Ultra-high energy cosmic rays: lessons from Pierre Auger Observatory

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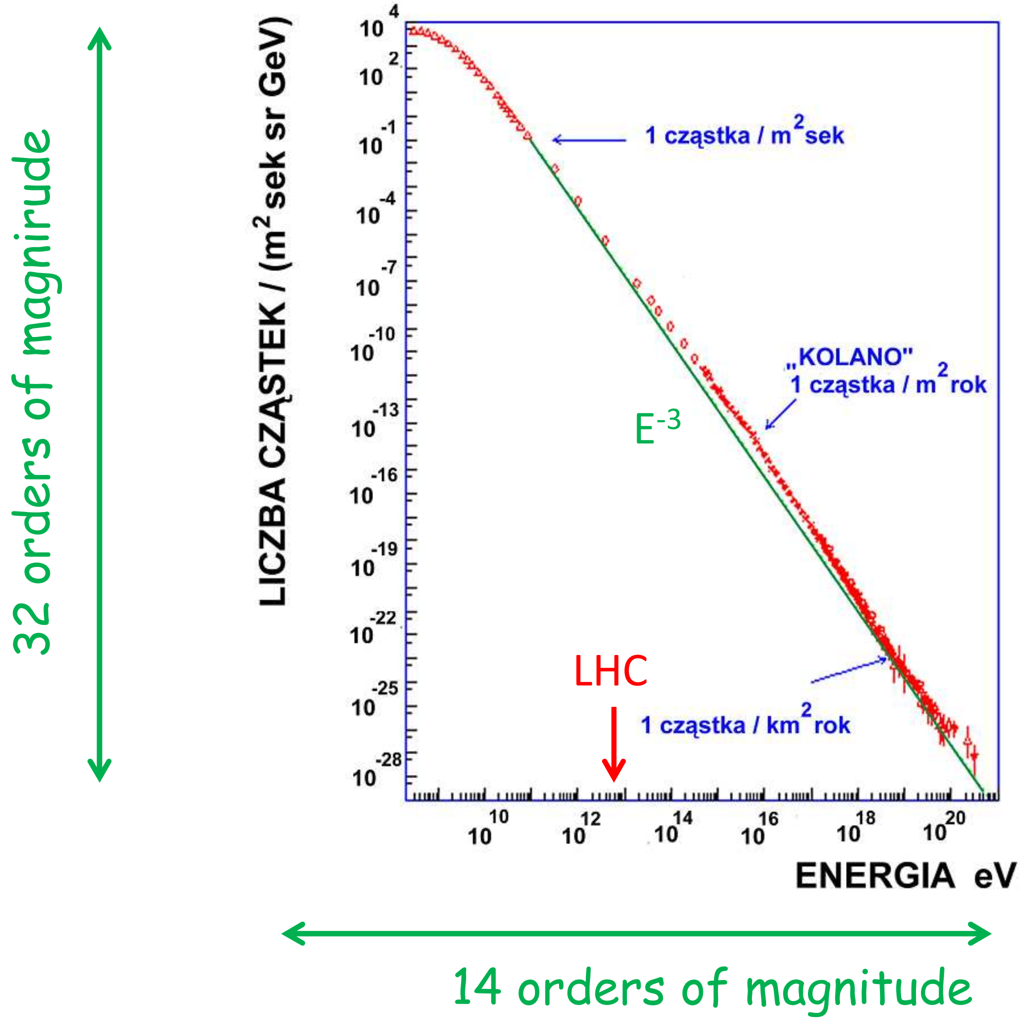
Cosmic ray energy spectrum



10^{20} eV in LHC technology $\rightarrow$ need accelerator size of Mercury orbit

Ultra-high energy cosmic rays

Key questions:

- Where do they come from?
- What are they made of?
- How do their accelerators work?
- Is there a limit to their energy?
- What can they tell us about the fundamental and particle physics?

Expect the Greisen-Zatsepin-Kuzmin (GZK) effect

interactions with CMB photons at $E > \sim 5\times10^{19}$ eV:

$$p + \gamma \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$

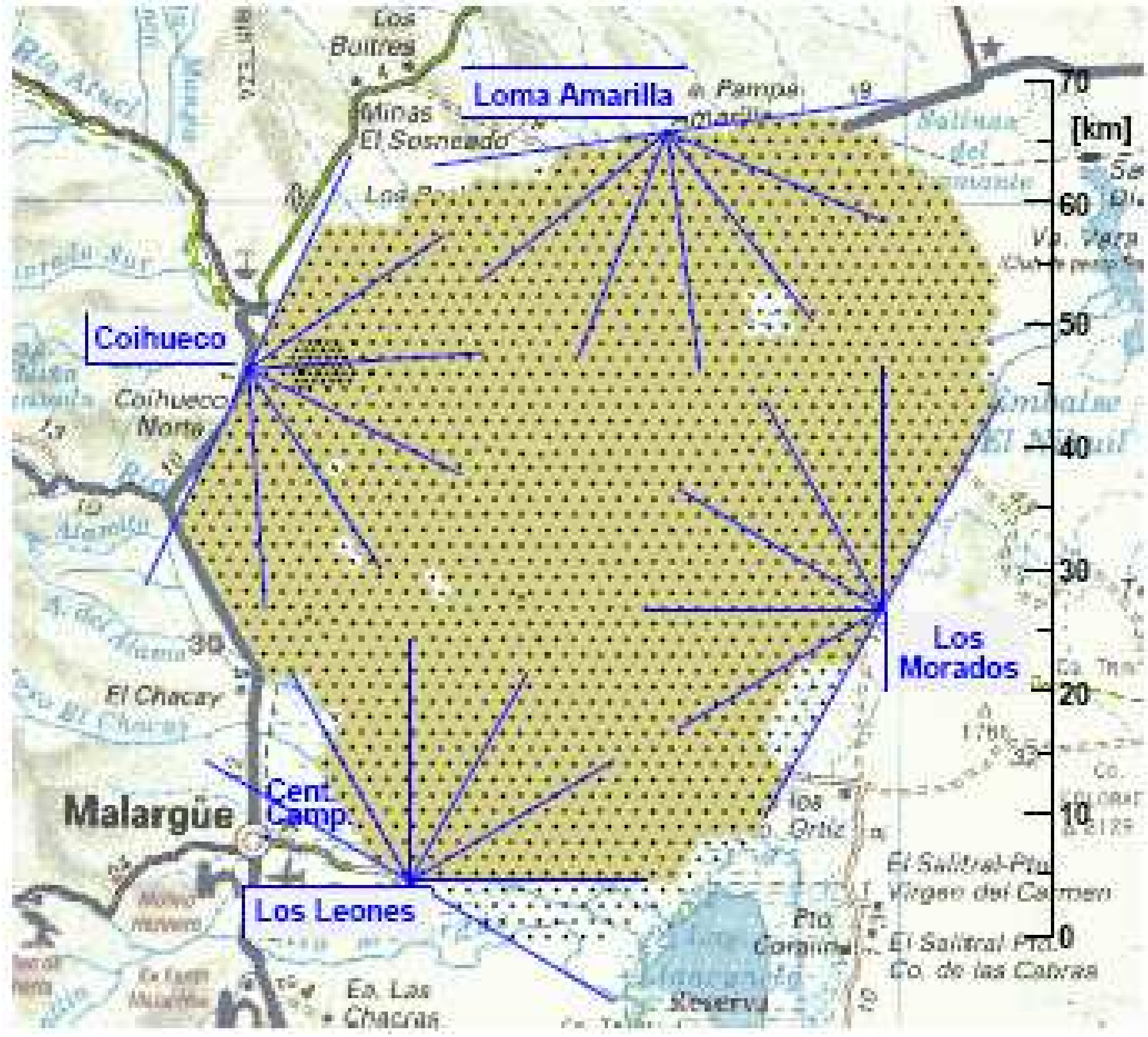
$$n + \pi^{+}$$

$\rightarrow$ reduction of proton energy

$\rightarrow$ spectrum suppression above the threshold

The Pierre Auger Observatory

Located in Mendoza province, Argentina

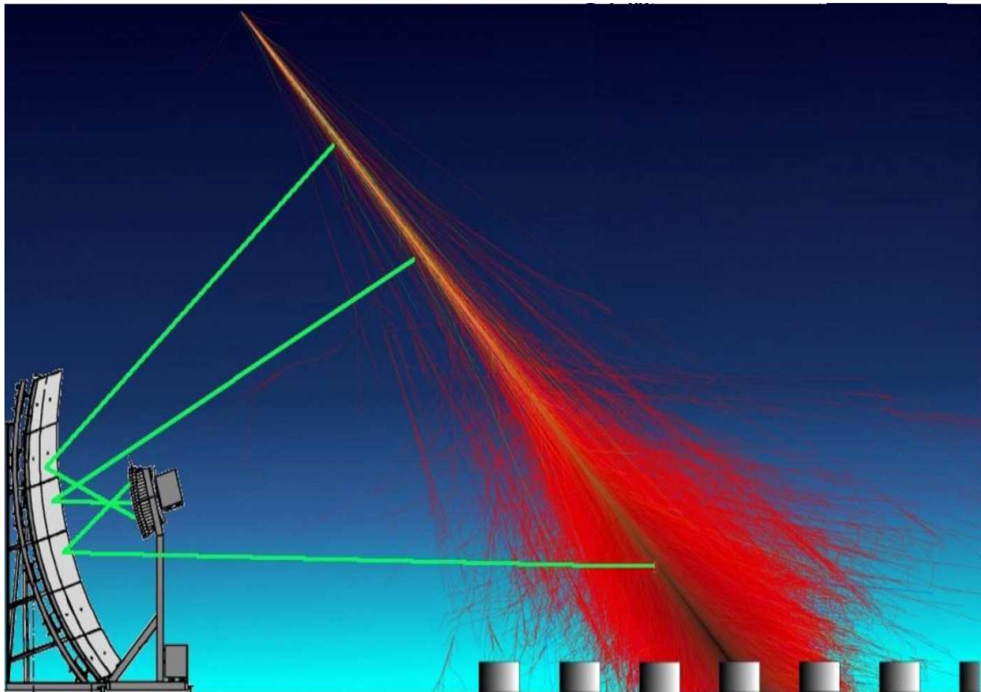


Surface Detector (SD)

1600 detector stations
1.5 km spacing
3000 km^2
100% duty cycle
exposure calculated geometrically

Fluorescence Detector (FD)

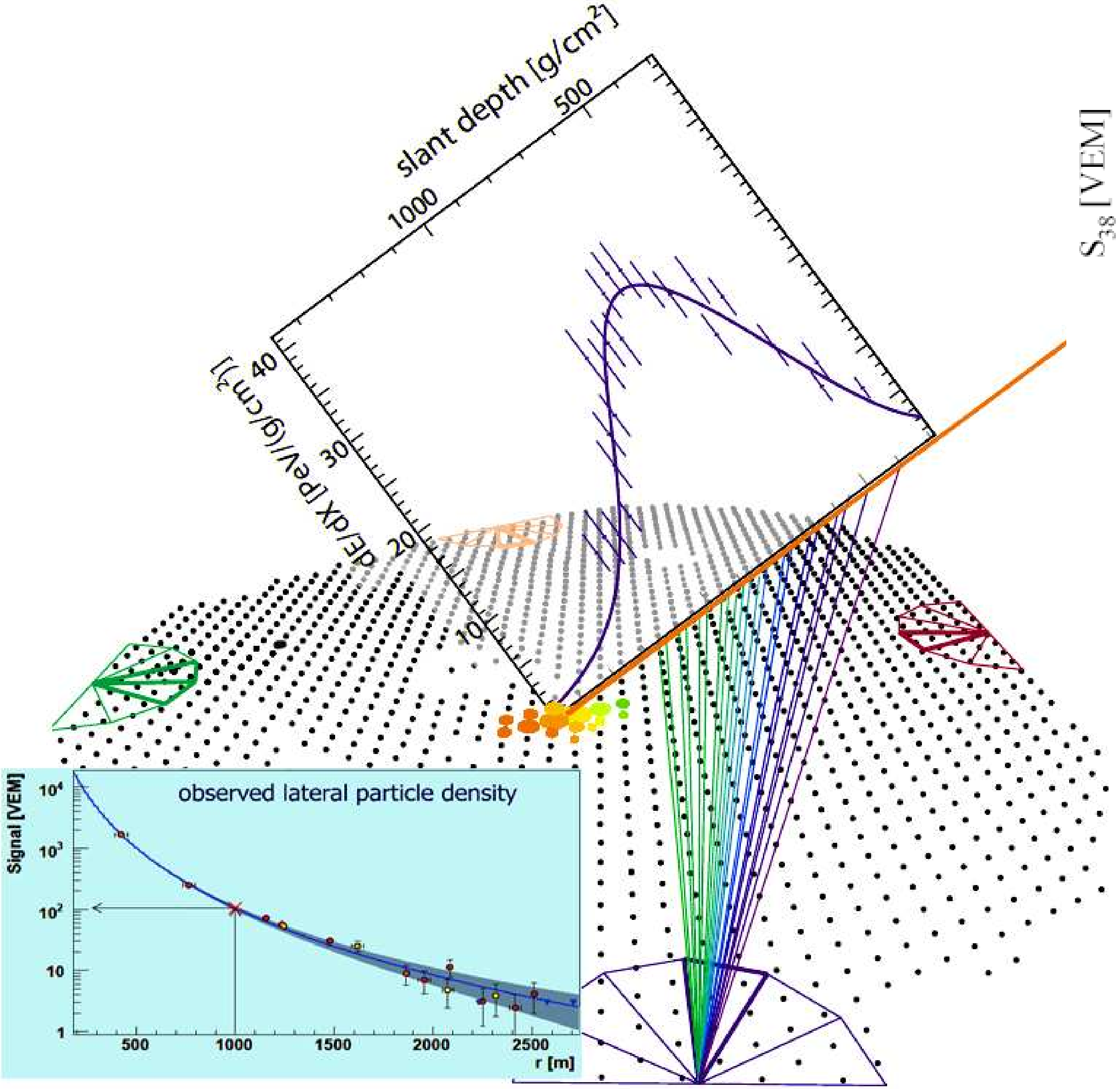
27 telescopes
calorimetric energy
duty cycle ~13%
exposure based on MC

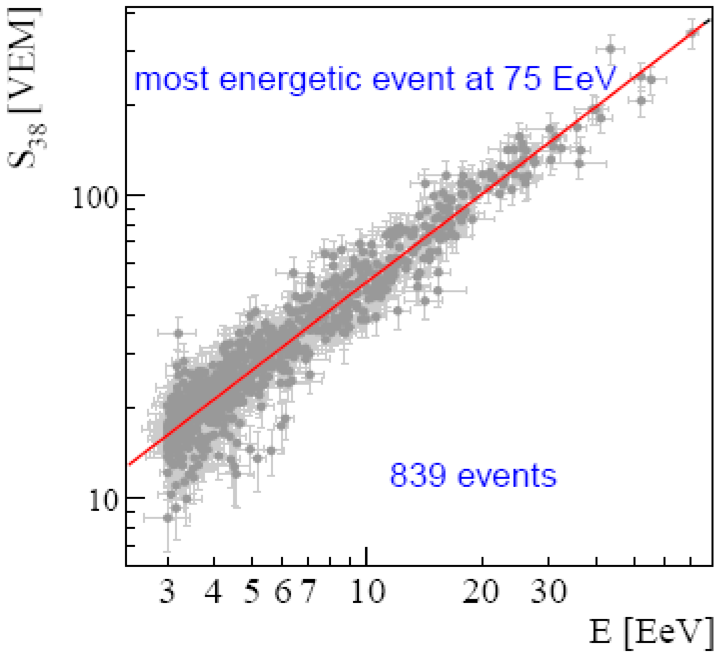


Hybrid detection of extensive air showers

Use simultaneously both FD and SD techniques

Hybrid reconstruction

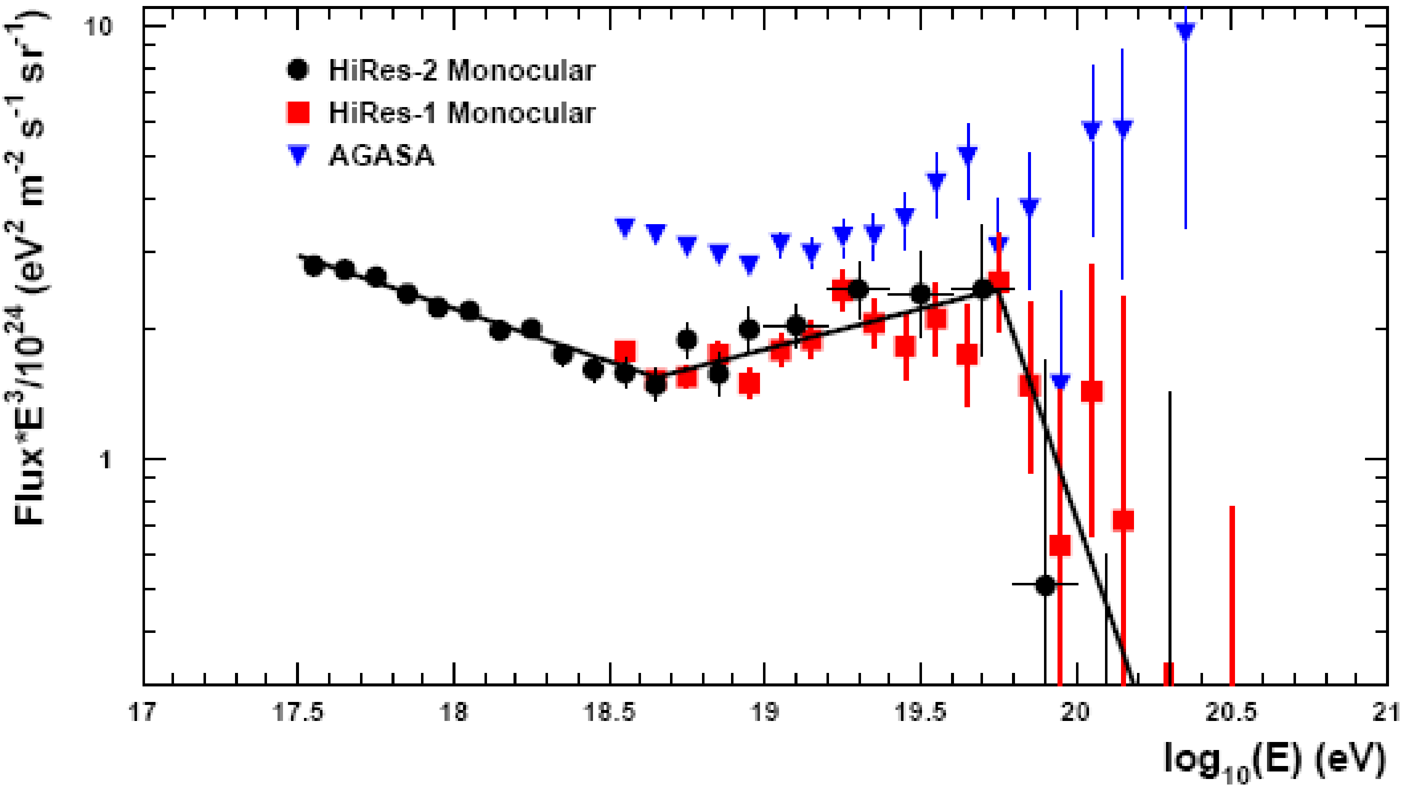




FD-SD energy calibration

Unprecedented accuracy of shower measurements

UHECR spectrum ~10 years ago



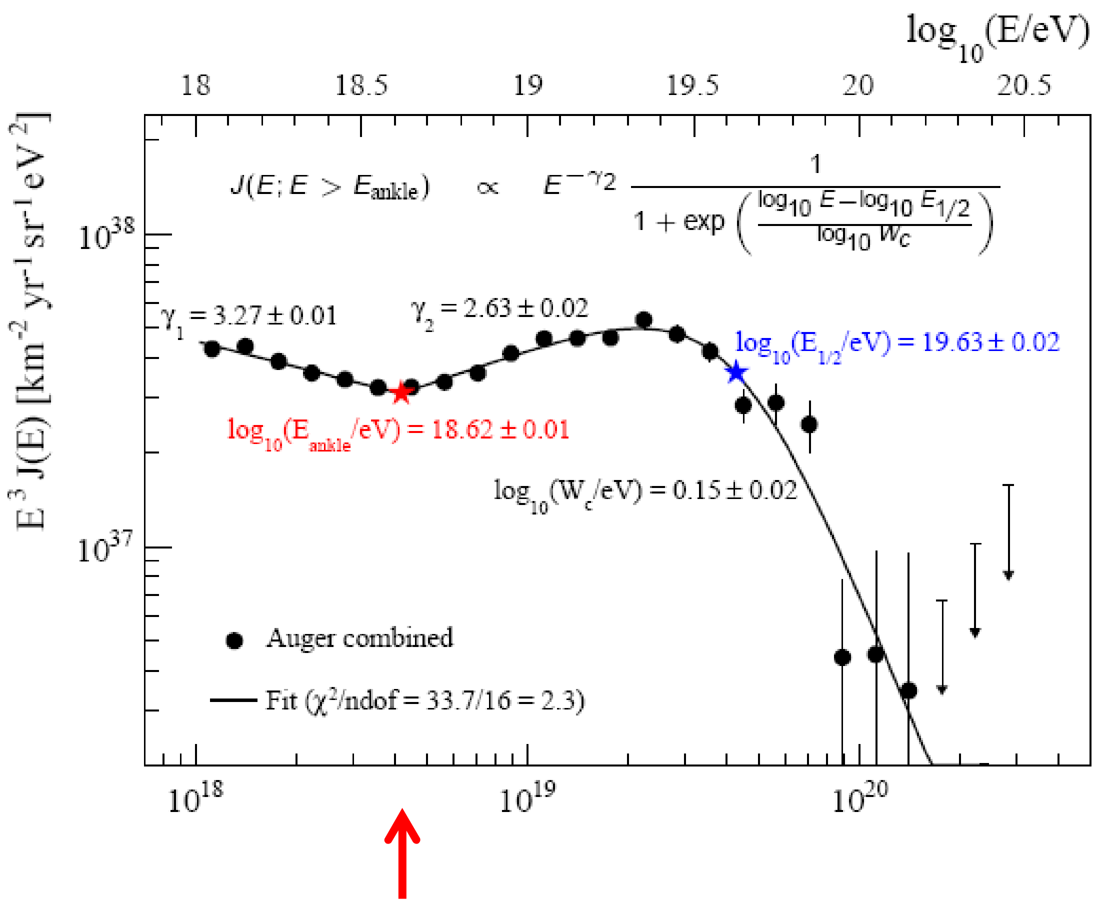
Is there the GZK suppression?

AGASA: NO

HiRes: YES

Directional isotropy → where are the sources?

CR energy spectrum from Auger



E_{ankle} ~ 4 EeV (gal. → Xgal?)

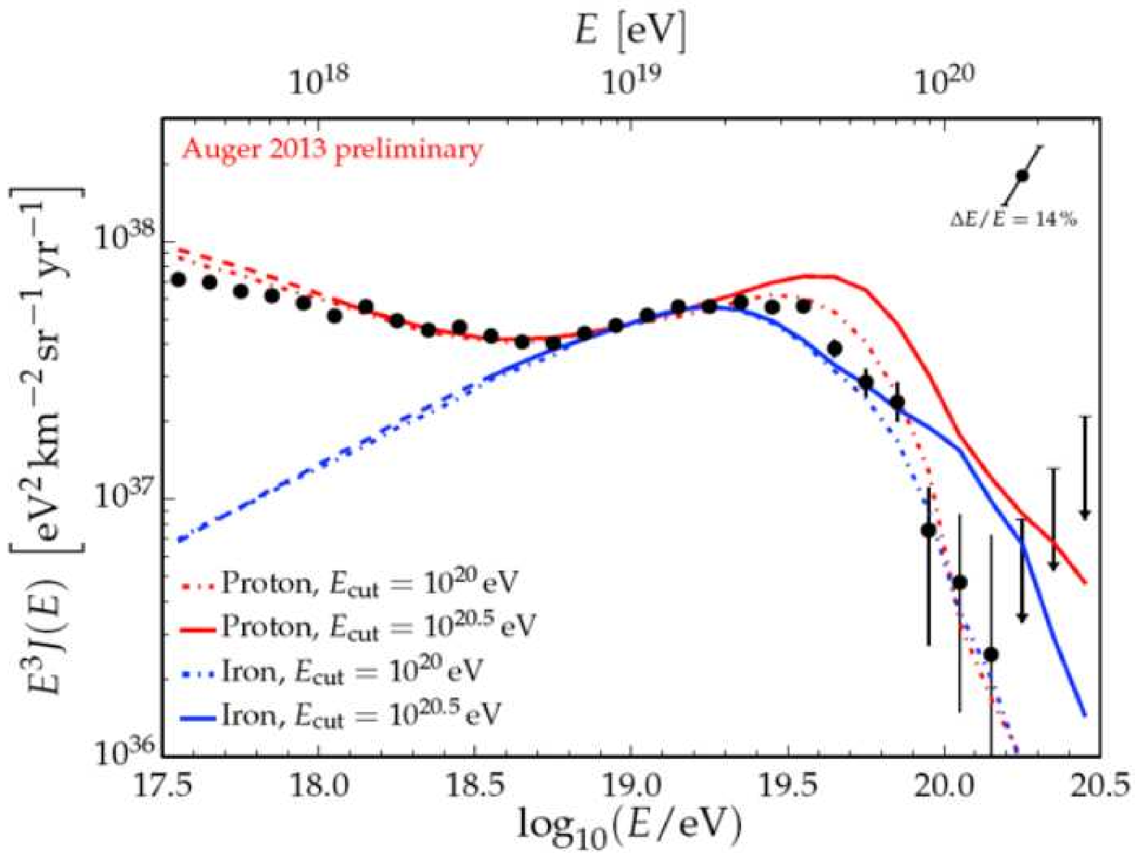
Spectrum suppression:

due to the GZK cutoff,
or
maximum
energy of accelerators ?

Composition
measurement is crucial

Data compared to GZK effect

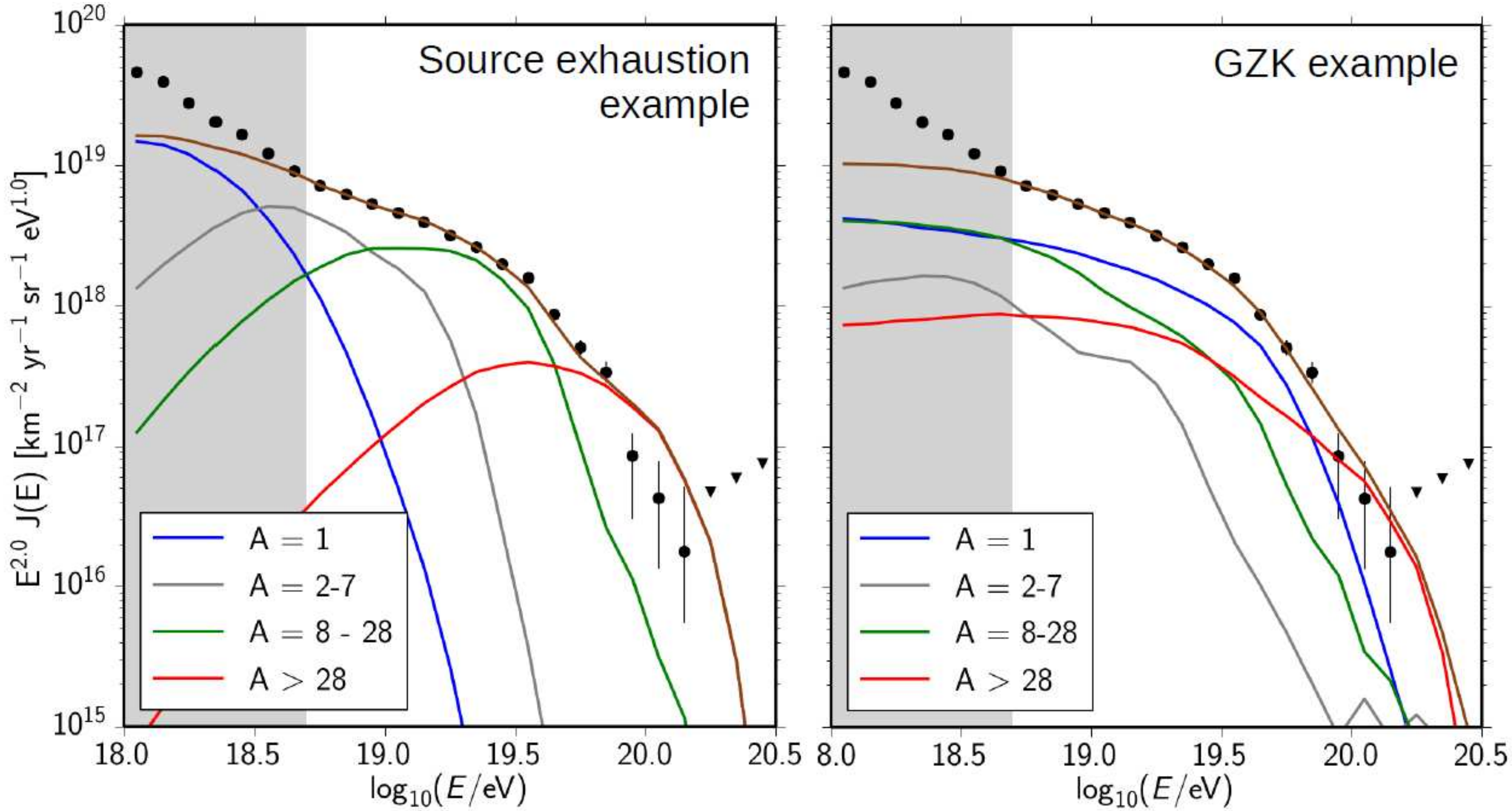
Example: assume uniform distribution of only proton or iron sources



Spectrum alone is not enough to select the right scenario
→ need composition measurement

Interpretation of the spectrum

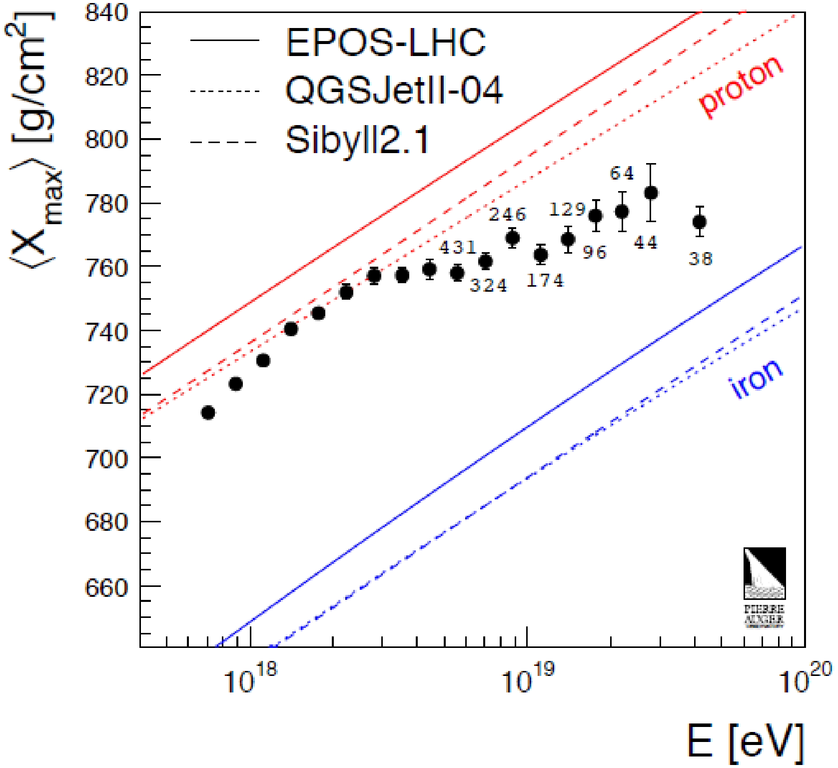
Spectrum fits in different scenarios

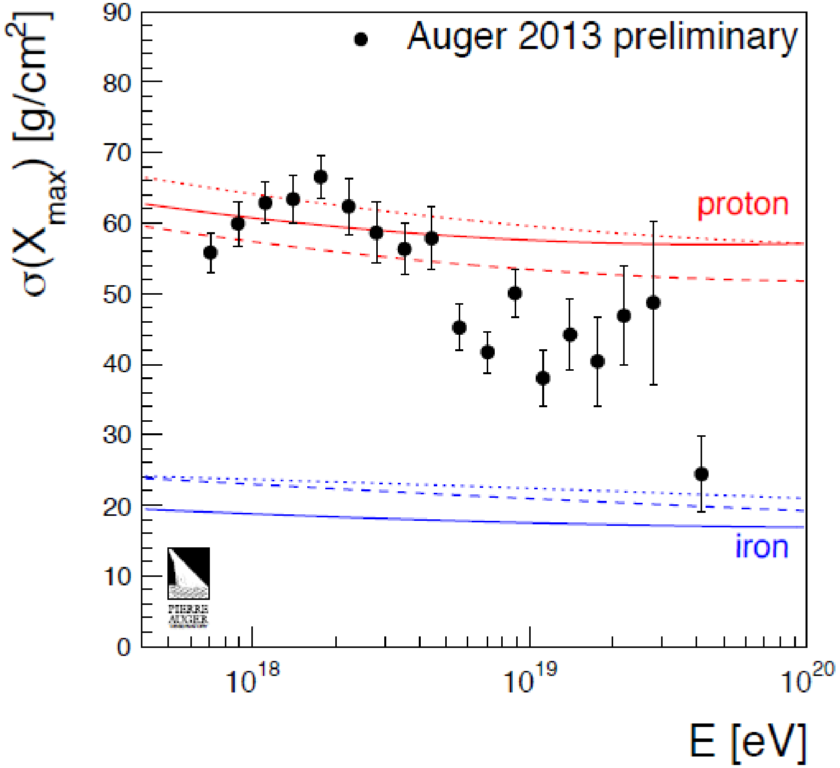


Need for excellent composition measurement to determine the nature of the flux suppression

Mass composition

Depth of shower maximum, X_{max}



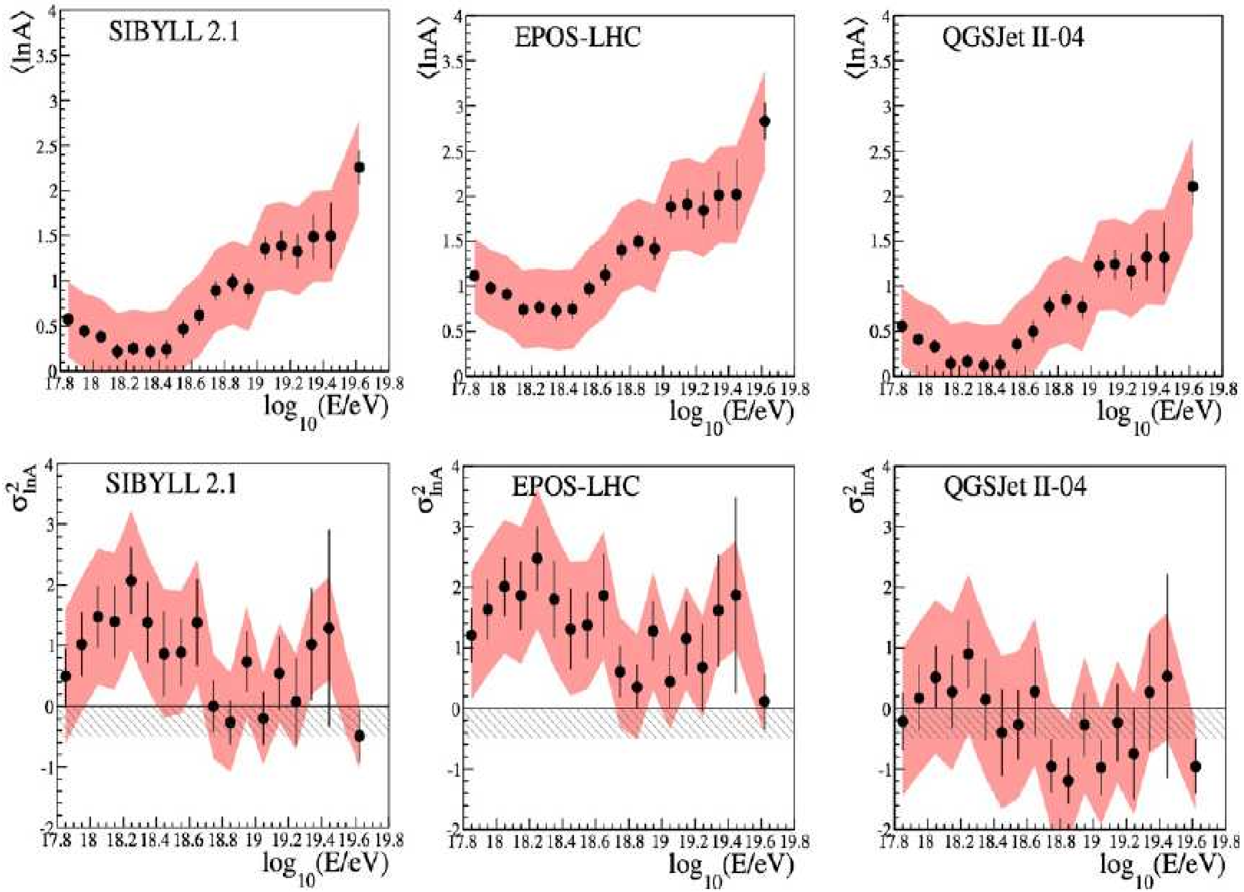


Smooth change from a light/mixed composition to a heavier one ?

Mass composition - from X_{max} to ln A

$$\langle \ln A \rangle = \frac{\langle X_{\max} \rangle - \langle X_{\max} \rangle_p}{f_E}$$

$$\sigma^2_{\ln A} = \frac{\sigma^2(X_{\max}) - \sigma^2_{sh}(\langle \ln A \rangle)}{b\ \sigma_p^2 + f_E^2}$$



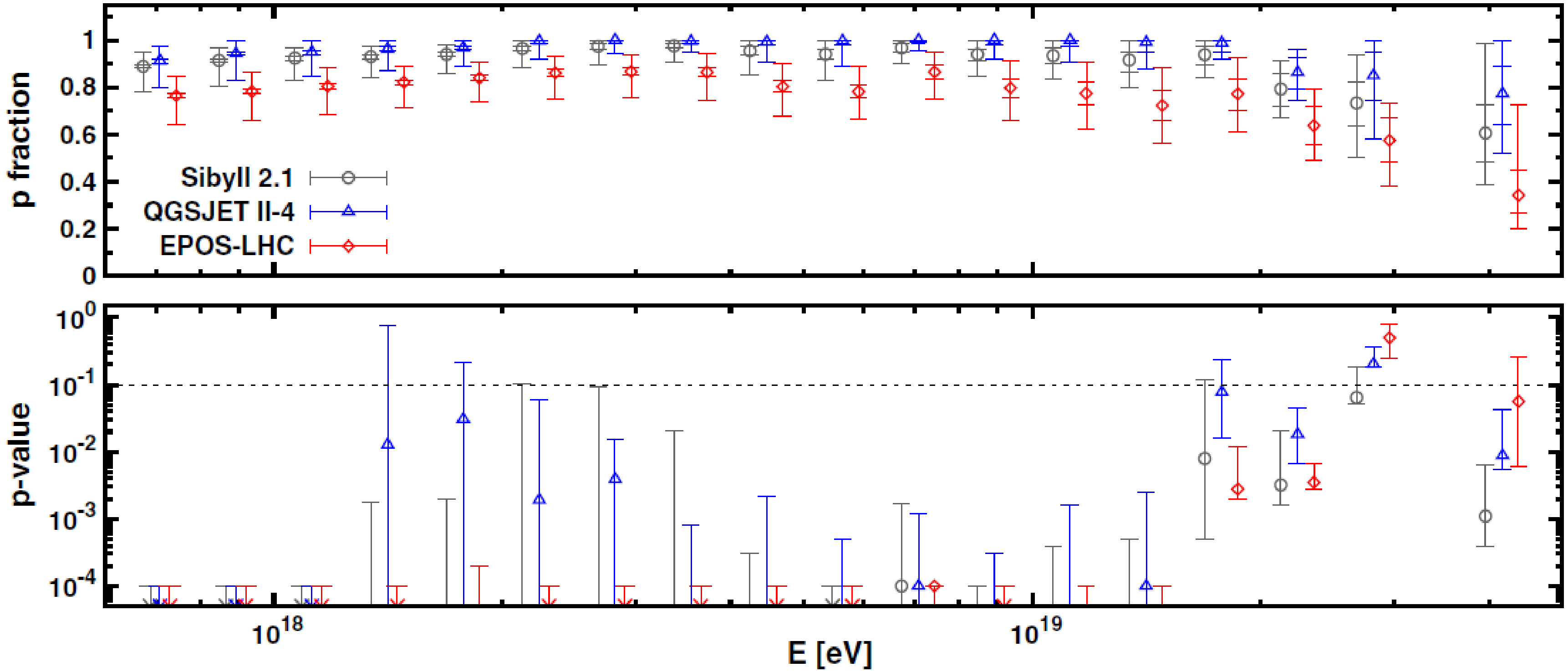
Average ln A
<ln A> =4 pure Fe
<ln A> ~2 50% Fe 50% p
<ln A> =0 pure p

Dispersion of masses
(due to source or propagation)
σ^2(ln A)=4 50% Fe 50% p
σ^2(ln A)=0 pure p or Fe

<ln A> has a minimum in the ankle region
The mix must include intermediate nuclei

Mass composition – protons vs Fe

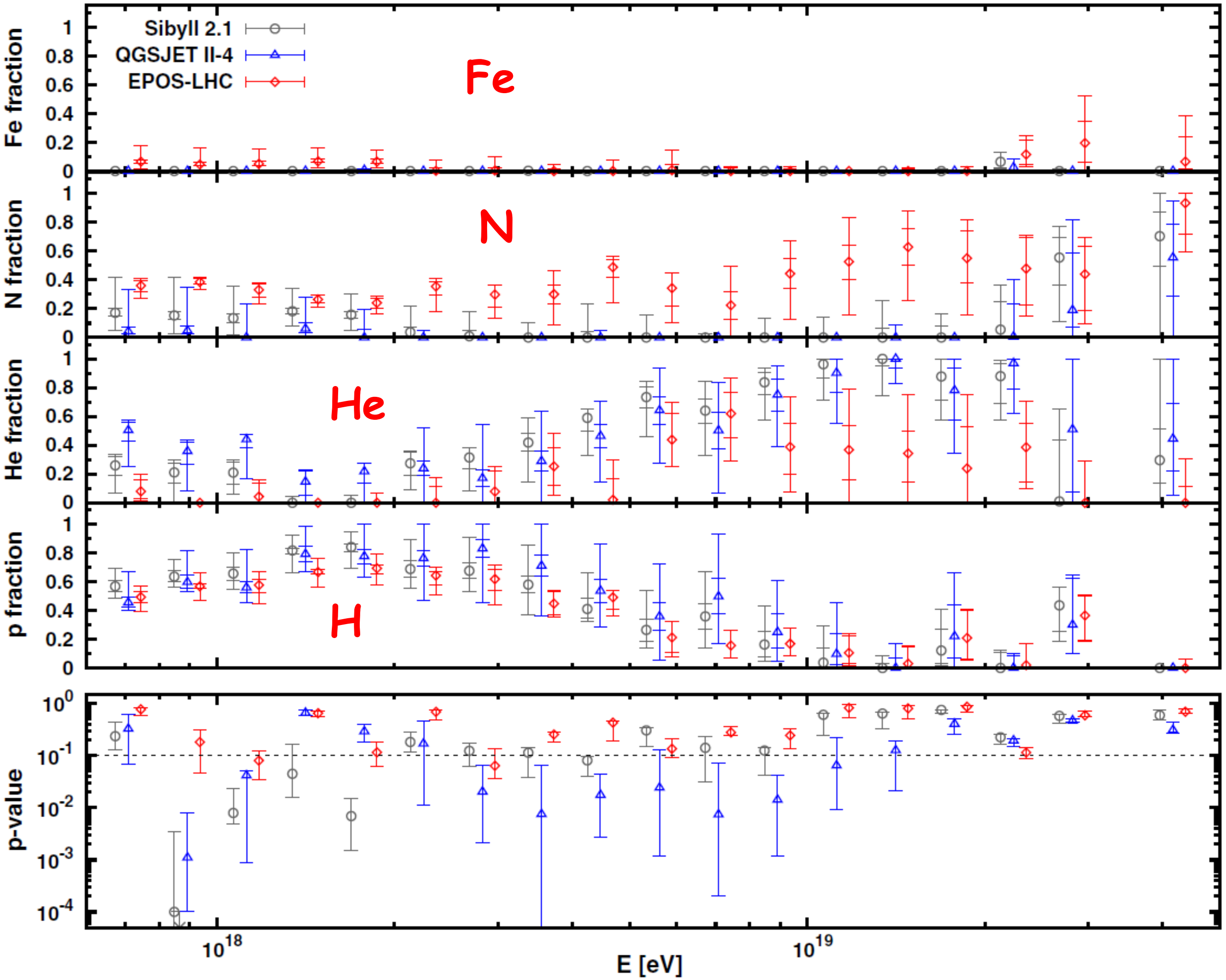
Fitted fraction and quality: p and Fe only



Very poor fit to the data

None of the models can reproduce the Xmax with p and Fe only

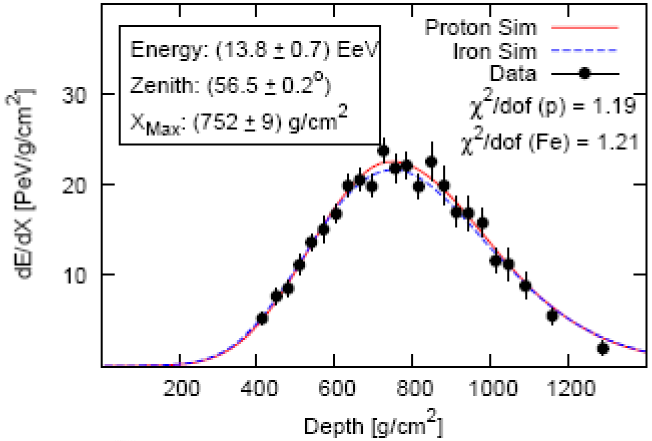
Mass composition with intermediate nuclei



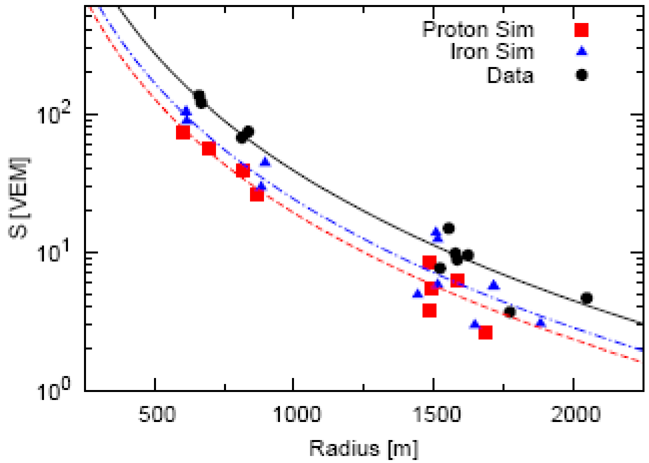
Acceptable fit quality with 4 nuclei

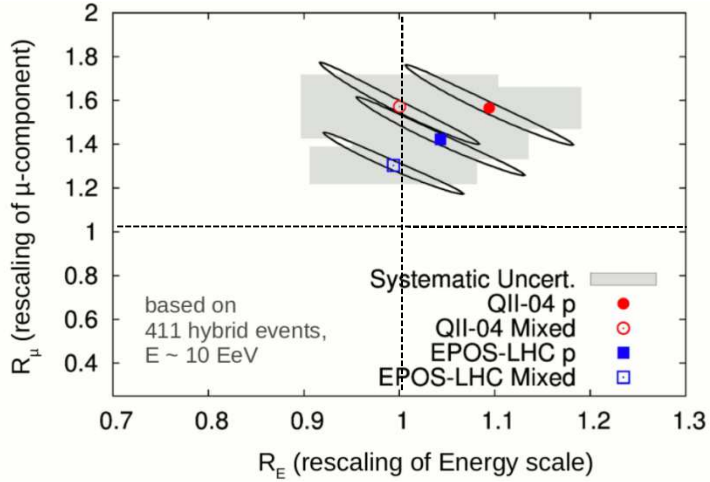
Muon deficit in shower simulations

Measured event with simulated FD long. profile

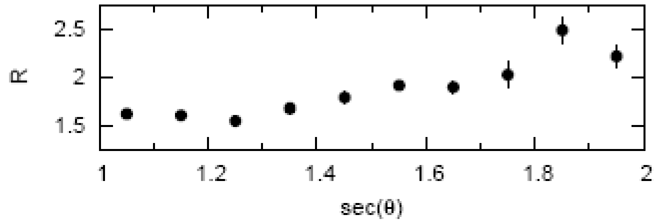


The same event with simulated SD signal





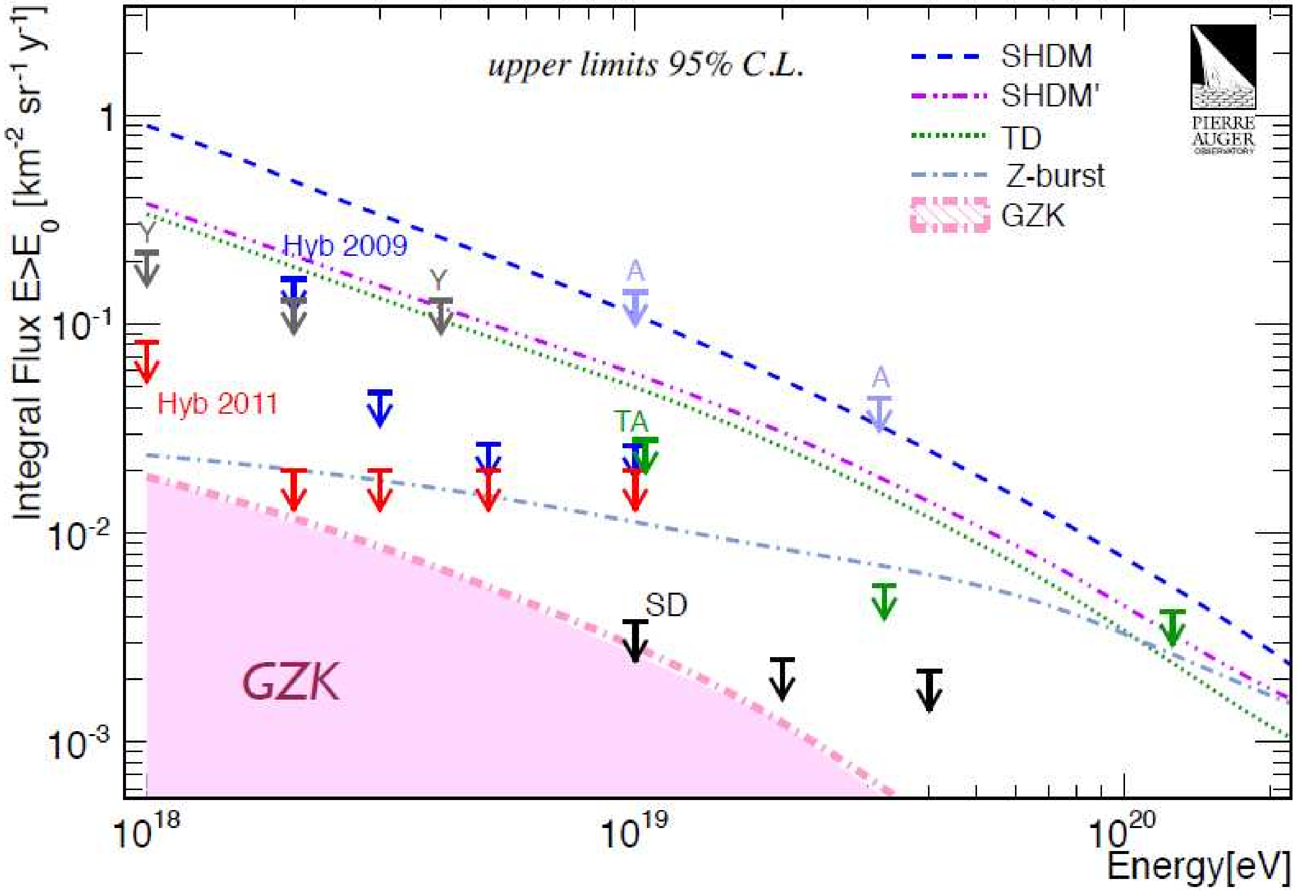
Ratio S(data)/S(sim)



Models underestimate N_μ
Energy ~ OK

The existing models of HE interactions cannot consistently describe the data

Diffuse photon limit



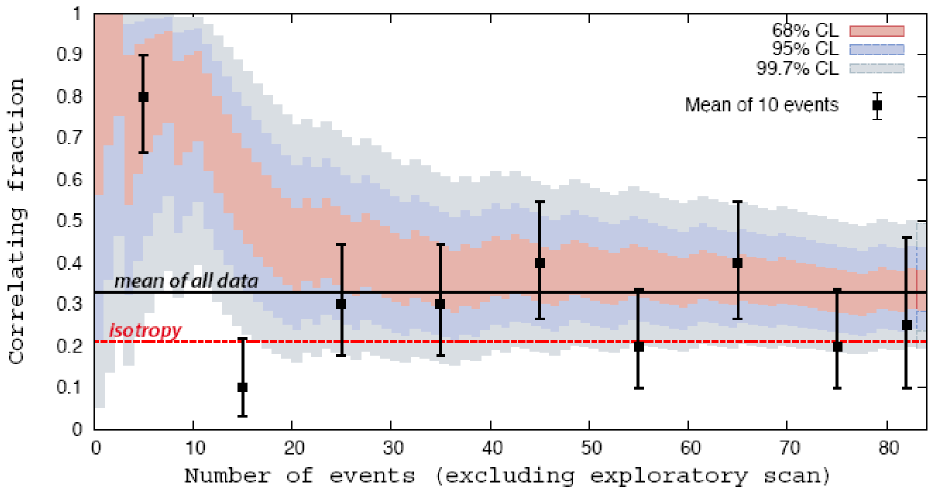
Photon upper limits rule out Top-Down models of CR origin

Observation of GZK photons and neutrinos will verify the GZK effect

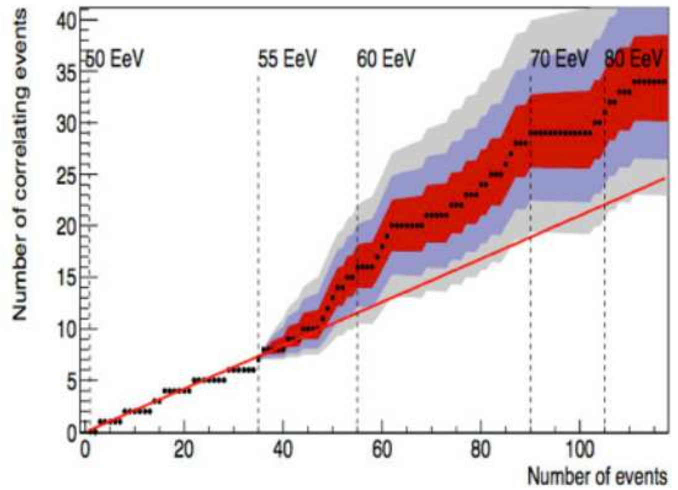
Point sources?

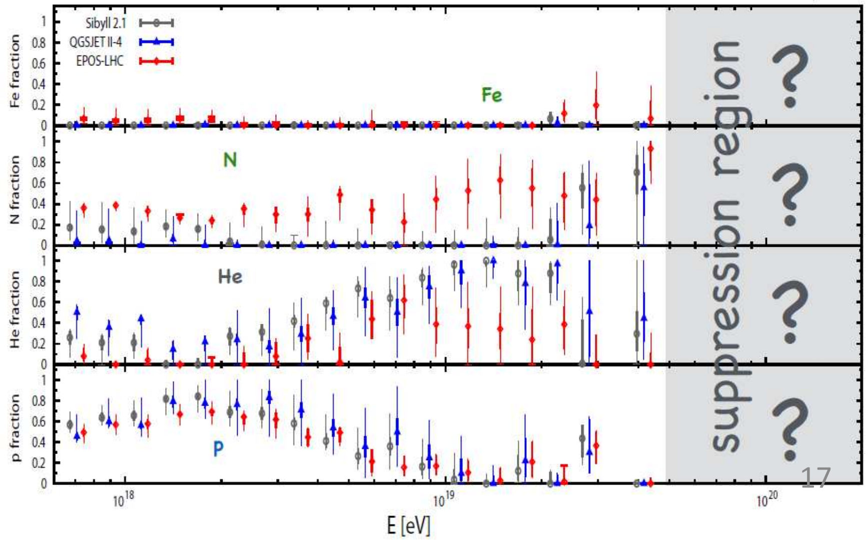
Correlation to AGNs at E>55 EeV within 3.1 deg

time ordered



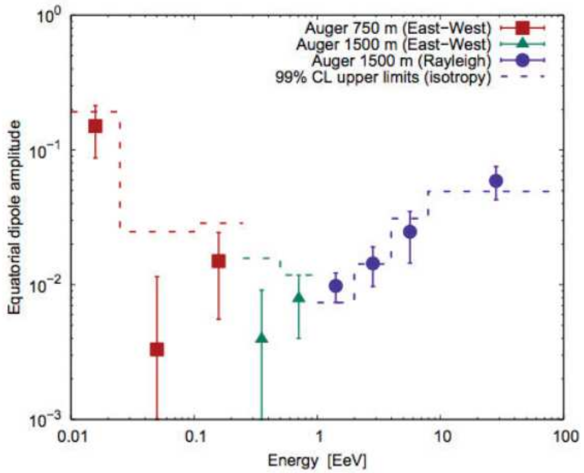
energy ordered



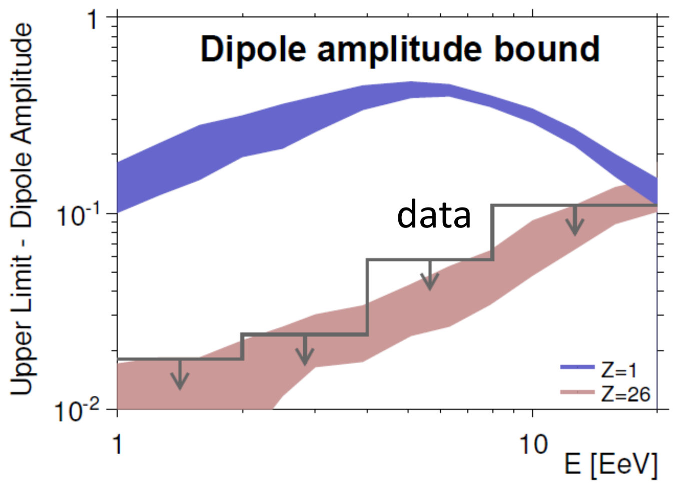


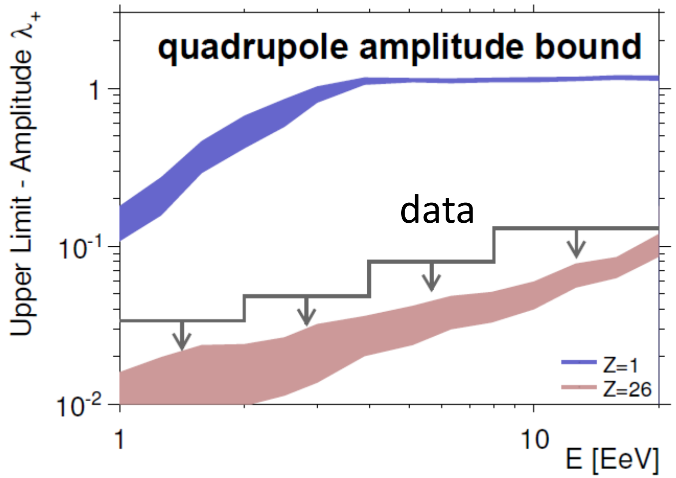
Weak correlation: ~33%
while isotropic background =21%
but
are there protons at E>55 EeV?

Large scale anisotropy



Equatorial dipole amplitude: no anisotropy seen





Galactic sources at E>1 EeV strongly disfavoured

What have we learned with Auger

The data so far indicate the main problems to be solved:

Elucidate the origin of the flux suppression, i.e. GZK vs maximum energy

measure composition into the flux suppression region – use Surface Detector for higher statistics

Disentangle composition from interaction properties

air shower physics and hadronic multiparticle production

reliable muon counting in air showers

Search for a flux contribution of protons up to the highest energies, at a level of 10%

proton astronomy up to the highest energies – composition event-by-event!

→ **<u>Need to upgrade detectors of the Pierre Auger Observatory</u>**

better EM/muon component separation

better shower modelling