Pierre Auger Observatory

studying the universe's highest energy particles

Anisotropy and chemical composition of ultra-high energy cosmic rays using arrival directions measured by the Pierre Auger Observatory

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for the Pierre Auger Collaboration

GH , July 13, 2011, INAOE

SCIENTIFIC OBJETIVES:

Spectrum: CR flux for $E > 10^{18}$ eV

Arrival directions: search for anisotropies (identify the sources)

Composition: light or heavy nuclei, photons, neutrinos, others?

Study of interactions at energies unreachable at accelerators

Science Latest Results

- Spectrum with clear ankle and "GZK" suppression
- Anisotropy of arrival directions above 55 EeV
- Limit on photon flux at 10 EeV using surface detector
- Limit on photon flux at 3 EeV using fluorescence detector
- Limit on Earth-skimming tau neutrinos
- New limit on all flavors of neutrinos using near-horizontal showers
- Statistical analysis of X_{max} values for energies up to 30 EeV

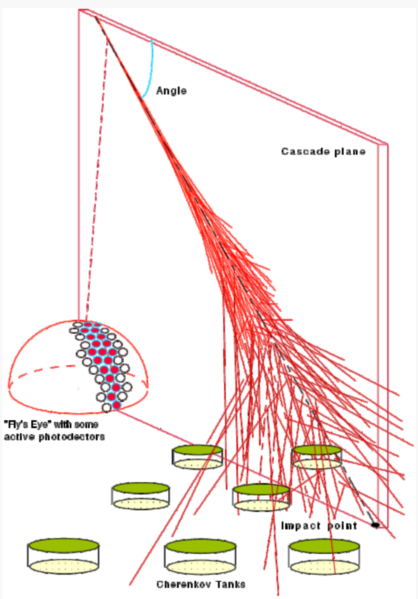
The Auger Observa

One observatory in two hemisphe

Southern site completed June 2008

18 Participating Countries

Argentina	France	Portugal
Australia	Gemany	Slovenia
Bolivia	Italy	Spain
Brazil	Mexico	United States
Croatia	Netherlands	United Kingdom
Czech Republic	Poland	Vietnam



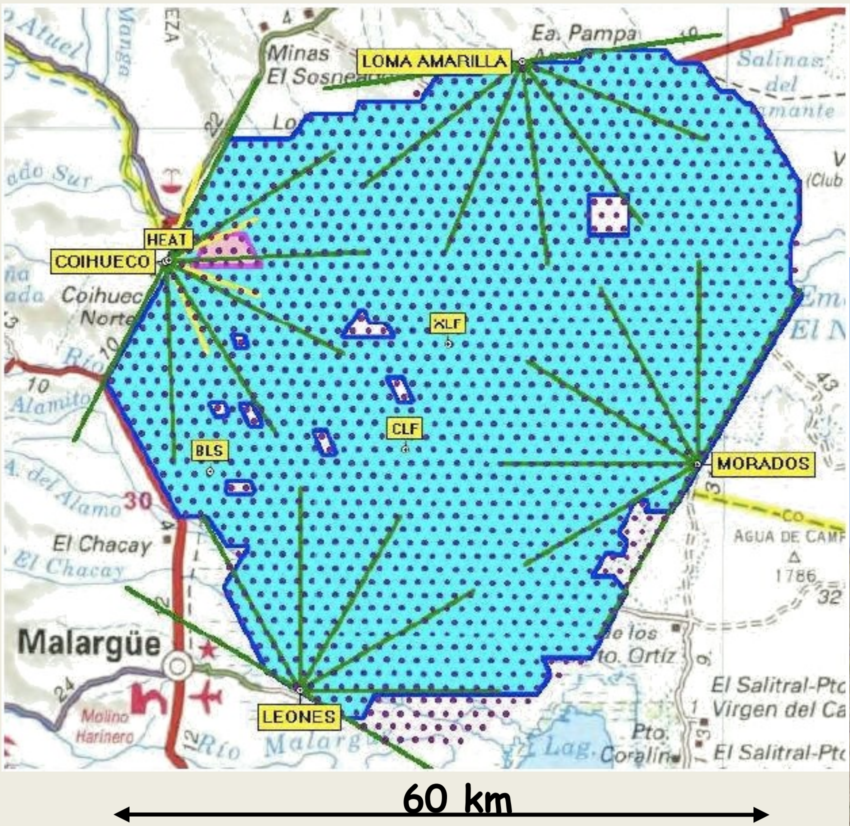
Hybrid shower measurements:

Surface array + air fluorescence

Spokesperson: Karl-Heinz Kamper

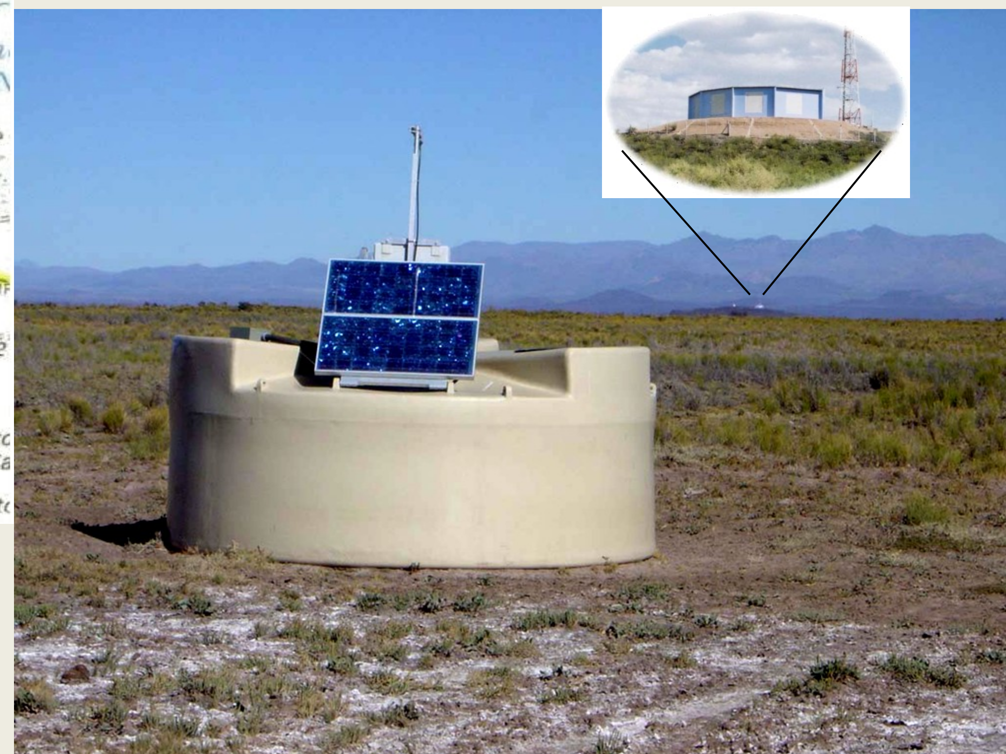
Founders: Jim Cronin and Alan Watson

The Auger Observatory in the Southern Hemisphere
Now fully deployed in Argentina

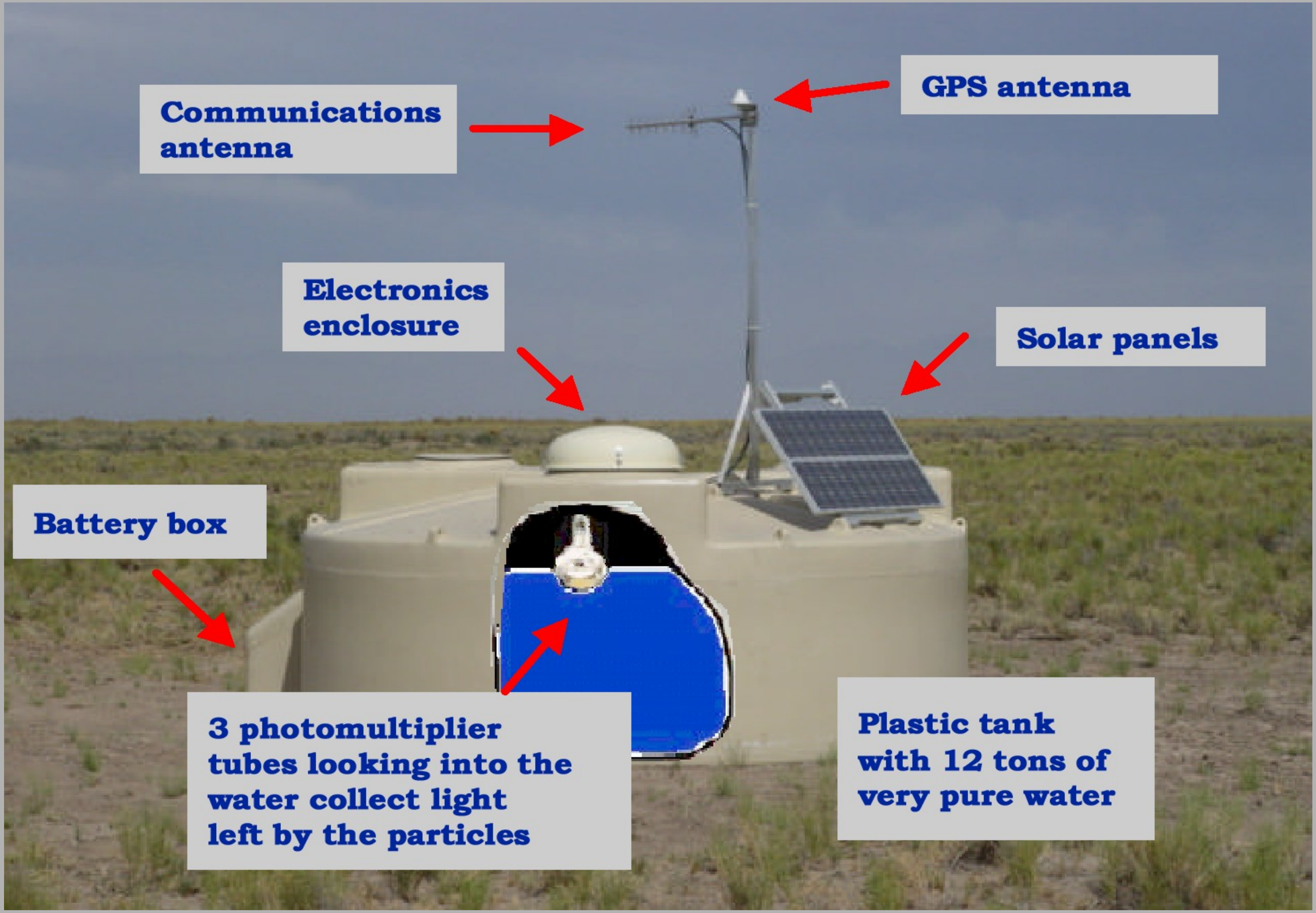


1600 water Cherenkov stations

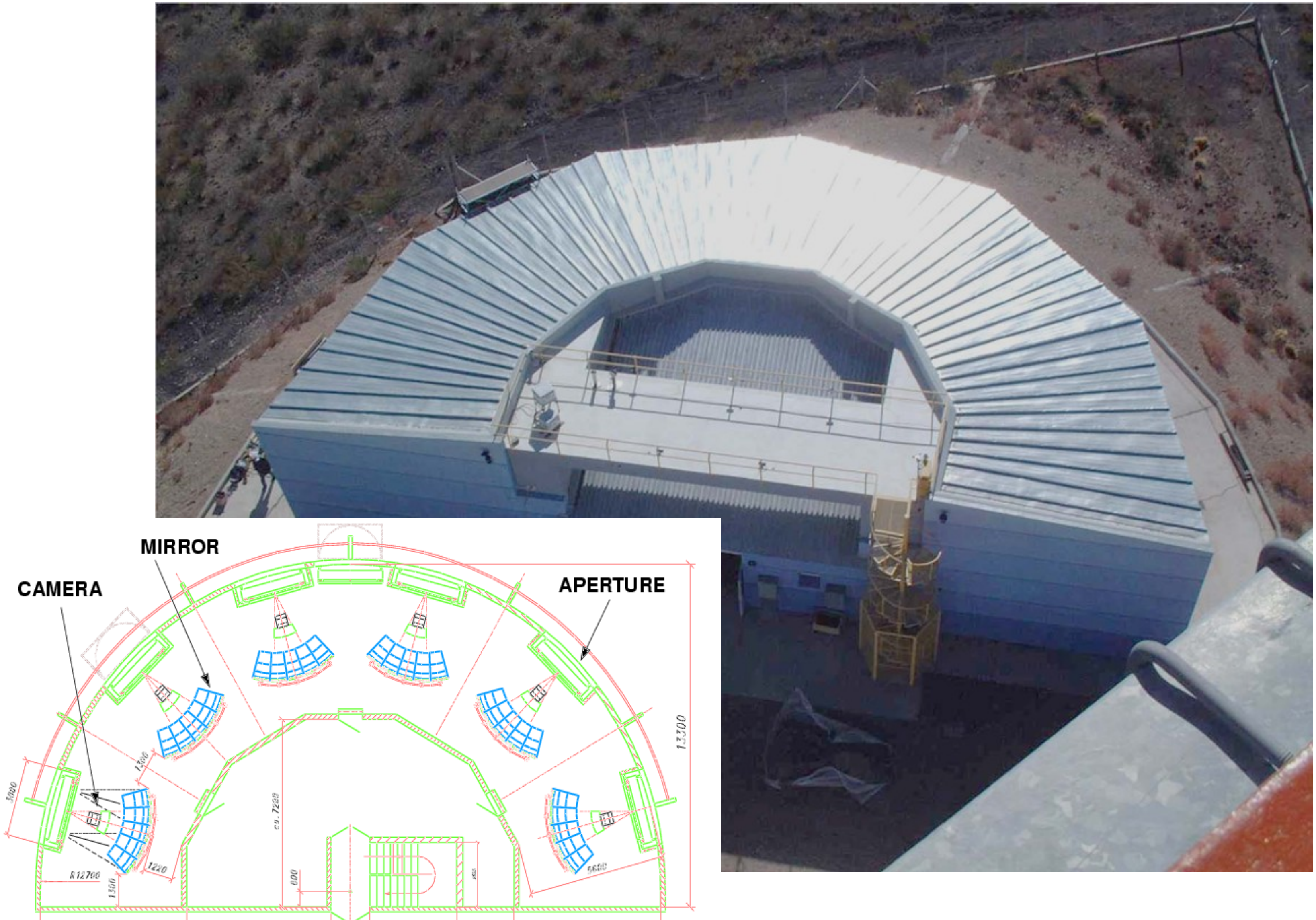
24 fluorescence telescopes (30˚x30˚)



A Water Cherenkov Station



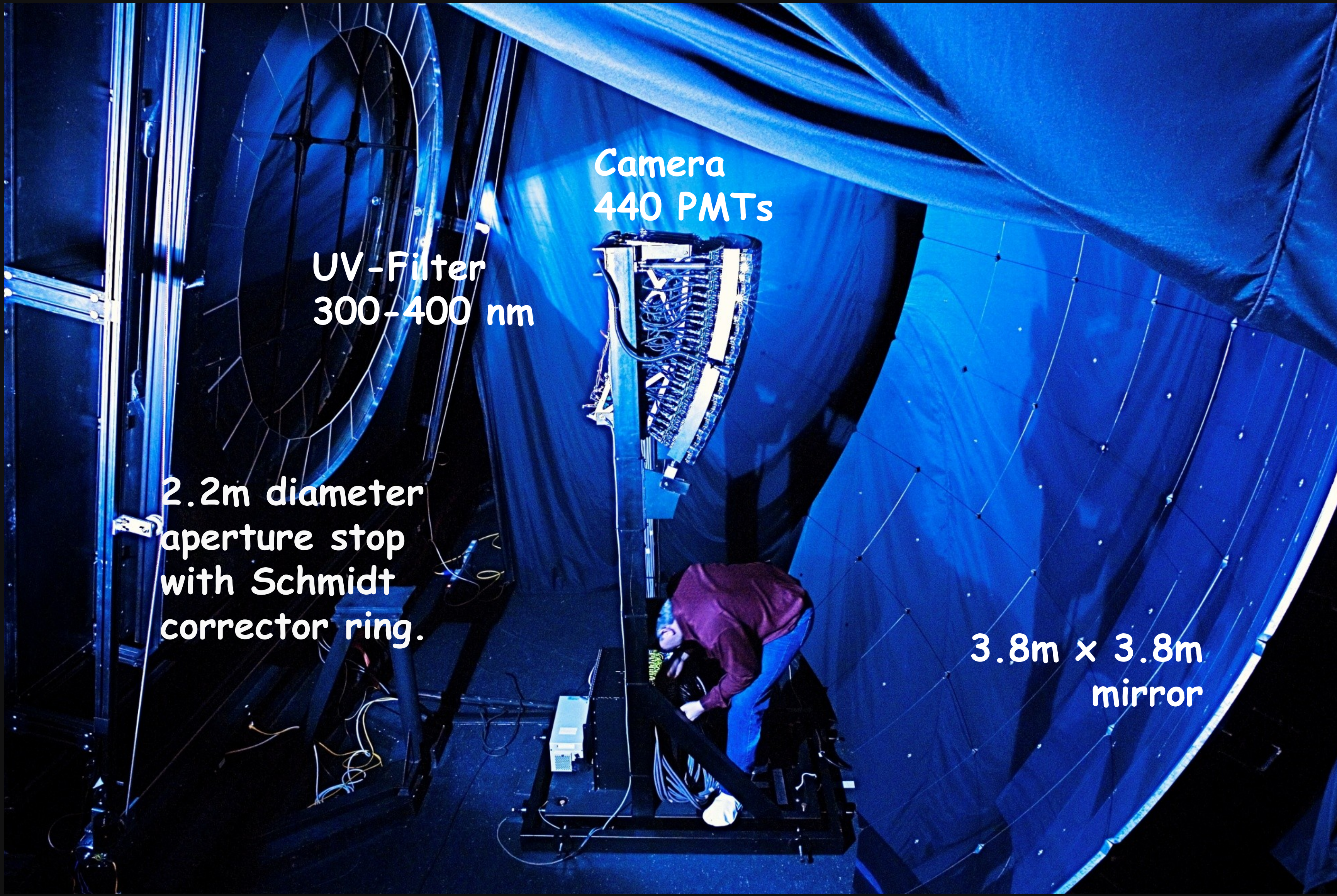
4 Fluorescence Detector Eyes with Six Telescopes (30° x30°) each



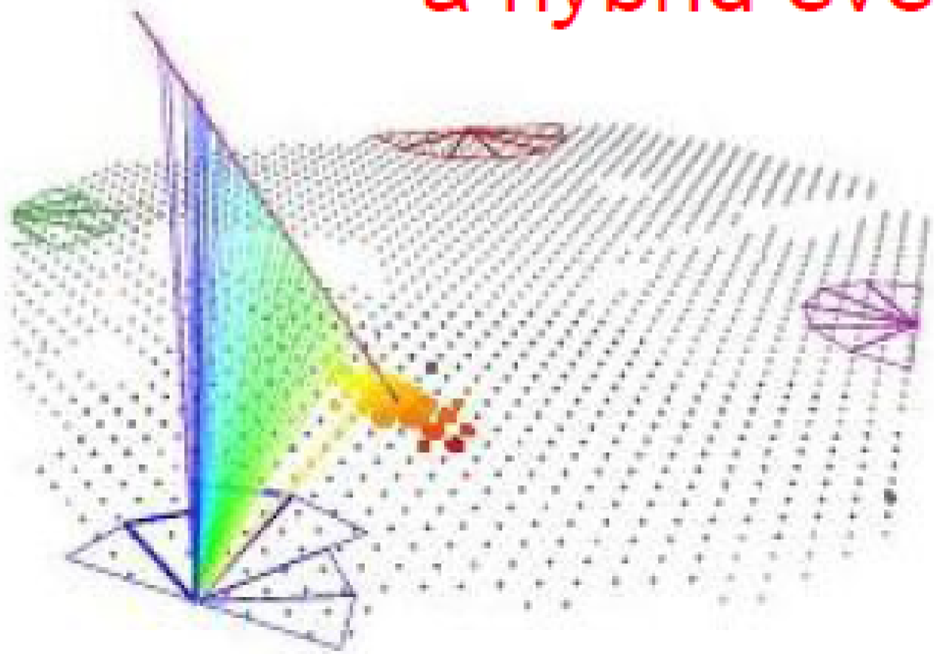
An Air Fluorescence Telescope

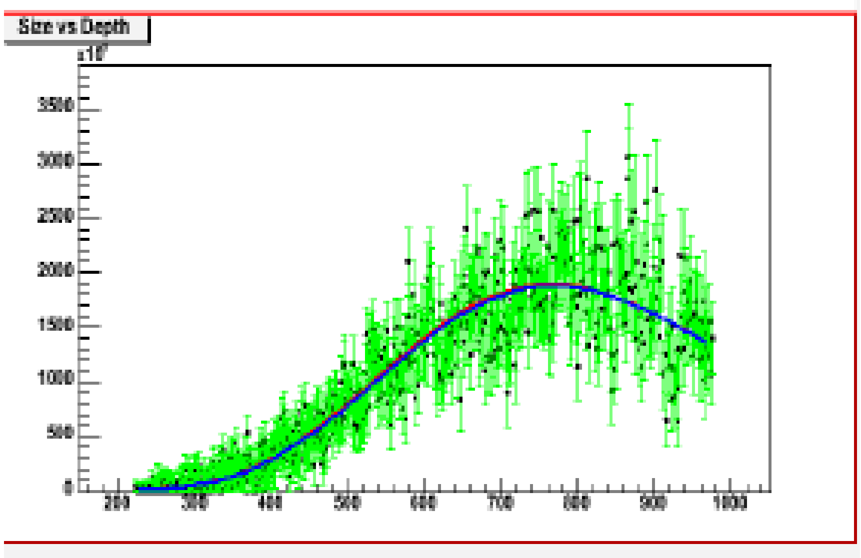
$30^o \times 30^o$

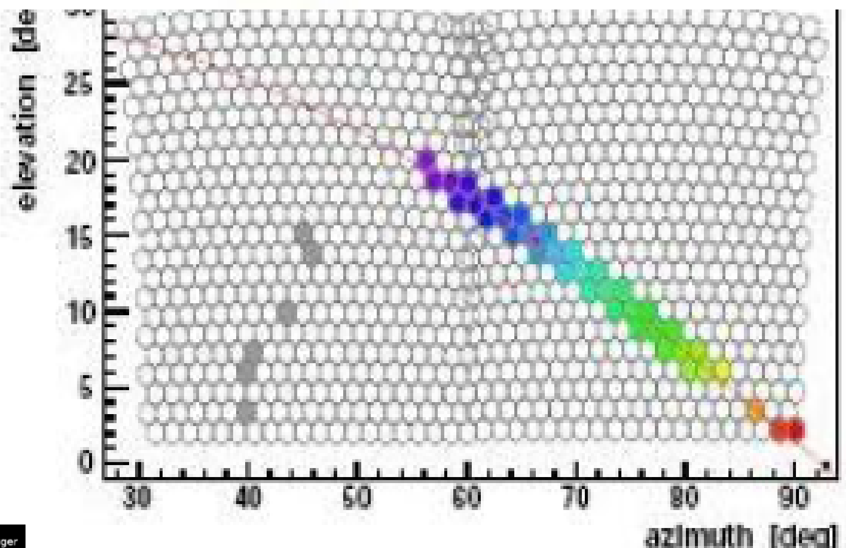
Field of View



a hybrid event







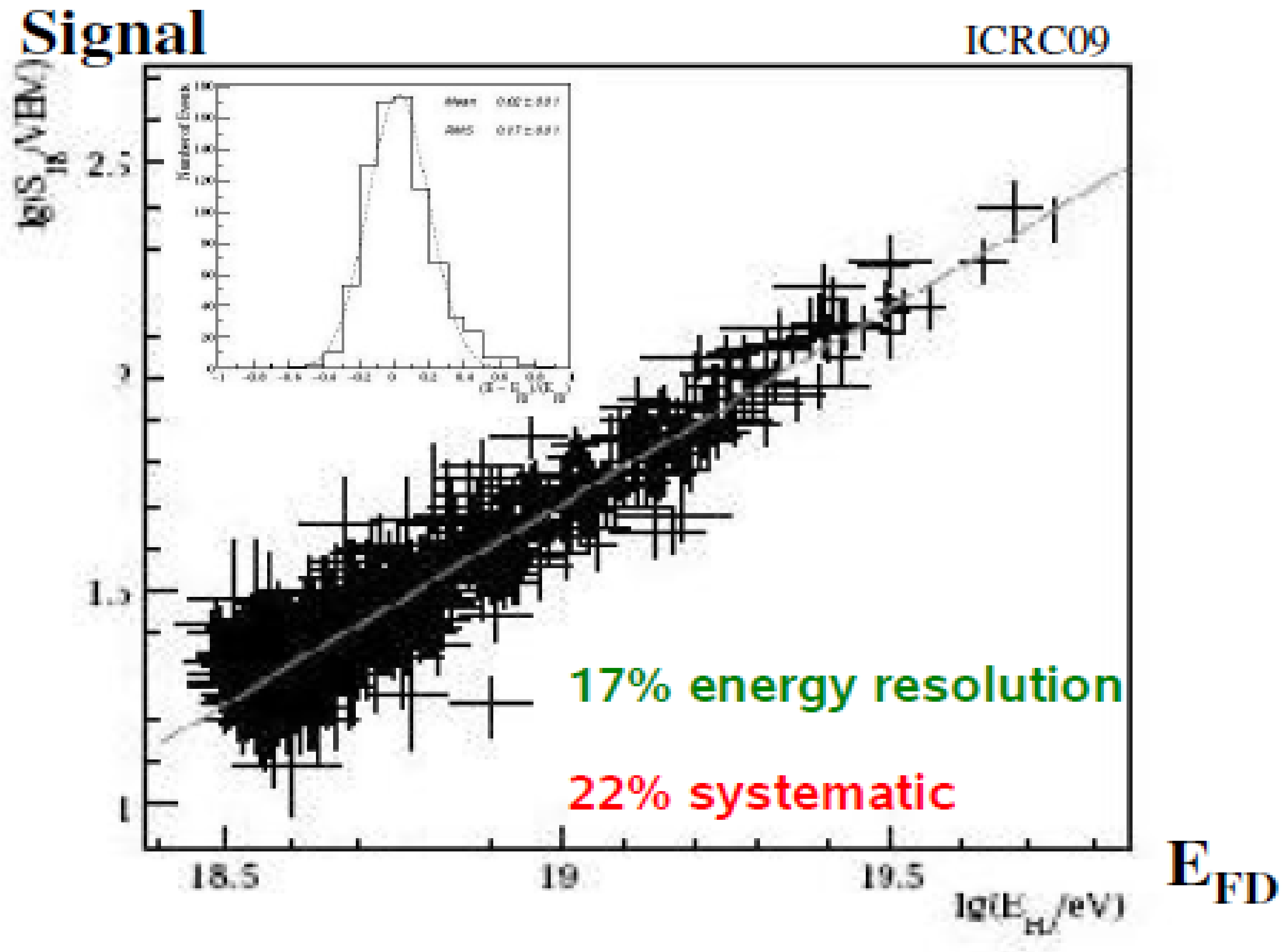
Measure Xmax

Energy calibration

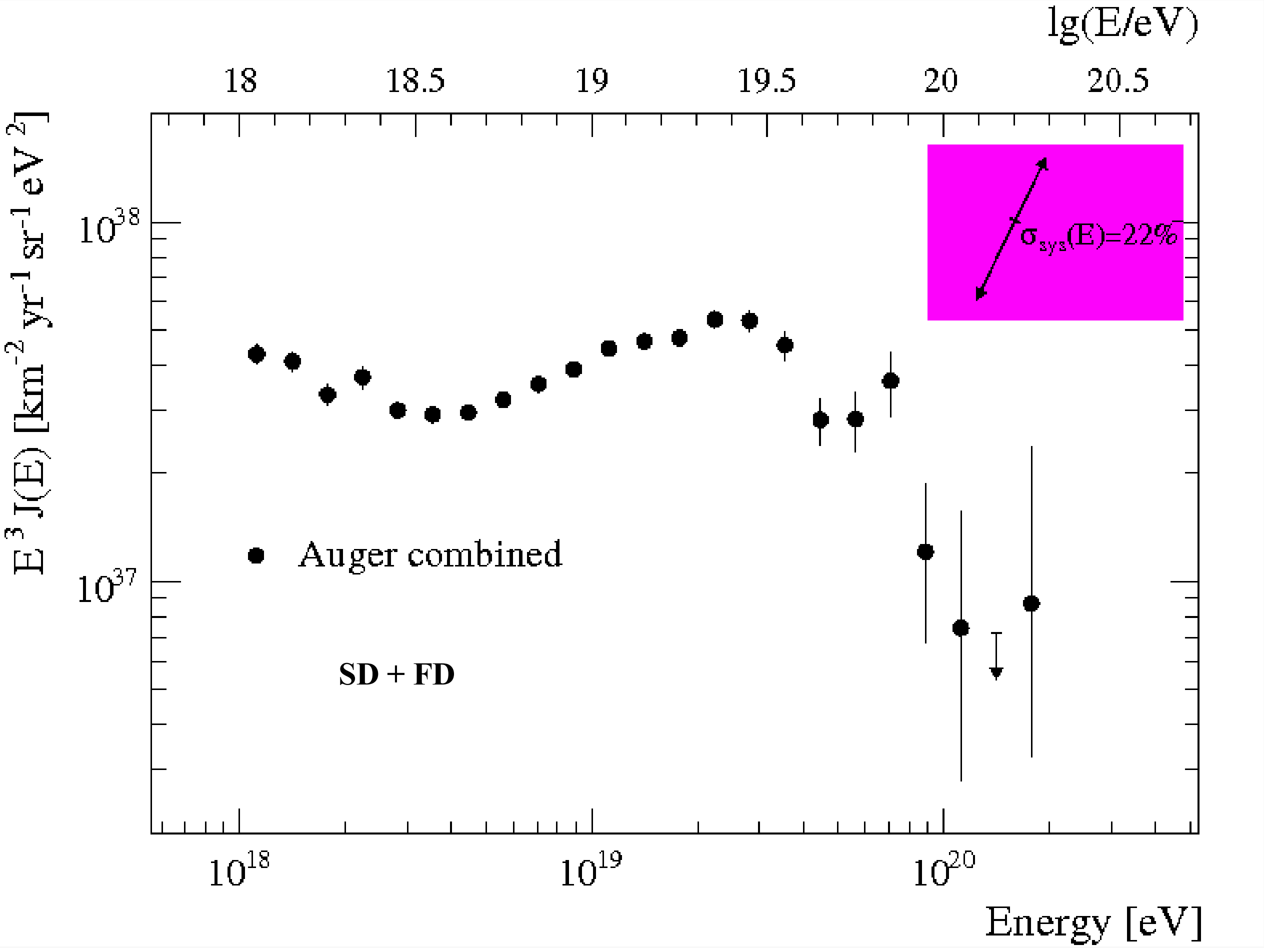
angular resolution studies ...

(but duty cycle ~15%)

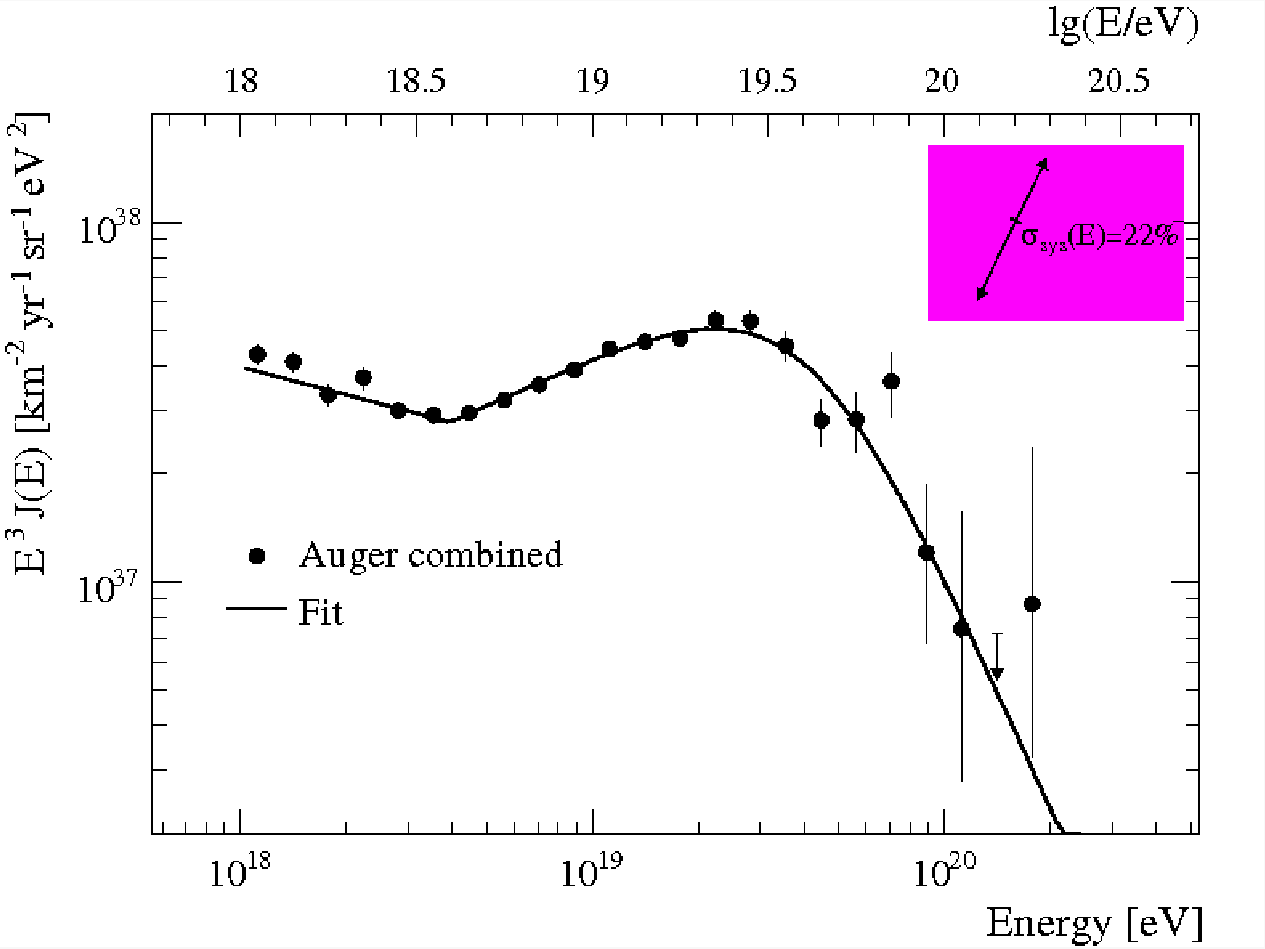
Energy calibrated using hybrid events



The Auger Energy Spectrum

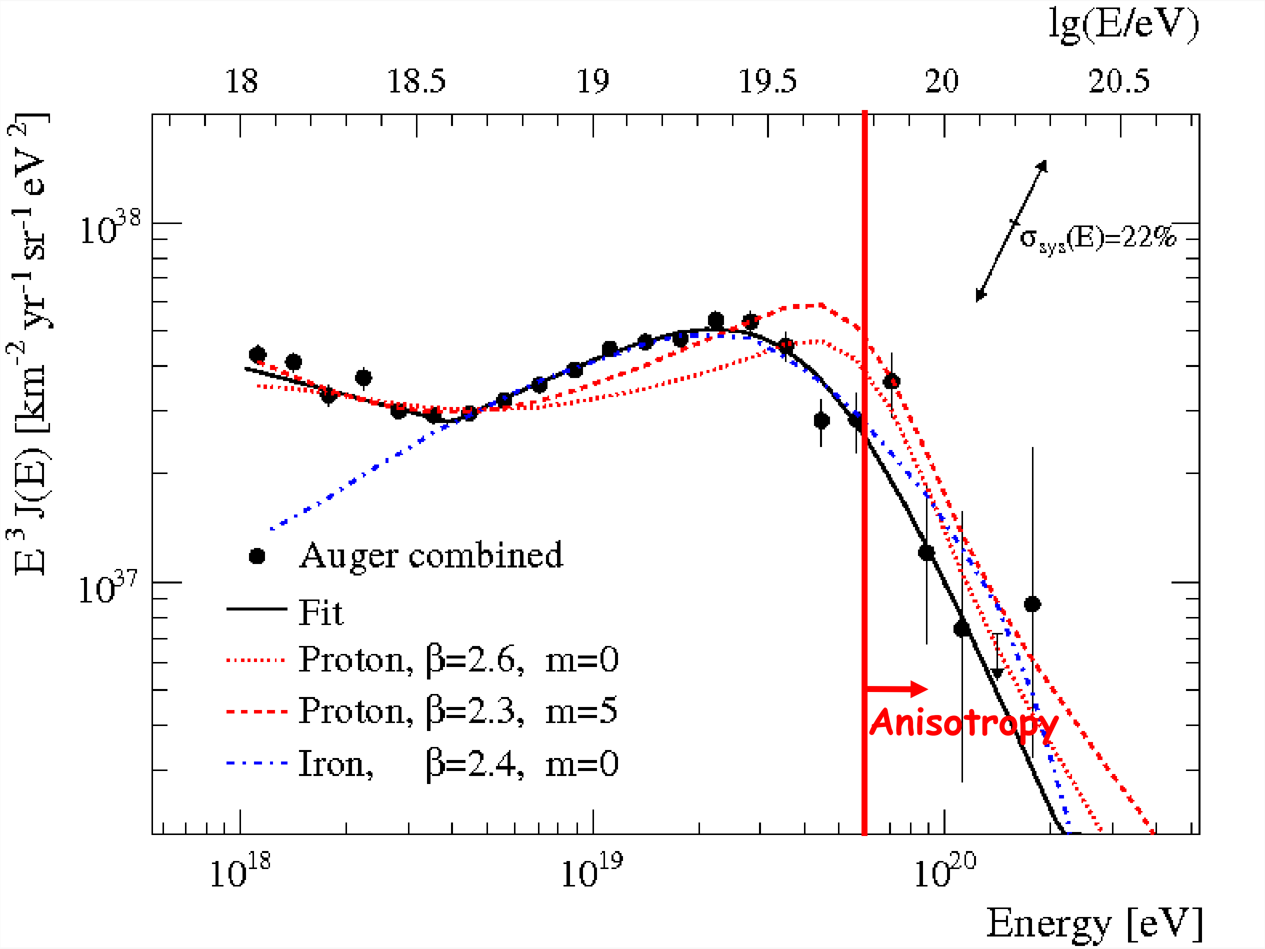


The Auger Energy Spectrum



Five-parameter fit: index, breakpoint, index, critical energy, normalization

The Auger Energy Spectrum



Comparison with models

The Auger Energy Spectrum

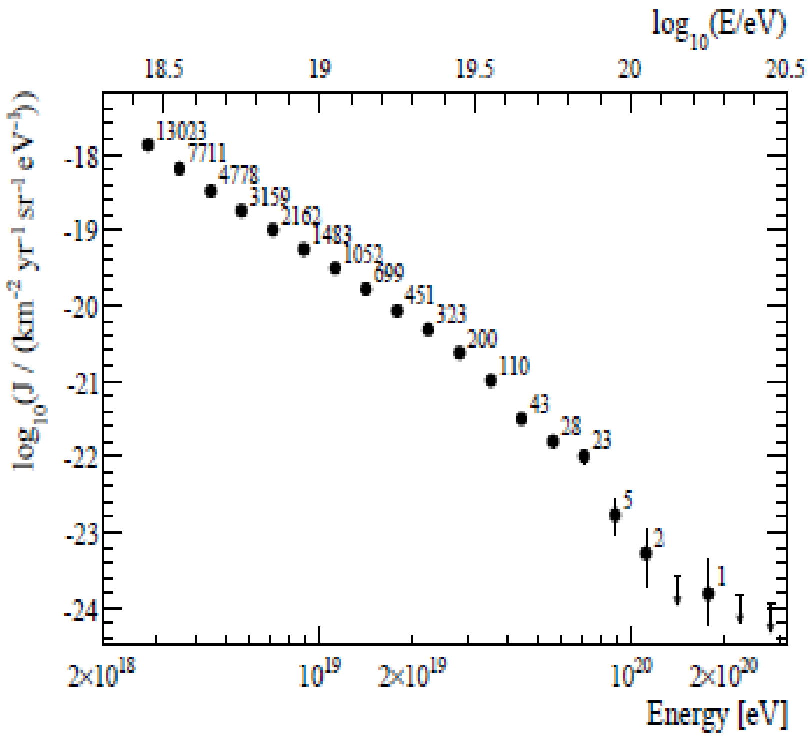


Figure 5: Energy spectrum derived from surface detector data calibrated with fluorescence measurements. Only statistical uncertainties are shown. The upper limits correspond to 84% CL.

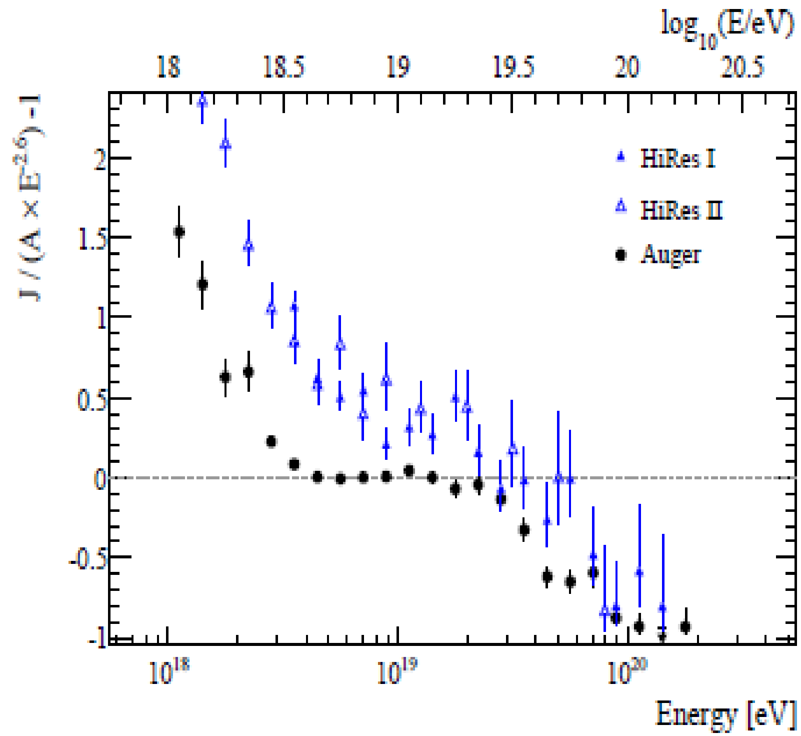
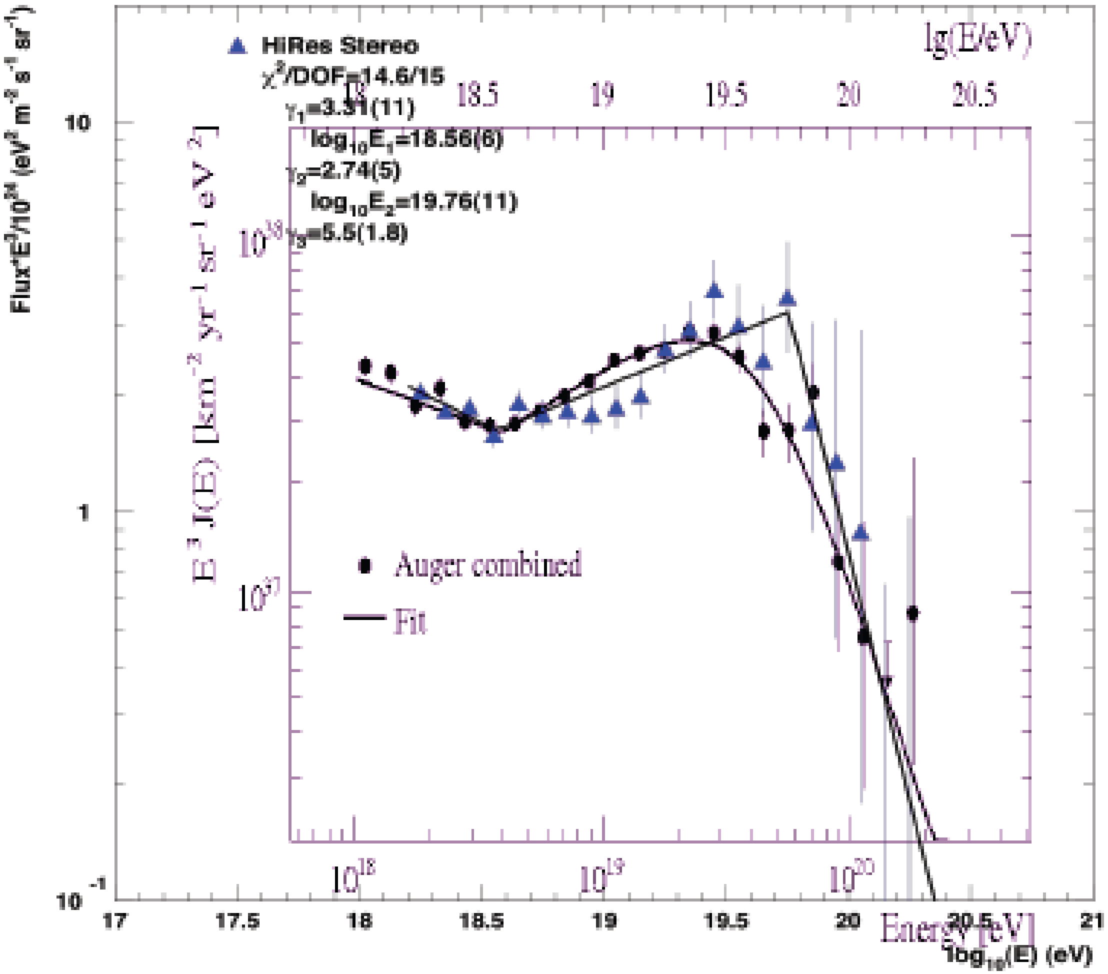


Figure 6: The fractional difference between the combined energy spectrum of the Pierre Auger Observatory and a spectrum with an index of 2.6. Data from the HiRes instrument [1, 41] are shown for comparison.

J. Abraham et al. (The Pierre Auger Collaboration), "Measurement of the energy spectrum of cosmic rays above 10^{18} eV using thePierre Auger Observatory," Physics Letters B, vol. 685, pp. 239–246, 2010.

HiRes (Stereo) vs. Auger (combined)



In general terms they are compatible.

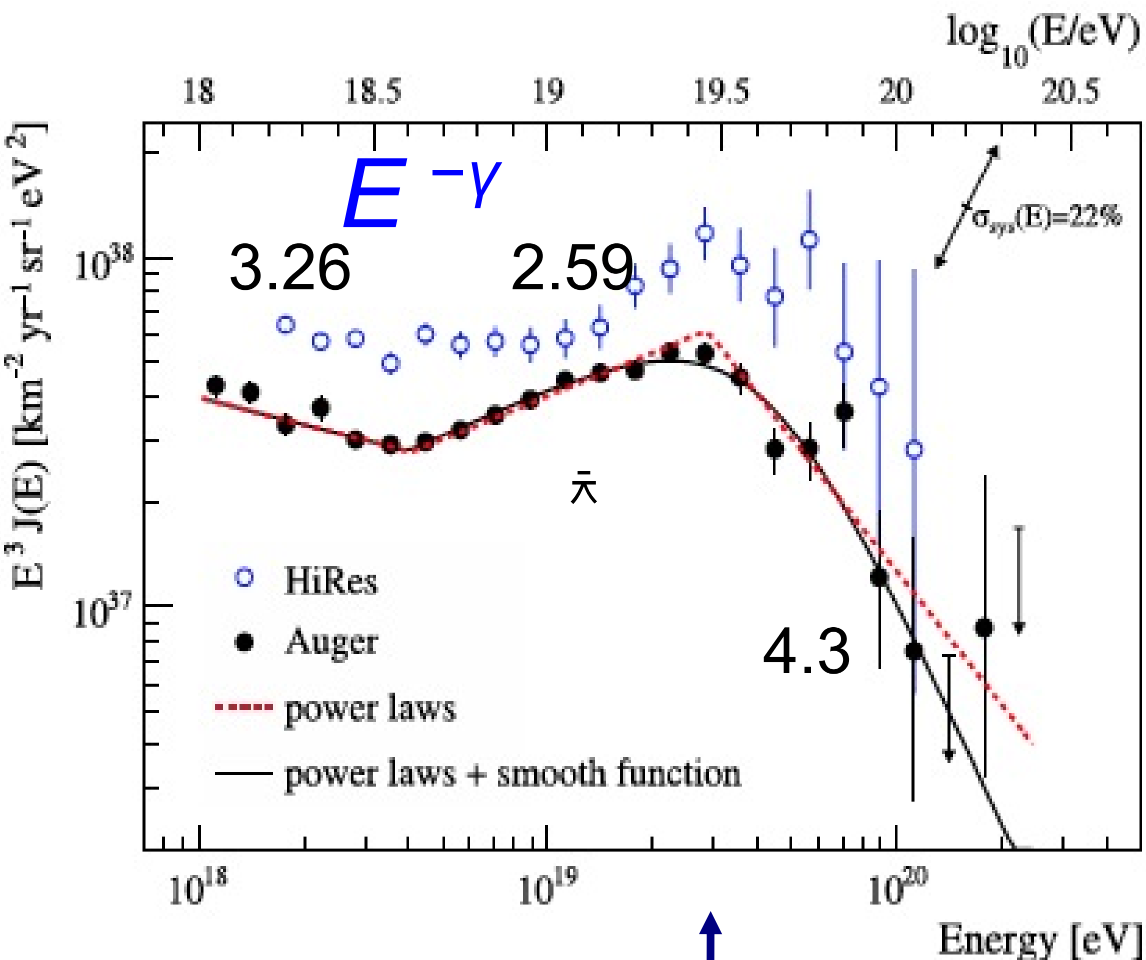
However, they are *astrophysicaly* quite different.

Point differences:

-Slopes before and after the center of the ankle
-High energy (GZK?) break point
-$E_{1/2}$
-Suppression slope

Note: there still seems to remain a real difference in flux since the ankle values are almost the same and flux transformation factor is 3.14×10^{13}

Energy Spectrum from Auger Observatory



4400 events above 10^{19} eV
Only 3 above 10^{20}eV

2.59 ± 0.02

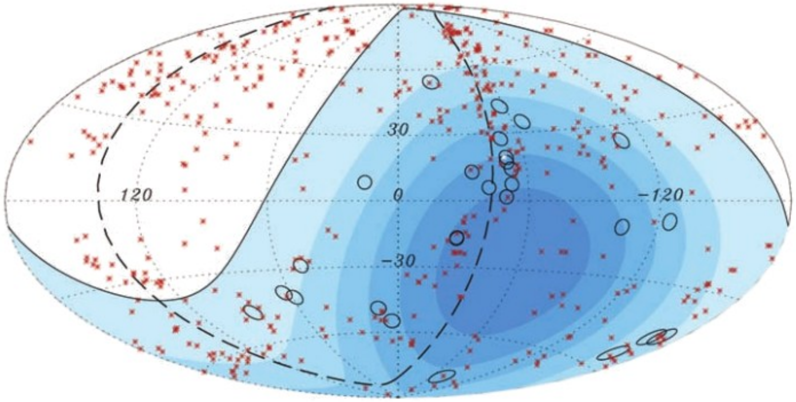
Physics Letters B 685 (2010) 239–246

Ankle at 4.1x10^18 eV

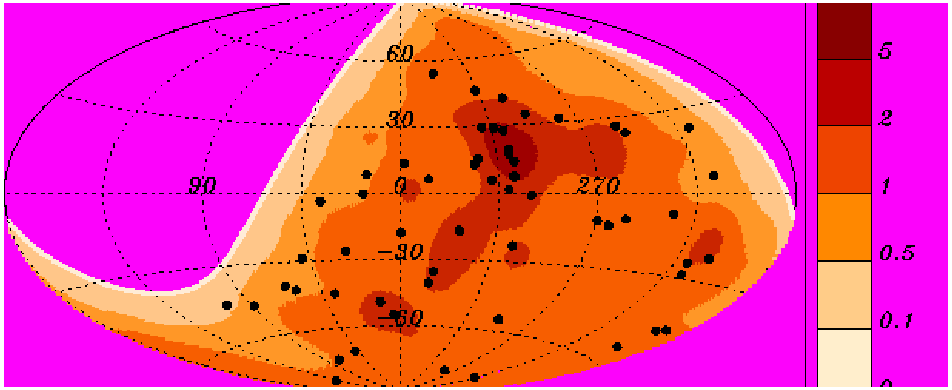
2.9 x 10^19 eV

Suppression of flux significat at 20 σ, GZK or Injection cutoff at sources?

The Auger Sky above 60 EeV

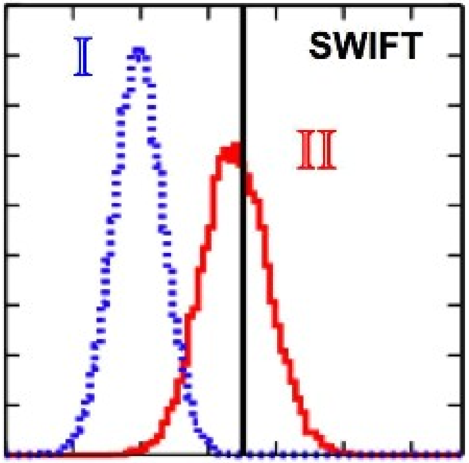


27 events as of November 2007



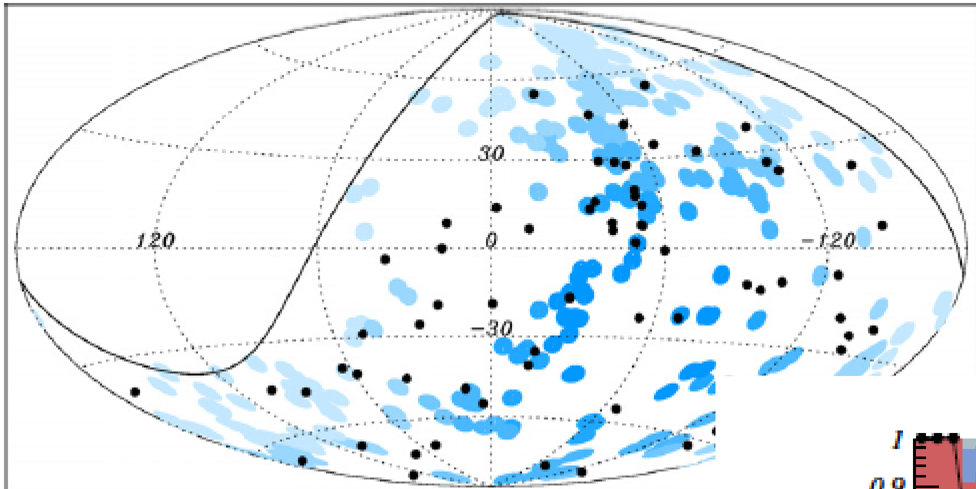
58 events now (with Swift-BAT AGN density map)

Simulated data sets based on isotropy (I) and Swift-BAT model (II) compared to data (black line/point).



Log(Likelihood)

The Auger Sky above 55 EeV



Astroparticle Physics 34 (2010) 314–326

69 event

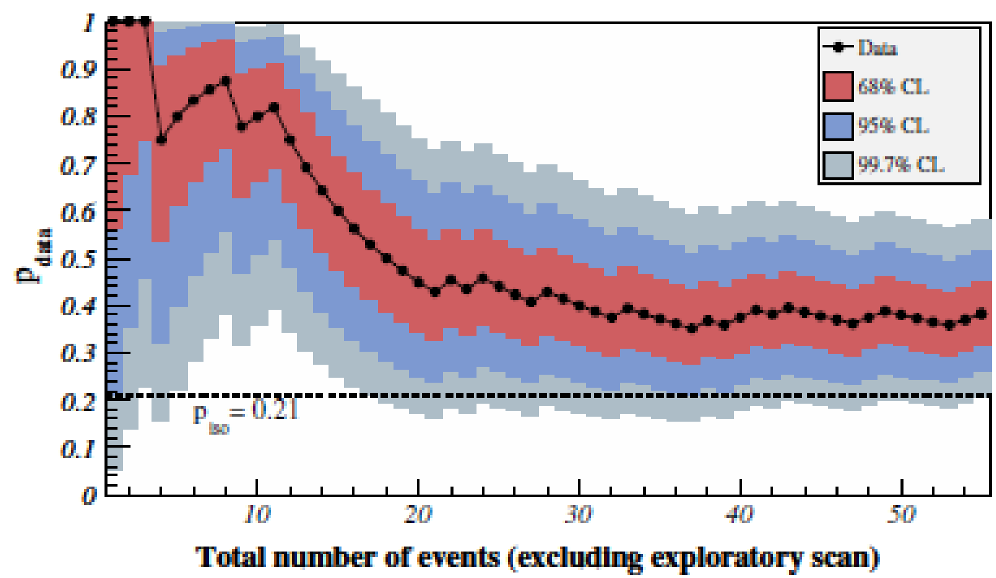
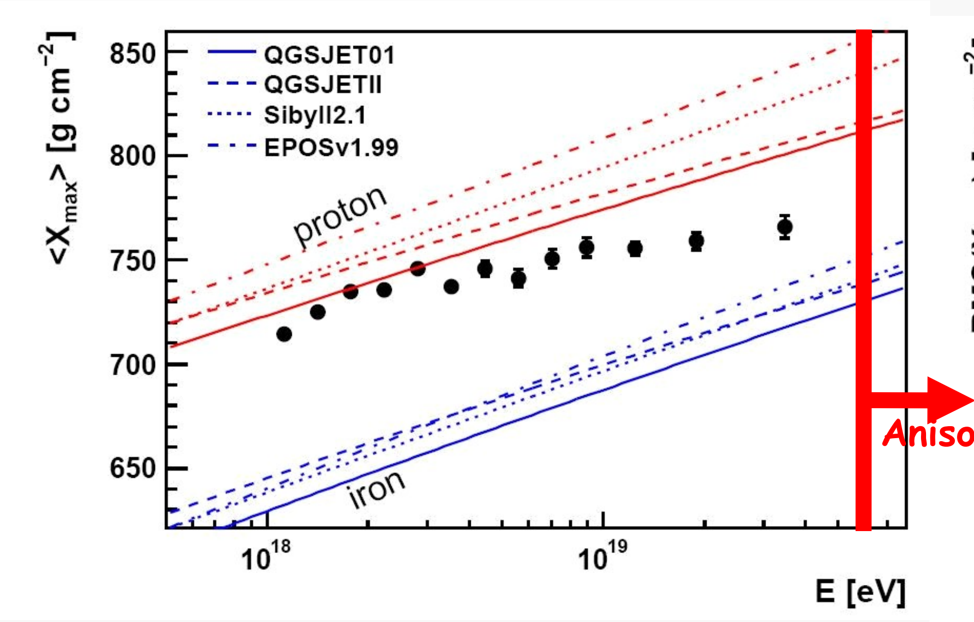
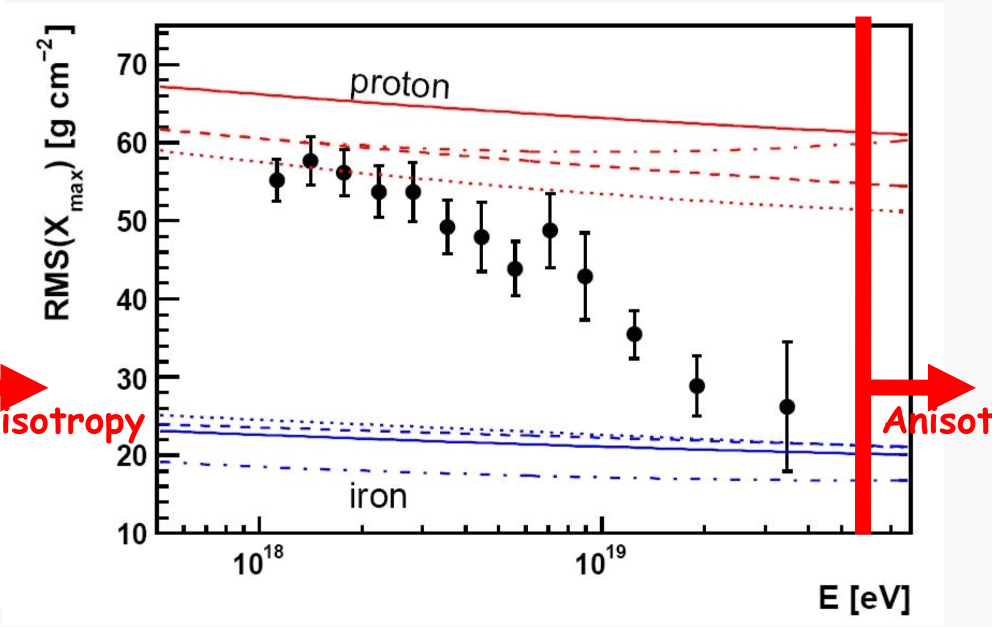


Fig. 2. The most likely value of the degree of correlation $p_{data} = k/N$ is plotted with black dots as a function of the total number of time-ordered events (excluding those in period I). The 68%, 95% and 99.7% confidence level intervals around the most likely value are shaded. The horizontal dashed line shows the isotropic value $p_{iso} = 0.21$. The current estimate of the signal is $\left(0.38^{+0.07}_{-0.06}\right)$.

The correlating fraction went down to from 69 (2007) to 38%
But there is still evidence of anisotropy for E>55 EeV at 99% CL

Shower Depths of Maximum X_{max}





These suggest high cross section and high multiplicity at high energy.

Heavy nuclei?

Or protons interacting differently than expected?

Information lacking for the (anisotropic) trans-GZK energy regime!

(Crucial for calculation of the diffuse cosmogenic neutrino flux)

Shower Depths of Maximum X_{max}

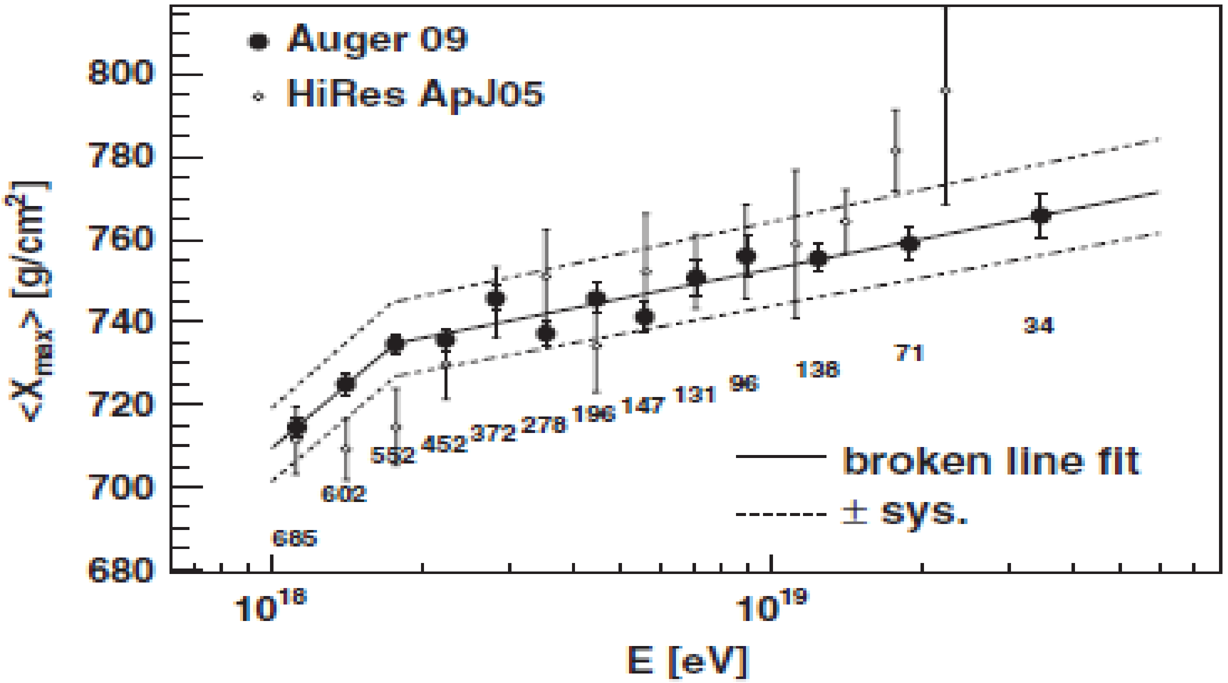
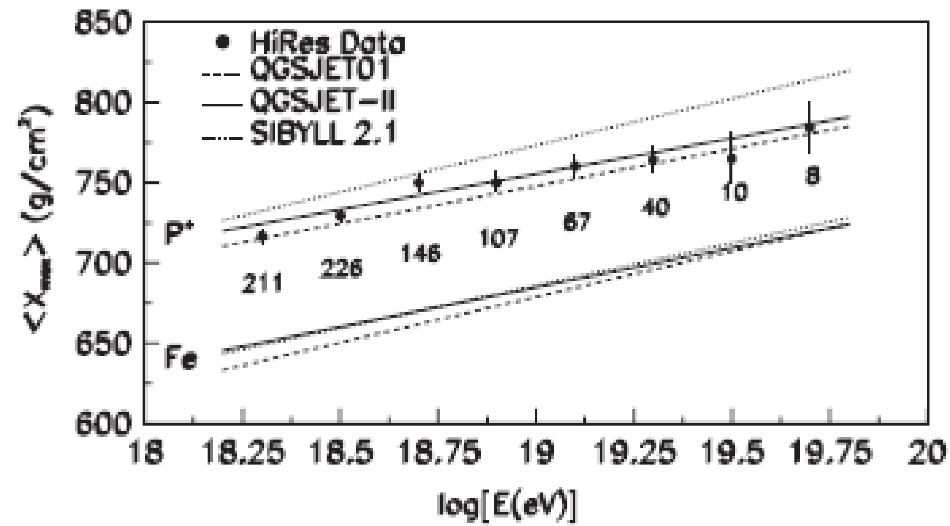


FIG. 2. $\langle X_{max} \rangle$ as a function of energy. Lines denote a fit with a broken line in lg$E$. The systematic uncertainties of $\langle X_{max} \rangle$ are indicated by a dashed line. The number of events in each energy bin is displayed below the data points. HiRes data [10] are shown for comparison.

PRL **104,** 091101 (2010) PHYSICAL REVIEW LETTERS week ending 5 MARCH 2010

Measurement of the Depth of Maximum of Extensive Air Showers above 10^{18} eV

Hi-Res X_m - results favor protons

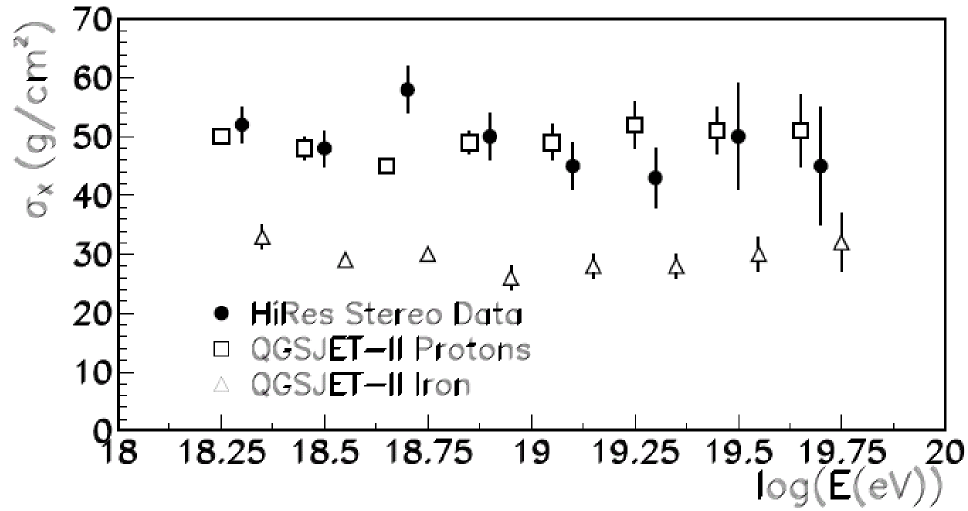


Mean depth of maximum vs energy

Evidence for proton dominated composition above 1.6 EeV

PRL 104 161101 (2010)

HiRes Collaboration arXiv:0910.4184



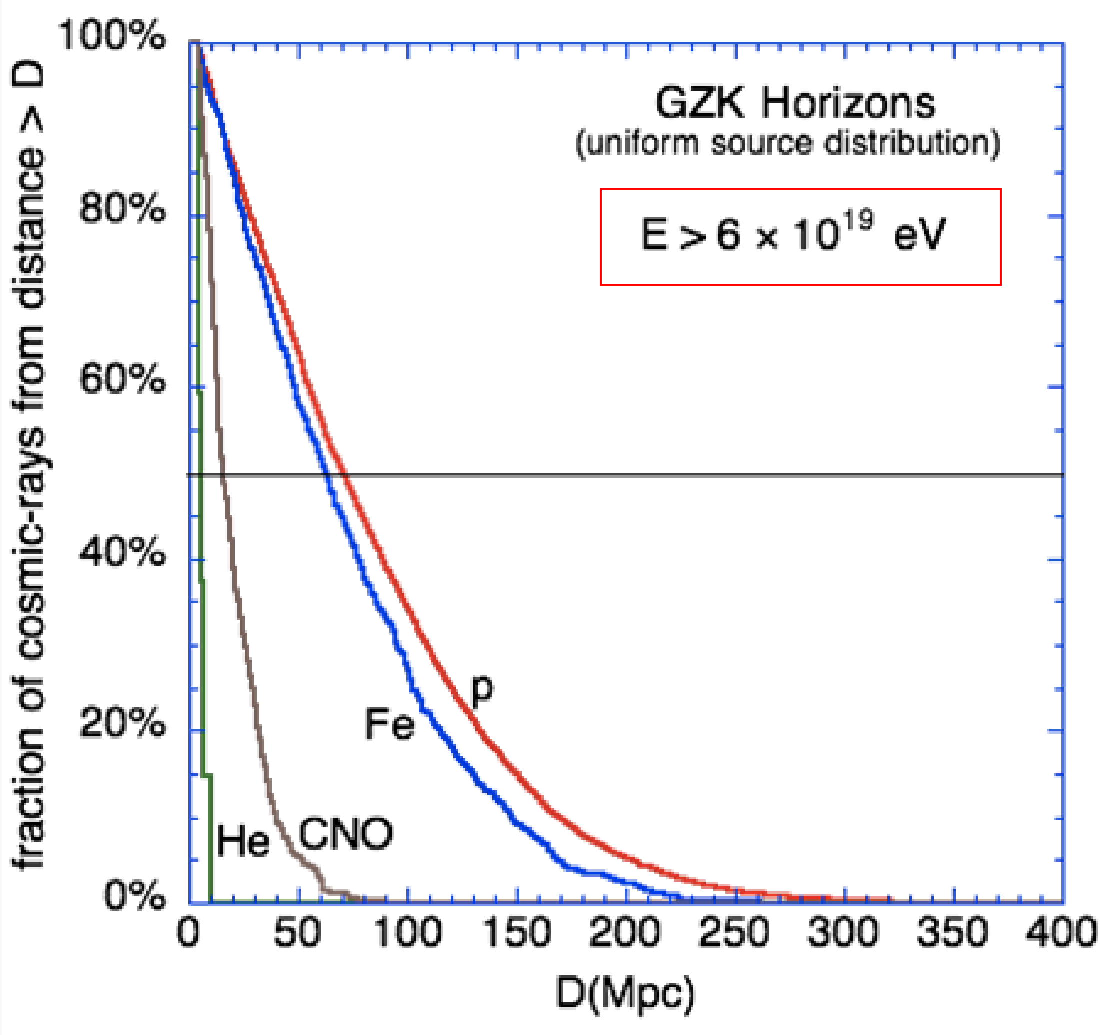
Width of distribution vs energy

Trans-GZK composition is simpler

Light and intermediate nuclei photodisintegrate rapidly.

Only protons and/or heavy nuclei survive more than 20 Mpc distances.

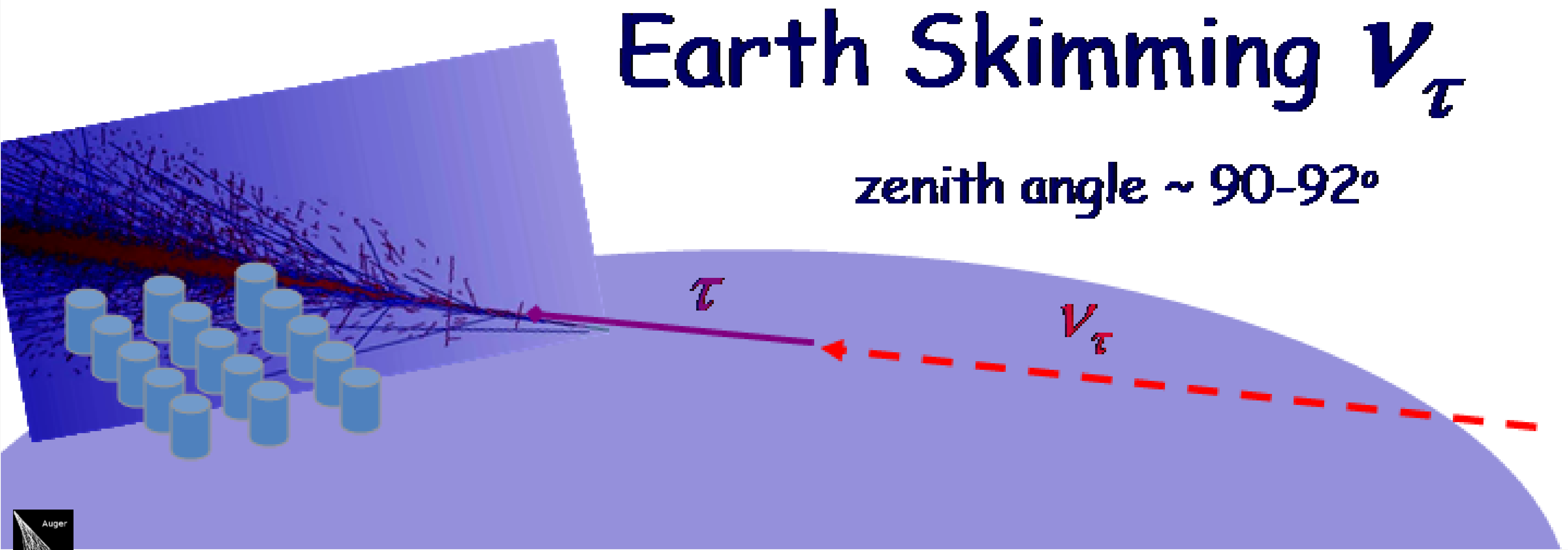
Cosmic magnetic fields should make highly charged nuclei almost isotropic.



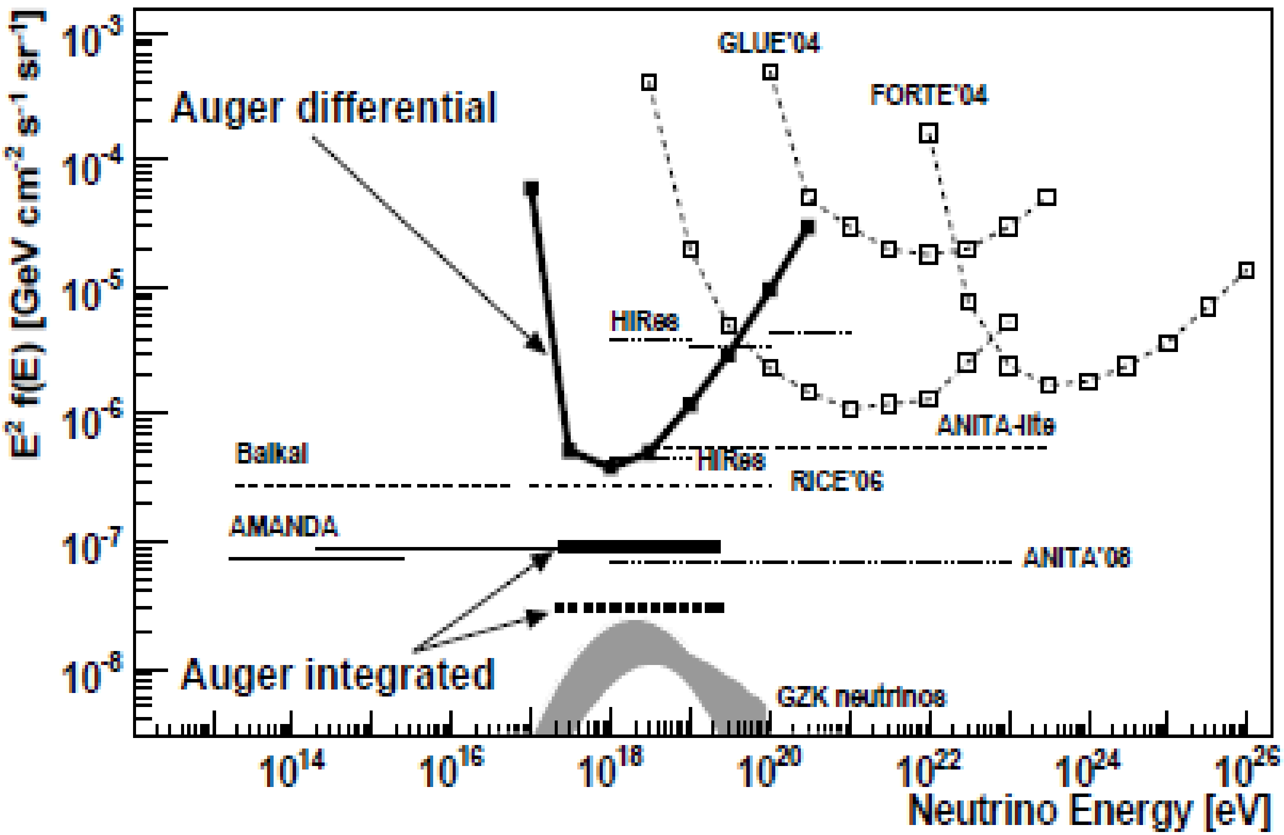
The Auger UHE Neutrino Observatory

Neutrinos can be identified as "young" showers at very great atmospheric slant depth (either upward or downward).

Auger exposure to tau Neutrinos



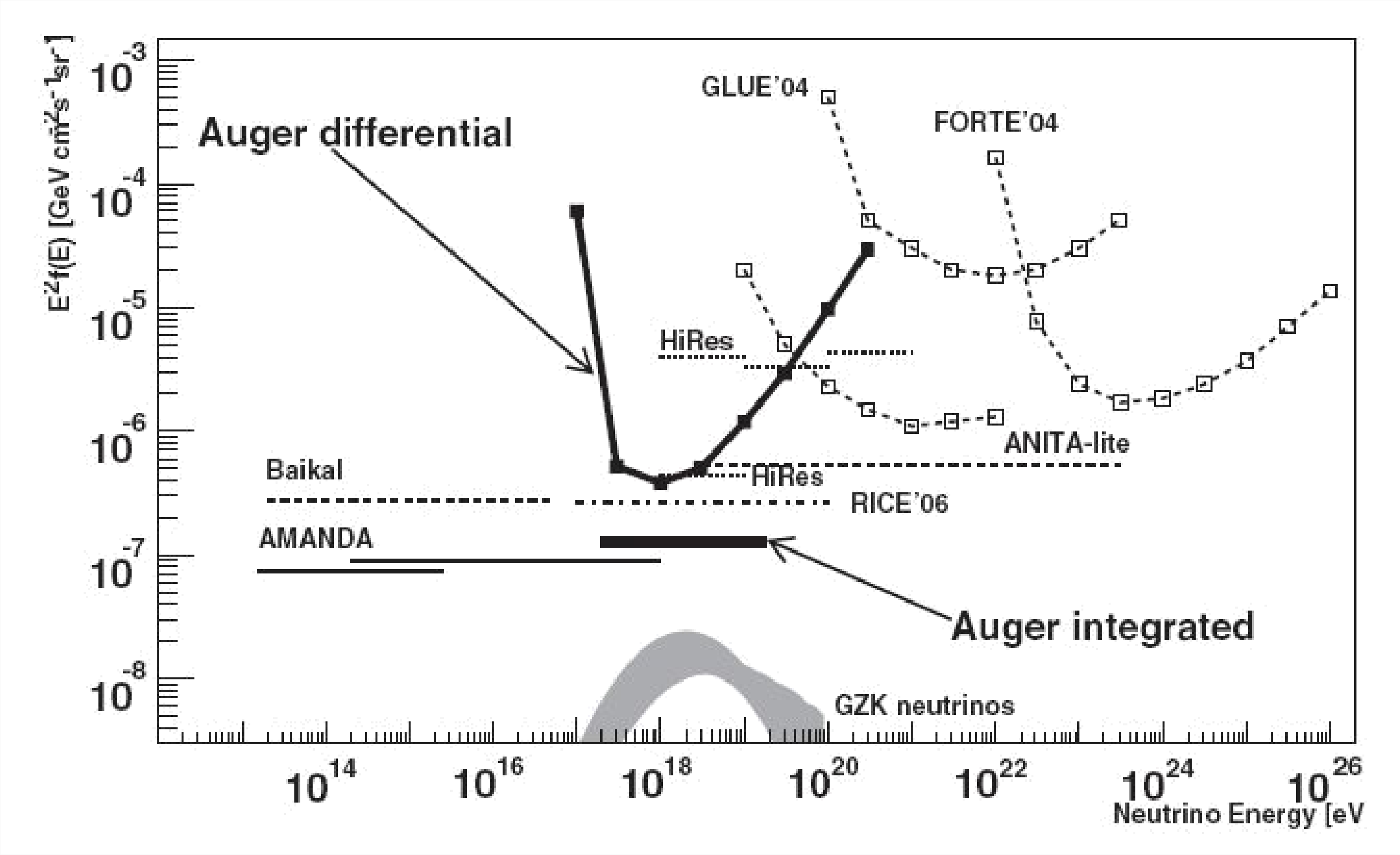
Limit on the diffuse flux of ultra-high energy tau neutrinos



Phys.Rev.D79: 102001, 2009

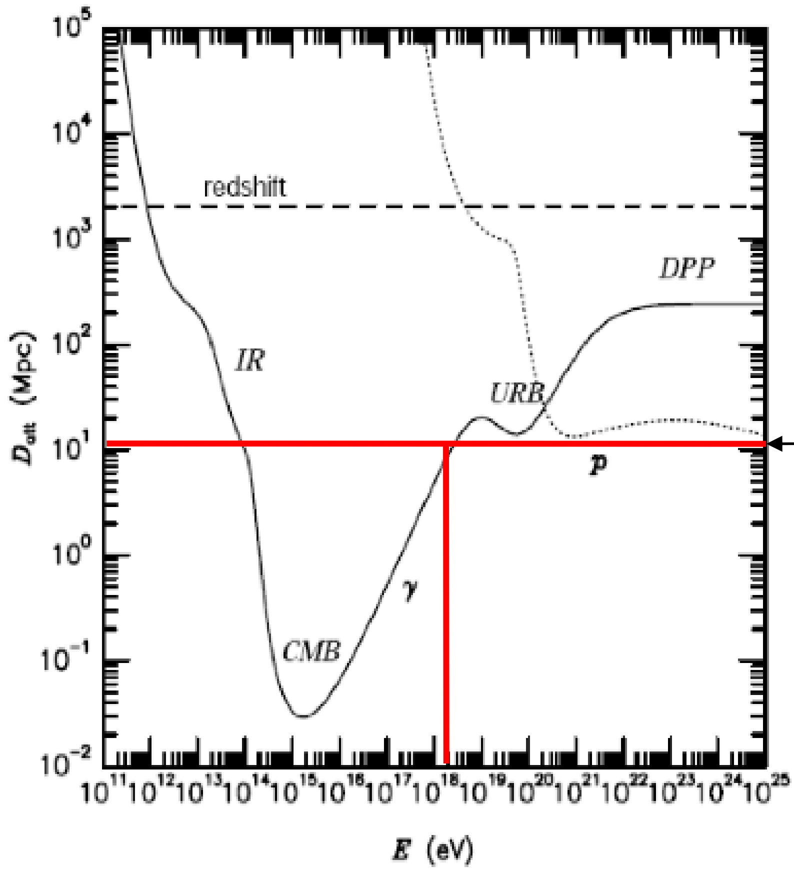
FIG. 9: Limits at 90 % CL for *each flavor* of diffuse UHE neutrino fluxes assuming a proportion of flavors of 1:1:1 due to neutrino oscillations. The Auger limits are given using the most pessimistic case of the systematics (solid lines). For the integrated format, the limit that would be obtained in the most optimistic scenario of systematics is also shown (dashed line). See text for the references to the other experimental limits. The shaded area corresponds to the allowed region of expected GZK neutrino fluxes computed under different assumptions [69, 70, 71, 72], although predictions almost 1 order of magnitude lower and higher exist.

Limit on Tau Neutrinos



[Physical Review Letters 100 (2008), 211101]

The UHE Gamma Ray Astronomical Window



Photon attenuation length exceeds 10 Mpc for E > 2 EeV

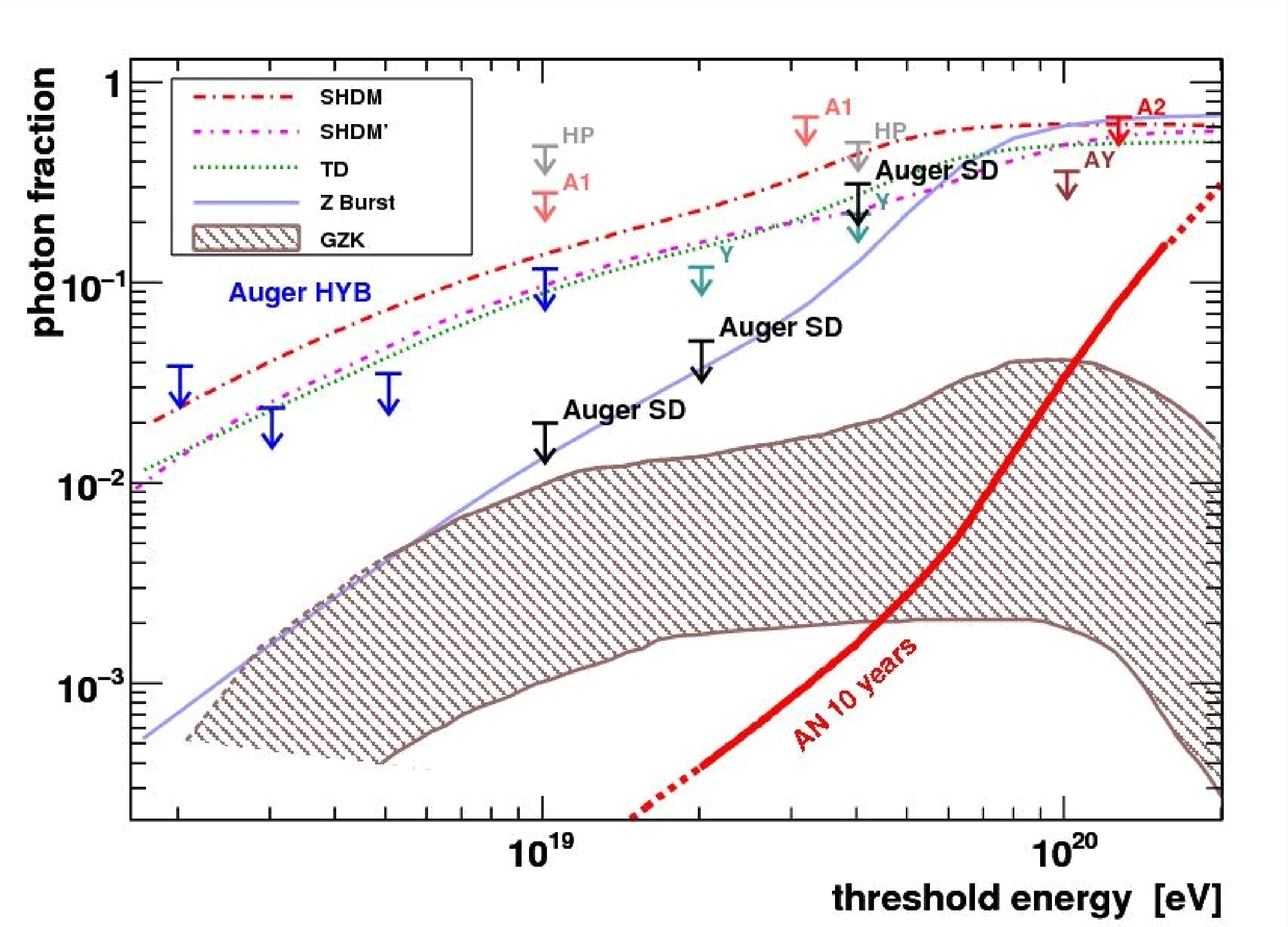
Photon showers penetrate deeper than hadronic showers.

They can be recognized individually with hybrid measurements.

A photon component can be measured statistically by the surface array.

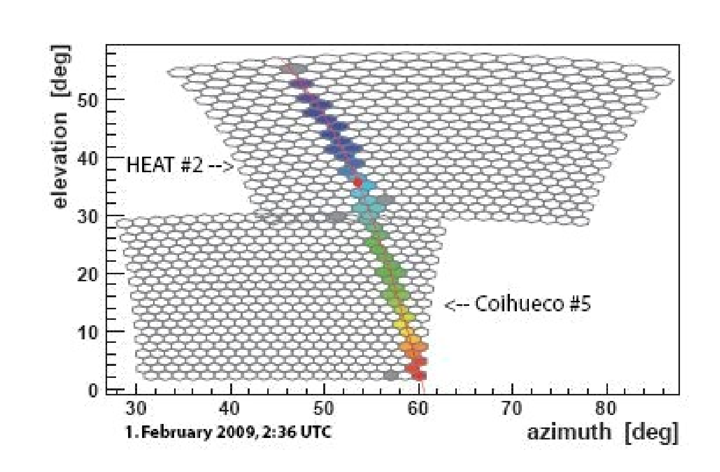
UHE Photon Limits

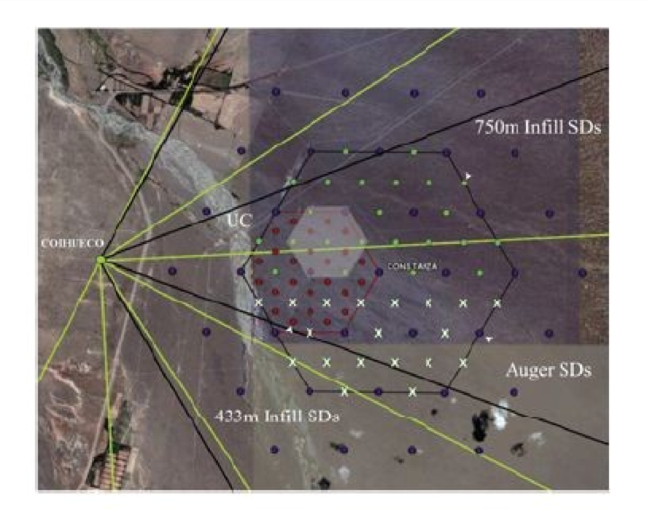
(strongly constrain top-down scenarios)



Enhancements at Auger South

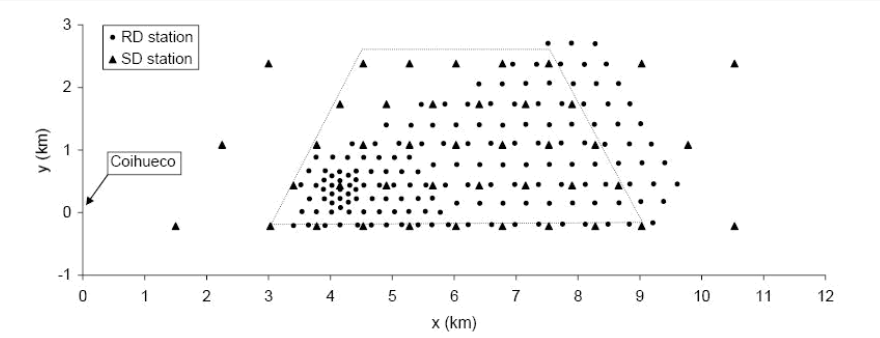
HEAT: High Elevation Auger Telescope





AMIGA: Auger Muon and Infill Ground Array

AERA: Auger Engineering Radio Arra



Pierre Auger Observatory

studying the universe's highest energy particles

Anisotropy and chemical composition of ultra-high energy cosmic rays using arrival directions measured by the Pierre Auger Observatory (JCAP06,2011,022)

Abstract. The Pierre Auger Collaboration has reported evidence for anisotropy in the distribution of arrival directions of the cosmic rays with energies $E > E_{th} = 5.5 \times 10^{19}$ eV. These show a correlation with the distribution of nearby extragalactic objects, including an apparent excess around the direction of Centaurus A. If the particles responsible for these excesses at $E > E_{th}$ are heavy nuclei with charge Z, the proton component of the sources should lead to excesses in the same regions at energies E/Z. We here report the lack of anisotropies in these directions at energies above E_{th}/Z (for illustrative values of $Z = 6,\ 13,\ 26$). If the anisotropies above E_{th} are due to nuclei with charge Z, and under reasonable assumptions about the acceleration process, these observations imply stringent constraints on the allowed proton fraction at the lower energies.

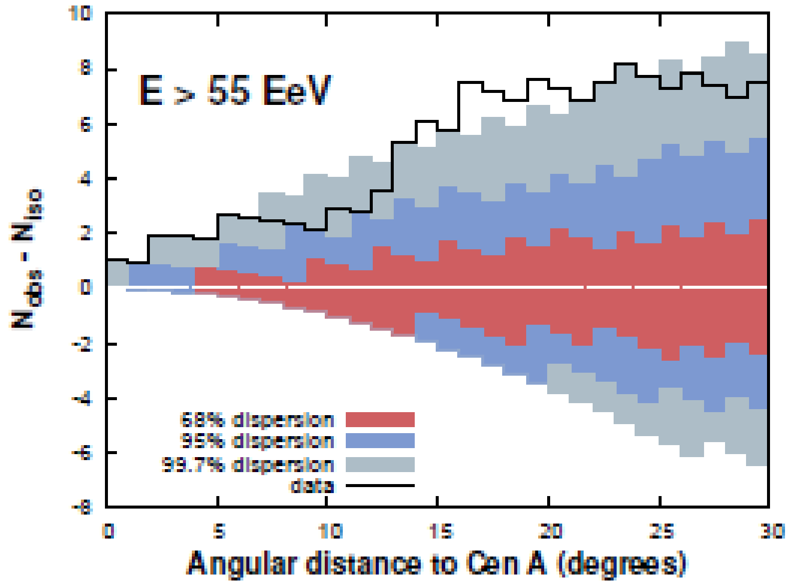


Figure 1. Cumulative number of events with $E \geq 55$ EeV (subtracting the average isotropic expectations) as a function of angular distance from the direction of Cen A. The bands correspond to the 68%, 95% and 99.7% dispersion expected for an isotropic flux.

Z	$E_{\rm min}$ [EeV]	$N_{\rm tot}$	$N_{\rm obs}$	$N_{\rm bkg}$
6	9.2	4455	219	207 ± 14
13	4.2	16640	797	774 ± 28
26	2.1	63600	2887	2920 ± 54

Table 1. Total number of events, $N_{\rm tot}$, and those observed in an angular window of 18° around Cen A, $N_{\rm obs}$, as well as the expected background $N_{\rm bkg}$. Results are given for different energy thresholds, corresponding to $E_{\rm min} = E_{\rm th}/Z$ for the indicated values of Z and $E_{\rm th} = 55$ EeV.

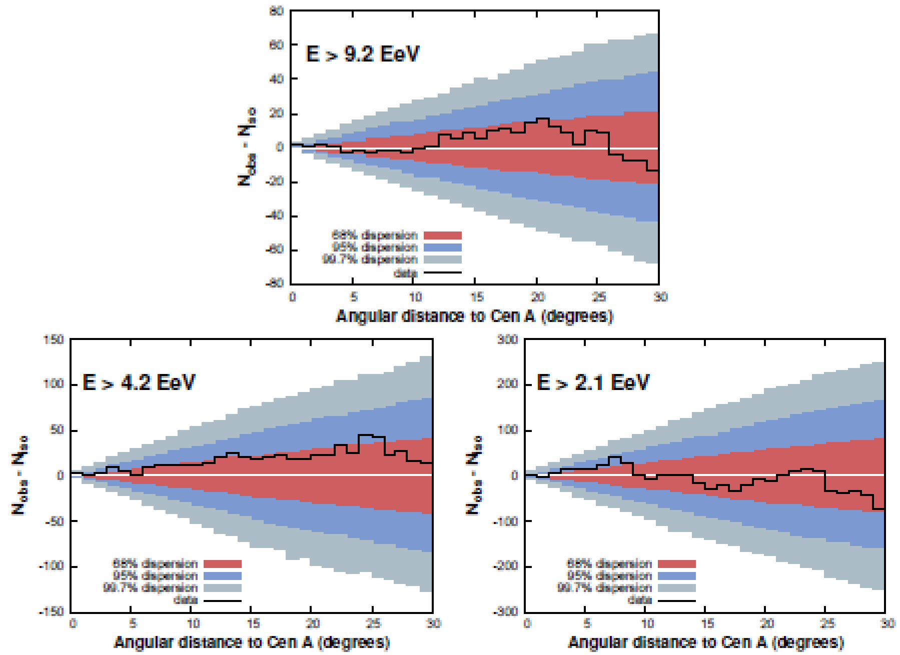


Figure 2. Similar to figure 1, events with $E \geq 55$ EeV/Z for $Z = 6$ (top), 13 (bottom left) and 26 (bottom right).

The main underlying hypothesis is that the cosmic ray acceleration depends just on the particle rigidities, i.e. on E/Z. It is therefore natural to assume that at the sources the spectra of the different charge components scale as

$$\frac{\mathrm{d}n_Z}{\mathrm{d}E} = k_Z \Phi(E/Z), \tag{4.1}$$

with k_Z being constant factors. The function Φ may display a high energy cutoff resulting from the maximum rigidities attainable by the acceleration process. If, in this scenario, the maximum proton energies were below $E_{\rm th}$, the higher energy cosmic rays from the source could be dominated by a heavy component.

If $N(> E)$ is the number of events with energies above the threshold E which come within a certain solid angle around a source and if the acceleration process at the source depends only on rigidity, then the number of nuclei of charge Z above $E_{\rm th}$ and those of protons above $E_{\rm th}/Z$ are related by

$$N_{\rm p}(> E_{\rm th}/Z) = \frac{k_{\rm p}}{Z k_Z} N_Z(> E_{\rm th}). \tag{4.2}$$

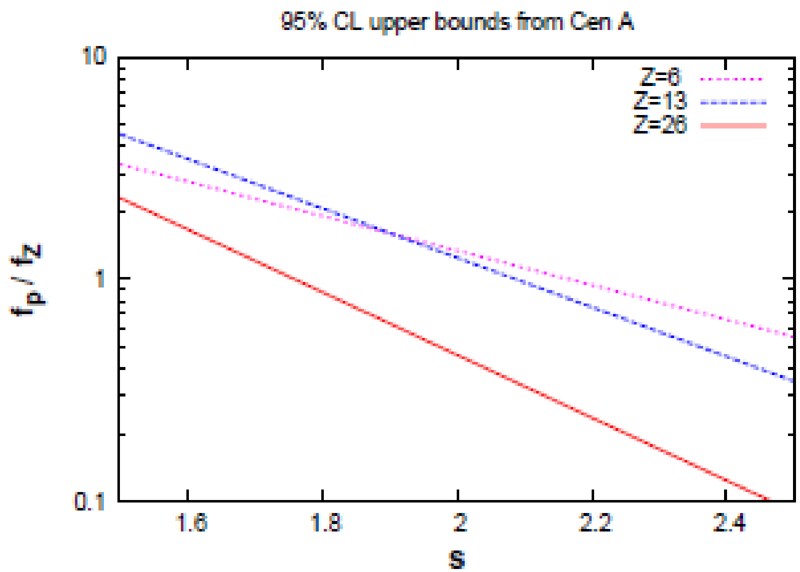


Figure 3. Upper bounds at 95%CL on the allowed proton to heavy fractions in the source as a function of the assumed low energy spectral index s. The different lines are for charges $Z = 6$, 13 and 26, as indicated.

- Far greater exposure is needed to
  - Identify the class of sources via anisotropy
  - Measure the spectra of bright sources or source regions
  - Determine the particle type(s) above 55 EeV
  - If protons, measure interaction properties above 250 TeV (CM)
  - Determine the diffuse cosmogenic intensity of neutrinos and photons
  - Detect cosmogenic neutrinos and photons

Summary

Deployment is complete for the Auger Observatory in Argentina

There IS a suppression of the energy spectrum
Arrival directions correlate with matter in the nearby universe above 55 EeV
Energy loss (e.g. GZK) is confirmed above that energy
  (The spectral steepening is not just due to sources "running out of steam")
There ARE detectable UHE sources within the GZK sphere
Intriguing trend in X_{max} distributions for energies up to 30 EeV
New Auger limits on diffuse neutrinos
New Auger limits on diffuse photons (disfavoring exotic production scenarios)

Future Work:
Identification of the class of UHECR sources via anisotropy
- Trans-GZK spectrum and composition (with dependence on direction)
- Determination of the diffuse flux of cosmogenic photons and neutrinos
- Hadronic interaction properties at CM energies above 250 TeV
- UHE gamma ray astronomy and neutrino astronomy