# Ultra High Energy Cosmic Rays in the North

*The High Resolution Fly's Eye (HiRes) and Telescope Array Project (TA/TALE)*

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University of Utah

# Outline:

- Introduction to HiRes Detector and Data
- Spectrum
- Chemical Composition
- Anisotropy / Sources
- proton-air Cross-section
- Neutrinos / Exotics
- Telescope Array and Its Low Energy Extension

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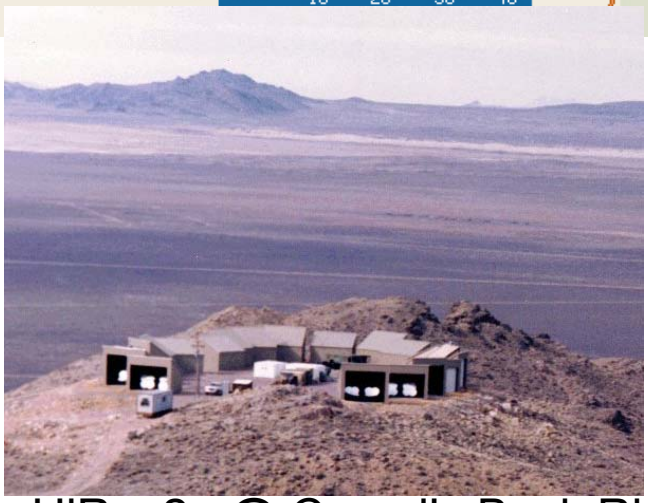
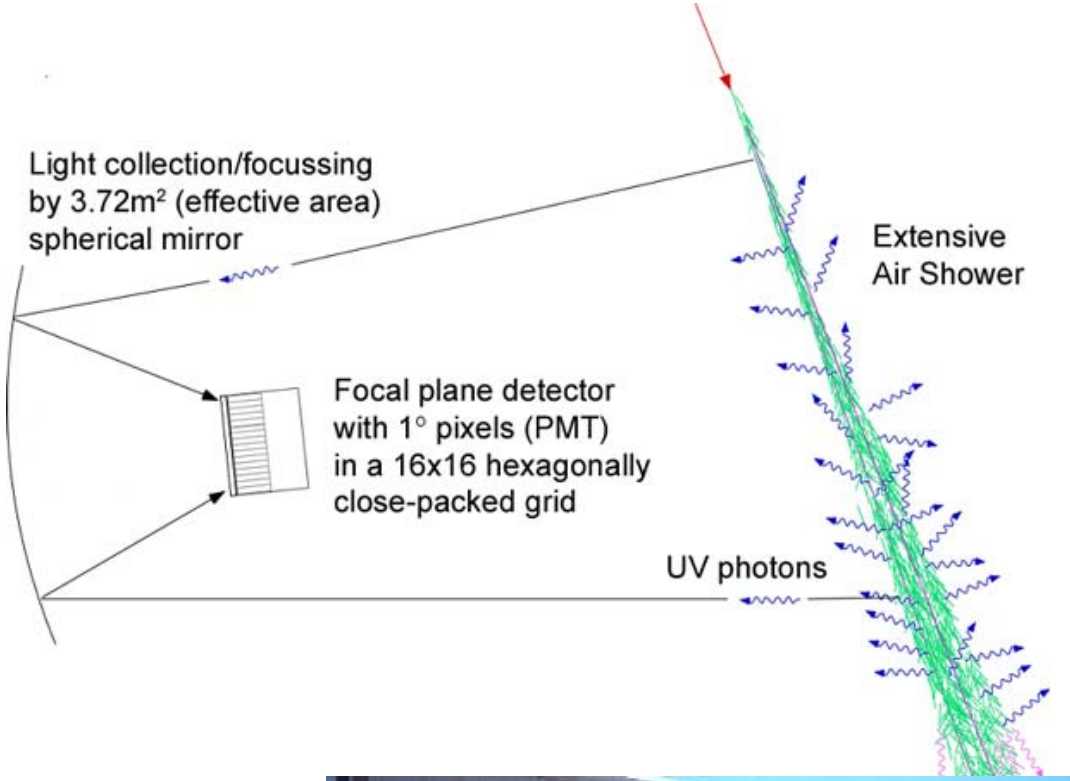
# Until 4/2006, HiRes was operating on the U.S. Army's Dugway Proving Ground, ~2 hours south-west of The University of Utah


- HiRes1: @ Five Mile Hill (aka Little Granite Mountain)
- 21 mirrors, 1 ring ($3^{o}$<altitude<$17^{o}$)
- Sample-and-hold electronics (pulse height and trigger time)



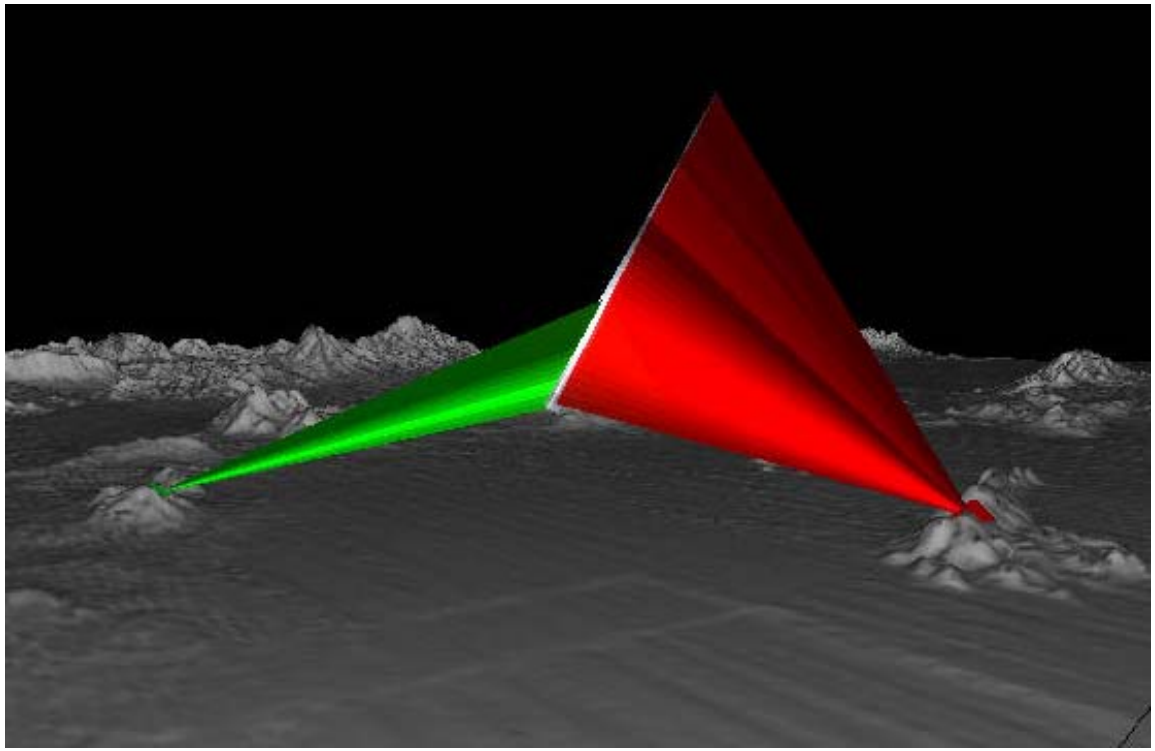
- HiRes2: @ Camel's Back Ridge 12.6 km south-west of HiRes1.
- 42 mirrors, 2 rings ($3^{o}$<altitude<$31^{o}$)
- FADC electronics (100 ns period)

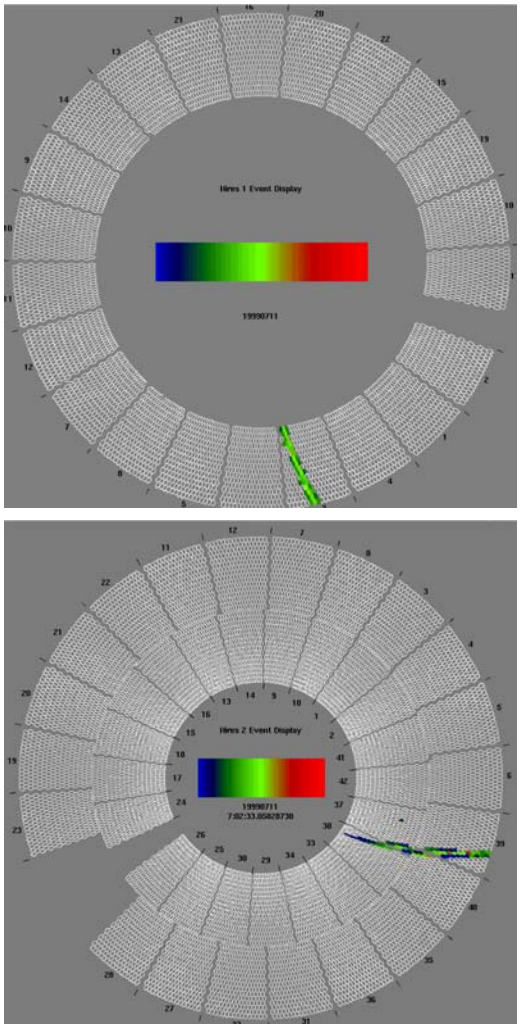
# Detector Design




- UV-filter (300-400 nm band pass) to reduce sky+ambient background light
- Steel housing - 2 telescopes each

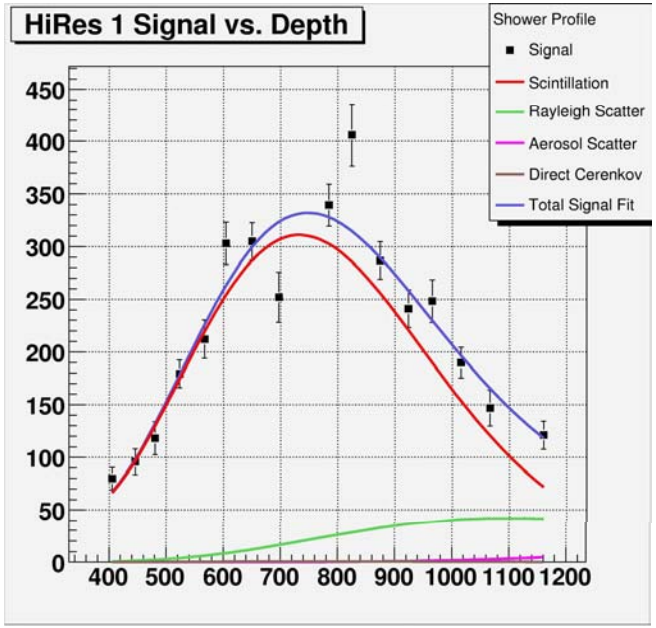
# Typical HiRes Event

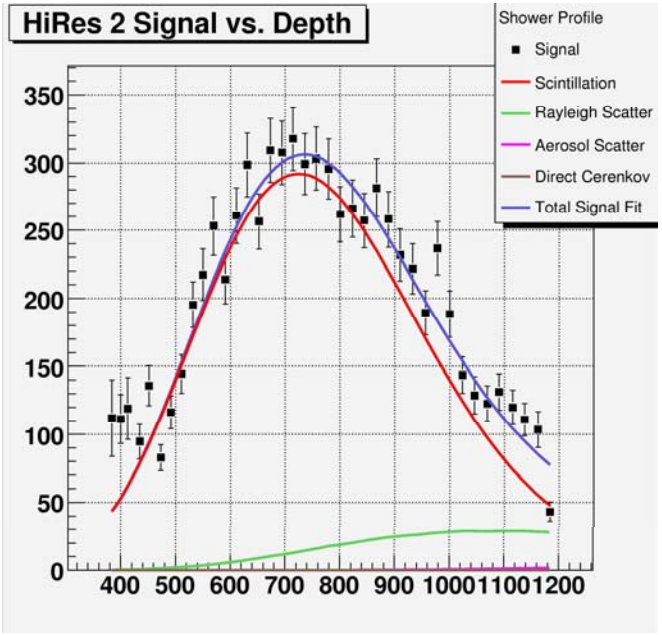





- ~$2\times10^{19}$ eV event observed in 1999
- (3× vertical scale)

# Measured Shower Profile




## Measured shower parameters.

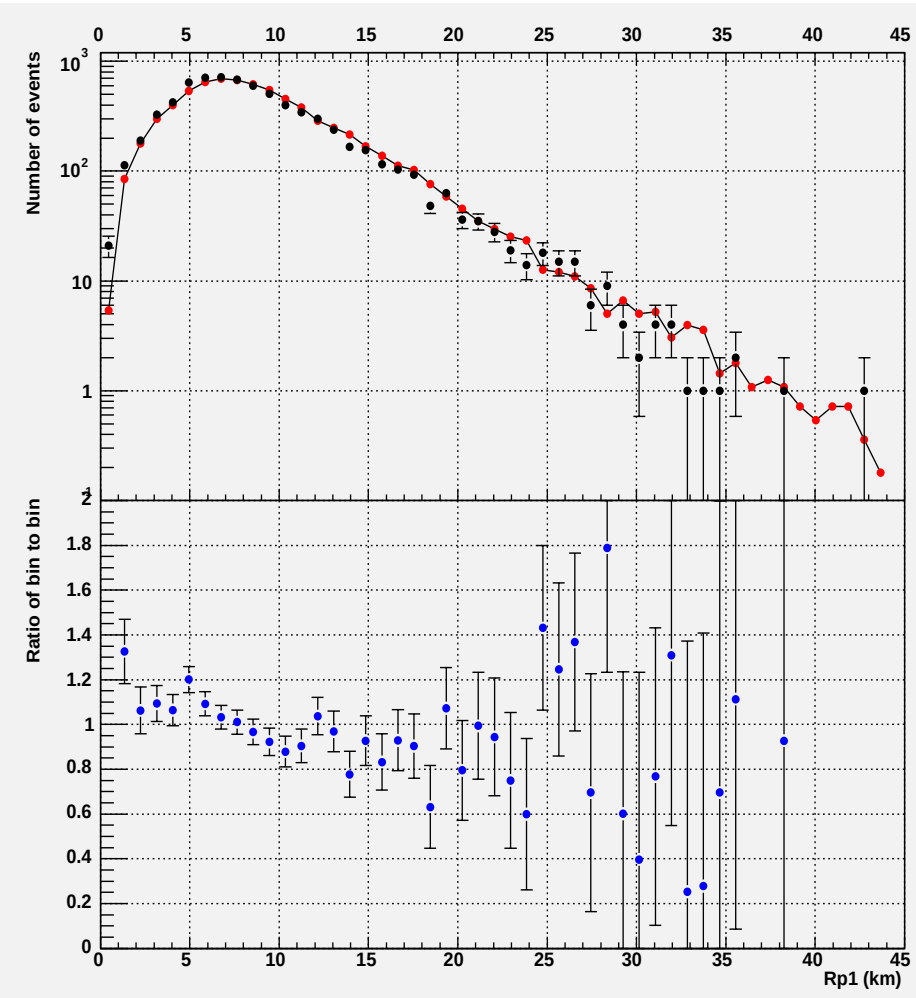
*Event by event:*

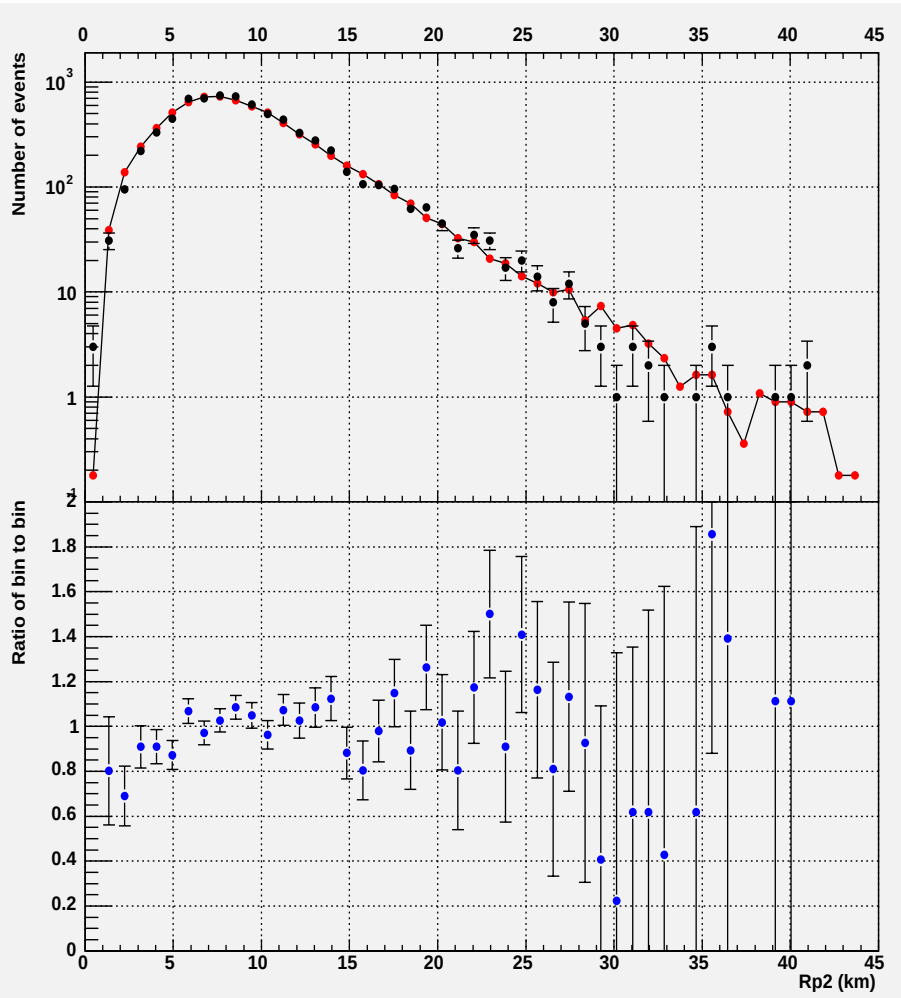
- $X_{max}$ in g/cm$^2$;
- Total energy of the primary particle:
- Arrival direction

*Statistically:*

- Mass composition
- *p*-air inelastic cross-section

# Data vs MC(proton): Impact Parameter (Rp) Distribution

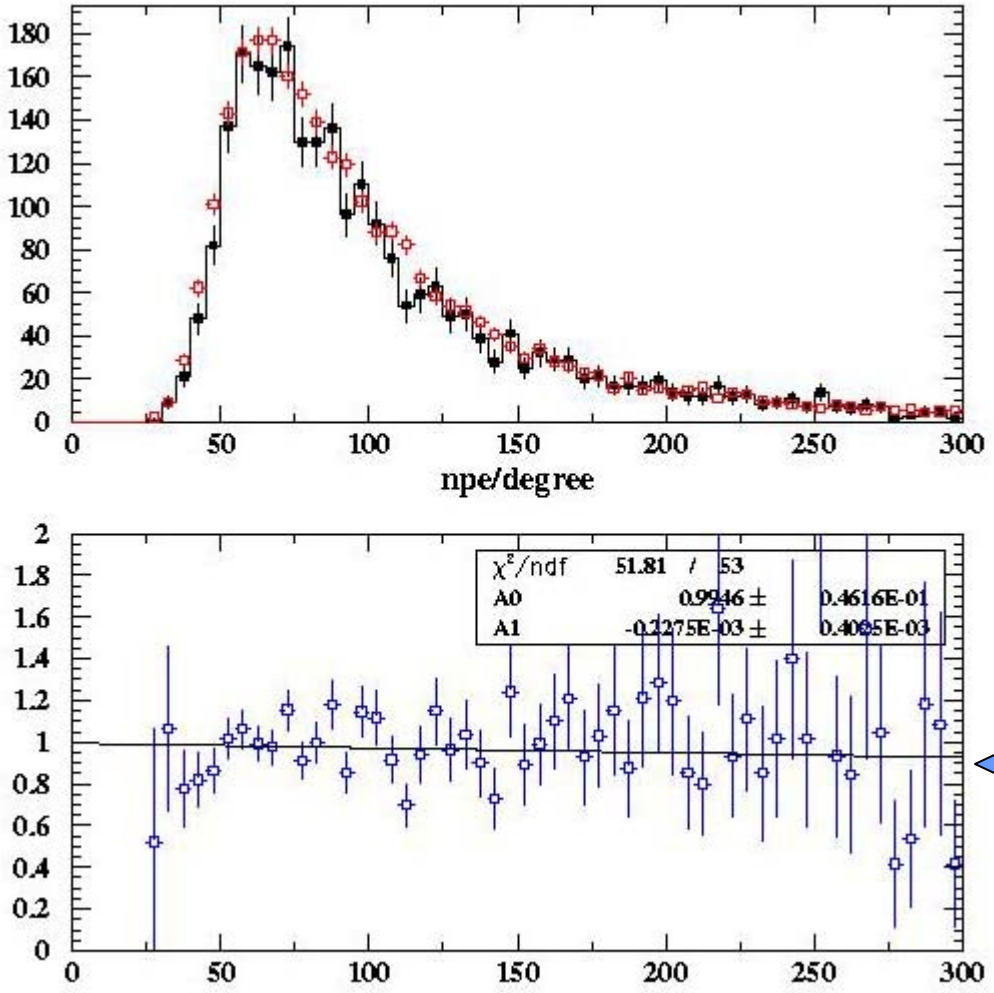



Rp1 (km)

Rp2 (km)

# Photoelectrons per degree of track

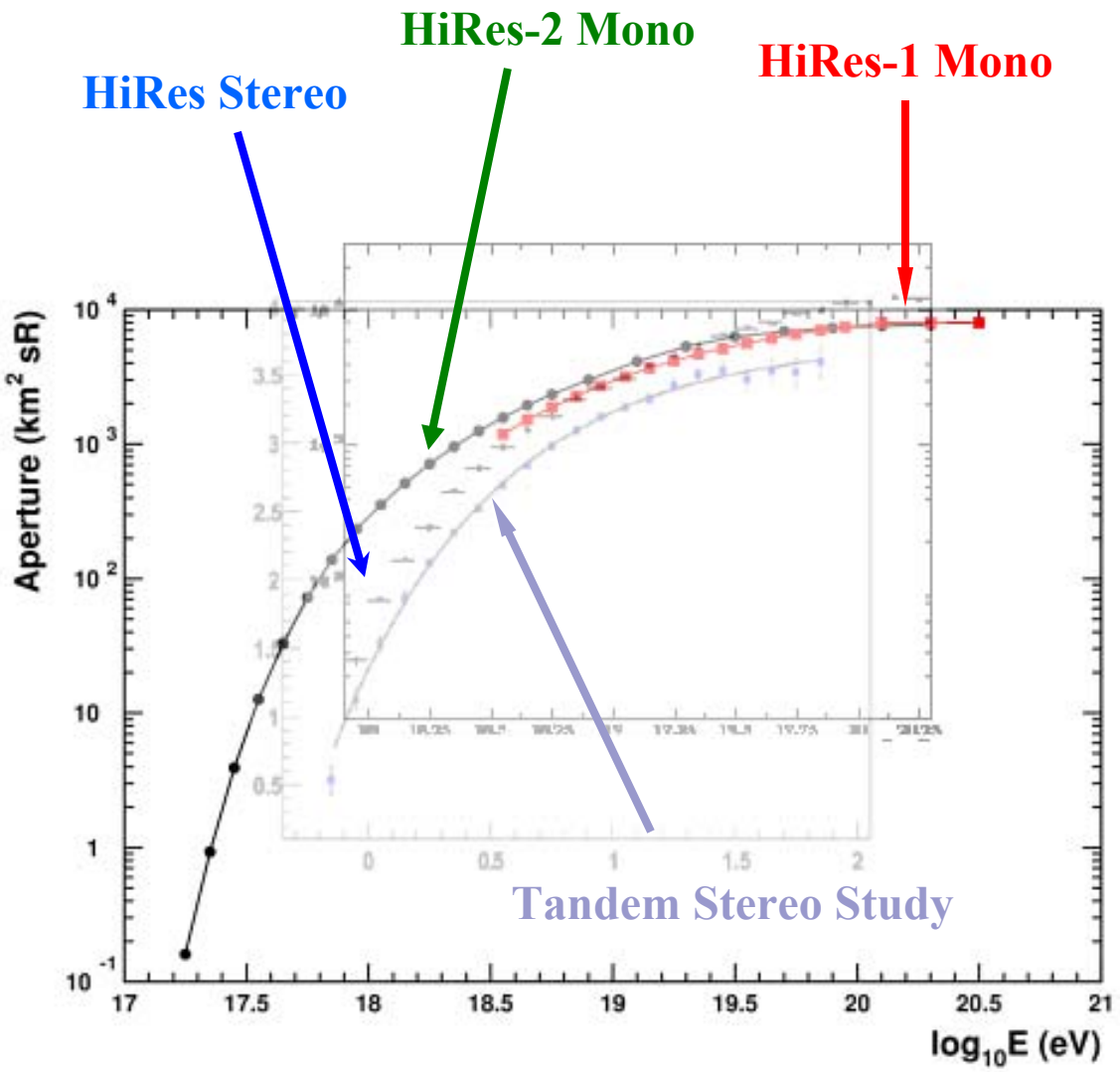



- black: HiRes-2 data
- red: Monte Carlo (5 x data statistics)

$$\frac{\text{data}}{\text{Monte Carlo}}$$

# Physics with HiRes Data

- ***HiRes-1 monocular:*** ~3 yr head start, thus *largest statistics*
- ***HiRes-2 monocular:*** views up to 31° - can reconstruct events $E > 10^{17.2}eV$
- ***Stereo data***: best geometry and resolution - required for composition, but optimized for $E > 10^{18.5}eV$

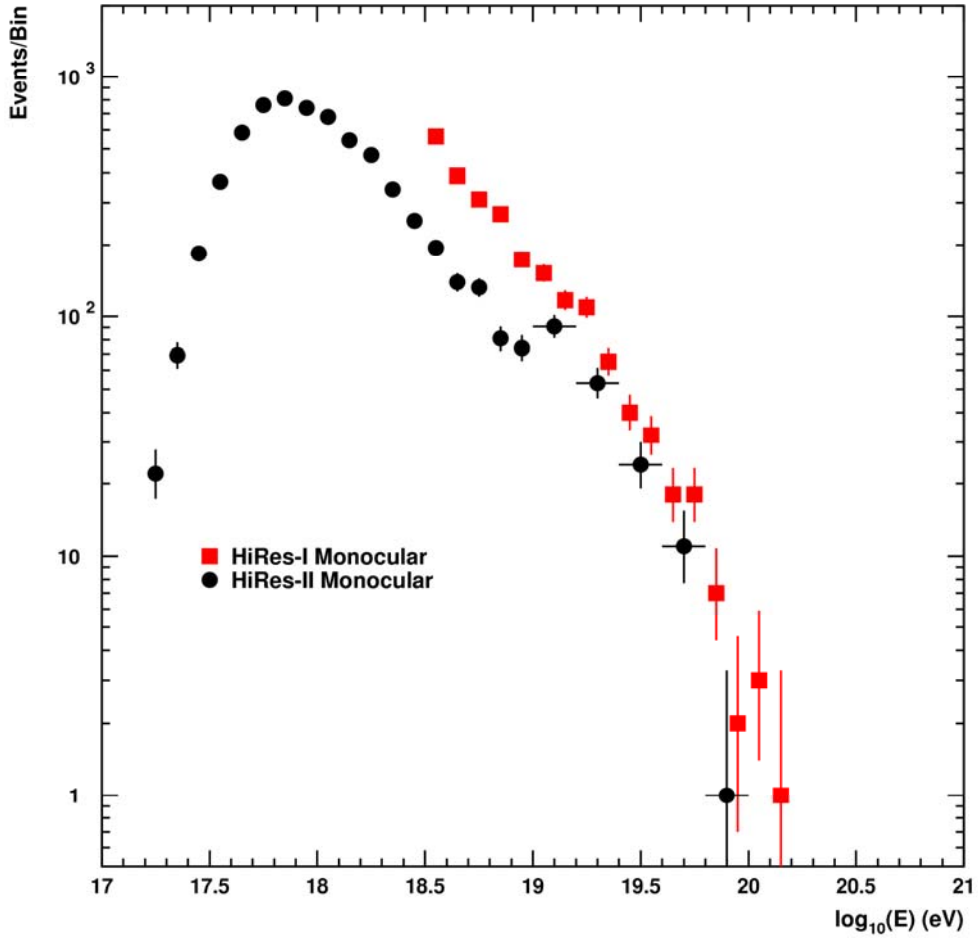


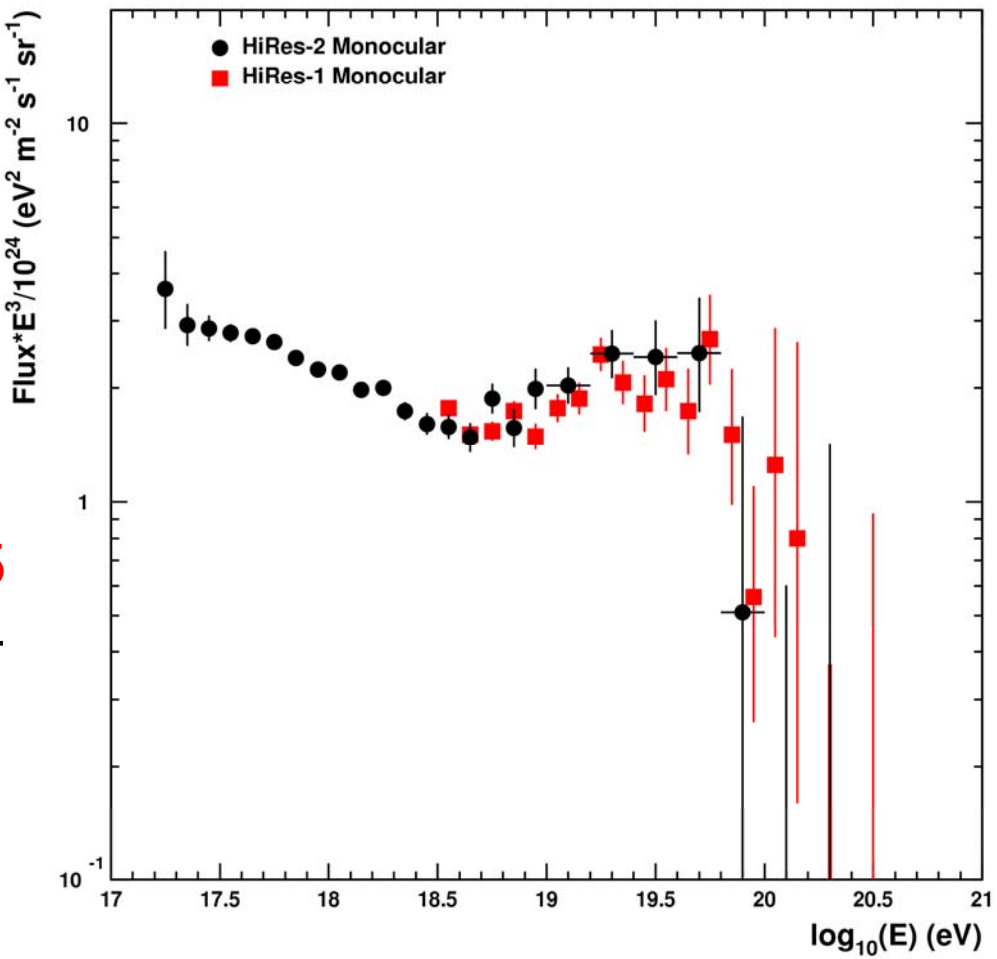
# Event Distribution

HiRes-I
5/1997 – 6/2005

HiRes-II
12/1999 – 08/2004

Ankle is clearly visible even in the raw data distribution



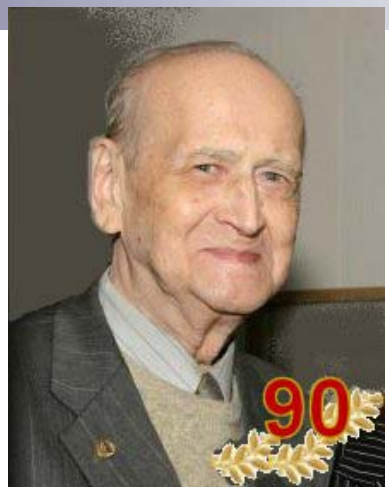


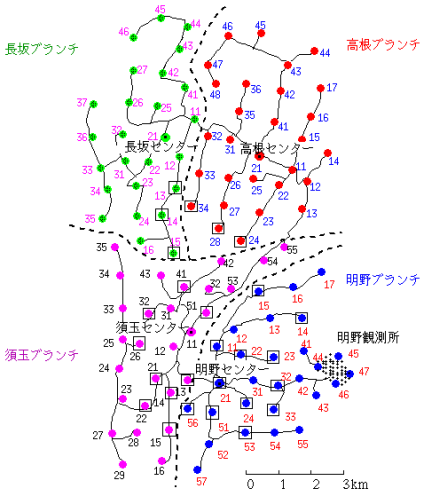

# Data:

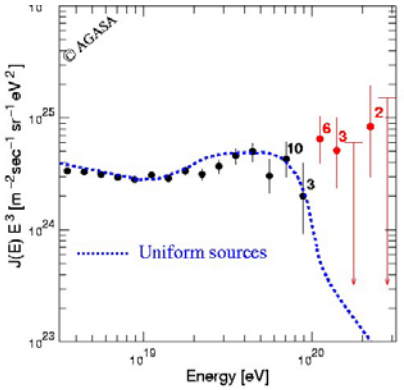
HiRes-I: 5/1997-6/2005

HiRes-II: 12/1999-8/2004

# Spectral features?




AGASA spectrum

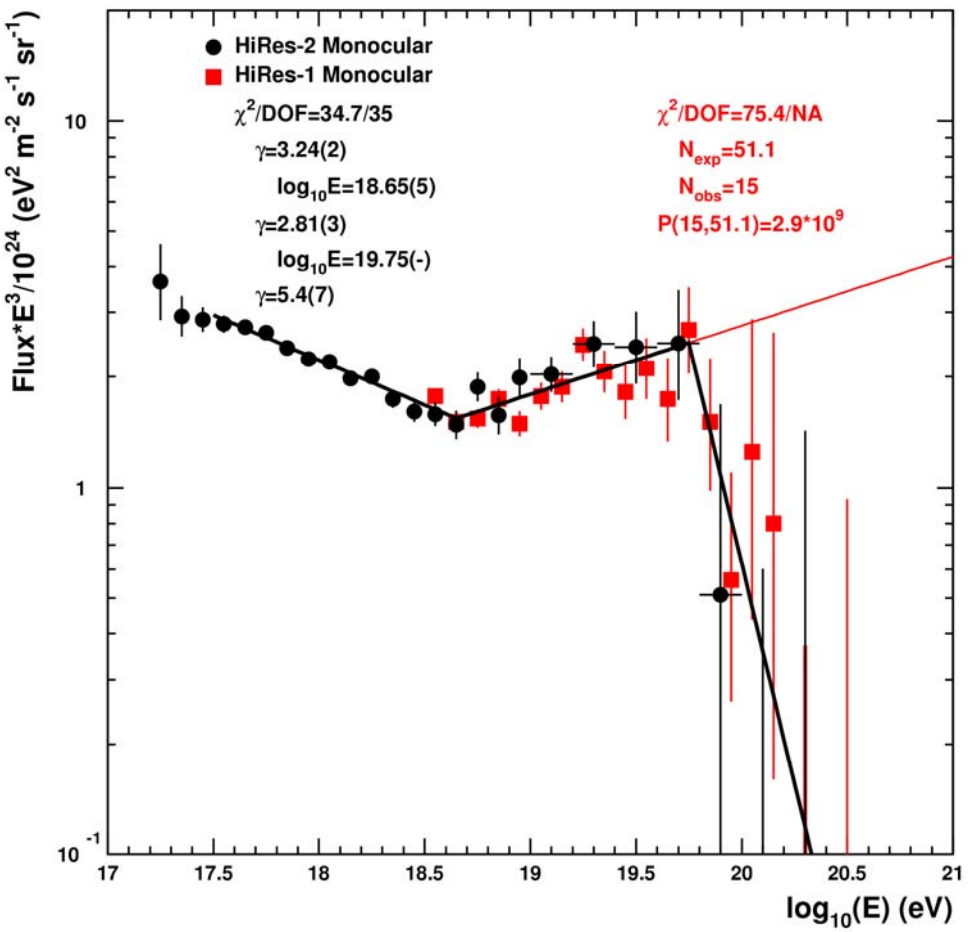
- Cutoff predicted in 1966 by K.Greisen, G.Zatsepin, and V.Kuzmin.
- Photons of CMBR interact with cosmic ray protons of extragalactic origin.
- Photoproduction of pions; $\Delta$ resonance is near threshold.
- Pion carries away 20% of proton's energy ➔ strong energy-loss mechanism for protons that travel > 50 Mpc.
- Causes a strong break in the spectrum if sources are distant.
- Should occur at about $6 \times 10^{19}$ eV (10J) if sources ~ universally distributed



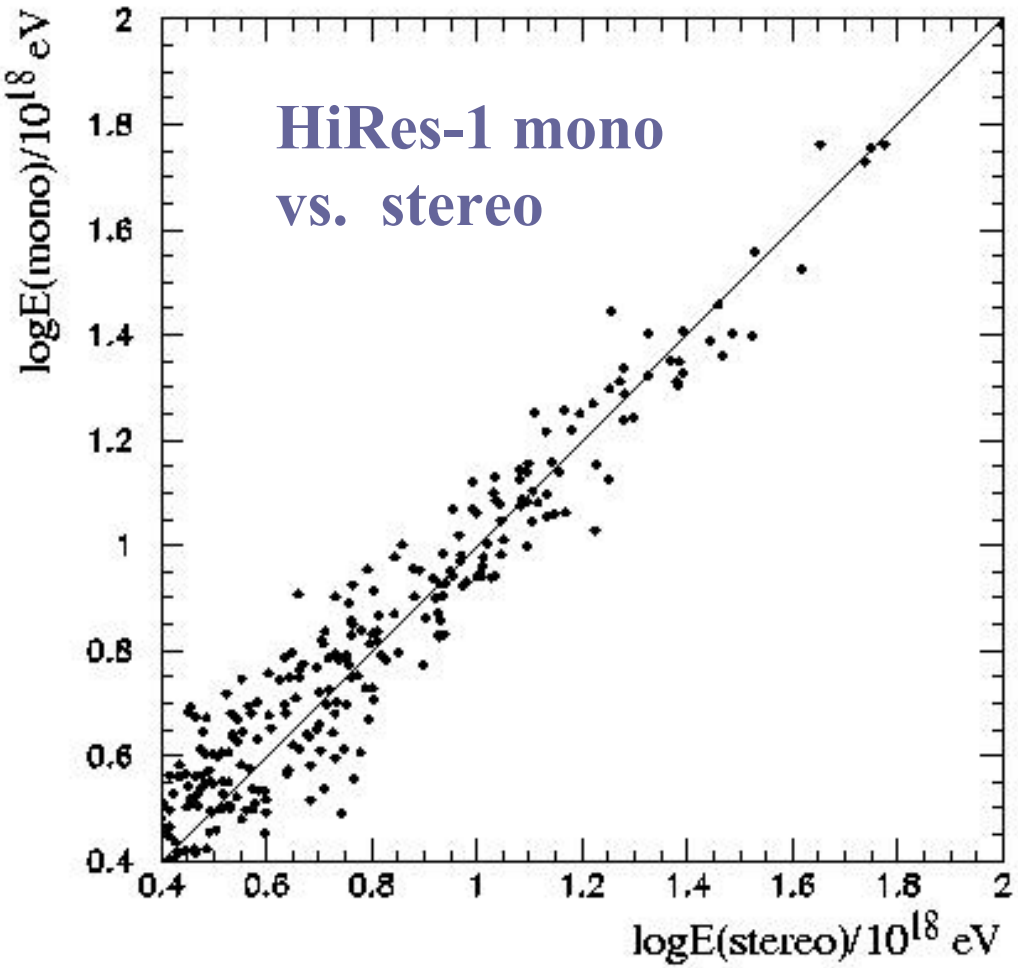
HiRes

# 5σ Observation of the GZK Suppression

- **Broken Power Law Fits (independent data)**
  - No Break Point
    - $\chi^2$/DOF = 162/39
  - One Break Point
    - $\chi^2$/DOF = 63.0/37
    - BP = 18.63
  - Two BP's
    - $\chi^2$/DOF = 35.1/35
    - 1st BP = 18.65 +/- .05
    - 2nd BP = 19.75 +/- .04
  - BP with Extension
    - Expect 43.2 events
    - Observe 13 events
    - Poisson probability: P(15;51.1)= 7**x10**$^{-8}$ (5.3σ)

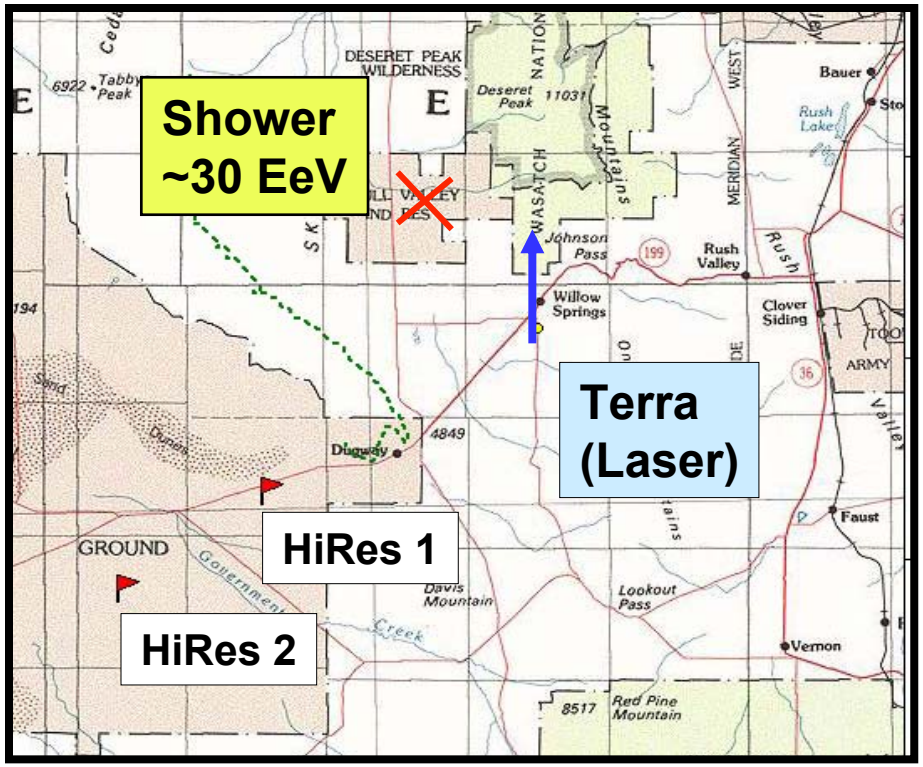


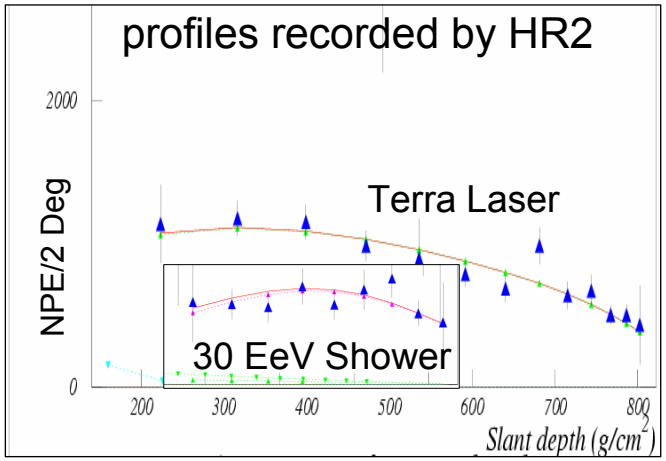
# Mono versus Stereo Energy Measurements

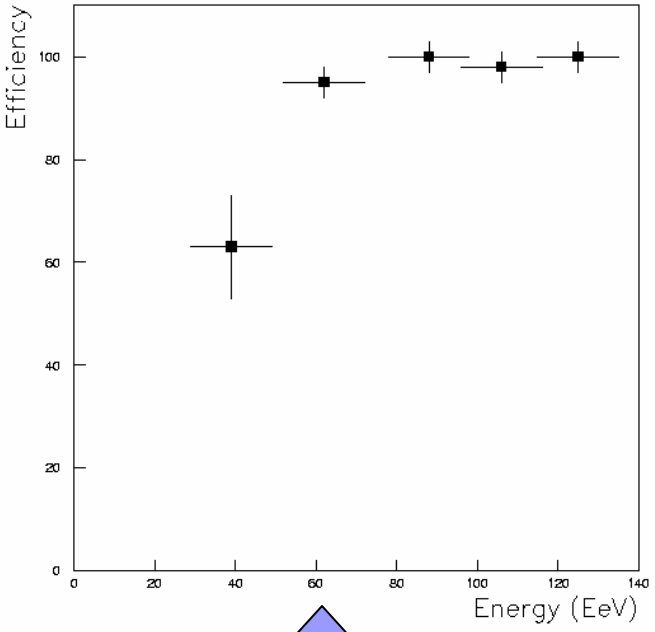



The HiRes monocular energy is in excellent agreement with stereoscopic measurements !

# HE Aperture Test




**Laser tests the reach of our HE aperture - 34 km from HiRes-2 Detector.**

**Light production equivalent to ~$6\times10^{19}$ - $10^{20}$ eV air shower**

**Detectors have no trouble seeing this laser under good to worse than acceptable viewing conditions.**

**GZK Cutoff**

# Stereo $N_{max}$ and $X_{max}$ Resolution

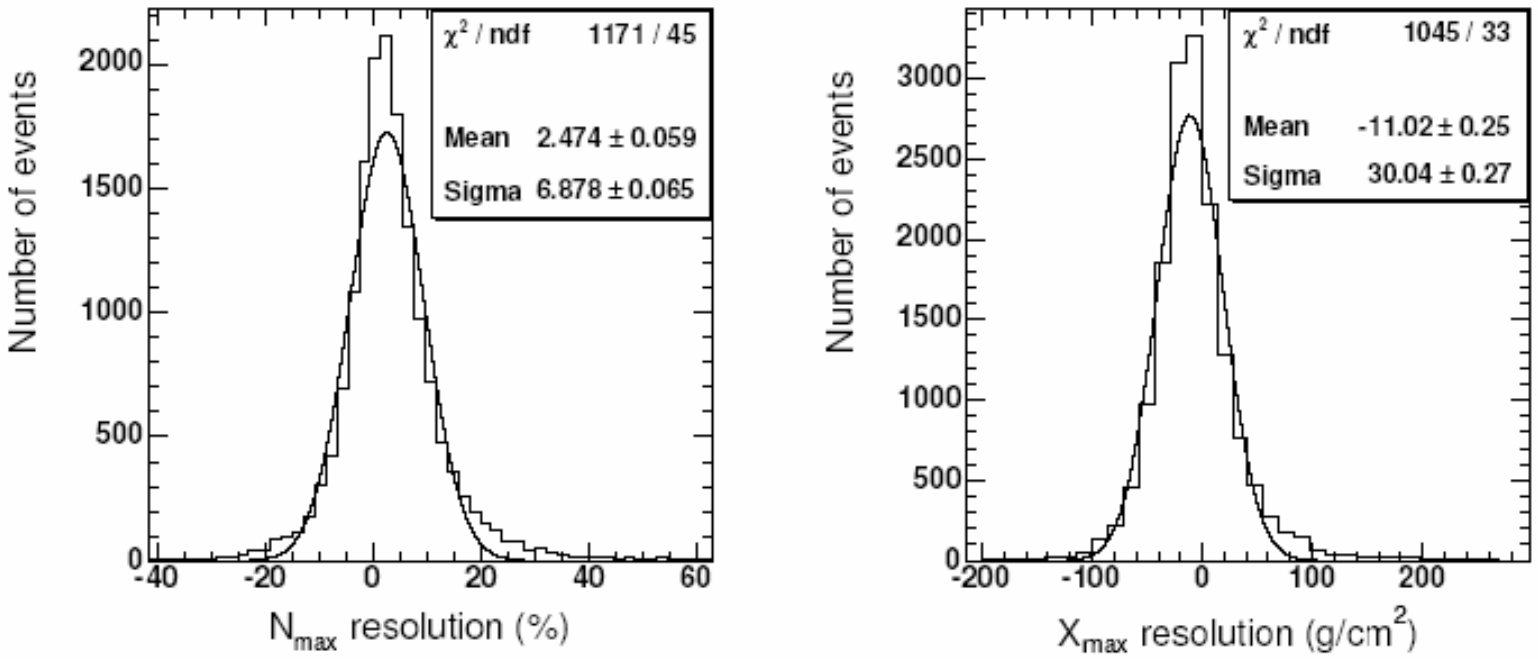
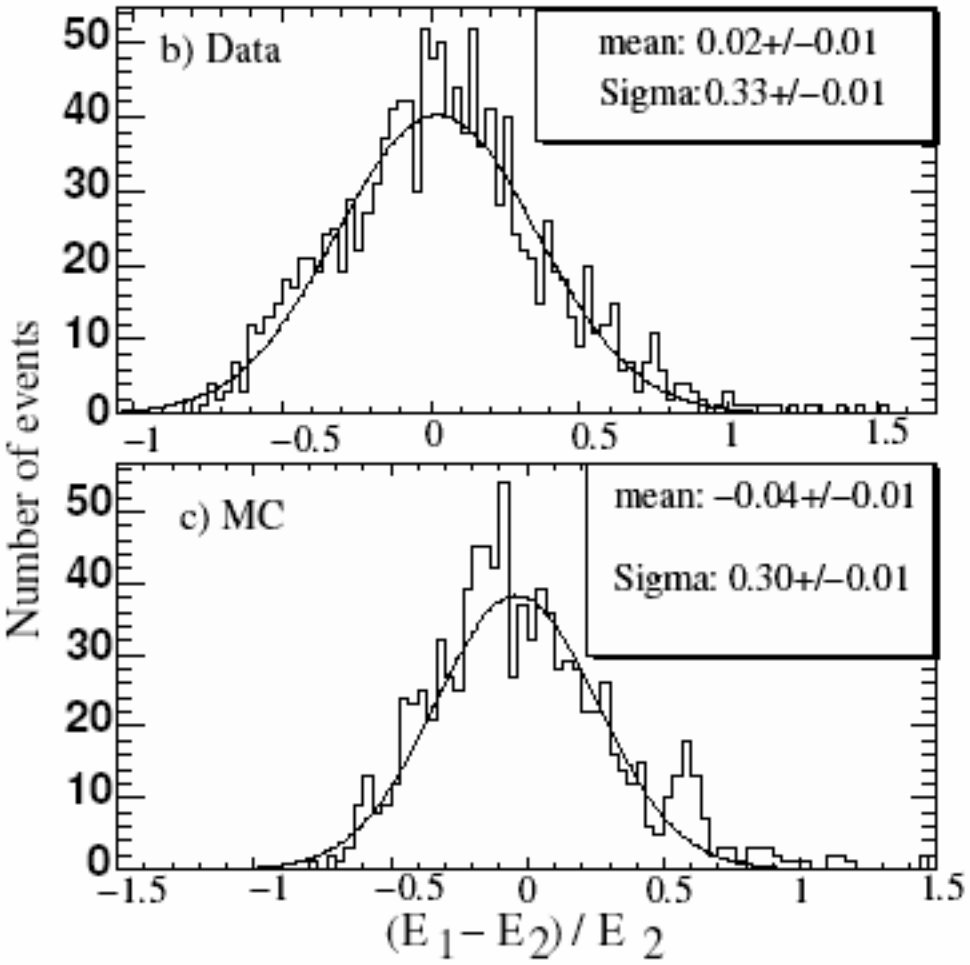



FIG. 10: Shower parameter resolution functions estimated using simulated showers with Gaussian fit. Left: shower size at maximum has a minor systematic shift of about 2.5% and a standard deviation of 9%; Right: depth of shower maximum has also a minor shift of -11g/cm$^2$ and a standard deviation of 30g/cm$^2$.

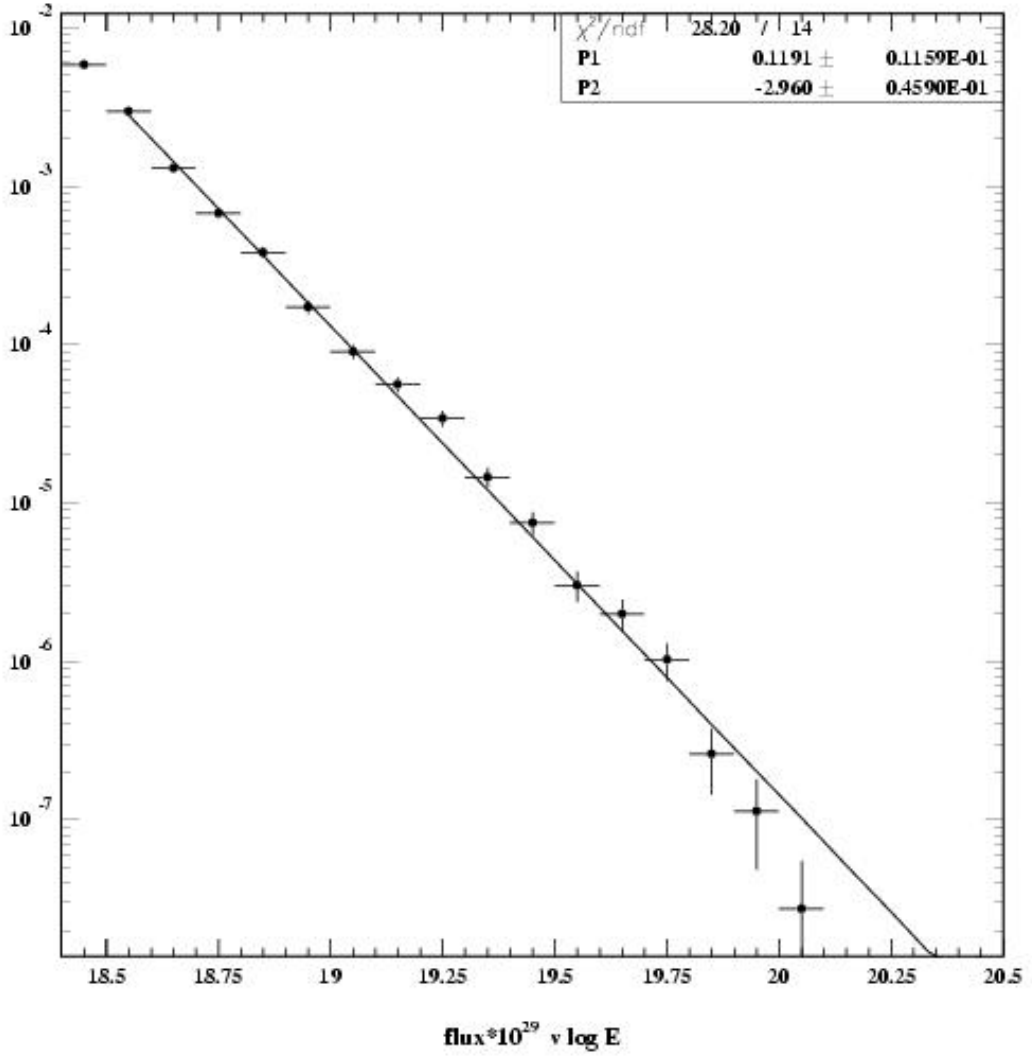
# Stereo Energy Resolution

With Stereo Measurements, you have redundant measurements of Xmax and Energy

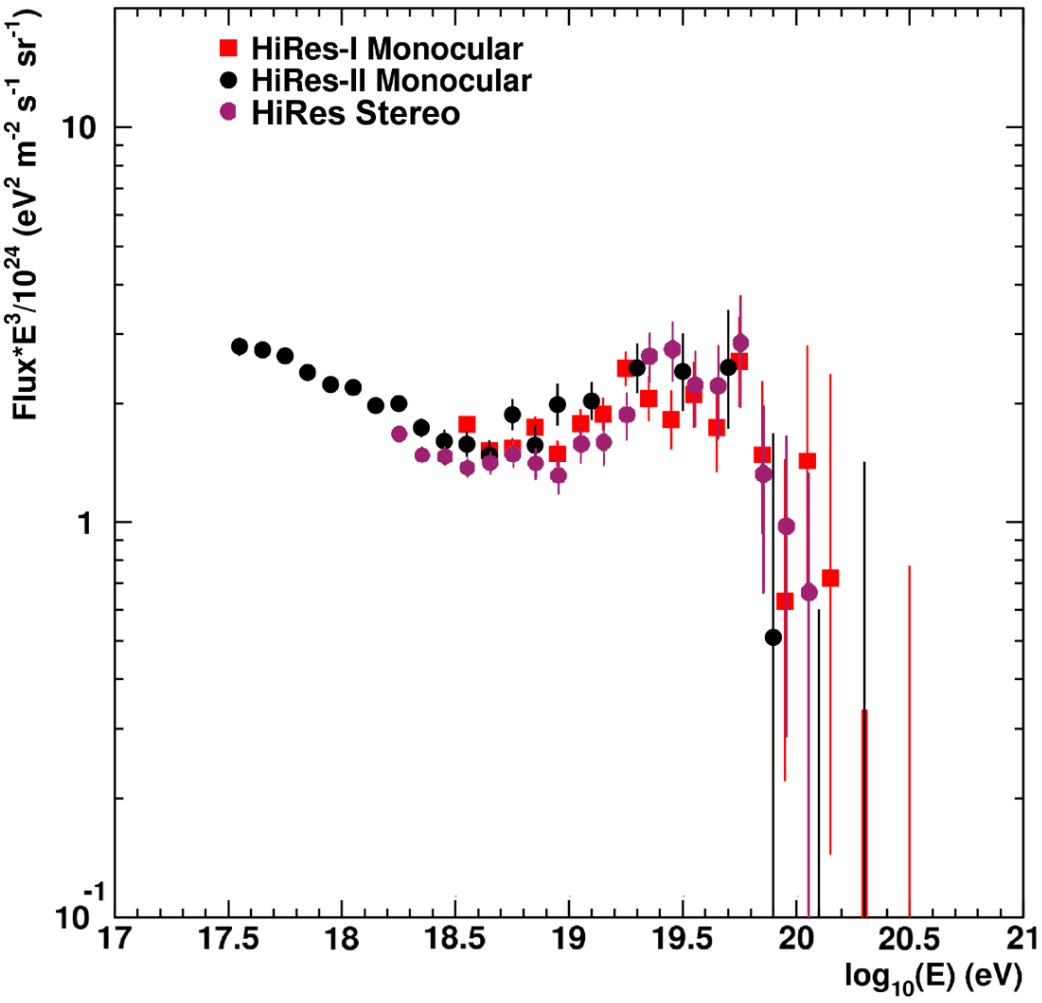


# Stereo Spectrum

- Fit to power law.
- Single index gives poor $\chi^2$
- Evidence for changing index near ~$10^{19.8}$ eV



HiRes Monocular & Stereo Spectra are in excellent agreement



# First Observation of the Greisen-Zatsepin-Kuzmin Suppression

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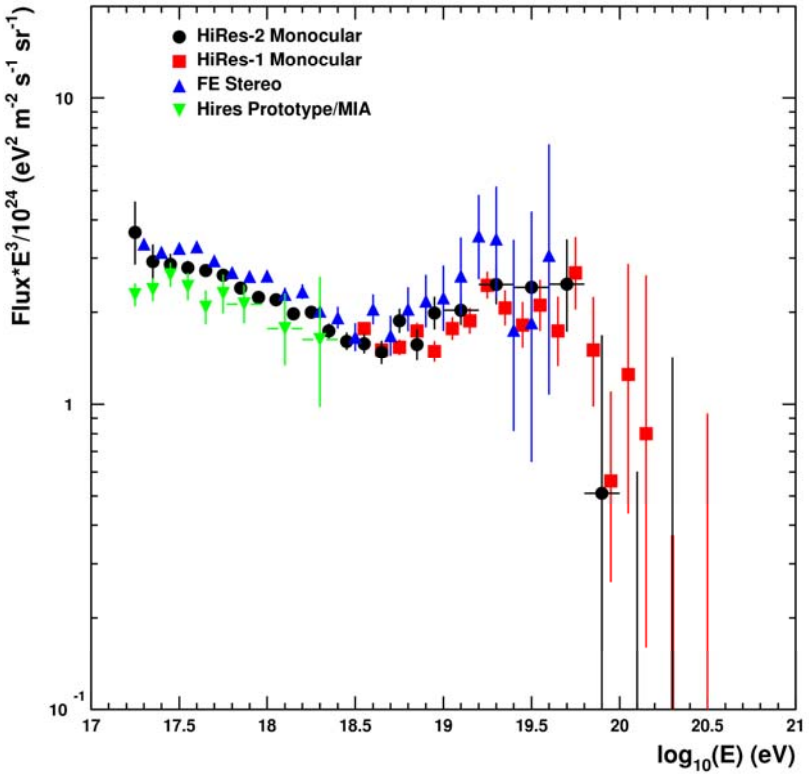
The High Resolution Fly's Eye (HiRes) experiment has observed the Greisen-Zatsepin-Kuzmin suppression (called the GZK cutoff) with a statistical significance of five standard deviations. HiRes' measurement of the flux of ultrahigh energy (UHE) cosmic rays shows a sharp suppression at an energy of $6 \times 10^{19}$ eV, consistent with the expected cutoff energy. We observe the "ankle" of the cosmic-ray energy spectrum as well, at an energy of $4 \times 10^{18}$ eV. We describe the experiment, data collection, analysis, and estimate the systematic uncertainties. The results are presented and the calculation of the statistical significance of our observation is described.

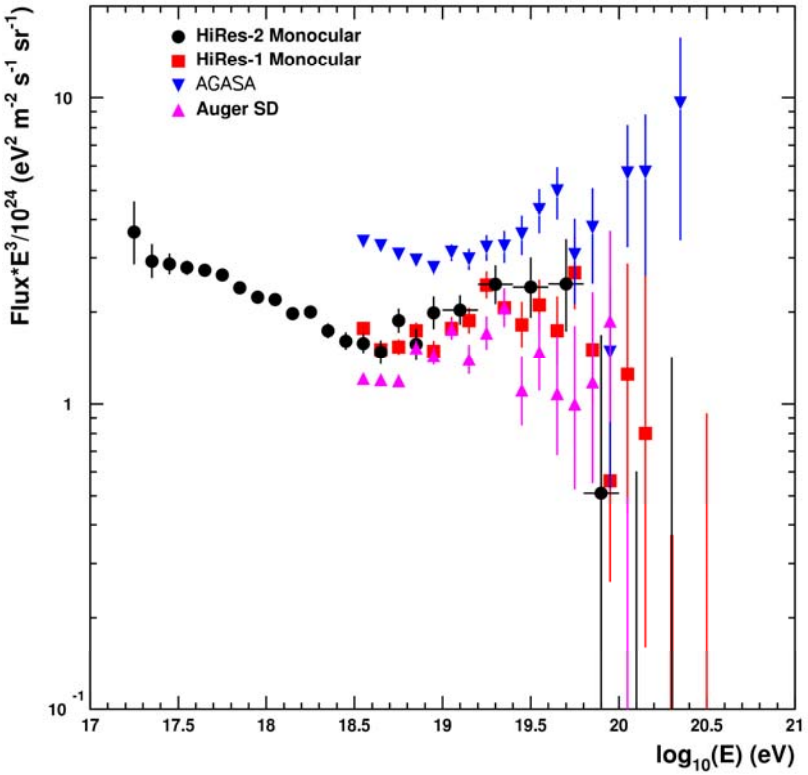
PACS numbers: 98.70.Sa, 95.85.Ry, 96.50.sb, 96.50.sd

Appears in Feb `08 - Phys Rev Lett

# HiRes and Other Experiments




HiRes, Fly's Eye Stereo, and HiRes/MIA




HiRes, AGASA, and Auger(2005)

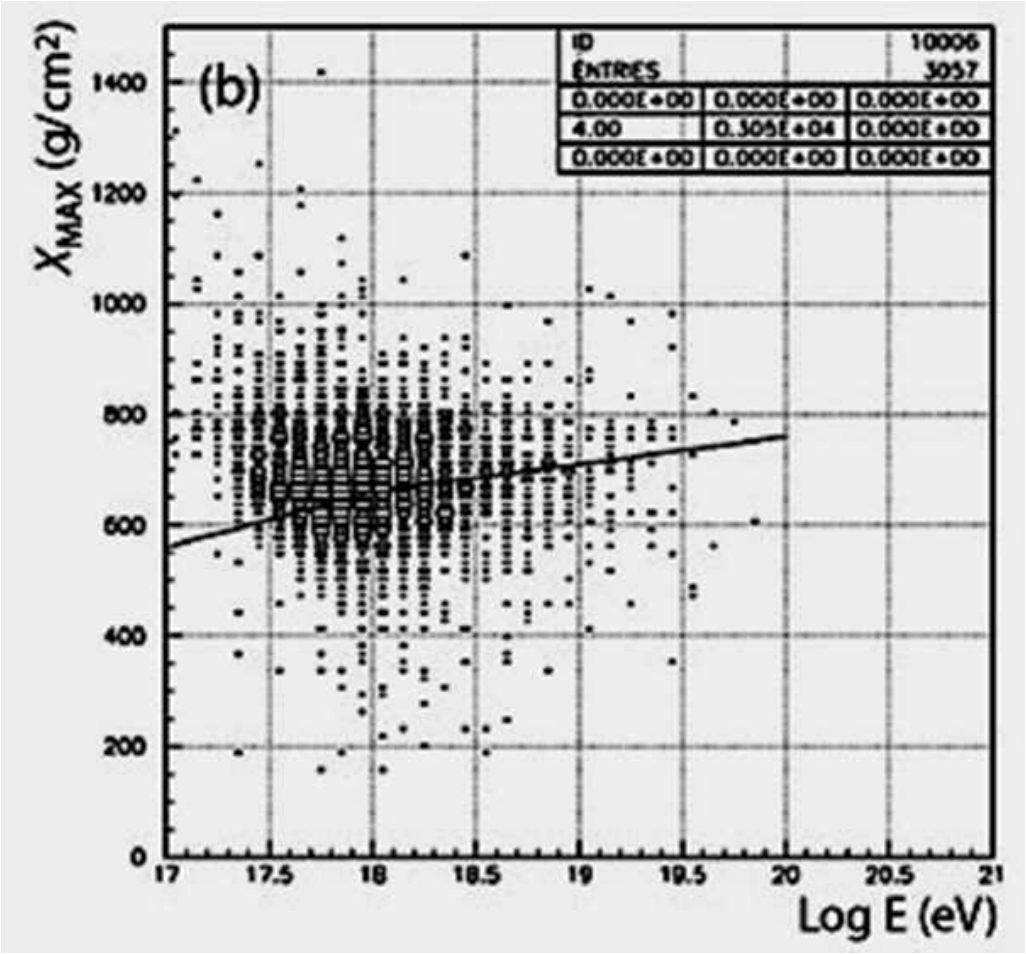
AGASA 30% high wrt HiRes

# Composition

- Simulate p, CNO, Fe interactions using Hadronic models
- Generate simulated data
- Compare simulated data to real data
- Xmax distribution, mean, and fluctuations - All carry composition information

# Data Quality Cuts

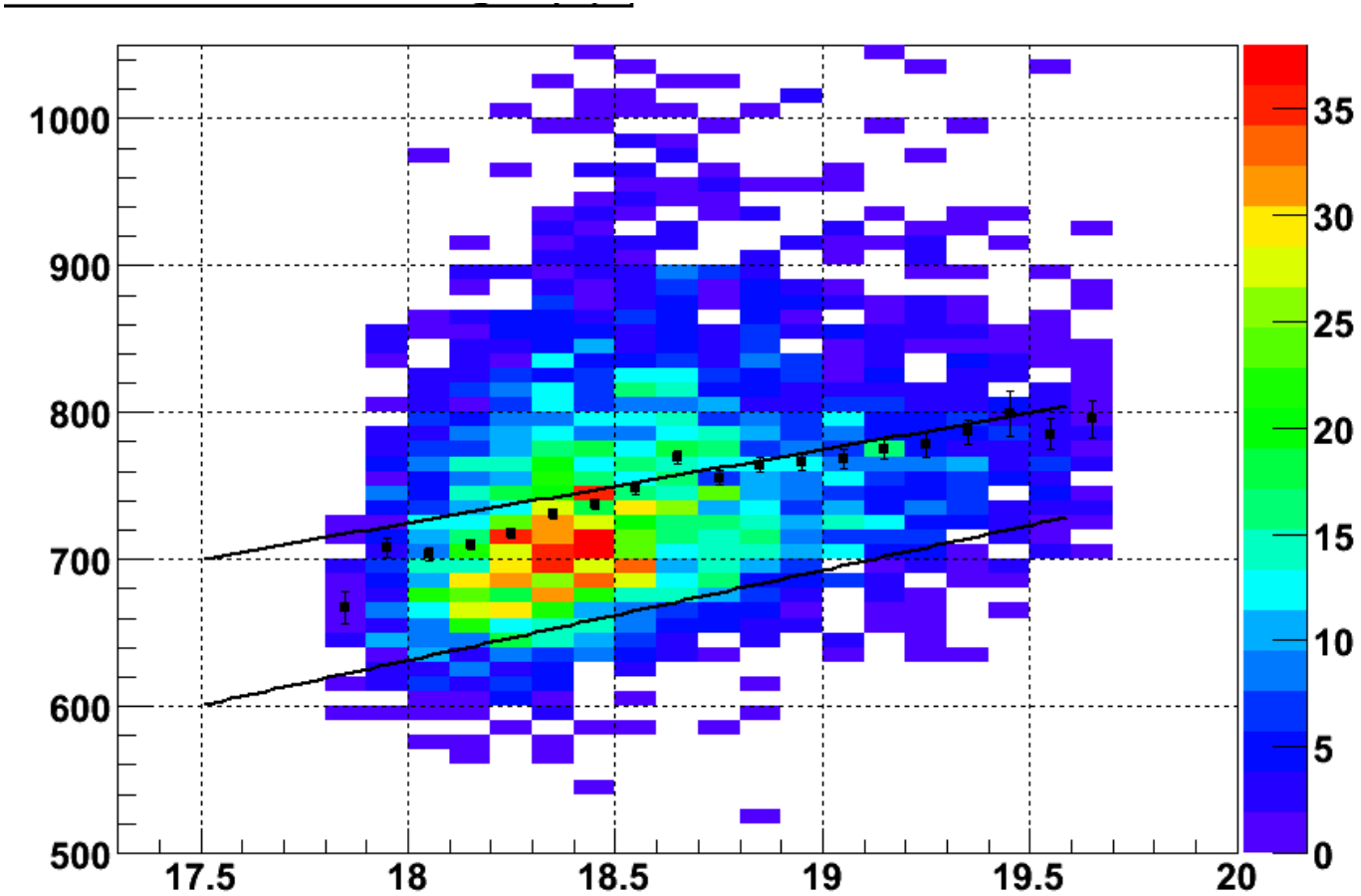
- *Cuts to insure* Fe/p reconstruction ratio is flat over the entire energy range.
- Particularly important at low energies
  $E < 10^{18}$ eV : due to limited elevation angle coverage ( < 31°)



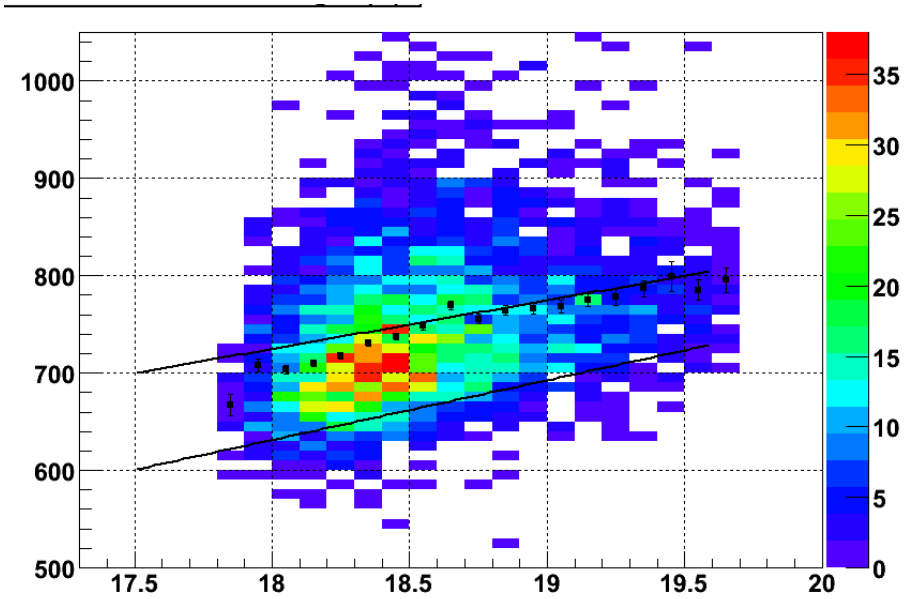
# Effect of cuts

- Xmax resolution is between 25 gm/cm$^2$ and 30 gm/cm$^2$.
- Fe/p trigger and reconstruction efficiency is 0.9 +/- 0.1 over the entire energy range
- Input elongation rates for p and Fe from Corsika well reproduced

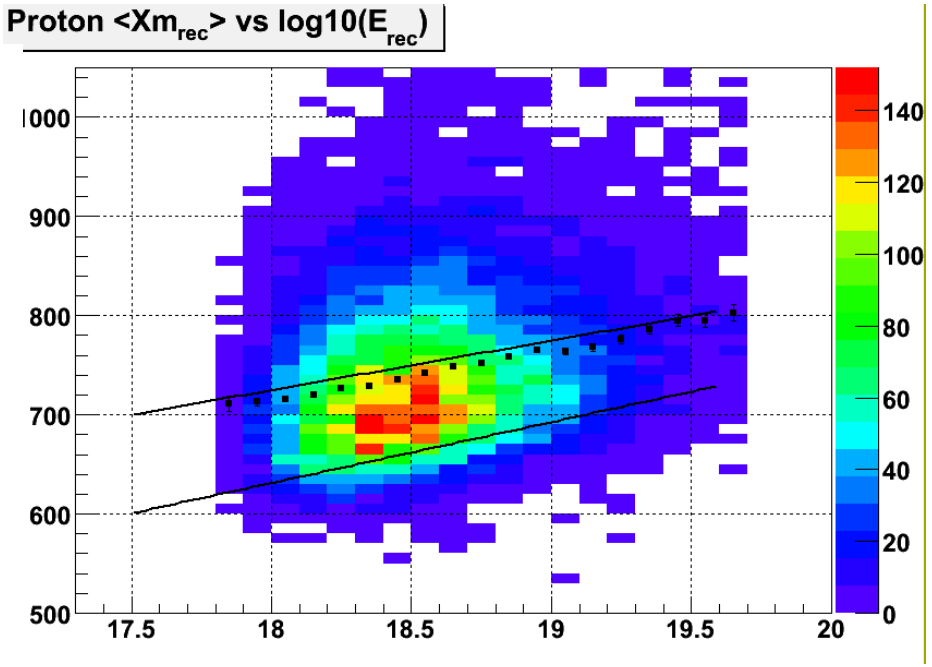
# HiRes Data


Xmax
1000
900
800
700
600
500
17.5
18
18.5
19
19.5
20
35
30
25
20
15
10
5
0
Log(E)

# Stereo Data and Proton MC

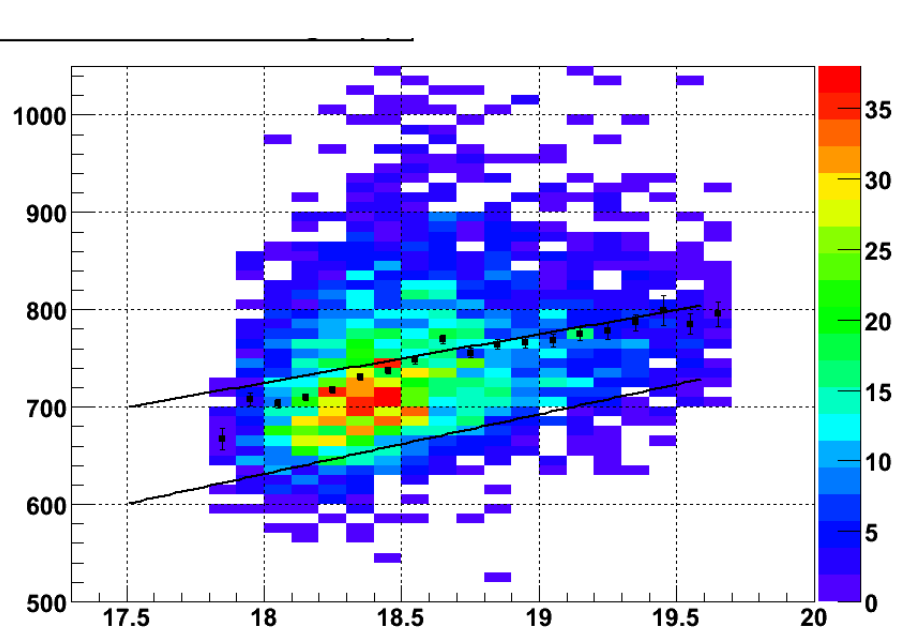



HiRes Data

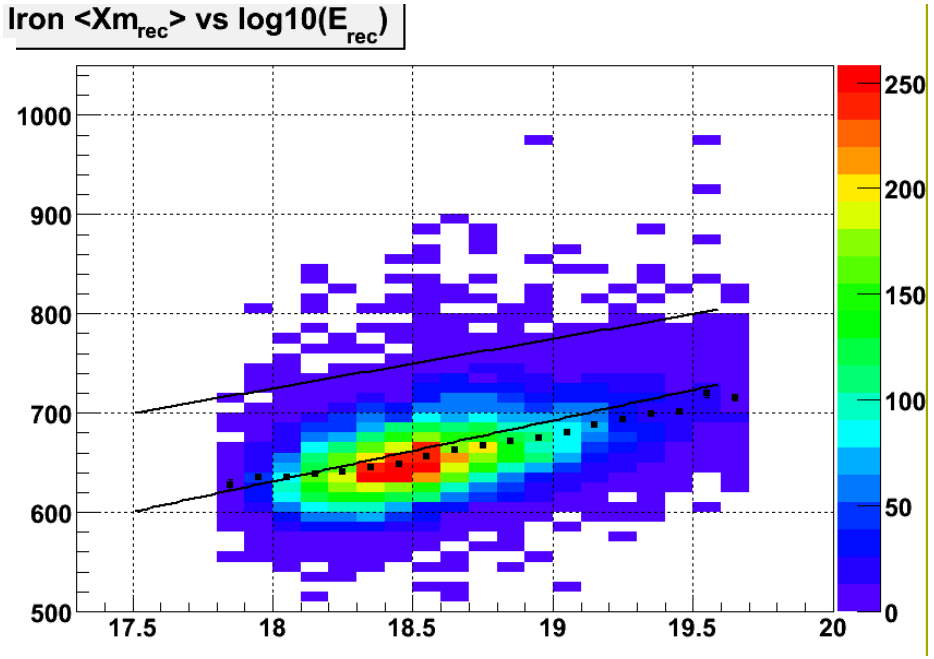



Proton MC

# Stereo Data and Fe MC

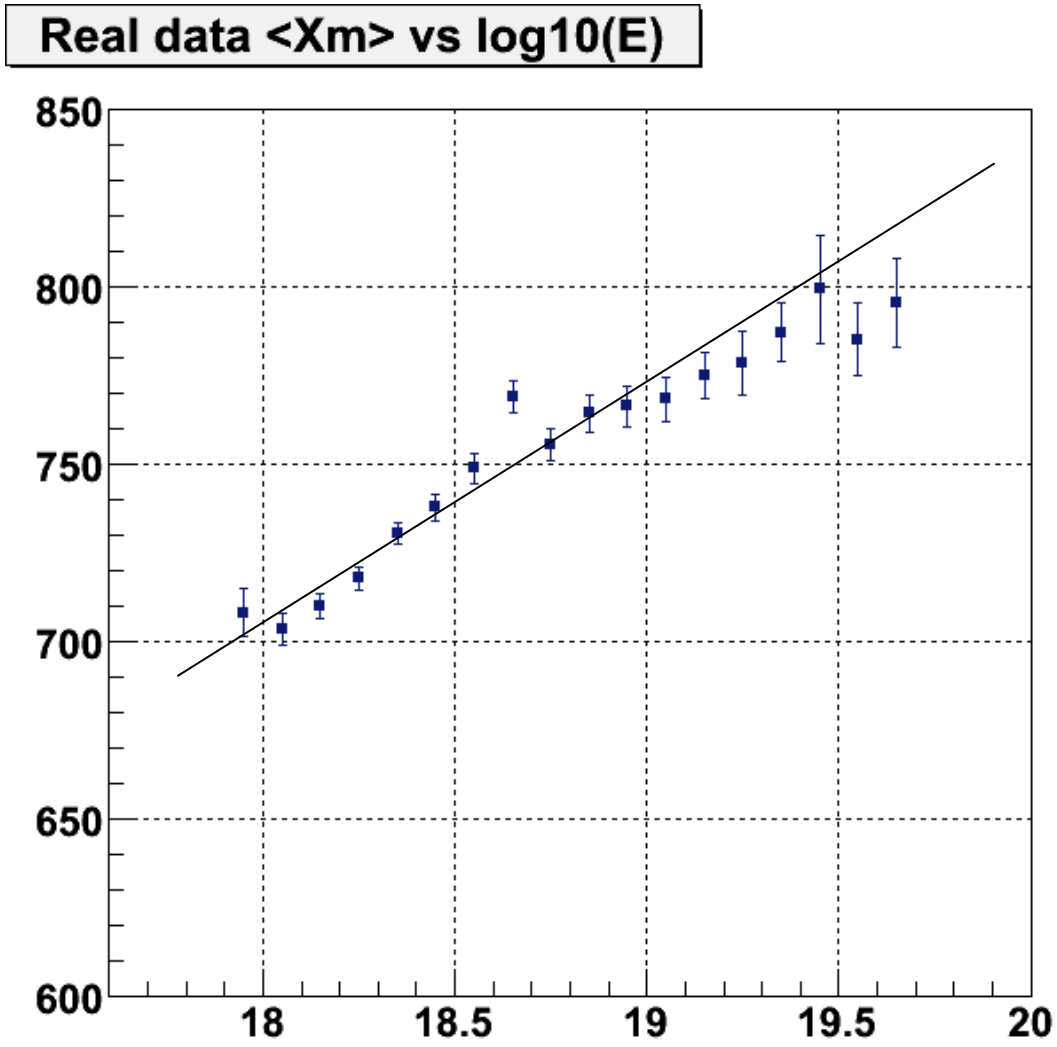



HiRes Data

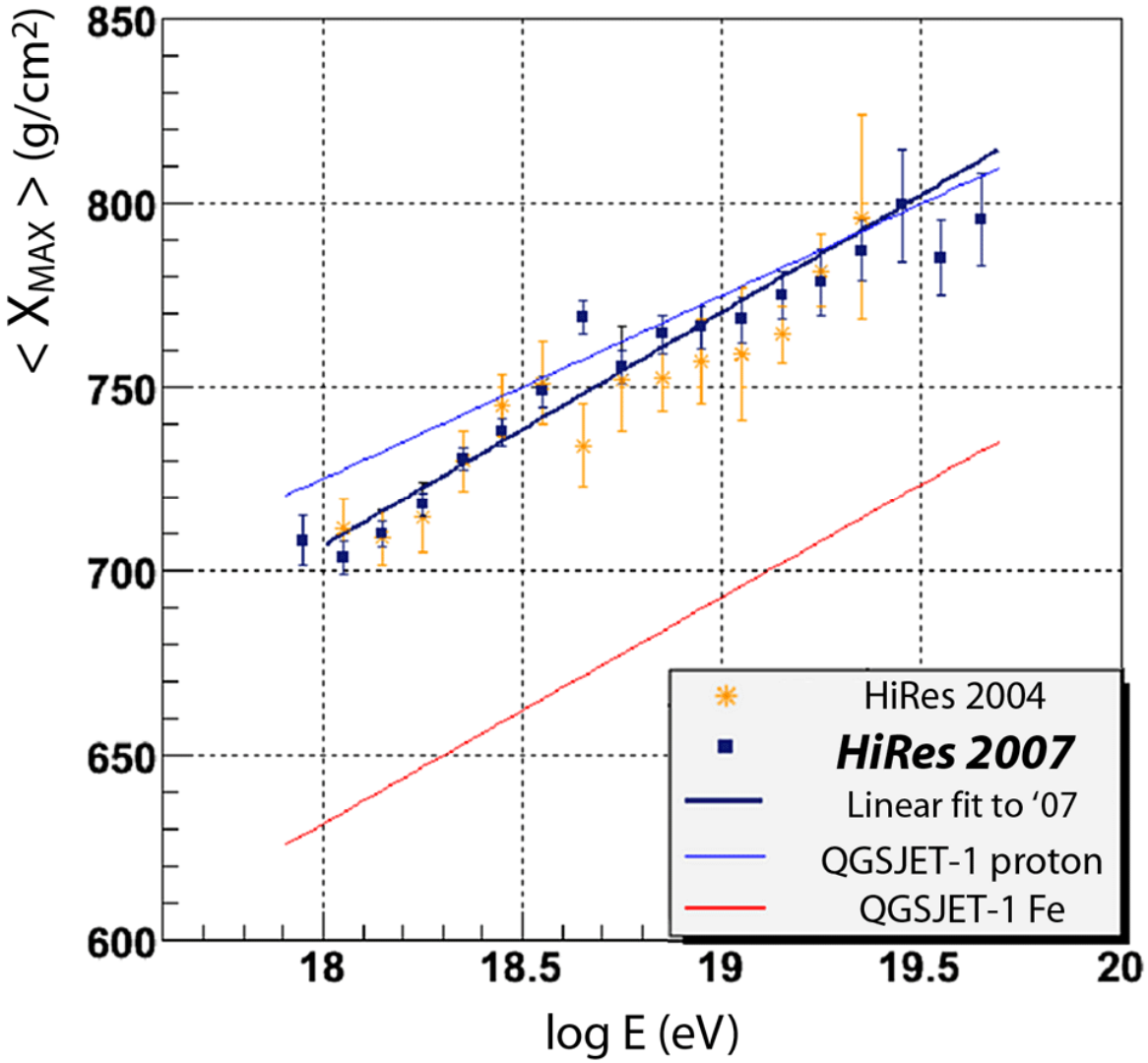



Iron MC

# HiRes Stereo Elongation Rate



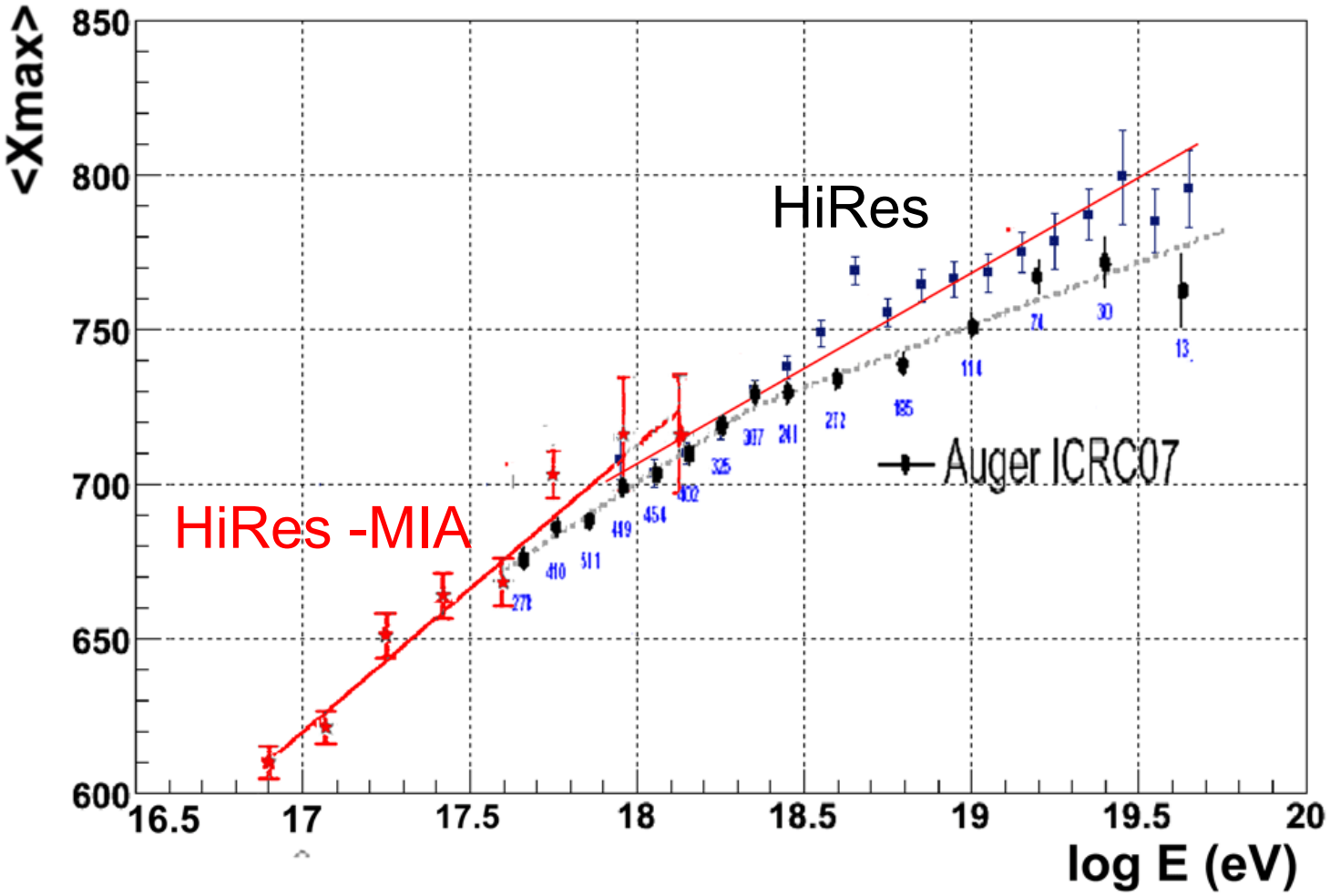
# Comparison with QGSJet01 p and Fe




2007 Data Set has 4 times the events of the 2004 Set

Elongation Rate Fit
63.7 +/- 3.2 (stat) gm/cm$^2$/decade

# Stereo Elongation Rate
# Comparison of HiRes and Auger



# Conclusions Composition

- Elongation rate and Xmax distribution consistent with a constant – light, mostly protonic flux
- Auger claim of correlation of cosmic ray events - just below the GZK cutoff - with nearby AGN's, if confirmed, would also require a proton flux.
- HiRes and Auger data in reasonable agreement
- Detailed comparison with other hadronic models and composition mixtures is proceeding.

# Hot Sources?

- Performed an autocorrelation study using HiRes Stereo data with excellent (~0.6°) resolution
  Consistent with isotropy at all angular scales…

- There are six widely discussed “clusters” containing 13 events in the AGASA data
- Assume that these represent the six brightest sources in the sky
- Test this hypothesis

# Maximum Likelihood Point Source Search

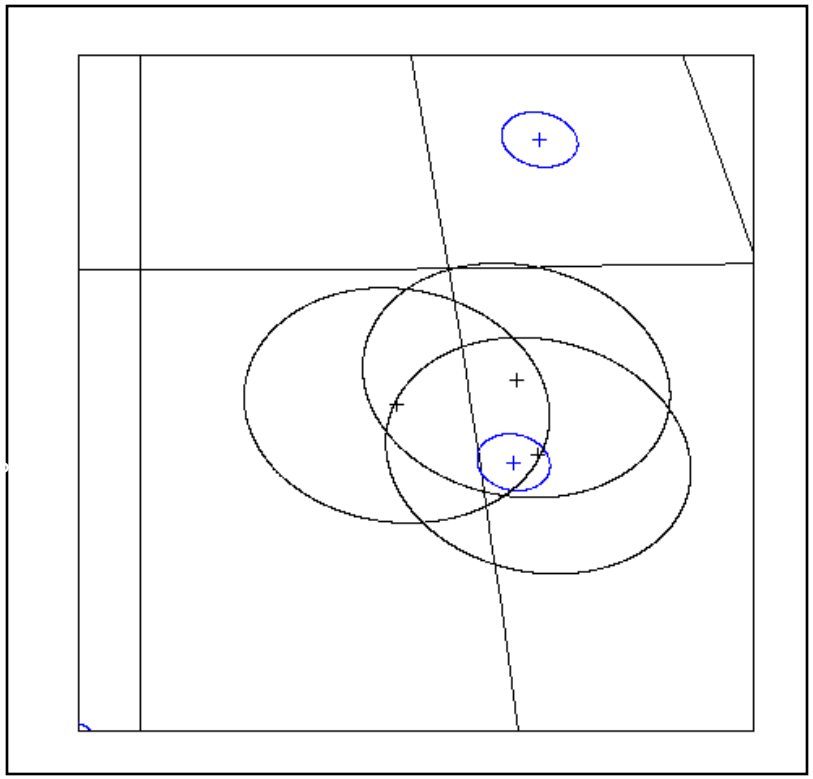
**No Correlation found in combined HiRes-AGASA data with E > $4 \times 10^{19}$ eV**

**If** the HiRes threshold is lowered to $3 \times 10^{19}$ eV, one more event lands near the triplet.

There are now 57 AGASA & 40 HiRes events. Fraction of MC sets with higher ln(R) is 0.5%

This result contains some biases:

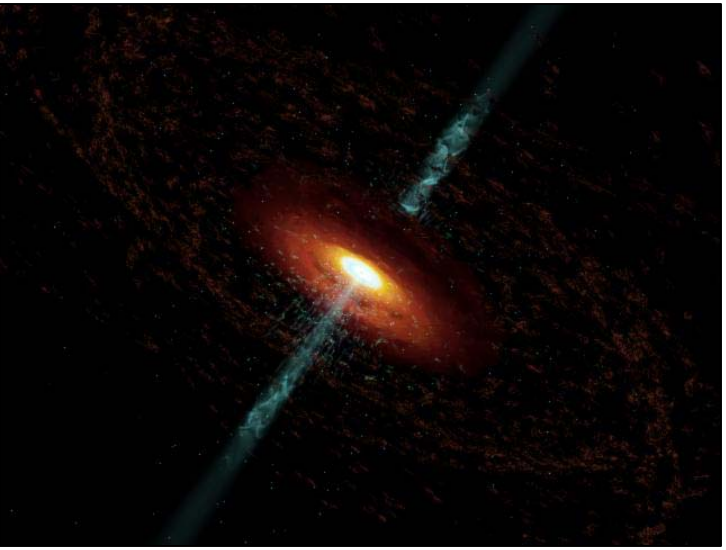
- the clustered AGASA events which were originally used to *establish* the $4 \times 10^{19}$ eV threshold are still included in the sample
- the HiRes energy threshold has to be *changed* to include an event that contributes to the cluster



Abbasi et al., Astrophys.J. 623 (2005) 164.

**These biases imply that 0.5% is a *lower bound* on the chance probability.**

# Correlations with BL Lacs ?

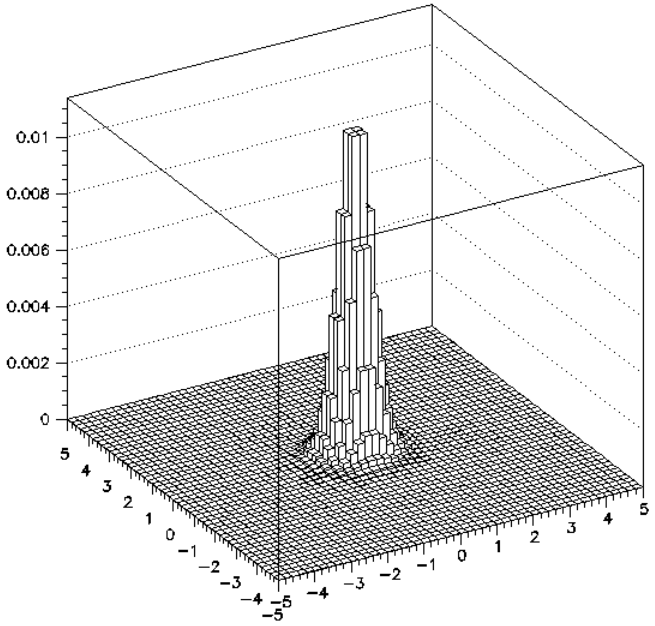


- BL Lacertae - blazar, active galaxy, jet aligned with our line of sight
- established sources of TeV gamma-rays
- Candidates for accelerating cosmic rays to EeV energies

- Modest correlation between most luminous BL Lacertae objects and HiRes stereo events $E>10^{19}$ eV
- 11.0 of 271 events correlate within (stereo) angular resolution
- Chance probability $10^{-5}$
- Not a confirmation of an *a priori* claim, so **needs to be confirmed with independent data**
- Correlations are at ~$10^{19}$ eV, indicating neutral primaries ?
- **Not confirmed by PAO in the Southern Hemisphere**

# HiRes Anisotropy Results

Stereo point spread function




## Monocular Anisotropy Results

- ***Autocorrelation functions*** (histogram of $\cos\theta$ between all possible pairs) for HiRes-1 monocular (left) and AGASA (right) events above ~4x$10^{19}$eV
  **Astropart. Phys. 22, 139 (2004)**
- Search for dipole enhancement in the direction of nearby a-priori sources: ***null results*** for the ***Galactic Center, Centaurs A, and M87***
  **Astropart. Phys. 21, 111 (2004)**
- Point source search: null result
  **Submitted to Astropart Phys.**
- Search for cross-correlation with AGASA doublets and triplet:
  - Observed overlap no greater than that expected by chance from an isotropic

  **Submitted to Astropart Phys.**

## Stereo Anisotropy Results

- Stereo angular resolution ***~0.6°***
- HiRes stereo data ($E$ > $10^{19}$ eV) is consistent with isotropy at all small angular scales
  **Astrophys. J. Lett. 610 (2004) L73**
- Search for Point Sources of Ultra-High Energy Cosmic Rays above 4.0 $10^{19}$ eV Using a Maximum Likelihood Ratio Test
  **Astrophys. Journal 623 (2005) 164**

# PAO AGN Correlations

- Scan ½ of data and Veron-Cetti-Veron AGN catalogue for optimum correlation cuts
- Open second half of data with same cuts. Find ~ 3 sigma correlation

- AGN distance < 75 Mpc
- Cosmic ray energy > 6 x $10^{19}$ eV
- Strongest correlation < 3.1 degree
- Consistent with protons bending in B fields?

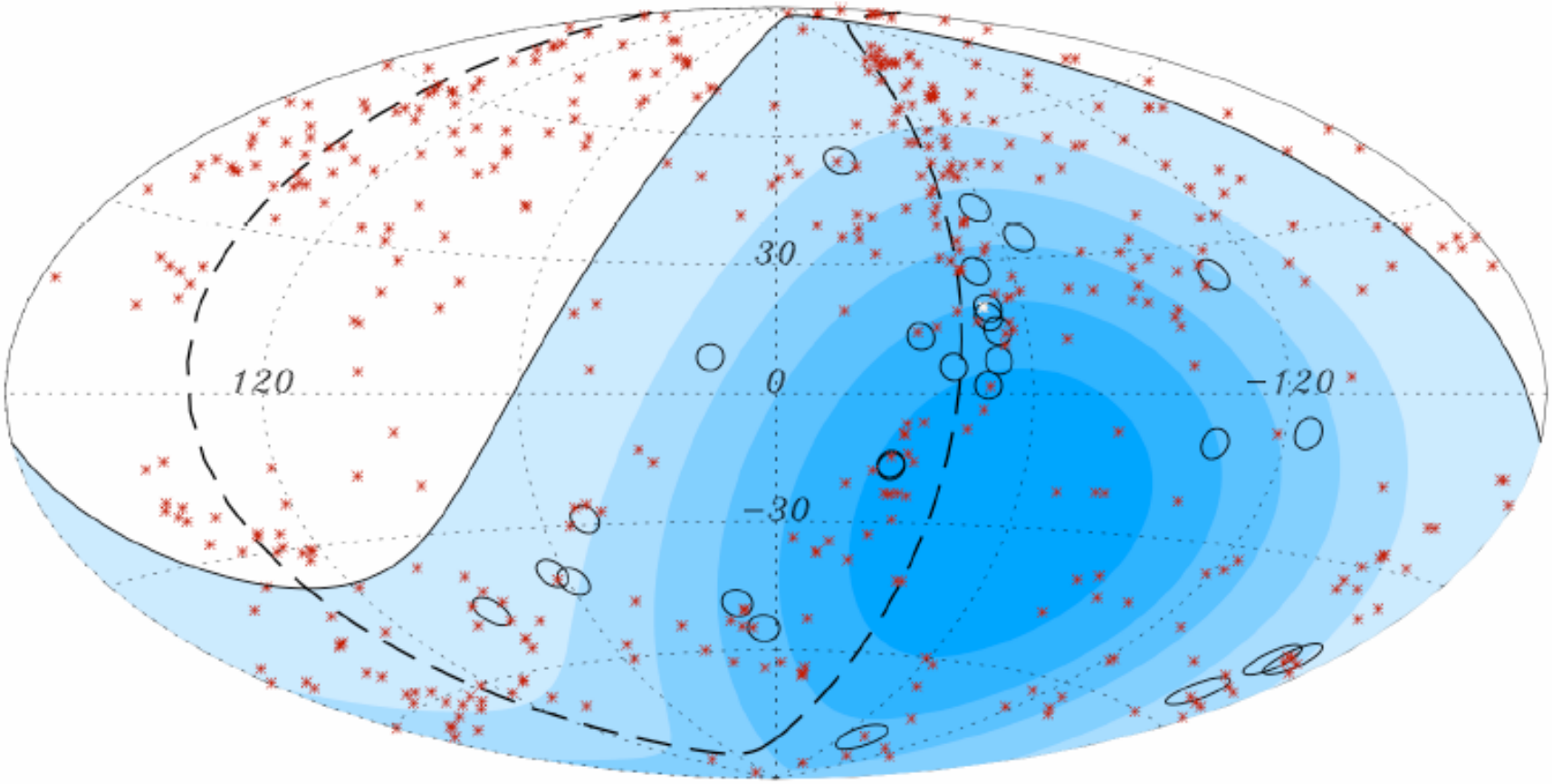



Figure 2: Aitoff projection of the celestial sphere in galactic coordinates with circles of radius 3.1° centered at the arrival directions of the 27 cosmic rays with highest energy detected by the Pierre Auger Observatory. The positions of the 472 AGN (318 in the field of view of the Observatory) with redshift $z \leq 0.018$ ($D < 75$ Mpc) from the $12^{th}$ edition of the catalog of quasars and active nuclei (*12*) are indicated by red asterisks. The solid line draws the border of the field of view (zenith angles smaller than 60°). Darker color indicates larger relative exposure. Each colored band has equal integrated exposure. The dashed line is, for reference, the super-galactic plane. Centaurus A, one of our closest AGN, is marked in white.

# HiRes AGN Correlation Study

- Apply PAO cuts - **no significant correlation**
- Tried again shifting our energies 10%,
  **- no significant correlation**

- Split data in half and scan for cuts
- Apply cuts to second half of data
  **- no significant correlation**
- Use total data taking into account penalty for scanning over entire data set taken into account
  **- no significant correlation**

# Independent HiRes search

- First data set scan
  - Strongest correlation 1.7 deg., 15.8 EeV, zmax = 0.02 (chance prob = 0.005)
- Apply to second data set
  - 14 correlations out of 101 events
  - Chance probability 0.15
- Also tried scanning entire data set taking into account penalties
  - Best correlation at 2.0°, 15.8 EeV, zmax=0.016
  - 36 correlated events out of 198
  - Chance probability = 0.24
- **No Significant Correlation**

# Anisotropy conclusions

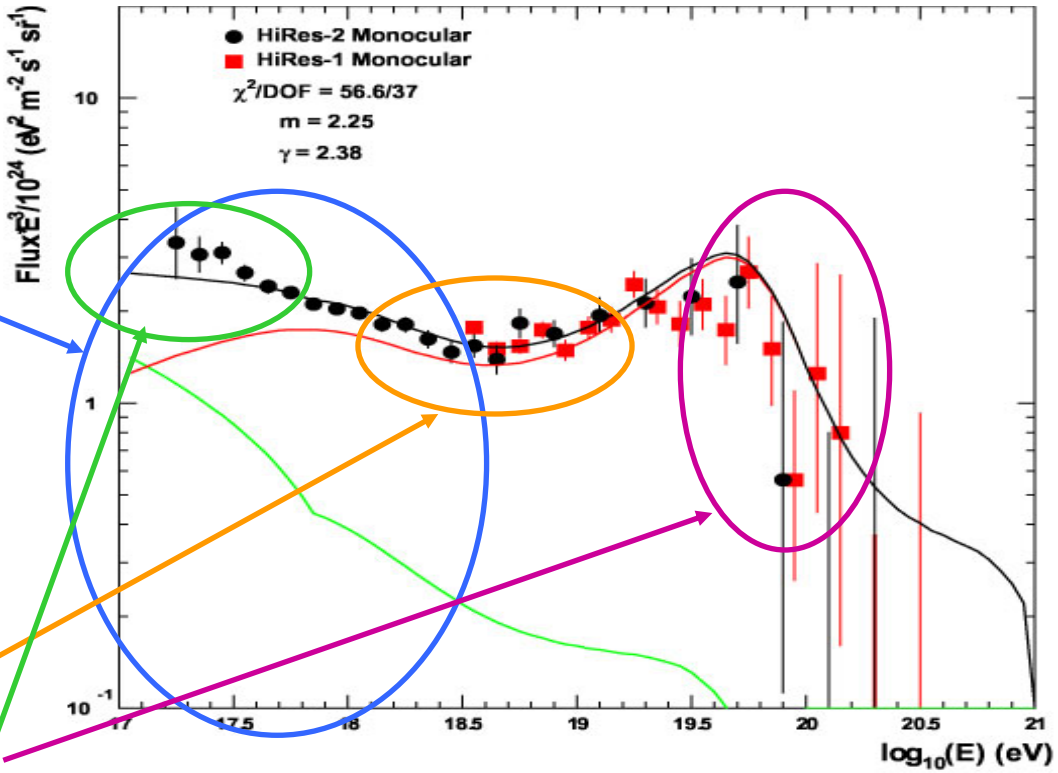
- While HiRes cannot confirm PAO correlations, statistics are still very limited
- Biases in Veron catalogue are problematic
- Underlying source of PAO anisotropy could be different.
- BL-Lac correlations are tantalizing, but confirmation is elusive

# What next?

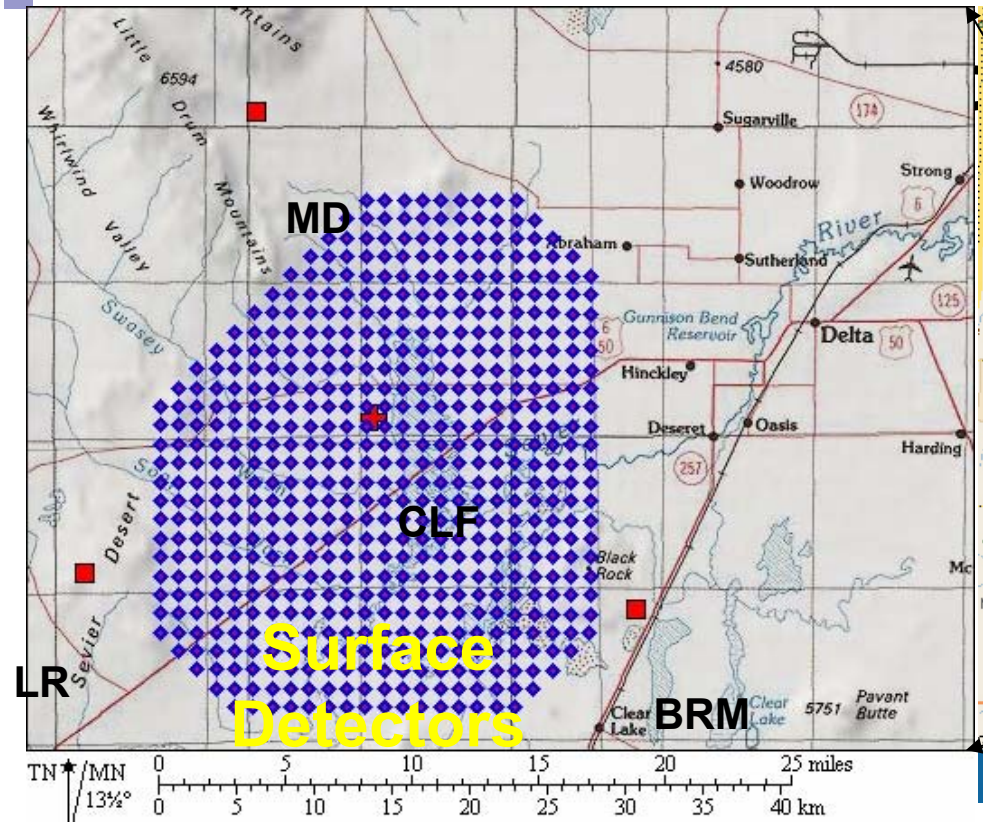
- HiRes has completed data taking
- Final papers out this year
- Many of us have joined forces with Japanese, Korean and now Russian groups to build and operate the Telescope Array project

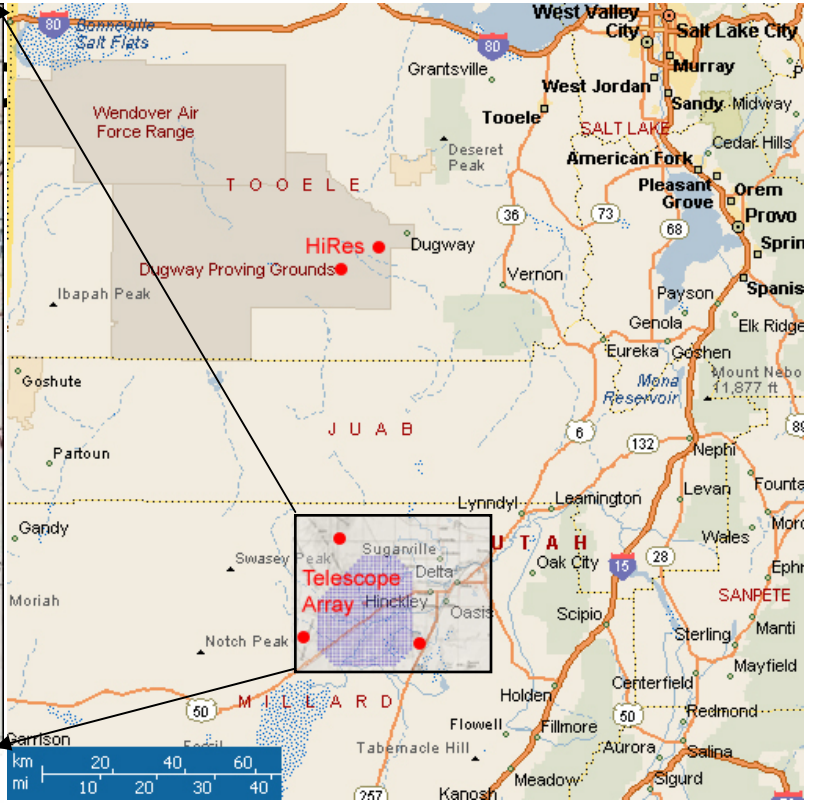
# Goal: Reach from $10^{16.5}$ eV up!

- Study the **Transition Region** from Galactic to Extra-galactic cosmic ray flux
- TA/TALE coverage to include all three cosmic ray spectral features in the UHE regime:
  1. **The GZK Suppression**
  2. **The Ankle**
  3. **The Second Knee**




**It is important than we establish a single unified energy scale for the measurement of all three features**




## Surface Detector Stations covering (blue diamonds):

~800 km$^2$ Rectangular grid with **1.2km** spacing; **3.0 m$^2$** plastic scintillation detectors

## Three fluorescence Stations: **12** x 3m dia. mirrors each at

Black Rock Mesa (BRM) and Long Ridge (LR), **14**x 2m dia. Mirrors at Middle Drum (MD)

## Central Laser Facility (CLF): atmospheric monitoring **laser**

seen by all 3 FD

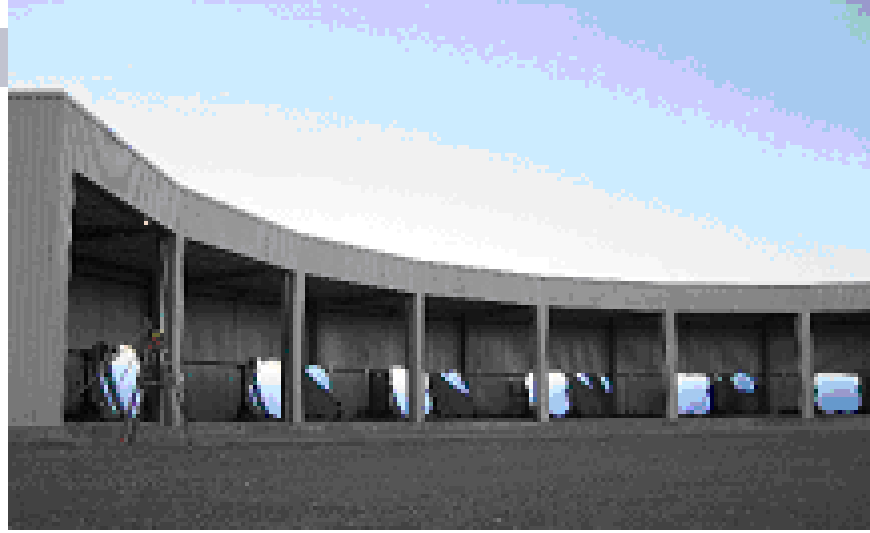
# Very Fast Deployment of Array

- 485 (90%) Deployed in 4 mos! (10/2006–2/2007)
- Currently 505 of 512 Deployed
- Remainder This fall


TELESCOPE ARRAY
PROJECT

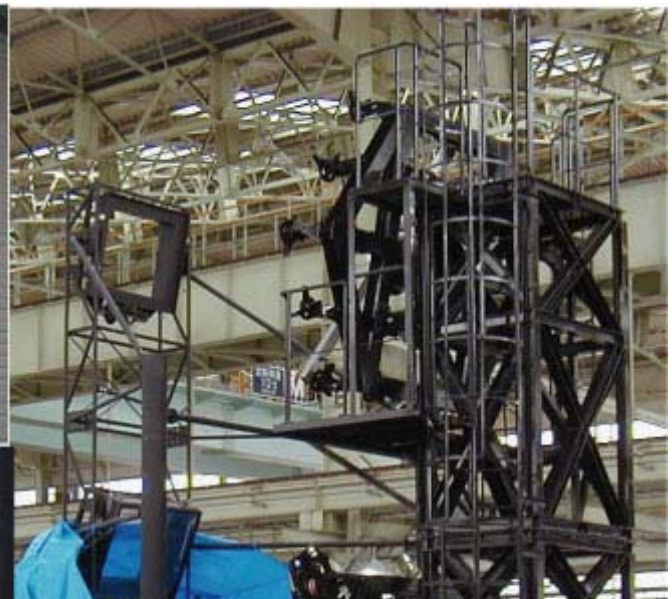
# Some Old

- 14 (2 rings x 7) refurbished HiRes-1 telescopes instrument  the Middle Drum (**MD**) station
- 1 degree pixels
- Sample and Hold Electronics

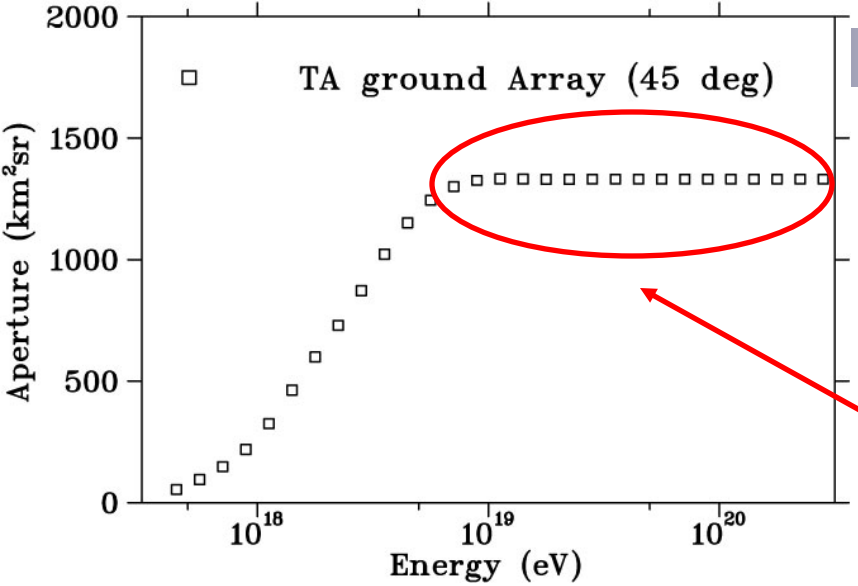


# Some New

- New FADC DAQ electronics at **BRM** & **LR**
- Built in Japan with trigger and comm. system designed in Utah (~ HiRes-1)



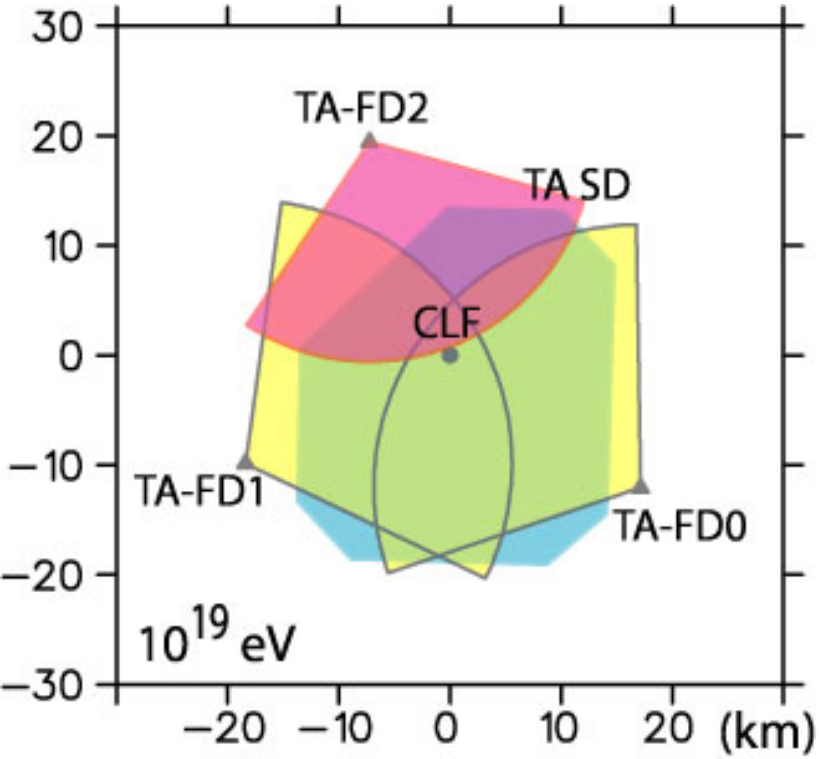
- 12 Telescopes (2 rings x 6)/site
- 1° pixels
- 3m dia mirrors

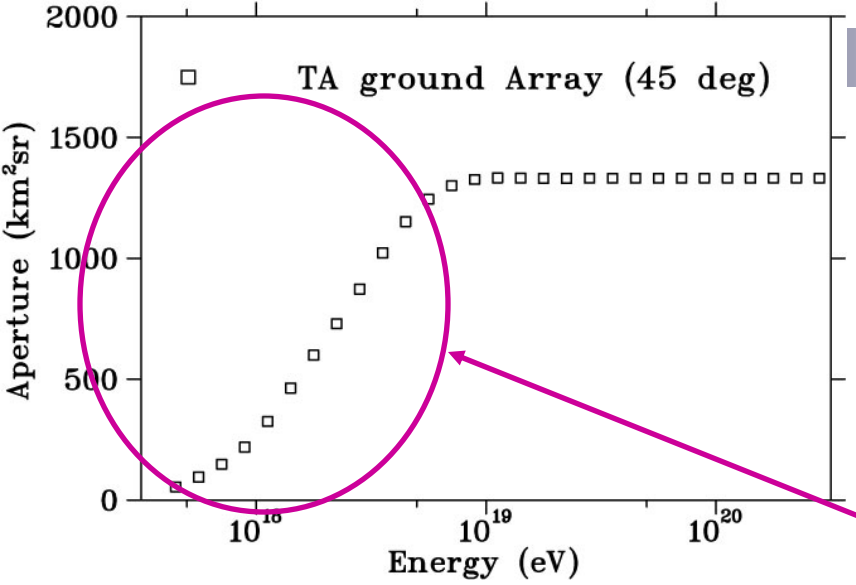



# TA Stage-1

- $E > 10^{19}$ eV is well-covered by the existing TA detectors
- Ground Array becomes fully efficient at ~$5 \times 10^{18}$ eV
- The three FD stations
  - TA-FD0 at Black Rock Mesa
  - TA-FD1 at Long Ridge
  - TA-FD2 at Middle Drum

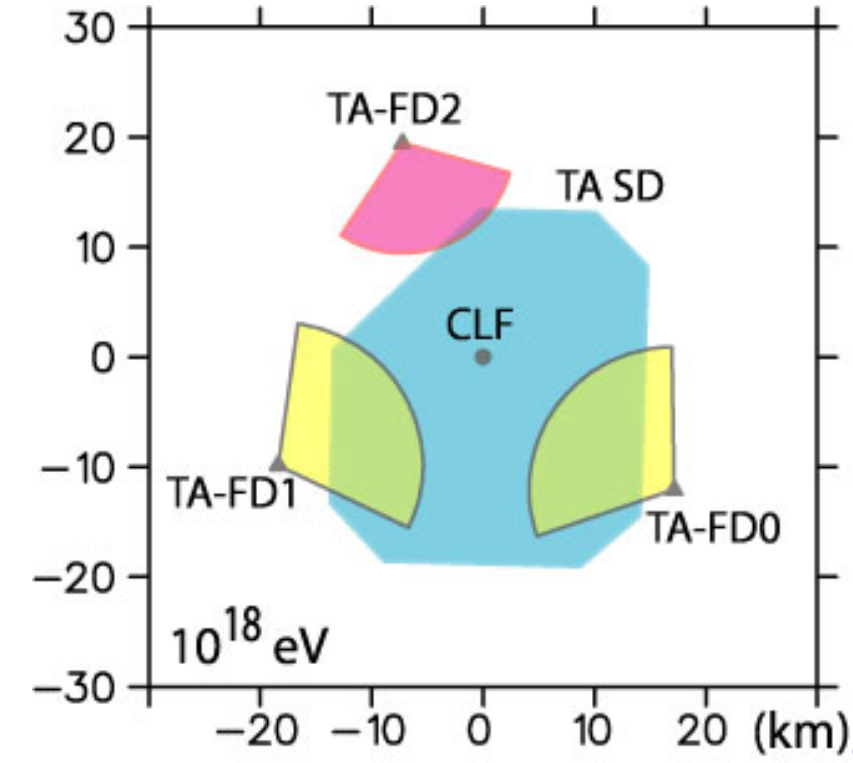
  provide ~100% coverage of the ground array at $10^{19}$ eV and above





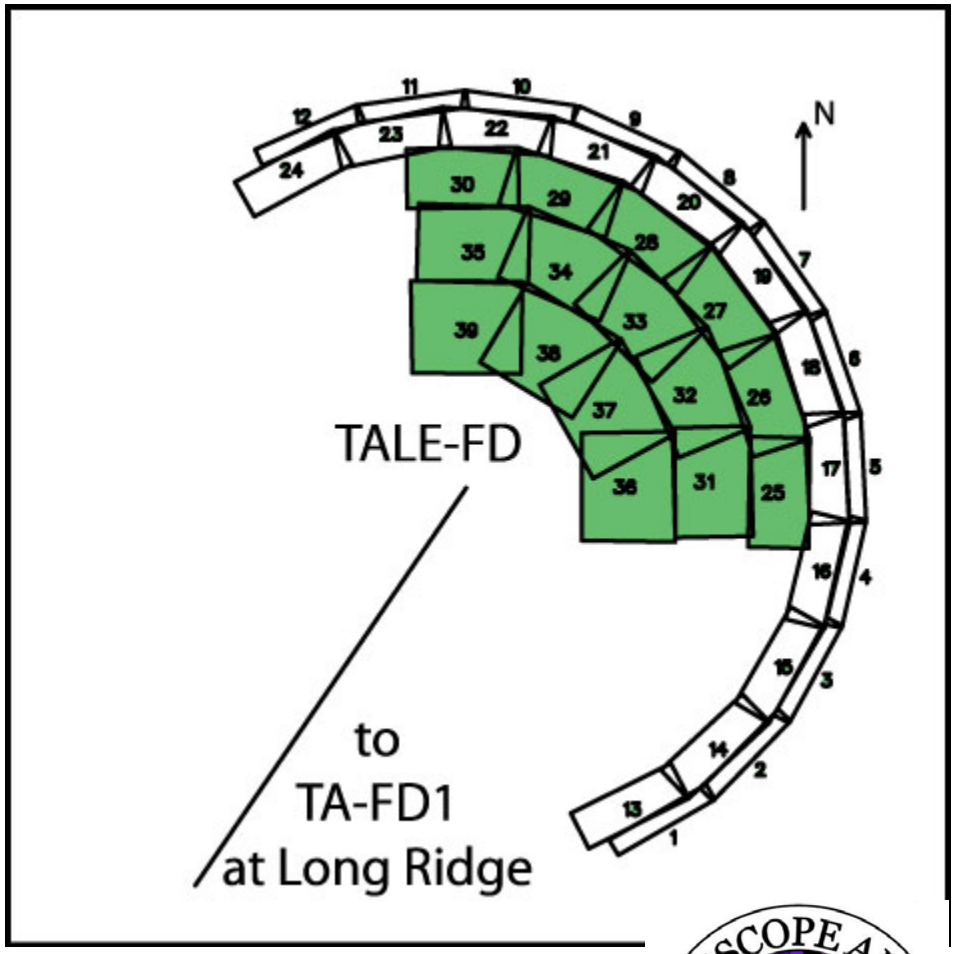

# However, below $10^{19}$eV

- **Stage-1** of TA was not designed for physics below $10^{19}$ eV.
- **The ground array** efficiency drops quickly in the $10^{18}$-$10^{19}$ eV decade
- There is no overlap at all in the aperture of the three **fluorescence detectors** at $10^{18}$ eV



# TALE Telescopes

- **TALE 6 km Stereo**
  24 Telescopes (2 rings x 12) provide coverage in the Ankle region
- **TALE Tower**
  15 Telescopes in three “rings”:
  - 6 at 31-45°
  - 5 at 45-59°
  - 4 at 59-73°
- Stereo overlap with TA-FD1 at Long Ridge for direct validation of MC resolutions

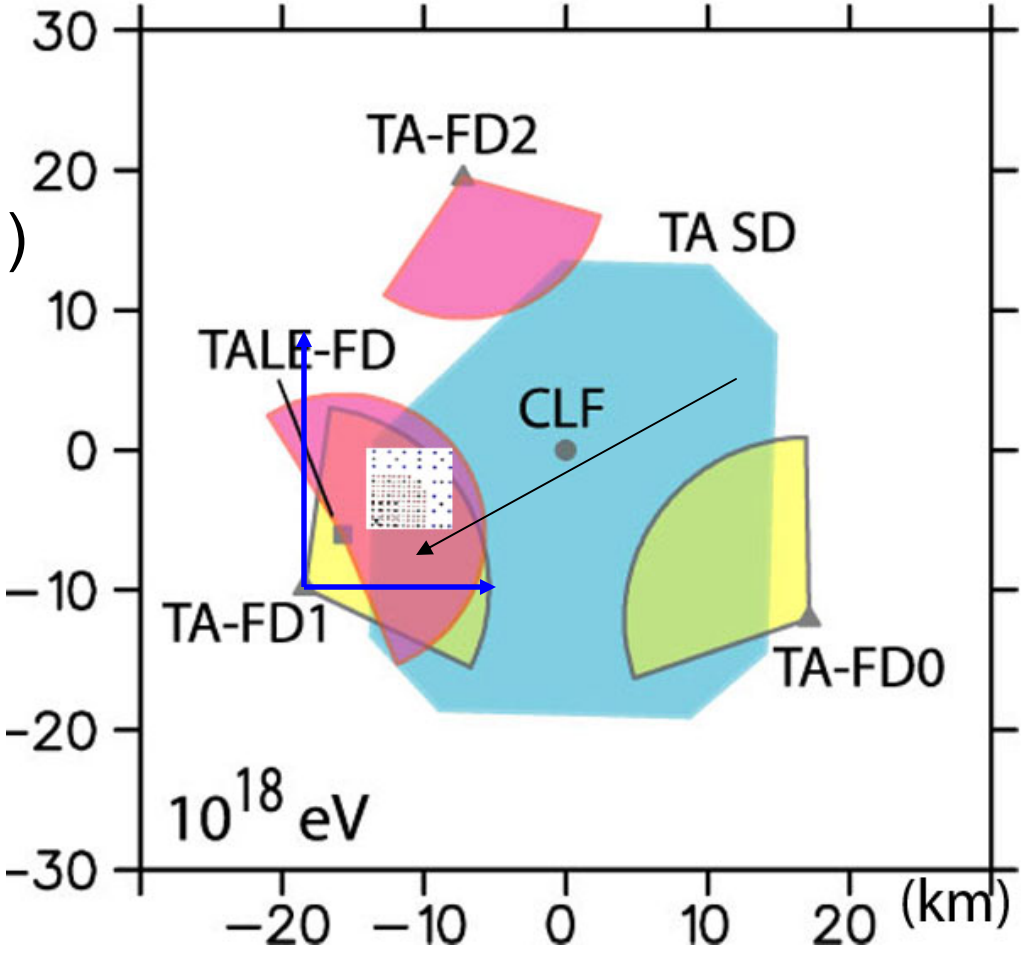



Top view projection of the viewing solid angles of the TALE telescopes

# Hybrid Operation

- **Infill Scintillator Array** (111)
  4km x 4km - 400m spacing provides hybrid coverage in $10^{16.5} < E < 10^{19}$ eV

- **Muon Detectors** (25)
  2.5km x 2.5km – buried 3m under surface - provide orthogonal composition measurement (compliment Xmax) $10^{16.5} < E < 10^{18}$ eV



# TA/TALE Summary

- Four different detector systems provide seamless coverage for $E > 10^{16.5}$ eV
- Cost shared by U.S., Japan, South Korea, & Russia
- Study all three spectral features in the UHE regime and measure the composition over the entire energy range.
- Around the Second Knee (where we suspect Galactic/Extragalactic transition occurs) we will have two orthogonal composition measurements: FD shower profile & e/$\mu$ ratio.

# Take Home:

- Spectrum clearly shows structure (ankle, GZK suppression) – galactic/extra-galactic cosmic rays – See PRL
- Xmax AND Width important to measuring composition
- Composition is constant and light $10^{18}<\text{Log}(E)<10^{19.6}$
- Point Sources/BL Lacs tantalizing – need verification
- No Confirmation of Auger AGN correlation
- p-air cross-section and neutrino limit – didn't show today
- More to come…
  - HiRes data taking concluded 4 April 2006
  - Analysis will continue for about another year
- ***The Telescope Array Project***
  - *Phase-1 is taking data (98% complete)*
  - *Phase-2 - Low Energy Extension – coming soon*


HiRes