



Latest results of the Telescope Array experiment on ultra-high energy cosmic rays

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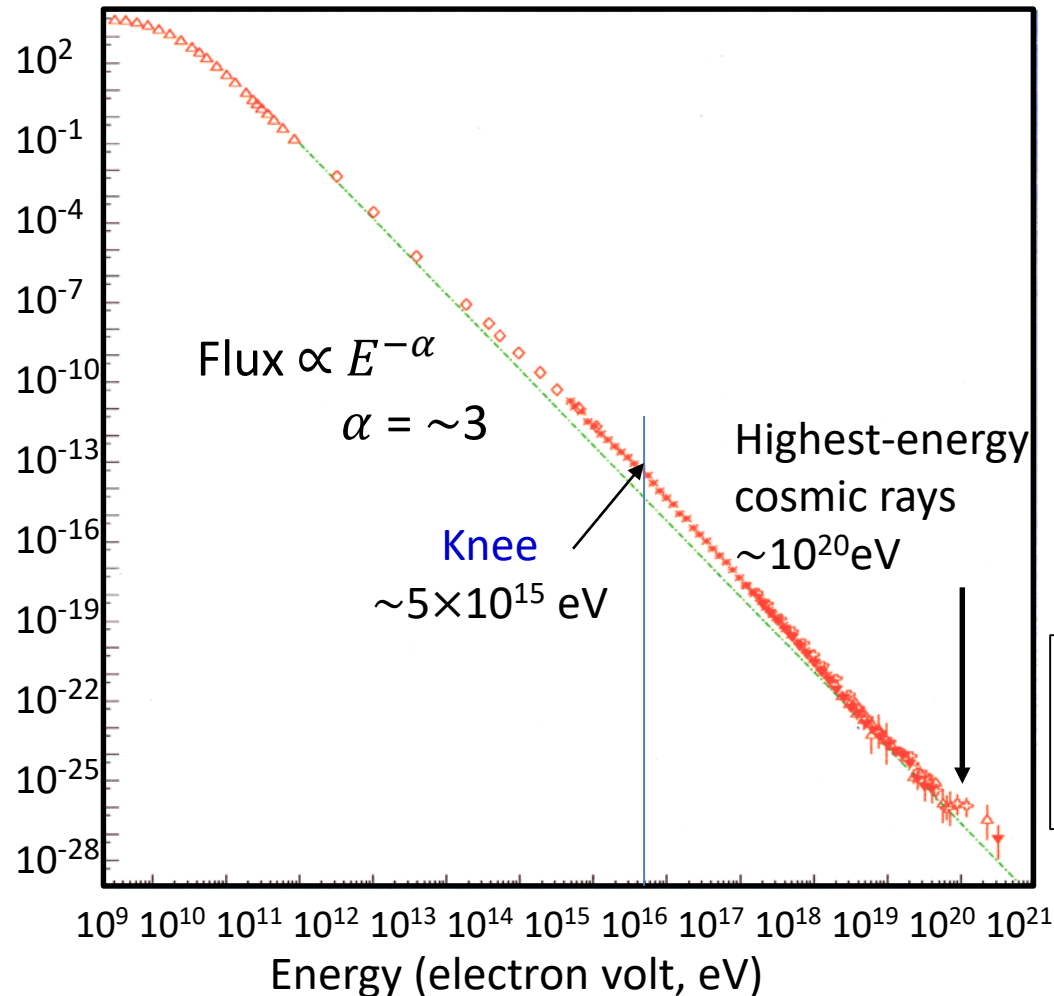
Content

- Telescope Array (TA)
- Latest results
 - Energy Spectrum
 - Composition
 - Anisotropy
- Future of Telescope Array

The results were reported at ICRC2017

Energy spectrum of cosmic rays

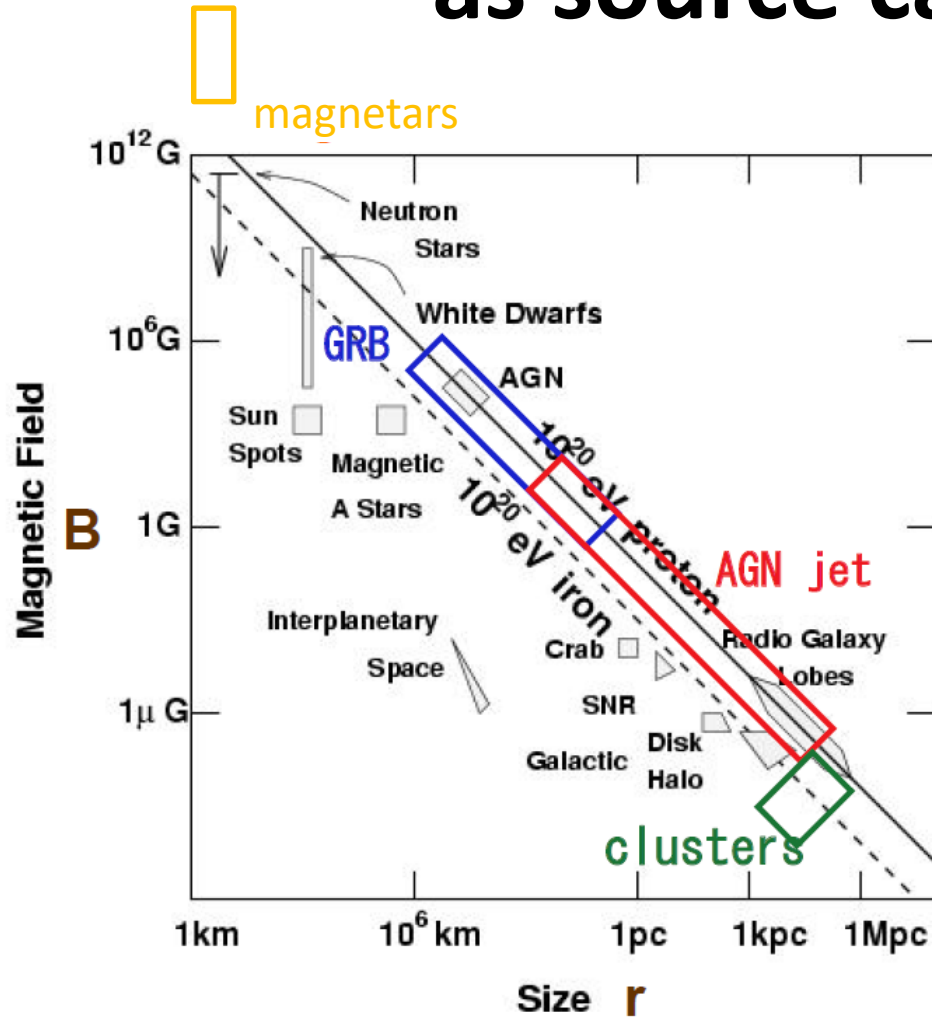
Cosmic-ray flux



Acceleration of cosmic rays to Knee energy ($\sim 5 \times 10^{15} \text{ eV}$) could be explained by shock wave acceleration (source spectral index $\alpha = 2.0 \sim 2.2$) at supernova explosions in the Galaxy

What are the most powerful accelerators that generate cosmic rays of 10^{20} eV in the universe?

Astrophysical cosmic-ray accelerators as source candidates



Telescope Array Collaboration

5 countries, ~130 researchers



Japan



USA



Korea



Russia



Belgium

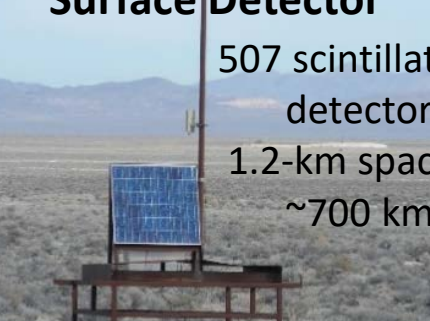
R.U. Abbasi¹, M. Abe², T. Abu-Zayyad¹, M. Allen¹, R. Azuma³, E. Barcikowski¹, J.W. Belz¹, D.R. Bergman¹, S.A. Blake¹, R. Cady¹, B.G. Cheon⁴, J. Chiba⁵, M. Chikawa⁶, A. Di Matteo²⁹, T. Fujii⁷, M. Fukushima^{7,8}, G. Furlich¹, T. Goto⁹, W. Hanlon¹, Y. Hayashi⁹, M. Hayashi¹⁰, N. Hayashida¹¹, K. Hibino¹¹, K. Honda¹², D. Ikeda⁷, N. Inoue², T. Ishii¹², R. Ishimori³, H. Ito¹³, D. Ivanov¹, S. Jeong²³, C.C.H. Jui¹, K. Kadota¹⁴, F. Kakimoto³, O. Kalashev¹⁵, K. Kasahara¹⁶, H. Kawai¹⁷, S. Kawakami⁹, S. Kawana², K. Kawata⁷, E. Kido⁷, H.B. Kim⁴, J.H. Kim¹, J.H. Kim¹⁸, S. Kishigami⁹, S. Kitamura³, Y. Kitamura³, V. Kuzmin¹⁵, M. Kuznetsov¹⁵, Y.J. Kwon¹⁹, B. Lubsandorzhiev¹⁵, J.P. Lundquist¹, K. Machida¹², K. Martens⁸, T. Matsuda²⁰, T. Matsuyama⁹, J.N. Matthews¹, M. Minamino⁹, K. Mukai¹², I. Myers¹, K. Nagasawa², S. Nagataki¹³, R. Nakamura²⁵, T. Nakamura²¹, T. Nonaka⁷, A. Nozato⁶, S. Ogio⁹, J. Ogura³, M. Ohnishi⁷, H. Ohoka⁷, K. Oki⁷, T. Okuda²², M. Ono¹³, R. Onogi⁹, A. Oshima⁹, S. Ozawa¹⁶, I.H. Park²³, M.S. Pshirkov^{15,24}, D.C. Rodriguez¹, G. Rubtsov¹⁵, D. Ryu¹⁸, H. Sagawa⁷, K. Saito⁷, Y. Saito²⁵, N. Sakaki⁷, N. Sakurai⁹, L.M. Scott²⁶, T. Seki²⁵, K. Sekino⁷, P.D. Shah¹, T. Shibata⁷, F. Shibata¹², H. Shimodaira⁷, B.K. Shin⁹, H.S. Shin⁷, J.D. Smith¹, P. Sokolsky¹, B.T. Stokes¹, S.R. Stratton^{1,26}, T.A. Stroman¹, T. Suzawa², Y. Takahashi⁹, M. Takamura⁵, M. Takeda⁷, R. Takeishi⁷, A. Taketa²⁷, M. Takita⁷, Y. Tameda³³, M. Tanaka²⁰, K. Tanaka²⁸, H. Tanaka⁹, S.B. Thomas¹, G.B. Thomson¹, P. Tinyakov^{15,29}, I. Tkachev¹⁵, H. Tokuno⁷, T. Tomida²⁵, S. Troitsky¹⁵, Y. Tsunesada⁹, K. Tsutsumi³, Y. Uchihori³⁰, S. Udo¹¹, F. Urban^{24,31}, T. Wong¹, Y. Yamane⁹, M. Yamamoto²⁵, H. Yamaoka²⁰, K. Yamazaki²⁷, J. Yang³², K. Yashiro⁵, Y. Yoneda⁹, S. Yoshida¹⁷, H. Yoshii³³, Y. Zhezher¹⁵, Z. Zundel¹

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Telescope Array(TA)

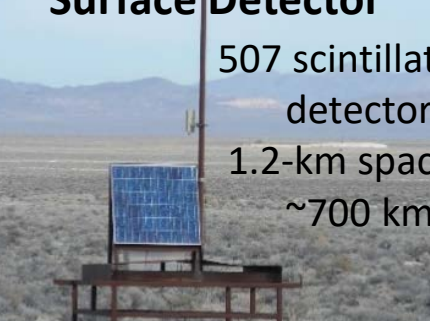
39.30° N
112.91° W
1370 m ASL

Utah, USA



Surface Detector

- 507 scintillator detectors
- 1.2-km spacing
- $\sim 700 \text{ km}^2$

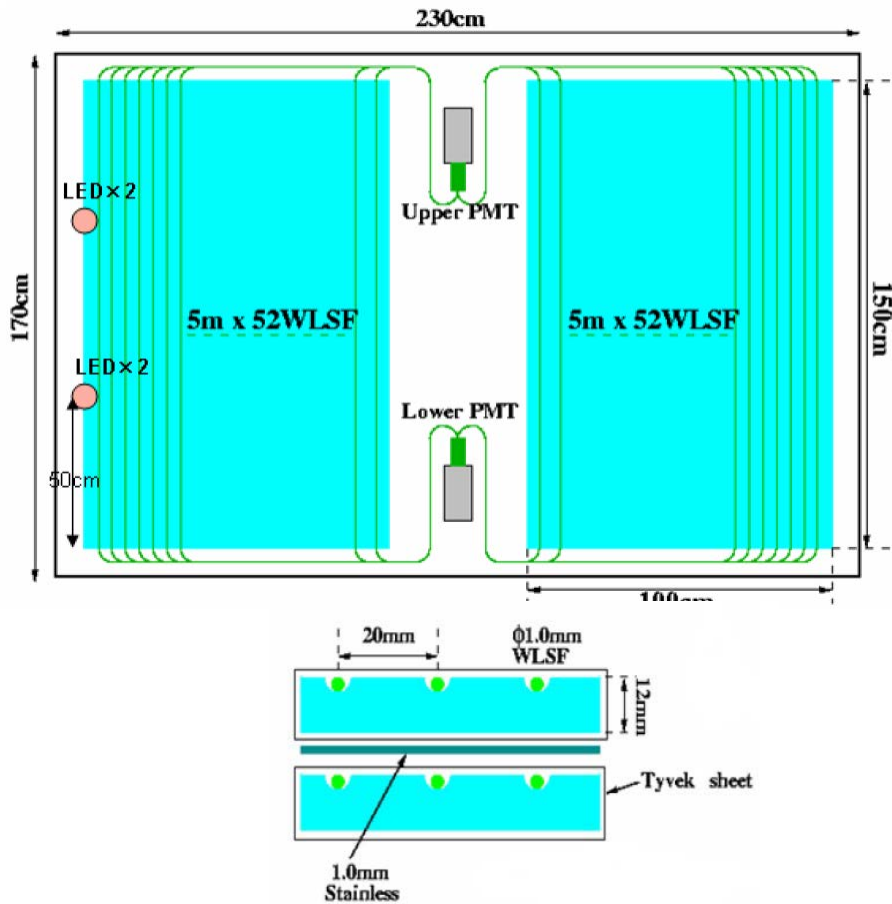


Surface Detector

- 507 scintillator detectors
- 1.2-km spacing
- $\sim 700 \text{ km}^2$

operational
since March, 2008

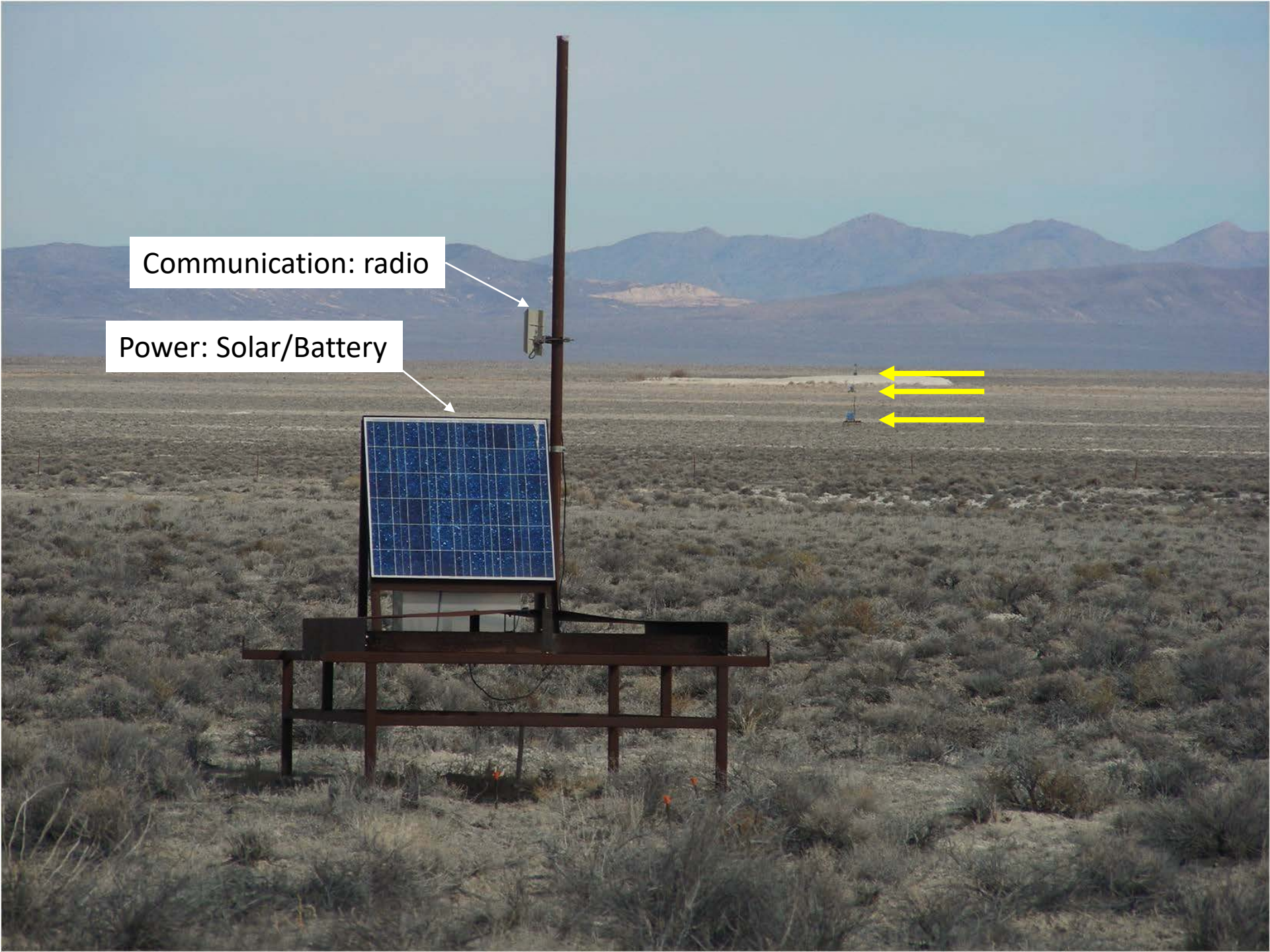
Surface Detectors (SD)



2 layers scintillator
1.2 cm thick, 3m² area
Optical fibers to PMTs

Communication: radio

Power: Solar/Battery

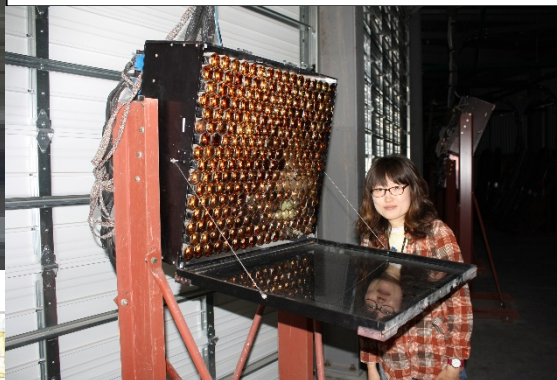


Fluorescence Detectors (FD)

Middle Drum

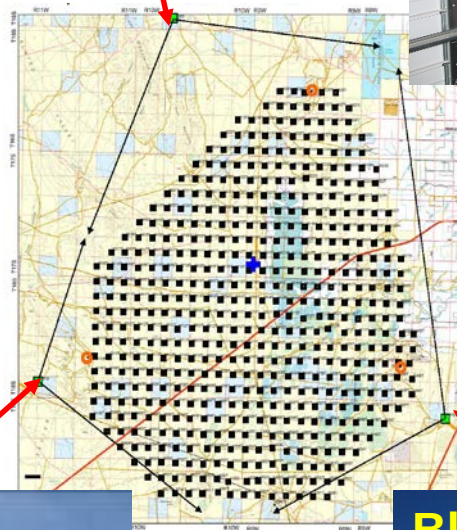


14 telescopes @ station
256 PMTs/camera



5.2 m²

Reutilized from HiRes-I



Long Ridge



12 telescopes/station
256 PMTs/camera

Black Rock Mesa



~1 m²

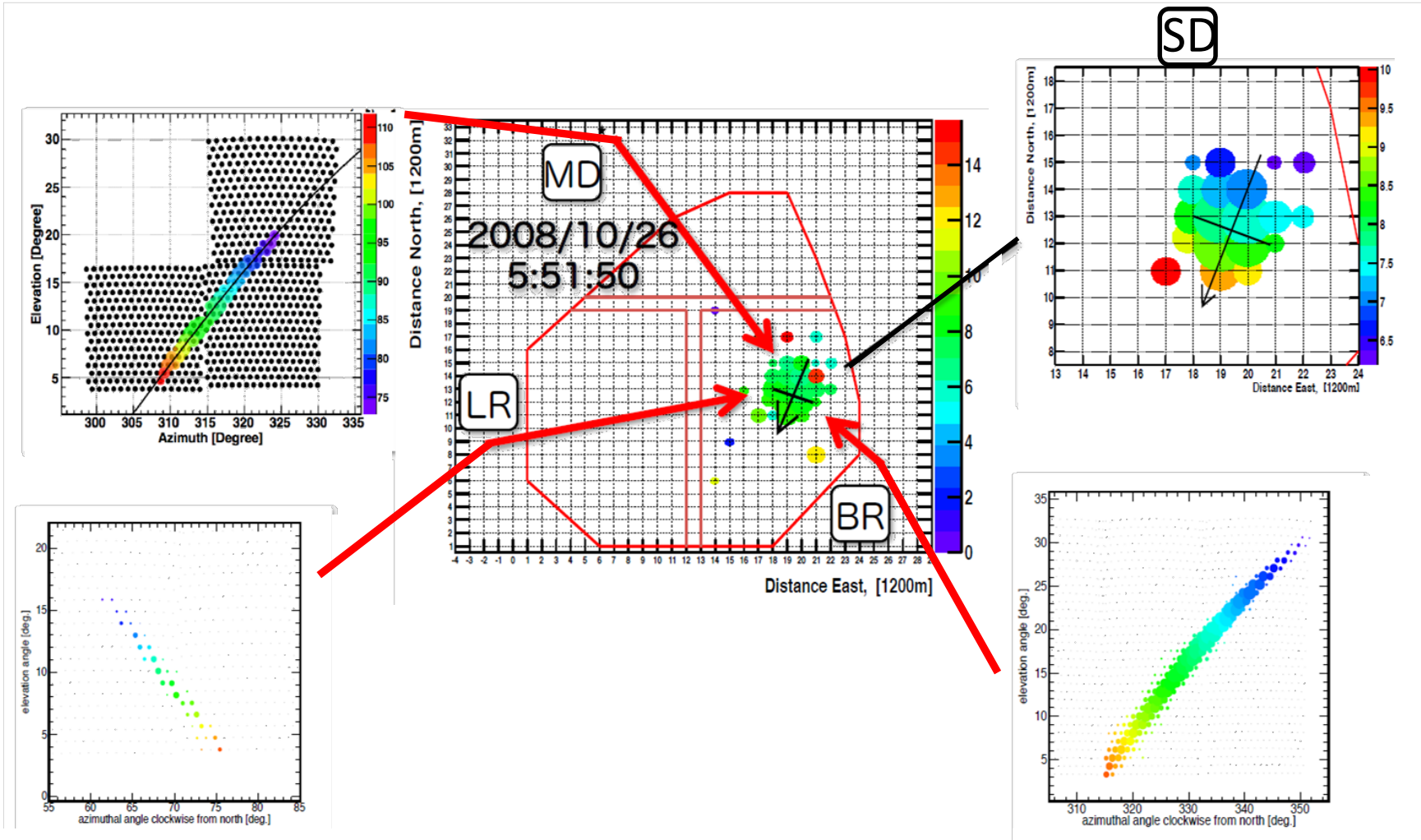
New Telescopes



6.8 m²

Beijing, China

Hybrid event example

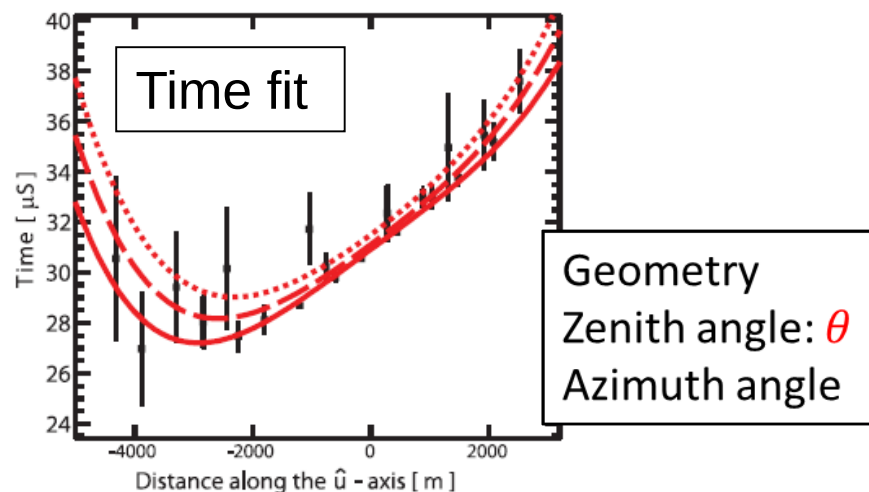
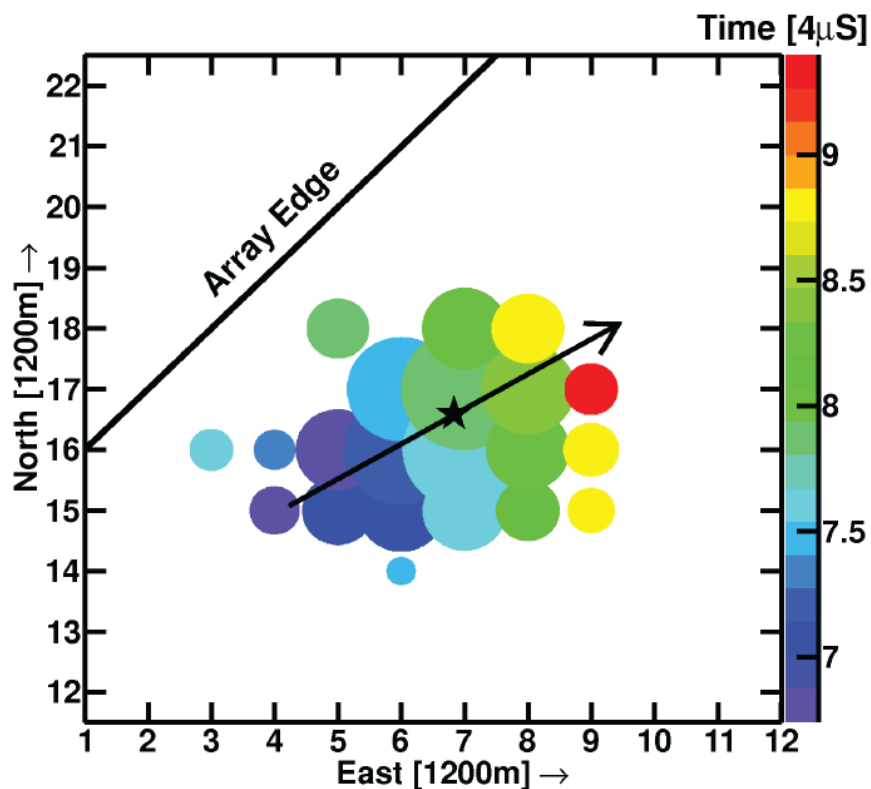


Content

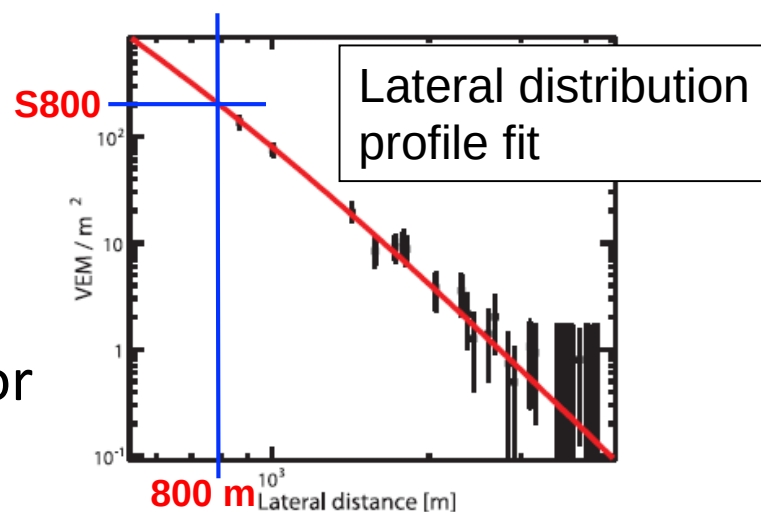
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TA shower analysis with SD

An SD hit map of a typical event



Use **S800** as an energy estimator

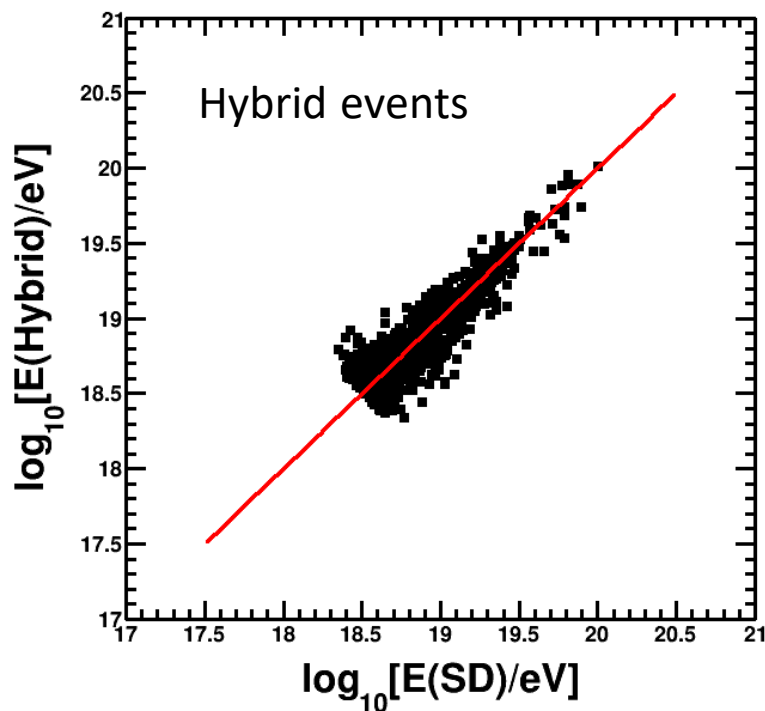


Energy Scale Check and Resolution

Final energy is scaled by 1.27

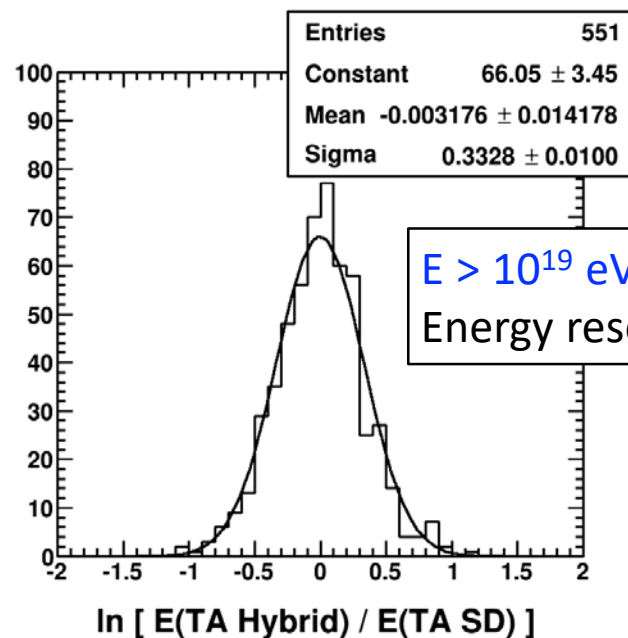
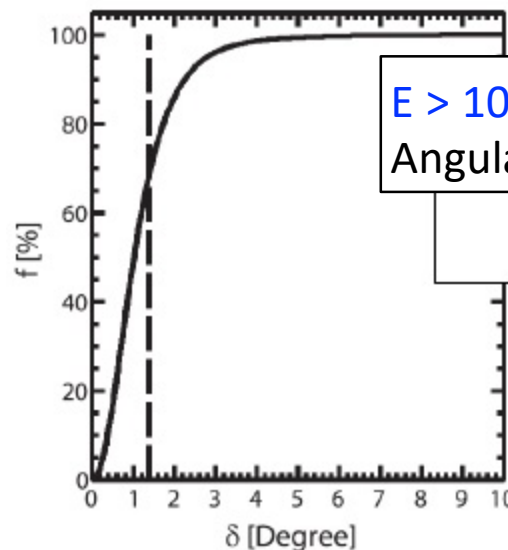
$$\left\langle \frac{E^{TBL}}{E^{FD}} \right\rangle_{\text{hybrid}} = 1.27$$

$$E^{TBL} = E(S800, \sec\theta)$$

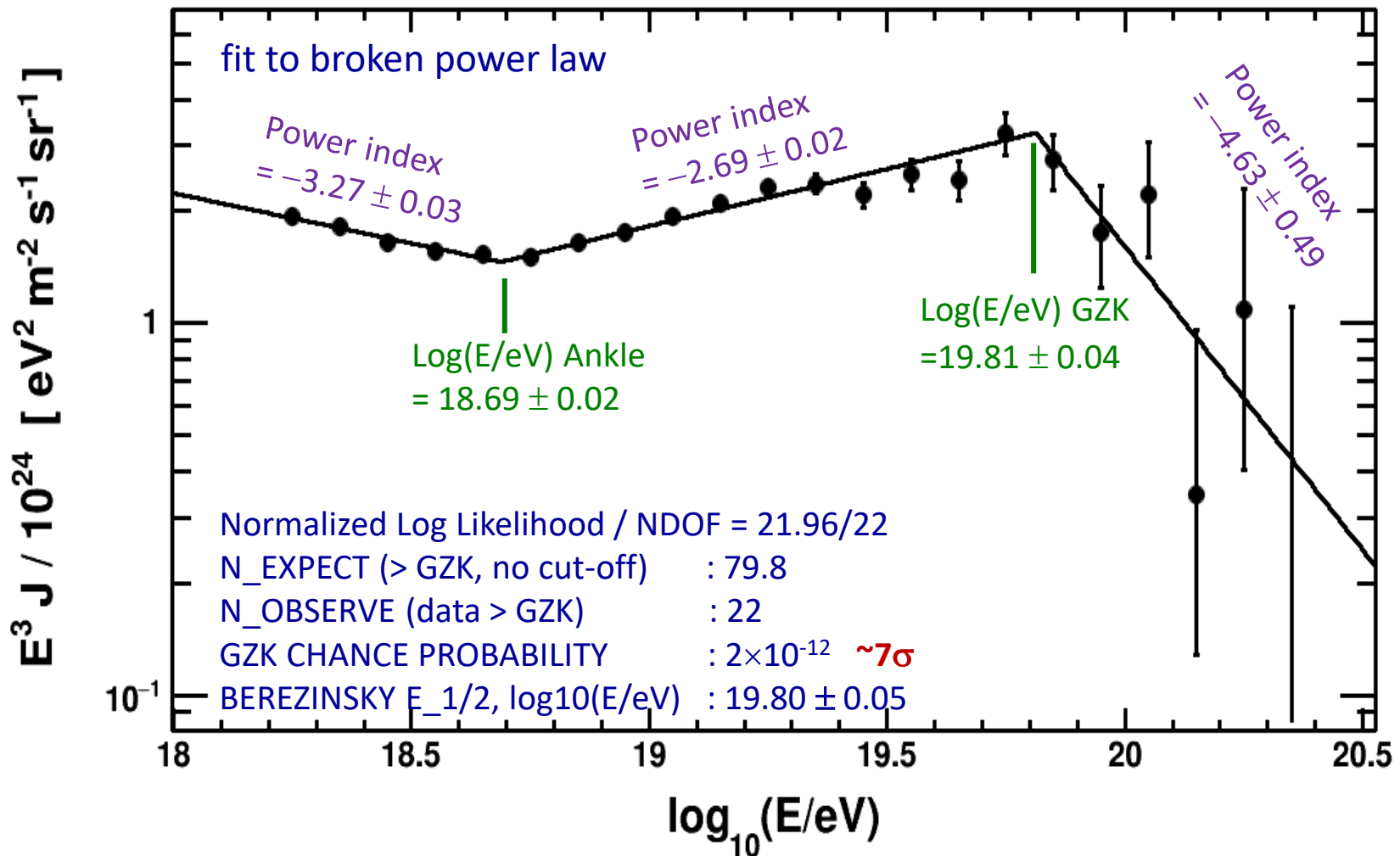


(SD scaled to FD energy: calorimetric)

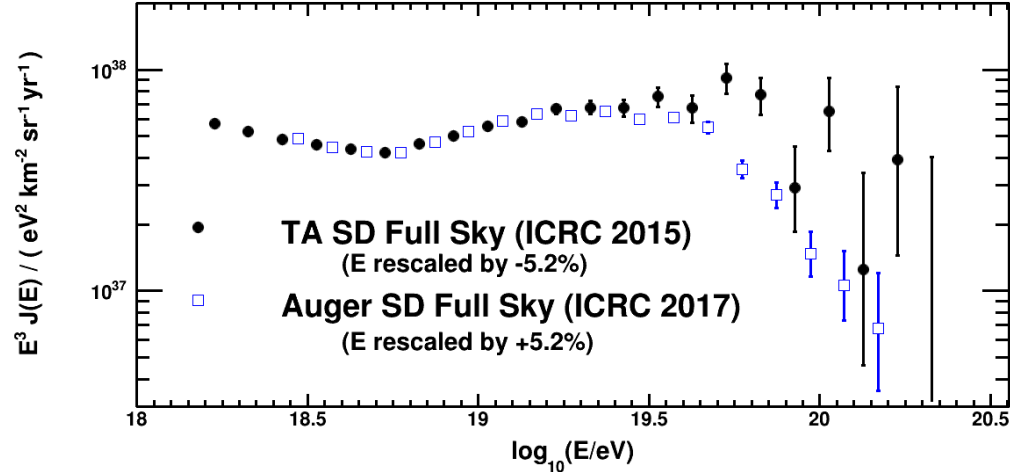
$$E(\text{SD}) = E^{TBL} / 1.27$$



TA SD Spectrum (9 years data)

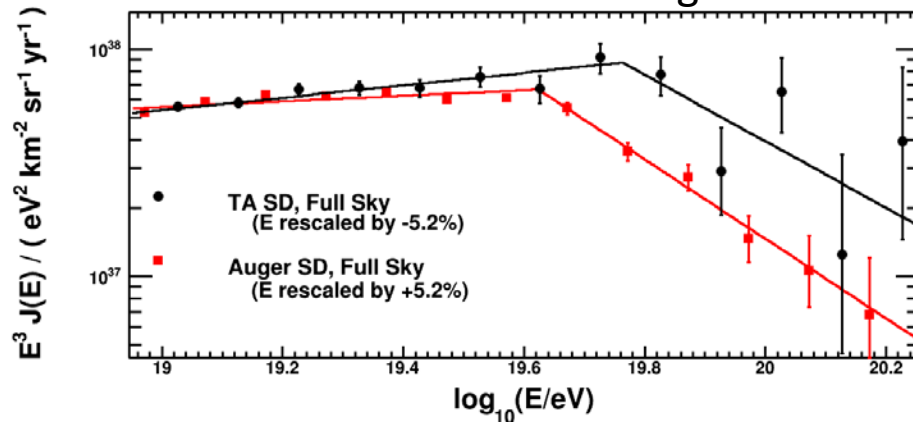


TA & Auger Spectrum WG report

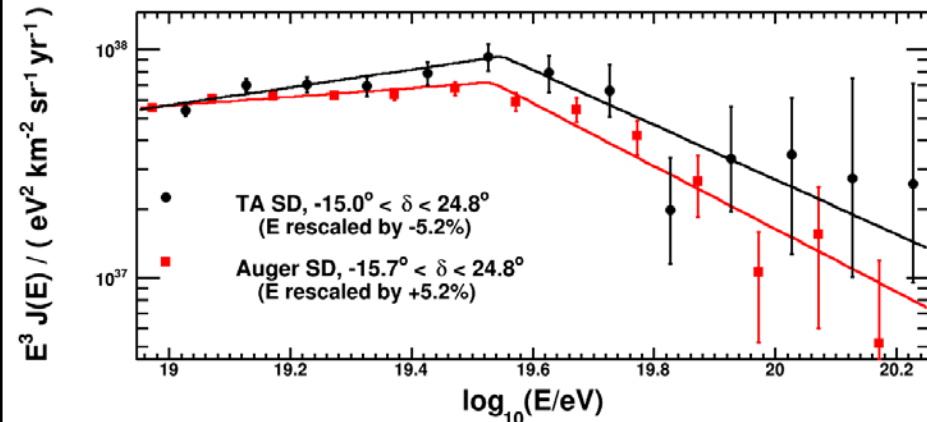


Fit above $E > 10^{19}$ eV

Entire skies of TA and Auger

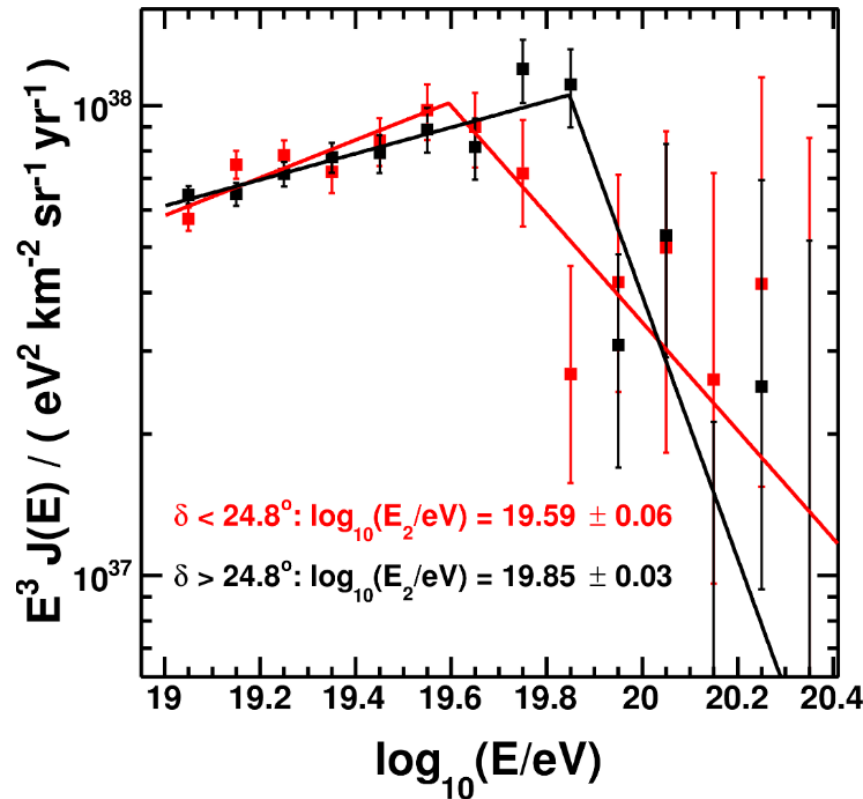


Common declination band



- Break points are roughly in agreement
- Smaller but significant difference remains

Declination dependence in TA



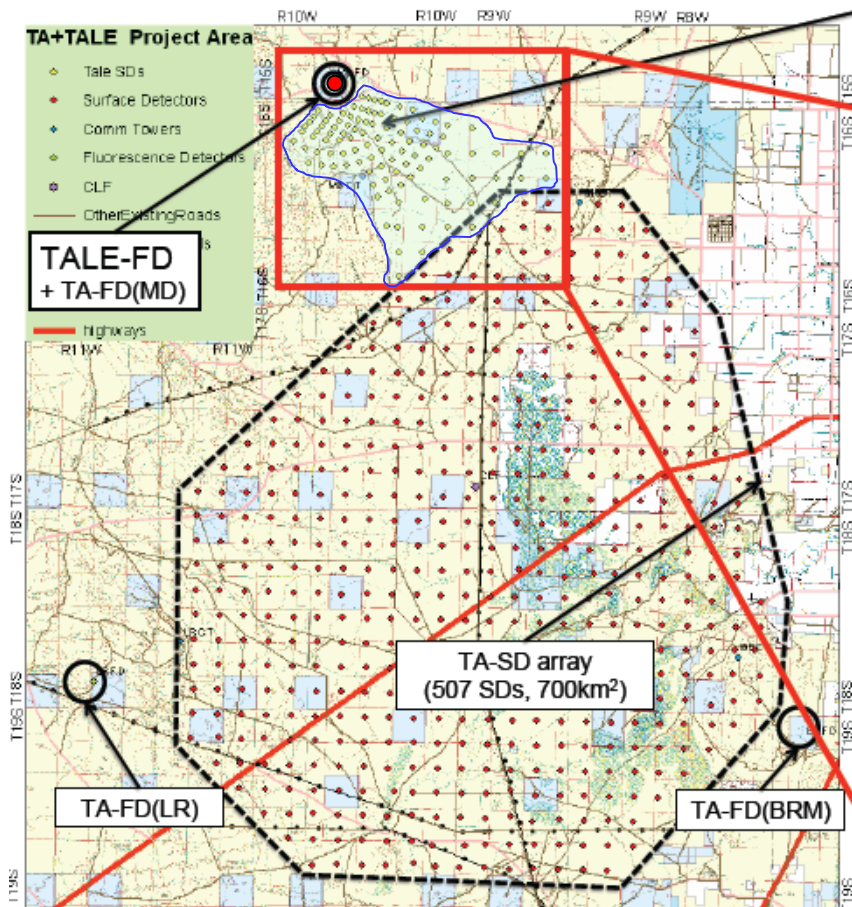
3.9 σ effect in TA using broken power law fit

TA Low-energy Extension (TALE)

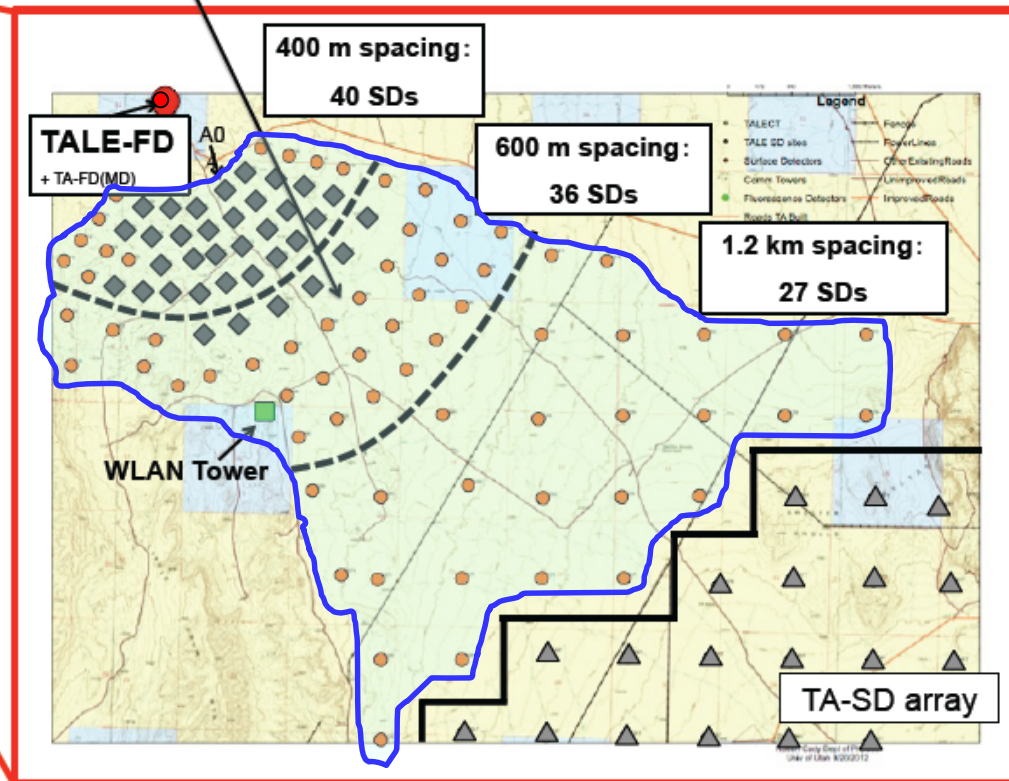
Galactic to Extra-Galactic Transition

TALE-FD: 10 reused HiRes telescopes to look higher in the sky ($31\text{--}59^\circ$) to see shower development to much lower energies

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



TALE-SD array (103 SDs, 70km²)





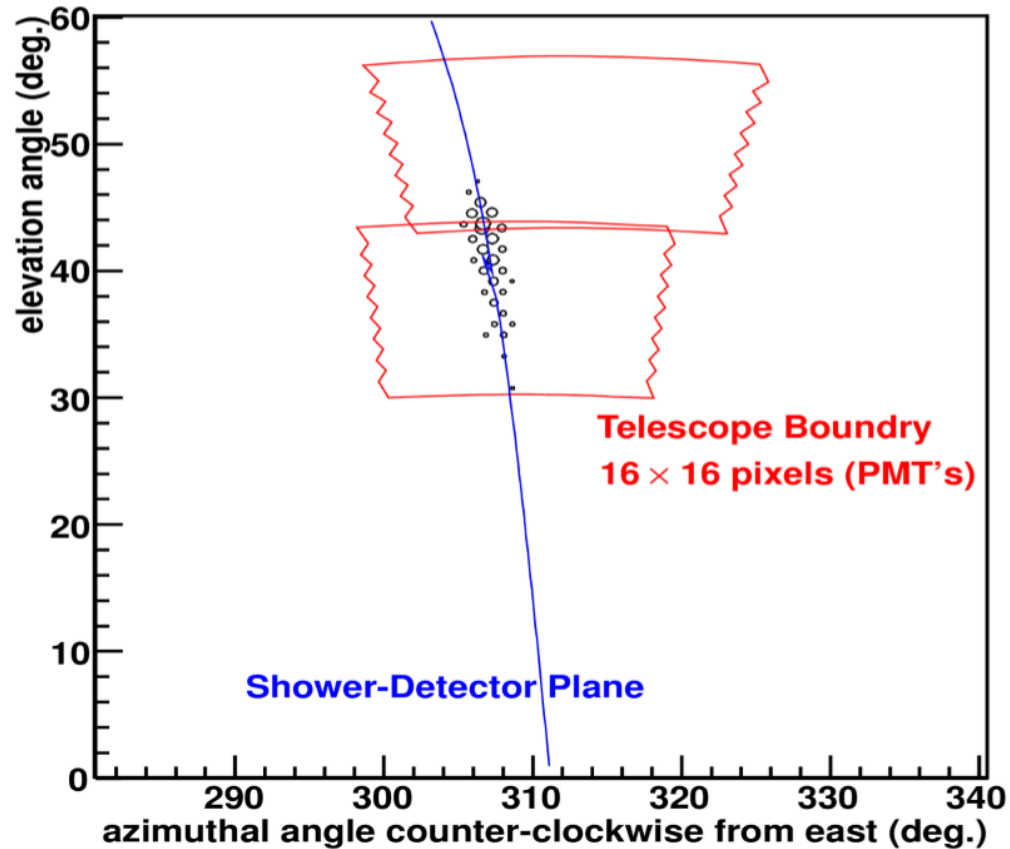
All 10 Telescopes installed and in operation since fall 2013

Test array of 16 scintillation SDs has been in operation → Totally 103 were deployed in Feb. 2017

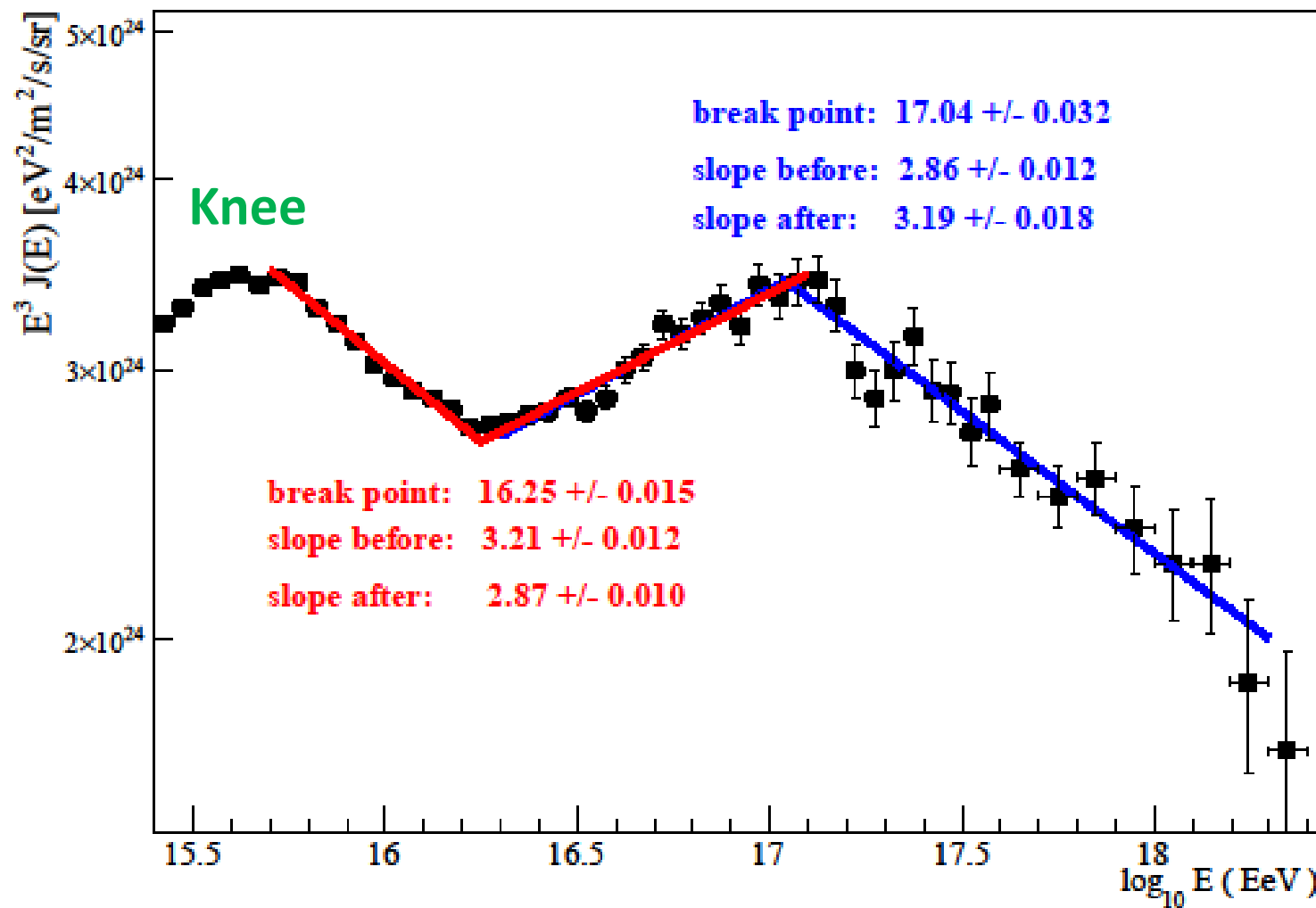


Nearby Events with Cerenkov

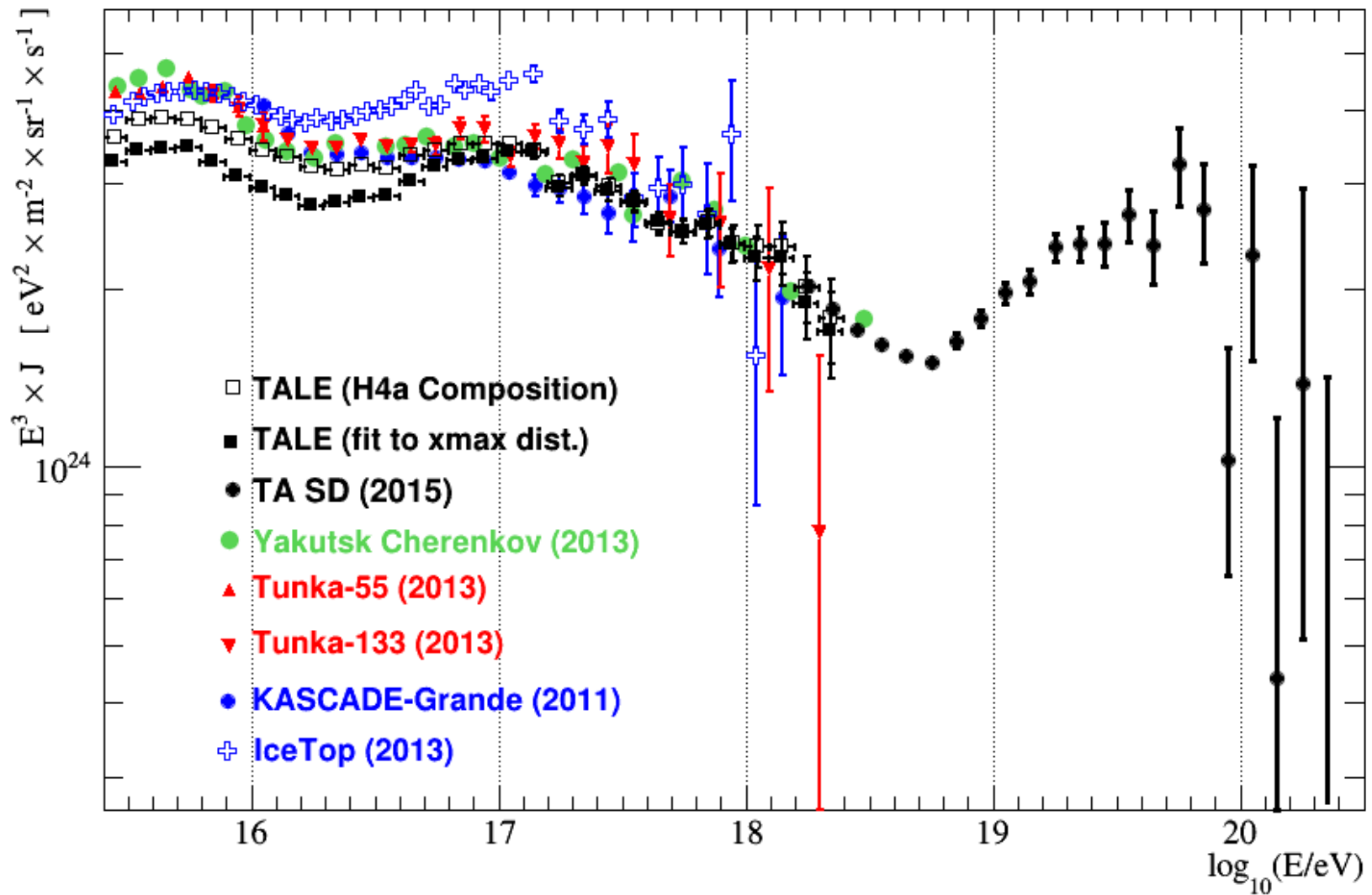
Cerenkov Event seen in two TALE Telescopes



TALE Energy Spectrum (Monocular)



Comparison with other measurements

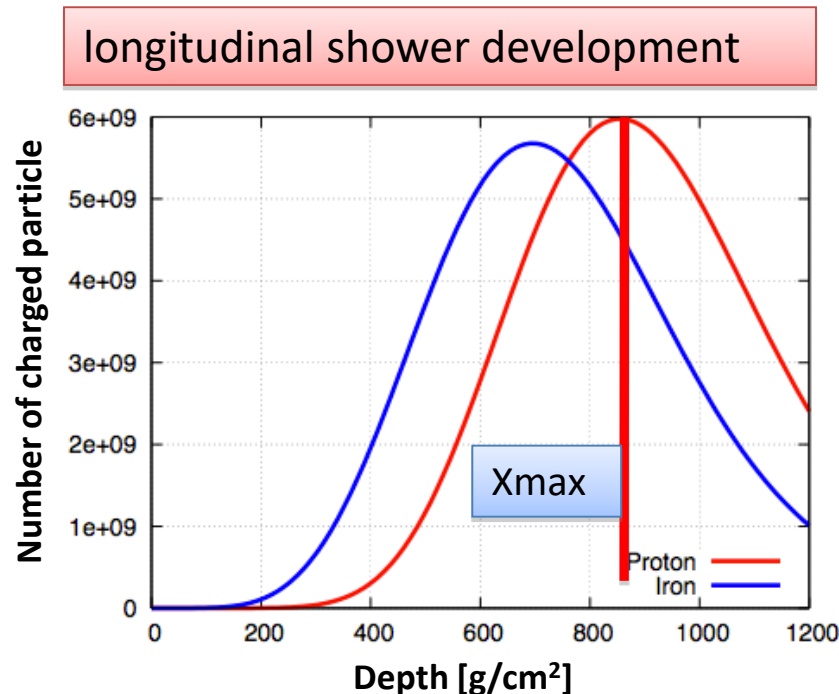


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Xmax Technique

- Longitudinal development of cosmic-ray showers depends on primary particle type
- FD observes longitudinal shower development
- **Xmax** (depth of shower maximum): the most efficient parameter for determining primary particle type

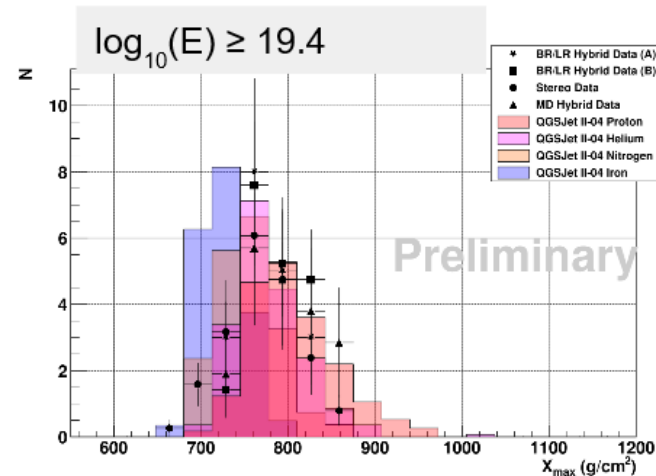
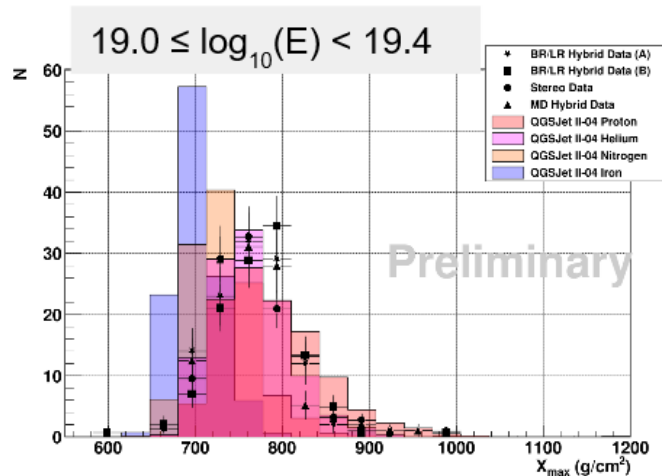
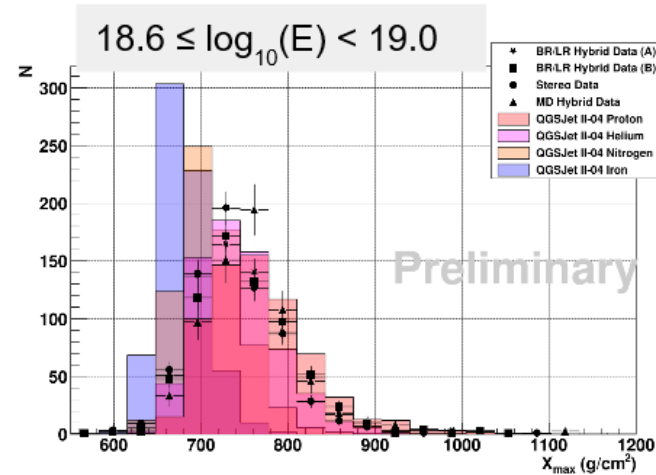
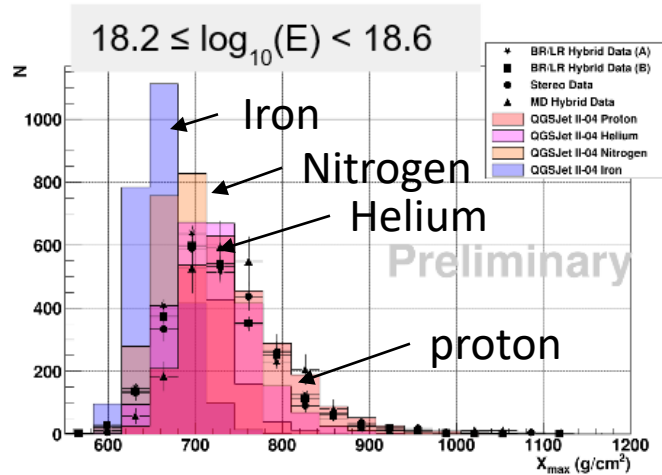


Xmax distributions (Hybrid, Stereo)

MD

MD/BRM/LR

BRM/LR



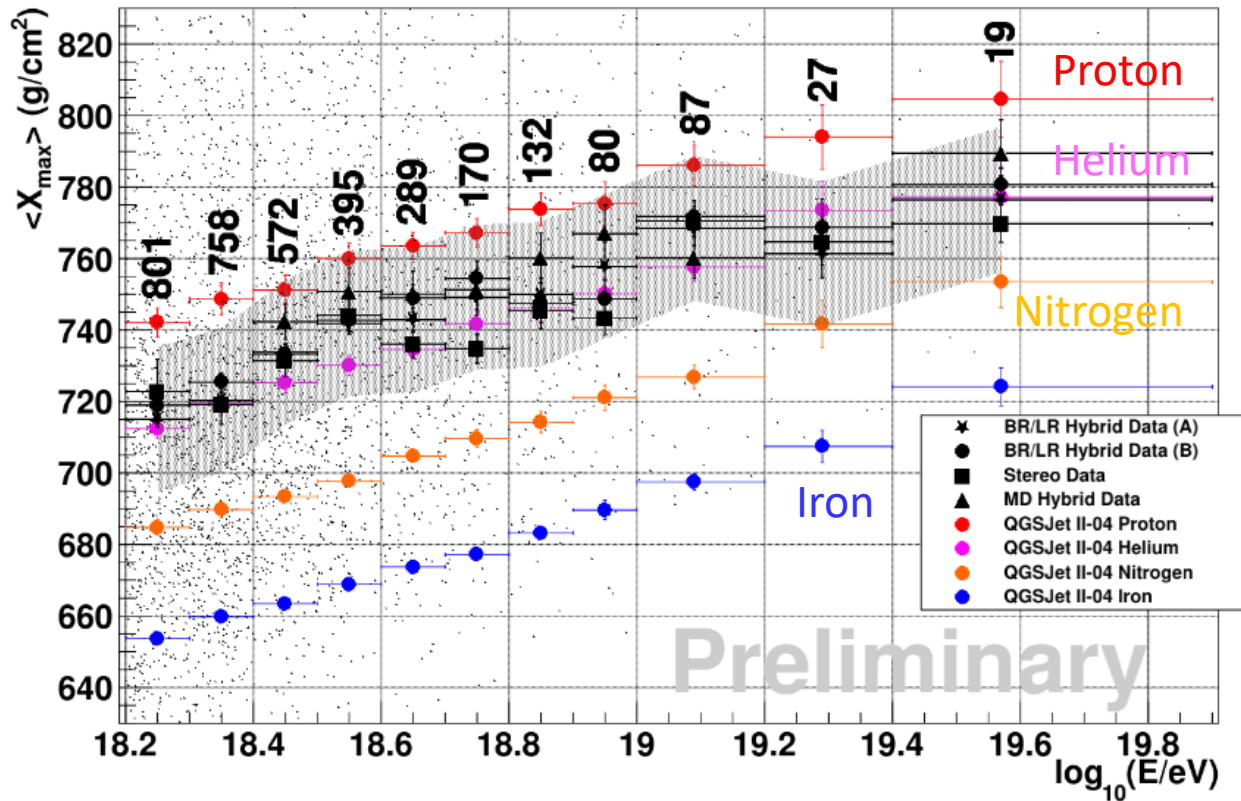
$X_{\max}$ distributions for all
TA $X_{\max}$ analyses.

QGSJet II-04 models
for four different
primary species are
also shown: proton,
helium, nitrogen, and
iron.

All analyses exhibit
similar shapes. Tails
characteristic of light
primaries are seen up
to until statistics begin
to be severely depleted
above $10^{19.4}$ eV.

Undersampling in the
tails due to insufficient
exposure is a risk at
these energies.

Elongation rate (Hybrid, Stereo)



Four TA independent $\langle X_{\text{max}} \rangle$ measurements:

2 BR/LR hybrid
1 MD hybrid
1 Stereo (BR $\otimes$ LR $\otimes$ MD)

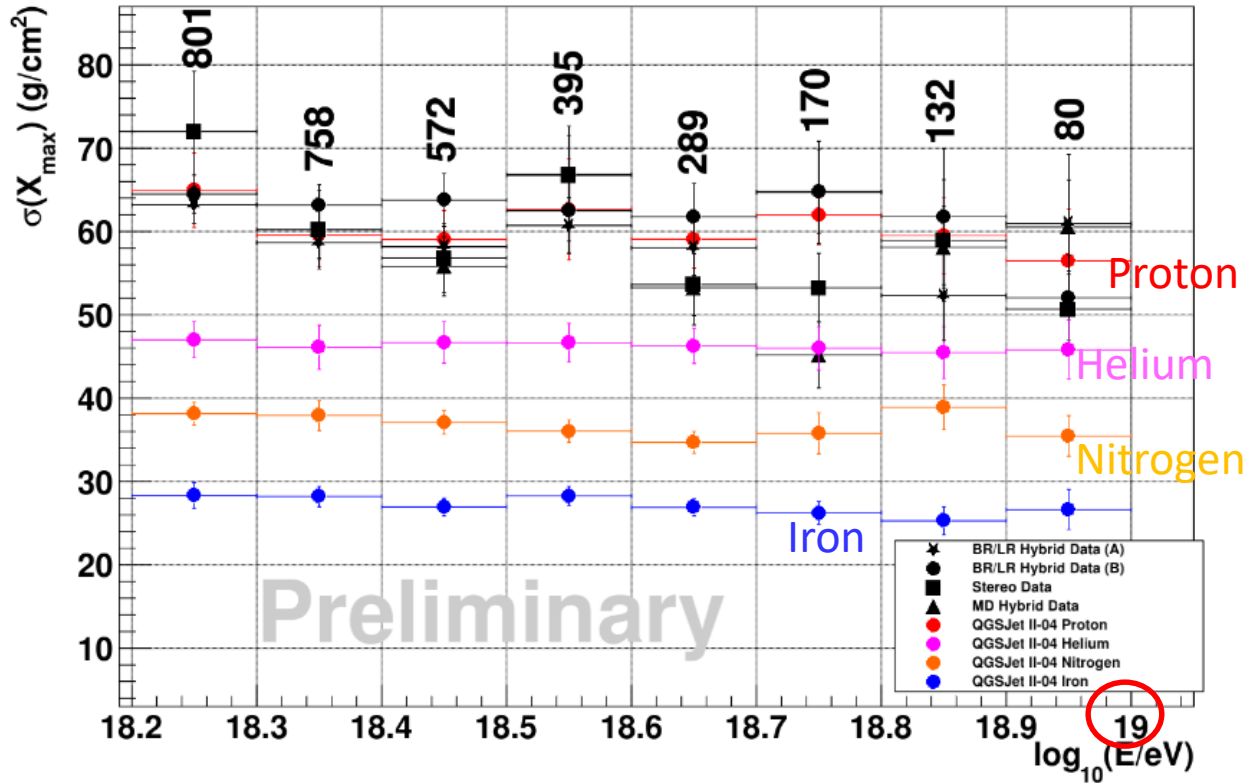
Event numbers shown are for BR/LR hybrid (A) data.

The gray band are model-independent systematics on BR/LR hybrid (A) data.

All models shown are QGSJet II-04 as reconstructed by BR/LR hybrid analysis.

Within systematics all independent measurements agree.

Xmax width (Hybrid, Stereo)



$\sigma(X_{\max})$ of all TA $X_{\max}$ measurements.

Event numbers shown are for BR/LR hybrid (A) data.

$\sigma(X_{\max})$ appears to agree with protons for all current $X_{\max}$ measurements from $10^{18.2}$ - 10^{19} eV.

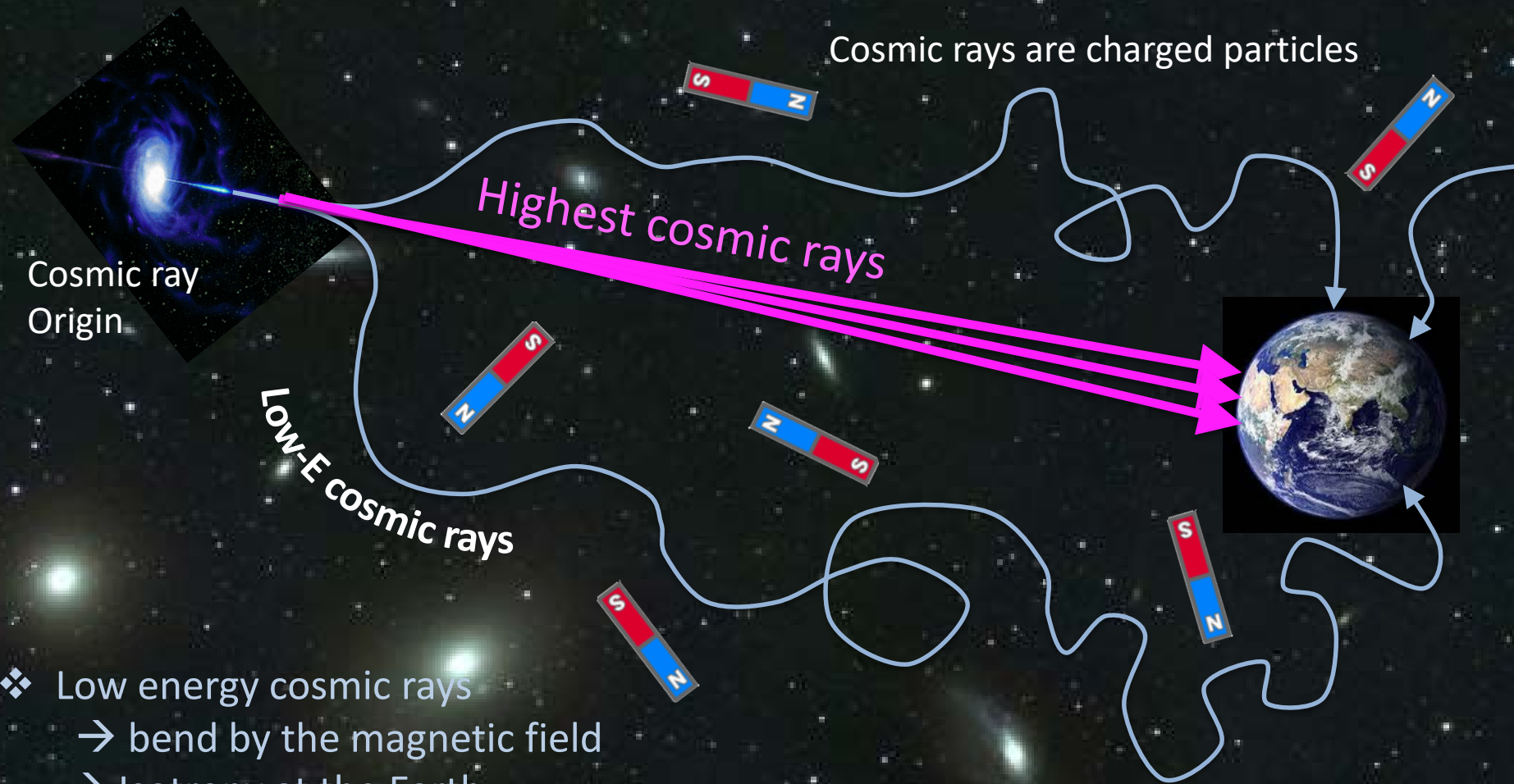
Above 10^{19} eV, statistics are falling too rapidly to make an accurate measurement. Even a couple of events will cause $\sigma(X_{\max})$ to change by ~25%.

All models shown are QGSJet II-04 as reconstructed by BR/LR hybrid analysis.

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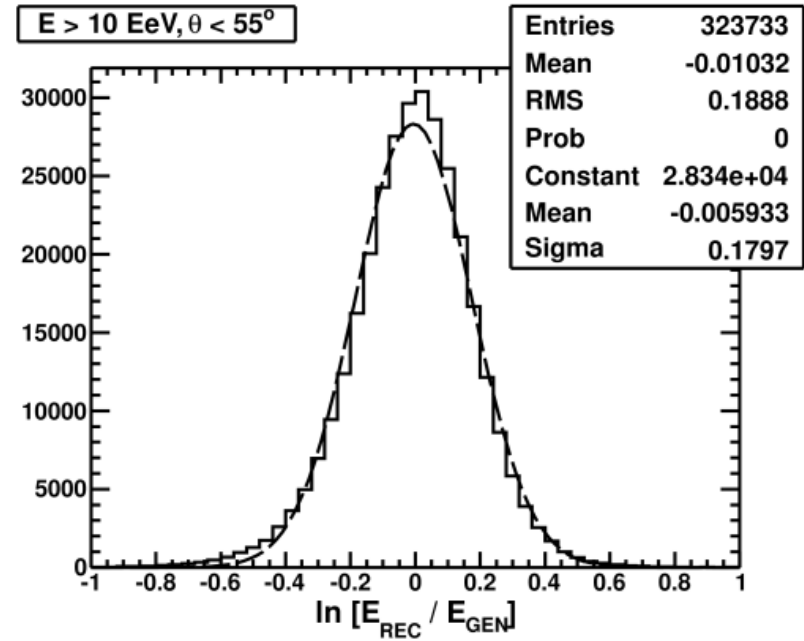
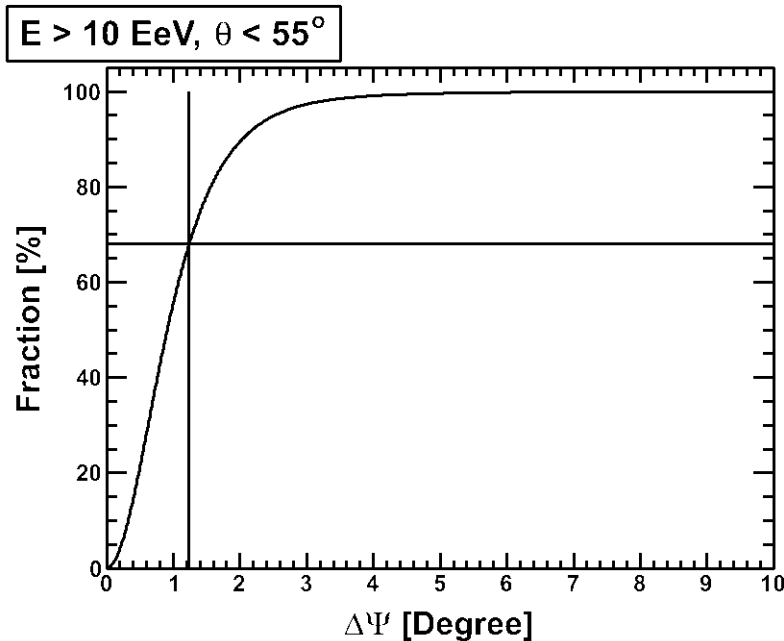
Why highest energy cosmic rays?



- ❖ Low energy cosmic rays
 - bend by the magnetic field
 - Isotropy at the Earth
- ❖ Highest energy cosmic rays
 - Almost go straight against magnetic field
 - Possible to find cosmic-ray hotspot

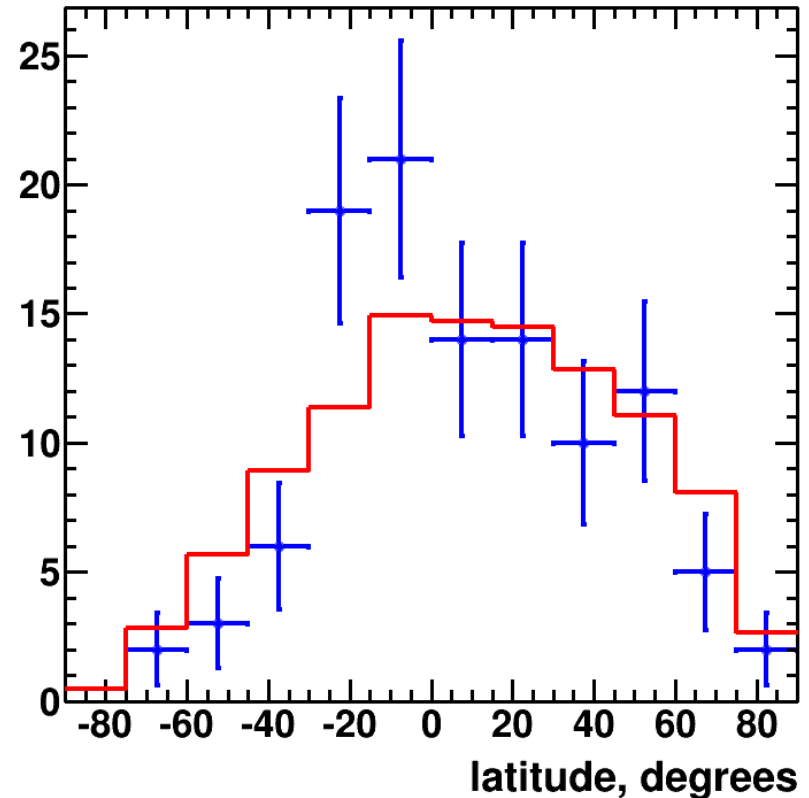
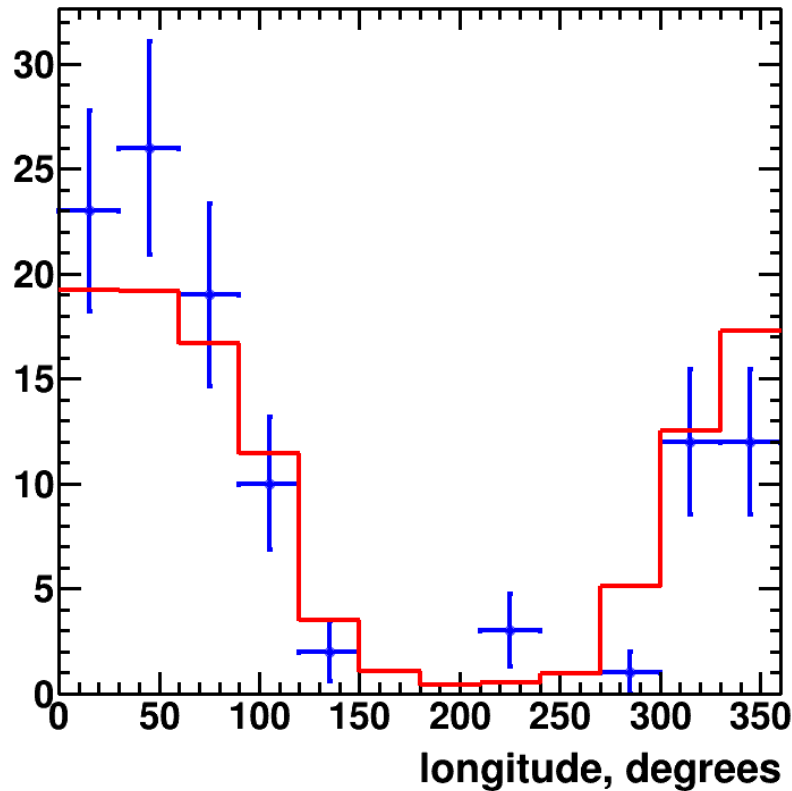
Anisotropy Analysis

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



Global anisotropy

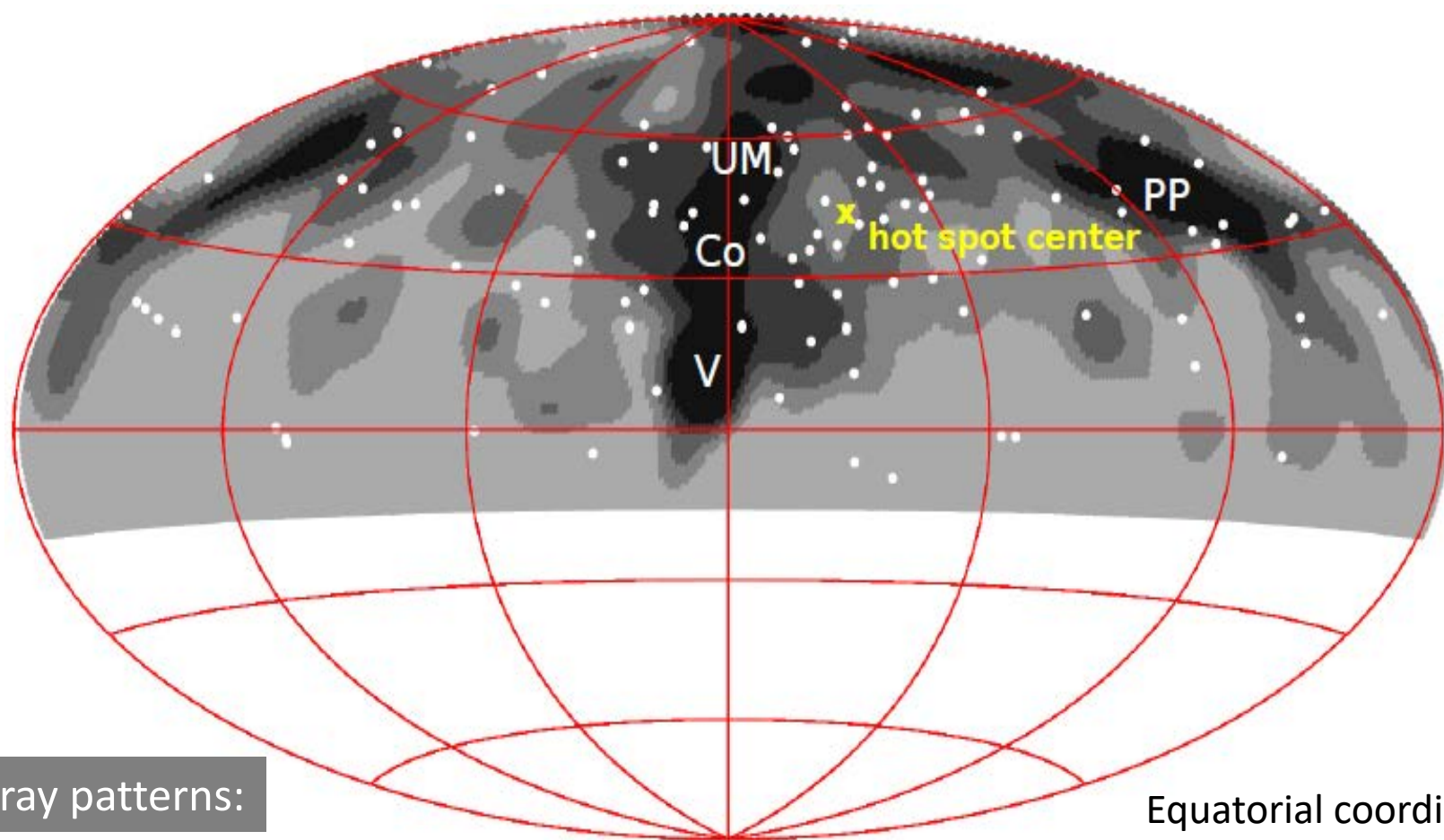
Super-Galactic (SG) coordinates



p-value for K-S test = 0.01 for SG latitude, & $E > 57$ EeV

Isotropic for other energy thresholds/coordinates

Correlation with Large-Scale Structure



Gray patterns:

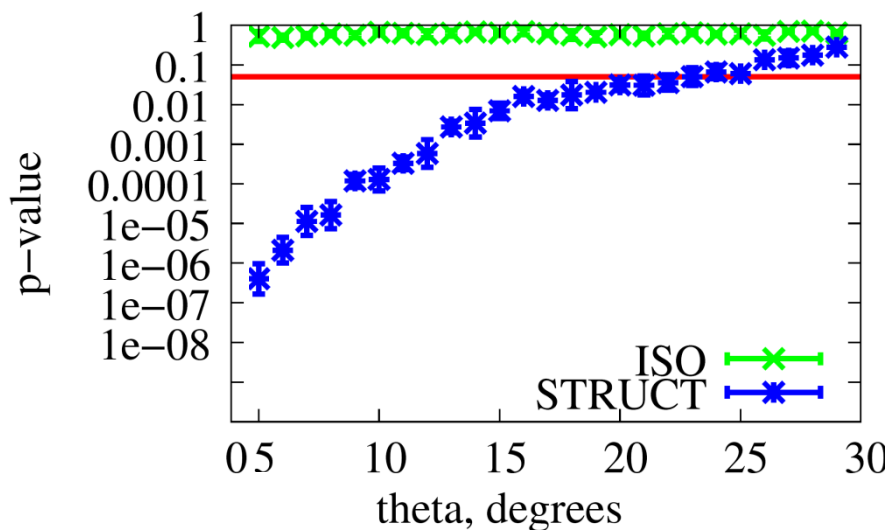
expected flux density from
proton ($E > 57$ EeV) LSS 2MASS
Galaxy Redshift catalog (XSCz)
Smearing angle = 6°

Darker color represents larger flux.

UM — Ursa Major; Co — Coma; V — Virgo; PP — Perseus-Pisces
(20 Mpc) (90 Mpc) (20 Mpc) (70 Mpc)

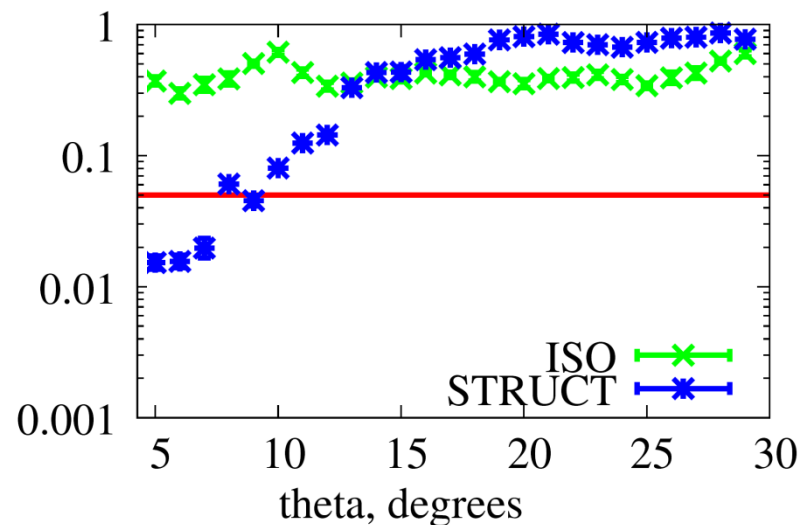
Global anisotropy

$E > 10$ EeV

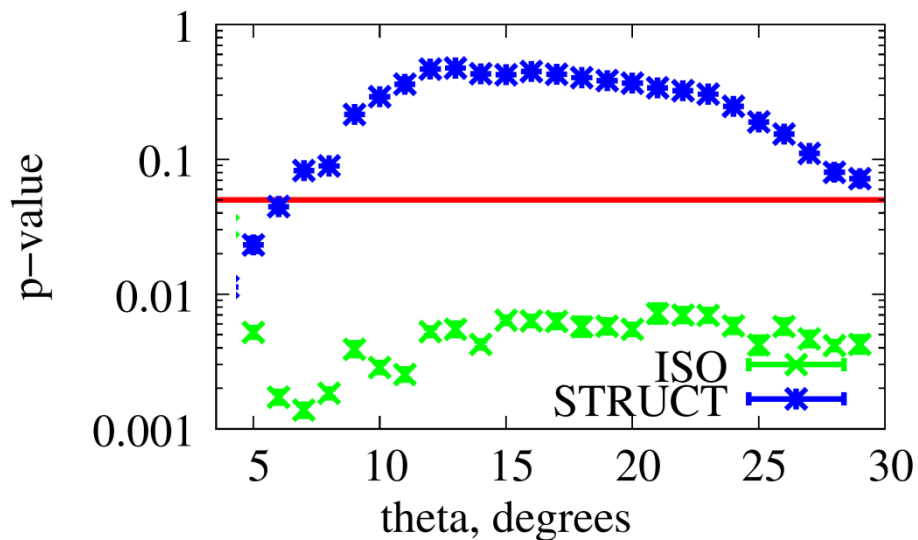


Large-scale structure

$E > 40$ EeV



$E > 57$ EeV



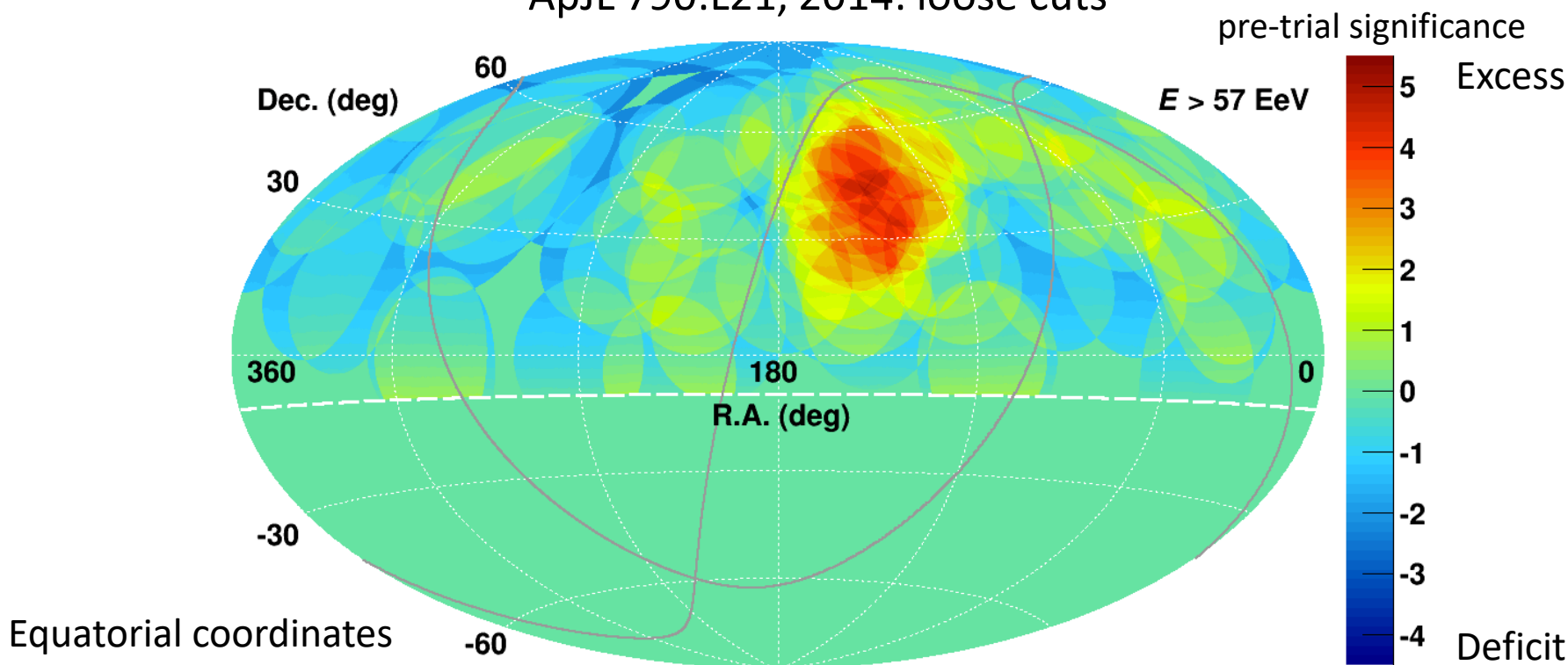
**For $E > 57$ EeV,
consistent with LSS
inconsistent with isotropy**

(theta = smearing angle)

TA Hotspot (5 years data)

72 events with $E > 57 \text{ EeV}$

ApJL 790:L21, 2014: loose cuts



Oversampling circle radius: 20°

Maximum pre-trial significance : $\sim 5\sigma$

at RA= 146.7° , Dec= $+43.2^\circ$

Post-trial significance: 3.4σ

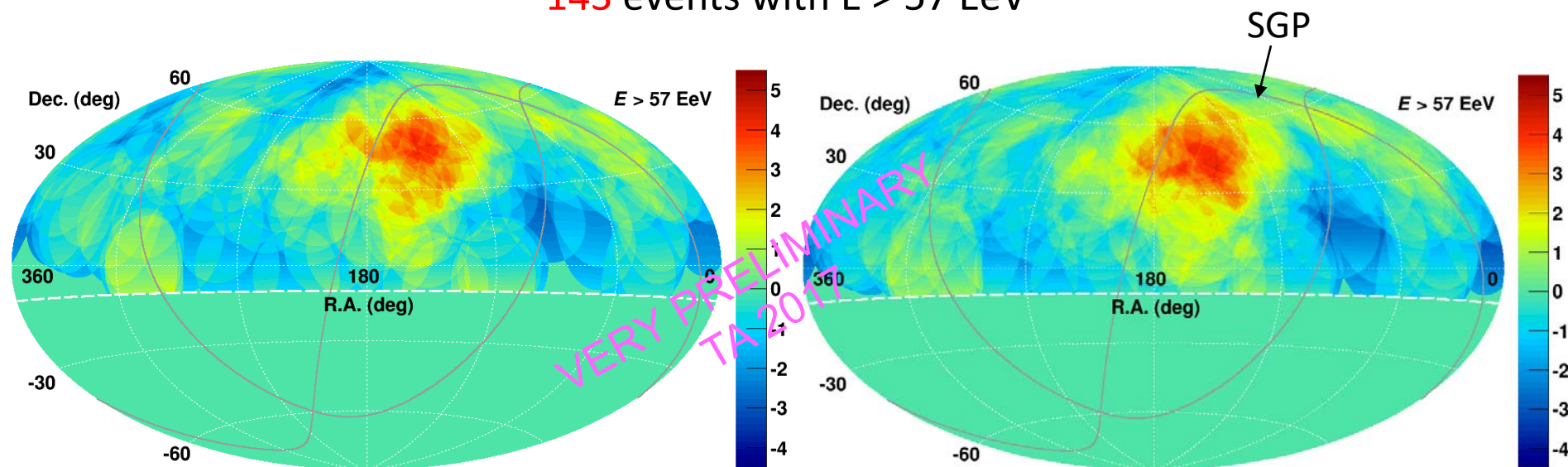
Observed: 19

Expected : 4.5

(26% of events in 6% of area)

Hotspot with 9 years data

143 events with $E > 57$ EeV



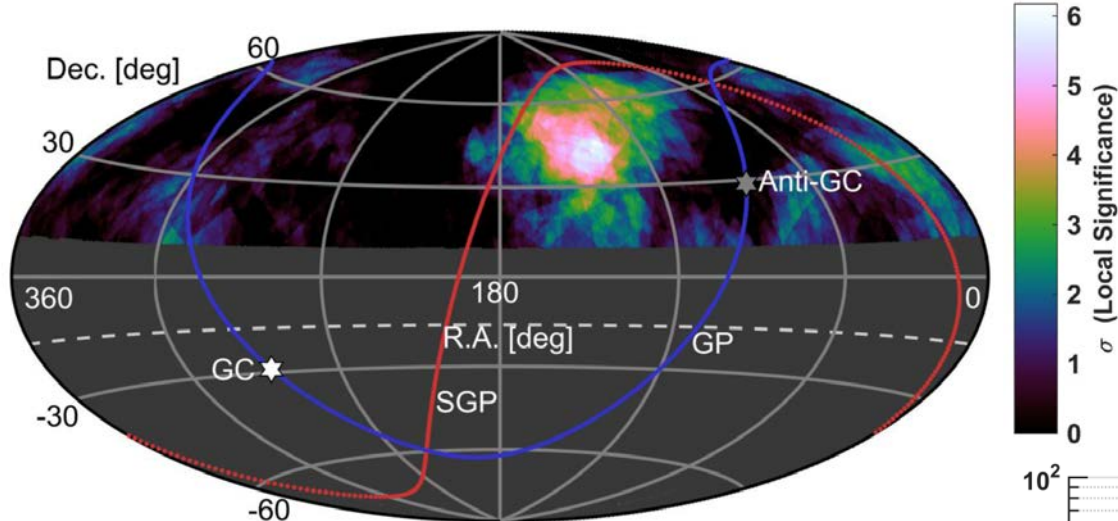
With original 20° oversampling, spot looks larger.... Thus, scan over 15° , 20° , 25° , 30° , & 35°

With 25° oversampling,
Maximum pre-trial significance: $\sim 5\sigma$
at RA= 144.3° , Dec= $+40.3^\circ$

(Observed: 34
Expected : 13.5)

Post-trial significance : 3σ

Spectral anisotropy



Maximum pre-trial signif. at (R.A., Decl.) = (139°, 45°)
for average spherical cap size $\langle r \rangle$ of radius 30°

“cold spot” at lower energies,
same place as the hot spot at high

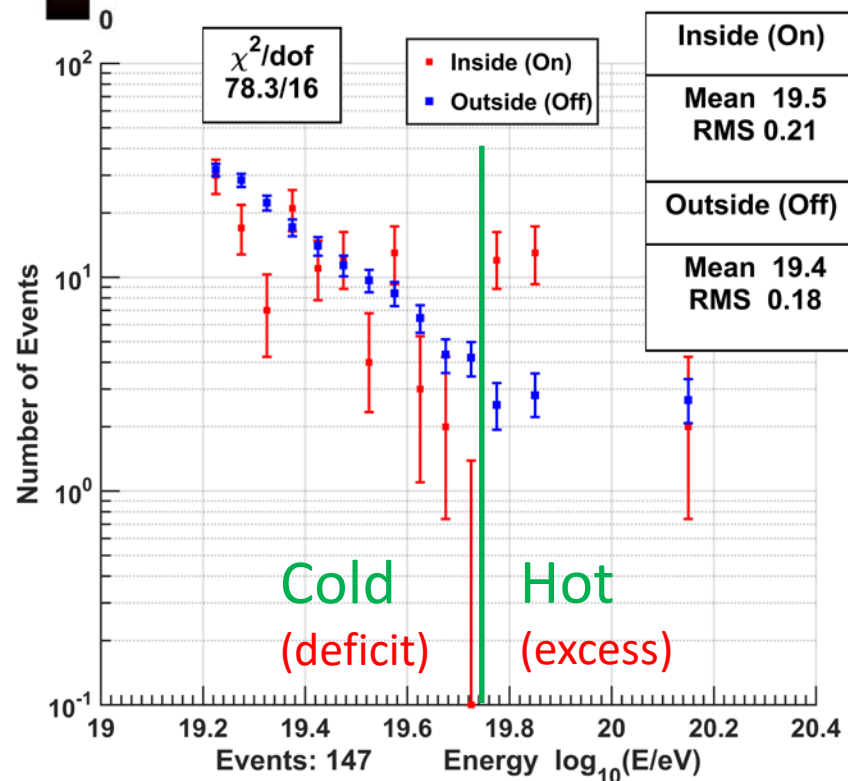
Post-trial significance: 3.7σ

Scanned for $\log_{10} E > 19.0, 19.1, 19.2, 19.3$
radius $\langle r \rangle = 15^\circ, 20^\circ, 25^\circ, 30^\circ$

7 years of TA SD data

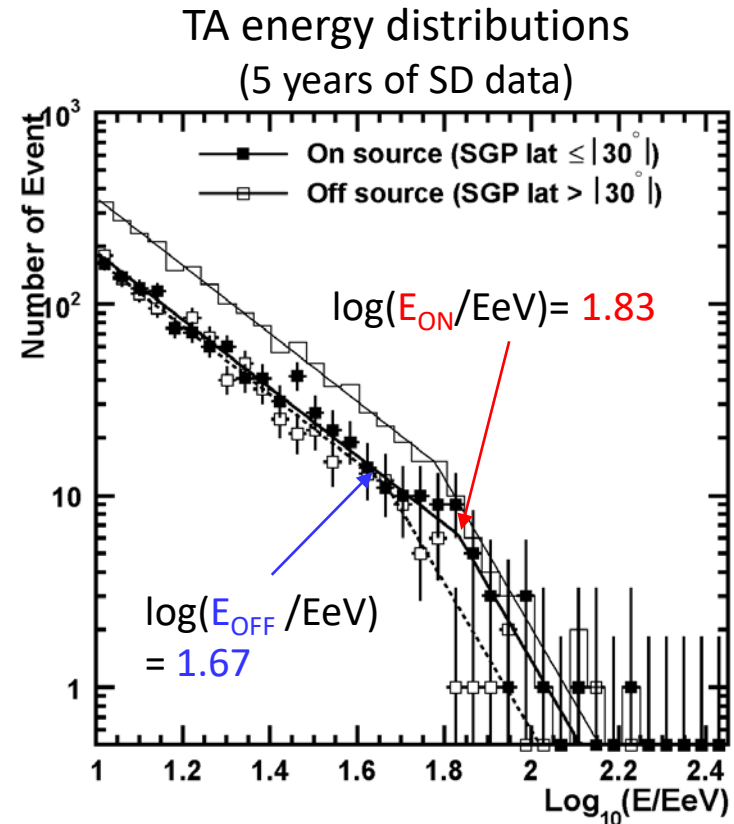
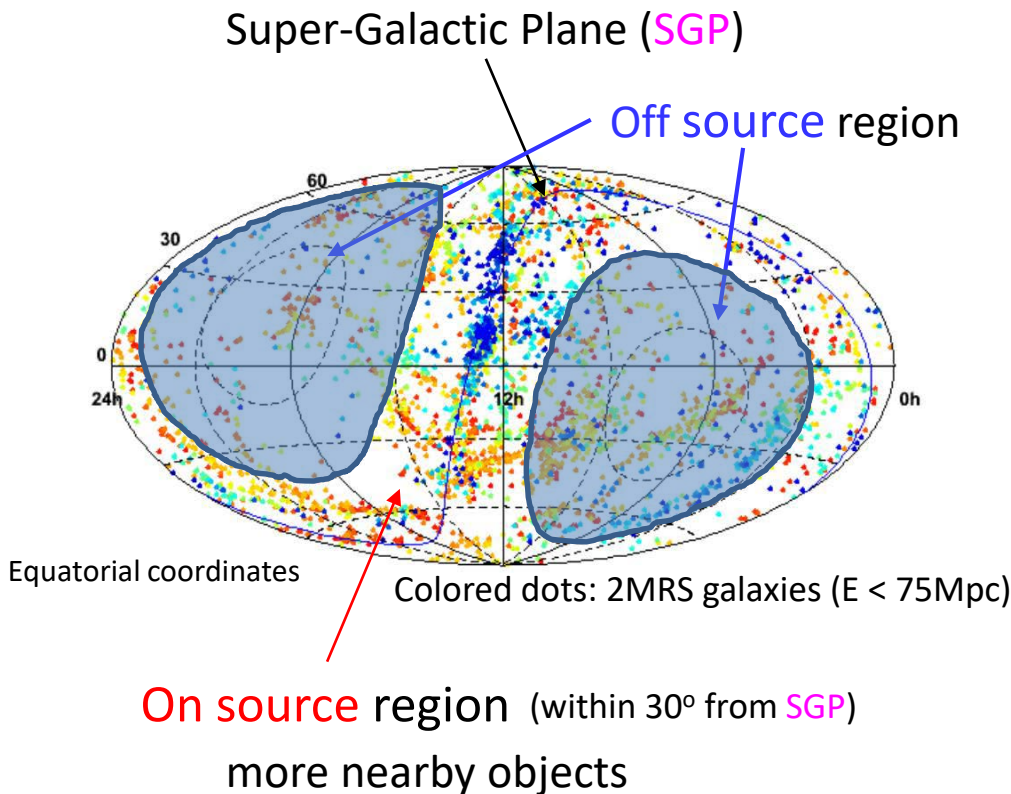
$E > 10^{19.2} \text{ eV}$

red points: events inside the circle
blue points: expectation defined
outside the circle



Spectral Anisotropy

(from the point of regions with more/less nearby objects)



E_{ON} and E_{OFF} : 3.2σ difference

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TAx4

• TA

- Surface Det. (● ← —)
 - 507 SDs (1.2 km spacing), ~700 km²
- Fluorescence Det. (● ← —): 3 stations

• TAx4 extension

- Surface Det. (● ← — —)
 - Additional 500 SDs (2.08 km spacing)
 - **Quadruple** TA SD (~3,000 km² incl. TA SD)
 - Funded by JSPS from JFY2015 for five years
- Fluorescence Det. (● ← — —)
 - additional 2 FD stations (12 HiRes Telescopes)
 - Approved by NSF in 2016
 - Northern site construction underway

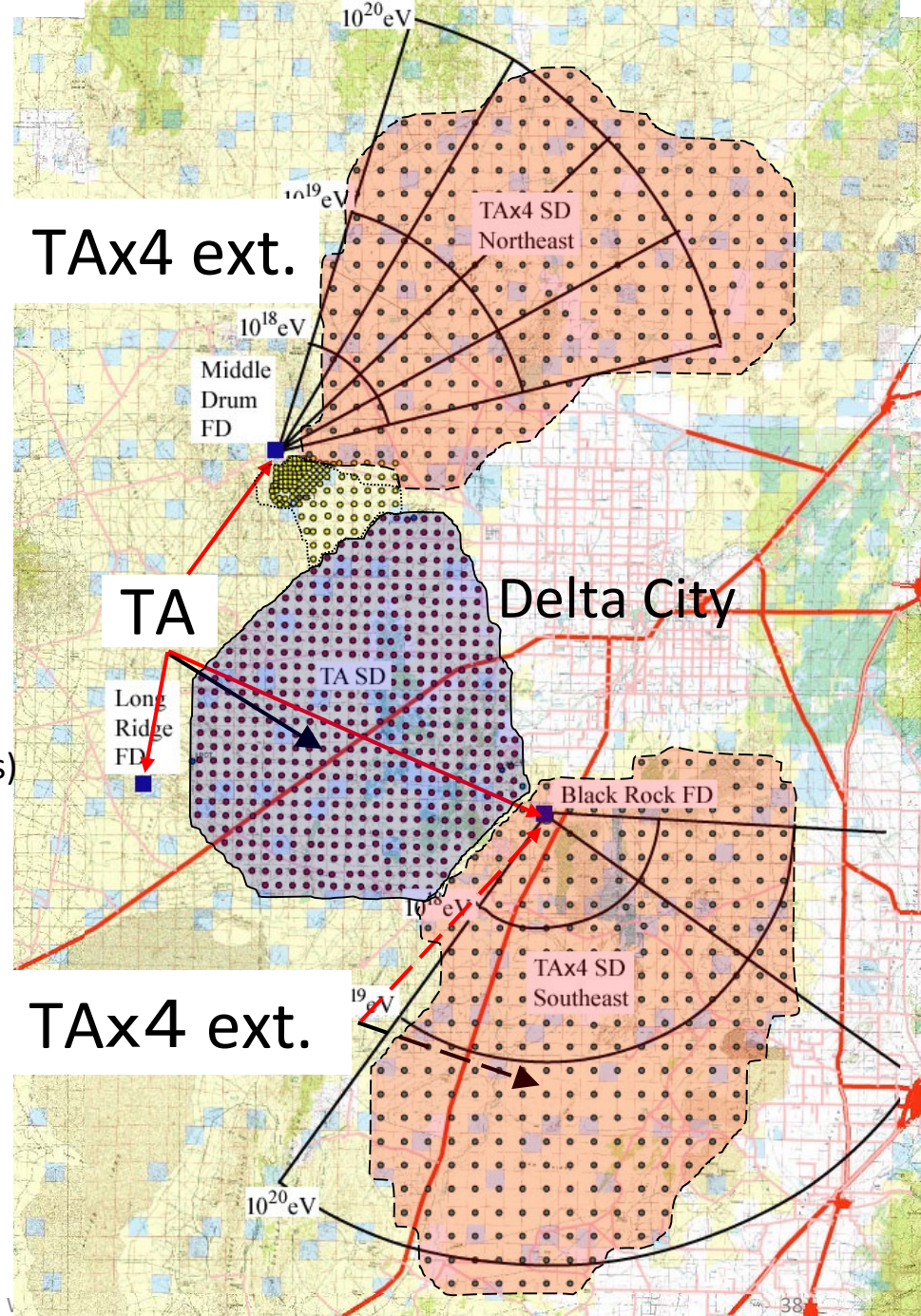
• Construction from JFY2015

- Add detectors in about three years
- TA 19 year data by 2020
 - ~300 highest-energy cosmic rays



- Detailed observation of the hotspot
- TA 16.3 years of hybrid data

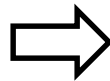
(JFY: Japanese Fiscal Year)



TAx4 SD

Japan

①



Utah, USA

②



③



④



① Scintillator counter assembly (Japan)

Utah, USA

② Final assembly (workshop)

③ Assembled SDs (workshop)

④ Staking (for SD positioning and follow-up surveys)

- 2/3 of TAx4 site finished by ATVs
- 1/3 will be finished this fall (2017) by helicopter

Plan

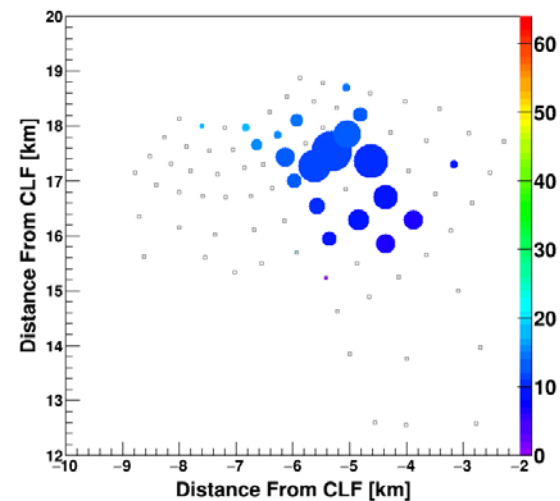
- Permission from Bureau of Land Management
- TAx4 SD deployment

TALE SD Array

Full TALE SD Array (103) deployed Feb 2017 – now commissioning

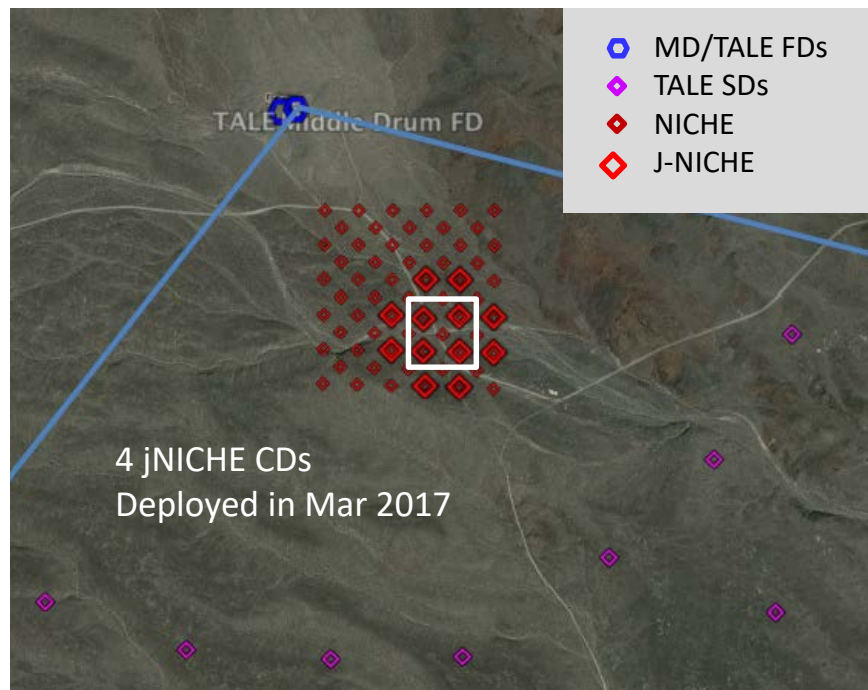


2017 March 13 10:23:06



NICHE

Non-Imaging **C**HERENKOV array



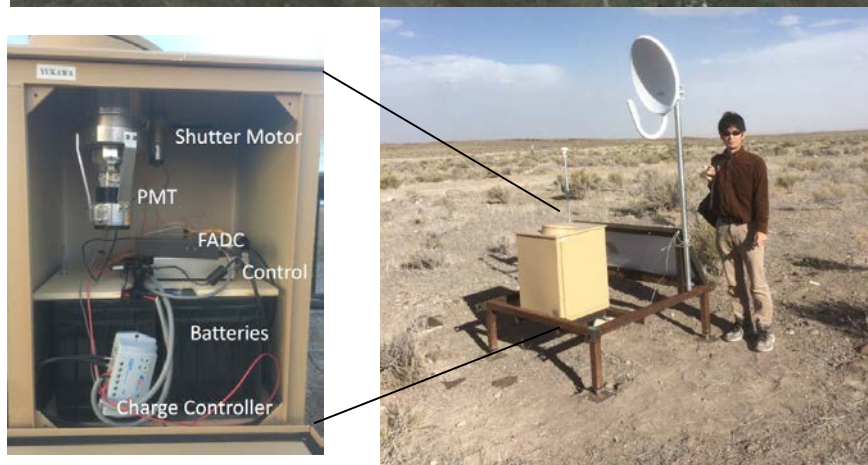
Use non-imaging light collection to extend the range of TA/TALE to below 10^{15} eV

- Hybrid with TALE Telescope (left figure)
 - 0.25 km^2 , 70-m spacing ($E > 10^{15.5} \text{ eV}$)
- Stand-alone array overlapping with TALE SD
 - 1.5 km^2 , 200-m spacing ($E > 10^{17} \text{ eV}$)
 - 100-m spacing (E down below 10^{15} eV)

Array of 15 Cerenkov detectors (jNICHE) are being added

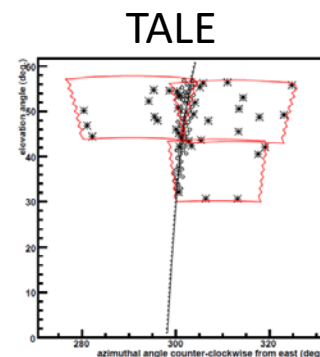
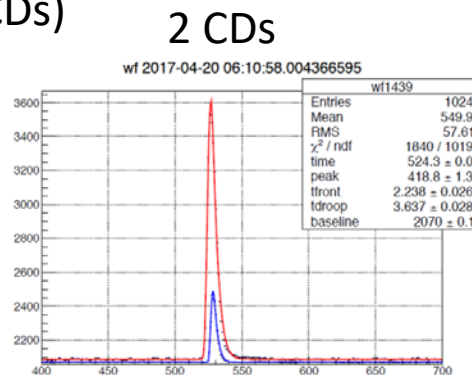
jNICHE: funded by JSPS (JFY2014-2017)

March 2017: Deployed 4 Cherenkov Detectors (CDs)



17 August 2017

H. Sagawa



Triple coincidence

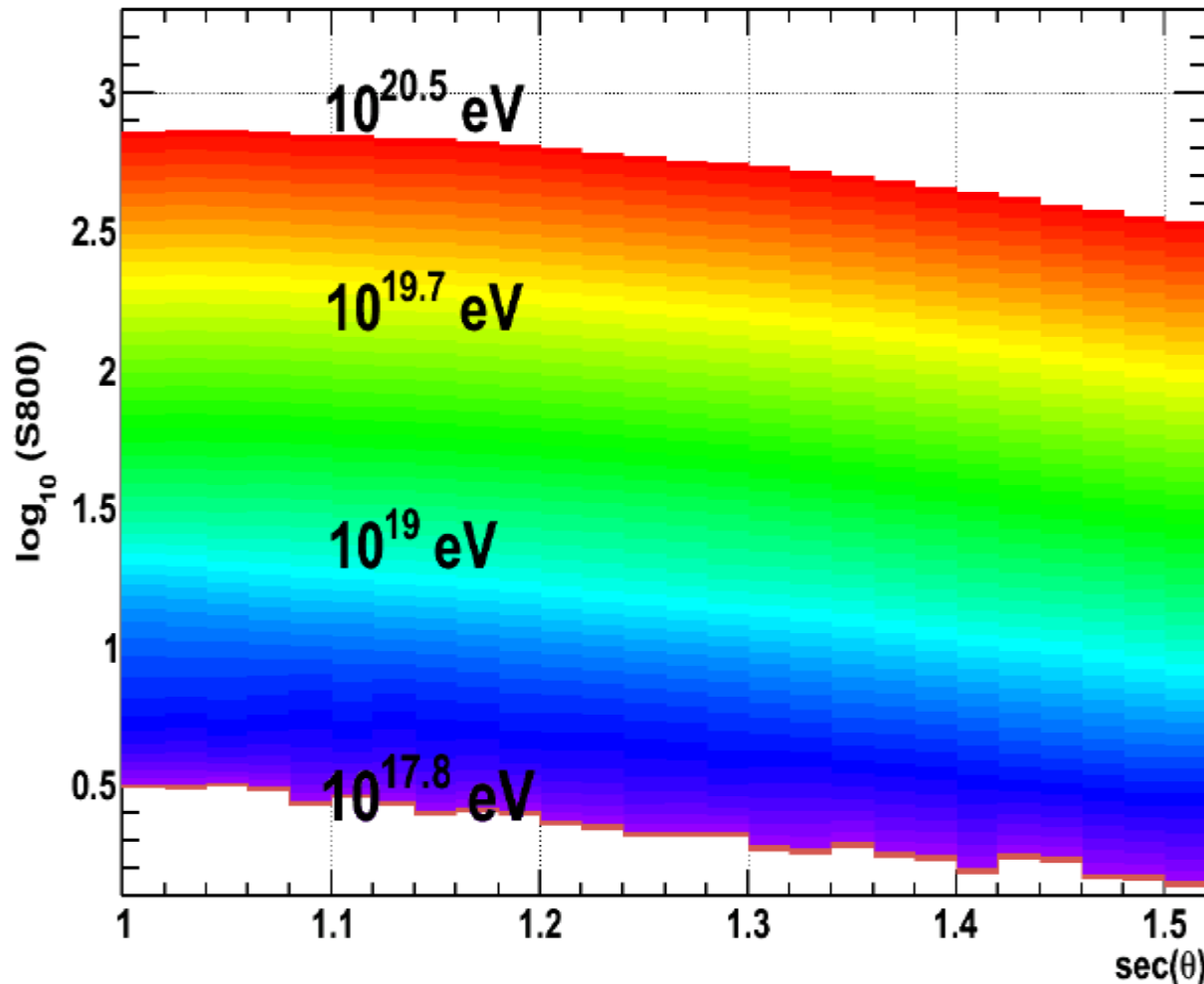
KIAA-WAP II, Beijing, China

Conclusions

- TA SD/FD and TALE FD **energy spectrum** shows spectral features ($10^{15.4} \text{ eV} < E < \text{over } 10^{20} \text{ eV}$)
 - ankle ($10^{18.69} \text{ eV}$), cutoff ($10^{19.81} \text{ eV}$)
 - 2nd ankle, 2nd knee in lower energy region
- **TA Xmax**: compatible with **light composition** ($E > \sim 10^{18.2} \text{ eV}$)
- **TA hotspot** (3σ) now appears **larger** than we originally thought
- **TAx4** is coming soon; construction underway
- **Full TALE SD** was recently deployed and is coming on line.

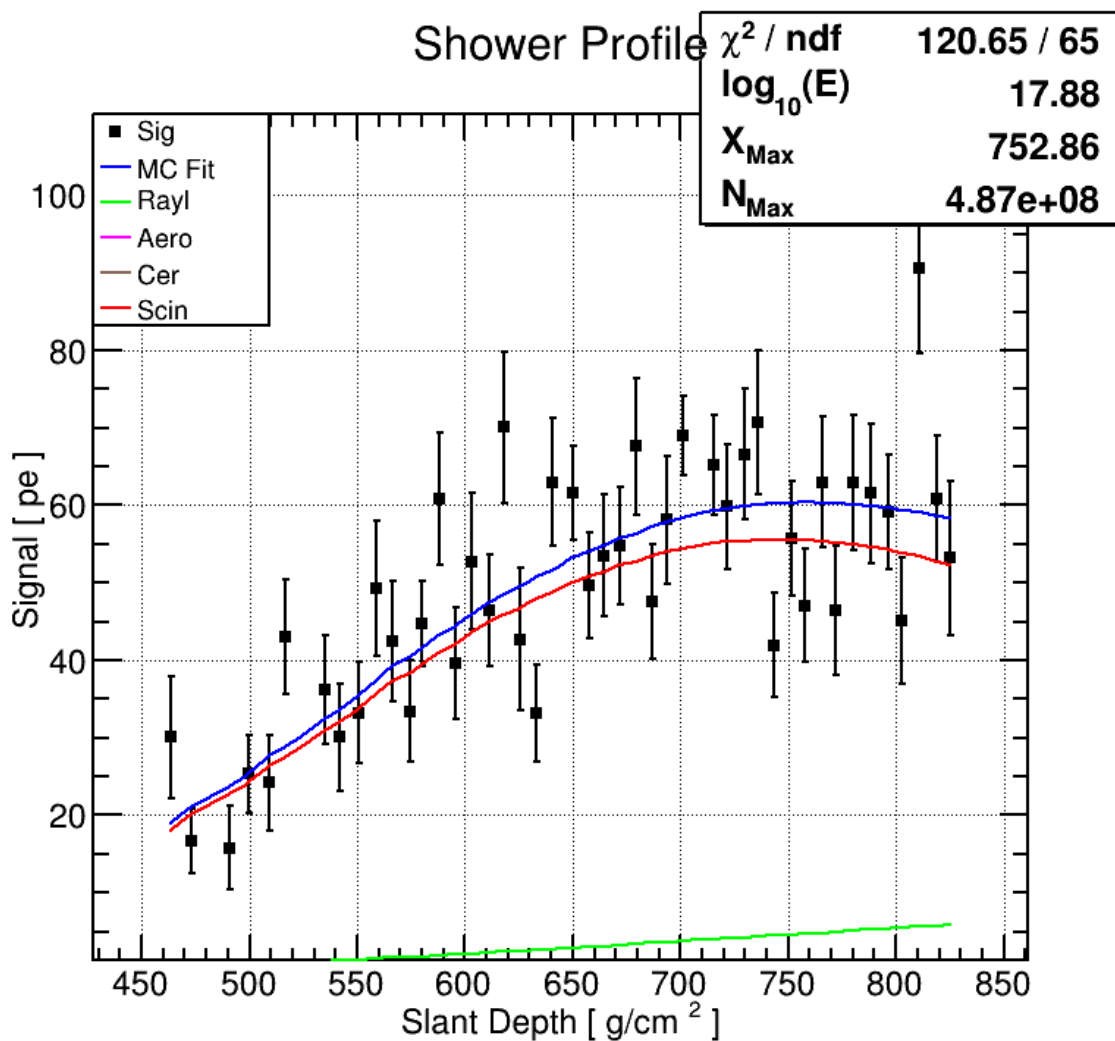
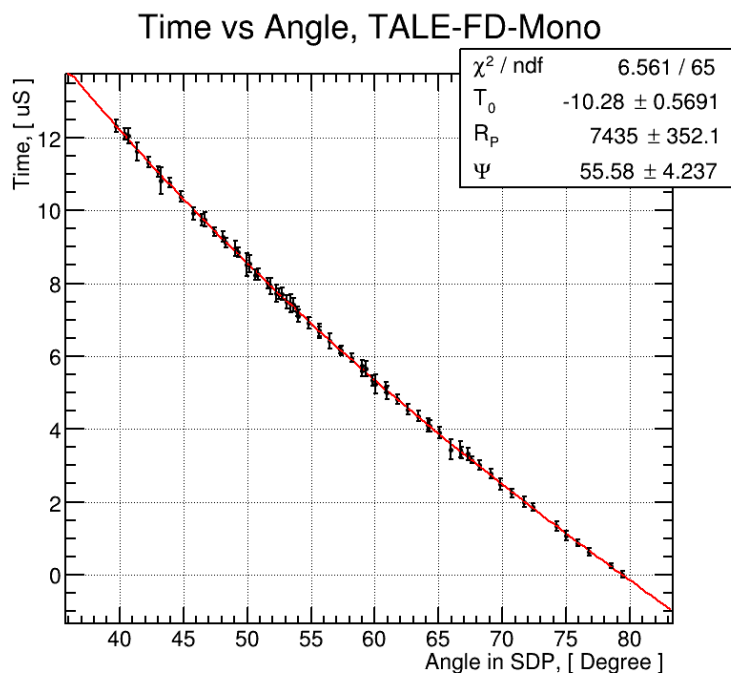
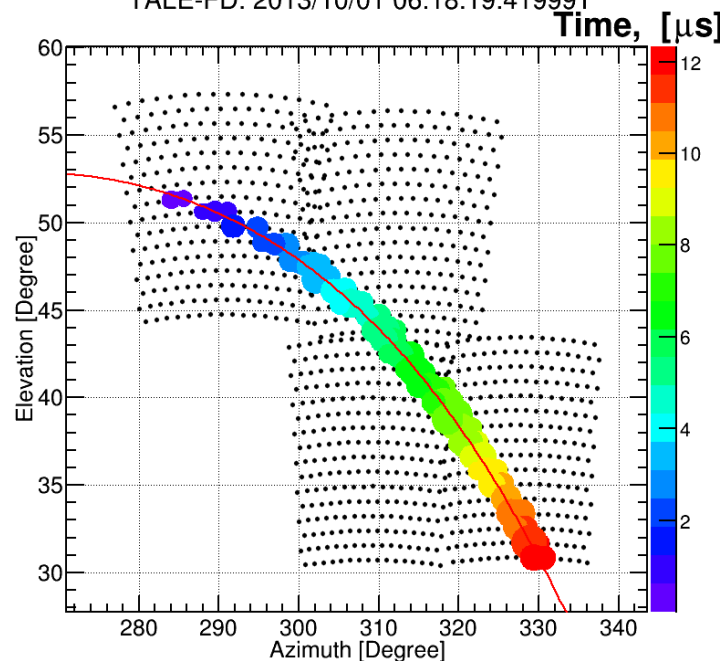
backup

Surface Array Energy Measurement

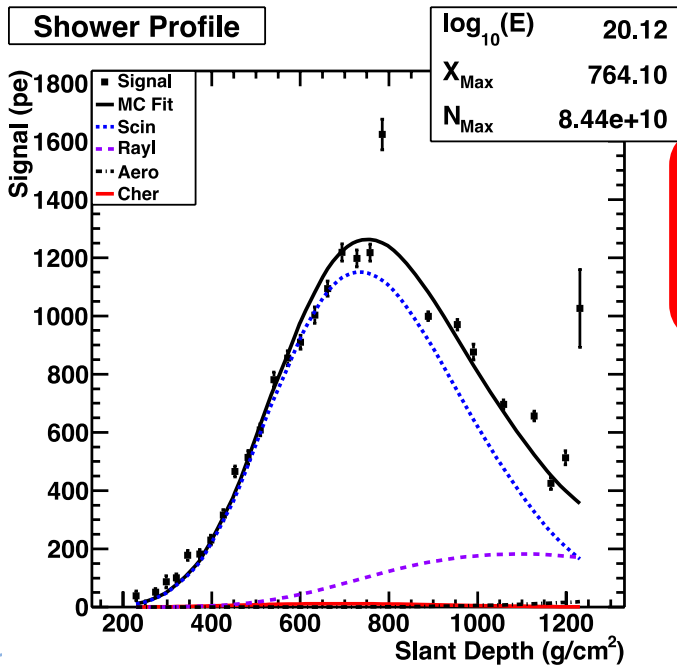
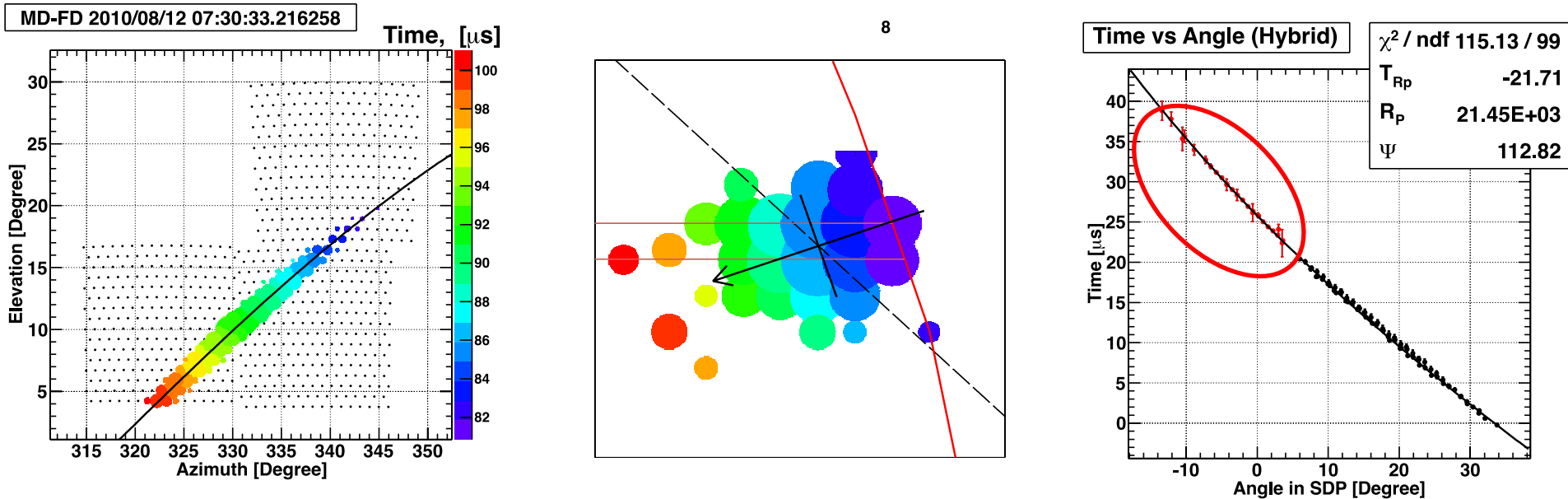


- Energy table is constructed using the MC (CORSIKA)
- Determination of event energy by interpolating between S800 vs. $\sec(\theta)$ lines
- Uses novel “de-thinning” of CORSIKA (paper draft in internal review)

TALE Fluorescence-dominant Event



High Energy Hybrid Event

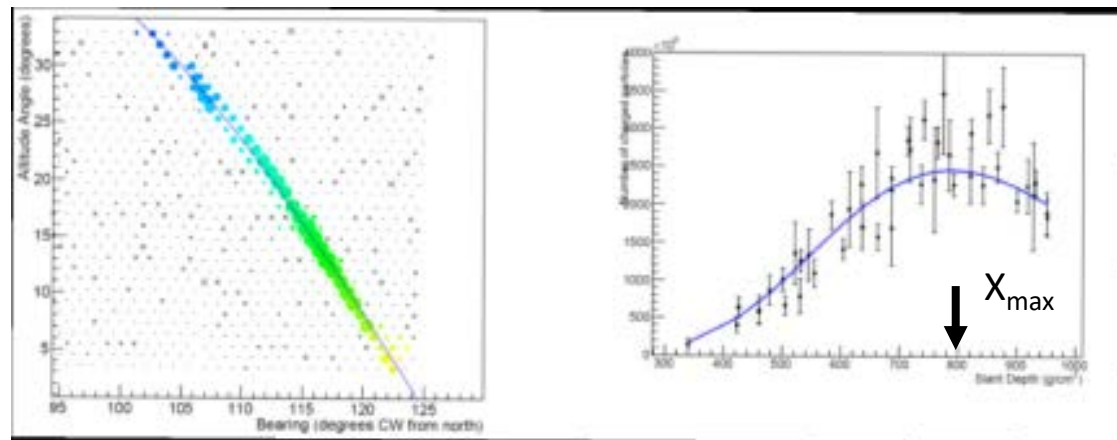
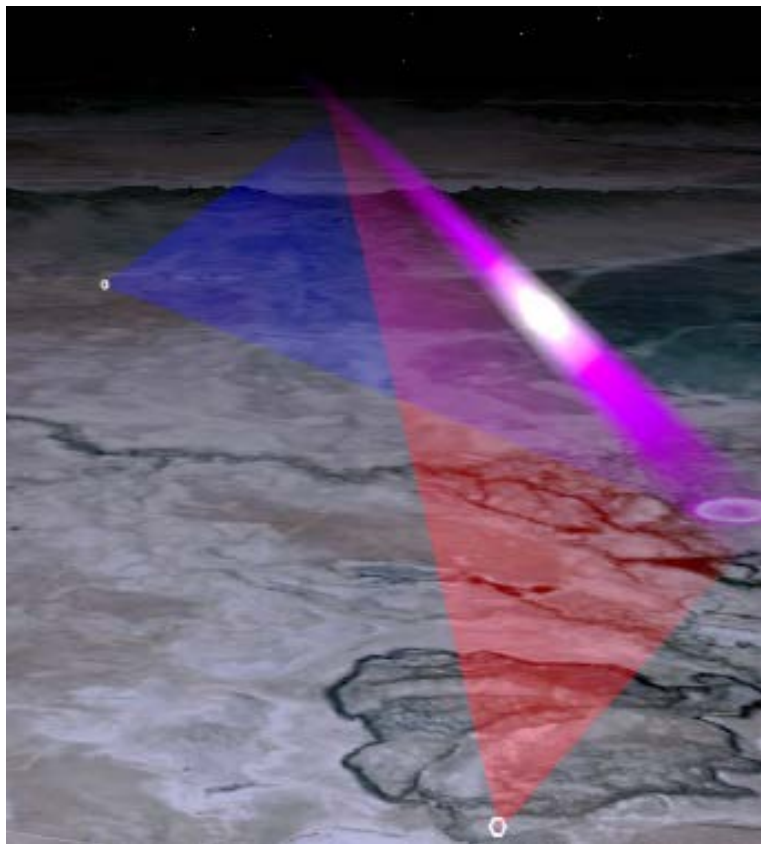


Energy: 1.3×10^{20} eV

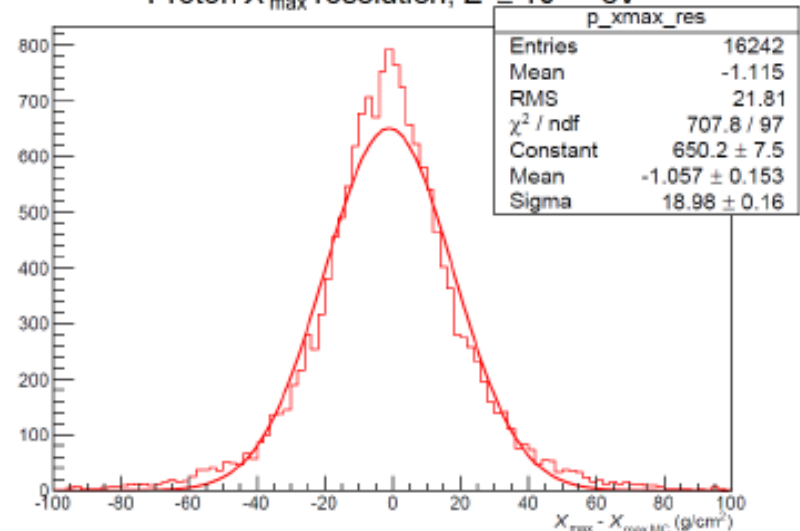
Zenith Angle: 55.7°

Surface array constrains
geometry fit via extra timing
& core information

Stereo Observation



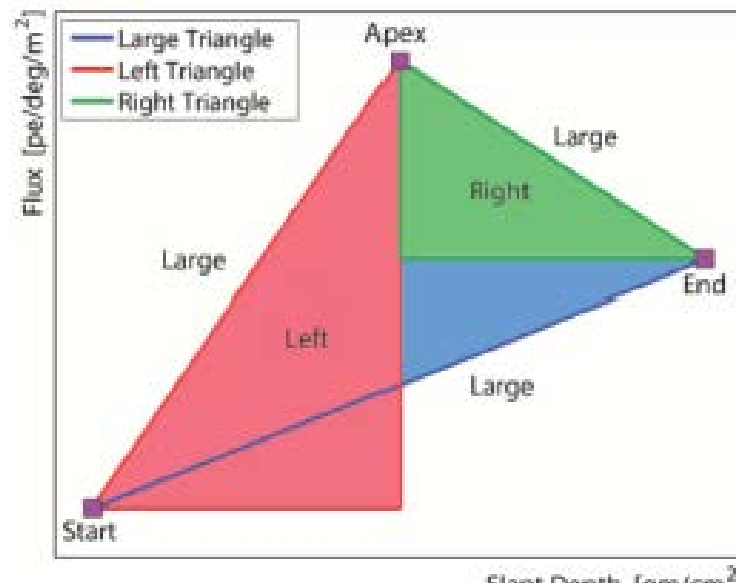
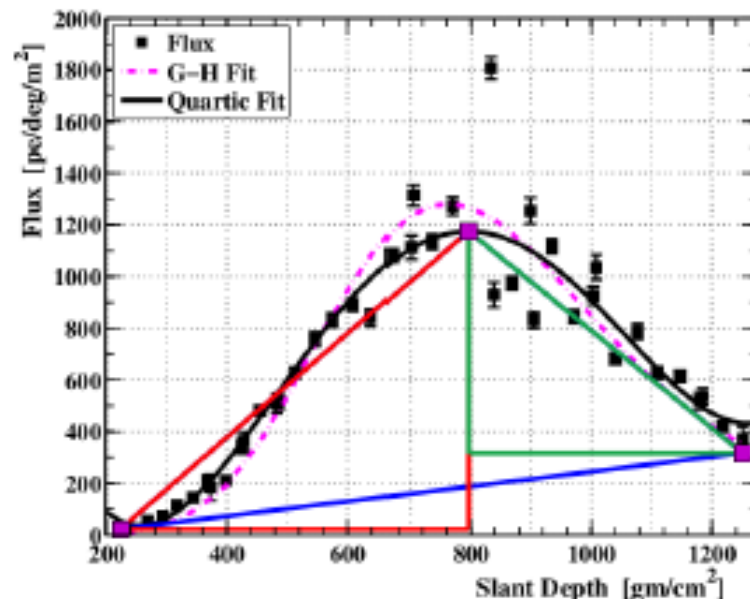
Proton $X_{\max}$ resolution, $E \geq 10^{18.4}$ eV



Intersect shower planes to get more precise geometry

Hybrid Observation

- Astropart. Phys. 64 49 (2014).
4 yrs, 297 Events $> 10^{18.4}$ eV
- Cuts based on pattern recognition technique to improve resolutions $s \leq 25$ g/cm², all energies.
- Update:
7 yr, 613 Events $> 10^{18.4}$ eV



Mean Xmax Comparison

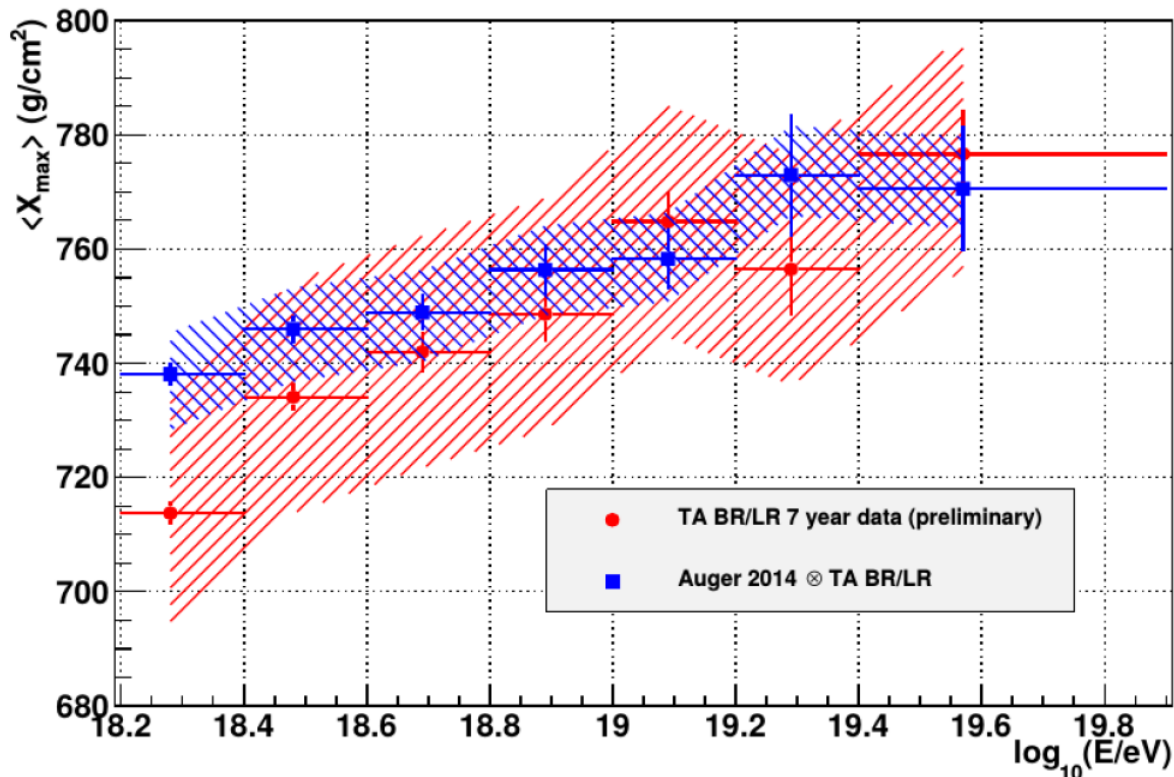
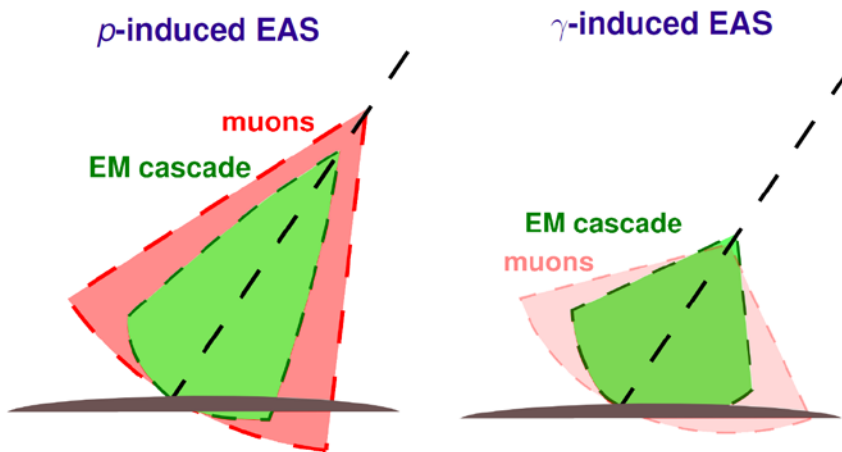


Fig. 5. Preliminary $\langle X_{\max} \rangle$ derived from TA seven-year BR/LR hybrid data compared to the $\langle X_{\max} \rangle$ of the reconstructed Auger composition mix using QGSJetII-04. Systematic uncertainties on the data and mix are also shown. Within systematic uncertainties the TA data agrees with the mix, which is derived from a fit to Auger data.

WG - UHECR 2016

Search for UHE photons

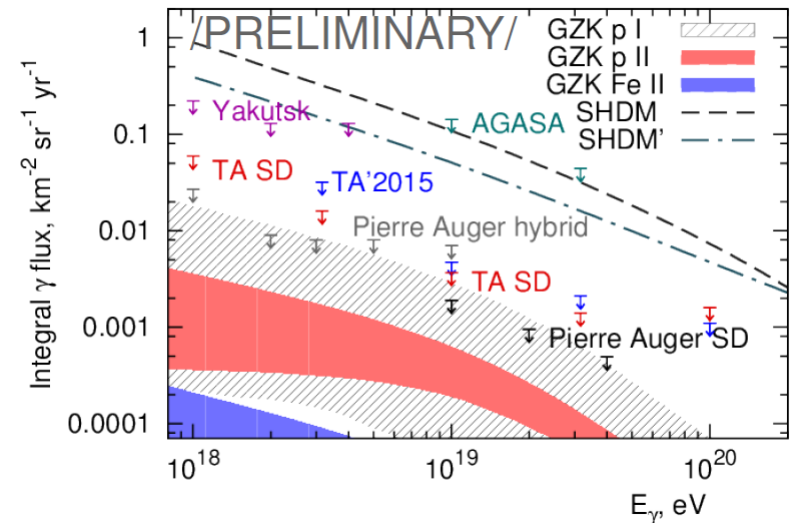
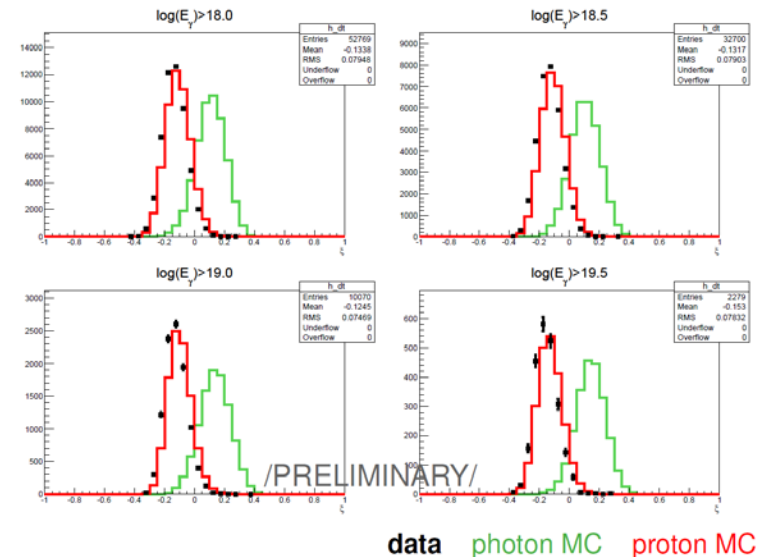


Photon-induced showers:

- ▶ arrive younger
- ▶ contain less muons
- ▶ $\Rightarrow$ multiple SD observables affected:
 - ▶ front curvature, Area-over-peak, number of FADC signal peaks, $\chi^2/d.o.f.$, S_b

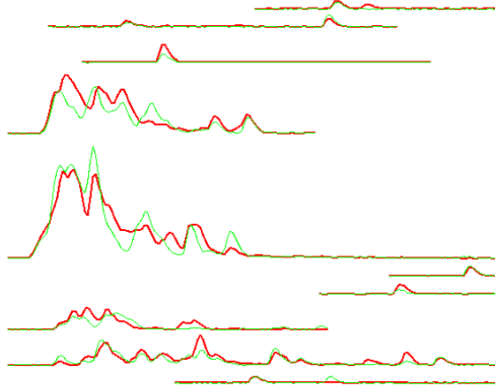
Multi-Variable Analysis (MVA)

MVA estimator (ξ)

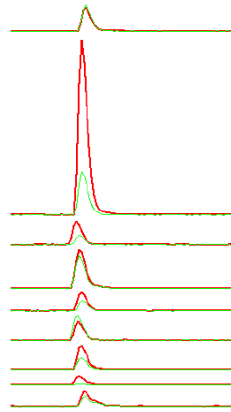


Search for UHE neutrinos

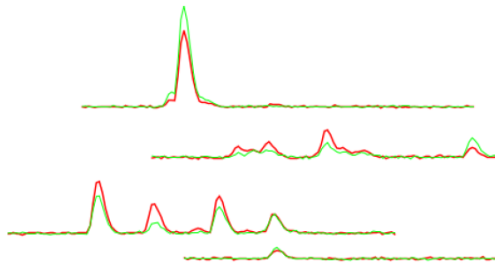
young shower, $\theta = 19.5^\circ$



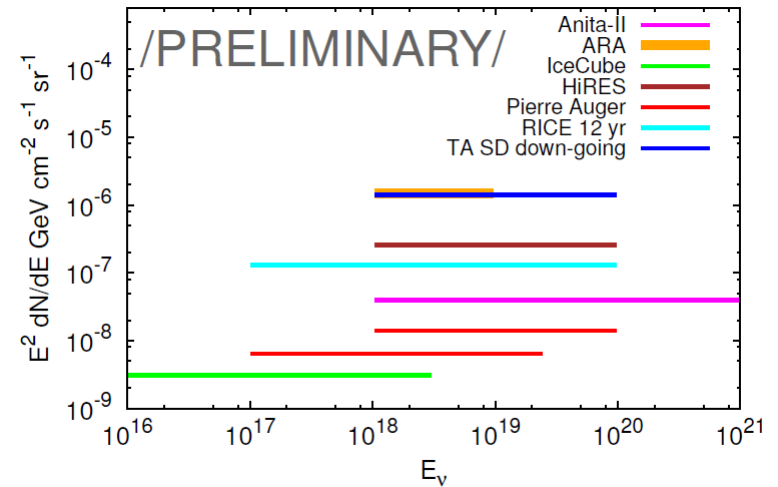
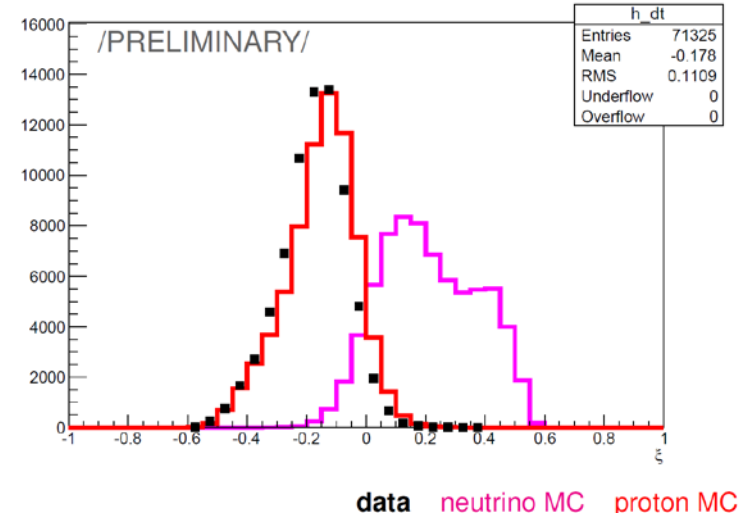
old shower, 78.3°



neutrino shower, $\theta = 78.6^\circ$

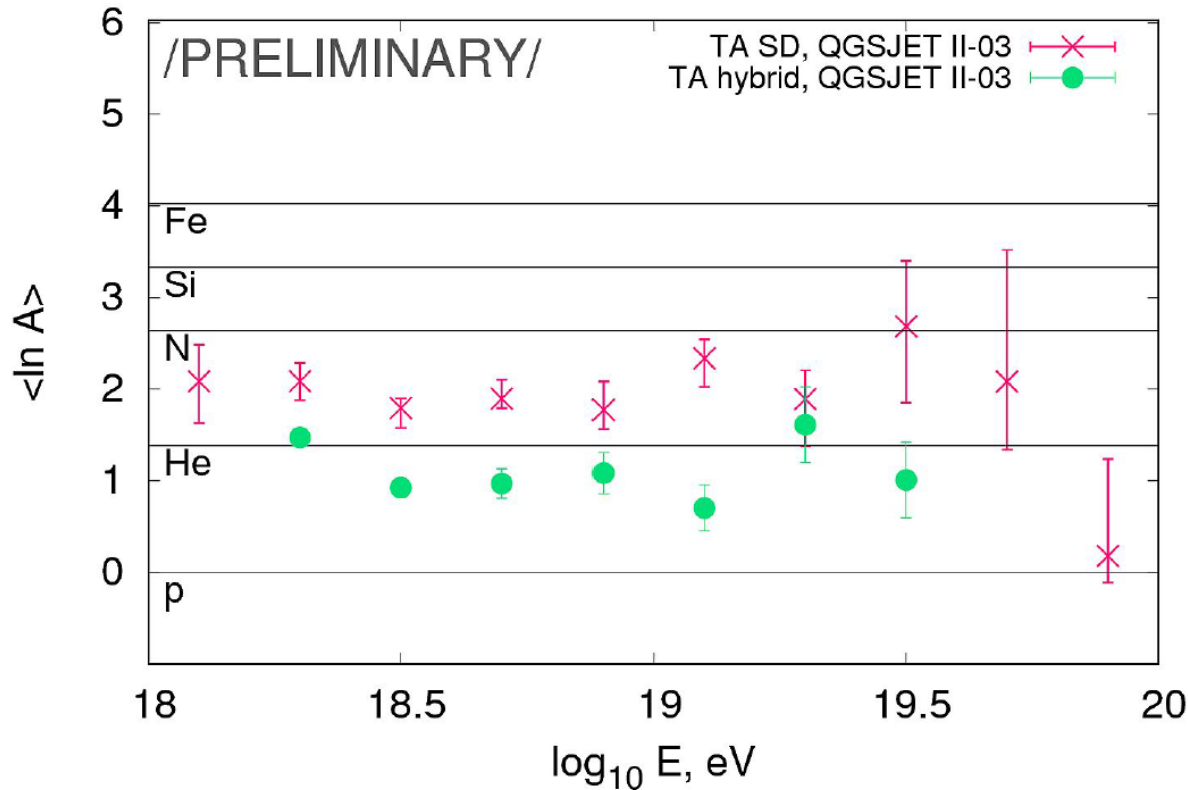


MVA estimator (ξ)



TA SD composition (MVA)

(with TA hybrid composition (Xmax))



CRI070 - TA SD Composition Results, Y. Zhezher

TA SD only measurement of composition.

Nearly 100% ontime.
Much higher statistics.

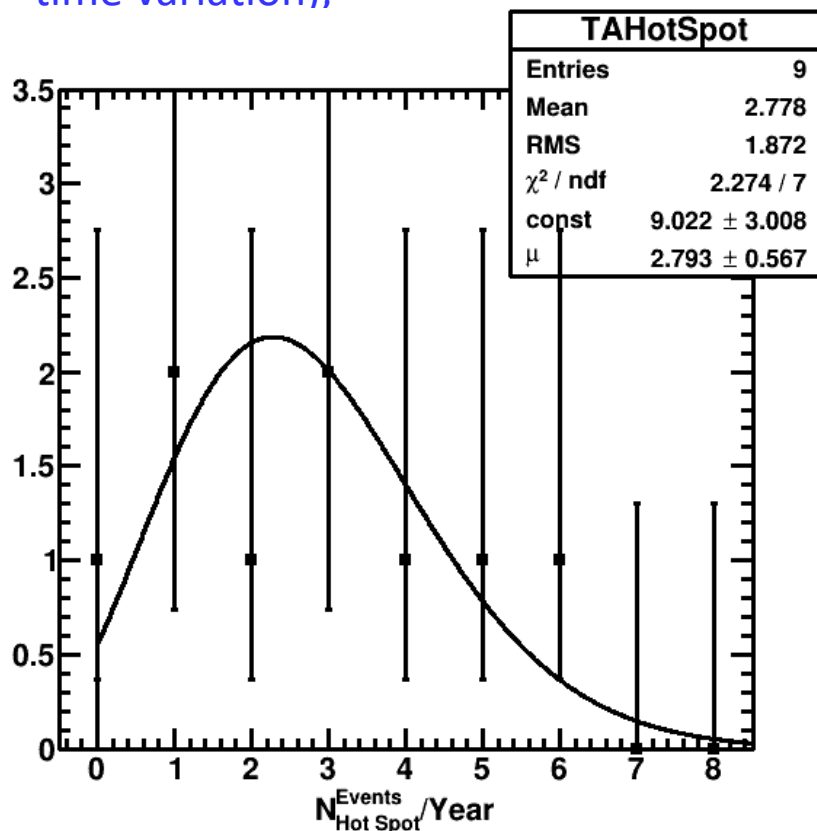
X_{max} not observed.

Boosted decision tree is built using SD 13 observables and trained using model dependent two-component MC (proton and iron).

Observed composition can be inferred by KS test of proton/iron fraction.

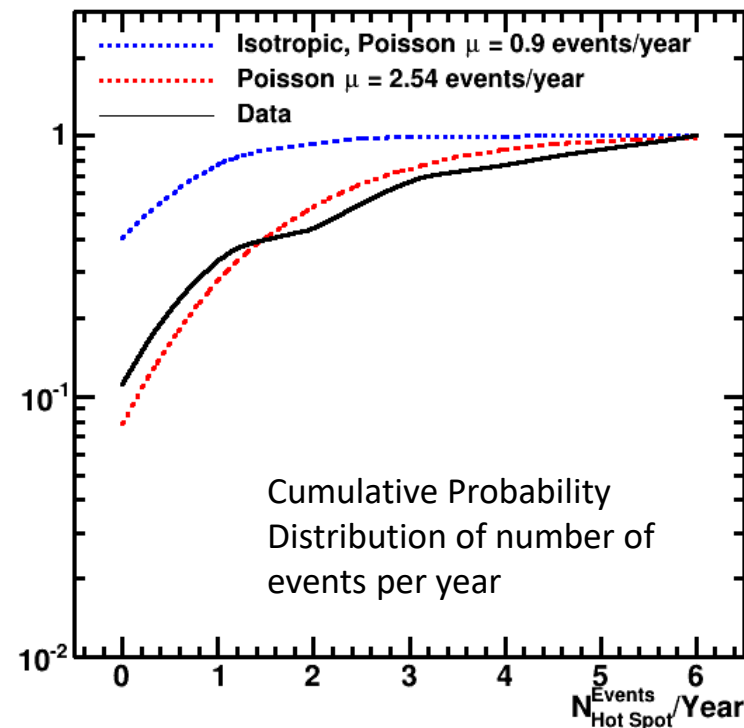
Consistent with Fluctuation

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



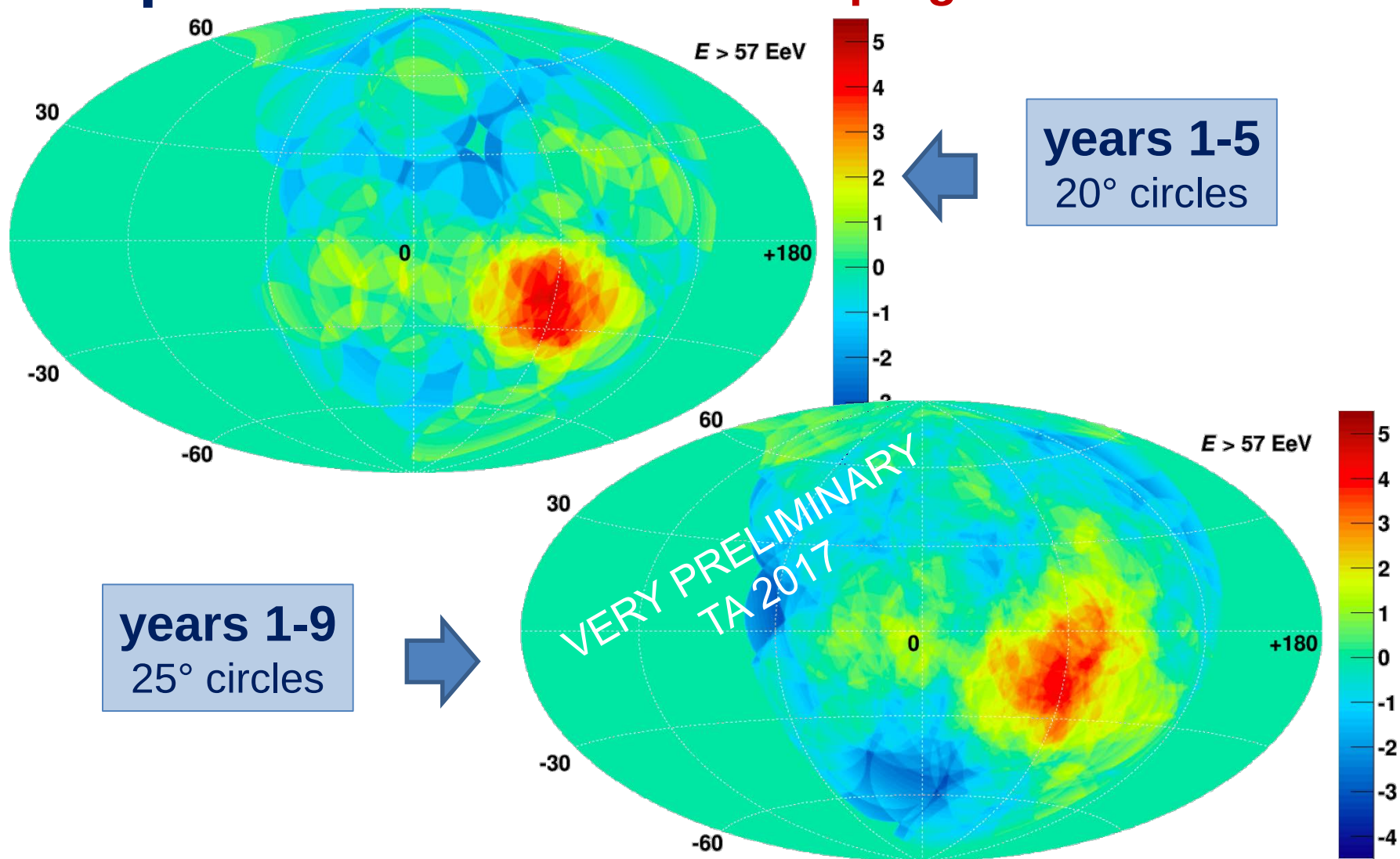
BUT, inconsistent with chance excess from isotropic distribution (Poisson: average = 0.9 per year) at $\sim 2.6\sigma$

9 years of TA Data



Hot spot

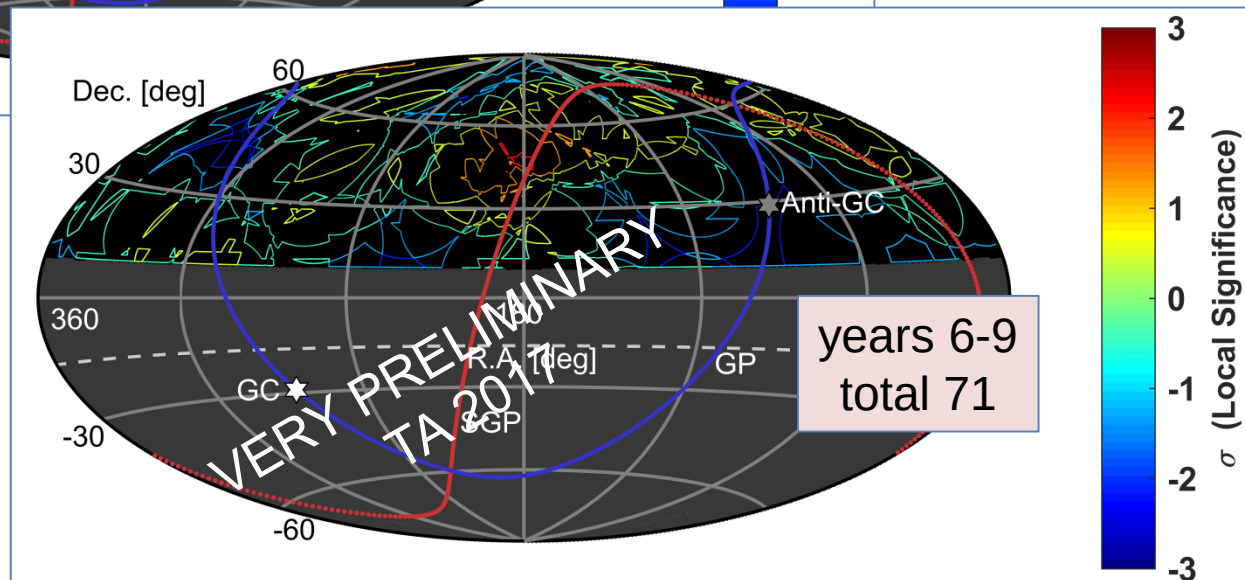
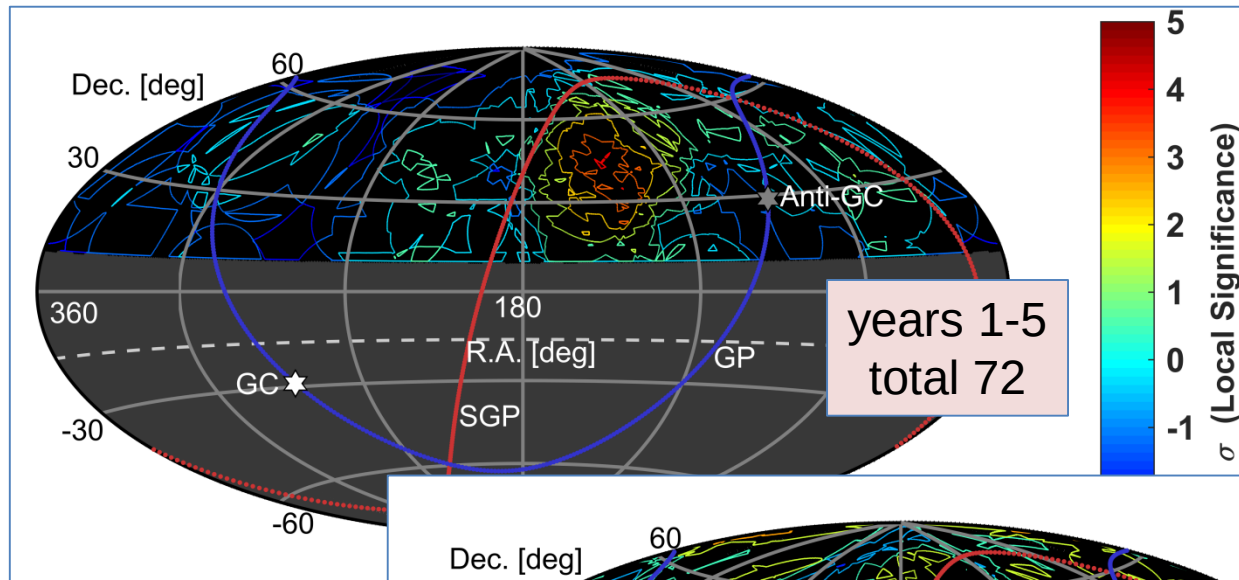
Supergalactic coordinates



Hot spot

Years 6-9 vs. 1-5

no hypothesis – no tests



TA anisotropy summary//ICRC2017

19.07.2017

slide 55 of 17

17 August 2017

H. Sagawa

KIAA-WAP II, Beijing, China



All sky survey with TA and Auger

TA 7 years (>57 EeV)

Auger 10 years (>57 EeV)

(no E scale adjust.)

with Nearby Galaxy Clusters

Ursa Major Cluster

($D=20$ Mpc)

Perseus-Pisces

Supercluster

($D=70$ Mpc)

Virgo Cluster

($D=20$ Mpc)

Eridanus

Cluster

($D=30$ Mpc)

Fornax Cluster

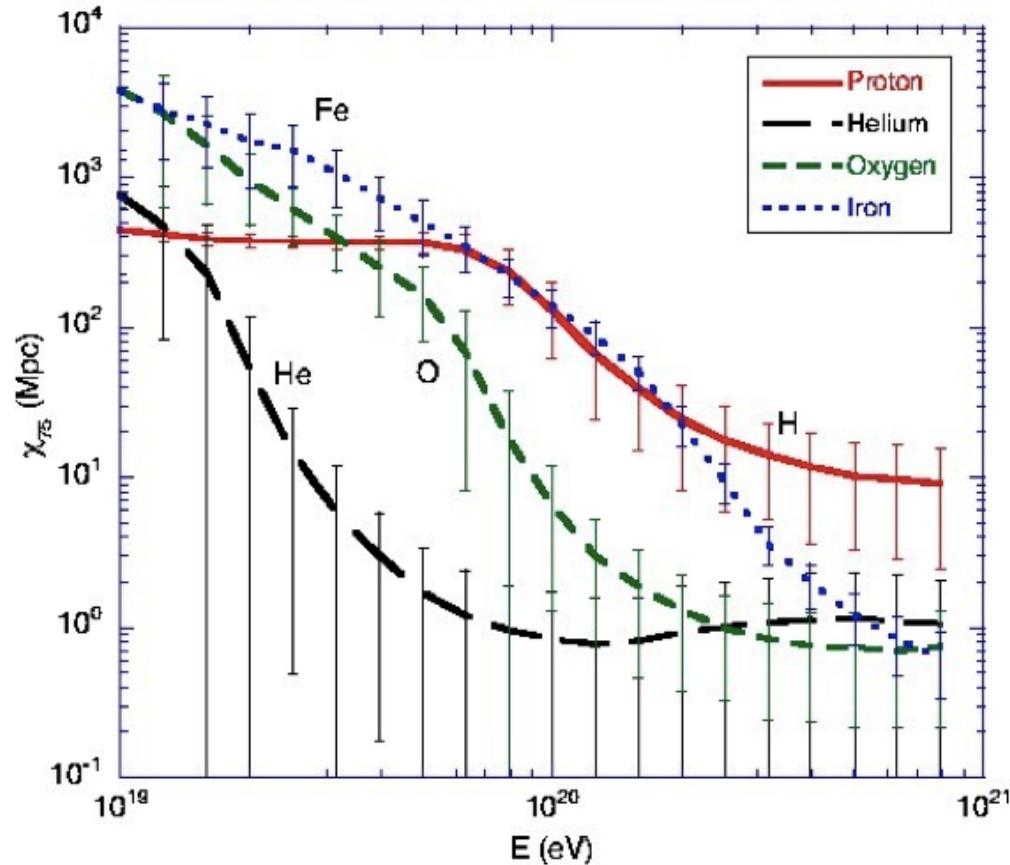
Centaurus

Supercluster ($D=60$ Mpc)

dots ($\bullet$): *Huchra, et al, ApJ, (2012)*
2MASS catalog Heliocentric velocity <3000 km/s ($D < \sim 45$ Mpc)

TA hotspot is found near the Ursa Major Cluster

Astrophysically p and He are very different



Interaction lengths of p, He, O and Fe

Clarify the details of the Hotspot

Simulated TA 19 year-equiv. data

(1) One Hotspot

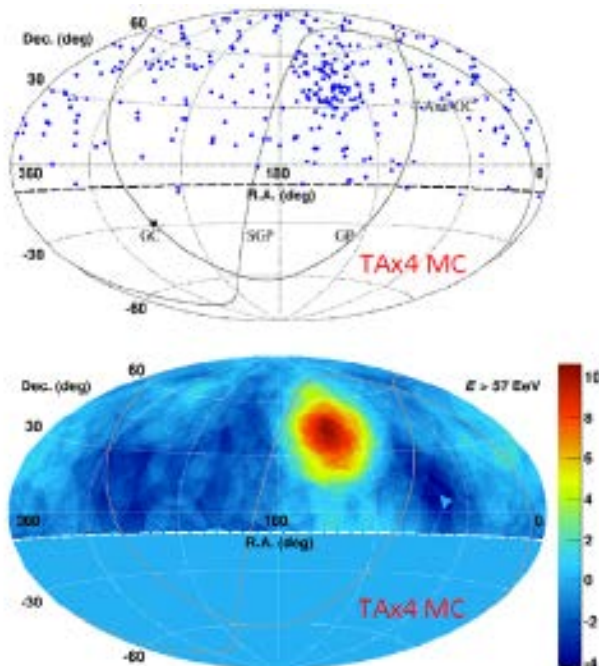
Hotspot Signal

80-18.9=61 events
(RA, Dec)=(145°, 45°)
Gaussian $\sigma=10^\circ$

Isotropic B.G.

305-61=244 events

Oversampling
20° radius circle



Single Source

(2) Double Hotspot

Hotspot Signal

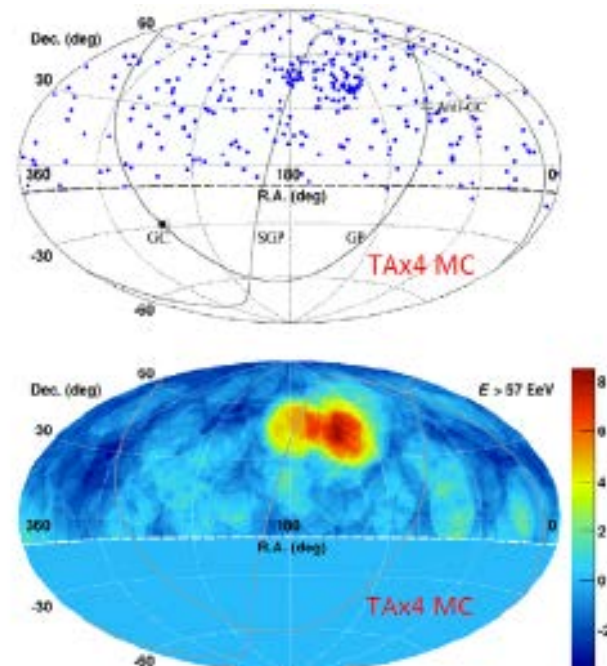
Total 61 events

1. 41 events
(RA, Dec)=(145°, 40°)
Gaussian $\sigma=10^\circ$
2. 20 events
(RA, Dec)=(175°, 40°)
Gaussian $\sigma=5^\circ$

Isotropic B.G.

305-61=244 events

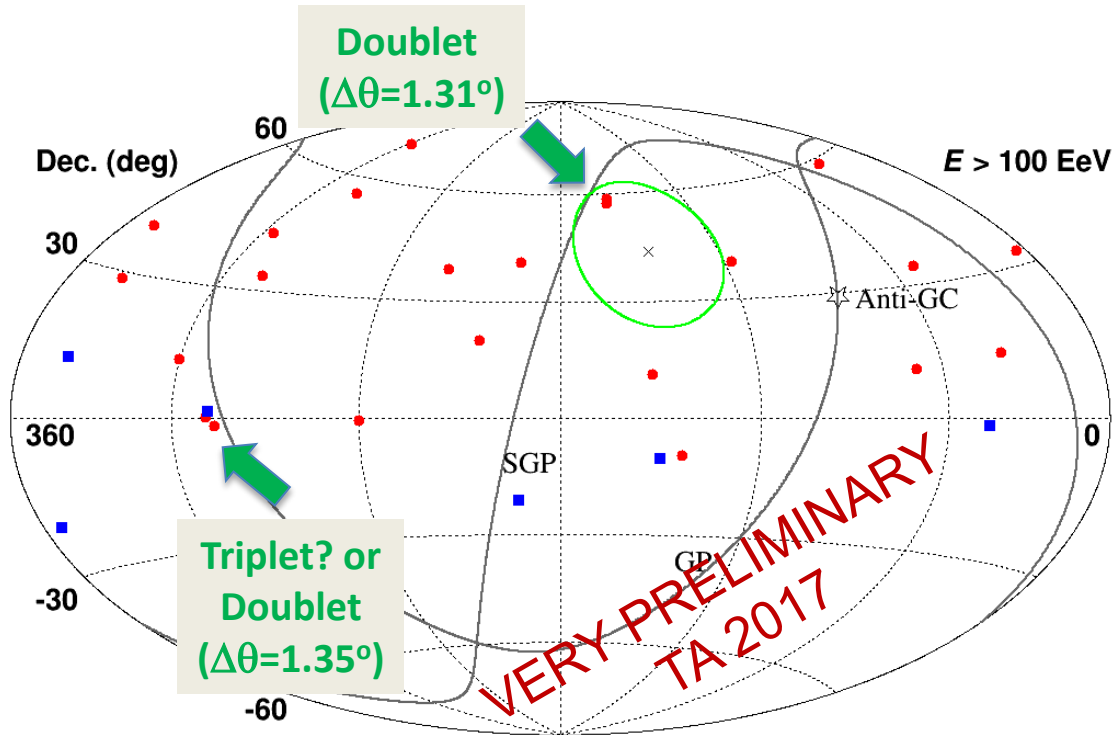
Oversampling
15° radius circle



Two Separated Sources

Small-scale anisotropy

Autocorrelations



TA 9 years (23 events)

Auger 10 years (6 events)

2 doublets above 100 EeV.

→ the probability to have ≥ 2 doublets with $\Delta\theta = \sqrt{2}$ deg

$$P = 0.30\% (2.8\sigma)$$