

Air Fluorescence Calorimetry with the High Resolution Fly's Eye and Telescope Array Experiments

CALOR 2006 Chicago

June 6, 2006

Charles Jui

University of Utah

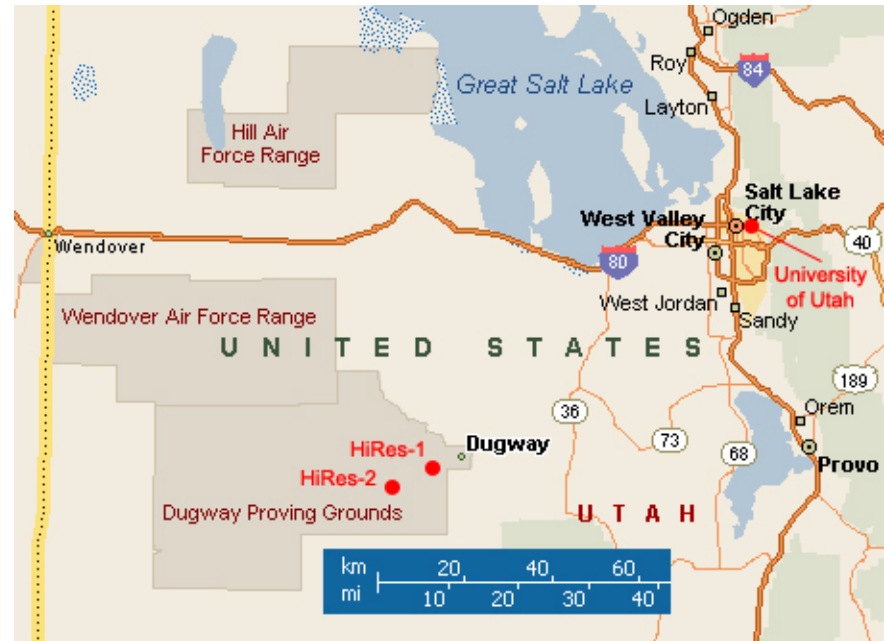
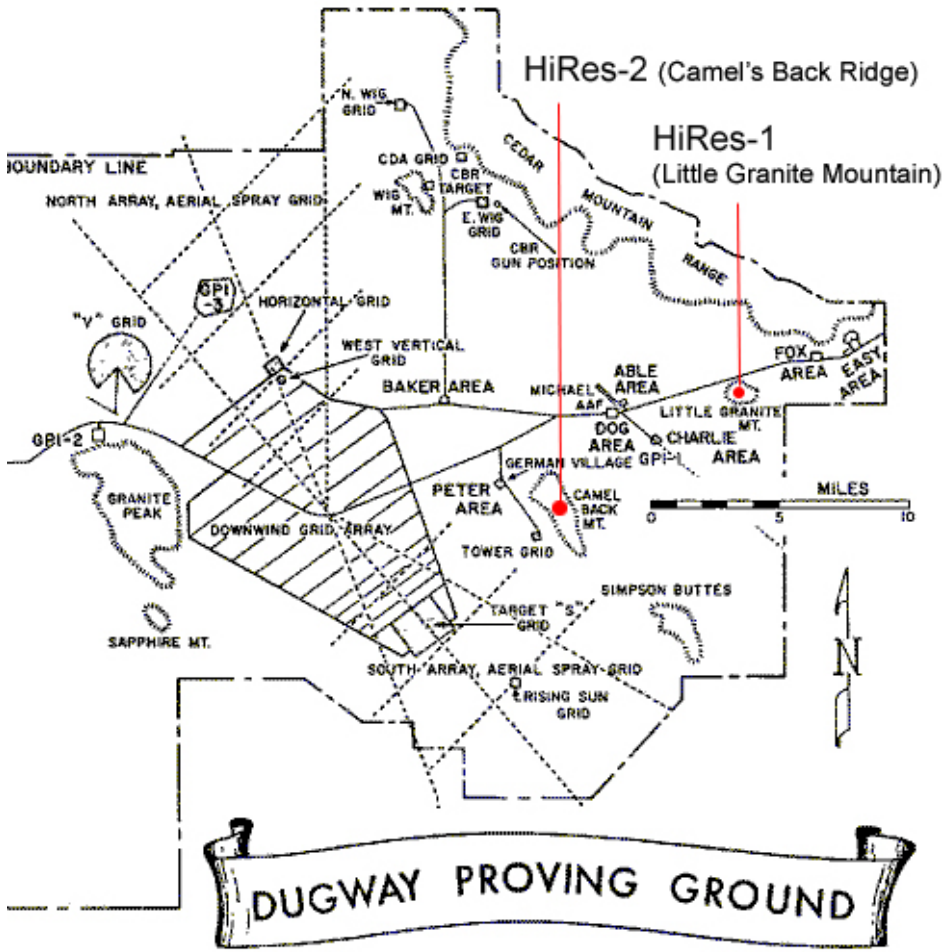
The High Resolution Fly's Eye (HiRes)



HiRes Collaboration:

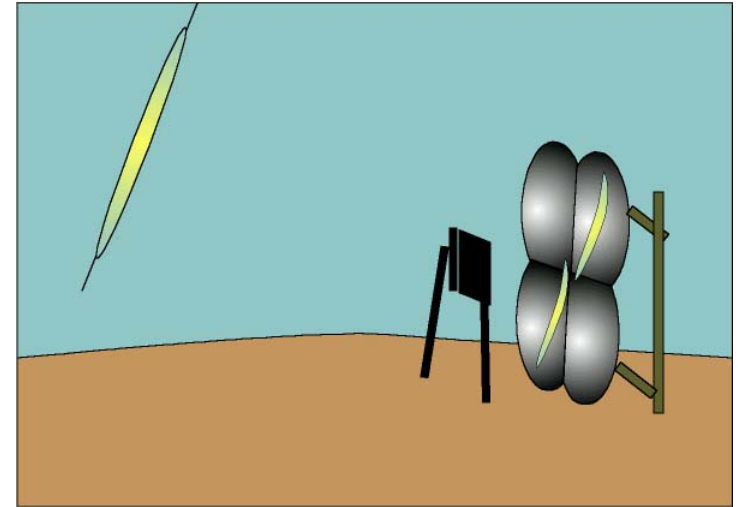
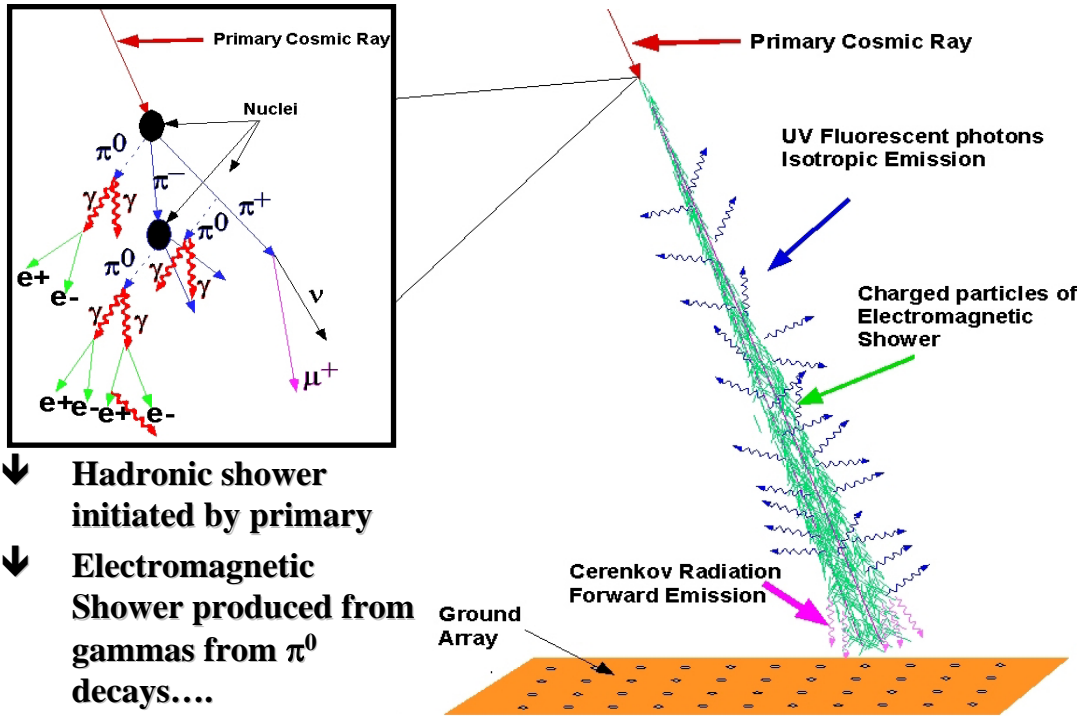
- *University of Utah*
- *Columbia University*
- *Rutgers University*
- *University of New Mexico*
- *University of Montana*
- *University of Adelaide*
- *Los Alamos National Laboratory (LANL)*
- *University of Tokyo*
- *IHEP (Beijing, China)*

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

Extensive Air Showers & the Fluorescence Technique



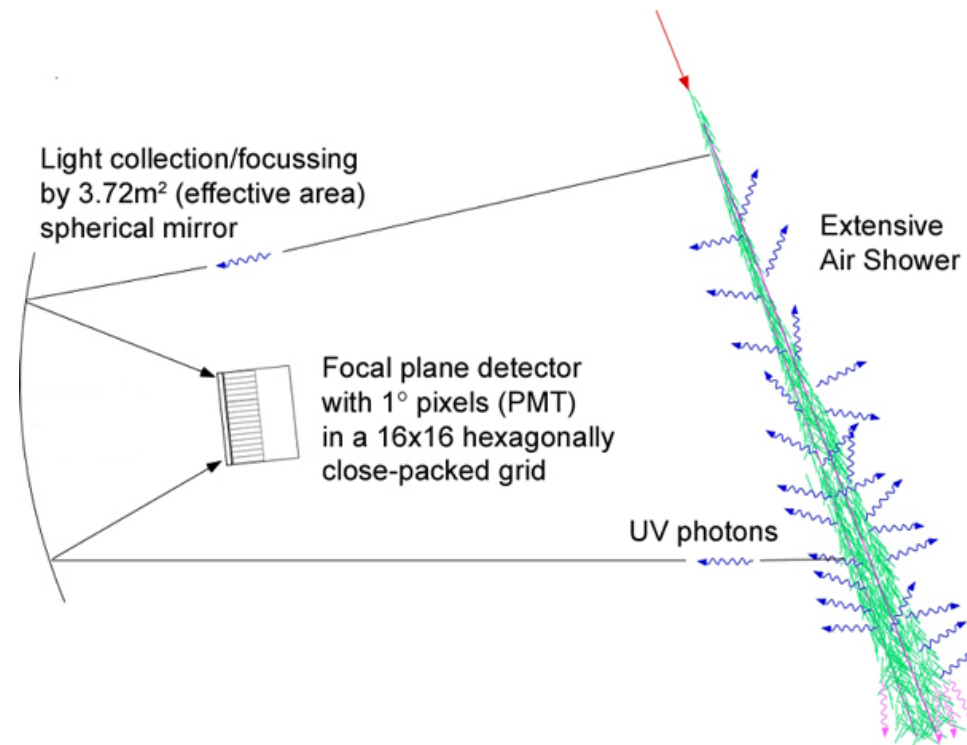
- ↓ Hadronic shower initiated by primary
- ↓ Electromagnetic Shower produced from gammas from π^0 decays....

- HiRes observes *scintillation light* emitted from *nitrogen* molecules in the wake charged particles in an *extensive air shower (EAS)*, from collisions of the primary cosmic ray particle with nuclei in the upper atmosphere

- At its maximum, an EAS contains approximately one charged particle per GeV of primary energy
- Each charged particle emits ~ 5 photons in the range 300–420nm
- **Fluorescence** light from EAS ($E > 10^{19}$ eV) can be detected at more than ~ 25 km away on *clear, moonless nights* ($\sim 10\%$ duty cycle)

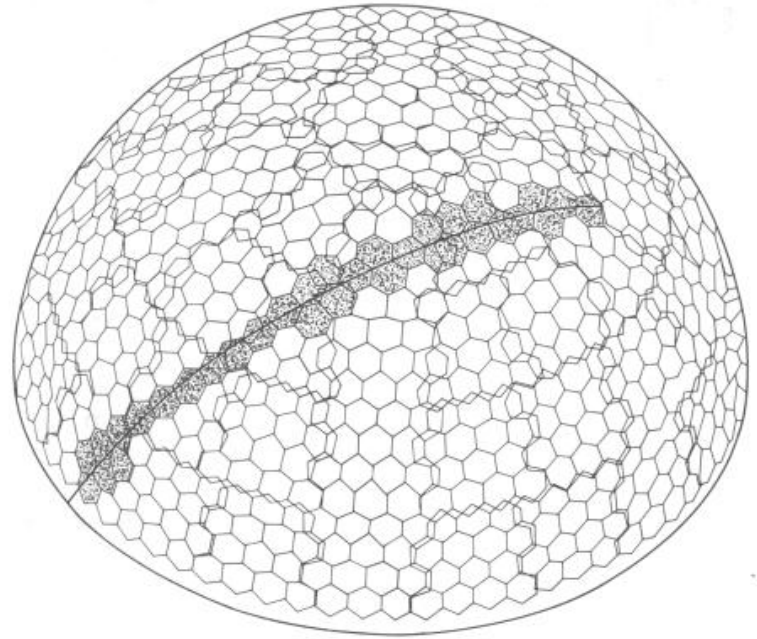
Detector Design

- Each HiRes detector unit (“*mirror*”) consists of:
 - spherical mirror w/ $3.72m^2$ unobstructed collection area
 - 16x16 array (hexagonally close-packed) of PMT pixels each viewing 1° cone of sky: giving $\times 5$ 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



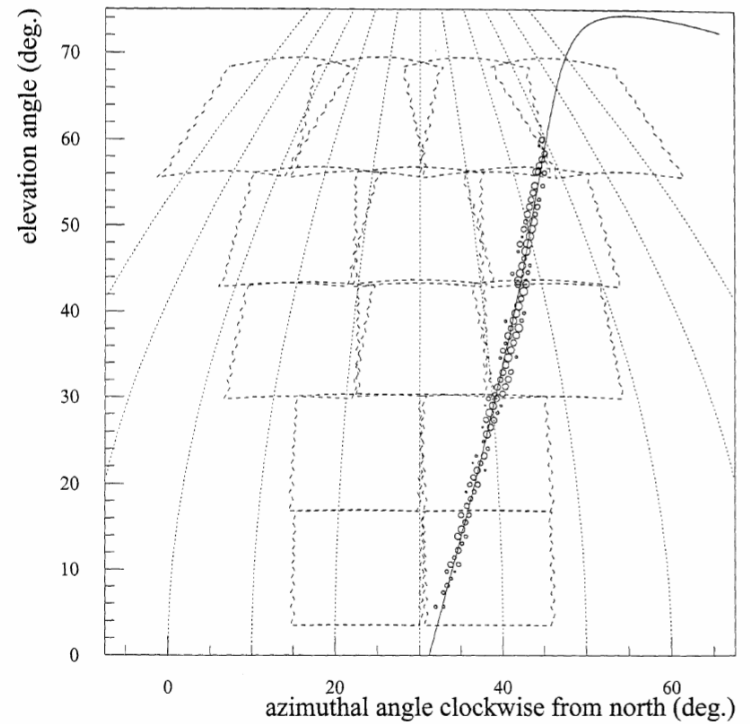
History: The Fly's Eye

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



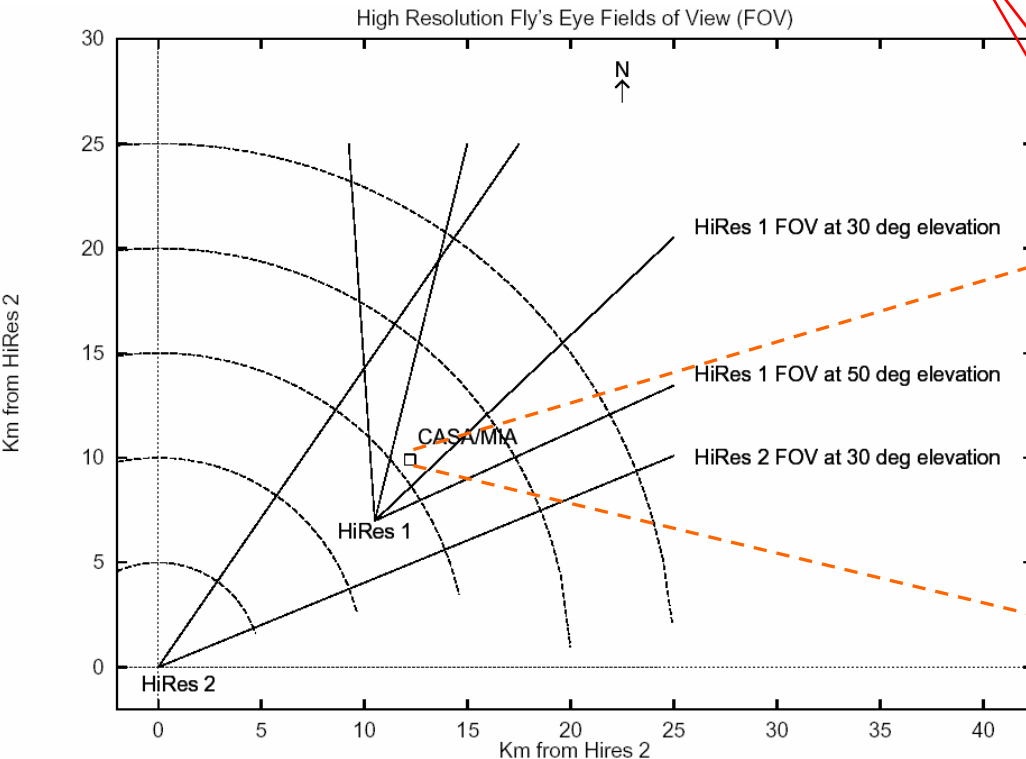
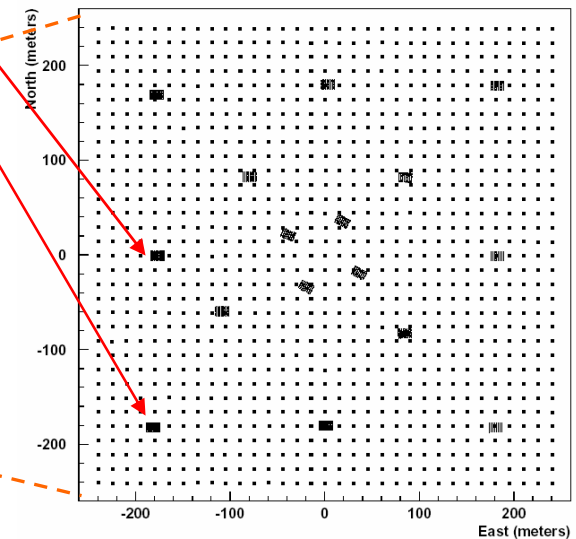
1992-1996: HiRes Prototype

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

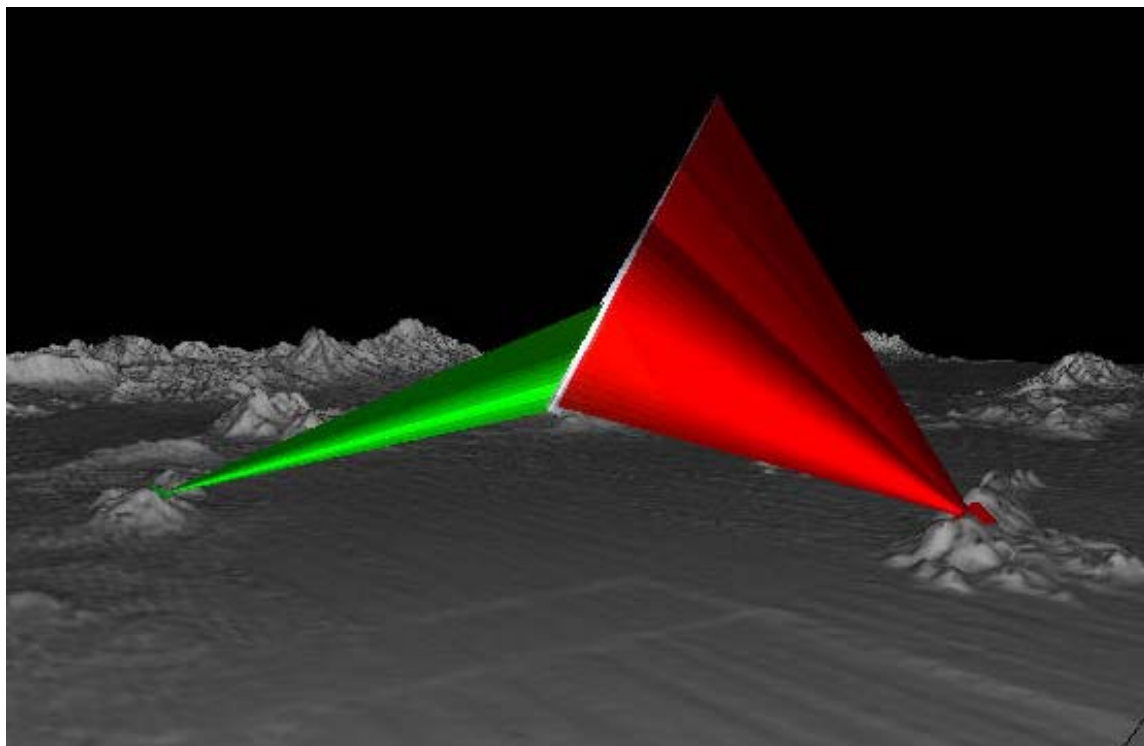


HiRes1 9750.01841315 1995-FEB-01 : 12:26:30.000 000 000

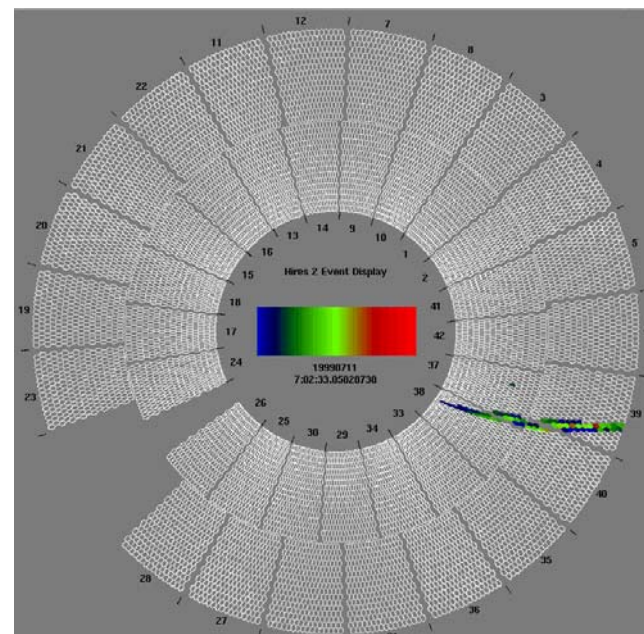
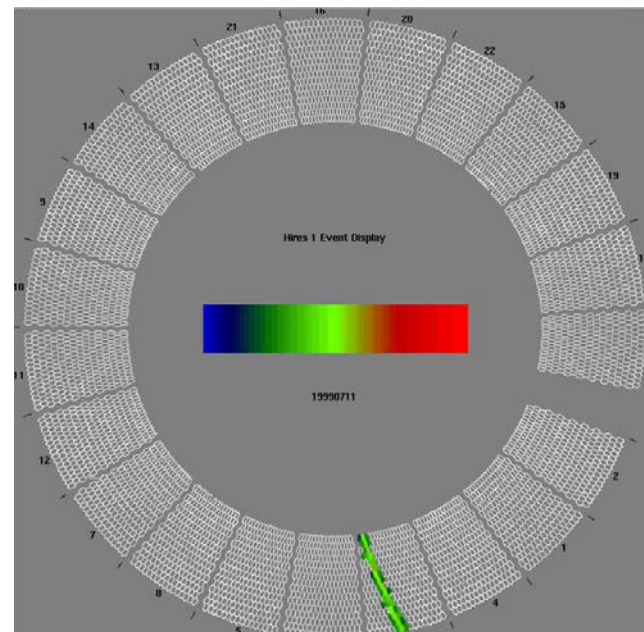
CASA-MIA detectors



Typical HiRes Event

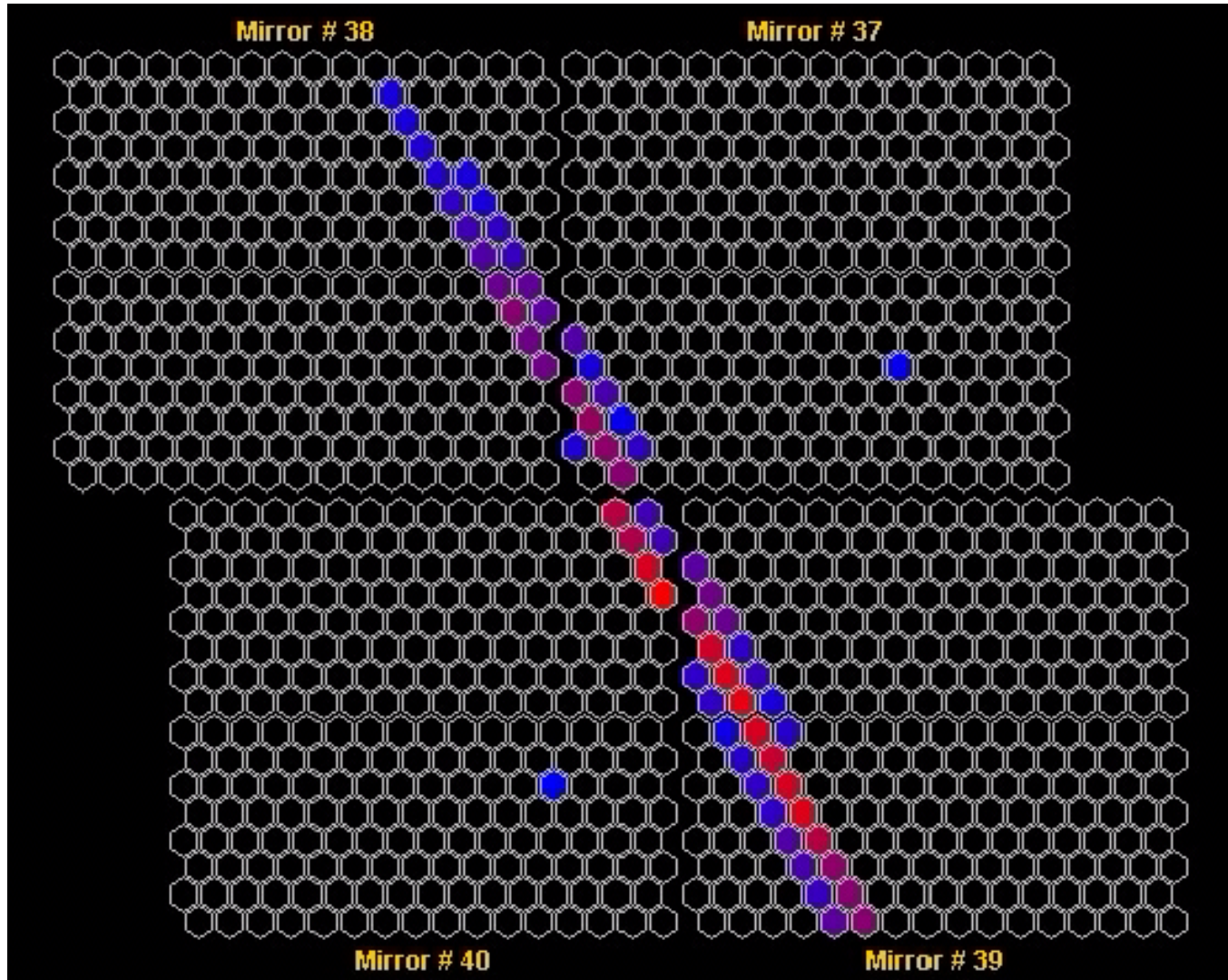


$\sim 2 \times 10^9 \text{eV}$ event seen in 1999
(3 \times vertical scale)



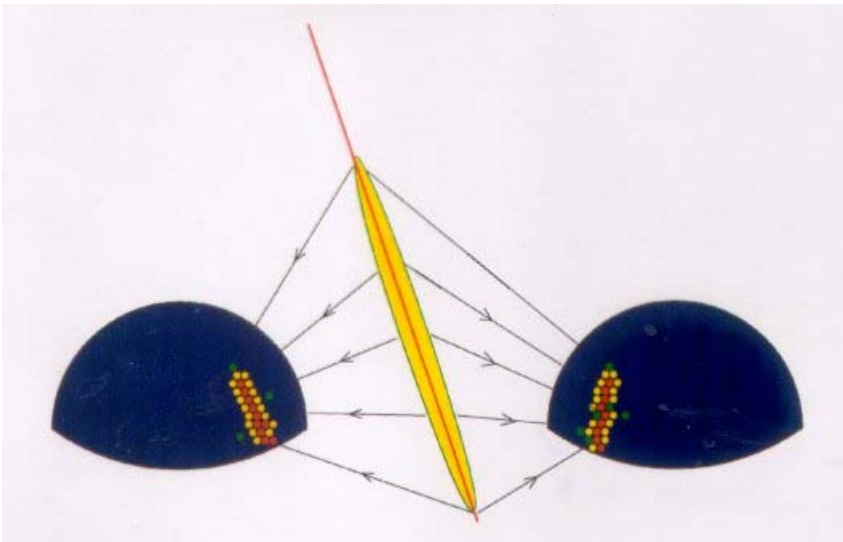
A 25 Microsecond Movie

(playback at 1/500,000 speed)

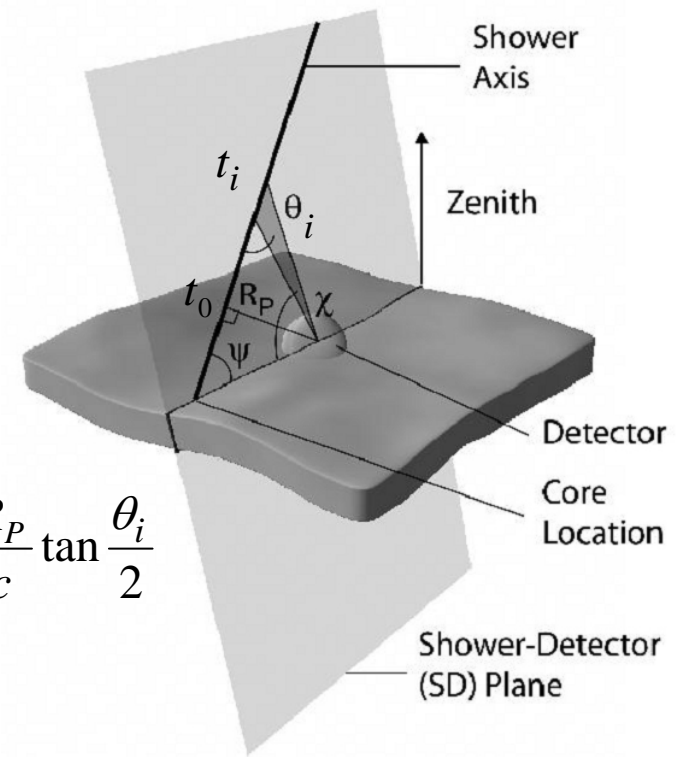


Reconstruction of EAS from HiRes Data

- 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.

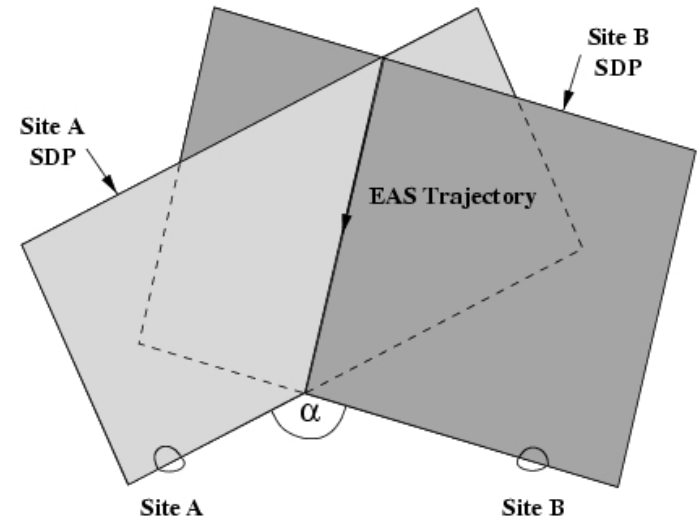


1.)

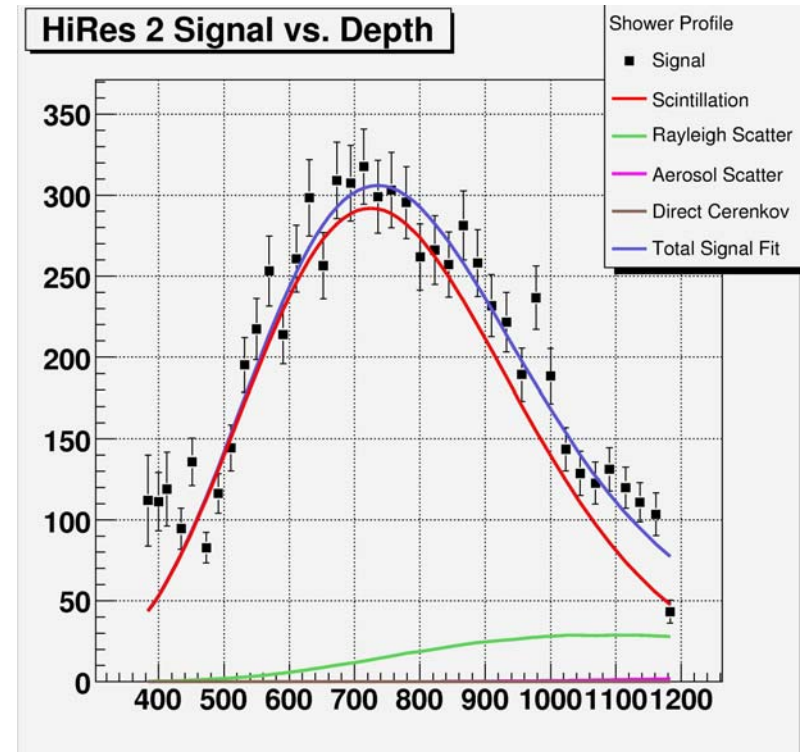
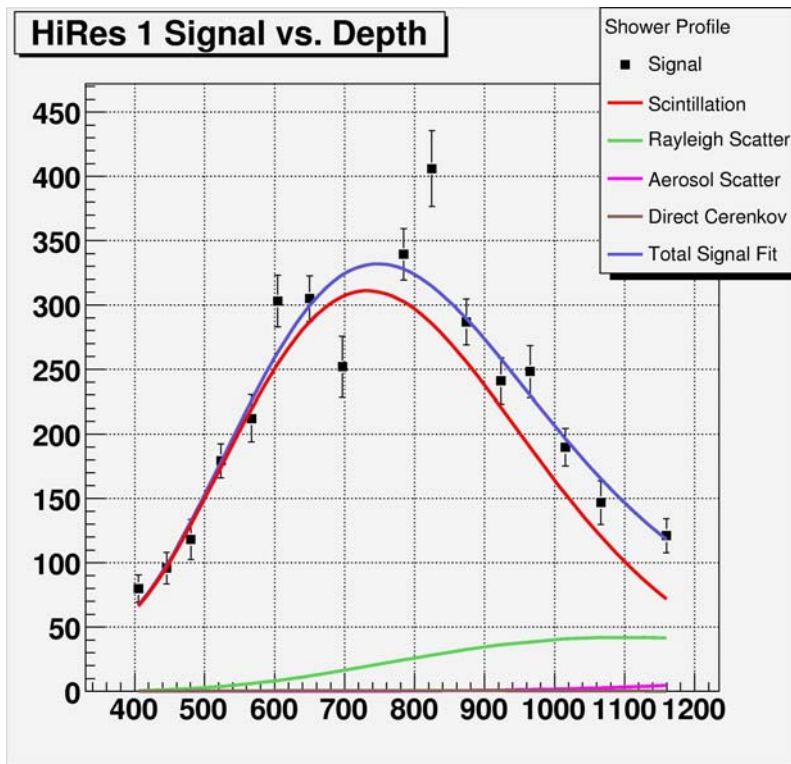


$$t_i = t_0 + \frac{R_P}{c} \tan \frac{\theta_i}{2}$$

2.)



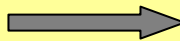
Measured shower profile.



Measured shower parameters.

Event by event:

- X_{\max} in g/cm²;
- Total energy of the primary particle:
- Arrival direction



Statistically:

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

Monocular Spectra

HiRes1: 7/97-5/05

HiRes2: 12/99-8/04

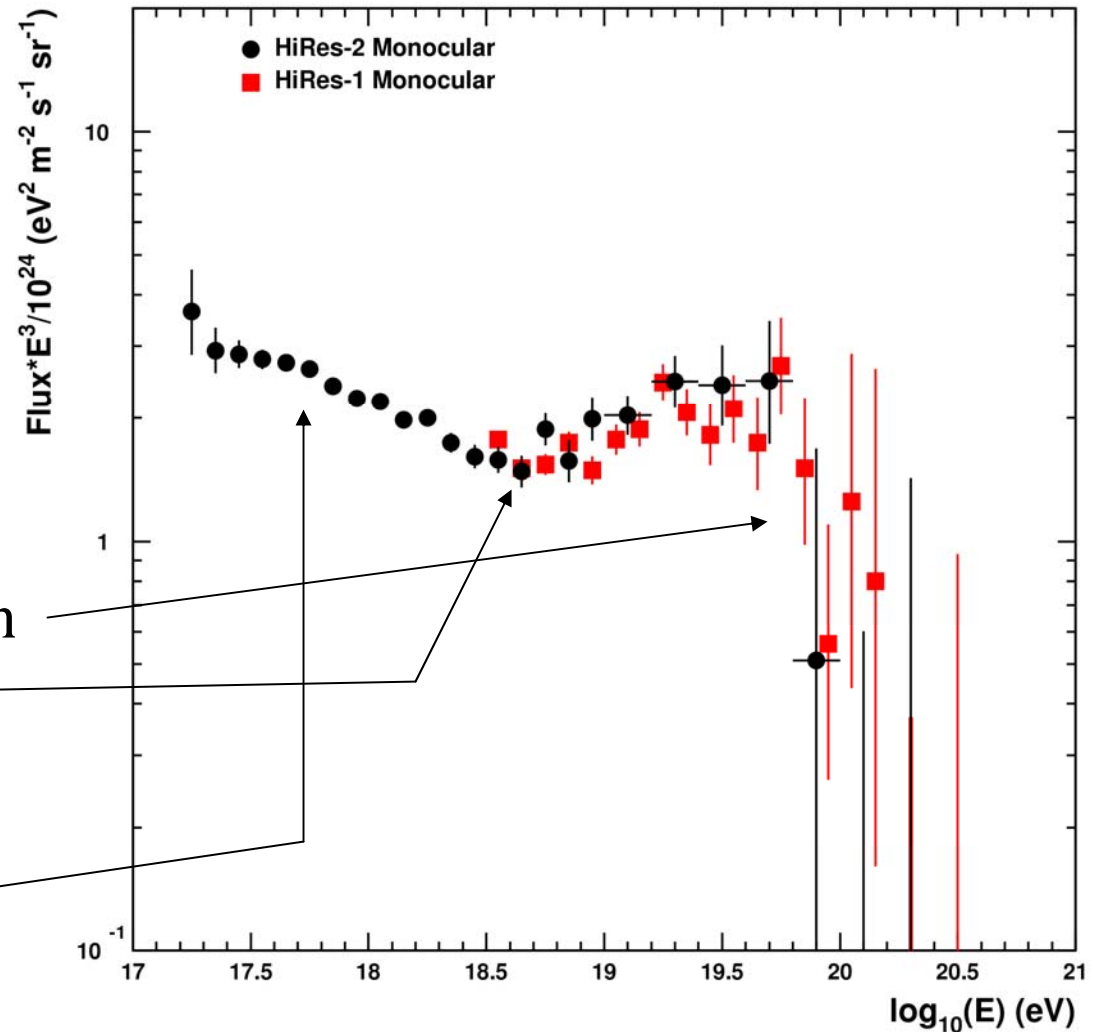
We observe:

(1) high-energy suppression

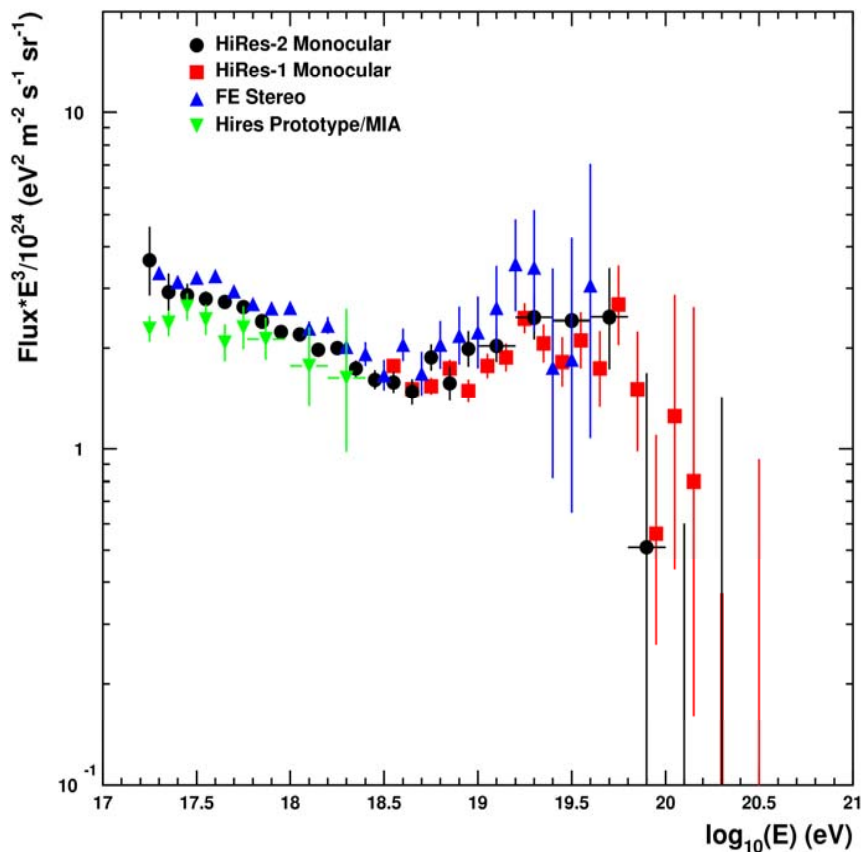
(2) ankle;

and...

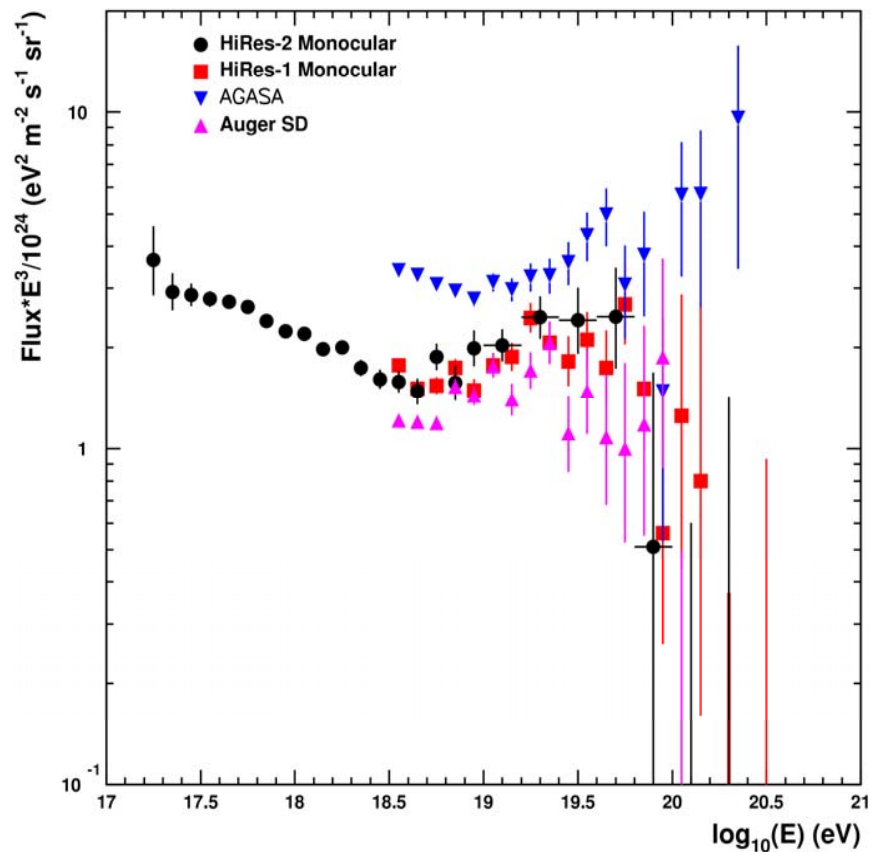
(3) second knee??



HiRes and Other Experiments



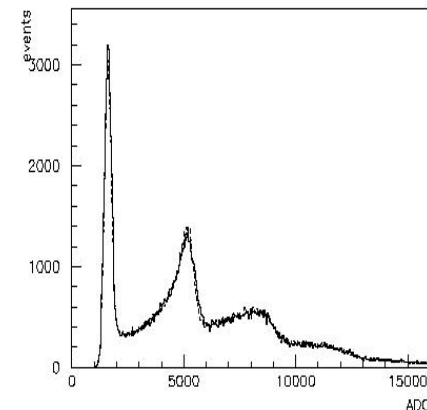
HiRes, Fly's Eye Stereo, and HiRes/MIA



HiRes, AGASA, Auger(2005)

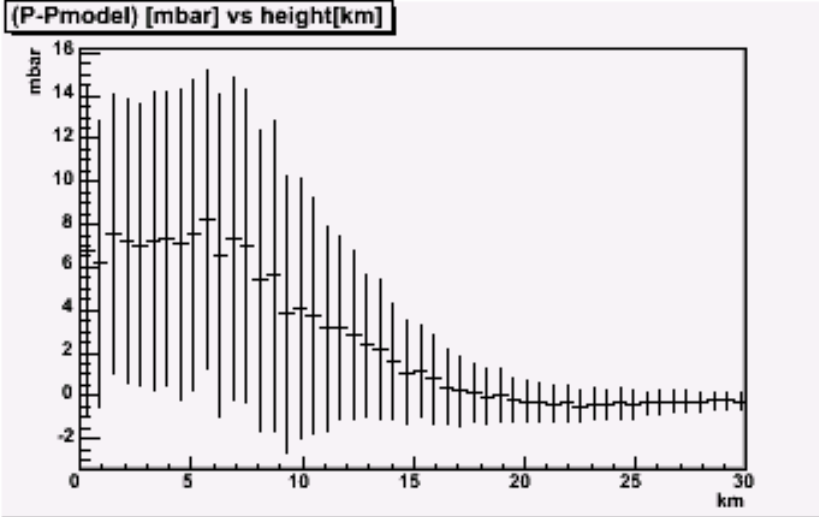
Calibrations: Photon Scale

- Photon Scale
 - Absolute calibration: Xenon flasher (stable to 2%) carried from mirror to mirror; runs done monthly.
 - Two analysis methods agree: absolute light level, and photoelectron statistics.
 - Calibrated via **NIST-traceable photodiodes**.
 - Checked with **HPD and 4-km laser shots**.
 - Night-to-night relative variations monitored with YAG laser.
- **Achieve 10% accuracy.**

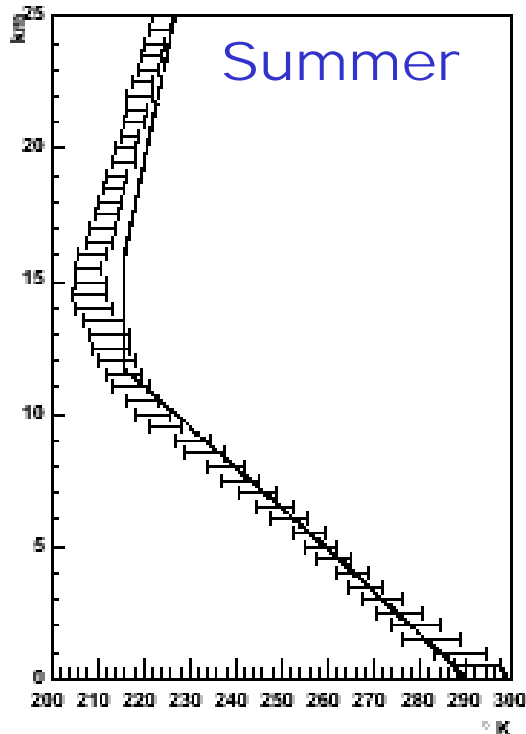


Updated Atmospheric

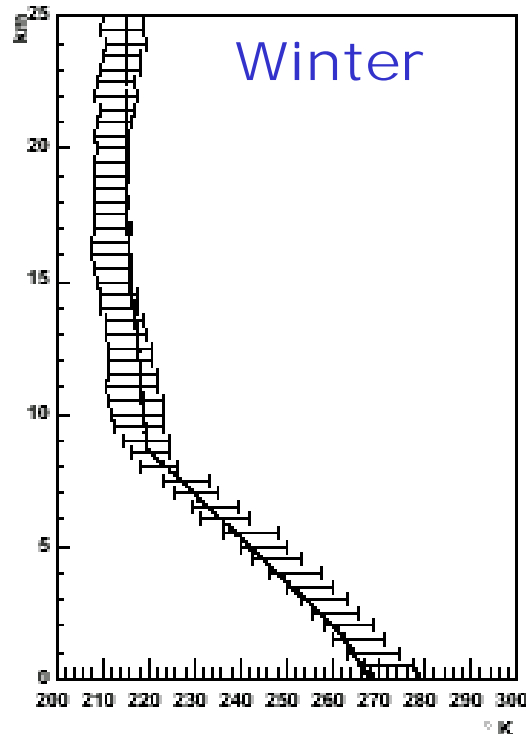
- The atmosphere over Utah appears stable and in **good agreement with seasonal “Standard atmosphere” Models**
- Residuals between measurements and model are typically less than ~10 mBar in the troposphere.



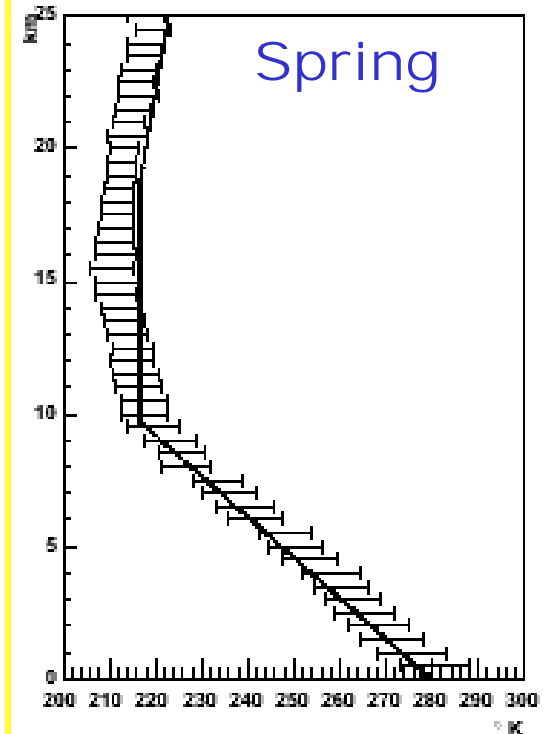
Temperature profile (summer)



Temperature profile (winter)

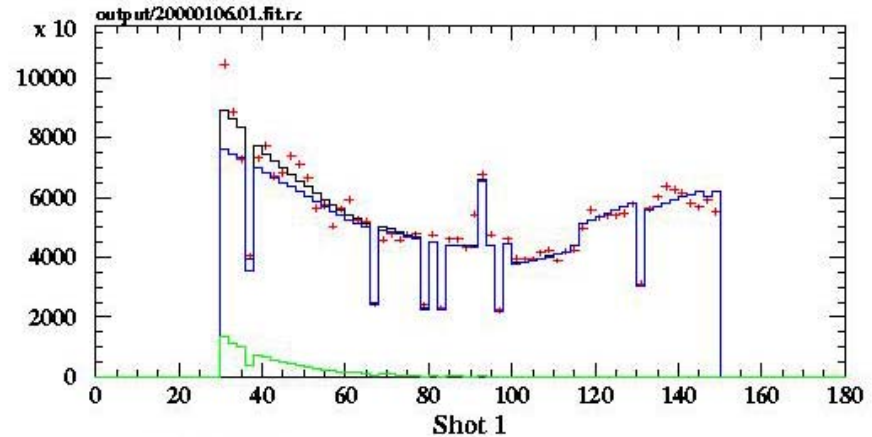
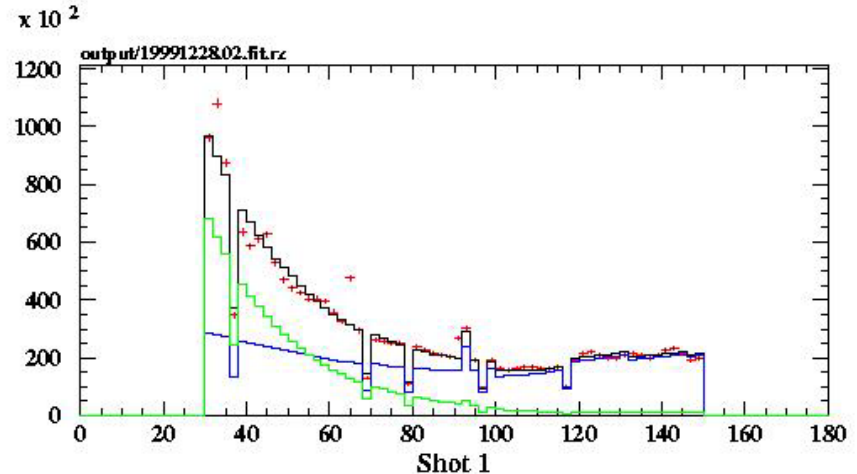


Temperature profile (spring)



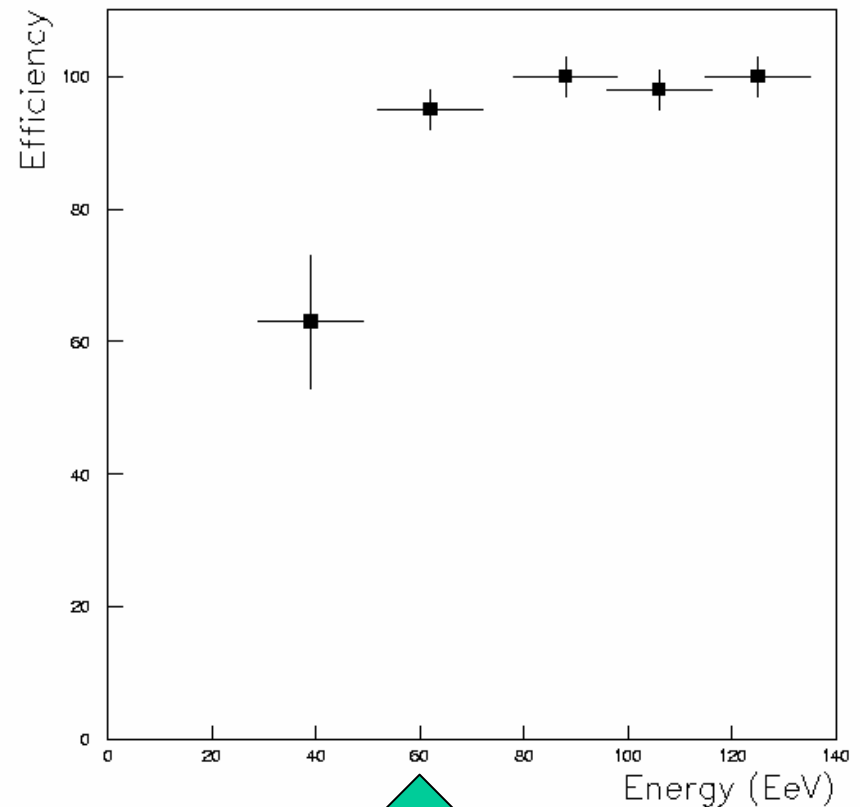
Calibrations: Atmospheric Monitoring

- Atmospheric Scattering: molecular portion measured by radiosonde balloons at two nearby airports.
- Measure aerosols.
 - Two 355 nm lasers, located at HiRes1, 2, fire pattern of shots into the air, covering the field of view.
 - Scattered light viewed by HiRes2,1.
 - Measure VAOD, HAL, aerosol phase function.
- **Very clear, stable skies:**
 - ~70% of nights are cloudless.
 - **Low aerosol levels:**
 $\langle \text{VAOD} \rangle = .04$
 - **Aerosols vary slowly:**
typically constant over several nights.
- **HiRes has an excellent site.**



“Test Beam” of High Energy Events

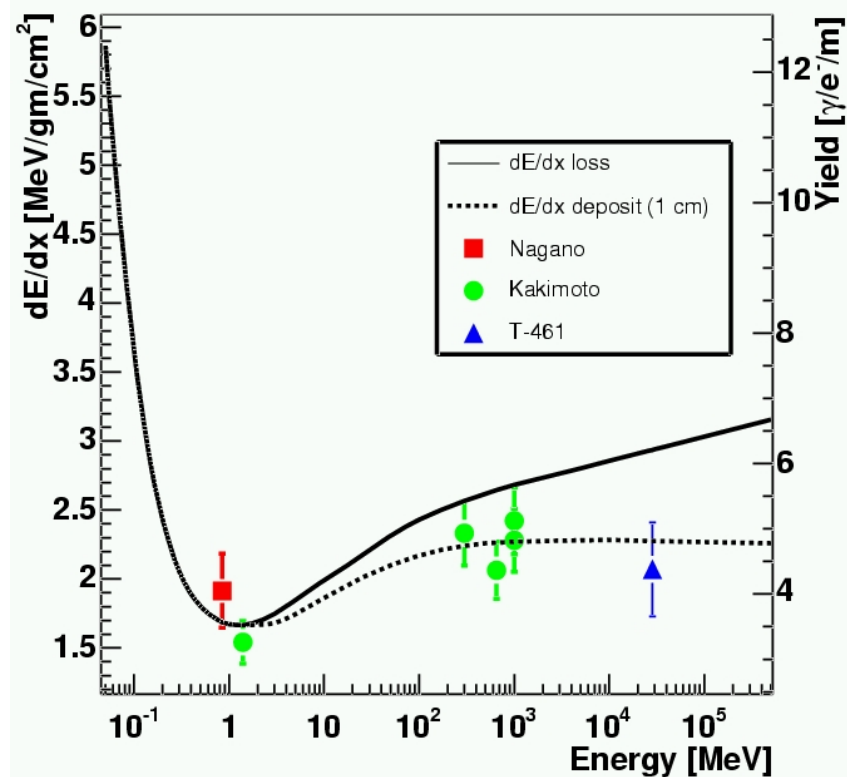
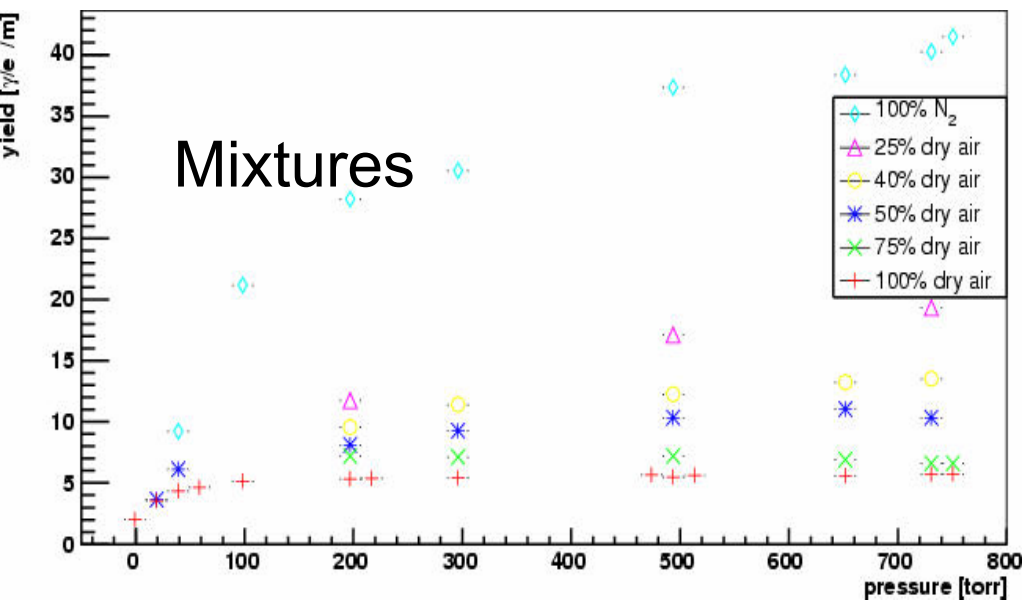
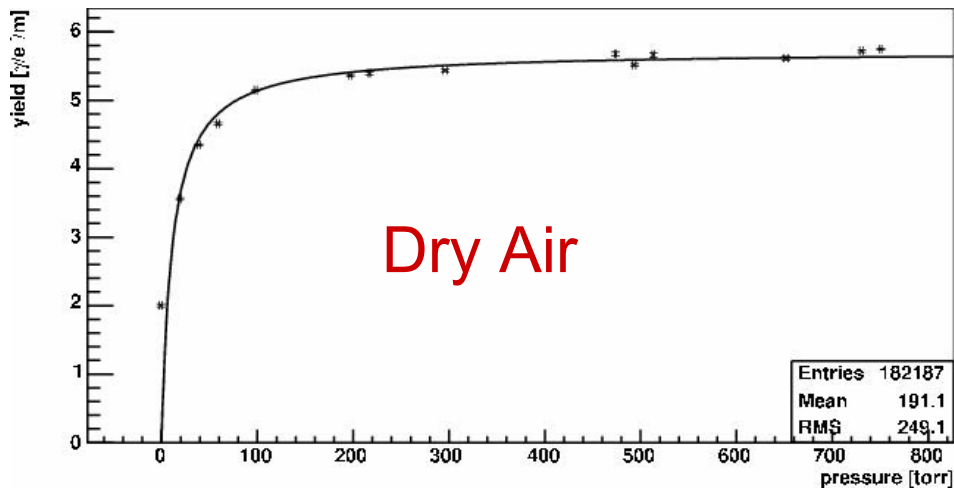
- Laser at Terra Ranch
- **35 km** from HiRes-2
- Vertical, 355 nm
- Fires at five energies, as bright as **40-125 EeV** showers.
- Efficiency for good-weather nights.
- Excellent trigger + reconstruction efficiency above 6×10^{19} eV.
- **We see high energy events with good efficiency.**



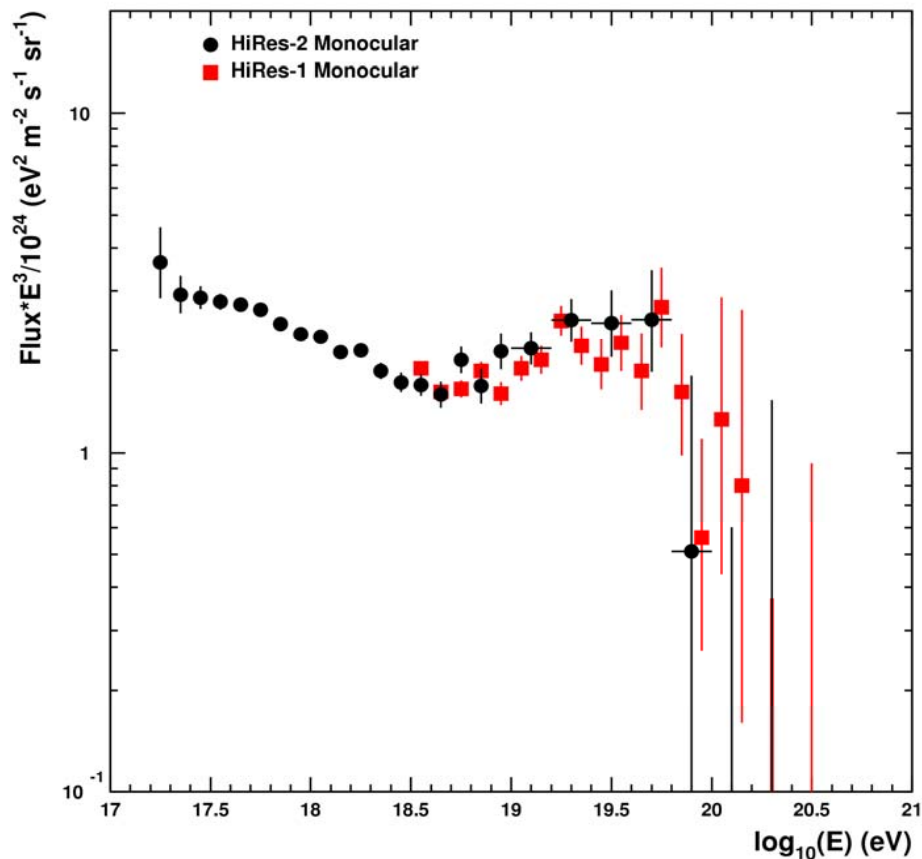
GZK Cutoff

Fluorescence Yield

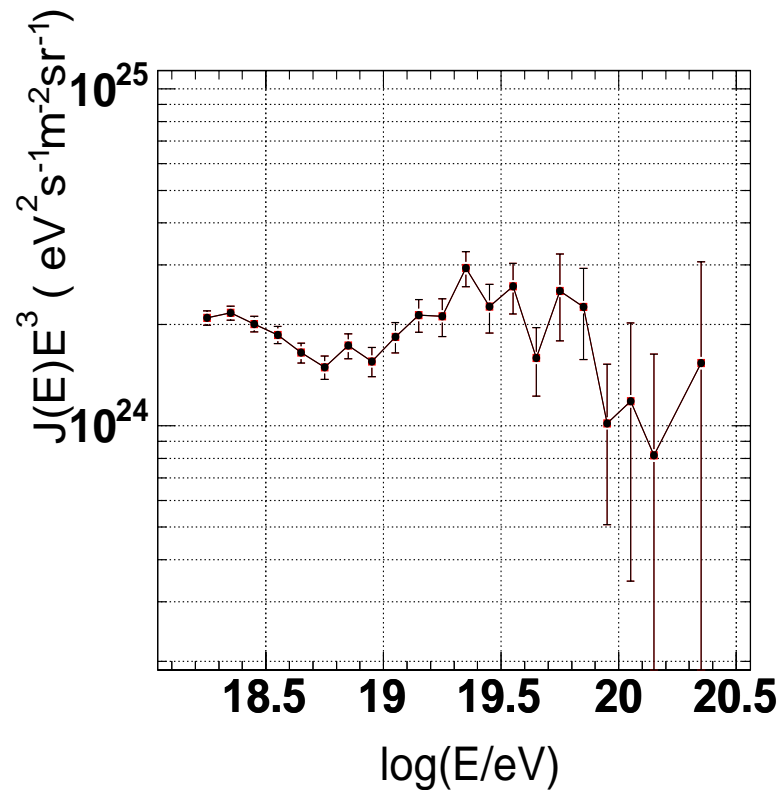
- Three published results: Kakimoto *et al.*, Nagano *et al.*, and T461.
- Ratio of fit to (Kakimoto, Nagano, and T461) to fit to Kakimoto
 $= 1.00 \pm 0.06$



Most recent Mono spectrum (with cloud cuts)



New “fully efficient” stereo Spectrum - no cloud cuts

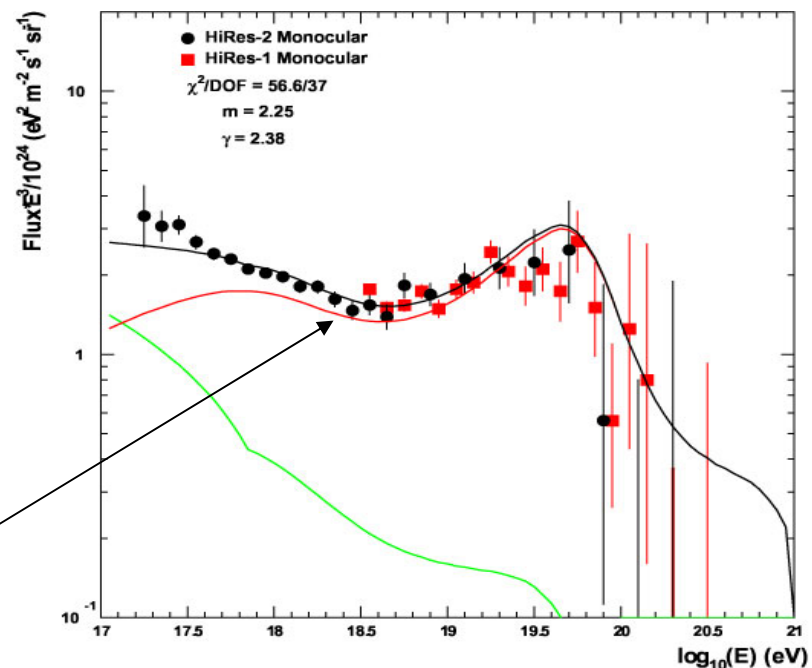
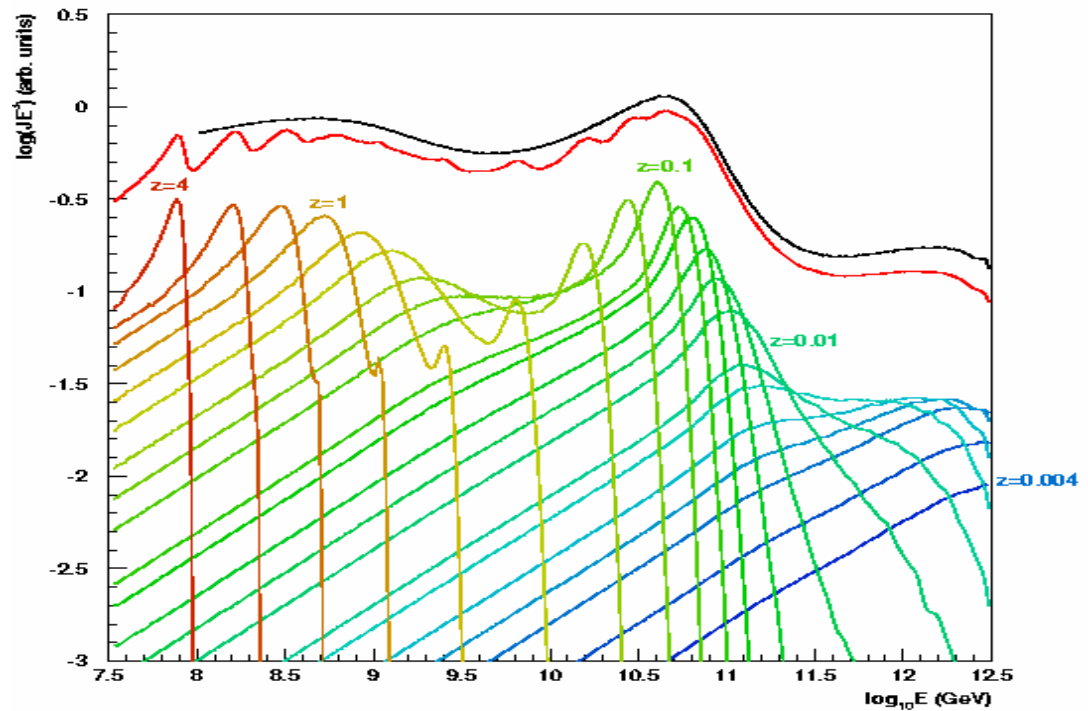


Monocular Spectra

Interpretation of the UHE Spectrum

- Interaction with the CMB 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](https://arxiv.org/abs/astro-ph/0501317)) update shown



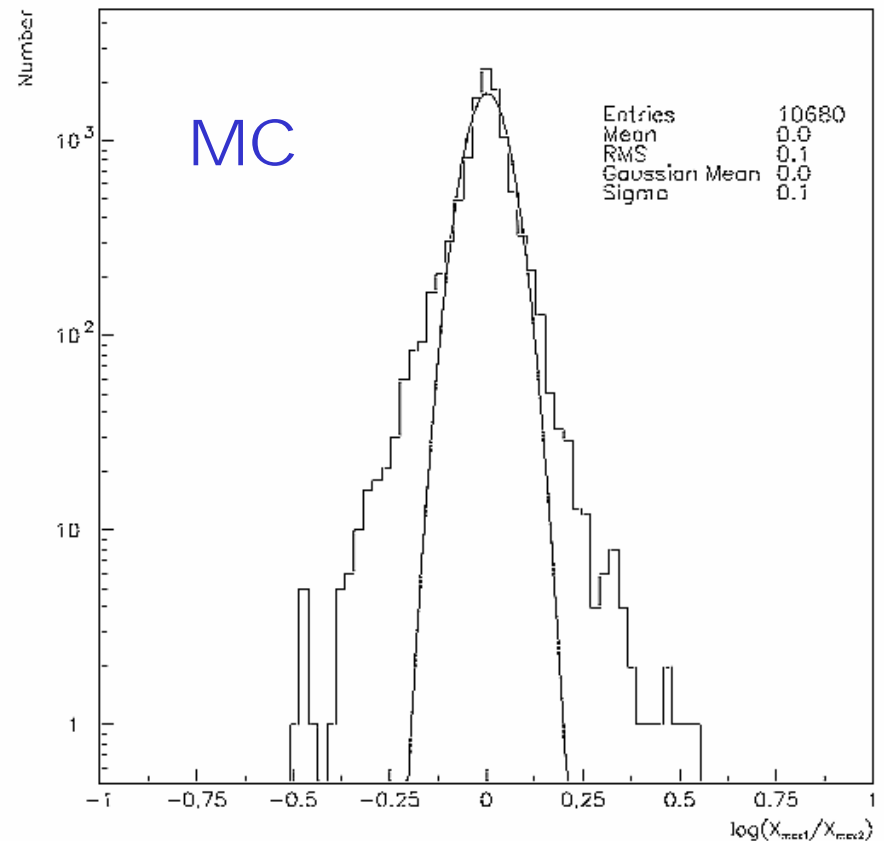
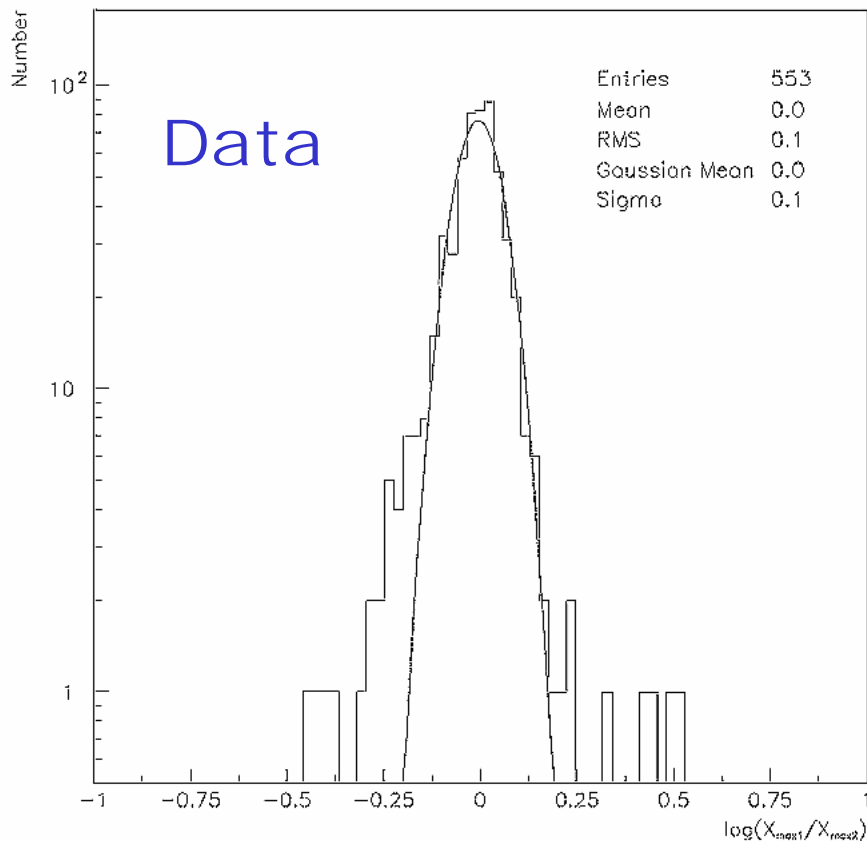
- Transition energy $E_c \approx 1 \times 10^{18}$ eV is a universal value, independent of propagation mode, including different diffusion regimes.
- **Prediction of the shape of the dip is robust.** It is practically not modified by all known phenomena:
 - propagation modes,
 - inhomogeneities in source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

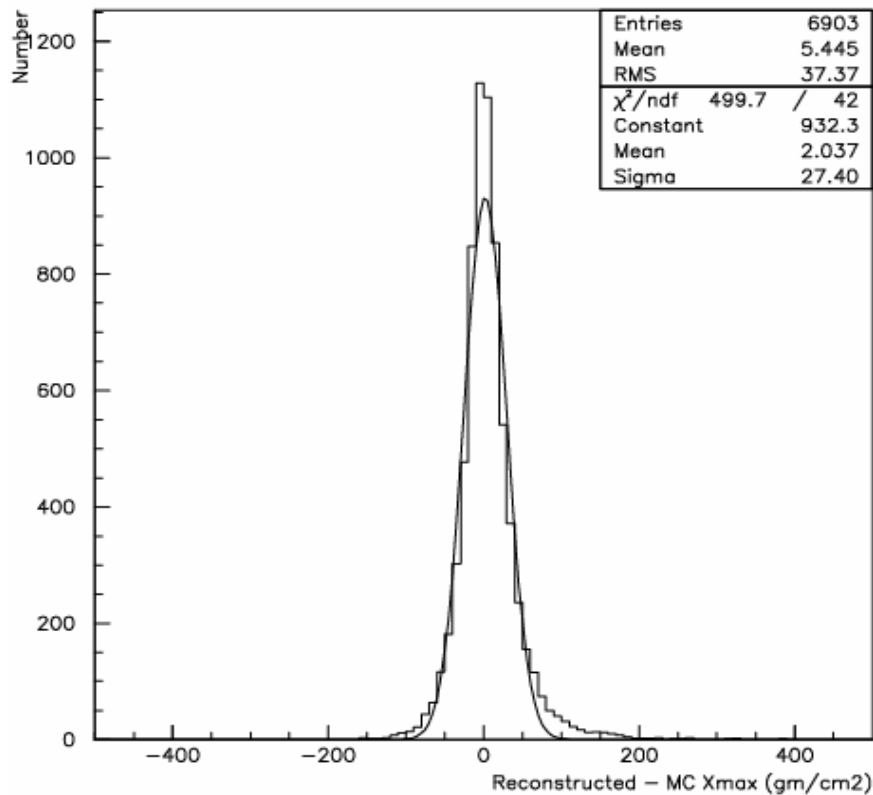
Stereo Xmax Measurement

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

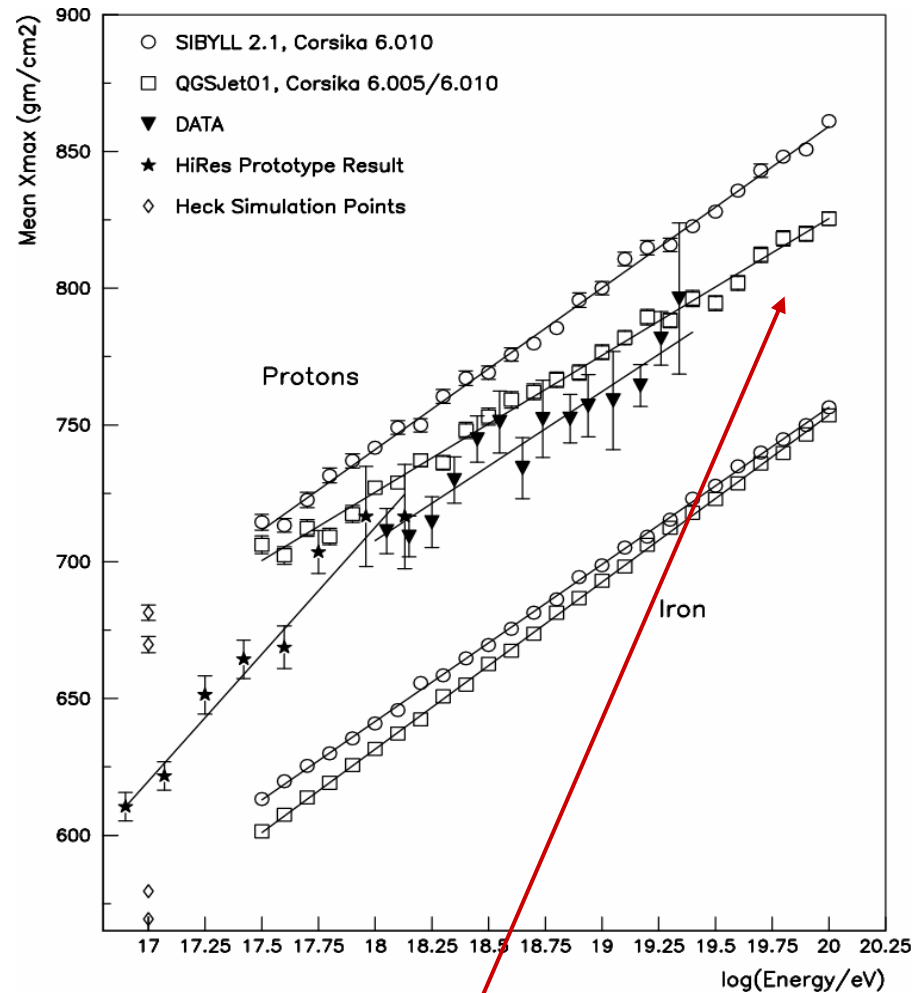


HiRes Composition Measurement

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

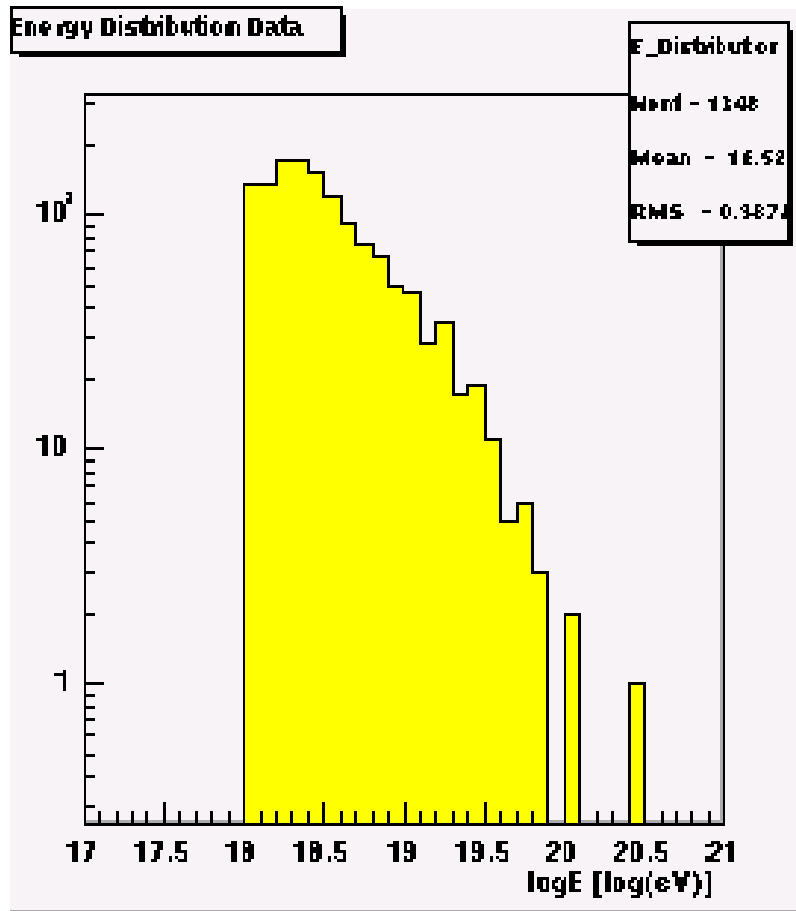


Systematic errors: mirror pointing direction, atmosphere, $\sim 22 \text{ g/cm}^2$.

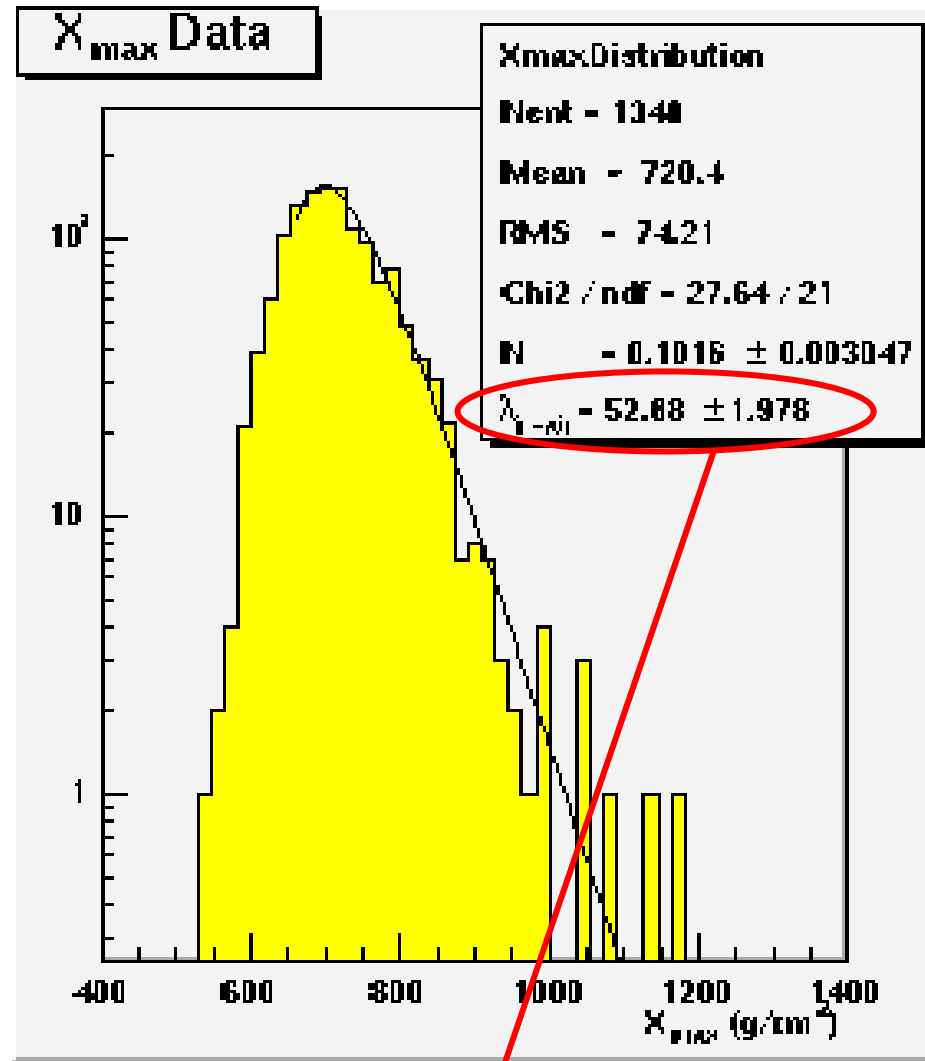


- ***Will have data on hand to extend analysis up to the GZK Threshold!***

Data and Deconvolution Result

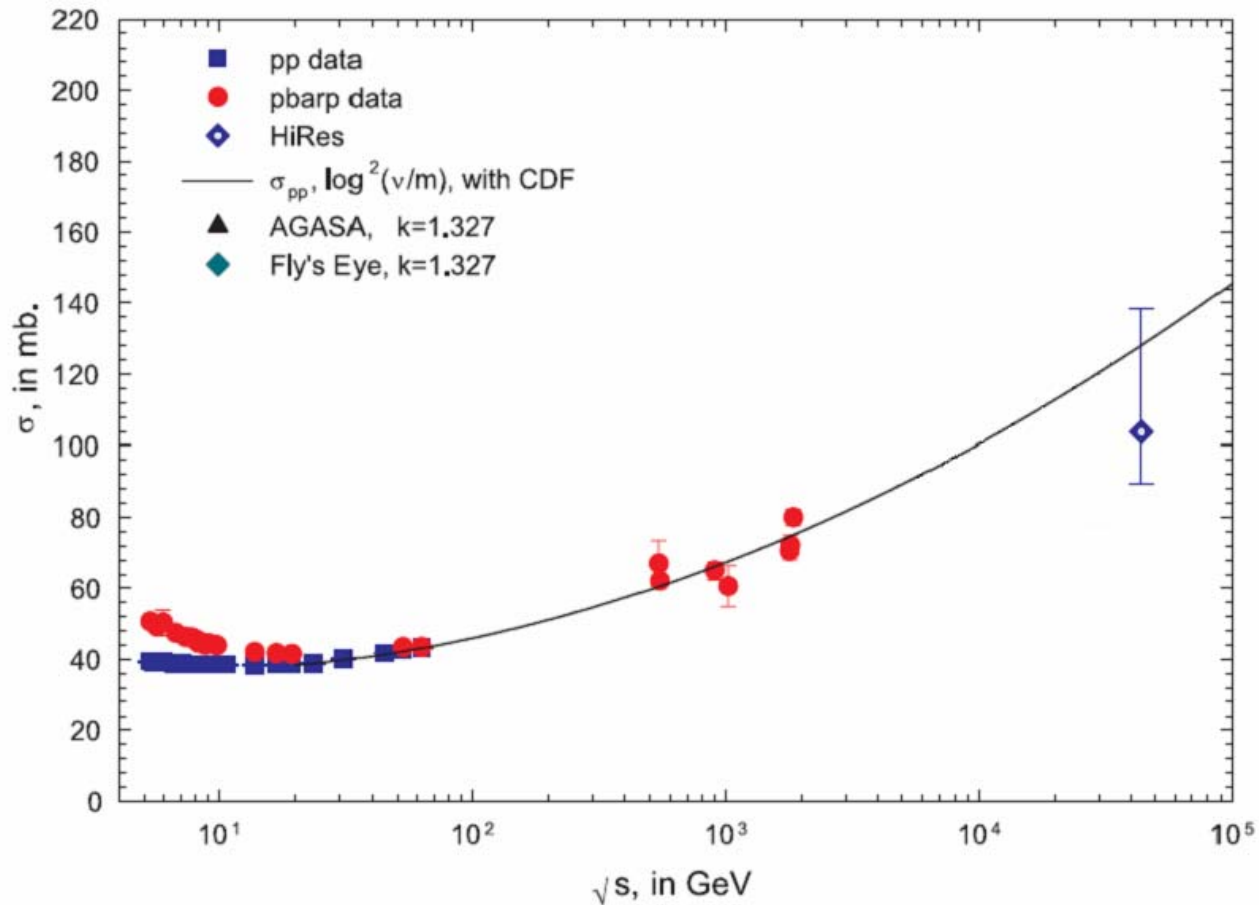


- 1348 out of 3346 stereo events pass the quality cuts (data:12/1999-3/2003)



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

HiRes Measurement



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

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 $\sim 4 \times 10^{19} \text{eV}$

Astropart. Phys. 22, 139 (2004)

- Search for dipole enhancement in the direction of nearby a-priori sources: **null results** for the *Galactic Center*, *Centaurus A*, and *M87*

Astropart. Phys. 21, 111 (2004)

- Point source search: null result

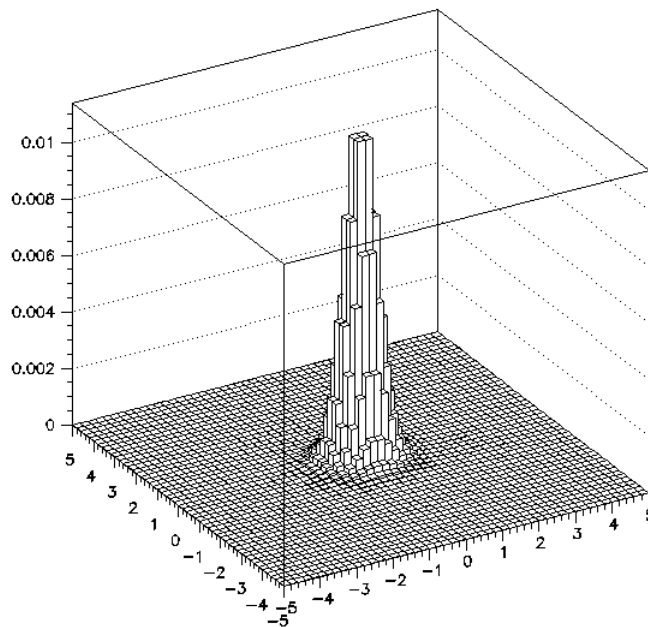
Submitted to Astropart Phys.

- Search for cross-correlation with AGASA doublets and triplet:

- Observed overlap no greater than that expected by chance from an isotropic

Submitted to Astropart Phys.

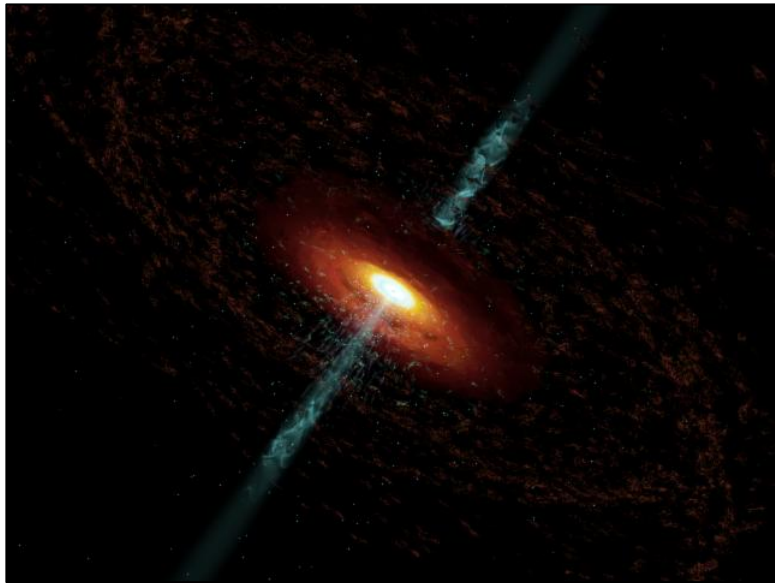
Stereo point spread function



Stereo Anisotropy Results

- Stereo angular resolution $\sim 0.6^\circ$
- HiRes stereo data ($E > 10^{19} \text{eV}$) 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 $4.0 \times 10^{19} \text{eV}$ Using a Maximum Likelihood Ratio Test
Astrophys. Journal 623 (2005) 164

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 γ -rays
- Candidates for accelerating cosmic rays to EeV energies

Somewhat controversial recent history regarding correlations of UHECR with BL Lac objects:

[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.](#)

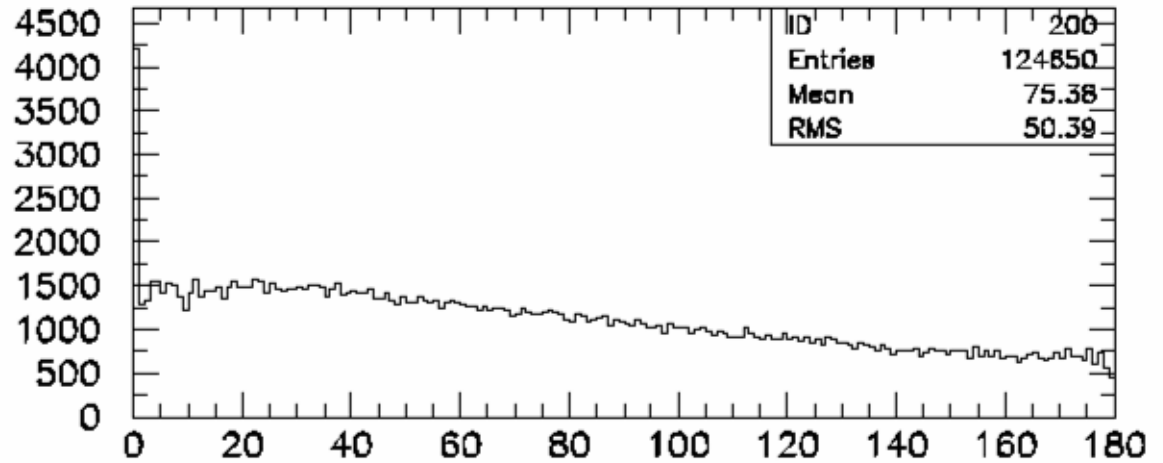
[Gorbunov et al., JETP Lett. 80 \(2004\) 145.](#)

[Stern and Poutanen, ApJ 623 \(2005\) L33.](#)

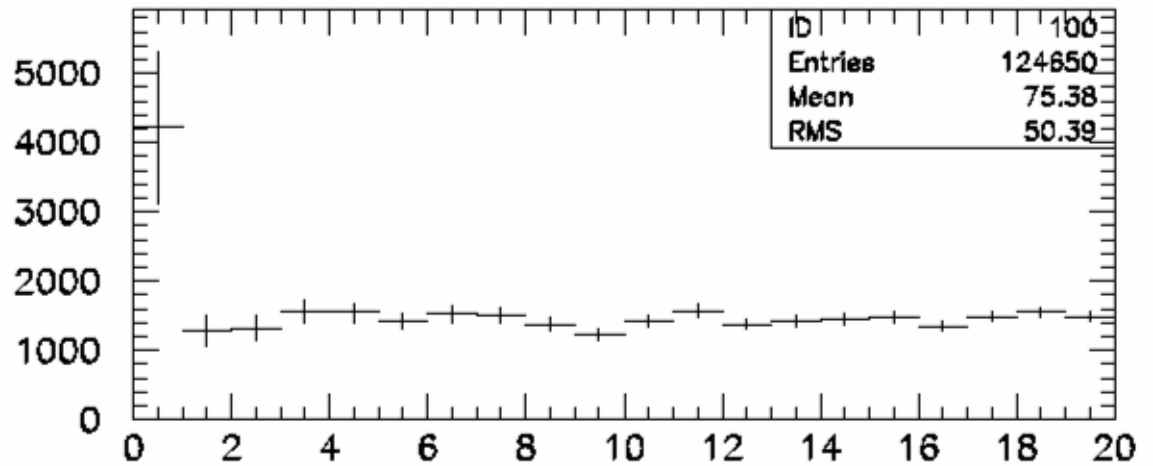
Cross-correlation
between:

Confirmed BL Lacs
 $m > 18$ (10th Veron)

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



space angle weighted $1/\sin$



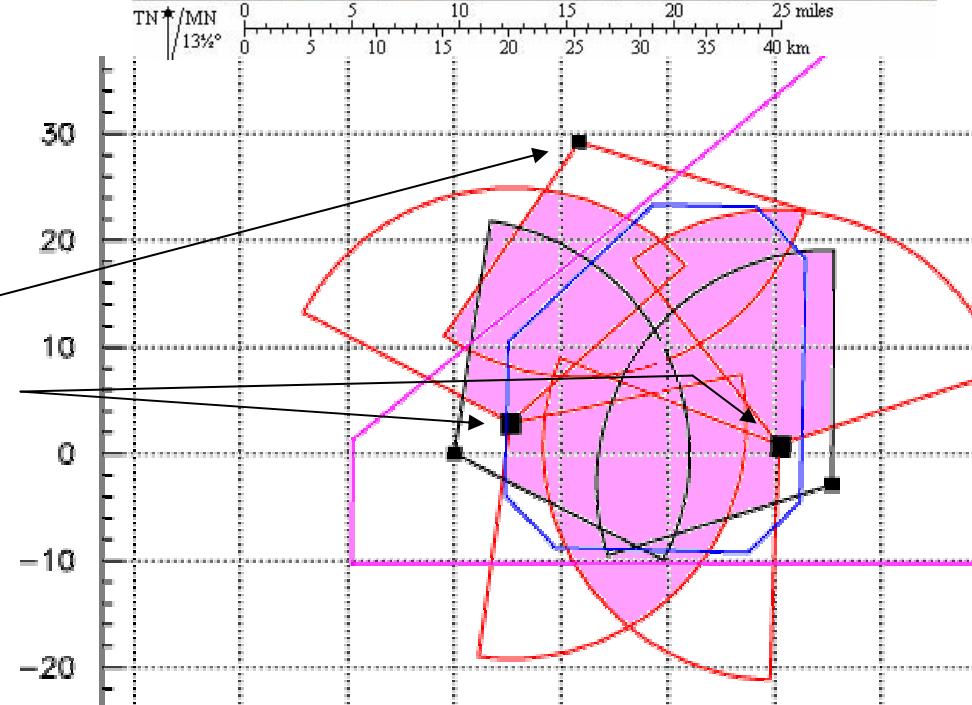
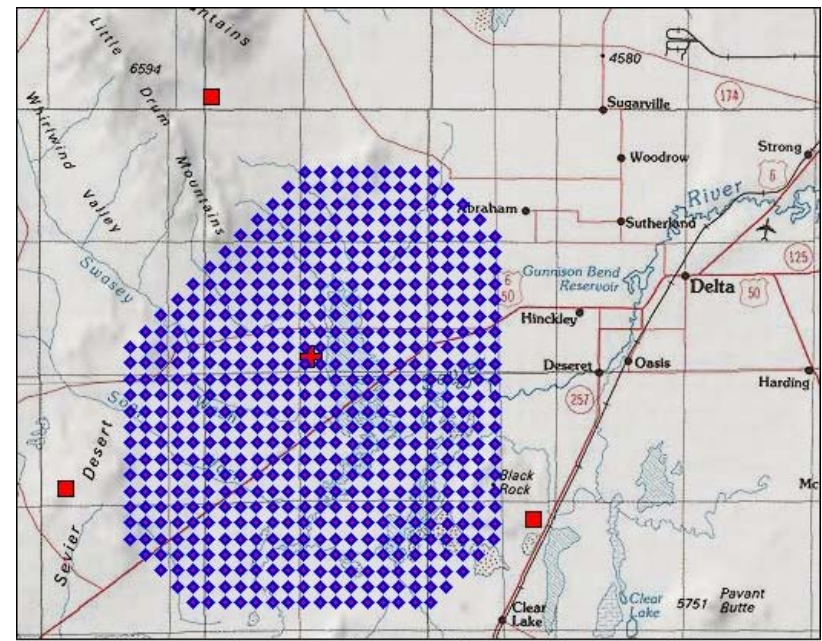
space angle weighted $1/\sin$

Summary of BL Lac Correlation:

- “BL”, $m < 18$, all HiRes events (no E cut): $F = 2 \times 10^{-4}$
- “BL+HP” with $m < 18$, HiRes $E > 10$ EeV: $F = 10^{-5}$
- Confirmed TeV blazars, all HiRes events (no E cut): $F = 10^{-3}$
- Analysis has been *a posteriori*, so above F values are not true chance probabilities.
- **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.
- **“New” data will unblinded soon...**

HiRes Telescope Array

- Last day of observation by HiRes : **April 3, 2006**
- Subgroups of HiRes have joined the Telescope Array (Delta, UT, USA)
 - Ground array of 576 (1.2km spacing) scintillation counters
- US contribution:
 - Northern TA fluorescence site
 - low-energy extension (TALE)
 - down to $10^{16.5}$ eV
 - Tower detector with 3 times larger mirrors: reach 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.

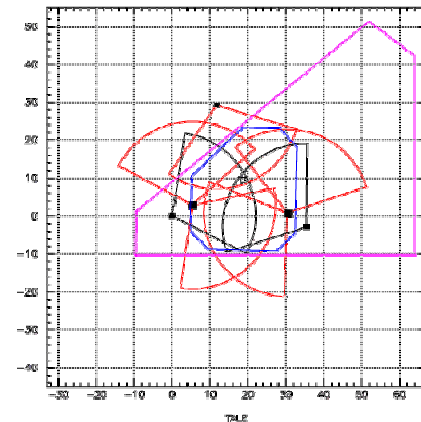


TA/TALE

- Apertures:
 - High energy aperture: 3000 km² ster, 3xHiRes
 - half SD,
 - half fluorescence (in mono, stereo, hybrid, stereo hybrid).
 - 10x HiRes stereo aperture at 10¹⁸ 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 Cascade and Cascade-Grande.
 - Watch the heavy elements die away ($\sim 10^{17.5}$ eV).
 - Observe light composition above 10¹⁸ eV.
- Do cosmology.

TA/TALE Anisotropy

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



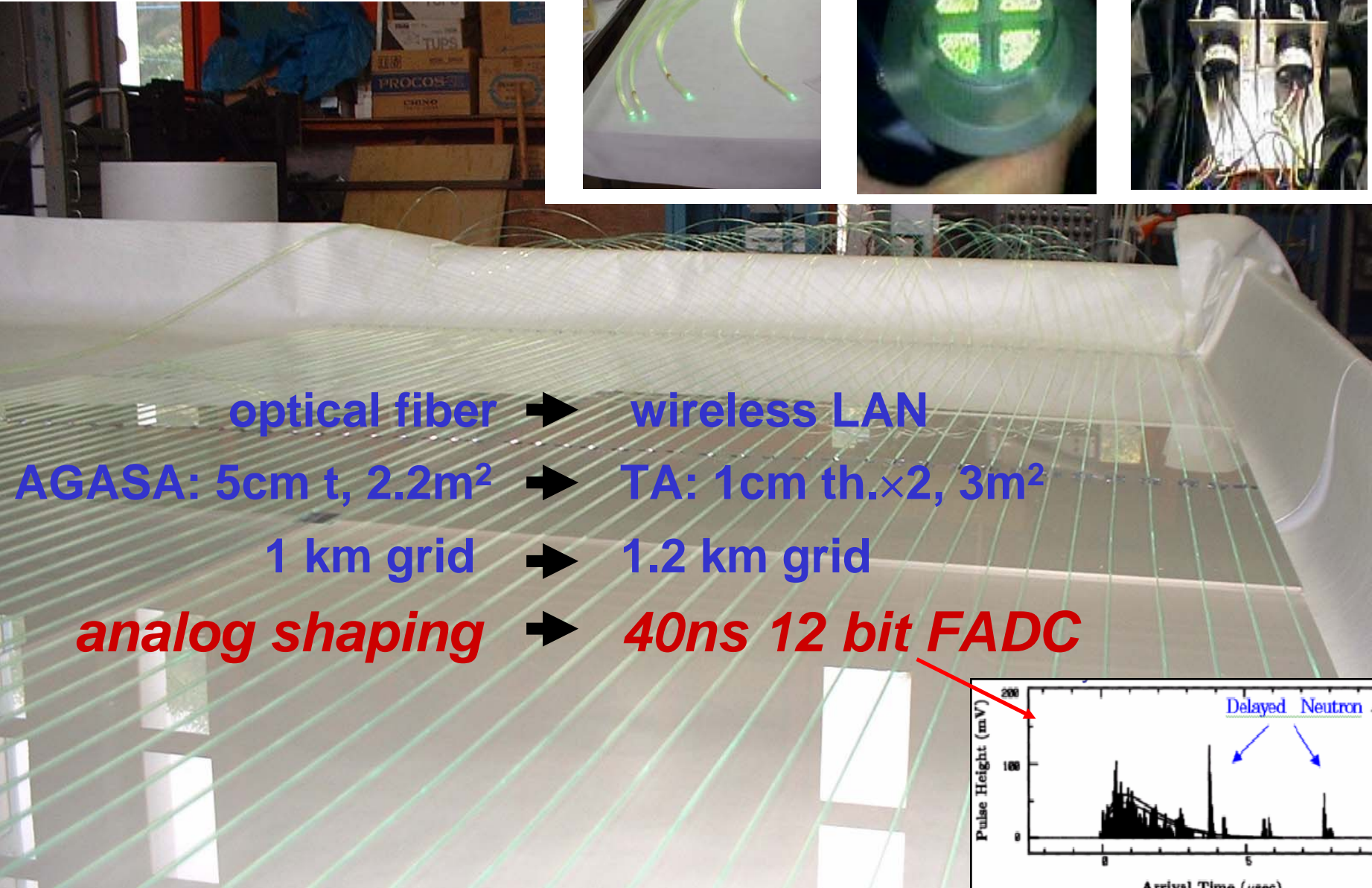
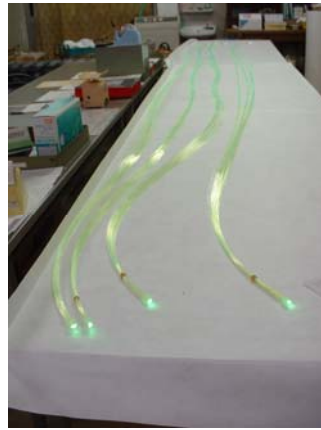
Experiment	Aperture (km ² ster)	Resolution	Figure of Merit (A/Resolution ²)
HiRes stereo	300 (avg)	0.5 deg	1200
TA/TALE stereo	340	0.5	1360
TA SD	1500	1.5	667
S. Auger SD	6600	1.5	2933
TA/TALE hybrid stereo	260	0.1	26000

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.

Ground Array : Plastic Scintillators

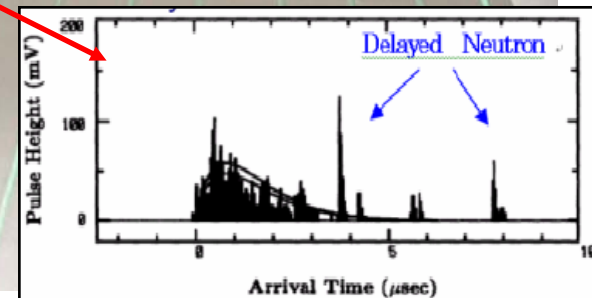


optical fiber → wireless LAN

AGASA: 5cm t, 2.2m² → TA: 1cm th.×2, 3m²

1 km grid → 1.2 km grid

analog shaping → *40ns 12 bit FADC*

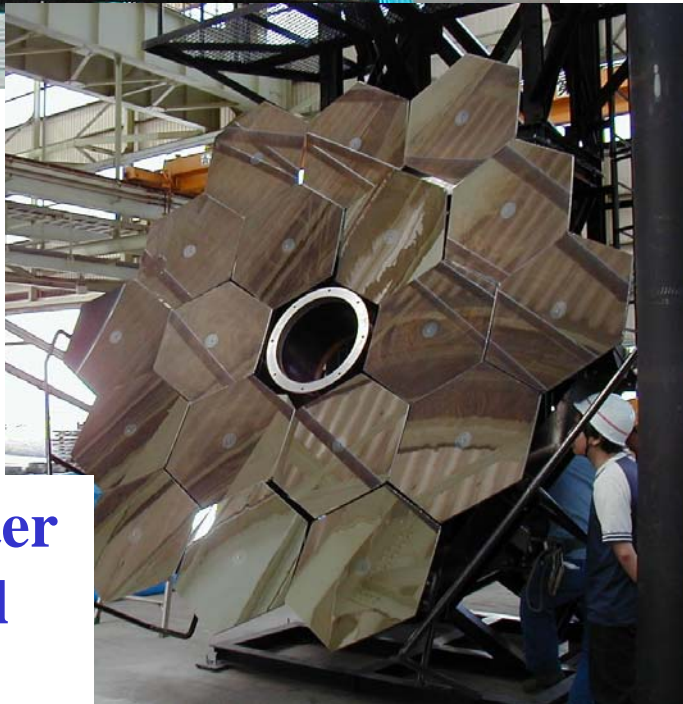


SD Stands



16 x 16 PMT array

Fluorescence Telescope

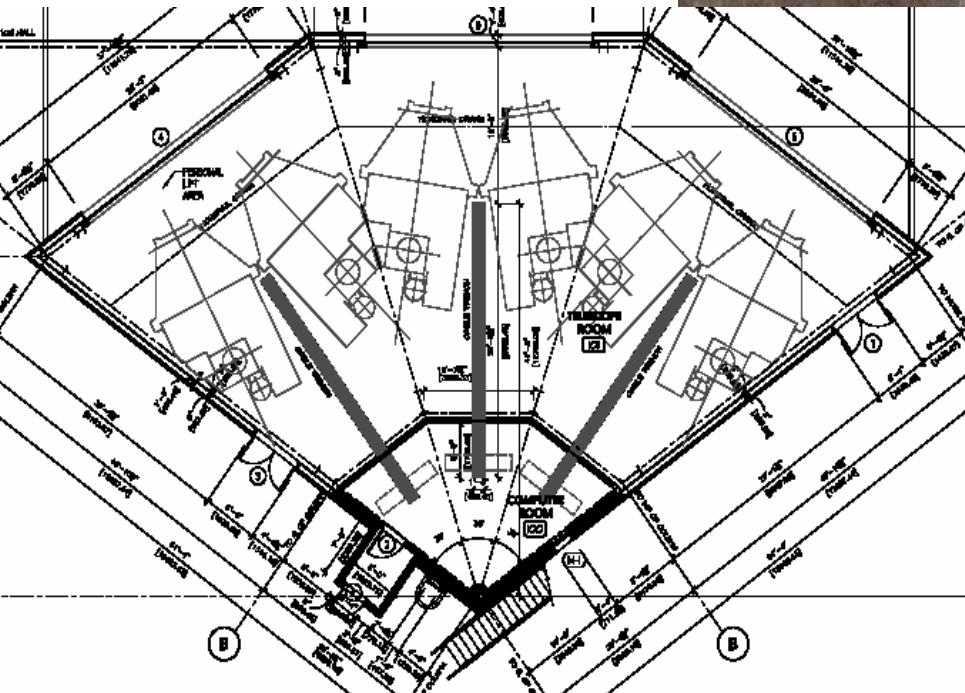


**3 m diameter
spherical
mirror**

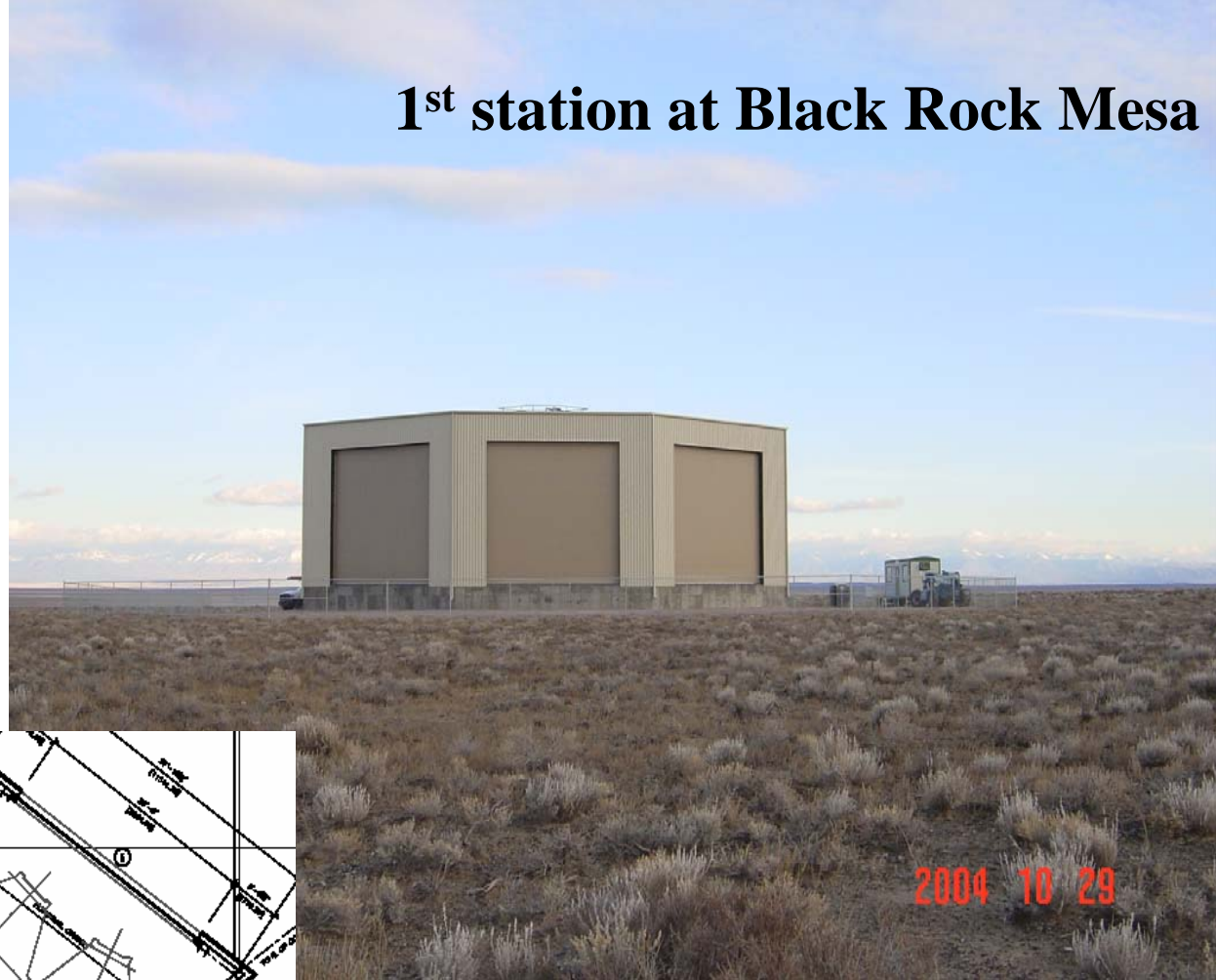
Fluorescence Telescope Station

108° in Azimuth
3°– 34° in Elevation

1° × 1°
pixel resolution



1st station at Black Rock Mesa



~ 1/3 HiRes-2 FoV and
resolution
40% more light collection area
14-bit 100ns ADC

Summary

- HiRes has measured the spectrum and composition of cosmic rays.
- We see two of the three spectral features in the ultrahigh energy regime: the GZK cutoff and the ankle.
- We see the galactic/extragalactic transition.
- We will continue these studies with TA/TALE.