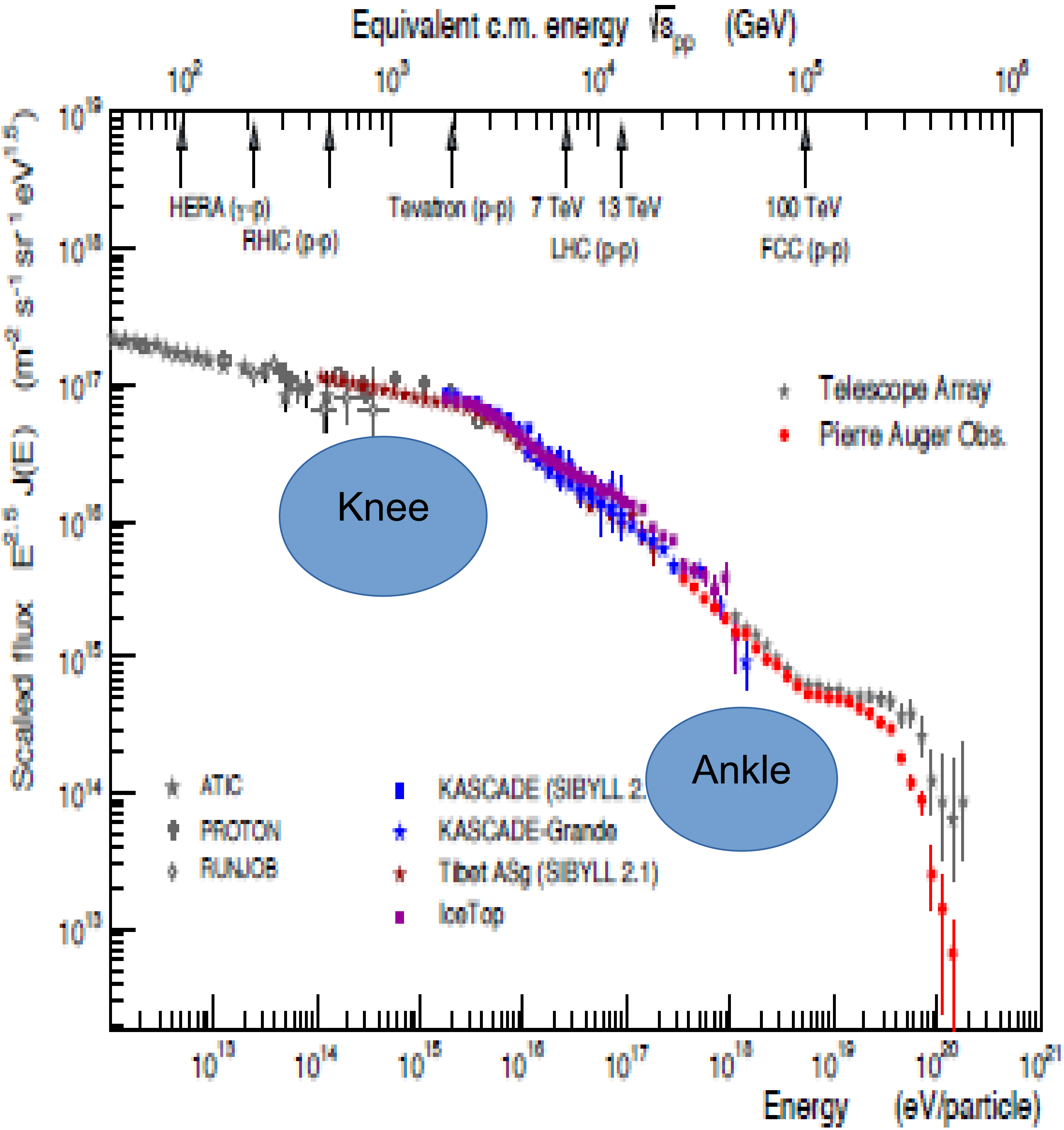
Ultra high energy cosmic rays

Analisa Mariazzi for the Pierre Auger Collaboration

IFLP - Departamento de Fisica
Universidad Nacional de La Plata

September 11-15, PIC 2018, Bogota, Colombia

Cosmic ray spectrum

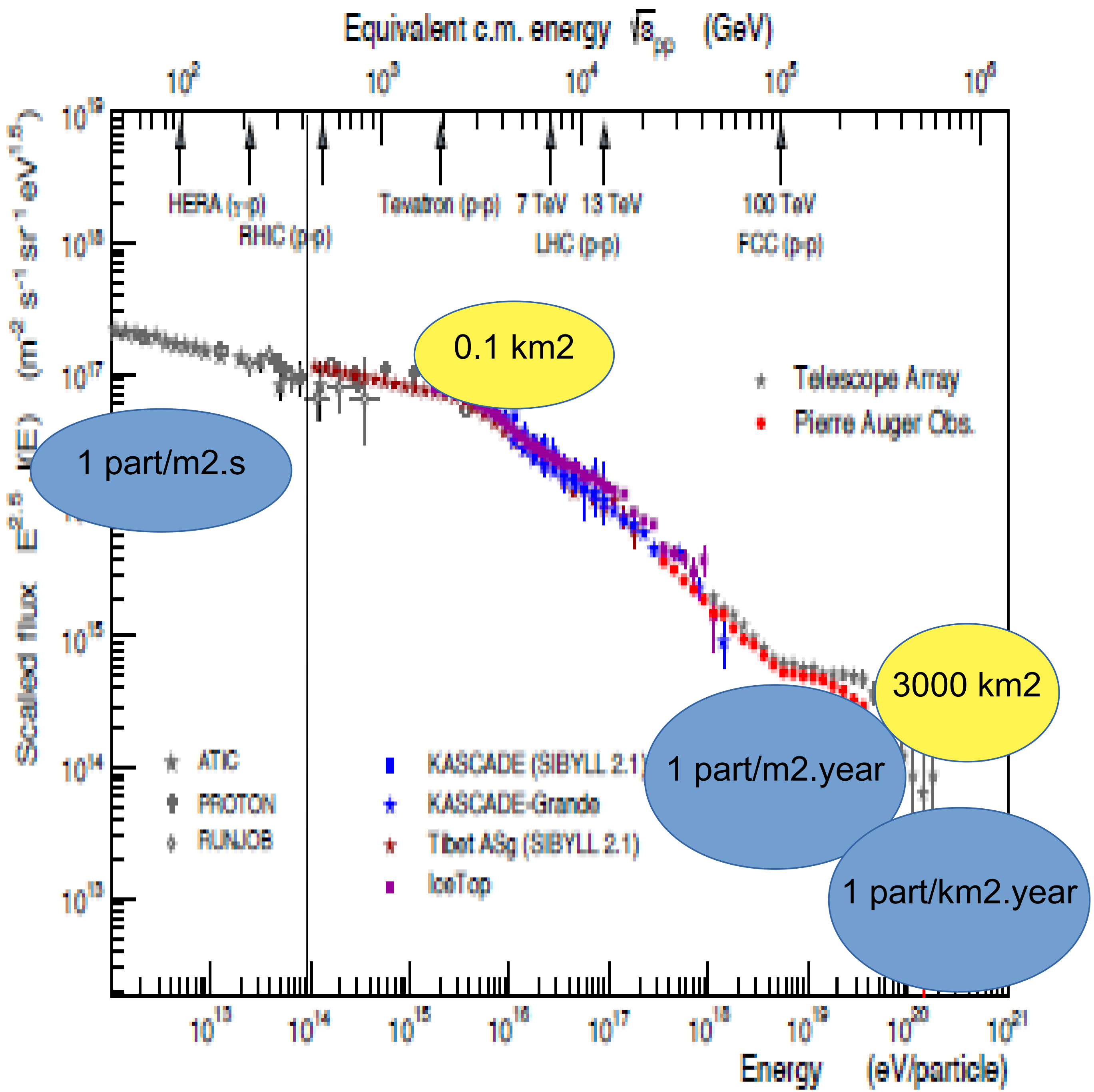


Power law index 2.7

12 orders of magnitud energy
32 orders of magnitud in flux

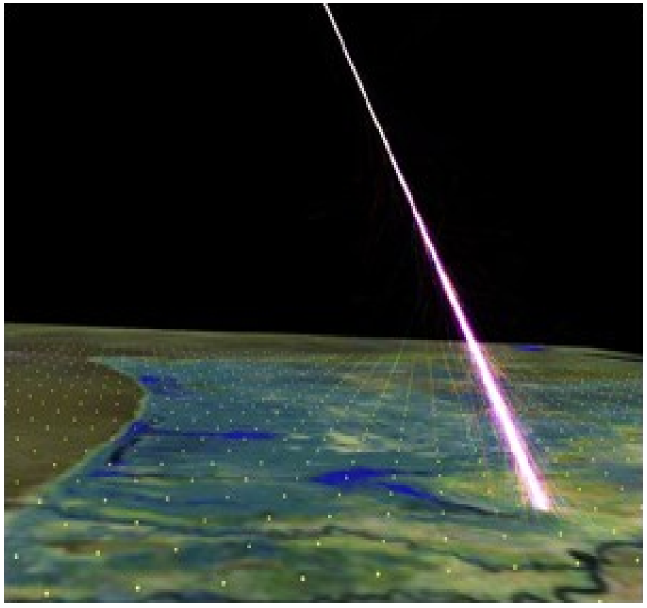
Only few features:
Knee
Ankle

How to detect cosmic rays?

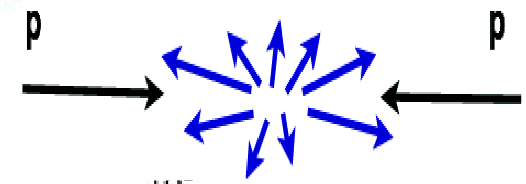


Direct detection: balloon or spacecraft measurements

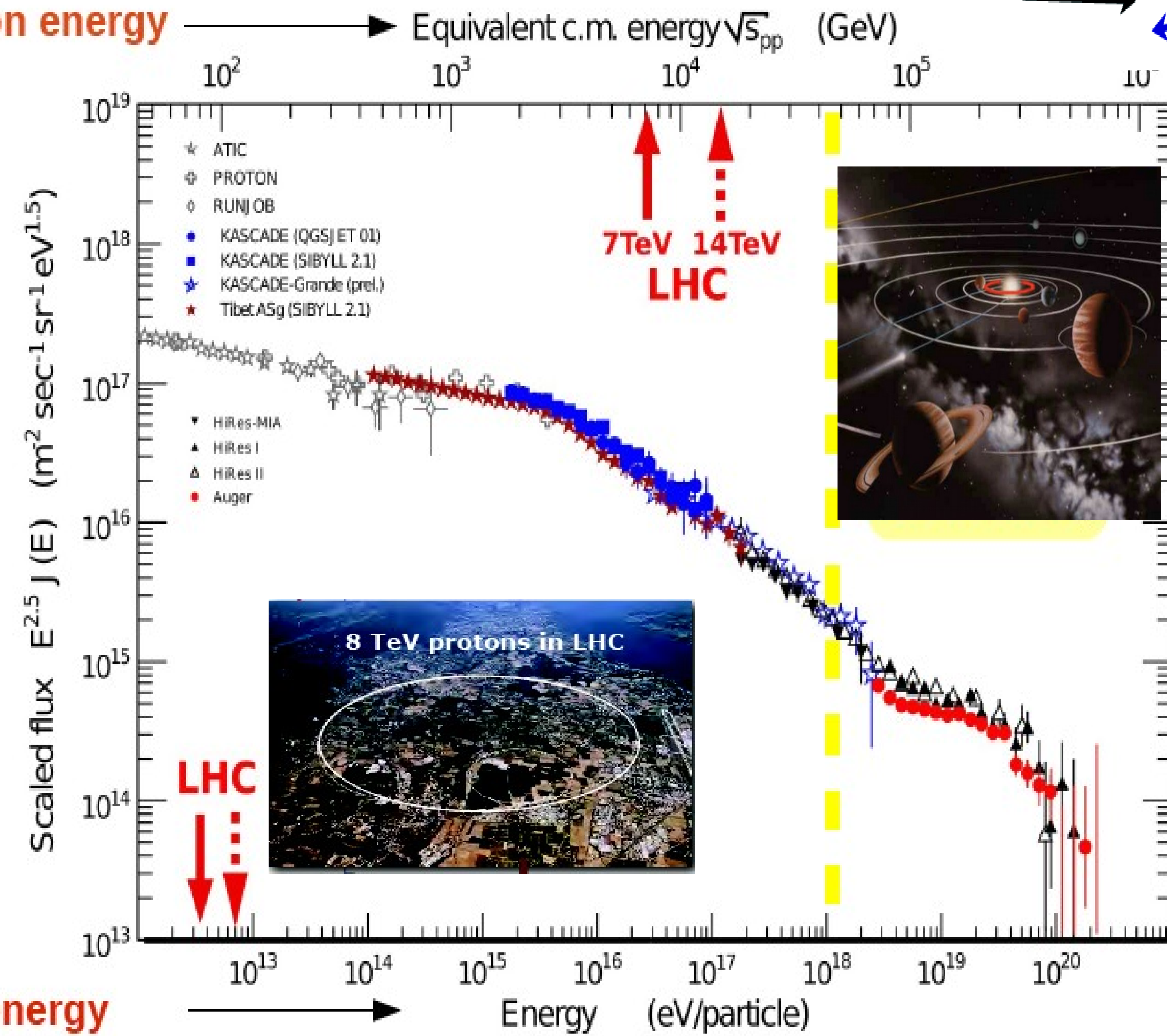
Detection via air showers measurements



Energy scale comparison: Cosmic Rays and LHC

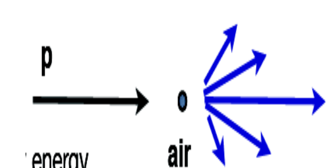


Interaction energy



Study of interactions at c.m. energy exceeding LHC reach

Beam energy



VOLUME 10, NUMBER 4 PHYSICAL REVIEW LETTERS 15 FEBRUARY 1963

EVIDENCE FOR A PRIMARY COSMIC-RAY PARTICLE WITH ENERGY 10^{20} eV†

John Linsley
Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received 10 January 1963)

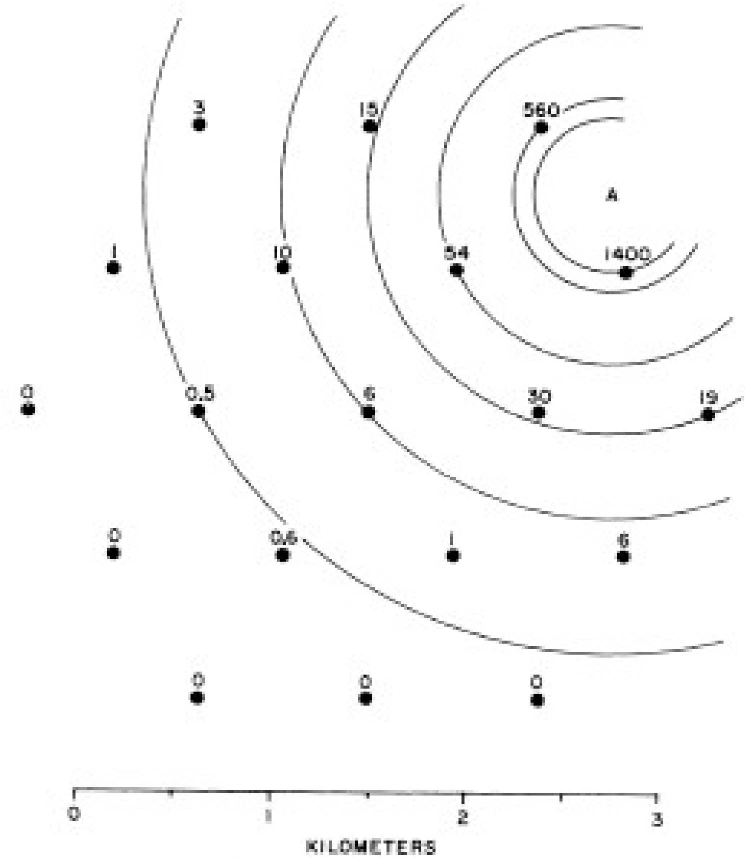
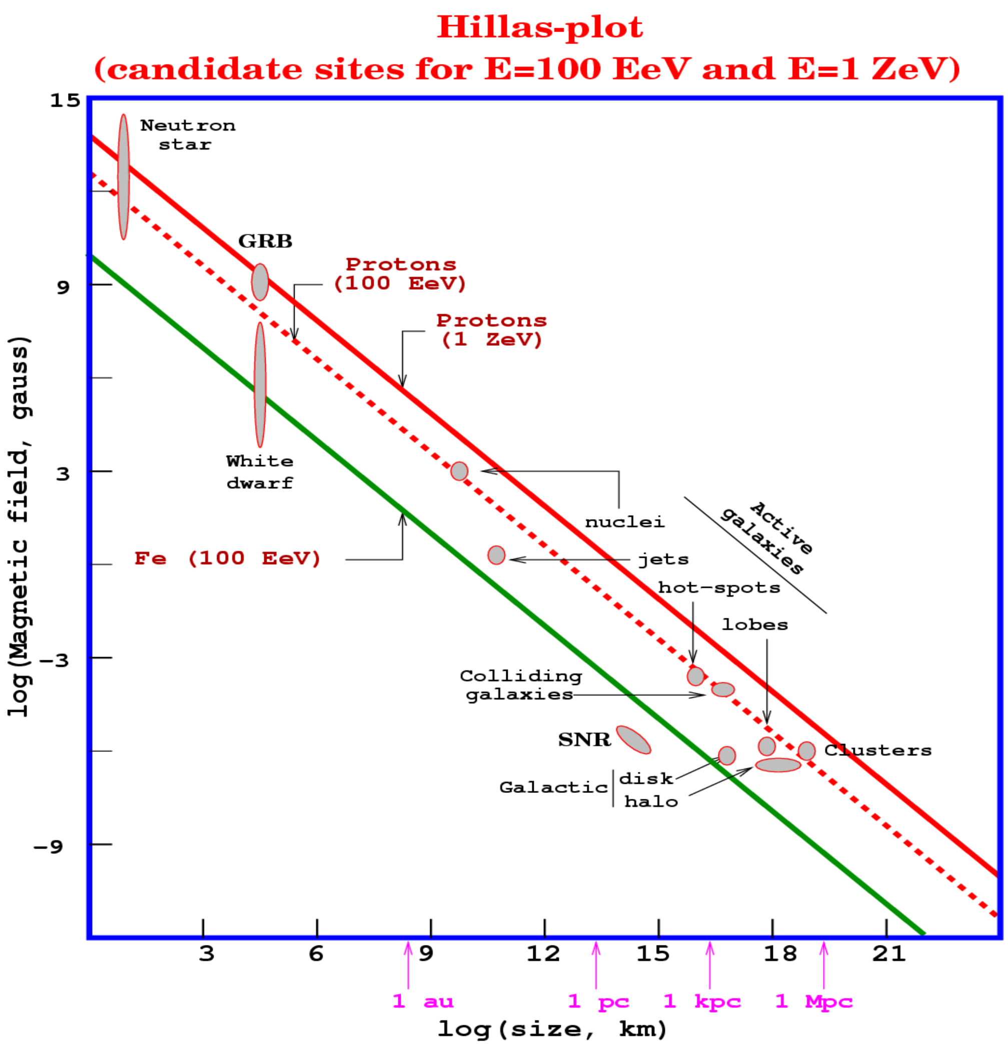


FIG. 1. Plan of the Volcano Ranch array in February 1962. The circles represent 3.3-m^2 scintillation detectors. The numbers near the circles are the shower densities (particles/m^2) registered in this event, No. 2-4834. Point "A" is the estimated location of the shower core. The circular contours about that point aid in verifying the core location by inspection.

UHECRs sources

Bottom up mechanism
Emax - Z.B.L



$E_{max} \sim$ ZBL (Fermi)

$E_{max} \sim$ ZBLΓ (Ultra-relativistic shocks-GRB)

Top down mechanism

Supermassive particle
Topological defect

↓

Expect EHE photons and neutrinos

UHECRs propagation: energy losses in the CMB

Photo-pion production

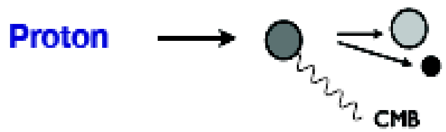
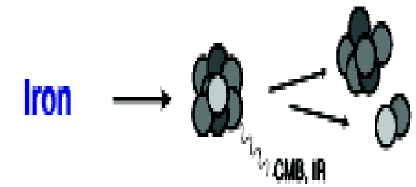
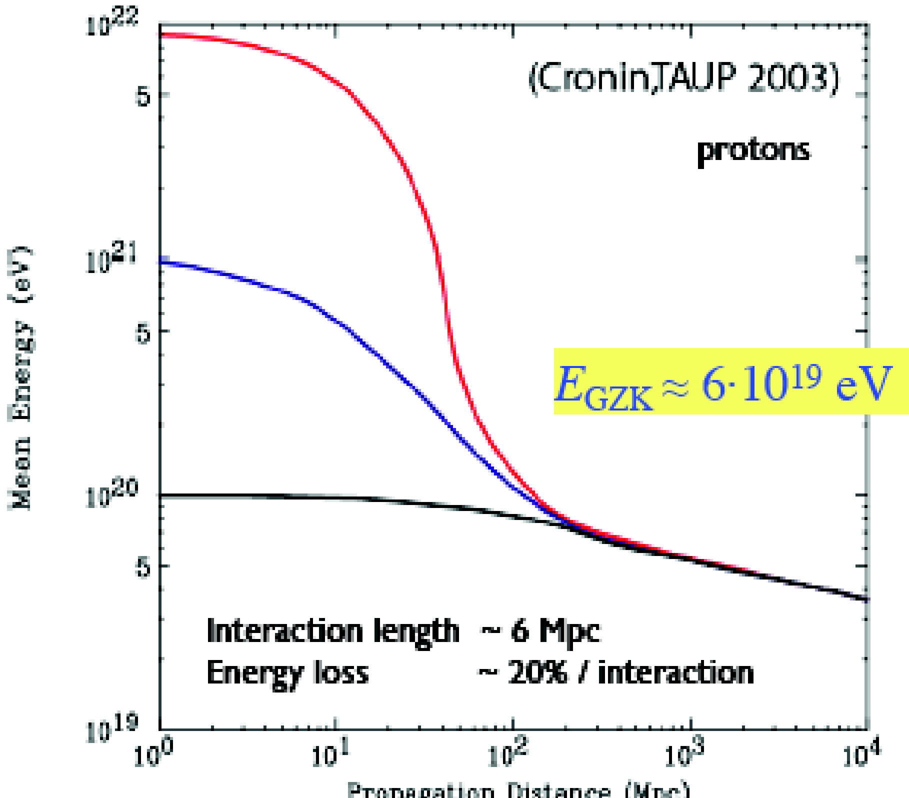
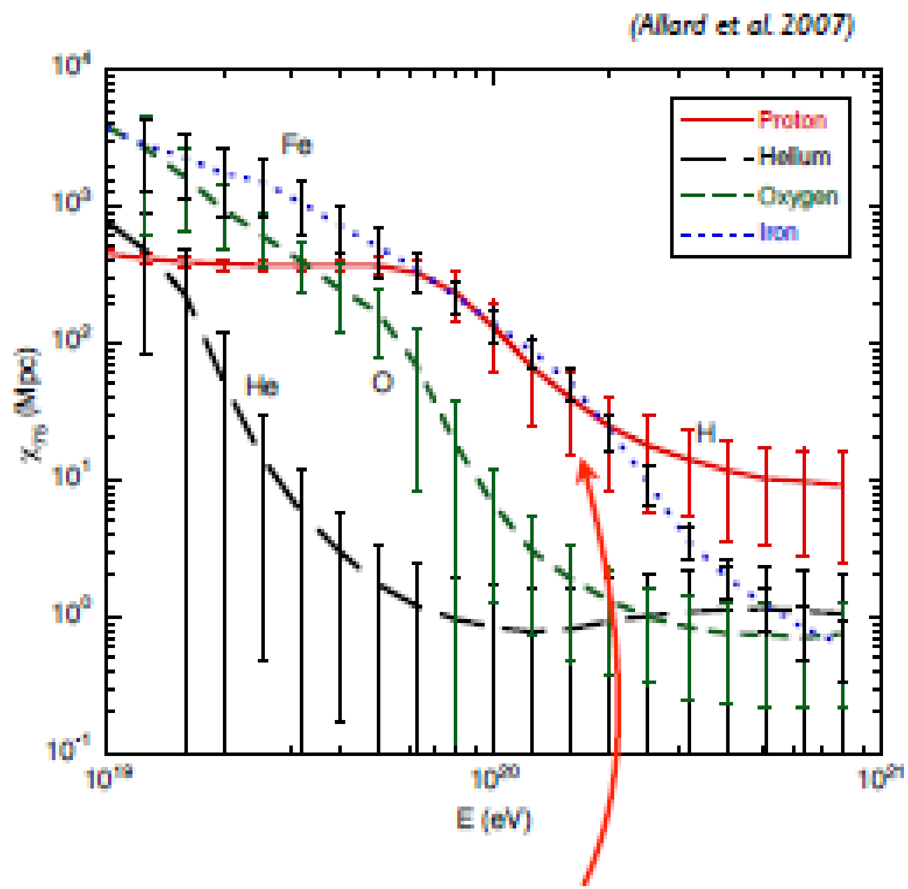


Photo-dissociation







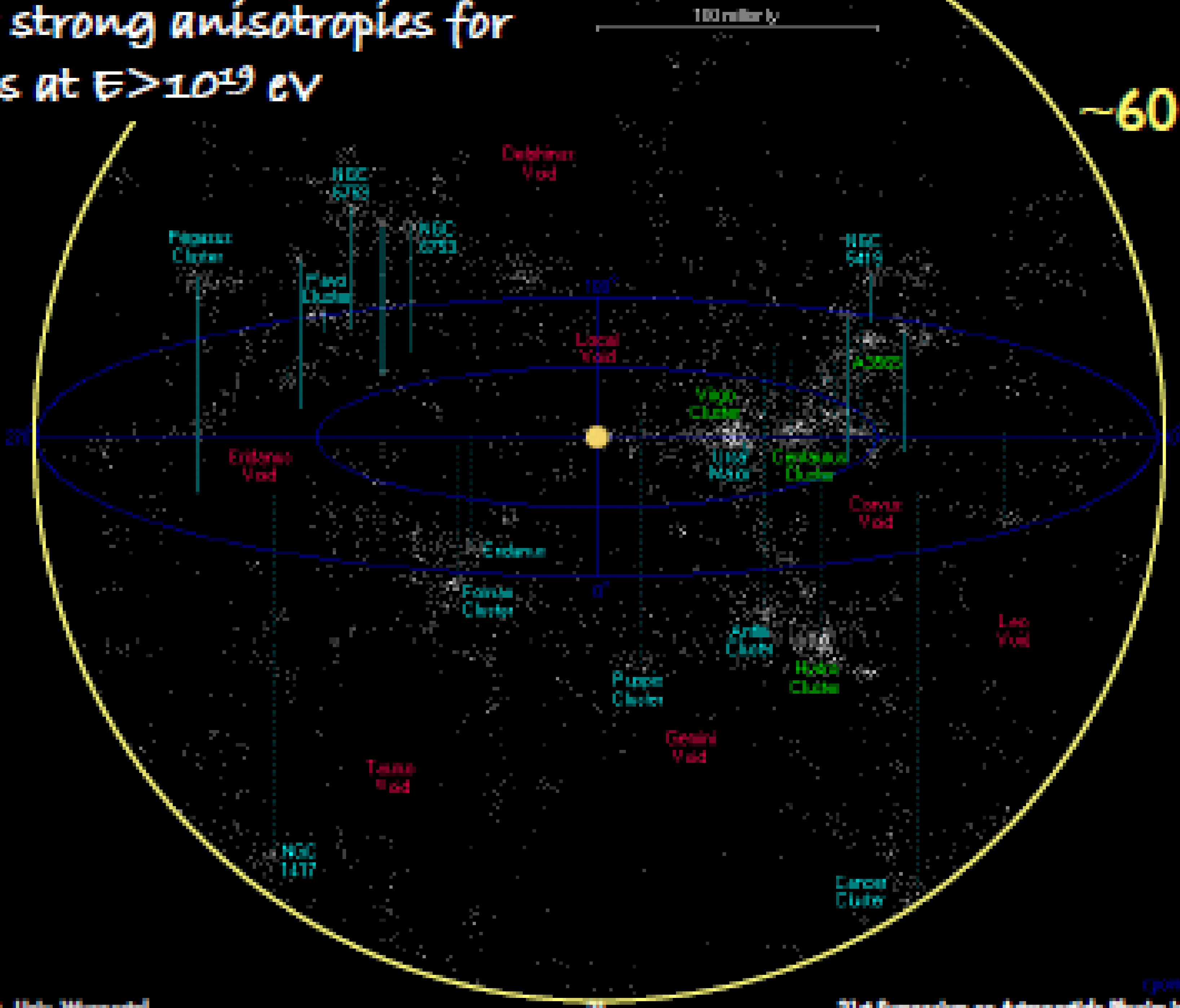
GZK cut off

Coincidence of very similar suppression energy of p and Fe

The GZK - Horizon

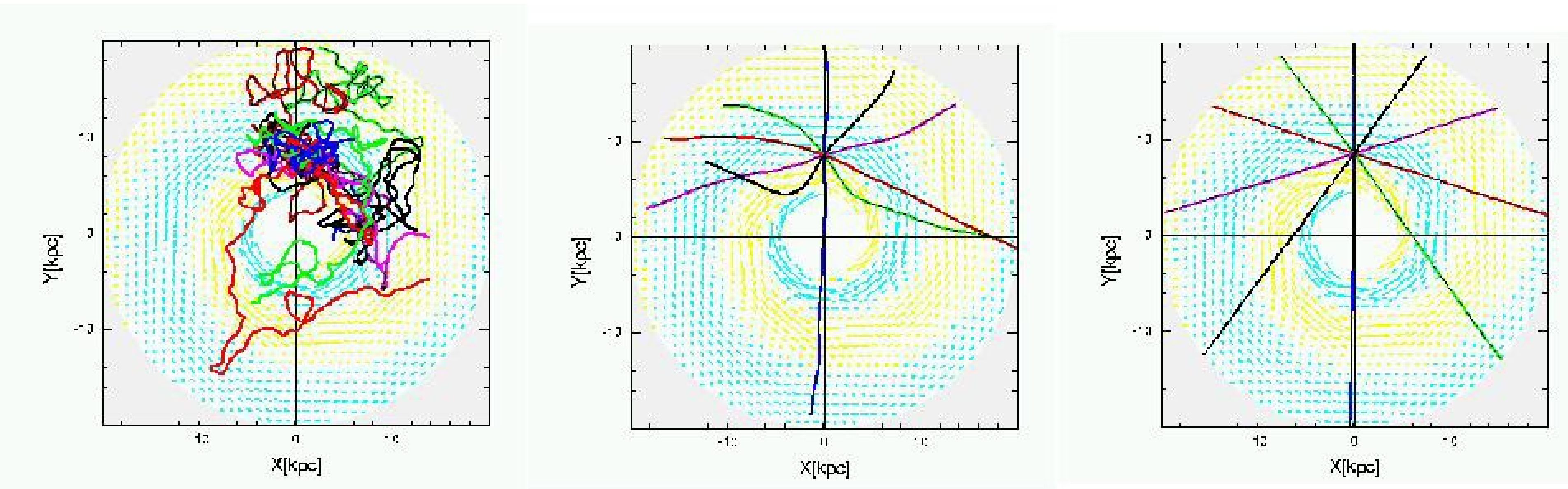
Expect strong anisotropies for protons at $E>10^{19}$ eV

~60 Mpc



UHECRs propagation: UHECR astronomy?

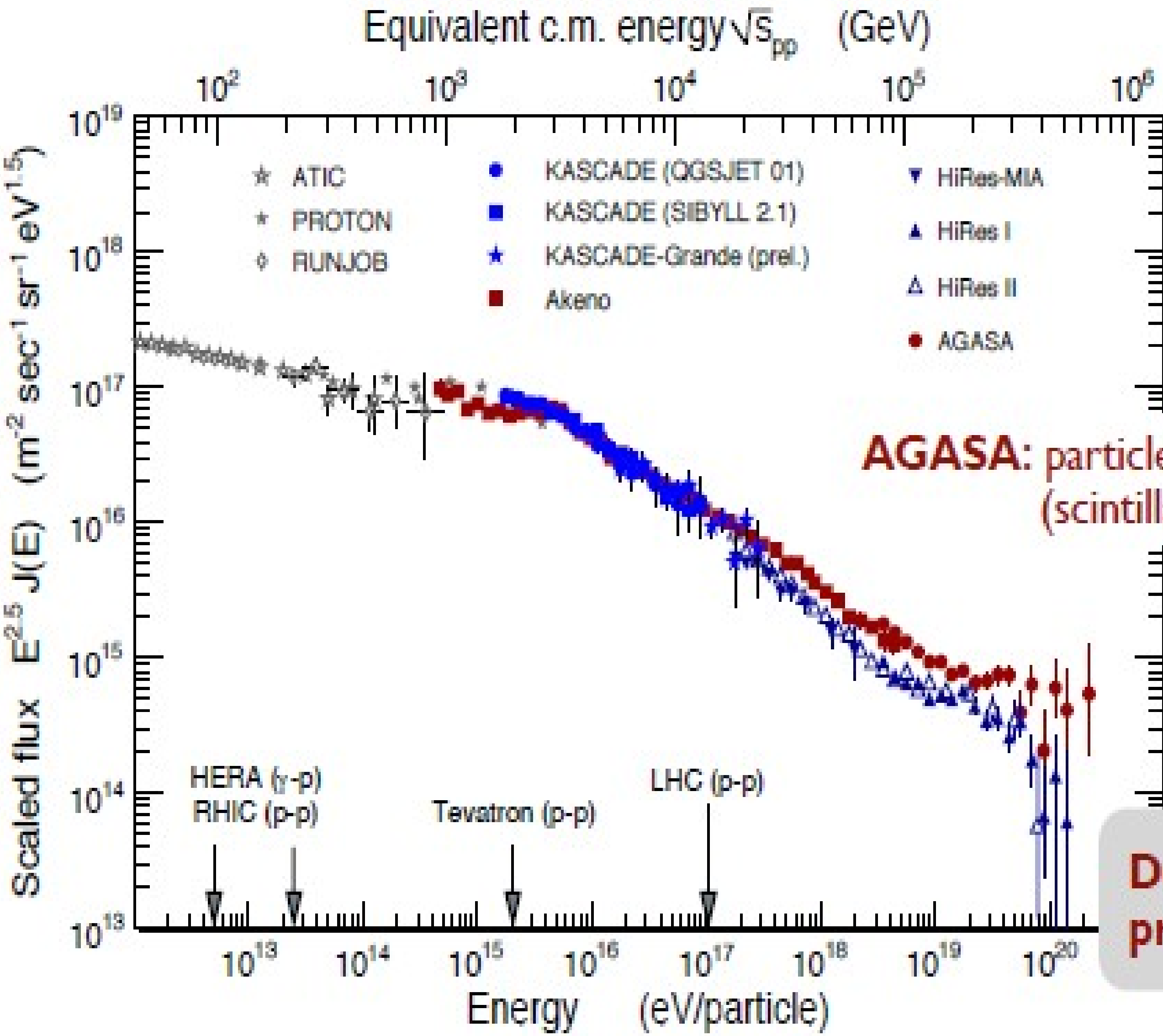
Low energy cosmic rays are deflected by galactic and extragalactic magnetic fields



10^{18} eV 10^{19} eV 10^{20} eV

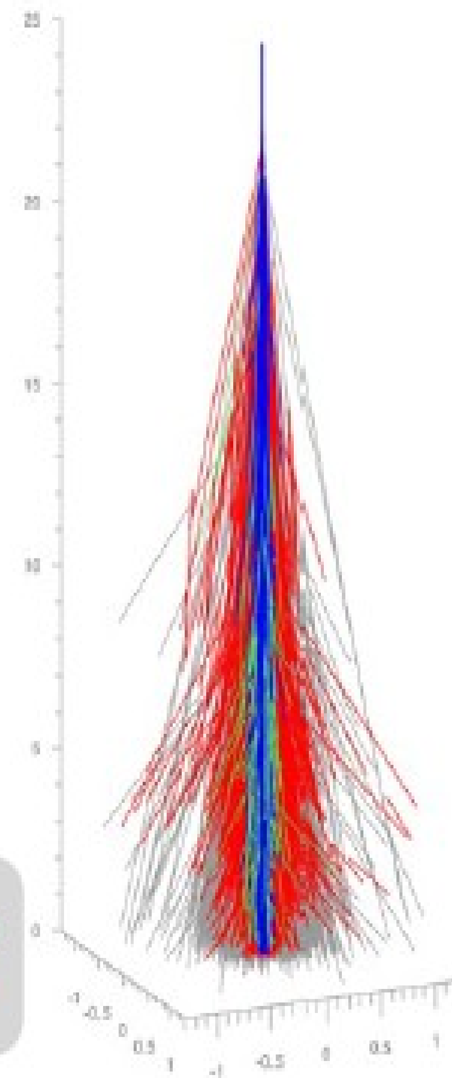
UHE protons should point to their sources

Situation before Pierre Auger Observatory:



AGASA: particles at ground
(scintillator array)

Does GZK suppression exist ?

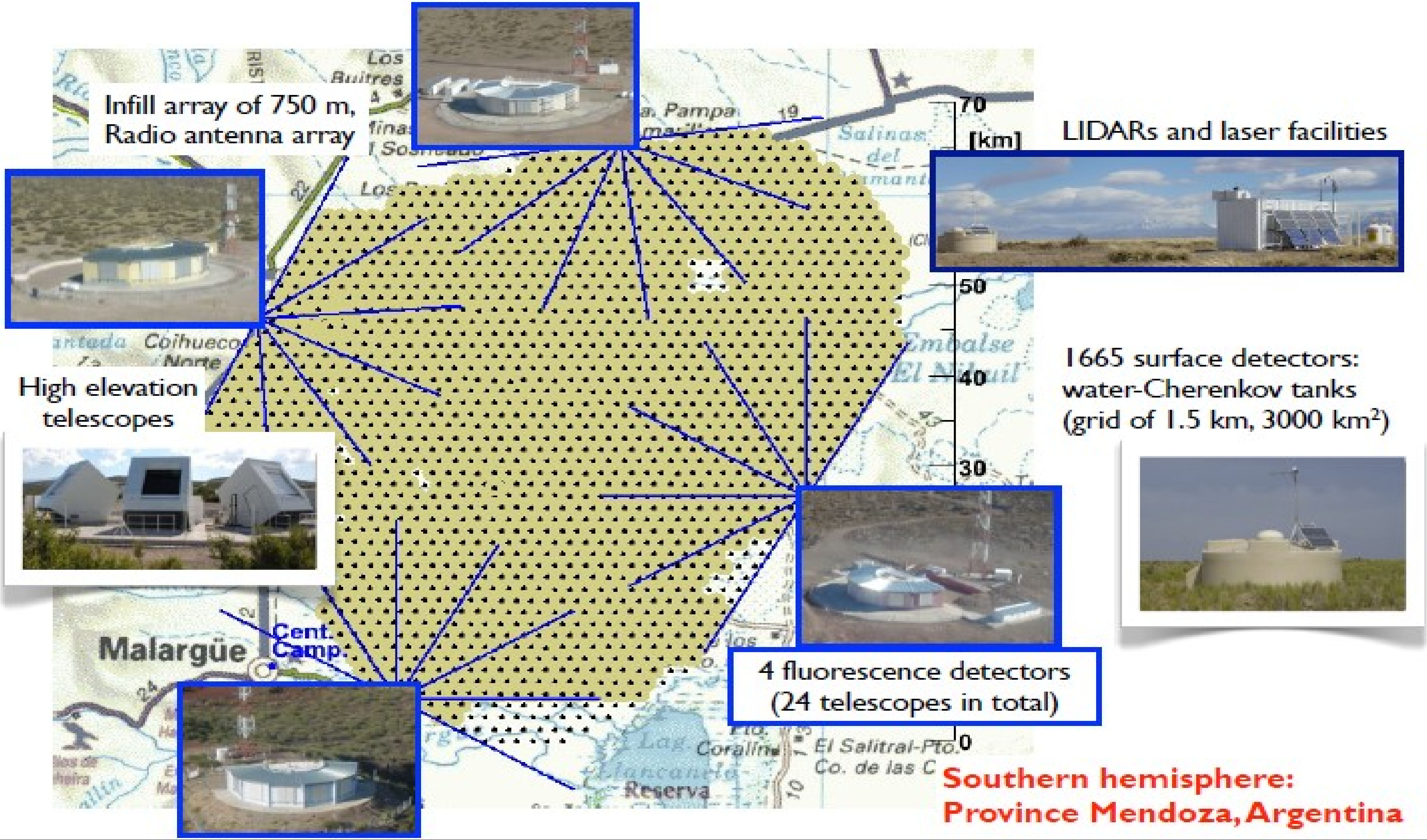


HiRes Fly´s Eye: longitudinal shower profile
(fluorescence telescopes)

- **Flux data contradictory**
- **Composition: protons ?**
- **Apparent isotropy**

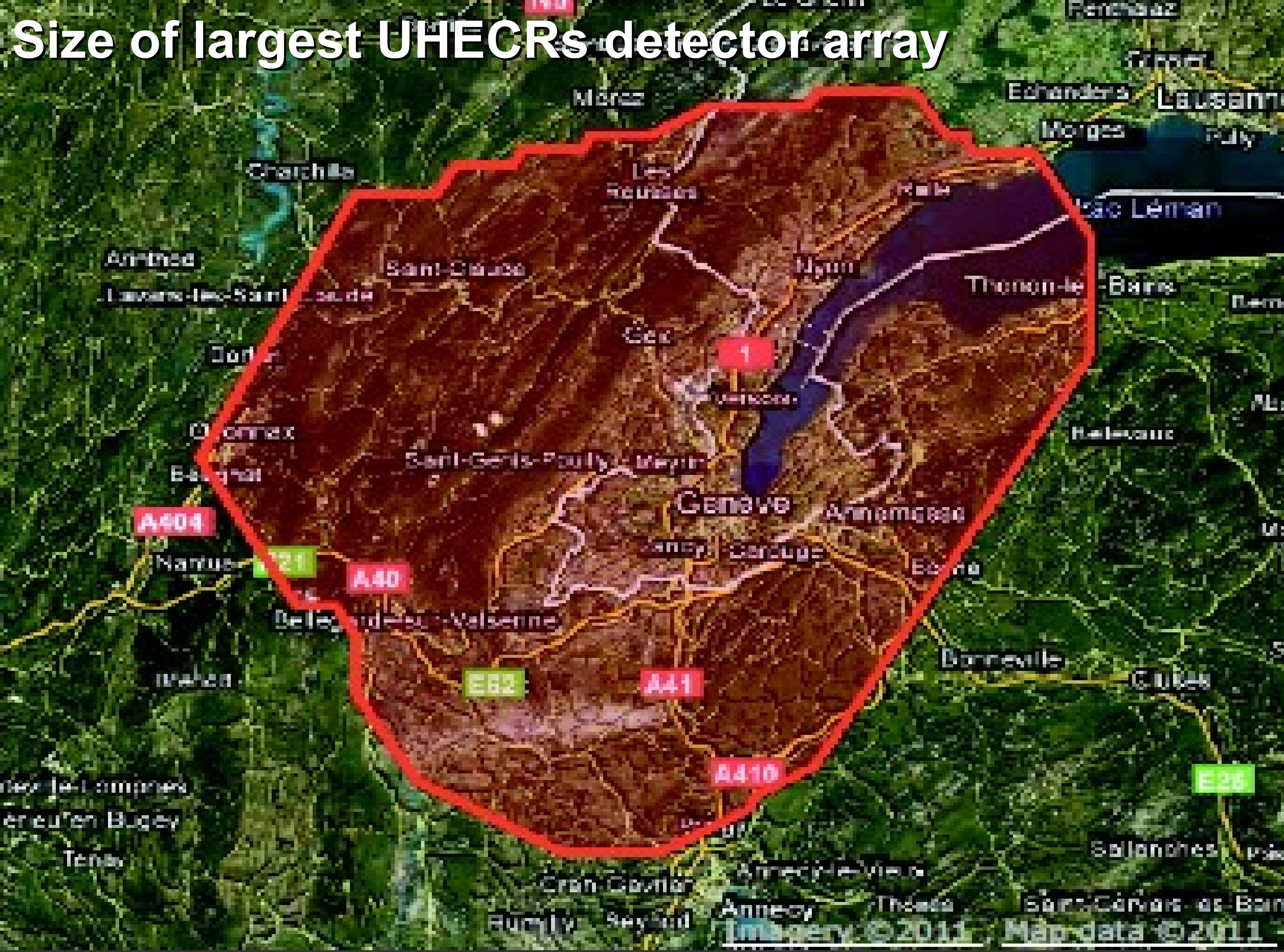
Pierre Auger Observatory

A unique and powerful design to observe ultra high energy cosmic rays and probe particle interactions at the highest energy frontier.

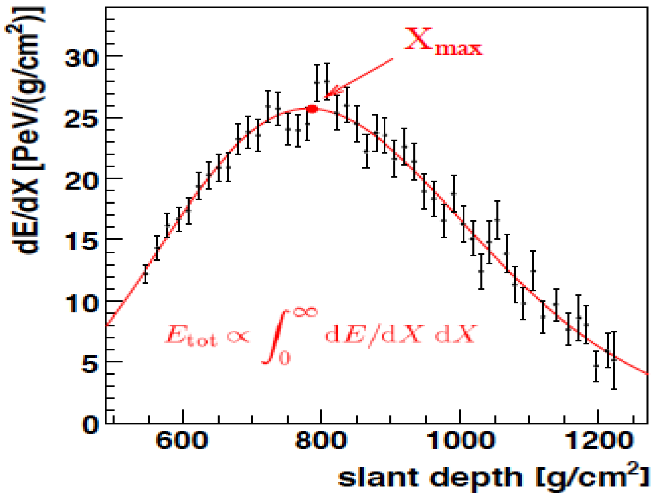


The Pierre Auger Observatory

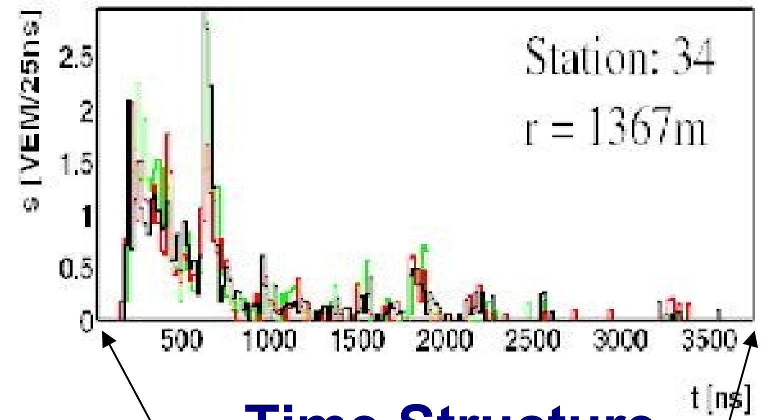
Size of largest UHECRs detector array



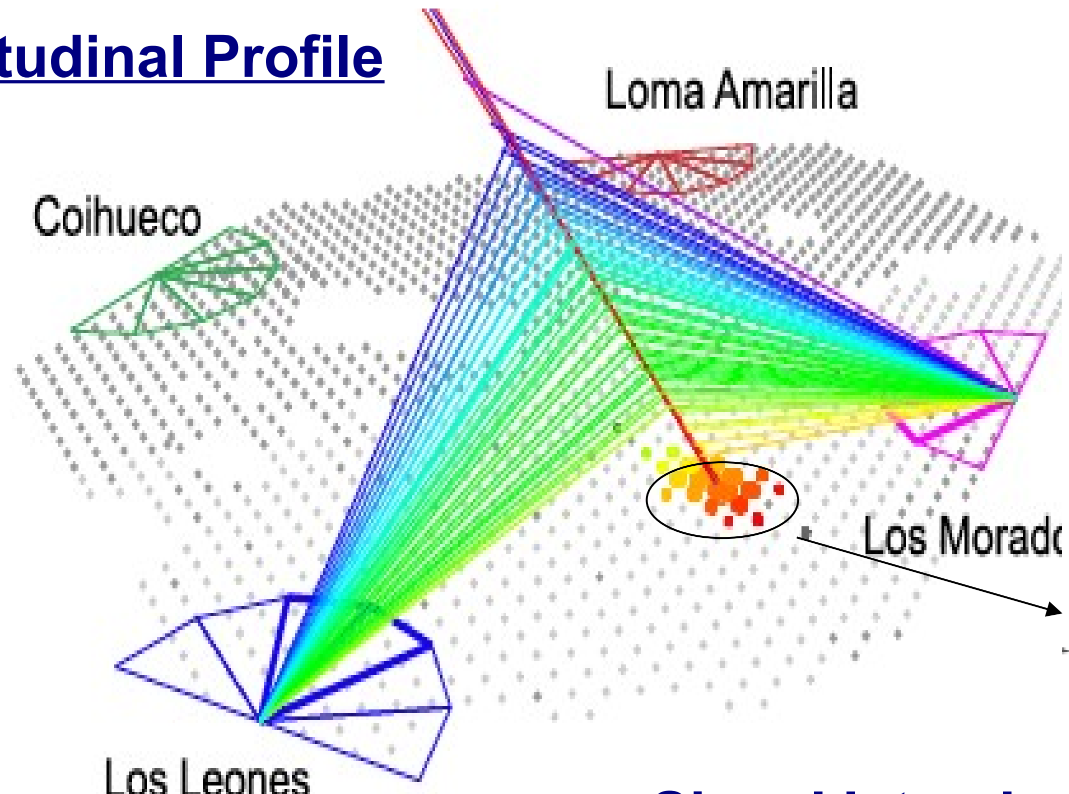
PAO detection of air showers

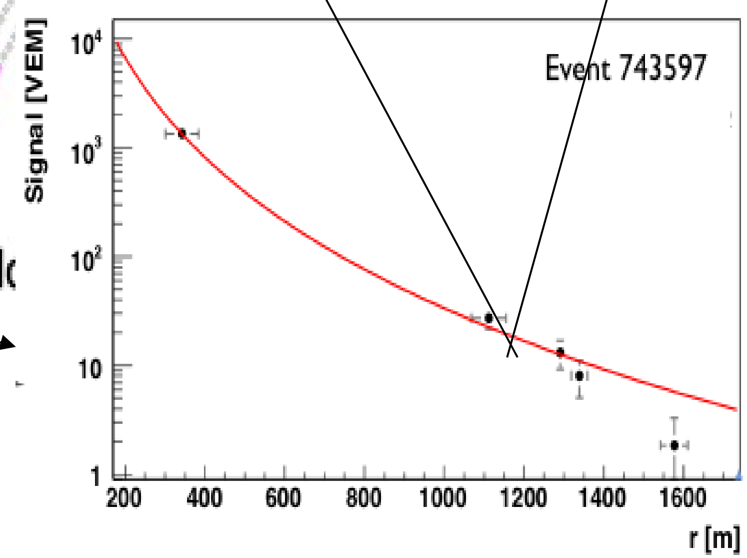


Longitudinal Profile



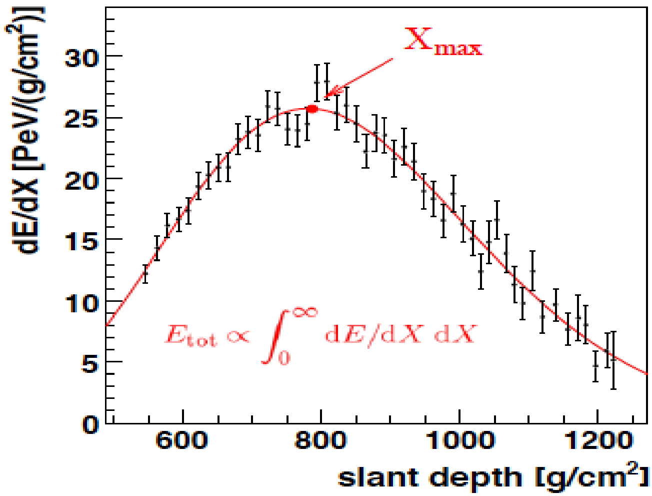
Time Structure

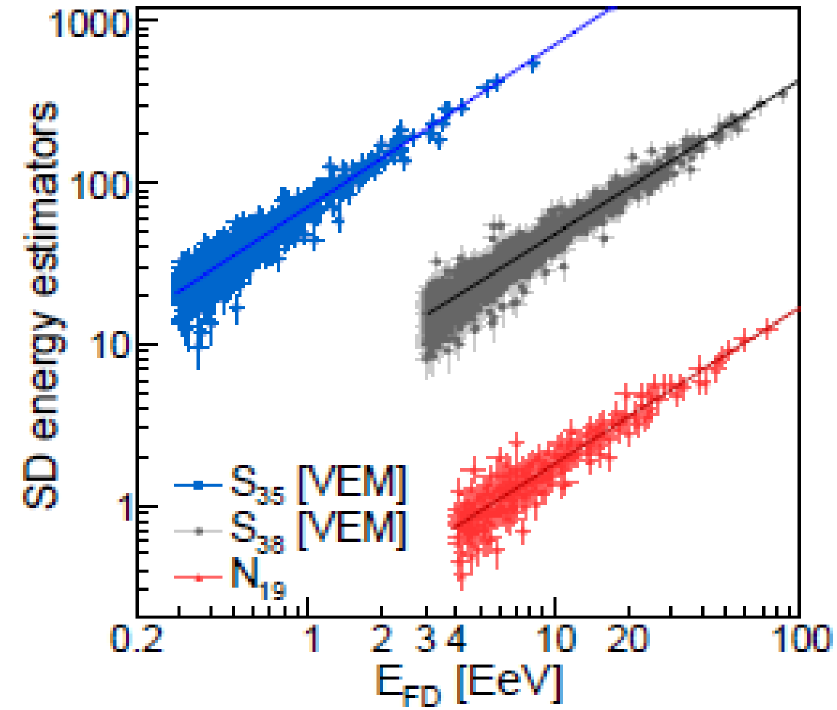




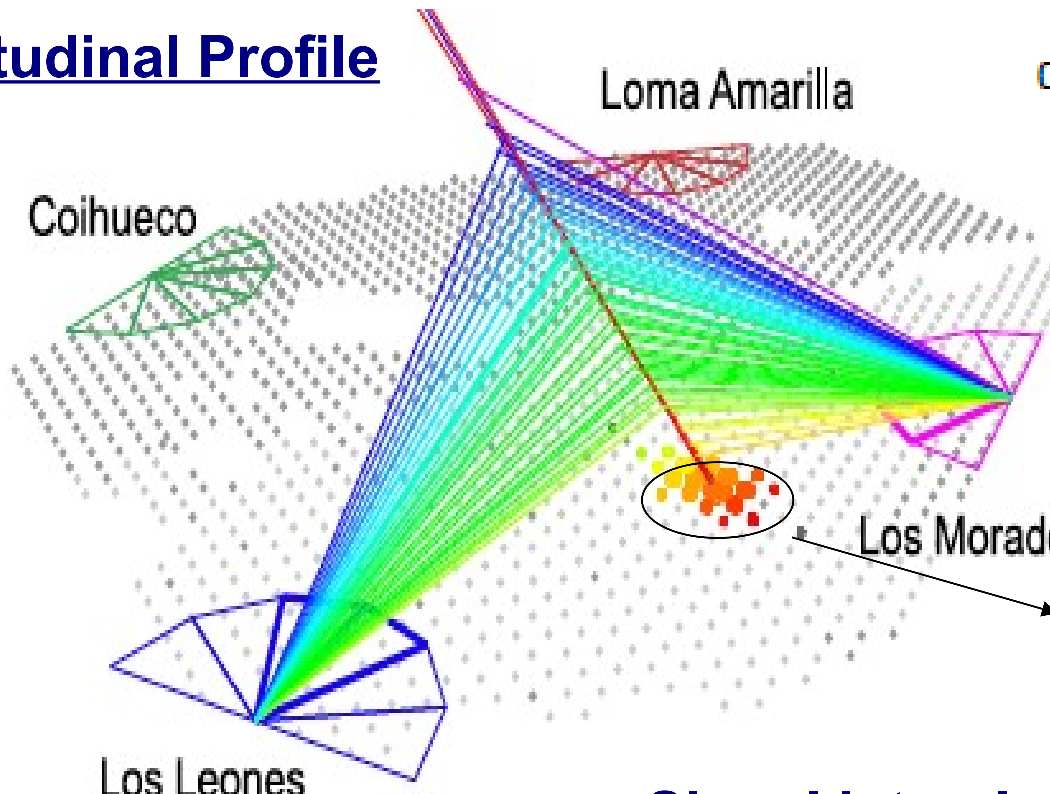
Signal lateral distribution

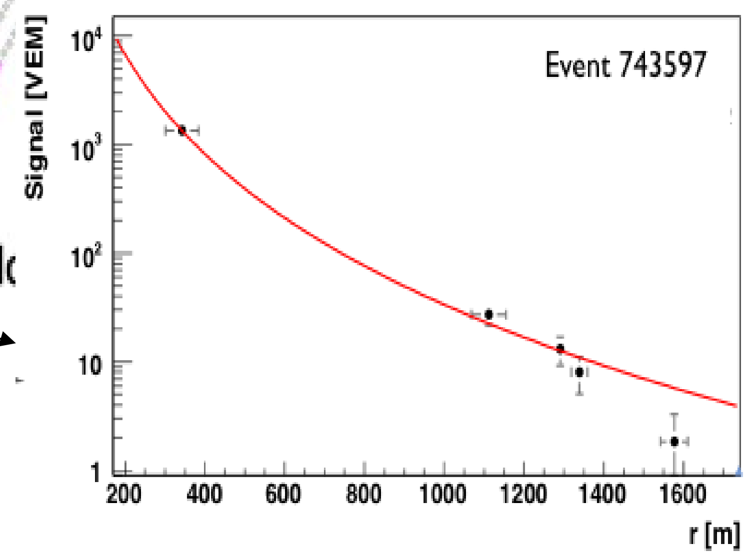
PAO energy calibration





Longitudinal Profile





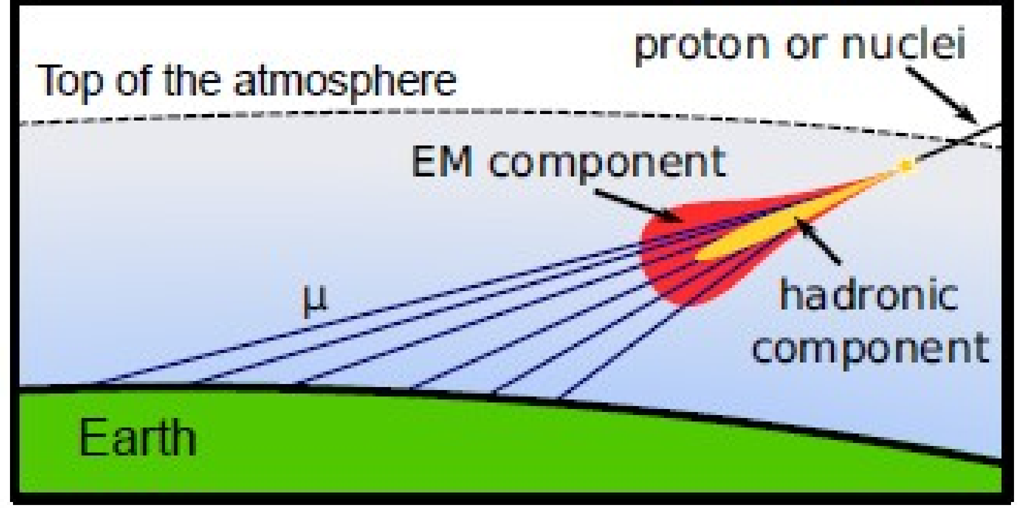
Signal lateral distribution

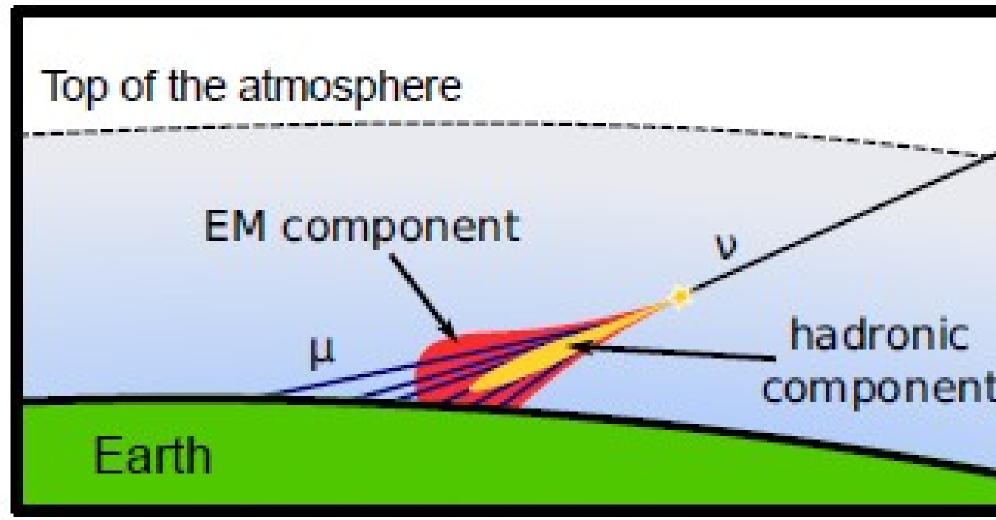
Key results from the Pierre Auger Observatory

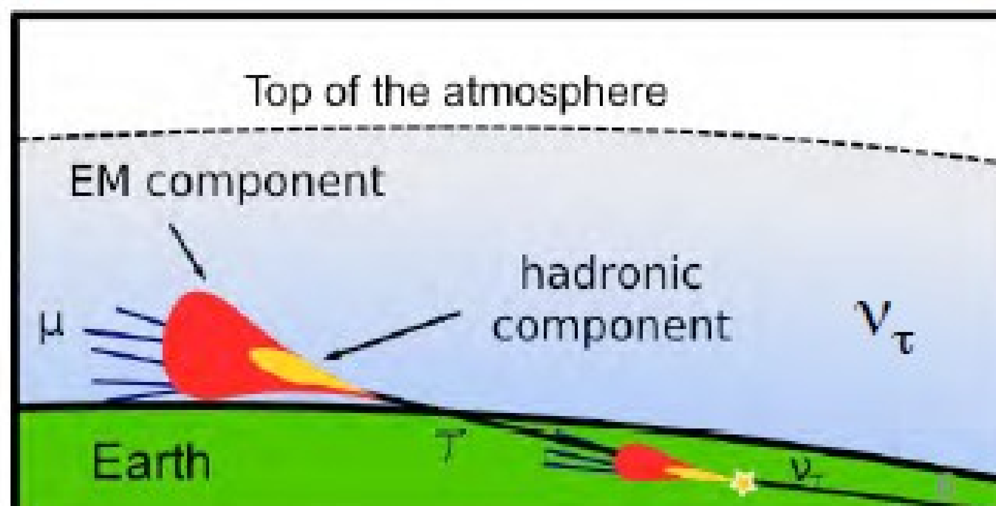
Search for EeV Neutrinos in inclined showers

- Protons & nuclei initiate showers high in the atmosphere.
  - Shower front at ground:
    - mainly composed of muons
    - electromagnetic component absorbed in atmosphere.
- Neutrinos can initiate "deep" showers close to ground.
  - Shower front at ground: electromagnetic + muonic components

Searching for neutrinos ⇒ searching for inclined showers with electromagnetic component

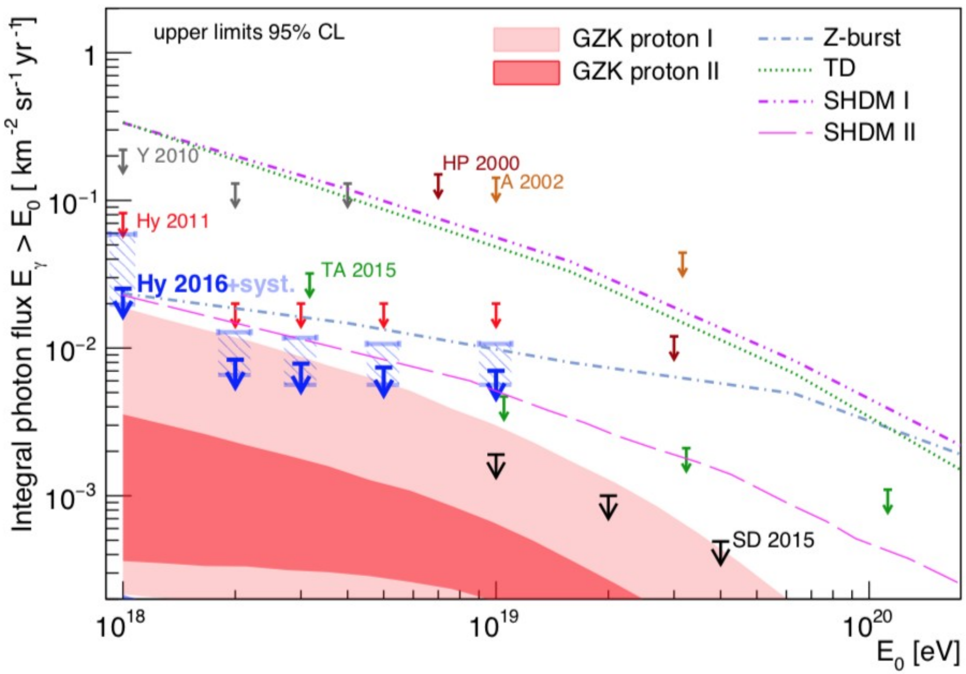


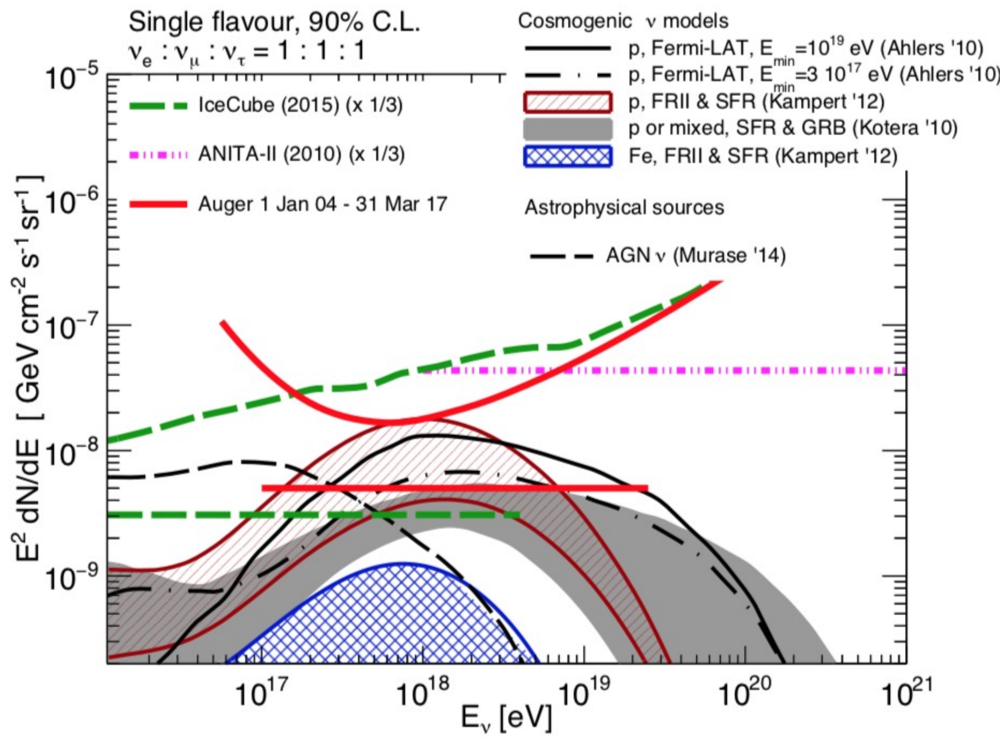




UHECRs sources: Bottom up vs. Top down

Top down model for UHECRs rejected by neutrino and photon limits





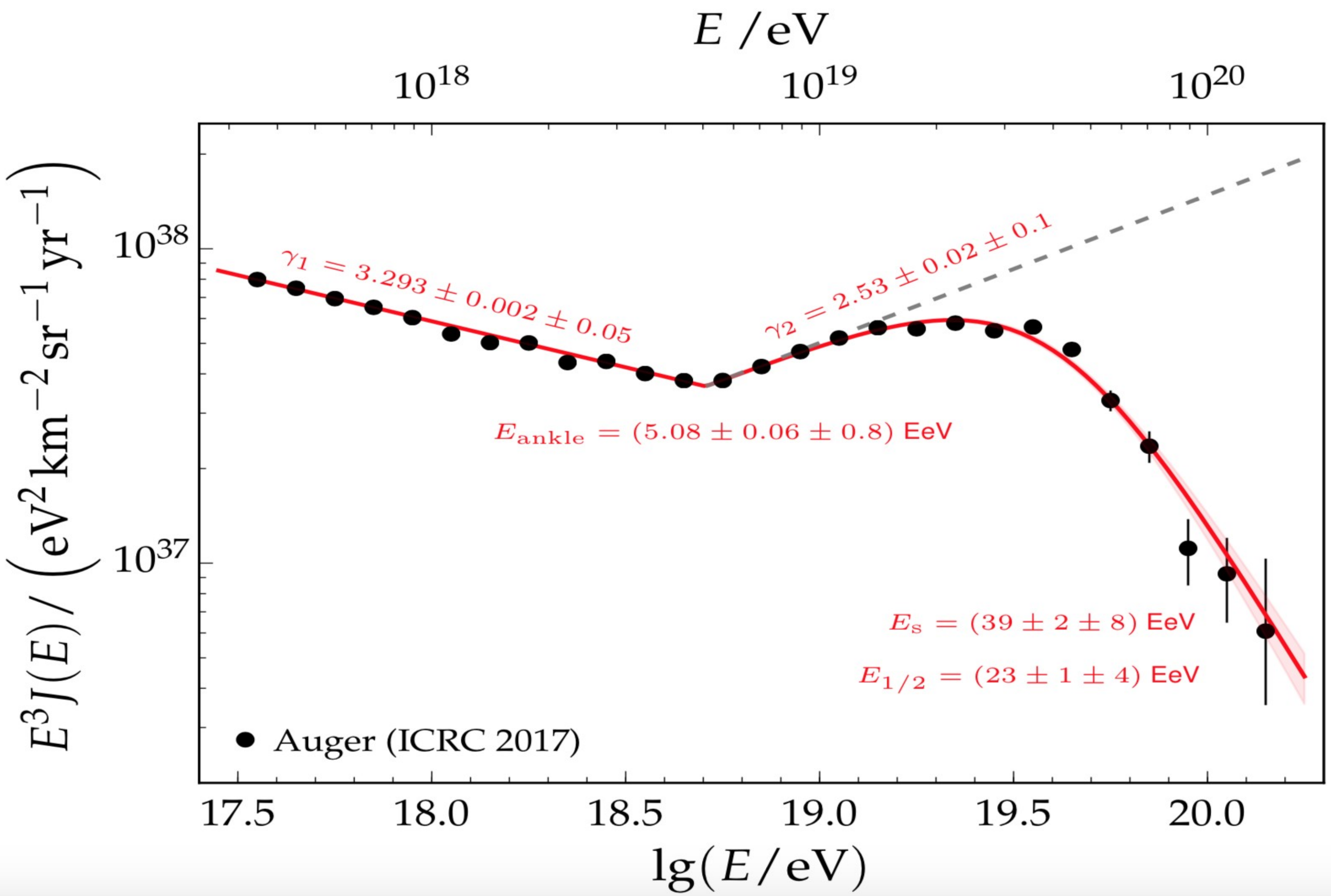
Photons vs Hadrons showers

- **Higher value of the Xmax**
- **Lower average number of muons**
- **Steeper LDF and consequently a smaller footprint at ground.**

Down-going (all flavors) neutrinos that develop deep in the atmosphere generating inclined showers and triggering the Auger surface detector can be identified provided their zenith angles exceed 60 degrees.

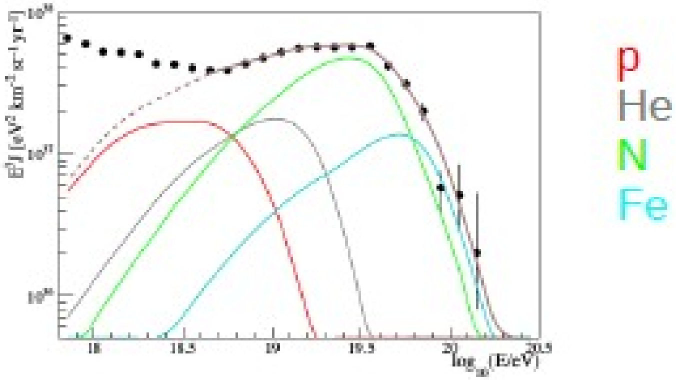
Tau neutrinos entering the Earth with a zenith angle close to 90 degrees can interact and produce a tau lepton that decays in the atmosphere inducing an "upward-going" shower that triggers the surface detector.

Energy spectrum ICRC2017

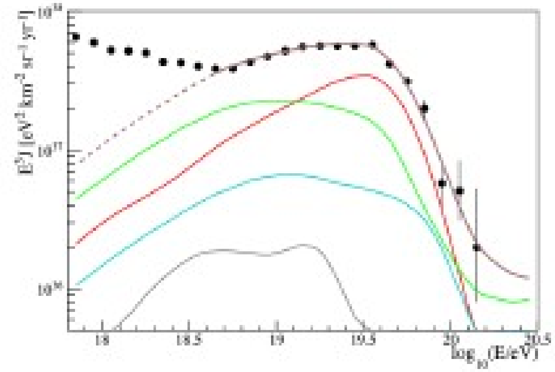


Flux suppression confirmed (CL > 20 sigma)
But why? GZK effect or exhaustion of sources ?

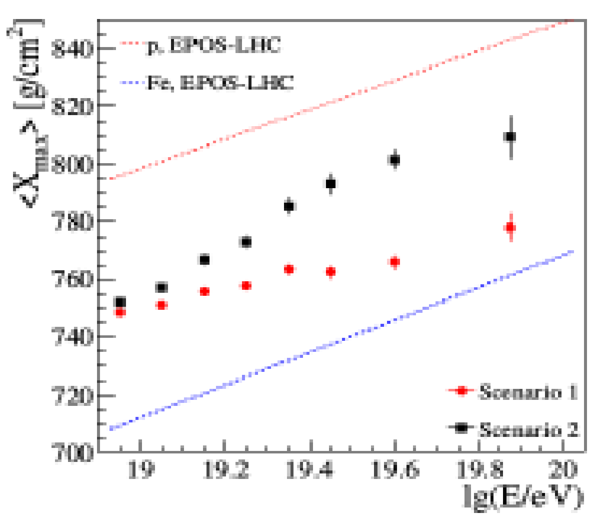
Astrophysical sources

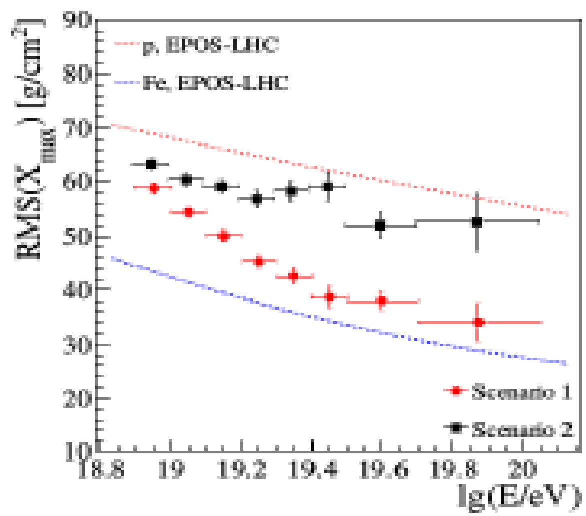


Scenario 1
Maximum rigidity: $E < ZE^{p}_{maz}$

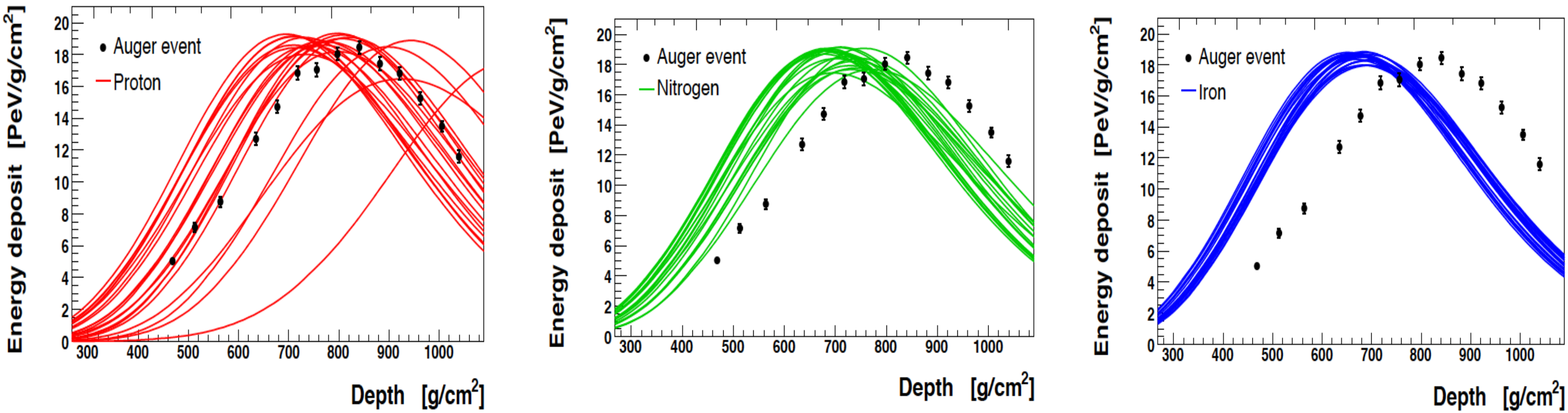


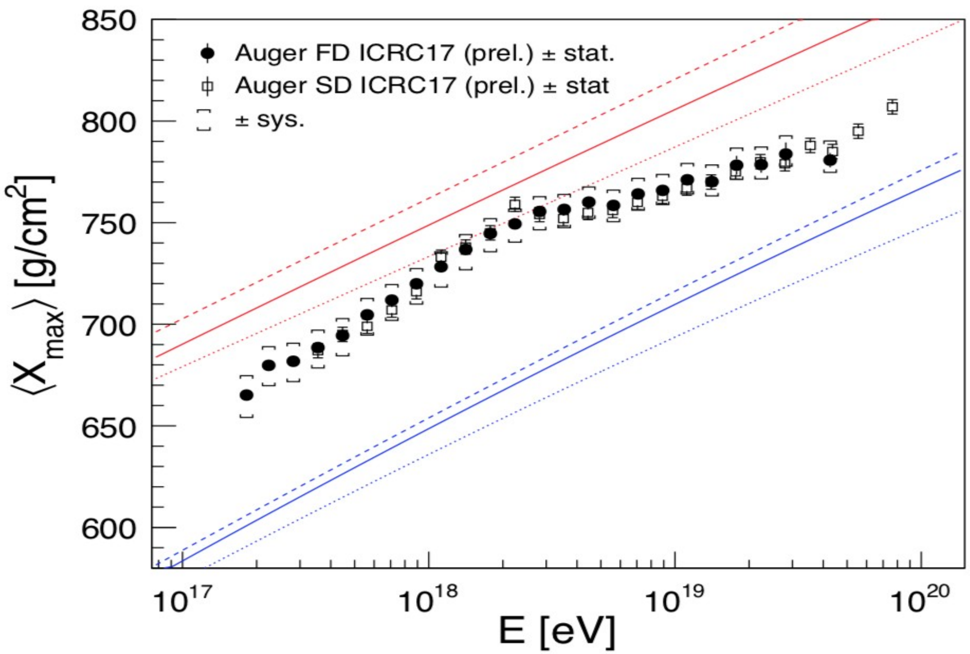
Scenario 2
Photo-disintegration

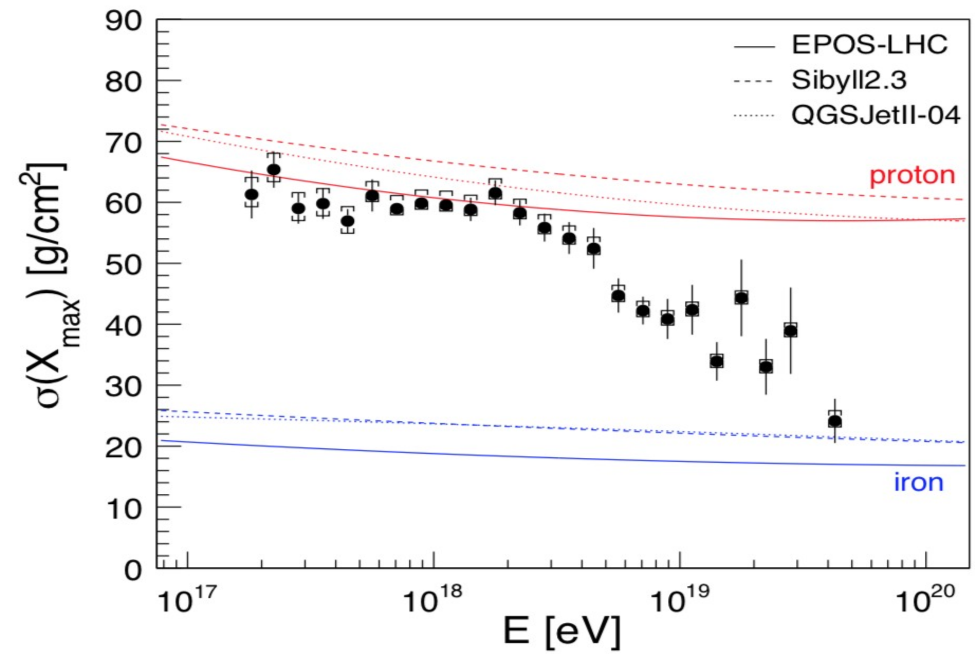




Mass composition: mean and fluctuations of depth of maximum development of the shower (Xmax)



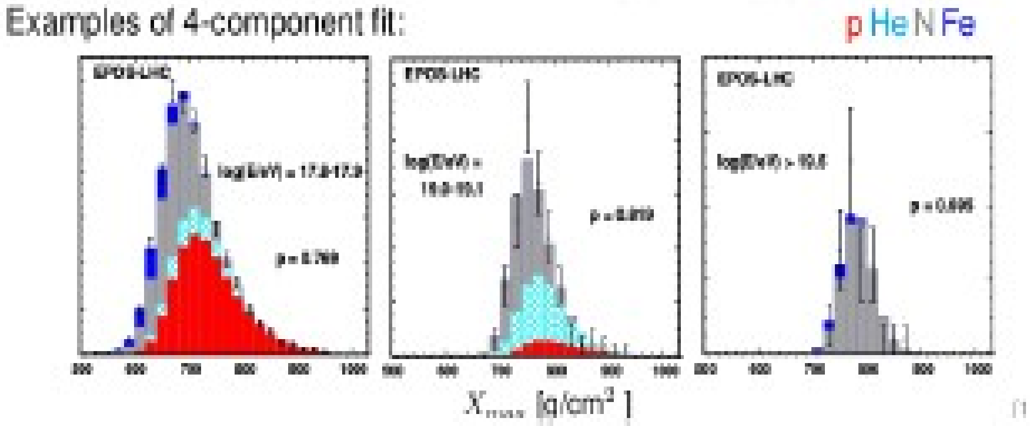


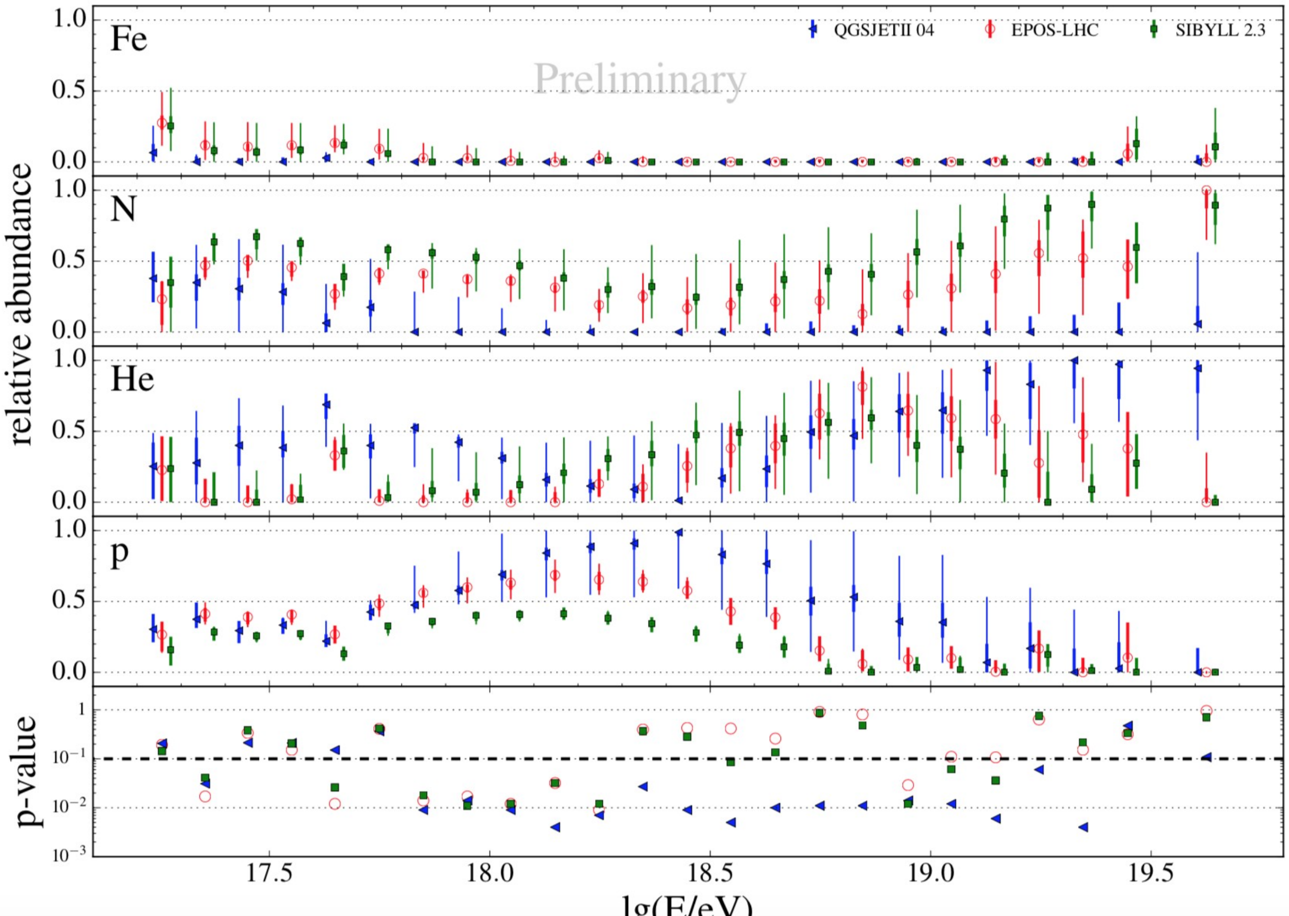


Lines from post-LHC models

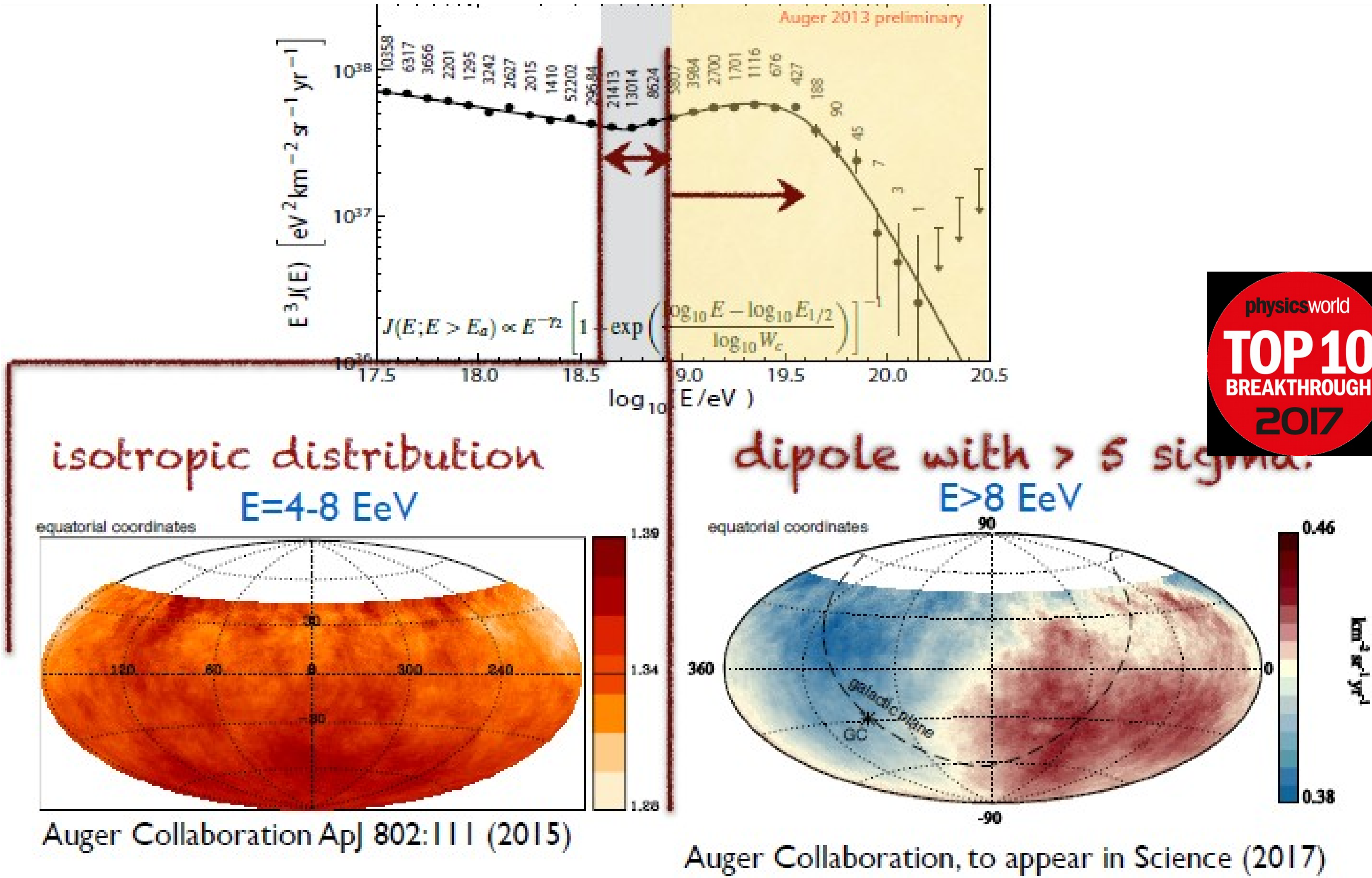
Composition trend changes around ankle. UHECR heavy

4 components fit to Xmax distributions





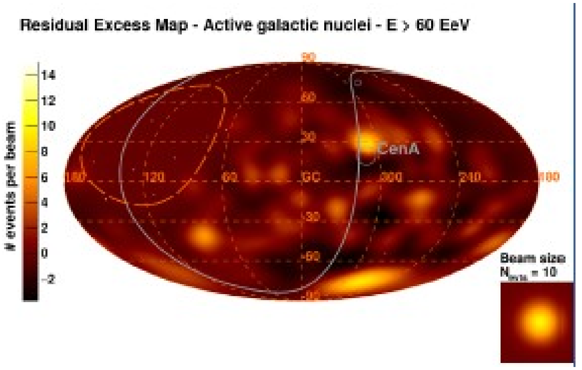
Arrival directions of UHECRs

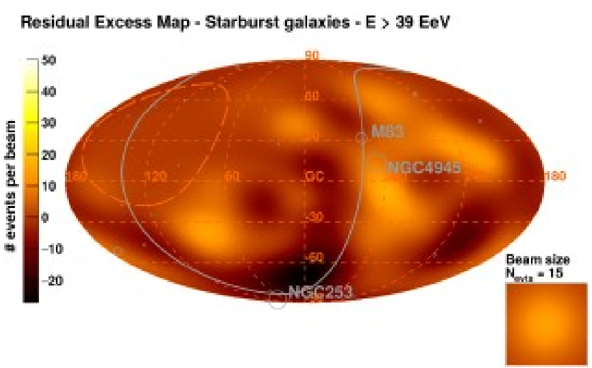


physicsworld TOP 10 BREAKTHROUGH 2017

Dipole in galactic coordinates

Arrival directions highlights from Auger

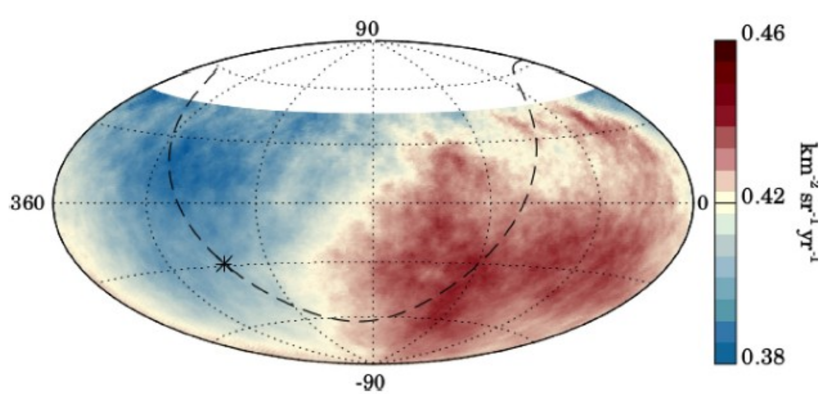




Centaurus A 3 σ excess E > 60 EeV

AGN 2.7 σ excess E > 63 EeV

Stabusrst galaxies 4 σ excess E > 39 eV

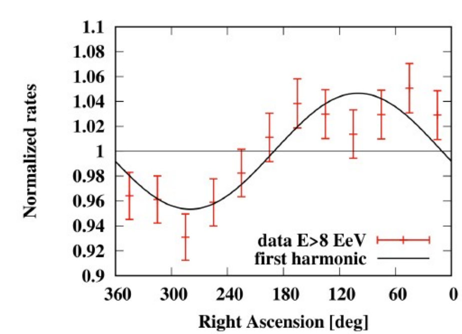


Equatorial coordinates - Hammer projection - E > 8 EeV
* Galactic center
- - - Galactic plane

Extragalactic origin favoured

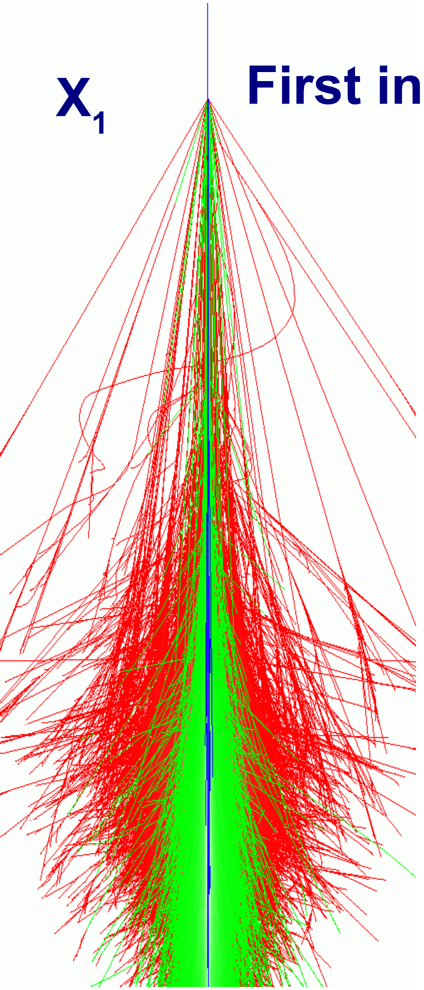
Anisotropy at 5,2 σ level, E > 8 EeV

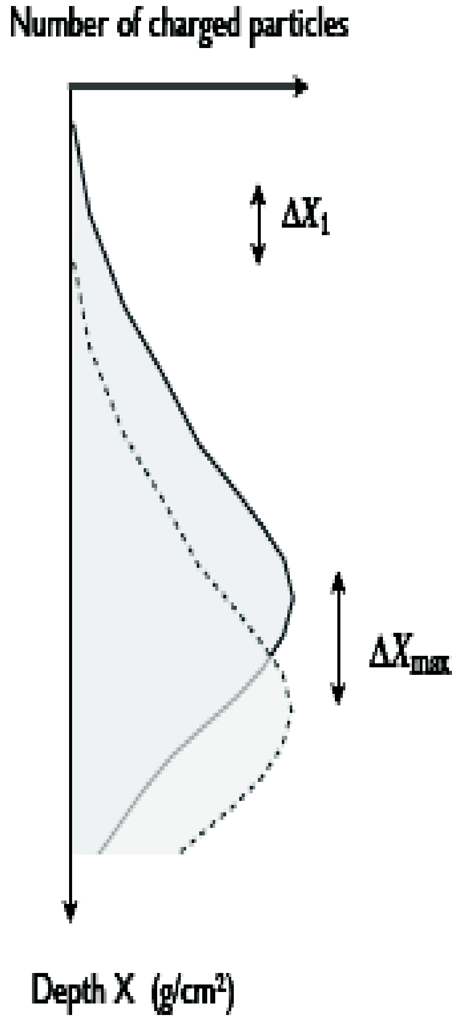
Dipole fits the data.



Proton-air cross section from air showers

X_1 First interaction depth



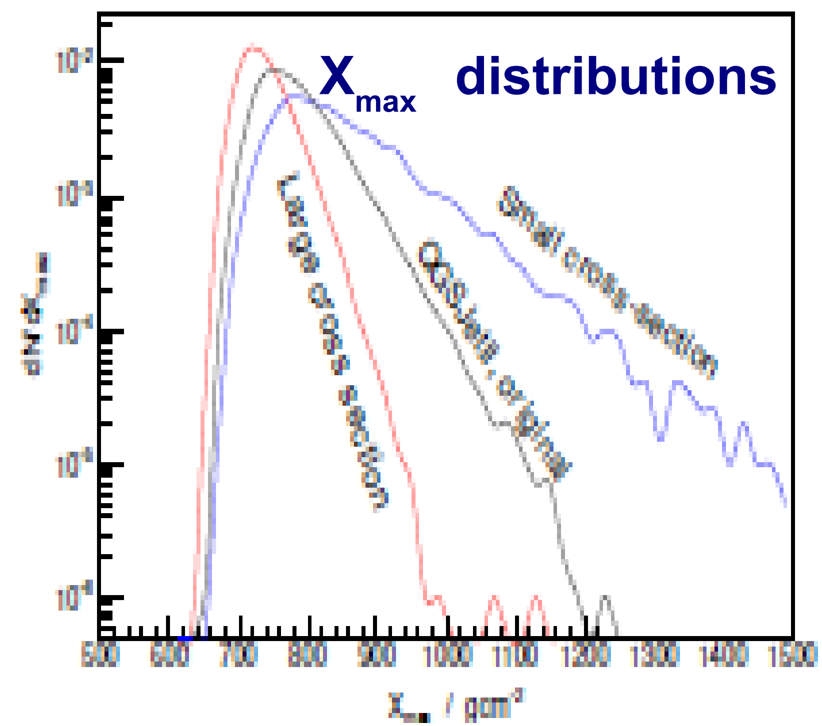


$$\mathrm{RMS}(X_1) \sim \mathrm{RMS}(X_{max} - X_1)$$

$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\mathrm{RMS}(X_1) = \lambda_{int}$$

$$\sigma_{p-air} = \frac{\langle m_{air} \rangle}{\lambda_{int}}$$

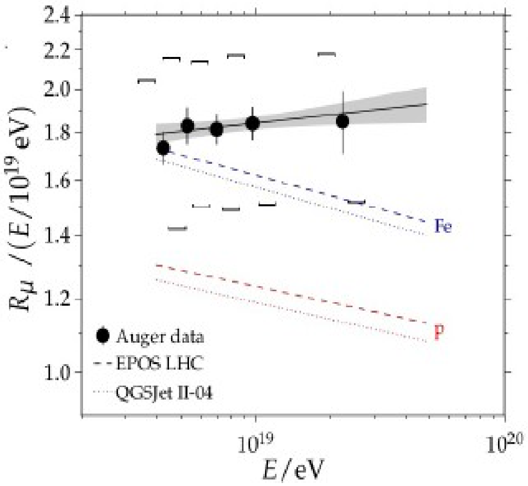


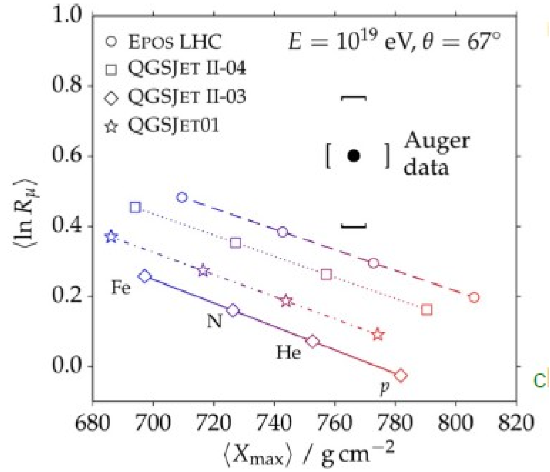
X_1 is not measured directly.

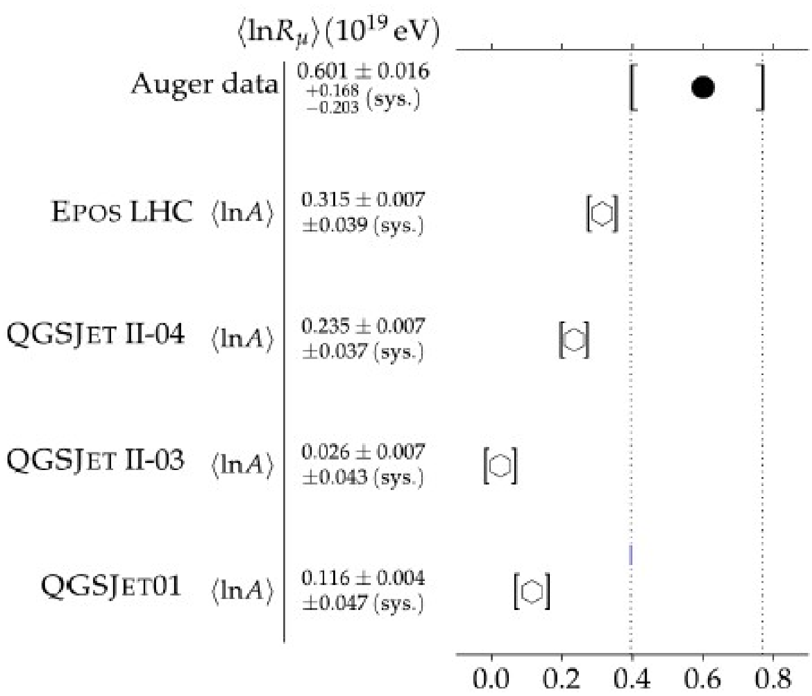
Use fluctuations in shower development

High Energy Physics with Auger

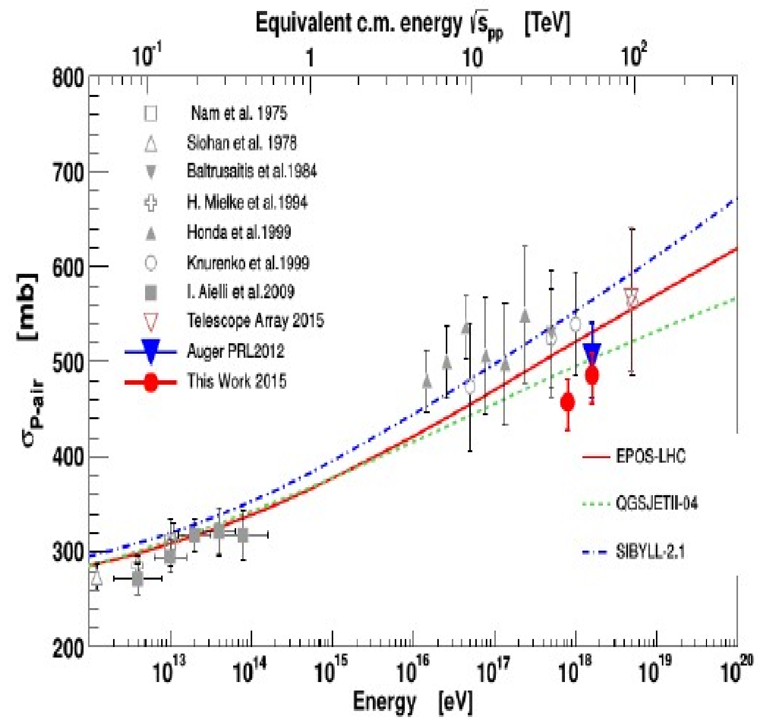
Muon deficit







Standard UHE P-Air cross section



What is next: Auger Prime

Event-by-event composition sensitivity for astronomy with light component at highest energies

- New muon detectors.
- Select proton showers
- Mass composition at logE[eV]>19.5
- Muon excess particle physics

Can we identify the sources?

Origin of flux suppression?

Can we explain why so many muons?

Summary

•10+ years of the Pierre Auger Observatory data changed greatly the community view of HECR
•Bottom Up CR acceleration . No new physics.
UHECR are accelerated in astrophysical sources
•Galactic - Extragalactic transition at Ankle. Not a propagation eff ect. Source effect.
•Data compatible with a rigidity dependent Emax.
•UHECR are extragalactic
•Flux suppression at highest energies: GZK e ffect? Source acceleration limit?
• Muon deficit in models at highest energies
• Auger Upgrade will address remaining questions
•Future: Event-by-event composition sensitivity with AugerPrime for astronomy with light component at highest energies