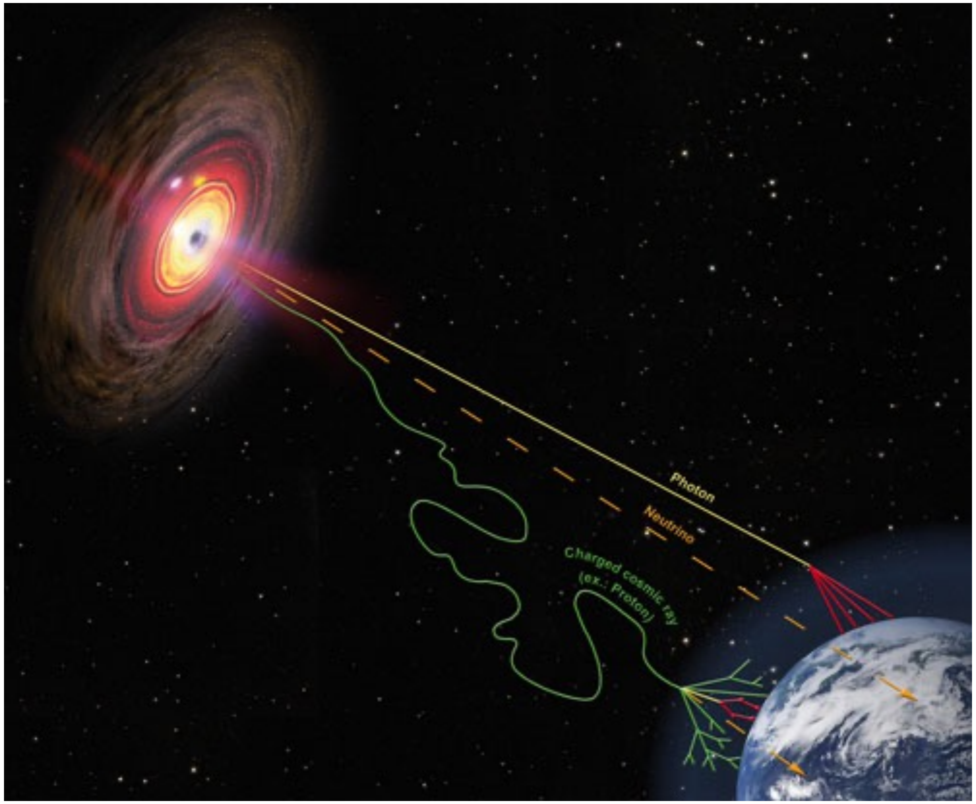
Physics and Applied Physics master programs - A.Y. 2024-2025

Introduction to astroparticle physics

Part 2 – Lesson 1 – April 11, 2025



Prof. **Chiara Perrina**

E-mail: Chiara.Perrina@epfl.ch

Learning outcomes and goals

- Describe the cosmic ray (CR) energy spectrum and composition. Discuss CR origin, acceleration and propagation.
- Explain the relationship between charged CRs, cosmic gamma-rays and cosmic neutrinos.
- Discuss the detection principles of the measured quantities (mass, charge, momentum, energy, rigidity, …) of astroparticle physics experiments.
- Interpret the main results of selected experiments
- Assess / Evaluate the state of the art of astroparticle physics

No history https://timeline.web.cern.ch/timeline-header/146

Cosmic rays were discovery by Victor Hess in 1912

In CRs we discovered:

- the positron (first antiparticle, 1932);
- the muon (first second-generation matter particle, 1936);
- the pion (first meson, 1947);
- the kaon (1947) and the lambda (1950) (first particles containing the strange quark).

Lesson 1 -- Bibliography

- **The Review of Particle Physics**

  S. Navas et al. (Particle Data Group) Phys. Rev. D **110**, 030001 (2024)

  https://pdg.lbl.gov

  https://pdg.lbl.gov/2024/reviews/contents_sports.html

  https://pdg.lbl.gov/2024/reviews/rpp2024-rev-cosmic-rays.pdf

- **Particle Astrophysics**

  Donald Perkins

  Oxford University (Second Edition)

  Chapter 9: Cosmic particles

- **Introduction to Particle and Astroparticle Physics**

  Alessandro De Angelis and Mário Pimenta

  Springer (Second Edition, 2018)

  Chapter 10: Messengers from the High-Energy Universe

  https://link.springer.com/book/10.1007%2F978-3-319-78181-5

Lesson 1 -- Bibliography

- **High Energy Astrophysics: Volume 2, Stars, the Galaxy and the Interstellar Medium**

  M. S. Longair

  Cambridge University Press (Second Edition, 1994)

  Chapter 21: The acceleration of high energy particles

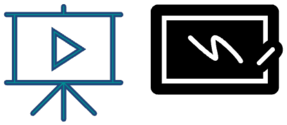
- **Cosmology and particle astrophysics**

  Lars Bergström and Ariel Goobar

  Springer (Second Edition, 2006)

  Chapter 12: Cosmic Rays

Method



Slides and blackboard, during lectures and exercises.

Slides and video recording (A.Y. 2021-2022) will be uploaded after each lecture on the Moodle page:

(https://moodle.epfl.ch/course/view.php?id=14967).

Evaluation

Oral exam:
Wednesday, June 18
from 08:15 to 18:15 (GR C0 01)

20/25 minutes:
preparation
+
20/25 minutes:
discussion

4 ECTS

We will prepare the schedule of oral exam with Wish https://wish.agepoly.ch

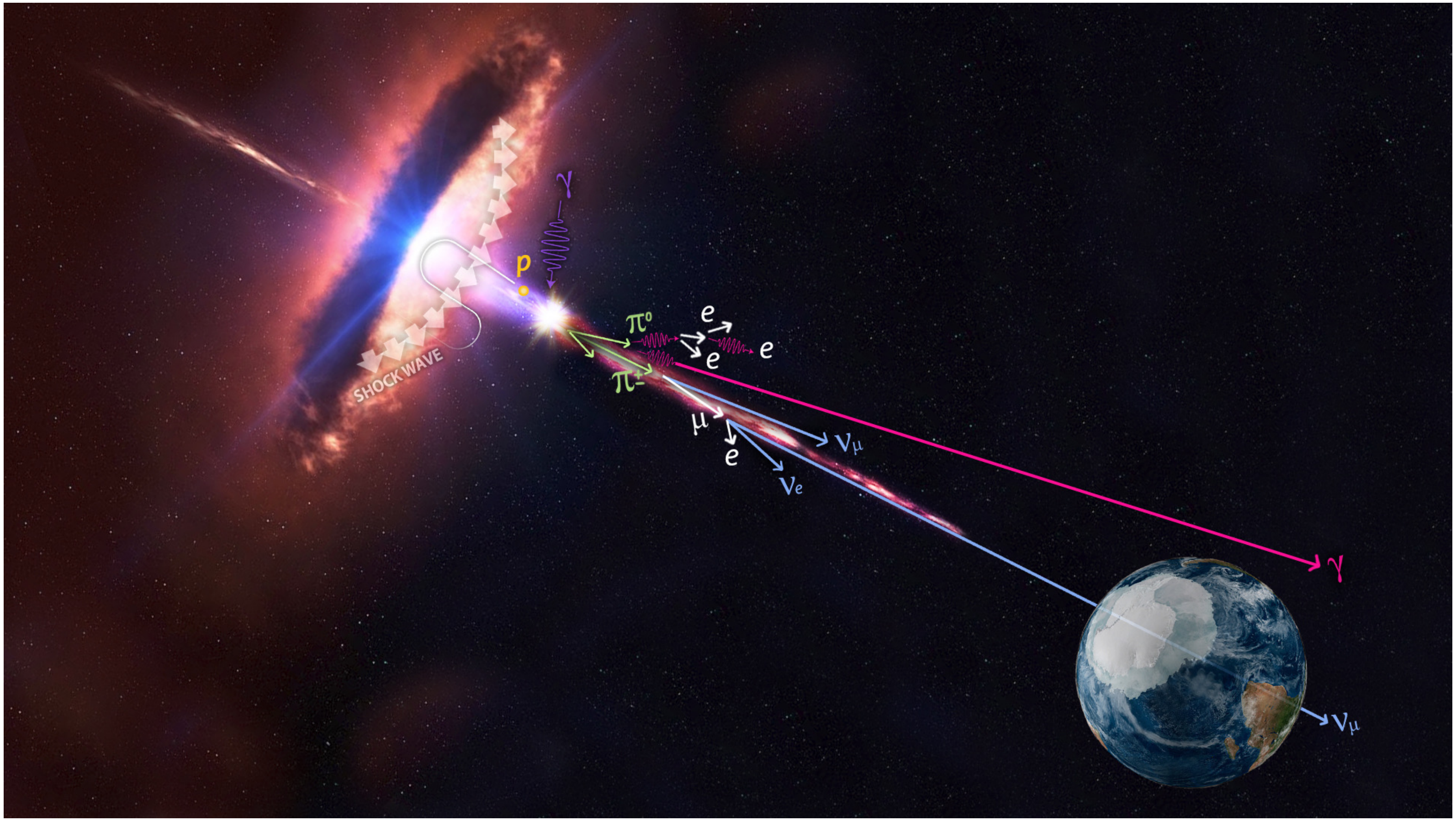
Wish distributes people in various slots maximizing the global satisfaction

Cosmic rays

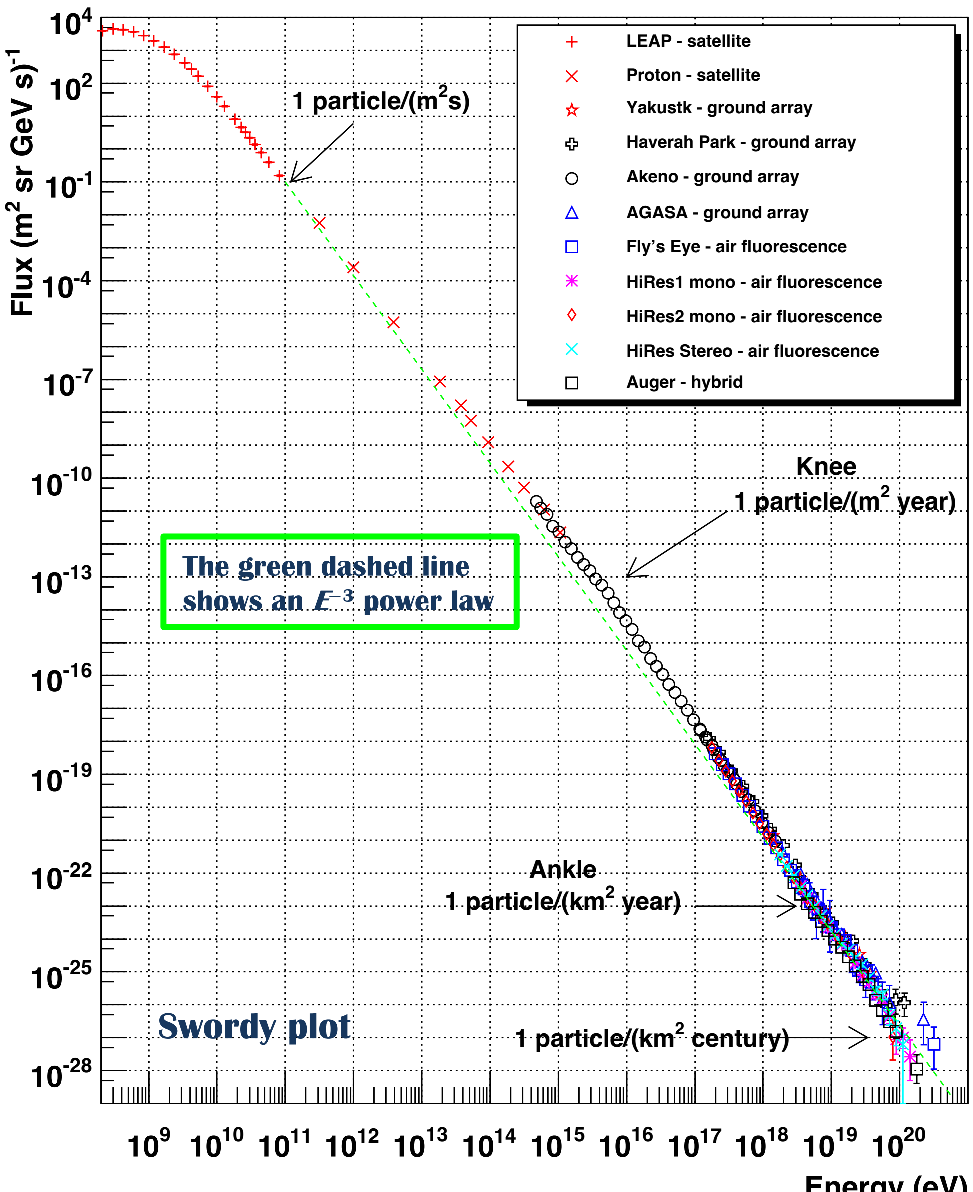
Energetic elementary particles and nuclei continually hitting the Earth's atmosphere

1) What is the energy of these particles/nuclei?
2) How many are there?
3) What kind of particles/nuclei are they?
4) Where are they produced?
5) How are they accelerated?
6) How do they propagate?
7) How can we detect them?

Charged elementary particles (p, e-, e+, anti-p) and nuclei (He, Li, Be, ...)



All-particle differential energy flux of CRs$^{\pm}$



The CR spectrum spans over
- > 12 orders of magnitude in **Energy (E)**
- > 32 orders of magnitude in **Differential Flux**

The differential flux above 10 GeV is a segmented/broken **power law of** E:

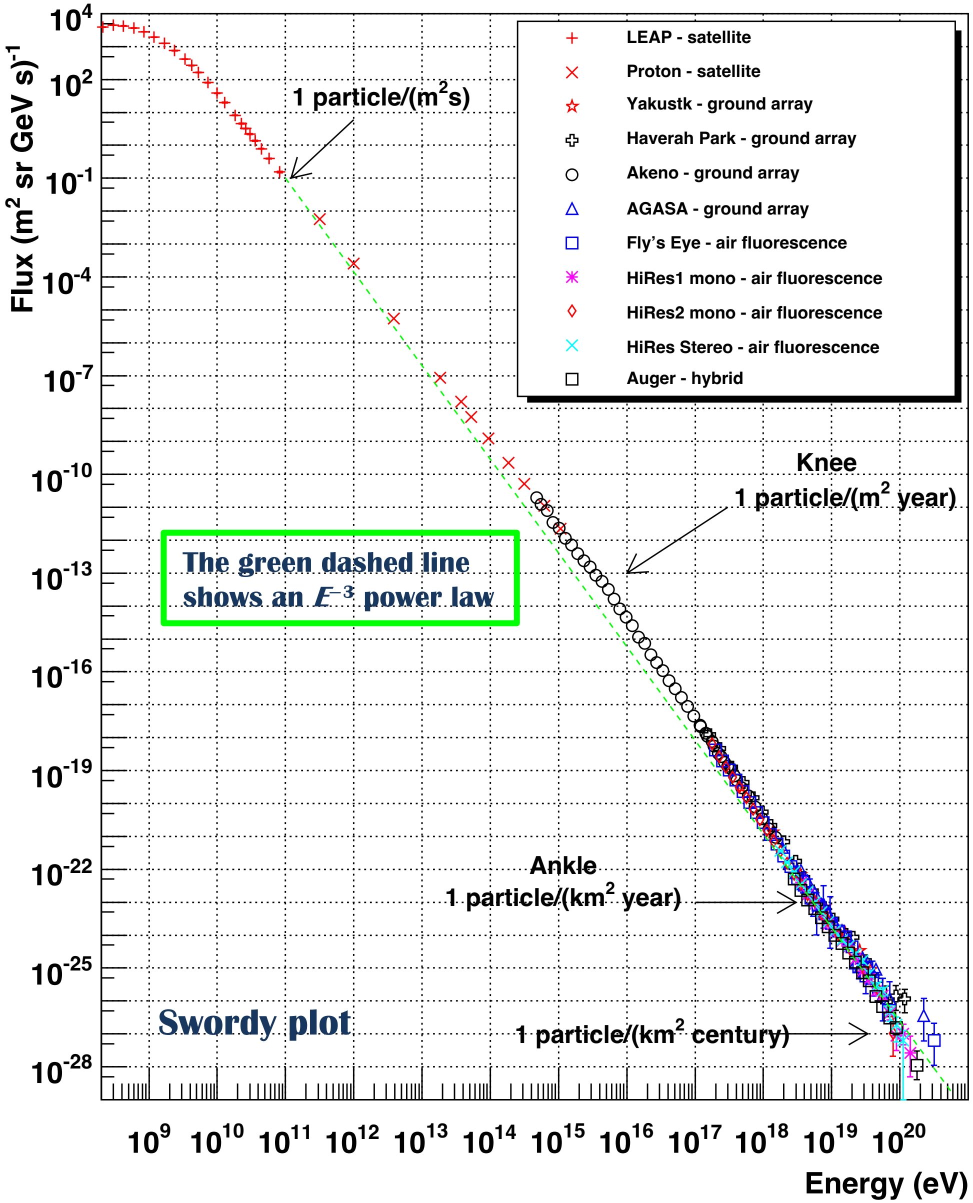
$$F(E) = \frac{N(E)}{dA\, d\Omega\, dE\, dt} = k\, E^{-\gamma}$$

- k is a constant that does not depend on E (from several GeV to beyond 100 TeV, $k = 1.8 \times 10^4\ \mathrm{GeV}^{1.7}\ \mathrm{m}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$)
- γ is the **differential spectral index**

Knee at $E_{\mathrm{knee}} \cong 5$ PeV
2nd Knee at $E_{\mathrm{2knee}} \cong 100$ PeV
Ankle at $E_{\mathrm{ankle}} \cong 5$ EeV
GZK cut-off at $E_{\mathrm{GZK}} \cong 10$ EeV

$$\gamma = \begin{cases} 2.7 & 10\ \mathrm{GeV} < E < E_{\mathrm{knee}} \\ 3 & E_{\mathrm{knee}} < E < E_{\mathrm{2knee}} \\ 3.3 & E_{\mathrm{2knee}} < E < E_{\mathrm{ankle}} \\ 2.5 & E_{\mathrm{ankle}} < E < E_{\mathrm{GZK}} \end{cases}$$

All-particle differential energy flux of CRs$^{\pm}$

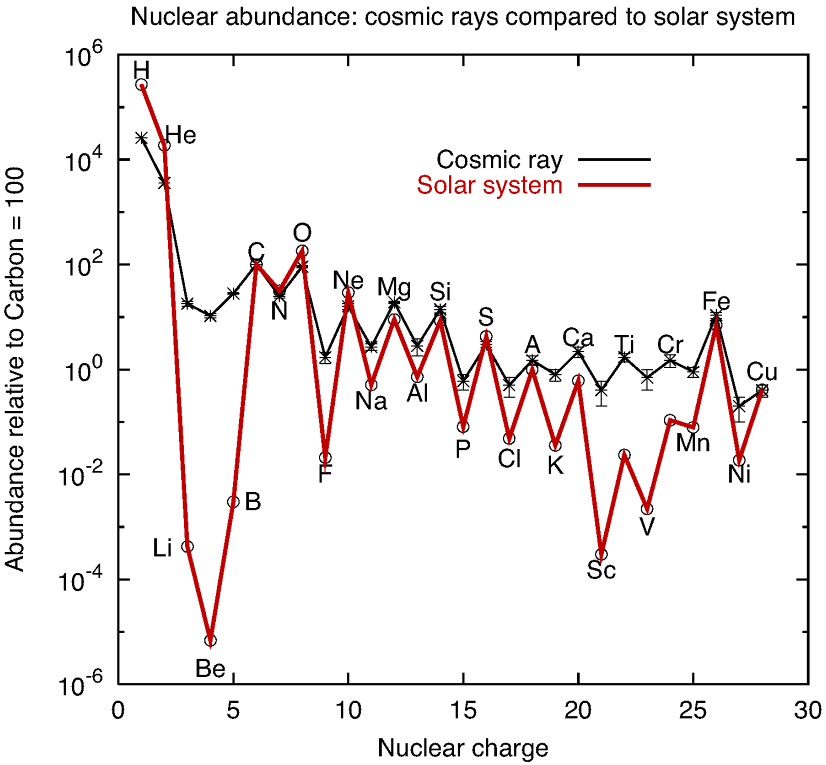


$E < 10$ GeV : charged CRs are affected by the Earth's magnetic field and by the modulation in time due to the solar wind

98 % nuclei (p, He, Li, …)
< 1 % electrons
~ 0.01 % positrons and anti-protons

Up to few PeV, CRs are believed to be of galactic origin; above a few EeV, the sources are most likely extragalactic.

Chemical composition of cosmic nuclei



Solar system abundances derived from the spectral lines in the photosphere of the Sun and from the studies of meteorites

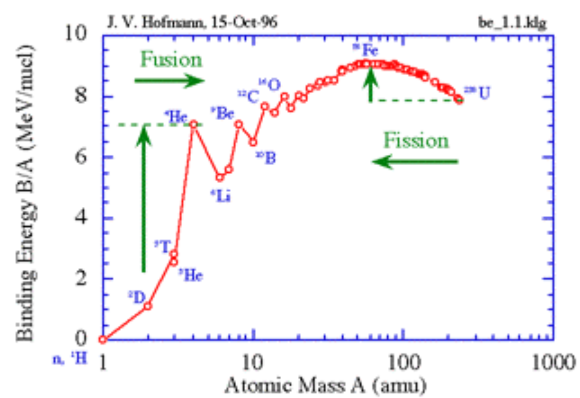
In both:

94%	H
6%	He
< 1%	others

- Protons and helium nuclei are **less abundant** in cosmic rays than in the solar system.

- In both cosmic rays and solar system abundances:

1) There is a peak for carbon (C), oxygen (O) and iron (Fe).
2) There is an even-odd effect: (A-Z, Z) even-even are more abundant.



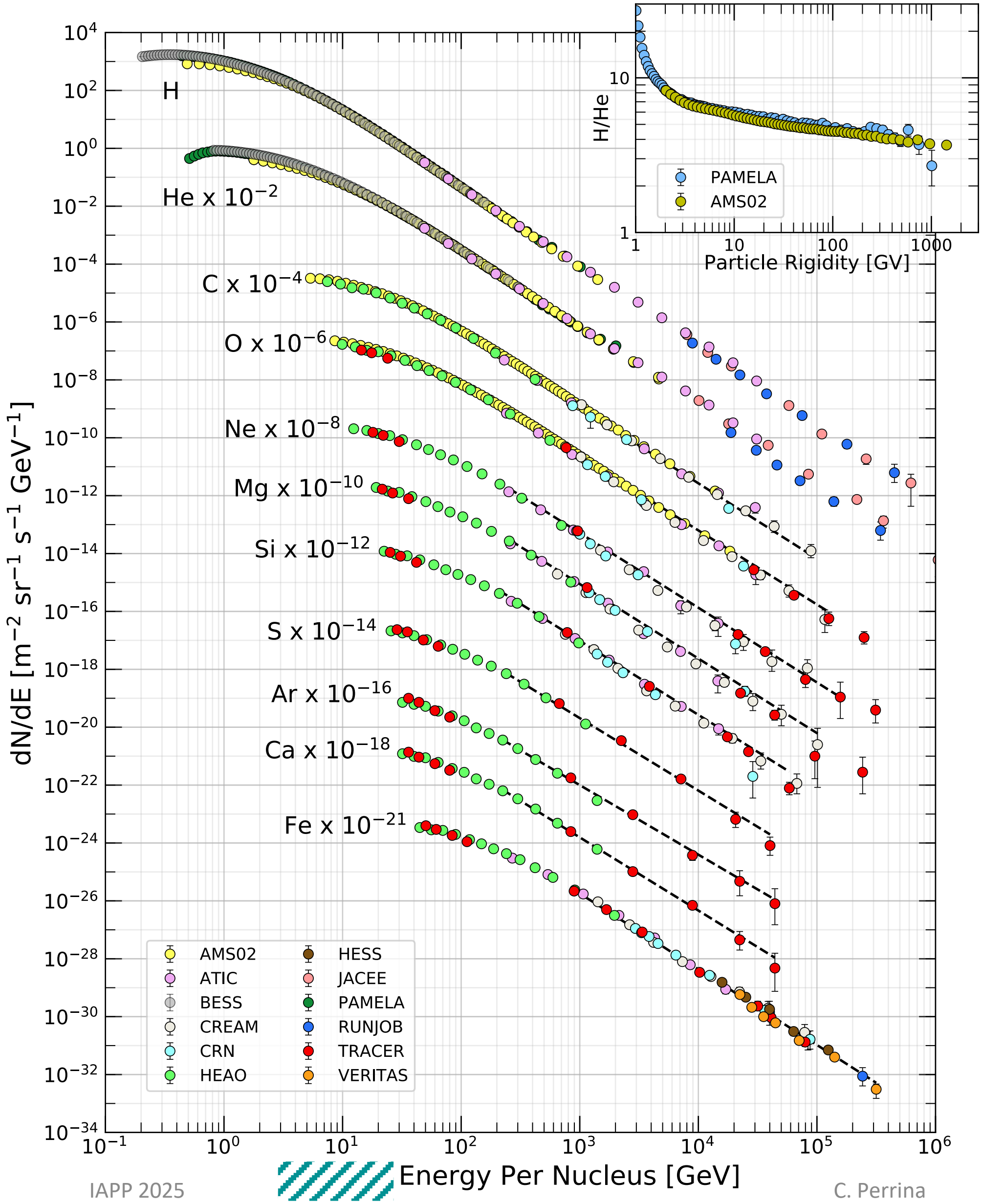
#p,#n	EE	OO	EO	OE	Tot
Stable	146	5	53	48	252

- Two groups of elements

1) lithium (Li), beryllium (Be), boron (B)
2) scandium (Sc), titanium (Ti), vanadium (V,) chromium (Cr), manganese (Mn)

are significantly more abundant in cosmic rays than in the solar system.

Chemical composition of primary CR nuclei



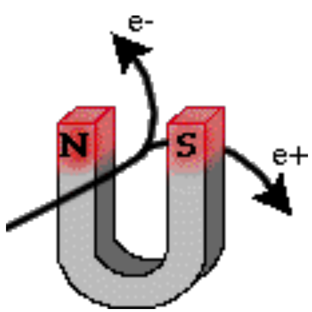
Is the x-axis showing total or kinetic energy?

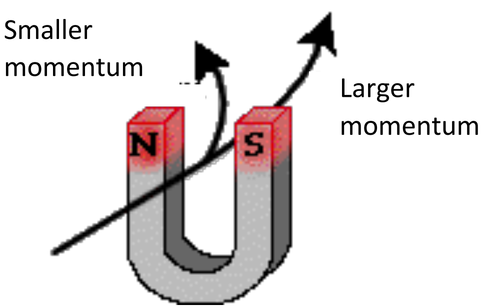
A. Total

B. Kinetic

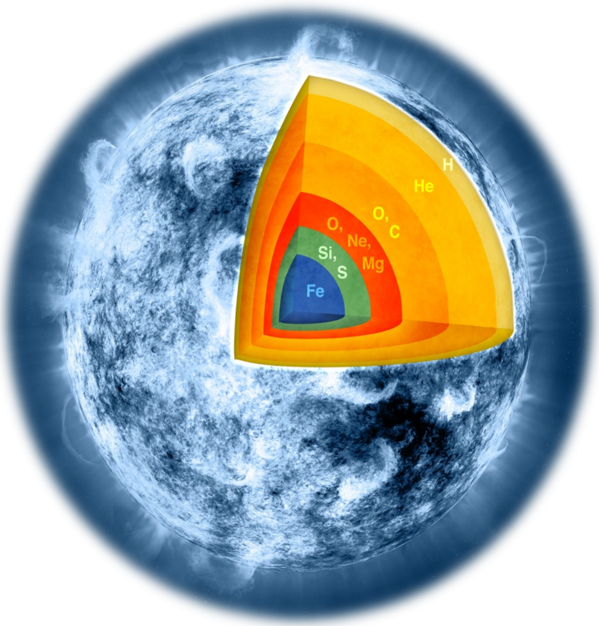
What is the magnetic rigidity of a charged particle?

$$R = \frac{pc}{q} = \frac{pc}{Ze} \qquad [R] = \text{Voltage} = [\text{V}]$$





Primary cosmic rays



Nuclear fusion in stars

Primary elements,
(protons, nuclei of He, C,
O, Ne, Mg, Si..., Fe)
are **produced**
during the lifetime of
stars.

Acceleration of cosmic rays

Perkins

How do CRs reach their huge energies?

Why a power law spectrum?

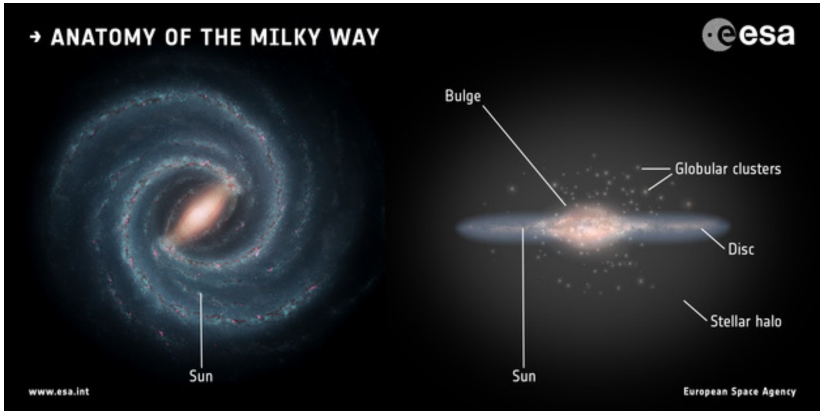
Acceleration mechanism

What can accelerate CRs?

How do CRs reach their huge energies?

The power required to accelerate CRs in the disc of our Galaxy is:

$$W_{\mathrm{CR}} = \frac{\rho_{\mathrm{CR}} \times V}{\tau}$$



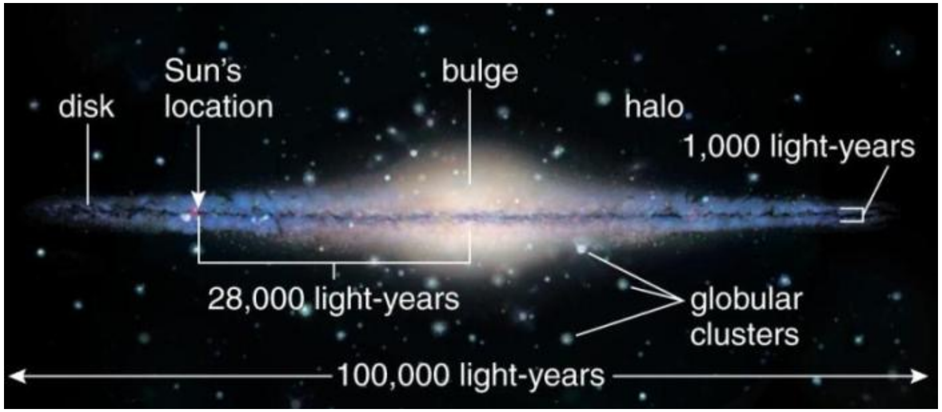
$\boldsymbol{\rho_{CR} = 1\ \mathrm{eV/cm^3}}$: cosmic-ray energy density

$\boldsymbol{\tau_{\mathrm{CR\ in\ MW}} = 3\ \mathrm{Myr}}$: CR residence time in the Galaxy (MW)

$\boldsymbol{V = \pi R^2 D}$: volume of the disc

$\boldsymbol{R = 50'000\ \mathrm{ly} = 15\ \mathrm{kpc}}$: radius of the disc

$\boldsymbol{D = 1'000\ \mathrm{ly} = 0.3\ \mathrm{kpc}}$: height of the disc



$\boldsymbol{1\ \mathrm{pc} = 3 \times 10^{16}\ \mathrm{m}}$

$\boldsymbol{1\ \mathrm{pc} = 3.3\ \mathrm{ly}}$

https://pdg.lbl.gov/2023/reviews/rpp2023-rev-phys-constants.pdf
https://pdg.lbl.gov/2023/reviews/rpp2023-rev-astrophysical-constants.pdf

How do CRs reach their huge energies?

The power required to accelerate CRs in the disc of our Galaxy is:

$$W_{\mathrm{CR}} = \frac{\rho_{\mathrm{CR}} \times V}{\tau}$$

$$[W_{\mathrm{CR}}] = [\mathrm{J/yr}]$$

$\boldsymbol{\rho_{CR} = 1\ \mathrm{eV/cm^3}}$: cosmic-ray energy density

$\boldsymbol{\tau_{\mathrm{CR\ in\ MW}} = 3\ \mathrm{Myr}}$: CR residence time in the Galaxy

$\boldsymbol{V = \pi R^2 D}$: volume of the disc

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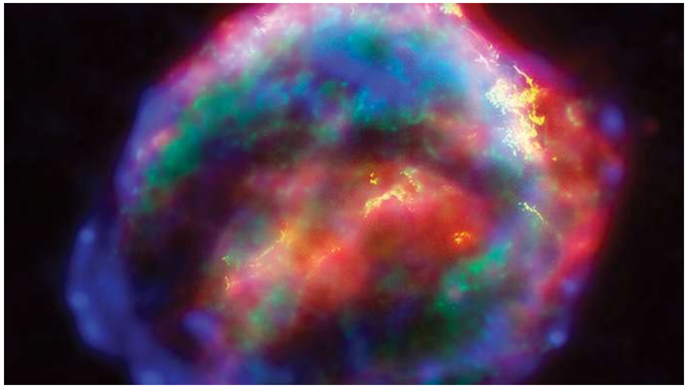
$\boldsymbol{1\ \mathrm{pc} = 3\times 10^{16}\ \mathrm{m}}$

$\boldsymbol{1\ \mathrm{pc} = 3.3\ \mathrm{ly}}$

$$W_{\mathrm{CR}} = 3 \times 10^{41}\ \mathrm{J/yr}$$

Who can provide this power?



A Type II Supernova is a Supernova (star at the end of its life cycle which goes through a violent explosion) which spectrum contains lines of hydrogen, ejecting in the interstellar medium a shell with:

$$M = 10\ M_{\odot}$$

$$v = 10^{7}\ \mathrm{m/s}$$

$$f = (2 \pm 1)/\text{century}$$

$$\boldsymbol{M_{\odot} = 2 \times 10^{30}\ \mathrm{kg}}$$

$$W_{\mathrm{SN-T2}} = \frac{1}{2}\ M\ v^{2}\ f$$

$$W_{\mathrm{SN-T2}} = 2 \times 10^{43}\ \mathrm{J/yr}$$

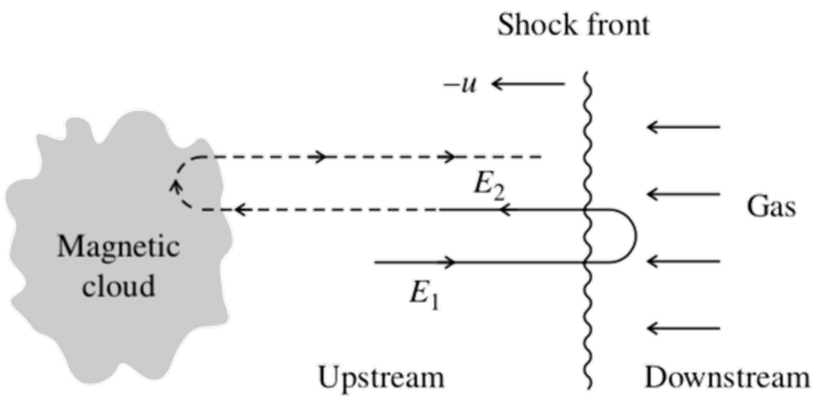
$$W_{\mathrm{CR}} = 3 \times 10^{41}\ \mathrm{J/yr}$$

Even if the shell transmits only a few percent of its kinetic energy to cosmic rays, it would be enough to account for the total cosmic ray energy density.

Acceleration mechanism

E. Fermi proposed that the CR acceleration could be due to shock fronts (acting as magnetic mirrors). There are many sources of shocks and Type II supernovae shells seem to be good candidates.

When a relativistic charged particle, travelling in the positive *x*-direction, is scattered backwards by the field due to a shock front moving with non-relativistic velocity *u* in the negative *x*-direction, it receives a **fractional energy increase** of order *u*/*c*.



$$\frac{\Delta E}{E} \sim \frac{u}{c} \equiv \alpha$$

At each step of the acceleration the particle can escape further cycles.
Let *P* be the probability that the particle stays for further acceleration.

Why a power law spectrum?

$\Delta E = \alpha E$

P is the probability that the particle stays in the process.

Step	Energy	Number of particles
0	E_0	N_0
n	$E_n = E_0(1+\alpha)^n$	$N_n = P^n N_0$

Why a power law spectrum?

$E = E_0(1+\alpha)^n$

$N = P^n N_0$

$$s \equiv -\frac{\ln(P)}{\ln(1+\alpha)}$$

$$\frac{dN}{dE} = \text{constant} \times E^{-s-1}$$

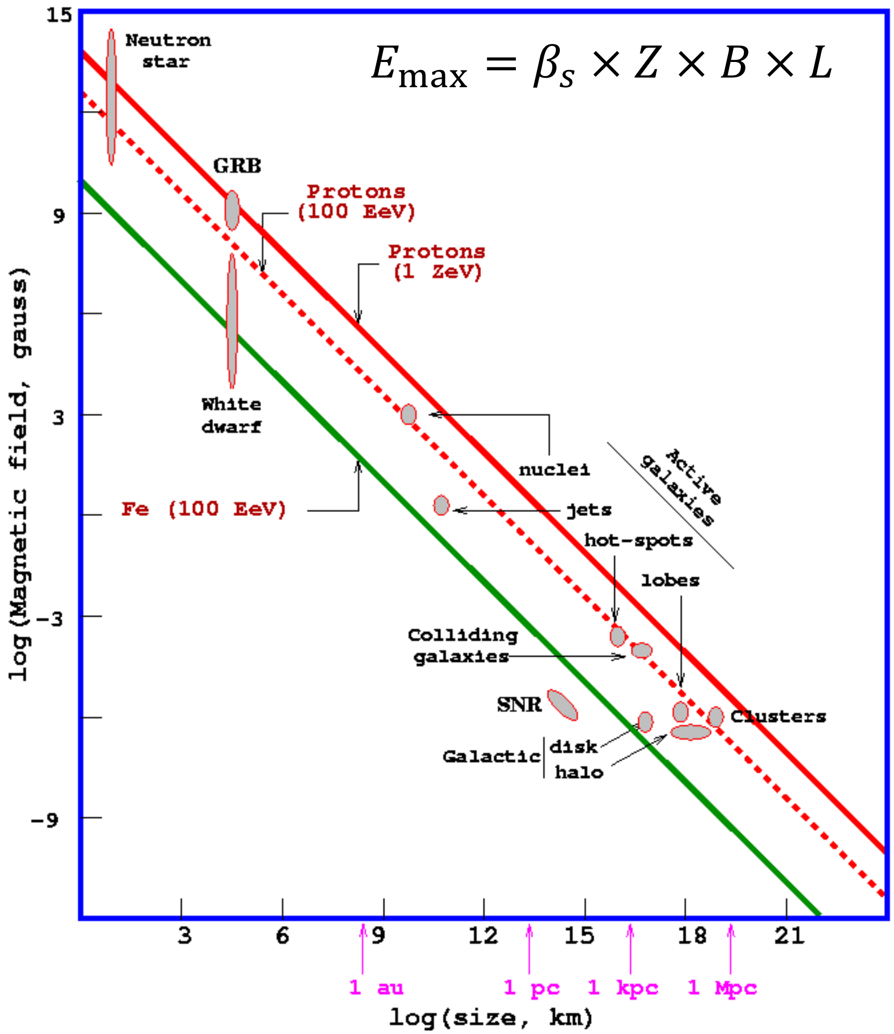
For shock-wave acceleration, typically *s* = 1.1

$$\frac{dN}{dE} = \text{constant } E^{-2.1}$$

The softer spectrum observed ($\gamma = 2.7$) could be explained if the escape probability (1−*P*) is energy dependent.

Who can accelerate CRs?

Hillas criterion: The source must have a **Size (*L*)** at least of the order of the **Larmor radius (r_L)**



$$\frac{E}{1\,\mathrm{PeV}} \simeq Z \frac{B}{1\,\mu\mathrm{G}} \times \frac{R}{1\,\mathrm{pc}} \simeq 0.2 Z \frac{B}{1\,\mathrm{G}} \times \frac{R}{1\,\mathrm{AU}}$$

β_s is the acceleration efficiency of the source and depends on the shock velocity and on the geometry

In the Galaxy, the prime candidate sources are **supernova remnants** where particles can be shock-accelerated by their shock waves. Other candidates are **pulsars, star cluster winds, stellar wind binaries, micro quasars** (a source powered by accretion from a donor star onto a stellar mass black hole) or the Galactic Center. The candidate sources for extragalactic CRs are **Active Galactic Nuclei** (AGN), **gamma-ray bursts**, **starburst galaxies** and **magnetars**.