Cosmic Rays

I An introduction

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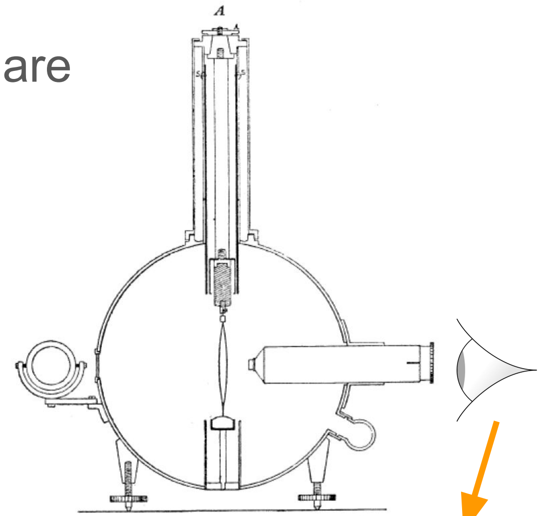
Why is the air getting ionised?

- In 1785 Coulomb discovered that charged objects in air are getting discharged: there are ions in the atmosphere!
- Ionization can be measured through an **electroscope**



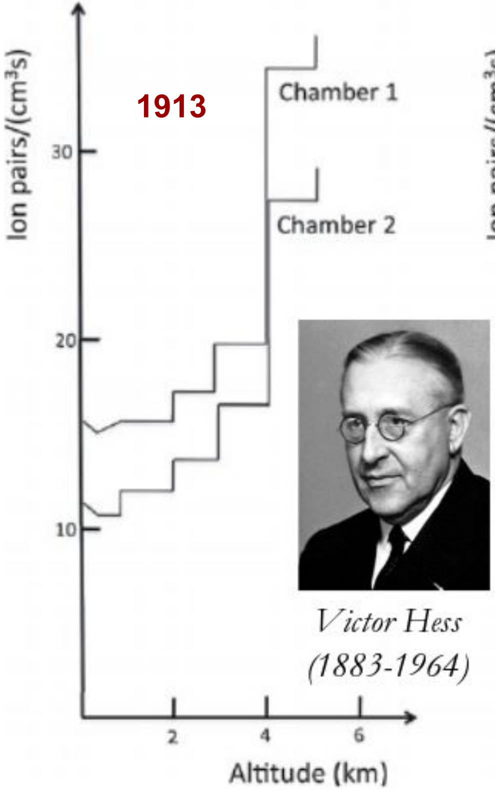
*Scheme of the **Wulf electroscope**: to the right is the microscope that measures the distance between two thin silicon glass wires. The separation of the two wires by the Coulomb force measures the charge. The rate of discharge determines the air ionization rate*

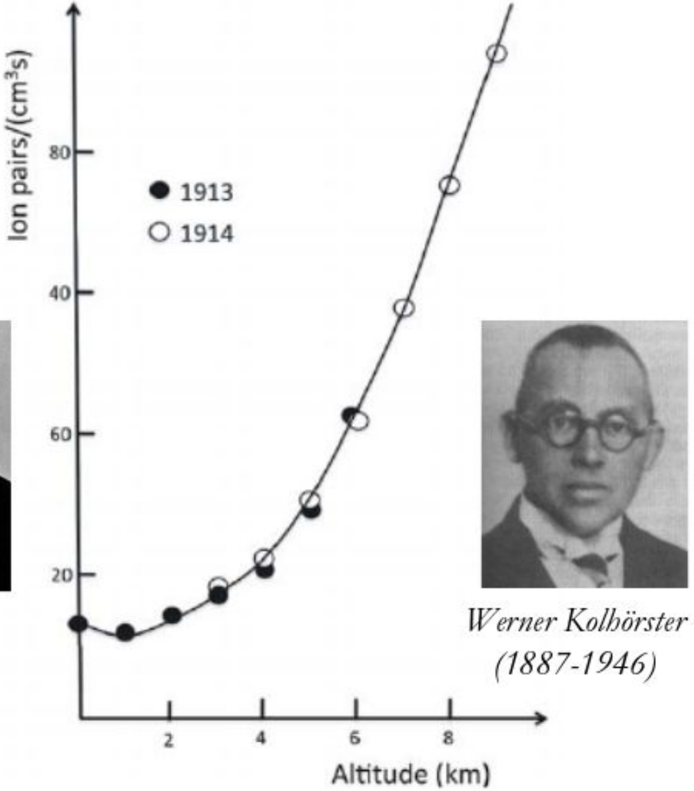
- But what is producing ionization of air?
- Early 1900s: discovery of **radioactivity**
- First hypothesis: air is ionized by radiation from the ground
- Ionization not affected by shields around the scopes that would stop α or β emitters: γ radiation was the first suspect

Is radiation coming from the ground?

- 1909: experiment by Theodor Wulf on the Eiffel Tower: 300 m from ground
- Slight decrease of ionization (but less than expected for gamma rays from the ground)
- Experiments underground or below water showed non-conclusive hints that ionization was decreasing
- Conclusive evidence obtained through measurements on balloons...

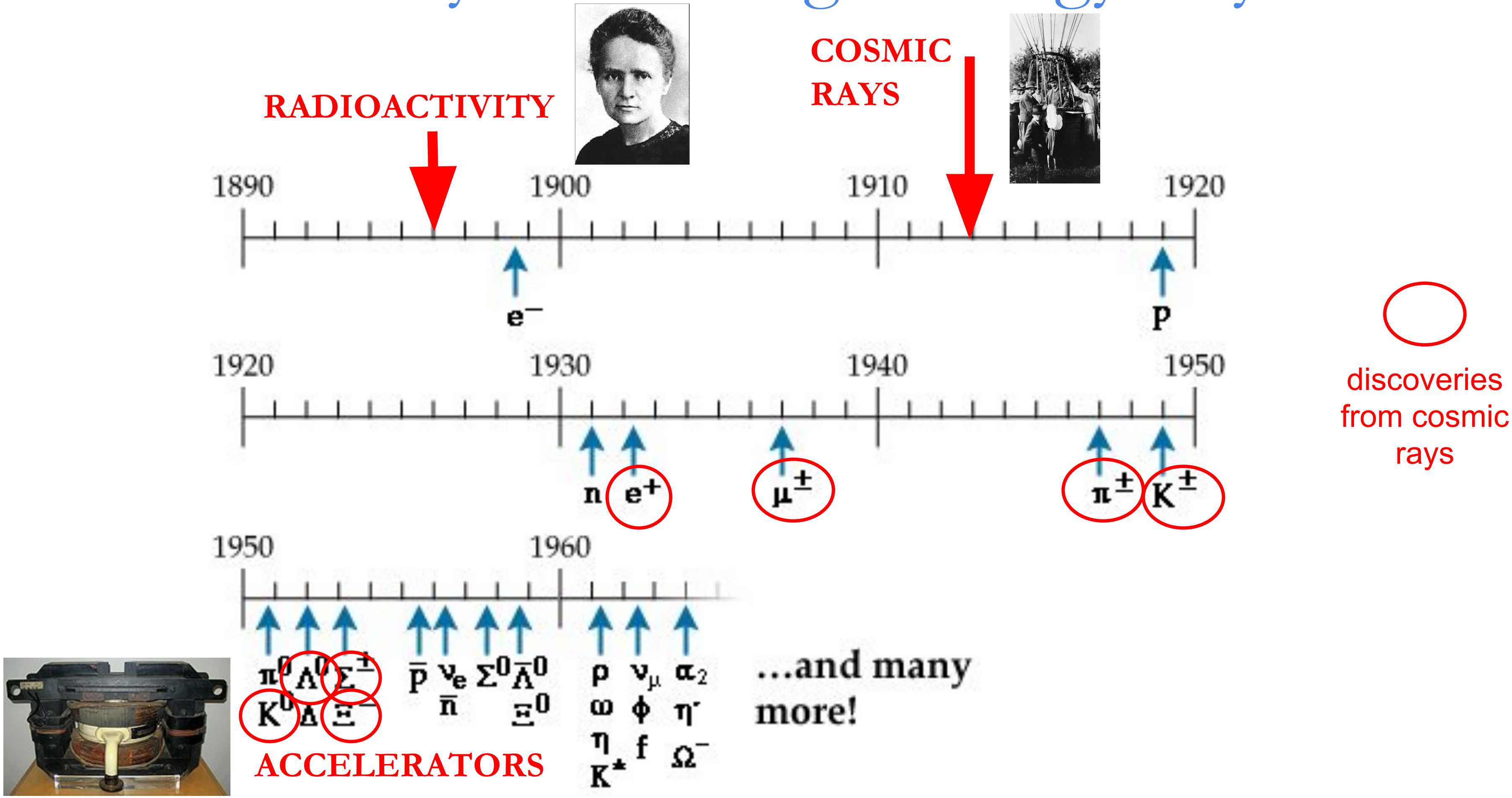
Radiation is coming from above!





No day-night variation: the origin is not the sun

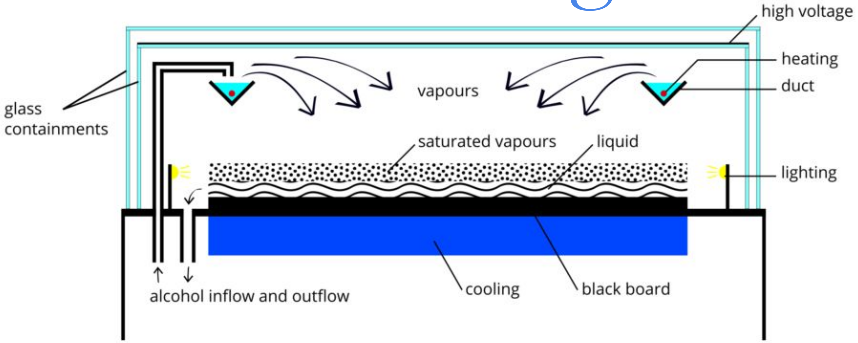
Cosmic rays boost High Energy Physics

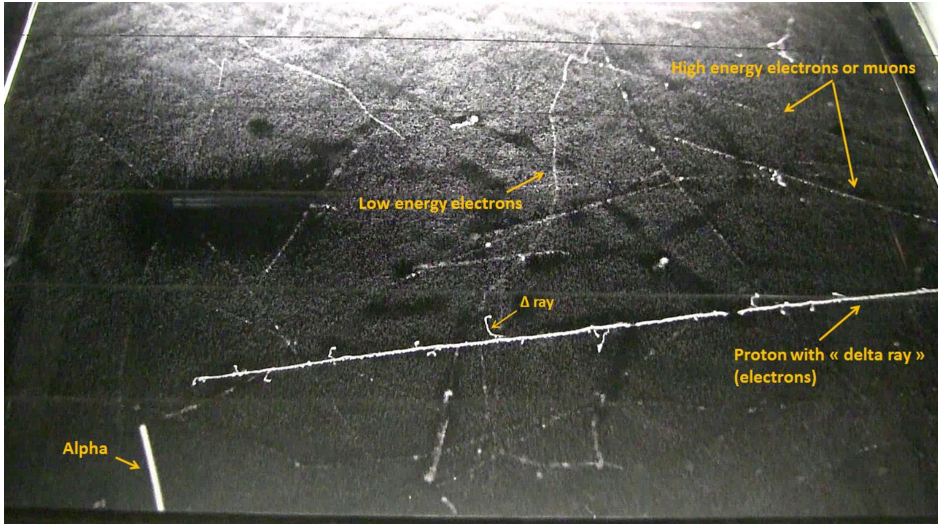


First detectors tracing cosmic rays

The Cloud Chamber

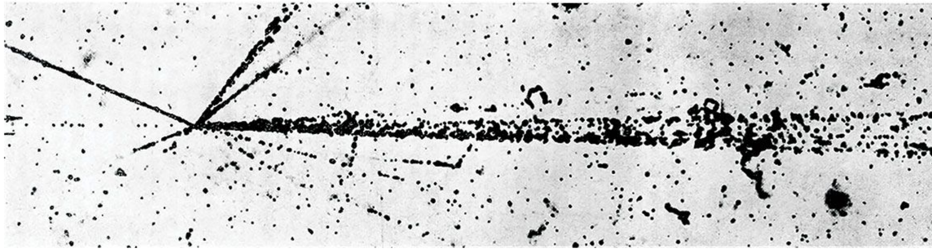
Ionizing particles leave trace of droplets in an over-saturated vapor (ions act as condensation centers), persisting for a few seconds





Photographic emulsions

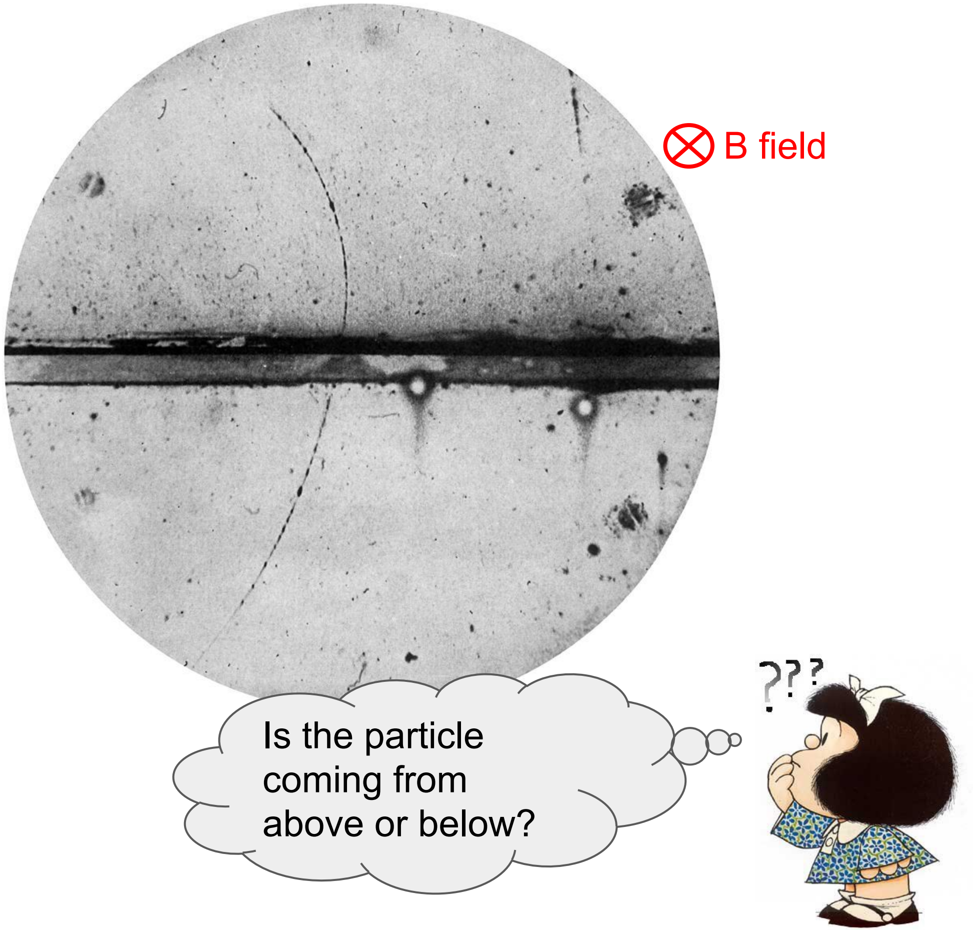
"Nuclear emulsions" are special thick photographic plates with very uniform and small (~ 1 µm) grains. Long time exposures, cumulative analysis after development. Lead to the discovery or rare events.



Cosmic ray induced collision with E~600 GeV (1952)

Discovery of anti-particles

- 1931: Paul Dirac proposes the existence of the **anti-electron**
- 1932: Carl David Anderson exposes a cloud chamber to cosmic rays at high altitude.
- Particles are bended by a magnetic field. A lead absorber in the middle allows him to determine the particle direction along the track, removing the ambiguity on the charge sign
- First evidence for a “positively charged electron”: the **positron**



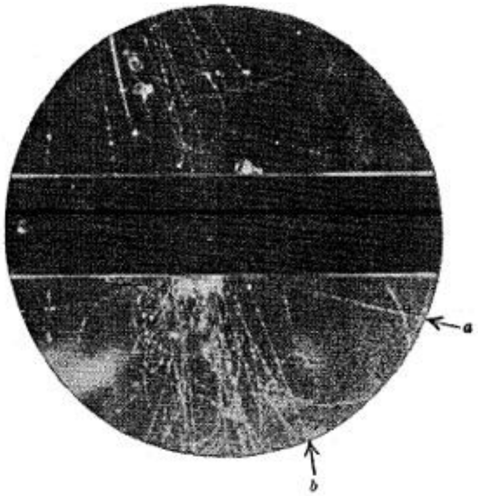
Discovery of mesons and strangeness

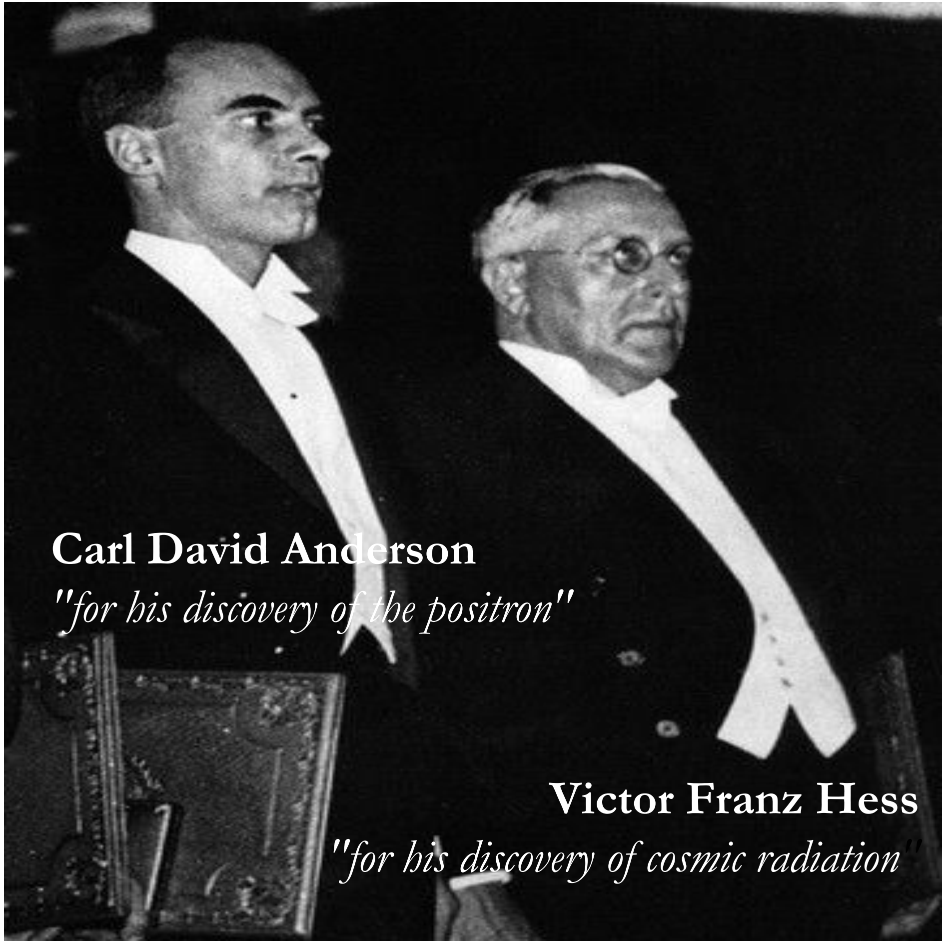
The Muon and the pion

- 1935: Yukawa proposes the existence of **mesons** (particles of mass ~ 100 MeV) as mediator of the strong nuclear forces
- 1937: Anderson identifies the **muon** using a cloud chamber
- 1947: Powell et al identify the Yukawa particle: the **pion** using nuclear emulsions

Strange decays

- During the 1940's unexpected events are observed: long-lived particles decaying to hadrons: the **K mesons** and the **Λ baryon** are discovered





1936 Nobel prize winners

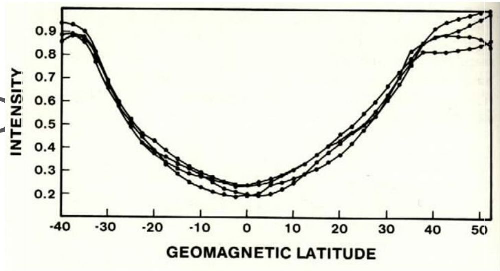
Other nobels from cosmic rays:

- 1948 Blackett ($e^{\pm}$ pair creation)
- 1950 Powell (pion)
- 2002 Davis and Koshiba (neutrino detection)
- 2015 Kajita and McDonald (neutrino osc.)

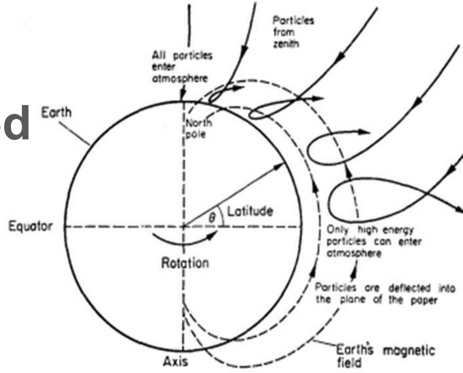
Exploring the nature of the cosmic radiation

- 1927: evidence for the geomagnetic effect on the cosmic radiation from the variation with latitude (first observed by C while traveling on a boat from Amsterdam to Indonesia)

⇨ cosmic rays are mostly **charged**

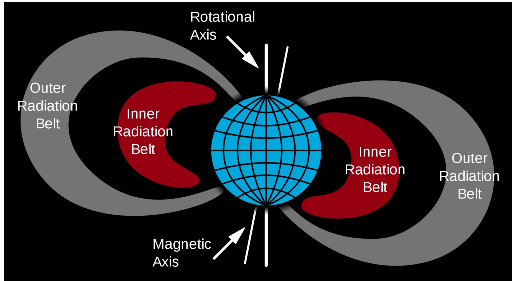


- 1934: the east/west asymmetry measured by Rossi at small latitudes shows that cosmic rays are mostly **positively charged**

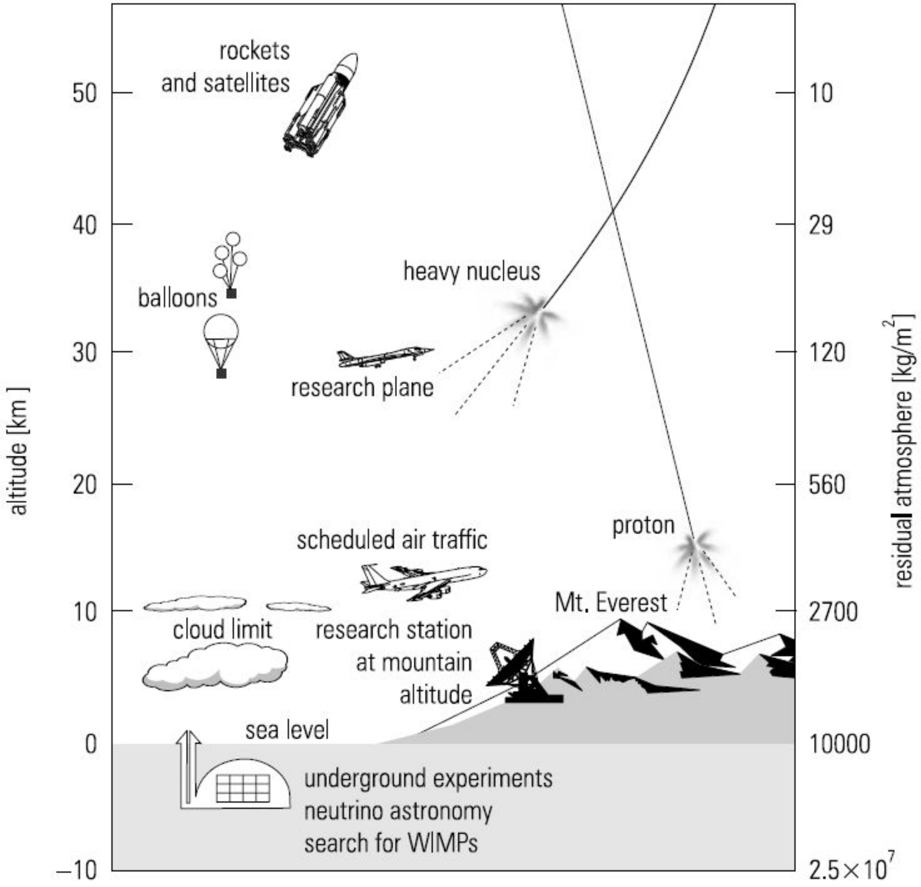


- Rossi (1934) and Auger (1937) detect cosmic **showers** via coincidences in detectors placed several meters apart
- 1948: direct detection of **primary CR** (nuclear emulsions on balloons@28 Km): mostly p, but ~ 10% He and 1 % heavier
- 1958: first measurements of radioactivity in **space** with Expl 1 (first american satellite).

  Discovery of **Van Allen belts** , where low-energy charged particles are trapped by the geomagnetic field

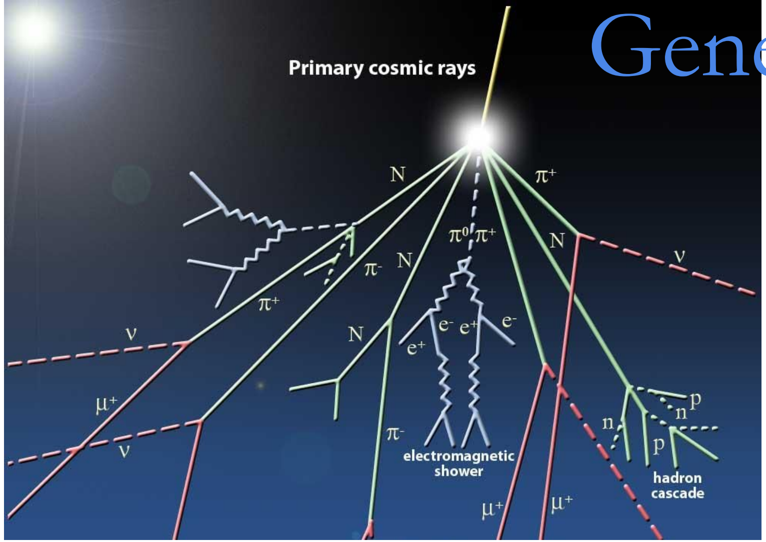


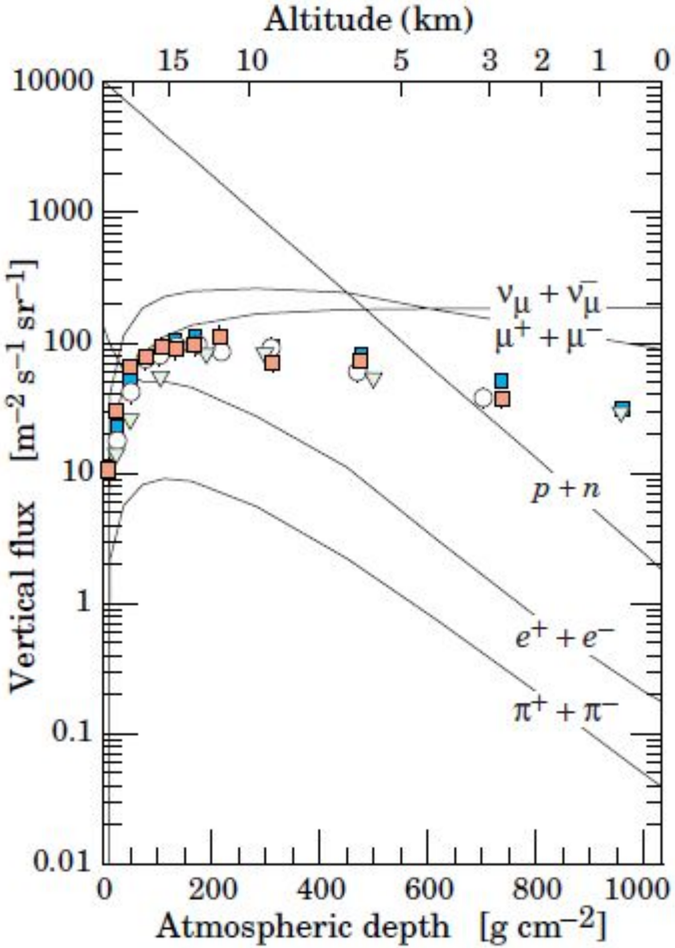
The current picture



- Experiments carried out in space, directly observing the primary radiation, and at different depth in the atmosphere (from balloons to underground labs) are providing detailed characterization of the cosmic radiation

General properties of Cosmic Rays





- Primary (charged) particles are mostly hadrons:

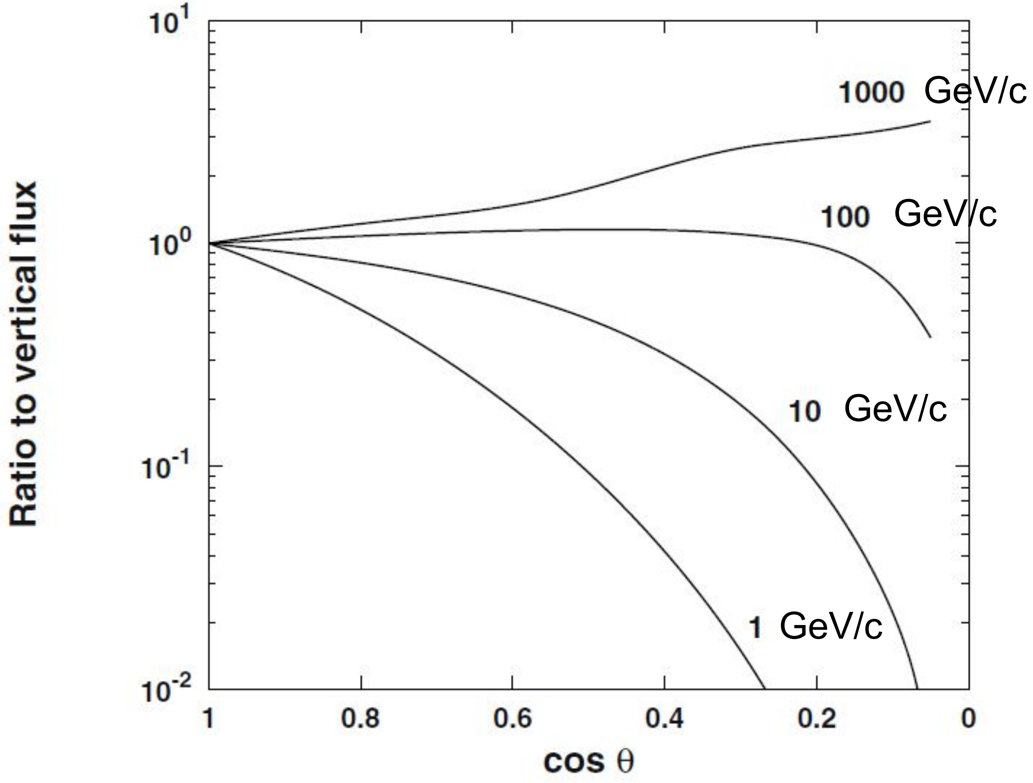
  protons 86% α particles 11%

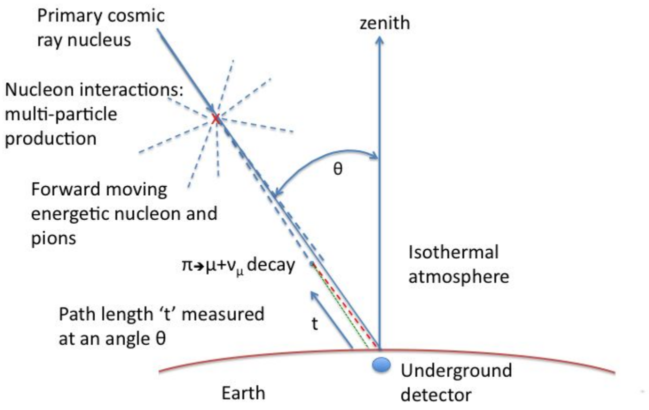
  heavier nuclei 1% electrons <2%

  anti-particles (positrons, anti-protons) <<1%

- The primary flux is **isotropic** to a very high degree
- Interaction with atmosphere produces particle showers
- Particle flux at ground level is dominated by muons (and neutrinos): roughly 1 muon per cm^2 per minute

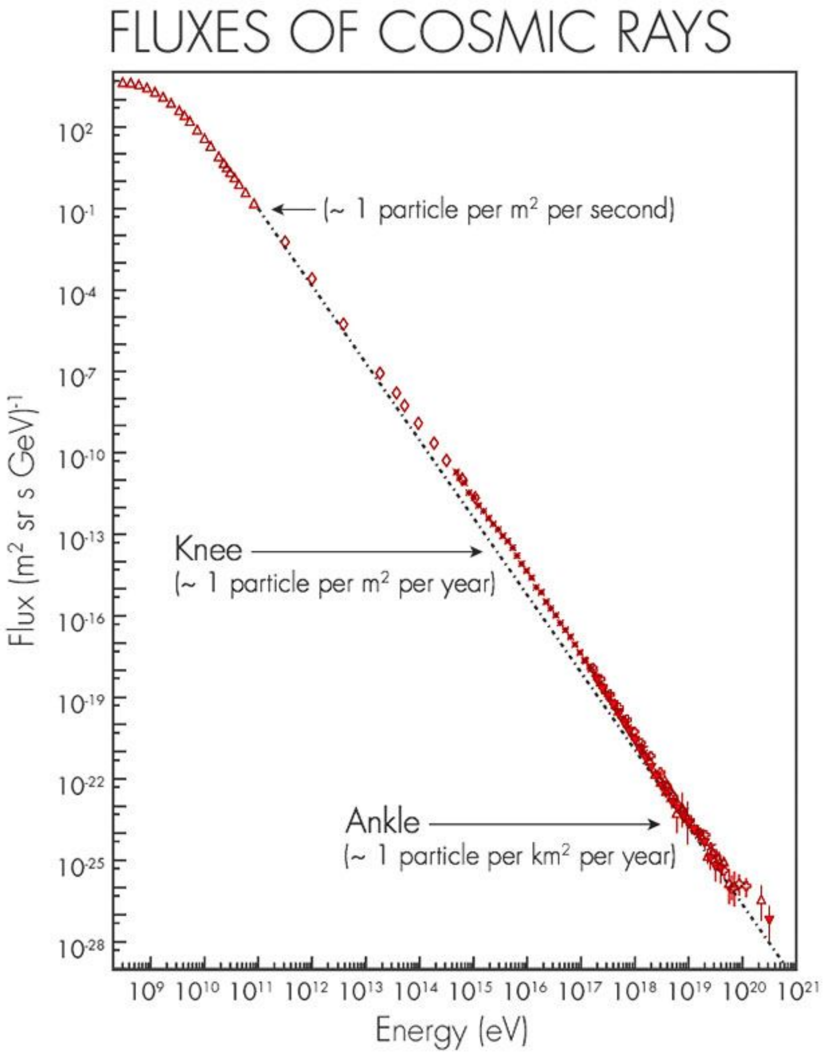
Zenith angle distribution of muons at ground level



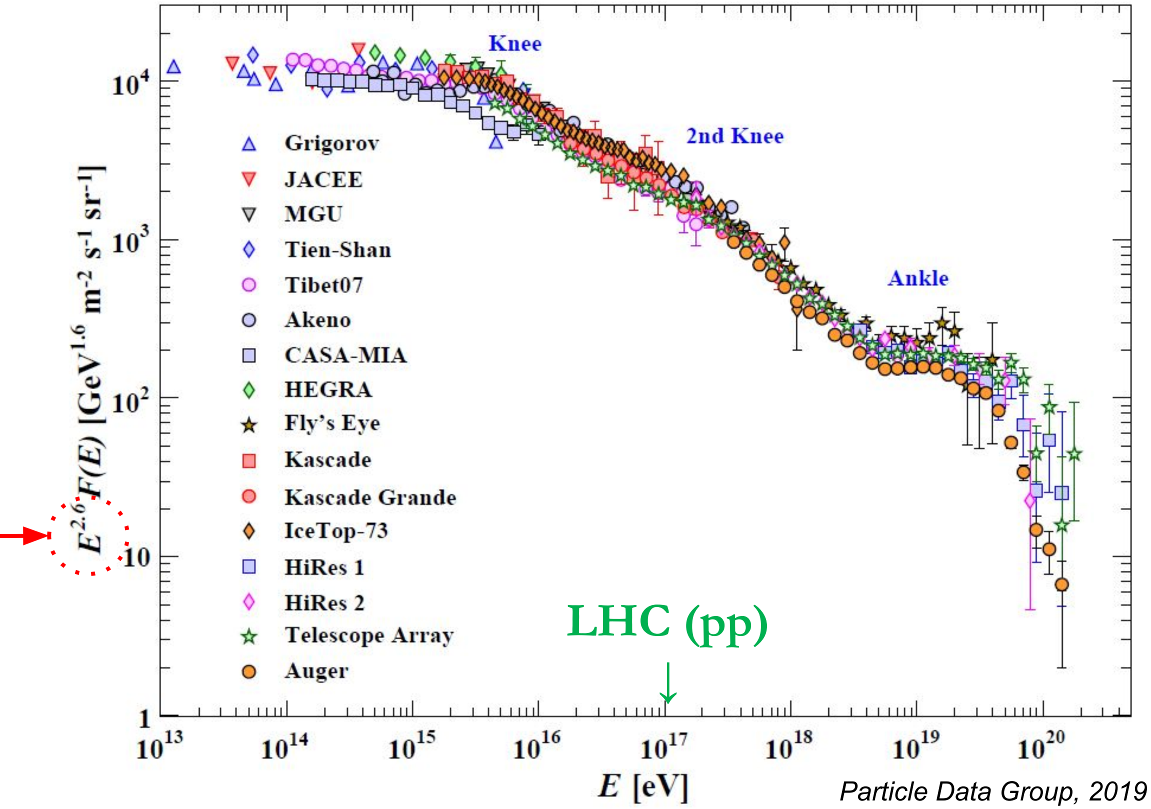


Energy spectrum

- Power-law spectrum ~ $E^{-2.6}$ up to the "knee" at 10^{16} eV
- Measurements cover some 30 orders of magnitude in flux and 15 in energy!
- Spectrum shows several interesting features at the highests detected energies



Spectrum at ultra-high energy



Particle Data Group, 2019

- Changes of slope at ultra-high energies could be due to different source mechanisms:

  different galactic sources at the knees? Or particles escaping galaxy?

  extra-galactic sources above the "ankle"?

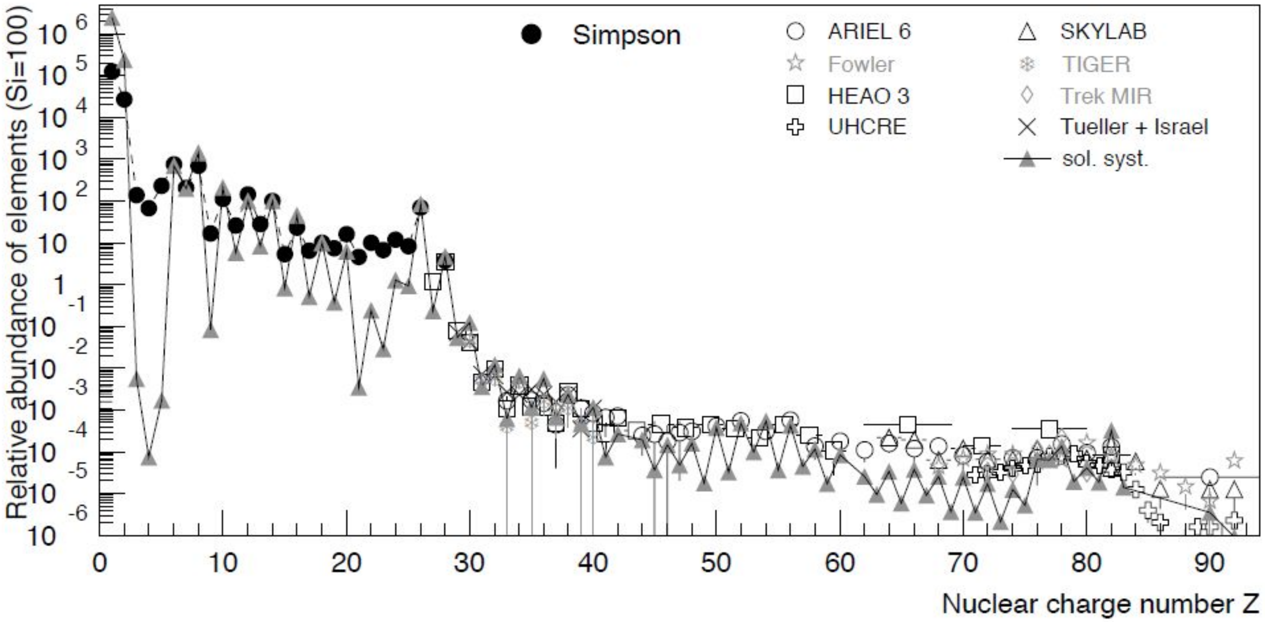
  cutoff from interaction with microwave backround (GZK) at 10^{19} eV ?

- Note that 14 TeV pp collisions at the LHC correspond to collisions of cosmic protons of energy

$$E = \frac{(14\mathrm{TeV})^2}{2 \cdot M_P} \sim 10^{17}\mathrm{eV}$$

Composition

- Similar to matter in the solar system, but:
  - higher fraction of nuclei with Z>2 (reason not well understood)
  - much higher rate of rare elements not produced in stellar nucleosynthesis: (Li, Be, B) and sub-Fe, these can be produced from heavier elements by spallation in high-energy collisions



Astroparticle Physics

Since the '90s, a revived interest in cosmic ray physics lead to the development of a great variety of large and ambitious projects. Motivations are both

Particle Physics:

- neutrino physics, discovery of **neutrino oscillations**
- search for **dark matter** candidates, **axions** and other hypothetical particles, that could be too massive or too rare to be seen at accelerators

Astrophysics:

- high energy particles (notably gamma and neutrinos, unaffected by magnetic fields) are novel probes to study "extreme" astrophysical systems (SuperNovas, Pulsars, Active Galactic Nuclei…)
- can be used in conjunction with other observations (optical, radio, X-rays, gravitational waves…) ⟹ **Multimessenger Astrophysics**

The field is evolving rapidly and promises exciting results in the near future