Ultra-High-Energy Cosmic Rays: A Window into the Extreme Universe

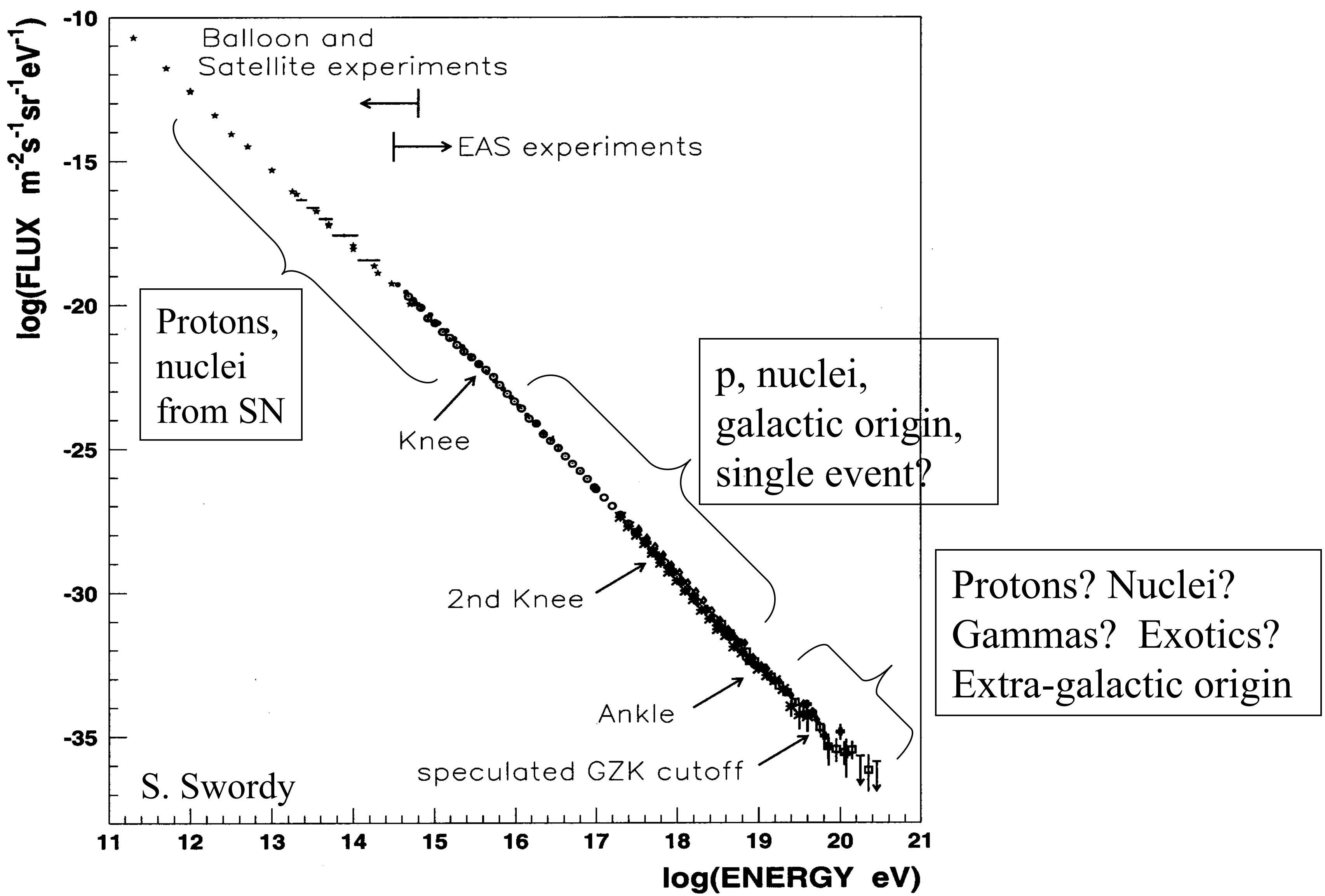
Aaron S. Chou

Fermilab

February 17, 2005

1. **UHECR and the GZK feature**
2. **Observations of super-GZK events**
3. **Astrophysical sources**
4. **Constraints on Top-down models**
5. **The Pierre Auger Observatory and the Telescope Array**

What are cosmic rays?

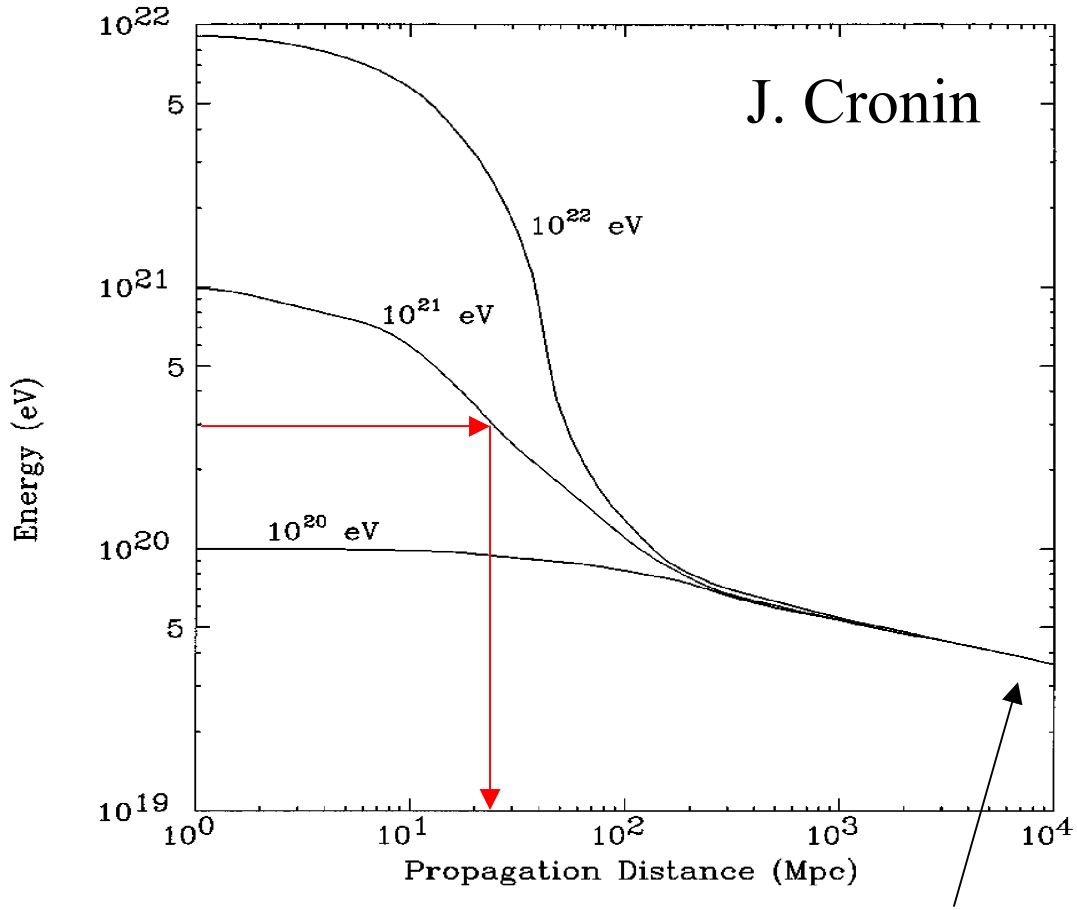


UHECR Interactions with the CMB

$$p + \gamma_{CMB} \rightarrow \Delta(1232) \rightarrow p + \pi^0 \rightarrow p\gamma\gamma$$
$$\rightarrow n + \pi^+ \rightarrow pe^-\bar{\nu}_e + e^+\nu_e\bar{\nu}_\mu\nu_\mu$$

The super-GZK sources must be local (R<100Mpc) unless:

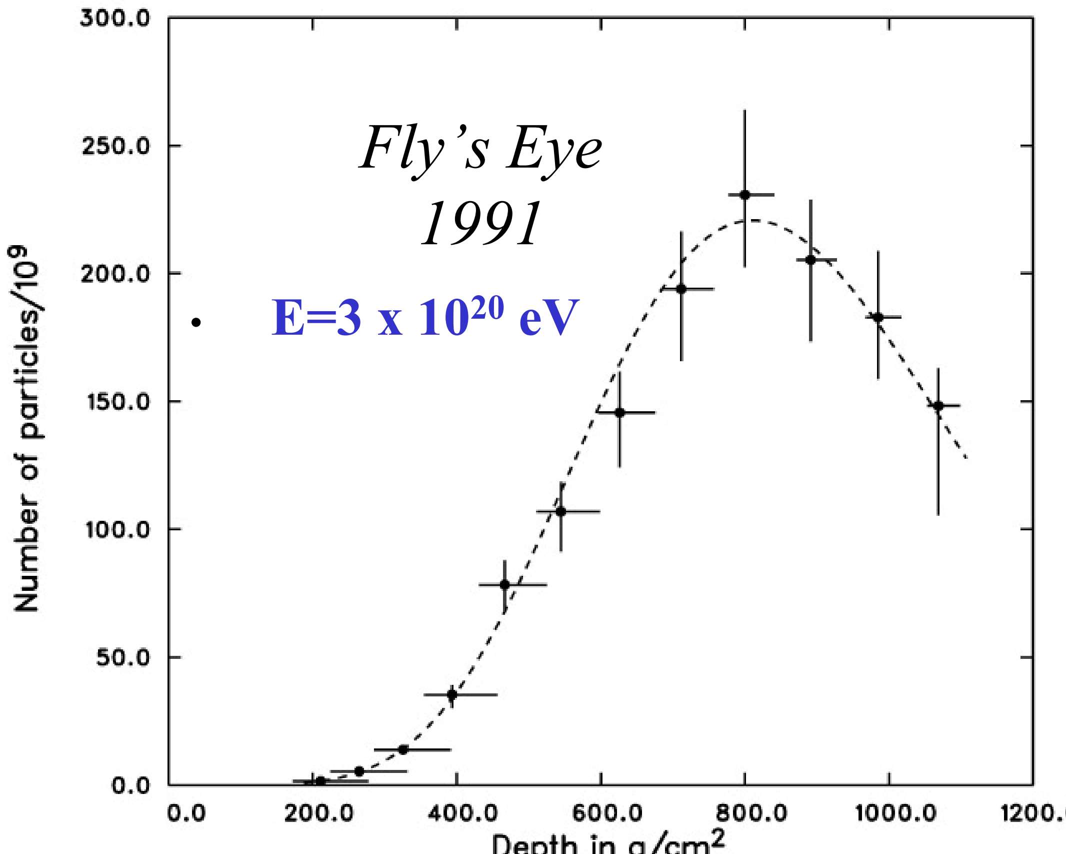
1. Lorentz invariance is broken or
2. $\sigma_{CR-\gamma}$ is suppressed (nuclei, shadrons, neutrinos, etc.)



GZK (Greisen, Zatsepin, Kuzman) energy

Super-GZK events have been seen by many experiments (flux~1/km^2/century)

Surface detectors: Volcano Ranch, Haverah Park, Yakutsk, AGASA
Air Fluorescence detectors: Fly's Eye, HiRes



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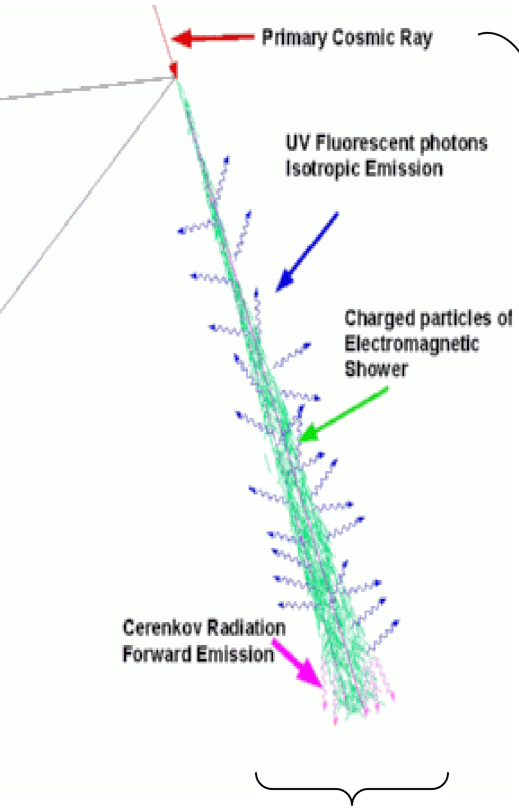
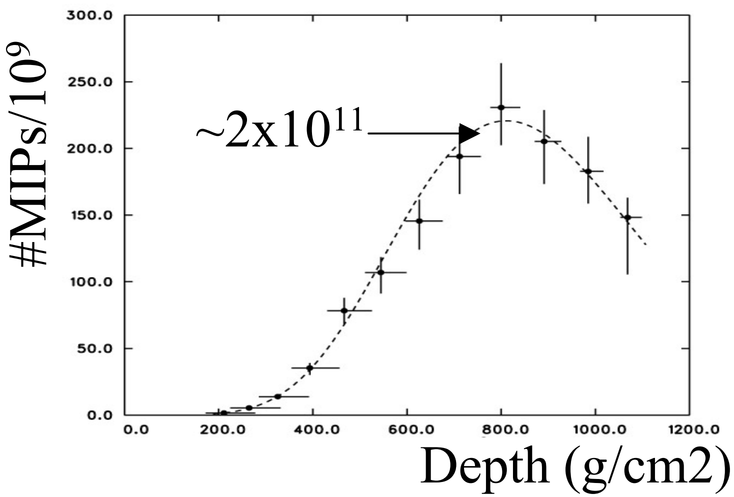
Measure both the longitudinal and transverse development of cosmic ray air showers.



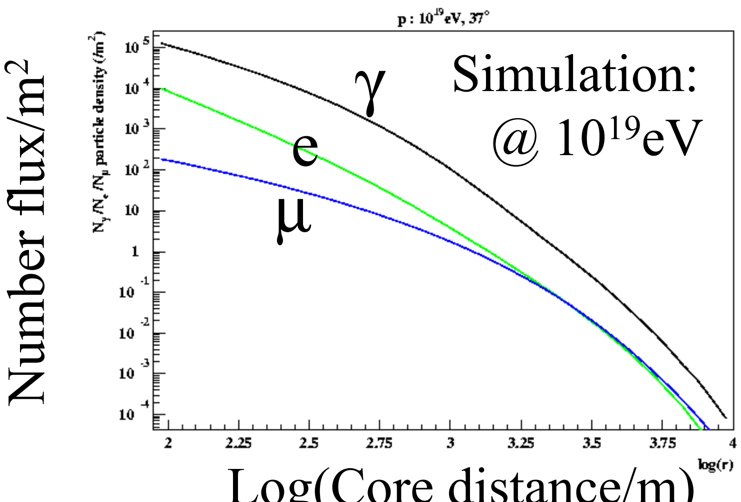
Atmospheric depth =875g/cm2 $\sim 11\lambda_I$ $\sim 22\ X_0$



Fly's Eye, 1991
$E=3\times10^{20}$eV

Fluorescence → dE/dx

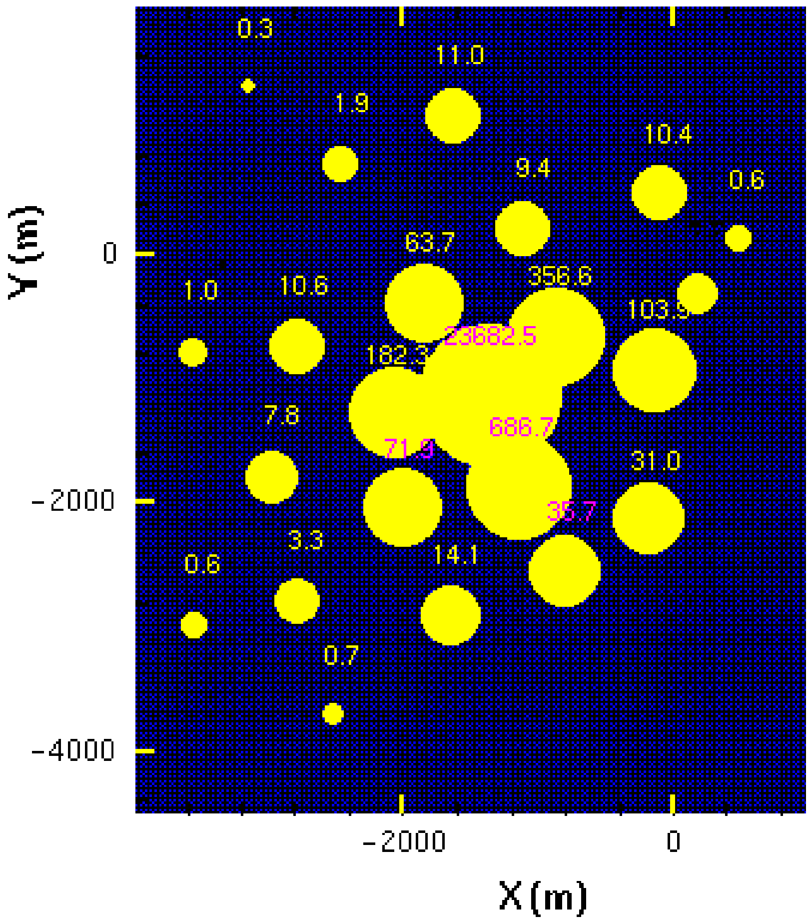
Footprint ~ few km,
$E_{EM} \sim 10$MeV,
$E_\mu \sim 1$ GeV

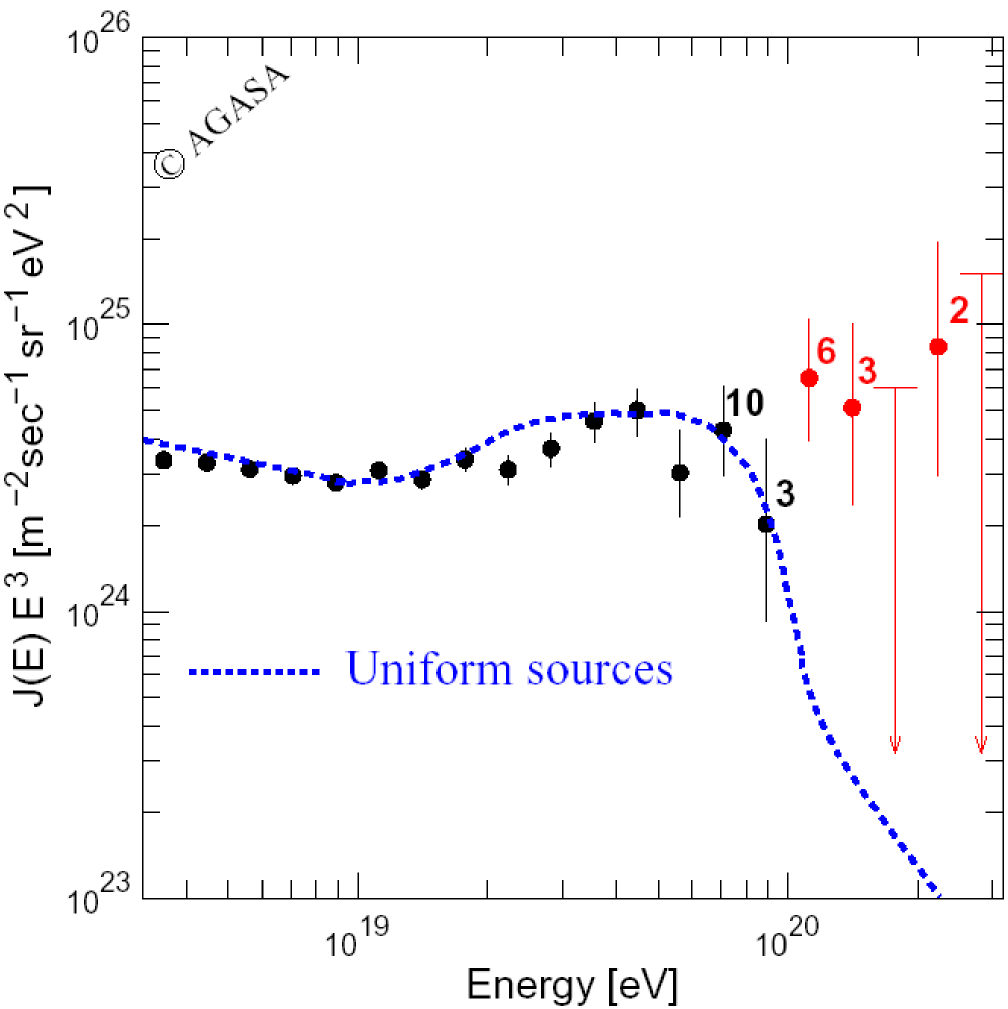


Sample the particle flux using sparse arrays of scintillators or water Cherenkov tanks. **Signal~E.**

AGASA sees 11 events $E>10^{20}$eV

$E = 2x10^{20}$eV (AGASA,1993)



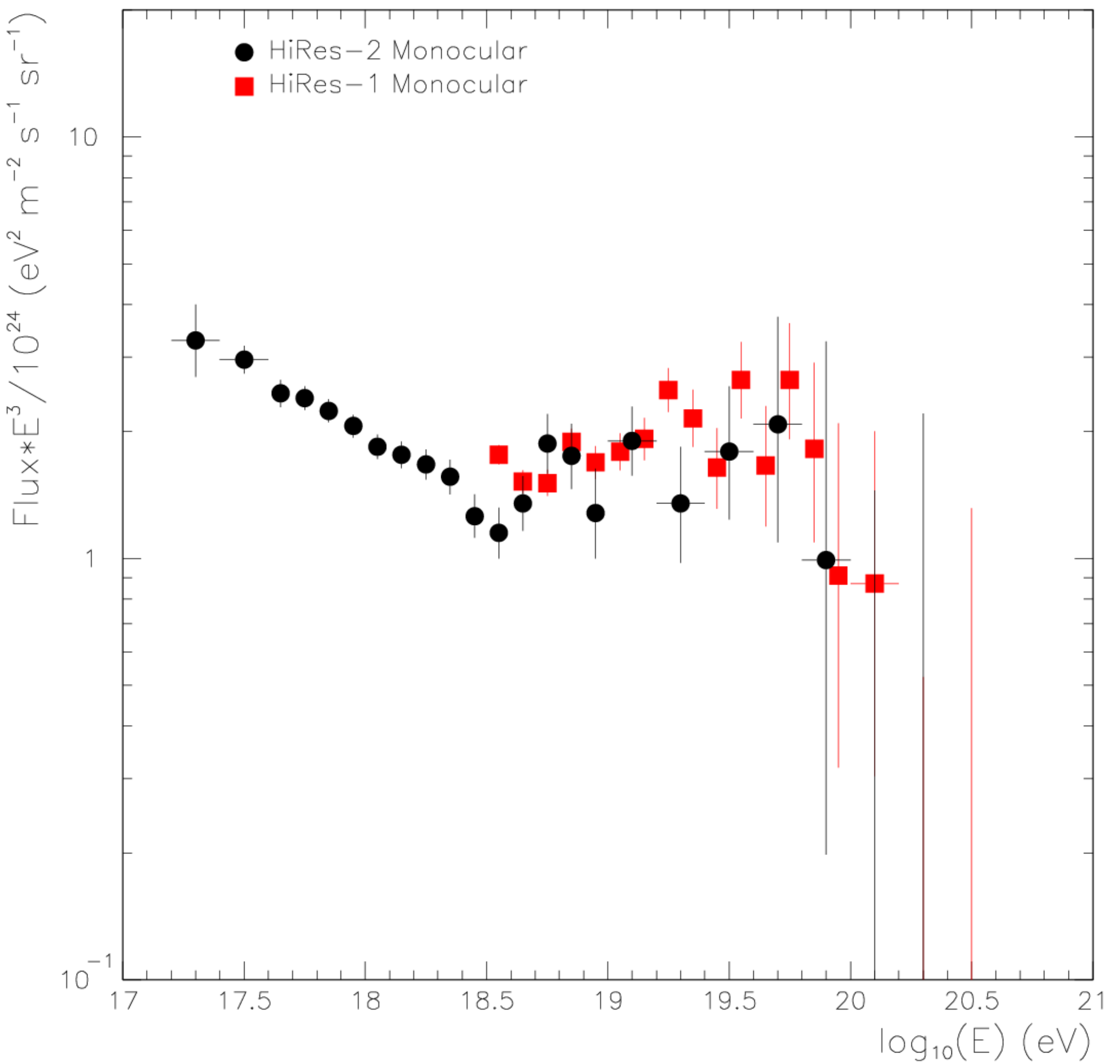


HiRes sees a GZK "feature", only 2 events with energy>10^{20}eV

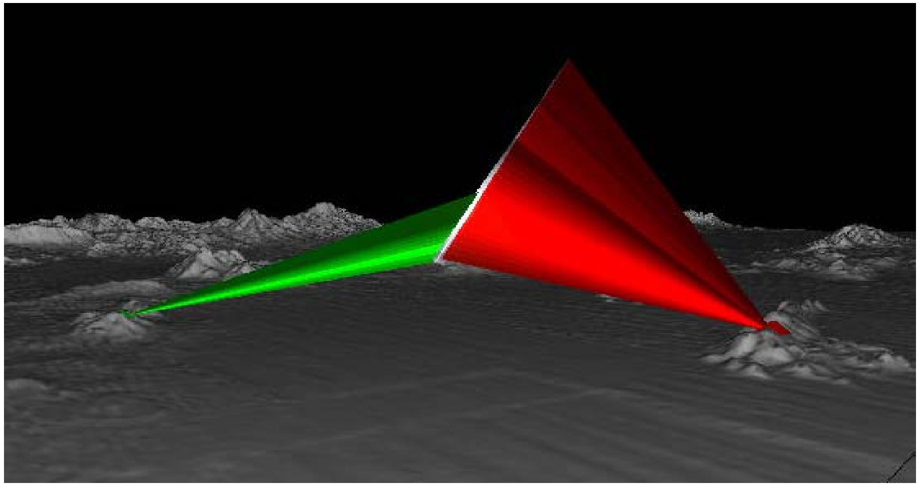
HiRes Monocular

Spectrum

2003



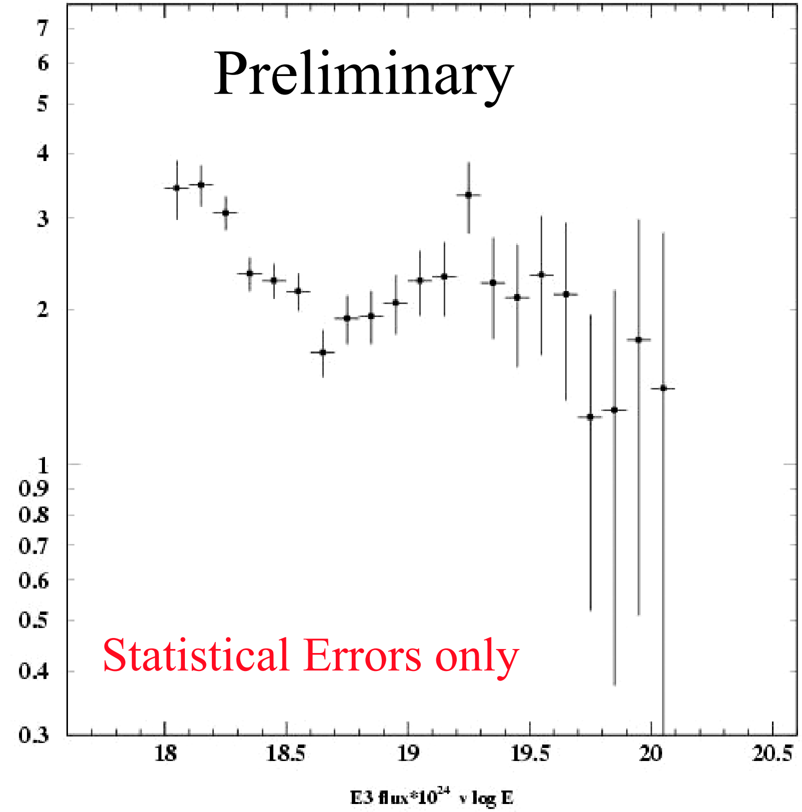
HiRes Stereo Spectrum



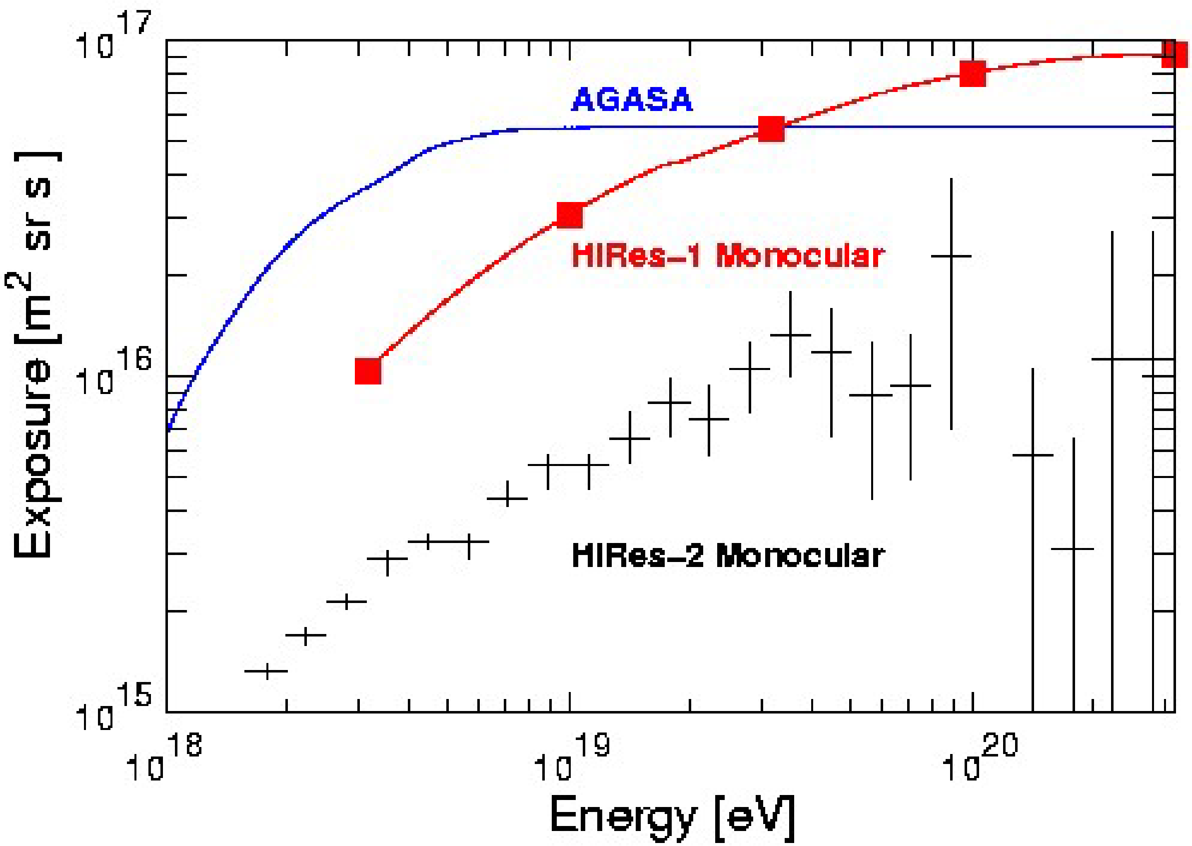
Much better geometric reconstruction than monocular.

Still evaluating systematic errors due to energy scale, **Fluorescence yield (15%),** atmospheric conditions.

R. W. Springer et al. ICRC03

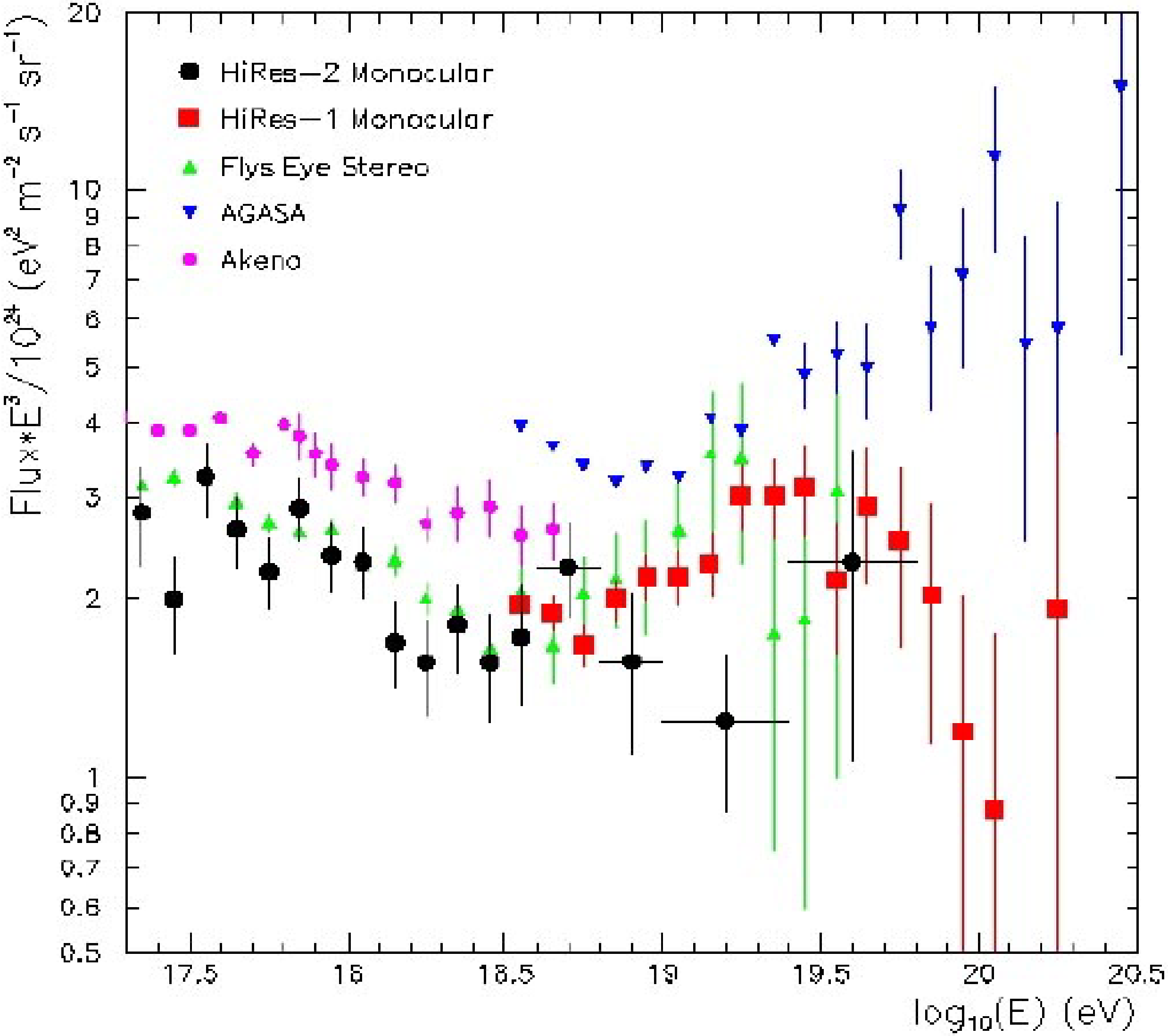


AGASA, HiRes Exposures (ICRC2003)



There must be a energy measurement problem…

Compare HiRes,AGASA

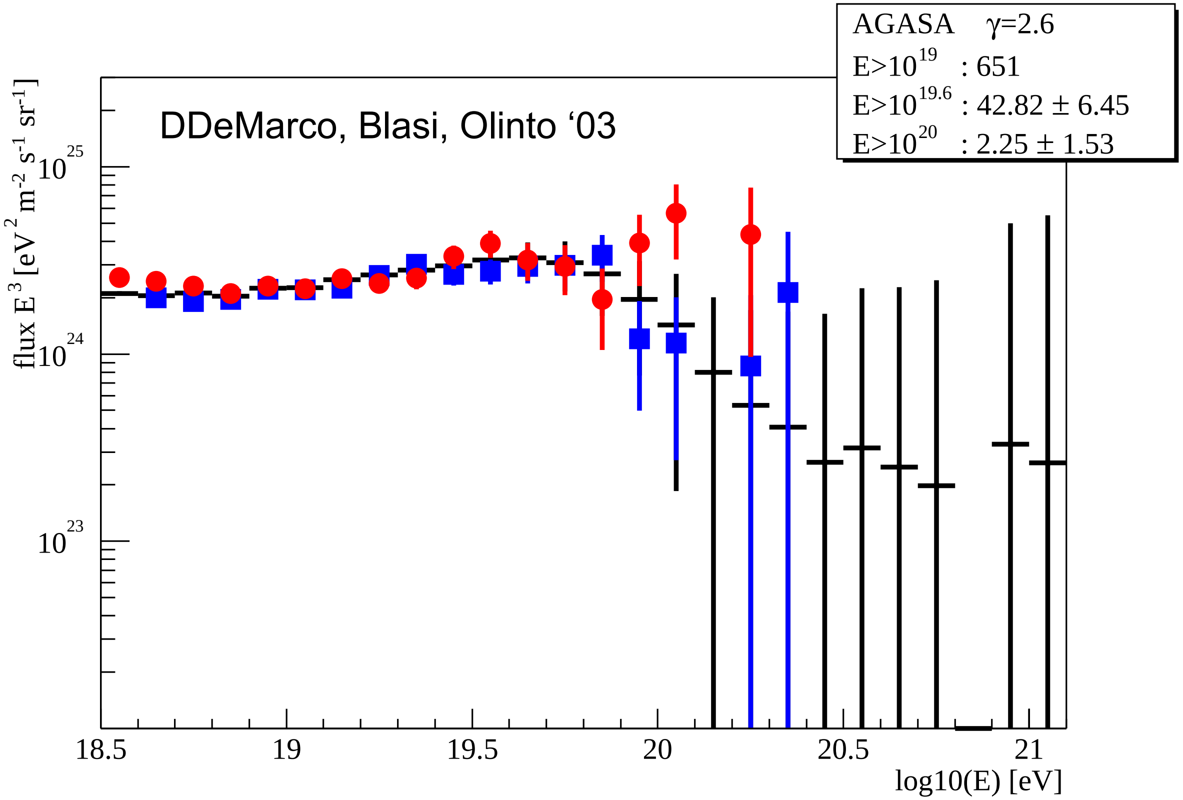


$\Delta E \sim 30\%$

Are highest energy events energy resolution tails?

Require 9σ tail on a sample of <100 trans-GZK events….

What about systematic ΔE?



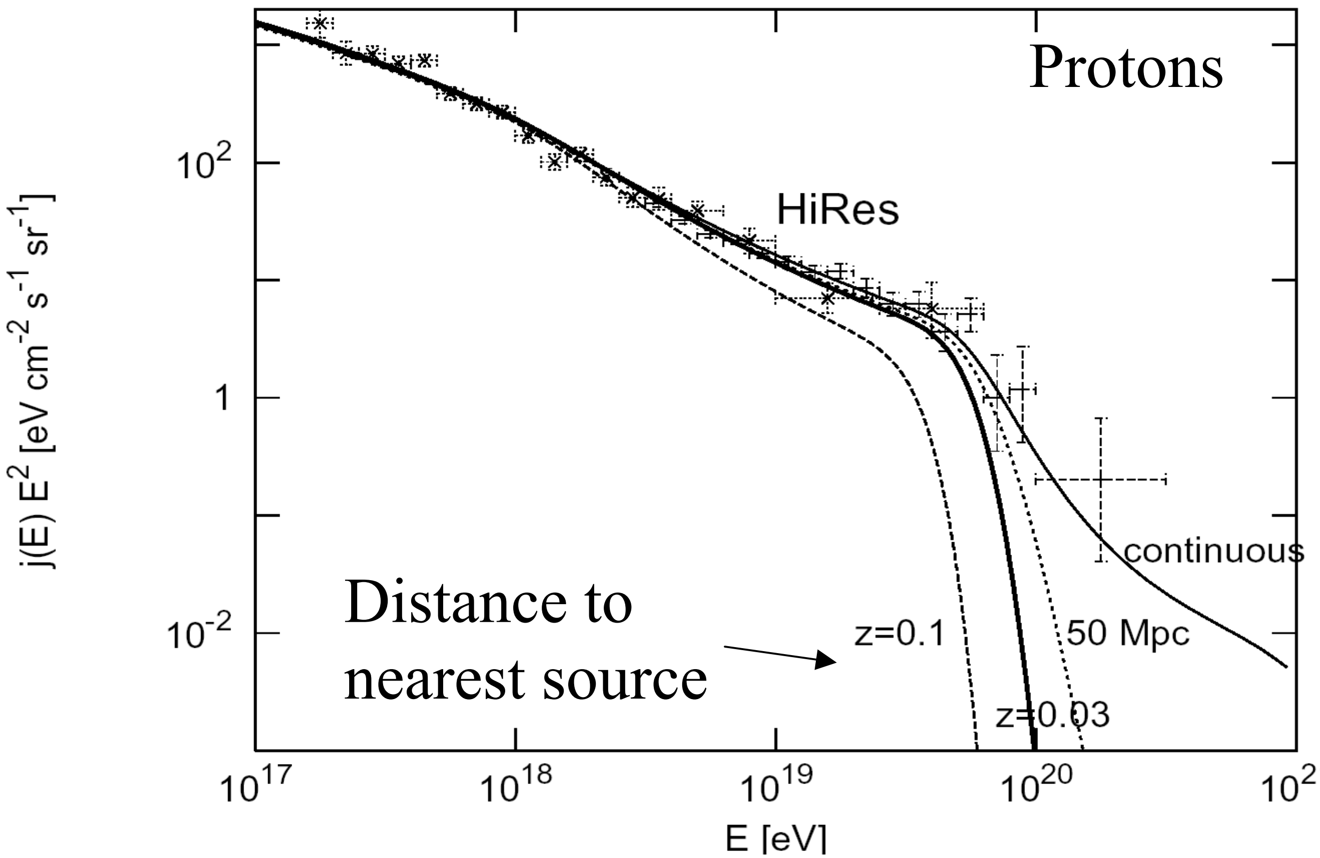
AGASA-15%

HiRes+15%

Before rescaling, expect ~18 HiRes events $>10^{20}$, see only 2.

After rescaling, expect ~13 HiRes events $>10^{20}$, see only ~3.

The shape of the GZK feature depends on the local source distribution (and on magnetic fields)



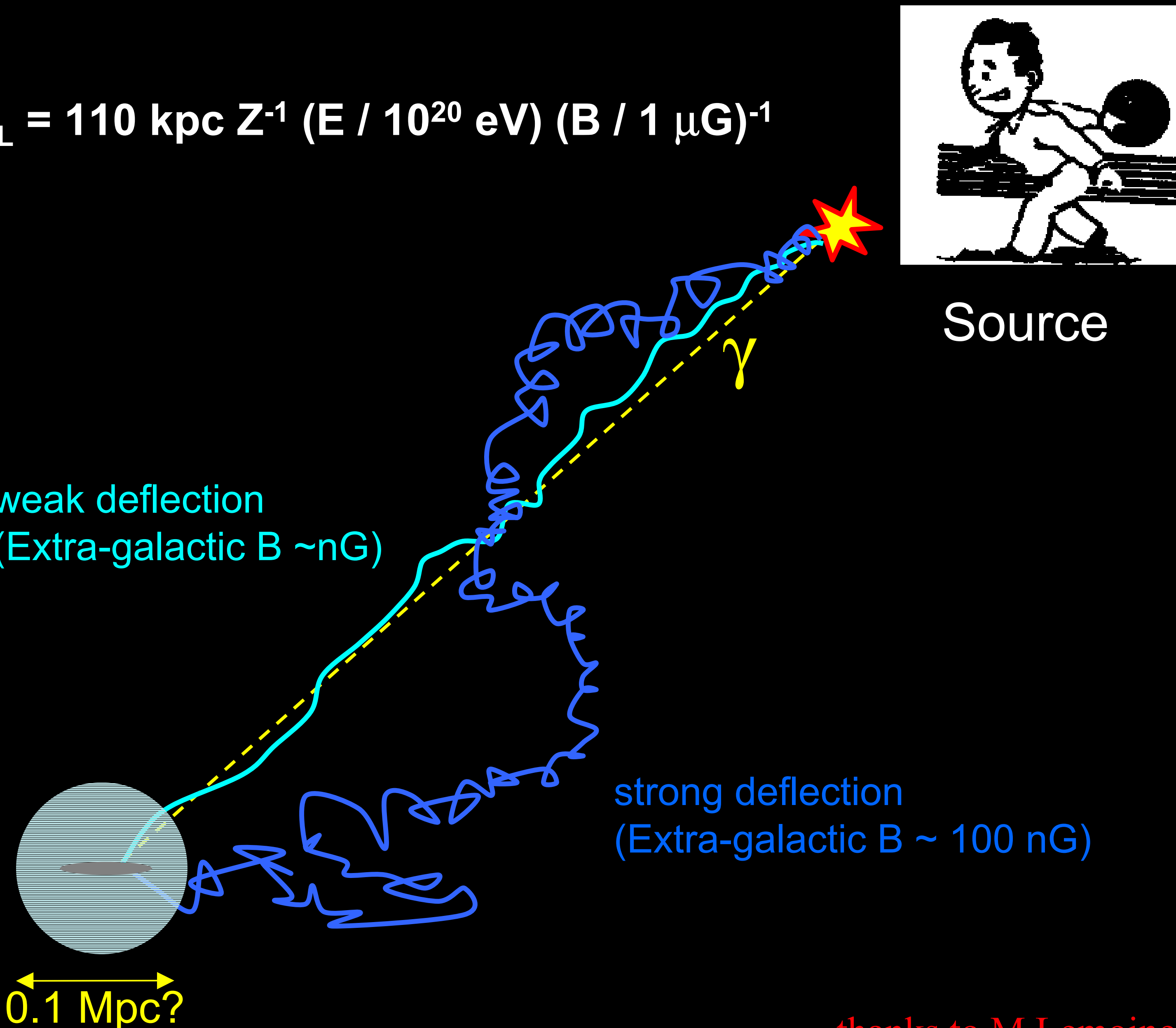
Kachelrieß, Semikoz, Tortola

→If CRs are protons, then both HiRes and AGASA data imply a local UHECR source!

→At the AGASA normalization, the local source overproduces the sub-GZK spectrum…

Influence of cosmic magnetic fields

Larmor radius: $\mathbf{r_L = 110\ kpc\ Z^{-1}\ (E / 10^{20}\ eV)\ (B / 1\ \mu G)^{-1}}$



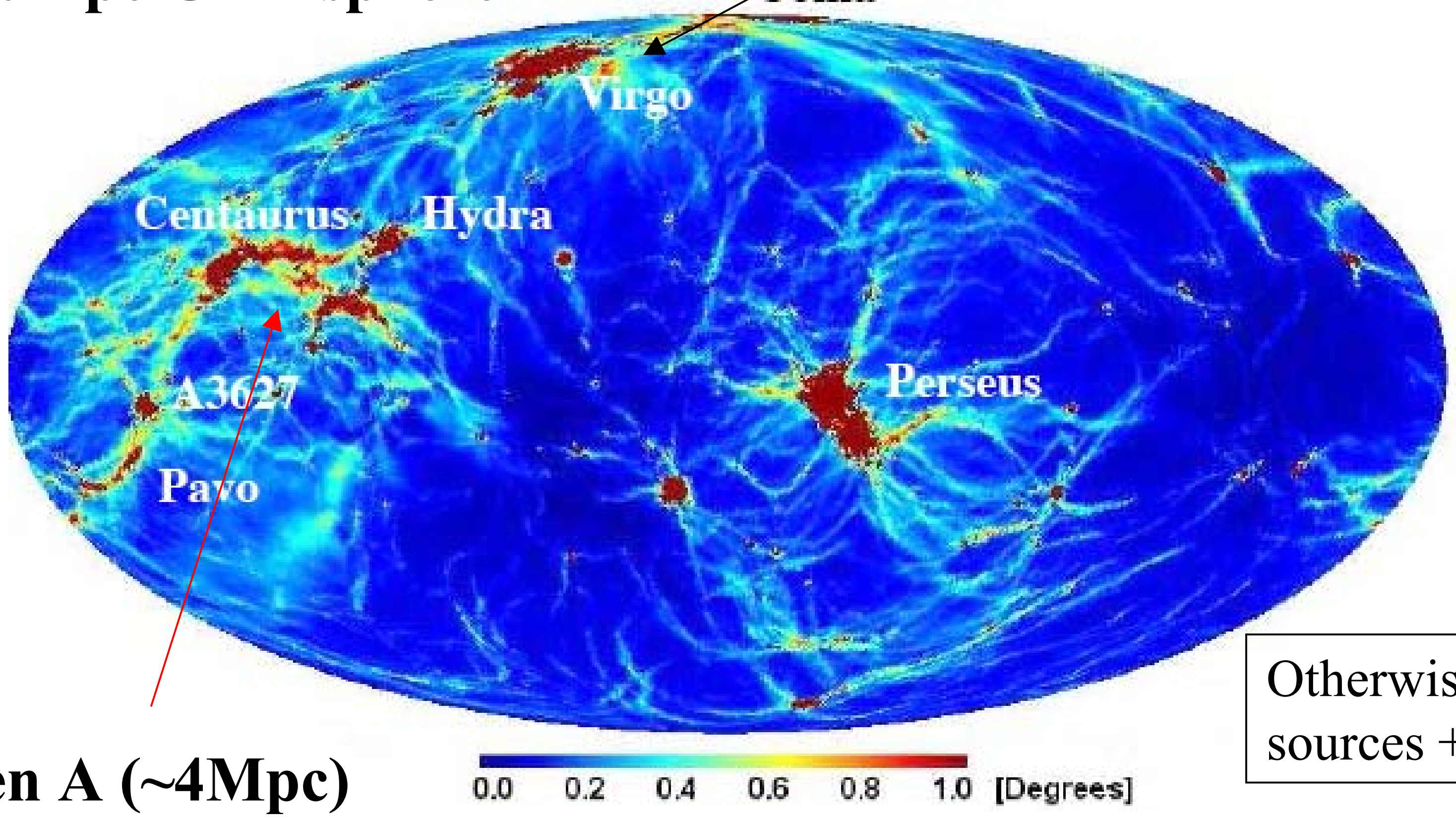
Halo B ~ μ**G**.
Confines E<10^{18},
Distorts trans-
GZK spectrum?

thanks to M.Lemoine

SuperGZK cosmic rays point to their sources if B~nG!

M87 (~20Mpc)

110Mpc GZK sphere



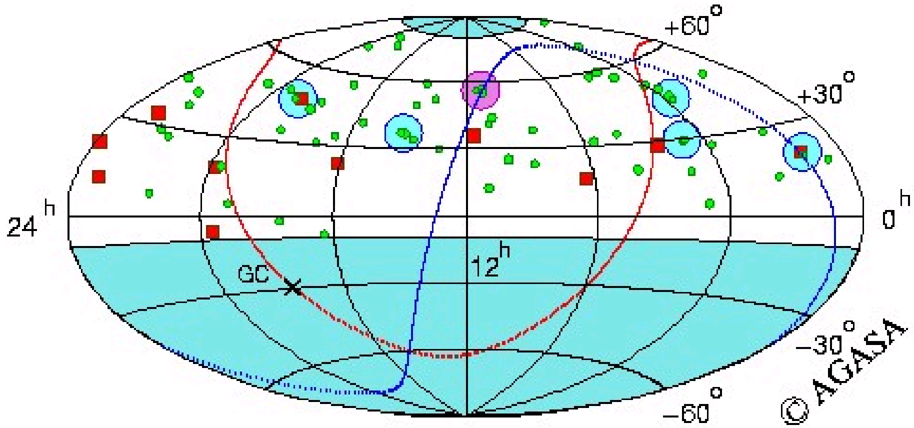
Cen A (~4Mpc)

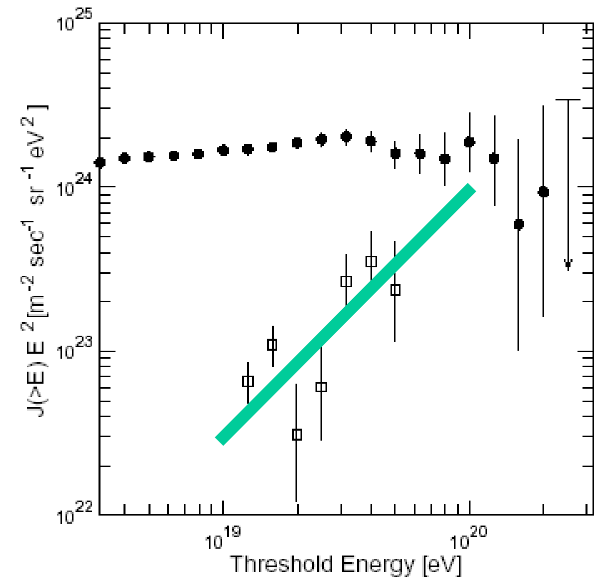
Otherwise, AGN sources + strong B

Simulated magnetic deflection angle for 10^20eV protons. Dolag, et.al, 2004

Anisotropy: AGASA sees 1 triplet, 6 doublets

Green > 4 10^{19}eV, Red > 10^{20}eV

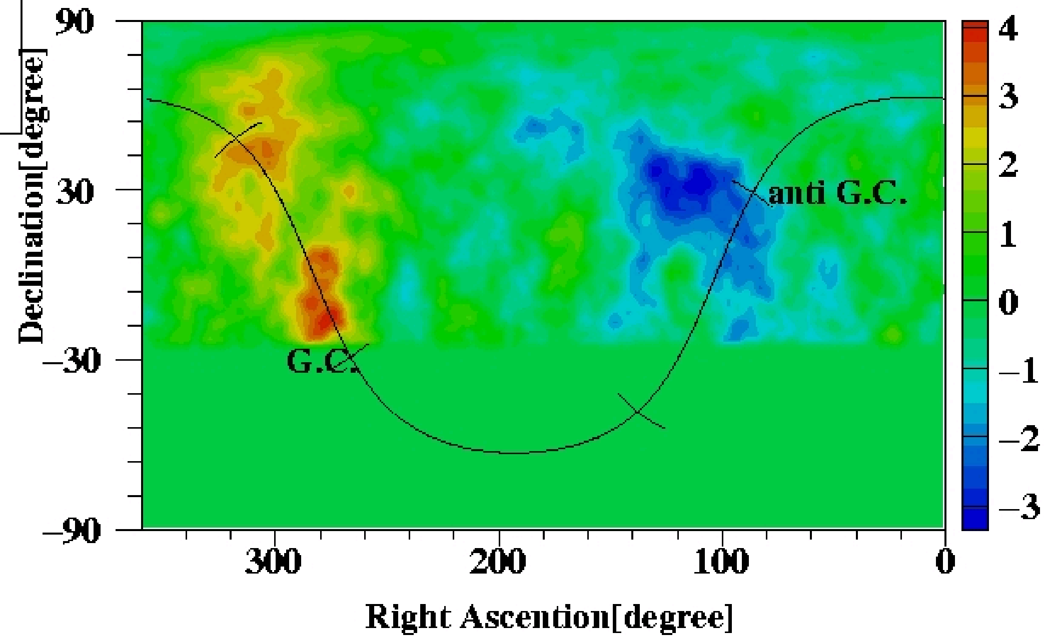




Without clustering, AGASA data are correlated with distant BL LACs (Tinyakov, Tkatchev)

AGASA also sees an excess of ($E>10^{18}$ eV) events from the Galactic center. (TeV gammas?)

HiRes does not see any anisotropy.



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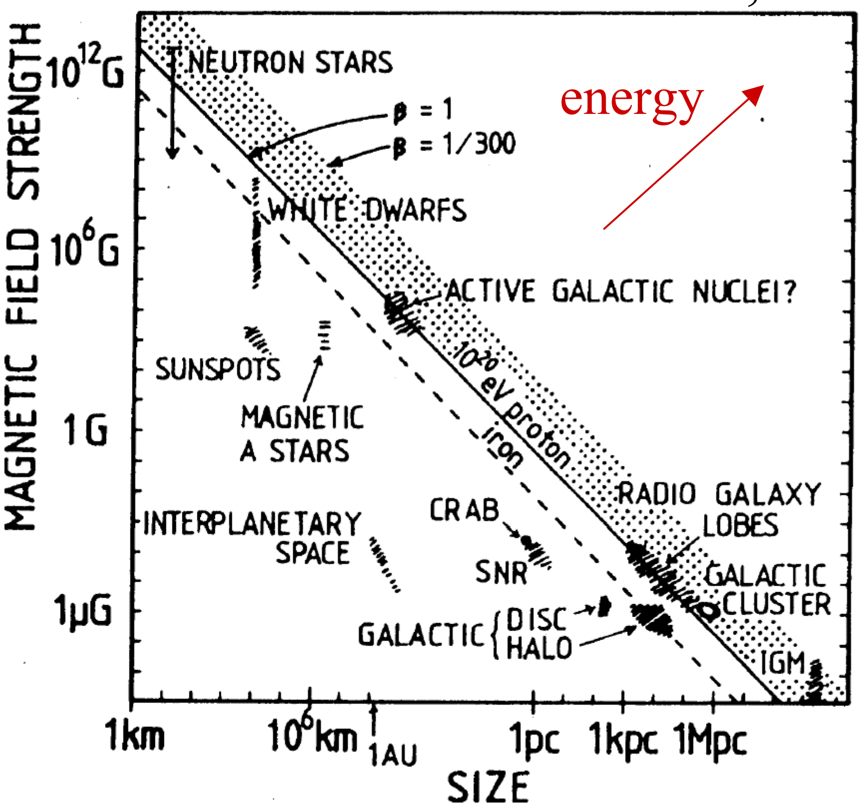
What are the GZK sources???

Hillas, 1984

Zevatrons
via Fermi shock
acceleration?

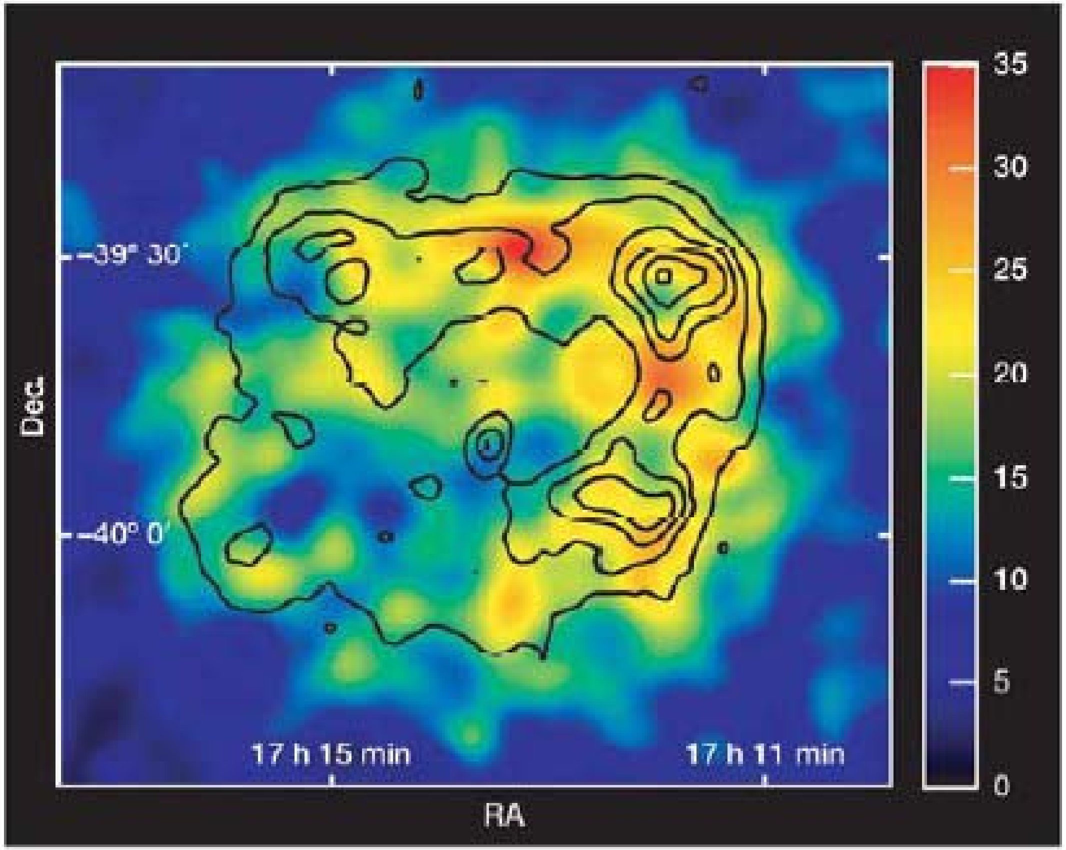


The super-GZK flux is difficult to produce in astrophysical accelerators. But maybe….

GRBs as synchrotron radiation from transient Zevatrons? (Bahcall/Waxman)

Evidence for Pevatrons

Galactic supernova remnant RX J1713.7-3946. (Aharonian, et.al. 2004)



HESS TeV Gamma ray image with ACSA X-ray image overlaid.

TeV fluxes are consistent with the decay of π^0 from p-p interactions in the Pevatron.

X-ray fluxes are consistent with synchrotron radiation

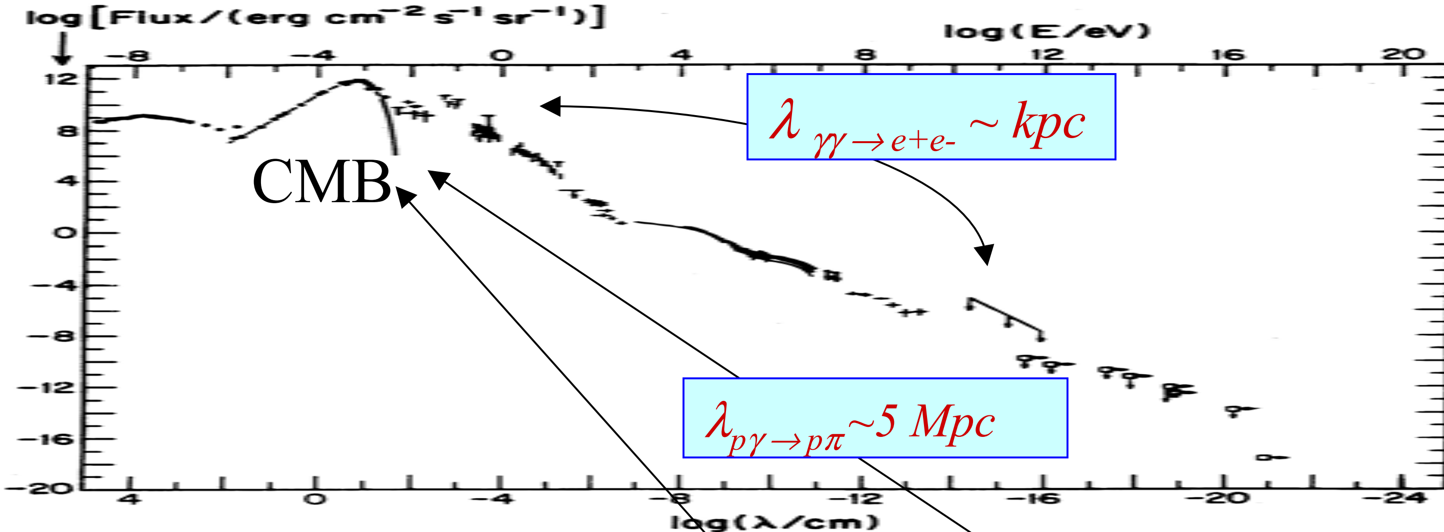
What are the GZK sources (cont.)???

ZeV Linacs via plasma wakefields in Gamma ray bursts?
(Chen, Tajima, Takahashi, 2002)
Testing at SLAC E164

Top-down?
Decay of nearby topological defects or meta-stable super-heavy dark matter. Yields lots of energetic photons→ **Models are constrained by the EGRET limit.** Large Super-GZK neutrino flux. Unlikely to produce nuclei.

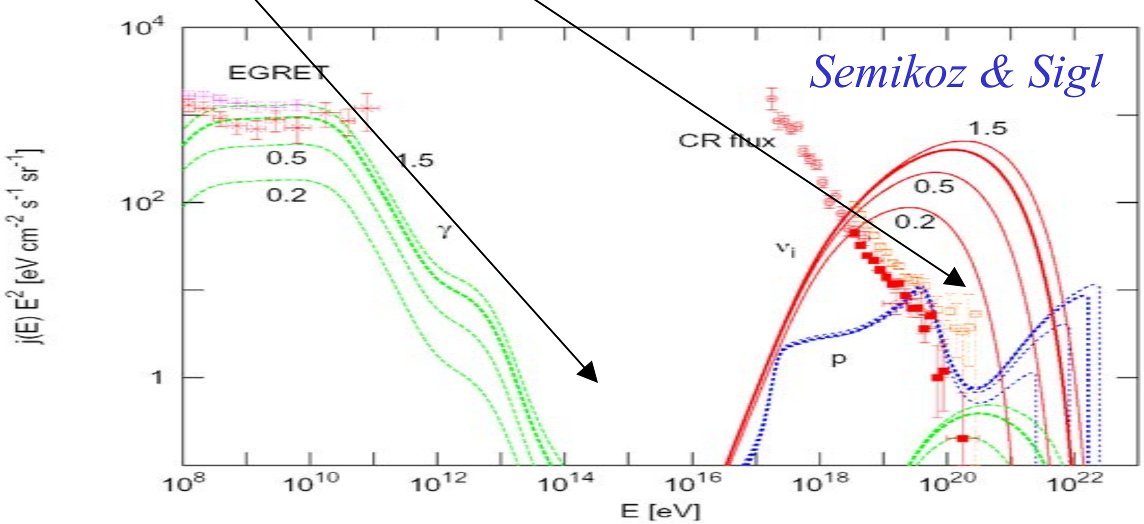
The CMB and diffuse IR makes the universe opaque to >TeV Gammas and super-GZK protons

Observed Photon Flux

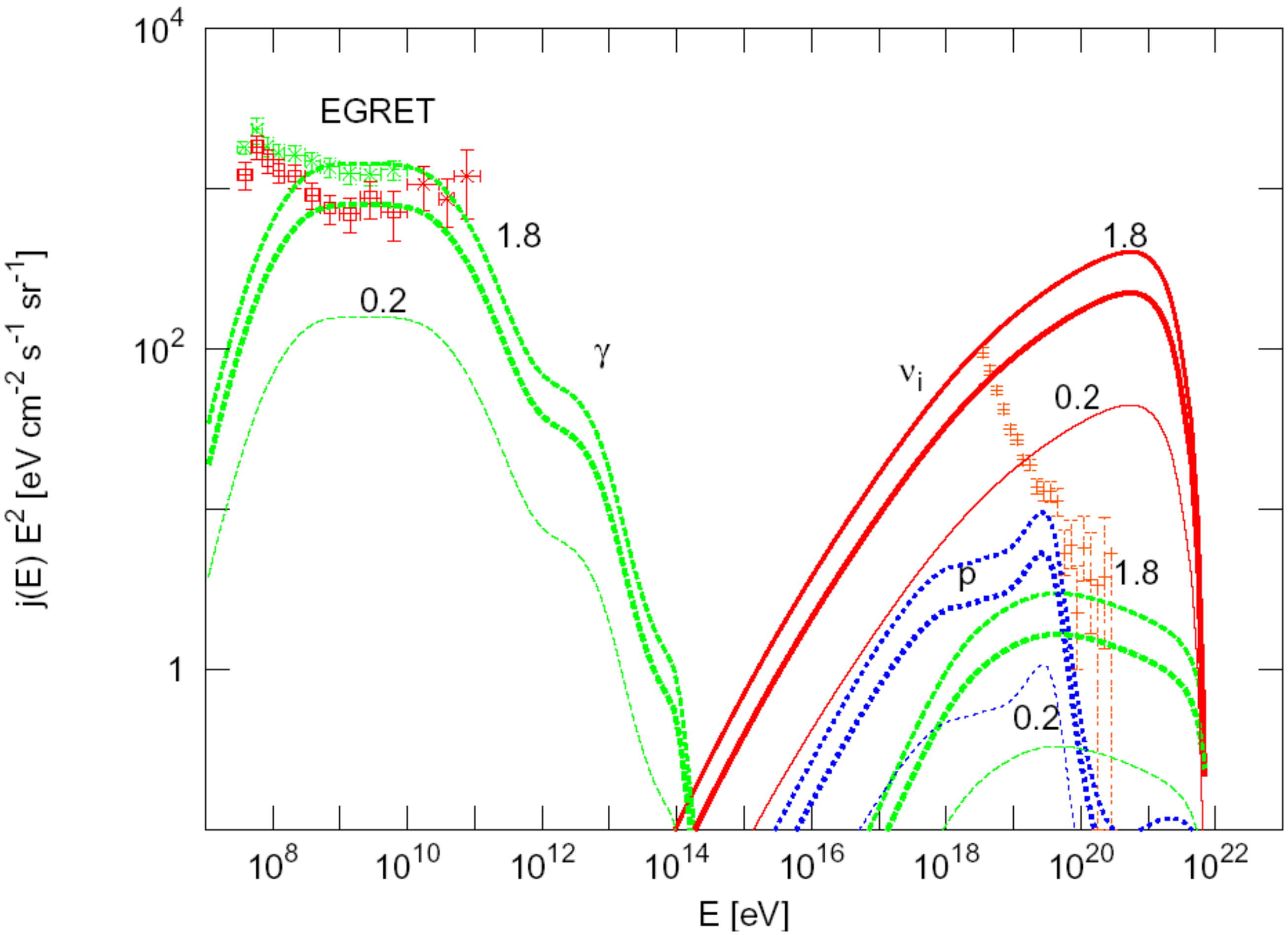


Halzen, Ressell & Turner

Predicted GZK particle fluxes for E^{-2} injection spectrum



UHECR sources also produce GeV gamma rays and UHE neutrinos

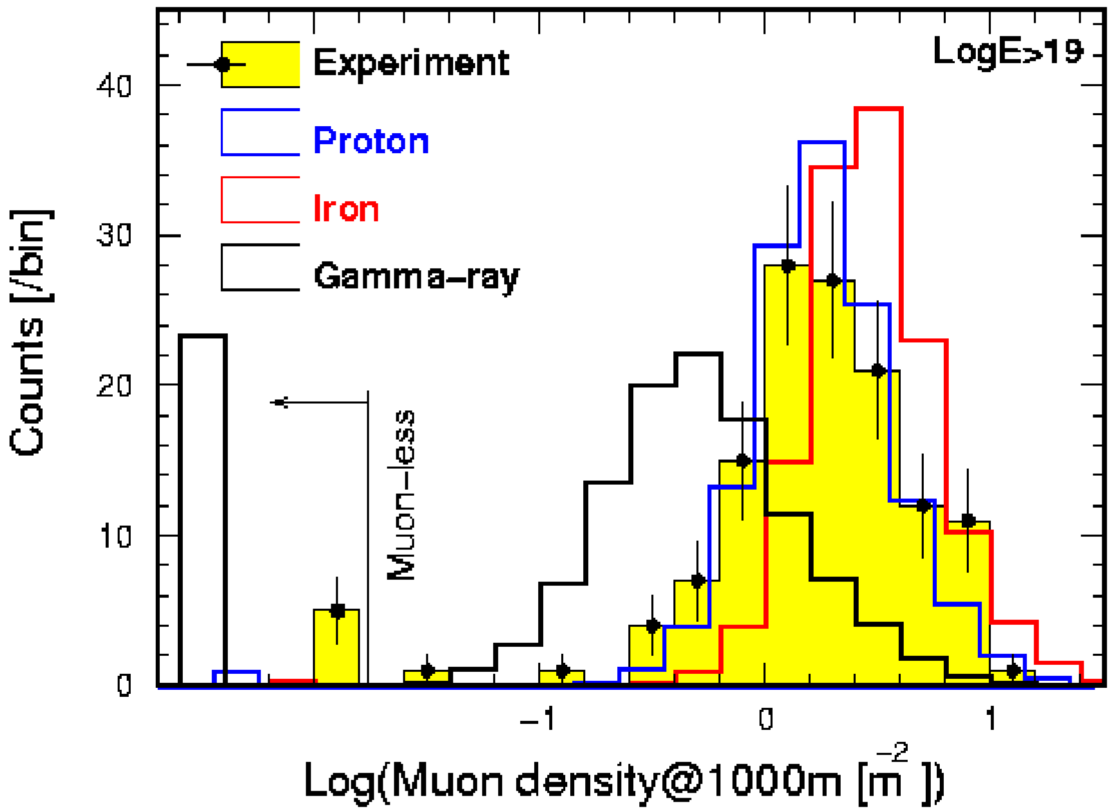


Flux predictions for a top-down model (Semikoz/Sigl)

The EGRET limit constrains model building.

Zburst/Graviburst is ruled out.

AGASA (preliminary) primary composition indicates few UHE gammas



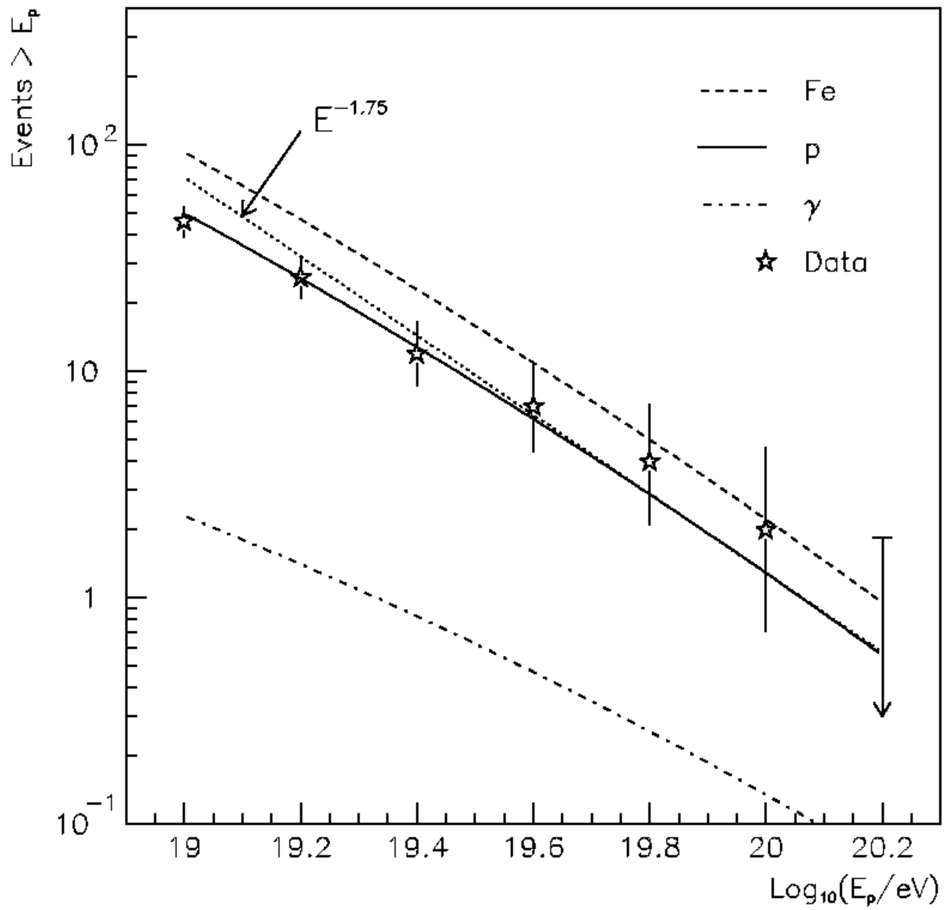
Shielded scintillators measure the muon flux.
→ Primaries are mostly hadronic @ $E>10^{19}$eV

Haverah Park composition also limits UHE gammas

Water tanks are sensitive to horizontal showers (30x vertical atmospheric depth). **Only muons survive the long travel distance.**

Use measured vertical spectrum to predict trigger rate of horizontal events based on various model assumptions.

→ Primaries look hadronic



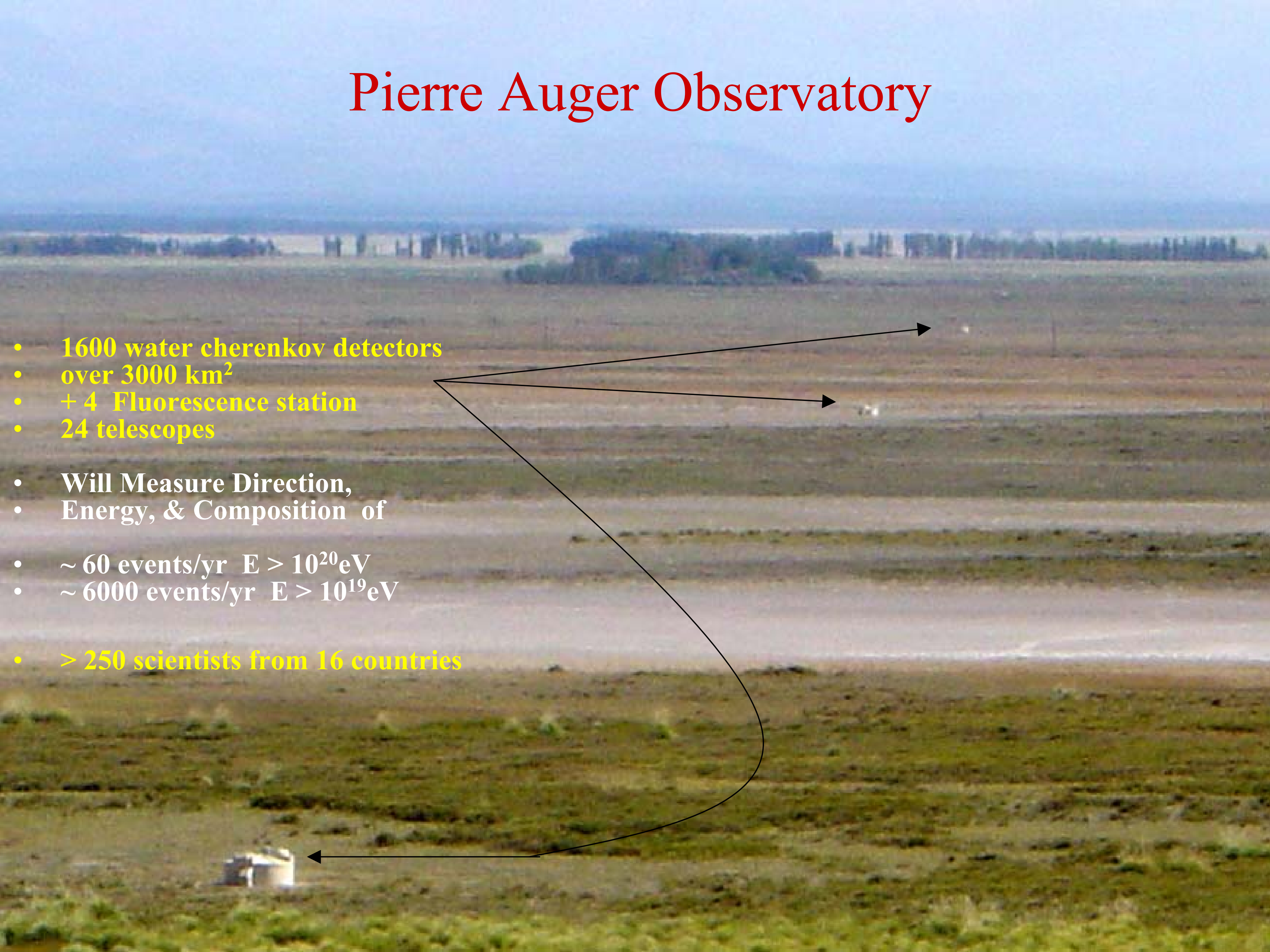
Ave, et.al.

The Future: Cross-calibration of FD and SD with simultaneous measurements

Southern Hemisphere:
Pierre Auger Observatory
(30x AGASA)
Already 1 year of data with partial array

Northern Hemisphere:
Telescope Array
(9x AGASA)
Data in 2007.

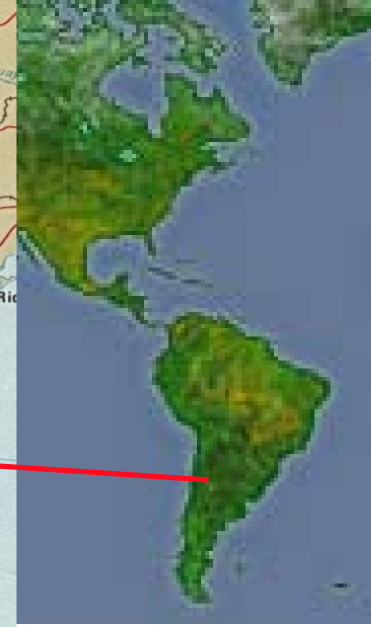
Auger North?

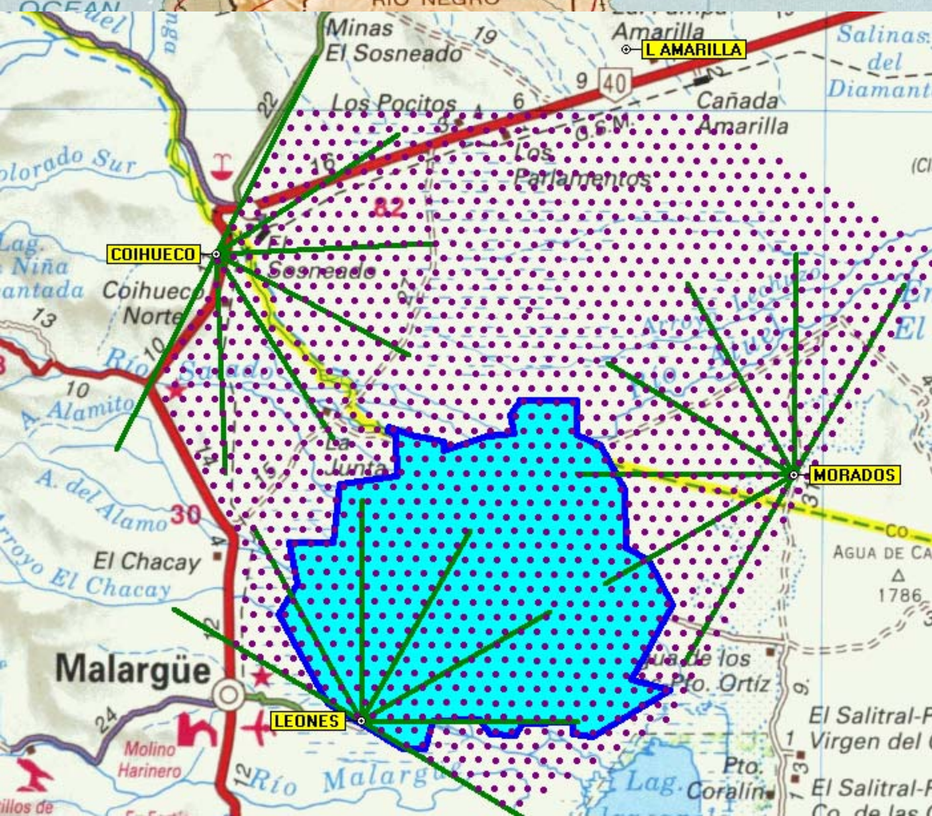

Pierre Auger Observatory
• 1600 water cherenkov detectors
• over 3000 km²
• + 4 Fluorescence station
• 24 telescopes
• Will Measure Direction,
• Energy, & Composition of
• ~ 60 events/yr E > 10²⁰eV
• ~ 6000 events/yr E > 10¹⁹eV
• > 250 scientists from 16 countries

Auger

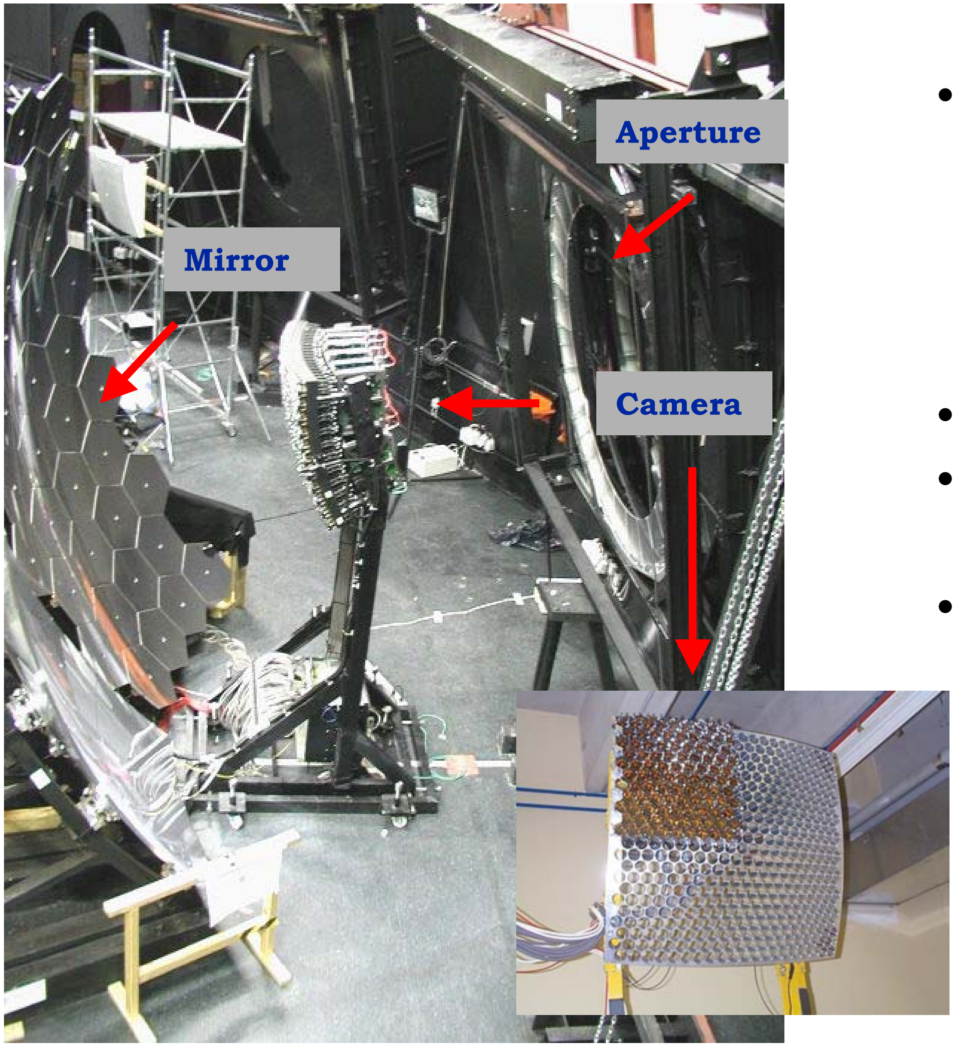
636 tanks deployed!
FD: 3 sites
12 telescopes.

2004 dataset ~ AGASAx2





The Auger Fluorescence Detectors(FD)



- **Measure N_2 fluorescence** from the EM portion of the shower which carries 90% of the shower energy

- 3.4m diameter mirror,
- 440 pixel camera (PMTs)

- Field of view of each telescope:
  - 30 deg by 30 deg by ~30km

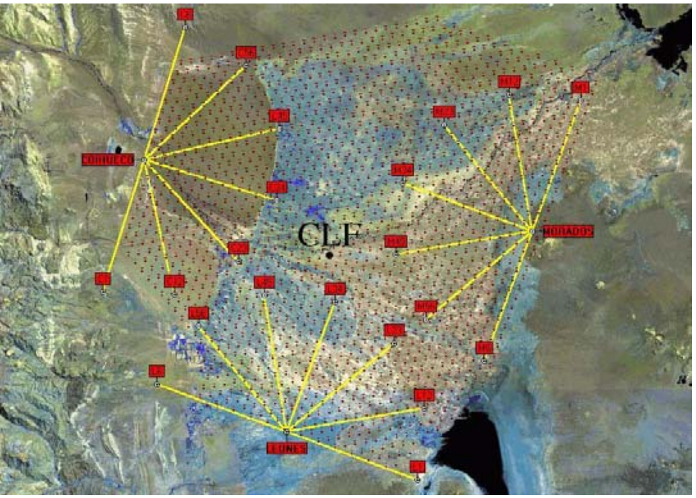
Atmospheric monitoring: LIDAR

- Measure the optical depth via backscattered light

$$\overline{\mathrm{pe}}(\mathrm{R}) = \frac{\mathrm{A}\epsilon\beta(\mathrm{R})}{\mathrm{R}^2}\mathrm{e}^{-2\int_0^{\mathrm{R}}\alpha(r)dr}$$

Extinction coef. α, backscatter coef. β
LIDAR modes: vertical shots, shoot-the-shower

Central Laser Facility (a la HiRES)



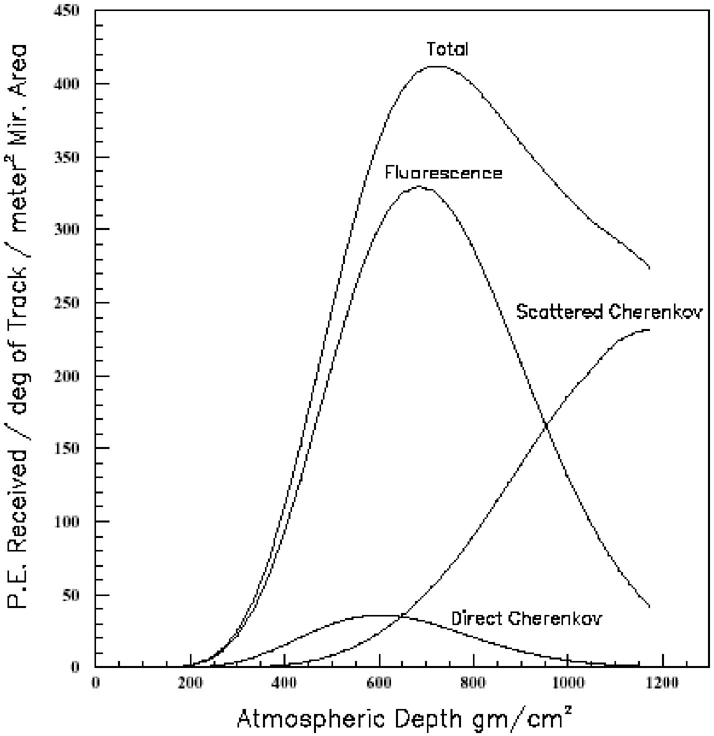
- 355nm laser (vertical + steerable)
- View with FDs to independently measure vertical optical depth
  - Calibrate relative timing between FDs
  - Calibrate timing between FD, SD with optical fiber to nearby tank.
  - Measure FD trigger efficiency as function of laser power

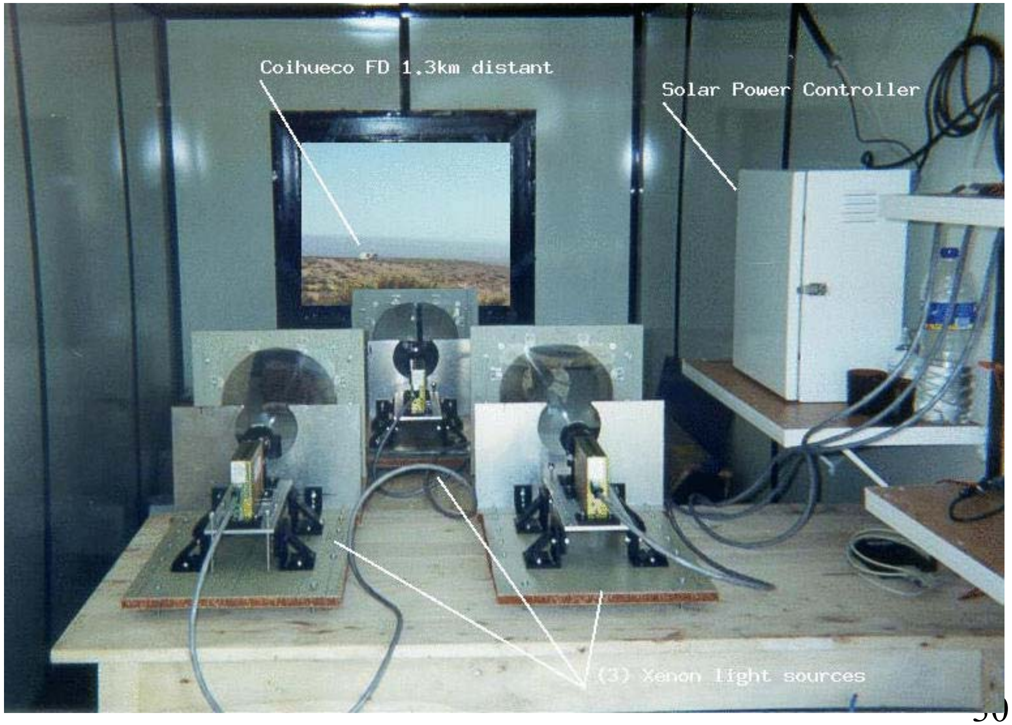
Calibrating the atmosphere monitoring

Radiosonde measures T, P

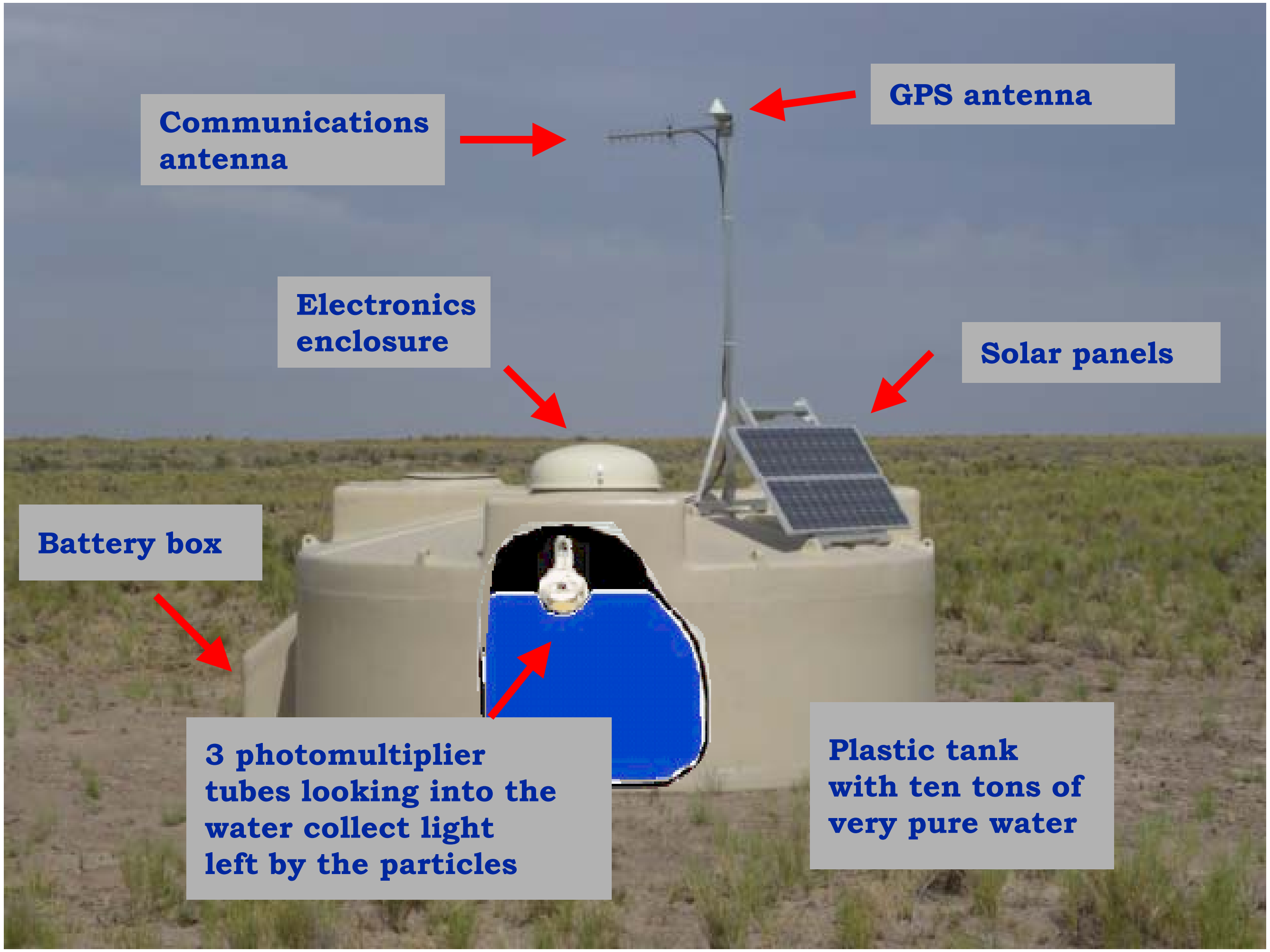
Correcting for Atmospheric Cherenkov contamination

- Scattering comes from molecules (Rayleigh) and aerosols (Mie)
- The Aerosol Phase Function $1/\sigma * d\sigma/d\Omega$ is measured using Xe flash lamps (330, 360, 390nm) aimed across the field of view of each FD.
- Rayleigh, Mie attenuation is modelled using T,P measurements, horizontal LIDAR shots



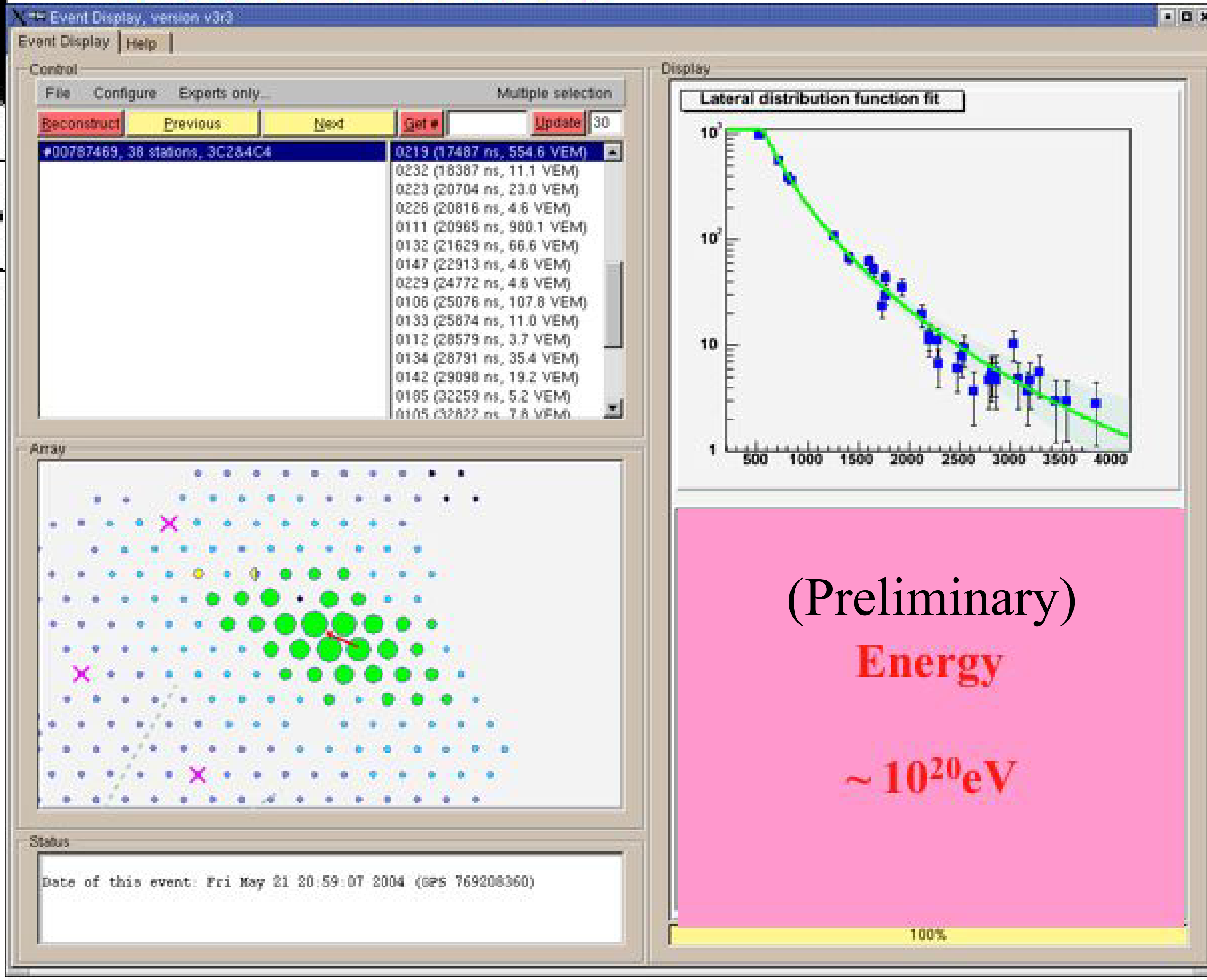


Auger Surface Detectors (SD)



LARGE EVENTS

38 stations - 4km signal!



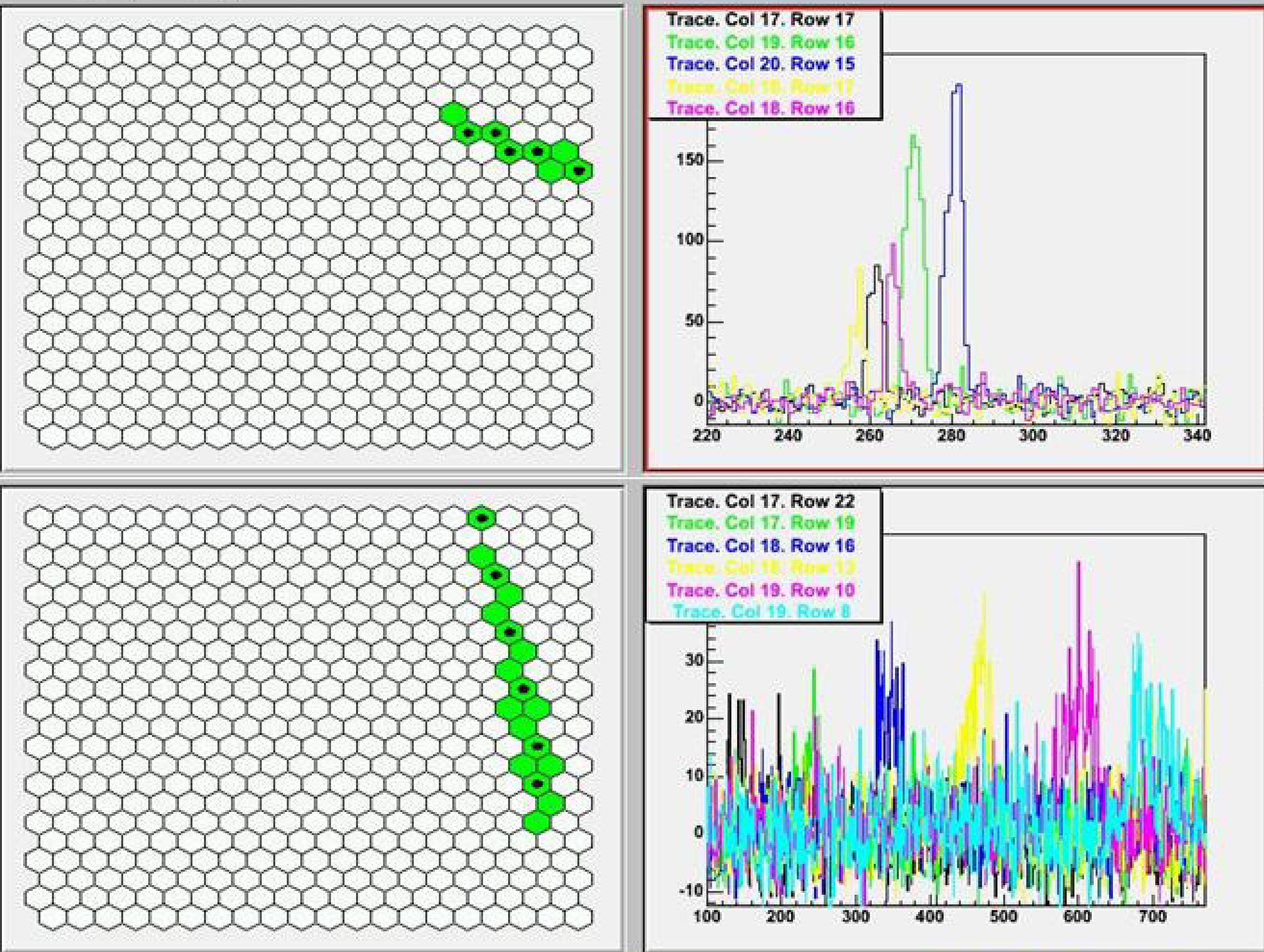
But no energy calibration yet…

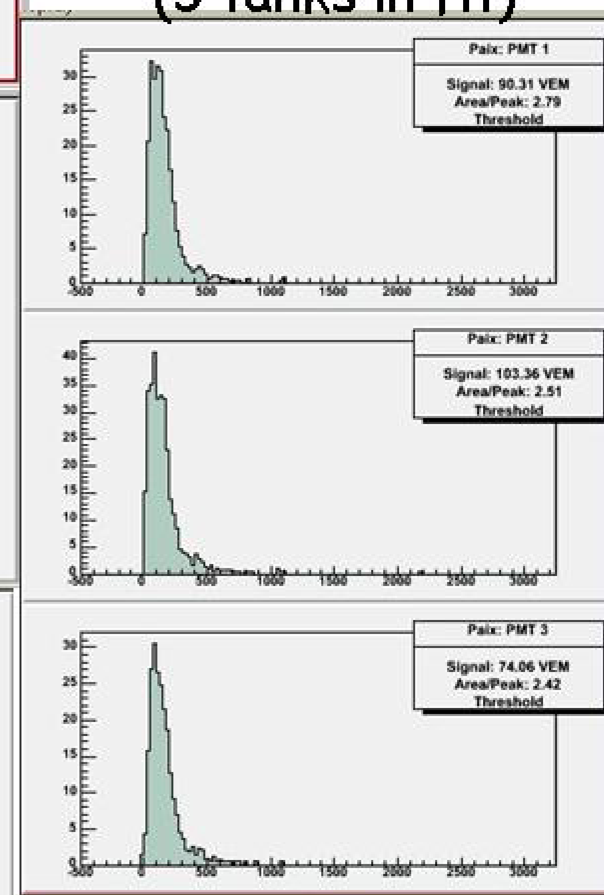
The First Platinum Event

(Stereo Golden Hybrid)

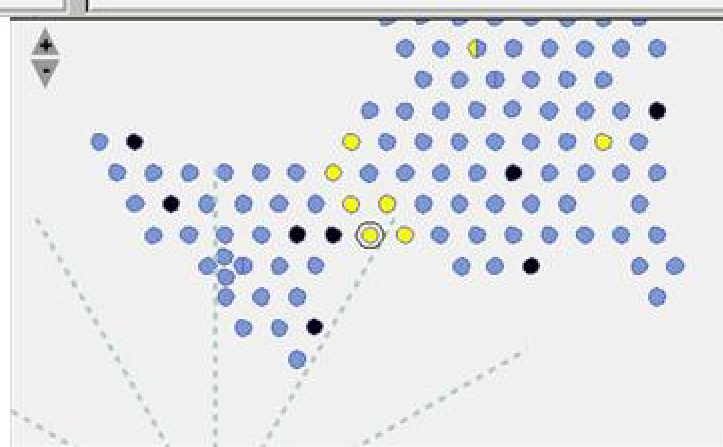
#584032

(5 tanks in fit)





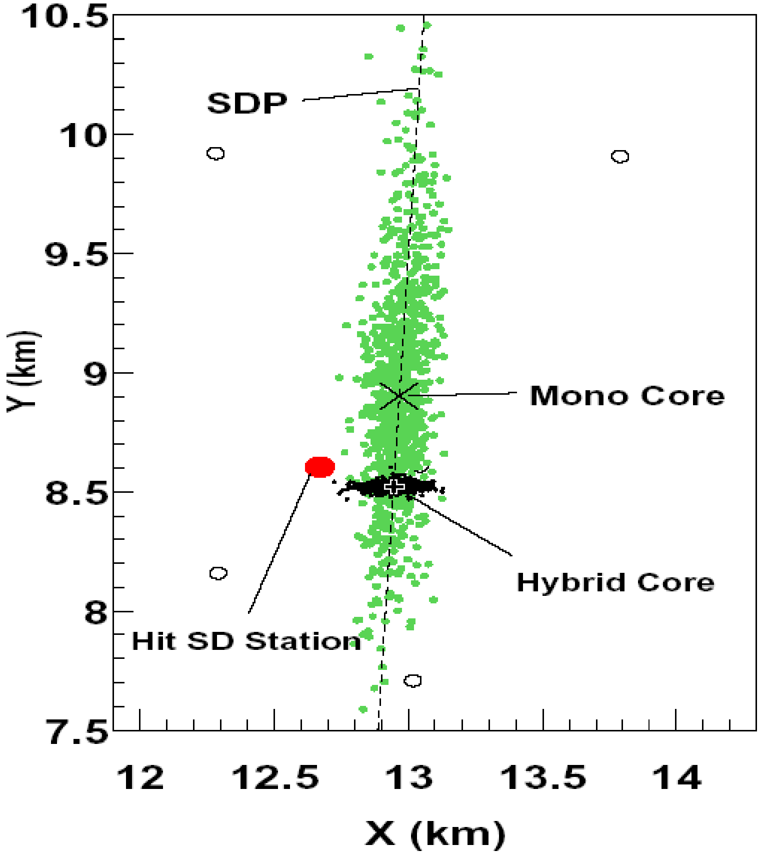
Pierre Auger Observatory



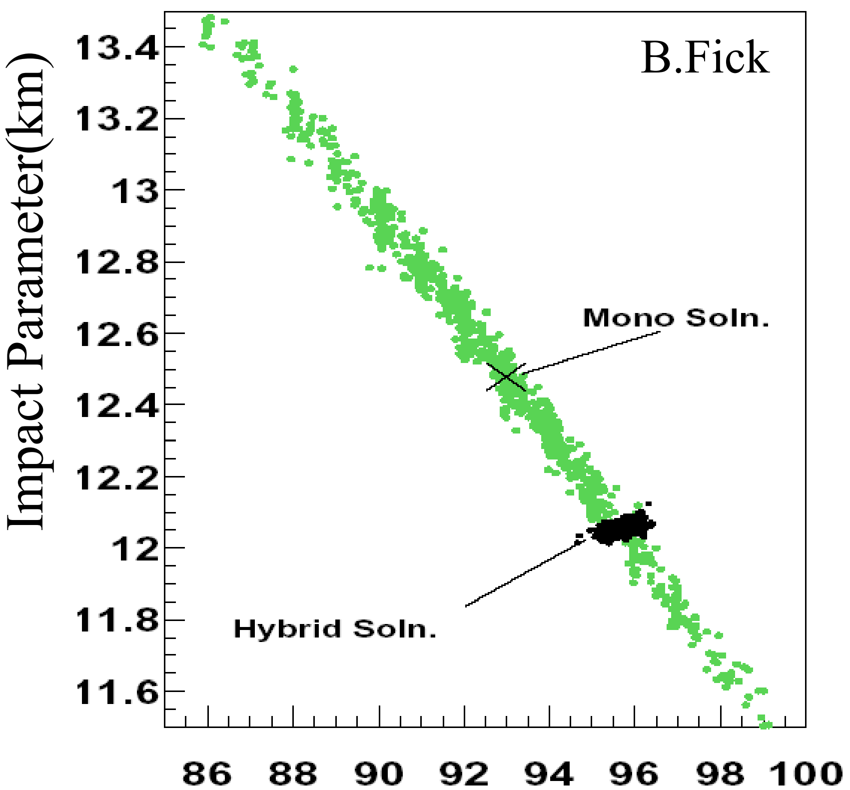
Unprecedented accuracy in geometric recon.

MC study with 1 hit SD tank:

- **Green** = FD-alone reconstructed core pos.
- **Black** = FD + timing from 1 SD tank



Core position on ground



Angle to ground in shower-detector plane (SDP)

Auger goals

- **Auger will:**
  - Measure the Southern sky energy spectrum
    - Cross-calibrate the energy determination methods
    - Hybrid observations give precise geometry.
  - Search for anisotropy, point sources,
  - Identify primary composition via Xmax and muon flux.
  - Validate the air shower models

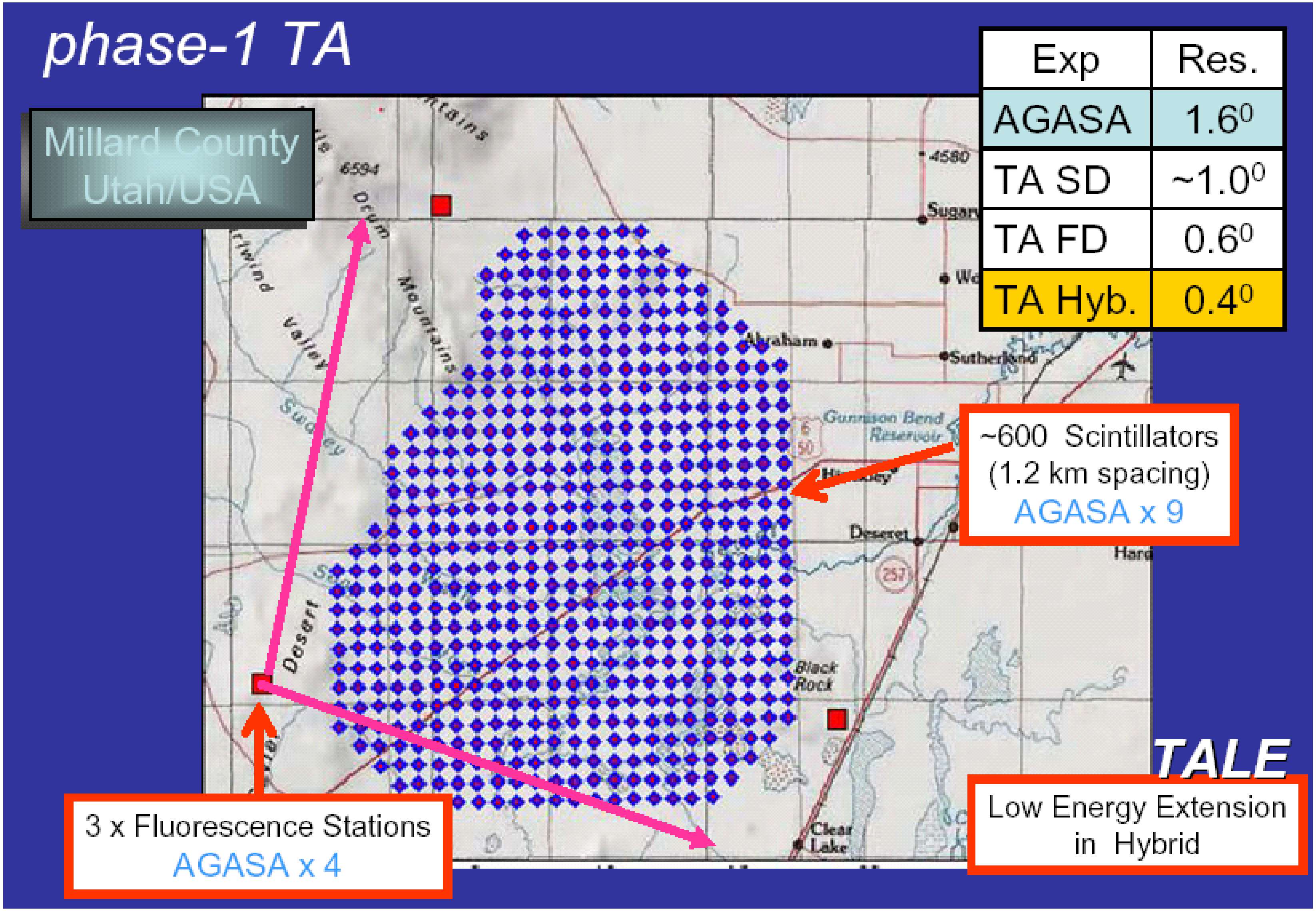
- **Auger will NOT necessarily resolve the HiRes-AGASA controversy**
  - HiRes/AGASA views Northern sky, Auger views South.
  - Auger uses water tanks which are EM calorimeters but S_μ~tracklength
    - $S \sim \gamma + e + 25\,\mu$
  - AGASA used unshielded scintillators which count MIPs and converted γ
    - $S \sim 0.1\,\gamma + e + \mu$

Auger cannot calibrate HiRes/AGASA: Need the Telescope Array

Water Cherenkov measures EM + 25x muons

TA unshielded scintillators measure mainly EM (like AGASA)

Telescope Array (Goal: confirm/refute AGASA spectrum, clustering)



Exp	Res.
AGASA	1.6^0
TA SD	$\sim 1.0^0$
TA FD	0.6^0
TA Hyb.	0.4^0

20 stations + 2FD deployed. Run starts 2007.

Summary

- **SuperGZK cosmic rays observations are a real conundrum**
  - AGASA/HiRes discrepancy, but both see them
  - Sources unknown
    - CRs don't point back to obvious astrophysical sources
    - Top-down models constrained by gamma ray flux
      - Muon flux measurements favor hadronic primaries
  - If no sources within GZK sphere, then Lorentz invariance may be violated at large energies. Or cross-sections are suppressed.
- **Multipronged investigation of cosmic ray sources:**
  - Auger, HiRes Stereo, Telescope Array will investigate UHECR
  - UHE Neutrino detectors: Auger, FORTE, ANITA will test models by constraining both the source and the GZK neutrino flux.
  - HESS, MAGIC, VERITAS, GLAST will probe gamma ray sources.

- **Auger: First results at ICRC, August, 2005. Also new HiRes results.**

- **Lot's of data→It's a very exciting time to be in particle astrophysics!**