Extremely/Ultrahigh Energy Cosmic Rays and the High Resolution Fly's Eye (HiRes) Experiment

The 6th Annual Workshop on Very High Energy Particle Astronomy

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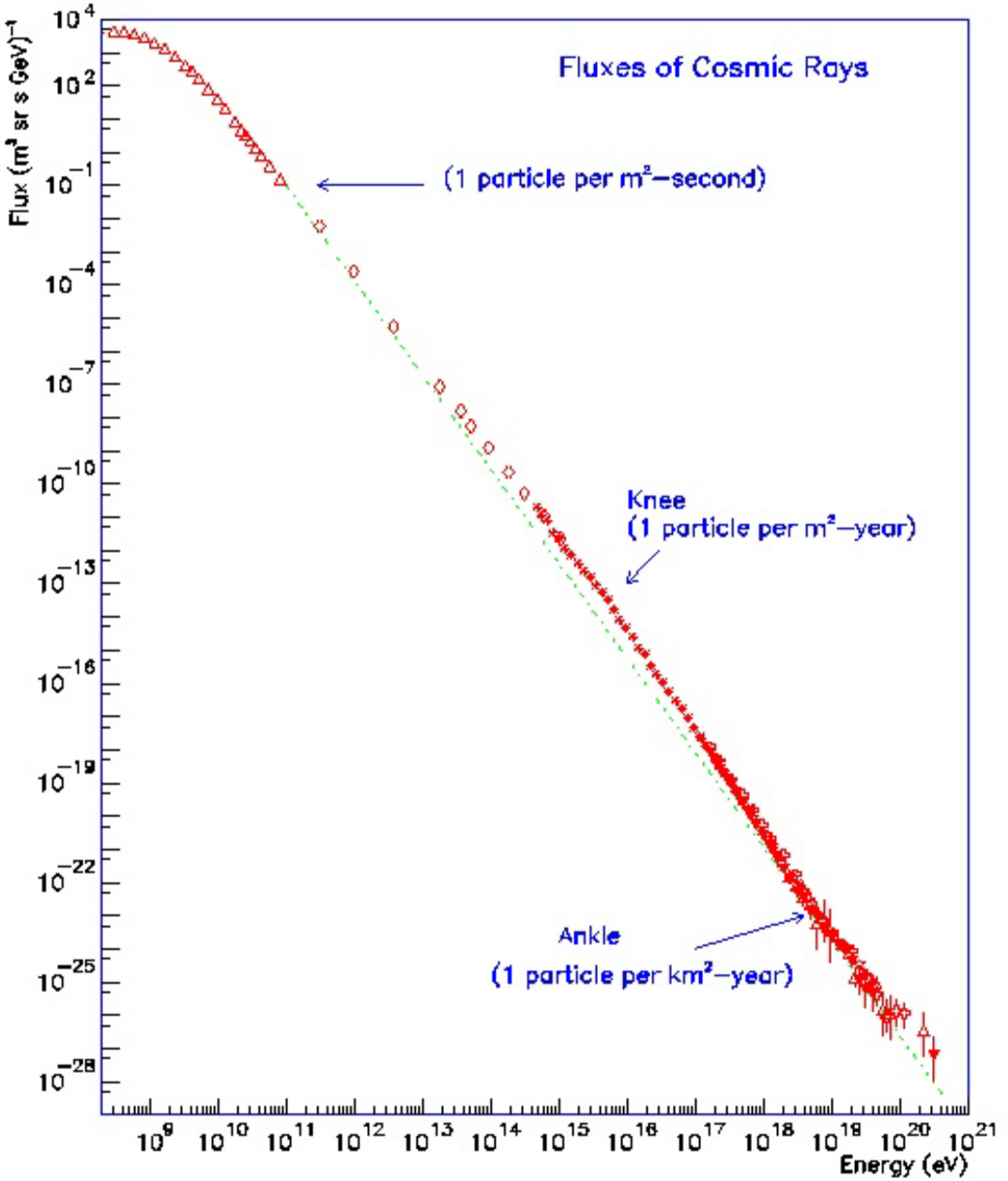
Cosmic Ray Energy Spectrum

- Cosmic Rays with energies in excess of **10^{20} eV** have been reported:
- Over the full range 10^9-10^{20} eV, the spectrum follows roughly a single power law of spectral index ~3 **(non-thermal!!!)**
- changes of slope appear at:
  - ~10^{15} eV (Knee)
  - ~5x10^{18} eV (Ankle)



Compilation by Simon Swordy

Ultrahigh Energy Cosmic Rays

- **Cosmic Rays @ E > ~10^{17} eV are referred to as "Ultra-High Energy Cosmic Rays" (UHECR) or extremely high energy cosmic rays (EHECR)**

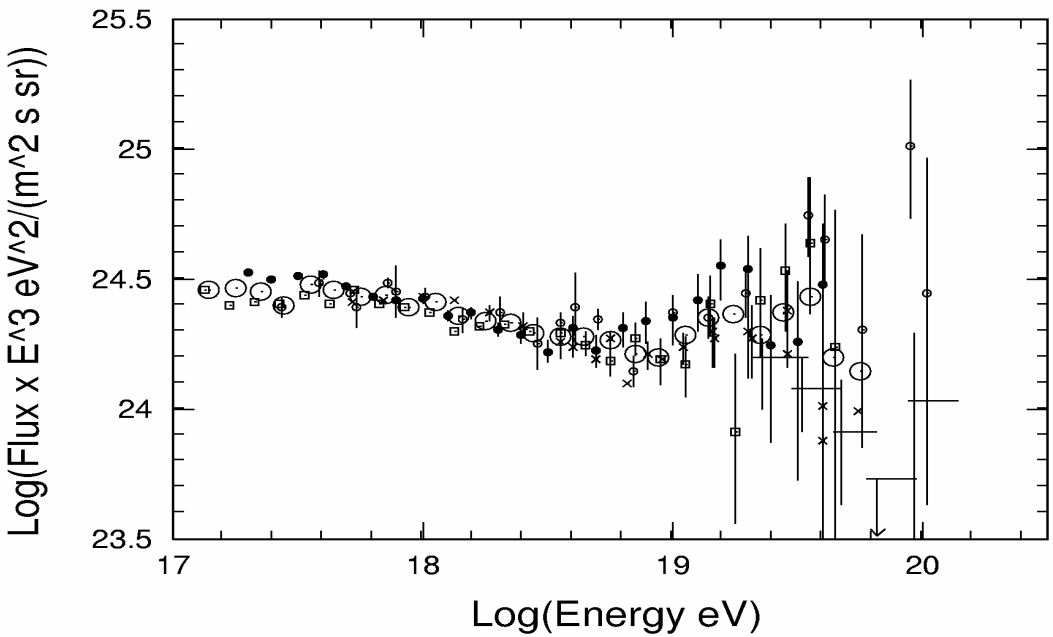


Figure 1: Combined differential energy spectra ($\times E^3$) from the Haverah Park, Fly's Eye (stereo), Yakutsk, and Akeno experiments. The energy scale of each experiment has been slightly shifted to match the Fly's Eye result at 10^{18} eV. Larger open circles are geometric averages of the four experiments.

It is customary to plot the UHECR flux multiplied by E^3 in order to reveal the subtler structures in the spectrum

The Physics Issues

- **What are they?**

  Apparent shift from heavy to light composition in the UHE regime (Galactic→Extra-Galactic flux? Where does this occur?).

  Proton dominance at the highest energies→GZK cutoff?

- **Where do they come from?**

  No **confirmed** reports/claims of significant excesses yet.

  Is UHECR astronomy even feasible?

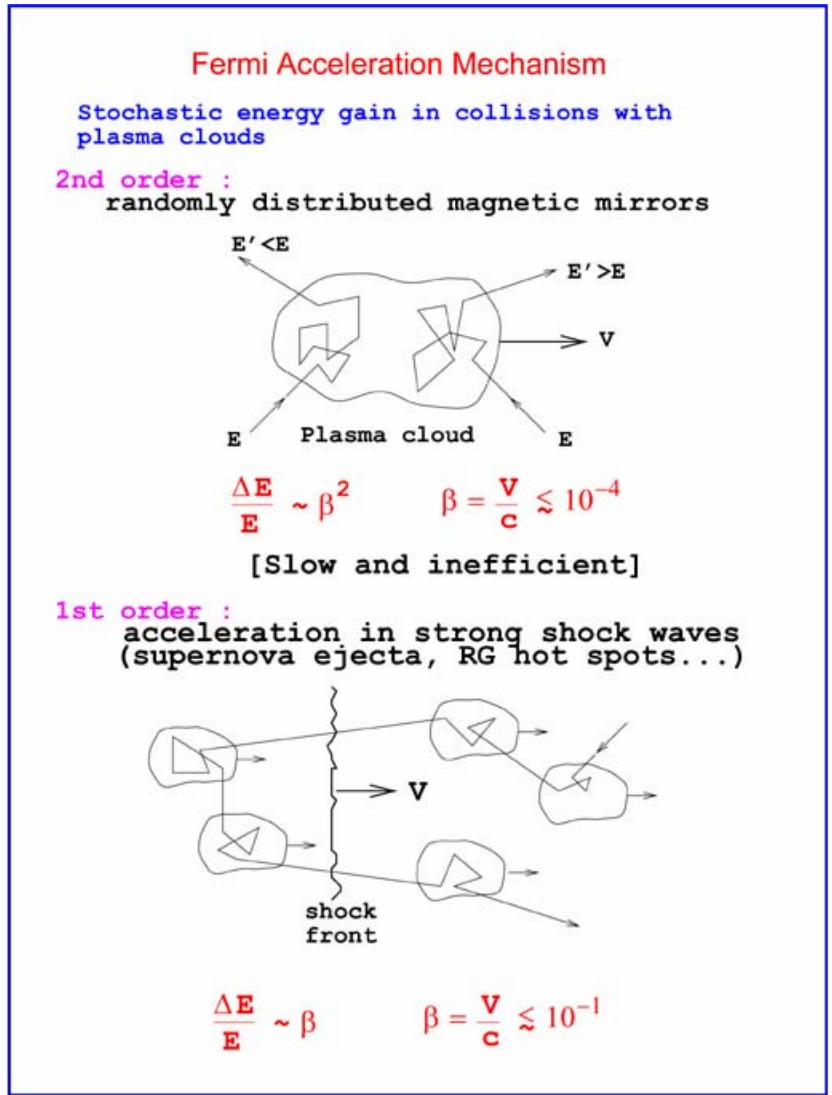
- **How are they made / accelerated?**

  Shock Acceleration? (from SNR? GRB?)

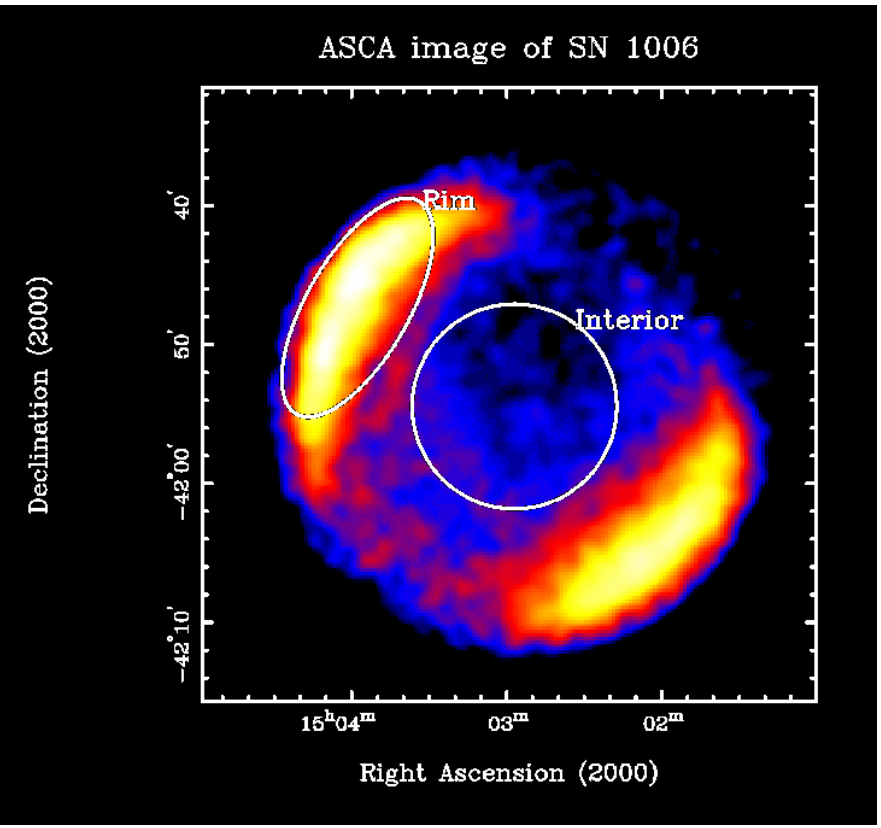
  must explain power law and index ~3.

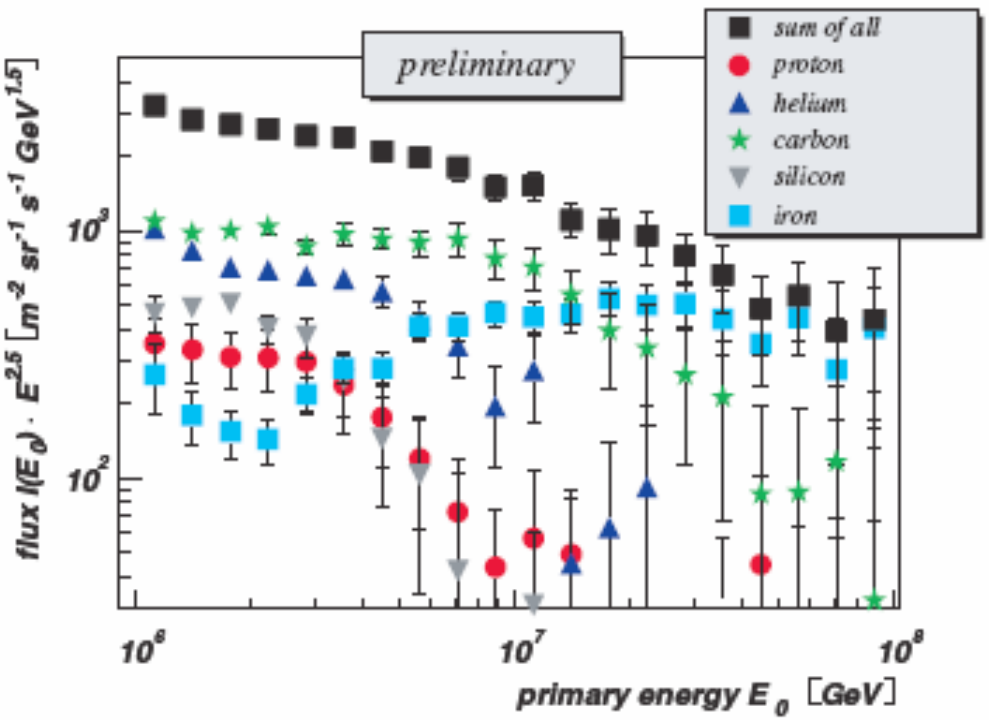
Everybody's (well…almost) Favorite Acceleration Mechanism

- Diffusive Shock Acceleration (1st Order Fermi Acceleration):
  - Particles repeatedly crossing a shock front: collisions are always "head-on"



Possible Source of Shock Acceleration: SNR





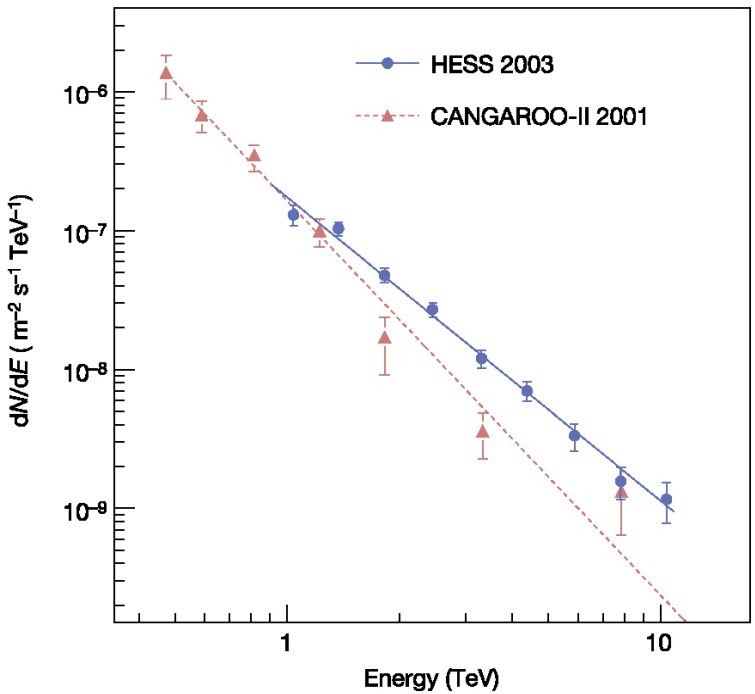
Observation of non-thermal X-rays from SN1006 by ASCA (1995) shows possible signature of shock acceleration of electrons

- KASCADE results compatible with SNR acceleration of cosmic rays up to ~10^{16} eV
- Z-dependent cut-off gives plausible explanation of the "knee".

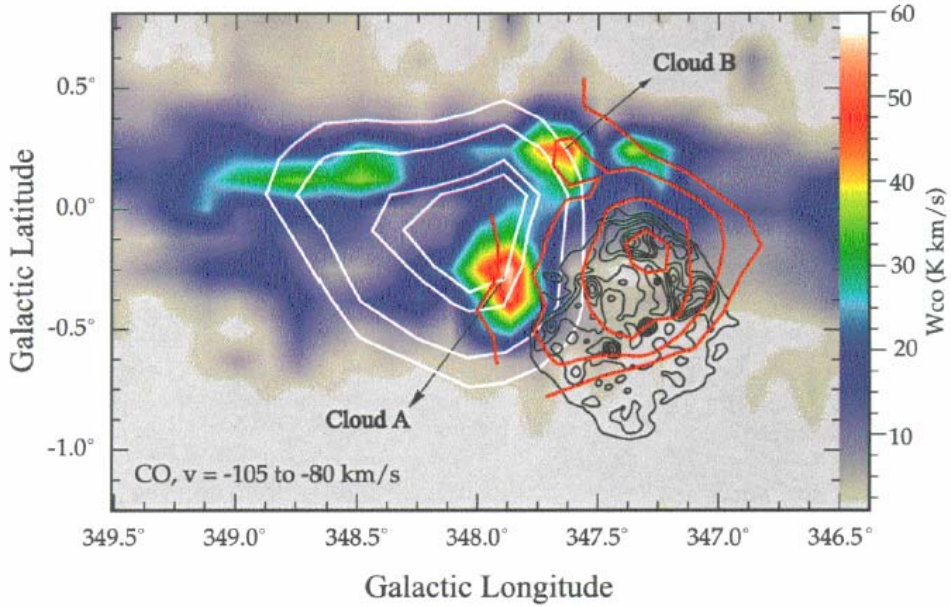
Shock Acceleration?

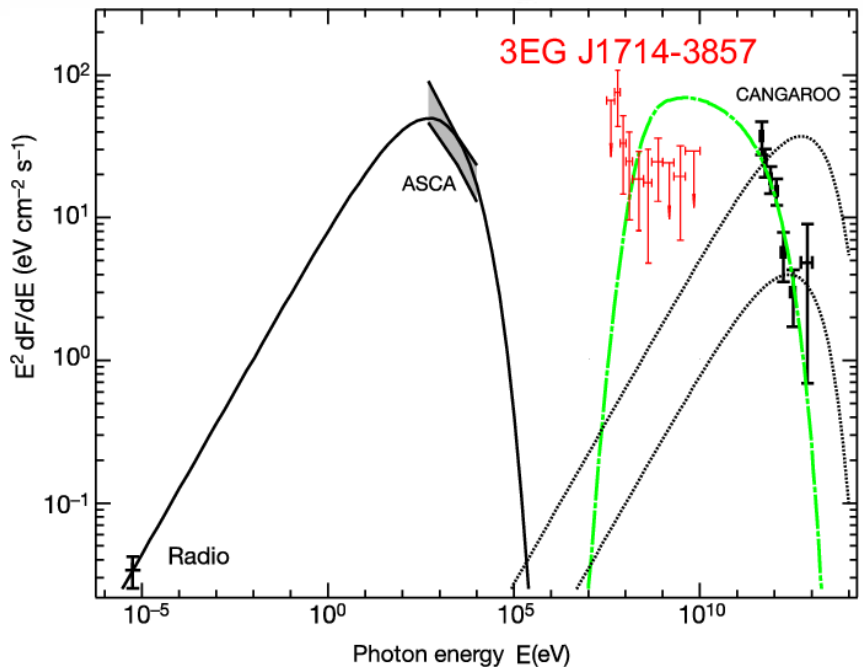
- SNR RX-J1713.7-3946:
  - Discovered by ROSAT in X-ray
  - EGRET GeV gamma source,
  - TeV γ seen by CANGAROO
  - ***"Confirmed" by HESS (???)***

CANGAROO: from NW dense spot (red contours) HESS: whole remnant spectrum



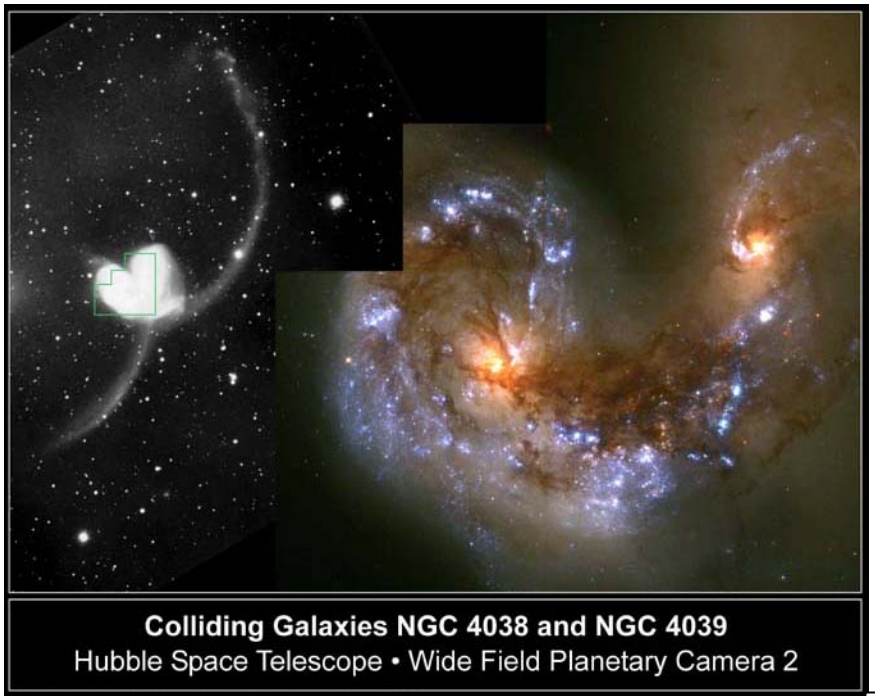
Black: ROSAT X-ray Red: CANGAROO TeV (2002)
White: EGRET: 3EG J1714-3857 Color: CO emission intensity



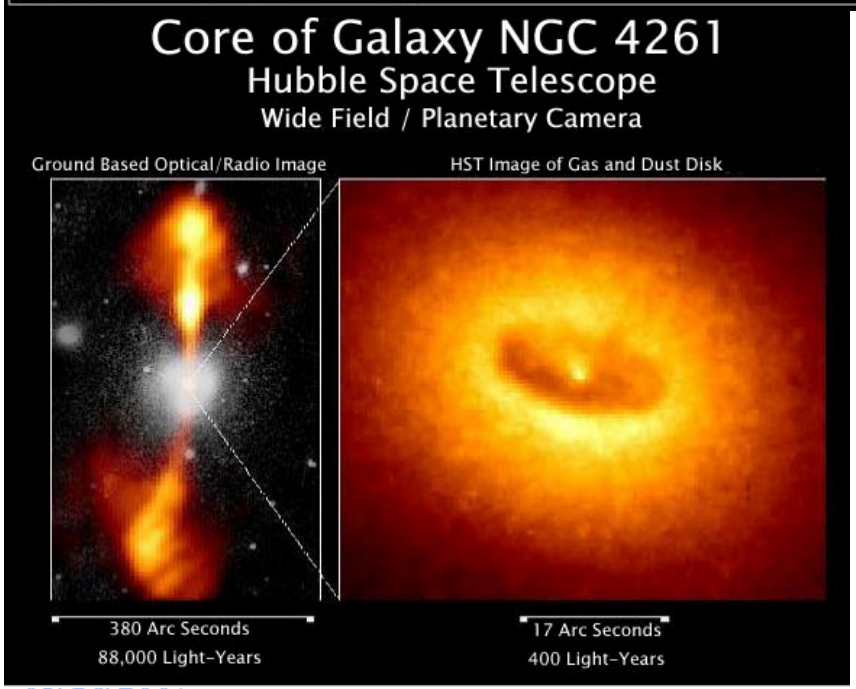


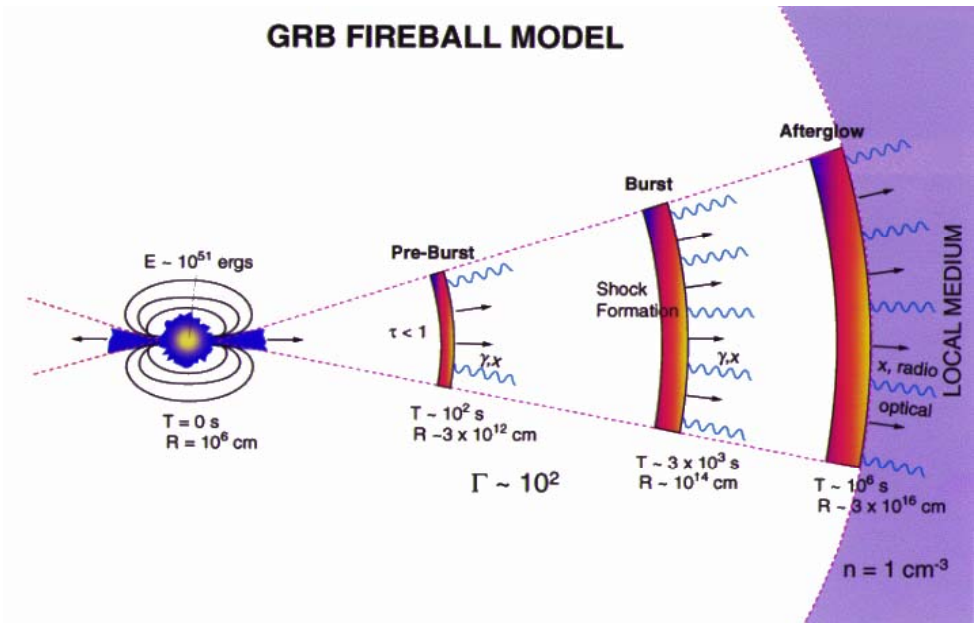
Bigger and/or More Violent Objects?

- Usual Suspects:
  - AGN (TeV γ–ray sources)?
  - Mergers?
  - GRB?



Colliding Galaxies NGC 4038 and NGC 4039
Hubble Space Telescope • Wide Field Planetary Camera 2

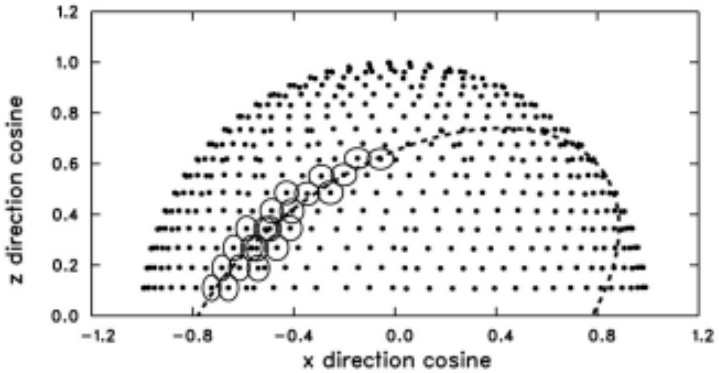


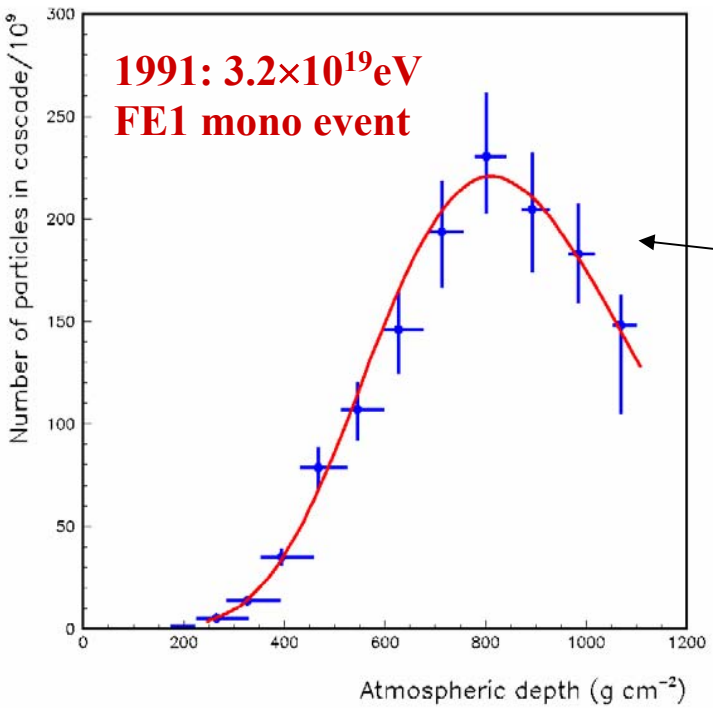


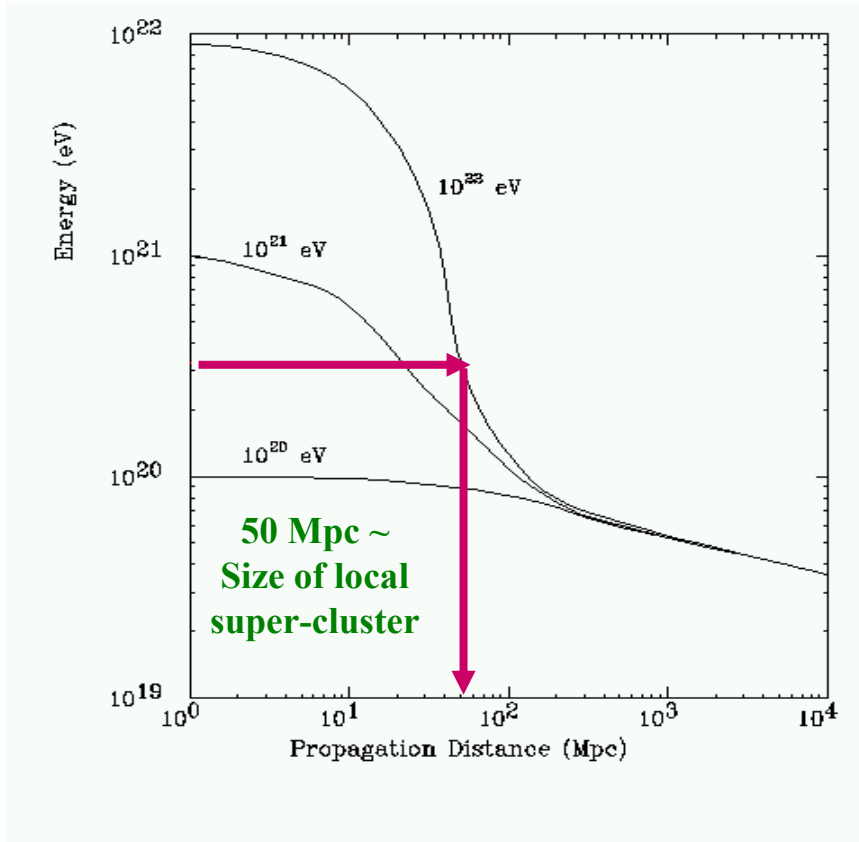
Exotic Mechanisms

- Top-Down" Models:
  - Decay or annihilation of some super-heavy particles
  - Cosmological relic particles (e.g. relic monopoles)
  - Cosmic Strings
  - Topological Defects
- Acceleration in Catastrophic events:
  - GRB's
- New Physics?
  - Violation of Lorentz "Symmetry" (might also eliminate the need for dark matter)

Greisen-Zatsepin-K'uzmin (GZK) Effect



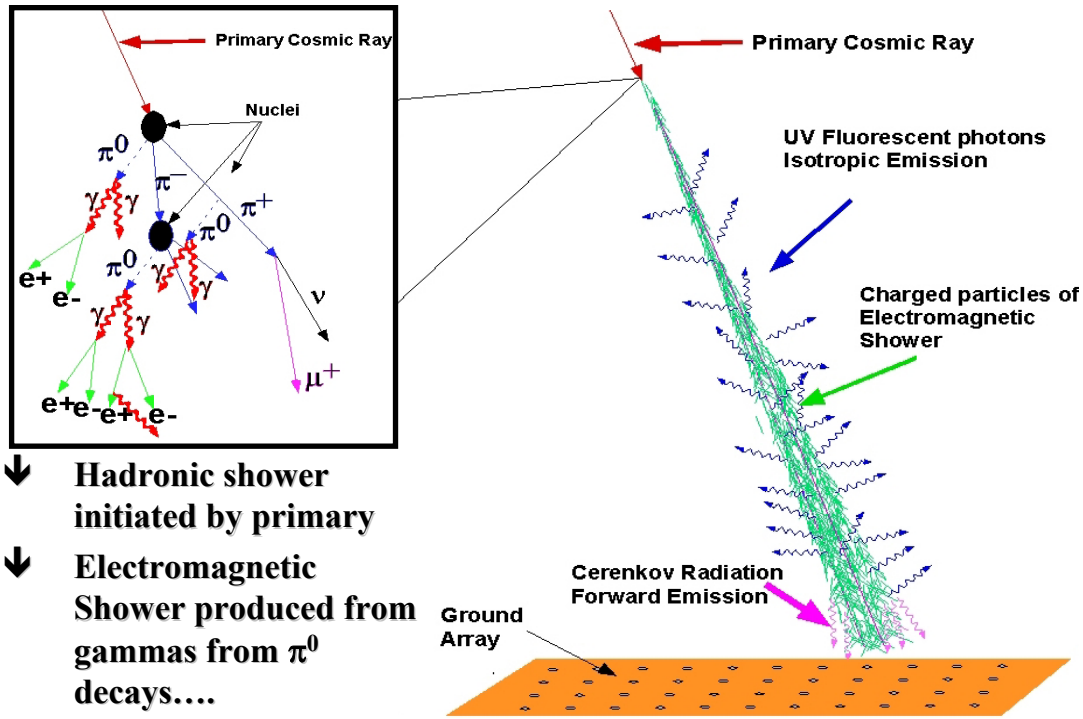




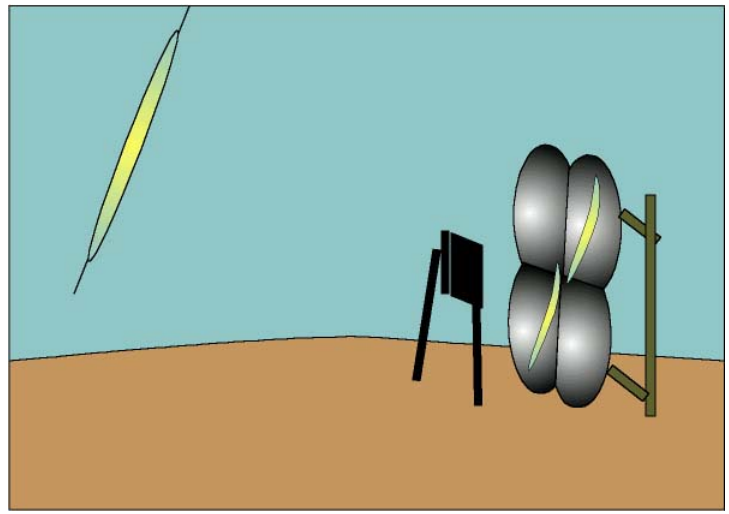
- ***3.2×10^20 eV*** event exceeds theoretical ***GZK threshold***:

Cosmic protons above ***6×10^19 eV*** suffer severe energy loss from ***photo-pion production***.
Proton or neutron emerges with reduced energy, further interaction occurs until energy is below ***GZK Threshold (1966).***

Extensive Air Showers & the Fluorescence Technique



- **Hadronic shower initiated by primary**
- **Electromagnetic Shower produced from gammas from π^0 decays….**



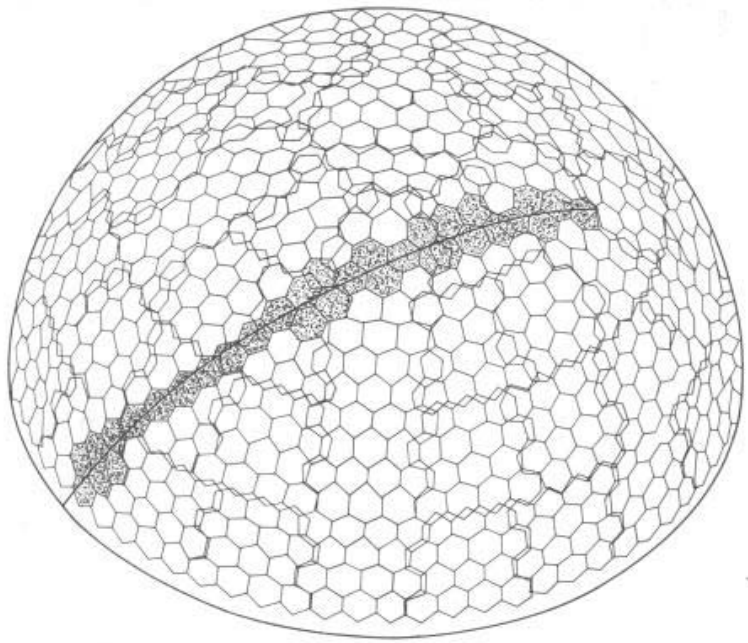
- Can measure direction and energy of cosmic ray by sampling the lateral distribution of particles at ground level: ***Ground Array***
  - Volcano Ranch, Yakutsk, Akeno, Tibet, AGASA
  - Haverah Park, SUGAR, AUGER (muons)

Fluorescence Technique:

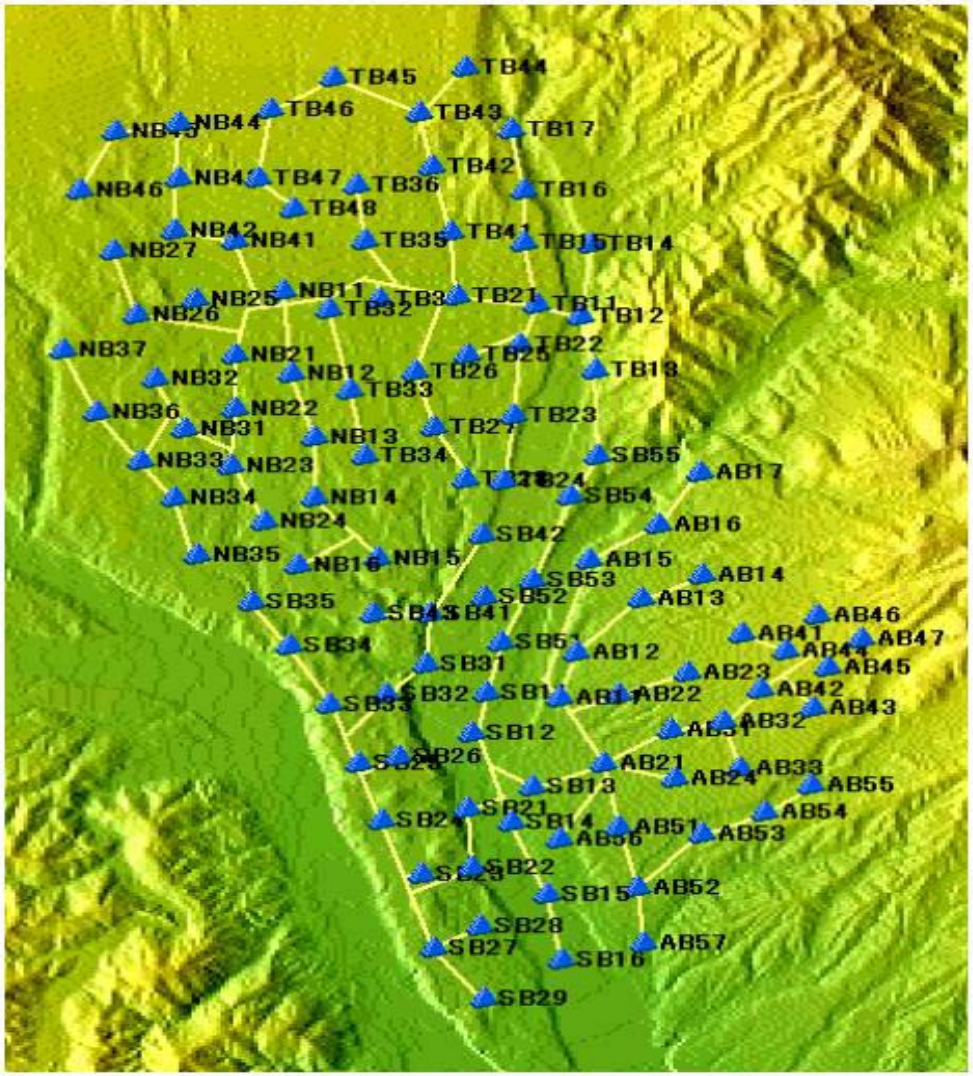
- Measure UV "fluorescence" light emitted by the charged particles in the air shower
- Can measure energy, direction, and also shower maximum depth (X_{MAX}: gives composition info)
- Fly's Eye, HiRes, AUGER FD, TA

History: The Fly's Eye

- HiRes was preceded by the Fly's Eye Experiment:
  - World's first operational air fluorescence detector
  - Time averaged (10% duty cycle) ***aperture*** of ~100 km^2sr at ~10^{20}eV.
  - Fly's Eye 1 detector (shown in photo) operated from 1981-1992 by University of Utah with 67 mirrors and full-sky coverage.
  - Fly'e Eye 2 detector operated from 1986-1992 with 34 mirrors covering 50% of the sky.



Akeno Giant Air Shower Array



Akeno Giant Air Shower Array (**AGASA**) have reported as many as 17 events $>10^{20}$ eV, but also observed a much higher flux than the other experiments.

High Resolution (1°) Fly's Eye (HiRes)

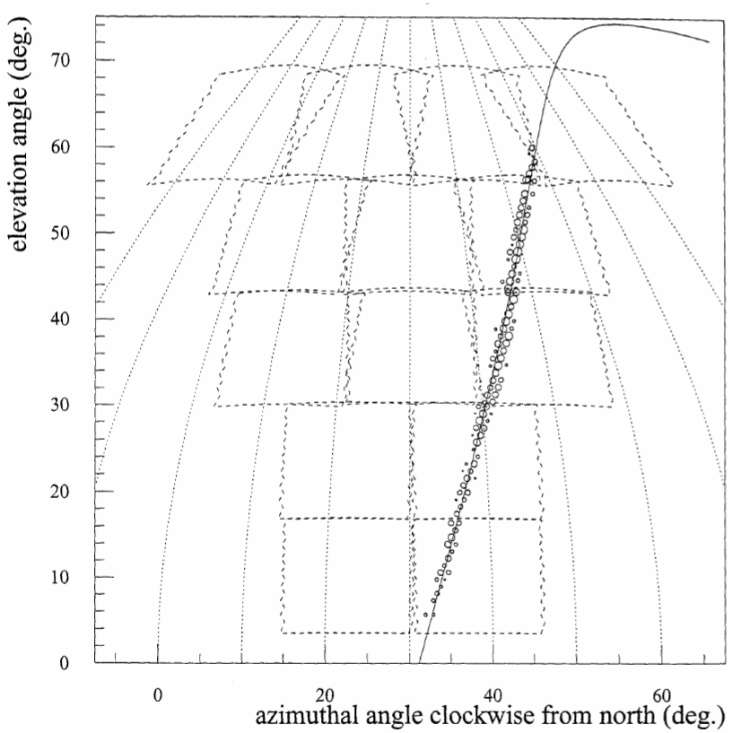
- Two Fluorescence Detector sites in Utah separated by 12.6 km.
- HiRes-1 began operation in ***June, 1997***
  - Traditional sample-and-hold ADC with 50 μs integration gate
- HiRes-2 site uses new ***FADC*** system developed at Columbia
  - 8-bit x 10 MHz sampling
  - Fully operational by Nov 1999
  - Stereo observation began ***Dec 1999.***

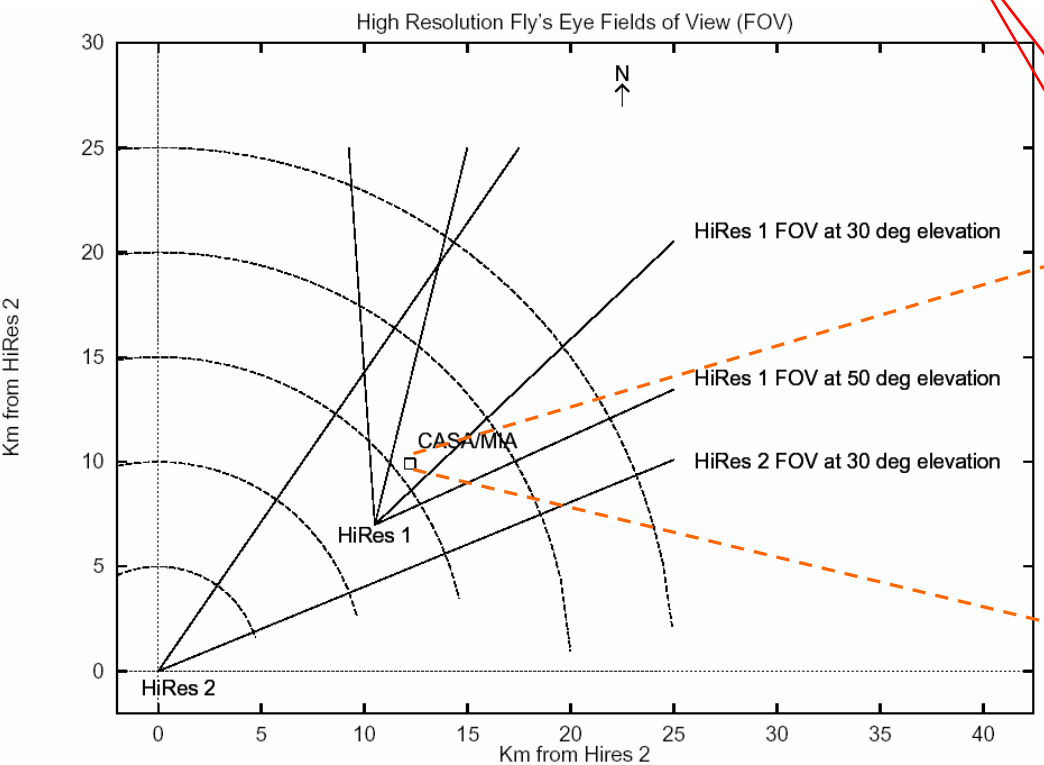
HiRes-1

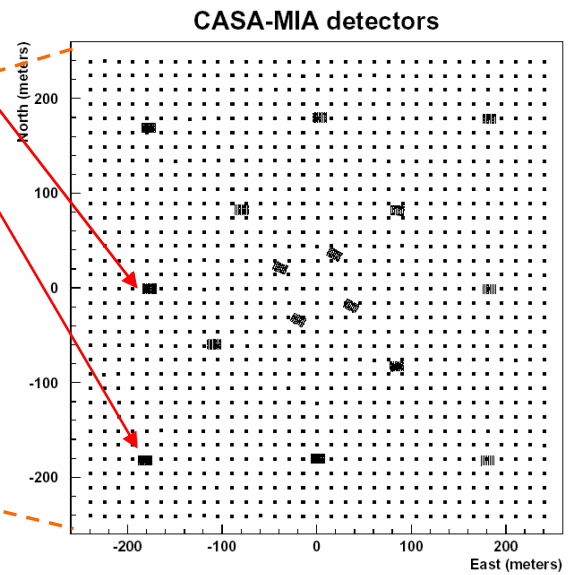
HiRes-2

1992-1996: HiRes Prototype

- 14 (HiRes-1) + 4 (HiRes-2) mirror prototype detector operated between 1992 and 1996
- HiRes-1 field of view up to ~70°.
- HiRes-1 operated in hybrid mode with the CASA and the MIA muon array (16 patches×64 underground scintillation counters each):

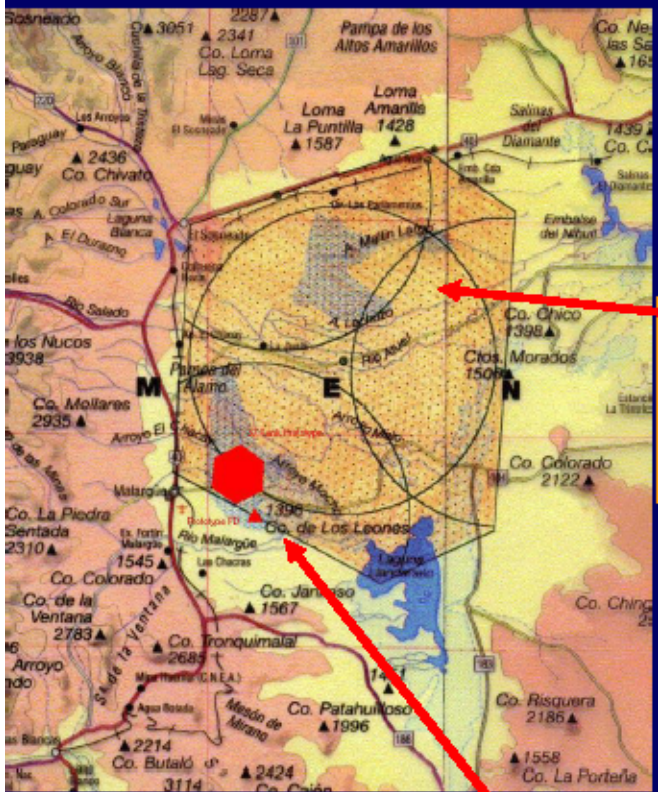






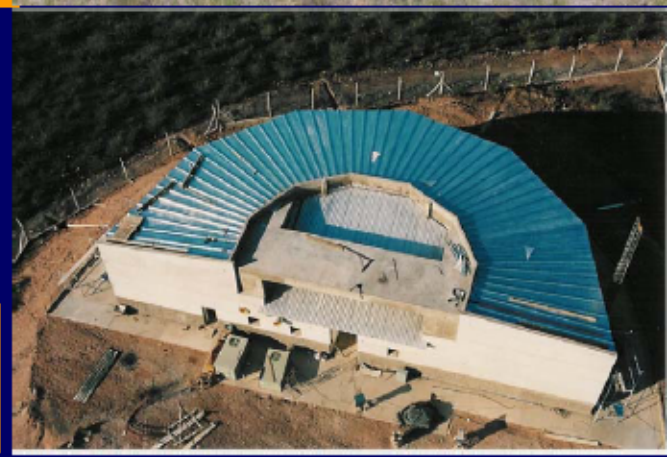
AUGER Experiment

Argentina + ~~Utah~~ sites (each 3000 km^2), E > 5 10^{18}eV



At Mendoza site (AR):

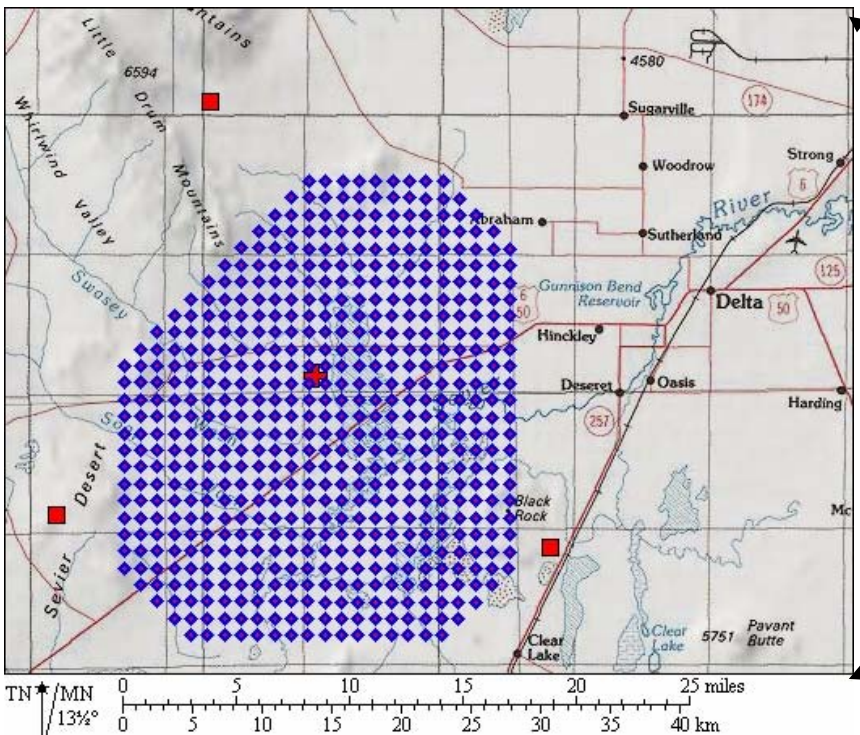
1600 water tanks (10m^2 each)

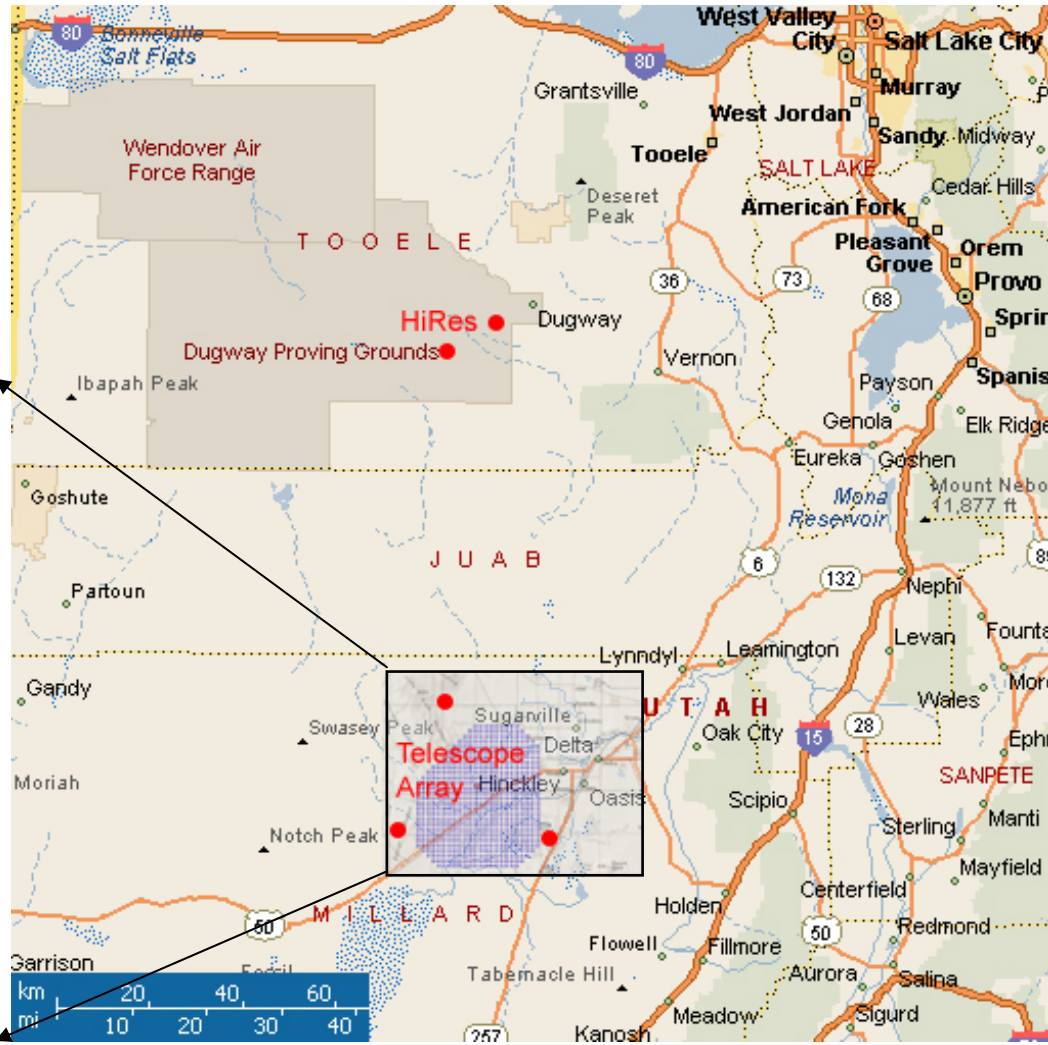


6 fluorescence telescopes (10 m^2 each)

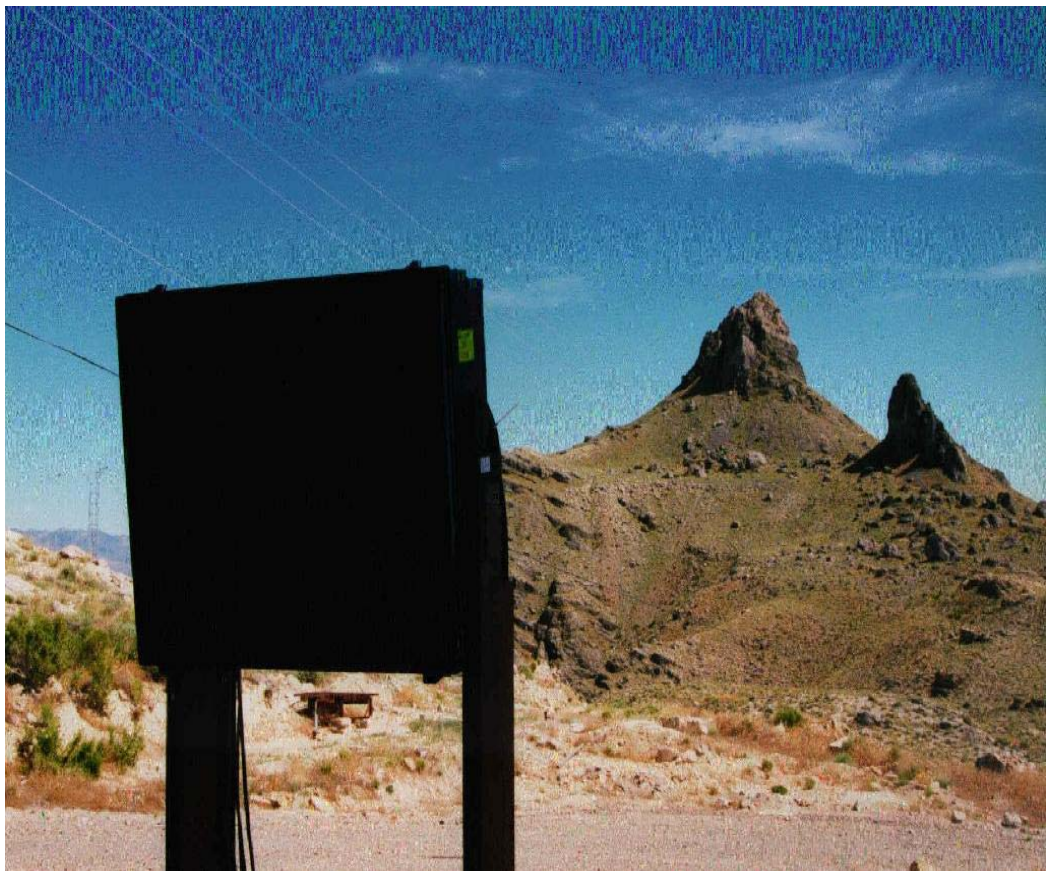
Telescope Array

- TA experiment (13M$ equivalent from Japan, US: 2.4M$ Stage 1 start-up approved). Construction underway – complete in 2007
  - Main ground array of 512 Scintillators
  - 3 Fluorescence Sites
- Japan-Korea-PRC-ROC-US Collaboration.





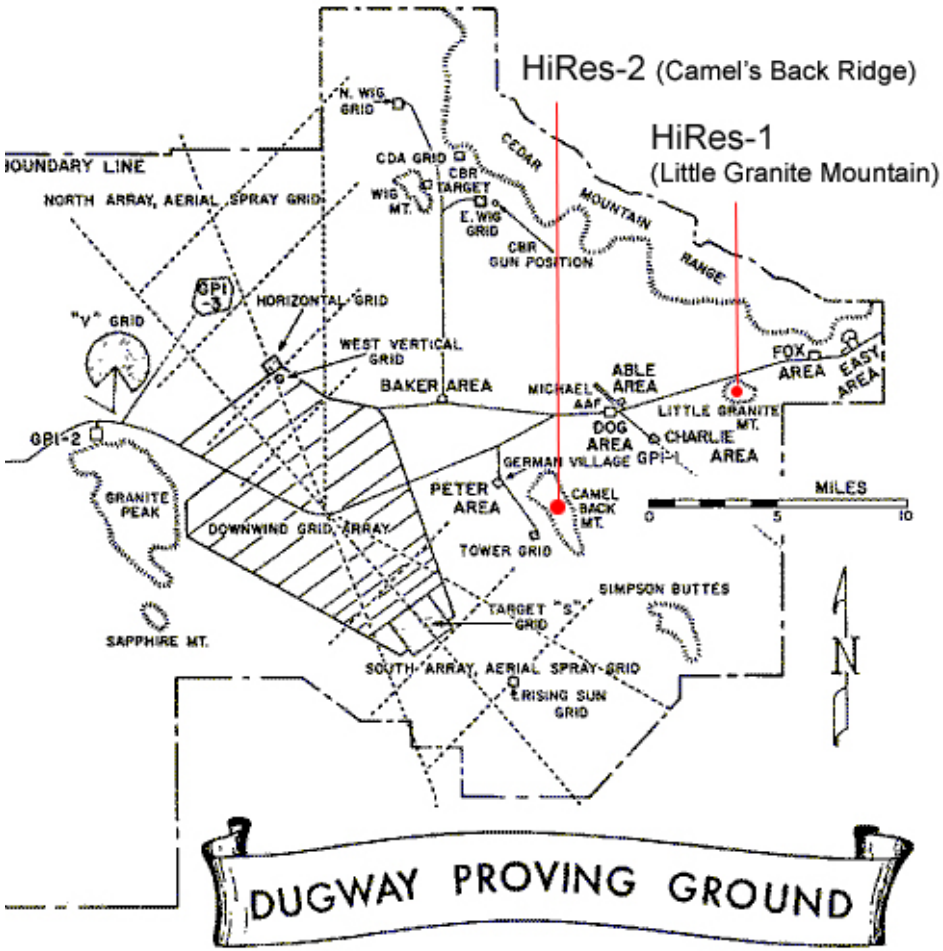
The High Resolution Fly's Eye (HiRes) 1997-2006



HiRes Collaboration:

- *University of Utah*
- *Columbia University*
- *Rutgers University*
- *University of New Mexico*
- *University of Montana*
- *University of Adelaide*
- *Los Alamos National Laboratory (LANL)*
- *University of Tokyo*
- *IHEP (Beijing, China)*

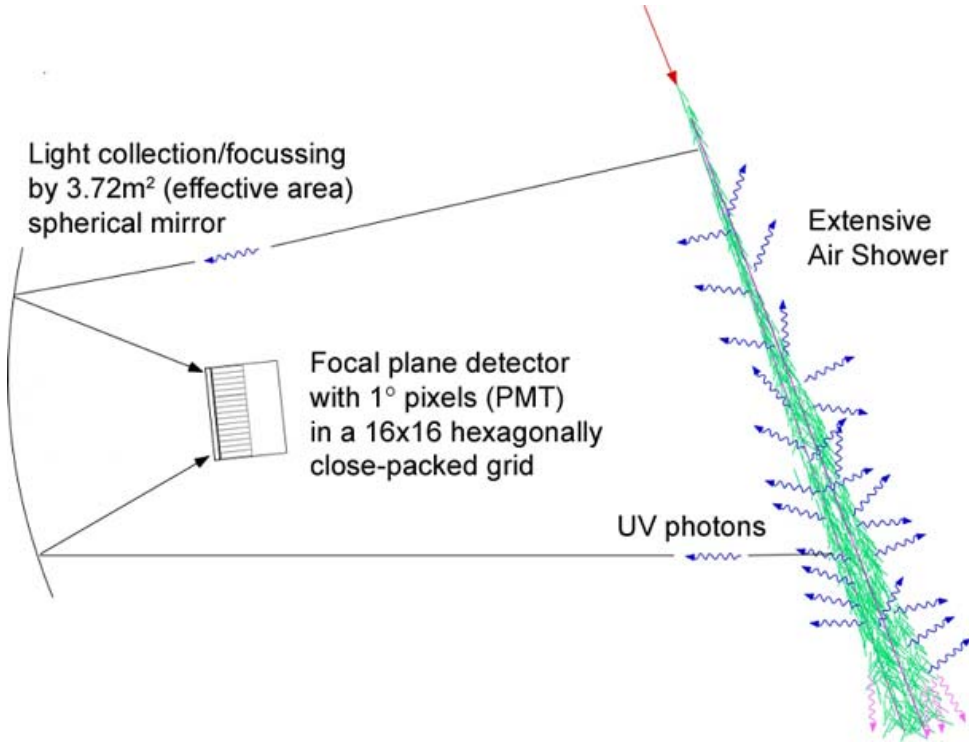
HiRes Location



- HiRes is located on the U.S. Army Dugway Proving Ground, ~2 hours from The University of Utah campus.
- The two detector sites are located 12.6 km apart at Little Granite Mountain and Camel's Back Ridge

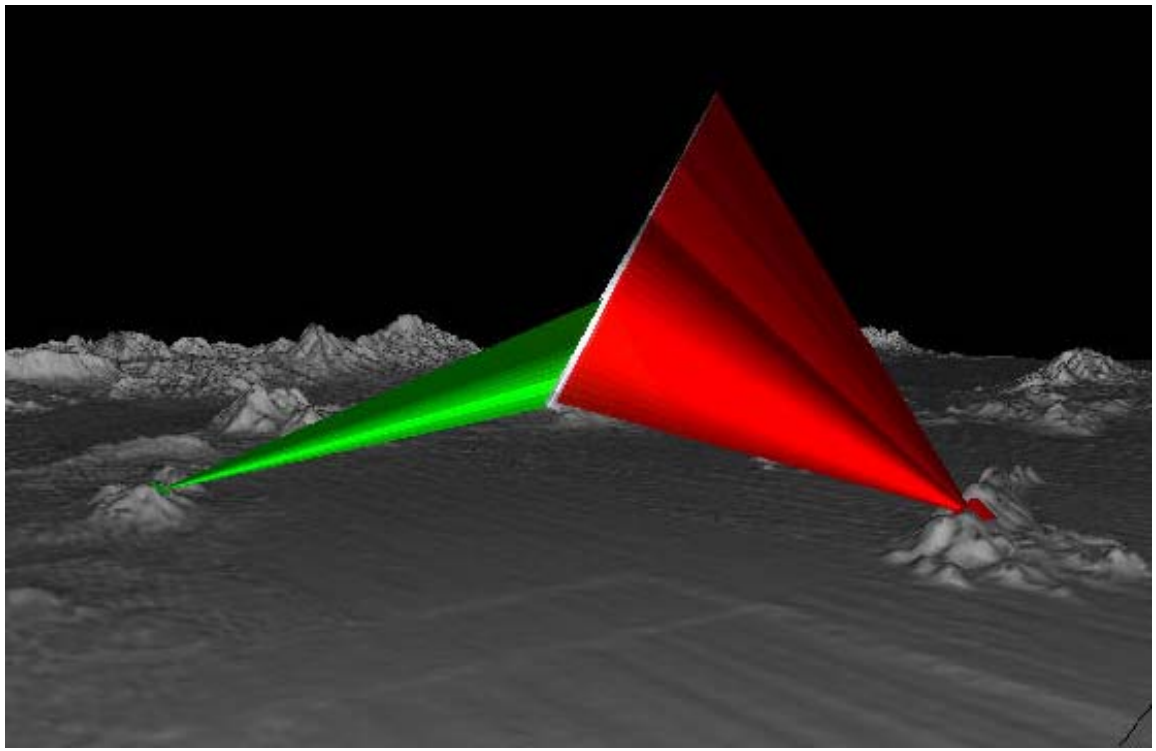
Detector Design

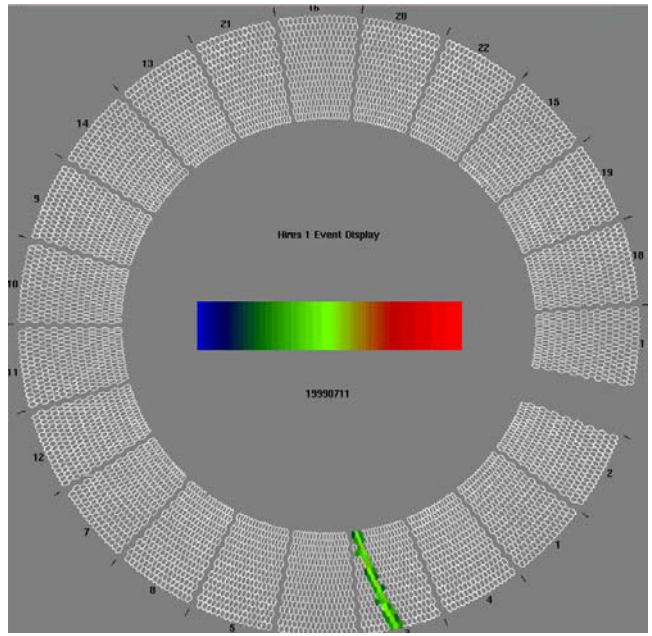
- Each HiRes detector unit ("*mirror*") consists of:
  - spherical mirror w/ ***3.72m²*** unobstructed collection area
  - 16x16 array (hexagonally close-packed) of PMT pixels each viewing ***1° cone*** of sky: giving ×5 improvement in S:N over FE (5° pixels)
  - UV-transmitting filter to reduce sky+ambient background light
  - Steel housing (2 mirrors each) with motorized garage doors

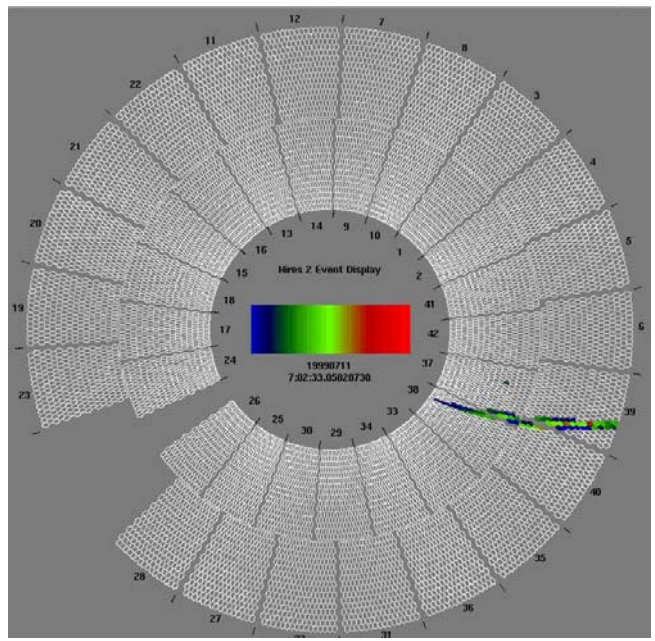


Mirror and Camera

Typical HiRes Event





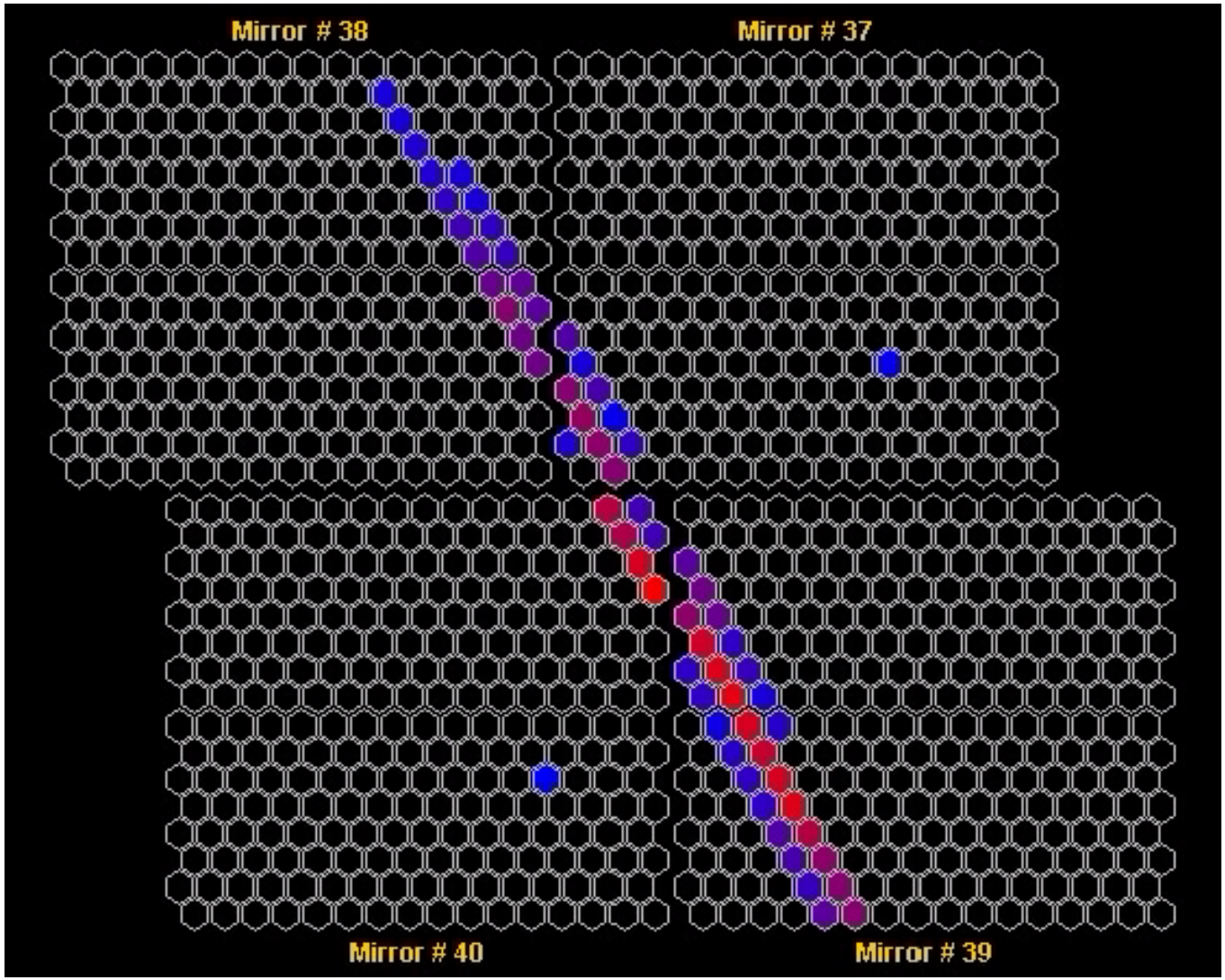


~2×10^{9}eV event seen in 1999

(3× vertical scale)

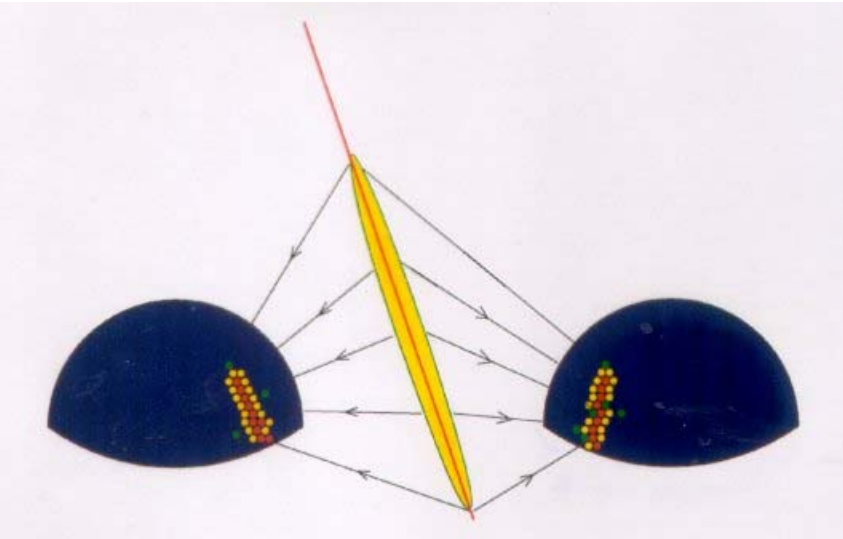
A 25 Microsecond Movie

(playback at 1/500,000 speed)

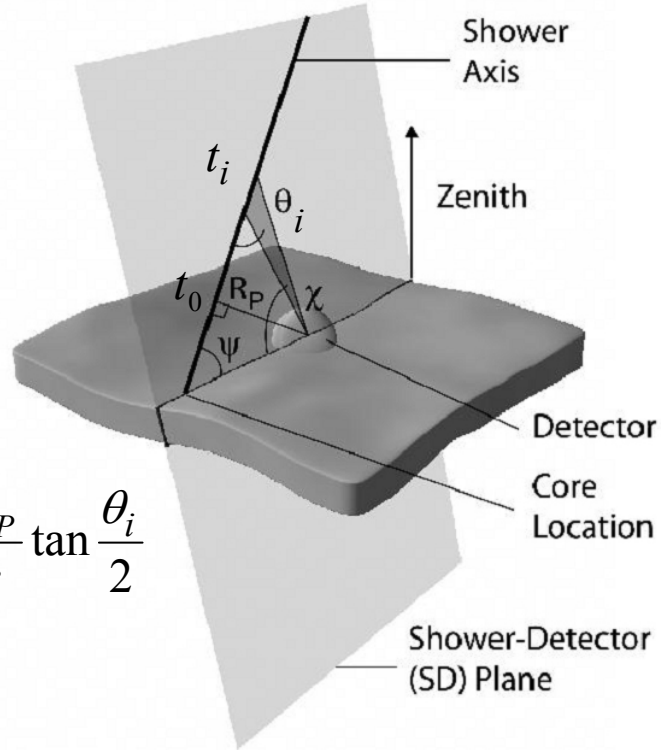


Reconstruction of EAS from HiRes Data

- 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.

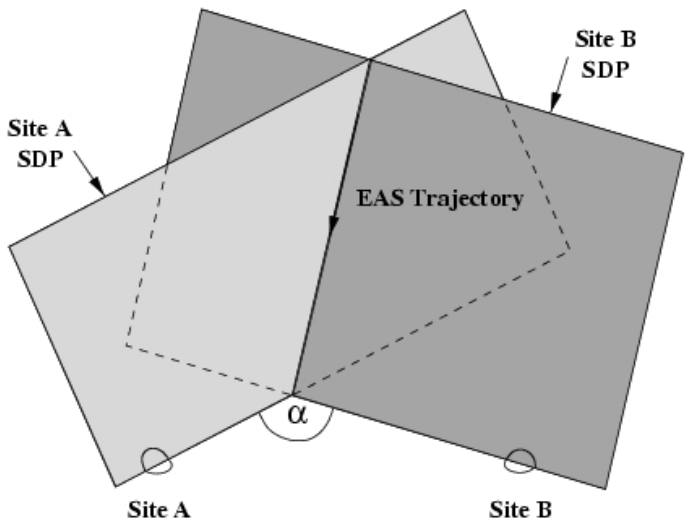


1.)

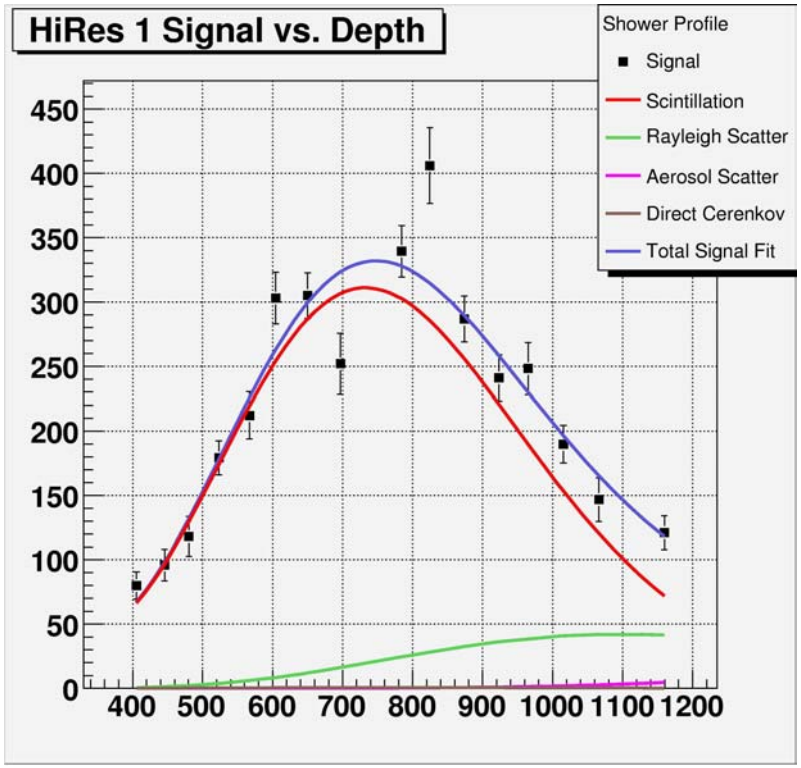


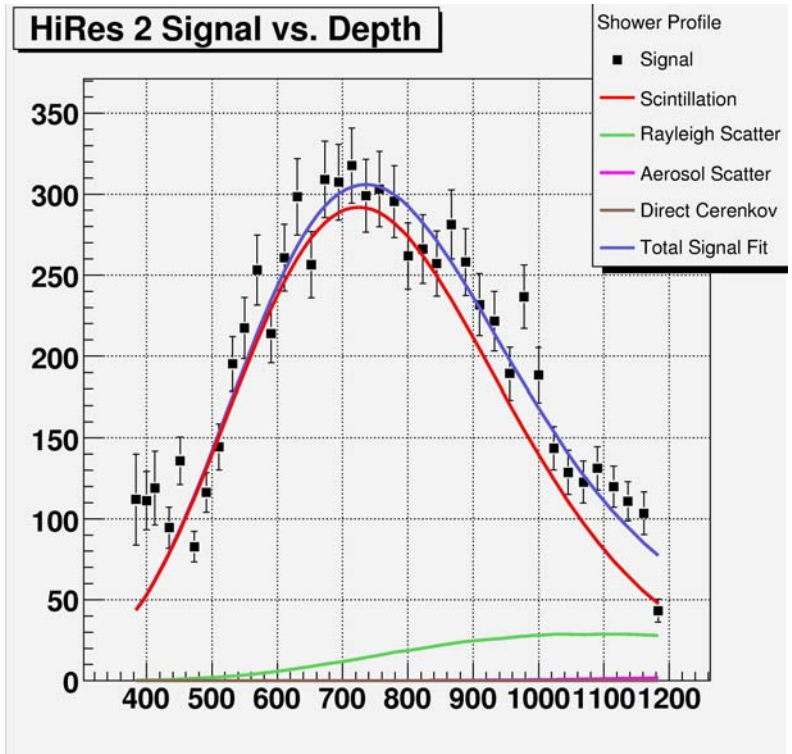
$$t_i = t_0 + \frac{R_P}{c}\tan\frac{\theta_i}{2}$$

2.)



Measured shower profile.





Measured shower parameters.

Event by event:

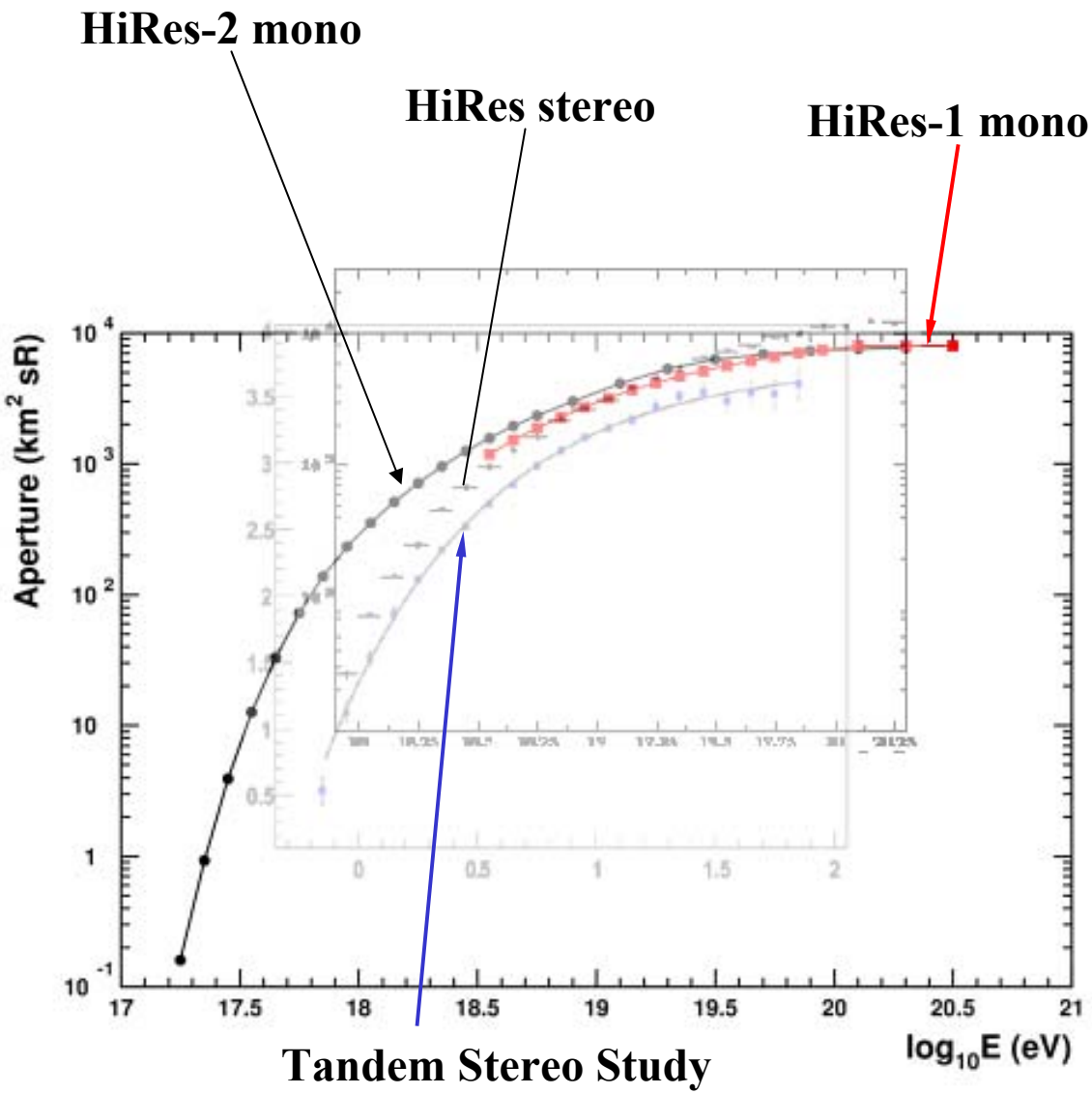
- X_{max} in g/cm^2;
- Total energy of the primary particle:
- Arrival direction

Statistically:

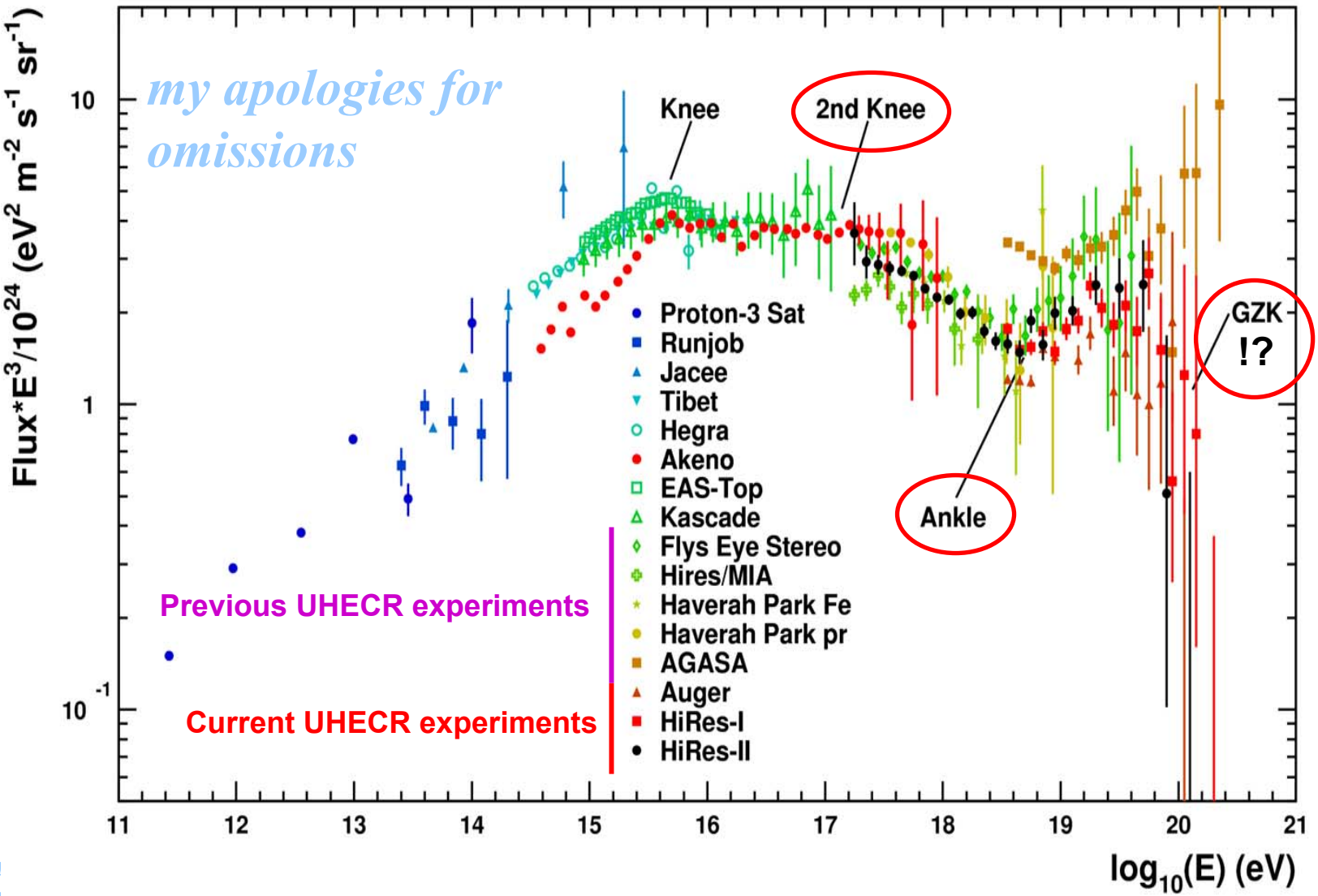
- composition.
- *p*-air inelastic cross-section;

Physics with HiRes Data

- ***Stereo data***: best resolution, optimized for $E>3\times10^{18}eV$
- ***HiRes-2 monocular***: can reach down to as low as $10^{17.2}eV$
- ***HiRes-1 monocular*** data began ~3 years earlier: ***largest statistics***,



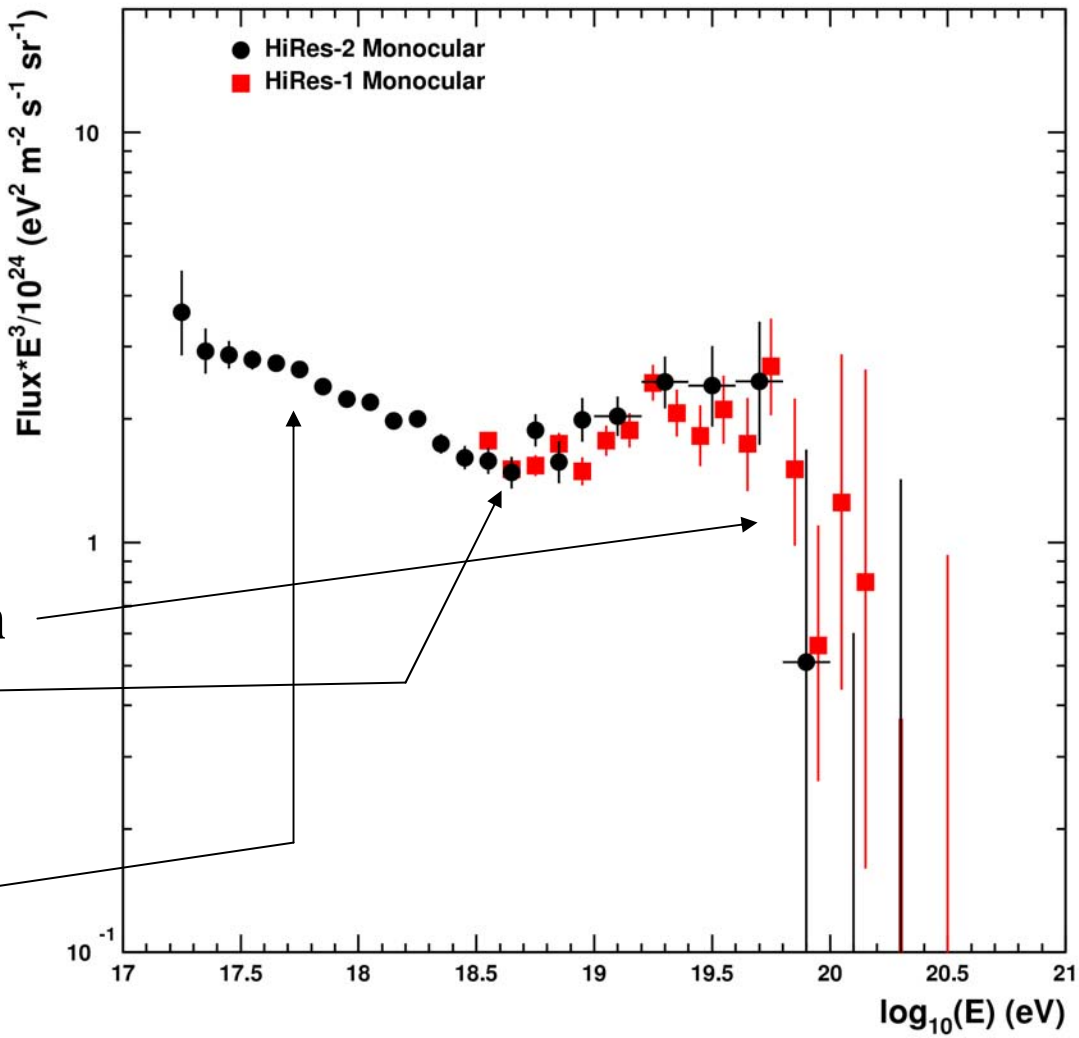
Status of EHECR/UHECR Physics
1. Energy Spectrum



Cha
03/1

HiRes Monocular Spectra

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



We observe:
(1) high-energy suppression
(2) ankle;

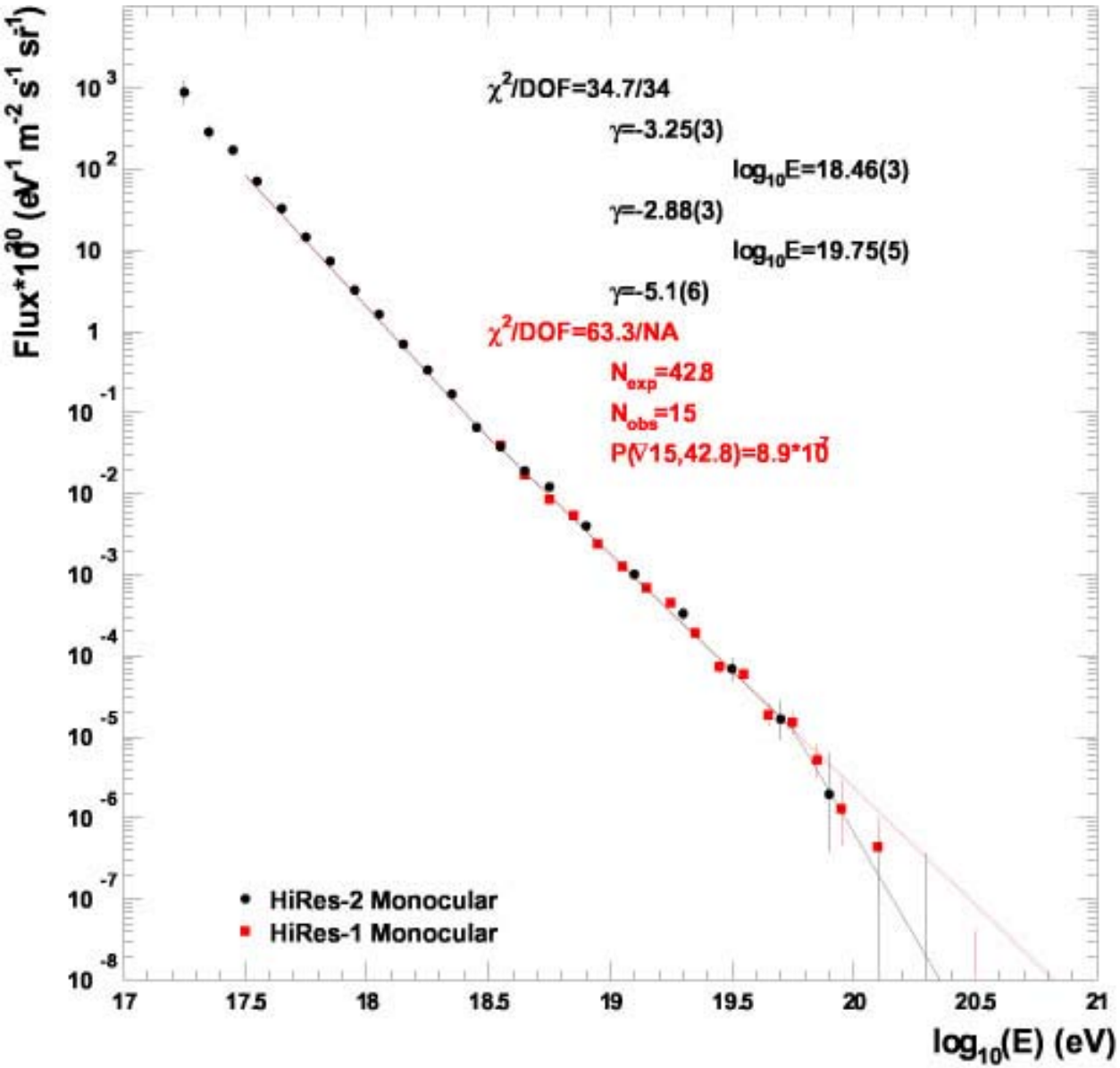
and…
(3) second knee??

- Significance of the deficit at high energy end relative to continuation of power law ?
- Extrapolate middle section:
  - Expect 42.8 events
  - Observe 15
  - Poisson

    $p = \sim 10^{-6}$

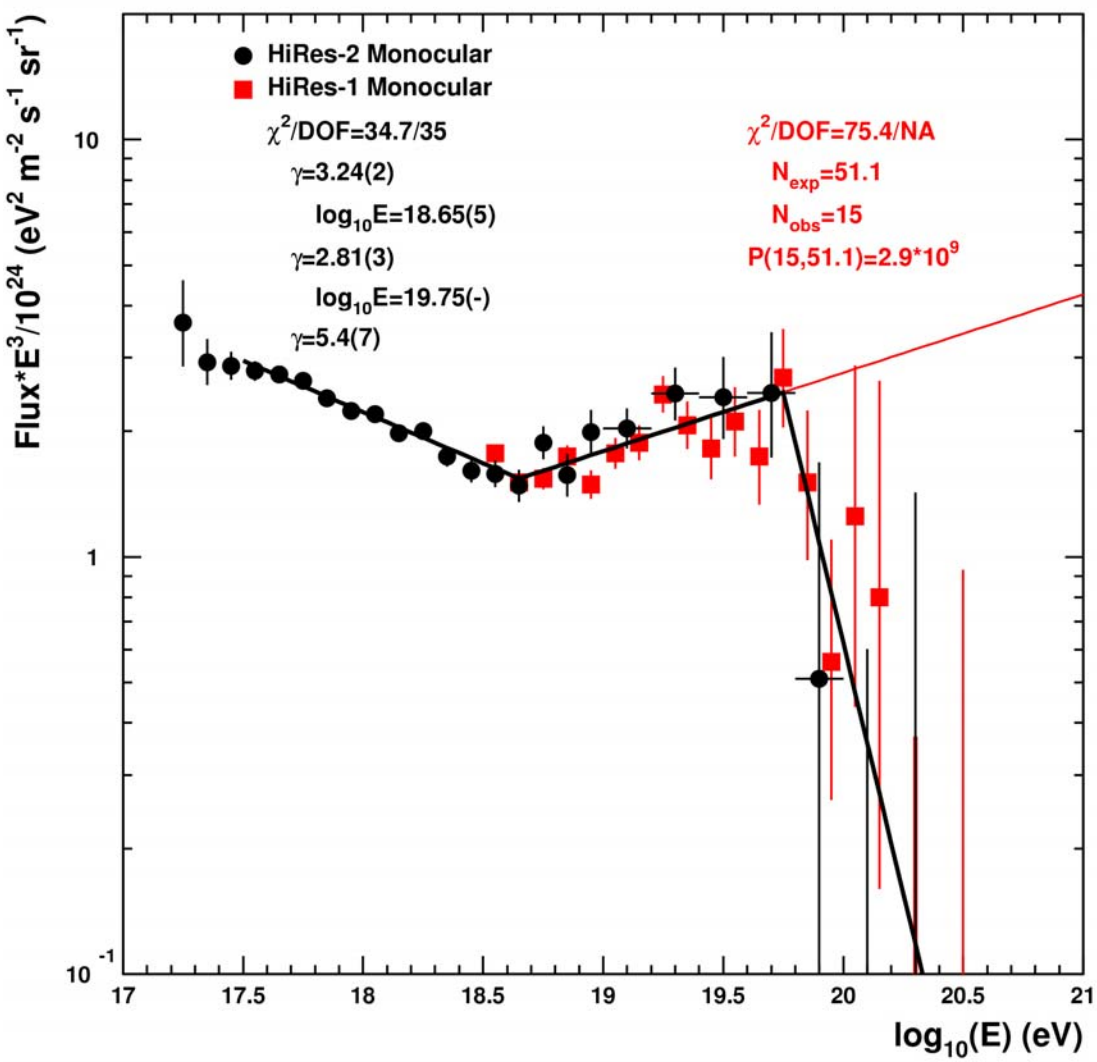
4σ is 3×10^{-5}

5σ is 3×10^{-7}



5σ Observation of the GZK Suppression

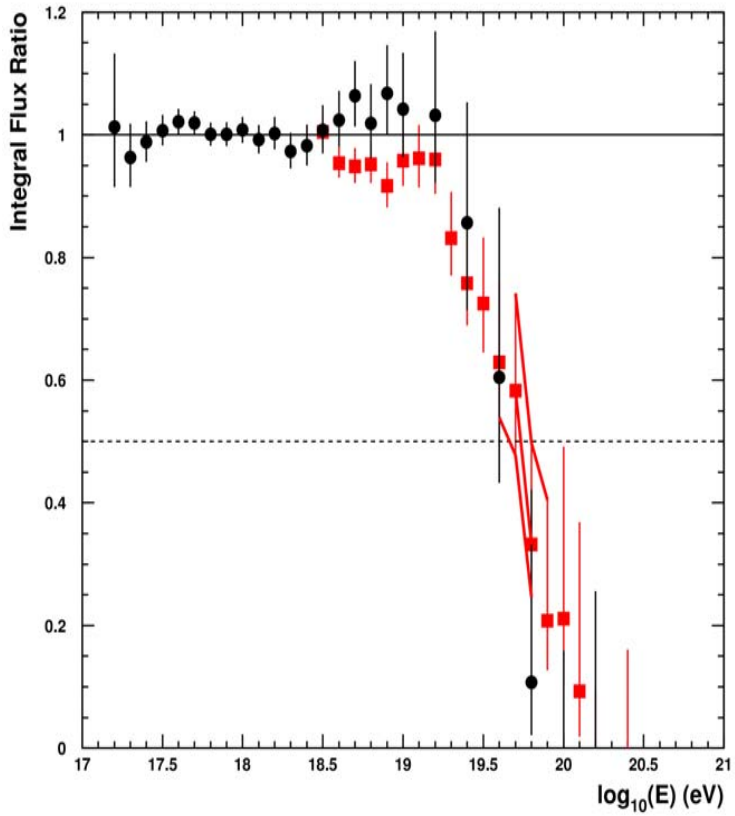
- **Broken Power Law Fits**
  - No Break Point
    - χ^2/DOF = 162/39
  - One BP
    - χ^2/DOF = 68.2/37
    - BP = 18.63
  - Two BP's
    - χ^2/DOF = 34.7/35
    - 1st BP = 18.63
    - 2nd BP = 19.75
  - Two BP with Extension
    - Expect 51.1 events
    - Observe 15 events
    - Poisson probability: P(15;51.1) = **3×10^{-9} (5.8σ)**
  - Independent statistics: P(14;44.9)=7×10^{-8} **(5.2σ)**



The Break is at the GZK Energy!

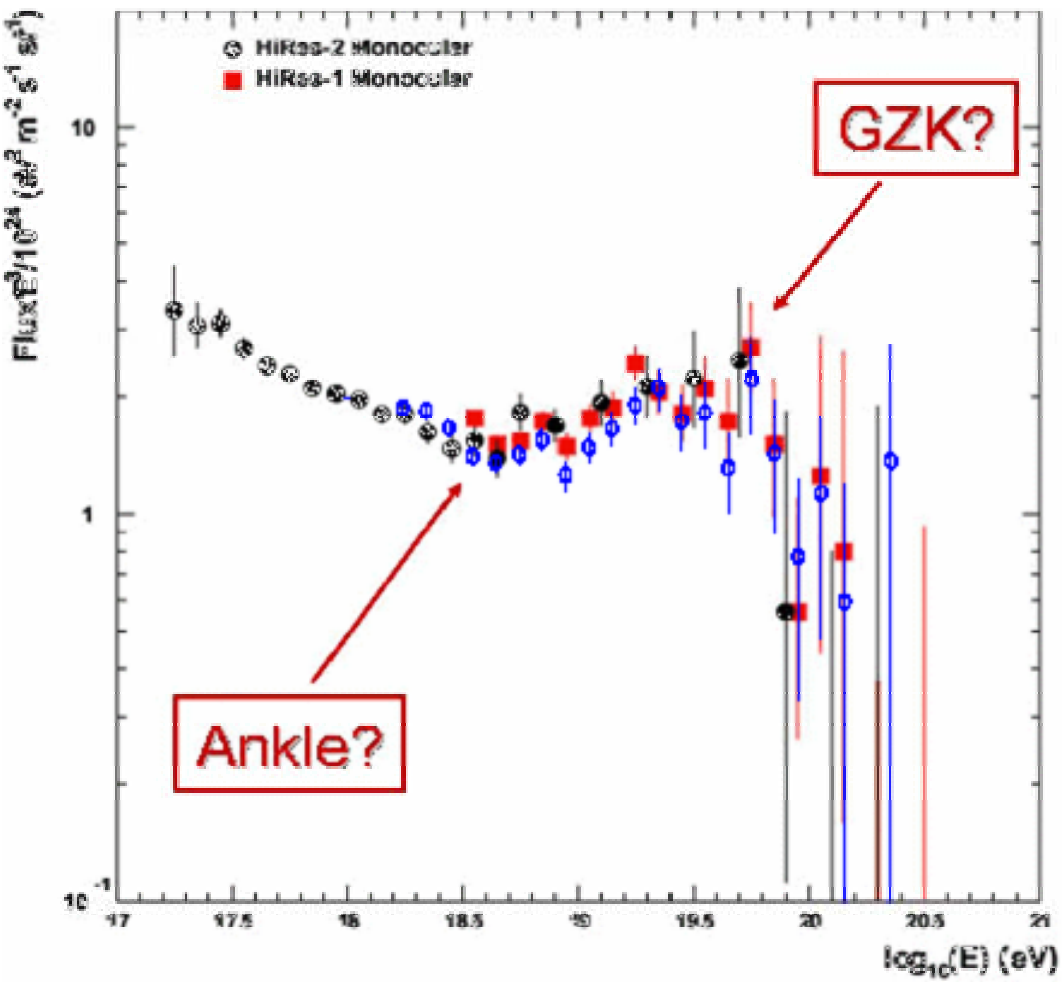
Use Berezinsky's Integral Spectrum Test

- $E_{½}$ 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.**

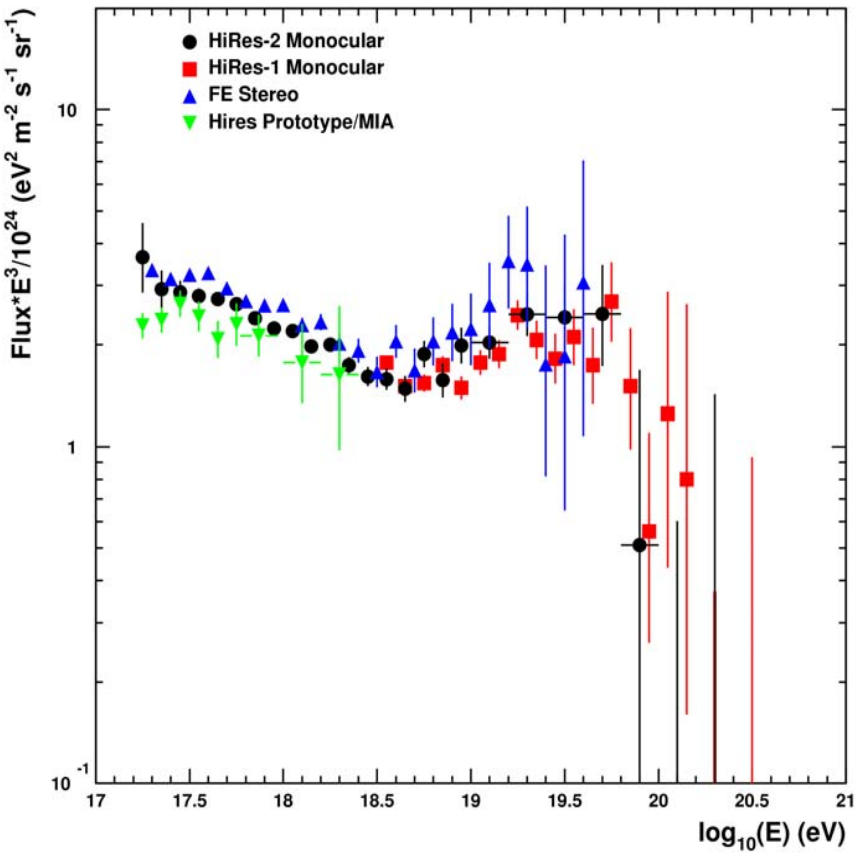


HiRes Stereo Spectrum

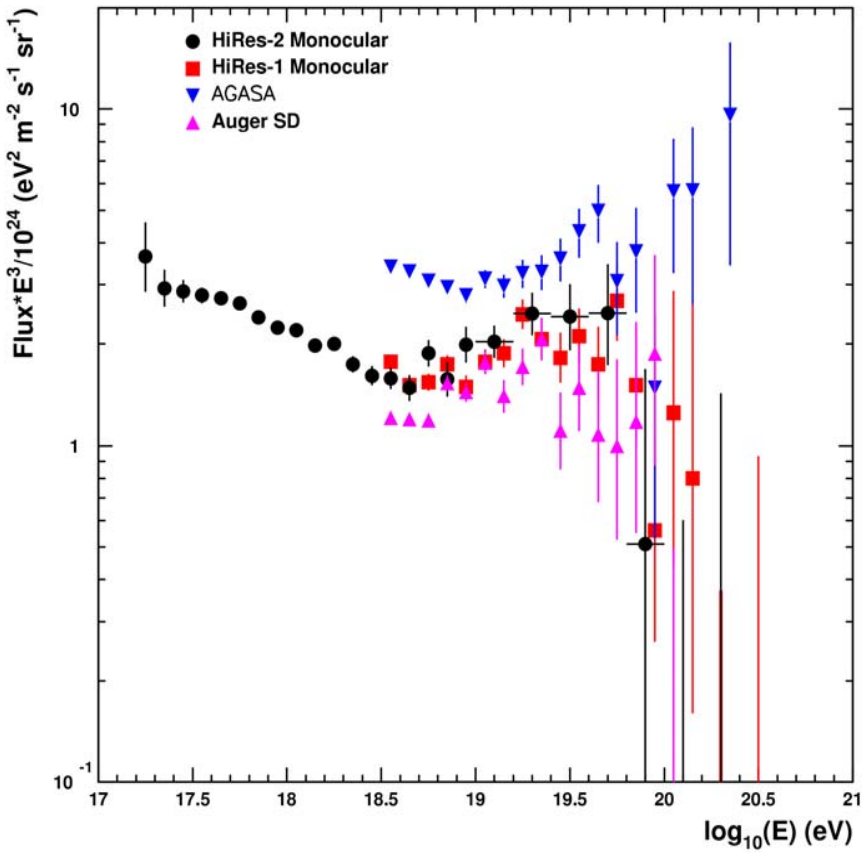
- HiRes Stereo spectrum (blue) has weaker statistical power but agrees in shape and normalization to the combined monocular spectra



HiRes and Other Experiments

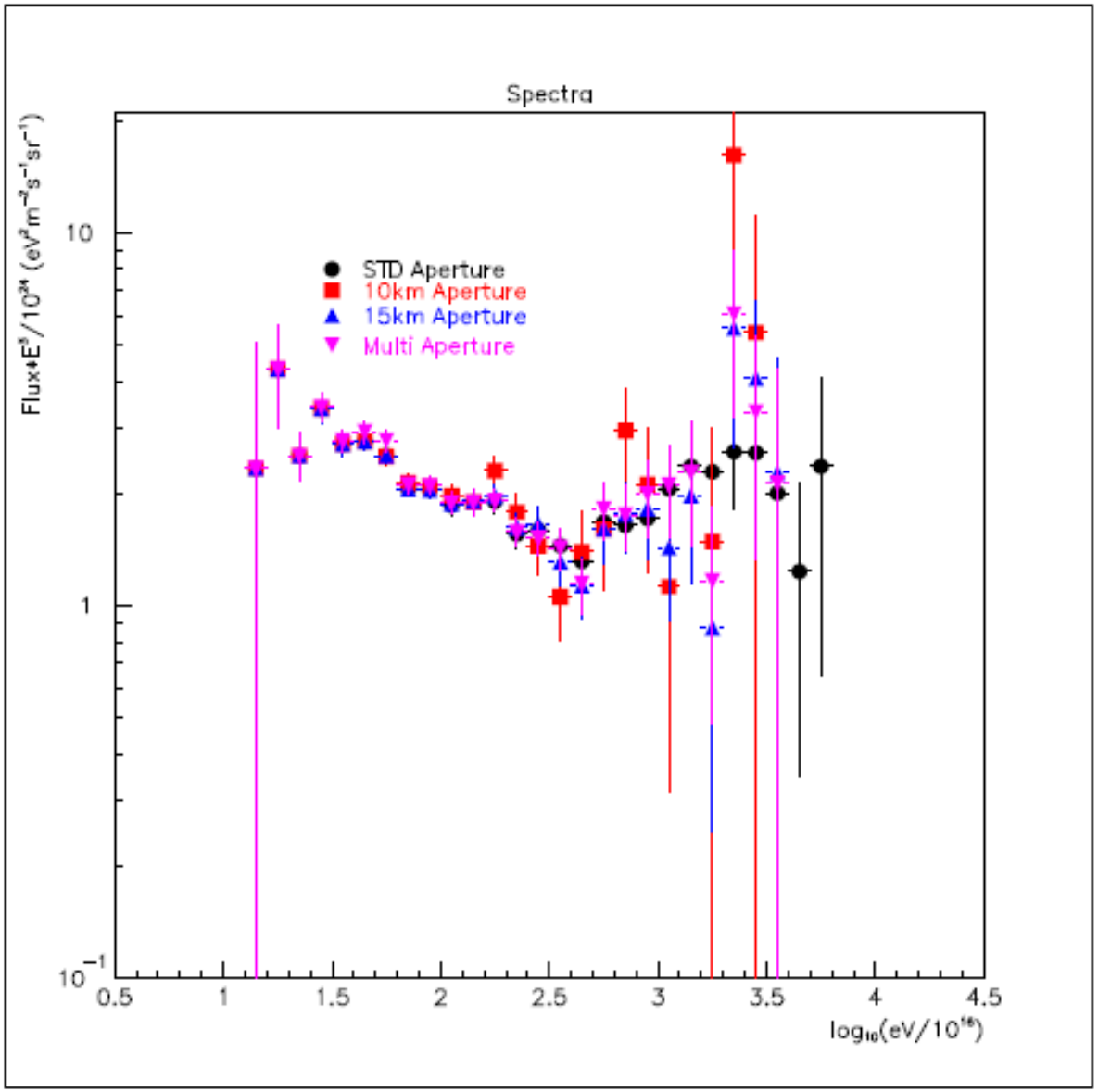


HiRes, Fly's Eye Stereo, and HiRes/MIA



HiRes, AGASA, Auger(2005)

Aperture Check



HiRes-2 Data:

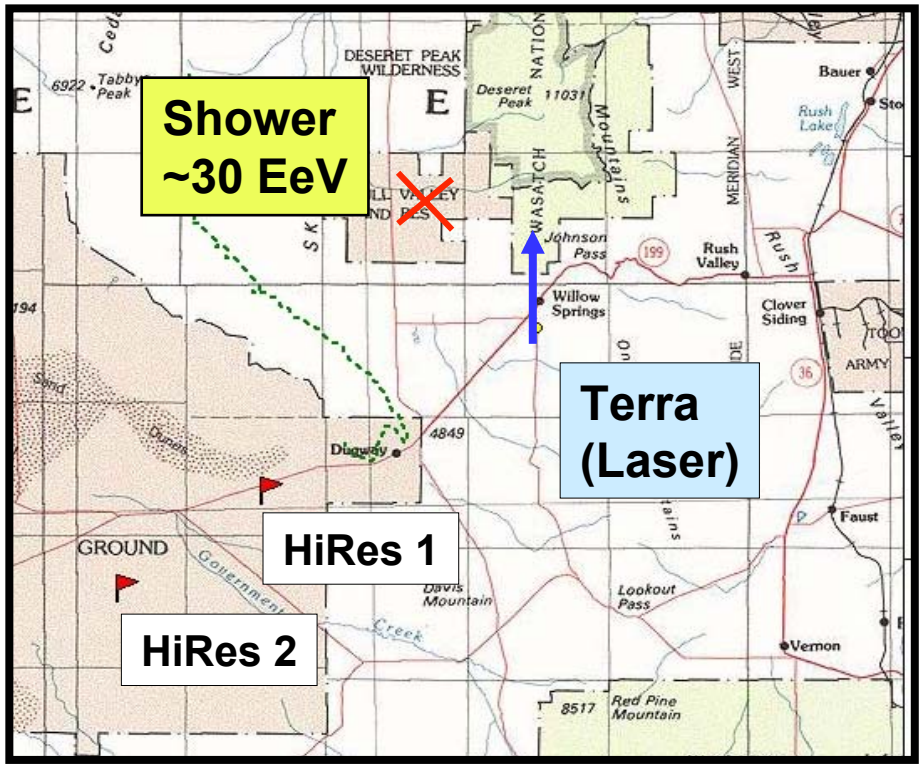
Artificially cut the data so that you are certain of the aperture.

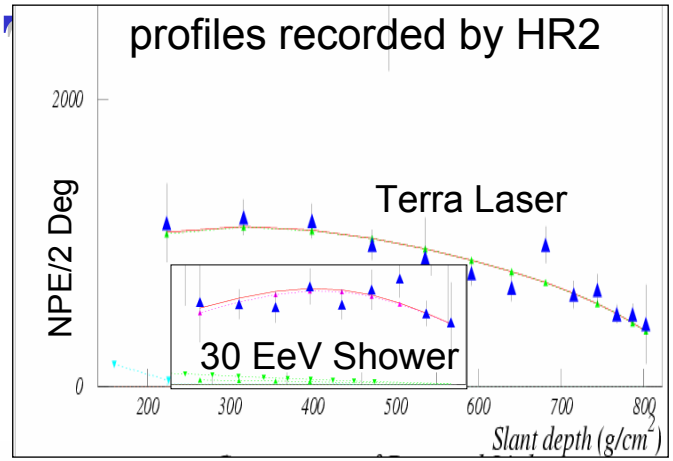
Cut data with an impact parameter > 15 km

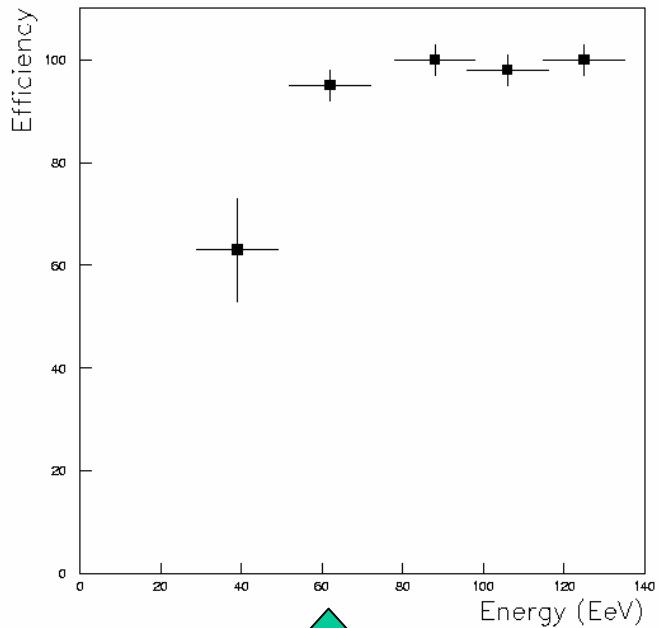
>10 km

<u>Excellent agreement!</u>
Confidence in aperture calculation

HE Aperture







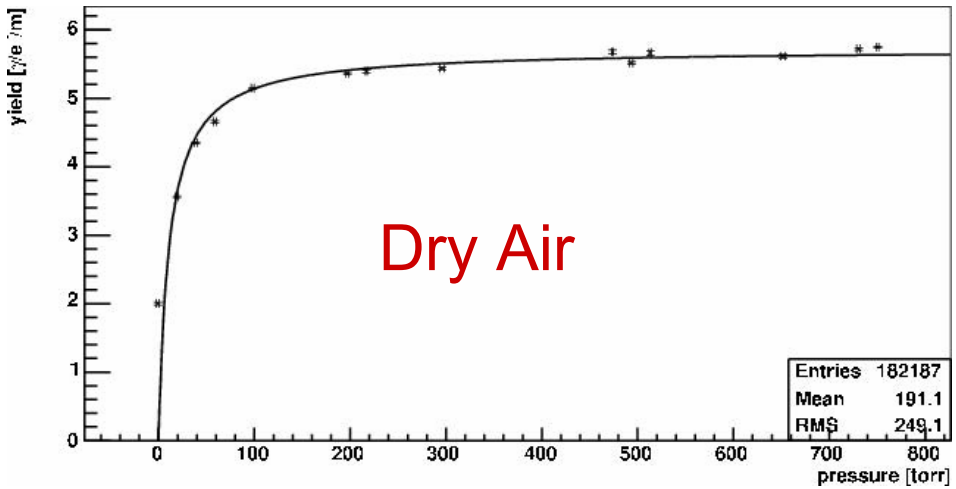
GZK Cutoff

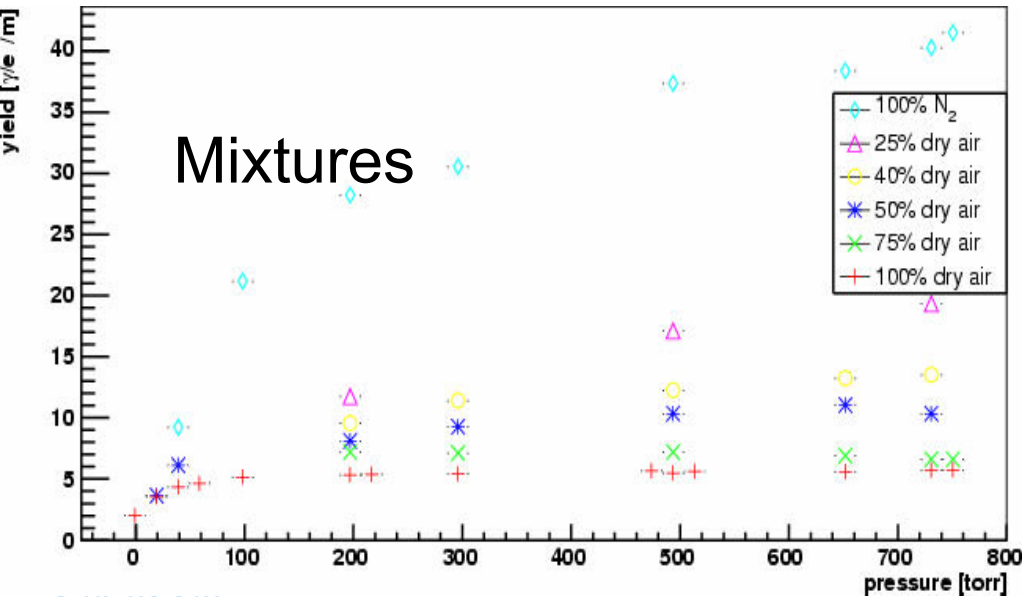
Laser tests the reach of our HE aperture - 34 km from HiRes-2 Detector.

Light production equivalent to ~6x10^{19} - 10^{20} eV air shower

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

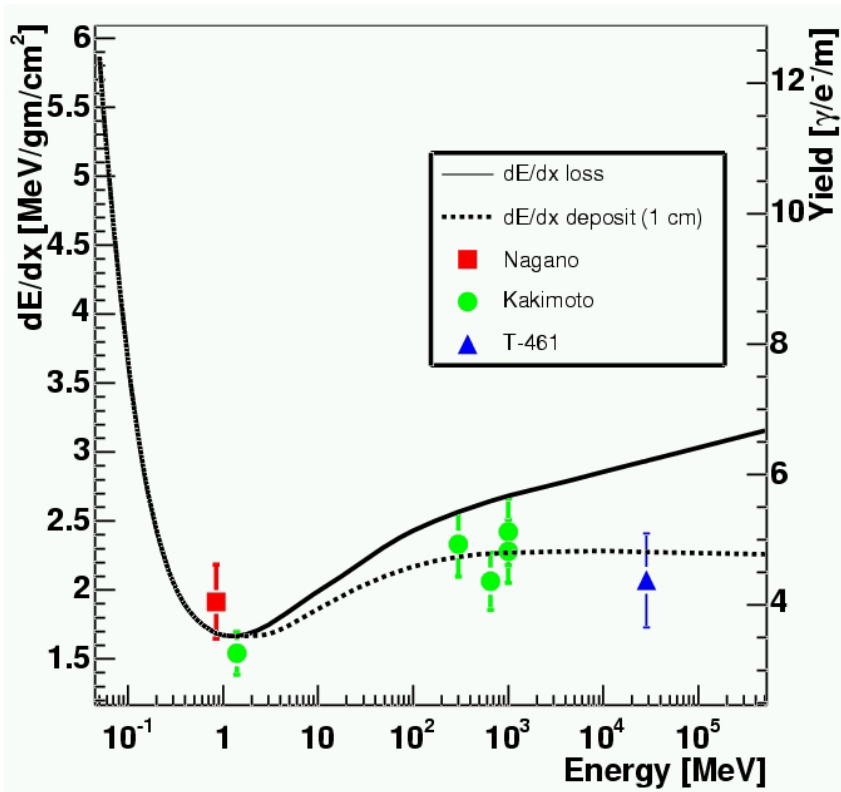
Fluorescence Yield



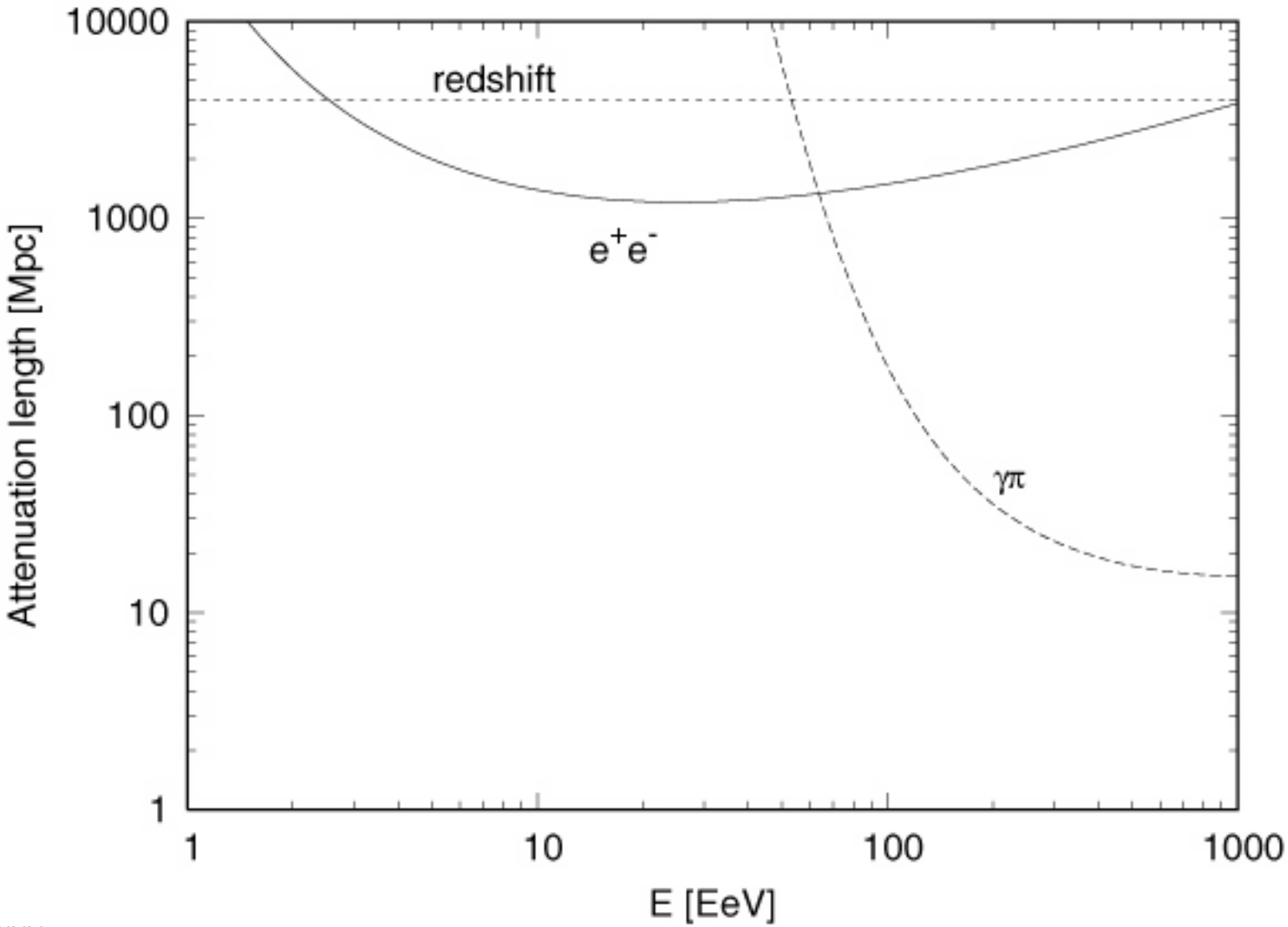


- Three published results: Kakimoto *et al.*, Nagano *et al.*, and T461.
- Ratio of fit to (Kakimoto, Nagano, and T461) to fit to Kakimoto

  = 1.00 ± 0.06

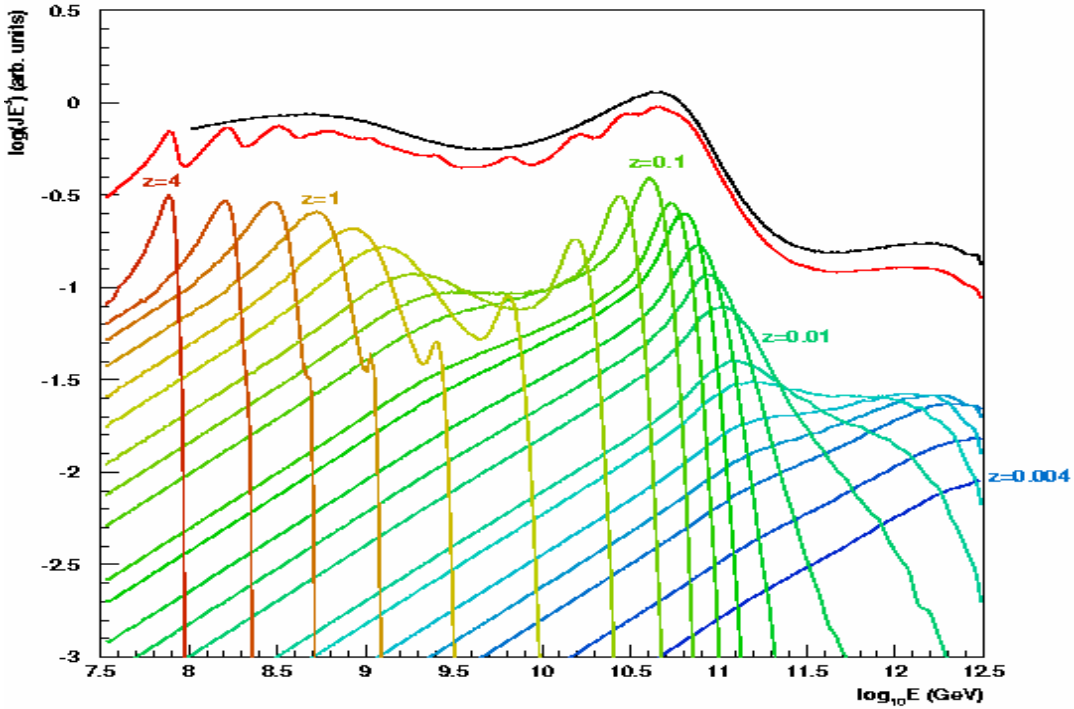


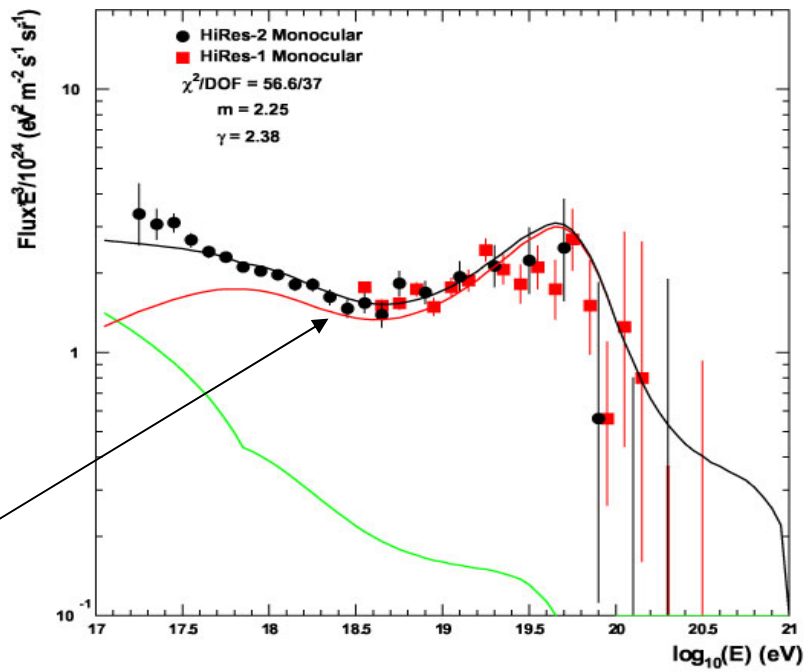
GZK: A More Complex Picture…



Interpretation of the UHE Spectrum

- Interaction with the CMBR fractionates the extragalactic flux of protons by red-shift/age
- Observed structures can be attributed to this process
- Pile-up from pion-production causes the bump at $10^{19.5}$ eV.
- e^+e^- pair production excavates the ankle.





See **Phys. Letters B 619, 271-280,** (arXiv:astro-ph/0501317) update shown

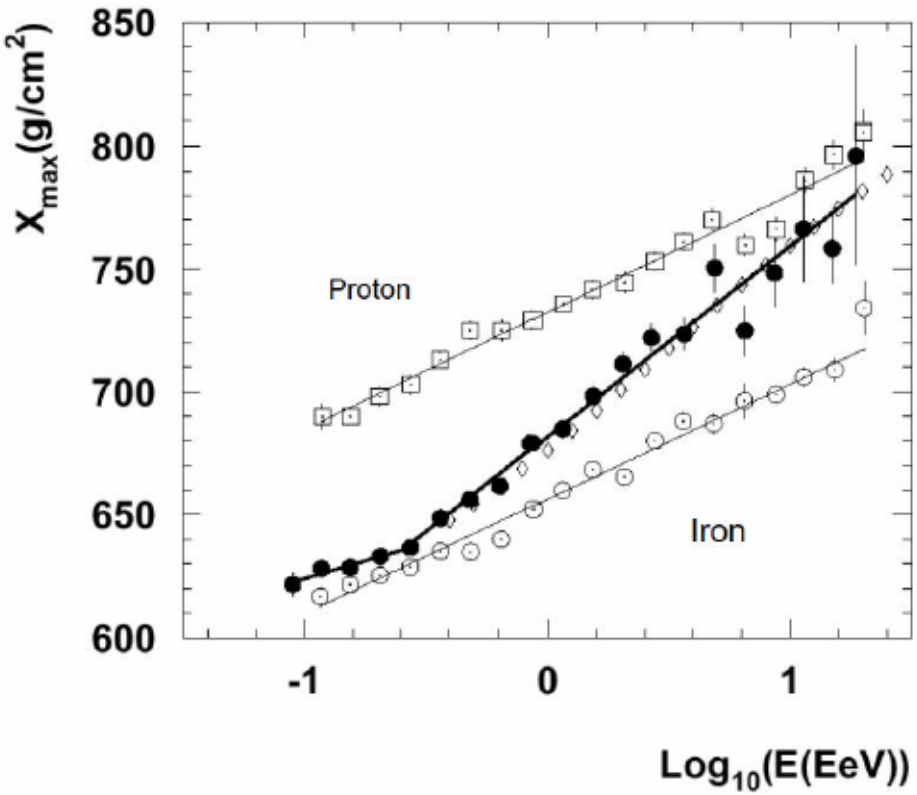
Charlie Jui
03/16/2007

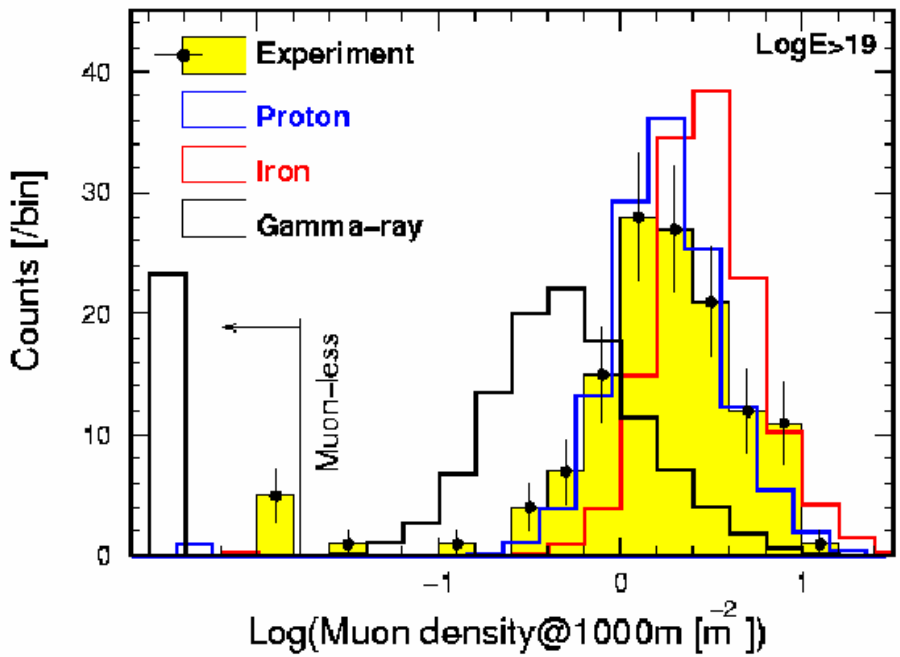
- Transition energy $E_c \approx 1 \times 10^{18}$ eV is a universal value, independent of propagation mode, including different diffusion regimes.
- Prediction of the shape of the dip is robust. It is practically not modifie by all known phenomena:
- propagation modes,
- inhomogeneities in source distribution,
- different distances between sources,
- fluctuations in interaction.

This makes the dip a more reliable signature of interaction with CMB than GZK cutoff.

V. Berezhinskii

Status of EHECR/UHECR Physics
2. Composition

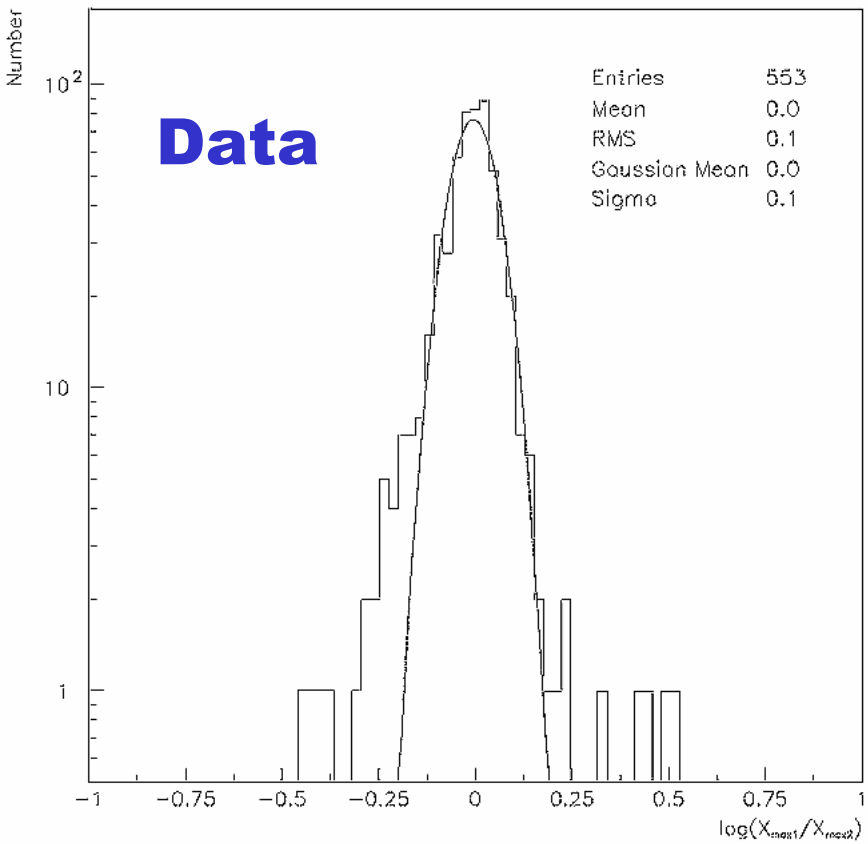


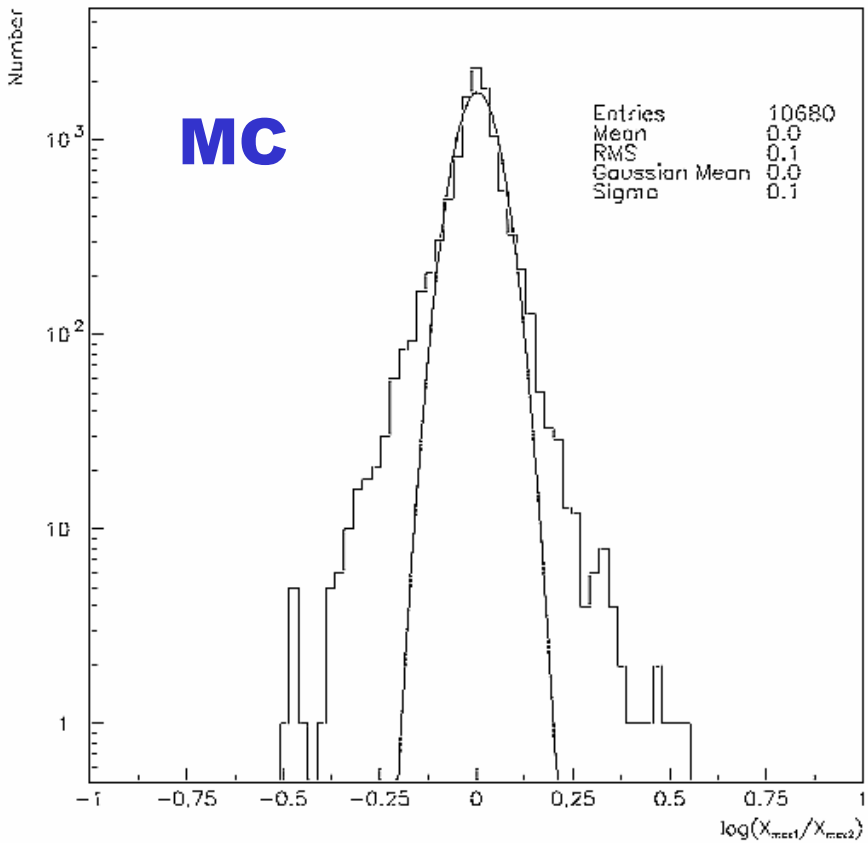


Both Fly's Eye (old FE) and AGASA results are consistent with light (protonic?) composition at above 10^{19} eV.

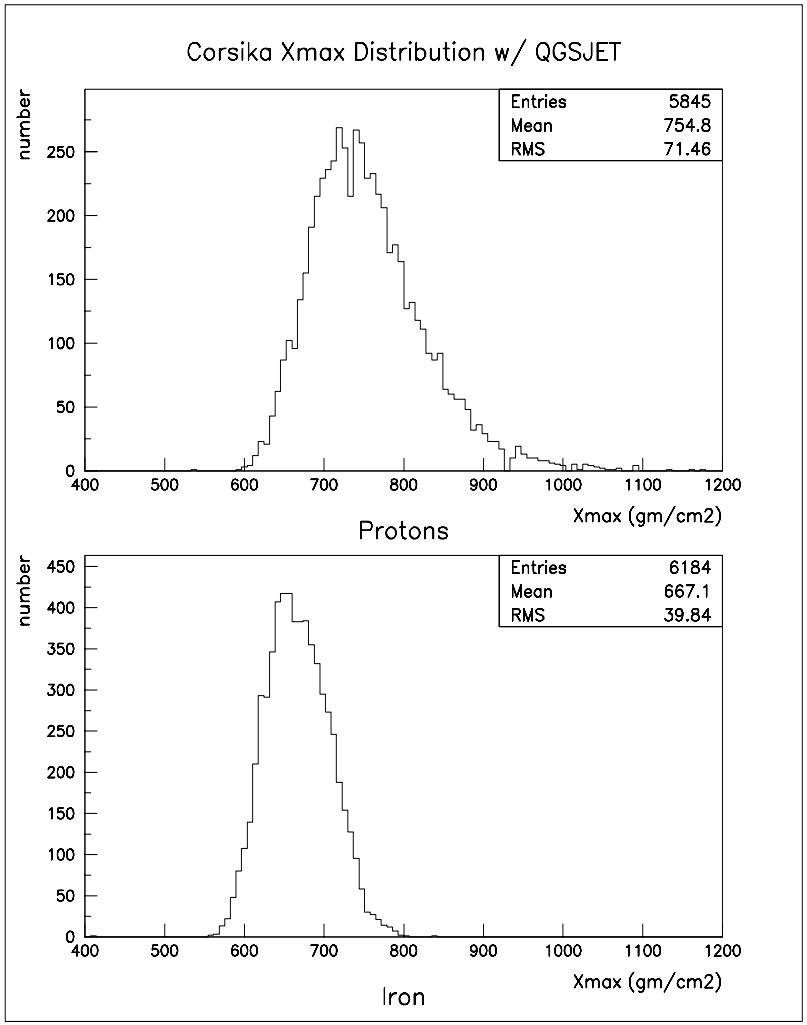
Stereo Xmax Measurement

- Two simultaneous measurements of the Xmax allows for ***direct verification*** of the MC resolution





Composition: X_{max} Distribution Width Predictions



MC with E = 10^{18} – 10^{19} eV

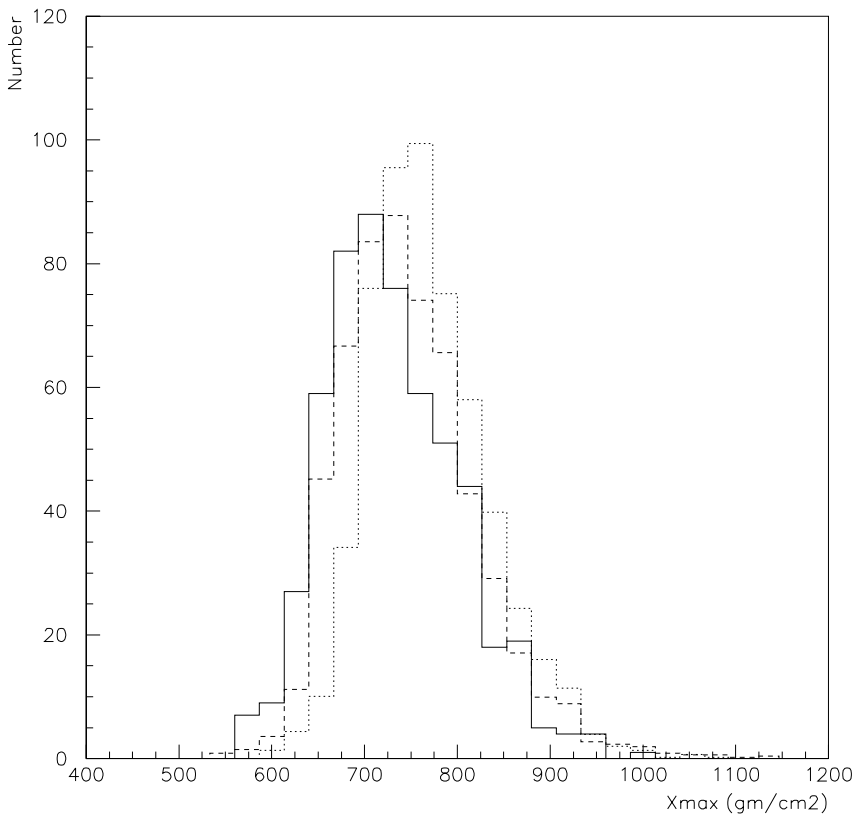
Protons: deeper **and** wider

The distributions overlap

Thus not an event by event measurement

Composition: **All-Energy X_{max} Distribution**

Data v Proton Models

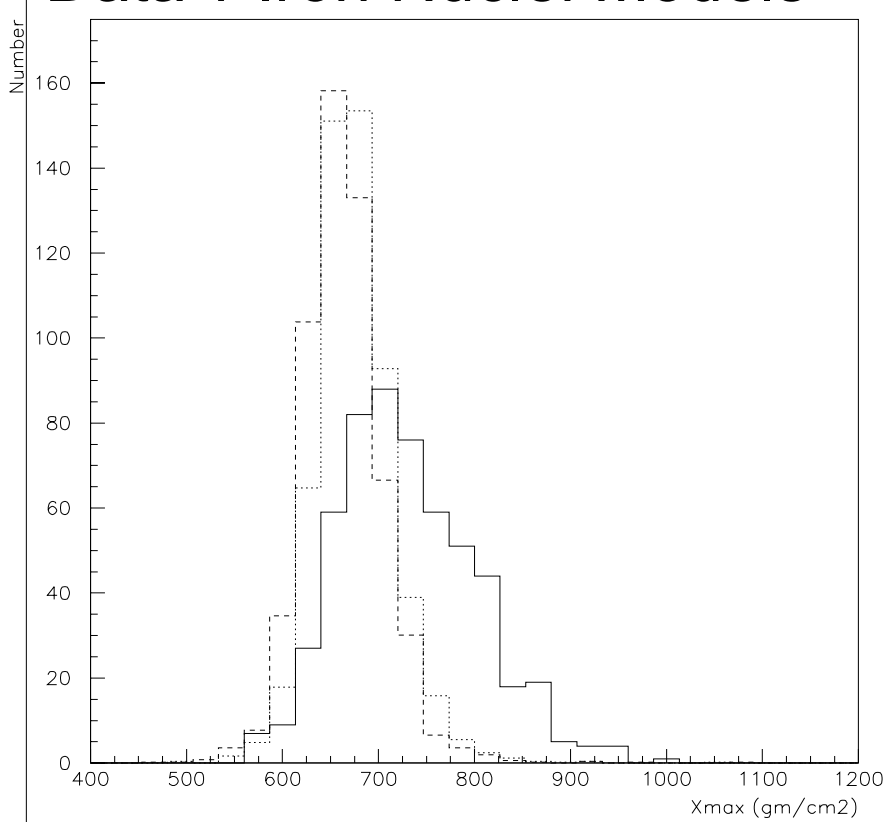


Solid Line: Data

Heavy Dots: QGSJet

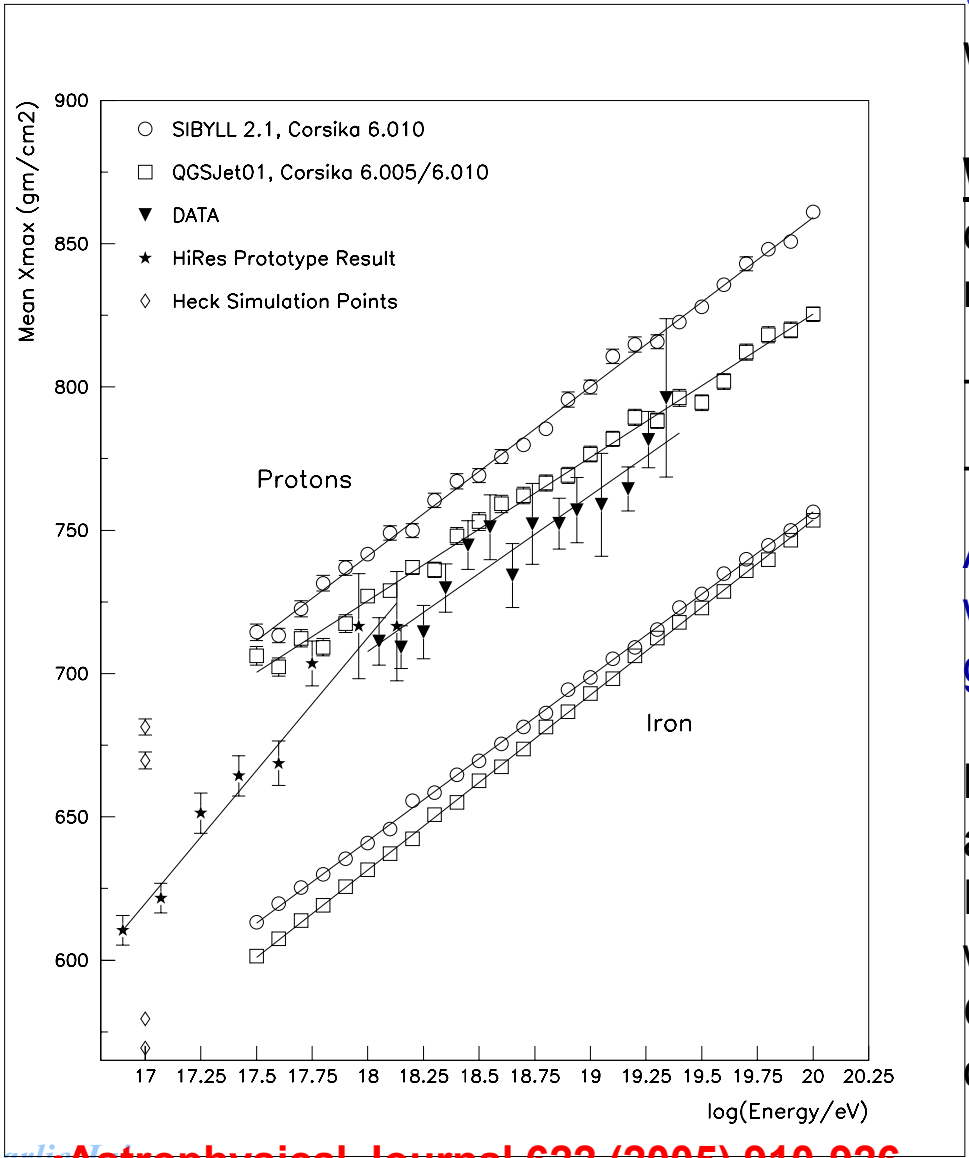
Light Dots: SIBYLL

Data v Iron Nuclei Models



Stereo Data:
~800 Events
11/1999 – 9/2001

Stereo HiRes Elongation Rate



Width is constant from ~10^{18} eV up

Width and **Xmax** (elongation) imply constant composition in this energy range

- QGSjet (1) prefers ~80% "protons"

- Sybil prefers ~60%

Application of radio-sonde data (SLC) will move the HiRes X_{max} up ~10 gm/cm^2 on average, thus lighter

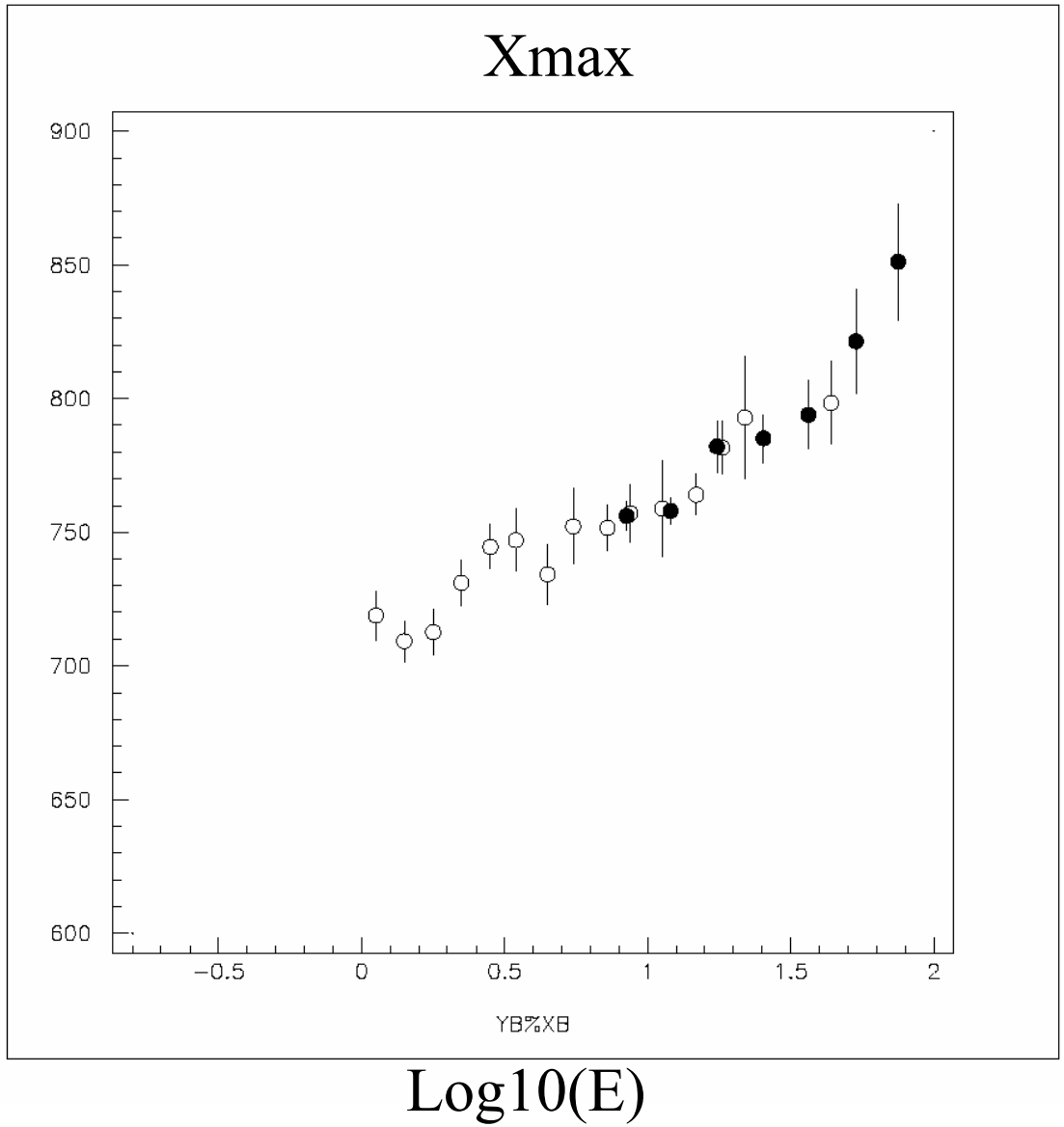
Model-independent break in slope at about 10^{18} eV.
Heavy (galactic) nuclei decrease, give way to light (extragalactic) composition.
Galactic/extragalactic transition is complete by about 10^{18} eV.

•**Astrophysical Journal 622 (2005) 910-926**

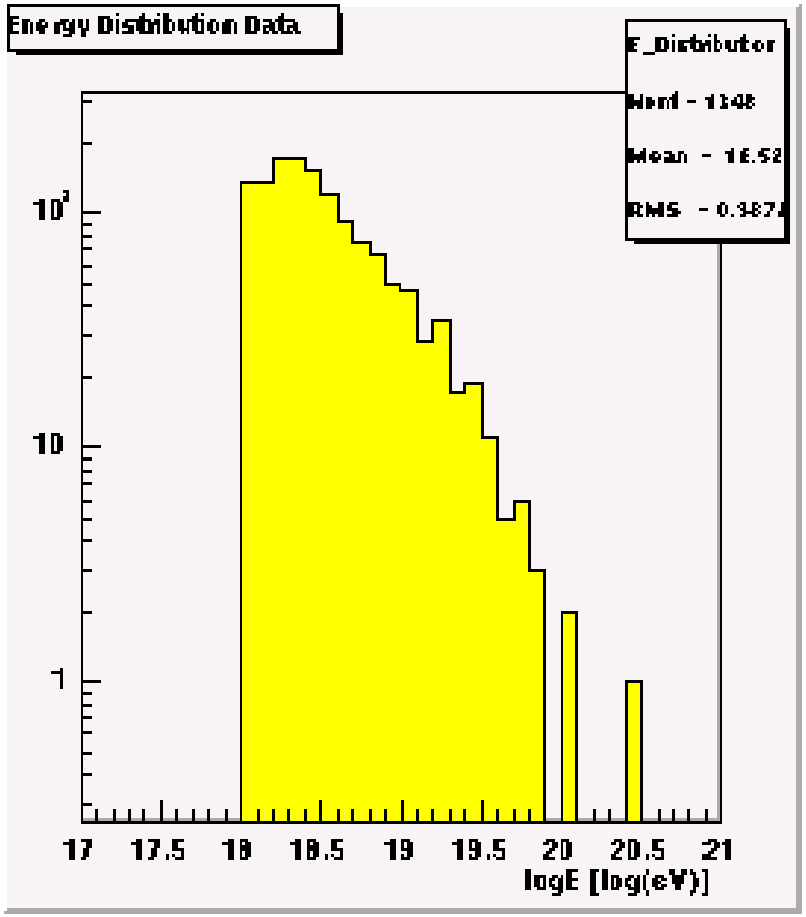
Extending the Analysis

A first look:

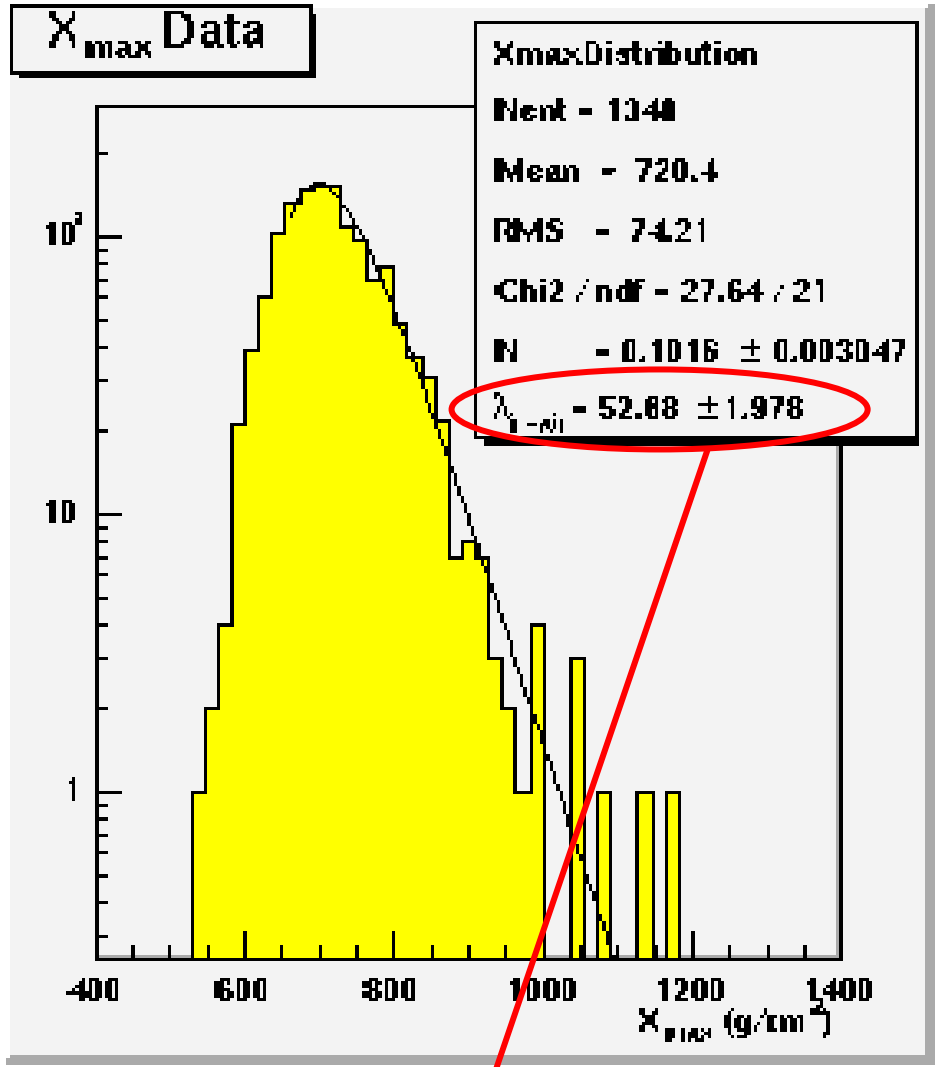
- Open circles: previous HiRes publication
- Filled circles: new HiRes "golden events"
- Composition appears to remain light approaching 10^{20} eV
- Student's Thesis on this is taking shape and expect an updated result this summer



Data and Deconvolution Result

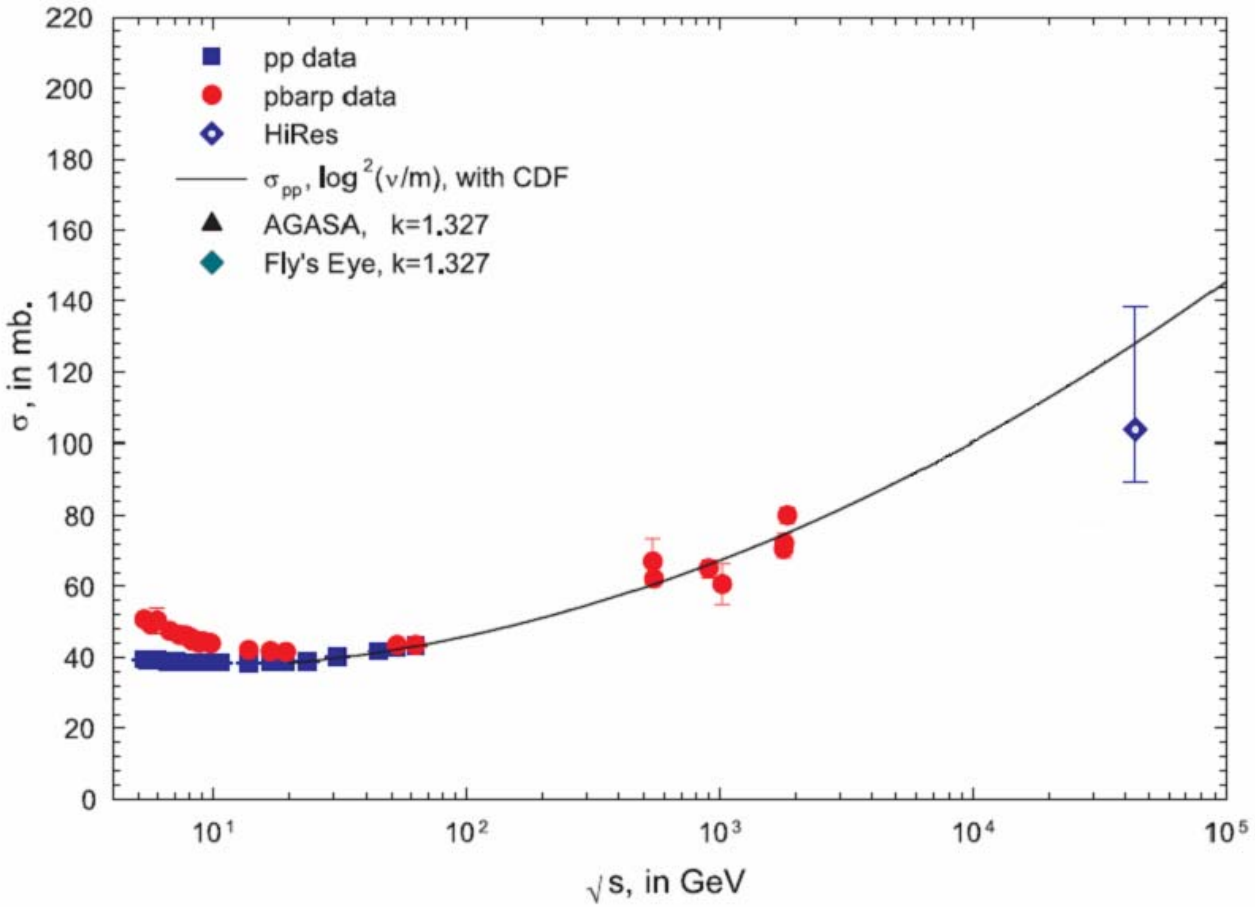


- 1348 out of 3346 stereo events pass the quality cuts (data:12/1999-3/2003)



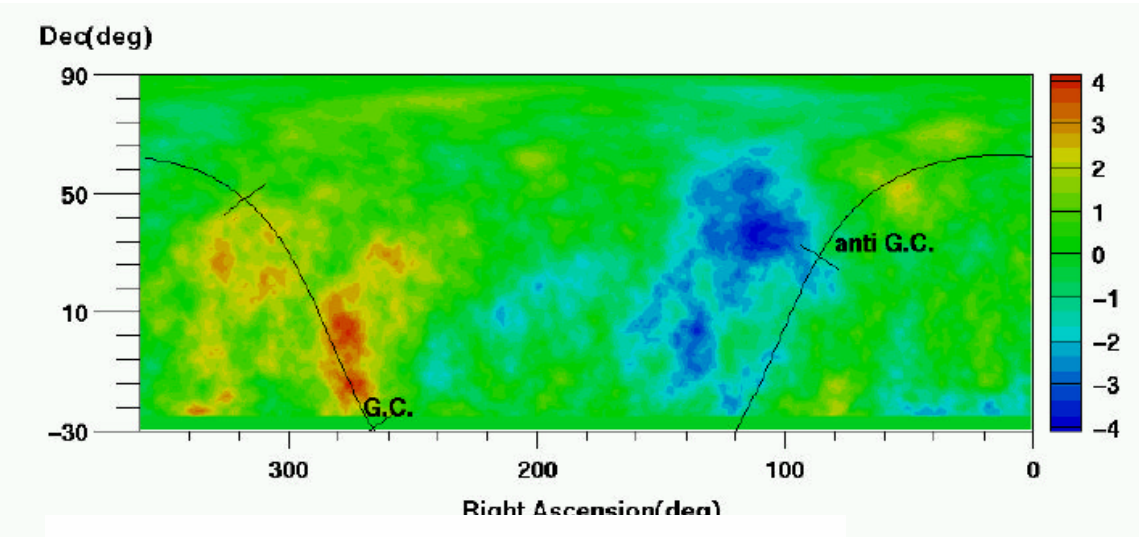
$$\sigma_{in}^{p-Air} = 456 \pm 17\ mb$$

HiRes Measurement



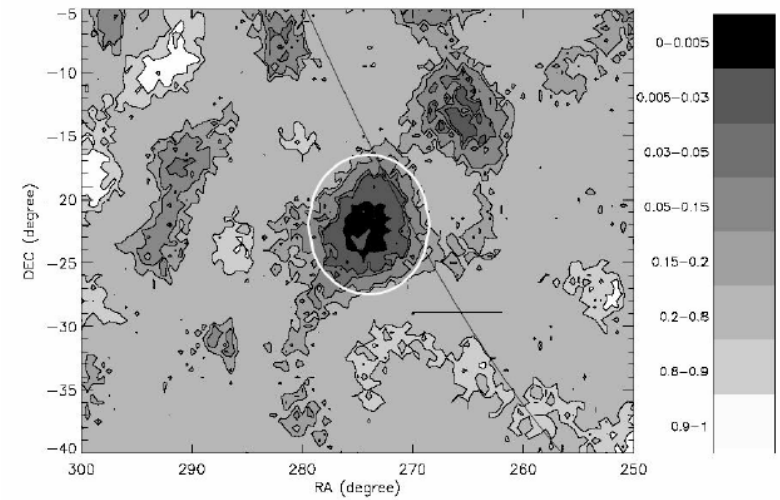
- HiRes: $\sigma_{in}^{p-Air} = 456 \pm 17(stat) + 39(sys) - 11(sys)\ mb \text{ at } 10^{18.5}\ eV$

Status of EHECR/UHECR Physics
3. Anisotropy



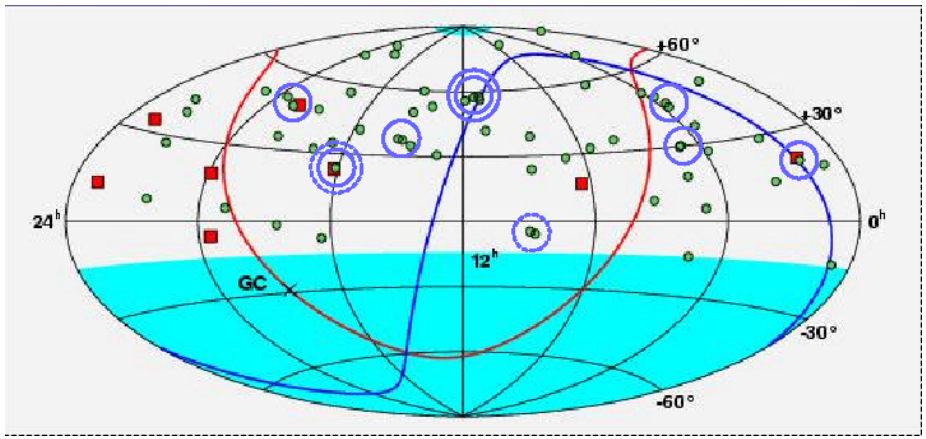
AGASA: in the range $10^{18.0}$-$10^{18.5}$ eV

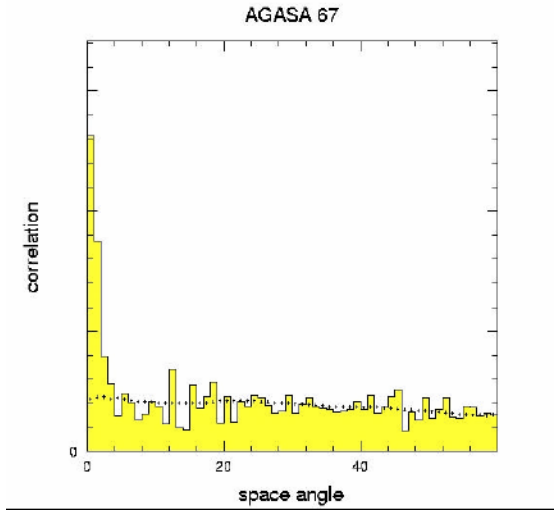
- ~4σ **excess** seen near G.C.
- ~4s **deficit** seen near A.G.C.



- Excess near GC also seen in re-analysis of SUGAR (Australia) data
- First AUGER results: did not see excess in the direction of G.C.

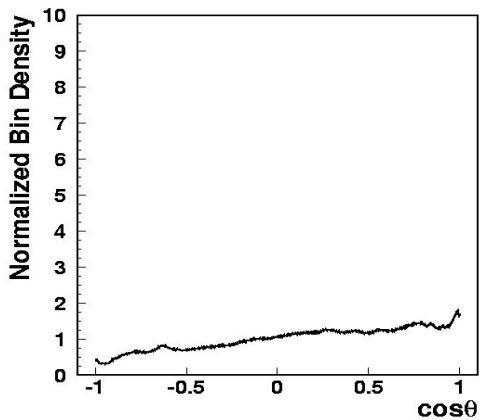
Status of EHECR/UHECR Physics
3. Anisotropy (continued)

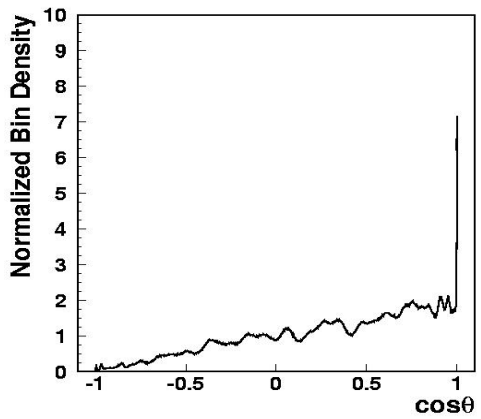




AGASA:

- Smaller-scale clustering $E>10^{19.4}$ eV
- Auto-correlation signal not confirmed by HiRes…however…





HiRes Anisotropy Results

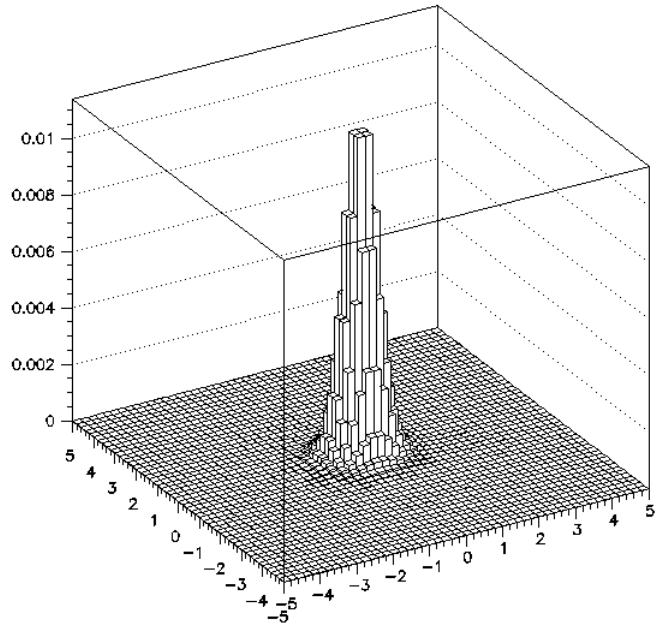
Monocular Anisotropy Results

- ***Autocorrelation functions*** (histogram of $\cos\theta$ between all possible pairs) for HiRes-1 monocular (left) and AGASA (right) events above ~4×10^{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

  accepted by Astropart Phys.
- Search for cross-correlation with AGASA doublets and triplet:
  - Observed overlap no greater than that expected by chance from an isotropic

  accepted by Astropart Phys.

Stereo point spread function

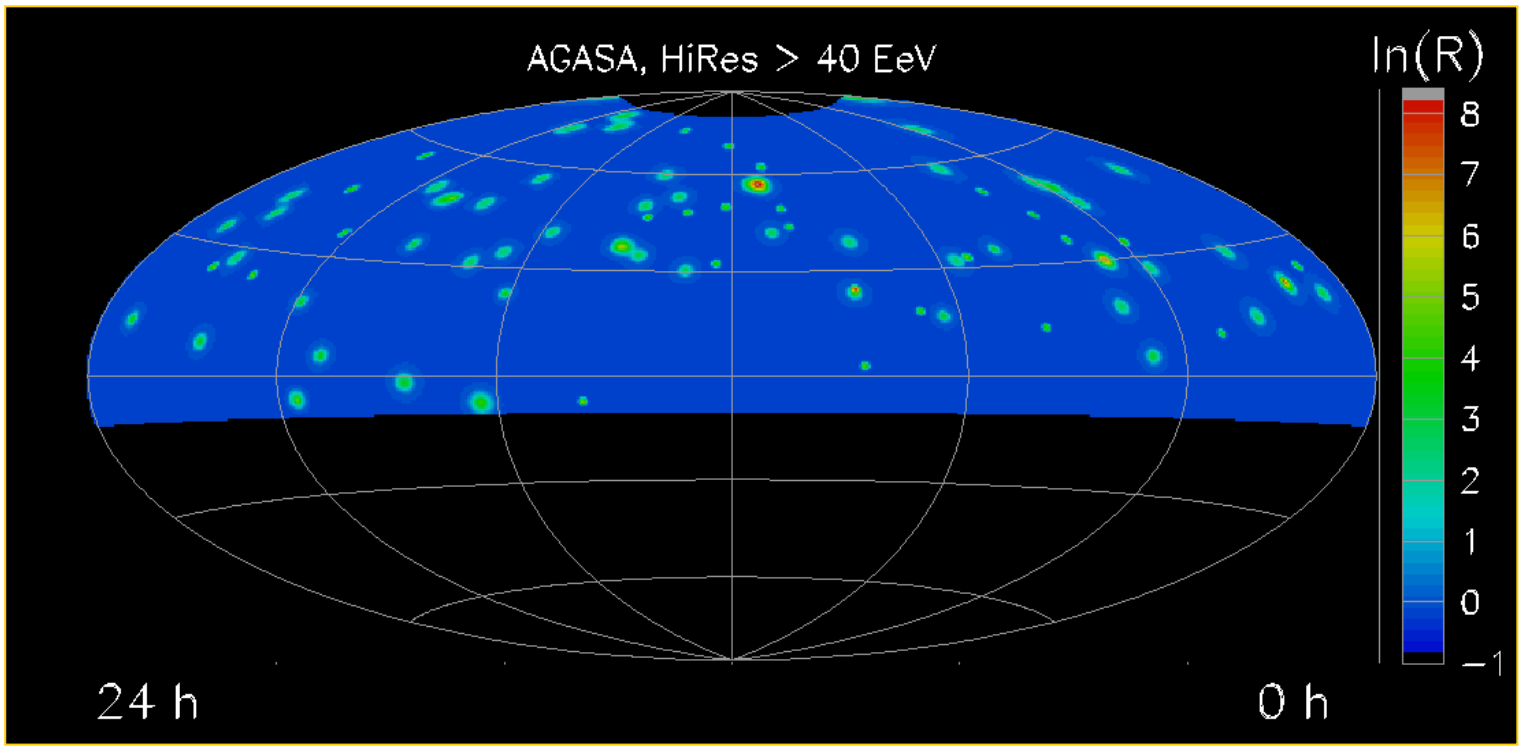


Stereo Anisotropy Results

- 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

Maximum Likelihood Point Source Search

Scan over a fine grid of locations in the sky, treating each as a potential source position, to identify the single spot with highest deviation from null source hypothisis. The significance is determined by scanning over Monte Carlo data sets and counting the fraction with $\ln(R_{MC}) > \ln(R_{data})$.

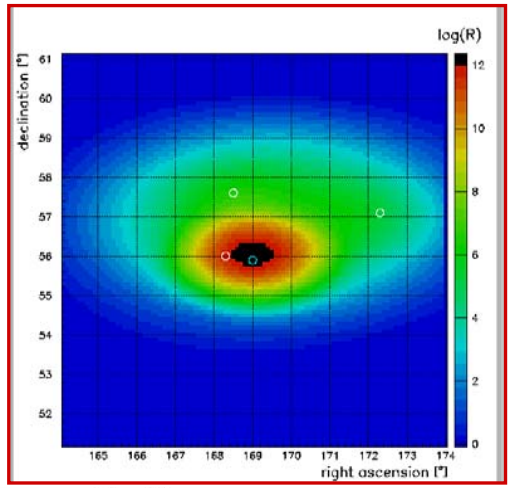


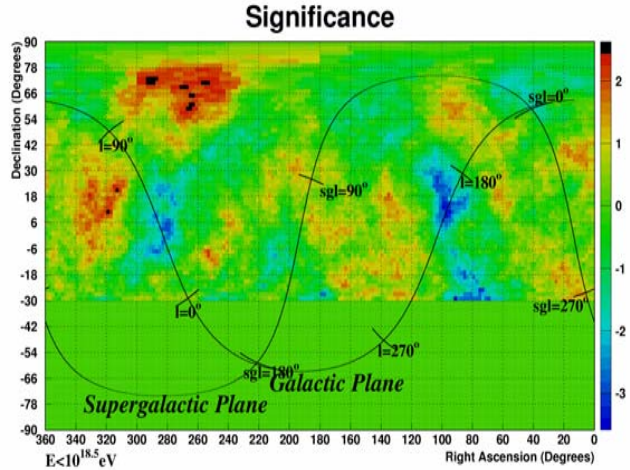
No significant point source is found in the combined set of HiRes and AGASA events above **4×10^{19} eV**.

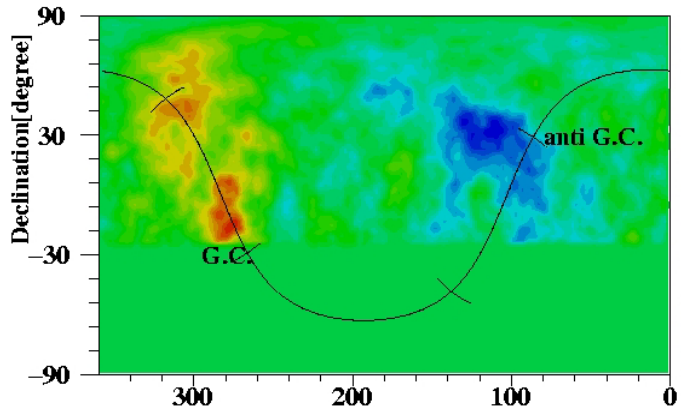
More Northern Hemisphere Anisotropy

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

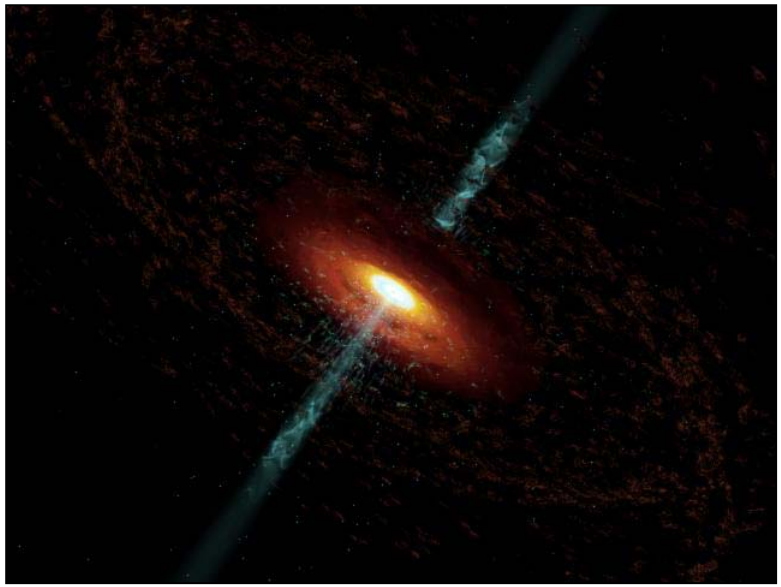
- Deficit is seen in HiRes-2 monocular data near A.G.C. (and it seems to occur along a great circle)







Correlation with BL Lacertae Objects



- BL Lacertae Object - special type of blazar, active galaxy with jet axis aligned with our line of sight.
- Blazars are established sources of TeV g-rays
- Candidates for accelerating cosmic rays to EeV energies

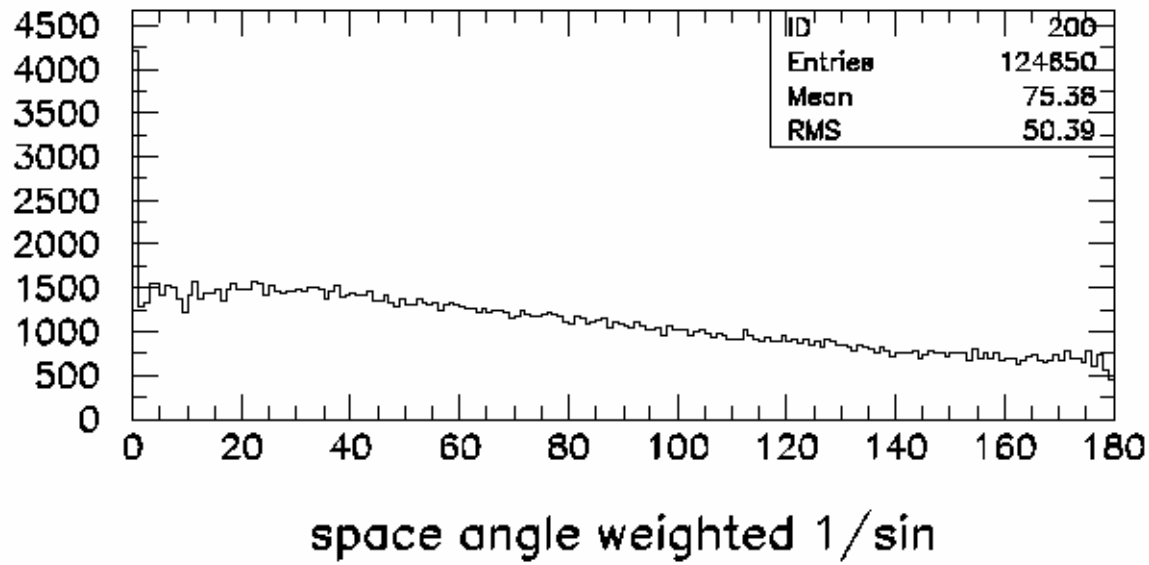
AGASA and HiRes both see (unconfirmed) BL-Lac correlation

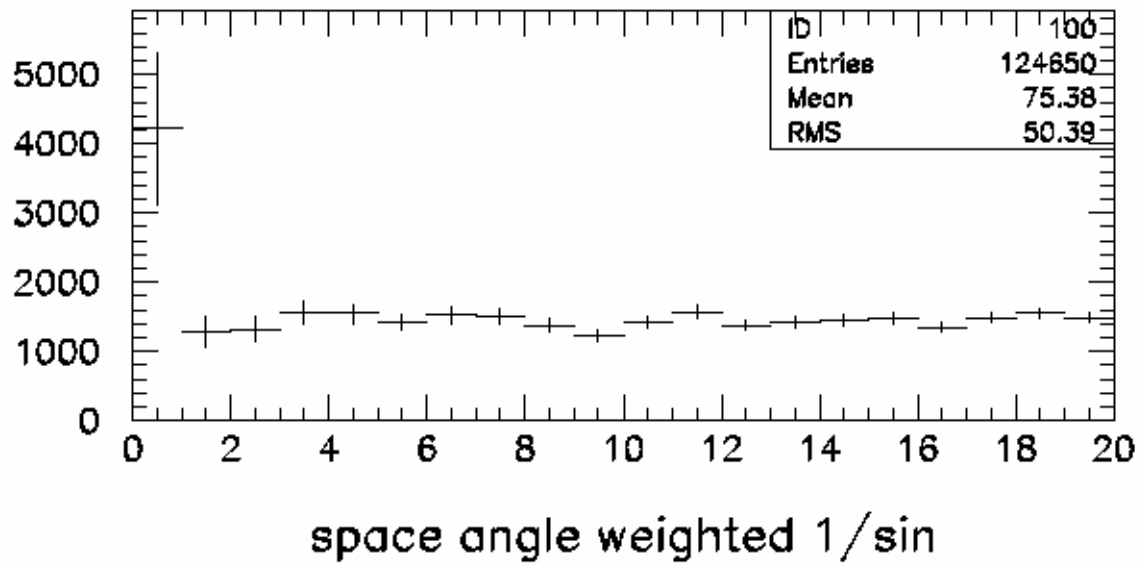
Tinyakov and Tkachev, JETP 74 (2001) 445.
Tinyakov and Tkachev, Astropart. Phys. 18 (2002) 165.
Gorbunov et al., ApJ 577 (2002) L93.
Evans, Ferrer, and Sarkar, Phys.Rev. D67 (2003) 103005.
Torres et al., Astrophys.J. 595 (2003) L13.
Gorbunov et al., JETP Lett. 80 (2004) 145.
Stern and Poutanen, ApJ 623 (2005) L33.

Cross-correlation between:

Confirmed BL Lacs m>18 (10th Veron)

HiRes Events E>10^{19} eV (Dec 1999-Jan 2004)





Summary of HiRes BL-Lac Correlation:

- ***HiRes data set does not confirm previous AGASA claims***

BUT:

- "BL", m<18, all HiRes events (no E cut): $F = 2\times10^{-4}$
- **"BL+HP" with m<18, HiRes E>10 EeV: $F = 10^{-5}$**
- Confirmed TeV blazars, all HiRes events (no E cut): $F = 10^{-3}$.
- **Correlations must be tested with independent data before any claim can be made.**
- Arrival directions of past year of data have not been analyzed. Data taking through **March 2006** will yield an independent data set ~70% of the current sample size: Independent test of BL Lac correlations should be possible.

Summary: HiRes Physics Results

- Energy Spectrum:
  - Good agreement between mono and stereo spectra, clear evidence of "ankle" near ~3 EeV
  - Inconsistent with continuing power law spectrum beyond 60 EeV; Consistent with GZK prediction (but cannot exclude weaker continuing flux).
  - Previous experiments show consistent evidence of second knee near .5 EeV
- Stereo composition measurement:
  - Composition is light from 10^{18} to $10^{19.4}$
  - Change in elongation at about 10^{18} eV.
- Measuring p-air total cross section
  - Cross section consistent with extrapolation of accelerator-based proton-proton and proton-anti-proton and cross-sections: consistent with proton dominance

HiRes Physics Results (cont'd.)

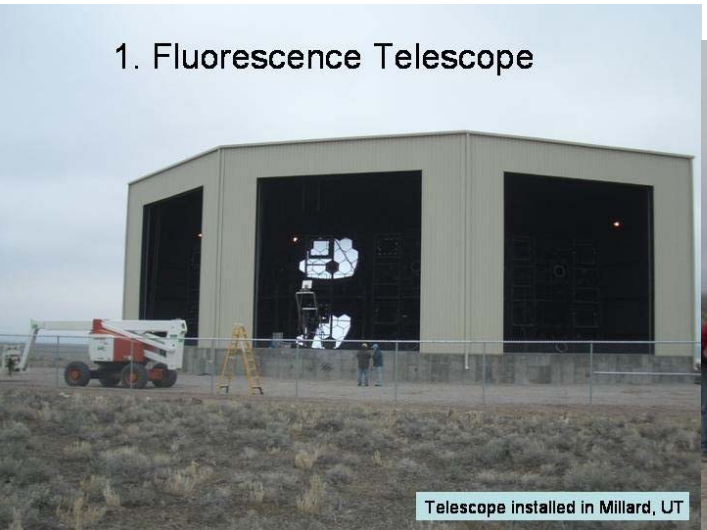
- Anisotropy:
  - No evidence for point sources from loking at the data by itself
  - No confirmation of clusters reported by AGASA
  - No dipole distributions seen (aas reported by AGASA).
  - A Cross-correlation is seen with BL-Lac objects…needs to be independetly confirmed
- FLASH experiment to calibrate fluorescence yield: key component in determining the energy scale
- **Telescope Array Project (TA) (Members of AGASA and HiRes combining forces) begininng construction on a hybrid detector near Delta Utah**

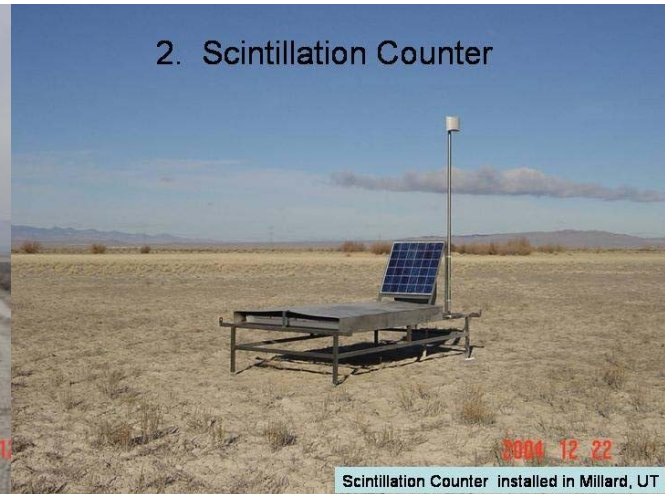
Telescope Array Status

Scintillator Detectors

- 485 Detectors deployed and tuned by helicopter as of Mar 14

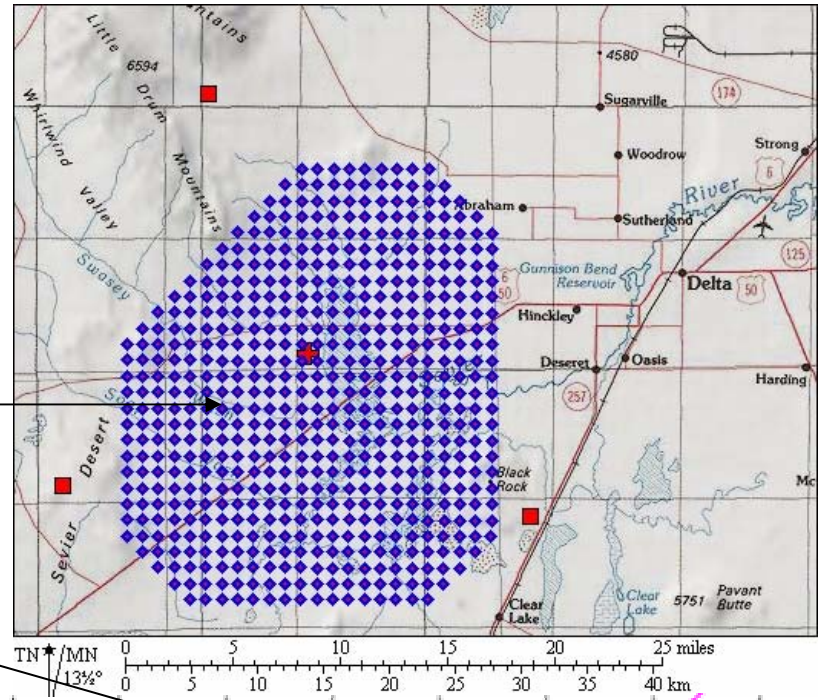
- Fluorescence Detectors
  - Three observatory sites, Buildings complete
  - 12-14 telescopes at each site
    - 6 new telescopes installed – testing –
    - 18 en route from Japan due in Delta any day
    - HiRes telescopes currently moving from Dugway to UofU for refurbishment… begin moving to Delta in March, 2007.
- Site Complete and Test data starting summer 2007

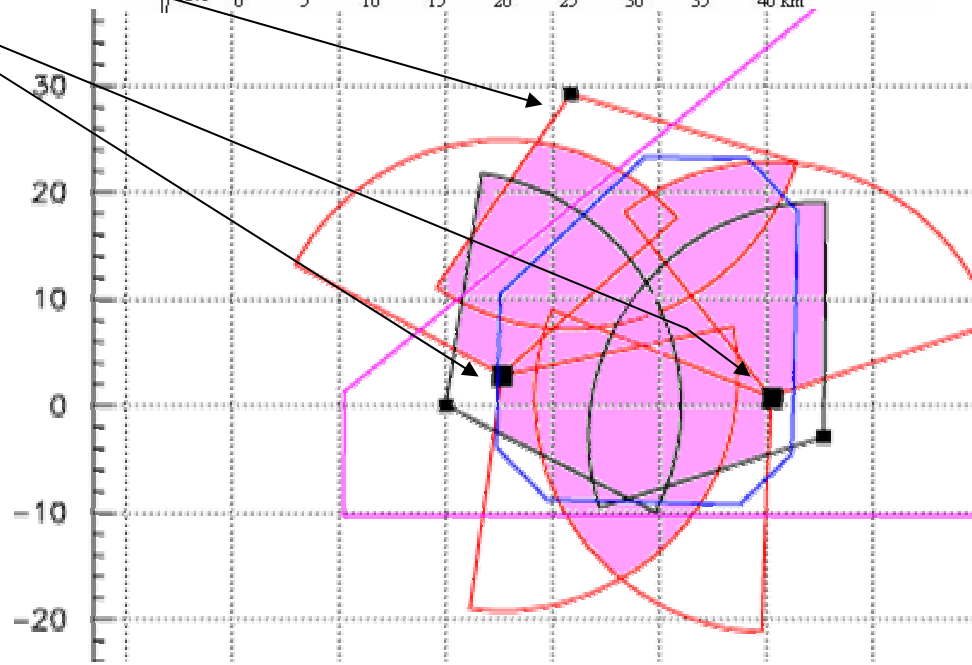


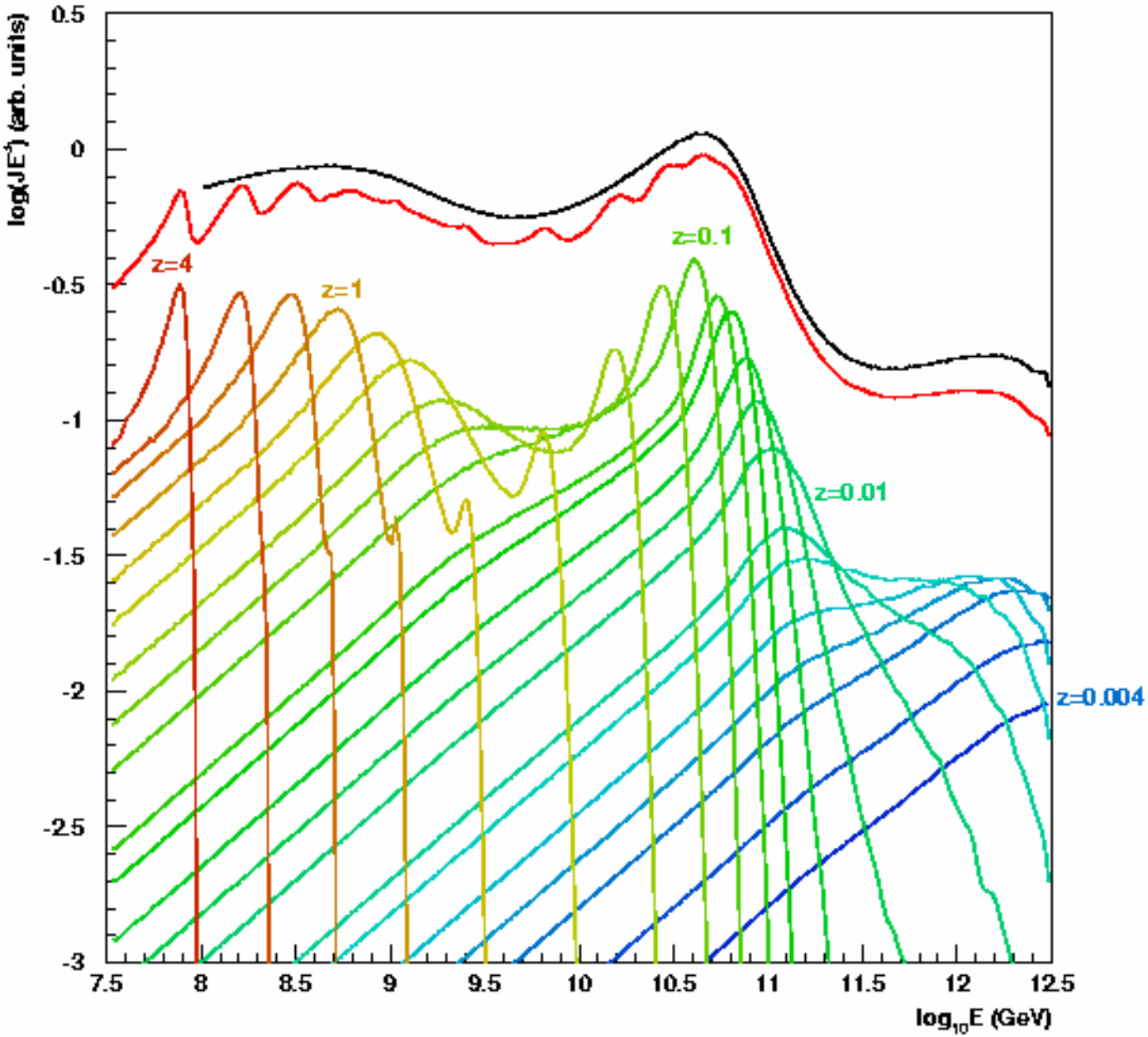


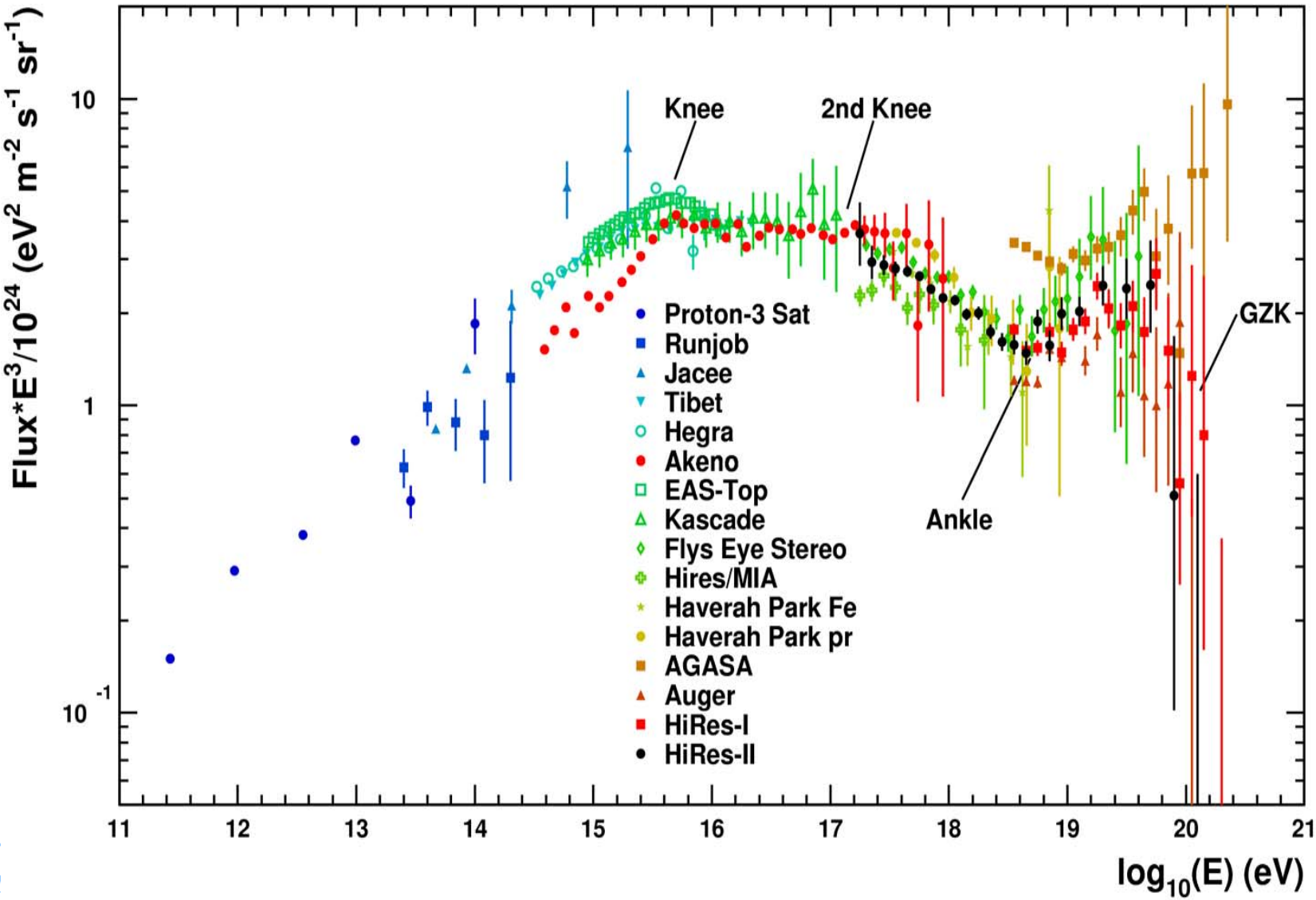
Telescope Array Stage-2: TALE

- Subgroups of HiRes have joined the Telescope Array (Delta, UT, USA)
  - Grond array of 512 (1.2km spacing) scintillation counters
- US contribution:
  - Northern TA fluorescence site
  - low-energy extension (TALE) with two additional Fluorescence stations (50 mirrors): down to $10^{17.5}$ eV
  - Tower detector (15 new mirrors) with 3X area: down to $10^{16.5}$ eV.
  - Infill array for hybrid observation at the lowest energies.
- TALE will also make TA into a **fully stereo-hybrid** detector at > 10^{19} eV.






log(JE³) (arb. units)
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
7.5
8
8.5
9
9.5
10
10.5
11
11.5
12
12.5
log10E (GeV)
z=4
z=1
z=0.1
z=0.01
z=0.004


Flux*E^3/10^24 (eV^2 m^-2 s^-1 sr^-1)
log10(E) (eV)
Knee
2nd Knee
Ankle
GZK
Proton-3 Sat
Runjob
Jacee
Tibet
Hegra
Akeno
EAS-Top
Kascade
Flys Eye Stereo
Hires/MIA
Haverah Park Fe
Haverah Park pr
AGASA
Auger
HiRes-I
HiRes-II