Introduction to Cosmic Rays Physics. First observational data

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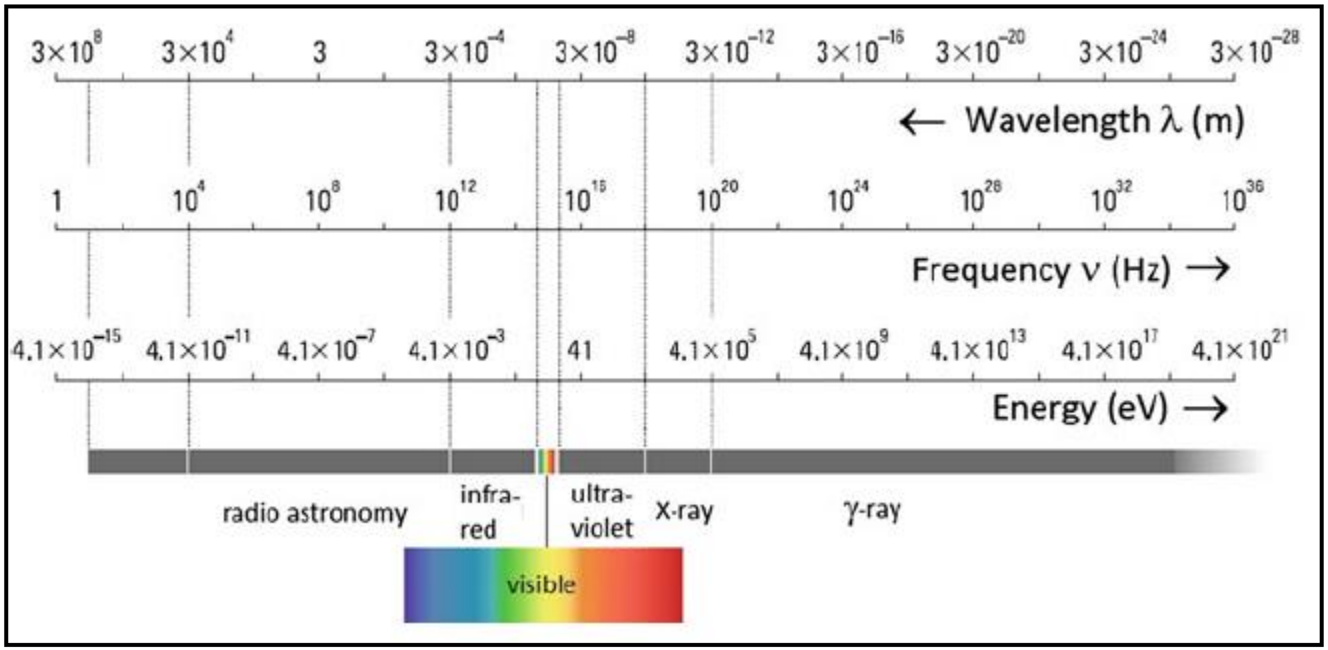
Using Particle Physics to Understand and Image the Earth
GSSI, L'Aquila, 11-21 July 2016
ISAPP

- Cosmic ray physics → study of the radiation coming from outside the earth's atmosphere
- Astrophysics or Astroparticle physics?
  - Astrophysics → electromagnetic radiation
  - Astroparticle → particles

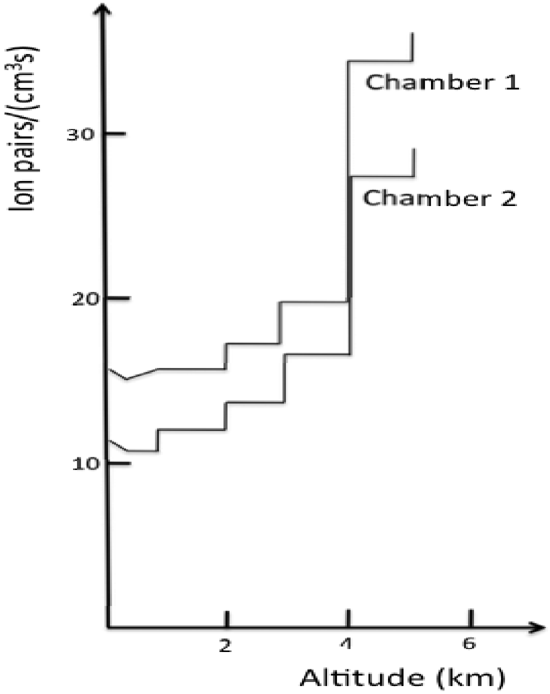


- Astroparticle messengers: charged particles (nuclei, e^-), γ, ν, gravitational waves → Multi-messenger astronomy

- The key instrument that led to the discovery of cosmic rays was the electroscope
- 1785 Coulomb observed that, even if insulated, *an electroscope spontaneously discharge*
- 1879 Crookes measured that the *speed of discharge decreased if the air pressure was reduced* → the cause is the ionized air
- 1896 Becquerel discovered the *spontaneous decay* of radioactive elements
- In the presence of a radioactive material, a charged electroscope promptly discharges
- The electroscope discharge can be attributed to charged particles emitted during radioactive decays
- Where does these element come from? → from the ground

V. Hess balloon's flights measurements

- 7th August 1912
- ~60 km from Aussig to Pieslow
- Maximum height 5200 m



Hess results

i) Slightly decrease just above ground level
ii) Between 1000 and 2000m, slight increase
iii) Between 3000 and 4000m, 50% increase respect ground level
iv) Between 4000 and 5000m, radiation is more than 100% compared to ground level

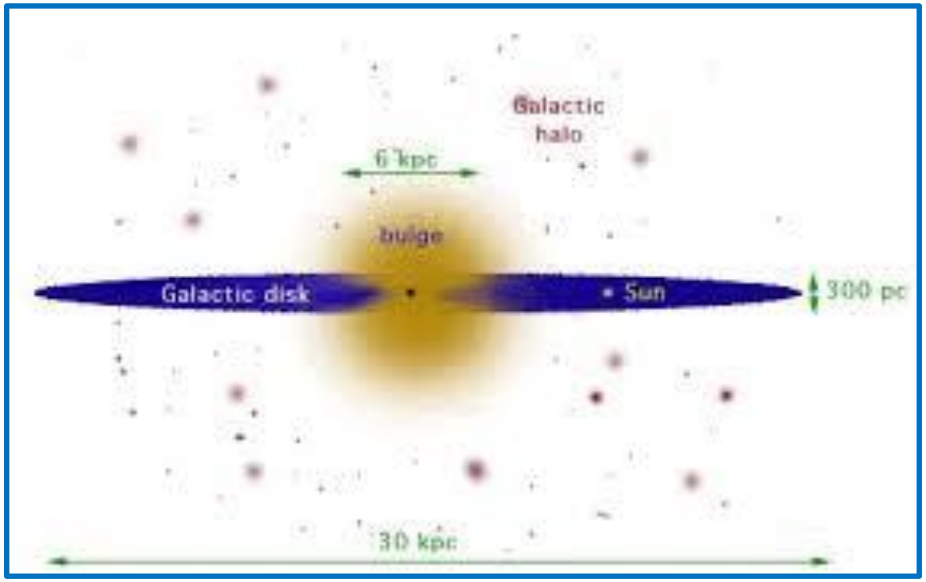
7. Fahrt (7. August 1912).

Ballon: „Böhmen" (1680 cbm Wasserstoff). Führer: Hauptmann W. Hoffory.
Meteorolog. Beobachter: E. Wolf. Luftelektr. Beobachter: V. F. Hess.

Nr.	Zeit	Mittlere Höhe		Beobachtete Strahlung				Temp.	Relat. Feucht. Proz.
		absolut m	relativ m	Apparat 1 q_1	Apparat 2 q_2	Apparat 3 q_3	Apparat 3 reduz. q_3		
1	15h 15—16h 15	156	0	17,3	12,9	—	—	—	—
2	16h 15—17h 15	156	0	15,9	11,0	18,4	18,4	1½ Tag vor dem Aufstiege (in Wien)	
3	17h 15—18h 15	156	0	15,8	11,2	17,5	17,5		
4	6h 45—7h 45	1700	1400	15,8	14,4	21,1	25,3	+6,4°	60
5	7h 45—8h 45	2750	2500	17,3	12,3	22,5	31,2	+1,4°	41
6	8h 45—9h 45	3850	3600	19,8	16,5	21,8	35,2	—6,8°	64
7	9h 45—10h 45	4800 (4400—5350)	4700	40,7	31,8	—	—	—9,8°	40
8	10h 45—11h 15	4400	4200	28,1	22,7	—	—	—	—
9	11h 15—11h 45	1300	1200	(9,7)	11,5	—	—	—	—
10	11h 45—12h 10	250	150	11,9	10,7	—	—	+16,0°	68
11	12h 25—13h 12	140	0	15,0	11,6	—	—	(nach der Landung in Pieskow, Brandenburg)	

Simple description of our Galaxy

- Only since 1930 it is well established that our galaxy is similar to other objects called *spiral nebulae*
- The recent images of the Galaxy using observations at different wavelengths show that it is basically a disk with a central bulge surrounded by a halo of globular clusters.
- The spheroidal component has a very massive nucleus (smaller than 3 pc of radius) with a black hole at its center (mass 2×10^6 solar masses), a bulge with radius of ~3 kpc and an extended halo of about 30 kpc. These three regions are approximately concentric. The disk is very thin (~200–300 pc thick) and a radius of about 15 kpc.
- The Sun is about 8.5 kpc from the center.
- The volume of the disk is $V \sim 5 \times 10^{60}\ m^3$



The galactic magnetic field

• The presence of a magnetic field inside the Galaxy was discovered (1949) when it was realized that the observed light from the stars has a high degree of polarization.

• $B \sim 4\ \mu G$

• The galactic field is oriented mainly parallel to the plane, with a small vertical component along the z-axis ($B_z \sim 0.2$–$0.3\ \mu G$ in the vicinity of the Sun).

Physical Dimensions frequently used in these lectures

- Galactic magnetic field → 4×10^{-6} G = 4×10^{-10} T
- Astronomical distances → 1pc = 3.08×10^{16} m
  - 1 parsec → distance from the earth of a star having an annual parallax of 1 arc second.
- Galactic disk → cylinder radium R~15 kpc, heigth h~300 pc
- Time → 1 year = 3.15×10^{7} s

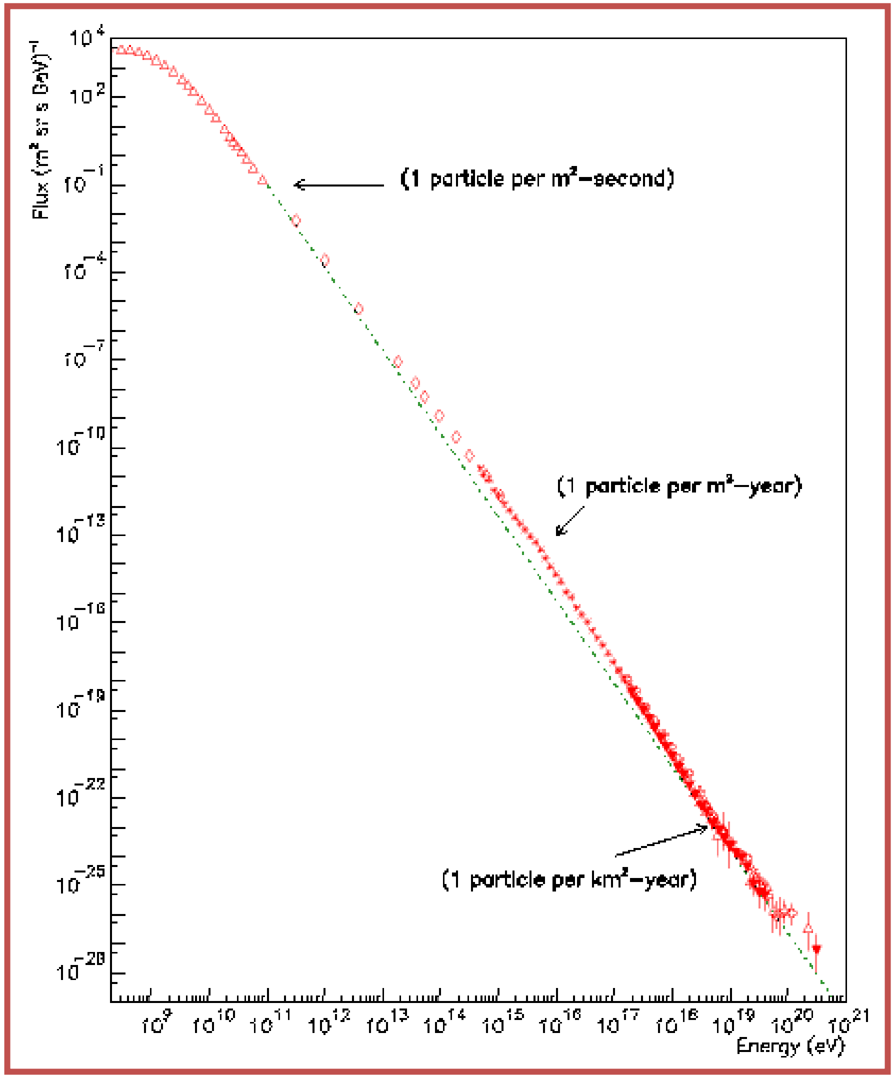
Cosmic Rays

- *Primary CRs* are high-energy protons and nuclei (plus a minority electron component) produced in astrophysical environments, filling the galactic space and arriving on Earth. Primary CRs can be identified if measured before they interact with the atmosphere.
- *Secondary CRs* are those particles produced in interactions of the primaries with interstellar gas or with nuclei in the Earth's atmosphere.
- Covers 12 order of magnitude in energy and 32 in flux
- The cosmic ray spectrum can be described by a power law

$$\frac{d\Phi}{dE} = A \cdot E^{-\gamma}$$

- Where Φ is the cosmic ray flux: the number of particles per unit surface, solid angle, time

Cosmic Ray Spectrum



$$\frac{d\Phi}{dE} = A \cdot E^{-\gamma}$$

$$\log\frac{d\Phi}{dE} = \log A - \gamma \log E$$

$$\log(E^{\beta}\frac{d\Phi}{dE}) = \log(A \cdot E^{-\gamma+\beta}) = \\ = \log A - (\gamma - \beta)\log E$$

$E < 10^9$ eV → Solar Origin

$10^{10} < E < 10^{17}$ eV → Galactic Origin

$E > 10^{18}$ eV → Extra Galactic Origin

Cosmic Ray Flux

- With any cosmic ray detector we can count the number of particles crossing a detector of surface Σ, per time unit at a given solid angle dΩ (event rate)
- The surface seen by arriving particles depends on the solid angle Ω. Therefore we define the so called geometrical factor

$$\Sigma\Omega = \int \Sigma(\Omega) d\Omega = \int \Sigma(\Omega) \sin\theta d\theta d\varphi$$

- The event rate in a detector (i.e. the number of events per second) is given by the particle flux (see below) times the geometrical factor.
- The intensity vs. energy is determined using detectors able to measure the energy of the incoming particle. Thus the number of CRs arriving in a given energy interval *dE and solid angle dΩ represents the differential intensity of particles of a given energy in the given solid angle:*

$$\Phi(E) = \frac{d^2\varphi}{dEd\Omega}(E) = \frac{dN}{\Sigma \cdot T \cdot d\Omega \cdot dE}$$

- If we can measure only the particles with energy greater than a threshold value E_0, or we are interested in the flux of particles with energy greater than E_0, we determine the *integral intensity of particles with energy > E_0*, i.e. the measurement of the CR intensity for particles with energy larger than the given threshold

$$\Phi(> E_0) = \int_{E_0}^{\infty} \frac{d^2\varphi}{dEd\Omega} dE$$

- $\Phi(E)$ → differential flux
- $\Phi(>E_0)$ → integral flux
- If we are using a planar detector the measured differential flux is:

$$\Phi(E) = \int \frac{d^2\varphi}{dEd\Omega} \cos\theta d\theta$$

- dΩ is as usual the elemental solid angle, θ the angle between the vector perpendicular to the area Σ (vertical direction) and the direction of the incoming particle.
- Having measured the cosmic ray flux we can derive the *number density* of cosmic rays moving with velocity *v*.
- To eliminate the energy range where the measured flux is modified by solar effects, we calculate the integral flux above E_0=3 GeV

$$\Phi(E) = KE^{-\gamma}(cm^{-2}s^{-1}sr^{-1}GeV^{-1})$$

$$K = 3.01, \gamma = 2.68^*$$

$$\Phi(>E_0) = \int_{E_0}^{\infty}\Phi(E)dE = \frac{K}{\gamma - 1}[E^{-\gamma+1}]_{\infty}^{E_0}$$

- * according to Wiebel-Sooth et al. (1998)

- From the integral flux we derive the cosmic rays number density.
- First we derive the particle number entering, with velocity v, a volume ΔV, with surface Σ and length l, in a unitary time.

$$\frac{\Delta N}{\Delta t} = 2\pi(sr)\Sigma(cm^{2})\Phi(cm^{-2}s^{-1}sr^{-1})$$

- The time Δt spent inside the volume is $\Delta t = l/v$

$$\Delta N = \frac{\Delta N}{\Delta t}\Delta t = 2\pi\Phi\Sigma\frac{l}{v} = 2\pi\Phi\frac{\Delta V}{v}$$

- The cosmic flux is isotropic, therefore particles enter the volume from both sides:

$$n(cm^{-3}) = 2\frac{\Delta N}{\Delta V} = 2\left(\frac{2\pi\Phi}{v}\right) = \frac{4\pi}{v}\Phi$$

- Then, using $v=c$, and the flux parameterization previously shown:

$$n_{CR}(>E_0) = \frac{4\pi}{c}\Phi(>E_0) \approx 1x10^{-10}\,cm^{-3}$$

- We can now derive the mean kinetic energy density of cosmic rays (i.e. the cosmic rays energy density)

$$\rho_{CR} = \int_{E_0}^{\infty} E \cdot n_{CR}(E)dE = \int_{E_0}^{\infty} E \cdot \frac{4\pi}{c} KE^{-\gamma} dE =$$

$$= \frac{4\pi}{c}\frac{K}{2-\gamma}[E^{-\gamma+2}]_{E_0}^{\infty} = 10^{-9}\,GeVcm^{-3} = 1eVcm^{-3}$$

- We can compare these numbers with other astrophysical quantities;
  - $n_{CR} \sim 10^{-10}$ cm^{-3} vs $n_{ISM} \sim 1$ cm^{-3} → only about one proton out of $\sim 10^{10}$ not bound in stars in the Galaxy is a relativistic particle, i.e. a cosmic ray.

- Energy density of the **interstellar magnetic field**:

$$\rho_B = \frac{B^2}{2\mu_0} = \frac{(4x10^{-10})^2}{2\cdot 4\pi 10^{-7}} \approx 0.6x10^{-13}\,Jm^{-3} \approx 0.4eVcm^{-3}$$

Taking into account all the approximations used in the calculations the two values can be considered if not equal at least similar.

- Energy density of the **Microwave Background Radiation**: the CMB radiation has a thermal black body spectrum at a temperature of 2.725 K. which corresponds to an energy of $E_{CMB} \sim 3kT = 7x10^{-4}$ eV. Using the measured number density of the CMB radiation:

  – $n_{\gamma CMB} \sim 400\ \text{cm}^{-3} \quad \rightarrow \quad \rho_{\gamma CMB} \sim 0.3\ eV\ cm^{-3}$.

- **Starlight density**. From photometric measurements of the light coming from galactic stars, astronomers have evaluated the visible photon density: $n_{\gamma vis} \sim 2x10^{-2}\ \text{cm}^{-3} \rightarrow \rho_{\gamma vis} \sim 4x10^{-2}\ \text{eV/cm}^{-3}$ assuming 2 eV/photon for the visible light.

Cosmic Rays Sources

- The sources of CRs are still unidentified. Astronomy with charged CRs is prevented by the presence of galactic magnetic fields. Only neutral probes (such as photons and neutrinos) can unambiguously point to a potential source or class of sources.

- Cosmic ray propagation in the interstellar space is the motion of charged particles in magnetic fields

- At Ultra High Energies ($E>5\times10^{19}$ eV) the arrival direction of charged particles is not significantly affected by magnetic fields. In this case proton astronomy will became possible.

- **Motion of a particles** with rest mass m_0, charge ze and Lorentz factor $\gamma=(1-v^2/c^2)^{-1/2}$ **inside a uniform and static Magnetic field B**

$$\frac{d}{dt}(\gamma m_0\vec{v}) = ze(\vec{v}\times\vec{B})$$

$$m_0\frac{d}{dt}(\gamma\vec{v}) = m_0\gamma\frac{d\vec{v}}{dt} + m_0\vec{v}\frac{d\gamma}{dt}$$

$$\frac{d\gamma}{dt} = \gamma^3\frac{\vec{v}\cdot\vec{a}}{c^2} = 0 \Rightarrow$$ Because **v** and **a** are perpendicular in a magnetic field

$$\gamma m_0\frac{d\vec{v}}{dt} = ze(\vec{v}x\vec{B})$$

- Breaking up the speed in the components parallel and perpendicular to the magnetic field.

- The **v** component parallel to **B** is constant.
- Therefore the acceleration is perpendicular both to **B** and $\mathbf{v}_\perp$. Resulting in a rotation around **B**. We can thus obtain the *gyroradius*:

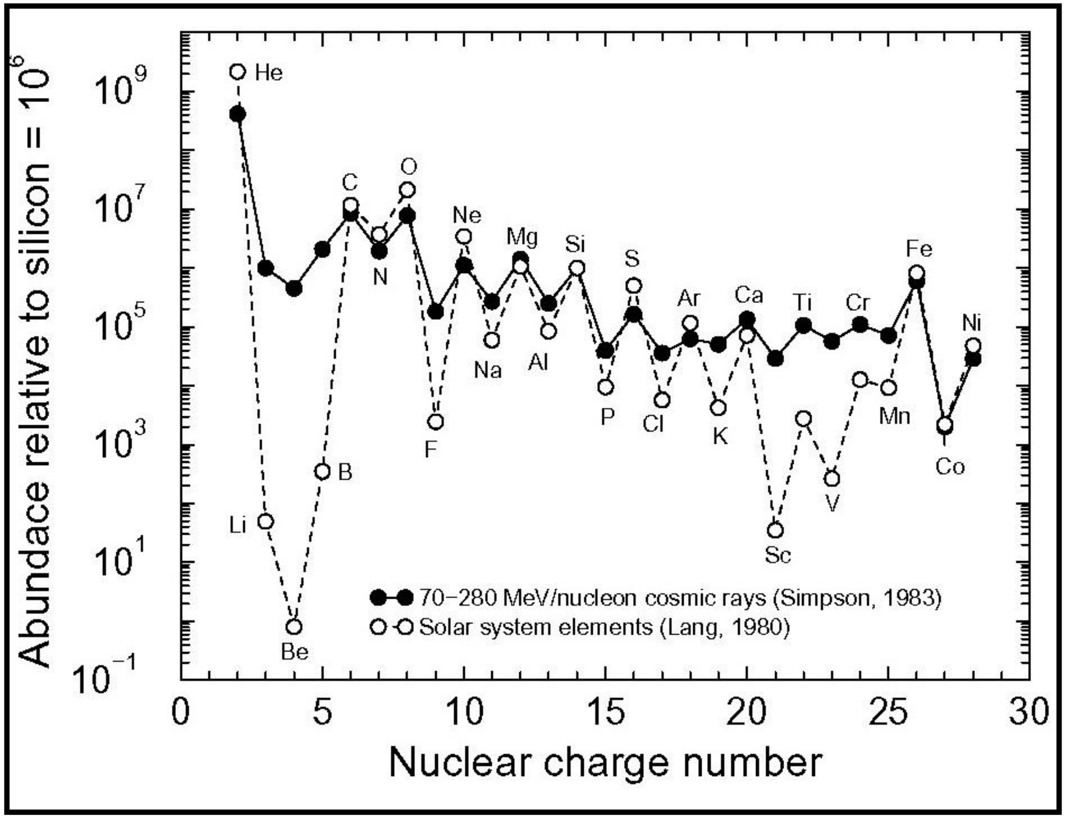
$$\frac{(v\sin\vartheta)^2}{r} = \frac{zev\sin\vartheta B}{\gamma m_0}$$

$$r = \frac{\gamma m_0 v\sin\vartheta}{zeB}$$

$$r = \frac{\gamma m_0 v}{ze}\frac{\sin\vartheta}{B} = \frac{pc}{ze}\frac{\sin\vartheta}{Bc}$$

- r values derived (in the galactic magnetic field) for protons:
  - **E=10^9 eV → r~5×10^{10} m~2×10^{-7} pc**
  - **E=10^{12} eV → r~10^{13} m=3×10^{-4} pc**
  - **E=10^{15} eV → r~10^{16} m=0.3 pc**
  - **E=10^{18} eV → r~10^{18} m=300 pc**

Cosmic rays elemental abundances



i. CNO Fe abundances are very similar both in the solar system and in CR

ii. The "odd-even" effect, in the nuclei stability, observed in the solar system is also present in CR (even if reduced)

iii. Light elements (Li, Be, B) are much more abundant in CR than in the solar system.

iv. In CR is observed a major abundance of the sub-iron elements

v. The H and He abundance is lower in CR than in the solar system.

Can we identify possible galactic sources that can explain the cosmic rays energetic budget?

- Supernovae remnants.
- We assume that:
  - Galaxy uniformly filled by relativistic CR.
  - CR sources are uniformly distributed in the galaxy.
  - CR are trapped by galactic magnetic field.
- The total kinetic energy in cosmic rays is:

$$E_{CR} = \rho_{CR} V_{GAL} = 1 eV cm^{-3} \cdot 5x10^{66} cm^{3} = 5x10^{66} eV = 8x10^{47} J$$

- If particles are confined in the galaxy this number should increase with time
- ρ_{CR} decreases because of escape of particles from the galaxy

- The CR confinement time inside the galaxy can be measured: $\tau_{ESC} \sim 10^7$ years = $3x10^{14}$ s
- Therefore the energy loss due to CR escape from the galaxy is:

$$P_{CR} = \frac{\rho_{CR} V_{GAL}}{\tau_{ESC}} = \frac{8x10^{47}\,J}{3x10^{14}\,s} \approx 3x10^{33} W$$

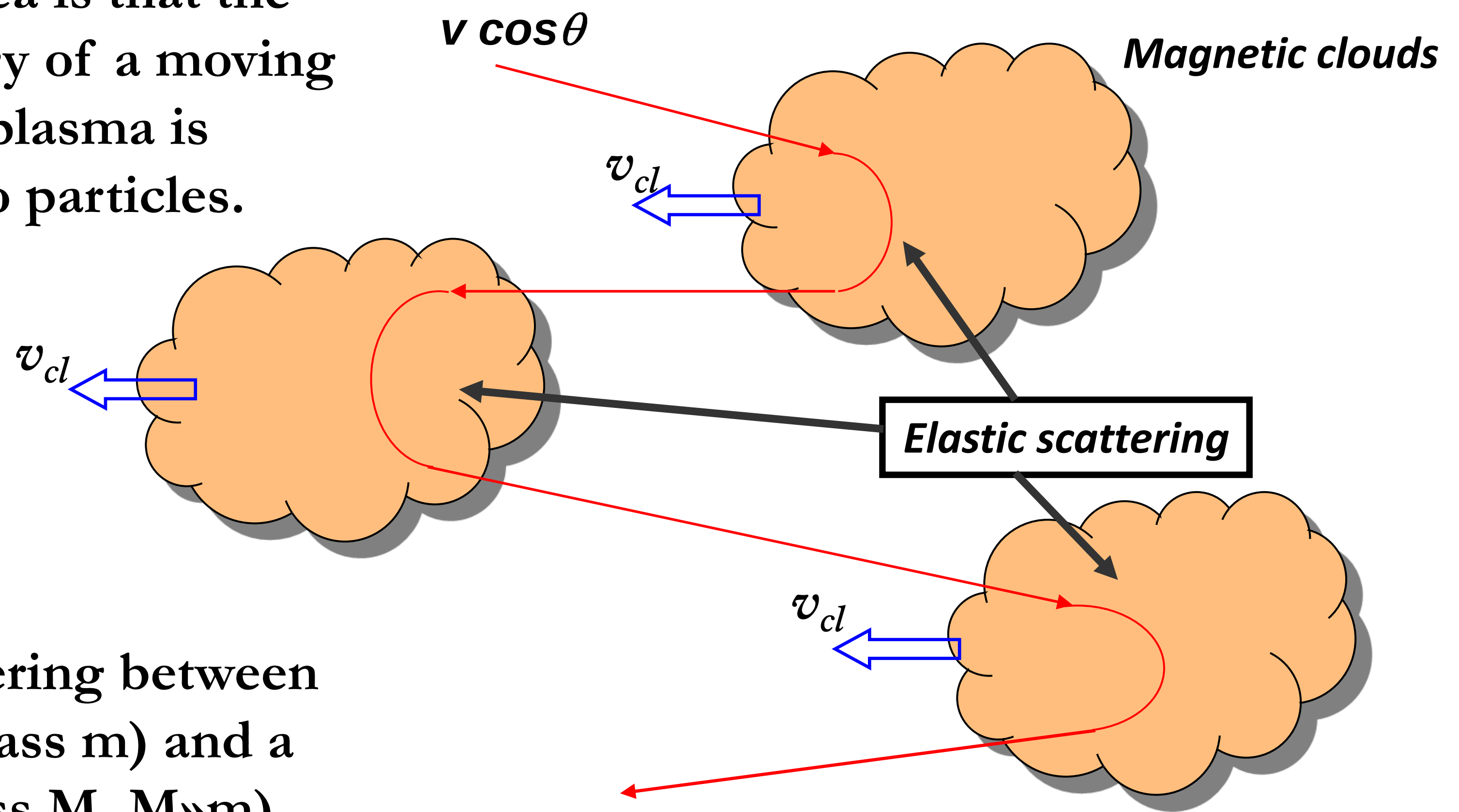
- Thus, the power required by cosmic accelerators to replenish the galactic volume corresponds to P_{CR}.
- A supernova explosion of 10 solar masses releases about 10^{46} J, 99% in form of neutrinos and 1% in form of kinetic energy of expanding particles (shock wave). The supernova rate f_{SN} in a galaxy like our own is about 3 per century ($f_{SN} \sim 10^{-9}$ s^{-1}). If a physical process able to accelerate charged particles exists, it transfers energy from the kinetic energy of the shock wave to CRs with an efficiency η:

$$P_{SN} = \eta \cdot f_{SN} \cdot 10^{44} = \eta \cdot 10^{35} W$$

- A process with efficency $\eta \sim 10^{-2}$ is enough to have $P_{CR} \sim P_{SN}$.

- **Supernovae explosions** not only can originate **the energy required for particle acceleration**, but are also sites where, through following scatterings with the shock emitted in the explosion, we can derive **a power law spectrum**.

The basic idea is that the kinetic energy of a moving magnetized plasma is transferred to particles.



Elastic scattering between a particle (mass m) and a "cloud" (mass M, M»m)

- In each scattering the particle energy is increased by an amount proportional to its energy:

$$\Delta E = \kappa E$$

- After *n* scattering

$$E_n = E_0 (1+\kappa)^n$$

- Being E_0 the particle energy at the injection into the accelerator
- The scattering number needed to reach an energy E_n is:

$$n = \frac{\ln(E_n / E_0)}{\ln(1+\kappa)}$$

- P_{esc} is the probability that the particle comes out of the acceleration region at each scattering. The probability of being inside the same region after *n* scattering therefore is:

$$(1-P_{esc})^n$$

- In order to reach the energy E_n a particle must be confined inside the acceleration region for at least n scatterings.
- We can calculate the number of particles with energy E_n:

$$N_n = N_0(1-P_{esc})^n = N_0(1-P_{esc})^{\ln(E_n/E_0)/\ln(1+\kappa)}$$

$$N_n = N_0 e^{\ln(1-P_{esc})^{\ln(E_n/E_0)/\ln(1+\kappa)}} = N_0 e^{\ln(E/E_0)^{\ln(1-P_{esc})/\ln(1+\kappa)}}$$

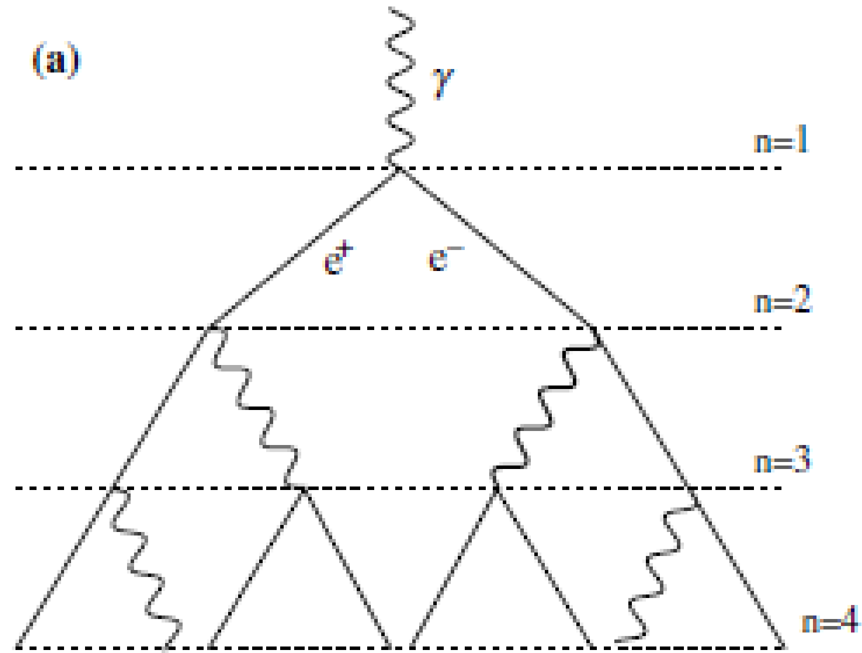
therefore

$$N_n = N_0\left(\frac{E}{E_0}\right)^{\gamma}$$

$$\gamma = \frac{\ln(1-P_{esc})}{\ln(1+\kappa)} \Longrightarrow$$ n.b. $\gamma<0 \rightarrow (1-P_{esc})<1$

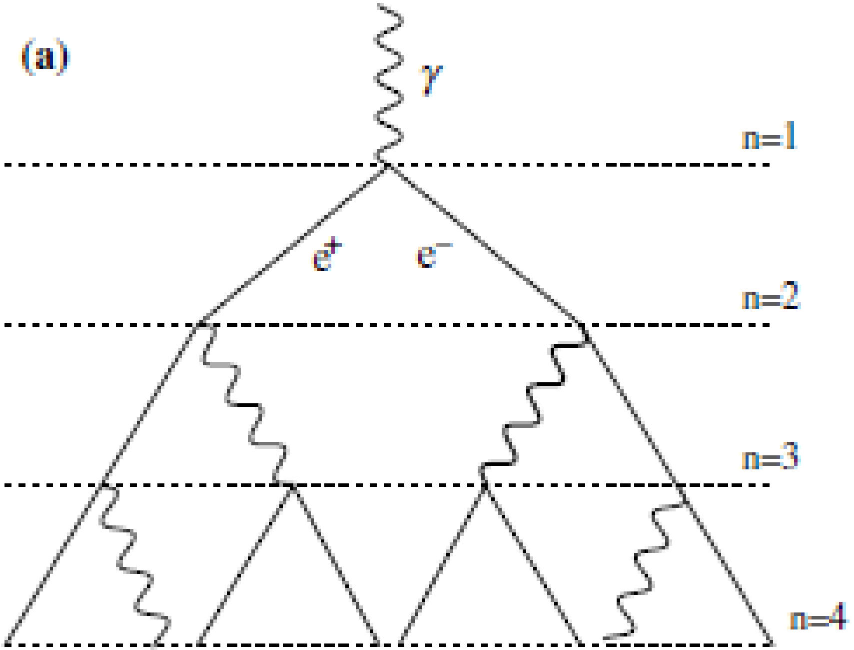
CR interaction with an atmospheric nucleus

- Shower generated by a E_0 energy γ
- γ crossing the distance $d = \lambda_T \ln 2$ (d being the distance after which an electron looses, on average, half of its energy, "half-length", in air → $\lambda_T = 37\ g\ cm^{-2}$) produce a $e^+ e^-$ pair
- A γ is radiated by an electron (bremmstrhalung) after the same distance d
- In both processes we suppose that the energy is equally divided between the two emitted particles



- Having crossed *n* "half-lengths" (corresponding to an amount of matter $x=nd$) the shower is made by 2^n particles, each one of energy: $E/2^n$.

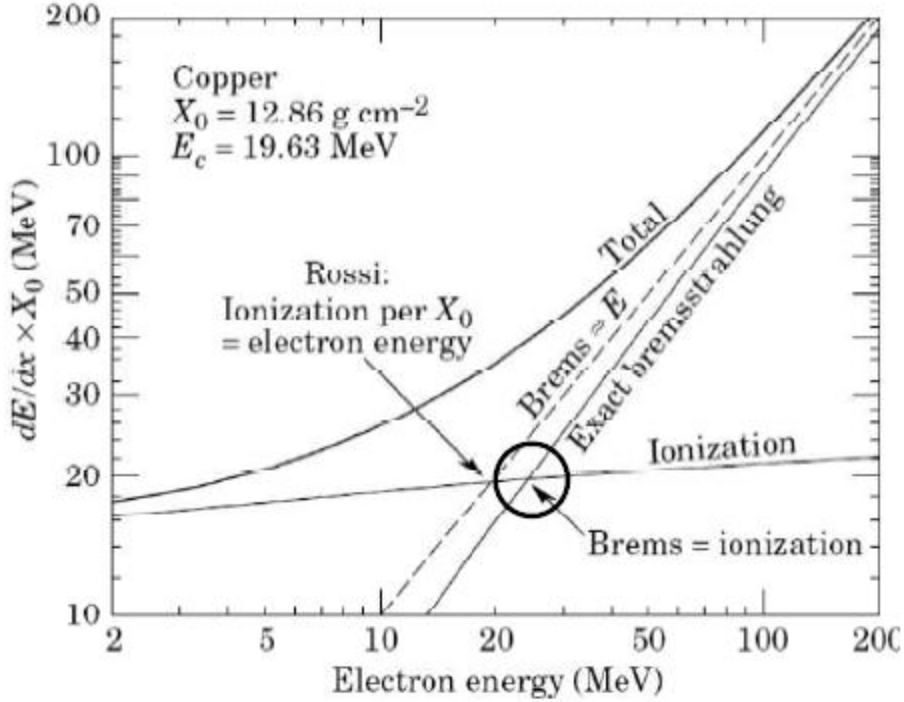
  $x = n\,\lambda_T\, ln2$



- $N=2^n \rightarrow 2^{\frac{x}{\lambda_T \ln 2}}$
- $\ln 2 = \log_2 2 \;/\; \log_2 e$
- $N = 2^{\frac{x}{\lambda_T}\log_2 e} = e^{\frac{x}{\lambda_T}}$
- $\mathbf{E_n = E_0/2^n}$

- **Extensive Air Shower (EAS)**

- This growth ends when particle's energy becomes smaller than the critical energy (E^{γ}_{cr}, energy where radiation energy losses get smaller than the ionization's ones.
In air E^{γ}_{cr}=85 MeV).



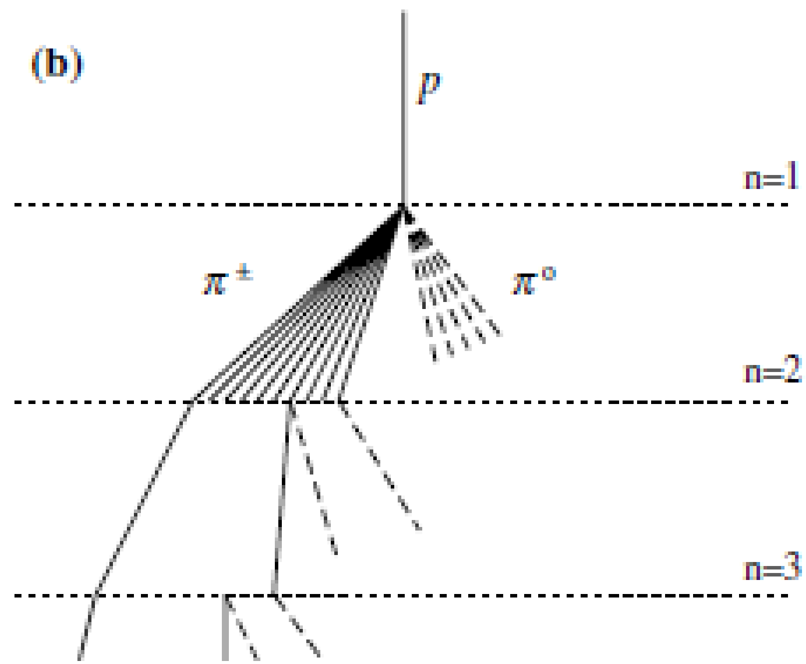
- Therefore the particle number at shower maximum development is:

$$E_0 = N_{max} E^{\gamma}_{cr} \qquad N_{max} = 2^{n_{cr}} \qquad n_{cr} = \frac{1}{\ln 2} \ln \frac{E_0}{E^{\gamma}_{cr}}$$

➢ $N_{max} \propto E_0 \qquad X_{max} \propto n_{cr} \propto \ln E_0$

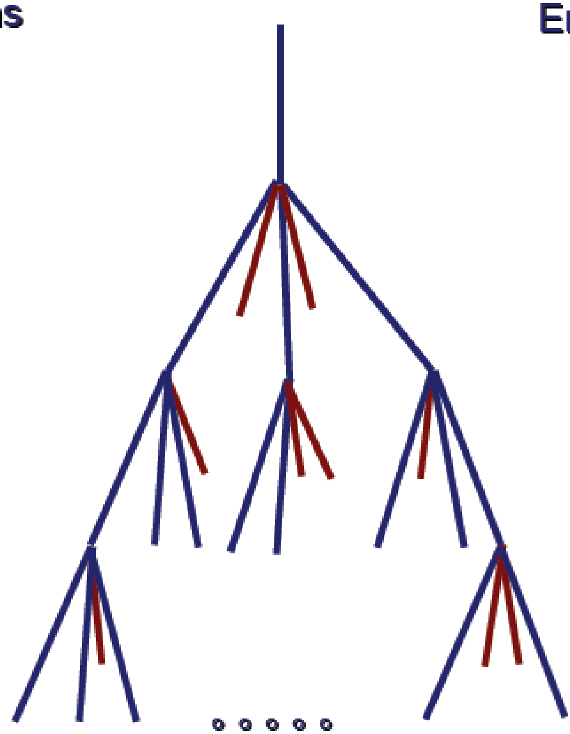
Hadronic Showers

- Atmosphere is represented as layers of depth $\lambda_I ln2$. Where λ_I is the interaction length for particles suffering strong interactions. We assume that λ_I is constant, for π in air $\lambda_I \approx 120\ g\ cm^{-2}$
- Having crossed one layer an hadron generates N_{ch} charged pions and ½ N_{ch} neutral pions.
- $\pi^0 \rightarrow 2\gamma$ (τ=8.5x10^{-17} s)
- Shower development continues until the charged pions energy gets smaller than the pion critical energy (E^{π}_{cr}), below which all pions decay
- $\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$ (τ=2.6x10^{-8} s)



Energy transfer in air showers

Energy of all hadrons		Energy of all em. particles
E_0		0
$\frac{2}{3}E_0$		$\frac{1}{3}E_0$
$\frac{2}{3}\left(\frac{2}{3}E_0\right)$		$\frac{1}{3}E_0+\frac{1}{3}\left(\frac{2}{3}E_0\right)$



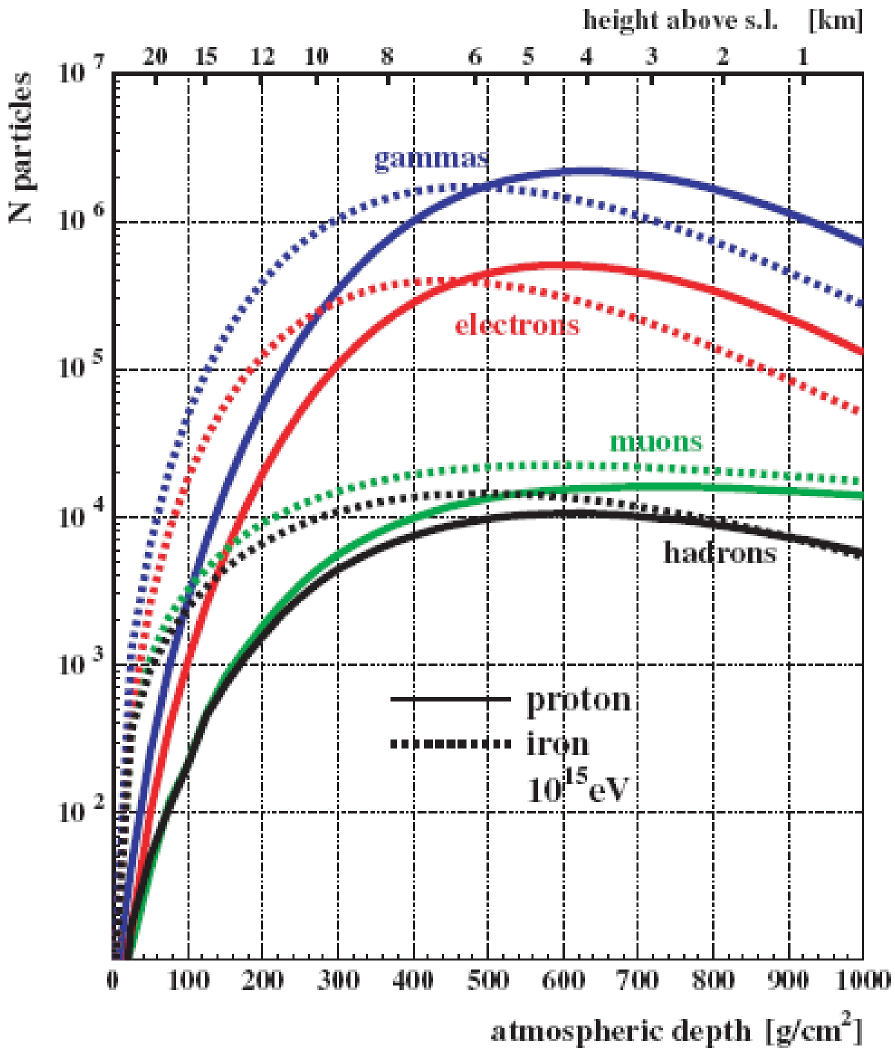
After *n* generations

$$E_{\text{had}}=\left(\frac{2}{3}\right)^{n}E_0$$

(n=5, E_{had}~12%
n=6, E_{had}~8%)

$$E_{\text{em}}=\left[1-\left(\frac{2}{3}\right)^{n}\right]E_0$$

EAS evolution in atmosphere



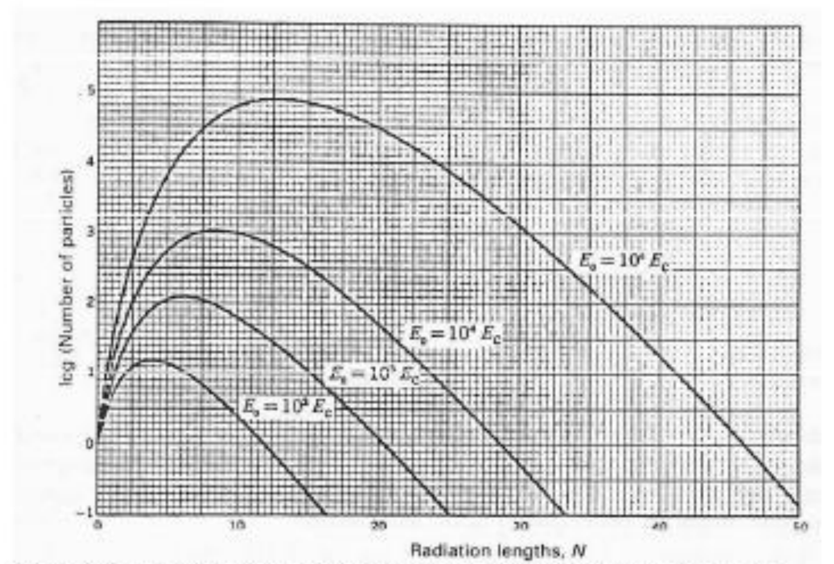


Figure 4.18. The total number of particles in a shower initiated by an electron of energy E_0 as a function of depth through the medium measured in radiation lengths N; E_c is the critical energy. (From B. Rossi and K. Greisen (1941). *Rev. Mod. Phys.*, **13**, 240.)

EAS development and detectable signals reaching observation level