Effects on the propagation of Ultra High Energy Cosmic rays

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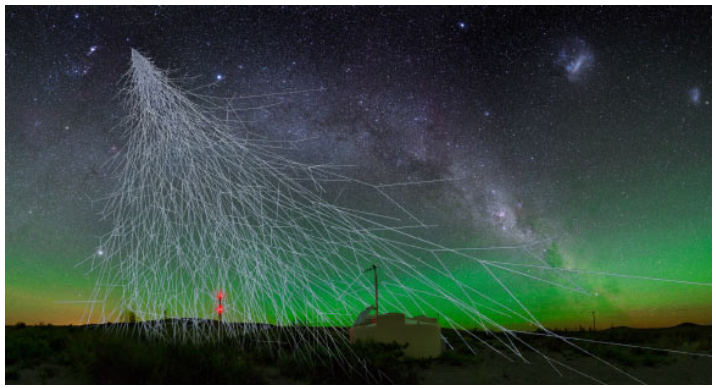
Outline

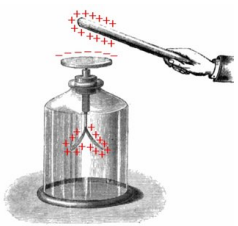
Cosmic Rays

- Cosmic rays are highly energetic particles that propagate through the universe interacting with magnetic fields, gas and radiation
- At low energies, these ionized nuclei are mostly protons and α-particles
- A fraction of them have ultra relativistic energies up to 10^{20}eV



Artistic reconstruction of Cosmic ray showers detected by Pierre Auger Observatory
(A. Chantelauze *et al.*, DOI: 10.1038/nature.2017.22655)

A brief history of Cosmic rays



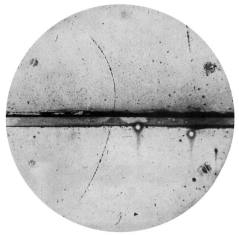
Victor Hess's balloon flights experiment for measuring radiation in atmosphere

Carl Anderson discovers positrons in CR observations

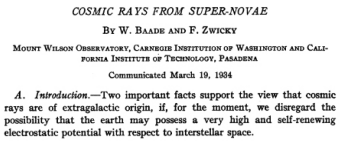
1910 **1912** **1927** **1932**

Theodor Wulf investigated changes in radiation with height

First cloud chamber photo by Dimitry Skobelzyn



A brief history of Cosmic rays



COSMIC RAYS FROM SUPER-NOVAE

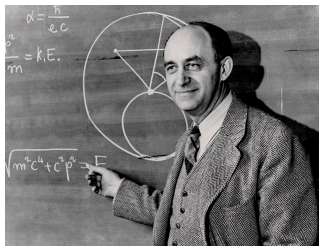
By W. Baade and F. Zwicky

Mount Wilson Observatory, Carnegie Institution of Washington and California Institute of Technology, Pasadena

Communicated March 19, 1934

A. Introduction.—Two important facts support the view that cosmic rays are of extragalactic origin, if, for the moment, we disregard the possibility that the earth may possess a very high and self-renewing electrostatic potential with respect to interstellar space.

Pierre Auger and collaborators discovered extensive air showers



Volcano ranch experiment detected the first CR with an energy of about 10^{20} eV

1934

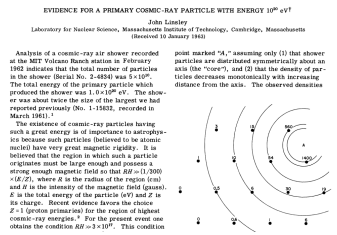
W. Baade & F. Zwicky proposed CR's originate in Supernovae

1938

1949

Fermi proposed his theory of CR acceleration

1962



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)

Analysis of a cosmic-ray air shower recorded at the MIT Volcano Ranch station in February 1962 indicates that the total number of particles in the shower (Serial No. 2-4834) was 5×10^{9}. The total energy of the primary particle which produced the shower was 1.0×10^{20} eV. The shower was about twice the size of the largest we had reported previously (No. 1-11632, recorded in March 1961).[1]

The existence of cosmic-ray particles having such a great energy is of importance to astrophysics because such particles (believed to be atomic nuclei) have very great magnetic rigidity. It is believed that the region in which such a particle originates must be large enough and possess a strong enough magnetic field so that $RH \approx (1/300)\times(R/Z)$, where R is the radius of the region (cm) and H is the intensity of the magnetic field (gauss). E is the total energy of the particle (eV) and Z is its charge. Recent evidence favors the choice $Z=1$ (proton primaries) for the region of highest cosmic-ray energies.[2] For the present event one obtains the condition $RH \approx 3\times10^{18}$. This condition

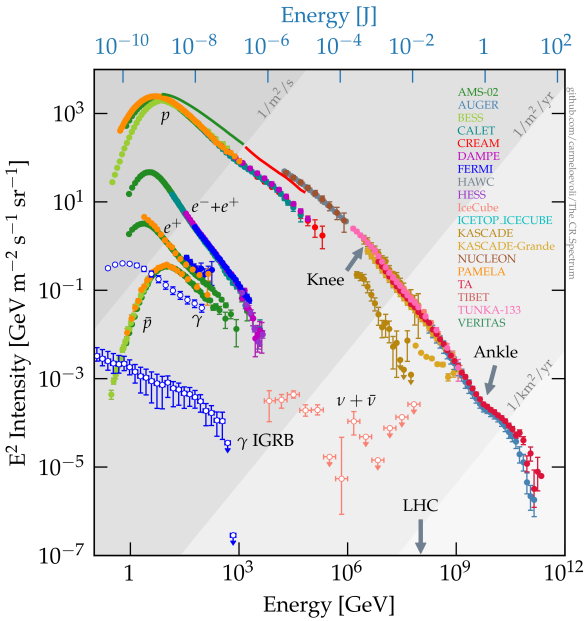
point marked "A," assuming only (1) that shower particles are distributed symmetrically about an axis (the "core"), and (2) that the density of particles decreases monotonically with increasing distance from the axis. The observed densities

Open questions

- The origin and the acceleration mechanisms of the production of UHECR's remain a mystery
- The key observables for addressing these questions are:
  1. Energy spectrum
  2. Mass composition
  3. Arrival directions

Energy Spectrum

- Energy spectrum ranges from 10^9 eV to more than 10^{20} eV
- It follows a power law spectrum as $E^{-\gamma}$
- Important features of the power law spectrum are:
  1.<u>Knee:</u> Change of slope at 3×10^{15} eV
  2.<u>Ankle:</u> Change of slope at 5×10^{18} eV



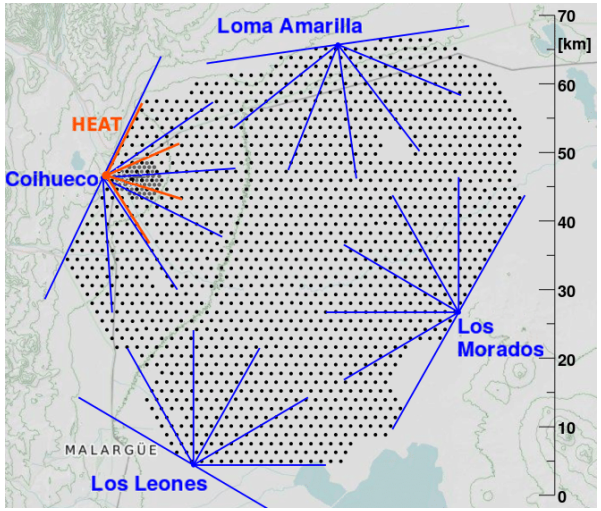
The Cosmic-Ray Energy Spectrum

(C. Evoli, DOI:

10.5281/zenodo.4396125)

Pierre Auger Observatory

- The largest UHECR Observatory in the world, located in Argentina
- The total exposure exceeds 100,000 km^2 sr yr
- The detectors covers an area of around 3,000 km^2
- During *Phase I*, the observatory had two main detectors:
  1. Surface Detector (SD)
  2. Fluorescence Detector (FD)
- It underwent an upgrade called AugerPrime that includes new detectors



Schematic of the Pierre Auger Observatory array

(A. Aab *et al.*, DOI:

10.1016/j.astropartphys.2017.09.001)

Hybrid Detection

Surface Detector (SD)

- Consists of 1,660 water-Chereknov detector tanks
- Each tank is spaced at 1.5 kilometers with respect to each other

Photograph of an SD station

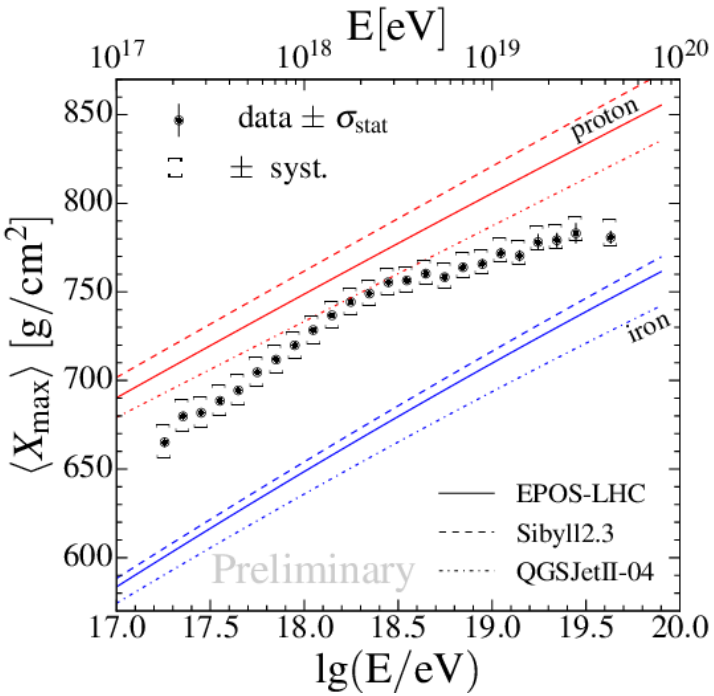
Fluorescence Detector (FD)

- Consists of 27 fluorescence telescopes
- These are distributed into four different stations with six at each location

Photograph of the Los Morados FD station

Mass composition

- UHECR's consist of many atomic nuclei species, ranging from protons to iron nuclei
- For lower energies, lighter elements are more abundant in cosmic rays
- Pierre Auger Collaboration has found evidence that the composition becomes heavier for higher energies

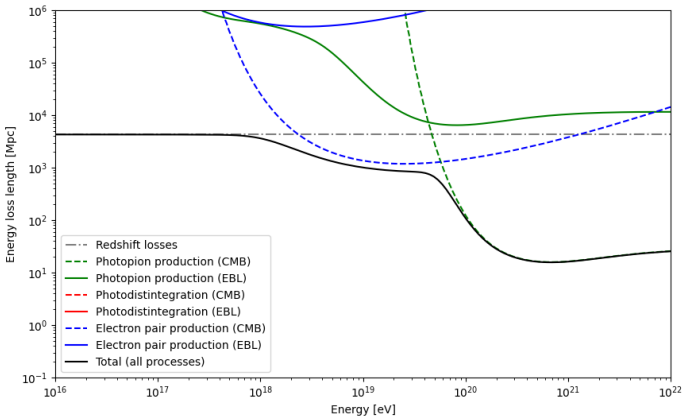


Measurement of X_{max} by the Pierre Auger Observatory

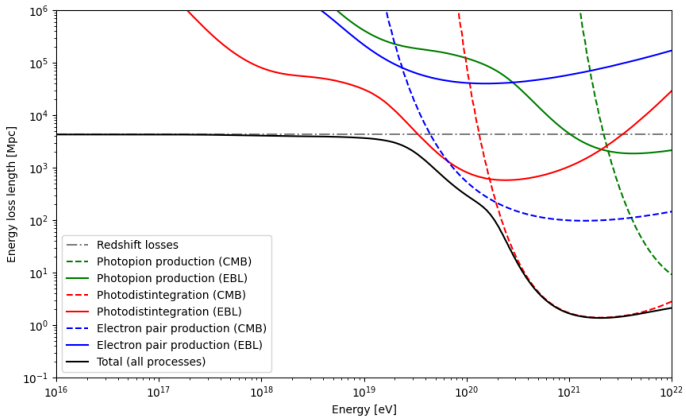
(A. Yushkov *et al.*, DOI: 10.22323/1.358.0482)

Energy loss length

- During the extragalactic propagation, CR's interact with the photon background mainly the CMB and EBL



Energy loss lengths for proton

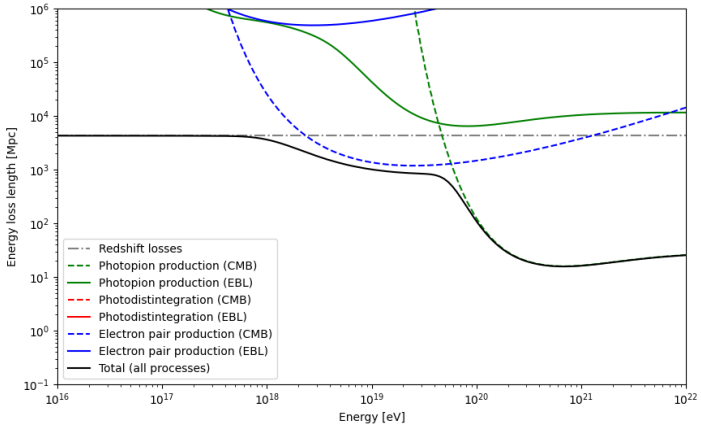


Energy loss lengths for Iron-56

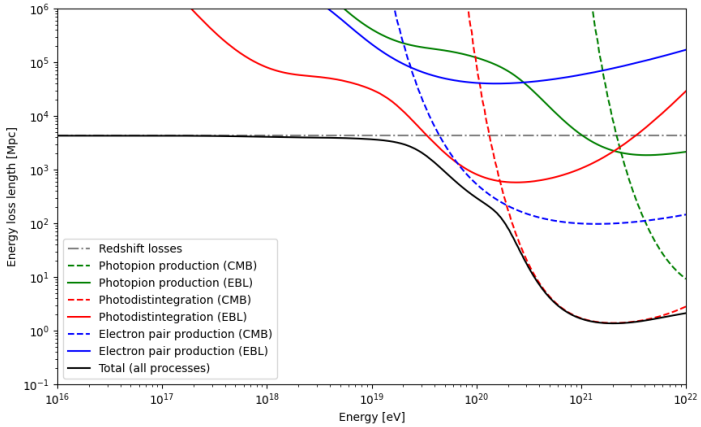
- Pair production, photo-pion production and photo-disintegration play an important role in the modification of the nuclear species of CR's

Energy loss length

- In case of a pure proton composition, photo-disintegration would not be possible



Energy loss lengths for proton

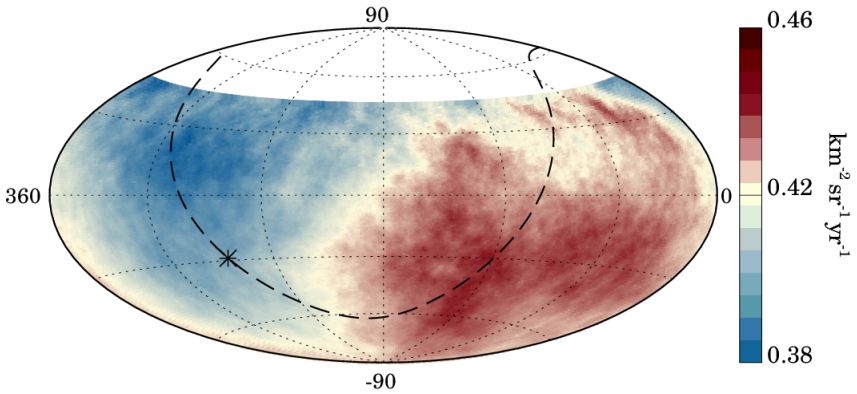


Energy loss lengths for Iron-56

- In the case of Iron-56, pion production is shifted towards higher energies as compared to the case of protons

Anisotropies

- In 2017, first detection of large-scale anisotropy in UHECR arrival directions at 5.2σ significance was made



Sky map in equatorial coordinates showing the cosmic-ray flux above 8 EeV

(A. Aab *et al.*, DOI: 10.1126/science.aan4338)

- 32,187 cosmic ray events above 8 EeV were analyzed
- Ultra-high-energy cosmic rays above 8 EeV show clear anisotropy
- It provides strong evidence for extragalactic origin

Aim of Thesis

- We aim to use CRPropa[1] to simulate the propagation of CR's at energies above 8 EeV
- We plan to consider the effect of cosmic magnetic fields and take into account all relevant interactions
- We intend to simulate composition dependent anisotropies for a range of astrophysical scenarios using CRPropa
- Finally, we will compare such predictions with the data from the Pierre Auger experiment and explore what kind of constraints on astrophysical scenarios can potentially be derived

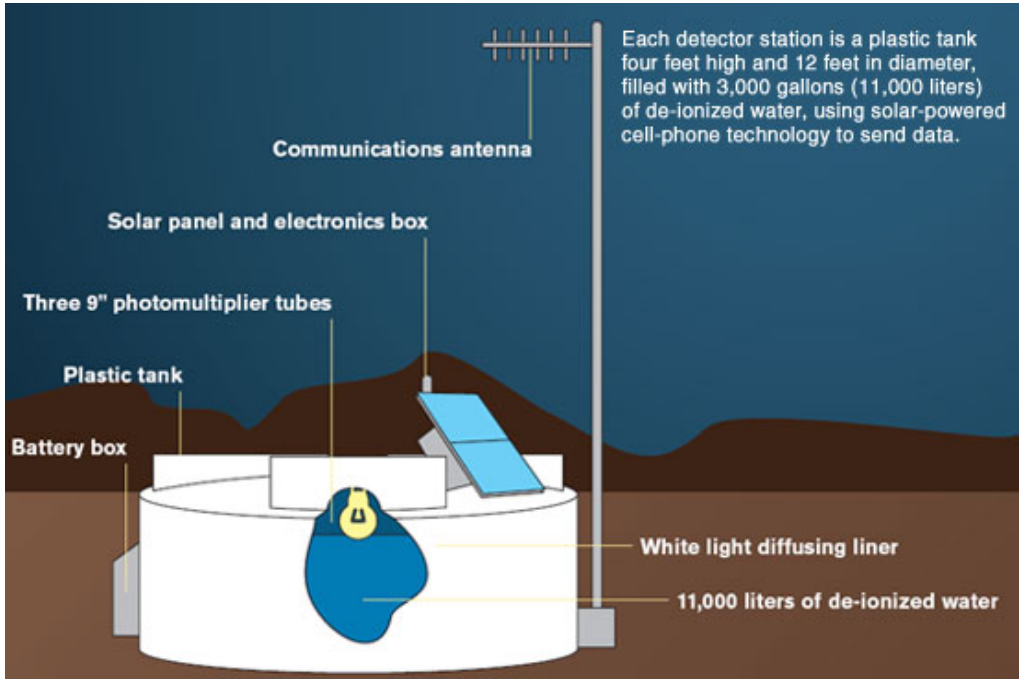
[1] R. Alves Batista *et al.*, DOI: 10.22323/1.444.1471

THANK YOU!

Back-up slides

Pierre Auger Observatory

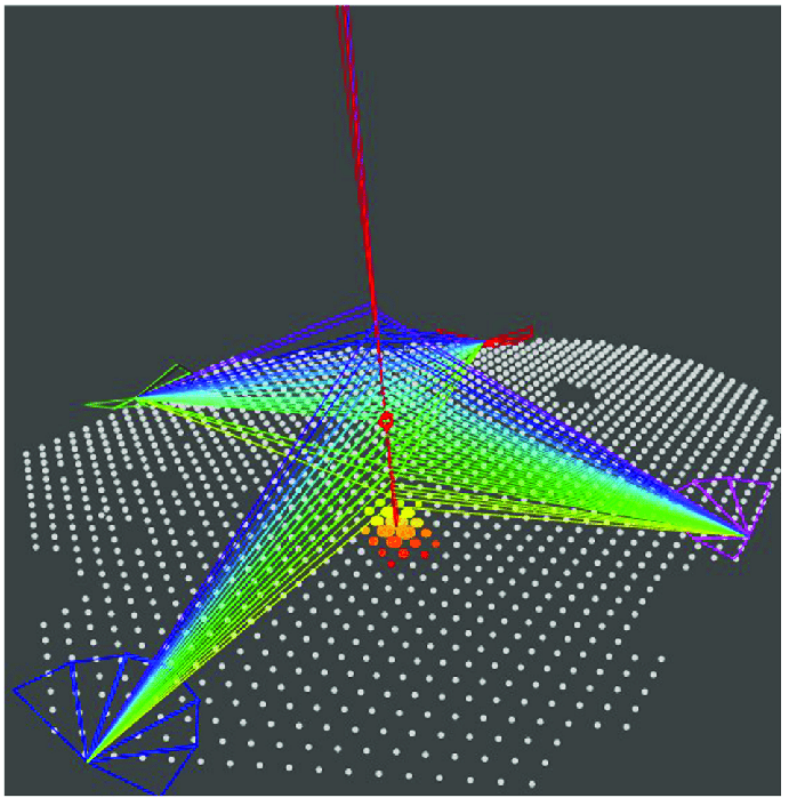
1. Surface Detector



Schematic of the surface detector

Pierre Auger Observatory

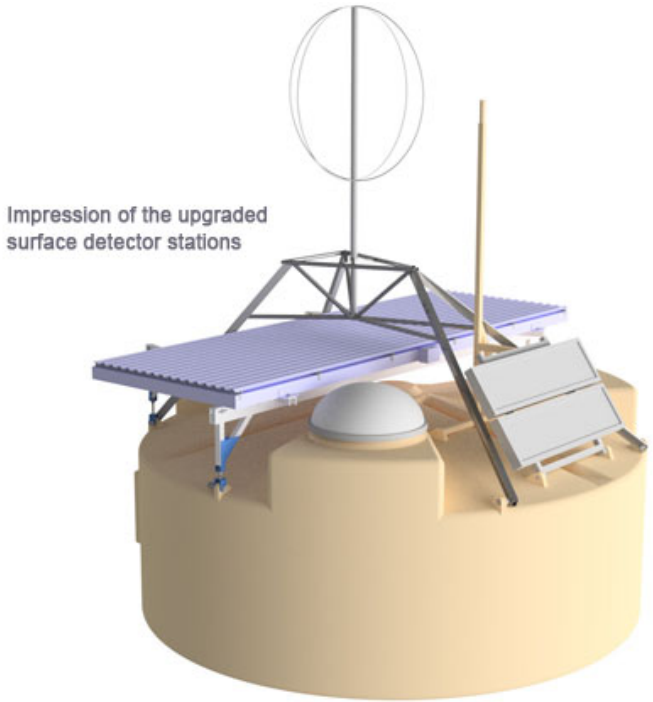
2. Fluorescence Detector



Representation of fluorescence detector

Pierre Auger Observatory

3. AugerPrime



Impression of the upgraded surface detector stations