Ultra High Energy Cosmic Rays

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Experimental Gravitation & Astrophysics

Outline

- Cosmic Rays
  - What are UHECR?
- GZK Effect
  - Why study UHECR?
- Pillars of Research
  - Energy Spectrum
  - Composition
  - Source/Arrival Direction

Cosmic Rays

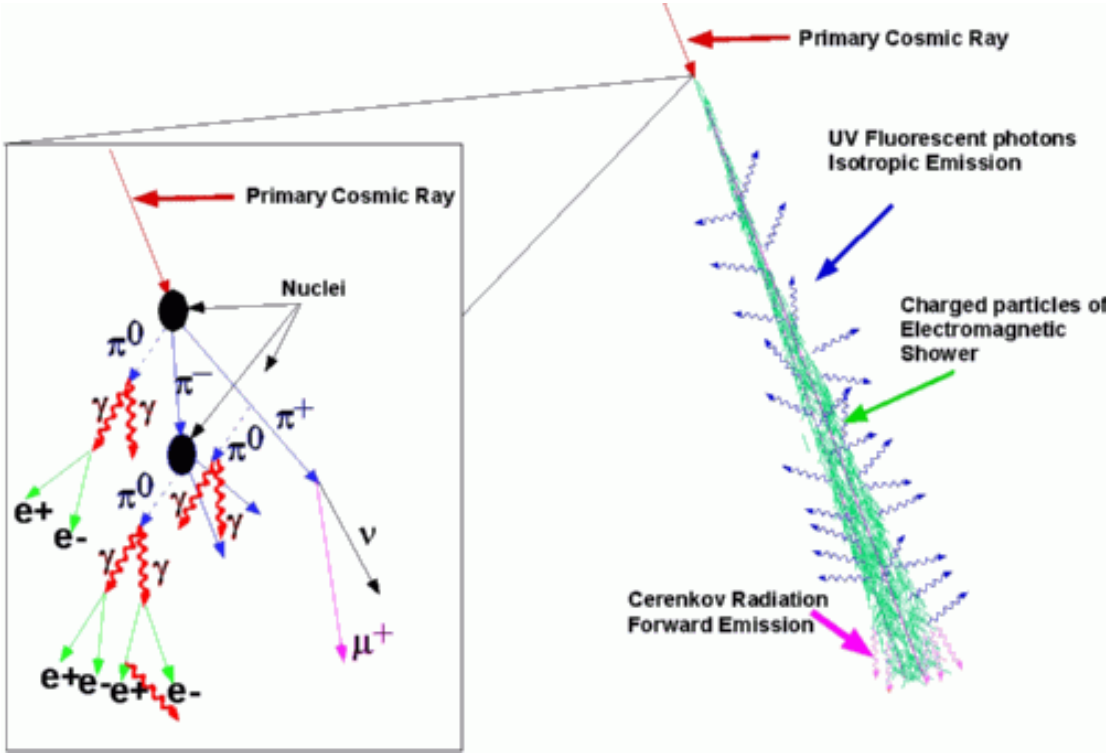
- Victor Hess –1912
- Elementary particles: protons, nuclei, photons, etc.
- "Cosmic Rays": Particles which bombard Earth.
- Roughly two cosmic rays through a square foot every second.

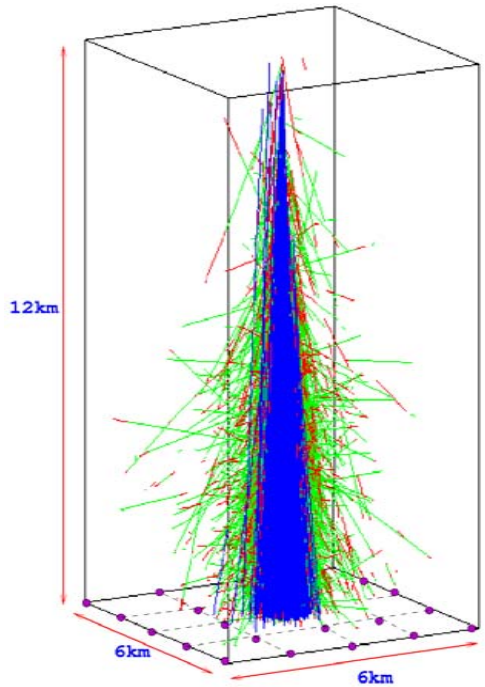
Ultra High Energy Cosmic Rays

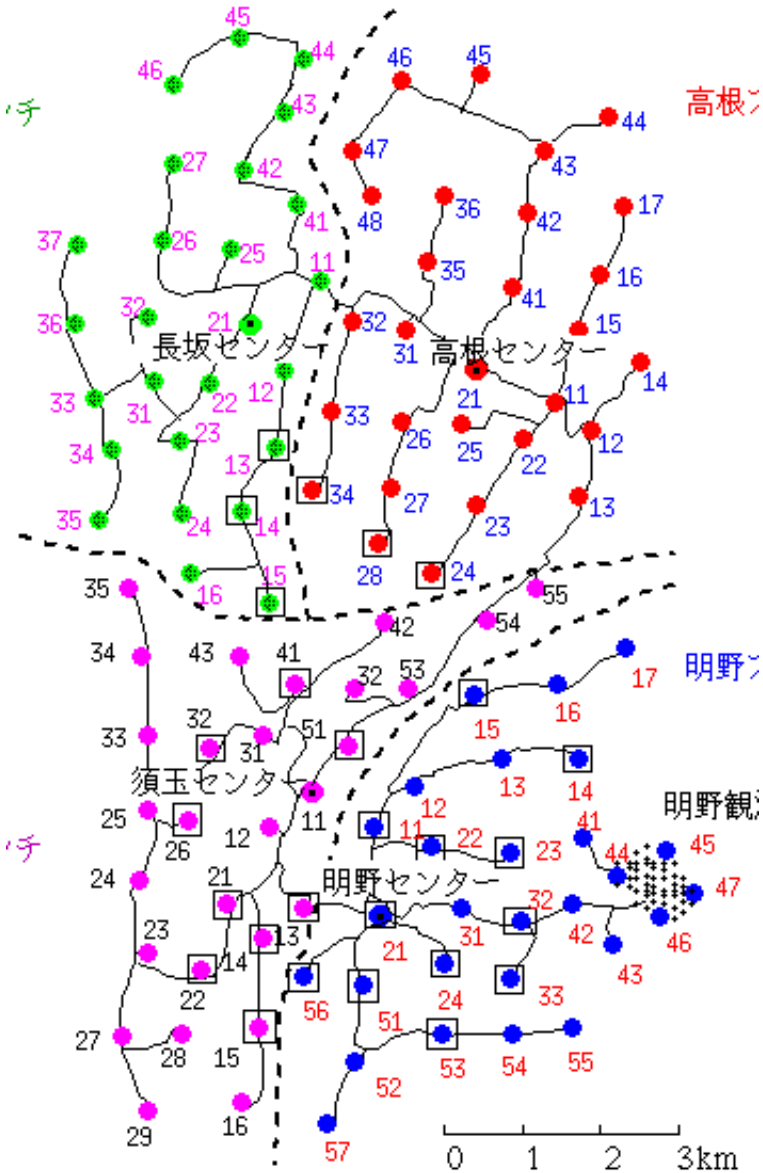
- A single UHECR has energy from 10^{17} – 10^{20} eV. LHC will only be able to accelerate protons to 10^{12} eV.
- UHECR have energy of the order of a thrown baseball.
- UHECR are rare: occur at a flux of ~1/km^2/year

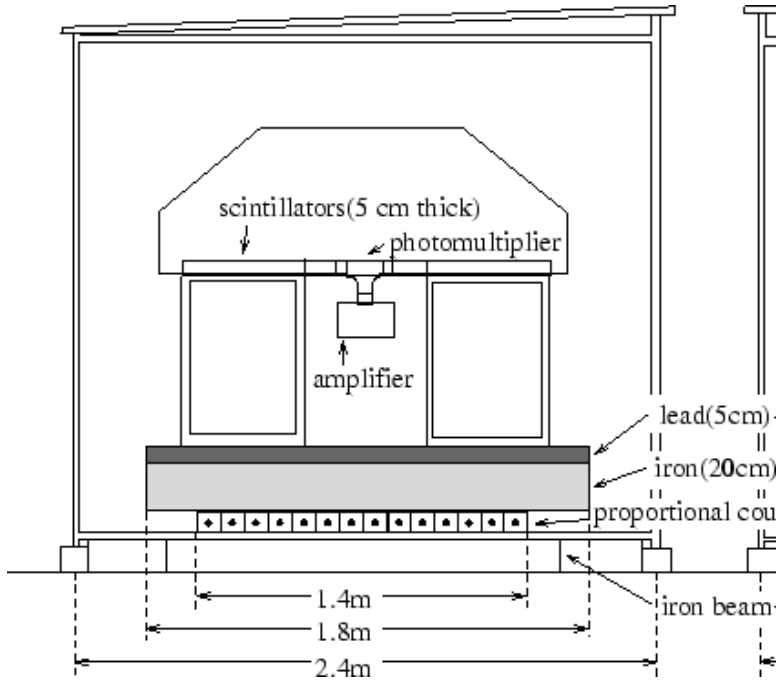
Cosmic Ray Showers

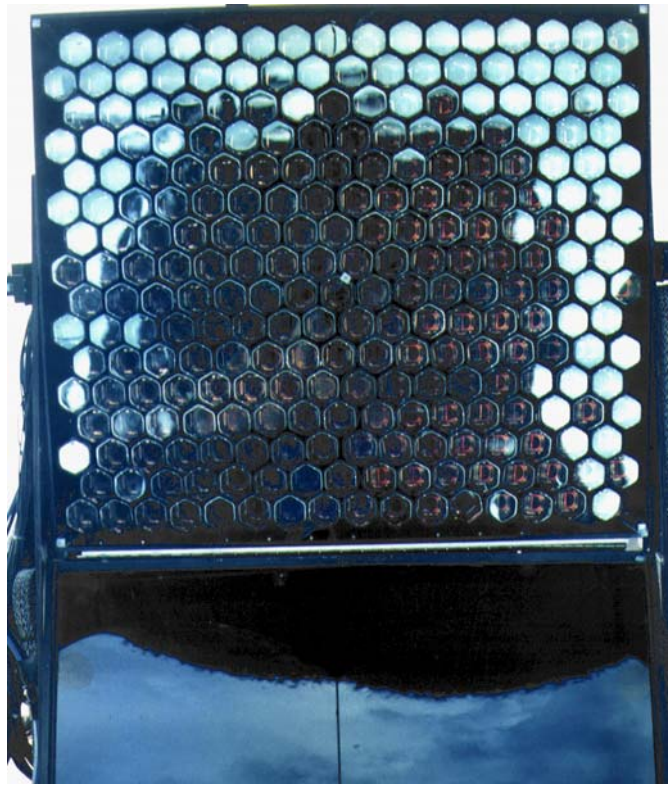
- Footprint directly detected by ground arrays such as AGASA.
- Entire shower indirectly detected by nitrogen fluorescence detectors such as HiRes.






長坂センター
高根センター
須玉センター
明野センター
0 1 2 3km


scintillators(5 cm thick)
photomultiplier
amplifier
lead(5cm)
iron(20cm)
proportional cou
iron beam
1.4m
1.8m
2.4m

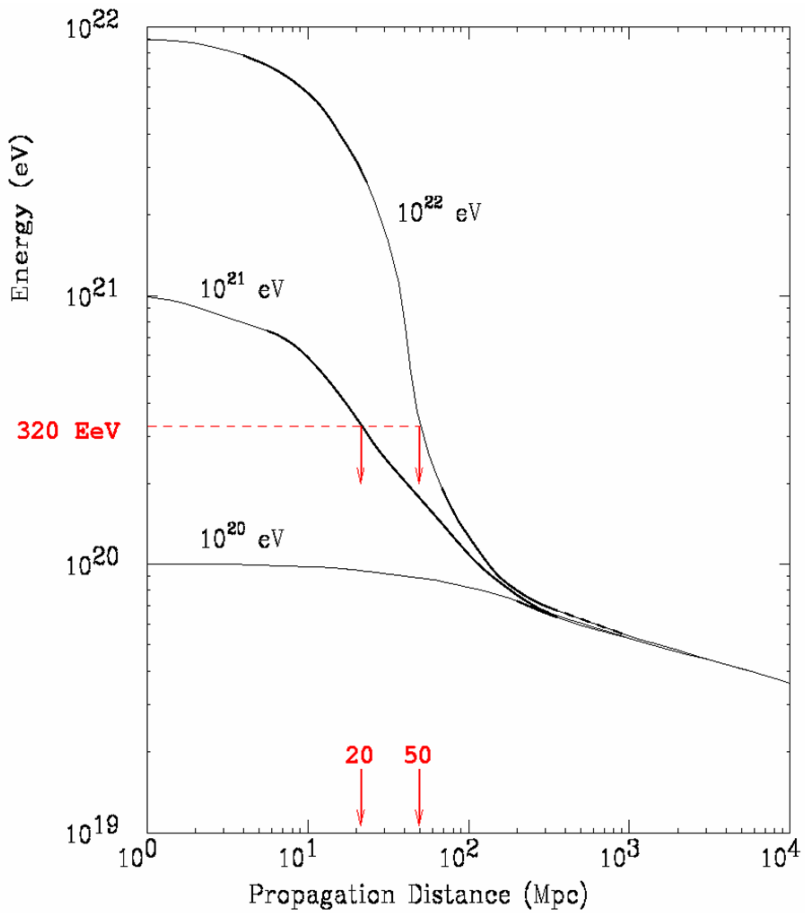


The Puzzle

- Relativity predicts that significant sources of UHECR must be nearby.
- There are no known sources of UHECR nearby.
- The February 2002 issue of Discover magazine ranked finding the source of UHECR one of the top eleven mysteries of Physics.

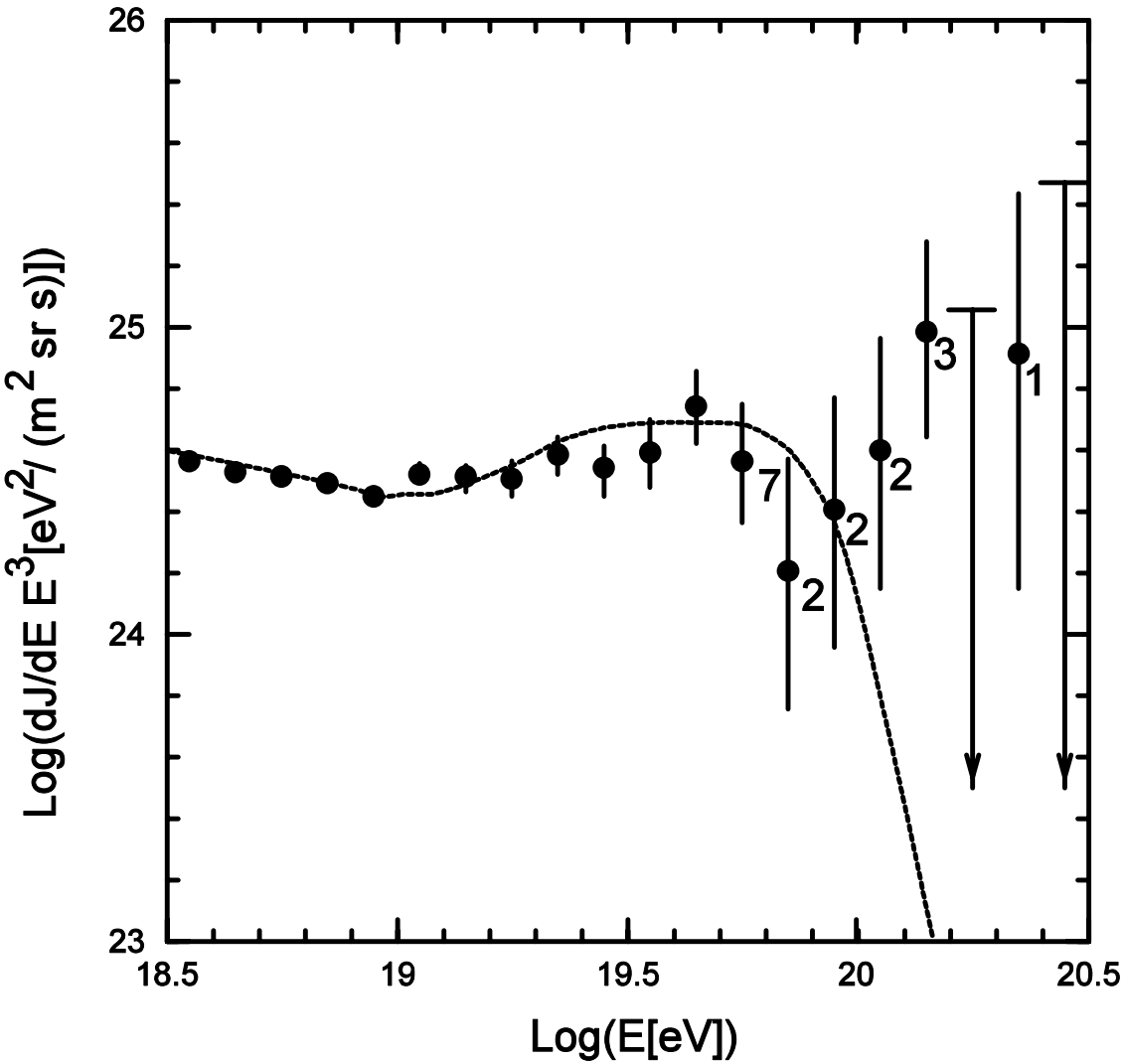
The GZK Feature

- Due to interactions with the CMB:
  - $p + \gamma \rightarrow \Delta^{+} \rightarrow p+\pi^{0}, n+\pi^{+}$
- "Pion production threshold"
- Protons: order 100 Mpc
- Iron Nuclei: order 10 Mpc
- Milky Way diameter is ~30 kpc
- Andromeda is ~.9 Mpc away

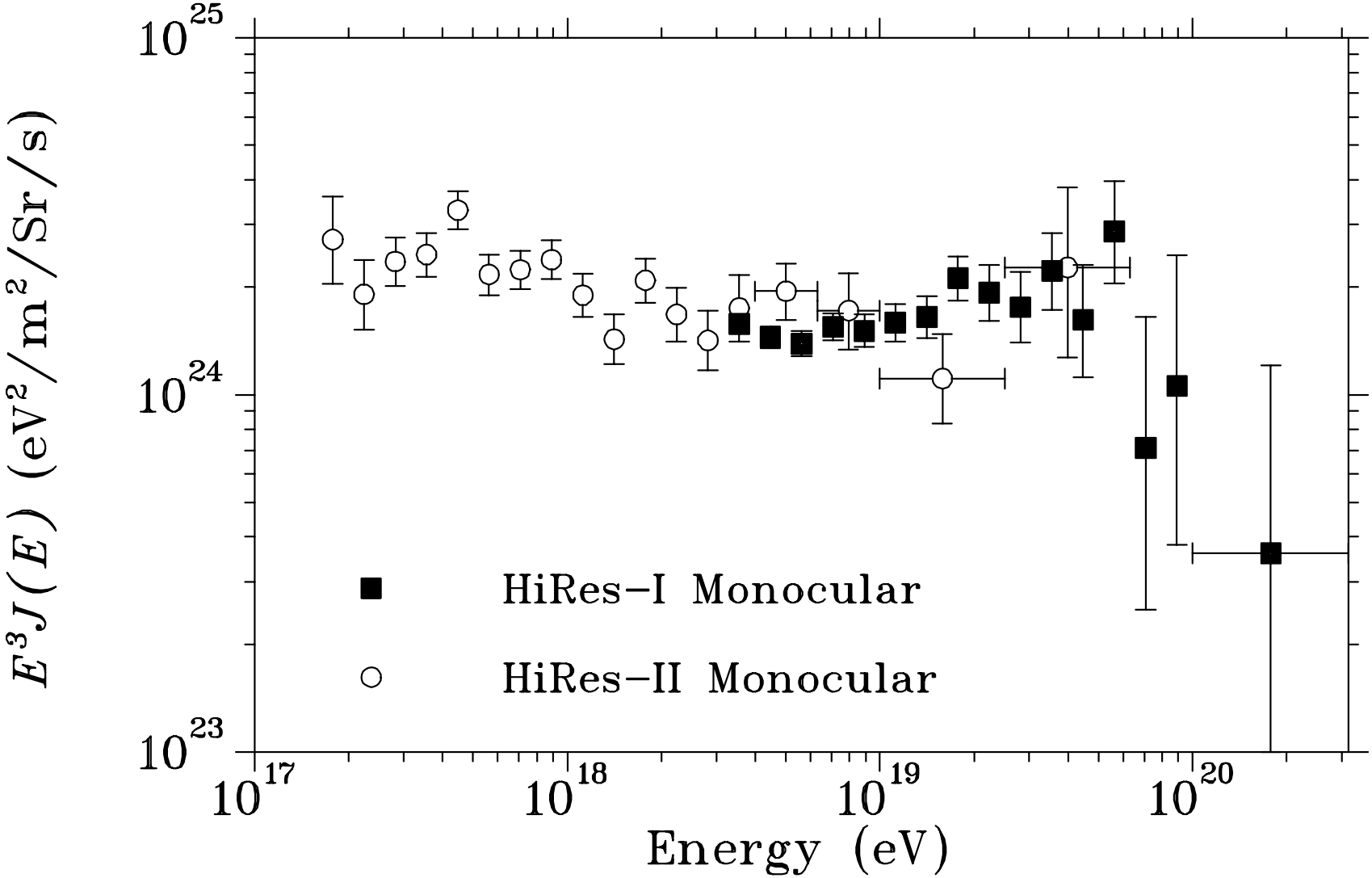


Energy attenuation of protons

The AGASA Spectrum

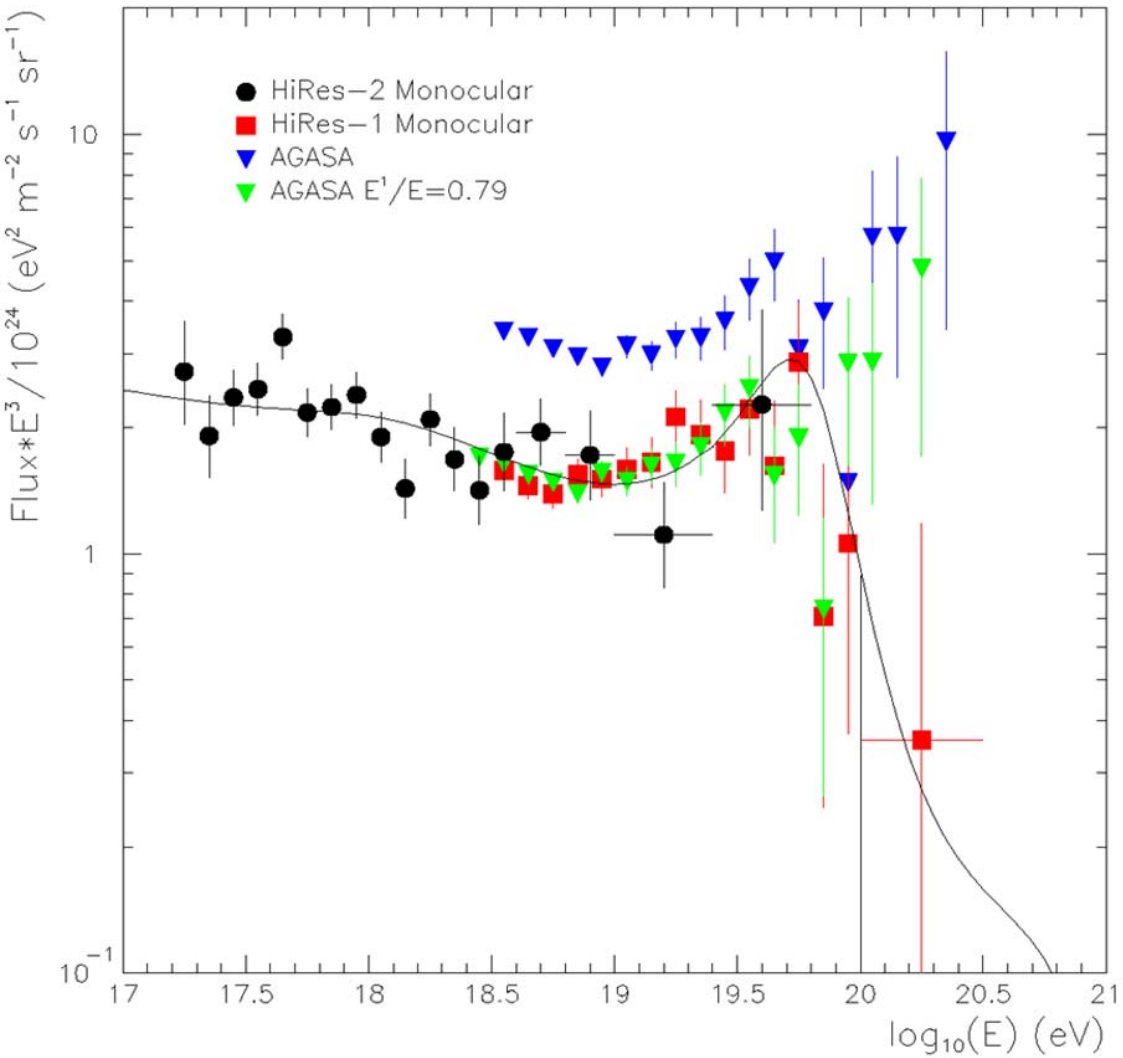


The HiRes Spectrum



Energy Spectrum

- "Second knee"
  - Near $10^{17.8}$ eV
  - Unknown
- "Ankle"
  - Near $10^{18.6}$ eV
  - Pair production
- GZK feature
  - Near $10^{19.8}$ eV
  - Pion production
- ~30% disparity!

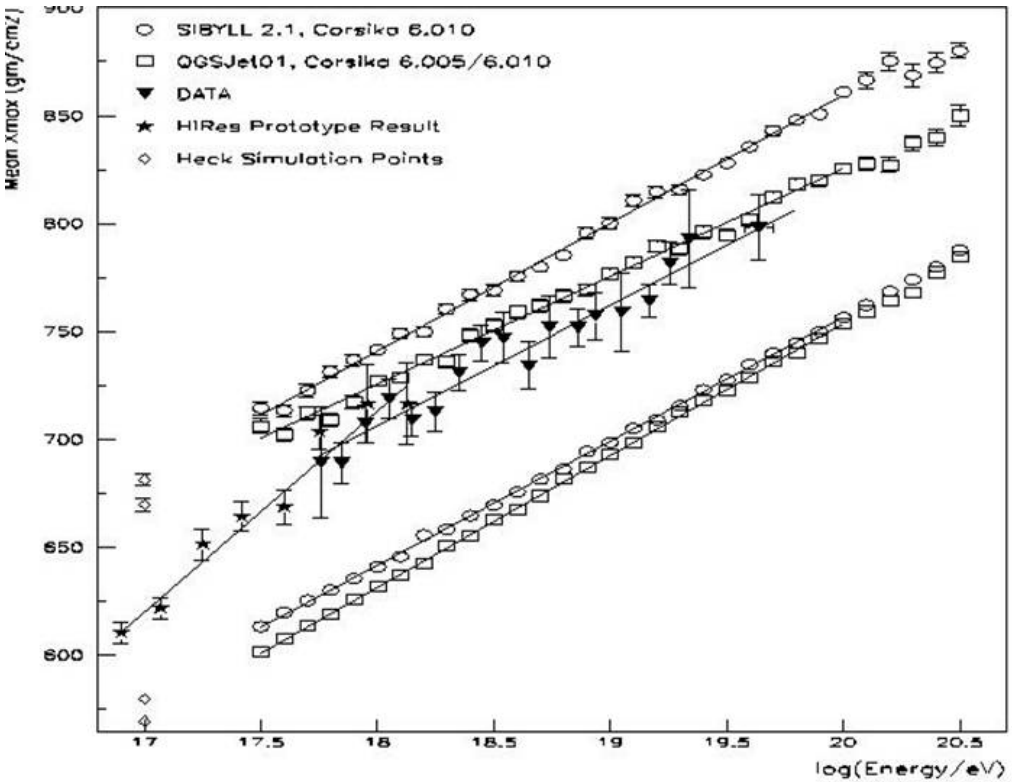


Super-GZK

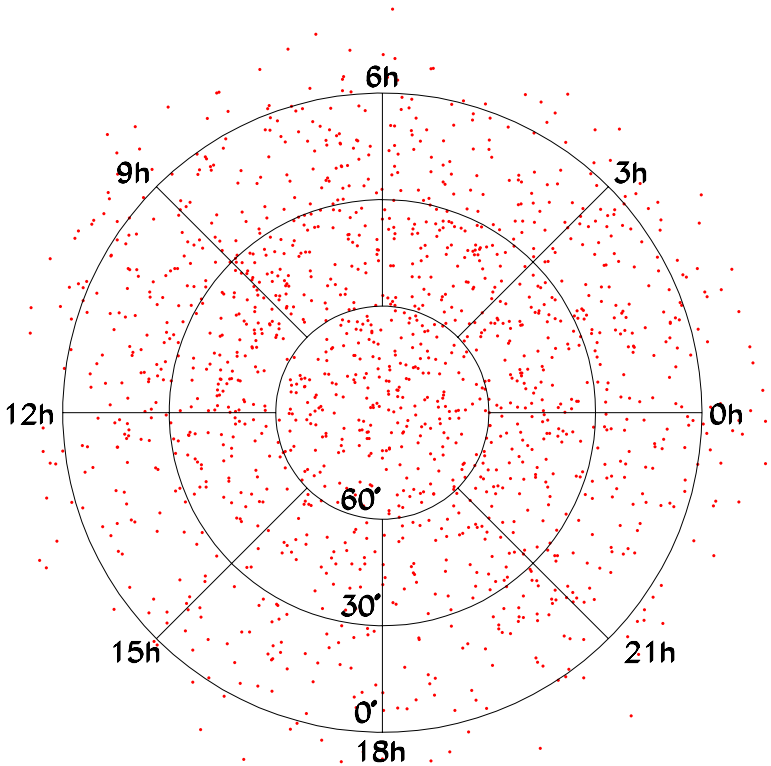
- Possible causes:
  - Exotic particles
  - Violation of special relativity at high energies
- Possible sources:
  - Active Galactic Nuclei (M87)
  - High mass X-Ray Binaries (Cygnus X-3)
  - Supergalactic Plane
  - Cosmological Defects

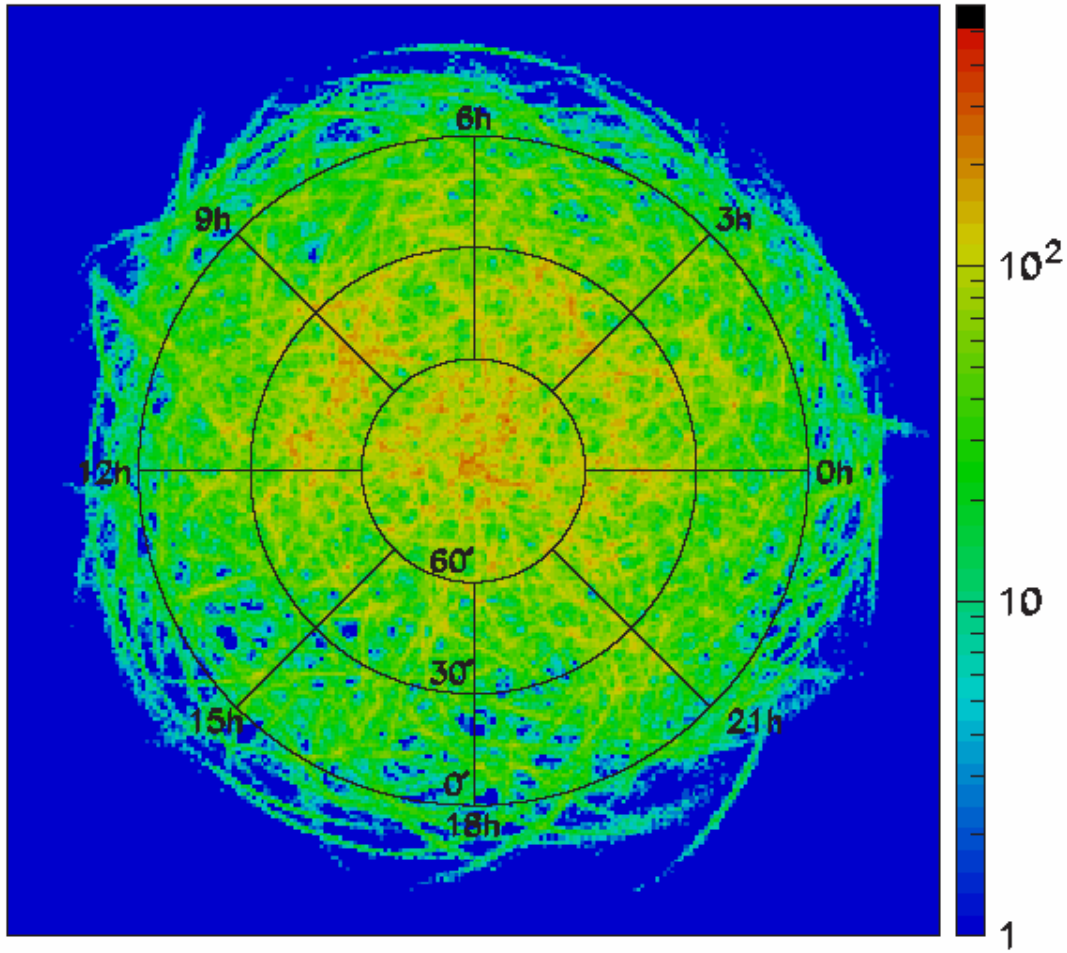
Composition

- Penetration depth *vs.* energy: high energy interact late, high mass interact early
- Potential composition change at 10^{18} eV (change in slope)
- Heavy → Light



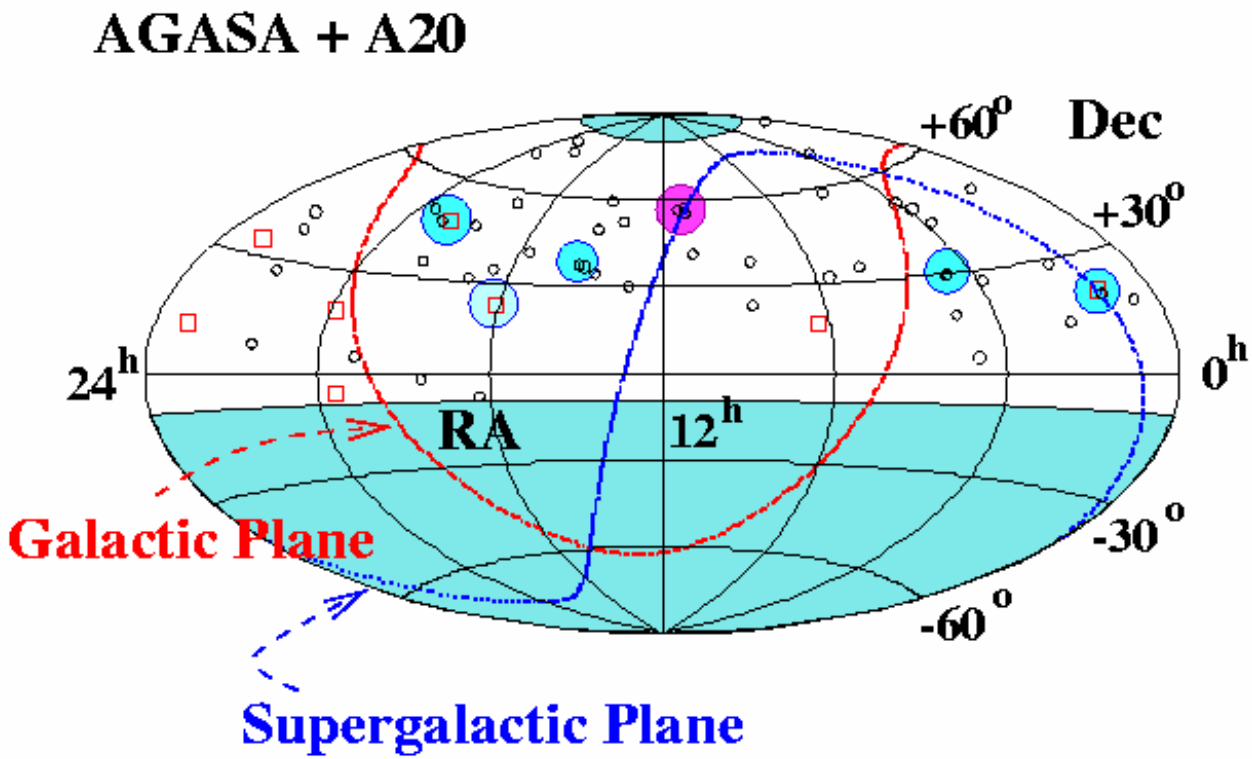
Anisotropy Searches



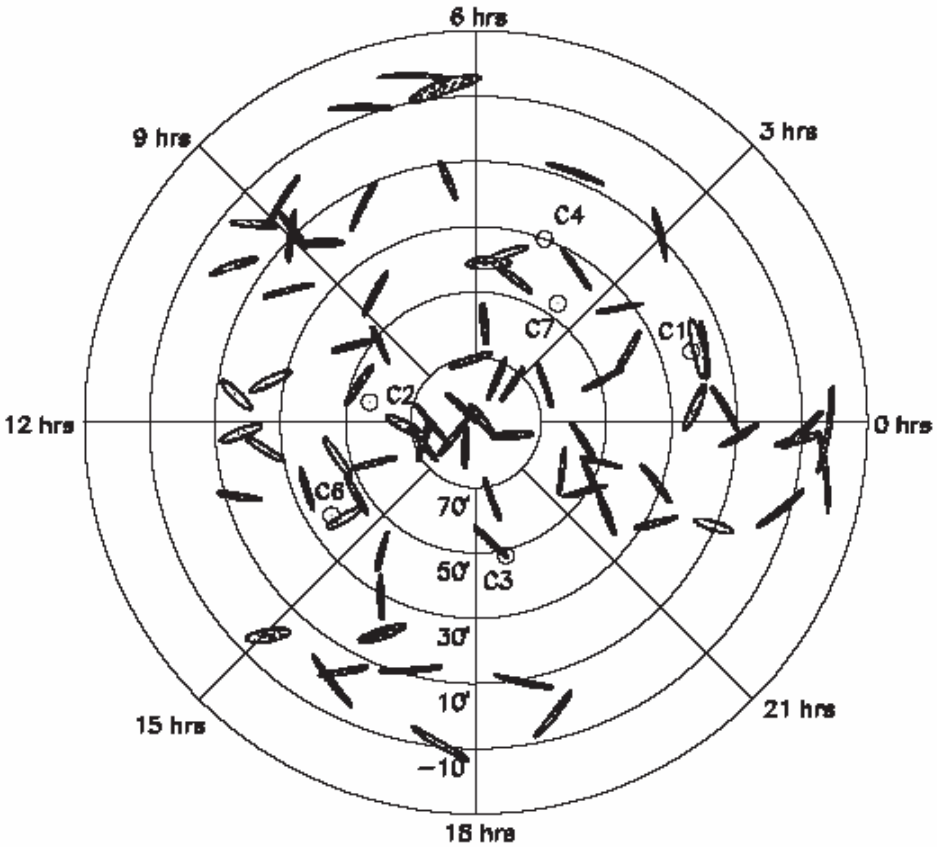


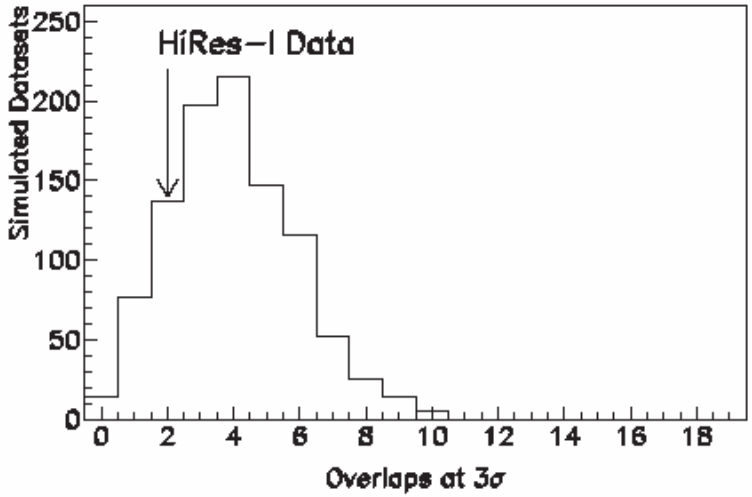
AGASA Point-Sources

- AGASA: Akeno Giant Air Shower Array
- Pink circle: the "AGASA Triplet"
- Nothing of astrophysical interest near the AGASA Triplet
- No theoretical motivation for point-sources



HiRes Overlaps with AGASA Point-Sources

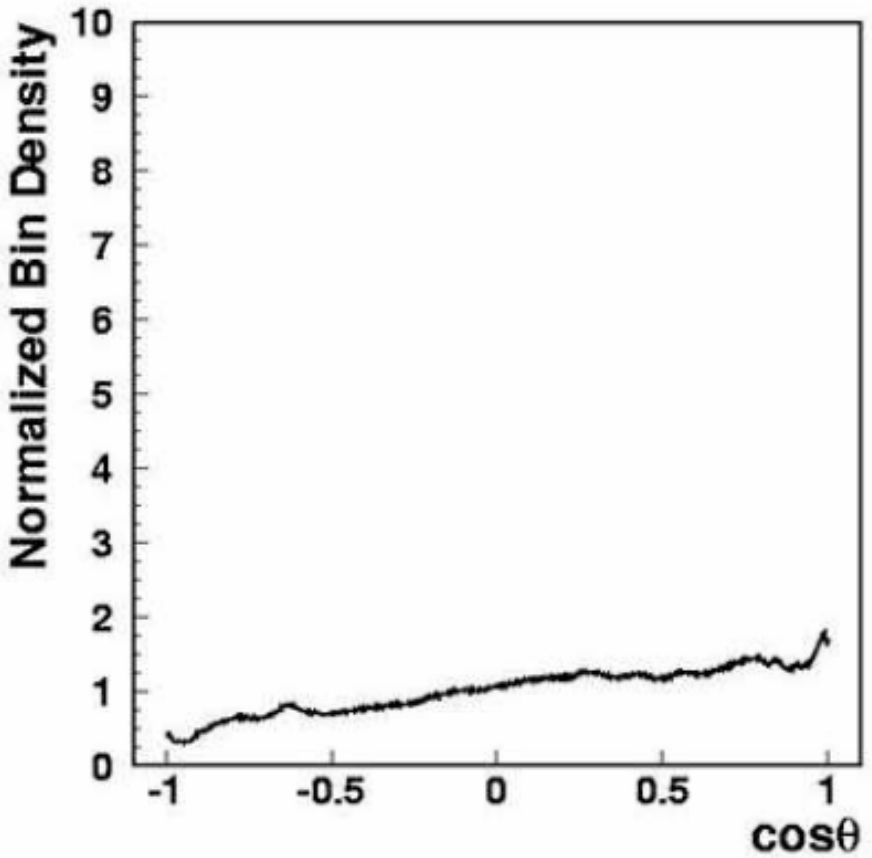




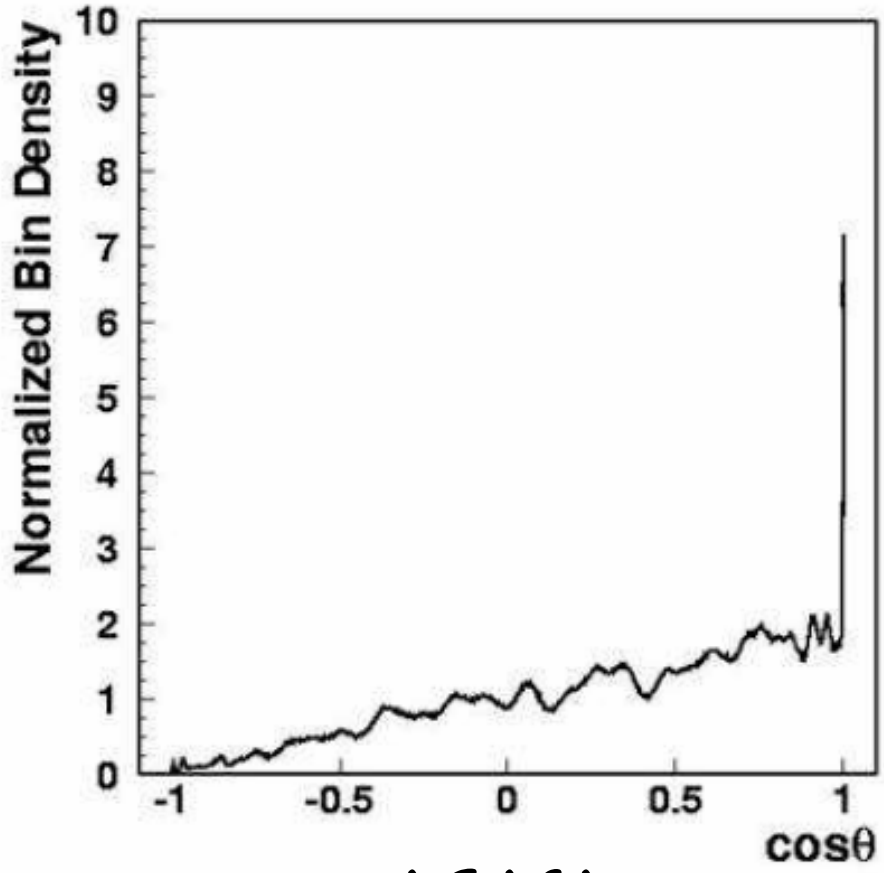
- Null result
- Histogram: MC isotropic prediction
- Arrow: Observation

Autocorrelation

- Calculate cos(θ) between all pairs of events to measure "clumping"

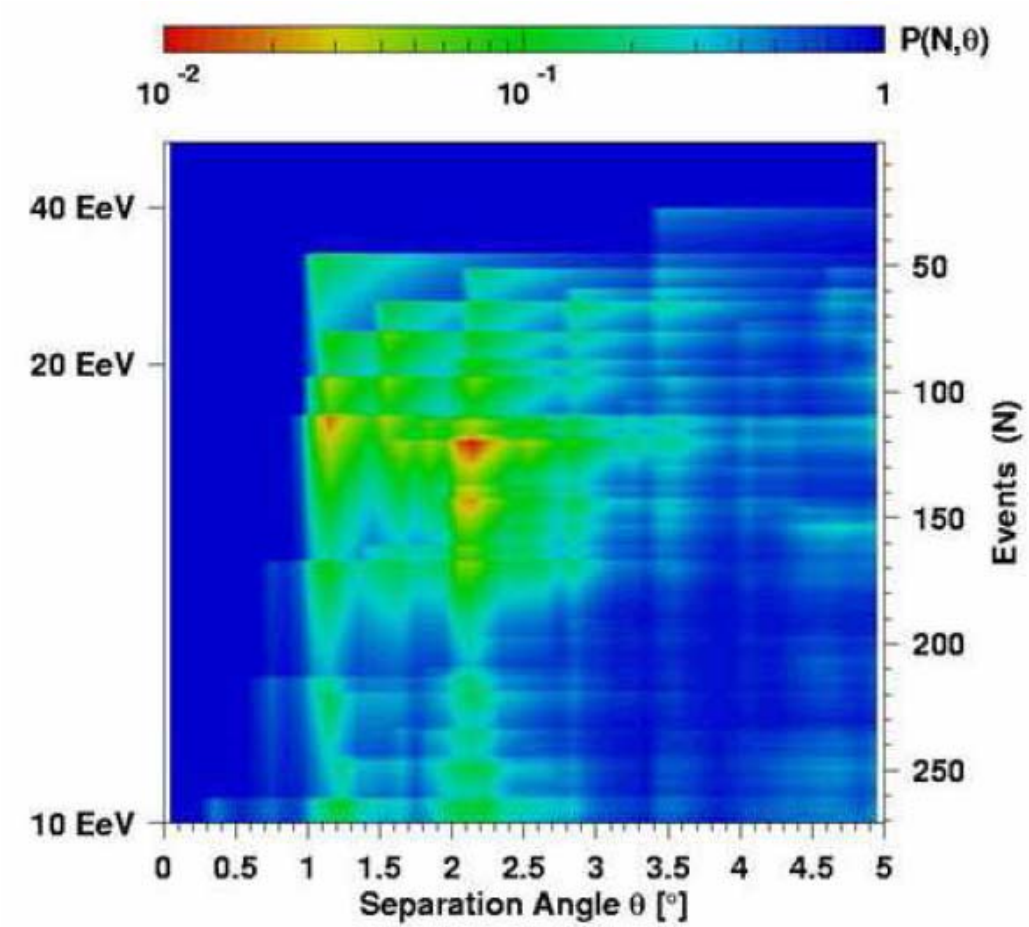


HiRes



AGASA

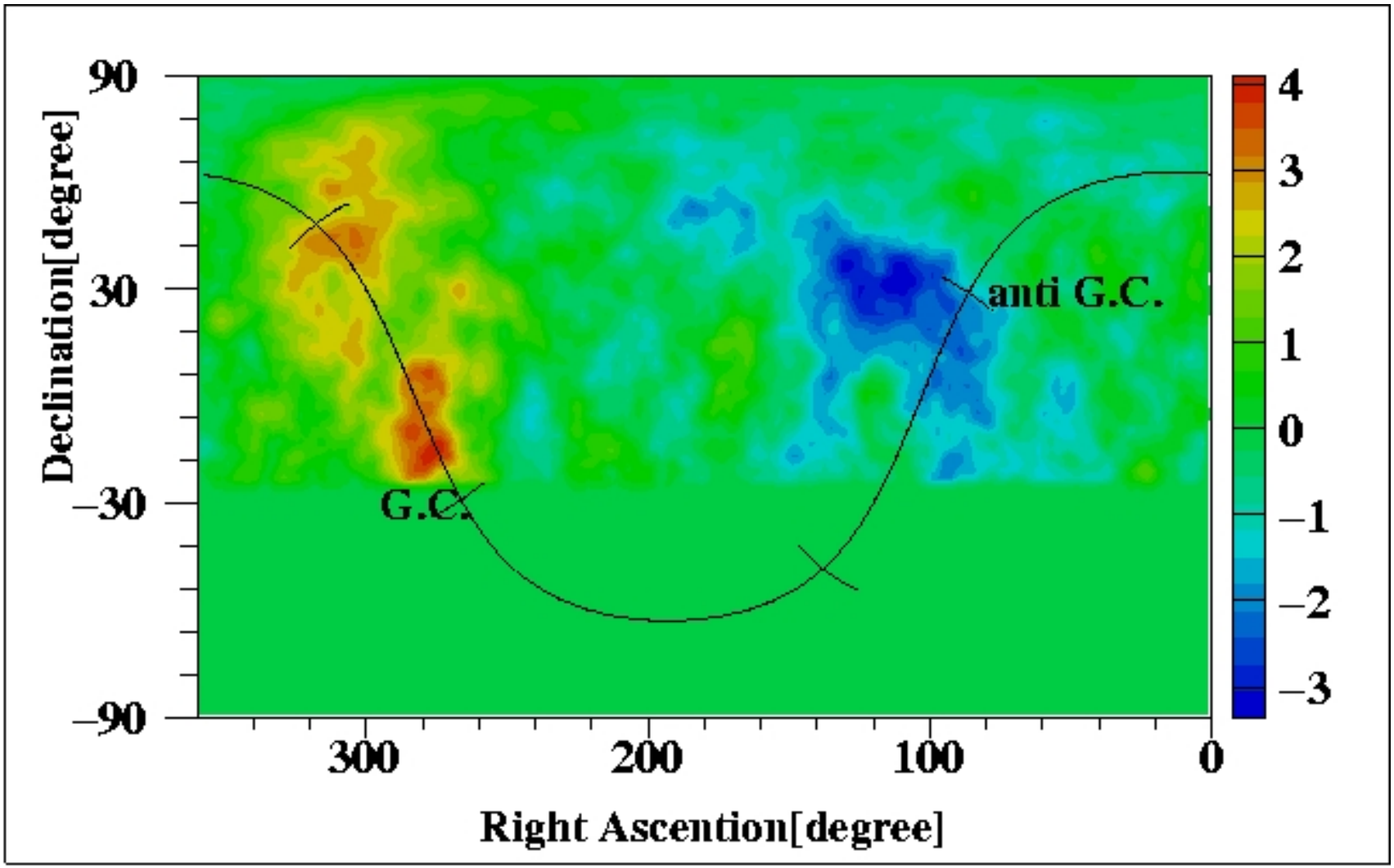
HiRes Autocorrelation as a Function of Energy



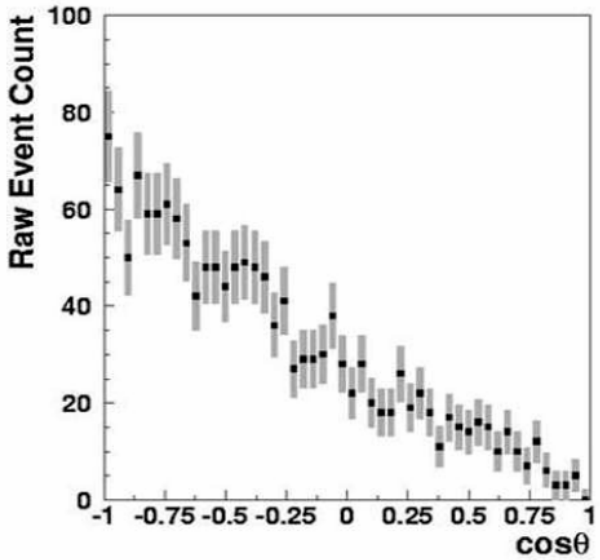
Null result:

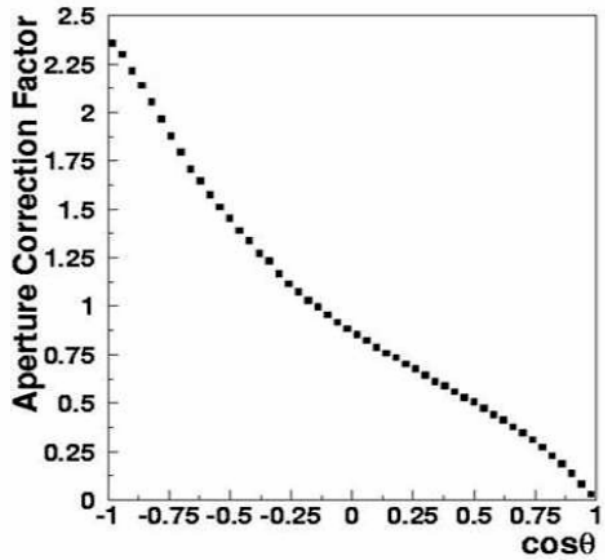
Most significant point corresponds to a chance probability of 52%.

AGASA Galactic Dipole



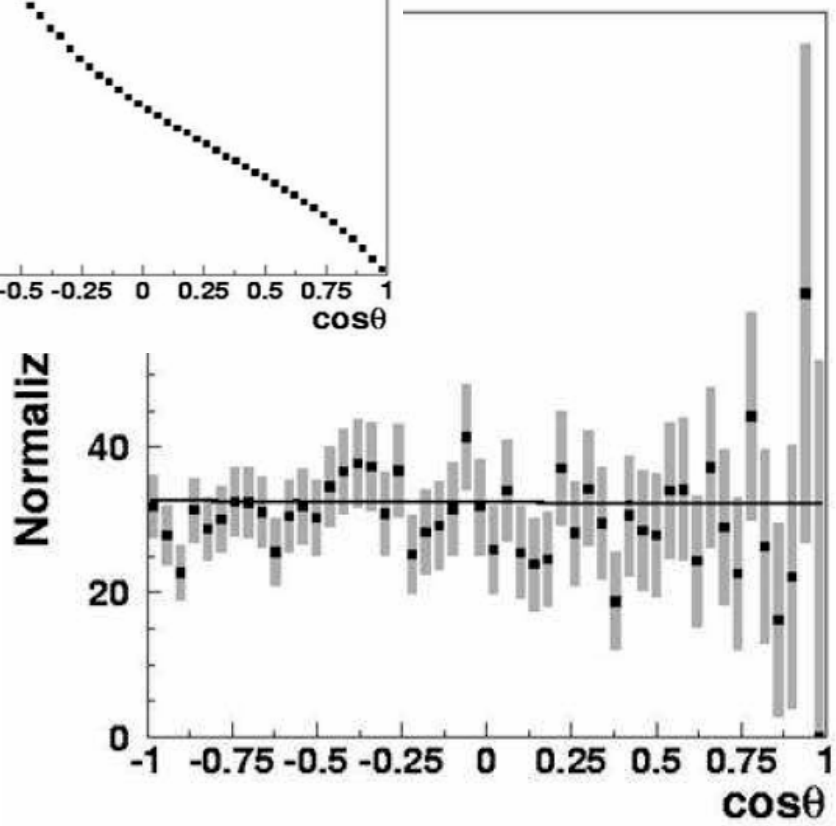
HiRes Galactic Dipole Search





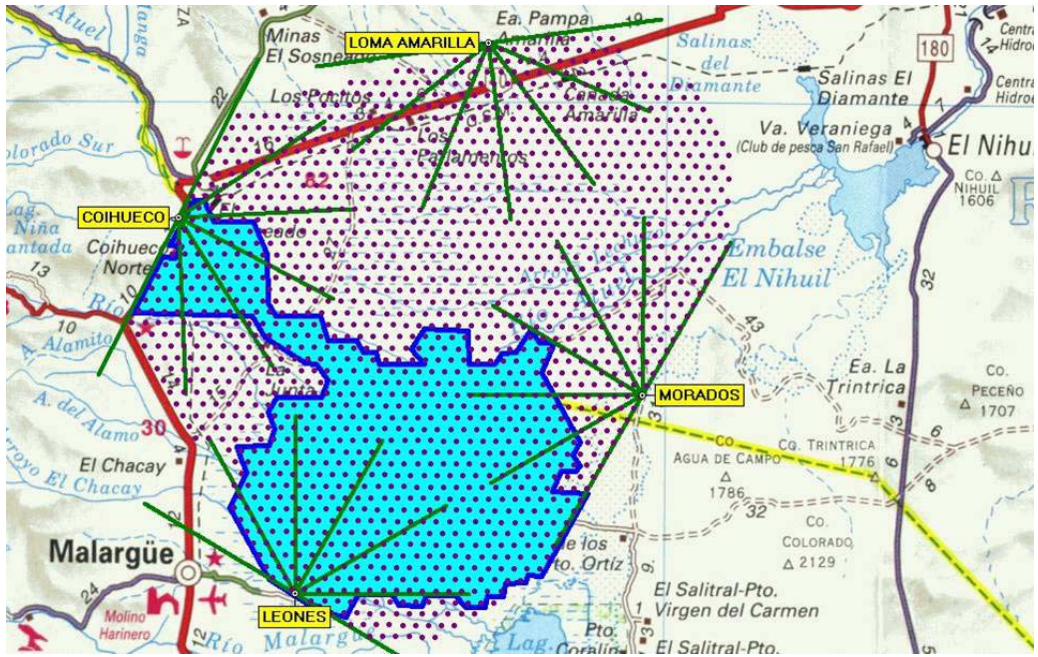
Measure cos(ɵ) from galactic center.

Left: HiRes Data
Right: Isotropic Prediction
Bottom: Data corrected by isotropic →null result



Future of UHECR: Auger

- ✧ In southern hemisphere: Argentina
- ✧ Hybrid detector: hoped to resolve energy disparity
- ✧ Largest aperture yet at 10^{19} eV and above
- ✧ Should determine if GZK feature there or not (6×10^{19} eV)
- ✧ Won't measure full ankle(4×10^{18}eV) or "second knee"(6×10^{17}eV)



Future of UHECR: TA

- In northern hemisphere: Millard County, Utah
- Hybrid detector: hoped to resolve energy disparity
- Largest energy range yet: $10^{17} \rightarrow 10^{20.5}$ eV
- Energy range achieved through local topography
- First complete spectrum