The Observation of Ultra-High Energy Cosmic Rays using the HiRes Detector

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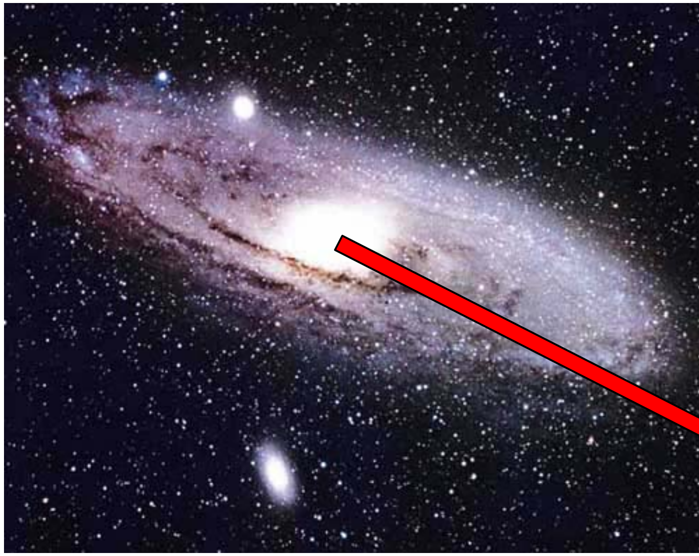
University of Utah

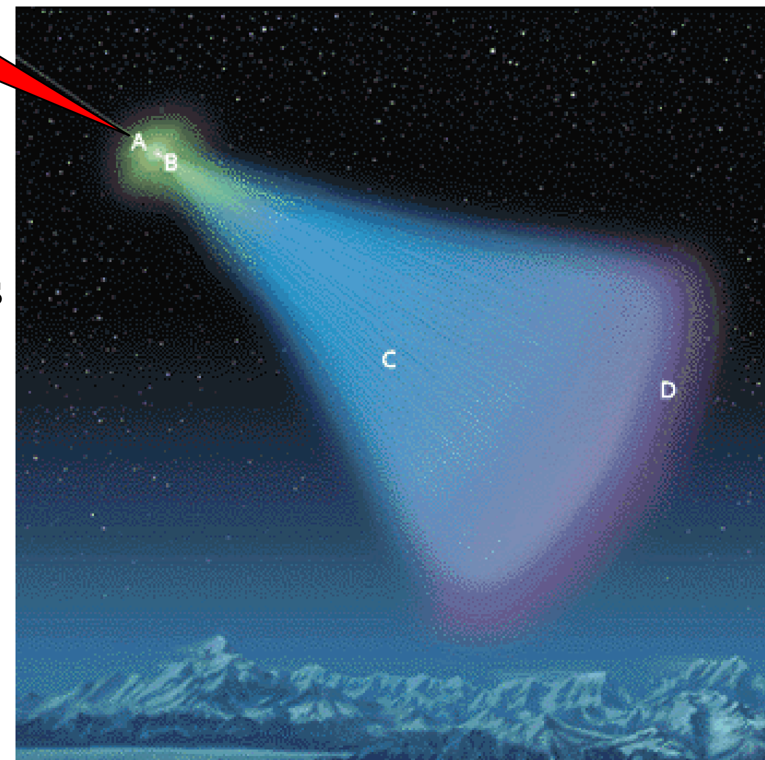
- Physics of Ultra-High Energy Cosmic Rays
- Detection of Ultra-High Energy Cosmic Rays
- Description of the HiRes Detector
- Results (some preliminary) from the HiRes Detector

Les Rencontres de Physique de la Vallee d'Aoste
March 10,2003

Cosmic Rays

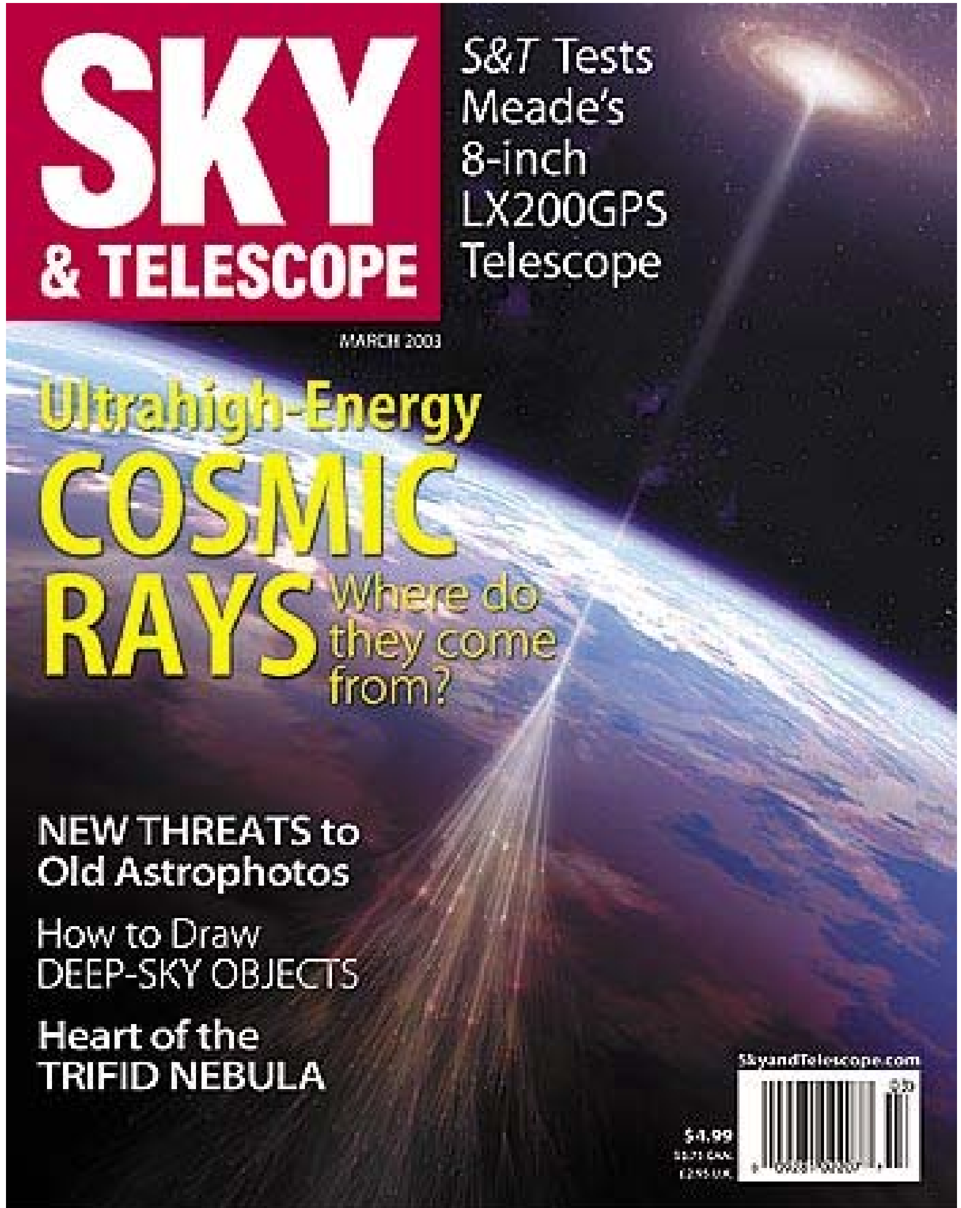


- Mainly Consist of Atomic Nuclei…(protons)
- Extra-terrestrial origin



- ➔ Fundamental particle physics
  - ➔ Discovery of several elementary particles
- ➔ Astrophysics
  - ➔ Messengers from objects/processes

UHECR in the media



Cosmic Ray Flux

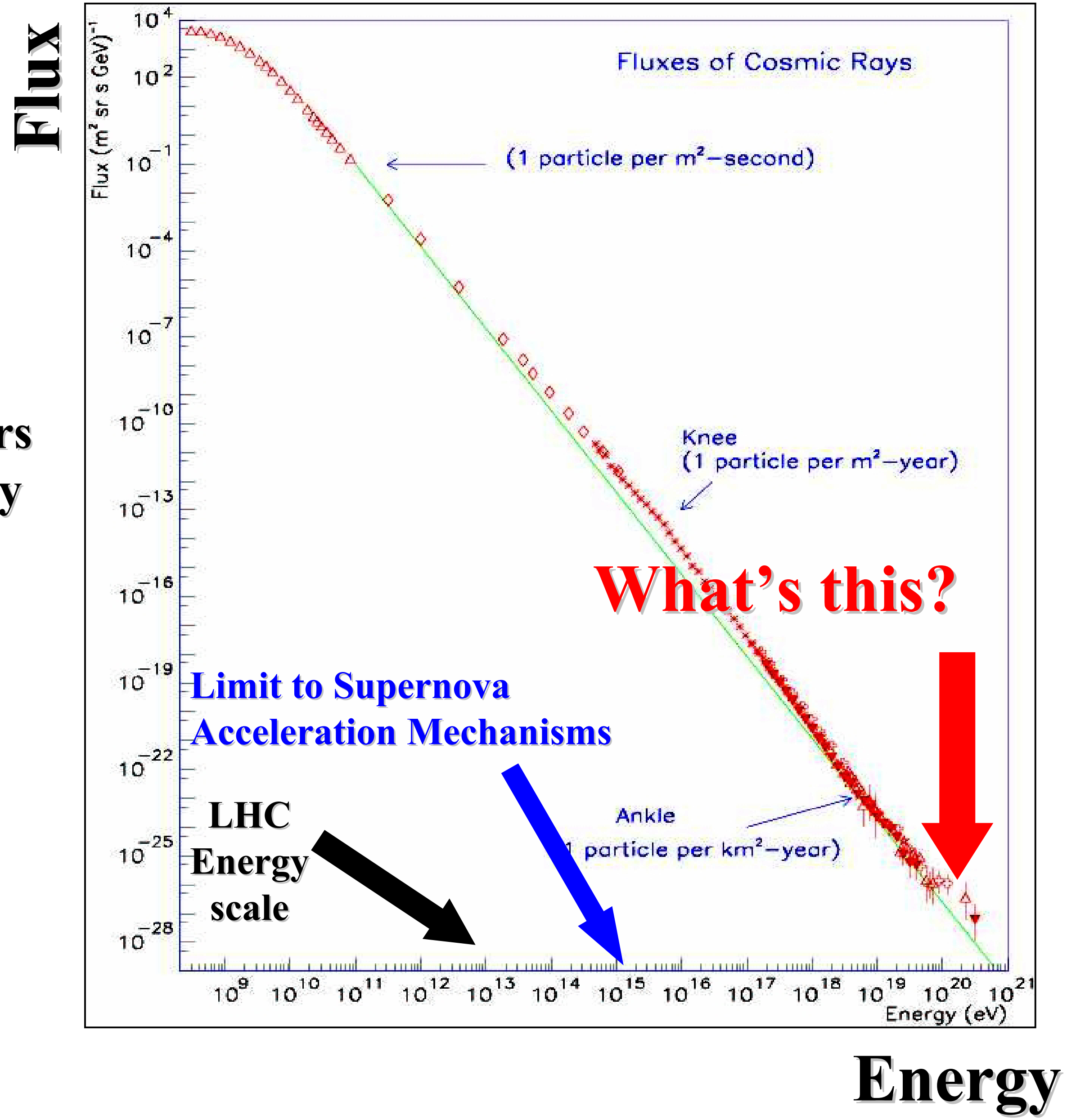
- Flux roughly follows Power law

Flux~E$^{-3.0}$

- Structure in Spectrum
- Flux varies by 32 orders of magnitude over energy range 10^8 eV 10^8 TeV

- Cosmic Ray Particles with energies extending beyond 10^8 TeV???

- Where does it stop?



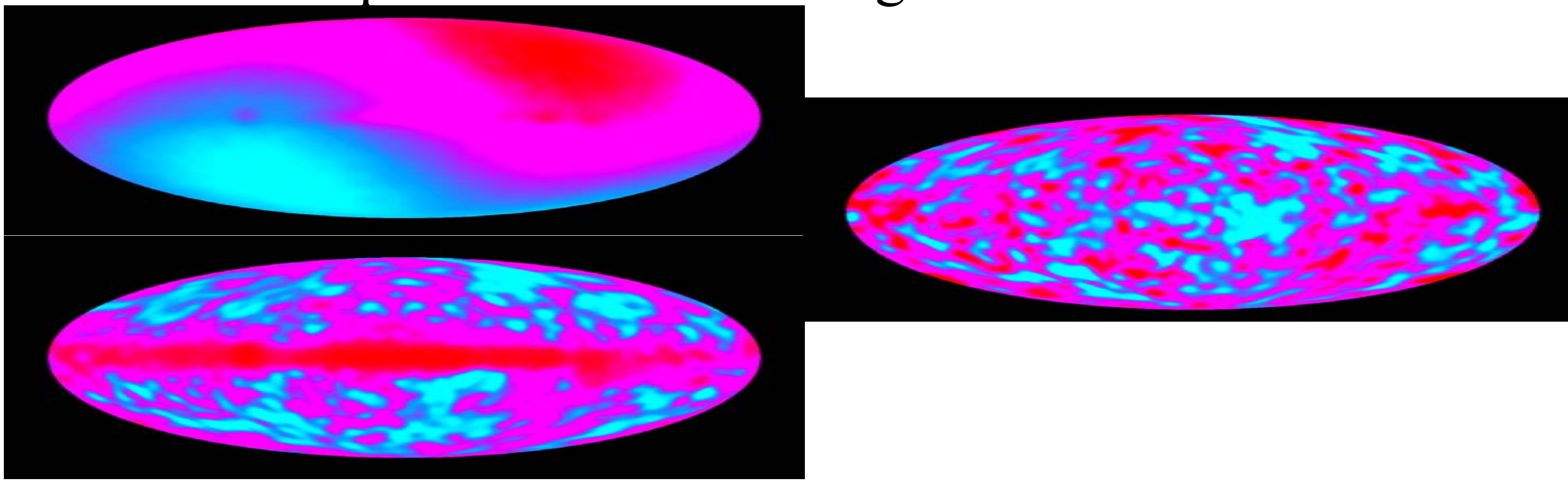
Physics of Ultra-High Energy Cosmic Rays (UHECR)

- **Basic Questions:**
  - How are such energetic ($E>10^{17}$ eV) particles produced? Astrophysical sources such as supernovae are NOT believed to be able to accelerate particles to $> 10^{15}$ eV.
  - Where are they produced? Perhaps related to how they are produced and the following...
- **Further Complication**
  - If they are produced in distant (>50 MpC) sources how do they propagate through the ubiquitous cosmic microwave background?

"GZK Cutoff" in Energy Spectrum

Propagation through Universe

COBE map of microwave background



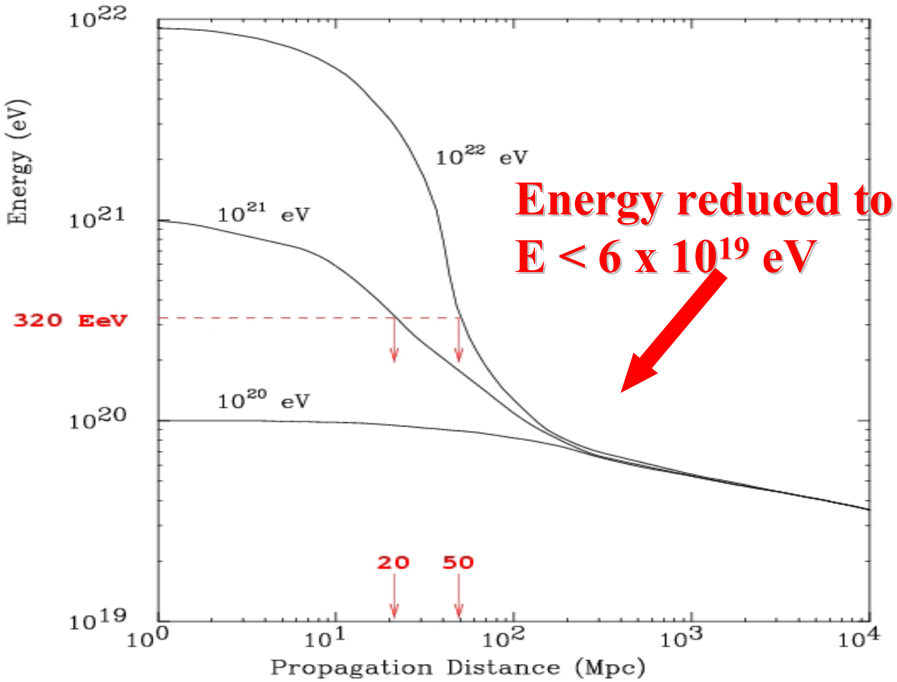
For protons with energy exceeding E_{GZK}=5 x 10^{19} eV,
s> $m_{\pi}c^2$ for collisions between the proton and cosmic microwave background photons and pion photoproduction becomes possible...

$$p + \gamma\left(2.7^{\circ}\,\mathbf{K}\right) \rightarrow p + \pi^{0}$$

GZK Cutoff

The Greisen-Zatsepin-Kuzmin cutoff results in the degradation of the energy of protons after a distance of 50 Mpc.

The Paradox of the GZK cutoff



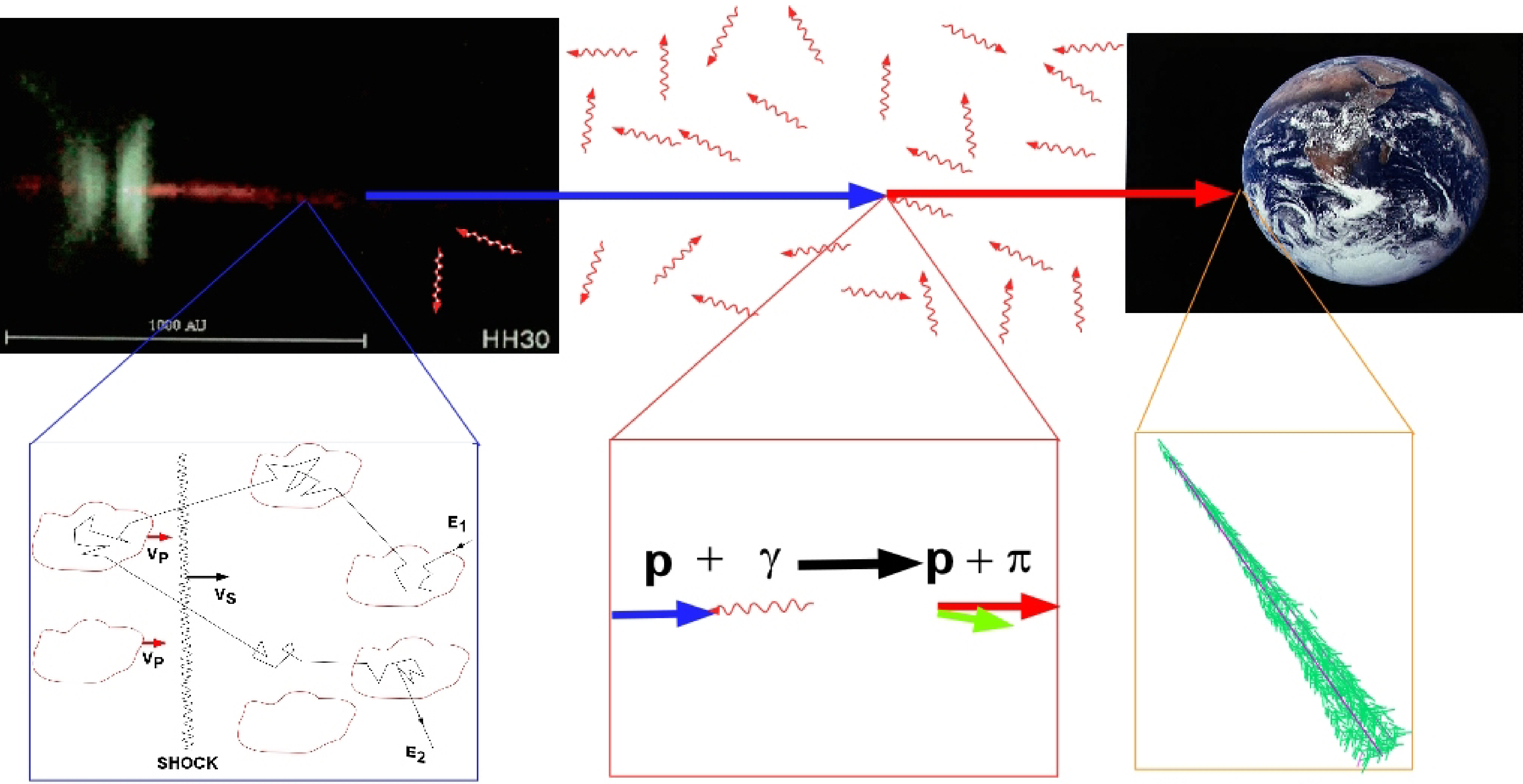
- Interaction of UHECR with photons from Cosmic Microwave Background ==> Charged particles with E > 5 x 10^{19} eV will travel at most 100 Mpc before their energy drops below the cutoff…

- Observed UHECR must originate within <100 Mpc …BUT none of the observed Fly's eye UHECRs above the GZK cutoff point back to a possible astrophysical source inside the GZK volume….

- There is some evidence of clustering in the AGASA data set however….

➔Recall that observable horizon of universe is approximately 6000 Mpc GZK volume < 6 x 10^{-7} of volume of observable universe...

UHECR From Source to Detector



Acceleration

Propagation

Detection

What can HiRes determine about Ultra High Energy Cosmic Rays (UHECR)

➔ **Energy Spectrum (Flux vs. Energy)**

➔ **Composition** (**on a statistical basis, also including neutrino and gamma searches)**

➔ **Arrival Directions**

Charged Particle Astronomy?

Detection of Ultra-High Energy Cosmic Rays

➢ULTRA LOW FLUX

For $E>10^{17}$ eV flux < 10^{-10} particle/m^2/sr/sec ==> a 1 m^2

2π sr detector would collect only 1 event/ 50 years !!!!

➢ULTRA LARGE DETECTOR

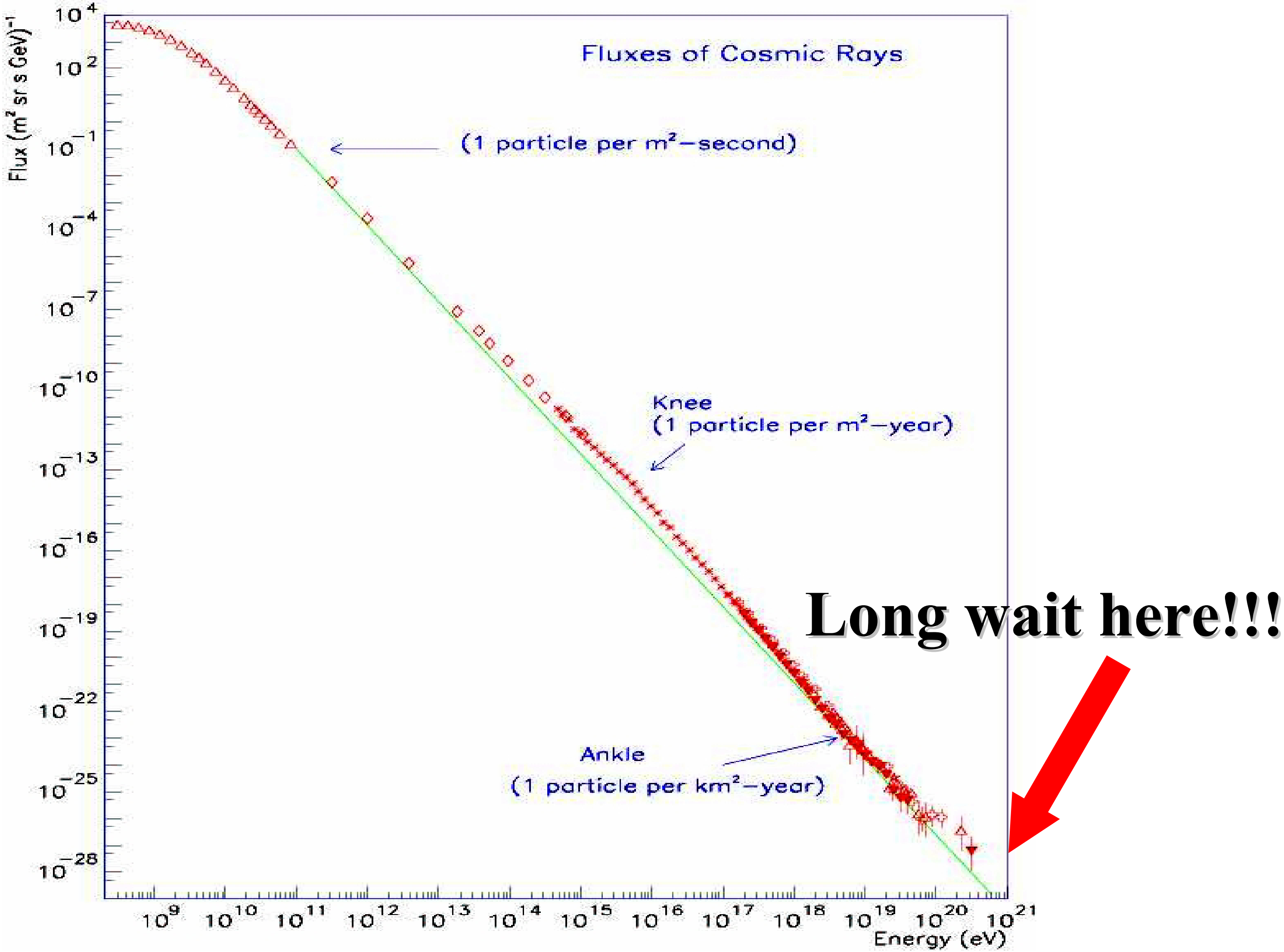
Need detectors with **very large apertures**

(~10,000 km^2 sr) to compensate for low flux…

Atmospheric Calorimeter

Exploit ***Extensive Air Showers*** using the atmosphere as part of your detector system...

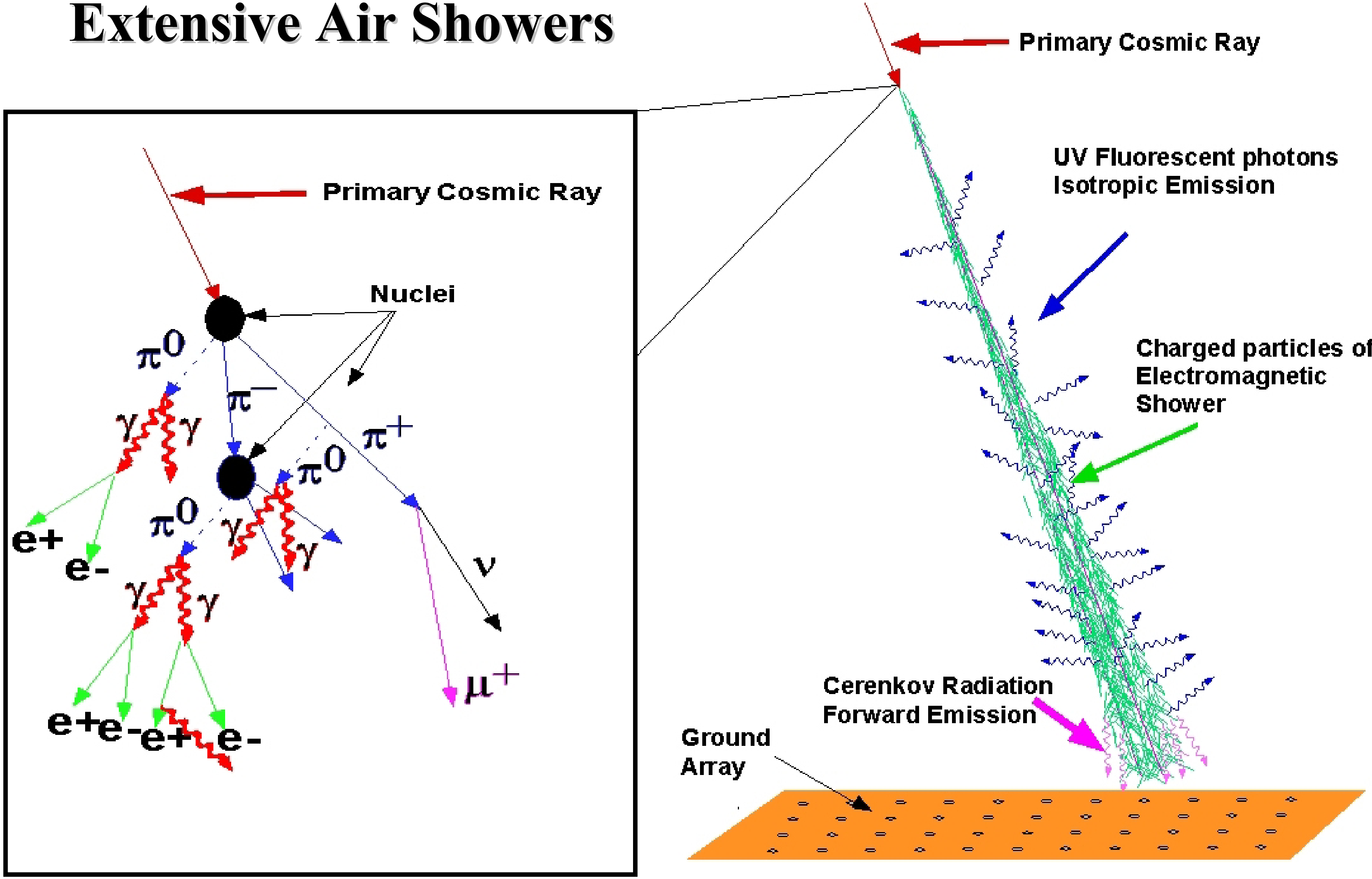
Cosmic Ray Flux



At energies above 10^{20} eV the flux is **extremely low**!!!

Namely **1 particle/km^2-steradian/century**

Extensive Air Showers

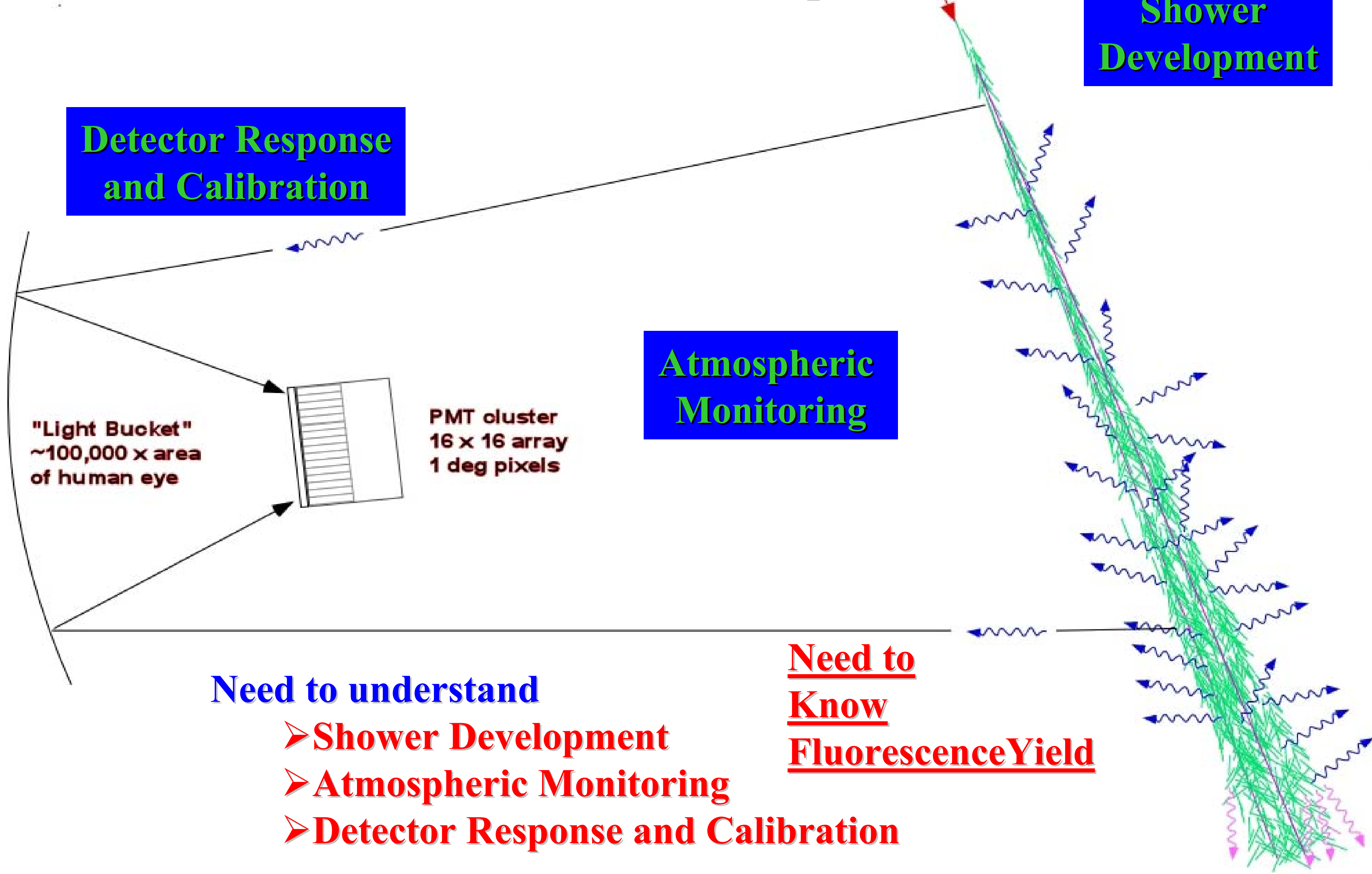


- Hadronic shower initiated by primary
- Electromagnetic Shower produced from gammas from π^0 decays….

Using the Atmosphere as a Calorimeter

- Shower Development
  - Development of hadronic and electromagnetic showers at Ultra-High energies… ➔ reconstruct primary UHECR's energy and composition
  - **UV fluorescence light yield**
- Atmospheric Monitoring
  - Need to know how UV light is attenuated in atmosphere
    - Energy reconstruction
    - Aperture determination
- Detector Response and Calibration
  - Optics
  - PMT response
  - Electronics
  - Absolute and Relative calibrations of detector system...

The Air Fluorescence Technique



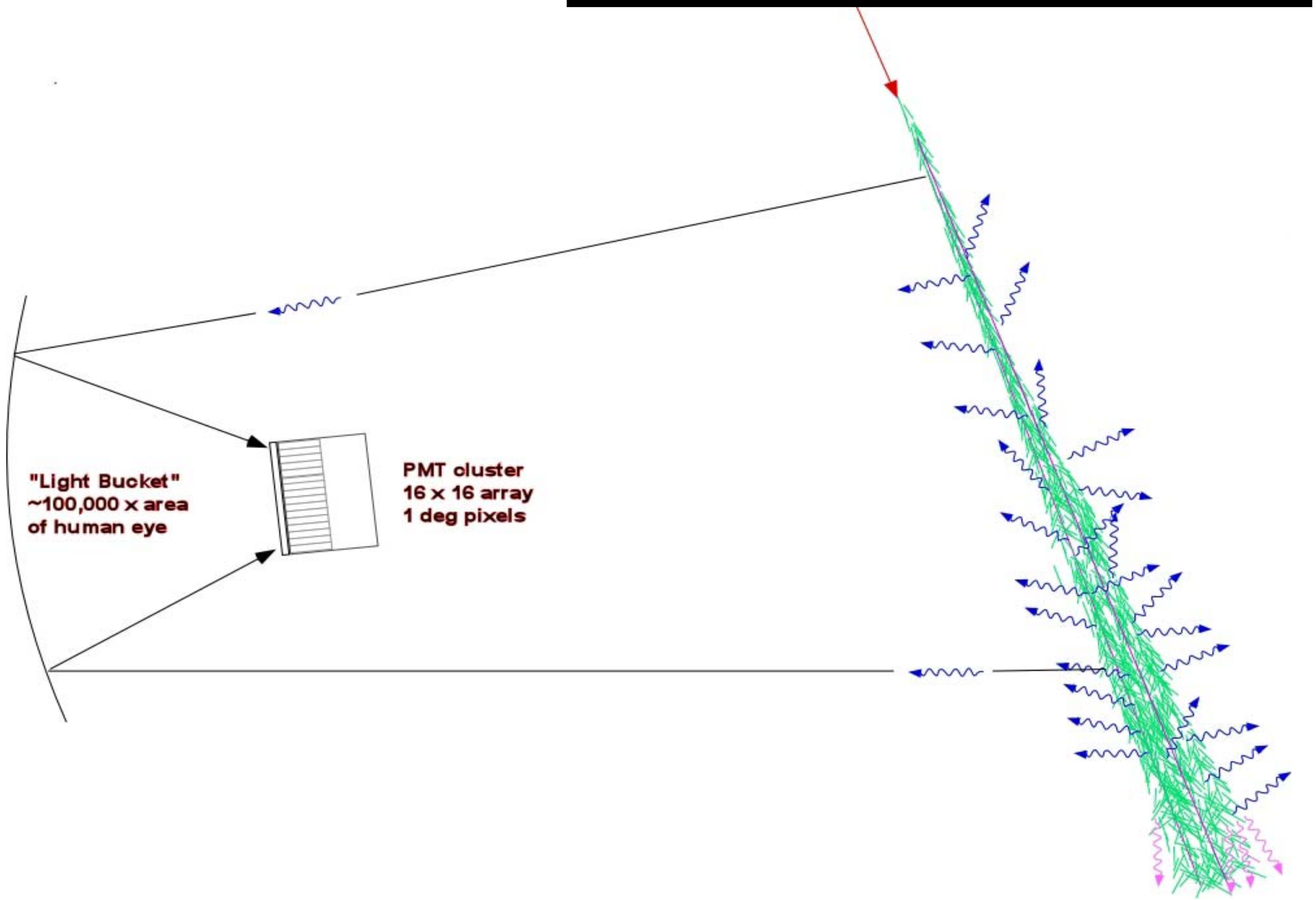
Need to Know FluorescenceYield

Need to understand

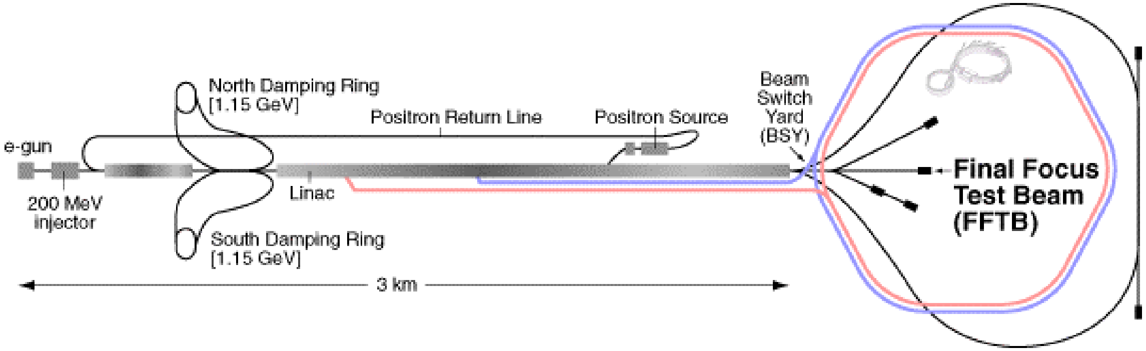
- Shower Development
- Atmospheric Monitoring
- Detector Response and Calibration

Lack of Test Beam Calibration

10^{18} eV proton accelerator
In geo-synchronous orbit over
Utah….



FLASH experiment at SLAC



- **How about 10^{10} 28 GeV Electrons instead?**
- **Measure Fluorescence Yield**
- **Study Shower Development using thick targets**
- **Test beam in 6/2002**
- **Experimental Program 6/2003**

T-461 Experimental Setup

The Air Fluorescence Technique

The ***fluorescence technique*** was first investigated as a means for estimating ***yields of atmospheric nuclear tests.***

LA-3409-MS Supplement
UC-34, PHYSICS
TID-4500

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H.C. $3.00; MN .75

LOS ALAMOS SCIENTIFIC LABORATORY
of the
University of California
LOS ALAMOS • NEW MEXICO

Report written: September 1965
Report distributed: May 4, 1966

Prompt Air Fluorescence Excited by High Altitude Nuclear Explosions

Photoelectric Instrumentation
and the High Altitude Fluorescence (HAF)
and High Altitude Resonance Absorption Calculation (HARAC) Codes

by

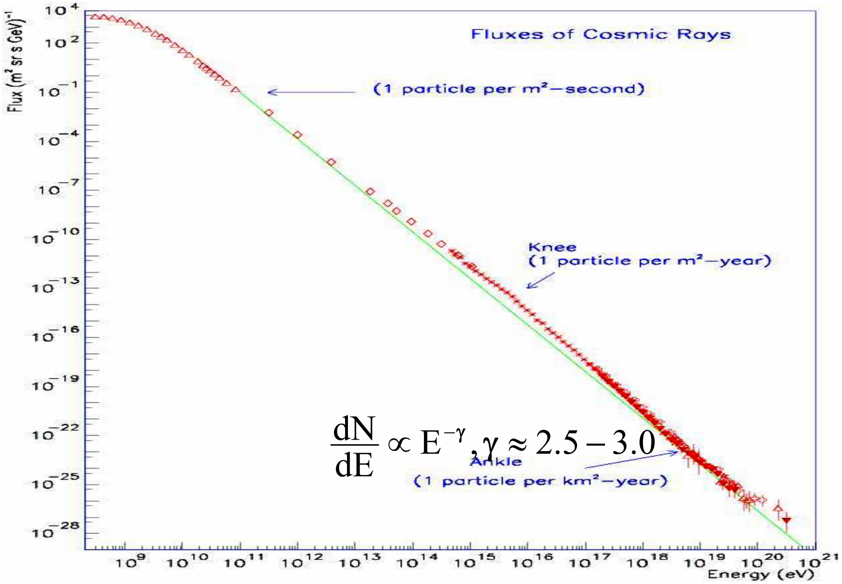
E. W. Bennett and R. F. Holland

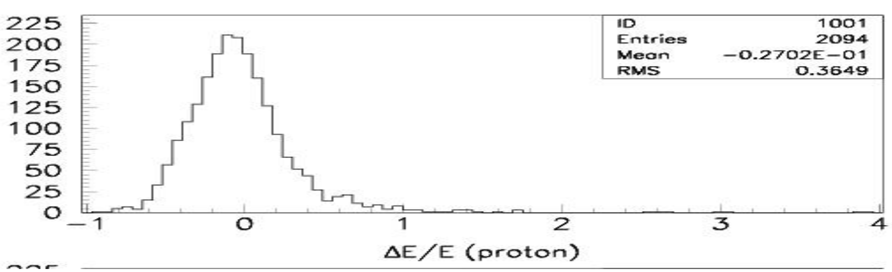
LEGAL NOTICE

Measuring Energy Spectrum

- Count Particles vs. Energy
  - Observe and measure energy
  - Correct energy for atmospheric effects
  - "Fill histogram" Number v Energy
- Determine Exposure vs. Energy
  - Evaluate on-time exposure taking into account dead mirrors etc.
  - Aperture Determination for each exposure
  - Correct aperture for Atmospheric Effects
- Divide! ➔ Energy Spectrum

The Measurement of the Energy Spectrum





Important to understand the following…

- **Energy Measurement**
  - **Detector Calibration**
  - **Shower Geometry (STEREO HELPS!!)**
- **Aperture**
  - **Trigger**
  - **Reconstruction**
  - **Atmospheric Monitoring**
  - **Detector Monitoring**

Need to ensure that there are no tails in Energy distribution!!!!

Reconstruction Techniques

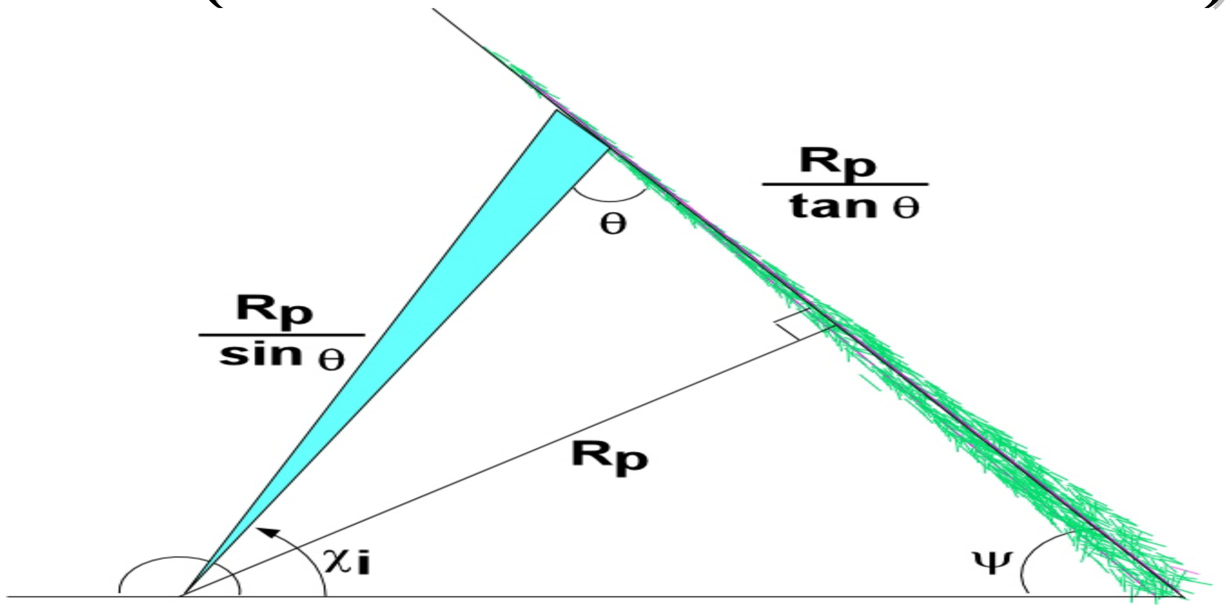
➢ Monocular Reconstruction

- ➢ Uses only one “eye” ==> Monocular
- ➢ Curvature of timing profile can be used to resolve ambiguity in distance and orientation of shower geometry.
- ➢ Constraining shower profile to give reasonable value of X_{max} helps ease problem of fitting for geometry ==> Can’t determine X_{max} when this is done however

➢ Stereo Reconstruction

- ➢ Uses two “eyes” ==> Stereo
- ➢ Shower geometry determined in straightforward manner by interesecting the shower-detector planes…
- ➢ Much more robust and reliable method to determine shower geometry and hence energy...

EAS trajectory in the shower-detector plane (Monocular Reconstruction)

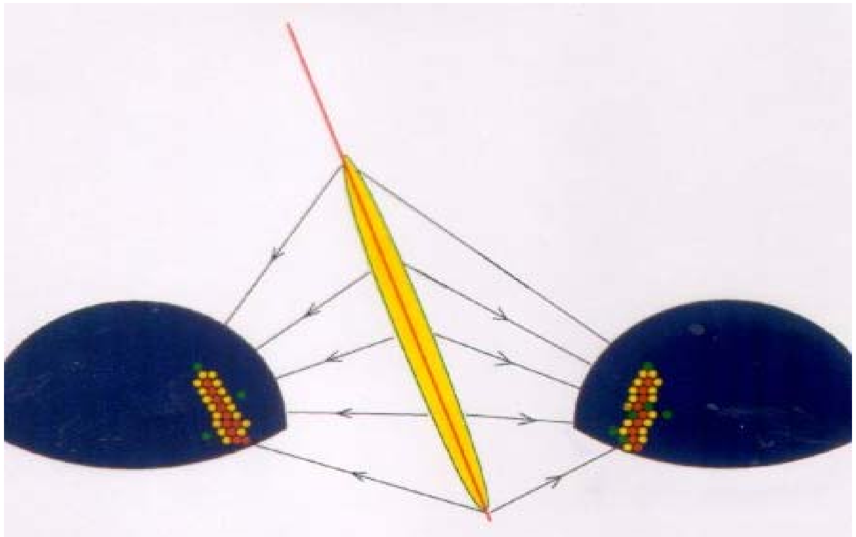


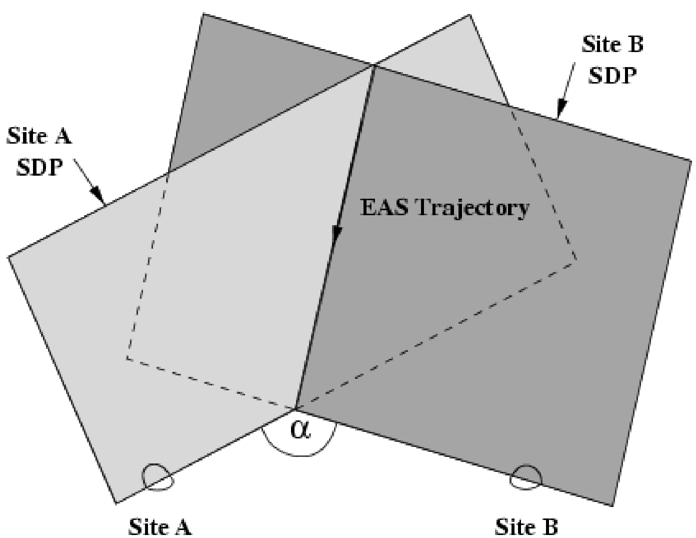
- Measure arrival time of light at tube #i.
- Do not know Ψ nor R_P
- Minimize following function

$$\chi^2_{tim} = \sum_i \frac{1}{\sigma_i^2}\left\{t_i - \left(t_o + \frac{R_p}{c}\tan\left(\frac{\pi - \psi - \chi_i}{2}\right)\right)\right\}^2$$

- Requires sufficiently long tracks to "resolve" the tangent function

Stereoscopic Observation with HiRes

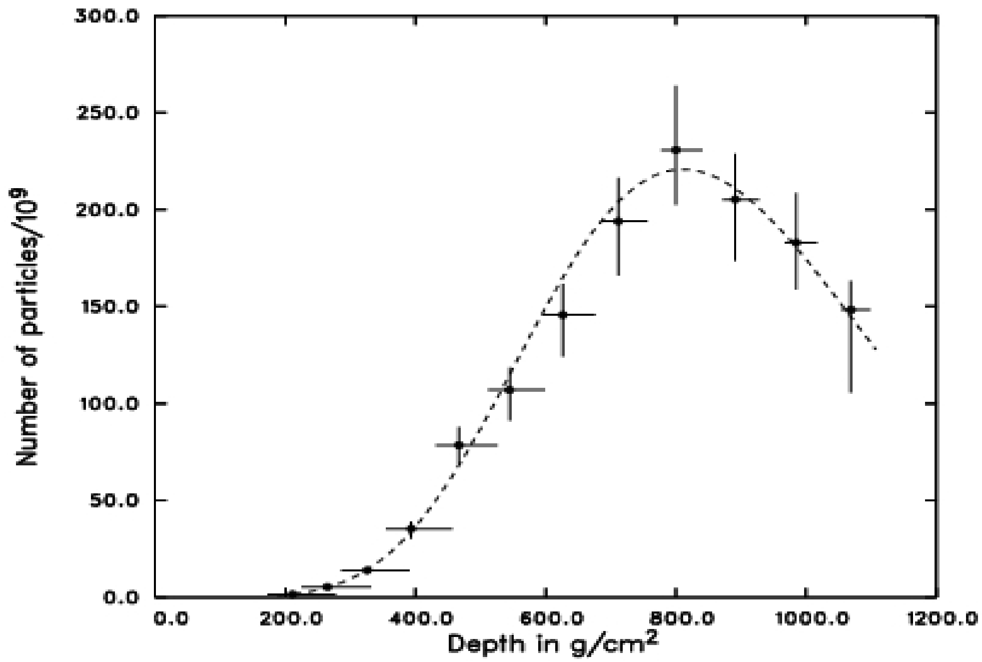




- The ***two detector sites*** are located ***8 miles apart***
- ***Geometry*** of an ***air shower*** is determined by ***triangulation.***
- ***Energy*** of ***primary cosmic ray*** calculated from ***amount of light*** collected.

Shower Development

Fly's Eye
"Big Event"



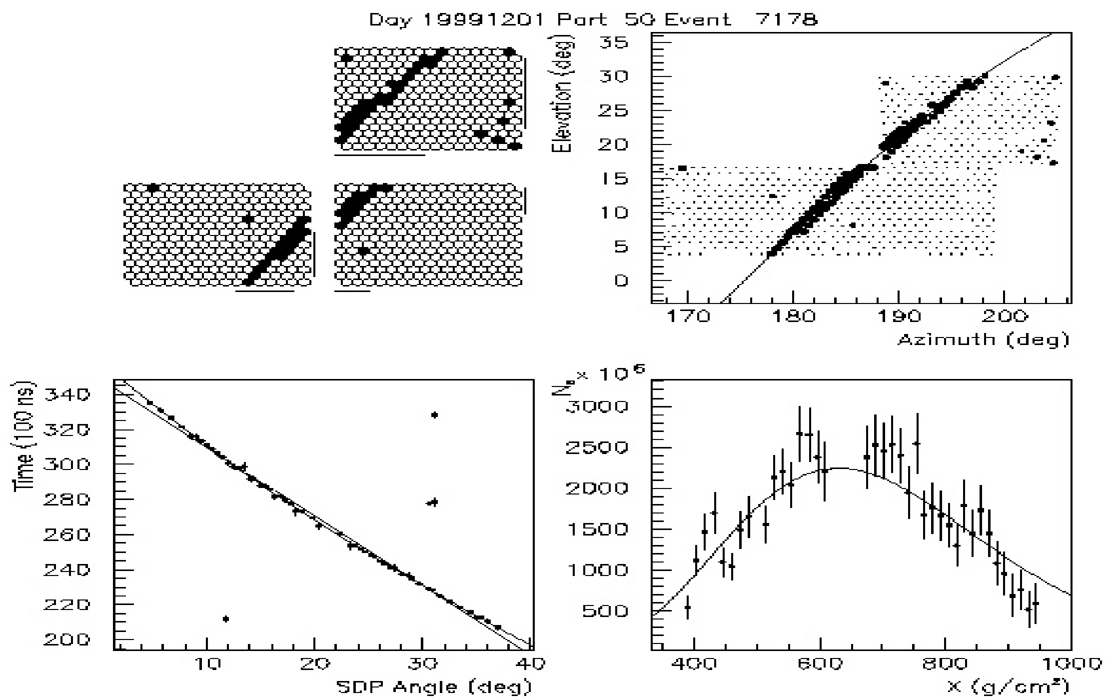
➢Energy of Primary can be obtained from the **integral** of the Number of secondary **shower particles vs depth**.

➢Need to know:

- ➢Shower Development dE/dx….
- ➢fluorescence yield
- ➢**Geometry of shower** (i.e distance, orientation to subtract Cerenkov light)
- ➢attenuation of UV light in atmosphere
- ➢Detector Response

Data Analysis

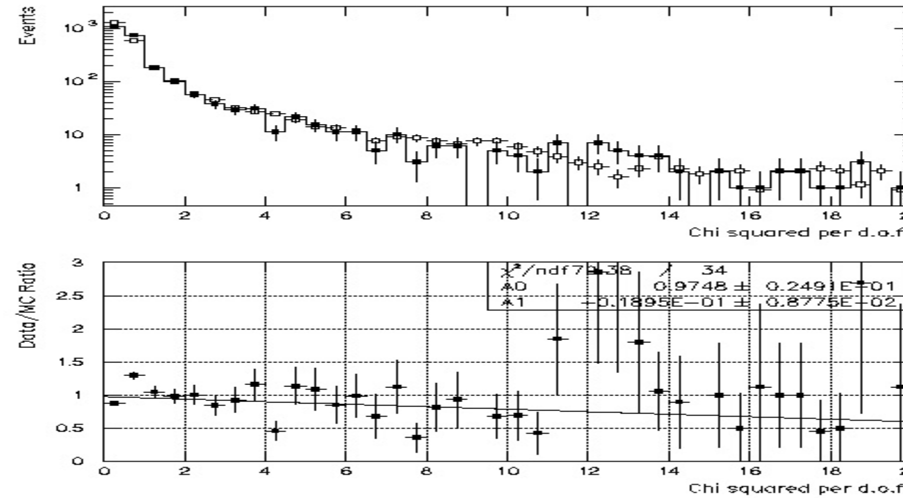
- Pattern recognition, time fit, profile plot, Gaisser-Hillas fit.



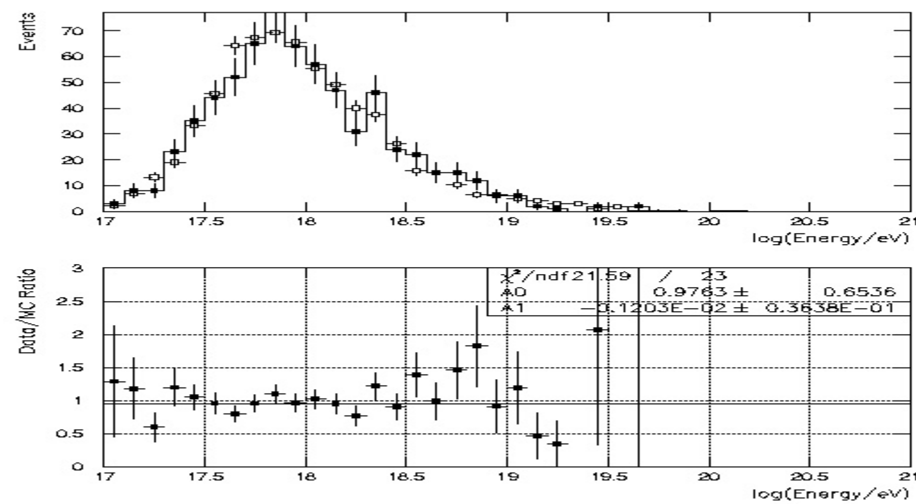
$$N(x) = N_{max} \left(\frac{x - x_0}{x_{max} - x_0} \right)^{\frac{x_{max} - x_0}{\lambda}} \exp\left(\frac{x_{max} - x}{\lambda} \right)$$

Data – MC Comparisons

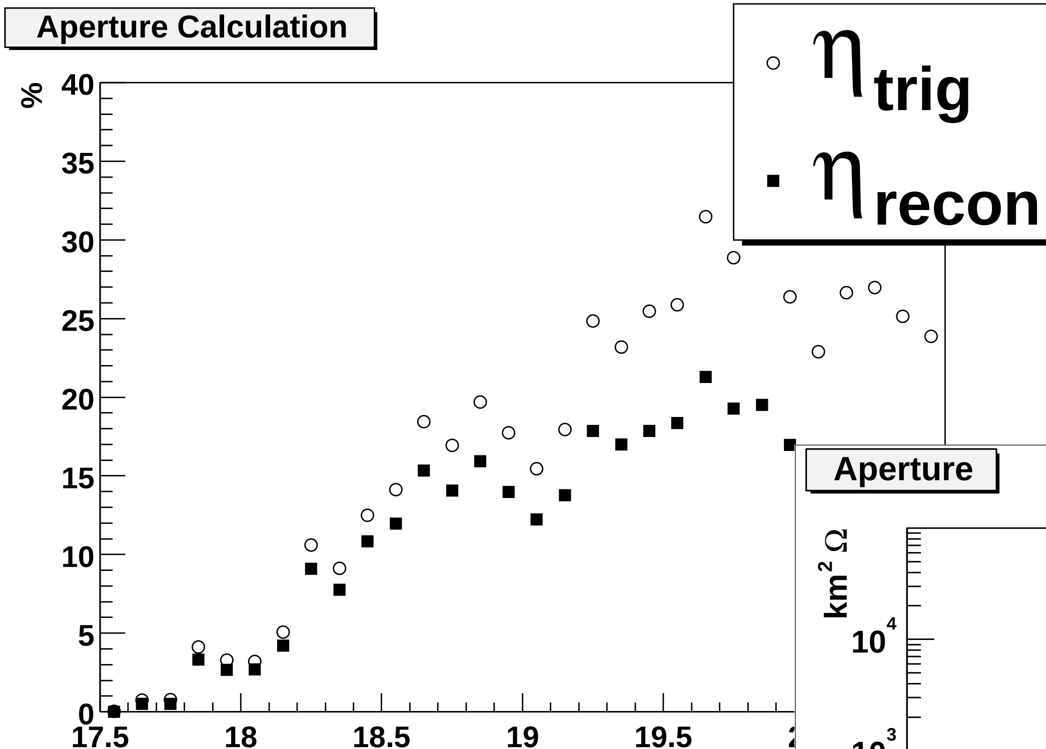
- Chisquared of time fit.



- Energy.

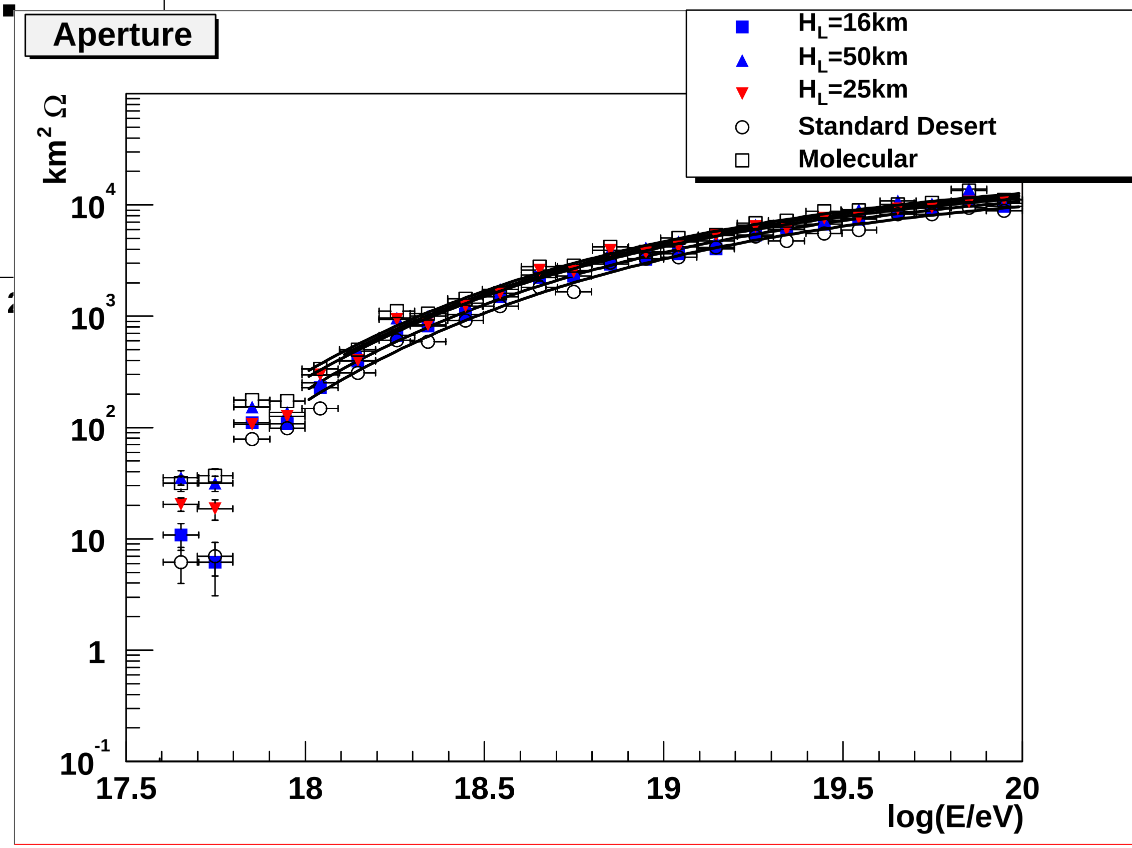


Determination of Aperture

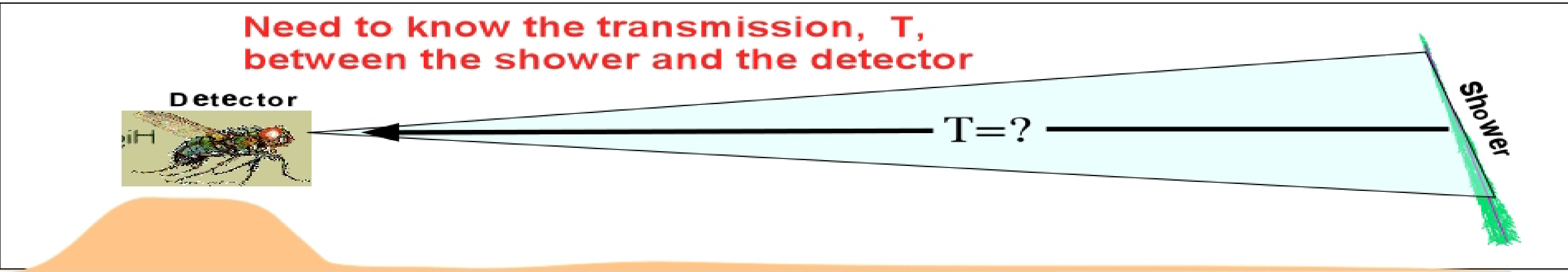


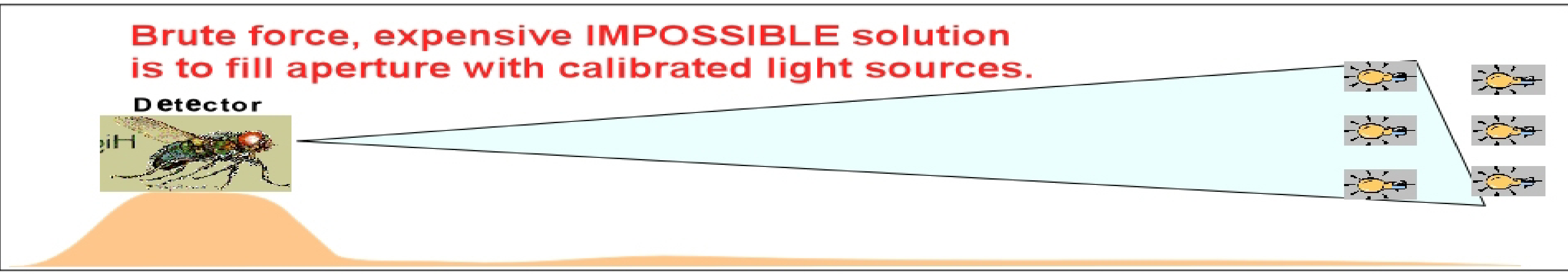
$$J(E) = \frac{\Delta N / \Delta E}{A\Omega \; \Delta t}$$

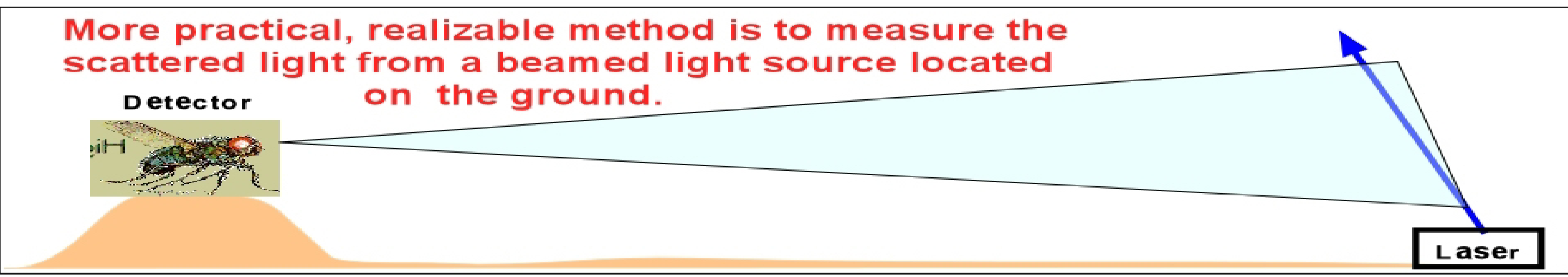
$$\eta(E_i) = \frac{N_{recon}}{N_{thrown}}$$



Atmospheric Monitoring

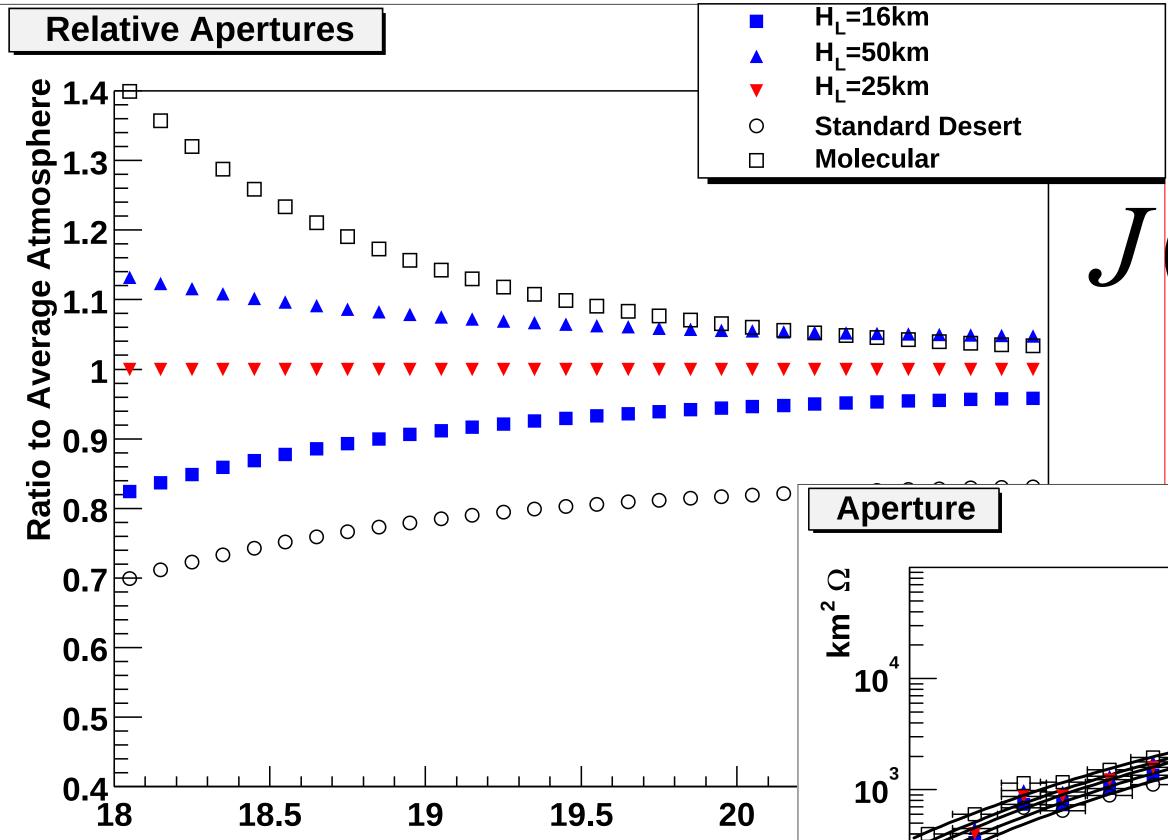




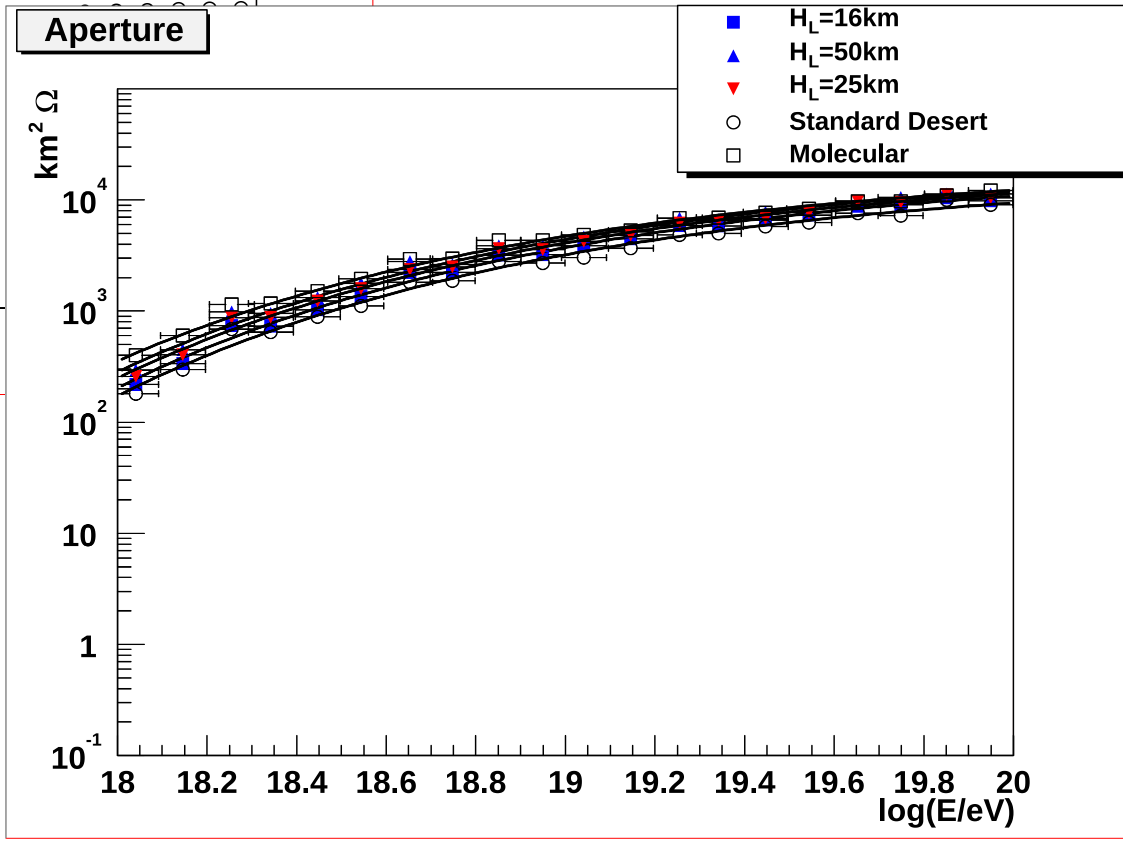


Atmospheric monitoring is realized by observing the scattered light from beamed light sources such as lasers and radio-controlled vertical flashers

Atmospheric Effects on Aperture



$$J(E) = \frac{\Delta N / \Delta E}{A\Omega \ \Delta t}$$



Performance of HiRes

Energy Reconstruction

- Primary Energy Range(EeV): 0.1 - 200+
- Energy Resolution @ 1EeV: 20%
- X_{max} Resolution 20-30 g/cm^2

Pointing Accuracy

- Point source resolution at 1 EeV: 0.6 degree

Event Rates

- E>10^{20} eV : "dozens"/year ? (no GZK)
- E>10^{18} eV : >2000/year

Description of the HiRes Detector

- Sites
  - Two "eyes" separated by 12.6 km
  - "Eyes" located ~500 feet above Desert floor.
  - Located in West Desert of UTAH, elevation ~4800 feet (870 g/cm^2). Excellent visibility
  - Aperture ~10,000 km^2-sr for E>10^{20}eV
  - Duty Cycle ~ 10%
  - Viewing Distance up to 30+ km
- Detector Components
  - Optics
    - 3.8 m^2 mirrors (21 @ HiRes1 covering 3-15 deg) (42 @ HiRes2 covering 3-31 deg)
    - PMT field of view 1 x 1 degree (arranged in ~ 16 x 16 cluster at focal plane of each mirror for a total of 16128 PMTs)
  - Readout Electronics
    - HiRes1: Sample and Hold
    - HiRes2: FADC 100ns clock

Little Granite Mountain (***HiRes-1***)

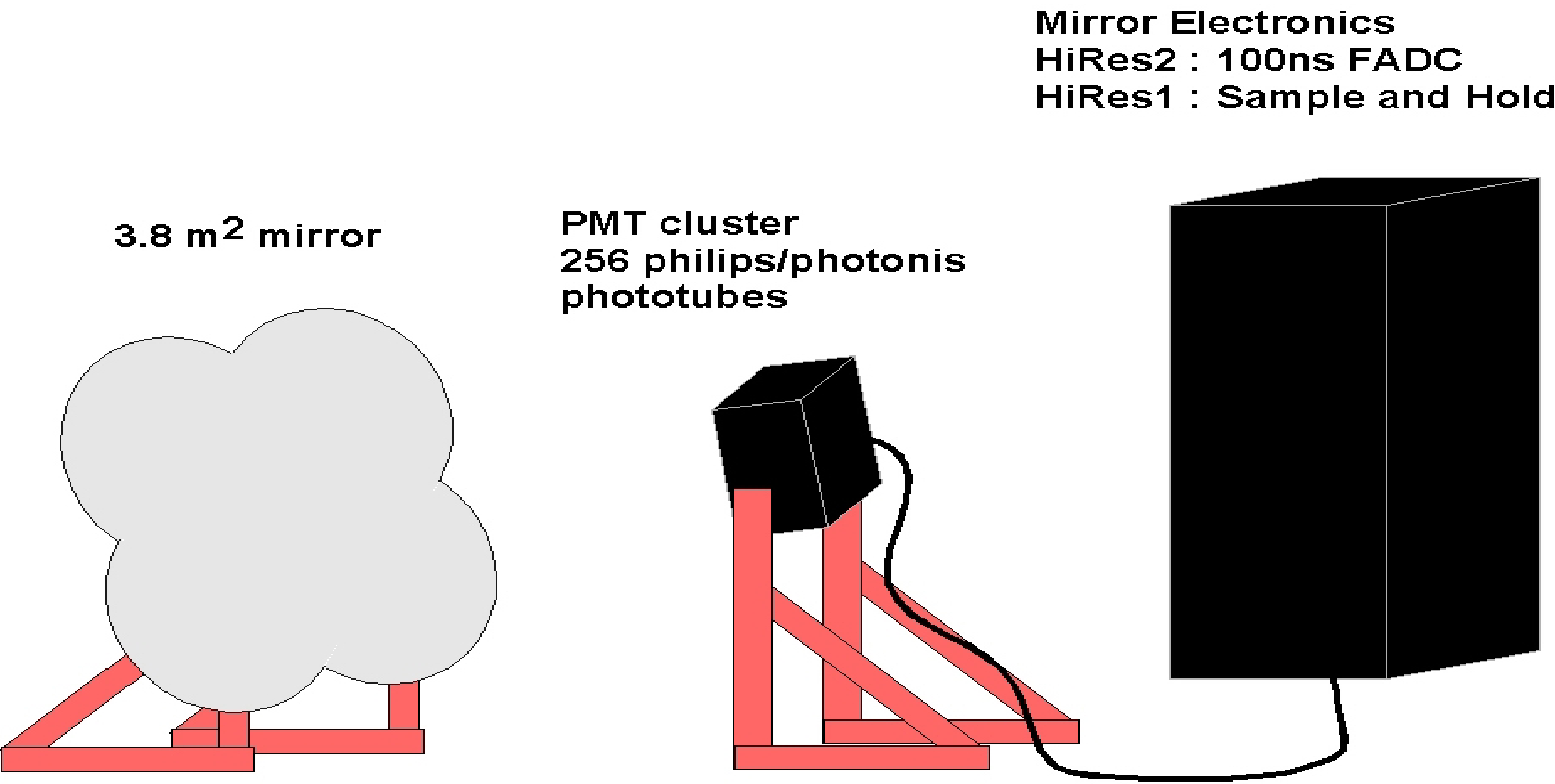
Began observation 6/1997.

- 22 mirrors covering 360 degrees in azimuth and up to 17 degrees in elevation.

The HiRes Detector Volume

Photograph of the "Camels' back" site (HiRes2) looking Northeast…

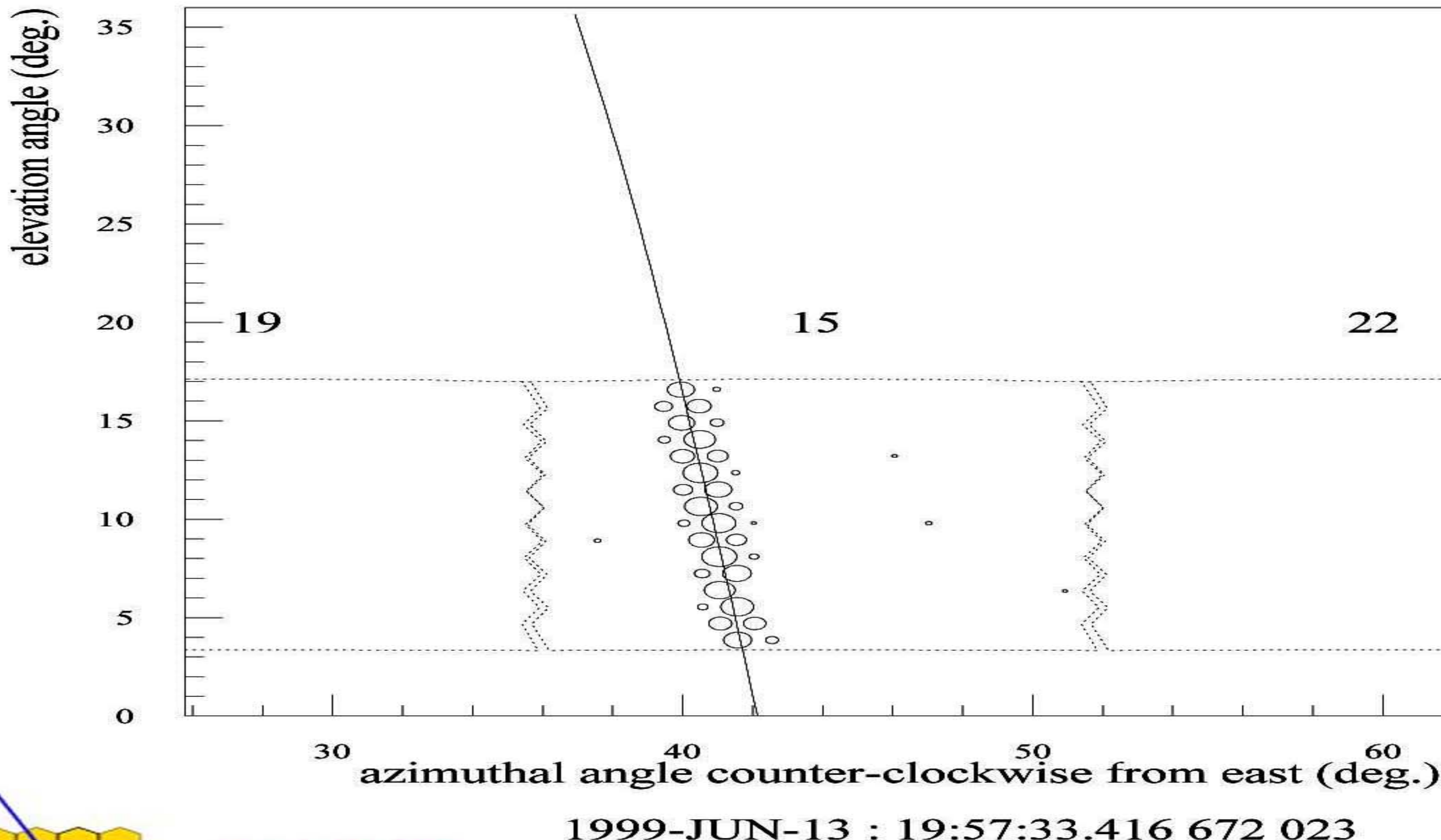
Schematic of HiRes Detector Elements



HiRes 1: 21 Mirrors 3-15 degree elevation
HiRes 2 42 Mirrors 3-31 degree elevation

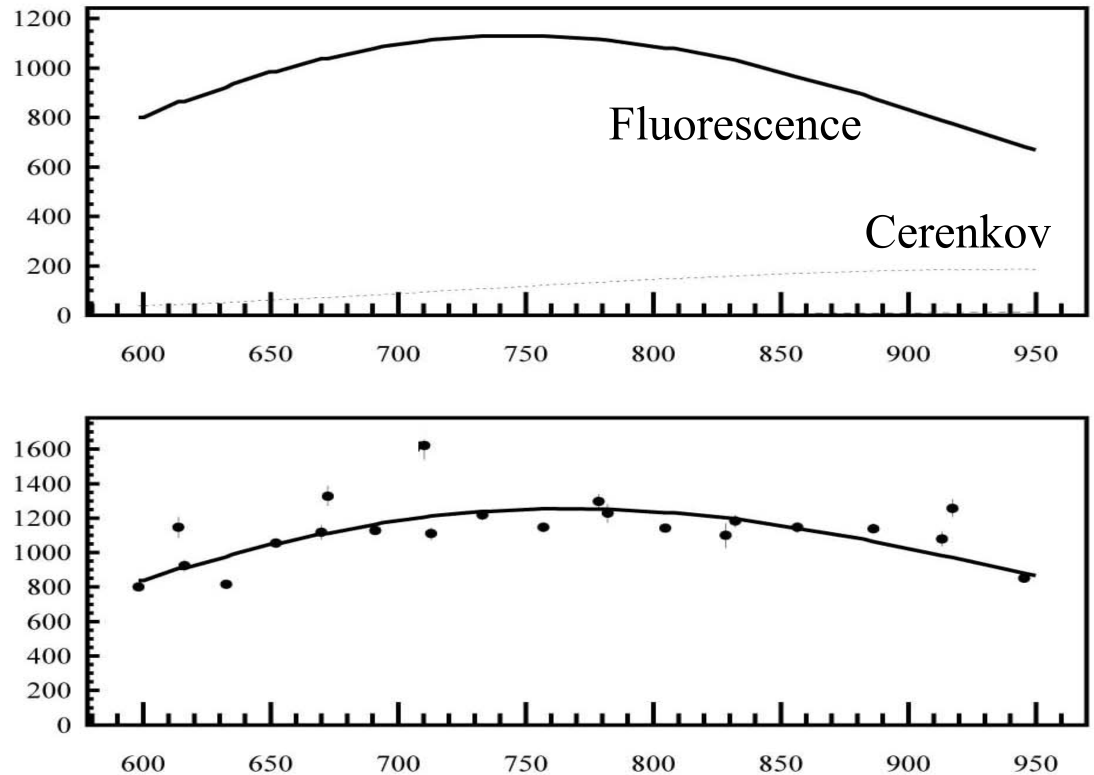
Photograph of HiRes Mirror and PMT cluster (prototvpe)

HiRes 1 Event Gallery



HiRes
Monocular

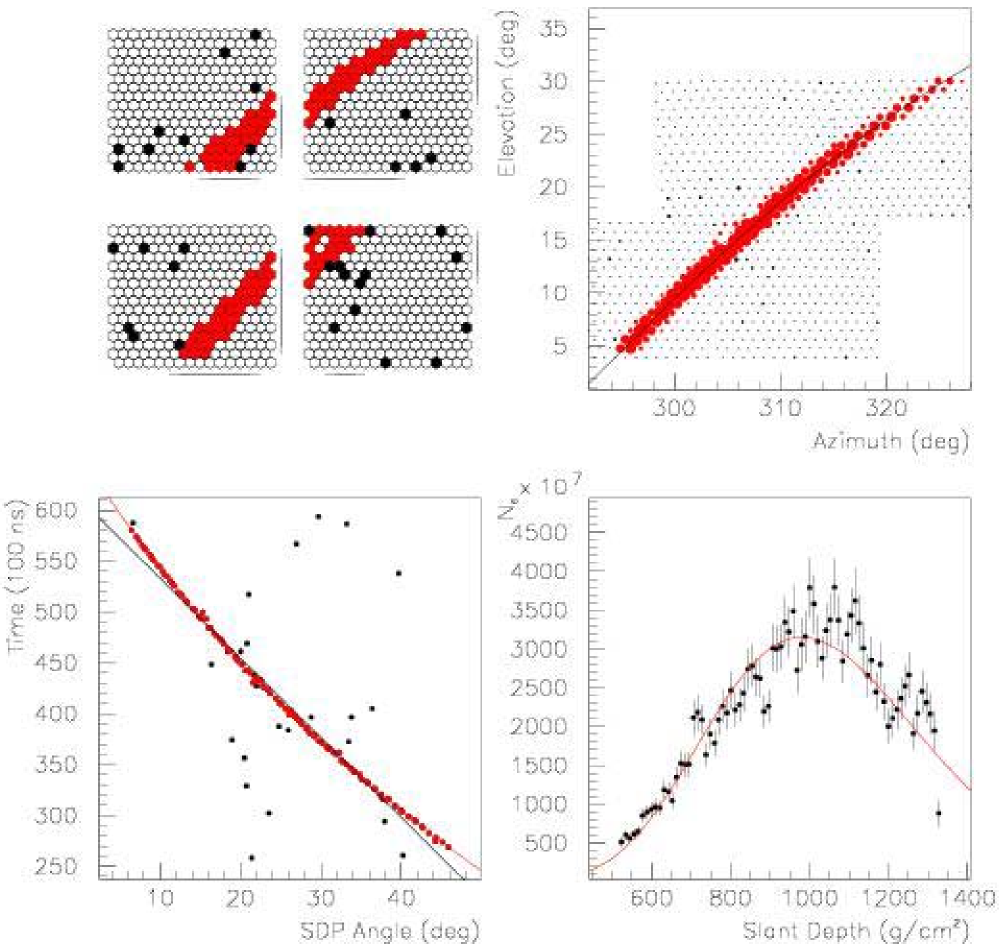
Number of Photo-electrons / deg / m^2



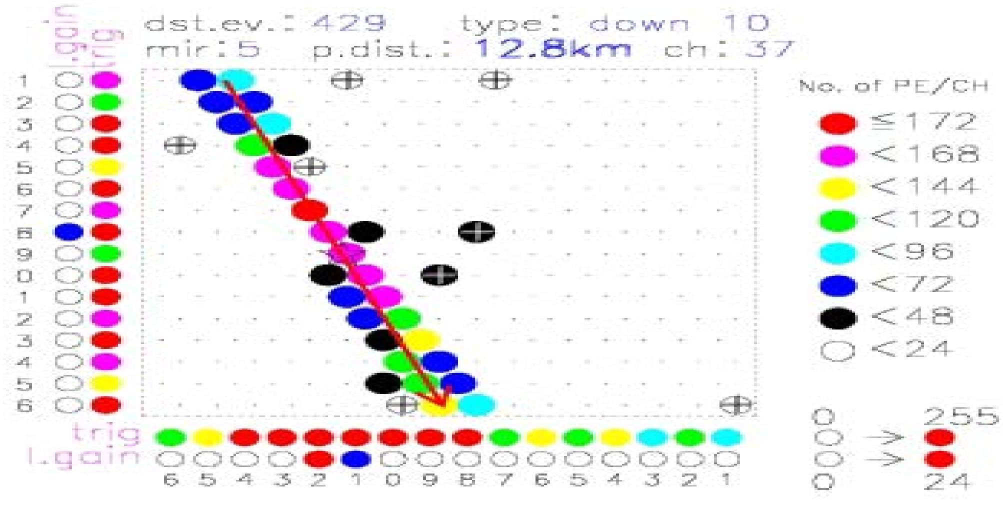
Slant Depth along Track (g/cm^2)

HiRes Monocular

HiRes2 Event Gallery
Profile through time binning

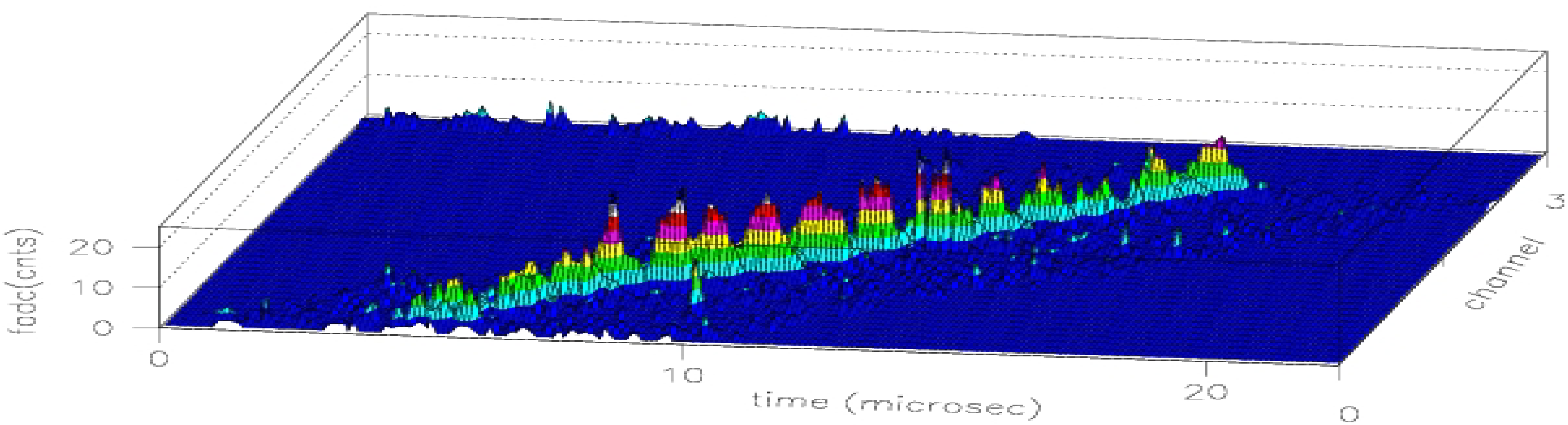


HiRes2 Event Gallery: Event 1



- FADC readout
- Time binning

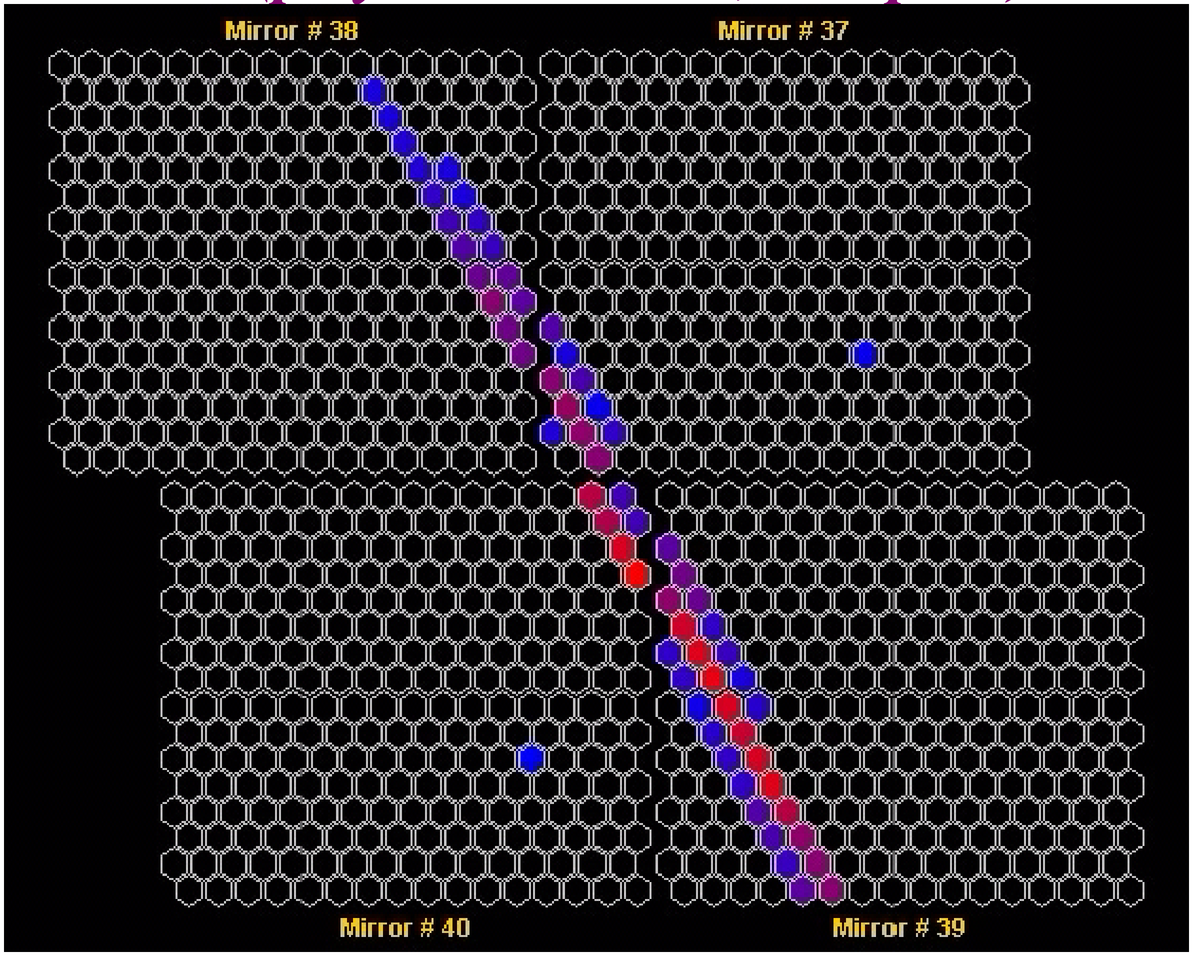
Mirror Display



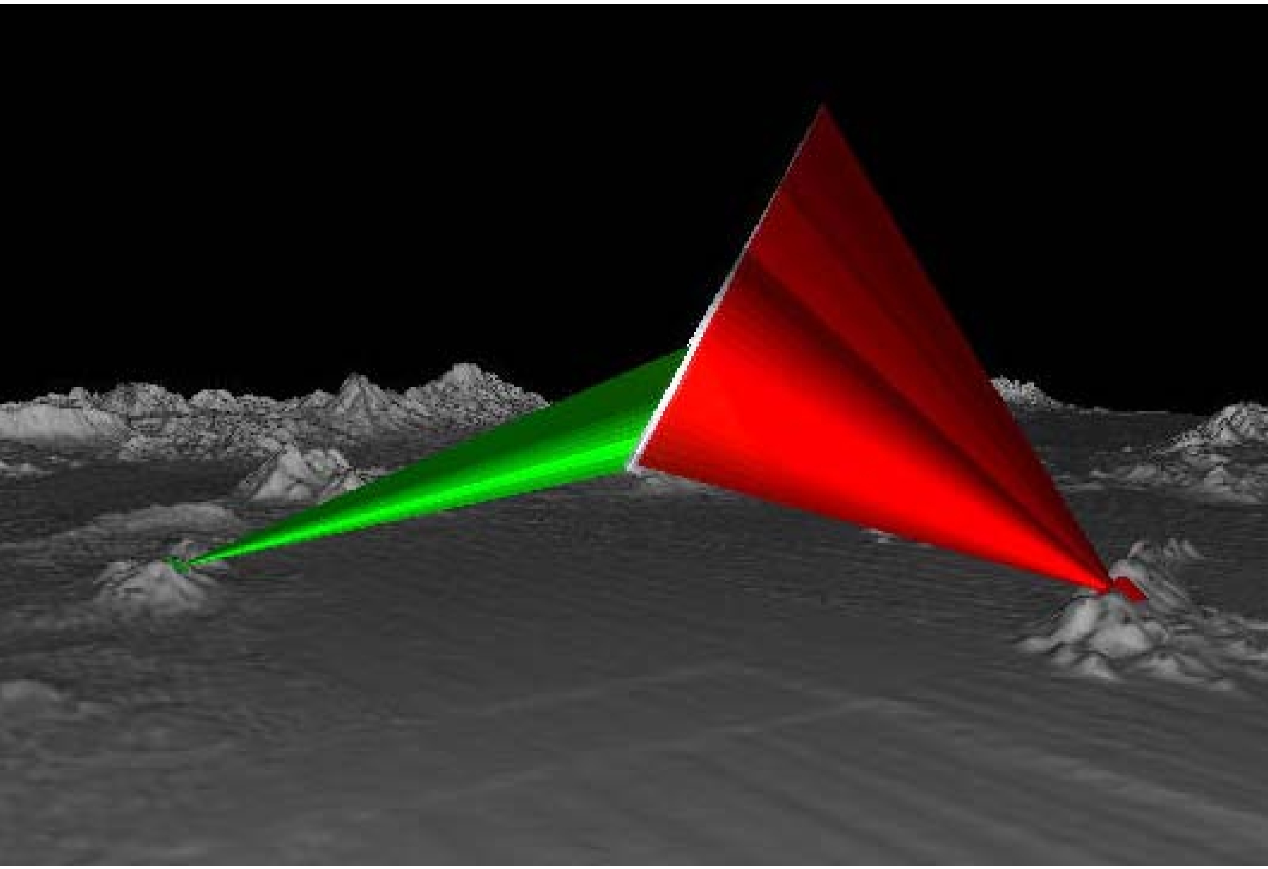
NPE v Time v Channel

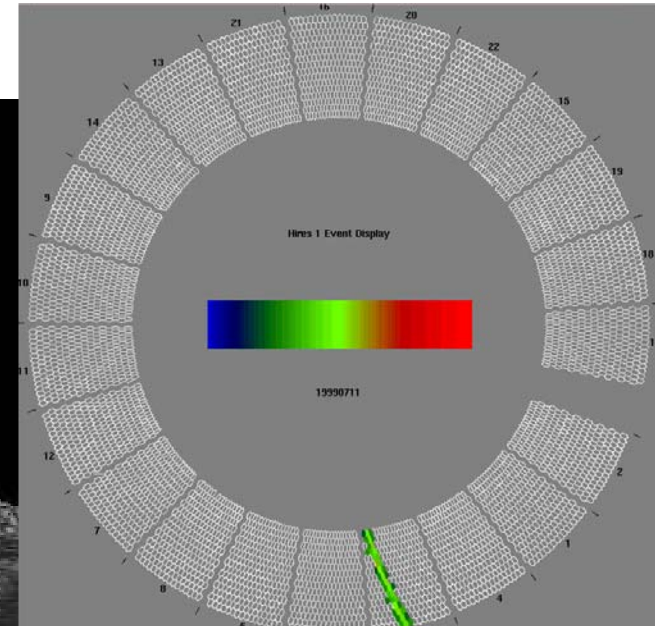
A 25 Microsecond Movie

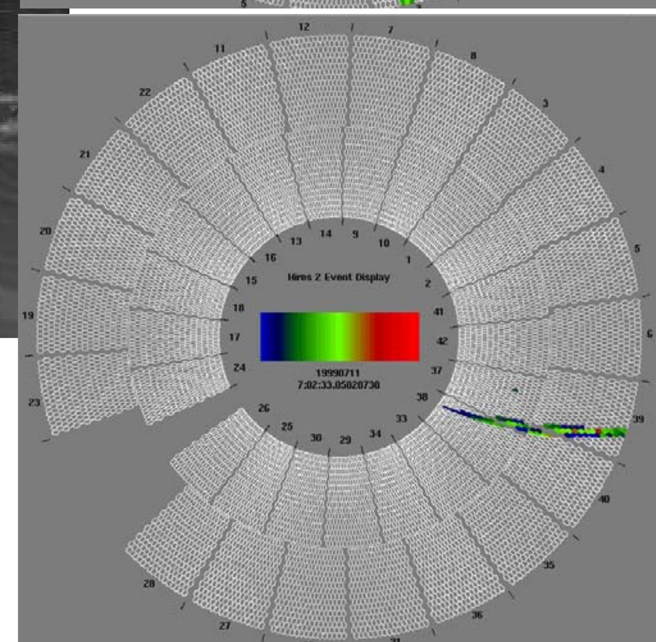
(playback at 1/500,000 speed)



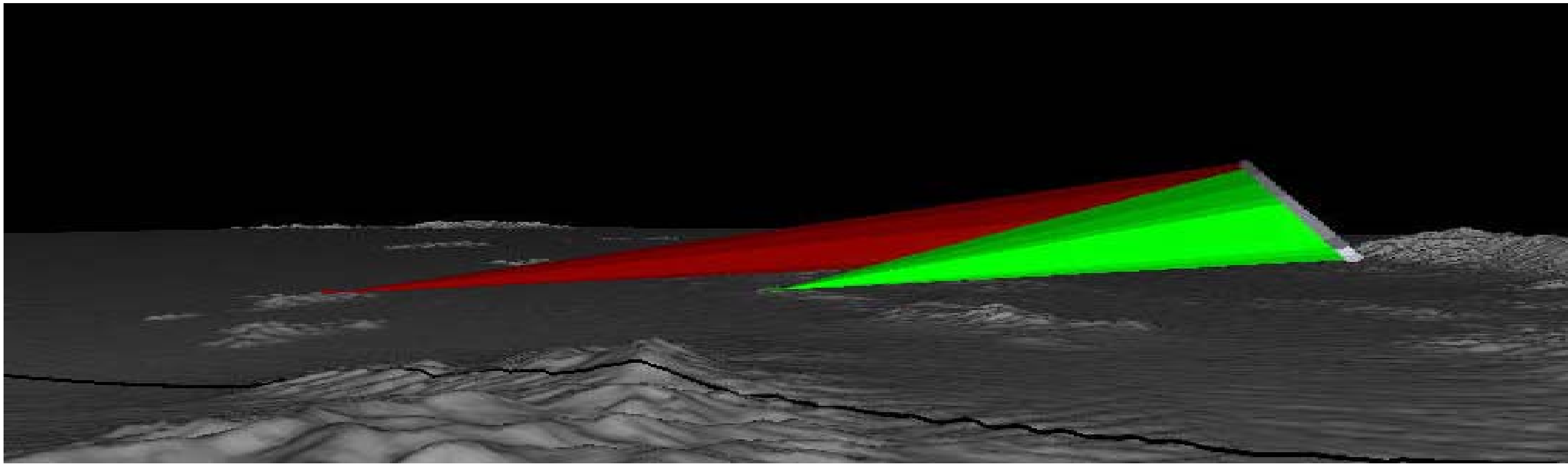
Typical Stereo HiRes Event:

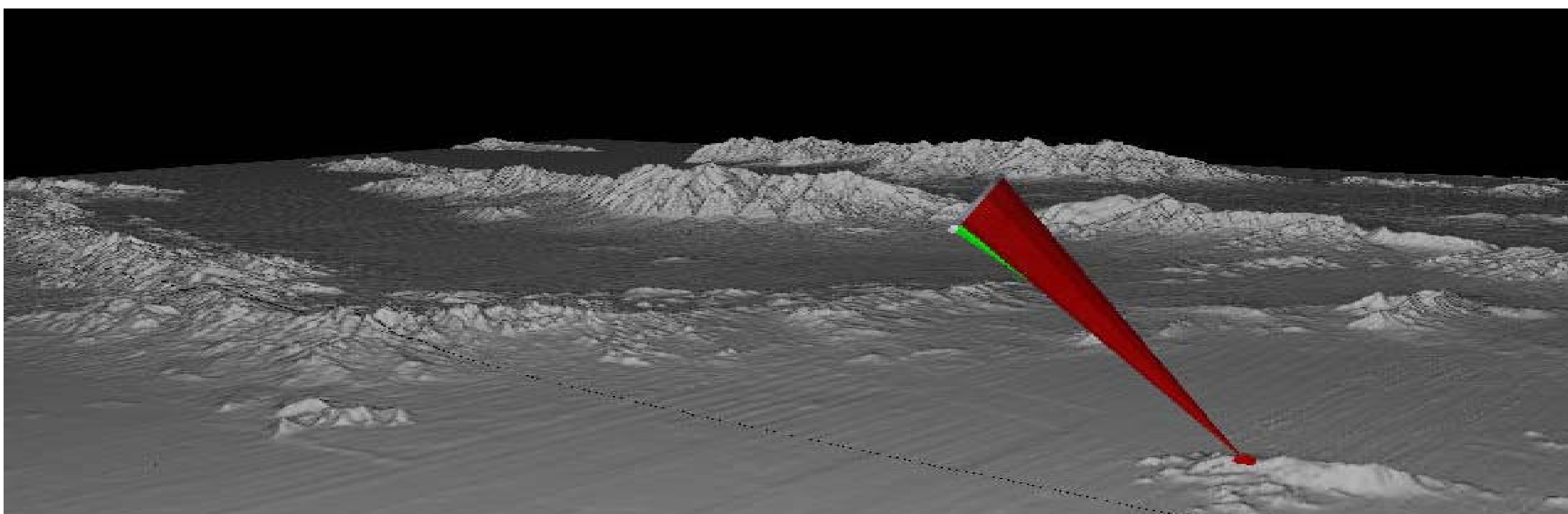






Atypical Stereo HiRes Event: (alternate view)





Results from the HiRes Detector

Monocular Results

- Measurement of energy spectrum obtained separately from each of the detector sites
- Used Profile Constrained Geometry Fit to determine shower geometry at HiRes I
- No profile constraint for HiRes II but require Xmax to be seen in profile

Stereo Results

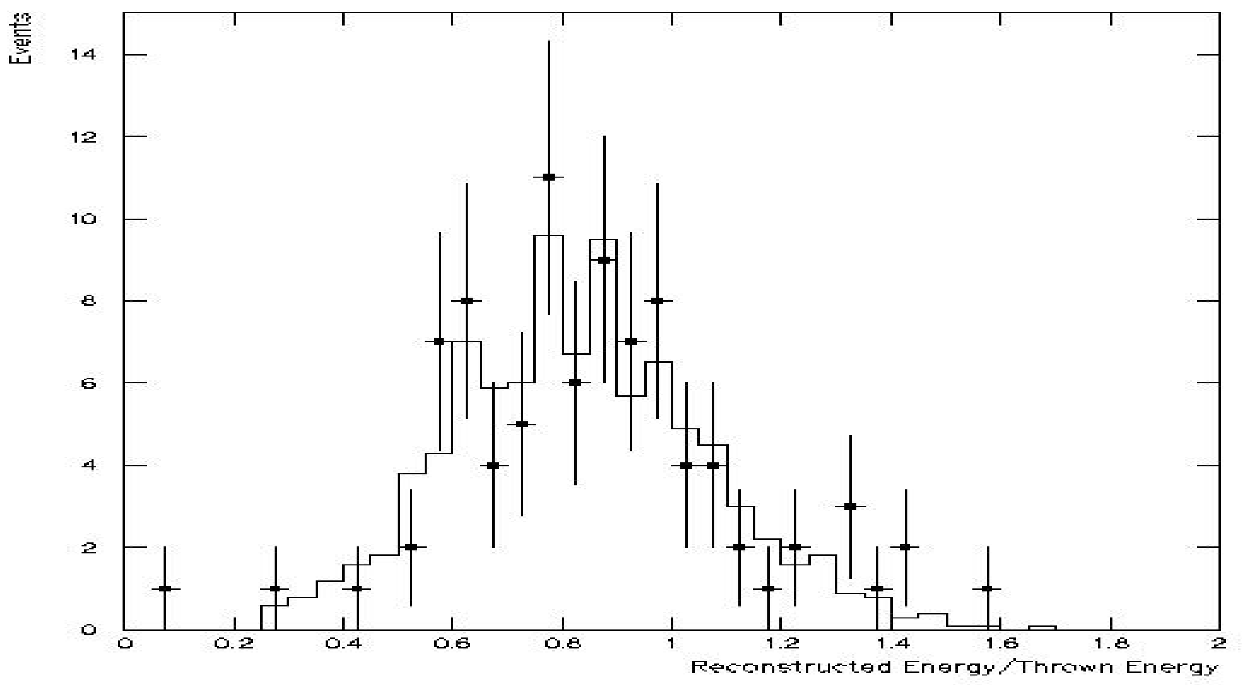
- Use of Stereoscopic Geometry leads to superior resolution.
- Smaller data set than HiRes 1 Monocular data
- Stereo analysis proceeding. First results now coming in…

HiRes1 Monocular Spectrum

- Period: June, 1997 – May, 2001
- 50915 mirror hours.
- Cuts:
  - Clear weather.
  - Downward going track.
  - Track length > 7.9 degrees
  - Pseudodistance > 5 km
  - .85 < tubes/degree < 4.
  - Photoelectrons/degree > 25
  - Constrained fit converges.
  - Shower max in view
- Minimum energy is $3x10^{18}$ eV due to shorter tracks.

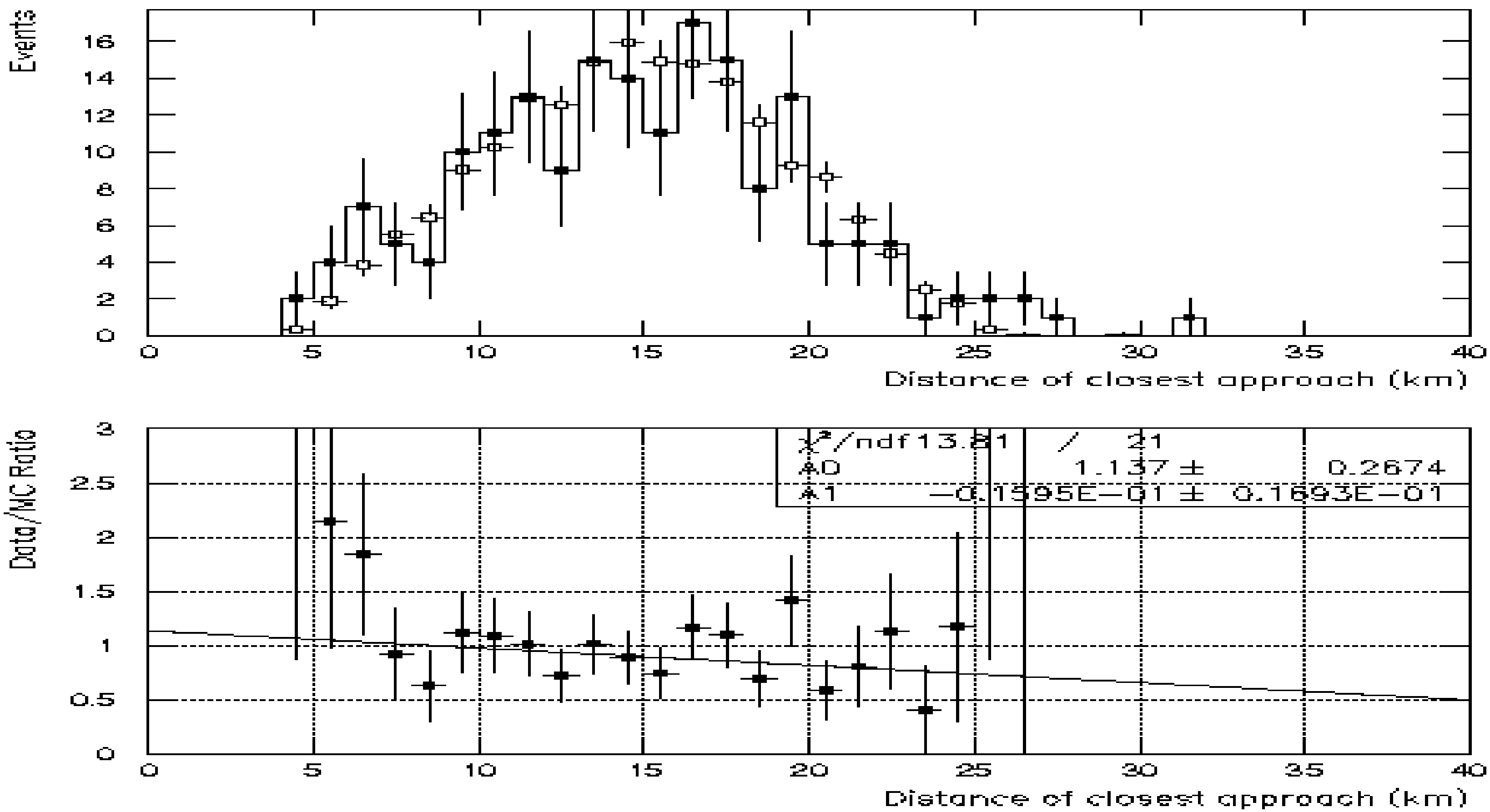
Profile-Constrained Fit

- Shorter tracks in HiRes1 have less curvature.
- Use constraint that profile must fit G-H function: leads to bias, same in MC and ste



HiRes1 Data-MC Comparison

R_p, 18.4<log(E/eV)<18.6



Systematic Uncertainties

- PMT calibration: 10%
- Fluorescence yield: 10%
- Unobserved energy: 5%
- Atmospheric absorption: most sensitive to vertical aerosol optical depth (VAOD)
  - Mean VAOD = 0.04
  - VAOD RMS = 0.02
  - VAOD systematic is smaller.
  - Modify MC and analysis programs to use VAOD = 0.02 and 0.06, reanalyze.
  - J(E) changes by 15%
- Total systematic uncertainty = 21%

HiRes2 Monocular Spectrum

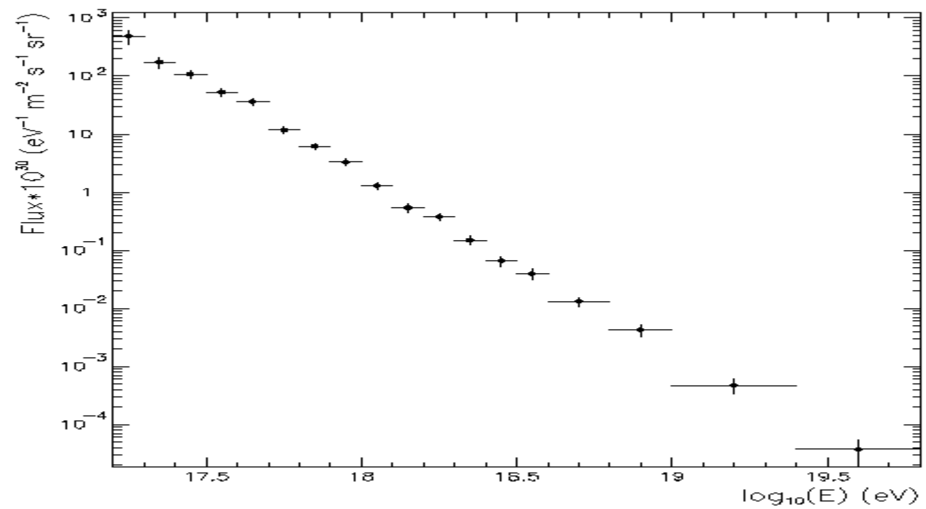
- Dec., 1999 – May, 2000 (first stable HiRes2 running). ~30% of data.
- Consistent trigger (big change after May).
- Cuts:
  - Clear weather.
  - Downward going track.
  - Track length > 7 degrees
  - Linear fit chisquared/tube < 20
  - Pseudodistance > 1.5 km
  - .85 < tubes/degree < 3.
  - Photoelectrons/degree > 25
  - Zenith angle < 60 degrees
  - Shower max in view

HR2 Mono Spectrum Results

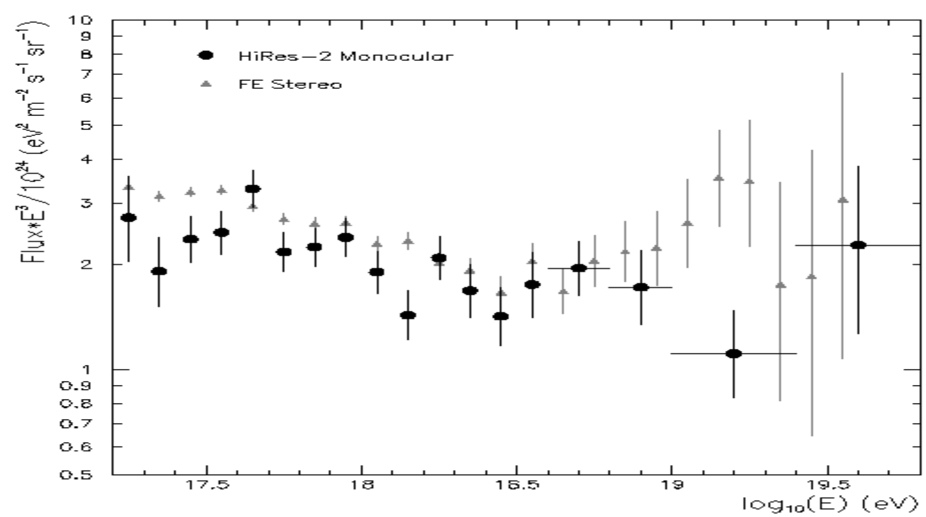
- J(E)

$$= \frac{N_D}{N_A} \times \frac{N_T}{A \ \Omega \ T \ \Delta E}$$

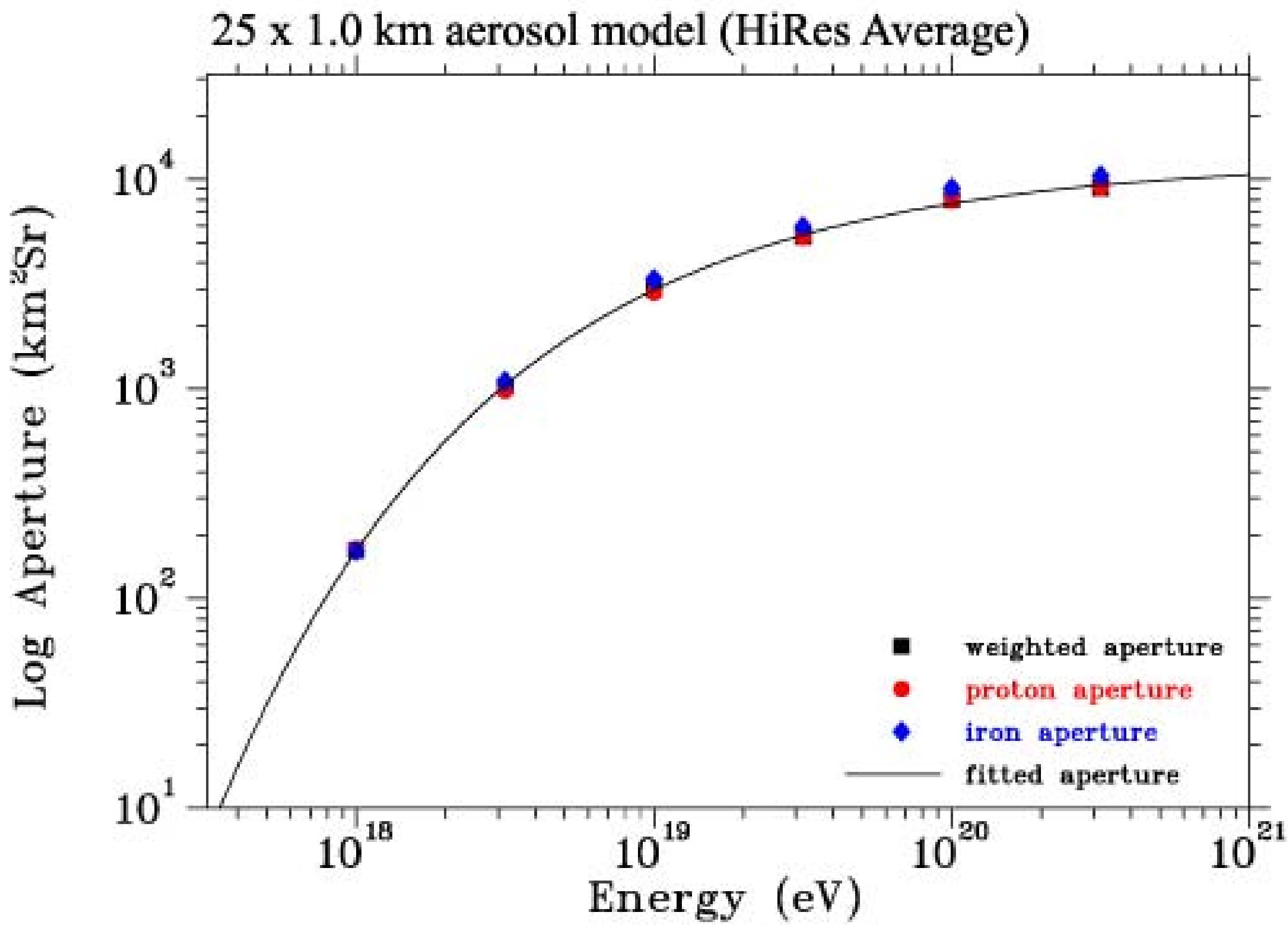
(correct for resolution)



- E^3 J(E)

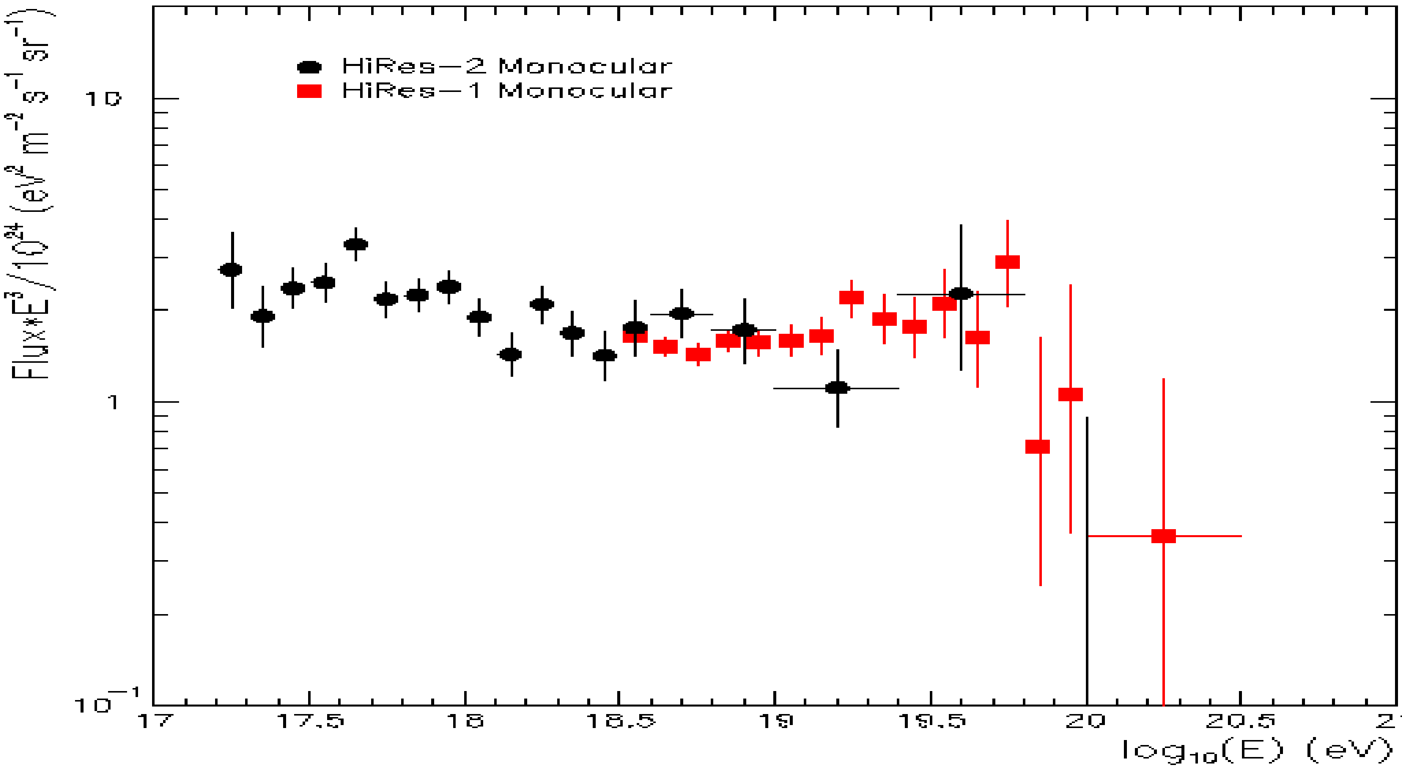


HiRes March 2002



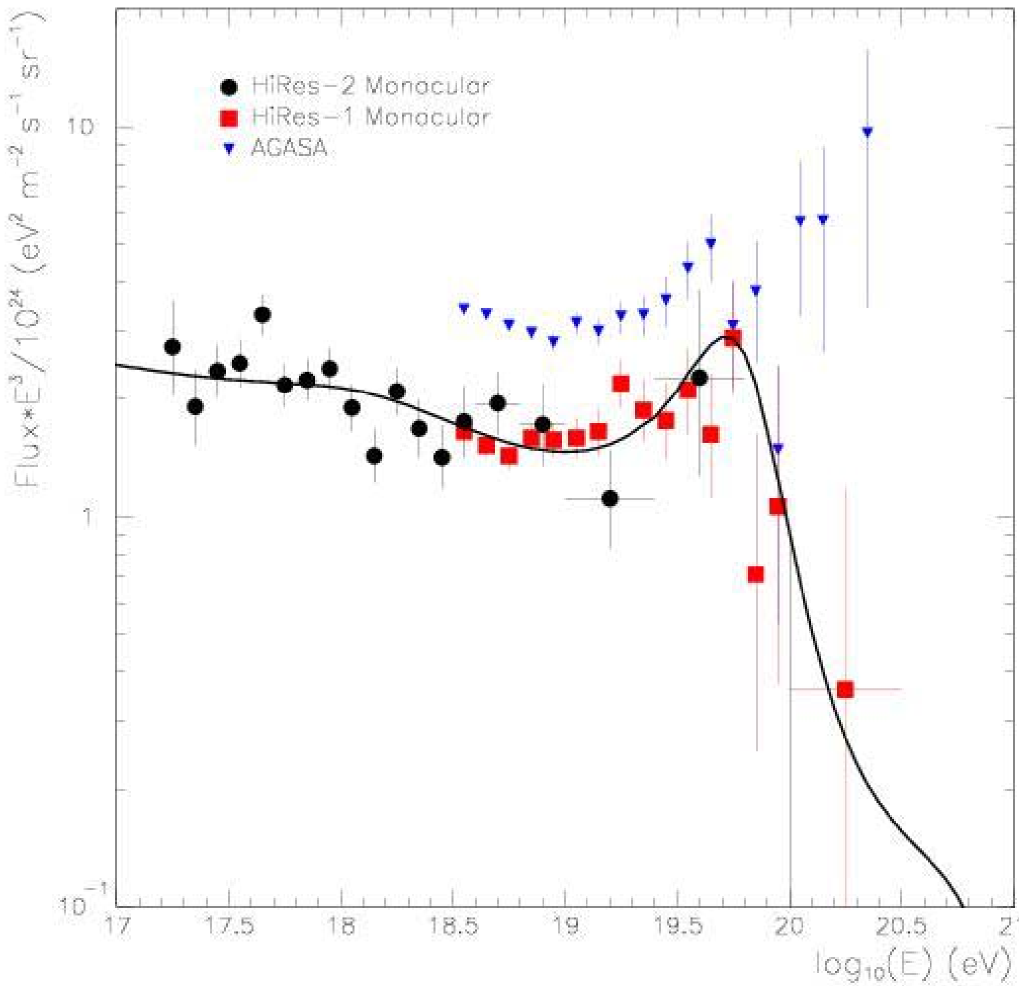
HiRes

HiRes Monocular Spectra

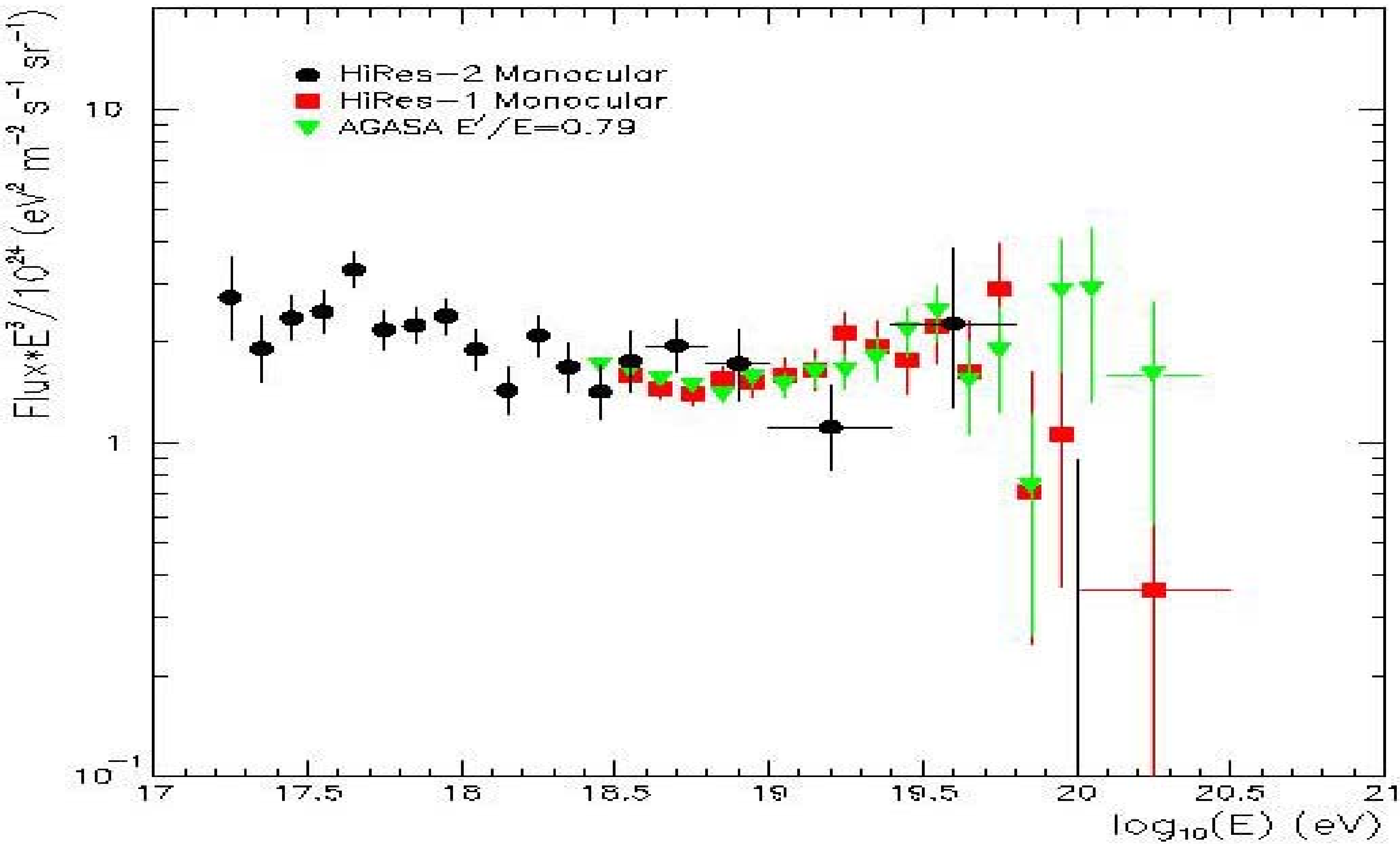


- Fit: $E^{-2.8}$ from 18.7 to 19.8; Predicts 19.1 events, logE>19.8; See 5. Probability = 1.4 x 10^{-4}

UHECR Spectra
Monocular HiRes and AGASA

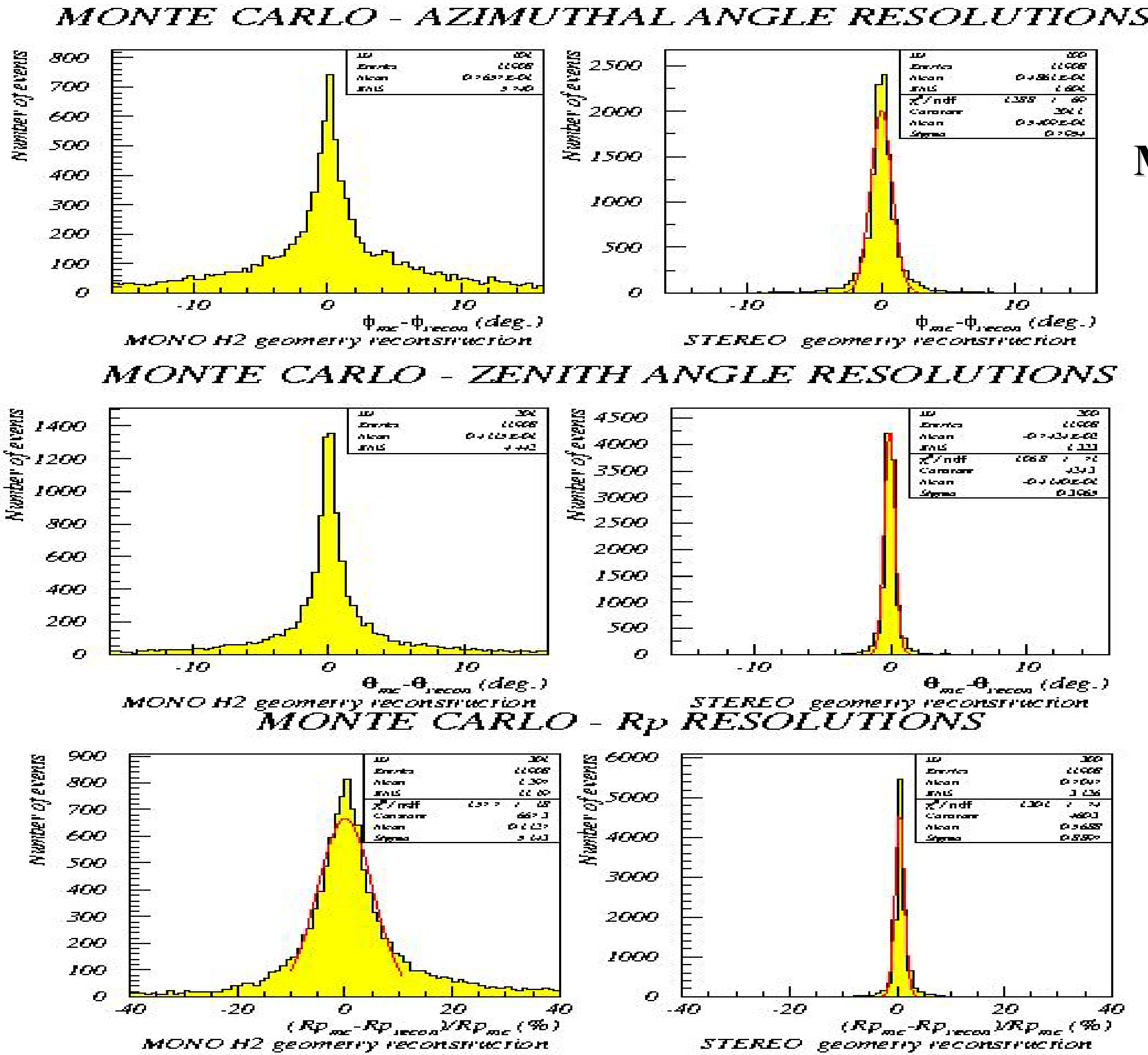


AGASA Energy Rescaled by 0.79



Stereo Resolution

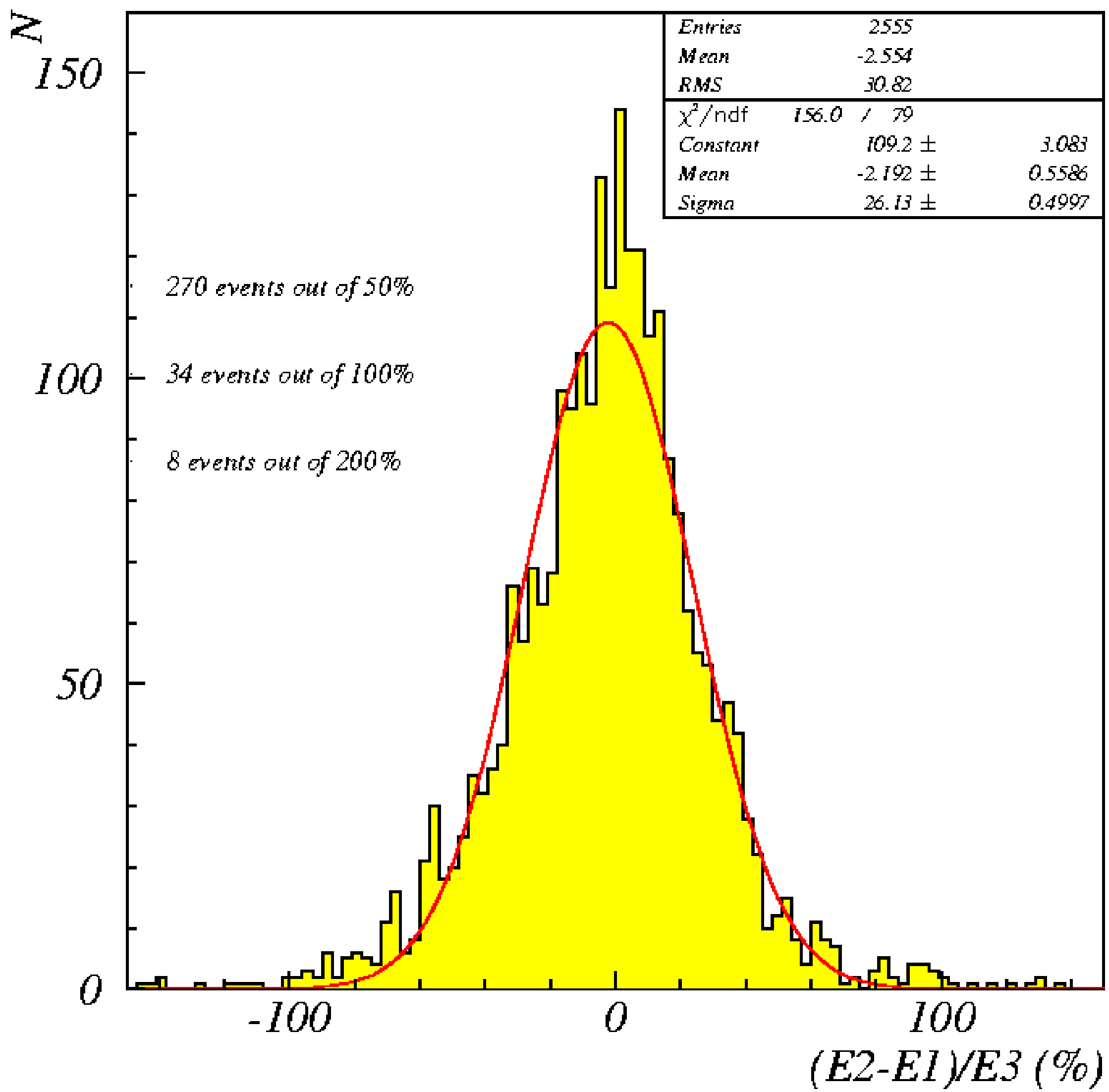
M. Seman



DATA 1 - Energy Resolution

M. Seman

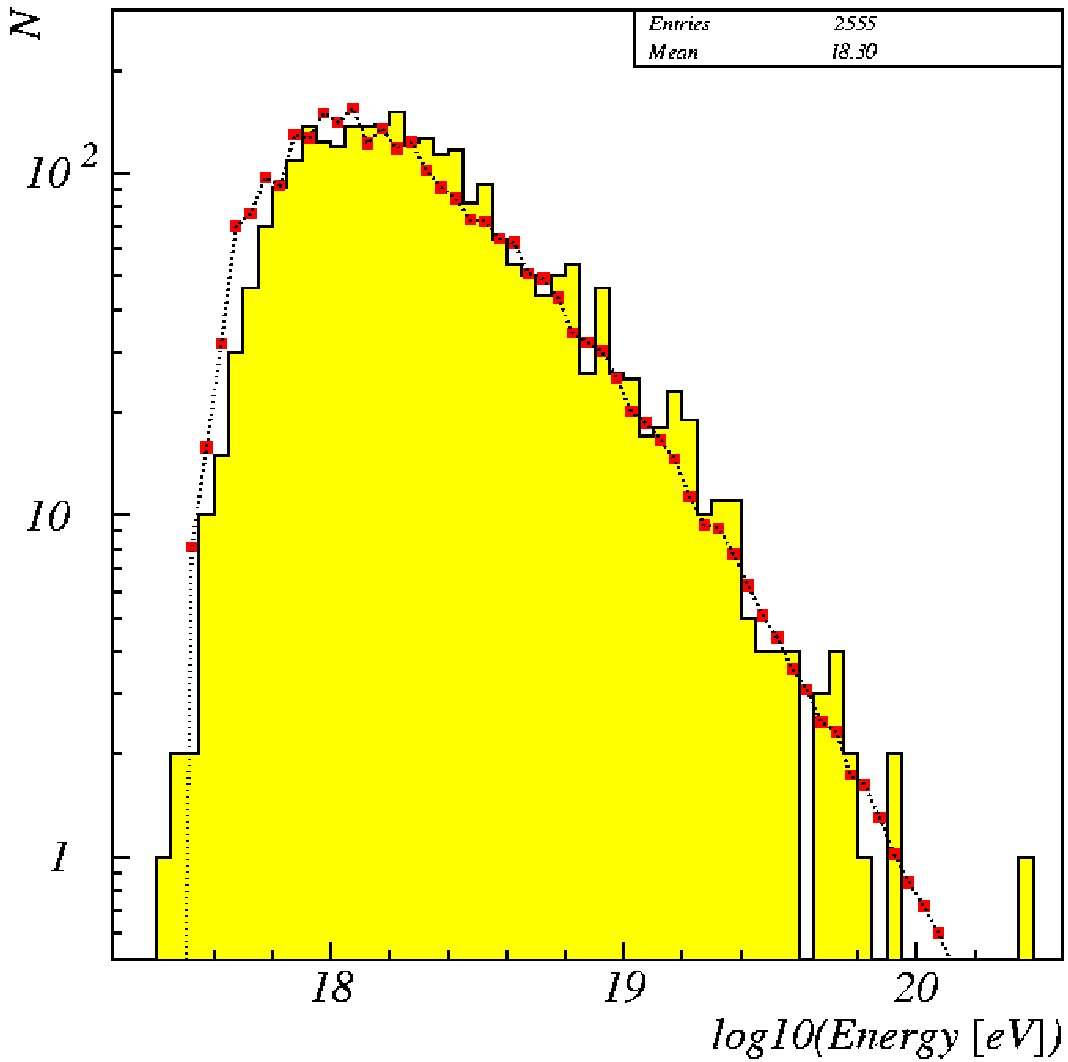
- Expected from MC :
  - RMS ~ 30%
  - σ 23%
  - Number of events in tails :
    - 262 > 50%
    - 78 > 100%
    - 26 > 200%



DATA 4 – Energy Distribution

M. Seman

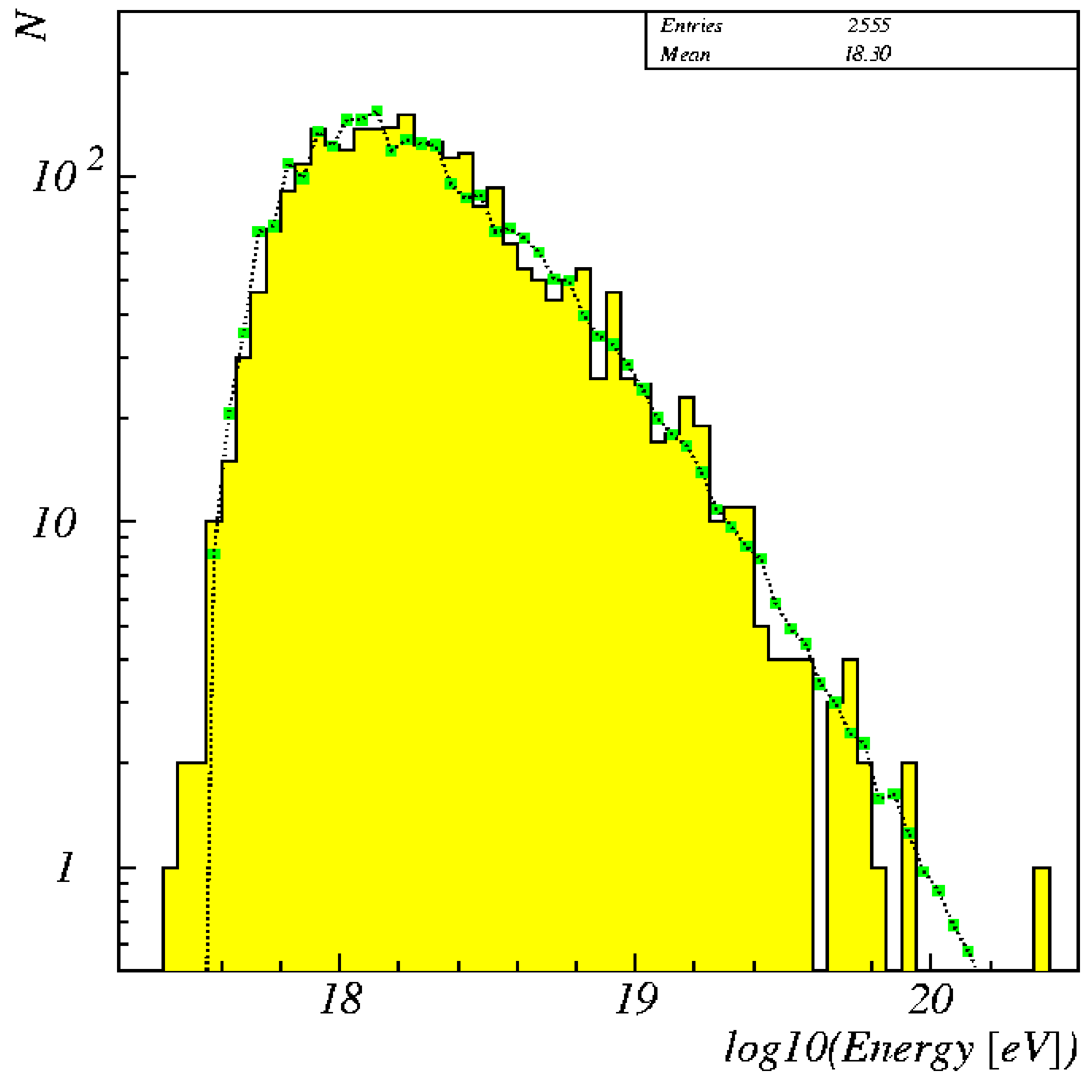
- Data compared to MC
- Current energy scale
- If photometric detector scale is considered calibrated correctly, than MC generates by ~10% less signal per energy unit



DATA 6 – Energy Distribution

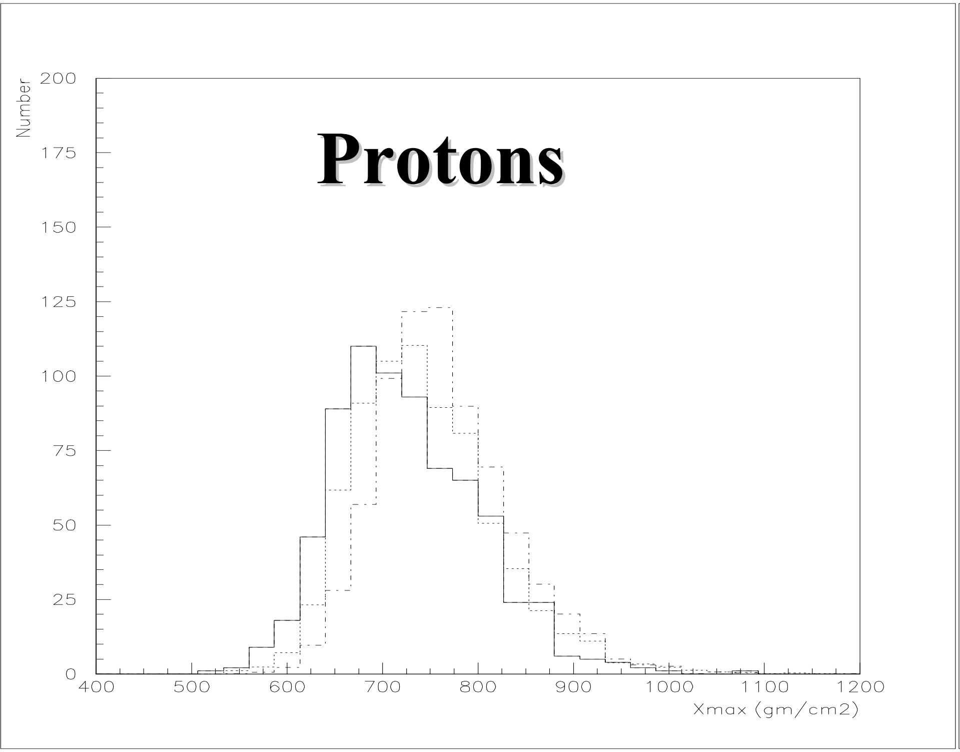
- Data compared to MC (+10%)

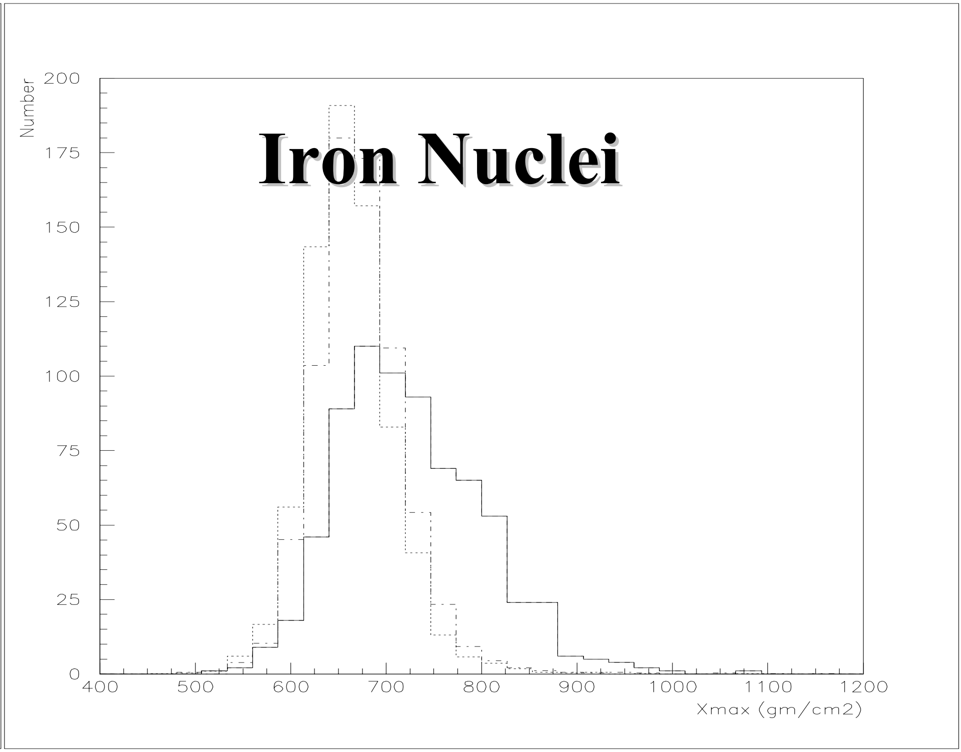
M. Seman



Composition

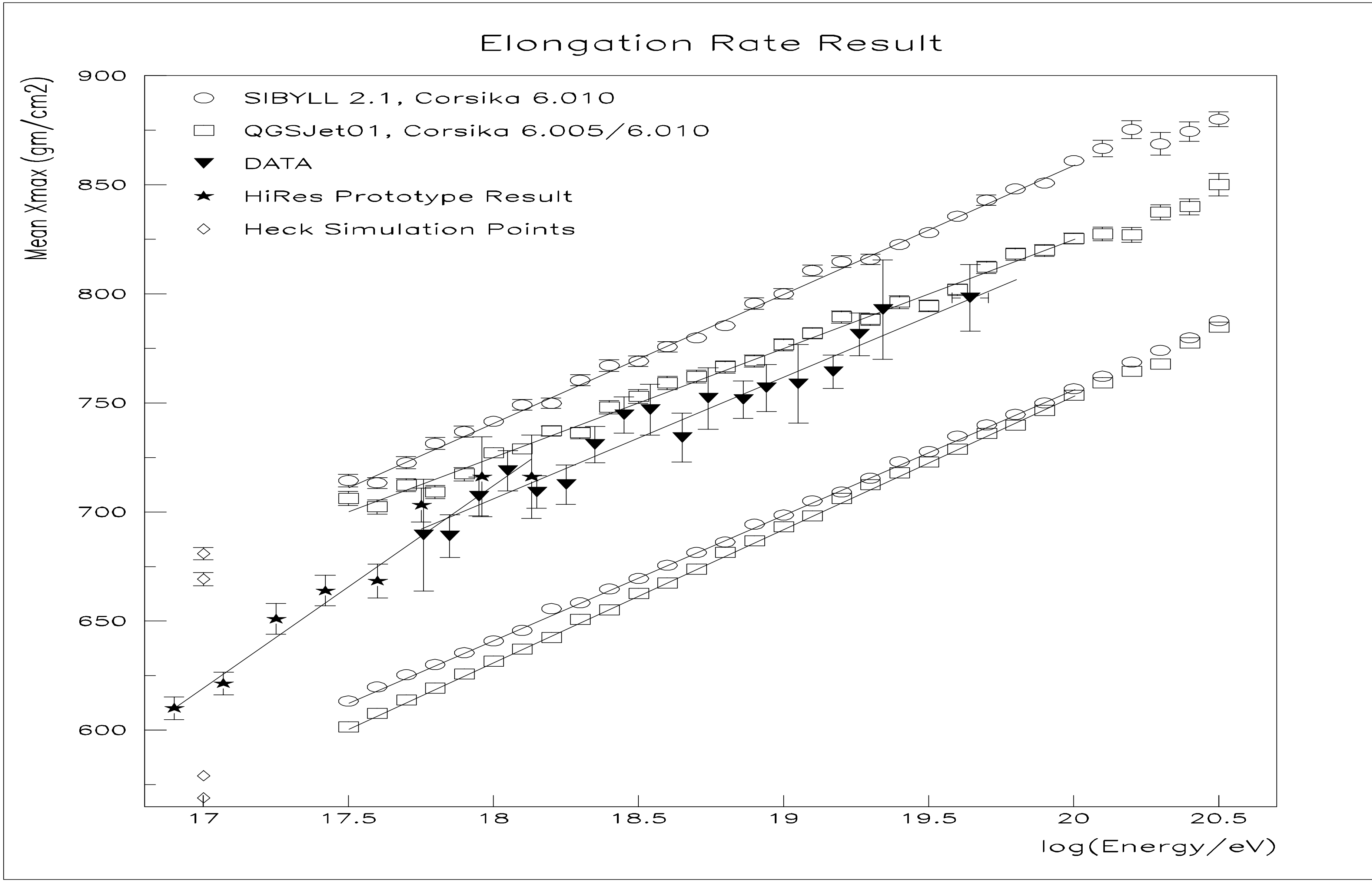
All-Energy X_{max} Distribution





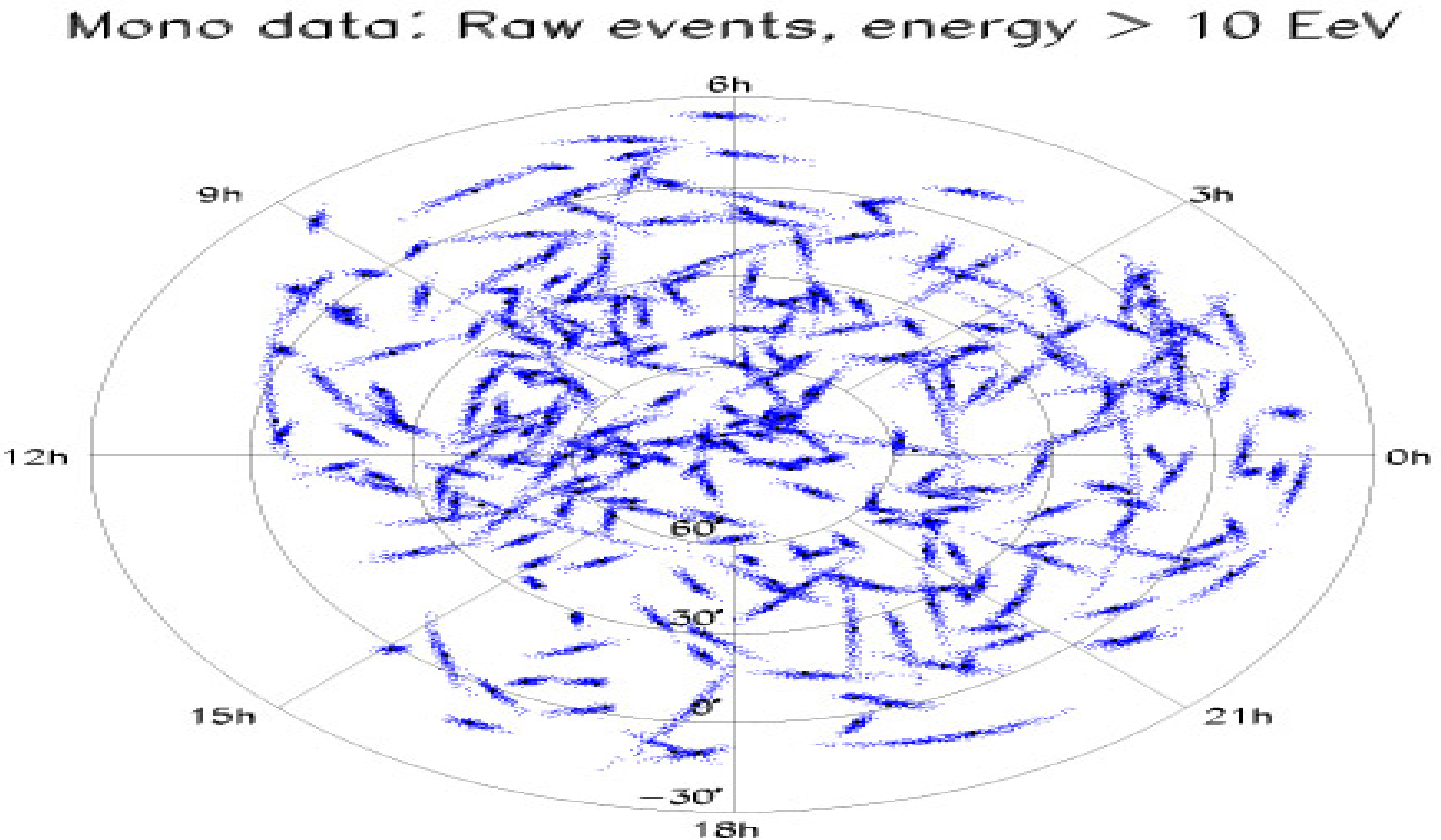
Solid Line: Data. Dotted: QGSJet.
Dot-dashed: SIBYLL

HiRes Stereo Composition Measurement

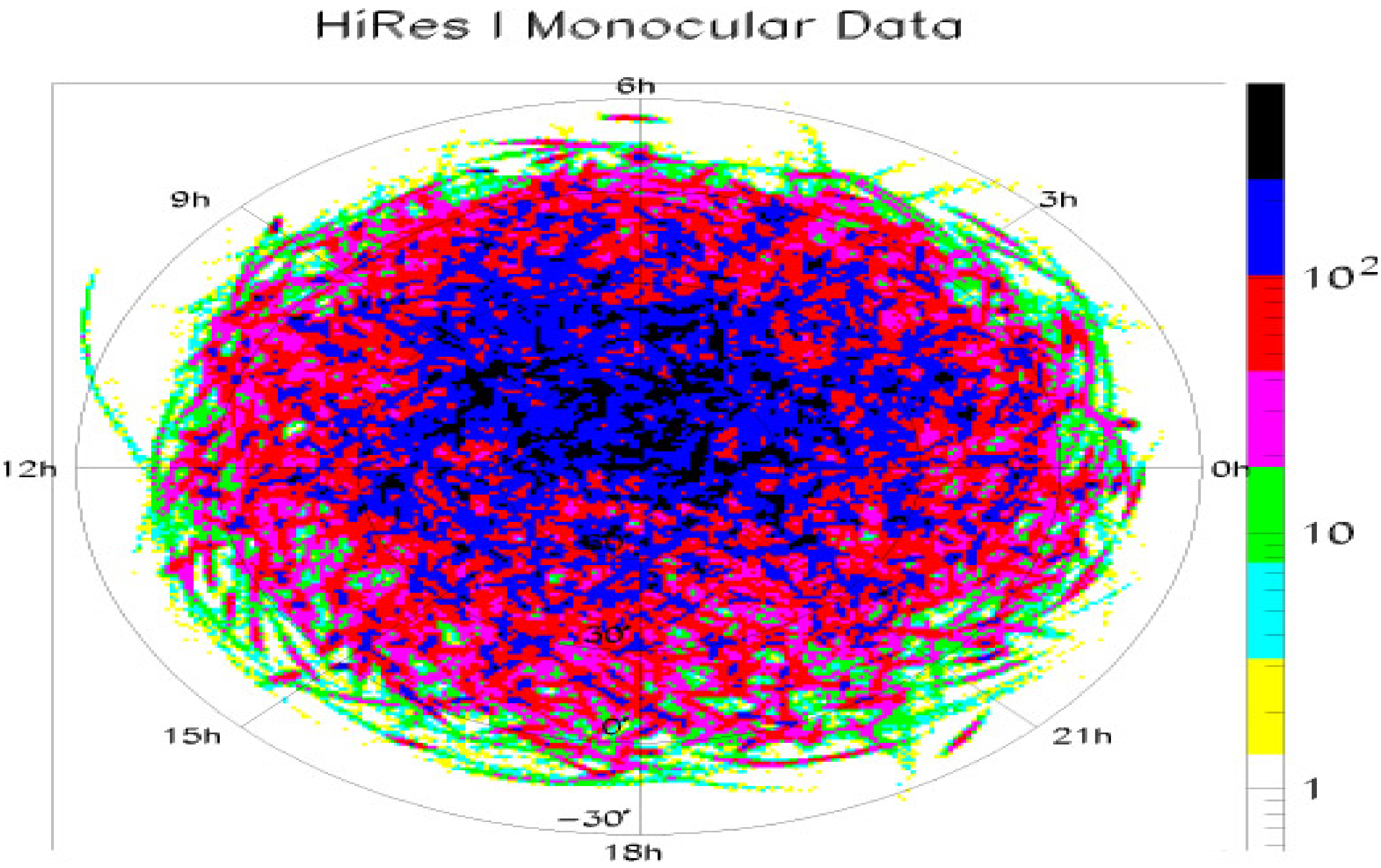


Anisotropy:

Search for Point Sources in HiRes1 Mono Data



Anisotropy All Energies



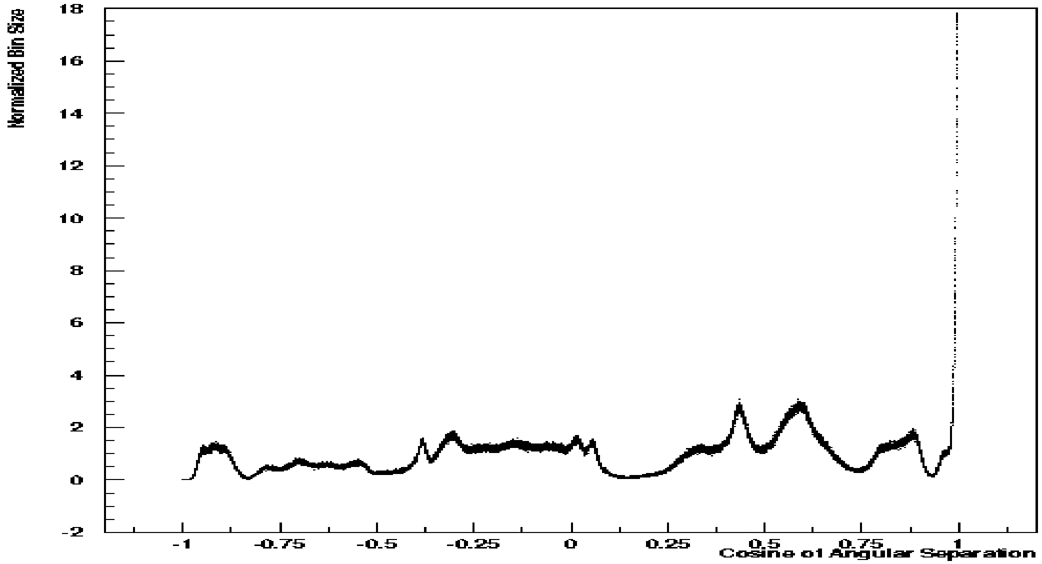
Point Source Results: HiRes1 Monocular

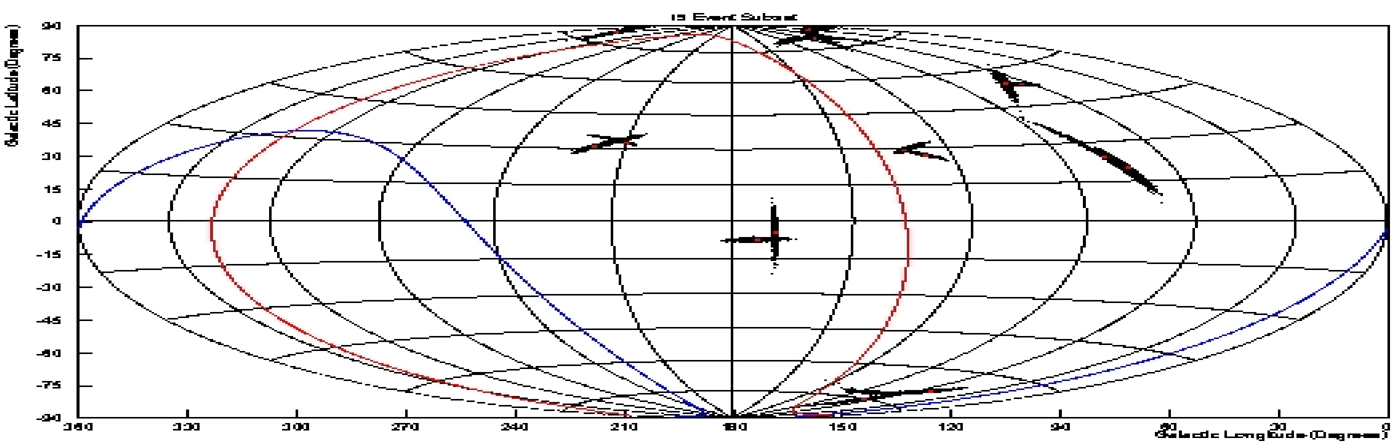
- For all energies (3,115 events above 10^{18} eV), we rule out the existence of point sources at >90% confidence level. Source strength ~ 50 events.
- For events of $E > 10^{19}$ eV, we rule out point sources at the >90% confidence level. Source strength ~ 16 events.

Anisotropy
Autocorrelation

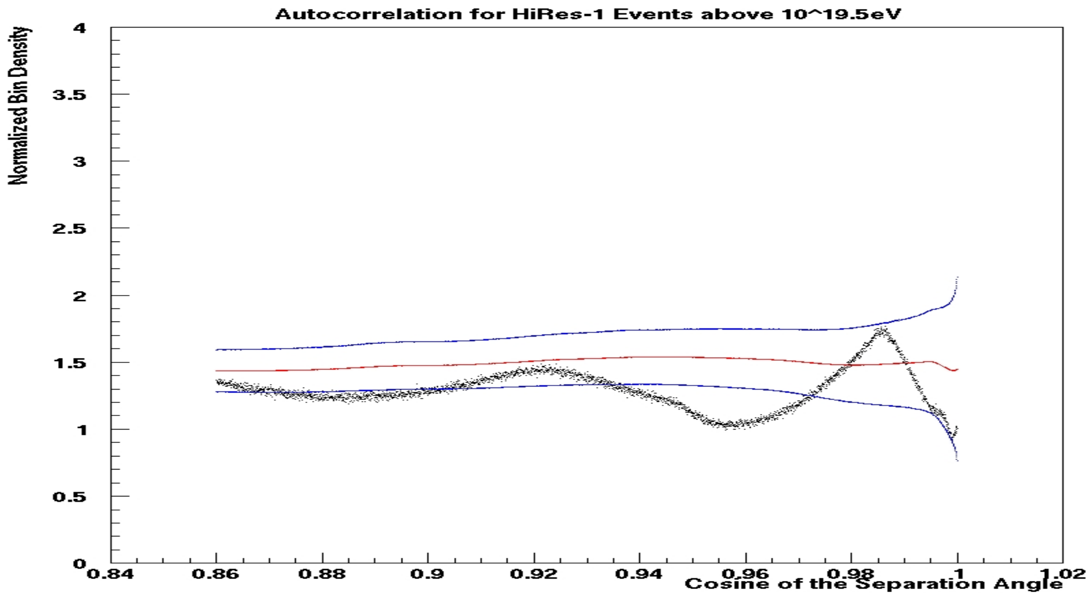
- Autocorrelation is the distribution of space angles between pairs of events
  - An autocorrelation function is created by doing the following:
    - Take any pair of events
    - Calculate the cosine of the space angle between the events
    - Enter into a histogram of the cosine of the space angle
    - Repeat until every possible pair in the event sample has been considered
- If we have point sources, we will see enhancements in our autocorrelation function at small space angles.

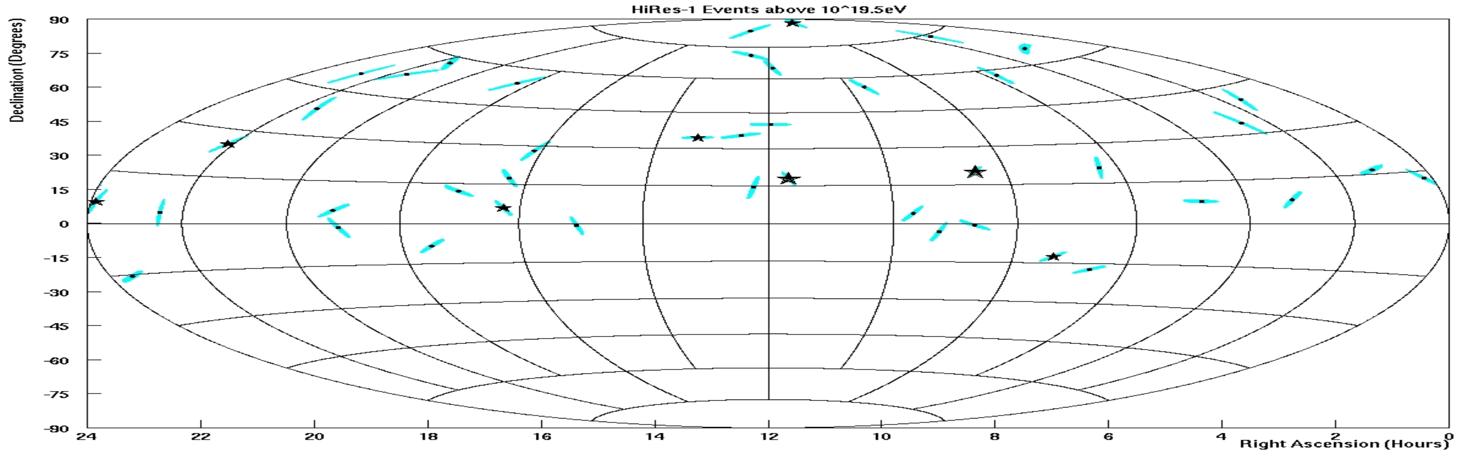
What would an autocorrelation function from a sample resulting from point sources look like?





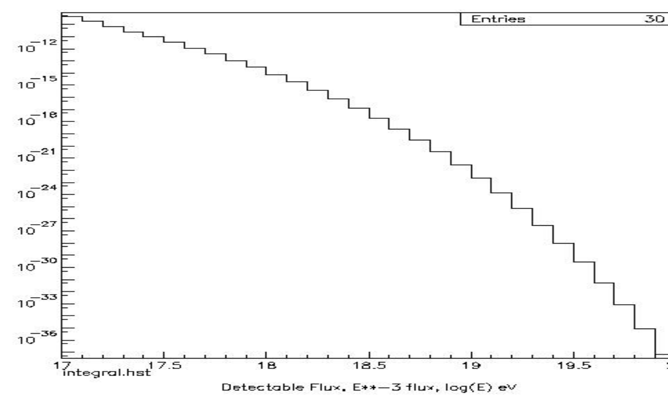
The Autocorrelation function for HiRes-1 events above $10^{19.5}$eV



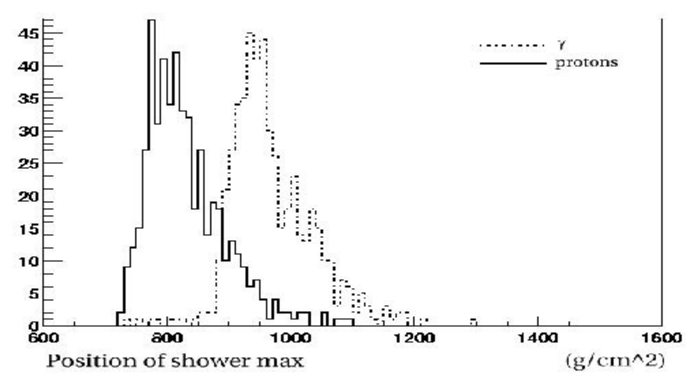


Searches for CR Neutrinos and Gamma Rays

- Neutrinos = upward-going events
  - $E_{min} = 2x10^{17}$ eV.
  - Earth is opaque, even for tau neutrinos. For regeneration need $E_{min} \sim 10^{16}$ eV.
  - Factor of 500 away from seeing neutrinos (if same flux as charged CRs).



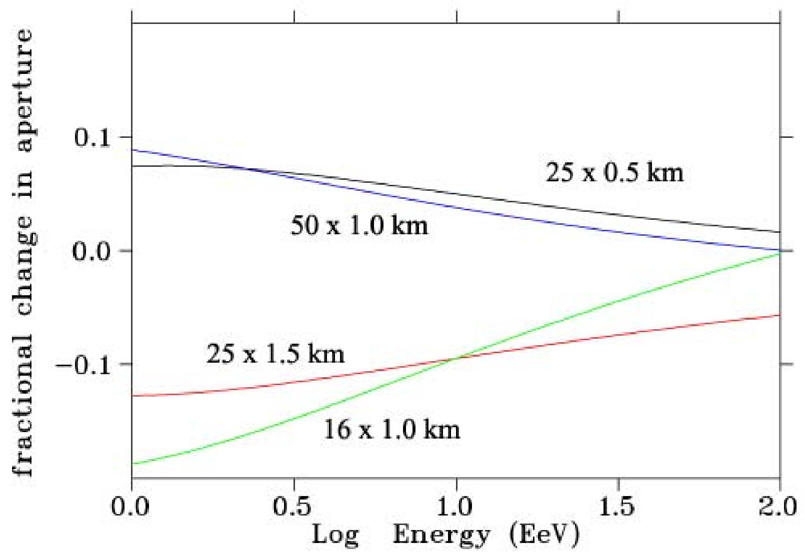
- Gamma rays: showers develop late due to LPM effect.



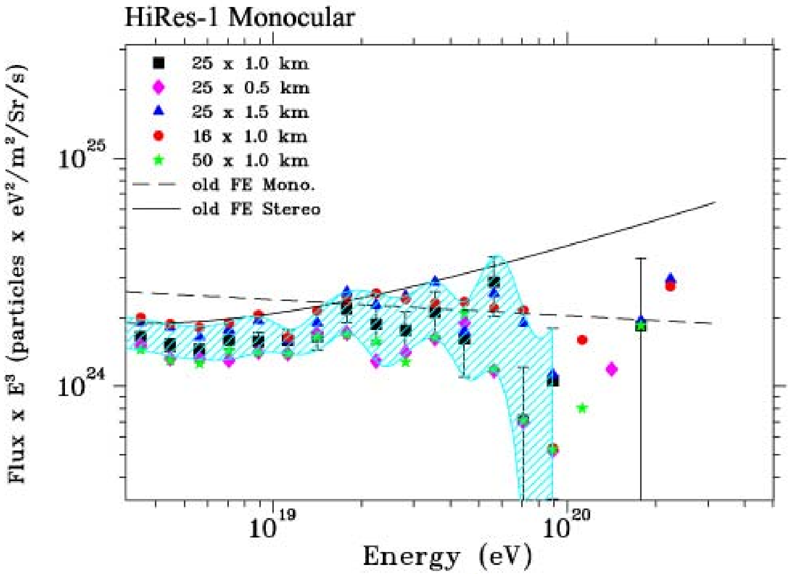
Conclusions

- The two HiRes detectors continue to collect data.
- Measured flux agrees with Fly's Eye experiment.
- We see spectral features.
- Our monocular spectra supports the existence of the GZK cutoff
- Need more statistics and study of systematics

HiRes March 2002



HiRes March 2002



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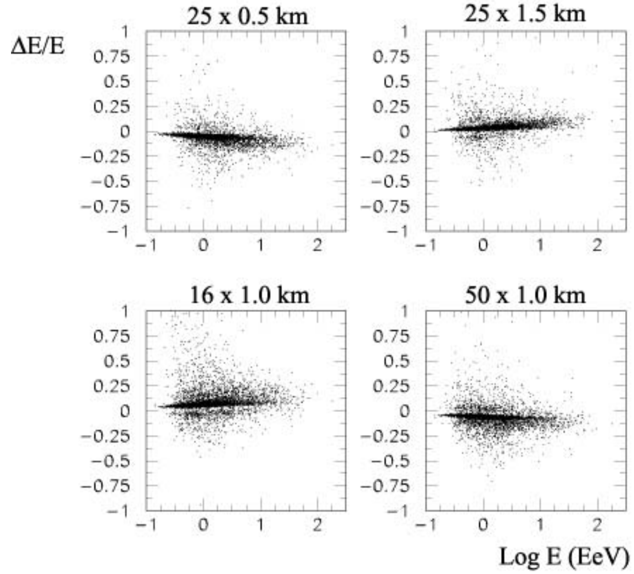

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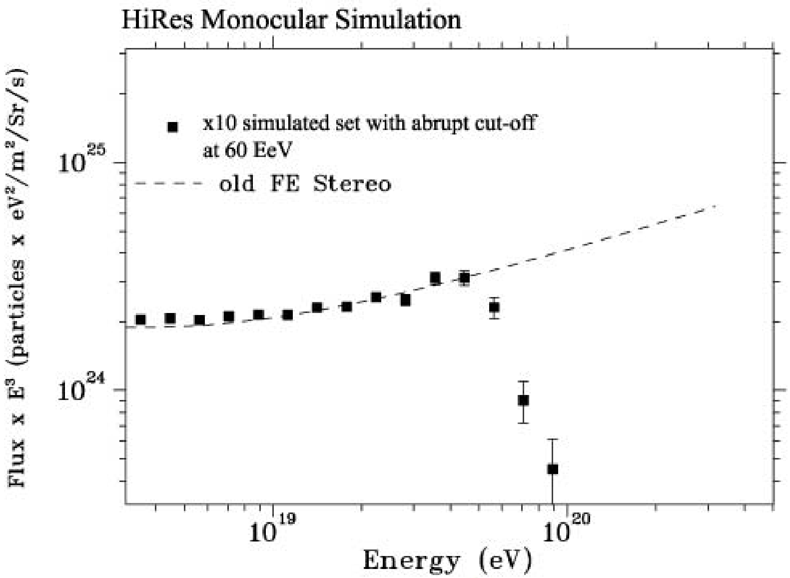

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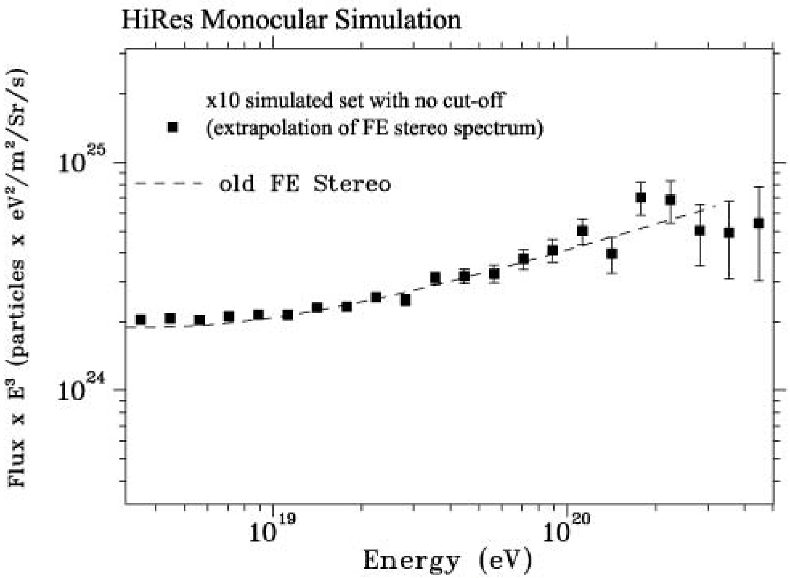

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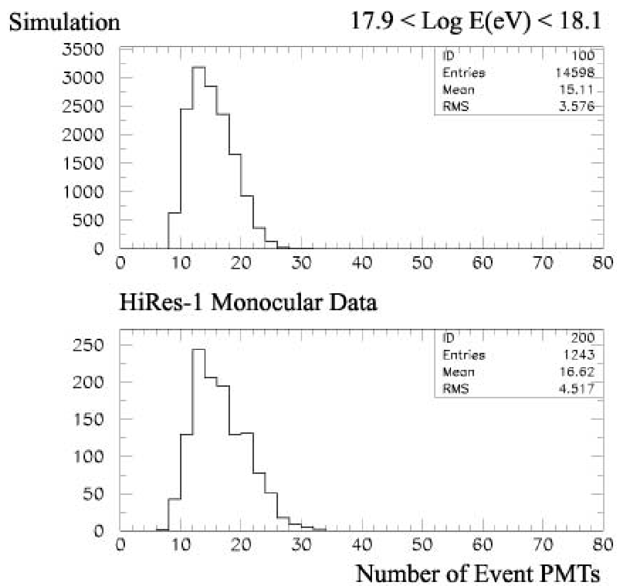

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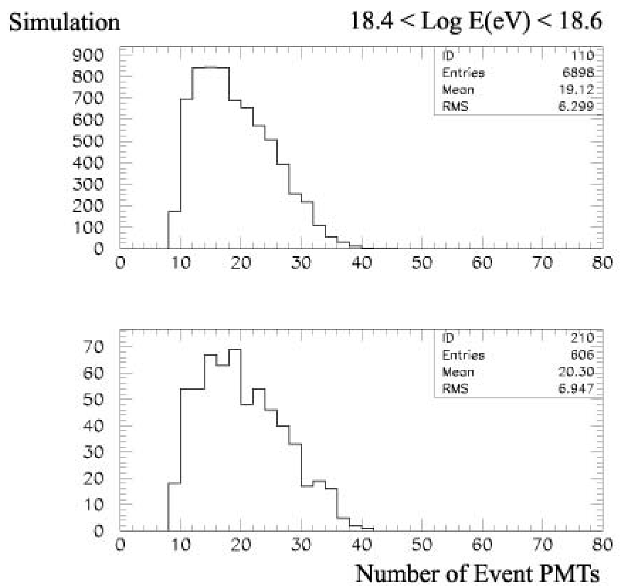

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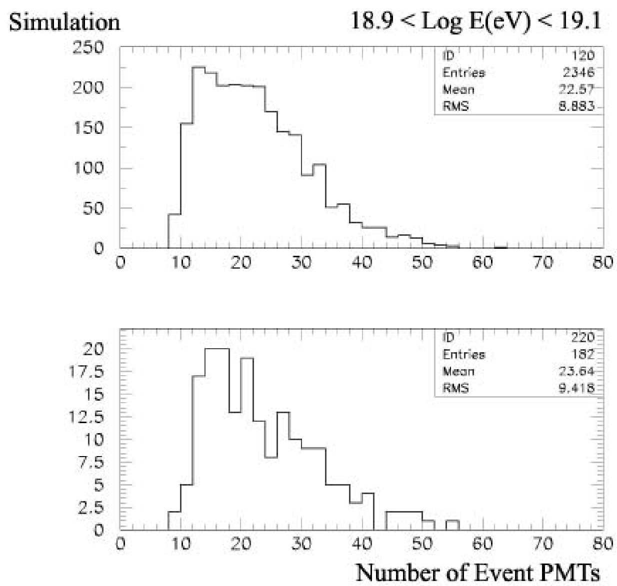

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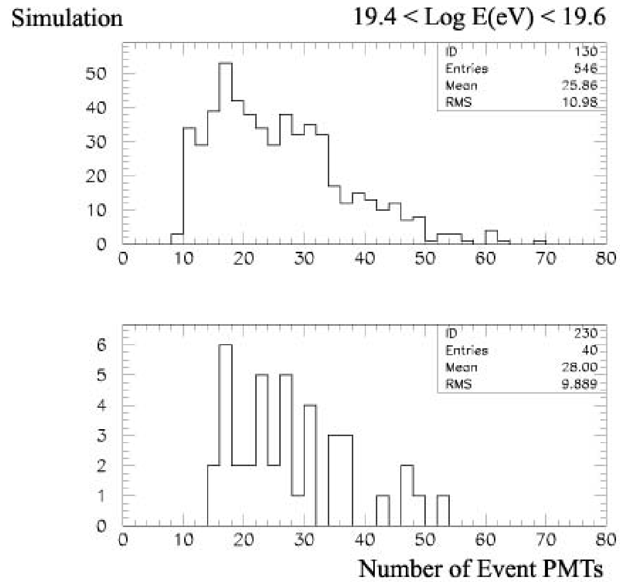

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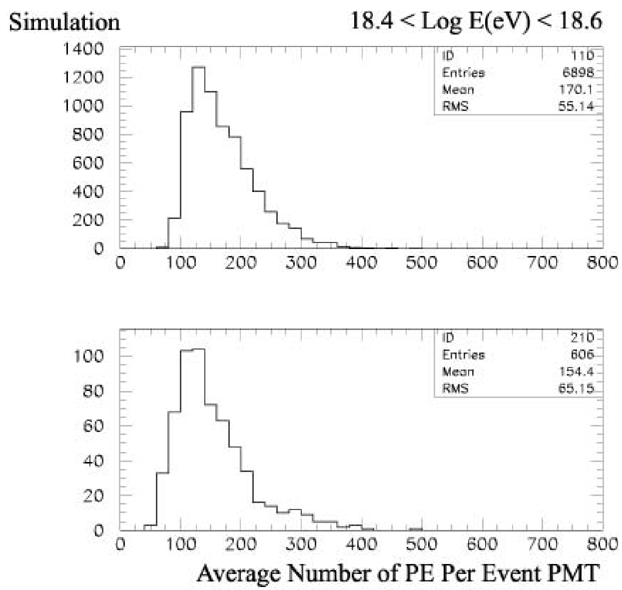

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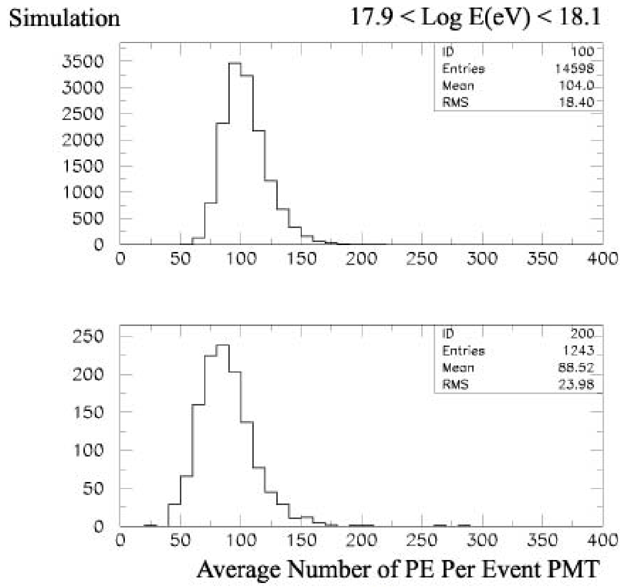

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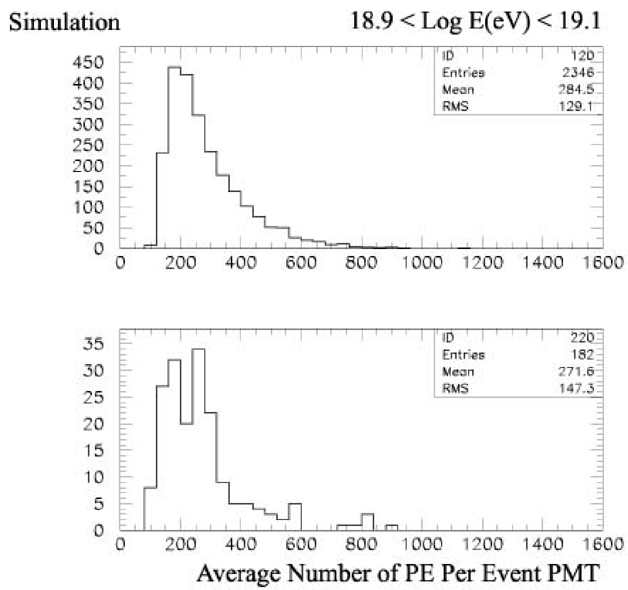

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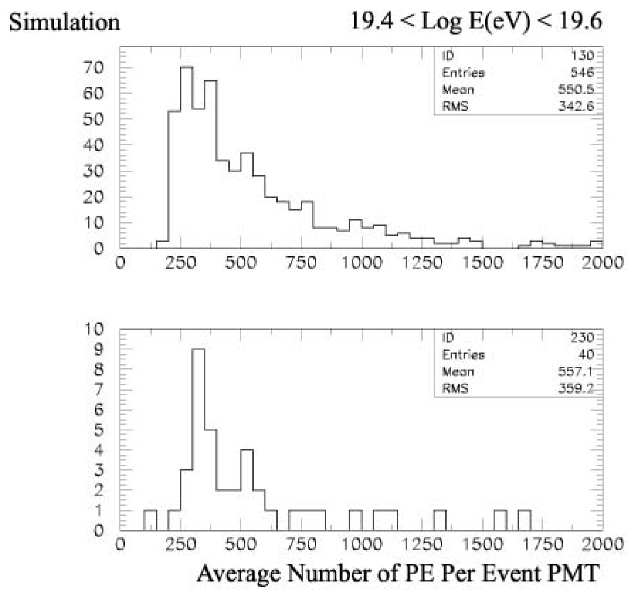

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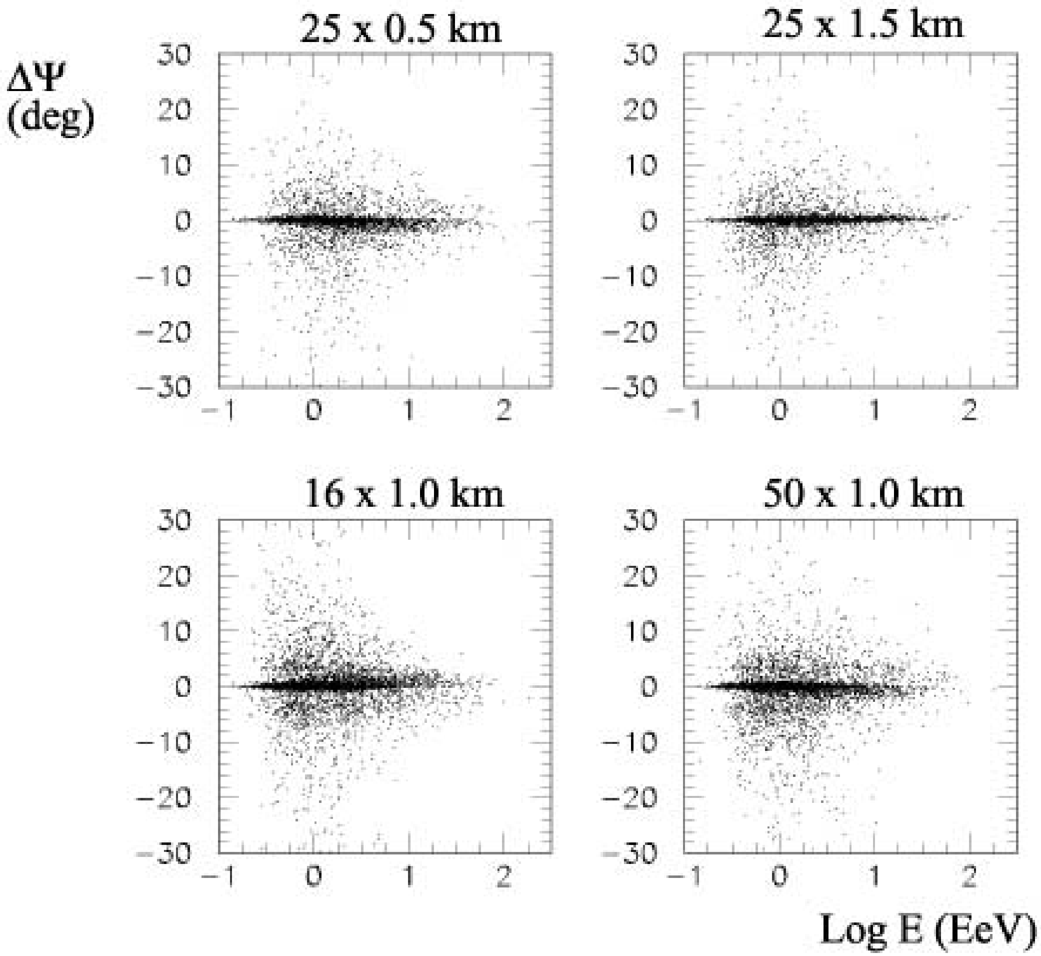

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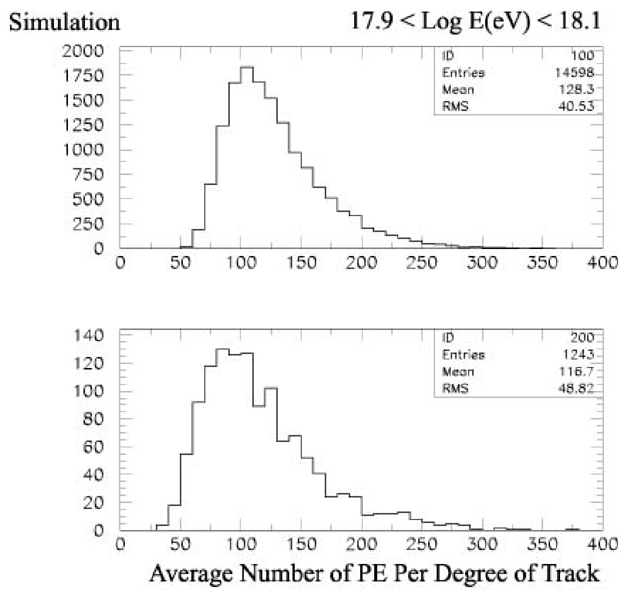

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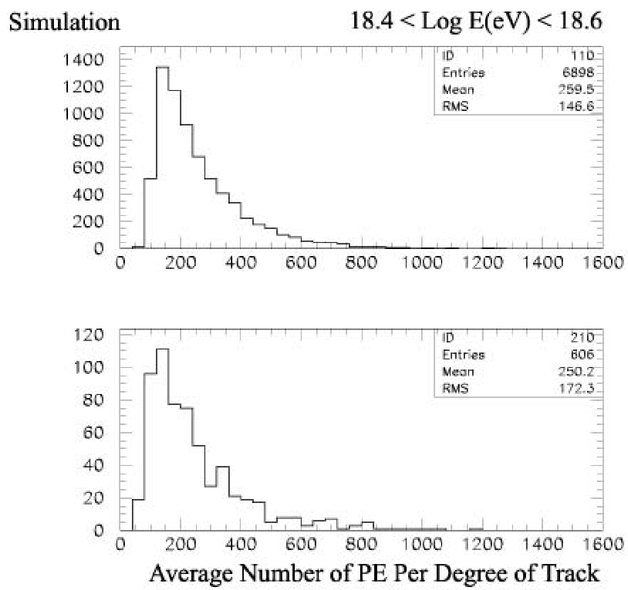

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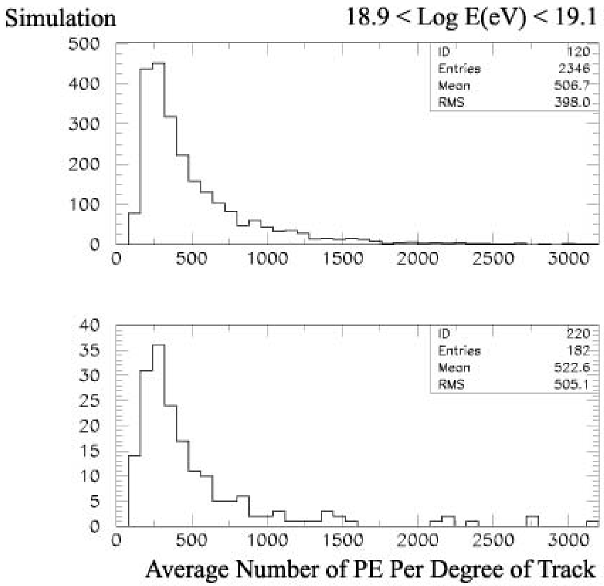

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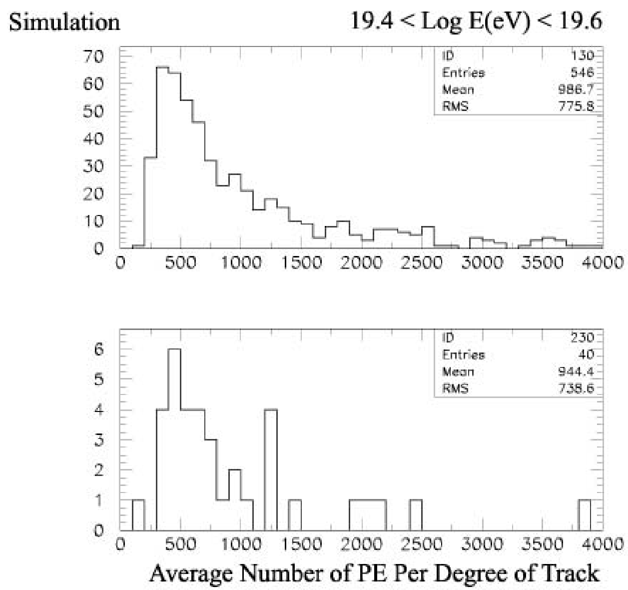

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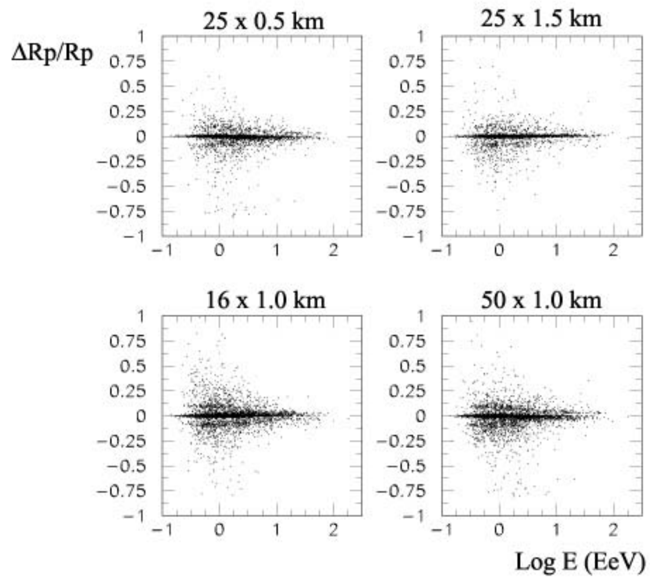

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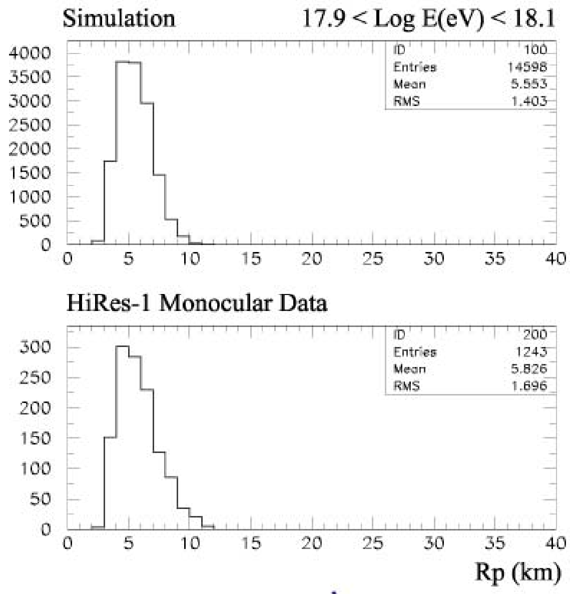

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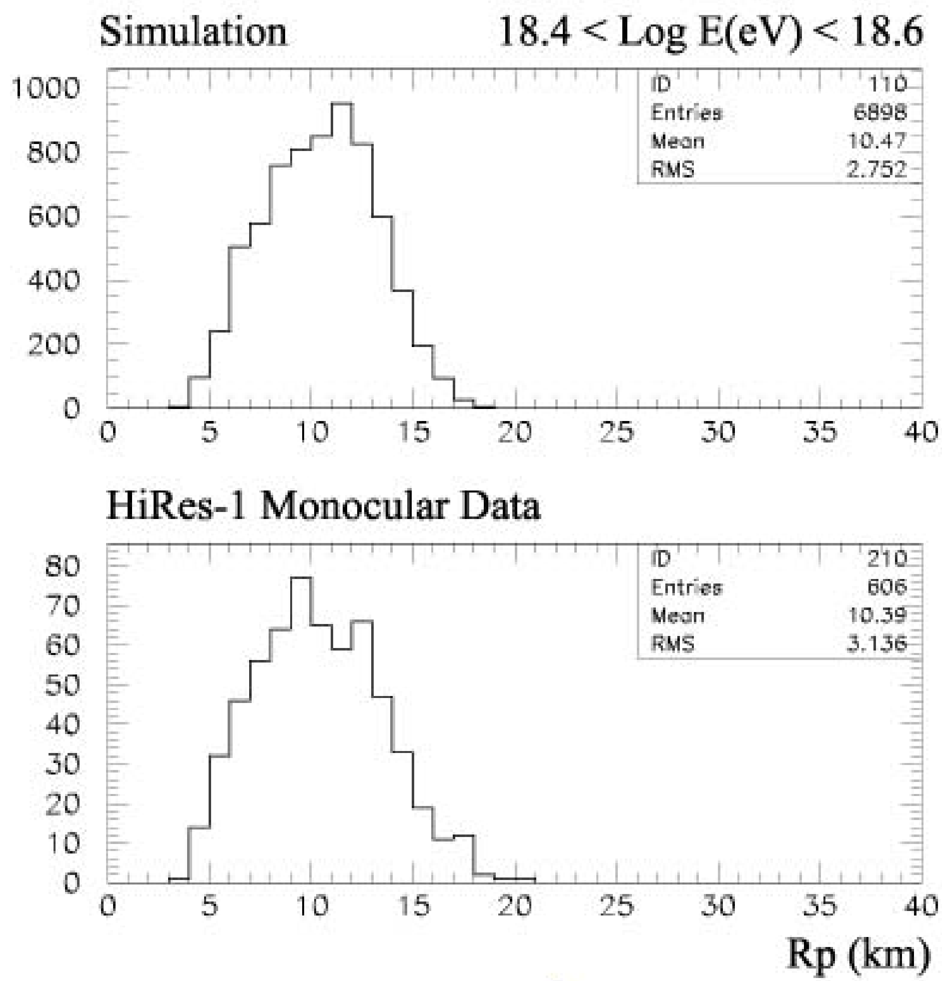

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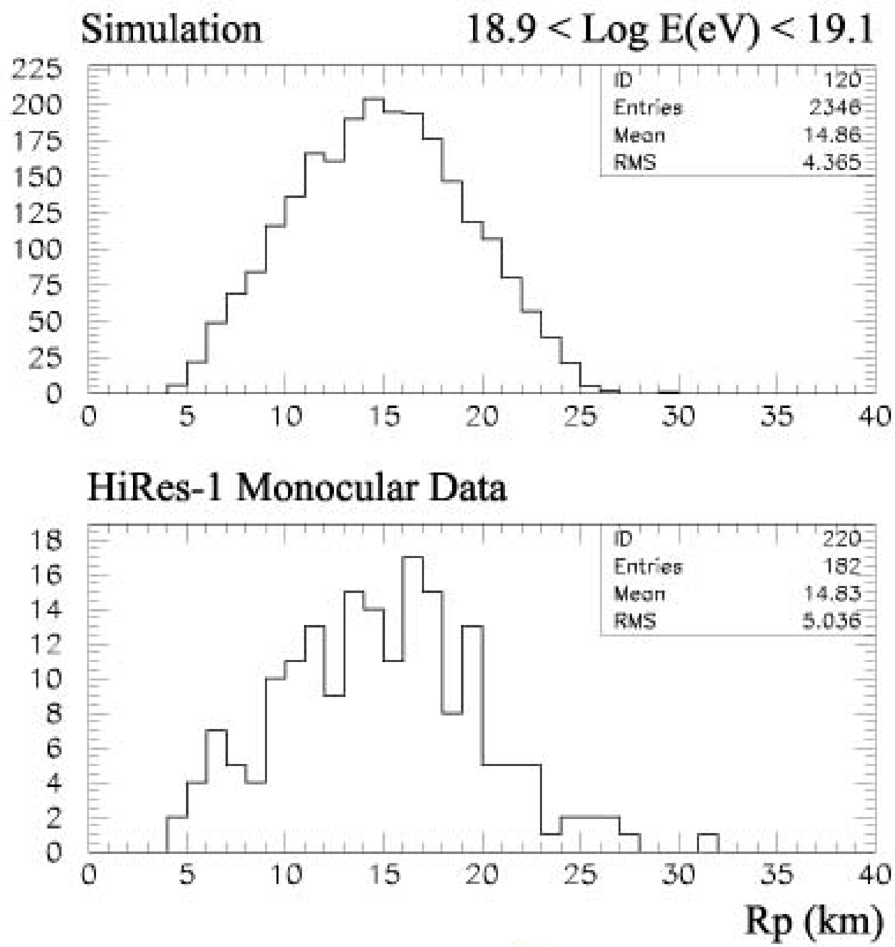
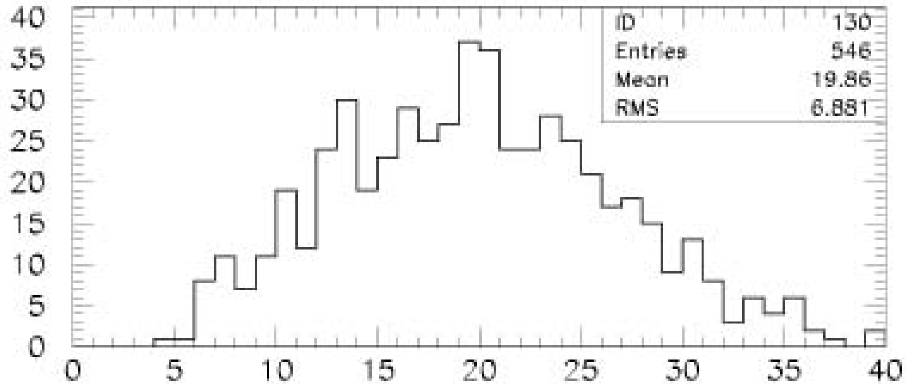
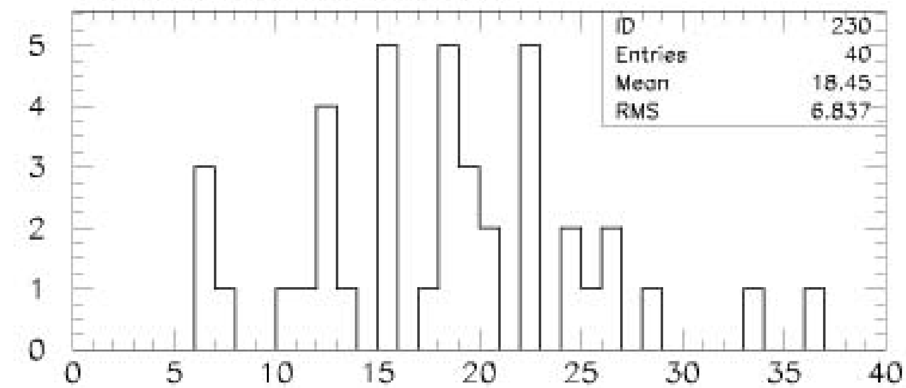


HiRes March 2002

Simulation 19.4 < Log E(eV) < 19.6

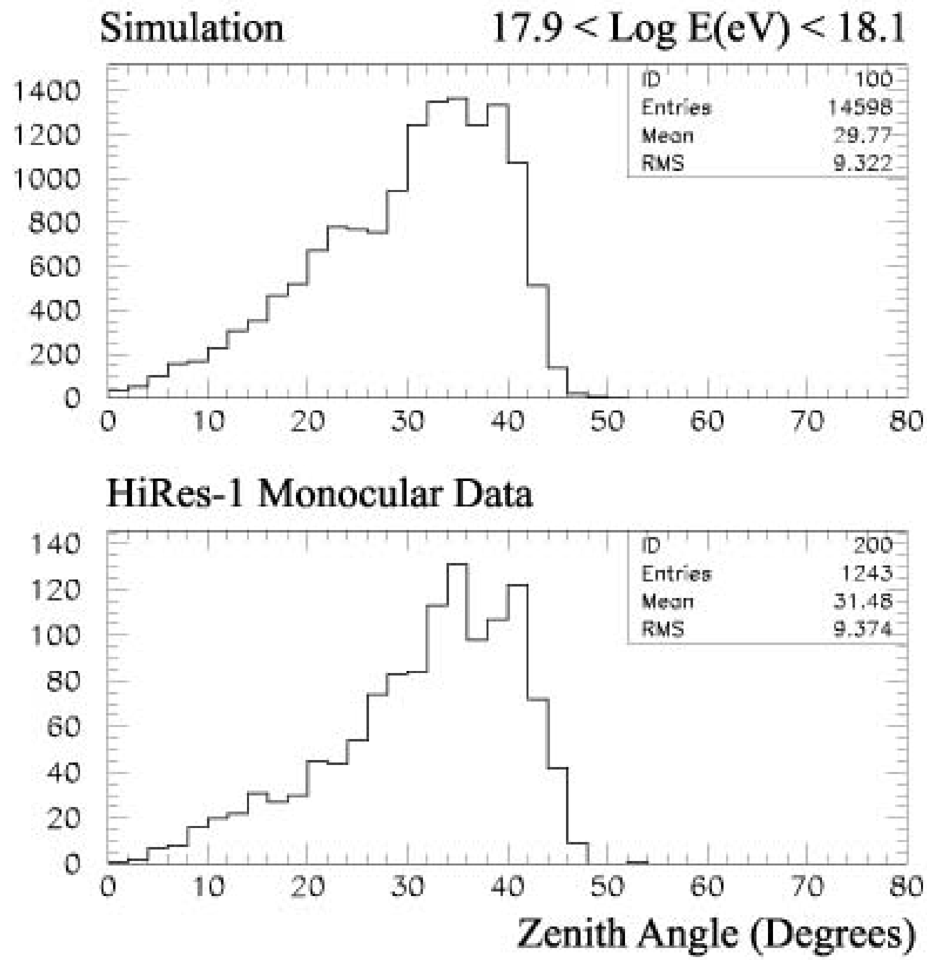


HiRes-1 Monocular Data



Rp (km)

HiRes March 2002



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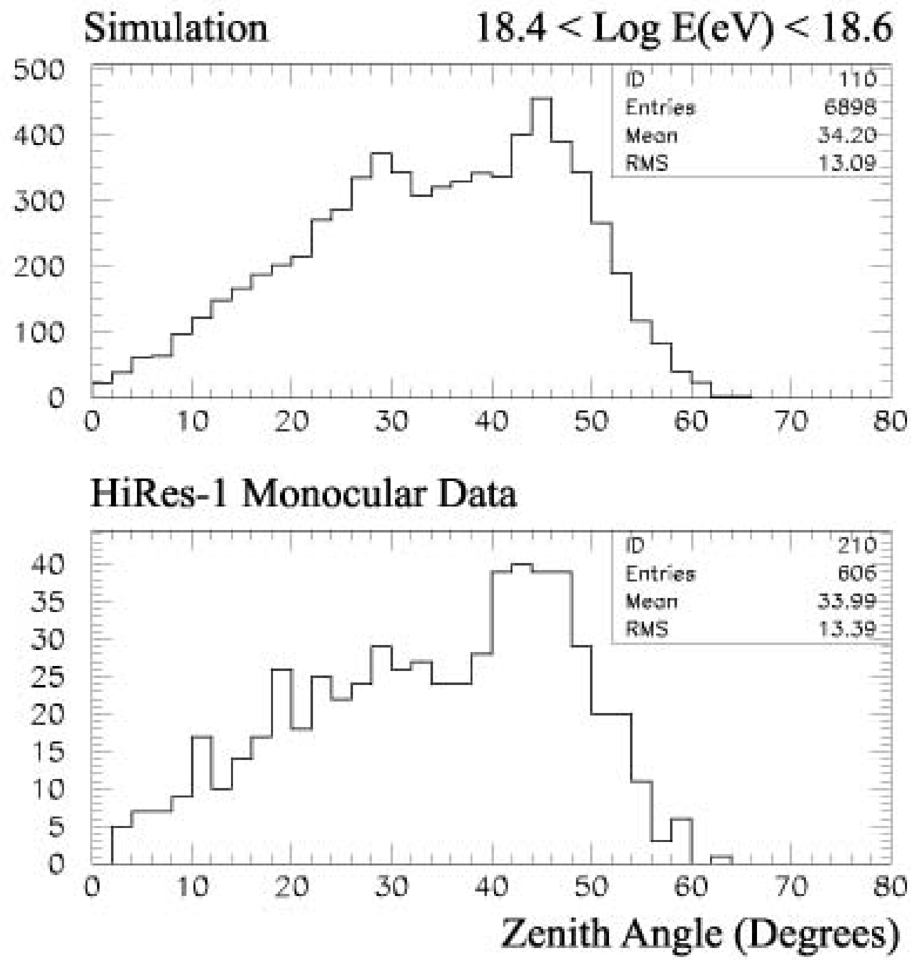

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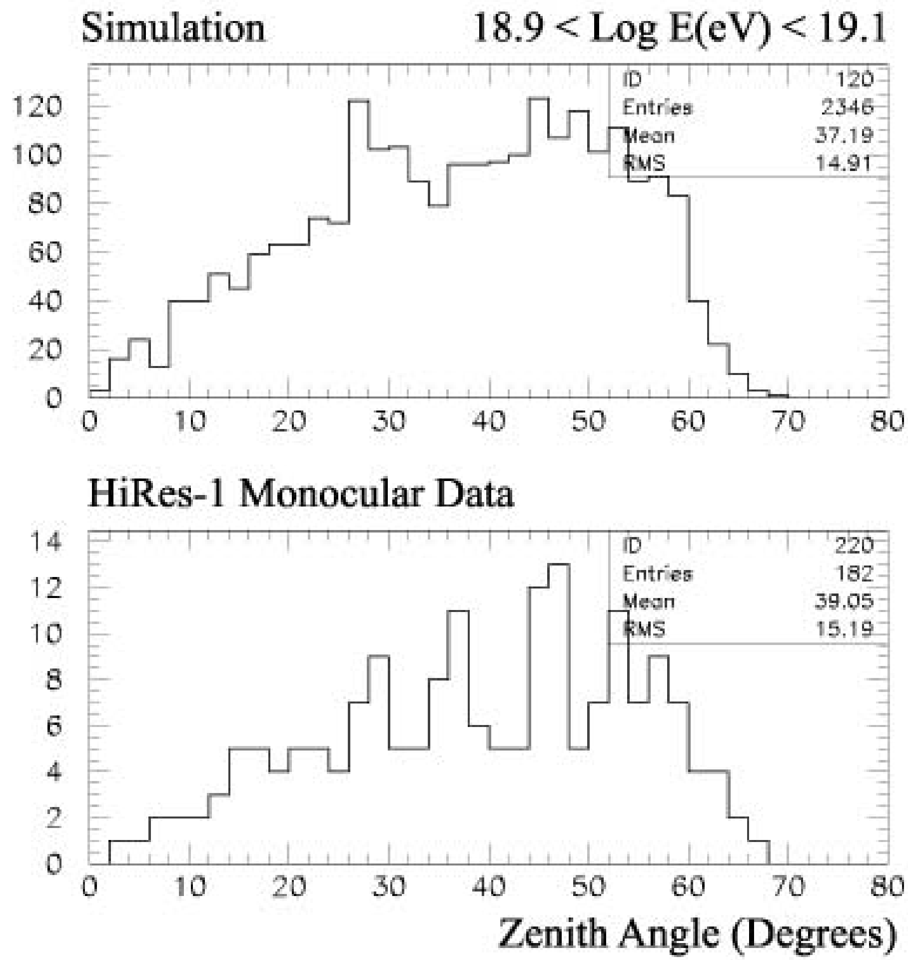

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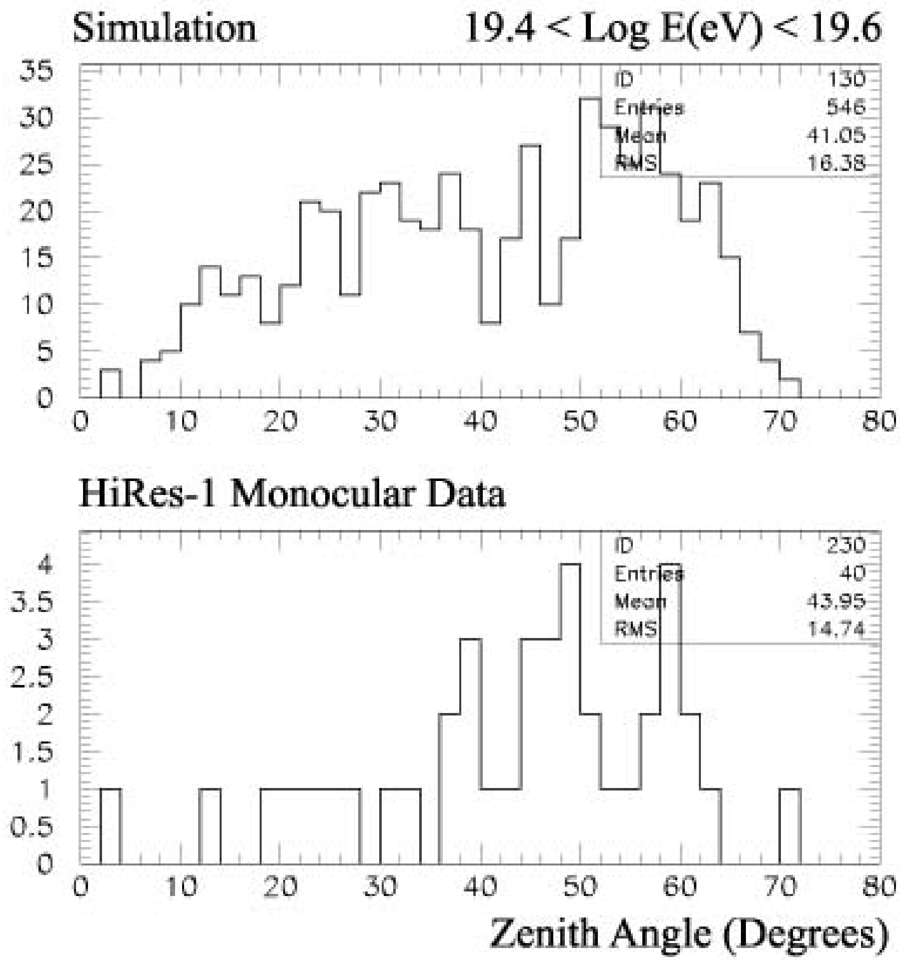

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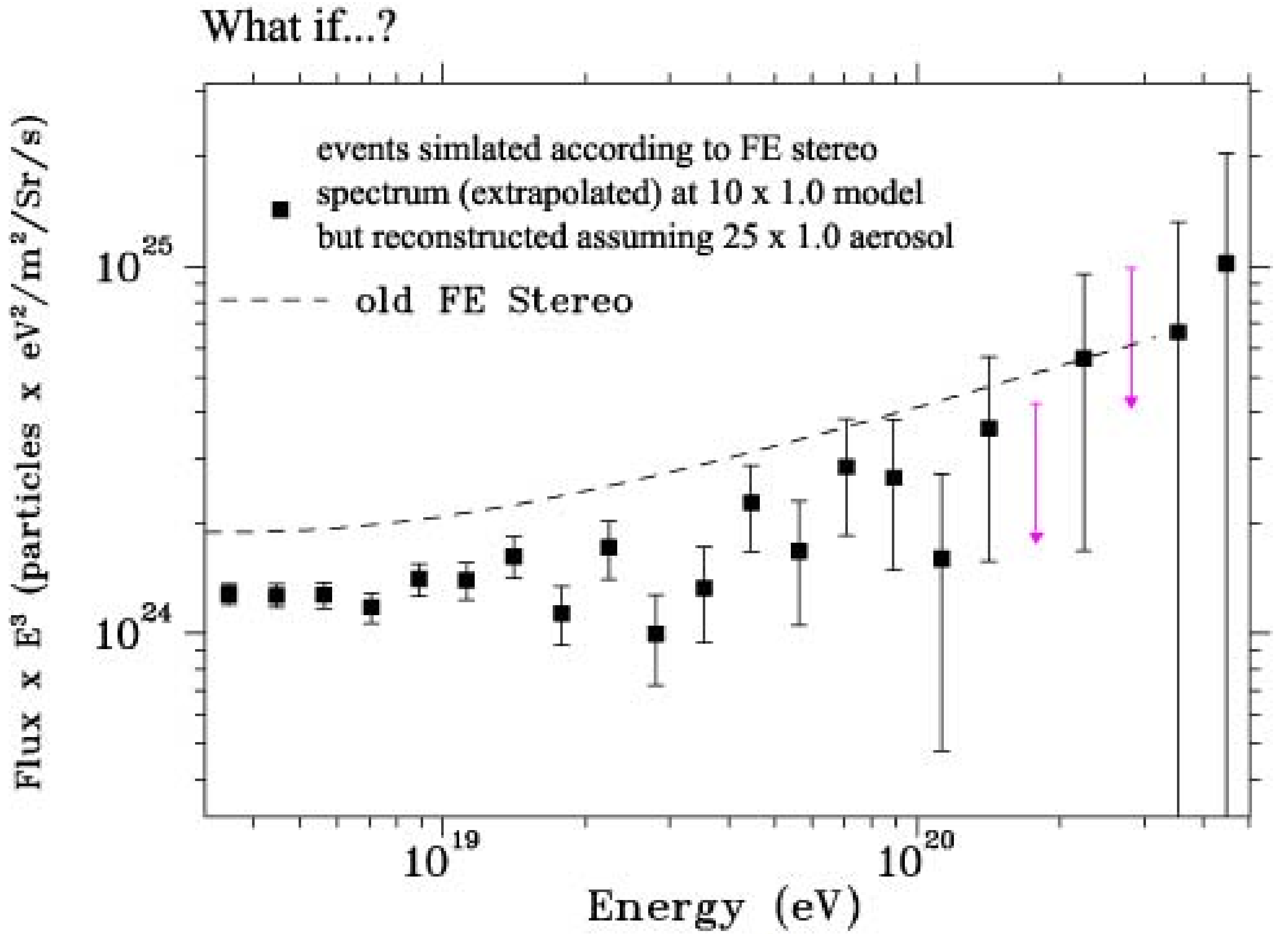

HiRes