Recent Results from the Telescope Array Project

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High Energy Astrophysics Institute & University of Utah

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Telescope Array Collaboration

THE UNIVERSITY OF UTAH
大阪市立大学 OSAKA CITY UNIVERSITY
愛媛大学 EHIME UNIVERSITY
RUTGERS THE STATE UNIVERSITY OF NEW JERSEY
YONSEI UNIVERSITY
東京工業大学 Tokyo Institute of Technology
UtahState University
이화여자대학교 EWHA WOMANS UNIVERSITY
ICRR Institute for Cosmic Ray Research University of Tokyo
東京大学 THE UNIVERSITY OF TOKYO
千葉大学 Chiba University
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HANYANG UNIVERSITY
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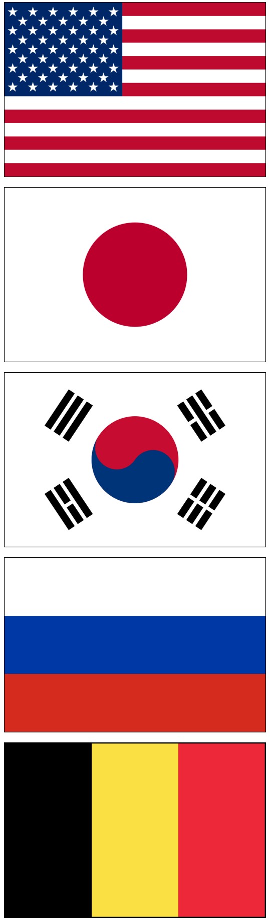
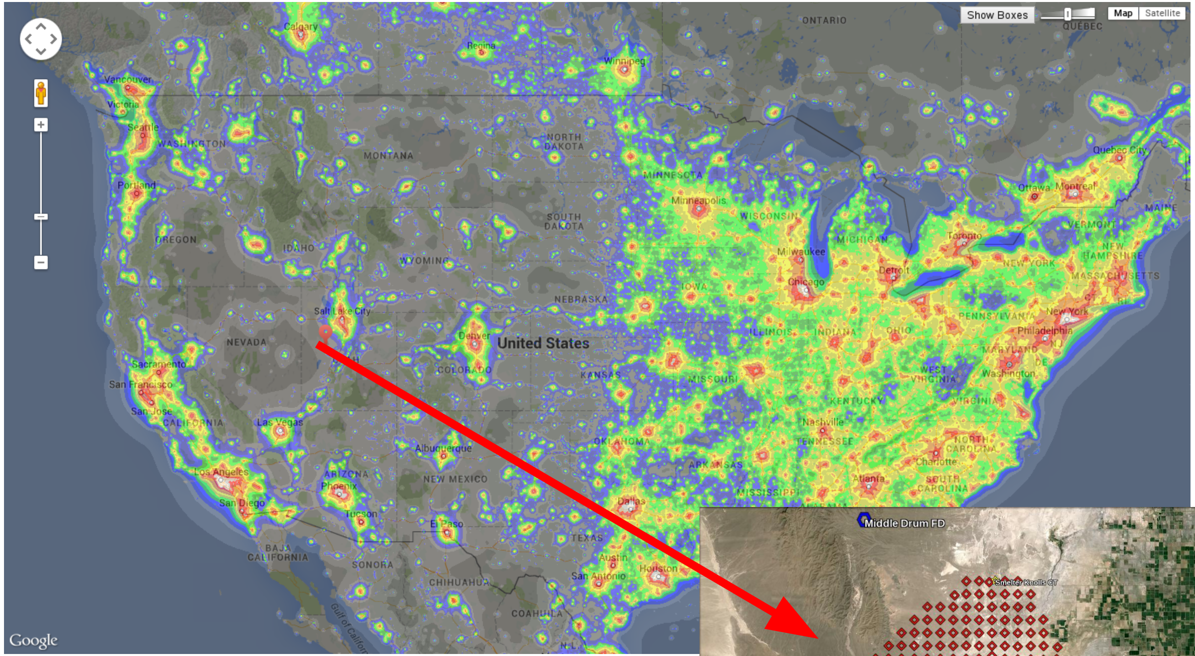
TELESCOPE ARRAY PROJECT
ИНСТИТУТ ЯДЕРНЫХ ИССЛЕДОВАНИЙ РОССИЙСКОЙ АКАДЕМИИ НАУК INSTITUTE FOR NUCLEAR RESEARCH OF RUSSIAN ACADEMY OF SCIENCES
Tokyo University of Science
SHIBAURA INSTITUTE OF TECHNOLOGY
KINKI UNIVERSITY
National University Corporation Kochi University
Saitama University
NIRS National Institute of Radiological Sciences 独立行政法人 放射線医学総合研究所

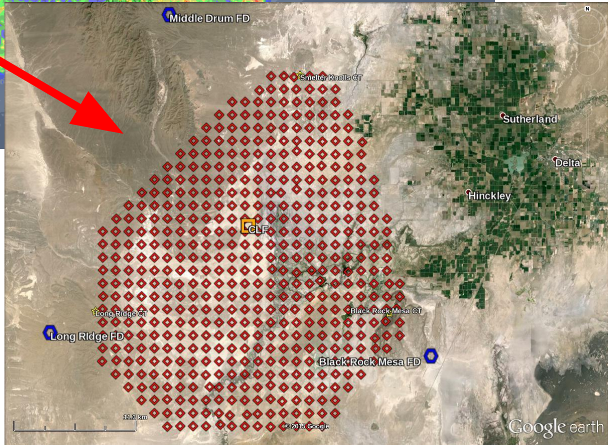
5 nations, 33 institutions, 124 members



TA Observatory



Light pollution map of the U.S.



Largest cosmic ray observatory in the Northern hemisphere.

~750 km^2 → ~ land area of New York City.

Millard County, Utah

39° 17’ 48.90457”
112° 54’ 31.43708”
1370 m

~800 g/cm^2 vertical depth

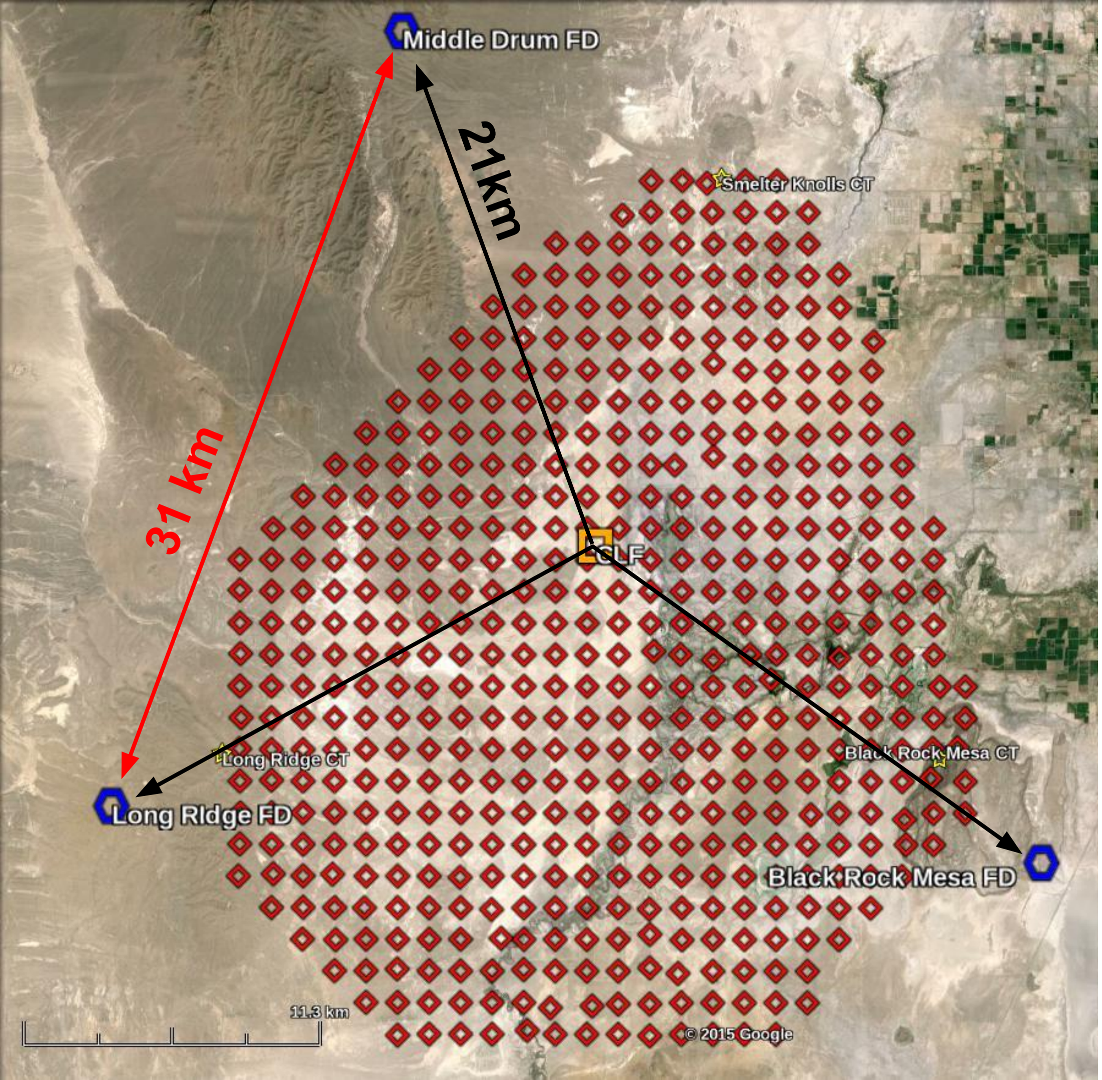
Scintillator surface counters

Air fluorescence telescopes

25 kW radar transmitter

Lightning detection array

40 MeV linear accelerator



TA Detectors

507 scintillation counters surface detector

1.2 km grid spacing (3 m^2 area)

Total detection area: 700 km^2

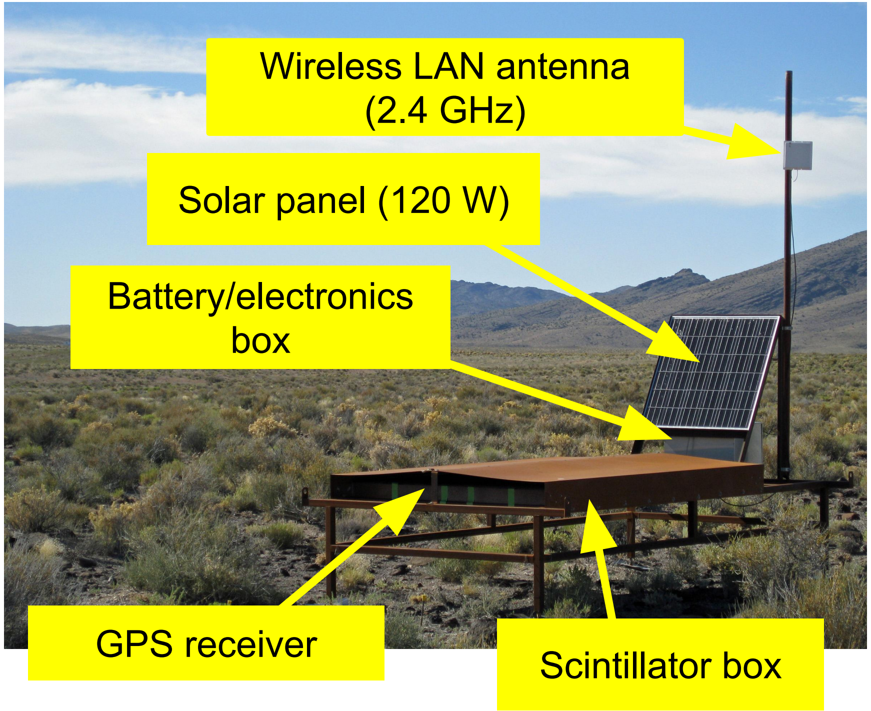
~100% duty cycle

3 fluorescence detector stations

48 FD telescopes

In operation since March 2008

TA Surface Detectors



Solar cell and battery

Wireless LAN (2.4 GHz) communications

12 bit FADC, 50 Msps: 20 nS time resolution, dynamic range of 4096 FADC counts

Event readout/monitoring/calibration via 3 communication towers

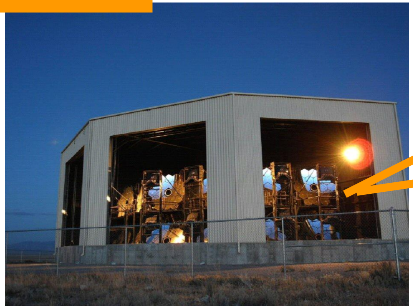
Scintillator:

2 layers (upper and lower), each 3 m^2 x 1.25 cm

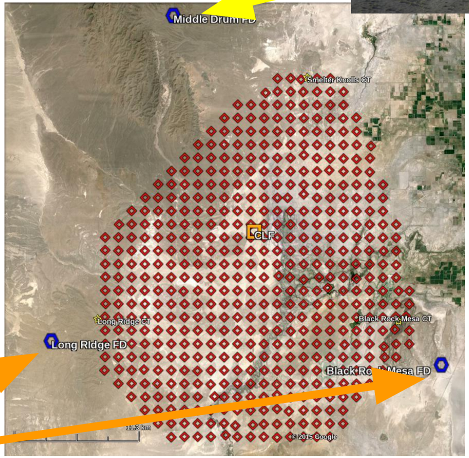
1 PMT for each layer

TA Fluorescence Detectors

6.8 m^2

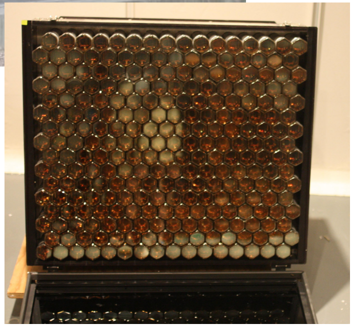


Operation start date
BR: Jun. 2007
LR: Nov. 2007



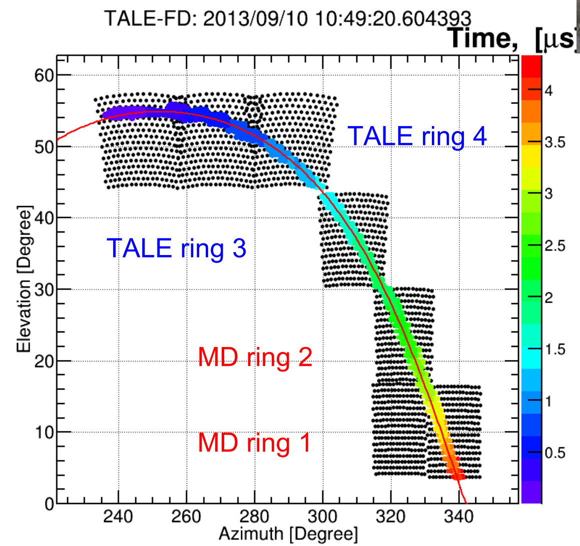
BRM & LR FD stations:
12 telescopes each
256 pixels/telescope @ 1°/pixel
108° azimuth, 3°-33° elevation view
10 MHz FADC readout

5.2 m^2



MD FD station:
14 telescopes
256 pixels/telescope @ 1°/pixel
112° azimuth, 3°-31° elevation view
S/H electronics (HiRes1)
Operation start date: Oct. 2007

TA Low Energy Extension (TALE)



In operation since May 2013

10 additional telescopes

10 MHz FADC (HiRes2)

100° azimuth, 31°- 57° zenith

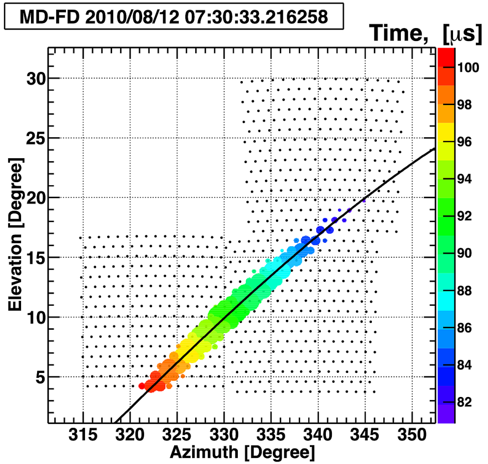
Infill array of 16 scintillation counters now operational (31 in place)

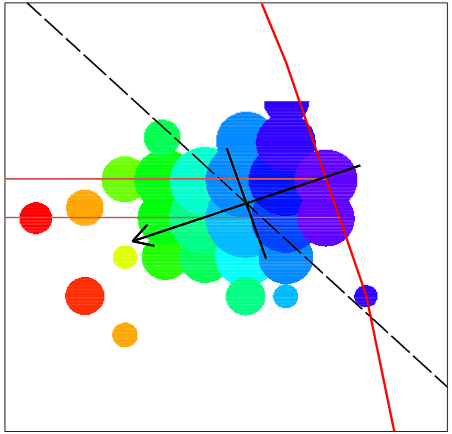
400 m [600 m, 1200 m] spacing

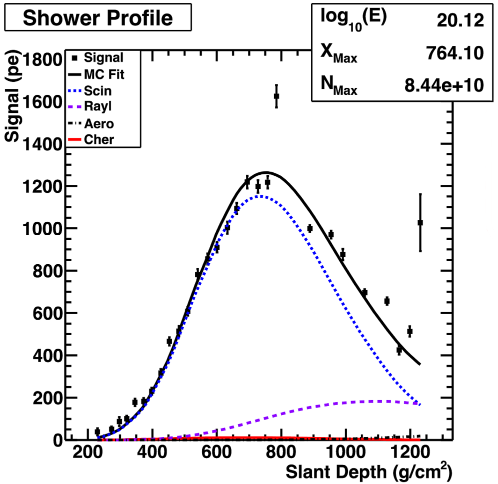
Sensitive $10^{16.5} < E < 10^{18.5}$ eV

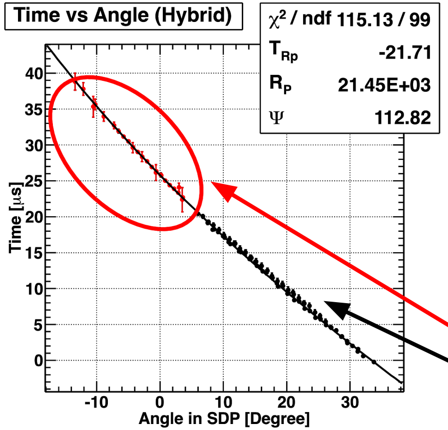
1 detector, 1 energy scale, 1 systematic → galactic to extra-galactic transition in cosmic ray flux → GZK cutoff

TA Hybrid High Energy Event









SD counter hits

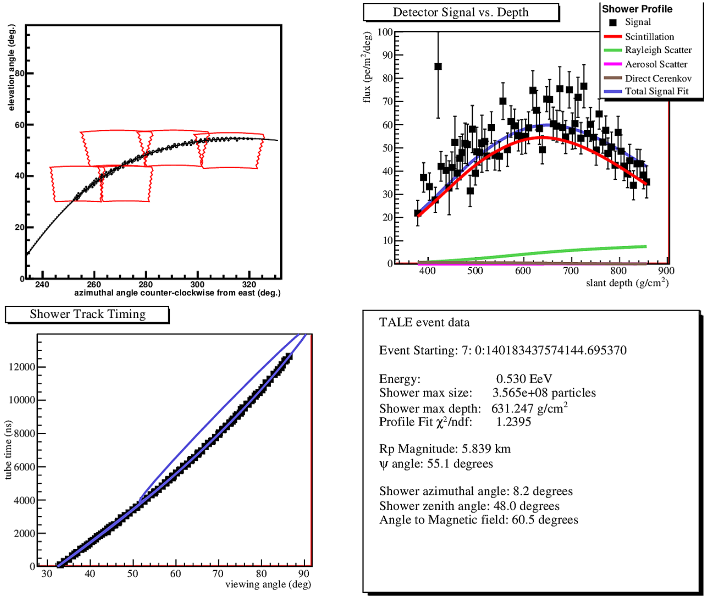
FD tube hits

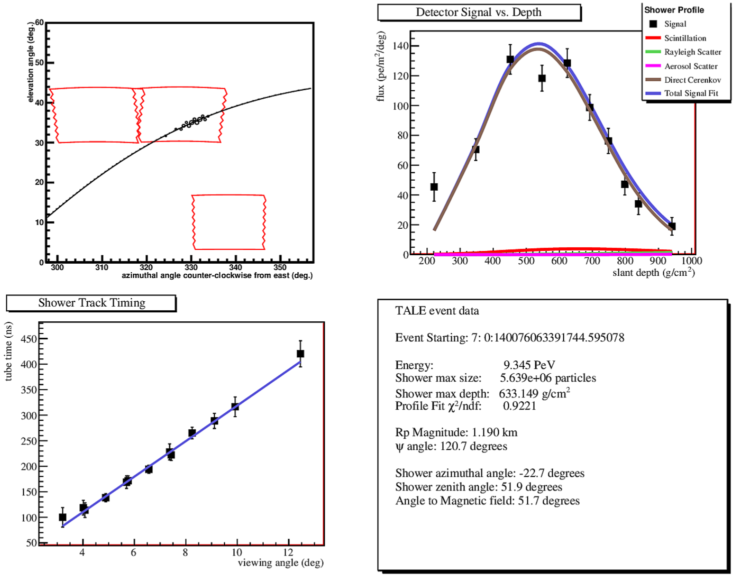
Hybrid combines SD information (core, timing at the ground) with FD information (profile, timing in the atmosphere) to make improved shower measurement.

Energy: 1.3 x 10^{20} eV
R_p: 21 km
zenith: 55.7 deg

Spectrum

TALE as IACT





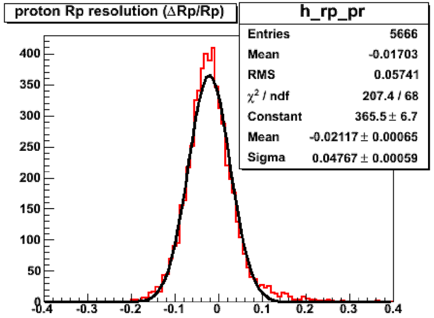
T. AbuZayyad, ICRC2015

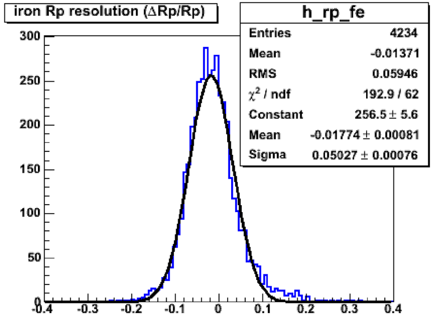
Typical fluorescence event:
5 TALE telescopes (3 MD not shown)
Event duration: ~ few microseconds
Long angular extent
Threshold ~ 3 × 10^{16} eV

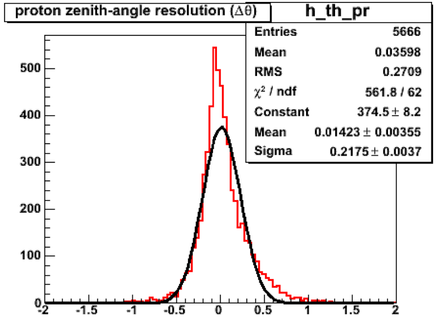
Typical Cherenkov event:
1 TALE telescope
Event duration: 100 - 600 nanoseconds
Short angular extent
Threshold ~ 3 × 10^{15} eV
Viewing angle ~ 10°, detection volume limited

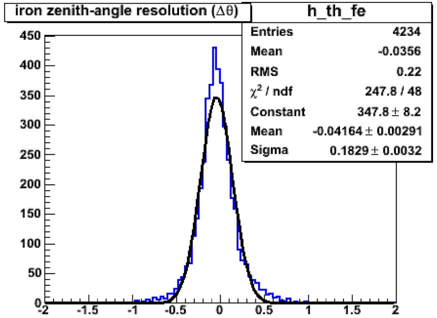
TALE Cherenkov

Geometry

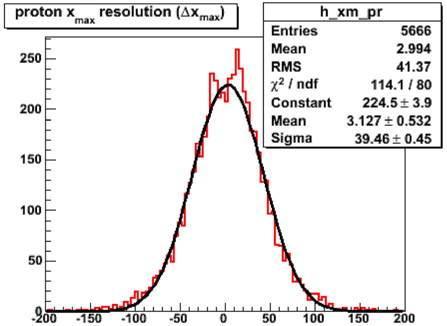


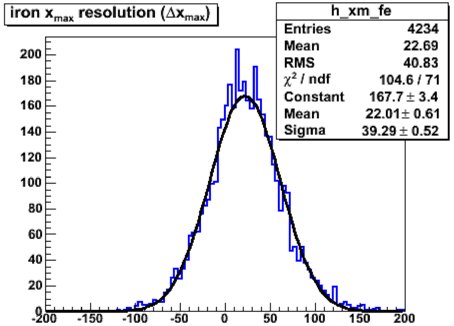


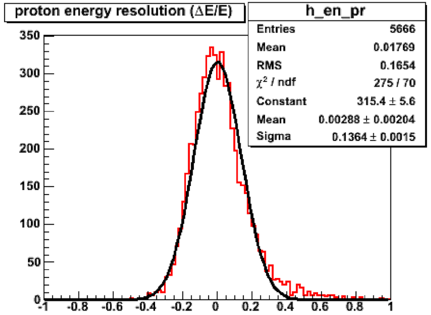


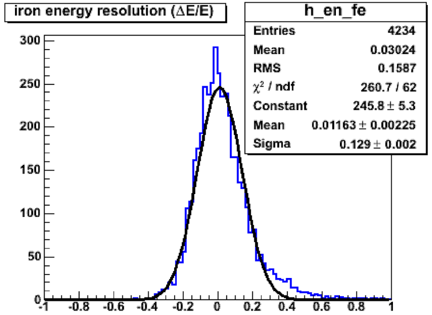


Profile

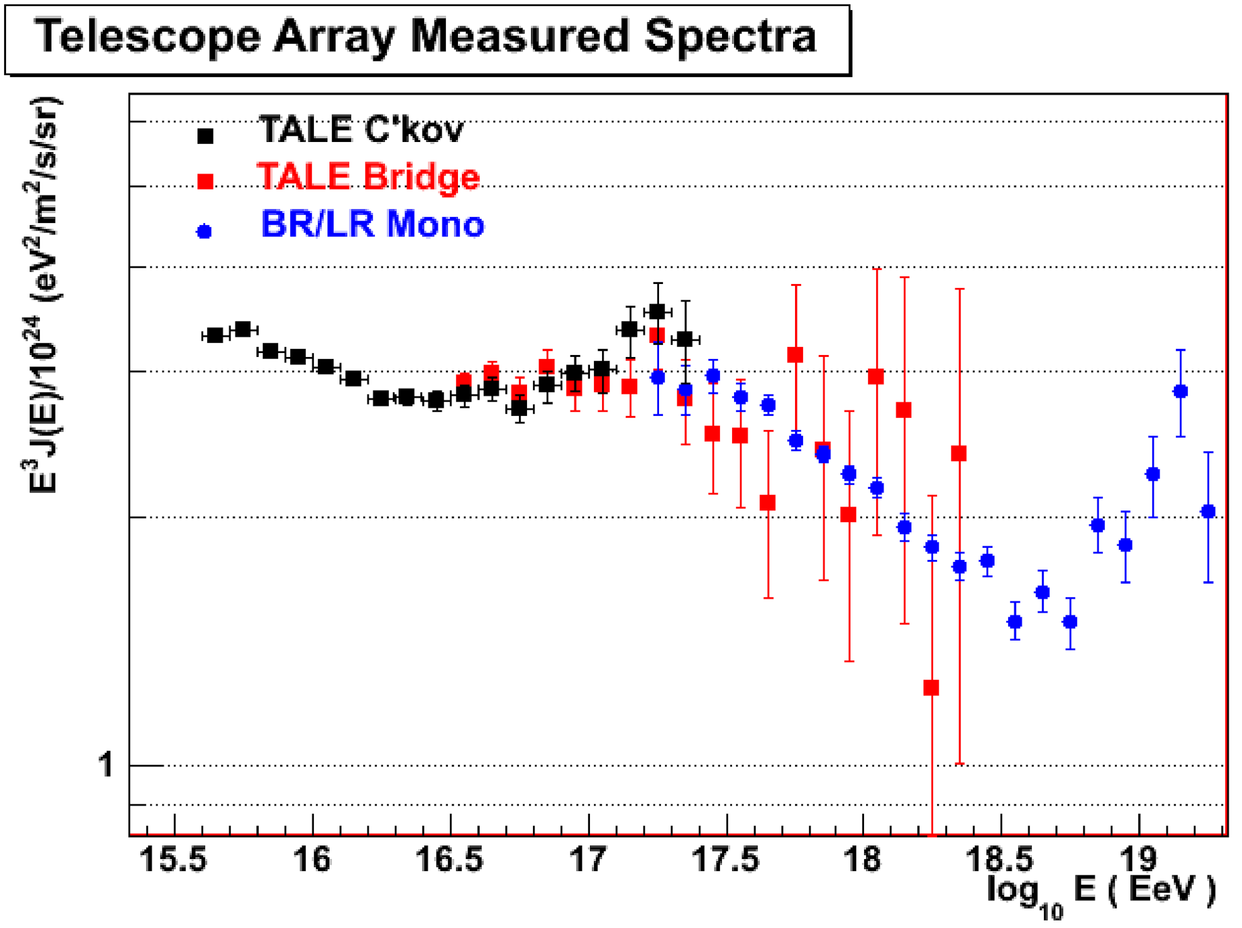








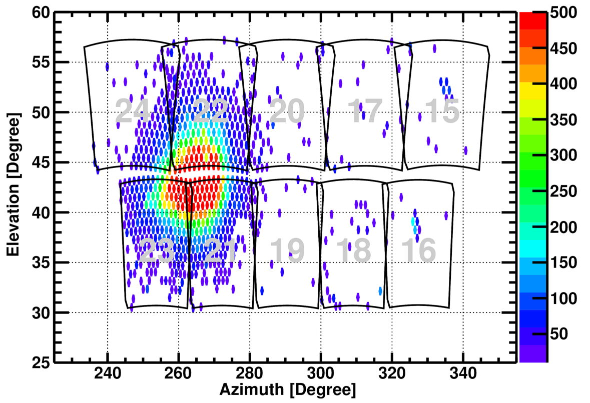
TALE Spectrum via Cherenkov - 1st measurement



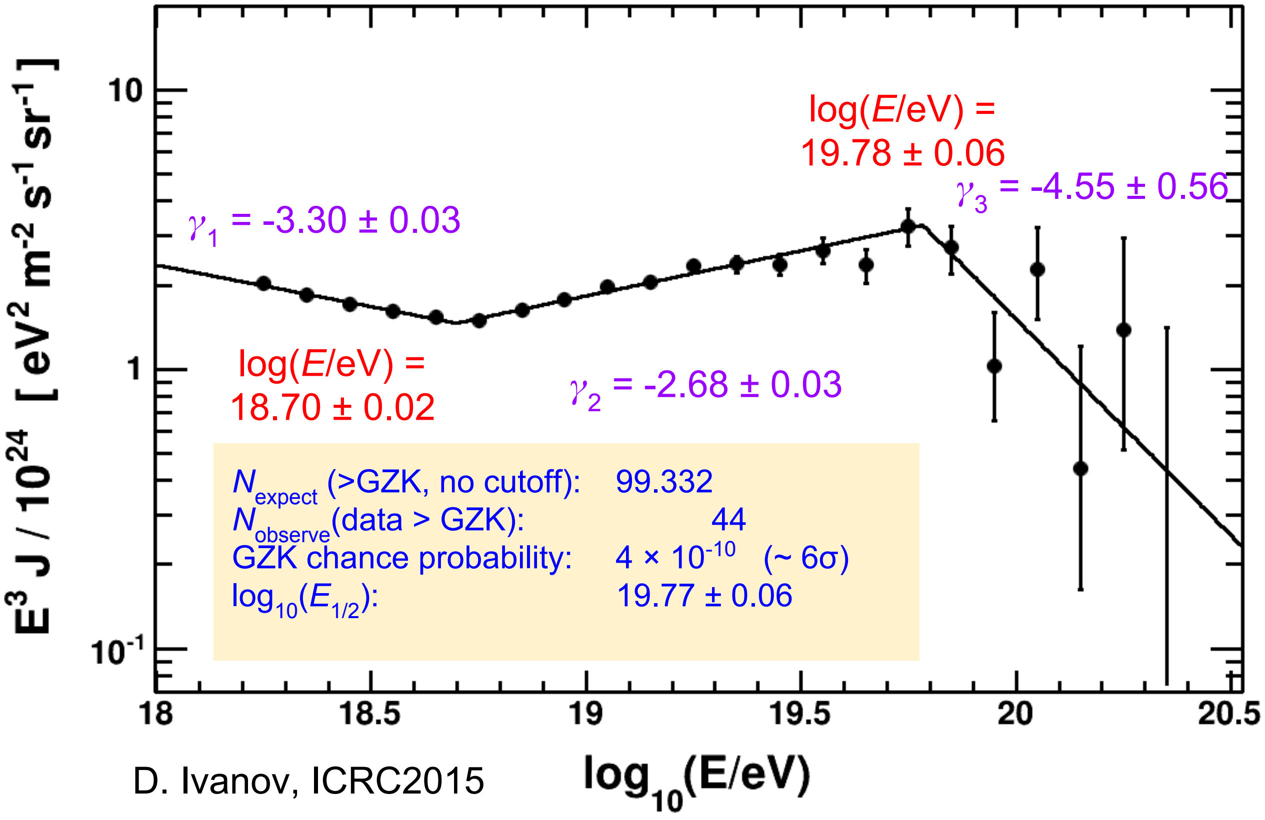
PCGF method - same as used for HiRes1 mono

Simultaneous geom/profile fit. Zenith angle is well constrained.

Extends ~ 2 decades below FD mono, ~ 1 decade below TALE bridge.

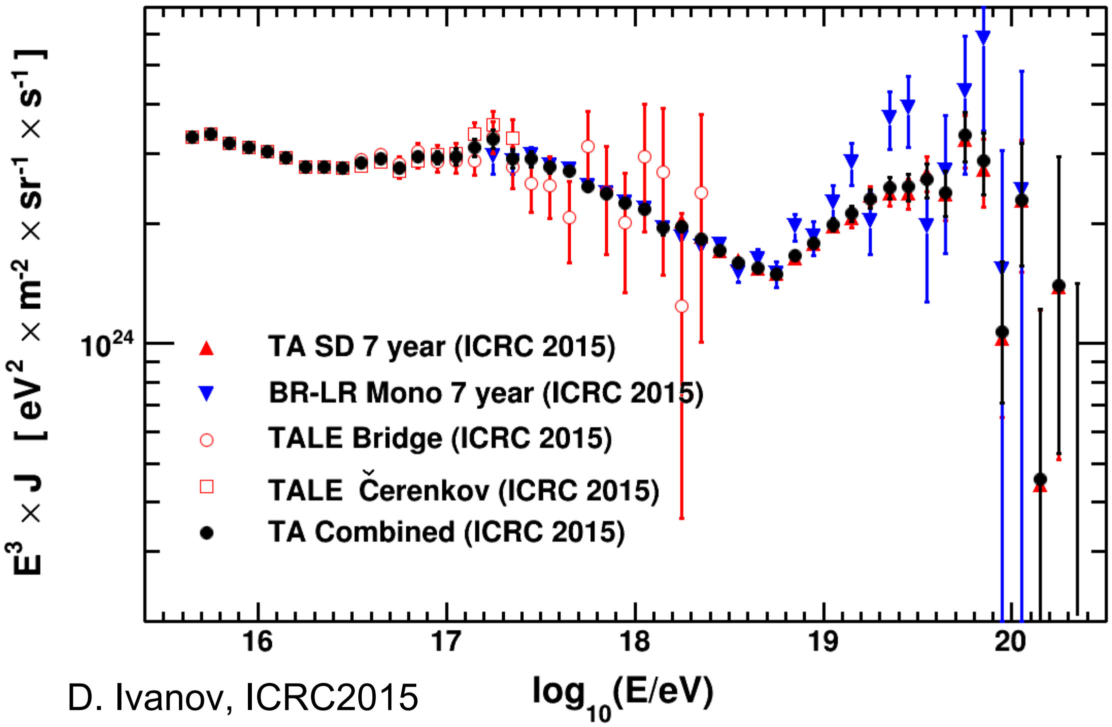


TA 7 year SD Spectrum



D. Ivanov, ICRC2015

TA Combined Spectrum

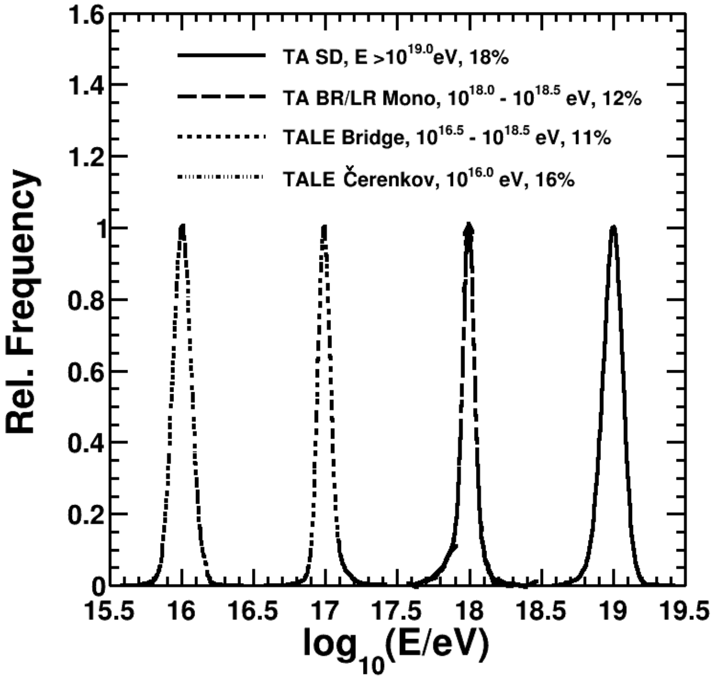


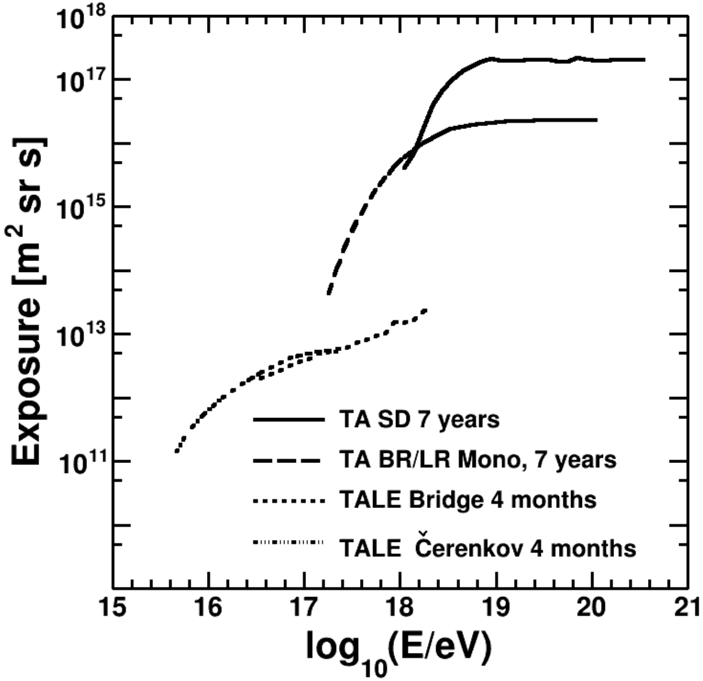
D. Ivanov, ICRC2015

TA observes 4 distinct features of the cosmic ray spectrum:

Low energy ankle	$10^{16.34 \pm 0.04}$ eV
2nd knee	$10^{17.30 \pm 0.05}$ eV
High energy ankle	$10^{18.72 \pm 0.02}$ eV
GZK cutoff	$10^{19.80 \pm 0.05}$ eV

TA Combined Spectrum Energy Resolution & Exposure

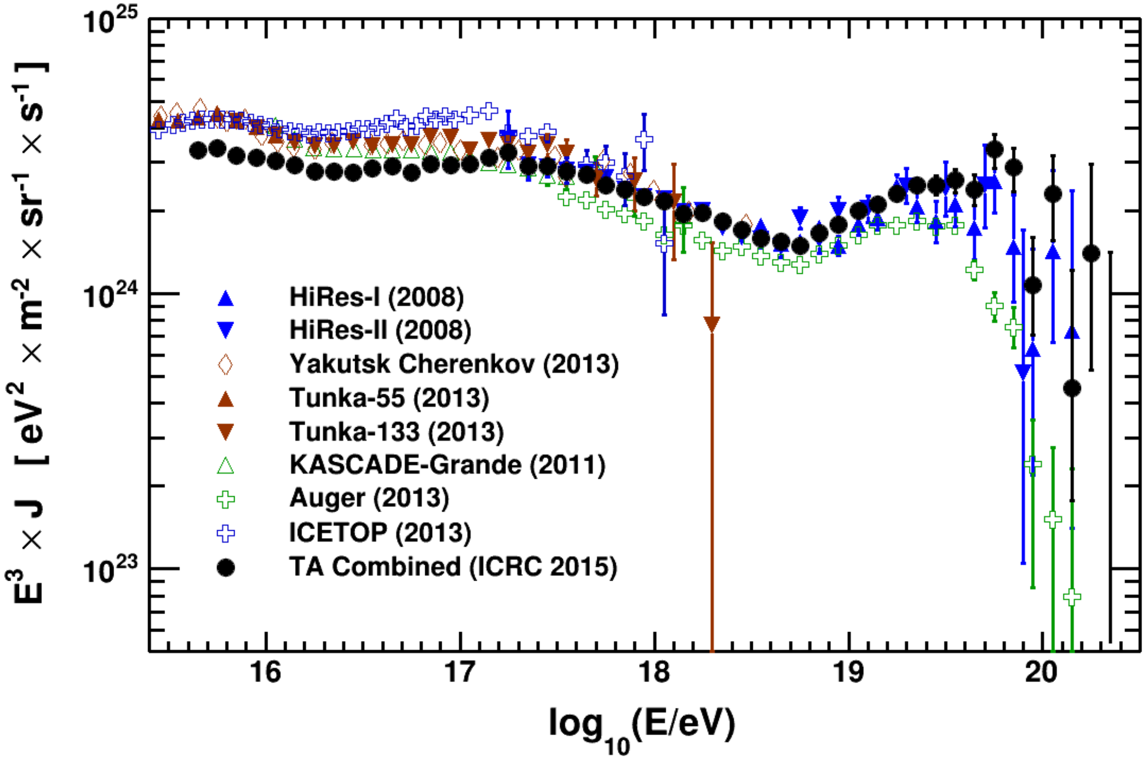




D. Ivanov, ICRC2015

4 components of TA spectrum: TALE Cherenkov, TALE bridge, TA BR/LR monocular, TA SD.

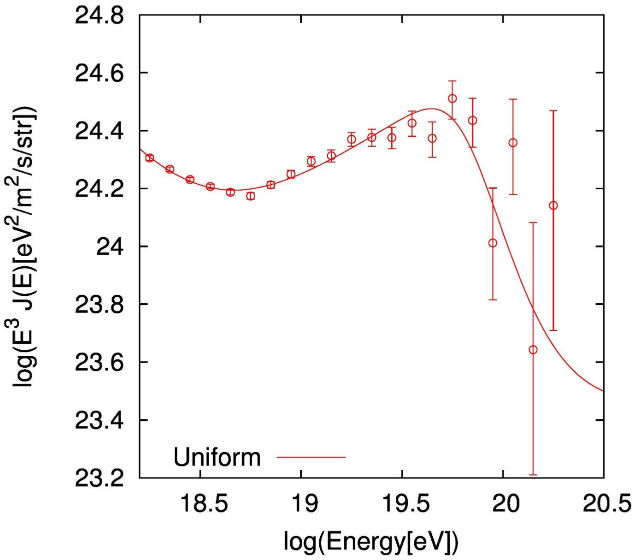
TA Combined Spectrum Comparison

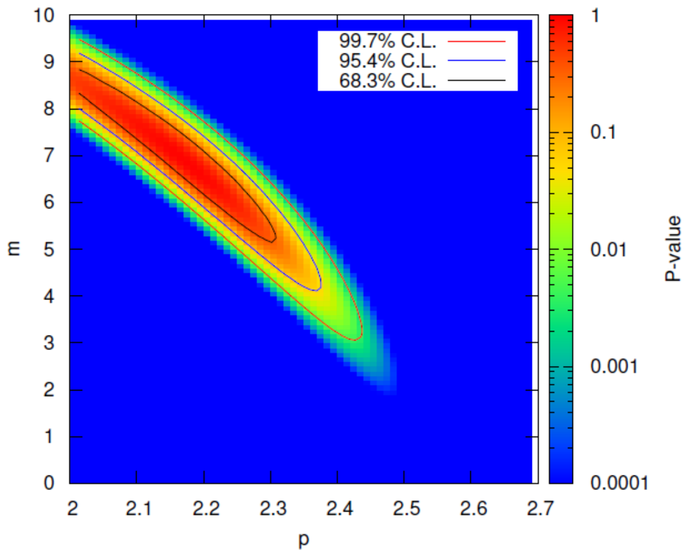


Fitting TA UHECR Spectrum

7 year TA SD spectrum
Uniform proton source distribution, $E > 10^{18.2}$ eV
Injection spectrum E^{-p}, $E_{max} = 10^{21}$ eV
Evolving source density $\propto (1 + z)^m$
Energy losses with CMB and IRB simulated
$z < 0.7$, $B_{IG} < 10^{-10}$ G

p = 2.18 + 0.08 - 0.14 [stat. + sys.]
m = 6.8 + 1.6 - 1.1 [stat. + sys.]
χ^2 = 18.0/17

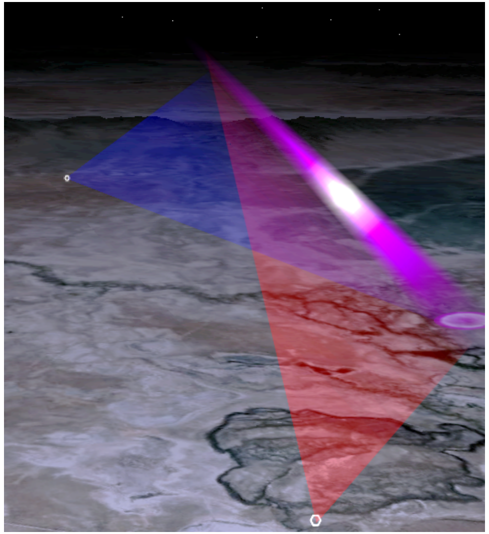


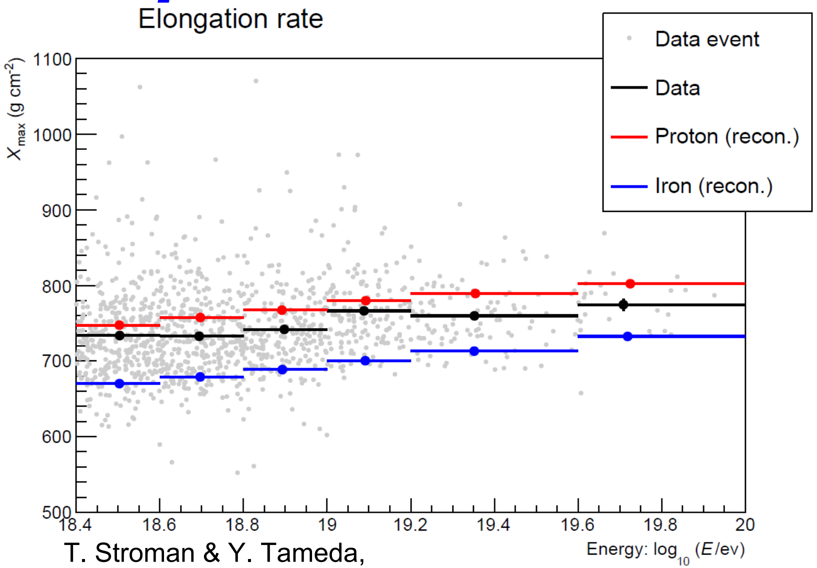


E. Kido, ICRC2015

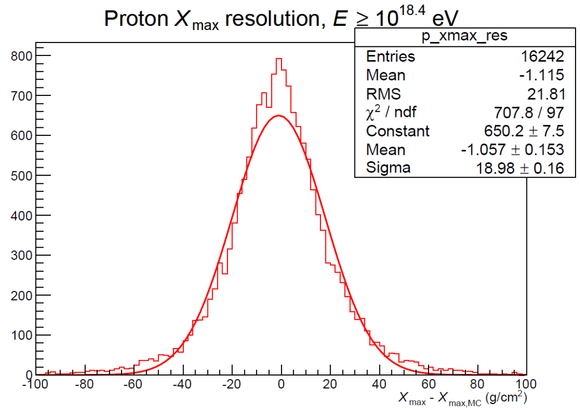
Composition

TA Composition - Stereo



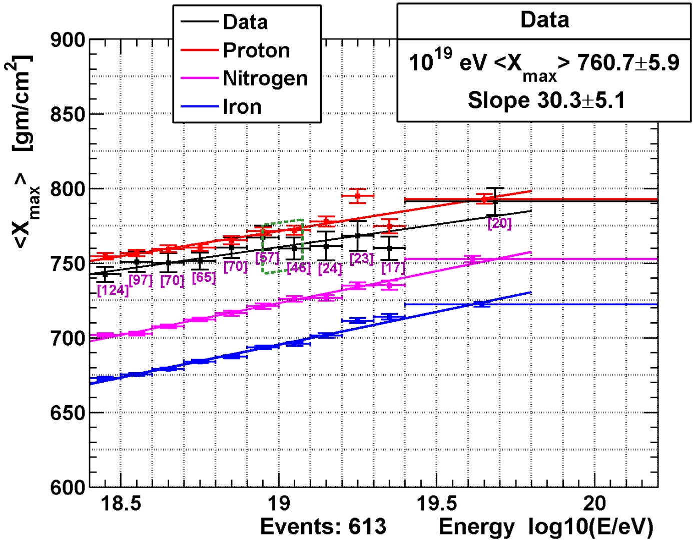


T. Stroman & Y. Tameda, ICRC2015

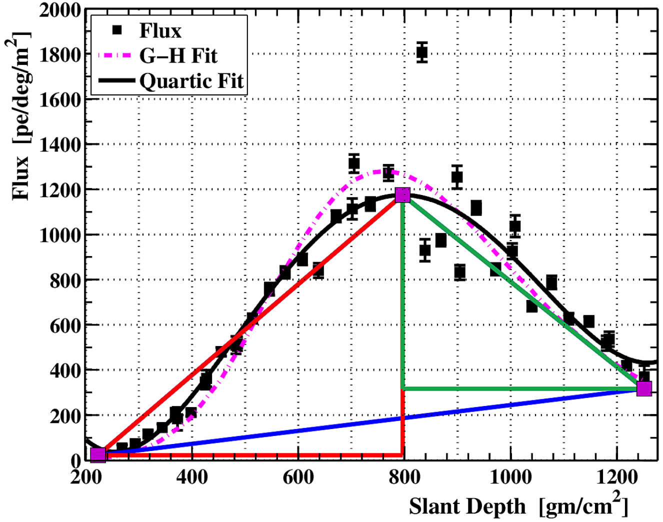


7 years data - all FD stations (excluding TALE) - 38 telescopes
Events must be observed by multiple FDs
$\log_{10}(E/\mathrm{eV}) > 18.4$
1160 events
X_{max} resolution ~ 19 g/cm^2, reconstruction bias ~ 1 g/cm^2
Energy resolution ~ 6%

TA Composition - MD Hybrid



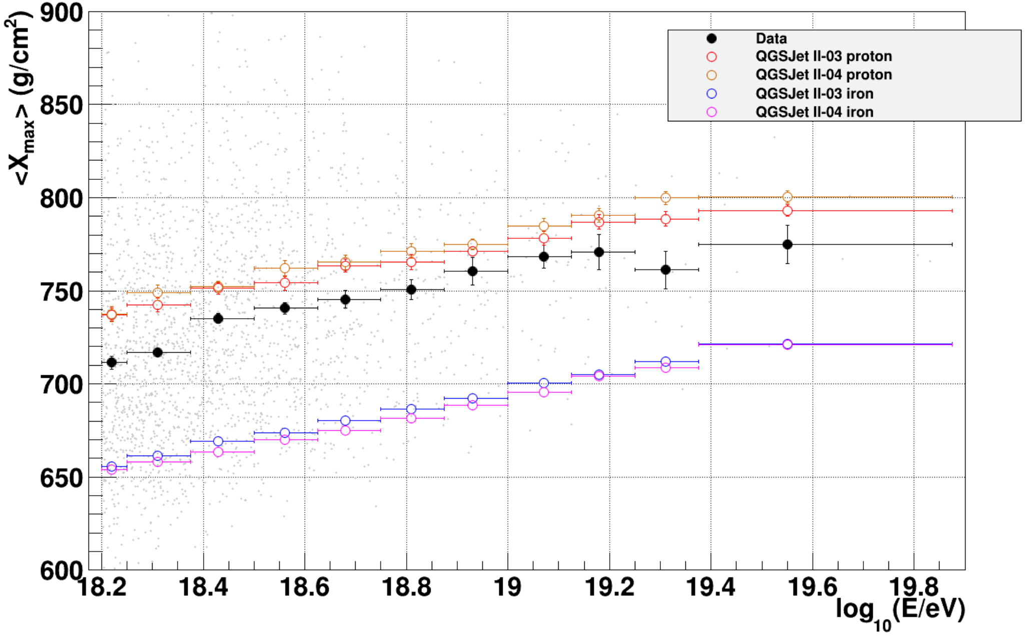
J.P. Lundquist, ICRC2015



R. Abbasi et al., Astropart.Phys. **64** (2014)

7 years of MD FD hybrid data - 623 events [$\log_{10}(E/\mathrm{eV}) > 18.4$]
Improved reconstruction via *pattern recognition* method → ensures curvature of profile is well measured.
X_{max} resolution ~ 22 g/cm^2, reconstruction bias < 2 g/cm^2
Energy resolution ~ 7%

TA Composition - BR/LR Hybrid



W. Hanlon, ICRC 2015

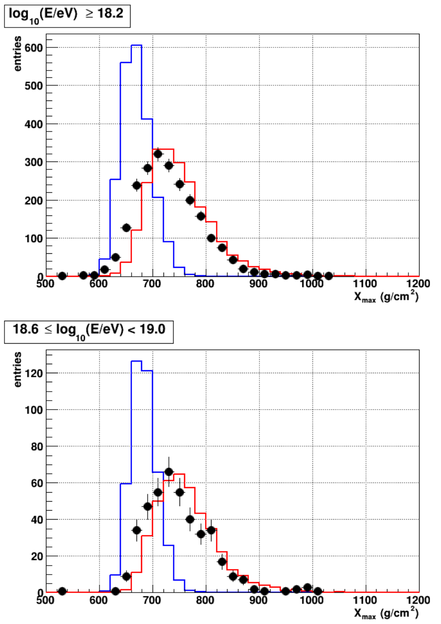
6 years BR/LR hybrid composition

X_{max} resolution 20 g/cm^2

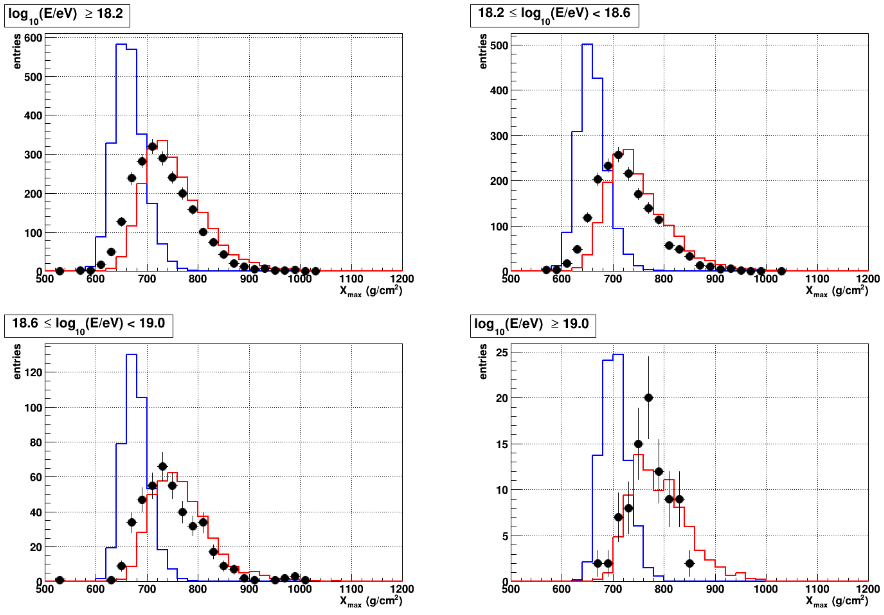
"Standard" quality cuts:
zenith < 57 degrees
Profile & geometry chi^2 cuts
X_{max} bracketing
track length > 10 degrees

Highest statistics composition - 2211 events
vs. 1160 (stereo)
vs. 623 (MD hybrid)

TA Composition - Comparison to Models I



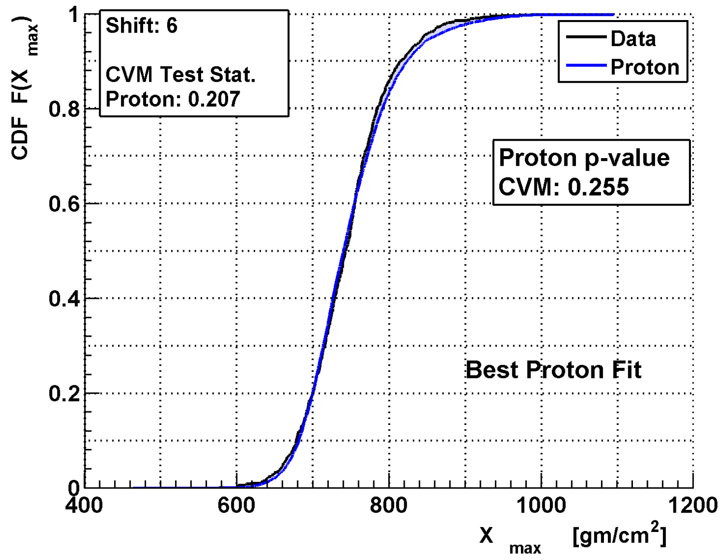
QGSJet II-03

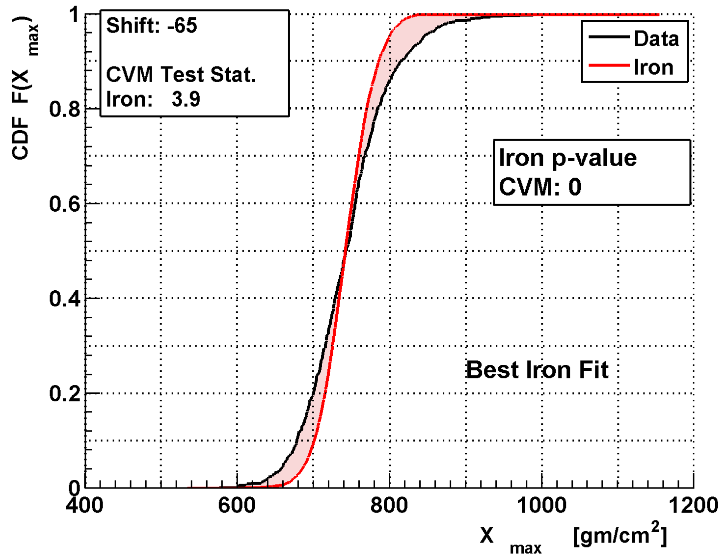


QGSJet II-04

Iron is ruled out. Light composition is favored above $10^{18.2}$ eV.

Composition - Statistical Tests



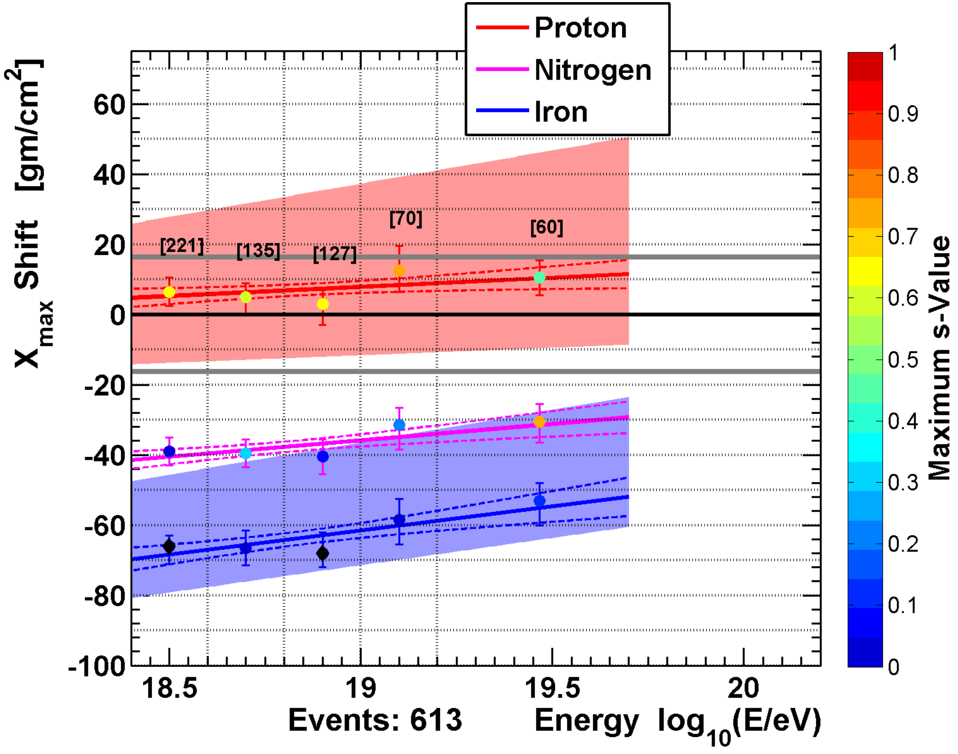


Cramér-von Mises test

$$\omega^2 = \int_{-\infty}^{\infty} \left[F_n(x) - F^*(x)\right]^2 dF^*(x)$$

No binning required
Uses square of the differences of the cumulative distributions
Removes problems in comparing only 1st and 2nd moments which get pulled heavily by missing or poorly sampled tails.

TA Composition - Comparison to Models II

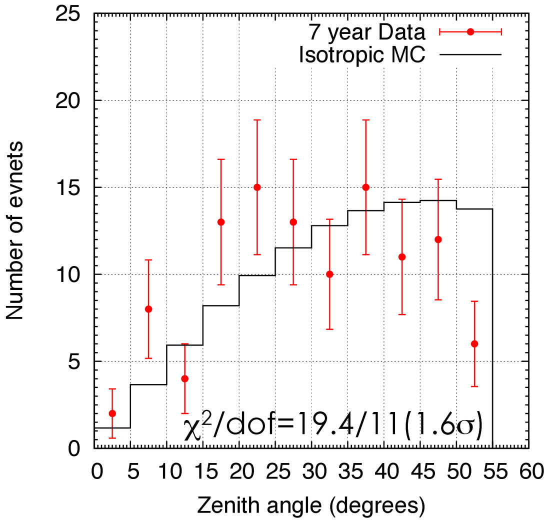


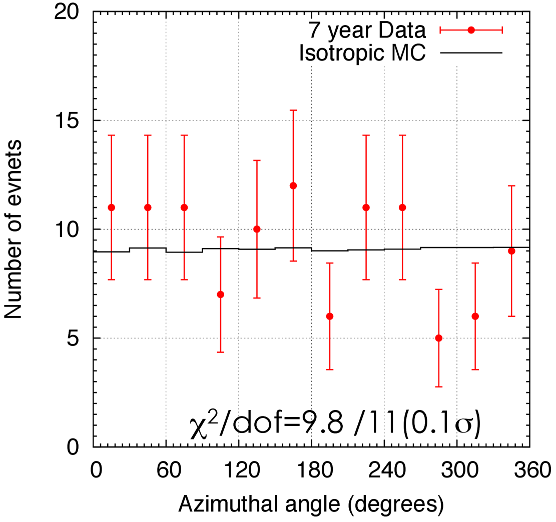
TA is consistent with light composition below $10^{19.5}$ eV.

TA data excludes iron using all QGSJet, Sibyll, EPOS models. Nitrogen is disfavored as well.

Anisotropy

TA Anisotropy - Method



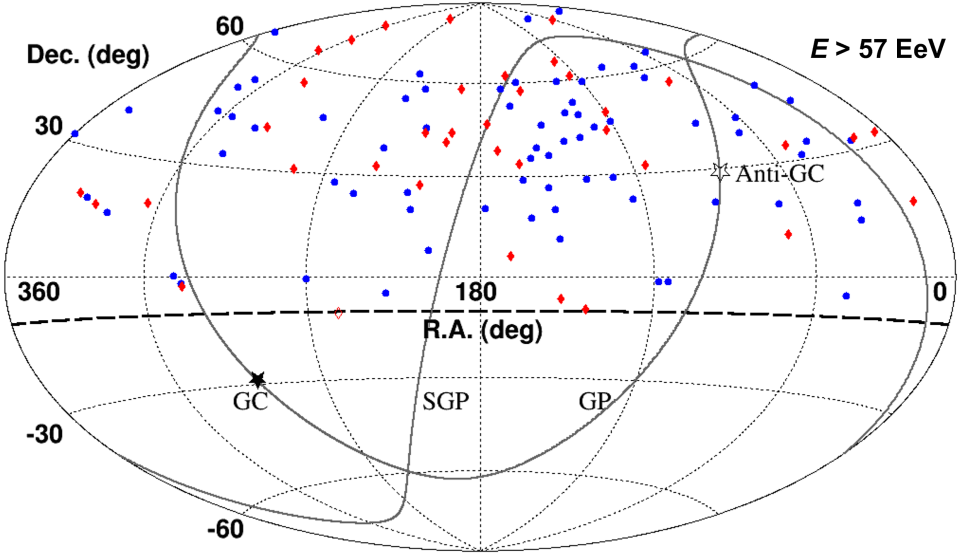


Period: 2008 May - 2015 May (7 years)
Angular resolution: ~ 1°

Cuts:
# of counters >= 4
zenith angle < 55°
energy > 57 EeV
loose boundary cut

Procedure:
- For each point on the sky map grid, cosmic ray events are summed in 20° circles (oversampling): N_{sig}
- Generate 100,000 MC sets assuming isotropic flux and geometric exposure, sum in 20° circles: N_{bg}
- Normalize N_{bg} to the total number of data events observed.
- Significance is excess is computed using Li-Ma.
- Chance probability to observe this excess: Generate 1 million MC sets each having N_{sig} events for uniform distribution over TA SD exposure, max significance is calculated for each set. Count the sets that have signficiance >= that found in "hotspot".

TA Anisotropy - Hotspot (7 yr update)

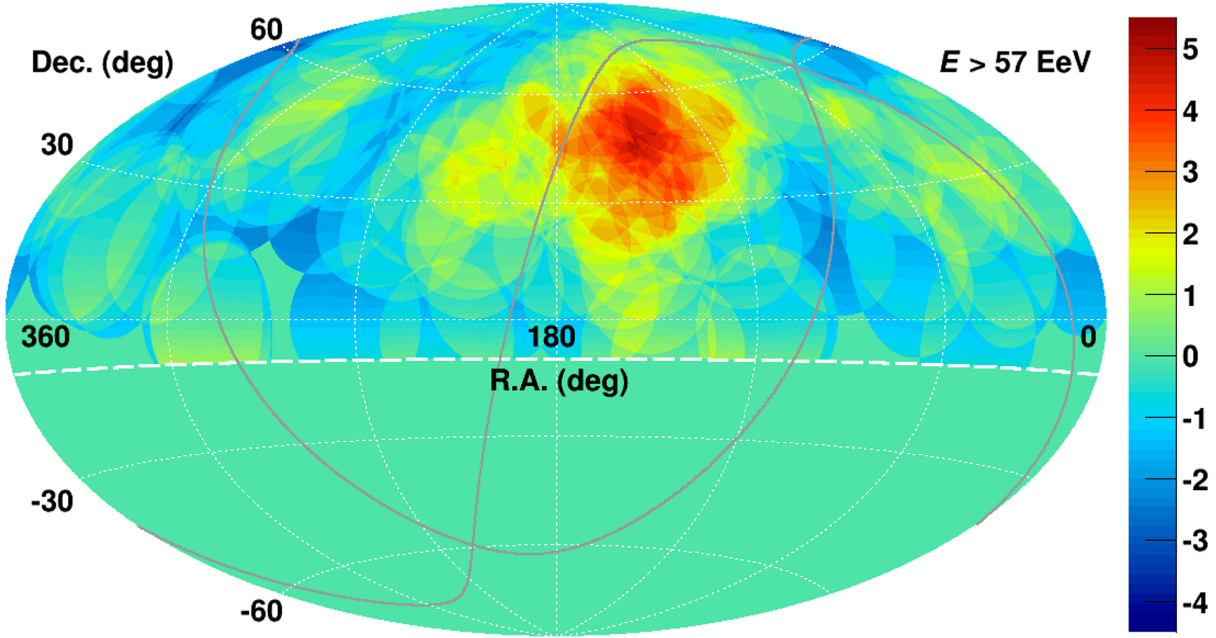


First 5 year data → 72 events, 3.4 σ [ApJ 790 L21 (2014)]
New 2 year data → +37 events, 3.4 σ
Total 109 events (7 years SD, 2008 May 11 - 2015 May 11)

K. Kawata, ICRC2015

Period	Total (E > 57 EeV)	Hotspot signal	Background	Chance Prob (%)	Center position (RA/Dec)
6th year	15	3	0.94	7	146.7°, 43.2°
7th year	22	1	1.37	74	146.7°, 43.2°
6th + 7th year	37	4	2.31	20	146.7°, 43.2°

TA Anisotropy - Significance Map



K. Kawata, ICRC2015

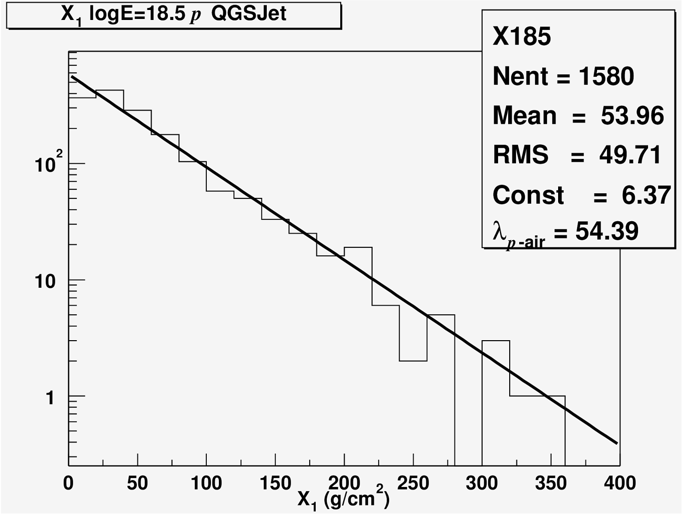
Oversampling with 20° radius circle

TA sees excess significance below the super galactic plane near the Ursa Major Cluster.

Max significance 5.1 σ (N_{sig} = 24, N_{bg} = 6.88) for 7 years SD data
Centered at RA/Dec = 148.4°, 44.5° (Shifted from SGP by 17°)
Global excess chance probability: $3.7 \times 10^{-4} \rightarrow 3.4\ \sigma$

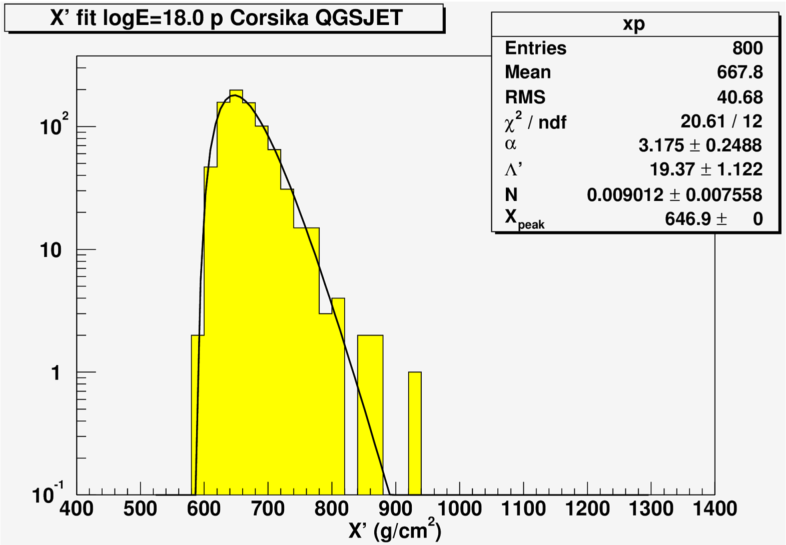
p-air Cross Section

Measuring $\sigma_{p\text{-}air}$



Depth of first interaction X_1. Slope is direct measure of $\lambda_{p\text{-}air}$. X_1 depends only on $\sigma_{p\text{-}air}$.

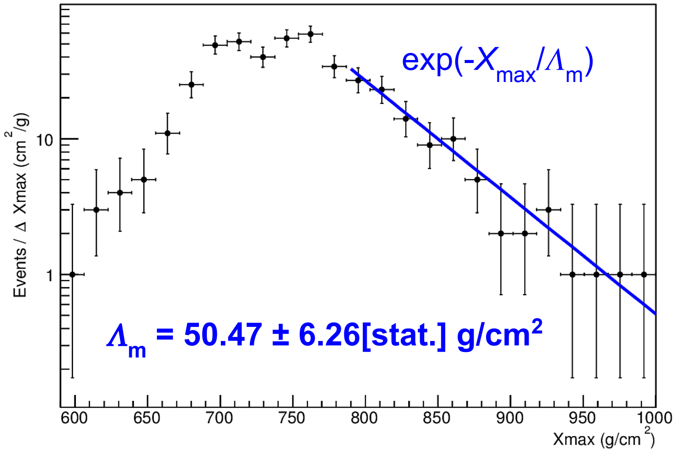
Not observed by FDs though.

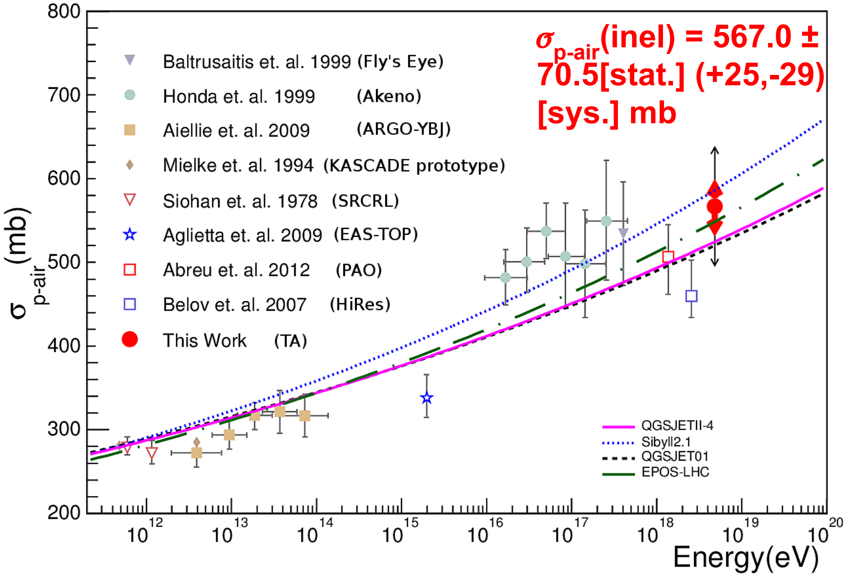


Air shower development after X_1 is affected by fluctuations in first interaction depth, as well as hadronic cross section, inelasticity, multiplicity.

* Model dependence

TA $\sigma_{p\text{-}air}$ (inel) measurement





R. Abbasi, ICRC2015

K factor method:

$$\Lambda_m = K\,\lambda_{p\text{-}air} = K\,(14.45\ m_p/\sigma_{p\text{-}air})$$

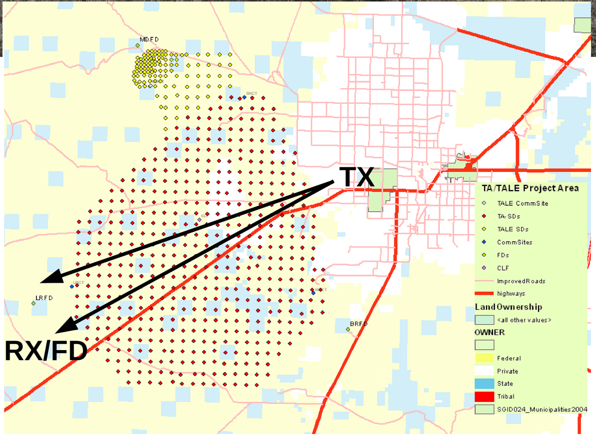
K is model dependent.

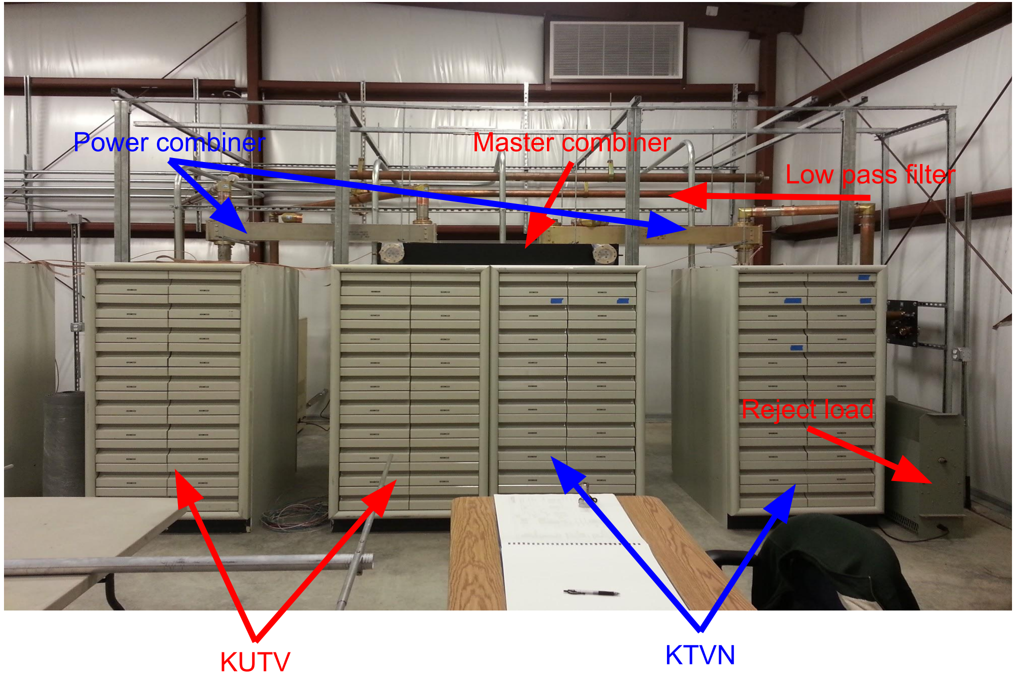
Systematic source	Systematic (mb)
Model dependence	± 17
20% Helium	+18
gamma<1%	-23
Total	(+25, -29)

$\langle E \rangle = 10^{18.68}$ eV → $\sqrt{s}$ = 95 TeV

Radar Cross Section

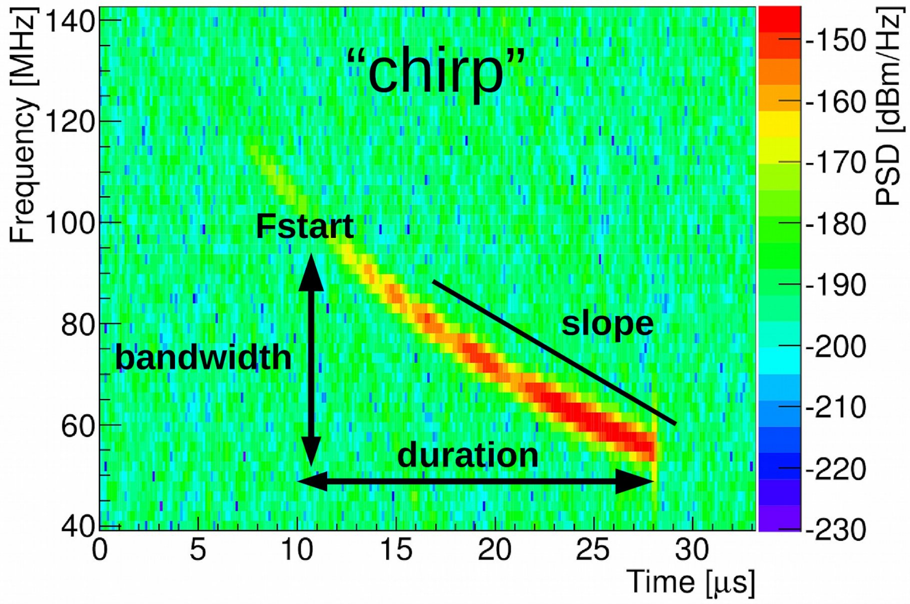
TA Radar (TARA)





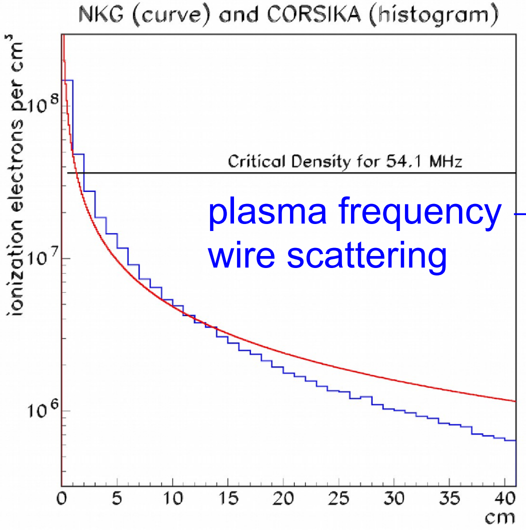
Bistatic radar technique
25 kW CW, 54.1 MHz transmitter (max cap 40 kW - 8 MW ERP)
22.6 dBi gain → 5 MW ERP
4 channel, 250 MS/s, broadband, dual polarization receiver
Trigger logic: on-the-fly chirp match filter or FD coincidence
Chirp detection limit via match filter: ~ -10 dB
Chirp frequencies expected: ~ 1 - 10 MHz/μsec

TARA Radar Echo Simulation



$$P = \frac{P_T G_T}{4\pi R_T^2} \sigma_{TW} \frac{G_R \lambda^2}{(4\pi)^2 R_R^2}$$

σ_{TW} = thin-wire radar cross section

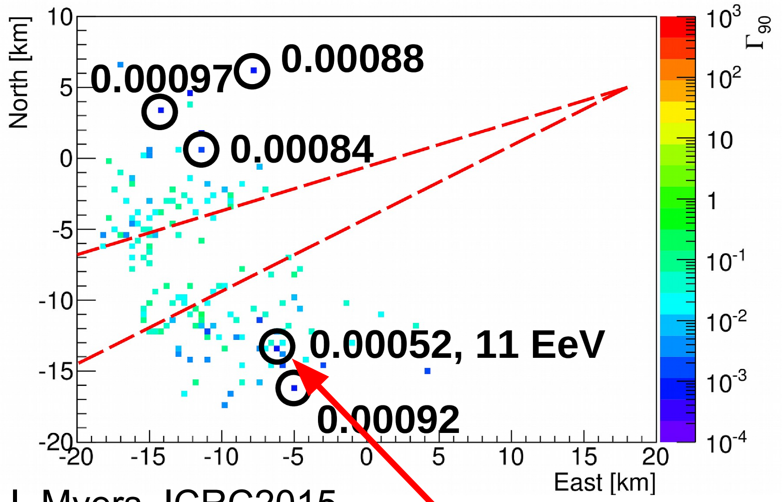


plasma frequency → thin wire scattering

Frequency response is not model dependent

Signal response is model dependent (collisional dampening, electron recombination time, EAS core free electron density)

TARA RCS Upper Limit Measurement



I. Myers, ICRC2015

6 months of FD triggered data between 2013 Aug - 2014 Apr.
Time match with well reconstructed events: 1292.
Match filter threshold by snapshot events: 3 x RMS is threshold for triggered events.

17 events out of 1292 pass threshold.
17.8 from snapshot match filter distributions also exceed threshold.
60 % chance probability → no detection

Date	$\Gamma_{90} \times 10^4$	Energy (EeV)
20130809	8.4 + 5.0	1.22
20130816	8.8 + 2.0	1.43
20130926	9.7 + 2.8	1.38
20131105	9.2 + 3.9	1.83
20131202	5.2 + 2.5	11.04

RCS calculation:
- insert simulated chirp waveform in snapshots with scale factor Λ
- find Λ_{90} such that 90% of snapshots exceed threshold
- $\Lambda_{90}^2 = \Gamma_{90}$, proportional to RCS
- $\sigma_{EAS} < \Gamma_{90} \times \sigma_{TW}$ (90% c.l.)

Peak RCS ~ 42 cm^2 (11.04 EeV event)

TA Expansion (TA × 4)

Fourfold increase in the size of the TA SD array.

Add 500 scintillator SDs @ 2.08 km spacing.

Add 2 FD stations, 28 telescopes

Get 20 TA years of data by 2020.

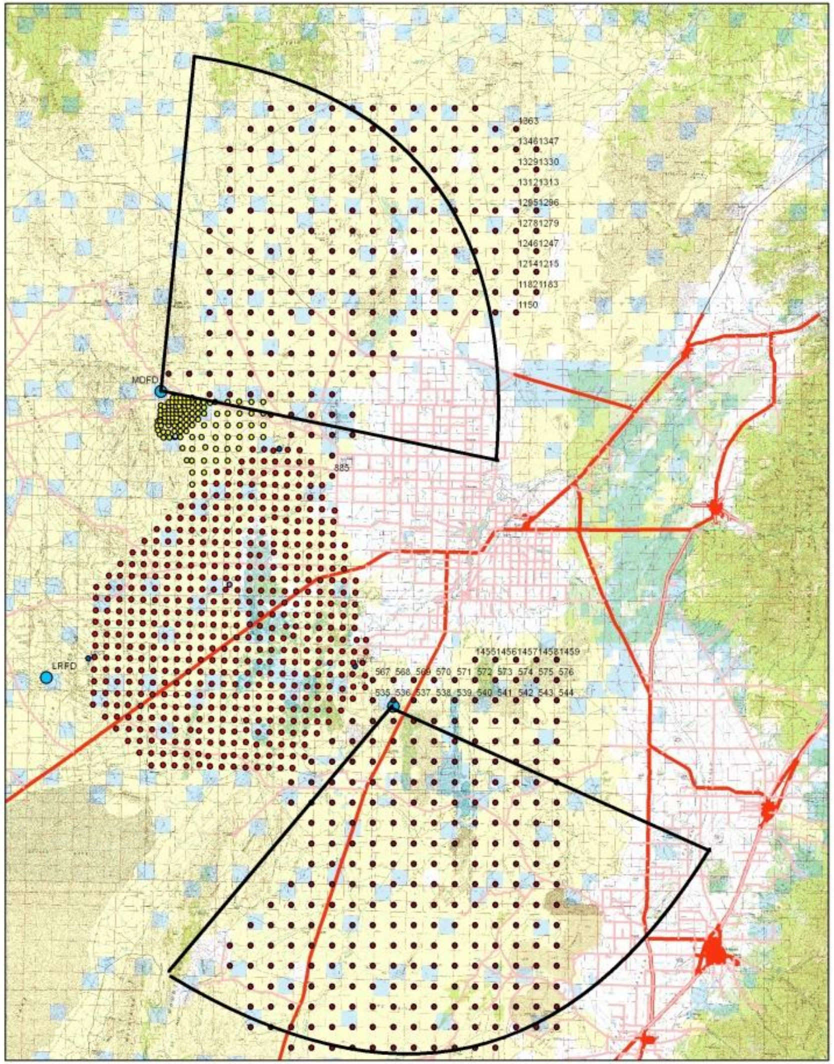
Increased statistics for highest energy range (> 57 EeV) to answer the question of the hotspot.

Proposals:

~~SD: April 2015.~~ Approved in Japan!

FD: October 2015 submission

See Dr. Hiroyuki Sagawa's presentation @ 17:30 for further discussion.

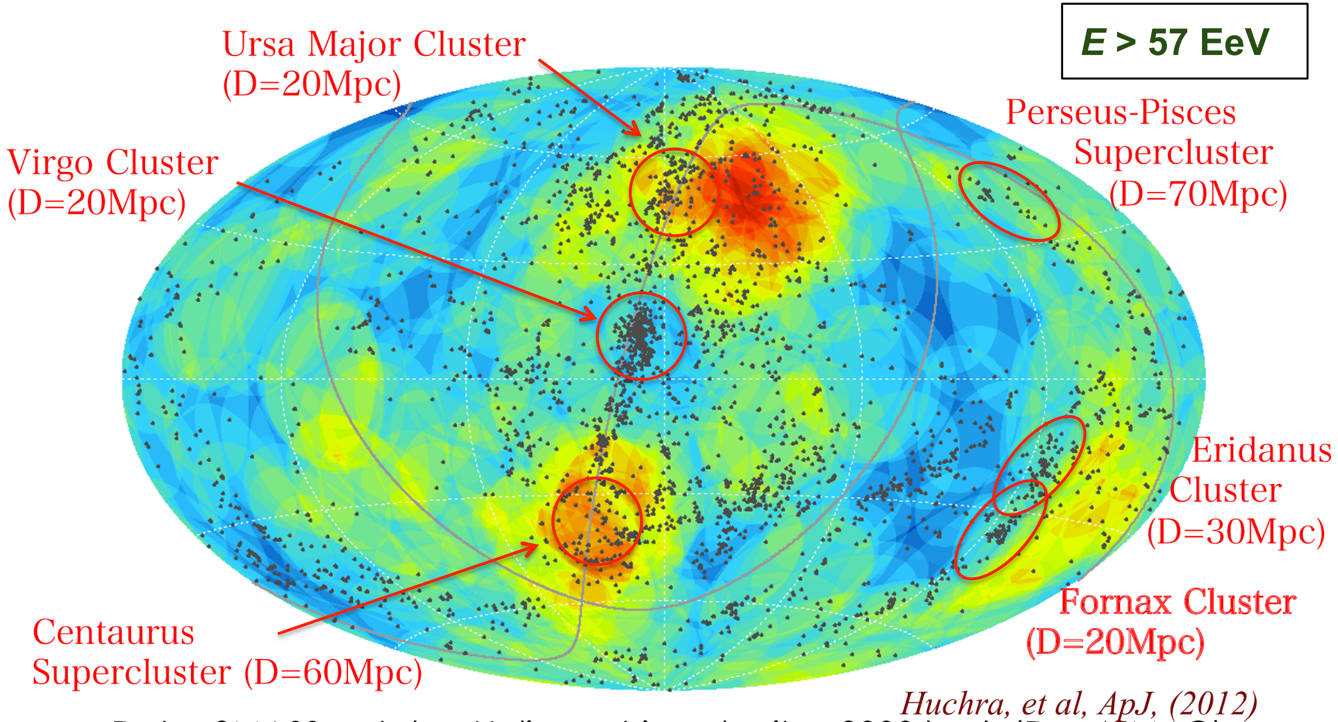


Conclusions

- TA has entered its 8th year of data collection
- TA measured the energy spectrum, composition, arrival directions, cross section of UHE cosmic rays.
- TA/TALE covers 4.4 decades in energy and observes 4 distinct spectral features.
- The spectrum & composition above the ankle remains consistent with a predominantly light primary above $10^{18.4}$ eV.
- We have extended our measurement of the hotspot in the vicinity of Ursa Major with 2 years of additional data, and see hints of anisotropy with 3.4σ significance.
- TAx4: Fourfold expansion of TA SD array is approved → more data to answer questions about the hotspot.

Supplemental Material

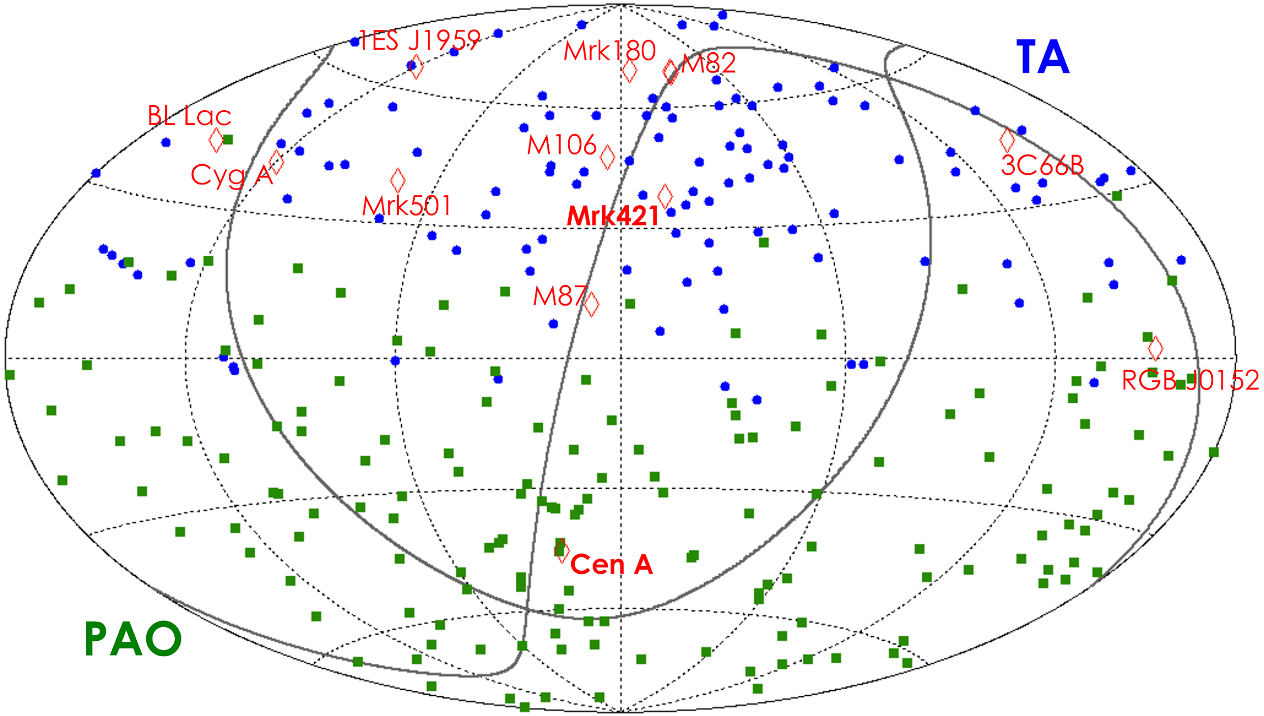
TA Anisotropy - Nearby Galaxy Clusters



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

All-sky significance: TA Northern and PAO southern.
No energy scale correction between TA & PAO.

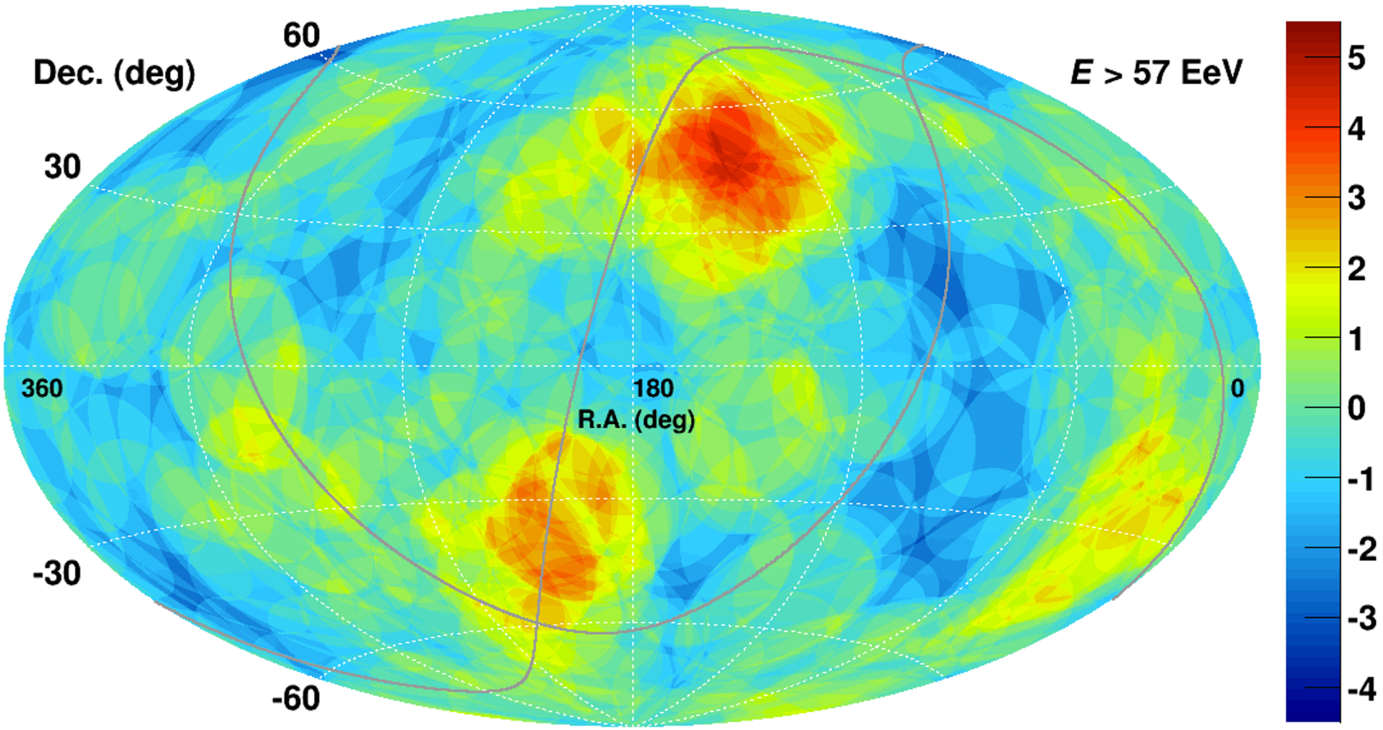
TA Anisotropy - Nearby Prominent Sources



Suggested possible sources near Ursa Major cluster:
Blazar Mrk 421 (134 Mpc)
Blazar Mrk 180 (192 Mpc)
Starburst galaxy M82 (3.4 Mpc)

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

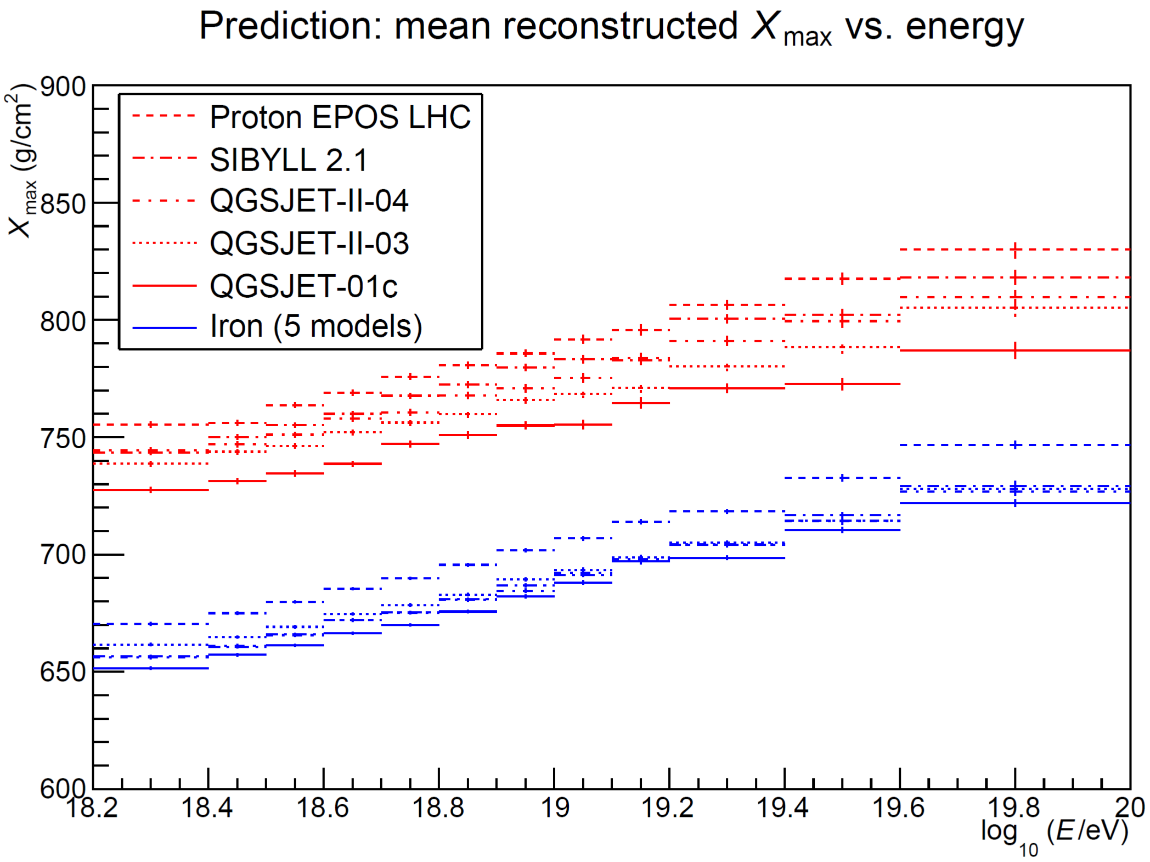
TA & PAO Anisotropy - All-sky survey



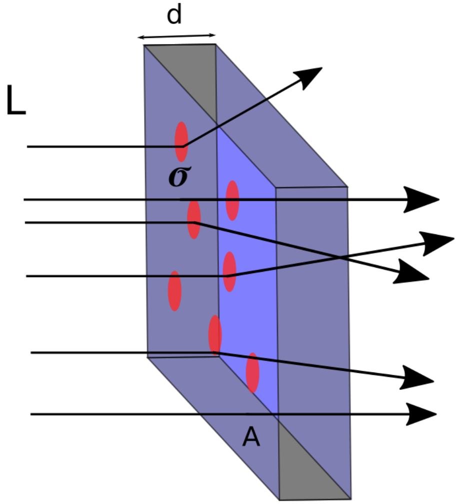
TA: 109 events, 7 years exposure
PAO: 157 events, 10 years exposure
No energy scale correction between TA & PAO is applied

Northern hotspot near Ursa Major Cluster
Southern hotspot at Centaurus A

Composition Model Dependence



Measuring $\sigma_{p\text{-}air}$



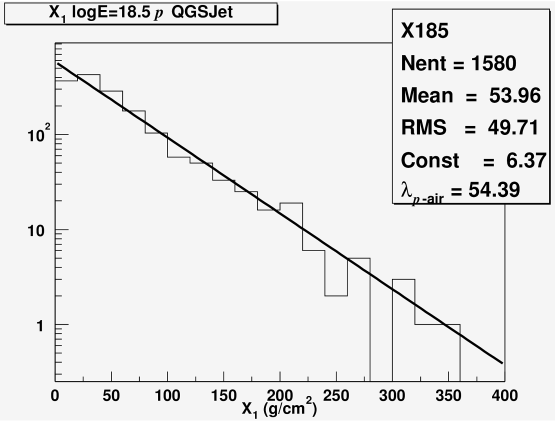
$$dN/dt = L\sigma$$

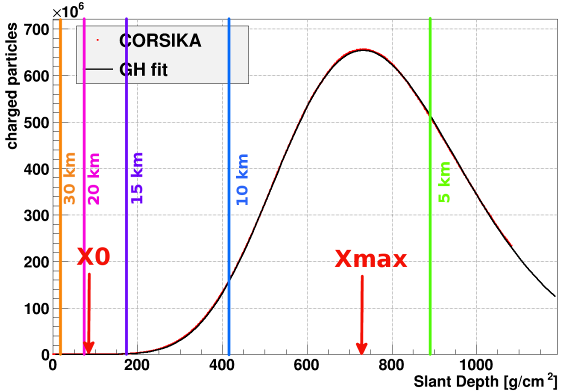
$$P(x) = exp(-x/\lambda)$$

FDs don't observe X_1. Too far, too dim, out of the FOV.

Air showers: X_1 depends only on particle total cross section. Any arbitrary point in shower after depends on model dependent fluctuations (multiplicity, inelasticity, cross section).

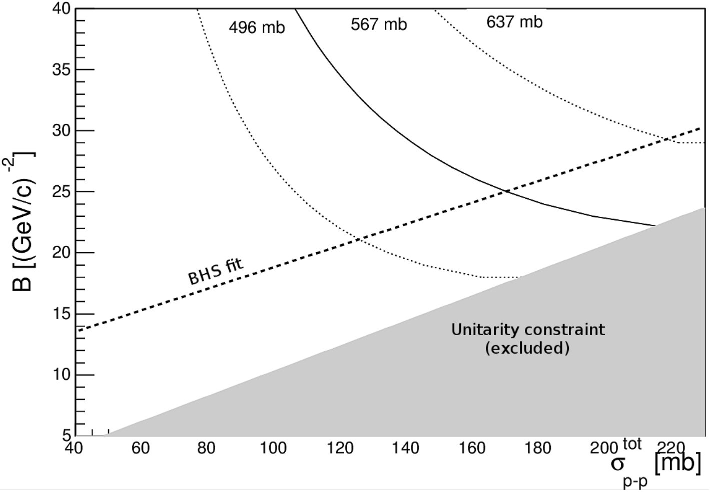
Choose X_{max} as the observation point, examine models to measure fluctuations between X_1 and X_{max}.



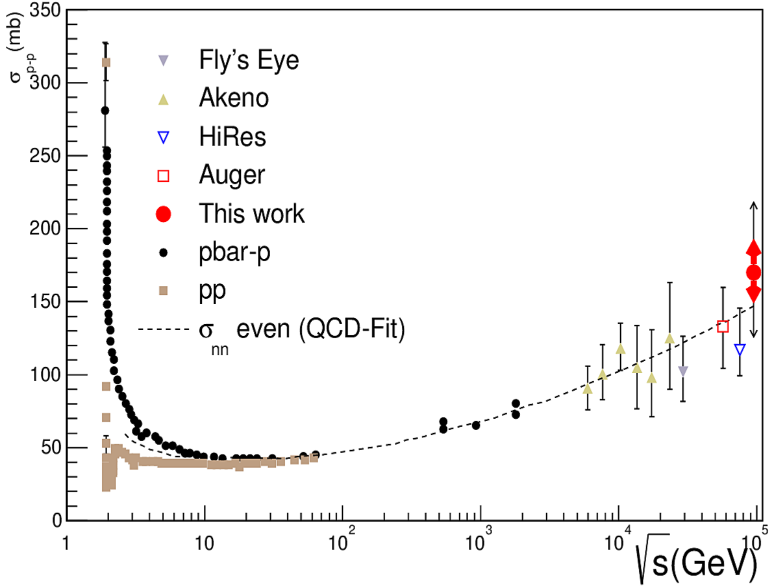


Minimum depth viewed of a shower as a function of core distance

TA σ_{pp}^{total} measurement



B (forward scattering elastic slope) relates $\sigma_{p\text{-}air}$ (inel) to $\sigma_{p\text{-}p}$ (tot). Constant values of $\sigma_{p\text{-}air}$ (inel) are shown. Intersection with BHS fit gives $\sigma_{p\text{-}p}$ (tot).

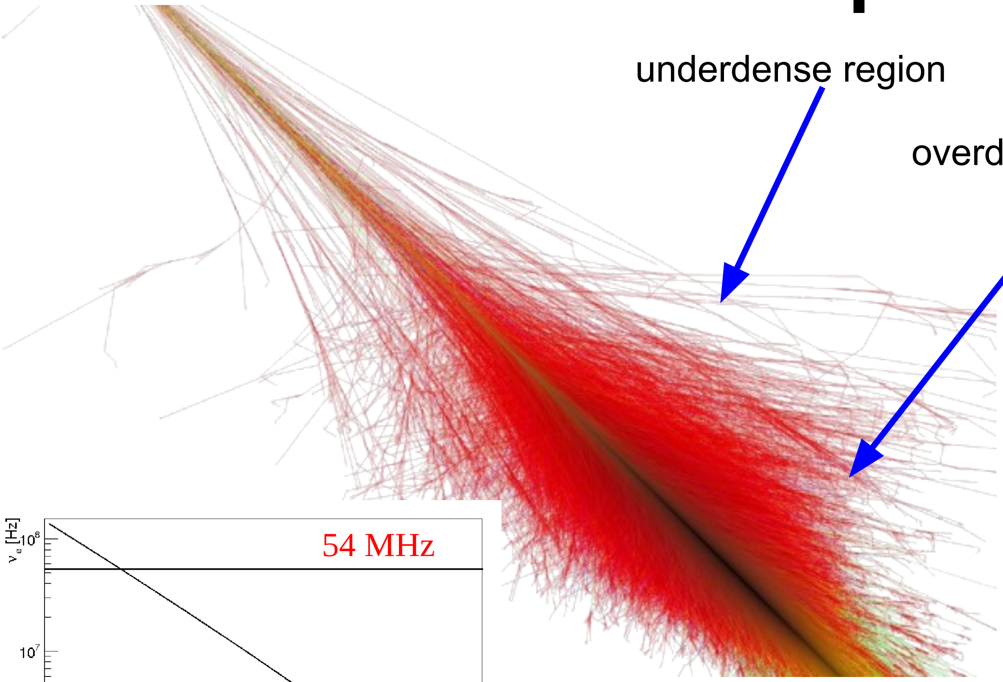


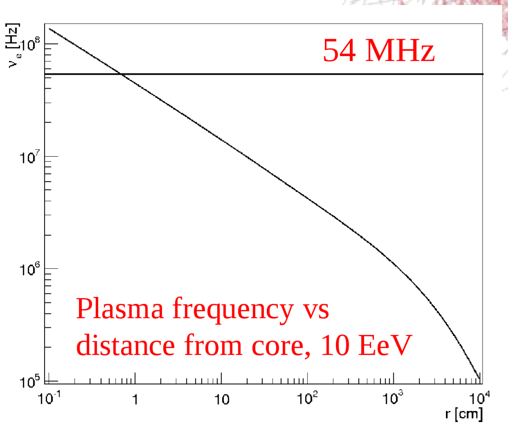
TA first measurement of $\sigma_{p\text{-}p}$ (tot) shown in red.

Dashed line is BHS QCD inspired fit to pp and pp-bar Tevatron data. Auger, HiRes, TA data are consistent with this prediction.

$\sigma_{p\text{-}p}$ (tot) = 170 (+48, -44) [stat] (+19, -17) [sys]
$\sqrt{s}$ = 95 TeV

Bistatic Radar Technique





- Radar cross section depends on charged particle density.
- Plasma frequency goes as square root of charged particle density.
- NKG approximation estimates radar frequency of 54.1 MHz exceeds the plasma frequency within 1 cm of the core.
- Thin wire approximation.
- Carrier signal scattered.

$$\nu_e = \sqrt{\frac{n_e e^2}{m_e \epsilon_0} \frac{1}{2\pi}}$$

Theory of Radar Detection of EAS

- Particles with energy > 10^{17} eV should produce ionization densities (> $10^{13}/m^3$) great enough to scatter EM radiation around 10 - 100 MHz.
- Directly interrogate the overdense region of the EAS with sounding frequency which is specularly reflected by plasma (this is not emission from the shower).
- Scattering is greatest in the forward direction.
- Bistatic radar setup gives best chance of detection of radar echos.

$$P_t = P_r \underbrace{\boxed{\left(\frac{G_t}{4\pi R_t^2}\right)\left(\frac{G_r}{4\pi R_r^2}\right)}}_{\text{TX -> target -> RX path geometry}} \underbrace{\boxed{\sigma}}_{\text{radar cross section}} \underbrace{\boxed{\left(\frac{\lambda^2}{4\pi}\right)}}_{\text{RX effective area}}$$