A Brief Overview of the History of Cosmic Rays

Anderson Fauth

State University of Campinas – UNICAMP, Brazil

Encuentro CyTED LAGO INDICA   3-5/12/2025
Esc Física Unìversidad Industrial de Santander, Bucaramanga, Colombia

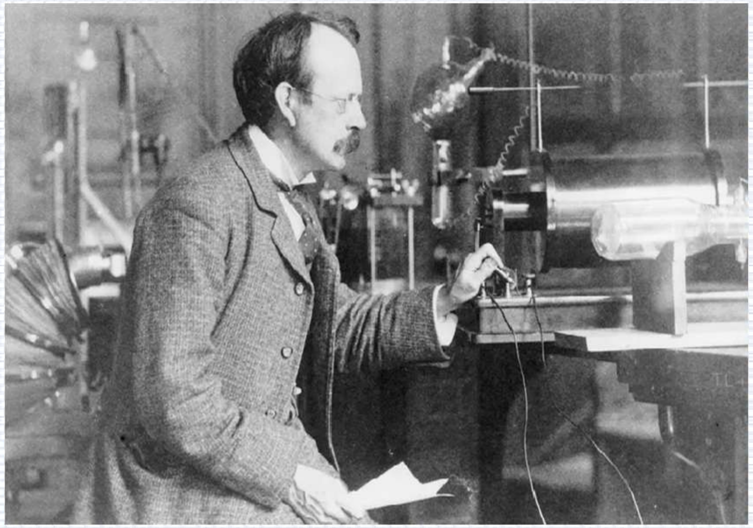
Summary

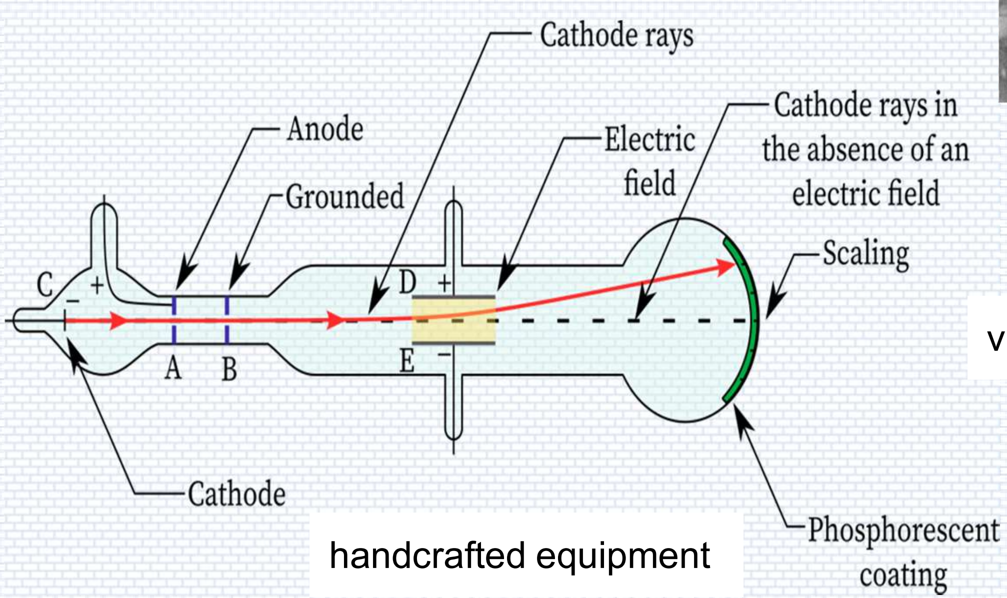
- A brief history of cosmic rays
- Cosmic rays
- Particle detectors
- Water-Cherenkov Detector

J.J. Thomson discovered the electron in 1897.

1906 Nobel Prize

The indivisible has an internal structure!

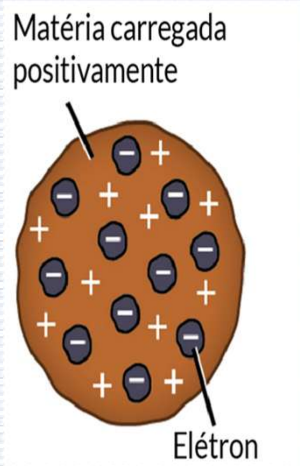




handcrafted equipment

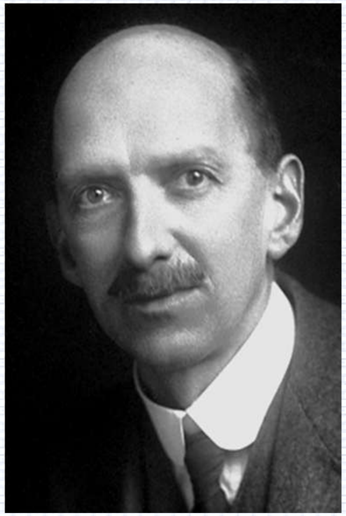
visual observation

plum pudding

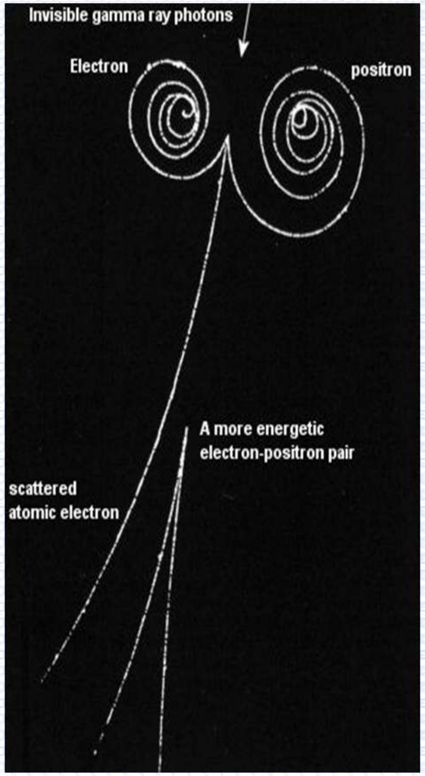


Wilson invented the cloud chamber.

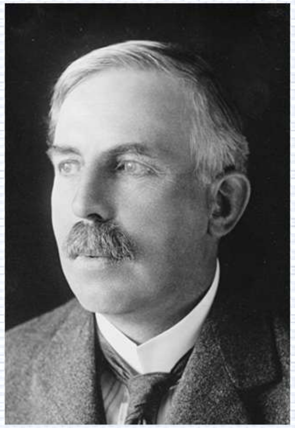
Wilson invented the particle detector **cloud chamber** and recorded traces of ionisation. In 1900, he discovered the **continuous ionisation of the atmosphere**. Its cause was attributed to the Earth's natural radiation.



1927 Nobel Prize



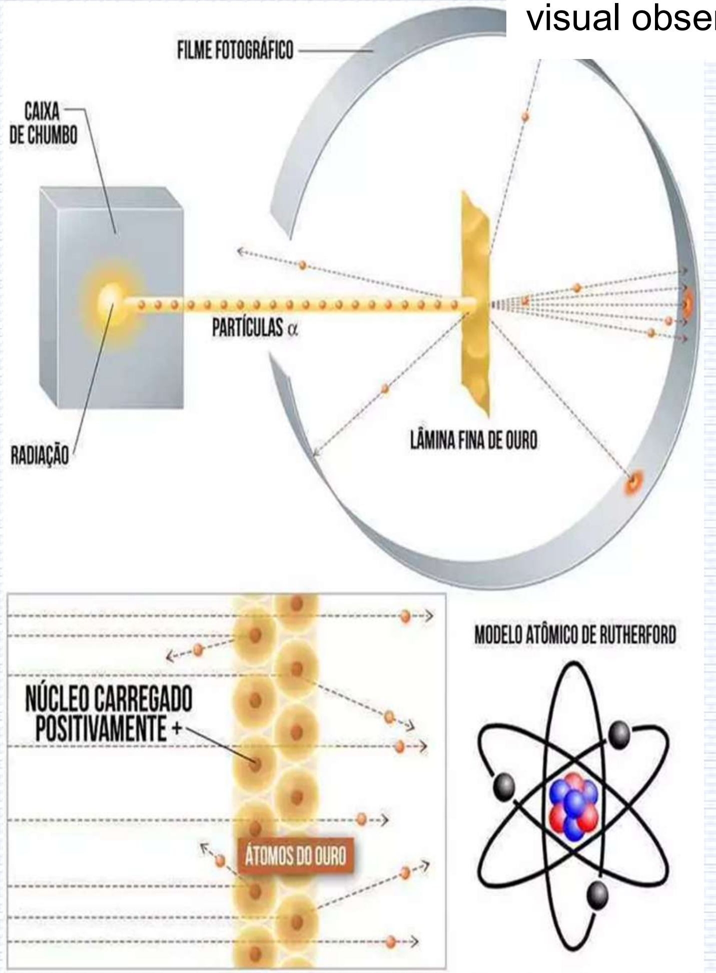
Rutherford discovers the nucleus of the atom in 1911

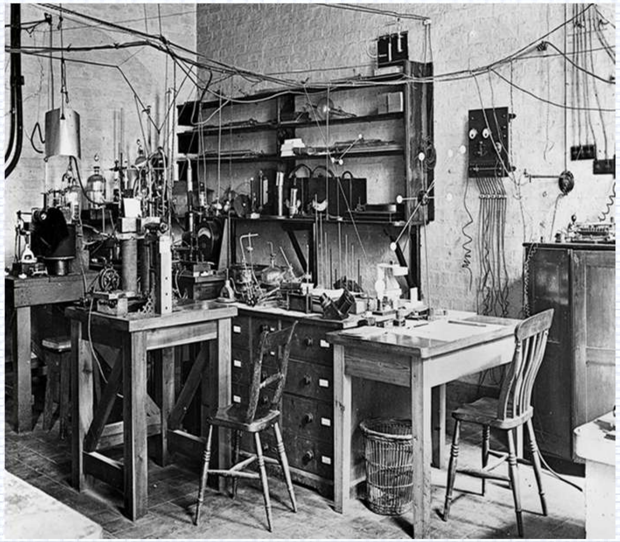


1908 Nobel Prize
(Chemistry)

Rutherford's gold foil experiment showed that the atom is mostly empty space with a tiny, dense, positively charged nucleus.

visual observation

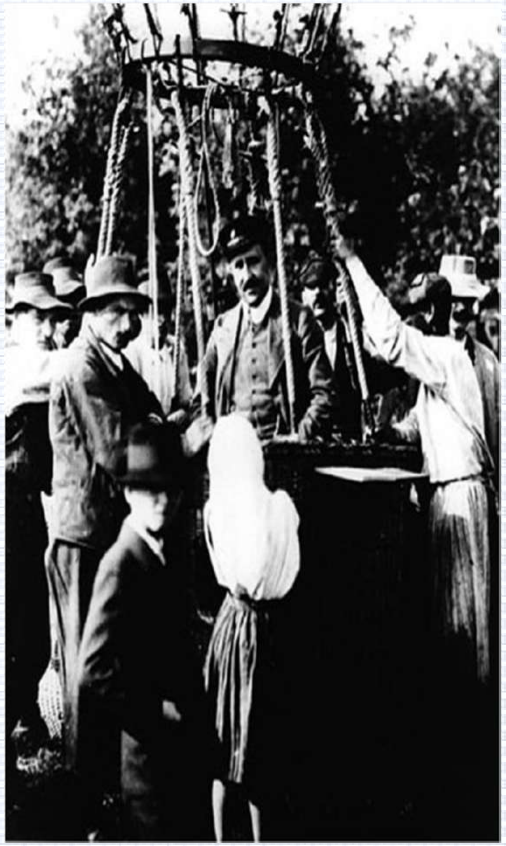




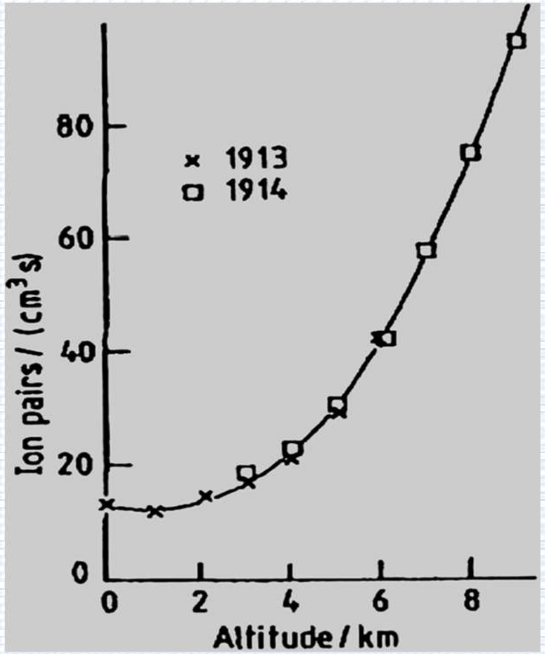
handcrafted equipment

Victor Hess discovered - 1912

1936 Nobel Prize



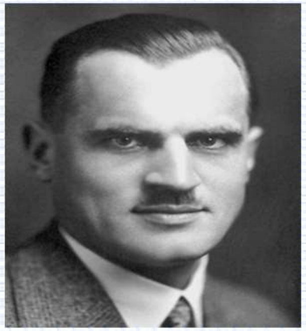
In 1912, Victor Hess used electroscopes to discover that up to 700 m the ionisation rate decreases, but then increases with altitude, showing that the origin comes from outside the Earth.



Millikan named it - 1925

In 1925, Millikan perfected the electroscope and took measurements in lakes and mountains. He introduced the term **Cosmic Rays**.

1923 Nobel Prize



Compton
1927 Nobel Prize

The New York Times

VOL. LXXXII....No. 27,370. December 31, 1932

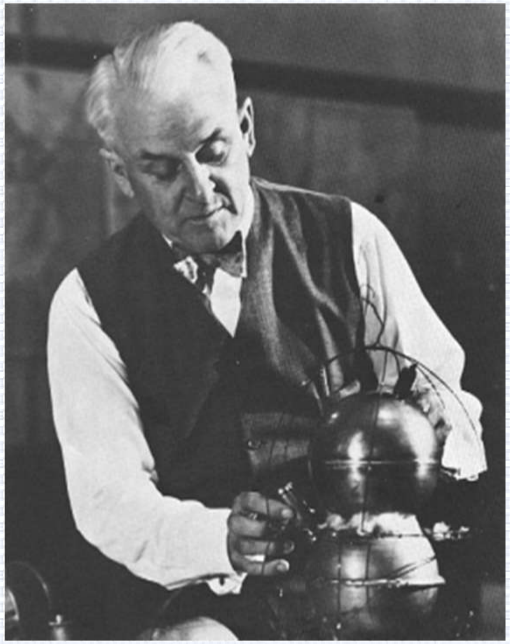
MILLIKAN RETORTS HOTLY TO COMPTON IN COSMIC RAY CLASH

Debate of Rival Theorists Brings Drama to Session of Nation's Scientists.

THEIR DATA AT VARIANCE

New Findings of His Ex-Pupil Lead to Thrust by Millikan at 'Less Cautious' Work.

Compton x Millikan



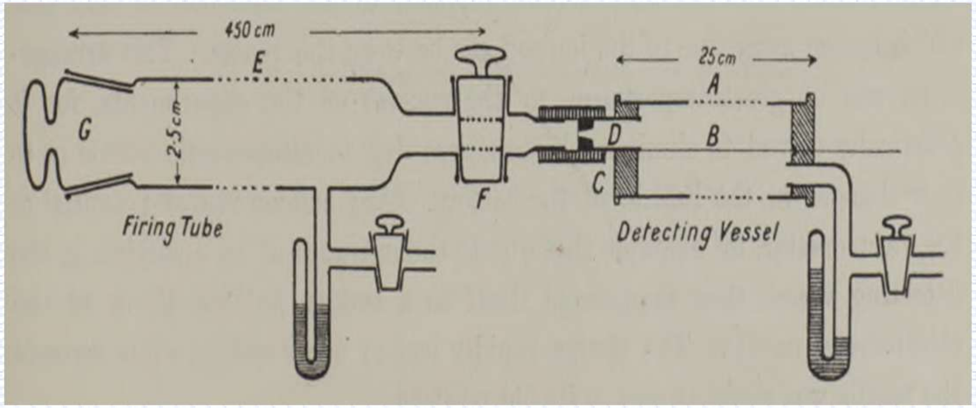
First **electric** particle counter: Geiger-Mueller

An Electrical Method of Counting the Number of α-Particles from Radio-active Substances.

By E. RUTHERFORD, F.R.S., Professor of Physics, and H. GEIGER, Ph.D., John Harling Fellow, University of Manchester.

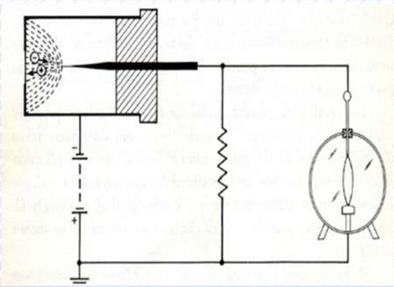
(Read June 18; MS. received July 17, 1908.)

In 1908, Rutherford and Geiger



Geiger-Mueller

1911

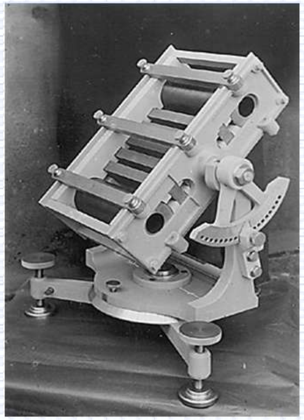


Rossi – Coincidence circuit – 1930

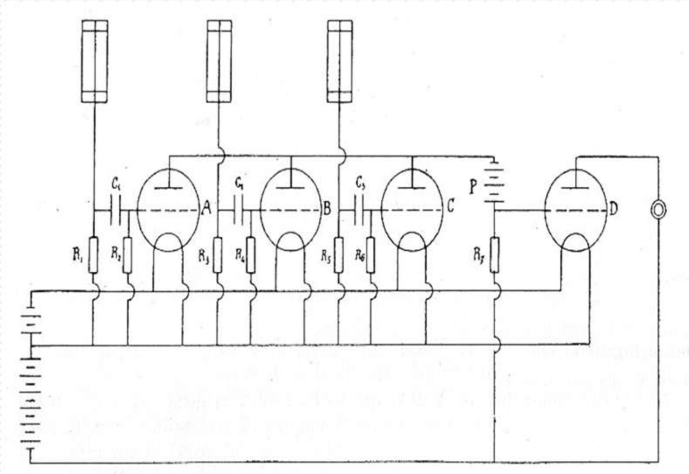
Nature **125**, 636-636 (26 April 1930) | doi:10.1038/125636a0

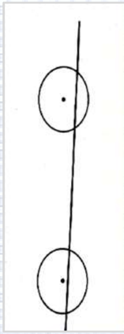
Method of Registering Multiple Simultaneous Impulses of Several Geiger's Counters

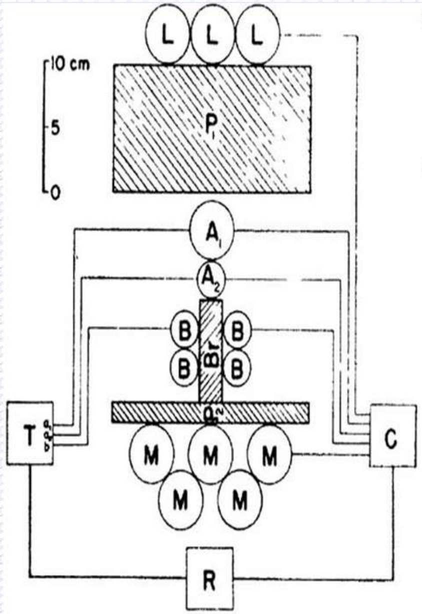
BRUNO Rossi

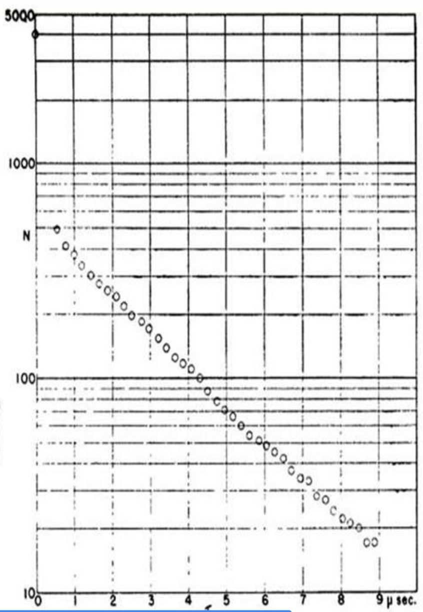


Trigger = temporal coincidence of pulses









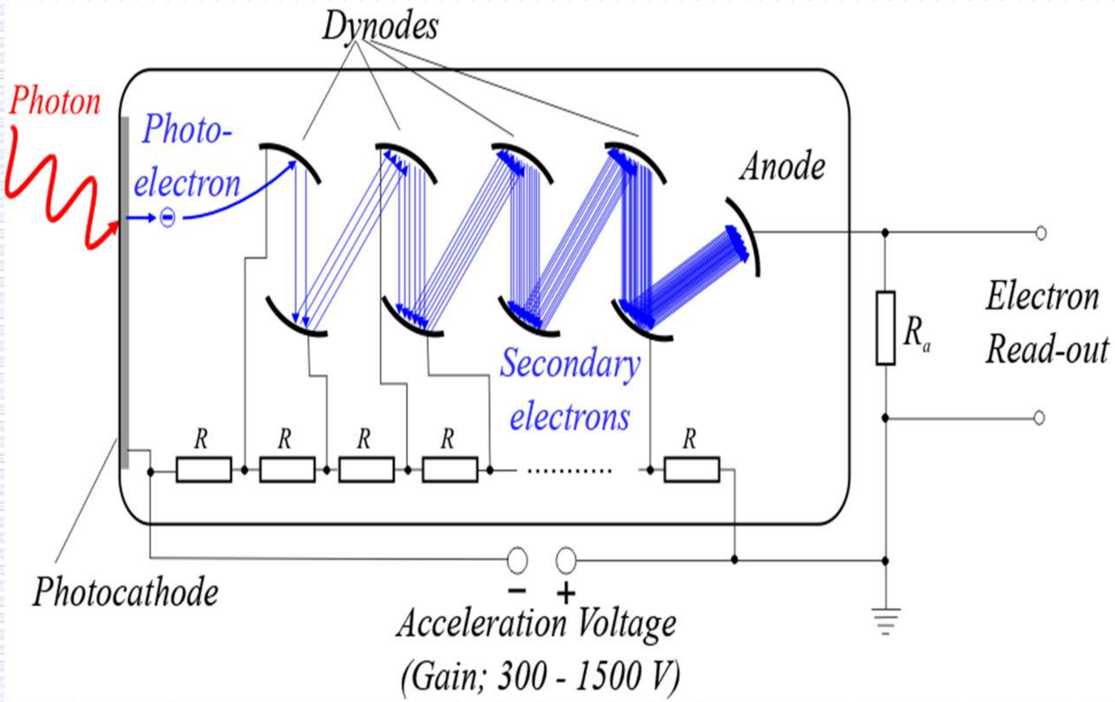
average lifetime of unstable particles

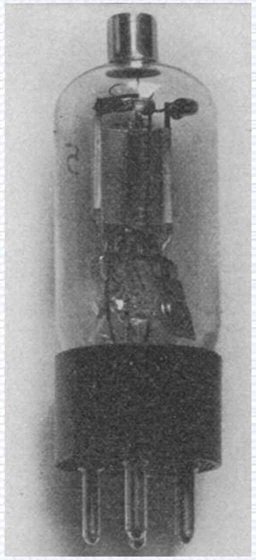
Invention of the vacuum tube *photomultiplier* (PMT) - 1934

Physicists Harley Iams and Bernard Salzberg, at the RCA (Radio Corporation of America) laboratories, first PMT. PMT technology was perfected by Vladimir Zworykin (also at RCA) and became a commercially viable device, although initially expensive.

Integration of a photocathode (photoelectric effect) and a single amplification stage

1930
Kubetsky's tube
URSS





RCA
USA

Extensive Atmospheric Showers - 1939

- In the 1930s, Rossi carried out measurements with atmospheric showers.
- **Auger** using coincidence circuits discovers **extensive atmospheric showers**.

Energies greater than **10^{15} eV** !

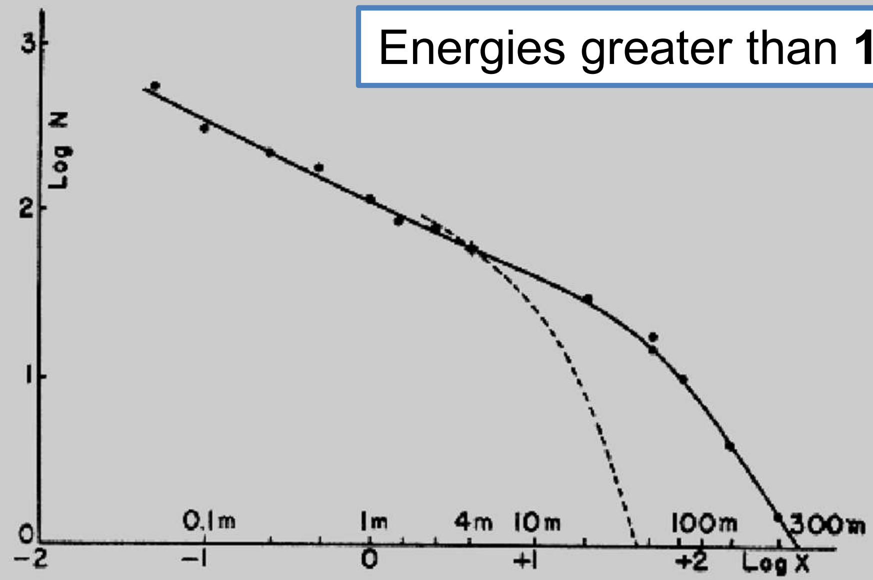
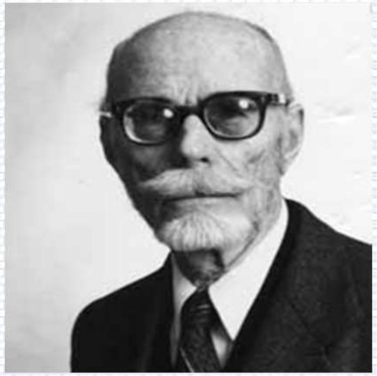


FIG. 1. Results with two parallel and horizontal counters.



Pierre Auger

Coincidence circuit with horizontal detectors

JULY–OCTOBER, 1939 REVIEWS OF MODERN PHYSICS VOLUME 11

Extensive Cosmic-Ray Showers

PIERRE AUGER
In collaboration with
P. EHRENFEST, R. MAZE, J. DAUDIN, ROBLEY, A. FRÉON
Paris, France

First experiments with EAS – 1946

1934: Bethe and Heitler develop the electromagnetic cascade theory, the particles observed on the surface are secondary.

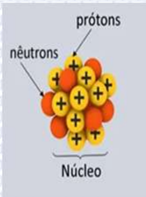
1946: Groups led by Bruno Rossi in the United States and Georgi Zatsepin in Russia began experiments on the structure of atmospheric showers. These researchers constructed the first experiments for detecting CAEs.

Grigory Zatsepin
setting up air shower detectors in Russia.

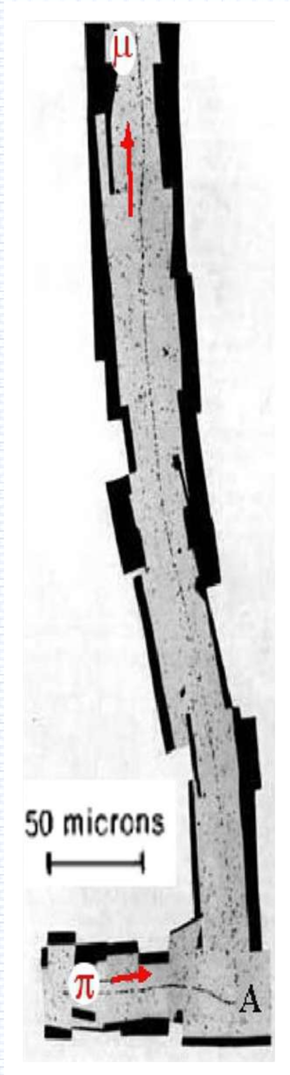
Cesar Lattes - Discovery of the π Meson - 1947

Lattes **improves nuclear emulsions** and detects π meson at Chacaltaya

Chacaltaya, 5,200 metres



$$\pi^{+/-} \rightarrow \mu^{+/-} + \bar{\nu}_\mu$$



Yukawa
1949 Nobel Prize

What keeps the core cohesive?
Short-range strong nuclear force

Birth of the **Standard Model** of Elementary Particles

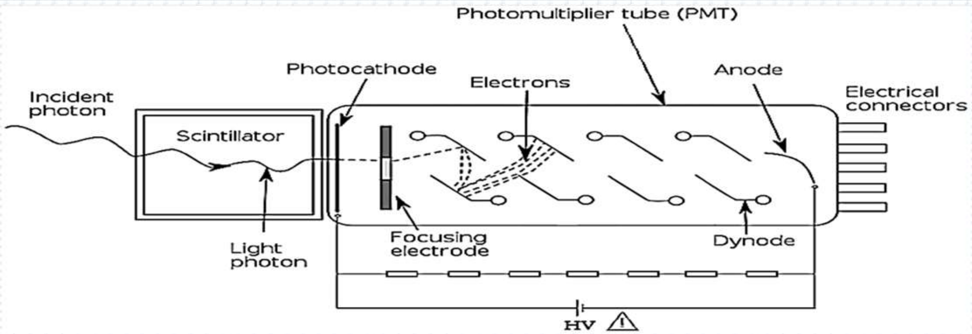
Scintillator + PMT (1950)

Hartmut Kallmann demonstrated that naphthalene (a component of mothballs) was a very efficient scintillator. Soon afterwards, anthracene proved to be even better. This paved the way for future plastic and liquid scintillators.

Scintillator + PMT

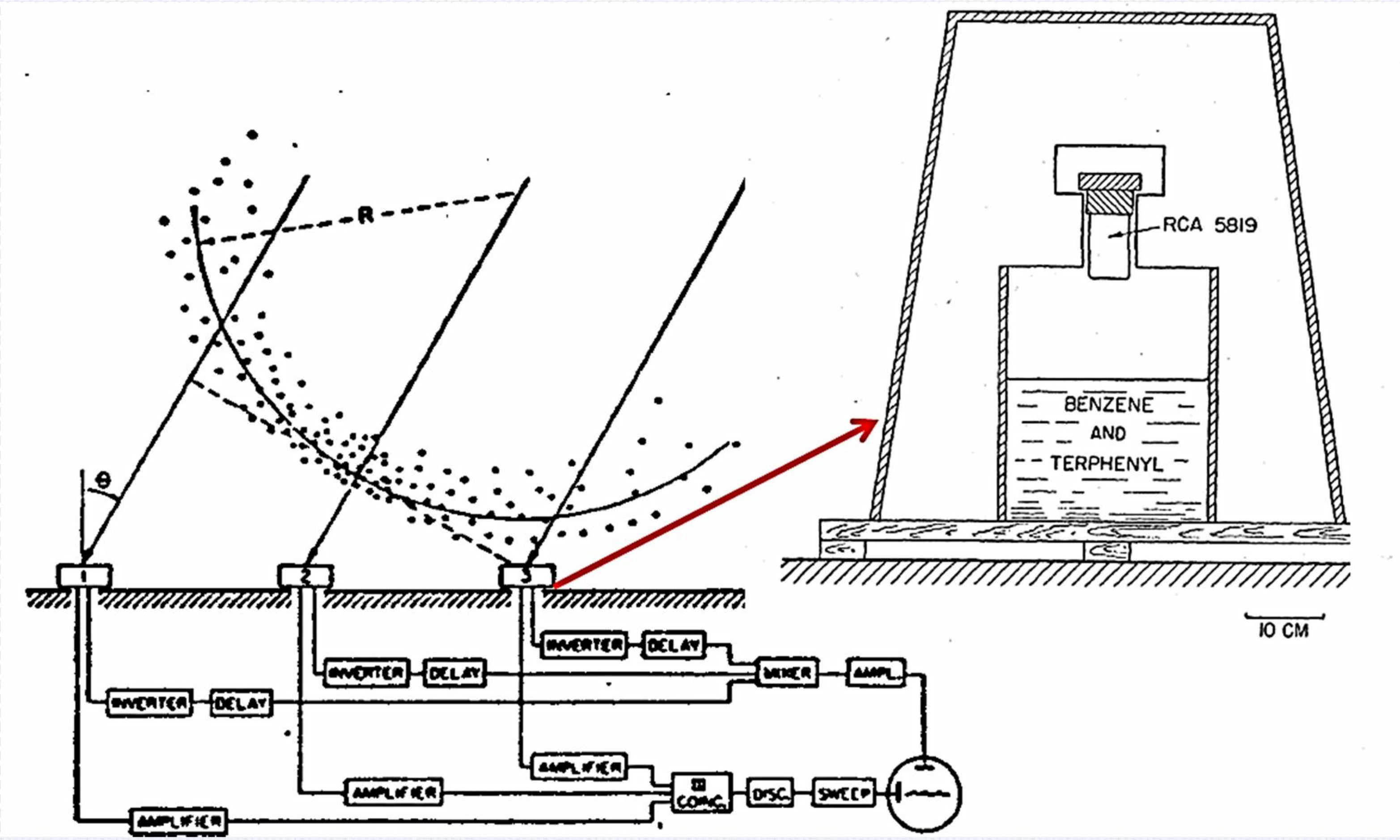
In 1950, Robert Hofstadter coupled NaI(Tl) crystals to RCA PMTs, creating the first modern "scintillation counter".

- Speed: The PMT + scintillator assembly was thousands of times faster than the Geiger-Müller counters used at the time (nanoseconds).
- Energy measurement: the amount of light produced in the scintillator is proportional to the energy deposited by the particle. Energy measurement.
- Coincidence Experiments: multiple detectors in line allow the particle's "flight time" to be measured and its direction and speed to be determined.

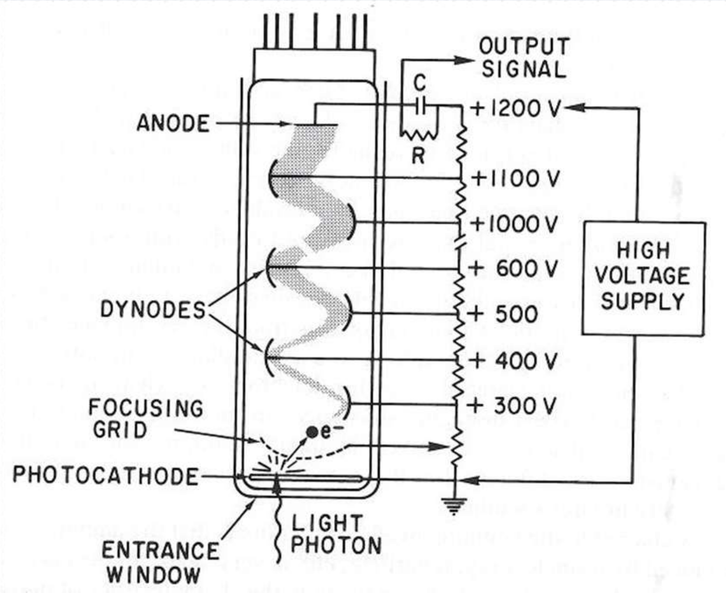


scintillators and fast timing - 1953

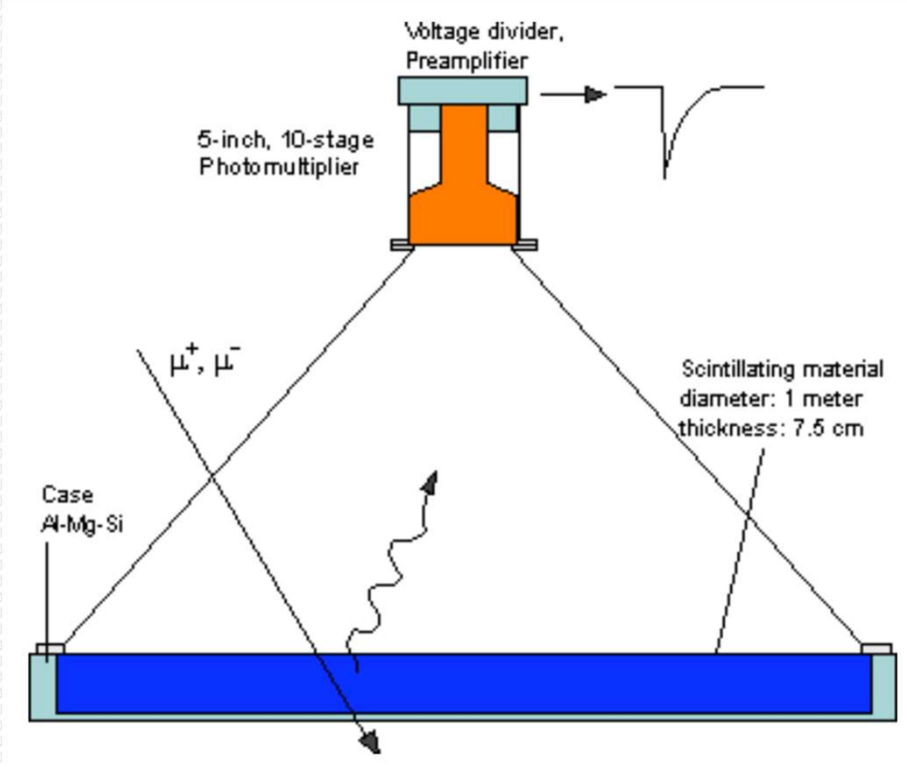
Bassi, Clark and Rossi



Scintillator: PMT and light guide

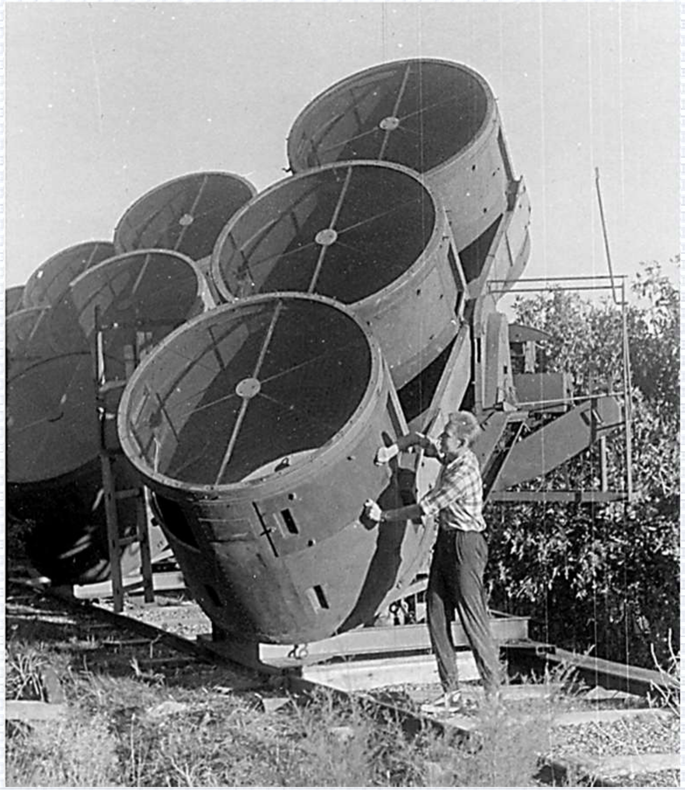


PMT: converts photons into electrons and gain G ~10^7

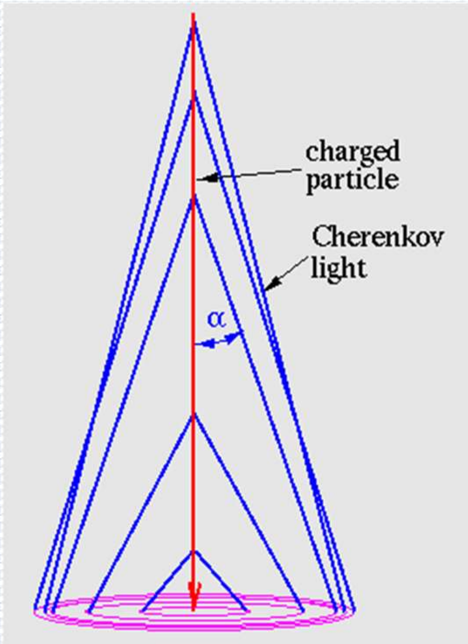


Plastic scintillator
- linear response (proportional to energy)
- fast response (<0.2ns organic plastic scintillator)

First Cherenkov detectors in the atmosphere – 1959



Chudakov conducts the first experiment with cosmic rays of Cherenkov light in the Earth's atmosphere, in the USSR.



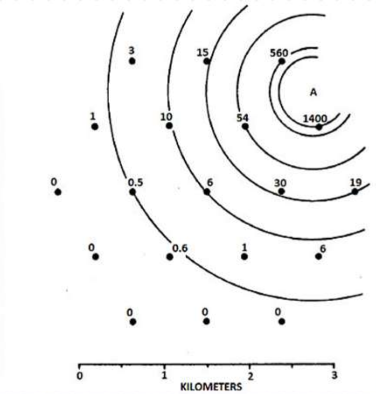
First surface water Cherenkov detectors – 1967

Haverah Park in the United Kingdom, in 1967, was the first major cosmic ray experiment to use surface detectors based on water tanks (water-Cherenkov detectors, WCD) to observe extensive atmospheric showers.
The Haverah Park arrangement covered approximately 12 km², with more than 200 tanks scattered across the ground.

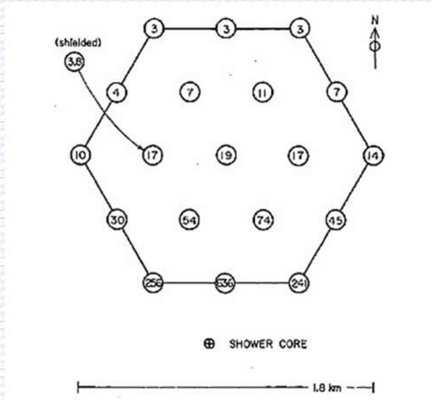
Water from a tank after 25 years

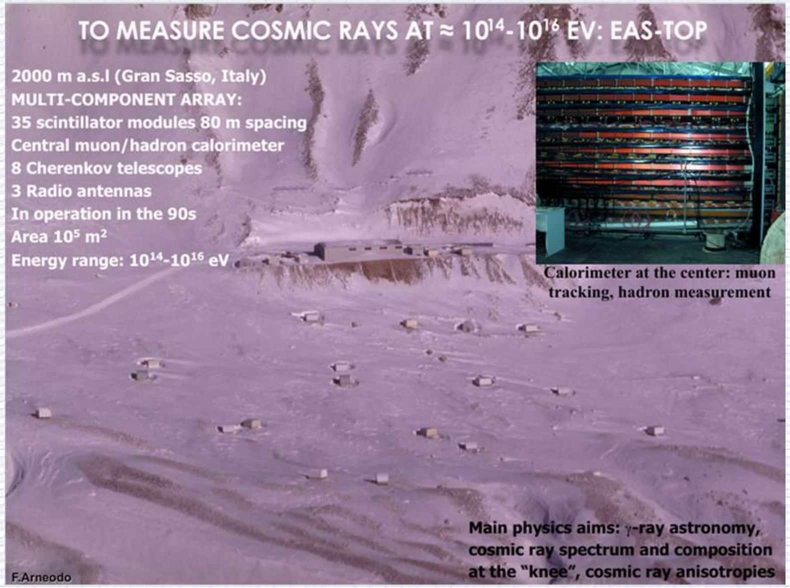
EAS experiments

John Linsley



Volcano Ranch EAS experiment, New Mexico, USA (1960)



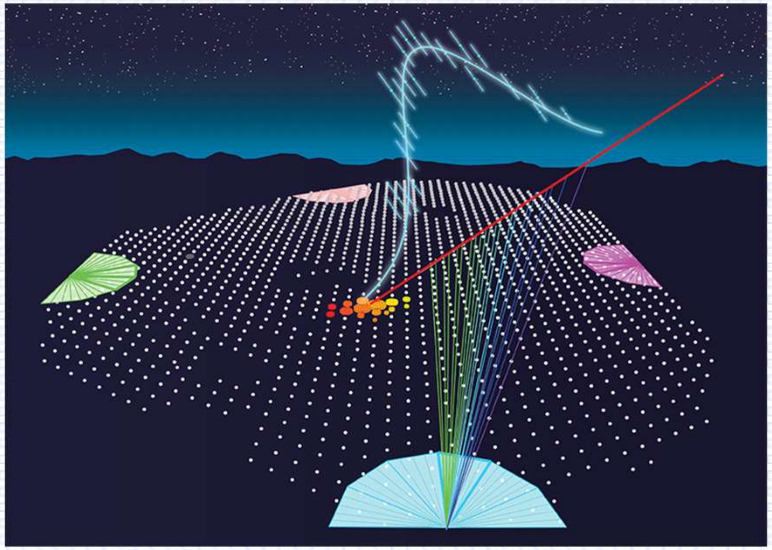


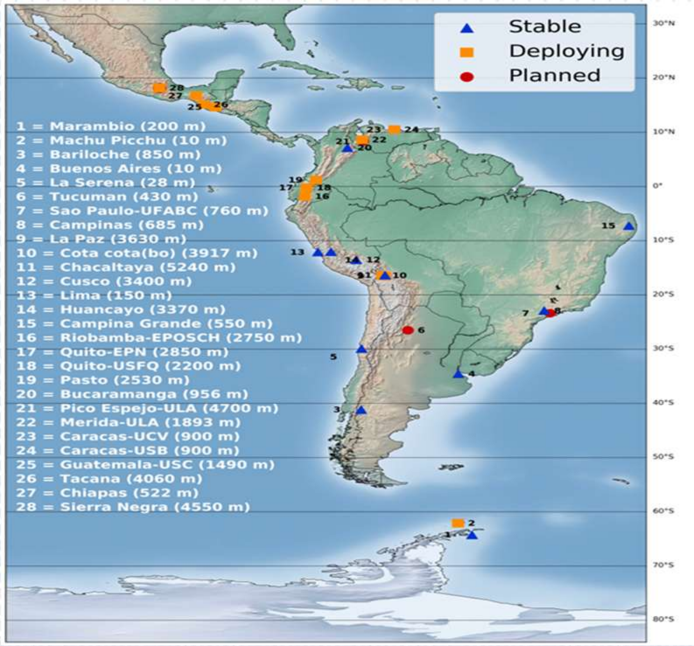
G. Navarra, EAS-TOP experiment, Italy (1994)

Today: Cosmic rays in Latin America -1

Pierre Auger Observatory (Malargüe, Argentina) the world's largest ultra-high energy cosmic ray observatory; array of 1,660 water tanks (surface detectors) + 27 fluorescence telescopes; several sub-collaborations/structures (AMIGA, HEAT, AERA) to measure composition, muons, energy.

LAGO — Latin American Giant Observatory (distributed network)
network of Cherenkov detectors in water spread across 10 Latin American countries. Focus: high-altitude gamma-ray bursts, space weather studies/Forbush decreases, and formation of an educational-scientific network.





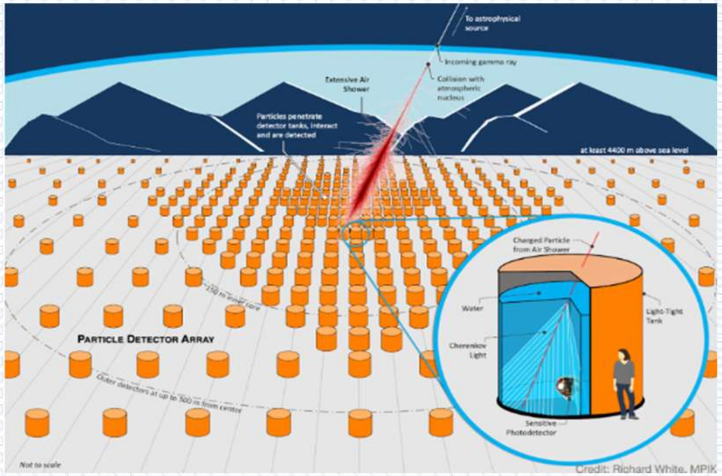
Today: Cosmic rays in Latin America-2

ALPACA (ALPAQUITA prototype) — Andes / Chacaltaya (Bolivia) — project **under construction** (Bolivia–Japan–Mexico collaboration) for a large array of air showers and muon detectors targeting sub-PeV / PeV γ-astronomy in the Southern Hemisphere.

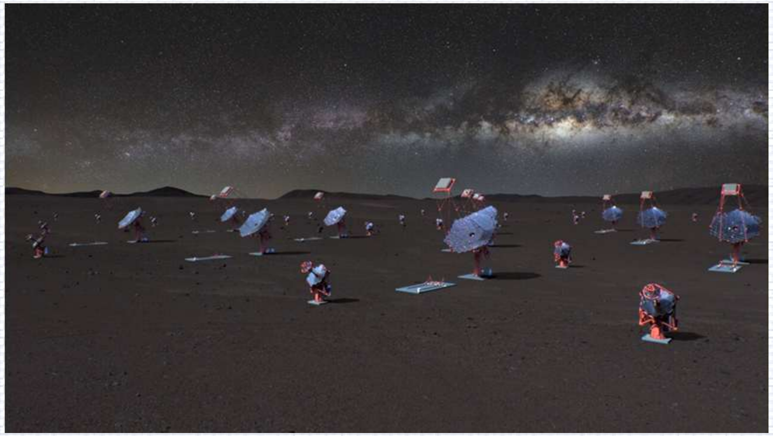
HAWC — High-Altitude Water Cherenkov Observatory (Sierra Negra, Mexico) — 300 large altitude water detectors for very energetic gamma rays and also sensitive to cosmic rays in the TeV range; operates continuously with a large field of view.

Today: Cosmic rays in Latin America-3

SWGO — Southern Wide-field Gamma-ray Observatory
(Atacama, Chile — project under development) — next generation wide-field observatory in the Southern Hemisphere (WCDs concept in km² area); in final R&D phase.



CTAO-Sul
The next major experiment in the region is CTAO-South (Cherenkov Telescope Array Observatory). Atacama Desert, Chile. It will be the southern location of the world's most sensitive gamma-ray observatory.



LAGO & national development

- Mestrado Daniel Consalter (2009), TANCA, Auger => CEO Fitinstrument
- Complete development of magnetic resonance imaging equipment
- Leading company in the oil quality control market
- Operates in 20 countries, 4 continents

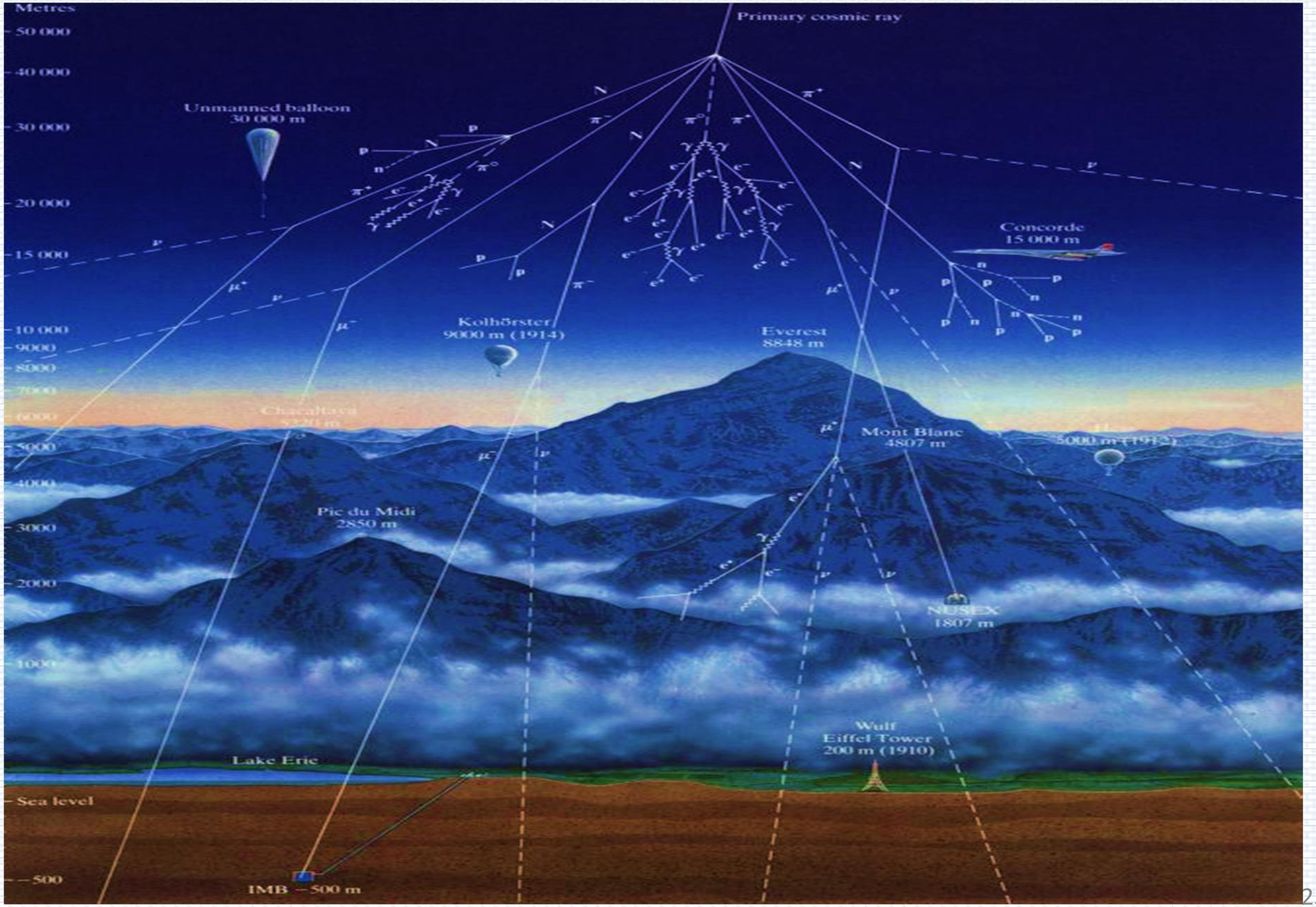
Nuclear Magnetic Resonance Technology evaluate quality and adulteration in coffee

SpecFIT technology analyzes Oils and Fats that replace Trans Fat

https://fitinstrument.com/

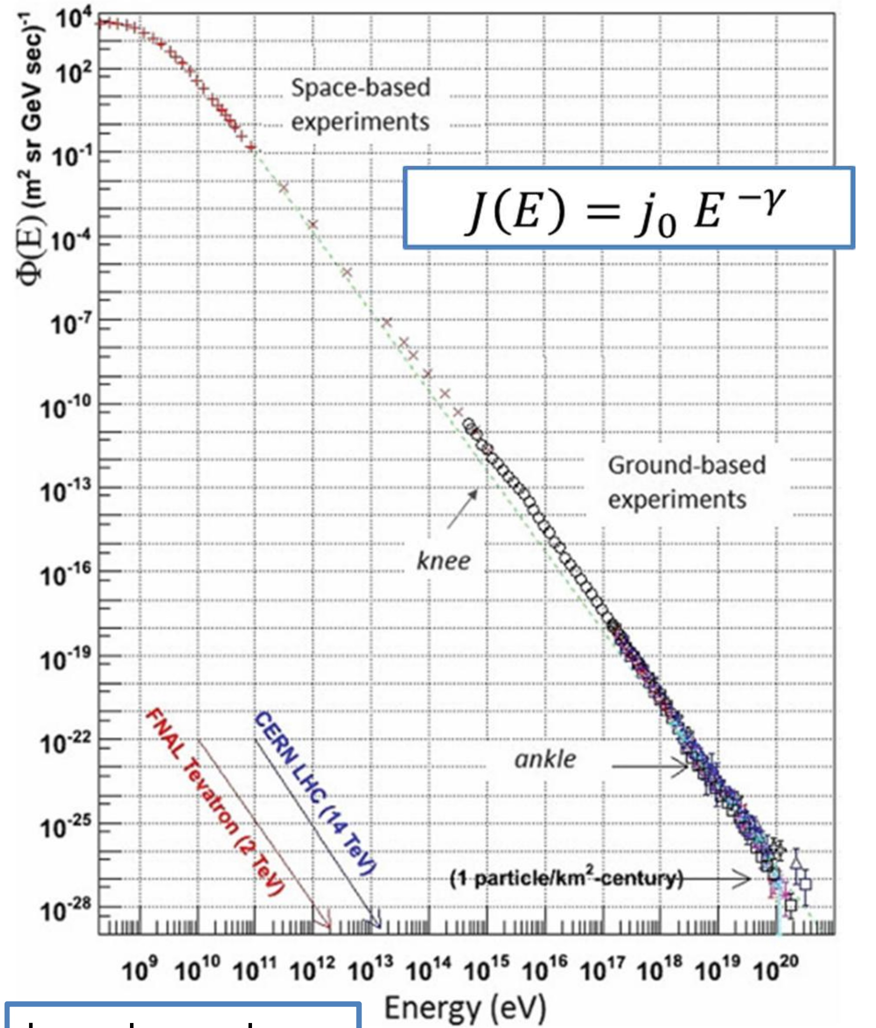
Primary and secondary cosmic rays

Cosmic rays Where to place the detector?



Energy spectrum of primary cosmic rays

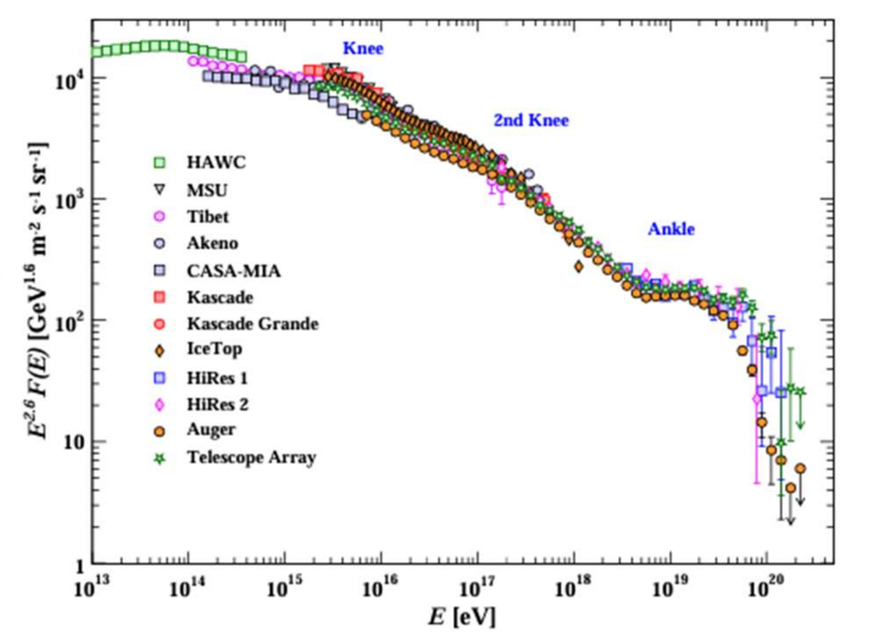
$$J(E) = \frac{dN}{dt\, dA\, d\Omega\, dE}$$



$$J(E) = j_0\, E^{-\gamma}$$

Log x log scale

Log x log scale and x $\mathbf{E^{2.6}}$



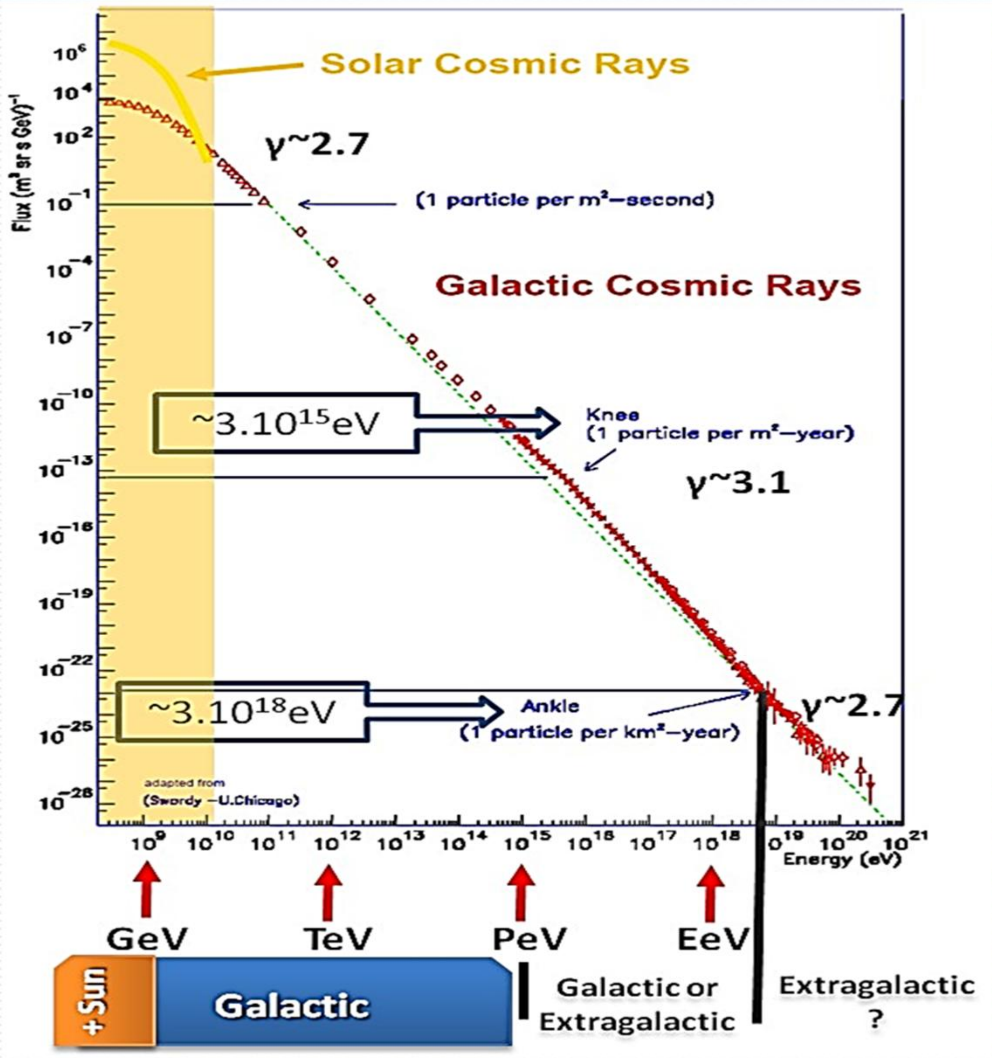
These features carry important information on the acceleration and transport of CRs.

$\mathscr{F}(> 10^{9}\ \text{eV}) \simeq 1000\ \text{particles/s m}^2\ ,$

$\mathscr{F}(> 10^{15}\ \text{eV}) \simeq 1\ \text{particle/year m}^2\ ,$

$\mathscr{F}(> 10^{20}\ \text{eV}) \simeq 1\ \text{particle/century km}^2\ .$

Energy spectrum of cosmic rays



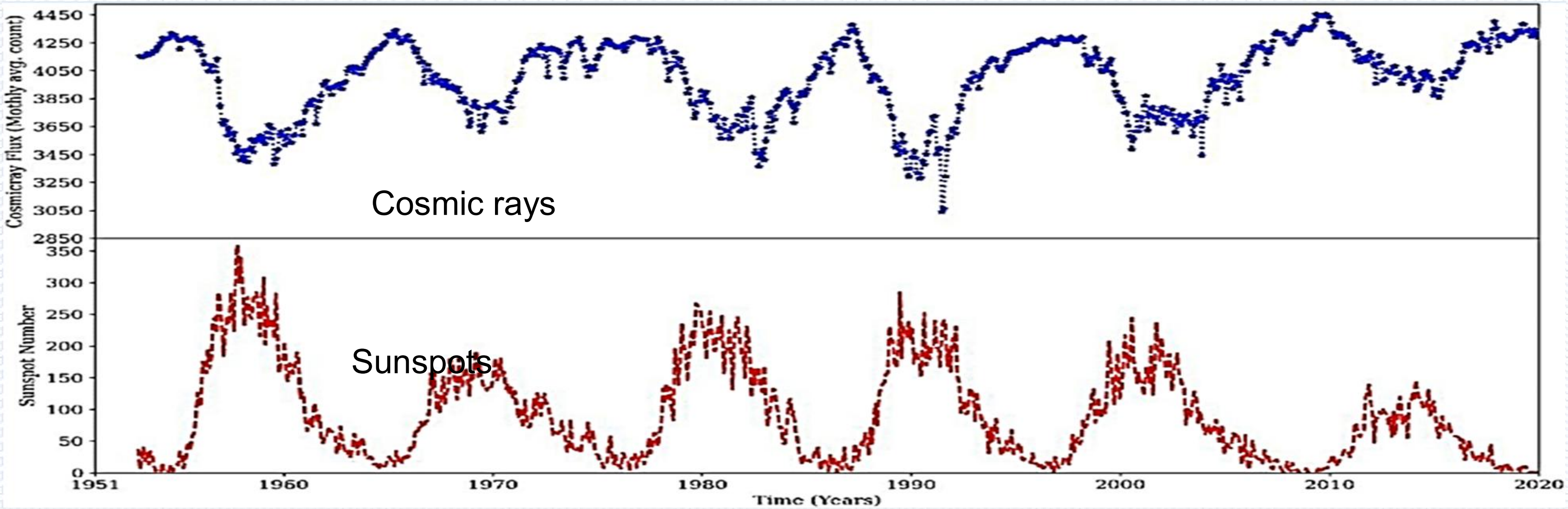
$$J(E) = \frac{dN}{dt\, dA\, d\Omega\, dE}$$

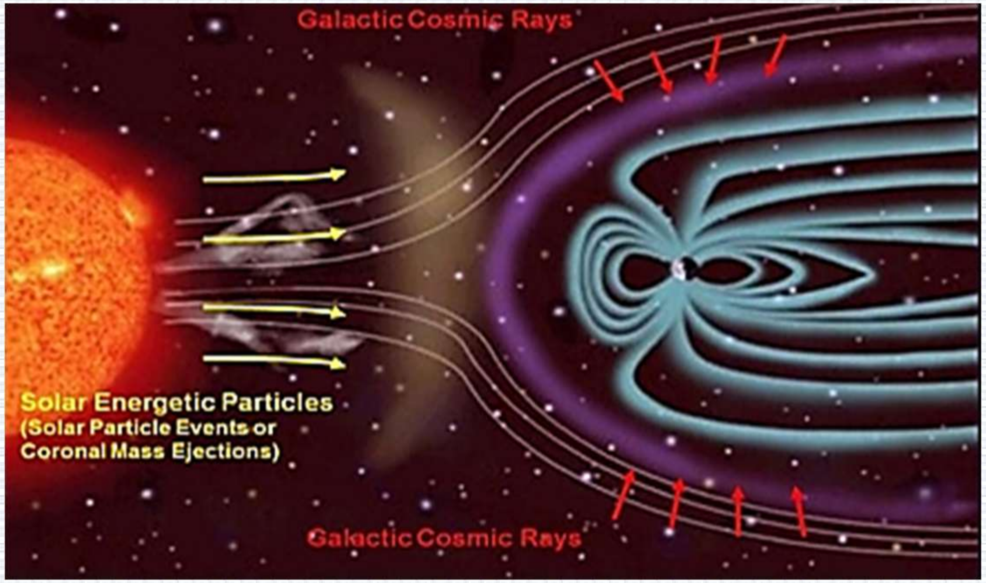
$$[\frac{1}{m^2\ s\ sr\ GeV}]$$

Power law

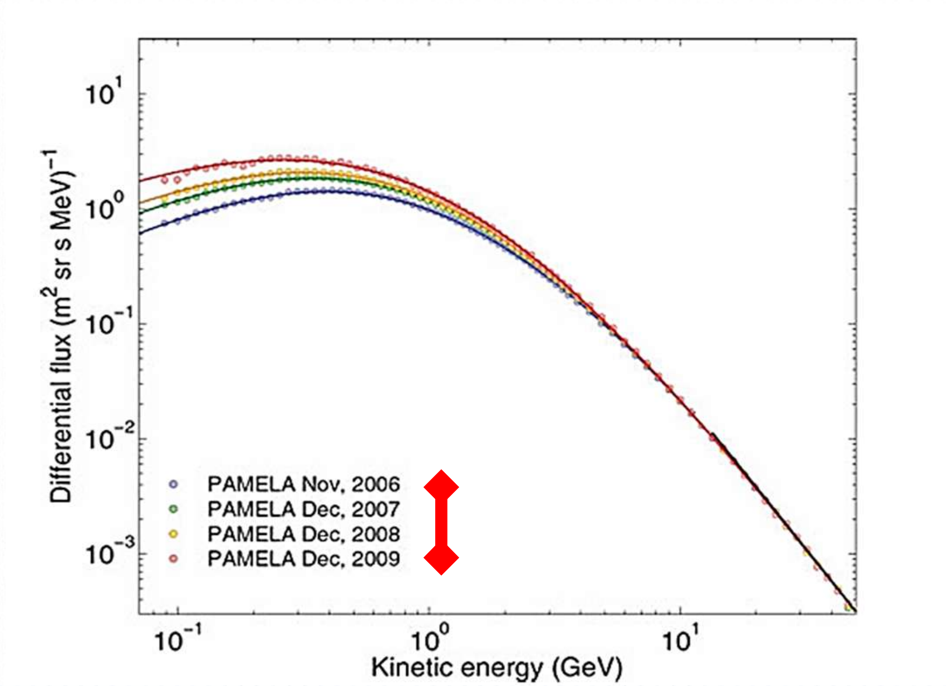
$$J(E) = j_0\, E^{-\gamma}$$

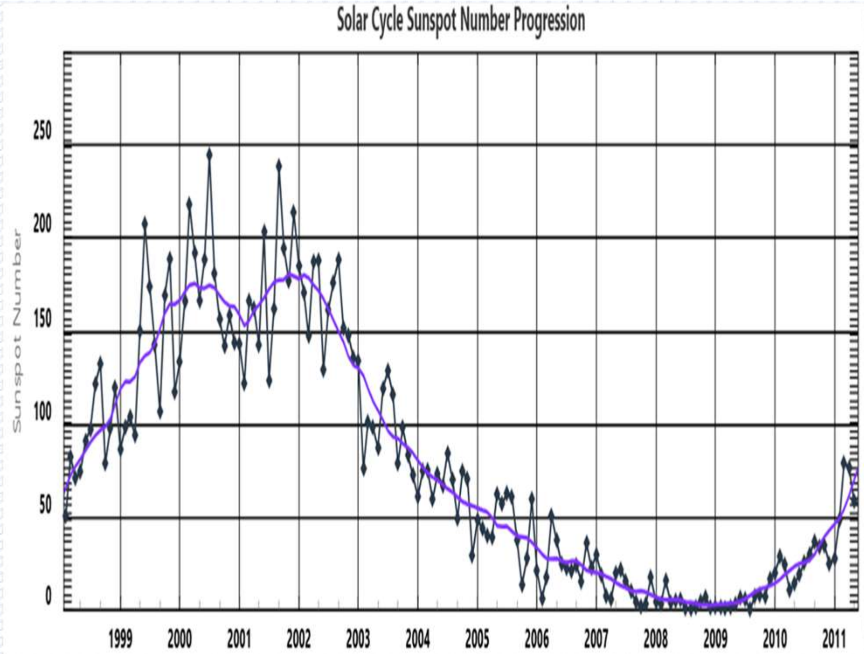
Effect of the solar cycle on cosmic rays



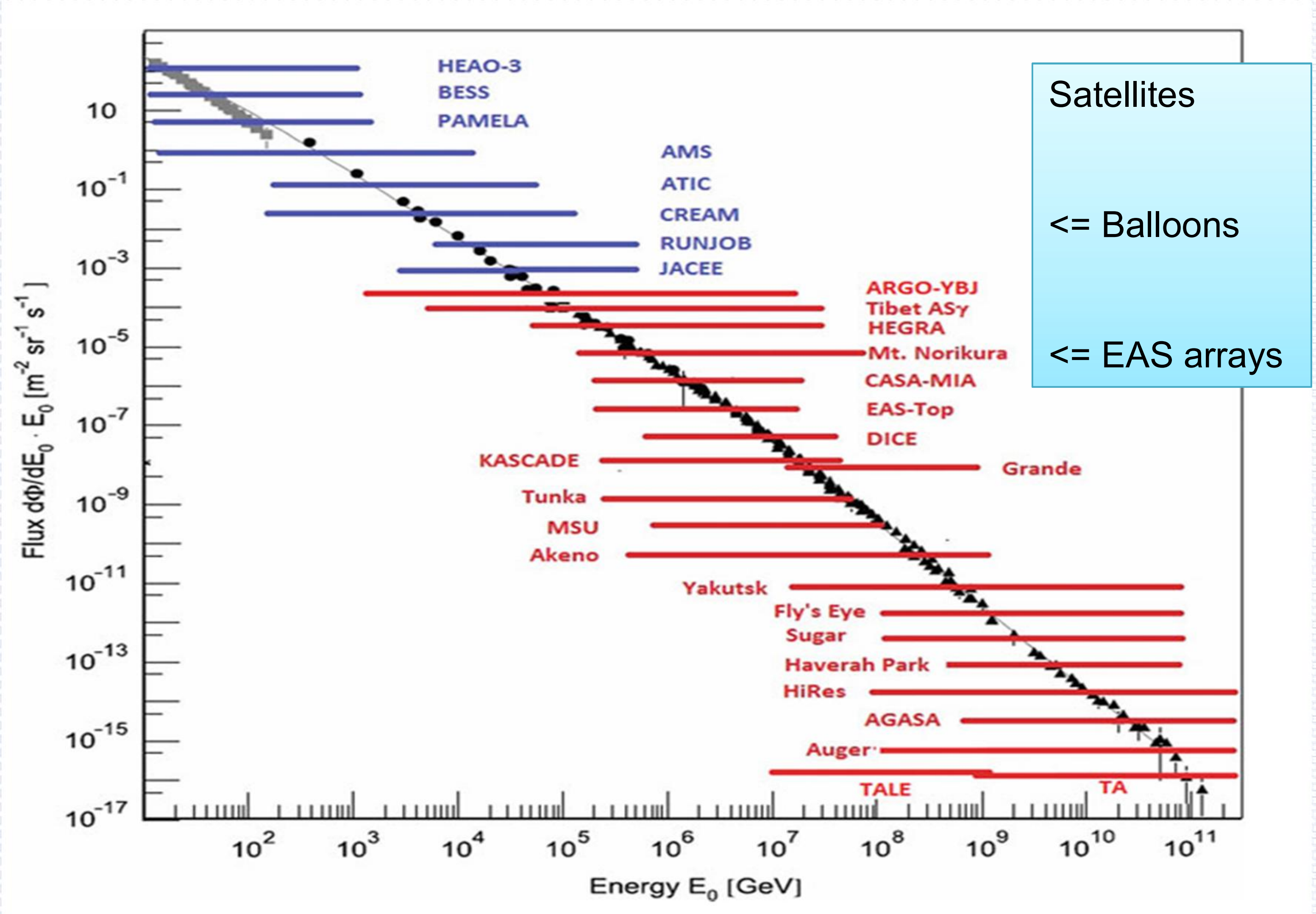


GeV cosmic rays and solar cycle



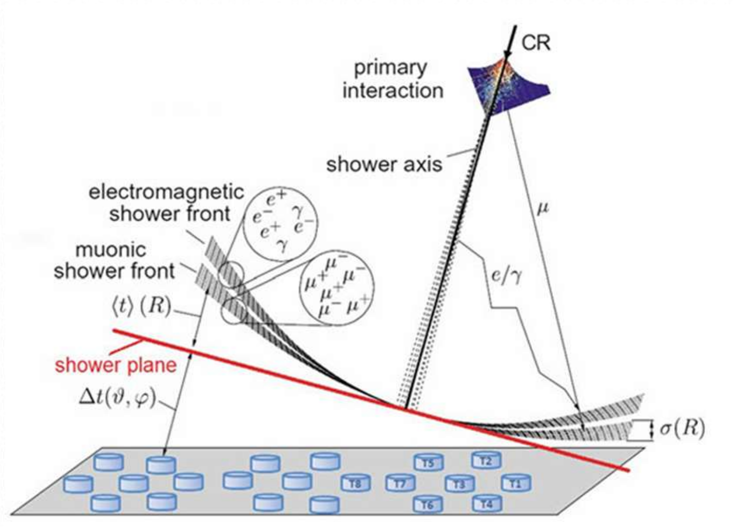


Primary cosmic ray flux - direct and indirect measurements

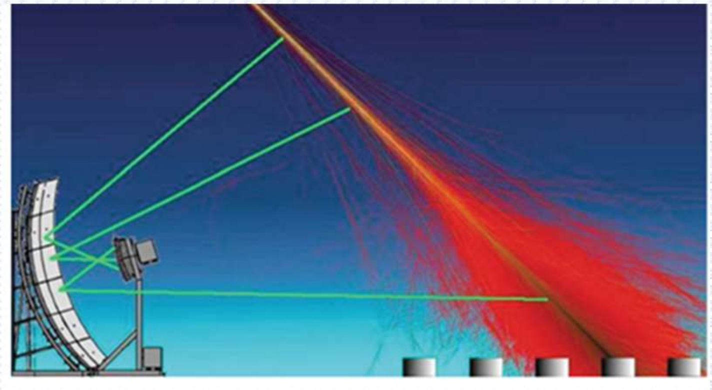


EAS observation techniques

Particles



Fluorescence



Cherenkov

Radio

Ground particle detectors used in EAS detection

Tape	Componente medida	Faixa de energia típica do experimento	Resolução	Vantagens	Limitações	Experimentos
Scintiladores plásticos	e±, γ, μ	$10^{14} – 10^{18}$ eV	Boa temporal, moderada espacial	Baratos, fáceis de modular, resposta rápida	Pouca discriminação entre EM e muônica	Telescope Array (SD), AGASA, KASCADE
Tanques de Água Cherenkov	e±, γ, μ	$10^{15} – 10^{20}$ eV	Boa para densidade e tempo, baixa para identificação EM/μ	Alta robustez, operação 24/7, sensível a partículas rápidas	Não distingue elétrons de múons sem técnicas auxiliares	Pierre Auger, HAWC, LHAASO-WCDA
Muonímetros (scint. enterrados, Cherenkov subterrâneo)	μ	$10^{15} – 10^{20}$ eV	Boa identificação de múons	Mede componente muônica diretamente, crucial p/ hadrônica	Instalação e manutenção custosa (enterrado)	AMIGA (Auger), GRAPES-3, KASCADE-Grande
RPCs (Resistive Plate Chambers)	e±, μ	$10^{13} – 10^{17}$ eV	Excelente temporal (~ns)	Alta resolução temporal e espacial, grandes áreas	Sensíveis a condições ambientais	ARGO-YBJ, LHAASO-KM2A

Atmospheric optical detectors used in EAS detection

Cherenkov Telescopes

Tipo	Componente medida	Faixa	Resolução	Vantagens	Limitações	Experimentos
Telescópios IACT	Luz Cherenkov atmosférica	$10^{11} – 10^{14}$ eV (TeV)	Excelente angular e energética	Ótima separação gama/hadrão, baixíssimo limiar de energia	Operação somente em noites claras e escuras	HESS, MAGIC, VERITAS, CTA

Diffuse Cherenkov

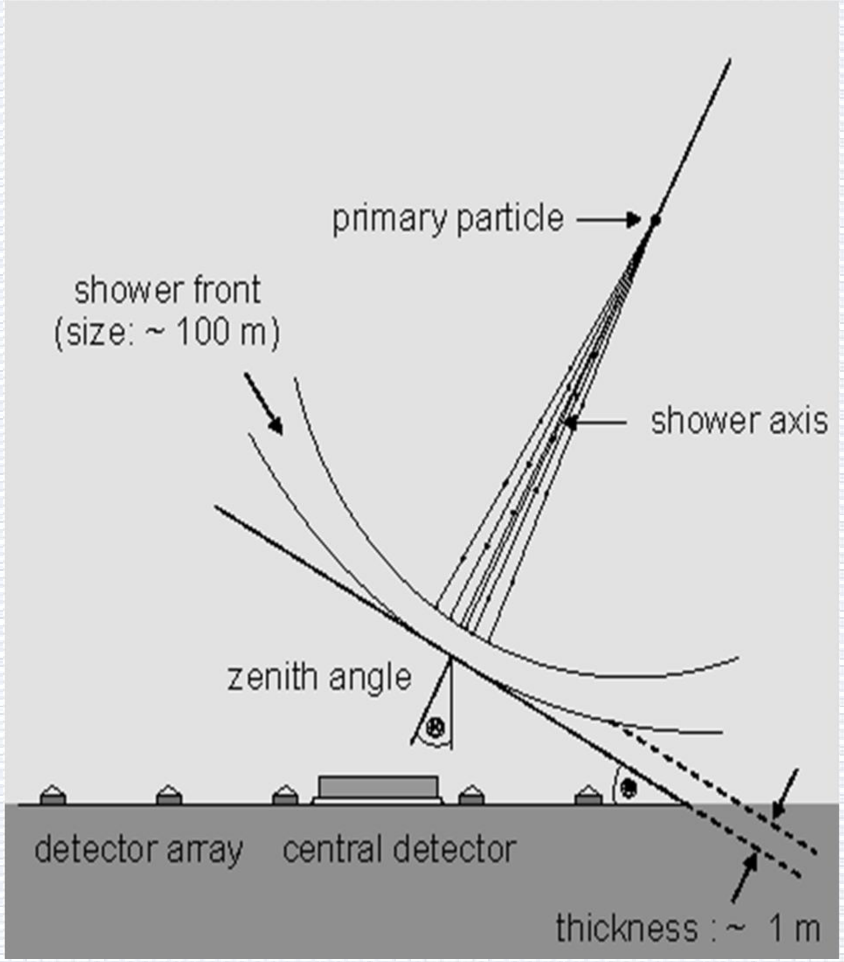
Tipo	Faixa	Resolução	Vantagens	Limitações	Experimentos
Detecção de Cherenkov no solo	$10^{14} – 10^{18}$ eV	Baixa a moderada	Array barato para grandes áreas	Baixa resolução, forte dependência atmosférica	BLANCA, TUNKA

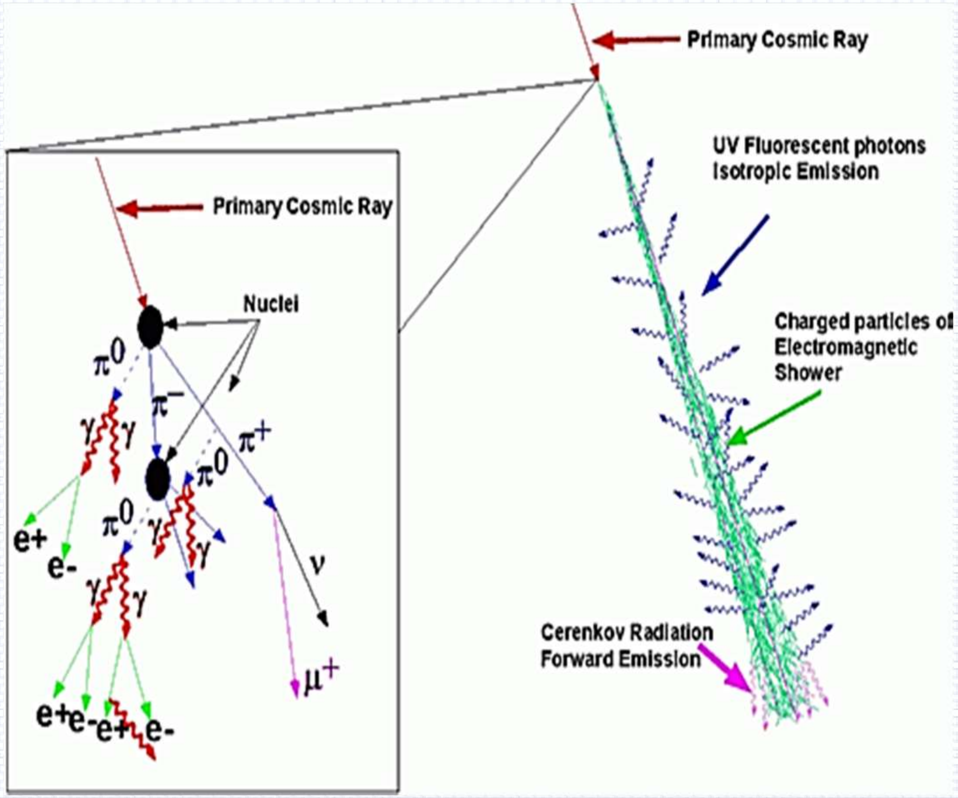
Atmospheric fluorescence detectors and radio waves used in EAS detection

Tipo	Componente medida	Faixa	Resolução	Vantagens	Limitações	Experimentos
Telescópios de fluorescência	Perfil longitudinal da cascata (EM dominante)	$10^{17} – 10^{20}$ eV	Excelente para Xmax e energia (~15%)	Medição calorimétrica direta, ótima para composição	Só opera em noites claras e sem Lua (~10% duty cycle)	Pierre Auger FD, TA FD, Fly's Eye, HiRes

Tipo	Componente medida	Faixa	Resolução	Vantagens	Limitações	Experimentos
Antenas de rádio (30–80 MHz)	Radiação geomagnética da cascata	$10^{16} – 10^{19}$ eV	Boa para direção e Xmax	Opera 24/7, baixo custo, boa estimativa de Xmax	Requer supressão de ruído humano (RFI)	LOFAR, AERA (Auger), CODALEMA, GRANDProto 300

Extensive Air Shower - EAS



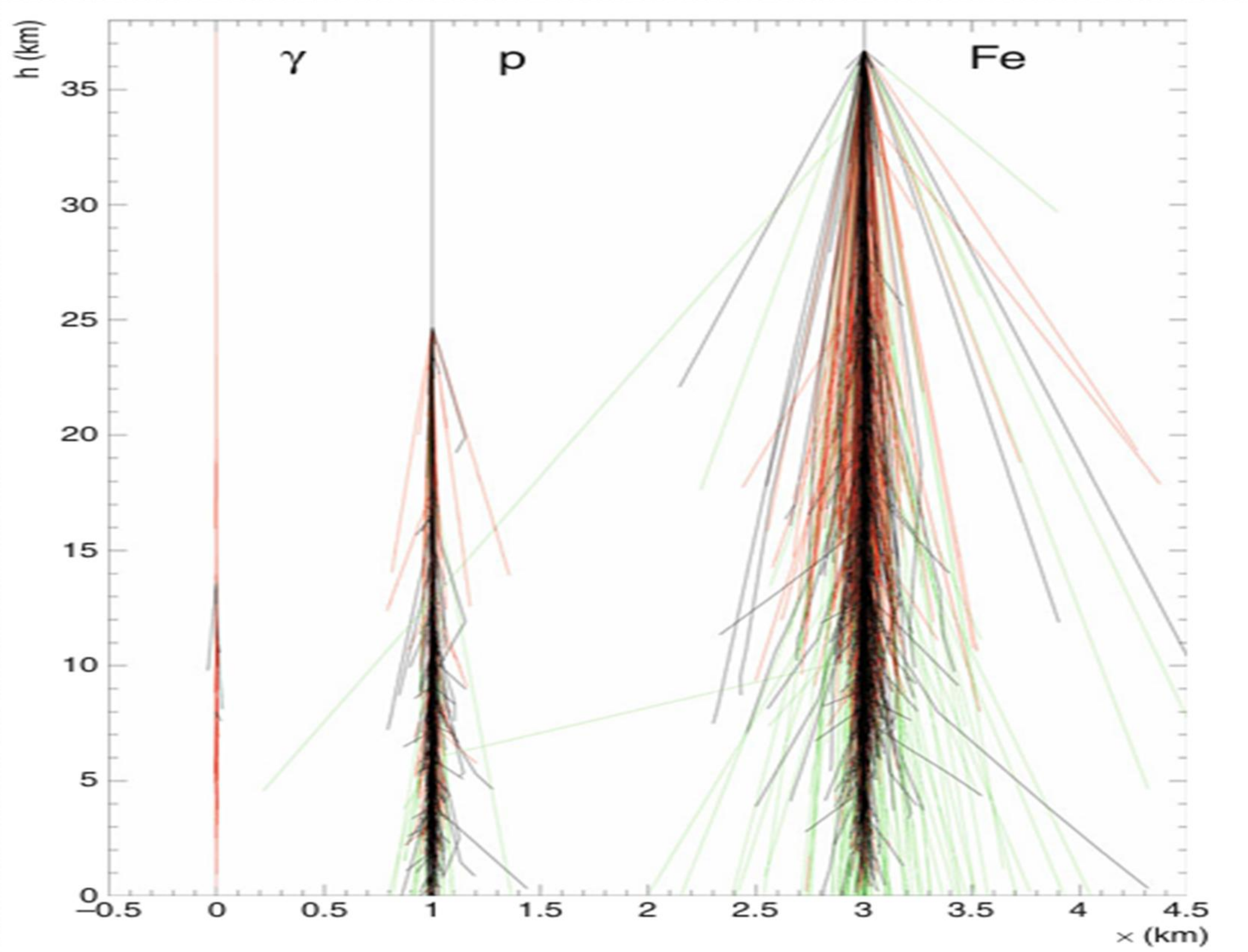


Electrons, positrons, gamma rays, mesons, protons, neutrons

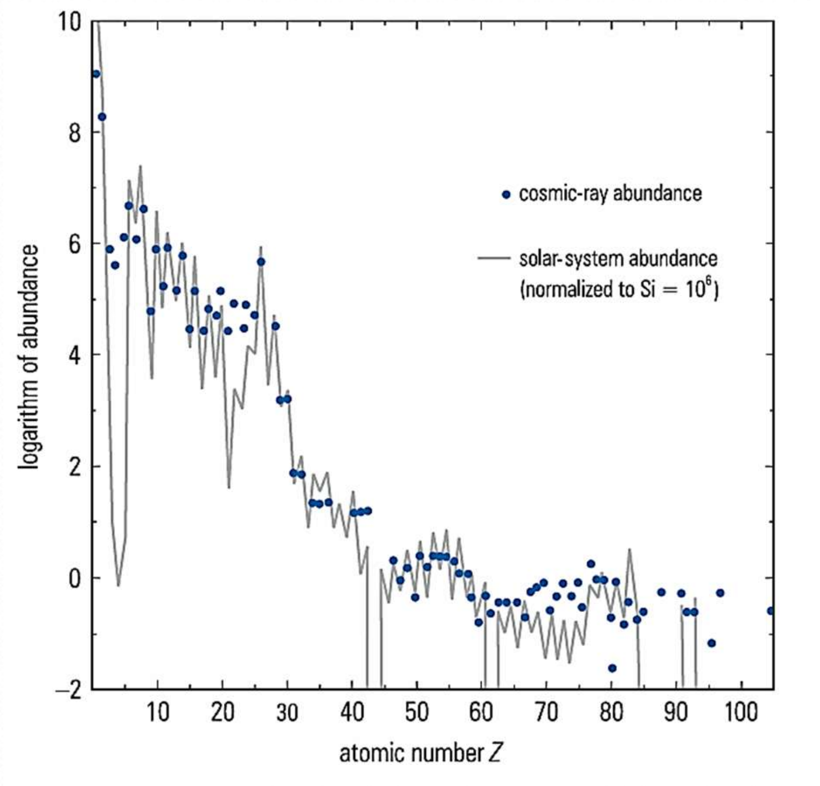
Cherenkov, fluorescence, radio

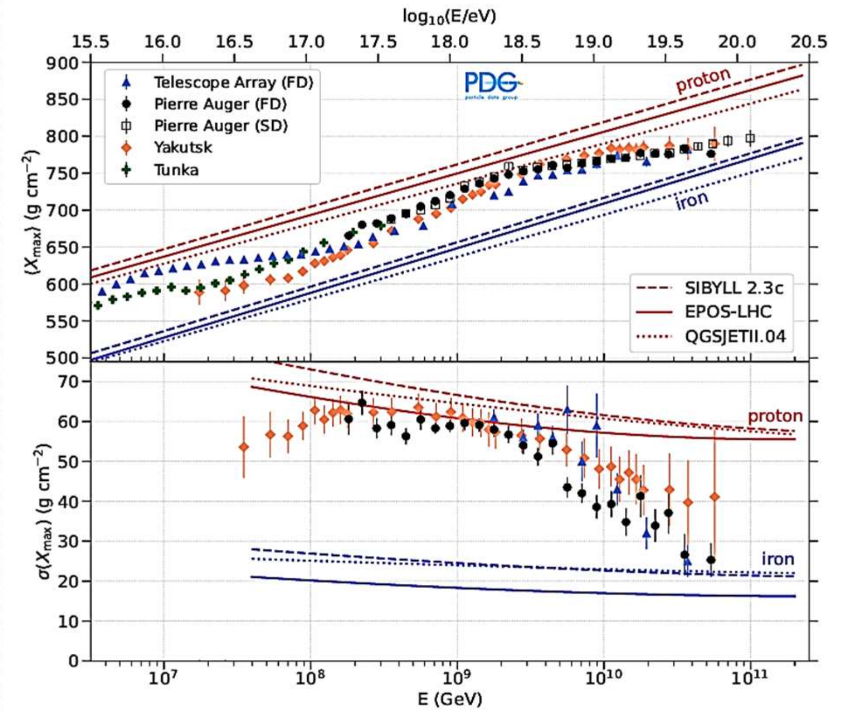
EAS - gamma, proton e iron

primary energy of 10^5 GeV



Composition of primary cosmic rays





- Protons are the dominant particle species (≈85%)
- followed by α particles (≈12%).
- Elements with a nuclear charge Z ≥ 3 represent only a 3% fraction of charged primary cosmic rays.

Lateral and longitudinal development of an EAS

Vertical proton of 10^{19} eV

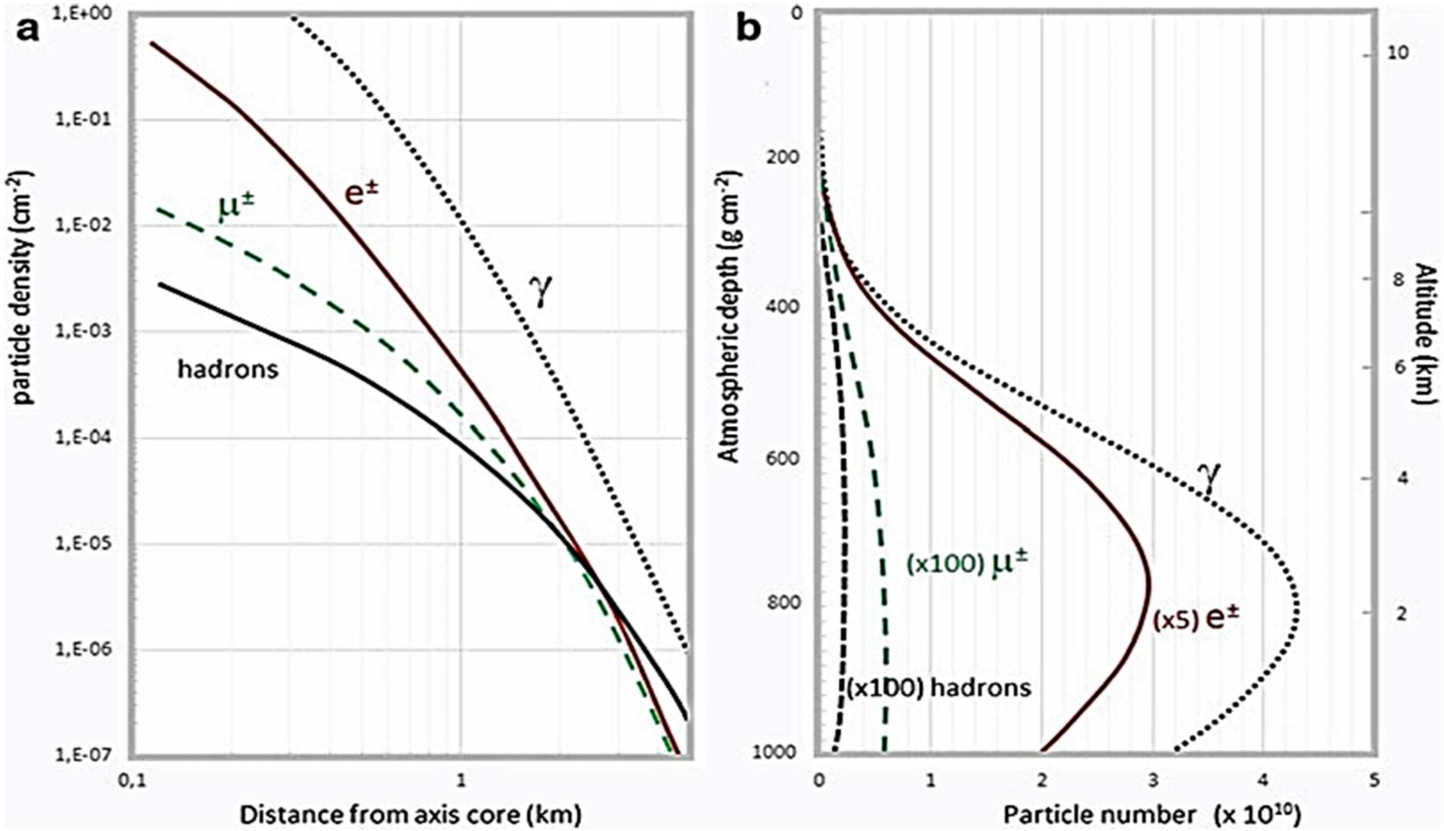
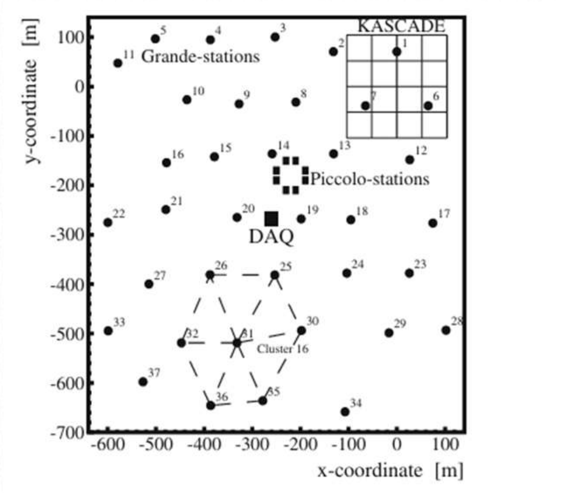


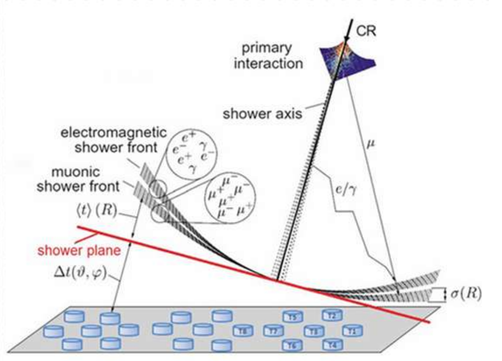
Fig. 4.10 Average **a** lateral and **b** longitudinal shower profiles of the hadronic, muonic and electromagnetic components generated with the CORSIKA code. The showers are induced by vertical protons of energy 10^{19} eV. The lateral distribution of the particles at ground level is calculated for 870 g cm^{-2}, the depth of the Pierre Auger Observatory (Sect. 7.8). Only photons and $e^{\pm}$ with energy larger than 0.25 MeV are followed in the simulation. For muons and hadrons, the energy threshold is 100 MeV

Trigger for detectors on the Earth's surface

Trigger:
temporal coincidence of the pulse of N detectors.
EAS detector



ure 1. The arrangement of the KASCADE-Grande detectors



Trigger:
Temporal coincidence of two overlapping detectors.
Muon detector

Trigger:
All pulses above a discrimination threshold.
Single particle detector

Muons from atmospheric showers

particles with τ < 10^{-9} s generally decay before interacting

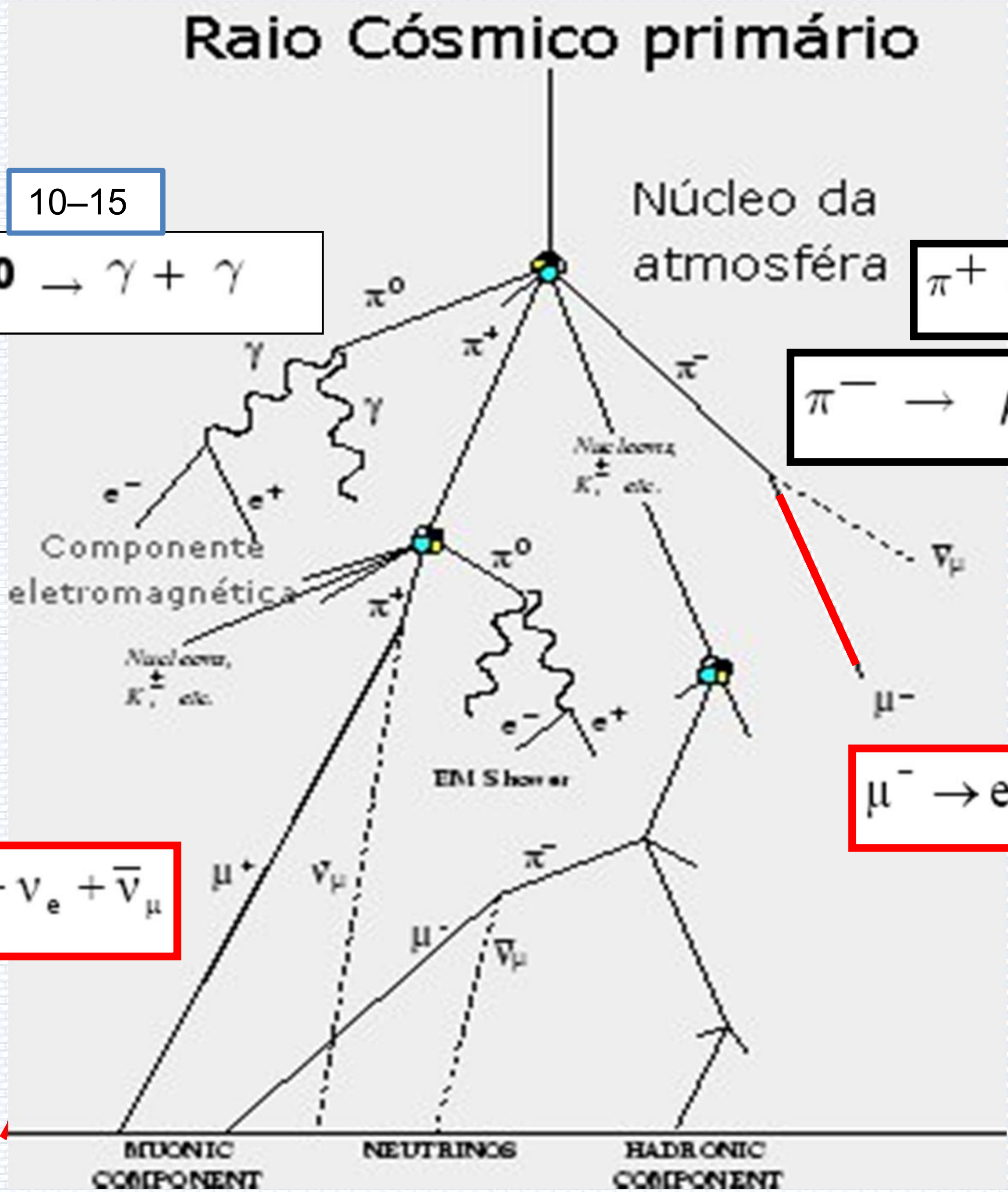
particles with τ > 10^{-9} s produce new interactions in the air

10–15

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu$$

$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$$

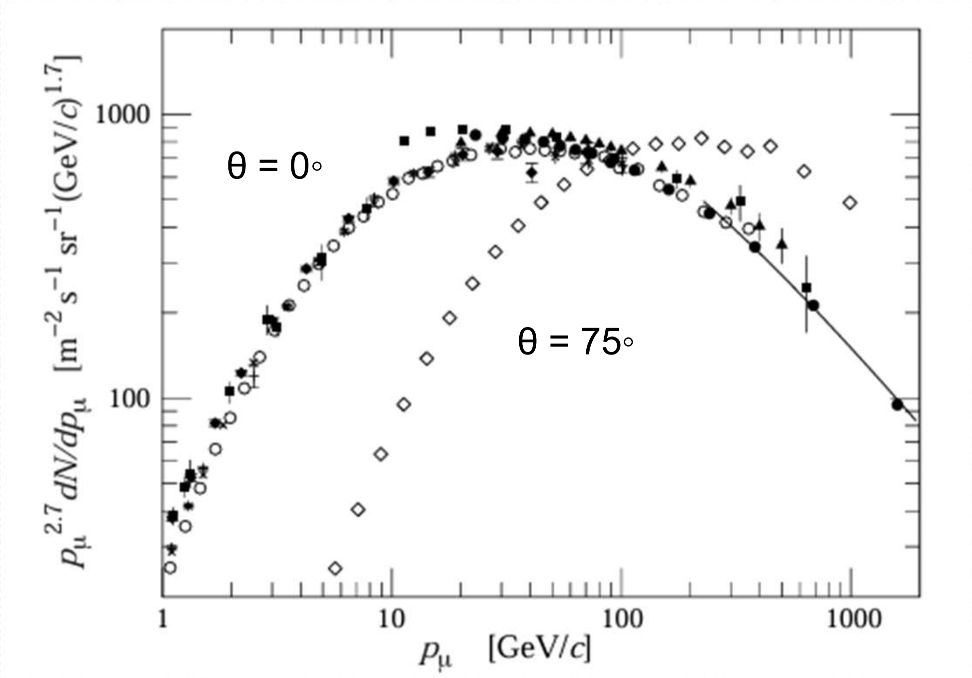


$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

10^{-6}seg

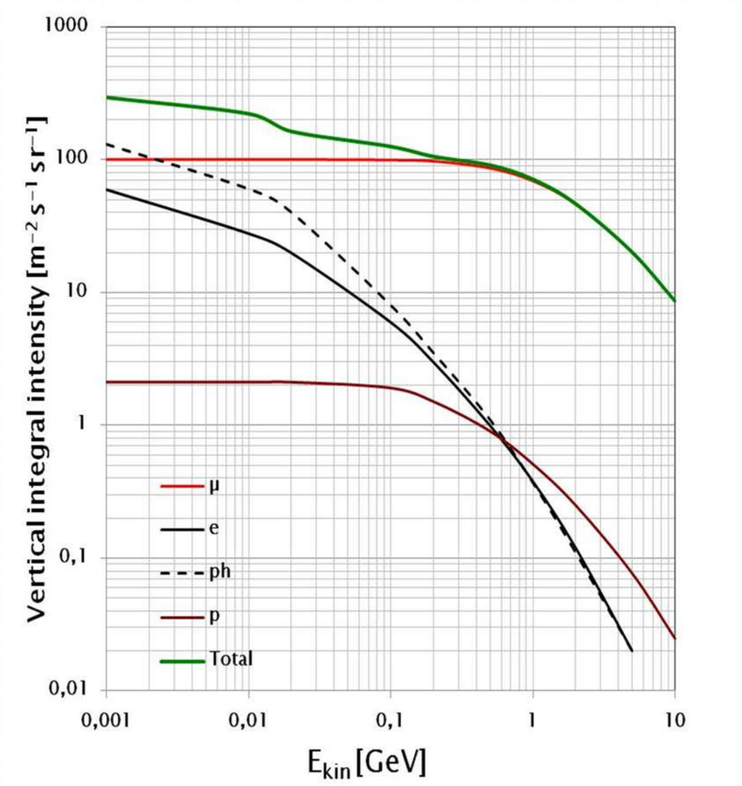
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

Muon spectrum at the surface



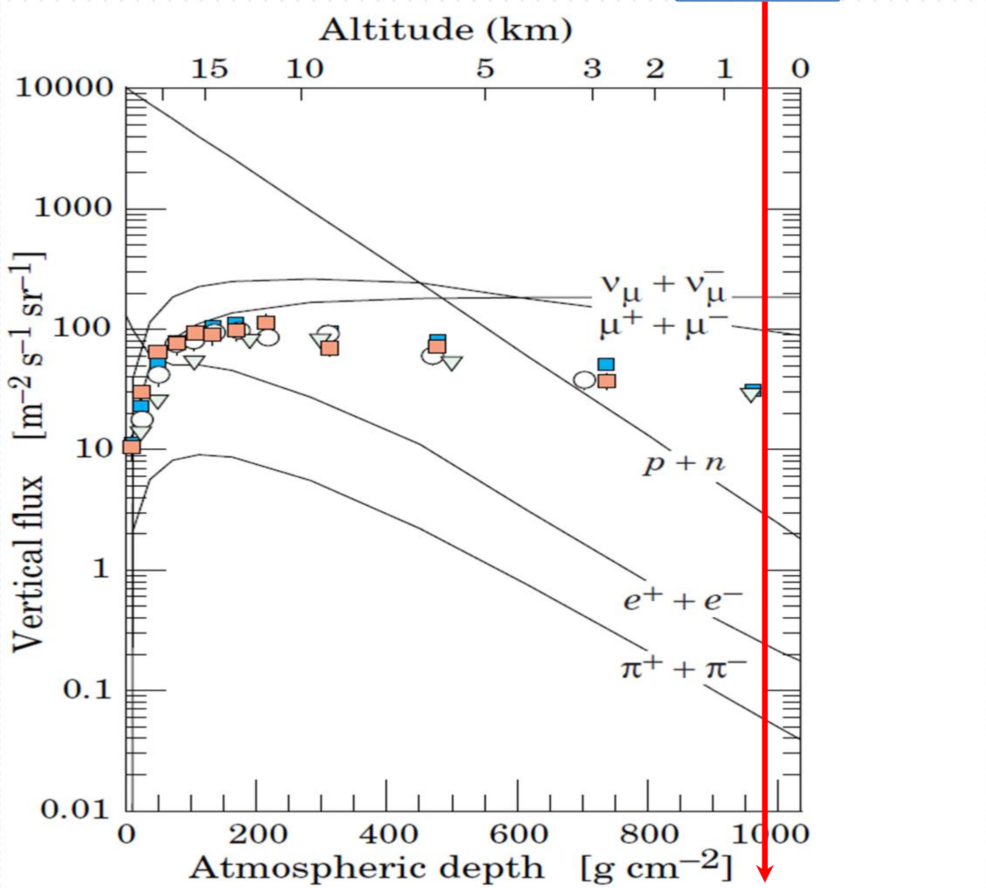
$$\frac{dN_\mu}{dE_\mu d\Omega} \approx \frac{0.14\, E_\mu^{-2.7}}{\mathrm{cm^2\ s\ sr\ GeV}} \times \left\{ \frac{1}{1+\frac{1.1 E_\mu \cos\theta}{115\,\mathrm{GeV}}} + \frac{0.054}{1+\frac{1.1 E_\mu \cos\theta}{850\,\mathrm{GeV}}} \right\}$$

Vertical flow in the atmosphere



Isolated muons

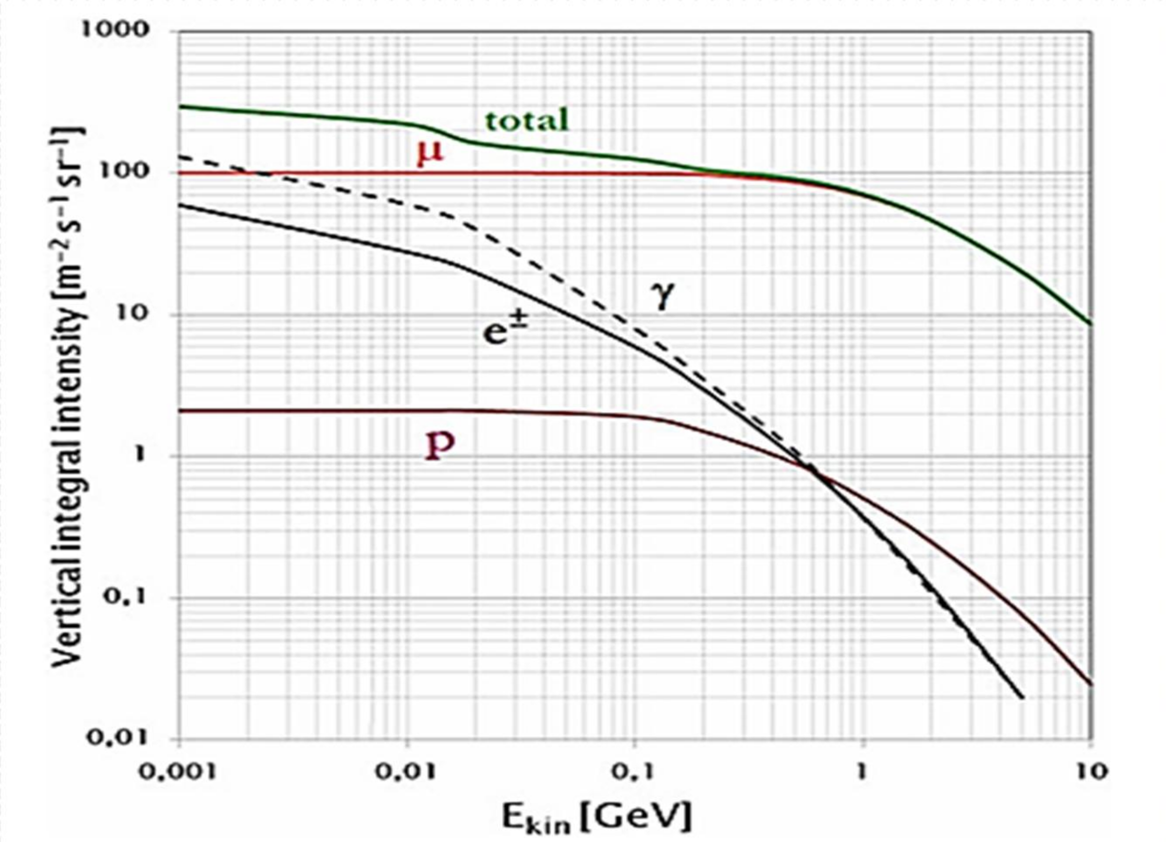
Tanca



Vertical fluxes of cosmic rays in the atmosphere with $E > 1$ GeV

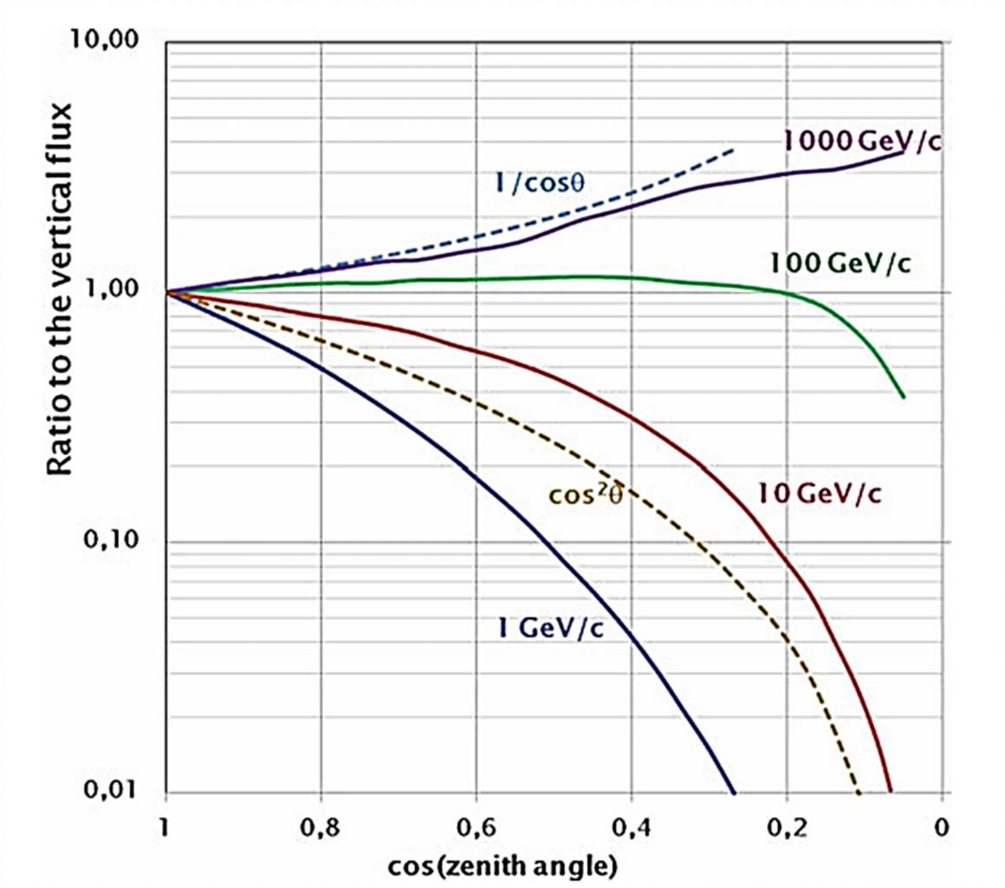
Vertical integral intensity

The integral intensity of vertical muons above 1 GeV/c at sea level is ≈ 70 m−2s−1sr−1



geomagnetic latitudes ∼40◦

Angular distribution of muons



- The overall angular distribution of muons measured at sea level is
- cos^2 (θ),
- which is characteristic of muons with Eμ ~ 3 GeV

Acknowledgements

I would like to thank **Universidad Industrial de Santander** for their wonderful hospitality and the organization of the Encuentro CyTED LAGO INDICA, especially **Prof. Luis Nunes**.

A.Fauth acknowledges the Brazilian National Council for Scientific and Technological Development (CNPq), grant 310473/2025-0 and UNICAMP.