# Particle Astrophysics

B. Fick & D. Nitz

Study of Matter at very smallest scales. (or highest energy)

+

Study of Matter at very largest scales.

Our Specialty : Ultra-High-Energy Cosmic Rays

Nagging Questions:

Where do they come from ?

Importance: phenomenon farthest from thermal equilibrium in the Universe!

Astrophysics

Can we learn anything about matter at the smallest scales from them?

Particle Physics

Importance: Collisions can probe matter 100x smaller scale than the LHC.

# We observe Cosmic Rays above E ~ 2 *Joules* ($10^{19}$ eV)

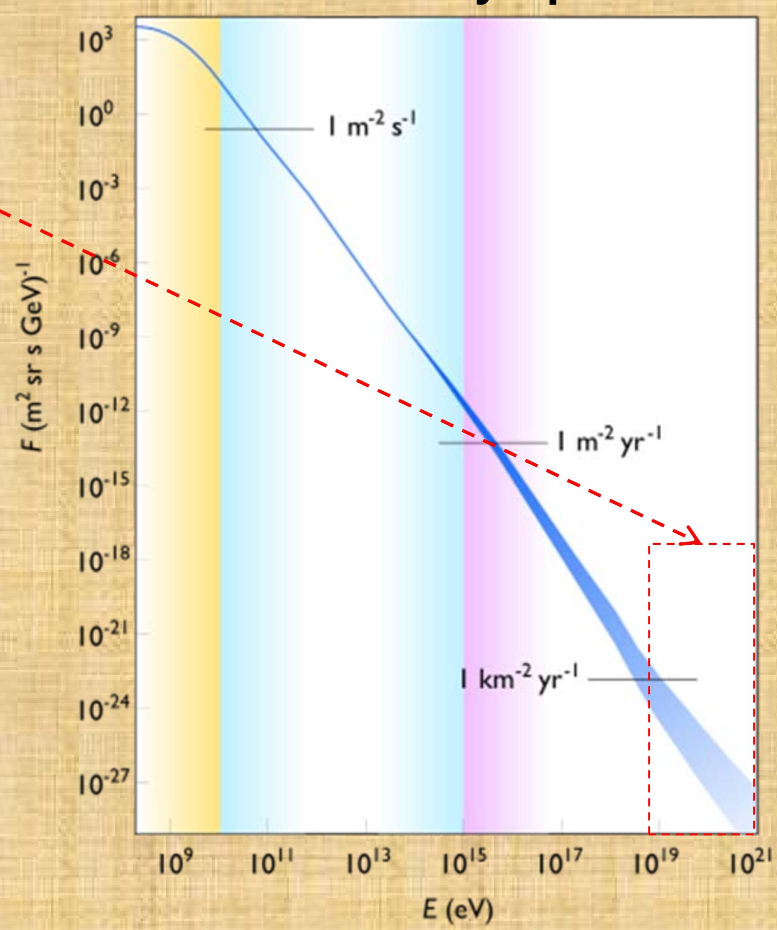
**Paths are least distorted by Galactic Magnetic fields**

**Can “look back” to the source.**

## Problem : Such cosmic rays are very rare !

**1 per square kilometer per year !**

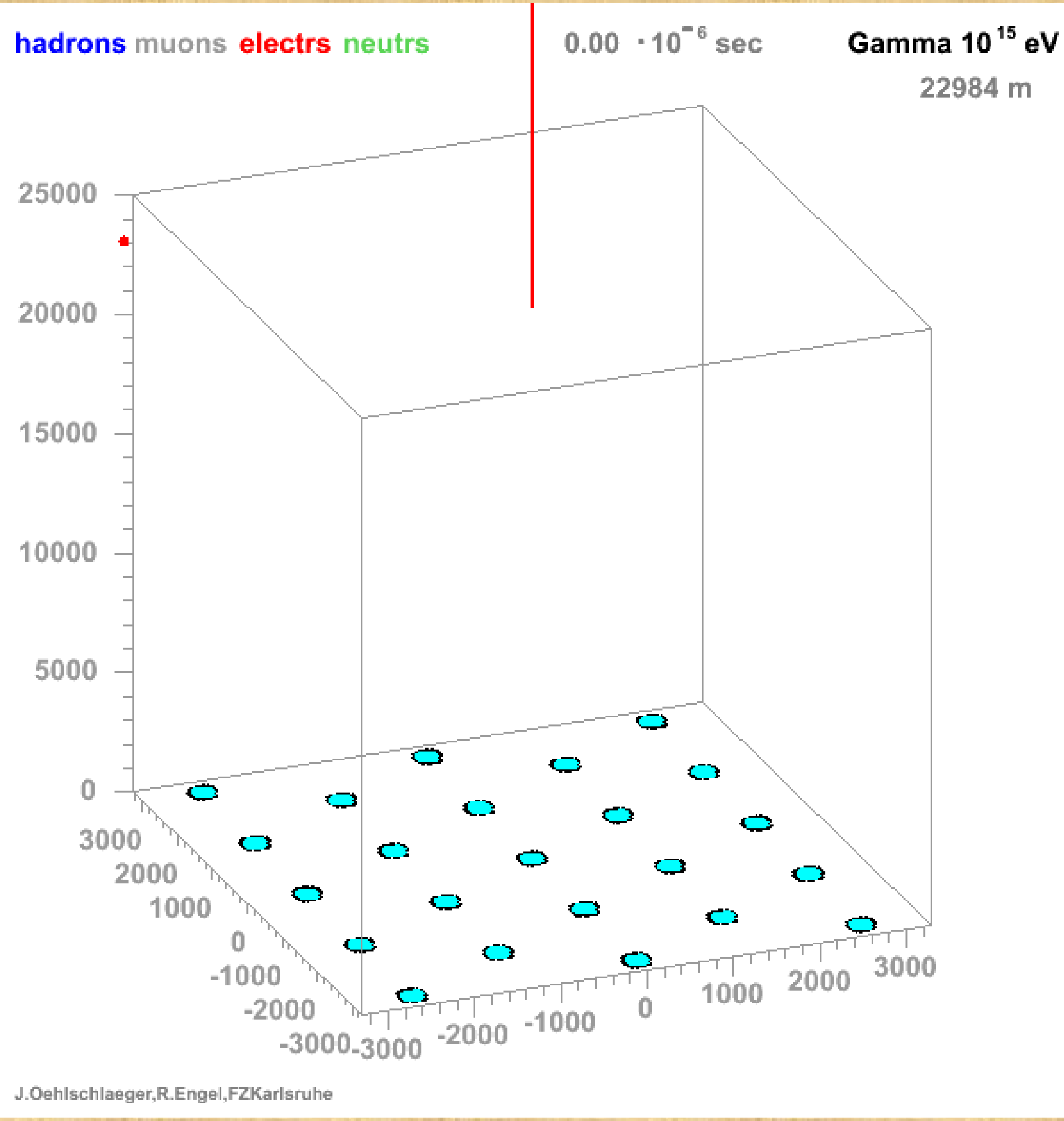
The Cosmic Ray Spectrum



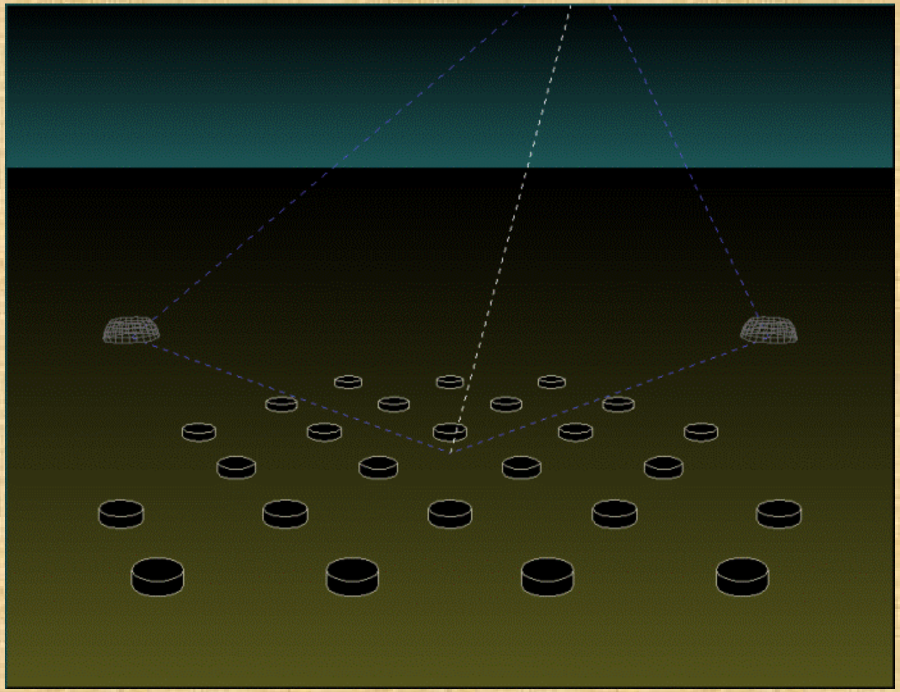

**Must build an enormous detector ~ 3000 km2**

**Incorporate the atmosphere as part of the detector.**

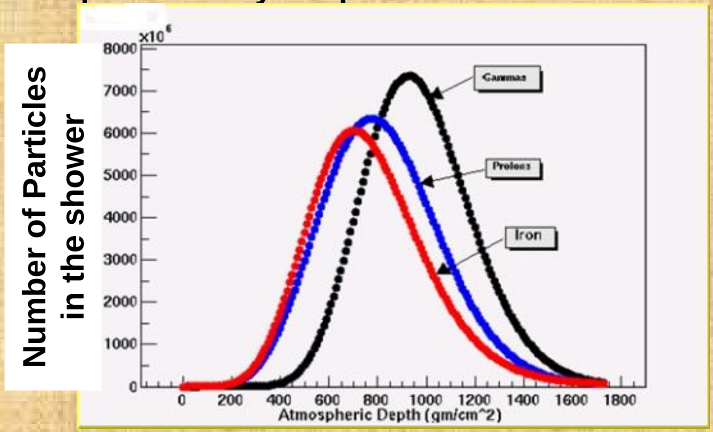
# *Air-Showers* Make UHE Cosmic rays visible.



# How do you measure the properties of a UHE cosmic rays using Air-Showers?



**Fluorescence Telescopes** record the time progression of the shower via the light produced by the particles.

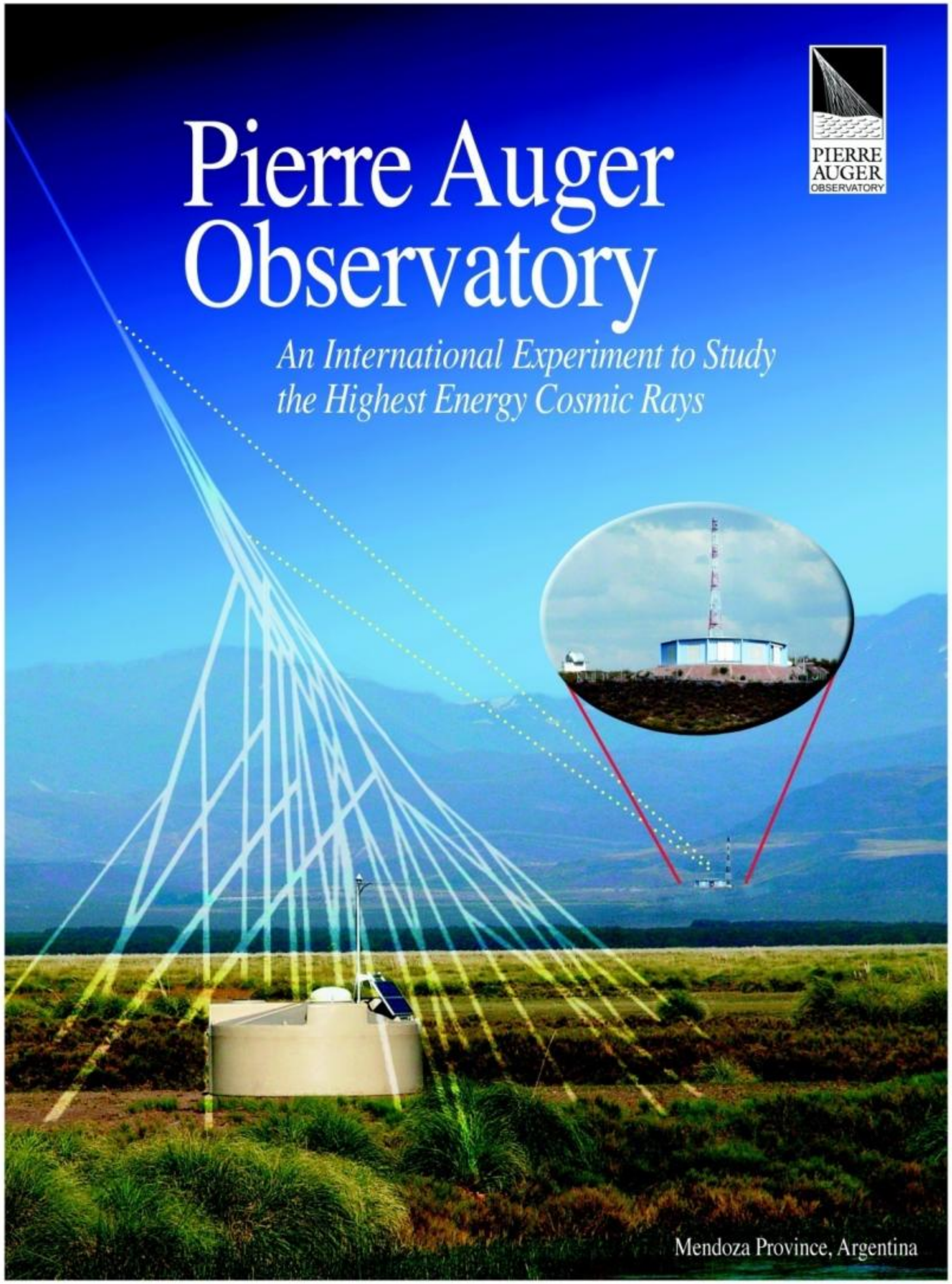



**Surface Array** records the time and location of shower particles as they strike the ground.

Number particles recorded at 1000 m from core. → **Cosmic Ray Energy**

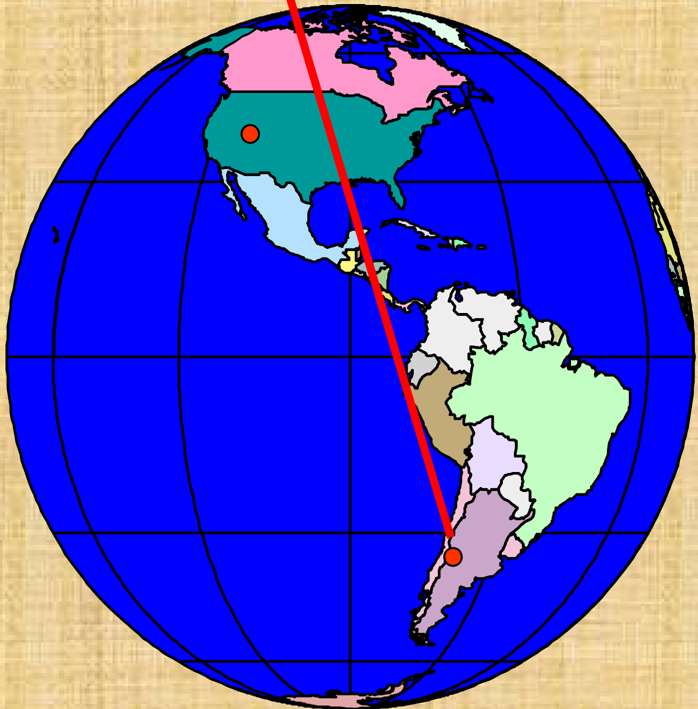
Relative particle arrival times → **Cosmic Ray Direction**

Position of maximum shower development → **Cosmic Ray Interaction Strength**

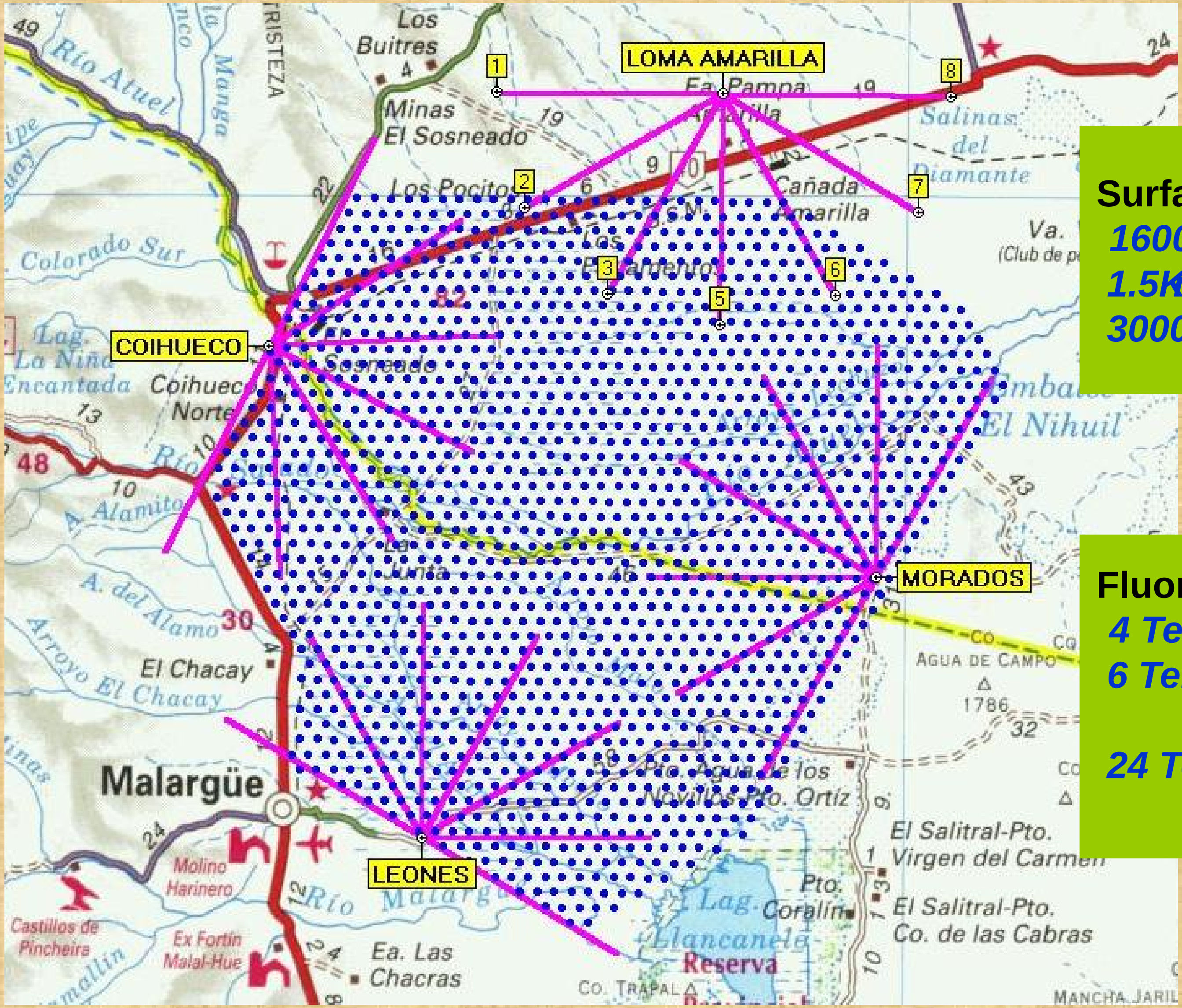




**Malargue, Argentina**



# Auger Observatory Layout




**Surface Array**

*1600 detector stations*

*1.5Km spacing*

*3000Km$^2$*

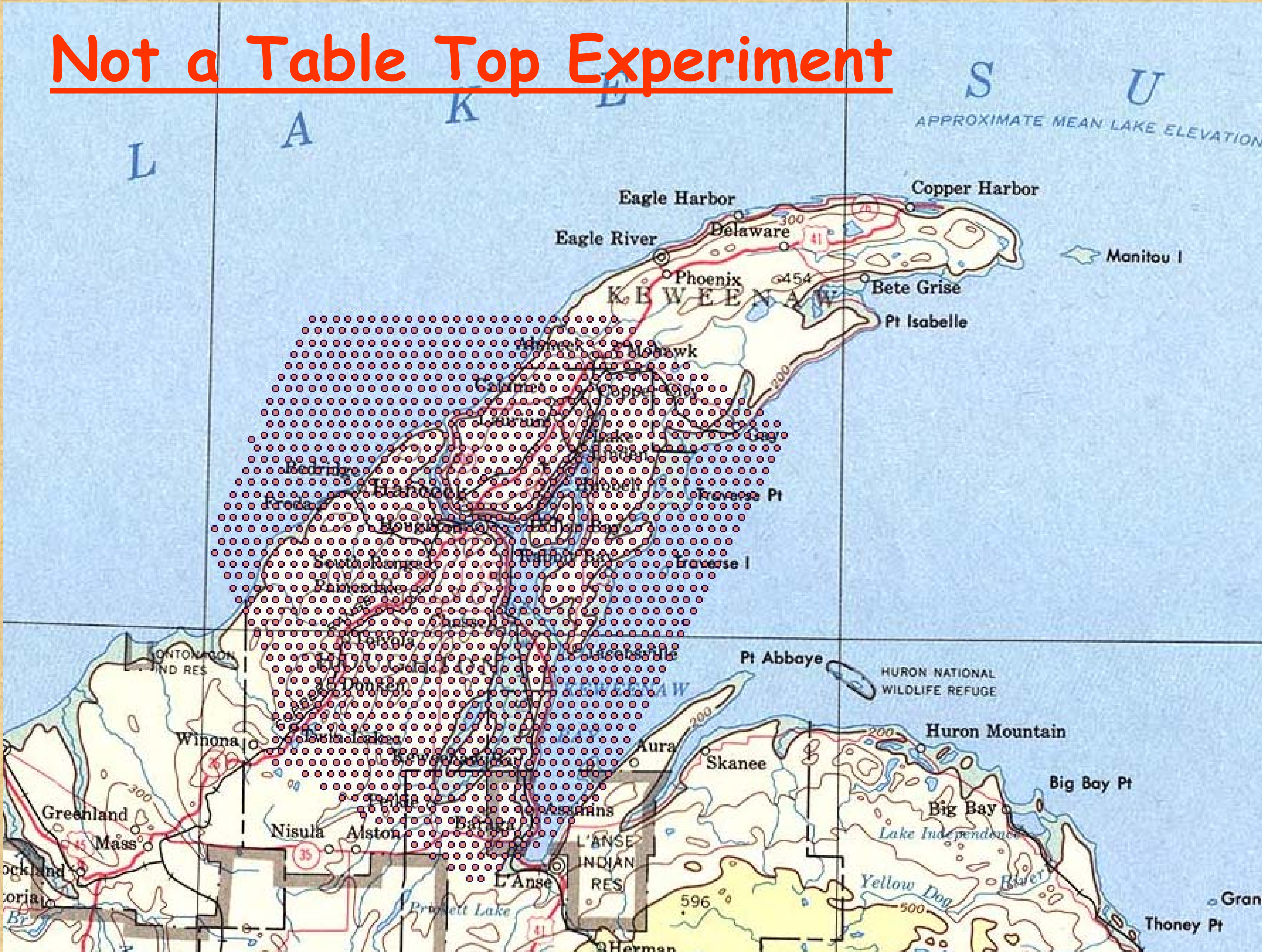
**Fluorescence Detectors**

*4 Telescope enclosures*

*6 Telescopes per enclosure*

*24 Telescopes total*

# Not a Table Top Experiment



# The Auger Collaboration

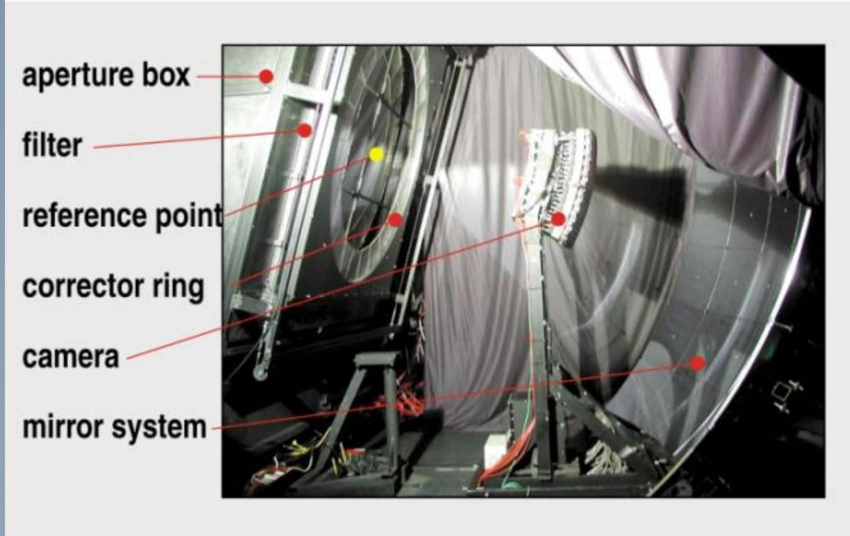
**Participating Countries - 50 Institutions, >250 Scientists**

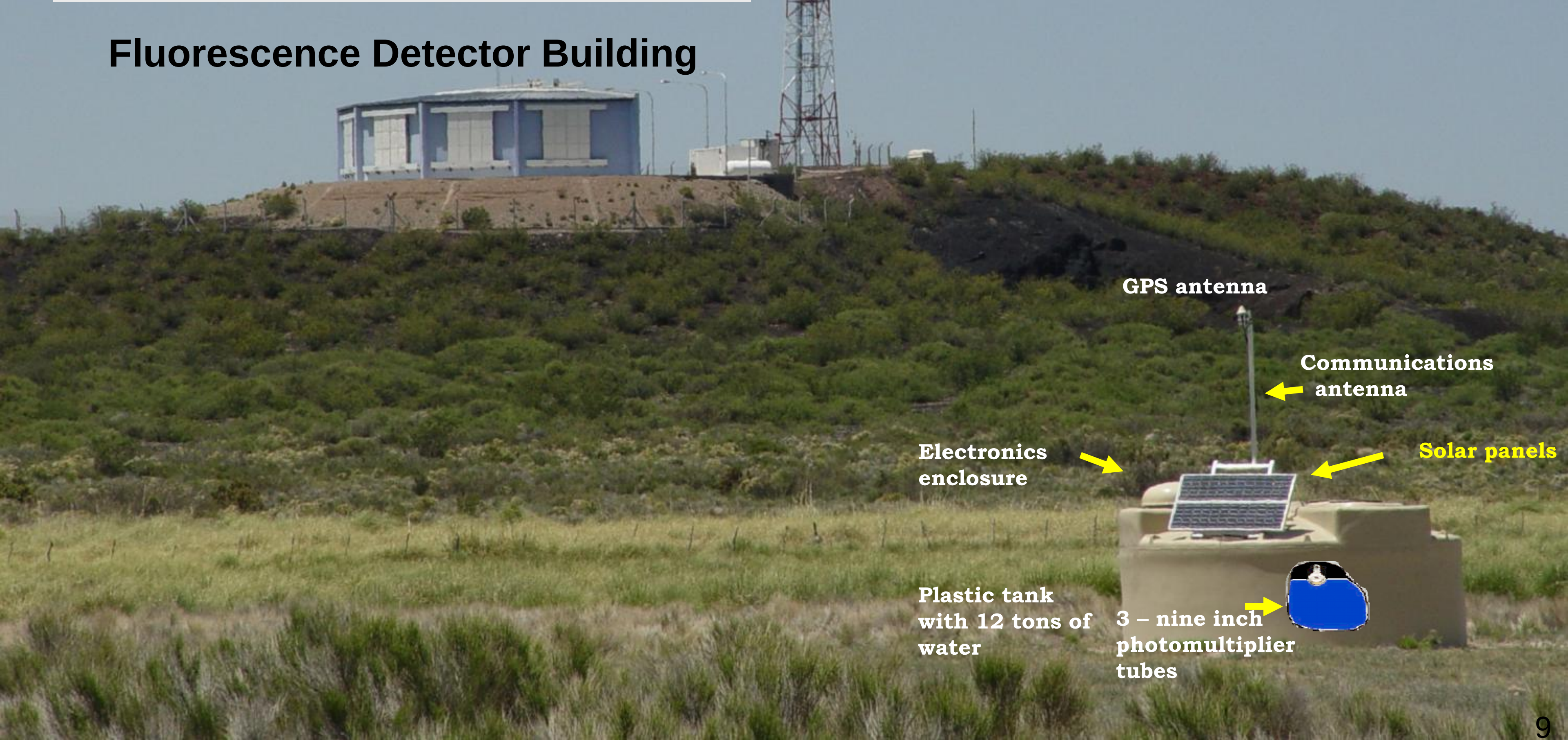
**Argentina**
**Australia**
**Bolivia***
**Brazil**
**Czech Republic**
**France**
**Germany**
**Greece**
**Italy**
**Mexico**
**Netherlands**
**Poland**
**Portugal**
**Slovenia**
**Spain**
**United Kingdom**
**USA**
**Vietnam***

***Associate***

**Participating US institutions:**

**Case Western**
**Chicago**
**Colorado**
**Colorado State**
**Fermilab (and ANL)**
**Louisiana State**
**Michigan Tech**
**Minnesota**
**Nebraska**
**New Mexico**
**Northeastern**
**Penn State**


aperture box
filter
reference point
corrector ring
camera
mirror system


Fluorescence Detector Building
GPS antenna
Communications antenna
Electronics enclosure
Solar panels
Plastic tank with 12 tons of water
3 – nine inch photomultiplier tubes

ecord 10 events per day above 1x1

The Senate Page Image for 201

Event 3476250 :-)
Time 863776055 s 395274000 ns
3TOT & 4C1; 5T5
Candidates: 15 (Acc: 7, Bad: 35)

E = ( 1.26 ± 0.09 ) × $10^{19}$ eV **2 J**

(θ, ϕ) = ( 65.5 ± 0.1, 196.5 ± 0.1 ) deg

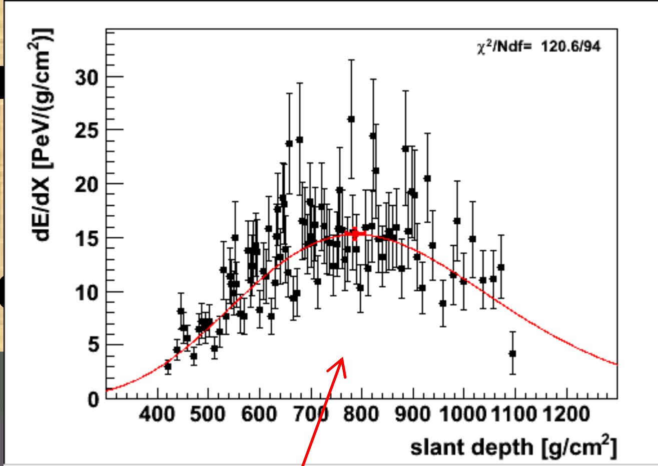
S(1000 m) = 21.9 ± 1.4 ( ± 0.2) VEM

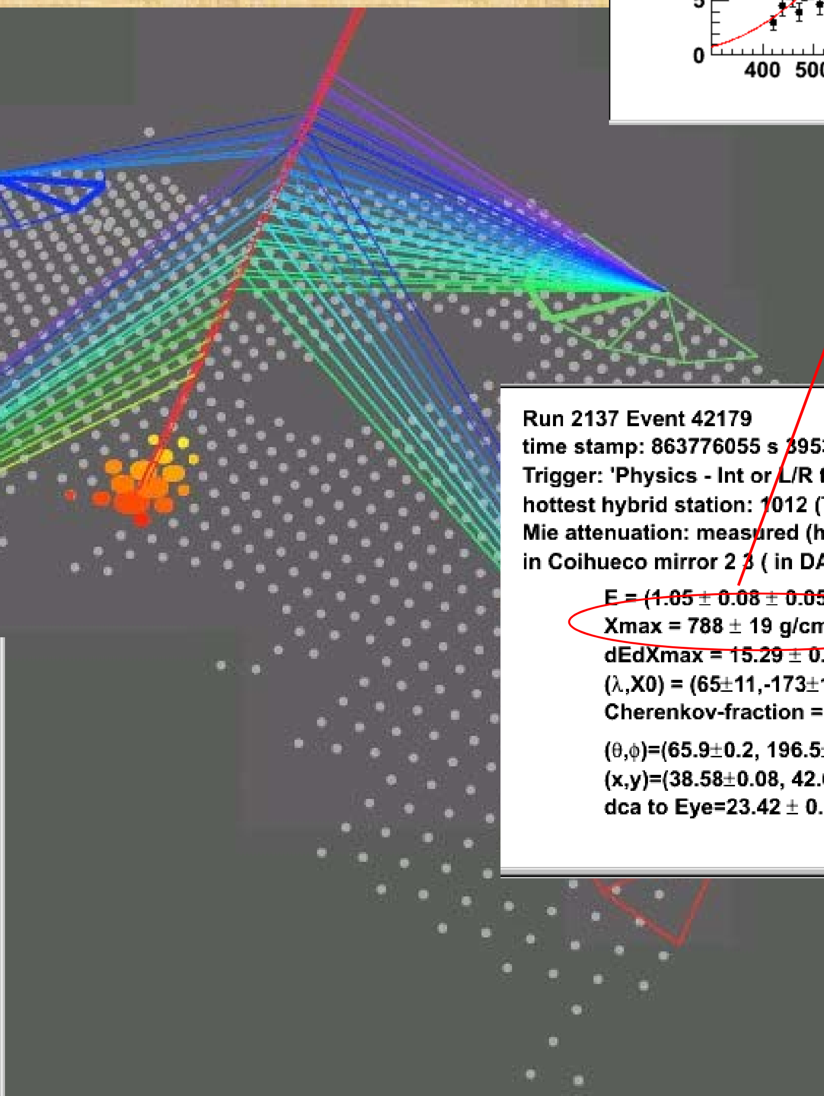
(x,y) = (39.19 ± 0.06, 42.88 ± 0.03) km

β (fixed) = -1.57 ( ± 0.25 )

R = 22.87 ± 0.02 km

$r_{opt}$ = 994.92 m



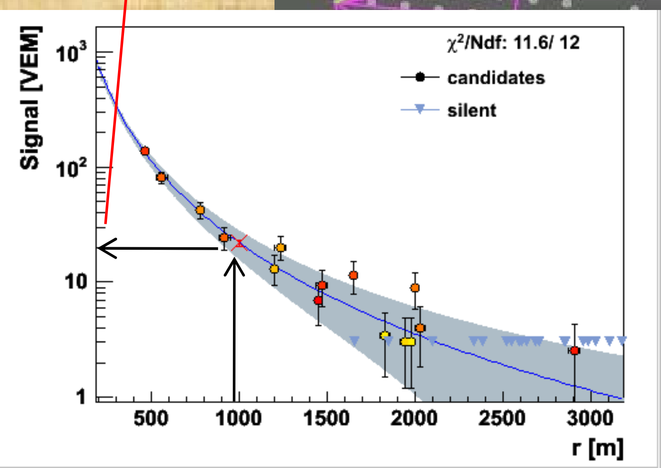



**A Proton ?**

Run 2137 Event 42179
time stamp: 863776055 s 395337284 ns
Trigger: 'Physics - Int or L/R trigger', 'Shower Candidate'
hottest hybrid station: 1012 (TOT), ΔSP = 377 m
Mie attenuation: measured (h<13.2 km, VAOD at 3km: 0.027)
in Coihueco mirror 2 3 ( in DAQ: 1 2 3 4 5 6 )

E = (1.05 ± 0.08 ± 0.05) × $10^{19}$ eV
Xmax = 788 ± 19 g/cm²
dEdXmax = 15.29 ± 0.50 PeV/(g/cm²)
(λ,X0) = (65±11,-173±132) g/cm²
Cherenkov-fraction = 4%

(θ,ϕ)=(65.9±0.2, 196.5±0.5) deg
(x,y)=(38.58±0.08, 42.63±0.23) km
dca to Eye=23.42 ± 0.03 km



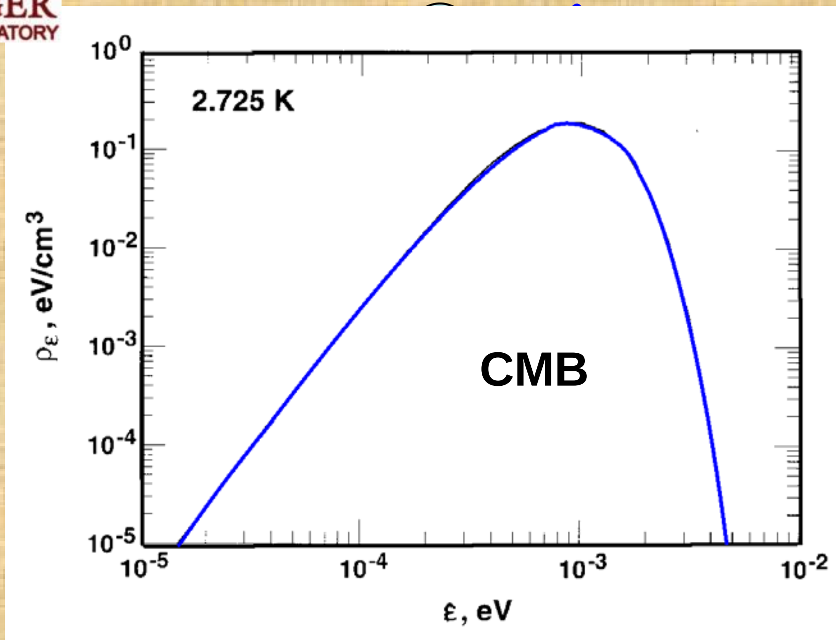
# The Ultra-High Energy Cosmic-Ray Environment

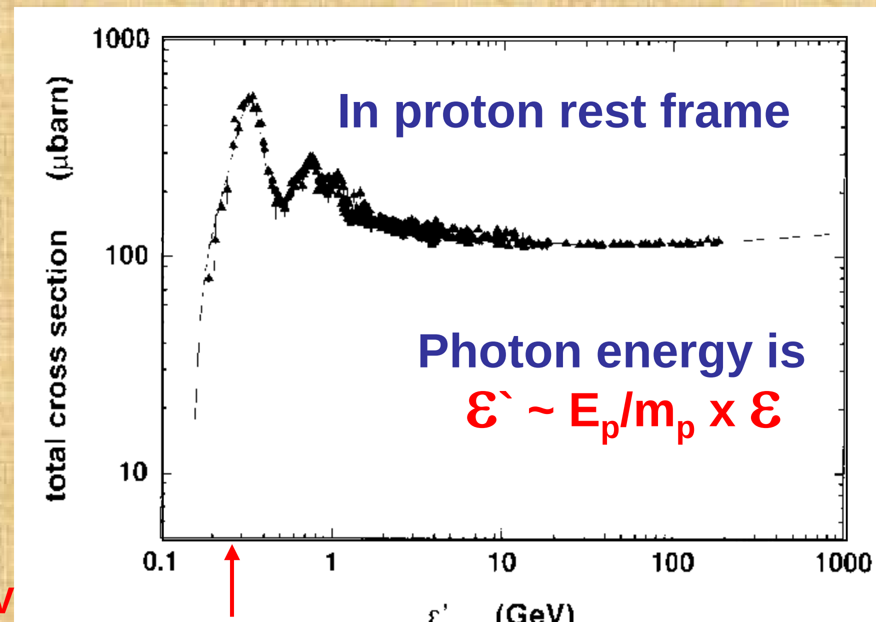
Space is filled with this radiation

~ 400 photons cm$^{-3}$

Energy too low to bother protons at rest

But for moving protons the situation changes




~pion mass

Corresponding Proton Energy In our frame

$$E_{th} = \frac{2m_p m_\pi + m_\pi^{\ 2}}{4\varepsilon}$$ ~ 6 X 10$^{19}$eV

**Above this energy protons lose energy by producing new particles.**

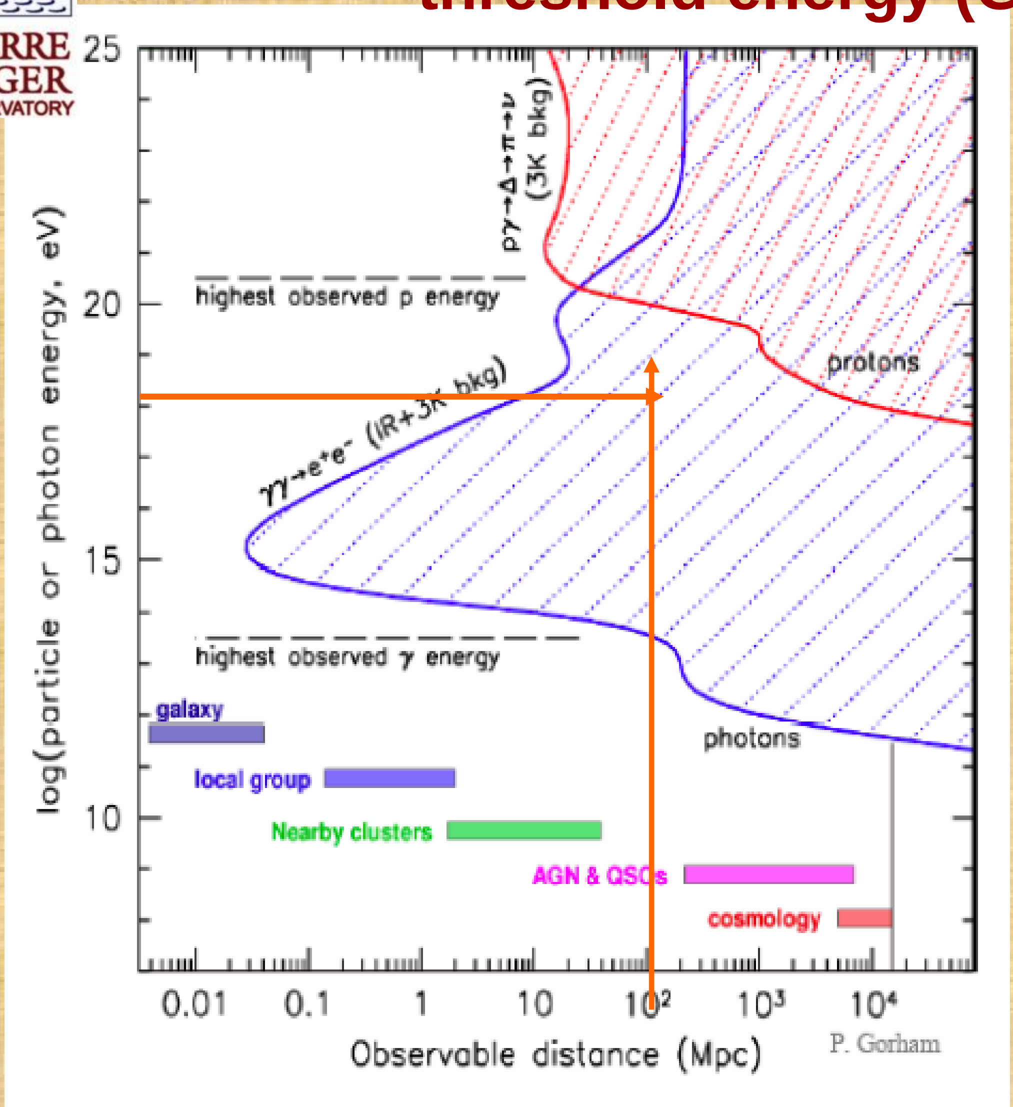
Proton + $\gamma_{mbr}$ ⟶ Δ(1234) ⟶ $\pi^+$ + Neutron

Δ(1234) ⟶ $\pi^0$ + Proton


K. Greisen, Phys. Rev. Lett. 16 (1966); G. T. Zatsepin & V. A. Kuzmin, JETP Lett. 4 (1966);

A. A. Penzias & R. W. Wilson, Ap. J. 142 (1965); J. L. Puget, F.W. Stecker, & J. H. Bredekamp, Ap. J. 205 (1976)

# A Distance limit for Cosmic rays above the threshold energy (GZK Limit)




~ 100 Mpc at ~ $6x10^{19}$ eV

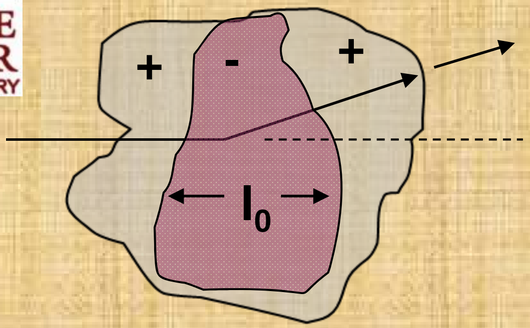
## Consequences

- Ignoring magnetic fields, we can see lower energy cosmic ray sources out to the Hubble distance.
- We see higher energy cosmic ray sources out to < 100 Mpc

Expect a spectrum cutoff or steepening at the threshold energy.


**1 gm of these particles have the same energy as 20,000 Gigawatt power plants operating for 1,000 years**

# Charged Cosmic Ray Deflection in Magnetic Fields
# Angular Deviation depends on distance D and scale length $L_c$




$$\theta_{rms} \approx 4^o \frac{60\ \text{EeV}}{E/Z} \frac{B_{rms}}{10^{-9}\ \text{G}} \sqrt{\frac{D}{100\ \text{Mpc}}} \sqrt{\frac{L_c}{1\ \text{Mpc}}}$$

**Galactic Effects** $10^{20}$ eV D ~ 1 kpc, $L_c$ ~ 1 kpc

**Proton** → $\theta_{rms}$ ~ 0.5 deg

**Iron** → $\theta_{rms}$ ~ 12 deg

**ExtraGalactic Effects** $10^{20}$ eV D~10 Mpc, $L_c$ ~ 1 Mpc

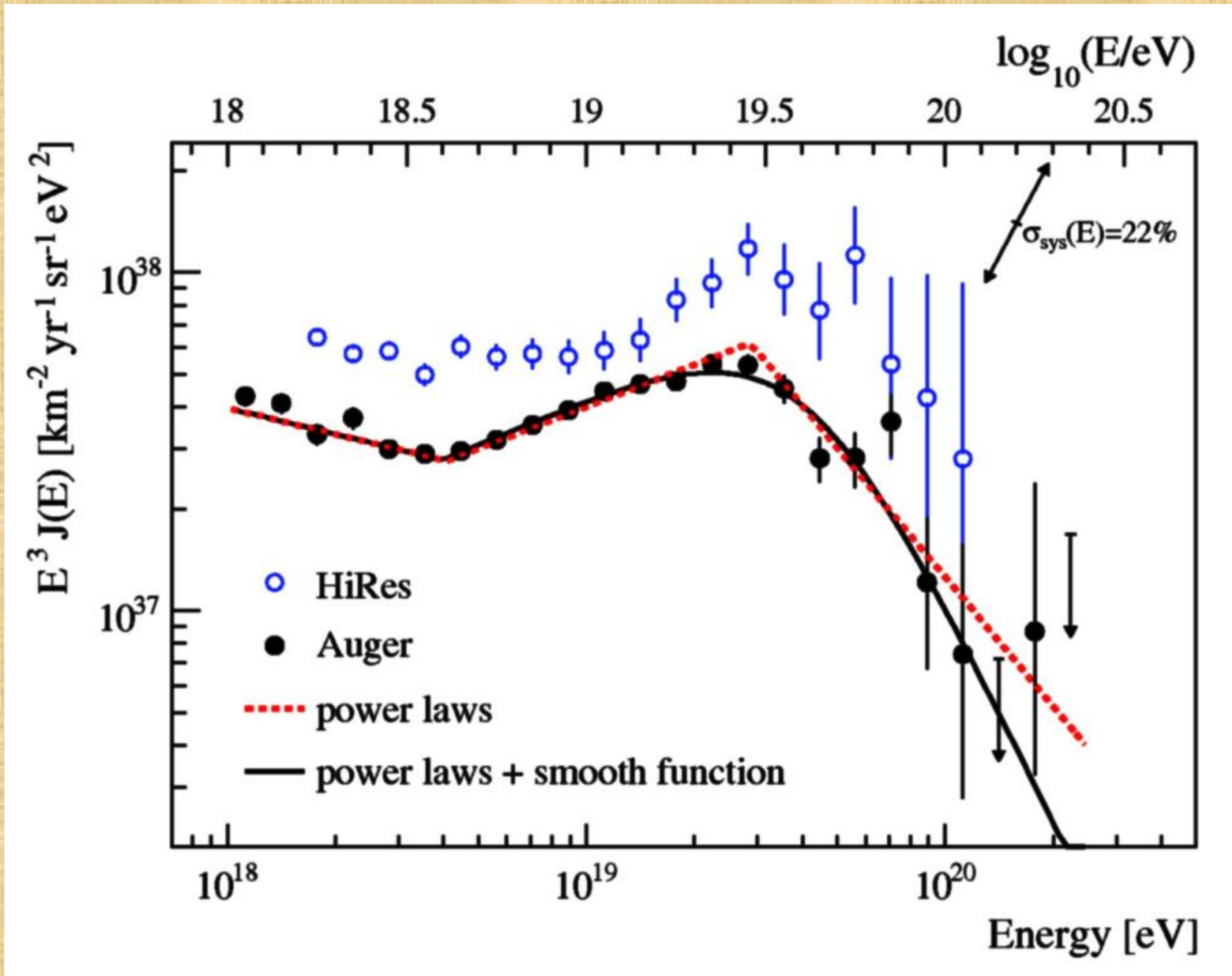
**Proton** → $$\theta_{rms} \approx 0.8^o \frac{B_{rms}}{10^{-9}\ \text{G}}$$

**Iron** → $$\theta_{rms} \approx 20^o \frac{B_{rms}}{10^{-9}\ \text{G}}$$

# Auger Observatory Science Highlights

- Observed GZK feature in the spectrum
- Discovered sky anisotropies >60 EeV
- Puzzling muon and $X_{max}$ results
- Strongest UHE tau neutrino limit
- Strongest UHE photon limit

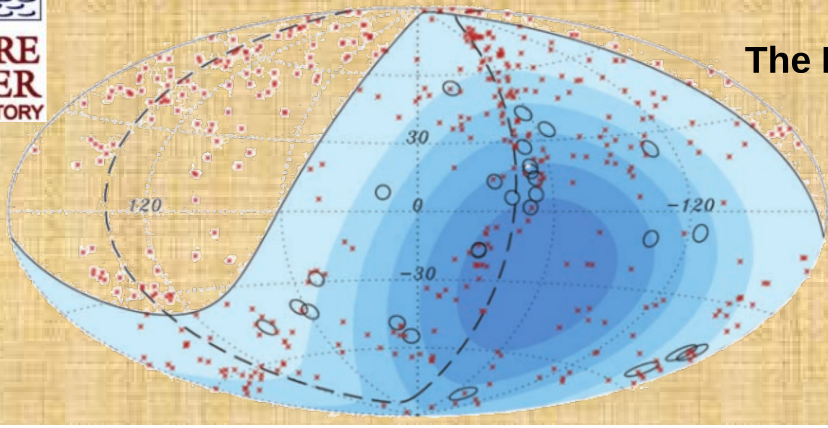
# Cosmic Ray Energy Spectrum




**Pierre Auger Collaboration, Physics Letters B685 (2010) 2395 (2010) 239**

**R.U. Abassi et al. (HiRes Collab.), Astropart. Phys. 32 (3008) 53**

# Cosmic Ray Anisotropy




**The Pierre Auger Collaboration, Science 318 (2007) 938**

**27 events shown as black circles**



**2010**

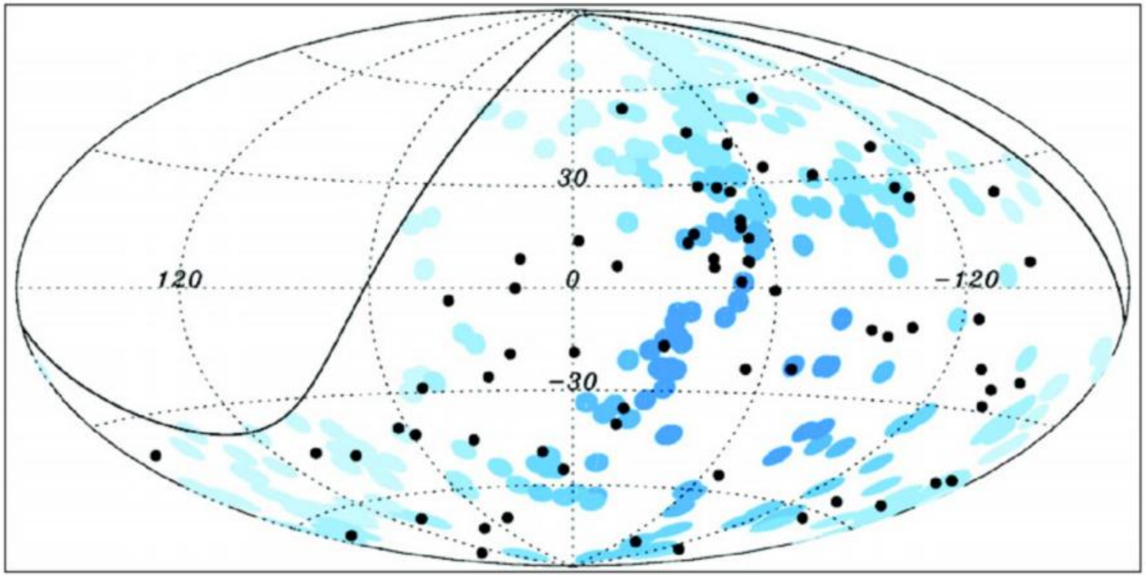
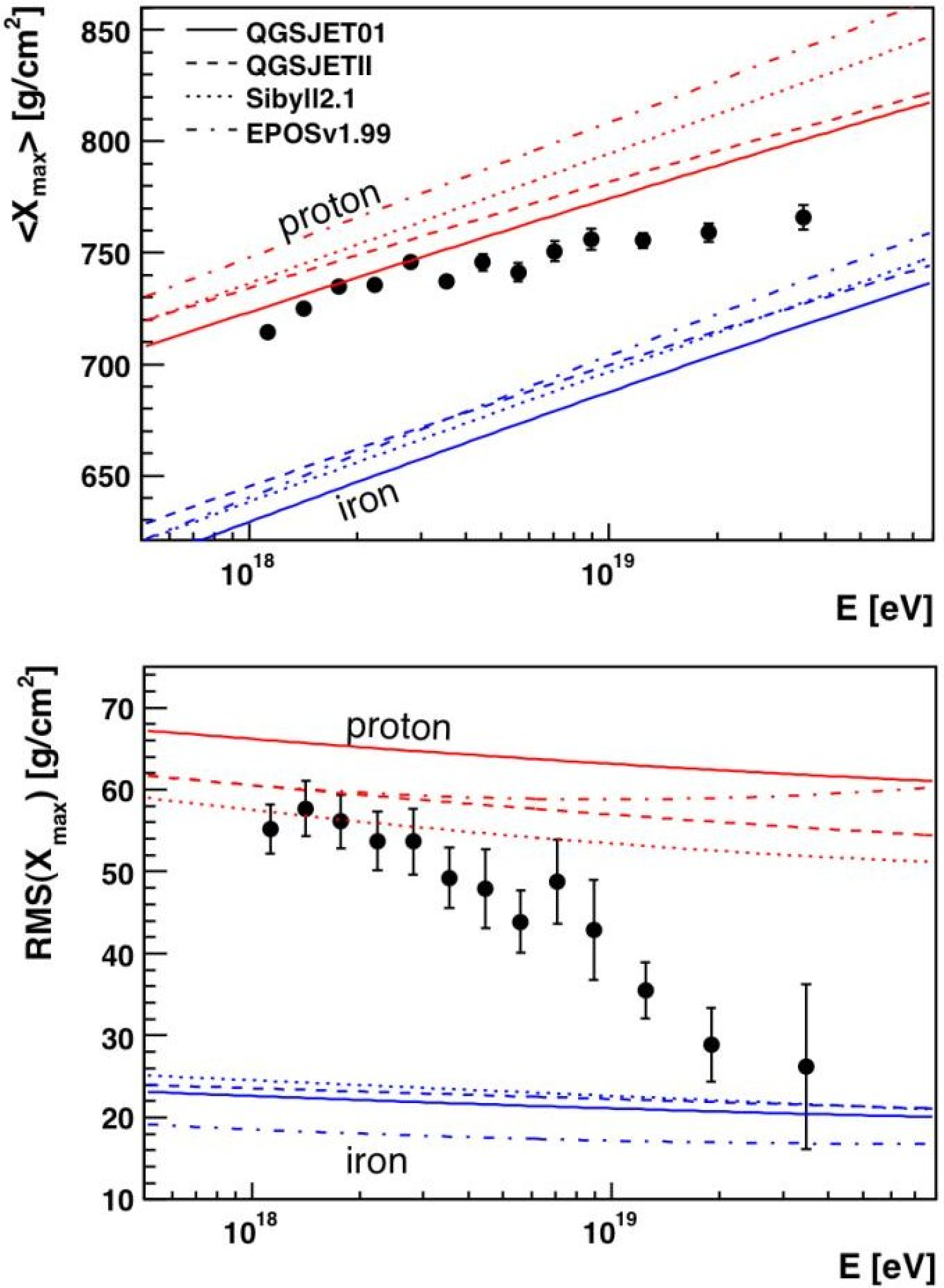



**Fig. 1.** The 69 arrival directions of CRs with energy $E \geqslant 55$ EeV detected by the Pierre Auger Observatory up to 31 December 2009 are plotted as black dots in an Aitoff-Hammer projection of the sky in galactic coordinates. The solid line represents the border of the field of view of the Southern Observatory for zenith angles smaller than 60°. Blue circles of radius 3.1° are centred at the positions of the 318 AGNs in the VCV catalog that lie within 75 Mpc and that are within the field of view of the Observatory. Darker blue indicates larger relative exposure. The exposure-weighted fraction of the sky covered by the blue circles is 21%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)




# Puzzling Air Shower Development

- Average interaction probability increasing (compared to proton expectation)
- Mix of protons and heavier nuclei changing with energy?
  - Inconsistent with anisotropy above 60 EeV
- Proton interaction cross-section increasing?
  - Models wrong: new hadronic physics?
- Caveat: All these measurements are below 40 EeV and anisotropy is above 60 EeV

**Pierre Auger Collaboration, Phys. Rev. Lett. 104 (2010) 091101**