Astrophysics and Nuclear Astrophysics

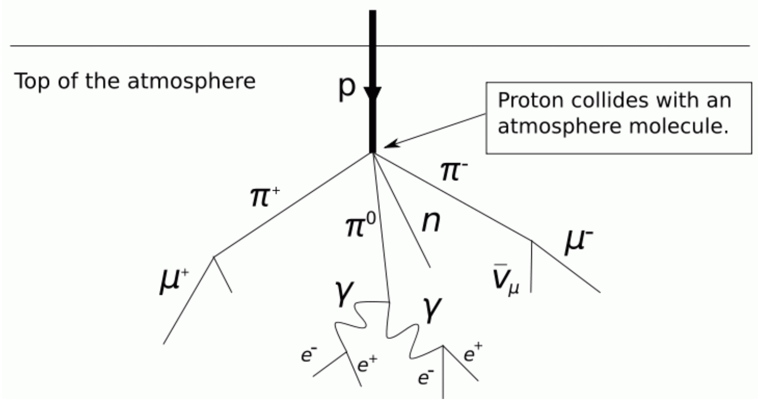
(LPHY2263)

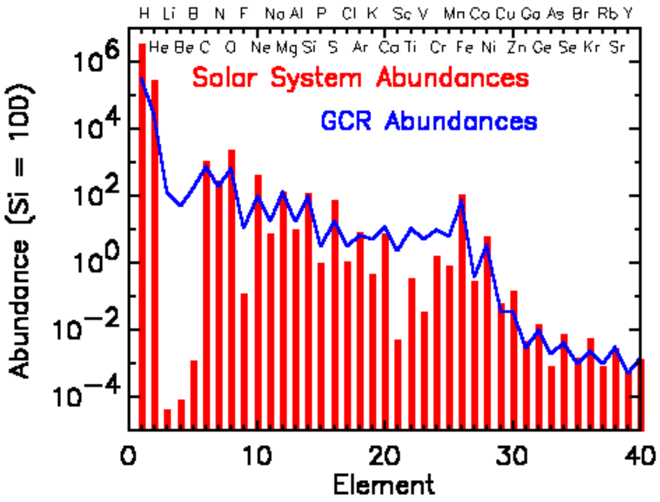
Andrea Giammanco, UCL

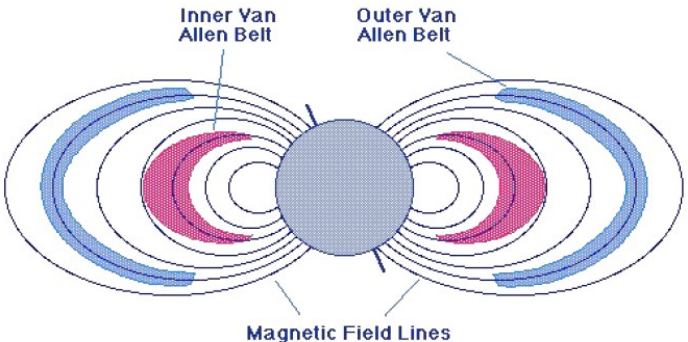
Academic Year 2015-2016

Chapter #6

- Cosmic rays
  - Discovery
  - Origin and spectrum
  - Detectors
    - Example: AMS experiment
  - Applications



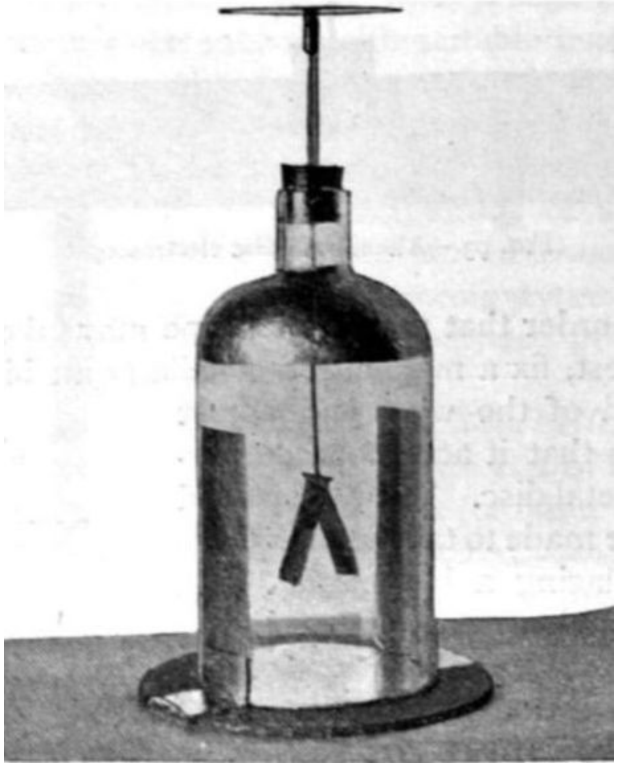


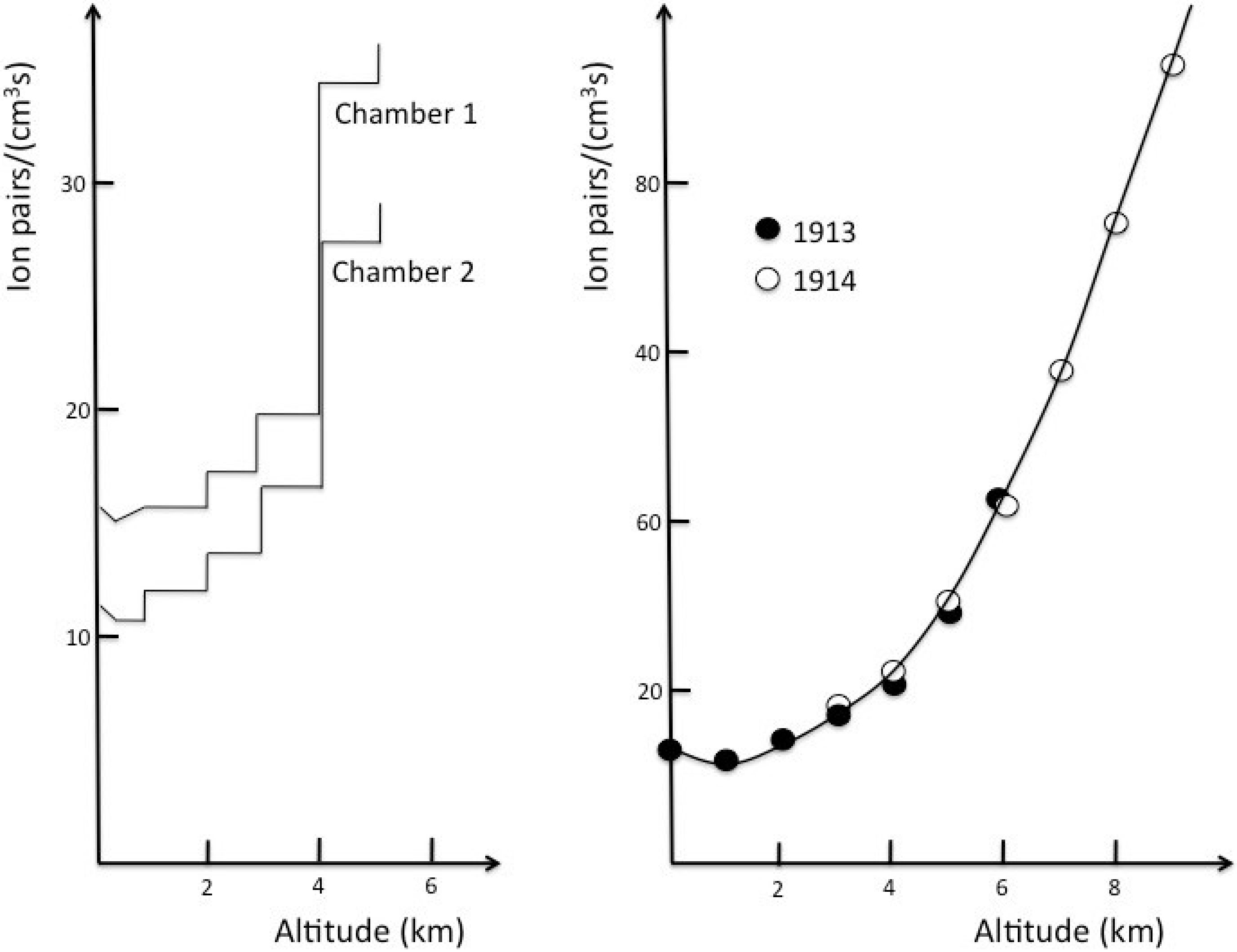


Discovery of cosmic rays

- Early 1900s: hypothised that there is a natural background of ionizing radiation that discharges all the electroscopes
- People believed it was mostly due to radioactive rocks
- 1909: Theodor Wulf uses Tour Eiffel to measure this background at different heights; surprisingly, he reported that it increases with the altitude, but measurements were not so precise and he was met with skepticism
- 1911-12: Victor Hess improved the instrument and used a balloon to study the phenomenon between 1000 and 5000 m over sea level

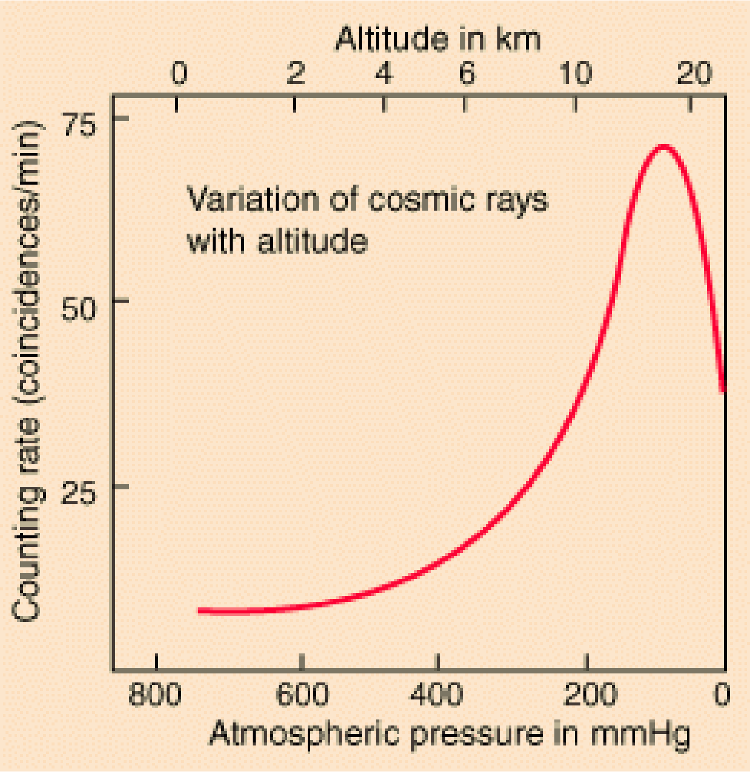
When the device is charged, the sheets move apart. Ionization of the gas leads to a discharge, and the sheets move towards each other.
Picture from here



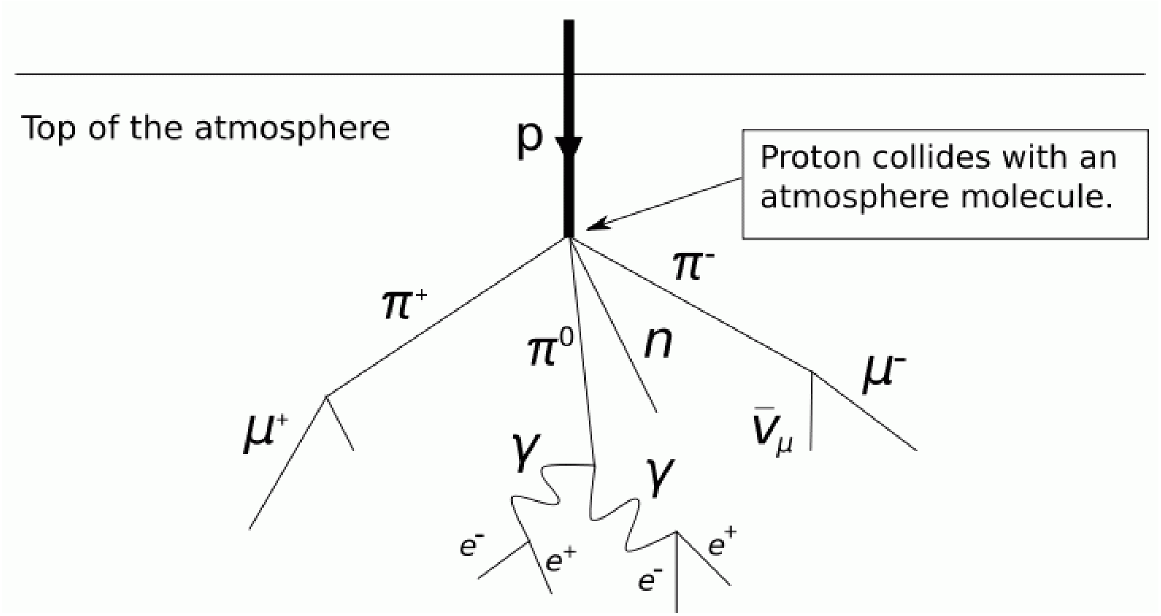


Increase of ionization with height as measured by Hess in 1912 and by Kolhörster in 1913 and 1914 (from wikipedia)

Primary and secondary cosmic rays



Picture from here



From wikipedia

The number of charged particles increases as the cascade progresses, but eventually most of them are absorbed

Primary cosmic rays

- Stable (>10^6 years) charged particles and nuclei
- Electrons: 2%
- The rest:
  - Protons: 87%
  - Alphas: 12%
  - Heavier nuclei (C,O,Fe, ...): 1%
- Also photons, neutrinos, antimatter

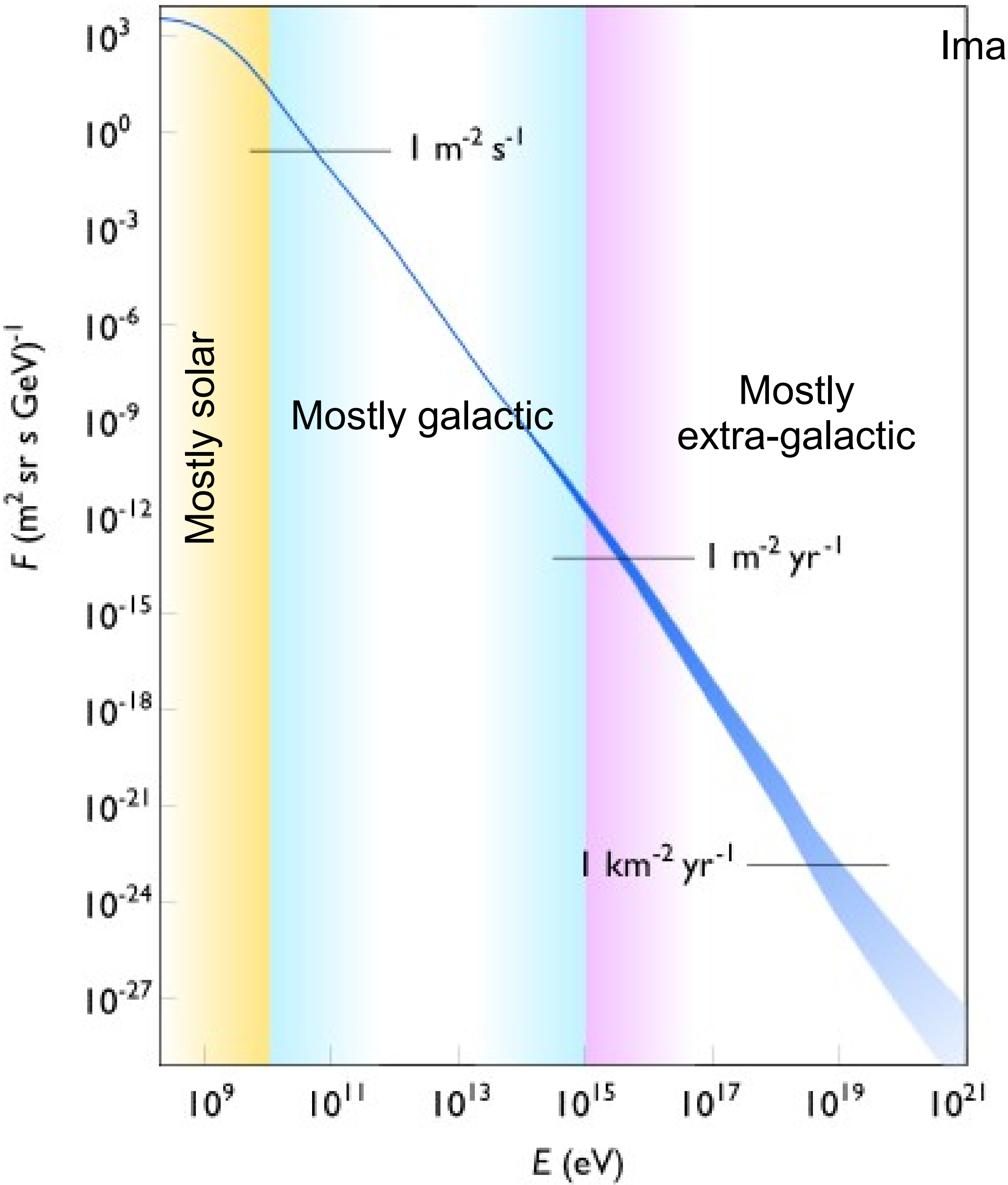


Image from wikipedia

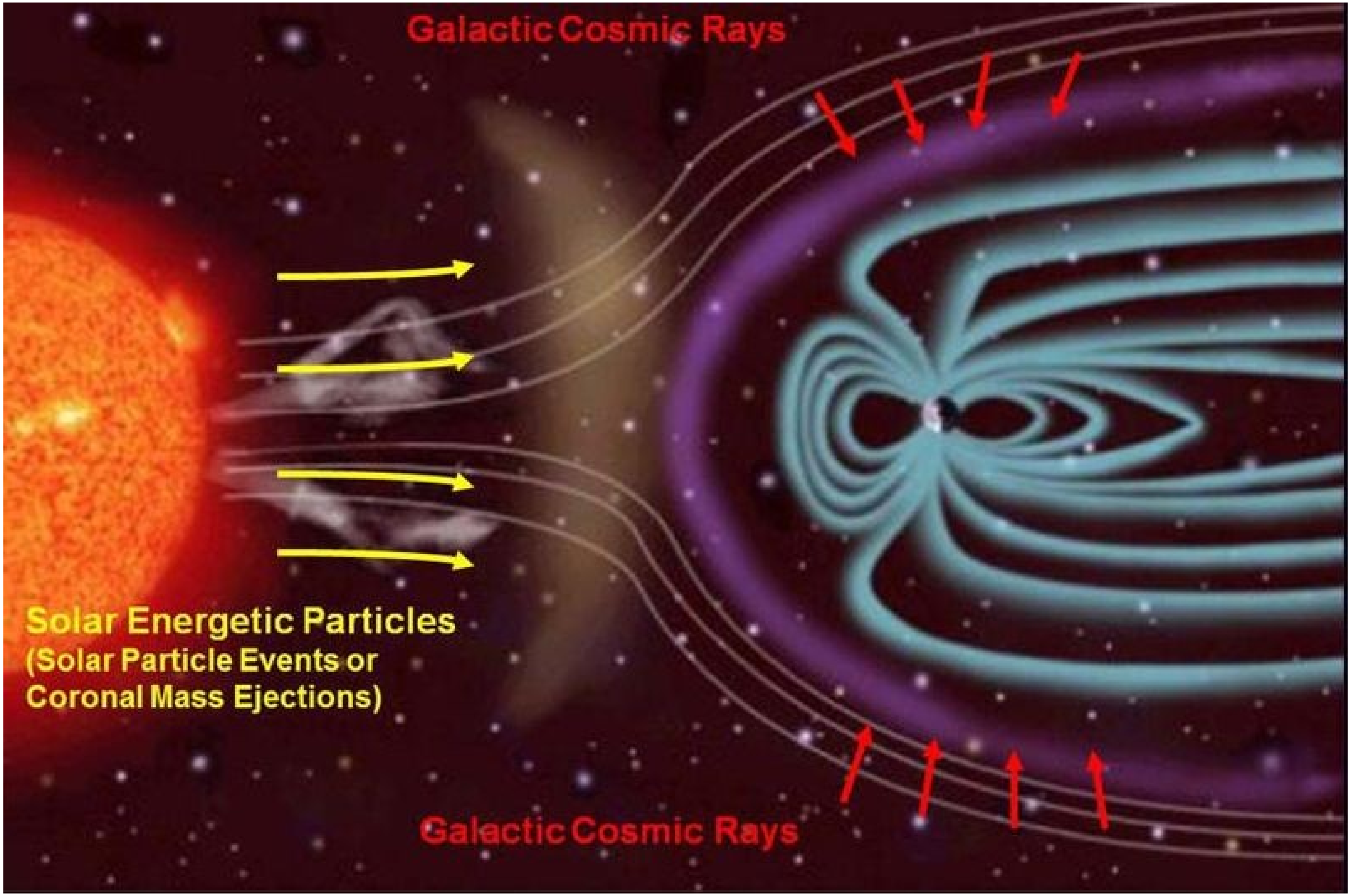
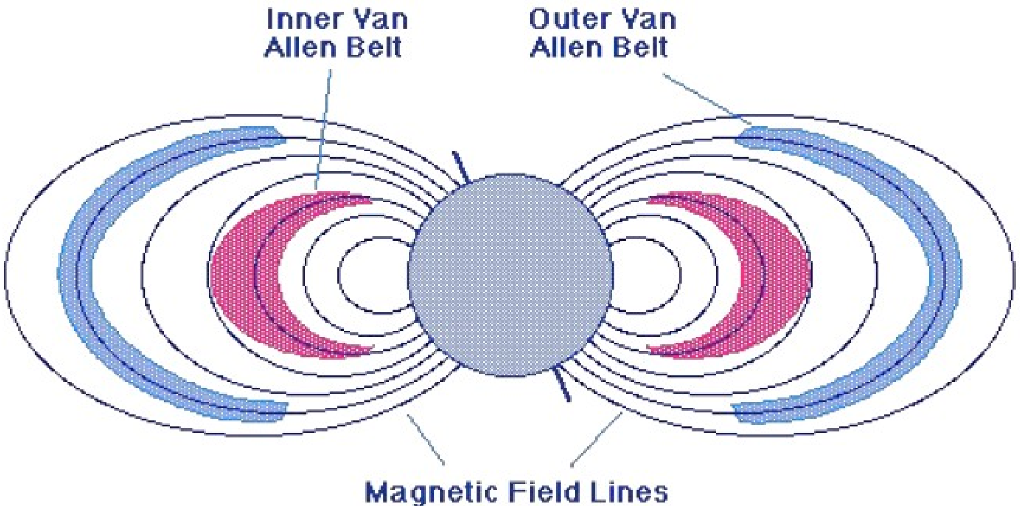


Image from wikipedia

Shielding by Earth's magnetic field

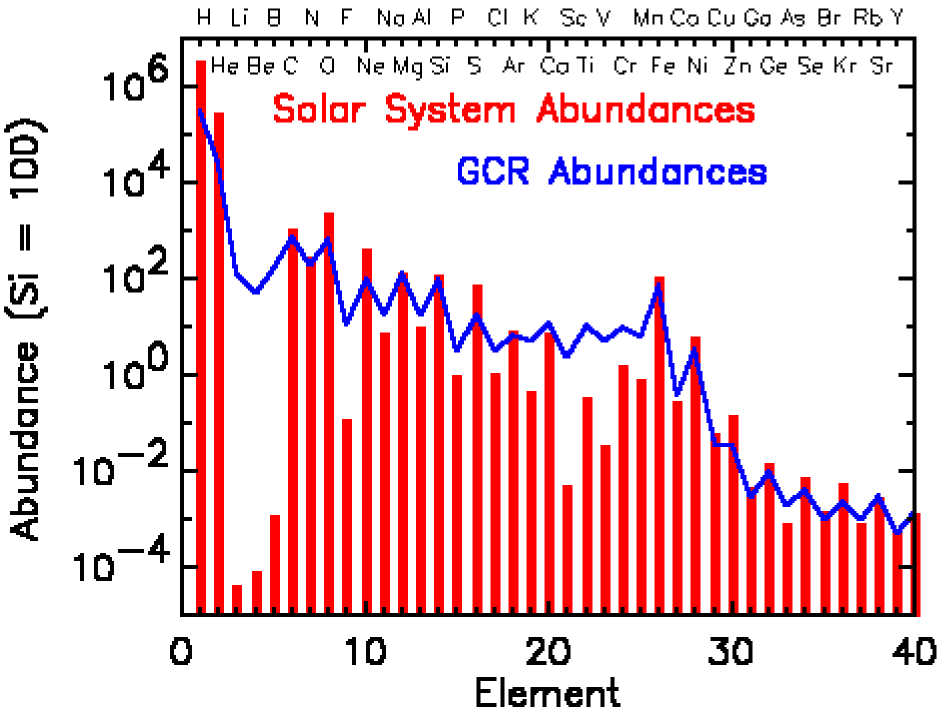
$$p_{\perp}(MeV/c) = 3 \times 10^{-4} BR(\text{gauss cm})$$

- Earth's magnetic field: B~0.3 Gauss
- For a trapping radius of O(1000 km) this formula gives O(10 GeV) as momentum of a trapped proton
- Below this momentum, it would not manage to penetrate towards the Earth but it would be deflected



For this reason many CR experiments are done with high-altitude balloons at the poles, where the magnetic field is less intense and is more perpendicular to the surface

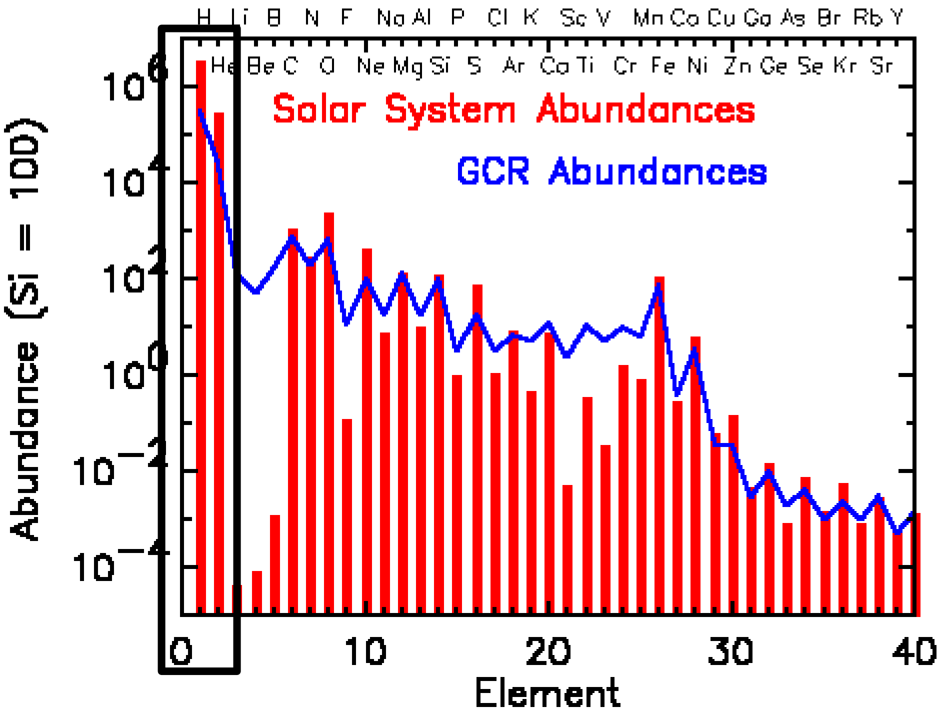
Galactic cosmic rays (GCR)



Picture from here

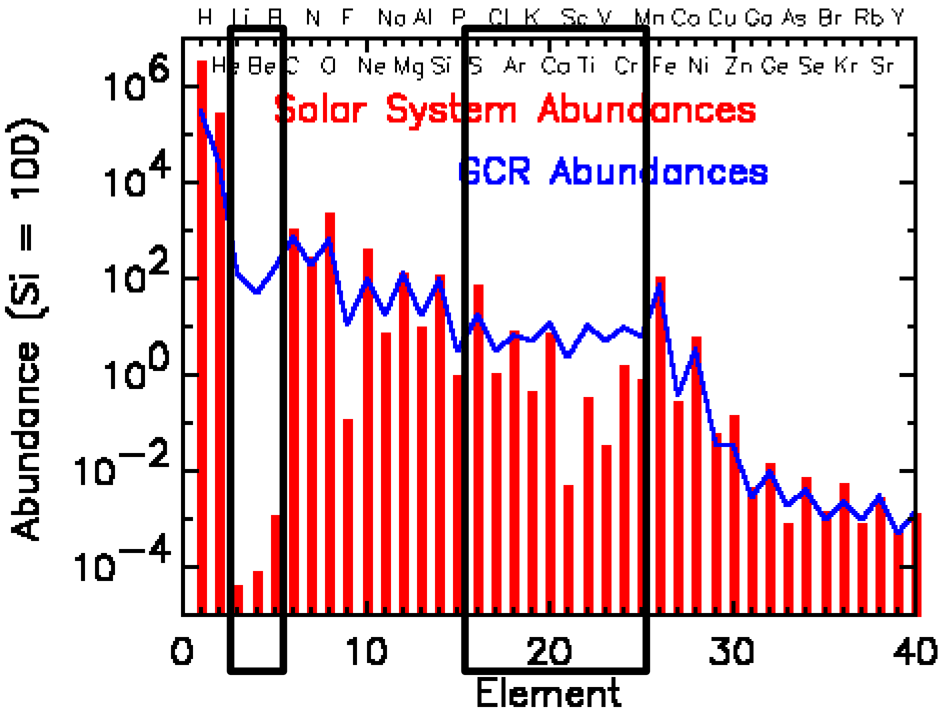
- With respect to the solar system composition:
  - Less H and He
  - More Li, Be, B
  - More elements lighter than Fe

Galactic cosmic rays



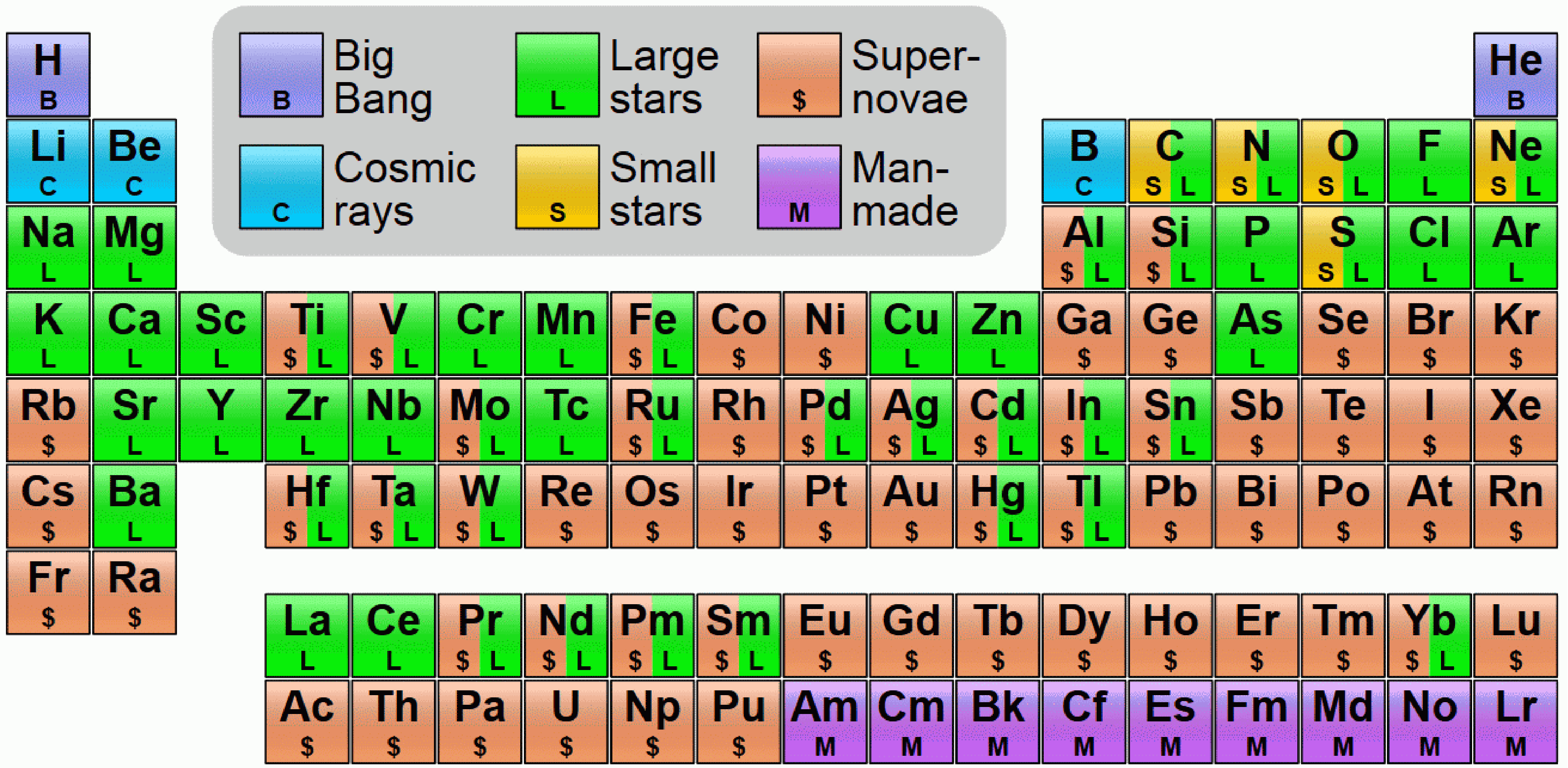
- Why less H and He
  - Small Z: more difficult to accelerate them to high speed

Galactic cosmic rays



- Why more Li, Be, B
  - Those are mostly **"secondary" cosmic rays**: the result of "spallation" reactions with interstellar gas (mostly H)
  - The same mechanism populated the elements between Silicon and Iron

Main producer of each element



B Big Bang
L Large stars
$ Super-novae
C Cosmic rays
S Small stars
M Man-made

H B																	He B
Li C	Be C											B C	C S L	N S L	O S L	F L	Ne S L
Na L	Mg L											Al $ L	Si $ L	P L	S S L	Cl L	Ar L
K L	Ca L	Sc L	Ti $ L	V $ L	Cr L	Mn L	Fe $ L	Co $	Ni $	Cu L	Zn L	Ga $	Ge $	As L	Se $	Br $	Kr $
Rb $	Sr L	Y L	Zr L	Nb L	Mo $ L	Tc L	Ru $ L	Rh $	Pd $ L	Ag $ L	Cd $ L	In $ L	Sn $ L	Sb $	Te $	I $	Xe $
Cs $	Ba L		Hf $ L	Ta $ L	W $ L	Re $	Os $	Ir $	Pt $	Au $	Hg $ L	Tl $ L	Pb $	Bi $	Po $	At $	Rn $
Fr $	Ra $																
			La L	Ce L	Pr $ L	Nd $ L	Pm $ L	Sm $ L	Eu $	Gd $	Tb $	Dy $	Ho $	Er $	Tm $	Yb $ L	Lu $
			Ac $	Th $	Pa $	U $	Np $	Pu $	Am M	Cm M	Bk M	Cf M	Es M	Fm M	Md M	No M	Lr M

Picture taken from wikipedia

Age of cosmic rays (1)

- Assuming that the difference in distribution between solar system and GCR is due to secondary cosmic rays, we can try to deduce the typical lifetime of the primary cosmic rays
- For this we need to know the density of interstellar gas and the probability of nuclear reaction ("cross section")
  - Cross section is measured with particle accelerators
  - Density of interstellar gas in the galactic disk of the Milky Way is ~1 atom/cm^3
- With this method, one can determine an average cosmic ray age of about 2-3 million years
- But this is wrong...

Age of cosmic rays (2)

- Age of cosmic rays can be measured by radioactive isotopes, similarly to the way ^{14}C is used in archaeology
- Unstable isotopes ^{10}Be, ^{26}Al, ^{36}Cl, etc., are almost entirely secondaries (not produced in nucleosynthesis); after they are created, they begin to decay
  - ^{10}Be halftime is 1.5 million years
  - Its observed abundance in CR is 20-30% of what we predict by comparing with other Li/Be/B isotopes and by knowing its and their production rates from accelerator experiments
  - ⇒ CR travel time is O(10) million years (Homework)
- The reason why the previous slide is wrong is that cosmic rays make very complex paths in the Galactic magnetic field, passing several times through the galactic disk and spending much time in the low-density galactic halo

Sources of galactic cosmic rays

- We are not sure
  - Because they are deflected several times by galactic magnetic field, they reach Earth from random directions
- Abundance of heavy elements suggests an origin from supernovae, for most but maybe not all of them
  - Remember: ~ 1 SN every 50 years in the Milky Way
- Cosmic rays are probably accelerated by the shock waves in the interstellar gas due to supernovae
- Energy of typical SN explosion: ~10^{51} ergs
  - It would be sufficient that O(%) of this energy is converted in kinetic energy of the cosmic rays; the exact way is unknown
  - Data from Fermi satellite recently proved that SN are sources of CR, with ~ 10^{49} – 10^{50} ergs of CR kinetic energy

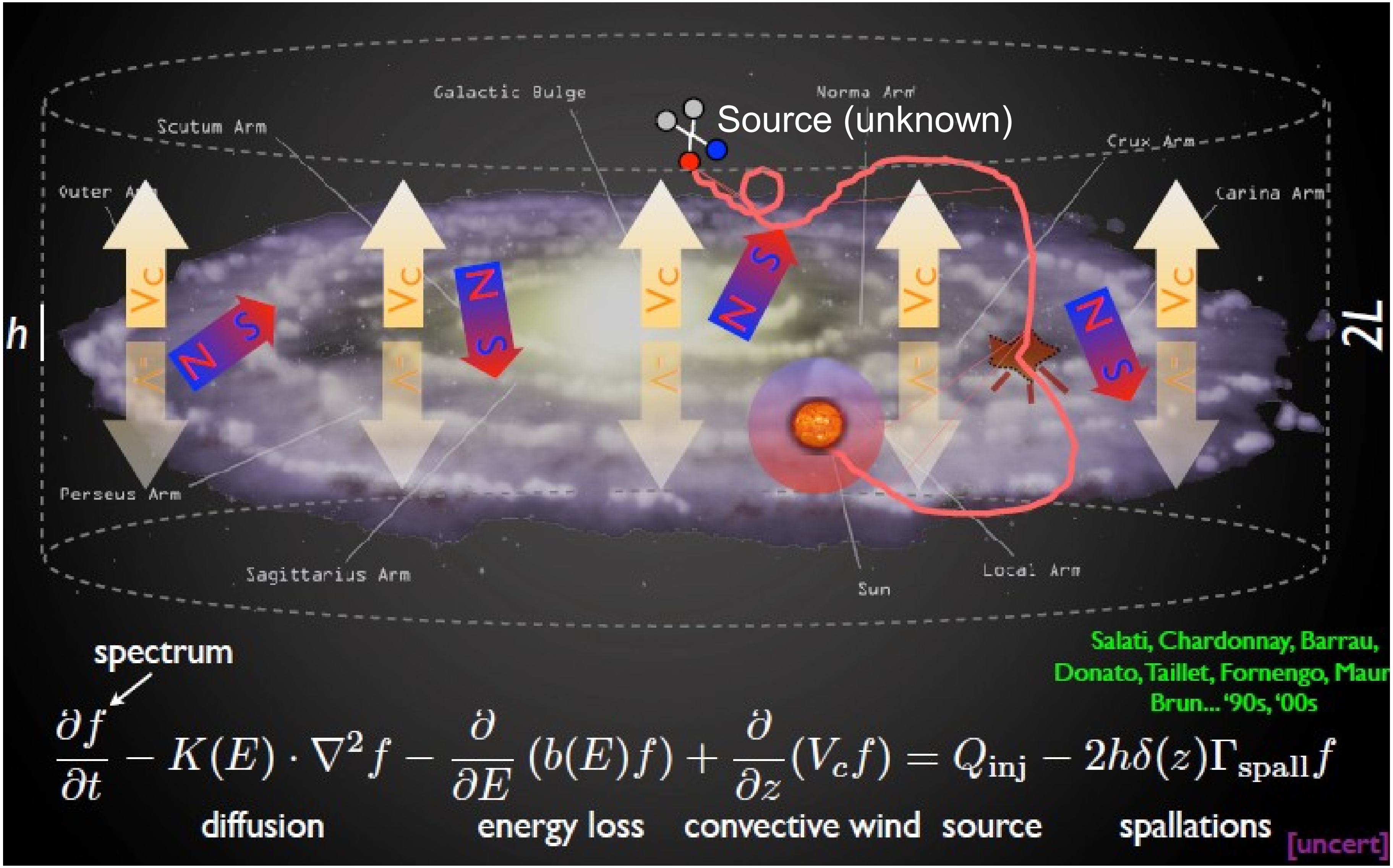
"Leaky box" model

- Simple approximation that assumes that CR are confined to the galactic disk (where density is high) by the galactic magnetic field (~10^{-7} Gauss), with some gradual leaking out of the disk

$$p_{\perp}(MeV/c) = 3 \times 10^{-4} BR(\text{gauss cm})$$

- So a 10^{14} eV proton's trajectory would have a radius of 3×10^{18} cm (~1 parsec) ⇒ much less than the distance from the nearest possible sources ⇒ several crossings of the disk ⇒ direction is randomized
- Instead, a 10^{18} eV proton's trajectory would have a radius of ~10,000 pc ~ galactic radius ⇒ it probably has extra-galactic origin

"Leaky box" model



Salati, Chardonnay, Barrau, Donato, Taillet, Fornengo, Maur Brun... '90s, '00s

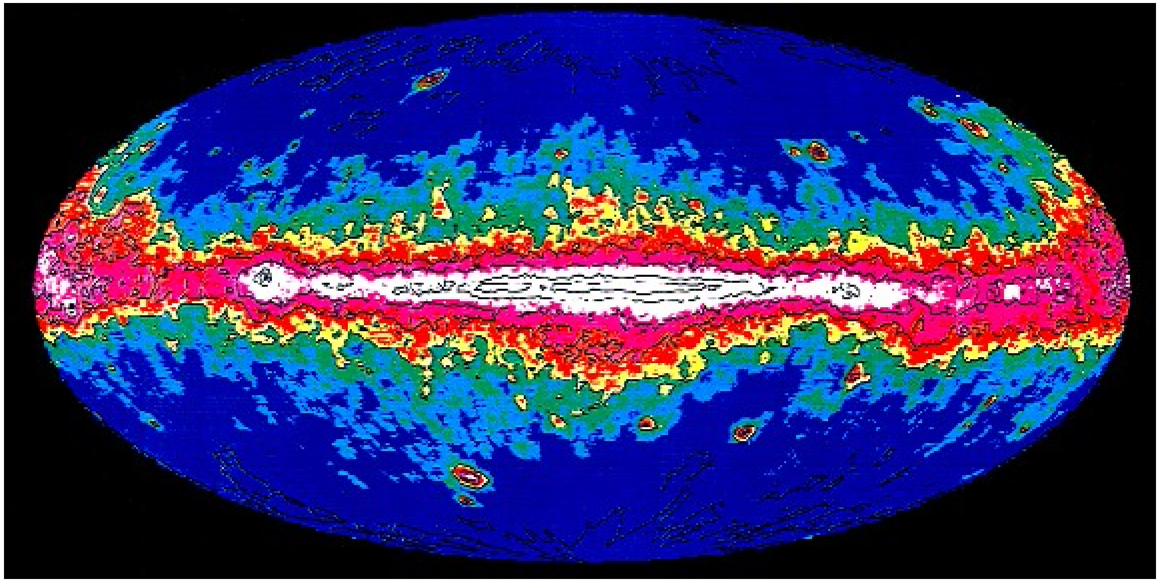
$$\frac{\partial f}{\partial t} - K(E)\cdot\nabla^2 f - \frac{\partial}{\partial E}\left(b(E)f\right) + \frac{\partial}{\partial z}(V_c f) = Q_{\mathrm{inj}} - 2h\delta(z)\Gamma_{\mathrm{spall}} f$$

diffusion energy loss convective wind source spallations [uncert]

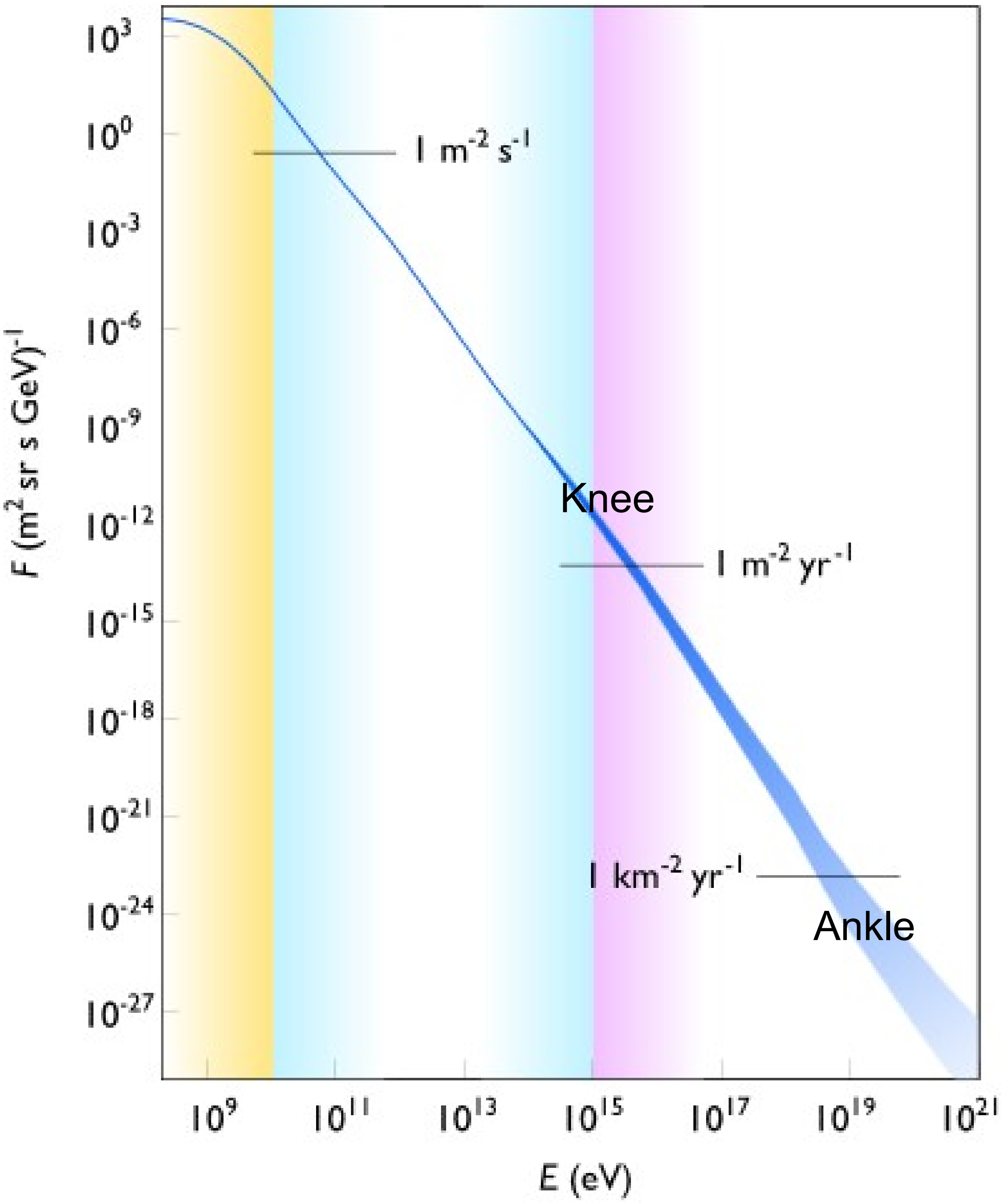
From M.Cirelli's seminar at CP3 - link

Gamma rays

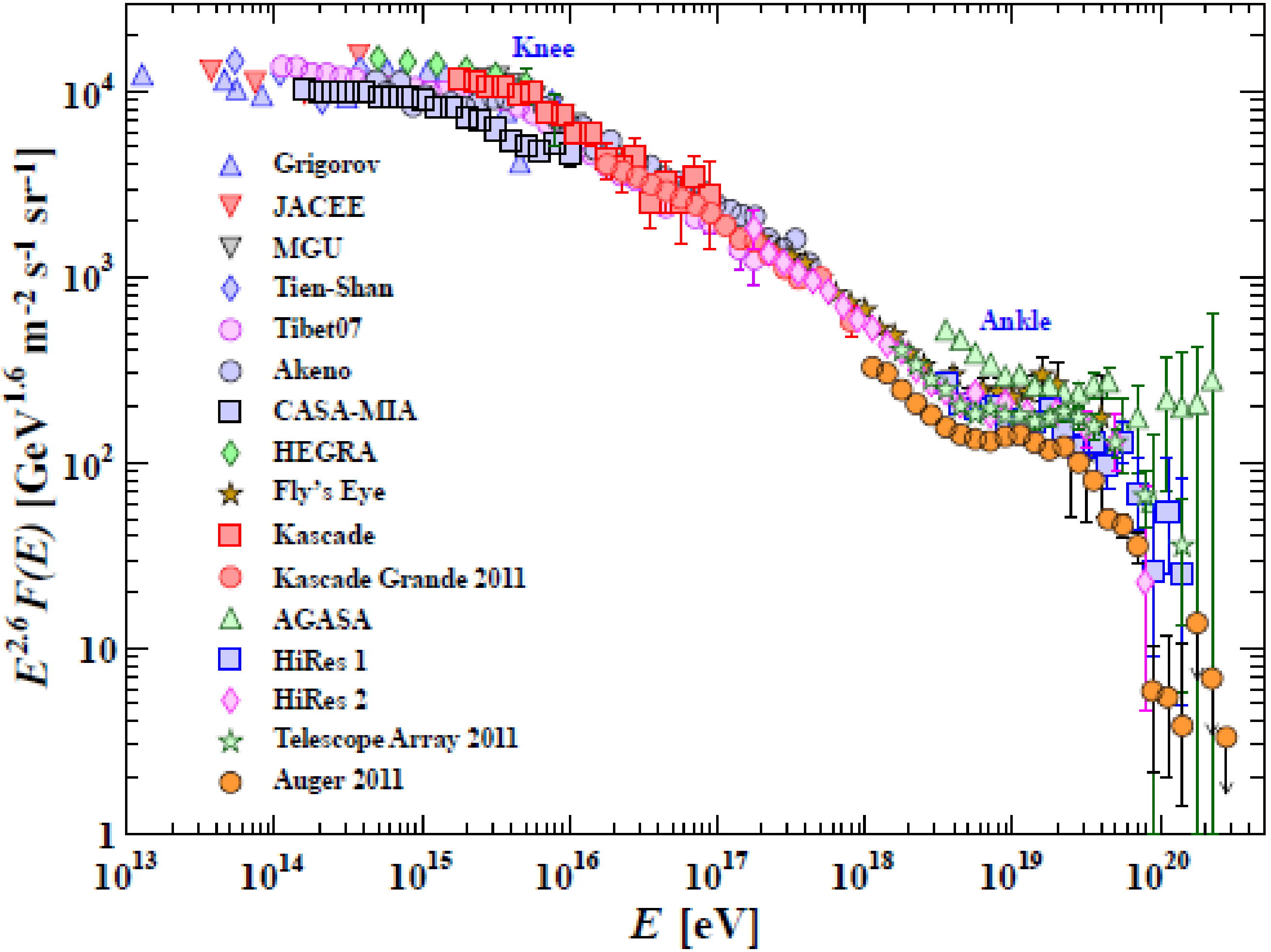
- As the cosmic rays interact with interstellar gas, they can produce gamma rays
    - This image is considered a proof that most cosmic rays are confined to the galactic disk:



Gamma ray image of the Milky Way from the EGRET satellite


F (m^2 sr s GeV)^-1
10^3
10^0
10^-3
10^-6
10^-9
10^-12
10^-15
10^-18
10^-21
10^-24
10^-27
1 m^-2 s^-1
Knee
1 m^-2 yr^-1
1 km^-2 yr^-1
Ankle
10^9
10^11
10^13
10^15
10^17
10^19
10^21
E (eV)

Picture from
Particle Data Group



Differences between the experiments show how difficult it is to calibrate the energy of the observed CR showers

Knee and ankle

- The "knee" and the "ankle" are changes in slope
- The knee has lead to the hypothesis that acceleration energies from SN shocks are limited to ~10^{15} eV
  - But the sharpness of this effect is difficult to explain
- The ankle may be explained by a flux of extra-galactic CR with a different energy spectrum with respect to the galaxy
- Another possibility is that the dip at the position of the ankle is due to the $\gamma p \rightarrow e^+ e^- p$ process, with γ from the Cosmic Microwave background (see later), which would decrease the energy of extra-galactic protons

The GZK cutoff (1)

- Greisen, Zatsepin, Kuzmin calculated that we should never see an extra-galactic cosmic ray above ~10^{20} eV
  - If we see it, it would be proof that it's not extragalactic
- The reason is the Cosmic Microwave Background (that we will discuss again in a future lesson) due to the Black Body radiation of the Universe itself ($T = 2.7$ K)
- It is a background of photons of average energy ~10^{-3} eV, moving in random directions
- Cosmic rays interact with them all the time, but usually the effect is negligible, due to the low energy of those photons
- But when the CR energy is sufficiently high, the center-of-mass energy of the photon+CR system is not small...

The GZK cutoff (2)

- Photon 4-momentum: $p_\mu = (\epsilon, \vec{p})$ $|\vec{p}| = \epsilon$
- Nucleus 4-momentum: $P_\mu = (\omega, \vec{P})$
- In the center of mass rest frame:

$$(P^\mu + p^\mu)(P_\mu + p_\mu) = (\omega + \epsilon)^2 = \epsilon_{CM}^2$$

- If this quantity is larger than $m_\pi + M_N$, this reaction can happen, decreasing the kinetic energy of the nucleus:

$$\gamma + N \to \pi + N$$

- Center-of-mass energy is Lorentz-invariant, so we can calculate it in whatever rest frame we want, e.g., lab frame:

$$\epsilon_{CM}^2 = M_N^2 + 2\omega\epsilon - 2\vec{P} \cdot \vec{p}$$

The GZK cutoff (3)

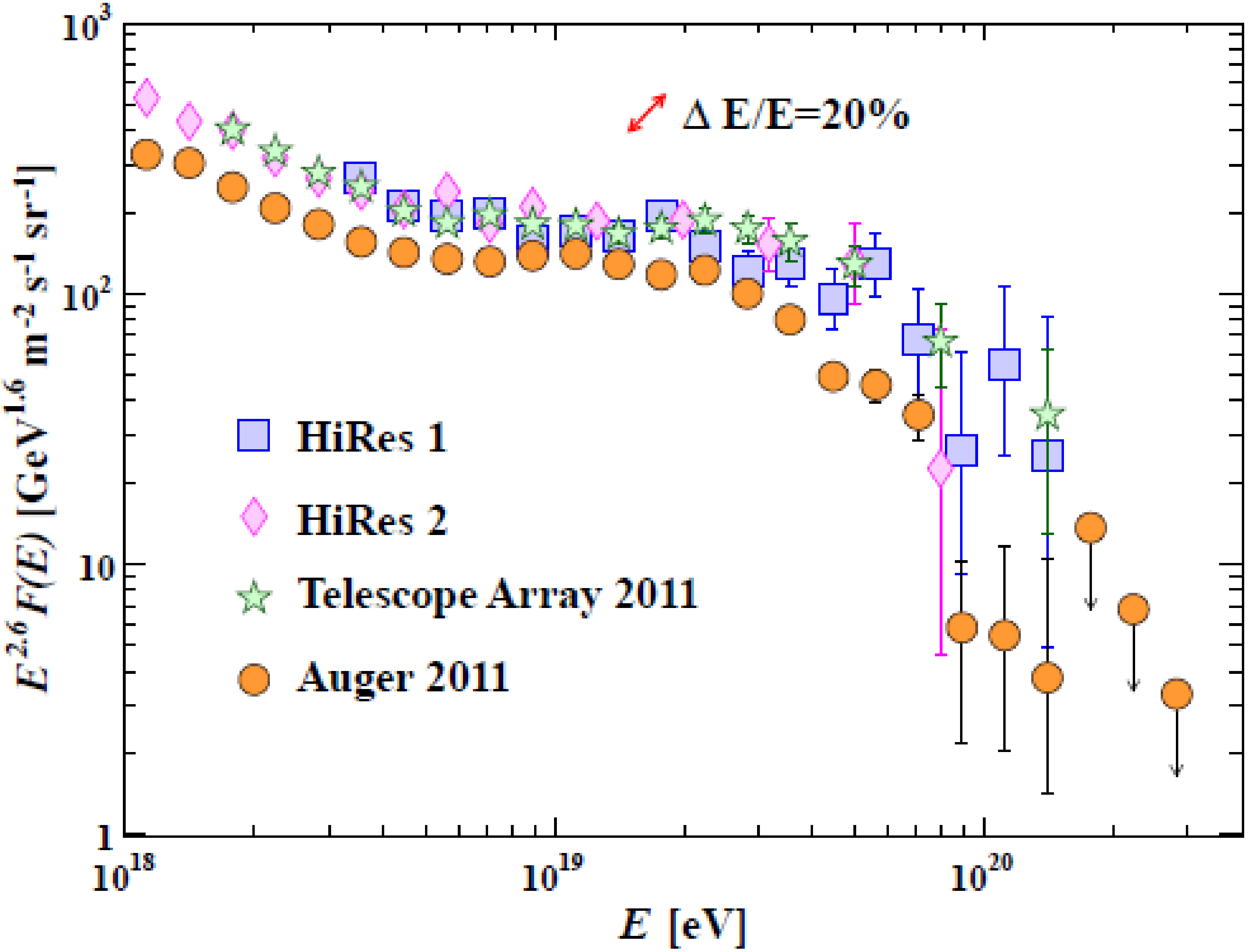
- Simplifications:
  - Consider only the extreme case that gives the maximum; this happens when they are back-to-back (cosθ ~ -1)
  - Nucleon is ultra-relativistic at these energies (ω~P)

$$(\epsilon_{CM}^{max})^2 \sim M_N^2 + 4\omega\epsilon$$

- Photoproduction of pions can happen when:

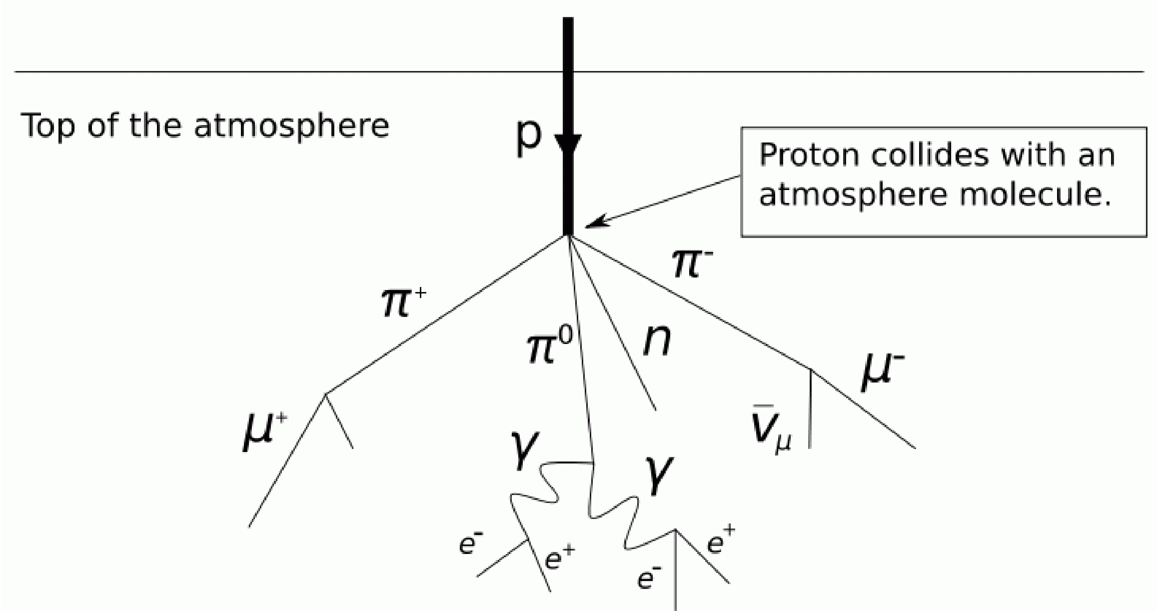
$$\epsilon_{CM}^{max} \gtrsim m_\pi + M_N \Rightarrow \quad \omega \gtrsim \frac{m_\pi^2 + 2M_N m_\pi}{4\epsilon} \sim \frac{M_N m_\pi}{2\epsilon} \sim 3 \cdot 10^{20} \left(\frac{2.7K}{E_\gamma}\right) \mathrm{eV}$$

The GZK cutoff (4)

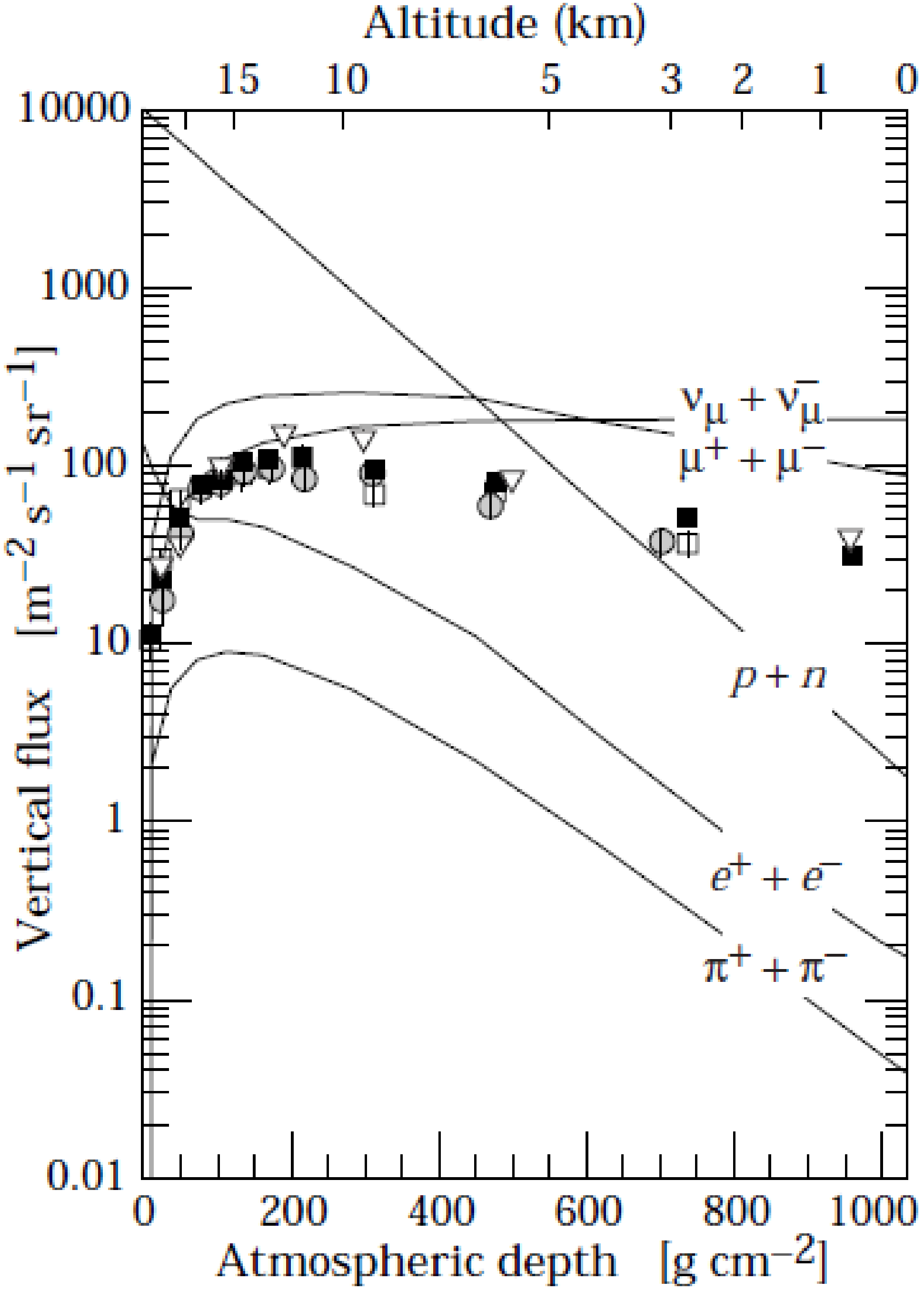


Picture from
Particle Data Group

Secondary cosmic rays in the atmosphere



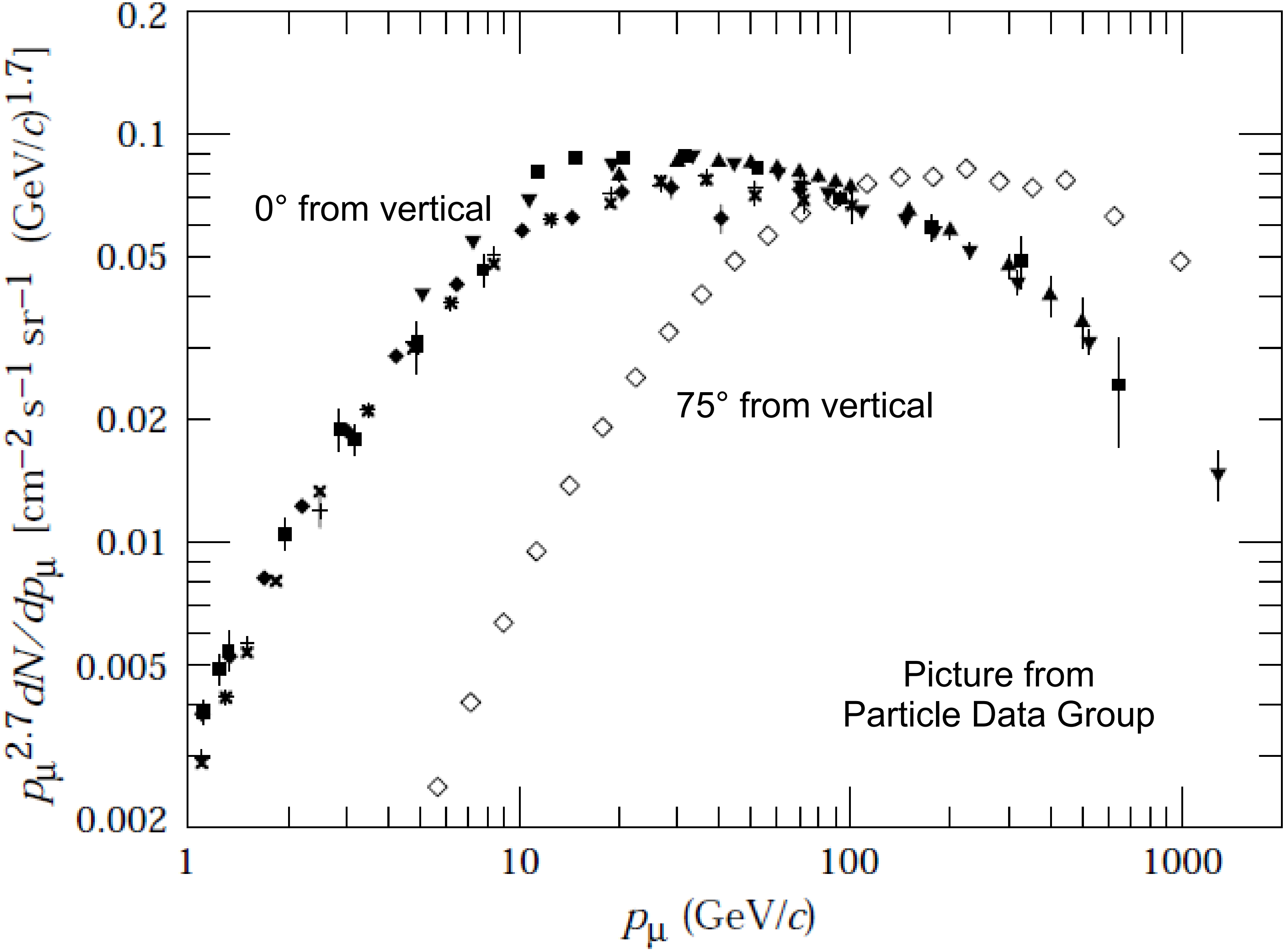
- Primary CRs entering the atmosphere collide mostly with Oxygen and Nitrogen, producing a shower of particles
- Mostly x-rays, muons, protons, alphas, pions, electrons, neutrons
- They tend to stay within 1° of the direction of the primary CR
    - *(Homework: what do you deduce, from that info, about their typical momentum?)*



At ground level, the visible flux is dominated by muons

Picture from
Particle Data Group
(link)

All curves are for E>1 GeV; points are experimental measurements for negative muons

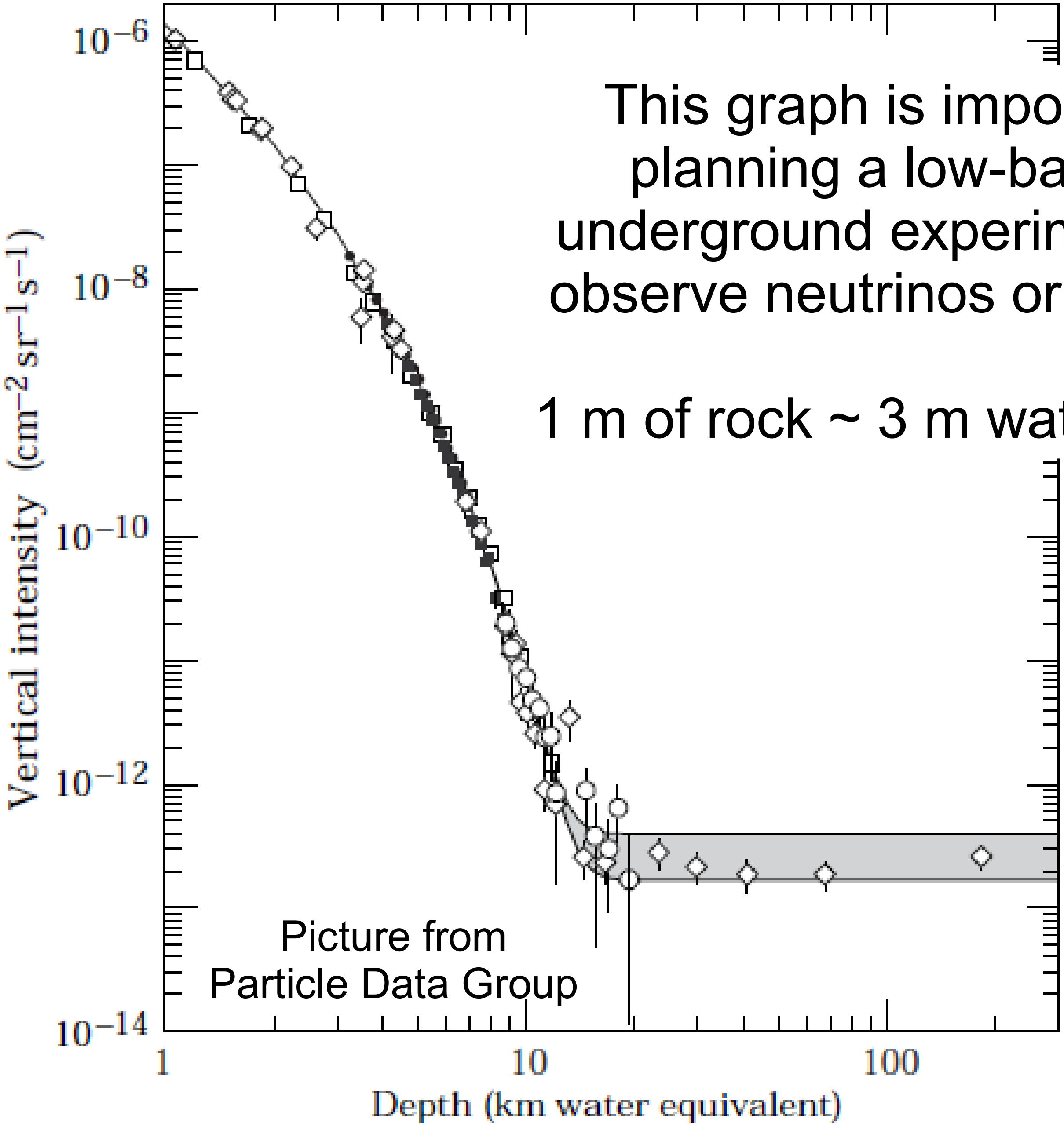


0° from vertical

75° from vertical

Picture from
Particle Data Group

<u>Question</u>: how do you explain the difference?



This graph is important when planning a low-background underground experiment (e.g., to observe neutrinos or dark matter)

1 m of rock ~ 3 m water equivalent

Picture from Particle Data Group

<u>Question</u>: explain the shape above 10 km w.e.

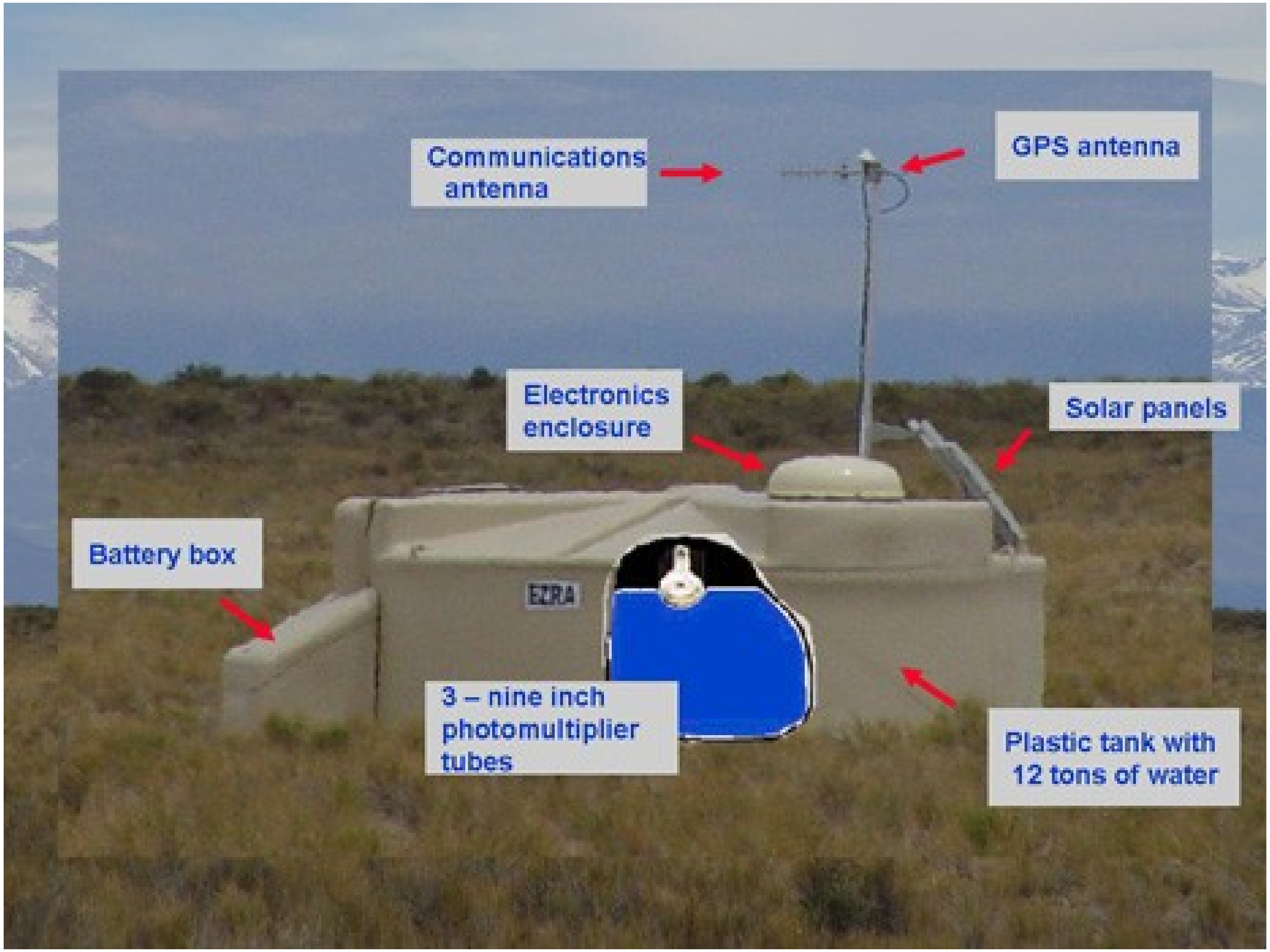
Cosmic ray detection

- Ground based
  - Can study the secondaries at the end of the atmospheric shower
- Balloons (like V.Hess)
  - Less atmosphere, therefore closer to the start of the atmospheric shower
  - Typically at the poles, to profit from smaller magnetic field (and more perpendicular to Earth)
- Satellites
  - No atmosphere, can study the primaries directly

Ground based

- Cherenkov telescopes
    - Measure the momentum of the secondaries in the shower by the angle of their Cherenkov light cone

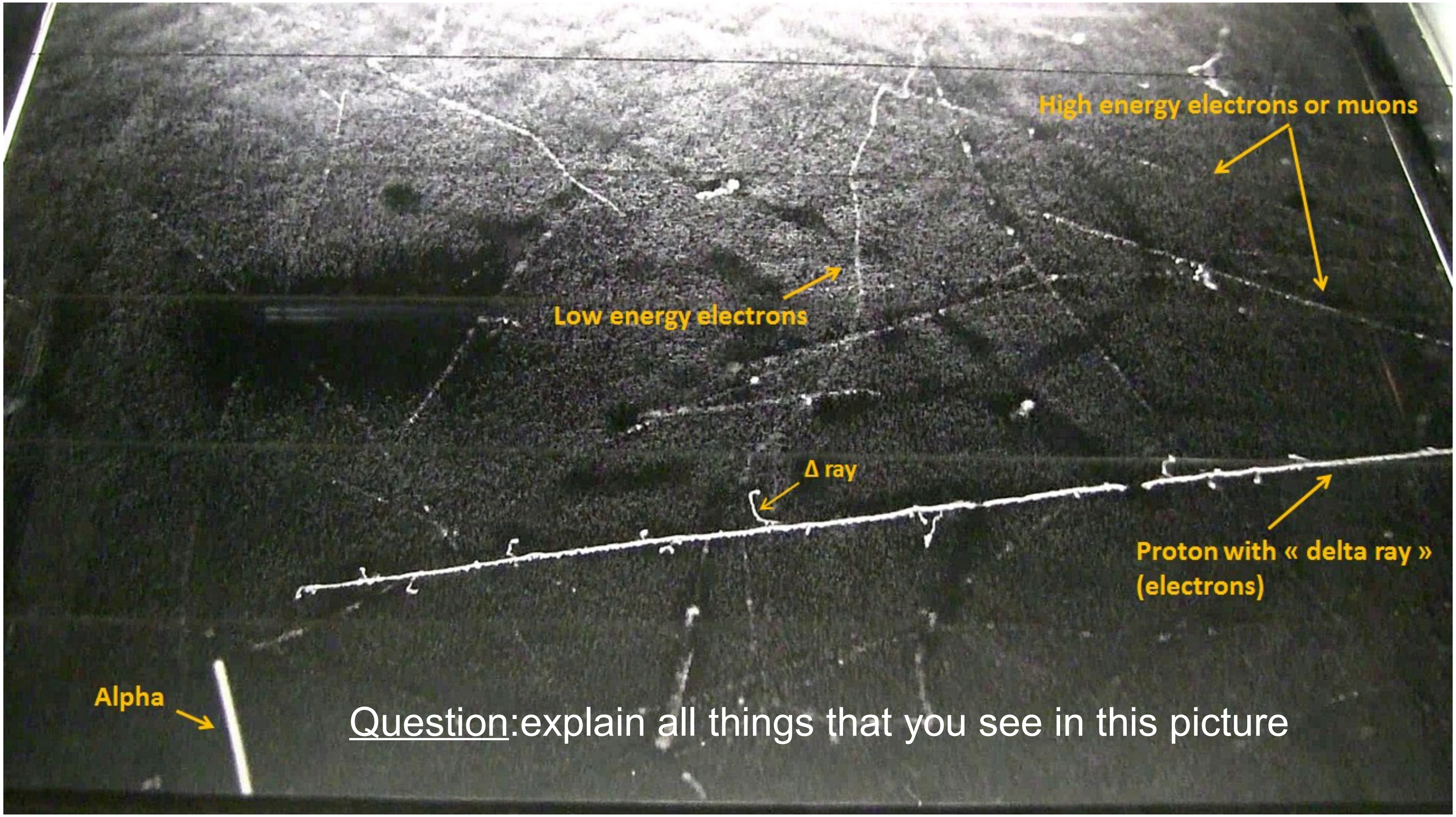
Pierre Auger Observatory



Also based on Cherenkov effect, but spread over a huge area in Argentina, because it is designed for the highest energy cosmic ray showers

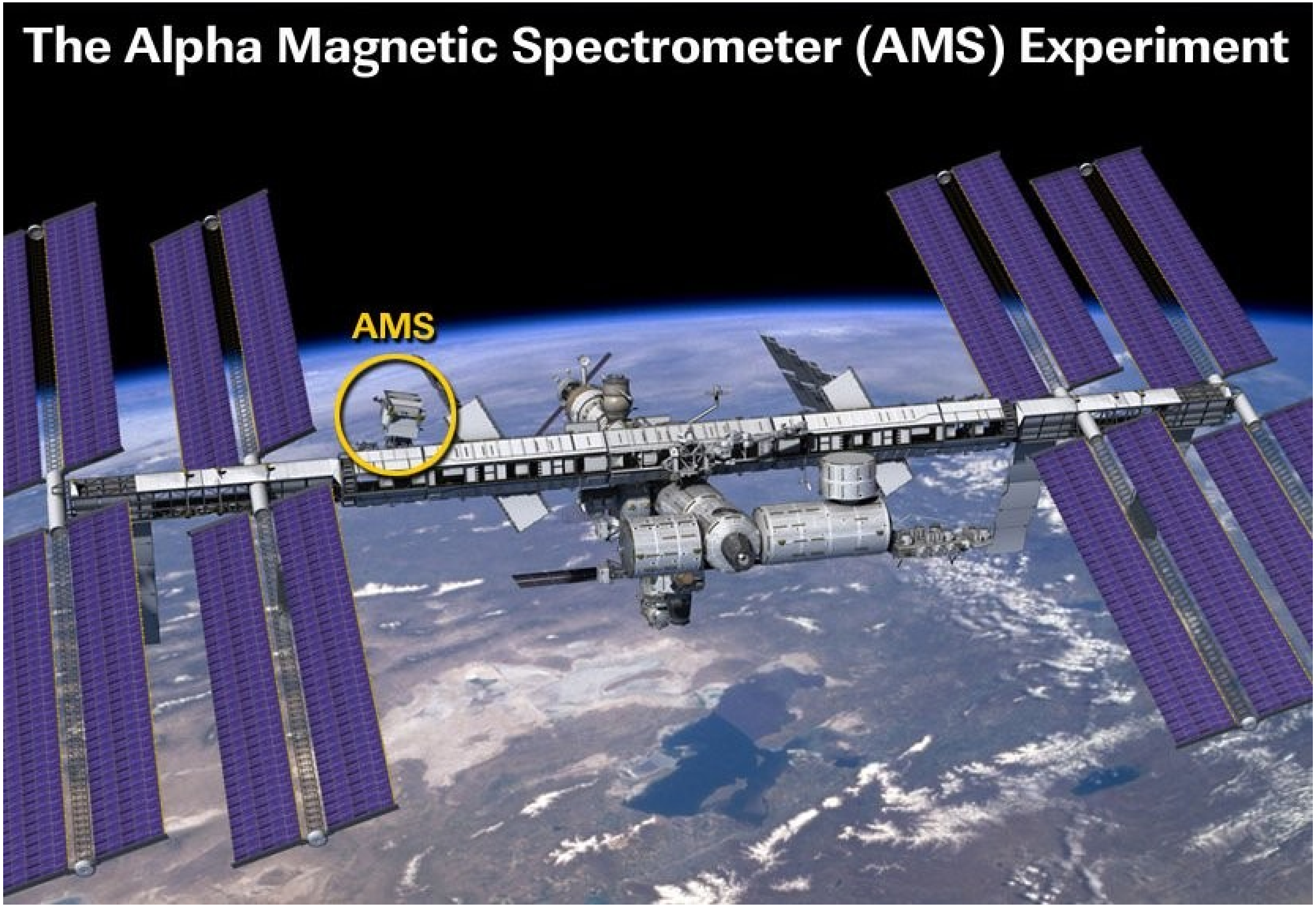
Ground based

- Cloud chambers
  - Passage of a charged particle condenses small drops

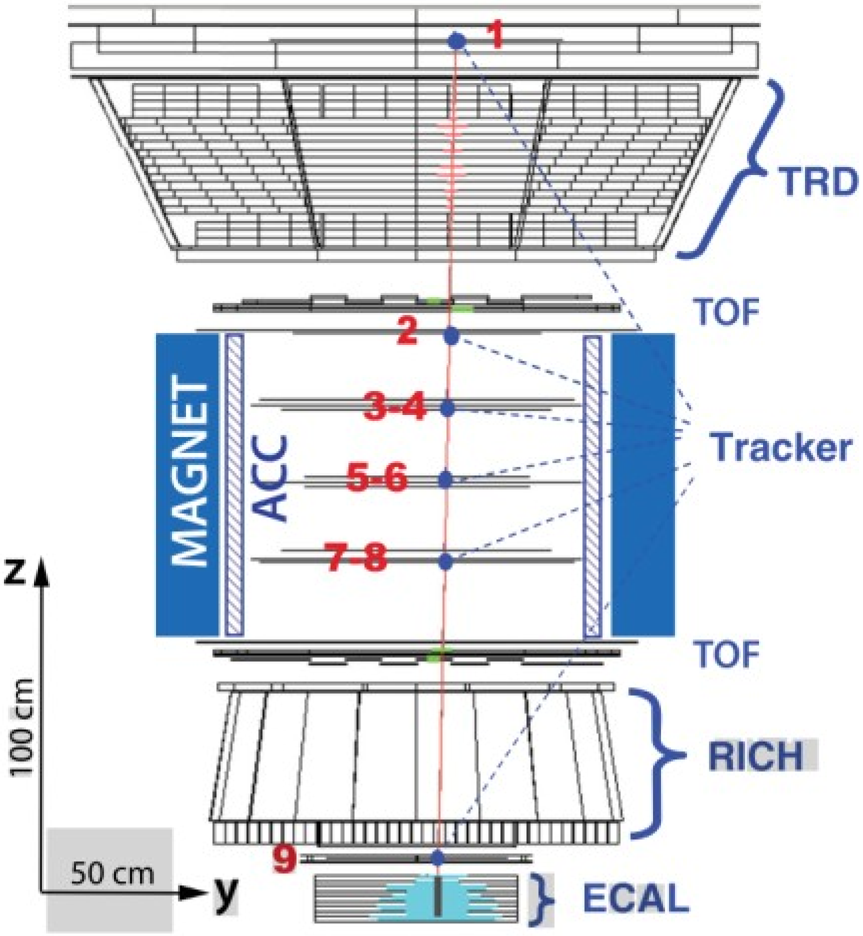


Question:explain all things that you see in this picture

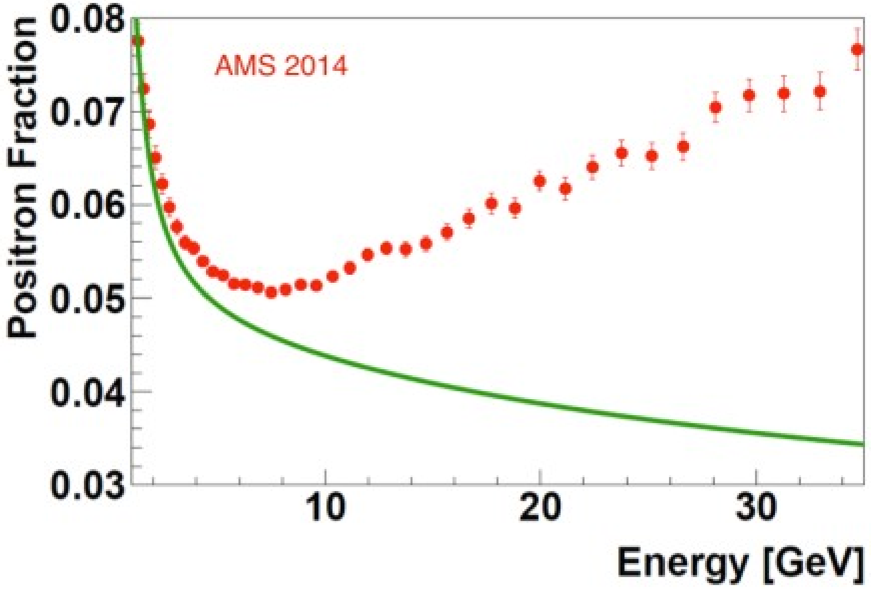
AMS

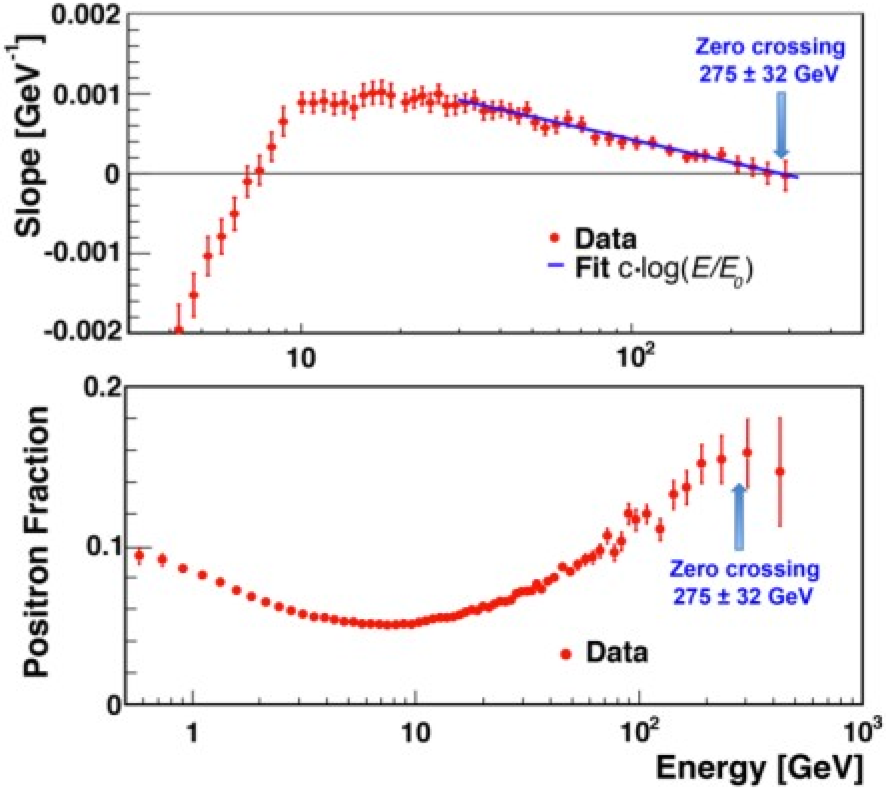


AMS


1
TRD
TOF
2
3-4
5-6
7-8
Tracker
MAGNET
ACC
z
100 cm
TOF
RICH
9
50 cm
y
ECAL

Recent result from AMS

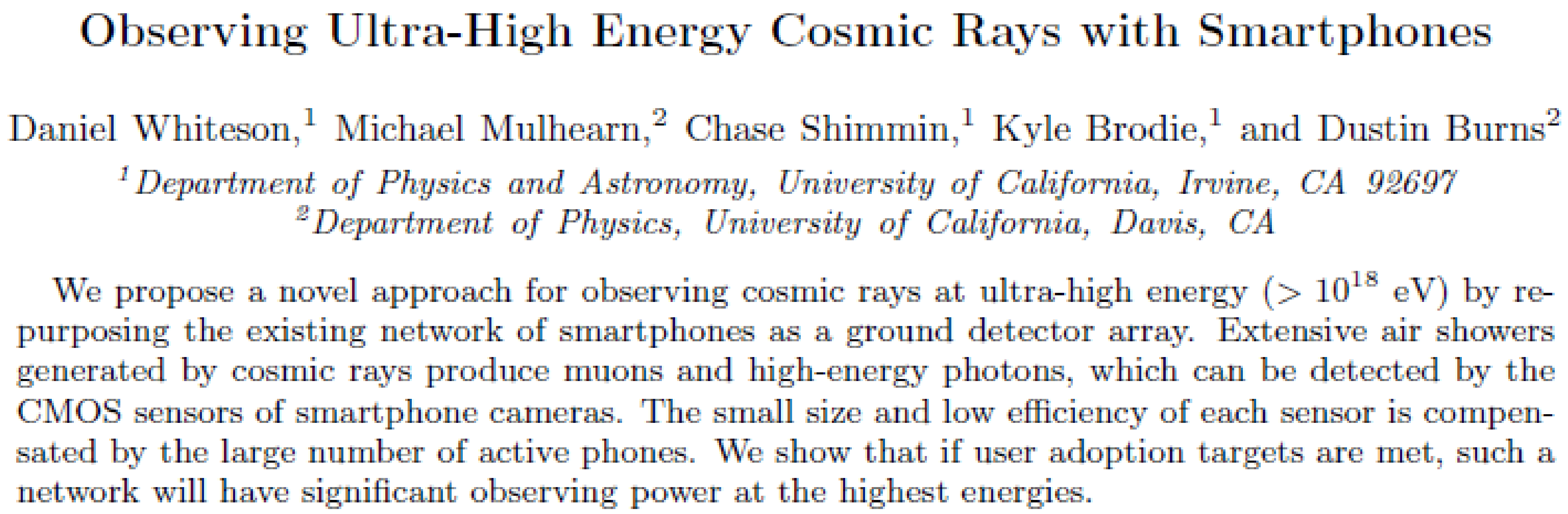




It is a new phenomenon, but we don't know of what kind.
An unknown astrophysical source of cosmic rays?
Or the decay of a new particle?
I will come back to these plots in a future lesson, after having introduced Dark Matter...

For your amusement...

- http://crayfis.ps.uci.edu/paper.pdf



Observing Ultra-High Energy Cosmic Rays with Smartphones

Daniel Whiteson,[1] Michael Mulhearn,[2] Chase Shimmin,[1] Kyle Brodie,[1] and Dustin Burns[2]

[1] Department of Physics and Astronomy, University of California, Irvine, CA 92697
[2] Department of Physics, University of California, Davis, CA

We propose a novel approach for observing cosmic rays at ultra-high energy ($> 10^{18}$ eV) by repurposing the existing network of smartphones as a ground detector array. Extensive air showers generated by cosmic rays produce muons and high-energy photons, which can be detected by the CMOS sensors of smartphone cameras. The small size and low efficiency of each sensor is compensated by the large number of active phones. We show that if user adoption targets are met, such a network will have significant observing power at the highest energies.

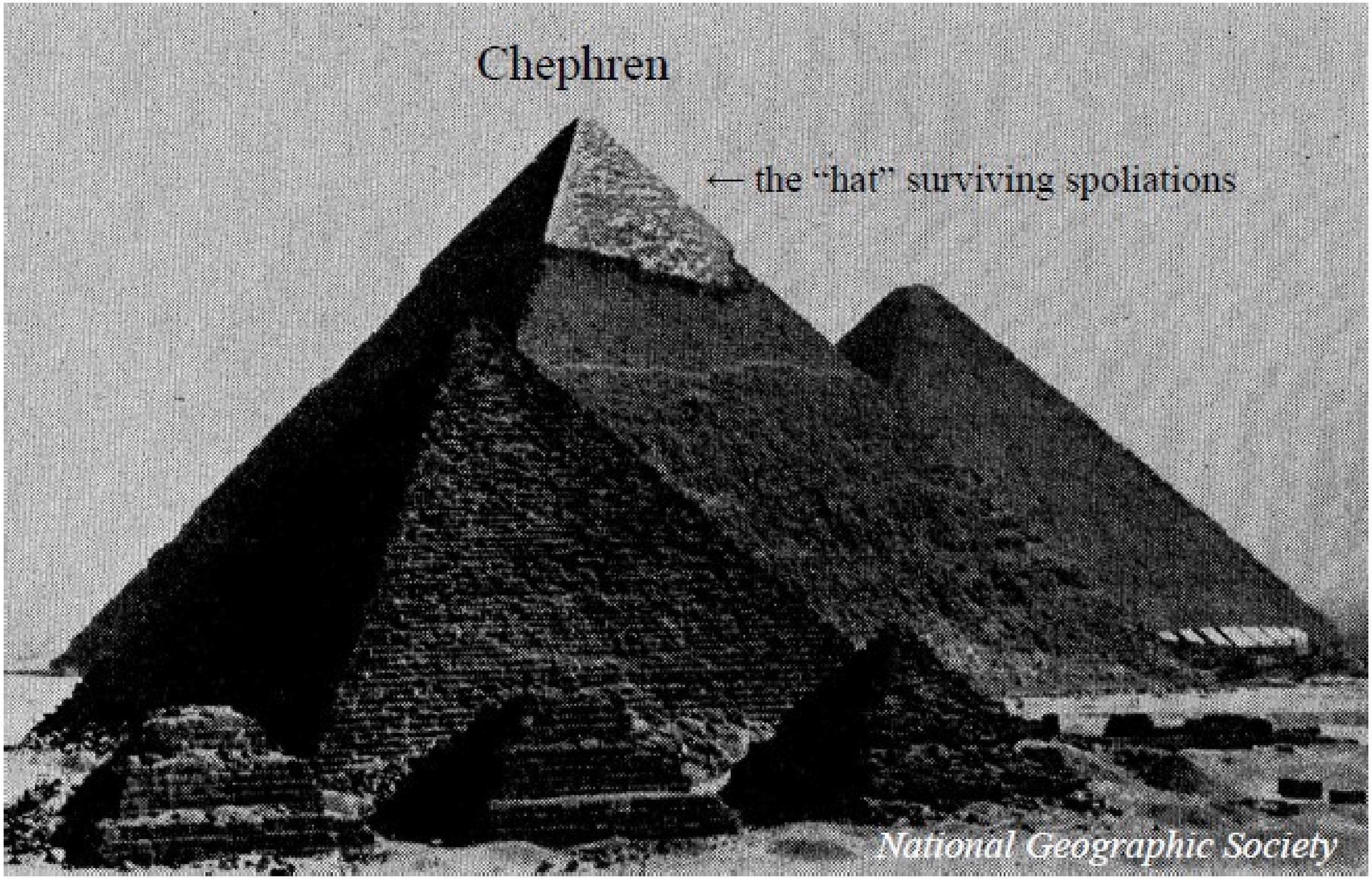
The sensitive element in a smartphone is the camera, a CMOS device in which silicon photodiode pixels are designed to absorb visible photons and convert them to current which is collected and read out. While these devices are designed to have reasonable quantum efficiency for visible light, the same principle allows the sensor to detect higher-energy photons [15] as well. In the case of muons, the photodiode is functionally equivalent to silicon-based trackers now common in particle physics experiments, such that the charged particle will leave electron-hole pairs along its path.

Conclusions

We propose a novel strategy for observing air showers due to ultra-high energy cosmic rays: an array composed of smartphones running a dedicated app. We have measured the per-phone sensitivity to the particles which comprise the showers and estimated the number of phones needed to achieve observing power to rival the most sensitive current observatories.

Building an installed user base of more than 1M devices operating reliably poses a social and organizational challenge. We have begun to address these by reducing the barriers to participation via automatic and inobstrusive operation, and providing incentives for users.

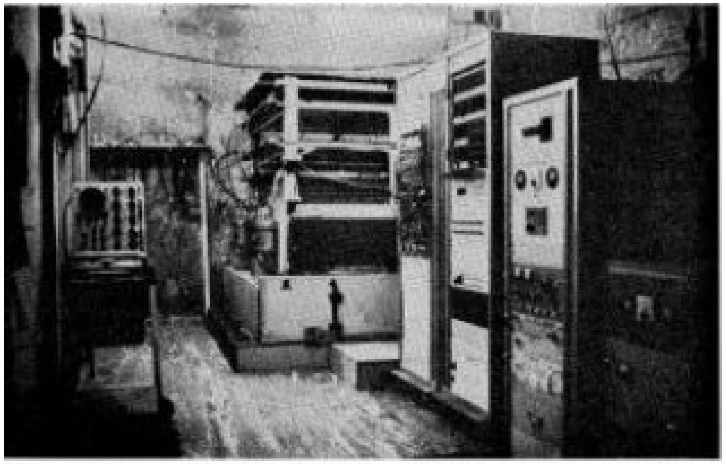
Cosmic ray tomography



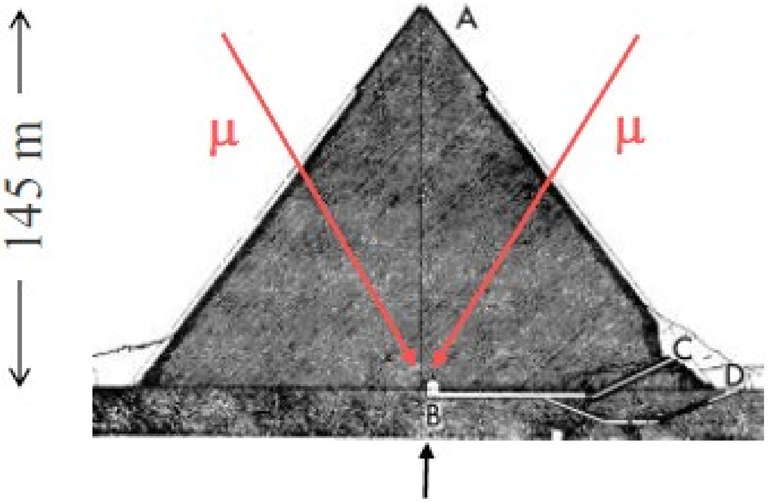
Search for hidden chambers in the Chephren's Pyramid

L.W. Alvarez et al. Science 167 (1970) 832

Result: no hidden chamber

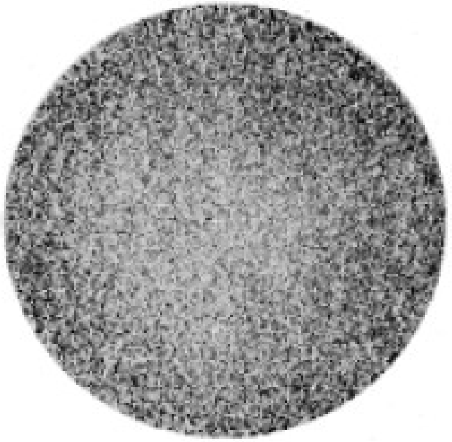


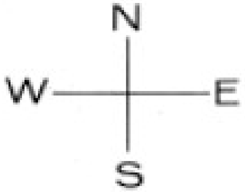
Spark chamber "muon telescope"



Telescope in Belzoni chamber

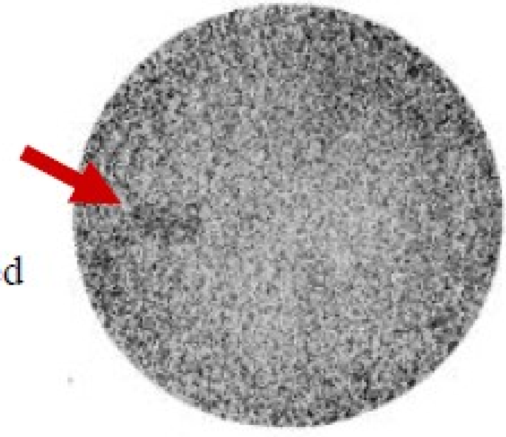
Data



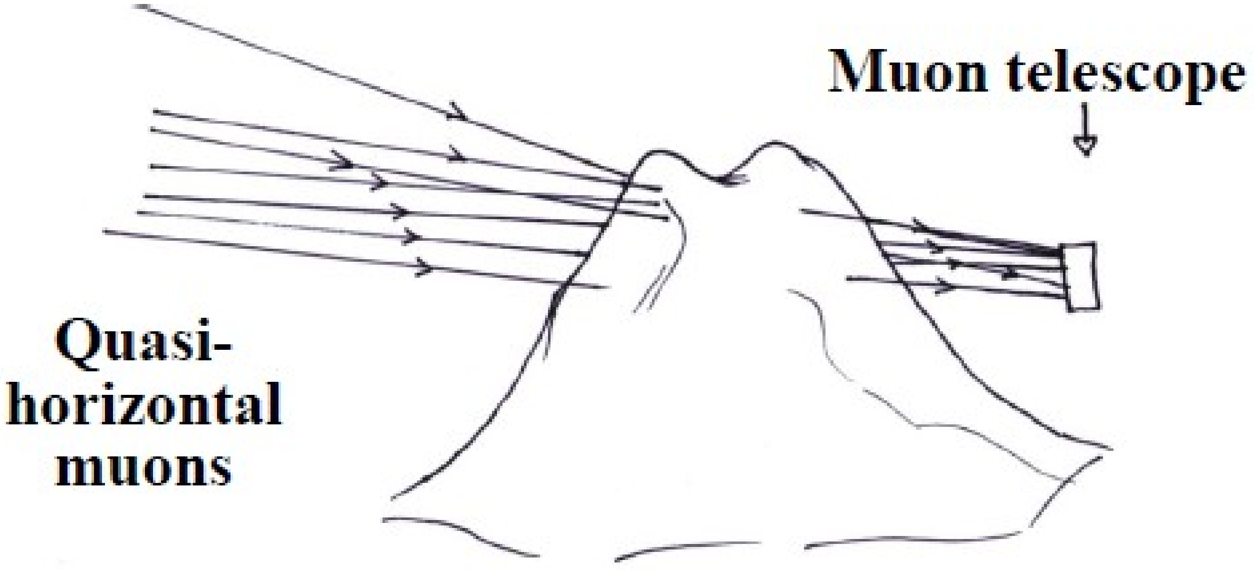


Data and simulation are corrected
for pyramid structure and
telescope acceptance

Simulation with hidden chamber



Volcano tomography



See slides of the seminar by
G.Macedonio, last year: link