Ultra High-Energy cosmic rays and GZK cutoff: paradox solved?

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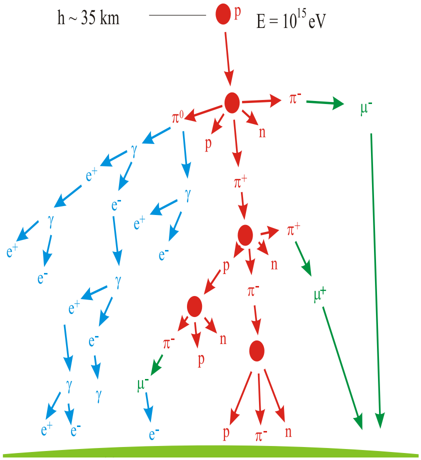
Overview:

- Introduction
  - Cosmic rays
- GZK vs experiments
  - GZK cutoff
  - The paradox
  - PIERRE AUGER experiment
- Conclusion

Cosmic rays

- Cosmic rays are particles coming from an extra-terrestrial source.
- They can be electrons, protons, atomic nuclei, antimatter,...
- Our planet is constantly bombarded by these particles, with an average flux of $\phi \simeq 10^6 \frac{particles}{cm^{-2} \cdot year}$!!!
- If they interact with atmosphere, showers of secondary particles are producted.

Primary vs Secondary



Primary cosmic rays:

- can be produced in our solar system (Sun), in our galaxy or outside of it;
- 99% is composed by protons or α-particles;
- have energy spanning from $\sim$GeV to $\sim 10^{21}$ eV;

Secondary cosmic rays:

- arise from spallation in the atmosphere;
- lead mainly to pions, photons, electrons and positrons;
- have decreasing energy with distance;

History

- Cosmic rays ("*penetrating radiation*") discovered in 1912 by Victor Hess
- positrons and muons discovery by Carl Anderson (1932-1937)
- experiments on air showers begun in 1946
- Fermi acceleration mechanism: 1949
- 1962: first Extreme-Energy Cosmic Ray $E \sim 10^{20}$ eV $\rightarrow$ 10 Joules!!

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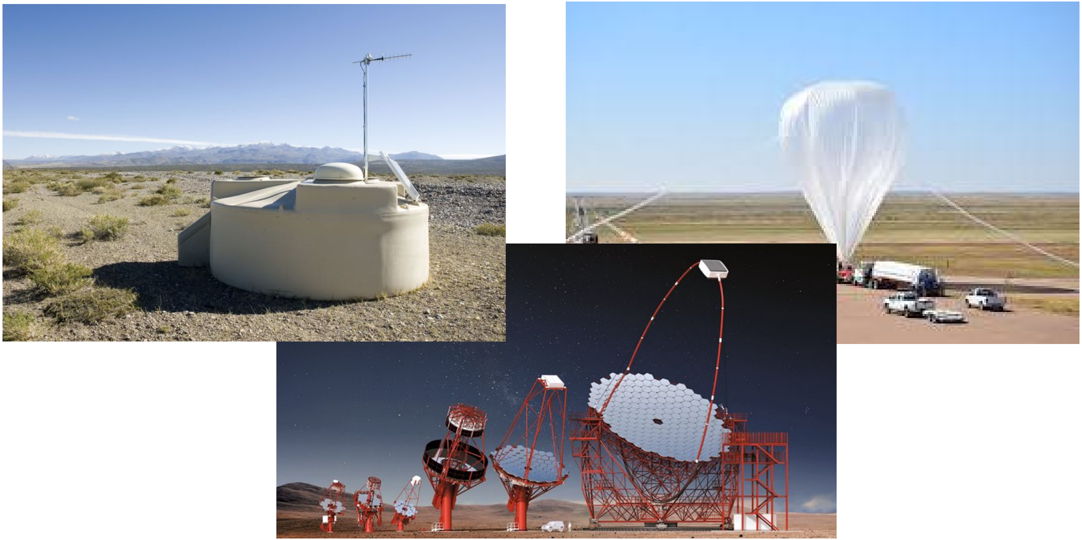
- GZK cutoff proposed in 1962
- most energetic UHECR: $3 \cdot 10^{20}$ eV measured. 1991.
- AUGER experiment suggests extragalactic origin of UHECR in 2007

How do we detect cosmic rays?



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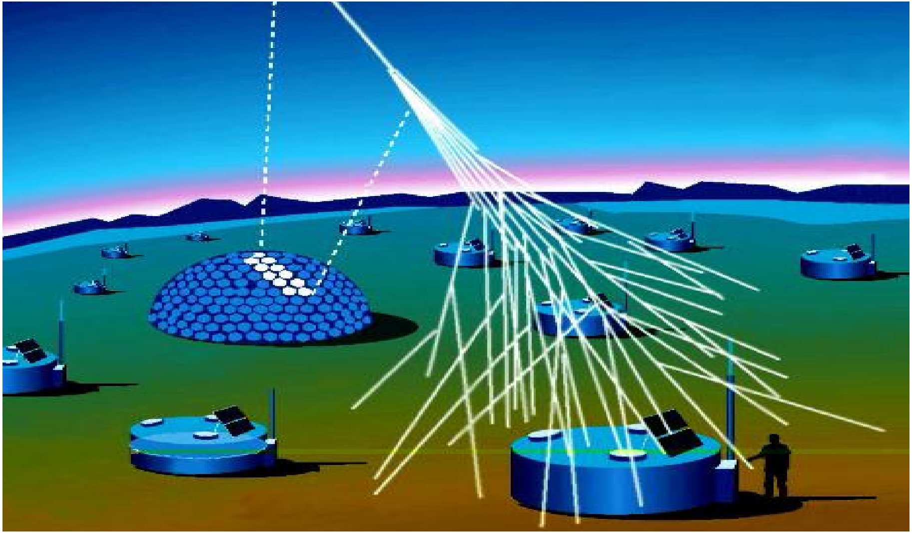
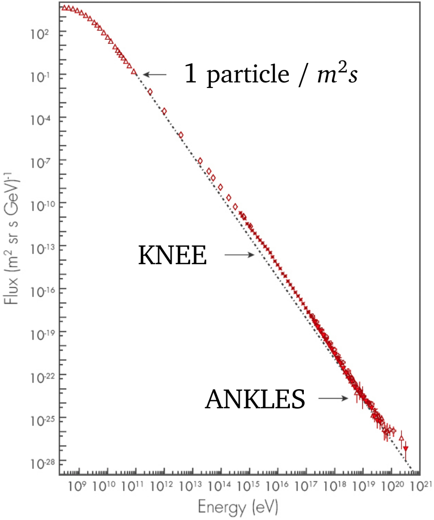
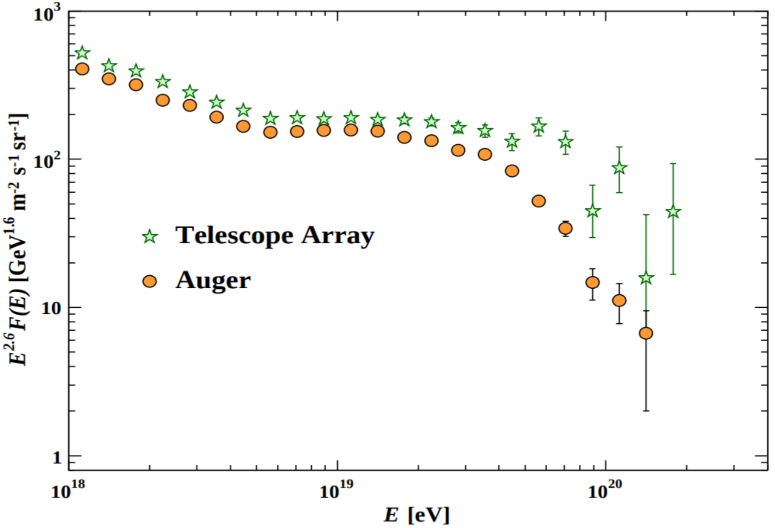


Energy spectrum



- **knee** ($\sim 10^{15}$ eV): change in spectrum slope. Higher energy less frequent;
- **ankle** (region $\sim 10^{19}$ eV): less decreasing flux $\rightarrow$ extragalactic sources?
- **2nd ankle** ($> 5 \cdot 10^{19}$ eV): **GZK cutoff**

The GZK cutoff



The GZK cutoff

GZK (Greisen, Zatsepin, Kuzmin): particles can interact with Cosmic Microwave Background (CMB) and lose energy. Threshold energy depends on particle.

GZK

A proton can interact with CMB to produce pions:

$$p + \gamma_{CMB} \to \Delta^+ \to p + \pi^0$$

or

$$p + \gamma_{CMB} \to \Delta^+ \to n + \pi^+$$

Given $T_{CMB} \simeq 2.7$ K (~ 0.25 meV), $m_p \simeq 1$ GeV, $m_\pi \simeq 130$ MeV, we find:

$$E_{thresh} \simeq 5 \cdot 10^{19} \text{eV}$$

The GZK cutoff

Knowing the proton-photon cross section $\sigma \sim 1$ mb, and the CMB photon density ($\sim$ 400 particles/cm^3) we can estimate the mean free path for a proton:

$$\lambda = \frac{1}{n\sigma} \simeq 10^{23} \text{ m} \simeq 10 \text{ Mpc}$$

Almost complete suppression at 5λ, known as *GZK horizon*.
We shouldn't see many highly energetic particles coming from further distances.

CR of energy $E \geq E_{thresh}$ are called Extreme-Energy Cosmic Rays (EECR).

Where do CR come from?

Possible CR sources:

- solar (<1 GeV)
- galactical ($10^9 \sim 10^{19}$ eV)

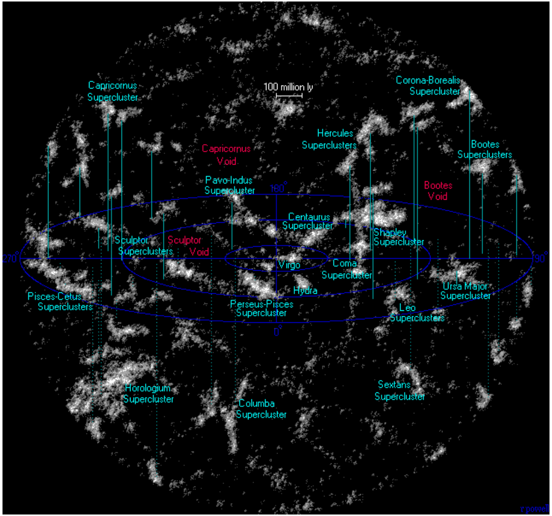
  supernovae
  supernovae remnants shocks
  galactic winds
- extragalactical ($> 10^{19}$ eV)

  powerful radio galaxies
  active galactic nuclei (AGN)
  distances $\gg 100$ Mpc

UHECR: the problem of the source

UHECR should not be too deflected by galactical or extragalactical magnetic fields → they should point the source.

Experiments until 2007 → *isotropy* !!
We have a problem!



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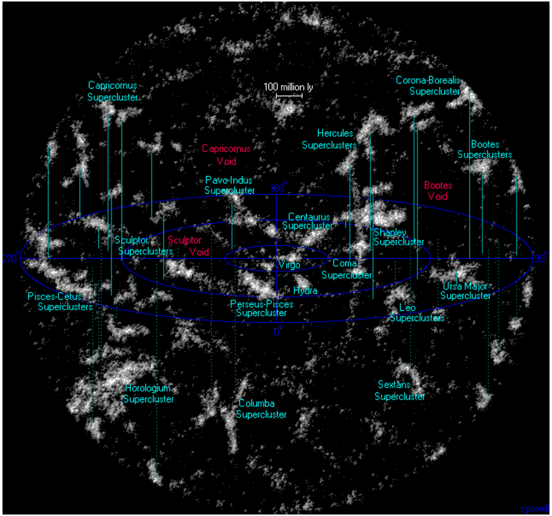
AUGER (2007) → anisotropy.
LATER ON THIS, but you can relax :)



Incompatible result

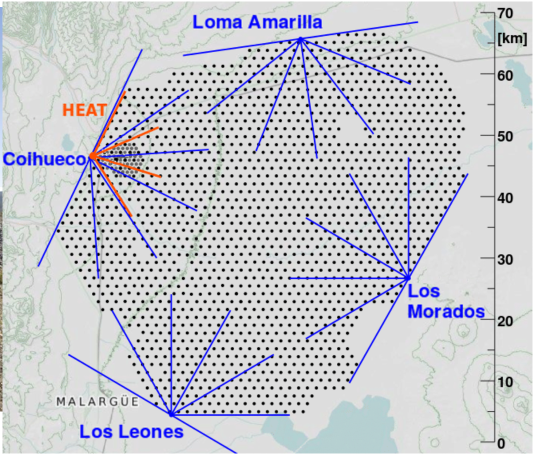
Problems:

- Flux doesn't go to 0 steeply after threshold energy. Why?
- no close sources identified
- flux seems (seemed) isotropic
- Proposed solutions: dark matter, experimental errors, new acceleration mechanisms, ...

"True" solution: make more refined experiments.

The Pierre AUGER experiment

Investigating cosmic rays of energy $E > 10^{17}$ eV



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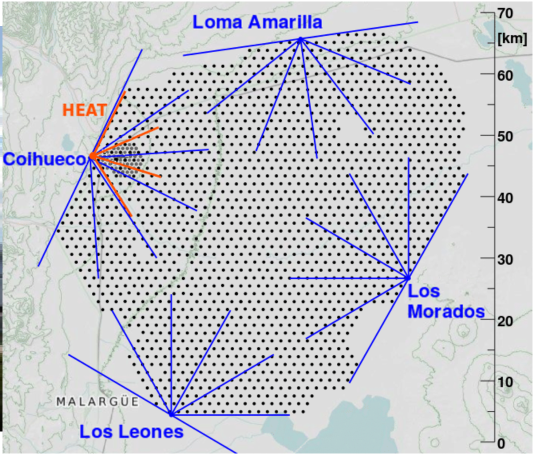
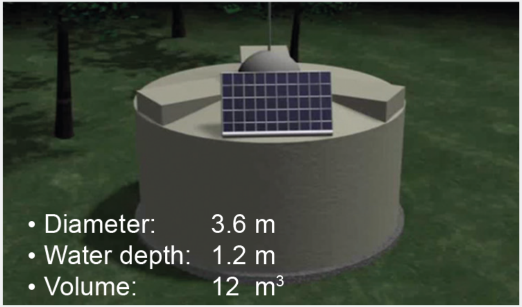
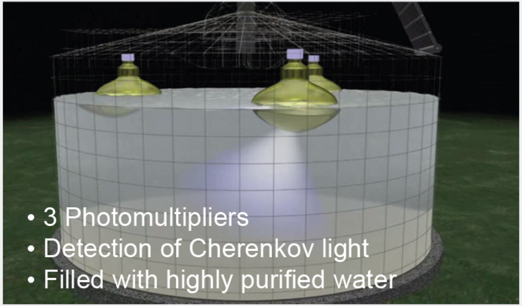


The Pierre AUGER experiment

Surface Detector

1,660 surface detector stations
(1,500 m apart from each other)



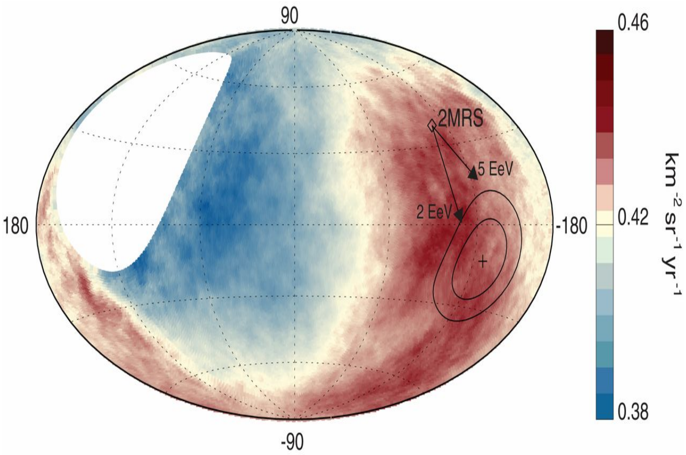


AUGER results

- confirmed GZK cutoff at 20σ significance
- confirmed anisotropy for energies $> 8 \cdot 10^{18}$ eV
- confirmed change in CR composition at $4 \cdot 10^{19}$ eV

UHECR anisotropy

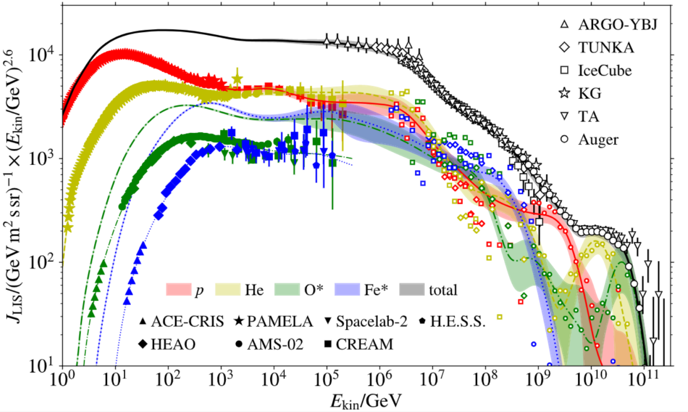
- Skymap anisotropy $4.5^{+0.8}_{-0.7}\%$
- 5.2σ significance



Heavier nuclei

Abundance of heavier ions at the end of the spectrum is somehow intriguing:

- GZK horizon is smaller for ions (bigger cross section with CMB)
- nearby sources?



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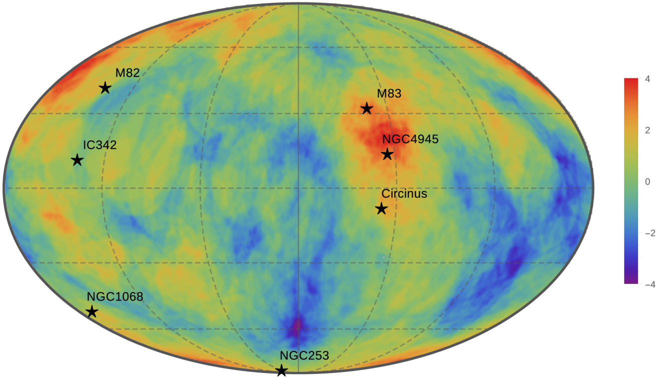
Starburst galaxies: acceleration of ions in *nearby metallic* galaxies

- anisotropy granted
- acceleration limit at $\sim 10^{21}$ eV
- ions at the end of CR spectrum



Conclusion

- GZK cutoff confirmed by AUGER experiment
- yet entity of cutoff seems too small
- too many events above threshold, suggesting that sources may be close
- EECR are mainly heavy ions, thus have shorter GZK horizon
- extragalactic but short-distance sources
- starburst?

SO, IS THE PARADOX SOLVED?

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NOT YET!

References

- Inferences on Mass Composition and Tests of Hadronic Interactions from 0.3 to 100 EeV using the water-Cherenkov Detectors of the Pierre Auger Observatory, *The Pierre Auger Collaboration*, doi: 10.1103/PhysRevD.96.122003
- Observation of a large-scale anisotropy in the arrival directions of cosmic rays above 8×10^{18} eV , *The Pierre Auger Collaboration*, doi: 10.1126/science.aan4338
- Heavy nuclei at the end of the cosmic ray spectrum?, *L.A. Anchordoqui*, doi: 10.1103/PhysRevD.60.103001
- Ultra-high-energy cosmic rays, *L. A.Anchordoqui*, doi: 10.1016/j.physrep.2019.01.002

Starburst galaxies

- higly active, merging galaxies
- high star formation rate
- huge supernovae number
- can be pretty close

M82, the closest starburst galaxy $\simeq 3.5$ Mpc

CR acceleration mechanisms in starburst

Nearby acceleration of ions through:

- supernovae events (multiple)
- stellar wind
- gamma ray bursts

Active Galactic Nuclei

- extreme luminous nucleus, but not thanks to stars
- Fermi-like centrifugal acceleration
- efficient acceleration mechanism
- could sustain 10^{21} eV energies
- prominent candidates as UHECR sources