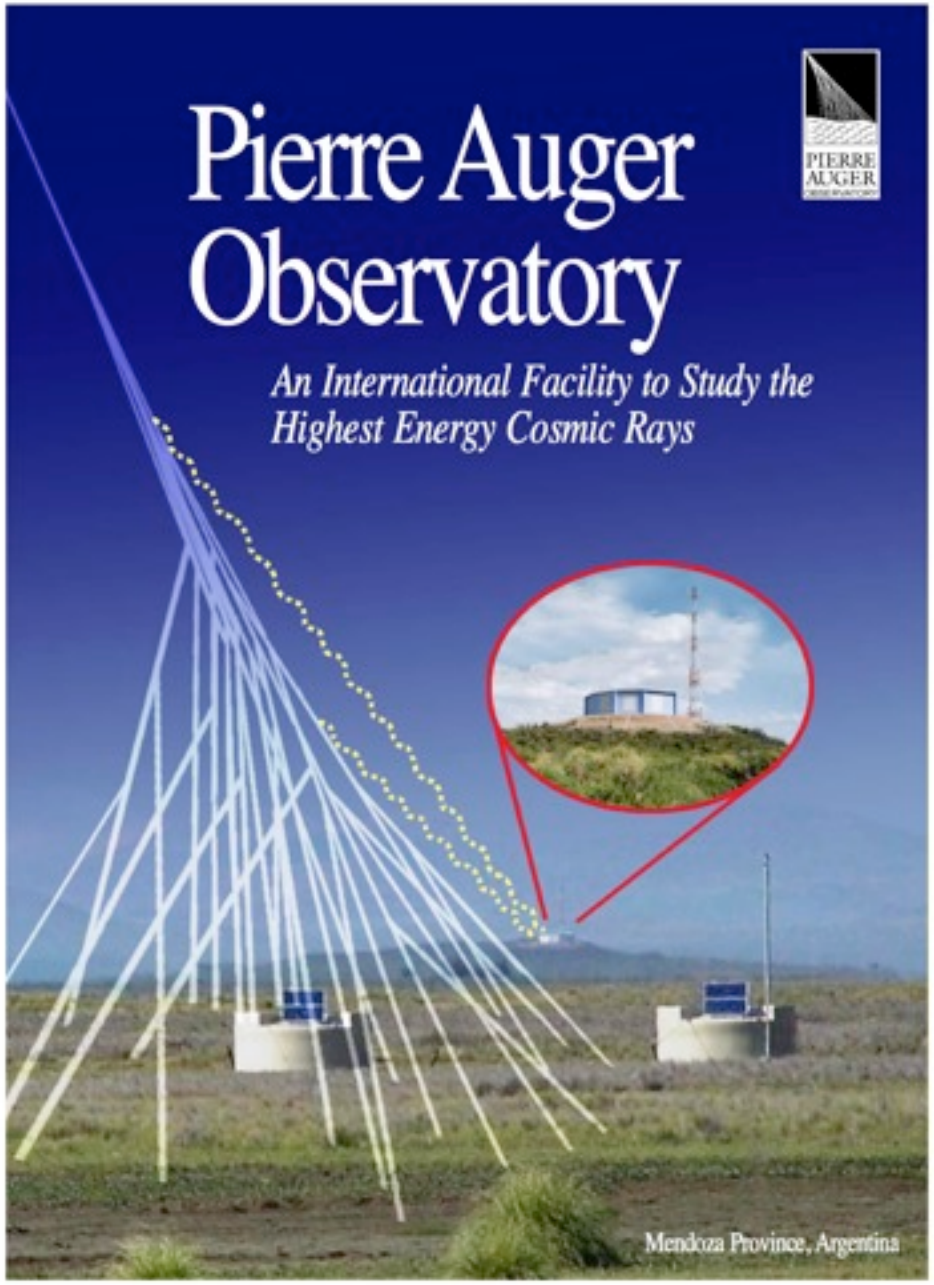


Results from the Pierre Auger Observatory

Paolo Privitera

THE UNIVERSITY OF CHICAGO
PHYSICAL SCIENCES

Department of Astronomy & Astrophysics
The Enrico Fermi Institute
The Kavli Institute for Cosmological Physics

for the Pierre Auger Collaboration

The UHECR 3-piece puzzle

1) The Greisen -Zatsepin-Kusmin cutoff:

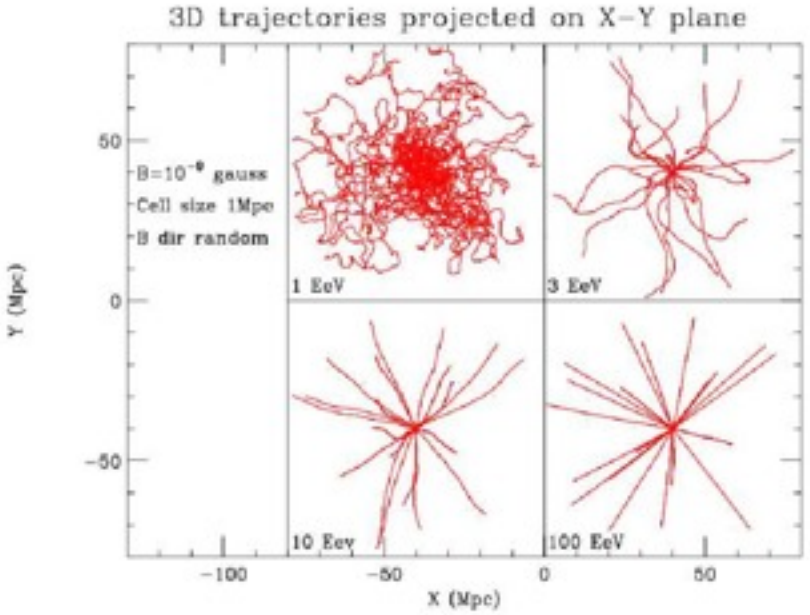
END TO THE COSMIC-RAY SPECTRUM?

Kenneth Greisen

Cornell University, Ithaca, New York

(Received 1 April 1966)

This note predicts that above 10^{20} eV the primary spectrum will steepen abruptly, and the experiments in preparation will at last observe it to have a cosmologically meaningful termination.



2) The UHECR sources:

Close-by astrophysical accelerators? Exotic Physics?

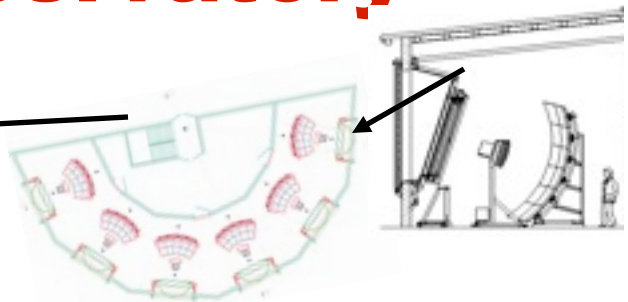
3) The UHECR composition:

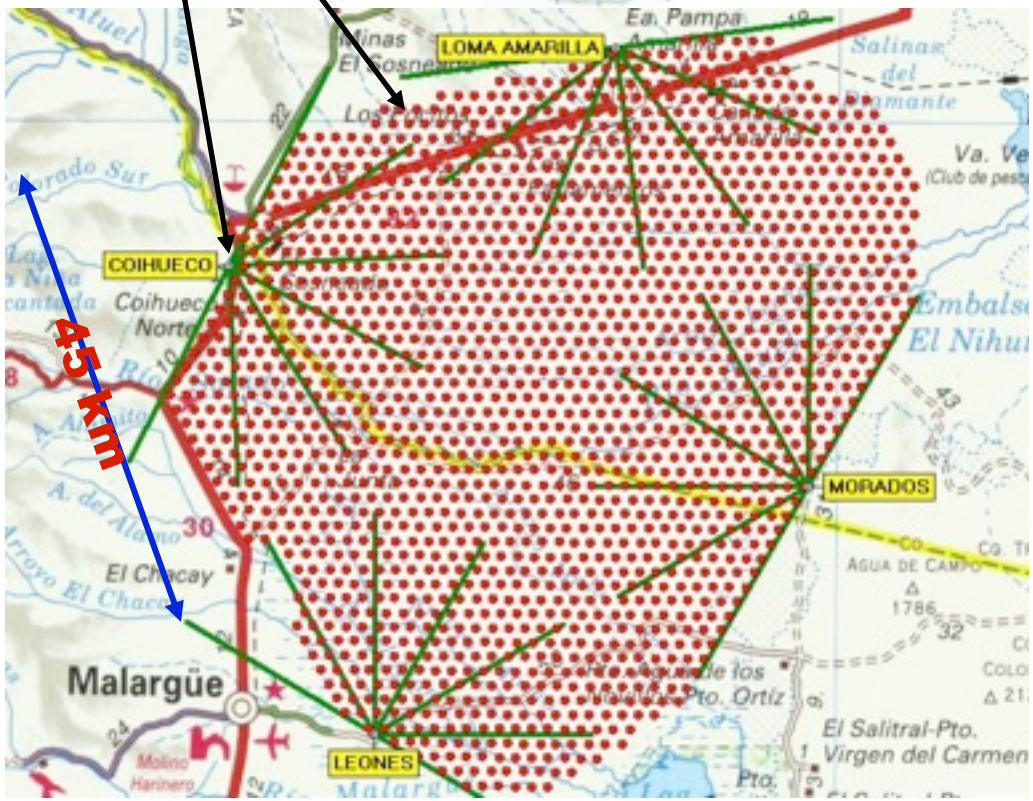
protons? Heavier nuclei (deviation in magnetic fields)

Only by understanding all of the three pieces we will unveil the true nature of UHECR

The Pierre Auger Observatory

Argentina, Mendoza, Malargue
1.4 km altitude, 870 g/cm^2





1600 water Cherenkov detectors,
1.5 km spacing, 3000 km^2,
4 x 6 fluorescence telescopes

Argentina
Australia
Bolivia*
Brazil
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Slovenia
Spain
United Kingdom
USA
Vietnam*

PIERRE AUGER OBSERVATORY

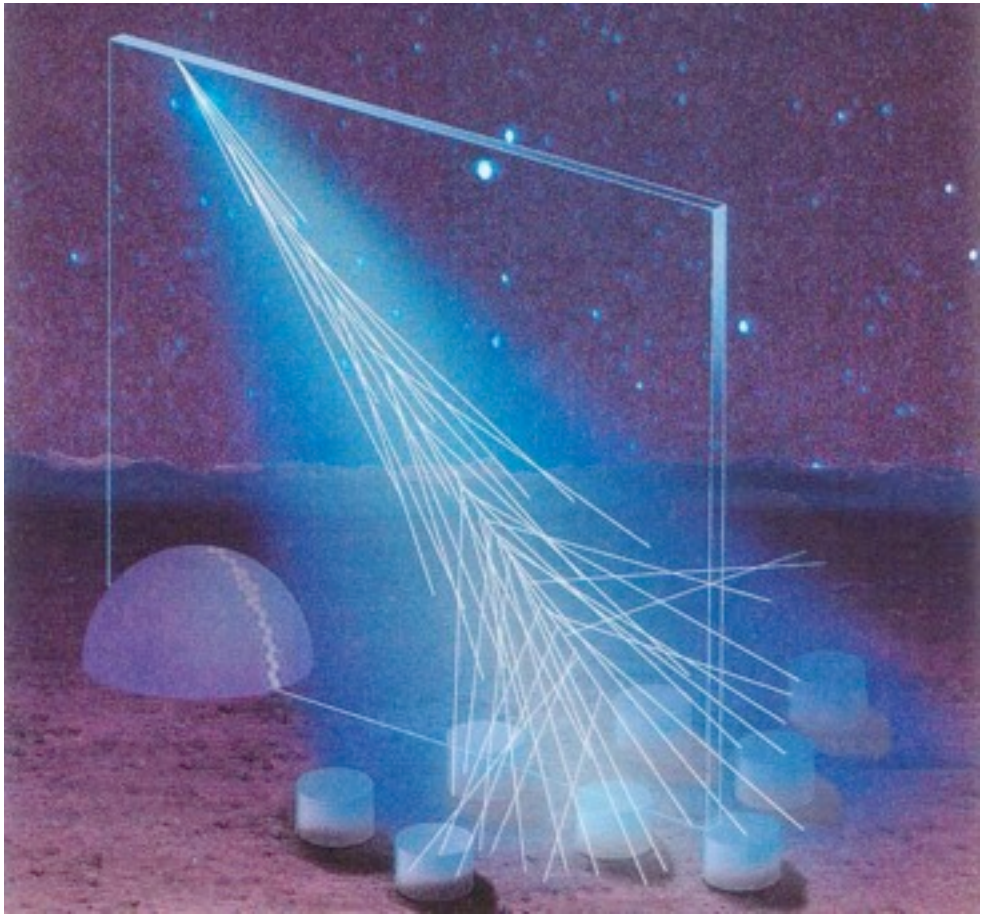
3000 km² !!!!!!

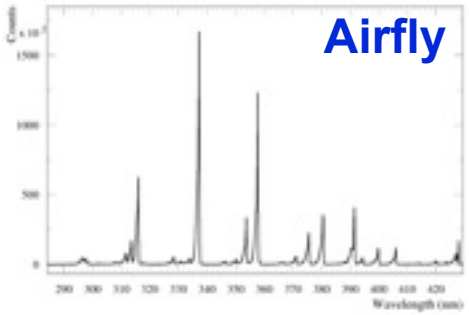
Rate ≈ 1 / Km² / sr / century!

The Auger site

SD physicists making friends

The Auger hybrid detector concept





300-400 nm light from de-excitation of atmospheric nitrogen (fluorescence light)
≈ 4 γ's / m /electron

10^{19} eV ⇨ 10^{10} e

Fluorescence Detector

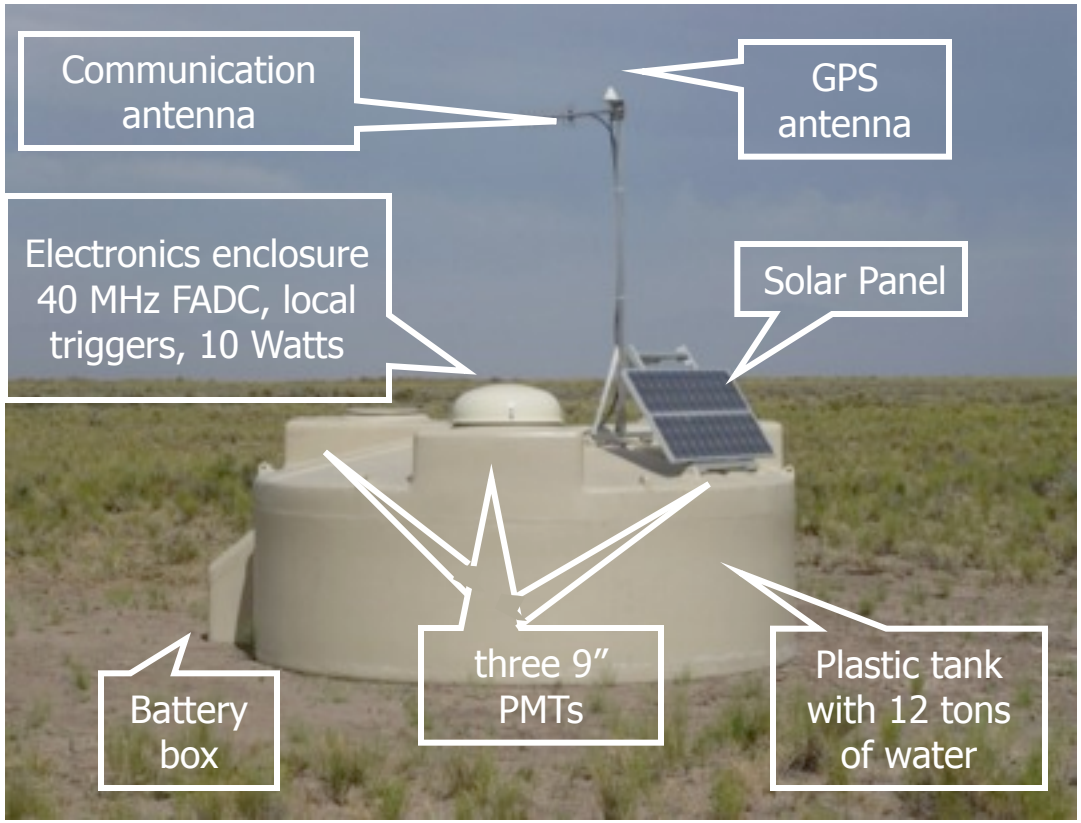
- E + longitudinal development
- Time ≈ direction
- ≈ 10% duty cycle

Trigger efficiency
Energy-direction calibration,
syst. uncertainties

Surface Detector

- Shower size ≈ E
- Time ≈ direction
- 100% duty cycle

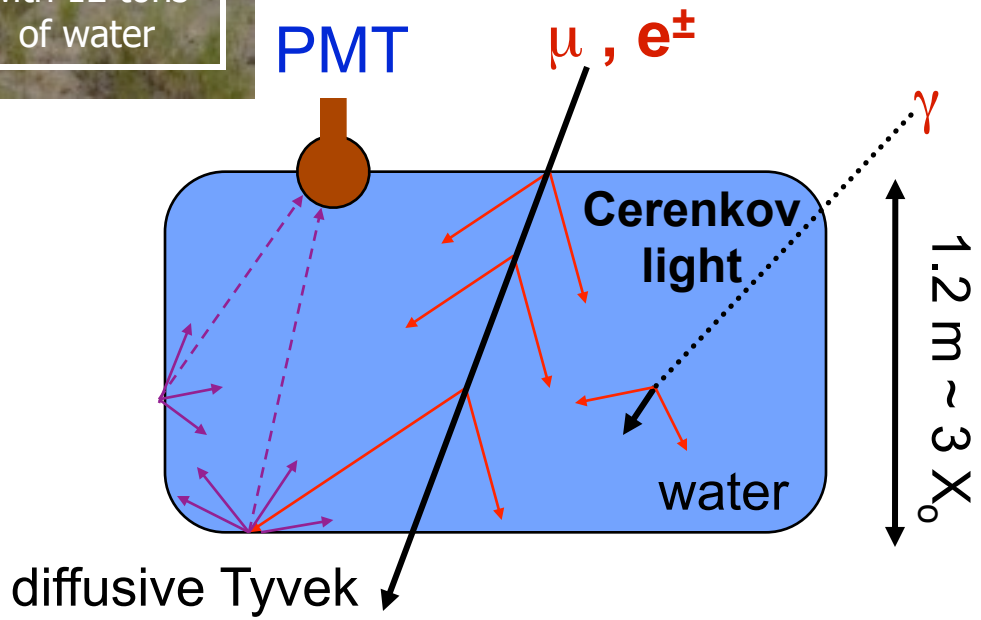
Auger Surface Detector



Overall tank array efficiency ~95%!

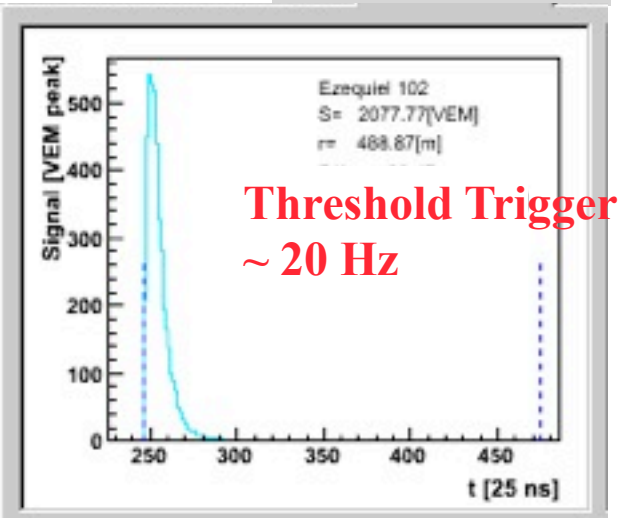
The tanks works like an "integrating sphere"

Time response for a single muon ~ 60 ns

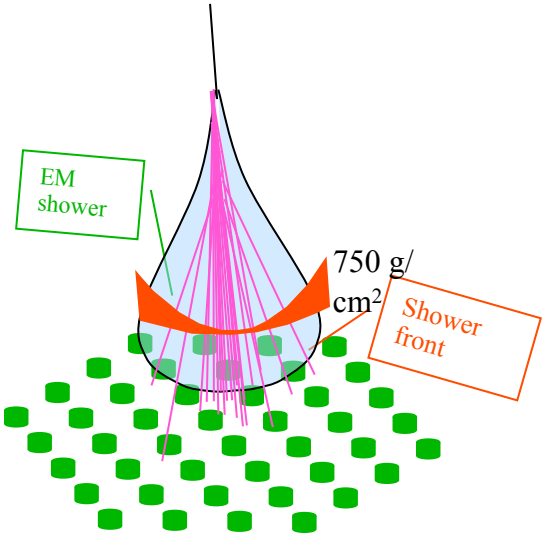


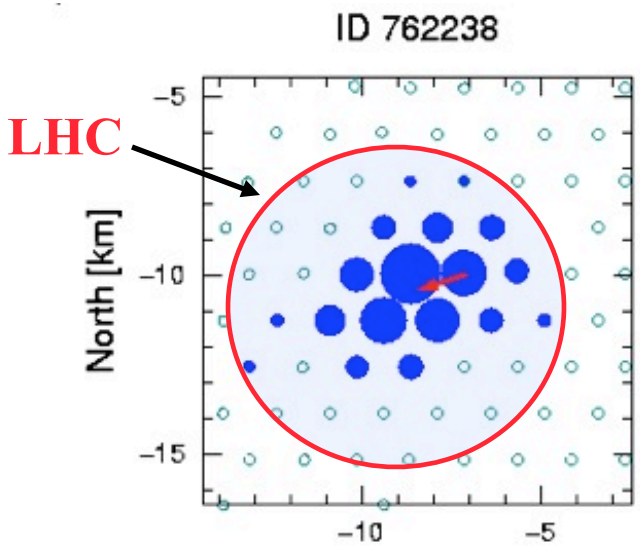
AUGER SD in action ~ 70 EeV

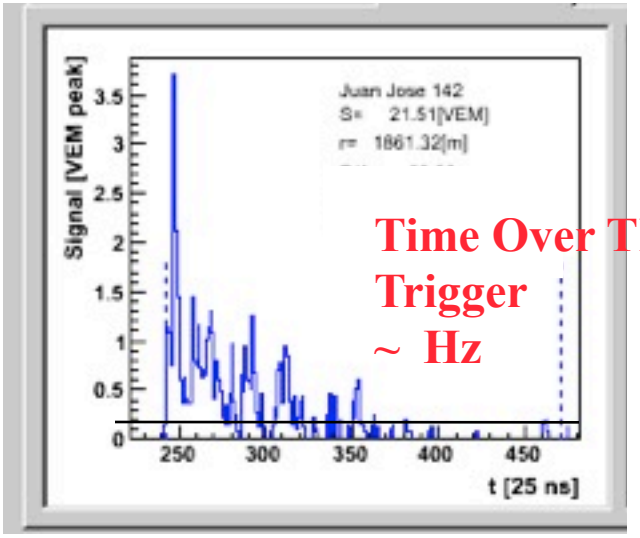
Flash ADC traces



Threshold Trigger
~ 20 Hz

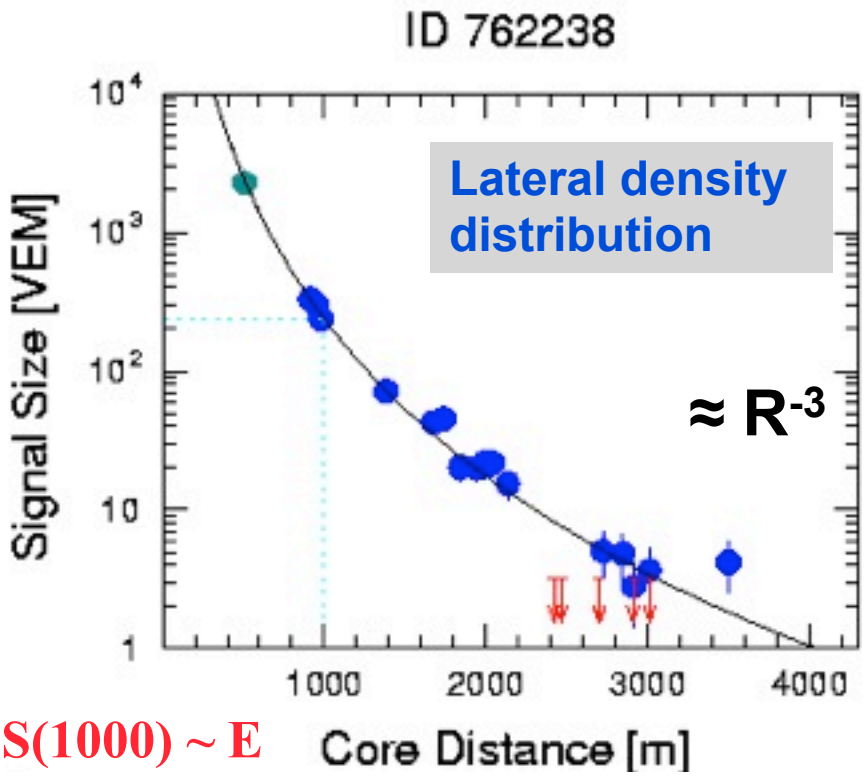






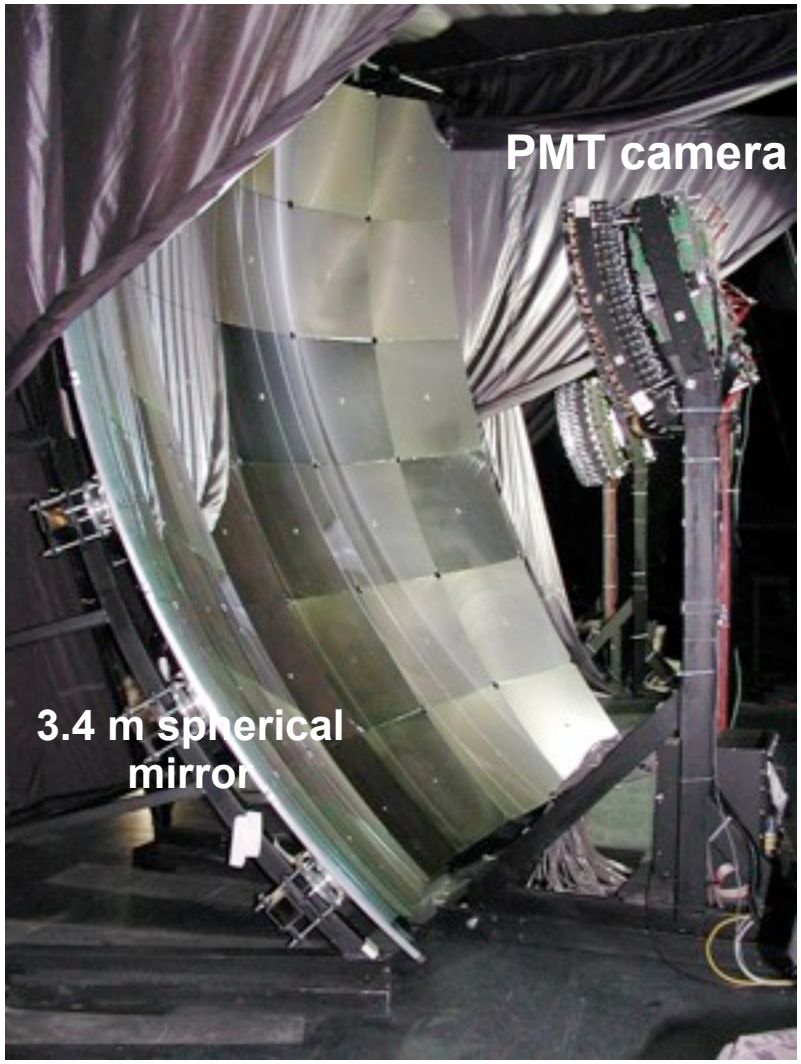
Time Over Threshold
Trigger
~ Hz

5 μs

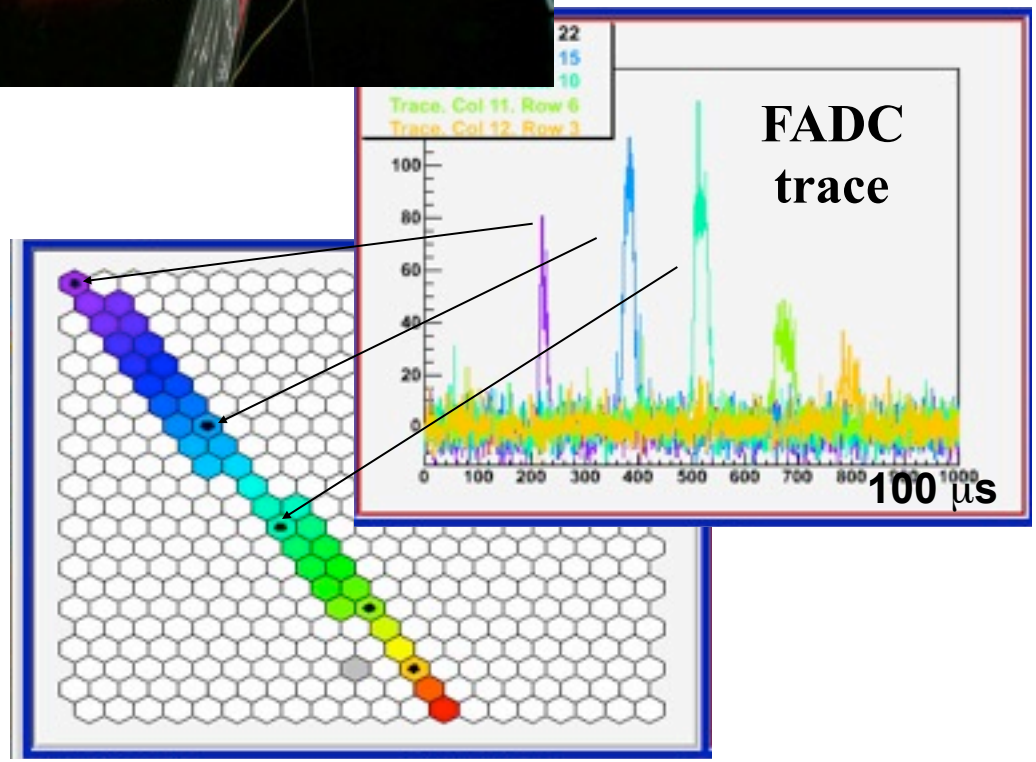


Lateral density distribution

S(1000) ~ E

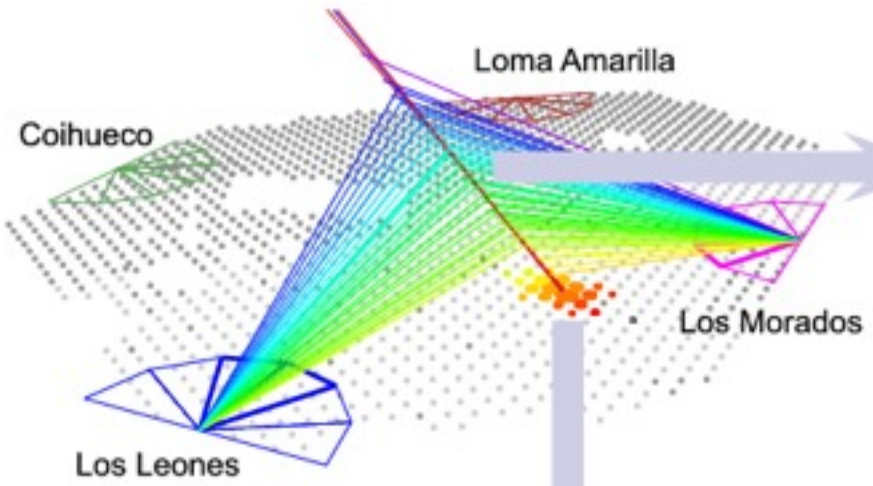


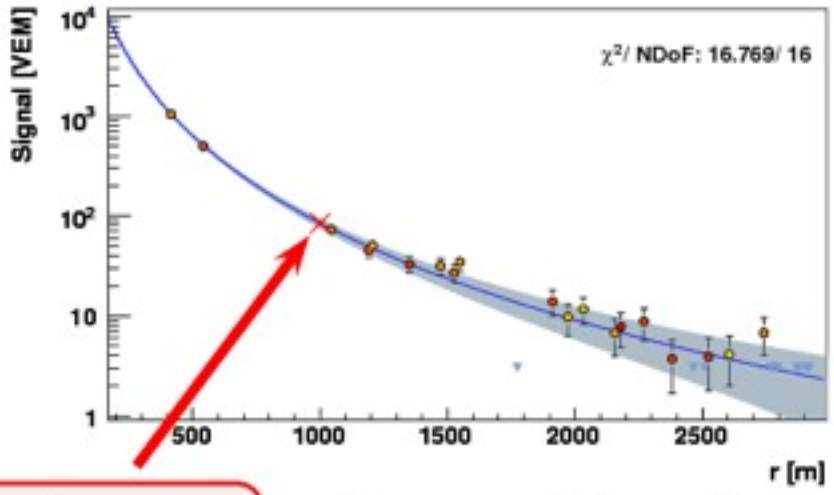
Spherical surface camera
440 PMT with light collectors
Large 30^0x30^0 field of view
1.5^o pixel fov
(spot 1/3 of pixel)



The

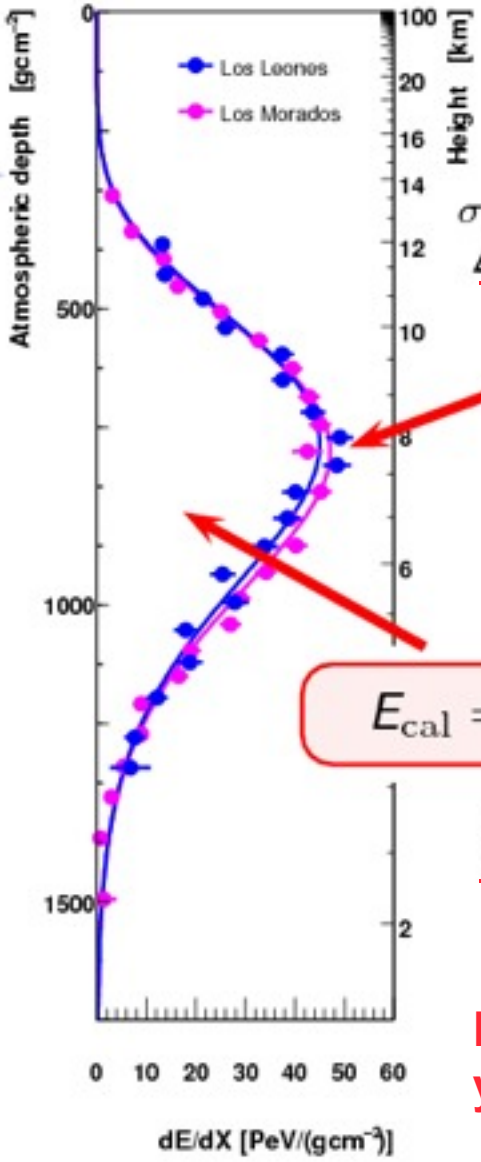
The Auger 'hybrid' detector





S_{1000}

$E_{\mathrm{surface}} = f(S_{1000}, \theta)$



$\sigma_{X_{\mathrm{max}}} < 20\,\mathrm{g/cm^2}$
$\Delta_{\mathrm{sys}} \approx 15\,\mathrm{g/cm^2}$

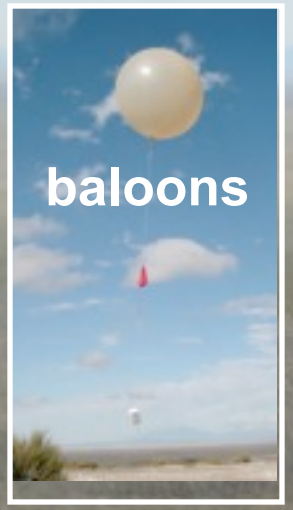
X_{max}

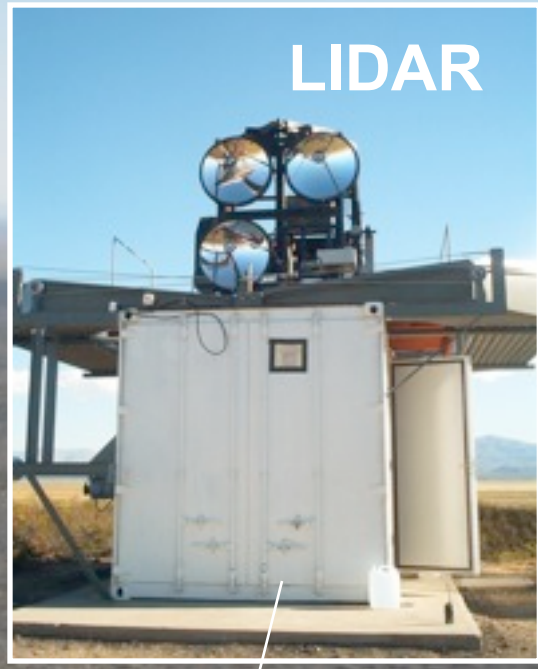
$E_{\mathrm{cal}} = \int \mathrm{d}X \, \frac{\mathrm{d}E}{\mathrm{d}X}$

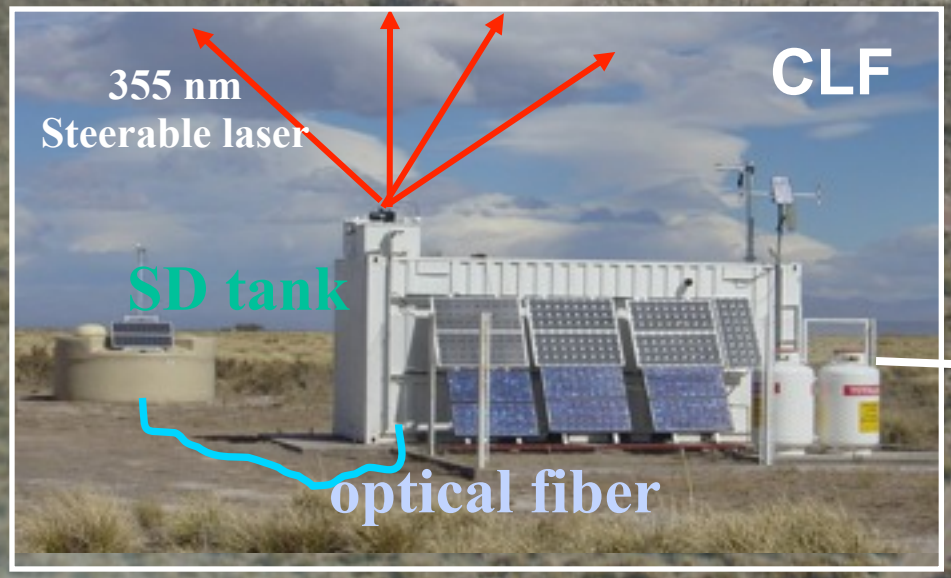
$\sigma_E/E \sim 8\,\%$
$\Delta_{\mathrm{sys}} \approx 22\,\%$

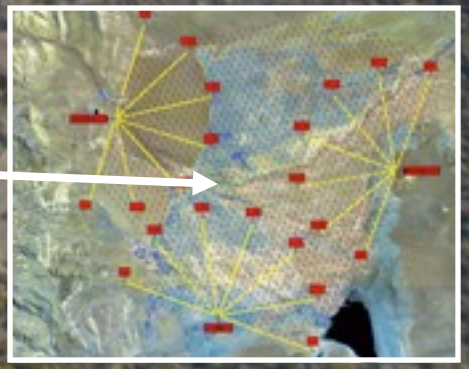
Fluorescence yield ~14%

Atmospheric Monitoring





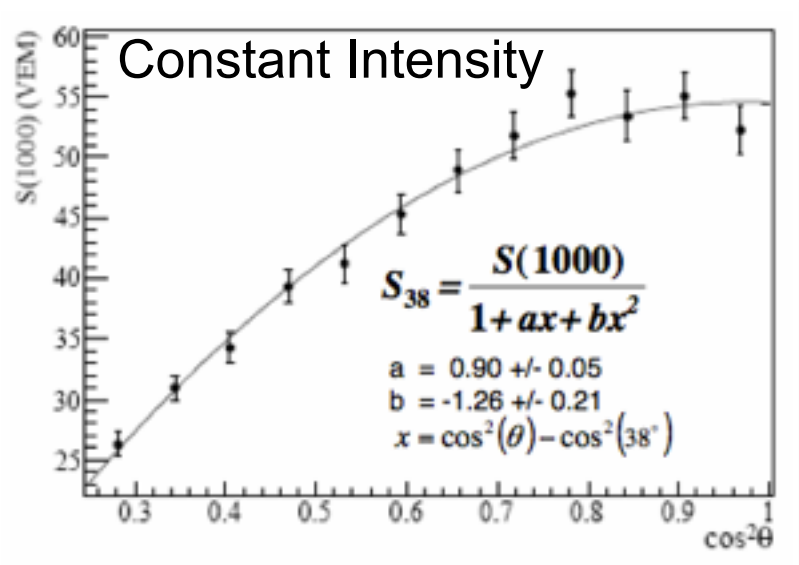




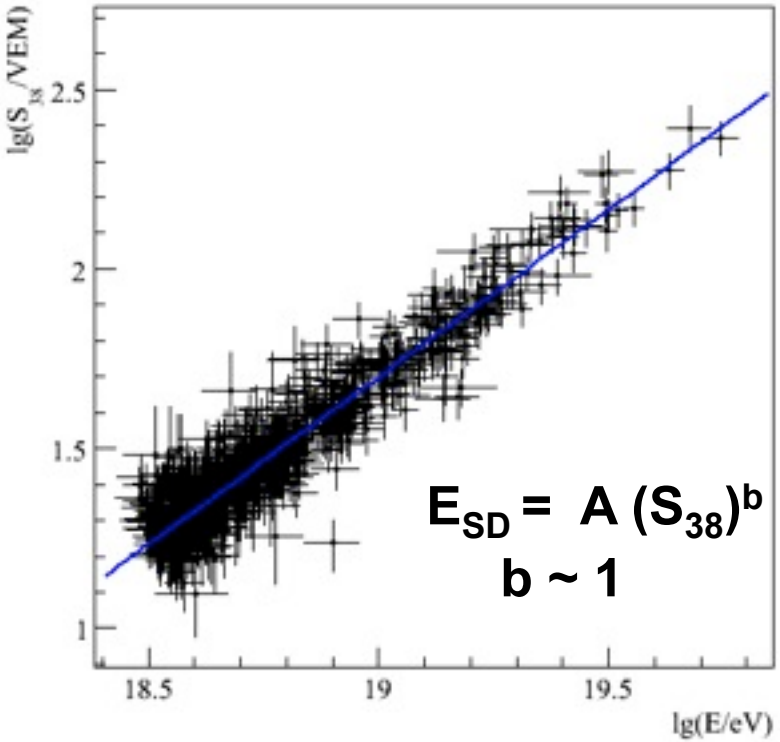
SD Energy Calibration

The power of hybrid.....

We DO NOT rely on shower simulation!

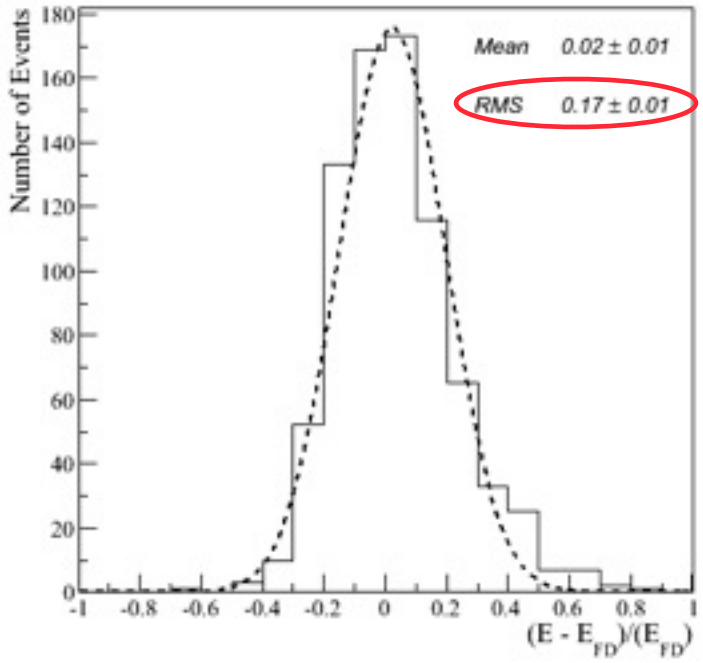


SD

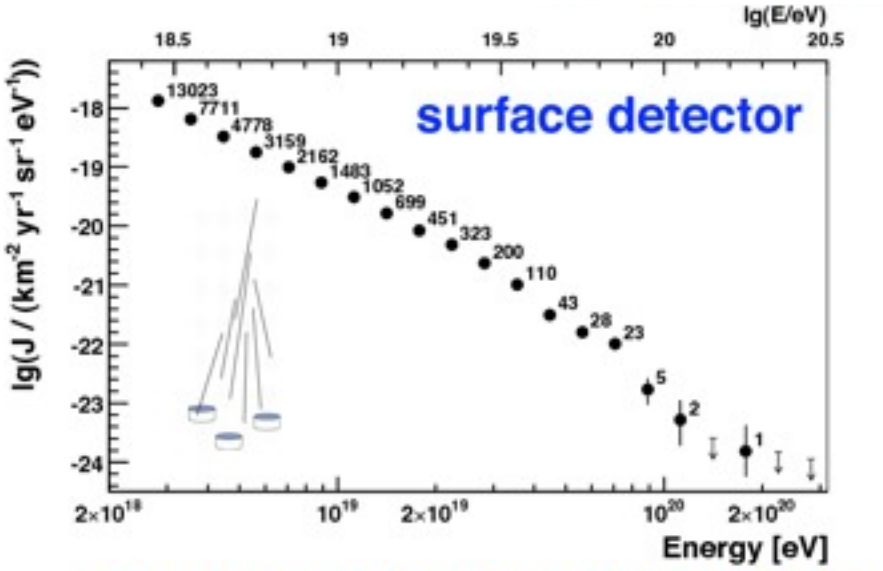


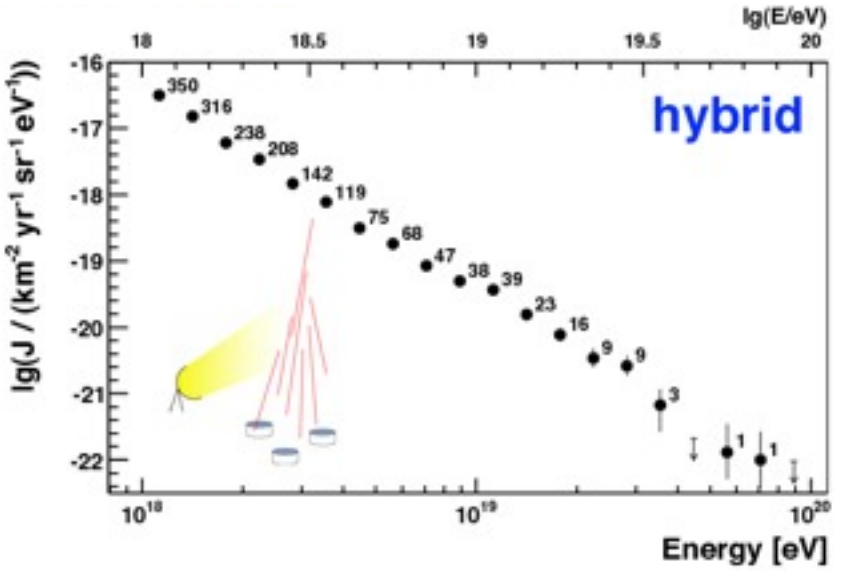
FD

SD Energy resolution better than 20%



Auger Energy Spectrum



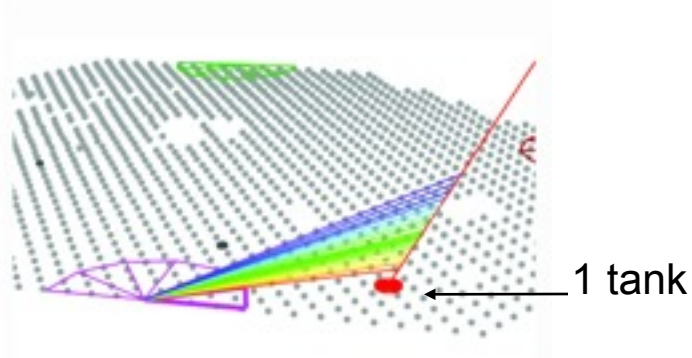


- high statistics (100% duty cycle)
- 100% efficient above $3 \cdot 10^{18}$ eV

over the whole array

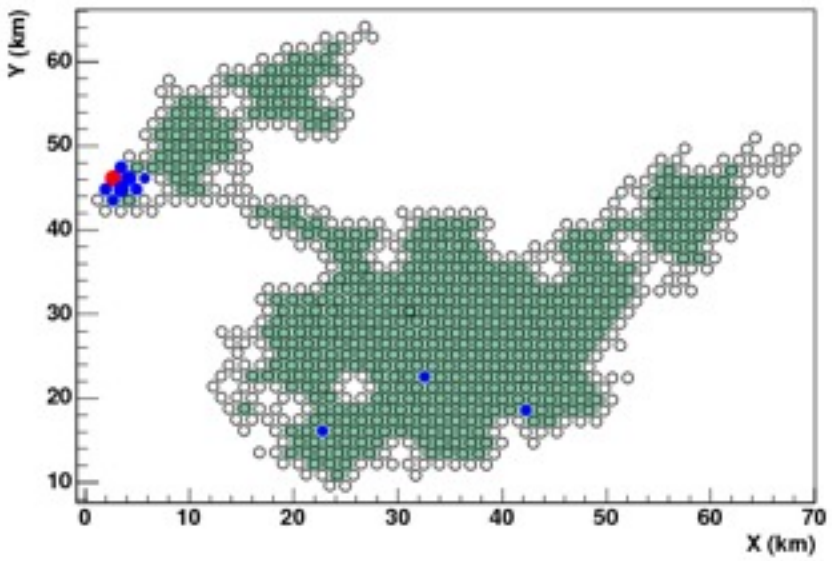
- lower statistics due to 12% duty cycle
- efficiency function of shower's distance, atmospheric conditions, etc. Complex analysis
- measurement down to $1 \cdot 10^{18}$ eV

Surface and Hybrid fluxes consistent within uncertainties (10% FD and 6% SD)

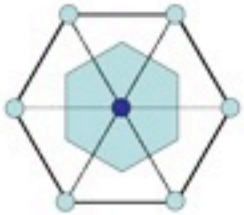


Exposure

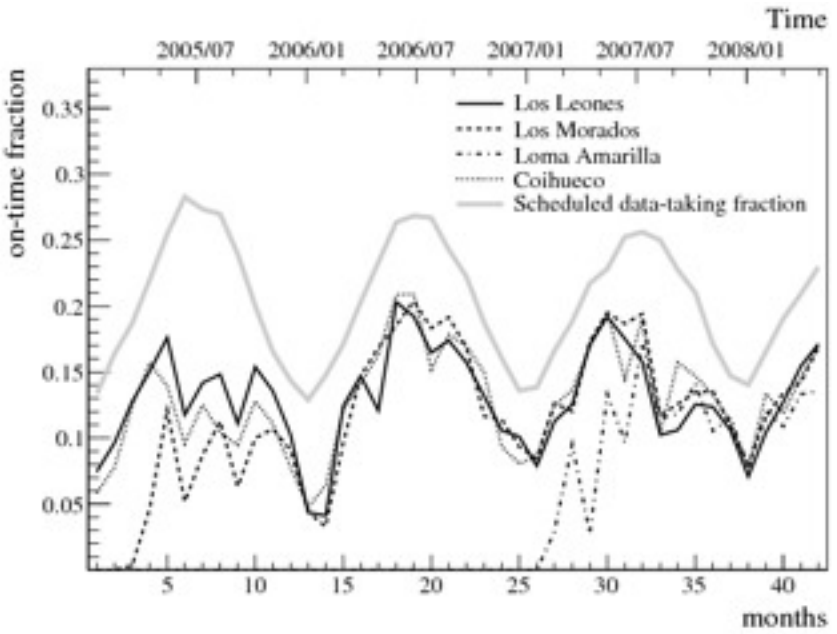
Surface Detector

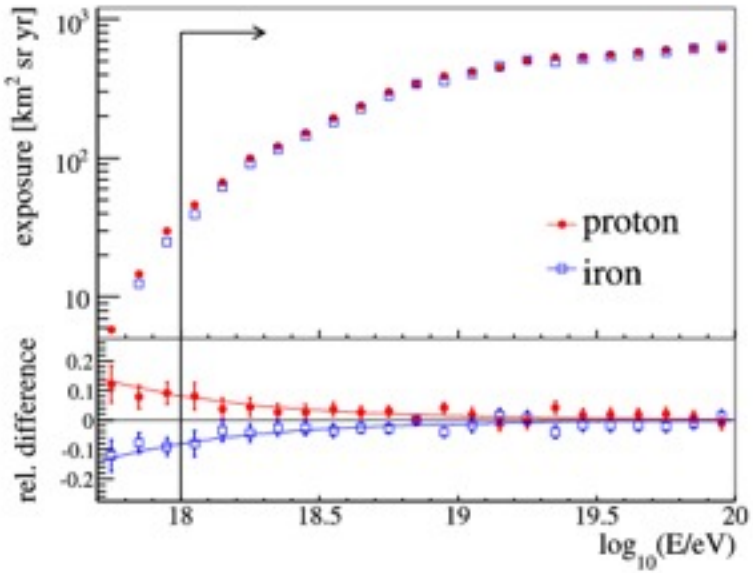


Count active hexagons, sum their area

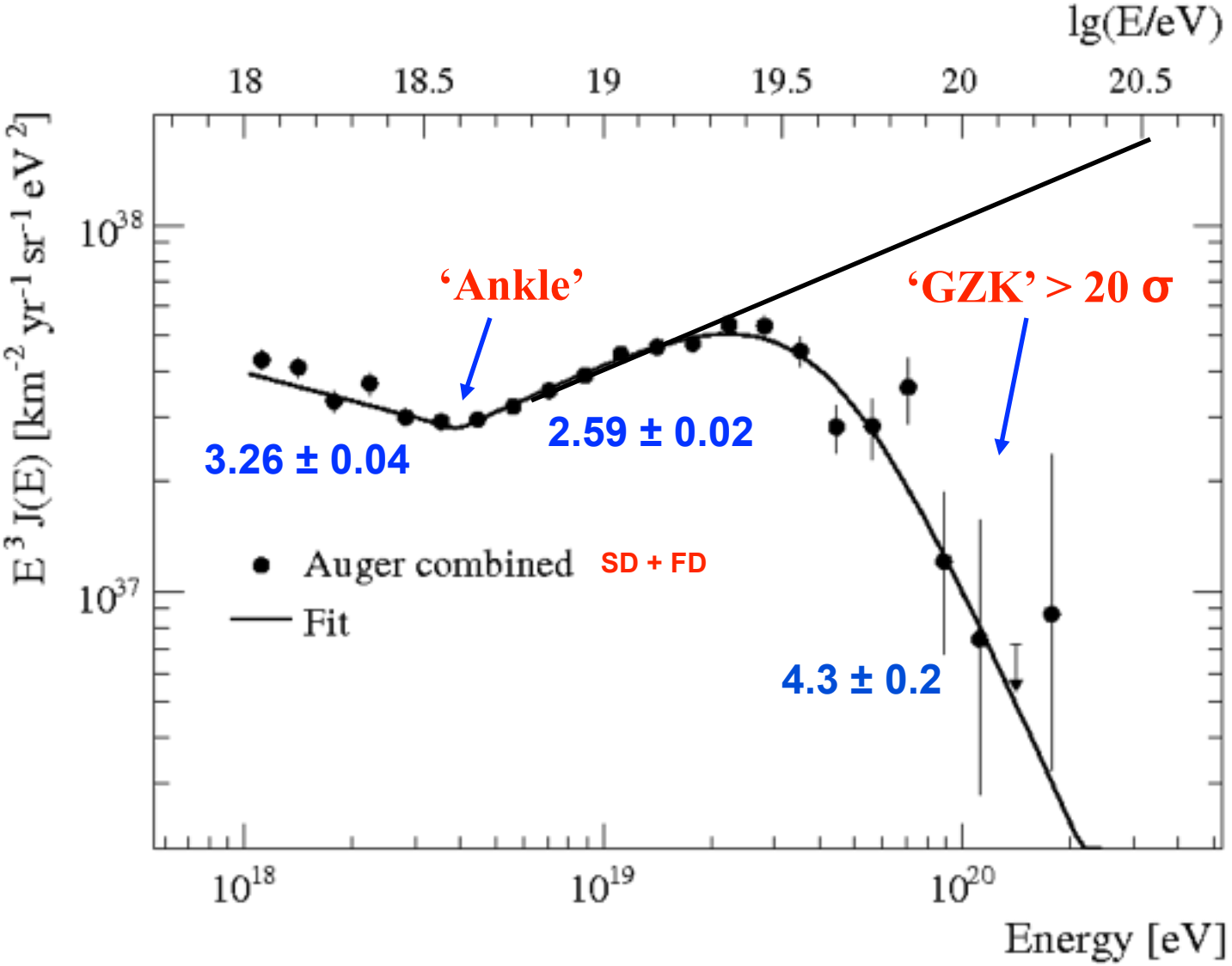


Fluorescence Detector





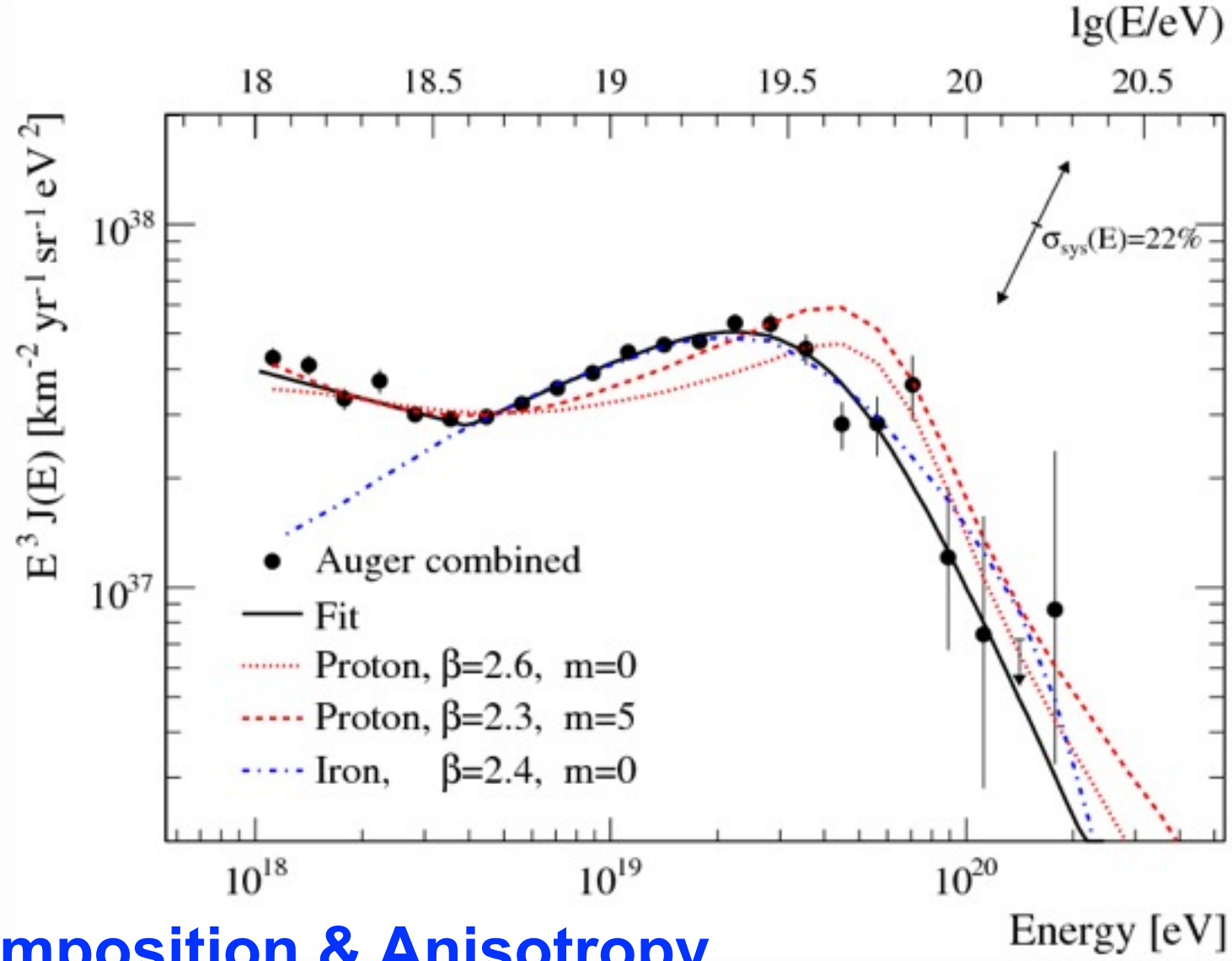
Auger Energy Spectrum



Phys. Lett. B 685 (2010) 239

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

Astrophysics and the Energy Spectrum



→ **Composition & Anisotropy**

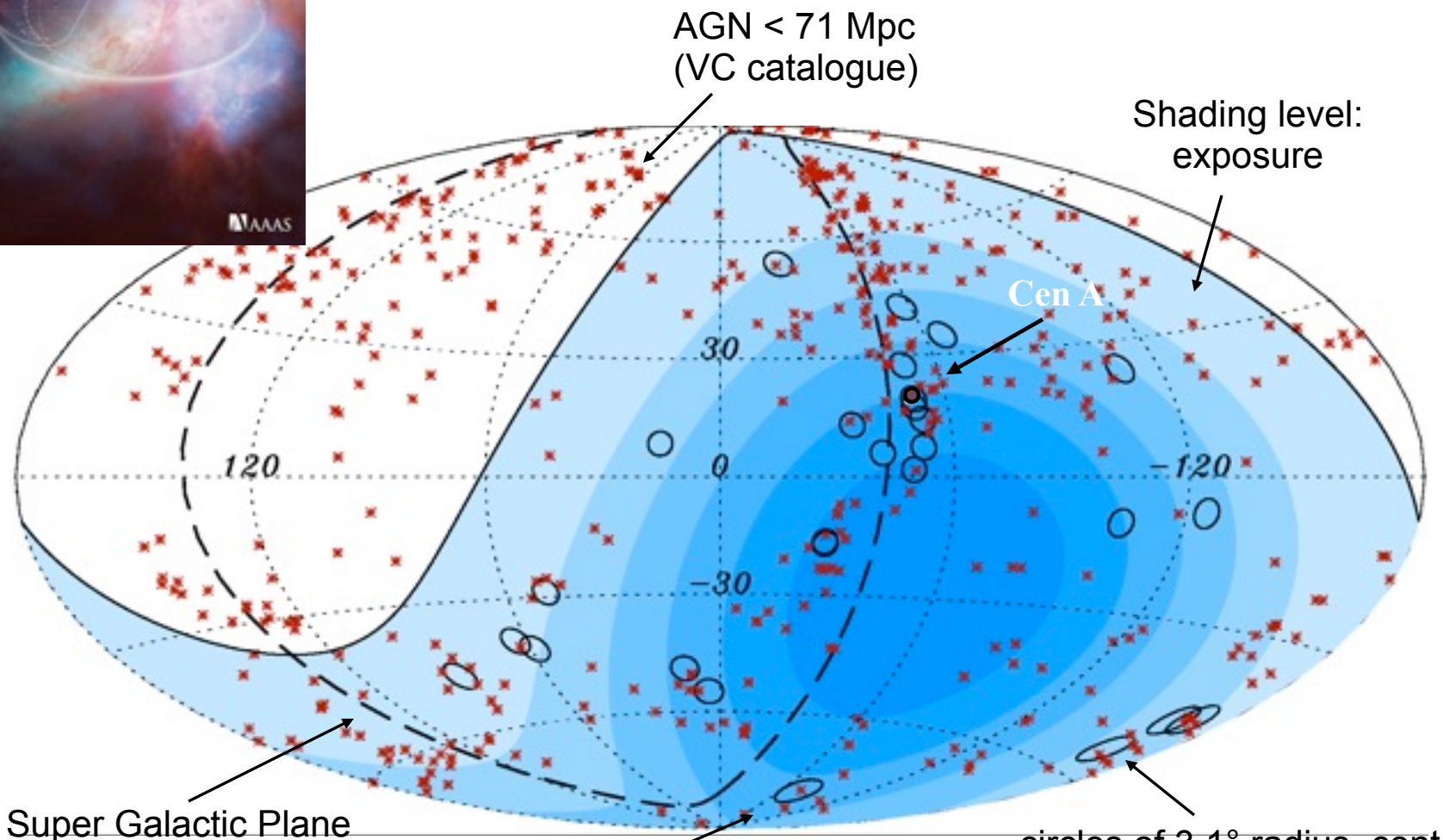
→ **Energy Scale**

$$J_{\text{source}} \propto E^{-\beta},\ (1+z)^m$$

November 9, 2007

"Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects"

Anisotropy of the UHECR sky



27 events E> $5.7 \cdot 10^{19}$ eV

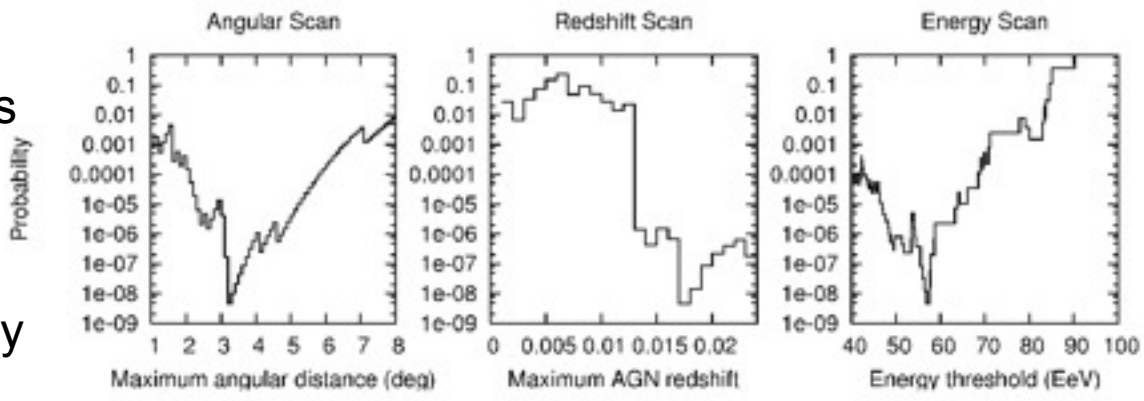
Angular resolution < 1°

Strategy for anisotropy analysis

$$P = \sum_{j=k}^{N} \binom{N}{j} p^j (1-p)^{N-j}$$

Probability that k out of N events from an isotropic flux correlate by chance (AGN used to track extragalactic matter)

No a priori hypothesis on the characteristics of correlation, thus exploratory scan of relevant variables: angular distance (resolution and magnetic fields), AGN redshift (GZK cutoff), energy (magnetic field)



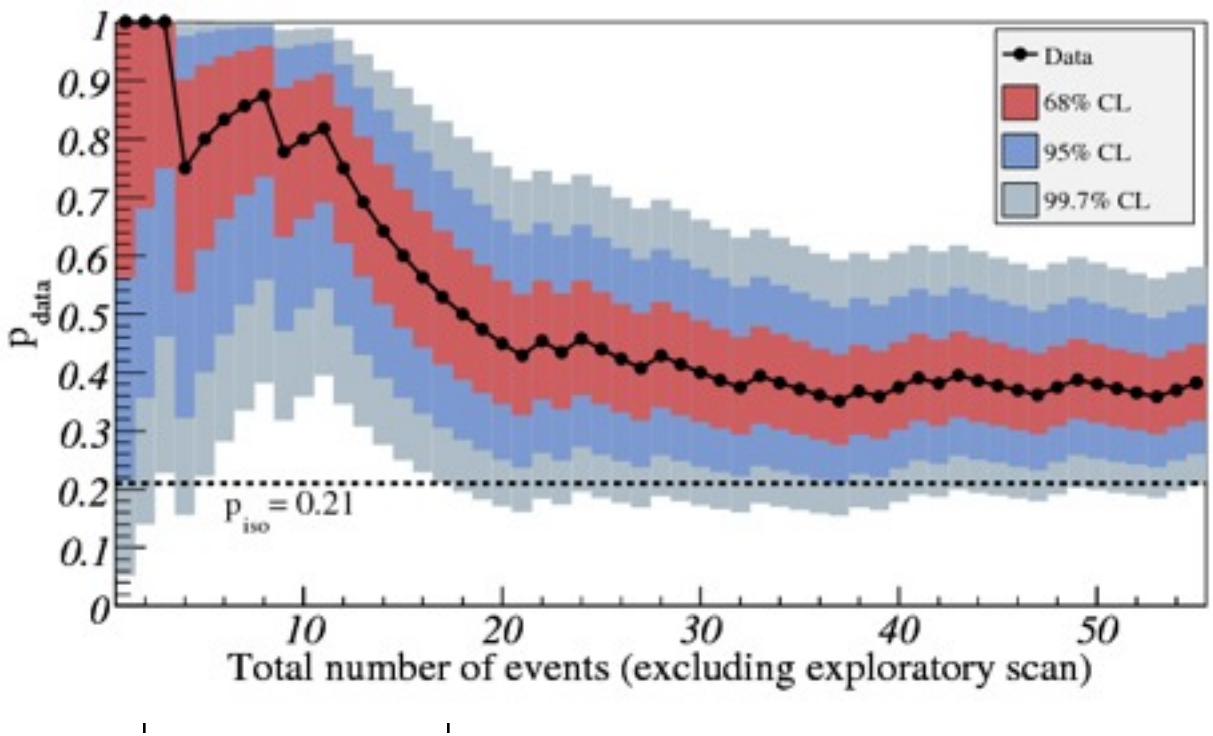
12/15 events correlated in the exploratory scan, 3.2 expected

Difficult to estimate probability, thus confirmation required with an **independent data set**.

→ **Prescription** → **8/13 events** found to correlate, **P = 1.7 ·10^{-3}**

- Null hypothesis (Isotropy of UHECR) rejected at 99% CL
- Tantalizing large correlation (~70%) with extragalactic objects (traced by AGN)

Update on anisotropy

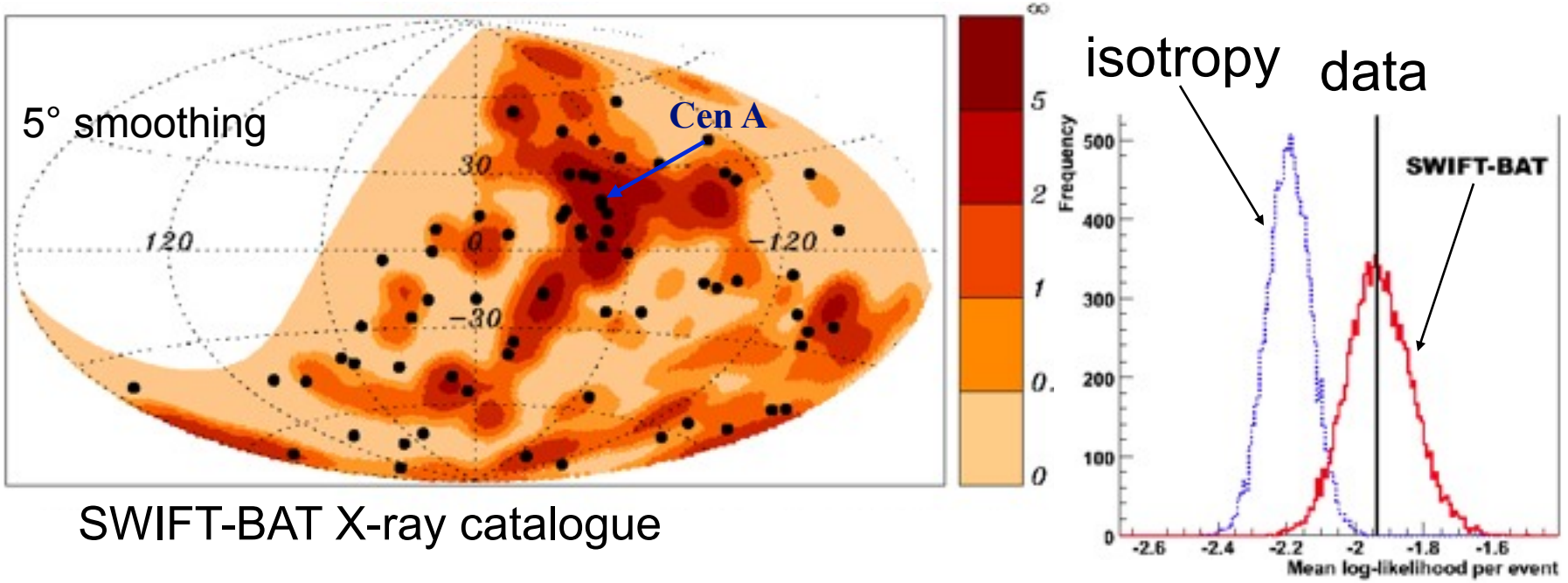


- Isotropy of UHECR rejected at 99% CL
- Correlation reduced from ~70% to ~40%

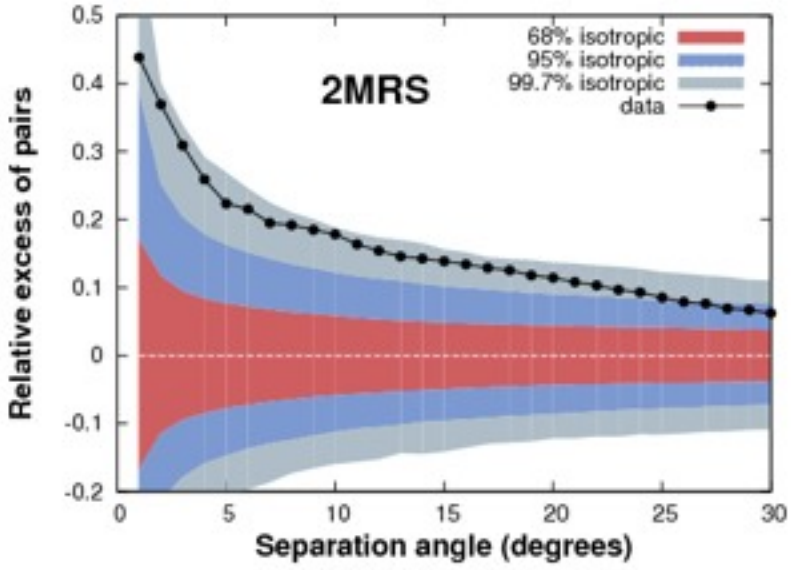
- nature
- catalogue

69 events E> $5.5 \cdot 10^{19}$ eV paper submitted

Correlation with other Catalogues



SWIFT-BAT X-ray catalogue

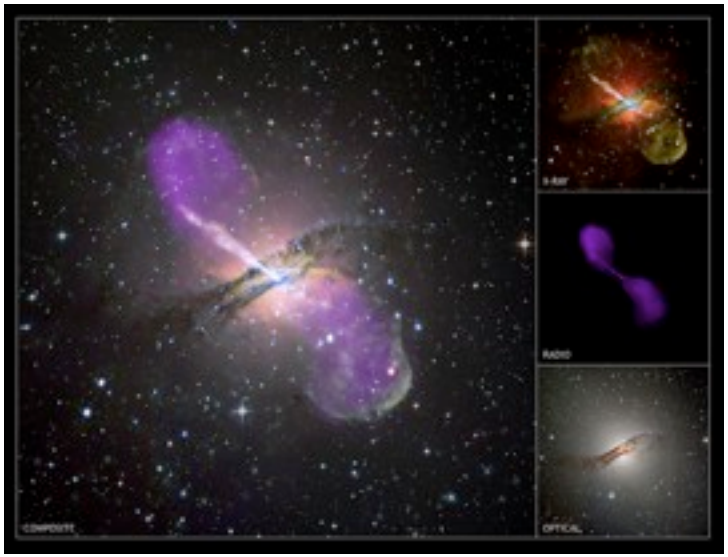


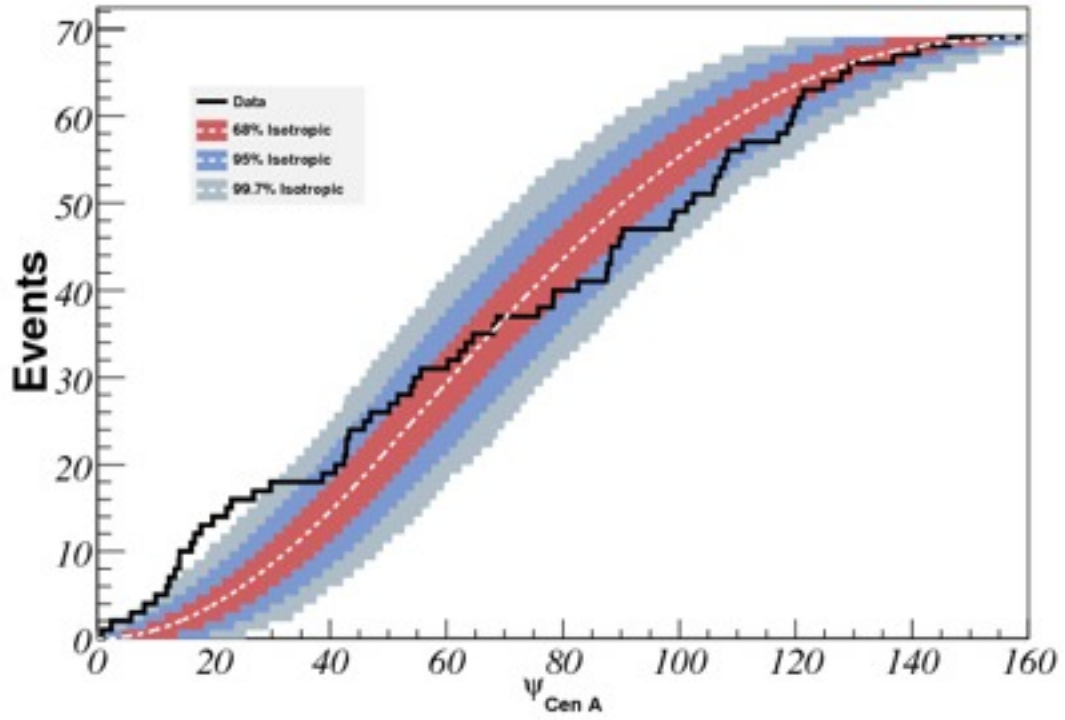
Cross correlation with 2MRS galaxies catalogue

NOTE: a posteriori analyses, but providing additional information on anisotropy

Cen A.....

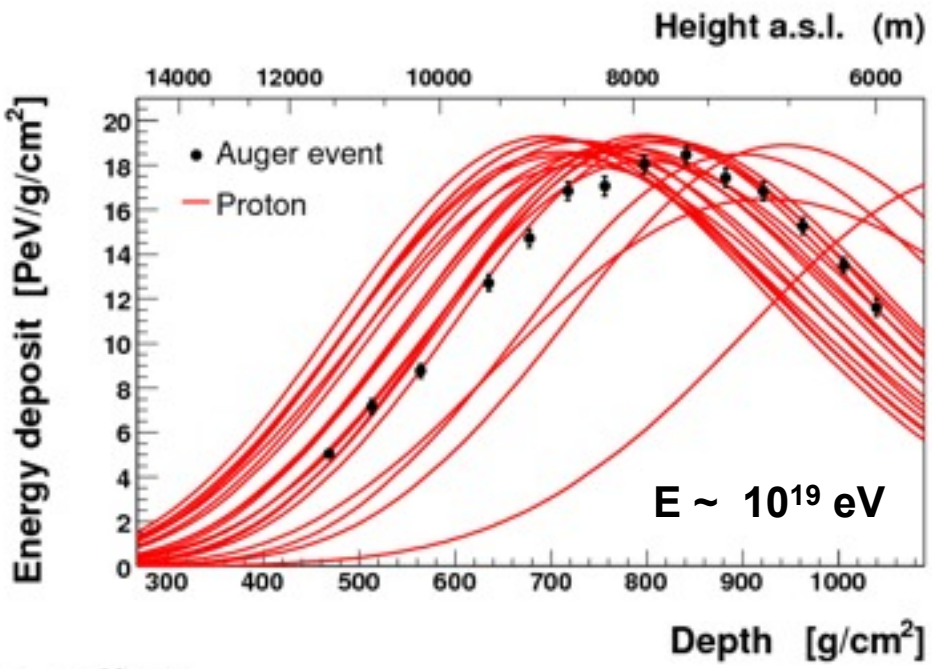
Closest (3.8 Mpc) powerful radio galaxy with characteristics jets and lobes, candidate for UHECR acceleration. Auger South.

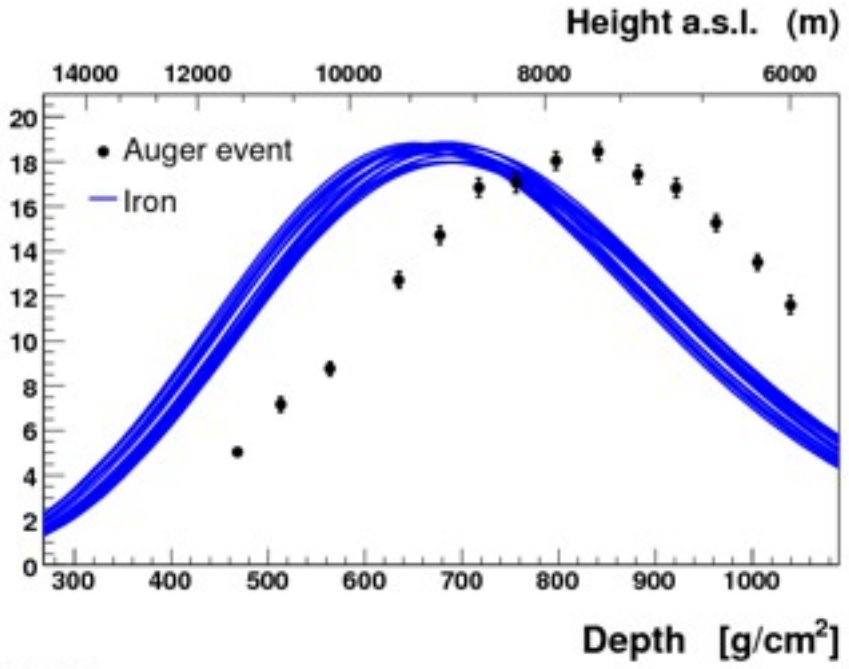


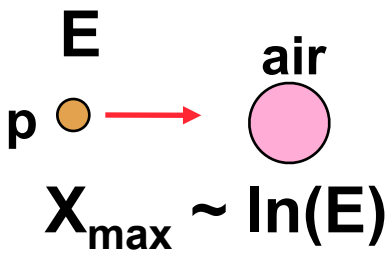


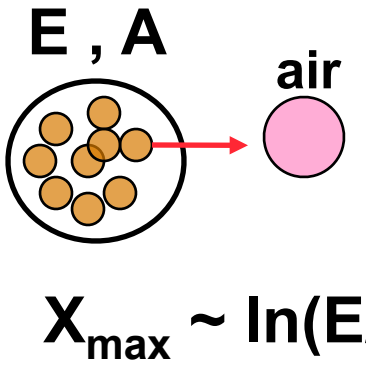
Significance few %, but we keep collecting data……

UHECR Composition





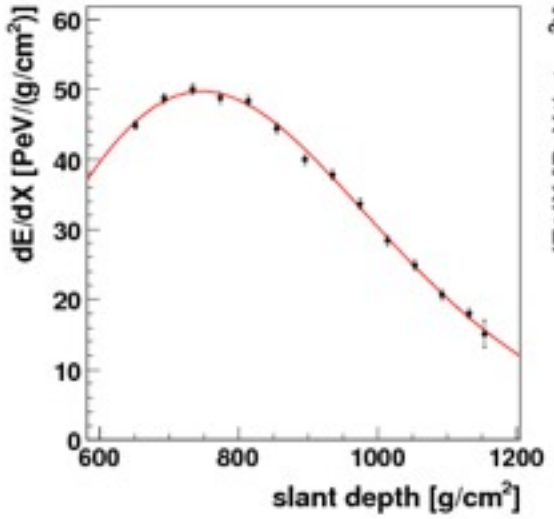




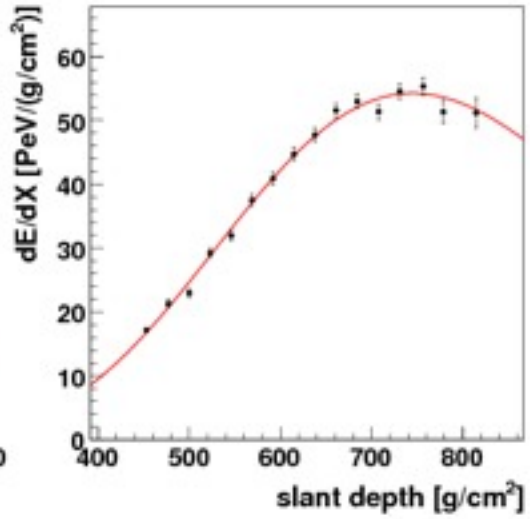
➡ mean X_{max} and RMS(X_{max}) are sensitive to composition

Reconstructed longitudinal profiles

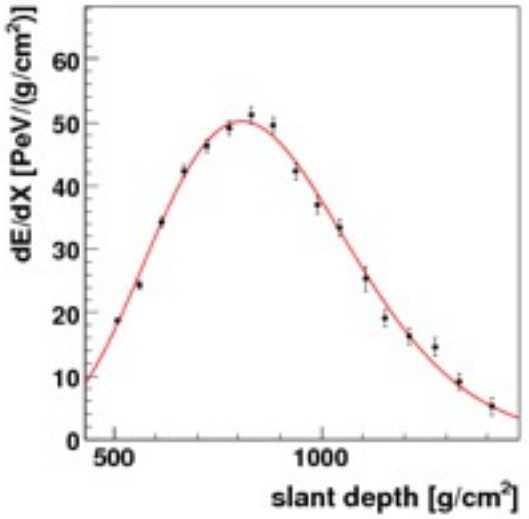
event 3262296, LM



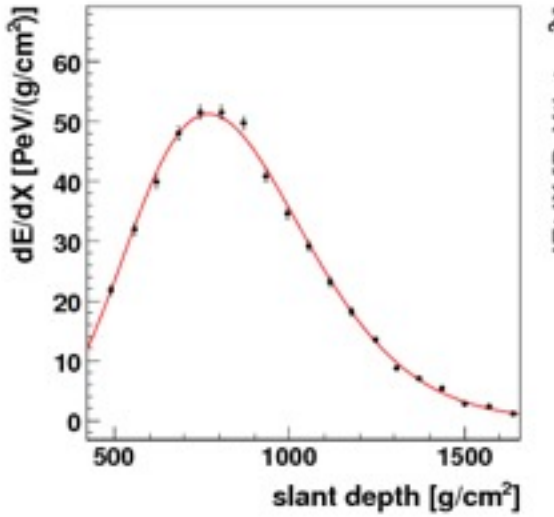
event 7294424, LM



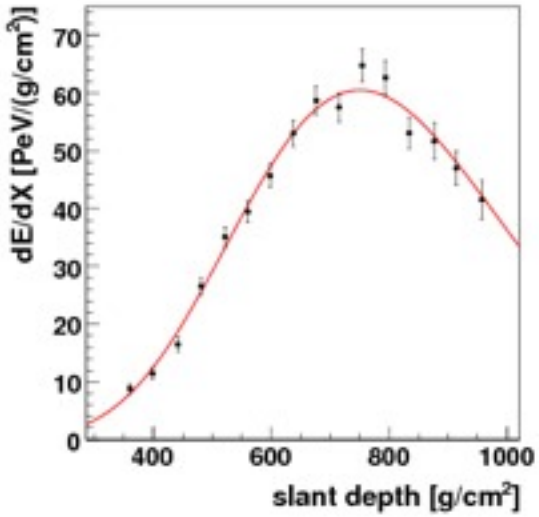
event 4871069, CO



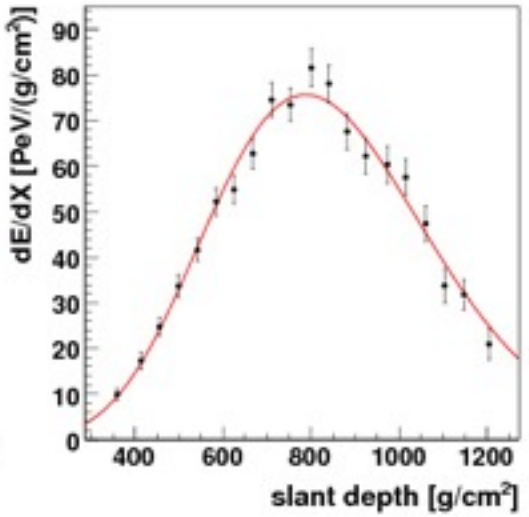
event 4742735, LM



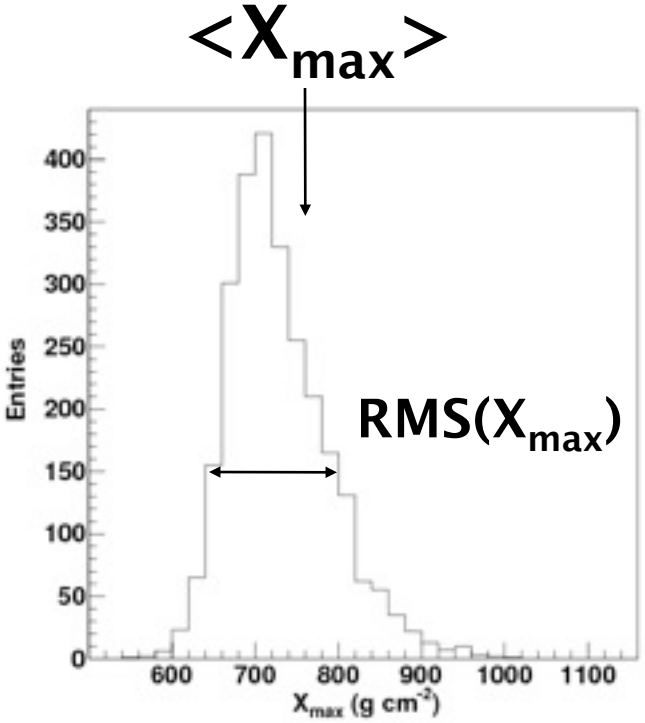
event 2694024, LL

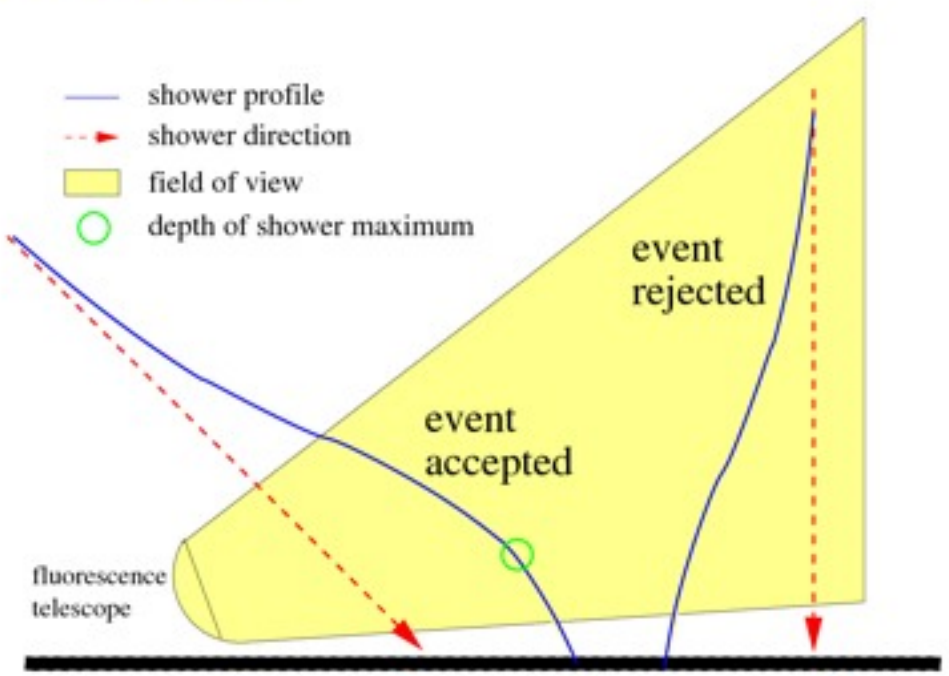


event 5153530, CO



Unbiased reconstruction of X_{max}

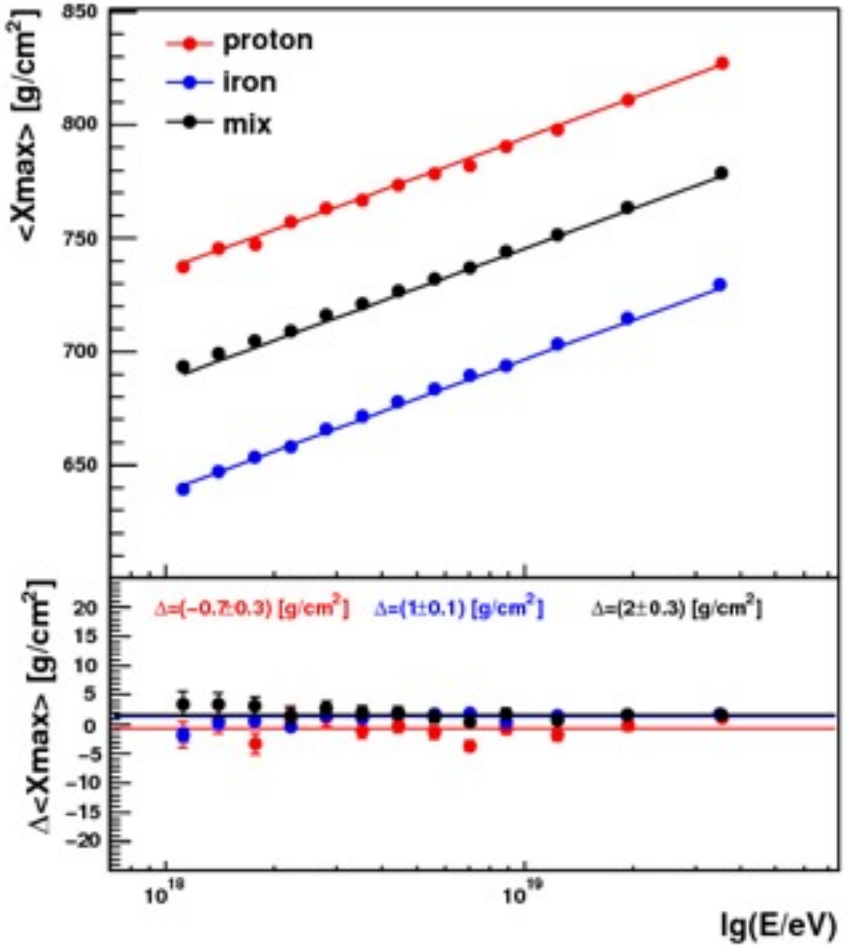


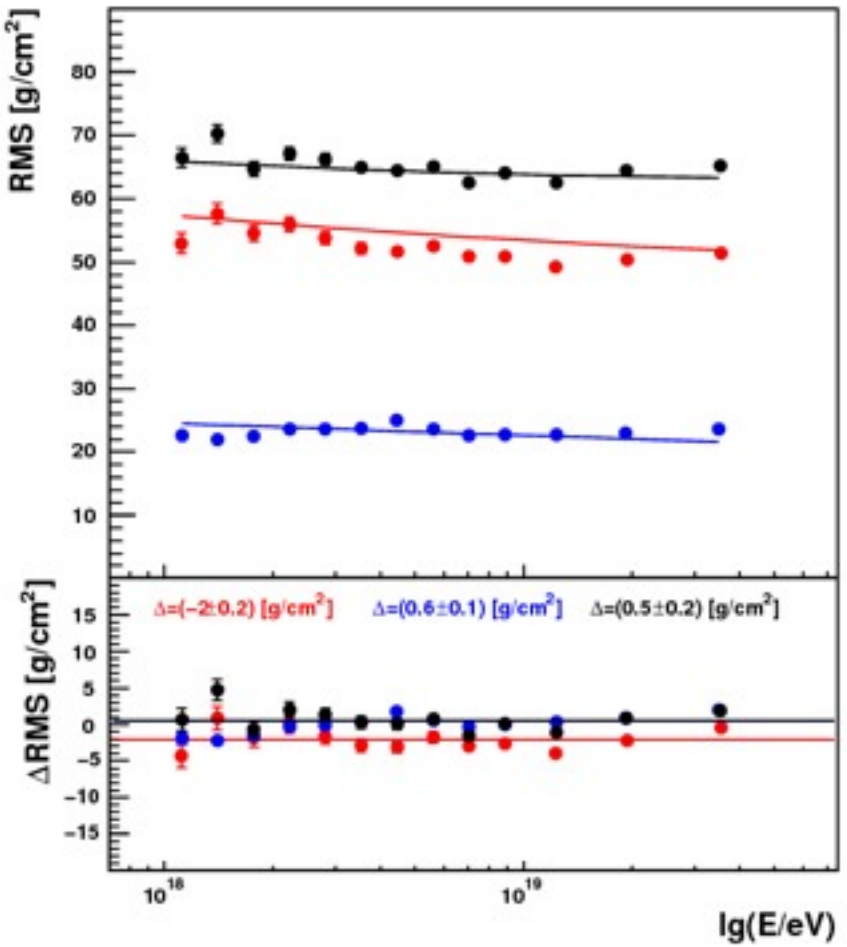


- Ex: X_{max} must be in the field of view to be reconstructed. This could introduce a bias, for ex. by selecting deeper showers close to detector
- Auger approach: devise selection criteria which produce an unbiased X_{max} distribution

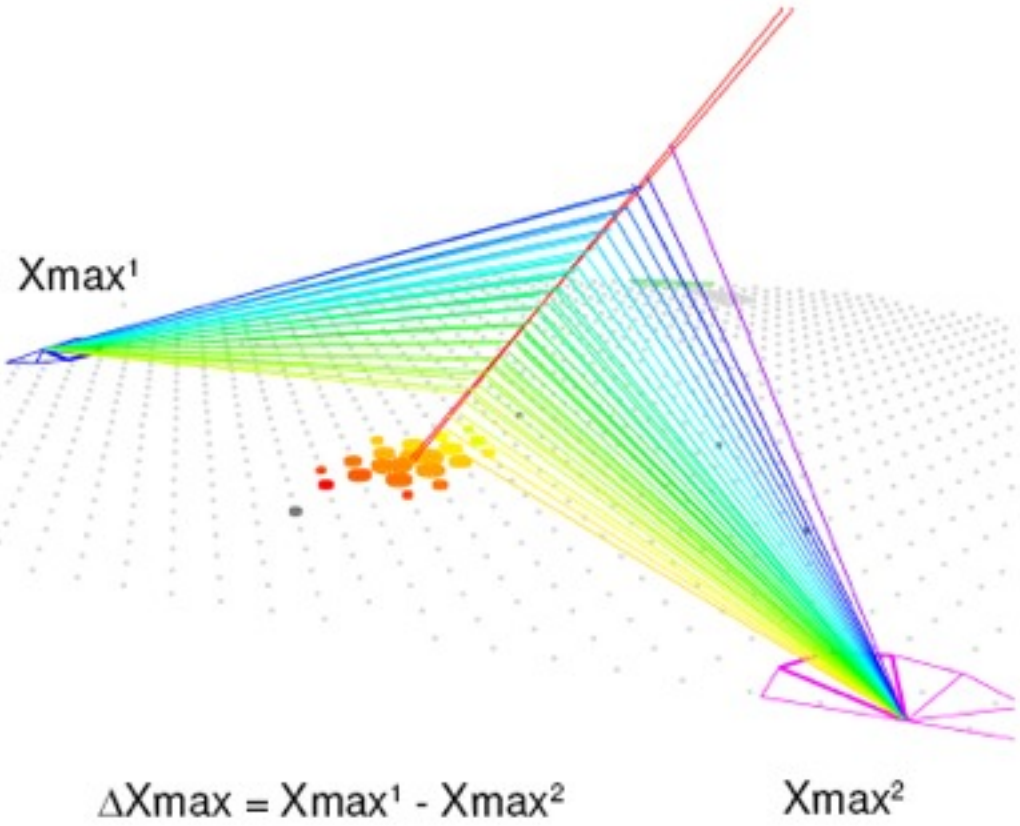
Monte Carlo Check

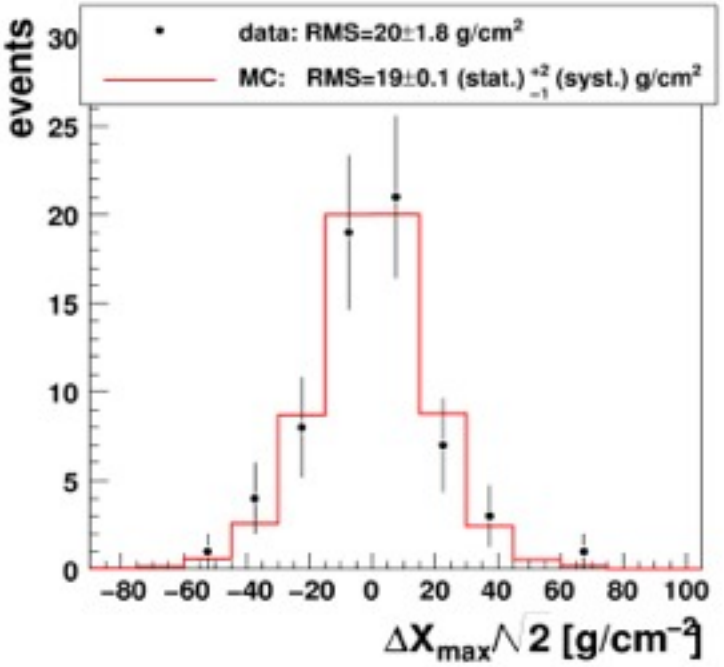
Lines corresponds to simulation input to the full detector MC: reconstructed MC data provide unbiased estimate of $<X_{max}>$ and $RMS(X_{max})$

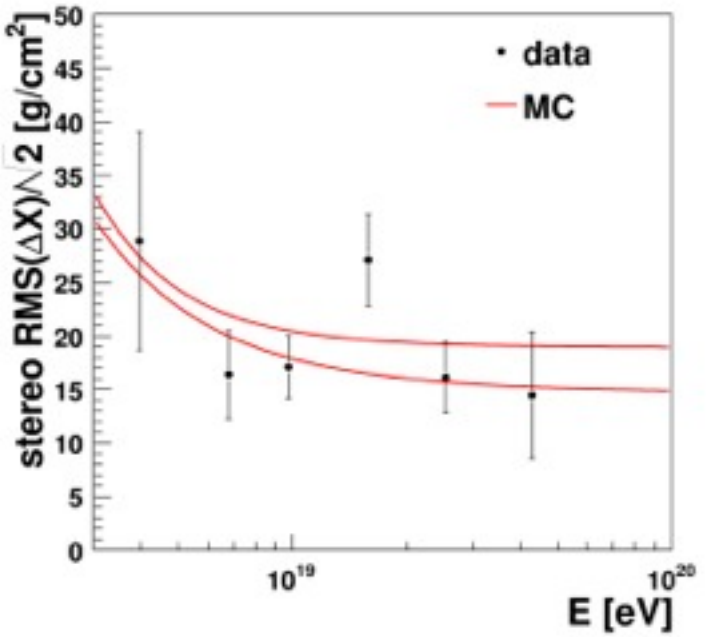




X_{max} resolution with stereo events

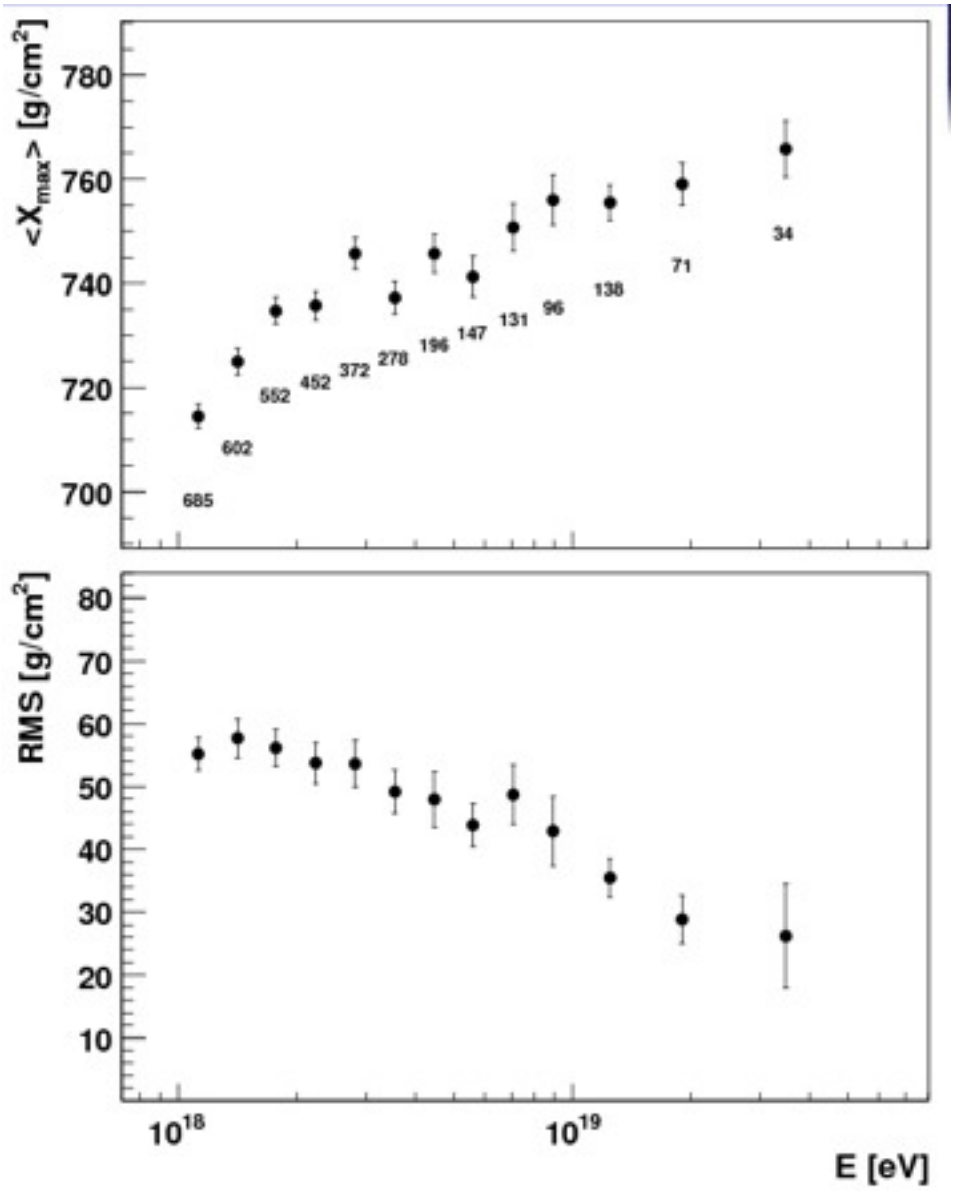






Hybrid statistics improve constantly…

Measurement of the depth of maximum

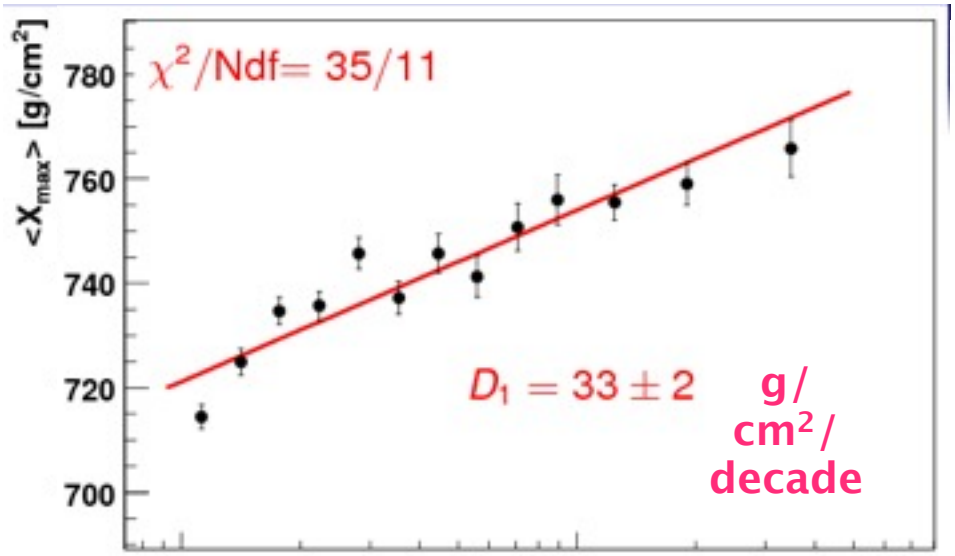


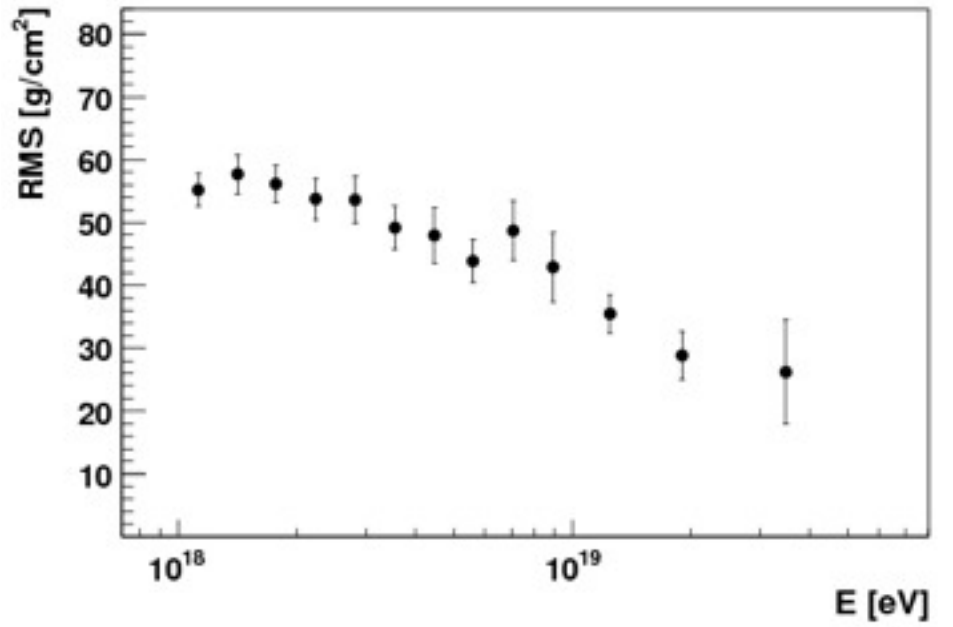
3754 hybrid events

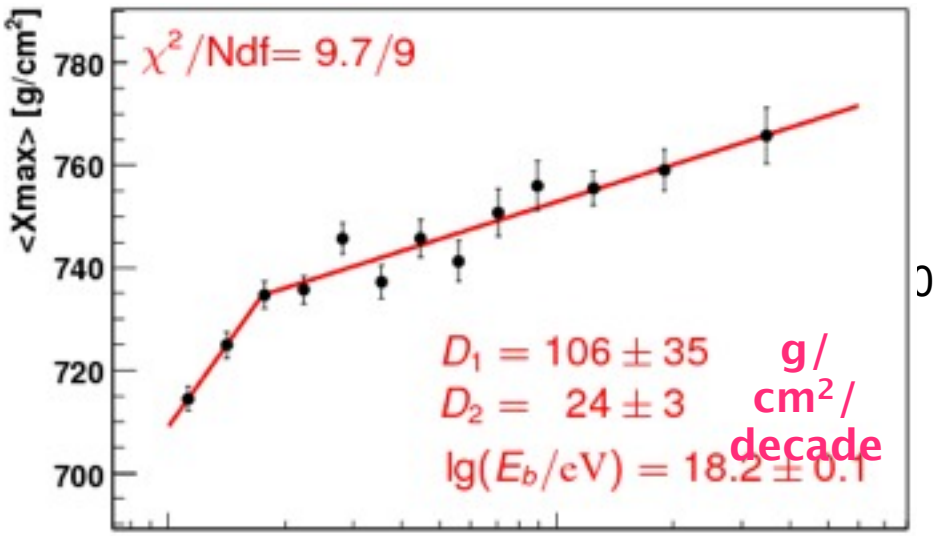
Phys. Rev. Lett., 1 March 2010, 104 091101 2010

RMS
(detector resolution subtracted)

Measurement of the depth of maximum



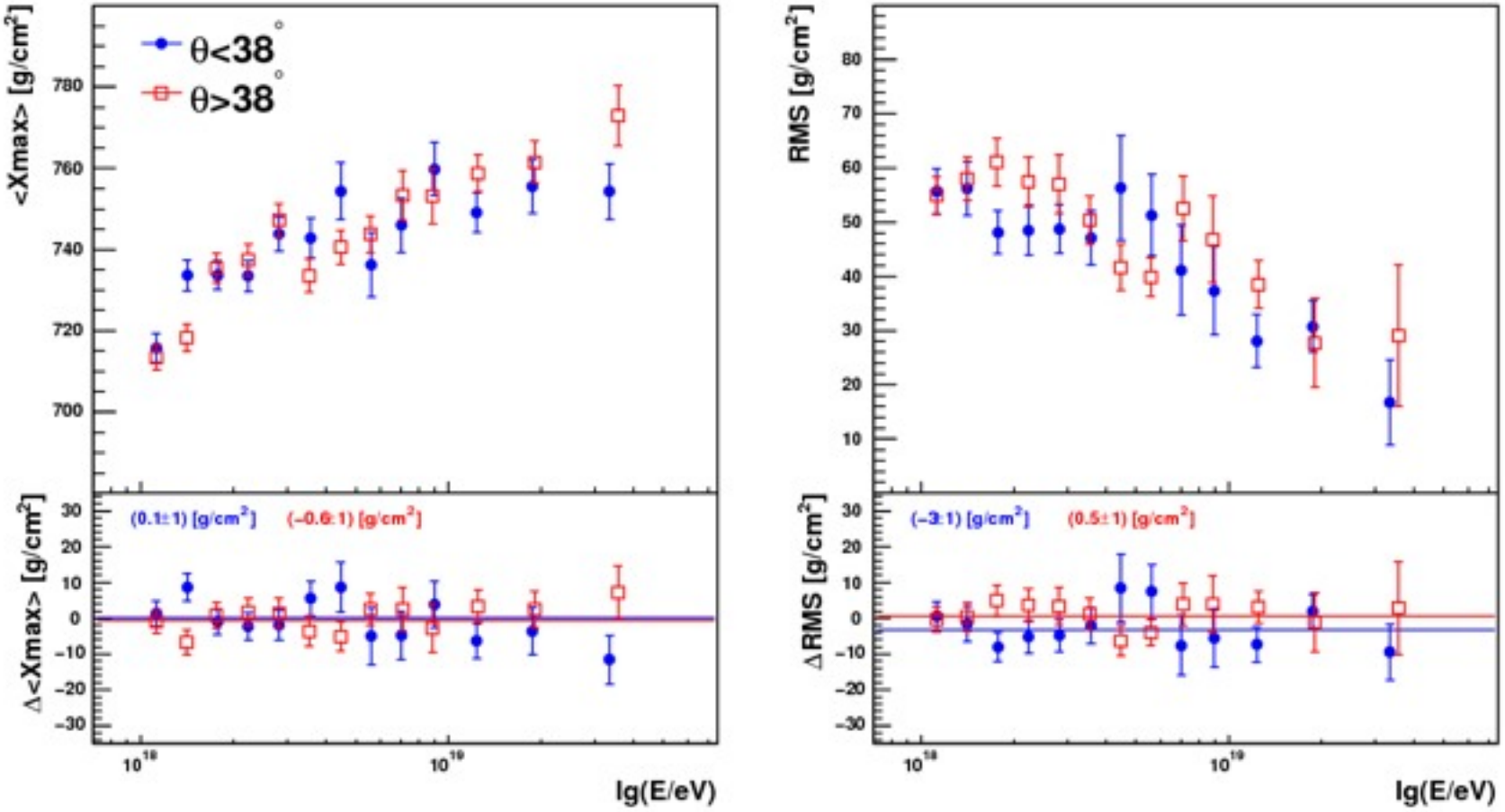




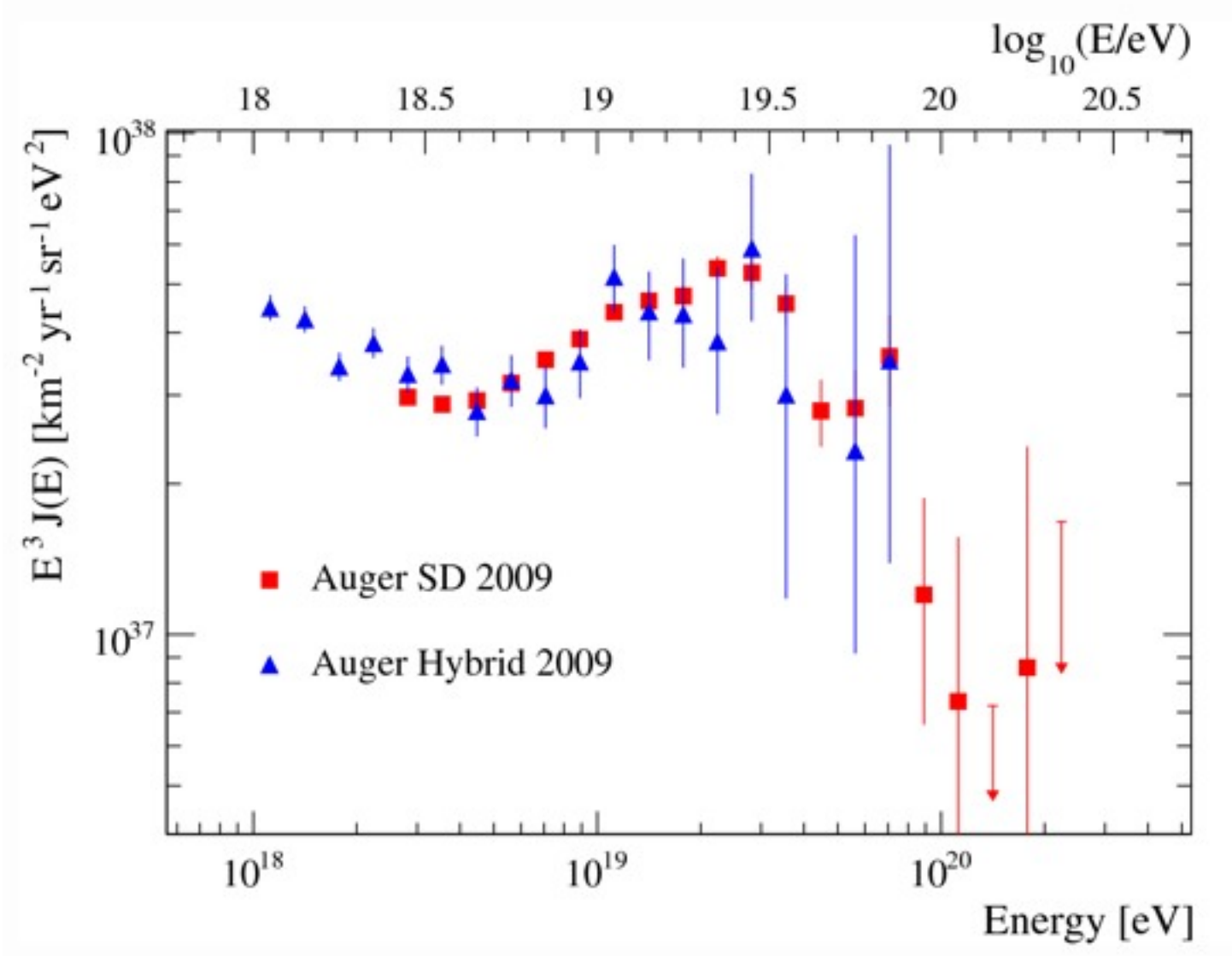
RMS
(detector resolution subtracted)

Examples of Systematic Checks

‘Vertical’ vs ‘inclined’ events

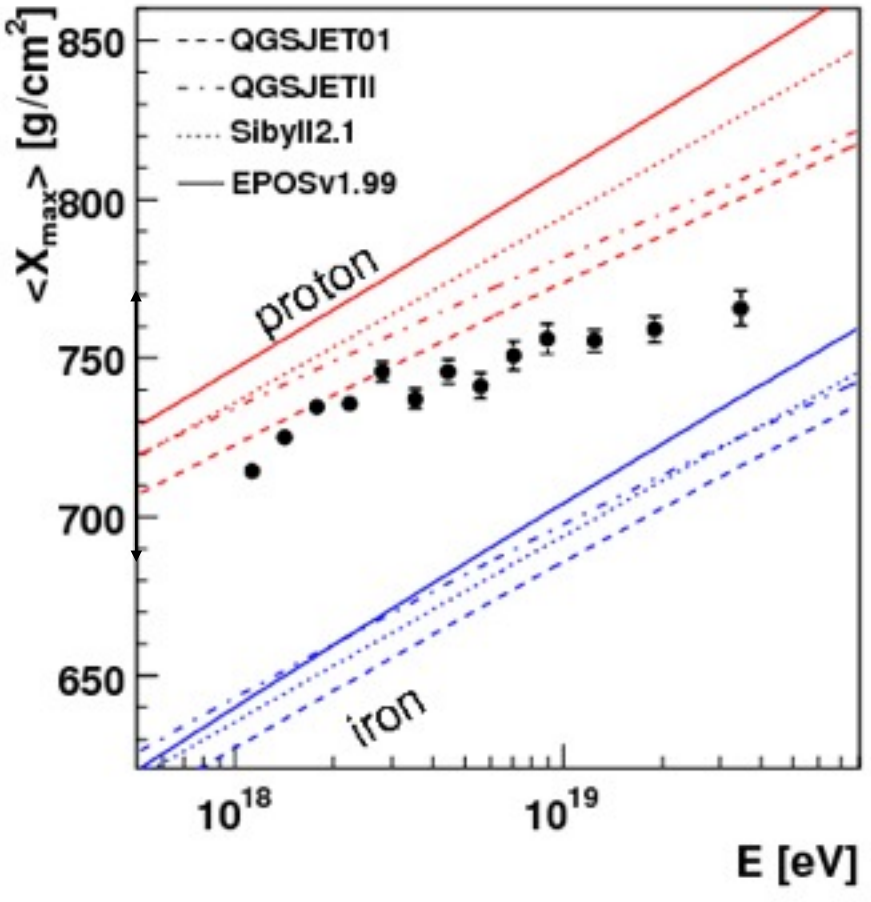


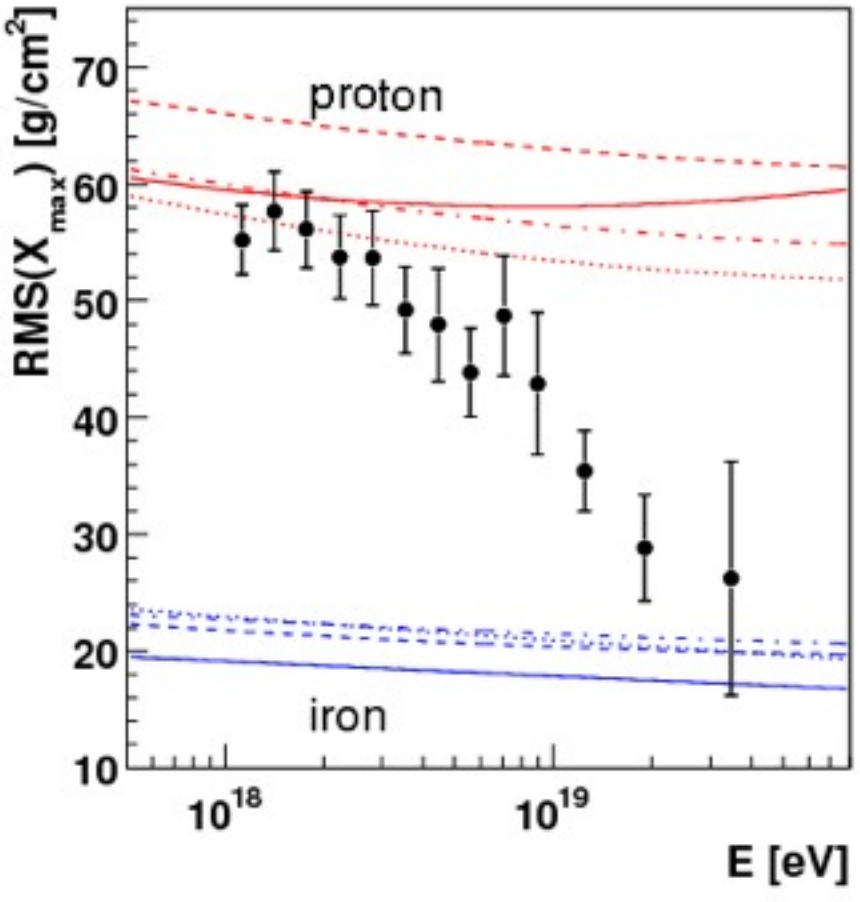
Examples of Systematic Checks



Agreement between hybrid and SD energy spectra: we are not missing events

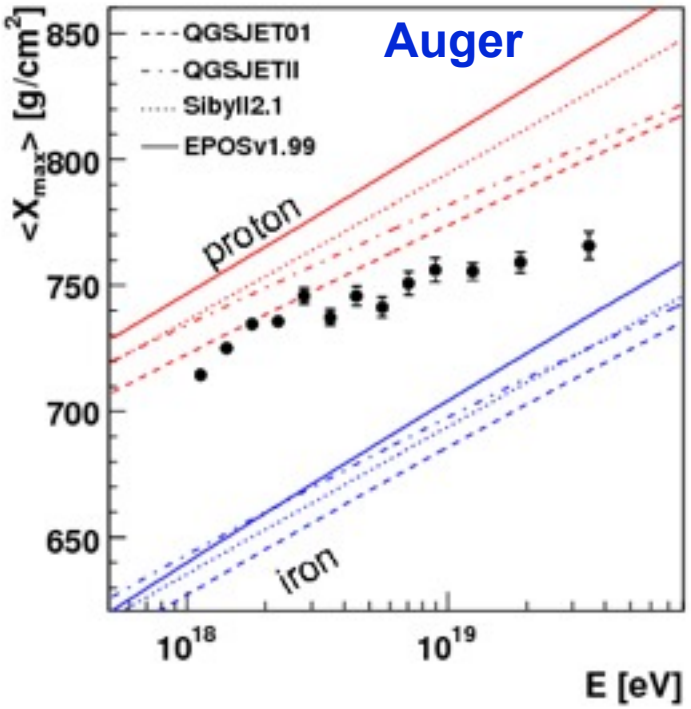
Auger X_{max} measurements vs Models

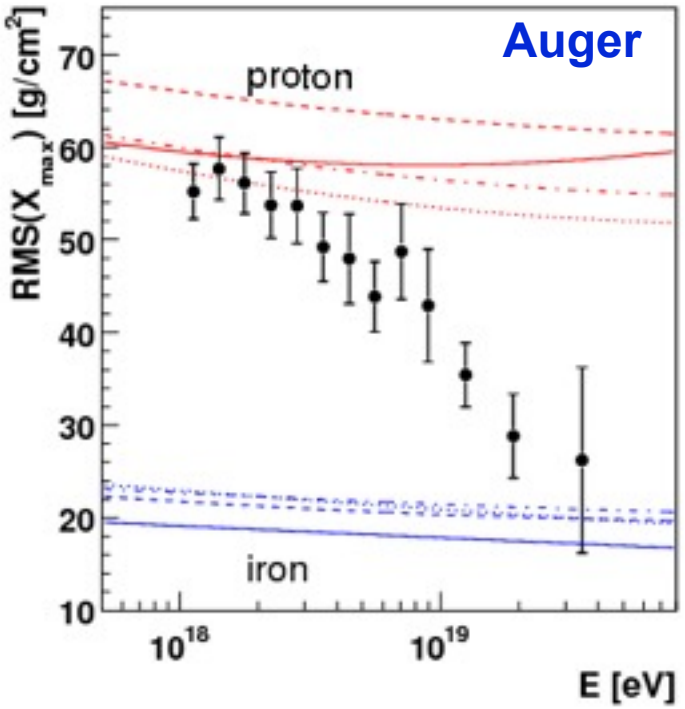




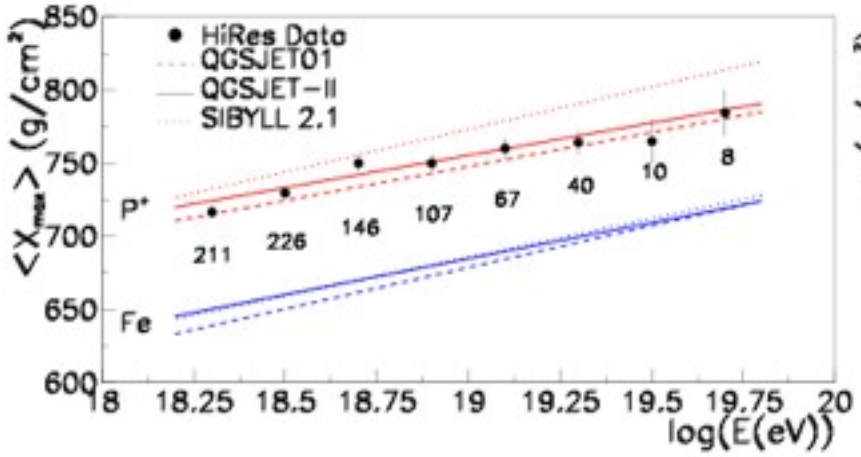
NOTE: highest energy event ~$6 \cdot 10^{19}$ eV (< onset of anisotropy)

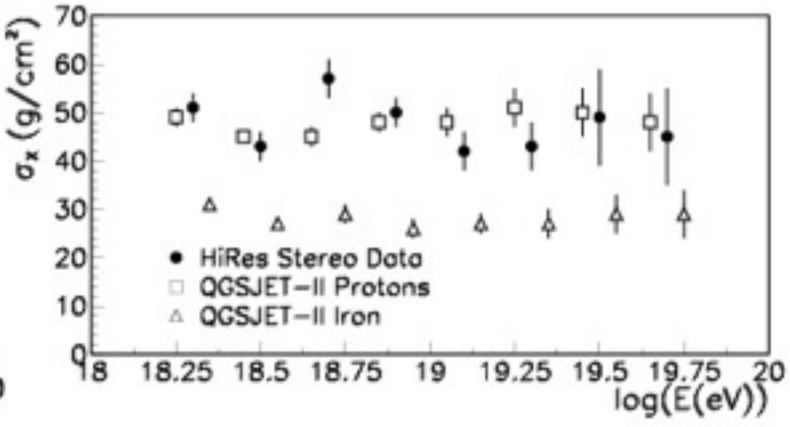
Comparison (?) Auger vs HiRes





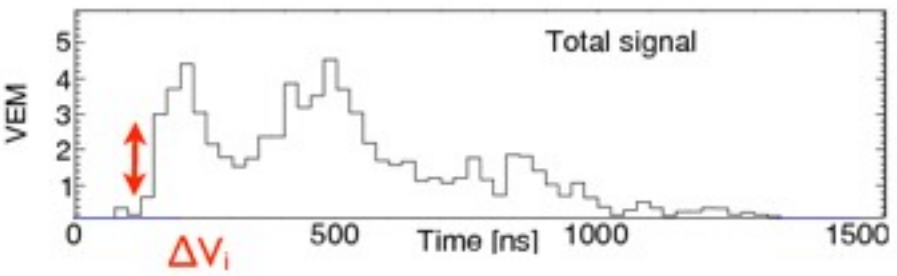
40 g/cm^2

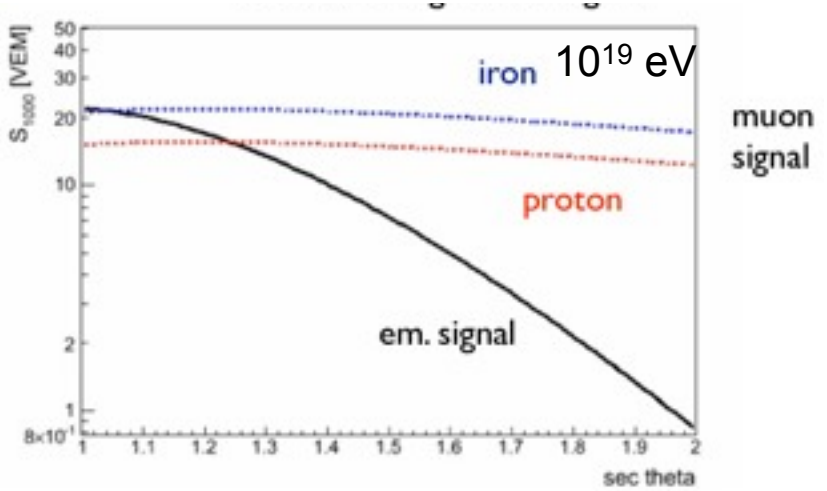


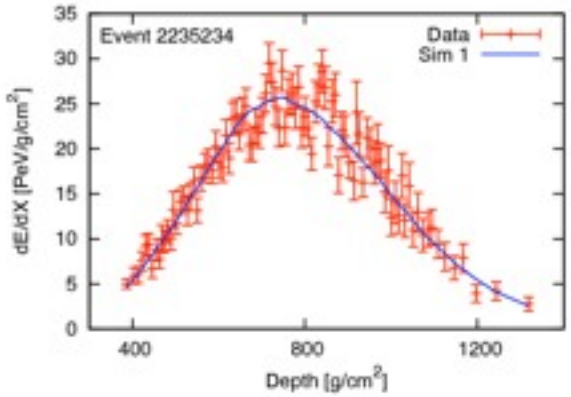


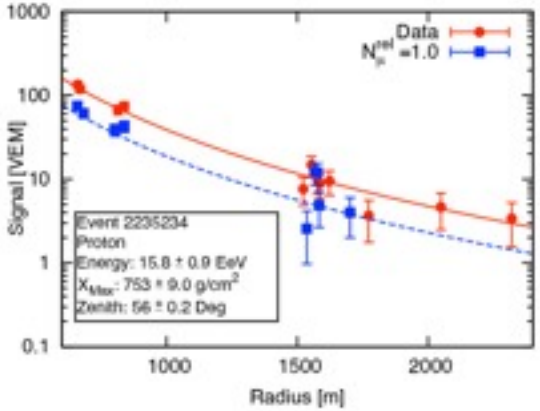
20 g/cm^2

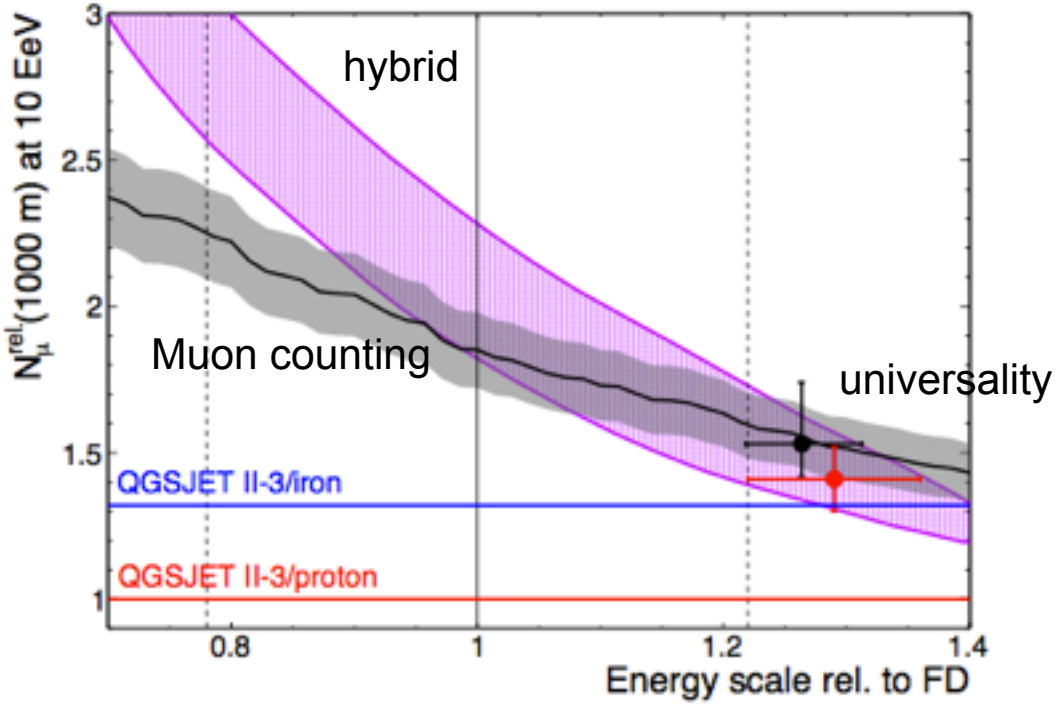
Muon content in UHECR





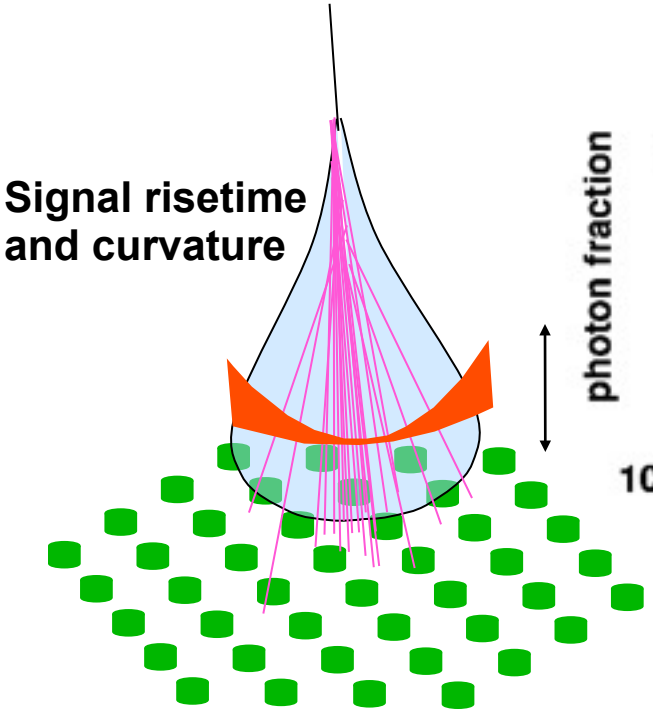


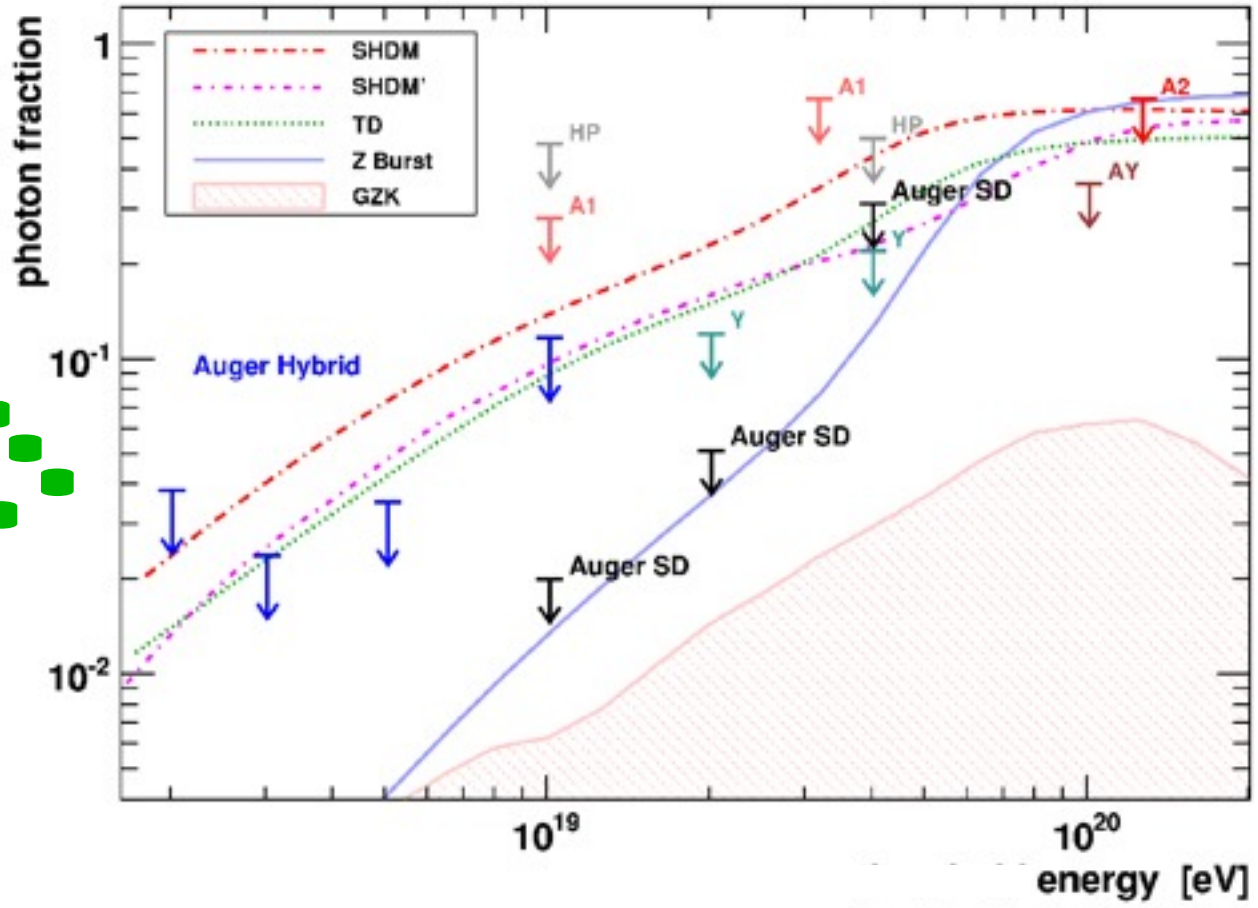




Significantly more muons than model predictions!

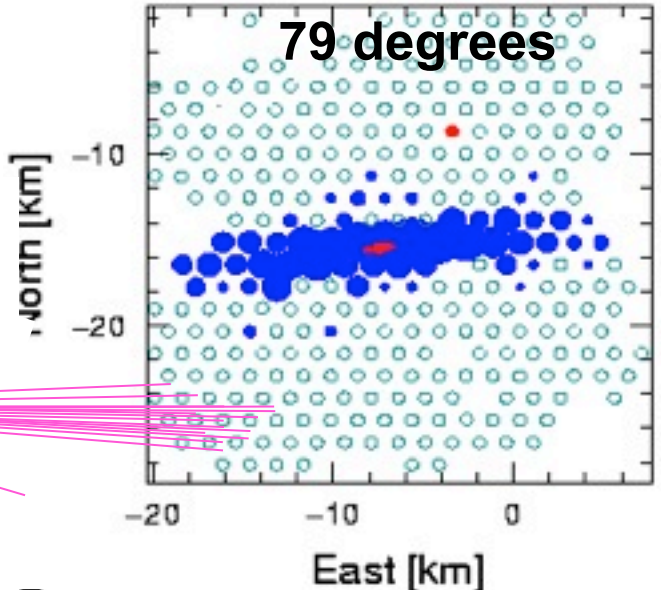
Search for UHECR photons

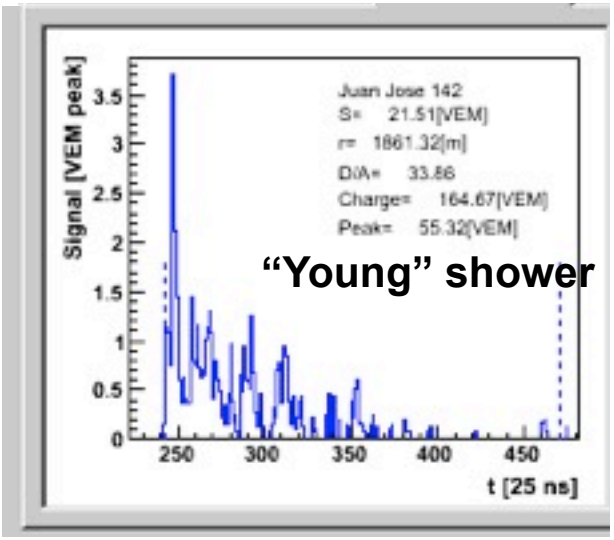


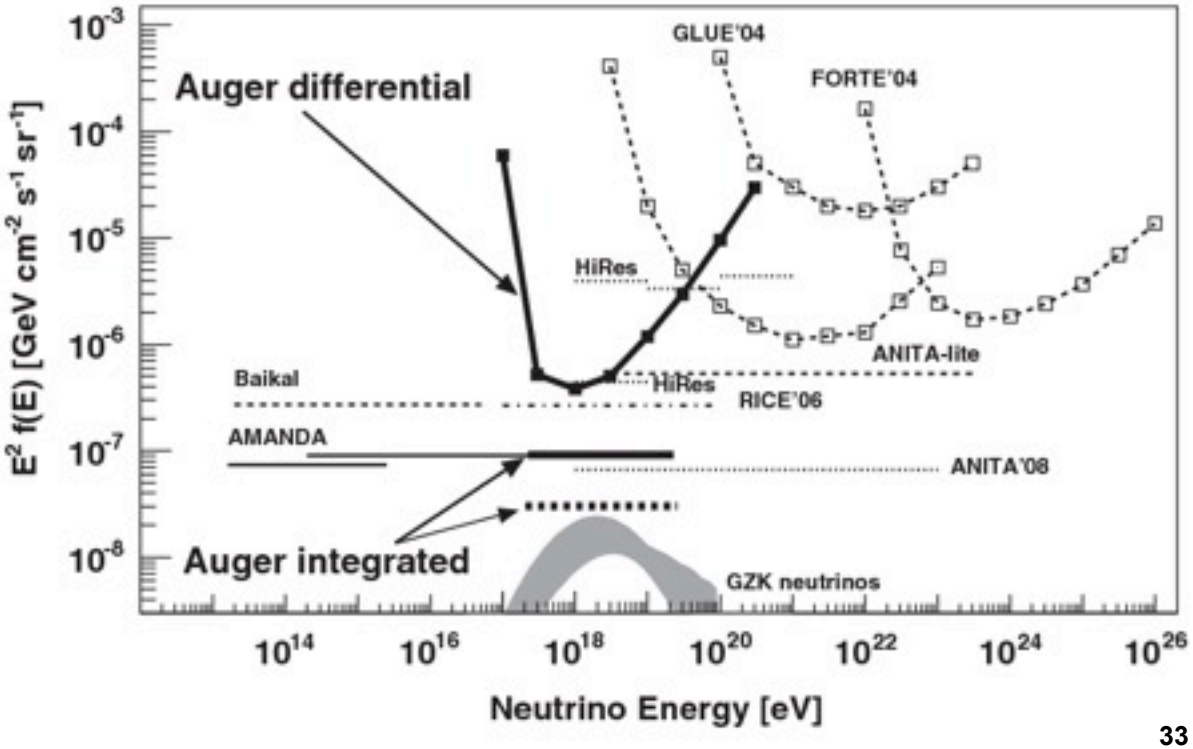


disfavour exotic "particle physics" models

Neutrino limits from inclined showers



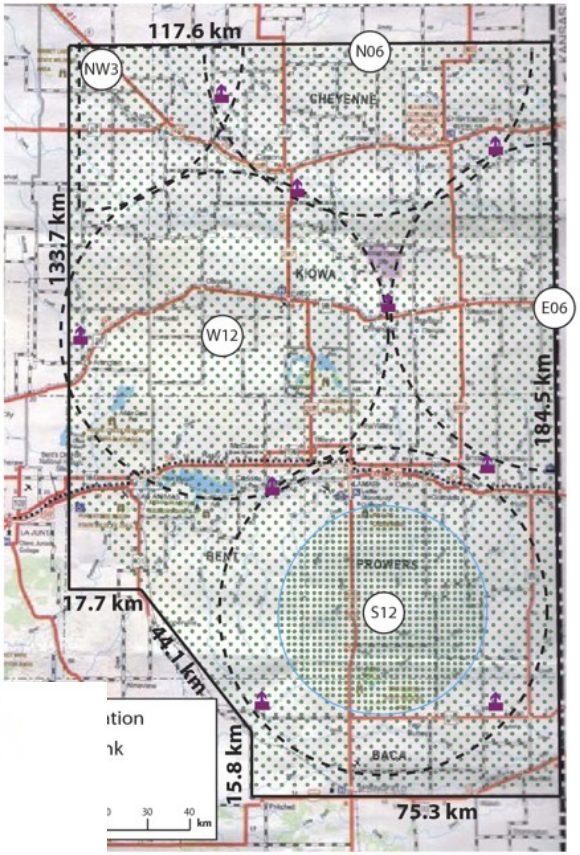




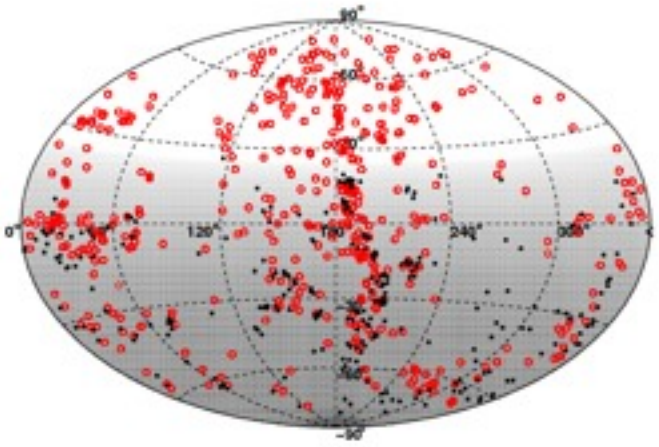
Auger North in Colorado

- 21,000 km^2
- 4400 SD tanks
- 39 Fluorescence telescopes
- Full sky coverage
- > 200 events/year

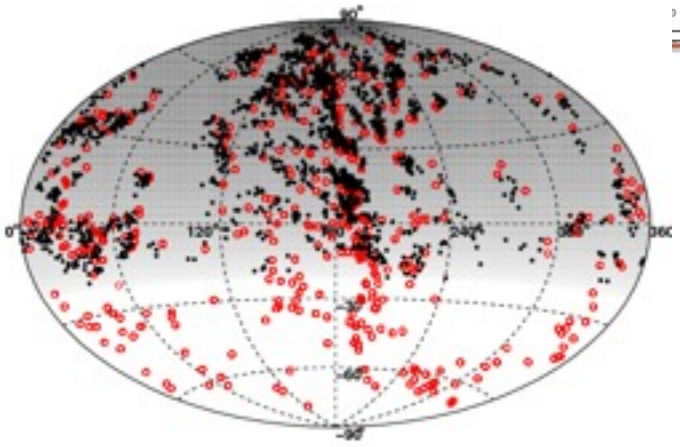
- R&D array under construction



Auger south, 10 years



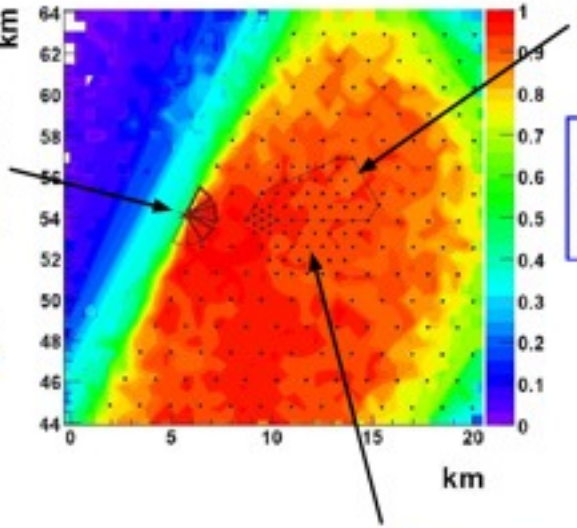
Auger north, 10 years



Auger North will provide the statistics to decipher the UHECR puzzle

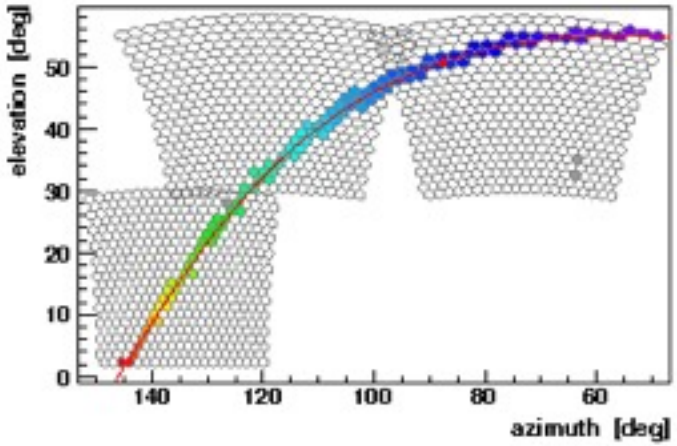
Auger South enhancements

High Elevation Auger Telescopes (HEAT)



Auger Engineering Radio Array (AERA)

24 km^2



Auger Muons and Infill for the Ground (AMIGA)

A rich physics program at lower energy is starting!

Outlook

- Two years of data of the Pierre Auger Observatory are already giving us novel insight into the UHECR puzzle:

  - flux suppression of UHECR unequivocally established (GZK?)

  - UHECR anisotropy at 99% CL (sources?)

  - Composition: intriguing results (Heavier? Models? Cross sections?). Muon content.

  - Exotic physics disfavored

- One question has been answered: there is a flux suppression at the highest energies. The event rate is not AGASA like. Breakthrough?

  - Be patient (Auger South is just at the beginning of its decade of data taking)

  - Be brave (Auger North)

Auger vs HiRes