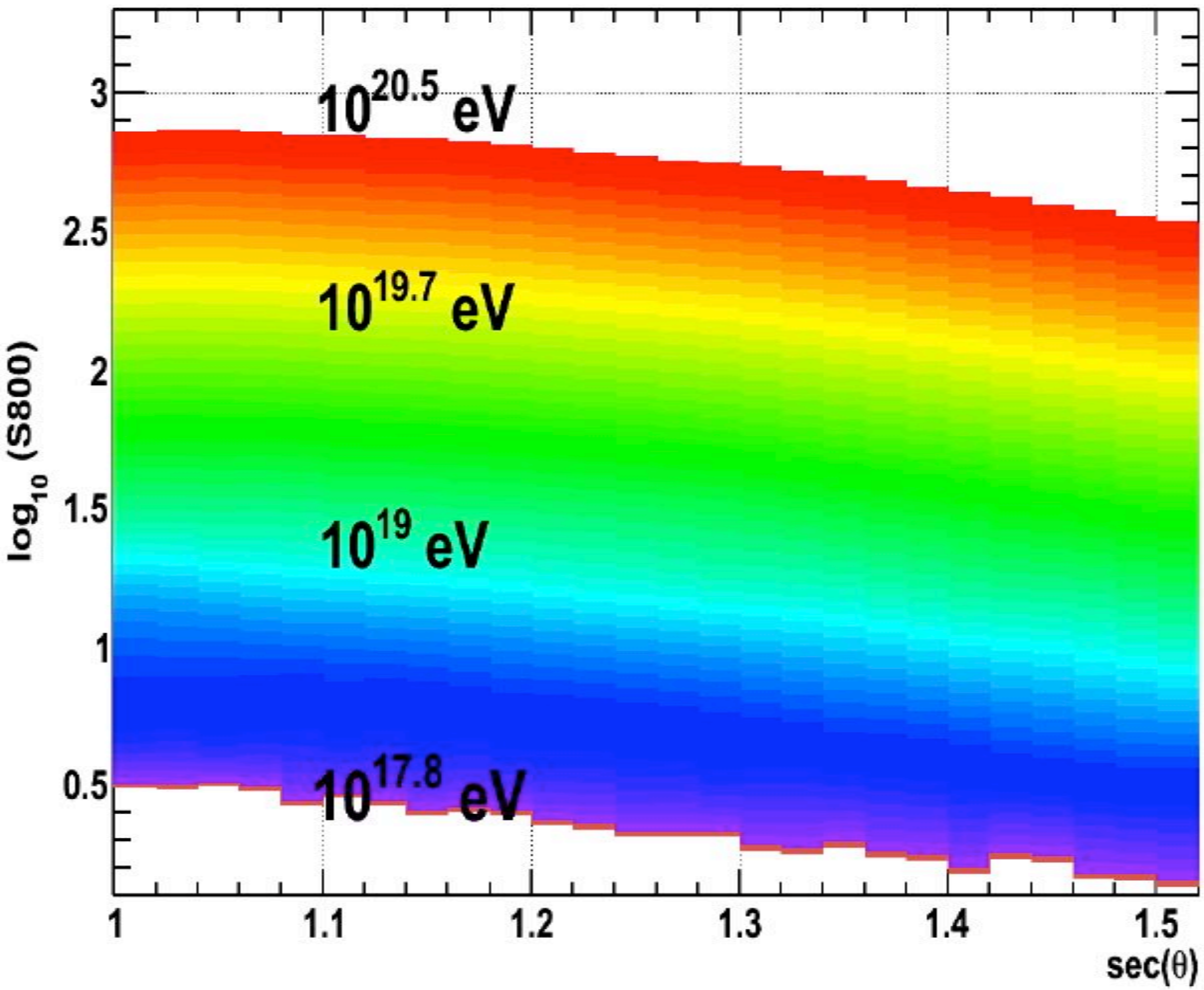
Fit with AGASA LDF

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

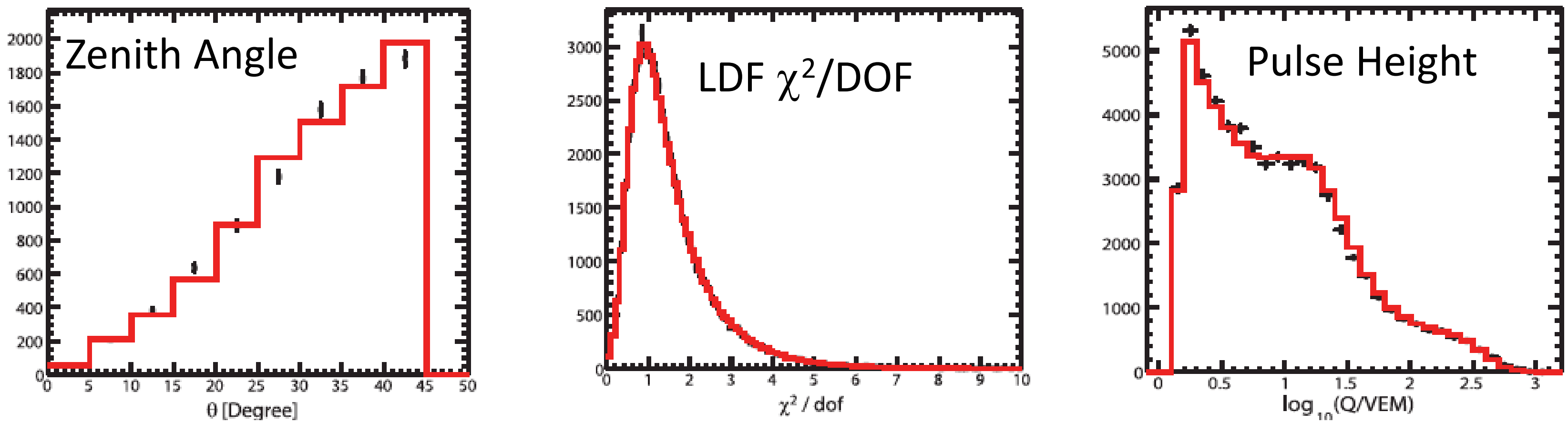
$$\eta = (3.97 \pm 0.13) - (1.79 \pm 0.62)\,(\sec\theta - 1)$$

- S(800): Primary Energy
- Zenith attenuation by MC

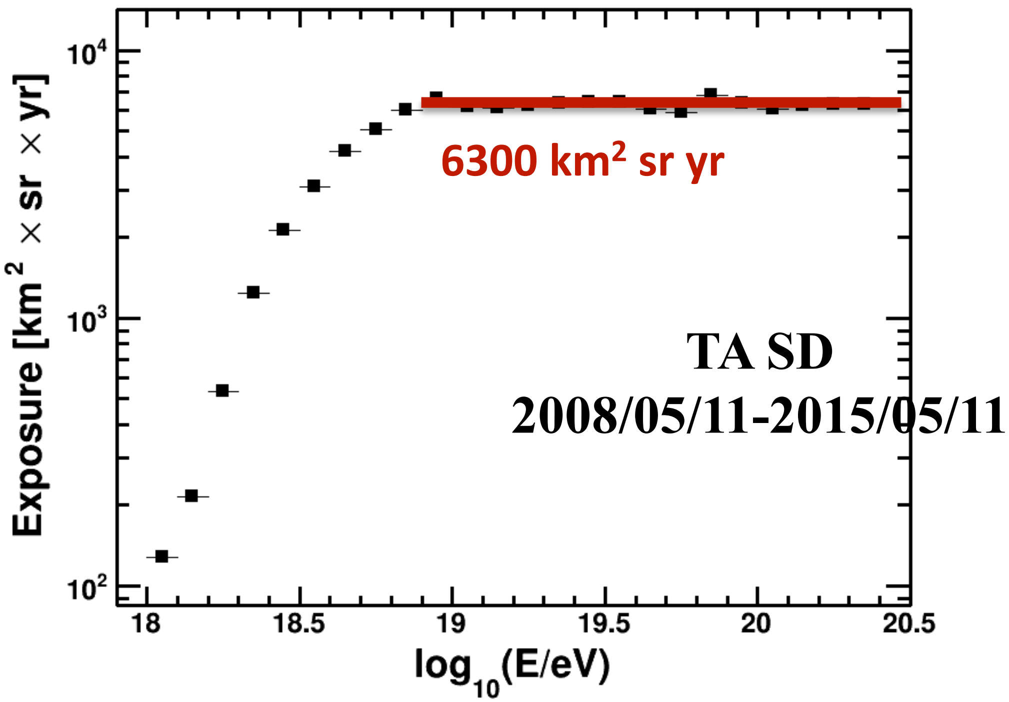
Surface Array Energy Measurement



- Energy table is constructed using the MC (CORSIKA)
- Determination of event energy by interpolating between S800 vs. sec(θ) lines
- Uses novel "de-thinning" of CORSIKA (paper draft in internal review)

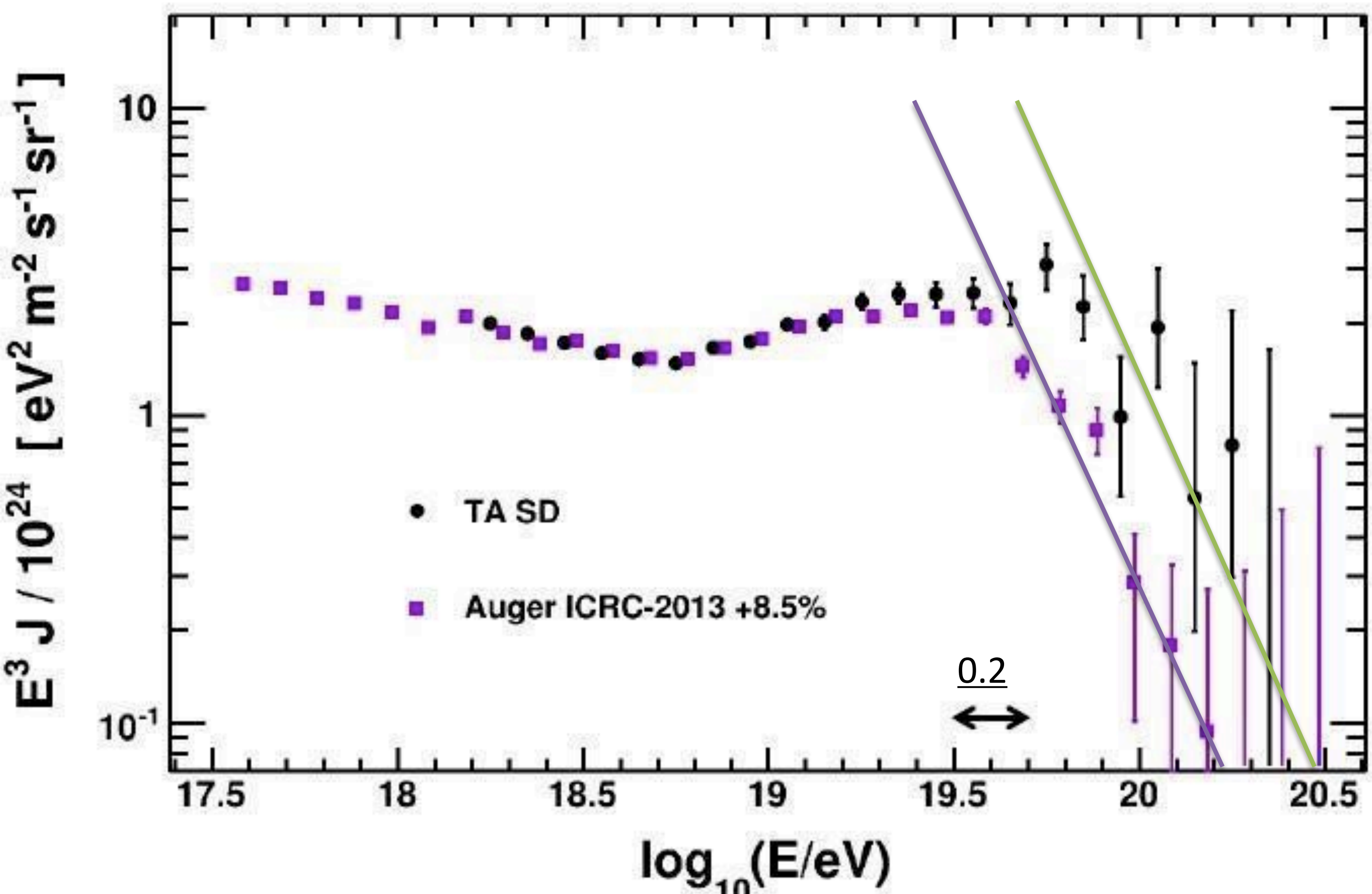


Surface Detector Data-MC Comparisons

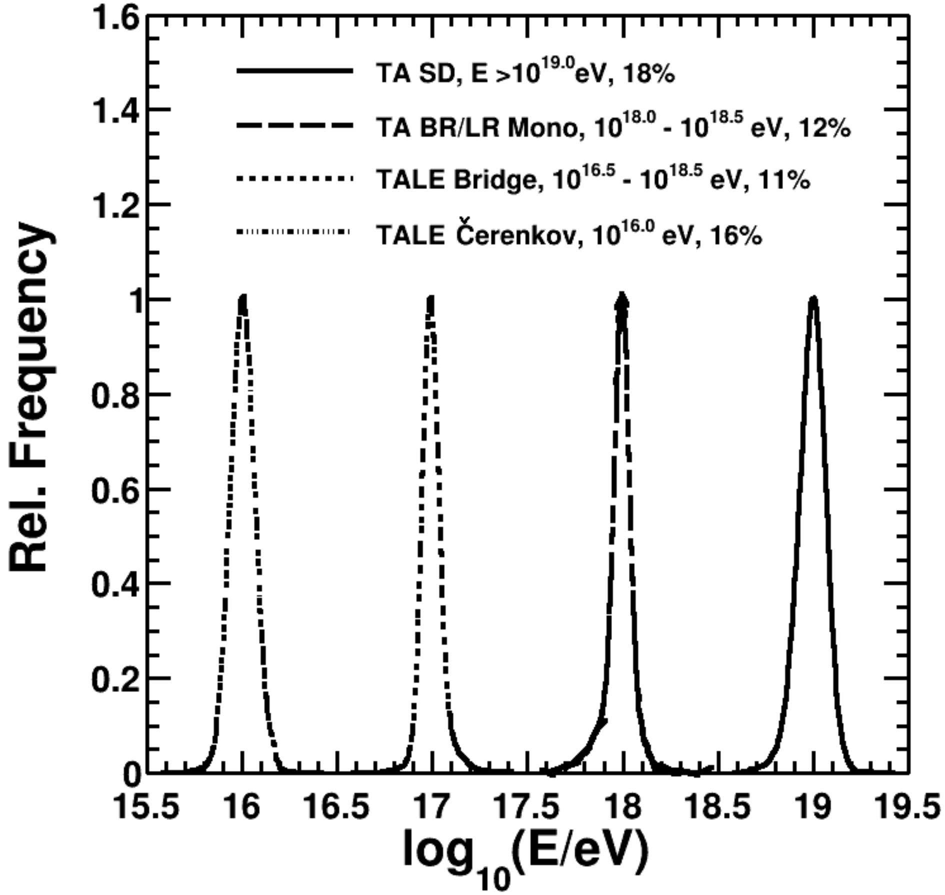


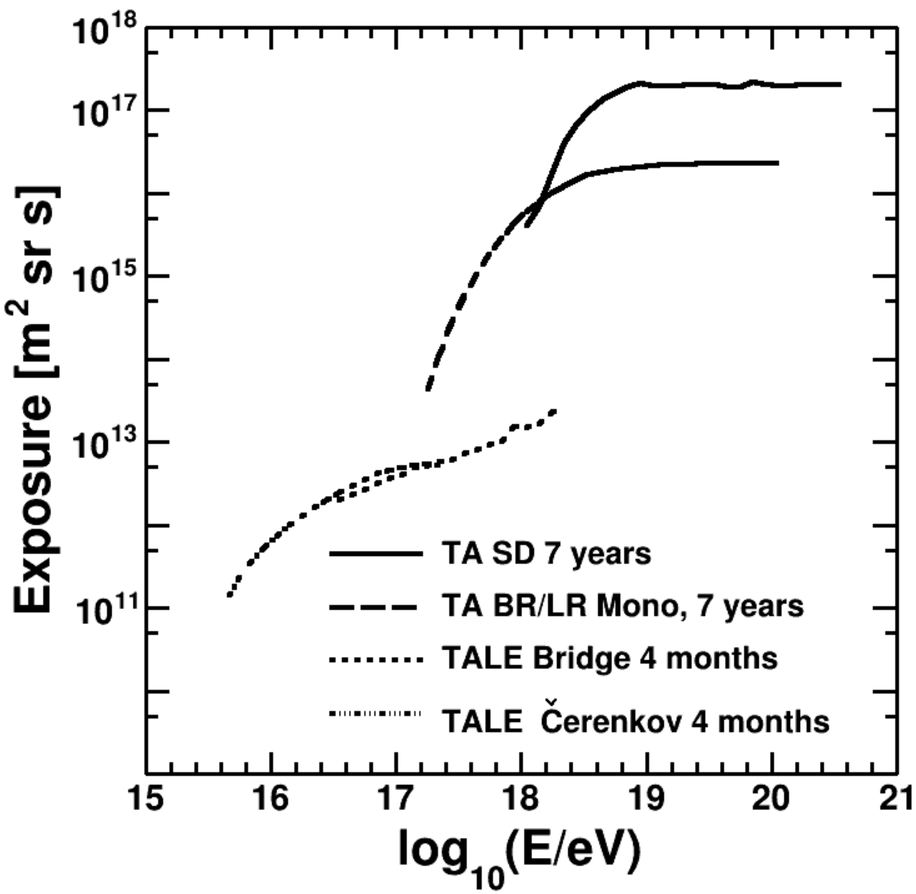
Surface Detector Exposure vs Log_{10}E

Comparison of TA and Auger (+8.5% energy scale)



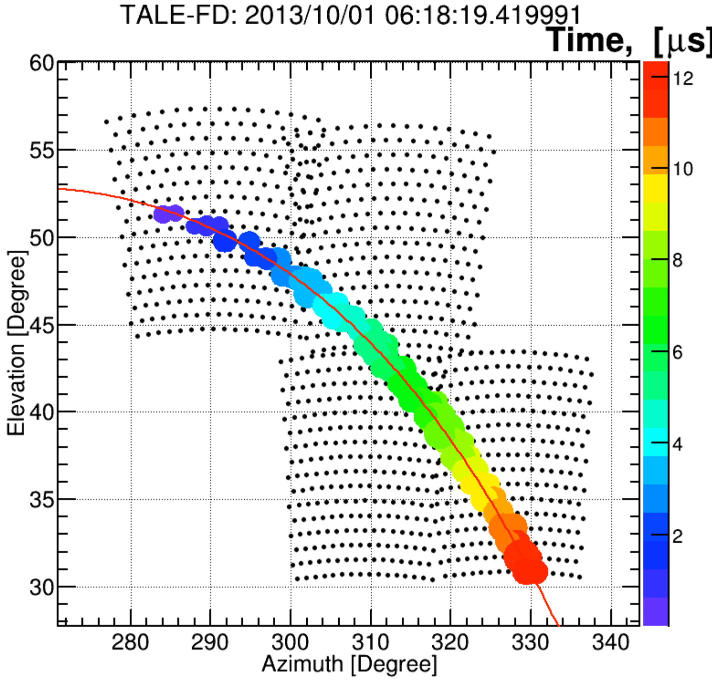
Energy Resolution and Exposure

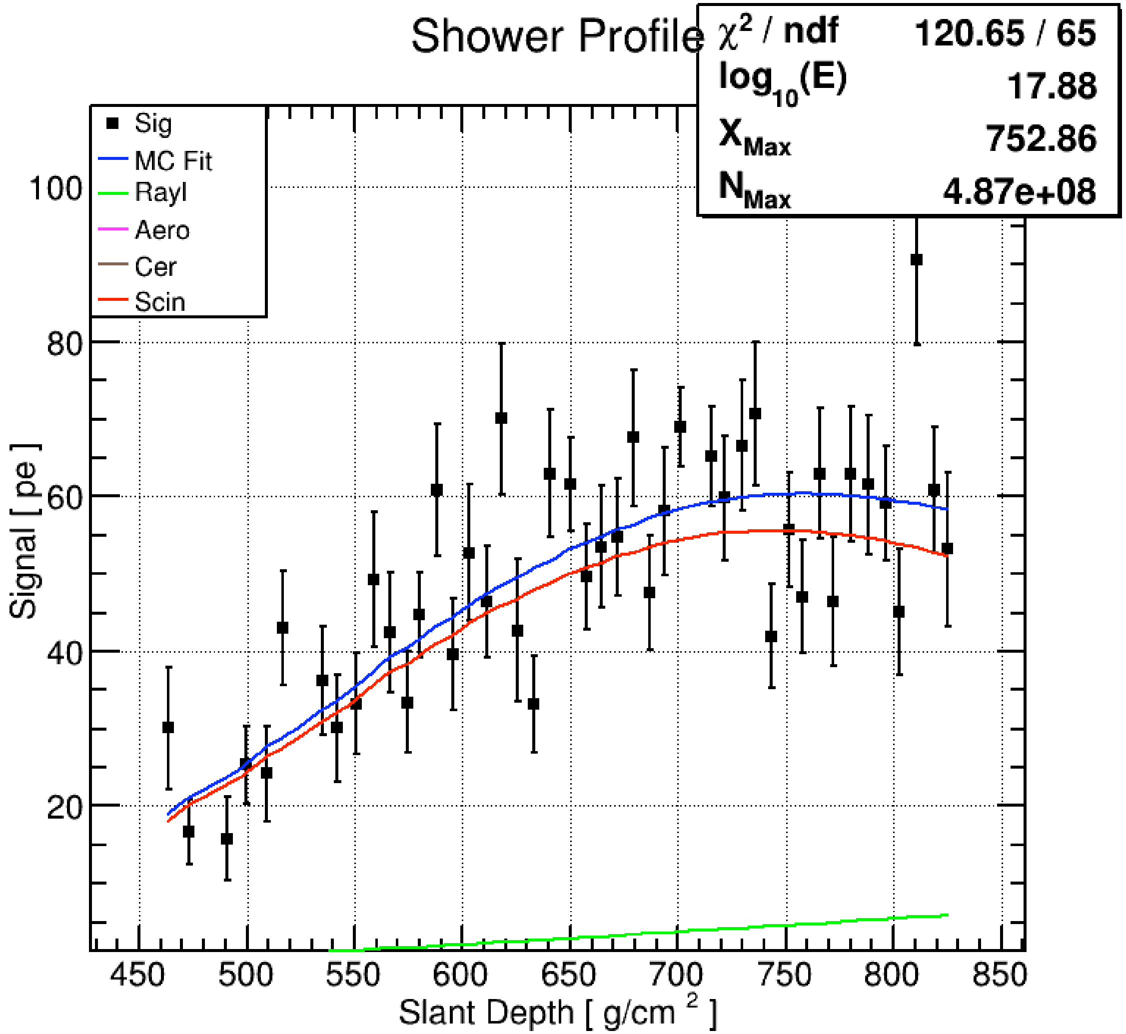


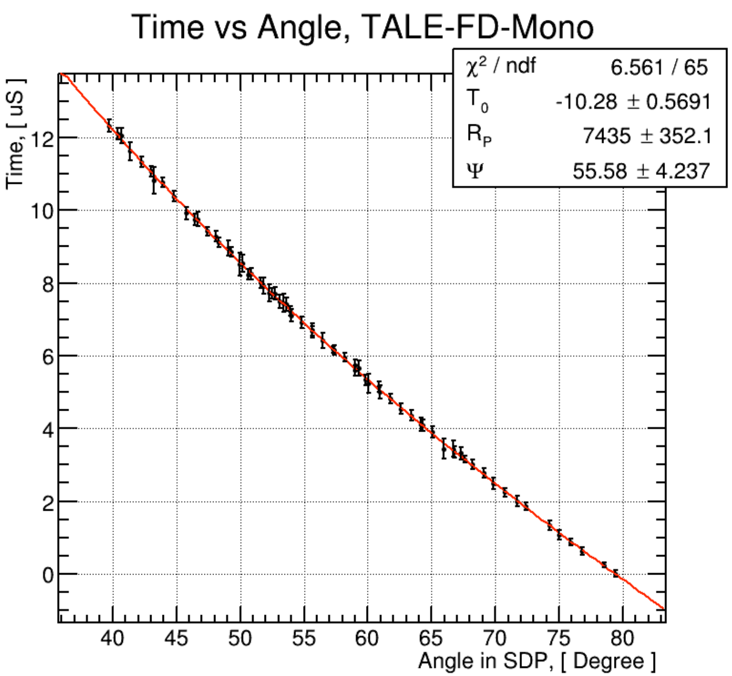


CR17 EAS spec, Presented by Dmitri IVANOV
on 4 Aug 2015 at 15:00

TALE Fluorescence-Dominant Event







Fitting the UHE Spectrum with TA

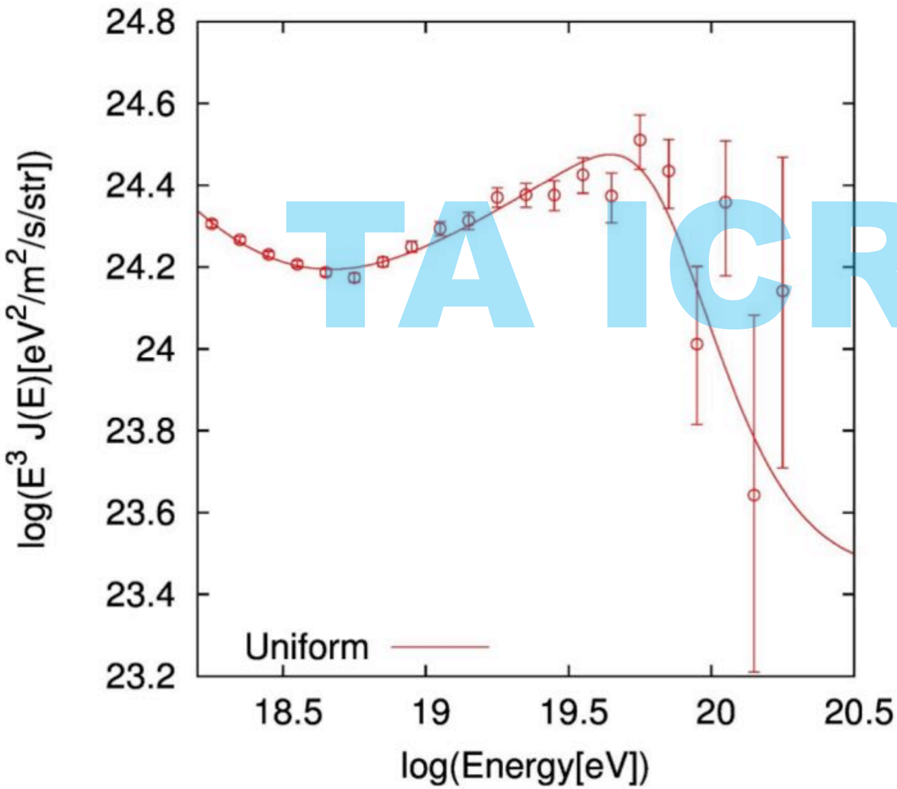
Fitting parameters:

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

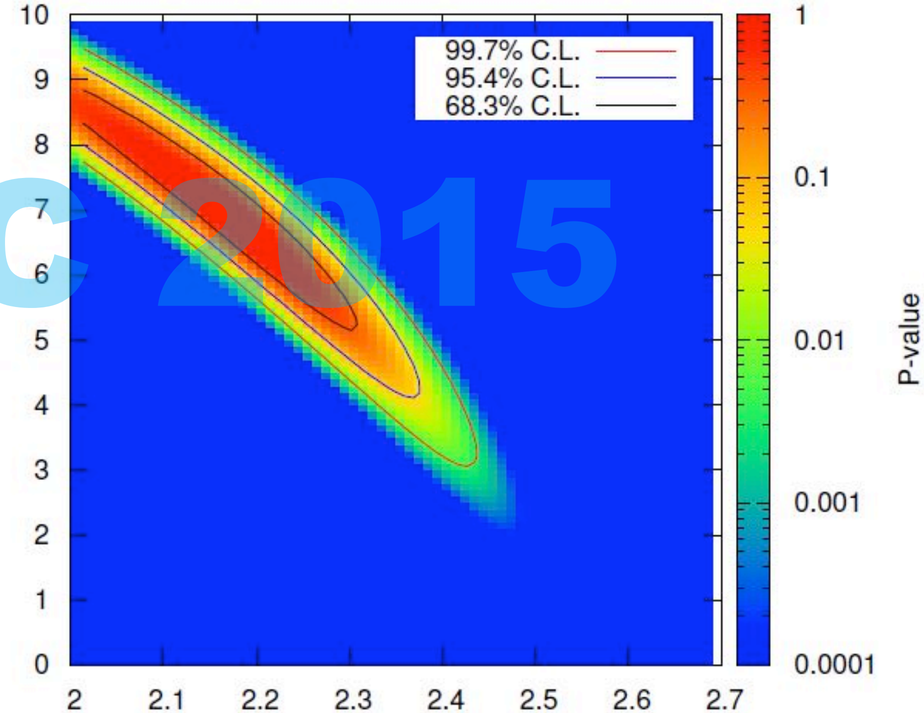
Evolution of the sources, $(1+z)^{m}$

$$p = 2.18^{+0.08}_{-0.14}, \quad m = 6.8^{+1.6}_{-1.1};$$

(stat. + sys.)

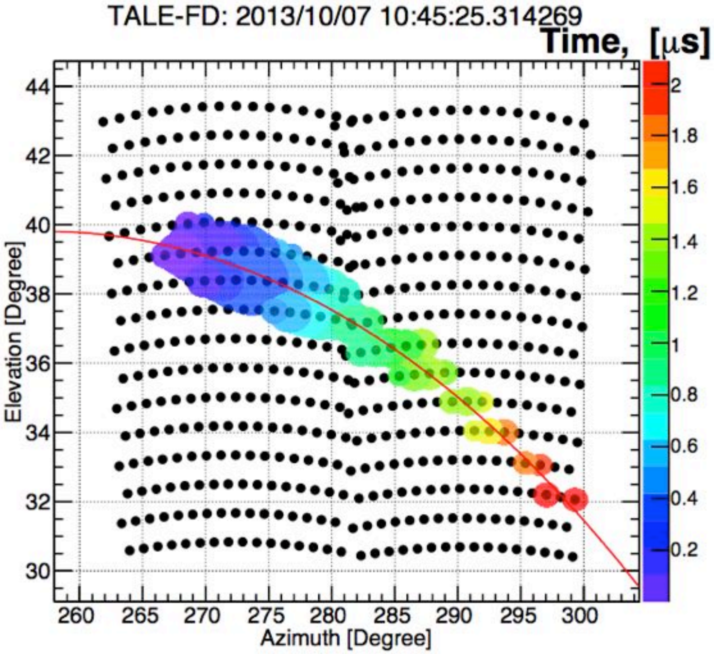


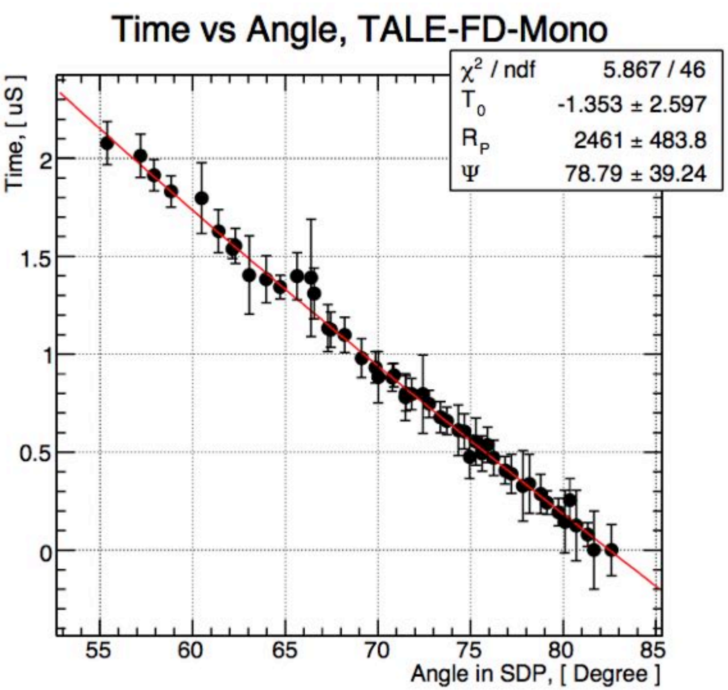
m

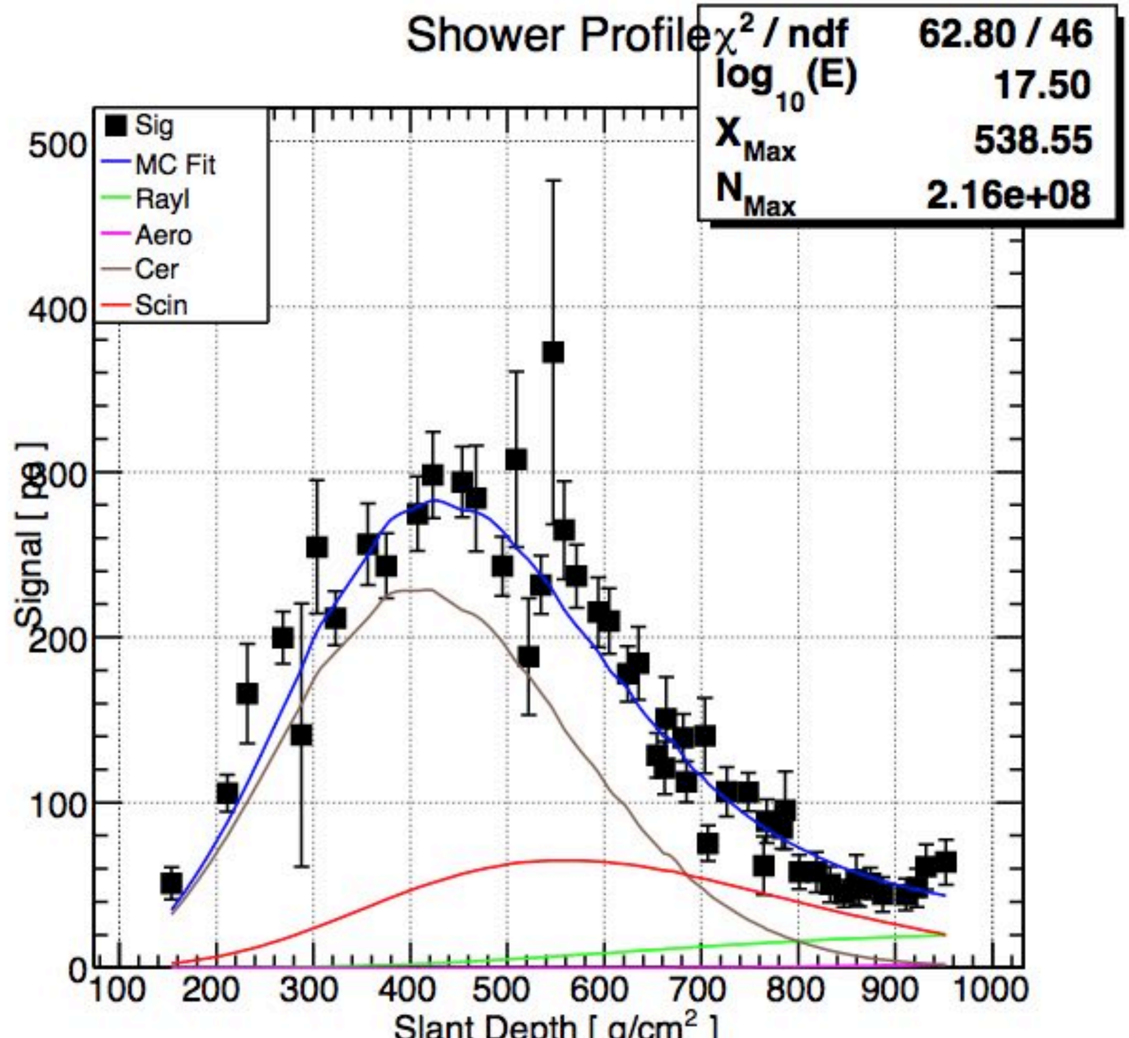


p

TALE Cherenkov Dominant Event

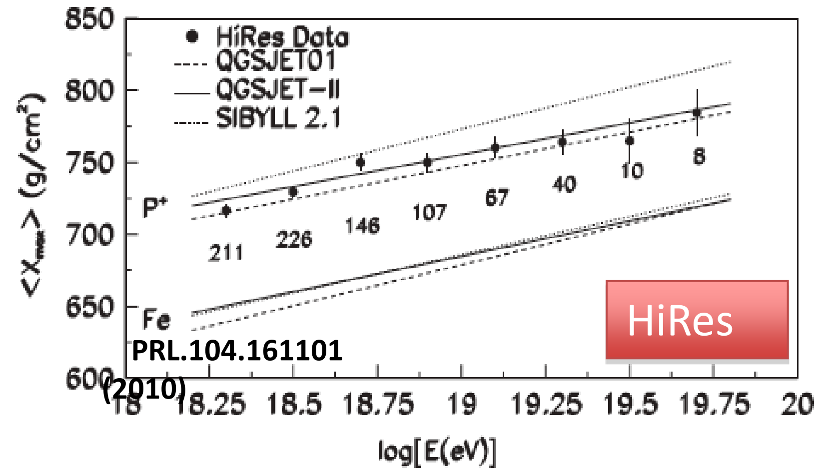




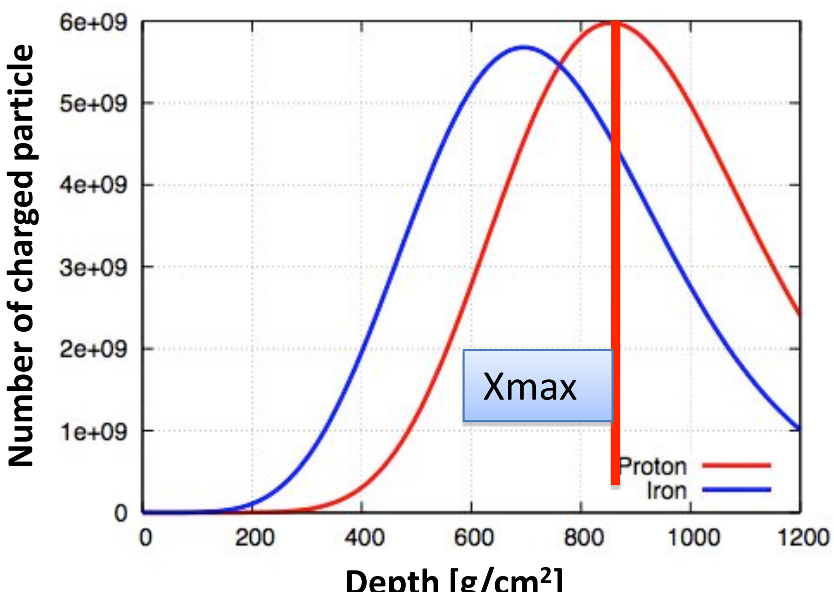


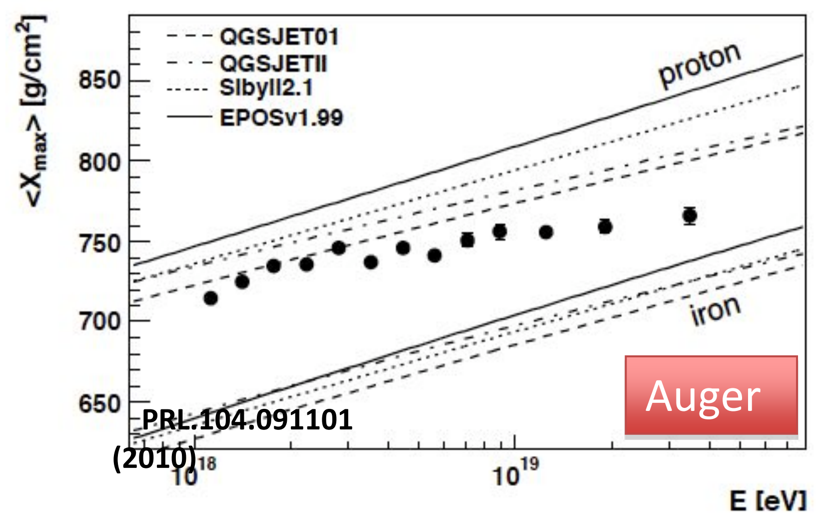
Composition: Xmax Technique

- 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

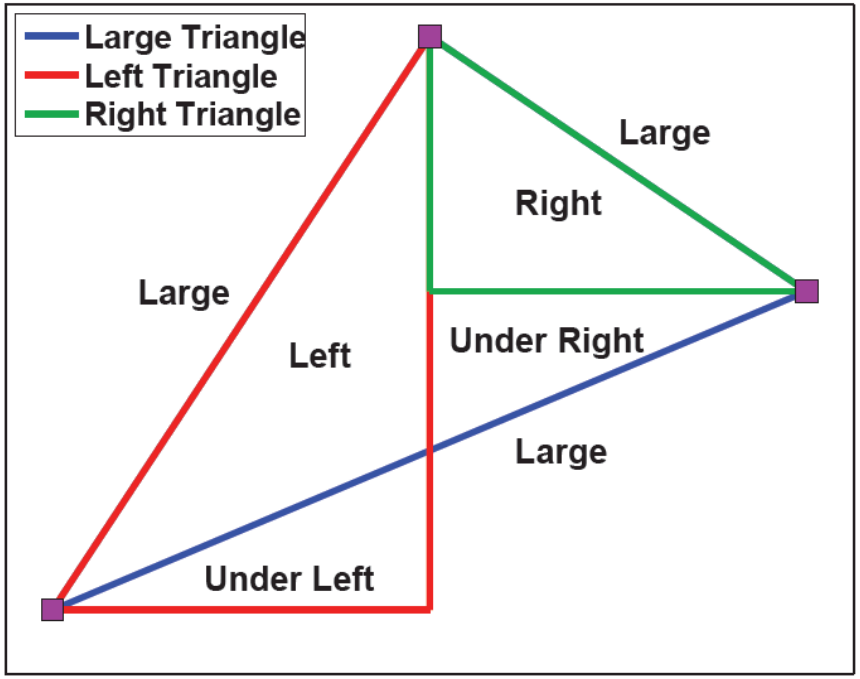


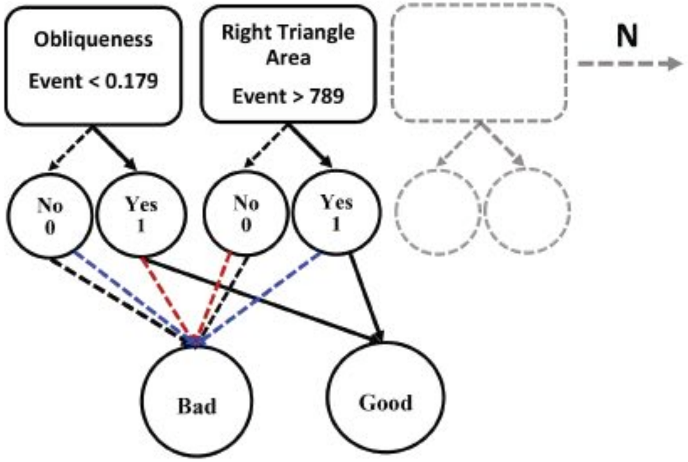


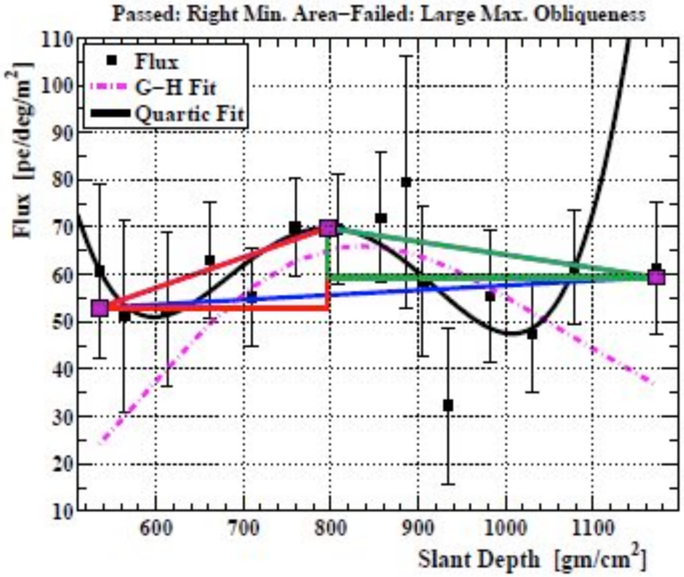
Latest TA Hybrid Composition Analysis

New: Patter recognition test on shower profile

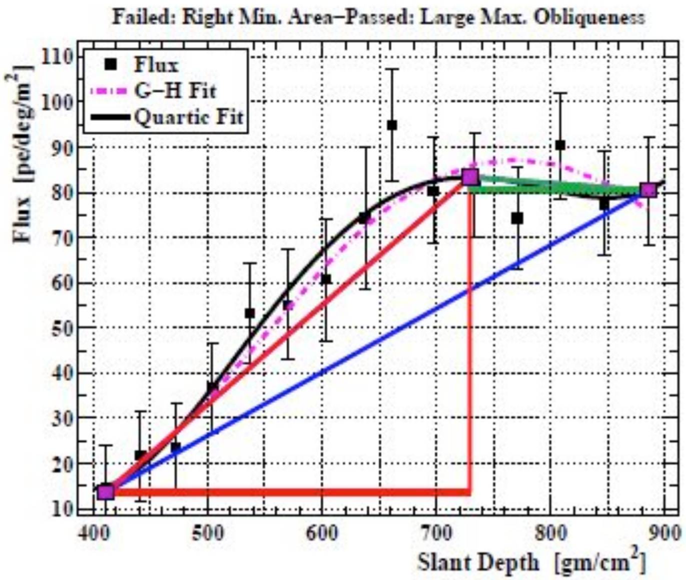
- 5 Years MD FD+SD hybrid data
- Geometrical Event Selection Criteria:
  - Geometry fit χ^2/dof < 4.5
  - $\text{Log}_{10}E(\text{eV}) > 18.2$
  - Hybrid core < 1600m from SD core
  - Hybrid Core inside SD array or < 500m outside
  - Zenith angle < 58°
  - Xmax within view (20g/cm^2 at start, and 0g/cm^2 at end)







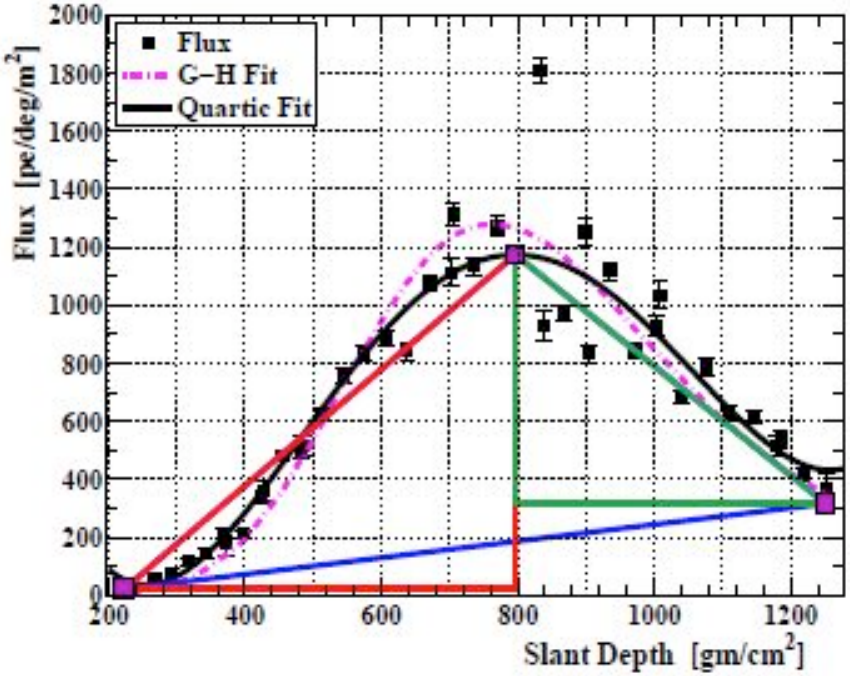
Failed: large triangle obliqueness test



Failed: Right triangle Area Test

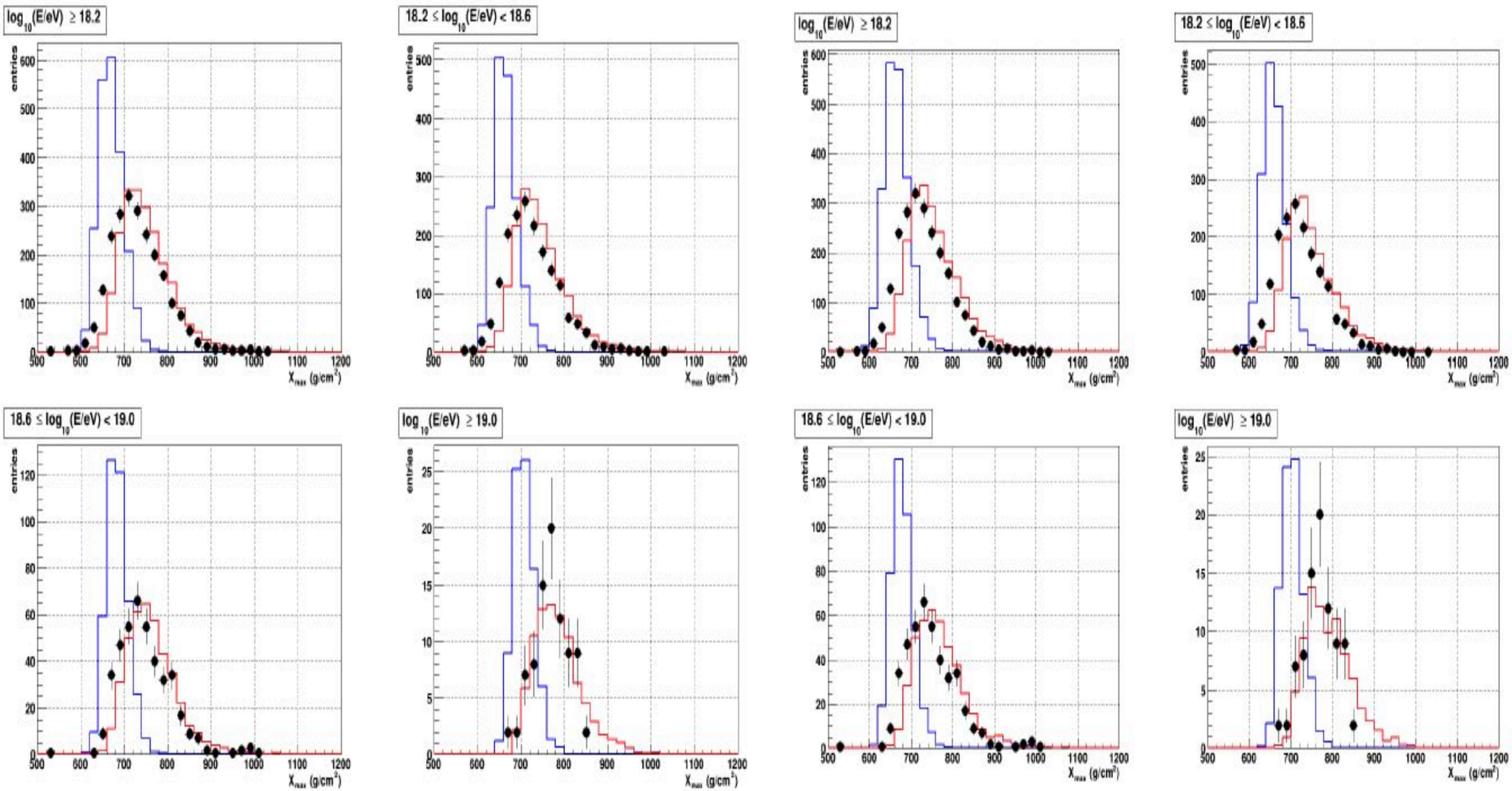
Quartic polynomial (weight squared) fit used to determine the apex of the large triangle

Large (blue) triangle obliqueness: Ratio of perimeter to area



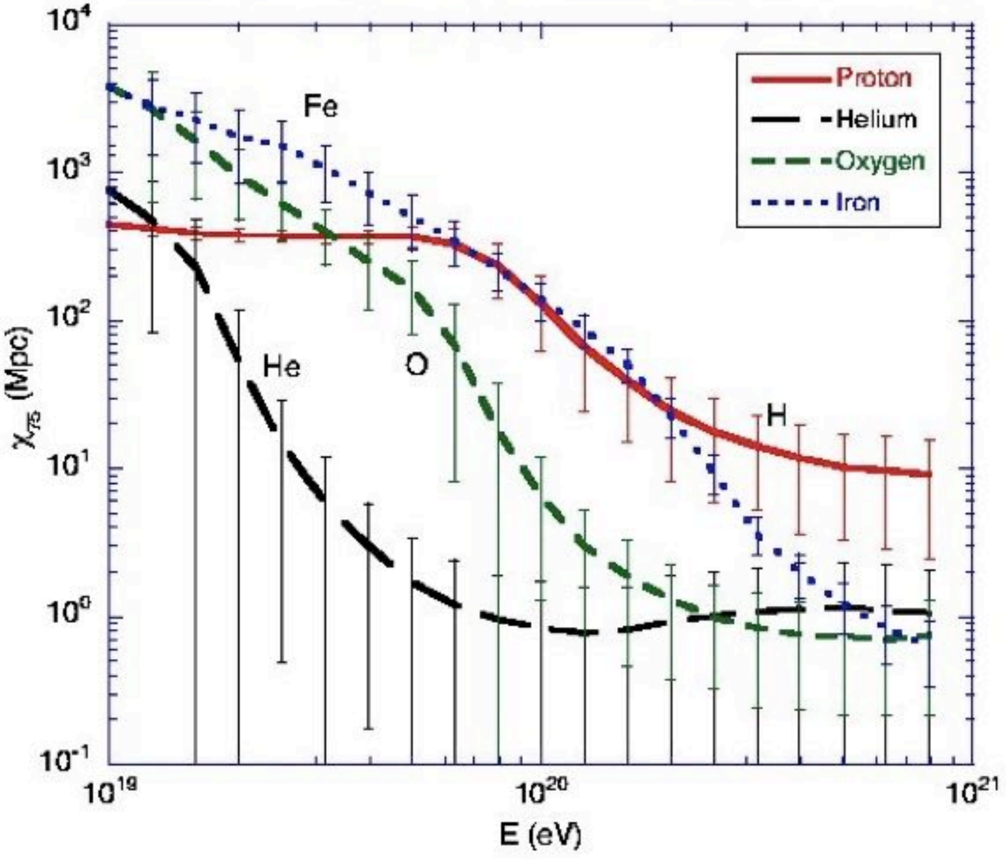
Passed: highest energy MD hybrid event

Hybrid X_{max} Measurement



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

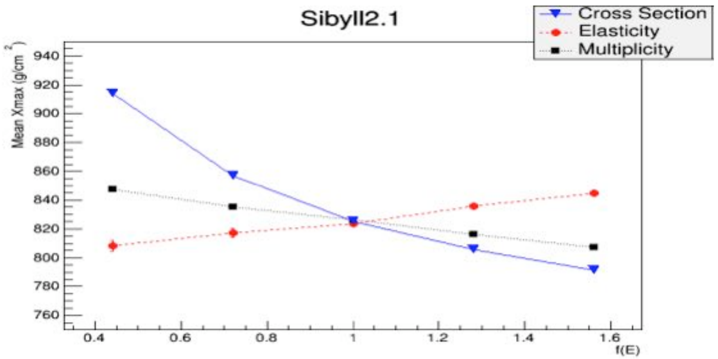
Astrophysically p and He are very different

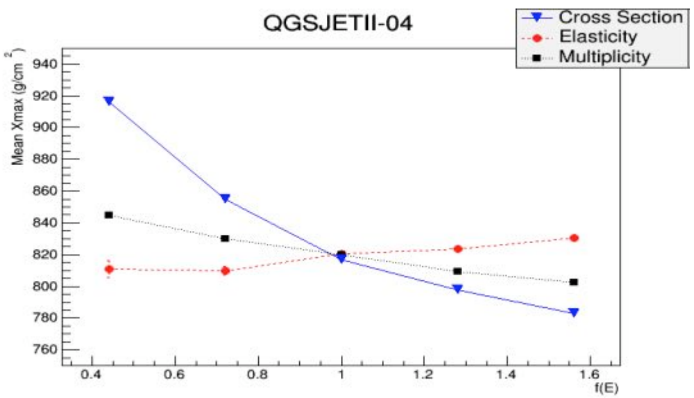


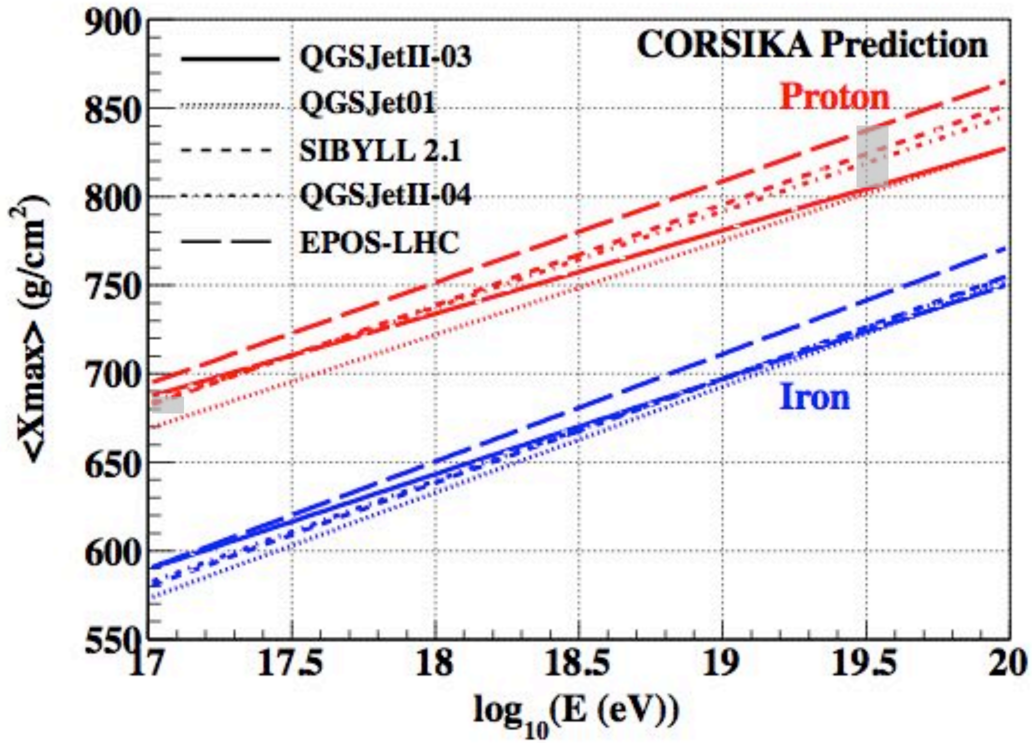
Interaction lengths of p,He,O and Fe

<Xmax> Uncertainty from Extrapolation of Cosmic Ray Air Shower Parameters

Study the effect on the <Xmax> of HE Model using CONEX4.44 at $10^{19.5}$ eV



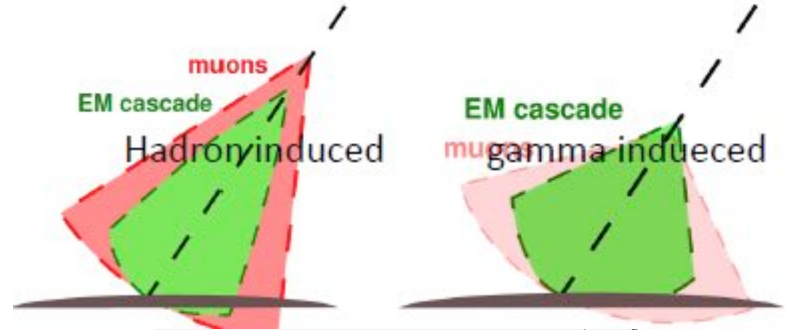


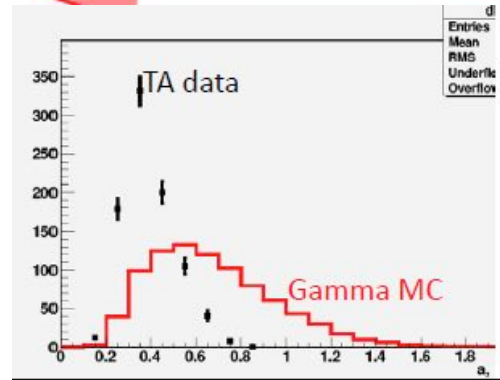


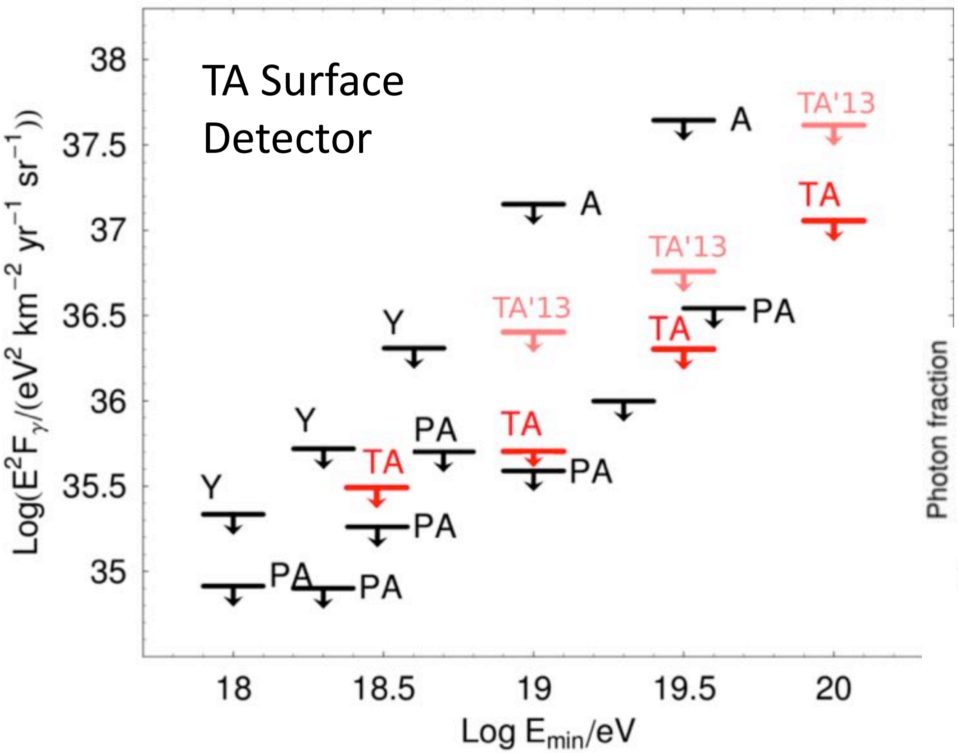
Gordon Thomson & R. Abbasi U12

Photon Limits

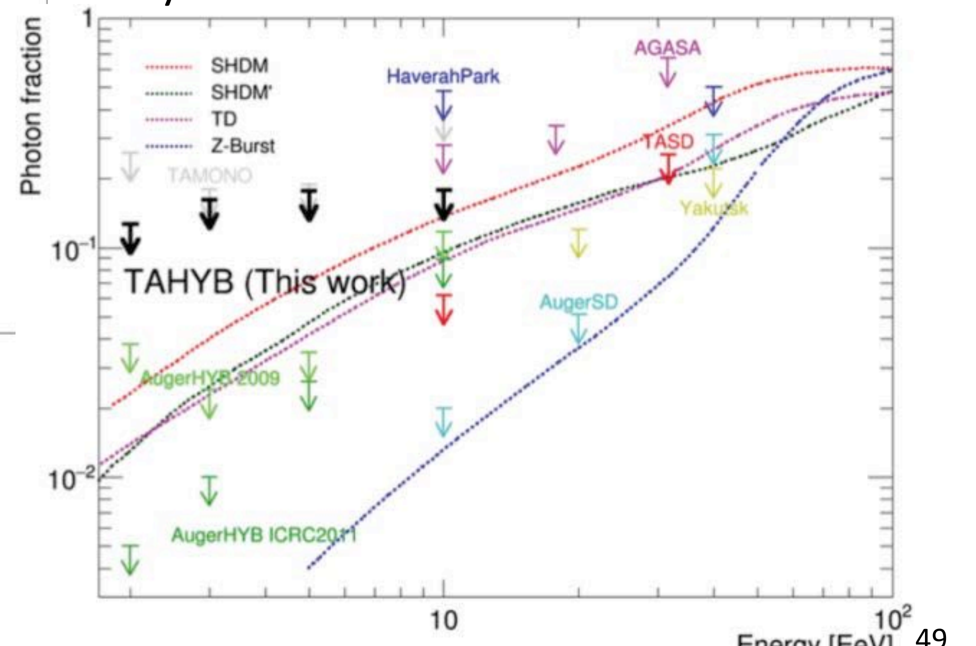
Photon-induced showers: arrive younger
contain fewer muons
⇒ multiple SD observables affected:
Front curvature, Area-over-peak, # of FADC signal peaks,χ2/d.o.f .





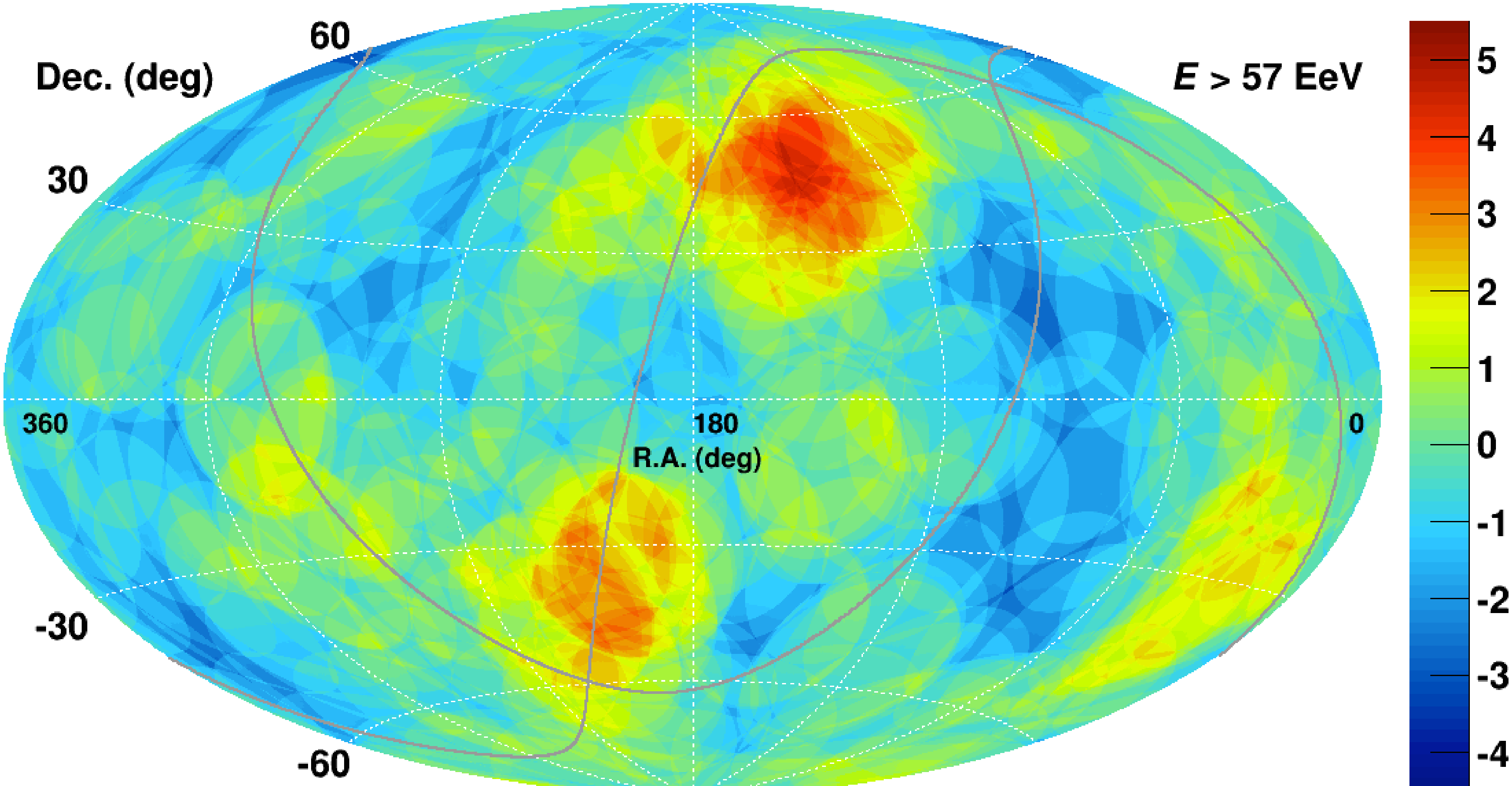


TA Hybrid



AGASA, Astrophys. J. **571**, L117 (2002)
Yakutsk, Phys. Rev. **D82**, 041101 (2010)
Auger, Astropart. Phys. **29**, 243 (2008); Astropart. Phys. **31**, 399-406 (2009)

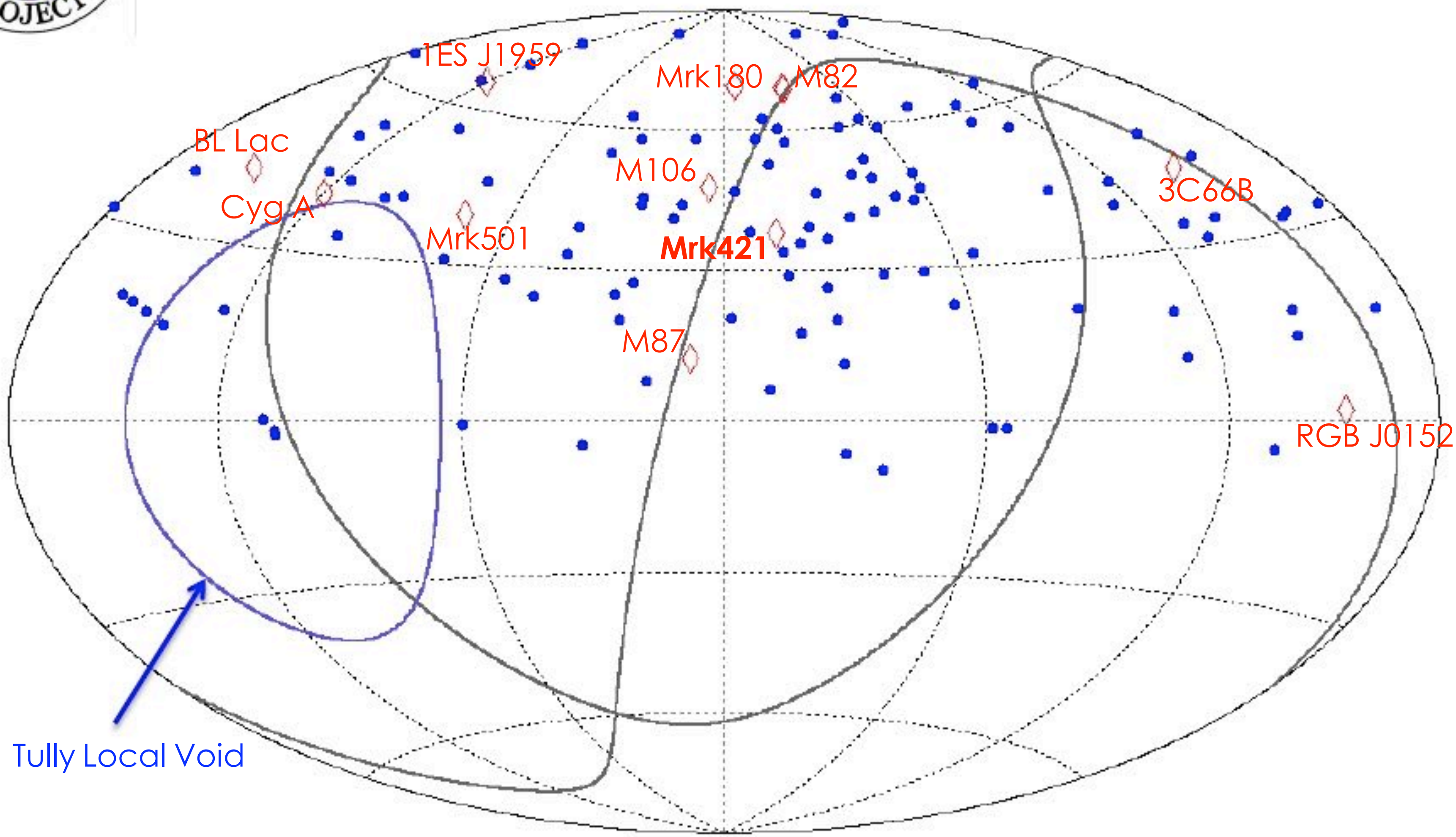
TA + PAO All Sky



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)

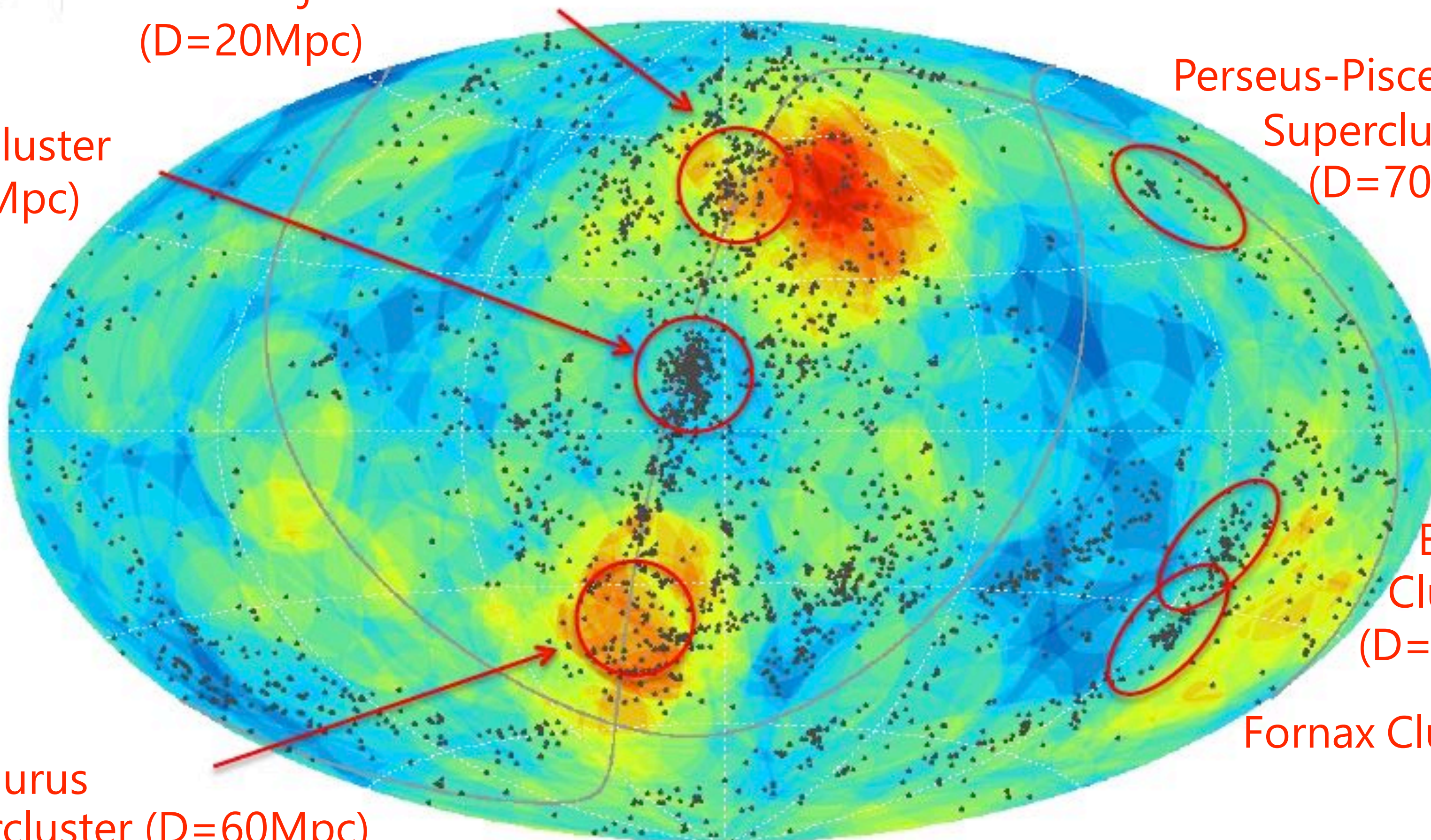
Nearby Prominent Sources



The blazar Mrk421, Mrk180 and starburst galaxy M82 are candidates?

K. Fang, et al., ApJ, 794, 126 (2014)
H.-N. He, et al., arXiv:1411.5273 (2014)

Nearby Galaxy Clusters

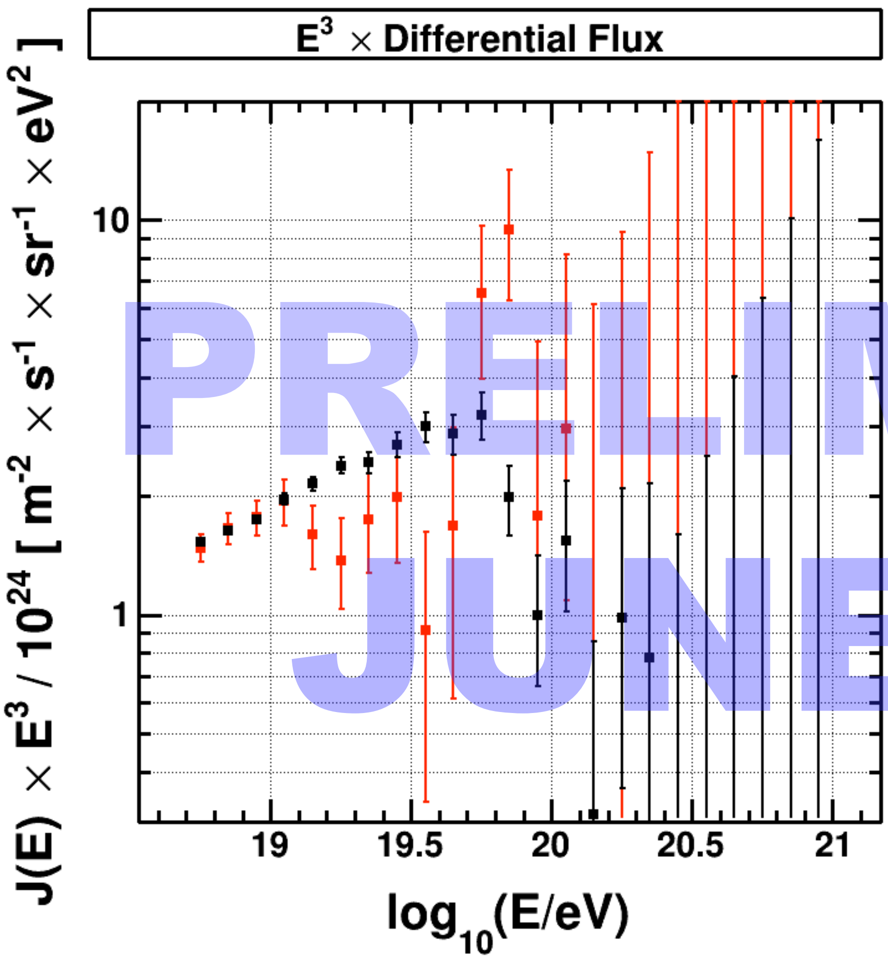


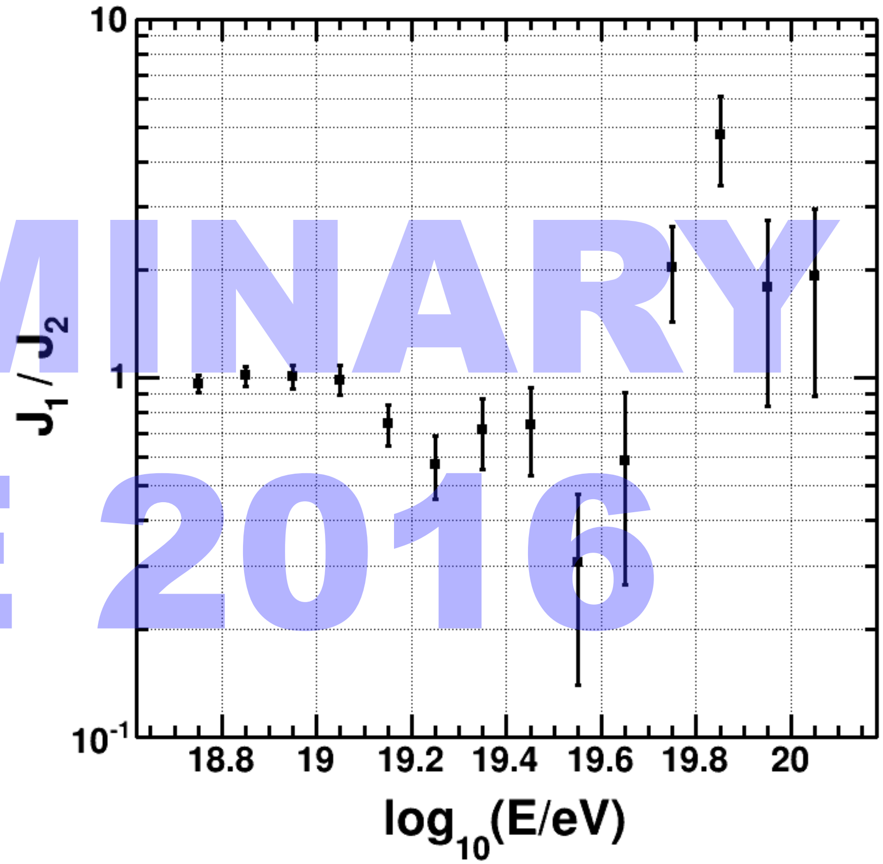
Huchra, et al, ApJ, (2012)

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

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

Energy Spectrum in the hot spot





The black line shows the best fit broken power law expressed by the function

$$\frac{\Delta N(E)}{\Delta \log_{10}\left(\frac{E}{E_o}\right)} = C_0\left(\varepsilon(E,E_b)\left(\frac{E}{E_o}\right)^{-\alpha_1} + (1-\varepsilon(E,E_b))\left(\frac{E}{E_o}\right)^{-\alpha_2}\right)$$

$$\varepsilon(E,E_b) = \{1 : (E < E_b),\ 0 : (E > E_b)\}$$

(E_o = 1 EeV).

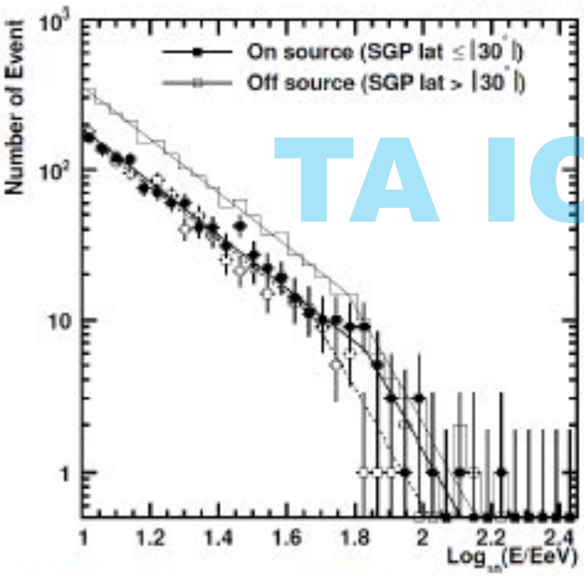


Fig. 1: The energy distributions of observed events for the On/Off areas using SGP.

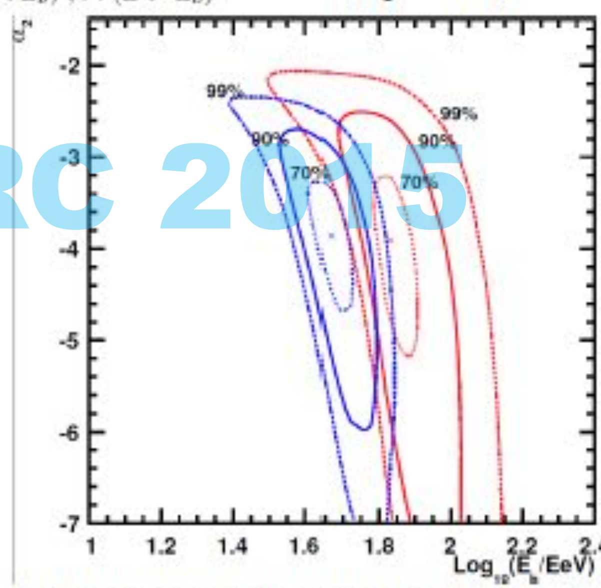


Fig. 2: The confidence contours of E_b and α_2. Red and blue colors denote CL for the On/Off regions respectively.

Observed cosmic ray energy spectra are compared between sky areas that have larger density of nearby objects, such as the super-galactic plane, and others that do not. The distributions differ. We found the chance probability to obtain the difference in statistically equivalent distributions is estimated as 6.2×10^{-4} (3.2σ).

… observed energy distributions of events within 11° from VCV AGNs and out of this region were compared. Chance probability to obtain observed difference in statistically equivalent distributions is estimated as 1.5×10^{-2} after considering penalty factor.

Same analysis with SGP case are repeated for energy distribution from On/Off area.

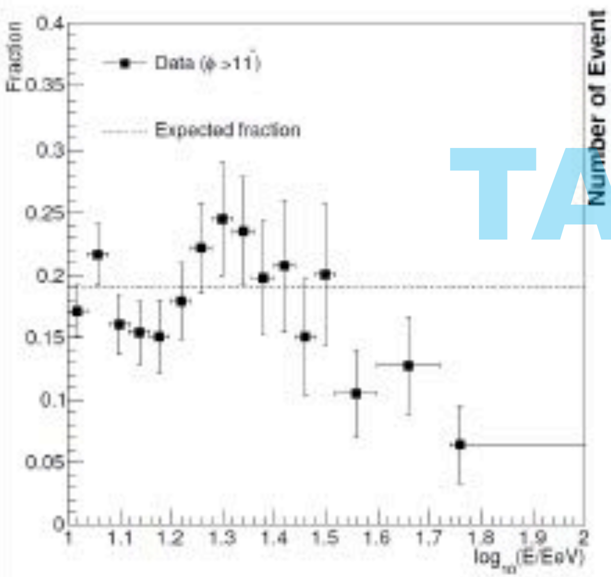


Fig. 4: Fraction of number of events in the Off source area to the expected Number. ("fraction plot")

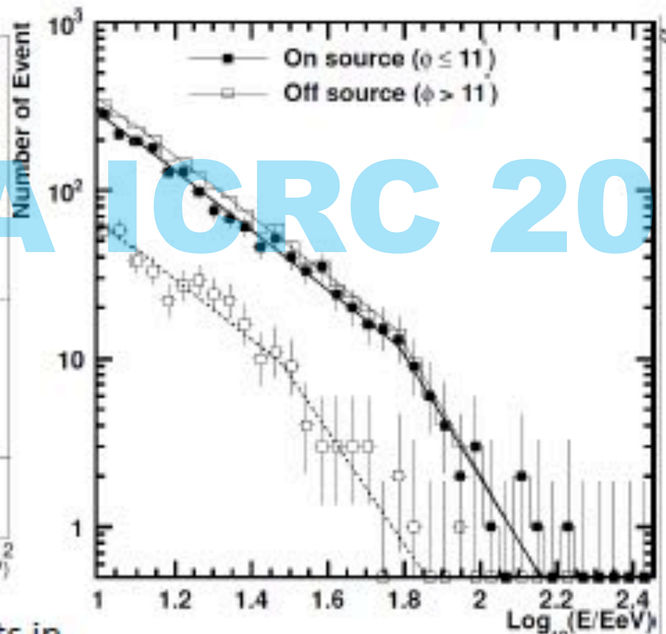


Fig. 5: The energy distributions of observed events for the On/Off areas using VCV AGNs.

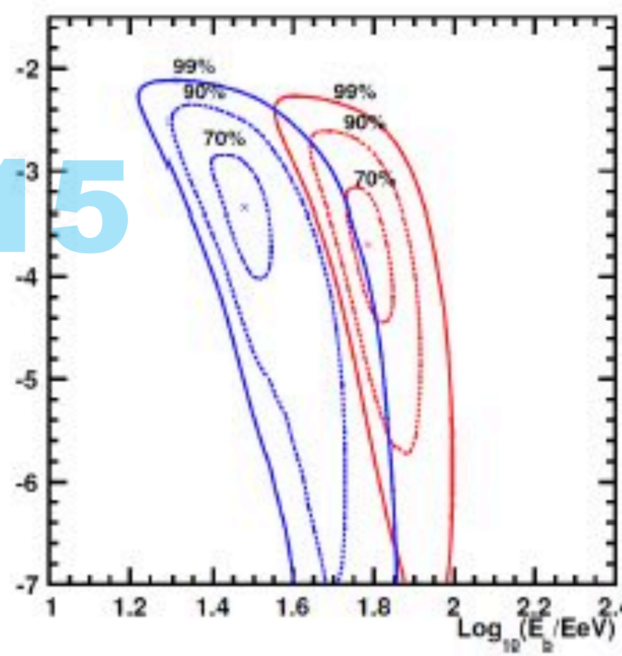
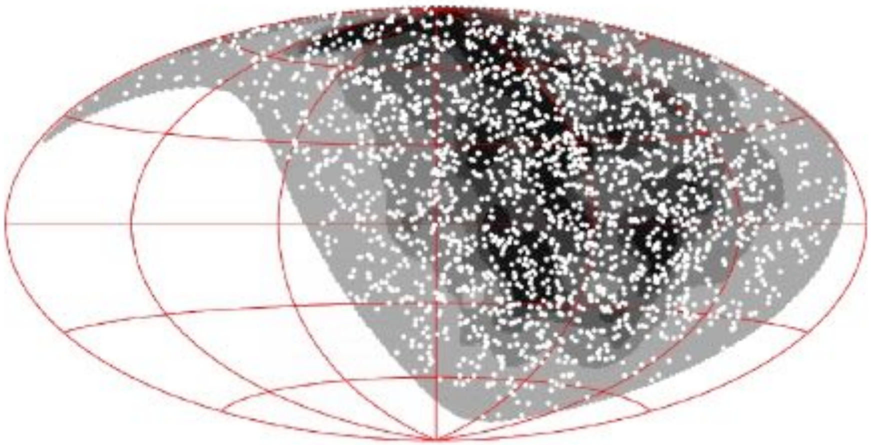


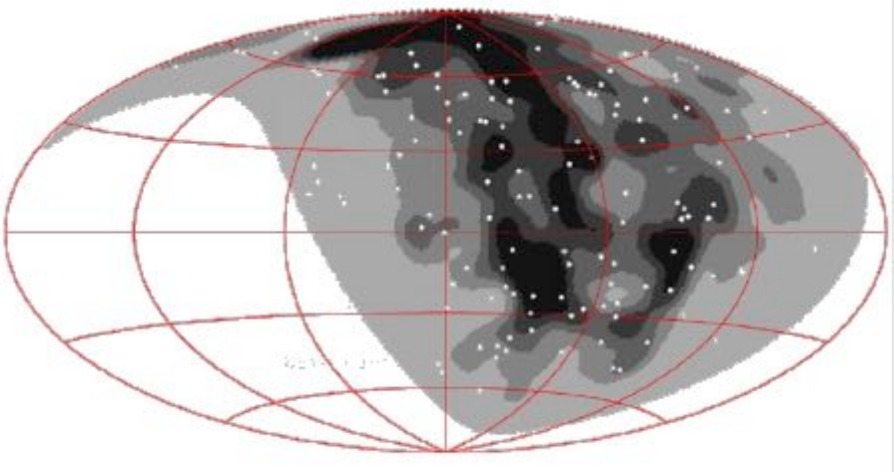
Fig. 6: The confidence contours of E_b and α_2. Red and blue corresponds On/Off regions respectively.

Comparison with Large-Scale Structure (LSS)

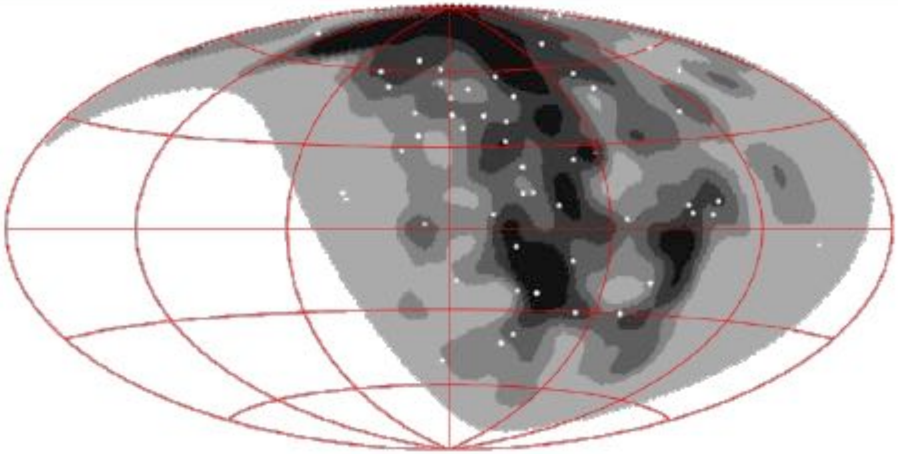
E > 10 EeV: 2130 events



E > 40 EeV: 132 events



E > 57 EeV: 52 events



White dots: 5-year TA data with zenith angle < 55 deg.

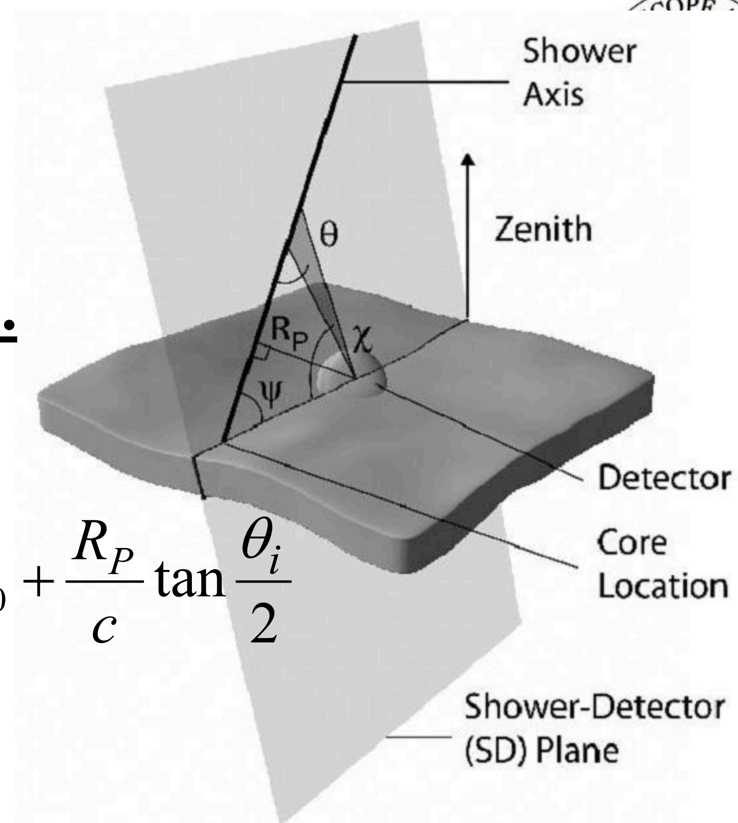
Gray patterns:
expected flux density from
proton LSS 2MASS Galaxy Redshift catalog (XSCz)

FD Geometrical Reconstruction

The trajectory of the EAS can be determined in one of two ways:

1. Monocular reconstruction using the arrival time of light signal at the detector.
2. By intersecting the shower-detector planes (SDP) seen from the two detector sites.

1.



$$t_i = t_0 + \frac{R_P}{c}\tan\frac{\theta_i}{2}$$

2.