Cosmic Rays from 10^{16} - 10^{21} eV

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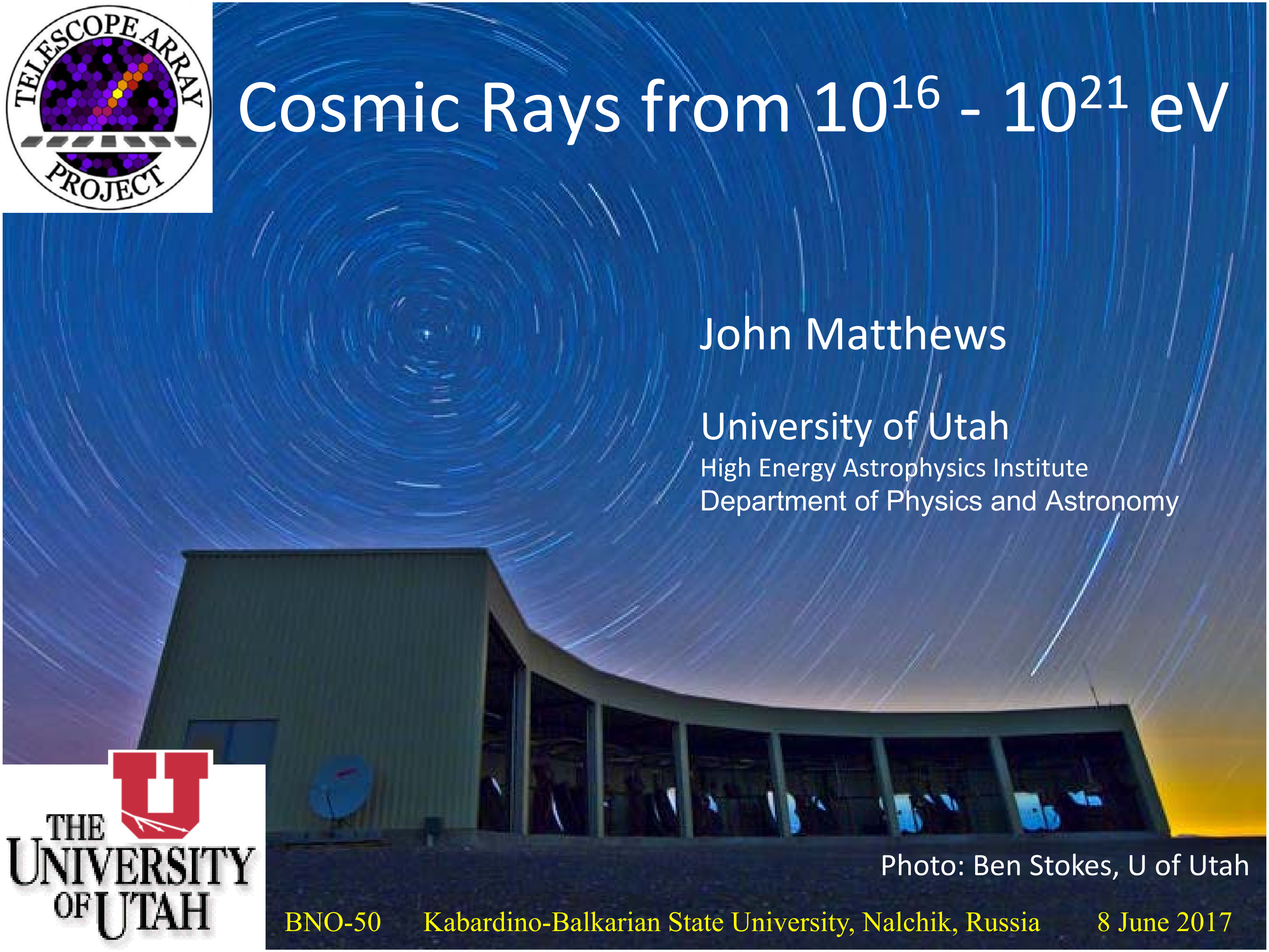
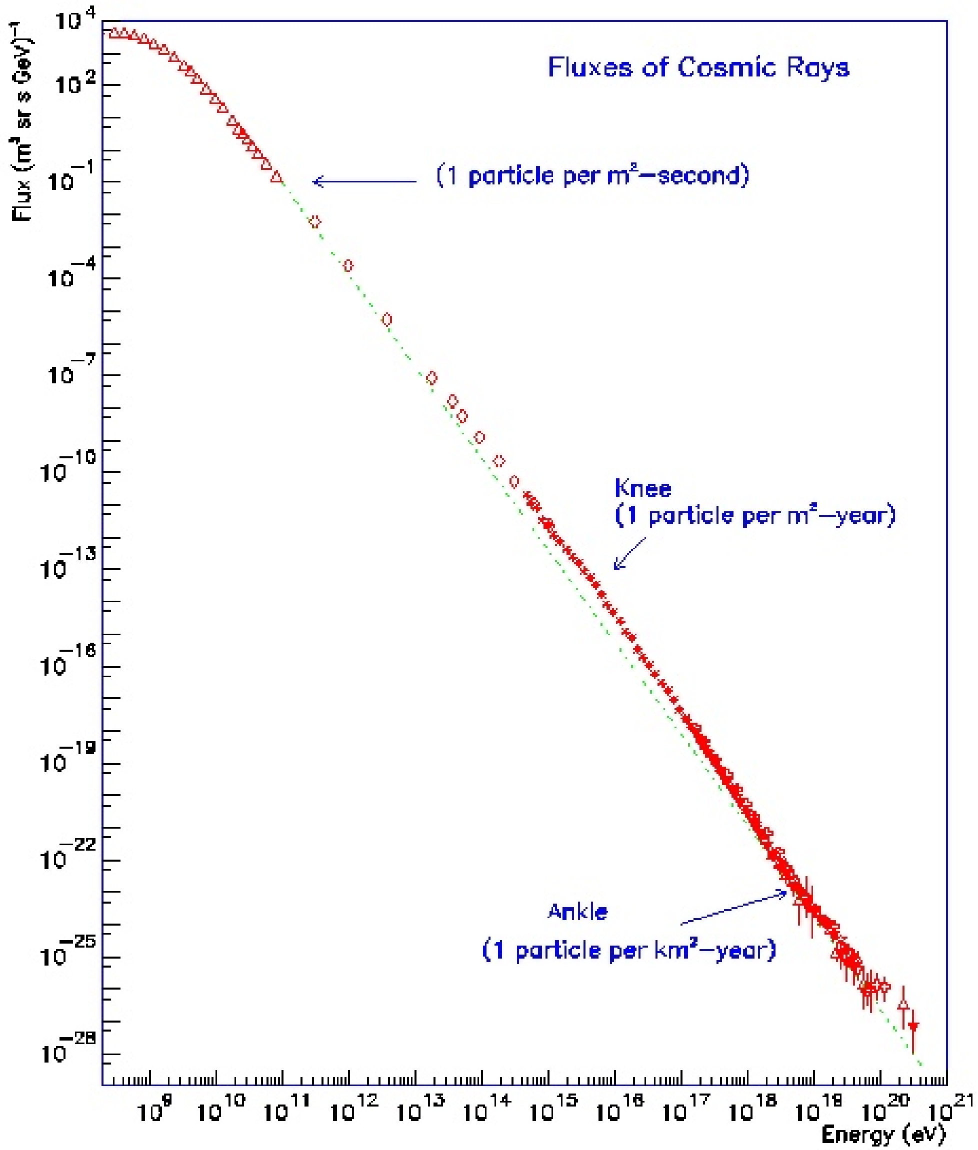


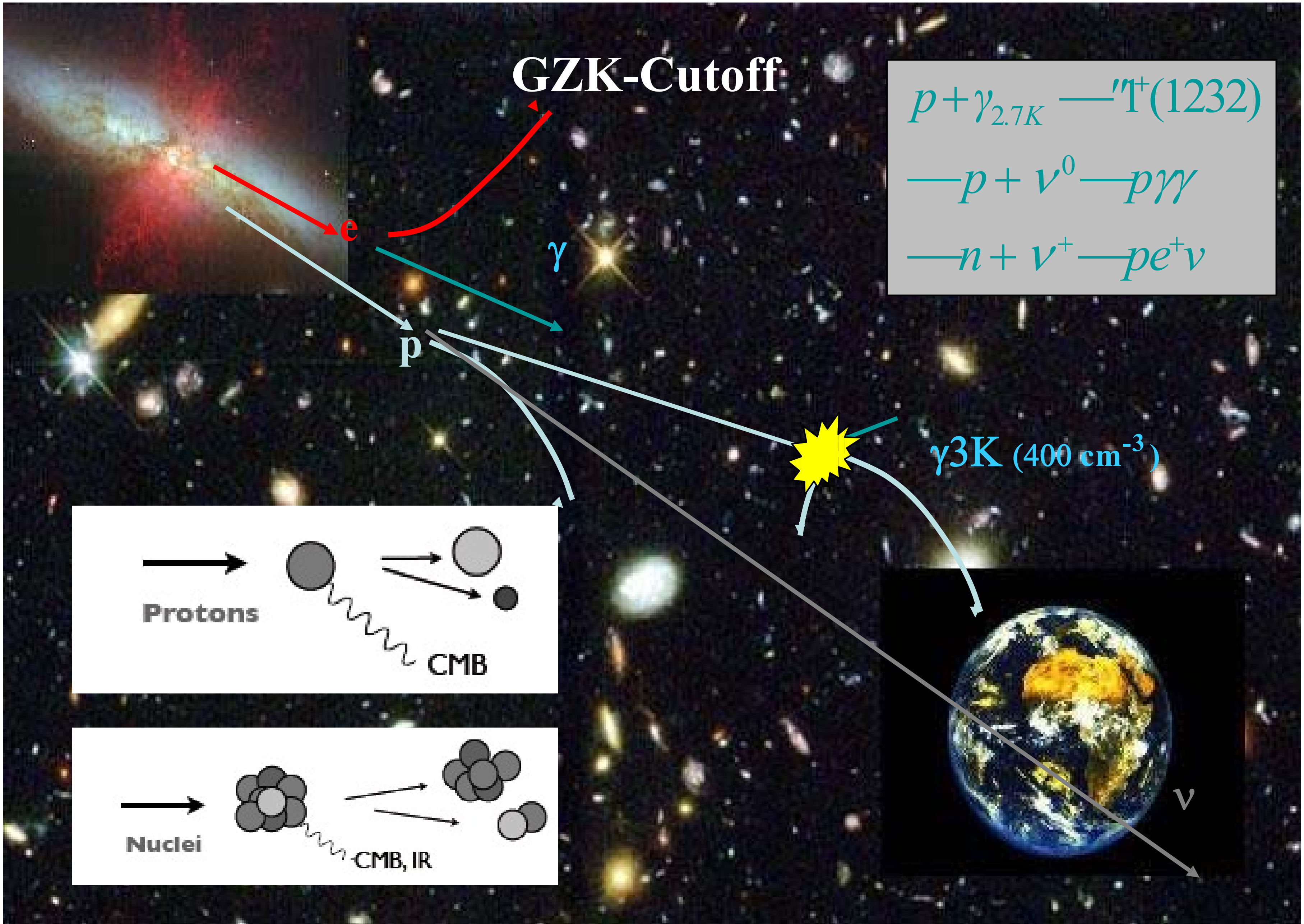
Photo: Ben Stokes, U of Utah

BNO-50 Kabardino-Balkarian State University, Nalchik, Russia 8 June 2017

Cosmic Ray Flux

- Extends over a wide energy range
- Almost featureless
  - Slope ~(-3)
  - Slight “knee” at 3×10^{15} eV
- Flux is ~isotropic due to galactic magnetic fields.
- Direct Measurements ~$E<10^{15}$ eV
- Above this indirect measurements

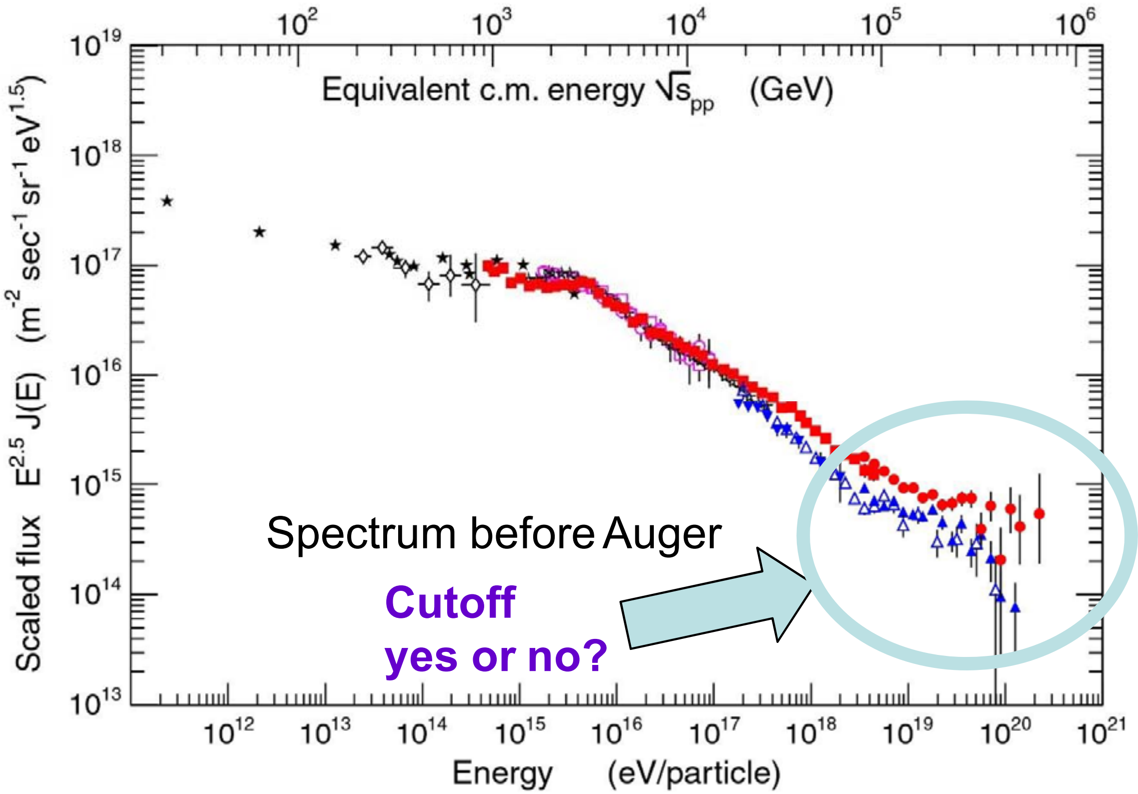


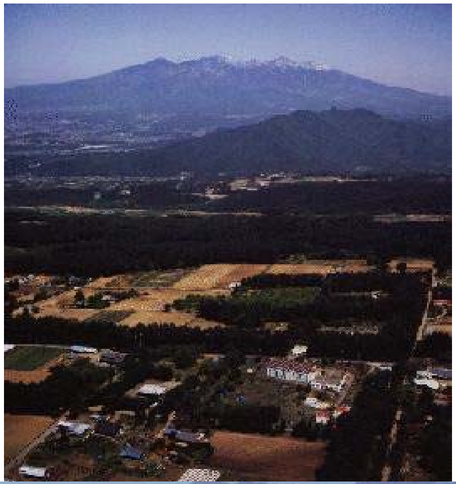

GZK-Cutoff
p+γ2.7K —'T+(1232)
—p + ν0—pγγ
—n + ν+—pe+ν
e
γ
p
γ3K (400 cm-3)
ν
Protons
CMB
Nuclei
CMB, IR

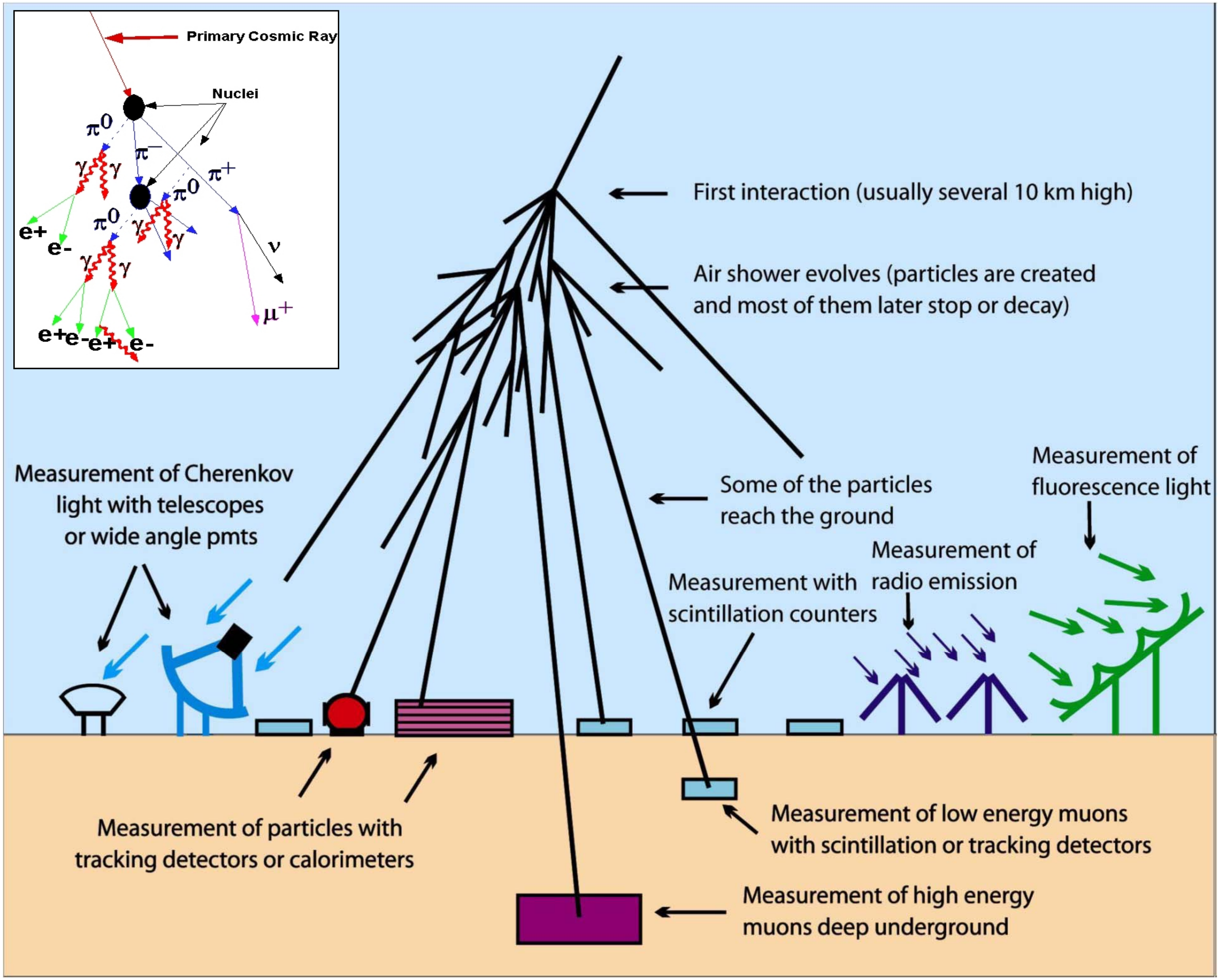
Cosmic Rays at highest energies in 2003

Source, acceleration, and mass of the particles unknown – but they exist !
Exists the cut-off? (strong extragalactic processes which happens very close are necessary)

Measurements by **large particle detector arrays (AGASA - no cutoff)**
or **fluorescence telescopes (HiRes cutoff** (observed 11 events while expecting 30, if no cut-off $7x10^{-5}$ probability)**)**

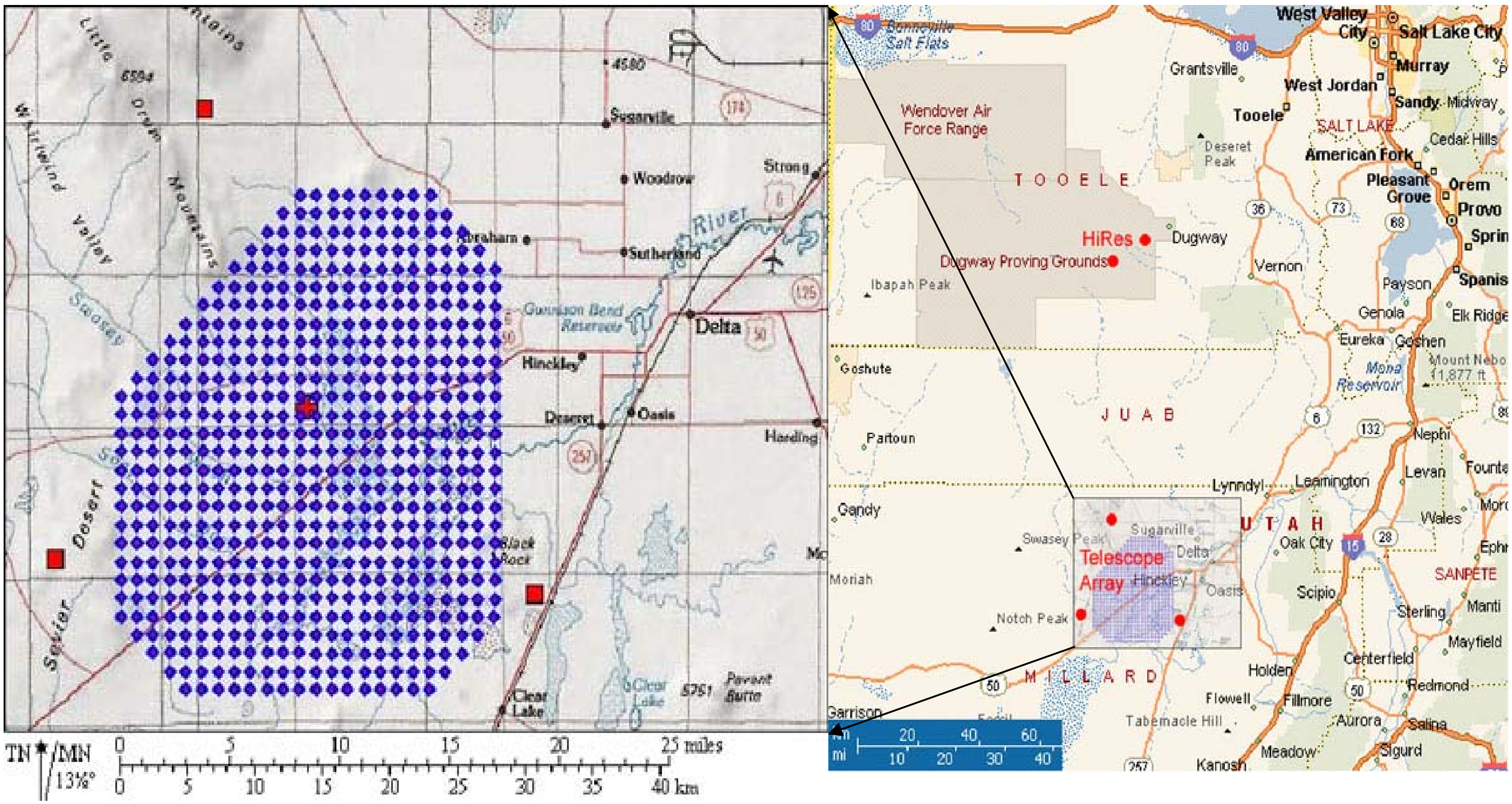






Primary Cosmic Ray
Nuclei
π^0
π^-
π^+
γ
e+
e-
ν
μ^+
e+e-e+e-
First interaction (usually several 10 km high)
Air shower evolves (particles are created and most of them later stop or decay)
Some of the particles reach the ground
Measurement of fluorescence light
Measurement of Cherenkov light with telescopes or wide angle pmts
Measurement of radio emission
Measurement with scintillation counters
Measurement of particles with tracking detectors or calorimeters
Measurement of low energy muons with scintillation or tracking detectors
Measurement of high energy muons deep underground

Telescope Array



700 km^{2}:   Lat. 39.30°N, Long. 112.91°W   1550m ASL

The High Energy component of Telescope Array – 38 fluorescence telescopes (9728 PMTs) at 3 telescope stations overlooking an array of 507 scintillator surface detectors (SD) - complete and operational as of ~1/2008.

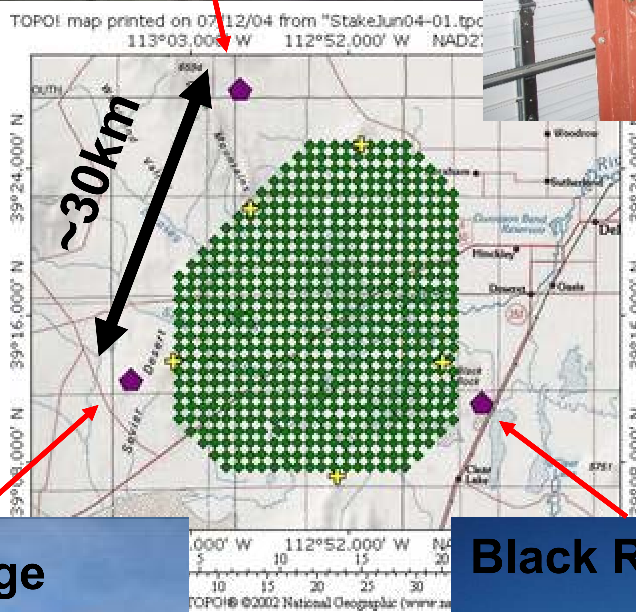
Telescope Array: Operational 3/2008

Middle Drum

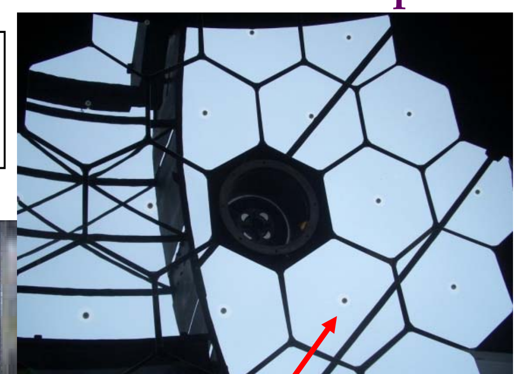
14 telescopes @ station
256 PMTs/camera

5.2 m²

Reutilized from HiRes-I



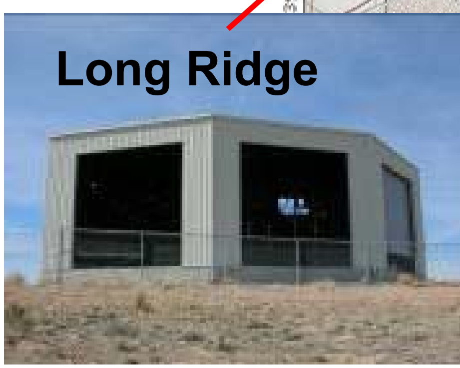
New Telescopes



12 telescopes/station
256 PMTs/camera

~1 m²

6.8 m²

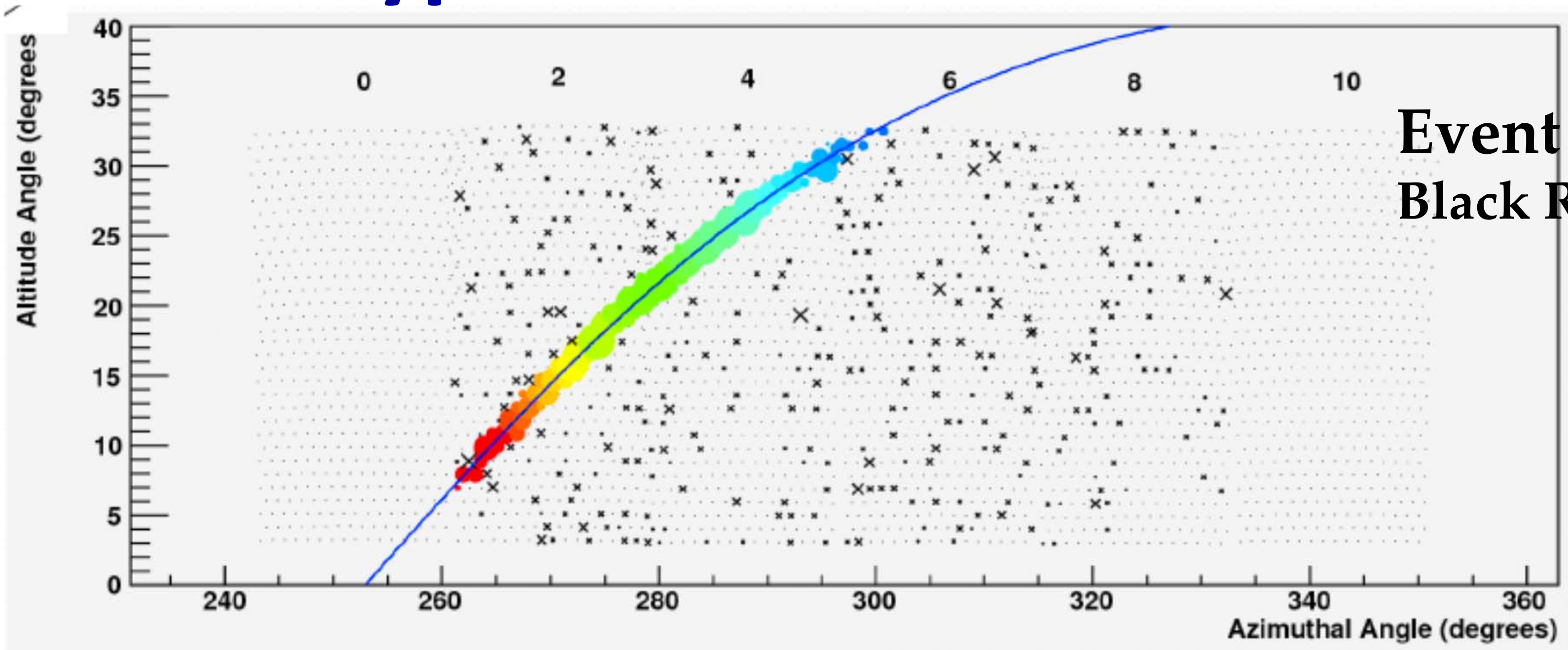


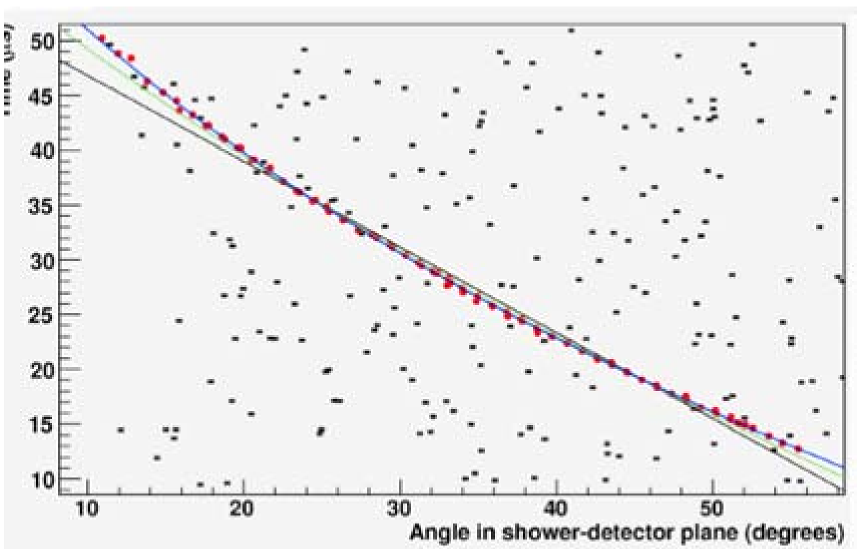
Long Ridge

Black Rock Mesa

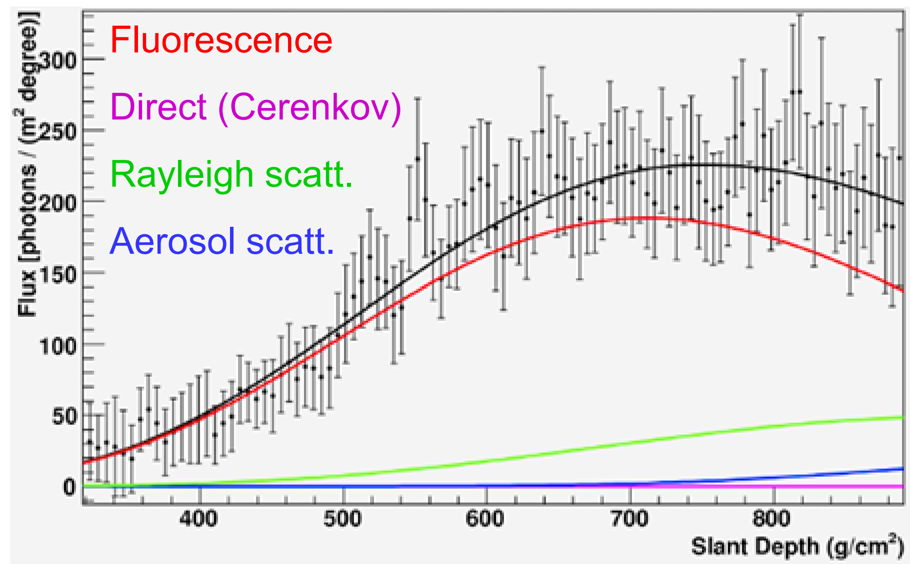

Photo: Oleg Kalachev, INR RAS

Typical Fluorescence Event





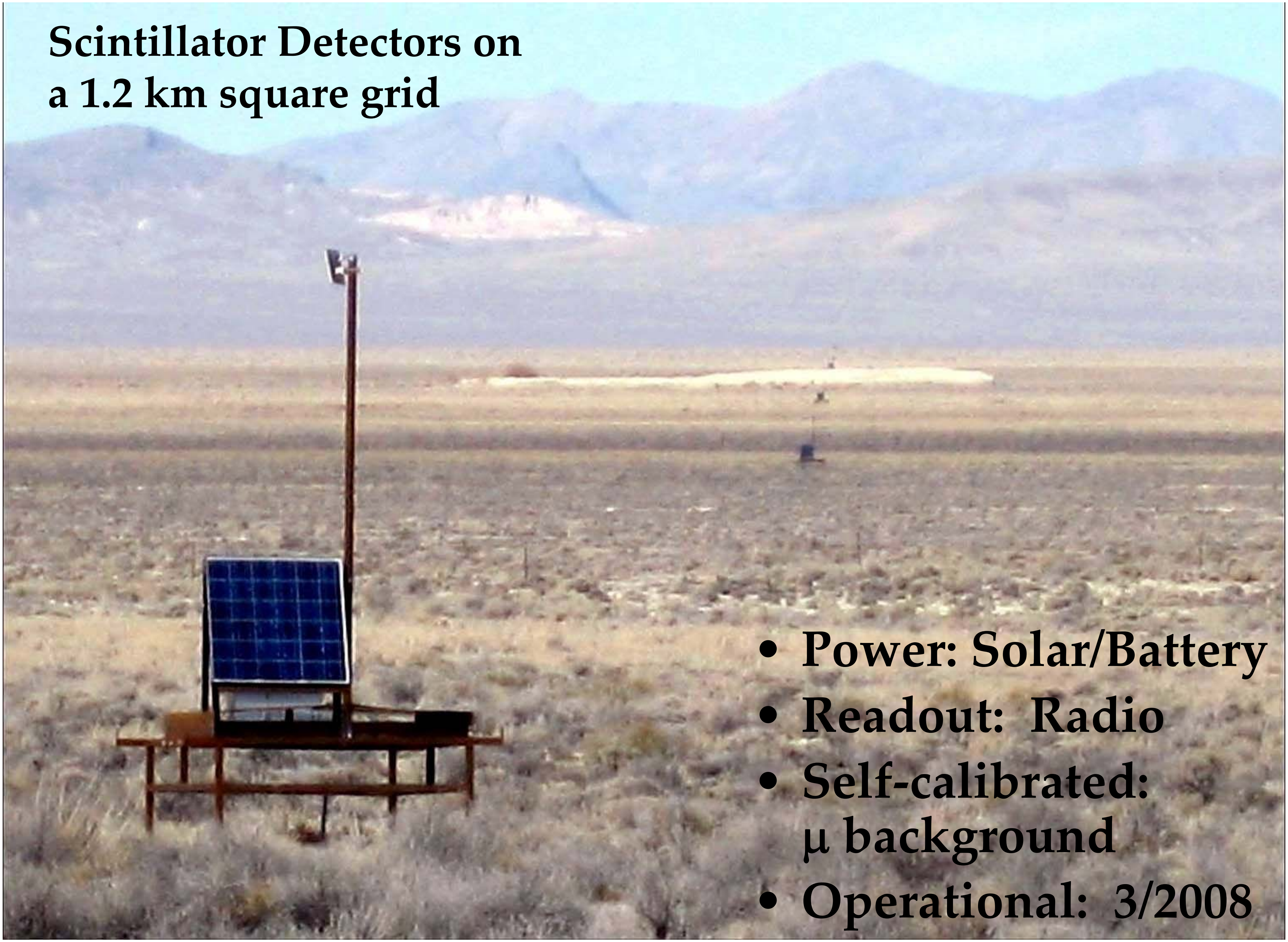
Monocular timing fit (time vs angle)



Reconstructed Shower Profile

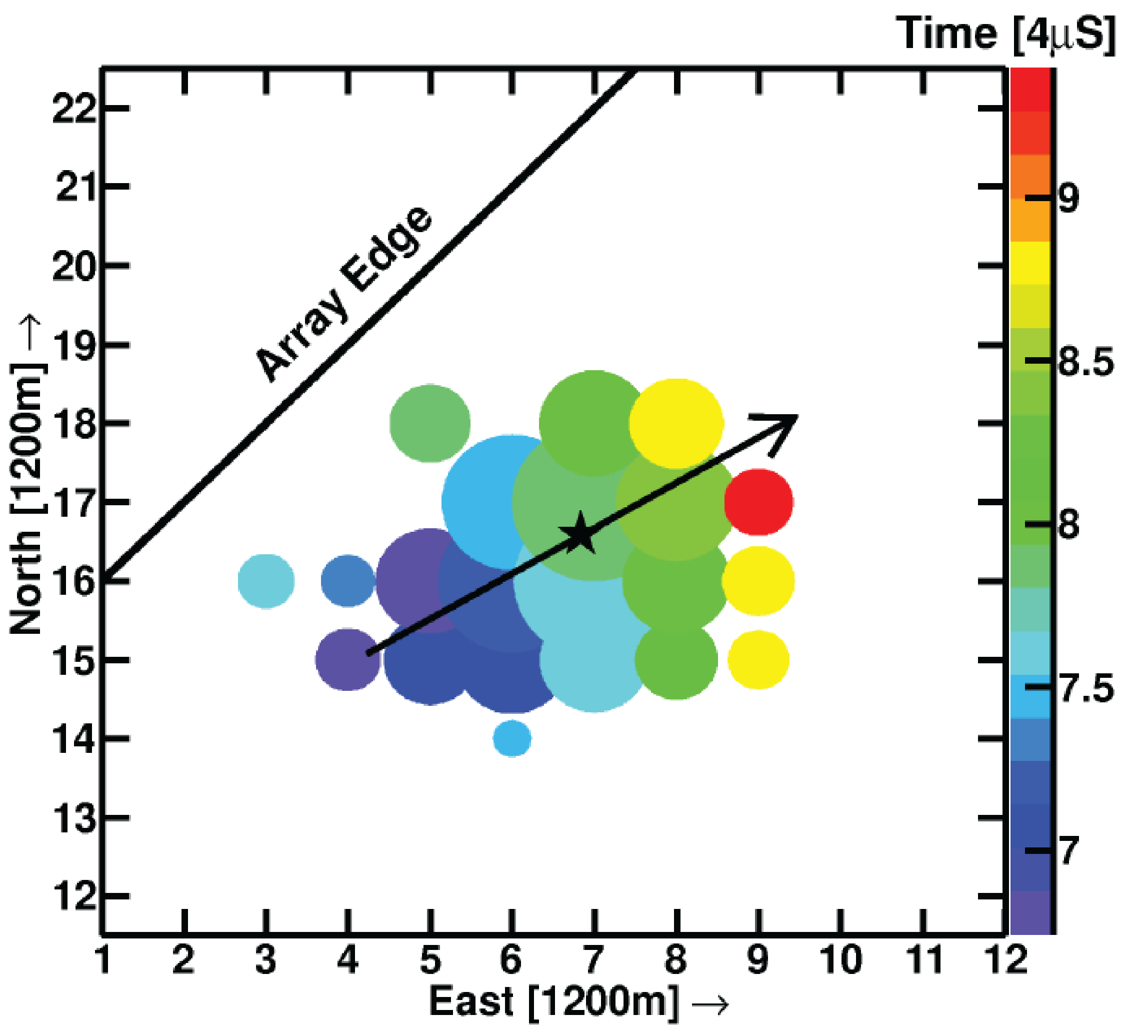
Scintillator Surface Detectors

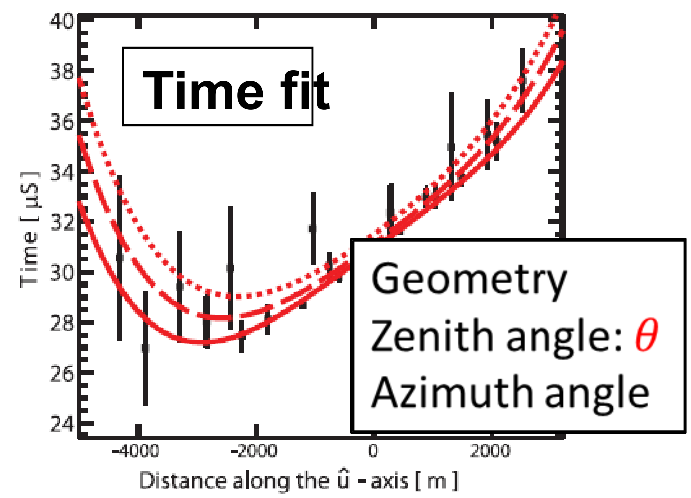
2 layers scintillator
1.25 cm thick, $3m^2$ area
Optical fibers to PMTs

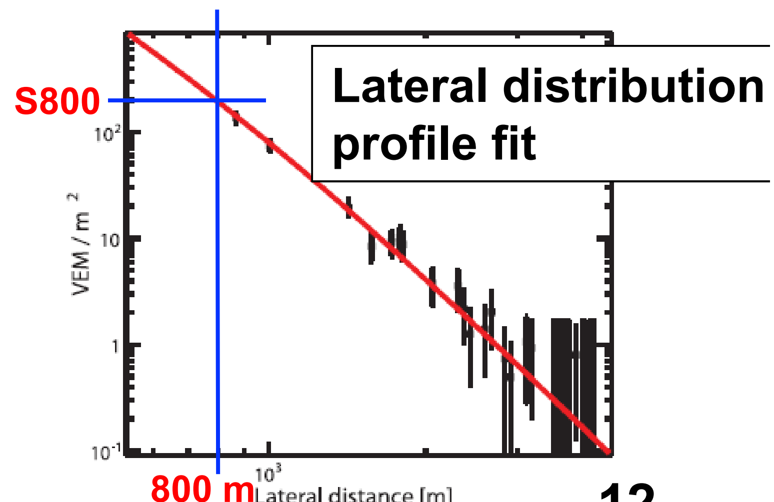

Scintillator Detectors on
a 1.2 km square grid
• Power: Solar/Battery
• Readout: Radio
• Self-calibrated:
μ background
• Operational: 3/2008

TA shower analysis with SD

An SD hit map of a typical high energy event

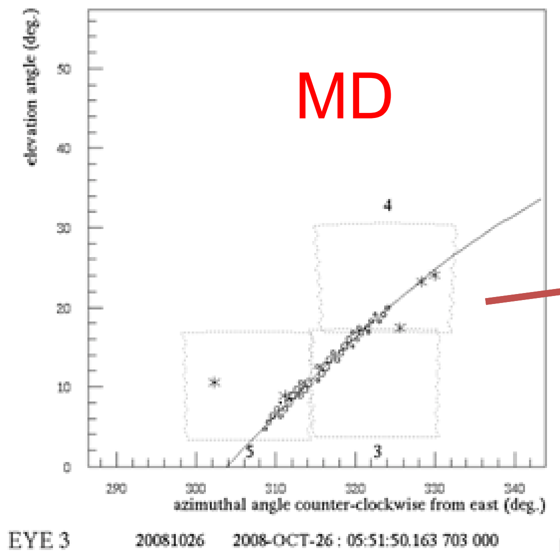






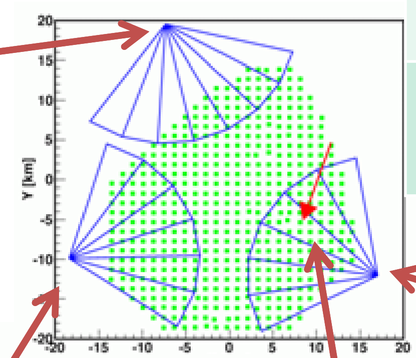
12

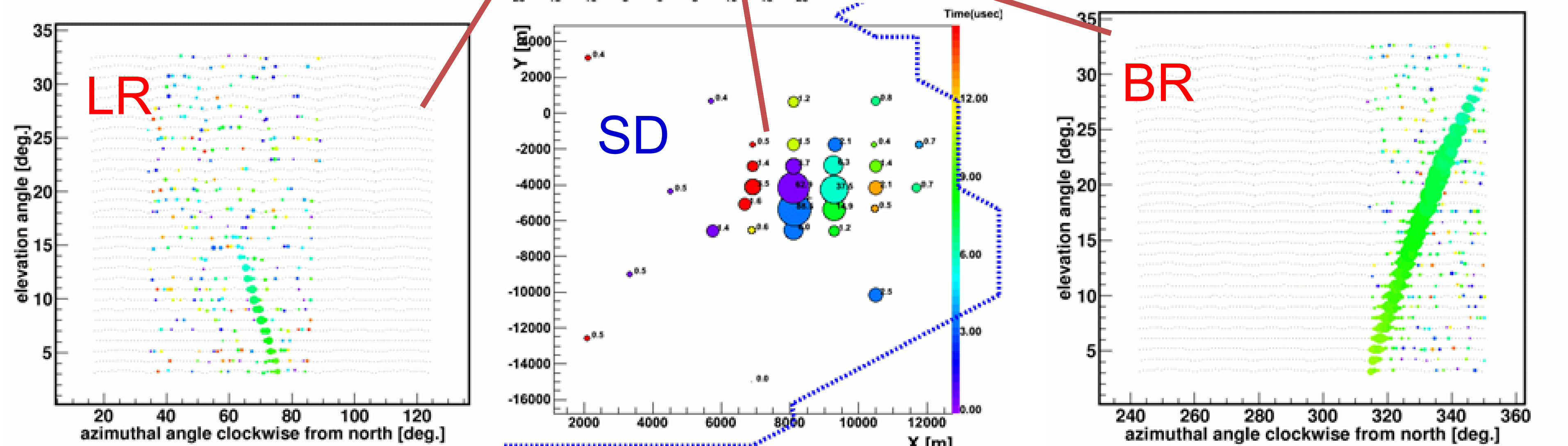
Example Event



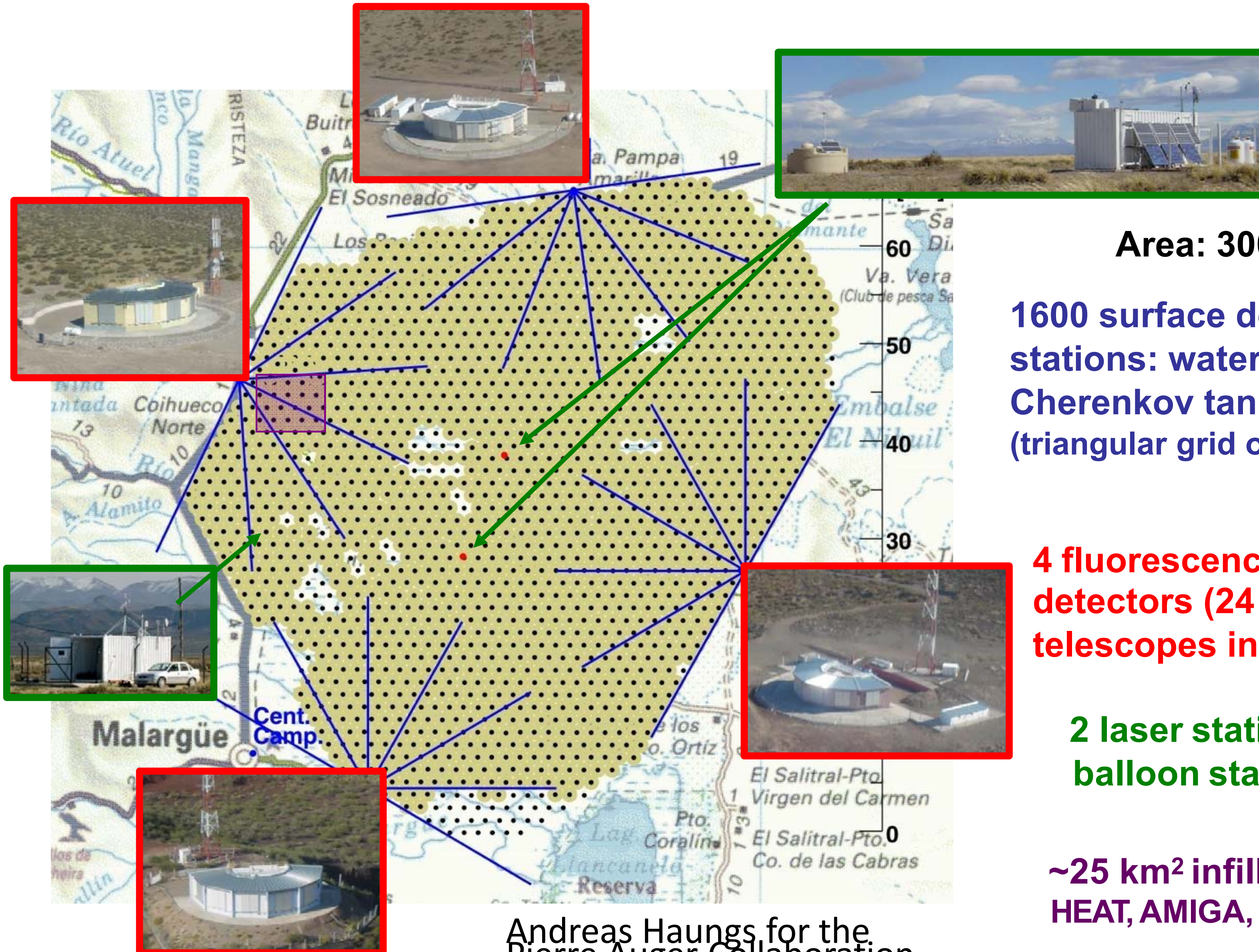
	θ [°]	ϕ [°]	x[km]	y[km]
MD mono	51.43	73.76	7.83	-3.10
BR mono	51.50	77.09	7.67	-4.14
Stereo BR&LR	50.21	71.30	8.55	-4.88

Event from 2008-10-26





Pierre Auger Observatory: completed 7/2008



Area: 3000 km²

1600 surface detector stations: water-Cherenkov tanks (triangular grid of 1.5 km)

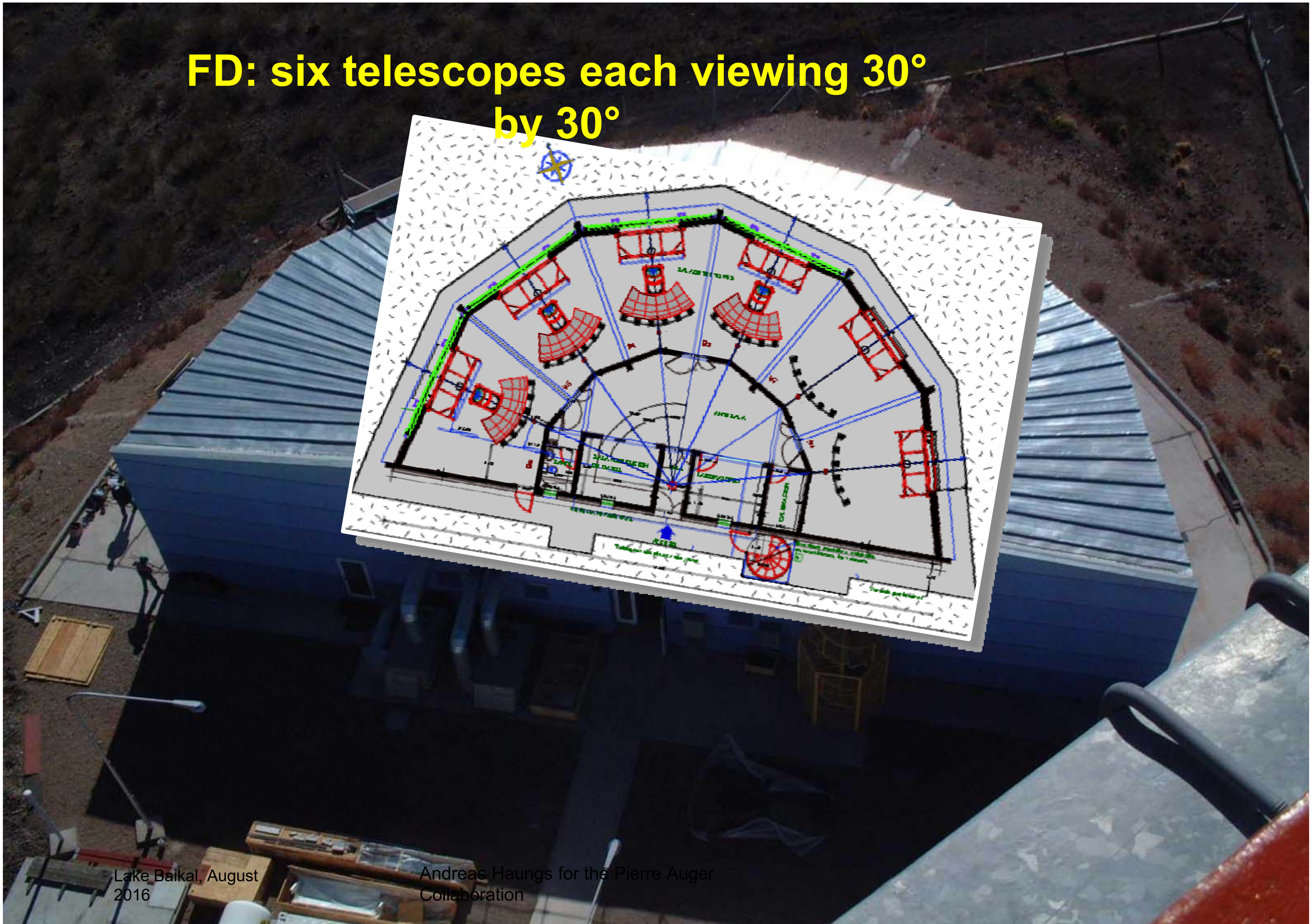
4 fluorescence detectors (24 telescopes in total)

2 laser stations
balloon station

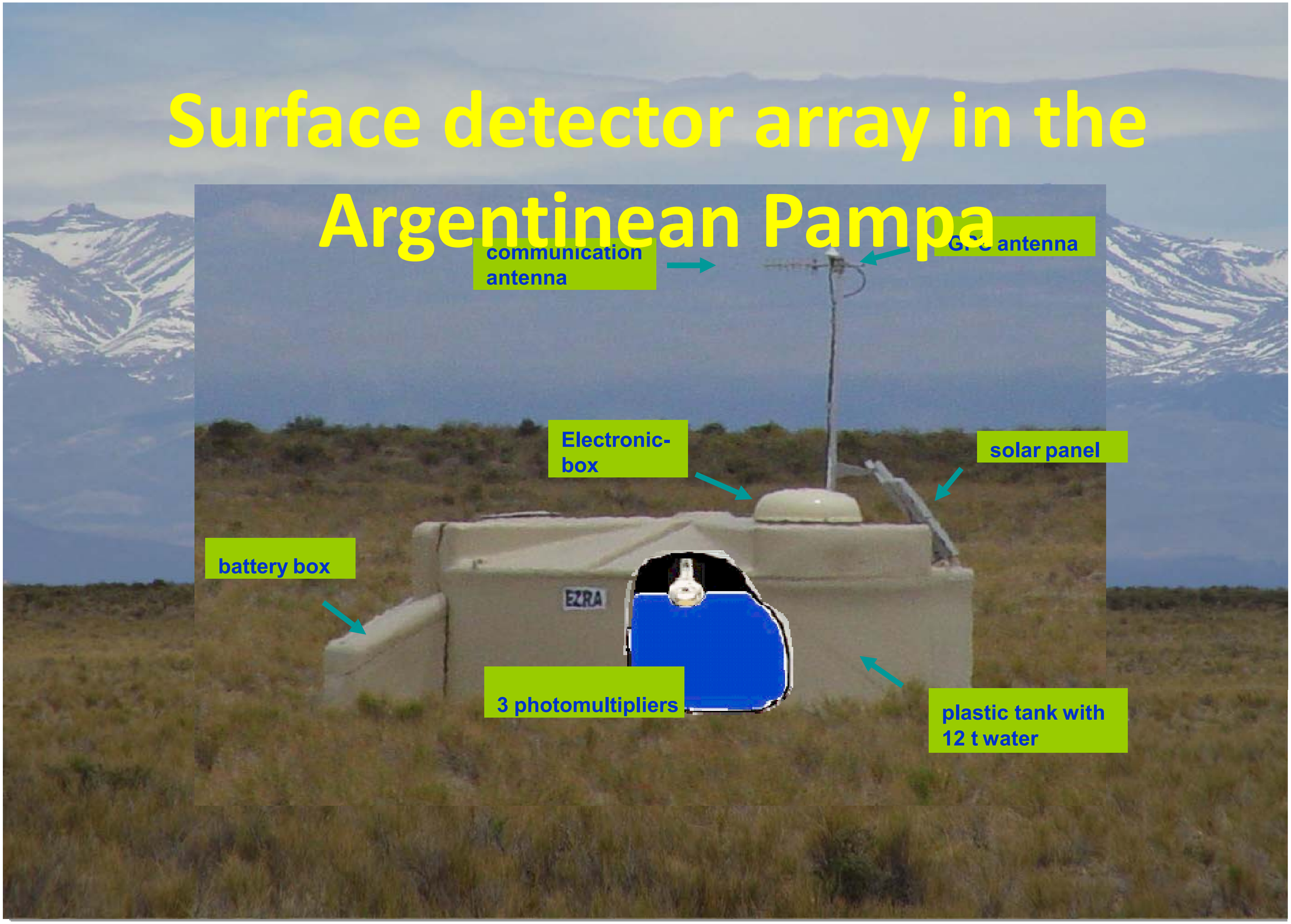
~25 km² infill area
HEAT, AMIGA, AERA

Andreas Haungs for the Pierre Auger Collaboration

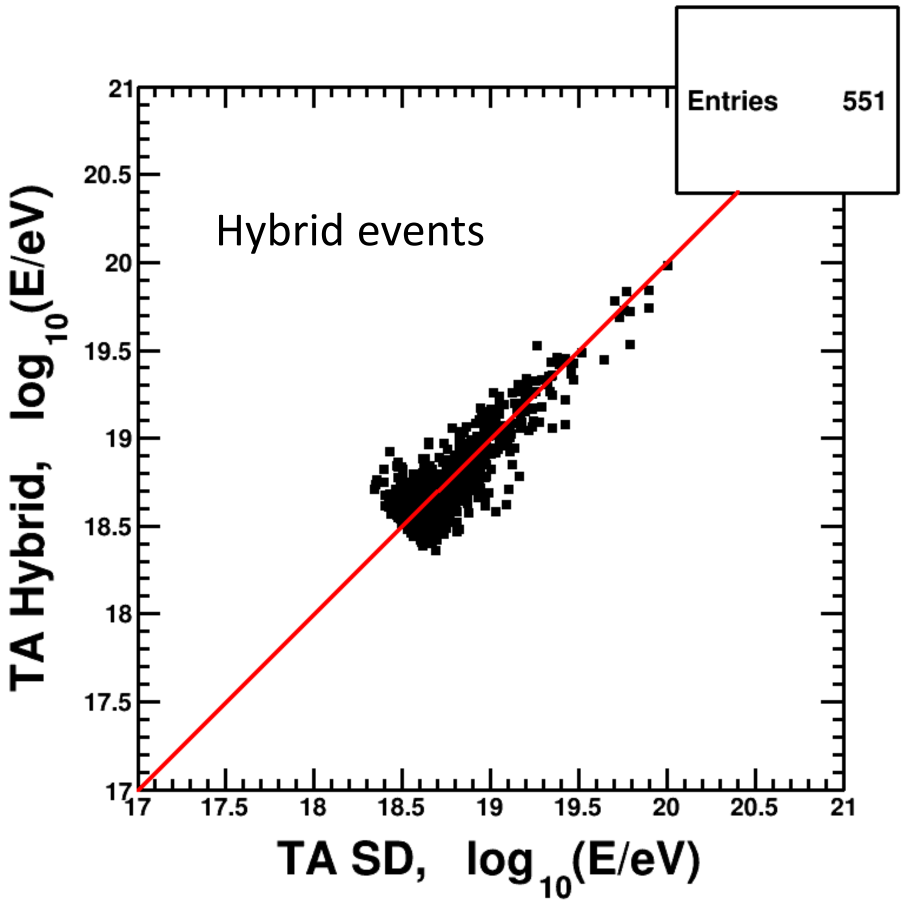
FD: six telescopes each viewing 30° by 30°



Surface detector array in the Argentinean Pampa

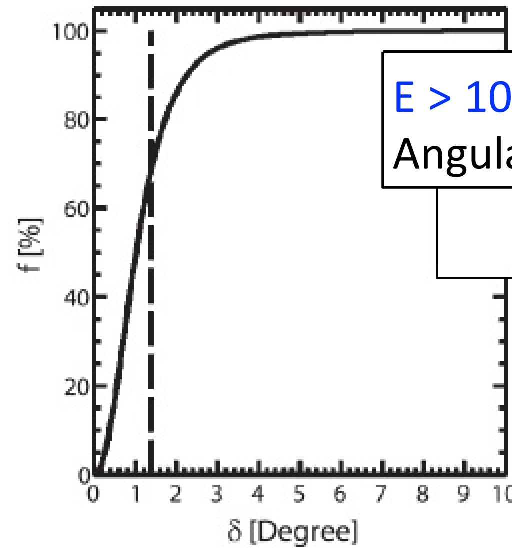


Energy Scale Check and Resolution

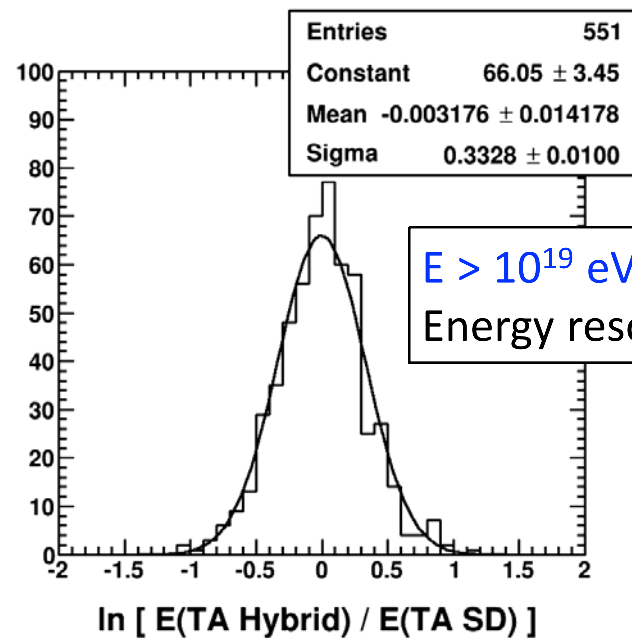


(SD scaled to FD energy: calorimetric)

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



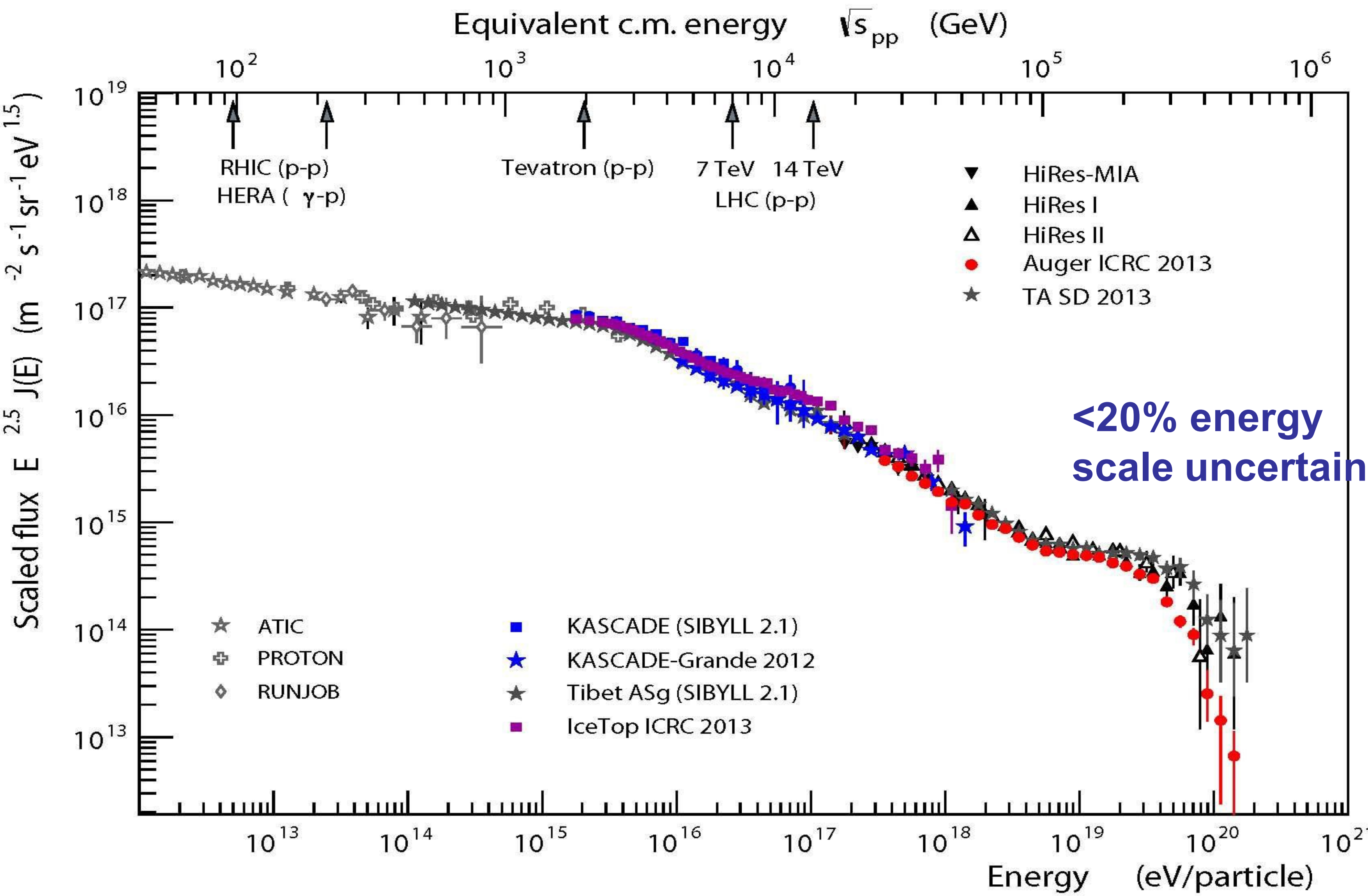
$E > 10^{19}$ eV
Angular resolution = 1.4°



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

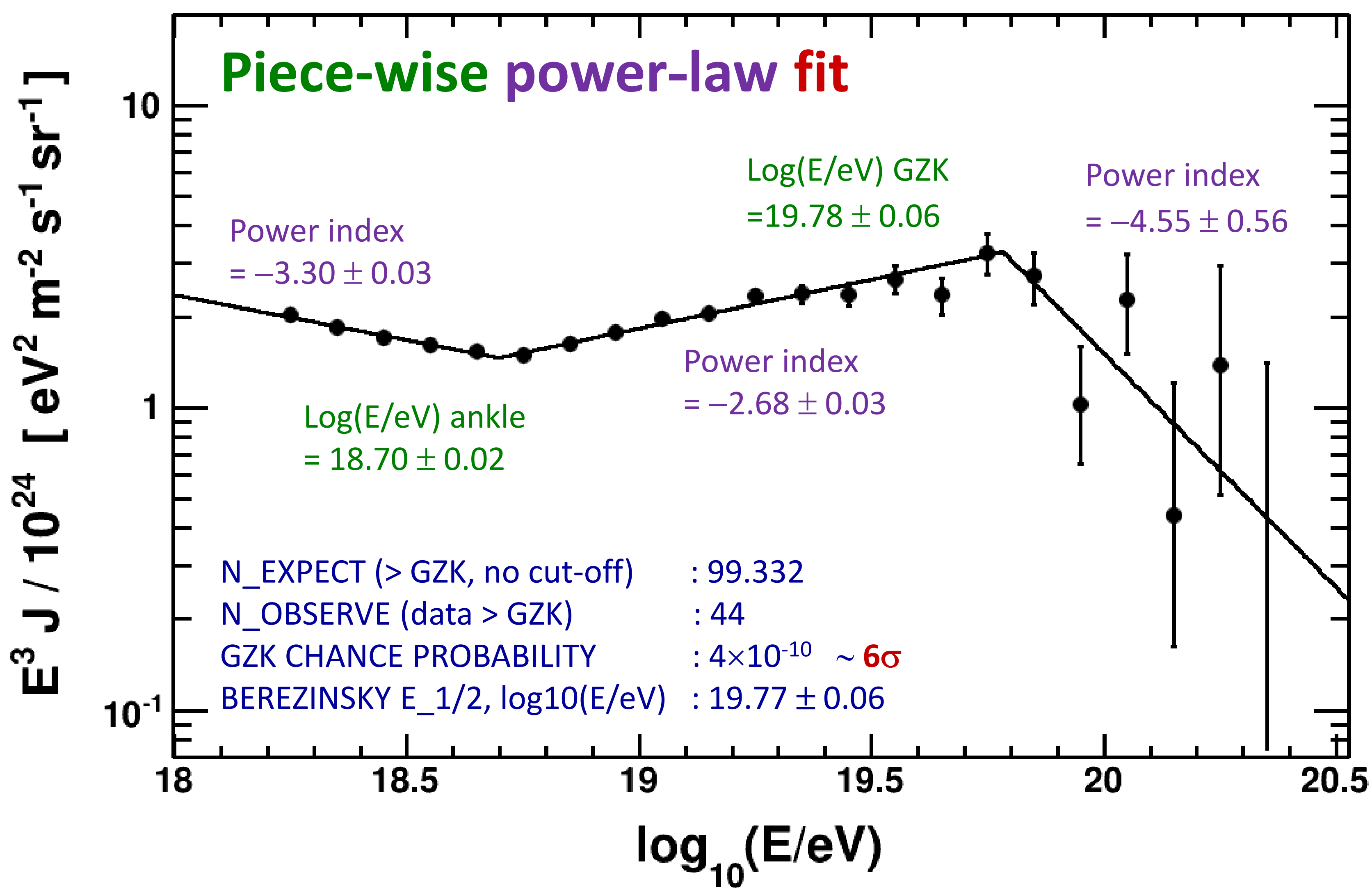
Energy Spectrum

Energy Spectrum



<20% energy scale uncertainty

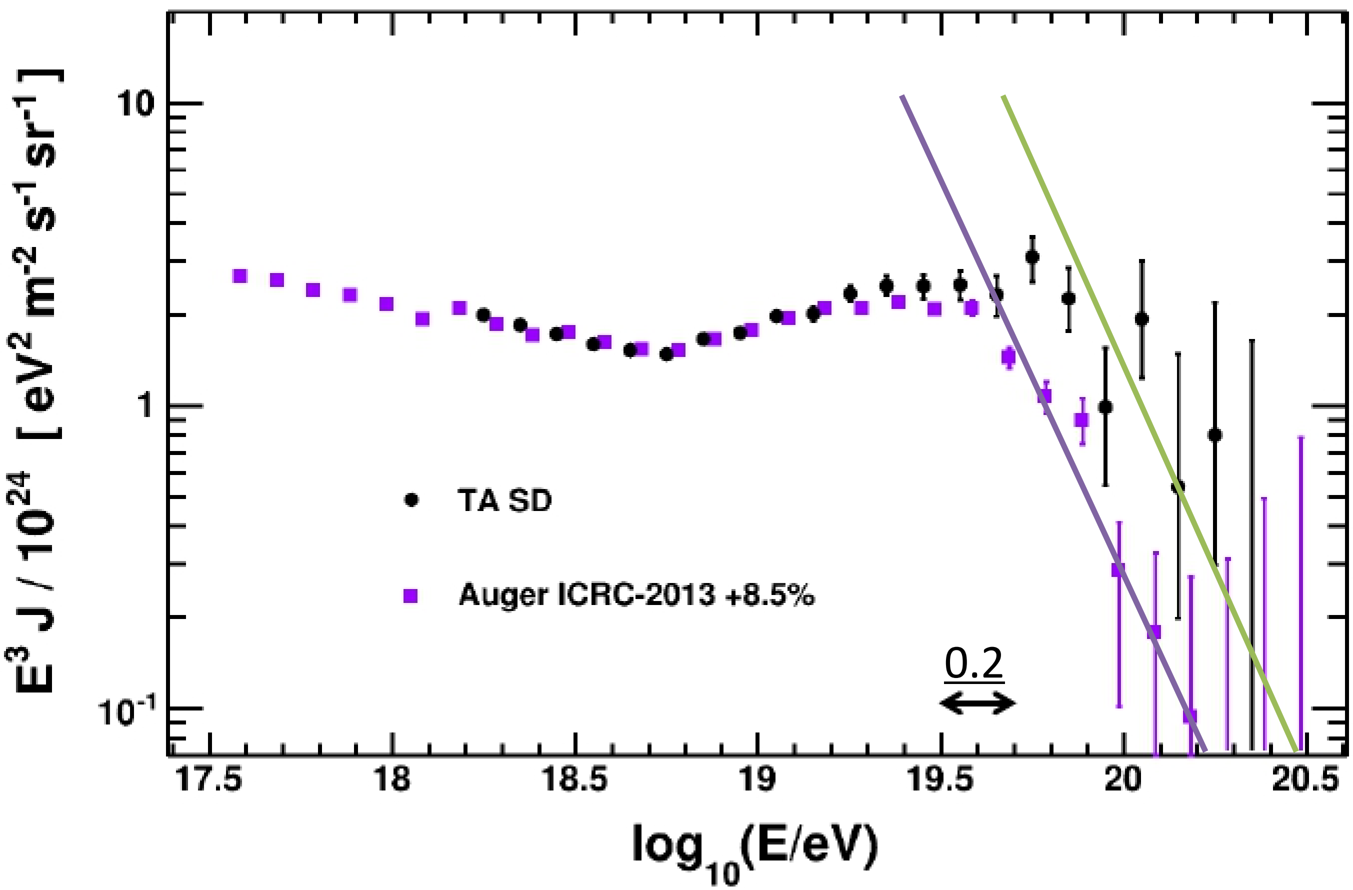
TA SD Spectrum (7 yrs data)



Previously Pubilshed: 4 year TA surface detector spectrum

Astrophysical Journal Letters 768 L1 (2013)

Comparison of TA and Auger (+8.5%) Spectra

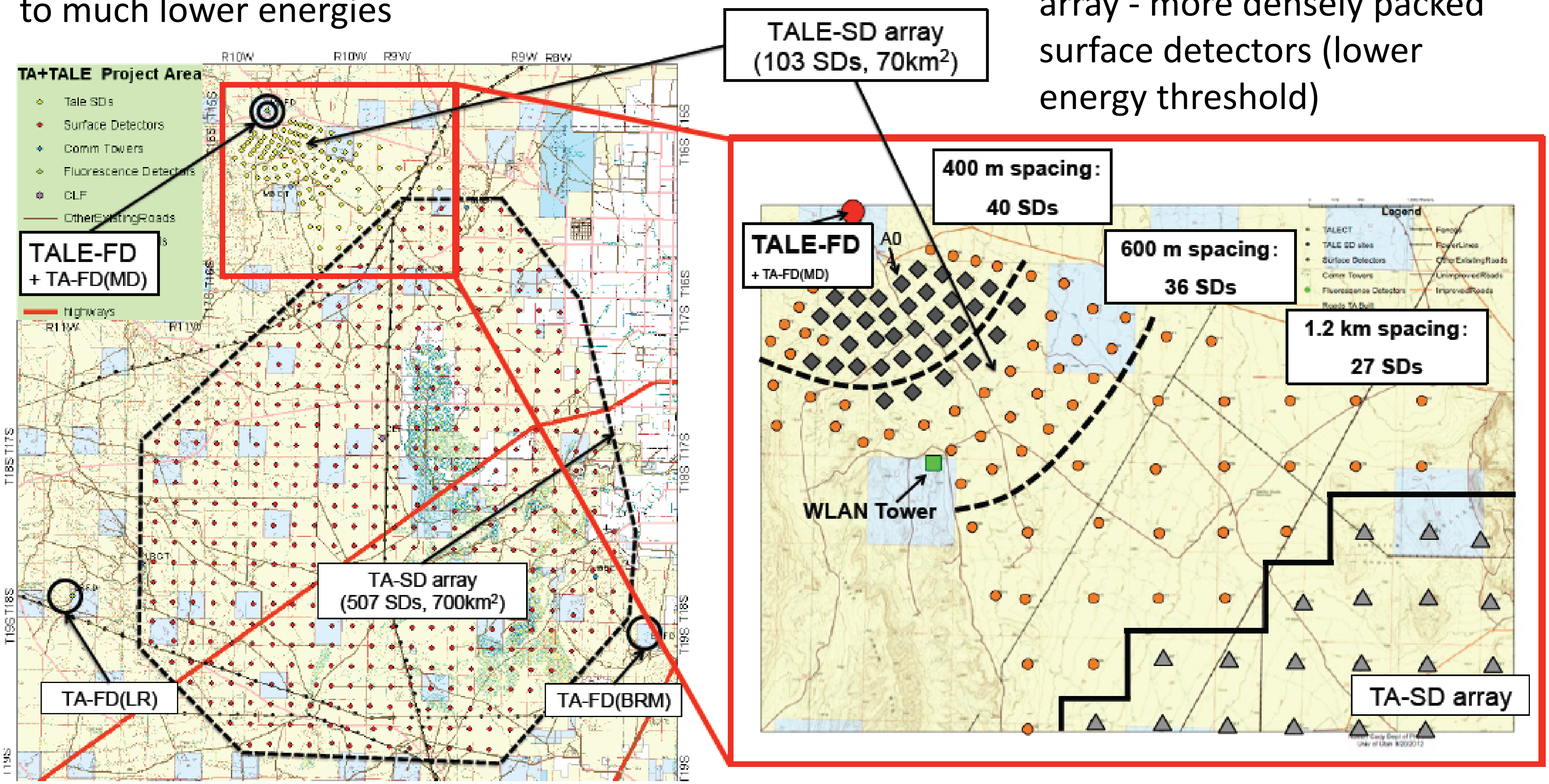


TA Low Energy Extension (TALE)

Galactic to Extra-Galactic Transition

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

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

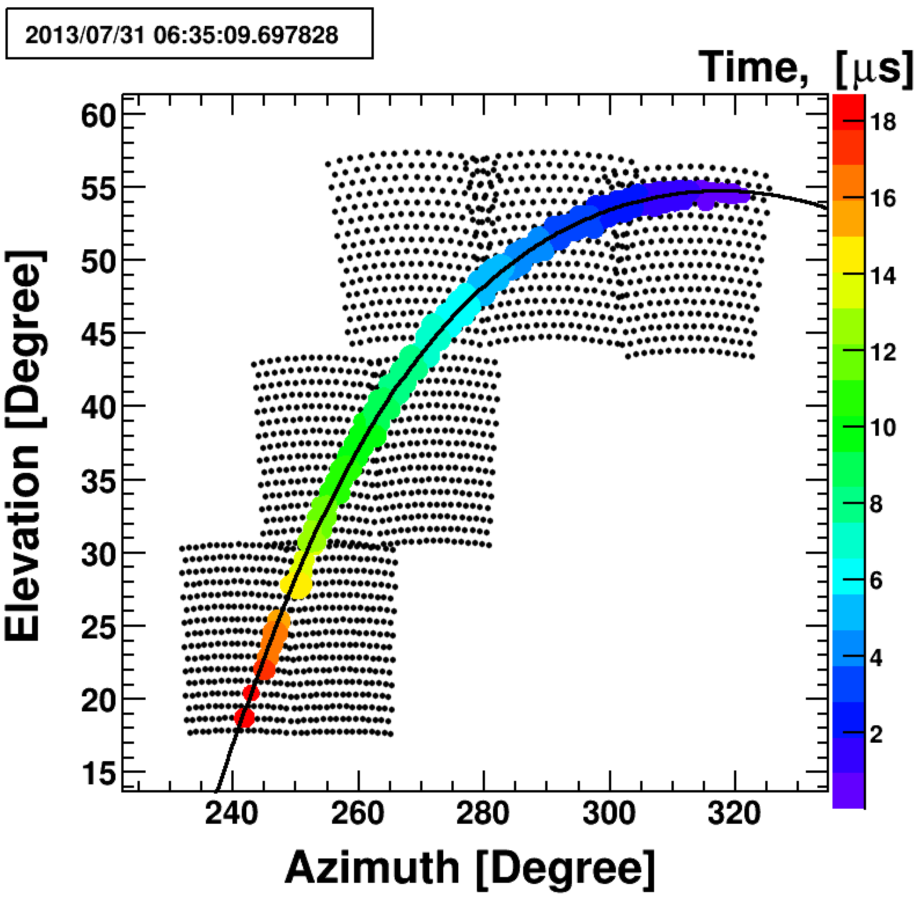


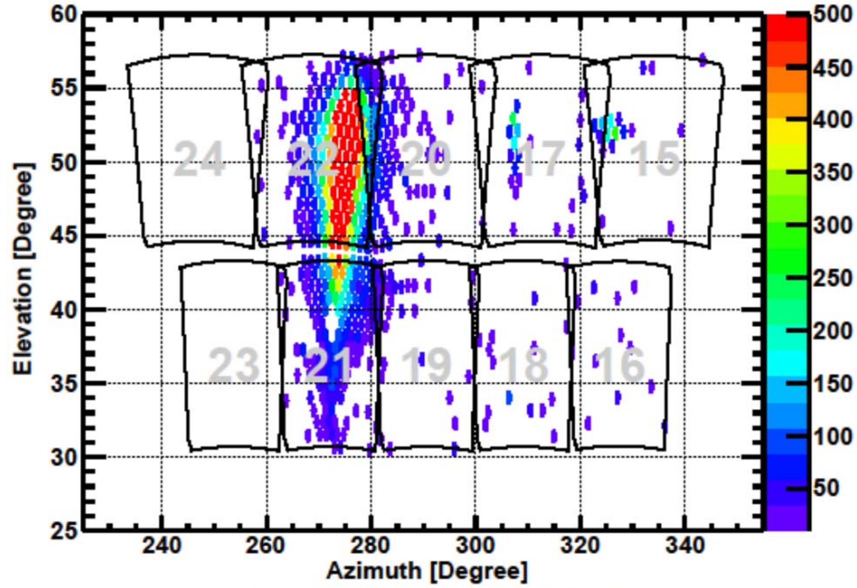
All 10 Telescopes installed and in operation since fall 2013

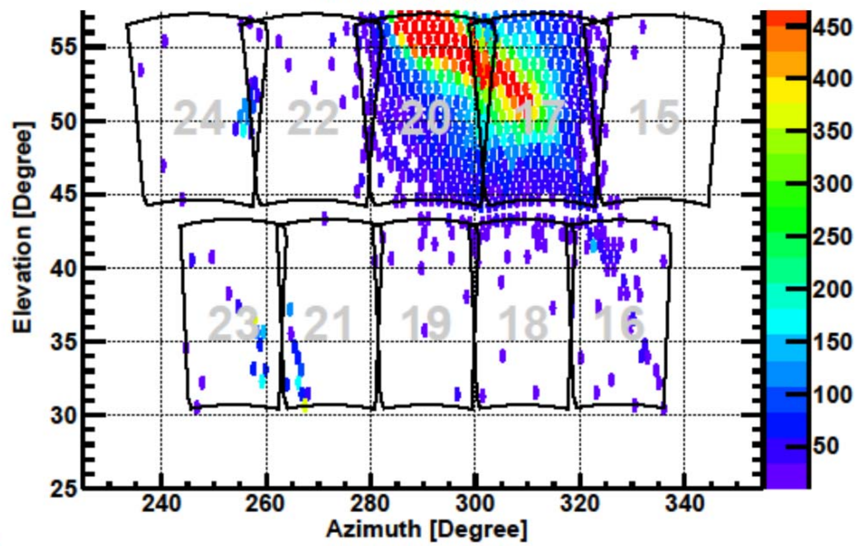
Test array of 16 scintillation surface detectors in operation

TALE SD infill array recently funded from Japan – deploy to field 2016-17

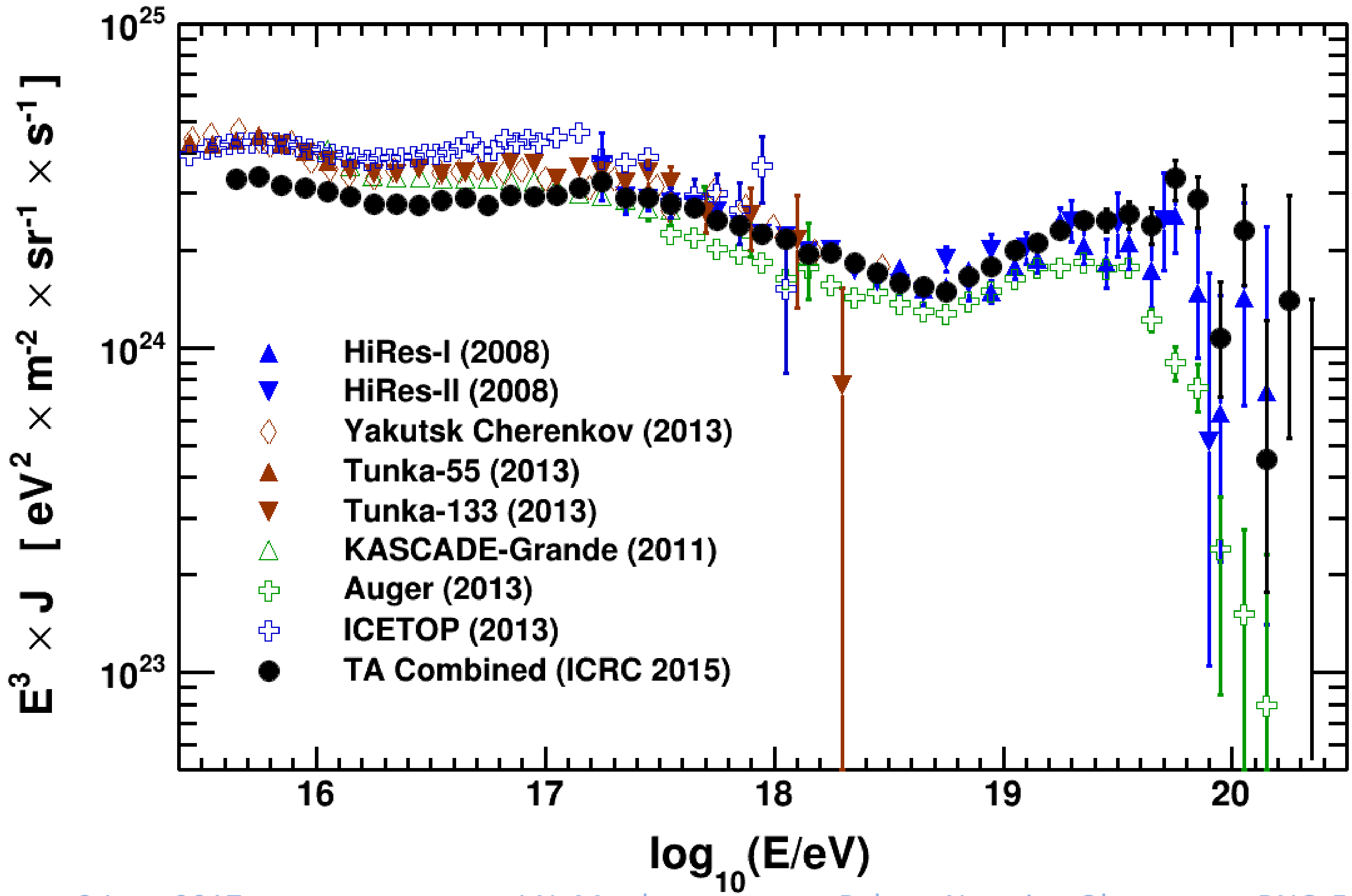
Nearby Events with Cerenkov



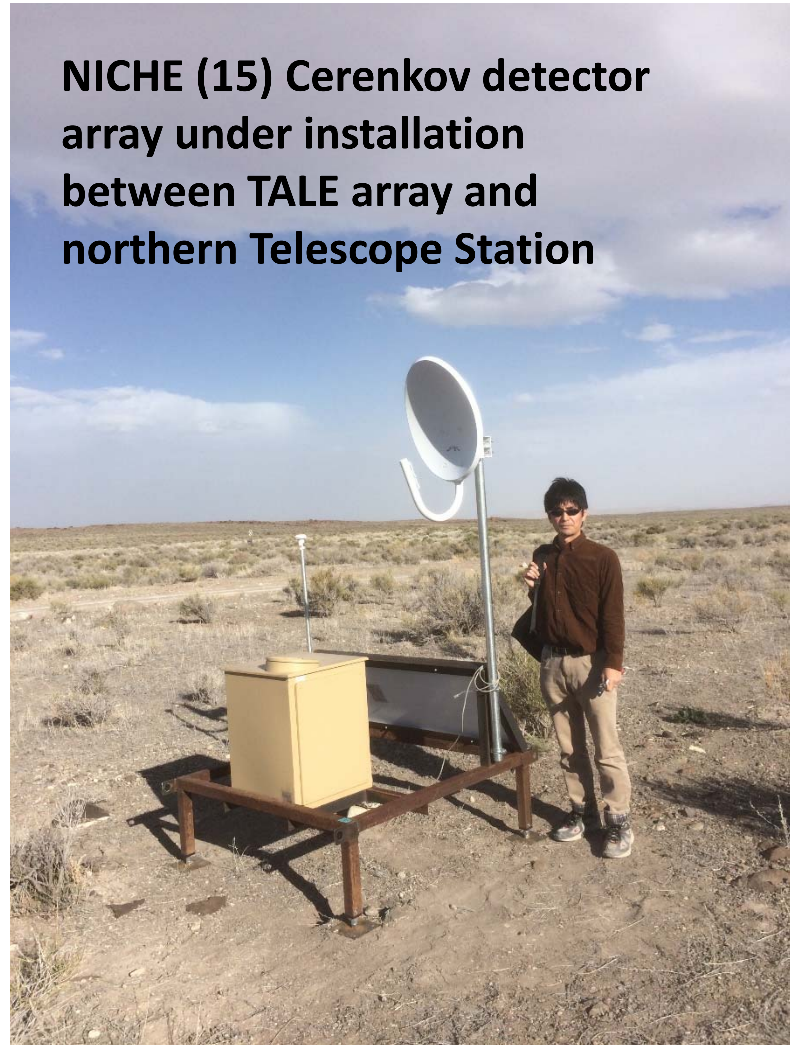




Comparison with other Measurements



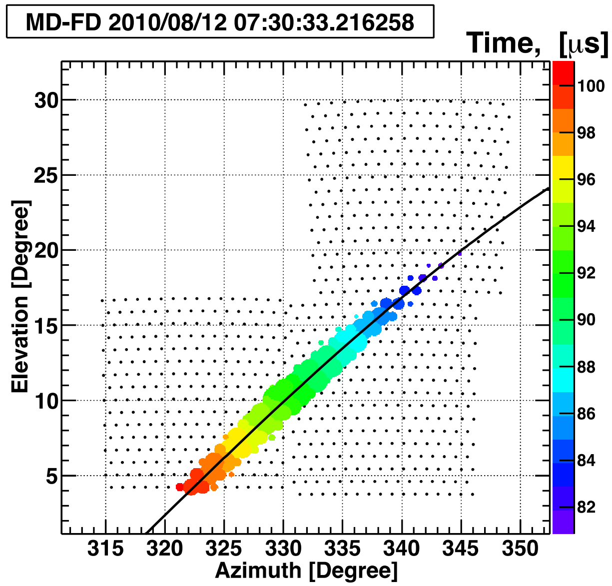
TALE/NICHE Low Energy

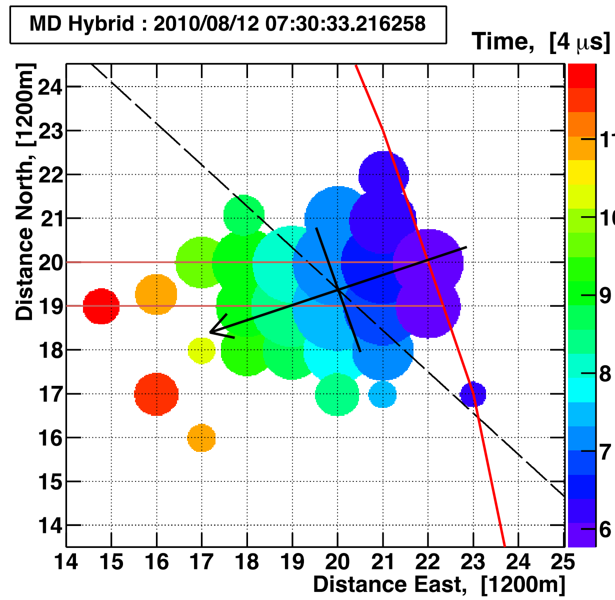


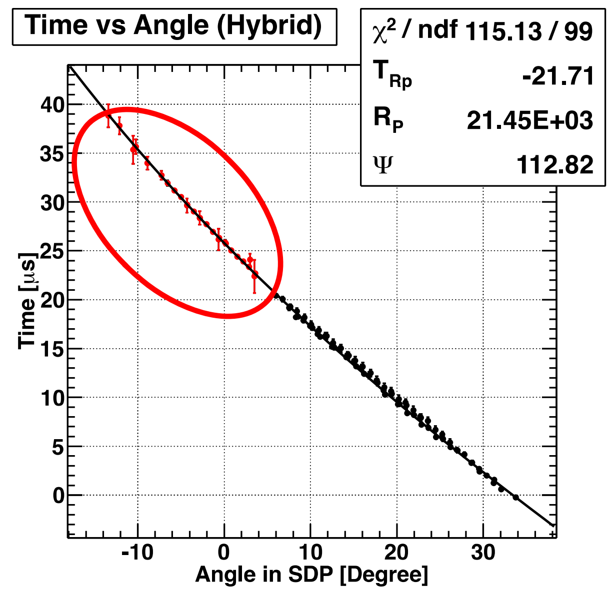
UHECR Composition

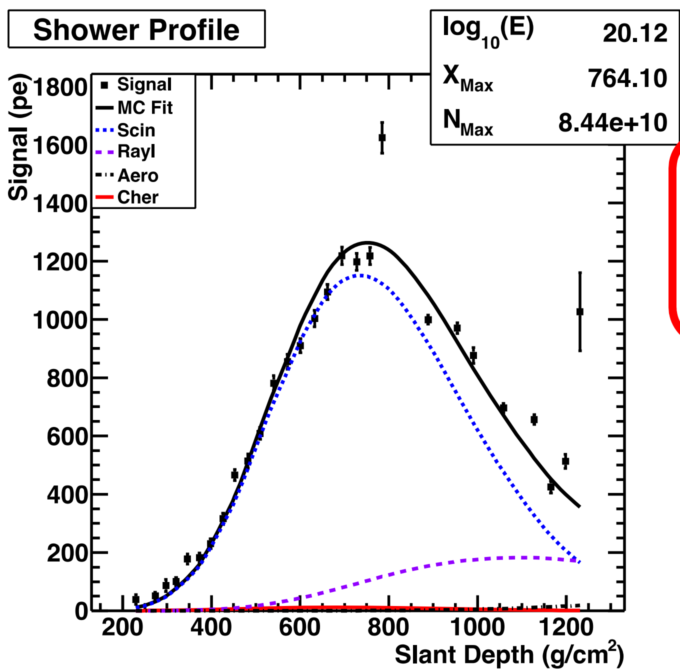
- Use hybrid or stereo to constrain geometry and know X_{max}
- Stereo also provides a redundant measurement of X_{max}

High Energy Hybrid Event







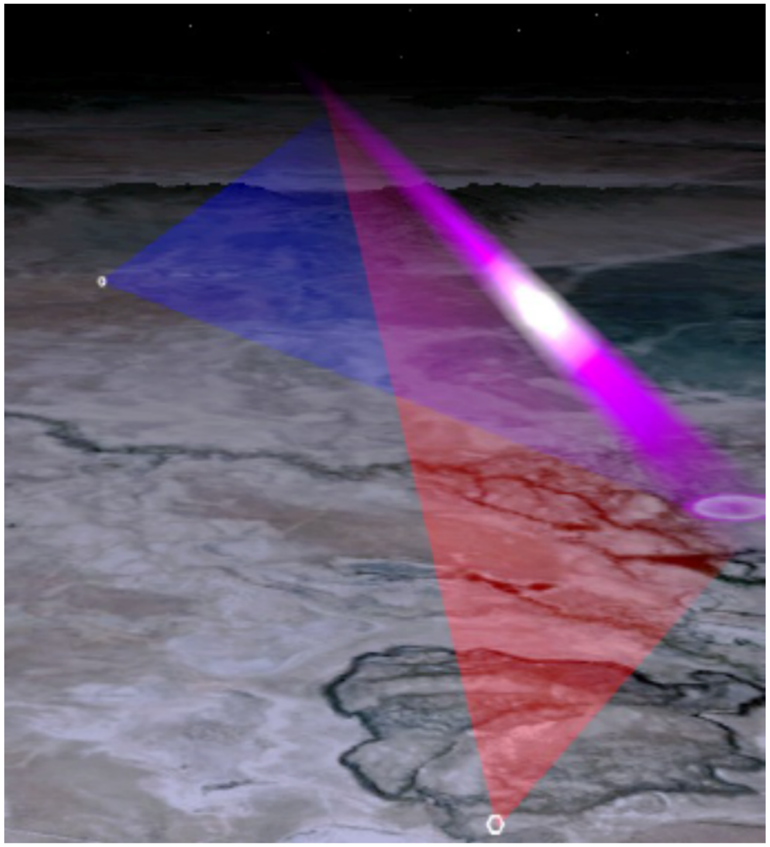


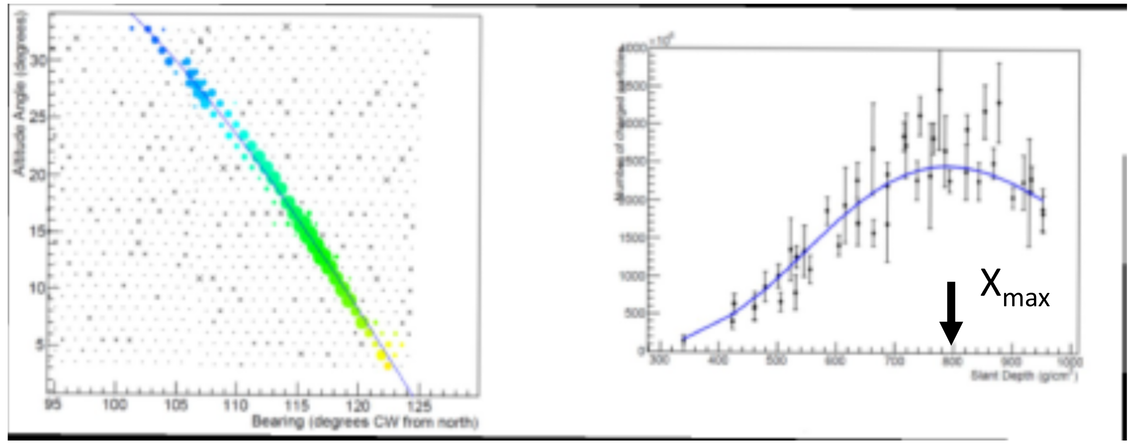
Energy: 1.3 × 10^{20} eV

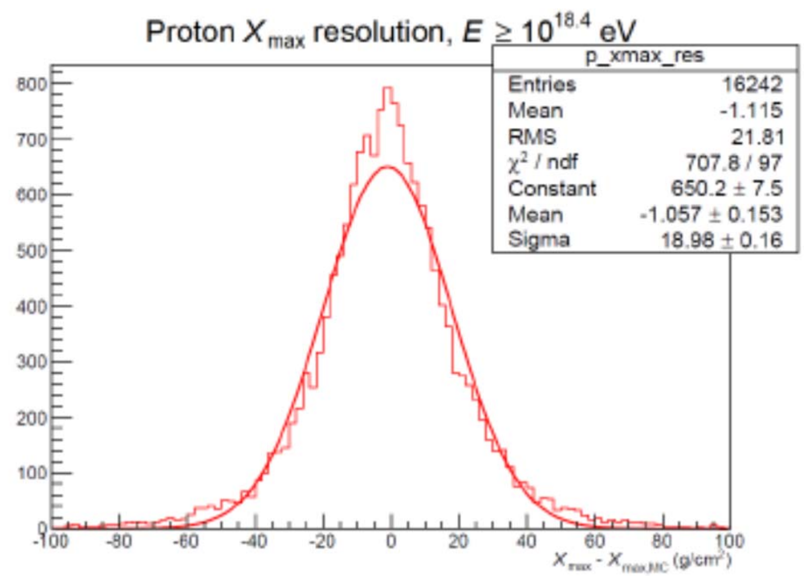
Zenith Angle: 55.7°

Surface array constrains geometry fit via extra timing & core information

Stereo Observation



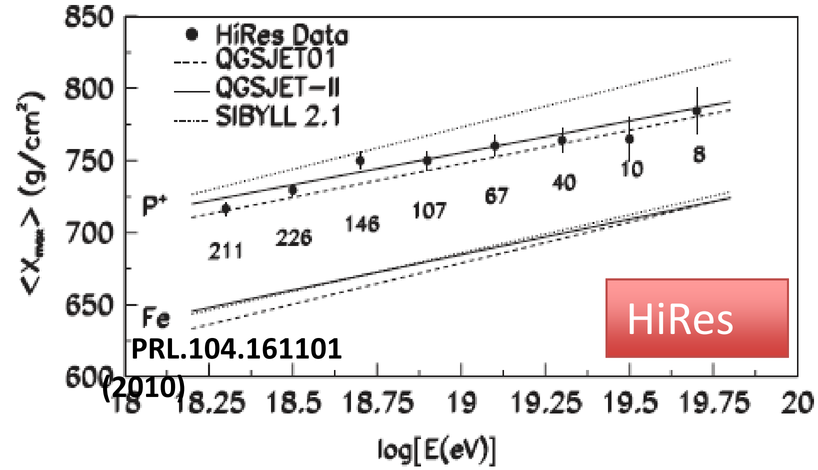




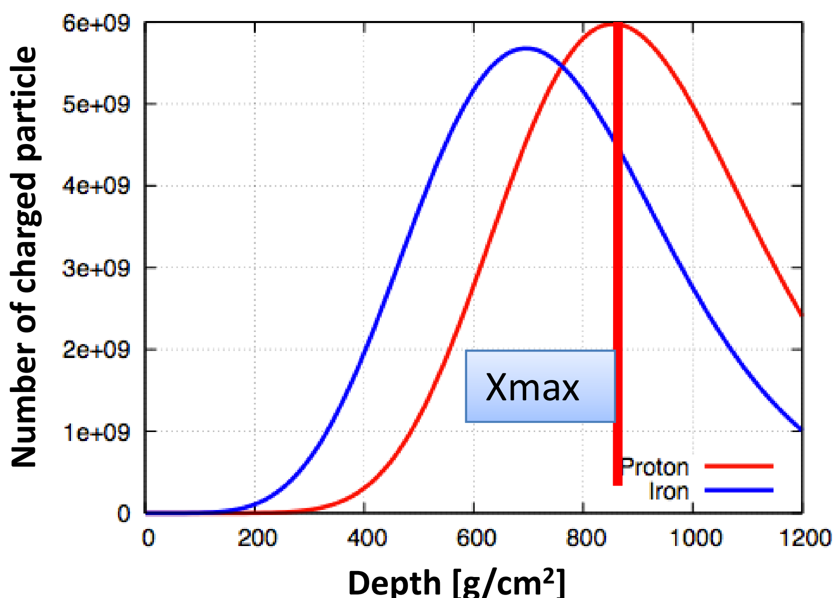
Intersect shower planes to get more precise geometry

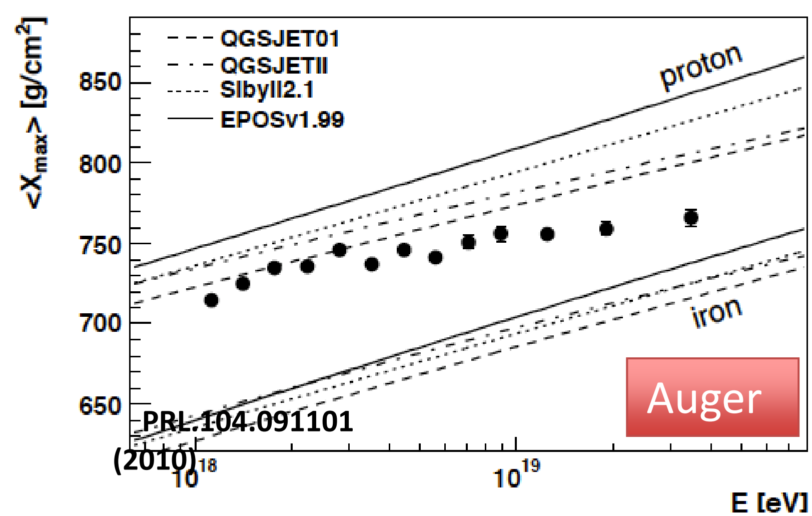
Xmax Technique

- 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

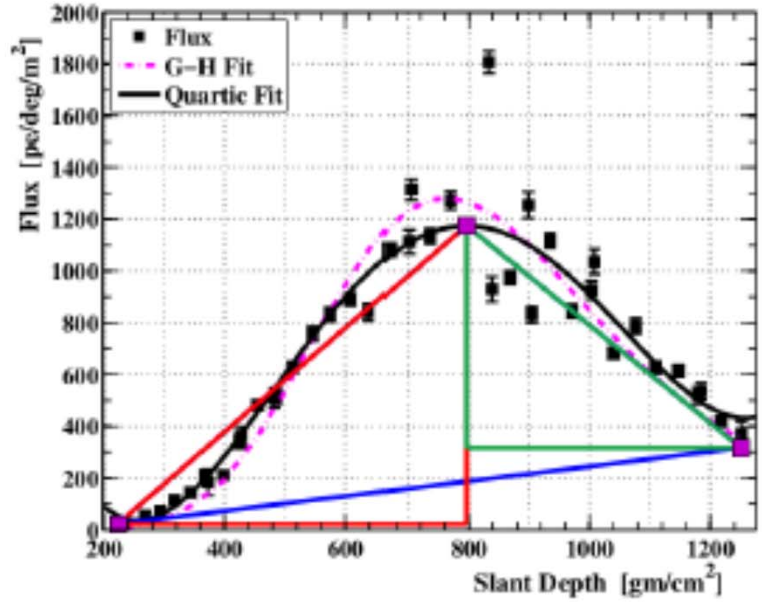


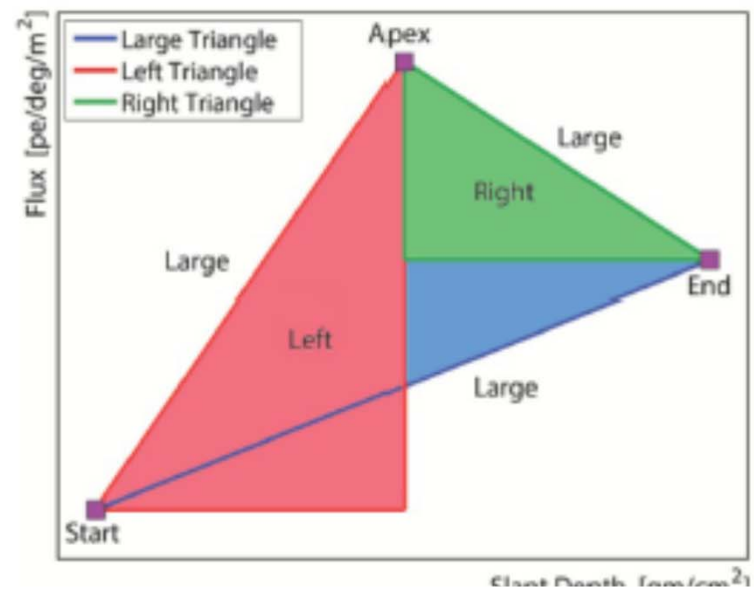


Hybrid Observation

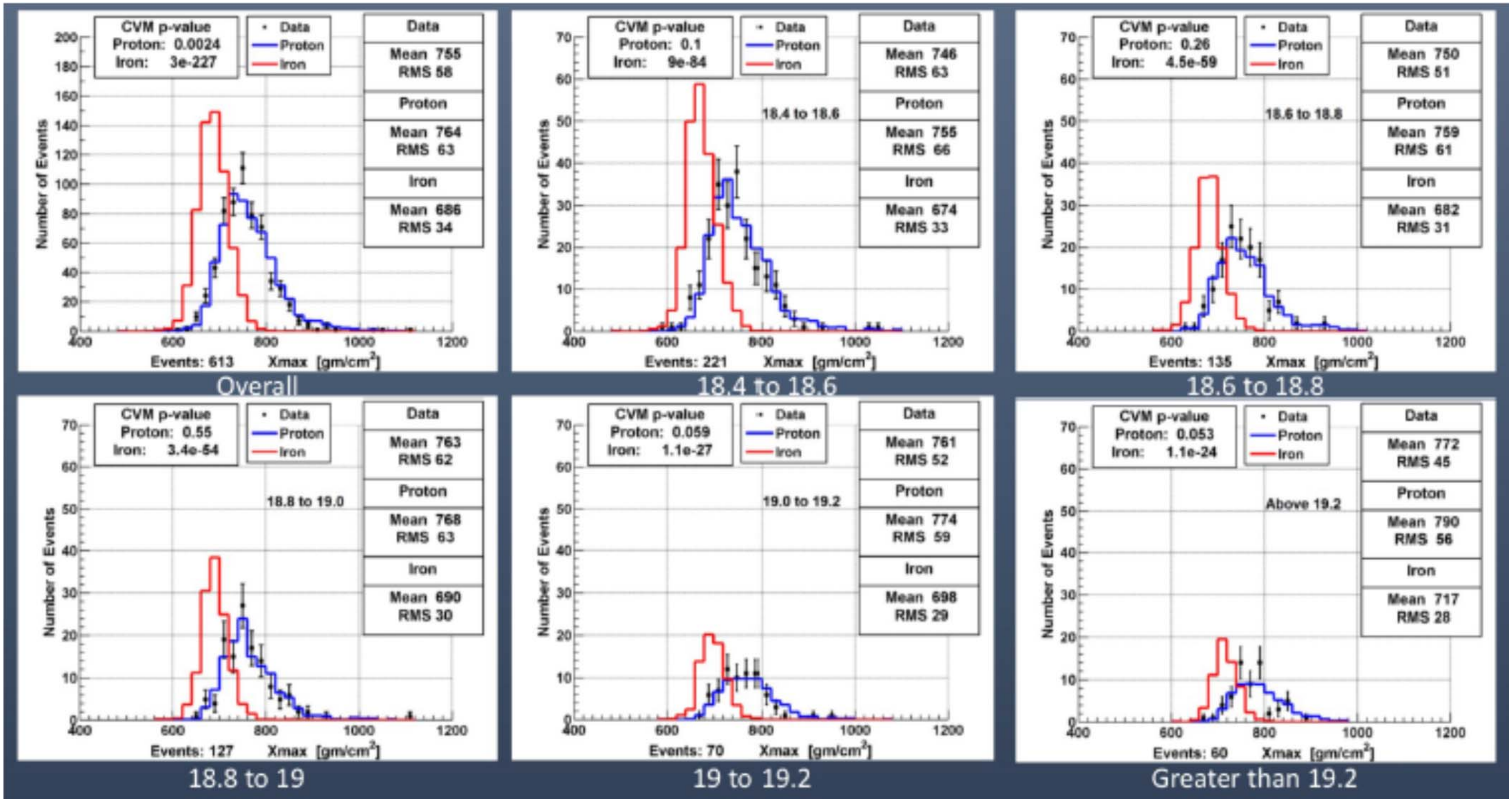
- Astropart. Phys. 64 49 (2014).
4 yrs, 297 Events > $10^{18.4}$ eV
- Cuts based on pattern recognition technique to improve resolutions s ≤ 25 g/cm^2, all energies.
- Update:

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





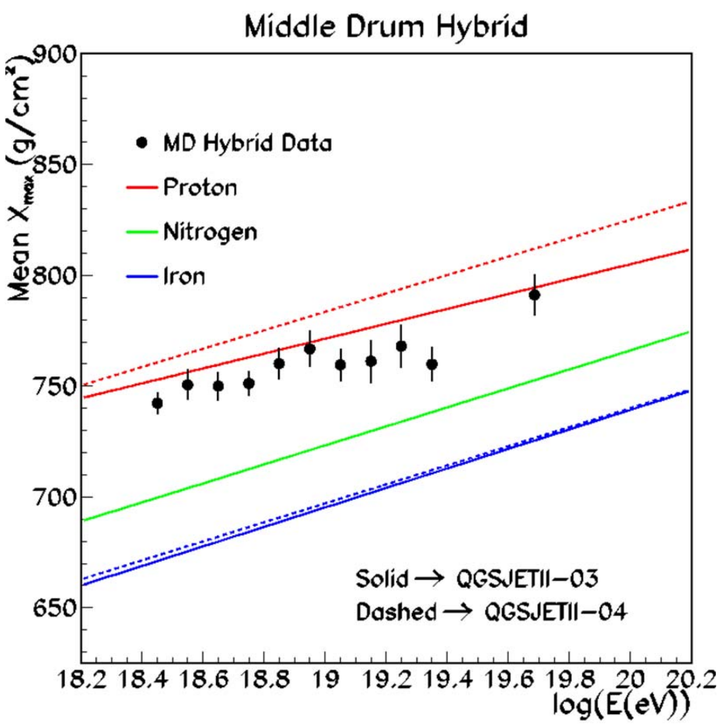
Hybrid X_{max} Measurement

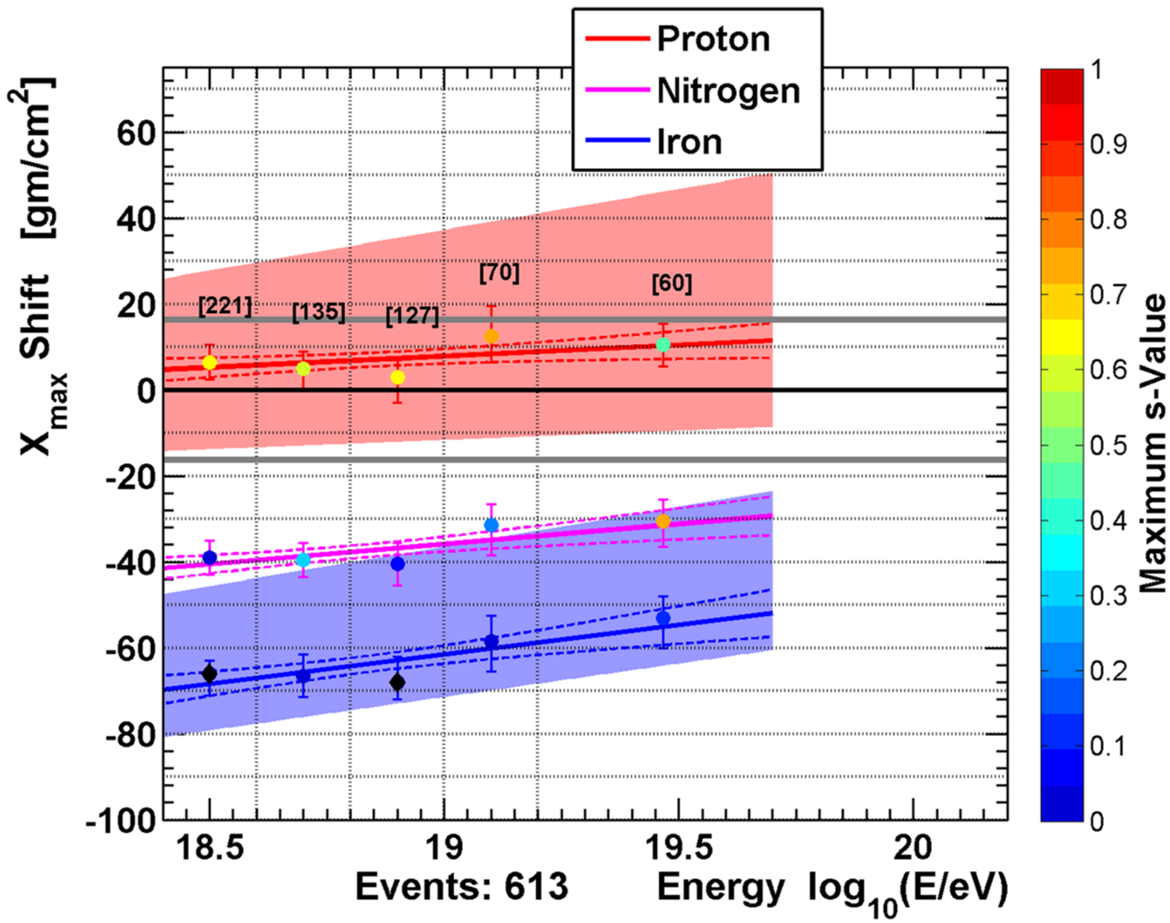


Xmax Data comparison to QGSjet II-03 **proton** and **iron** models

MD Hybrid

Elongation:
<Xmax> vs log(E) plot





"Shift Plot"

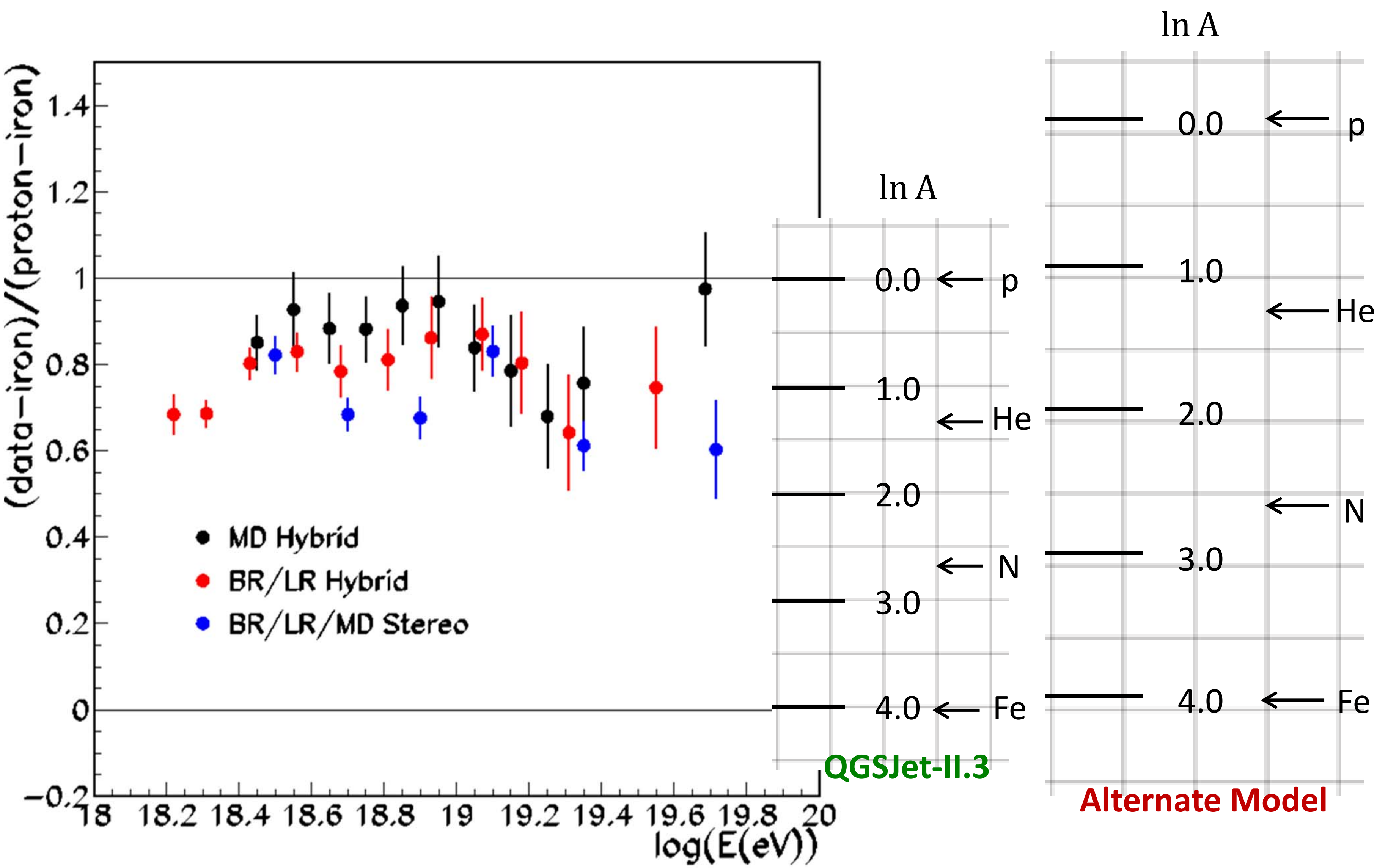
Plot ΔX_{max} required to maximize data/MC agreement (QGSJETII-03).

Standard statistical test on shifted distribution (points)

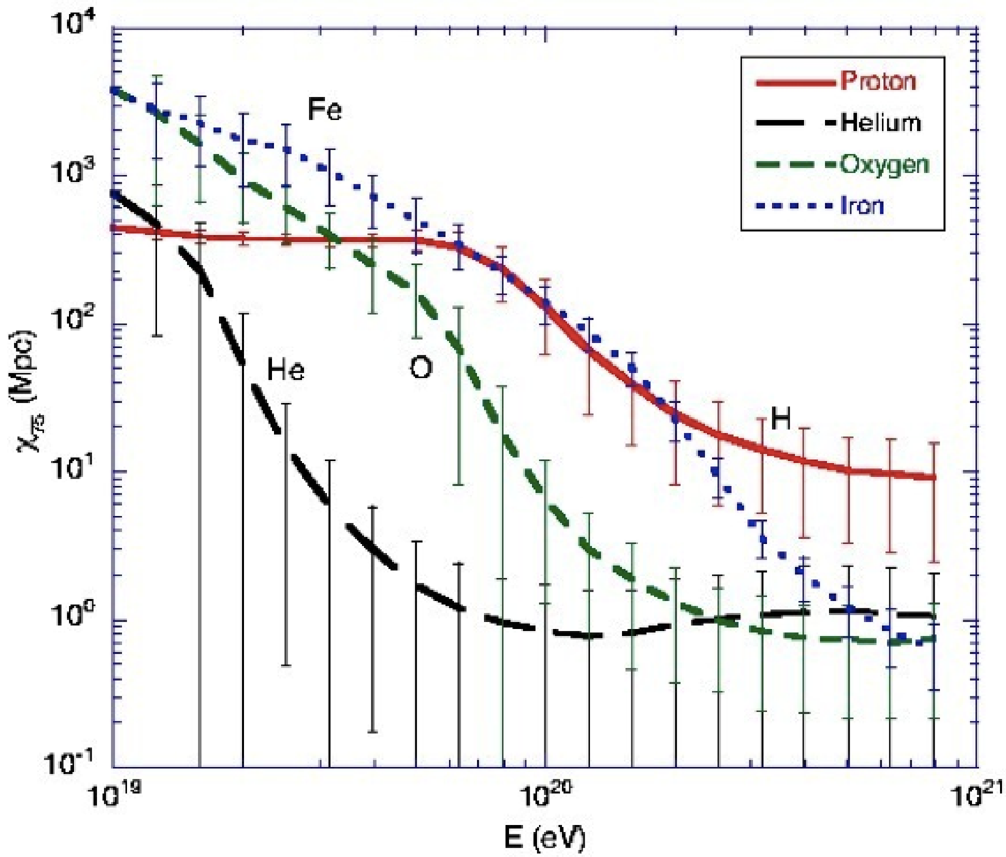
Pink, blue bands for other hadronic models

16 g/cm^2 systematic uncertainty

TA data compared to QGSJet-II.3

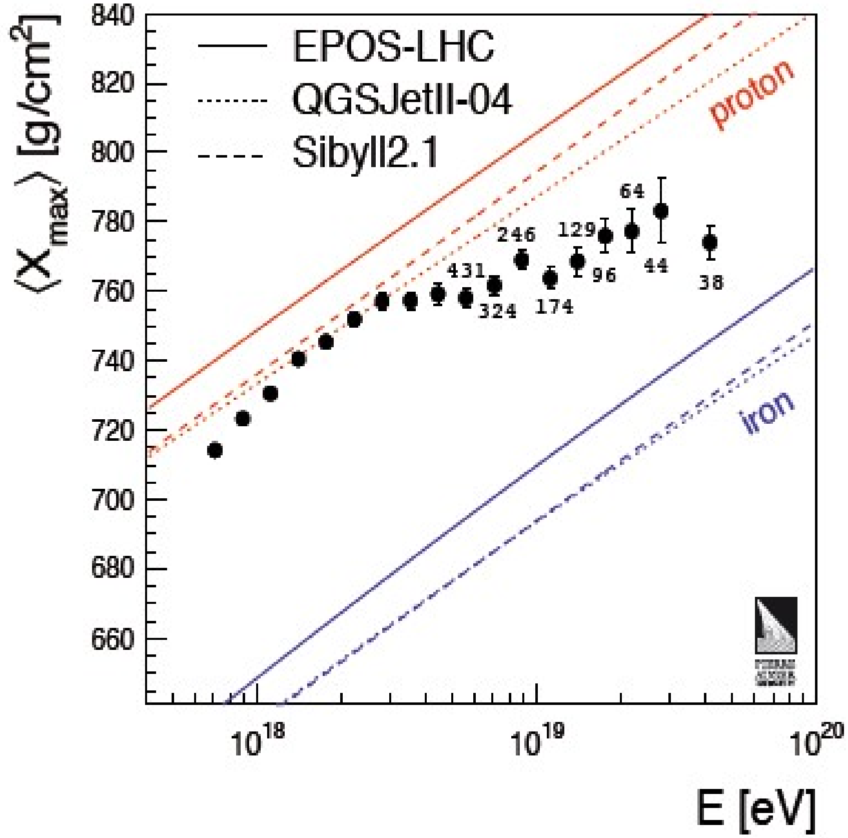


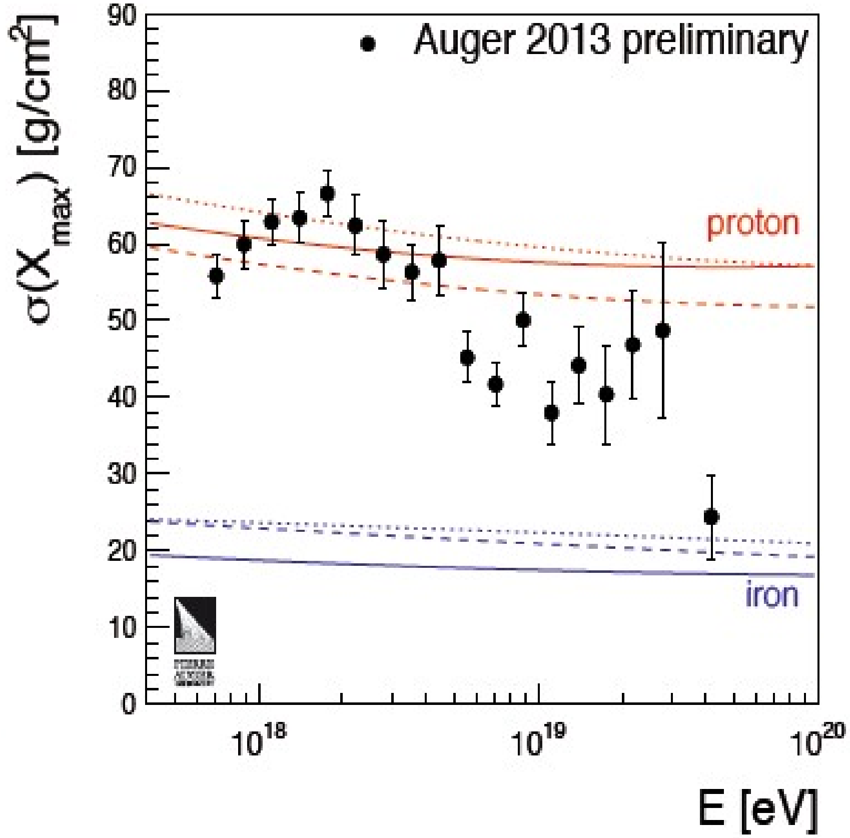
Astrophysically p and He are very different



Interaction lengths of p,He,O and Fe

Auger Composition: mean depth and rms of shower maximum





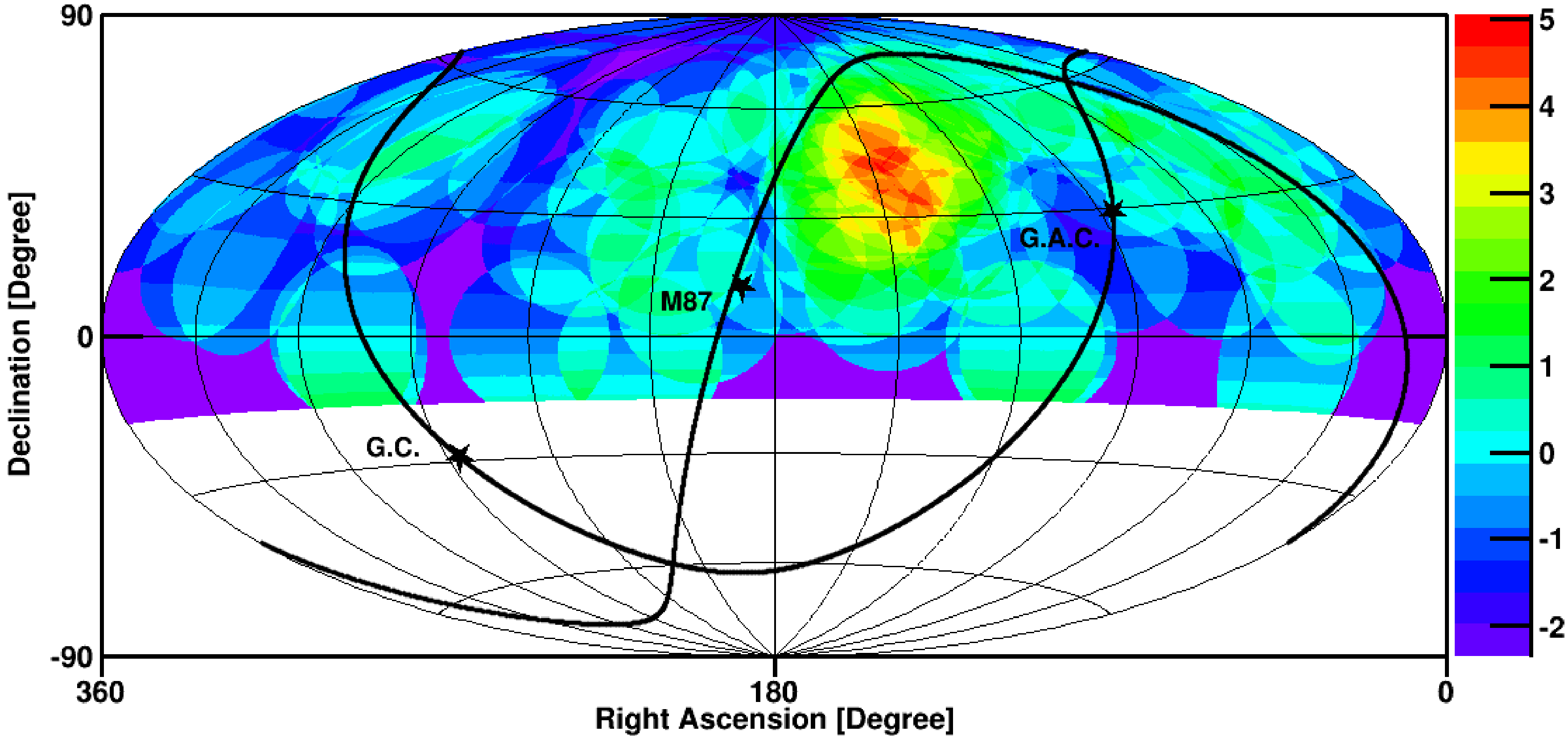
Composition is getting heavier with energy
Method only applicable up to 50EeV due to statistics

Photon/Neutrino Searches

- See Presentation by G. Rubtsov, INR

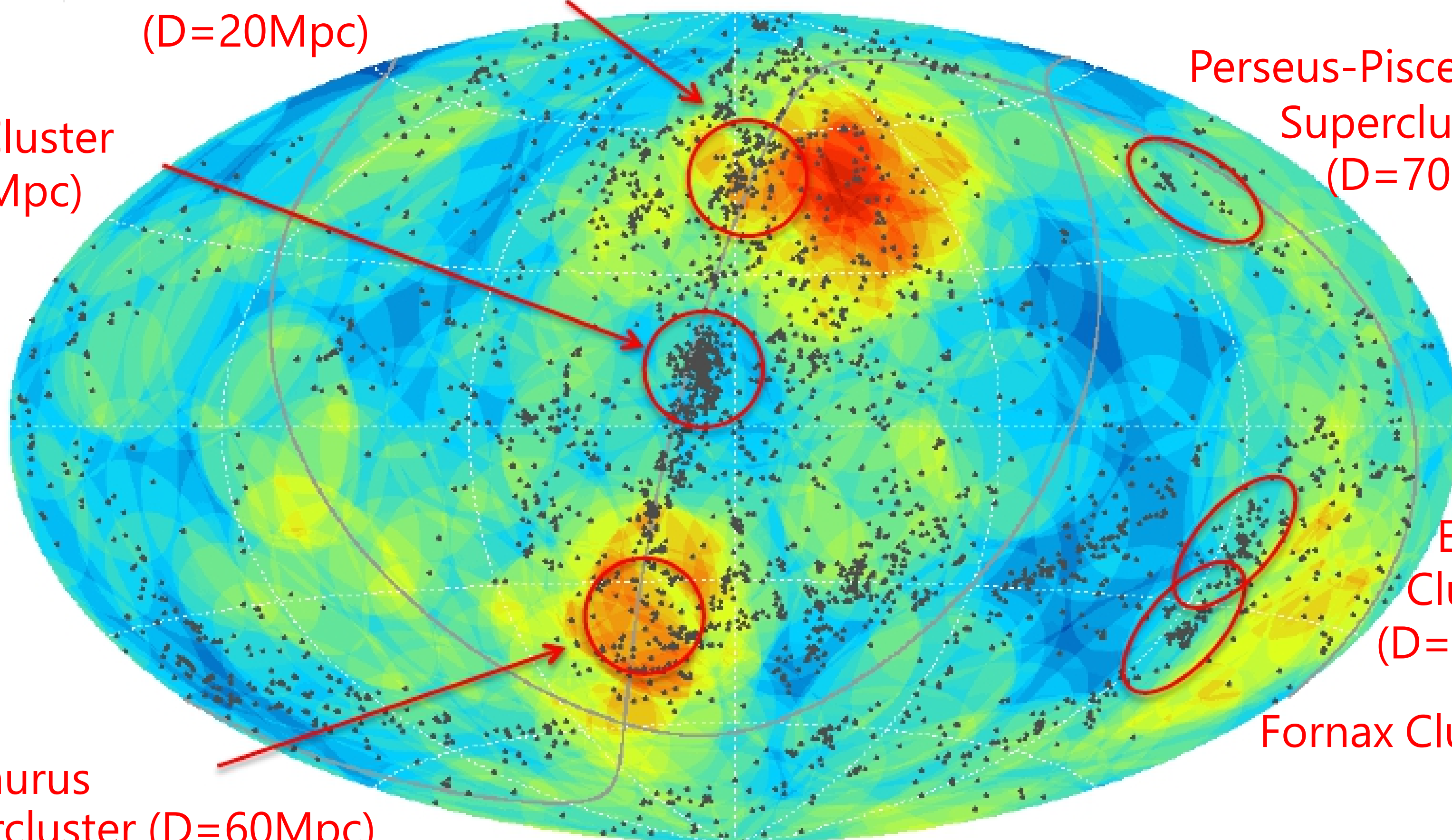
Anisotropy

Published Hotspot (5yr data)



E>5.7x10^{19} eV (72 events)
Aitoff projection in Equatorial Coordinates
Events over-sampled using 20° circles
19/72 events fall in hotspot (RA,dec) ~ (146.7°,43.2°)
4.5 events expected (26% of events in 6% of the area)
LiMa significance: 5.2σ Estimate 3.4σ chance probablity

Nearby Galaxy Clusters

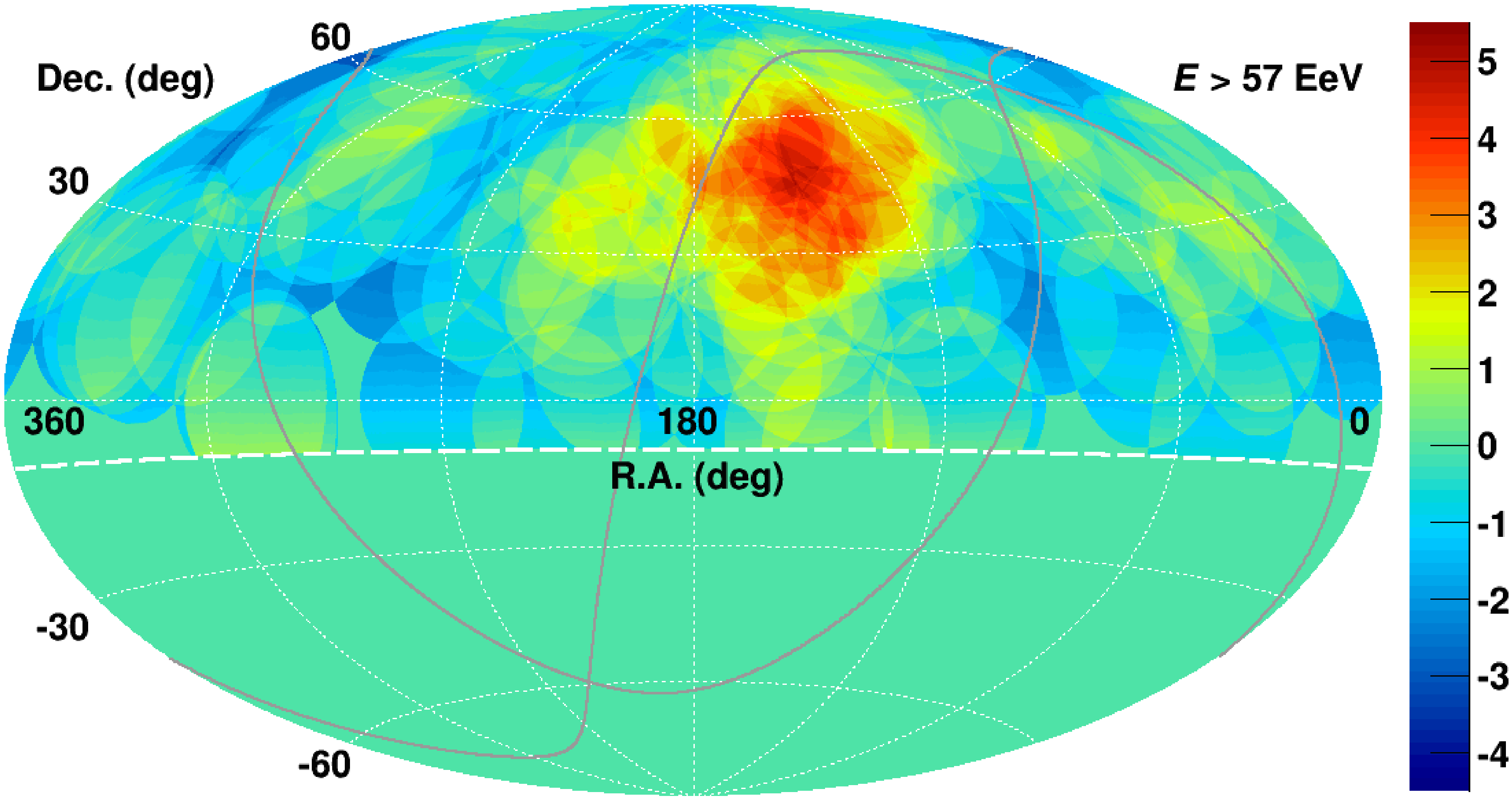


Huchra, et al, ApJ, (2012)

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

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

7 Year Excess Map



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

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

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

The Future:

TA×4 Project

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

500 scintillator SDs

2.08 km spacing

Approved in Japan 2015

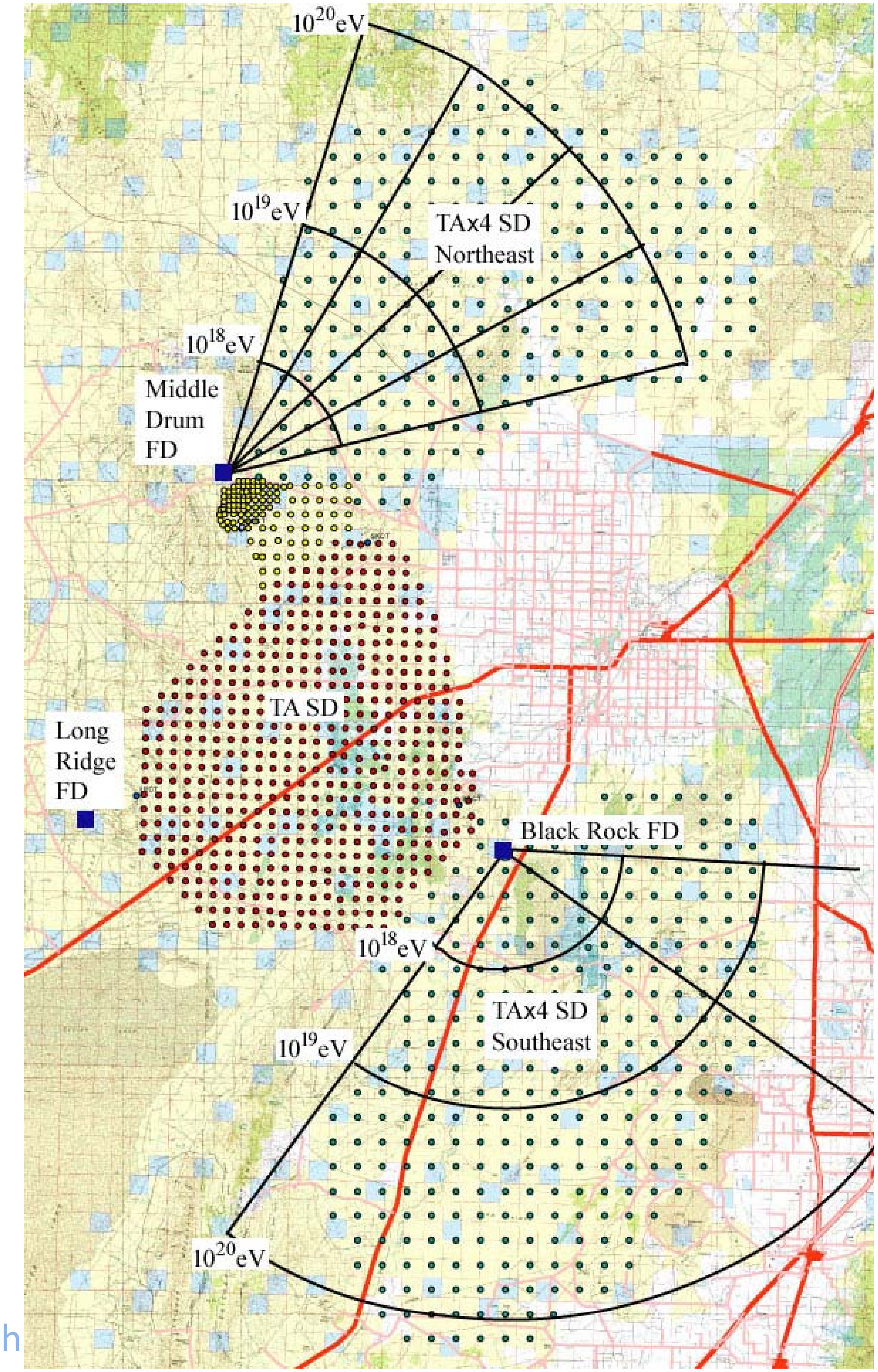
3 yrs construction, first 100 SDs have arrived in Utah (2016-05)

<u>2 FD stations (12 HiRes Telescopes)</u>

<u>Funding approved US summer 2016</u>

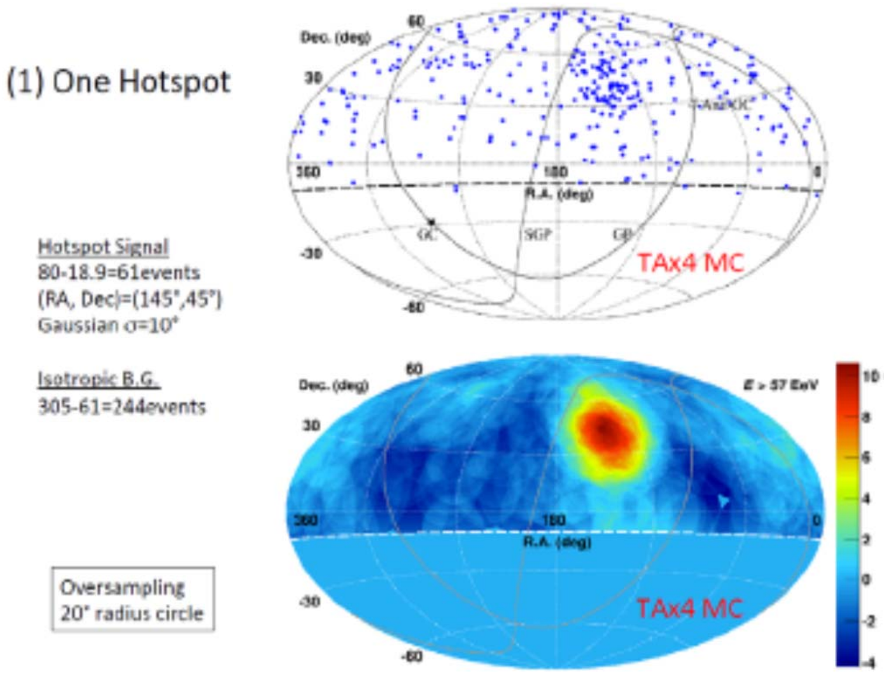
<u>**Get 19 TA-equiv years of SD data by 2020**</u>

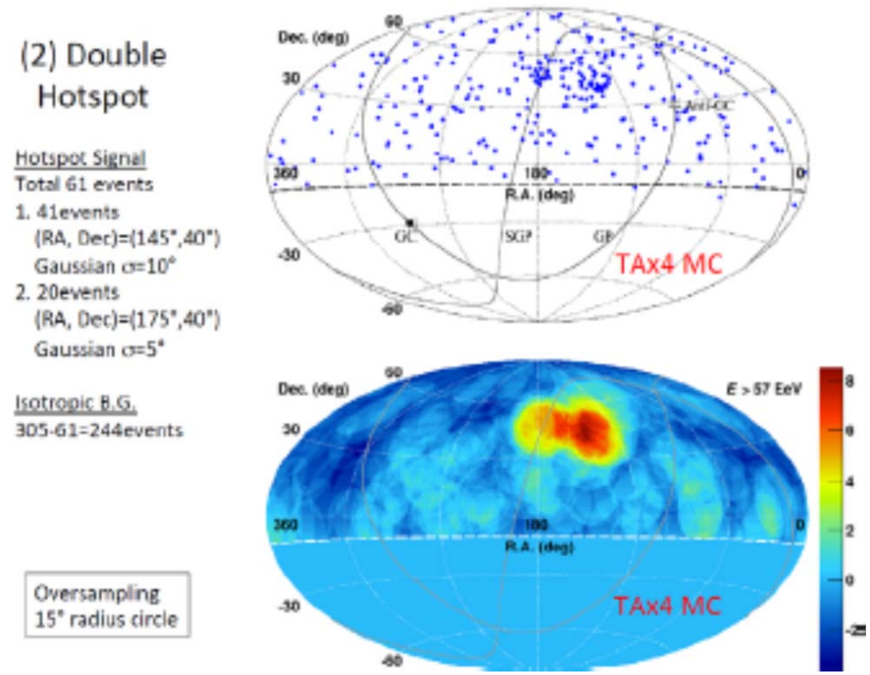
Get 16.3 (current) TA years of hybrid data



Clarify the details of the Hotspot

Simulated 19 TA-equiv yrs data

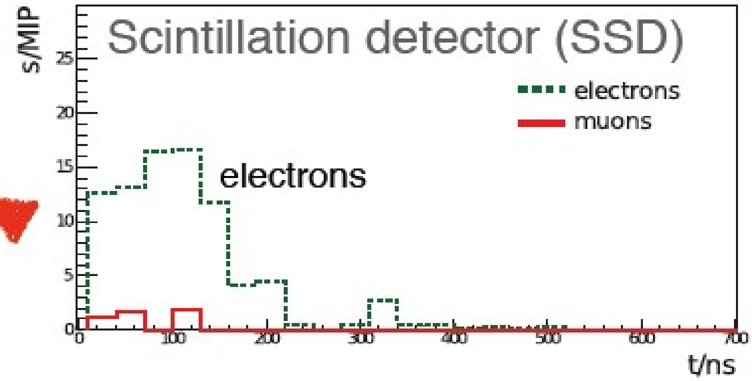


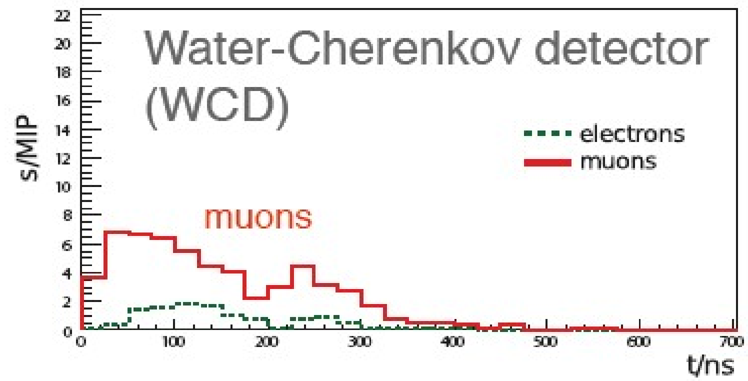


Single Source **Two Separated Sources**


Photo: Max Malacari, U of Chicago

Auger Prime Upgrade

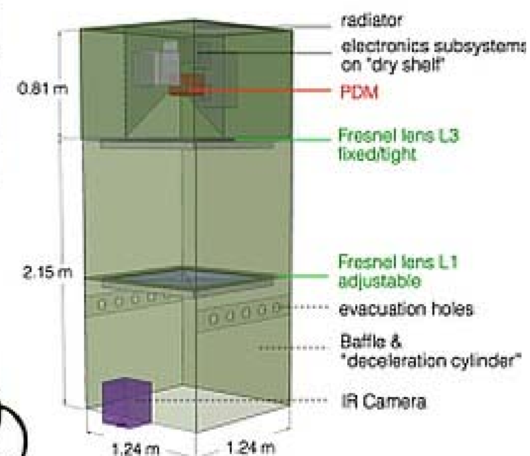


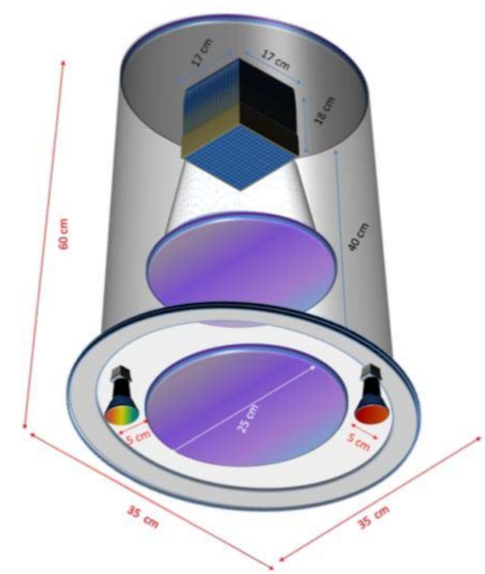


- **Engineering array in Argentina**
- **Construction 01/2017 - 2018**
- **Costs: 12.5 M€ >70% already committed**
- **Data taking into 2025**

EUSO / POEMMA

- JEM – EUSO
- KLEPVE – EUSO (MSU)
- EUSO – Balloon (CNES; Canada, Aug 2014, 5 hr)
- EUSO – SPB (CSOM; Apr-May, 2017)
- Mini – EUSO (MSU, RusCosmos; Fall, 2017?)
- ….
- POEMMA?



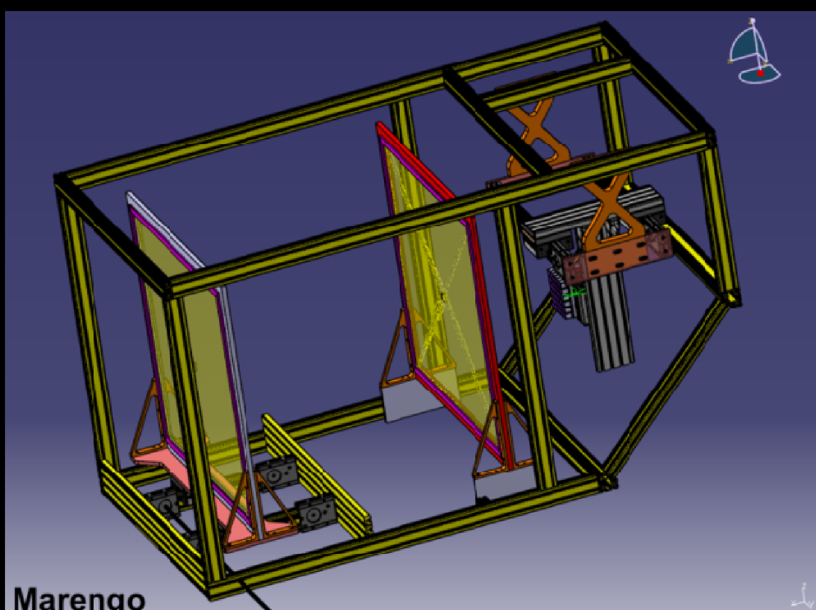


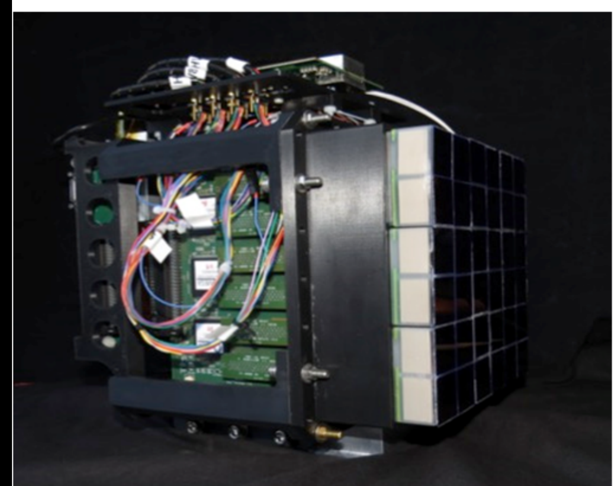
EUSO-TA

2013: Installation, building, lenses
2014: for Auger/FAST tests
2015:

- Detector installation
- FOV +/- 8°
- Initial CLF and CSOM laser observations
- Cosmic ray observations – UHECRs detected
- Internal trigger tests on the balloon PDM board

2016: Tests in conjunction with EUSO-SPB1

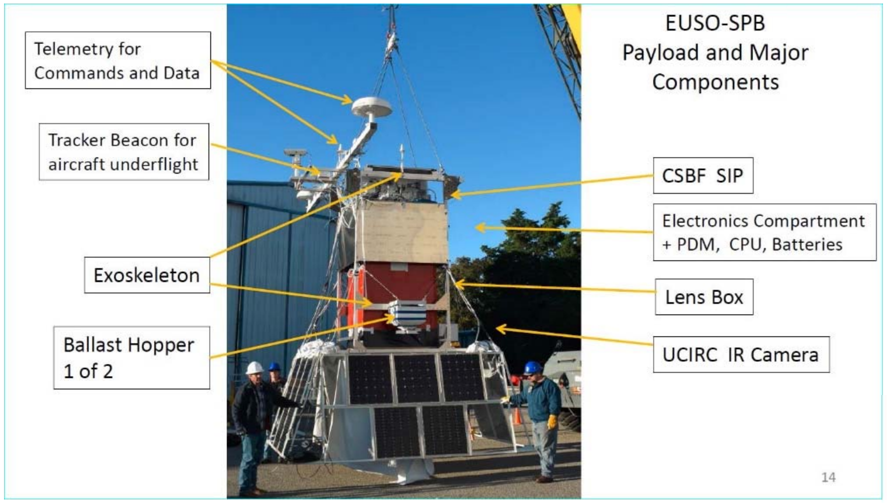




Photon Detection Module

48x48=2304 pixels
Single Photoelectron Counting
2.5 µS time bins
1 "video clip" = 128 bins = 320 µS
~15 watts

EUSO – SPB1



cast.htm

EUSO-SPB Specs

SPB Float Height	110,000 ft = 33.5 km
Weight	
Detector	2250 lbs
Payload	2700 lbs w/ SIP, Antennas, Empty Ballast Hoppers
Dimensions	1.2m x 1.2m x 3m
Power consumption	40 W Day, 70 W Night (assumes 20W PDM heater @ 50%)
Telescope	Refractor with 2 Fresnel lenses
FOV	11. deg (measured w/ stars)
Camera:	2,304 pixels; 36 MAPMTS (Hamamatsu R11265-113-M64-MOD2)
Data volume:	Downlinked ~1-1.5 Gb/day
Recorded	~3 GB/Day w/ 10 hour dark run
	with trigger rate of 0.2 Hz
Energy threshold	for h=33 km ~3 EeV
Ground equivalent Trigger Aperture	
	250 km^2sr @ 3 EeV to ~500 km^2 sr @ 10 EeV

1 of 2

6/7/17, 2:23 PM

Conclusions 1

- UHECR Flux suppression verified by Telescope Array and Pierre Auger
- Telescope Array consistent with GZK cutoff, Auger spectrum cuts off a bit lower energy
- Telescope Array energy range being expanded below 10^{16} eV with TALE – Spectral shape looks consistent with Yakutsk Cerenkov, Tunka-133, Kascade-Grande, and Ice Top – Normalization in progress
- Telescope Array observes four spectral features over >5 orders of magnitude in energy with one cross-calibrated set of detectors

Conclusions 2

- 10^{17} – 10^{18} eV composition goes heavy to light
- $>10^{19.3}$
  - Telescope Array light (protonic) composition
  - Auger composition getting significantly heavier

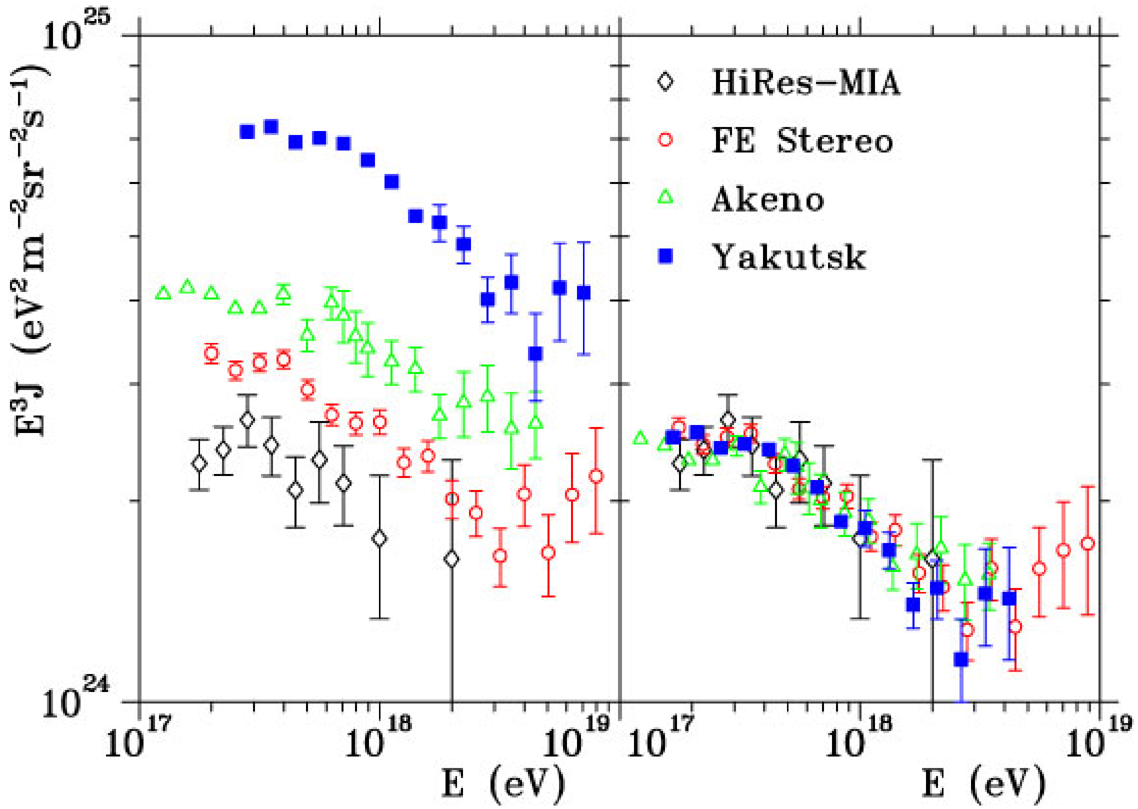
- E > $5.7x10^{19}$ Telescope Array observes indications (3.4σ) of medium scale anisotropy

- TAx4 -> expansion to ~ aperture of Auger
- Auger Prime – add Scintillators
- EUSO broad program moving forward

Summary

- TA has measured the energy spectrum, composition and arrival direction of UHE cosmic rays
- The spectrum and composition of UHE cosmic rays measured by TA remain compatible with a single light component at above the ankle (~6×10^{18} eV).
- We have reported a hot spot seen in the direction of Ursa Major with 3.4σ significance
- *New:* TA Low Energy Extension (TALE) is coming on line. TALE surface detector array was funded by the Univ . of Utah and was recently been funded by Gov't of Japan.
- TA and TALE have measured energy spectrum between 6×10^{15} eV to over 10^{20} eV with a single cross-calibrated set of detectors and have observed spectral features
- **Much more data are needed! – coming soon TAx4**

Galactic to Extra-Galactic Transition



- Previous suspected structure
- Unknown energy scale
- Tie down the energy scale and simultaneously measure spectrum and composition

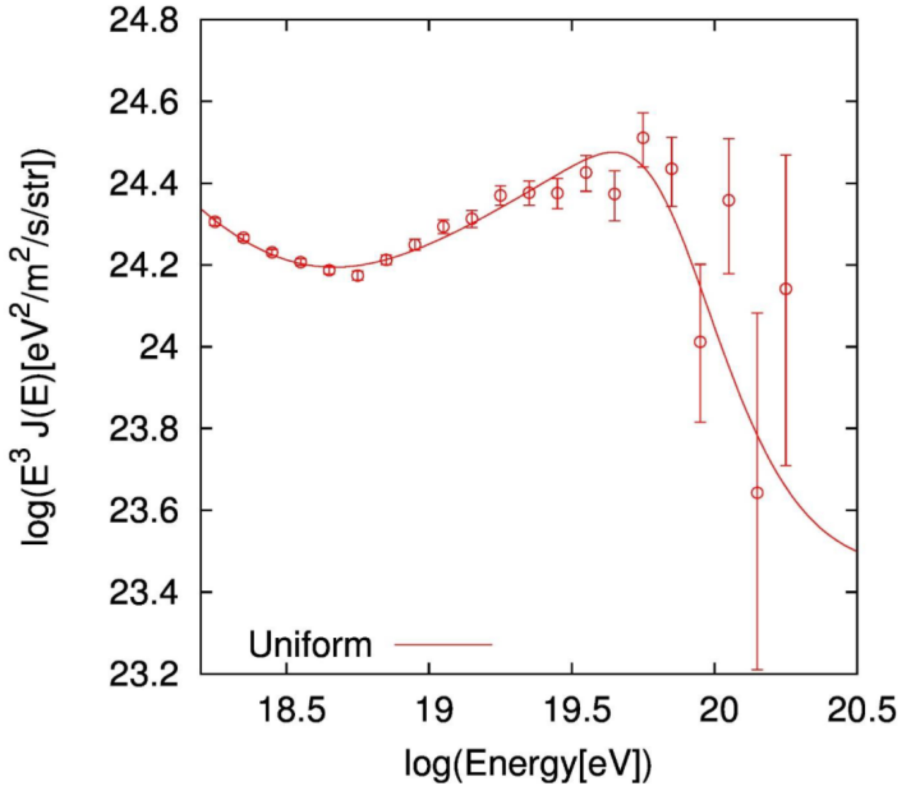
Fitting the UHE Spectrum with TA

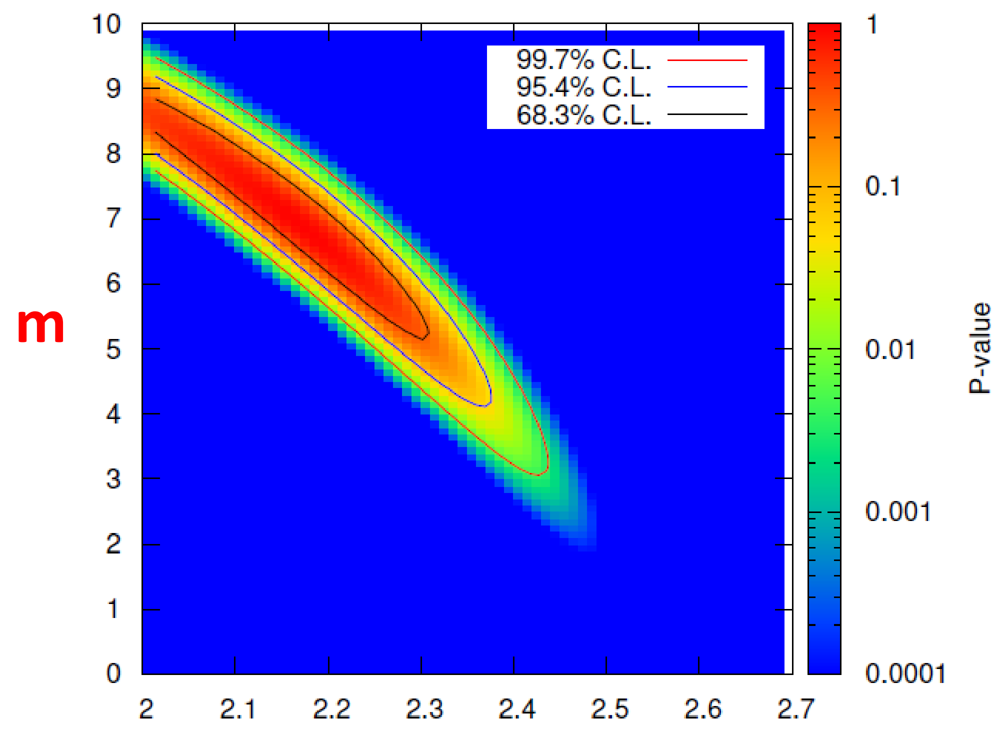
Fitting parameters:

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

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

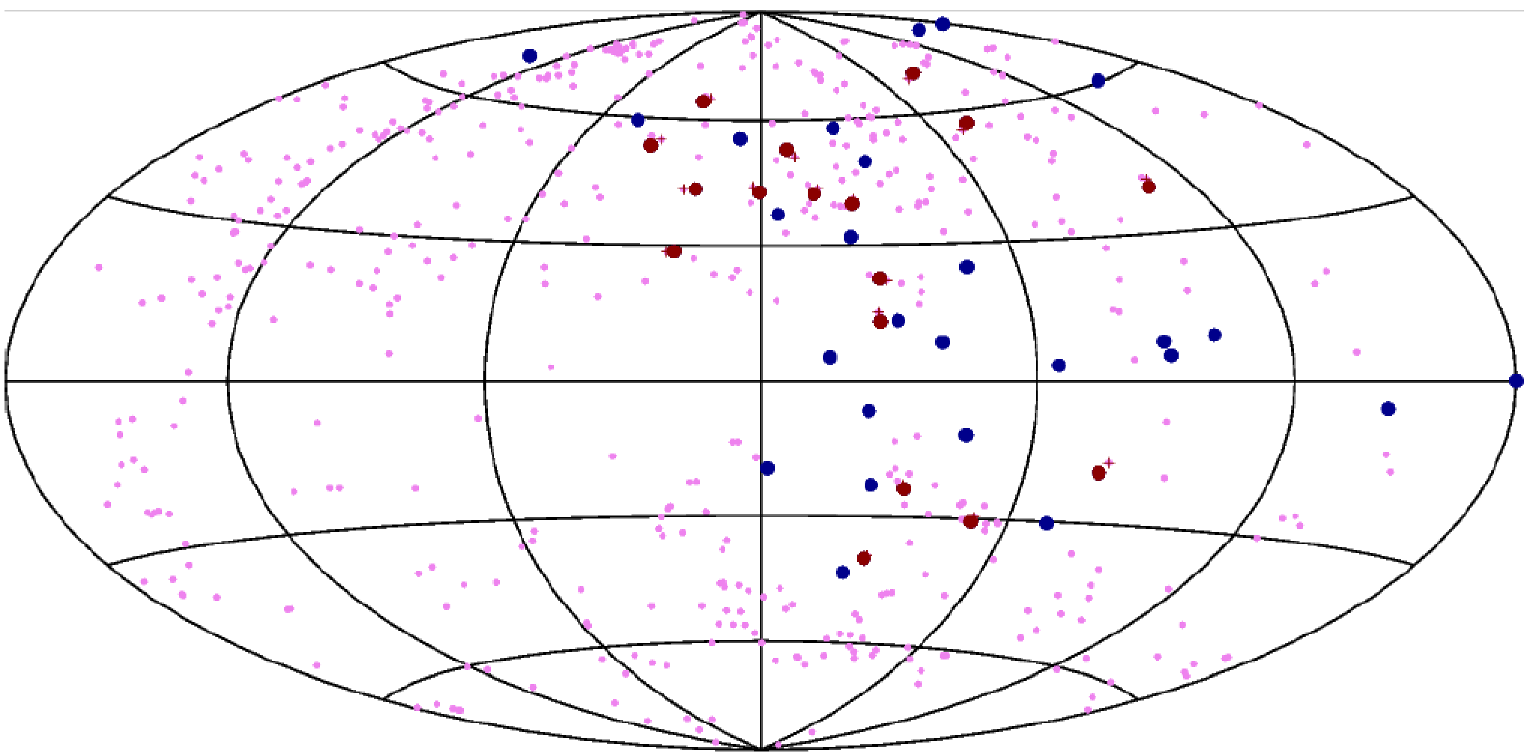
$p = 2.18^{+0.08}_{-0.14}$, $m = 6.8^{+1.6}_{-1.1}$;
(stat. + sys.)





Test Correlations with AGNs

- 472 AGN from 2006 Veron catalog with $z < 0.018$
- $E > 57$ EeV, zenith angle $< 45^o$, $N = 42$ (5 yr)
- Separation angle $= 3.1^o$



Correlations with AGNs

Probability of event overlapping with AGN is $p_o = 0.24$
Find 17 events correlate of 42 ⇨ $p = 0.014$