

Observation of ultra-high energy cosmic rays with the Telescope Array experiment

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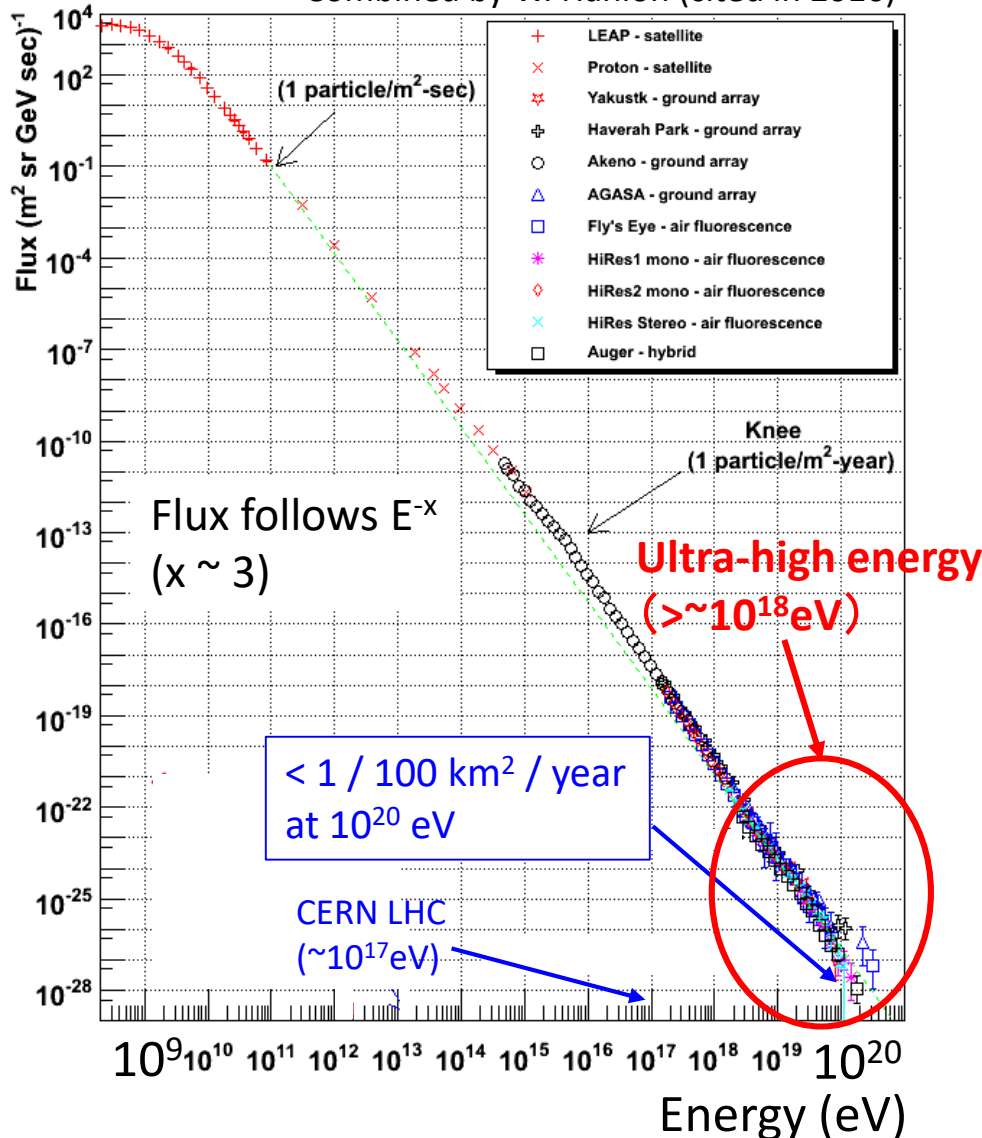
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2. Telescope Array (TA) experiment
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Ultra-high energy cosmic ray (UHECR)

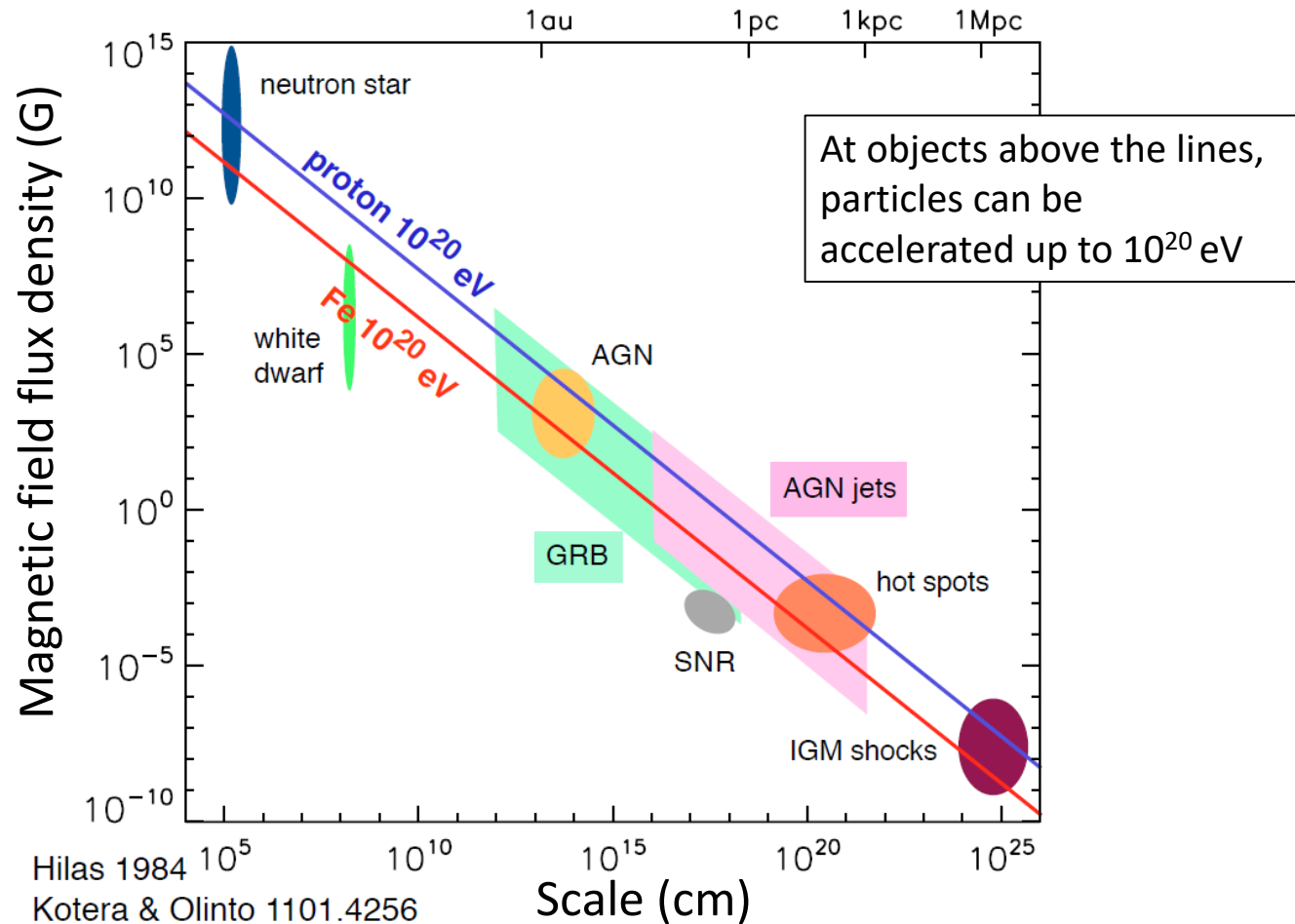
Observed cosmic ray spectrum

Combined by W. Hanlon (cited in 2016)



- Cosmic ray: charged particles from outside of the Earth
- Spectrum is power-law shape.
 - Suggests the generation with particle acceleration on astrophysical objects
- Acceleration and propagation information of cosmic rays is obtained from the spectrum.
- Due to low flux,
Origin of UHECRs is unrevealed.

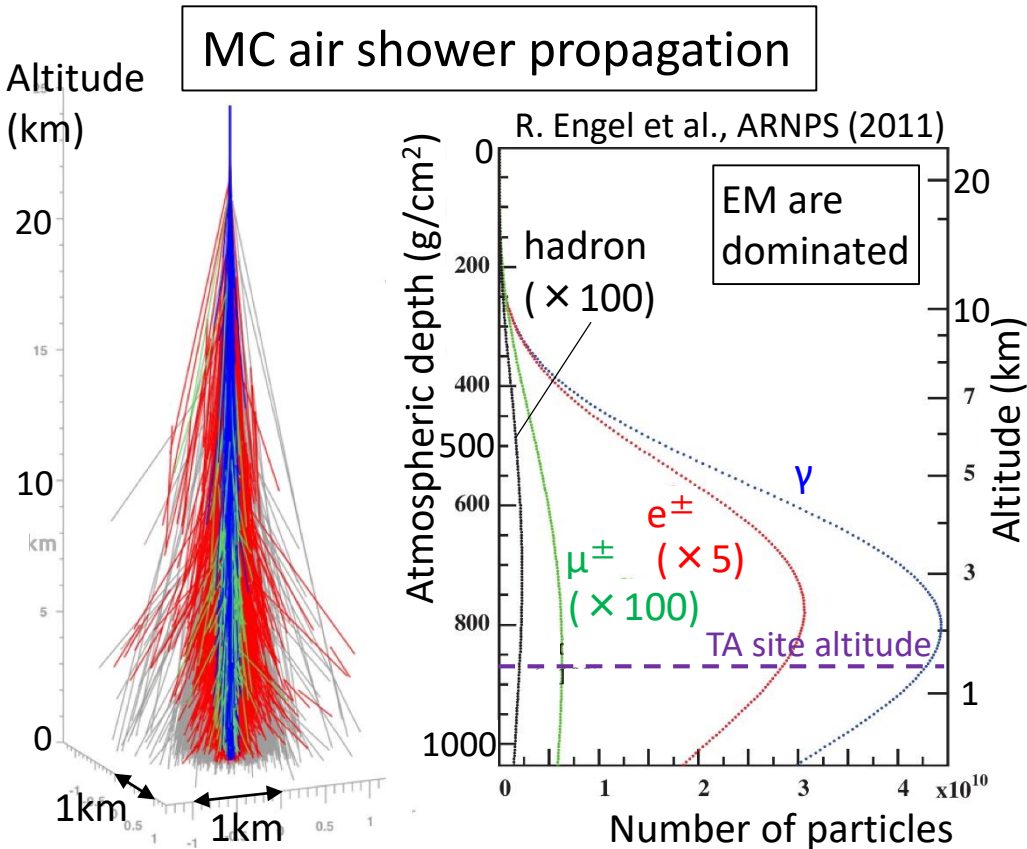
Possible sources of UHECR



- The source candidates are gamma ray burst, active galactic nuclei etc.
- Observation of spectrum and arrival direction anisotropy is necessary.
- Since cosmic rays are deflected by galactic and extragalactic magnetic fields, observation of mass composition is also needed.

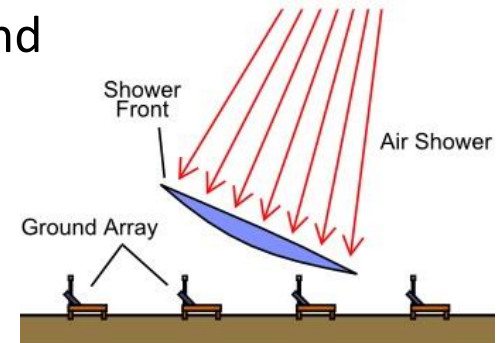
Method of UHECR observation

- UHECR is observed by using cascade reaction of primary cosmic rays with atmospheric particles, which is called air shower.
- Using air shower MC, spectrum and arrival direction of primary cosmic rays are reconstructed.



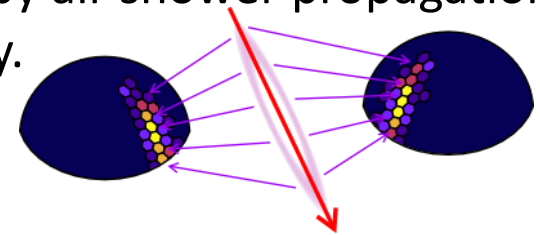
Surface detector (SD)

samples charged particles on the ground



Fluorescence detector (FD)

measures fluorescence light generated by air shower propagation in the sky.



Uncertainty of UHECR observation

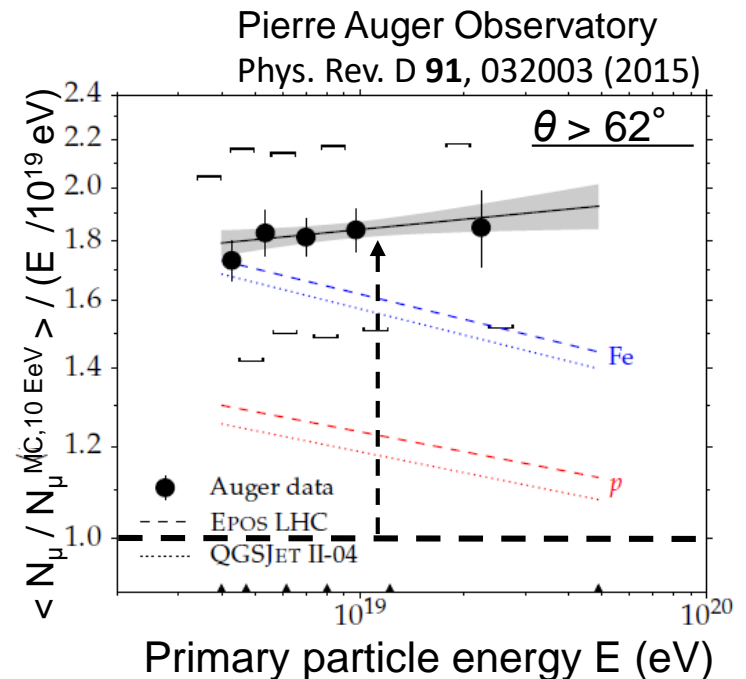
- UHECR energy range is beyond accelerator experiments.
- Hadronic interaction models of MC use extrapolated values for cross section from lower energy data.

Muon excess issue:

- Number of muons N_μ measured by the Auger experiment shows

$$N_\mu^{\text{data}} \simeq 1.8 N_\mu^{\text{MC}}$$

- Present hadronic models does not fully reproduce UHE air showers.





Telescope Array Collaboration



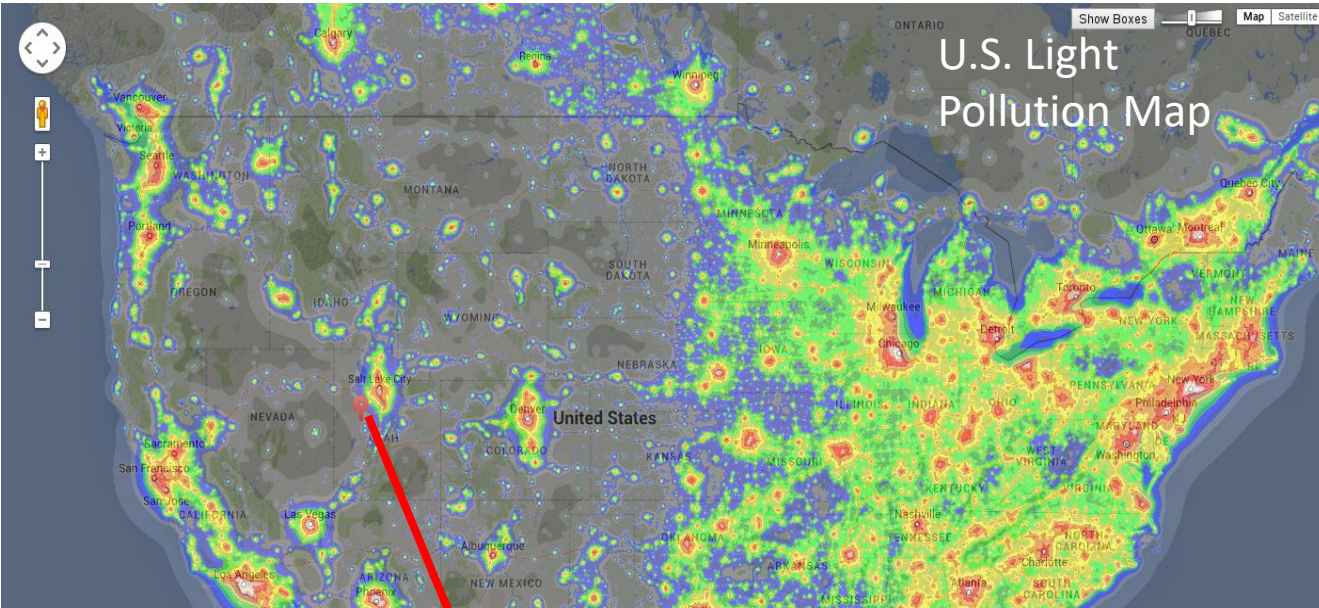
RU Abbasi¹, M Abe¹³, T Abu-Zayyad¹, M Allen¹, R Anderson¹, R Azuma², E Barcikowski¹, JW Belz¹, DR Bergman¹, SA Blake¹, R Cady¹, MJ Chae³, BG Cheon⁴, J Chiba⁵, M Chikawa⁶, WR Cho⁷, T Fujii⁸, M Fukushima^{8,9}, T Goto¹⁰, W Hanlon¹, Y Hayashi¹⁰, N Hayashida¹¹, K Hibino¹¹, K Honda¹², D Ikeda⁸, N Inoue¹³, T Ishii¹², R Ishimori¹², H Ito¹⁴, D Ivanov¹, CCH Jui¹, K Kadota¹⁶, F Kakimoto², O Kalashev¹⁷, K Kasahara¹⁸, H Kawai¹⁹, S Kawakami¹⁰, S Kawana¹³, K Kawata⁸, E Kido⁸, HB Kim⁴, JH Kim¹, JH Kim²⁵, S Kitamura², Y Kitamura², V Kuzmin¹⁷, YJ Kwon⁷, J Lan¹, SI Lim³, JP Lundquist¹, K Machida¹², K Martens⁹, T Matsuda²⁰, T Matsuyama¹⁰, JN Matthews¹, M Minamino¹⁰, K Mukai¹², I Myers¹, K Nagasawa¹³, S Nagataki¹⁴, T Nakamura²¹, T Nonaka⁸, A Nozato⁶, S Ogio¹⁰, J Ogura², M Ohnishi⁸, H Ohoka⁸, K Oki⁸, T Okuda²², M Ono¹⁴, A Oshima¹⁰, S Ozawa¹⁸, IH Park²³, MS Pshirkov²⁴, DC Rodriguez¹, G Rubtsov¹⁷, D Ryu²⁵, H Sagawa⁸, N Sakurai¹⁰, AL Sampson¹, LM Scott¹⁵, PD Shah¹, F Shibata¹², T Shibata⁸, H Shimodaira⁸, BK Shin⁴, JD Smith¹, P Sokolsky¹, RW Springer¹, BT Stokes¹, SR Stratton^{1,15}, TA Stroman¹, T Suzawa¹³, M Takamura⁵, M Takeda⁸, R Takeishi⁸, A Taketa²⁶, M Takita⁸, Y Tameda¹¹, H Tanaka¹⁰, K Tanaka²⁷, M Tanaka²⁰, SB Thomas¹, GB Thomson¹, P Tinyakov^{17,24}, I Tkachev¹⁷, H Tokuno², T Tomida²⁸, S Troitsky¹⁷, Y Tsunesada², K Tsutsumi², Y Uchihori²⁹, S Udo¹¹, F Urban²⁴, G Vasiloff¹, T Wong¹, R Yamane¹⁰, H Yamaoka²⁰, K Yamazaki¹⁰, J Yang³, K Yashiro⁵, Y Yoneda¹⁰, S Yoshida¹⁹, H Yoshii³⁰, R Zollinger¹, Z Zundel¹

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USA, Japan, Korea, Russia, Belgium

About 120 people

Telescope Array Observatory



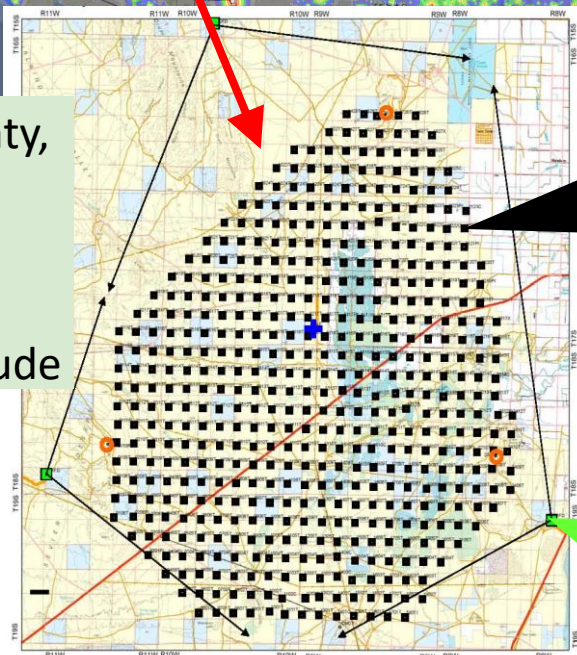
U.S. Light
Pollution Map

Largest cosmic ray
observatory in the
Northern hemisphere.

$\sim 700 \text{ km}^2$

$\rightarrow \lesssim 1/10$ of Crete

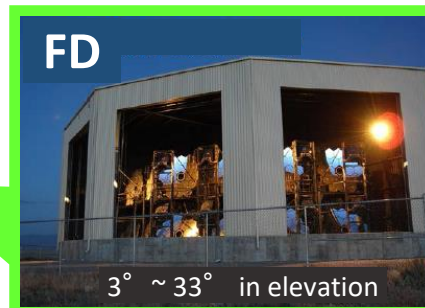
Millard County,
Utah
 39.30° N
 112.91° W
1400 m altitude



SD
3m² each



FD



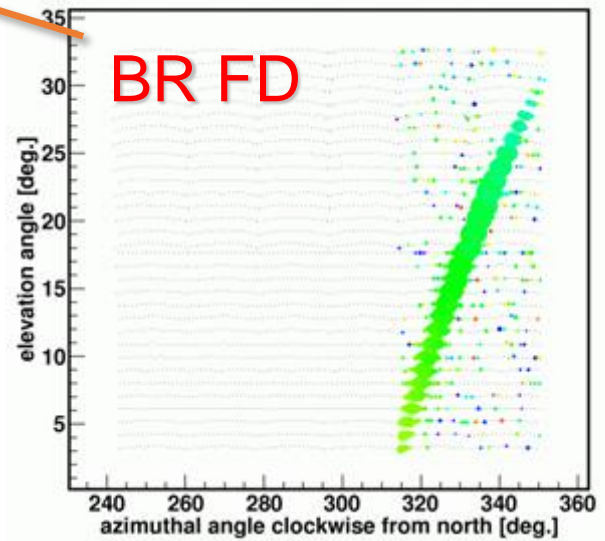
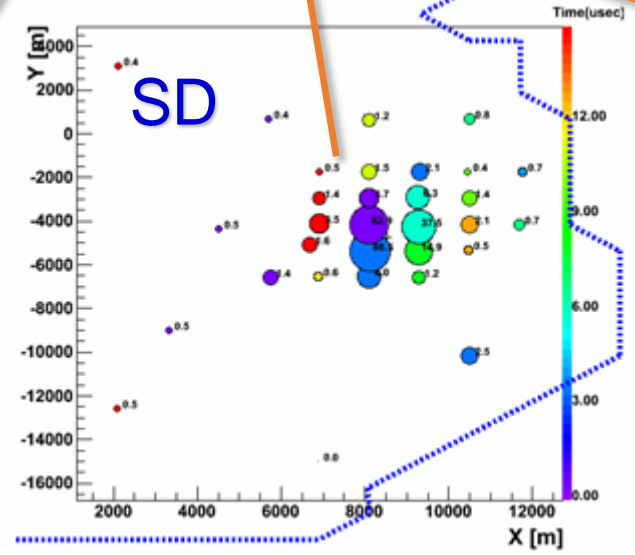
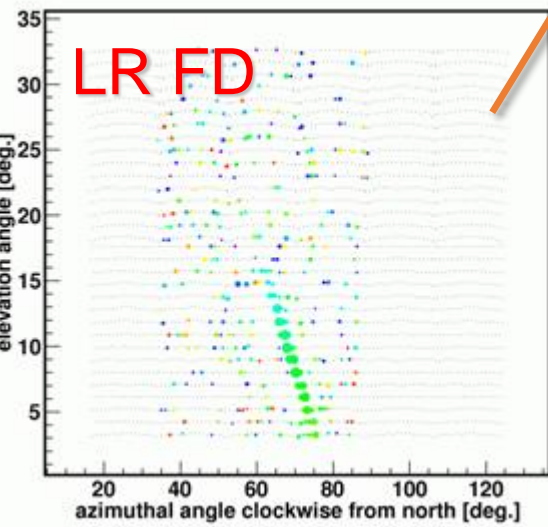
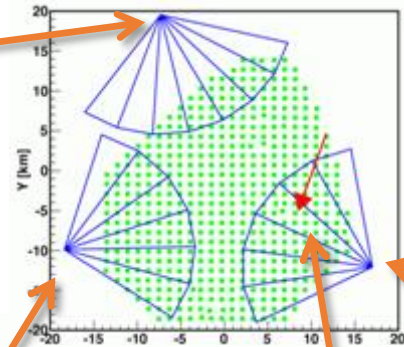
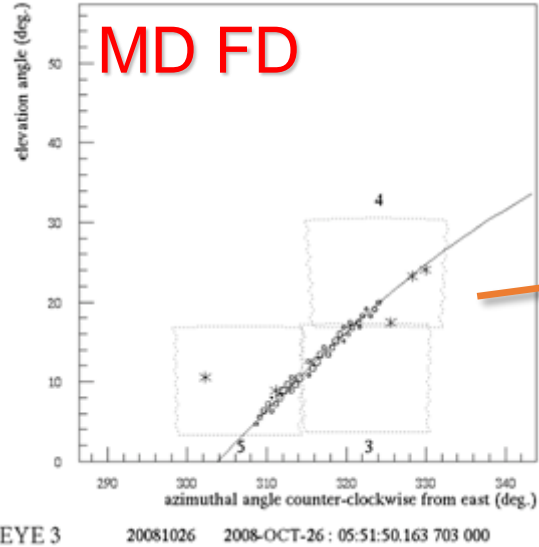
$3^\circ \sim 33^\circ$ in elevation

- An array of 507 scintillator SDs
- 3 FD stations overlooking the array
- Operational as of 2008

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

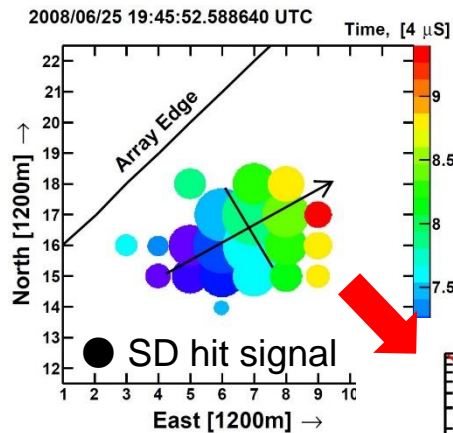
Event from 2008-10-26



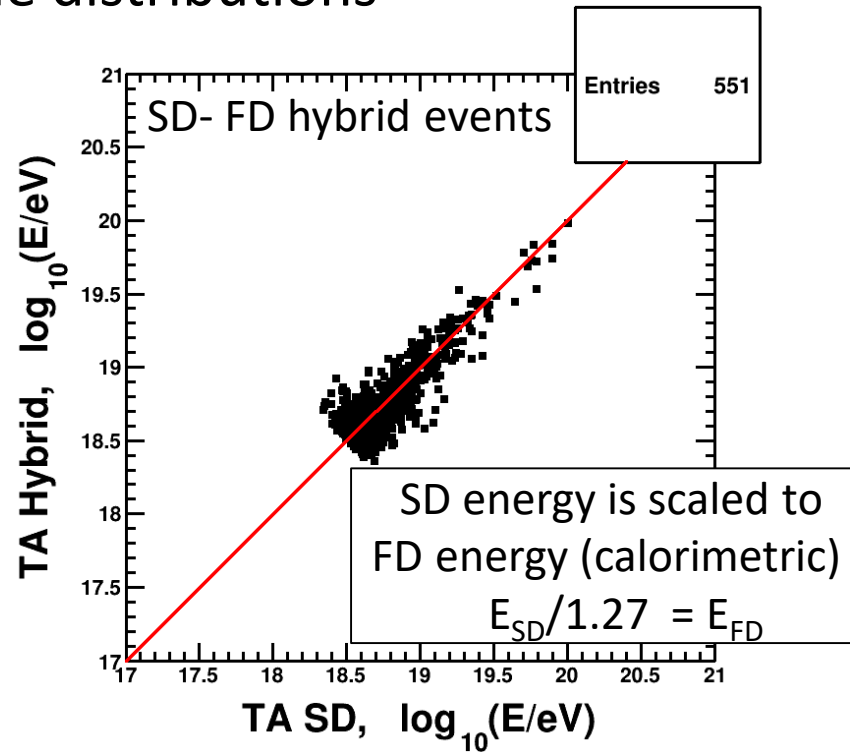
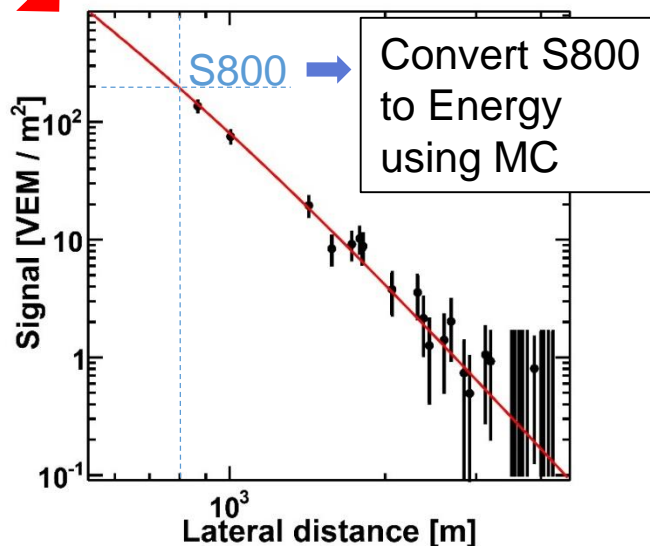
Air shower reconstruction

- Calculate primary cosmic ray energy and geometry from particle signal size and arrival time distributions

SD hit map for 1 event



Lateral distribution fit

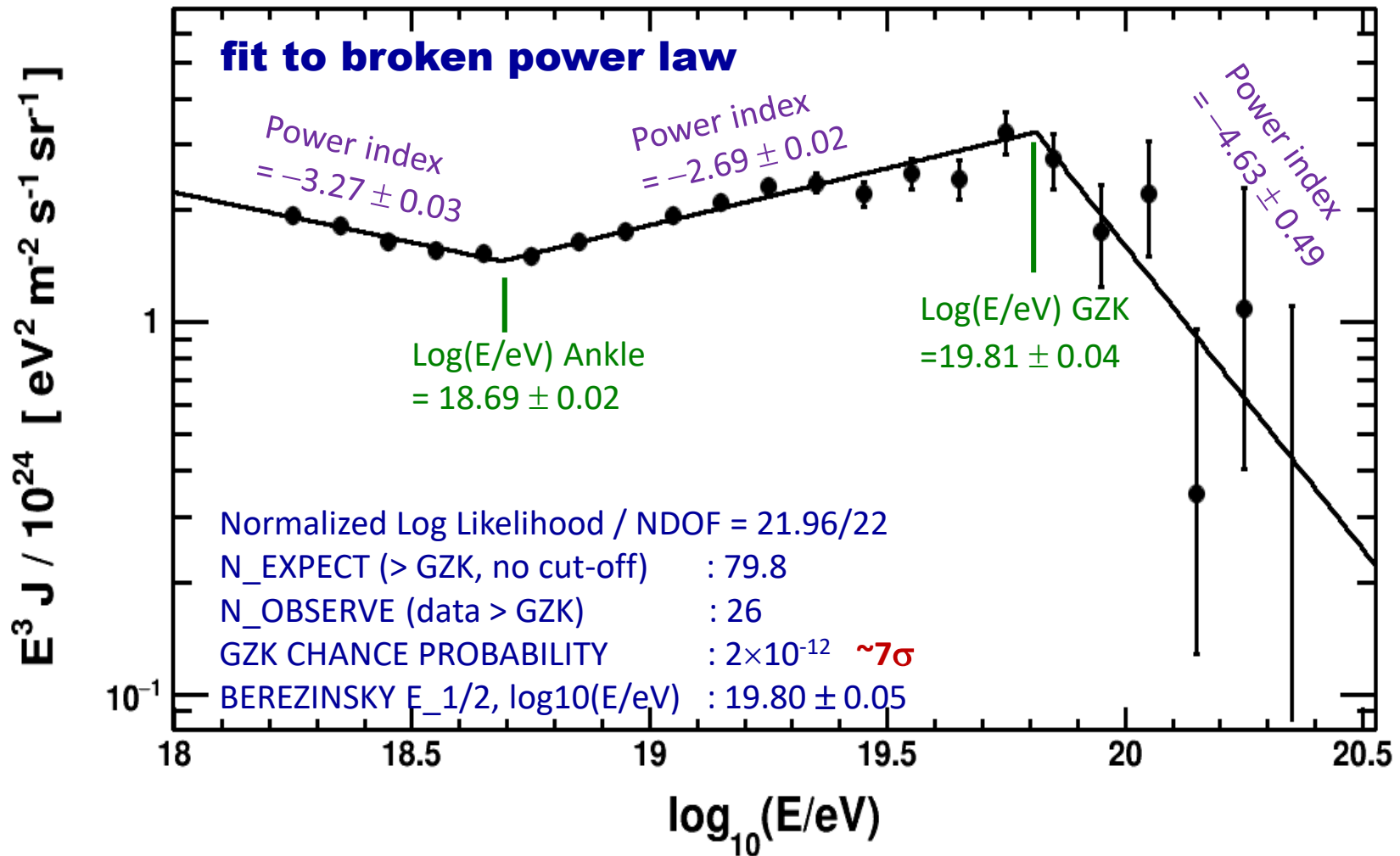


$E > 10^{19}$ eV

Angular resolution = 1.4°

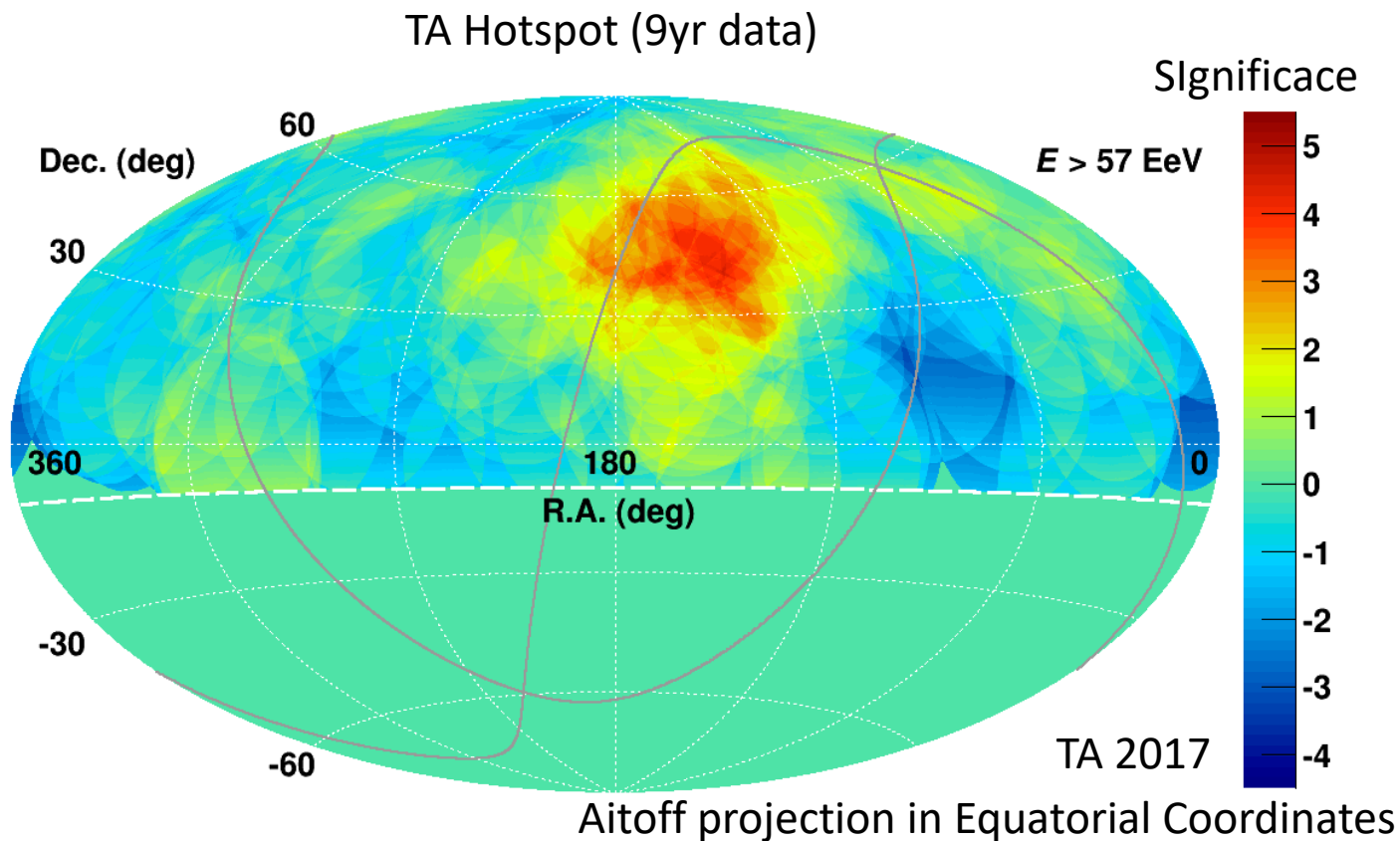
Energy resolution $< 20\%$

TA SD Spectrum (9 yrs data)



- Cutoff at highest energy corresponds to GZK cutoff (flux reduction by the reaction between cosmic ray and CMB photons).

Anisotropy results

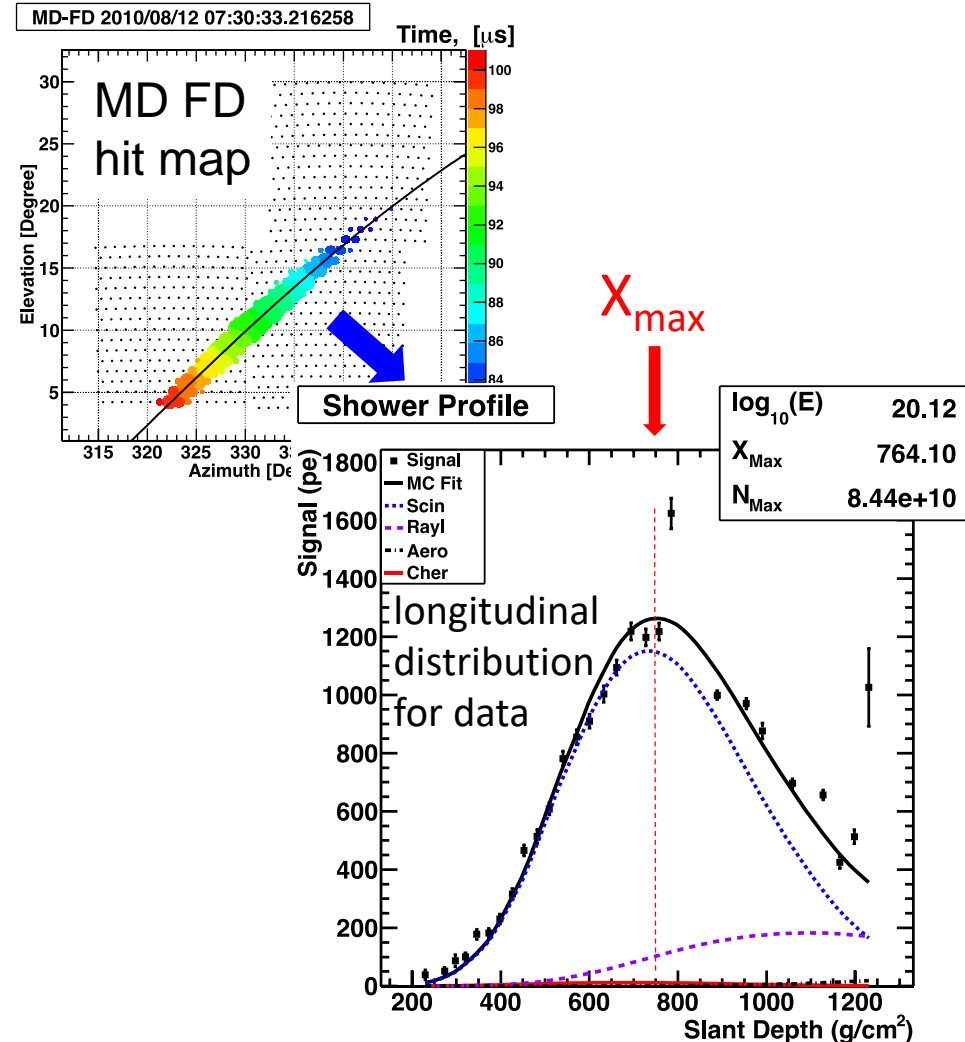
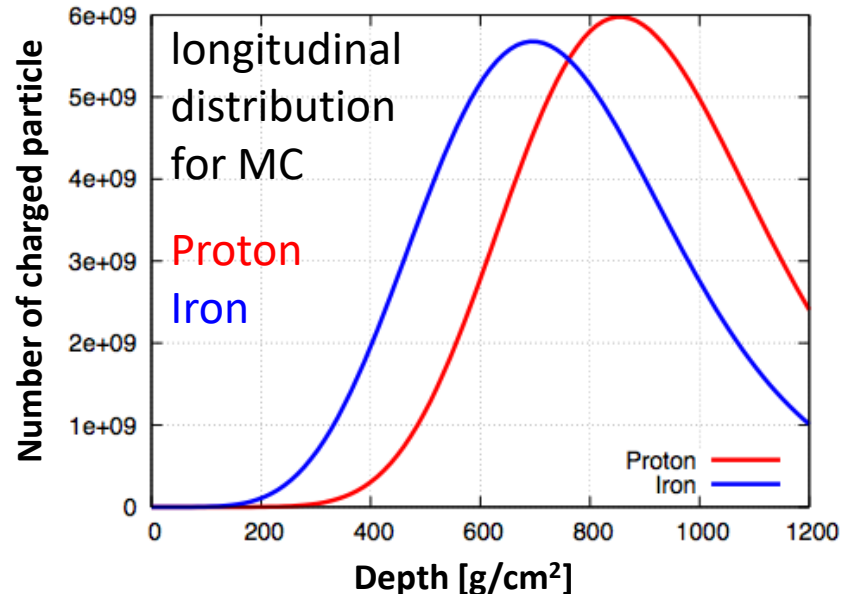
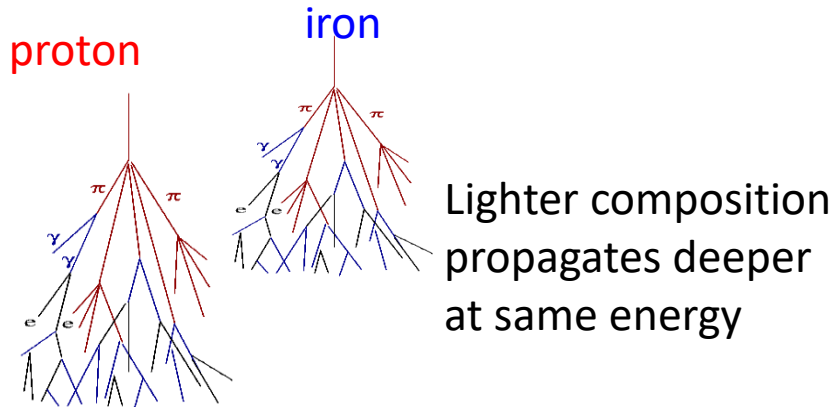


Total events: 143
Observed: 34
Expected : 13.5

Events over-sampled using 25° circles
Excess center: RA=144.3°, Dec=+40.3°
Li Ma significance: 5.06 σ
2.96 σ chance probability

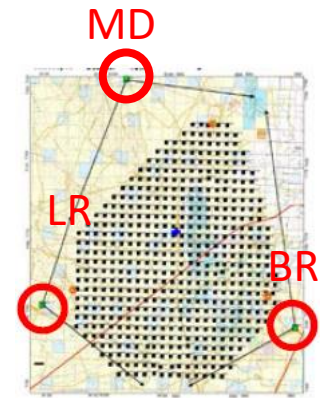
Mass composition analysis

- Estimate primary cosmic ray mass composition from the depth of the air shower maximum (X_{\max})

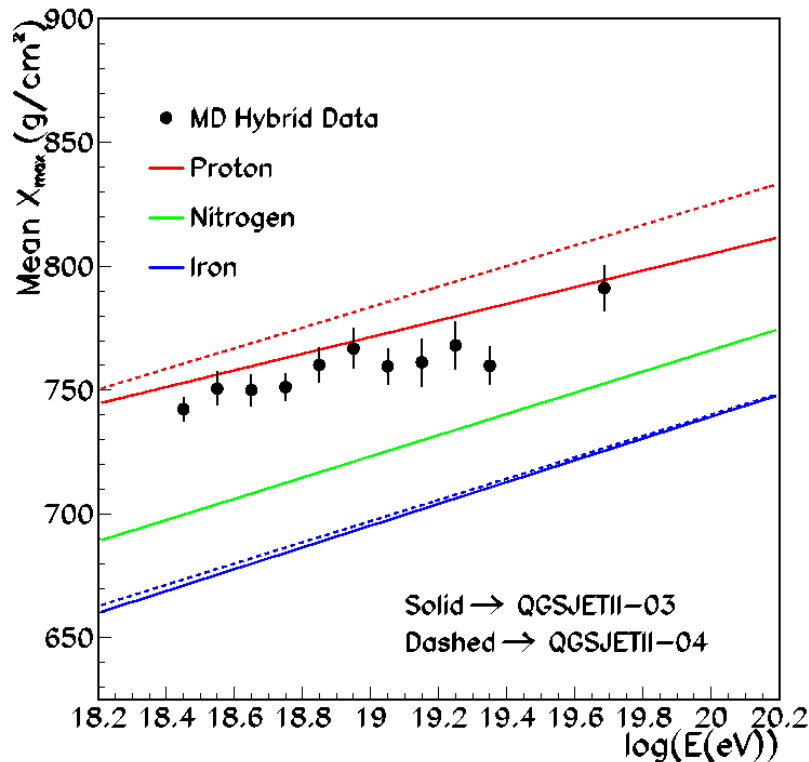


Composition results

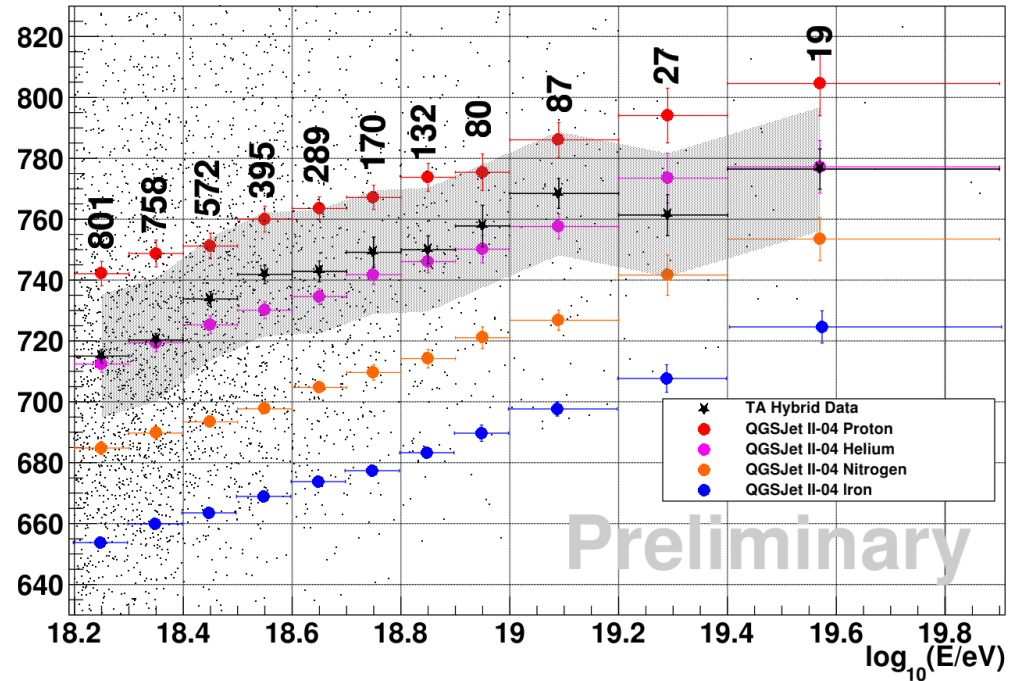
- TA uses different analysis techniques using 3 FDs and hybrid analysis with SD.



MD hybrid



BR/LR hybrid



- Mass composition from TA observation corresponds to light component.

Study of muons from air showers

- Muon excess issue
 - Present hadronic models do not fully reproduce air showers.
- Hadronic interaction models can be tested by comparing the measured number of muons with the MC prediction.
- We analyzed lateral distribution of muons and studied air shower structure using TA SD data.

Study of muons from air showers

- Assume primary particle is proton
- 80 – 90% of TA SD signal derives from EM components.

Analysis approach:

- Search for the analysis condition where the muon purity in the SD signal becomes high using the MC
- Compare data with MC on the high muon purity condition

Analysis condition

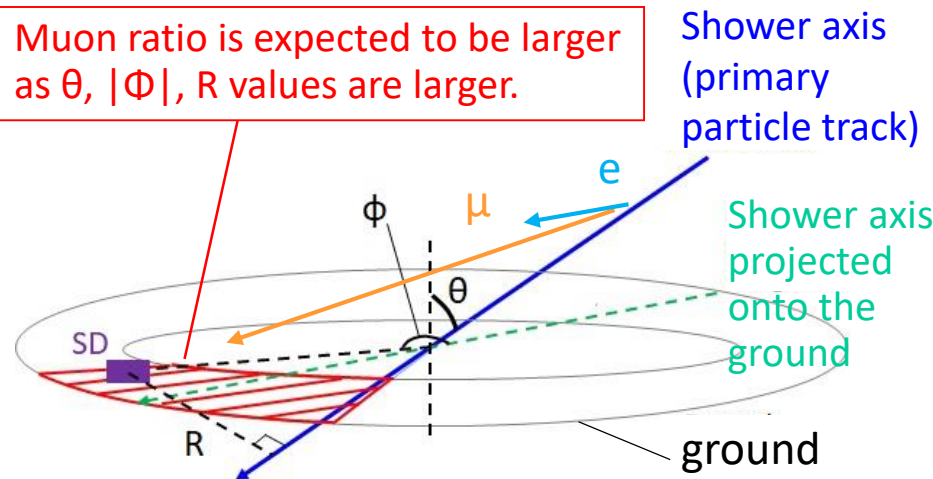
- Energy: $10^{18.8} \text{ eV} < E < 10^{19.2} \text{ eV}$
- Experimental data: 7 year dataset (2008/5/11 ~ 2015/5/11), ~3600 events
- MC: Firstly check QGSJETII-03 proton, then other hadronic models

~60000 events

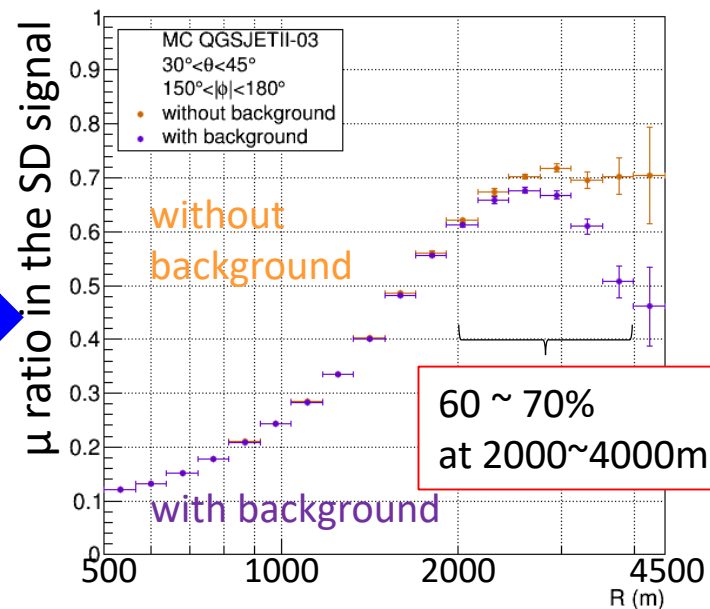
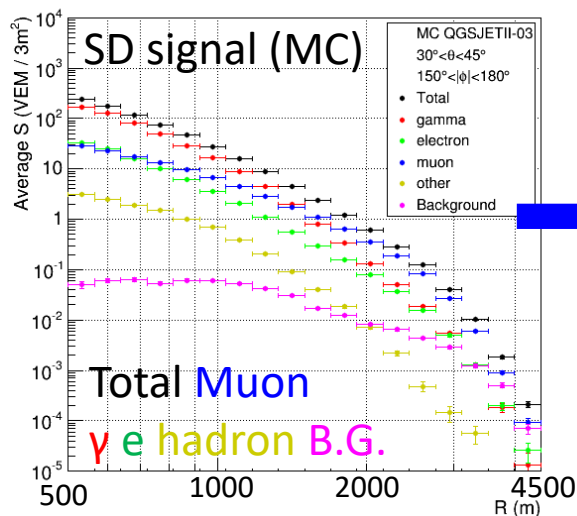
Muon analysis procedure

- EM components generated on the shower axis are attenuated faster than muons in the atmosphere.
- By using the SD in the shower forwarding direction, 60 – 70% of the signal becomes muons.

Muon ratio is expected to be larger as θ , $|\Phi|$, R values are larger.

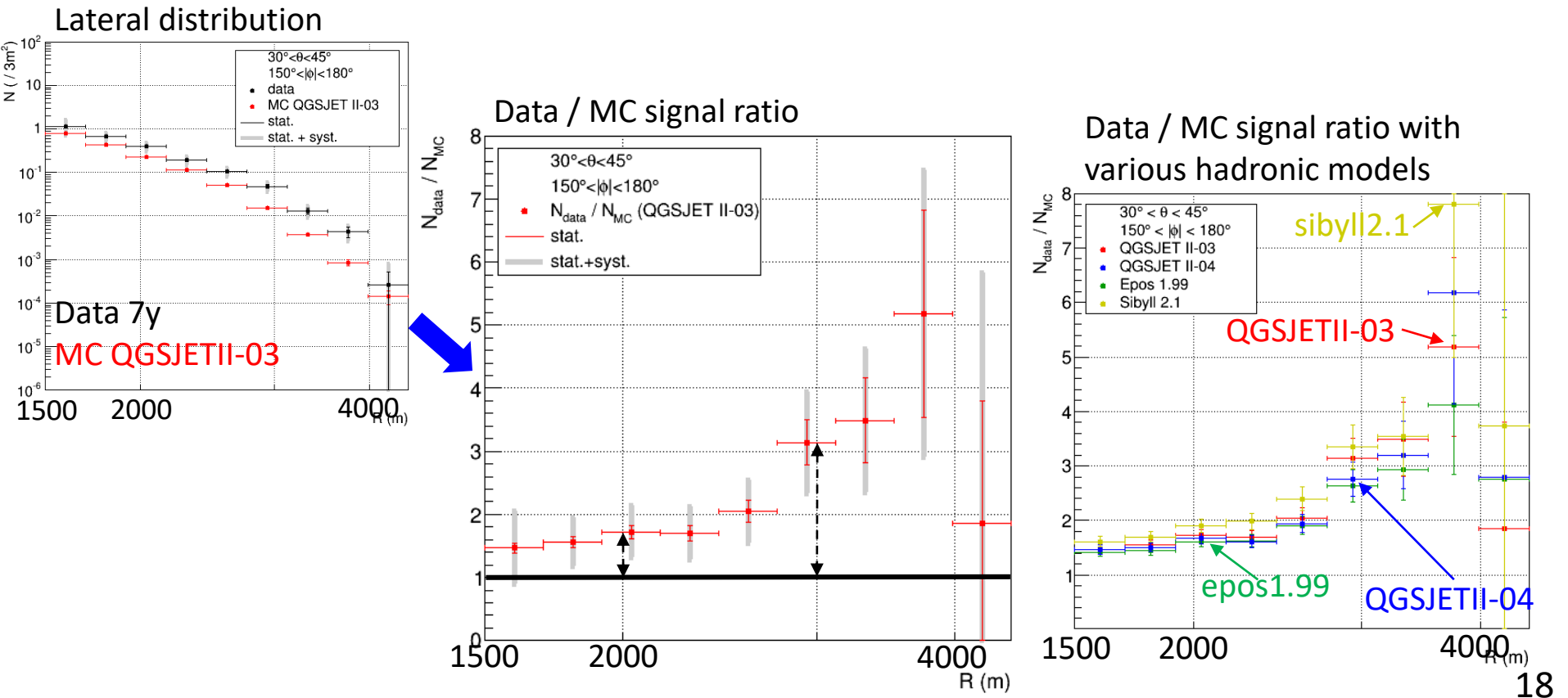


Analysis range
 θ : $[0^\circ, 45^\circ]$
 Φ : $[-180^\circ, 180^\circ]$
 R : $[500\text{m}, 4500\text{m}]$



Muon analysis results (7 yrs data)

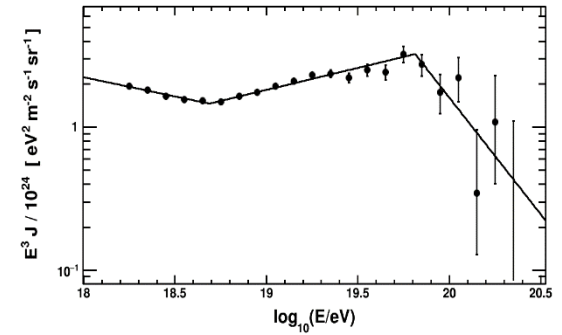
- Lateral distribution on condition μ purity 60~70% and data/MC ratio
- **Data is larger than MC by more than 1.5 times, with R dependence.**
 - $1.72 \pm 0.10(\text{stat.}) \pm 0.40(\text{syst.})$ ($1910 \text{ m} < R < 2160 \text{ m}$) (1.8σ)
 - $3.14 \pm 0.36(\text{stat.}) \pm 0.72(\text{syst.})$ ($2760 \text{ m} < R < 3120 \text{ m}$) (2.7σ)
- **Muon excess in the data is suggested. MC models need to be revised.**



Summary of Results

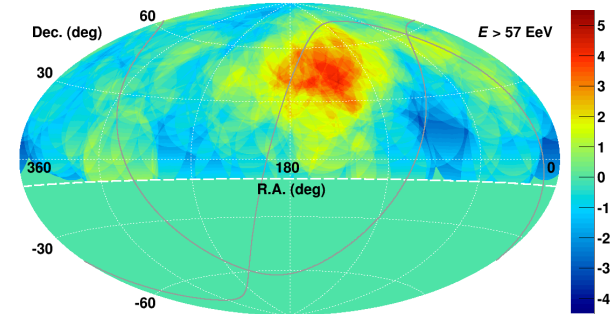
- Spectrum

Flux suppression at the highest energy



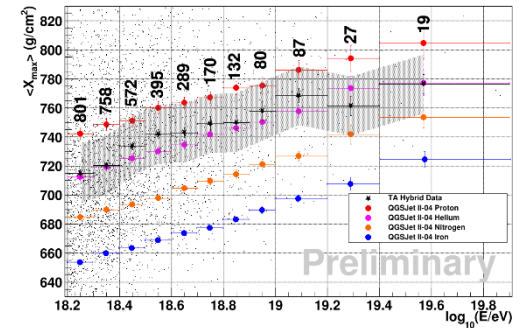
- Arrival direction

Observation of hotspot in the northern hemisphere



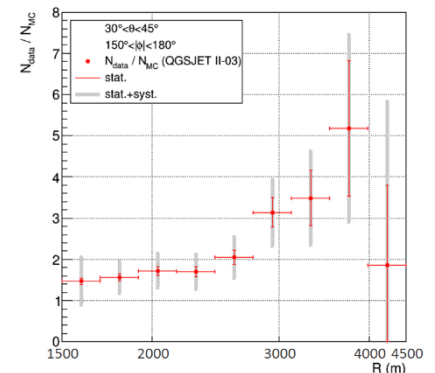
- Mass composition

Compatible with a light component

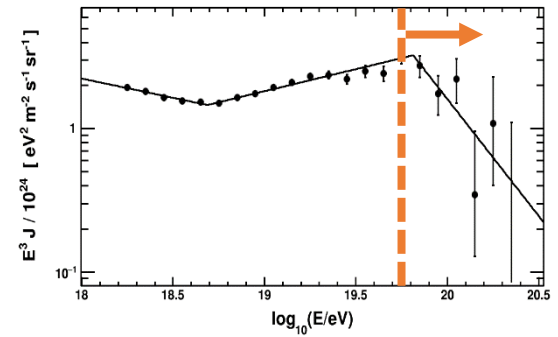
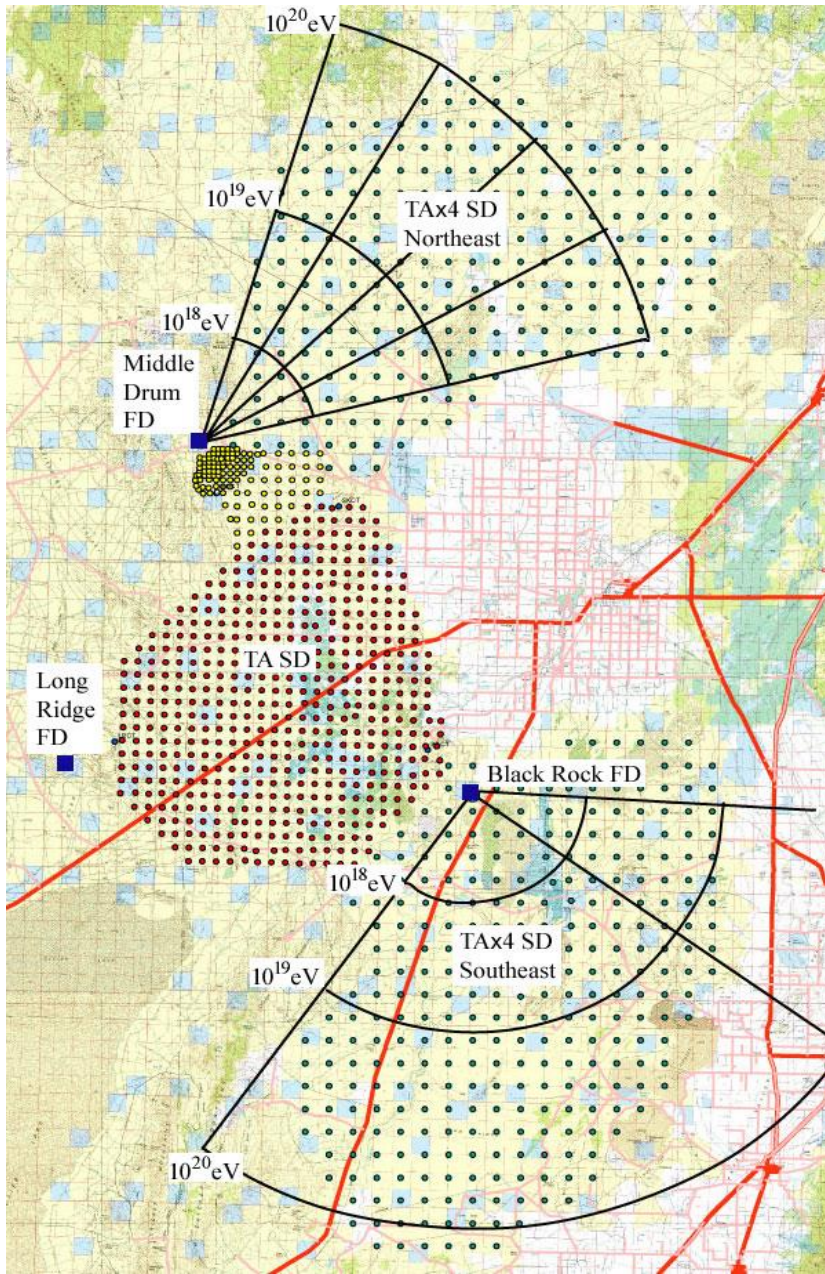


- Hadronic interaction

Muon excess in the data \rightarrow Information about more reliable models is obtained



TAx4 Project



Get ~20 years of TA SD data by 2020

Clarify the details of hotspot at > 57 EeV

TA SD (~3000 km²): **Quadruple area**

500 additional scintillator SDs

173 SDs have arrived in Utah for assembly, 77 SD is prepared in Japan.

2 FD stations (12 Telescopes)

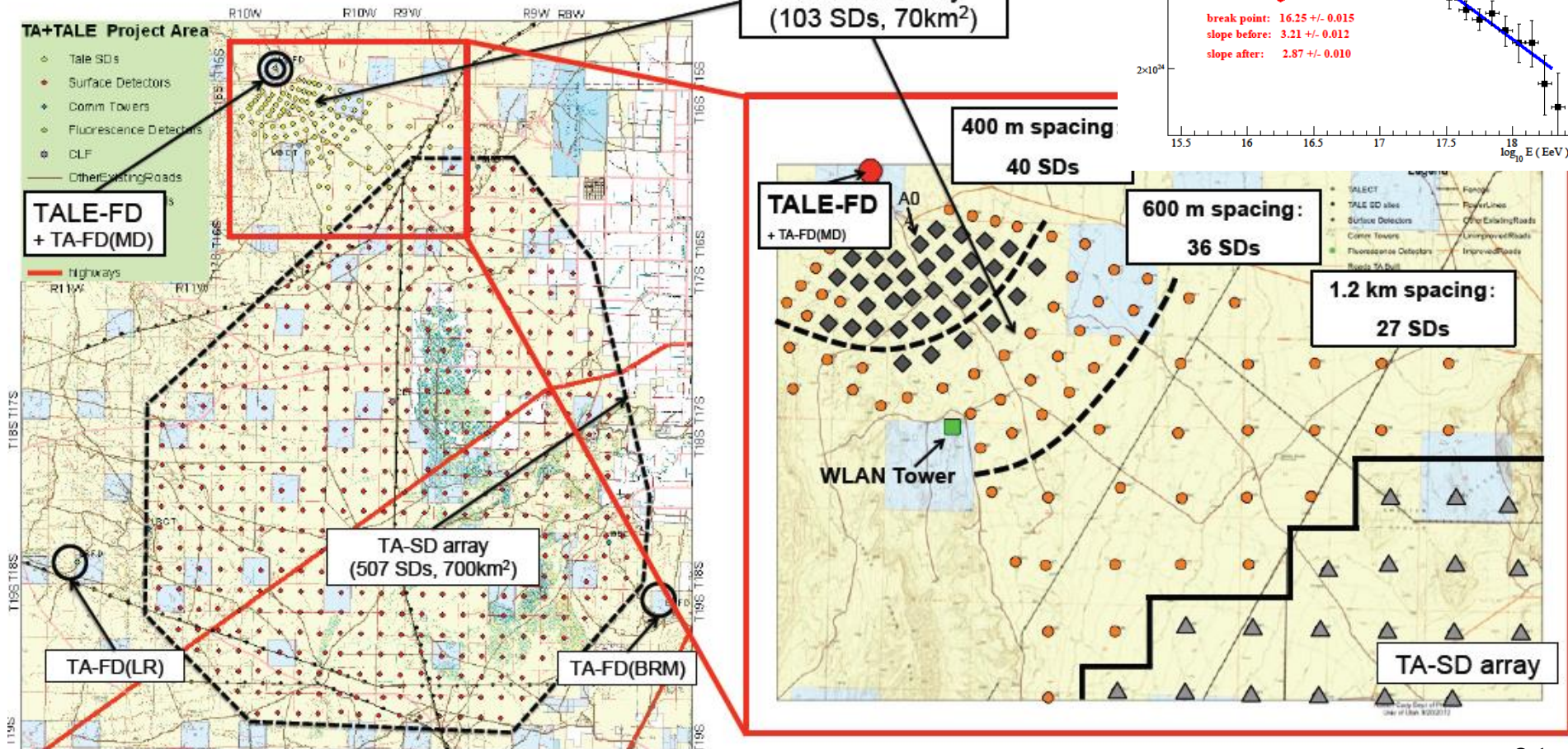
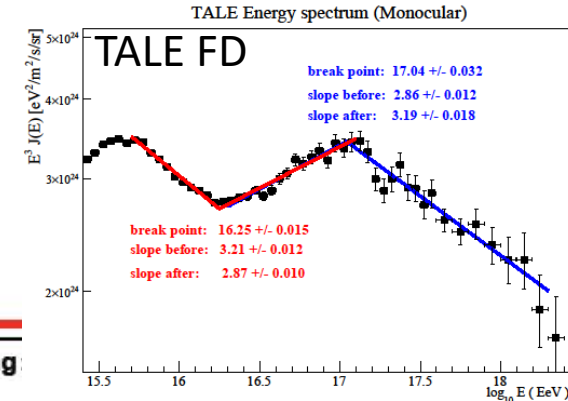
telescopes/electronics being prepared at Univ. Utah

Site construction underway at the northern station.

TA Low Energy Extension (TALE)

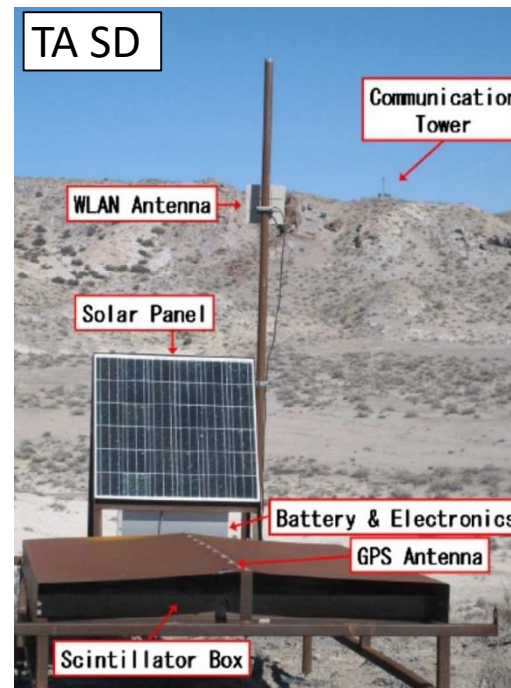
Observe Galactic to Extra-Galactic Transition

- 10 FD telescopes to look higher in the sky (31-59°) to see shower development
- More dense SDs (lower energy threshold)

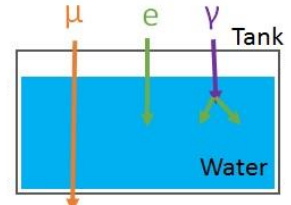


TA SD

- Two layers of flat scintillators
- It records energy deposit when charged particles penetrate the scintillator (~ 2 MeV for vertical injection)
- It obtains charged particles from air showers
- From time and number density distribution of air shower particles, primary particle energy and arrival direction are reconstructed.

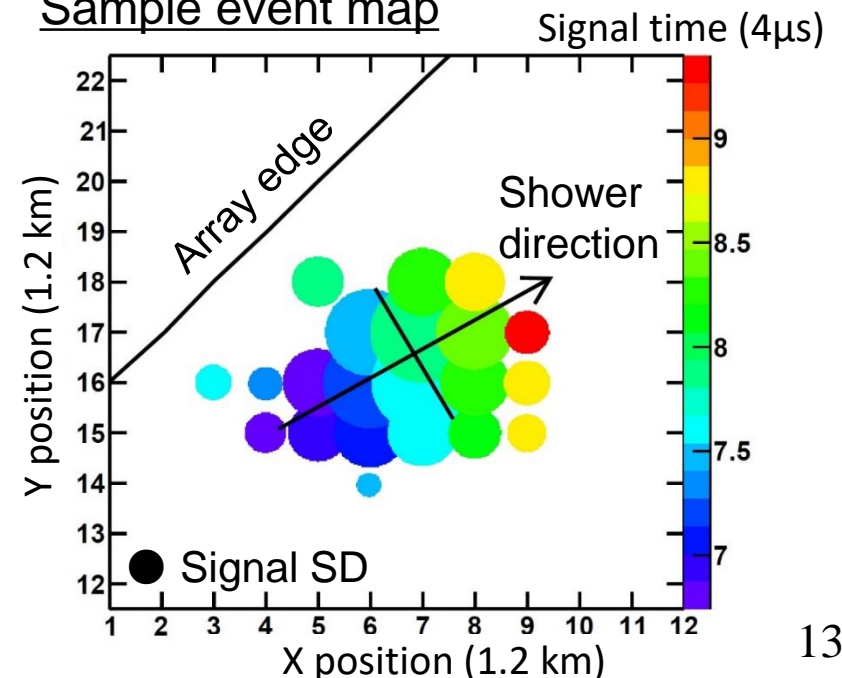


Auger SD



Signal is mainly from muons

Sample event map

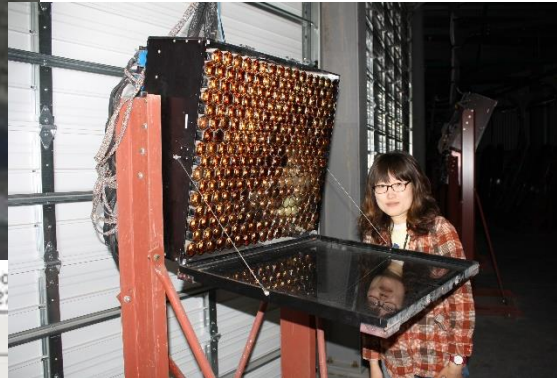


TA Fluorescence Detectors

Middle Drum

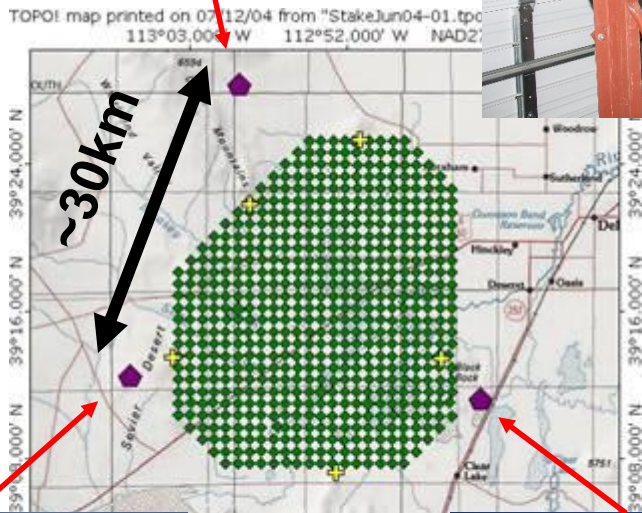


14 telescopes @ station
256 PMTs/camera



5.2 m²

Reutilized from HiRes-I

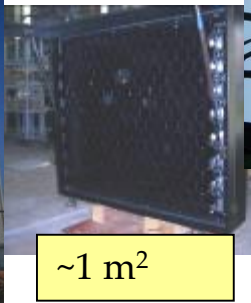


12 telescopes/station
256 PMTs/camera

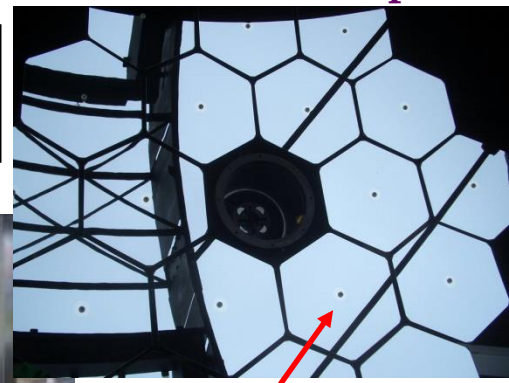
Long Ridge



Black Rock Mesa



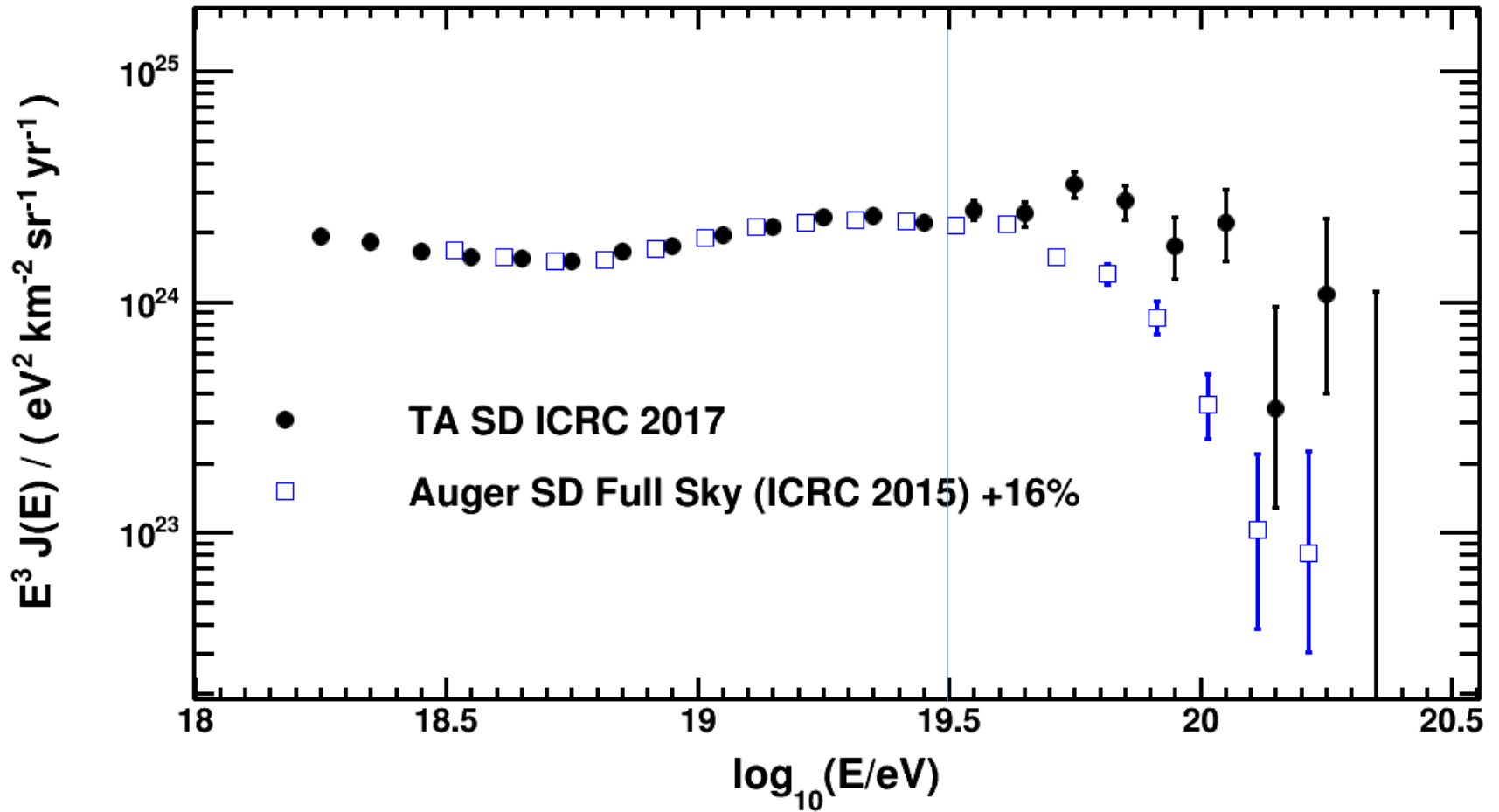
~1 m²



6.8 m²

New Telescopes

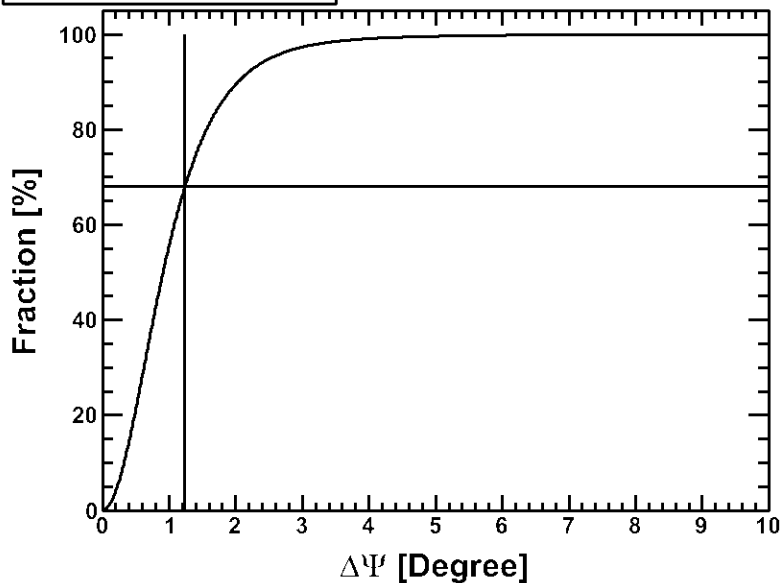
Telescope Array & Pierre Auger Spectra



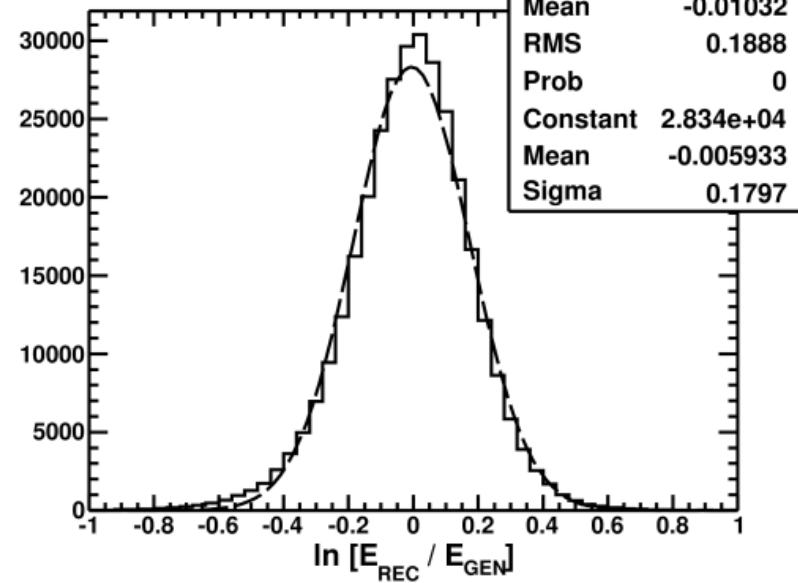
Anisotropy Analysis

- SD data full 9 years
- 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%

$E > 10 \text{ EeV}, \theta < 55^\circ$



$E > 10 \text{ EeV}, \theta < 55^\circ$





Nearby Galaxy Clusters

Ursa Major Cluster
(D=20Mpc)

Virgo Cluster
(D=20Mpc)

Perseus-Pisces
Supercluster
(D=70Mpc)

Eridanus
Cluster
(D=30Mpc)

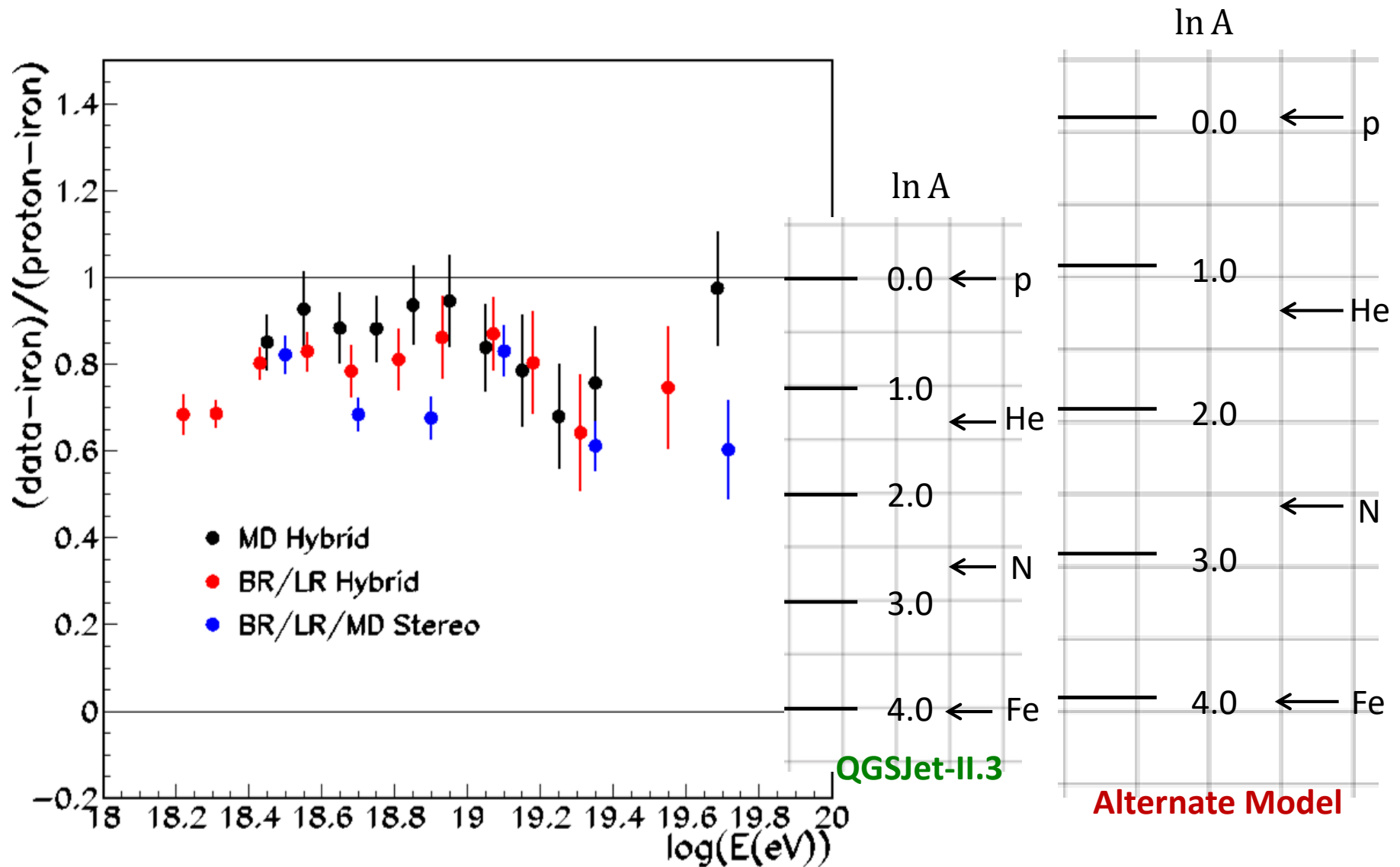
Fornax Cluster

Centaurus
Supercluster (D=60Mpc)

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

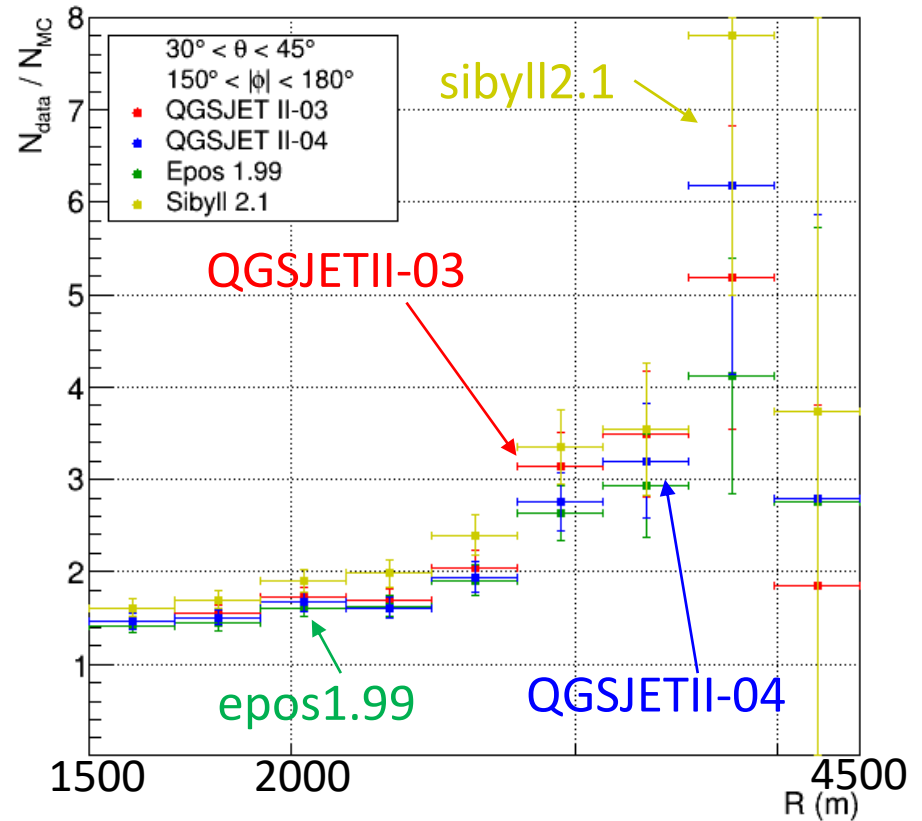
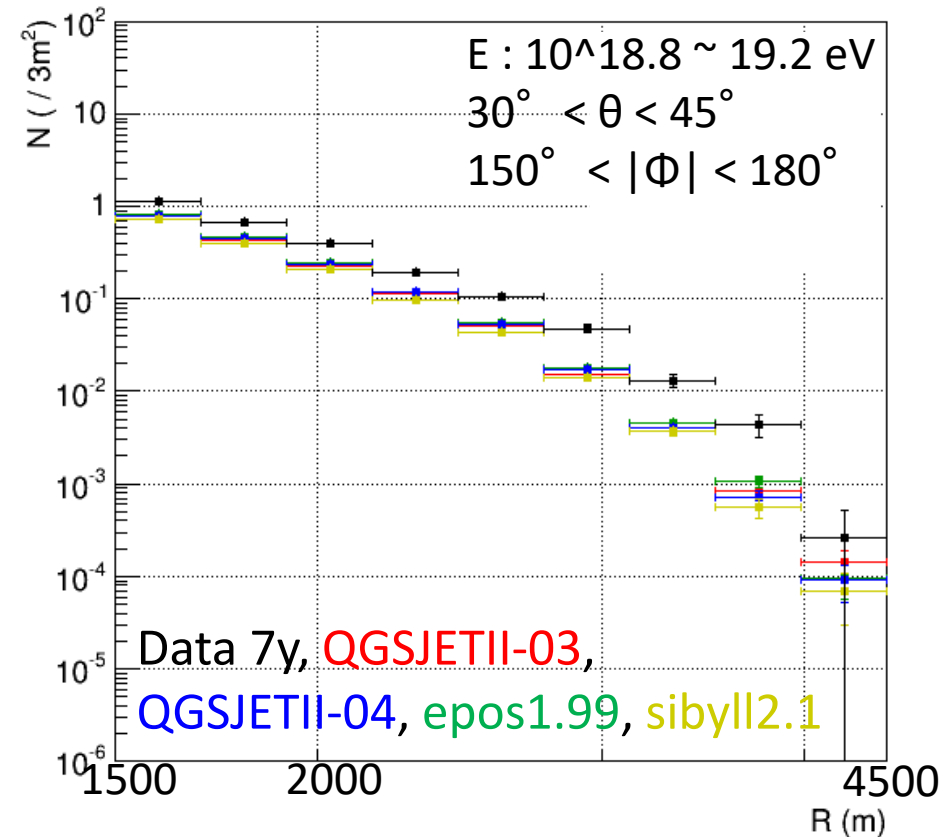
TA hotspot is found near the Ursa Major Cluster
TA & PAO see no excess in the direction of Virgo.

TA composition compared to QGSJet-II.3



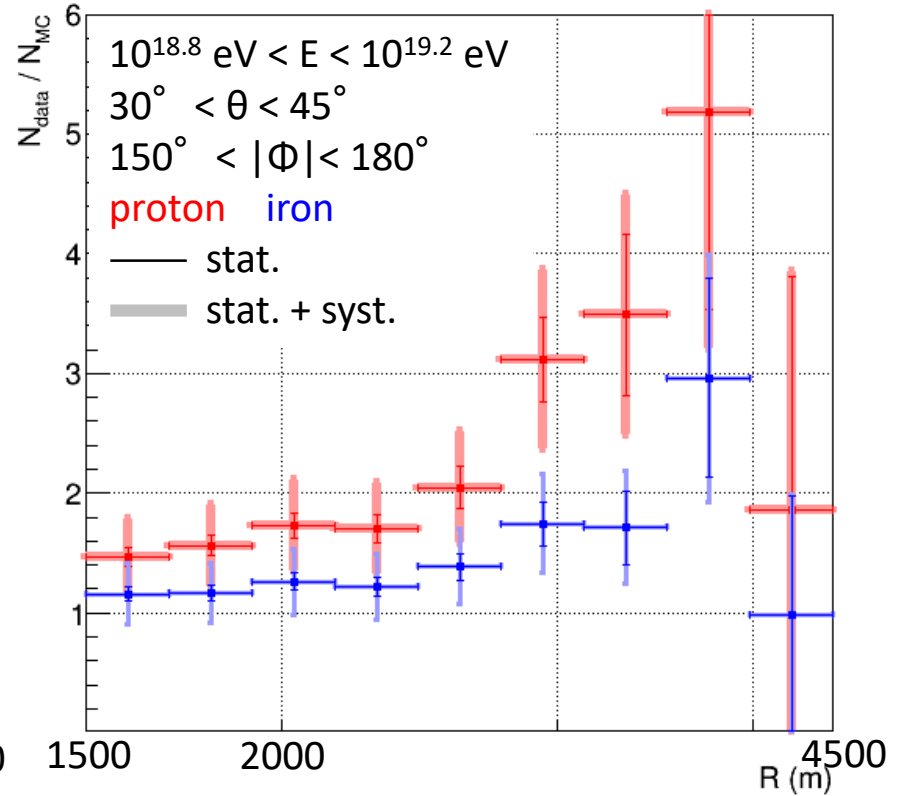
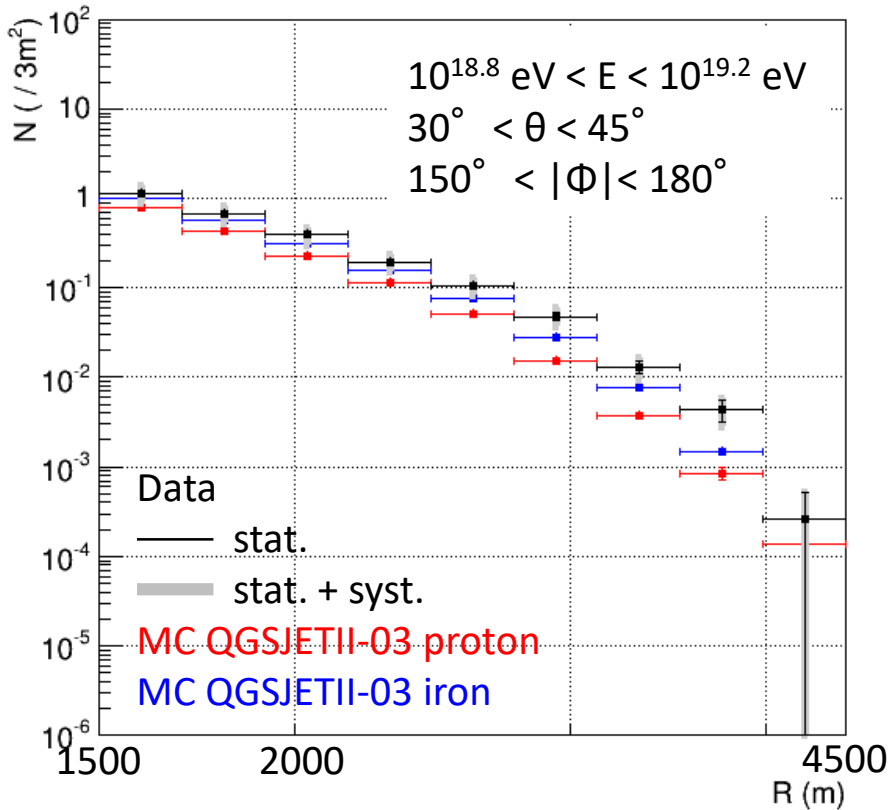
Results

- Lateral distribution with various hadronic models
- Data is larger than MC for all considered models.



Results

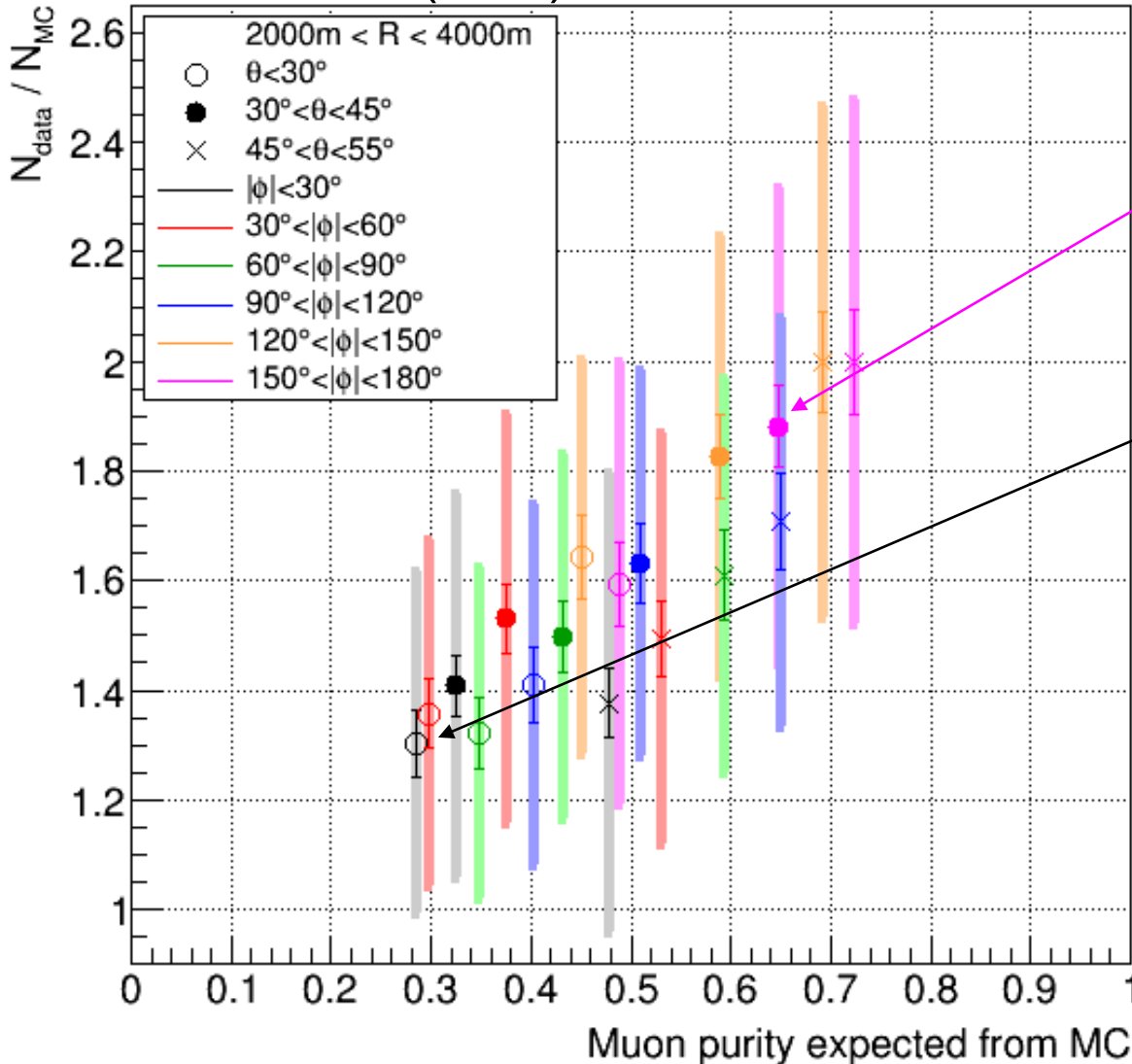
- Data-MC comparison assuming iron composition



R (m)	Data/MC proton	Data/MC iron
[1910, 2160]	$1.72 \pm 0.10(\text{stat.}) \pm 0.40(\text{syst.})$	$1.26 \pm 0.07(\text{stat.}) \pm 0.29(\text{syst.})$
[2760, 3120]	$3.14 \pm 0.36(\text{stat.}) \pm 0.72(\text{syst.})$	$1.74 \pm 0.19(\text{stat.}) \pm 0.40(\text{syst.})$

(θ, Φ) - μ purity comparison

Correlation plots between muon purity and $N_{\text{data}} / N_{\text{MC}}$ in different (θ, Φ) conditions



- For $30^\circ < \theta < 45^\circ$
 $150^\circ < |\Phi| < 180^\circ$,
 μ purity = $\sim 65\%$ and
Data/MC = 1.88
 $\pm 0.08(\text{stat.}) \pm 0.40(\text{syst.})$

- For $\theta < 30^\circ$
 $|\Phi| < 30^\circ$,
 μ purity = $\sim 28\%$ and
Data/MC = 1.30
 $\pm 0.06(\text{stat.}) \pm 0.27(\text{syst.})$

Larger number of particles of data than that of MC with larger muon purity.

part of the discrepancy between data and MC is due to muon excess.

Discussion

- Lateral distribution of MC does not reproduce data on muon-enriched condition, and the discrepancy is partially due to muon excess.
- Lateral distribution of data is broader than MC, which possibly indicates air shower development of the data is faster than MC.
- This feature suggests
 - larger hadron interaction cross section
 - larger pion multiplicity

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

Inelastic cross section between proton and air calculated from UHECR X_{max} distribution

Hadronic interaction at $E > 10^{18}$ eV is being revealed by air shower experiments.

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