HiRes Spectrum and Energy Scale

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Outline

- Introduction: the HiRes experiment
- Spectrum calculation and methods
- Results and Summary

High Resolution Fly's Eye (HiRes) Collaboration

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Mirrors and Phototubes

- 3.8 m^2 spherical mirror
- 16 x 16 array of phototubes, .96 degree pixels.

The Two HiRes Detectors

- HiRes1: atop Five Mile Hill
- 21 mirrors, 1 ring (3<altitude<17 degrees).
- Sample-and-hold electronics (pulse height and trigger time).

- HiRes2: Atop Camel's Back Ridge
- 12.6 km SW of HiRes1.
- 42 mirrors, 2 rings (3<altitude<31 degrees).
- FADC electronics (100 ns period).

Two Calibrations

Photon scale

- Absolute calibration by Xenon flasher
- Referenced to NIST- traceable photodiodes
- Checked by HPD, laser shots.
- **Achieve 10% absolute calibration.**

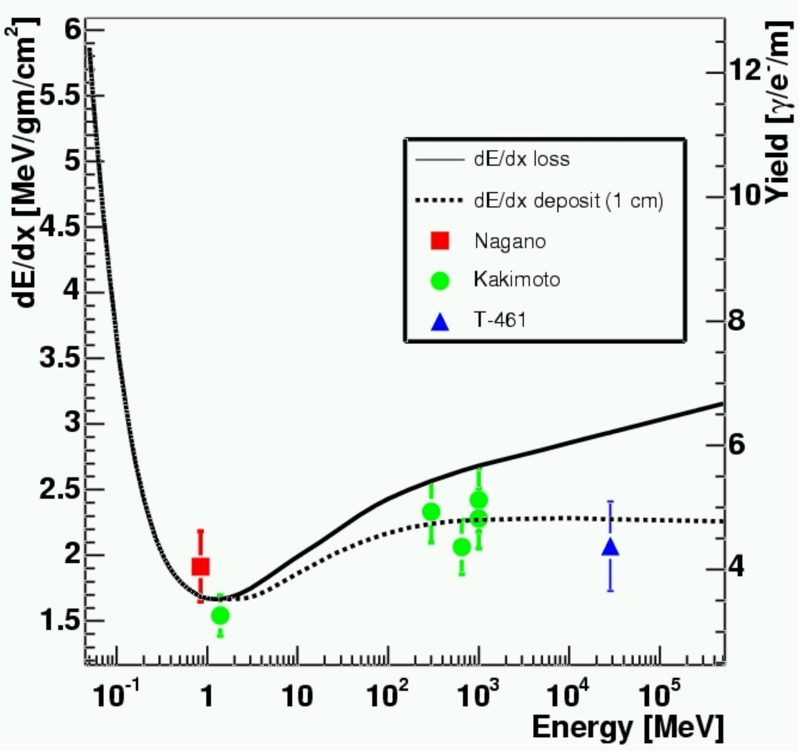
Atmospherics

- Molecular: density checked by radiosonde balloons from nearby airports.
- Aerosols: measured *in situ* by laser systems.
- Very clear, stable skies.
- <VAOD> = 0.04
  - 1/10 of molecular optical depth
  - Correction is 15% at 25 km.
- Aerosols vary slowly: typically constant over a night or two.
- **HiRes has an excellent site.**

Measurement of Fluorescence Yield

- Three published results: Kakimoto *et al.*, Nagano *et al.*, and T461.
- Ratio of fit to (Kakimoto, Nagano, and T461) to fit to Kakimoto

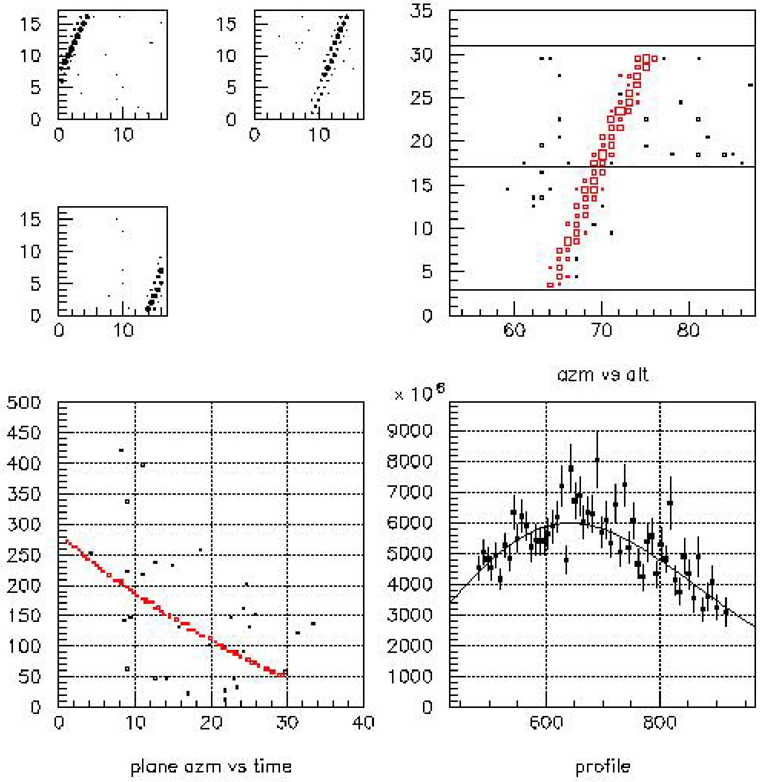
  = 1.00 ± 0.06



This is a slide from a colloquium I gave at Fermilab in 2007. Things have changed.

Monocular Data Analysis

- Pattern recognition.
- Fit SDP.
- Time fit (HiRes2), 5^o resolution.
- Profile plot.
- Gaisser-Hillas fit.
- Profile-Constrained time Fit (HiRes1 PCF), 7^o resolution.



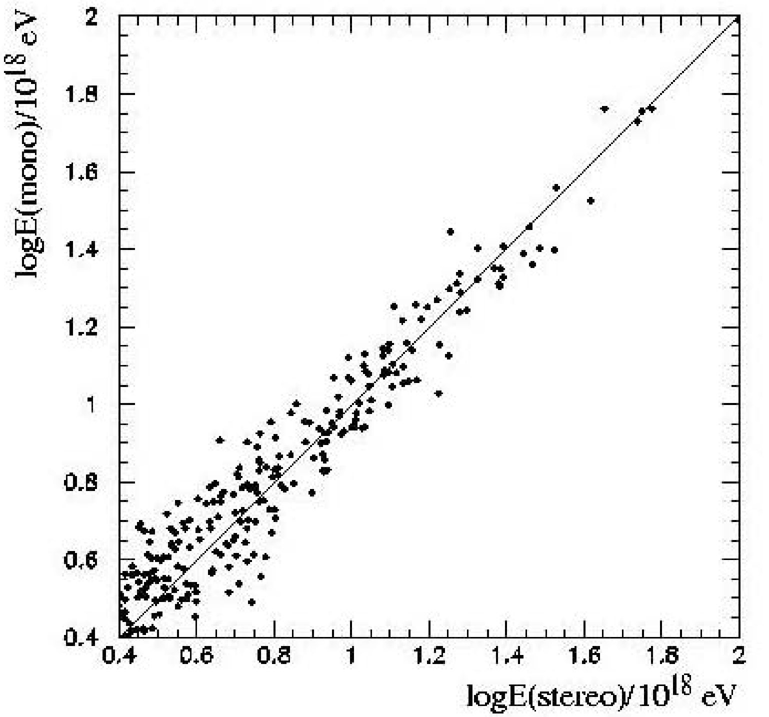
Energy Calculation

- Use method of Song *et al.*[1]
  - Integrate the G-H fit.
  - Multiply by <dE/dx> (corrected for Corsika thresholds) to get calorimetric energy.
  - Correct for missing energy (ν, μ), similar for p and Fe, weak energy dependence, ~10%.

1. C. Song et al., Astropart. Phys. **14**, 7 (2000)

HiRes1 Energy Reconstruction

- Test HiRes1 PCF energy reconstruction using events seen in stereo.
- Reconstructed energy using mono PCF geometry vs. energy using stereo geometry.
- Get same answer.



Systematic Uncertainties

- Energy scale: total = 17%
  - Photon scale 10%
  - Mean dE/dx 10%
  - Fluorescence yield 6%
  - Missing energy 5%
  - Atmosphere 5%

- Spectrum: total = 30%

The Monte Carlo Technique in Cosmic Ray Physics

- Two–step process: Corsika shower code, using QGSjet or Sibyll hadronic generators, to generate showers. Followed by a detector simulation.
- Success is difficult for ground arrays, due to "thinning" and poor prediction of tails of shower, particularly for muons.
- Success is good in the center of the shower, the part seen by fluorescence detectors.
- Techniques from HEP:
  - Shower libraries: every event is an actual Corsika event.
  - Simulation using previous measurements of the spectrum and composition.
  - Simulation using exact detector conditions as a function of time.
  - The data/MC comparison method for judging success of simulation.
- Development of model-independent acceptance calculation.
- Result for HiRes is an excellent calculation of the acceptance.

Aperture Calculation

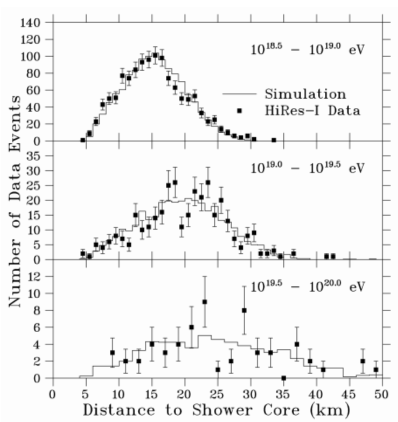
$$\text{Aperture} = \frac{Acc(E)}{Thr(E)} A\Omega$$

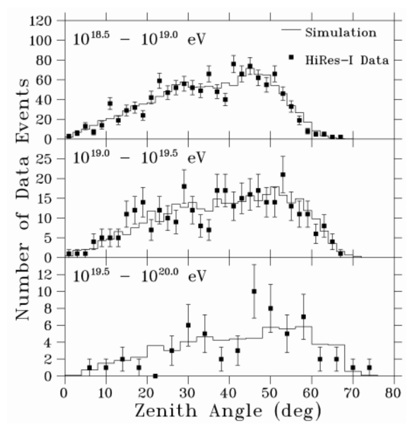
acceptance

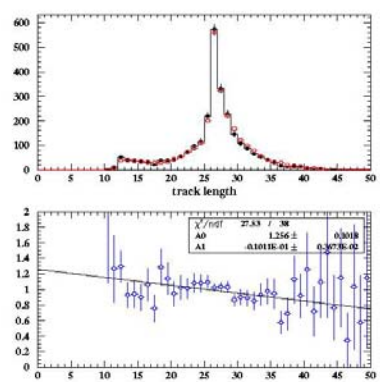
- Need complete simulation of detector: create MC sample identical to the data.
  - Put in spectrum, composition, as measured by Fly's Eye, HiRes-MIA, HiRes stereo experiments; use actual Corsika showers.
  - Shower development
  - Light emission, transmission, and collection
  - Trigger and readout electronics
- Write out MC in same format as data.
- Analyze both with same program.
- Compare histograms of data and MC to judge success (or failure) of simulation.

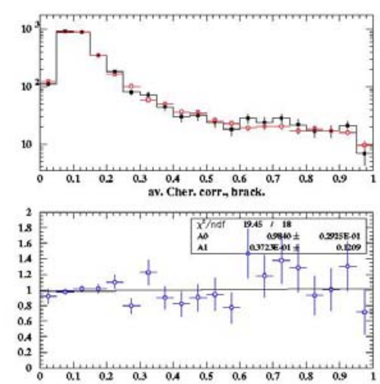
Compare Data to Monte Carlo: Judge success of simulation and acceptance calculation.

Inputs to Monte Carlo:
Fly’s Eye stereo spectrum; HiRes/Mia and HiRes Stereo composition;
Library of Corsika showers.
Detailed nightly information on trigger logic and thresholds, live mirrors, etc.









Result: excellent simulation of the data, and an accurate aperture calculation.

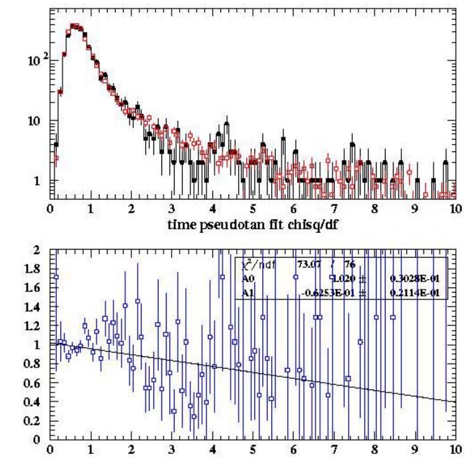
(Steeply Falling) Spectrum Calculation

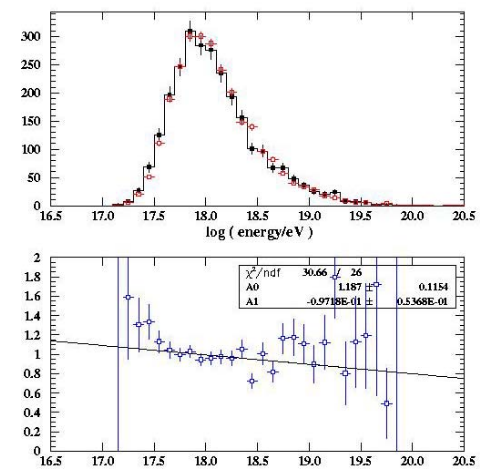
$$J(E) = \frac{D(E)}{A(E)} \frac{T(E)}{Area \times \Omega t dE}$$

- If spectrum + resolution correctly modeled, D(E)/A(E) = constant.
- First order correction for resolution.
- Possible bias: GZK appears in data, but not in MC.
- Second order correction:

$$b(E) = \left(\frac{T(E, noGZK)}{A(E, noGZK)} - \frac{T(E, GZK)}{A(E, GZK)} \right) D(E)$$

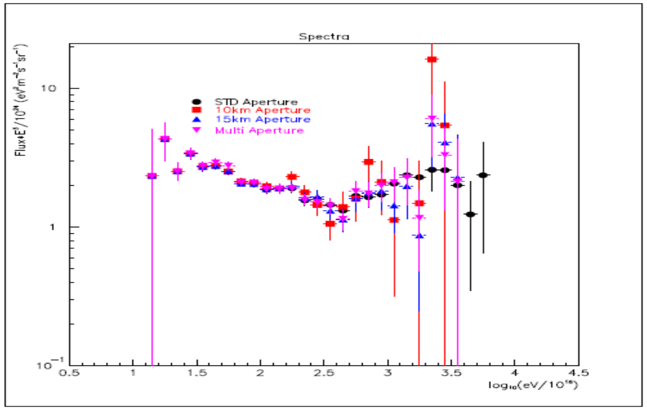
- Bias is smaller than statistical uncertainties; correction reduces J(E).

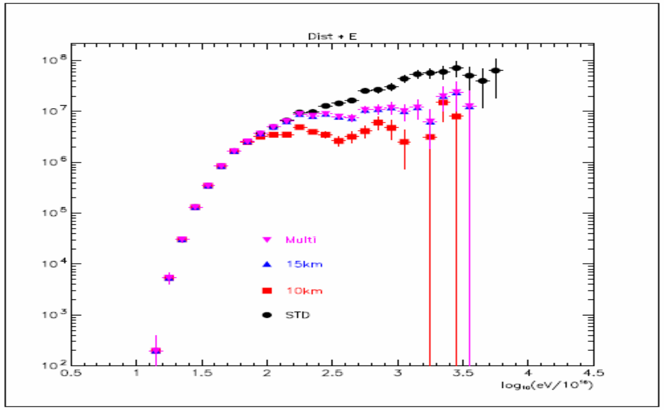




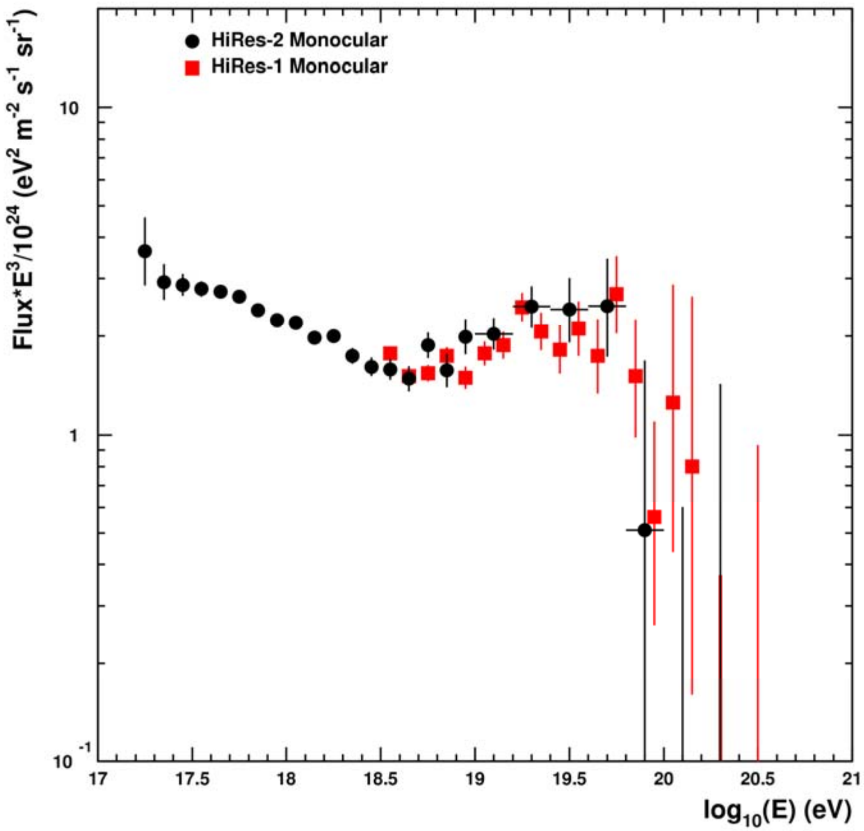
Testing the Aperture

- Test the aperture calculation by limiting distances to the region to where the detector is fully efficient.
- Spectrum is invariant.
- Histogram of events' energies shows ankle, high energy suppression.





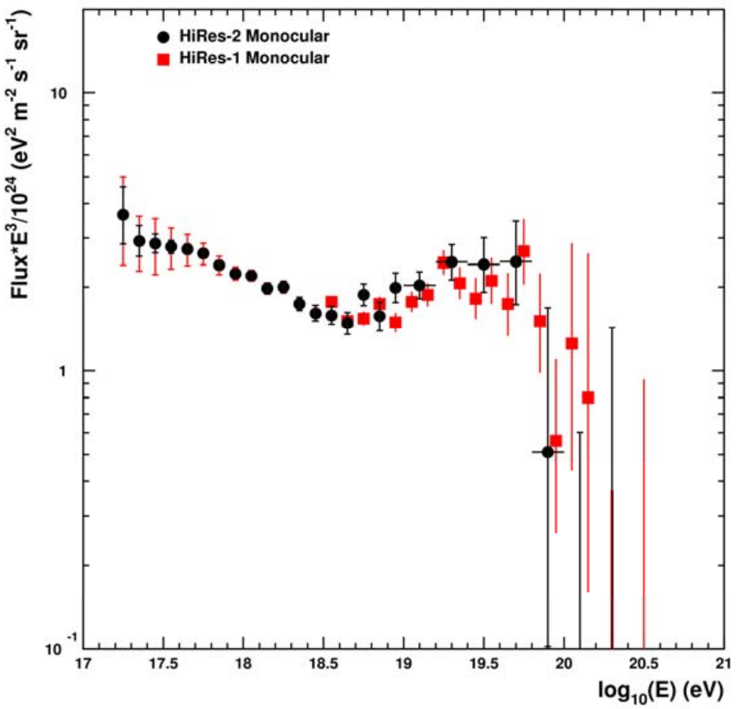
Monocular Spectra



We observe: GZK cutoff;
ankle;
second knee?

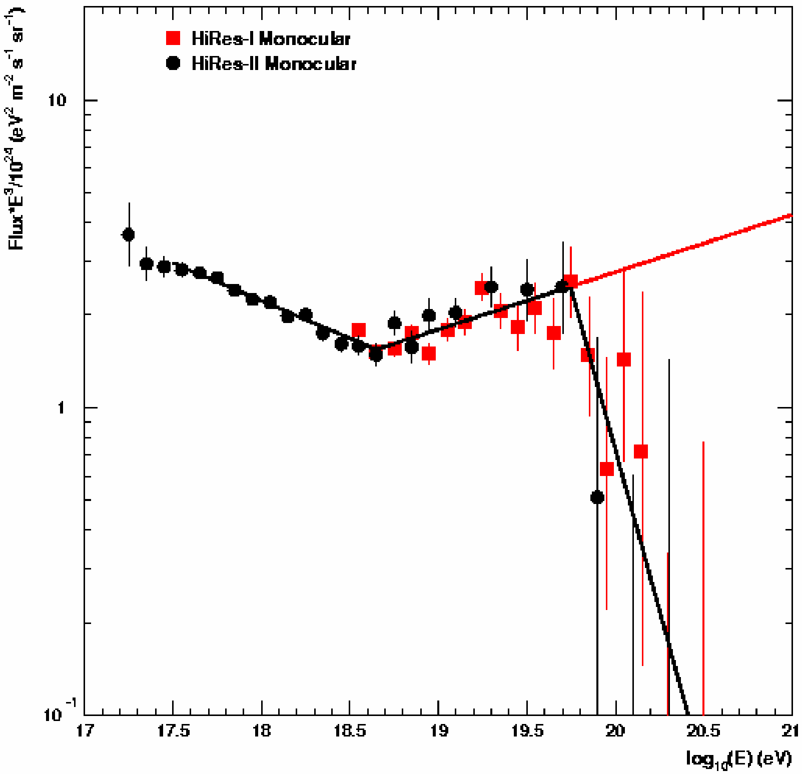
Spectrum with Systematic Uncertainty from Composition

- Composition determines whether <Xmax> is in HiRes' field of view, or above.
- Different apertures for Corsika/QGSJet protons and iron; leads to systematic uncertainty below 10^{18} eV, which is larger than statistical uncertainty.
- HiRes can't say much about the second knee.



5σ Observation of the Break in the Spectrum

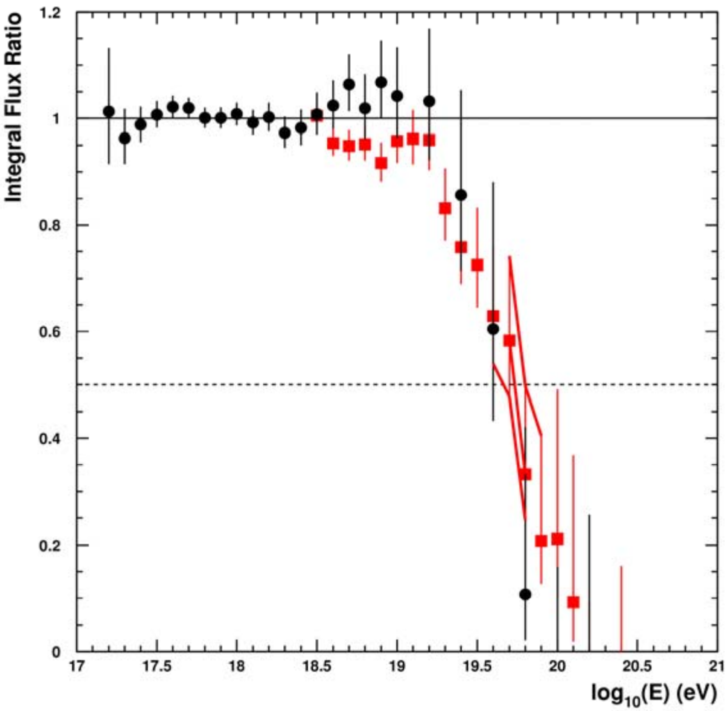
- Broken Power Law Fits
  - No Break Point
    - Chi2/DOF = 162/39
  - One BP
    - Chi2/DOF = 62.9/37
    - BP = 18.65
  - Two BP's
    - Chi2/DOF = 39.5/35
    - 1st BP = 18.65 ± 0.05
    - 2nd BP = 19.75 ± 0.04
    - Difference in chi2 is equivalent to 4.5 σ observation.
  - Two BP with extension to test hypothesis that a break is present.
    - Expect 51.1 events
    - Observe 15 events
    - Poisson probability: P(15;51.1) = $7\text{x}10^{-8}$ (5.3σ)
  - **The break is present.**



Break is at $(5.6 \pm 0.5) \times 10^{19}$ eV;
GZK expected at 5-6 x 10^{19} eV.
The break is the GZK cutoff.

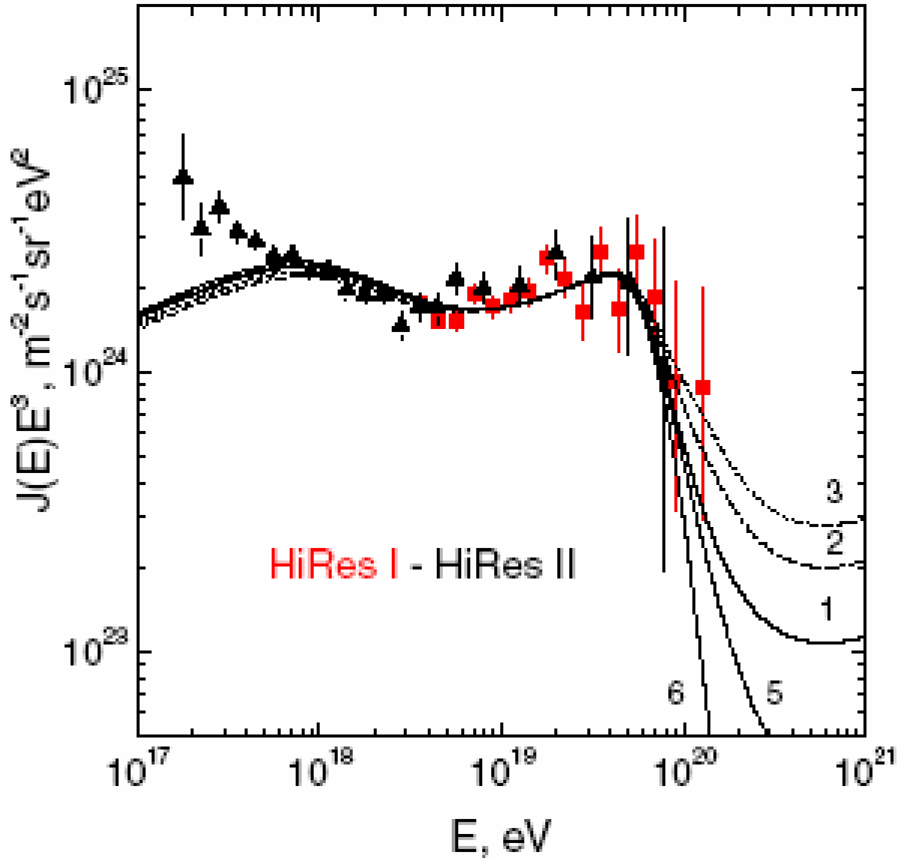
Use Berezinsky's $E_{½}$ Method to Test

- $E_{½}$ is the energy where the integral spectrum falls below the power-law extension by a factor of 2.
- Berezinsky *et al*.: $\log_{10}E_{½} = 19.72$, for a wide range of spectral slopes.
- Use 2 Break Point Fit with Extension for the comparison.
- $\log_{10}E_{½} = 19.73 \pm 0.07$
- **Passes the test.**



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.

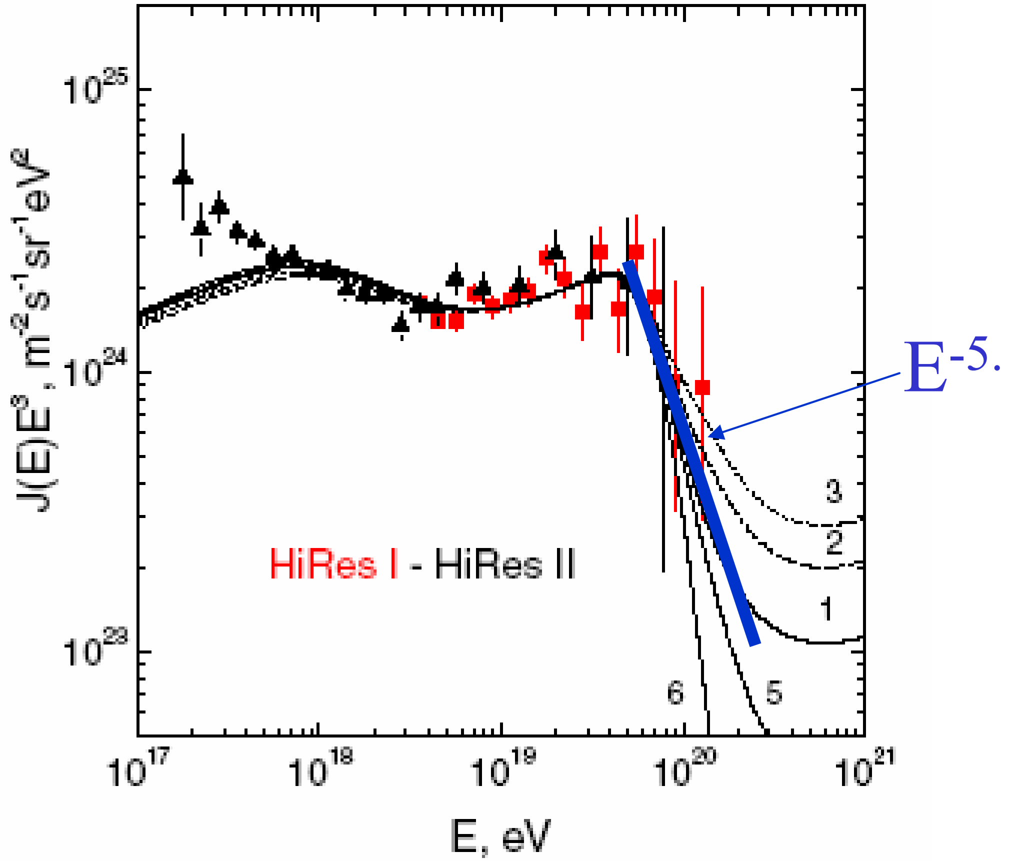


Berezinsky, Gazizov, and Grigorieva, Phys. Rev. D**74**, 043005 (2006) (uses older HiRes spectrum)

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.
  - HiRes: $E^{-5.1}$ fall-off.
- More work is needed to make a better comparison, but...

- **Constant density of sources is favored.**



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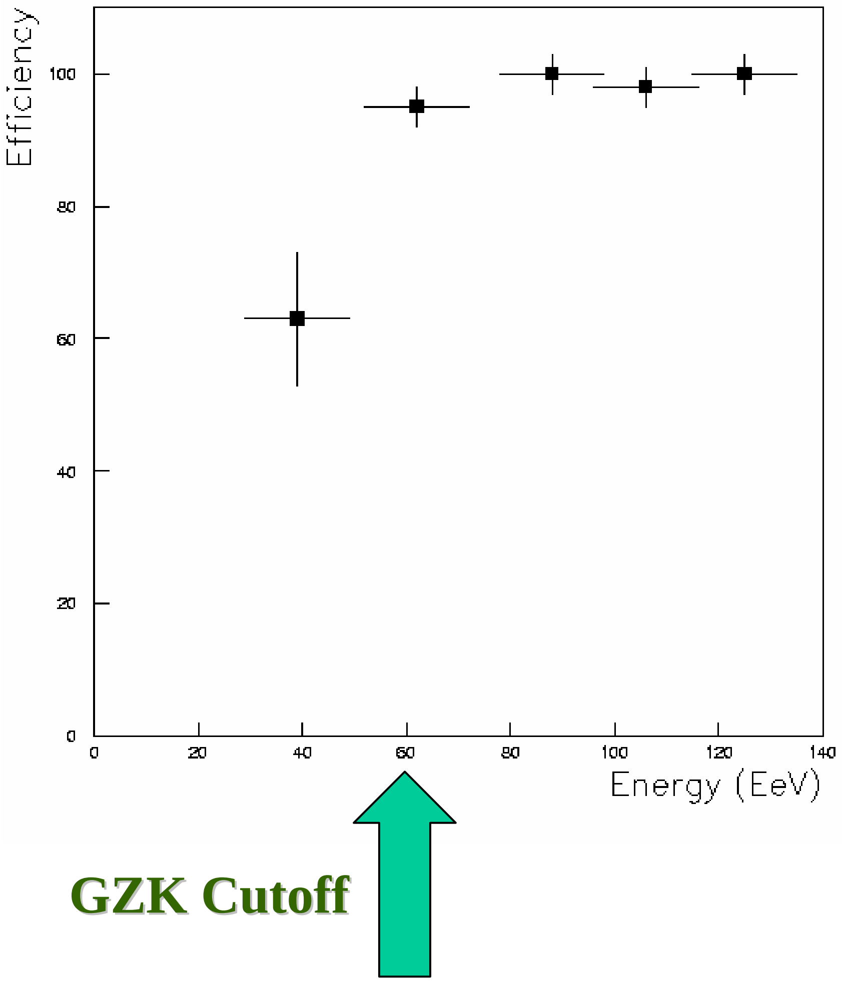
“Test Beam” of High Energy Events

- Laser at Terra Ranch
- 35 km from HiRes-2, at edge of aperture.
- Vertical, 355 nm
- Fires at five energies, as bright as 40-125 EeV showers.
- Efficiency for good-weather nights.
- Excellent trigger + reconstruction efficiency above GZK energy.
- **The lack of high energy events is not an instrumental effect. It is due to physics.**



Summary

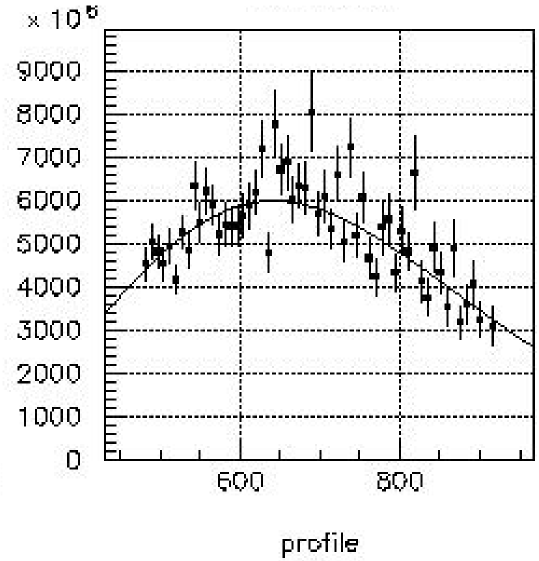
- **HiRes performed the first observation of the GZK cutoff**.
  - It occurs at $(5.6 \pm 0.5 \pm 0.9) \times 10^{19}$ eV.
  - Flux α $E^{-5.1 \pm 0.7}$ above the cutoff.
- We see the "ankle" at $10^{18.6}$ eV.
  - $E^{-3.3}$ below and $E^{-2.8}$ above.
- HiRes energy scale is determined by
  - Measured photonic scale and atmospheric corrections
  - Measurements of FY published by 2007
  - Consistent reconstructions between HiRes-1, HiRes-2, and stereo methods.
  - Ecal method of Song et al.
  - Corsika determination of missing energy correction.

Back of Envelope
Energy Calculation

$$E = area \times \frac{dE}{dx}$$

$$E = \frac{1}{2} N_{\max} \times 1000 g/cm^2 \times 2 \frac{MeV}{g/cm^2}$$

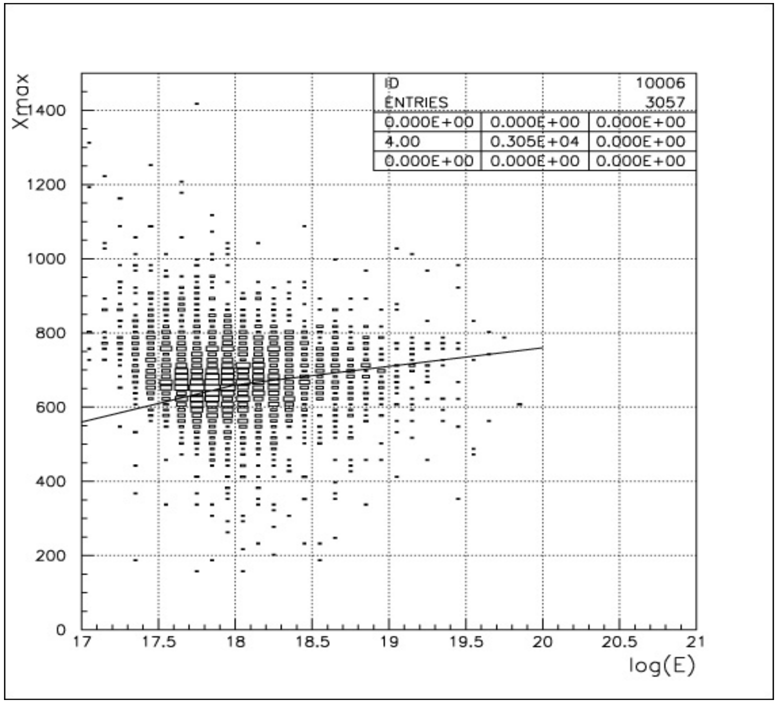
$$E = 1 \times 10^9 N_{\max} \quad (\text{actually } 1.3 \times 10^9)$$



- Energy determination is robust.
- Based on center of shower, not tails.
- Easy to Monte Carlo.

HiRes (plus Auger and TA) Lower-energy Limitations

- HiRes observes elongation above $10^{18.0}$ eV clearly.
- HiRes looks up to 31^{o}, can't see X_{max} for close-by (low energy) events.
- Makes spectrum measurements difficult below $10^{17.5}$ eV.
- Composition bias for E < $10^{18.0}$ eV.



Before bracketing and Cerenkov cuts