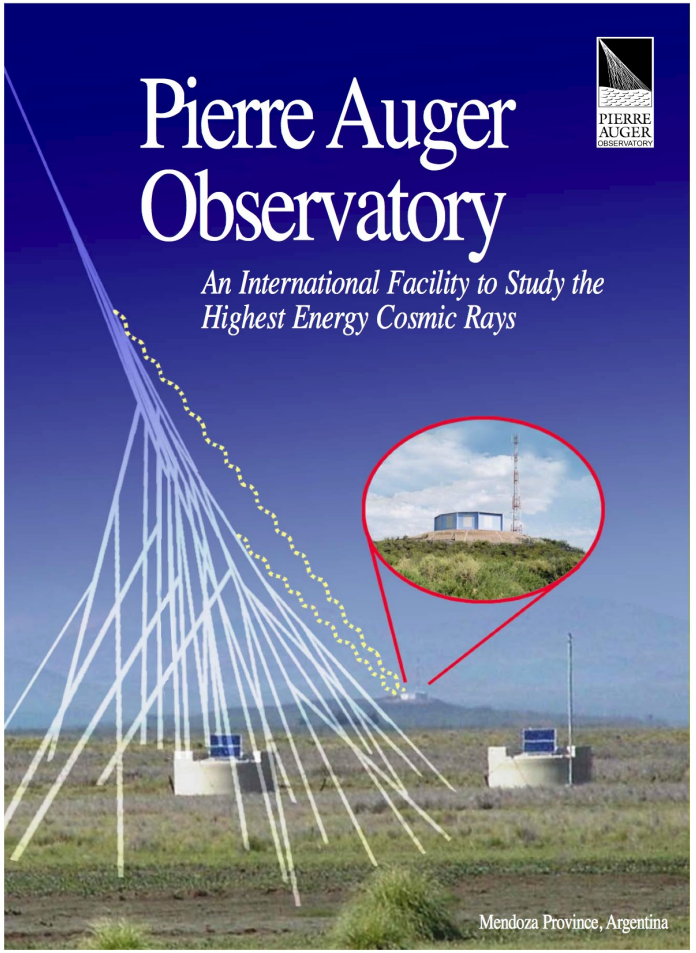
2011 BCVSPIN Advanced Study Institute in Particle Physics and Cosmology,
Huê´, Vietnam, 25-30 July 2011

Ultra High Energy Cosmic Rays



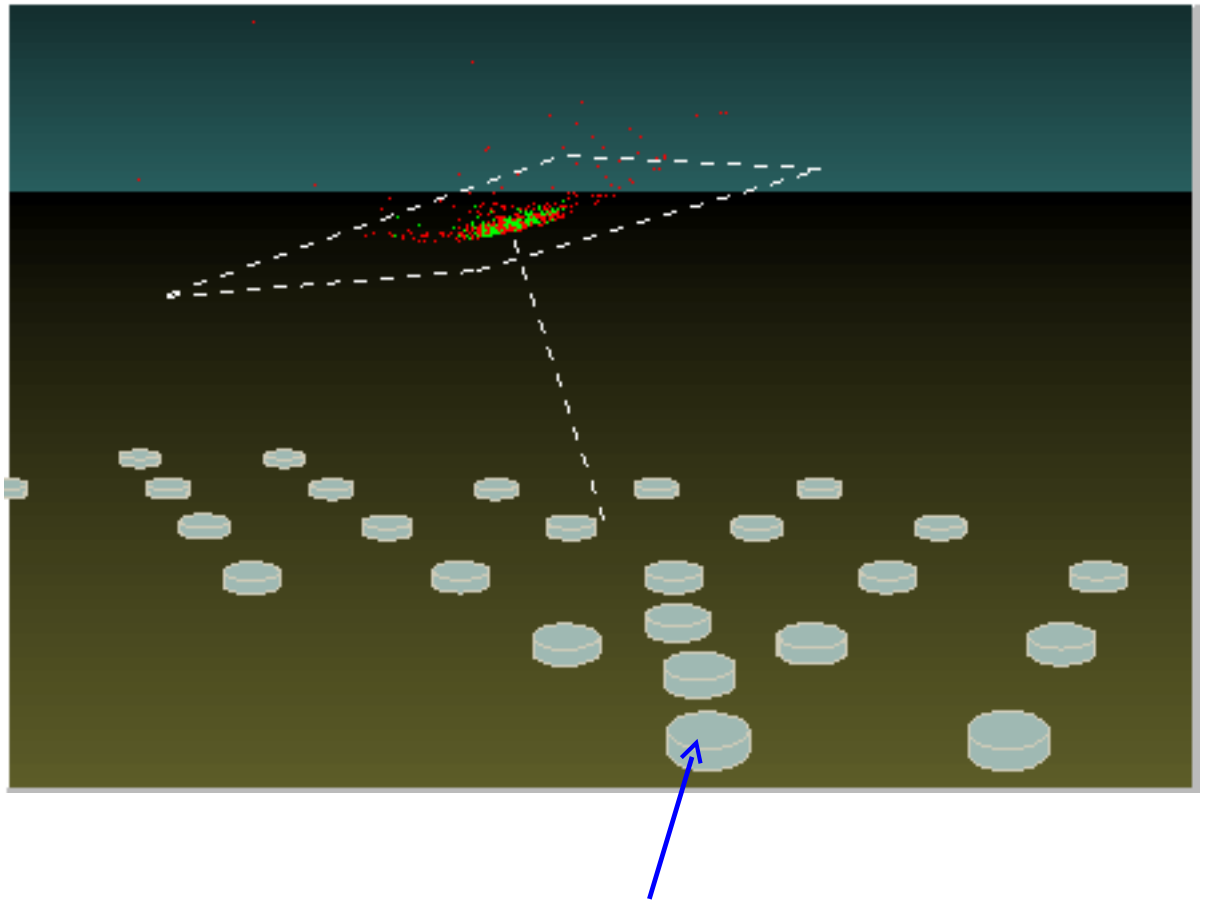
and_

The Pierre Auger Observatory

Paolo Privitera

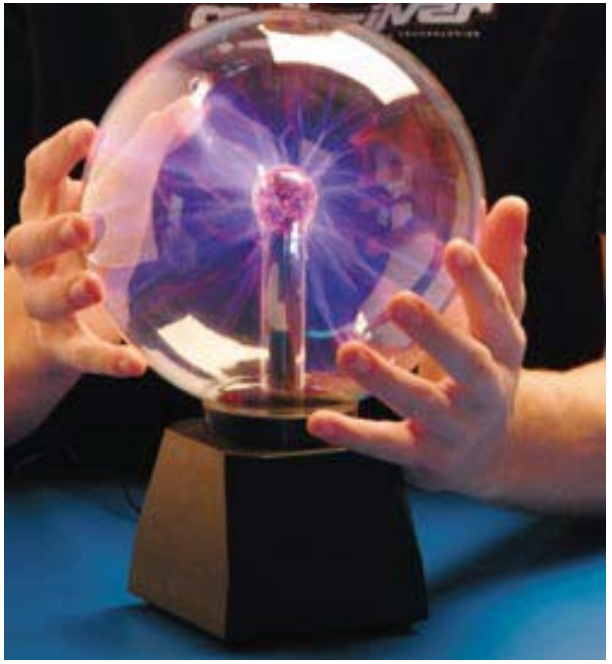
THE UNIVERSITY OF CHICAGO
PHYSICAL SCIENCES

Surface Detection of UHECR



A sparse array of particle detectors detects the extensive air shower particles reaching ground

Fluorescence Detection of UHECR

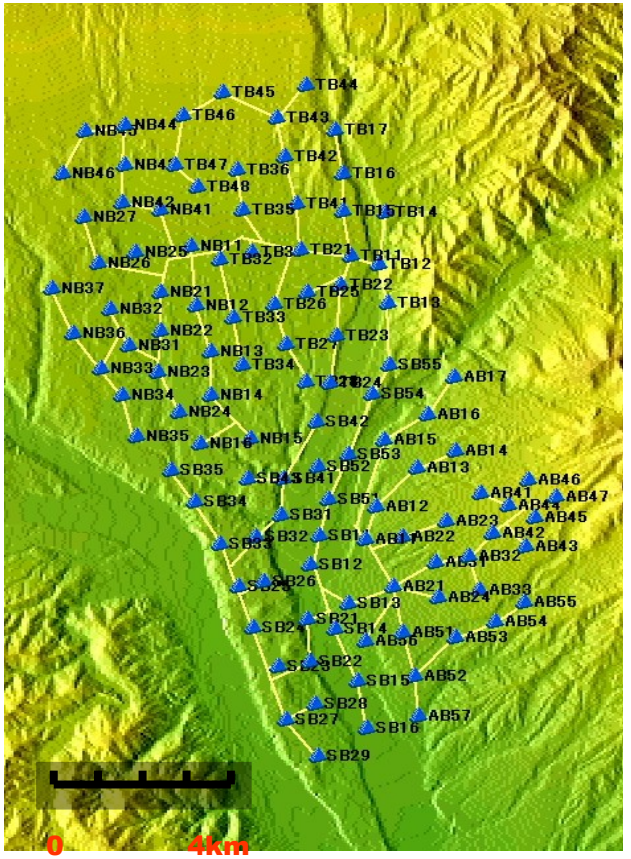


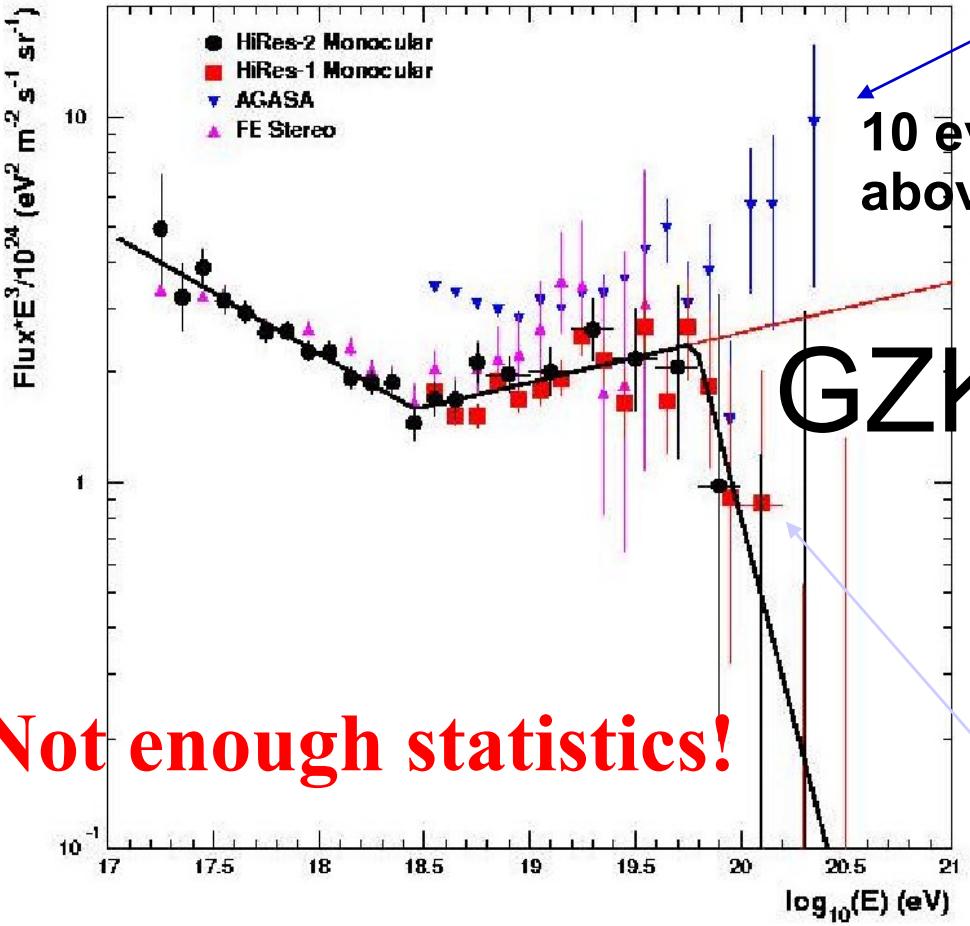
Fluorescence emission from gas molecules excited by charged particles

UV emission from the nitrogen molecules in air, excited by the shower particles (mostly $e^{\pm}$), imaged by a fast “digital camera”

Why Auger?

AGASA (Japan) 100 km²





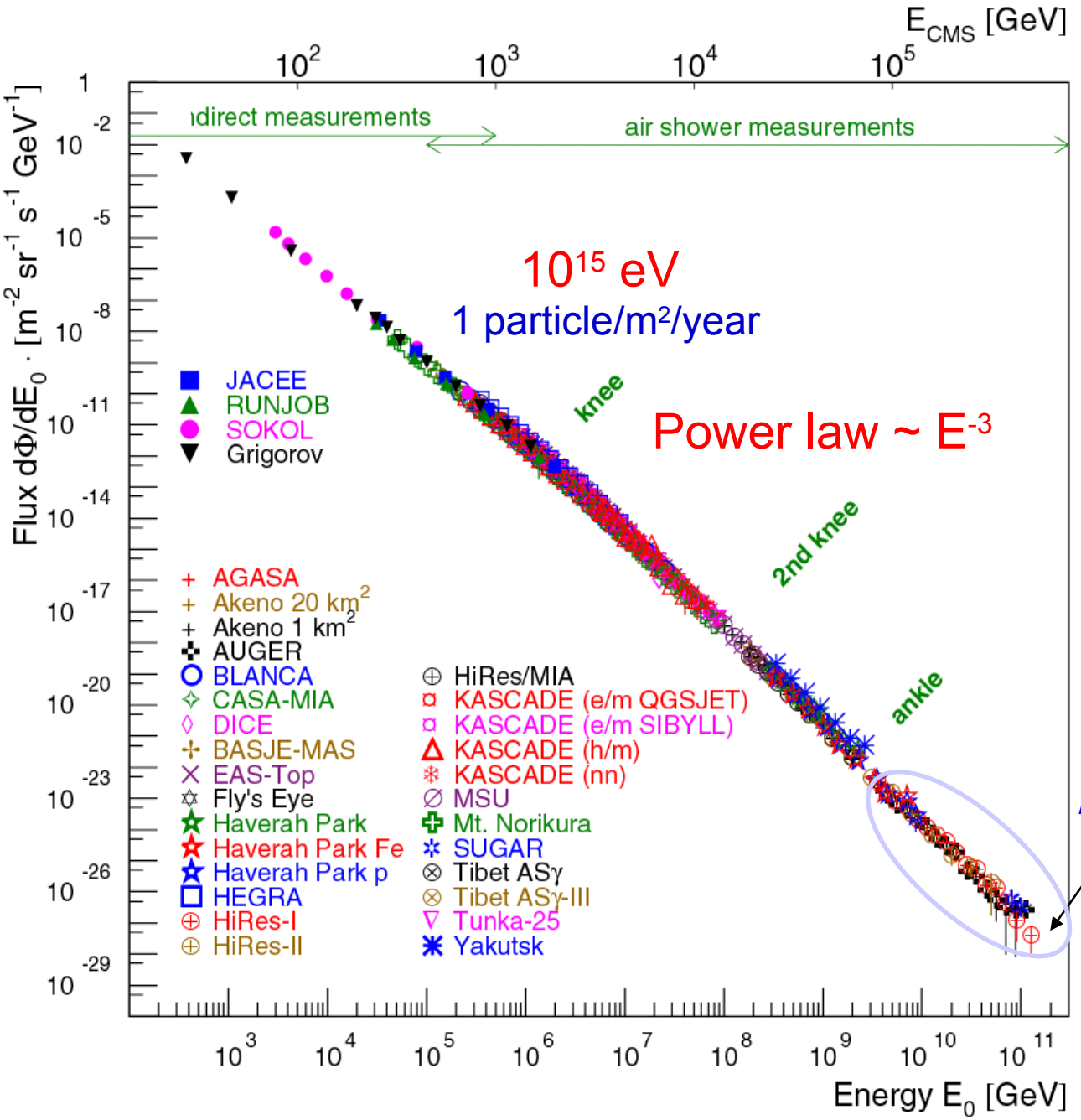
10 events (?) above GZK

GZK?

Not enough statistics!

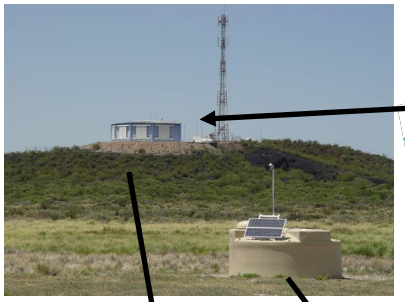
HiRes
Utah (US)

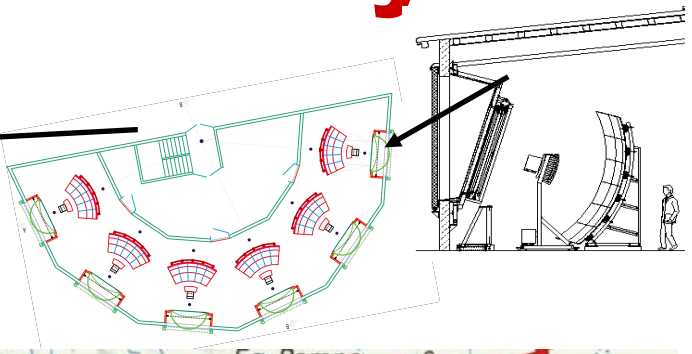
Ultra High Energy Cosmic Rays

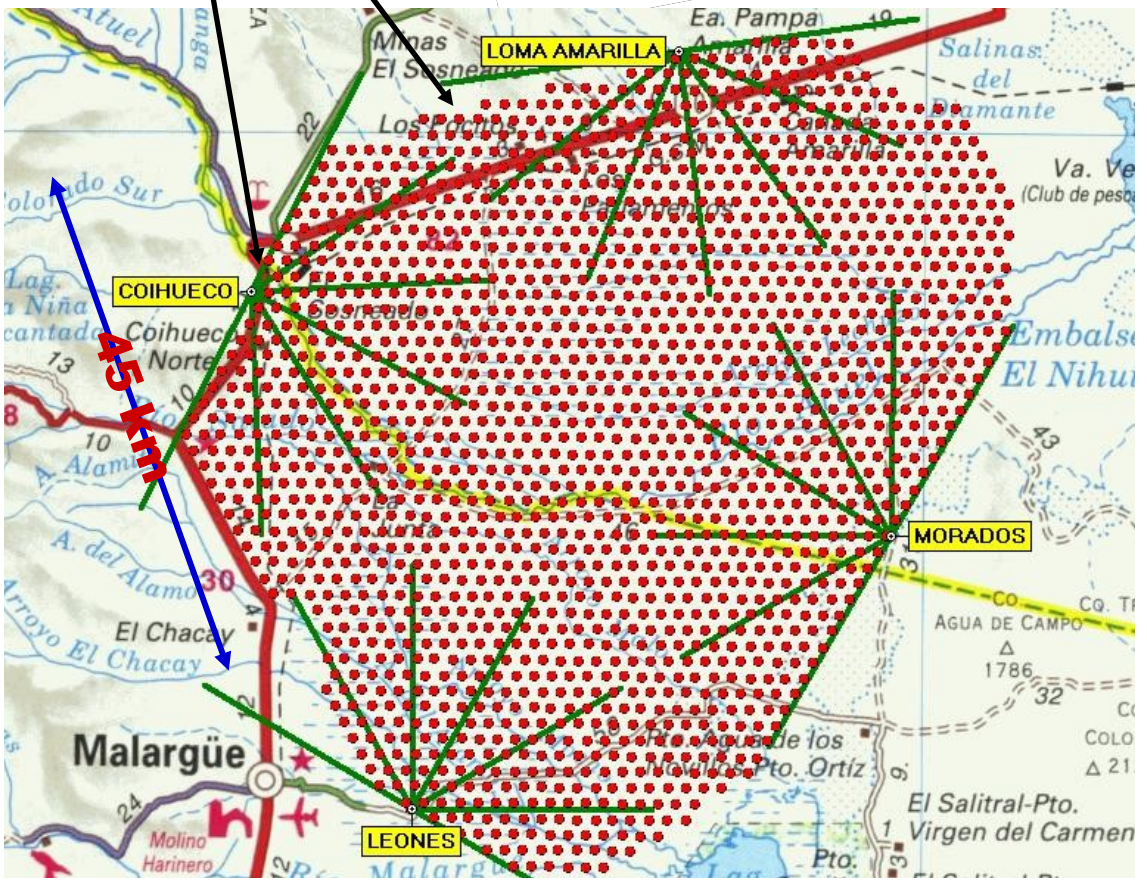


The Pierre Auger Observatory

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





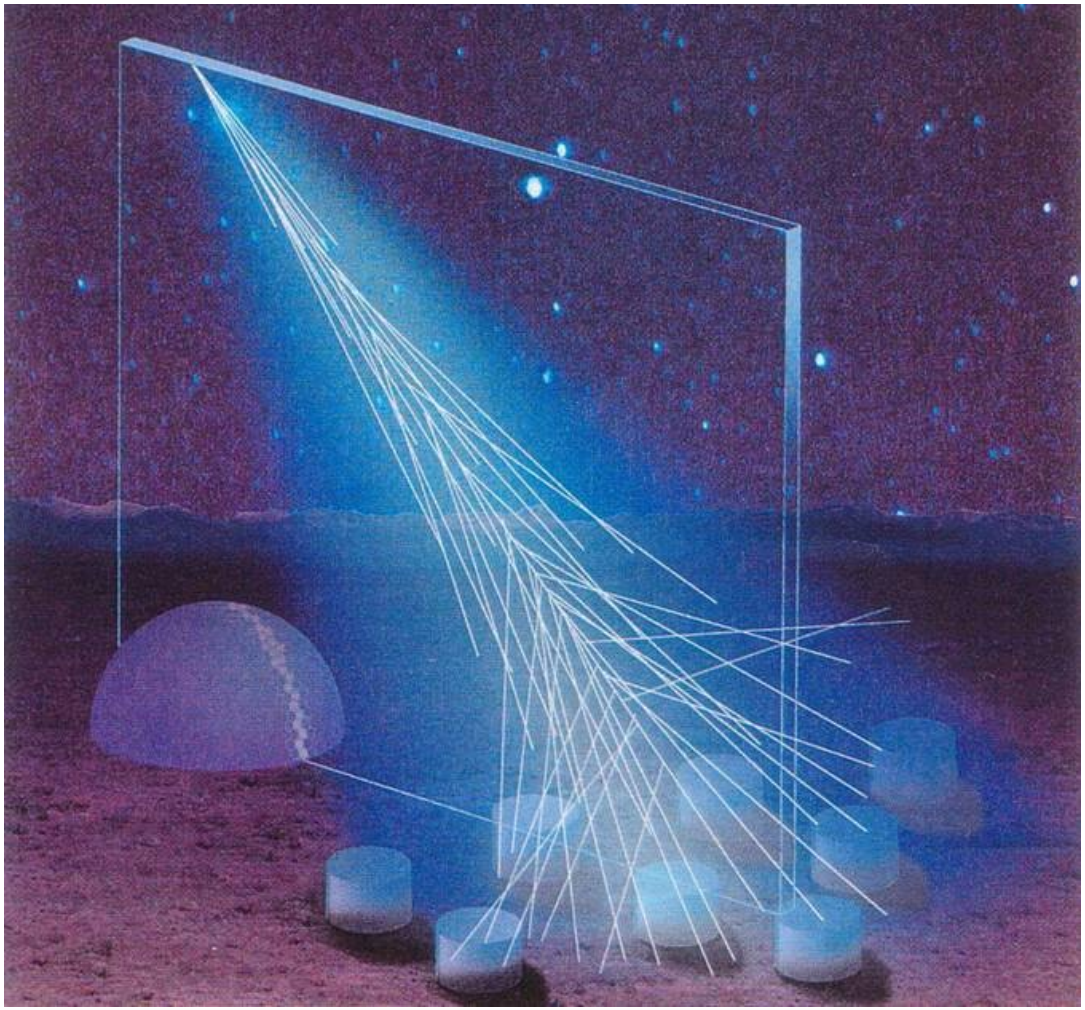


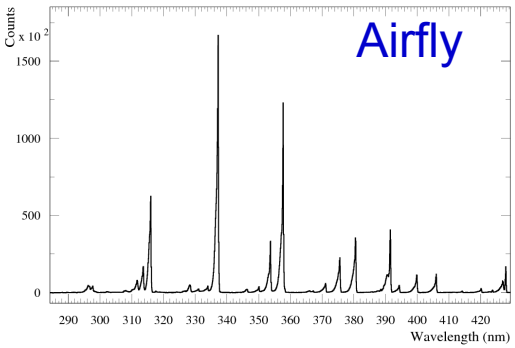
Argentina
Australia
Bolivia*
Brazil
Czech Republic
France
Germany
Italy
Mexico
Netherlands
Poland
Slovenia
Spain
United Kingdom
USA
Vietnam*

PIERRE AUGER OBSERVATORY

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

UHECR detection techniques





300-400 nm light from de-excitation of atmospheric nitrogen (fluorescence light)

≈ 4 γ / m /electron

10^{19} eV → 10^{10} e

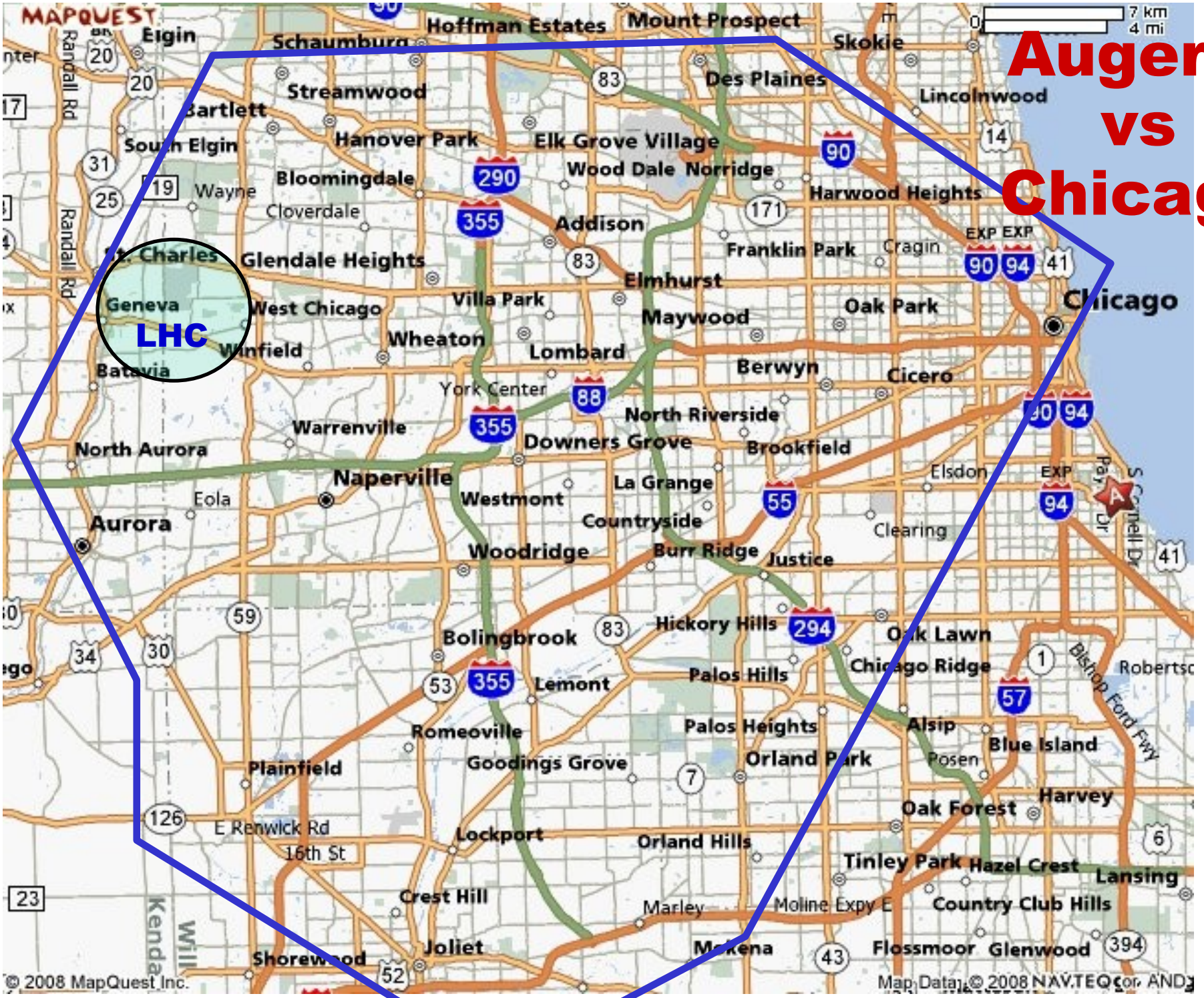
Fluorescence Detector

- 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



3000 km^2 !

Rate ≈ 1 / Km^2 / sr / century!

Surface array deployment

Tank

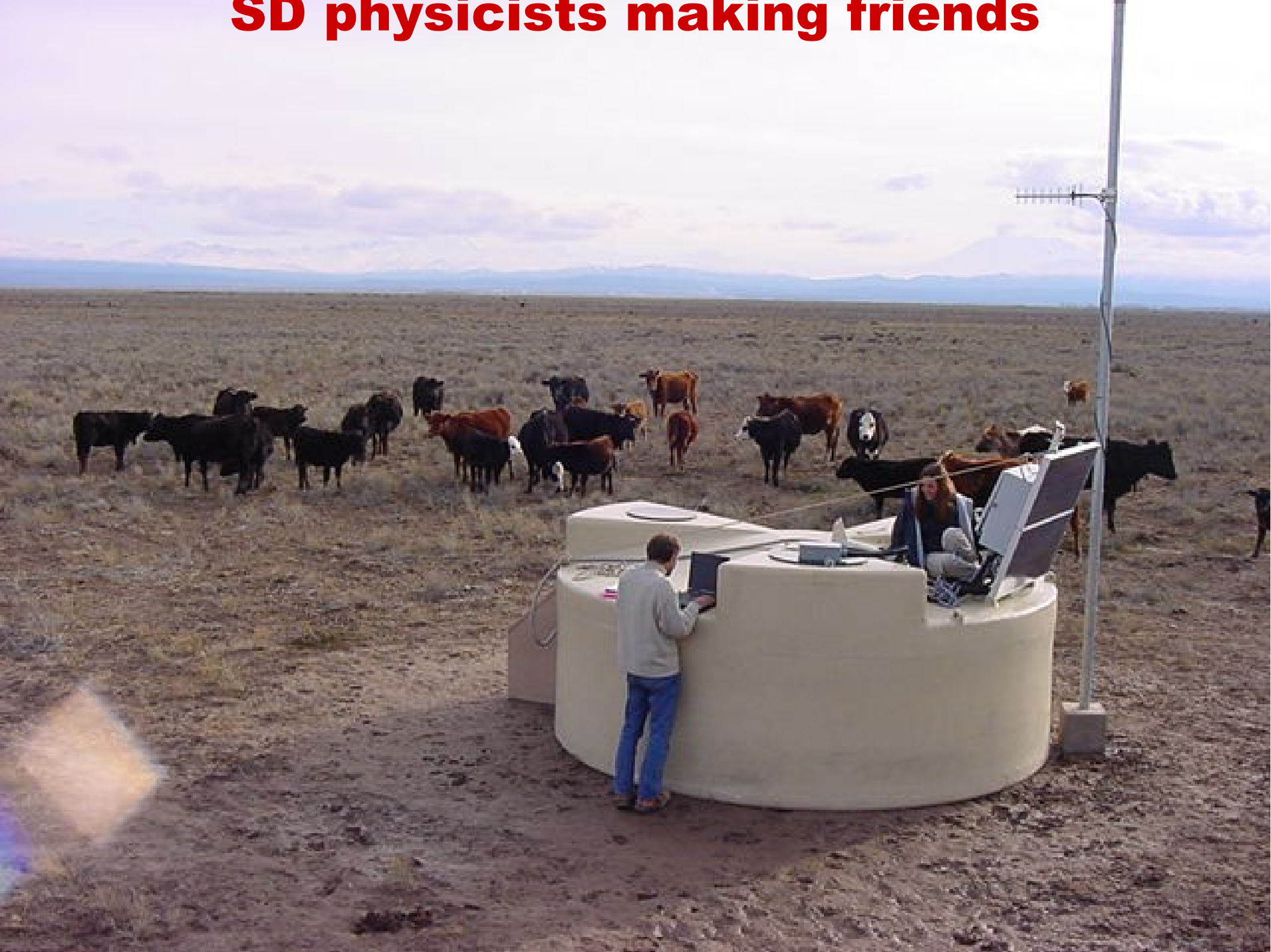
Tar

Electronics installation

Good old days: Haverah Park (U.K.) Cosmic Ray Detector late 60‘s

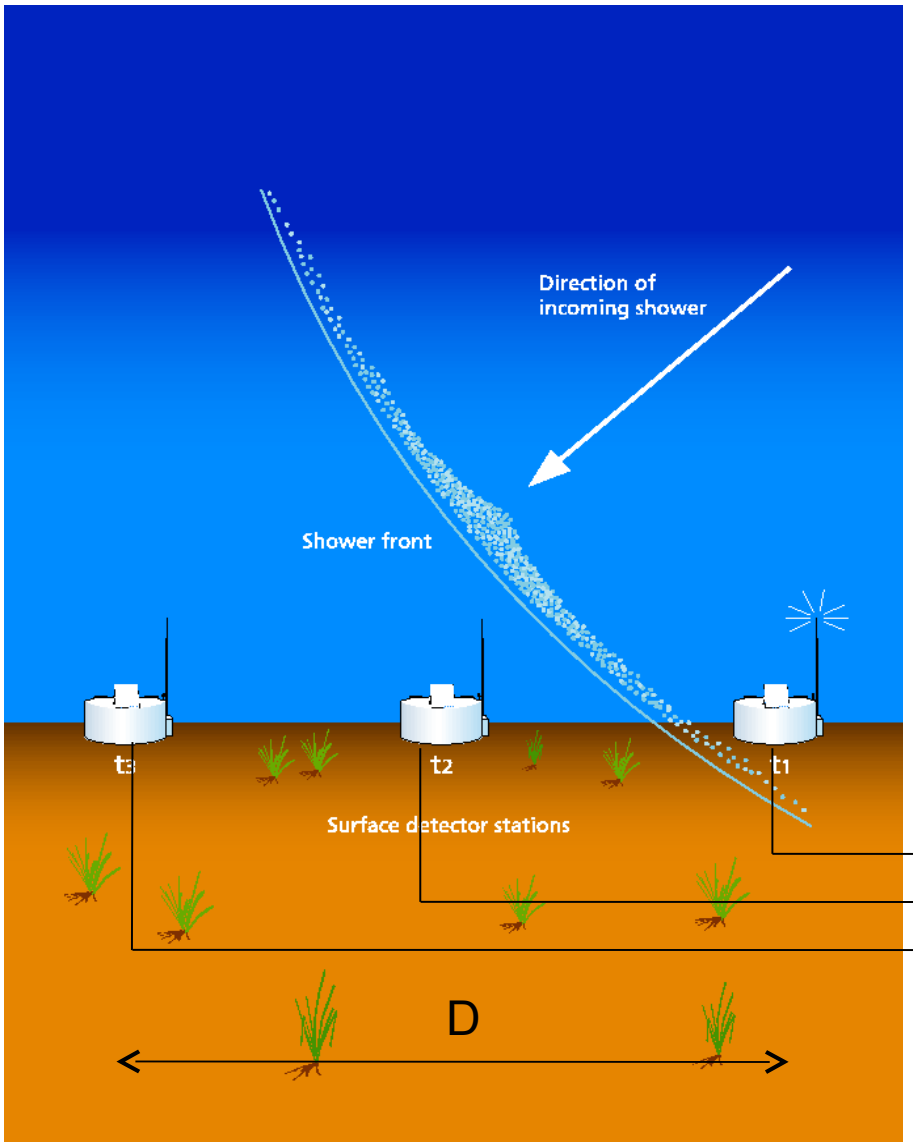

PIERRE
AUGER
OBSERVATORY
Malargue 2006…
Do you think
they need help?

SD physicists making friends




Cosmic Rays?????

Triggering on EAS

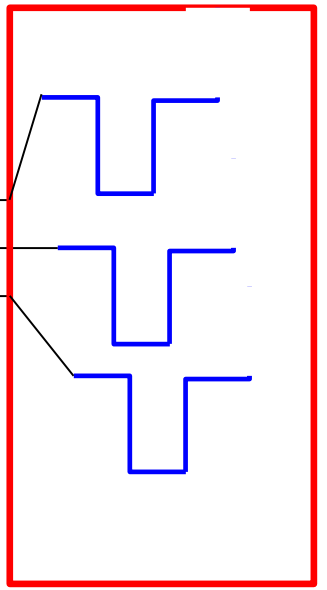


A cosmic ray shower will produce signals correlated in time in the different detectors.

$$c\,\Delta t = D \cos\theta$$

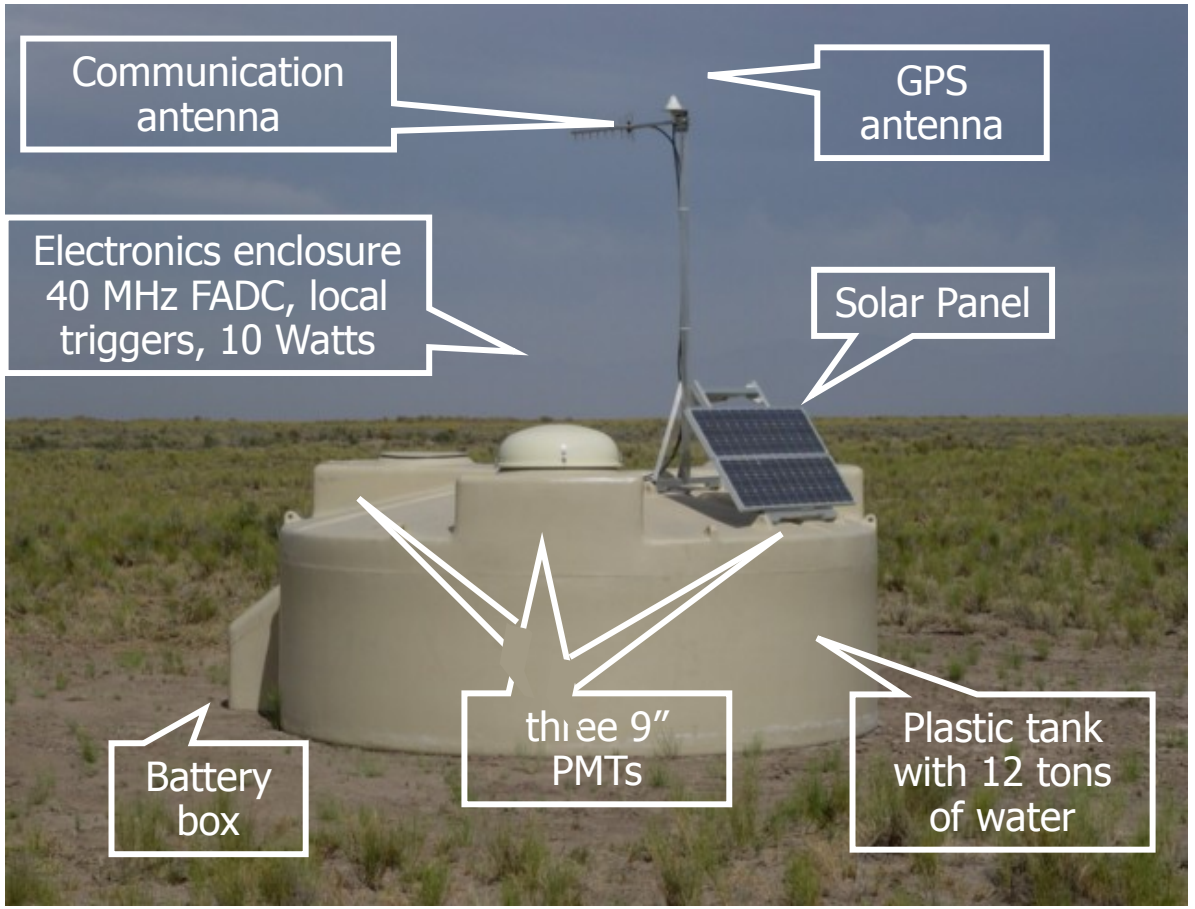
$$\Delta t \leq D / c$$

Ex: D=3 km, $\Delta t \leq 10\ \mu s$



Require a coincidence to record the event

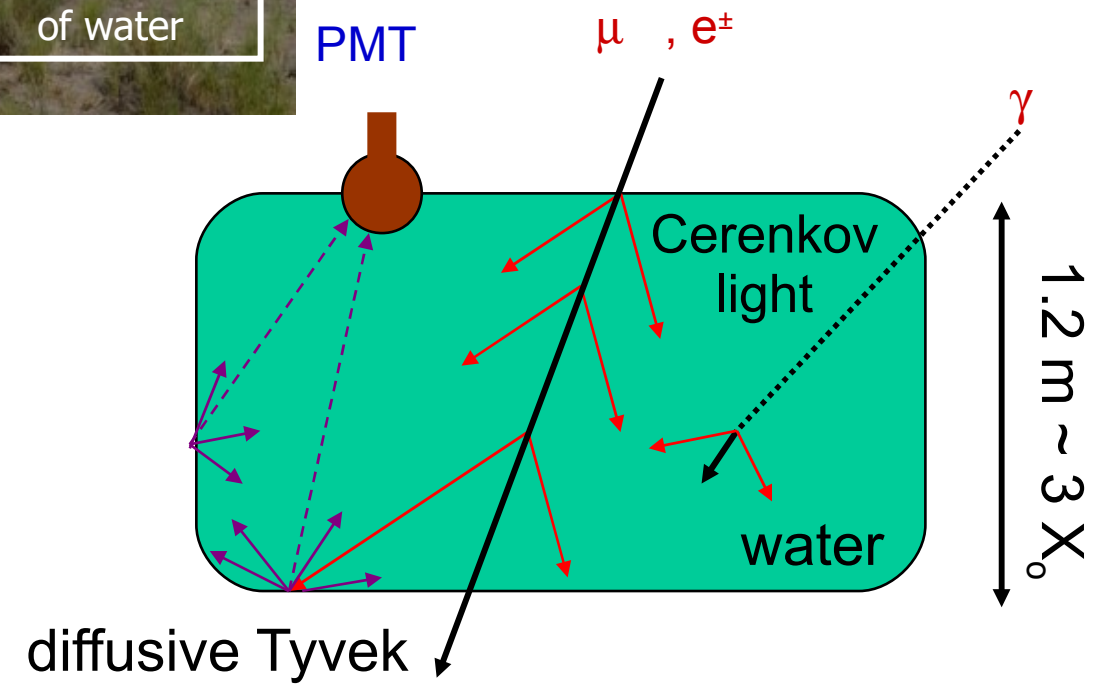
Auger is too big to use cables!



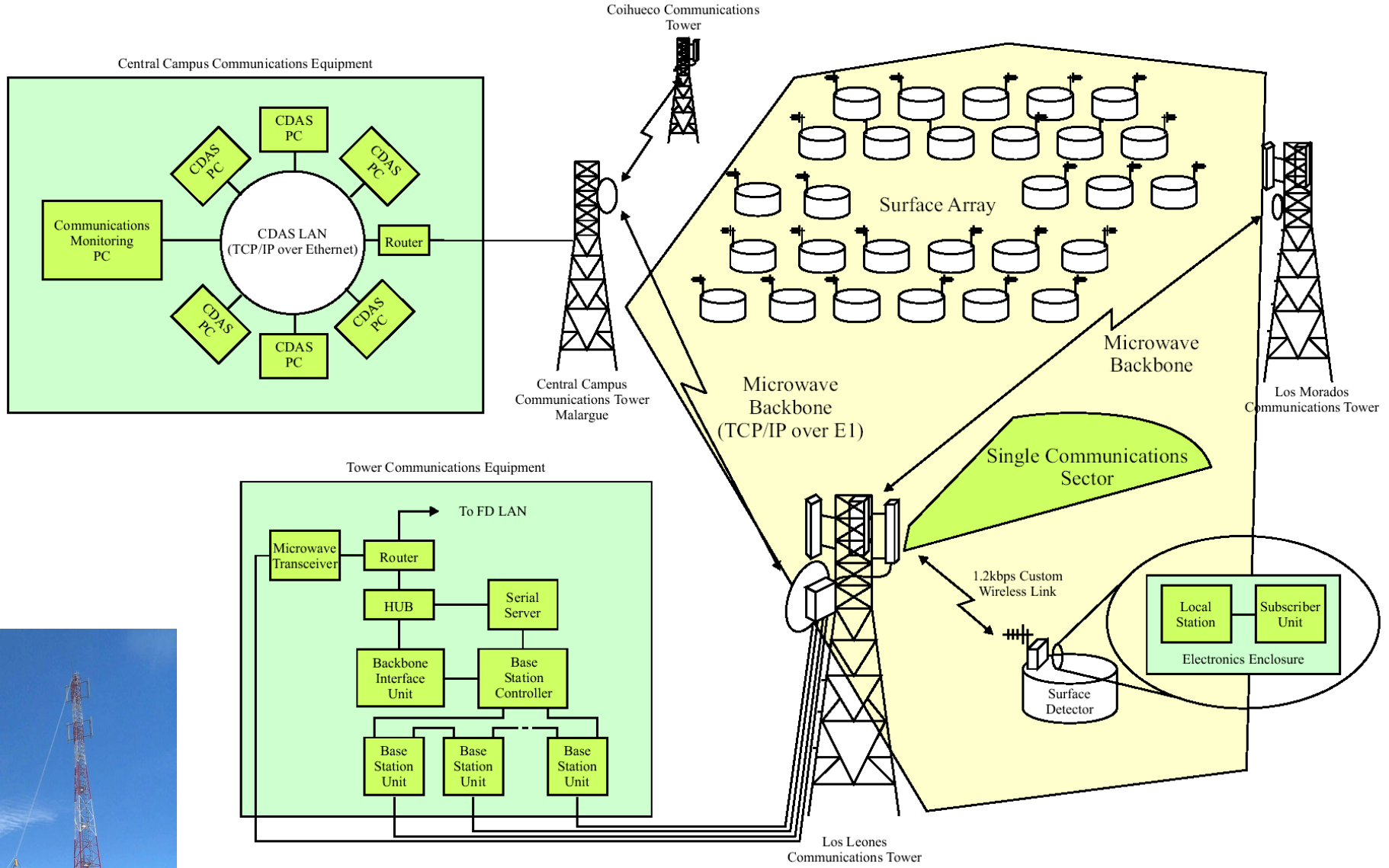
Auger Surface Detector

The tanks works like an "integrating sphere"

Time response for a single muon ~ 60 ns

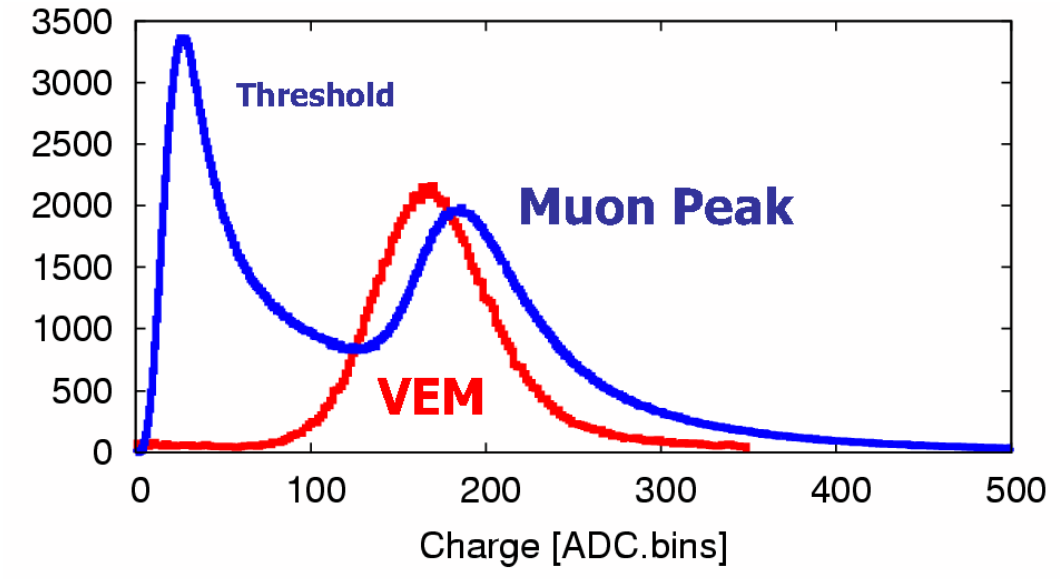


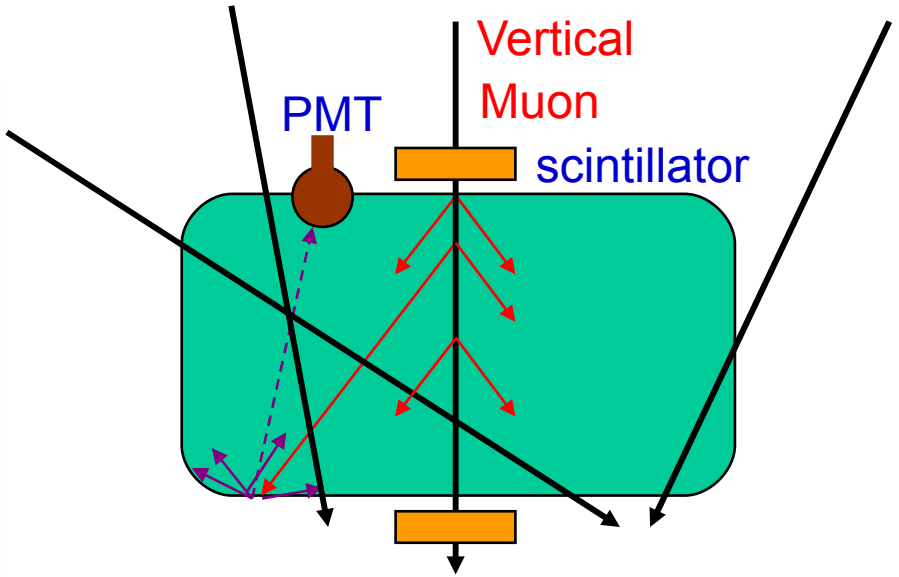
Telecommunications



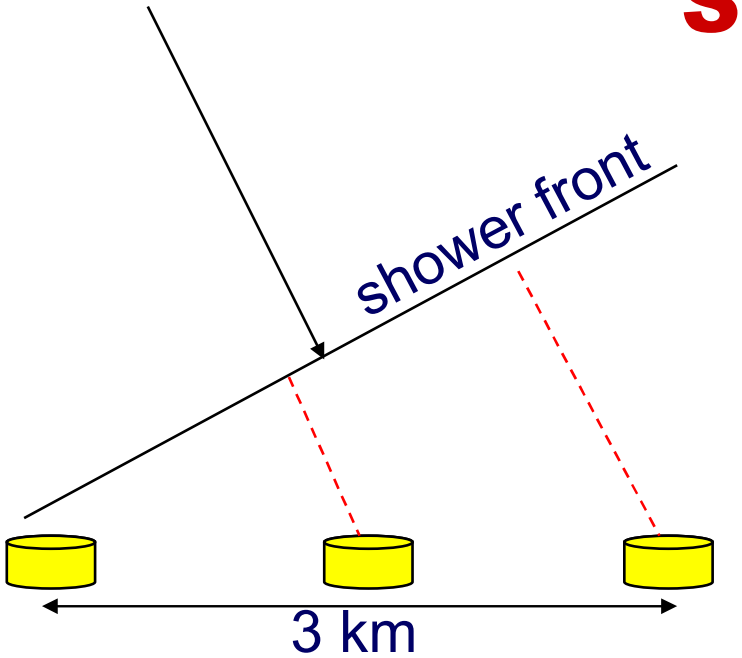
Signal calibration with background muons (online 2 kHz)

1 VEM ≈ 100 p.e.





Shower arrival direction



≈100 ns timing accuracy x c

↓

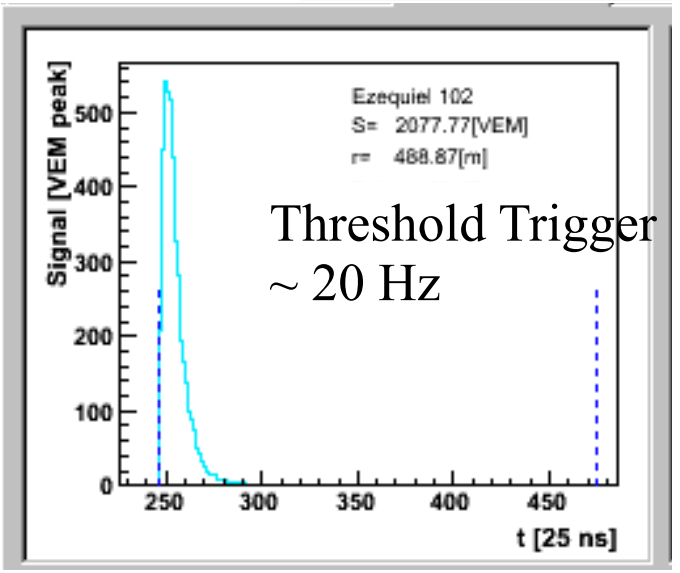
≈30 m

↓

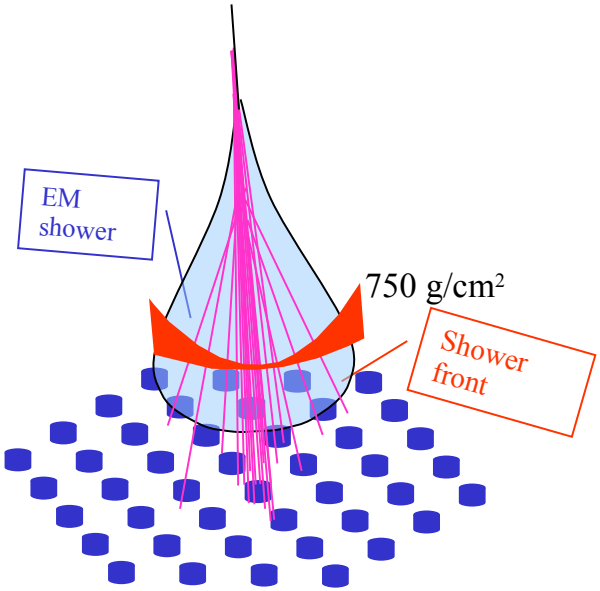
Δθ ≈ 30/3000 = 10 mrad ≈ 0.5°

AUGER SD in action ~ 70 EeV

Flash ADC traces

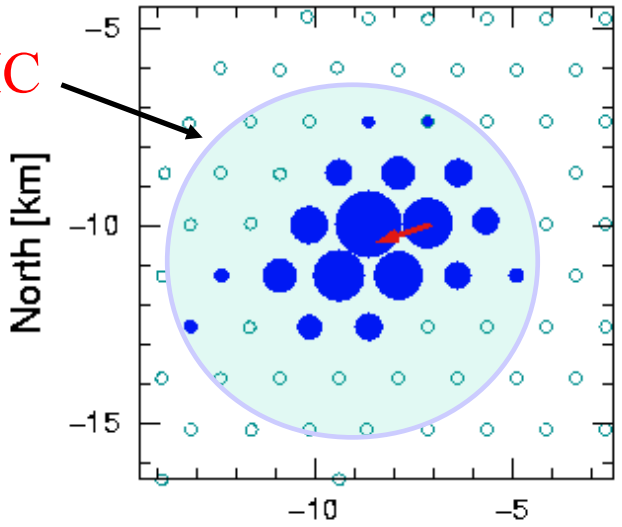


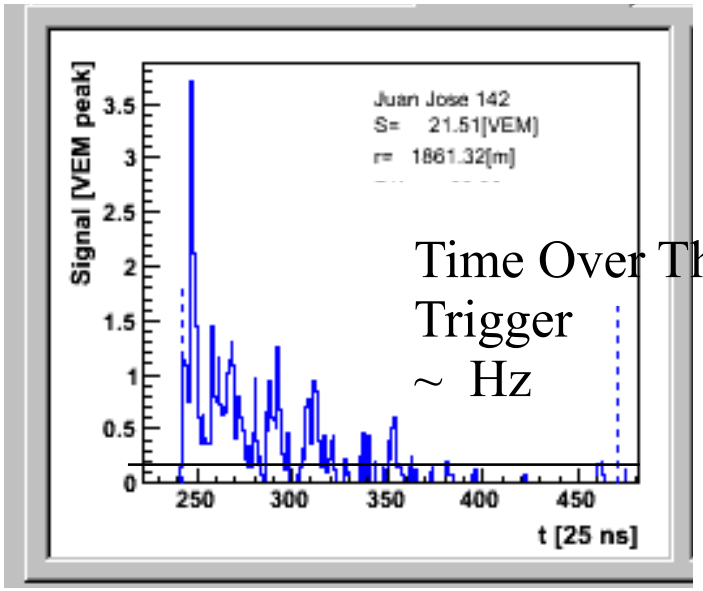
Threshold Trigger
~ 20 Hz



ID 762238

LHC



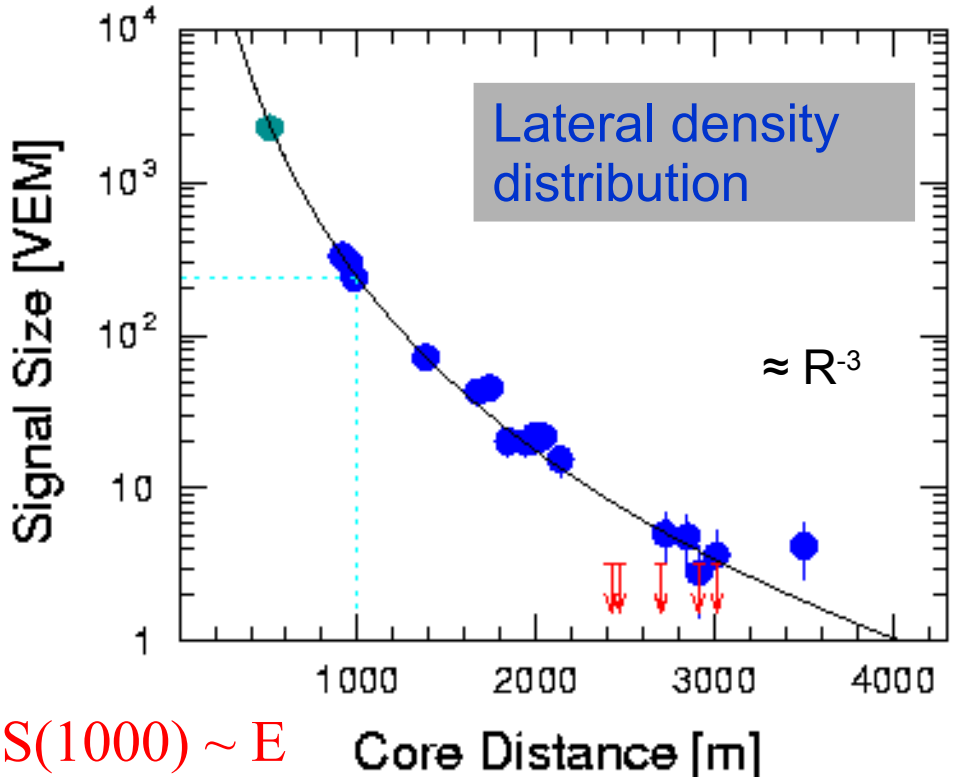


Time Over Threshold
Trigger
~ Hz

5 μ s

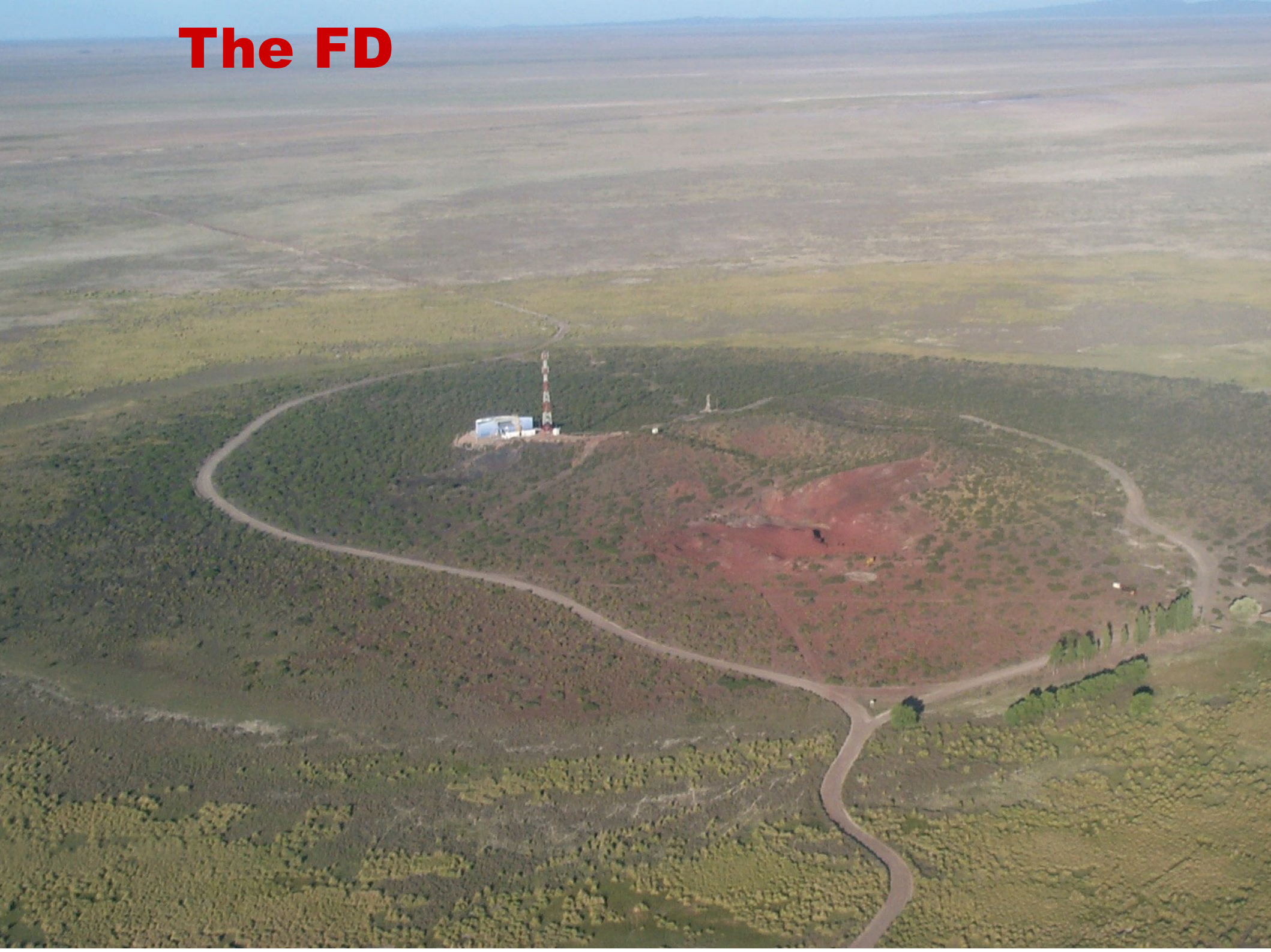
ID 762238

Lateral density distribution

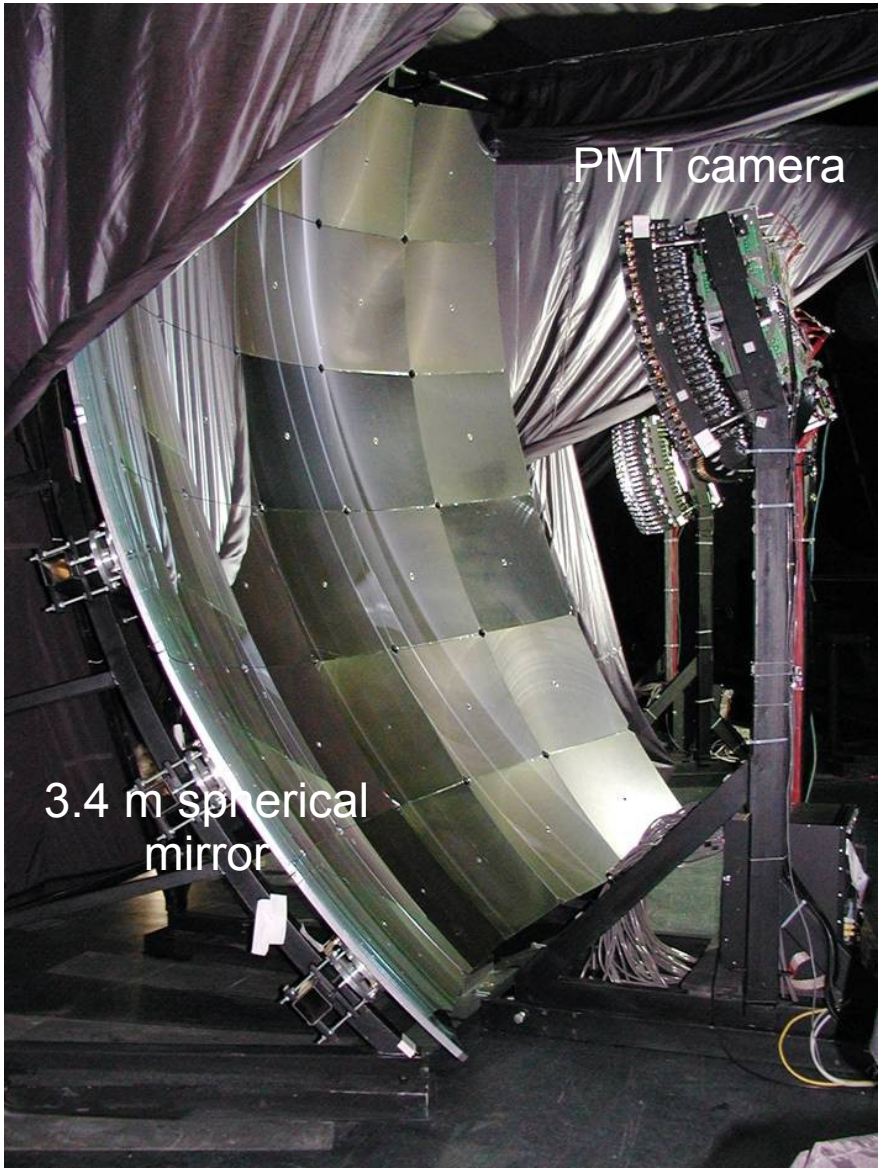


S(1000) ~ E

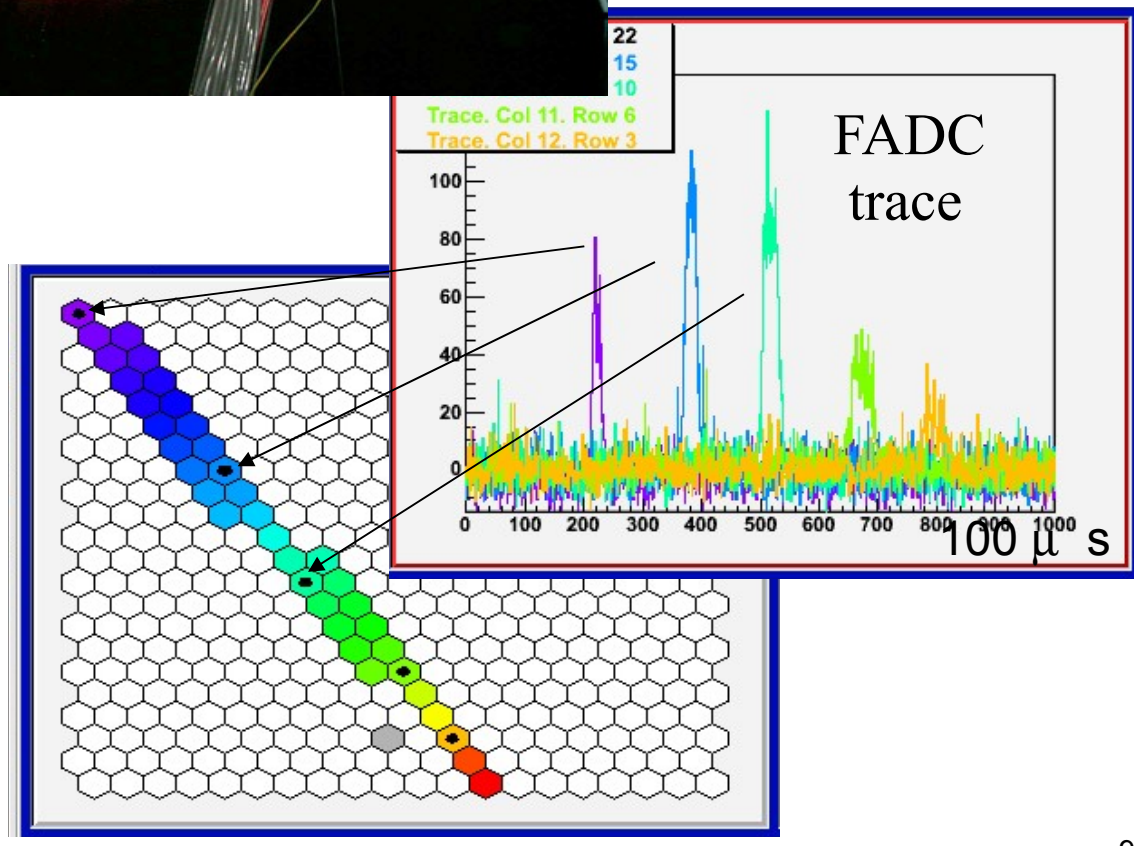
The FD



The FD

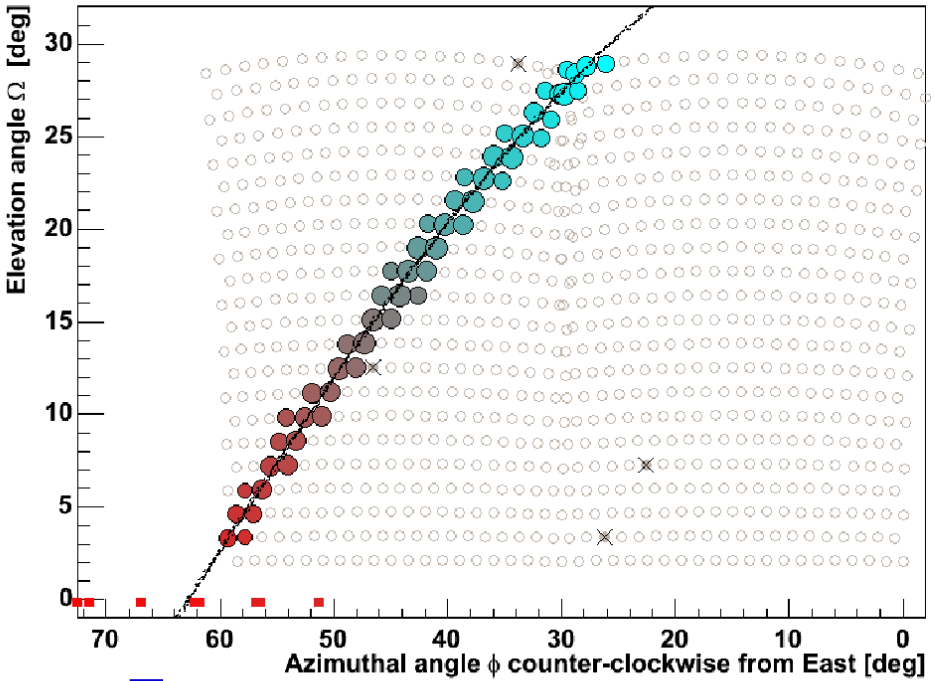


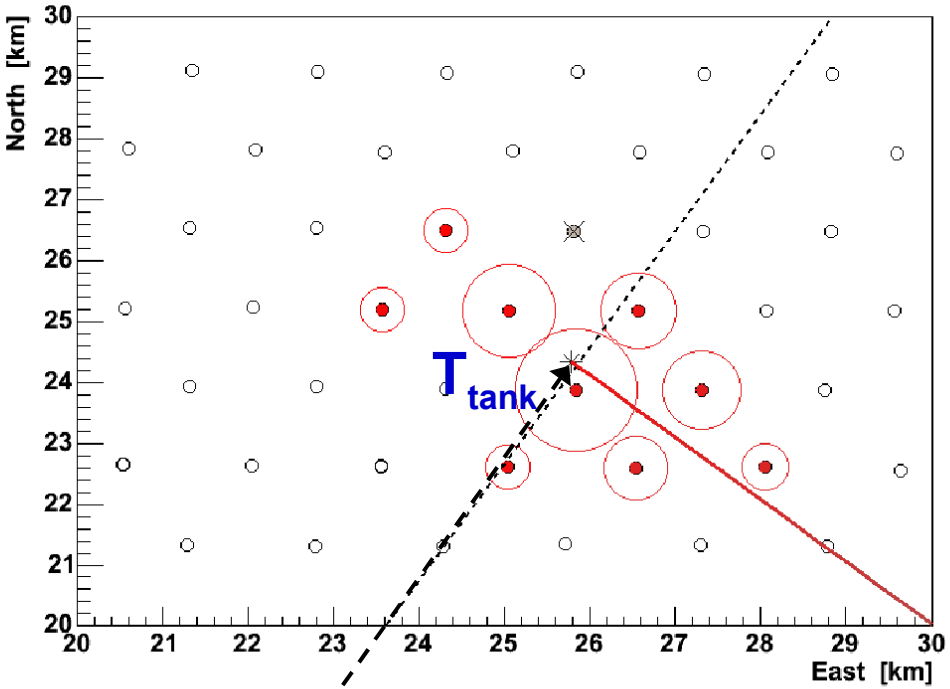
Spherical surface camera
440 PMT with light collectors
Large 30^0x30^0 field of view
1.5º pixel fov
(spot 1/3 of pixel)



The Auger Fluorescence Detector

Auger Hybrid Event

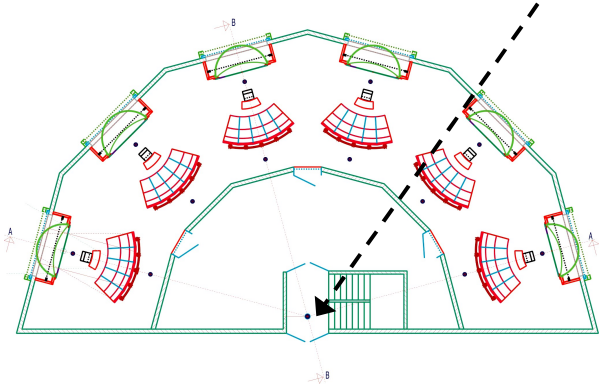




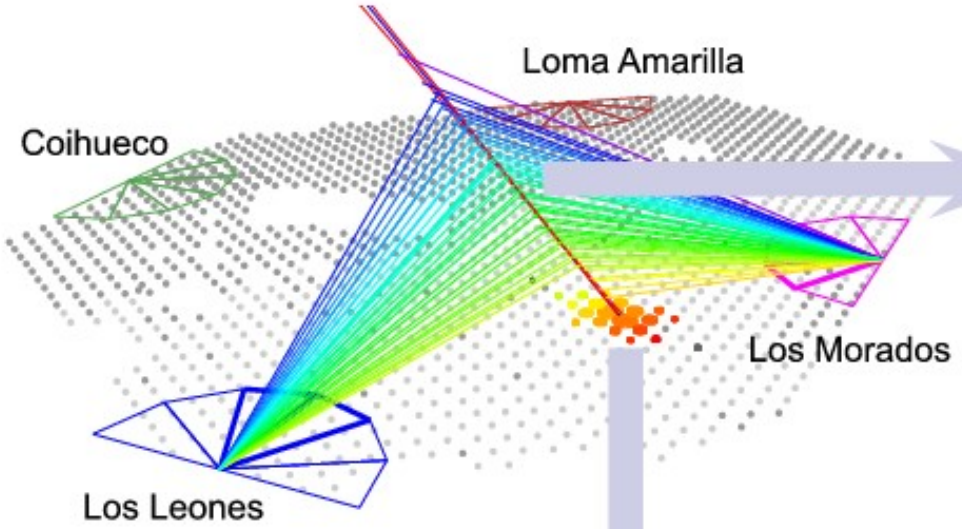
R_{tank}

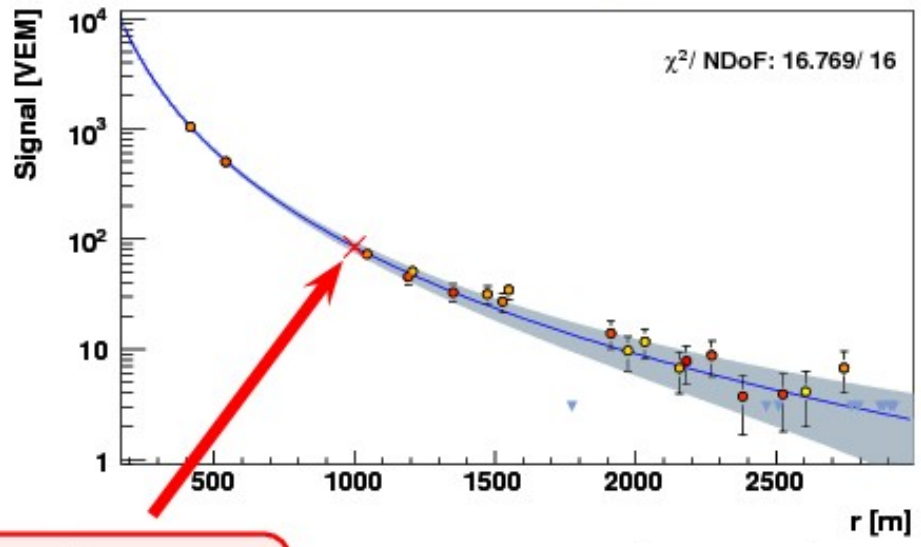
$T_{tank} + R_{tank} / c \approx T_{FD}$

Time coincidence over 40 km distance!



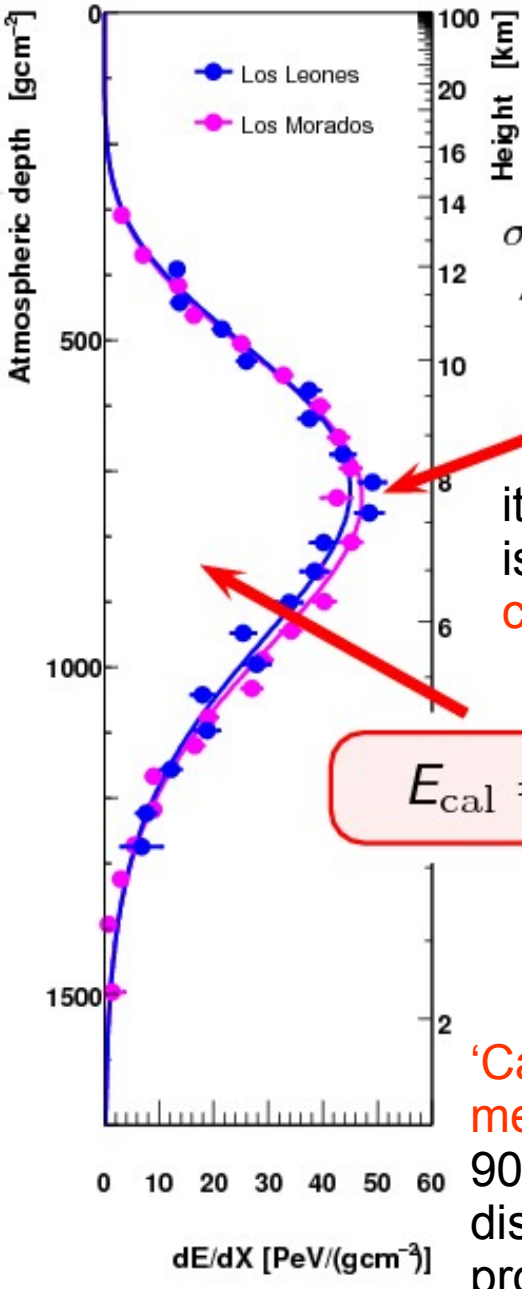
Auger 'hybrid' detector





S_{1000}

Calibrated by FD



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

$X_{\max}$

its mean and r.m.s. is sensitive to composition

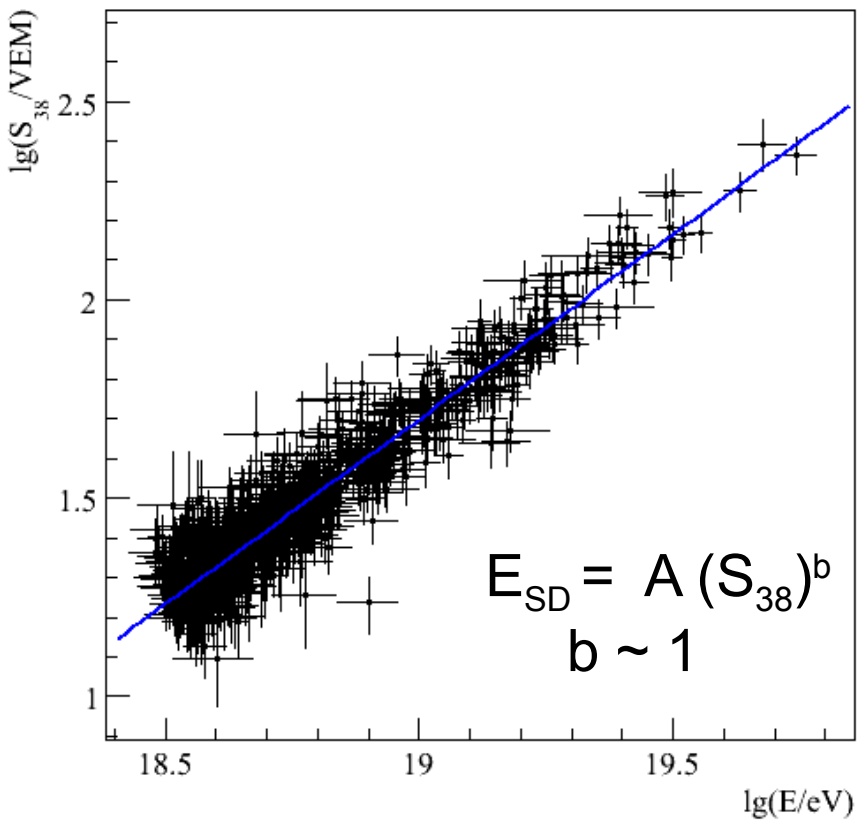
$$E_{\mathrm{cal}} = \int \mathrm{d}X \, \frac{\mathrm{d}E}{\mathrm{d}X}$$

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

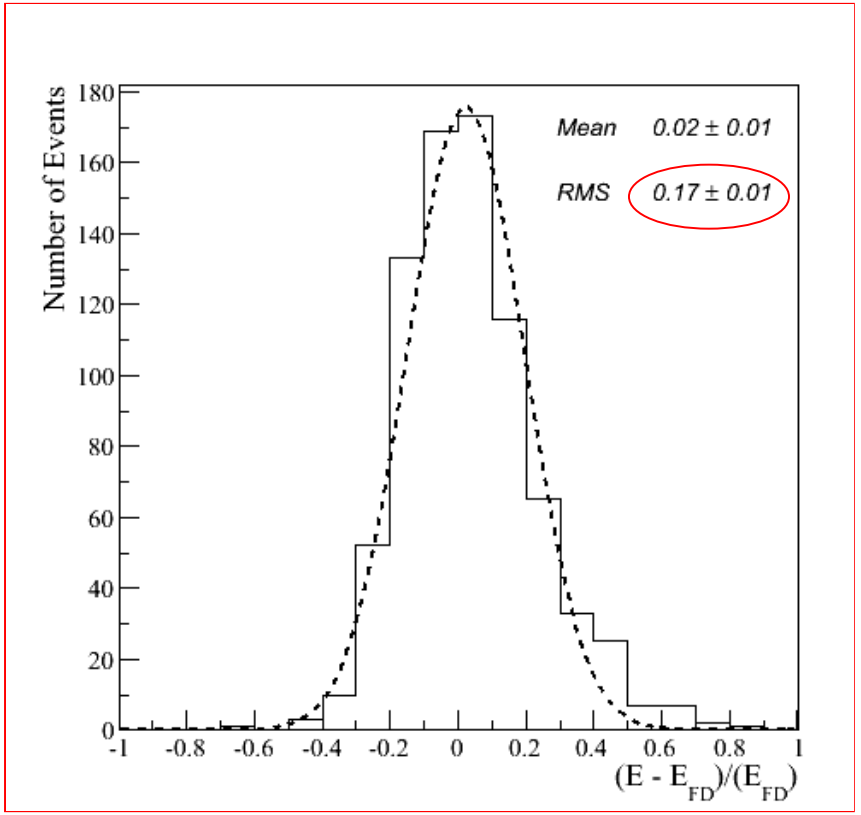
'Calorimetric' energy measurement, 90% of primary energy dissipated through e.m. processes (Air 25 X_0 15λ)

Auger 'hybrid' detector

SD



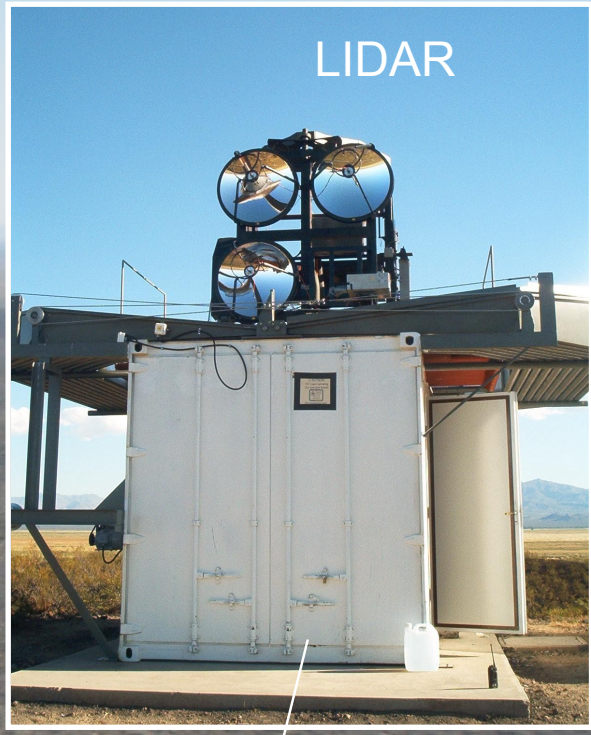
FD

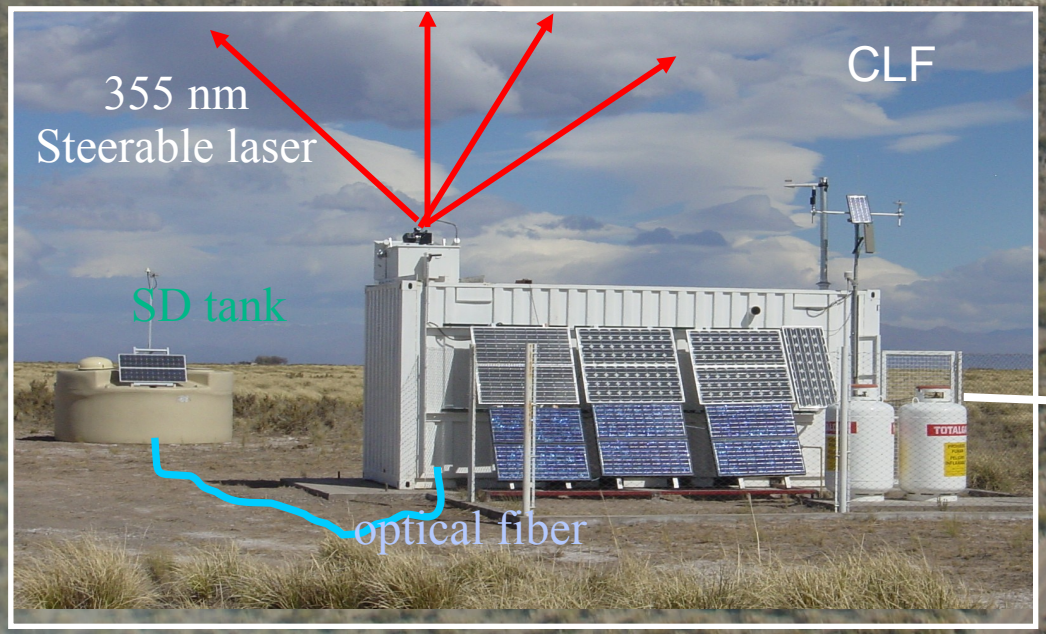


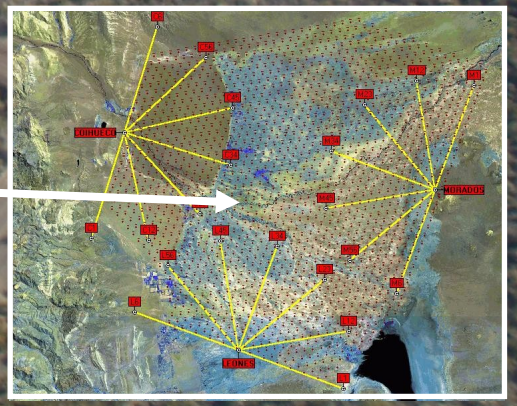
In previous array experiments (e.g. AGASA), the energy assignment was based on Monte Carlo simulations, with significant uncertainties (hadronic models tuned with Tevatron measurements must extrapolated several order of magnitudes for UHECR simulations!)

The Fluorescence detector calorimetric calibration is almost model independent.

Atmosphere and Calibration



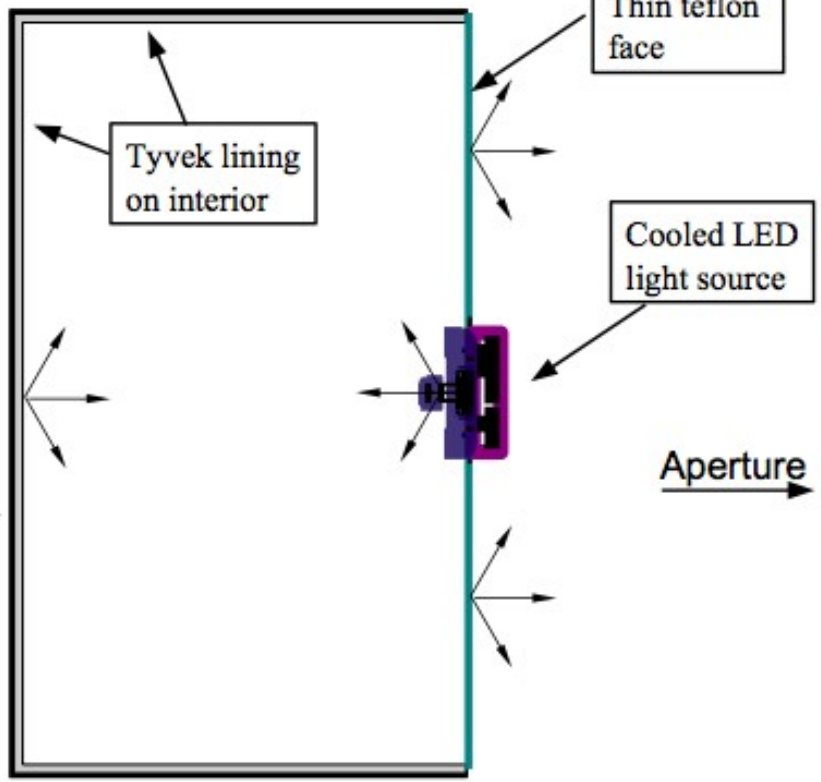




Optical calibration of fluorescence telescopes

Construction:
- 2.5m dia, uniform light source
- Hard outer shell
- Diffusively reflecting liner
- Diffusively transmitting face
- Diffuser covers LED

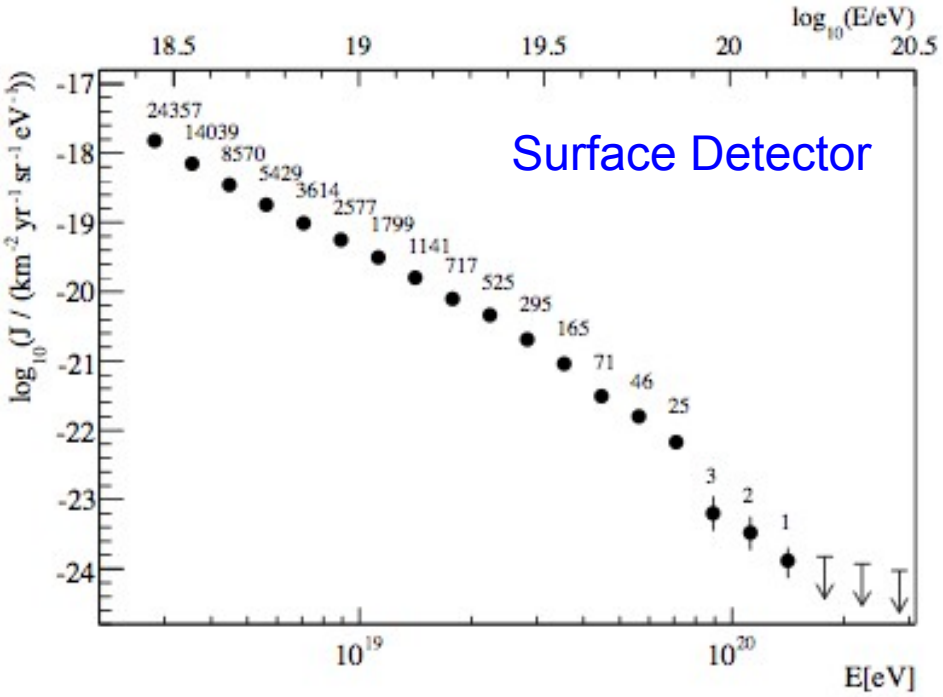
==> ~2% uniformity of illumination at output surface

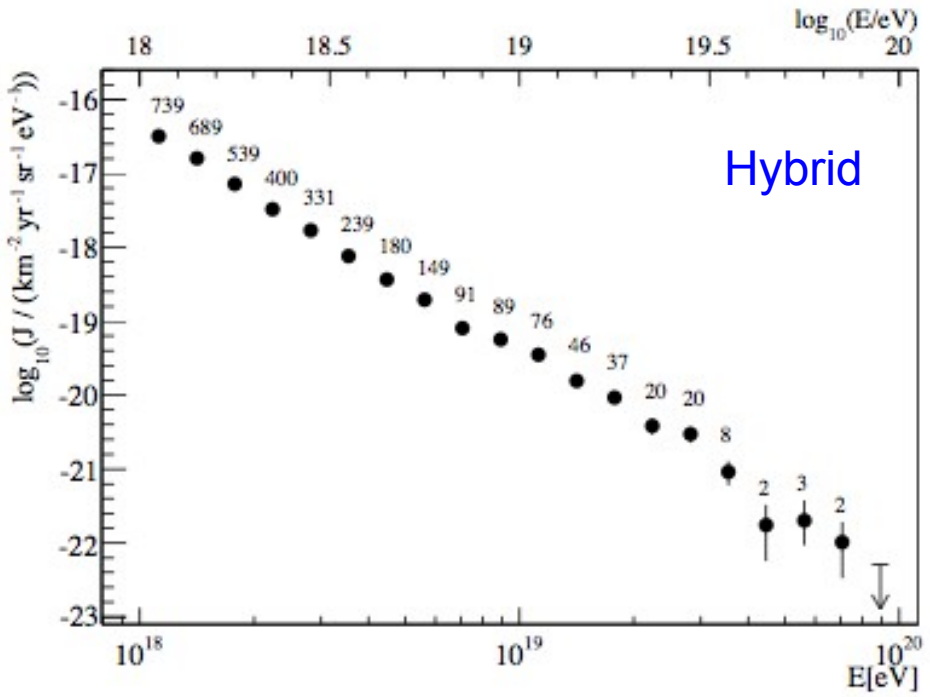


Auger Physics Results (a selection)

for International Cosmic Ray Conference
Bejing, China, August 2011

Auger Energy Spectrum





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

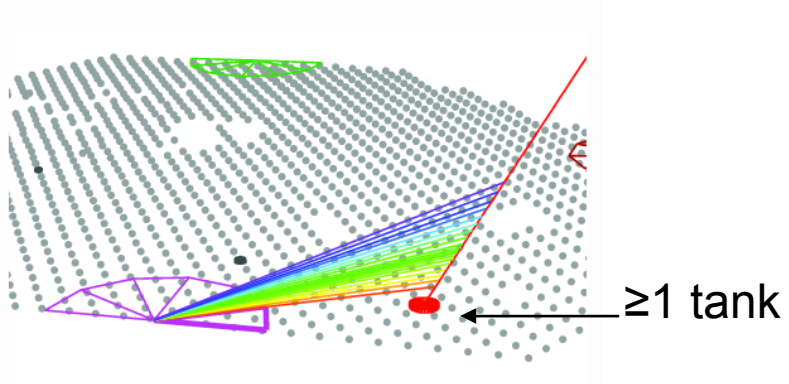
over the whole array

- lower statistics due to 12% duty cycle
- efficiency function of shower's distance, atmospheric conditions, etc.

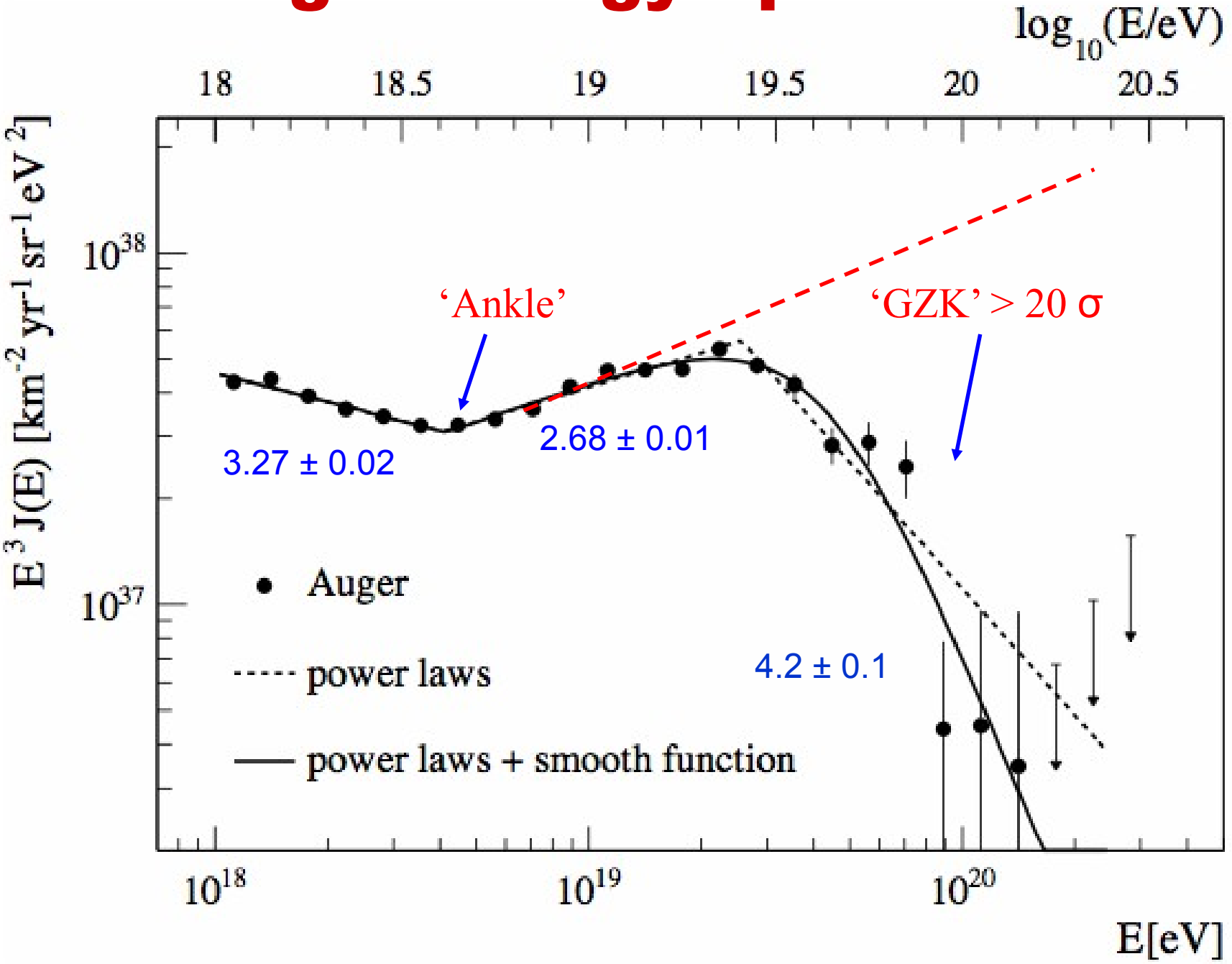
Complex analysis

- measurement down to 1· 10^{18} eV

Surface and Hybrid spectra consistent within uncertainties

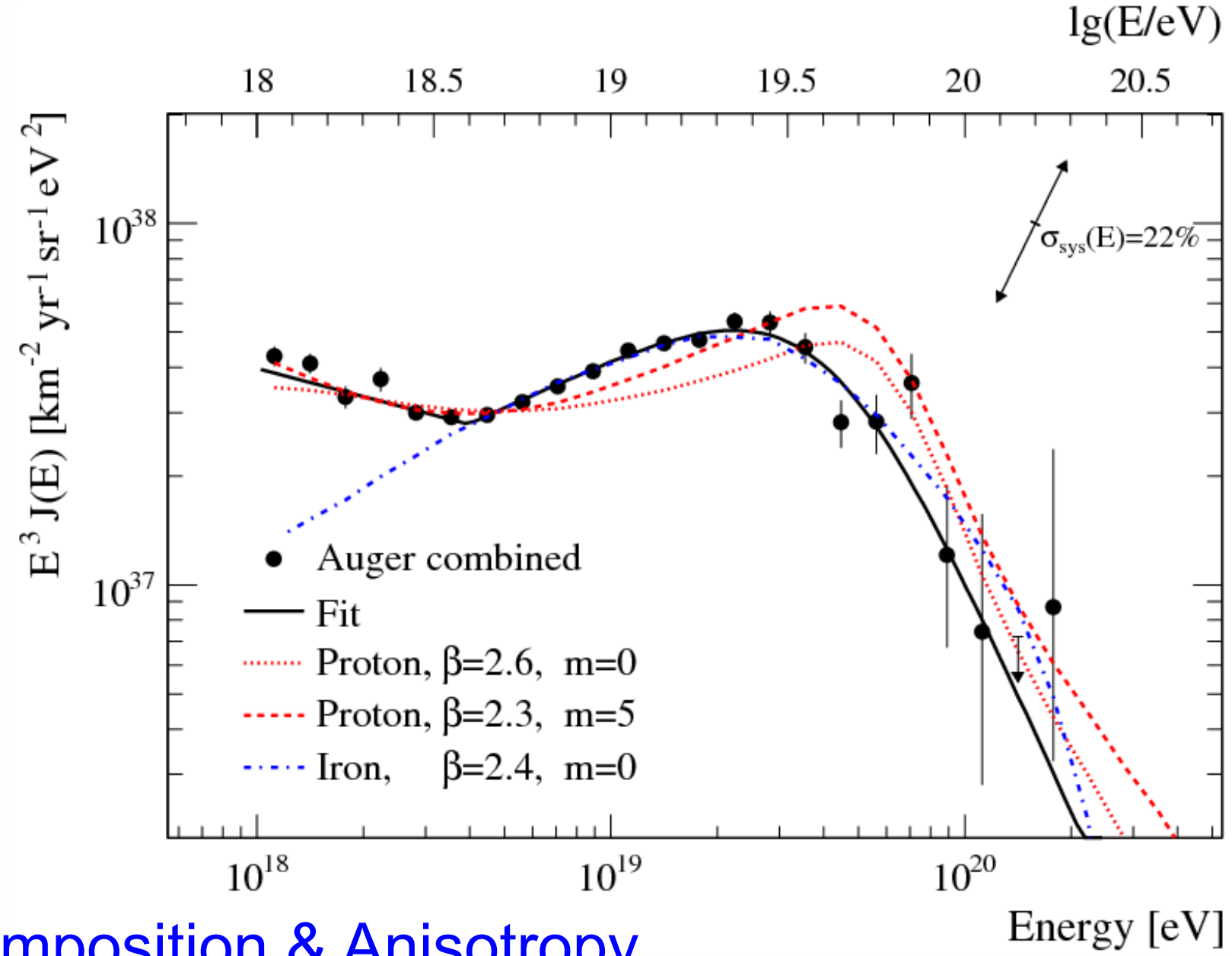


Auger Energy Spectrum



≈ 5000 events above 10^{19} eV, only 3 above 10^{20}eV

Astrophysics with 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

AGN < 71 Mpc
(VC catalogue)

Shading level:
exposure

Cen A

30

0

−30

120

−120

Super Galactic Plane

Prob. chance correlation =21%

circles of 3.1° radius centered at UHECR arrival direction

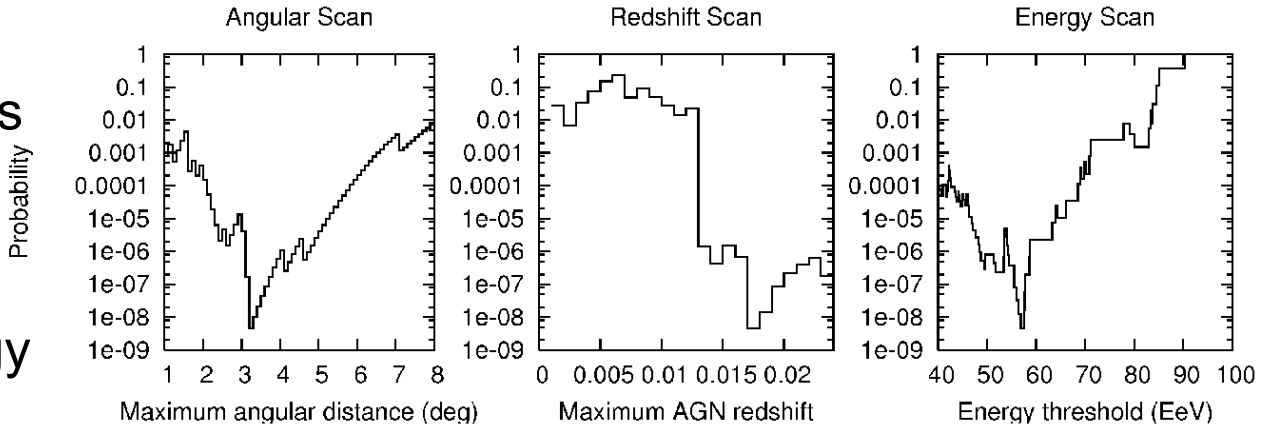
27 events E> 5.7· 10^{19} eV

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

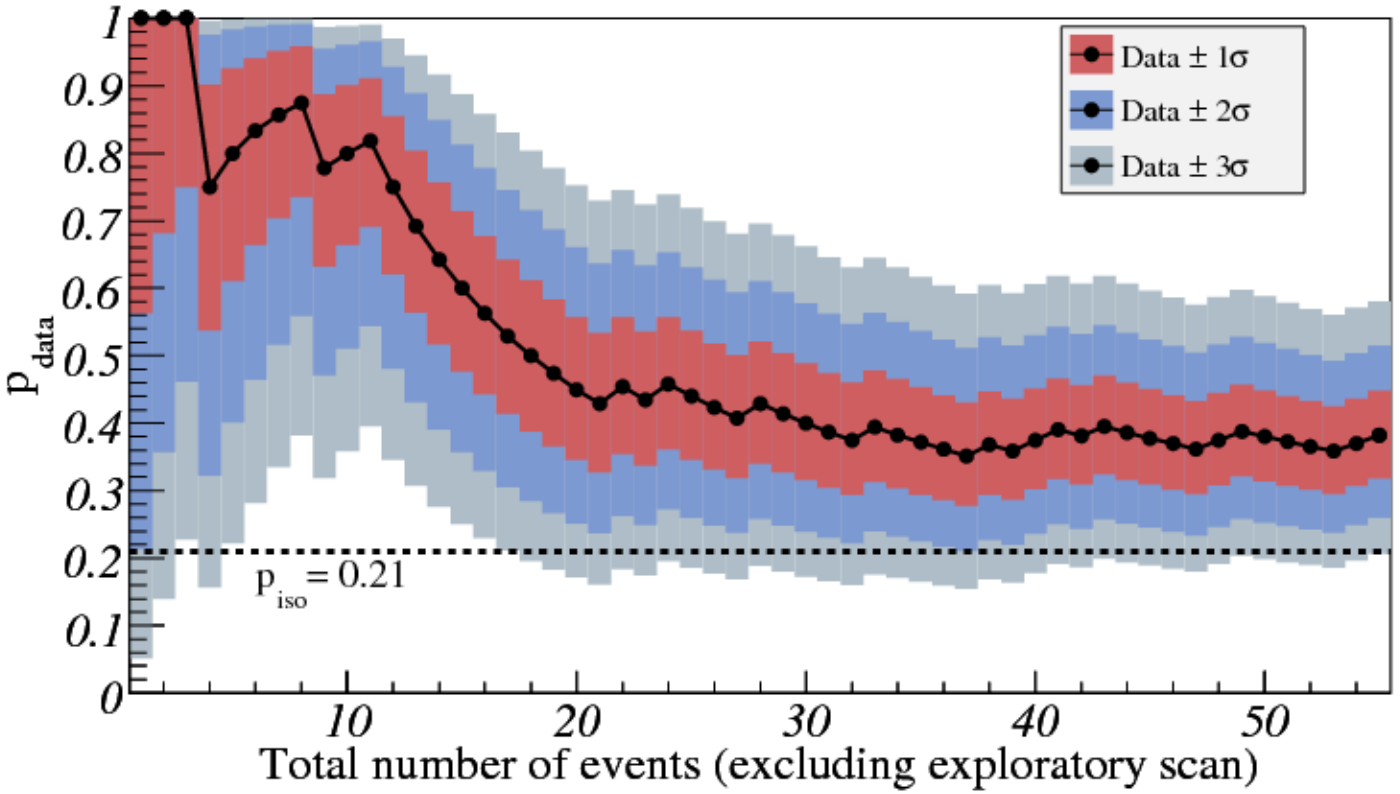
Difficult to estimate probability, thus confirmation required with an independent data set.

Prescription

8/13 events found to correlate, P = $1.7 \cdot 10^{-3}$

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

Update on anisotropy



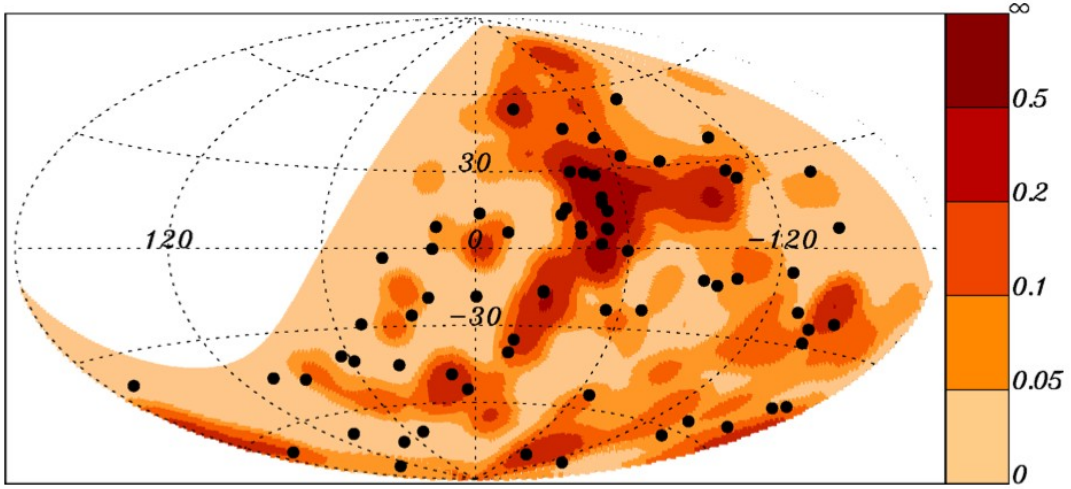
- Isotropy of UHECR rejected at 99% CL
- Correlation reduced from ~70% to ~40%

- ~~experimental~~
- nature
- catalogue

69 events E> 5.5· 10^{19} eV (≈30/year)

Auger UHECR anisotropy

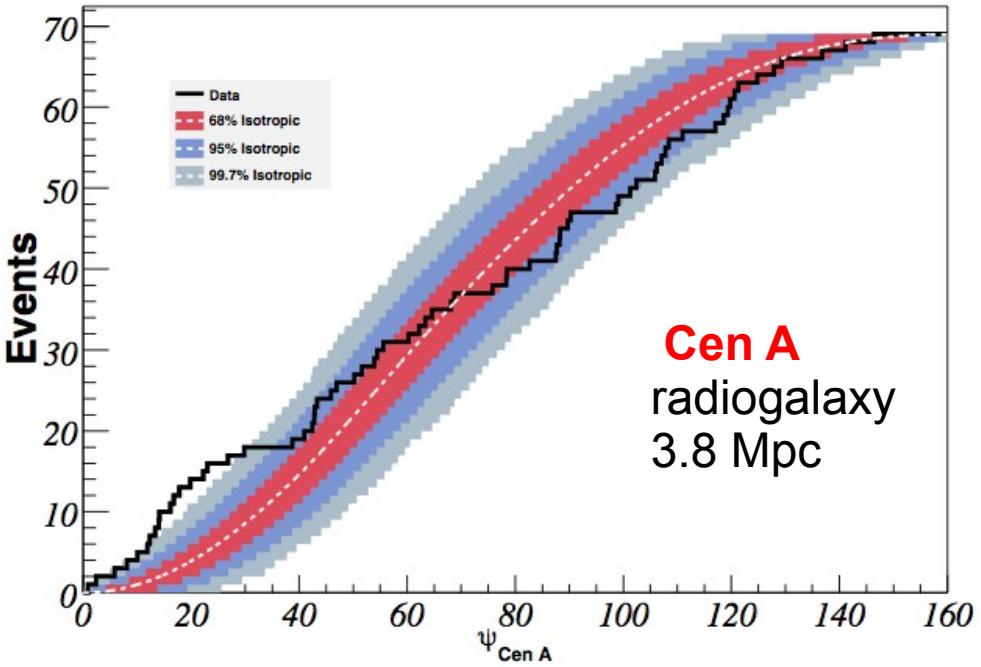
Swift-BAT catalog X-ray AGN < 200 Mpc



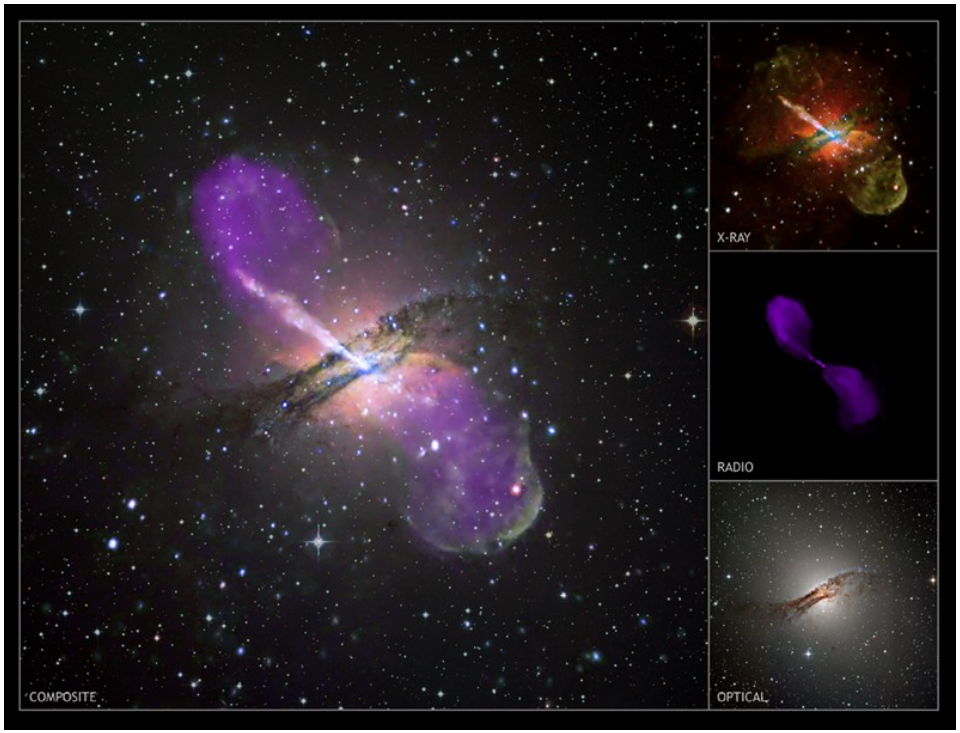
- A posteriori study of correlation with AGN and matter distribution

  Correlation ~40%

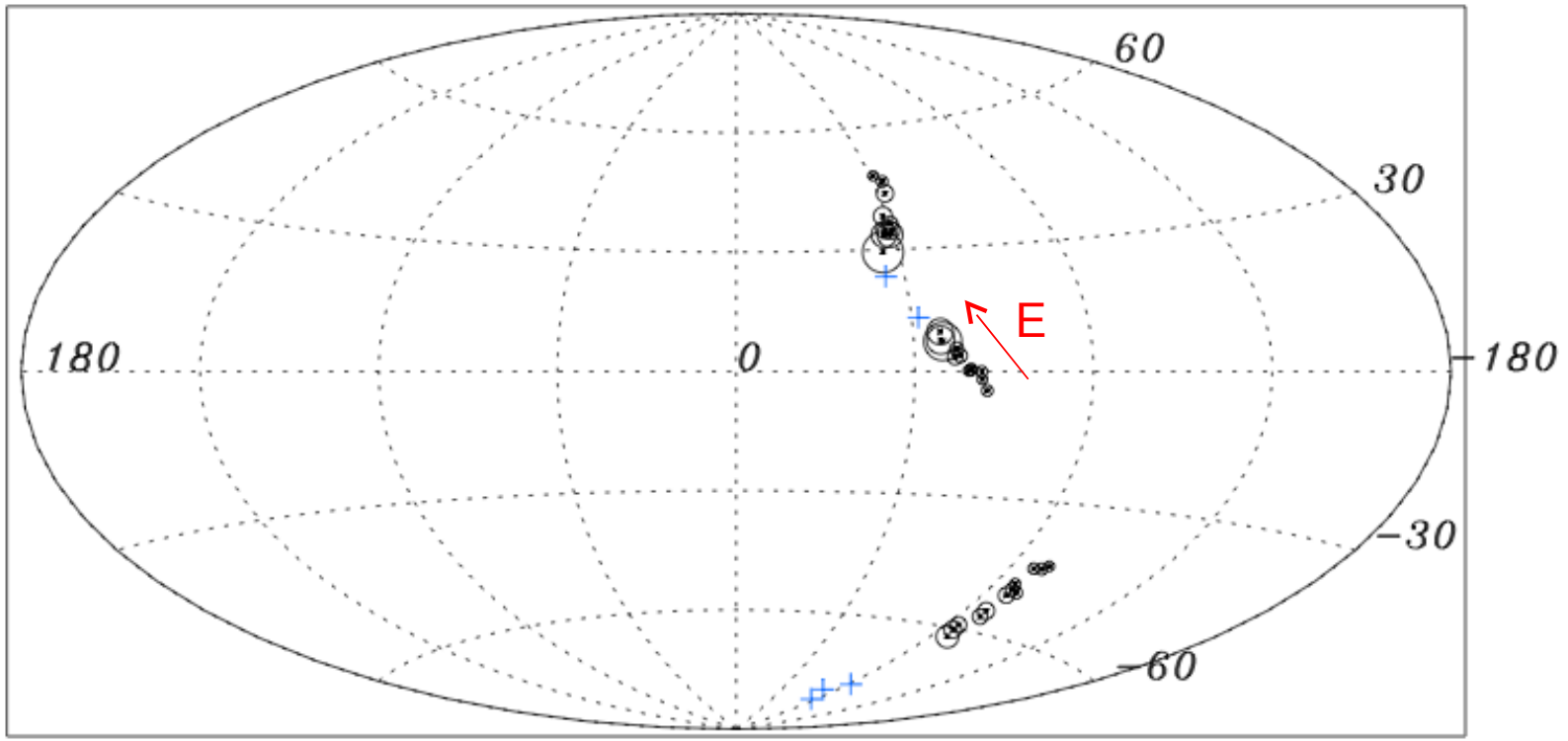
- Hints of accumulation from Cen A, the closest AGN (only 3.8 Mpc)



Cen A
radiogalaxy
3.8 Mpc



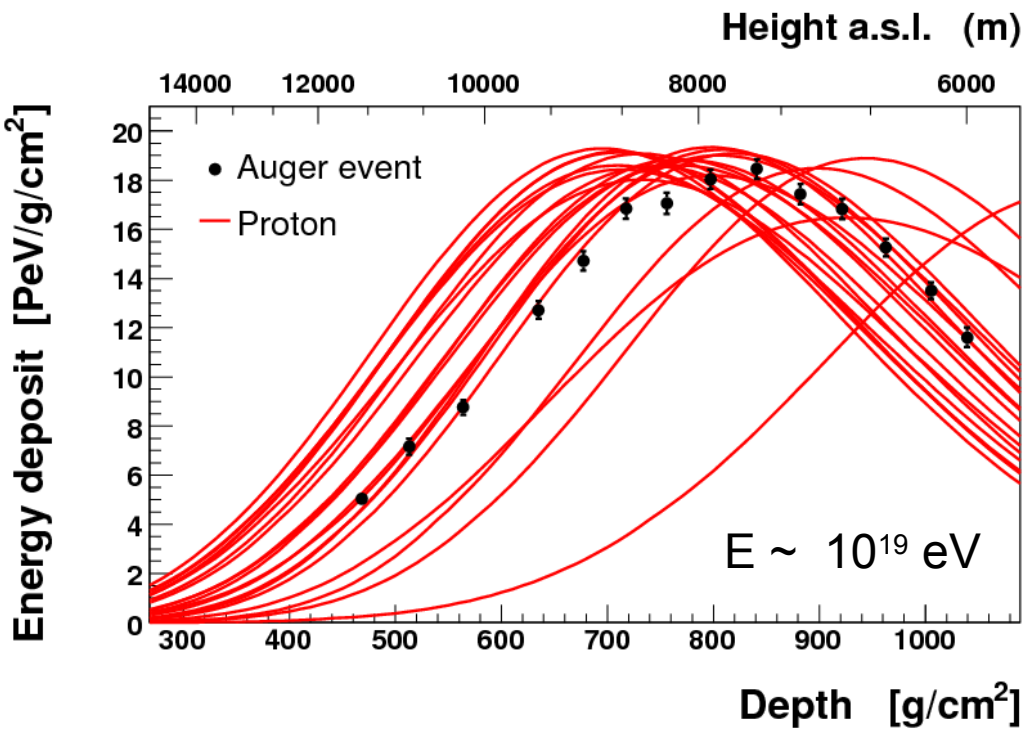
A search for UHECR multiplets

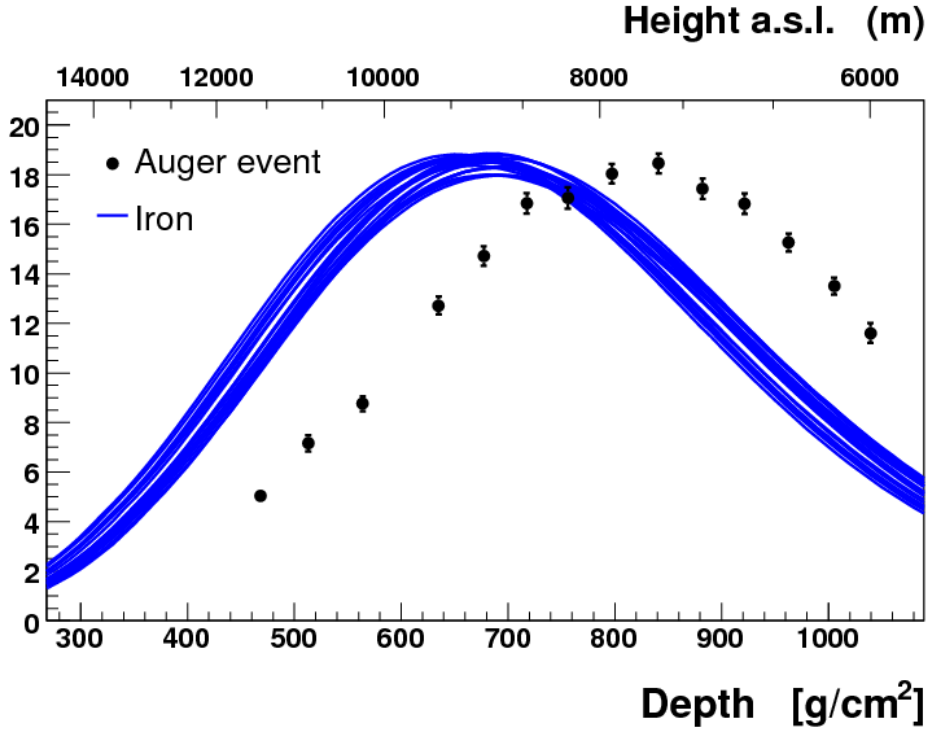


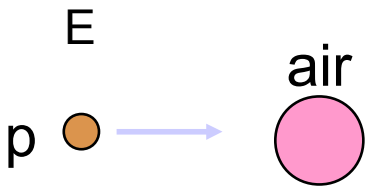
- Magnetic field as a spectrometer! Search for energy-angular deviation ordered clusters of events

- So far compatible with expectations from isotropic background

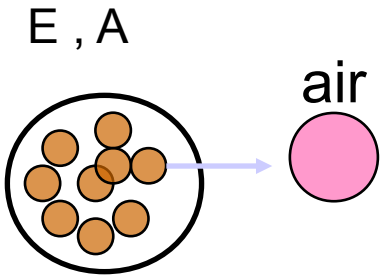
UHECR Composition







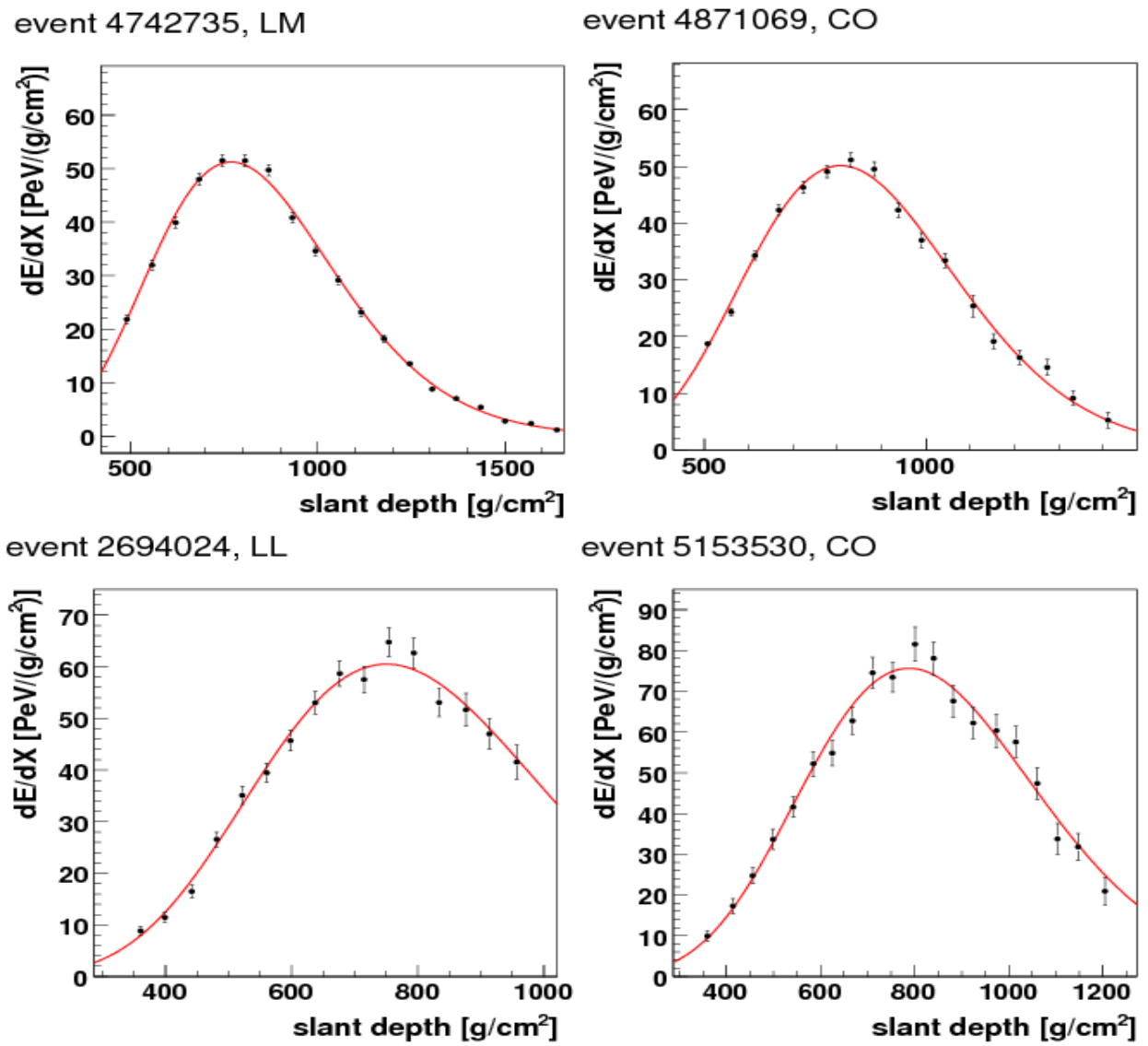
$X_{max} \sim \ln(E)$



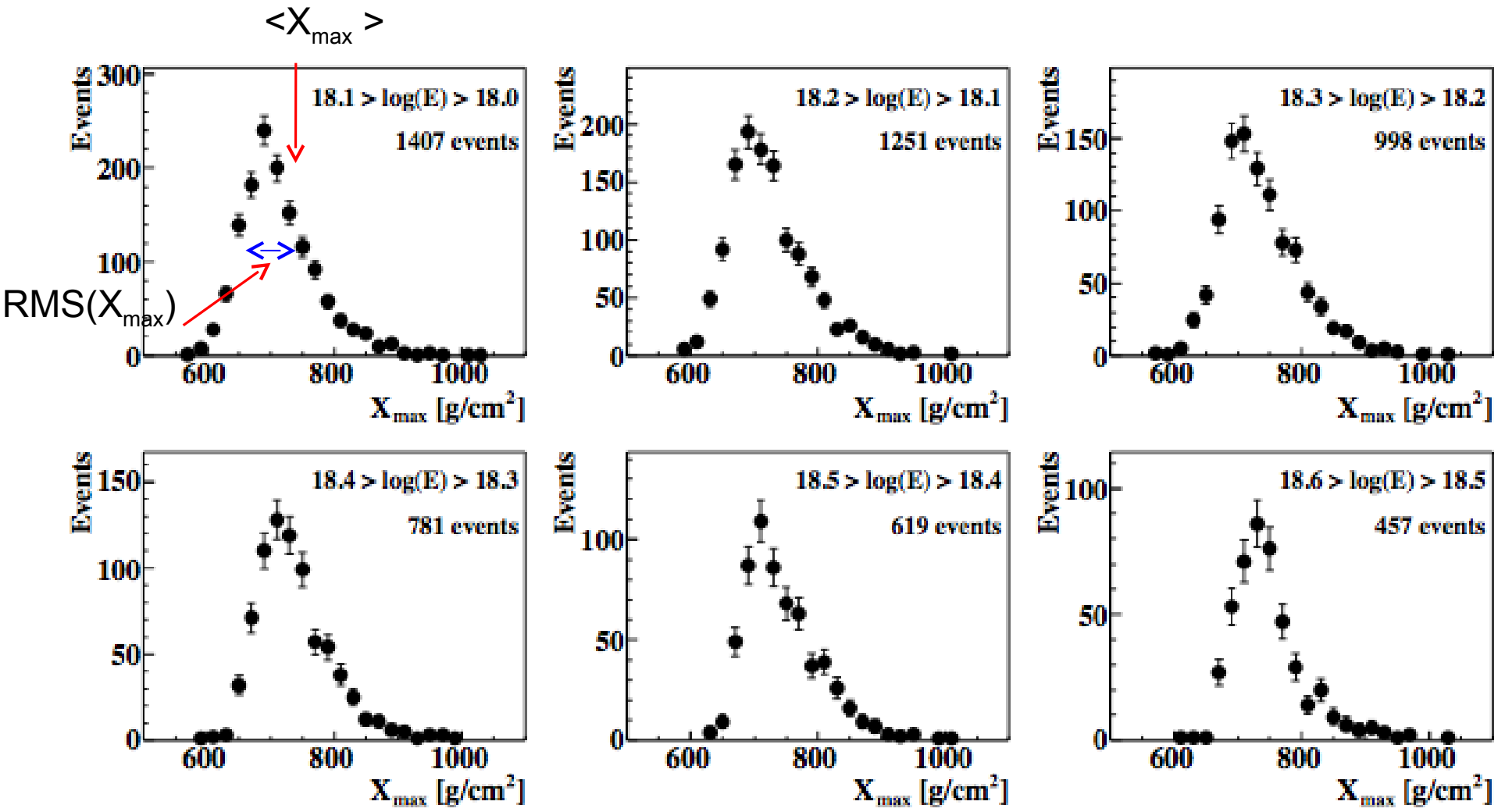
$X_{max} \sim \ln(E/A)$

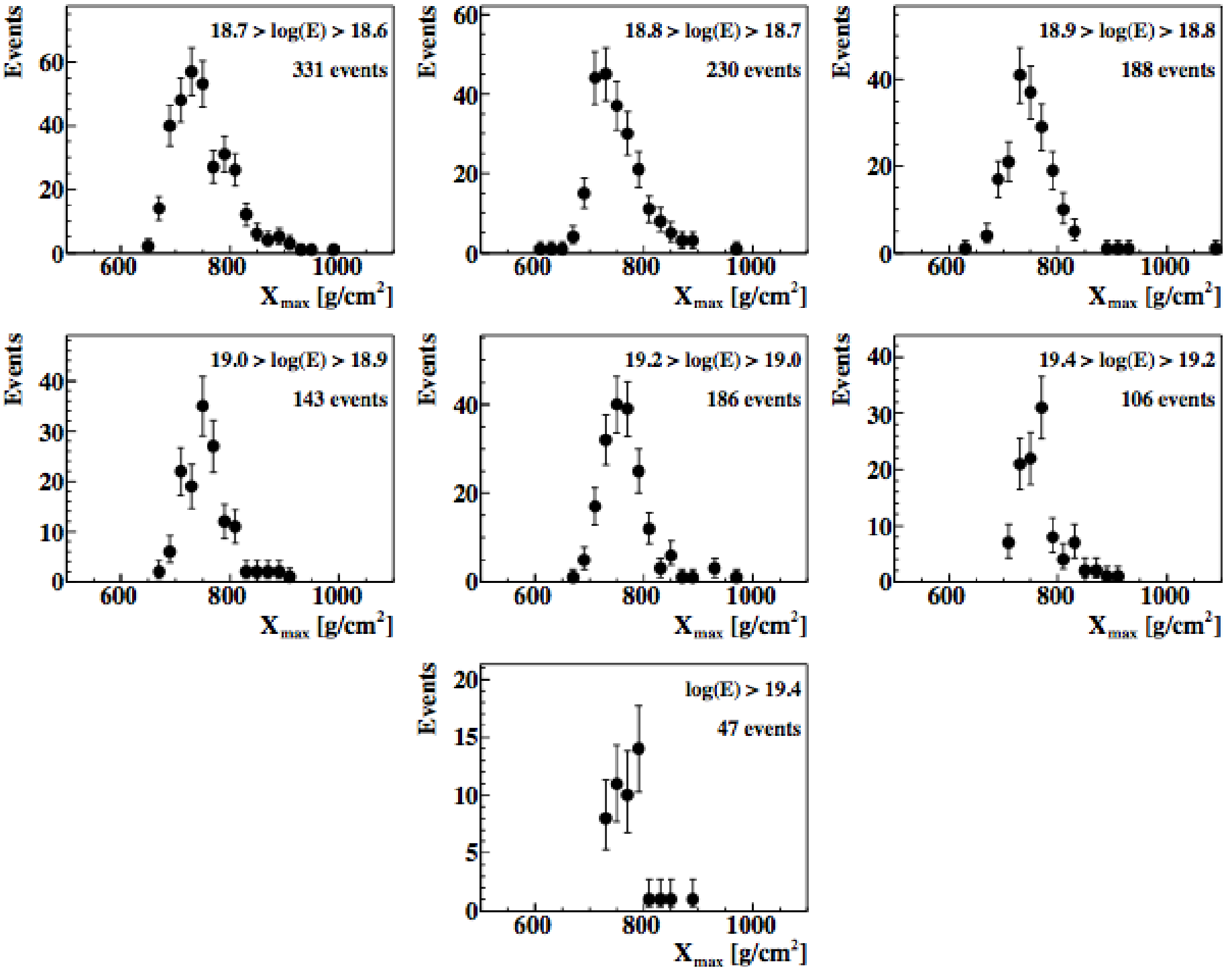
mean X_{max} and RMS(X_{max}) are sensitive to composition

Examples of X_{max} measurements

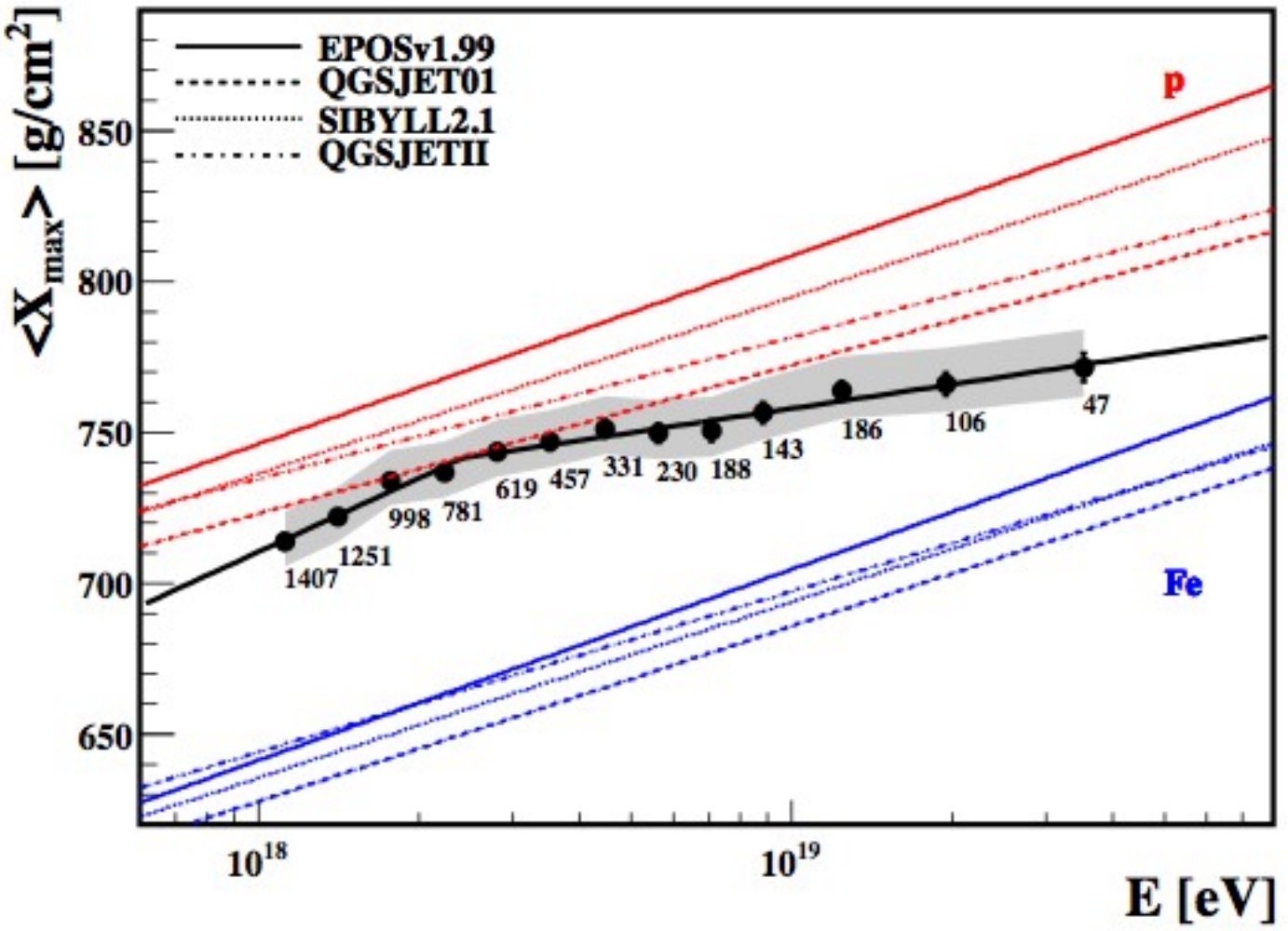


Auger X_{max} measurements




18.7 > log(E) > 18.6
331 events
18.8 > log(E) > 18.7
230 events
18.9 > log(E) > 18.8
188 events
19.0 > log(E) > 18.9
143 events
19.2 > log(E) > 19.0
186 events
19.4 > log(E) > 19.2
106 events
log(E) > 19.4
47 events
Events
X_max [g/cm^2]

$< X_{max} >$ measurements



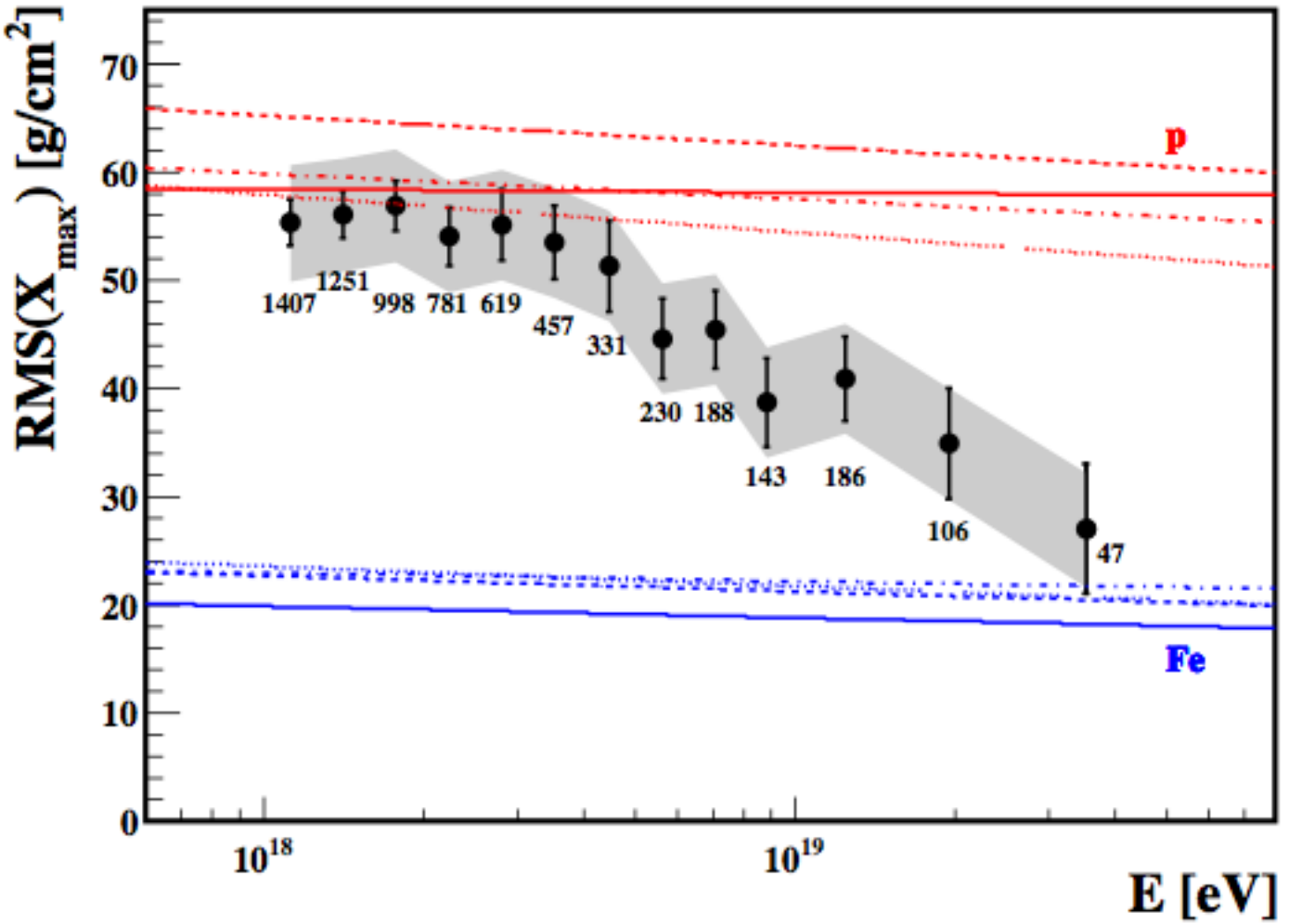
$X_{max} \sim \ln(E)$

$X_{max} \sim \ln(E/A)$

Data show a change of slope, towards heavier composition

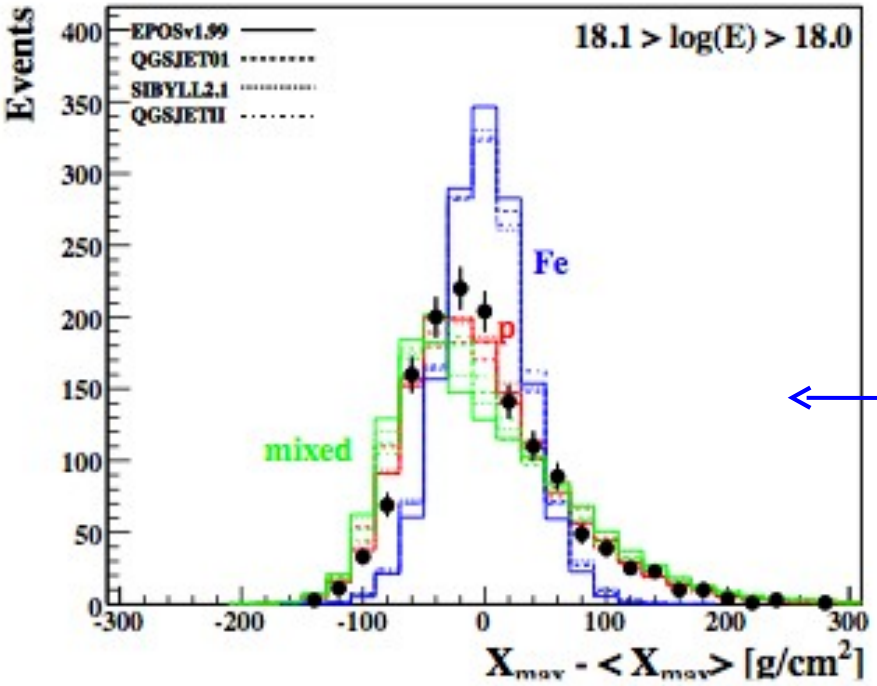
Large uncertainties in the hadronic models predictions

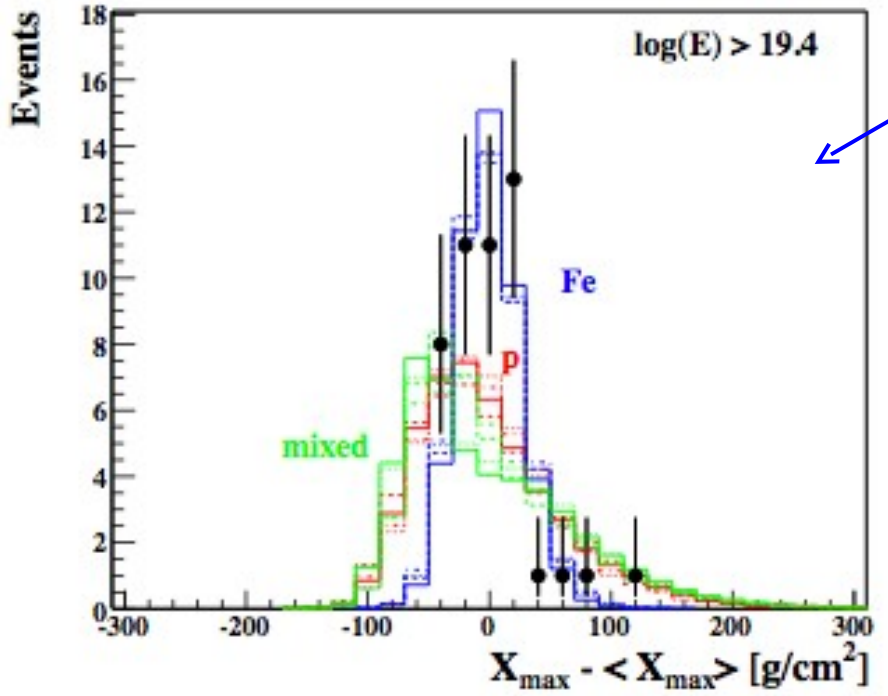
RMS(X_{max}) measurements



idem

X_{max} shape



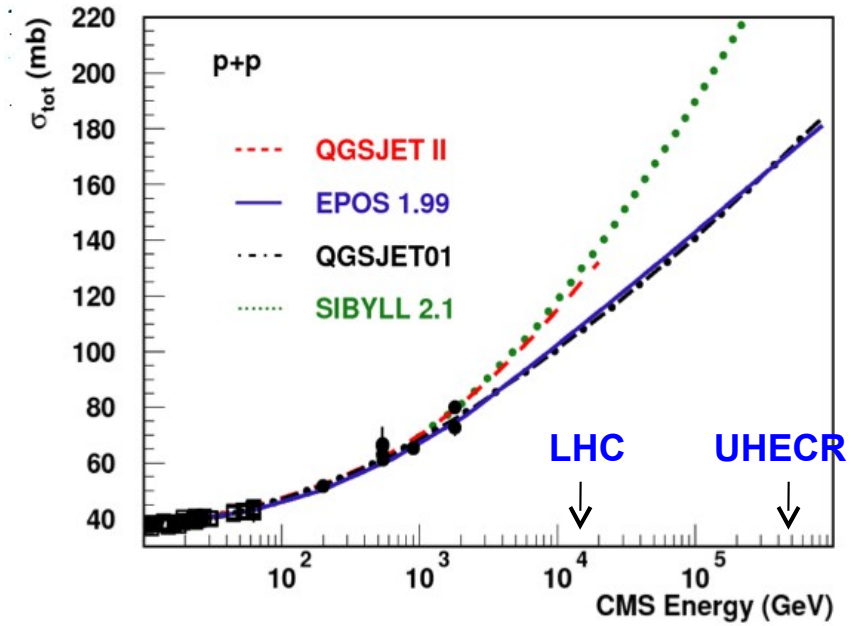


At low energy, shape consistent with a large fraction of protons

Still limited by statistics at the highest energy

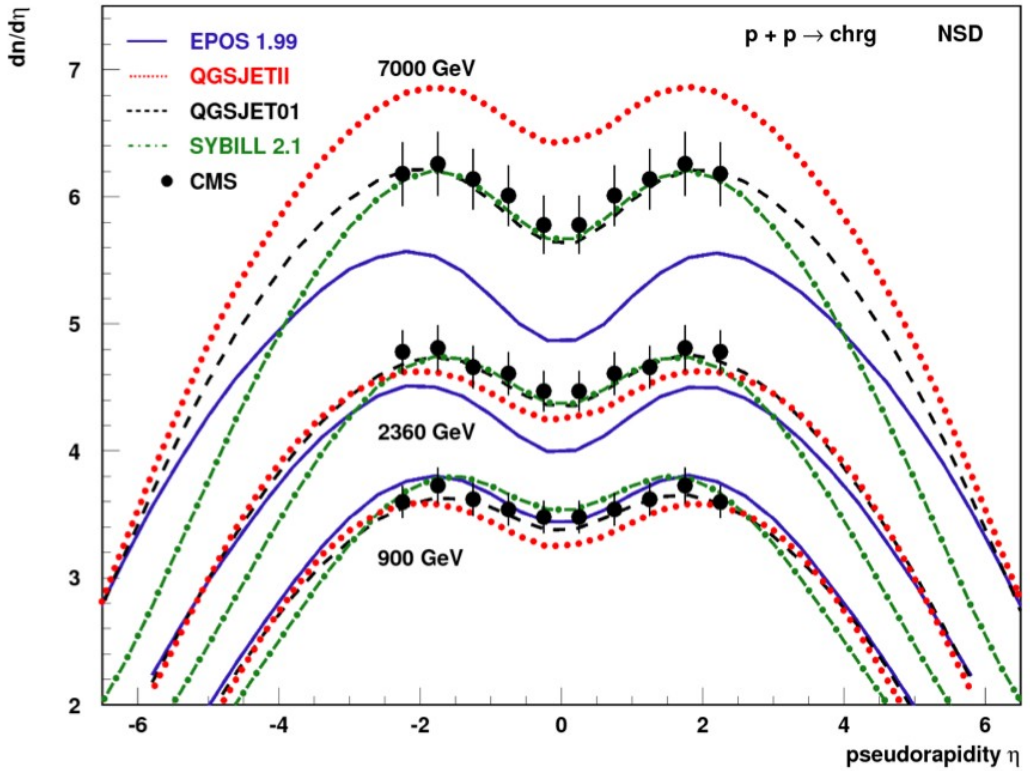
Composition and anisotropy results must be consistent…..

UHECR and LHC



T. Pierog (KIT)

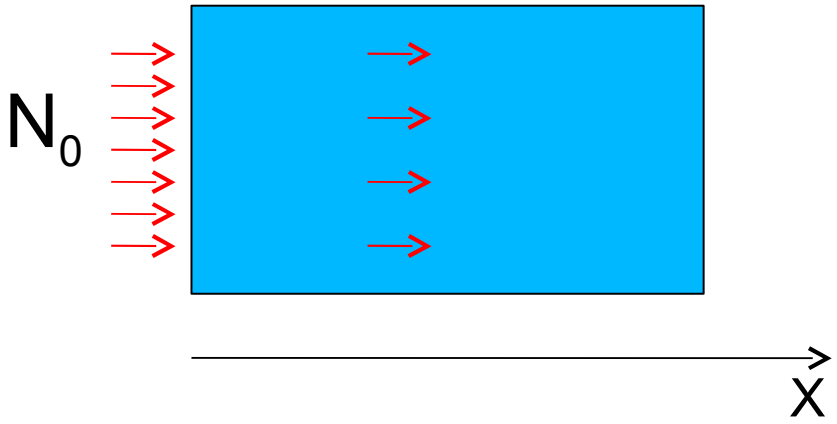
Hadronic models tuned with Tevatron measurements must extrapolated several order of magnitudes for UHECR simulations!



Measurements at LHC (including the forward region with LHCf, ALFA/TOTEM) will significantly improve the situation

Measurement of proton-air cross section

Absorption of a particle beam due to interaction in the material

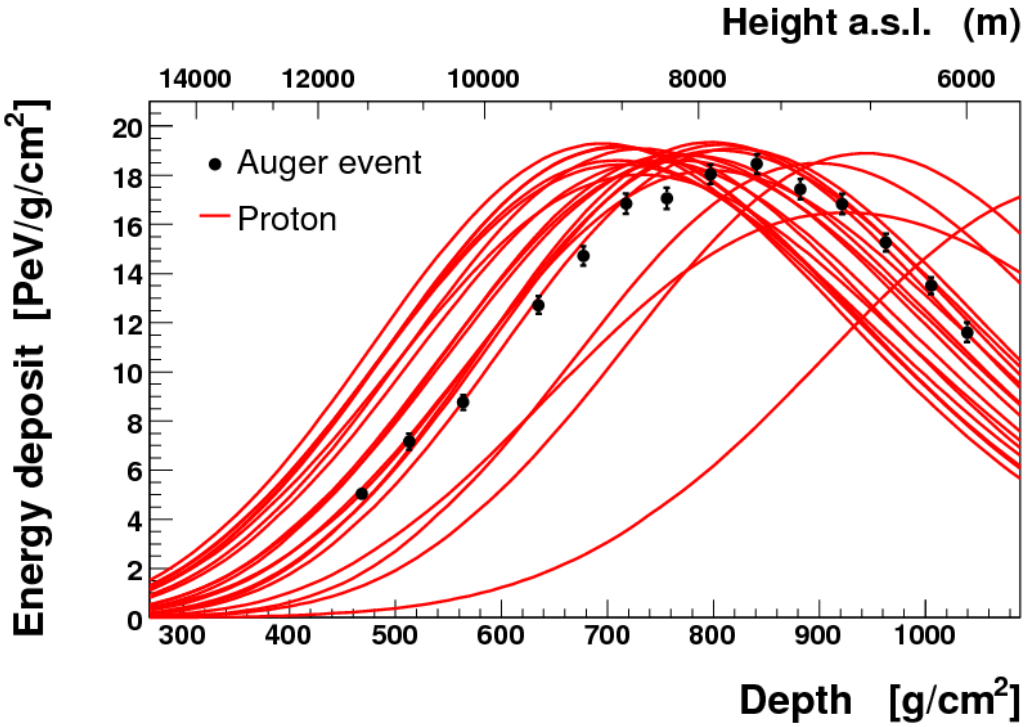


$$N(X) = N_0\, e^{-X/\lambda_{int}}$$

$$\lambda_{int} = 1 / (\rho\sigma)$$

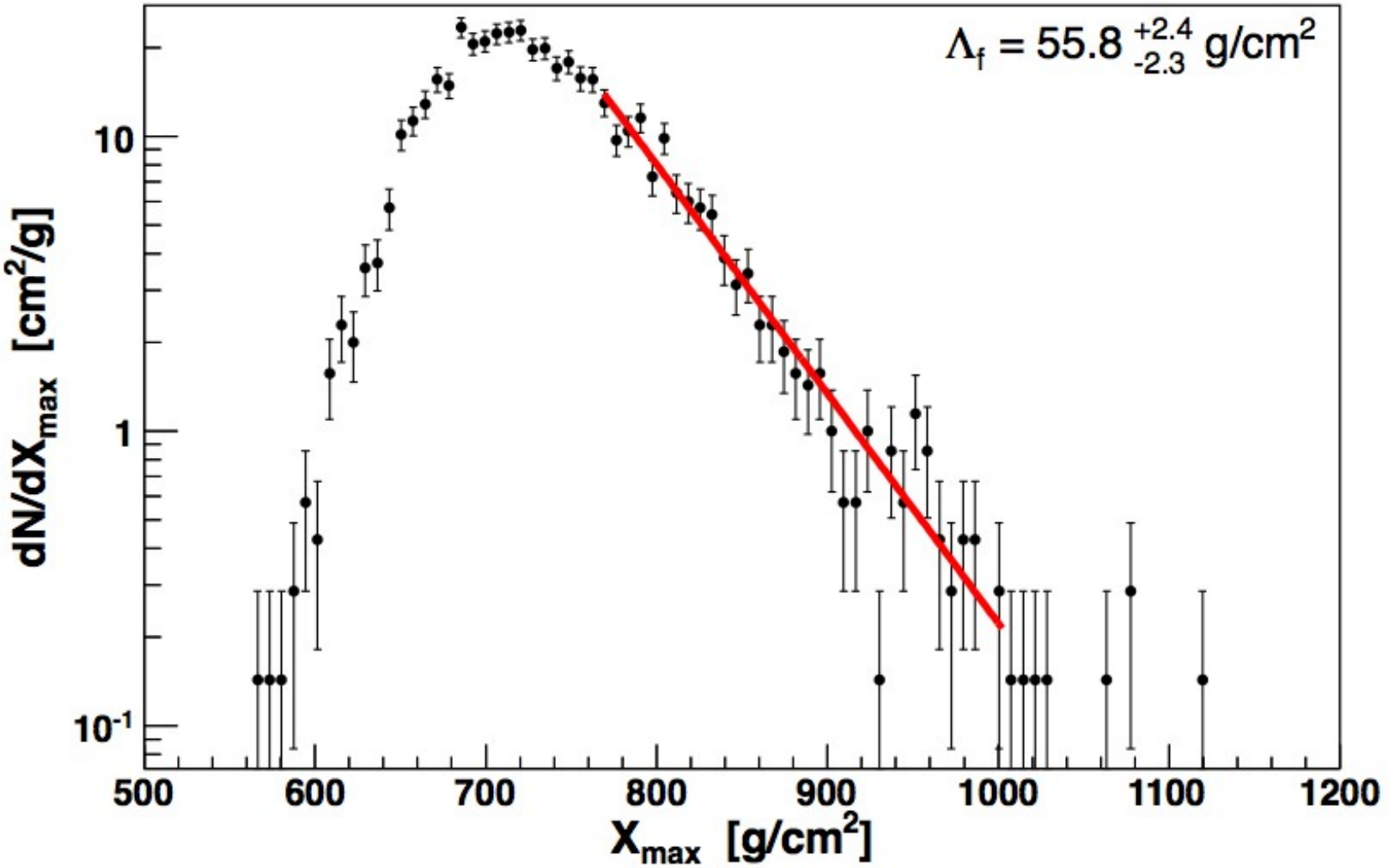
Cross section

Our UHECR "proton" beam absorbed in the atmosphere

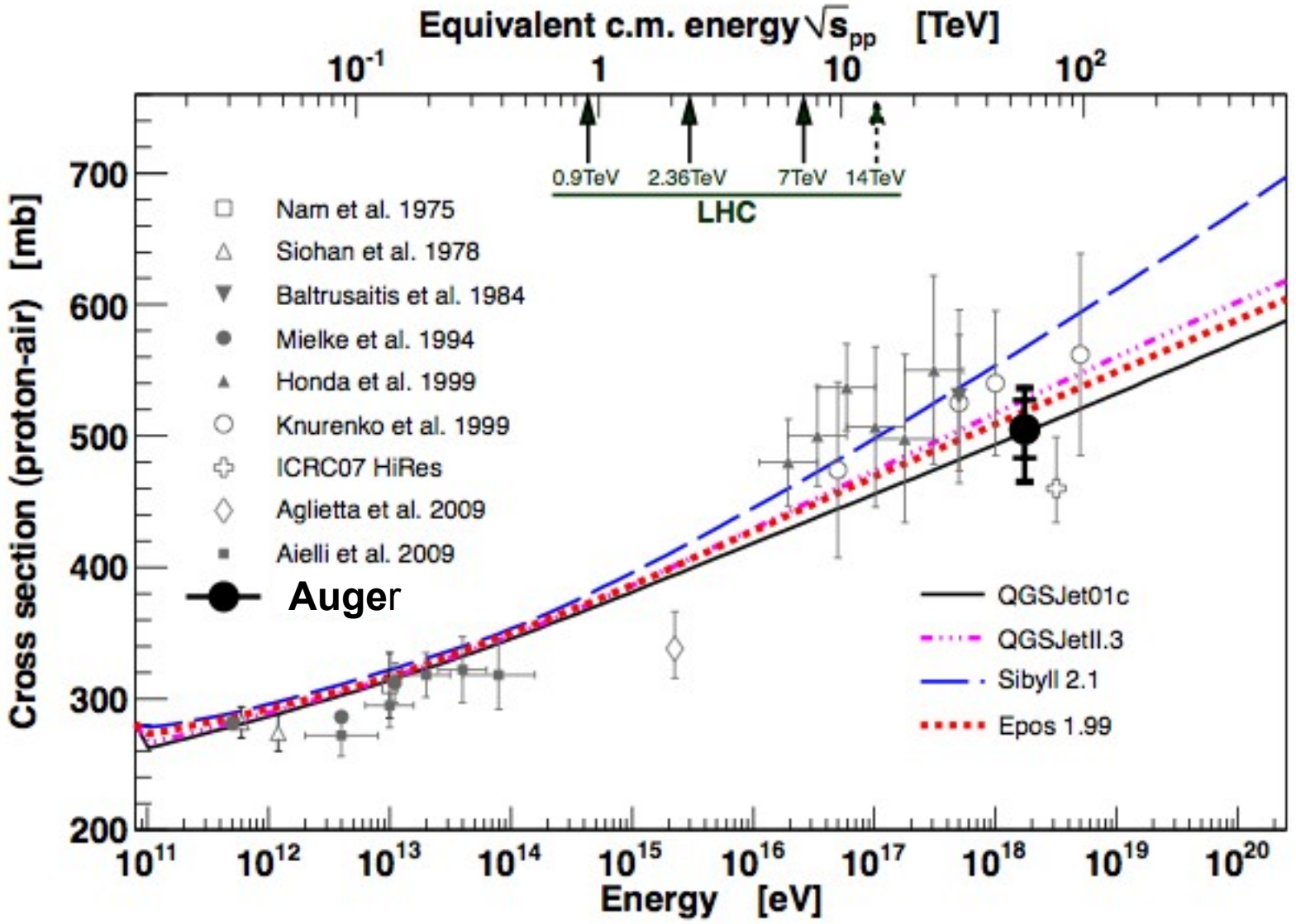


The exponential tail in the X_{max} distribution is sensitive to the cross section

Exponential tail of X_{max} distribution

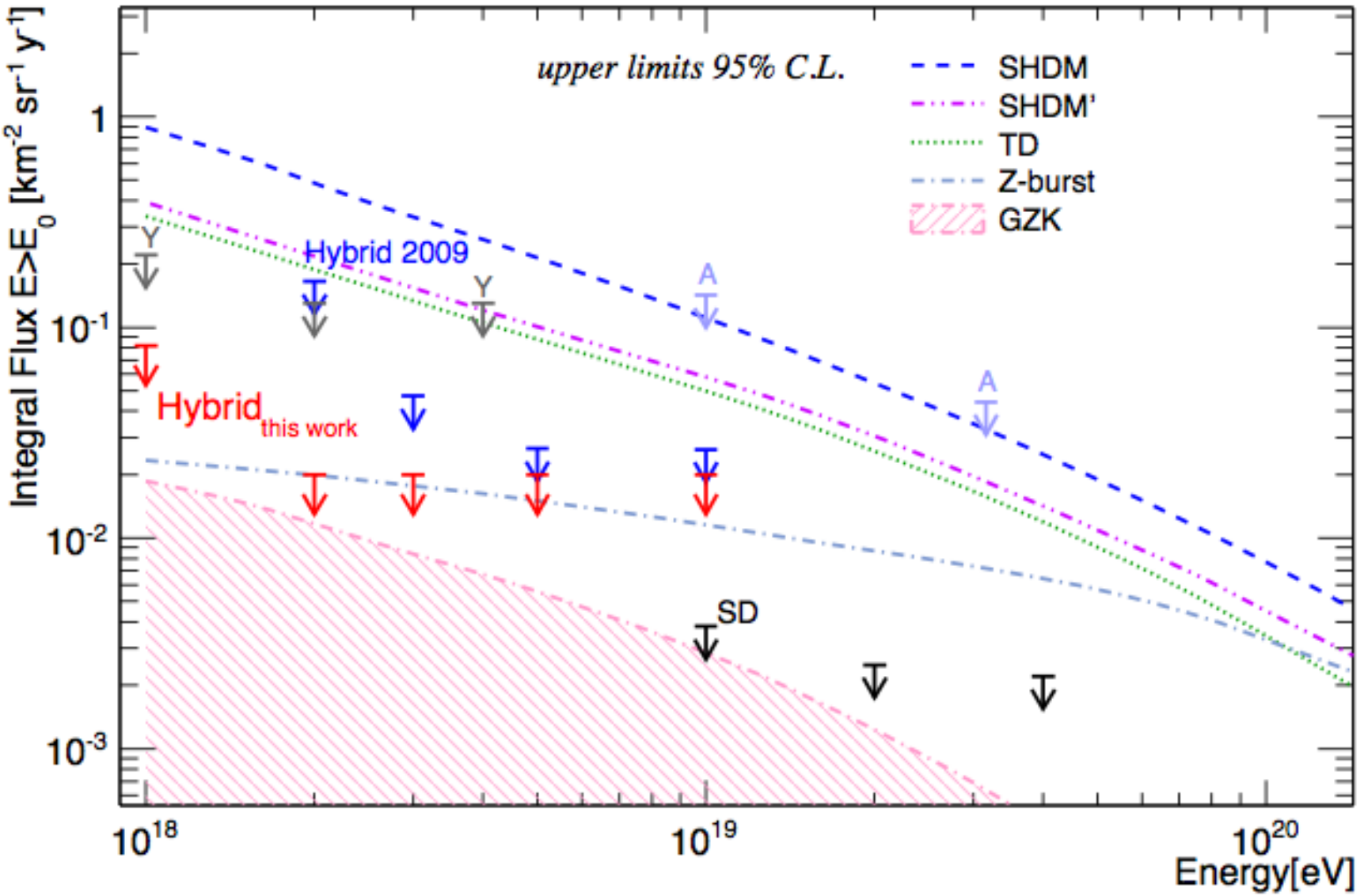


p – air cross section at 57 TeV



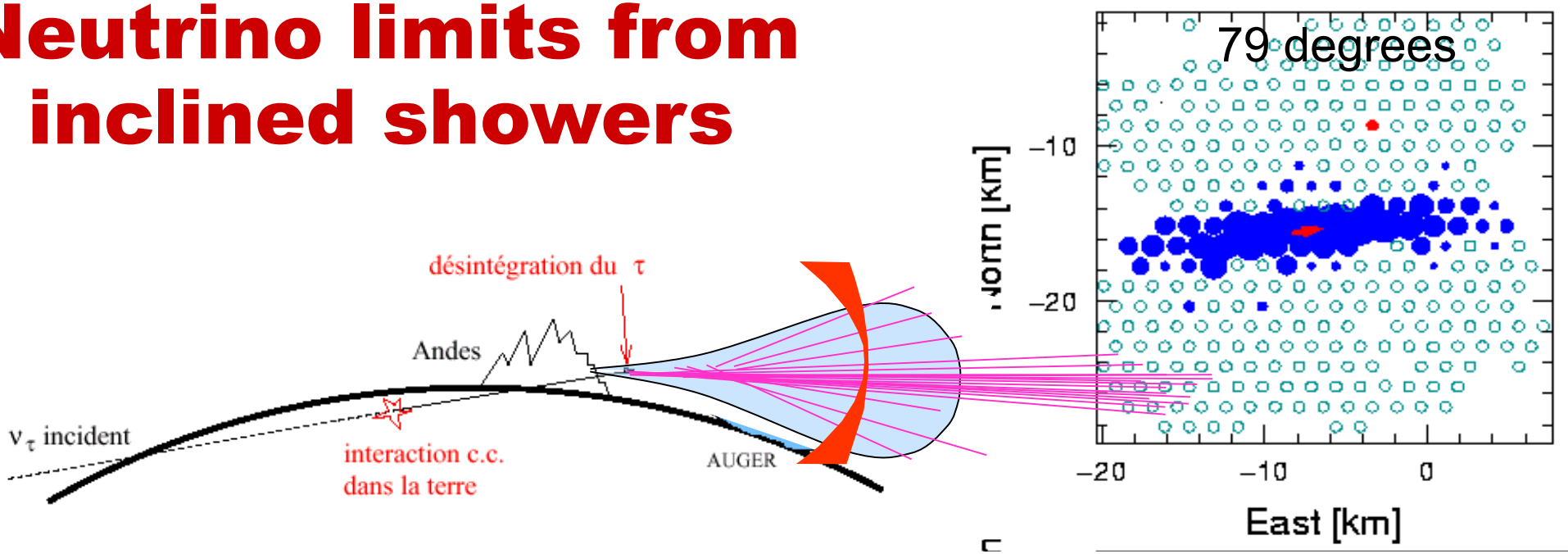
First step towards measurement at even higher cms energy.
Can be converted to p-p cross section (Glauber model) and compared to recent (and future) LHC measurements!

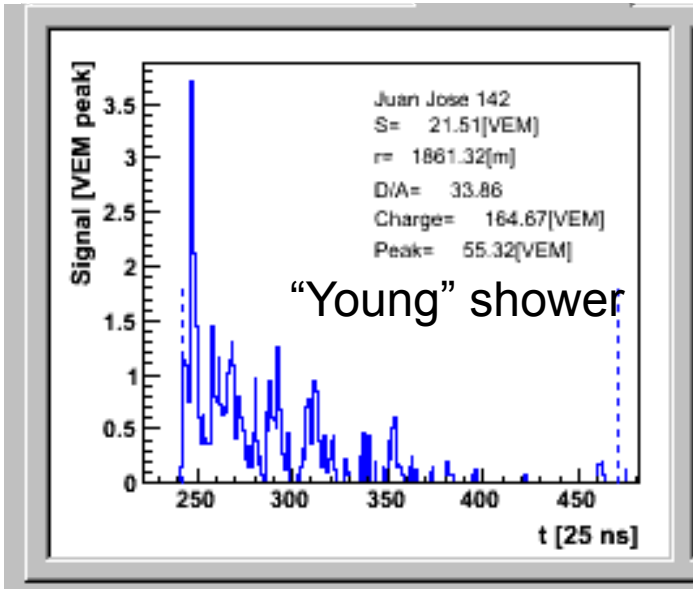
Search for UHECR photons



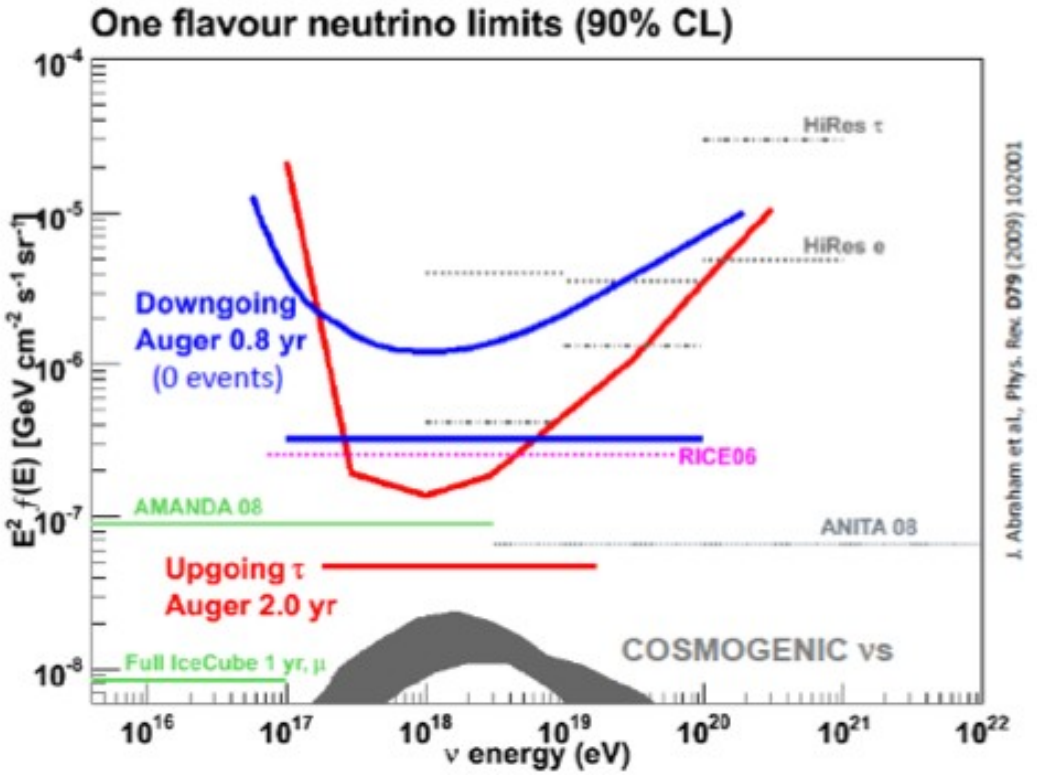
disfavour exotic “particle physics” models

Neutrino limits from inclined showers





"Young" shower



Outlook

- Novel insight into the UHECR puzzle by recent data:

  - flux suppression of UHECR unequivocally established (consistent with GZK)

  - UHECR anisotropy at 99% CL (where are the sources? Where is the isotropic component coming from?)

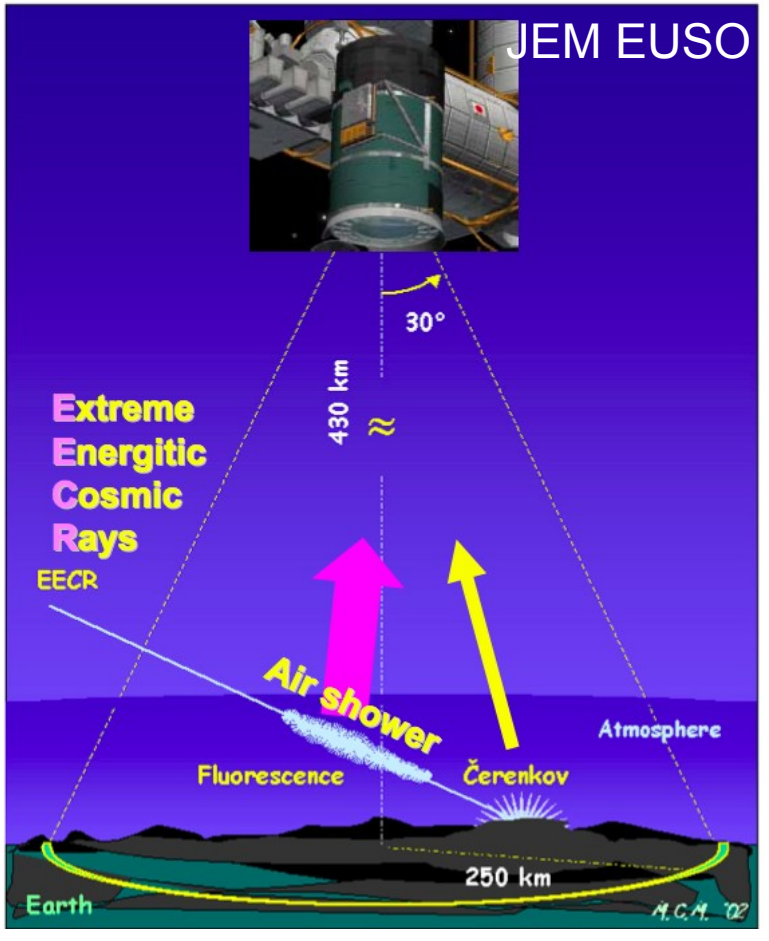
  - Composition: intriguing results (Heavier? Models? Cross sections?).

  - Exotic physics not favored

- The UHECR puzzle is not yet solved. Statistics at the highest energy is the limiting factor (GZK). Auger South Observatory will collect data for many years (TA in Utah only 20% of Auger). With cosmic rays one must be patient…..

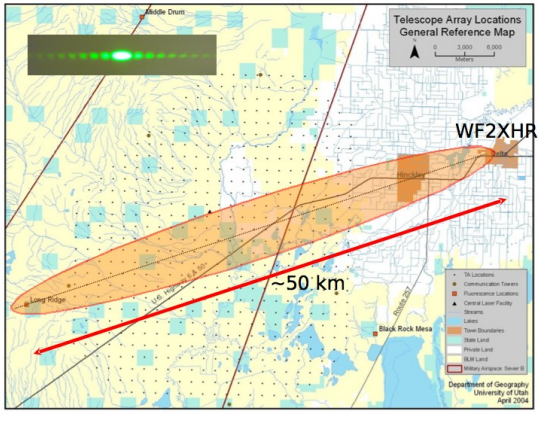
- But an order of magnitude in aperture is needed to address the puzzle. The UHECR community is following several approaches towards a larger aperture experiment

Conventional array techniques. Auger North in Colorado (not likely). Expansion of TA in Utah (up to Auger size)



Aggressive R&D on novel radio detection techniques

Bistatic radar (TA)



Microwave (Auger)