Introduction to Cosmic Rays

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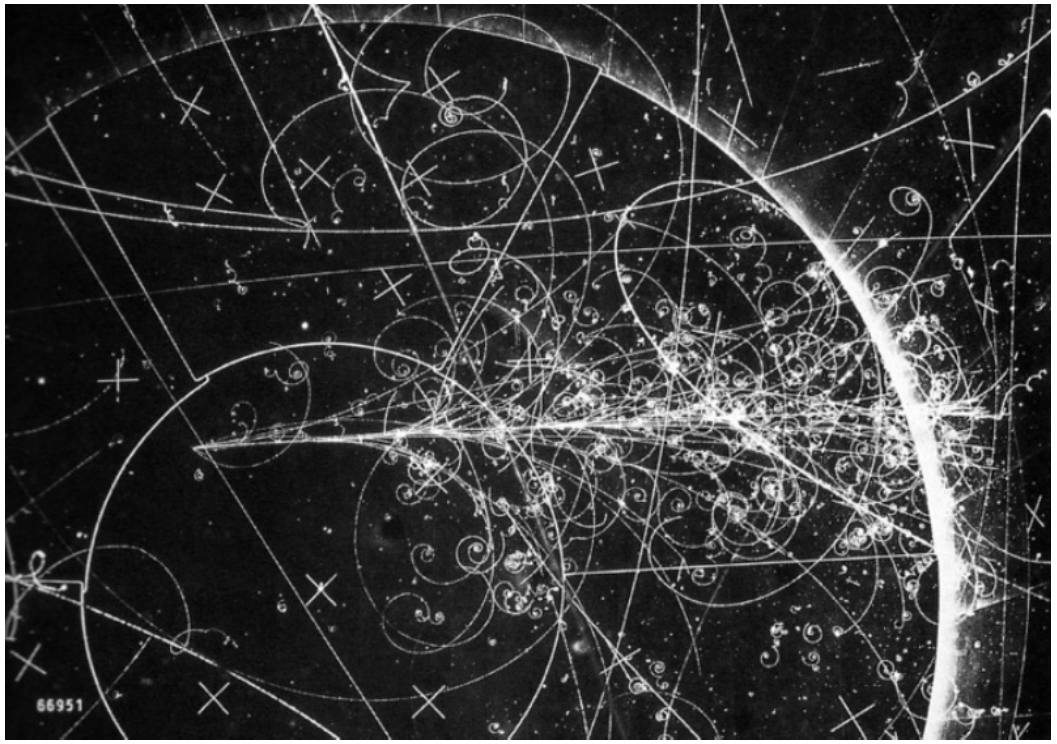
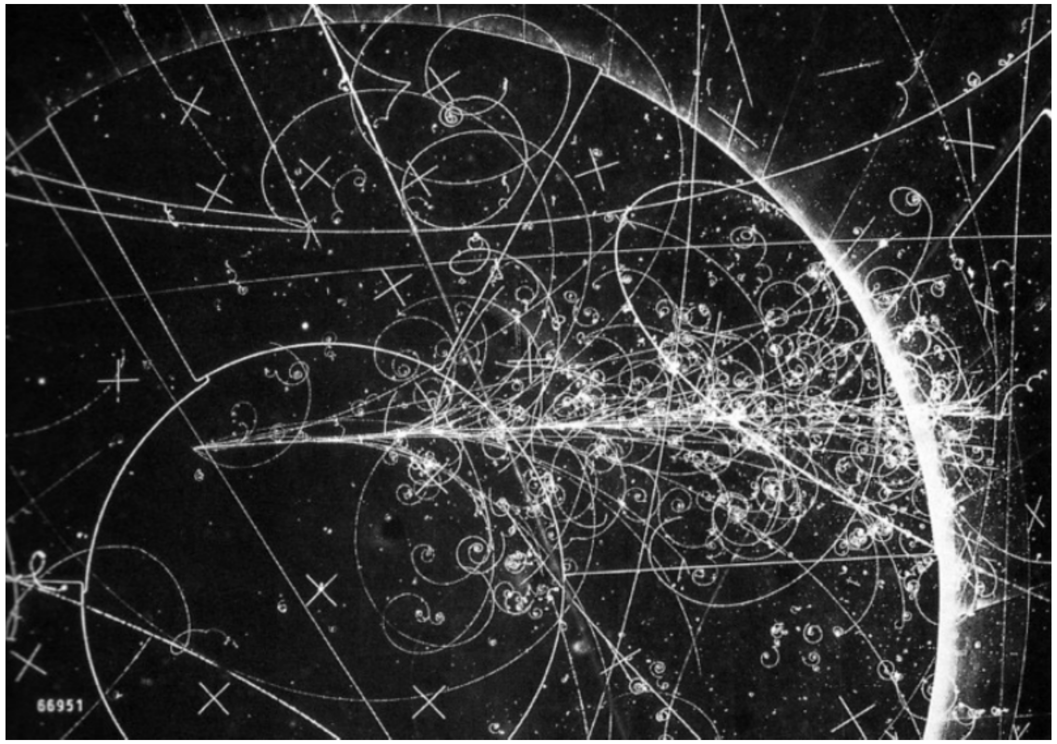


OUTLINE

- what are Cosmic Rays?
- their detection: a 100-years old tale
- Cosmic Ray observatories
- sources of Cosmic Rays
- some exciting news…
- further reading



1 - What are Cosmic Rays?

"*Coming out of space and incident on the high atmosphere, there is a thin rain of charged particles known as the primary* ***cosmic ray*** *radiation*"
(Cecil Powell, Nobel Prize Lecture, 1950)

cosmic ⇒ with an extraterrestrial origin

rays ⇒ a "misnomer" due to a historical accident as cosmic rays were at first, and wrongly, thought to be mostly electromagnetic radiation

to start with, some numbers which may be useful...

- **Cosmic Ray flux**: number of CRs arriving in a given energy interval *dE* and solid angle *dΩ* per unit time *T* per unit surface *A:*

$$\Phi(E) \equiv \frac{dN}{A \cdot T \cdot \mathrm{d}\Omega \cdot \mathrm{d}E} \quad \frac{\text{particles}}{\text{cm}^2\text{sr s GeV}} = K\left(\frac{E}{1\text{ GeV}}\right)^{-\alpha} \qquad K = 3.01; \quad \alpha = 2.68$$

- **Energy Densities in the Galaxy:**

$$\rho_{\text{CR}} \equiv \frac{1}{c}\int_{E_0}^{\infty} E \frac{\mathrm{d}^2\varphi}{\mathrm{d}E\,\mathrm{d}\Omega}\mathrm{d}E\,\mathrm{d}\Omega \simeq 1\text{ eV/cm}^3$$

$$\rho_B = \frac{1}{8\pi}B^2 \quad \text{erg/cm}^3 \simeq 1\text{ eV/cm}^3$$

$$\rho_{\gamma_{\text{vis}}} \sim 4 \times 10^{-2}\text{ eV/cm}^{-3}$$

$$\rho_{\gamma_{\text{CMB}}} \sim 0.3\text{ eV/cm}^{-3}$$

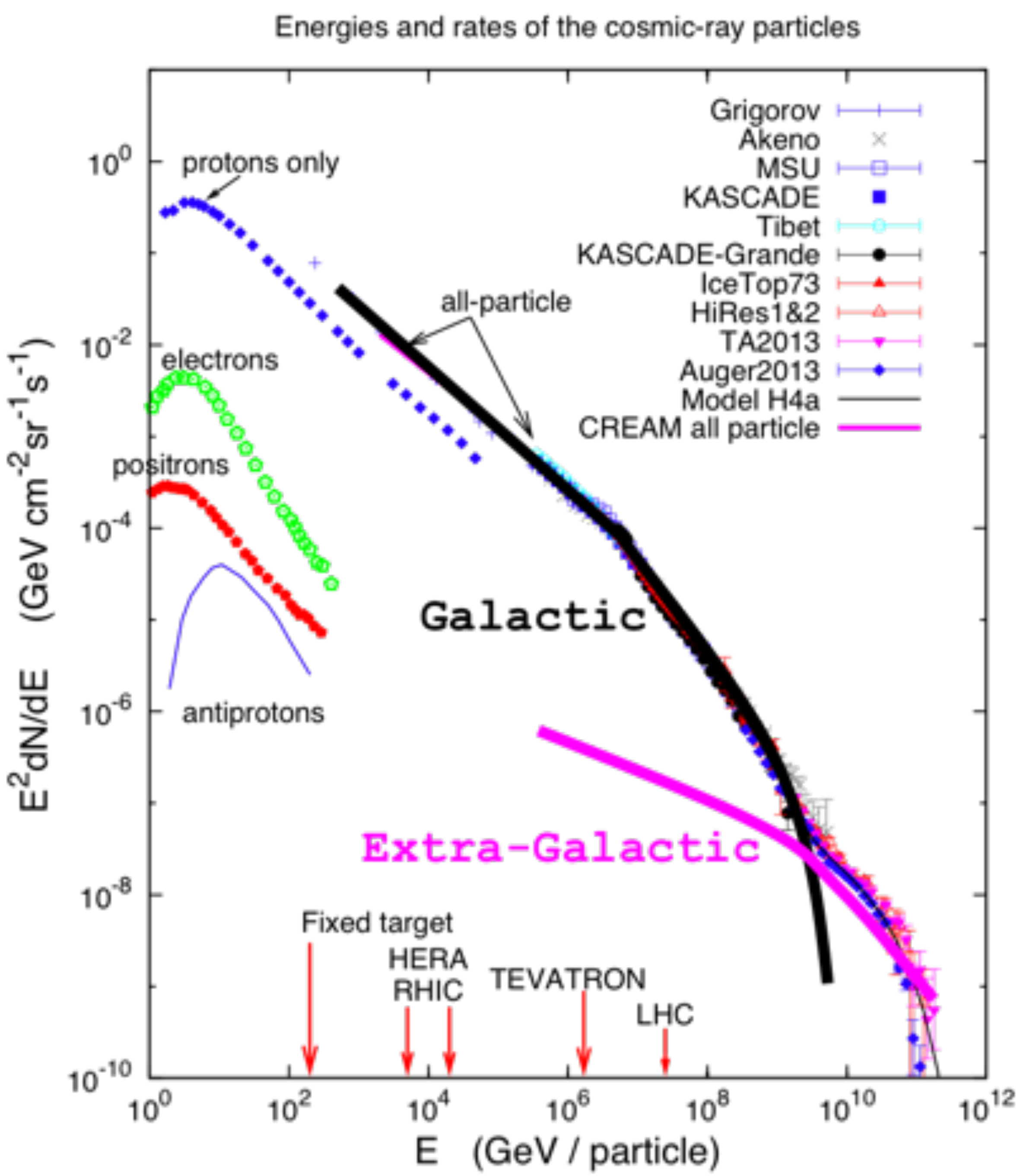
- **CRs in SNe: energetics**

$$\rho_{\text{CR}} \times \mathscr{V}_G = 8\ 10^{54}\text{ erg.}$$

$$P_{\text{CR}} \simeq \frac{\rho_{\text{CR}} \times \mathscr{V}_G}{\tau_{\text{esc}}} = \frac{8\ 10^{54}}{3\ 10^{14}} = 3 \times 10^{40}\text{ erg/s}$$

$$P_{\text{SN}} \simeq \eta \times f_{\text{SN}} \times 10^{51} = \eta \times 10^{42} \quad \text{erg/s}$$

Cosmic Rays (CRs) are fully ionized atomic nuclei and other particles accelerated at astrophysical sources and reaching the Earth.



Primary Cosmic Rays

- **about 50% of CRs are protons** - but the rest (heavy nuclei, neutrinos, gammas, antimatter) is crucial from a physics perspective
- ~25% are alpha particles (He nuclei)
- ~13% is C, N, O nuclei
- < 1% are electrons
- < 0.1% are gamma-rays

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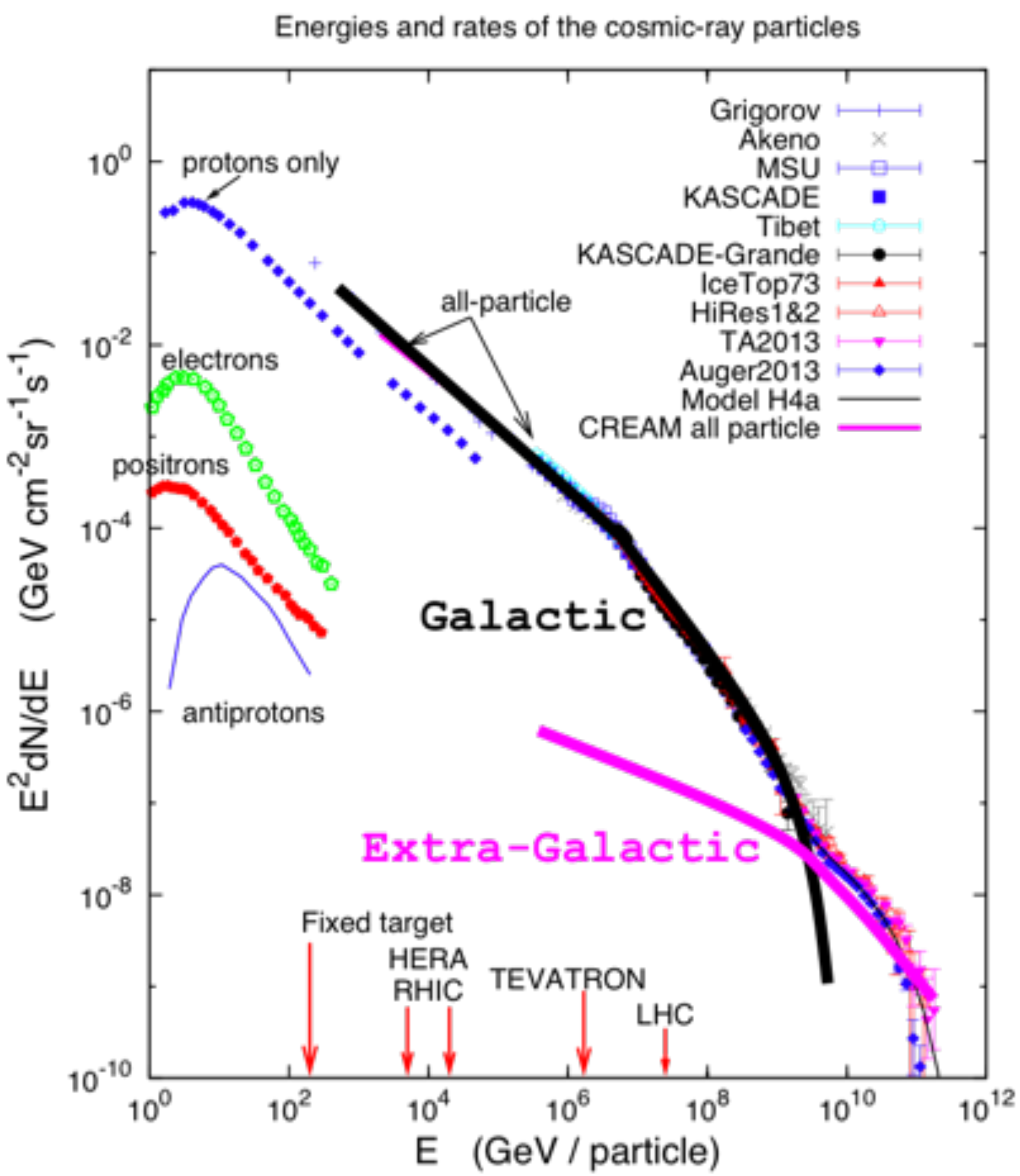

Primary Cosmic Rays

- CRs reach the **highest energies ever recorded**, up to 10^{21}eV

⇒ **40 million times that in CERN's LHC**
⇒ **~energy of a tennis ball at 115 km/h**

- The flux depends strongly on the energy:

$$\frac{dN}{dE} \propto E^{-2.7}$$

- spans more than 12 decades in energy and about 10 decades in energy flux

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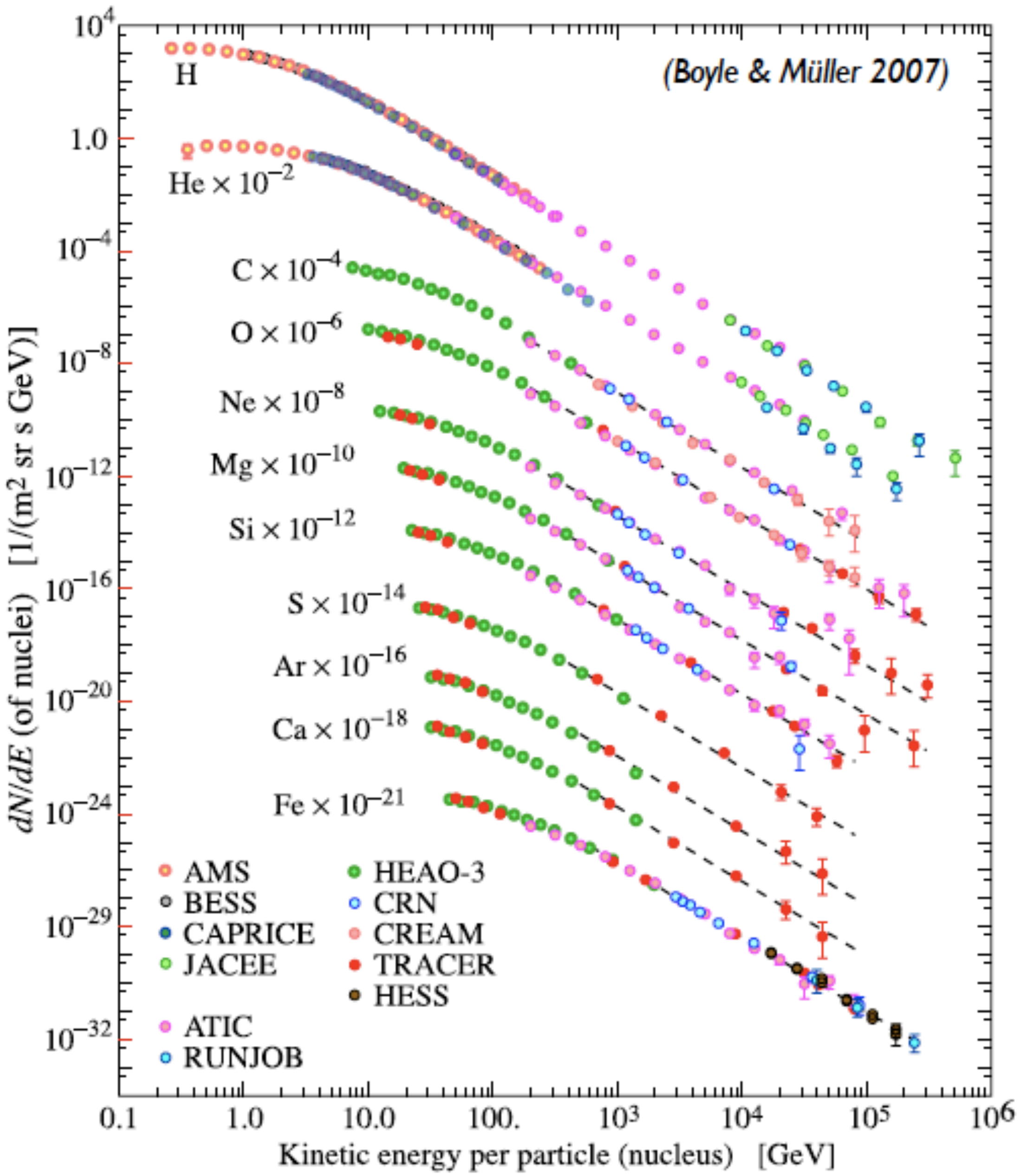
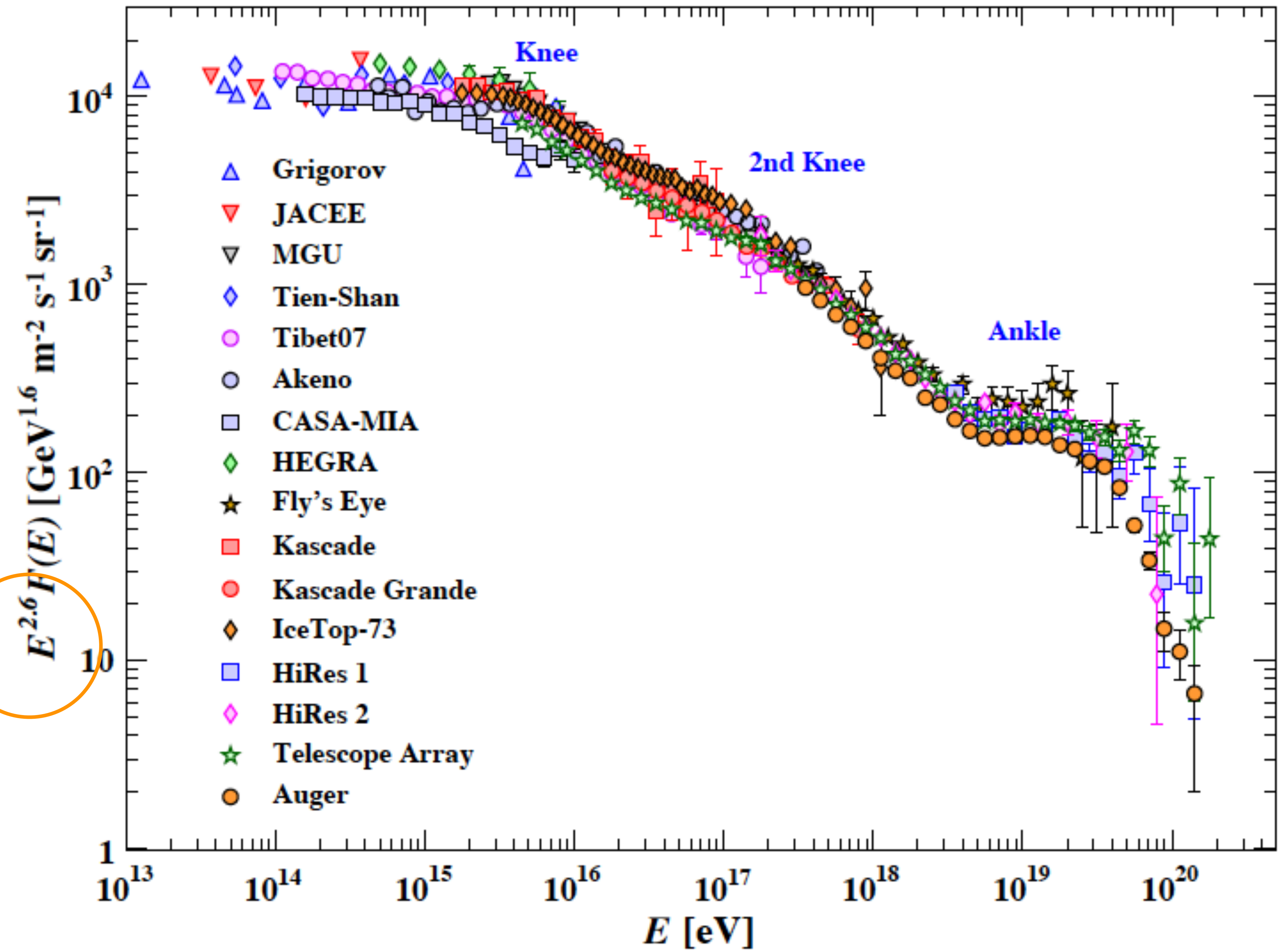


Primary Cosmic Rays

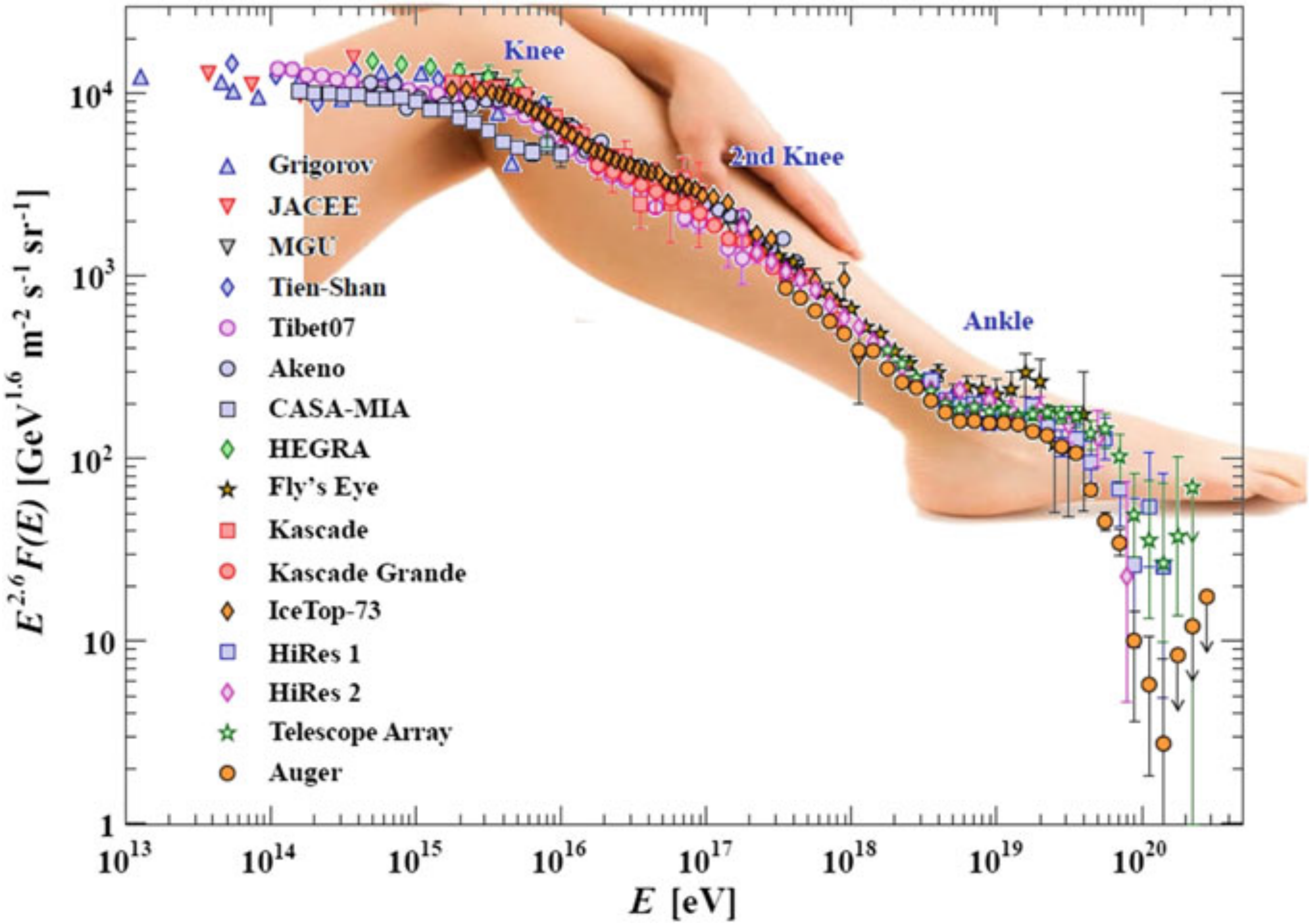
- power-law spectral shape also holds also for individual elements
- spectral shape (power-law index) almost identical for all elements - heavier elements slightly harder)
- (note: such a clear and unambiguous element spectral characterisation is only possible at the low-energy end)

Spectral Features of Primary Cosmic Rays

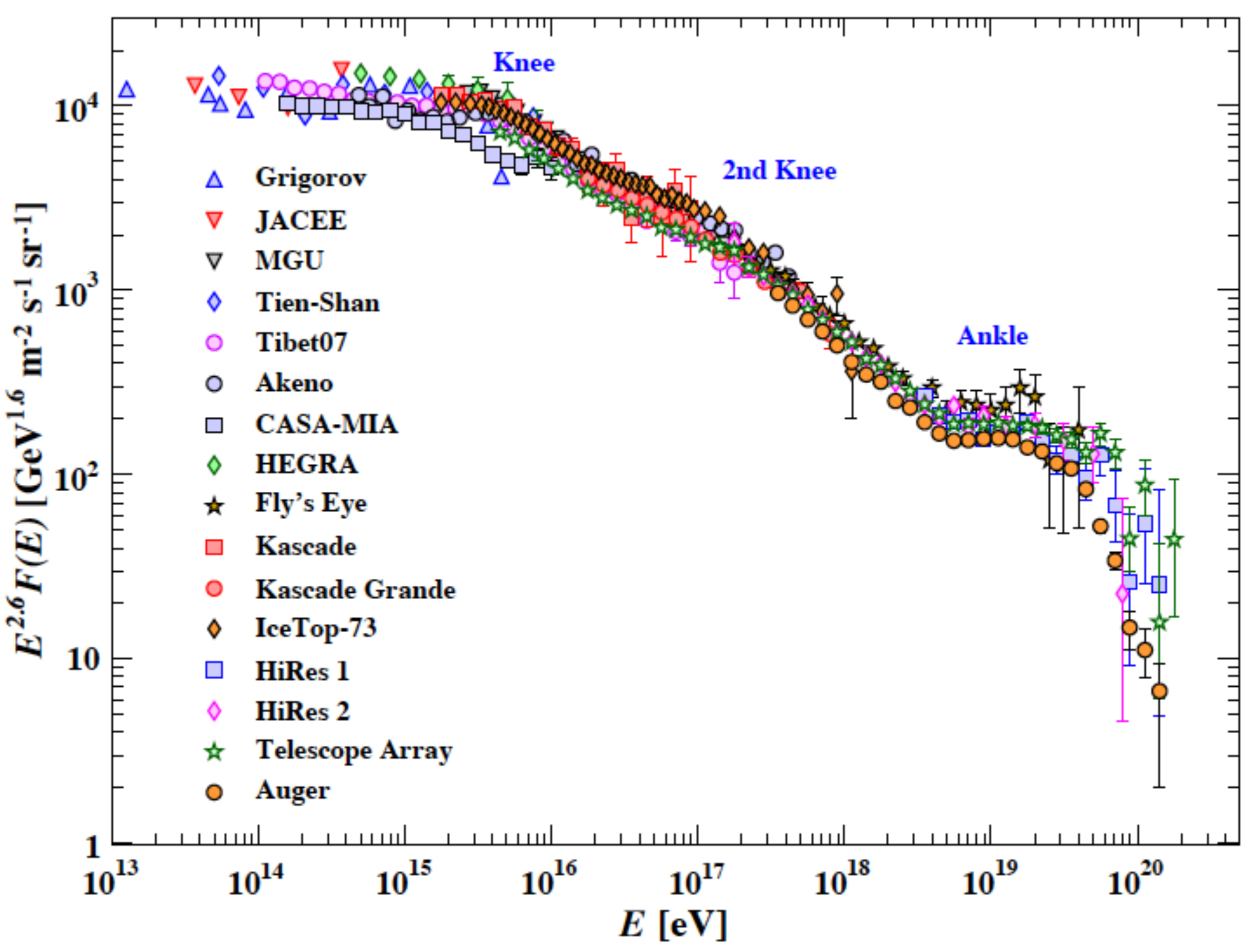
!



Spectral Features of Primary Cosmic Rays



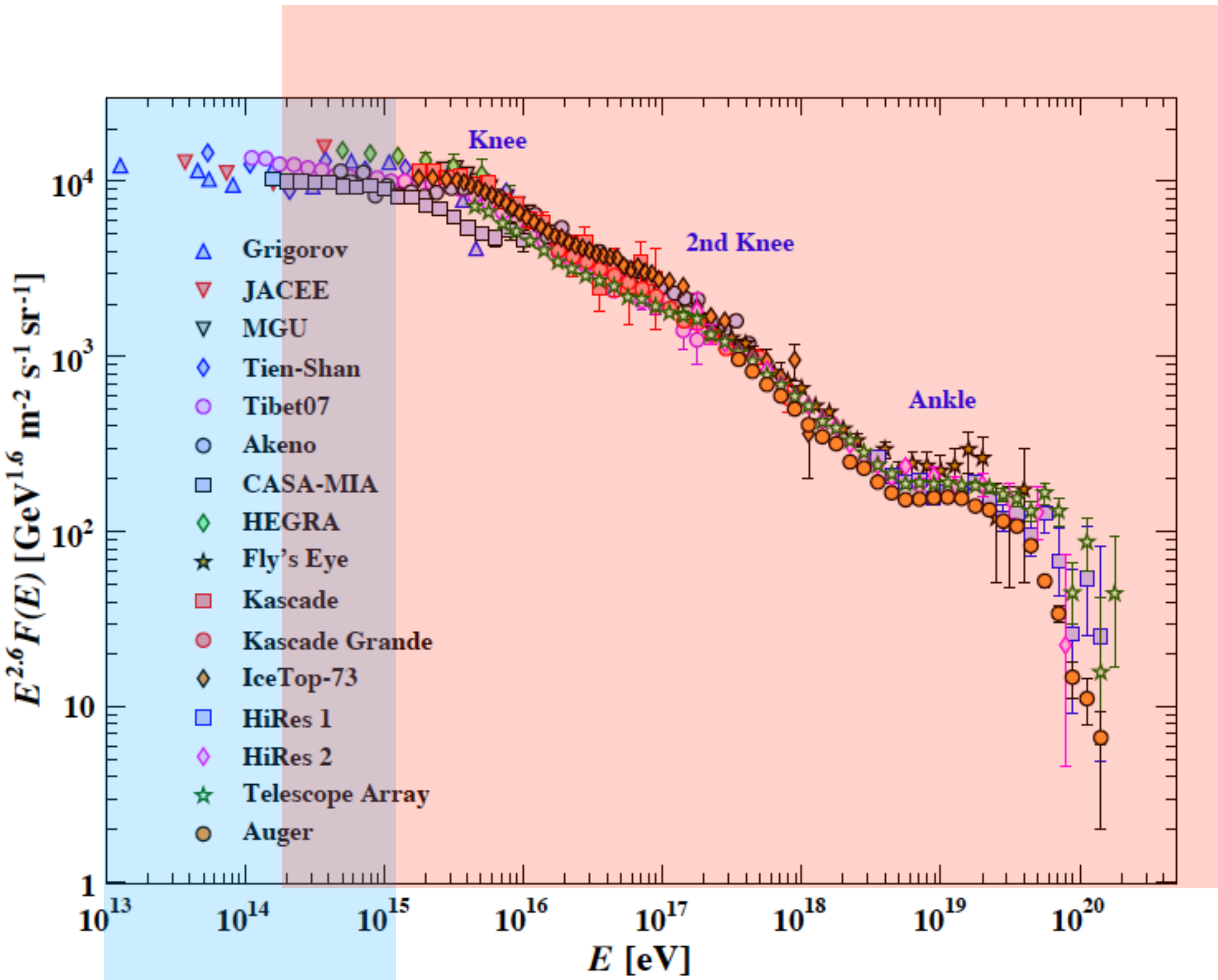
Spectral Features of Primary Cosmic Rays



- the spectrum of Primary CRs show several features, seen as “breaks” in the power-law fit:
- the **knee** at about 10^{15} eV: bending of the lighter elements. It could be a trace of the **maximum energies** that the source can accelerate, or due to **propagation effects**
- the **ankle** at 3×10^{18} eV: could mark the transition from Galactic to Extragalactic CRs, or the signature of E-Gal protons interacting with background photons (CMB)
- a “**suppression**" at about 5×10^{19} eV: due to propagation effect (GZK effect) or source limits (maximum energy/acceleration processes)

Detection Rate of Primary Cosmic Rays

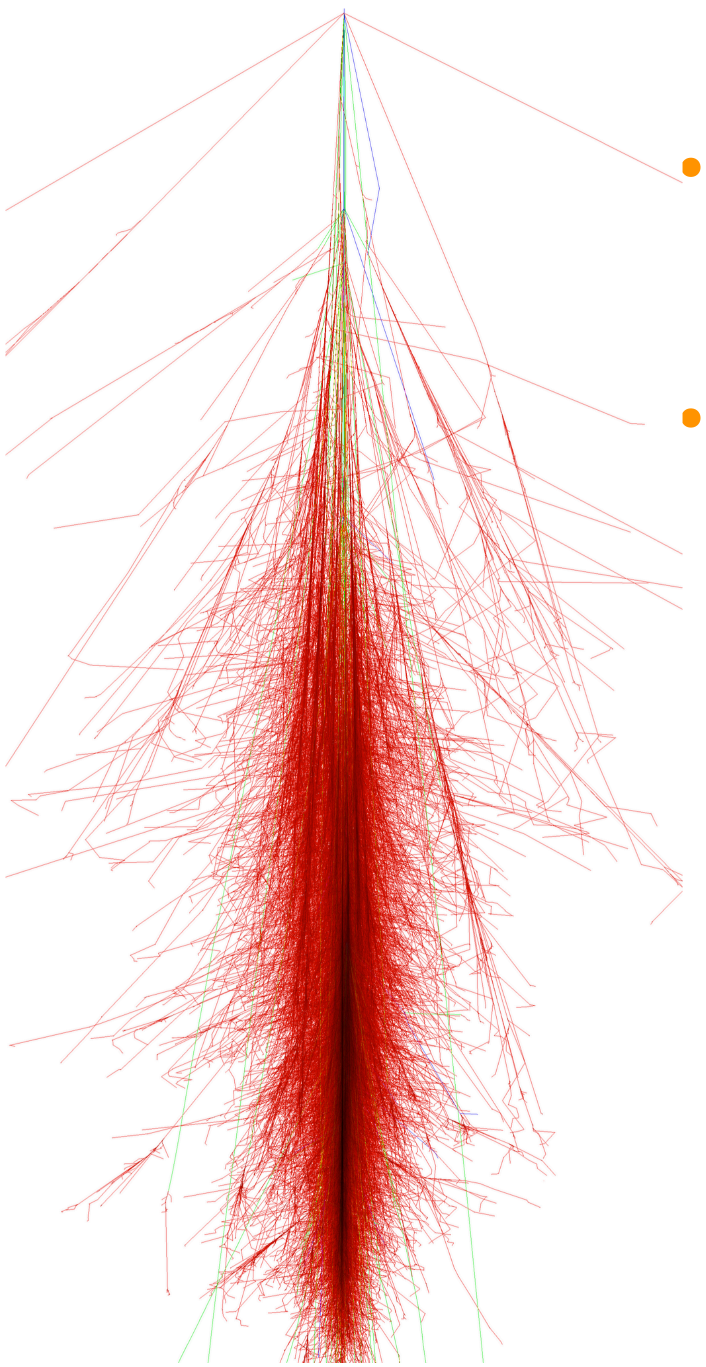
indirect detection



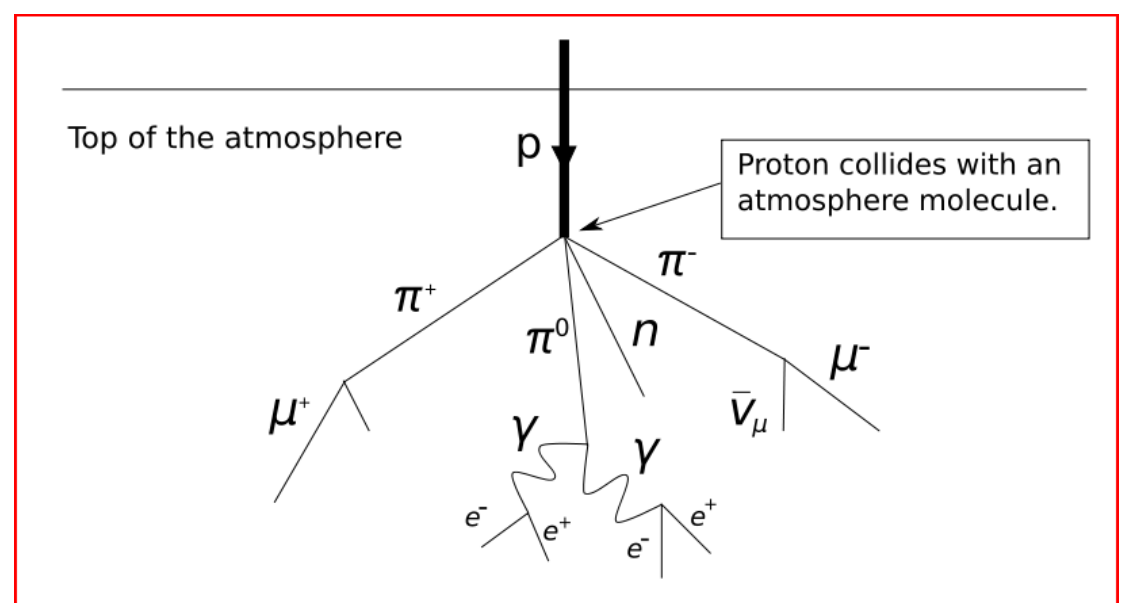
direct detection

- **Low-energy CRs**: rather high flux, **about 1/m²/s,** but absorbed in the upper atmosphere. *Direct detection* (top of the atmosphere or in space)
- Balloons
- Rockets
- Satellites
- **High energy CRs**: are very rare, **about 1/km²/year**, for the highest energies, but "penetrating" down to ground (atmospheric air-showers). *Indirect detection*: long-lived large arrays (ground level)
- Large telescopes
- Extensive Air showers arrays

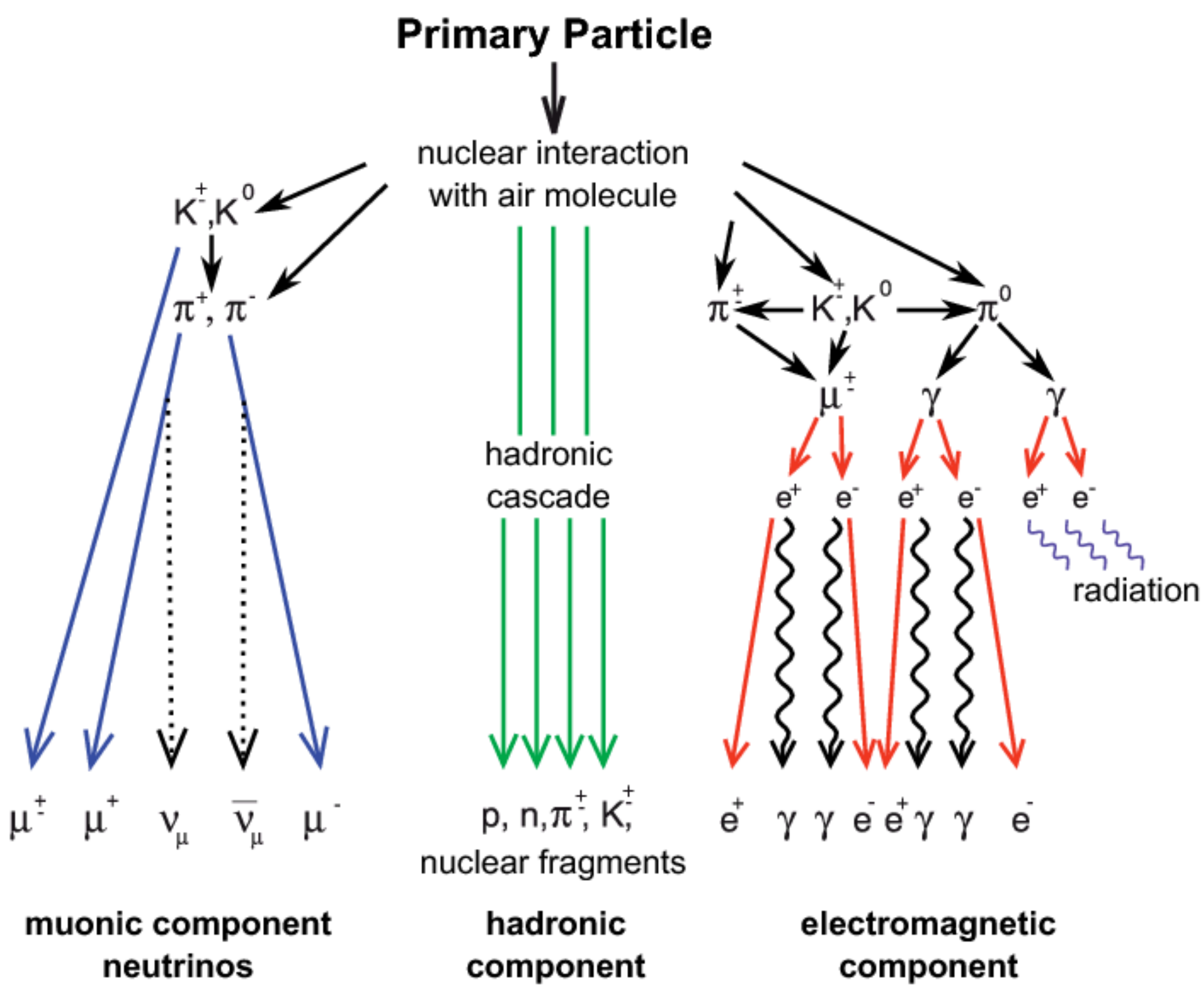
Secondary Cosmic Rays



- When cosmic ray particles enter the Earth's atmosphere they **collide with molecules**, mainly oxygen and nitrogen, to produce a cascade of lighter particles, a so-called **Extensive Air Shower**.
- secondary particles can further strike other atmospheric atoms and produce more secondaries, until $E < E_{th}$ and the cascade stops
- If energy of primary CR high enough (>500 MeV) particles produced in cascade can reach the Earth surface

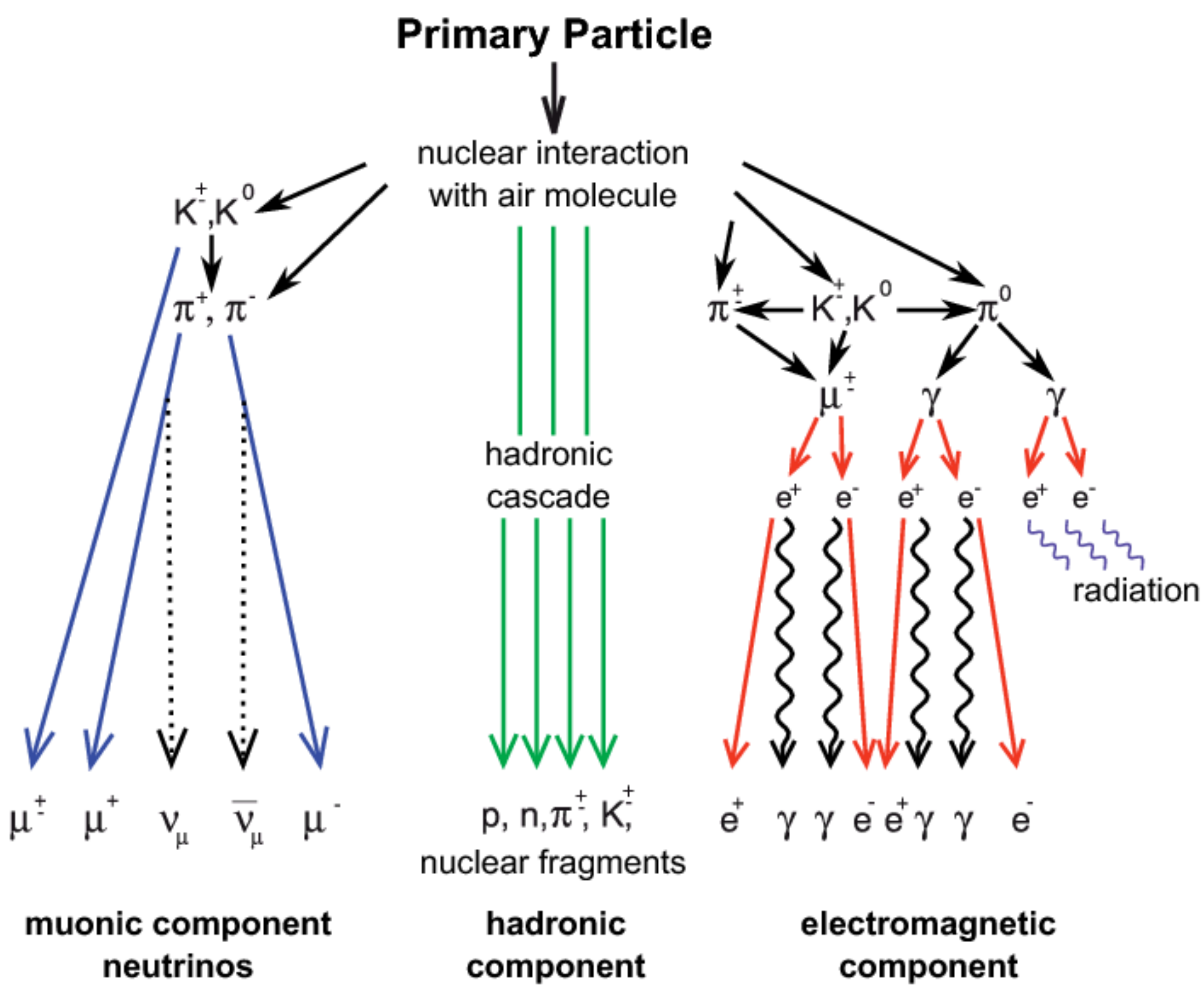


Secondary Cosmic Rays: Extensive Air Showers



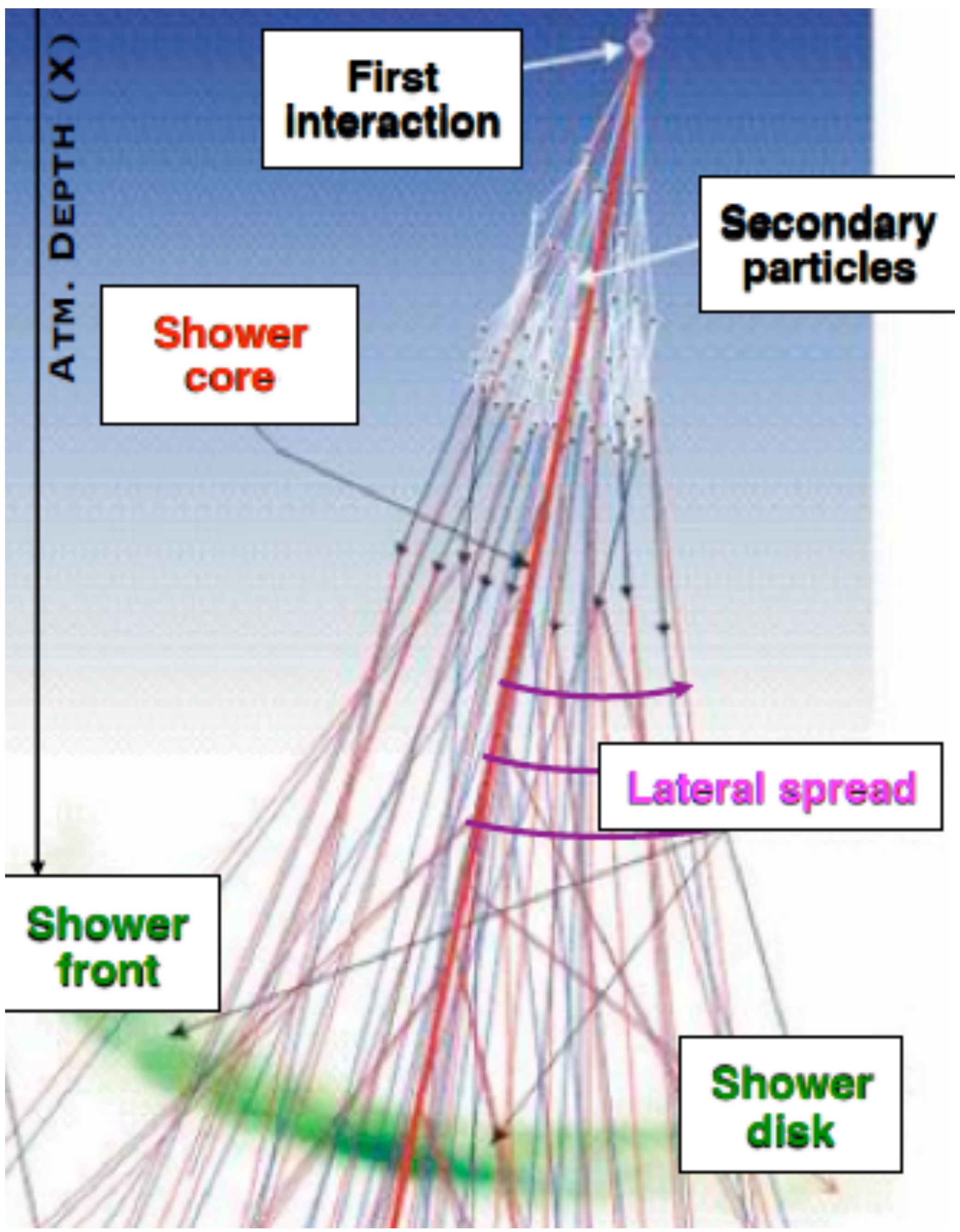
- **shower particles**: electrons, photons, kaons, pions, muons, neutrinos
- particles can travel **faster than the speed of light** in air (but still slower than the speed of light in vacuum)
- about 150 muons are striking every square meter of the Earth every second
- **Not all shower particles reach the ground** – some are stopped in the atmosphere (low-energy particles and/or transformed to radiation at relatively lower frequencies

Secondary Cosmic Rays: Extensive Air Showers



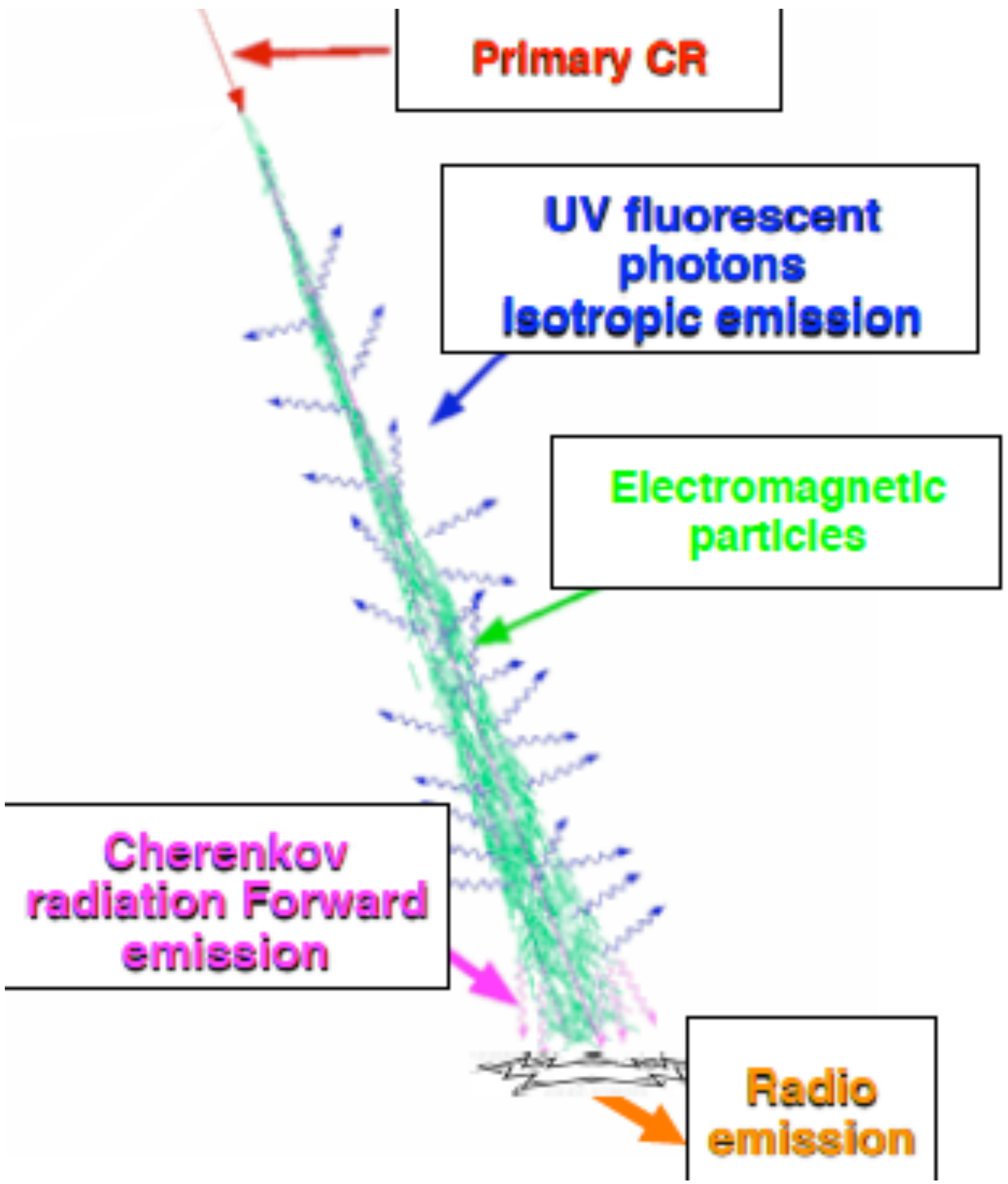
- **pion decay** is very fast, they do not reach the ground
- photons, electrons and positrons are absorbed by the atmosphere through interaction with atomic fields => **e.m cascade**
- muons can reach the sea level: decay time ~2.2 microseconds => 5km @ speed of light. Upper atmosphere: 10 km => **special relativity effects at place**: “slower clocks"
- neutrinos interact only weakly, they easily reach the sea level (and continue straight through the Earth!)

Secondary Cosmic Rays: Extensive Air Showers



- secondary particles form a narrow "bundle", the **shower core**
- initial transverse momentum and multiple scattering in atmosphere causes particles to spread out laterally from the core
- **lateral distribution** the particle density is greatest at the core and it decreases with increasing distance from it.
- due to different path lengths and velocities across the atmosphere shower particles are distributed over a wide area in a thin curved **shower disk**

Radiation from Extensive Air Showers

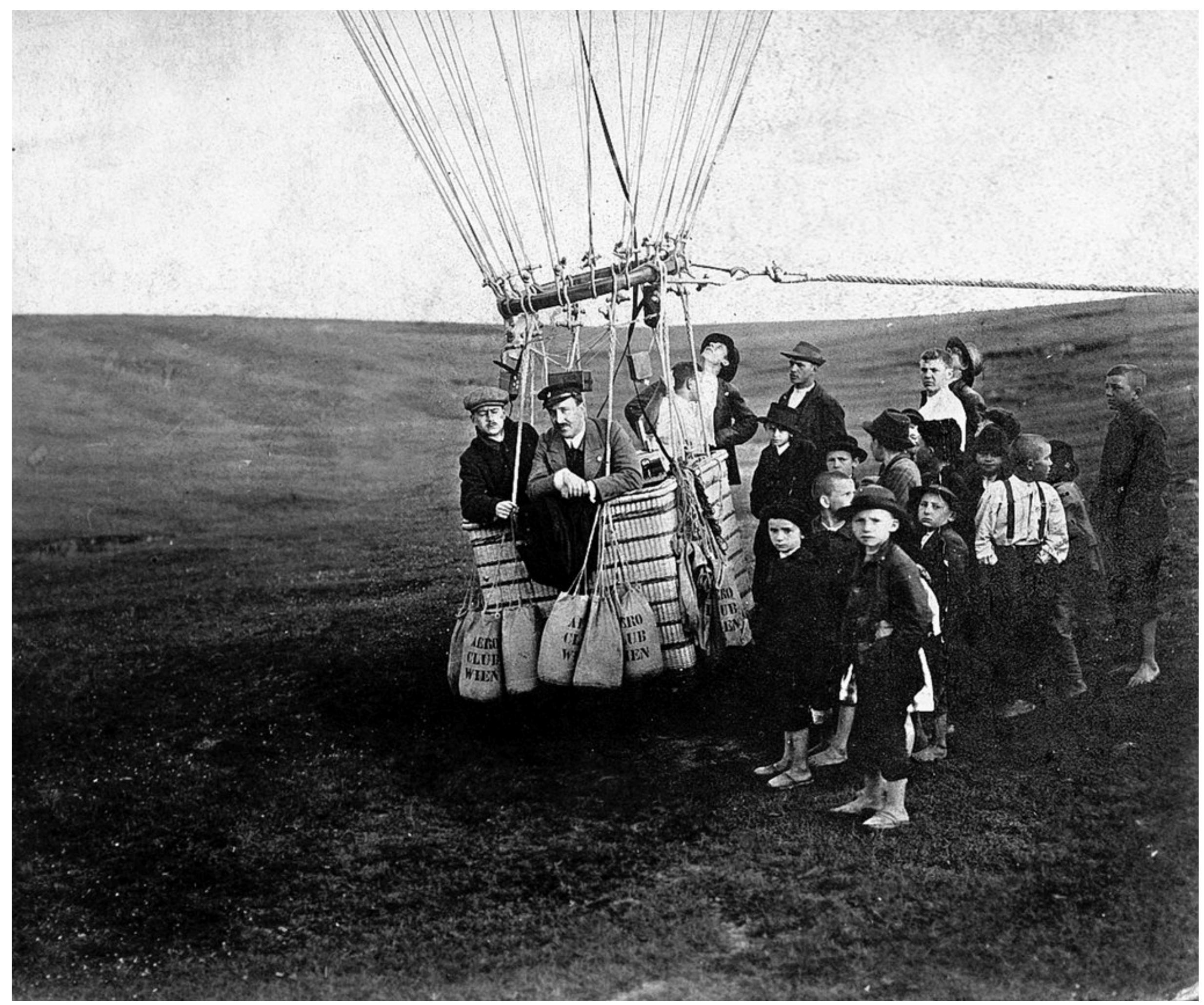


- **Cherenkov Radiation**: electrons and positrons in the shower travel faster than the speed of light in air and emit Cherenkov radiation, mostly in the forward direction
- **Fluorescence Radiation**: the passage of air shower e.m. particles in atmosphere results in the excitation of the gas molecules, mostly nitrogen. Some of this excitation energy is emitted in the frorm of isotropic visible and UV light
- **Radio emission**: air shower electrons and positrons are deflected in the Earth's magnetic field. Because of their relativistic velocities, they emit synchrotron radiation, beamed sharply downwards, at radio frequencies below 100 MHz.

2 - Cosmic Rays detection: a 100-years old tale

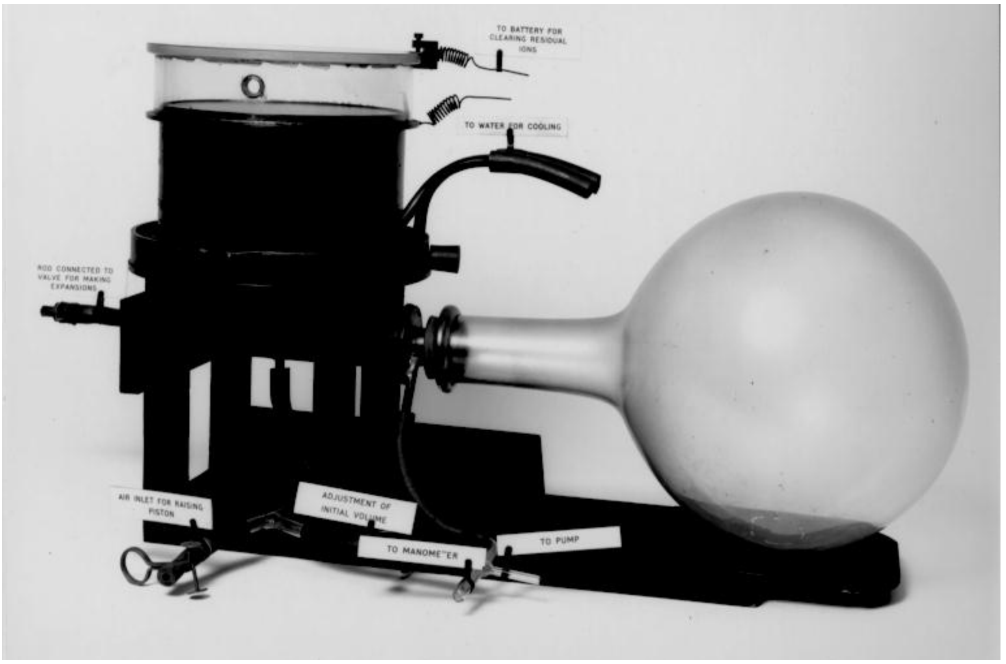
“The history of cosmic rays is much more than simply the recounting of some events. Many of the present key ideas and experimental procedures have a long and distinguished history which reflects the insight and ingenuity of the great scientists of the past. These are our legacy and the foundation of modern scientific experimental practice”

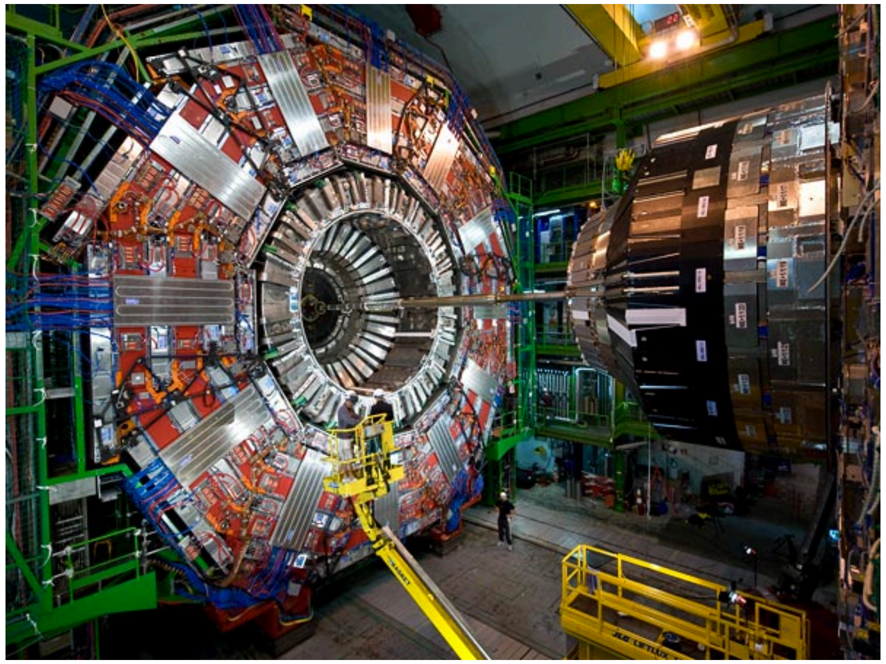
(Malcom Longair, 1995)



Cosmic Rays: a 100-years old tale

- It is (quite) easy today to talk about our knowledge of cosmic rays, and about the techniques used to detect them
- but many of the early **results were confusing** and clarity came very slowly: the exploratory phase lasted almost 50 years!
- During that time experimental tools slowly improved. As a result, the complexity of the processes was gradually recognised. In turn, experimental tools became more and more complex, thanks to the **birth of particle-physics** too (a daughter of cosmic-ray physics)

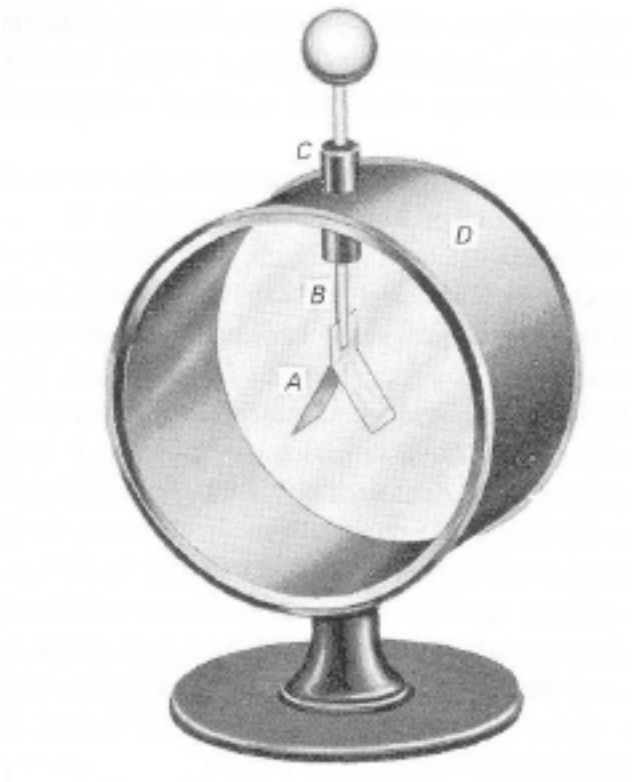




how did the detection oc cosmic rays start?

the electroscope

- first hints of the presence of cosmic rays came unexpectedly at the turn of **20th century**, during the golden days of **research into radioactivity**.
- Radioactive elements ionize gases, enabling the gas to conduct electricity. **Electroscopes** were widely used to explore radioactive materials
- When an electroscope is given an electric charge, the leaves repel each other and stand apart. Radiation can ionize the air in the electroscope and allow the charge to leak away: leaves or wires slowly come back together



Puzzling inference: No matter how good the electroscopes, the electric charge continued to leak away even when there was no obvious nearby source of X-rays or radioactivity!

how did the detection oc cosmic rays start?

electroscopes in balloons

- To reduce possible effect of sources of radiation at ground, electroscopes were carried to the tops of tall buildings (**Wulf 1910**, Eiffel Tower) or even to greater heights, using balloons (**Victor Hess 1912, Kolhorster 1913-1914**)
- the intensity of the ionizing radiation first **decreased as the balloon went up** and then was becoming more intense than at sea level.

***"The only possible way of interpret my findings was to conclude to the existence of a hitherto unknown and very penetrating radiation, coming from above and probably of extra-terrestrial origin"* [V. Hess 1912]**

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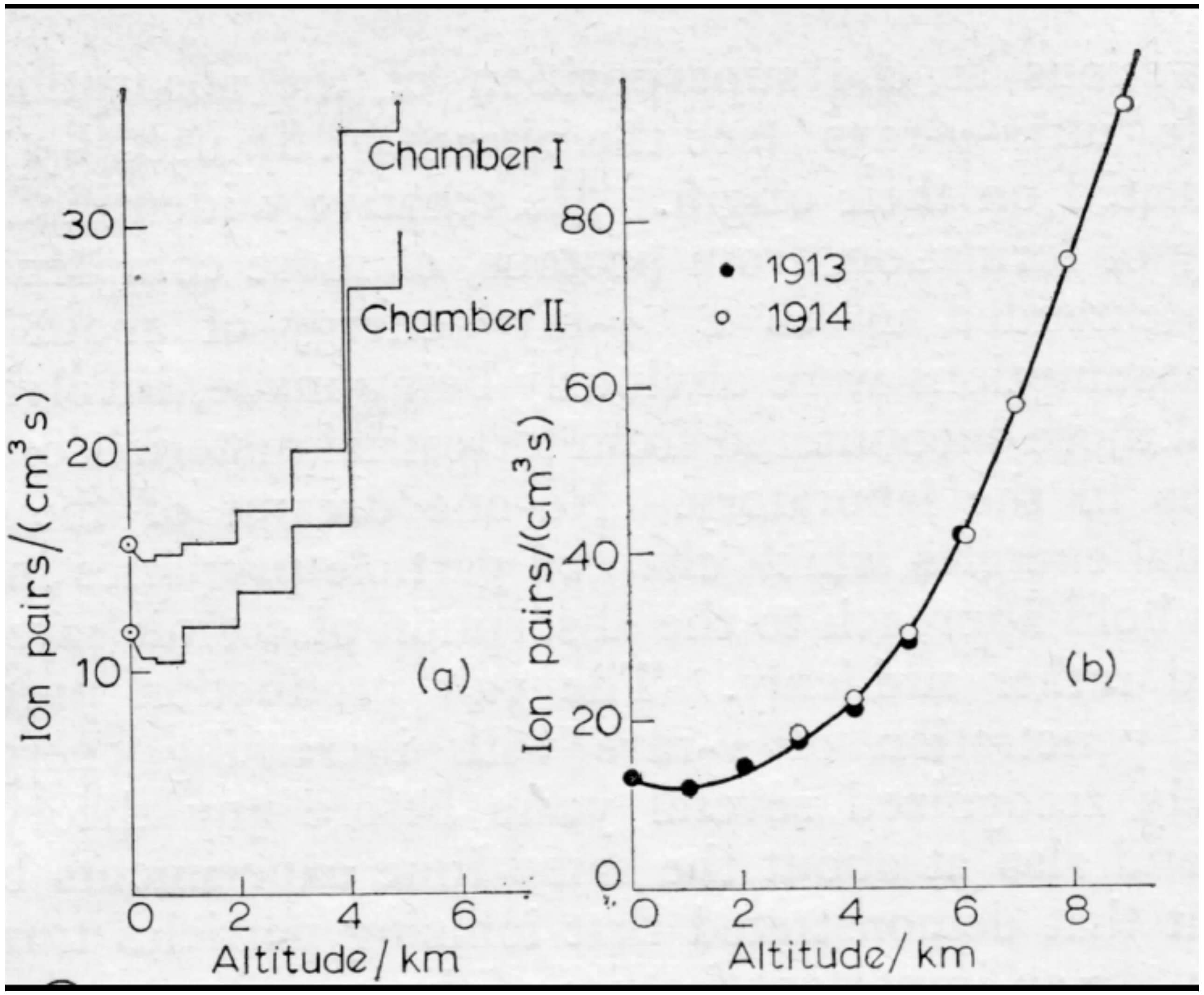

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how did the detection oc cosmic rays start?

ionization chambers

- in **ionization chambers**: the total ionisation is monitored in a **closed container**. Compton's chamber was shielded by layers of lead (against local radioactivity).
- the central container (filled with argon) held a probe connected to high voltage. High-pressure, noble gases enhance the probability of ion pairs creation by incident radiation
- ionization chambers were used to survey cosmic ray intensity variations in altitude (**Milikan, 1920s**) and in latitude (**Compton, 1930s**)

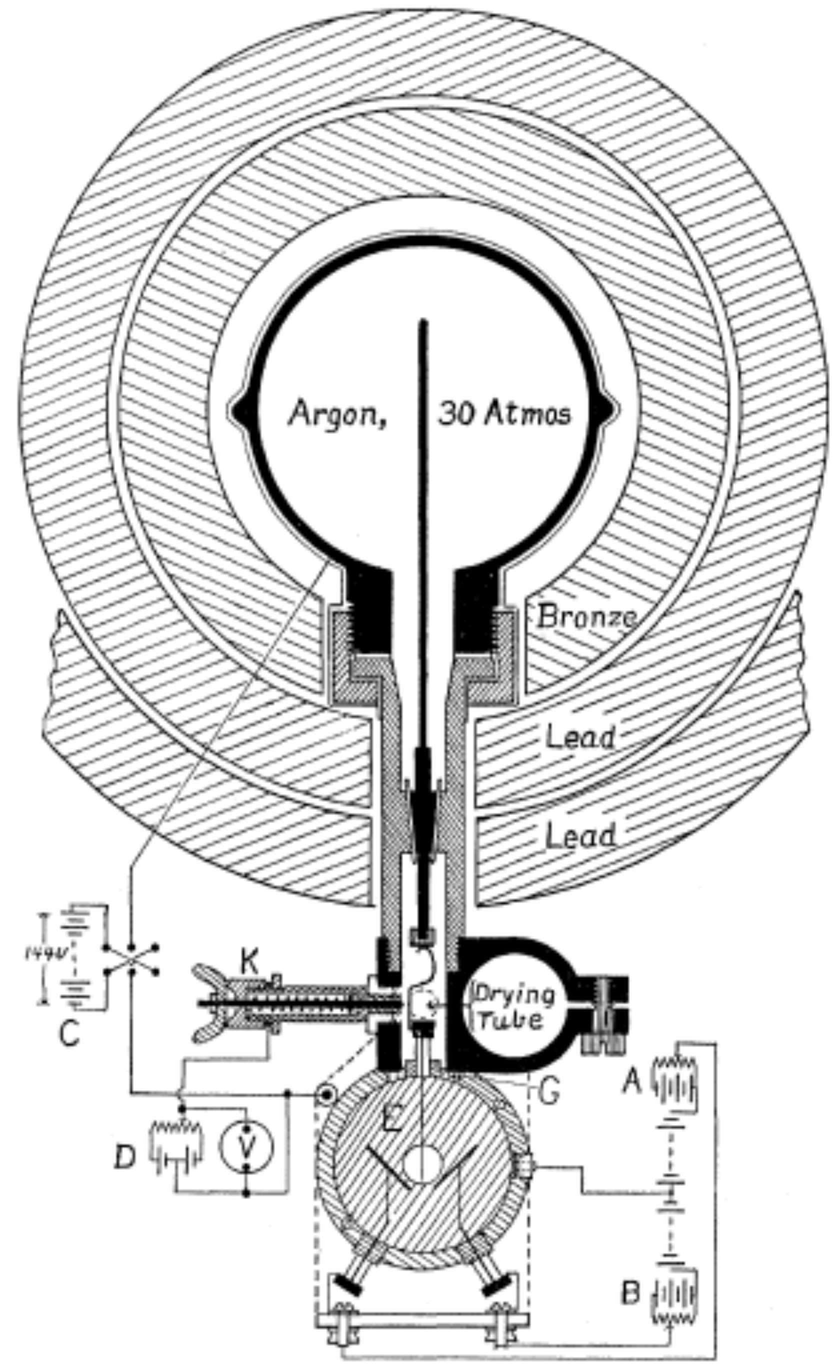

FIG. 2. Cosmic-ray ionization chamber, electrometer, and electrical connections.

Compton ionization chamber

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Compton (1933): 8 expeditions to 69 stations, > 60 scientists - two of whom died

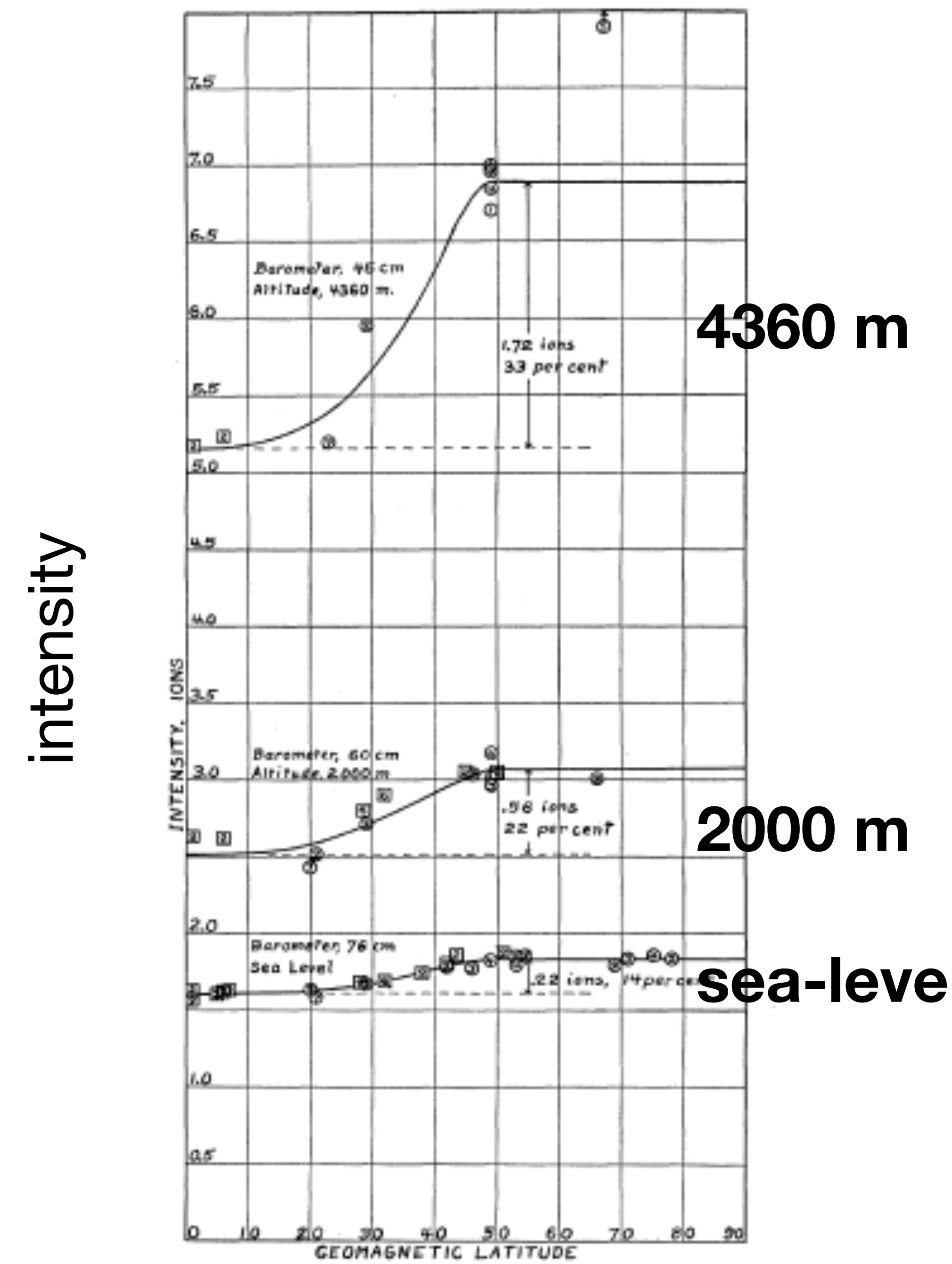
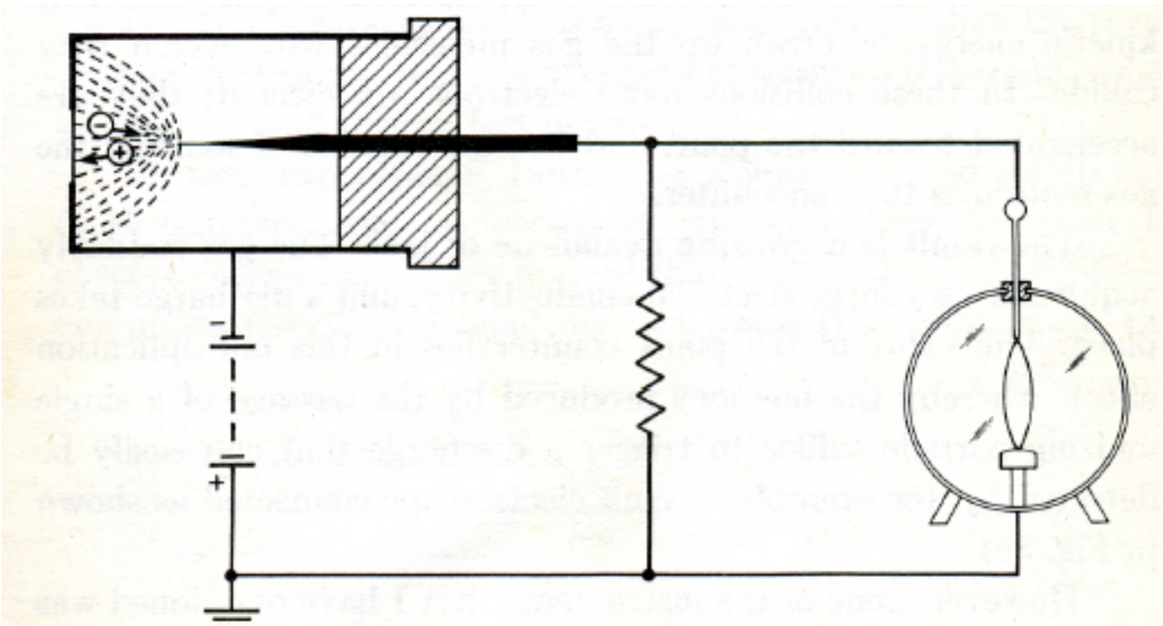


Fig. 6. Intensity vs. geomagnetic latitude for different elevations

geomagnetic latitude

Geiger point counter and Geiger-Müller counter

- The earliest detector for single particles was devised around 1911 by **H. Geiger** (the point counter), and later improved with his student W. Müller (**the GM counter**)
- It consists of a metal tube (evacuated and filled with a gas) with a thin metal wire stretched along its axis.
- a battery maintains the wire at a positive potential (~1000V) with respect to the box. Penetration of charged particles in the box produces ionization. Ions and electrons are accelerated: **an avalanche** of them constitutes a brief electrical current: the electroscope wires undergo a sudden deflection.

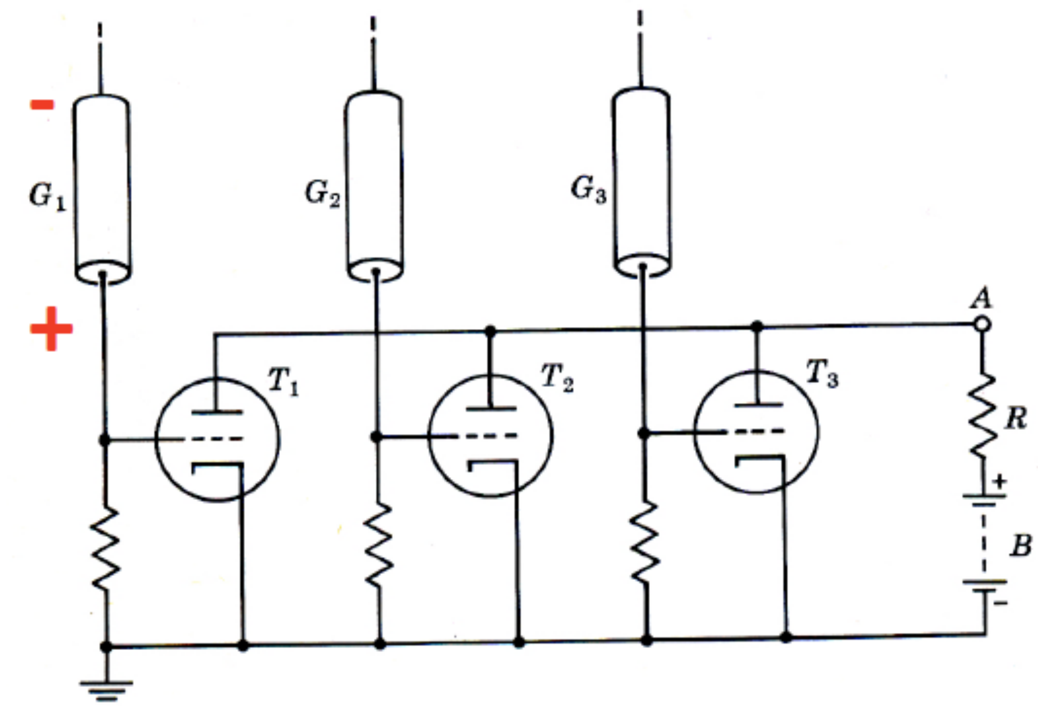


Geiger-Mueller counter

The G-M counter is easy to build and can be made in a variety of sizes. It can detect individual events and their arrival times. It became a crucial instrument to detect cosmic rays

Bothe-Kohloster coincidence counter

- **Bothe and Kohlhoster** (1929) pioneered the use of two G-M counters to study CRs. They connected each G-M counter to an electroscope, and noticed that when placed one above the other a small distance apart, often discharged simultaneously.
- these coincidences were not by chance as they became **less frequent when the distance increased**
- **Bruno Rossi** (1930) further improved the device adding an electrical circuit. This was probably the first CR telescope..



B.Rossi coincidence circuit

For the first time, physicists tried to determine the nature of CRs experimentally. By inserting absorbers (lead, gold) between the counters (and still finding coincidences) => "a corpuscolar radiation was detected…unlikely to be a gamma-radiation..."

Wilson Cloud chamber

- it consists of a sealed environment containing a **supersaturated vapor** of water or alcohol. CRs interact with the gas, resulting in a trail of ionized gas particles
- these ions act as condensation centers around which **small droplets** are formed.
- these droplets are visible as **cloud tracks** that persist for a few seconds, with characteristic shapes - alpha particles track is thick, electron track is more wispy

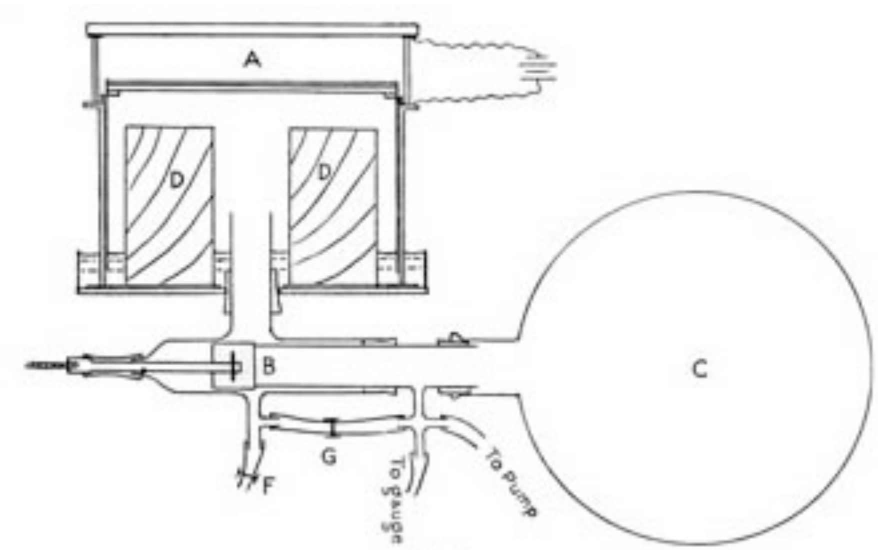


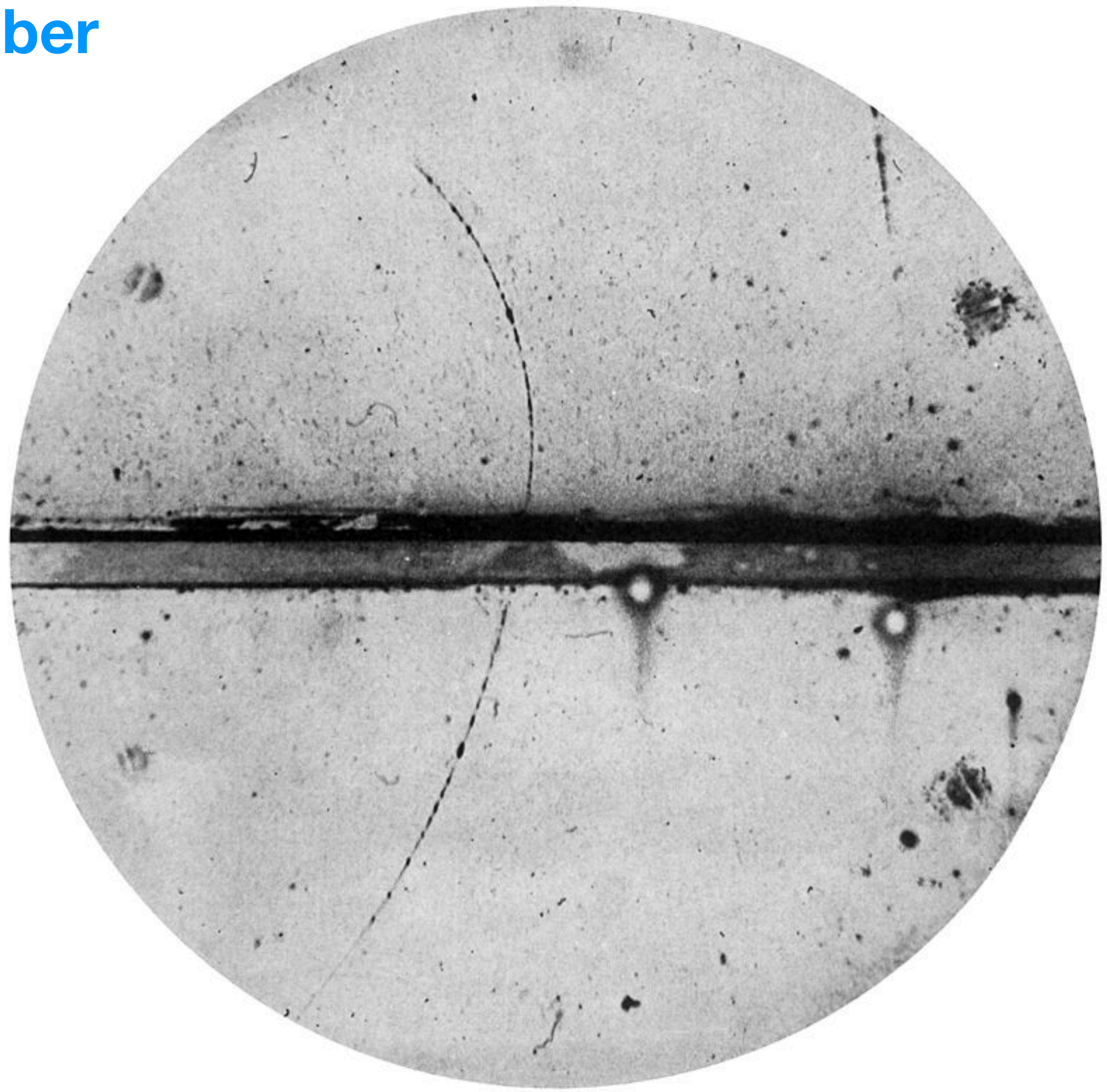
Fig. 1.

A diagram of Wilson's apparatus. The cylindrical cloud chamber ('A') is 16.5cm across by 3.4cm deep.

Wilson cloud chamber

Cloud chambers were combined with magnetic fields to deflect particles. The Wilson cloud chambers was the most widely used tracking detector of CRs and nuclear physics.

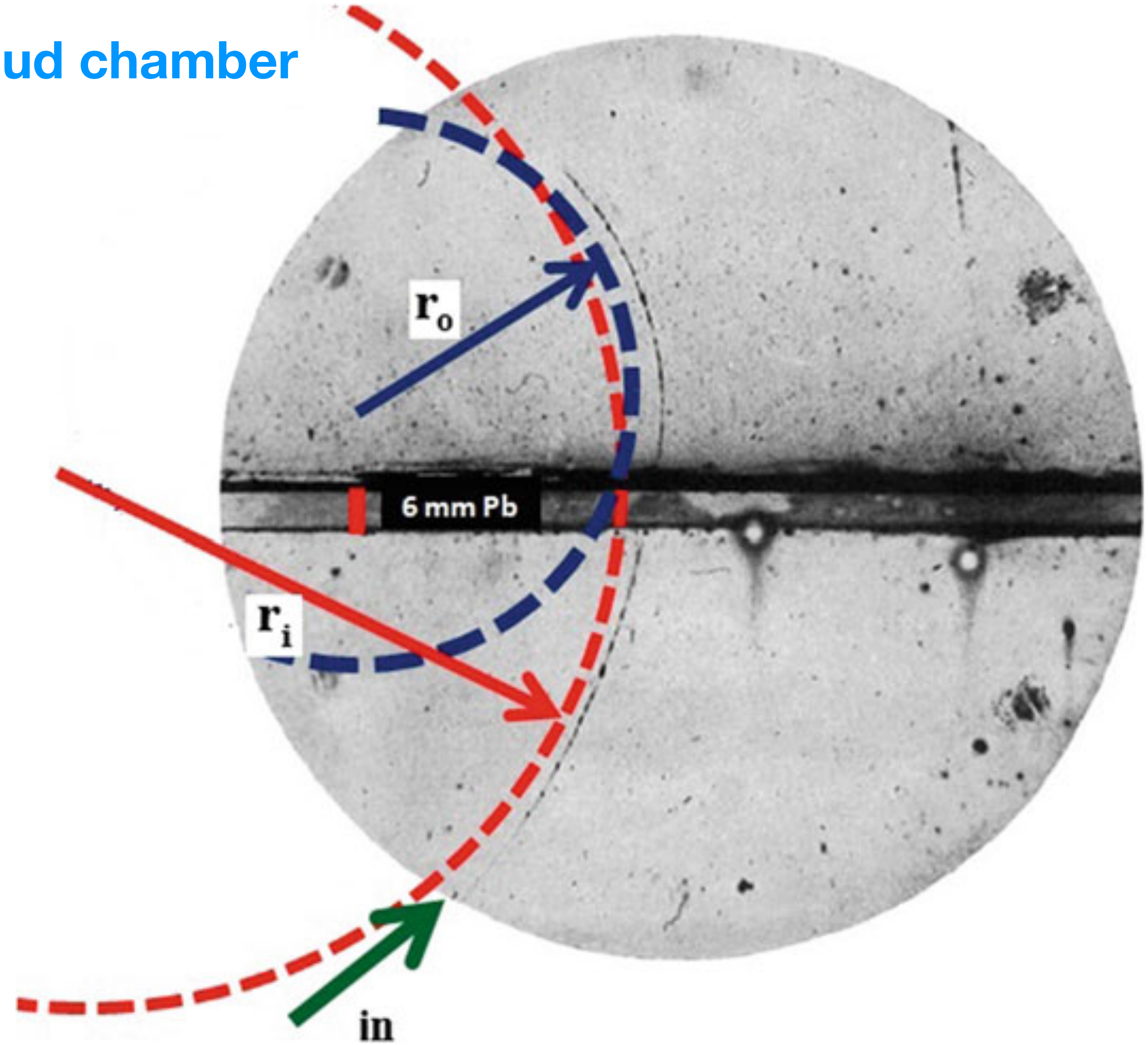
Wilson Cloud chamber



Cloud chamber track of the **positron**, discovered by **Carl Anderson in 1932**. The positron was predicted by **Paul Dirac**. Anderson discovered it in CRs for the first time, whereas later experiments with gamma-rays produced in radioactive nuclei resulted in the creation of positron-electron pairs. For this work Anderson shared the Nobel Prize in Physics in 1936.

how did the detection oc cosmic rays start?

Wilson Cloud chamber



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Photographic emulsions

- with **cloud chambers** physicists could "see" elementary particles, but because of the low density of gases, very **few particles** entering a cloud chamber collide with nuclei or stop.
- The observation of interactions and decays requires a **dense substance** (e.g., **photographic/nuclear emulsions**) in which particles can collide with high chance, or rest, leaving visible tracks.
- similar to light, when fast charged particles pass through a photographic emulsion, they produce **submicroscopic changes** that show up after chemical treatment

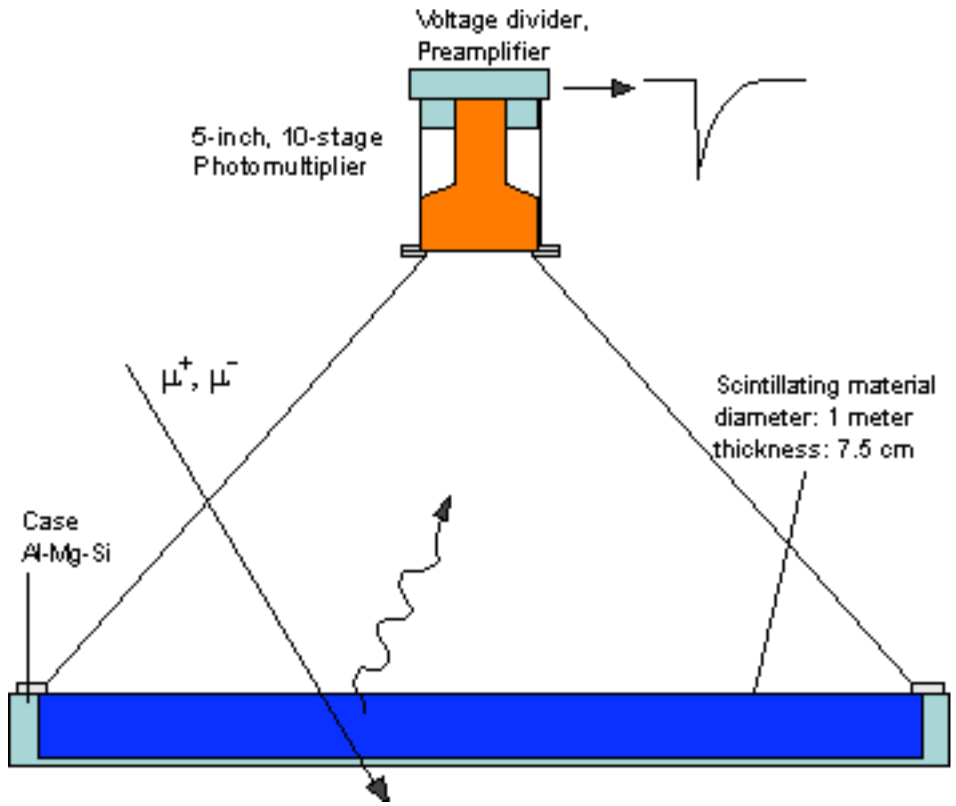
Perkins DH. 2005.
Annu. Rev. Nucl. Part. Sci. 55:1–26

C.Powell and G.Occhialini and two women operating a projection microscope

photographic emulsions were used in the 30's and 40's at mountain altitudes or in the stratosphere in balloons to study CRs

Scintillators and photomultipliers

- A **scintillation detector** works on the principle that an ionizinig particle produces a **brief flash of light** (scintillation) when it goes through a clear material.
- scintillators were widely used, e.g. by **nuclear physicists**. The photons were looked at by eye using microscopes in darkened rooms.
- a significant improvement arrived with the usage of **photomultiplier tubes** (PMT) in the 40’s. PMTs are devices that produce a voltage pulse when the light falls on the tube’s sensitive face.

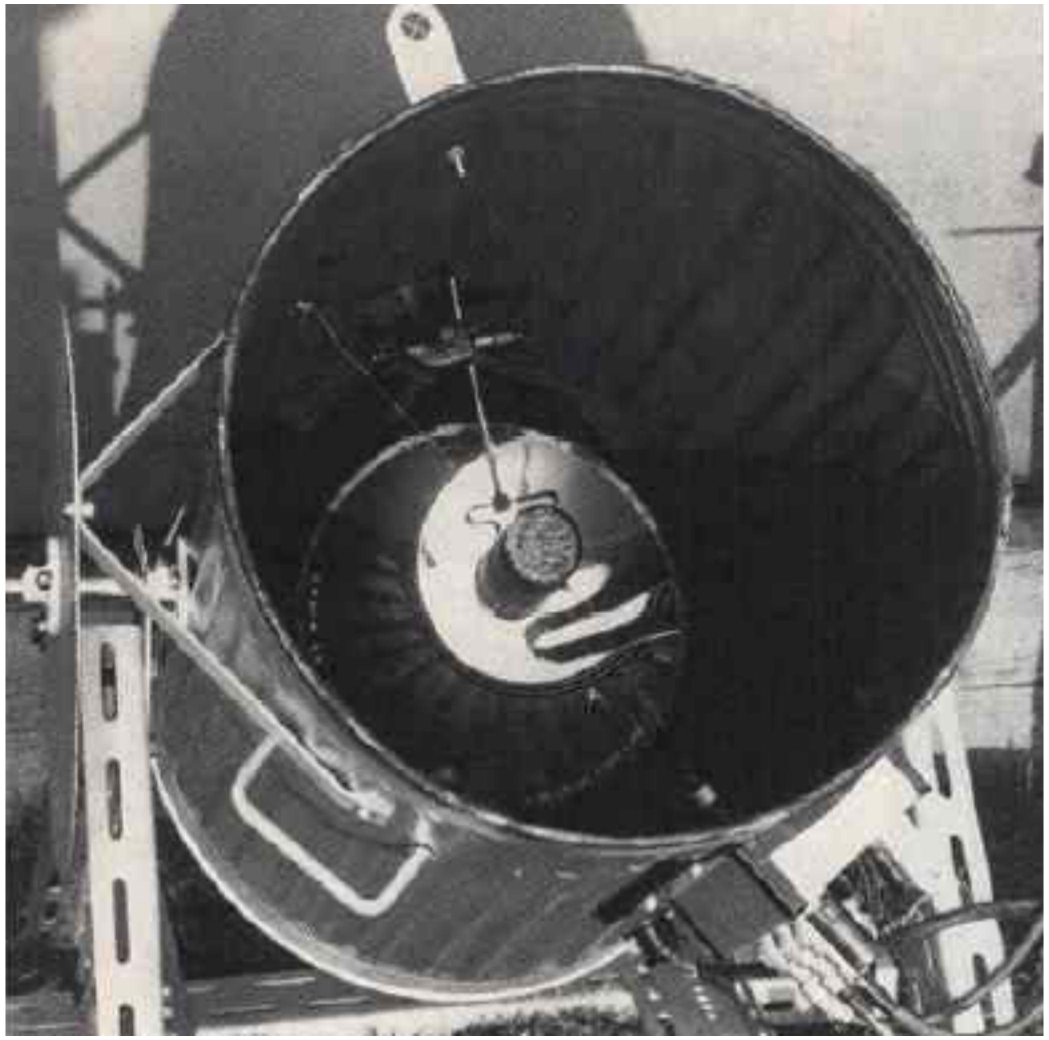


scheme of a scintillator coupled to a PMT

Cherenkov detectors

- When a particle moves through a medium at a **velocity greater than the speed of light**, it emits Cherenkov radiation (Cherenkov, Frank, Tamm, 1933).
- In 1948, **Blackett** was the first to discuss Cherenkov radiation in air, concluding that CR showers should produce a flash of light when entering the atmosphere
- Soon after PMTs were invented, they were used to detect **Cherenkov light** produced by showers (Galbraith and Kelley, 1952)

Cherenkov telescopes would trigger in the 90's the birth of ver-high-energy gamma-ray astronomy



Galbraith and Kelley (1952) Cherenkov light experiment in a garbage can collector

3 - Cosmic Ray Observatories

"All particle detectors are based on the same fundamental principle: the transfer of part or all of the energy to the detector mass where it is converted into some other form more accessible to human "perception". The form in which the converted energy appears depend on the detector and its design."

(P, Ghia, Cosmic-Ray Lectures
LPNHE, Paris, 2005)

→ the detection of CRs happens *via* their energy loss in the material it traverses

→ there is a wide choice of detectors.

- ionization detectors
- scintillation detectors
- Cherenkov, fluorescence, radio emission detectors
- transition-radiation detectors
- calorimeters

→ wide energy range of operations 10^{6} - 10^{21} eV

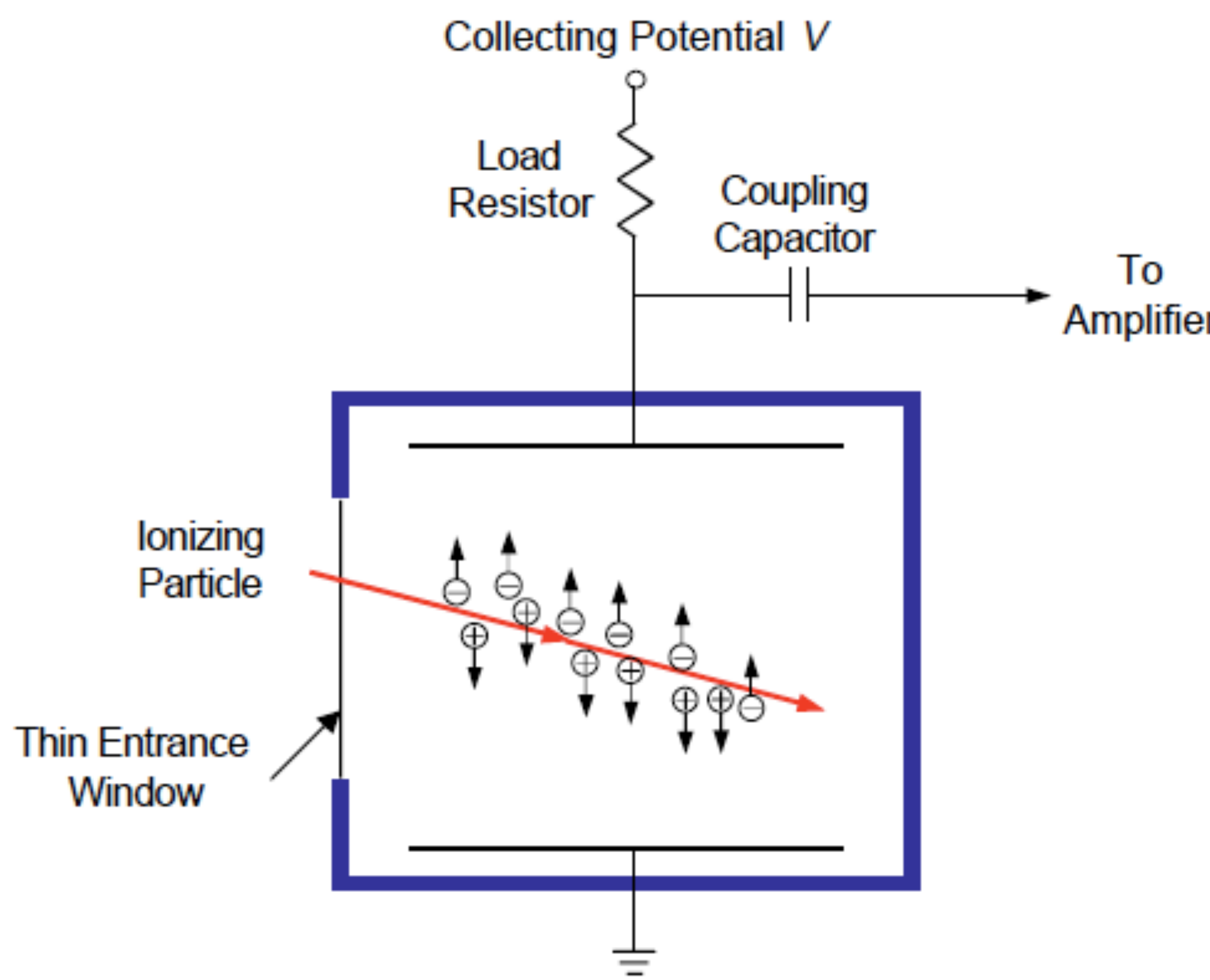
→ aims for all detectors

- particle identification - mass, charge
- energy reconstruction
- arrival direction

→ to identify a particle we need in general two different measurements that depend in different ways on mass, charge and velocity

Ionization detectors

- A particle passing through a gas-filled counter will ionize the gas along its path (see **electroscopes**).
- The applied voltage between the electrodes will sweep the positive and negative charges toward the respective electrodes causing a **charge Q to appear on the capacitor**.
- The charge Q collected (amplitude of pulse) depends on the voltage. **Higher mass particles produce more initial ions pairs**



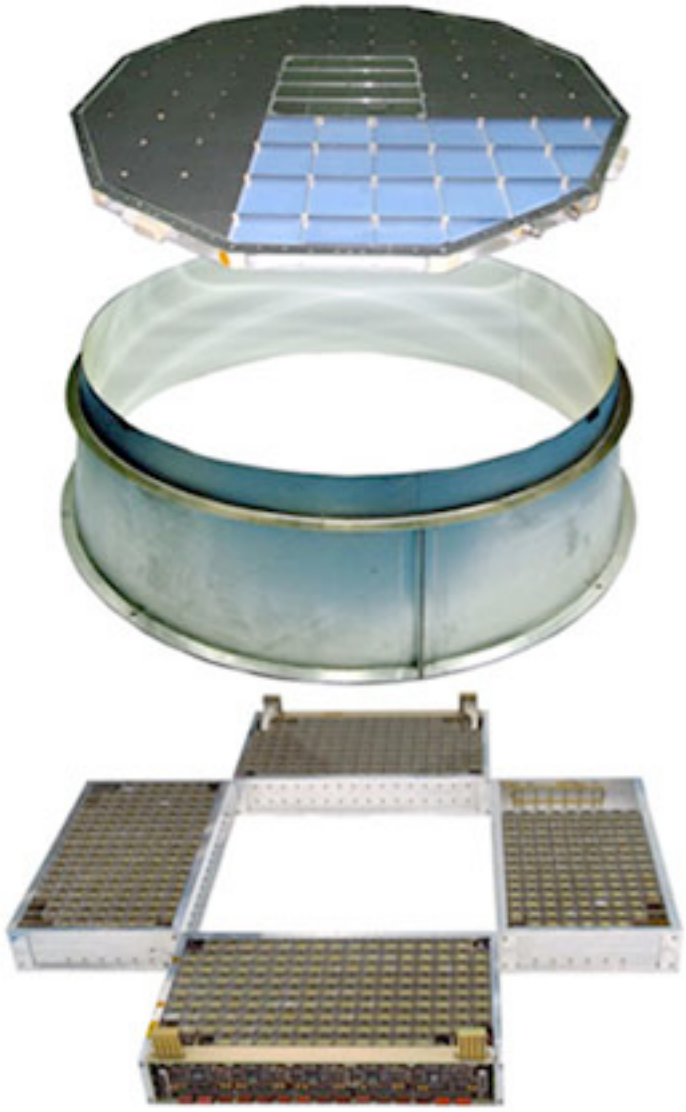
Scintillation detectors

- In scintillators, the **energy loss is converted into visible light** (by human light or photomultiplier)
- Scintillators can be **inorganic** (i.e., iodide, fluoride, liquid noble gases) or **organic** (hydrocarbon compounds), liquid, or plastic
- scintillators are easy to produce and cheap, so widely used for the study of CRs

a plastic scintillator in the Utah desert from the Telescope Array experiment

Cherenkov detectors

- When a particle moves through a medium at a velocity **greater than that of the light in that medium, Cherenkov radiation is emitted**.
- This phenomenon can be used to construct “**threshold” detector**, i.e., only if the velocity is large enough, it will emit radiation (and hence a signal)
- The total emitted light is measured, providing information on the **energy** and velocity of the particle
- The light yield is very small. The light is focalized through mirrors towards PMTs used to produce a **detectable signal**



AMS Cherenkov detector: radiator, mirror, and photomultipliers

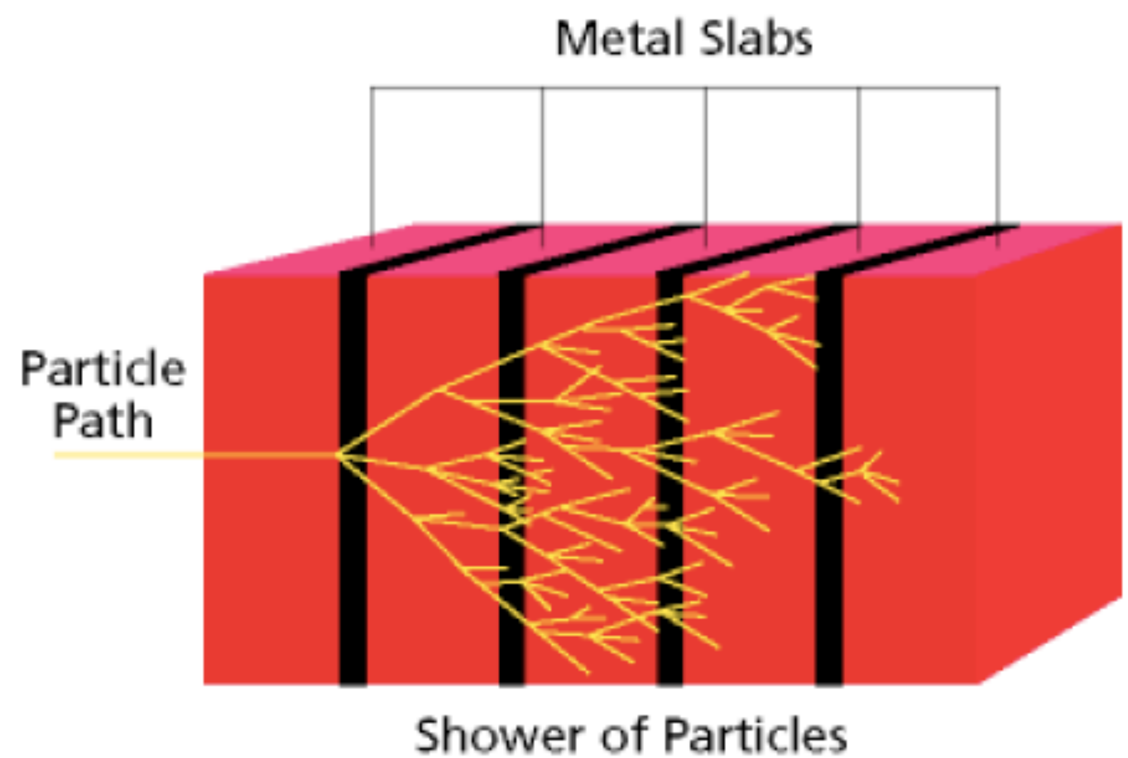
Transition-radiation detectors

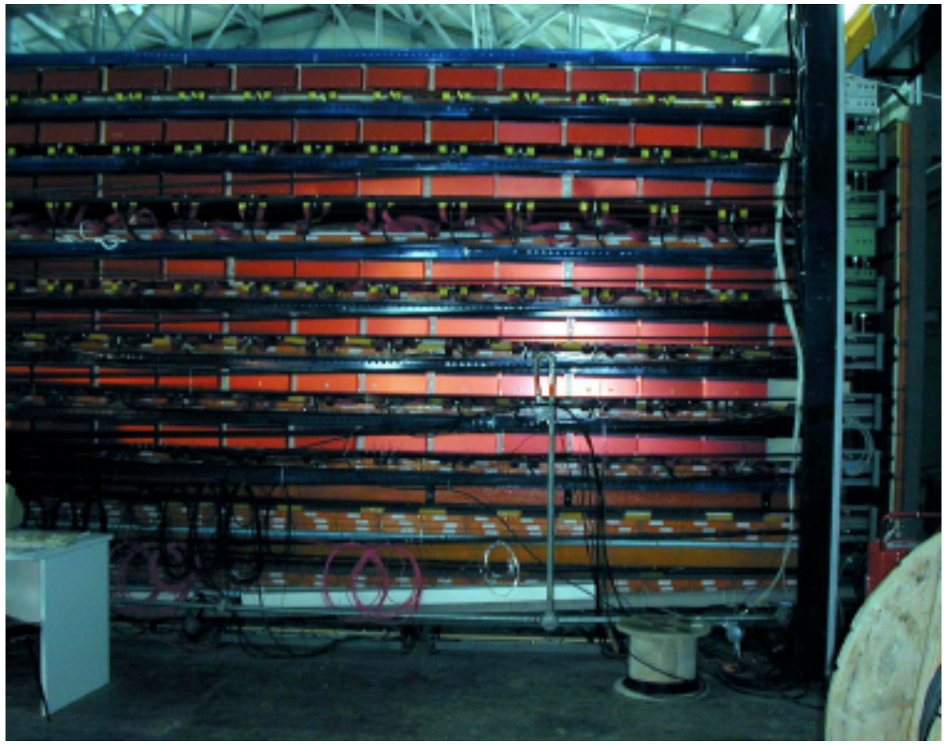
- The **transition radiation** (in the X-ray region) is produced by a fast charged particle as it **crosses the boundary between two media with different refraction indices**.
- The phenomenon is related to the energy of a particle and **distinguishes different particle types**.
- Emitted X-rays are then detected for example through ionizing detectors.

the transition-radiation detector of the PAMELA experiment

calorimeters

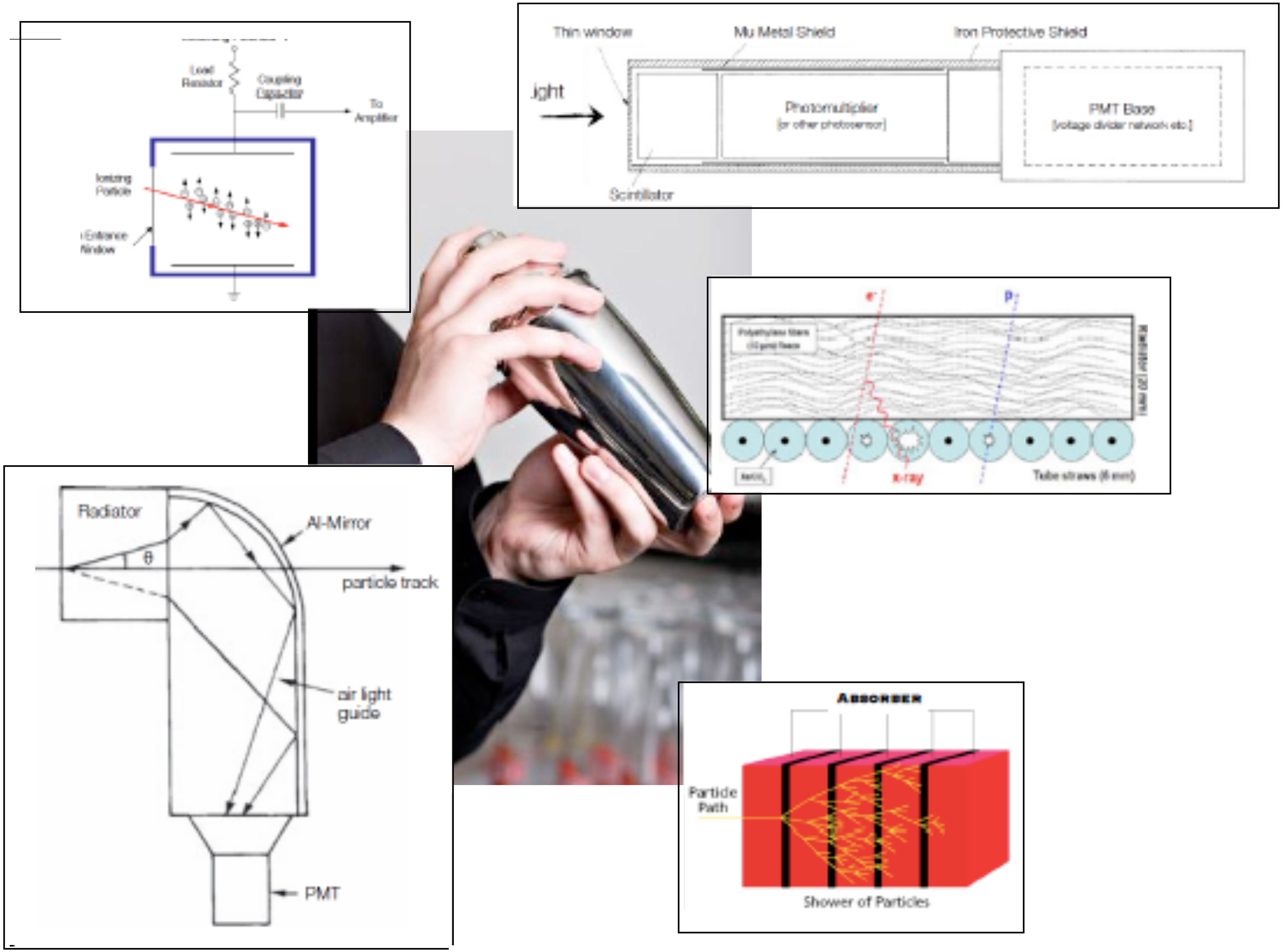
- A calorimeter measures the energy lost by a particle that goes through it, **absorbing most of the particles coming from a collision**
- Calorimeters typically consist of layers of ‘**passive**’ or ‘absorbing’ high–density material (lead for instance) interleaved with layers of ‘**active**’ medium such as scintillator or gaseous detectors
- Electromagnetic calorimeters measure the **energy of electrons and photons** as they interact with the electrically charged particles inside matter.
- Hadronic calorimeters sample the **energy of hadrons** as they interact with atomic nuclei.





calorimeter of the EAS-TOP experiment

CR detectors are particle detectors assembled into CR telescopes



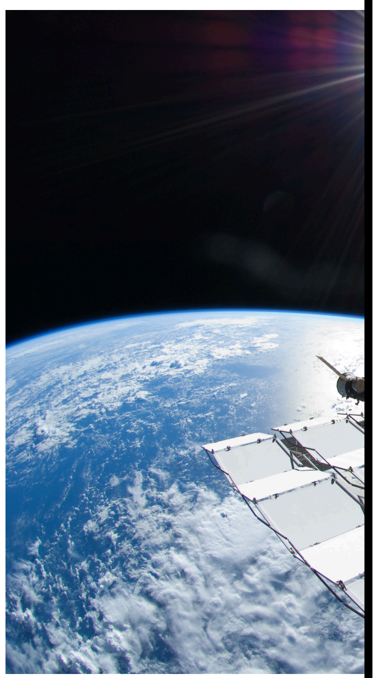
observatories in space

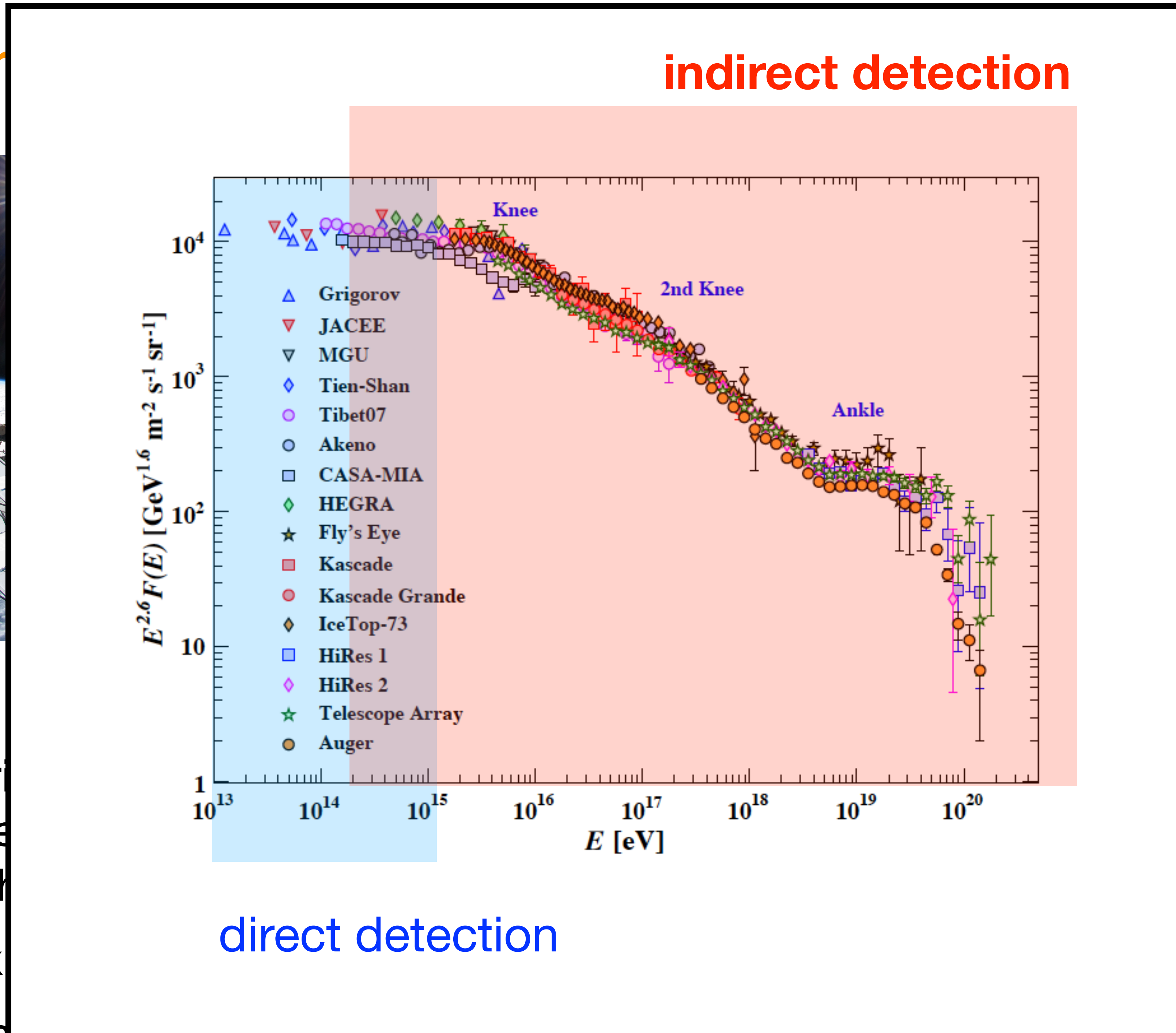
- study of **Primary CRs** without the interference of the atmosphere (a.k.a. air showers)
- typically **expensive** detectors
- **effective area are very small**: difficult to “catch” many of them

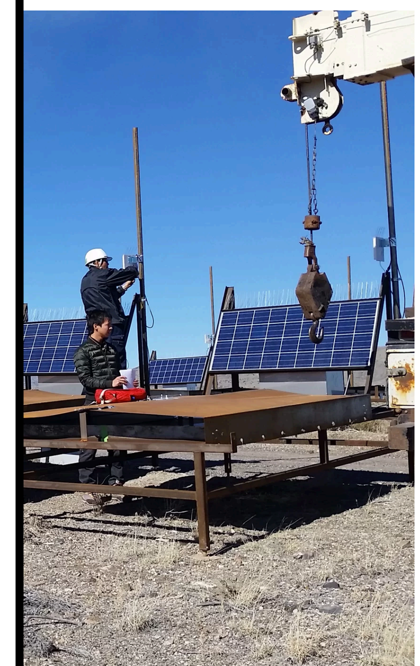
observatories in the ground

- they are **cheap, big**, and can detect a lot more (**large effective areas**)
- measure **cascades** induced by primary CRs: it takes some work to figure out what the primary is like
- can either detect **particles** or look for the **light** produced in showers

obser… …e ground







- study of Pri… interference… (a.k.a. air sh…
- typically ex…
- effective a… difficult to "catch" many of them

- …can detect …areas)
- …luced by …he work to …y is like
- can either detect particles or look for the light produced in showers

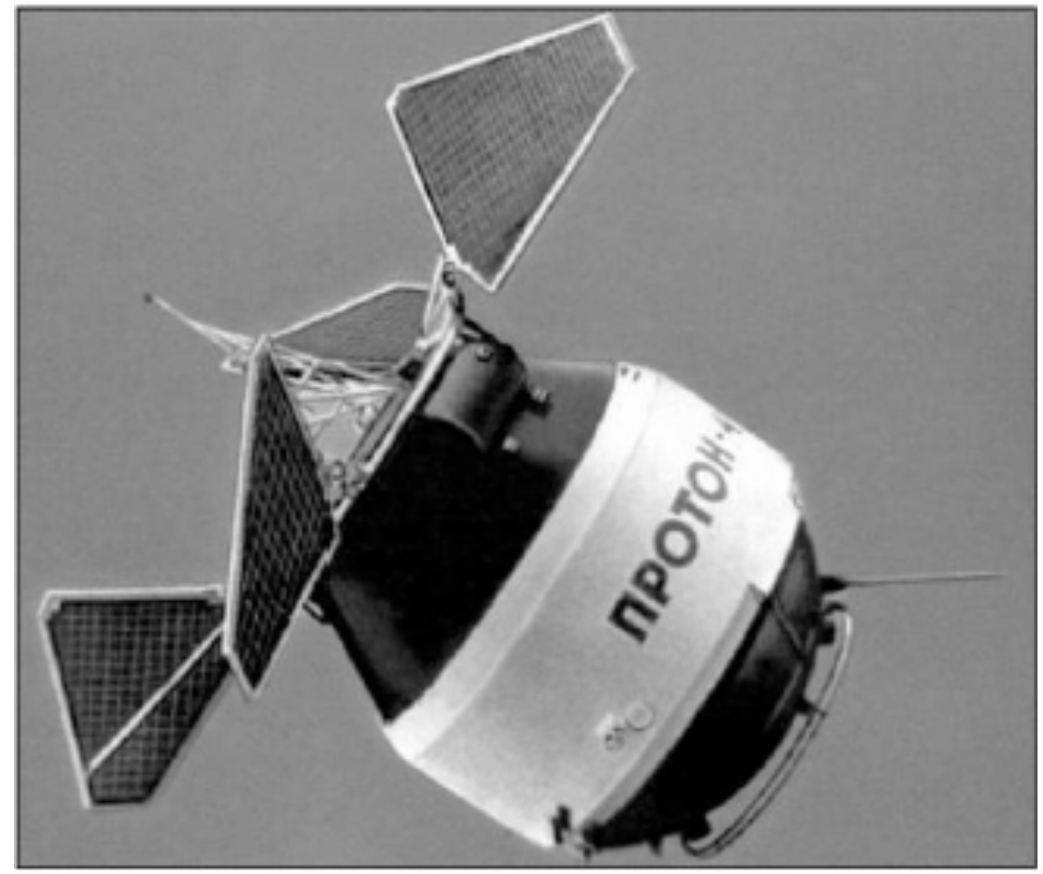
Balloon-based CR telescopes

- since 1930's til today, more and more **complex payloads** were carried by balloons. From Ge**iger-Mueller counters** to **photographic** or **nuclear emulsions** for tracking particles or **cloud chambers**, to combinations of **scintillators**, **silicon detectors** and **calorimeters** today
- initially scientists had to be on-board, later on the payloads had to be recovered for a scientific analysis, whereas today data is recorded **electronically in-flight** and transmitted to the ground

JACEE BALLOON Japanese-American Antartic base 1983-1996

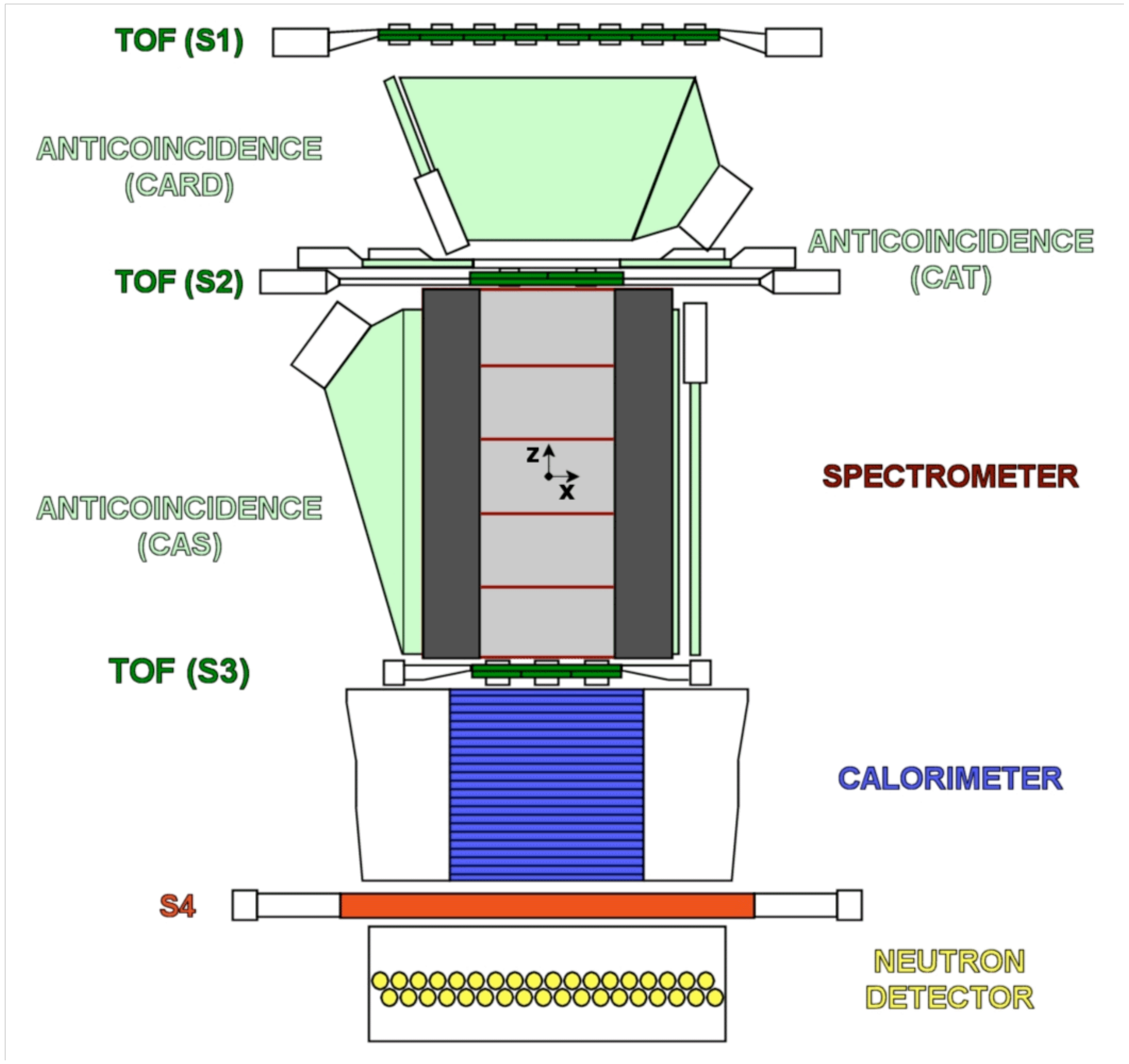
from balloons to satellites

- Due to the development of the space technique (starting from end of the 50s) the possibility arose to launch **heavy payloads** in **satellites** with scientific equipment weighting several tons
- Vernon et al (URSS) arranged the **first CR space experiment** on the Second Soviet Satellite (1957).
- In the same year, US scientists (**Van Allen et al)** launched the Explorer I satellite.
- First used instruments were simple G-M counters
- Earth's radiation belts (**Van Allen belts**) were discovered with first CR satellites

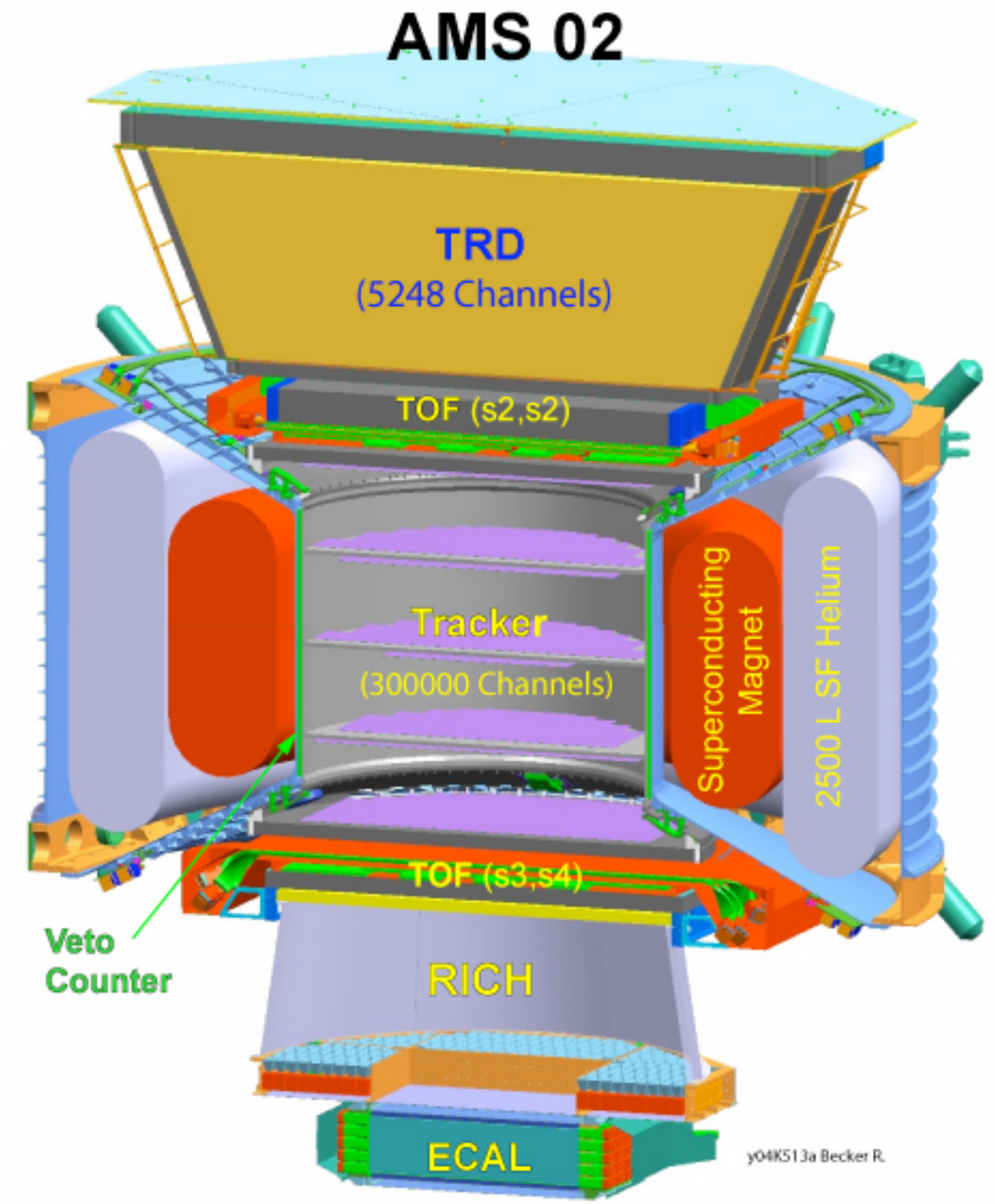


PROTON-4 satellite from Grigorov and Vernov (1969-1970)

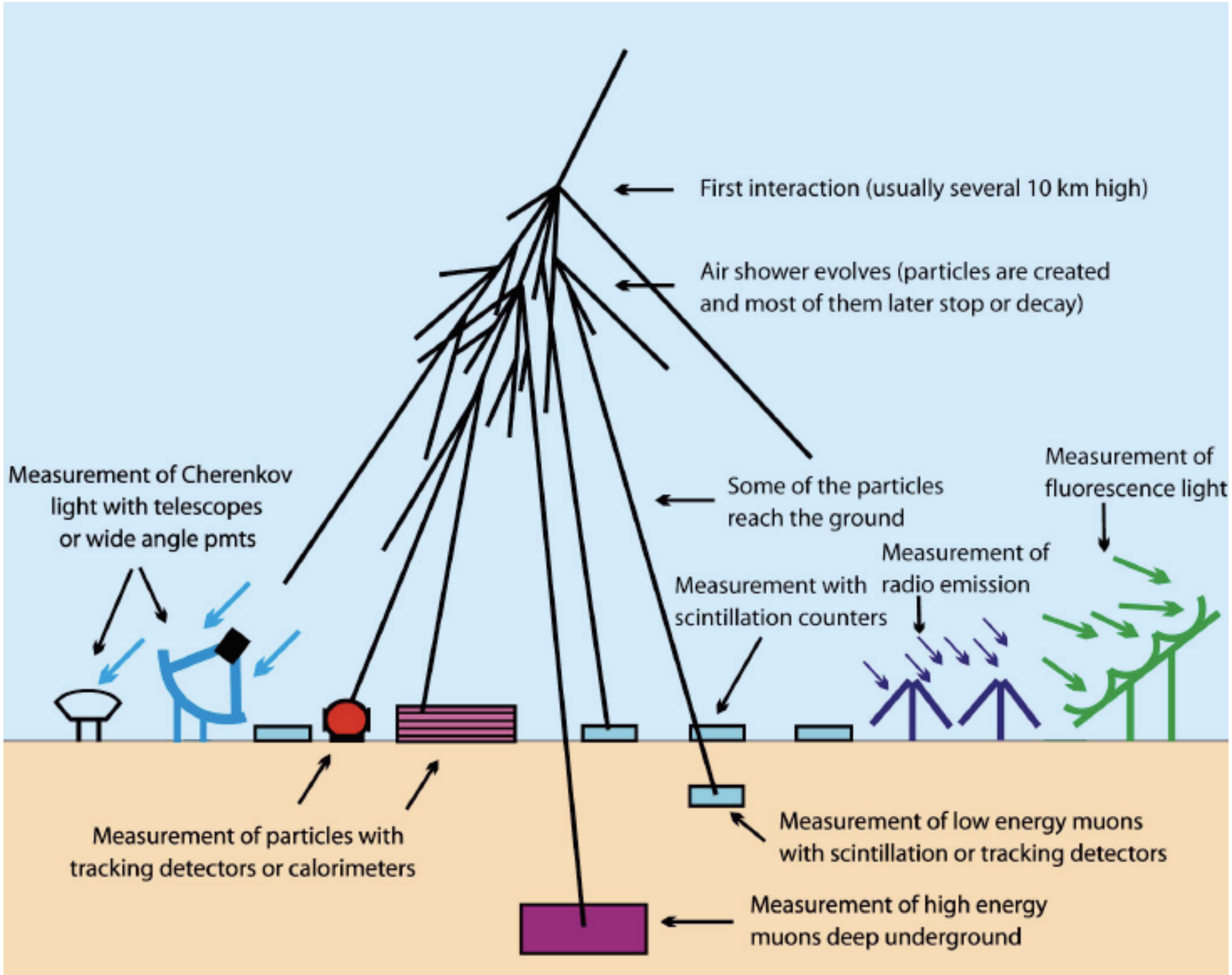
Satellite-based CR telescopes



Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) ,2006



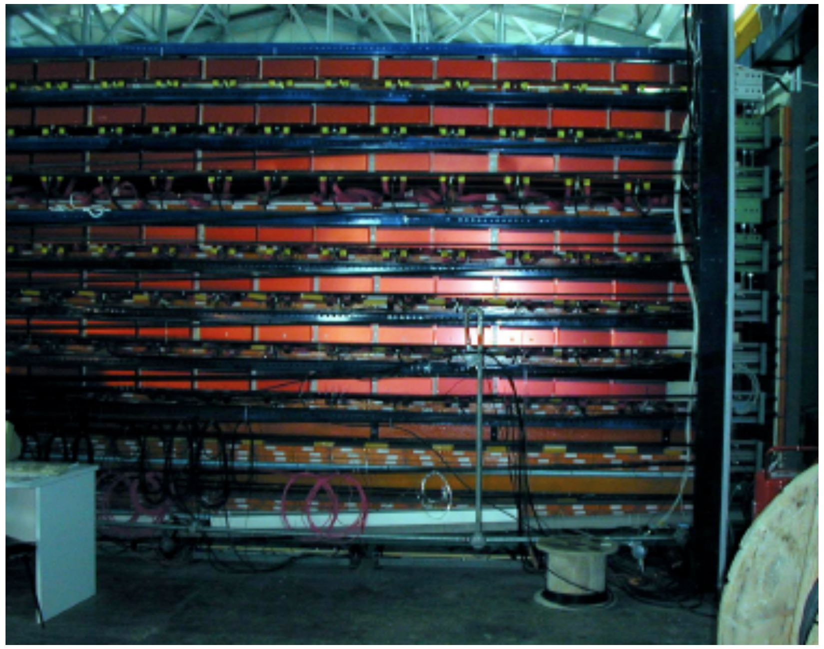
Alpha Magnetic Spectometer (AMS-02) International Space Station, 2011


First interaction (usually several 10 km high)
Air shower evolves (particles are created and most of them later stop or decay)
Measurement of Cherenkov light with telescopes or wide angle pmts
Some of the particles reach the ground
Measurement of fluorescence light
Measurement of radio emission
Measurement with scintillation counters
Measurement of particles with tracking detectors or calorimeters
Measurement of low energy muons with scintillation or tracking detectors
Measurement of high energy muons deep underground

ionization (resistive plate chambers) for electrons/photons and muons

scintillators + PMTs for electrons/ photons and muons

cherenkov detectors (in water) for electrons/photons and muons

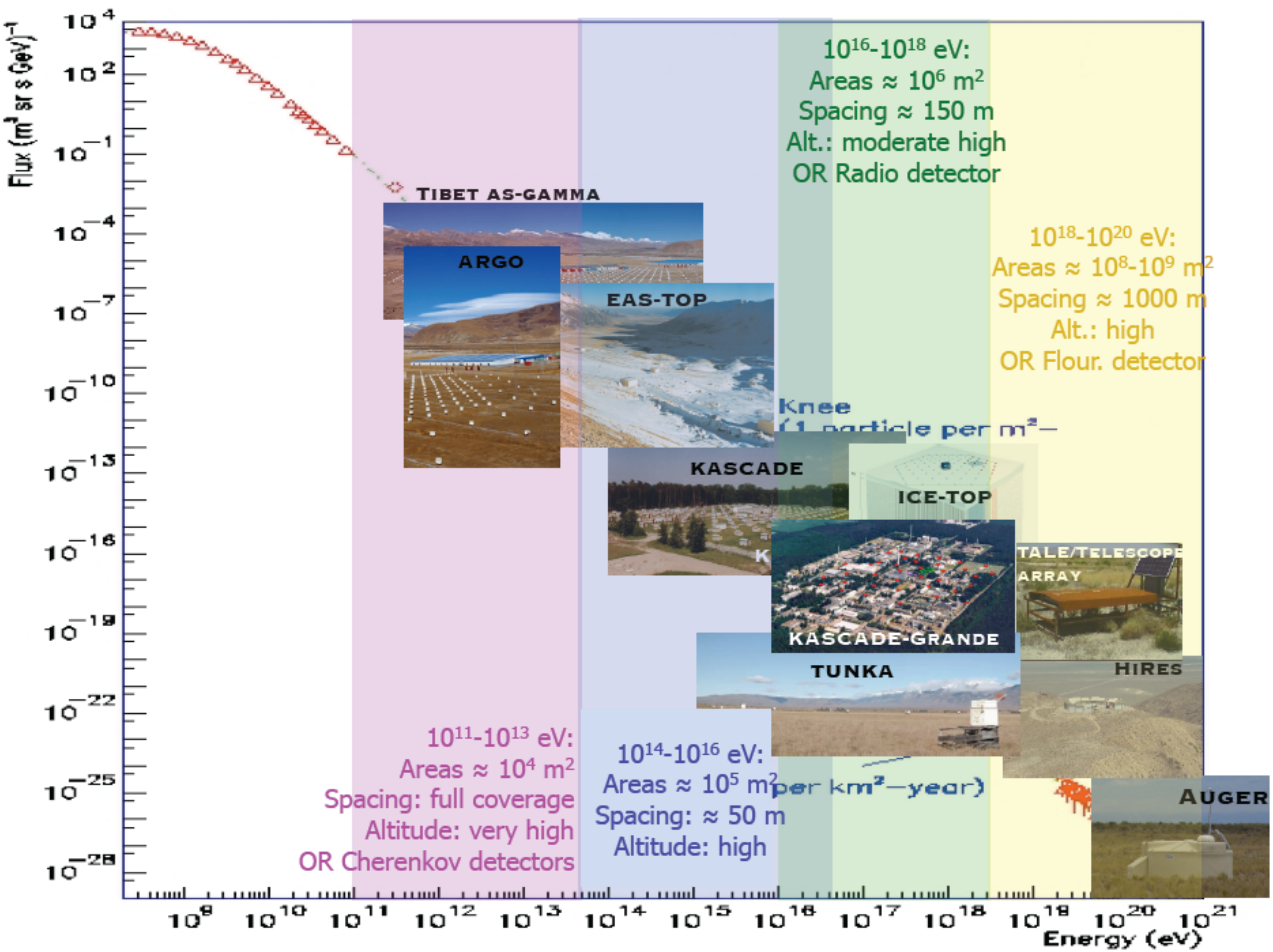


calorimeters for muons and hadrons

different EAS detectors depending on the energy of interest

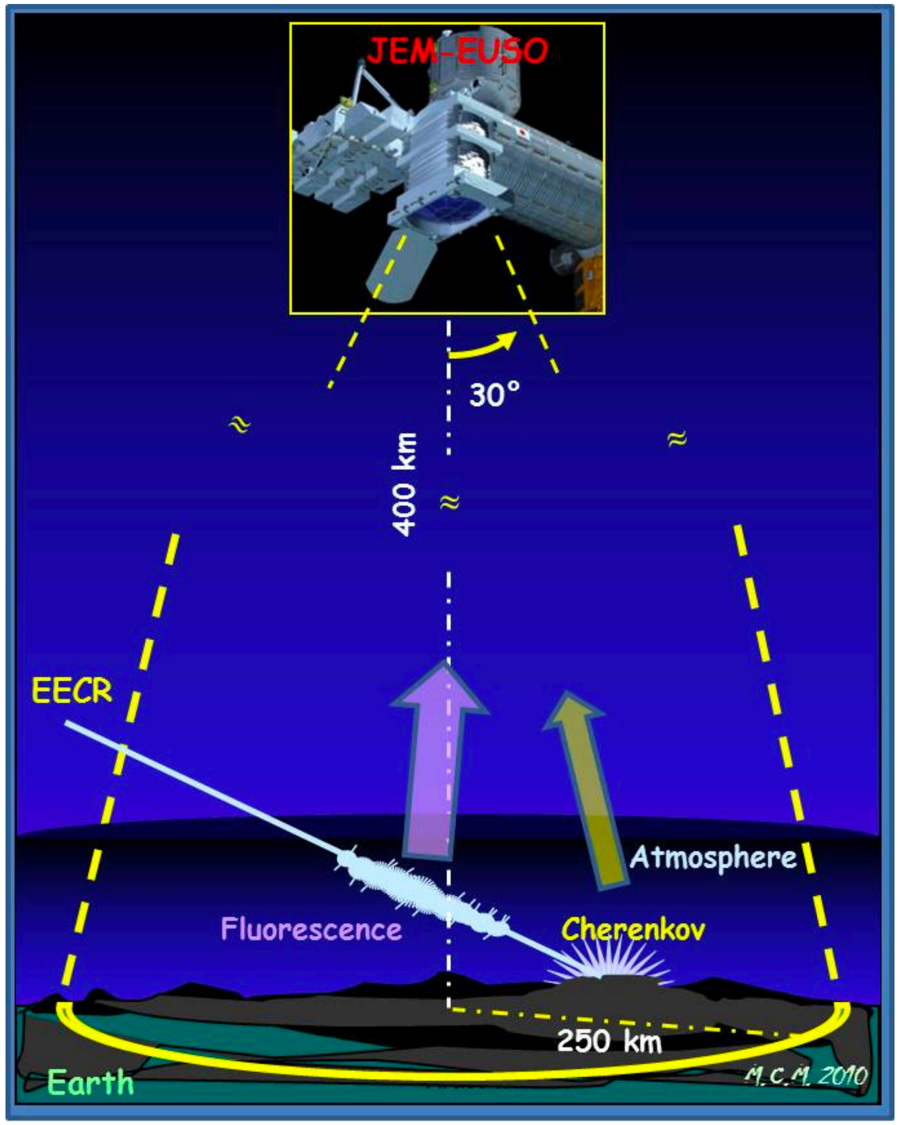
Choice of detectors spacing and array altitude impacts on energy threshold
Total area of the array limits the maximum energy

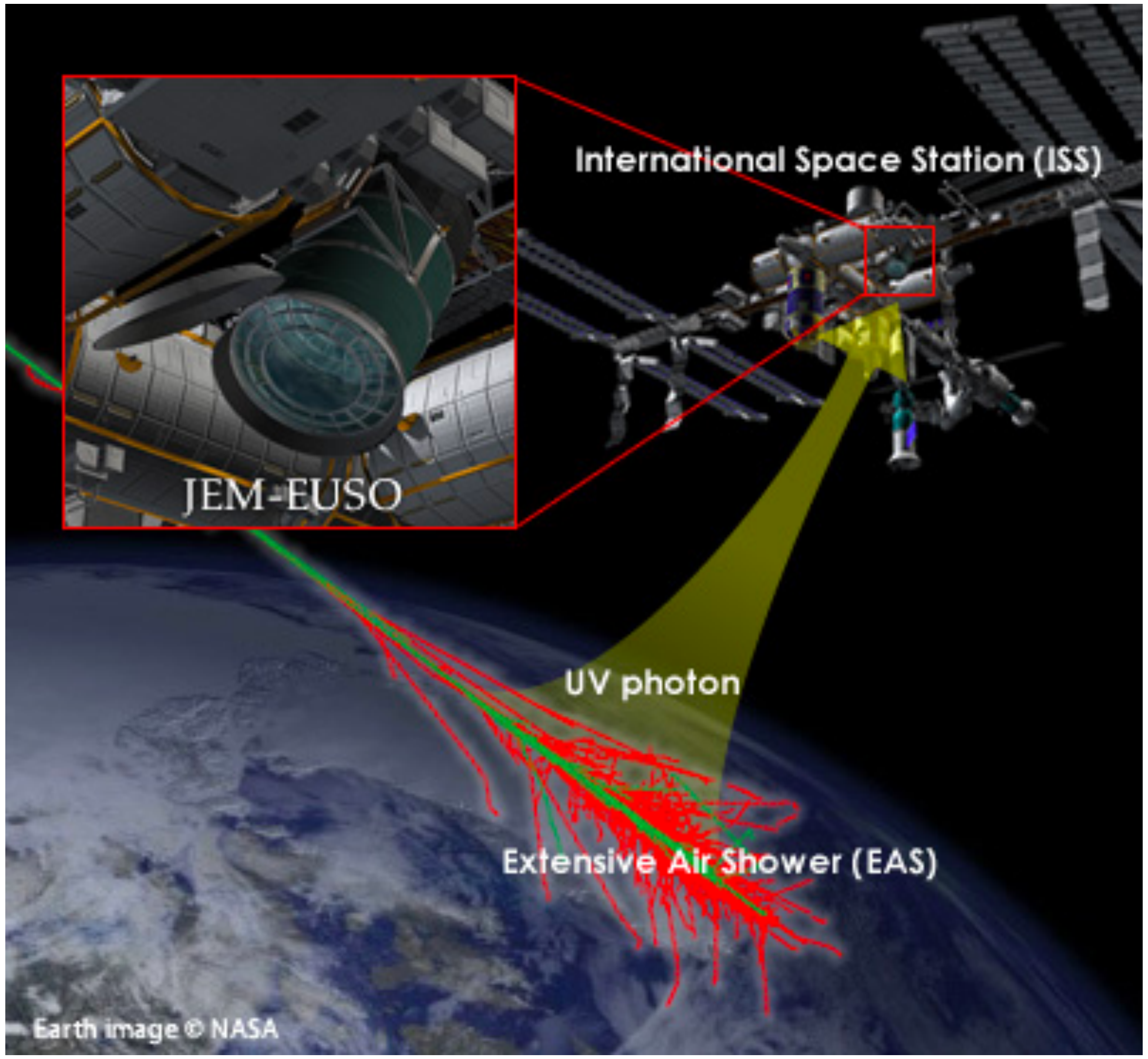
- **At 10^{11}-10^{13} eV** (superposition with direct measurements): air showers are re-absorbed high in the atmosphere. Very high altitude needed. Showers are “small”: small spacing needed or full ground coverage. High fluxes: “small” areas sufficient
- **At 10^{14}-10^{16} eV**: Shower maximum still high in the atmosphere: moderate mountain altitude needed. Moderate detector spacing needed (<100 m). Rather low fluxes: moderately large areas needed (0.1 km^2)
- **At 10^{17}-10^{18} eV**: Shower maximum deeper in atmosphere: sea level enough. Low fluxes: areas ≈ 1 km^2 needed (detector spacing ≈ 150 m)
- **Above 10^{18} eV**: Extremely low fluxes: huge area needed (≈1000 km^2). Giant showers: spacing ≈ 1000 m adequate



Flux (m² sr s GeV)⁻¹
Energy (eV)
TIBET AS-GAMMA
ARGO
EAS-TOP
KASCADE
ICE-TOP
KASCADE-GRANDE
TUNKA
TALE/TELESCOPE ARRAY
HIRES
AUGER
Knee
10^{16}-10^{18} eV:
Areas ≈ 10^6 m²
Spacing ≈ 150 m
Alt.: moderate high
OR Radio detector
10^{18}-10^{20} eV:
Areas ≈ 10^8-10^9 m²
Spacing ≈ 1000 m
Alt.: high
OR Flour. detector
10^{11}-10^{13} eV:
Areas ≈ 10^4 m²
Spacing: full coverage
Altitude: very high
OR Cherenkov detectors
10^{14}-10^{16} eV:
Areas ≈ 10^5 m²
Spacing: ≈ 50 m
Altitude: high
per km²–year)

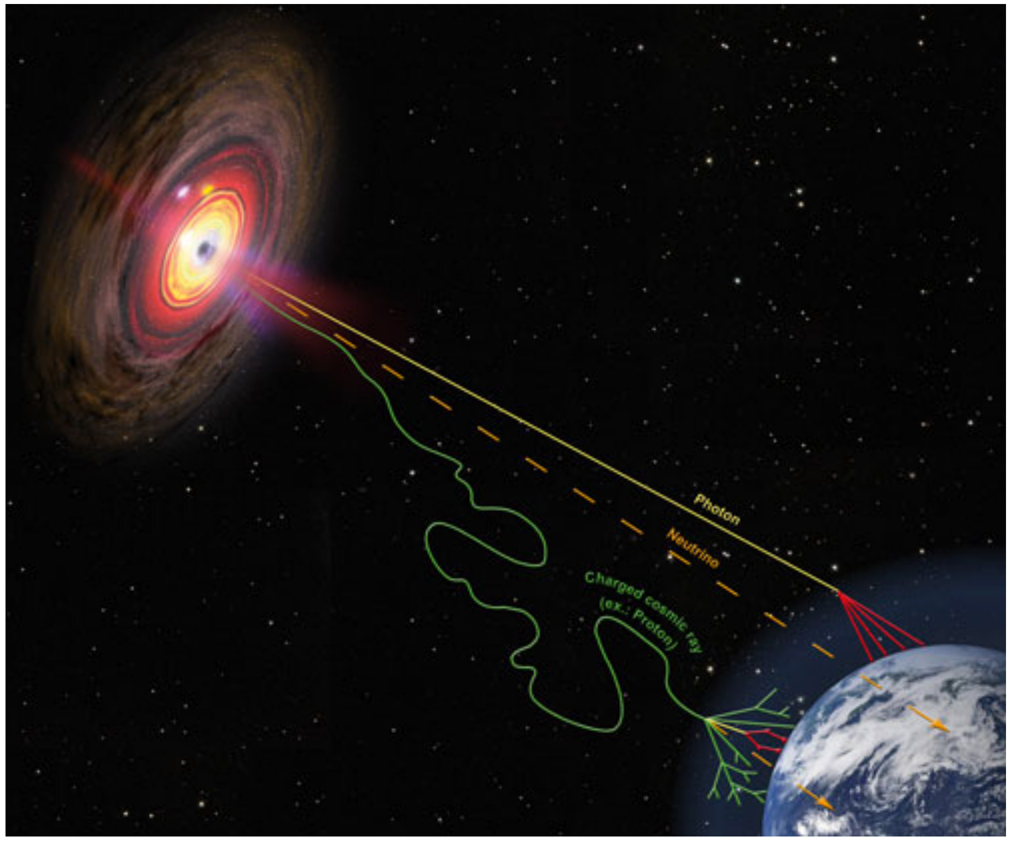
JEM-EUSO: indirect detection of EAS… from space





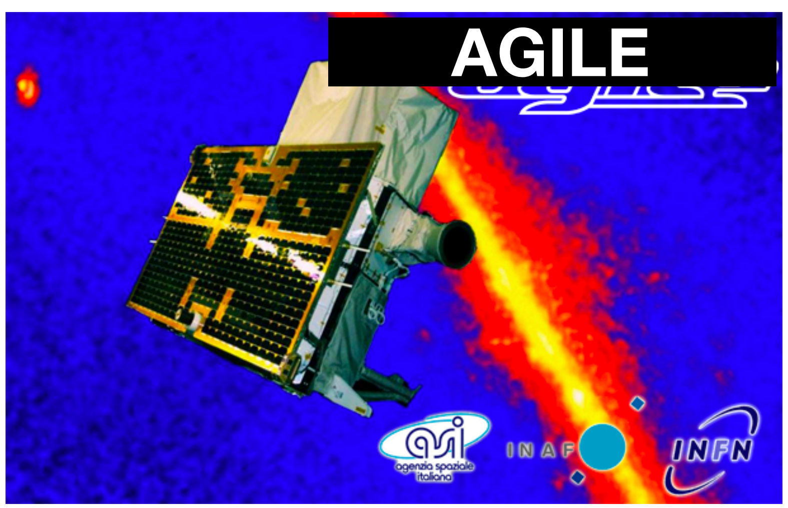
Gamma-ray and Neutrino Astronomy

- a **small fraction** (< 0.1%) of CRs are in the form of **gamma-ray photons and neutrinos**
- some of these photons/neutrinos can be produced **directly at the source** as a consequence of hadronic interactions of CRs with the Interstellar Medium or dense **Molecular Clouds**
- Gamma-ray and neutrino emission are expected following neutral-pion decay of *pp* collisions, and are **not deflected as particle CRs**

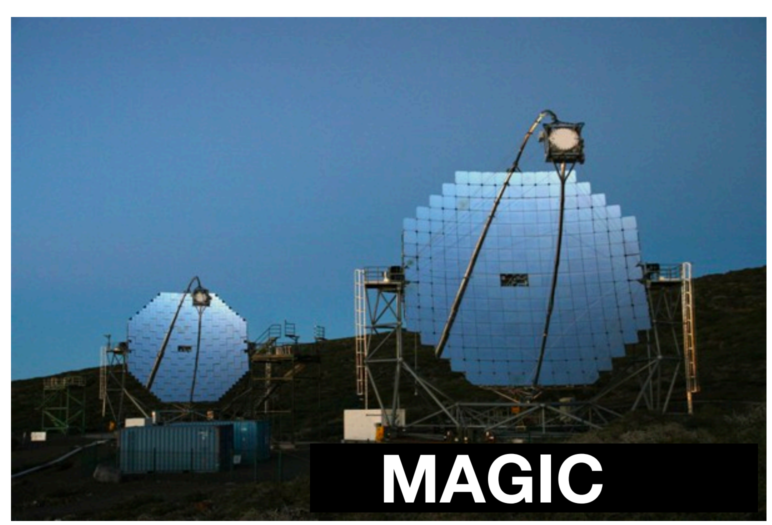


Indirect Detection of Cosmic Rays

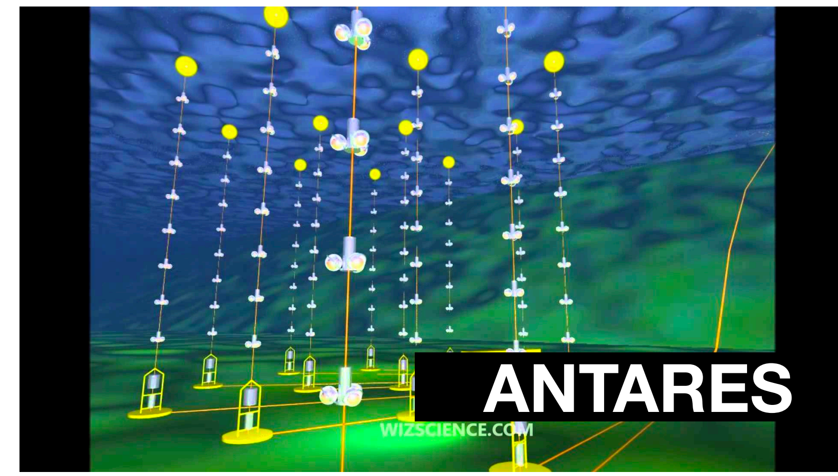
Gamma-ray satellites

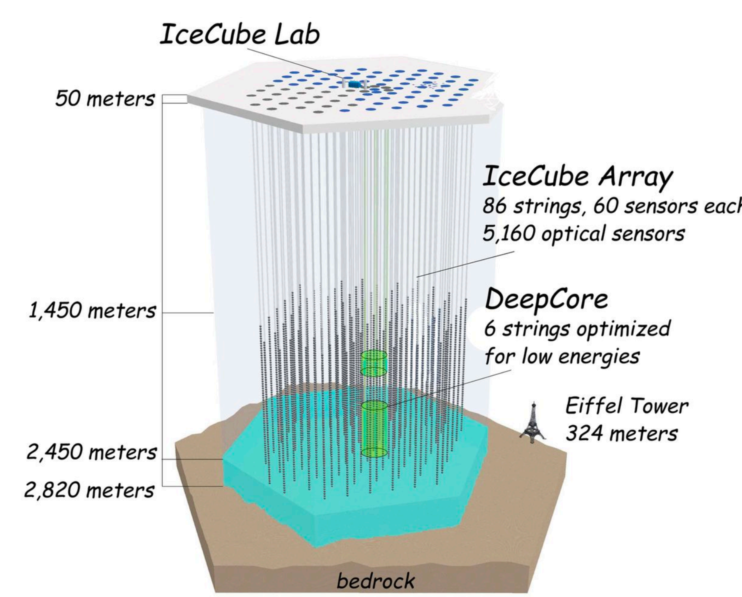


Gamma-ray IACTs



neutrino telescopes



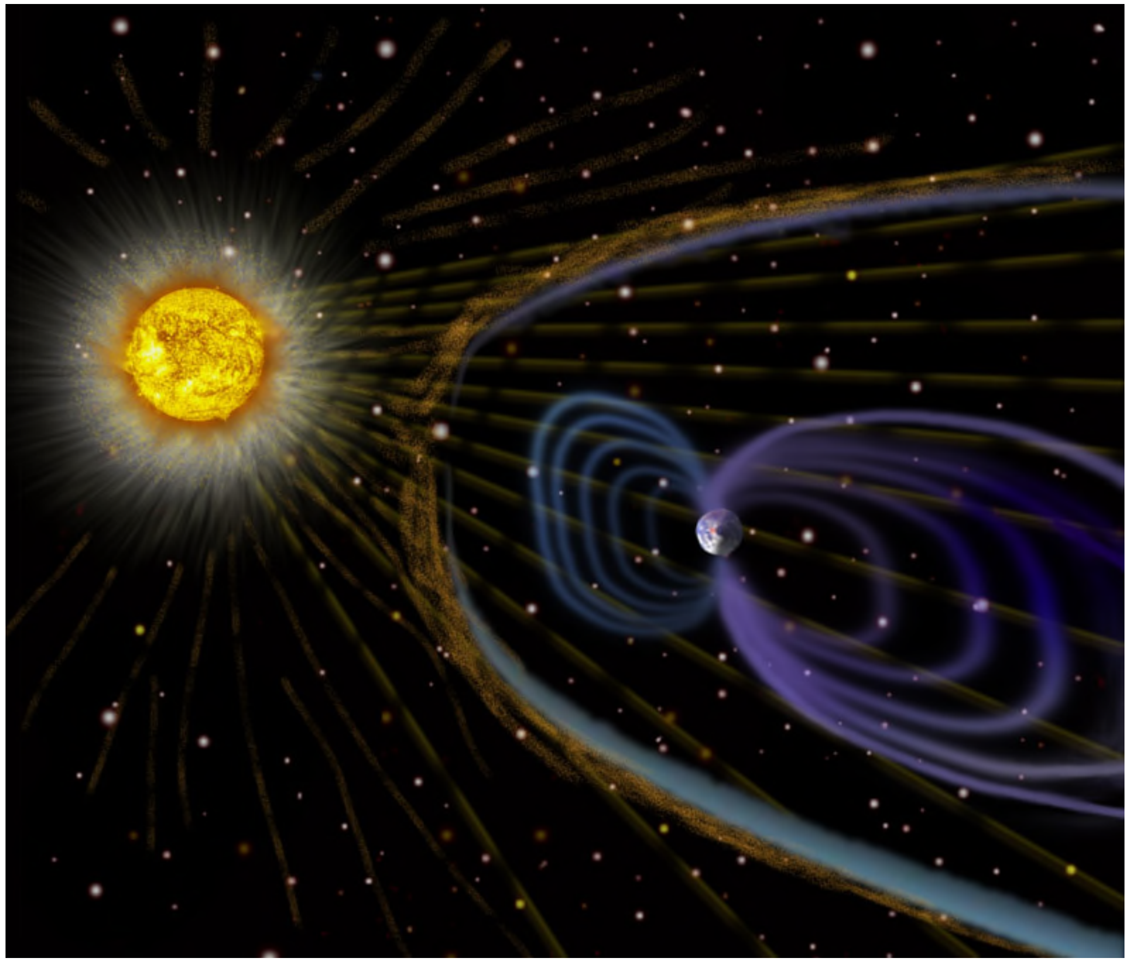


IceCube

4 - sources of Cosmic Rays

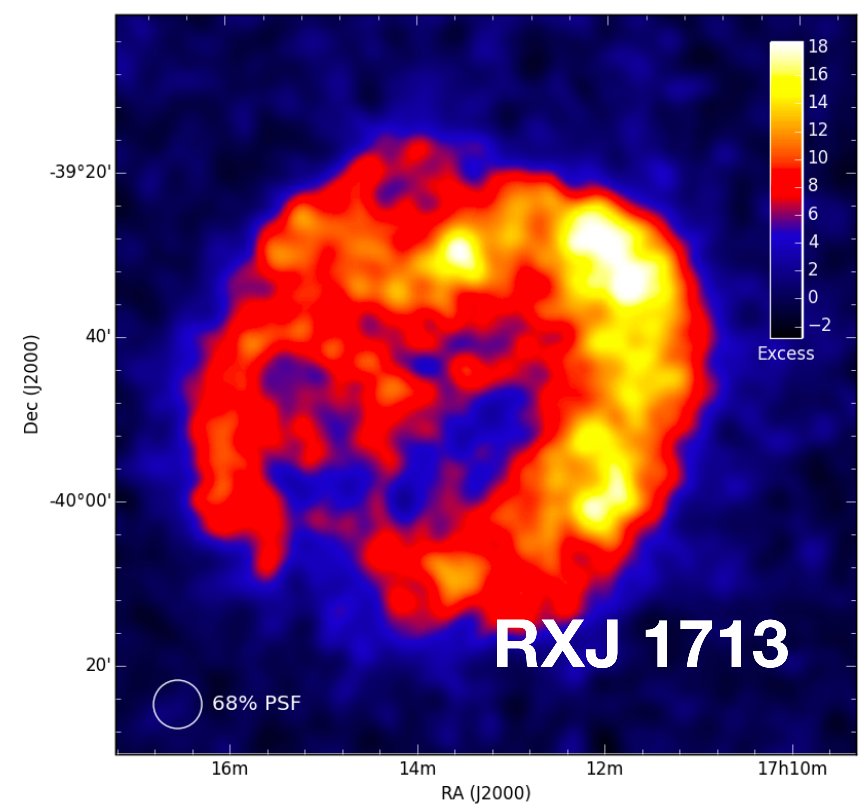
Low-Energy Cosmic Rays: Sola Wind

- The sun produces a constant stream of particles (mostly electrons and protons) called the **solar wind**
- Solar wind **shapes the Earth's magnetosphere**, and magnetic storms are produced.
- particles are deflected, some are trapped in the **Van Allen belts**, others are channeled to the poles, spiralling around the B-field lines and causing the **auroras**
- flux of solar CR is modulated with the **solar cycle every ~11 years**
- can have **effects on Earth climate**, as th egeneration of aerosols and hence cloud formation seem to be correlated with solar cycle



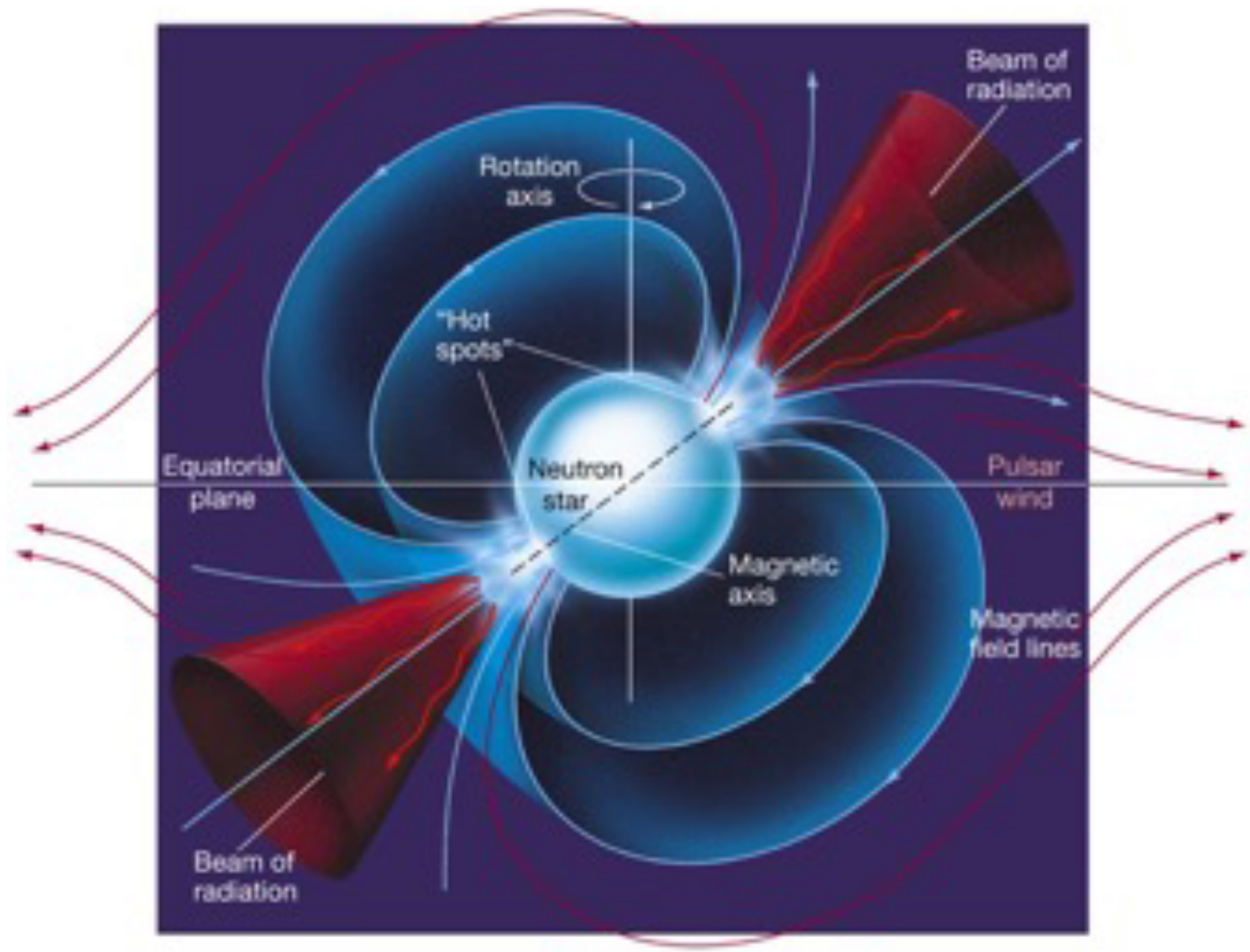
Supernovae

- **massive stars** end their life when they run out of the energy produced in nuclear fusion and **explode**
- in this **supernova explosion** the outer layers of the star are ejected at nearly relativistic speed
- it is believed that **most Galactic CRs are produced in SNe explosions**, occurring every ~50y in our Galaxy
- to sustain the observed intensity of CRs at the Earth it requires that **a few percent of the kinetic energy** released in a SN explosion, ~10^{51} erg, is converted to CRs
- however, theory predicts that SNe can accelerate CRs **up to "only" 10^{14}-10^{15} eV**



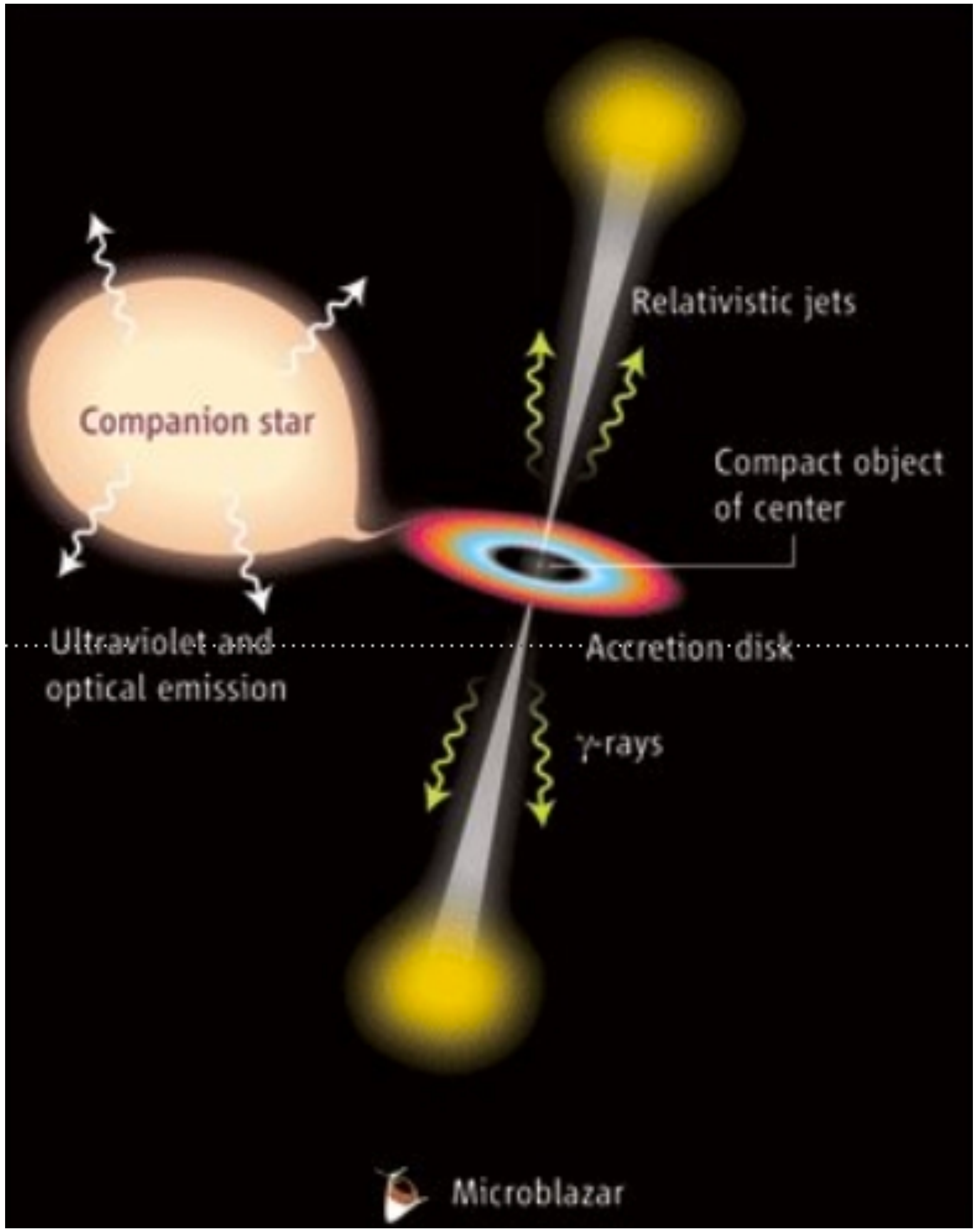
Pulsars

- pulsars **are rapidly rotating, highly magnetized neutron stars**
- pulsations are observed when emission beamed along the magnetic poles **point towards the observer**
- particles are **efficiently accelerated** in the strong electric/magnetic field close to the NS
- electrons and positrons, and perhaps protons and ions from the NS surface **can be ejected at relativistic energies**
- it is however unclear whether particle losses **may prevent reaching relatively high energies** - enough to explain CRs at E > 10^{15} eV



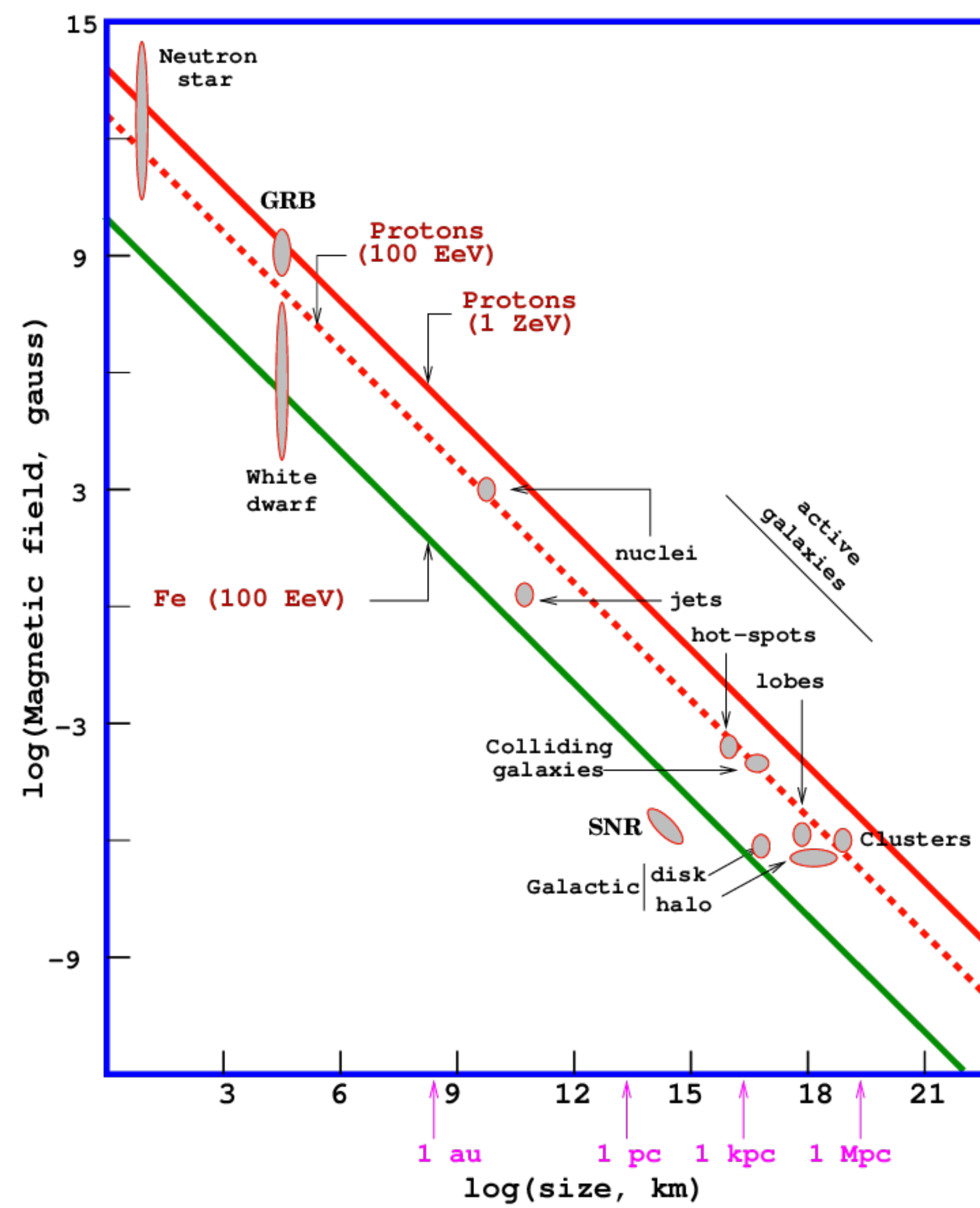
Galactic Black Holes

- stellar-mass black holes are **compact objects produced as a result of a supernova explosion** of a very massive star
- black holes **accrete matter** from the surroundings. If found in a binary system, they are fed by the companion's star wind.
- accretion onto a black hole produce **relativistic jets**, energetic beams of highly relativistic material
- the **composition** of jets in black-hole binary systems is **still unknown**, although in some cases baryons have been directly imaged through spectroscopic observations



Ultra-High-Energy Cosmic Rays

- CRs with energies $>10^{18}$ eV **cannot be "confined" by Galactic magnetic fields.**
- **particle acceleration** mechanisms thought to occur in SNe and other Galactic accelerators cannot attain such high energies
- **UHCRs cannot come from too large distances**, as they would interact with the CMB radiation (**CZK effect**) => limit of ~50 Mpc
- **origin still unknown**. Possible candidates include, colliding galaxies, giant BH spinning rapidly, sources of gamma-ray bursts (GRB), neutron star merging… something else we haven't thought about yet



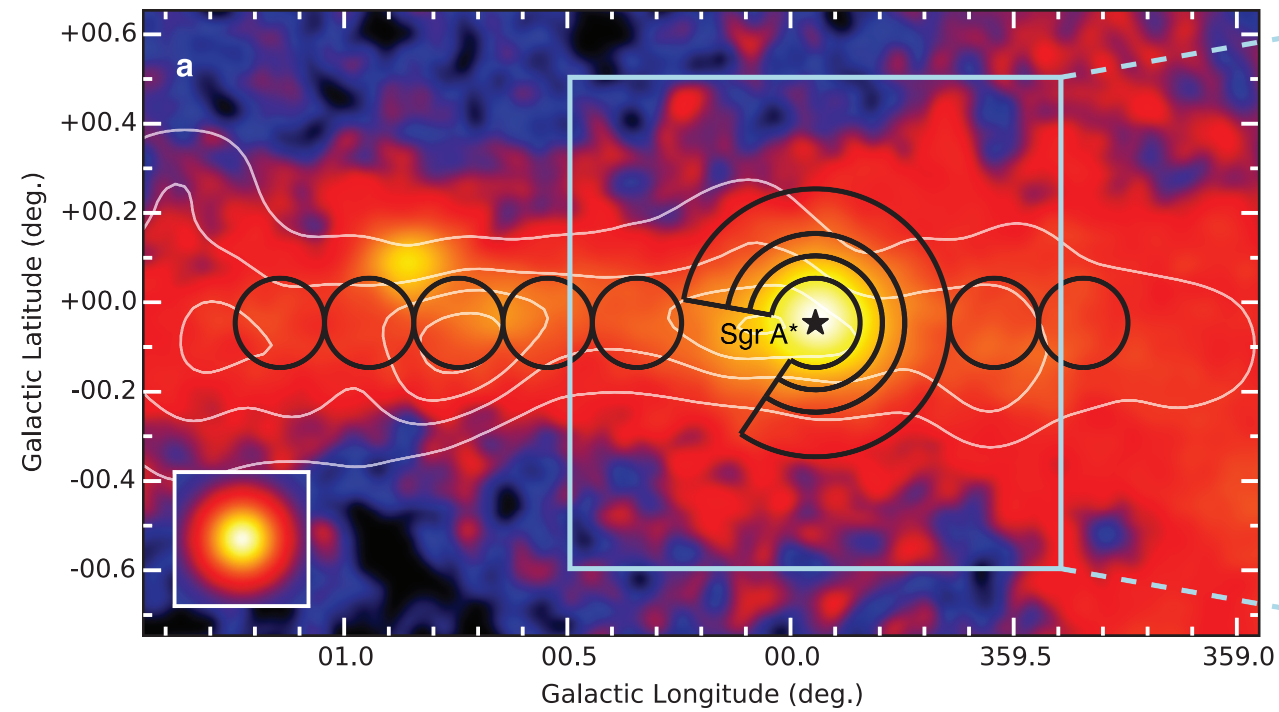
Hillas plot:

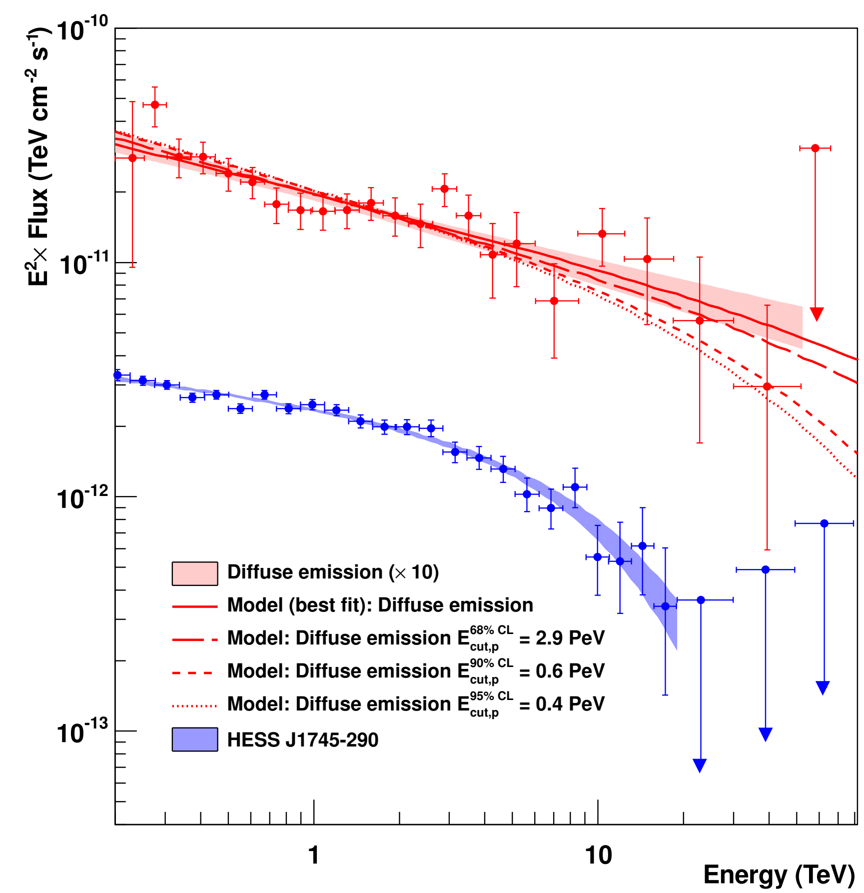
$$E_{\max} = 10^{18}\, Z \left(\frac{R}{kpc}\right)\left(\frac{B}{\mu G}\right)\ \mathrm{eV}$$

5 - some exciting news…

A *pevatron* at the Galactic Center

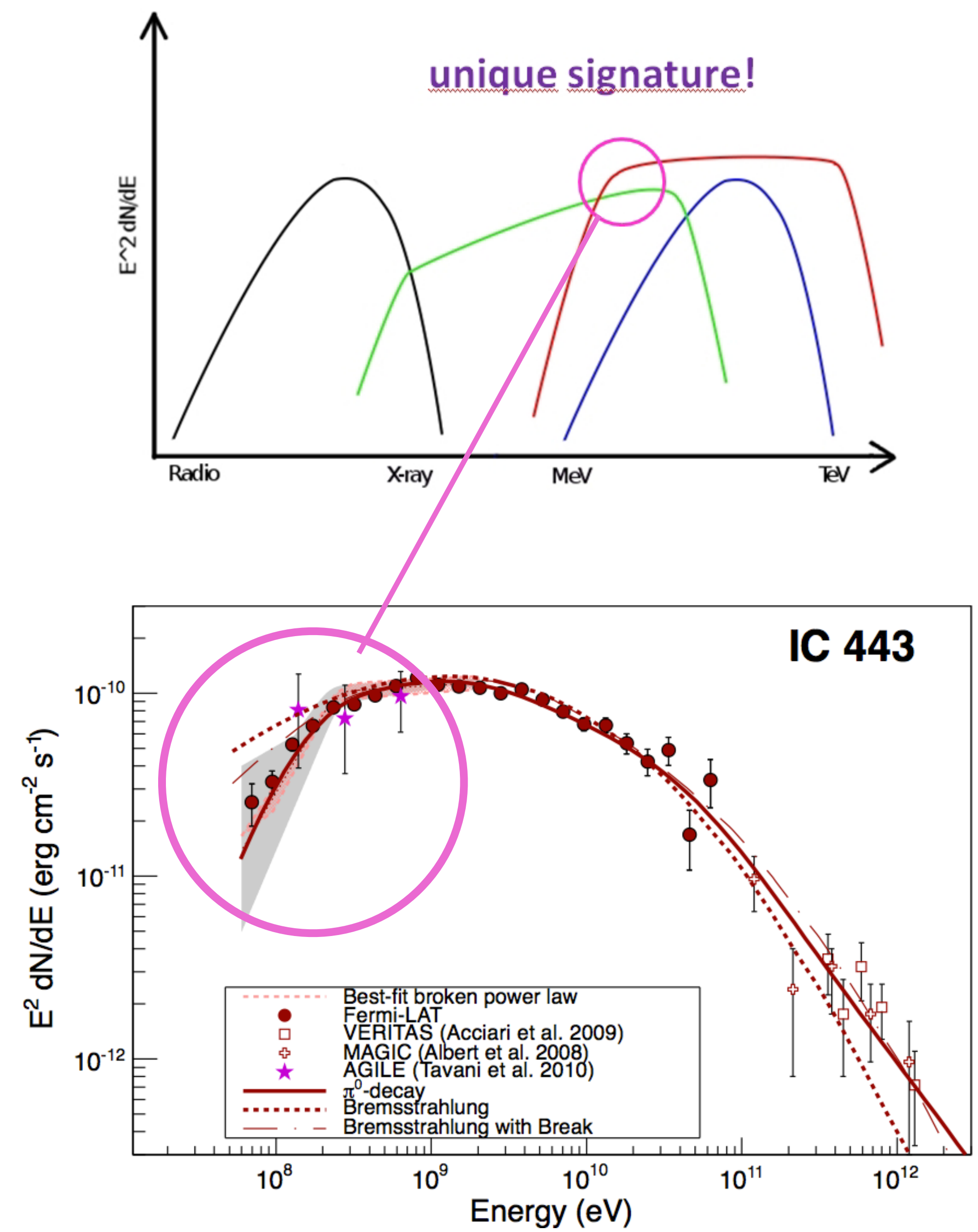
- **supermassive** (>10^6 solar mass) **black holes** are thought to be present at the center of all galaxies
- some of them show high levels of non-thermal emission (Active Galactic Nuclei, **AGN**)
- other are "quiet", although they may have been active in the past
- our own Galaxy **contains a black hola at its center** (non-active)
- gamma-ray emission from the GC and surrounding regions with H.E.S.S. suggests that the GC may be able to accelerate particles up to at least 10^{15} eV => a ***pevatron***





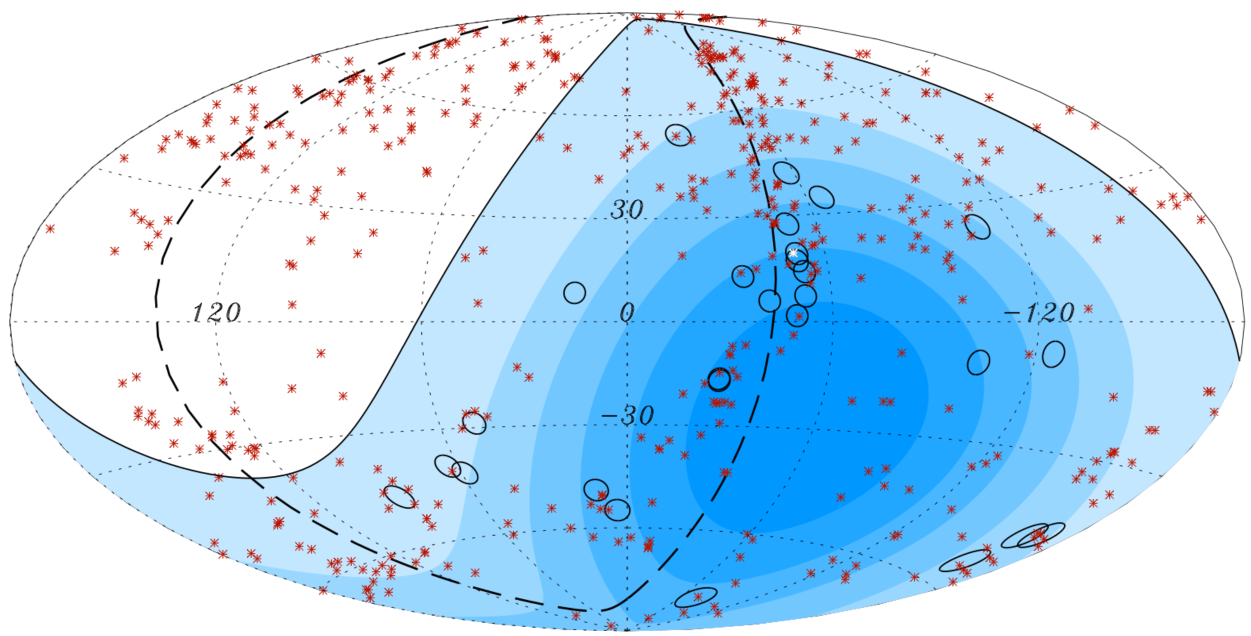
A Smoking Gun from SNR at HE gamma-rays

- SNRs are sites of cosmic ray acceleration, **supported by energy arguments** and the detection of non-thermal emission (X-rays) and gamma-ray fluxes (HE and VHEs)
- in hadronic scenarios, relativistic protons can inter**act with nearby molecular clouds** producing gamma-rays through π^0-decay
- **spectral signatures** should distinguish between hadronic scenarios and leptonic emission (gamma-rays produced by inverse Compton processes)
- 4 SNR/MC have been recently found to display such spectral signatures, **supporting that CR protons are indeed accelerated in these sources**



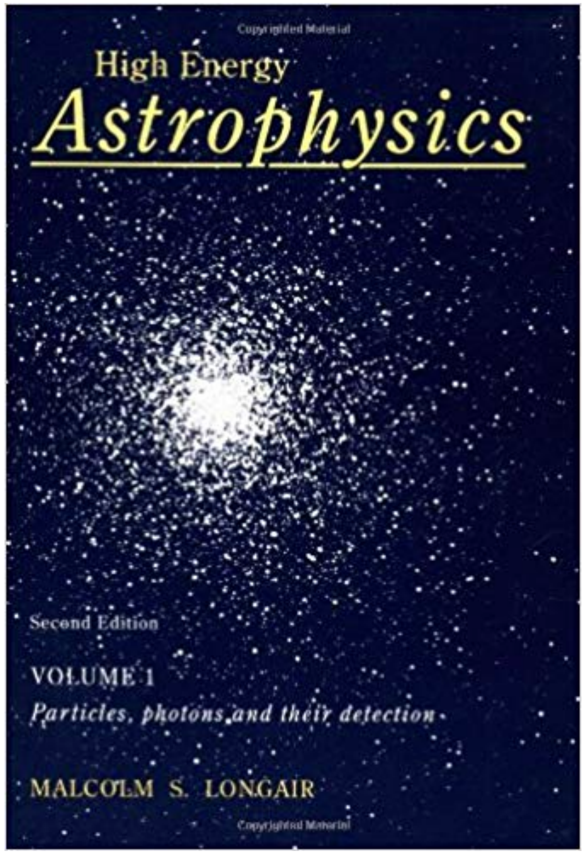
Anisotropic Distribution of UHECRs

- the Pierre Auger Observatory has been collecting data since 2004. **Latest results seem to indicate a correlation of the UHECRs with the location of catalogued AGNs**
- correlation is only looked at for sources within < 200 Mpc (**GZK effect**)
- anisotropy: either **self-clustering** of events from individual point-sources or as **correlation with known astronomical objects**
- quantitatively: probability P for a set of N events from an isotropic flux to contain k or more events at a maximum angular distance from any member of a collection of candidate sources



Arrival directions of UHECRs measured with Pierre Auger Obs. For $E > 57\times10^{18}$ eV, D_{max} = 75 Mpc, $\Psi = 3.1^{o}$, 8 out of 13 events correlate with AGN locations, implying $P < 1.7\times10^{-3}$ for these to occur by chance if flux is isotropic

References & further reading



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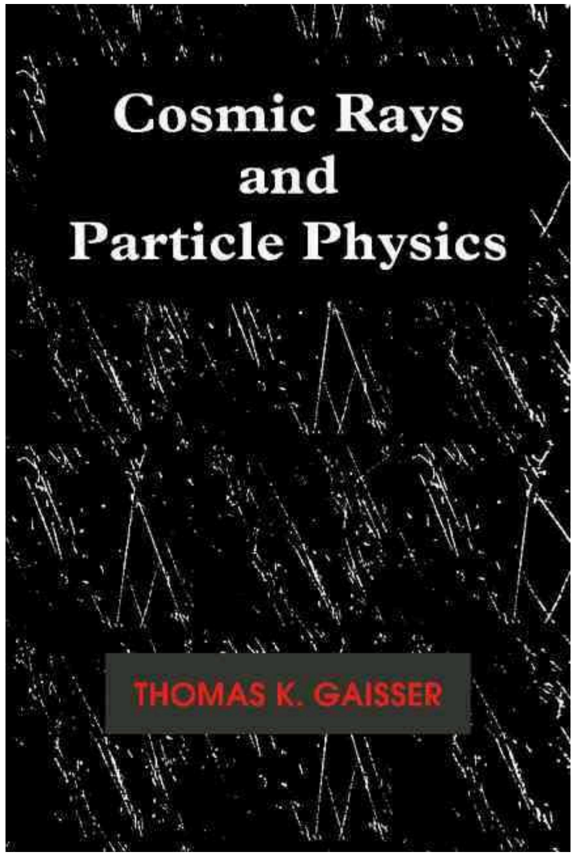

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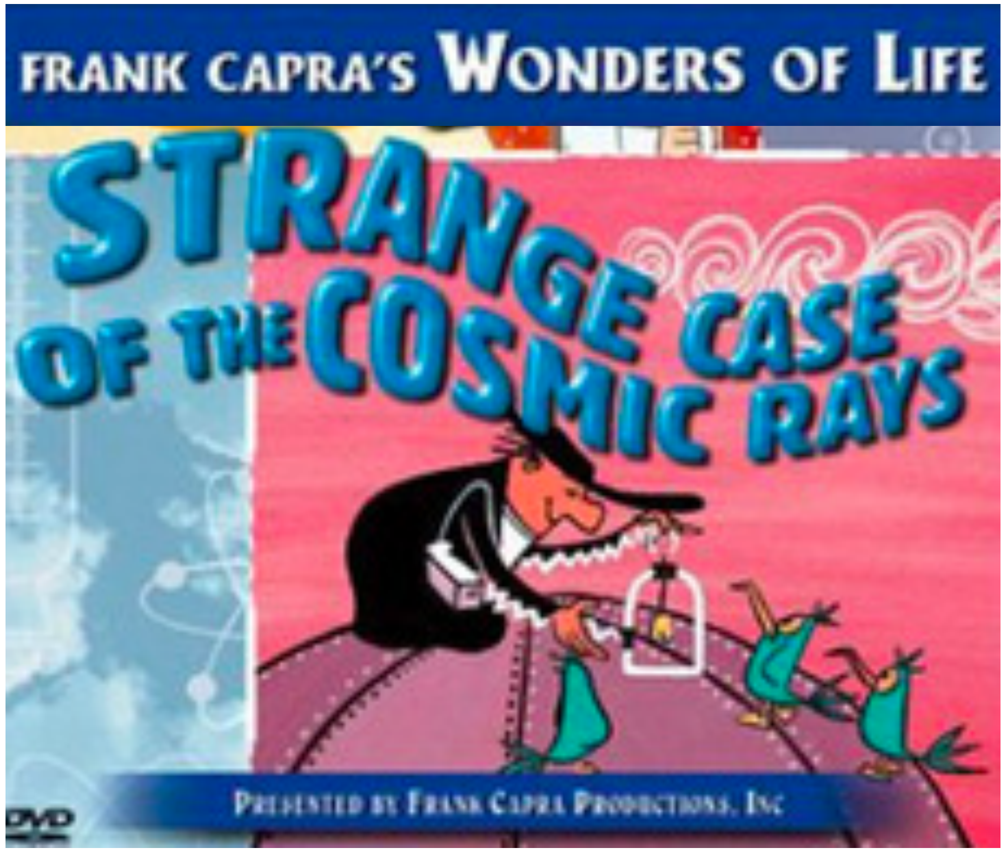

(F. Capra/W. Disney production,1957
movie written by Anderson & Rossi)

- **Piera L. Ghia** (LPNHE-CNRS, Paris), "*Cosmic Ray Detection*" International School on AstroParticle Physics, Paris 2012
- **Alessandro de Angelis** (INFN Univ. Udine), "*Spontaneous Ionization to Subatomic Physics: Victor Hess to Peter Higgs*", Spacepart CERN 2012

References & further reading

Fermi Proves Supernova Remnants Produce Cosmic Rays