THE UNIVERSITY OF UTAH

The High Resolution Fly's Eye (HiRes) Experiment

Charles Jui
University of Utah

The Symposium on "The Recent Progress of Ultra-high Energy Cosmic Ray Observations"

Nagoya, Dec 10, 2010

Outline

- Introduction to HiRes
- HiRes Energy Spectrum Results

  Please attend also: Friday 16:40 - 18:00 (90min)

  16:40 G. Thomson: Energy measurement and spectrum by HiRes (20)
- HiRes Composition Results
  - **HiRes composition data available at**: http://www.cosmic-ray.org/journals/prl.html
  - **Please attend also: Saturday** 16:30 - 18:00 (90min)

    16:30 J.W.Belz: Measurement of UHECR composition by HiRes (20)
- HiRes Anisotropy Results
  - **HiRes anisotropy data available at:** http://www.cosmic-ray.org/supplements.html
  - **Please attend also: Saturday** 16:30 - 18:00 (90min)

    16:00 P. Tinyakov: Measurement of anisotropy by TA (30)
- Summary

The High-Resolution Fly's Eye (HiRes) Collaboration

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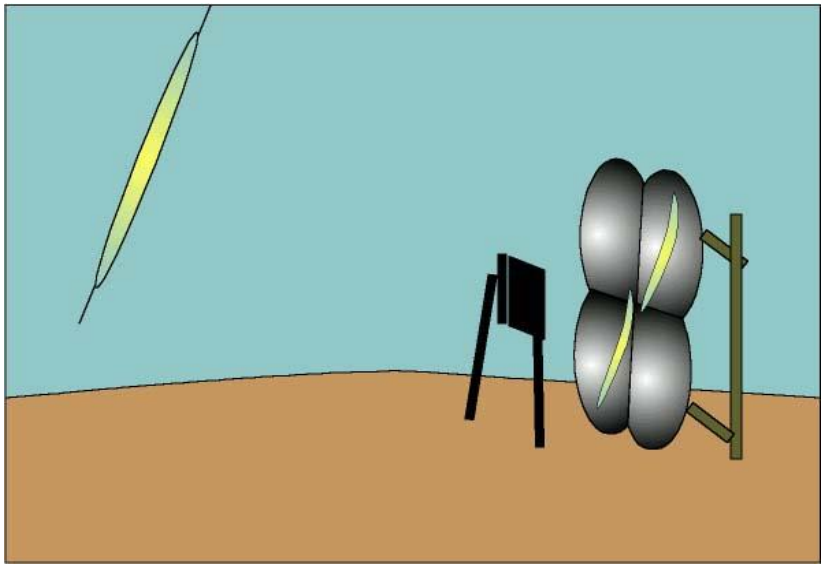
Two HiRes Detectors

HiRes-I:

- 21 mirrors, 1 ring, $3^o < \text{elev} < 17^o$
- Readout pulse height and time

HiRes-II:

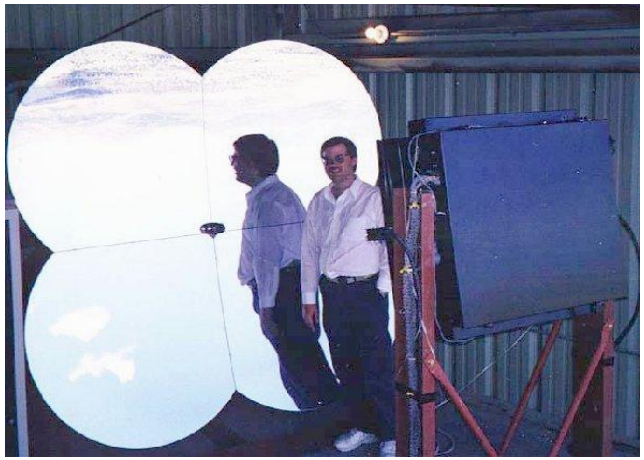
- 12.6 km SW of HiRes-I
- 42 mirrors, 2 rings, $3^o < \text{elev} < 31^o$
- Electronics stores pulse shape vs. time w/ 100 ns sampling



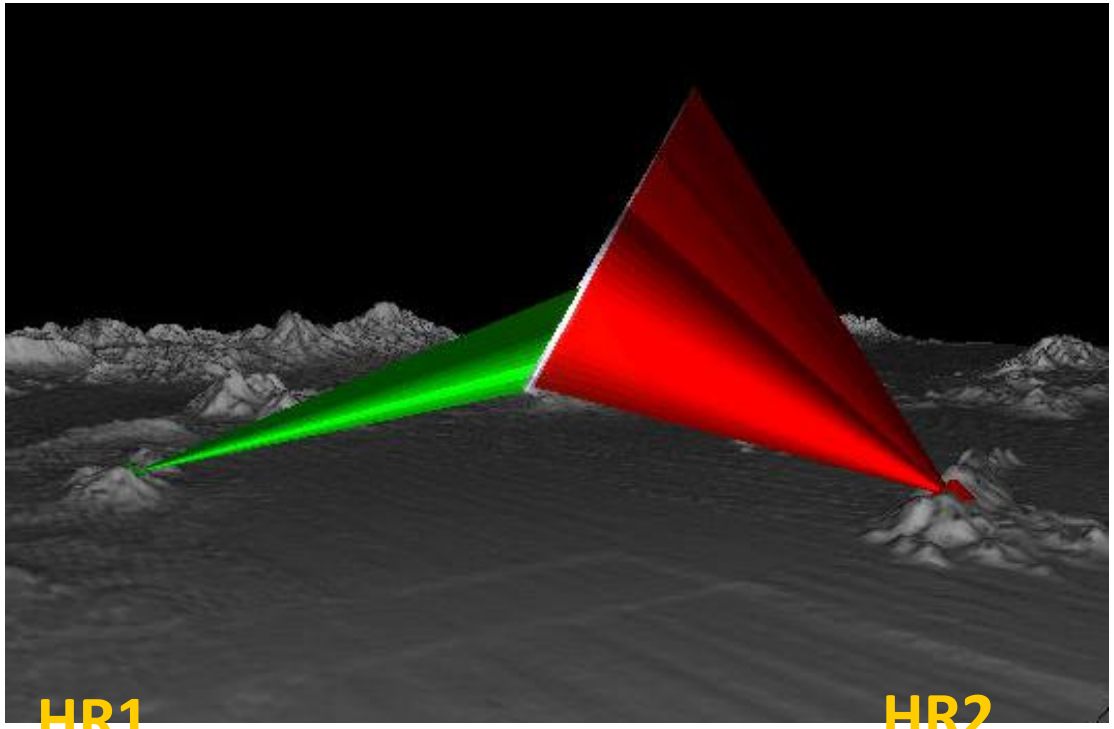
Observe nitrogen fluorescence from airshowers

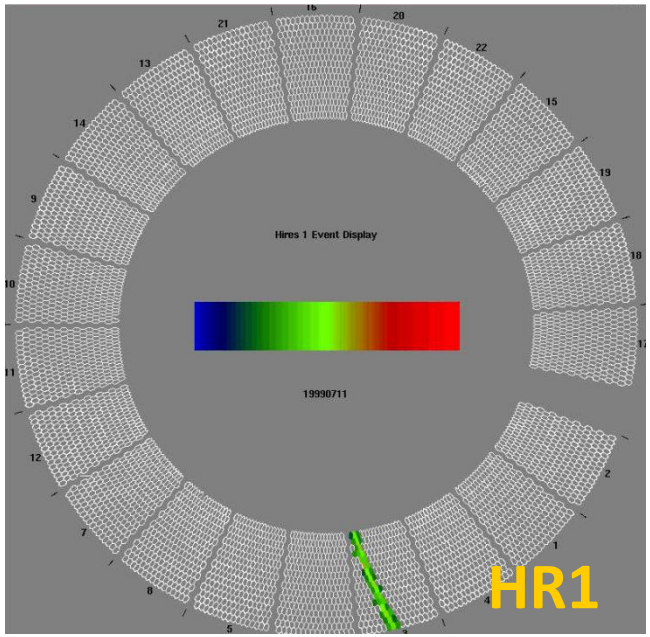
Mirrors and Phototubes

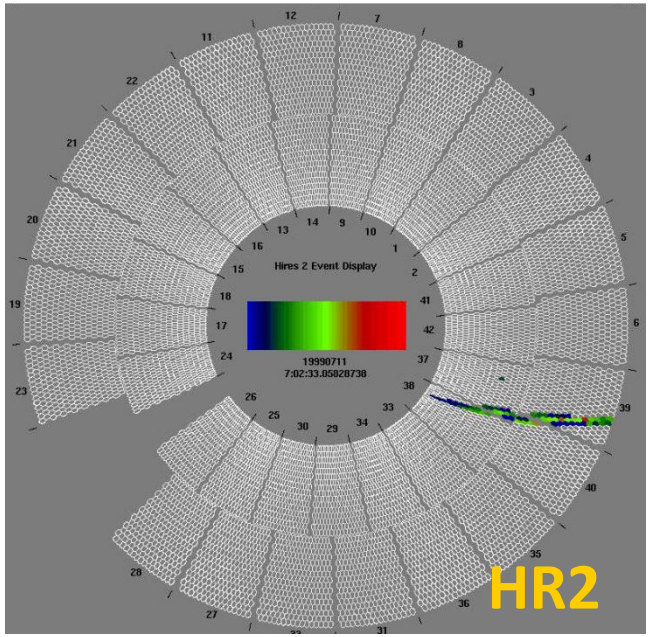
- Spherical mirror with 3.7 m^2 effective area
- 16 x 16 array of phototubes, ~1 degree pixels.



Extensive Air Shower Measurement from two detectors





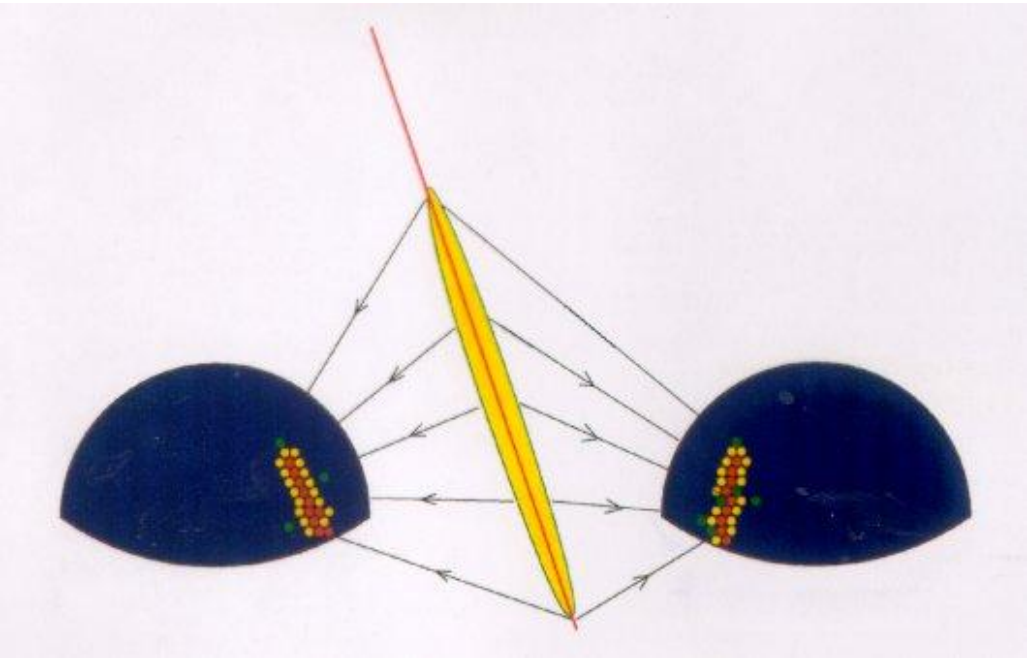


- HiRes-1 monocular data-taking started in 1997
- HiRes-2 and stereo observations started in 2000 (early stereo event shown)
- Experiment shut down in 2006

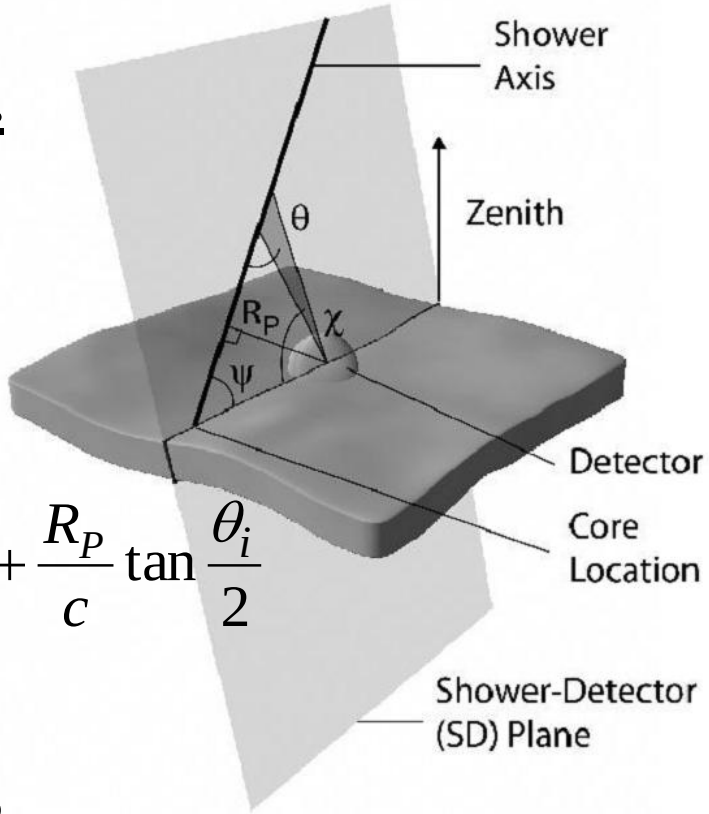
Geometrical Reconstruction

The trajectory of the EAS can be determined in one of two ways:

1. Monocular reconstruction using the arrival time of light signal at the detector.
2. By intersecting the shower-detector planes (SDP) seen from the two detector sites.

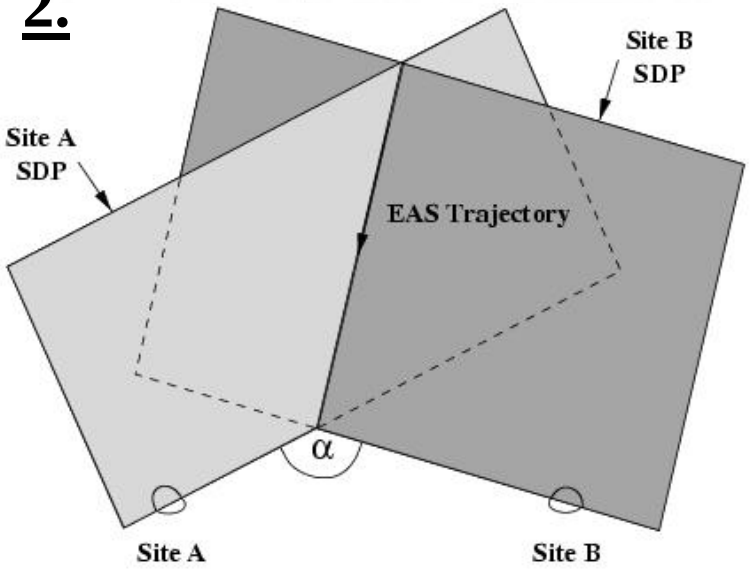


1.

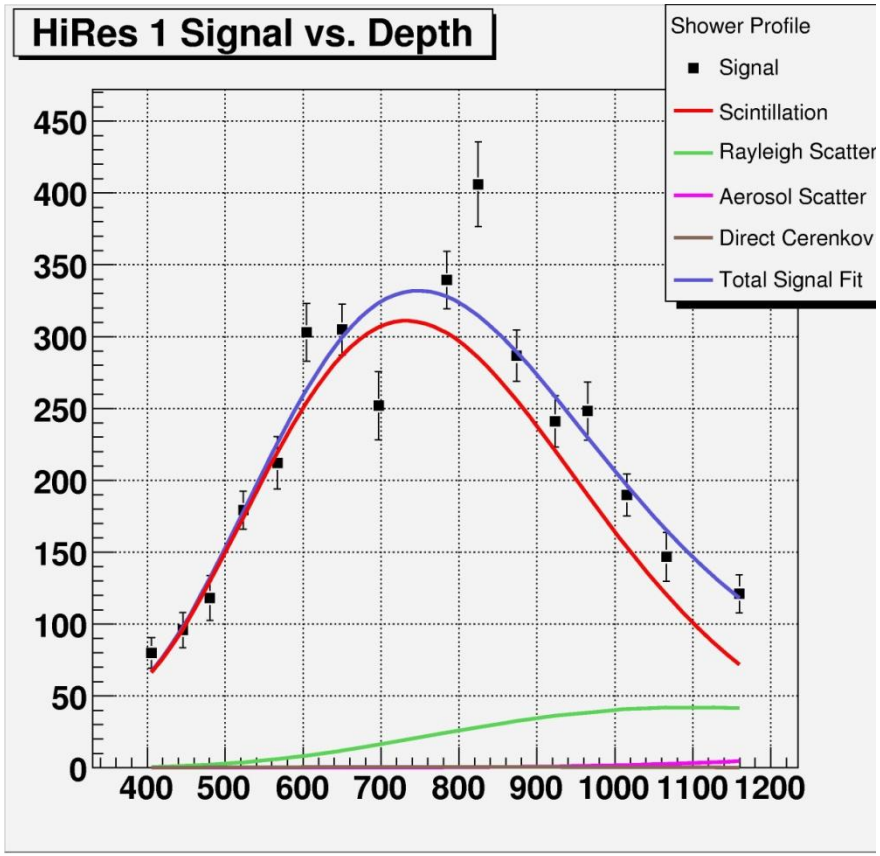


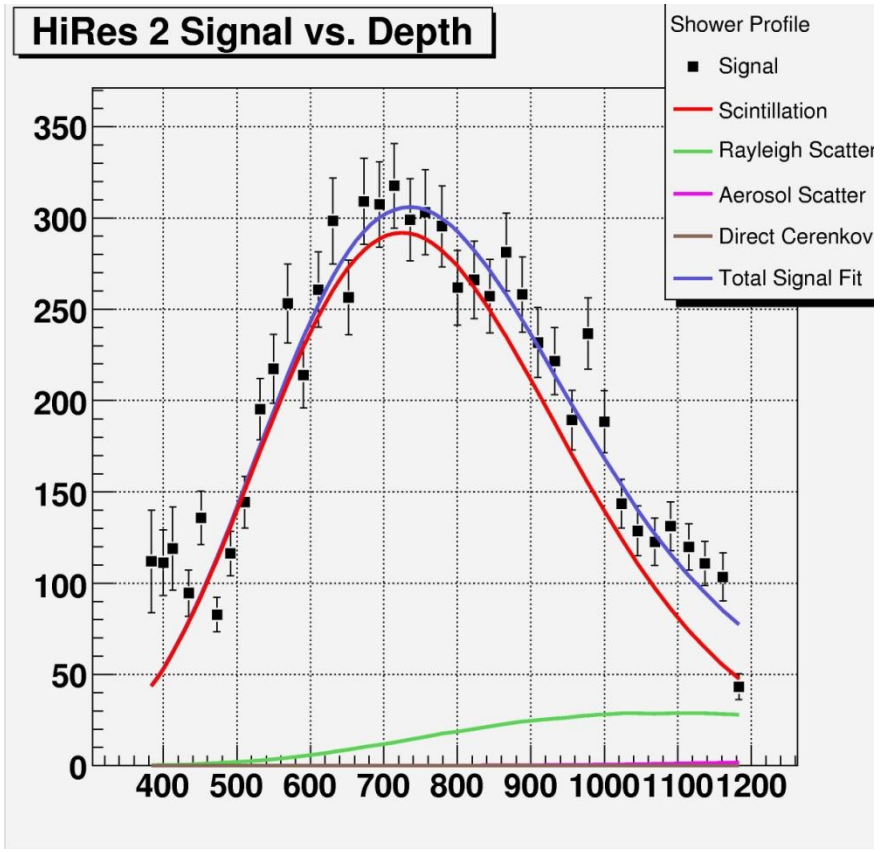
$$t_i = t_0 + \frac{R_P}{c}\tan\frac{\theta_i}{2}$$

2.



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

UHE Cosmic Ray Spectrum

- Monocular spectra – HiRe-1 and -2
- **HiRes-1**: largest statistics, limited elevation angle viewing → high threshold energy
- **HiRes-2**: best low energy response
- **Stereo** spectrum - best geometrical and energy resolution

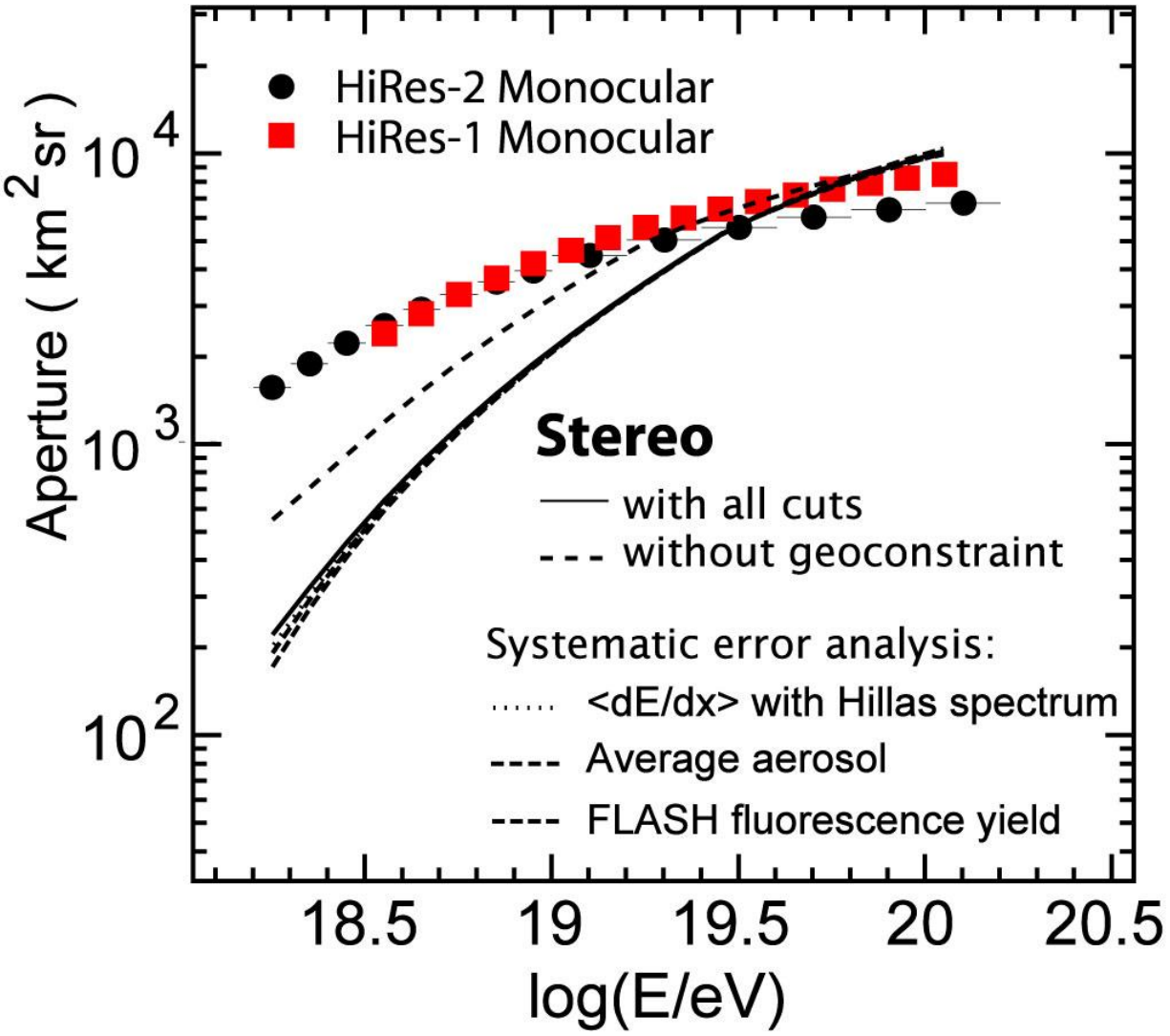
Monocular and Stereo Aperture

Monocular:

- HiRes-1 mono observation started in 1997 ➔ Mono energy spectrum has greatest statistical power.

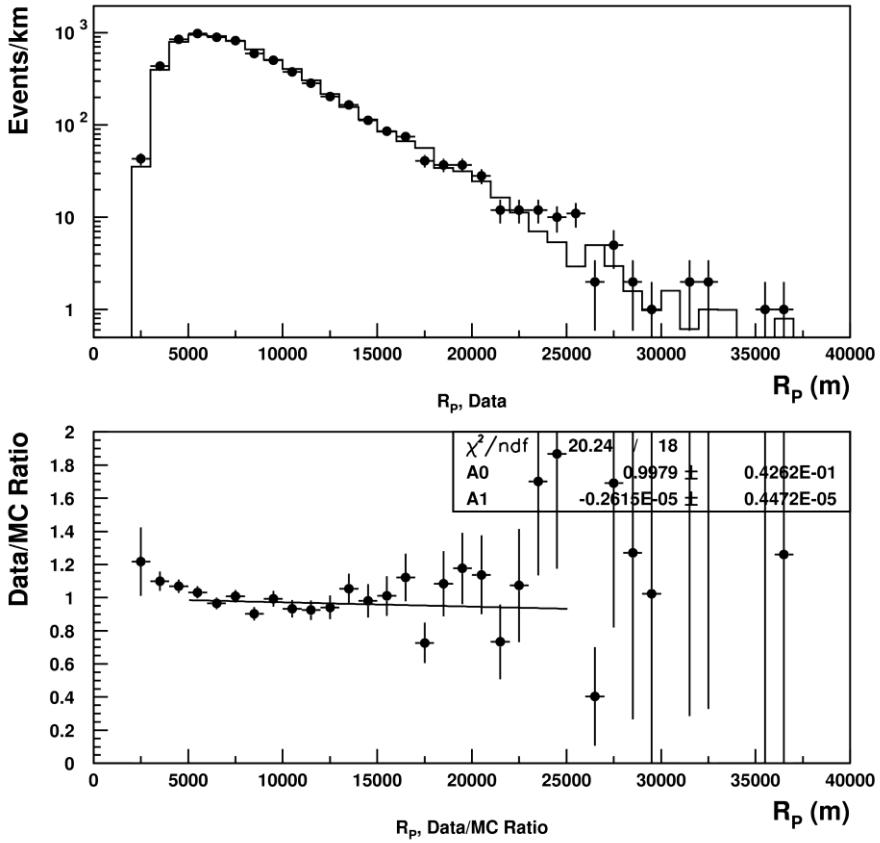
Stereo :

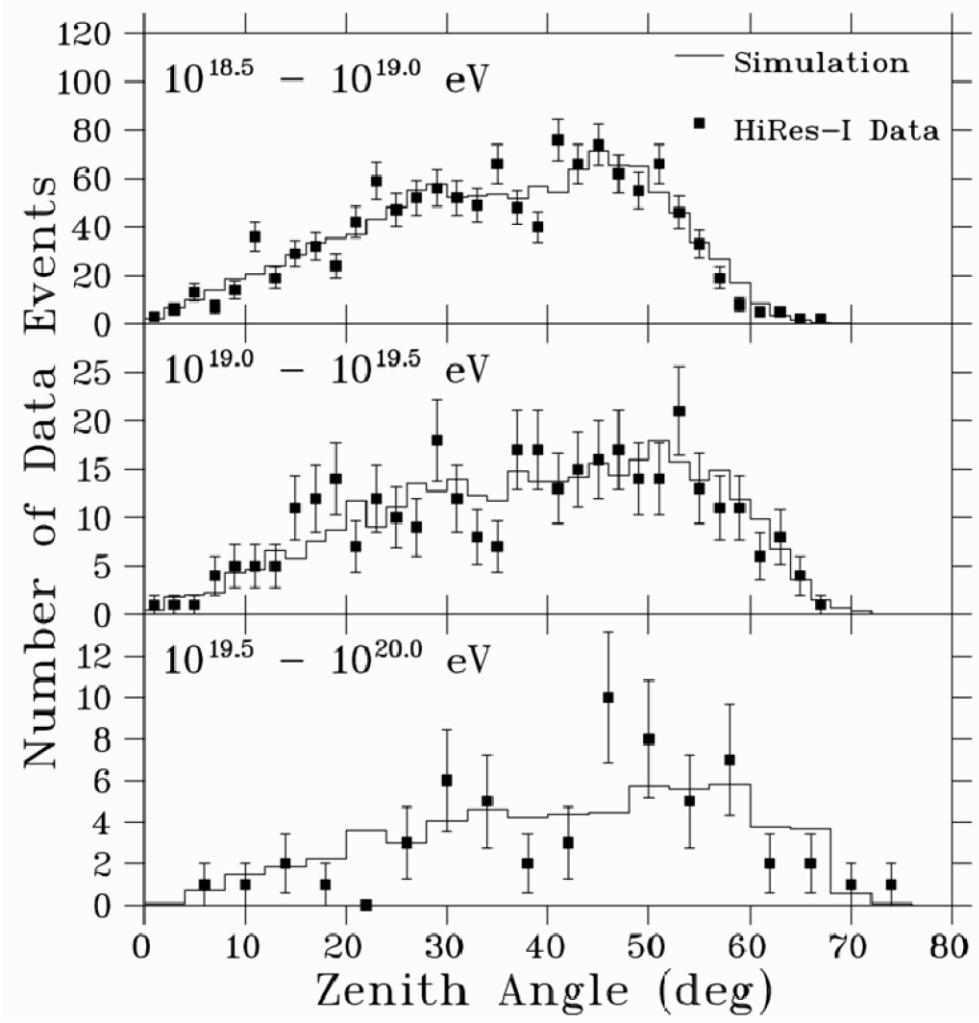
- Much more precise measurement of shower trajectory
- Better angular, and Xmax resolution for anisotropy and composition studies



Data/MC Comparison(mono)

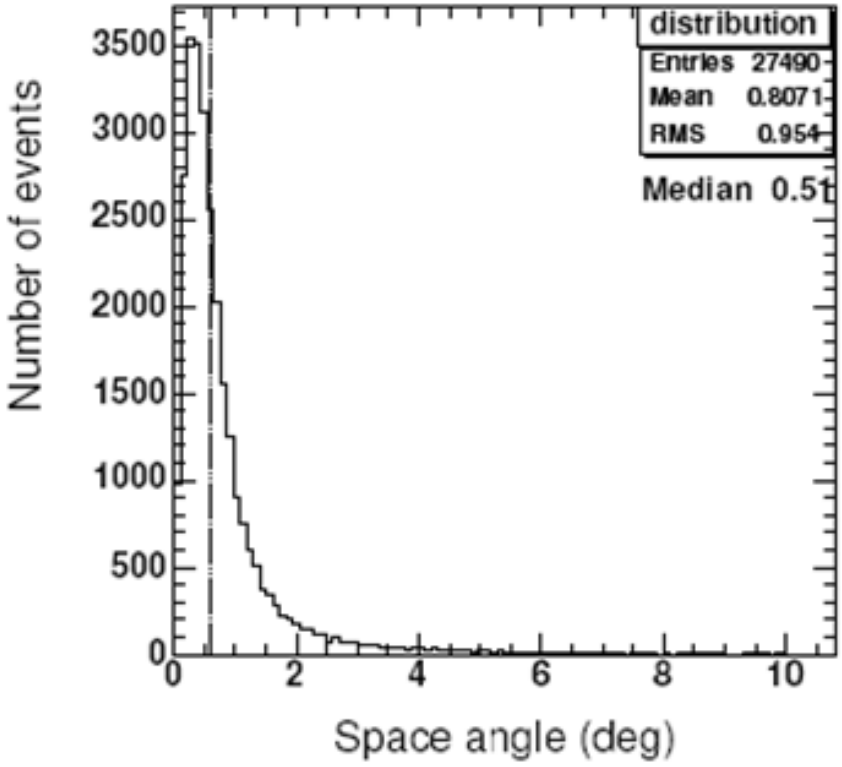
Good agreement between data and MC validates aperture calculation

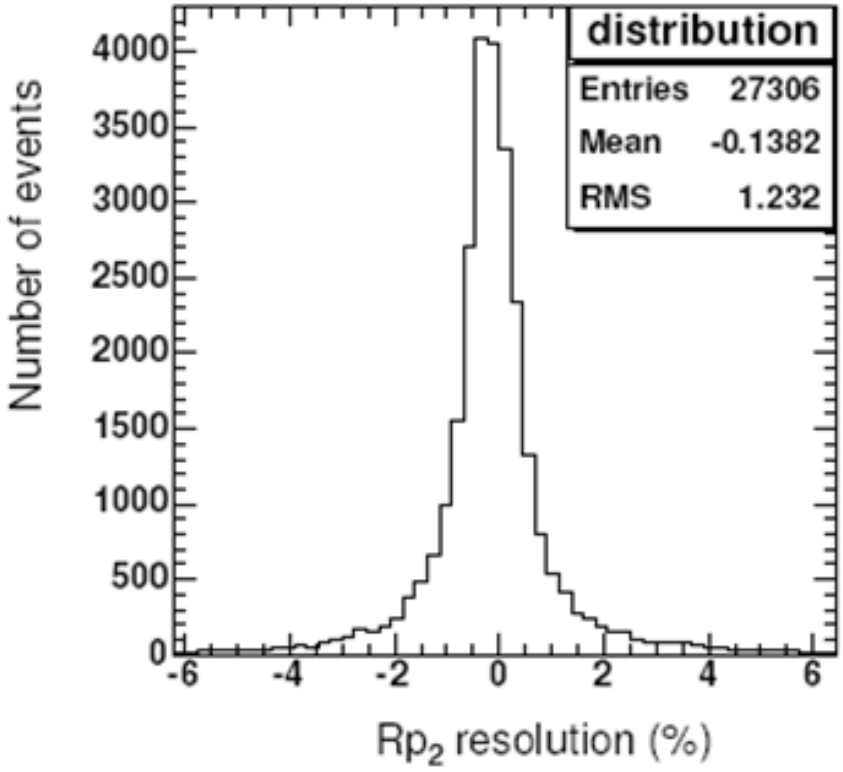




HiRes, Dec 2010

Detector Resolution





Stereo Data: Good geometrical resolution ➔ reliable arrival direction and Xmas measurements for anisotropy and composition studies

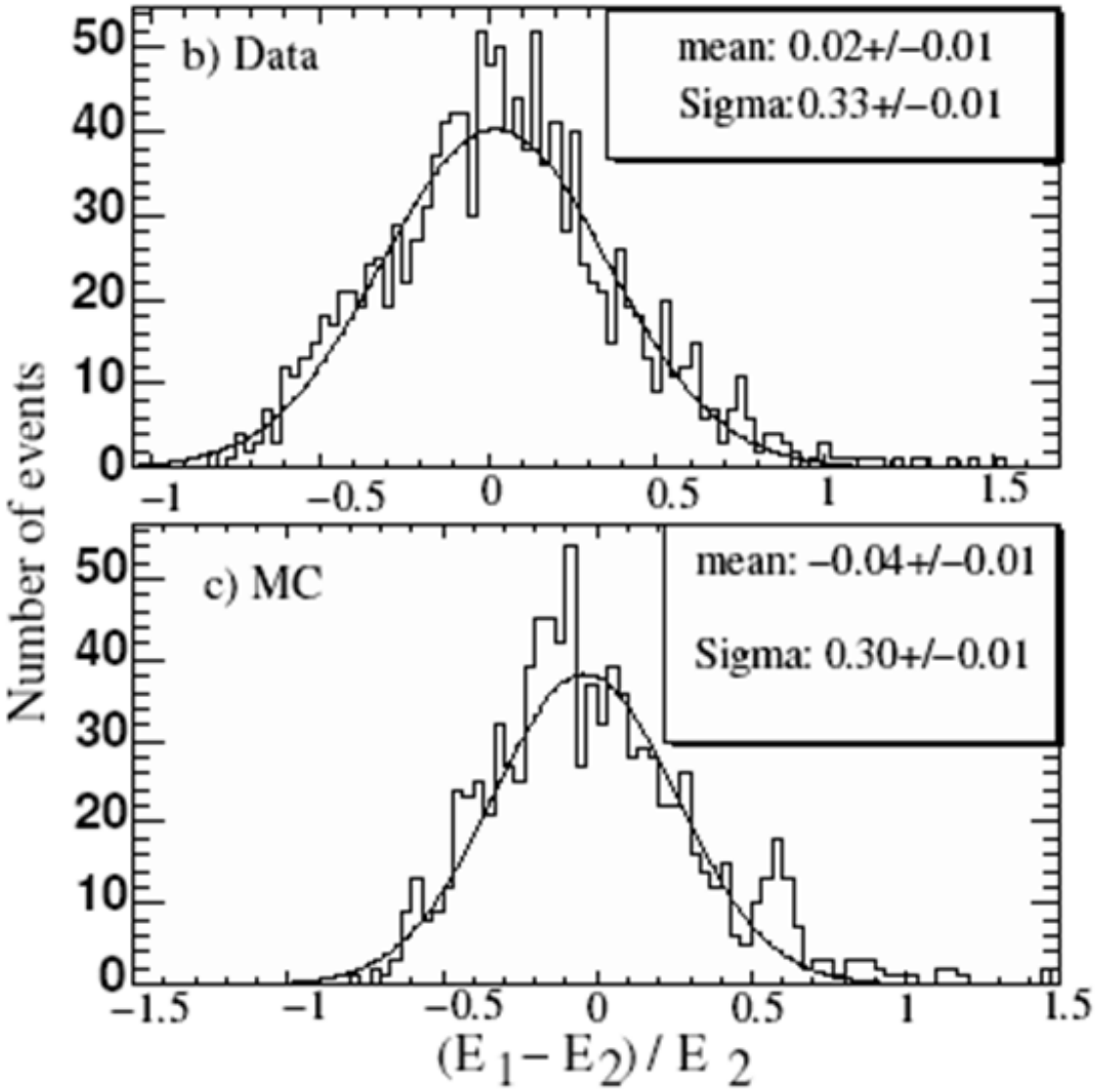
HiRes, Dec 2010

Advantage of Stereo

- Redundant measurements of Xmax and Energy
- Validates MC detector resolution

  HiRes-2 Energy Resolution: 15%

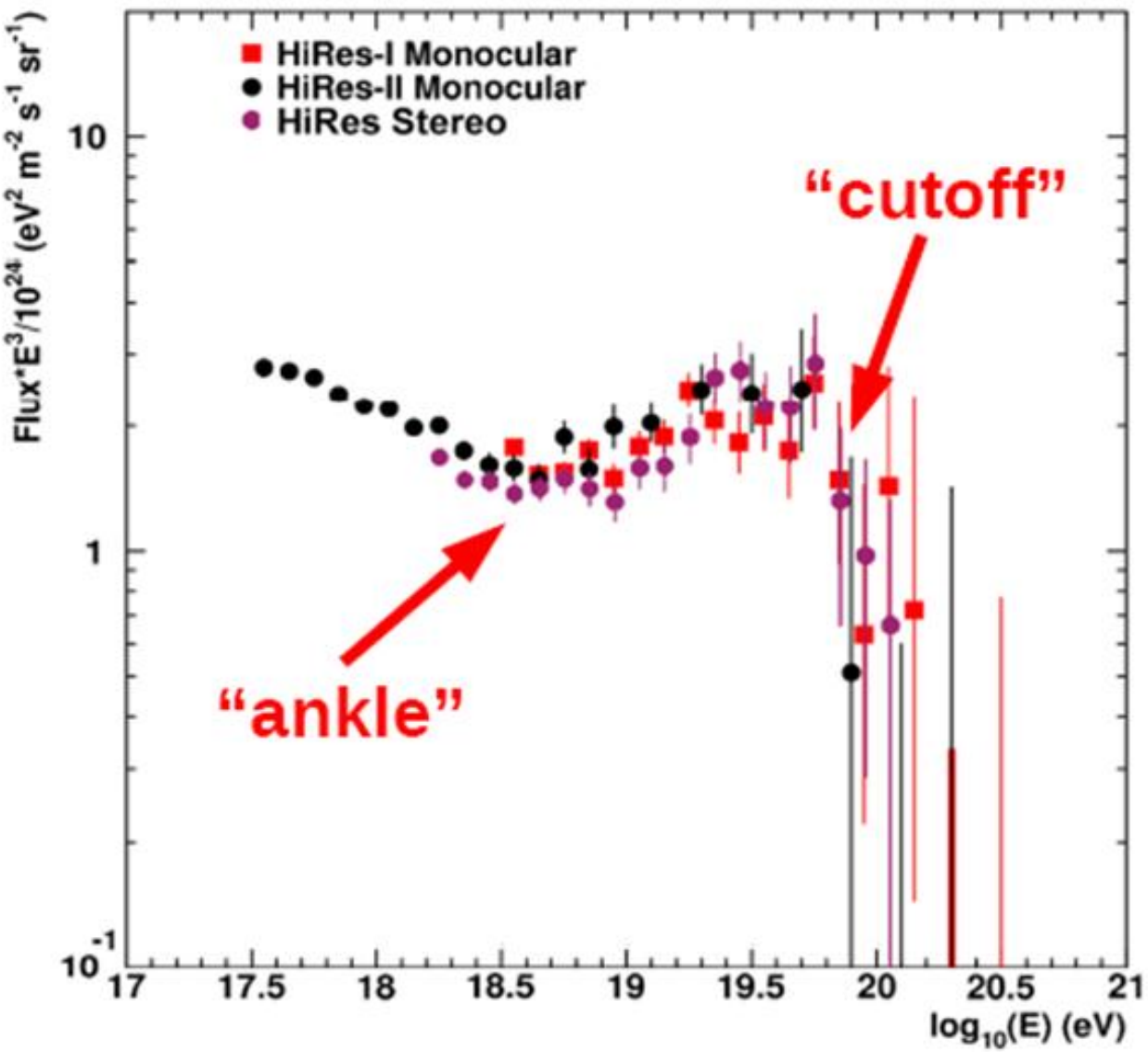
  Systematic: 17%



Energy Spectra

- Combined **HiRes-1+2** monocular, and the **stereo** spectra both show two major features:

1. **Ankle** / dip structure at ~$10^{18.6}$ eV
2. **Cutoff** of the spectrum at ~$10^{19.8}$ eV

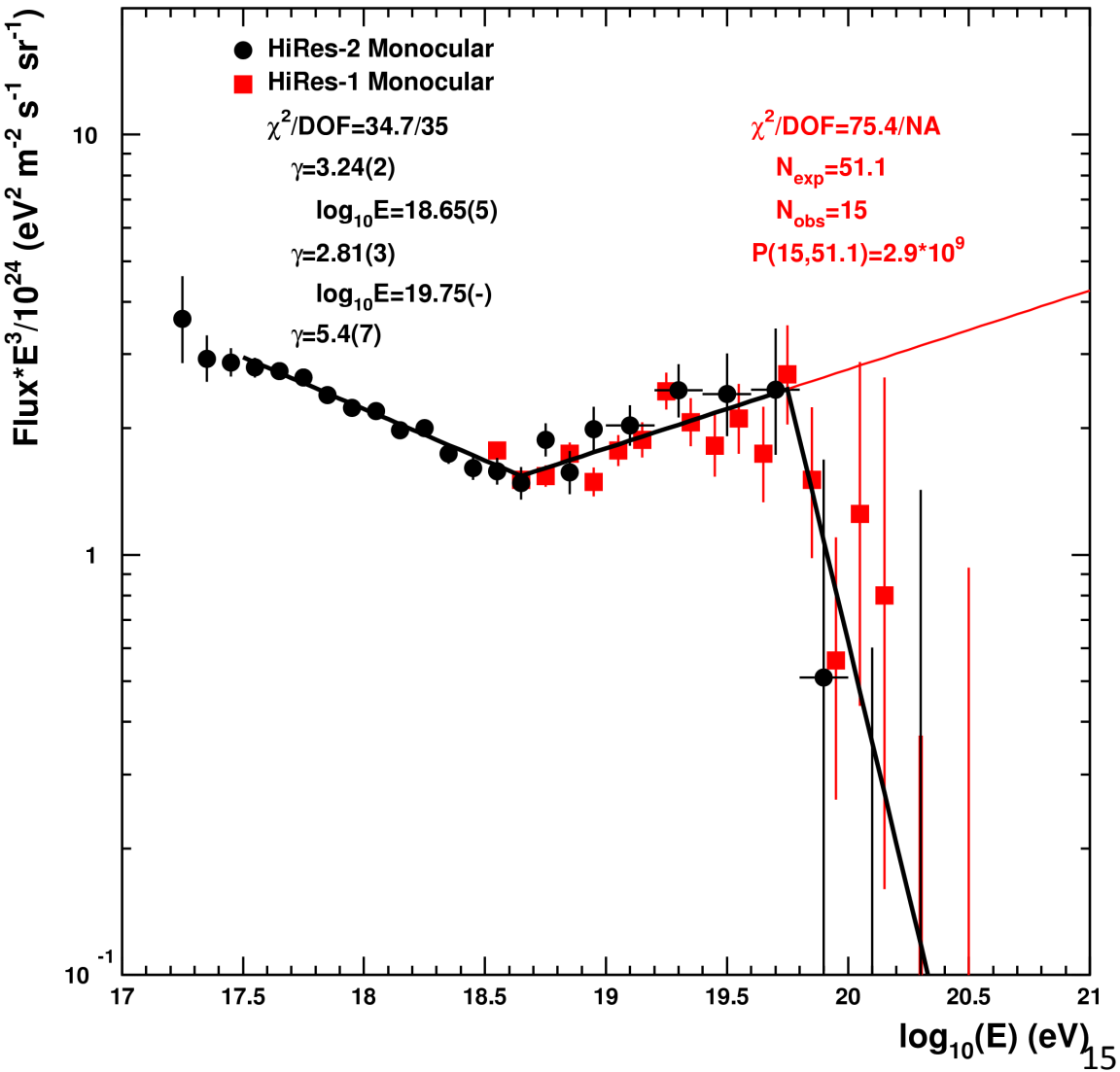


HiRes, Dec 2010

Observation of the GZK Suppression (mono)

Broken Power Law Fits (independent data)

- ***No Break Point***
  - χ^2/DOF = 162/39
- ***One Break Point***
  - χ^2/DOF = 63.0/37
  - BP = 18.63
- ***Two BP's***
  - χ^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)= **7×10^{-8} (=5.3σ)**

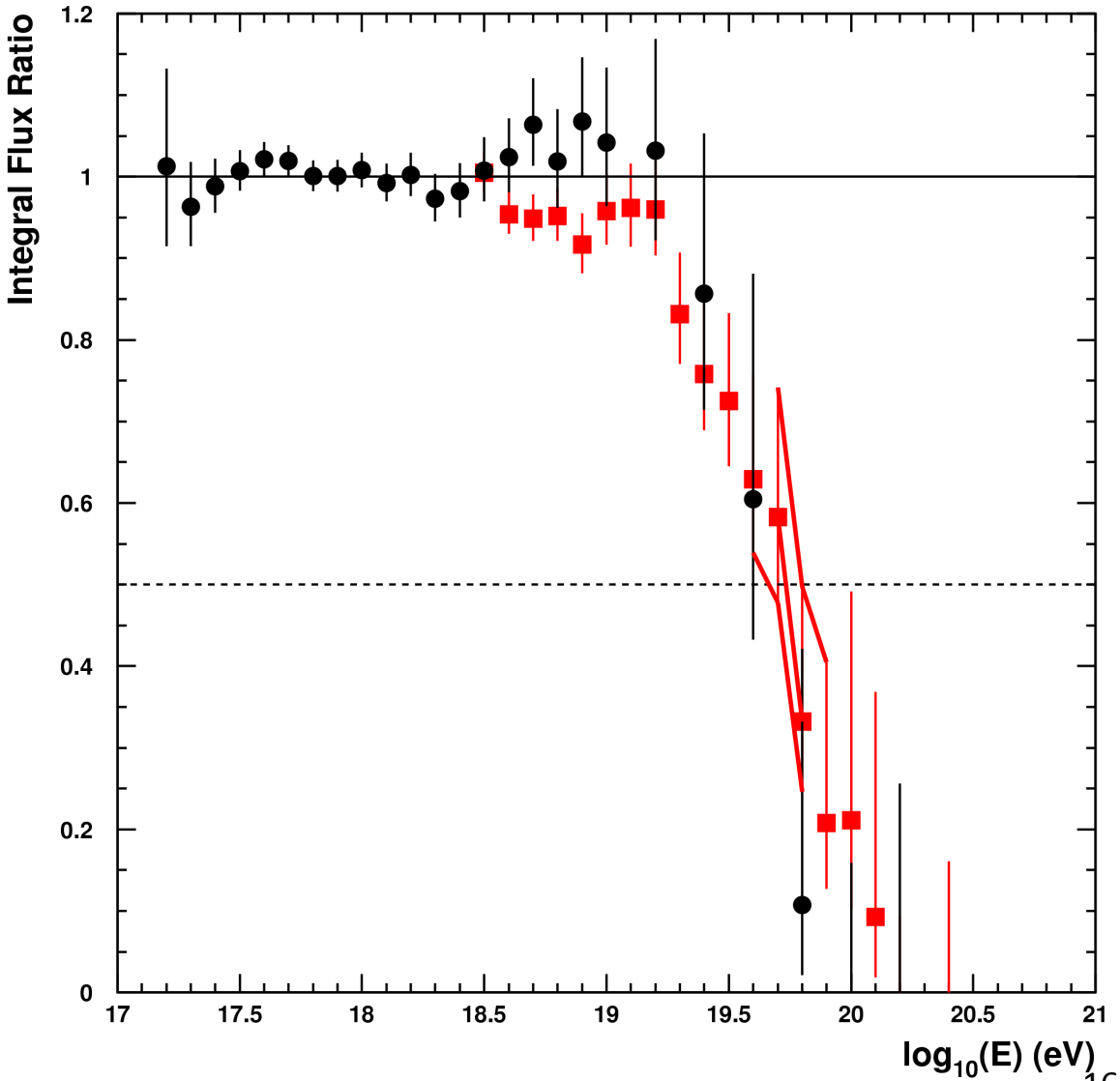


HiRes, Dec 2010

Berezinsky $E_{1/2}$ Test

- $E_{1/2}$ is the energy where the integral spectrum falls below **½ × power-law extension.**
- **Berezinsky *et al.*: $\log_{10}E_{1/2} = 19.72$**, for a wide range of spectral slopes.
- Use 2 Break Point Fit with Extension for the comparison.

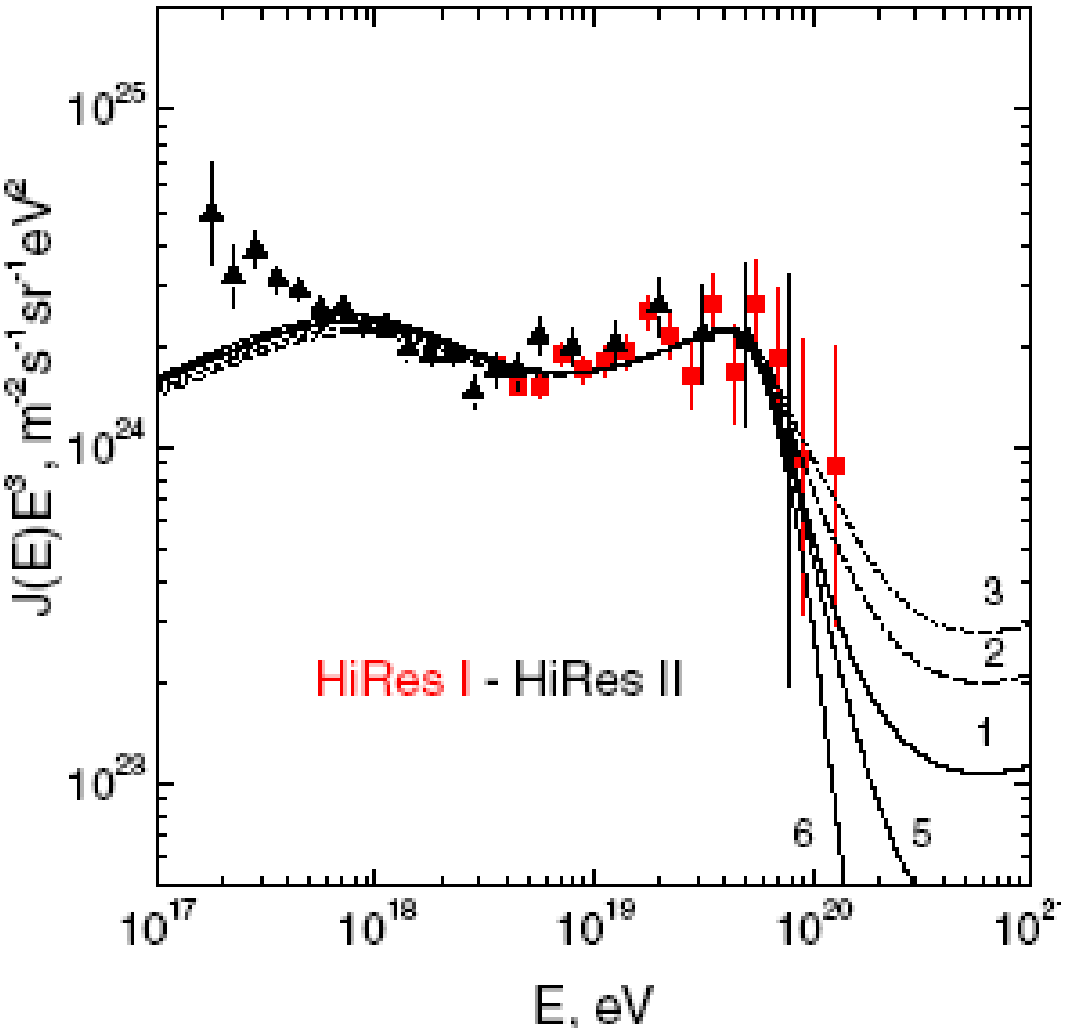
  $\log_{10}E_{1/2} = 19.73 \quad 0.07$



HiRes, Dec 2010

Local Density of Sources

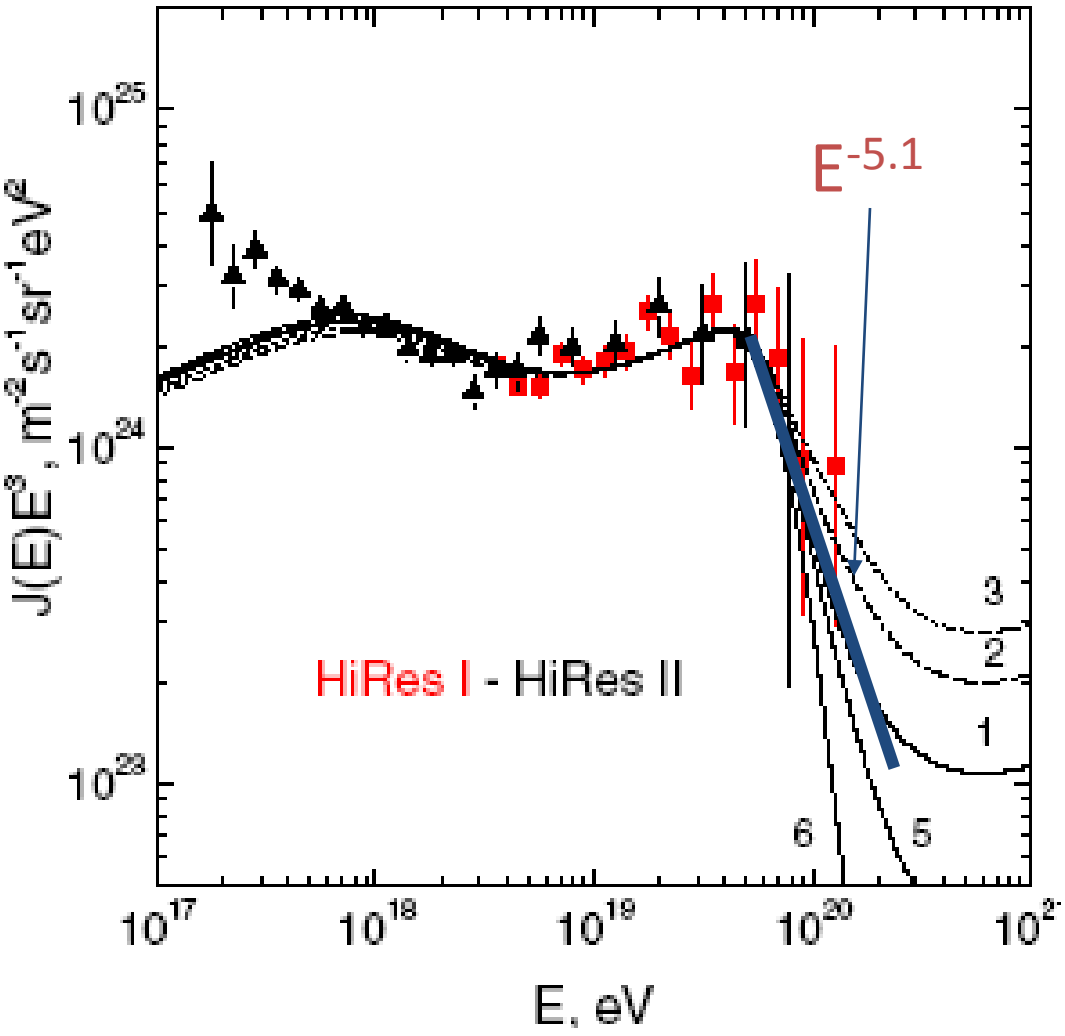
- Theoretical predictions for spectrum shape agree with HiRes measurements.
- Compare HiRes spectrum slope above the GZK energy to Berezinsky *et al*. predictions:
  - Line 1: constant density.
  - Line 5: no sources within 10 Mpc.
  - Line 2: double density within 30 Mpc.



Berezinsky, Gazizov, and Grigorieva, Phys. Rev. D**74**, 043005 (2006) (uses older HiRes spectrum)

Local Density of Sources

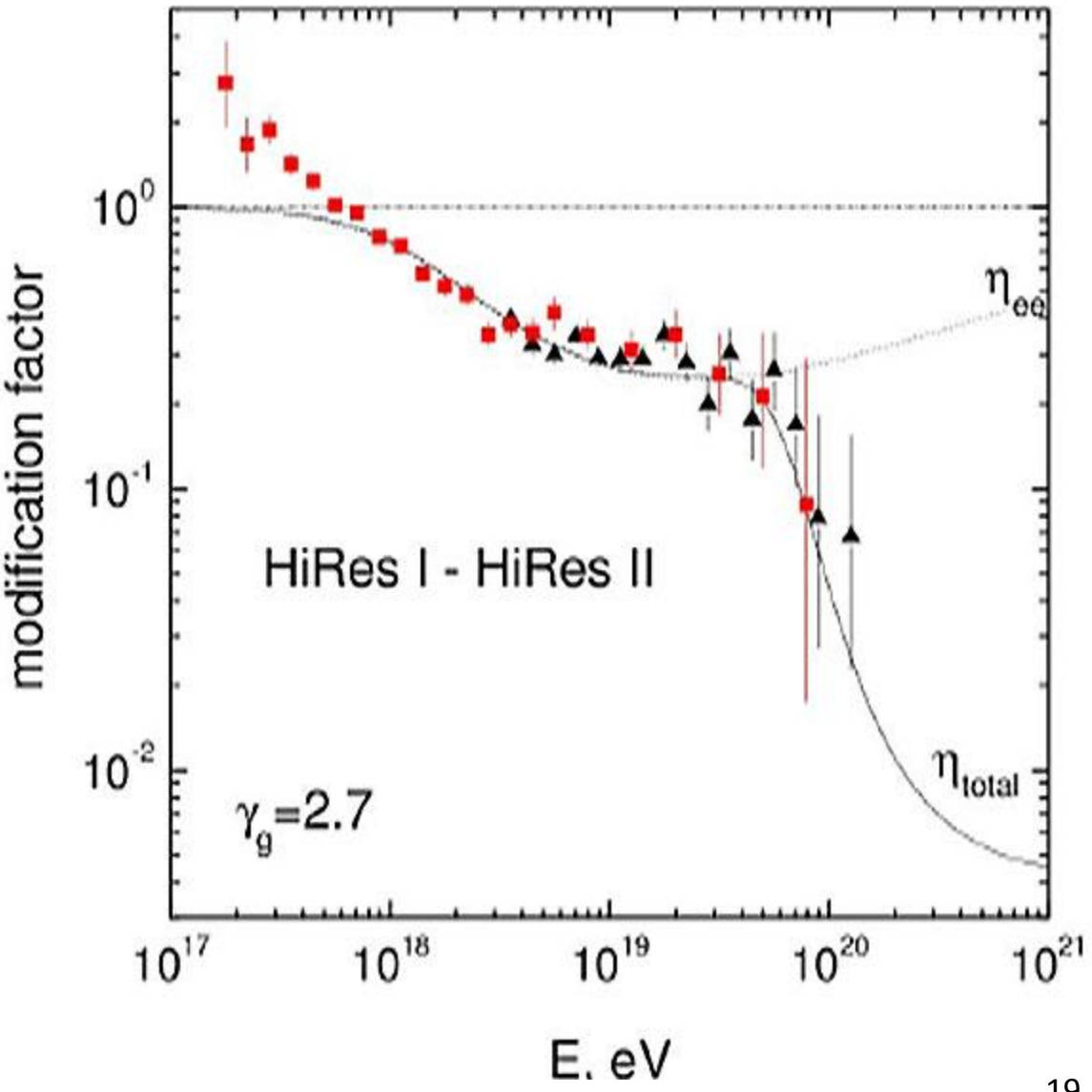
- Compare HiRes spectrum slope above the GZK energy to Berezinsky *et al*. predictions:
  - Line 1: constant density.
  - Line 5: no sources within 10 Mpc.
  - Line 2: double density within 30 Mpc.
  - Line 3: triple density within 30 Mpc.
  - HiRes: $E^{-5.1}$ fall-off.
- More work is needed to make a better comparison, but...
- **Constant density of sources is favored.**



Berezinsky, Gazizov, and Grigorieva, Phys. Rev. D**74**, 043005 (2006) (uses older HiRes spectrum)

Ankle Structure and Pair Production

- 2nd indication of CMBR interactions: Pair production by photons in the presence of high-energy nucleon
- Presence, shape essentially model-independent for proton primaries: Aloisio *et al.* **Astropart Phys. 27 (2007)**
- Consistent with ankle structure observed by HiRes (and others)



Summary of Spectrum Studies

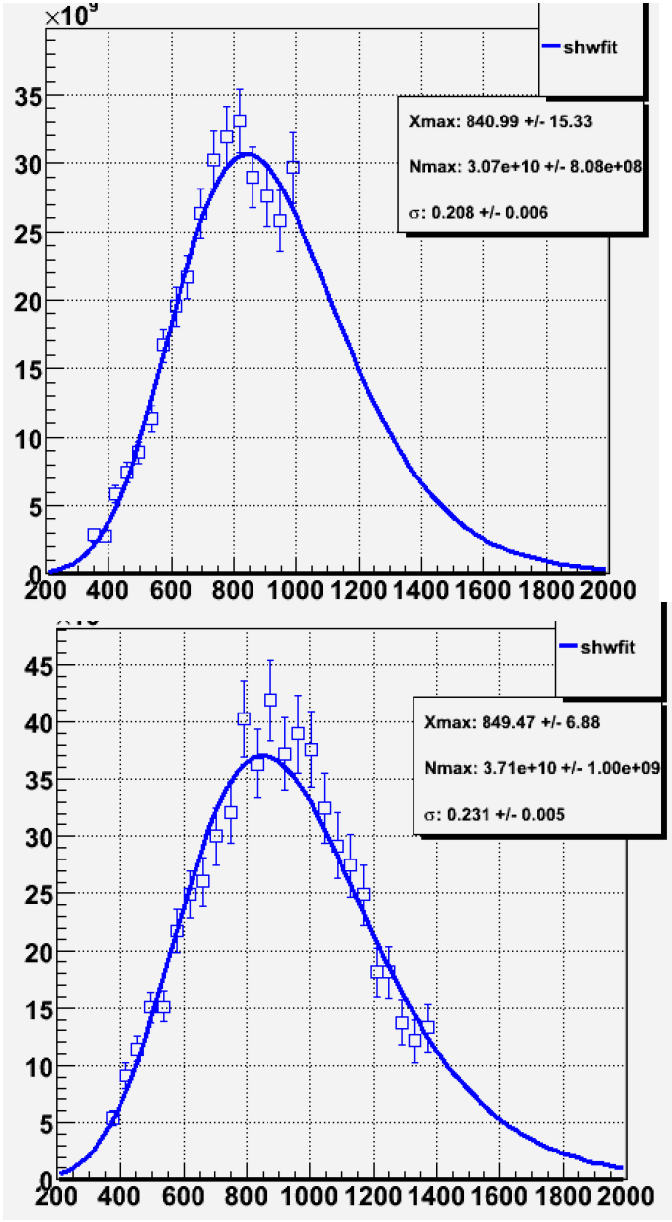
- **The GZK cutoff is present. The first observation was by the HiRes experiment.**
- **All details of the spectrum indicate the composition is protons.**
  - The energy of the GZK cutoff is as expected for **protons**.
  - Highest energy extragalactic cosmic rays travel > 50 Mpc.
  - The fall-off above the cutoff is evidence for a constant density of sources. CR's travel a long distance. Spallation breaks up all nuclei at high energies ➔ **proton** flux results**.**
  - The ankle has been observed by HiRes, at $10^{18.65}$ eV. The spectral index changes from -3.2 to -2.8
  - Shape and energy of the ankle are consistent with e^+e^- production in collisions between extragalactic **protons** and photons of the CMBR

Cosmic Ray Composition

- Fly's Eye had pioneered the Xmax method for composition.
- HiRes improved resolution: Fly's Eye Stereo ~ 60 gm/cm2
- HiRes-MIA prototype ~ 45 gm/cm2
- HiRes Xmax resolution ~ 25 gm/cm2
- HiRes had 10 x larger stereo aperture than Fly's Eye - extend measurement to near GZK energies.
  - Use Gaussian-in-age fits to find Xmax
  - Compare to QGSJET01, QGSJET02 and Sibyll
  - Quantify Xmax width distribution as function of energy

HiRes definition of Xmax

- Generate CORSIKA showers in atmosphere – QGSJET01,02, Corsika
  … etc.
- Define Xmax numerically or by fitting
  - "spline" numerical fit - previously uses
  - Gaisser-Hillas functional form - fit to simulation and data
  - Gaussian-in-age functional form
- **We now use Gaussian-in-age(GIA) for both data and simulated showers**



Gauss-in-age fit to two Highest energy events

Data MC comparisons: zenith angle

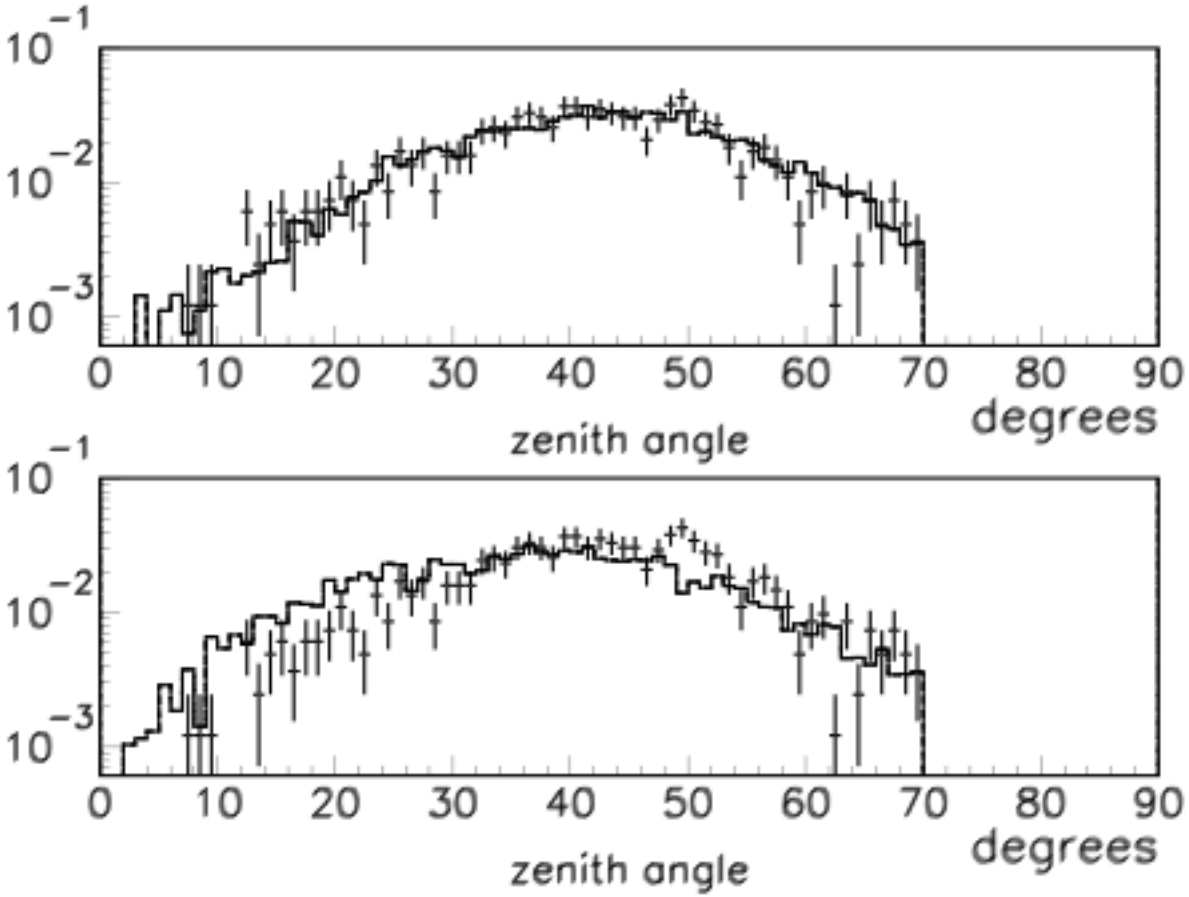


Figure 7: Data (points) Monte Carlo (histogram) comparison, distribution in zenith angle. *Top:* Comparison with QGSJET-II proton Monte Carlo. *Bottom:* Comparison with QGSJET-II iron Monte Carlo.

Data MC comparisons: Height of Xmax

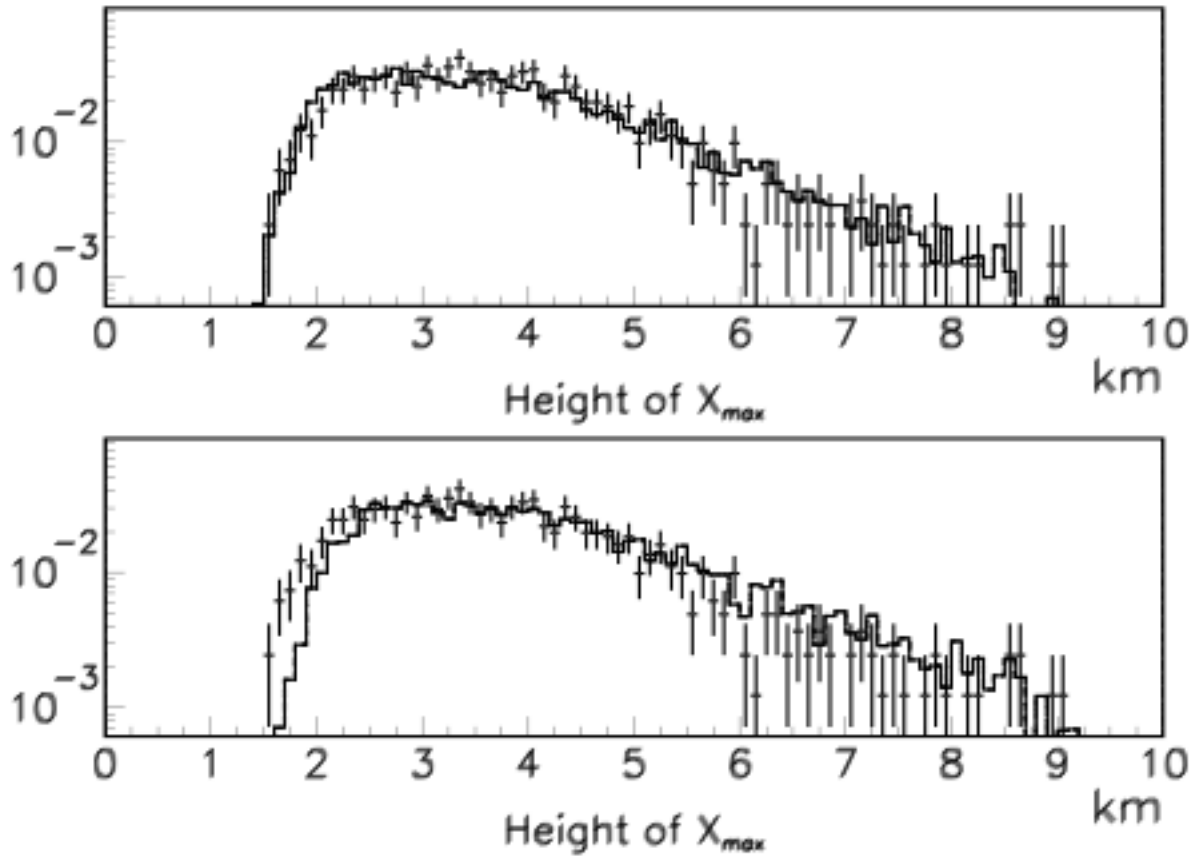
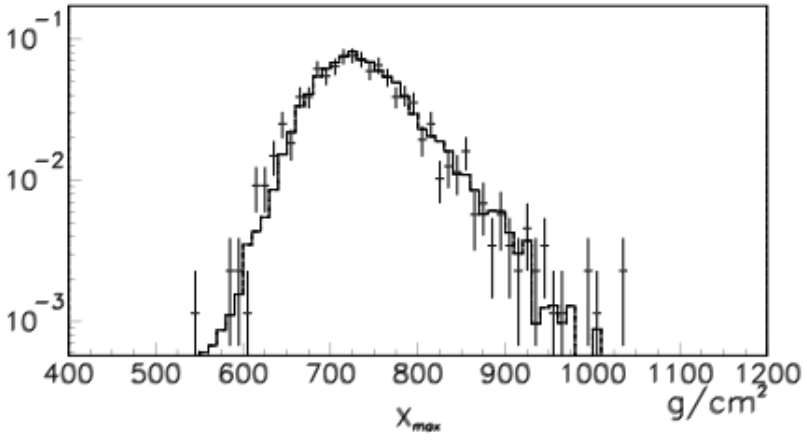


Figure 10: Data (points) Monte Carlo (histogram) comparison, distribution in height (km) of X_{max} above HiRes "ground". *Top:* Comparison with QGSJET-II proton Monte Carlo. *Bottom:* Comparison with QGSJET-II iron Monte Carlo.

Data MC comparisons: X_{max} and σ_{age}



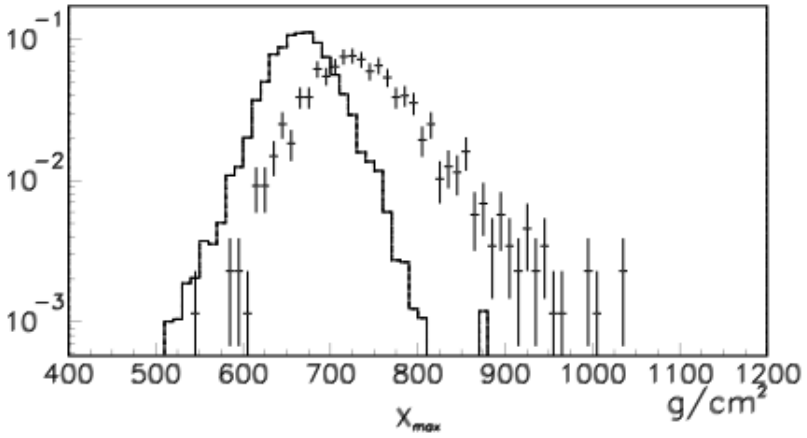
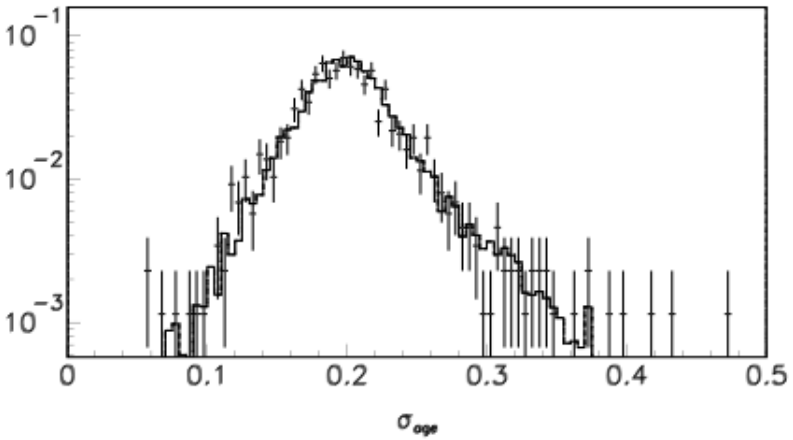


Fig. 11.— *Top:* X_{max} overlay of HiRes data (points) with QGSJET02 proton Monte Carlo airshowers after full detector simulation. *Bottom:* X_{max} overlay of HiRes data (points) with QGSJET02 iron Monte Carlo airshowers after full detector simulation.



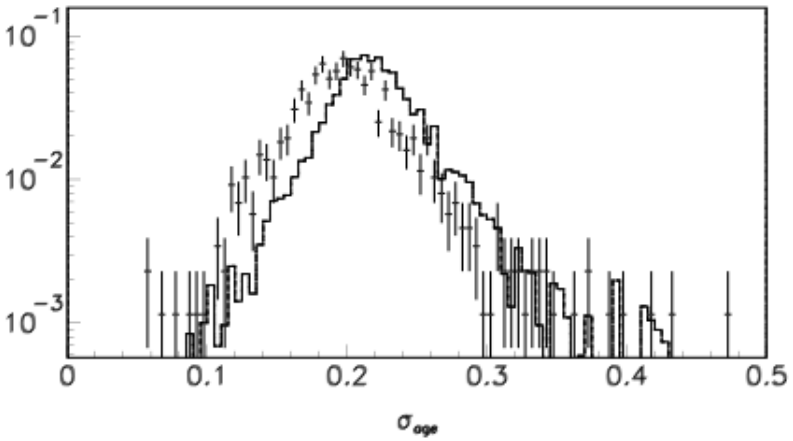


Fig. 12.— *Top:* σ_{age} overlay of HiRes data (points) with QGSJET02 proton Monte Carlo airshowers after full detector simulation. *Bottom:* σ_{age} overlay of HiRes data (points) with QGSJET02 iron Monte Carlo airshowers after full detector simulation.

Detector Simulation: Xmax vs. logE

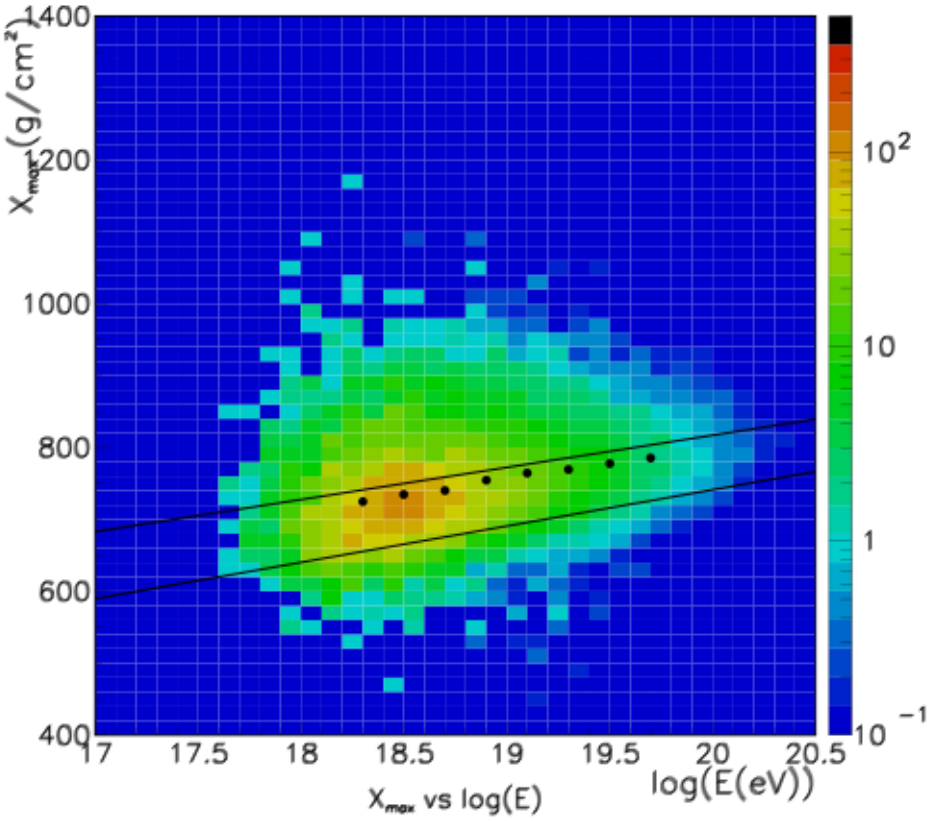


Fig. 15.— Scatter plot of X_{max} versus log E for QGSET02 proton Monte Carlo, after full detector simulation. Points represent the average X_{max} in each energy bin. Also superimposed are QGSJET02 proton (top) and iron (bottom) "rails" taken from simulated airshower events prior to detector effects. See also Figure 1. Final energy cuts have not yet been applied.

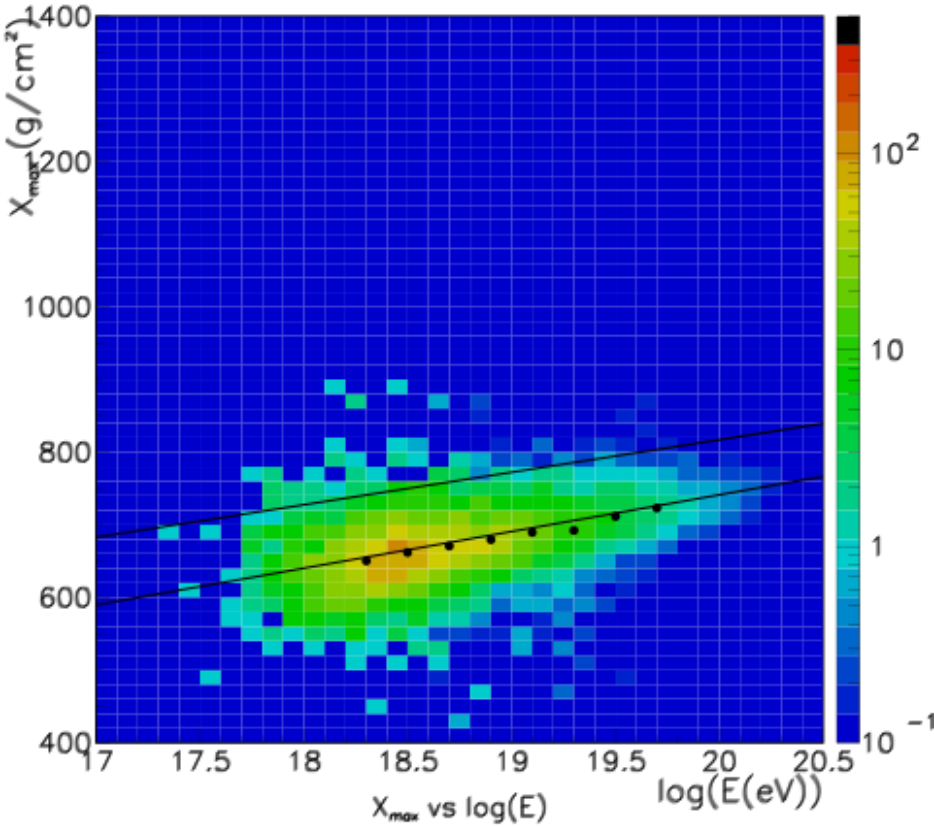
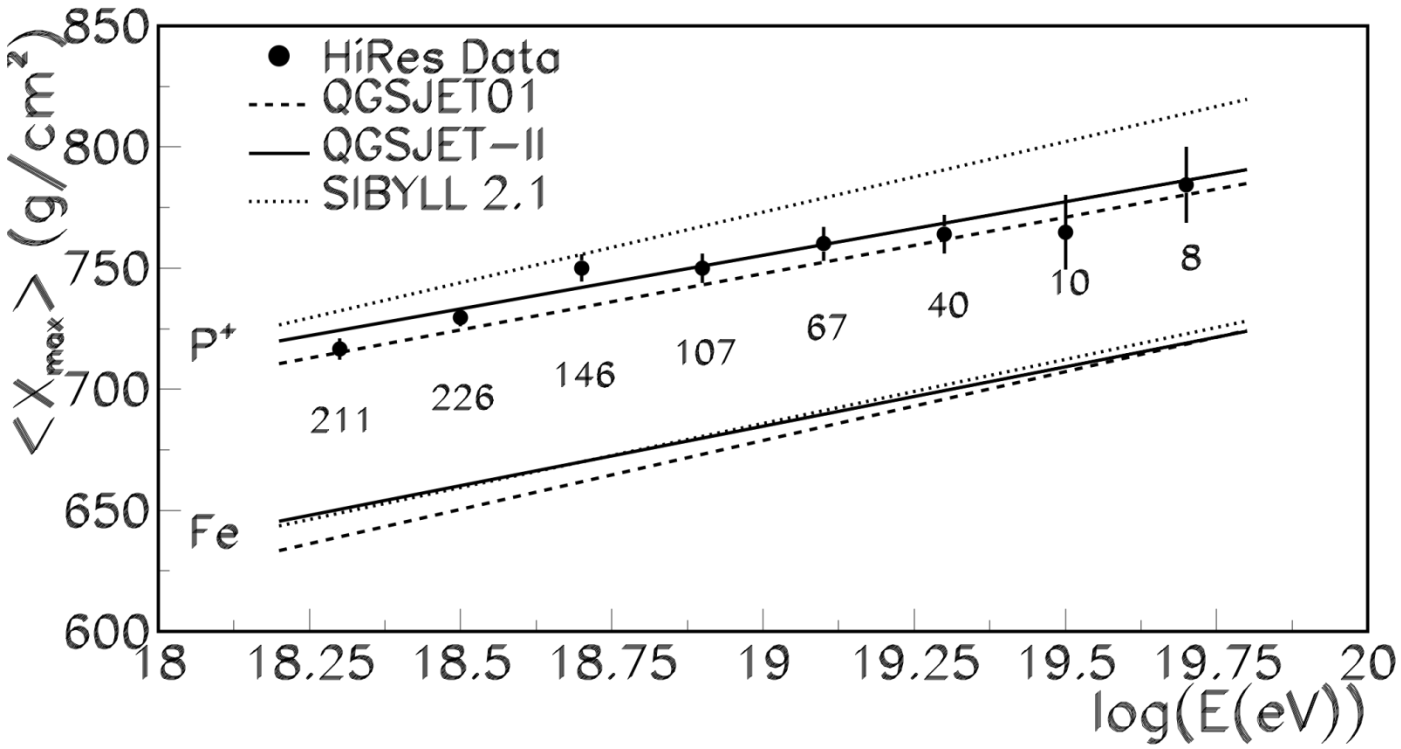


Fig. 16.— Scatter plot of X_{max} versus log E for QGSET02 iron Monte Carlo, after full detector simulation. Points represent the average X_{max} in each energy bin. Also superimposed are QGSJET02 proton (top) and iron (bottom) "rails" taken from simulated airshower events prior to detector effects. See also Figure 1. Final energy cuts have not yet been applied.

QGSJET02 p and Fe Xmax plots, full detector simulation

HiRes Elongation Rate – Simulated data includes all Detector resolution and bias effects.



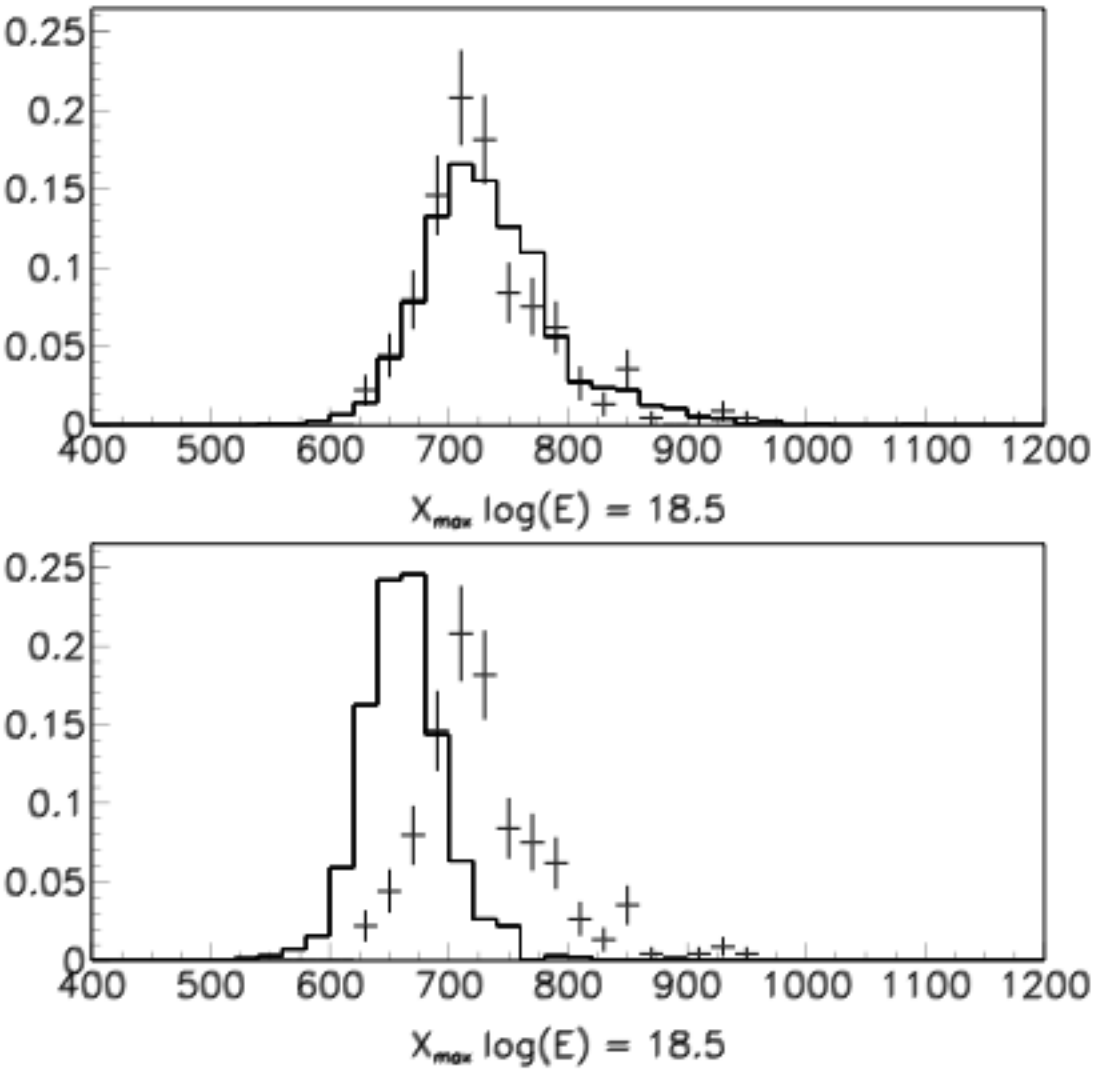


Figure 13: Data (points) compared to QGSJET-II Monte Carlo (histograms) X_{max} distributions, in bin centered at $\log E = 18.5$. Top plot is comparison with pure proton MC, bottom with pure iron MC.

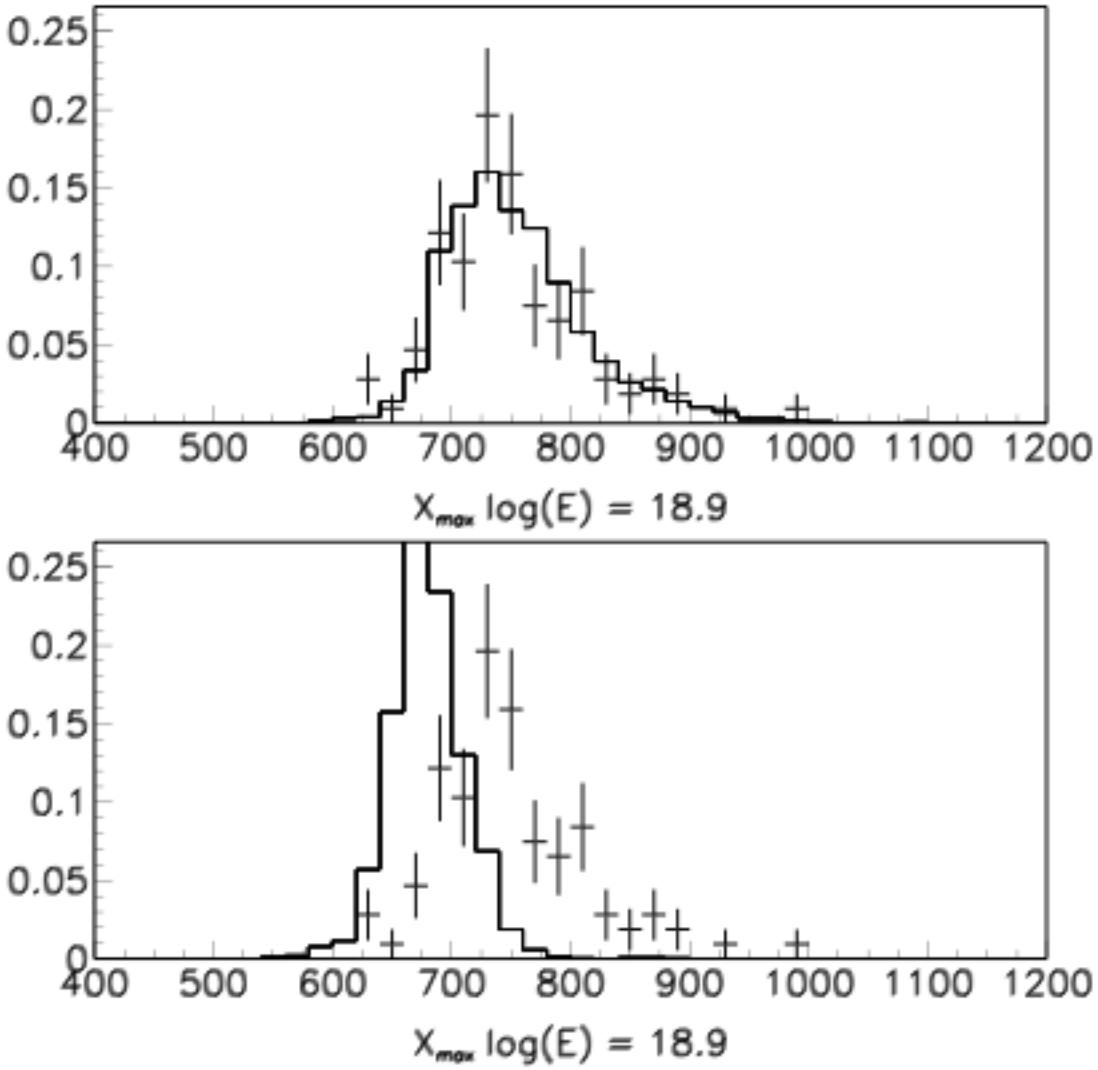


Figure 15: Data (points) compared to QGSJET-II Monte Carlo (histograms) X_{max} distributions, in bin centered at $\log E = 18.9$. Top plot is comparison with pure proton MC, bottom with pure iron MC.

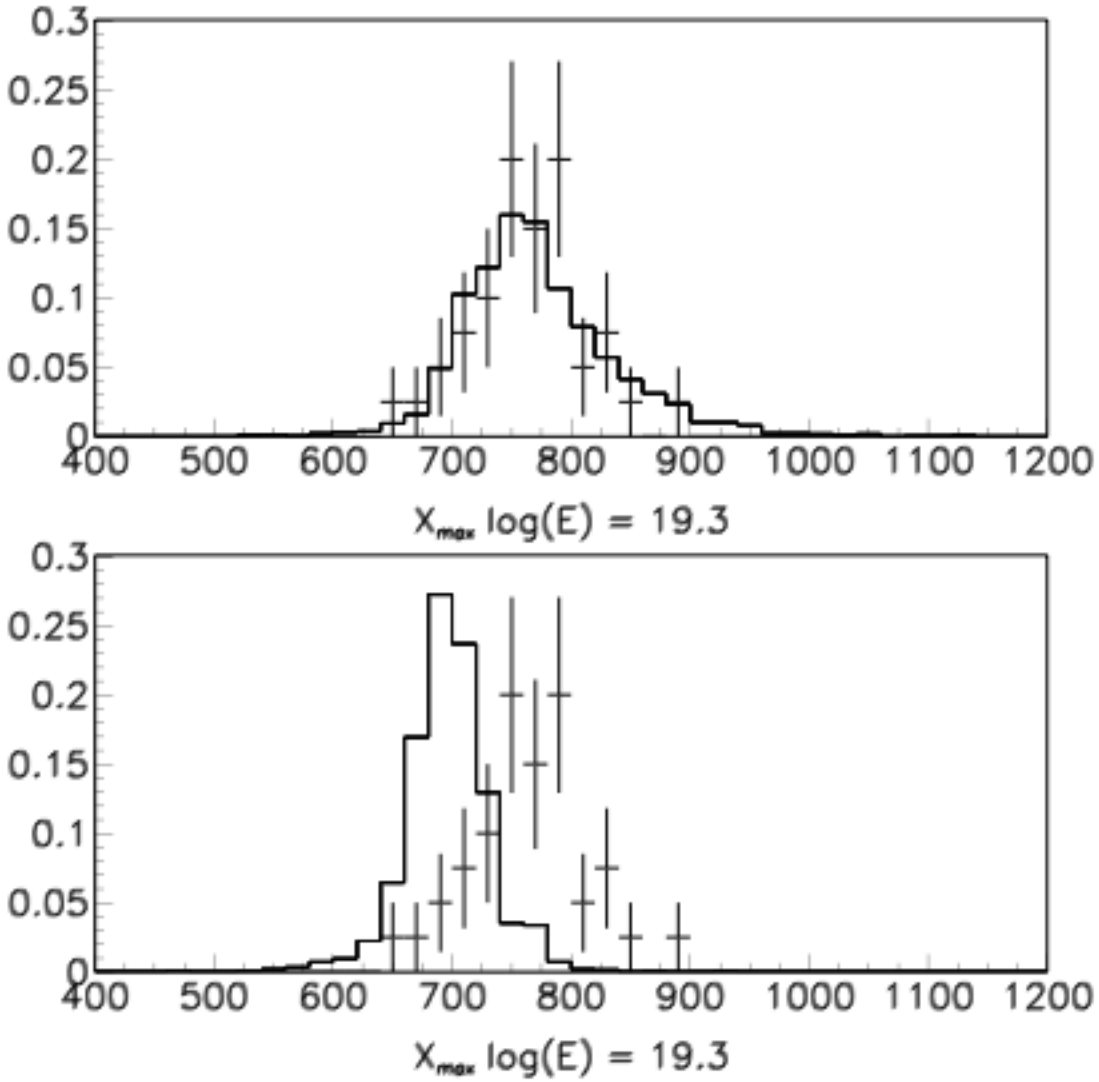


Figure 17: Data (points) compared to QGSJET-II Monte Carlo (histograms) X_{max} distributions, in bin centered at $\log E = 19.3$. Top plot is comparison with pure proton MC, bottom with pure iron MC.

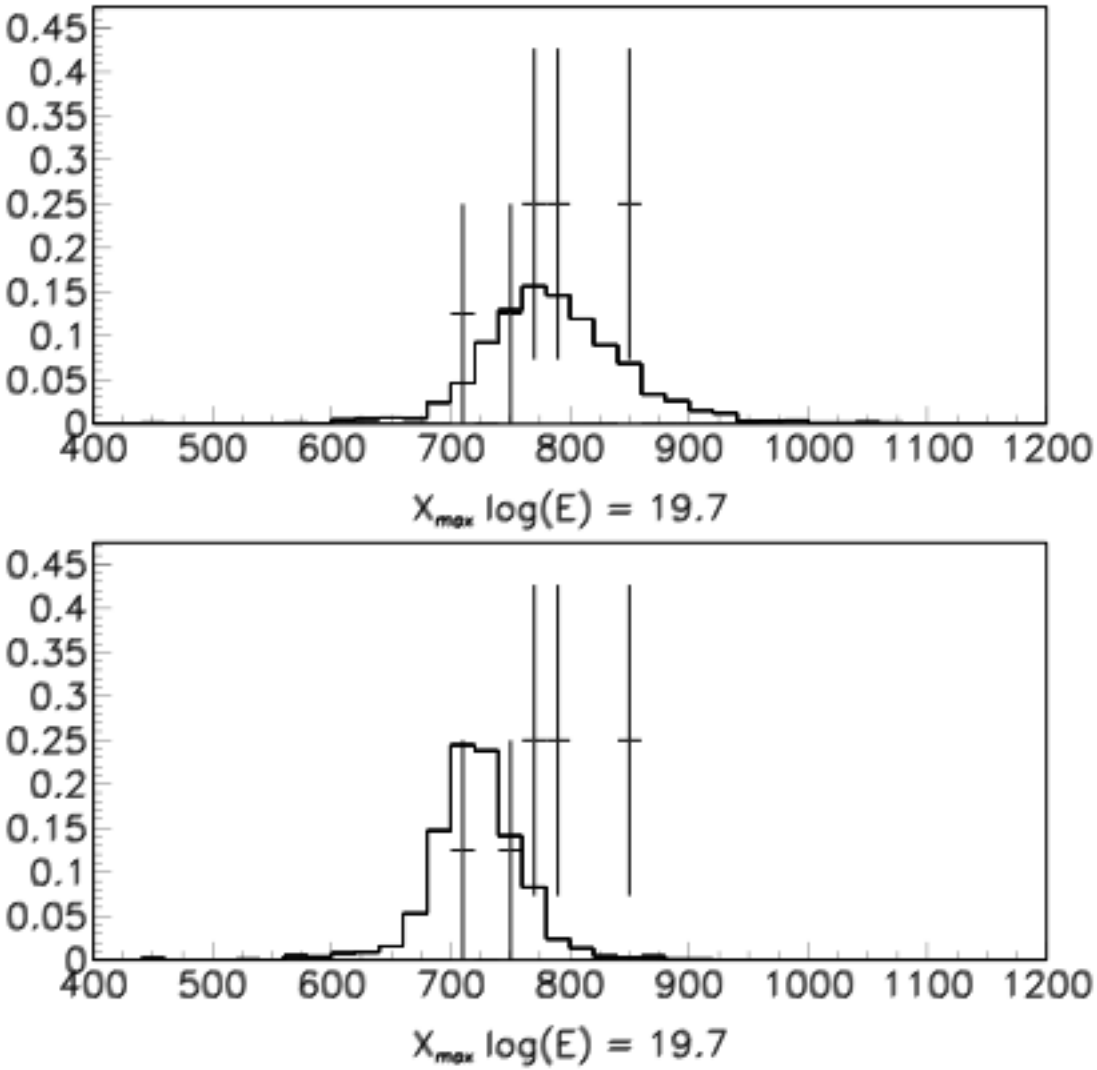
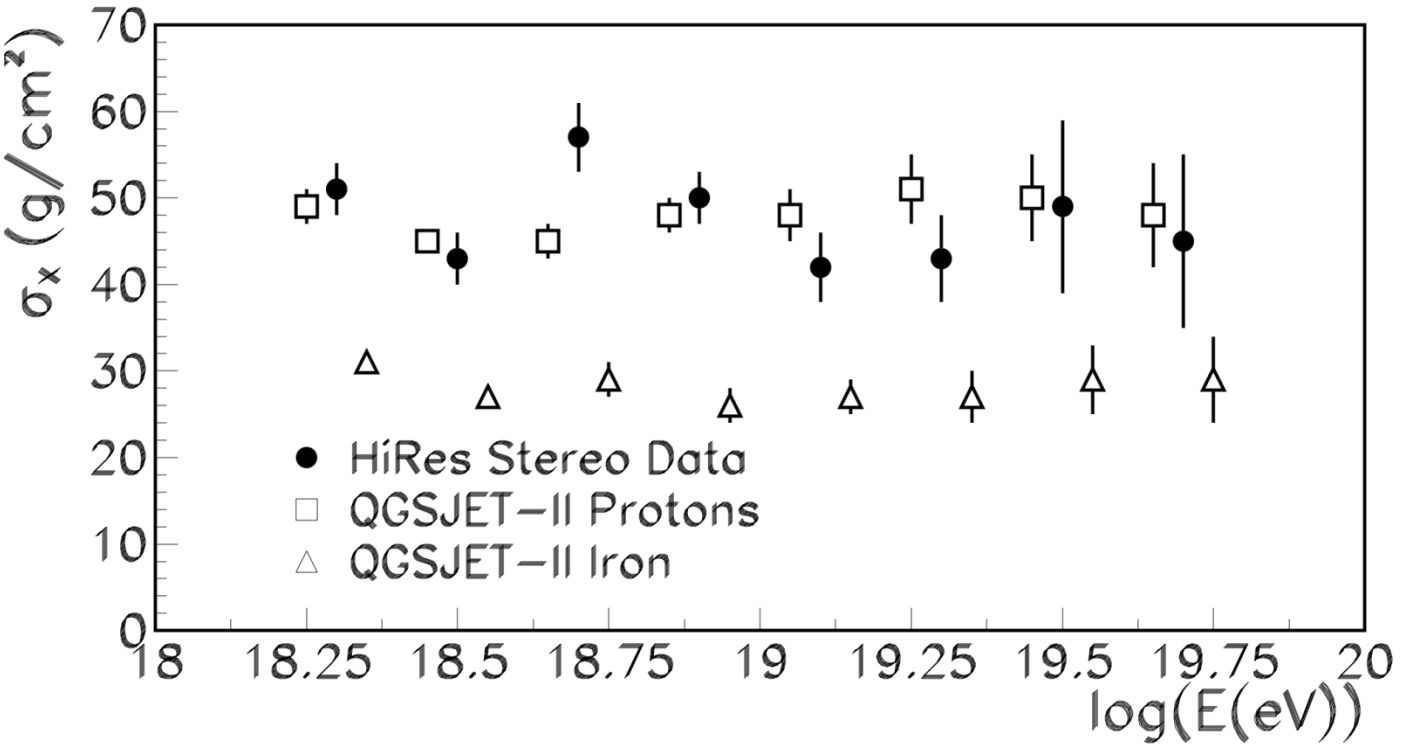


Figure 19: Data (points) compared to QGSJET-II Monte Carlo (histograms) X_{max} distributions, in bin centered at $\log E = 19.7$. Top plot is comparison with pure proton MC, bottom with pure iron MC.



Comparison of Xmax fluctuations with predictions for Proton and Iron using QGSJET-II. Truncated Gaussian fit.

Composition Summary

- The most direct indicator of composition is <Xmax>.
- **HiRes Xmax average and fluctuations measurements indicate a light composition**
- Consistent with our spectrum information.
- Data MC comparisons favors proton over iron

HiRes composition data available at:

http://www.cosmic-ray.org/journals/prl.html

Search for Anisotropy

- Goal is to identify UHECR sources.
- Two methods:
  - Make a sky plot and look for concentration of events
  - Look for correlations with known astronomical object types.
- All cosmic ray results thus far are of marginal significance:
  - Sky plots: AGASA doublets/triplet at 40 EeV
  - Correlations: BL Lac's at 10 EeV
  - Correlations: AGN's at 57 EeV

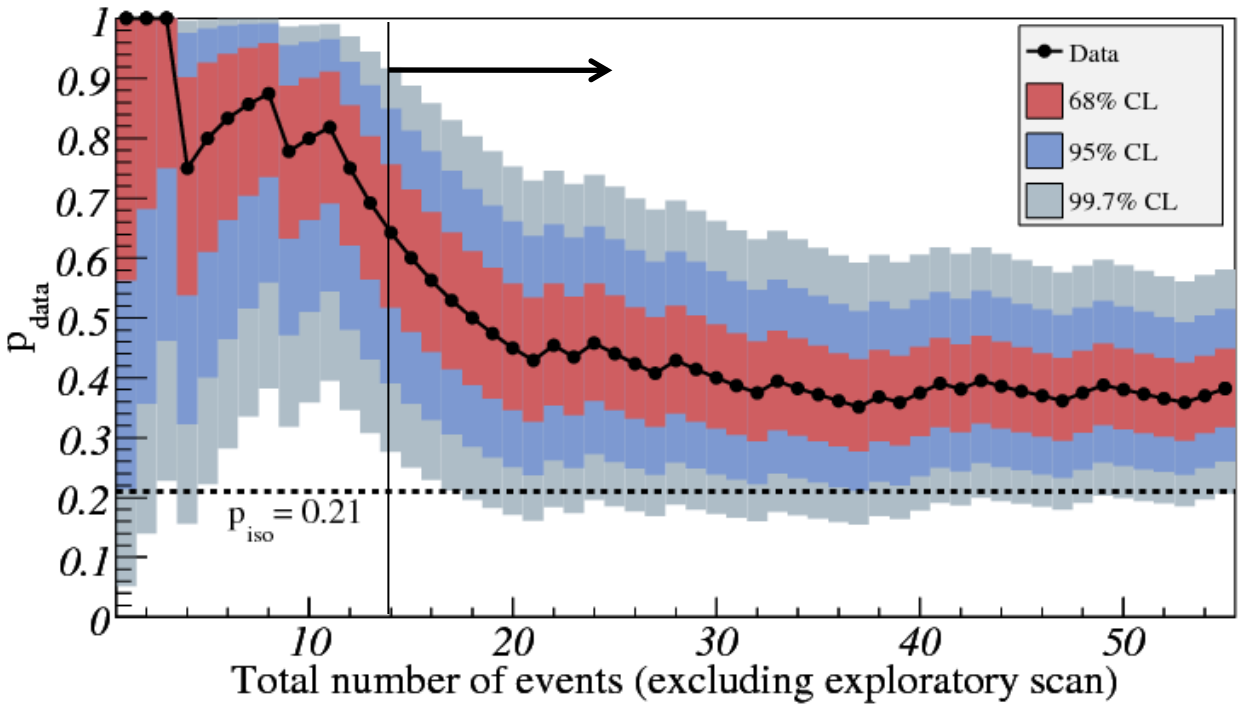
AGN Correlations

- PAO correlations with AGN's (south)
  - Early data set: scanned in (E_{min}, θ, z_{max}) using Veron-Cetty + Veron catalog, found best correlations at (57 EeV, 3.1 , .018).
  - Tested correlation with later data set, found 8/13 events correlated, chance probability of 0.002 (2.9σ).

- Auger test using later data:

  42 events, 12 correlated,

  expect 8.8 random, 1σ.

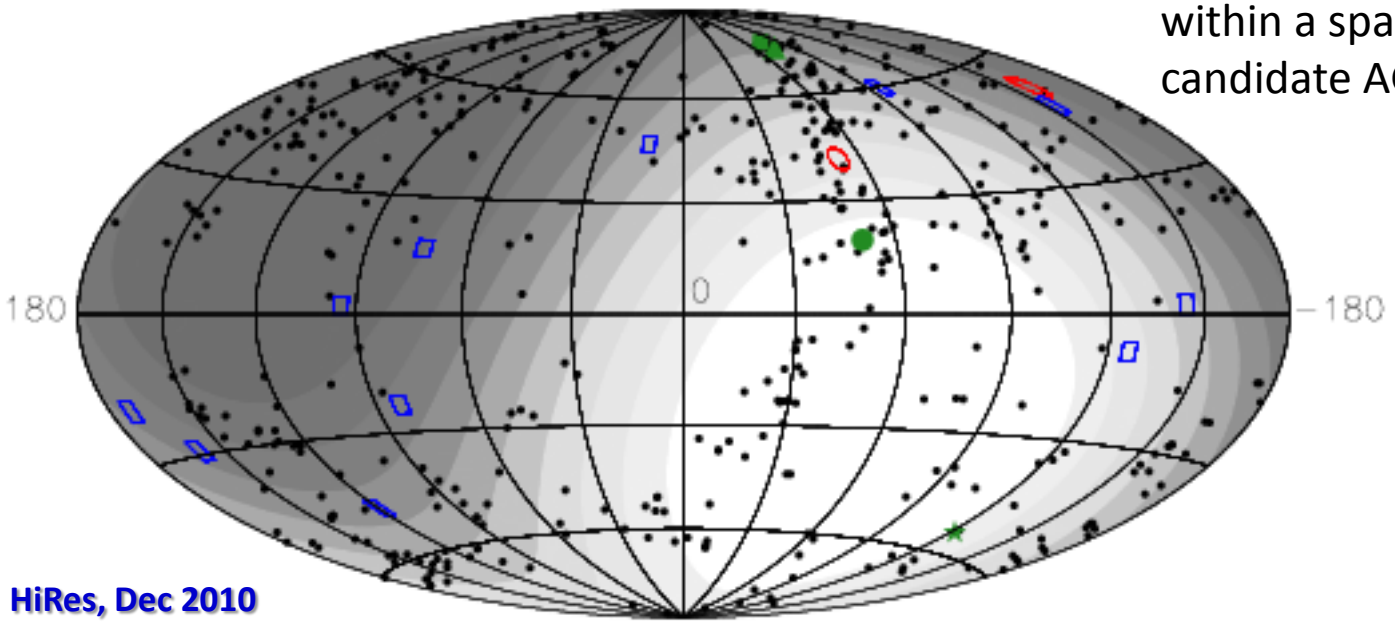


HiRes, Dec 2010

HiRes Stereo Data

- HiRes complete stereo data set, angular resolution ~0.8
- Events not within 10 of galactic plane:
  - 10 above 57 EeV
  - 27 above 40 EeV
  - 310 above 10 EeV
- 6636 events in all

Sky map in galactic coordinates.
Black circles: AGN with *z < 0.018.*
Blue squares*: uncorrelated* HiRes stereo events above 57 EeV.
Red circles: HiRes stereo events within a space angle θ < *3.1*◦ of a candidate AGN.



HiRes, Dec 2010

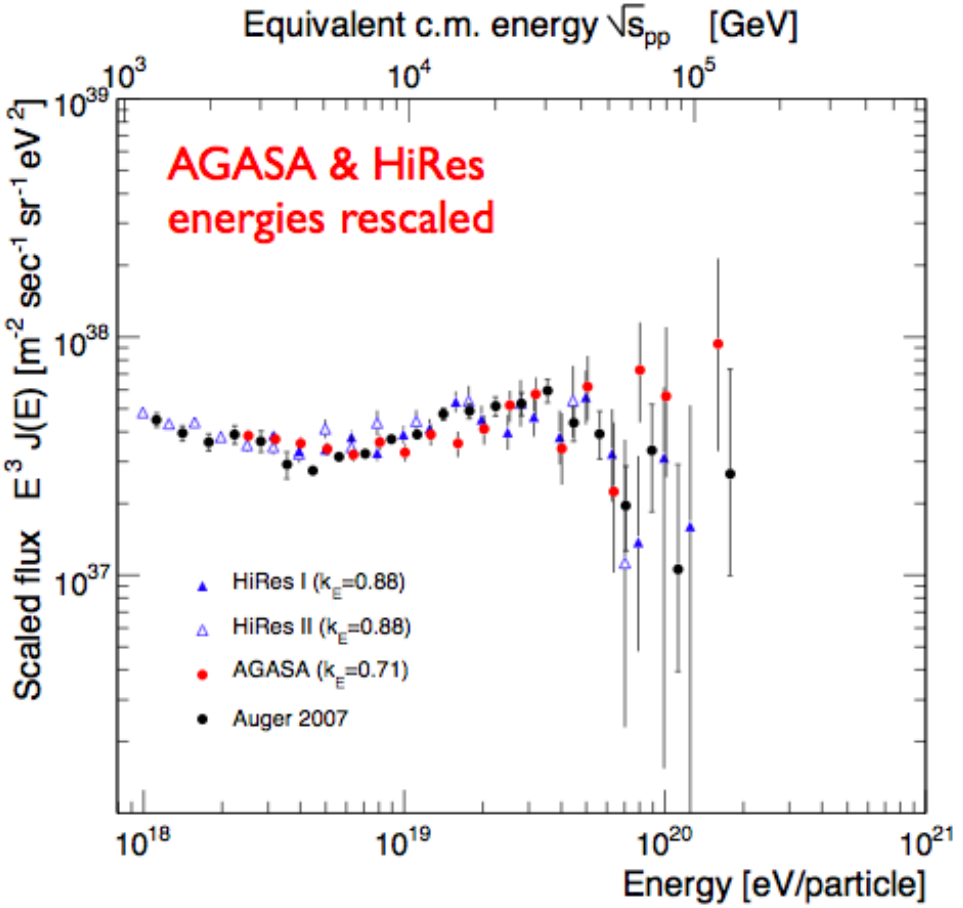
HiRes with PAO cuts

- Using earlier PAO has maximum significance (E_{min}, θ, z_{max}) = (57 EeV, 3.1 , .018)

HiRes with PAO cuts **(10% energy scale shift)**

- 2 pairings from 13 events
- Expect 3.2 chance pairings
- **HiRes chance prob. = 0.82**

➔ **HiRes does not confirm earlier PAO claim**



PAO spectrum, 10% energy shift, overlaid with HiRes Spectrum

Independent HiRes search

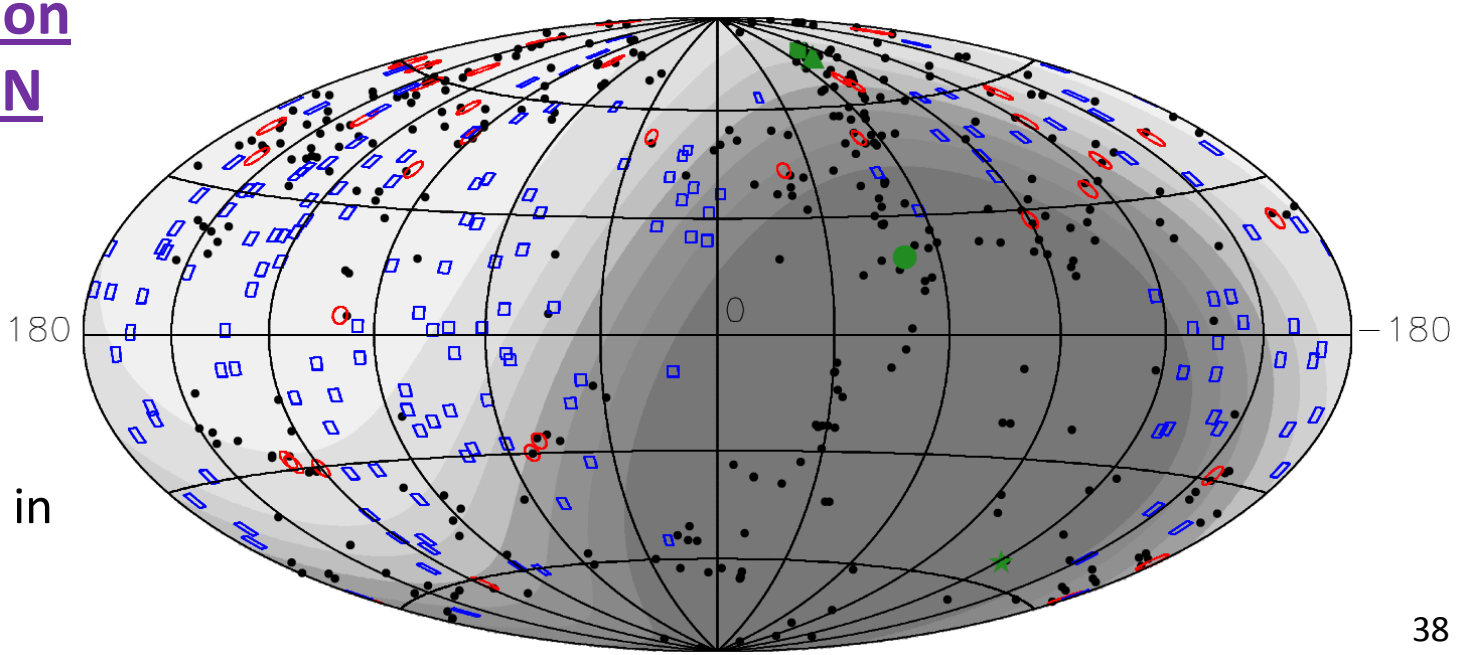
- Split HiRes stereo data into 2 equal parts
- First data set scan
  - Strongest correlation 1.7 deg., 15.8 EeV, zmax =0.02. (chance prob = 0.005)
- Apply to second data set
  - 14 pairings out of 101 events
- **Chance probability = 0.15 → no excess**

HiRes correlation with Veron AGN catalogue in North

Black - AGN's

Blue - HiRes data

Red - correlated events (from scan in z, θ and Emin)



HiRes, Dec 2010

Test of Correlations with Local Large Scale Structure

Hypothesis

- UHECR source distribution follows density distribution of matter (LSS)
- Magnetic effects can be described by a Gaussian smearing angle

Test

- Look for significance of correlation as a function of smearing angle and energy.

➔ Search for correlations with local large scale structure for high energy events with relatively close horizons.

A priori Lower limit energies of 10 (BL Lac), 40 (clusters), 57 EeV (AGN).

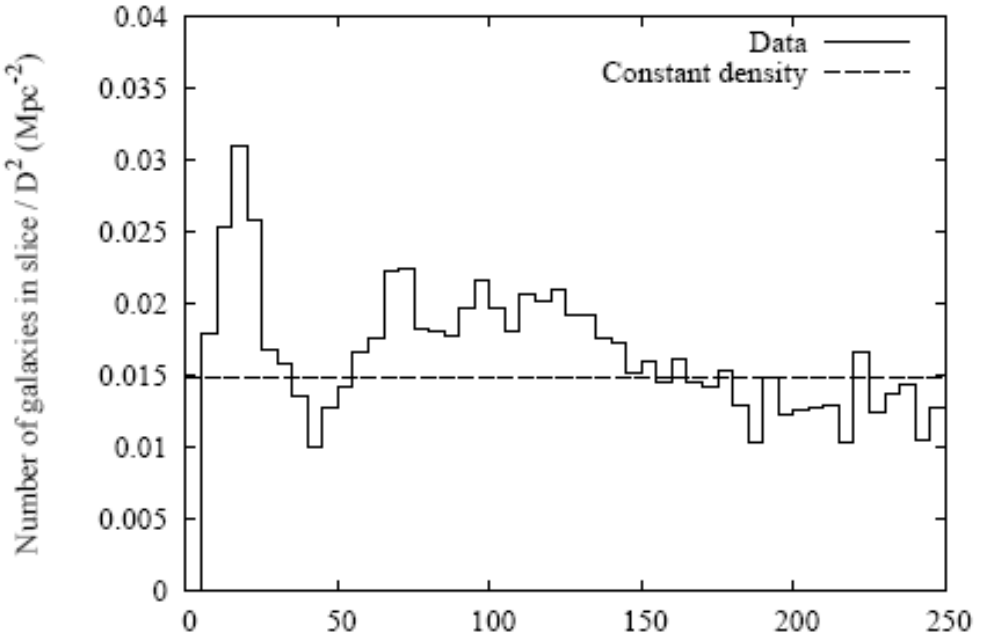
Also choose, *a priori*, to quote 95% CL.

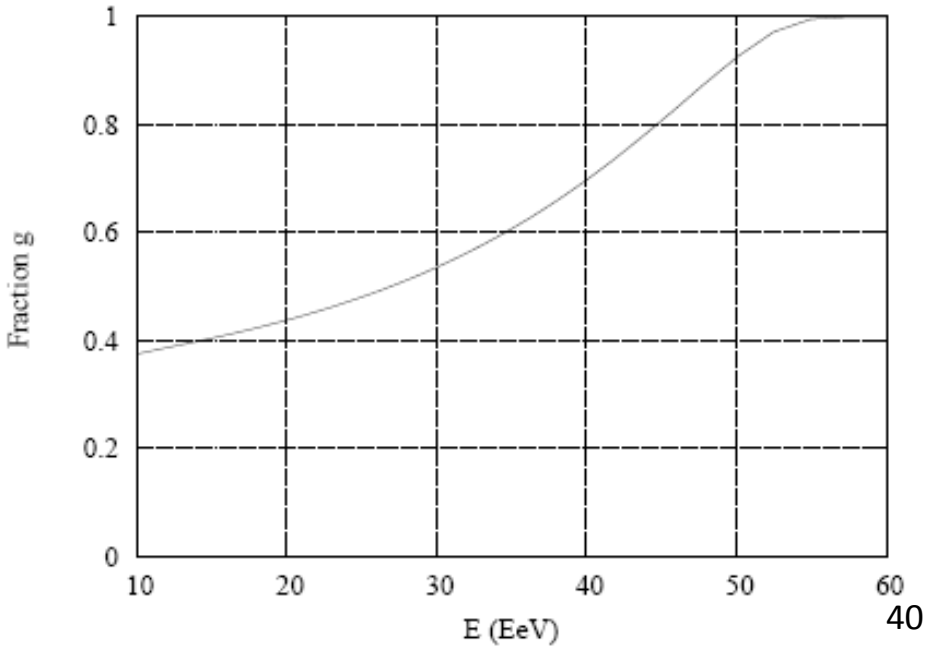
Note

- Matter is not distributed uniformly within the horizon of 57 EeV protons

Local LSS Model

- Based on 2 Micron All-Sky Redshift Survey (2MRS)[1], a flux-limited sample of galaxies with m ≤ 11.25
  - Remove galactic plane (|b| < 10) and objects within 5 Mpc.
  - Result is 15,508 galaxies between 5 and 250 Mpc treated individually assuming equal intrinsic source luminosity
  - Assume distribution is isotropic beyond 250 Mpc.

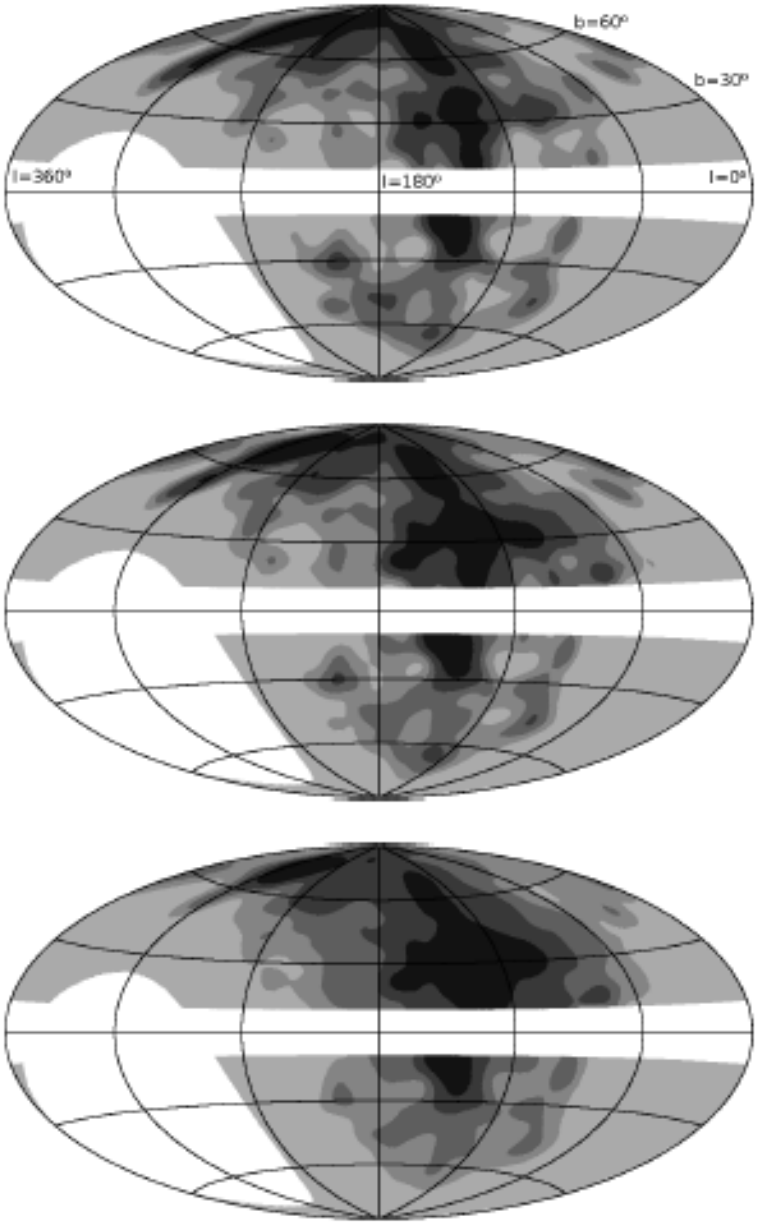




1. J. Huchra, L. Macri, T. Jarrett, et al., in preparation.

Procedure: set of MC events coming from LSS

- Start with local LSS model HiRes aperture.
- Simulate the data set; find average predicted event density.
- Two parameters:
  - Minimum energy
  - Angular smearing to simulate magnetic fields
    - Expect ~1 , extragalactic fields, for E≥40 EeV[1]
    - Expect 2 -4 , galactic fields.
- Perform K-S test between data and expectation from LSS.
- Repeat starting with an isotropic distribution.

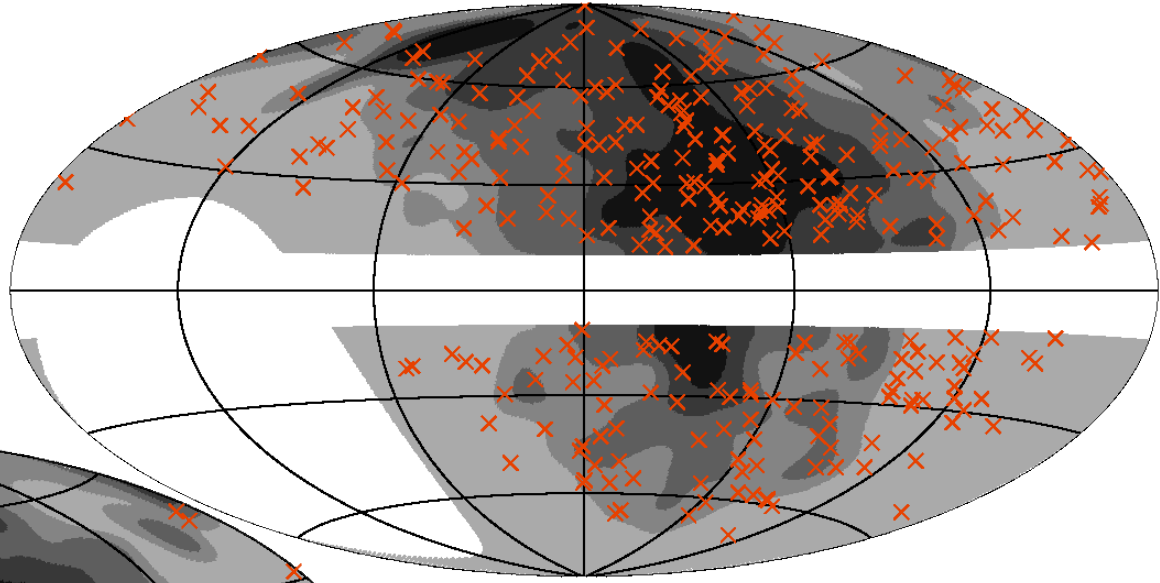


Smearing angle of 6

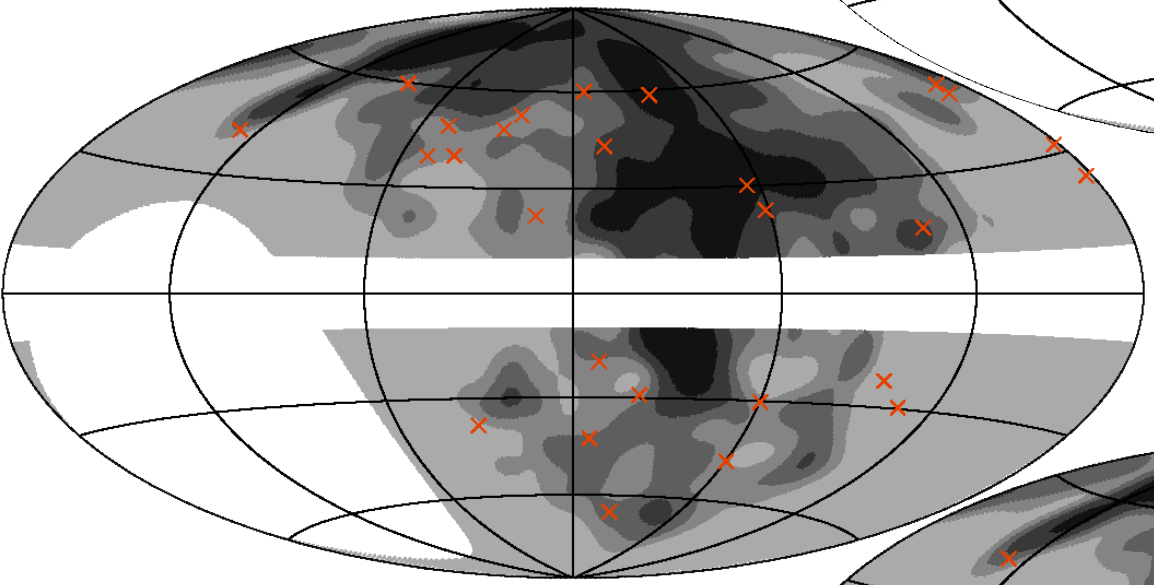
1. T. Kashti and E. Waxman, JCAP 0805, 006 (2008).

Sky Plots

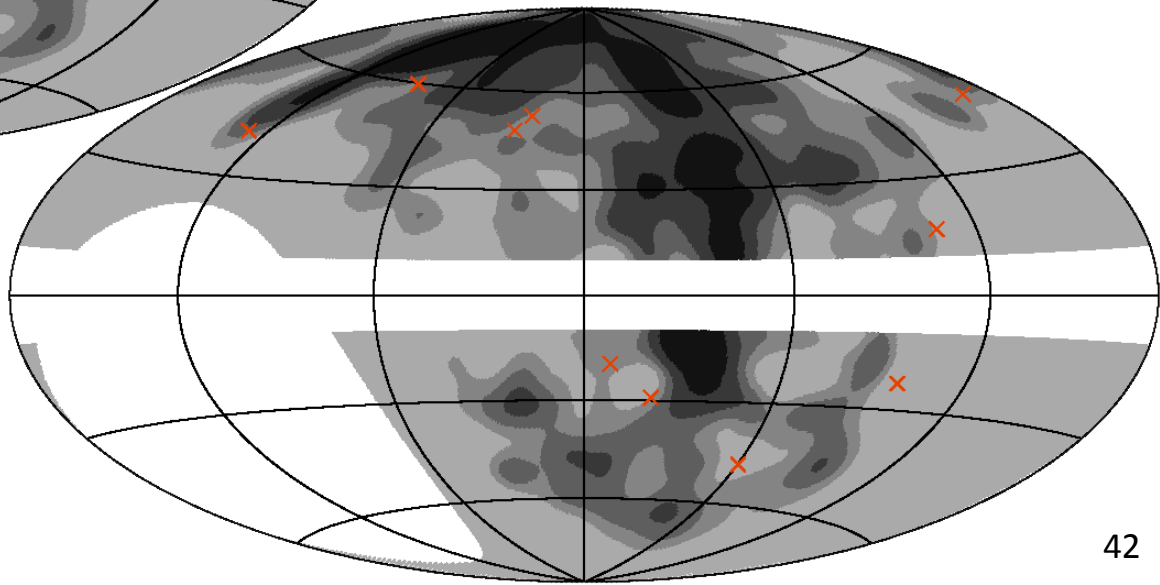
≥ 10 EeV



≥ 40 EeV



≥ 57 EeV

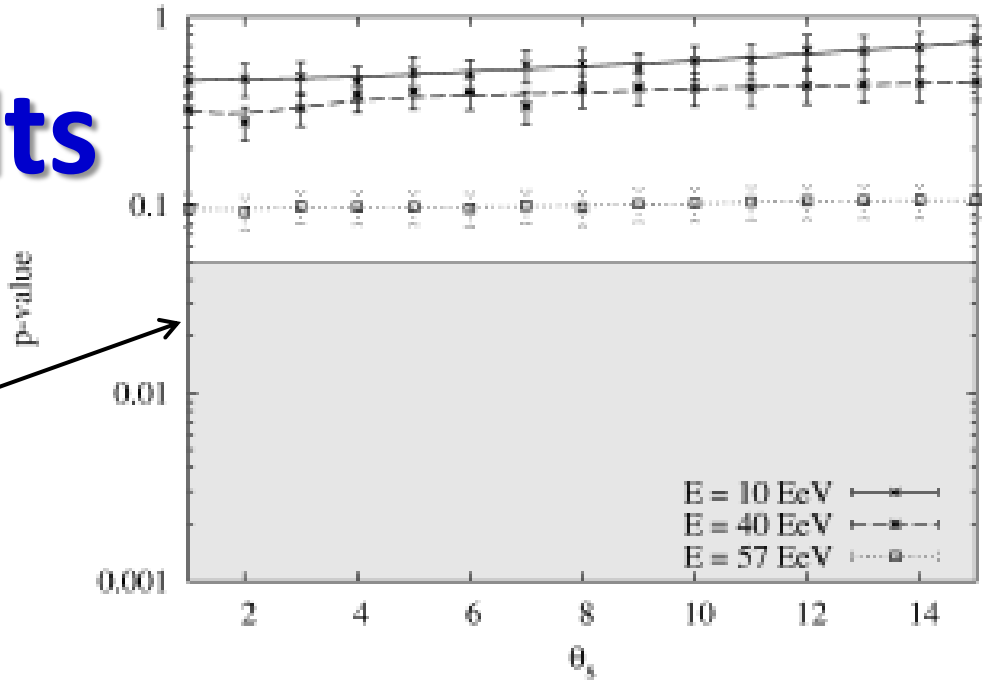


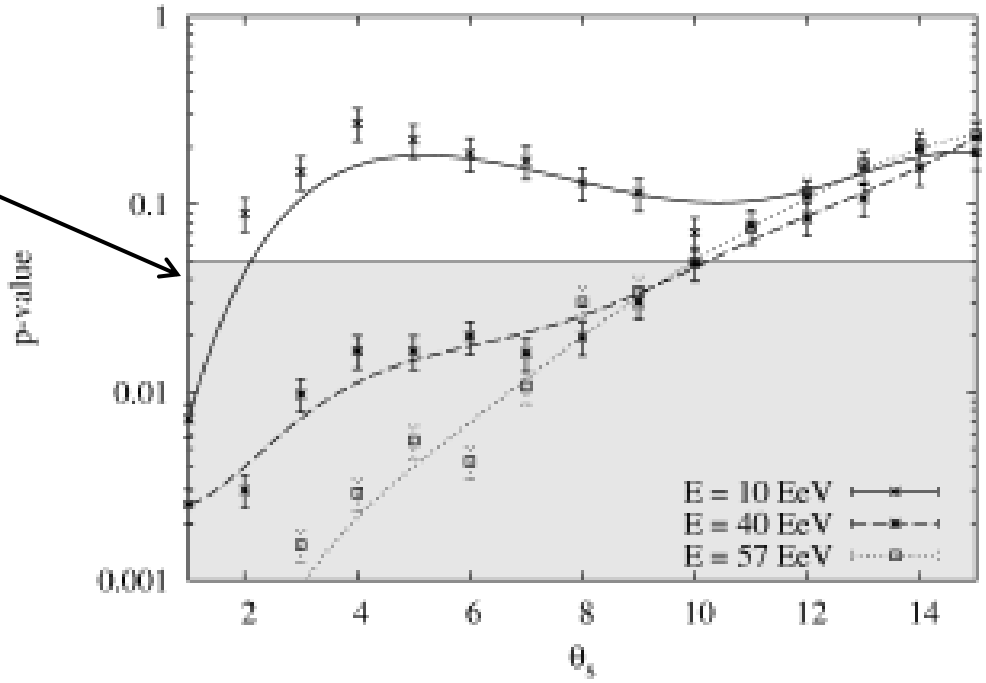
HiRes, Dec 2010

Local LSS Results

(Choose 95% c.l. exclusion to quote, *a priori*.)

- **Good Agreement with isotropic model**
- **Poor agreement local LSS model get poor agreement.**
- Exclude correlation at 95% c.l. for $\theta_s < 10$, E ≥ 40 EeV





HiRes, Dec 2010

Summary of HiRes Anisotropy Search

- HiRes: No significant large scale anisotropies at any energy.
- AGASA claim of clustering is not supported by HiRes data
- AGASA triplet + HiRes event →quartet (chance prob > 0.5%)
- Search for correlations with BL-Lacs – low statistical significance effect published by HiRes – not seen by PAO
- No evidence for correlations with AGN's applying PAO cuts.
- **No evidence for correlations with LSS**
  - **This is very surprising.**
  - **One expects to see correlations:** magnetic field smearing at the 4 -5 level.
  - With limited statistics we are able to place very significant limits.
  - Are the sources not in galaxies? Are magnetic field estimates wrong?
  - This study should be expanded by a new experiment in the north.

HiRes anisotropy data available at:

http://www.cosmic-ray.org/supplements.html

Summary

- HiRes was the first to observe the GZK cut-off
- Energy spectrum is consistent with light composition

  HiRes composition data available at:

  http://www.cosmic-ray.org/journals/prl.html
- Xmax measurements (mean and fluctuations) are consistent with light composition
- HiRes does not see any significant anisotropy
  - Does not reproduce PAO 2007 result of AGN correlation
  - Surprisingly, no correlation with local LSS

  HiRes anisotropy data available at:

  http://www.cosmic-ray.org/supplements.html

The End

Please attend also:

Friday 16:40 - 18:00 (90min)

16:40 G. Thomson: Energy measurement and spectrum by HiRes (20)

Saturday 16:30 - 18:00 (90min)

16:30 J.W.Belz: Measurement of UHECR composition by HiRes (20)

Saturday 16:30 - 18:00 (90min)

16:00 P. Tinyakov: Measurement of anisotropy by TA (30)

HiRes composition data available at:

http://www.cosmic-ray.org/journals/prl.html

HiRes anisotropy data available at:

http://www.cosmic-ray.org/supplements.html