Results from the HiRes Experiment

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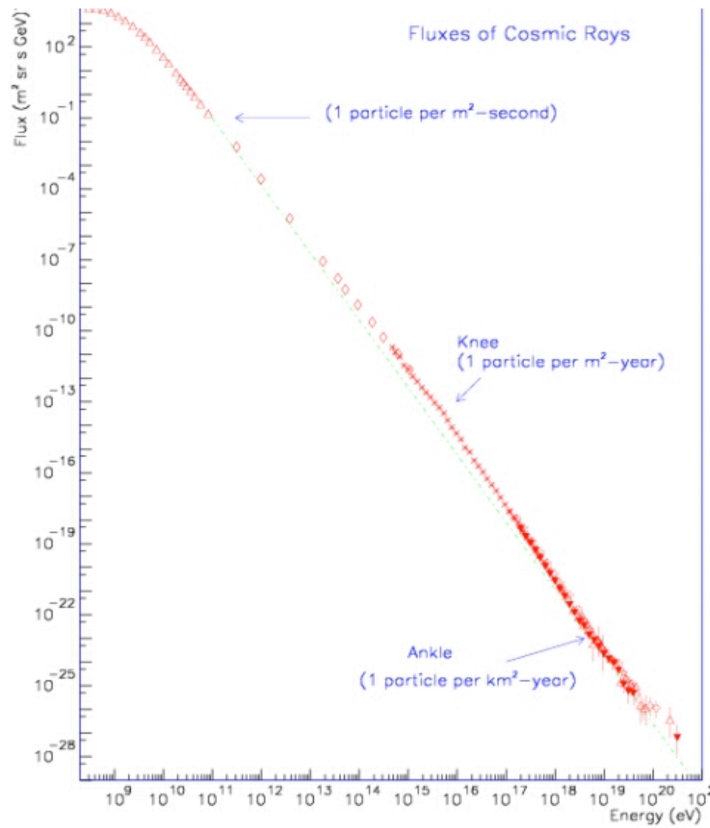
TeV Particle Astrophysics Workshop
July 13-15, 2005

Outline

- Introduction: the Important Questions
- Cosmic Ray Spectrum
- Composition of Primary Cosmic Rays
- Anisotropy Studies
- Summary
  - Some of the Answers
  - New Questions

Cosmic Rays over a Wide Energy Range

- At lower energies, spectrum of cosmic rays is almost featureless.
  - Only the “knee” at $10^{15.5}$ eV.
  - Learn about galactic sources.
- Big change expected at higher energies (>10^{17} eV.):
  - Change from galactic to extragalactic sources.
  - Expect features due to interactions between CR protons and CMBR photons.
  - Learn about extragalactic sources; and propagation over cosmic distances.



Important Questions about UHE Cosmic Rays

- Do extragalactic cosmic ray protons interact with photons of the CMBR?
  - Does pion production suppresses the flux above 6×10^{19} eV (the GZK suppression)?
  - Does e^+e^- pair production leave a signature?
- Where does the flux of galactic sources give way to that of extragalactic sources?
  - The Milky Way is a milquetoast galaxy; $E_{max} < 10^{18.5}$ eV
  - QSO's, AGN's are violent, give higher E_{max} ($>10^{20}$ eV)
- What are the extragalactic sources? What are their properties?
  - QSO's? AGN's? GRB's? ???
  - Can we point to any sources?
  - Spectral index and E_{max} distribution?
  - Evolution of the sources?

HiRes Experiment:
Has the World's Highest Exposure

- HiRes is a fluorescence experiment studying UHE cosmic rays.
- Fluorescence yield:
  - Charged particles excite N_2 molecules.
  - Emit ~5 photons/mip/meter.
  - 300-400 nm wavelength.
  - High energy showers are bright.
- HiRes has two detectors located atop desert mountains in west-central Utah.
- Collect 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, covers $10^{18.5} < E < 10^{20.5}$ eV.

High Resolution Fly's Eye (HiRes) Collaboration

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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).

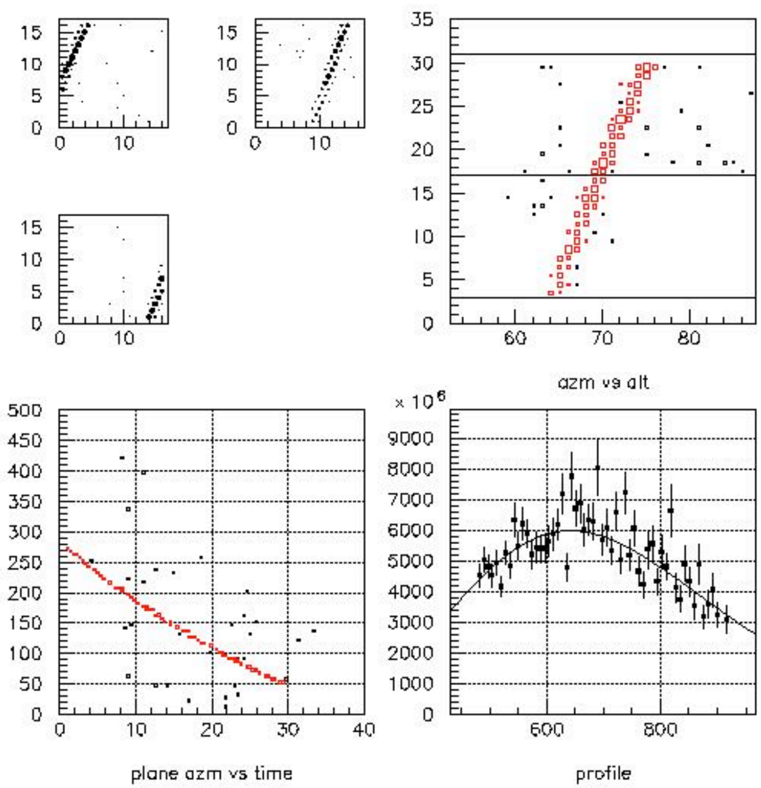
- HiRes2: Atop Camel's Back Ridge
- 12.6 km SW of HiRes1.
- 42 mirrors, 2 rings (3<altitude<31 degrees).
- FADC electronics (100 ns period).

Mirrors and Phototubes

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

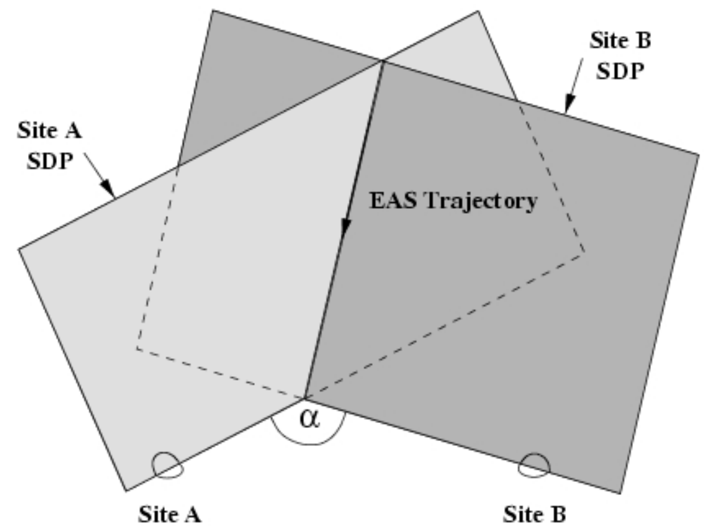
Monocular Data Analysis

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



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.
- See T. Abu-Zayyad's talk.

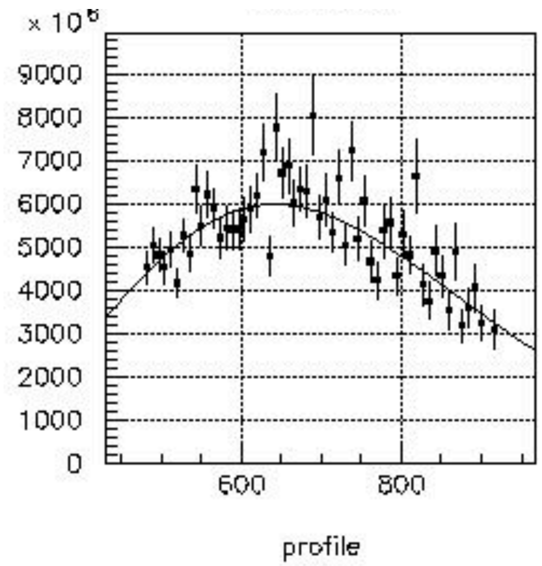


Back of Envelope
Energy Calculation

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

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

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

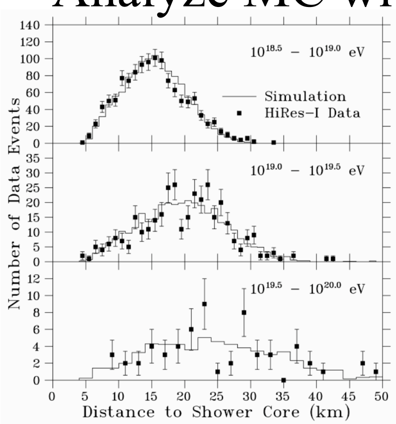


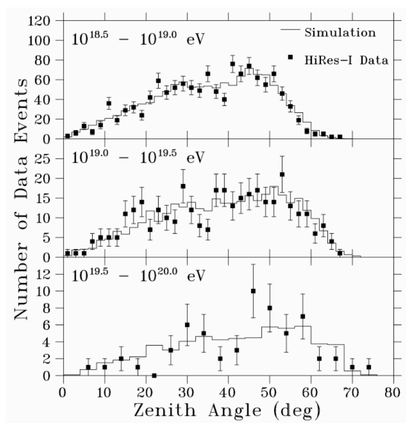
- Energy determination is robust.
- Based on center of shower, not tails.
- Easy to Monte Carlo.

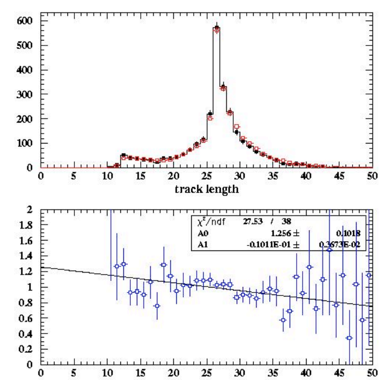
Monocular Spectra:

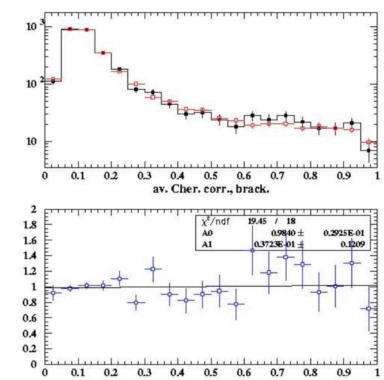
Data / Monte Carlo Comparisons

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.
Analyze MC with exact programs used for data.









Result: excellent simulation of the data.

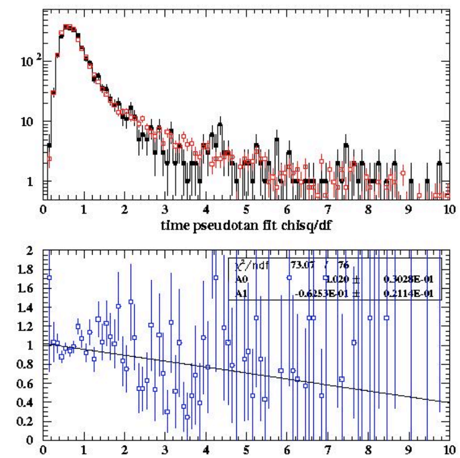
(Steeply Falling) Spectrum Calculation

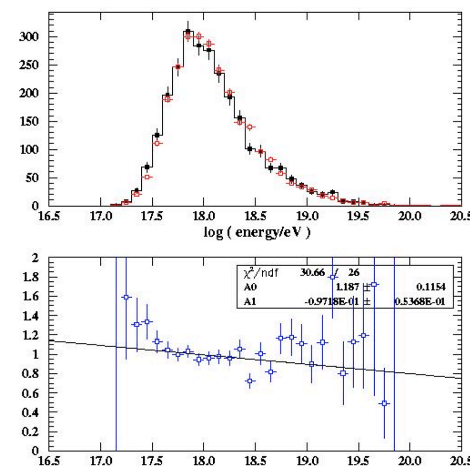
$$J(E) = \frac{D(E)}{A(E)} \frac{T(E)}{Area \times \Omega t dE}$$

- Resolution is correctly modeled; D(E)/A(E) = constant; shape of spectrum comes mostly from T(E).
- First order correction for resolution.
- Possible bias: GZK appears in data, but not in MC.
- Second order correction:

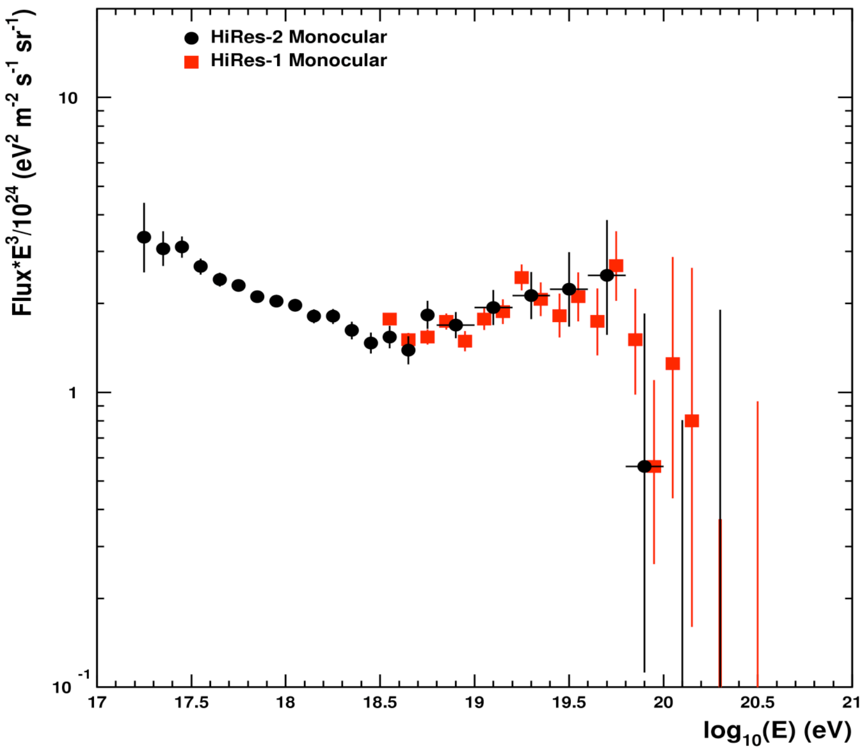
$$b(E) = \left(\frac{T(E, noGZK)}{A(E, noGZK)} - \frac{T(E, GZK)}{A(E, GZK)} \right) D(E)$$

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





Monocular Spectra

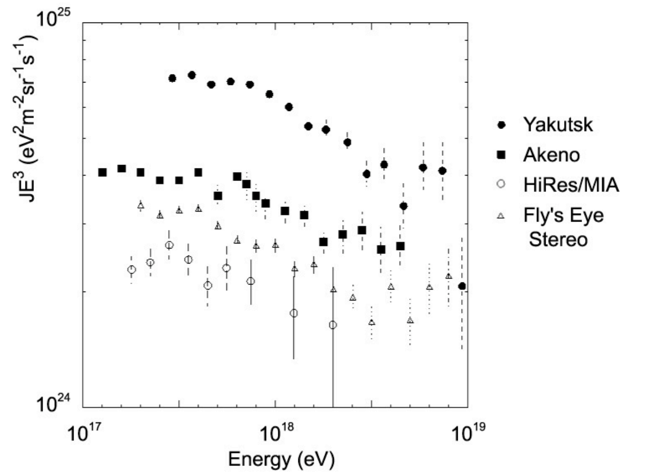


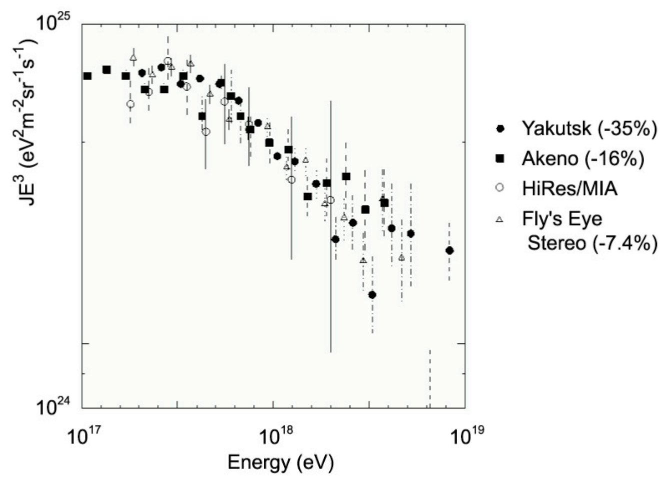
HiRes1: 7/97-5/05
HiRes2: 12/99-5/03

We observe: ankle;
high-energy suppression;
second knee?

Second Knee at $10^{17.6}$ eV

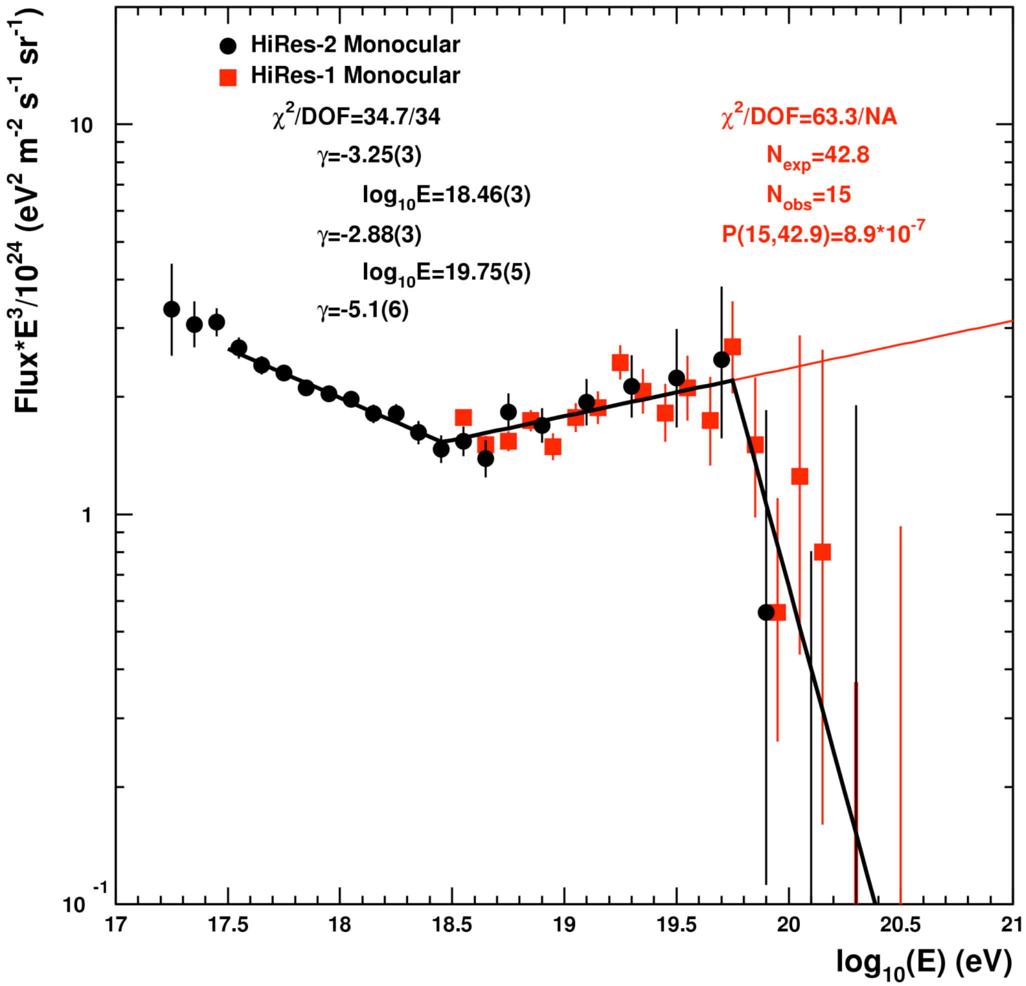
- Yakutsk, Akeno, Fly's Eye Stereo, HiRes Prototype/MIA all saw flat spectrum followed by a steepening in the power law. The break is called the second knee.
- Correct for varying energy scales: all agree on location of the second knee.
- There are THREE spectral features in the UHE regime.
- We need an experiment, with wide enough energy range, which would see the three UHE cosmic ray features with good statistics!





4.8σ Observation of the GZK Suppression

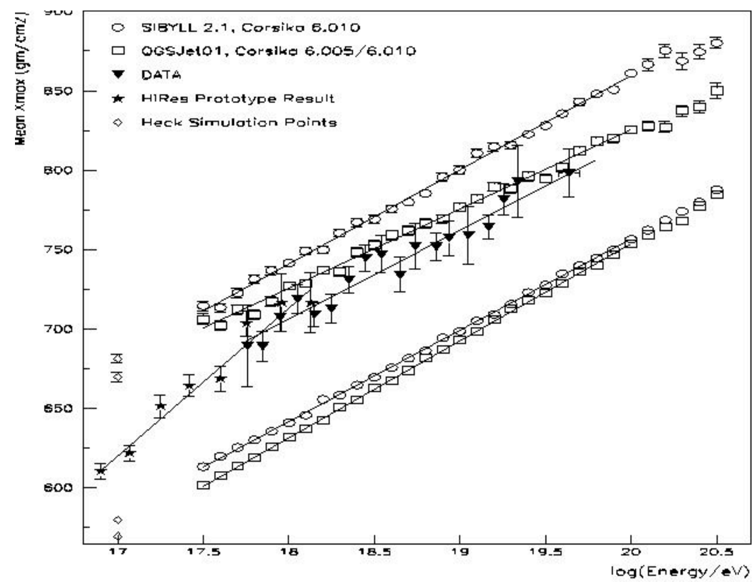
- Broken Power Law Fits
  - No Break Point
    - Chi2/DOF = 120/38
  - One BP
    - Chi2/DOF = 59.3/36
    - BP = 18.43
  - Two BP's
    - Chi2/DOF = 34.7/34
    - 1st BP = 18.46
    - 2nd BP = 19.75
  - Two BP with Extension
    - Expect 42.8 events
    - Observe 15 events
    - Poisson probability: P(15;42.8) = **8.9×10^{-7}** (5 $\sigma = 2.85 \times 10^{-7}$)



$\langle X_{max} \rangle$ ➔ Composition

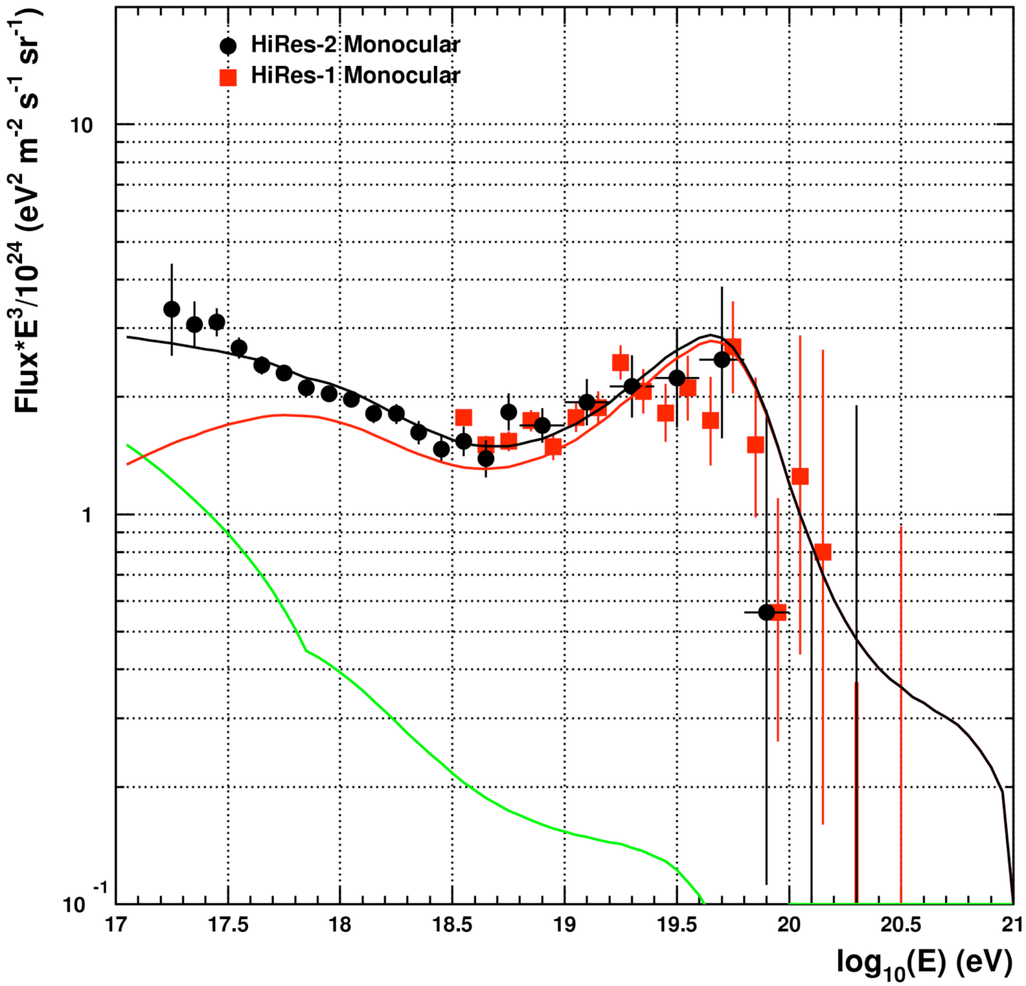
- Galactic – extragalactic transition is complete by 10^{18} eV.
- All fluorescence measurements of X_{max} are consistent.
- Only fluorescence experiments SEE X_{max}.
- Berezinsky, Hillas, Allard *et al.* agree that composition is very light at ankle:

➔ $\langle X_{max} \rangle$ of protons is ~10g/cm^2 above our measurement (radiosonde correction coming up in K. Belov's talk).



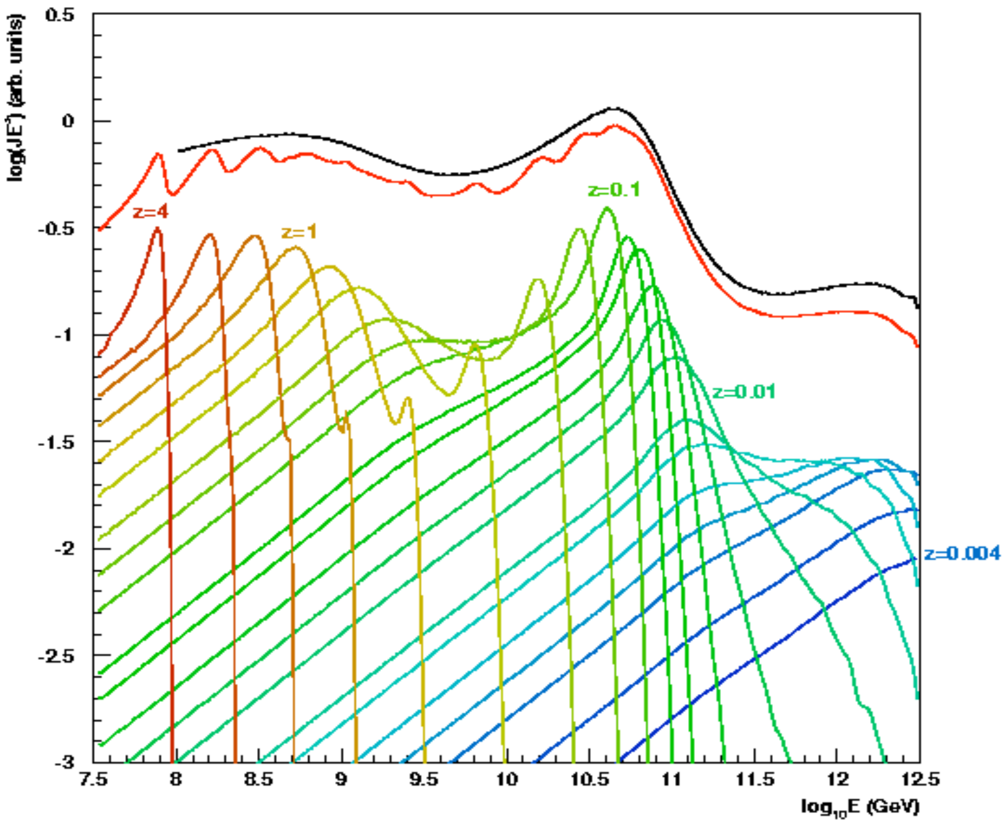
Fit Spectrum and Composition Simultaneously

- Fit composition and spectrum simultaneously.
  - Heavy = galactic,
  - Light = extragalactic.
- Extragalactic model:
  - Spectral index γ,
  - $E_{max} = 10^{21}$ eV,
  - $\rho = const*(1+z)^m$.
  - Energy loss from interactions with CMBR and uniform expansion.
- Best fit:
  - m = 2.25
  - γ = -2.385
  - Chi2 = 63/37



Interpretation of Extragalactic Spectrum

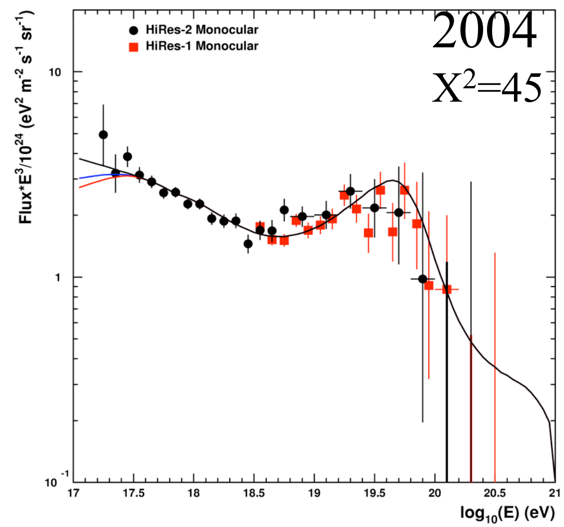
- Pion-production pileup causes the bump at $10^{19.5}$ eV.
- e^+e^- pair production excavates the ankle.
- Pileup at location of second knee.
- Fractionation in distance and energy; e.g., z=1 dominates at second knee.
- Can cosmic ray physicists see evolution of sources?

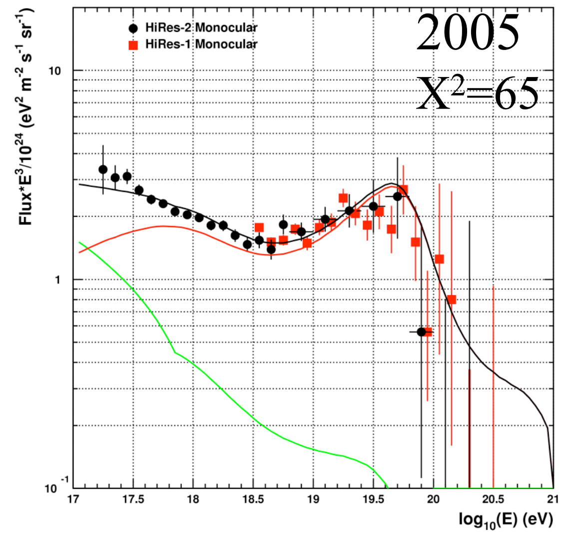


D. Bergman's plot of shells in z

Learning about UHECR Sources

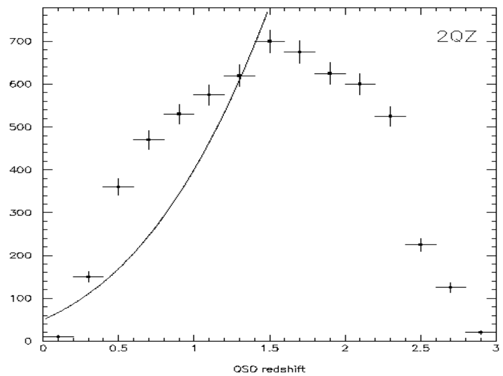
- Earlier spectrum fits: two problem areas.
  - Fit might be bad in $10^{19.6}$ eV region; not statistically significant.
  - Second knee is too weak in model, just where QSO evolution changes.
- Latest spectrum, better statistics: fit is bad in $10^{19.6}$ eV region.
- Better statistics yields information about sources.
- Collaboration with P. Biermann to include in our model his study of extragalactic source E_{max} distribution.

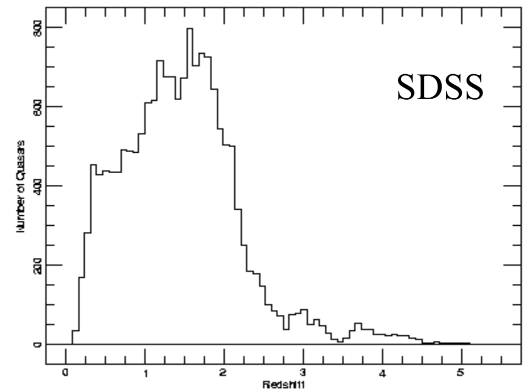




Cosmology with QSO's and AGN's

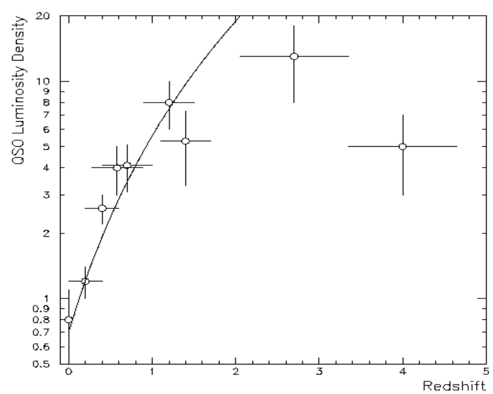
QSO density histograms:
Croom et al.,
Schneider et al.

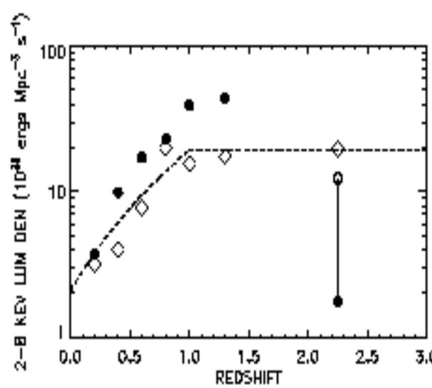




Lines: $(1+z)^3$

QSO luminosity density, optical
Boyle and Terlevich

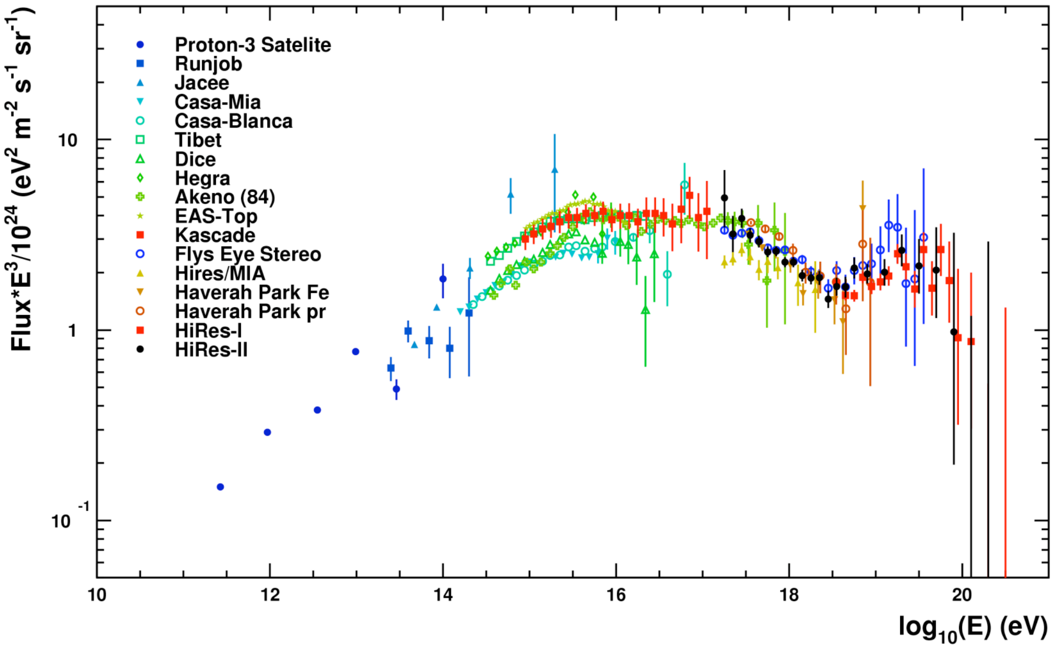




AGN luminosity density,
2-8 keV X-rays.
Barger et al.

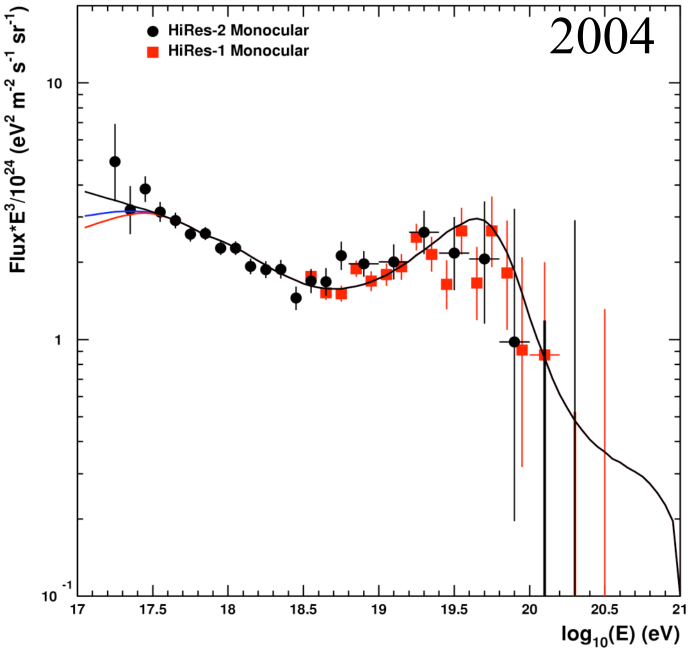
What Do the HiRes Data Say? One Assumption:

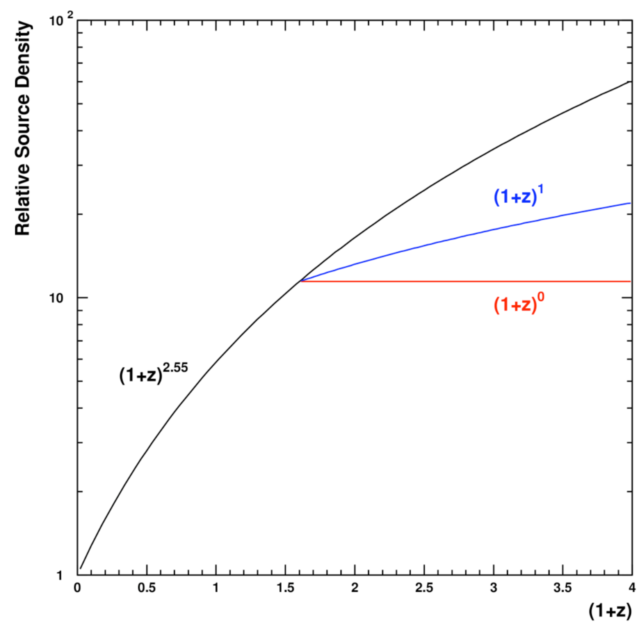
- Assume E^3J is flat below the second knee.



Cosmology *a la* HiRes?

- Adjust evolution to match QSO's:
  - m=2.6, z<1.6
  - Lower m, z>1.6
- HiRes has a hard time doing cosmology.
- Must extend spectrum and <Xmax> measurements lower by an order of magnitude.
- TA/TALE aim: measure spectrum from $10^{16.5}$ to over 10^{20} eV.



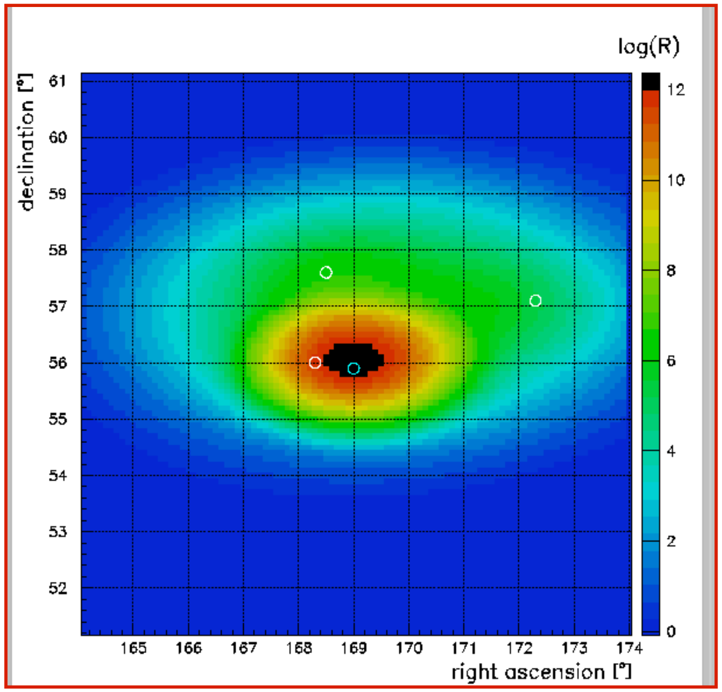


Anisotropy Studies

- Stereo anisotropy studies: excellent pointing resolution (0.6^o).
  - Search for point sources.
  - Search for BL Lac correlations.
- Monocular anisotropy studies: better statistics, wider energy range.
  - Search for large-scale structure.

Stereo Anisotropy: Good for Point Sources

- Max likelihood search in AGASA + HiRes data sets (include details of pointing accuracy) yields one possible joint source: the AGASA triplet + one HiRes event.
- Quartet may be first point source (Ursa Major). Chance probability = 0.006. **Needs confirmation.**
- See John Matthews' talk.

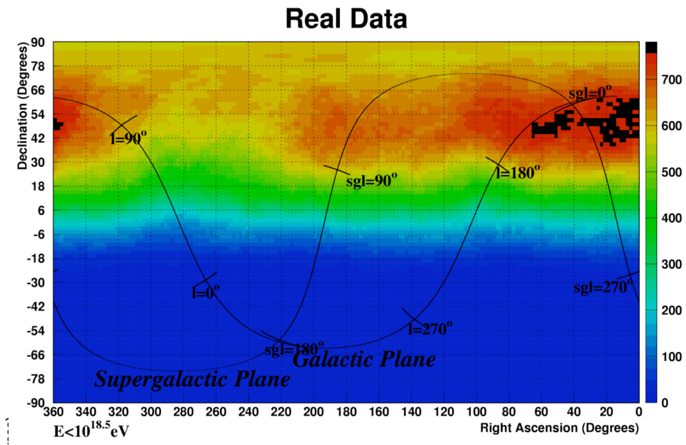


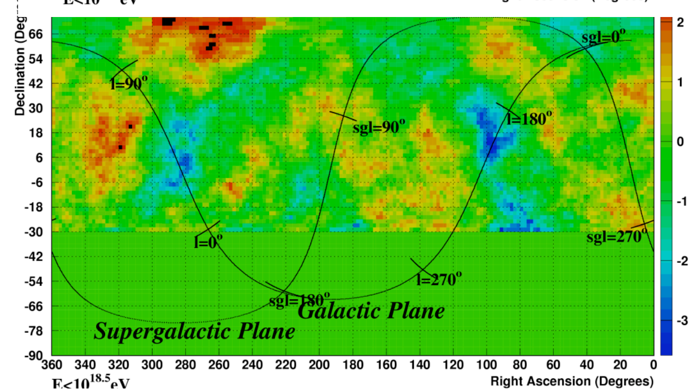
Stereo Anisotropy: Search for Correlations with BL Lac’s

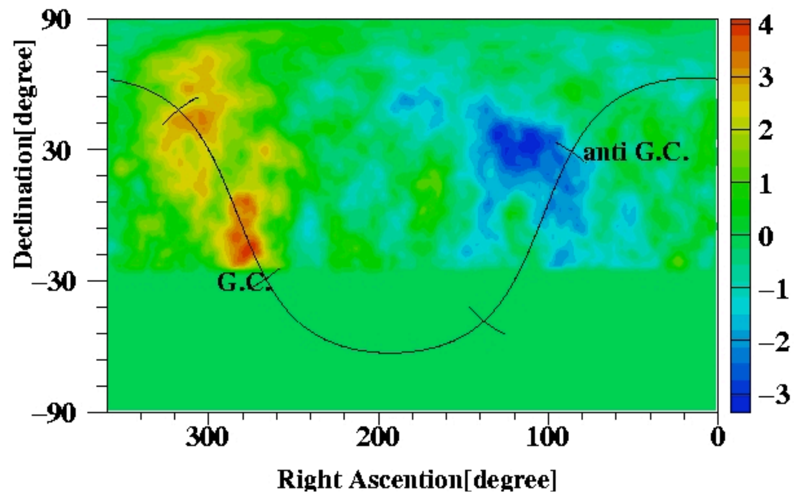
- Choose BL Lac sources from Veron catalog, m<18.
  - See correlations with HiRes events.
  - See correlations with TeV gamma ray sources.
  - **Needs confirmation.**
- Coming up in John Matthews’ talk.

Some Confirmation of Akeno/AGASA Large-Scale Structure

- HiRes-II mono anisotropy data: $10^{17.5} < E < 10^{18.5}$ eV, integrated over 20 deg. circle.
- Deficit of events along an arc in galactic anti-center direction.
- No ridge of events in Cygnus arm region.
- Need more summer data to see galactic center region.

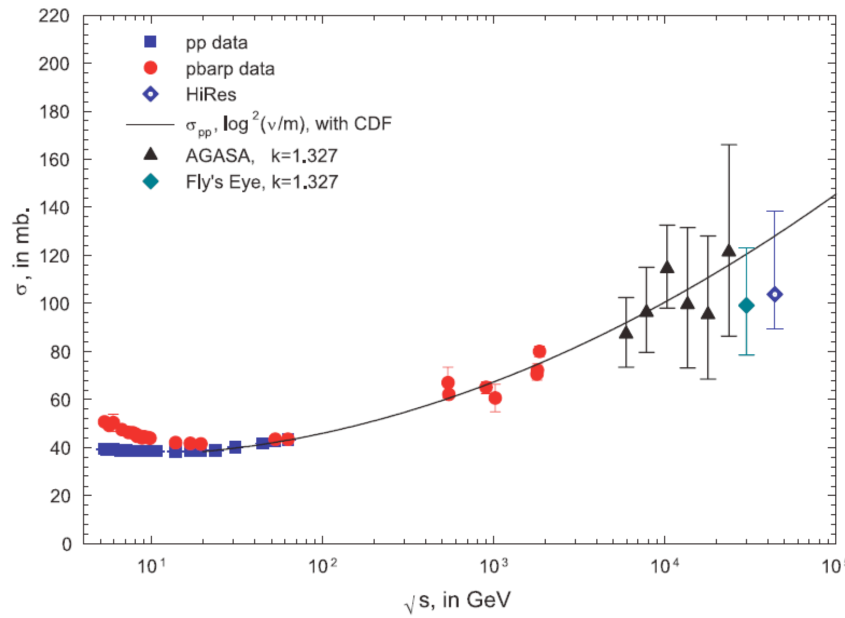






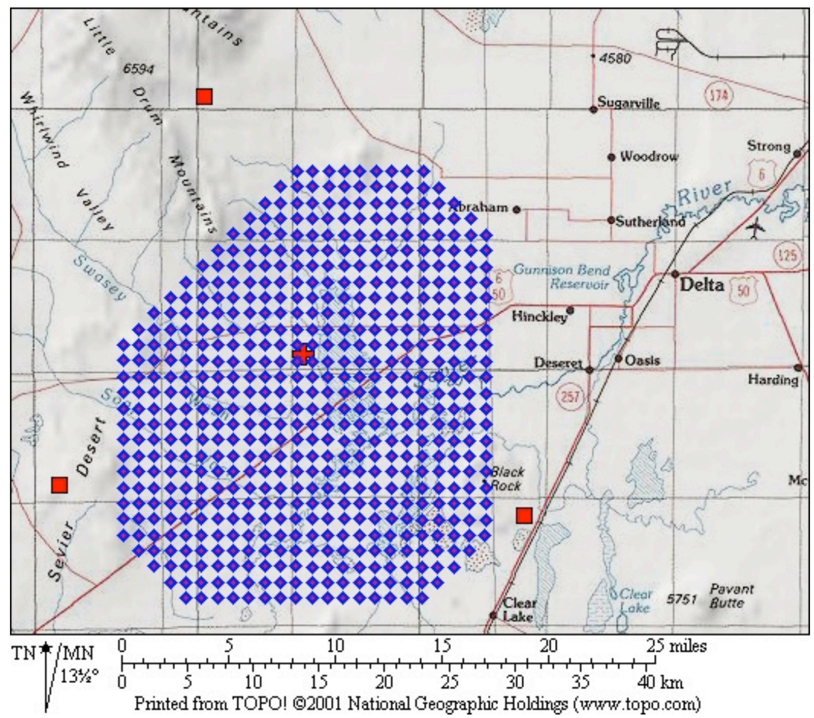
$\sigma_{p\text{-}air}$ Measurement

- New technique, less dependent on hadronic interaction models.
- Agrees with extrapolation of Block-Halzen fit to accelerator data.
- See K. Belov's talk.



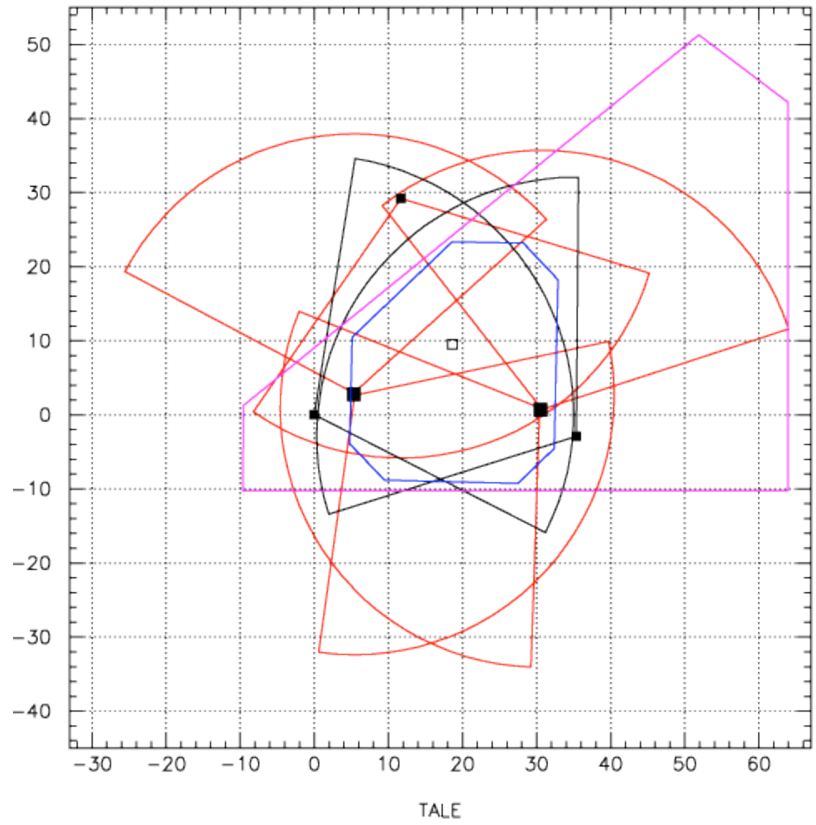
Future Experiment: The Telescope Array (TA) and TA Low Energy Extension (TALE)

- TA surface detector: 576 scintillation counters, 1.2 km spacing.
- 3 TA fluorescence detectors overlook SD, 108^{o} in azimuth each.
- 2 TALE fluorescence detectors plus infill array:
  - Observe the ankle with flat aperture.
  - Tower detector + infill array cover lower energies.
- Cover $10^{16.5} – 10^{20.5}$ eV.



TA/TALE Layout

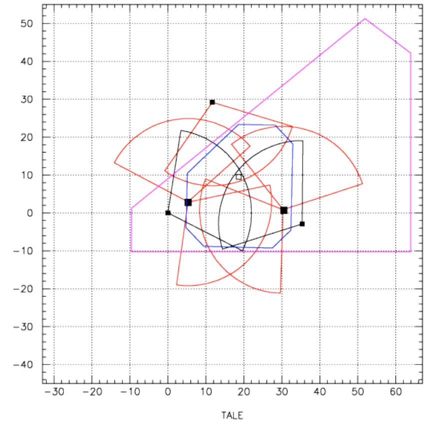
- Two 6-km stereo pairs: observe the ankle with flat aperture.
- Tower detector with 3 times larger mirrors: reach down to $10^{16.5}$ eV.
- Infill array for hybrid observation at the lowest energies.



TA/TALE

- Apertures:
  - High energy aperture: 3000 km^2 ster, 3xHiRes
    - half SD,
    - half fluorescence (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.
- Study the ankle with flat aperture.
- Study the galactic-extragalactic transition:
  - Mixed composition at low energies: several heavy elements contribute; compare with Kascade and Kascade-Grande.
  - Watch the heavy elements die away ($\sim 10^{17.5}$ eV).
  - Observe light composition above 10^{18} eV.
- Do cosmology.

TA/TALE (continued)



- 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
S. Auger SD	6600	1.5	2933
TA/TALE hybrid stereo	260	0.1	**26000**

Multi-energy observations are important!

TA/TALE is a Powerful Detector

- Spectrum measurements over four orders of magnitude in energy ($10^{16.5}$ to $10^{20.5}$ eV).
- Composition measurements in hybrid or stereo over entire energy range.
- Flat stereo aperture in ankle region.
- World's best point-source capability for multi-energy observations.

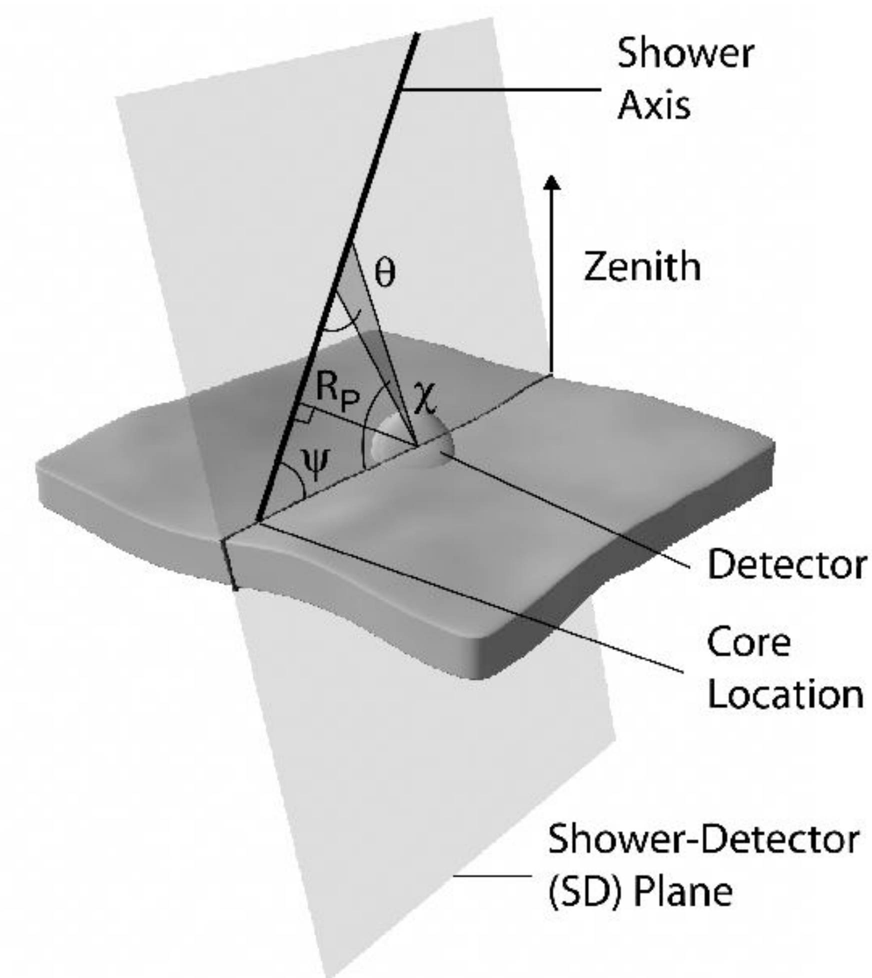
Summary

- HiRes has measured the spectrum and composition of cosmic rays.
- We see two of the three spectral features in the ultrahigh energy regime.
- We see the galactic/extragalactic transition.
- We have correlations with BL Lac's, other sources. These results must be confirmed.

Answers to Some Questions

- Do extragalactic cosmic ray protons interact with photons of the CMBR?
  - Does pion production suppresses the flux above $6x10^{19}$ eV (the GZK suppression)?
  - Does e^+e^- pair production leave a signature?
- Where does the flux of galactic sources give way to that of extragalactic sources?
  - The Milky Way is a milquetoast galaxy; $E_{max} < 10^{18.5}$ eV
  - QSO's, AGN's are violent, give higher E_{max} (>10^{20} eV)
- What are the extragalactic sources? What are their properties?
  - Can we point to any sources?
  - QSO's? AGN's? GRB's? ???
  - Spectral index and E_{max} distribution?
  - Evolution of the sources?

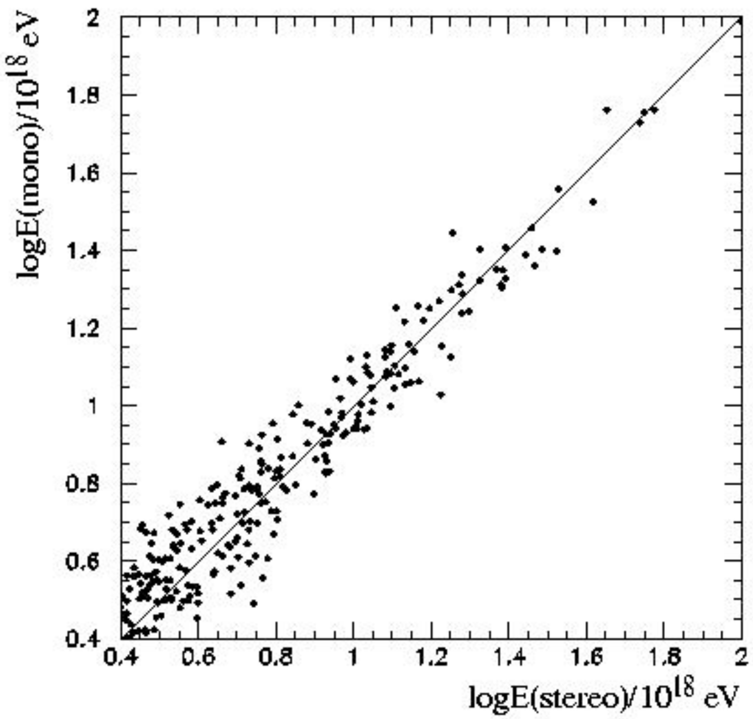
- YES! CR's interact with the CMBR.
  - GZK suppression is present.
  - e^+e^- pair production excavates the ankle.
- Transition is ~50/50 at 10^{17} eV; complete by 10^{18} eV.
- Extragalactic sources:
  - All source claims must be confirmed.
  - Breaks in evolution may show up in extragalactic spectrum in the 10^{17} eV decade.
  - γ can be measured. The E_{max} distribution will be tested soon.
  - The TA/TALE experiment will be able to observe source evolution.



Shower
Axis
Zenith
θ
R_P
χ
ψ
Detector
Core
Location
Shower-Detector
(SD) Plane

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.



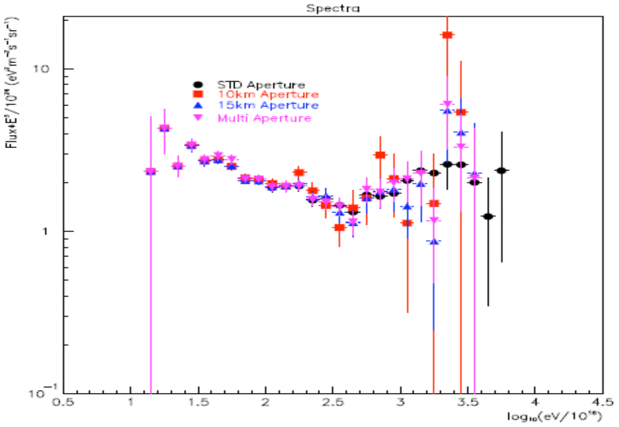
Main Systematic Uncertainties for Mono Spectrum Measurements

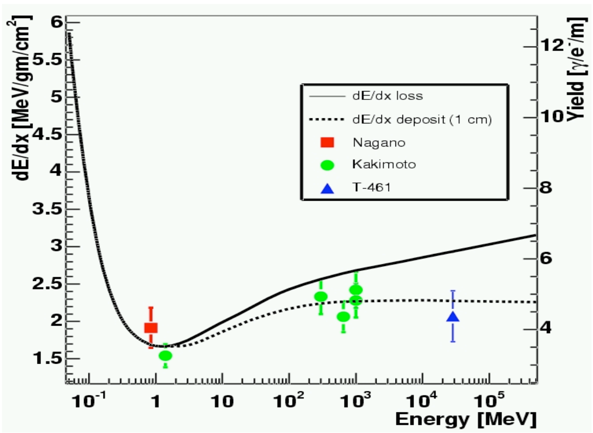
- Phototube calibration: 10%
- Fluorescence yield: 10% (being measured by the Flash experiment, among others)
- Unobserved energy in shower: 5%
- Modeling of the atmosphere: 15%

- Energy scale: 21%
- Flux: 31%

Mono Measurements are Robust

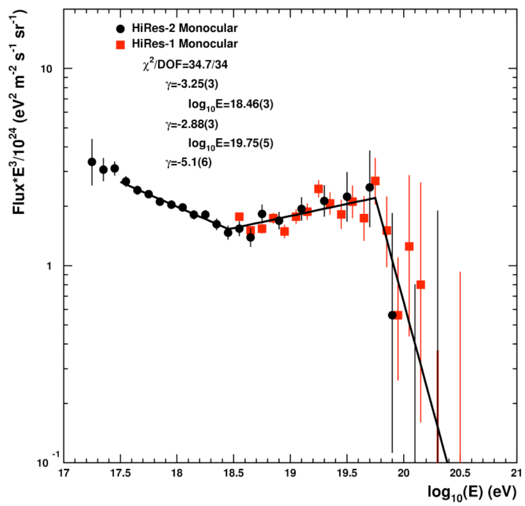
- Verified by stereo.
- Systematics:
  - Energy scale verified to ±10% (hpd + 4km laser shots).
  - Correction for hourly atmosphere is small (VAOD measured by two different techniques).
  - QGSjet and Sibyll MC's give same UHECR spectrum.
  - Check by limiting the aperture.
  - Fluorescence yield verified.





The Ankle is Important

- Berezinsky: ankle due to e^+e^- pair production.
  - Better evidence of CMBR interactions than GZK.
  - Shows that composition is protons [+ some Helium (Hillas); or "light" (Allard *et al.*)].
- Astrophysics: tells about cosmic ray sources.
  - rise from ankle ➔ spectral index at source.
  - fall to ankle ➔ evolution parameter, m.



Integral Spectra

- Want to test $E_{½}$ with integral spectra
- Use 2BP Fit with Extension for the comparison
- $\log_{10}E_{½} = 19.76_{-0.04}^{+0.12}$
- Berezinsky: $\log_{10}E_{½} = 19.72$, for wide range of conditions.