HIGH-ENERGY TRANSIENTS AND THE MULTIMESSENGER CONTEXT

A course for the Bachelor and Master Degree Programs

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University of Tirana – June 2026

OUTLINE

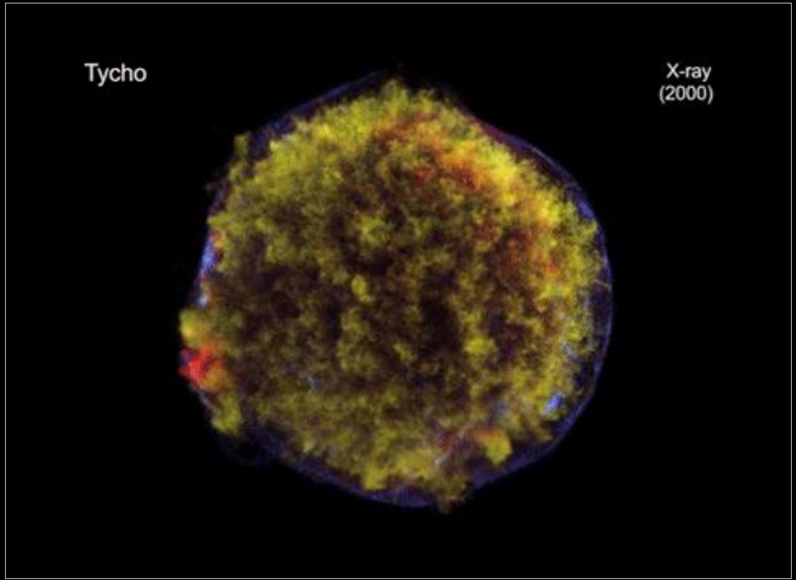
1. Introduction and overview of High-energy and Multimessenger astrophysics
2. **Cosmic rays in Our Galaxy**
3. Galactic and Extragalactic Accelerators, Acceleration Mechanisms
4. The sky seen in Gamma-Rays
5. Gamma-Ray Bursts
6. Gravitational Wave observations
7. HE neutrino observations
8. The TeV sky and multiwavelength observations

2. COSMIC RAYS IN OUR GALAXY

Properites, composition, propagation, acceleration

COSMIC RAYS

- Gamma-ray production is **intimately related** to the production of **Cosmic Rays (CRs)**
- **Charged particles**, mainly **protons**, whose **energy spectrum** covers a **very wide range in energy and flux**



- The nature of **cosmic accelerators** is one of the **major unsolved astrophysical problems**
  - The sites of **cosmic ray acceleration** in our Galaxy are strictly correlated with the **dynamics of formation**
    - **Massive stars**
    - **Stellar evolution**
    - **Supernova explosions**

➔ **Study of cosmic radiation helps understand the formation of our own solar system**

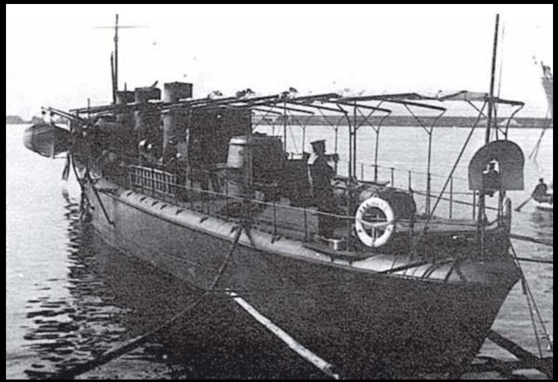
THE DISCOVERY OF COSMIC RAYS

- 1785
  - Coulomb finds that the air is a weak conductor (but chemically insulator) because the electroscopes spontaneously discharge by the action of air (electroscope and electrophorus invented by Volta in 1775) - open question!
- 1835
  - Faraday confirms the observations by Coulomb, with better isolation technology
- 1879
  - Crookes measures that the speed of discharge of an electroscope decreases when pressure is reduced (→ direct agent is the ionized air)
- 1896
  - Bequerel discovers radioactivity
- 1901
  - Two groups Elster and Geitel (Germany) and Wilson (England) conclude that some unknown source of ionizing radiation exists; Rutherford and other Canadian groups confirm
- 1903
  - Ernst, Mc Lennan, Burton, Rutherford, and Cooke confirm that the radiation is penetrating using a lead absorber
  - Radiation believed to be originated by the soil!

Julius Elster and Hans Geitel experimenting in the garden of Elster's house. The instrument on the table is a photometer. Photo Credit : Archiv Fricke

THE DISCOVERY OF COSMIC RAYS

- 1907
  - Wulf realizes a new electroscope
- 1907-1910
  - Pacini measures the ionization rate on the ground and on the sea
    - Radiation intensity doesn't decrease with the height as calculated taking into account the air absorption (and still considering the soil as the origin)
- 1910
  - Wulf develops an electrometer and uses it on top of Eiffel Tower and in a cave in Valkenburg (Holland)
    - Rate in the cave is less then that on surface, the rate on top of Eiffel tower doesn't decrease and his paper on Physikalische Zeitschrift is not widely accepted
- 1909-1910
  - Gockel flys with the balloon "Gotthard" up to 4500 m
    - At higher altitudes he records an increase in the rate, but he doubts his own reults
- 1911
  - Pacini performs measurements underwater
- 1912
  - Hess performs balloon flights (up to 5530 m), also during a solar eclipse
    Ionization of the atmosphere does not decrease with altitudine nor during the eclipse
    → source of radiation is not the Sun → coming from further out in space!

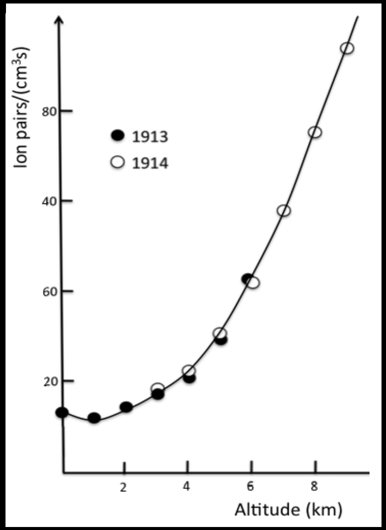

The cacciatorpediniere "Fulmine", used by Pacini for his measurements at sea. Photo Credit: Marina Militare Italiana


Hess preparing for a balloon flight. Photo Credit: APS

THE DISCOVERY OF COSMIC RAYS

- 1913
  - Hess and Kolhörster perform more balloon flights up to 9 km
- 1922-23
  - Measurements up to 16 km do not indicate changes with the height (terrestrial origin?)
- 1925
  - Millikan performs new measurements (less precise than Hess), proving the extraterrestrial origin (thinking about gamma rays);
    - Millikan first introduces the term "cosmic rays"
  - Start of the debate about neutral (gamma rays) or charged nature of the radiation
- 1927-37
  - HESS Nobel prize in physics in 1936
  - A wide variety of experimental investigations demonstrates that primary cosmic rays are mostly positively charged particles

Ionization measured by Hess and Kolhörster. After going through a minimum, it increases considerably with height.

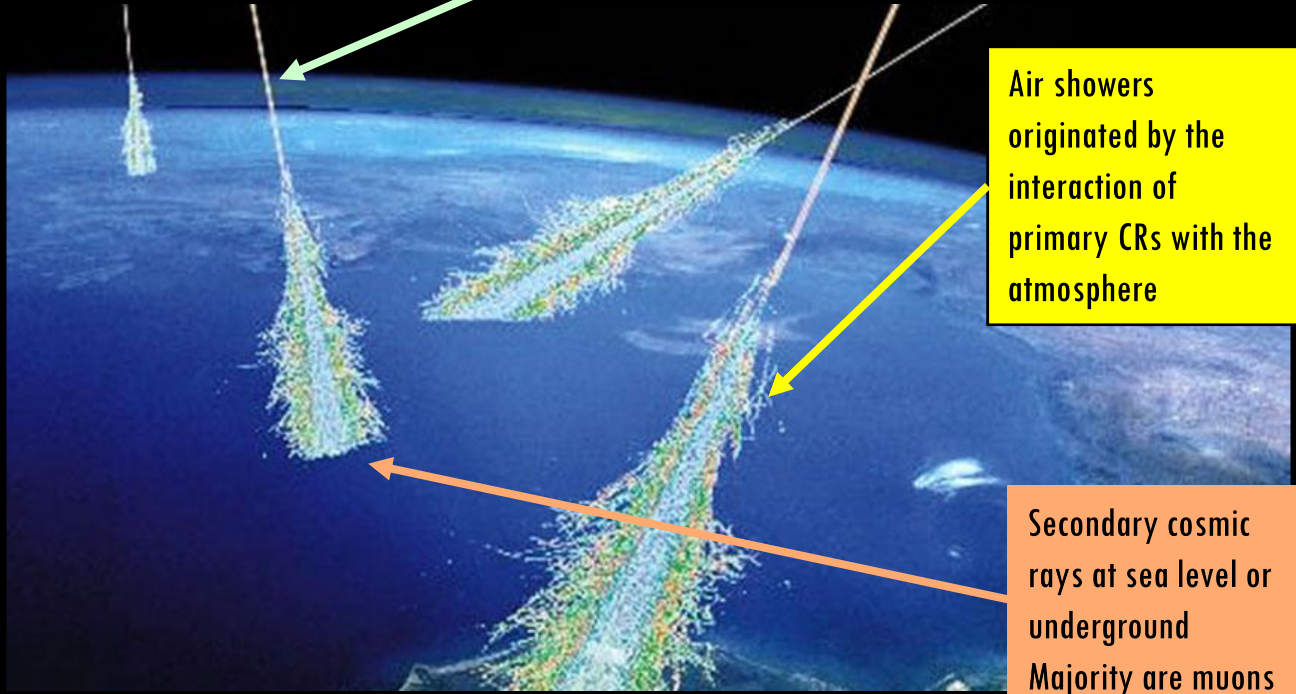


Millikan and Cameron holding their ionization chambers used in California and Bolivia mountain lakes to detect CRs. Credit De Maria & Russo 1989

COSMIC RAYS

- **Primary cosmic rays**:
  High-energy protons and nuclei (plus a minority electron component)
  - Produced in astrophysical environments
  - Filling the galactic space
  - Measured before they interact with the Earth's atmosphere

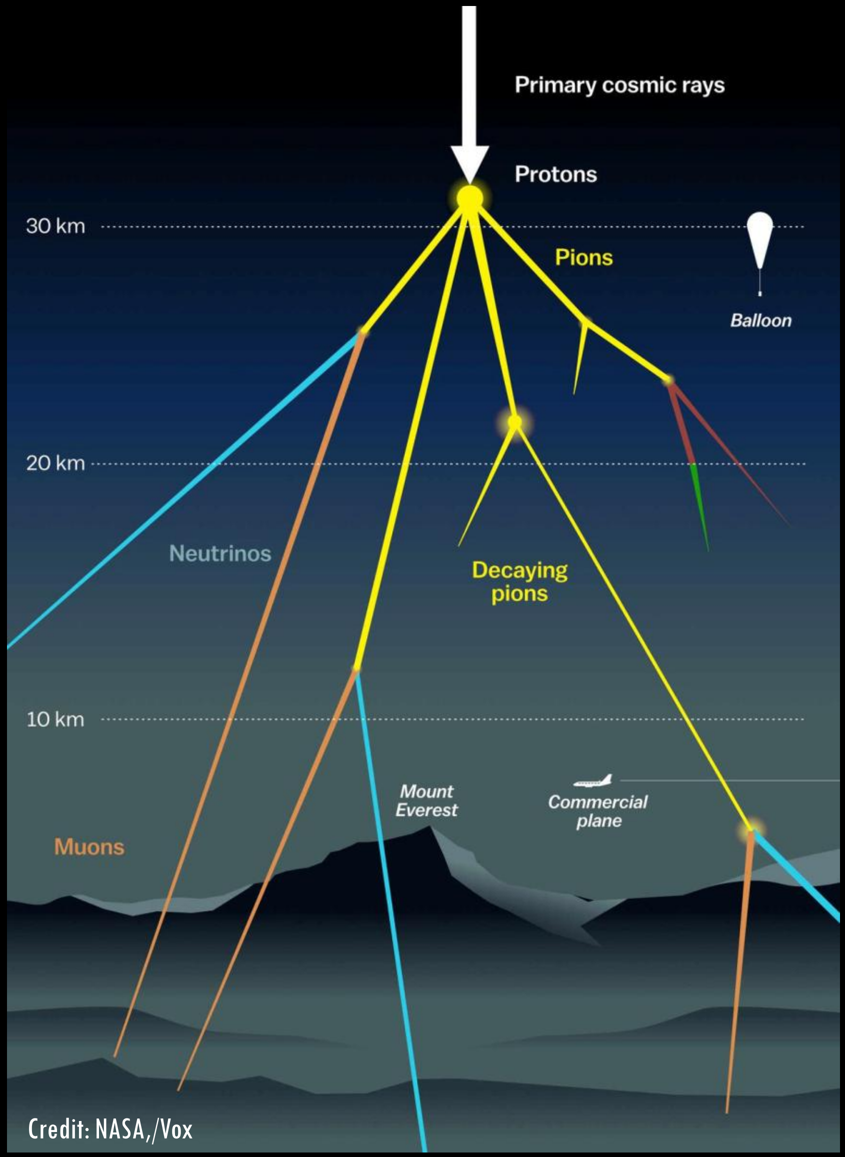
- **Secondary CRs**:
  Particles produced in interactions of the primaries with interstellar gas or with nuclei in the Earth's atmosphere
  - Nuclei such as lithium, beryllium, and boron (which are very rare end-products of stellar nucleosynthesis)
  - Antiprotons and positrons



Credit: NASA, S. Swordy/University of Chicago

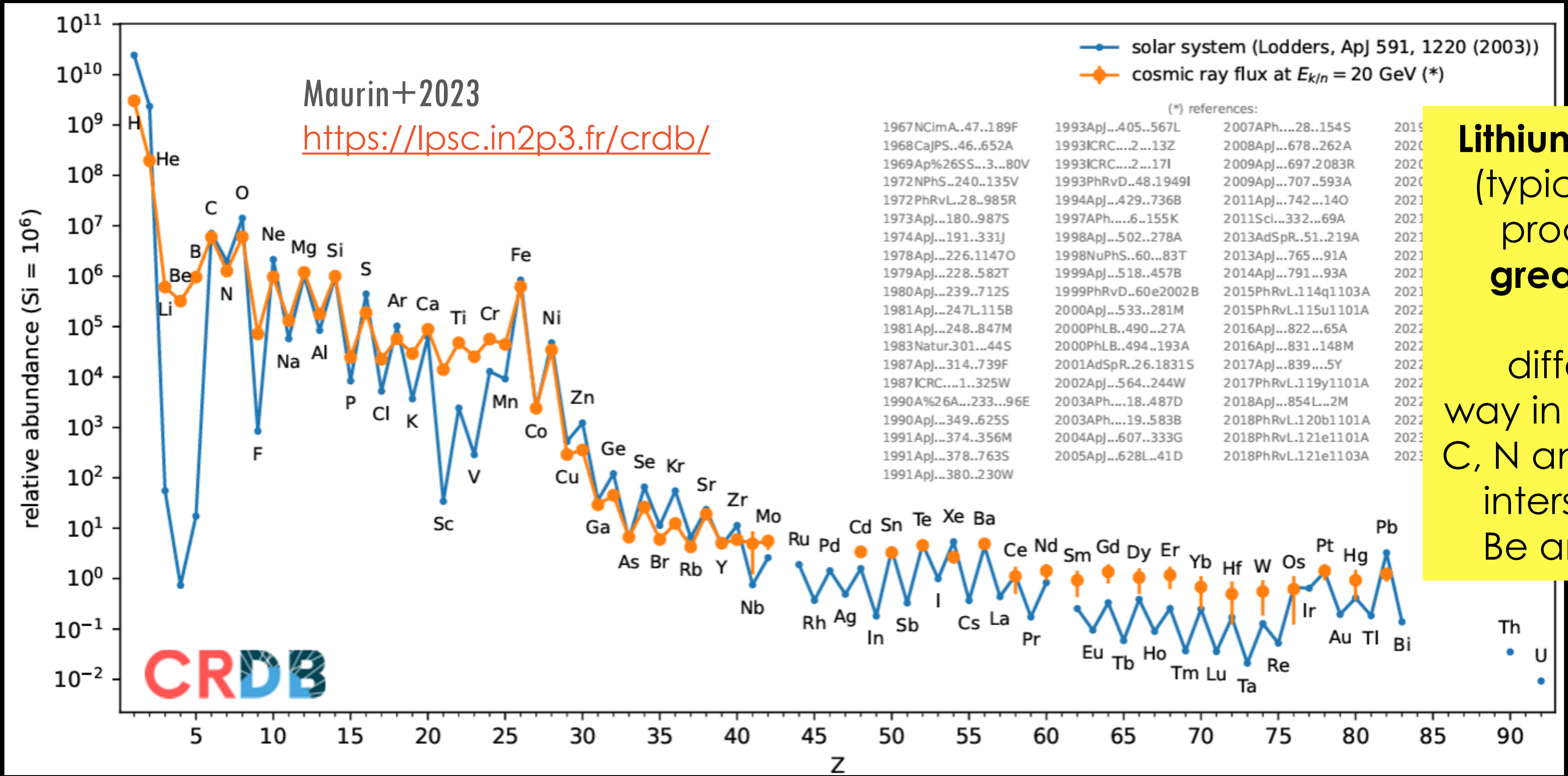
COSMIC RAYS

- **Direct CR measurements:**
  Experimental techniques used for measurement of primary CRs **below ~10^{14} eV**
  - **Balloons**, **satellites** and experiments on the **International Space Station (ISS)**
    - Study of the CRs impinging on the **top of the atmosphere**, before their first interaction with Earth matter
    - Measurement of the CR chemical composition
      - **Relative fraction of different nuclei** present in cosmic radiation and of their **isotopic composition**
- **CR particles** at the top of the atmosphere:
  - Protons (90%)
  - He nuclei (~9%)
  - Electrons~1%
  - ~0.1% heavier nuclei, neutrinos, gamma-rays, anti-particles



COSMIC RAYS

- Relative abundance of nuclei in CRs as a function of their nuclear charge number Z at energies around 1GeV/n, compared to the abundance of elements in the Solar System (based on both meteoritic and solar photospheric data)

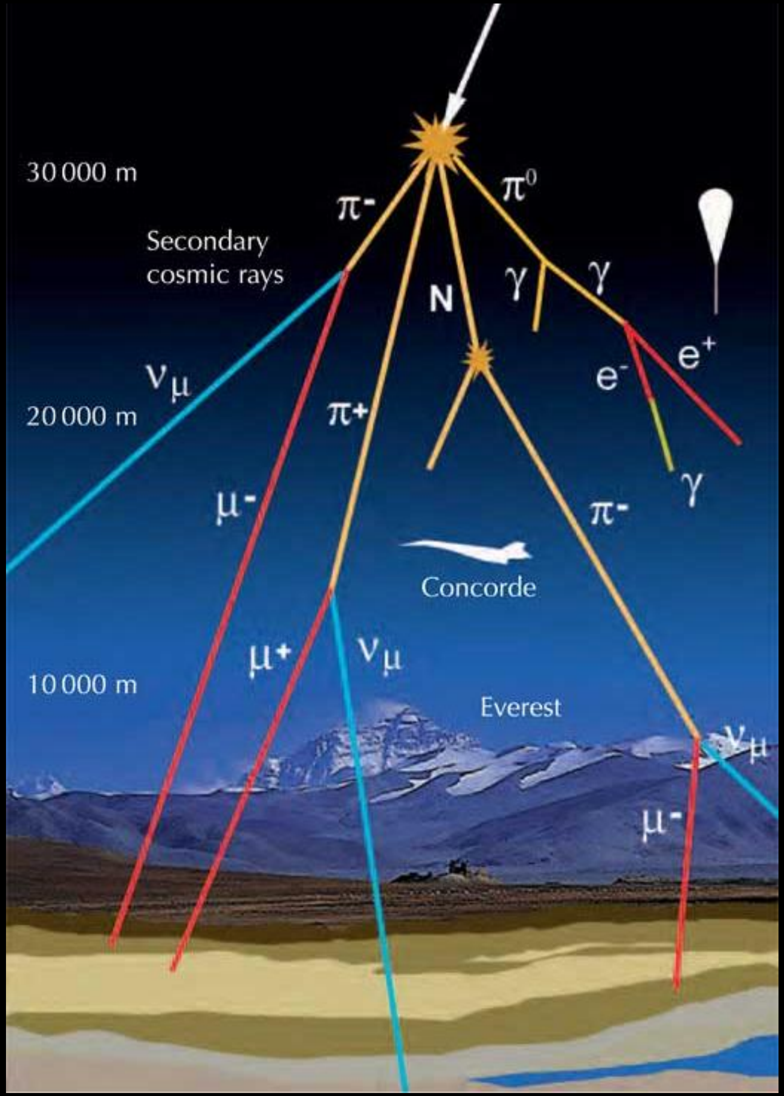


Lithium, beryllium, and boron (typical nucleosynthesis end products) appear in CRs in **greater abundance** than in our Solar System. This difference is a result of the way in which CRs are formed: C, N and O nuclei collide with interstellar matter to form Li, Be and B through **spallation**

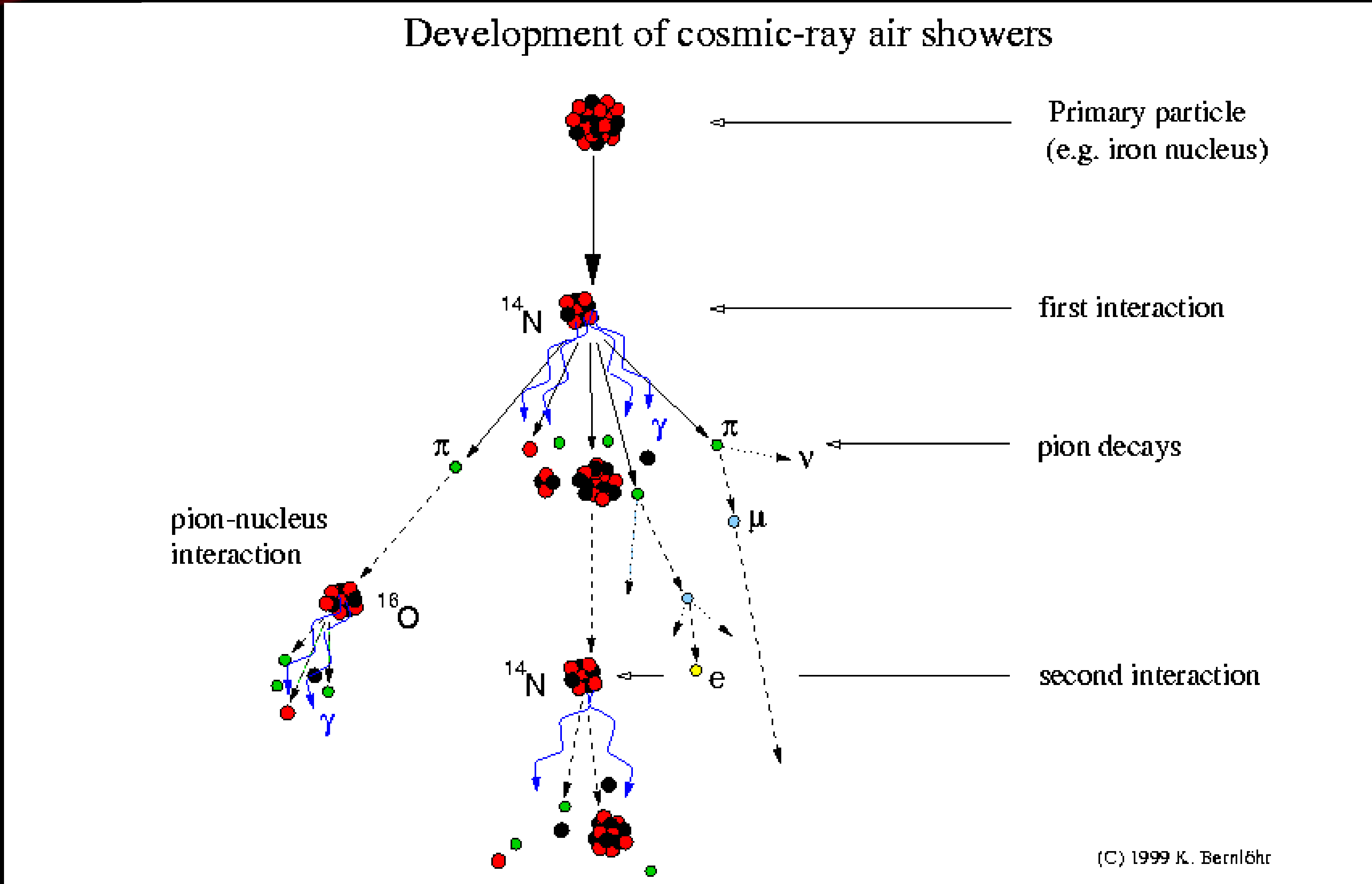
- **Air shower** (Gaisser 1991)
  - Production of a cascade of secondary particles due to CRs collisions with nucleons of atmospheric nuclei (mainly oxygen and nitrogen) in the Earth's atmosphere
  - Basic mechanism of air shower production of a CR proton on a nucleon N

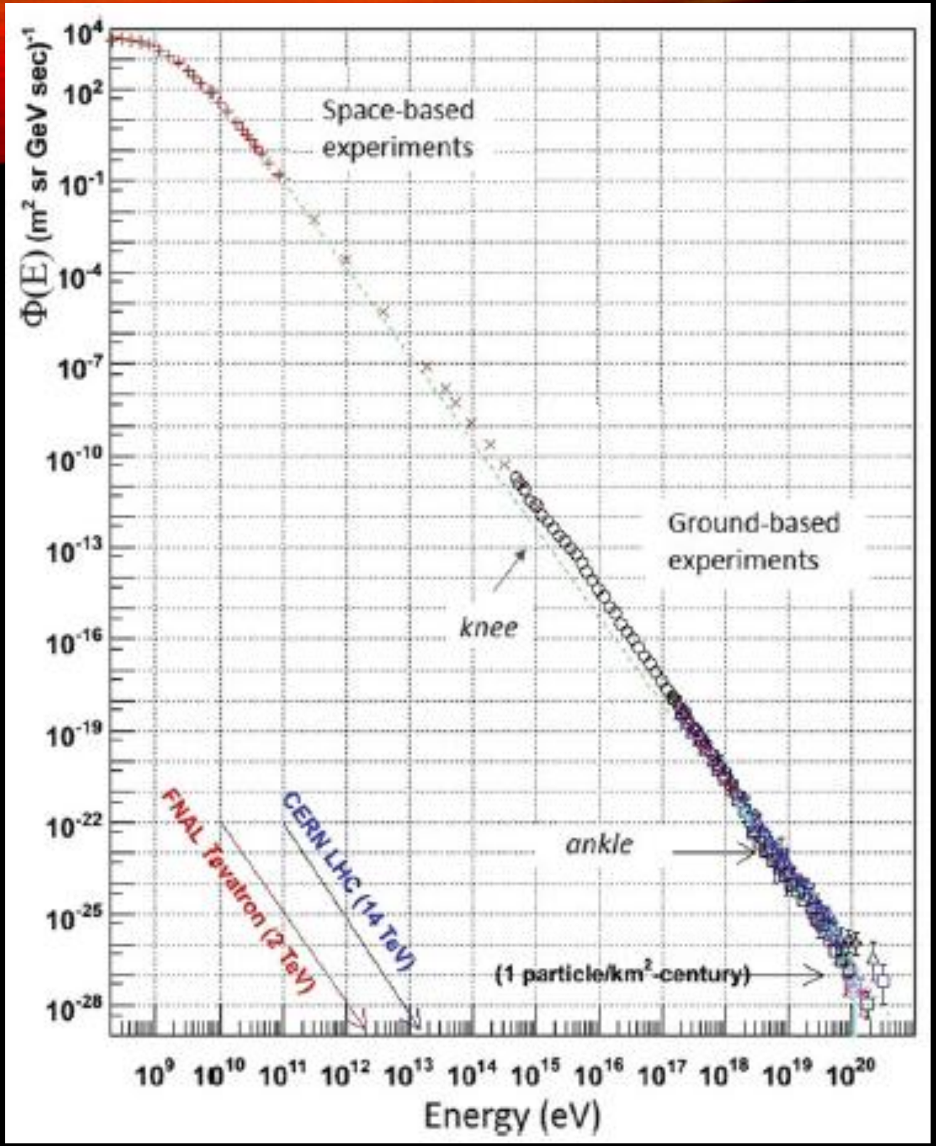
$$p + N \rightarrow \pi^{\pm}, \pi^{0}, K^{\pm}, K^{0}, p, n, \ldots$$

  - The decay of **short-lived hadrons** leads to
    - **EM component**: cascade of high-energy photons, electrons, and positrons
    - **Penetrating component** of muons and neutrinos
- **Indirect CR measurements:** Measurement of the secondary particles with ground-based detectors
  - Study of CR flux up to highest energies



Credit: physicsopenlab.org


Development of cosmic-ray air showers
Primary particle
(e.g. iron nucleus)
first interaction
pion decays
second interaction
pion-nucleus
interaction
14N
16O
π
ν
μ
γ
e
(C) 1999 K. Bernlöhr



Differential energy spectrum

- The differential energy spectrum of CRs covers over **eleven decades of energy**
  - **Red/blue arrows** indicate the equivalent center of mass energy reached at the Tevatron collider at Fermilab and at the LHC collider at CERN
  - The spectrum is **remarkably continuous** over the whole energy interval
  - The flux on the y-axis covers **33 decades**
  - The dashed line shows a **E^{-3} spectrum**
  - Two **transition points** (knee and ankle) where the slope of the spectrum changes
  - The integral flux gives

$$\mathscr{F}(>10^9\ \text{eV}) \simeq 1000\ \text{particles/s m}^2$$
$$\mathscr{F}(>10^{15}\ \text{eV}) \simeq 1\ \text{particle/year m}^2$$
$$\mathscr{F}(>10^{20}\ \text{eV}) \simeq 1\ \text{particle/century km}^2$$

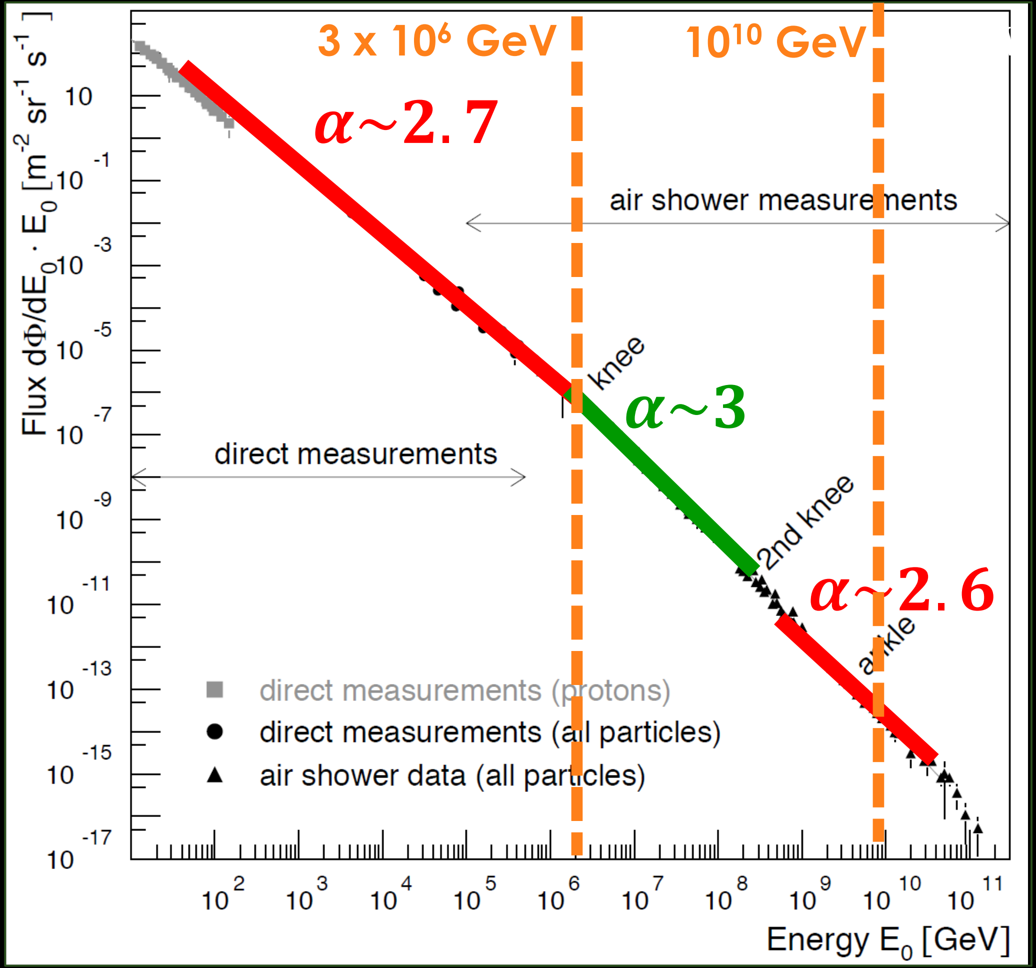
COSMIC RAYS

- CR flux decreases rapidly with energy: **CR energy spectrum of cosmic rays** is best described by a power law:

$$\Phi(E) = K\left(\frac{E}{E_0}\right)^{-\alpha}$$

  - **α: differential spectral index**
    - **NOT constant**, indicating a change in the properties of CRs, like their acceleration sites and chemical composition
  - "**Knee**": associated with the upper limit of acceleration by **galactic supernovae**
    - Above the knee, the CR flux decreases by a factor of ~100 when the energy increases by a factor of 10 → α becomes steeper
  - "**Ankle**": associated with the onset of an **extragalactic population**
    - It is less intense but has a **harder spectrum** that dominates at sufficiently high energy

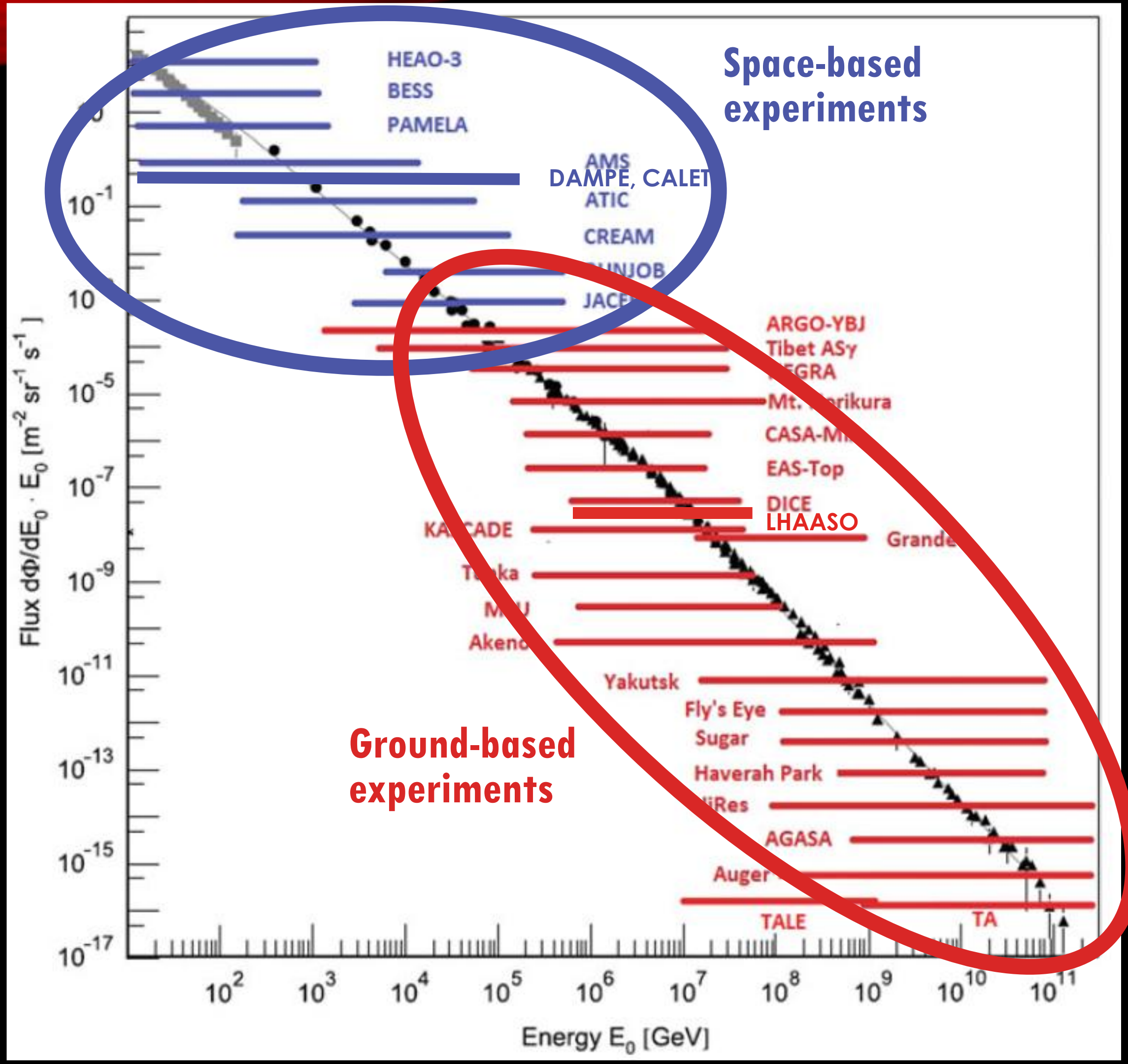
Integral energy spectrum



J. Blümer, R. Engel, & J. R. Höorandel, Prog. Part. Nucl. Phys. 63, (2009) 293

COSMIC RAYS

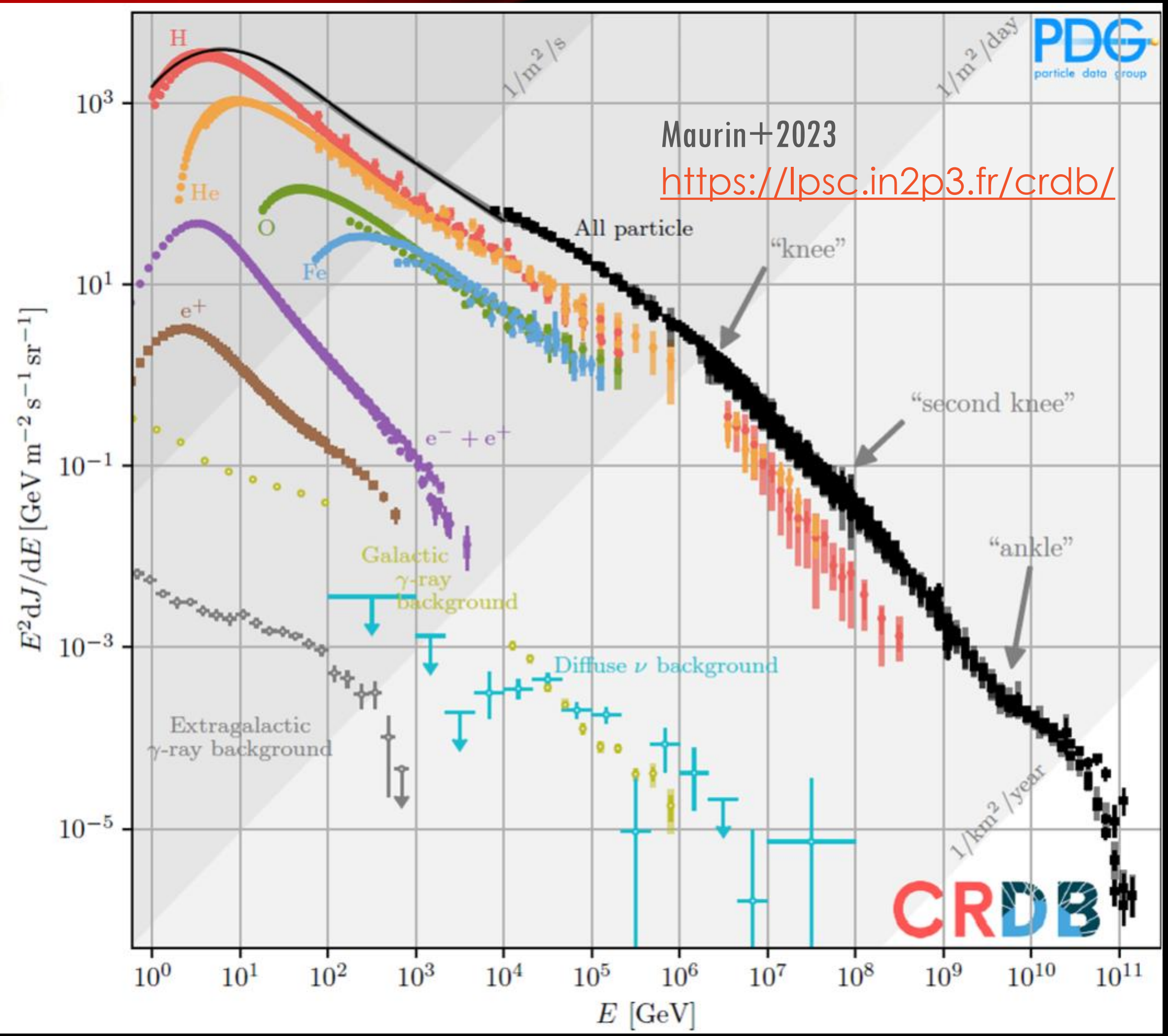
Integral energy spectrum



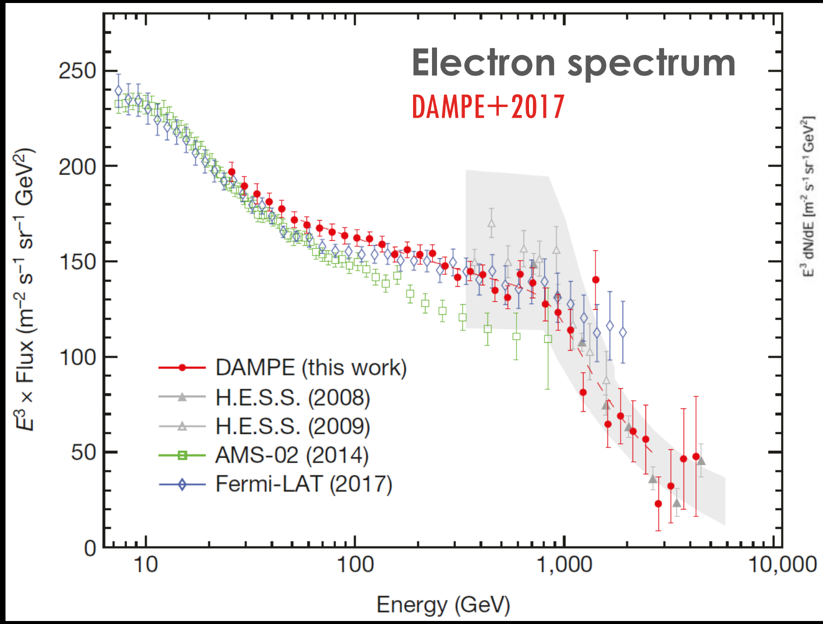
Credit: M.Spurio

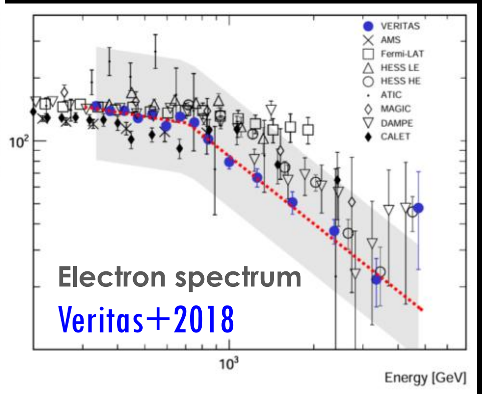
- Each experiment measures the CR flux within a given energy range
  - Different kinds of experiments cover more than 10 decades of energy
- Lower energy part (below GeV scale)
  ➔ Contribution from the Sun (solar flares)
- Higher energy part (above several GeVs)
  - CR originated outside the solar system, likely associated with most energetic processes in the Universe

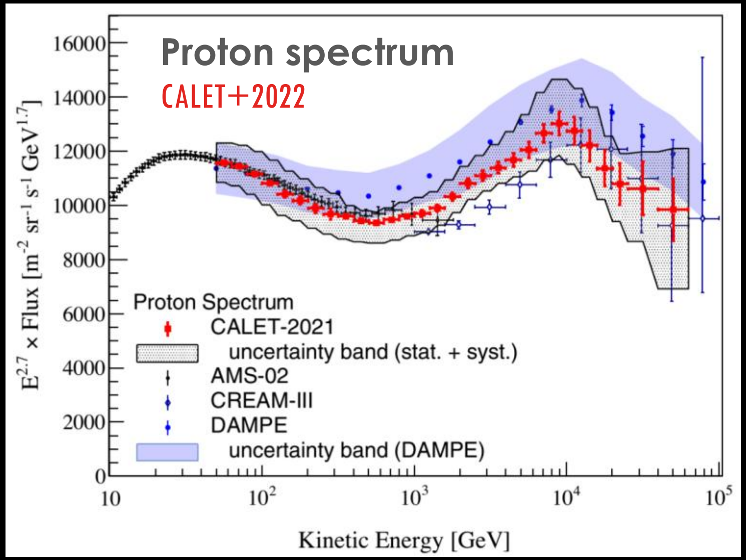
COSMIC RAYS



All particle energy spectrum







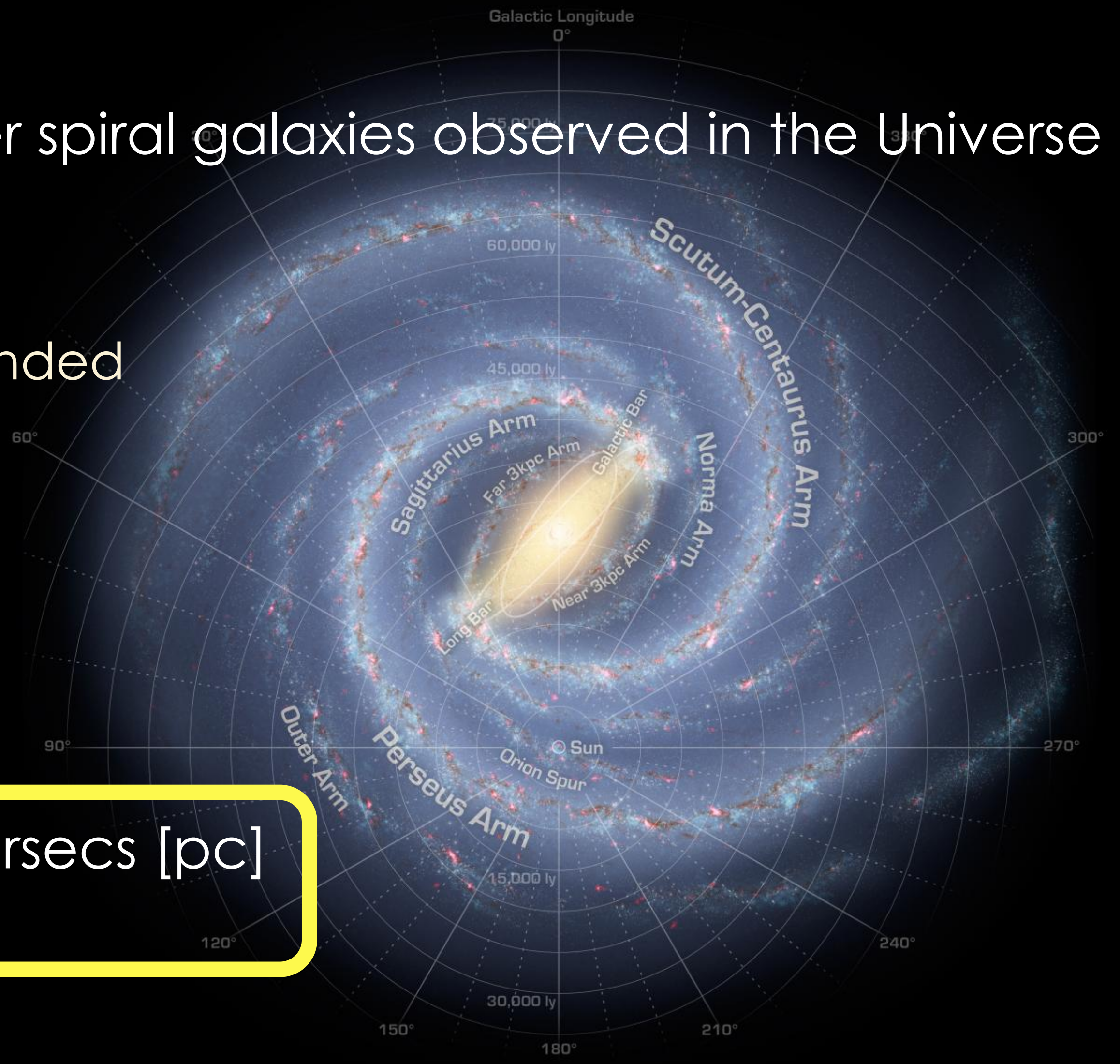
Physical Properties of Our Galaxy

- System of stars, which is very similar to other spiral galaxies observed in the Universe
  - Total number of stars ~ 10^{10}
- **Two components**
  - Spheroidal structure (central bulge), surrounded by halo of globular clusters
  - Disk structure

  ➔ Both contain stellar populations and other material with very different characteristics (chemical compositions, kinematic and dynamic properties and a diverse evolutionary history)

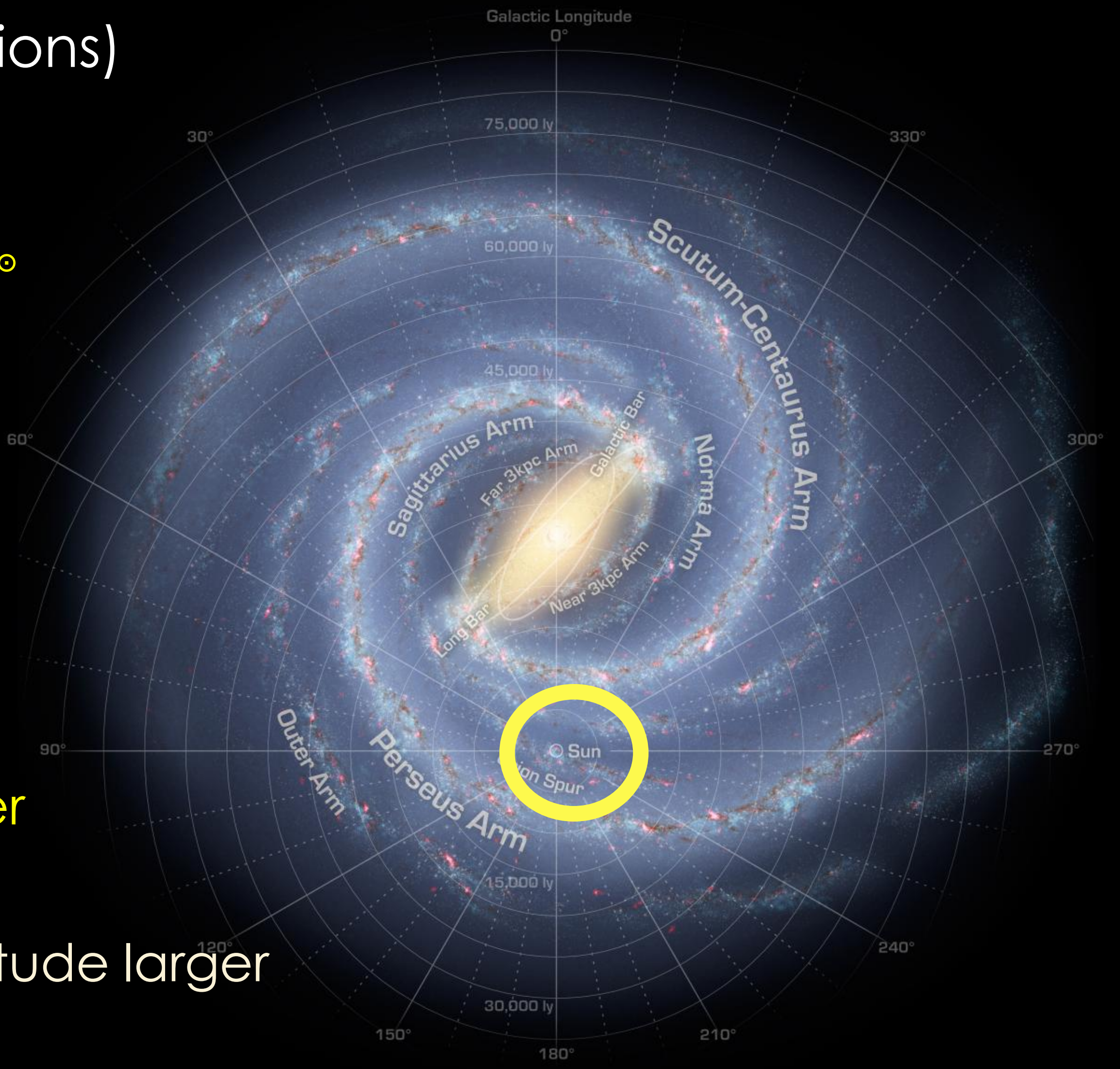
Distances and sizes usually expressed in parsecs [pc]

1 pc = 3.26 ly = 3.086×10^{16} m



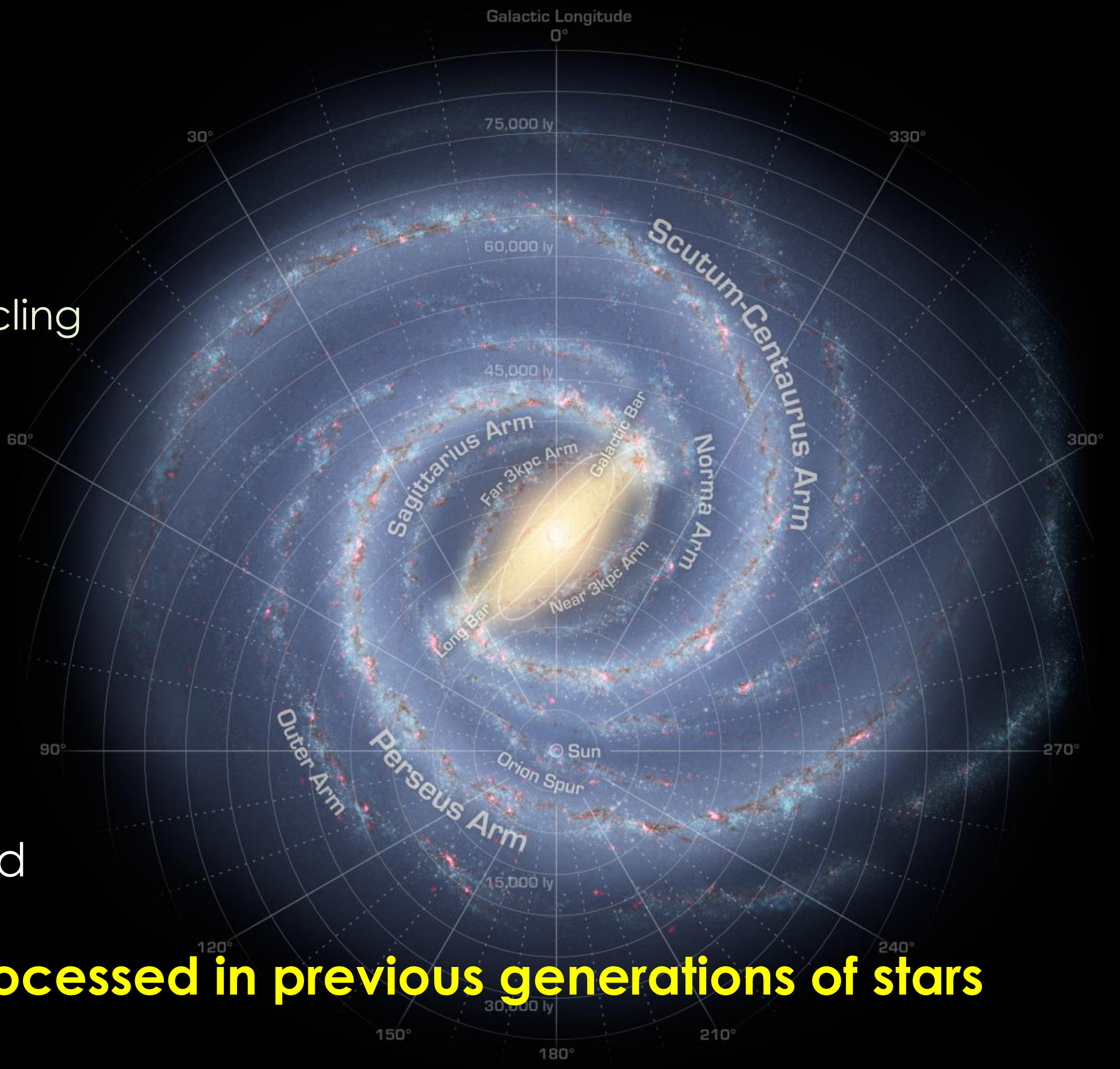
THE MILKY WAY

- **Spheroidal component** (3 ~concentric regions)
  - **Very massive** nucleus
    - Radius < 3 pc
    - Black Hole at its center, with mass $\sim 4 \times 10^6\ M_\odot$
  - Bulge
    - Radius ~3 kpc
  - Extended halo
    - Radius ~30 kpc
- **Disk component**
  - Very thin (~200–300 pc thick)
  - Radius ~15 kpc
  - Position of the Sun: ~8.5 kpc from the center
- **Galactic volume** $V_G = 5 \times 10^{66}\ cm^3$
  - Volume of galactic halo >1 order of magnitude larger



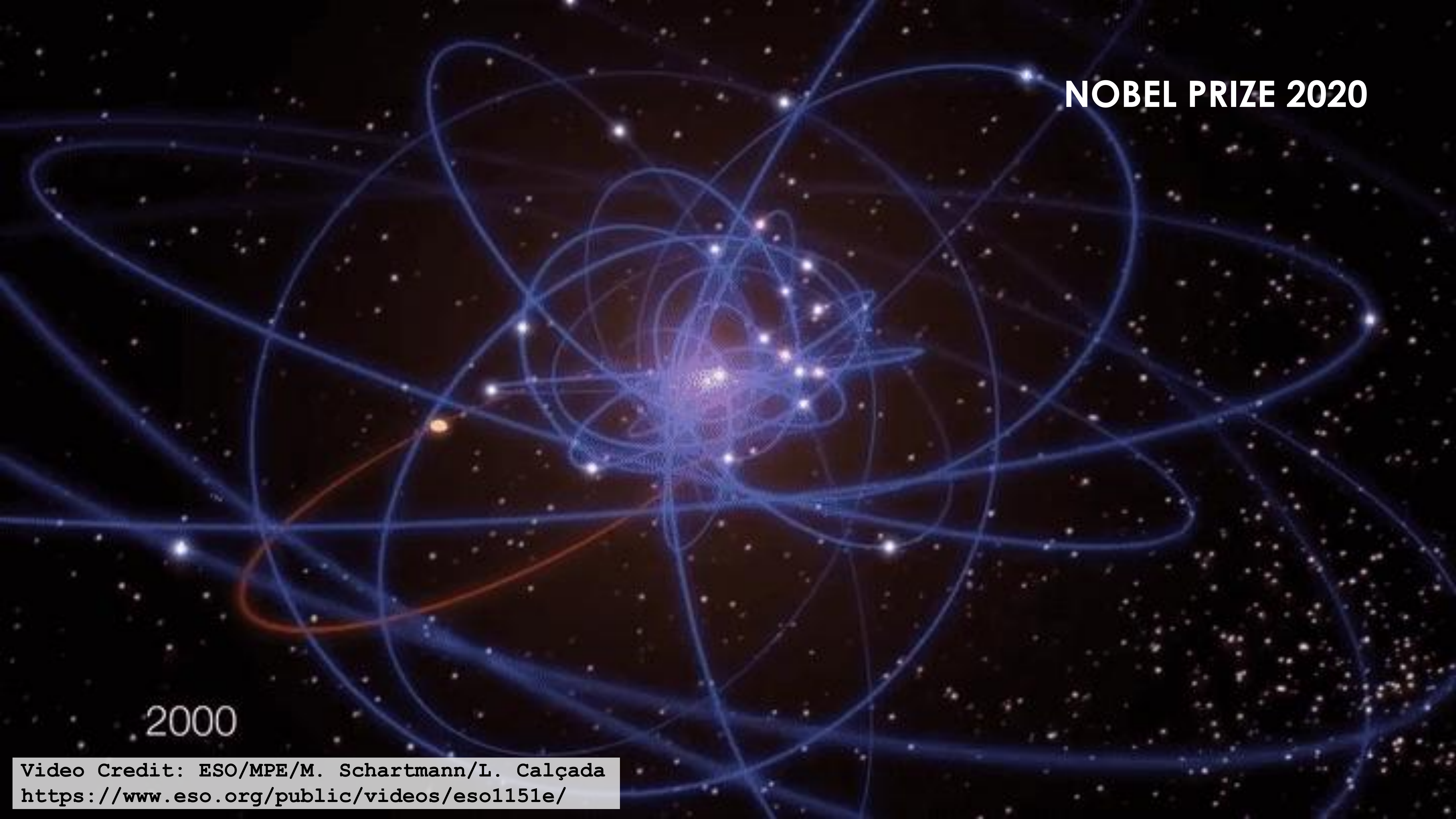
- **Spheroidal component**
  - Gas and dust very scarce
  - Main components
    - Stars: Metal poor (Pop. II stars)
      - Material that has not undergone much recycling through previous generations of stars
    - Globular clusters: very old stars

- **Disk component**
  - Large amount of gas and dust
    - Absorption of interstellar radiation!
  - Young and metal rich stars (Pop. I)
    - Distributed more or less uniformly, or grouped in stellar associations along the spiral arms



➔ Disk made entirely of materials already processed in previous generations of stars

NOBEL PRIZE 2020

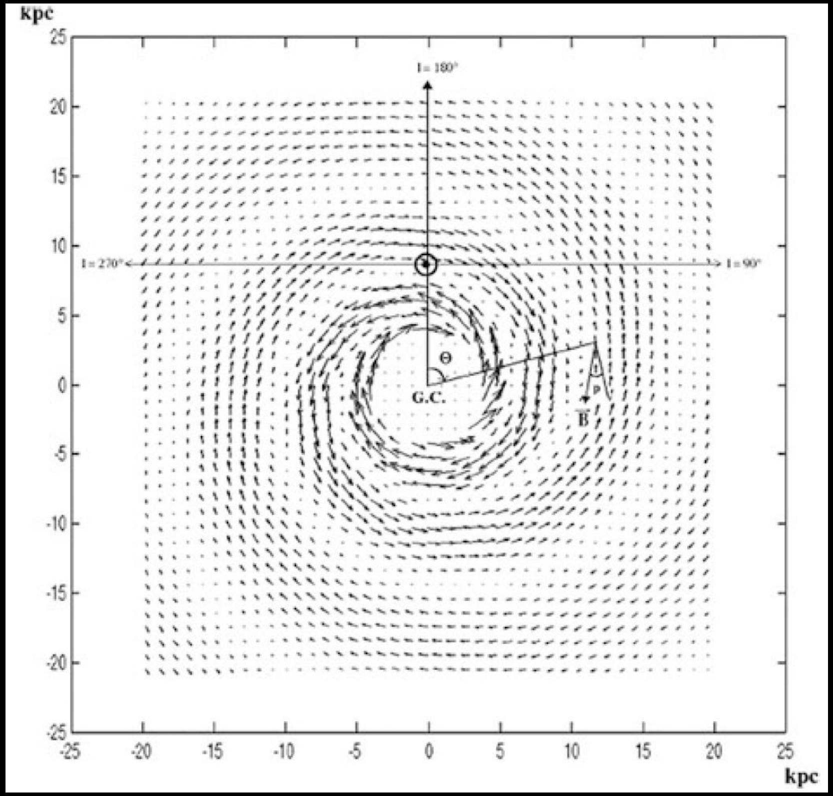


Video Credit: ESO/MPE/M. Schartmann/L. Calçada
https://www.eso.org/public/videos/eso1151e/

Galactic Magnetic Field (GMF)

- Discovered (1949)
  - Observed light from stars has a high degree of polarization
- Precise information on GMF from **radio astronomy**
  - At low frequencies (150 MHz) the emission from the Galaxy shows a **maximum of intensity along the galactic plane**, and decreases steadily with increasing galactic latitude
    - Diffuse radiation is composed of a nonthermal component and a thermal one from the disk
      - Nonthermal component is due to the synchrotron radiation of electrons moving in GMF
  - **Average intensity of regular GMF: B ~ 4 μG**

➔ Large-scale structure of GMF strongly influences the motion of charged particles



Prouza and Smída 2003

Direction and strength of the regular magnetic field in the Galactic plane

Outlying regions of the Galaxy

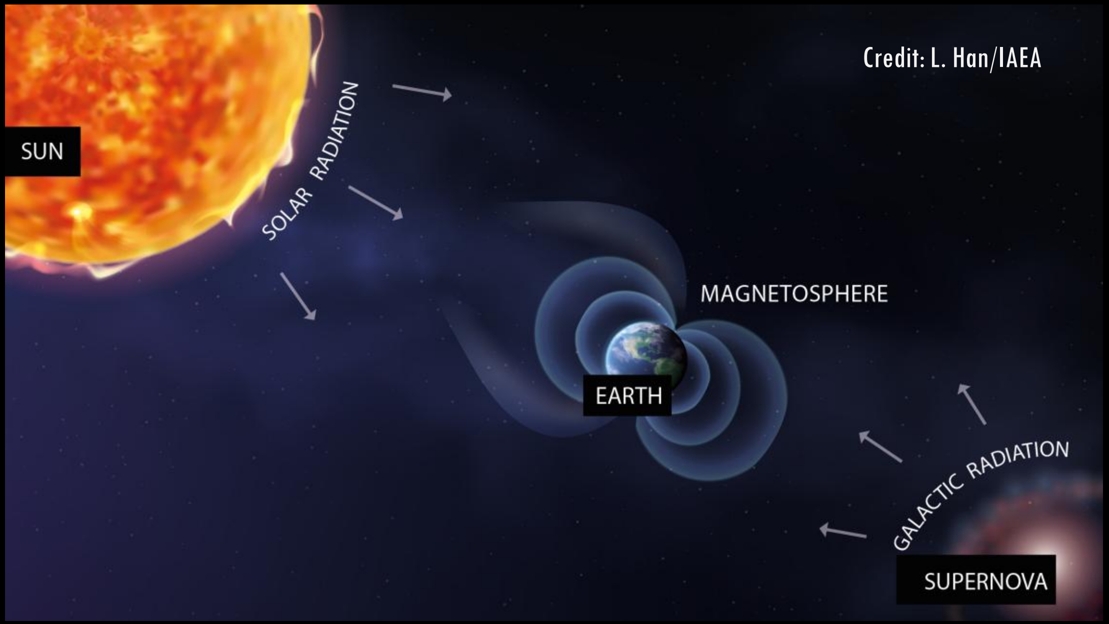
- Only a small fraction of the space volume (~4×10^{-23}) occupied by matter in form of stars
- **Large masses of gas**
  - Neutral (HI – main component), molecular (H_2) or ionized (HII) hydrogen
  - >100 different molecules (e.g. CO most abundant after H_2)
  - Revealed by the presence of absorption and emission lines, both in optical and radio
- **Interstellar dust**
  - Tiny solid particles, ice grains of various species, graphite, silicates and perhaps metals
  - Observations:
    - As large dark clouds obscuring the view of the stars behind them
    - In reflection nebulae that shine owing to the presence of nearby stars
    - Infrared emission in the vicinity of very hot stars.

➔ As a whole, **gas + dust = Interstellar Matter (ISM)**

- Represents 5–10% of the total mass of the Galaxy
- Average density: $\mathbf{n_{ISM} \sim 1\ proton/cm^3 = 1.6 \times 10^{-24}\ g/cm^3}$

LOW-ENERGY CR FROM THE SUN

- **Sun = main source of CRs of energy below ~4 GeV**
  - First observed in the early 1940s
  - Protons, electrons, and heavy ions [few tens of keV to a few GeV]
  - **CRs mainly originated by Solar Flares**
    - Sudden brightening observed over the Sun's surface - large energy release
    - Occurring in active regions around sunspots, where intense magnetic fields penetrate the photosphere to link the corona to the solar interior
    - Episodic solar activities and corresponding increase in the low-energy CR flux represent **occasional hazard** for astronauts and for electronics on satellites
  - **CRs in the Solar wind**
    - **Stream** of charged particles continuously released from the upper atmosphere of the Sun
    - Mostly **electrons and protons** with energies between 1.5 and 10 keV

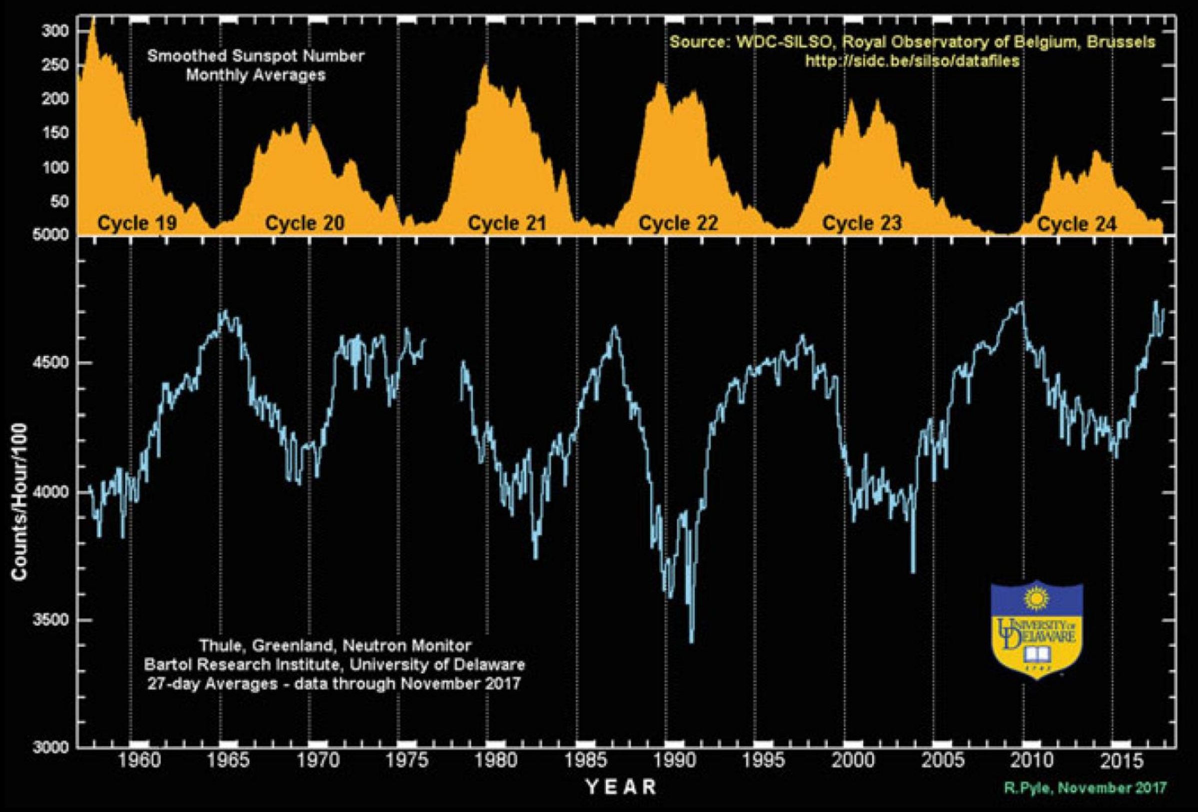


Solar Modulation

- The Sun's activity influences the probability that **CRs with energy below a few GeV** reach the Earth

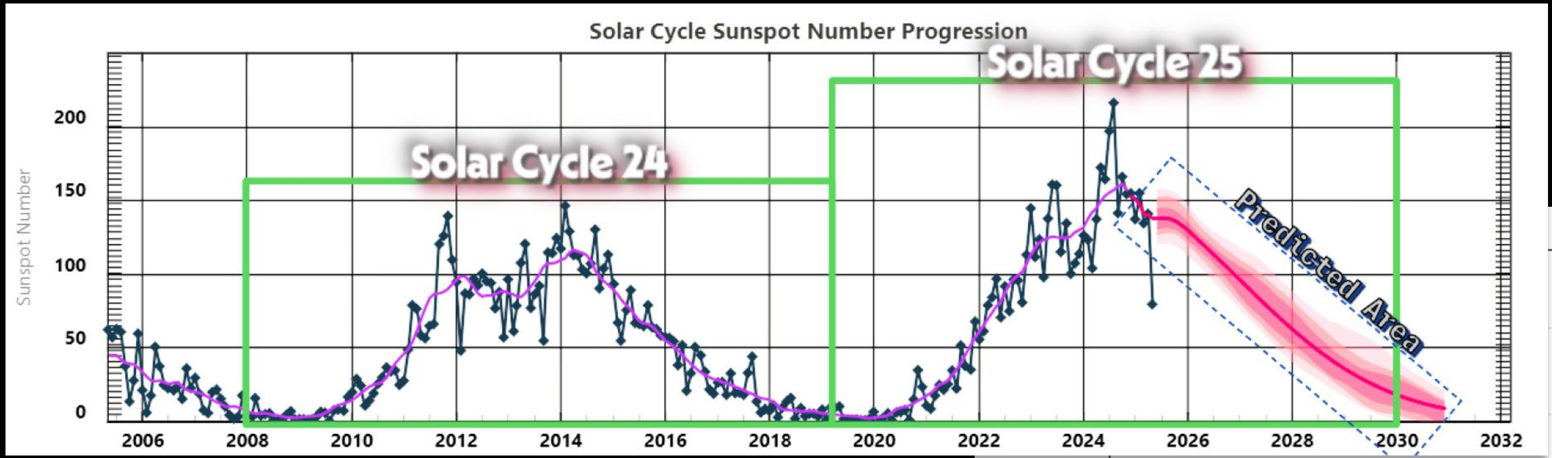
  - When CRs enter our solar system, they must **overcome the outward-flowing solar wind**
    - ➔ **Interaction with the magnetic field** carried by the expanding solar wind
    - **Deceleration and partial exclusion** of the lower energy particles from the inner solar system

  - **Variation over the solar cycle**



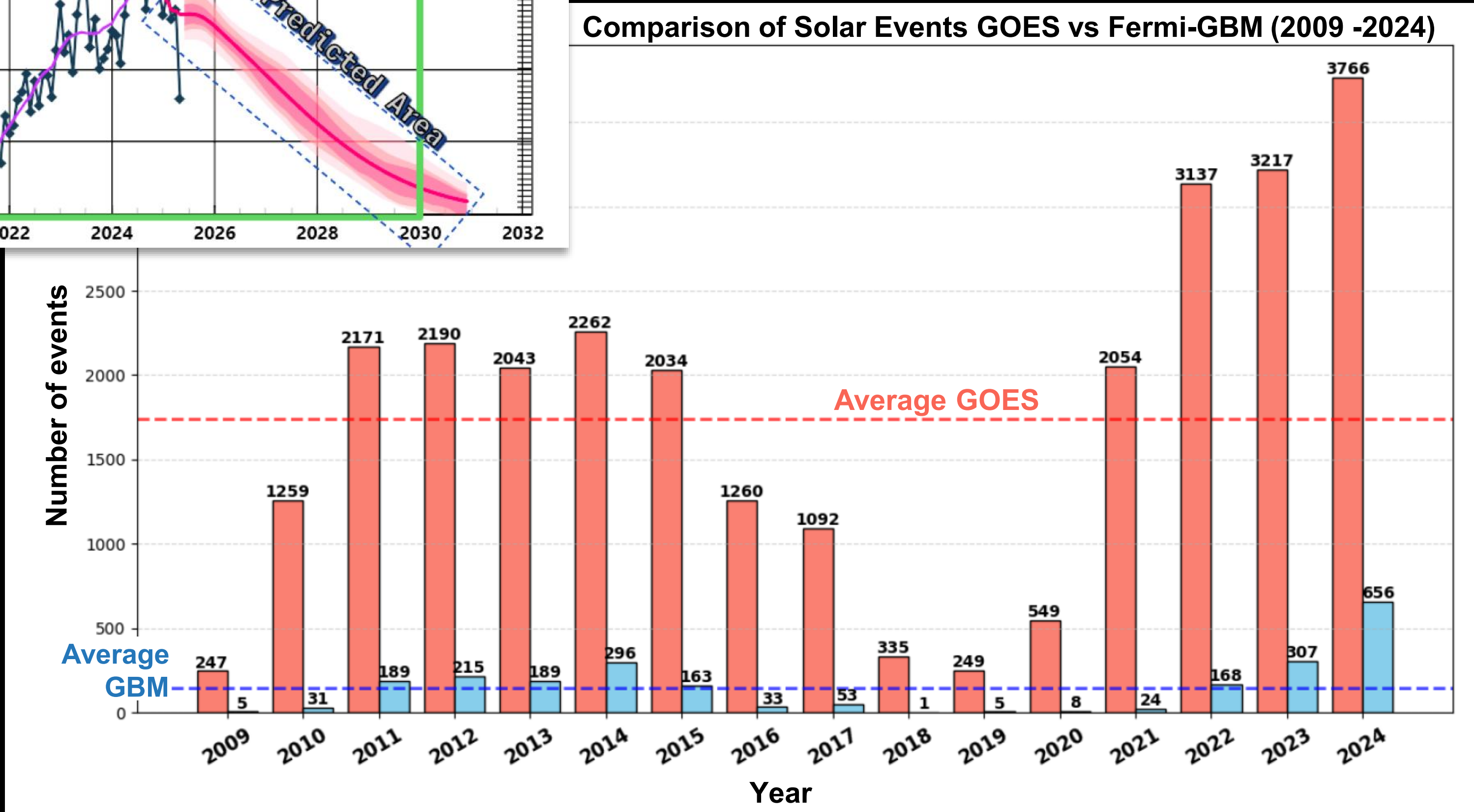
Credit: Bartol Research Institute

Solar Flare Monitoring



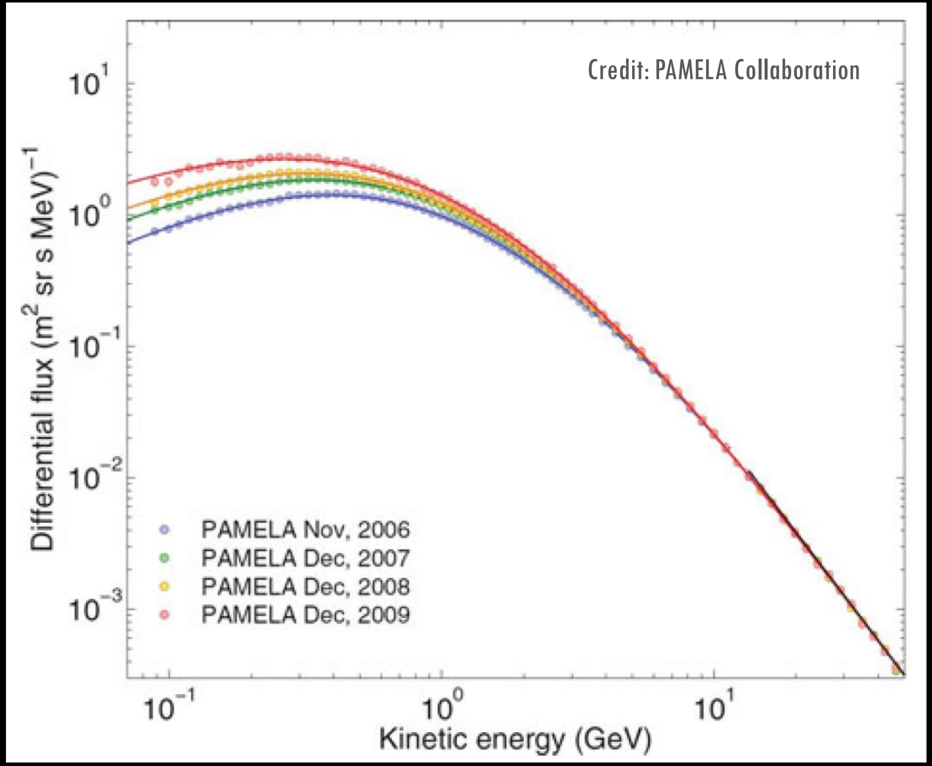
Credit: NOAA/SWPC, SILSO, e NASA

Credit: Bachelor Thesis D'Errico POLIBA 2025

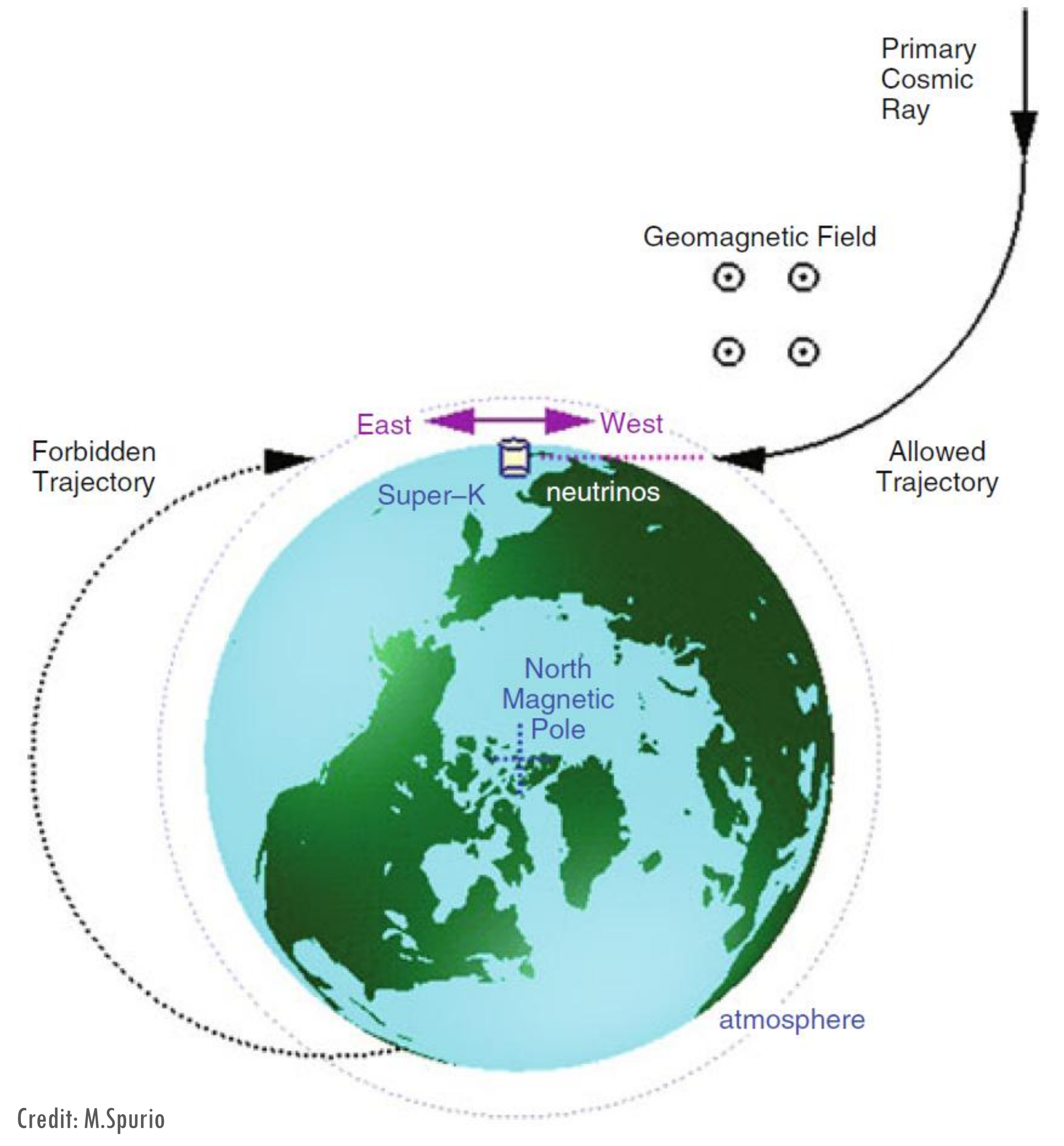


CR anti-correlation with Solar activity

- The magnetic activity and the solar modulations are manifested through sunspots
  - 11-year cycle
  - Most solar flares and coronal mass ejections originate in magnetically active regions around visible sunspot groupings
- Intensity of low-energy CRs on Earth measured through ground-based detectors called neutron monitors
  - Measurements are anti-correlated with the level of solar activity
    - When solar activity is high → many sunspots are visible → CR intensity on Earth is low



EFFECTS OF GEOMAGNETIC FIELD



- Primary CRs with energy below ~60 GeV are influenced by the Earth's magnetic field

EAST/WEST effect

- Low-energy CRs from the East are suppressed compared to those from the West
  - Earth itself effectively shadows certain trajectories (forbidden)
- Effect first detected in the 1930s, used **to infer that the charge sign of primary CRs is positive**

LATITUDE effect

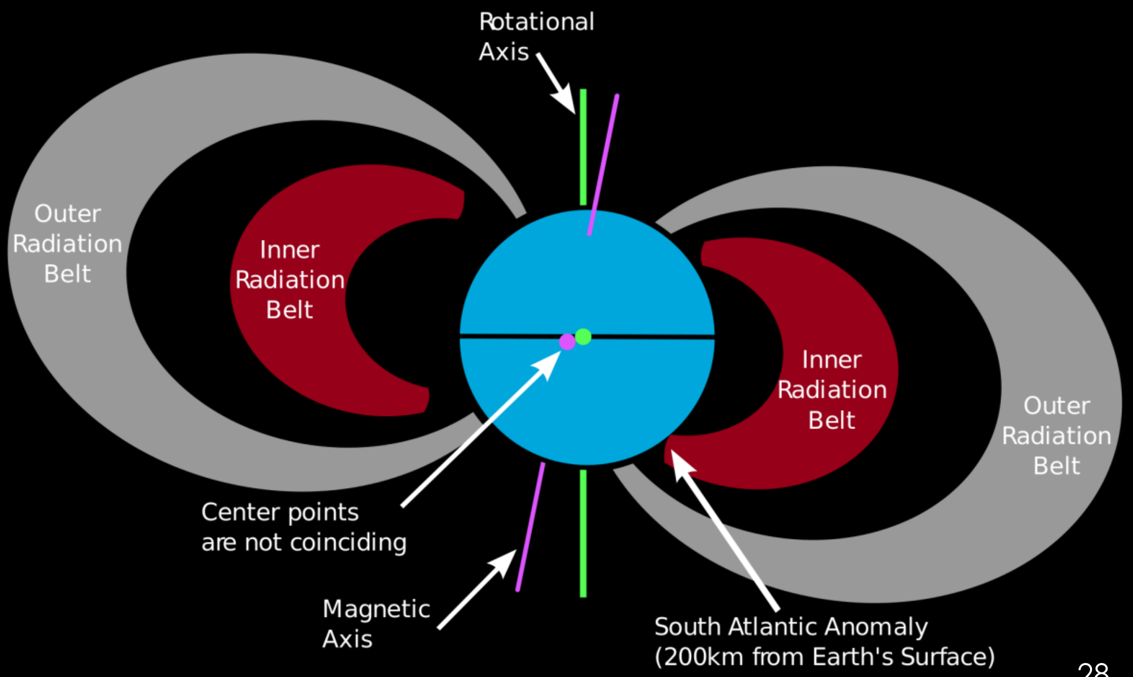
- Toward the poles, the influence of the dipole field becomes weaker (as the arriving particle velocity is almost parallel to the magnetic field)
  - The integrated CR intensity increases with the latitude for charged particles

Van Allen radiation belts

- 2 torus-shaped layers of energetic charged particles around the Earth, located in the inner region of the magnetosphere and held in place by the magnetic field
- Belt extending 1000–60,000 km above the surface
- **Outer belt** = energetic electrons
- **Inner belt** = combination of protons and electrons
- Hazard to satellites: must protect their sensitive components with adequate shielding if their orbit spends a significant amount of time inside the radiation belts

South Atlantic Anomaly (SAA)

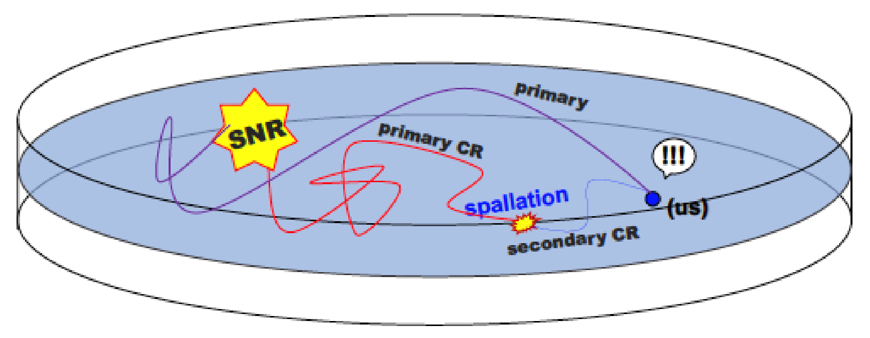
- Area where the inner belt comes closest to Earth's surface (down to ~200 km)
- Increased flux of energetic particles is dangerous for orbiting satellites
- Effect caused by non-concentricity of Earth and its magnetic dipole



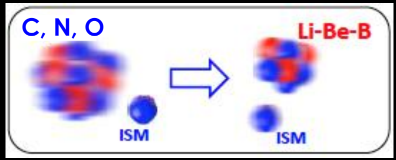
DIFFUSION OF CRs IN THE GALAXY

- The observed spectra of CRs depend on 2 basic processes
  1. **Acceleration in the astrophysical sources**
  2. **Propagation in the interstellar medium (ISM) of our Galaxy**

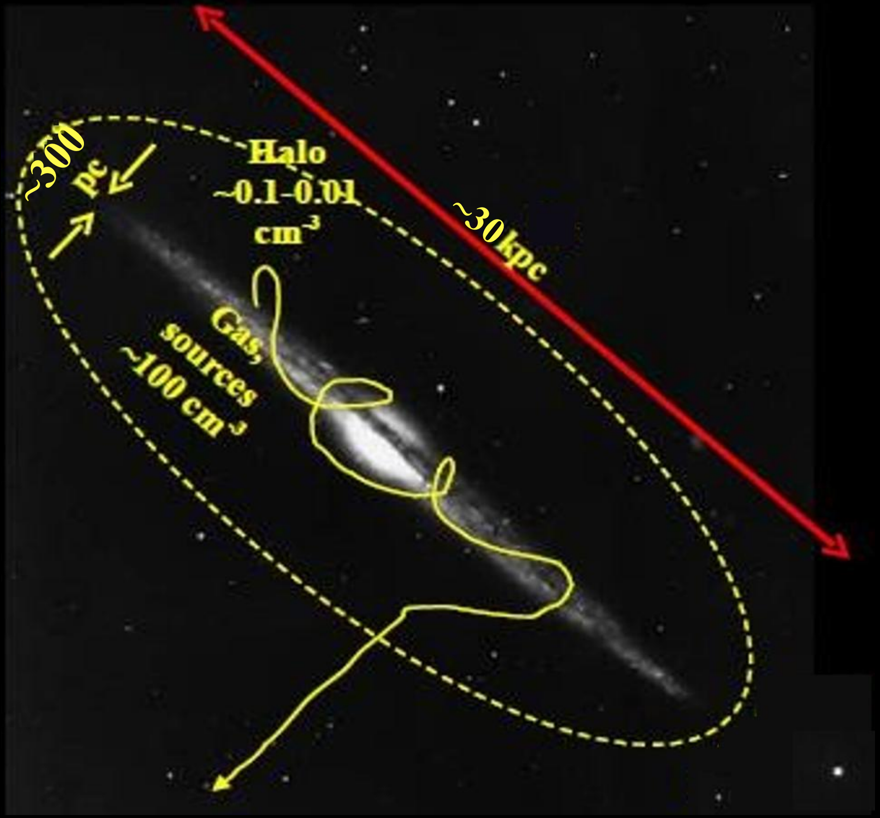
- After leaving the source region, high-energy charged particles **diffuse in the random GMF** that accounts for:
  - High isotropy of CRs
  - Long confinement time of CRs



- Most information on CR propagation arise from the measurements of the abundances of the so-called **light elements Li, Be, and B**
  - **Secondary origin**, i.e., produced as the result of interactions of heavier primary nuclei with the ISM (spallation or fragmentation process)



- We know from studies of the Faraday rotation of polarization that **GMFs** are of the order of a **few μG**
  - Structure highly directional (see GMF map)
  - It is possible to calculate
    1. **The average CRs escape time:** τ_{esc} **~ 3 x 10⁶ yrs**
       - Average time of permanence of CRs inside the confinement volume before escaping our Galaxy
    2. **The average CRs escape length** (from our Galaxy): x_{esc} **~ 1 Mpc**
       - BUT: Galaxy radius 15 kpc, thickness 300 pc

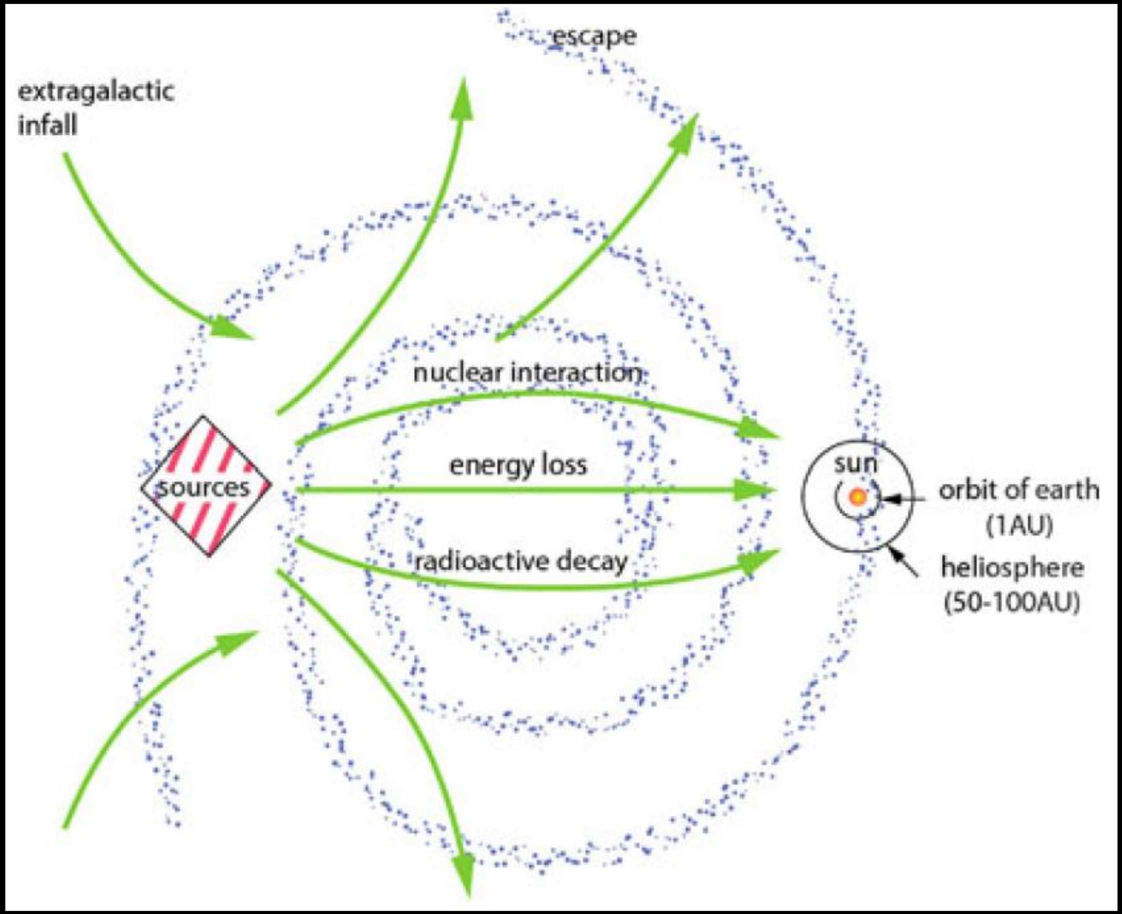


➔ Propagation of cosmic rays resembles that of a **random walk**

- **Tangled motion of charged particles in the galactic magnetic fields, confinement!**

DIFFUSION OF CRs IN THE GALAXY

- CRs produced in our Galaxy suffer
  - Diffusion in magnetic fields
  - Convection by Galactic winds
  - Spallation in the ISM
  - Radioactive decays
  - Other energy losses or gains (reacceleration)
    - ➔All these processes must be accounted for in **coupled transport equations** which then determine the density of each CR species
- So-called **diffusion equations** used to describe the CRs' journey through the Galaxy
  - This journey also modifies the CRs' energy spectrum from the sources to the observer



DIFFUSION OF CRs IN THE GALAXY

Diffusion Equation: $\frac{dN}{dt} = D\nabla^2 N + \frac{\partial}{\partial E}[b(E)N(E)] + Q$

- Describes the energy spectrum at different points in the ISM in the presence of:
  - **Observable variable N representing number of particles** in given volume and energy interval
  - Diffusion, represented by a **scalar diffusion coefficient D ~ 3 x 10^{28} cm^2 s^{-1}**
  - Energy losses → $b(E)$: Energy loss function, positive for losses, negative for gains
  - Other physics effects (fragmentation, radioactive decays, etc)
- $\boldsymbol{Q(E, x, t)}$: **source term**, representing the injection rate of particles per unit volume of coordinate space
- Full derivation of the diffusion-loss equation (Longair 2011, Spurio 2018)
  - Steady state solutions ($dN/dt = 0$)
- **Leaky box model**
  - Framework in which CRs propagate freely in a containment volume – Diffusion term approximated by leakage term $D\nabla^2 N \rightarrow -N/\tau_{esc}$
- **Advanced CR propagation codes** provide the most explicit solutions
  - → GALPROP (Strong & Moskalenko 1998), Usine (Maurin et al. 2001), DRAGON (Evoli et al. 2008), PICARD (Kissmann 2014)

Energy Spectrum of CRs at the Sources

- Derivation of a simple constraint for the spectral index of the CR energy spectrum near acceleration sites
- Assumptions:
  - Primary protons and stable nuclei ($N = N_P$) in a steady-state ($\frac{dN_P}{dt} = 0$)
    - Energy loss processes negligible ($b(E) \sim 0$)
  - Neglecting of fragmentation processes ($P_{ij} = 0$)
  - Particles' escape time τ_{esc} **decreases** with **increasing** energy E

$$\tau_{esc} \propto E^{-\delta}$$

    - $\delta \sim 0.6$ from recent measurements
- Rearranging all terms of the diffusion equation, we get

$$\boldsymbol{Q(P) \propto E^{-\alpha+\delta} = E^{-2.1}}$$

    - Where $\alpha \sim 2.7$ below the knee

➔ Models of CR sources should be able reproduce an energy dependence with index ~2