Observation of the GZK Cutoff by the HiRes Experiment

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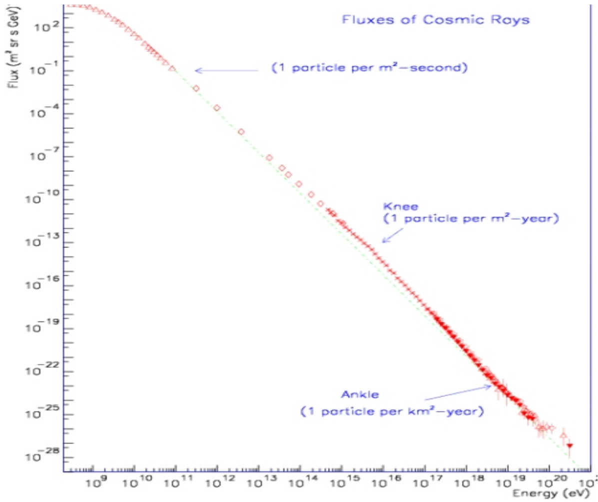
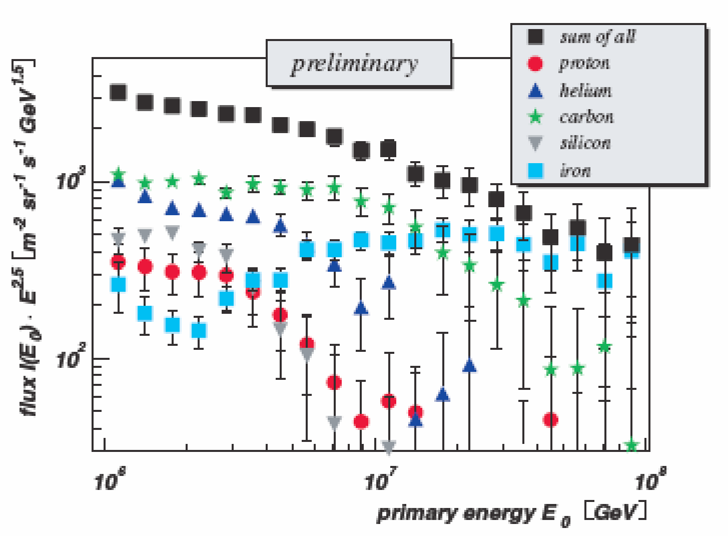
Outline

- Introduction
- The HiRes experiment
- Calculating the spectrum
- Results (plus composition and anisotropy)
- Future studies

Cosmic Rays over a Wide Energy Range

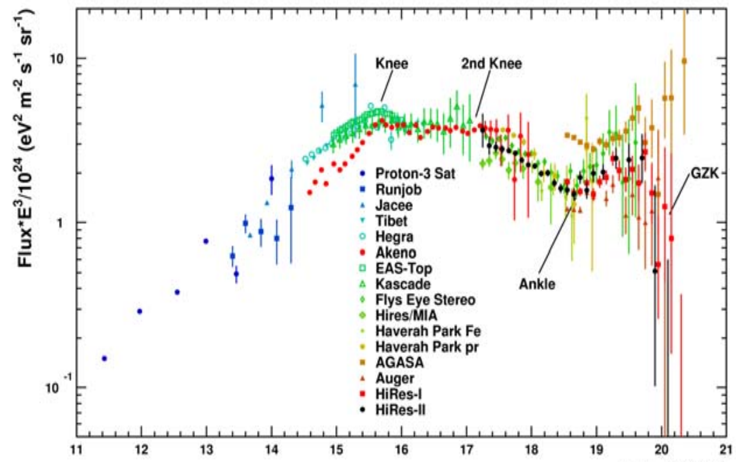
- At lower energies, spectrum of cosmic rays is almost featureless.
- Only the "knee" at $3\mathrm{x}10^{15}$ eV
- The knee is due to a rigidity-dependent cutoff, seen in composition.
  - Kascade experiment: measures electron and muon components of showers.
  - Model dependent, but indicative.
  - Is it E_{max} or containment?
  - Low energy (E_c=$3\mathrm{x}10^{17}$ eV) and sharp elemental cutoffs ➔ limit comes from E_{max}, rather than containment.
- Learn about galactic sources.
- Structure ➔ Physics

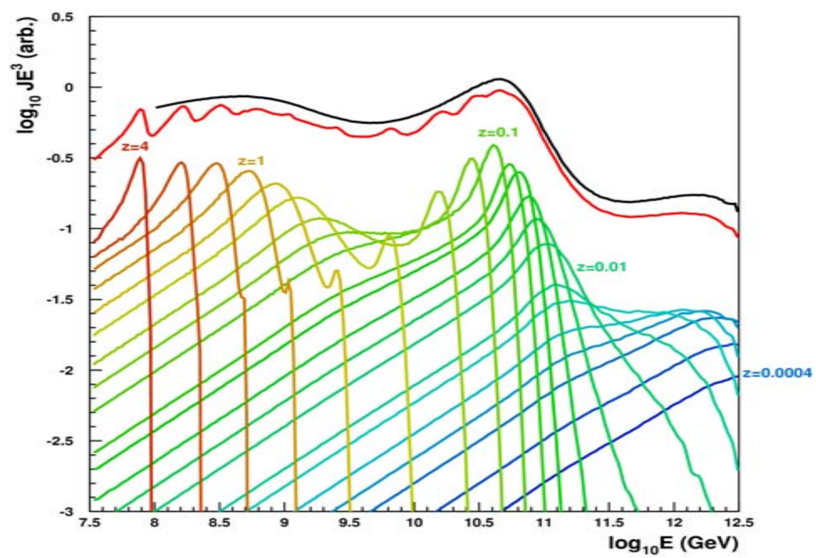




Big Change Expected at High Energies

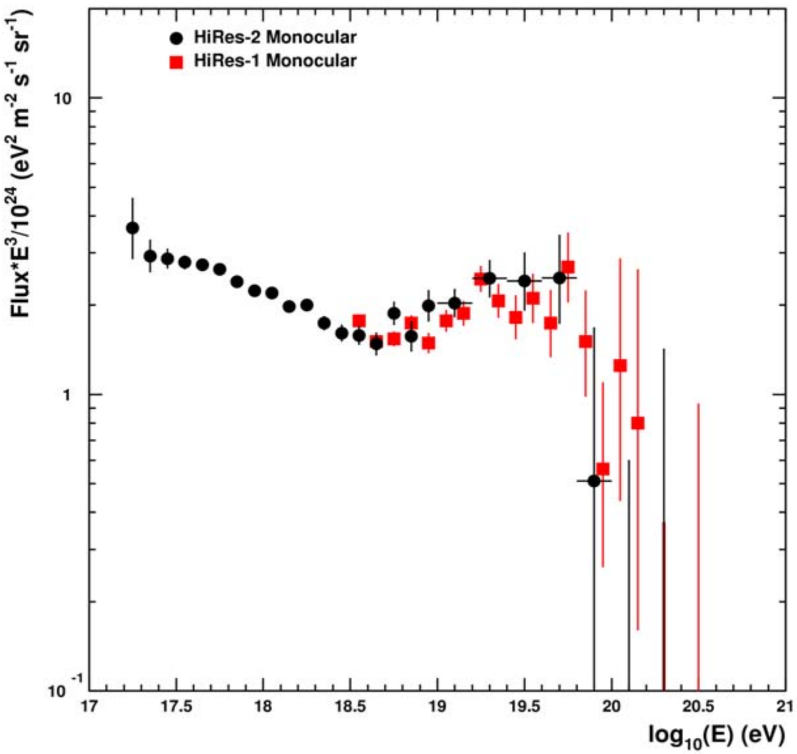
- Expect two spectral features due to interactions between CR protons and CMBR photons.
  - GZK cutoff due to pion production.
  - Dip in spectrum due to e+e- pair production (the ankle).
- A third spectral feature is seen (second knee).
- Galactic/extragalactic transition.
- Learn about extragalactic sources; and propagation over cosmic distances.





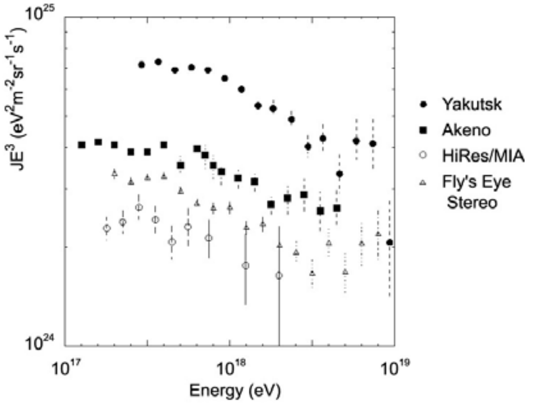
What Causes the Ankle? Two Interpretations

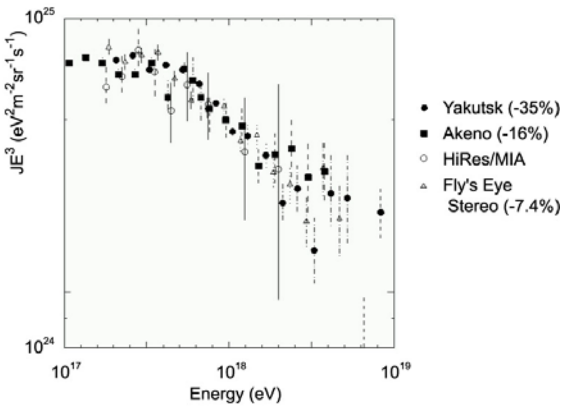
- 1. Extragalactic protons, losing energy by e^+e^- production, are pushed to the left, excavating the ankle.
- 2. The (heavy) galactic spectrum is giving way to the (light) extragalactic one.
- Composition should provide the answer.



Second Knee at $\sim 10^{17.6}$ eV

- Yakutsk, Akeno, Fly's Eye Stereo, HiRes Prototype/MIA all saw flat spectrum followed by a steepening in the power law. The break is called the second knee.
- Correct for varying energy scales: all agree on location of the second knee.
- There are THREE spectral features in the UHE regime. Location of second knee is not known accurately.
- Cause: galactic or extragalactic? source effect or propagation?
- Cause of second knee is unknown.



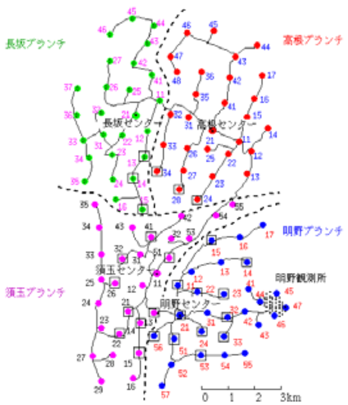


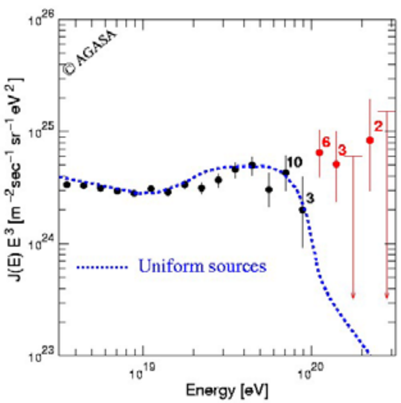
GZK Cutoff

- 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; Δ 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.
- Should occur at about 6×10^{19} eV (10J).

Previous Experiments

- Several smaller experiments saw one super-GZK event each: Volcano Ranch, Haverah Park, Yakutsk, Fly's Eye.
- Akeno Giant Air Shower Array (AGASA) was the first experiment to be large enough to measure the spectrum at the GZK energy; they didn't see the cutoff.
- AGASA main evidence: 11 events above 10^{20} eV.
- This led some to question whether the GZK cutoff exists, and how it might be evaded.





High Resolution Fly's Eye (HiRes) Experiment: Has the World's Highest Exposure (5xAGASA)

- HiRes is a fluorescence experiment.
- Fluorescence yield:
  - Charged particles in cosmic ray air shower excite N_2 molecules.
  - Emit ~5 UV photons/mip/meter.
  - 300-400 nm wavelength.
  - High energy showers are bright.
- HiRes has two detectors located atop desert mountains in west-central Utah. Operated from May, 1997 to April, 2006.
- Collected data on moonless nights: about 10% duty factor.
- Mono: wider energy range ($10^{17.2} < E < 10^{20.5}$ eV), best statistics.
- Stereo: best resolution, $10^{18.5} < E < 10^{20.5}$ eV, fewer events.

High Resolution Fly's Eye (HiRes) Collaboration

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Mirrors and Phototubes

- 4.2 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.**

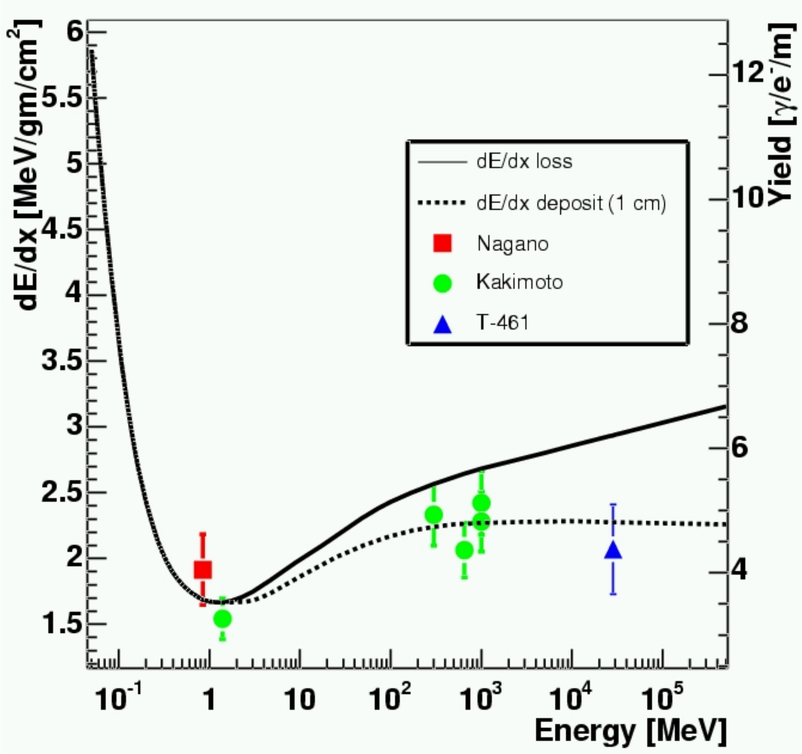
Atmospherics

- 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
  - Change by ±0.02 changes energy by 10% at 25 km.
- Aerosols vary slowly: typically constant over a night or two.
- **HiRes has an excellent site.**

Measurement of Fluorescence Yield

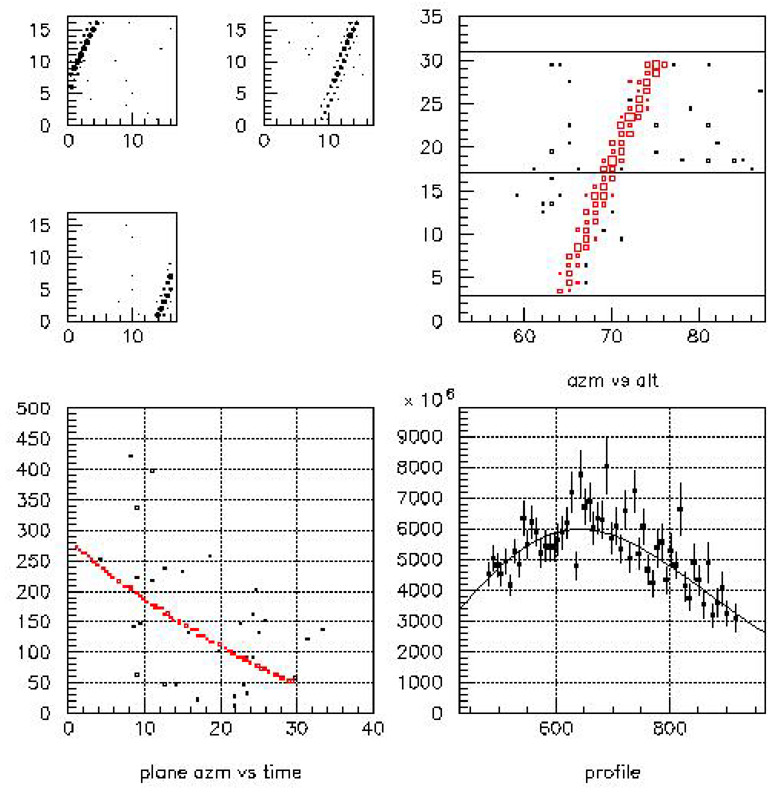
- Three published results: Kakimoto *et al.*, Nagano *et al.*, and T461.
- Ratio of fit to (Kakimoto, Nagano, and T461) to fit to Kakimoto

  $= 1.00 \pm 0.06$



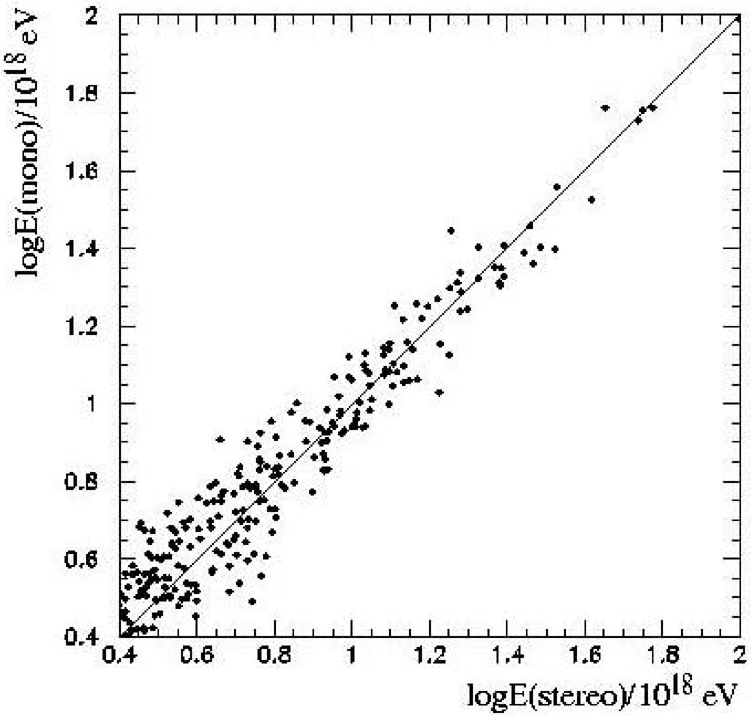
Monocular Data Analysis

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



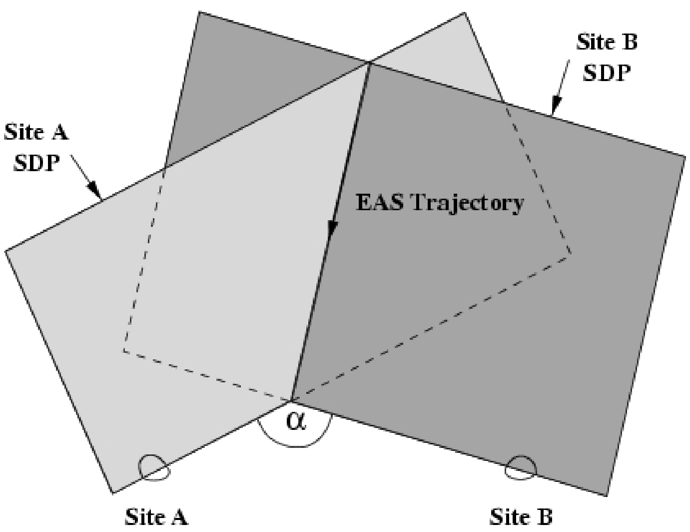
HiRes1 Energy Reconstruction

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



Stereo Analysis

- Intersection of shower-detector planes determines geometry, 0.6^0 resolution.
- Timing does as well for parallel SDP's.
- Two measurements of energy, X_{max}. Allows measurement of resolution.

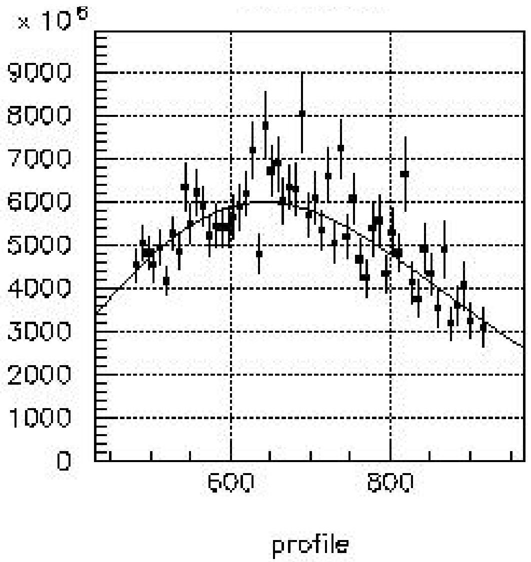


Back of Envelope
Energy Calculation

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

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

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



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

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 or Aires shower codes, using QGSjet or Sibyll hadronic generators, to generate showers. Followed by a detector simulation.
- Success is limited 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

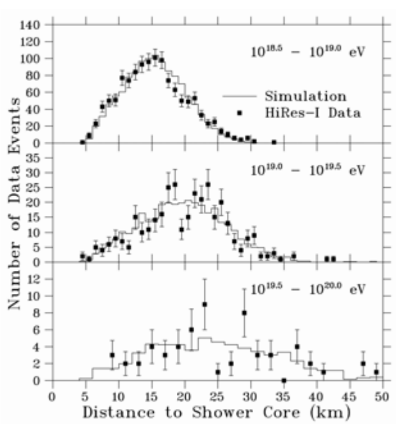
$$\text{Aperture} = \frac{Acc(E)}{Thr(E)} A\Omega$$

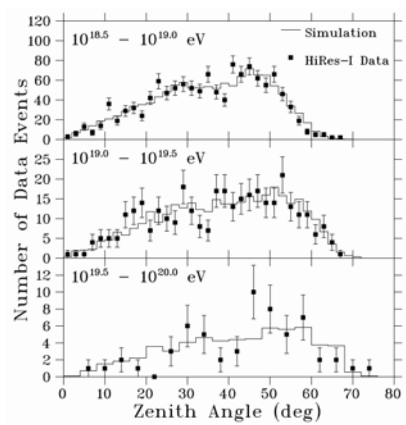
acceptance

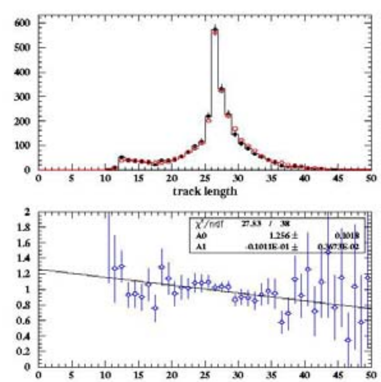
- Need complete simulation of detector: create MC sample identical to the data.
  - Put in spectrum, composition, as measured by Fly's Eye, HiRes-MIA, HiRes stereo experiments; use actual Corsika showers.
  - Shower development
  - Light emission, transmission, and collection
  - Trigger and readout 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.

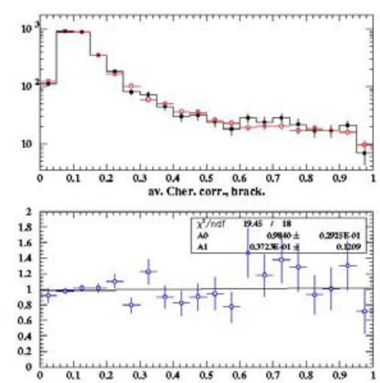
Compare Data to Monte Carlo: Judge success of simulation and acceptance calculation.

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.

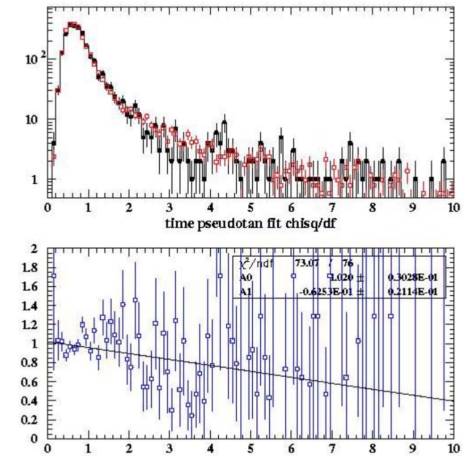
(Steeply Falling) Spectrum Calculation

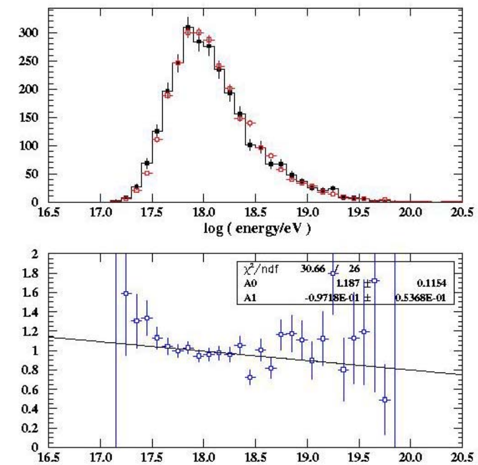
$$J(E) = \frac{D(E)}{A(E)} \frac{T(E)}{Area \times \Omega t dE}$$

- 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:

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

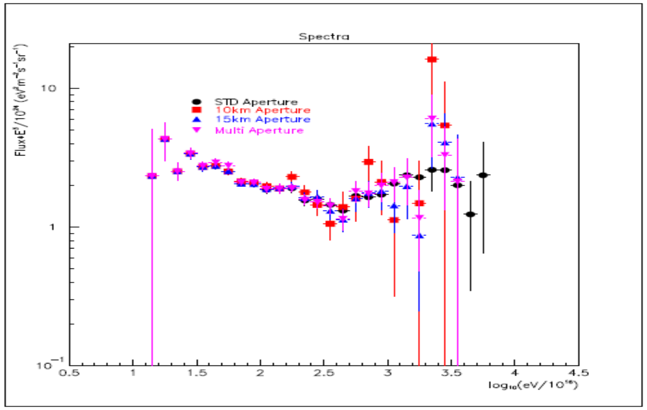
- Bias is smaller than statistical uncertainties; correction reduces J(E).

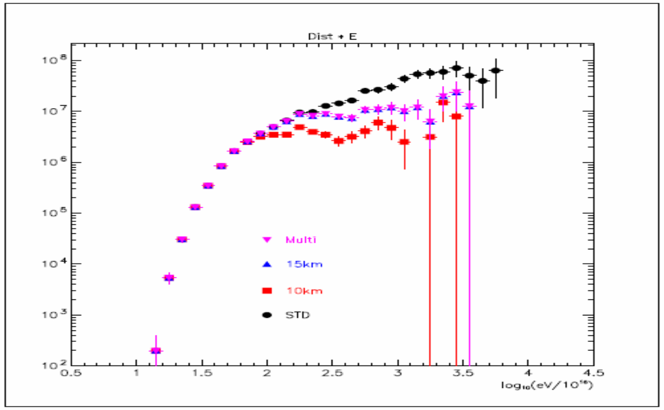




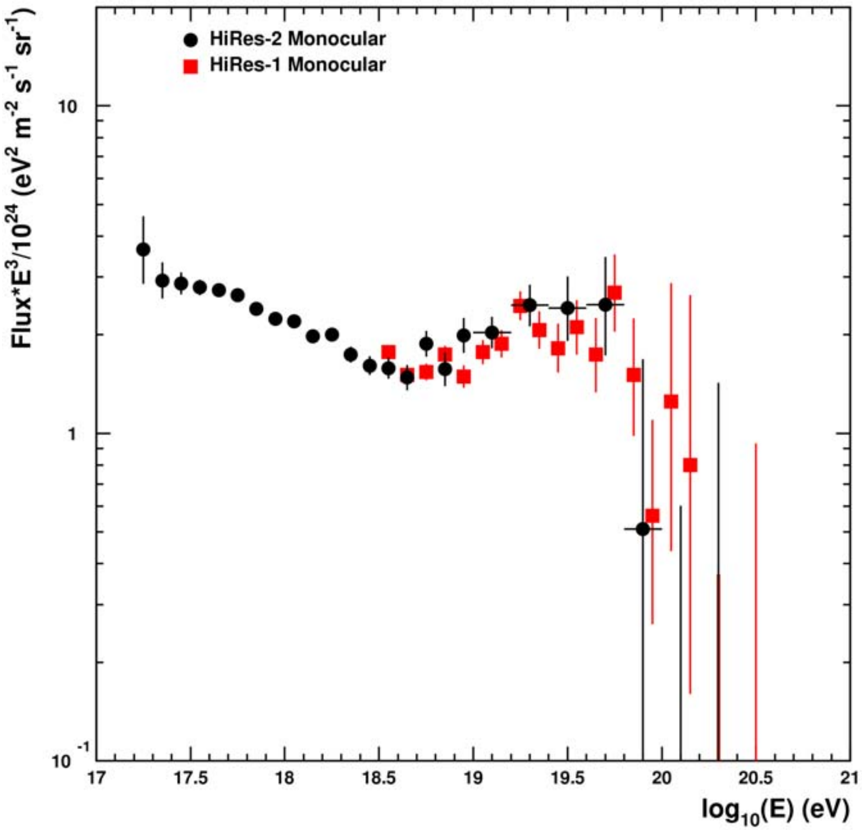
Testing the Aperture

- 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

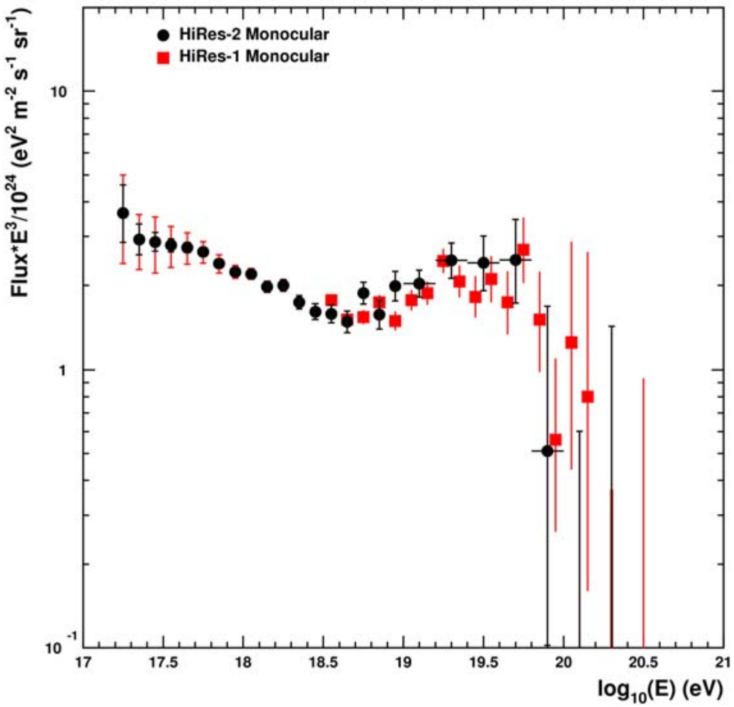


HiRes1: 7/97-5/05
HiRes2: 12/99-8/04

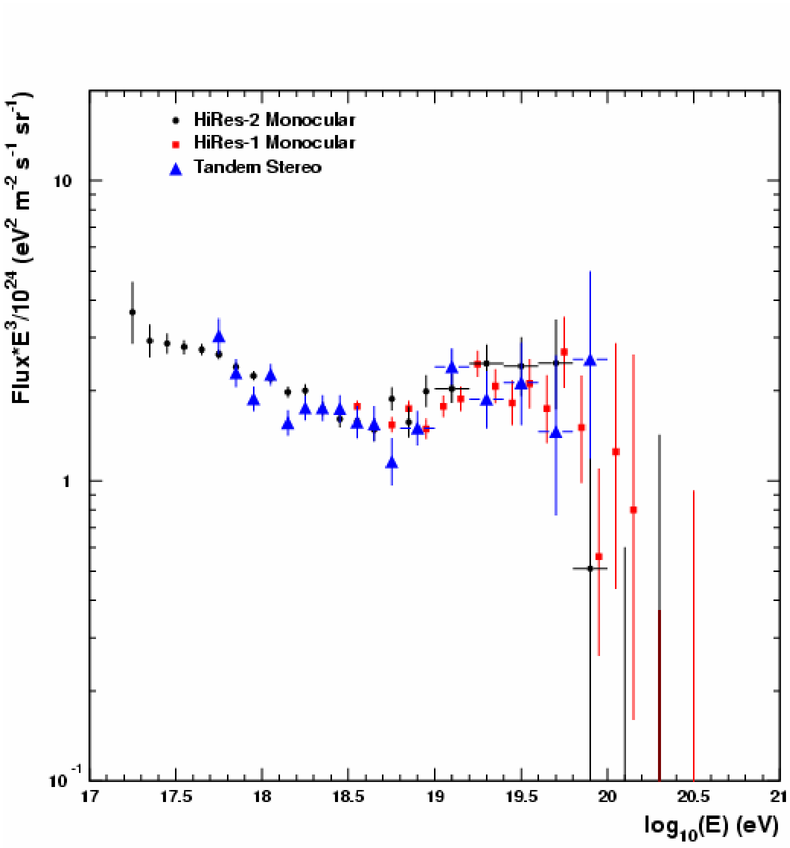
We observe: GZK cutoff;
ankle;
second knee?

Spectrum with Systematic Uncertainty from Composition

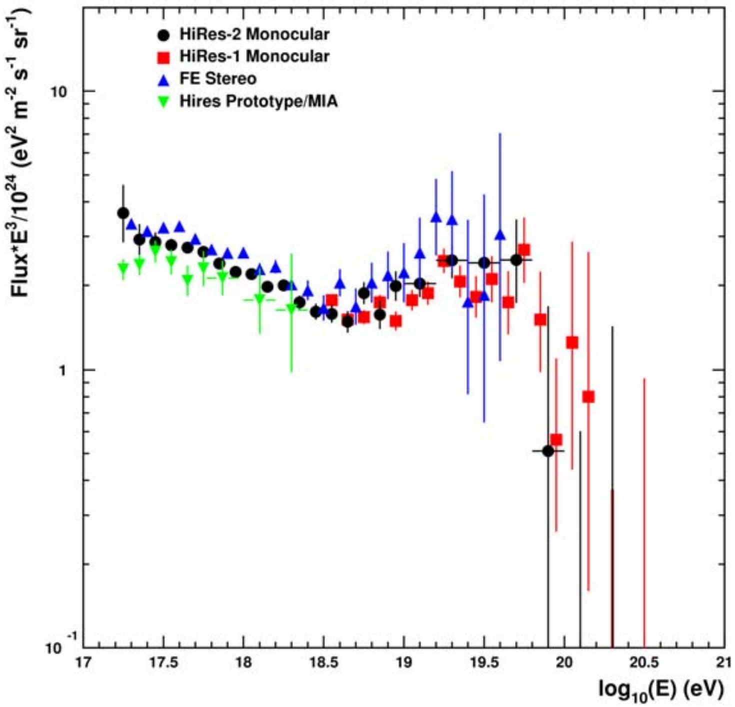
- Composition determines whether <Xmax> is in HiRes' field of view, or above.
- Different apertures for Corsika/QGSJet protons and iron; leads to systematic uncertainty below 10^{18} eV, which is larger than statistical uncertainty.
- HiRes can't say much about the second knee.
- **The field needs an experiment, with wide enough energy range, which would see all three UHE cosmic ray features with good statistics!**



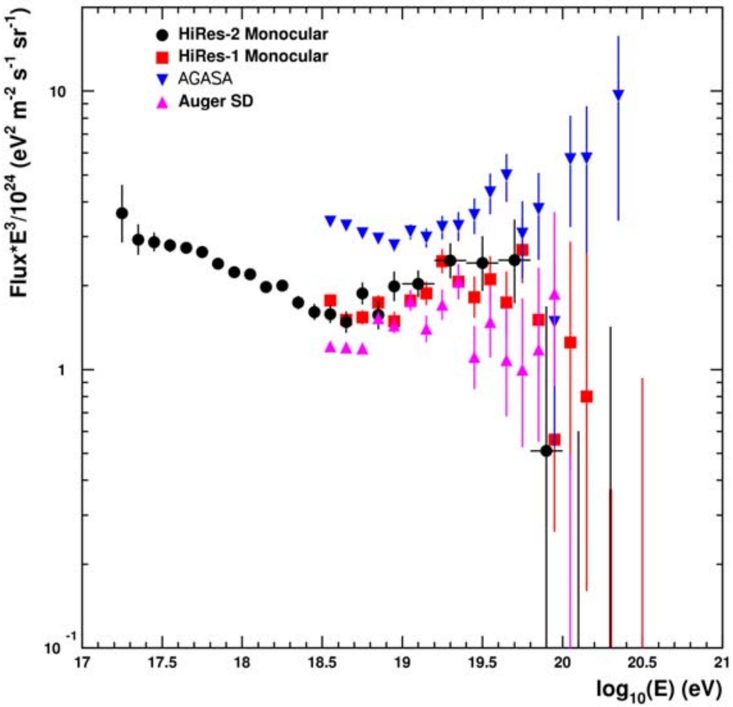
Add the HiRes Stereo Spectrum
(absolutely normalized)



HiRes and Other Experiments



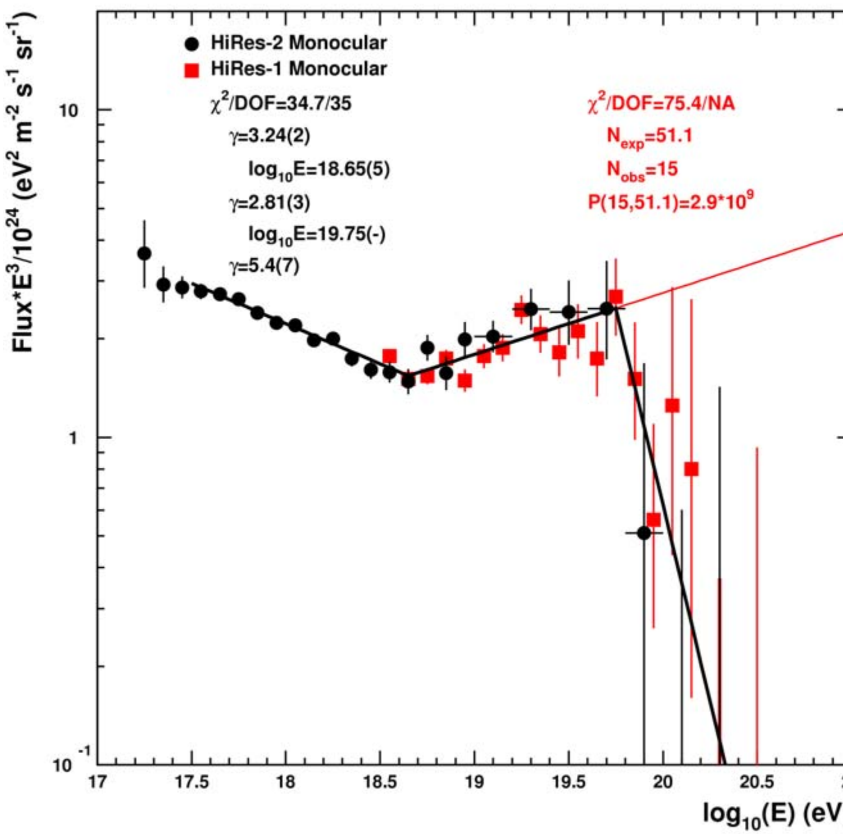
HiRes, Fly's Eye Stereo, and HiRes/MIA



HiRes, AGASA, Auger(2005)

5σ Observation of the Break in the Spectrum

- Broken Power Law Fits
  - No Break Point
    - Chi2/DOF = 162/39
  - One BP
    - Chi2/DOF = 68.2/37
    - BP = 18.63
  - Two BP's
    - Chi2/DOF = 34.7/35
    - 1^{st} BP = 18.63
    - 2^{nd} BP = 19.75
    - Difference in chi2 is equivalent to 5.6 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) = 3×10^{-9} (5.8σ)
  - Independent statistics: P(14;44.9)=7×10^{-8} **(5.2σ)**
  - **The break is present.**

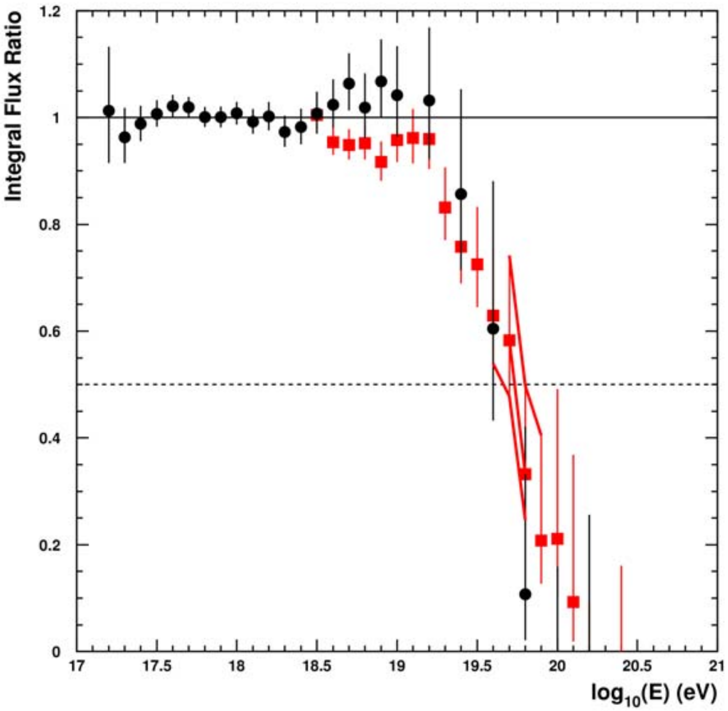


Break is at $(5.6 \pm 0.7) \times 10^{19}$ eV;
GZK expected at 6×10^{19} eV.
The break is at the GZK energy.

The Break is at the GZK Energy!

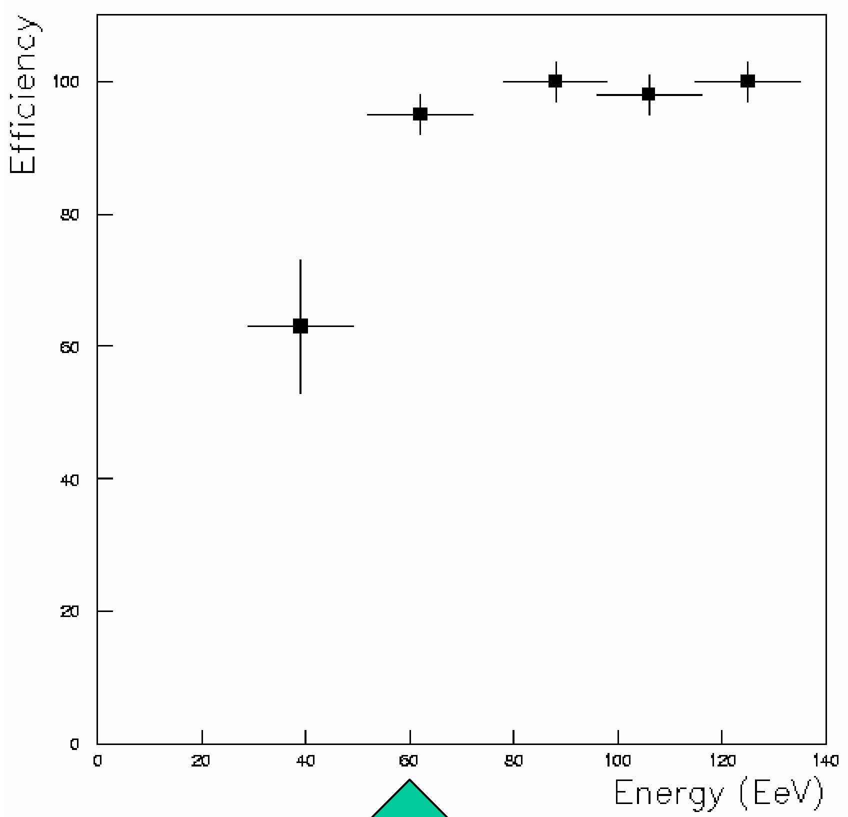
Use Berezinsky's Integral Spectrum Test

- $E_{½}$ 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 conditions.
- Use 2 Break Point Fit with Extension for the comparison.
- $\log_{10}E_{½} = 19.73 \pm 0.07$
- **Suppression is the GZK cutoff.**



“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.**



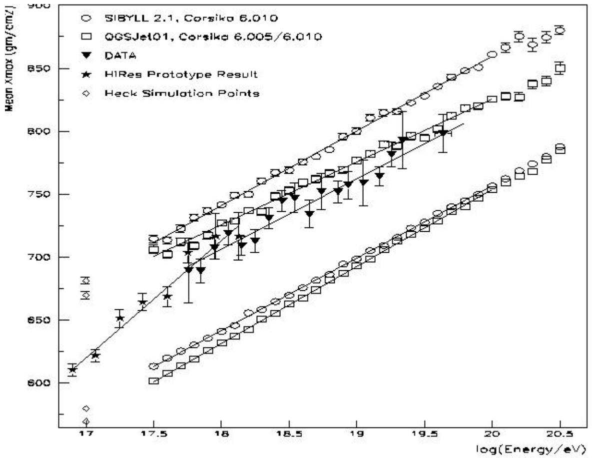
GZK Cutoff

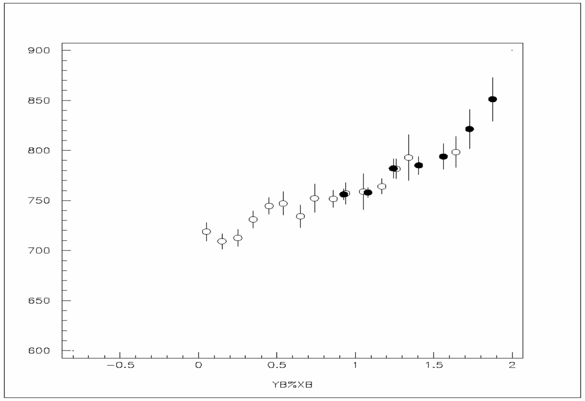
<Xmax> Indicates Composition

- $\langle X_{max} \rangle \rightarrow$ Composition $\rightarrow$ Galactic/Extragalactic Transition

- There is a **model-independent** break in slope at about 10^{18} eV.
- Heavy (galactic) nuclei decrease, give way to light (extragalactic) composition.
- Galactic/extragalactic transition is complete by about 10^{18} eV.

- The ankle is **not** the transition.





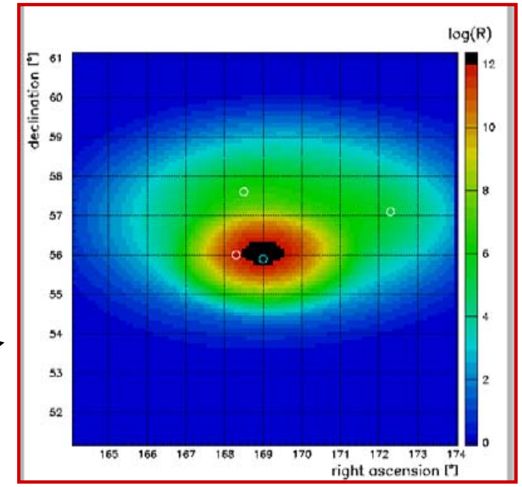
HiRes Anisotropy Results: BL Lac Correlations

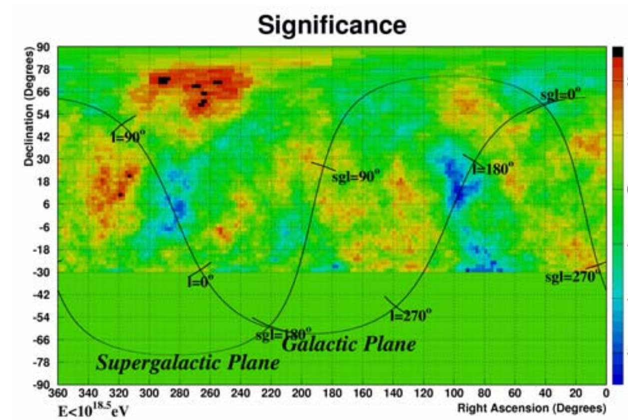
- Correlations between UHE cosmic rays' pointing directions, and BL Lac sources have been found individually in AGASA, Yakutsk, and HiRes stereo data, by P.Tinyakov, I.Tkachev, D.Gorbunov, S. Troitsky *et al*.
- HiRes stereo result:
  - BL with m<18: 10^{-4} chance probability.
  - Add HP sources: 10^{-5} chance probability.
- The HiRes result should not exist, since the ~0.5^{o} resolution is smaller than expected magnetic deflections.
- This is a northern-hemisphere effect, since many fewer sources are known in the southern hemisphere.

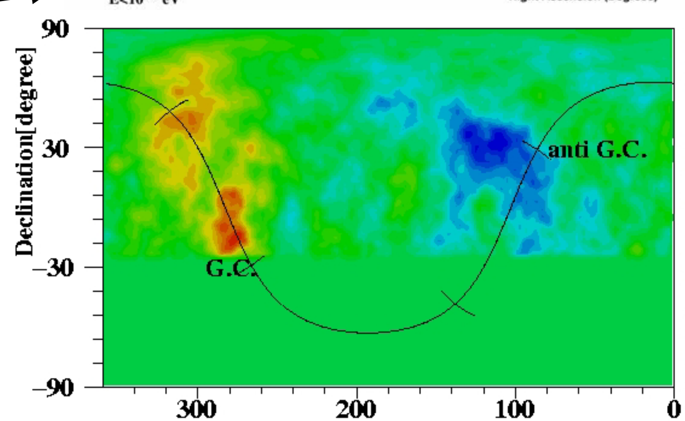
More Northern Hemisphere Anisotropy

- The Quartet: AGASA triplet + HiRes stereo high energy event; in Ursa Major.

- Dip near galactic anticenter, observed by AGASA and HiRes at lower energies.

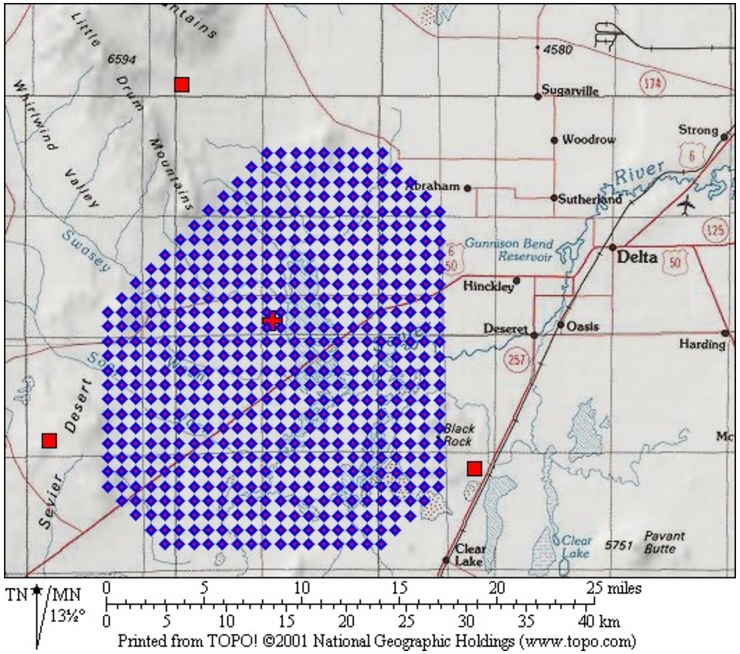






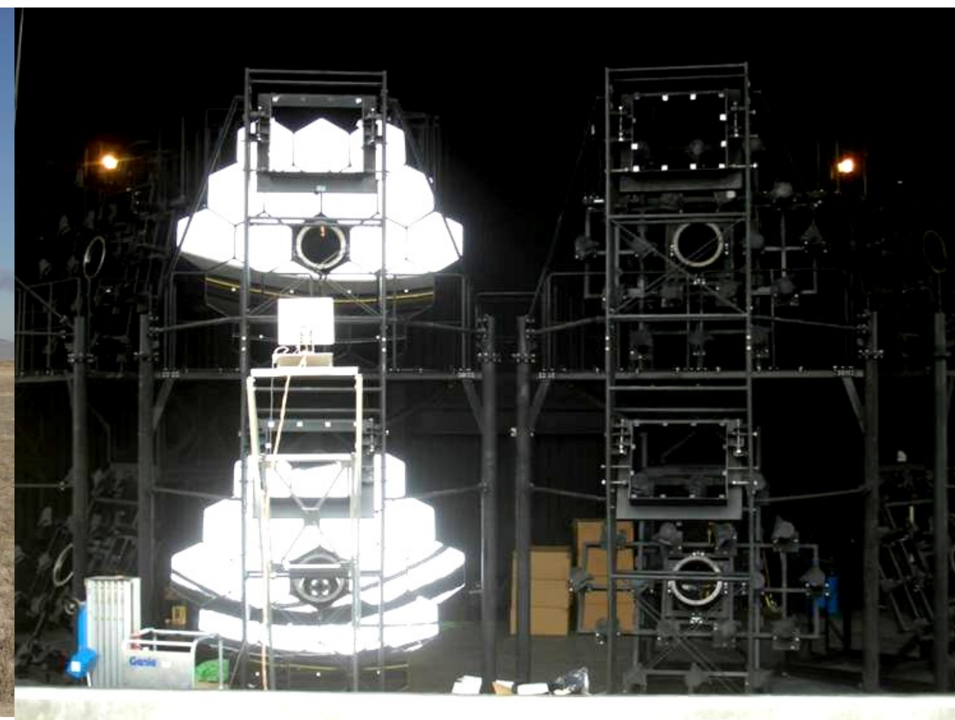
Upcoming Experiment: The Telescope Array (TA) and TA Low Energy Extension (TALE)

- TA surface detector: 576 scintillation counters, 1.2 km spacing.
- 3 TA fluorescence detectors overlook SD, 108° in azimuth each.
- TA will cover E > $10^{18.5}$ eV
- TA will be running in spring, 2007.
- 2 TALE fluorescence detectors plus infill array:
  - Stereo detector to observe the ankle with flat aperture.
  - Tower detector + infill array to cover lower energies.
- Cover $10^{16.5} – 10^{20.5}$ eV.



TA Detectors

SD in Millard County, Utah

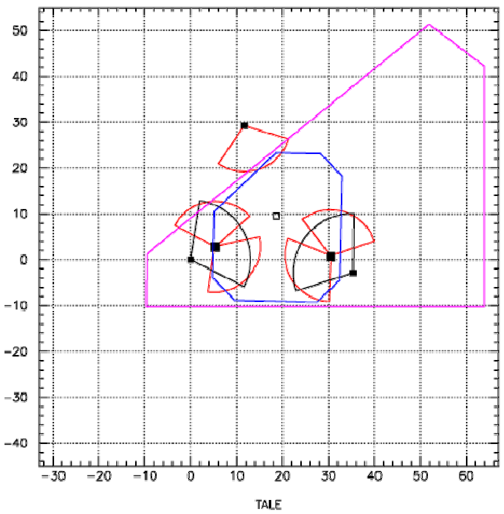


FD being deployed

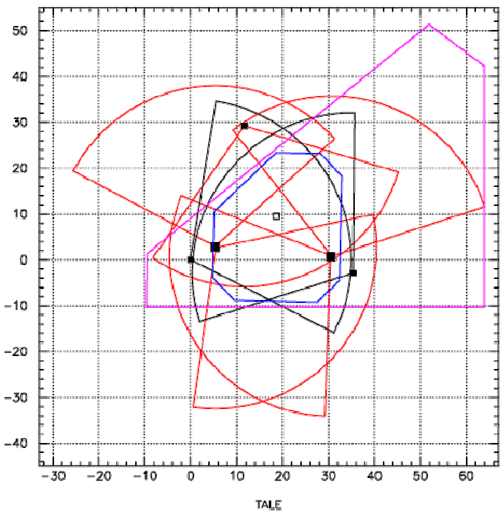
TA/TALE Layout

- Two 6-km stereo pairs: observe the ankle with flat aperture.
- Tower detector with 3 times larger mirrors: reach down to $10^{16.5}$ eV.
- Infill array for hybrid observation at the lowest energies.
- **Cover $10^{16.5} – 10^{20.5}$ eV.**

- TALE doubles the high energy aperture.



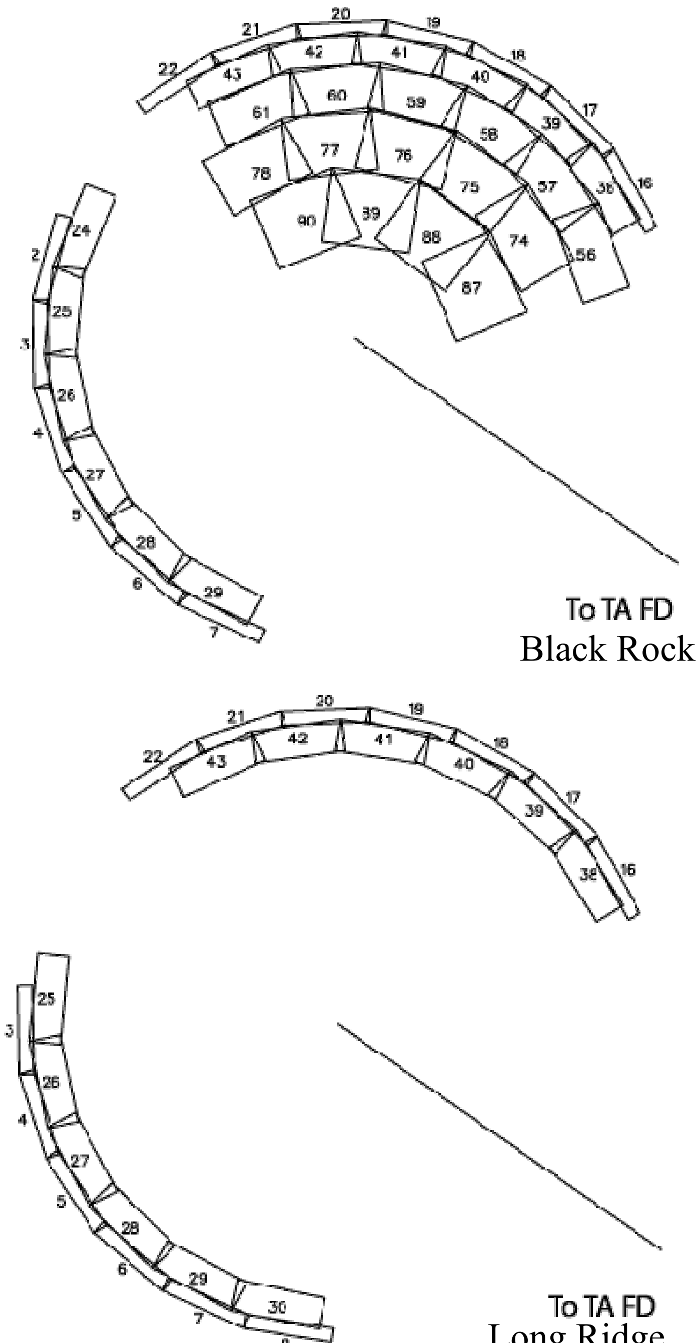
10^{18} eV



10^{20} eV

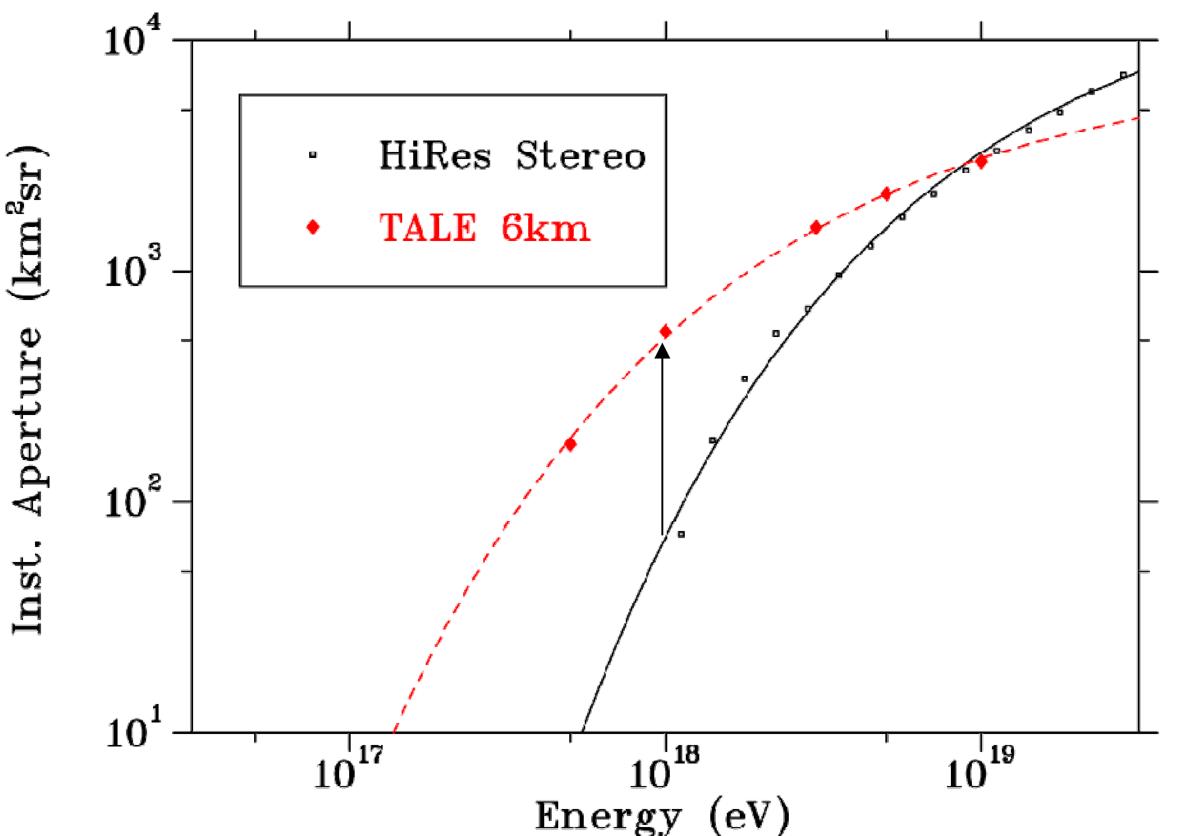
TA/TALE Aims

- Apertures:
  - High energy aperture: 3000 km^2 ster (3x HiRes)
    - half SD events,
    - half FD events (in mono, stereo, hybrid, stereo hybrid).
  - 10x HiRes stereo aperture at 10^{18} eV.
  - 10x HiRes/MIA hybrid aperture, $E < 10^{18}$ eV.
- Extend E_{min} down to $10^{16.5}$ eV.
- Measure all three spectral features in one experiment.
- Perform correlated spectrum-composition study at the second knee.
- Study the galactic-extragalactic transition:
  - Mixed composition at low energies: Watch the heavy elements die away ($\sim 10^{17.5}$ eV).
  - Observe light composition above 10^{18} eV.
- Study anisotropy in the northern hemisphere.



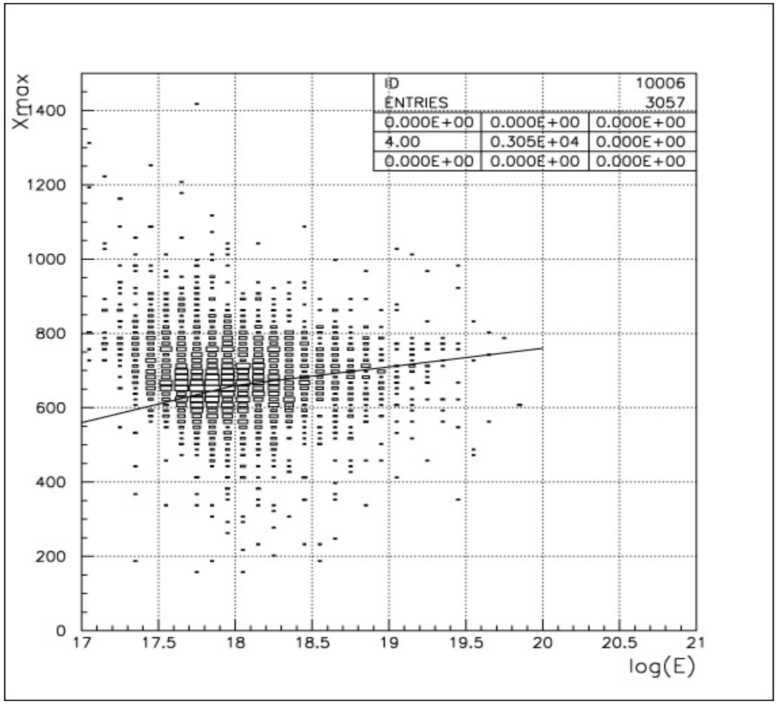
Site Configuration and Aperture Calculation

- Two very similar configurations: (3-31° elevation & 220° azimuthal) + ***Tower mirrors****
- Stereo trigger
- At least 6° track "length" in each "eye"
- Xmax is seen



HiRes (plus Auger and TA) Lower-energy Limitations

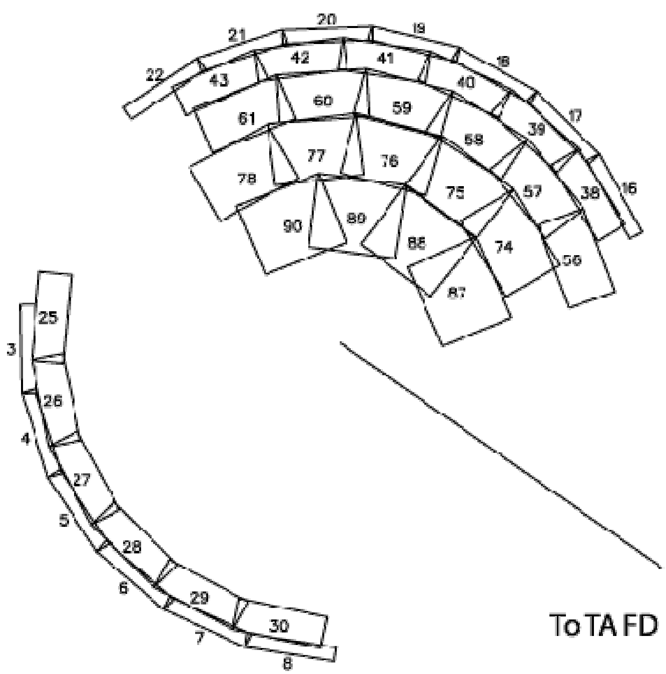
- HiRes observes elongation above $10^{18.0}$ eV clearly.
- HiRes looks up to 31°, can't see X_{max} for close-by (low energy) events.
- Makes spectrum measurements difficult below $10^{17.5}$ eV.
- Composition bias for $E < 10^{18.0}$ eV.

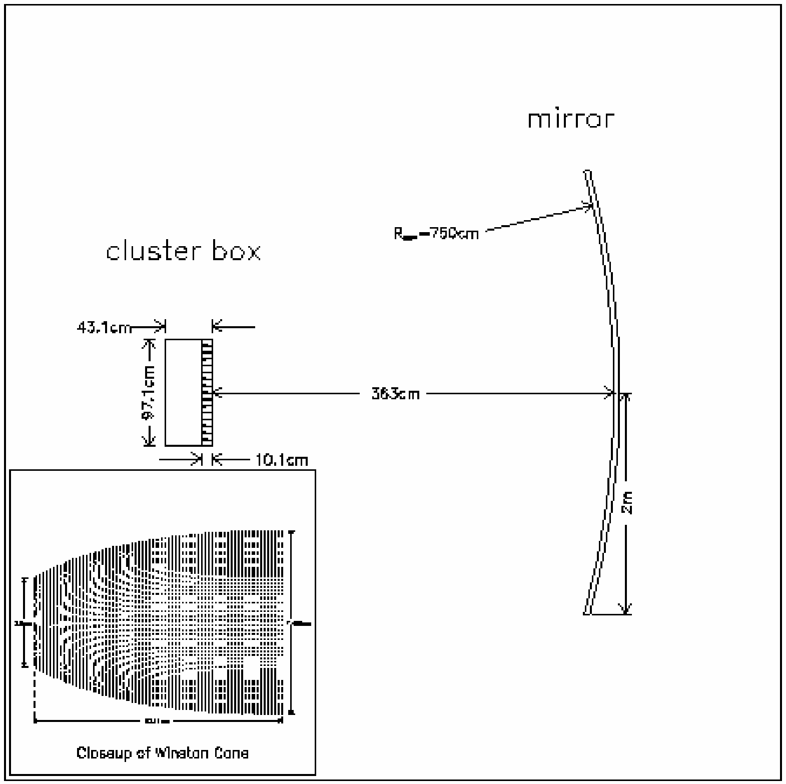


Before bracketing and Cerenkov cuts

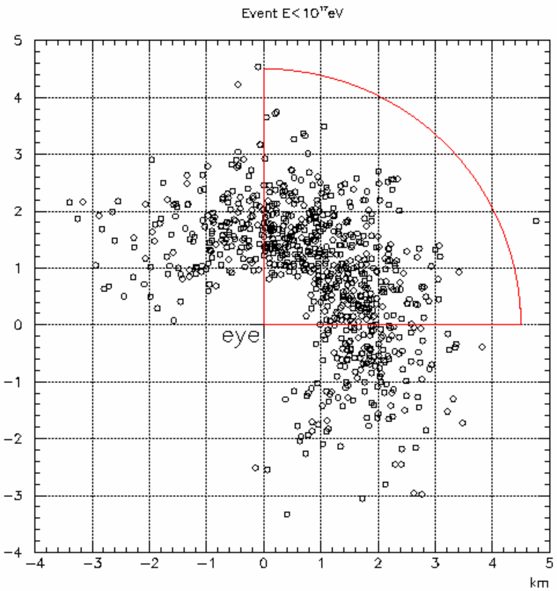
Observe the Second Knee in Hybrid Mode with a Tower Detector

- Two improvements
  - Use bigger mirrors.
  - Look higher up.
- Tower detector with 3x mirrors:
  - 750 cm radius of curvature.
  - Use HiRes-type phototubes with Winston cones.

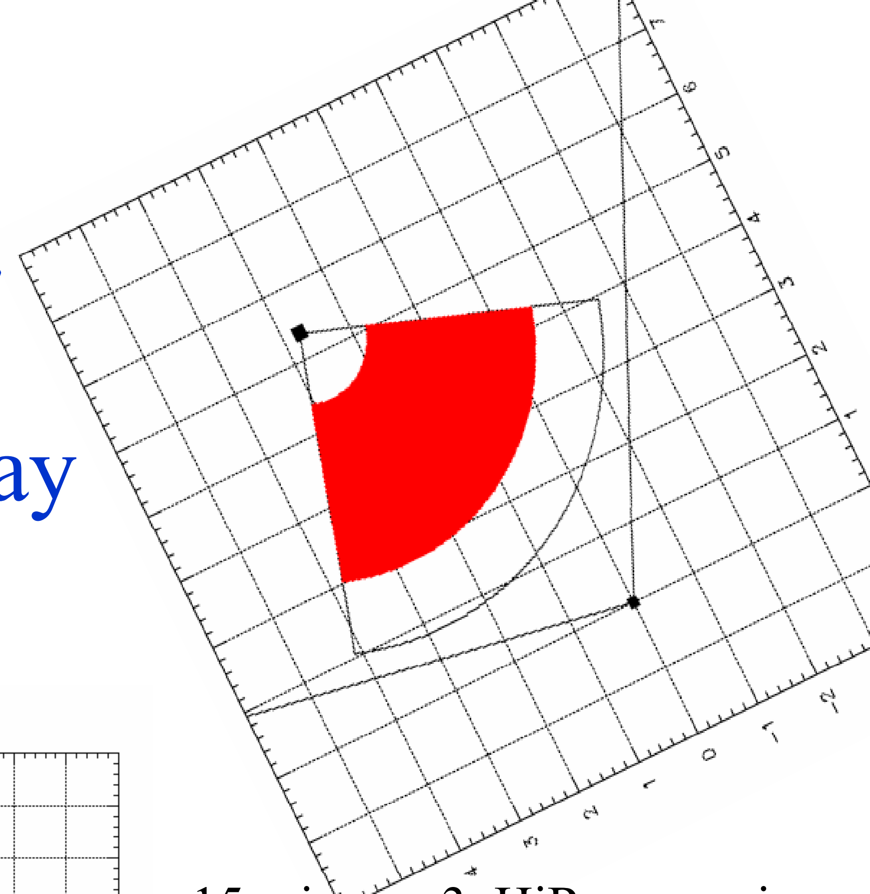


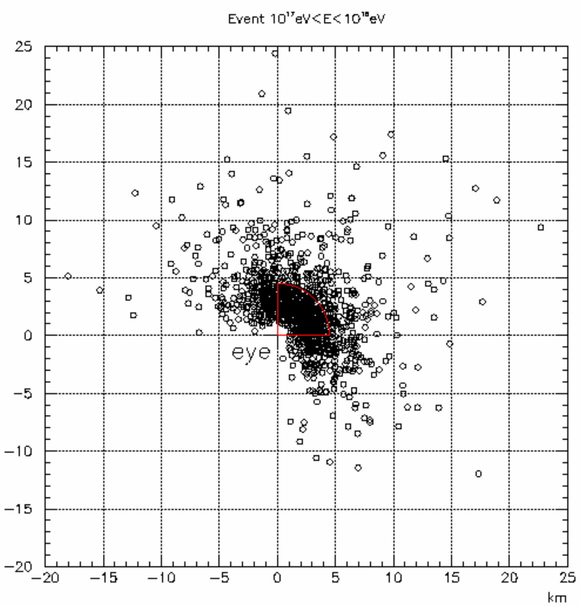


E<10^{17} eV

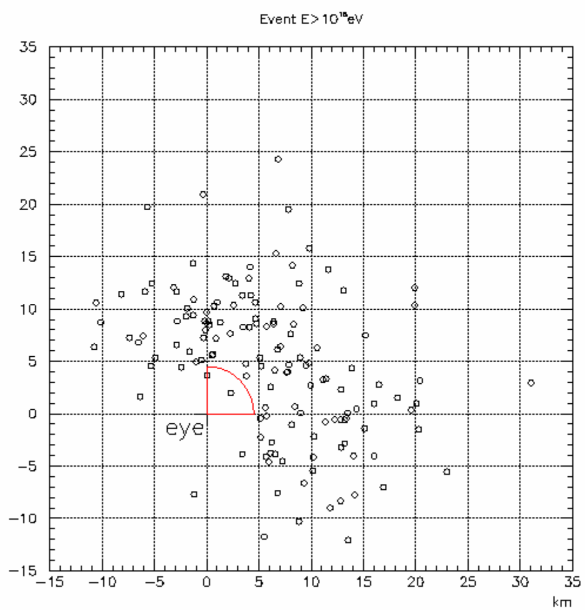


TA FD, Tower, Infill Array





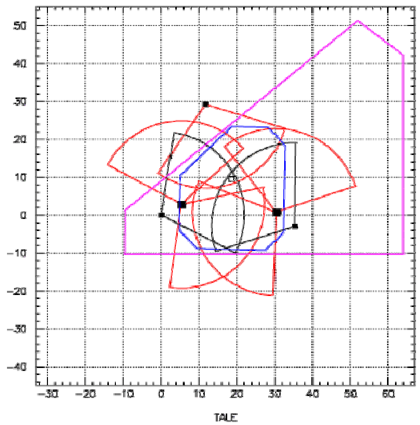
10^{17}<E<10^{18}



E>10^{18} eV

- 15 mirrors, 3xHiRes area, in rings 3,4,5.
- 111 AGASA counters, spacing of 400m, shown in red. Can see events hitting outside also.
- 10 x HiRes/MIA hybrid aperture.

TA/TALE Anisotropy



- HiRes + AGASA see correlations with BL Lac's.
- Point source figures of merit at 10^{19} eV:

(HiRes has 31 events above bkg correlated with BL Lac's)

Experiment	**Aperture** (km^2 ster)	**Resolution**	**Figure of Merit** (A/Resolution^2)
HiRes stereo	300 (avg)	0.5 deg	1200
TA/TALE stereo	340	0.5	1360
TA SD	1500	1.5	667
Auger SD	6600	1.5	2933 (1000)
TA/TALE hybrid stereo	260	0.1	**26000**

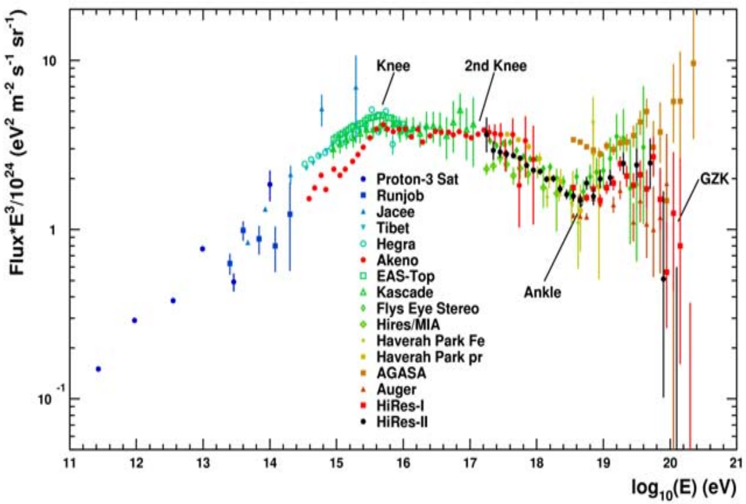
Multi-energy observations are important!

TA/TALE – Auger Comparison

Item	**TA/TALE**	**Auger**
Hemisphere	Northern	Southern
Energy range	$10^{16.5} – 10^{20.5}$ eV	$10^{18.5} – 10^{20.5}$ eV
Total Aperture	3000 km^2 ster	8000 km^2 ster
Good Resolution Aperture	1500 km^2 ster	800 km^2 ster
Poor Resolution Aperture	1500 km^2 ster	7200 km^2 ster
Galaxy Center/Anticenter	No/Yes	Yes/No
BL Lac’s	Yes	No

Structure → Physics

- We have a good idea what causes the
  - Knee
  - Ankle
  - GZK cutoff
- We have a pretty good idea where the galactic/extragalactic transition is.
- The biggest unanswered question is: What is the second knee?
- Study it using correlated spectrum/composition measurements.



Summary

- **HiRes has observed the GZK cutoff.**
  It occurs at $(5.6 \pm 0.7 \pm 0.9) \times 10^{19}$ eV.
- We see the "ankle" of the cosmic ray spectrum.
- We have evidence for the galactic/extragalactic transition.
- We have hints of interesting anisotropy.
- We will continue these studies with TA and TALE.