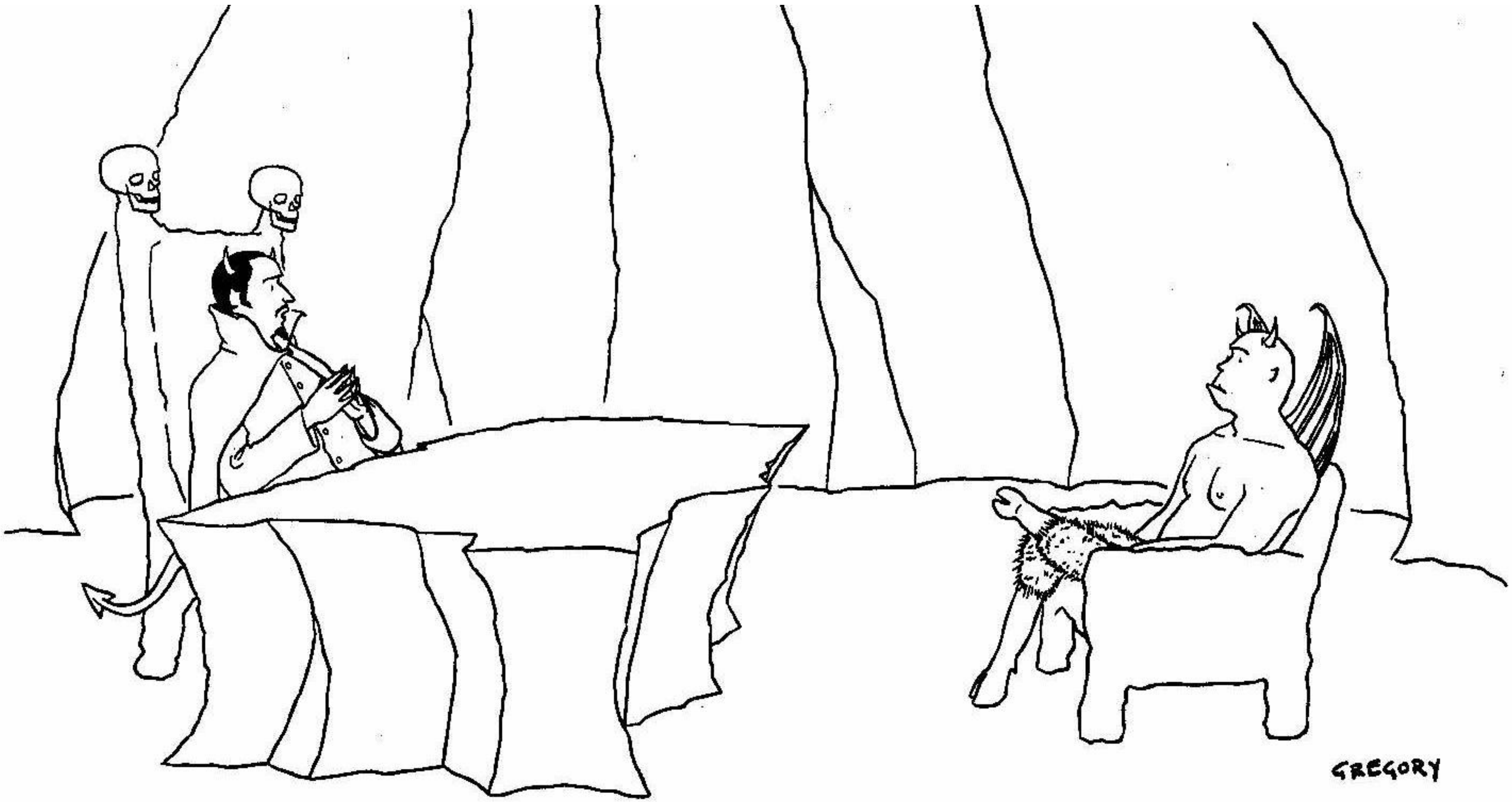
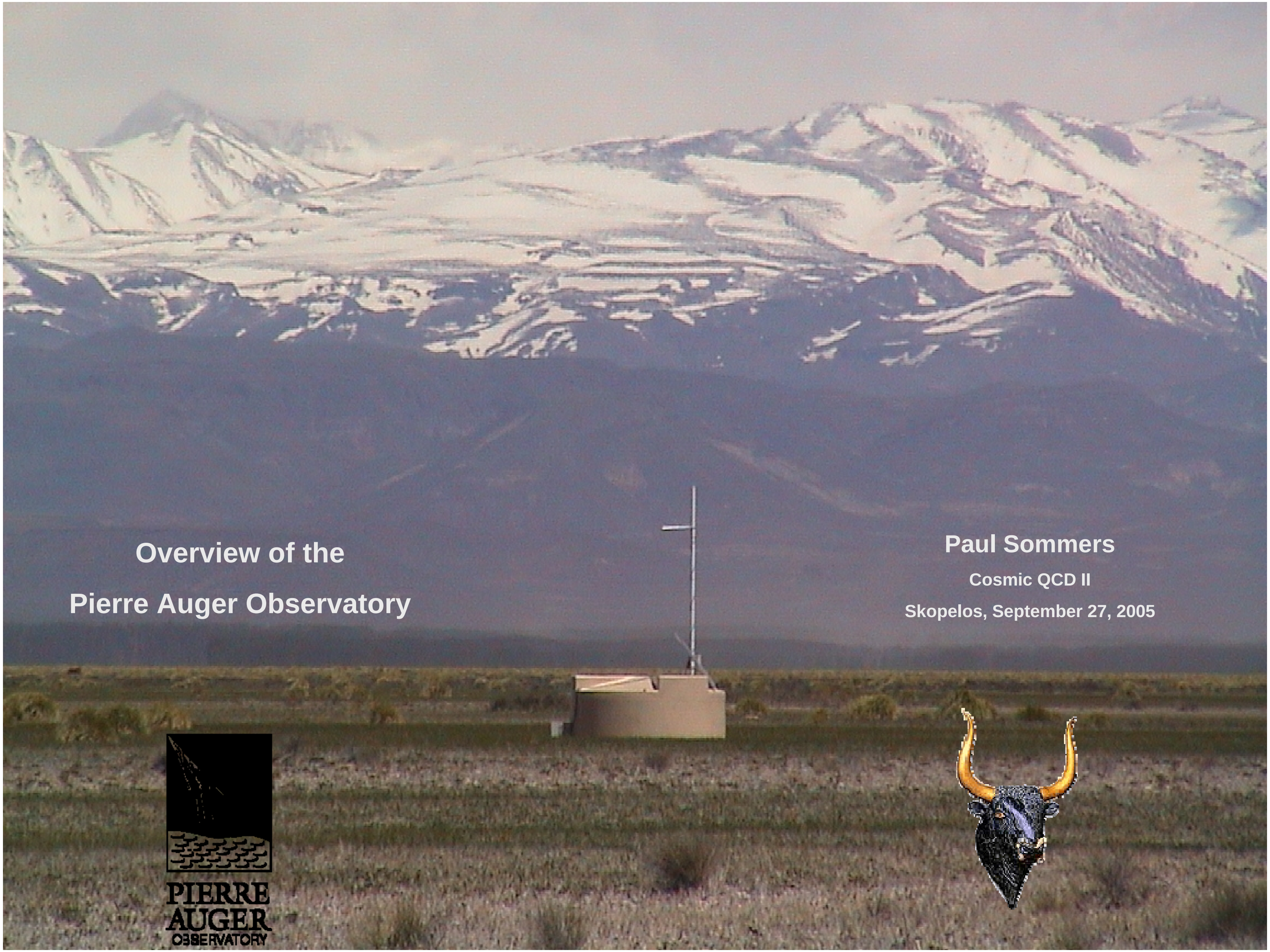


"I need someone well versed in the art of torture—do you know PowerPoint?"

From the *New Yorker*



Overview of the Pierre Auger Observatory

Paul Sommers

Cosmic QCD II

Skopelos, September 27, 2005

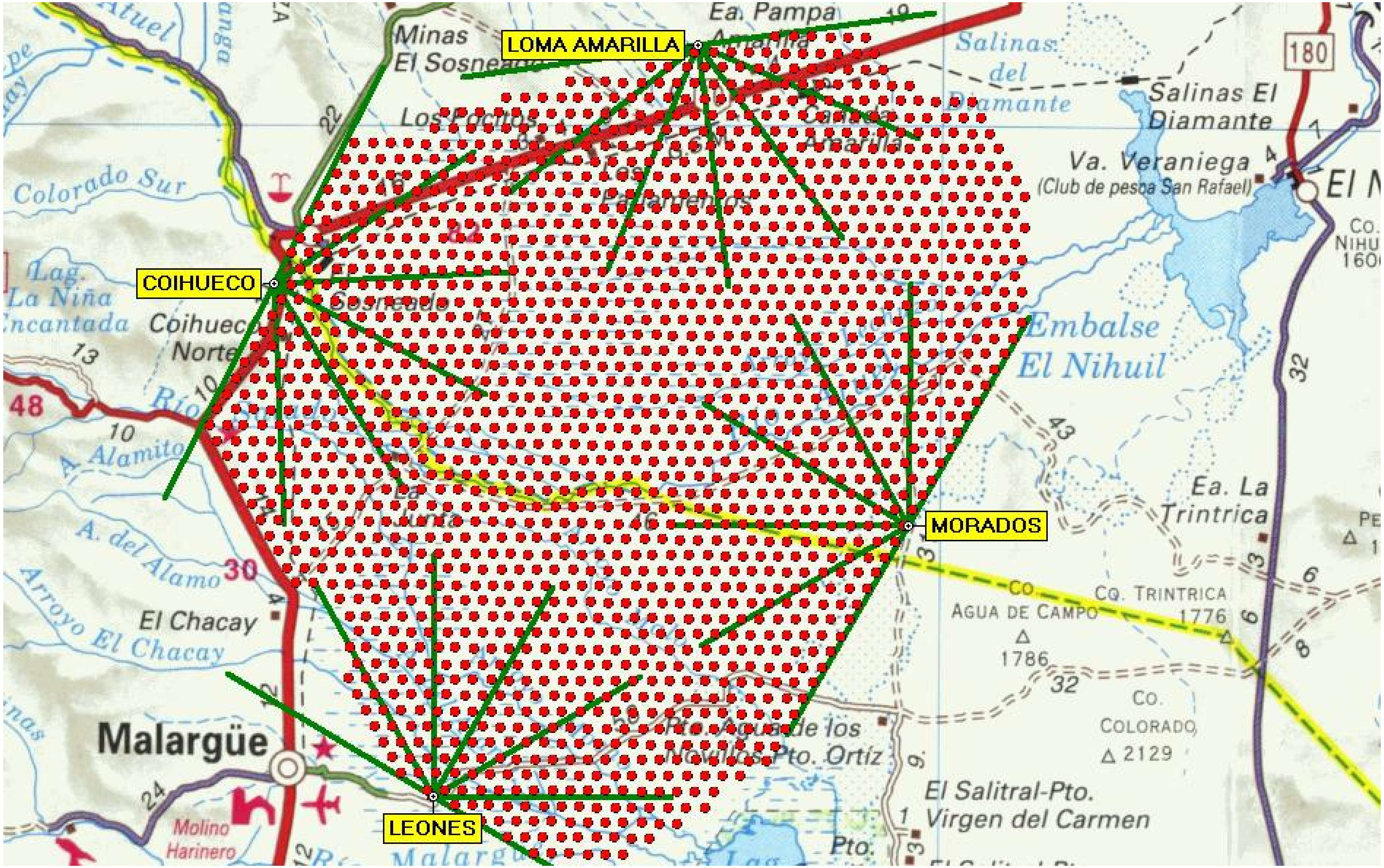
35° South, Argentina, Mendoza, Malargue

Spokespersons:
Jim Cronin (Emeritus)
Alan Watson
Giorgio Matthiae

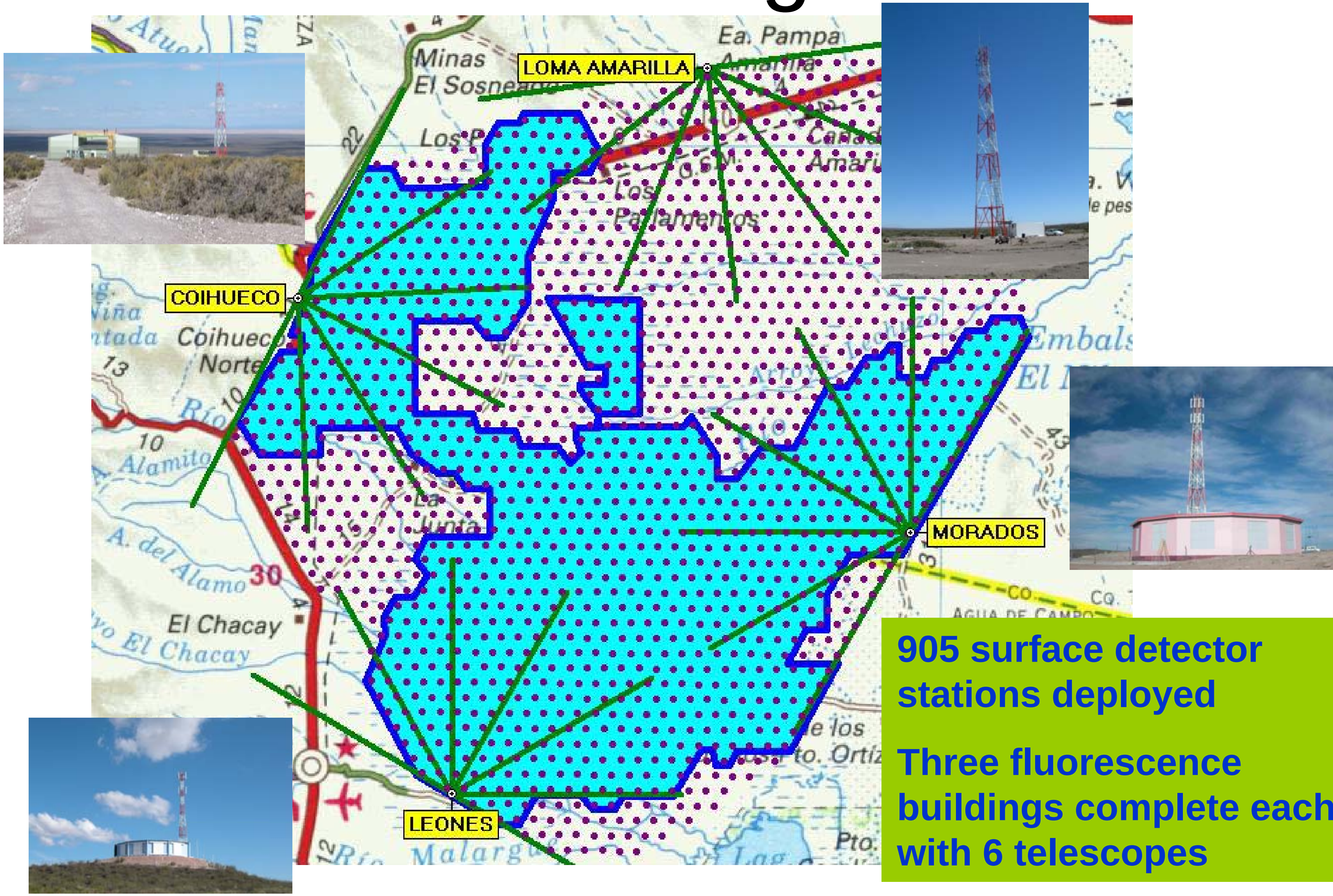
Collaboration:
>250 researchers
from 50 institutions and 15 countries:
Argentina, Australia, Bolivia, Brazil, Czech Republic, France, Germany, Italy, Mexico, Poland, Slovenia, Spain United Kingdom, USA, Vietnam

PIERRE AUGER OBSERVATORY

Layout of Auger South



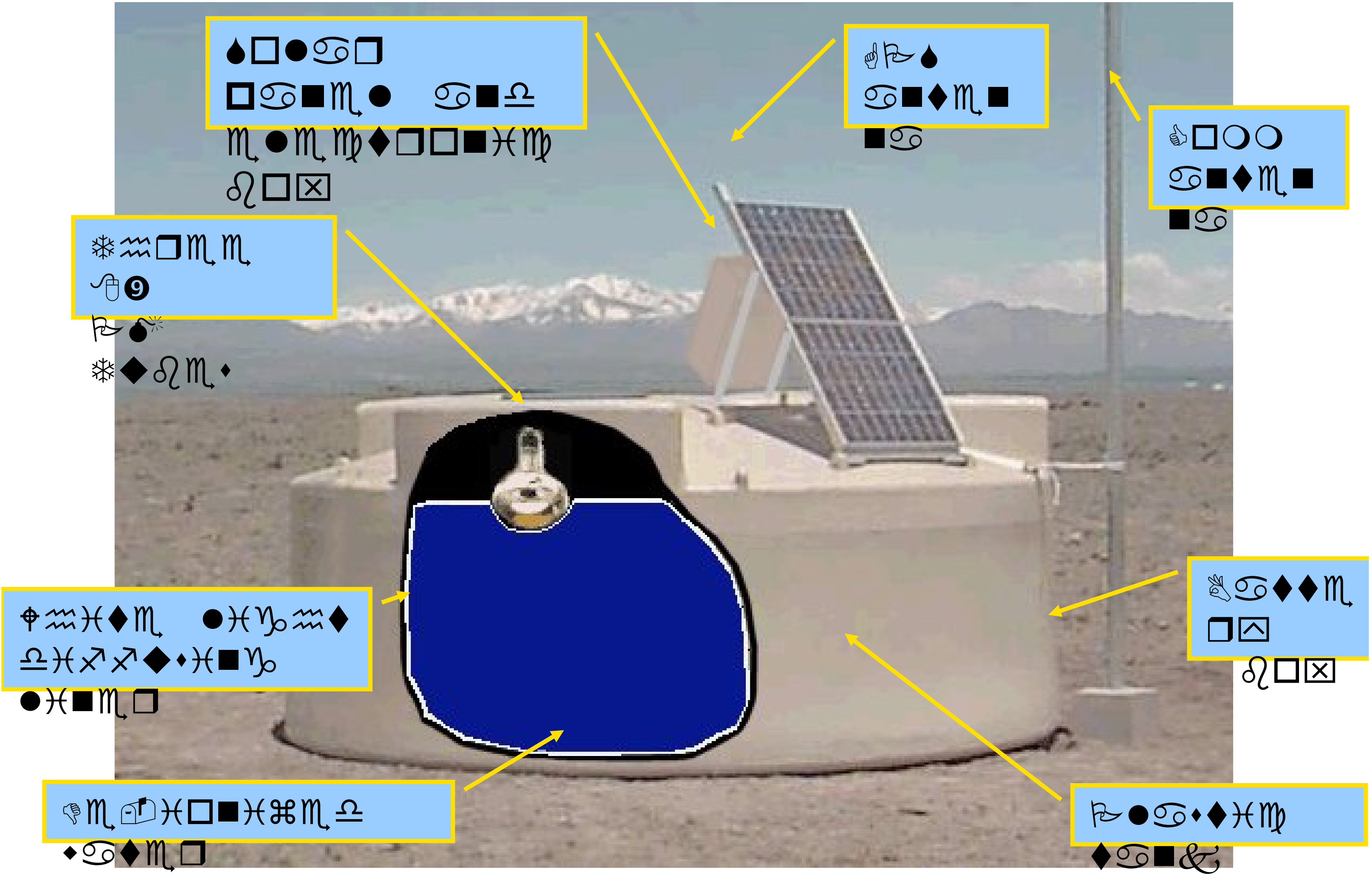
Construction Progress



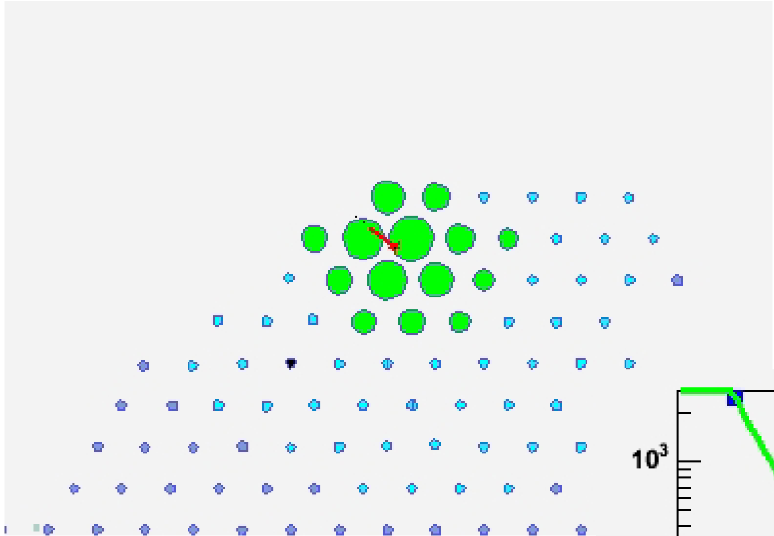
905 surface detector stations deployed

Three fluorescence buildings complete each with 6 telescopes

Auger Water Cherenkov Detector

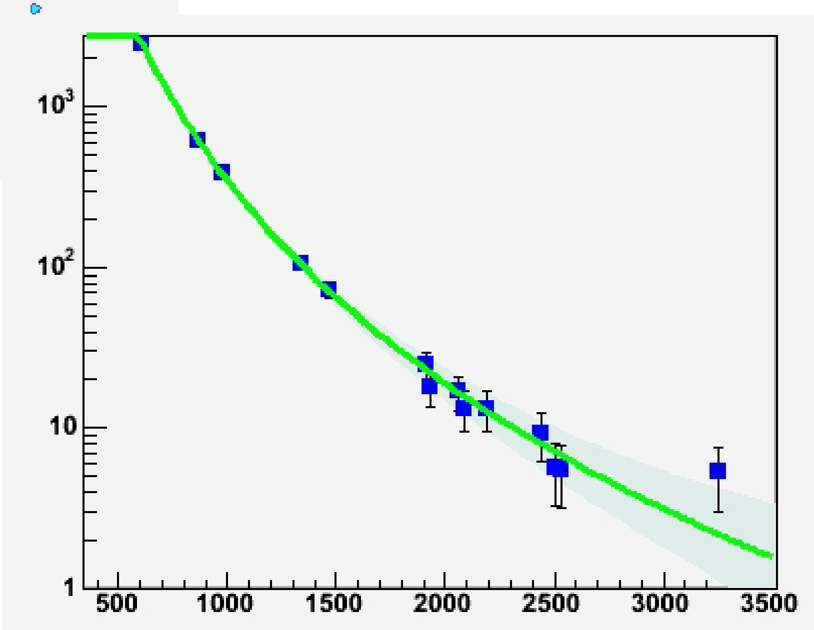


Typical (nice) Event



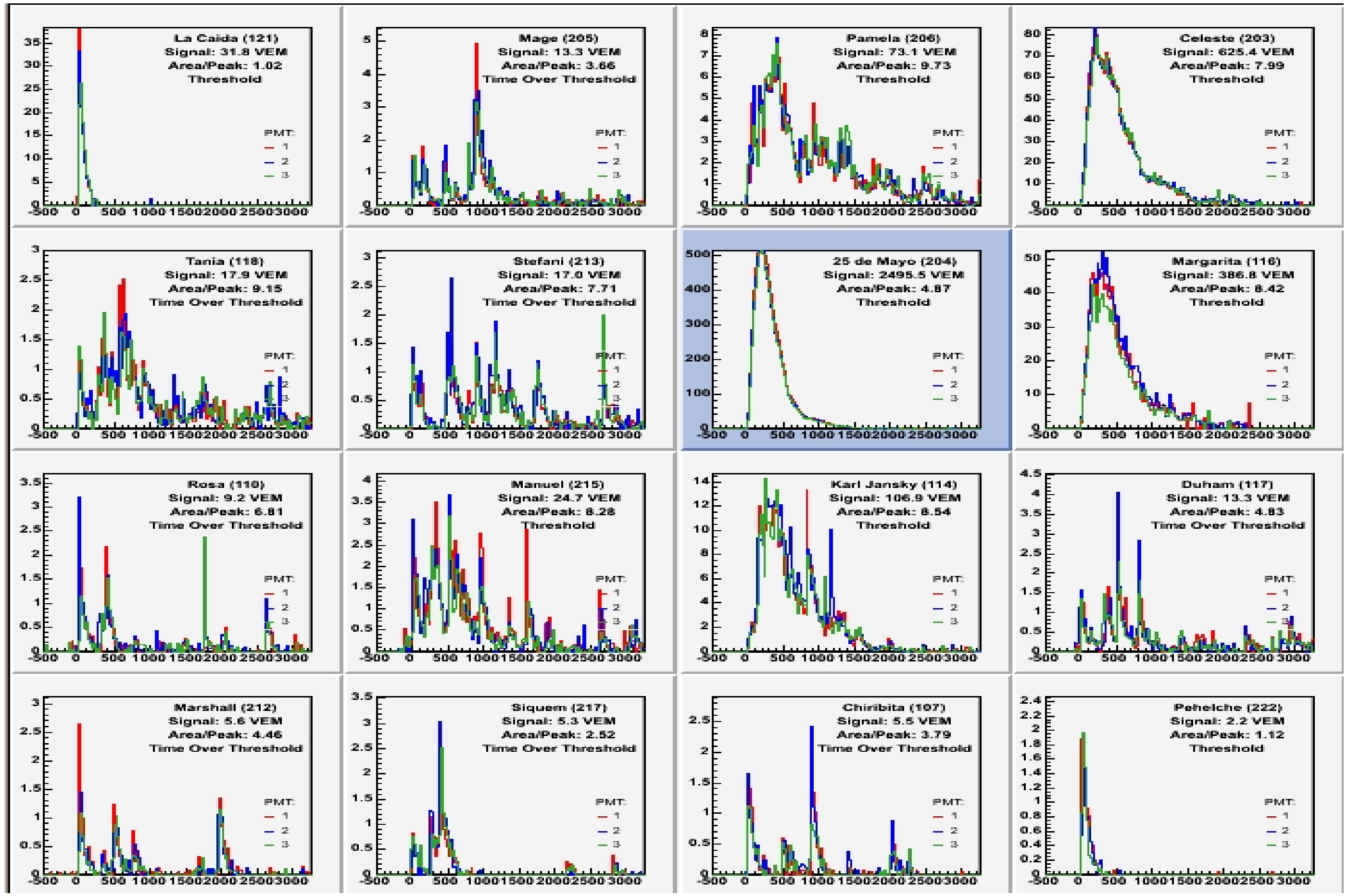
Surface array view

PRELIMINARY analysis shows
zenith angle 34°
energy ~75 EeV



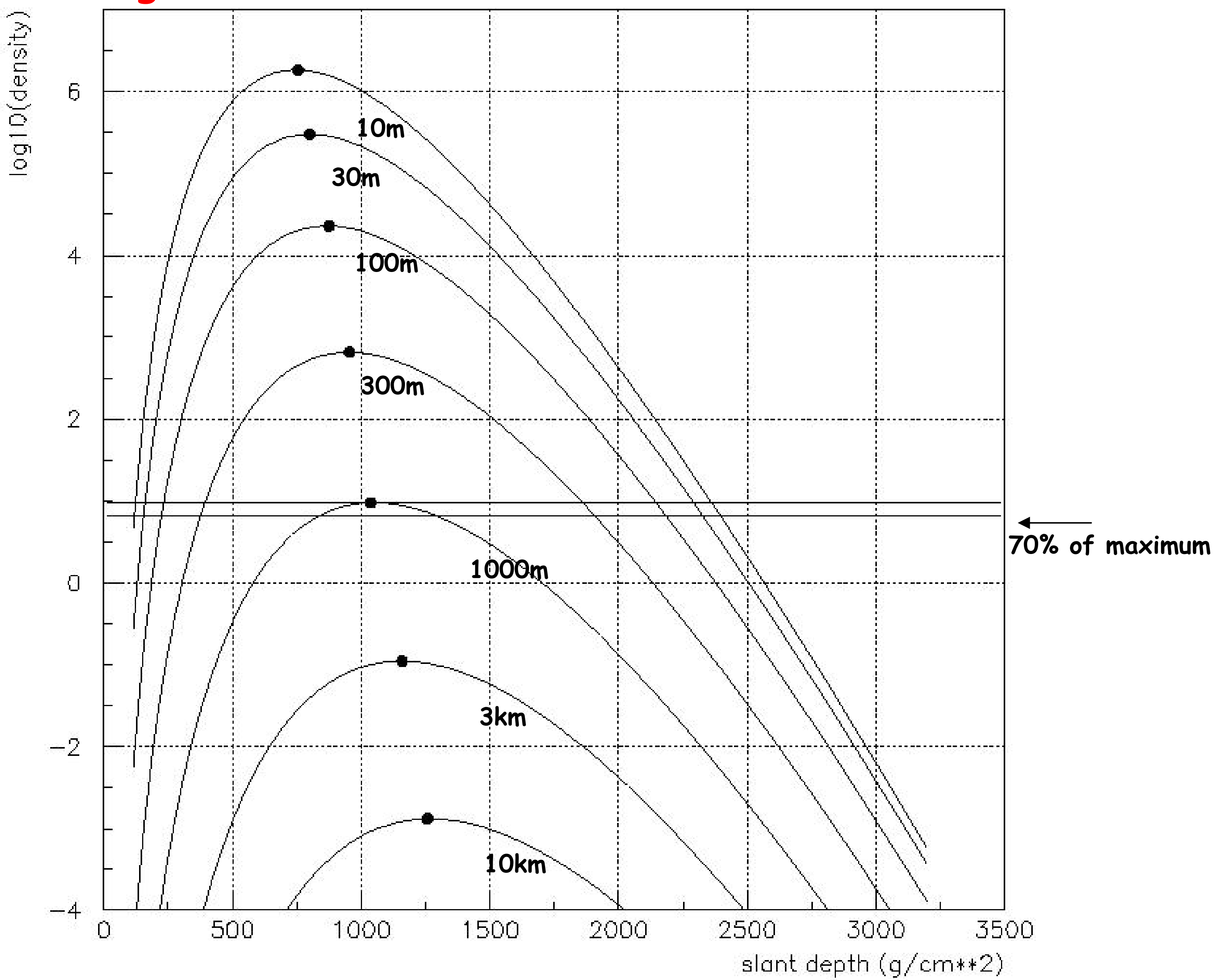
Lateral distribution function fit

Typical (nice) Event – (con`d)



PRELIMINARY analysis shows
zenith angle 34°, energy ~75 EeV

Longitudinal Profile at Various Core Distances



Gaisser-Hillas longitudinal profile with NKG lateral distribution function at each age, in Moliere units converted to meters at depth = 850 g/cm^2.

Surface Array Method of Energy Determination

Cosmic ray energy is proportional to N_{max} (maximum shower size).

Particle density at 1000m core distance also scales with energy.

Measure this detector signal ("S_{1000}") at 1 km from the core.

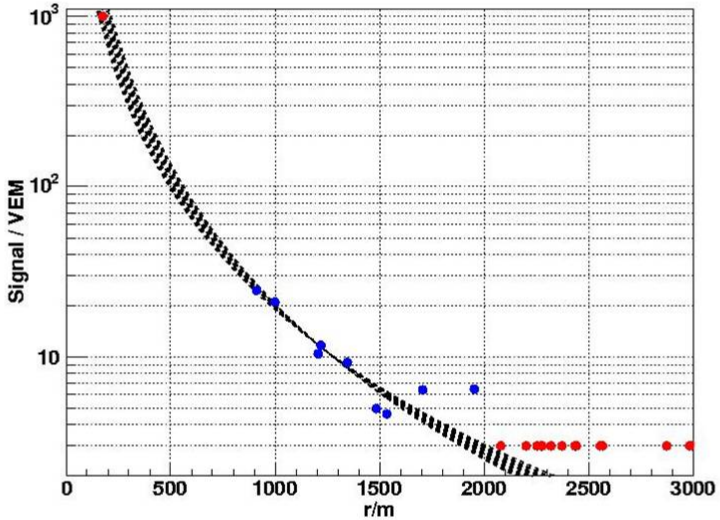
[You have to interpolate between measurements at greater and lesser distances.]

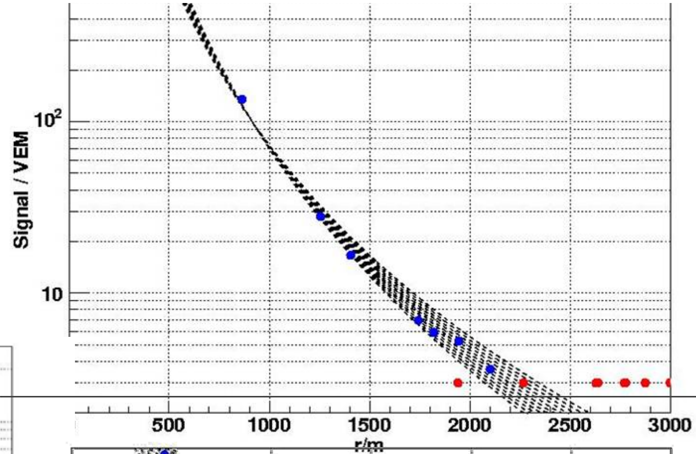
For greater accuracy, use non-linear interpolation -- based on expected, or average measured, Lateral Distribution Function (LDF) .

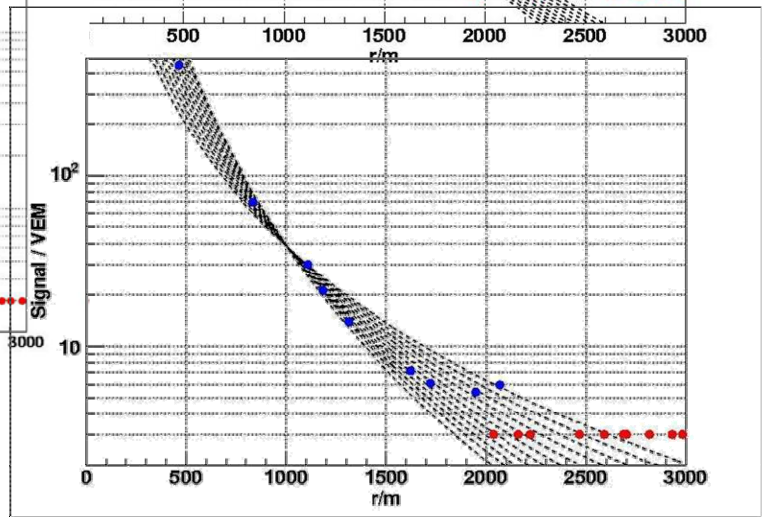
Example LDF (modified NKG function): $S(r) = r^{-\eta+(r/4000m)}$

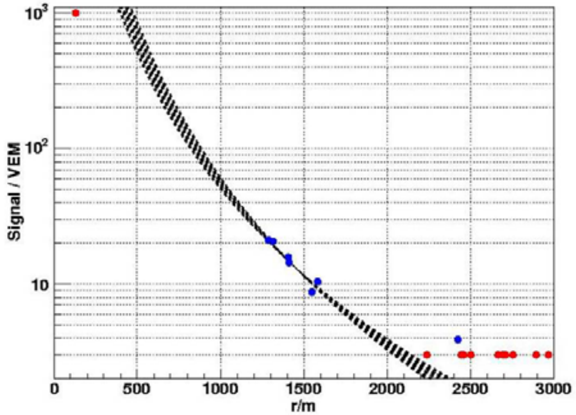
$\eta = \eta(\theta) \sim 3.8$

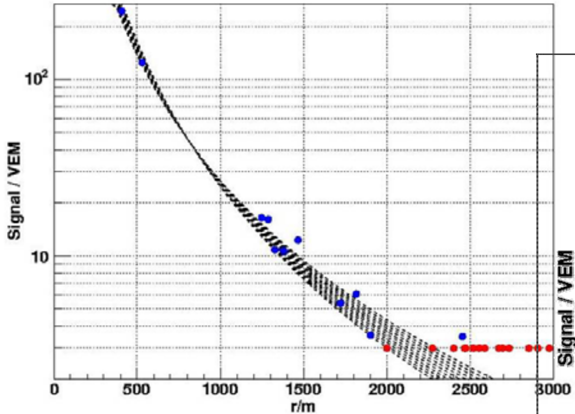
The signal at 1000 meters from the core (S_{1000}) is (almost) insensitive to the specific LDF that is used to fit the detector signals











[D. Newton]

OK. We can measure S_{1000} reliably. How do we convert that to energy E?

[The conversion factor must depend on zenith angle θ.]

Two step procedure:

1. Find the S(1000) values at different zenith angles that pertain to a single air shower energy. As "energy parameter" use S38, which is the S(1000) value that a shower would have had if it had arrived at $\theta=38°$ (median zenith angle).

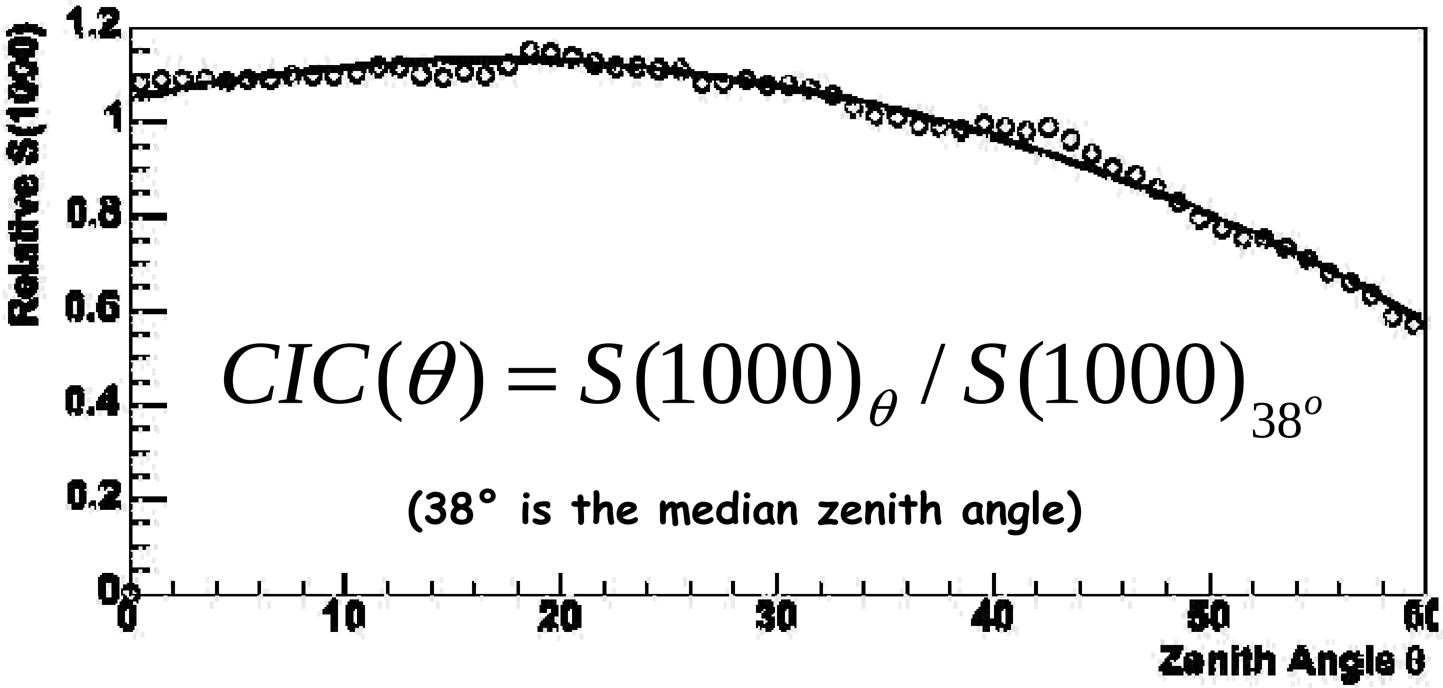
2. Calibrate E(S38) using air fluorescence measurements. That is to say, use the fluorescence detector to obtain the rule for converting S38 to energy.

Constant Intensity Cut: S_{38} from S(1000) and θ

Near isotropy of cosmic rays ⇒

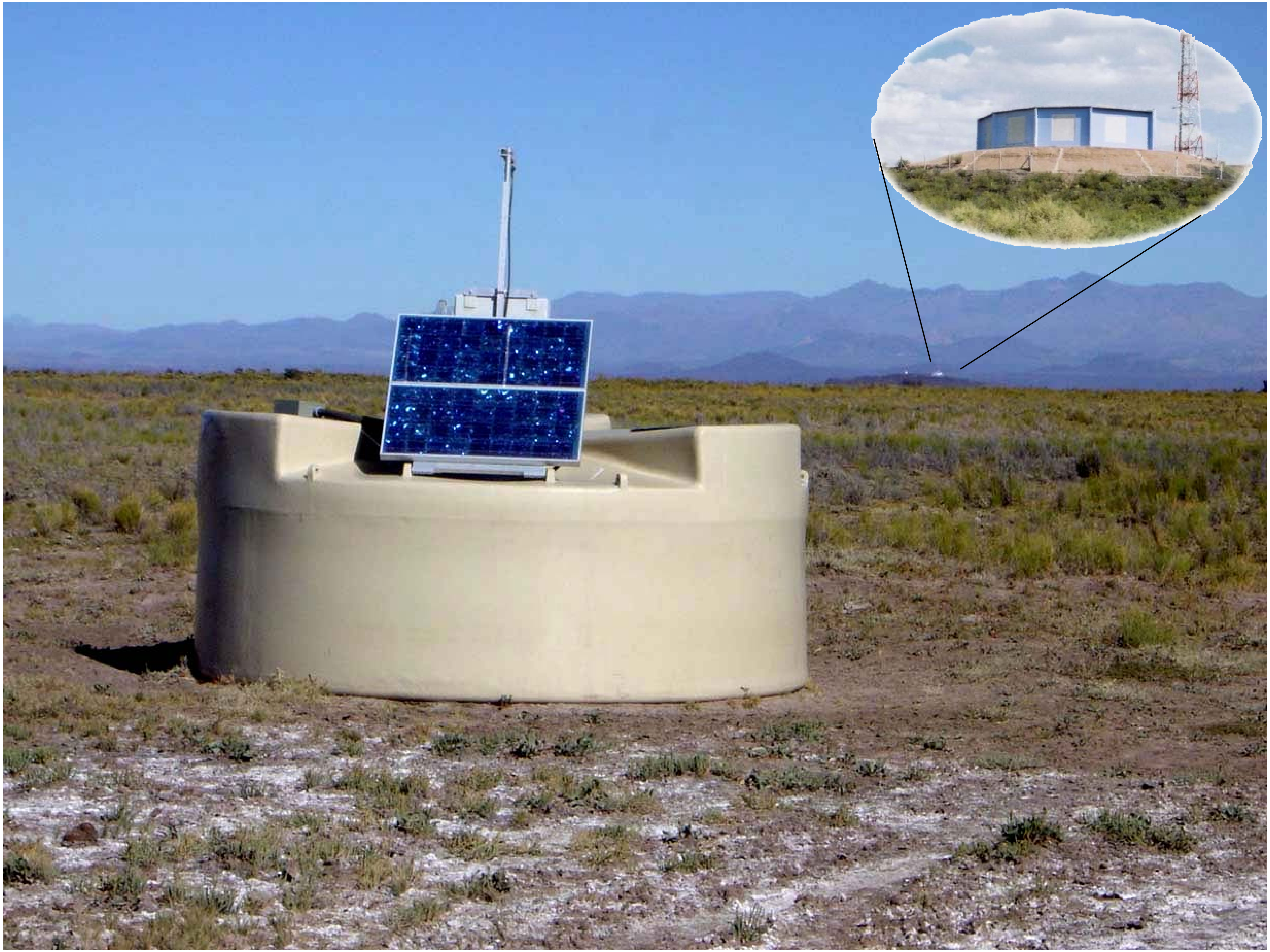
constant intensity cut ⇔ constant energy cut.

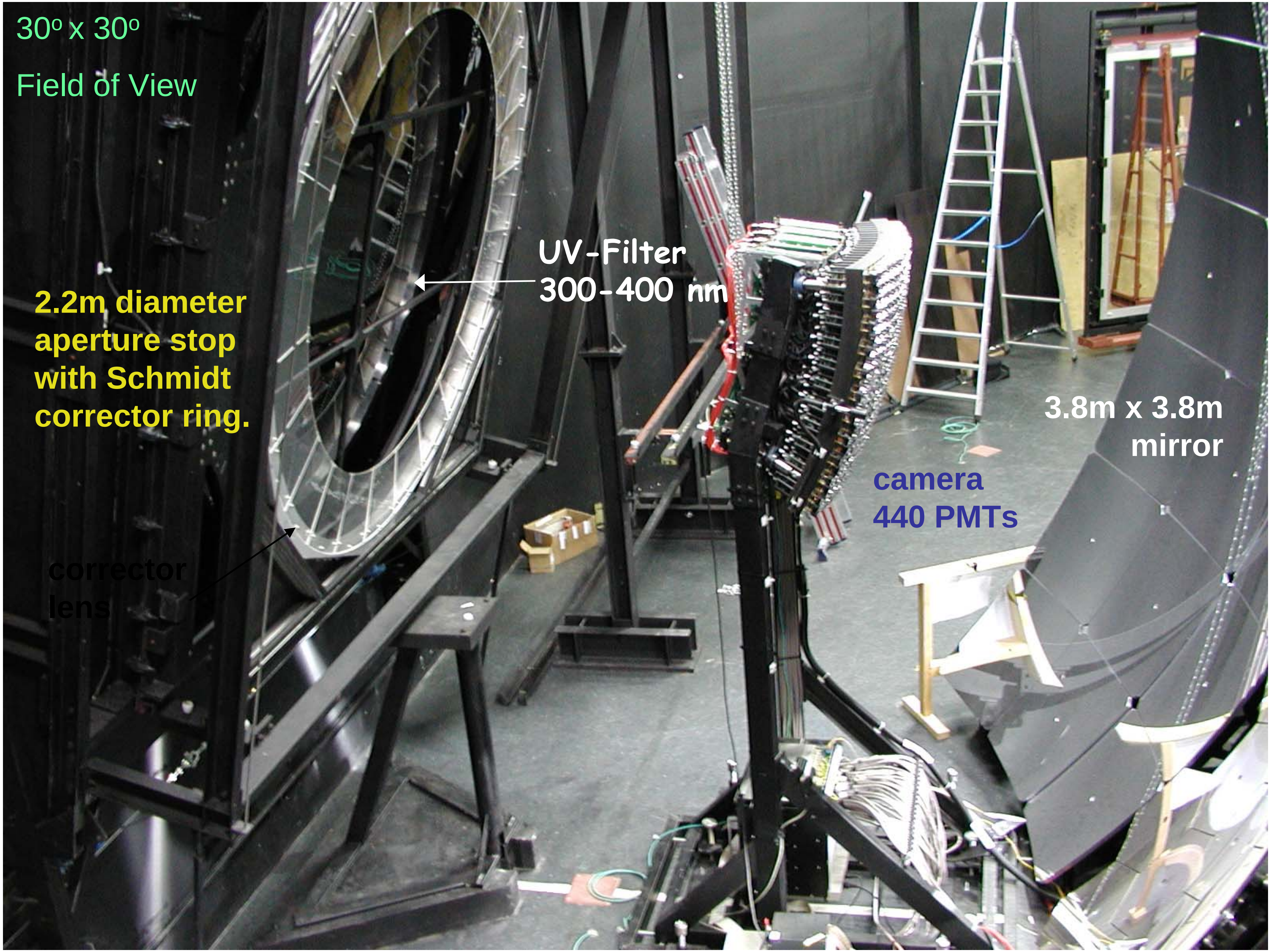
For a fixed I_0, find S(1000) at each θ such that I(>S(1000)) = I_0.



Define the energy parameter S_{38} := S(1000)/CIC(θ) for each shower:

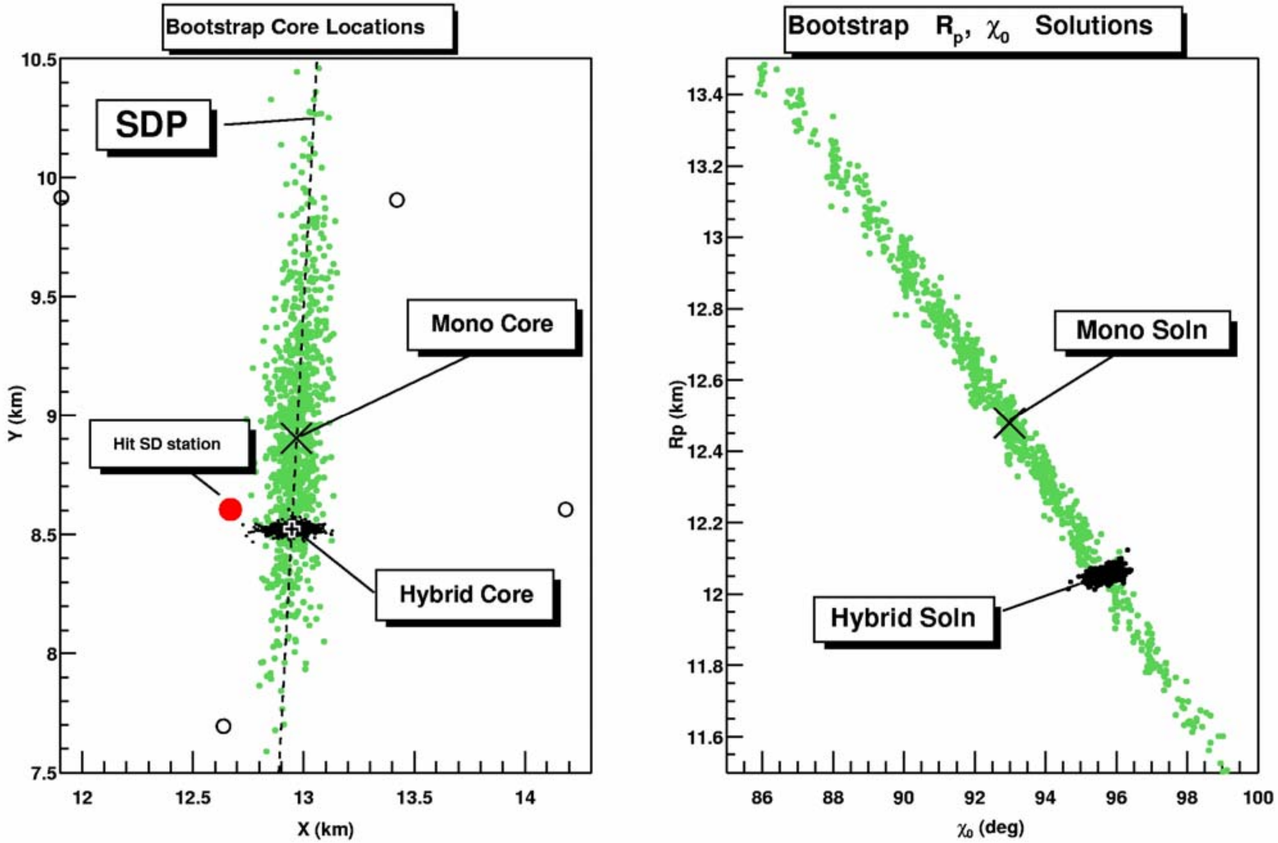
"the S(1000) it would have produced if it had arrived at 38° zenith angle"





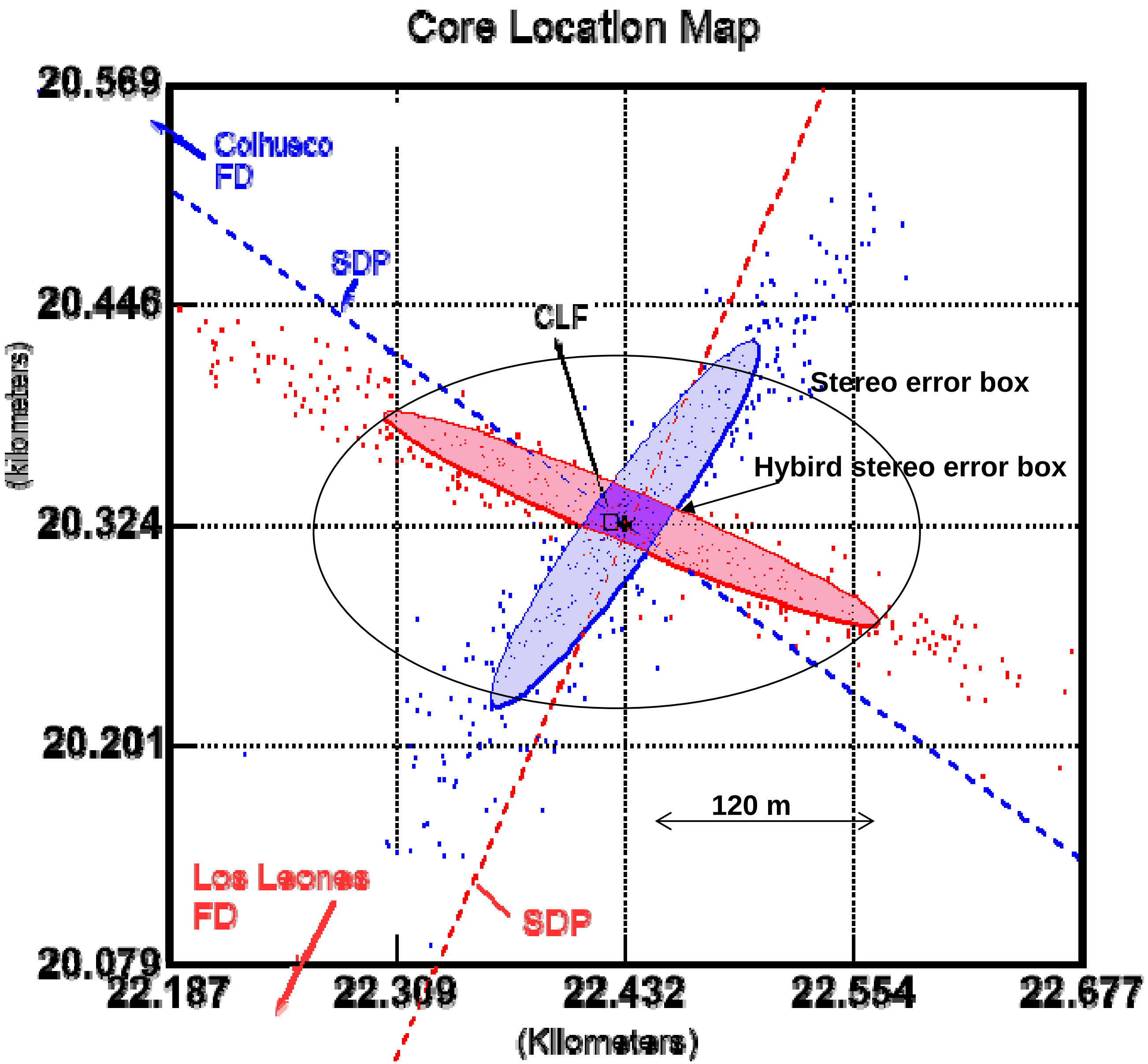
30º x 30º
Field of View
2.2m diameter
aperture stop
with Schmidt
corrector ring.
corrector
lens
UV-Filter
300-400 nm
camera
440 PMTs
3.8m x 3.8m
mirror

The use of the time from even one tank significantly improves the precision of geometric reconstruction



The width of the hybrid core distribution is narrower in the timing direction than in the SDP direction.

For stereo (2-telescope) events this property can be exploited to get a better geometry than with the normal stereo technique (intersection of 2 SDPs).

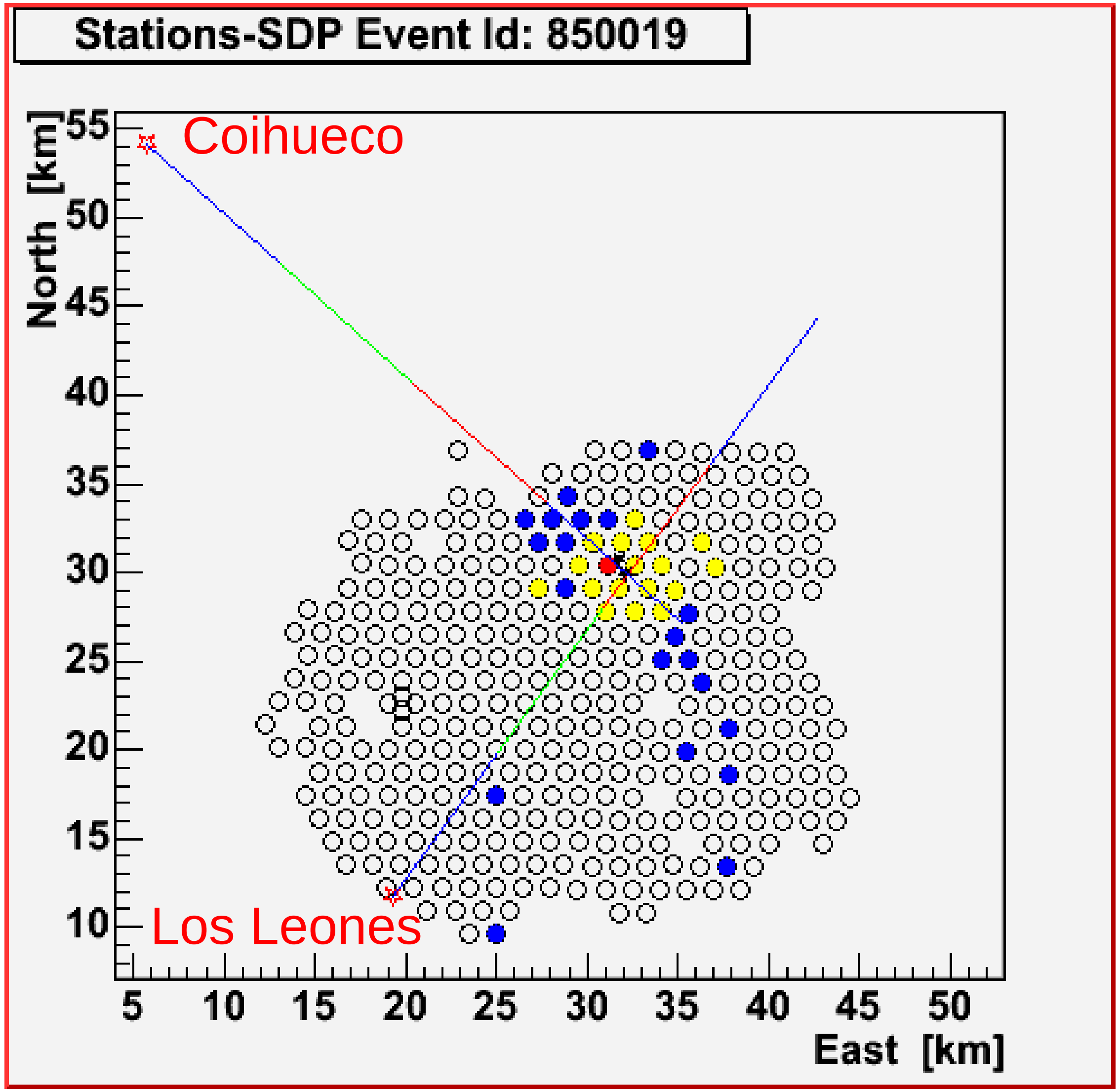


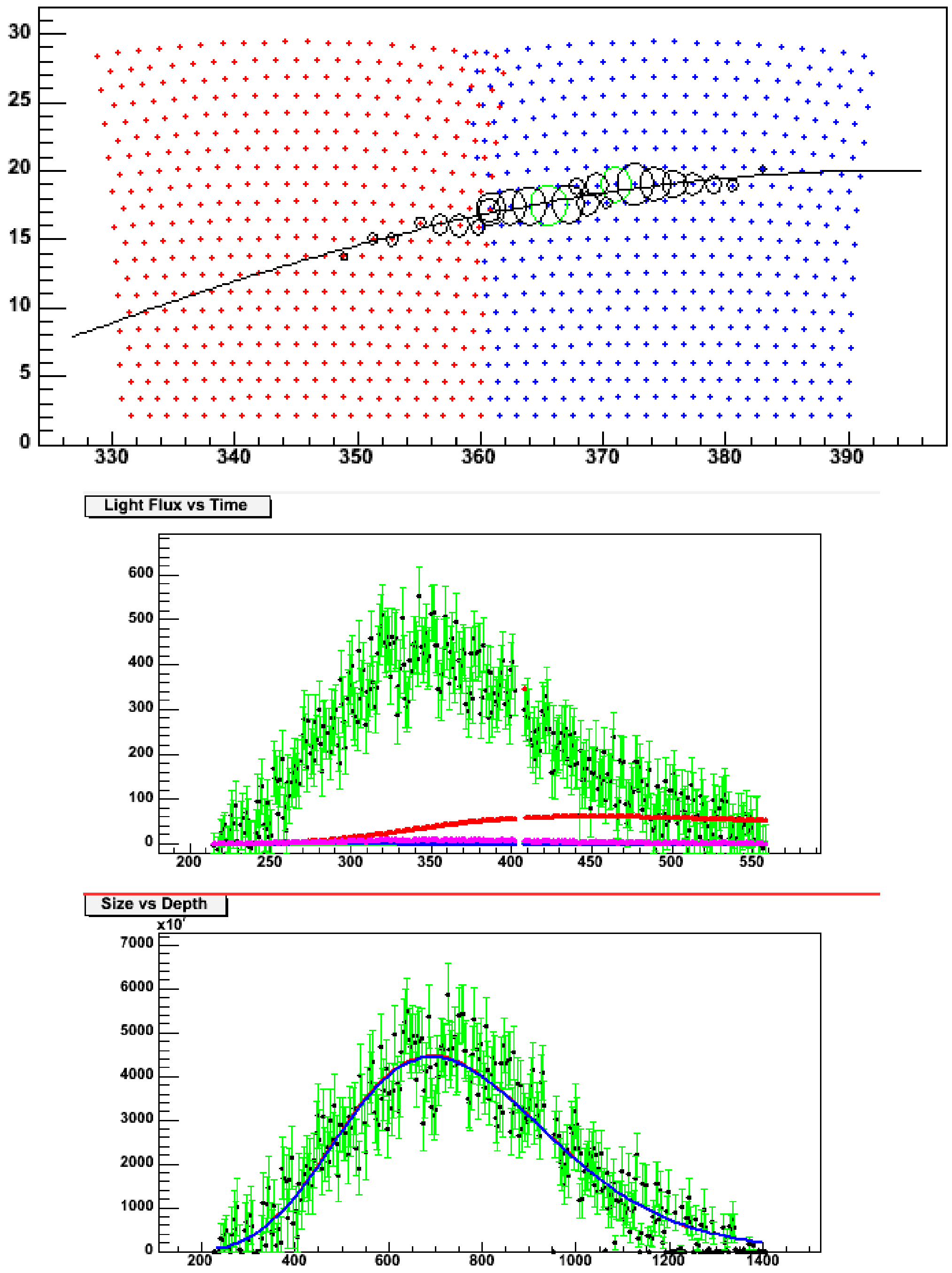
Arrival direction error box can be 0.1° x 0.1°

Core location error box 30m x 30m.

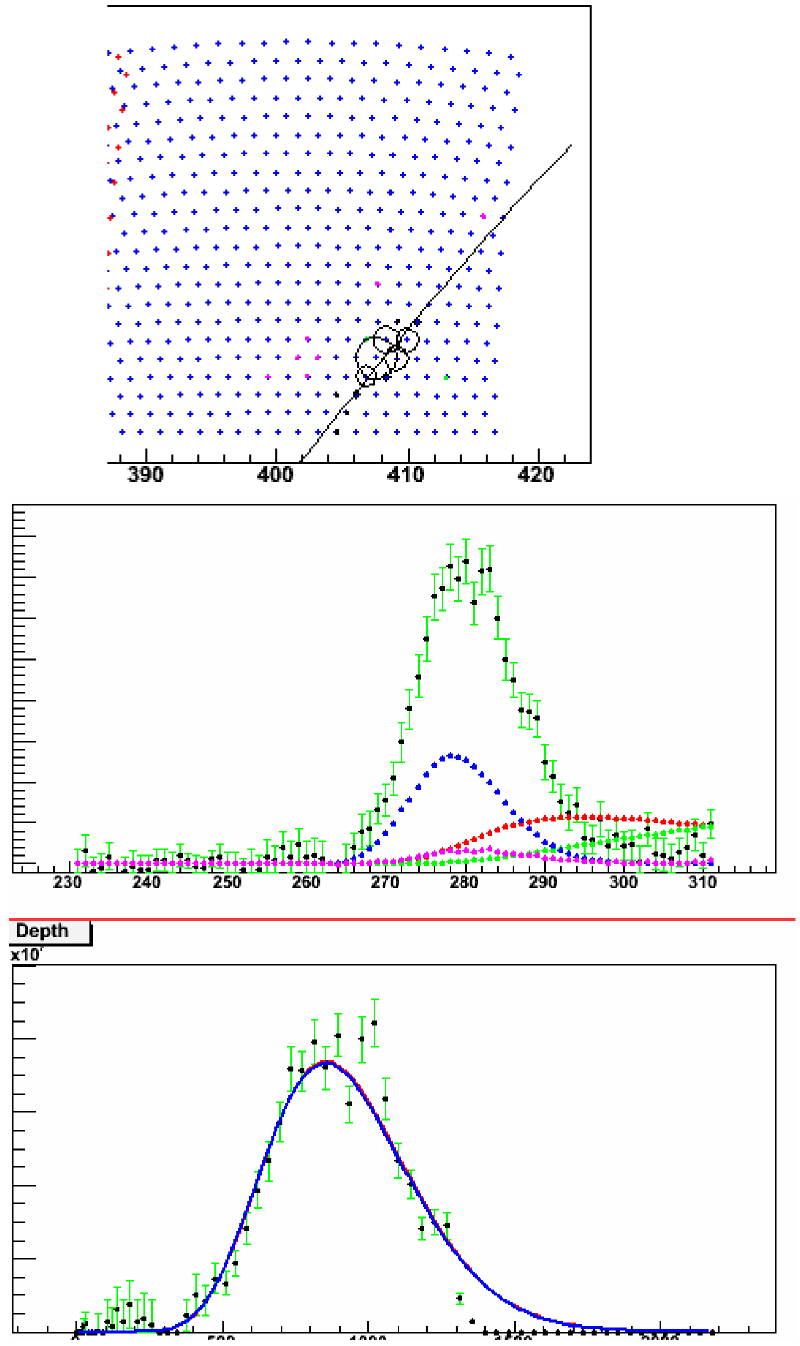
A stereo-hybrid event

- June 26 2004
- An example of an event seen by Los Leones and Coihueco FD eyes, and the SD
- Energy is at least 50 EeV.
- Zenith angle ~70 deg.





Los Leones



Coihueco

(Remark about the Gaisser-Hillas functional form)

It is used (instead of, say, a quadratic function) to fit the curve in order to make the best estimate of $X_{max.}$

It is used in order to extend the profile to small X-values in order to estimate the full Cherenkov beam.

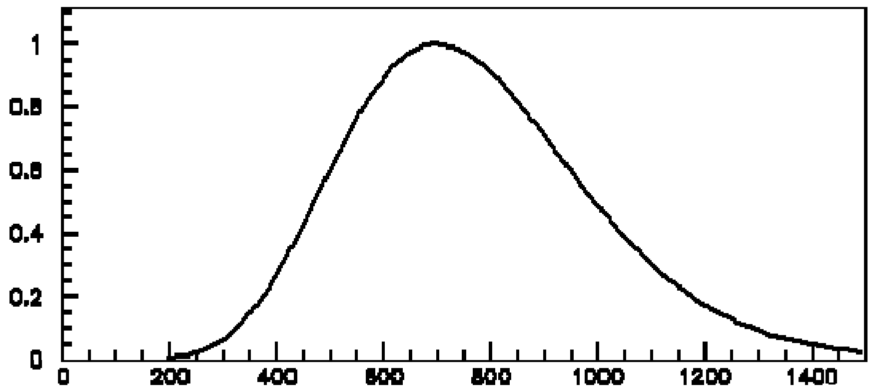
It is used to integrate the longitudinal profile beyond the observed X-range in order to determine the <u>total</u> electromagnetic energy.

$$F(x) = F_{max}\,(x/w)^{w}\;\; e^{w-x}$$

where $x=(X-X_0)/\lambda$ and $w=(X_{max}-X_0)/\lambda$.

There can be 4 free parameters (F_{max}, X_{max}, X_0, λ), or 3 by setting λ=70 g/cm^2, or 2 parameters by also setting X_0=0, or only F_{max} free by also setting X_{max}=700 g/cm^2.

Example with F_{max}=1, X_{max}=700, λ=70, and X_0=0:



Calibrating the Energy Parameter by Air Fluorescence -

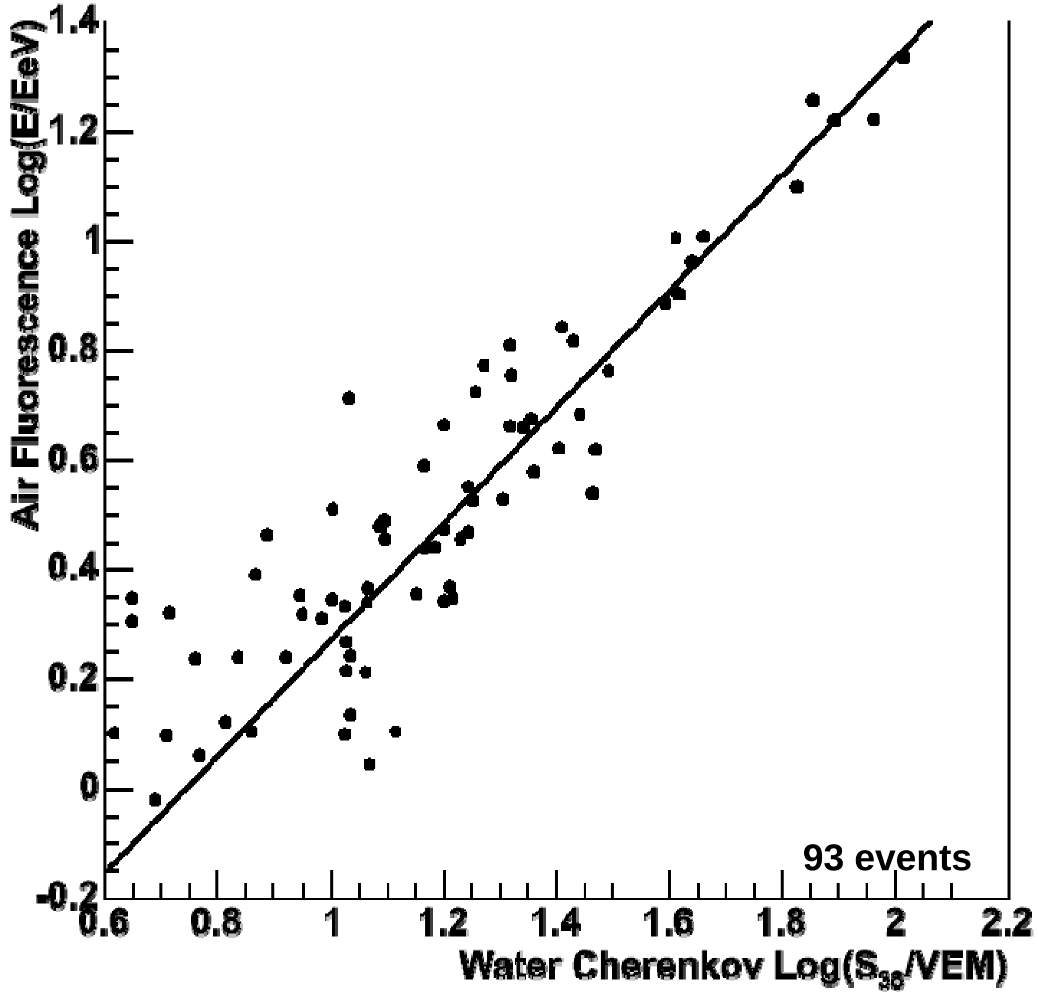
The Empirical Rule Derived using Hybrid Events

$$\text{Log}(E) = -0.79 + 1.06\ \text{Log}(S_{38})$$

$$E = 0.16\ S_{38}^{1.06}$$

(E in EeV, S_{38} in VEM)

Uncertainty in this rule increases from 15% at 3 EeV to 40% at 100 EeV



First Estimate of the Primary Cosmic Ray Energy Spectrum Above 3 EeV from the Pierre Auger Observatory

Full-time surface array exposure

Air fluorescence energy calibration

Analysis does NOT rely on
- Detailed air shower simulation
- Detector simulation
- Hadronic interaction model
- Assumption about primary mass

First estimation:
- Array is now $\frac{1}{2}$ complete in Argentina
- Statistical and systematic uncertainties will shrink rapidly

The Data Set used in the First Estimate of the Spectrum

Surface array of water Cherenkov stations

January 1 2004 – June 5 2005

Growing array

- Present size (1500 km^2) = ½ final size (3000 km^2)
- Time averaged area = 660 km^2 (22% of final size)

0-60° zenith angle range

Quality conditions:

- Core surrounded by equilateral triangle of working stations
- Station with highest signal has ≥ 5 working nearest neighbors

Full efficiency above 3 EeV ⇒ simple geometric aperture

Exposure = 1750 km^2 sr yr

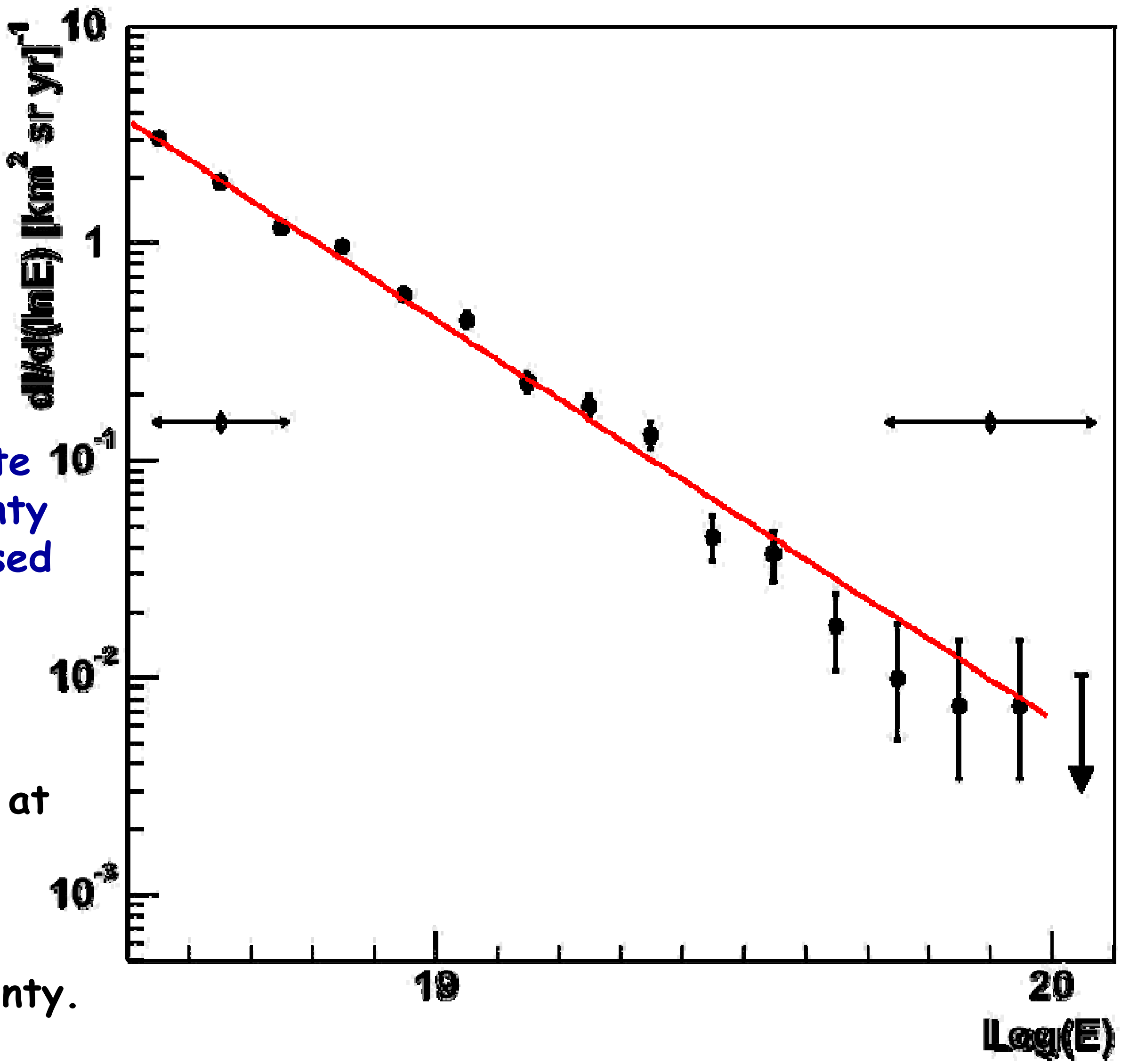
3525 events above $10^{18.5}$ eV

The Estimated Spectrum

$$\frac{dI}{d\ln(E)} \equiv E\frac{dI}{dE}$$

vs.

Log(E)



Error bars on points indicate Poisson *statistical* uncertainty (or 95% CL upper limit) based on the number of events.

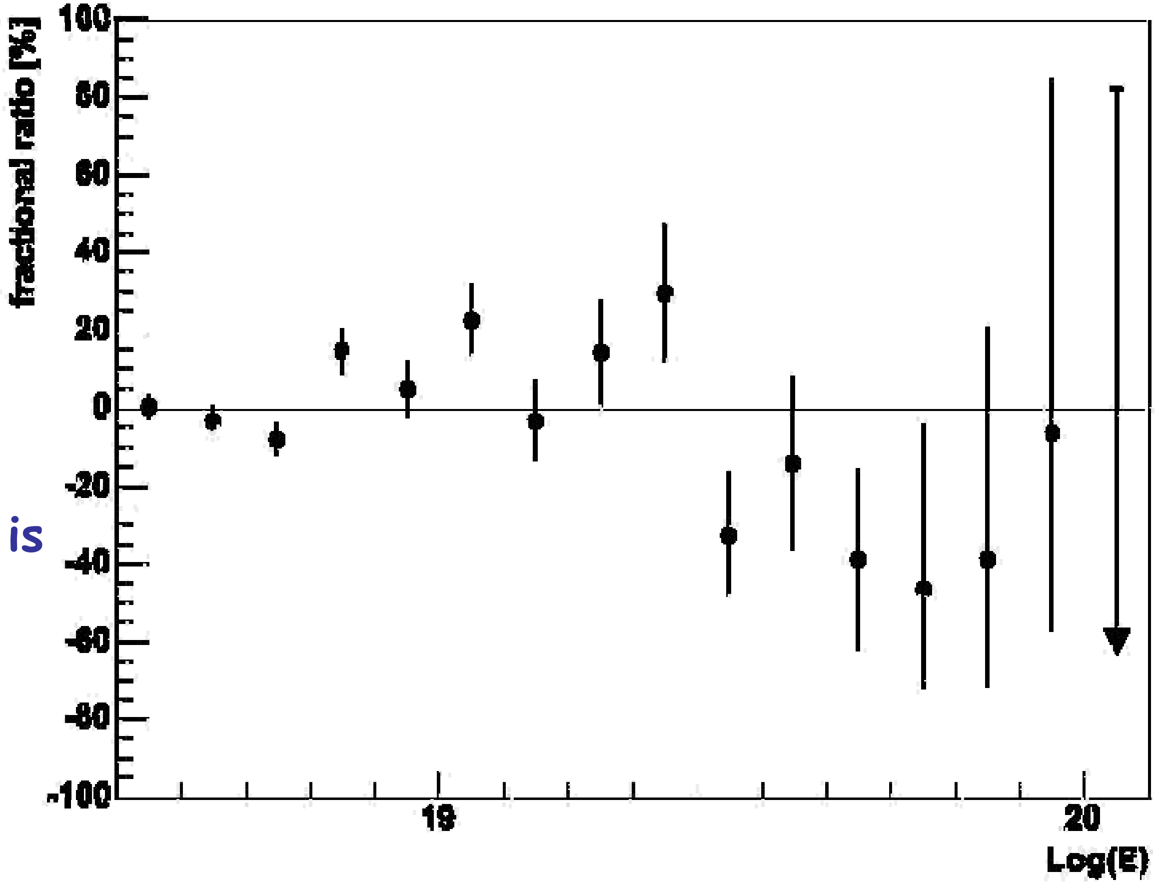
Systematic uncertainty is indicated by double arrows at two different energies.

Horizontal: Systematic ΔE.

Vertical: Exposure uncertainty.

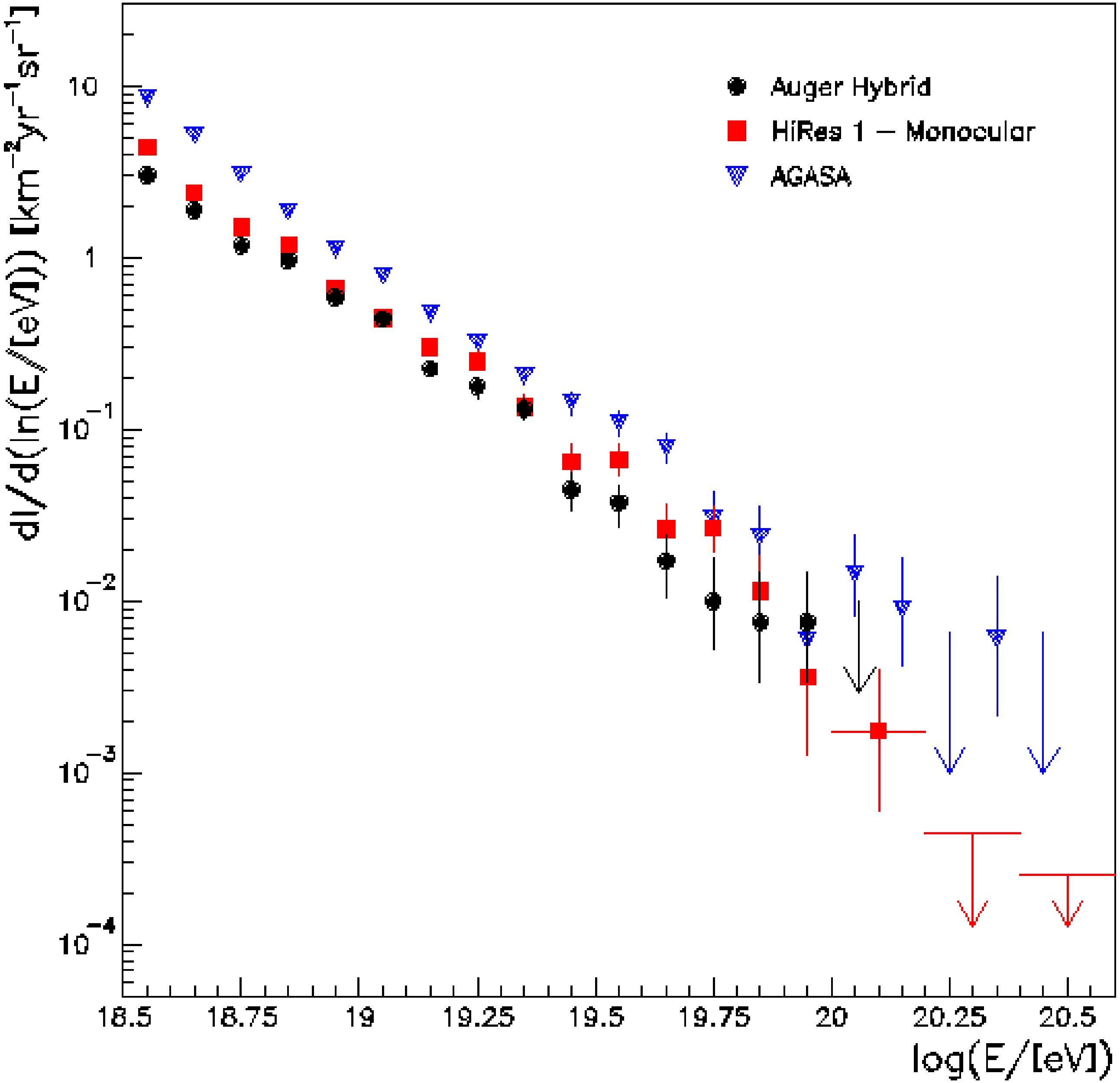
Percentage Deviation from the Power-Law Fit

$$\frac{100}{F}\times\left(\frac{dI}{d\ln(E)}-F\right)$$



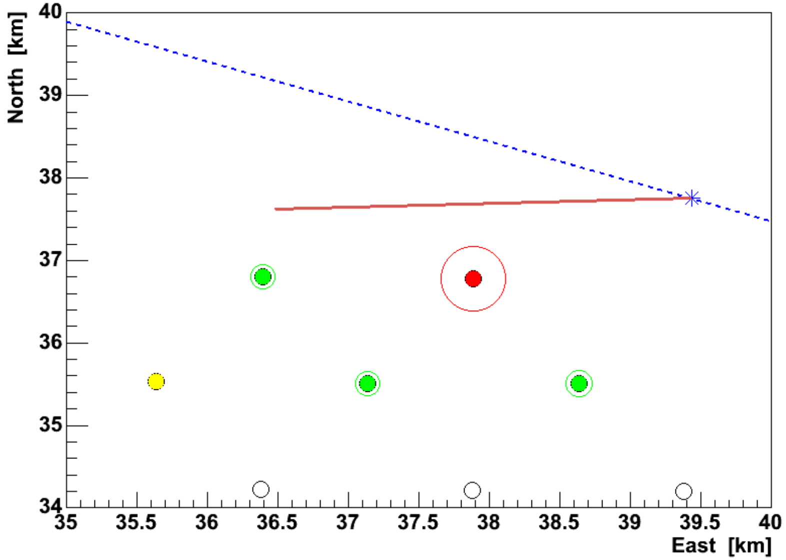
The fitted reference function is
$F=(30.9\pm1.7)*(E/EeV)^{-1.84\pm0.03}$

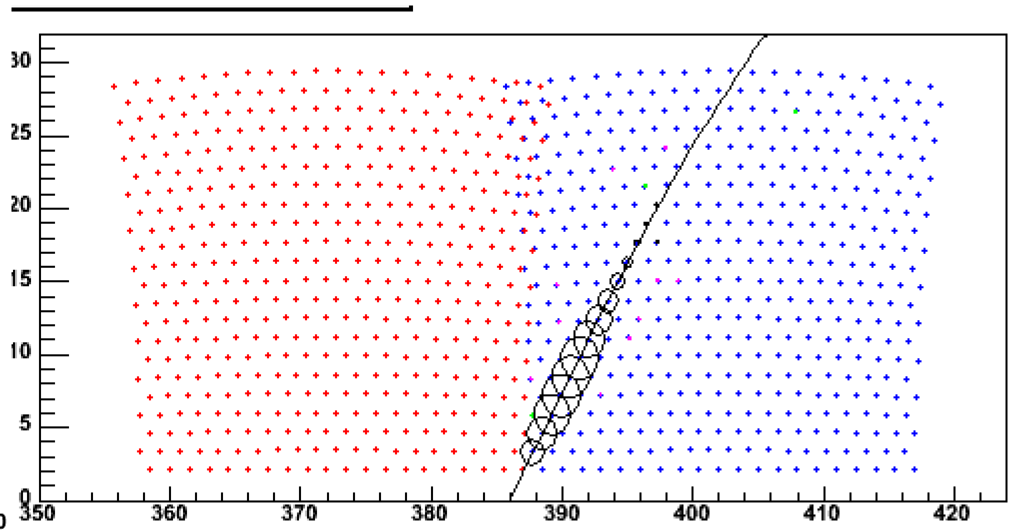
with chisquare 2.4 per degree of freedom.

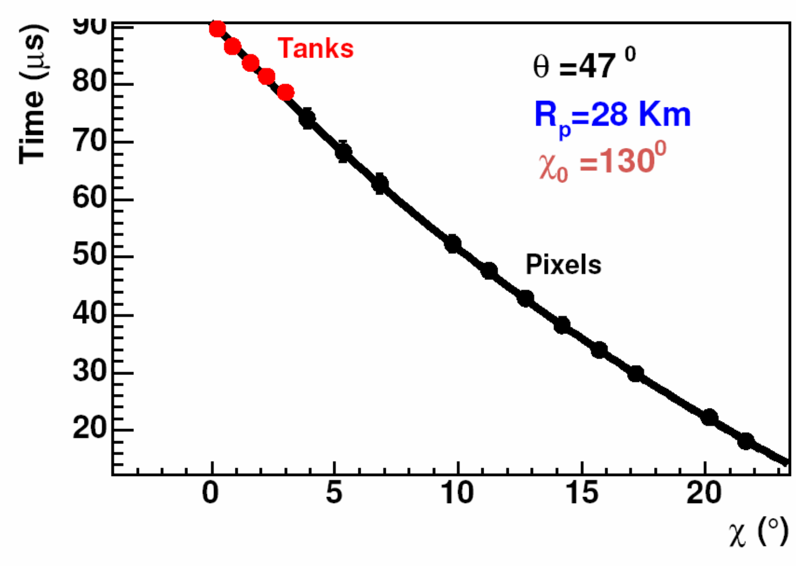


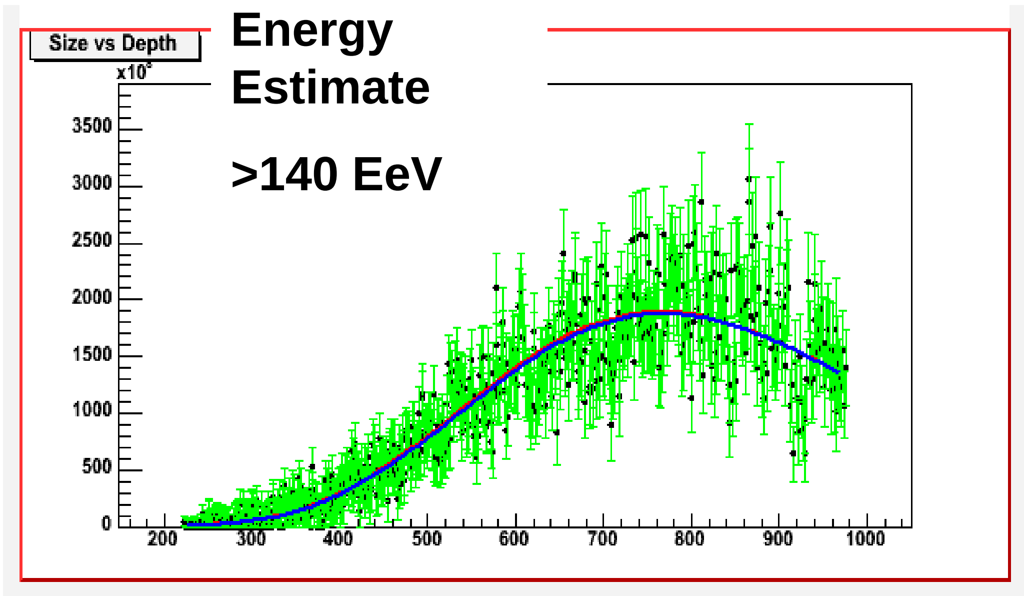
Auger Hybrid
HiRes 1 – Monocular
AGASA
dI/d(ln(E/[eV])) [km^{-2}yr^{-1}sr^{-1}]
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
18.5
18.75
19
19.25
19.5
19.75
20
20.25
20.5
log(E/[eV])

A Big Event - *One that got away!*









A Look to the Future

•The exposure will be ~7 times greater by the next ICRC.

•Systematic uncertainty in $E(S_{38})$ will shrink:

Increased hybrid statistics for the E-vs-S_{38} correlation.

Improved measurements of the air fluorescence yield.

Refinement of calibration for fluorescence detectors.

•Potential improvement in energy resolution using lateral distribution steepness, shower front curvature, signal rise times, etc.

•Higher statistics in each energy bin $\Rightarrow$ reduced Poisson uncertainty.

Superposition Model

An air shower by nucleus (E,A) behaves like the superposition of A proton showers, each with energy E/A. [A = 56 for iron (Fe)]

---

* Difference in X_{max} expectation:

$$\overline{X}^{\,p}_{max}(E) - \overline{X}^{\,Fe}_{max}(E) = \overline{X}^{\,p}_{max}(E) - \overline{X}^{\,p}_{max}(E/56)$$

$$= ER \cdot \mathrm{Log}\, 56$$

$ER \sim 57\,g/cm^2/\text{decade} \Rightarrow$

Proton $\overline{X}_{max} \sim 100\,g/cm^2$ deeper than iron $\overline{X}_{max}$.

---

* Expected difference in muons (using $N^p_\mu \approx \alpha E^\beta$):

$$N^{Fe}_\mu(E) = 56\, N^p_\mu\left(\frac{E}{56}\right) = 56\,\alpha\left(\frac{E}{56}\right)^\beta = 56^{1-\beta}\, N^p_\mu(E)$$

$$\therefore \quad N^{Fe}_\mu(E) / N^p_\mu(E) = 56^{1-\beta}$$

$$\beta \approx 0.93 \text{ for } \frac{10\text{ EeV}}{56} < E < 10\text{ EeV} \Rightarrow 56^{1-\beta} = 1.3$$

Iron showers have 30% more muons.

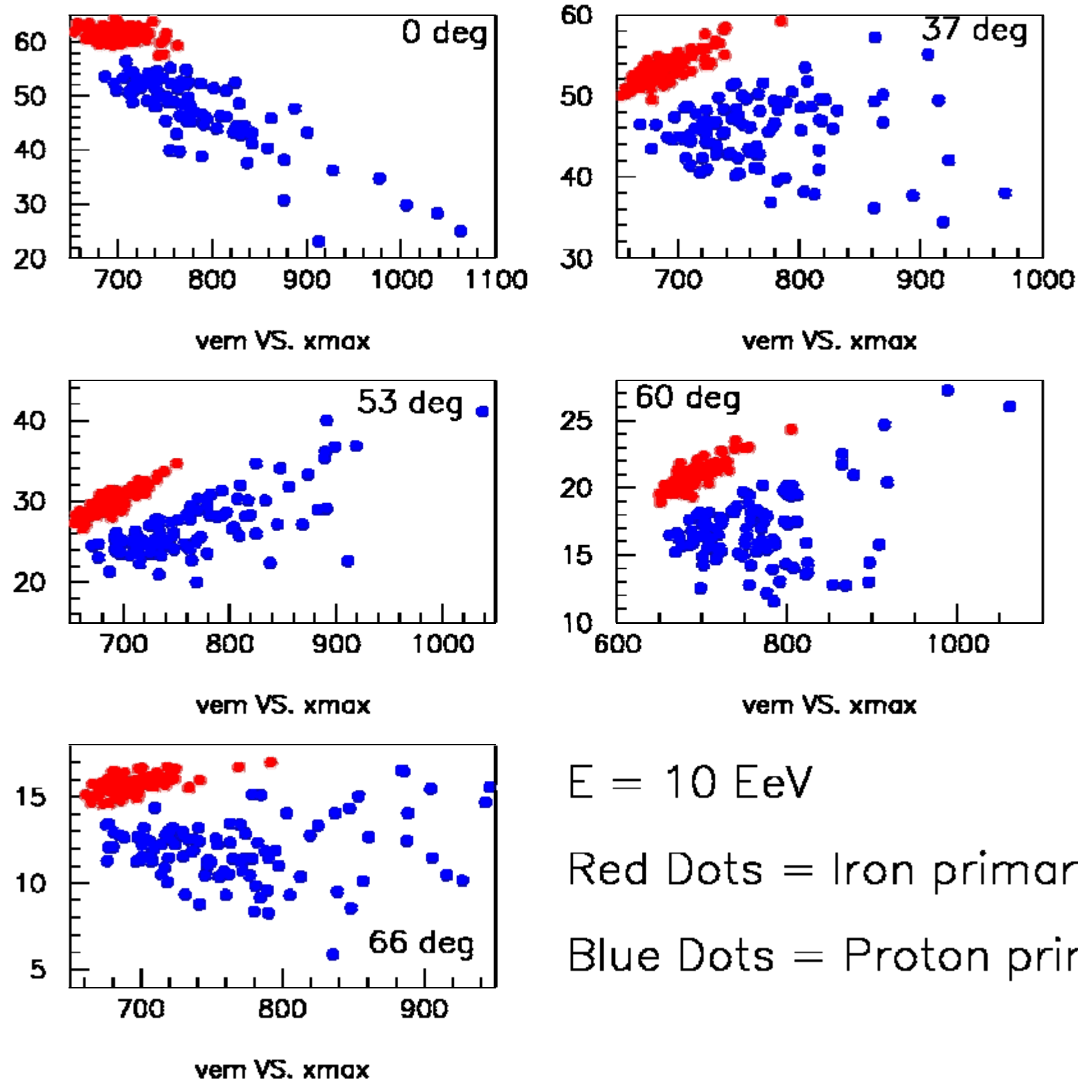
---

* Any measurable quantity is expected to have less fluctuation for a heavy nucleus than for a light nucleus — narrower X_{max} distribution, narrower N_μ distribution, etc. — because it is averaging many subshowers.

Composition analysis using showers measured in hybrid mode.

FD gives electromagnetic energy and Xmax. SD gives density at 1000 m from the core in units of "vertical equivalent muons" (vem).

Heavy-Light separation at various zenith angles.



E = 10 EeV

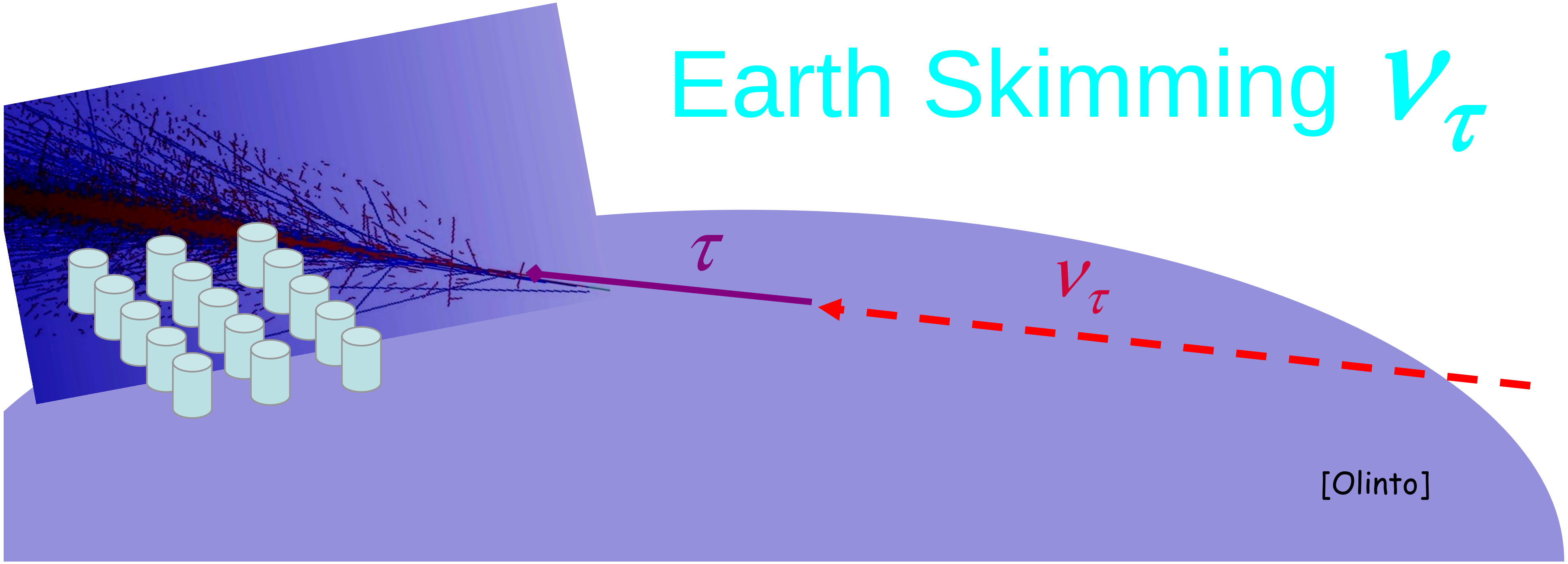
Red Dots = Iron primary

Blue Dots = Proton primary

Pierre Auger Neutrino Observatory

Auger exposure to tau Neutrinos

zenith angle ~ 90-92°



Neutrino Detection

Look for the maximally mixed tau neutrinos.

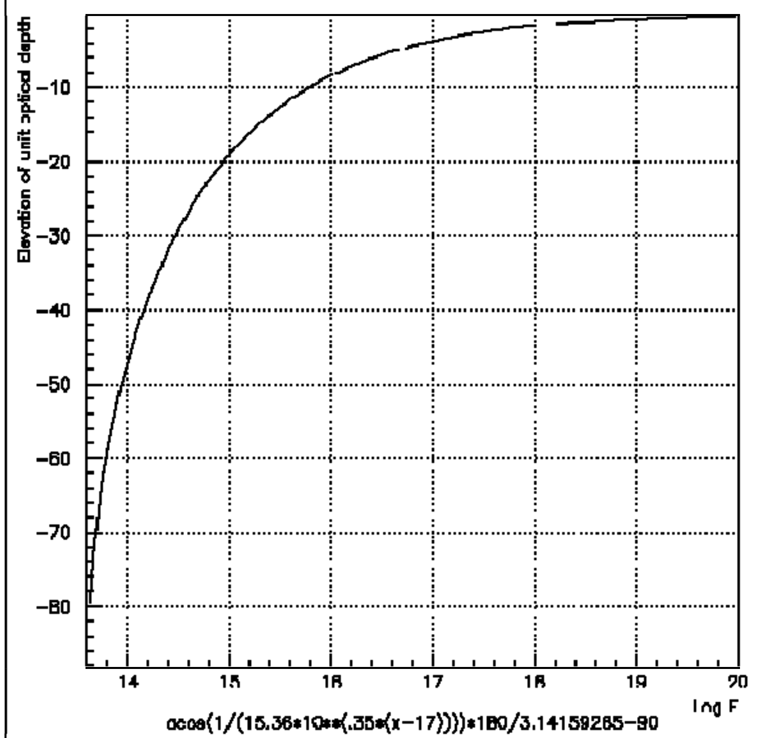
The τ lepton has a mean decay path length of 50km *(E/10^{18}eV).

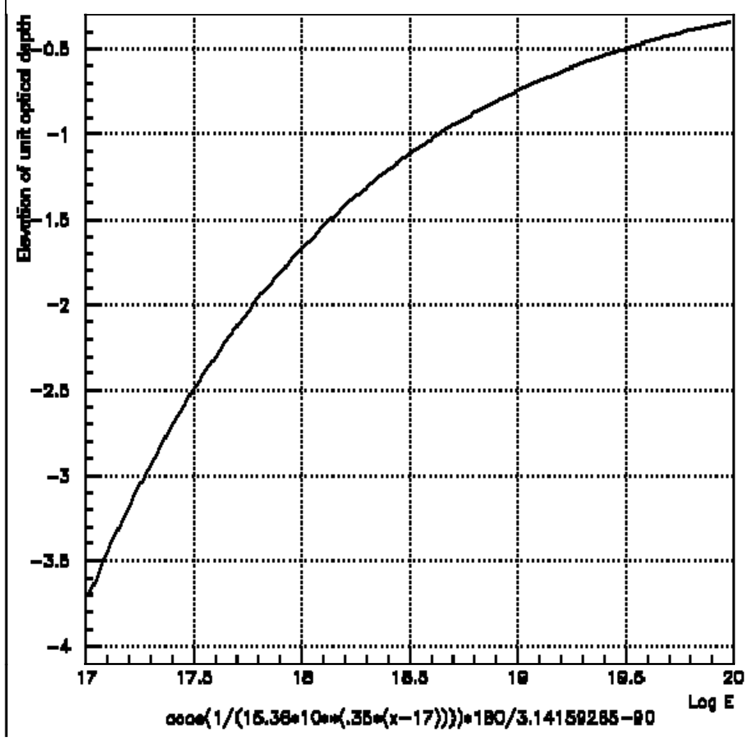
The τ decay usually puts most of its energy into an electromagnetic cascade.

The Earth is almost opaque to neutrinos above 10^{15} eV:

High energy neutrino cross section ~ 4×10^{-33} cm $(E/10^{17})^{.35}$ [Reno]

Elevation angle of chord through Earth with 1 mean-free-path for neutrinos:





How can you be sure it was caused by a neutrino?

Nearly-horizontal air showers caused by hadrons or gamma-rays high in the atmosphere are “old” showers:

(1) The shower front has very large radius.

(2) The FADC traces are impulsive, even far from the core.

A young (locally started) electromagnetic cascade would have

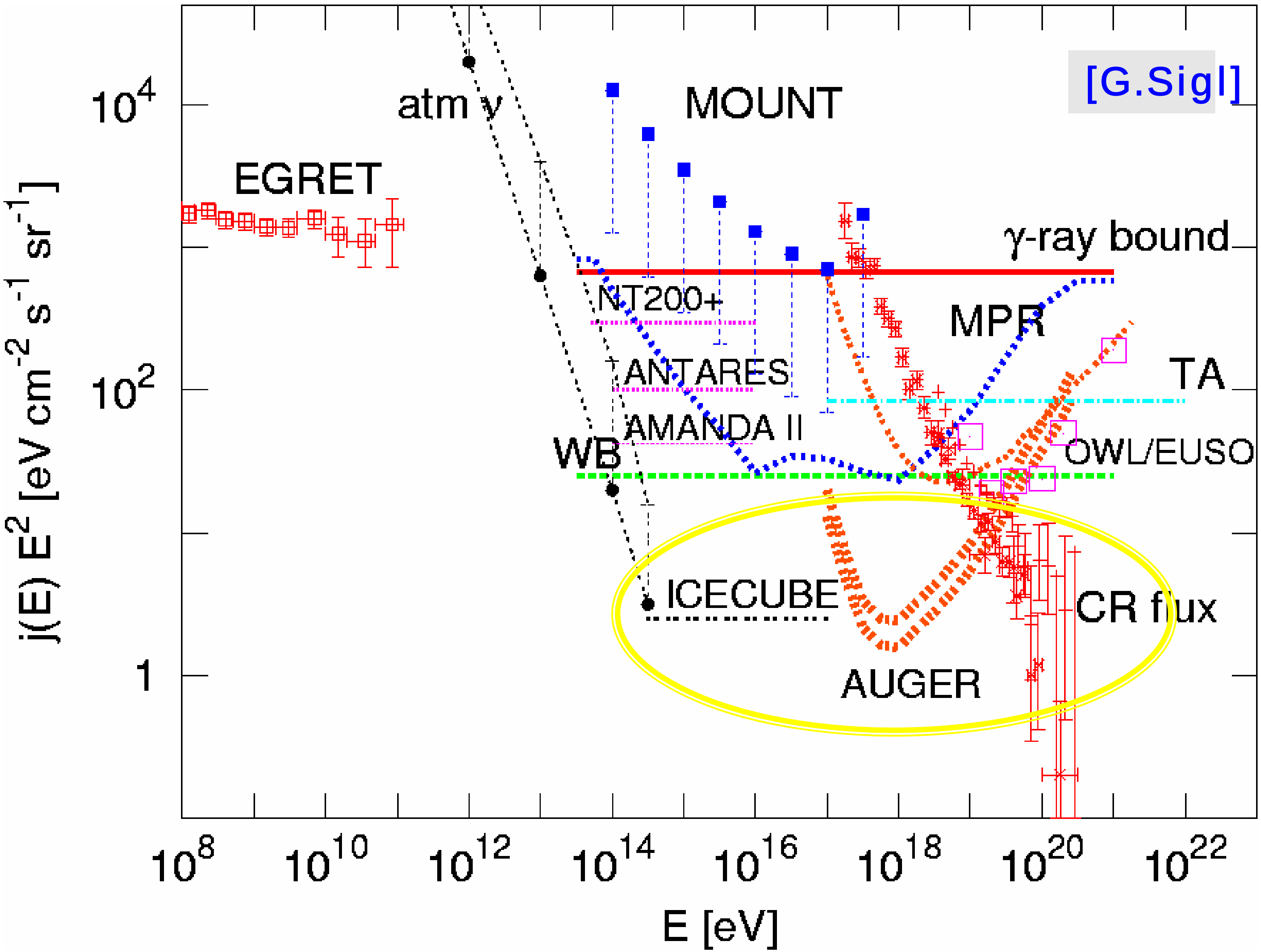
(1) a small shower front curvature

(2) broad FADC traces

If you can tell that its elevation angle is negative, what else could it be?

Experience so far indicates that there is no background of spurious young nearly-horizontal air showers.

neutrino flux sensitivity of Auger is ~comparable to IceCube, at higher energies



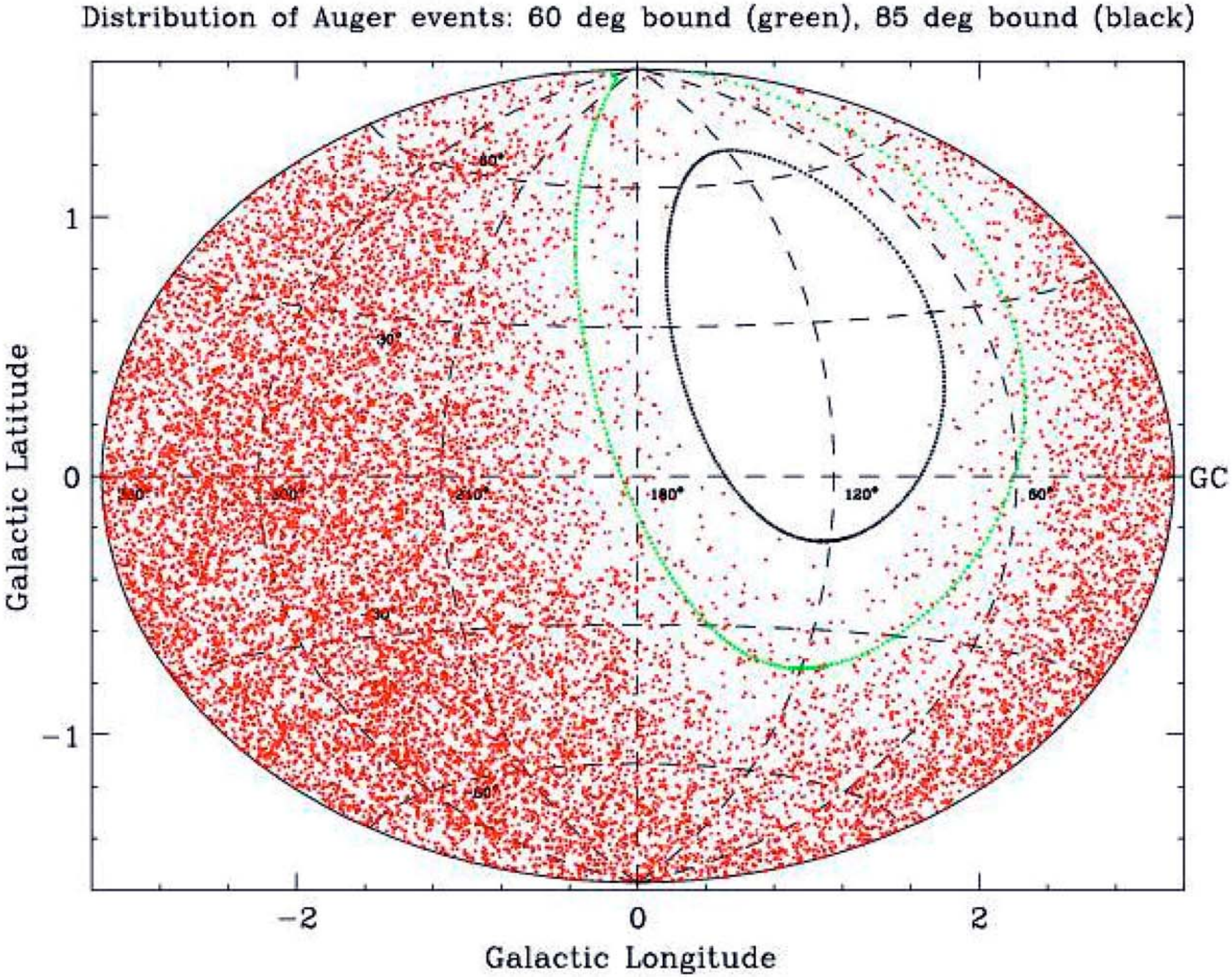
Anisotropy studies with full-sky coverage are crucial

Any spectrum and composition measurements can be explained by multiple models.

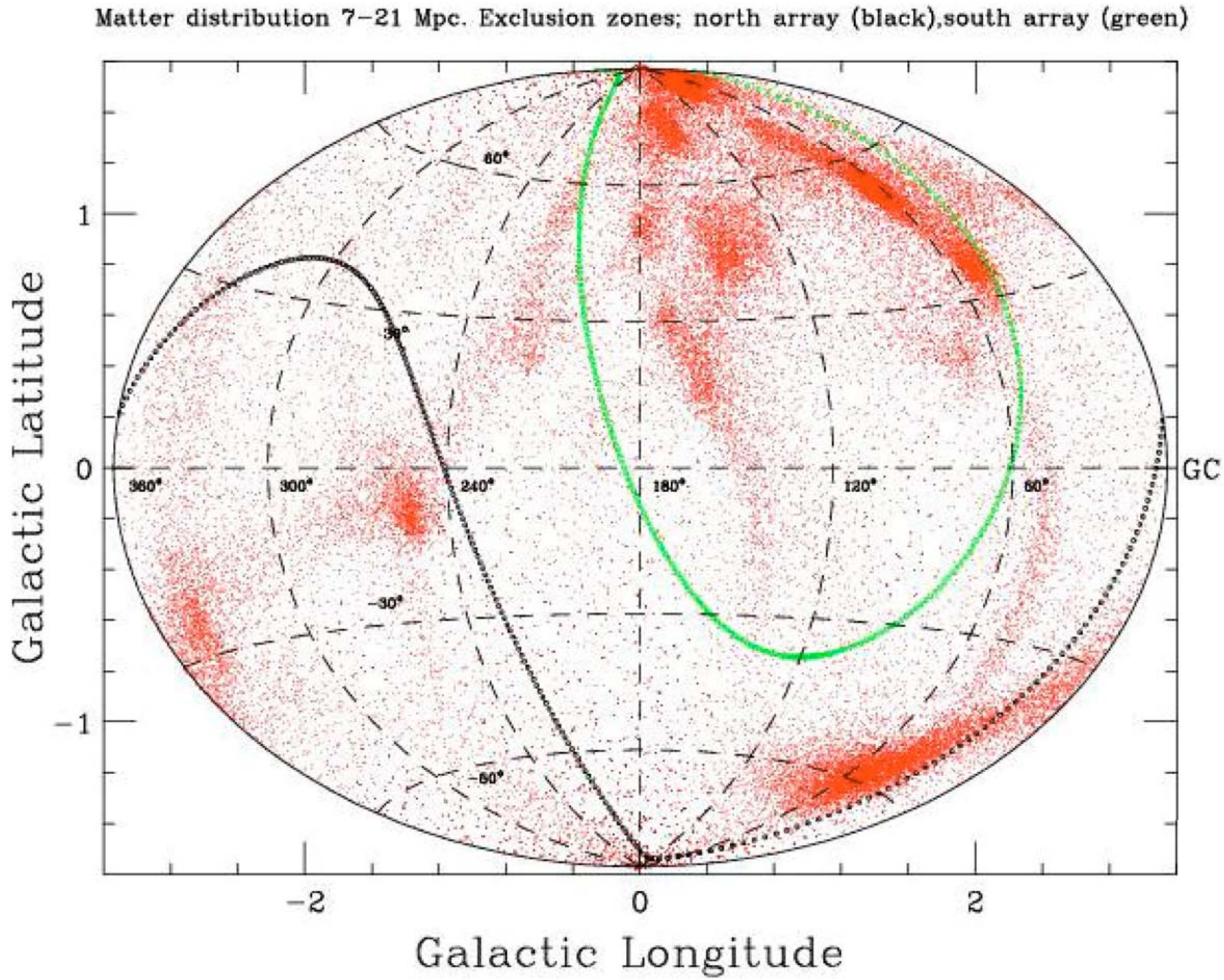
An anisotropy \fingerprint\ is needed for positive identification of the sources.

Spherical harmonic multipole moments (a_{lm}) are the canonical fingerprint. (The coordinate-independent \angular power spectrum\ is obtained from these moments.)

It is impossible to measure any a_{lm} without full sky coverage.

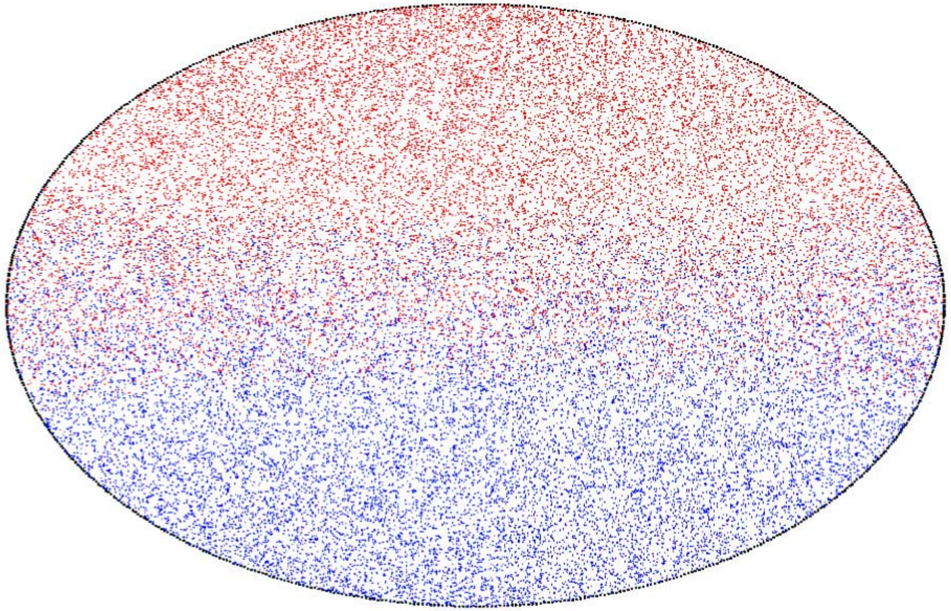

Distribution of Auger events: 60 deg bound (green), 85 deg bound (black)
Galactic Latitude
Galactic Longitude
1
0
−1
−2
0
2
GC
180°
120°
60°

Matter Distribution 7 Mpc < D < 21 Mpc



Cronin astro-ph/0402487 [Kravtsov]

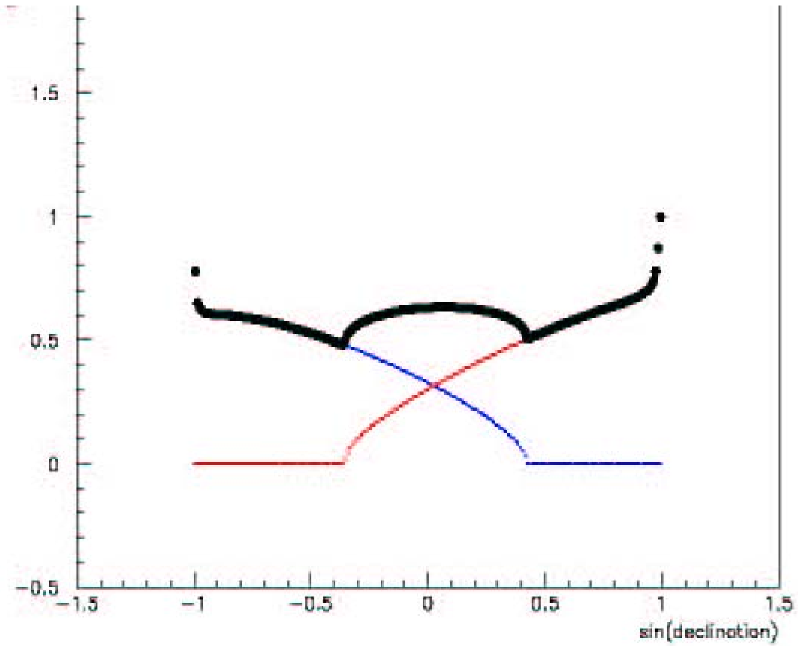
Auger North + Auger South



5-year Auger Full-Sky Simulation

(E > 10^{19} eV and θ < 60^o)

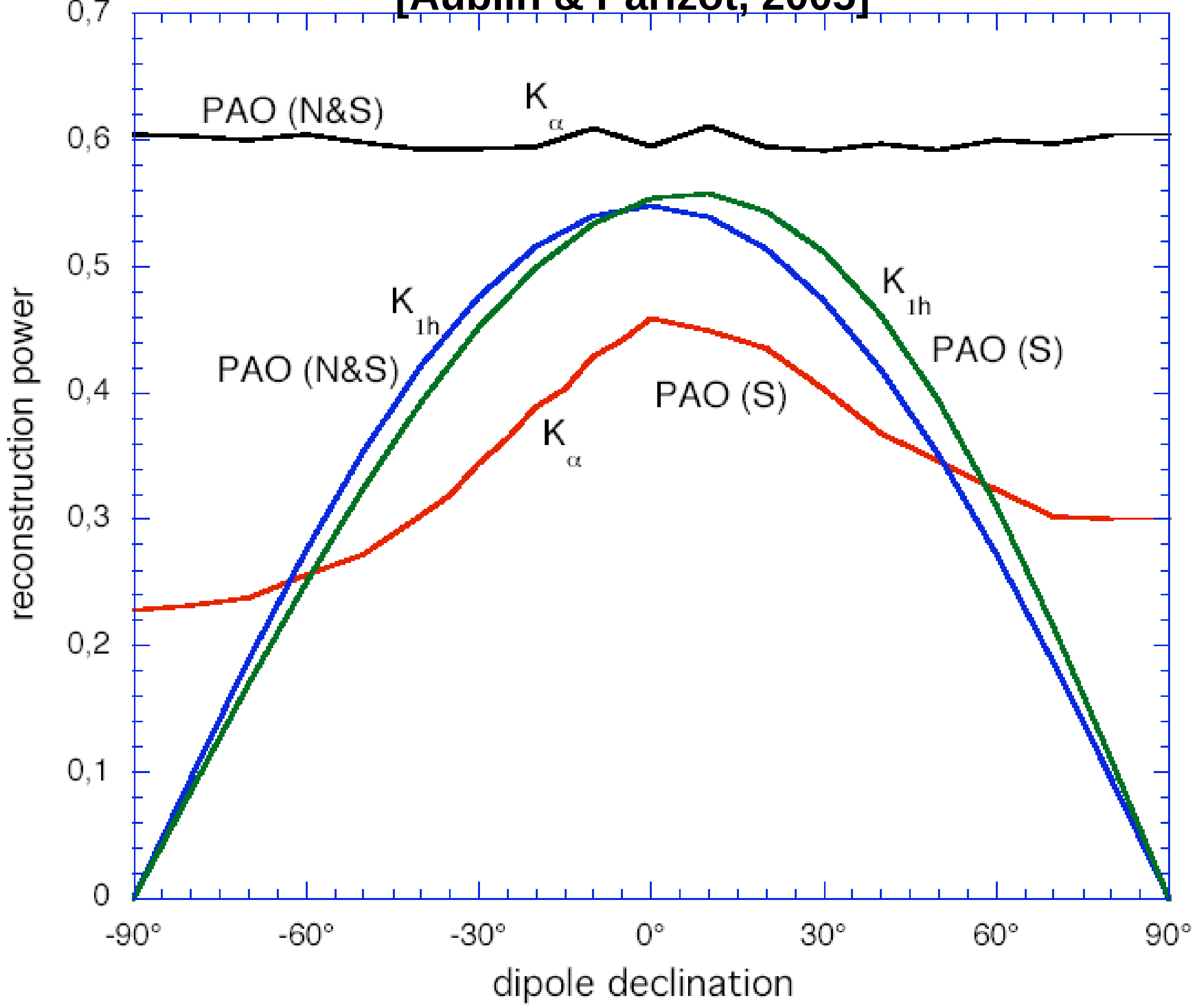
36000 arrival directions



Relative exposure as function of sin(declination)

Dipole measurement power, full-sky Auger vs. Auger South alone

[Aublin & Parizot, 2005]



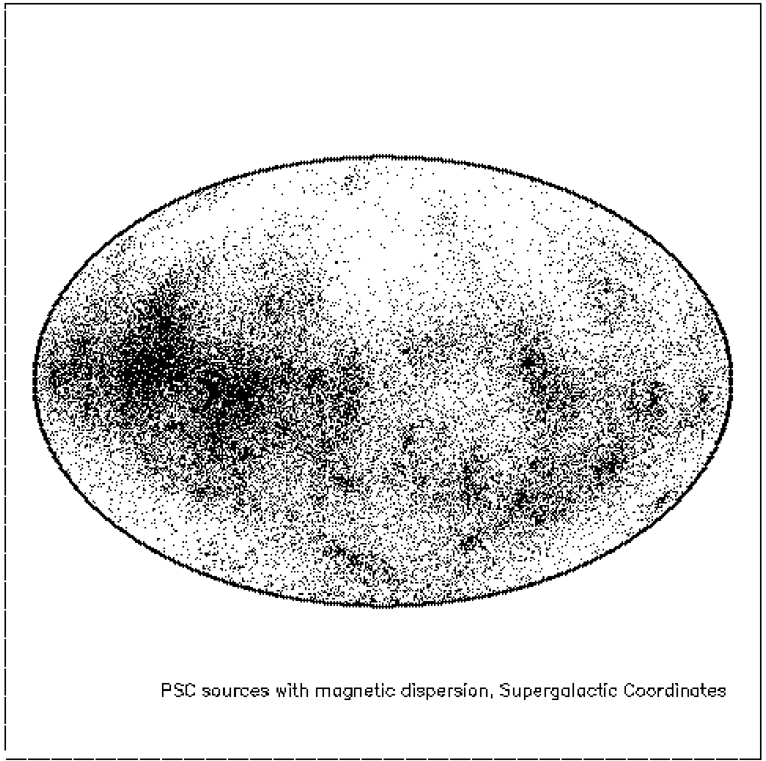
$$n_\sigma = K\,\alpha\,\sqrt{N}$$

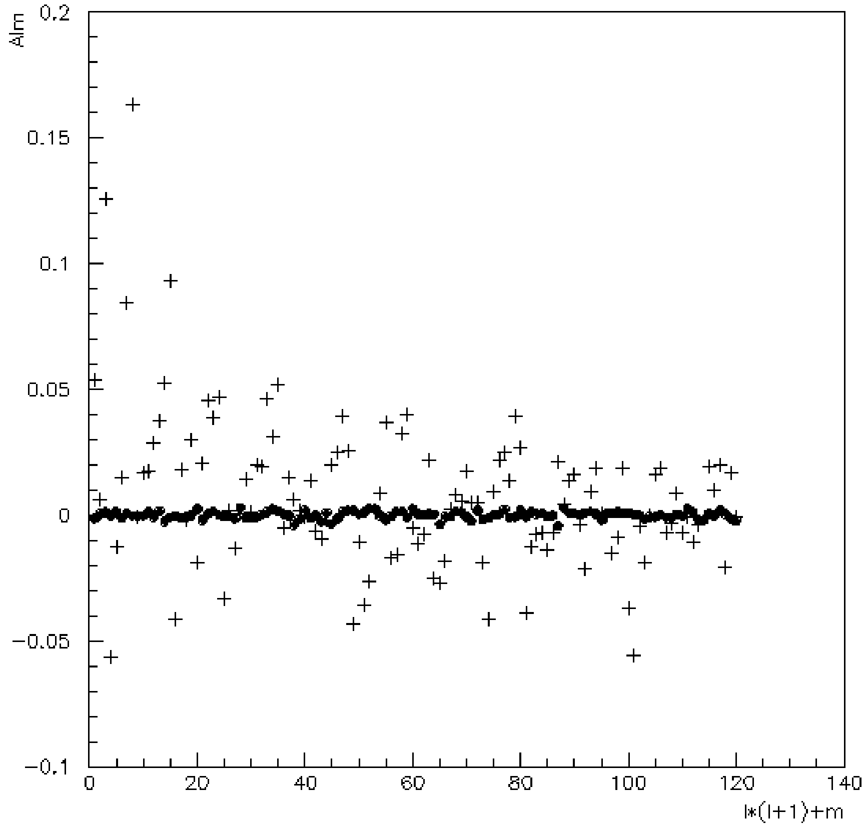
K is, on average, twice as big for N&S than for South-only.

So N can be 4 times smaller. With both sites, the number is achieved

8 times quicker!

Example of a spherical harmonic anisotropy fingerprint



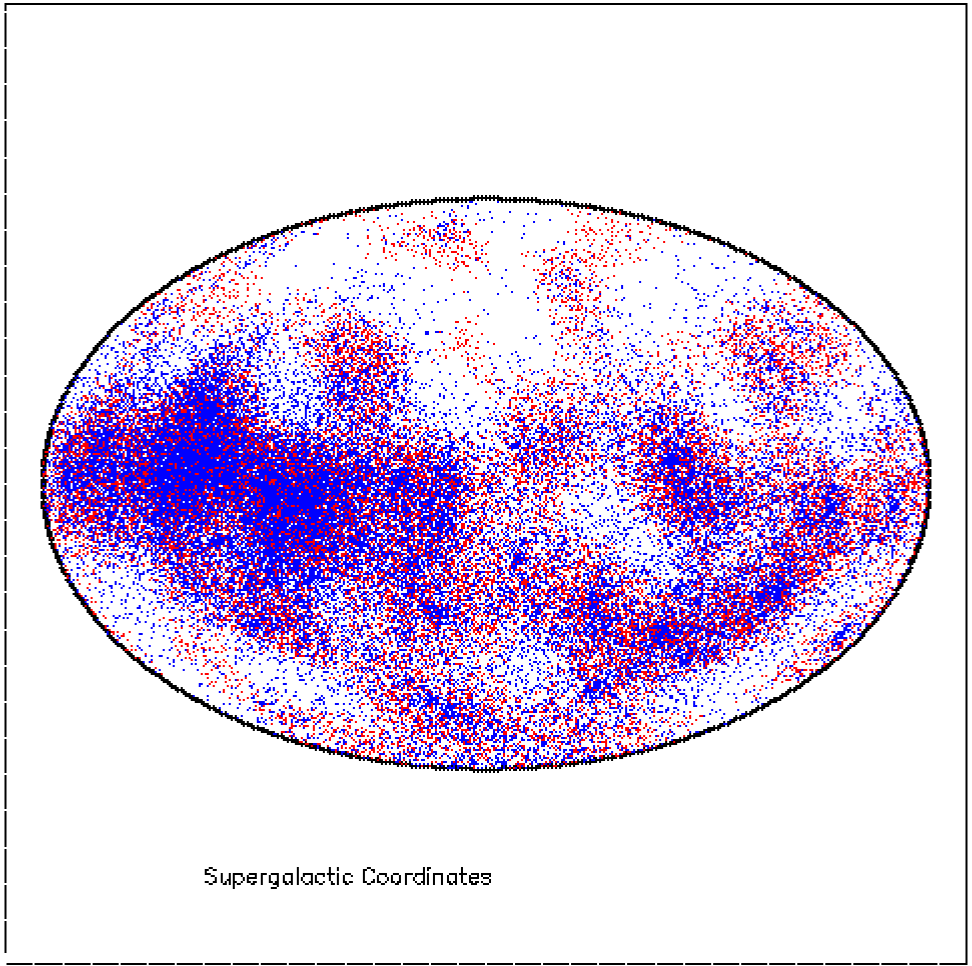


Simulated cosmic ray arrival directions (36,000) based on the infrared point source catalogue with magnetic deflection modeling.

Multipole moment (a_{lm}) \fingerprint\ (+)

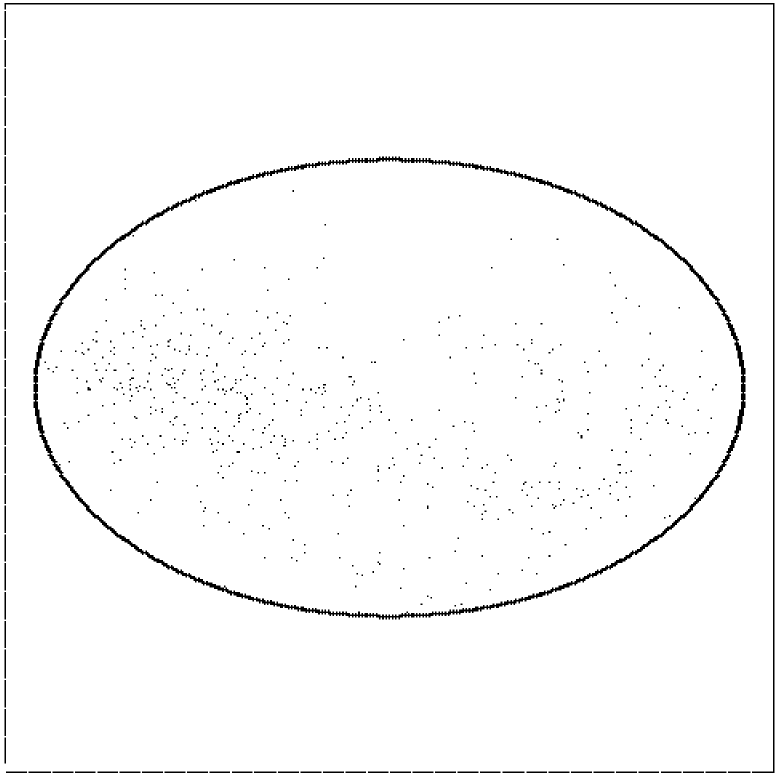
Isotropic simulation with 36,000 arrival directions gives multipole moments shown by filled dots.

Reconstructing the anisotropy from the fingerprint

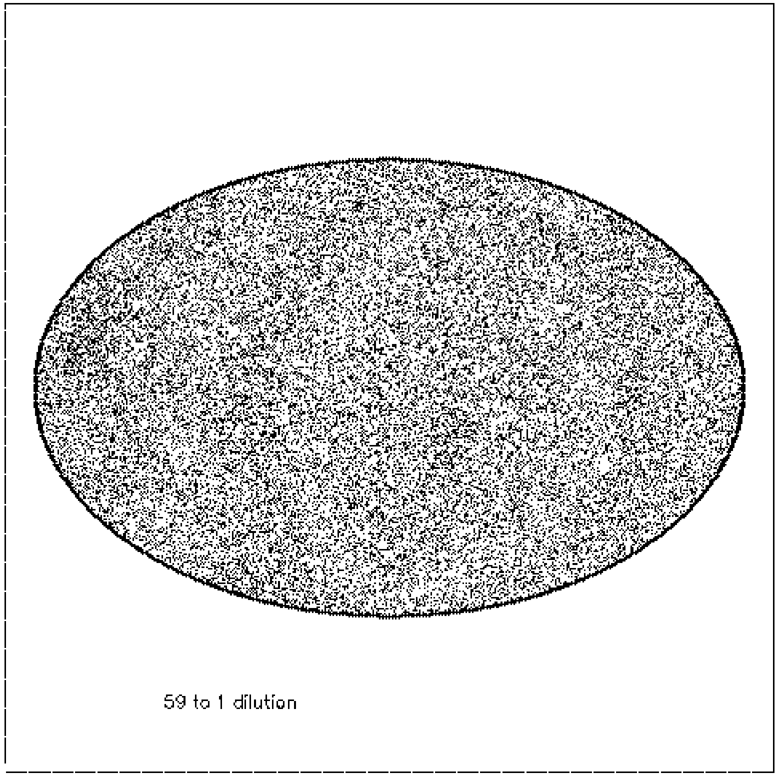


Sampling 36,000 arrival directions (blue) from the celestial function defined by the spherical harmonics recreates the original PSC pattern (red).

Anisotropy in the presence of a large isotropic background

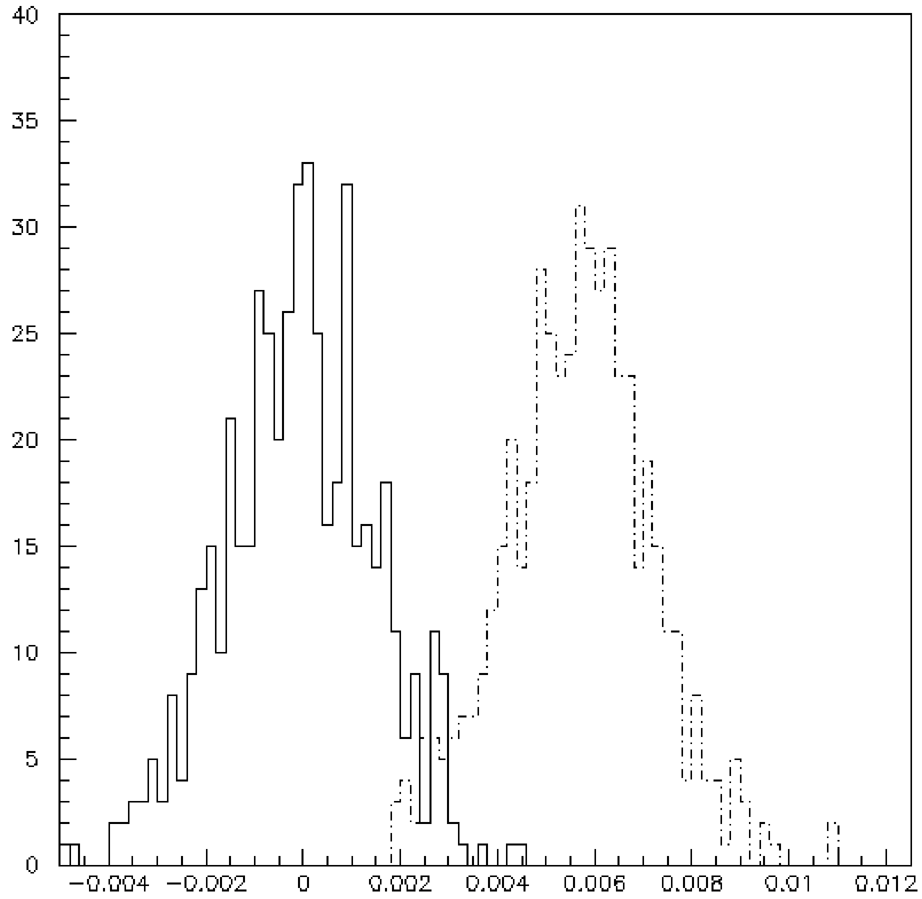


600 arrival directions sampled from the PSC distribution.



Those same 600 directions buried by including 35,400 additional directions sampled isotropically.

Recognizing the diluted anisotropy



Left: trials with 36,000 directions sampled isotropically.

Right: trials with 600 directions from the PSC distribution and the rest isotropically.

Sum of products: PSC-expected a_{lm} times measured a_{lm}.

Summary about Auger South in Argentina

Now more than ½ complete.

Already > 10 times the AGASA aperture.

Already world's largest cumulative data set above 10^{19} eV.

Exposure will grow by order of magnitude in next 3 years.

First spectrum estimate has been presented:

- Systematic uncertainty precludes conclusion on GZK cutoff or absolute flux normalization. This will improve quickly.
- Evidence for deviation from simple power law spectrum.

Fluorescence-based energies are systematically lower than energies derived from SD data compared to Monte Carlo.

- Interaction models flawed (e.g. too few muons)?
- Maybe fluorescence yield is really less than measurements indicate?

No composition determination...yet.

No evidence for flux from galactic center at previously suggested level.

No definitive anisotropy detected....yet.

Important to attain full-sky coverage in combination with Auger North.