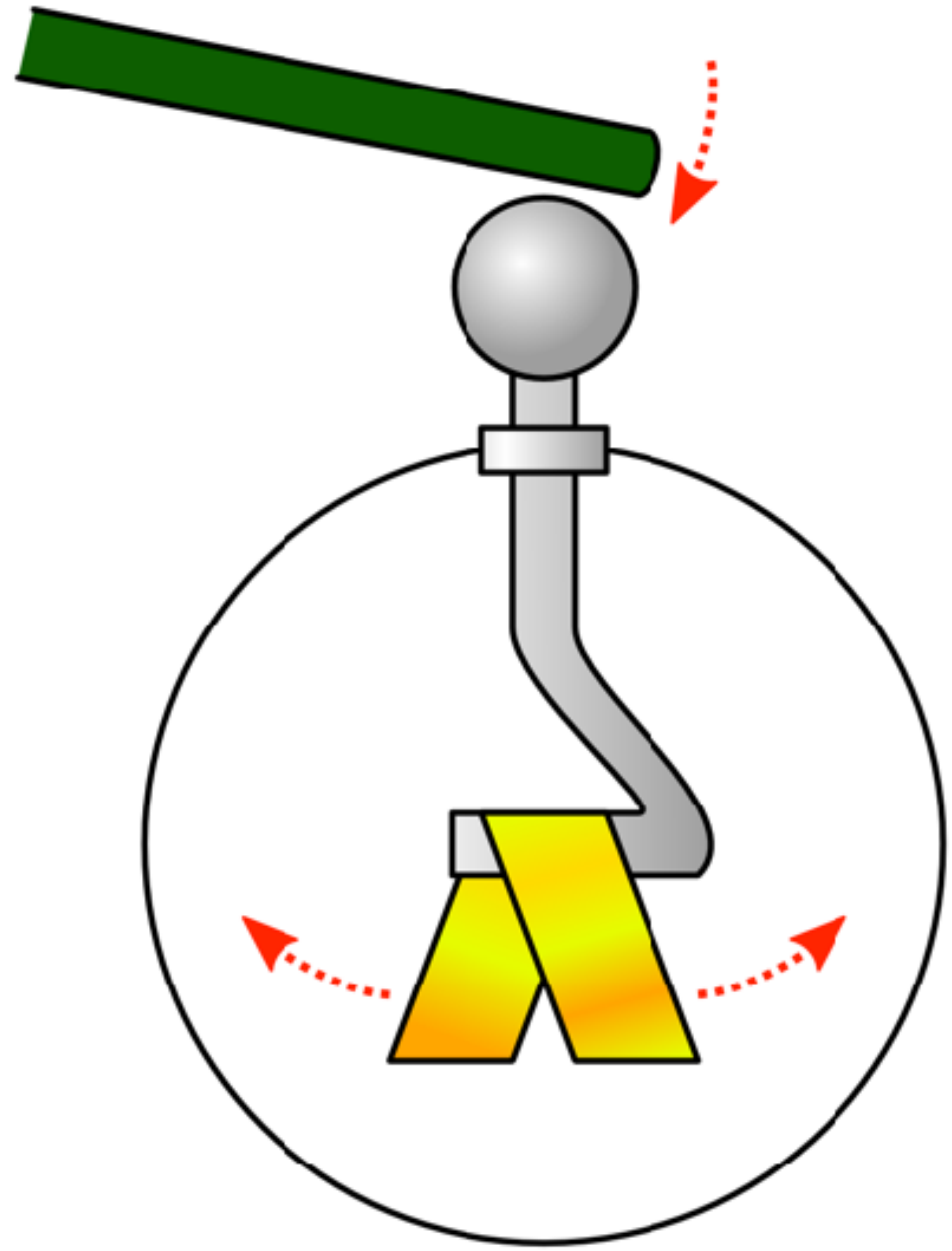
NPAC course on Astroparticles

II - Particle interactions: cosmic rays, gamma rays, and neutrinos

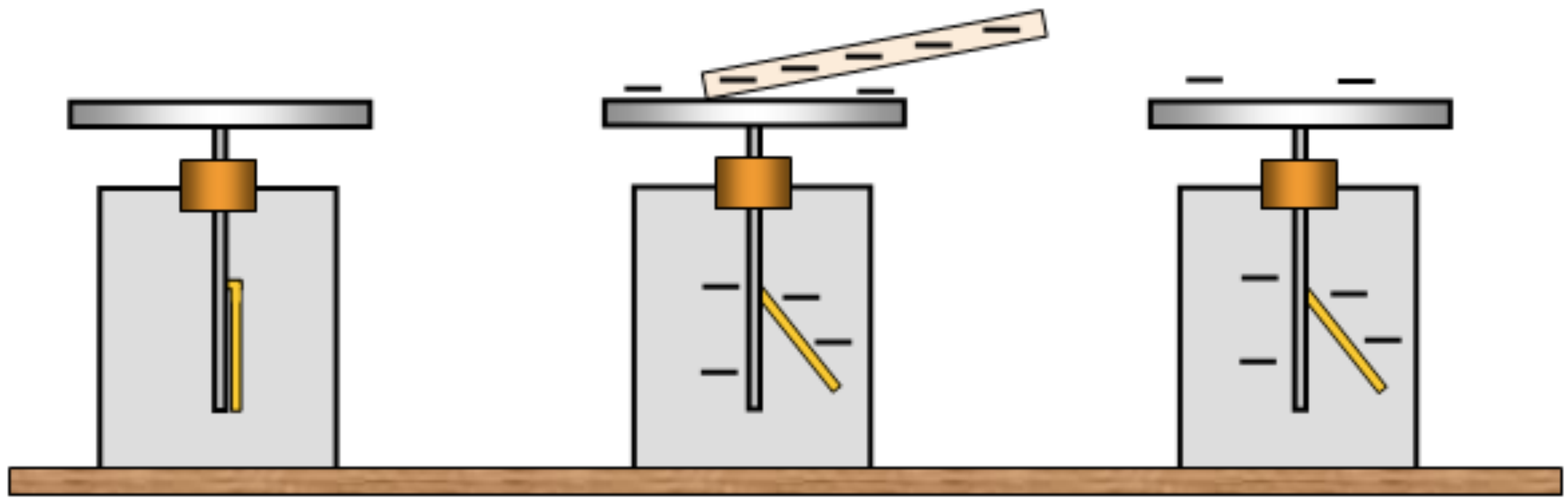
The electroscope

- simple device used to measure the electric charge of objects;
- it works because of the repulsion of objects of like charge

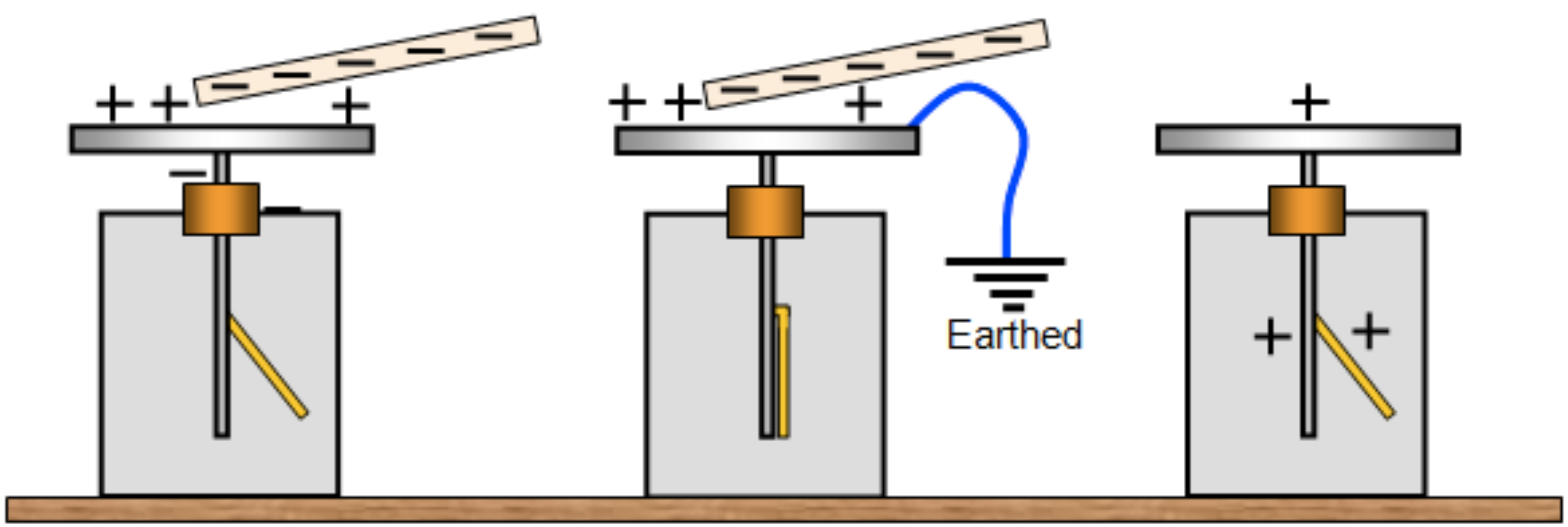


ELECTROSCOPE

How does it work



Charging by contact

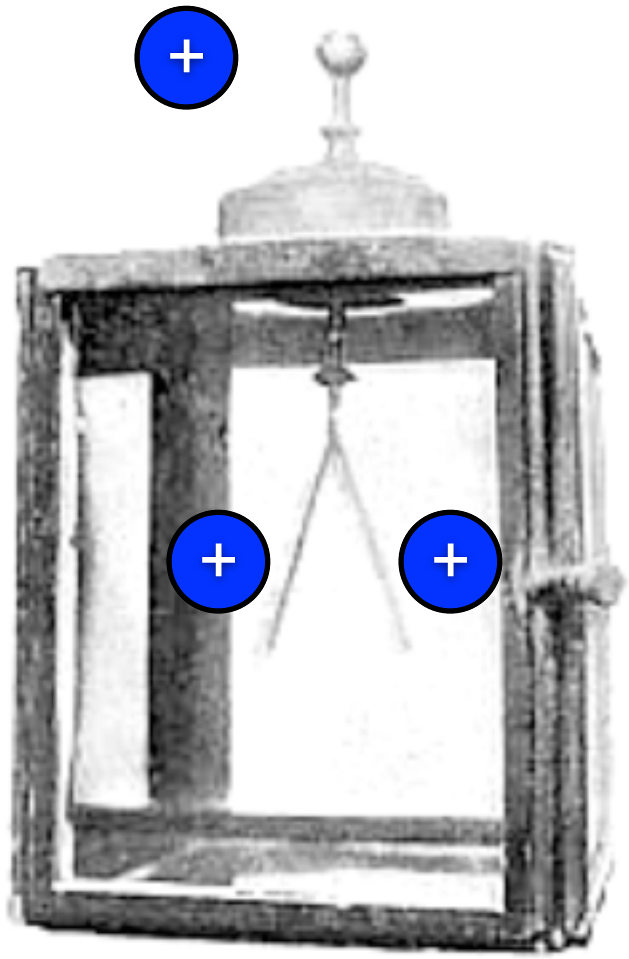


Charging by induction

The problem...

- in 1785 Coulomb noted that charged electroscopes discharge spontaneously;
- in 1835 Faraday confirmed Coulomb's results, using a better insulation system -> it is not an instrumental problem;
- in 1879 Crookes noted that the discharge time changes with the pressure of the air **-> the discharge is induced by the ionisation of the air**
- in 1896 Bequerel discovers **radioactivity**

Radioactivity from the Earth



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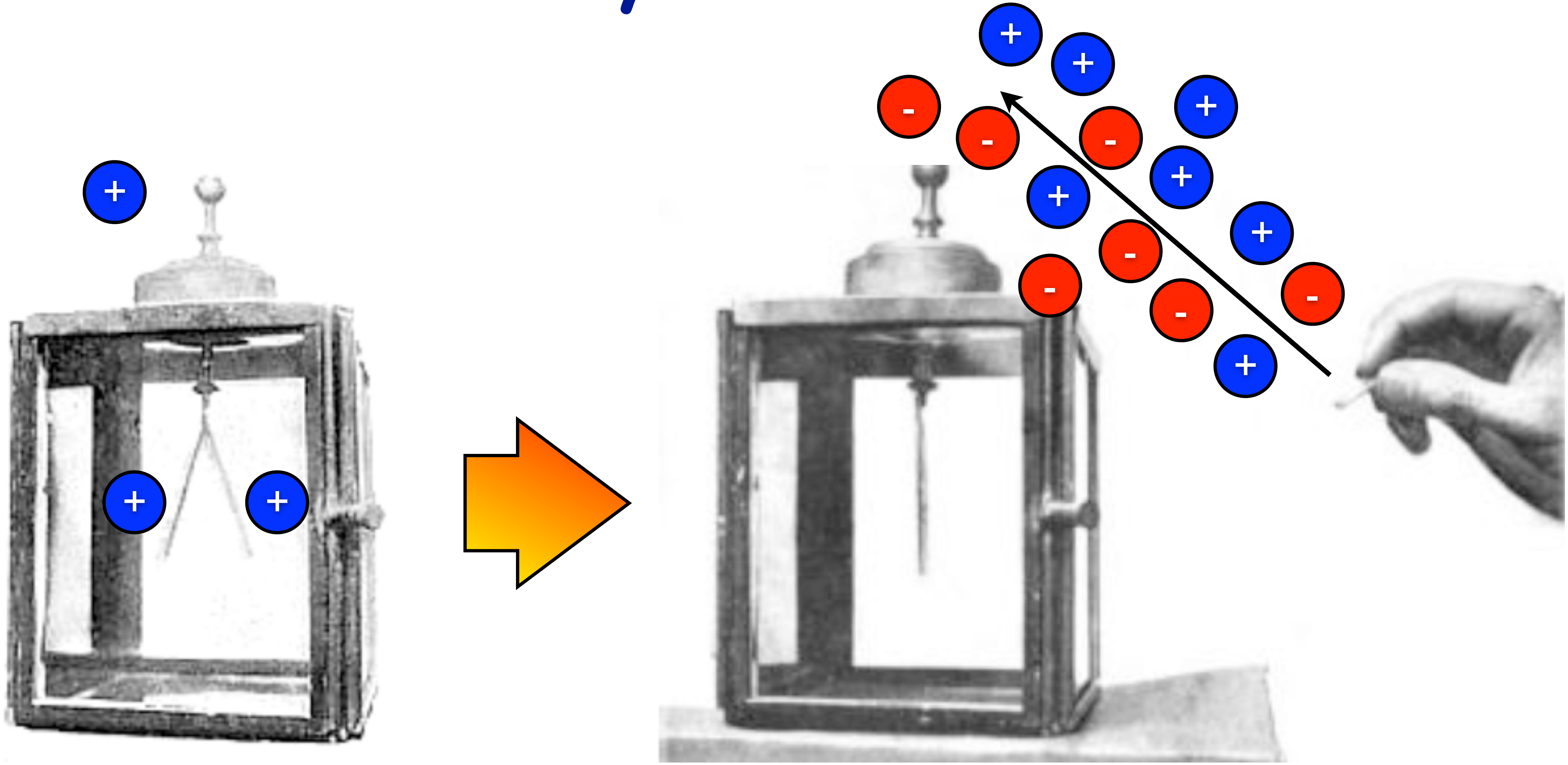

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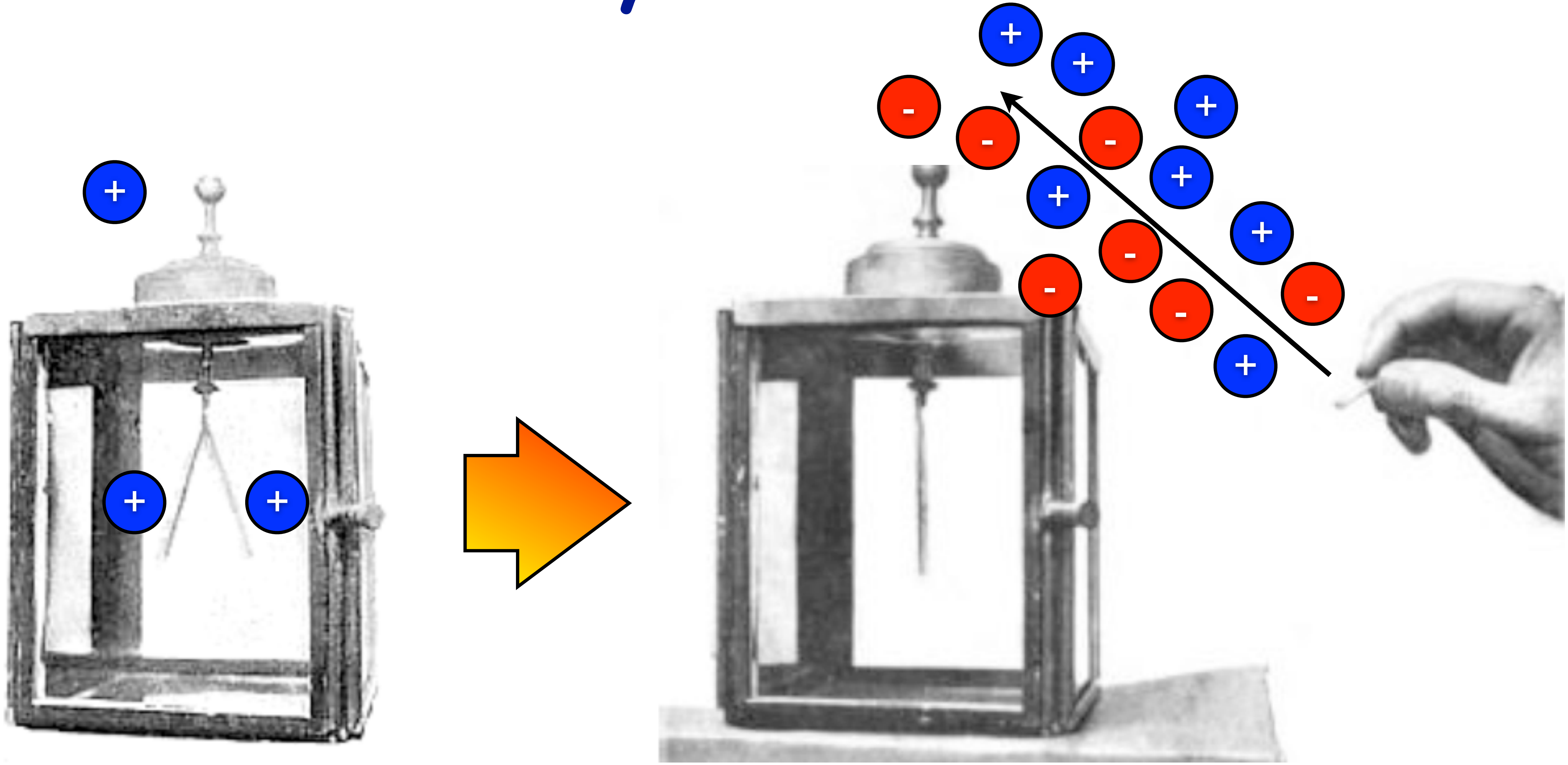

hypothesis: the Earth's crust contains radioactive isotopes (natural radioactivity) -> this might be the source of the ionizing radiation needed to explain the spontaneous discharge of electroscopes.

Father Theodor Wulf on the Tour Eiffel

Idea: if the source of radioactivity is the Earth, electroscopes should discharge less rapidly when located far away from it.

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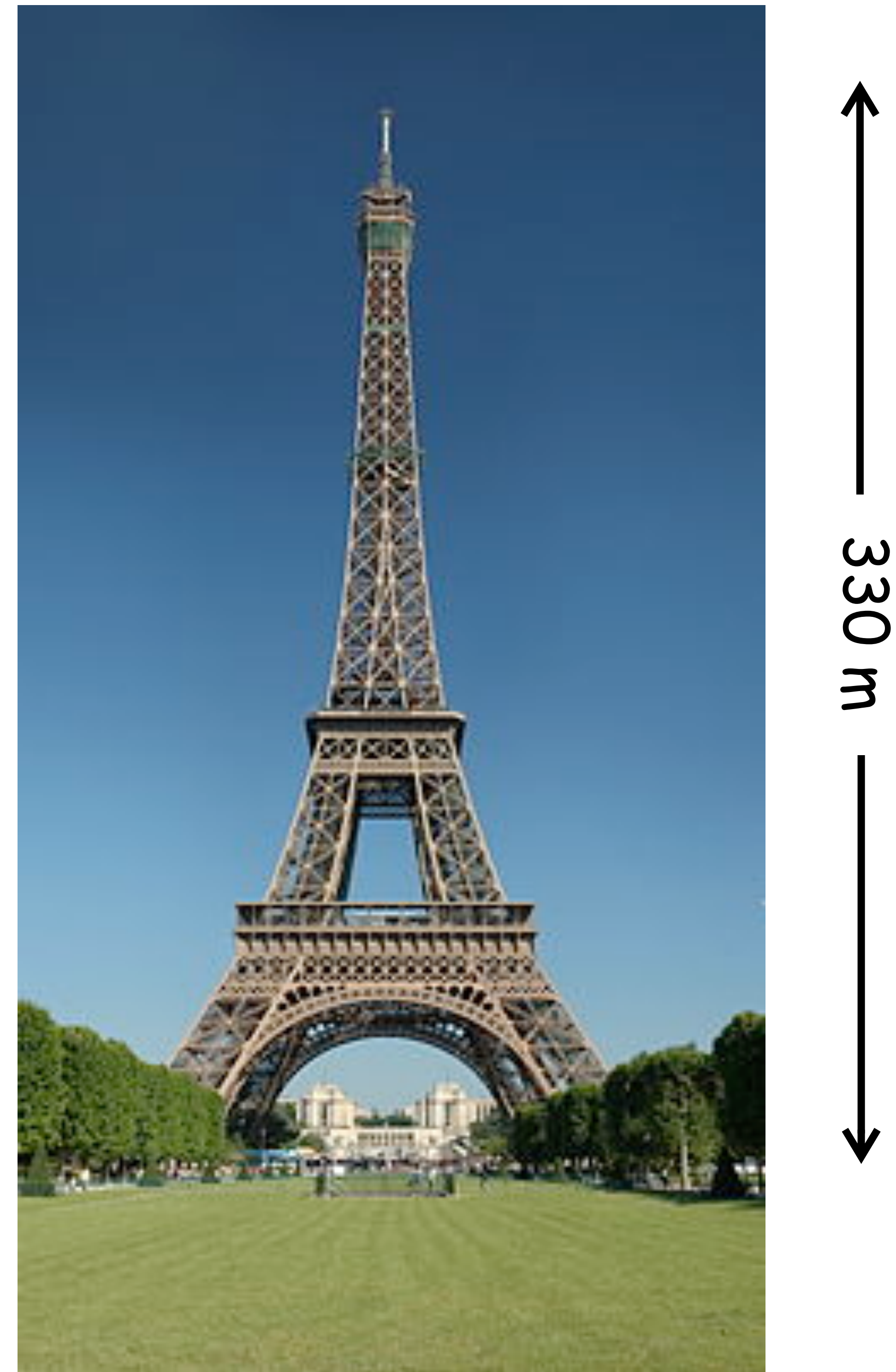
- in **1906-1908 Wulf** improves the electroscope making it a **portable** instrument;
- in **1910** spends his Easter holidays in Paris, where he brings his electroscopes to measure the discharge time at the top and at the bottom of the Eiffel tower, during the day and during the night (the sun?);



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28. März	Valkenburg	22,5
29. "	Paris, Boden	17,5
30. "	" Eiffelturm	16,2
31. "	" "	14,4
1. April	" "	15,0
2. "	" "	17,2
3. "	" Boden	18,3
4. "	Valkenburg	22,0

330 m

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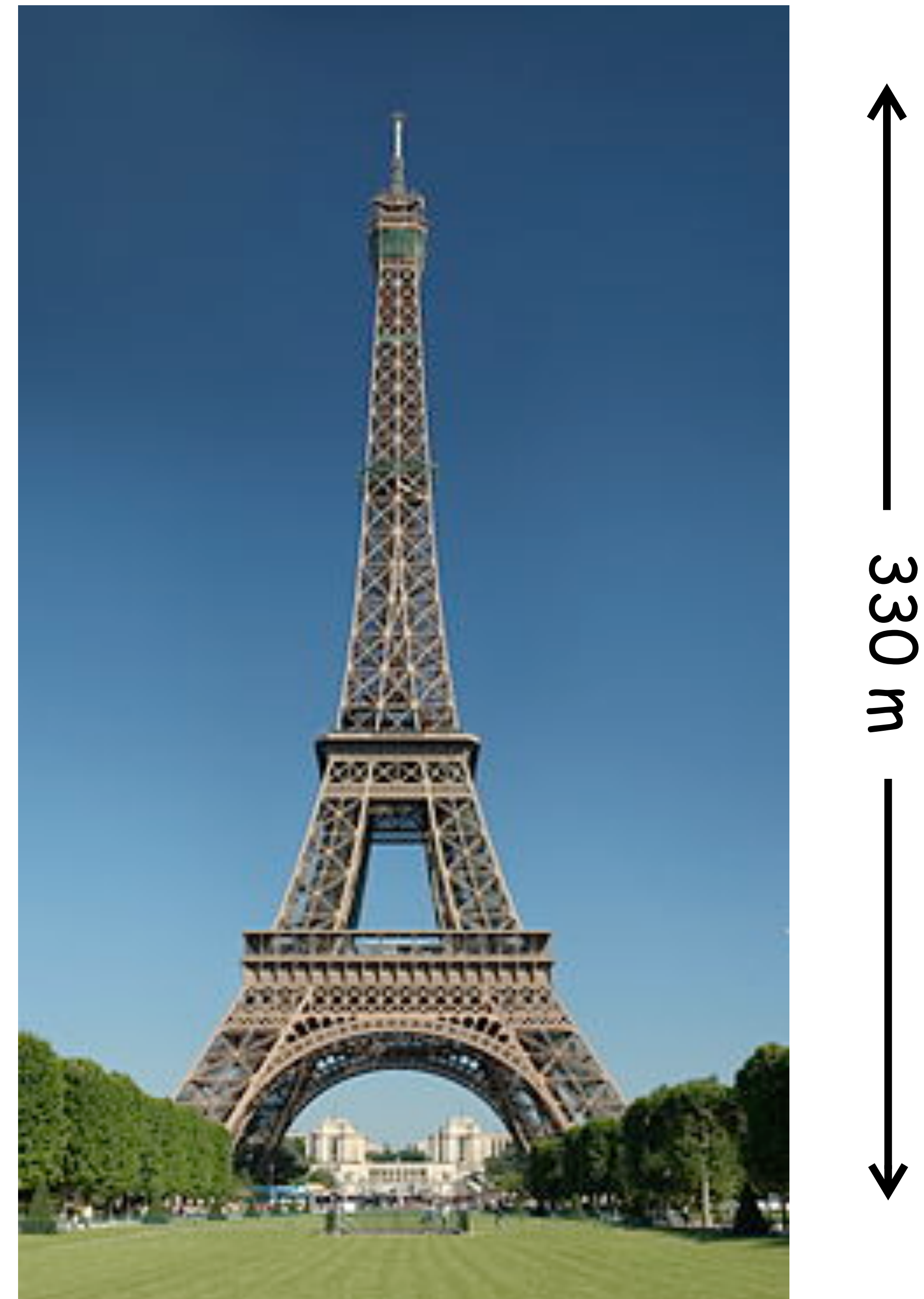

though the effect was smaller than expected, Wulf concluded that Earth's radioactivity remained the most plausible hypothesis

Pacini's (forgotten) experiment

in **1911** Pacini performed measurements on a boat off the coast of Livorno (300 m from the coast). Measurements were performed on the sea surface (8 m from sea bottom) and at 3 m of depth.

~20% drop of the ionization rate underwater
-> the ionization radiation comes from the atmosphere and NOT from the Earth!

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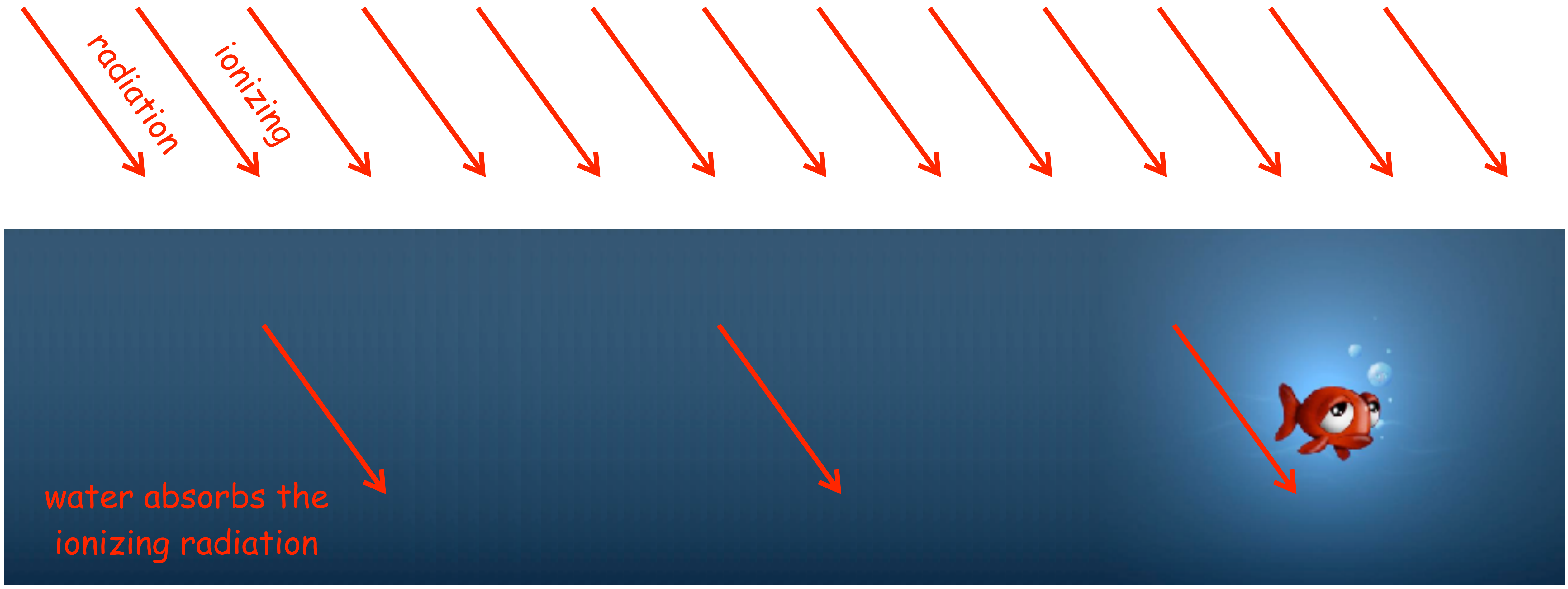
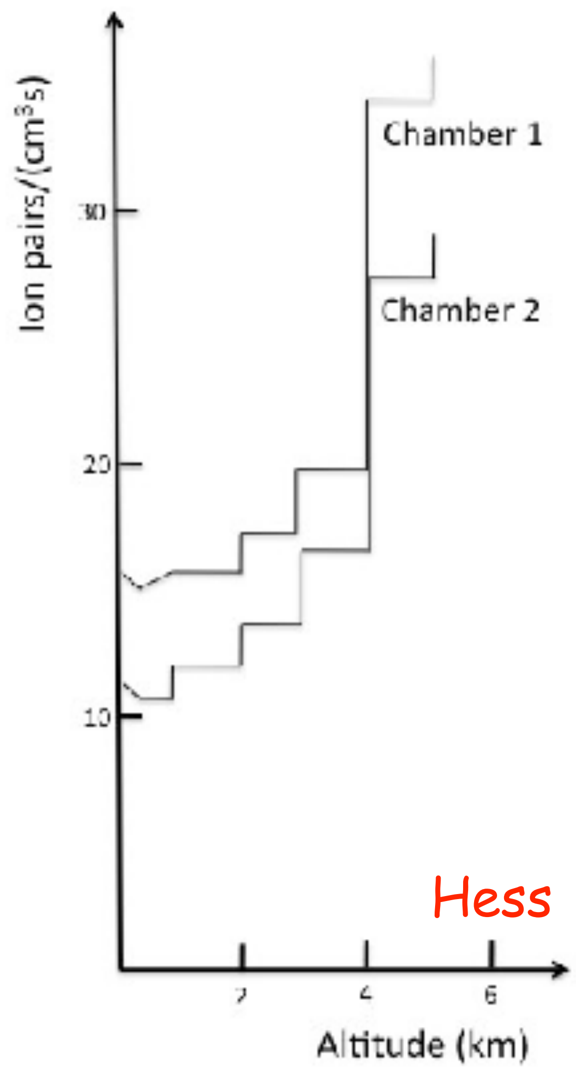
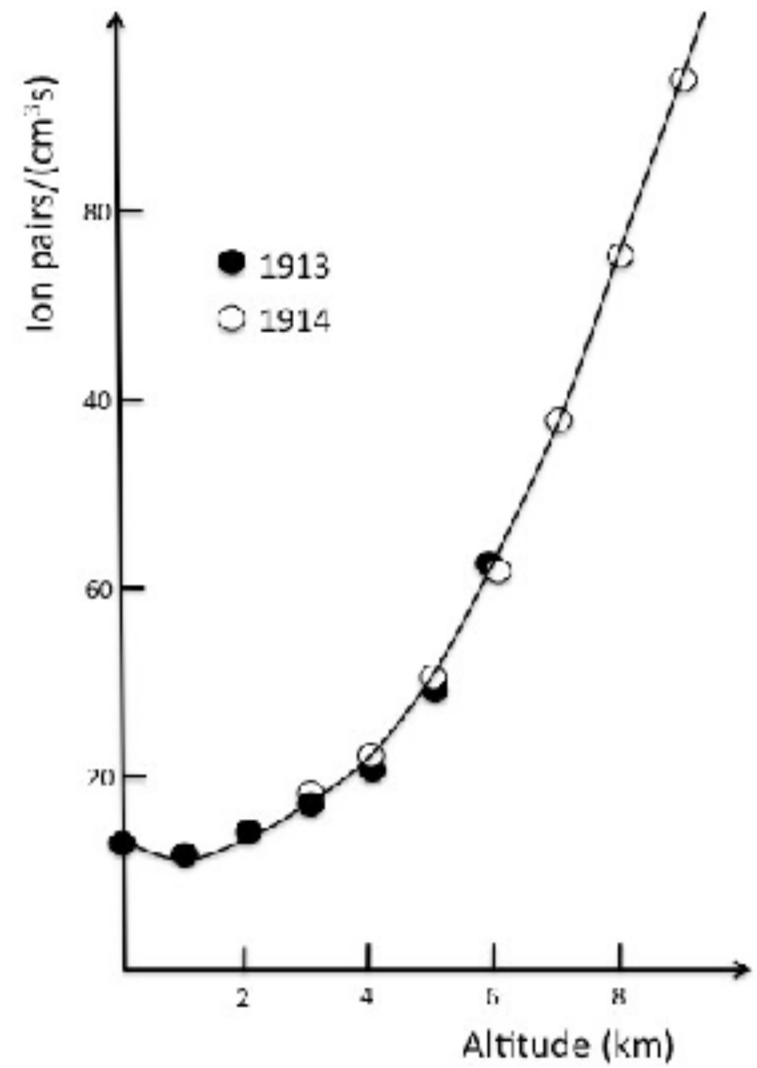


Which is the nature of the ionizing radiation in the atmosphere?

Victor Hess flies on a balloon

Between April and August 1912 Hess performed 7 balloon flights. During the 7th flight he reached an altitude of 5200 meters.





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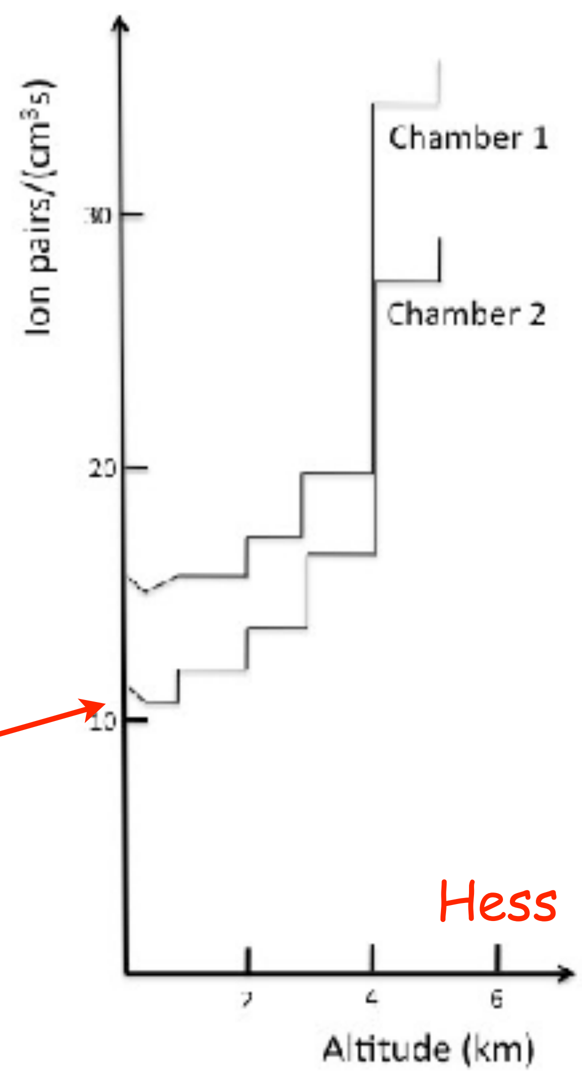

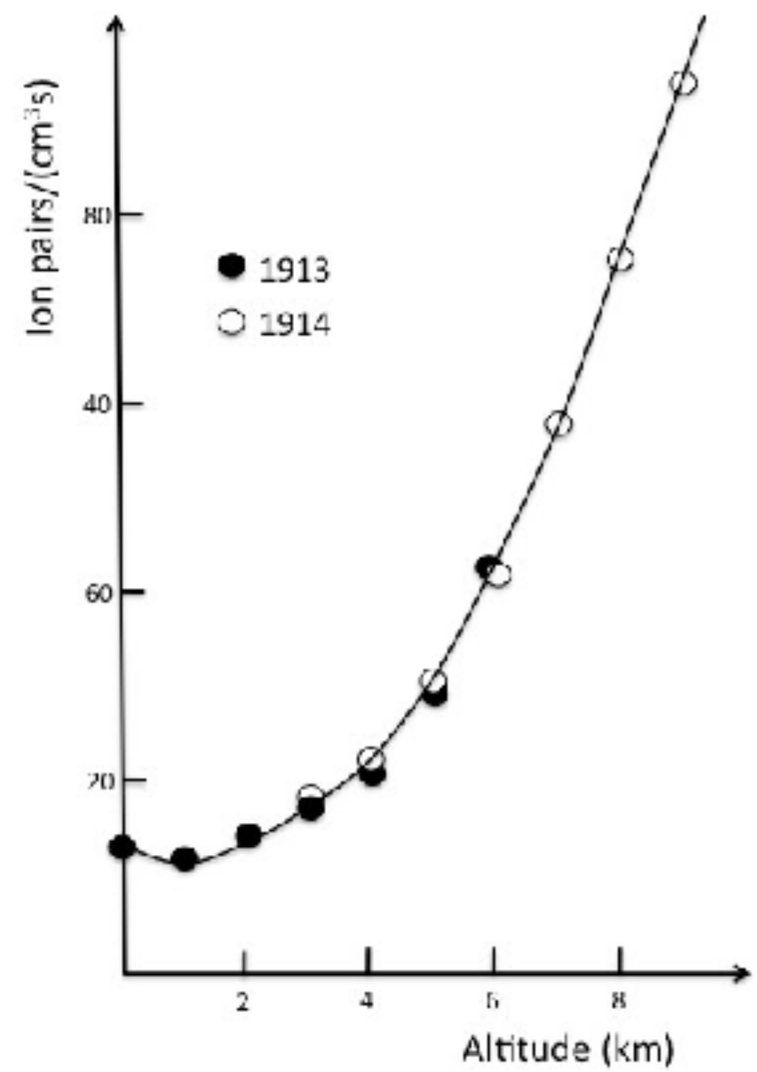

Wulf was right!

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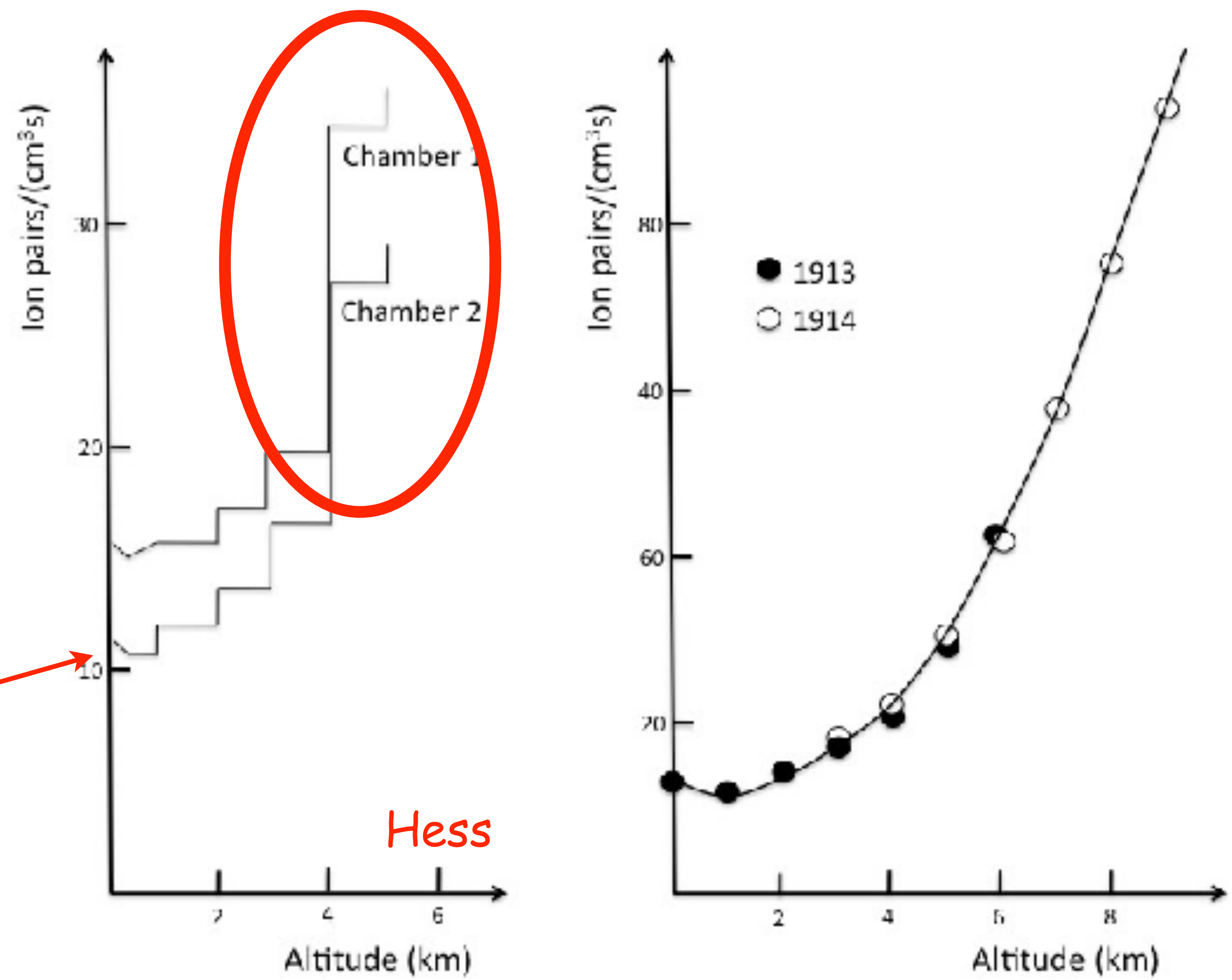

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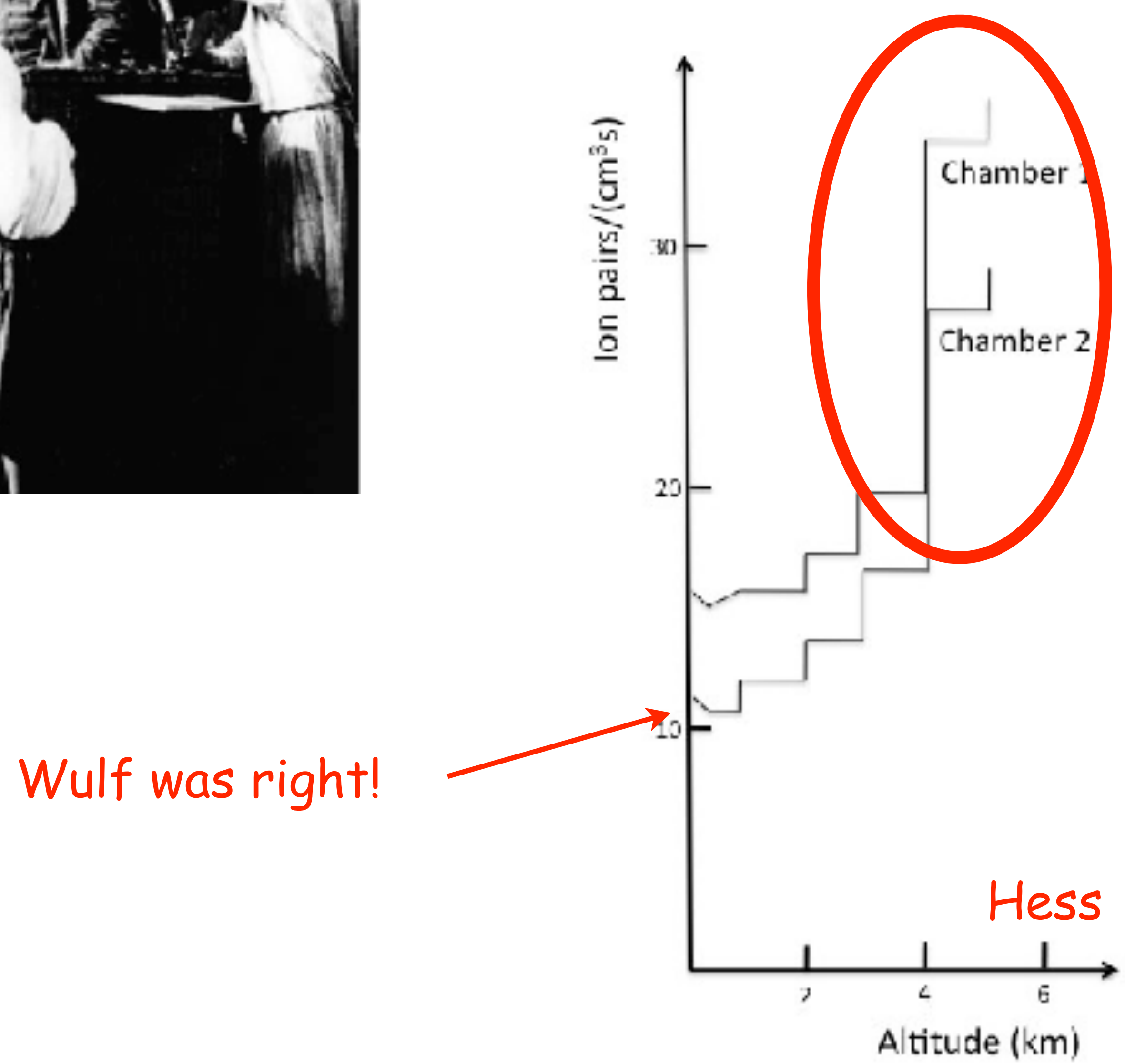

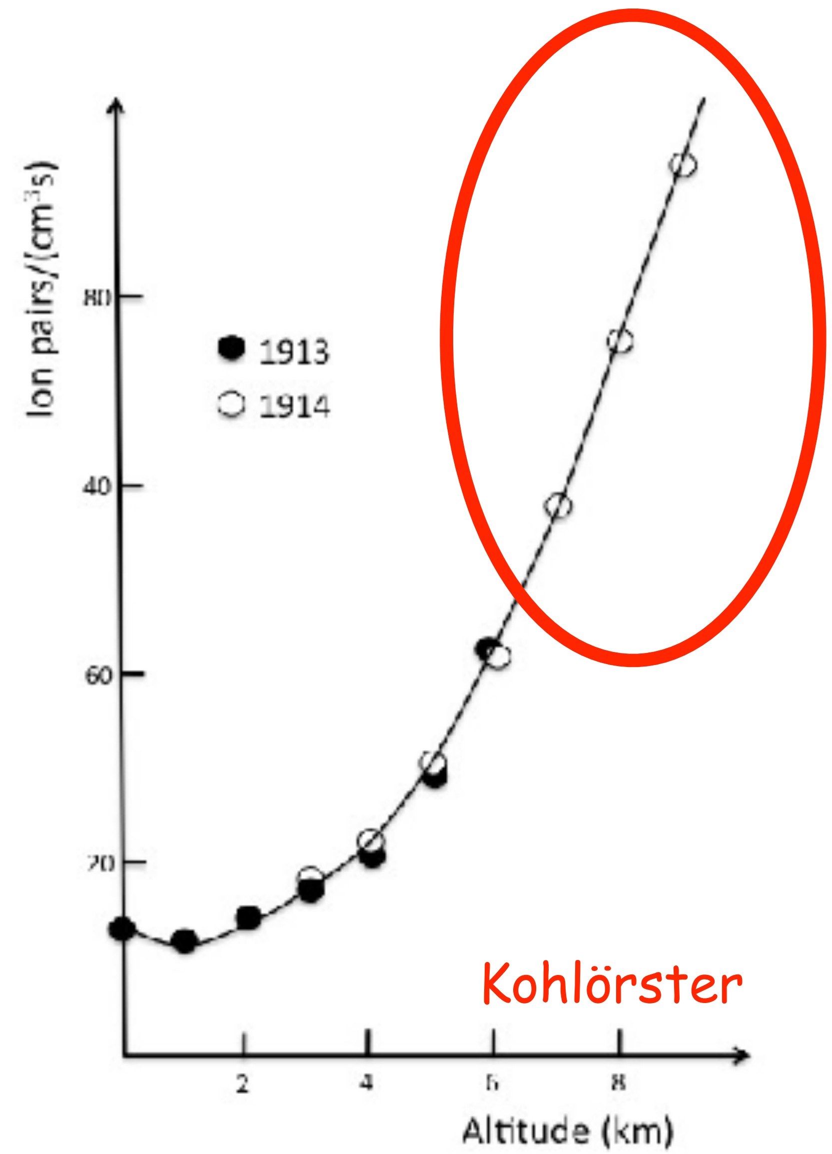

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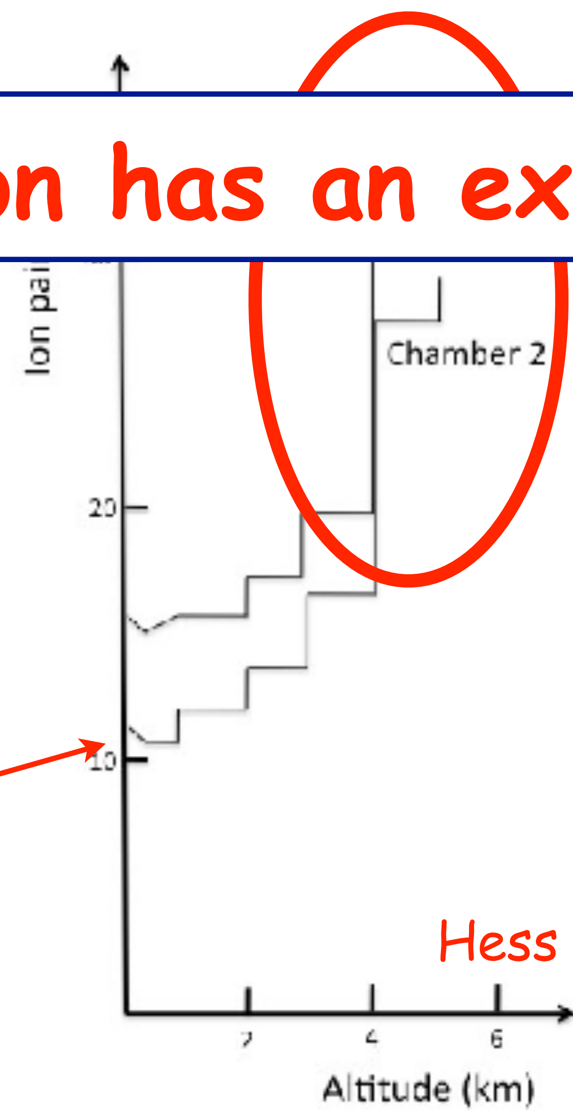
The ionizing radiation has an extra-terrestrial origin



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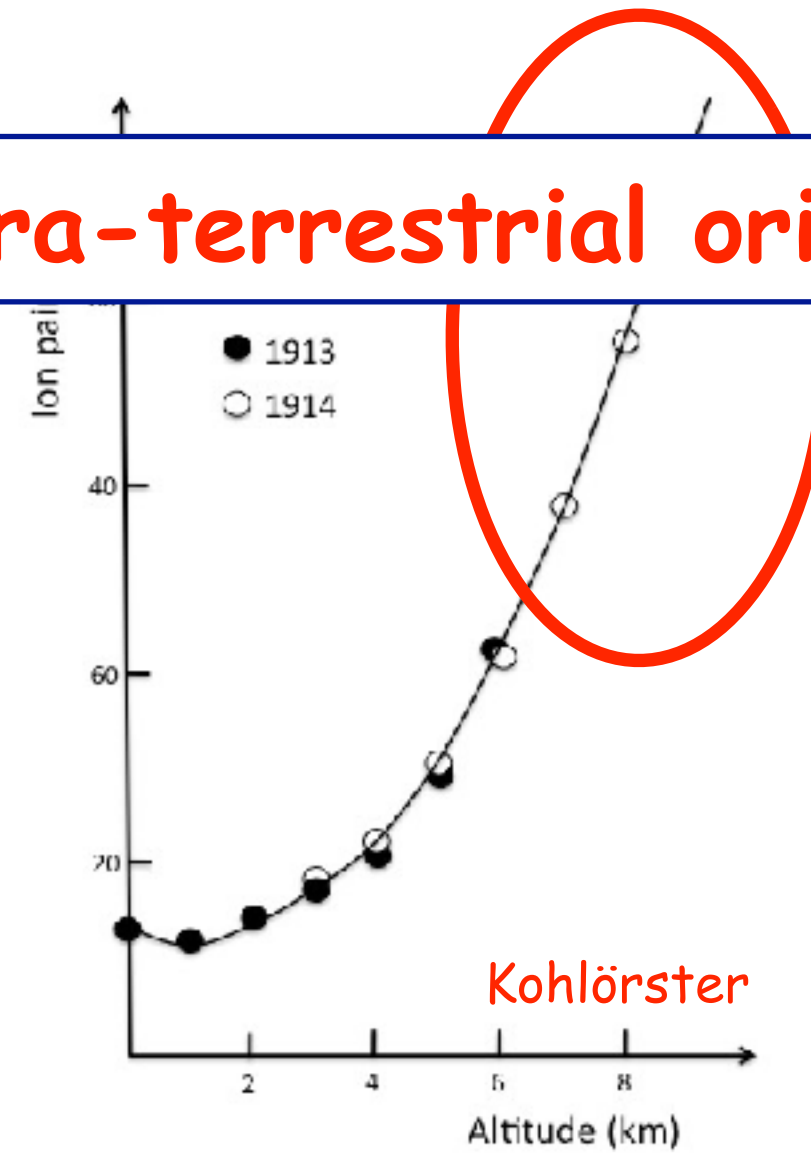


What are Cosmic Rays?

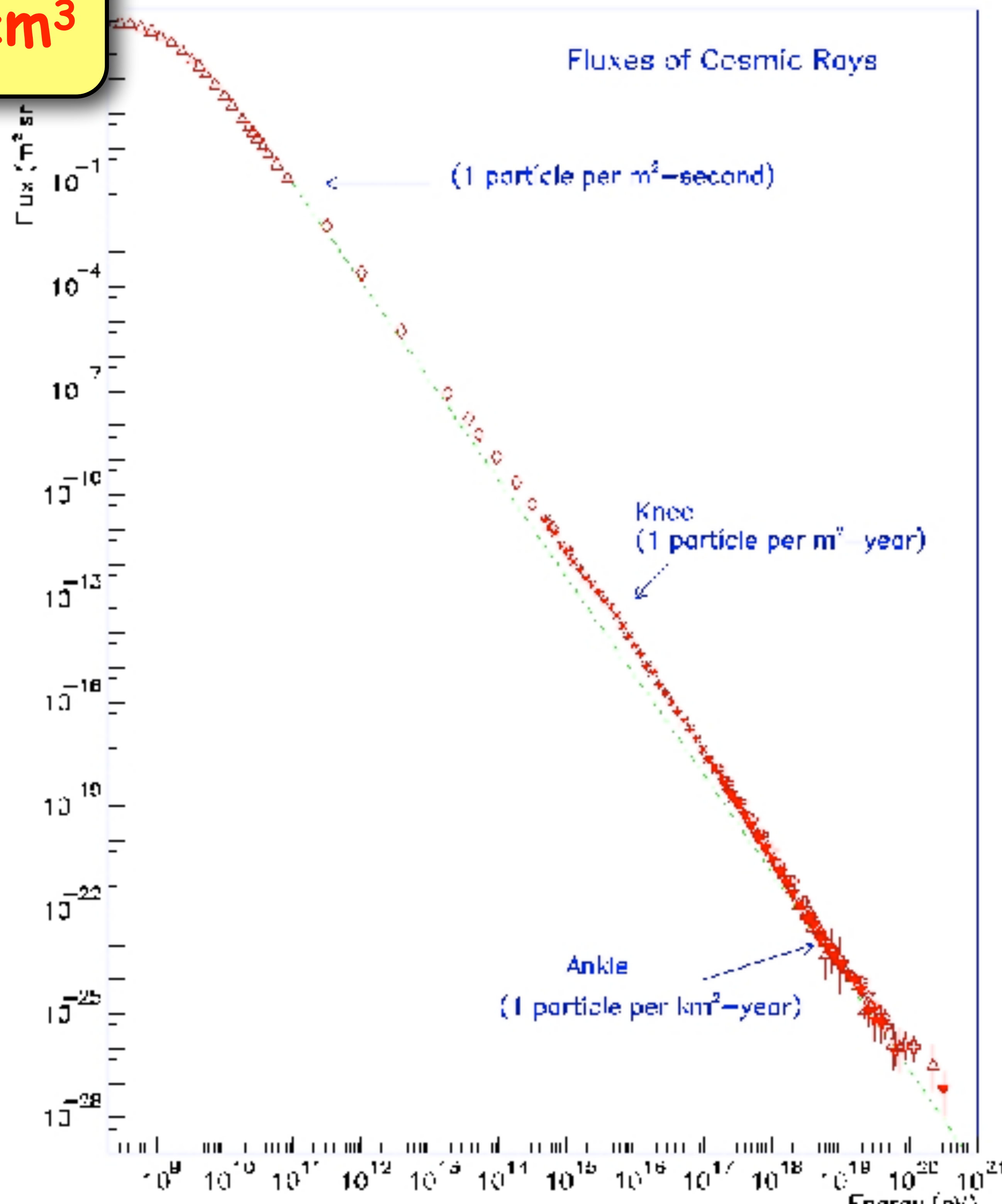
Cosmic rays particles hit the Earth's atmosphere at the rate of about **1000 per square meter per second**. They are ionized nuclei - about **90% protons**, 9% alpha particles and the rest heavy nuclei - and they are distinguished by their high energies. Most cosmic rays are **relativistic**, having energies comparable or somewhat greater than their masses. A very few of them have ultrarelativistic energies extending up to 10^{20} eV (about 20 Joules), eleven order of magnitudes greater than the equivalent rest mass energy of a proton. The fundamental question of cosmic ray physics is, **"Where do they come from?"** and in particular, **"How are they accelerated to such high energies?"**.

T. Gaisser "Cosmic Rays and Particle Physics"

Also **electrons** are present in the cosmic radiation -> **~ 1%**

The (local) Cosmic Ray spectrum

$w_{CR} \sim 1$ eV/cm^3



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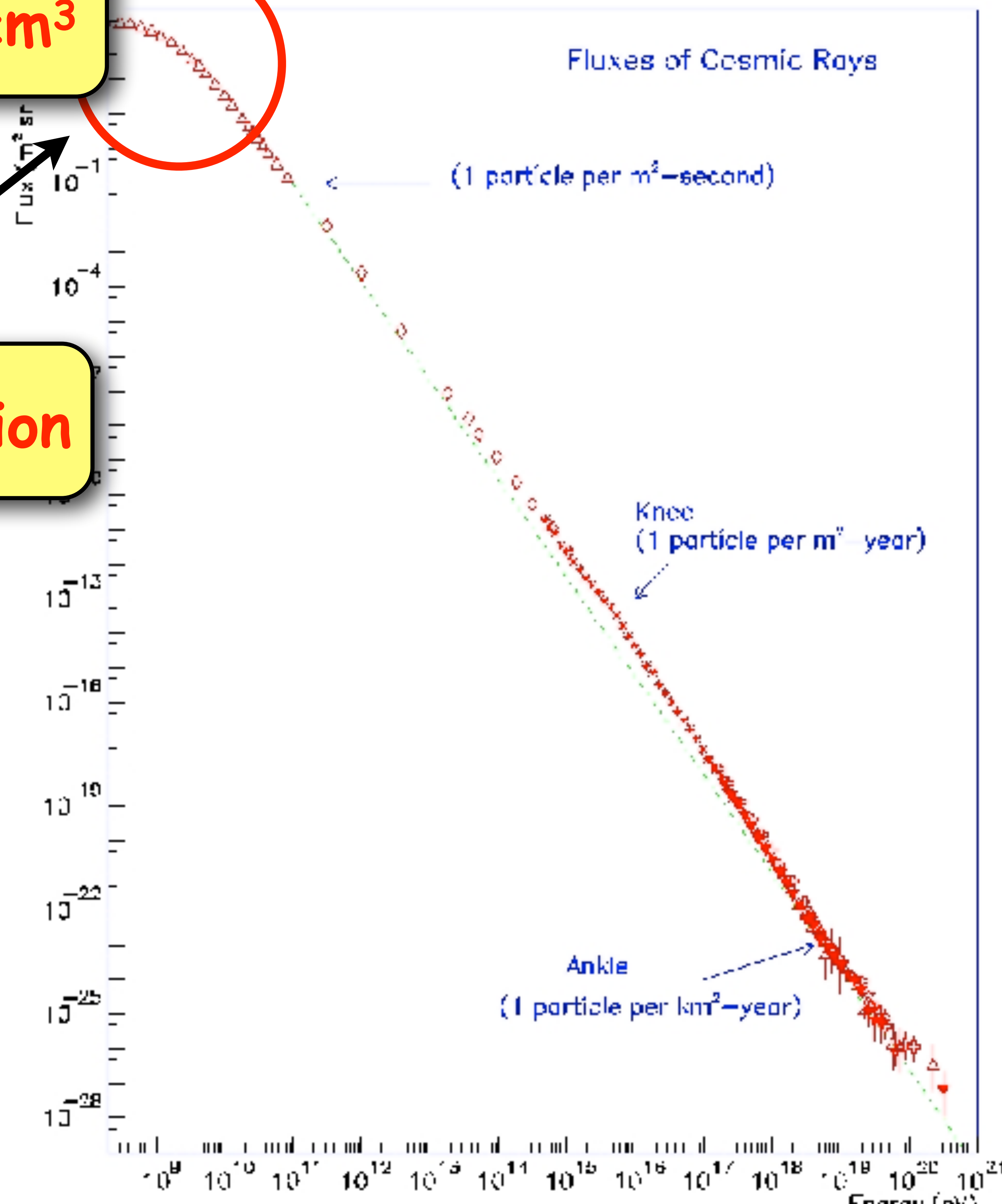
solar modulation



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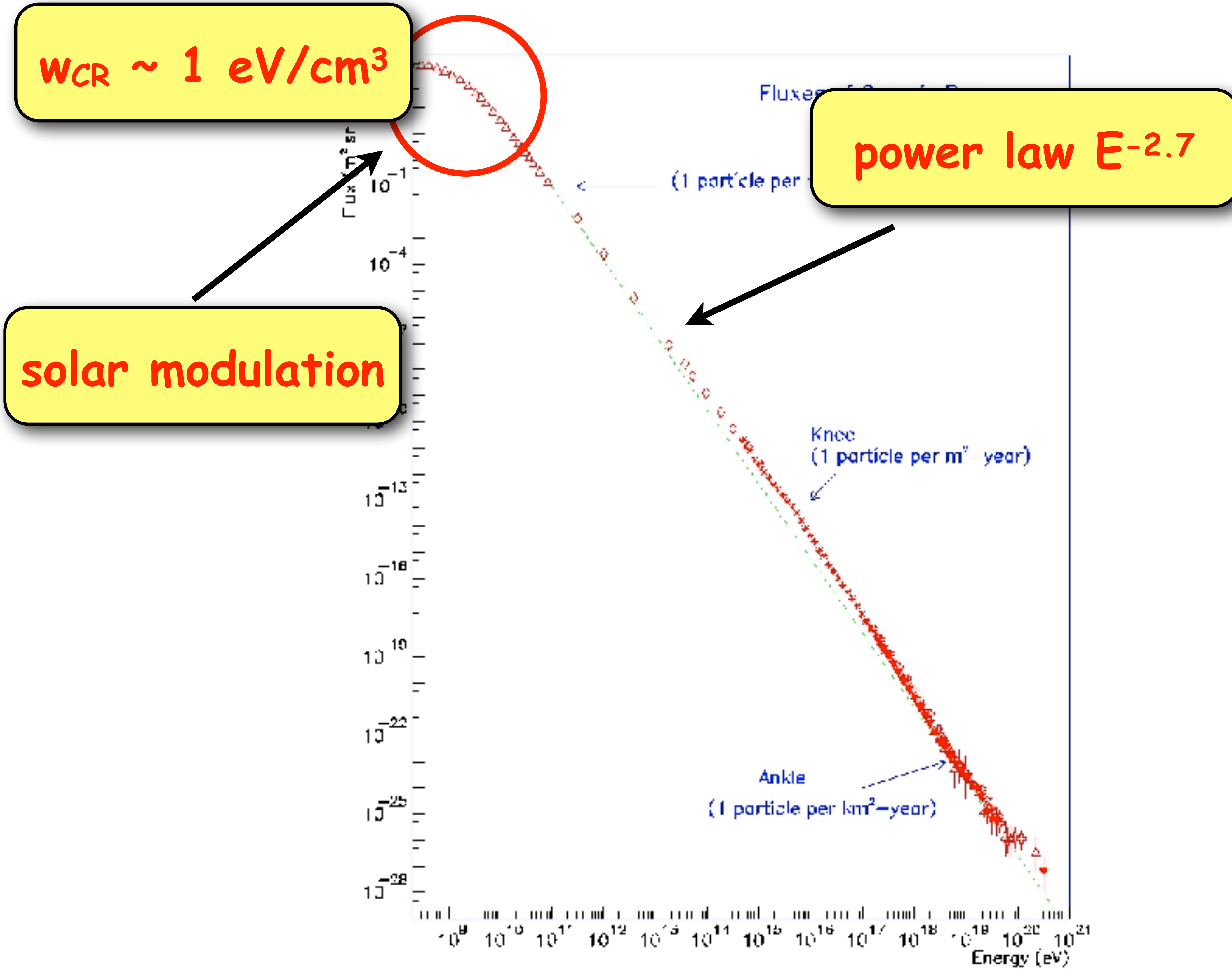

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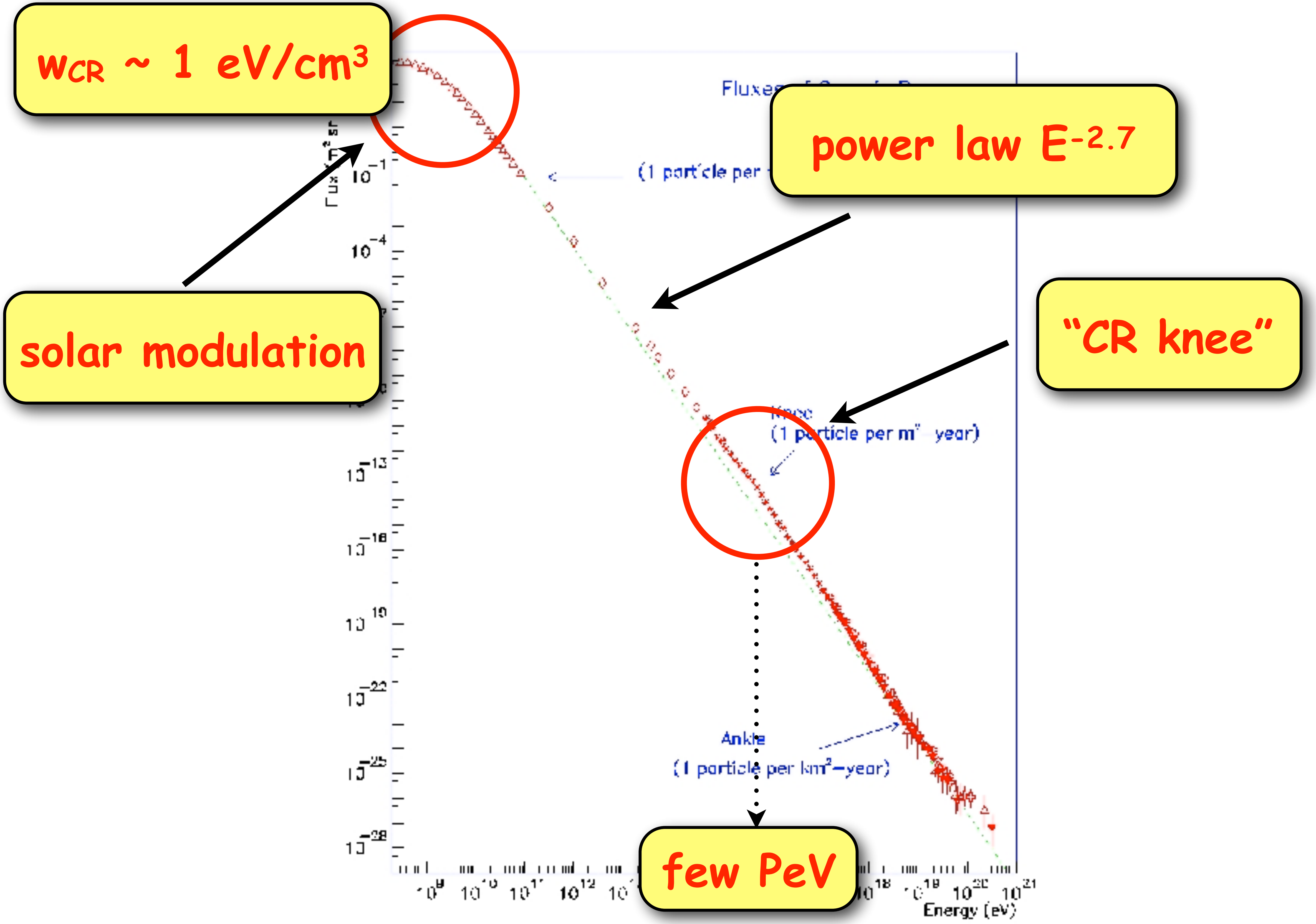

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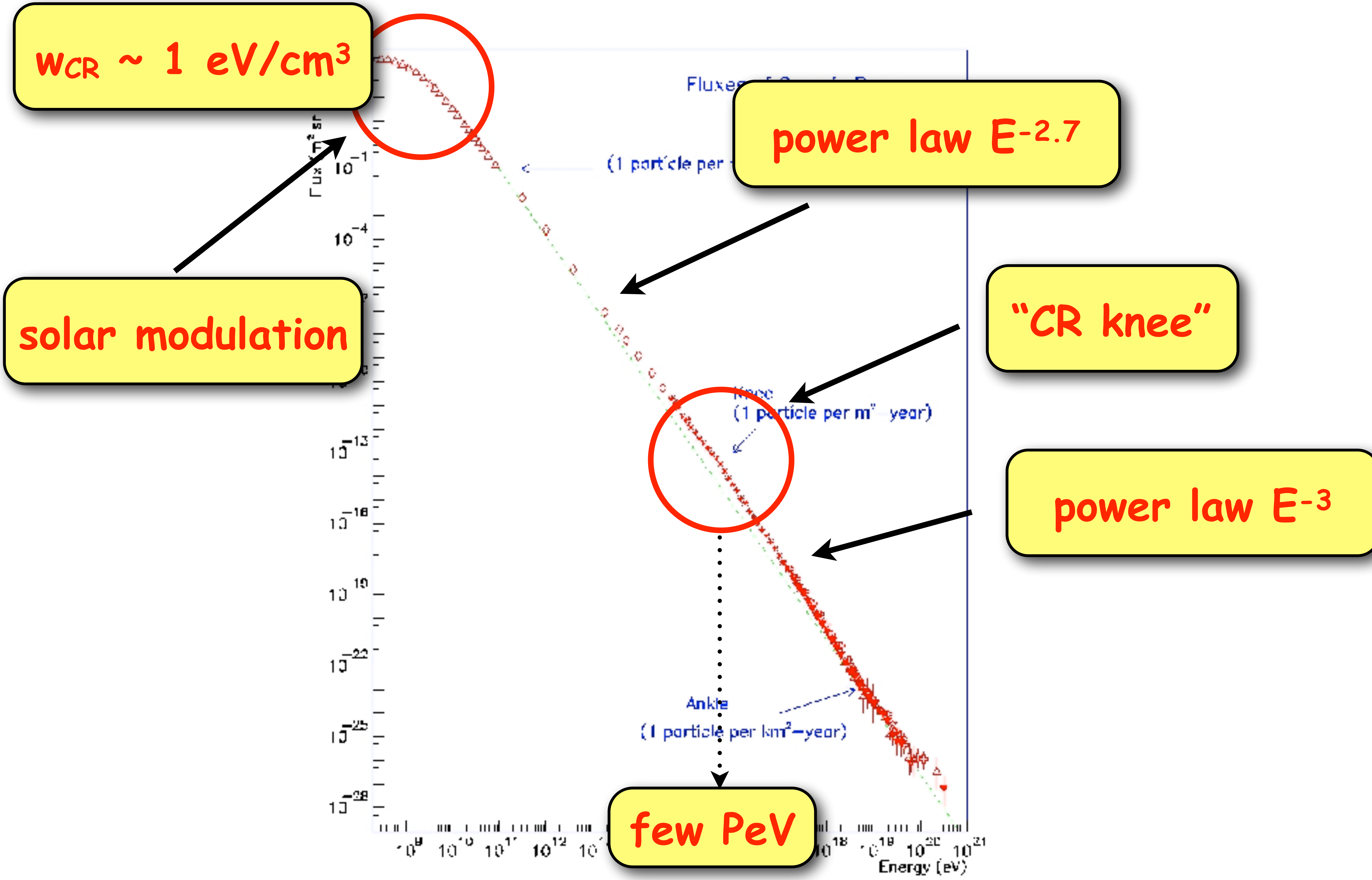

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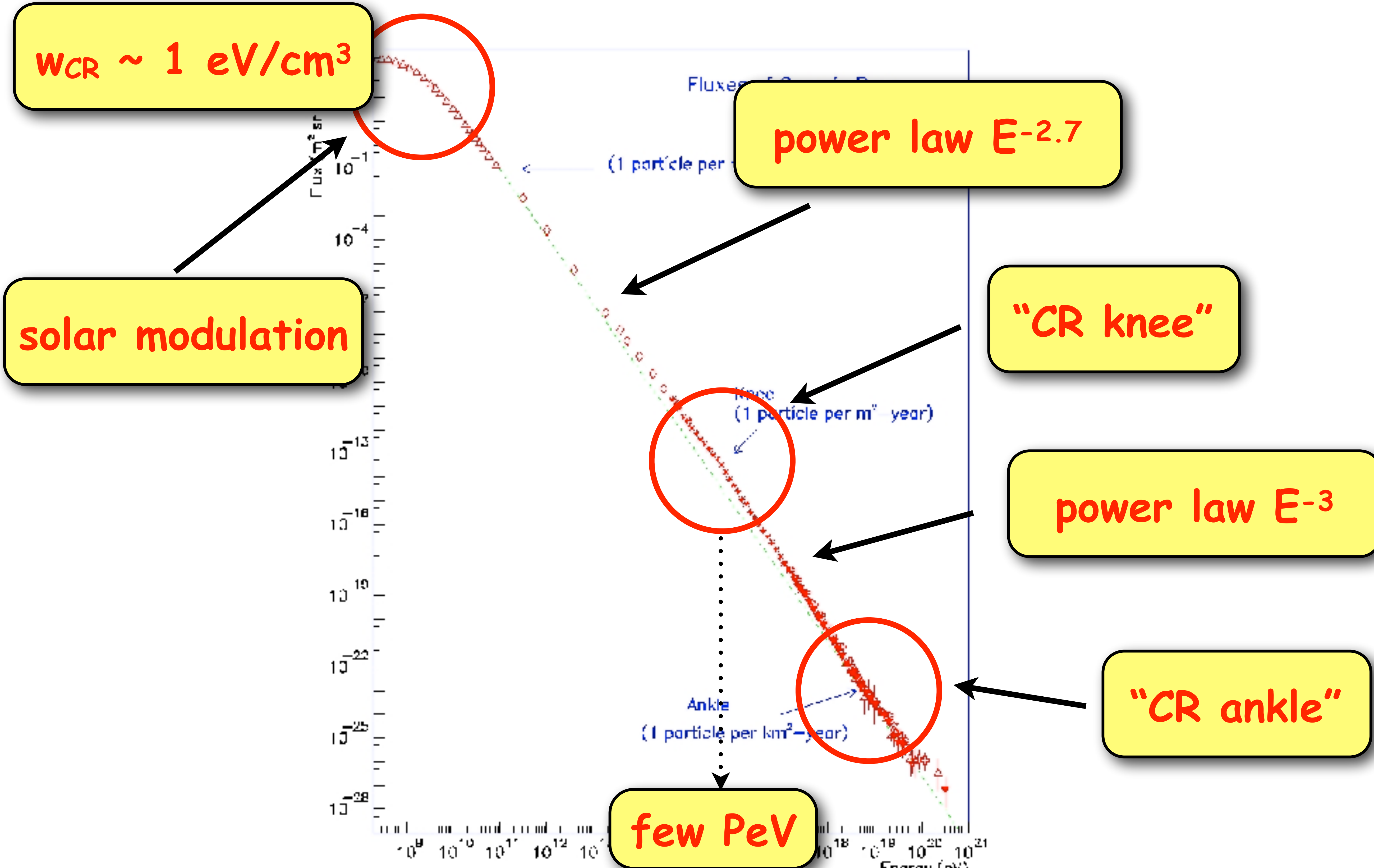

Energy density

Cosmic Ray energy density: $w_{CR} \sim 1 \text{ eV cm}^{-3}$

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Magnetic field energy density: $w_B = \dfrac{B^2}{8\pi} \sim \boxed{1 \text{ eV cm}^{-3}}$

Thermal gas energy density: $w_{gas}^{turb} = \varrho_{gas} v_{turb}^2 \sim \boxed{1 \text{ eV cm}^{-3}}$

Variations in time and space

- CR flux at Earth **constant during the last 10^9 yr** (from radiation damages in geological and biological samples, meteorites, and lunar rocks)
- thus the CR flux must be **constant along the orbit of the Sun** around the galactic centre (many revolutions in a Gyr)

Stability in time and (hints for) spatial homogeneity

Cosmic Rays are isotropic

Cosmic Ray anisotropy: $$\delta = \frac{I_{max} - I_{min}}{I_{max} + I_{min}}$$ (I -> CR intensity)

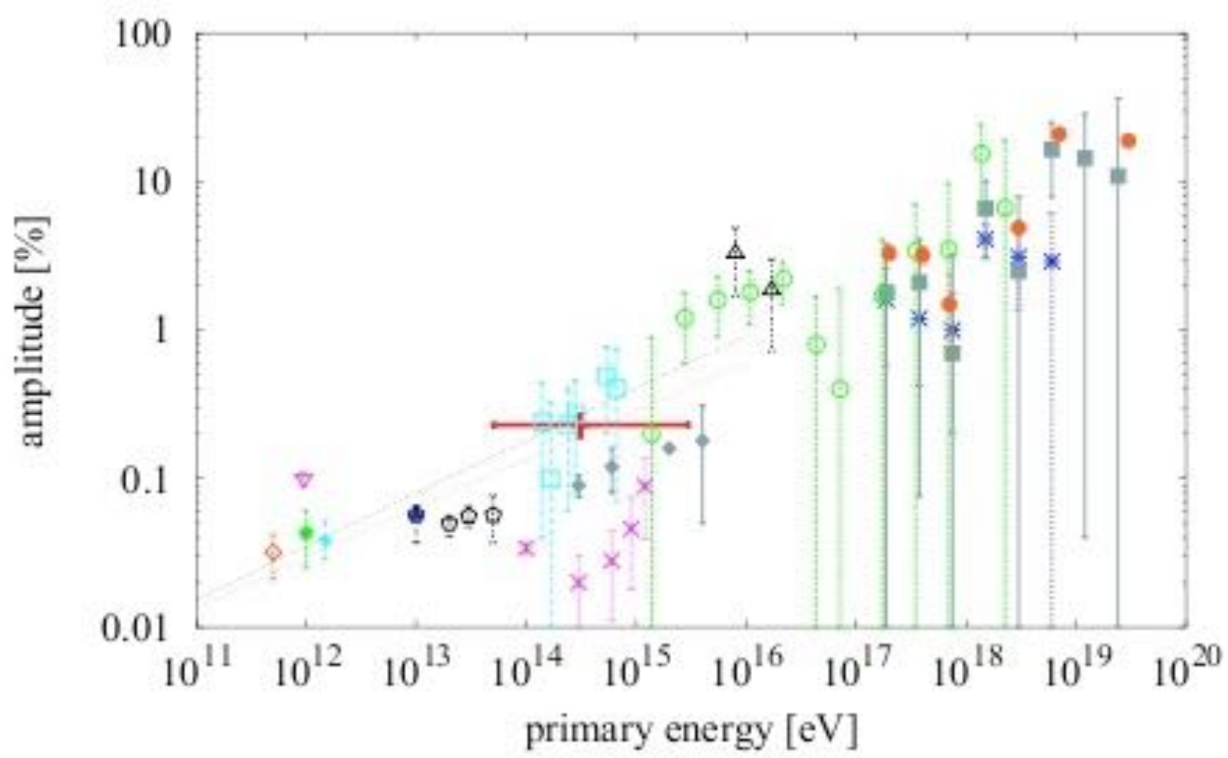

figure from
Iyono et al, 2005

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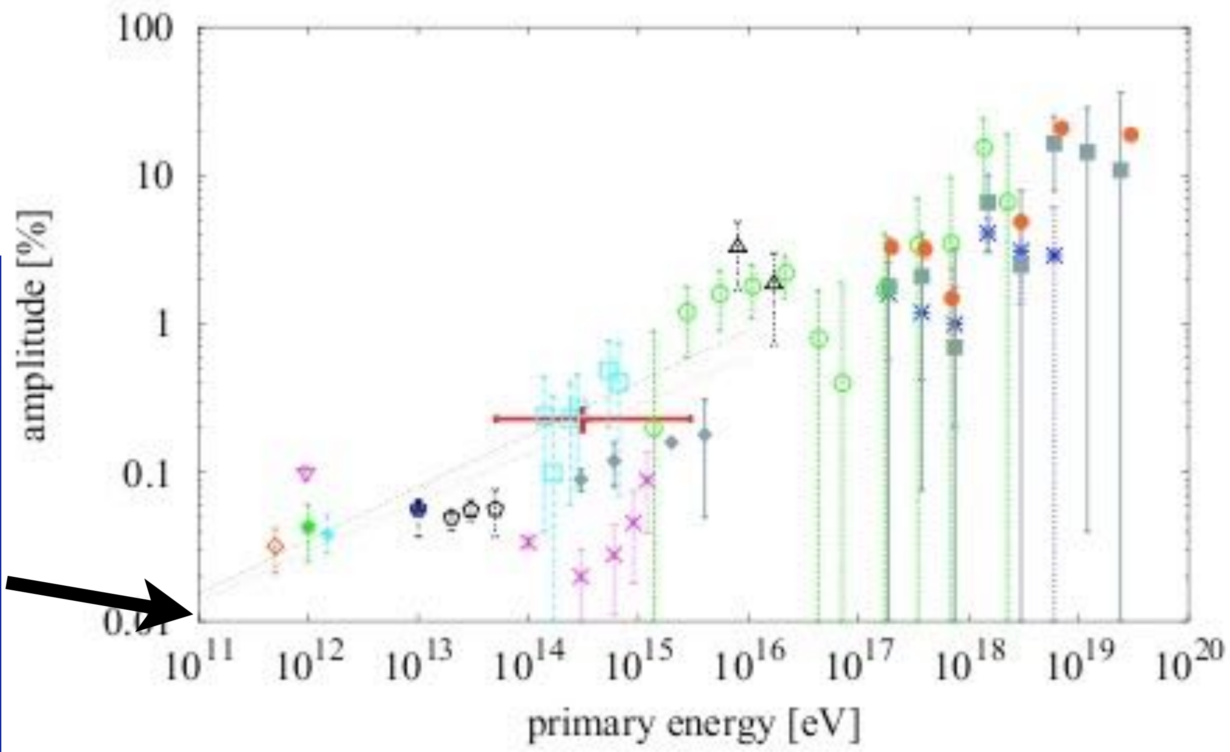
measures available only above ~500 GeV -> magnetic field of the solar system has no effect



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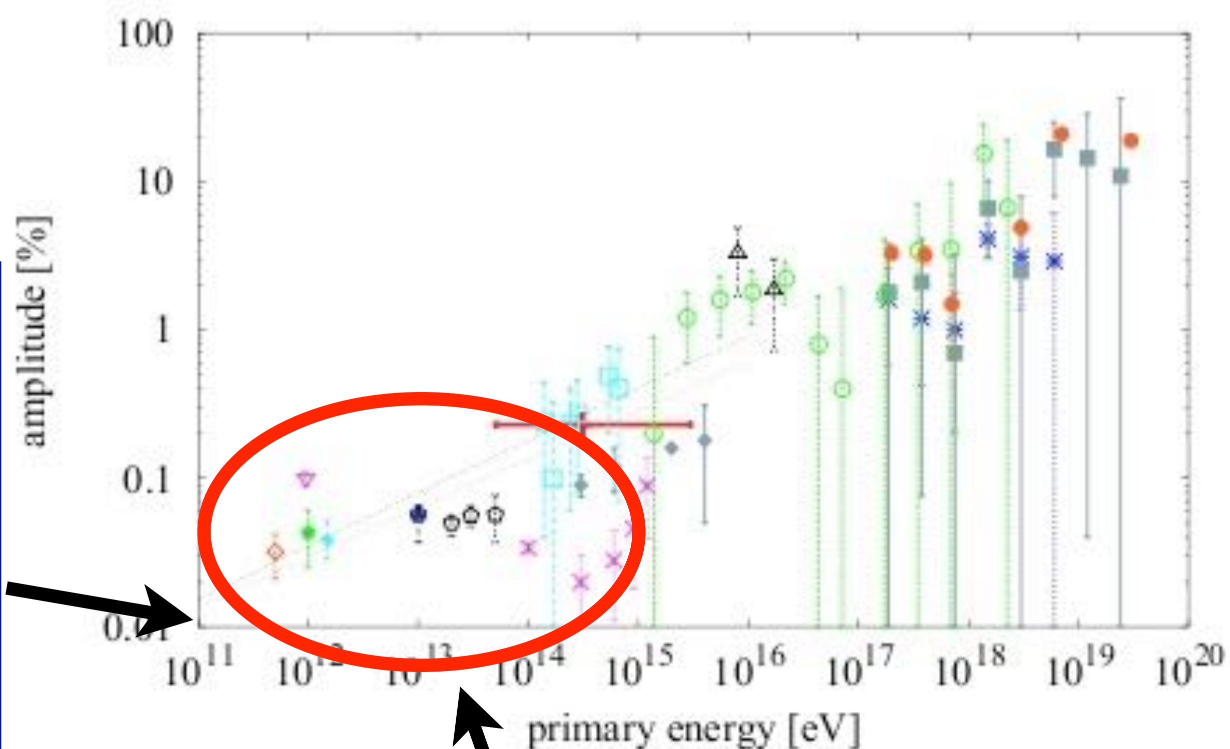

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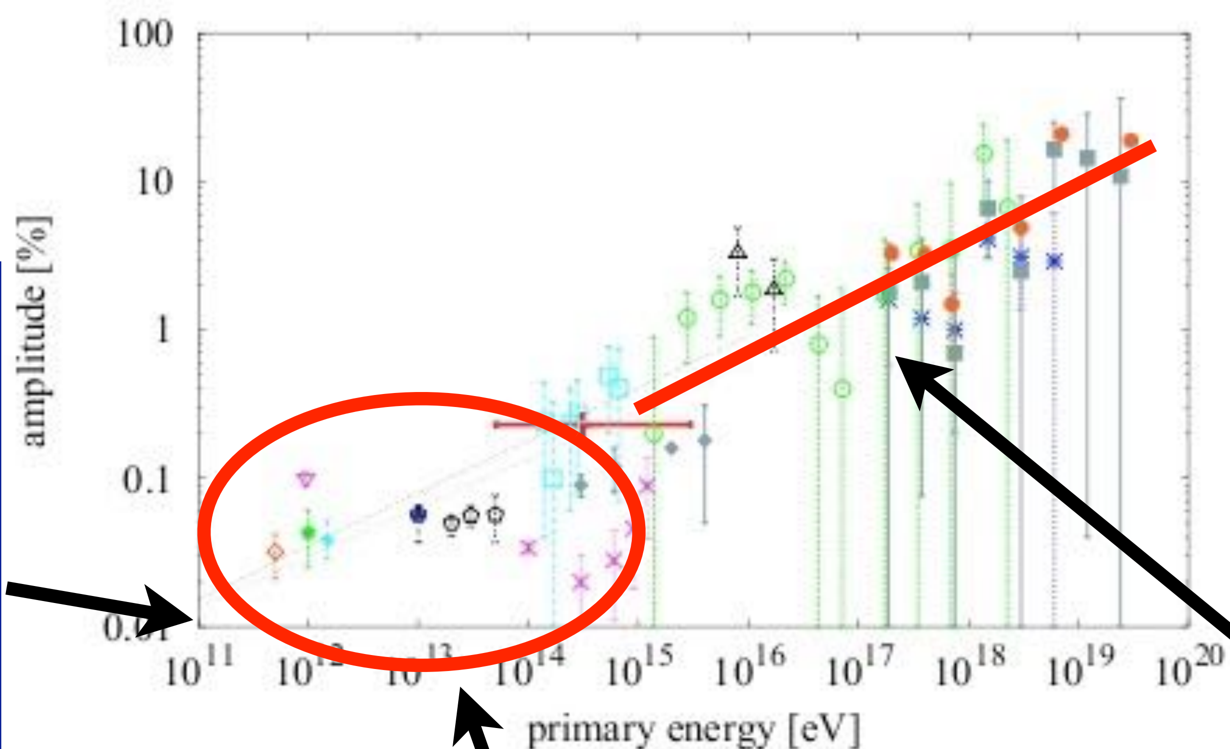

the anisotropy increases with particle energy

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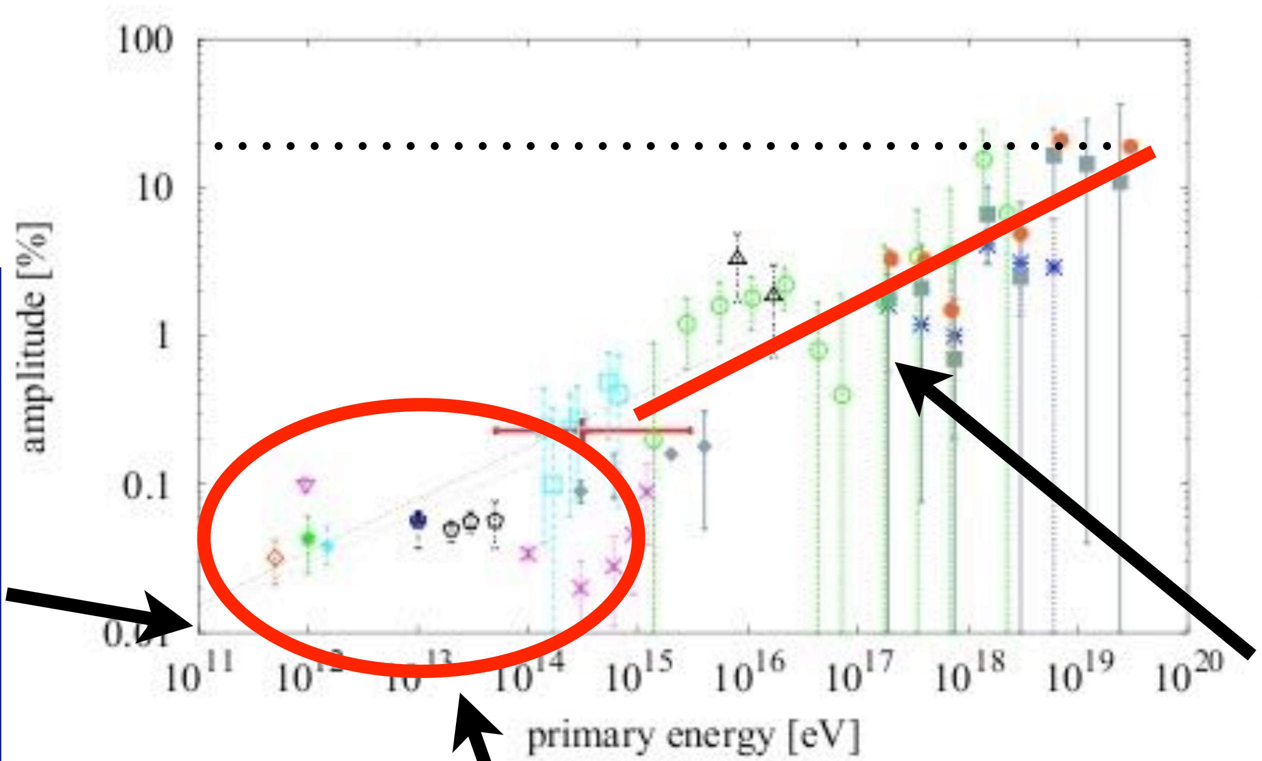


CRs are very isotropic in the sky

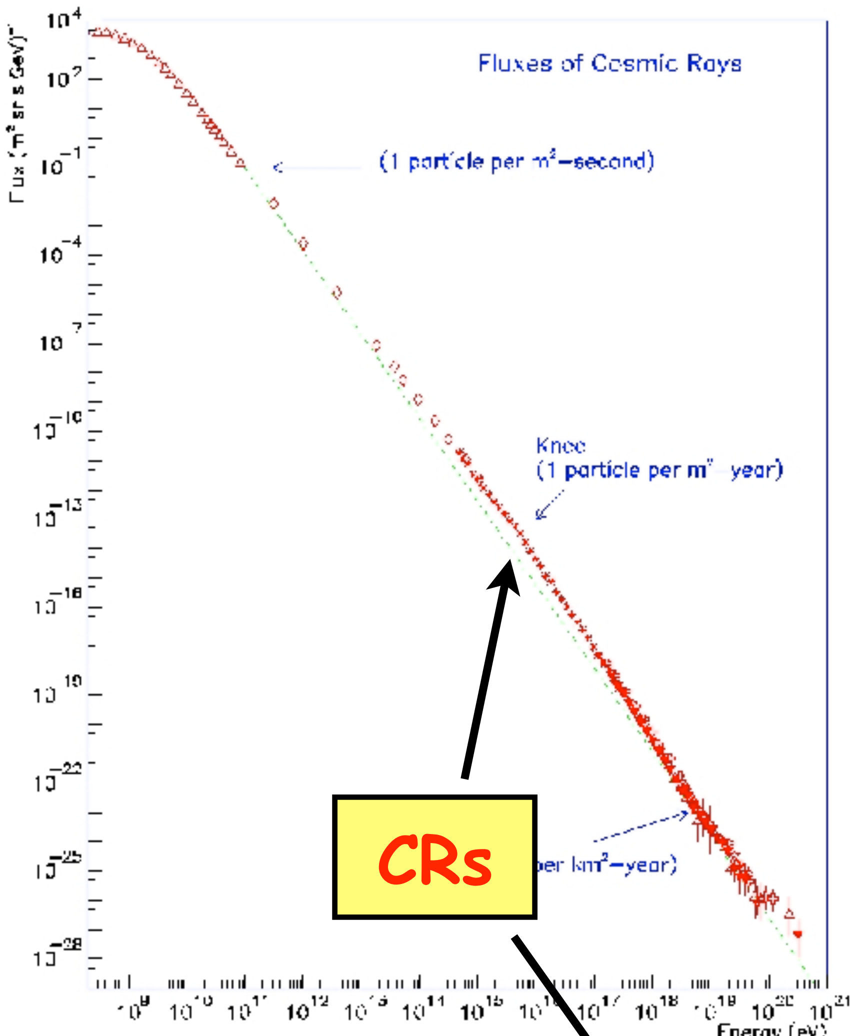
measures available only above ~500 GeV -> magnetic field of the solar system has no effect

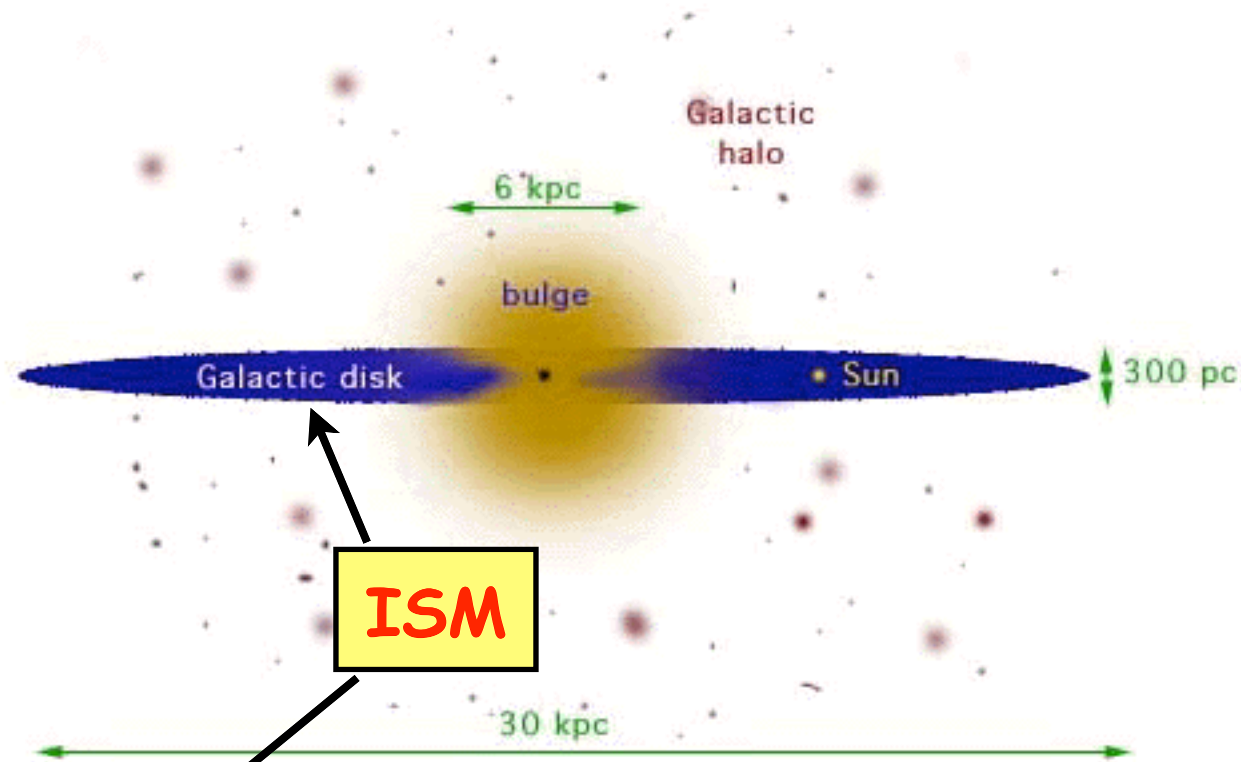
the anisotropy increases with particle energy

δ ~ 10^{-3}

figure from Iyono et al, 2005

Hayakawa's conjecture (1952)





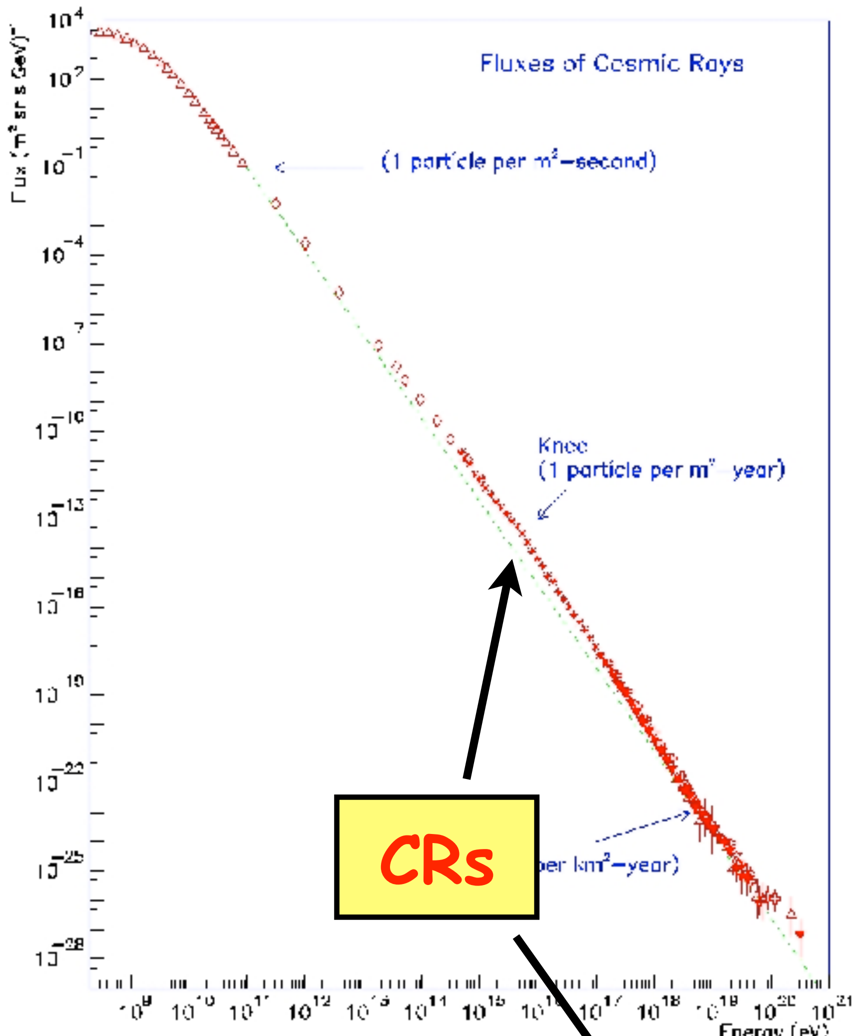
$$p + p \to p + p + \pi^0$$

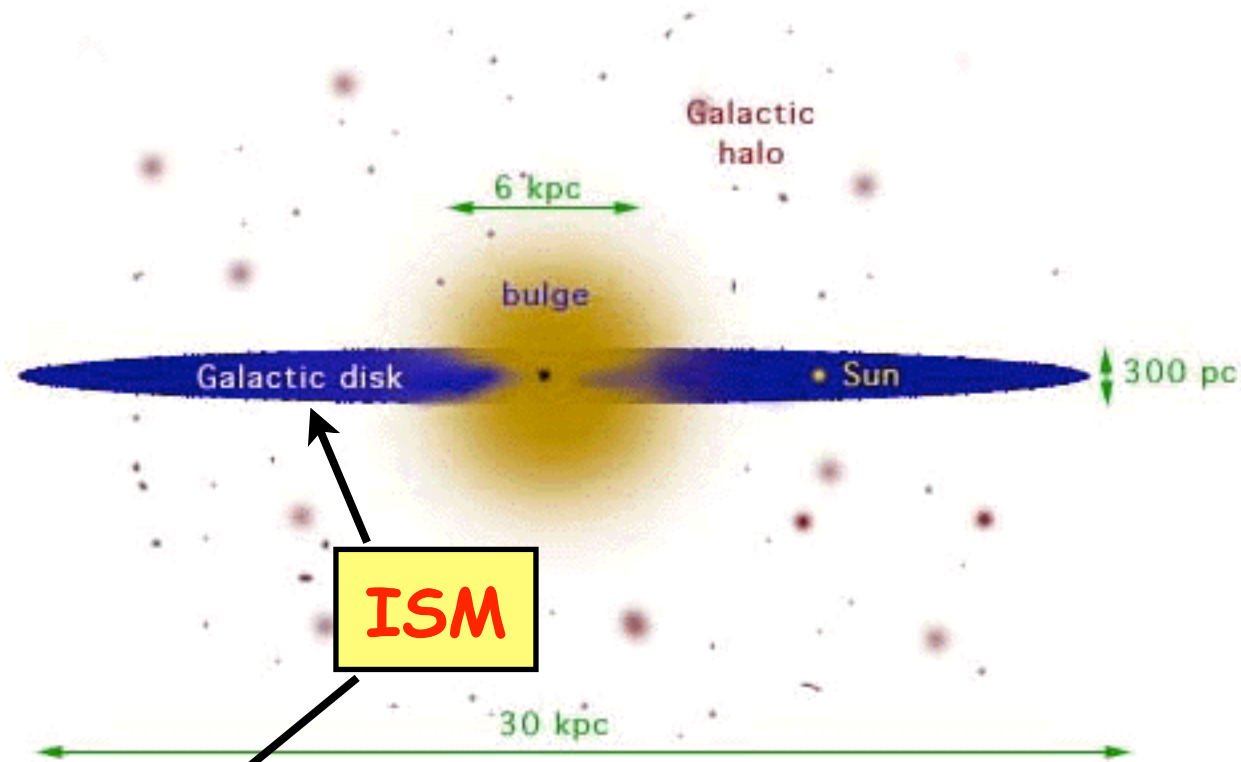
$$\pi^0 \to \gamma + \gamma$$

Cosmic Rays undergo hadronic interactions in the InterStellar Medium

-> the Galaxy should shine in gamma rays!

Hayakawa's conjecture (1952)





$$E_{th} \sim 280 \text{ MeV}$$

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$$E_\gamma \sim 0.1\ E_p$$

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γ-ray observations from ground…

Cherenkov telescopes/arrays

HESS

E_γ~0.1-10 TeV

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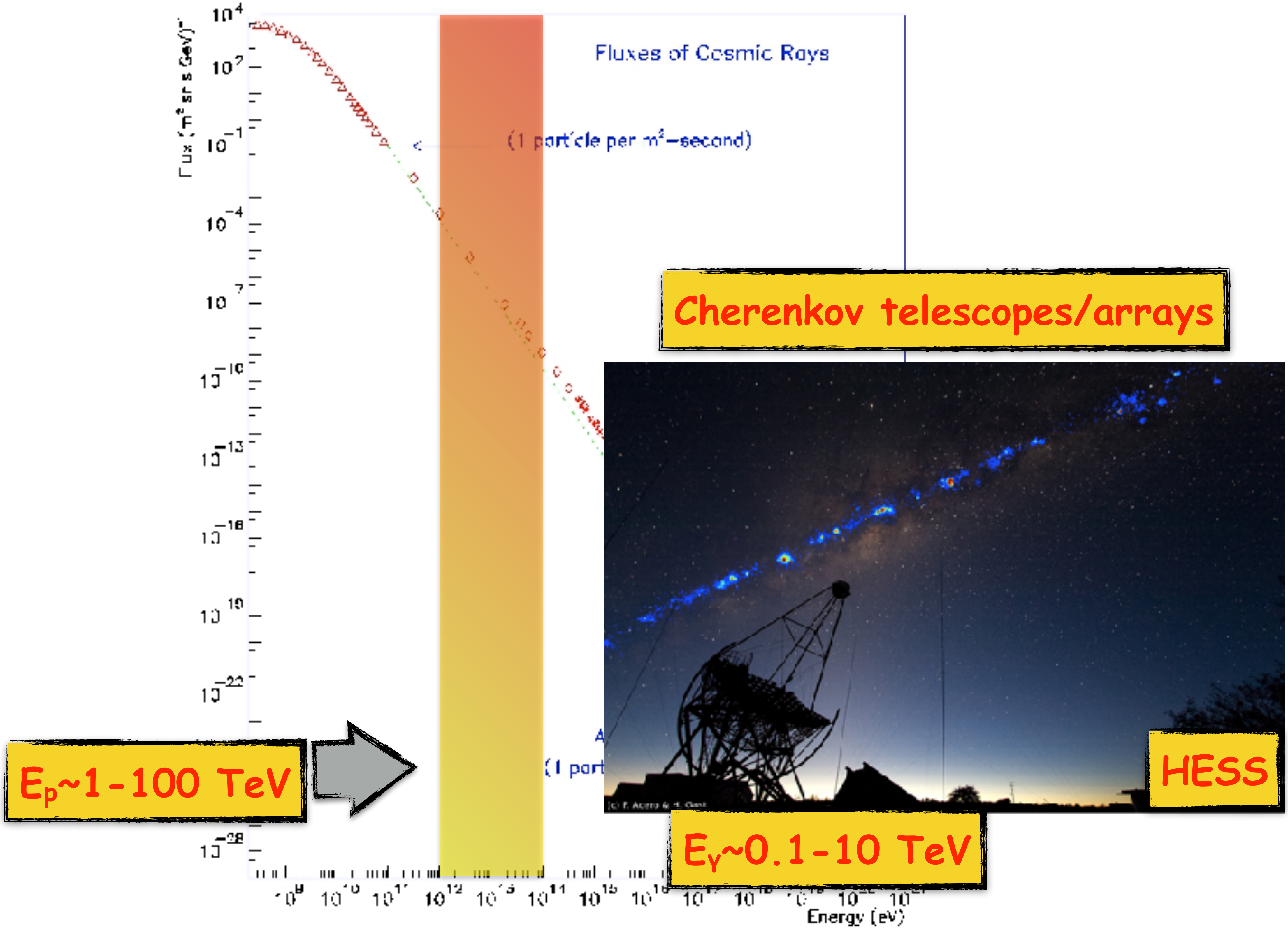

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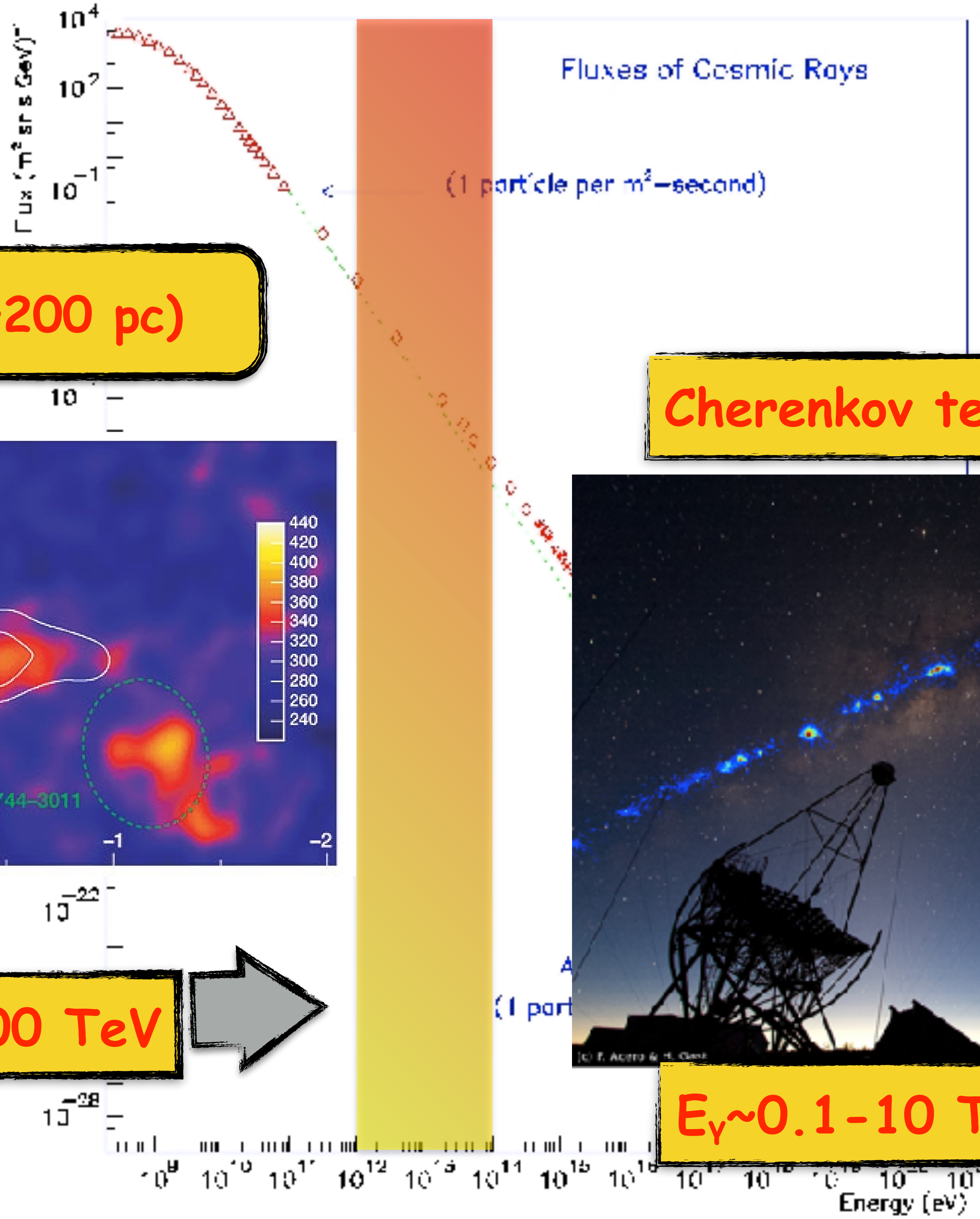
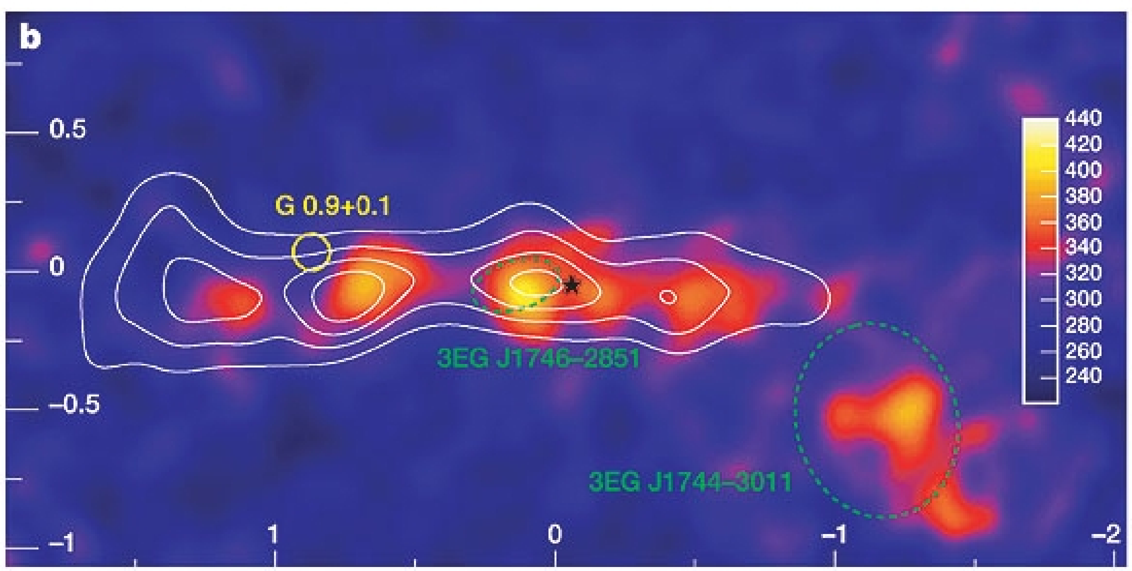


Inner galaxy (~200 pc)



E_p~1-100 TeV

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...and from space

FERMI

E_γ~0.1-10 GeV

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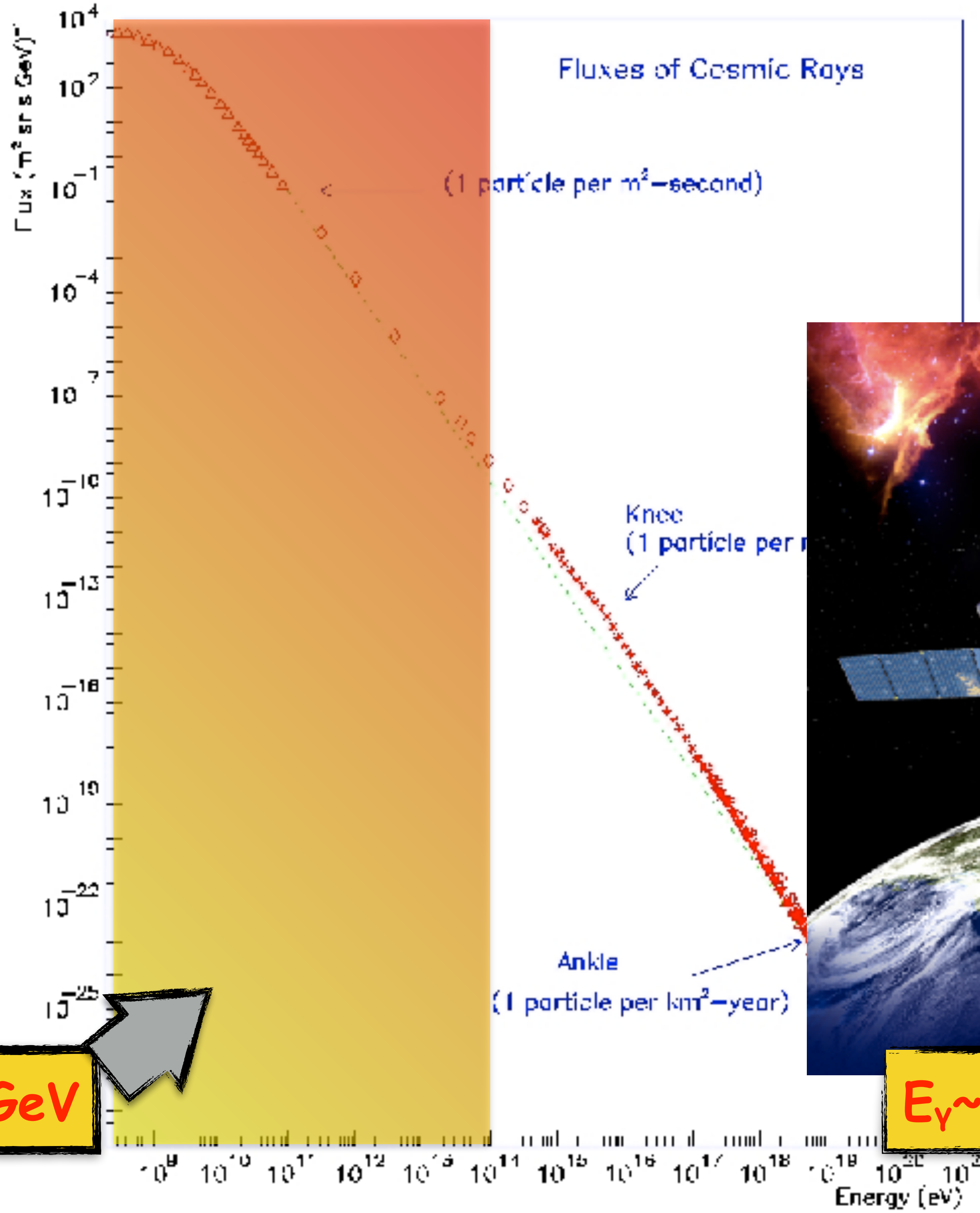

FERMI

E_p~280 MeV-100 GeV

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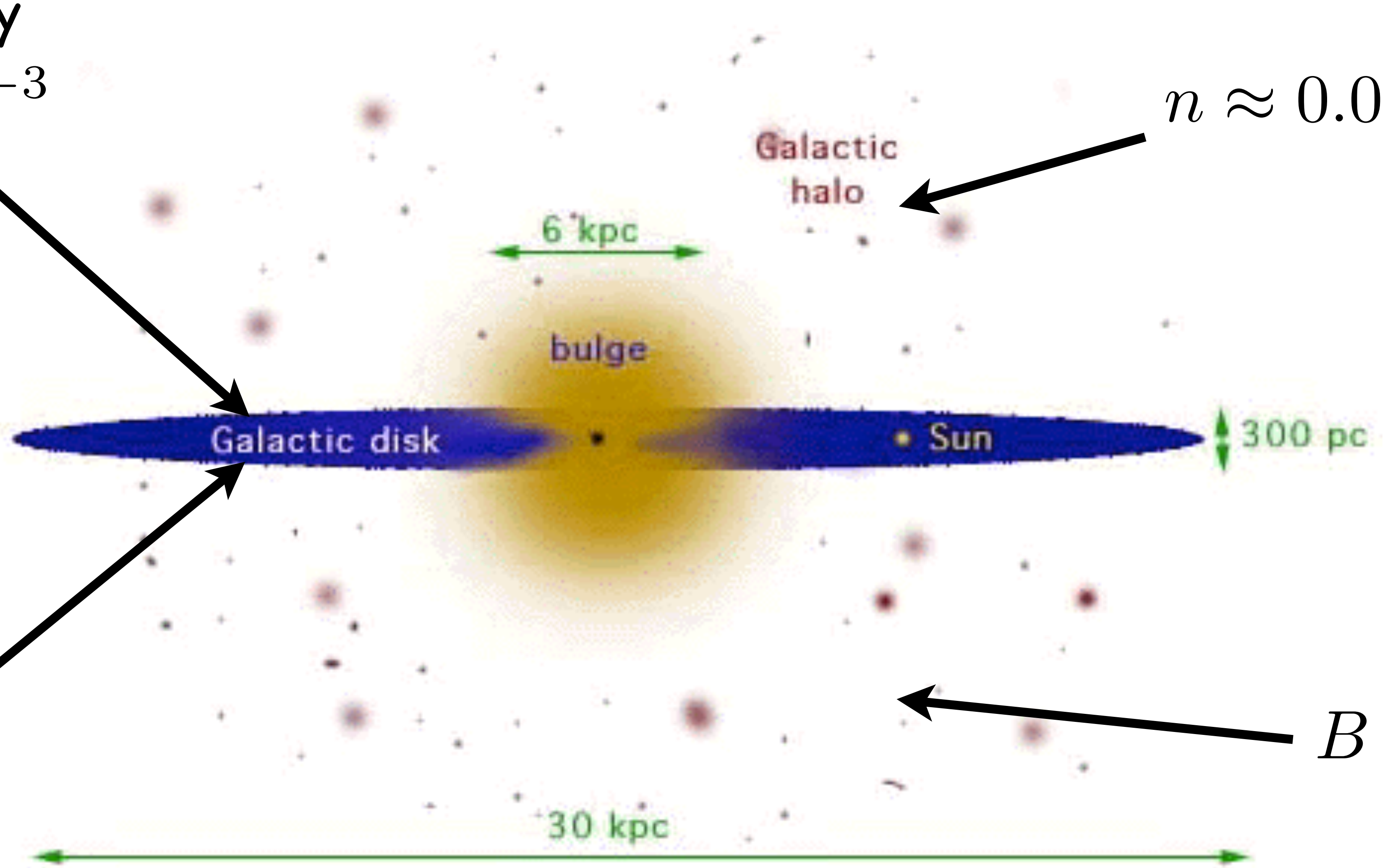
Gamma rays from the Milky Way

gas density

$n \approx 1\ \mathrm{cm}^{-3}$

$n \approx 0.01\ \mathrm{cm}^{-3}$



magnetic field

$B \approx 3\ \mu\mathrm{G}$

$B < 10\ \mu\mathrm{G}$

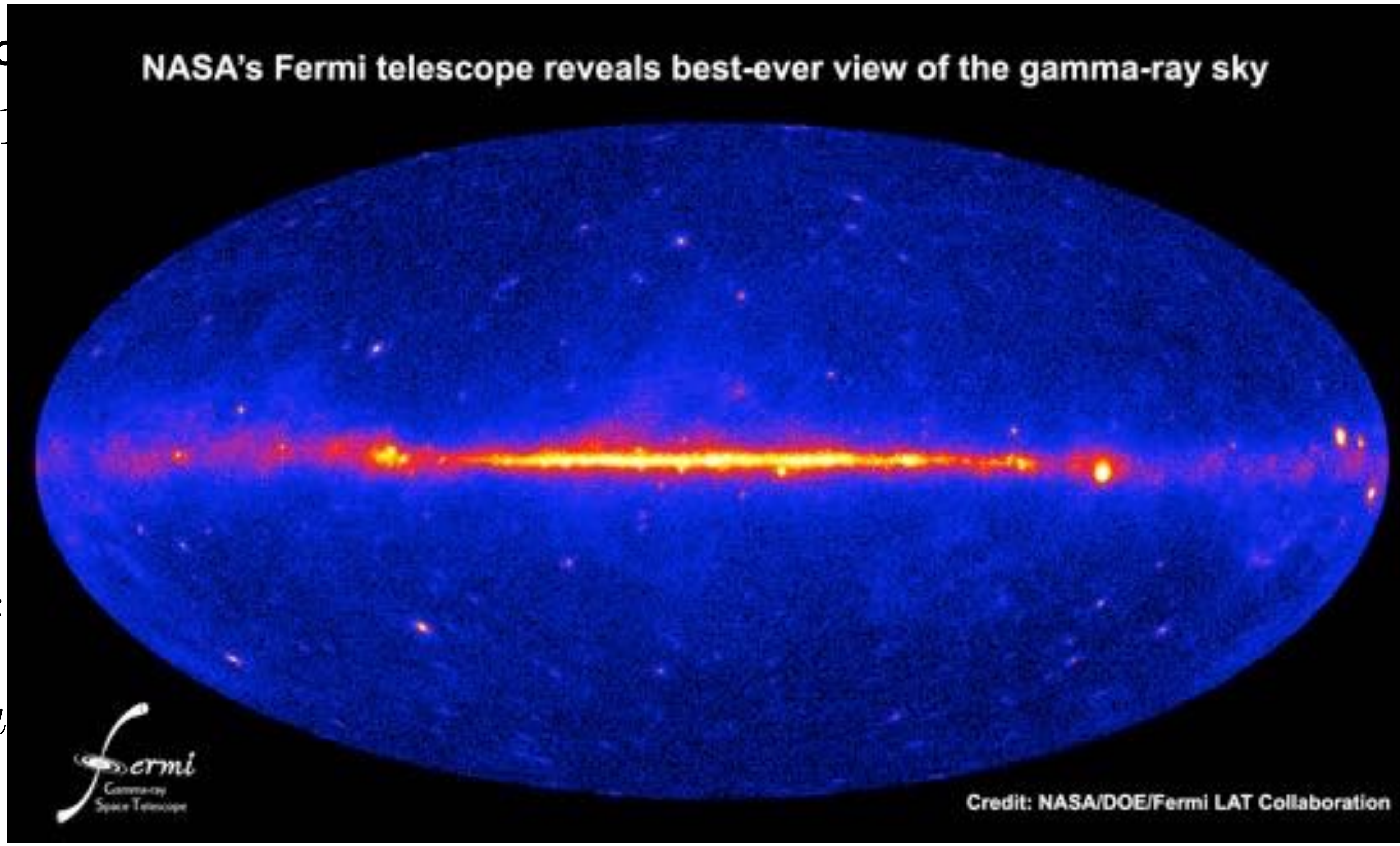
Schematic view of the Milky Way

Cosmic rays fill the whole galactic disk!

Gamma rays from the Milky Way

gas c

$n \approx 1$ ... n^{-3}



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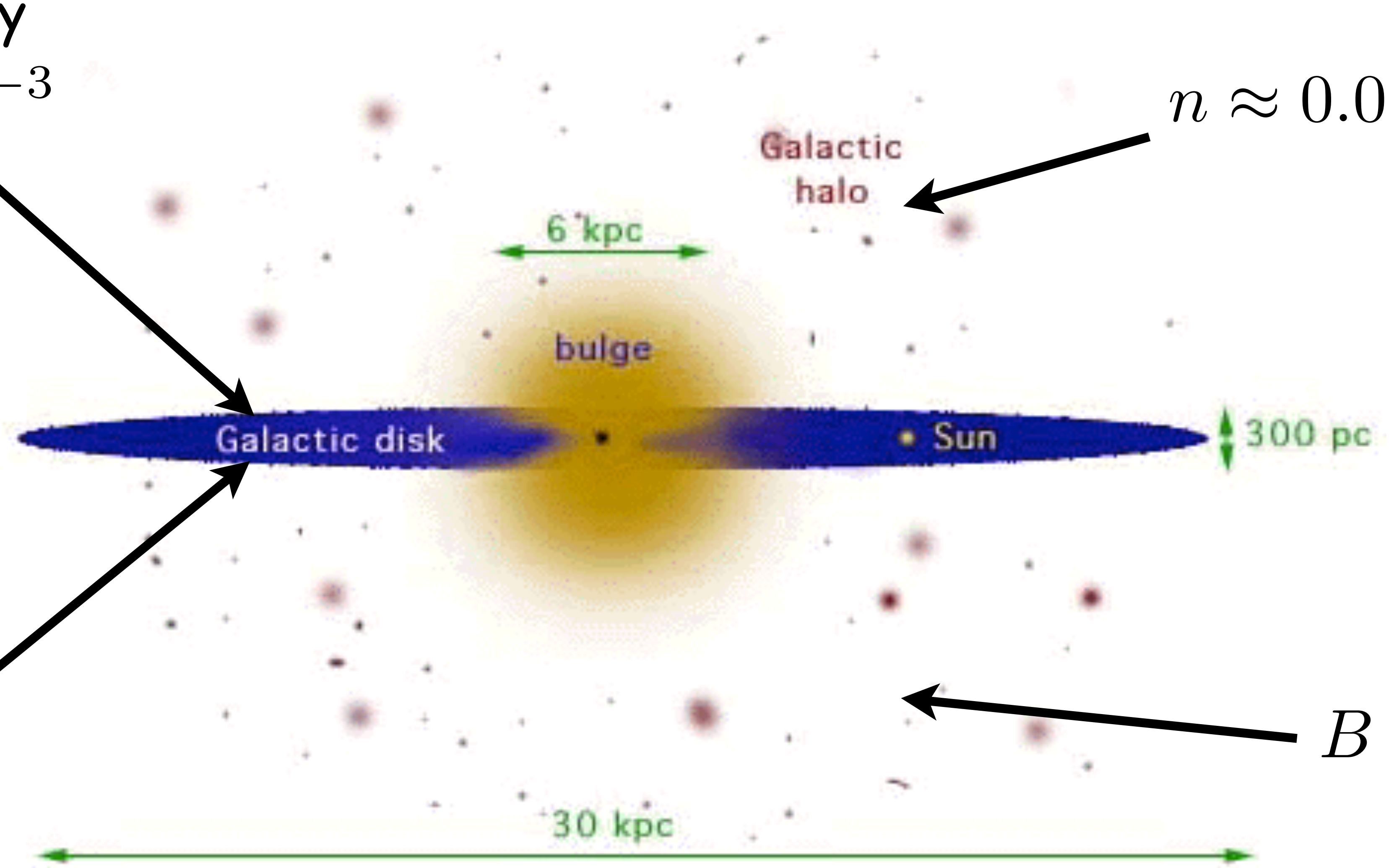

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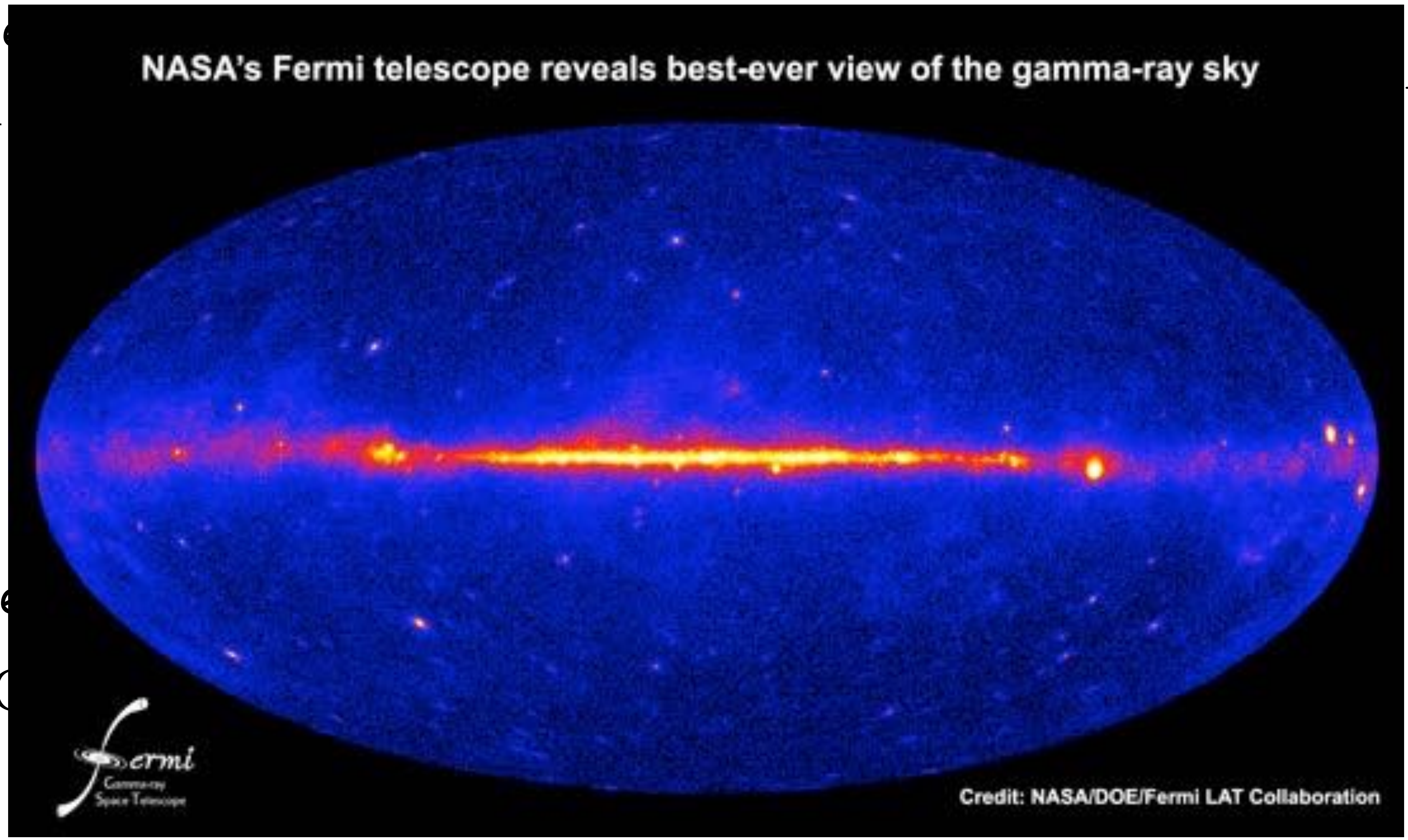

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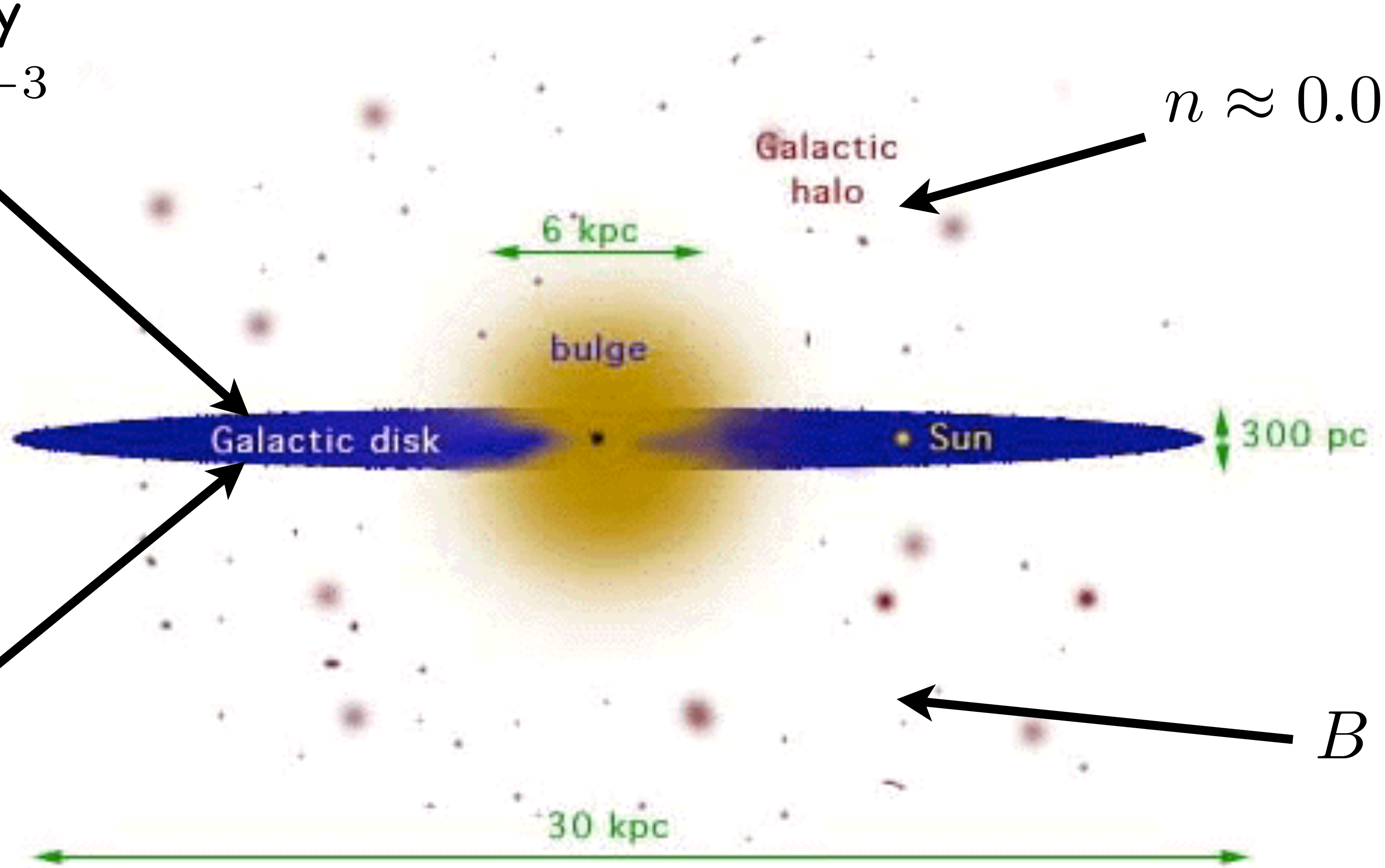

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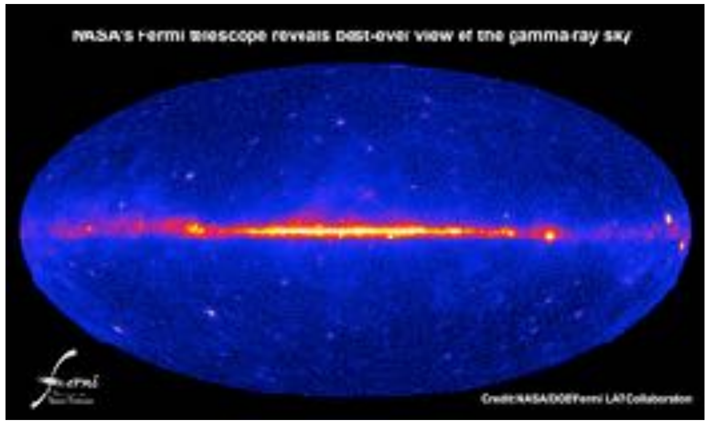
Are CRs universal?



Cosmic rays are homogeneously distributed in the galactic disk.

Hypothesis: are they homogeneously distributed in the whole Universe?

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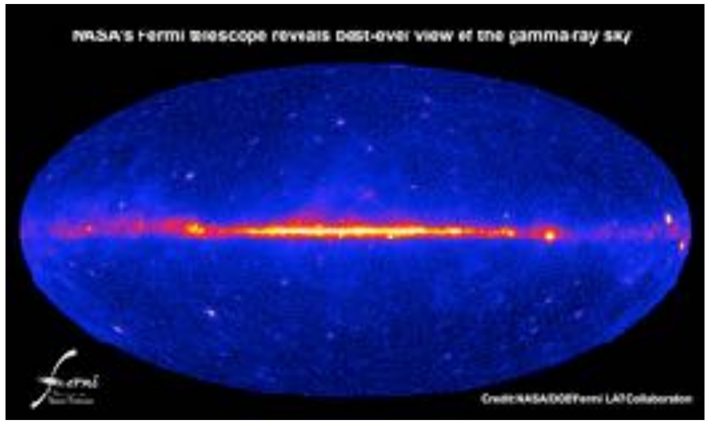

Cosmic rays are homogeneously distributed in the galactic disk.
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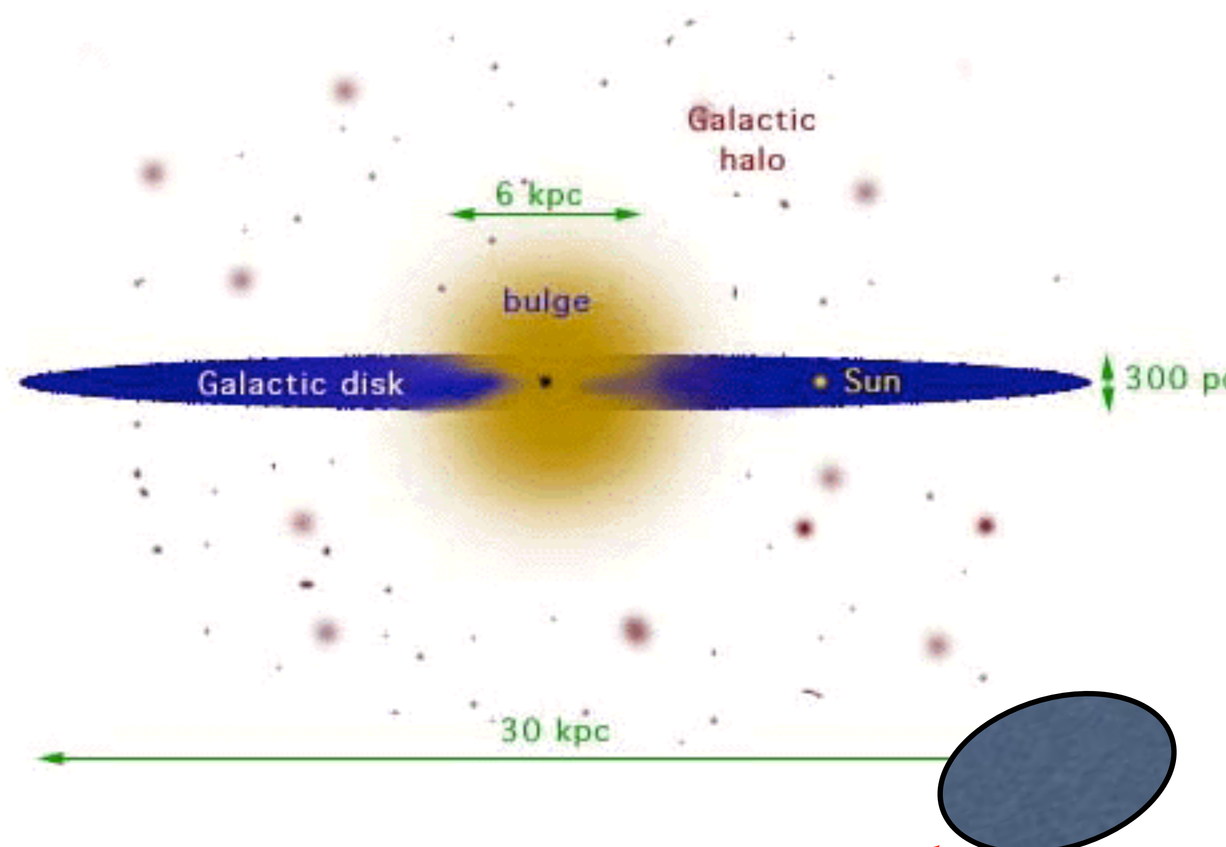
We play the same game with the Small Magellanic Cloud.
Total gas mass -> expected gamma rays

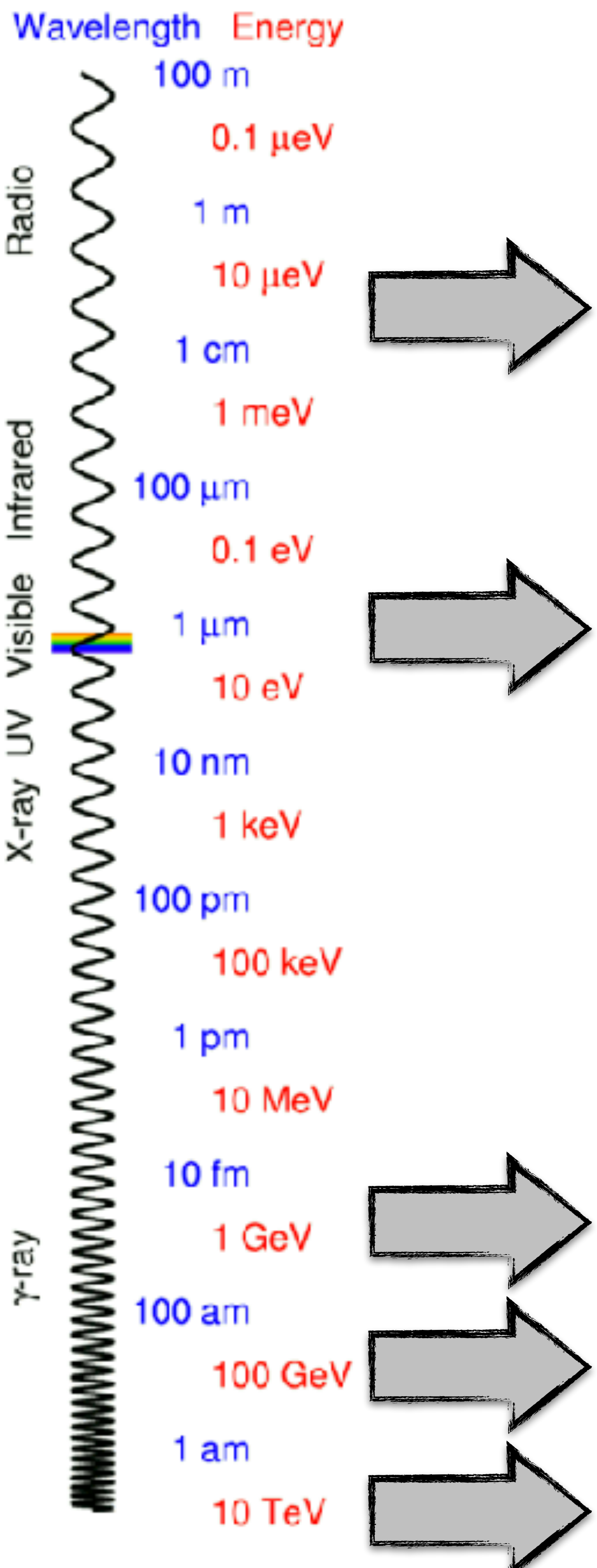
We observe less gammas than expected!

CRs come from the Galaxy



Small Magellanic Cloud

The electromagnetic spectrum



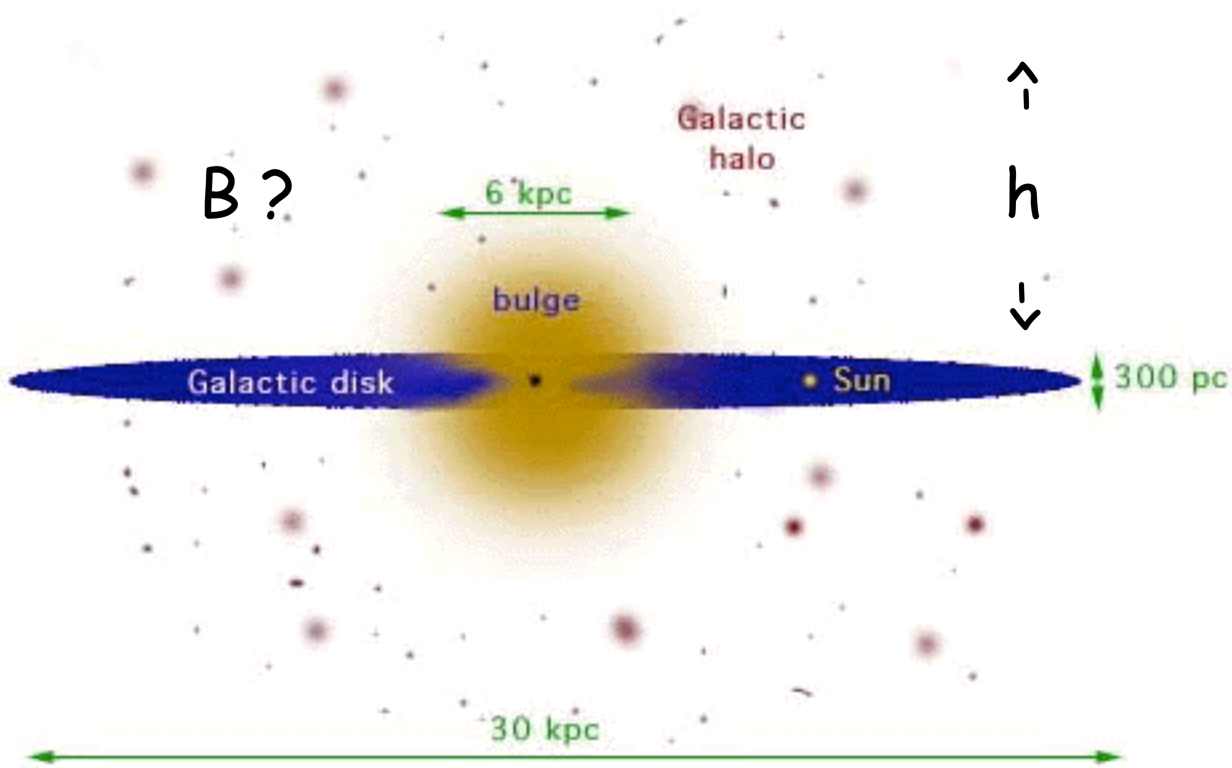
21 cm line -> atomic neutral Hydrogen (HI)

visible light -> stars

interactions of cosmic ray protons with matter

Galactic or extra-galactic?

Which CRs are confined in the Galaxy?



It depends on the values of the magnetic field and thickness of the halo (both poorly constrained...)

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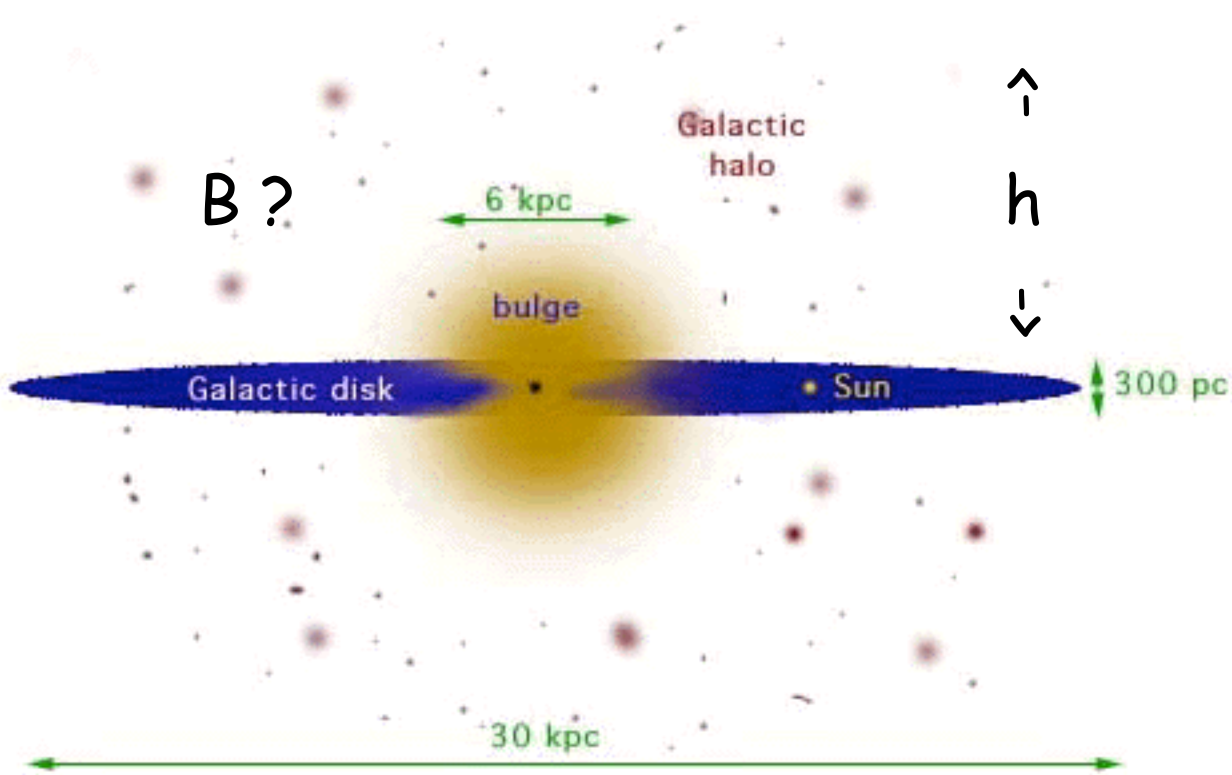

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Confinement condition:

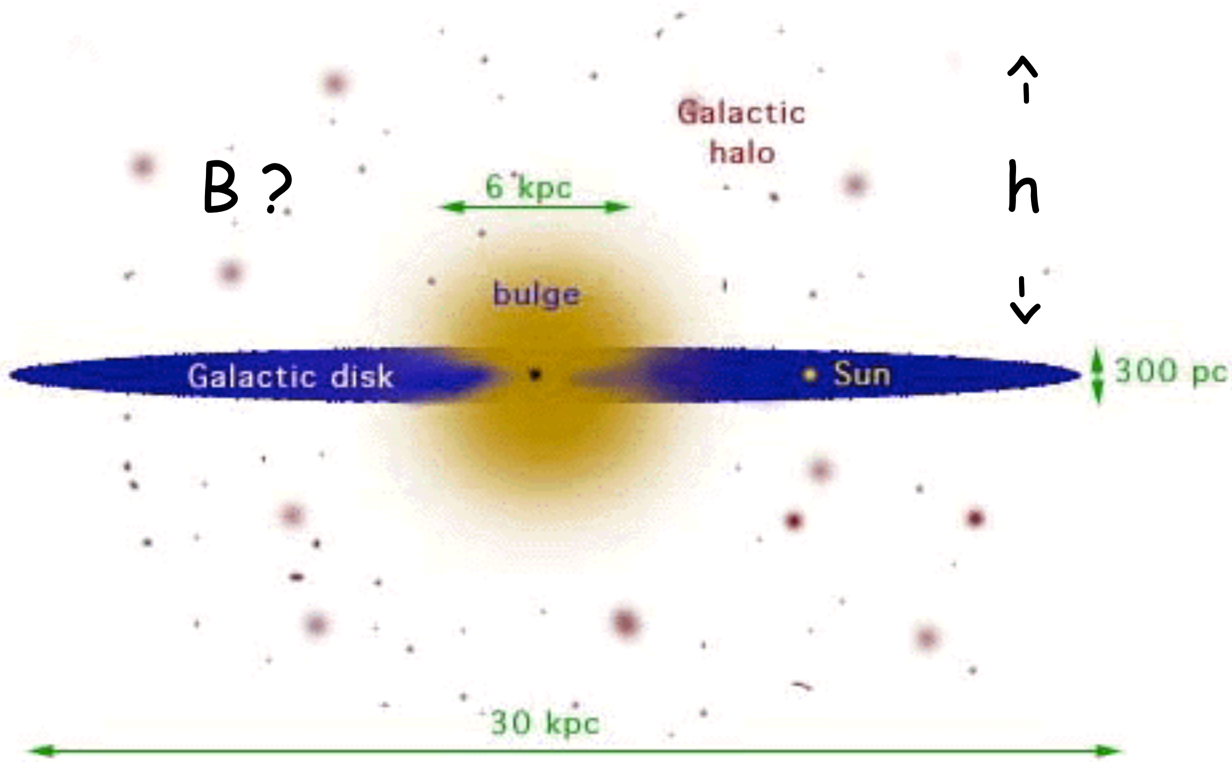
$$R_L < h$$

Larmor radius

halo size

Galactic or extra-galactic?

Which CRs are confined in the Galaxy?



It depends on the values of the magnetic field and thickness of the halo (both poorly constrained...)

Confinement condition:

$$\frac{E(\mathrm{eV})}{300\ B(\mathrm{G})} = R_L < h \Rightarrow E < 10^{18}\left(\frac{h}{\mathrm{kpc}}\right)\left(\frac{B}{\mu\mathrm{G}}\right)\mathrm{eV} = 10^{17} \div 10^{20}\ \mathrm{eV}$$

(cm)

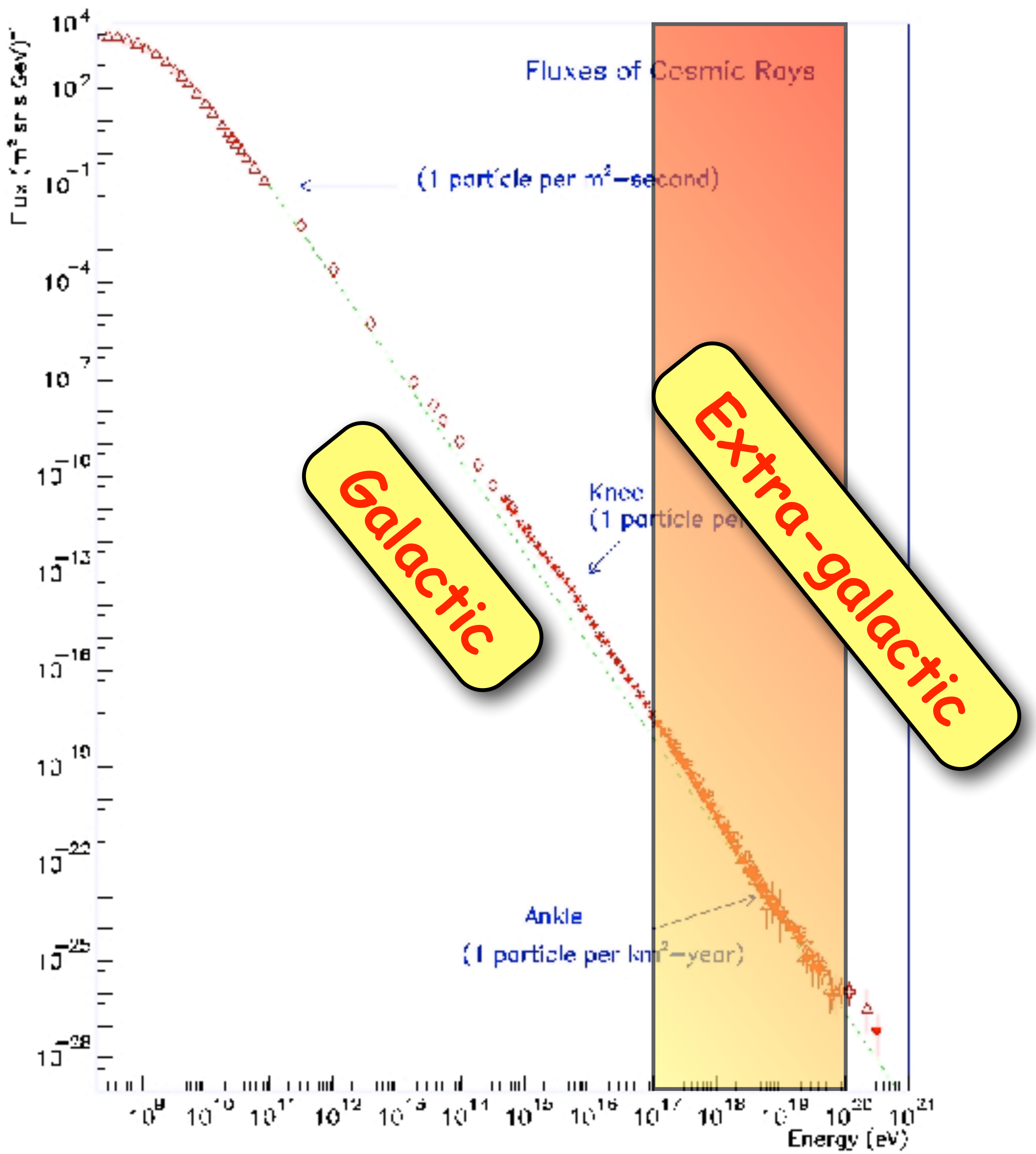
Larmor radius

halo size

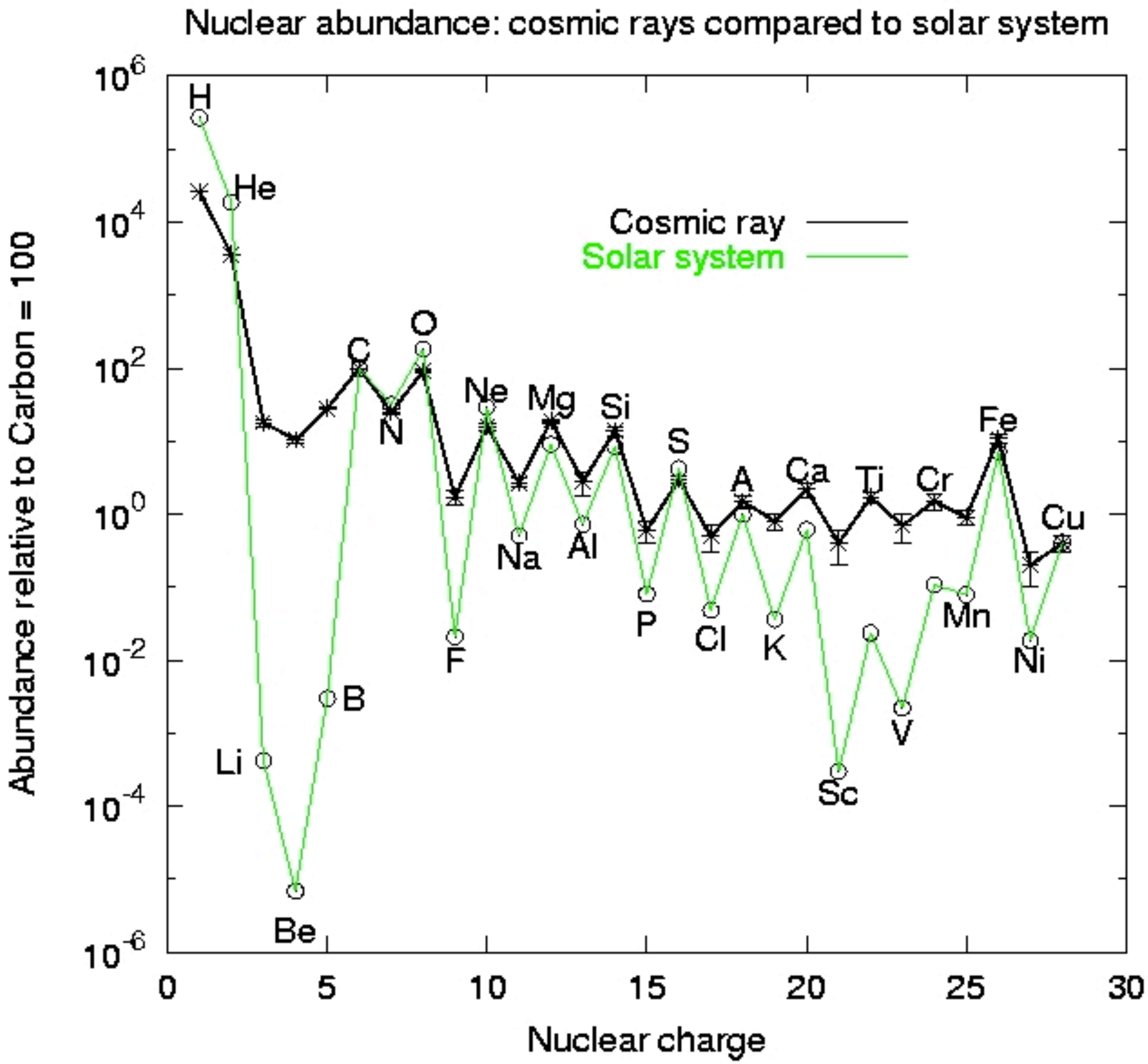
1 - 10

0.1 - 10

Galactic or extra-galactic?



Cosmic Ray composition



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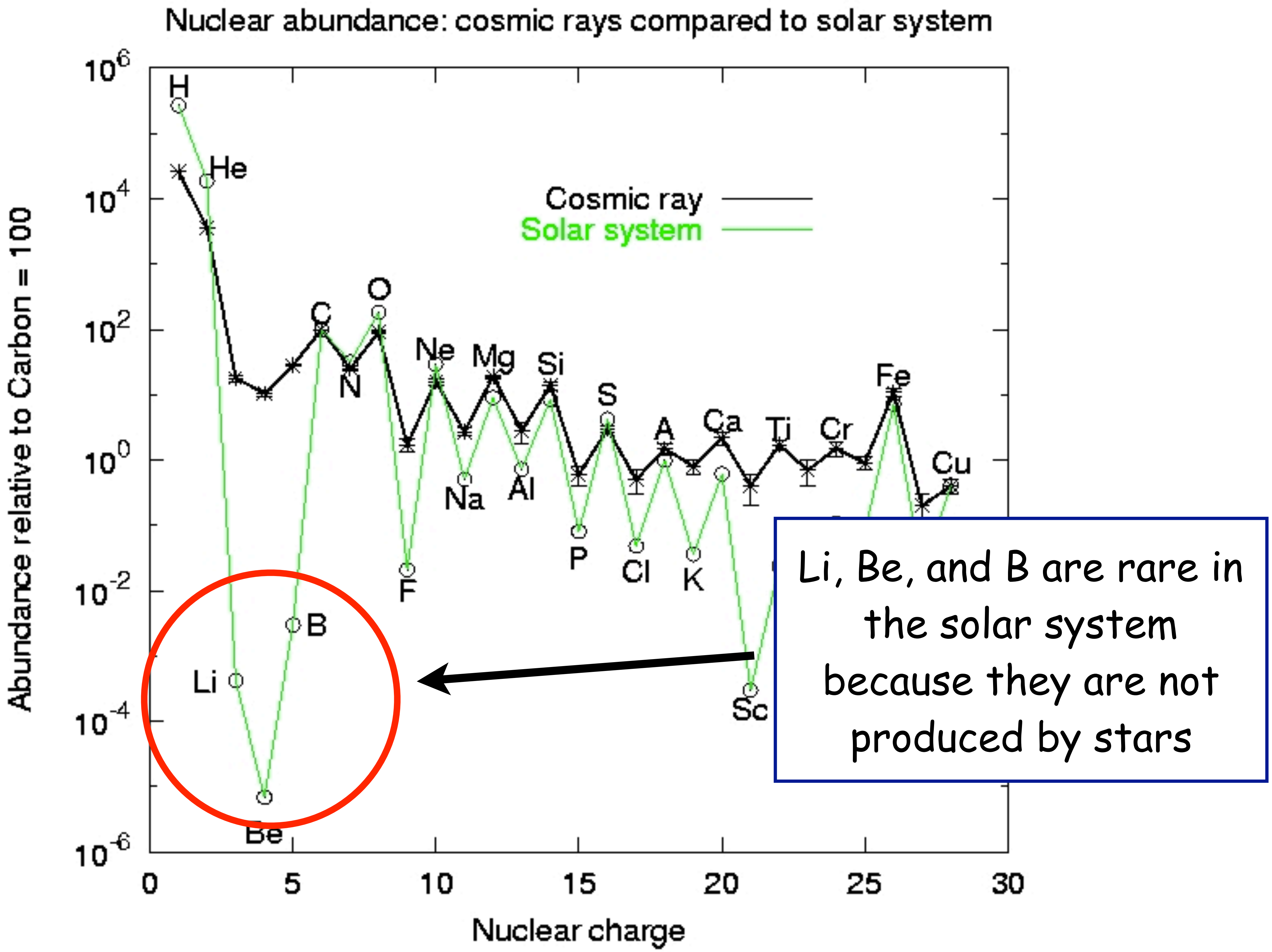

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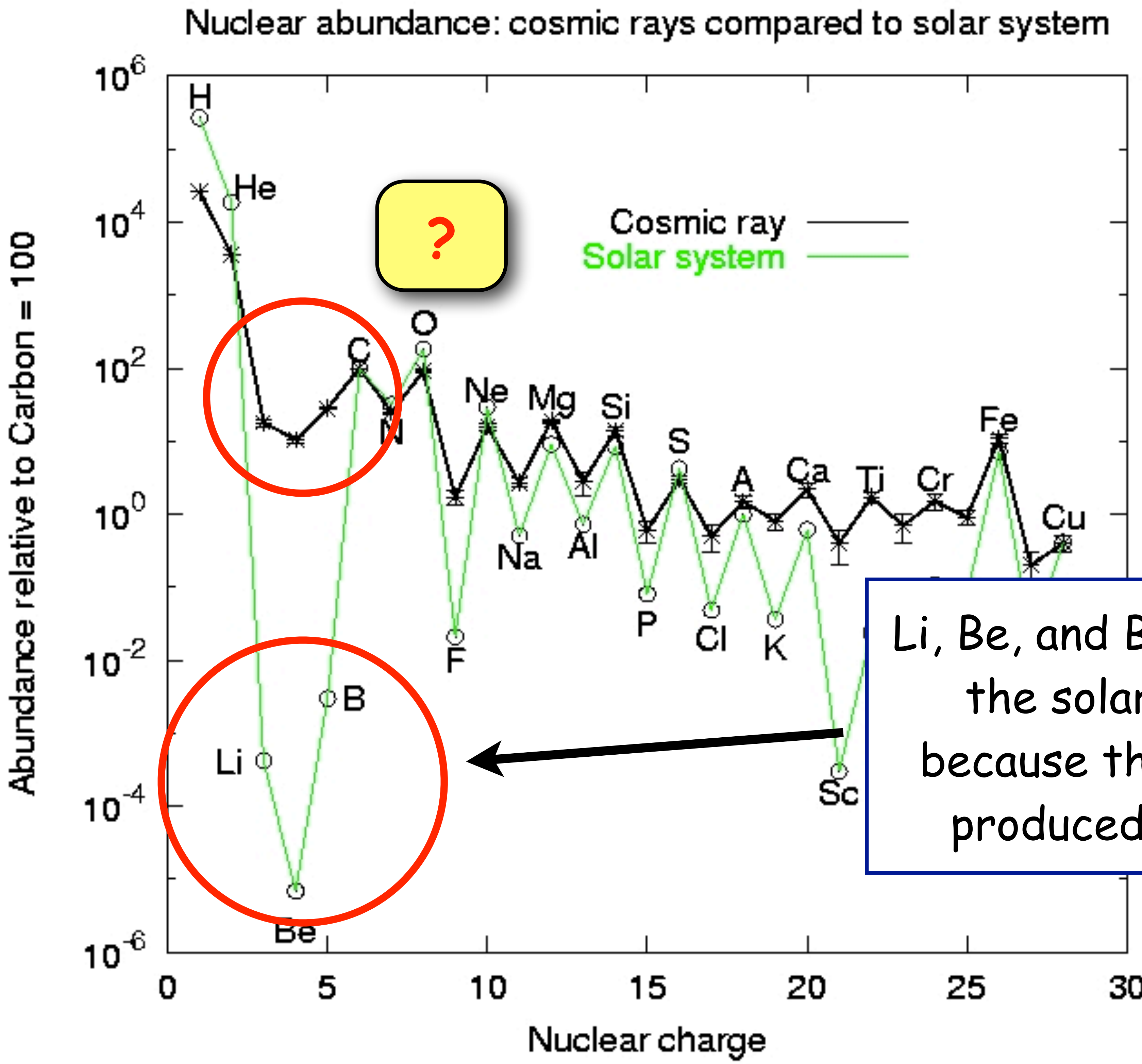

Li, Be, and B are rare in the solar system because they are not produced by stars

Cosmic Ray composition: spallation

Spallation: production of light elements as fragmentation products of the interaction of high energy particles with cold matter.

The anomaly is explained if (~ GeV) CRs transverse $\lambda \approx 5 \text{ g/cm}^2$

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The anomaly is explained if (~ GeV) CRs transverse $\lambda \approx 5 \ \mathrm{g/cm^2}$

Assuming propagation in the galactic disk: $l_s = \dfrac{\lambda}{\varrho_{ISM}} \approx 1 \ \mathrm{Mpc}$

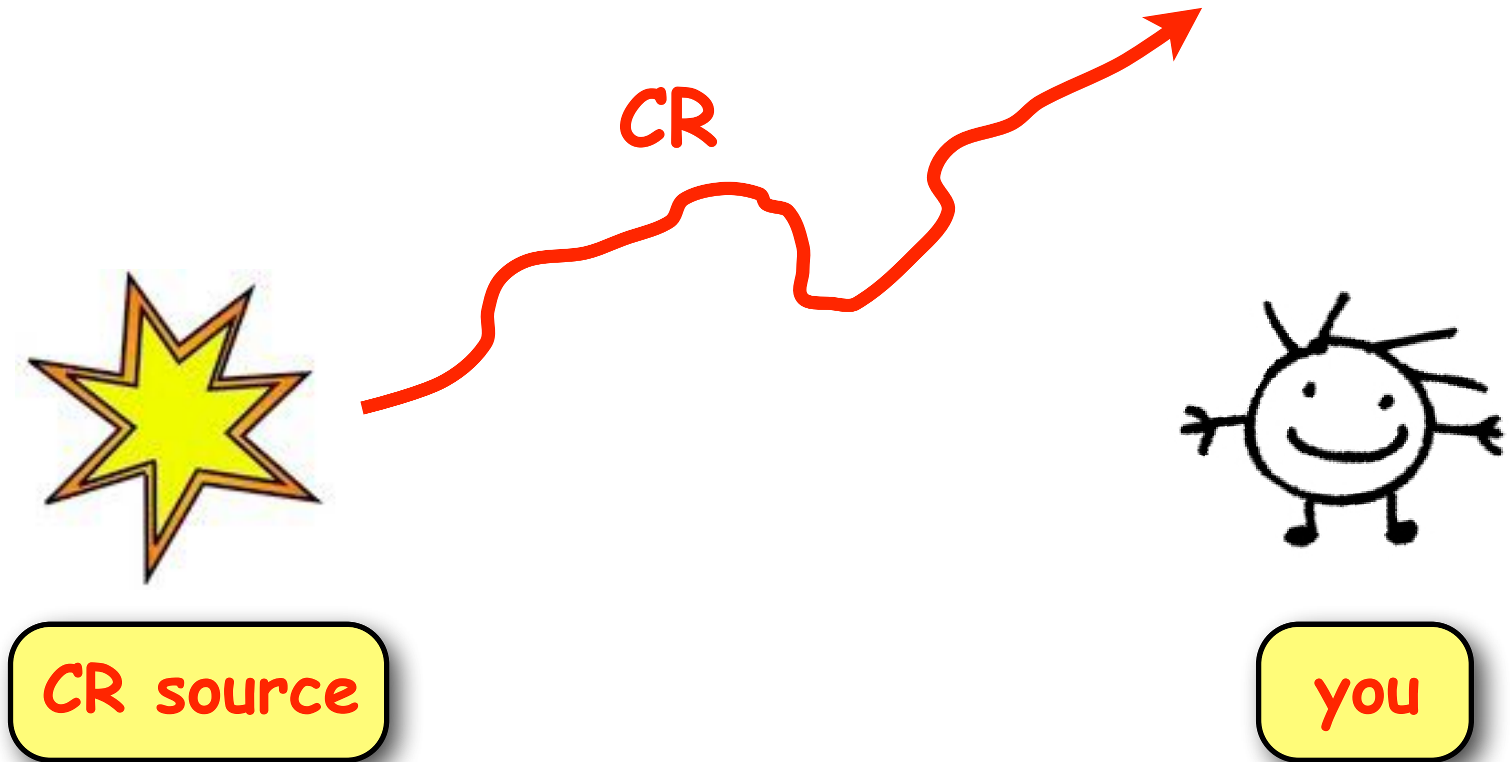
much larger than the size of the disk!!!

CRs don't go straight but are confined in the disk -> diffusive behavior -> isotropy!

CRs don't go straight: consequences

(1) We cannot do CR astronomy

-> difficult to identify sources



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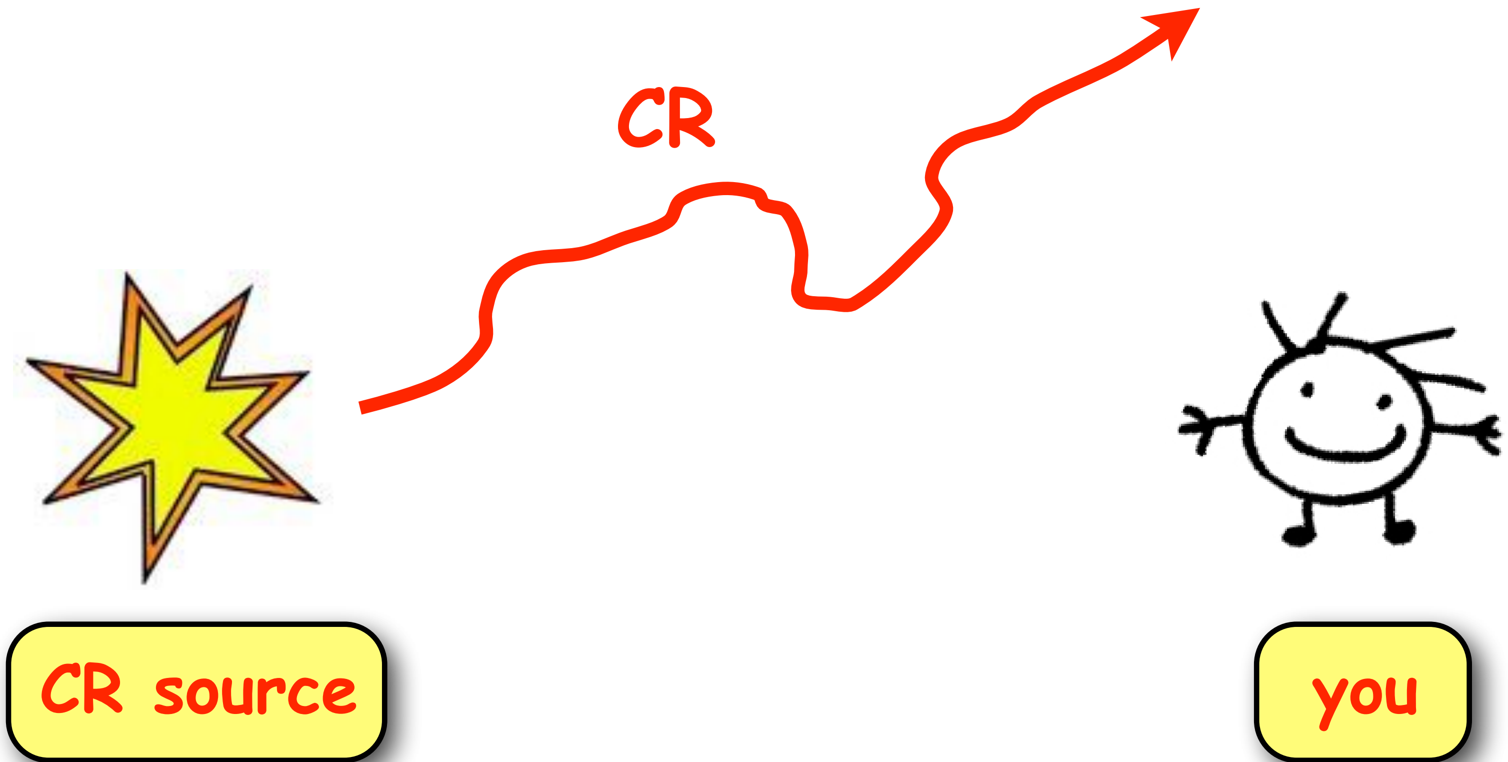
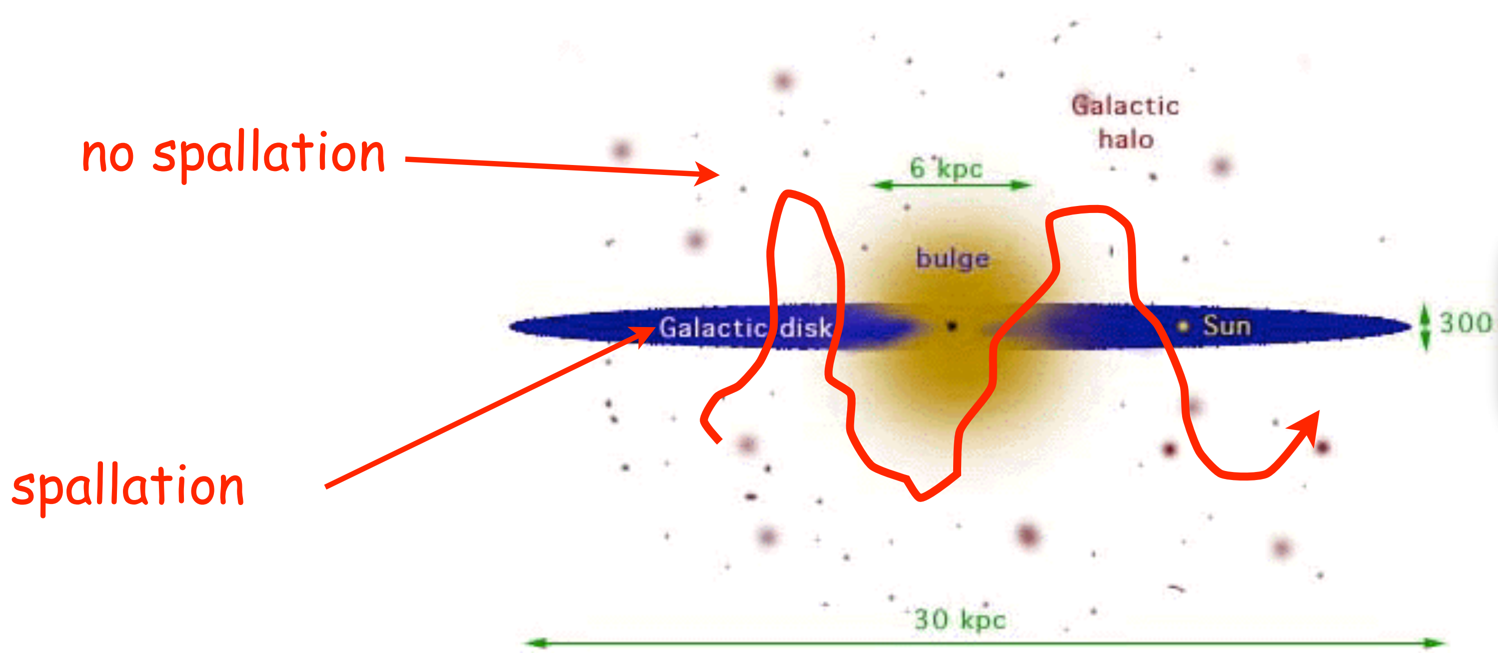


(2) CRs are confined in the Galactic disk

$$t_{disk} = \frac{l_s}{c} \approx 3 \times 10^6 \text{ yr}$$



$$t_{halo} \approx 10 \times 10^6 \text{ yr}$$

Cosmic Ray power in the Galaxy

CR energy density

total CR energy in the disk

MW disk volume

$$w_{CR} \sim 1 \text{ eV/cm}^3 \longrightarrow \mathcal{E}_{CR} = w_{CR} V_{disk}$$

spatial homogeneity

Cosmic Ray power in the Galaxy

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CR power from CR sources in the disk

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CR power from CR sources in the disk

$$P_{CR} = \frac{\mathcal{E}_{CR}}{t_{disk}} = 10^{41}\,\mathrm{erg/s}$$

Is this correct?

CRs interact with the gas -> $p + p \rightarrow p + p + \pi^0$

Should we use this equation instead?

$$\frac{\mathrm{d}\mathcal{E}_{CR}}{\mathrm{d}t} = P_{CR} - \frac{\mathcal{E}_{CR}}{t_{disk}} - \dot{\mathcal{E}}_{pp}$$

energy loss term due to p-p interactions

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$$t_{pp} = (n_{gas}\ \underbrace{\sigma_{pp}}_{4 \times 10^{-26}\ \mathrm{cm}^2}\ c\ \underbrace{k}_{0.45})^{-1}$$

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energy loss term due to p-p interactions

Energy loss rate:

$$t_{pp} = (n_{gas}\ \underbrace{\sigma_{pp}}_{4 \times 10^{-26}\ \mathrm{cm}^2}\ c\ \underbrace{k}_{0.45})^{-1} \approx 60 \left(\frac{n_{gas}}{\mathrm{cm}^{-3}}\right)^{-1} \mathrm{Myr} >> t_{disk} = 3\ \mathrm{Myr}$$

We can safely neglect CR energy losses

The diffusion of CRs

Spallation measurements tell us that cosmic rays follow tortuous paths before escaping the Galaxy. **Why?**

The galactic magnetic field or, better, **irregularities in the Galactic magnetic field** are responsible for the diffusive propagation of cosmic rays.

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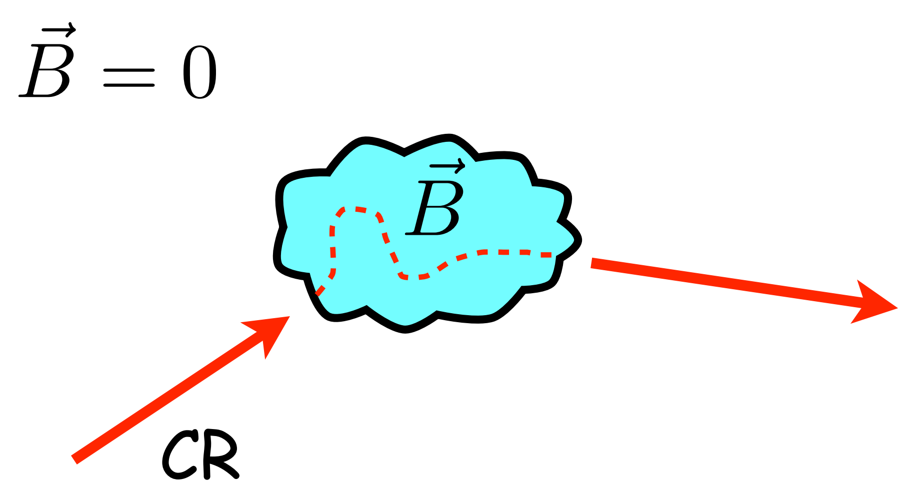
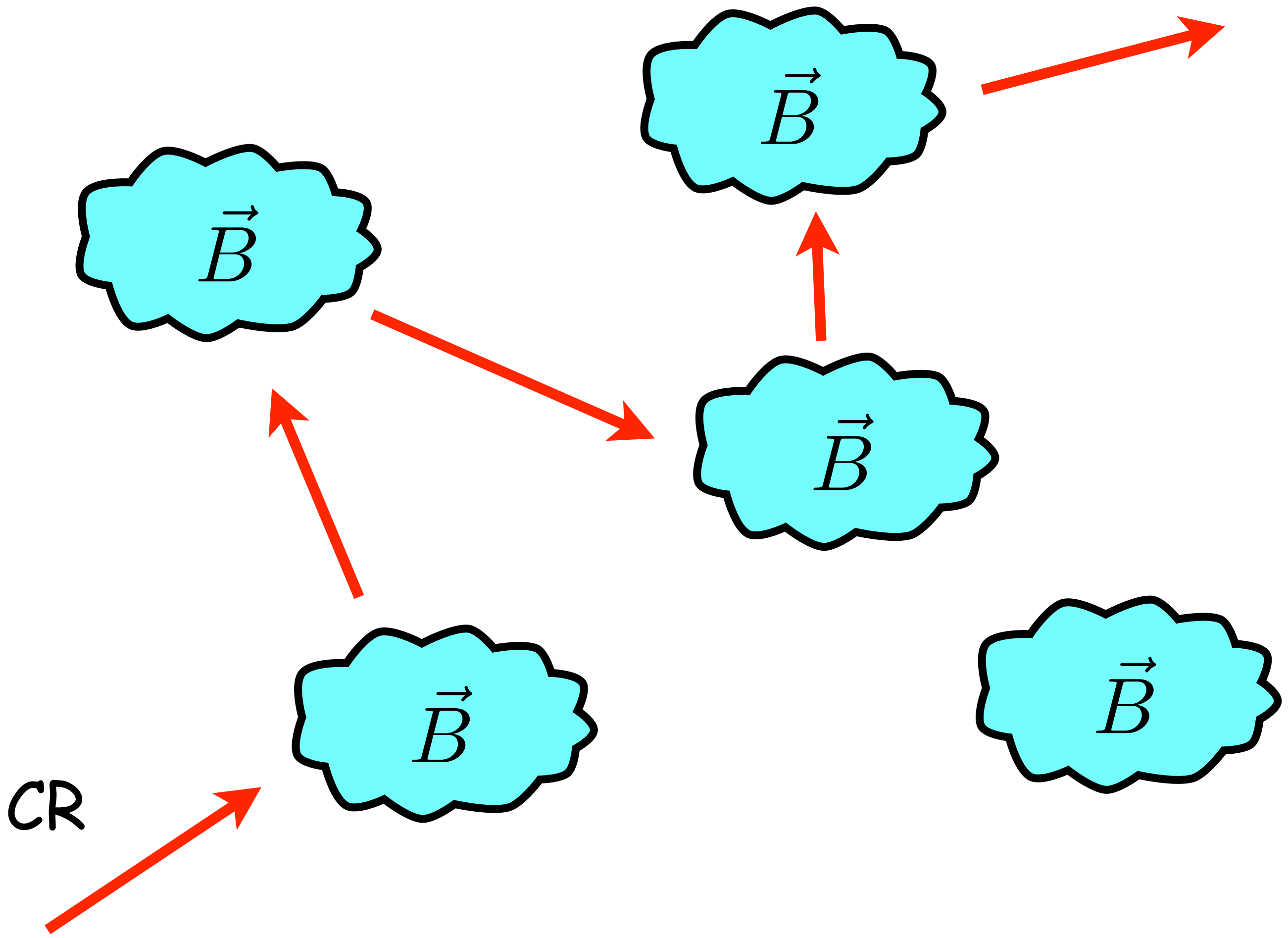
(Oversimplified picture)

magnetized cloudlets in an unmagnetized background



the particle energy is unchanged (Lorentz force)

The diffusion of CRs



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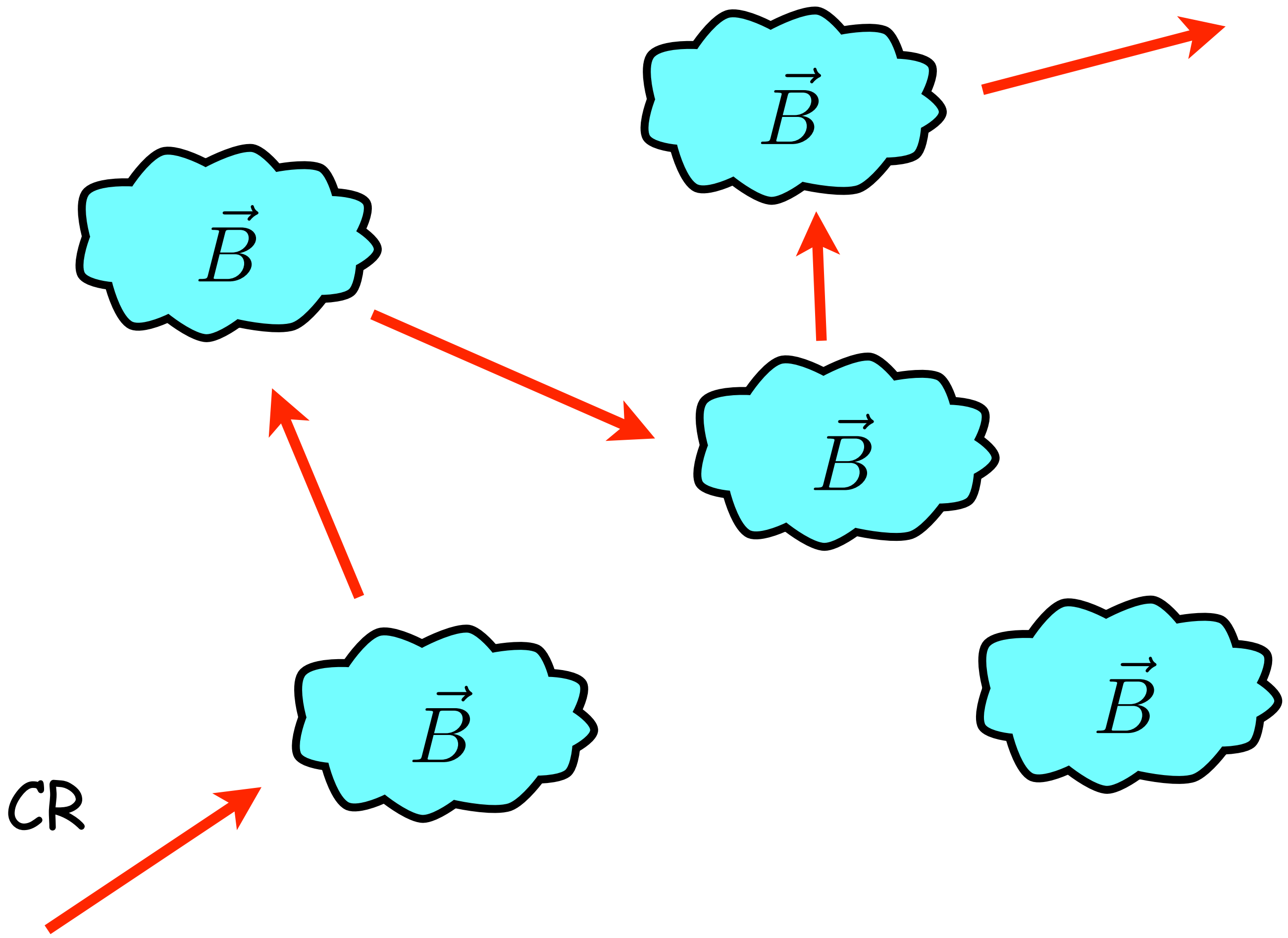
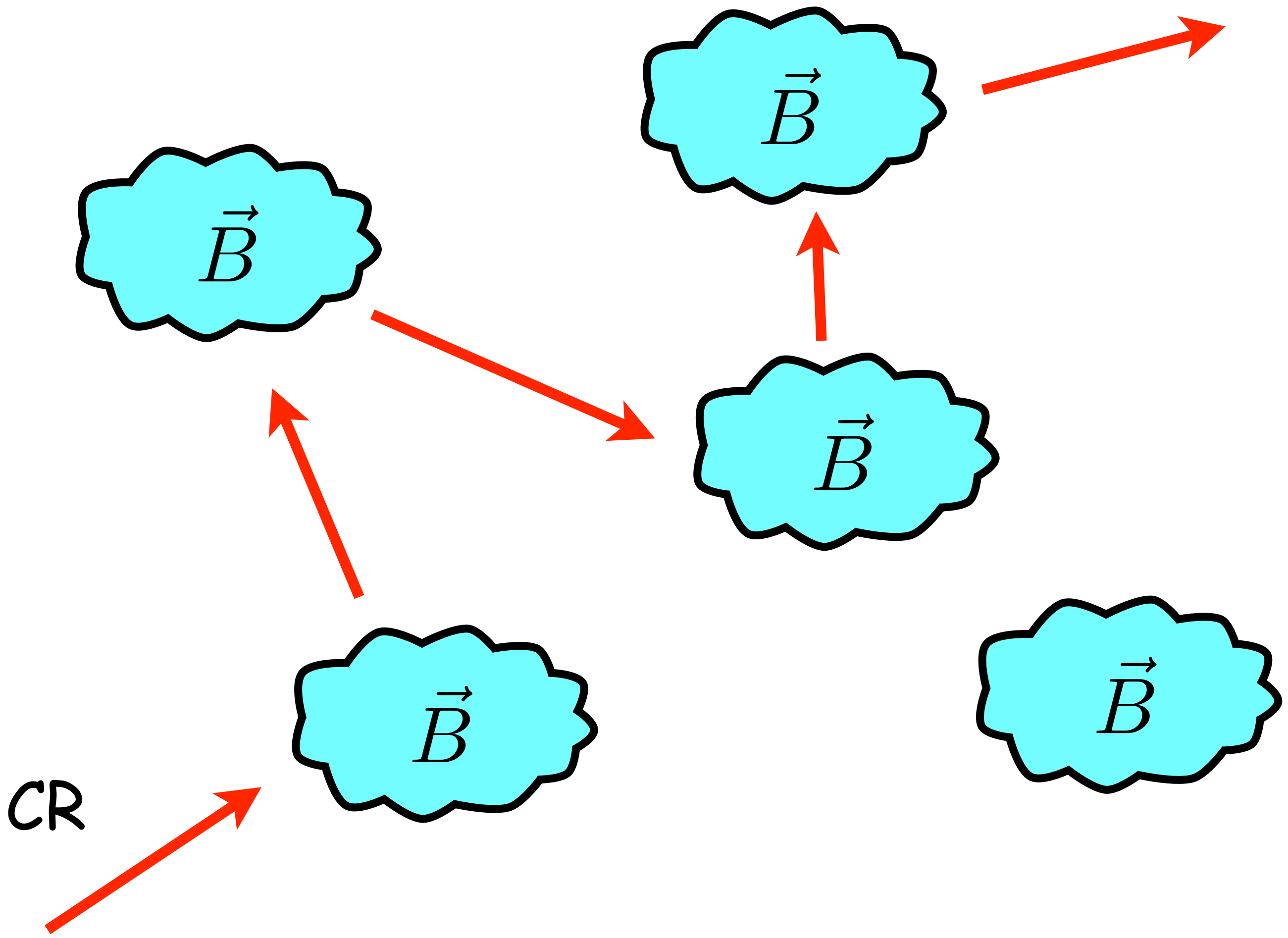


λ -> mean free path

The diffusion of CRs



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$\tau_c = \frac{\lambda}{c}$ -> collision time

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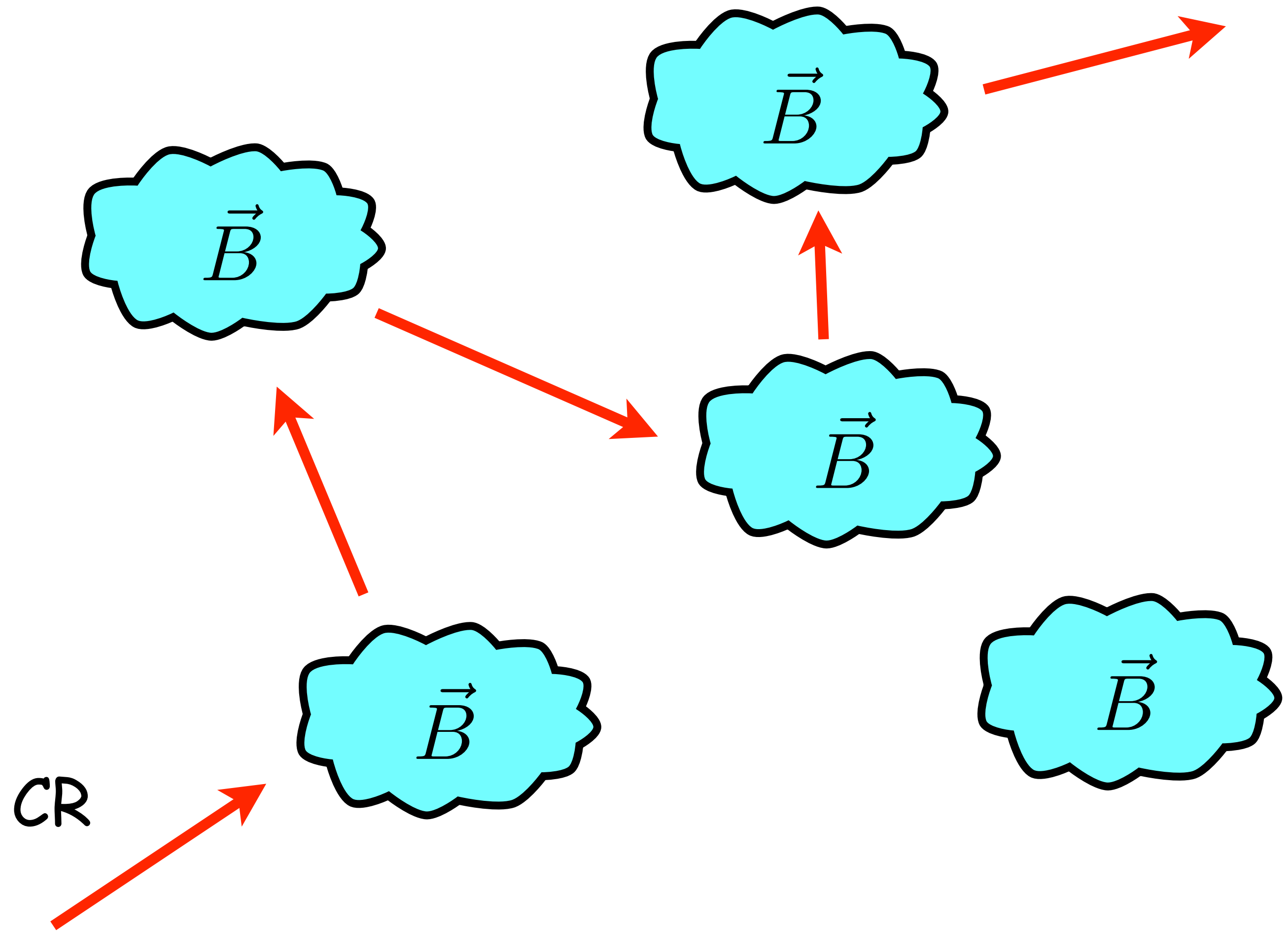

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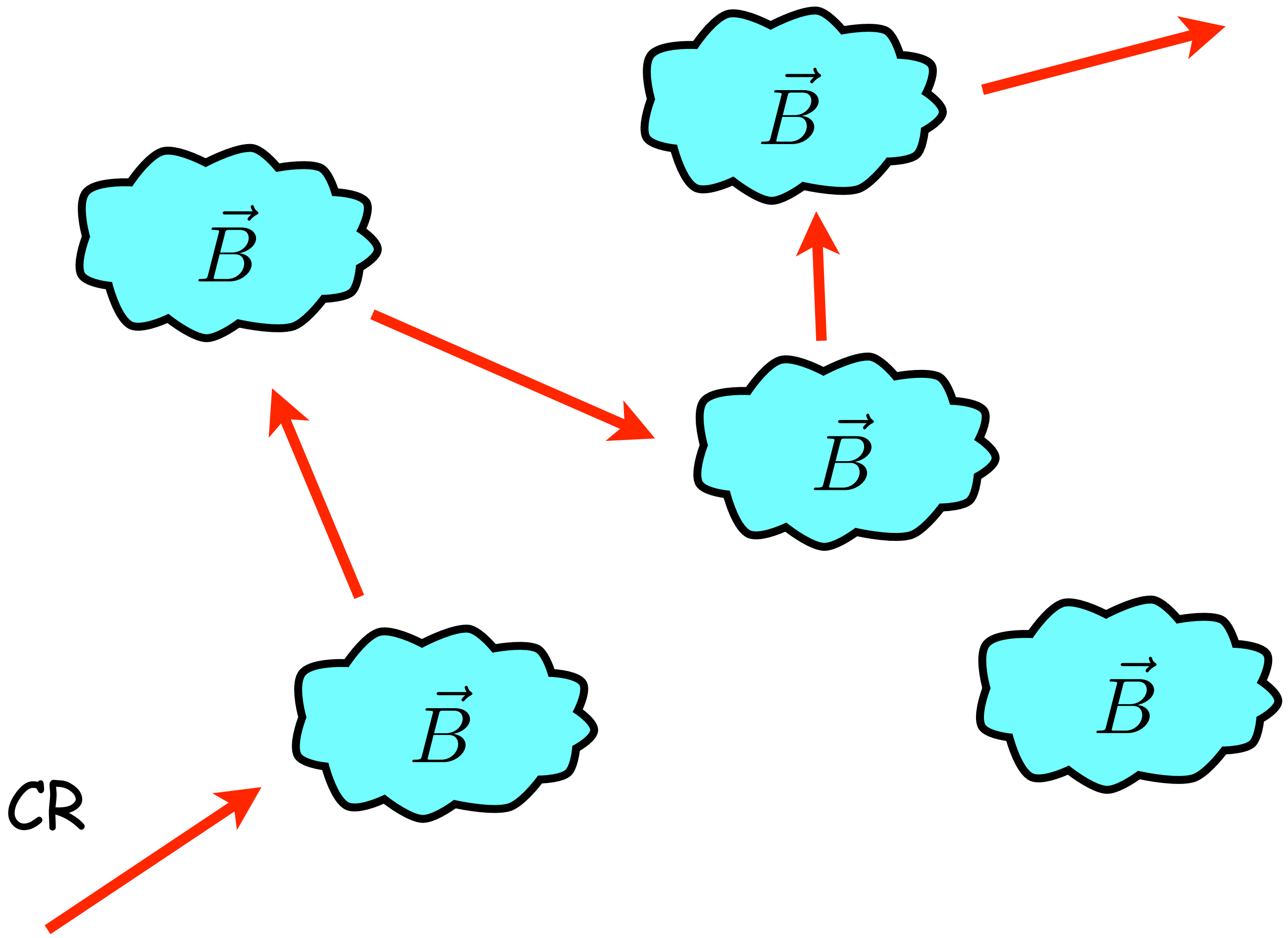

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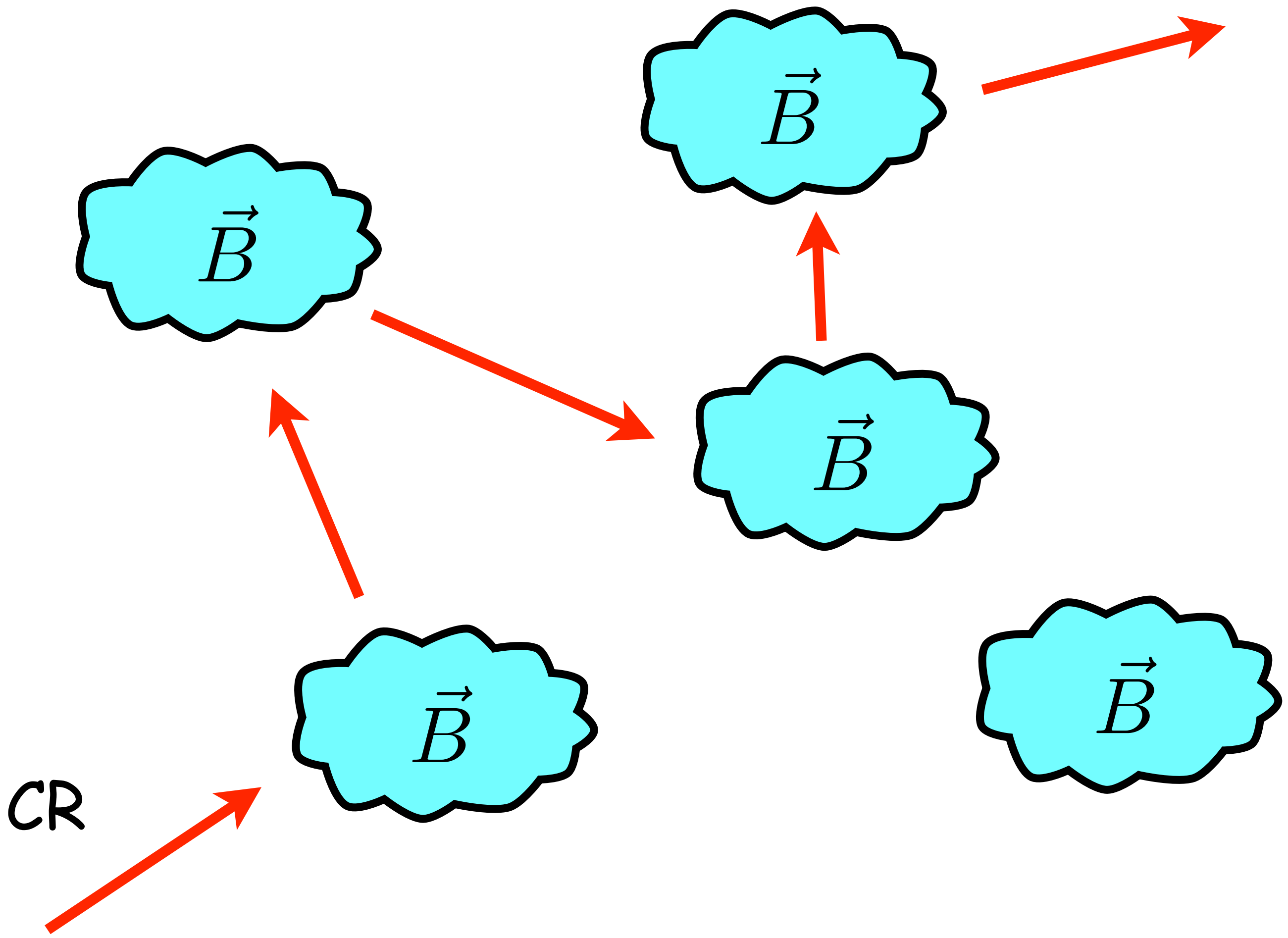
diffusion length -> $$l_d = \lambda \sqrt{N}$$

random walk

The diffusion of CRs



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diffusion length -> $$l_d = \lambda \sqrt{N} = \lambda \sqrt{\frac{t}{\tau_c}} = \lambda \sqrt{\frac{t\ c}{\lambda}} = \sqrt{\lambda\ c\ t}$$

random walk

this product determines the diffusion properties of the particle

The diffusion of CRs

It is convenient to define the quantity $D = \lambda\, c$ called **diffusion coefficient**

diffusive propagation -> $$l_d \; = \; \sqrt{D\, t} \; \propto \sqrt{t}$$

straight line propagation -> $$l_{sl} \; = \; c\, t \; \propto \; t$$

The diffusion of CRs

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straight line propagation -> $$l_{sl} = c\, t \propto t$$

Spallation measurements allow us to measure the average diffusion coefficient in the Galaxy

$$l_{disk} = \sqrt{D\, t_{disk}} \longrightarrow D = \frac{l_{disk}^2}{t_{disk}} = 10^{28}\ \mathrm{cm}^2/\mathrm{s}$$

~300 pc

3 Myr (from spallation)

@ 10 GeV

CR diffusion is energy dependent

Spallation measurements at different energies -> $t_{disk} \propto E^{-0.3}$

which corresponds to -> $D \propto E^{0.3}$

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We can now constrain the CR injection spectrum in the Galaxy

$$\frac{\mathrm{d}N_{CR}(E)}{\mathrm{d}t} = Q_{CR}(E) - \frac{N_{CR}(E)}{t_{disk}}$$

CRs injected from sources in the disk

escape rate from the disk

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stability in time

CRs injected from sources in the disk

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$$Q_{CR}(E) = \frac{N_{CR}(E)}{t_{disk}} \propto N_{CR}(E) D(E) \propto E^{-2.4}$$

measured -> $E^{-2.7}$

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injection*

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*which sources???

A remarkable coincidence

Total CR power in the Galaxy ->

$$P_{CR} = 10^{41} \mathrm{erg/s}$$

A **SuperNova** is the explosion of a massive star that releases ~10^{51} ergs in form of kinetic energy. In the Galaxy the observed supernova rate is of the order of 1/30 yr^{-1}.

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Total SN power in the Galaxy ->

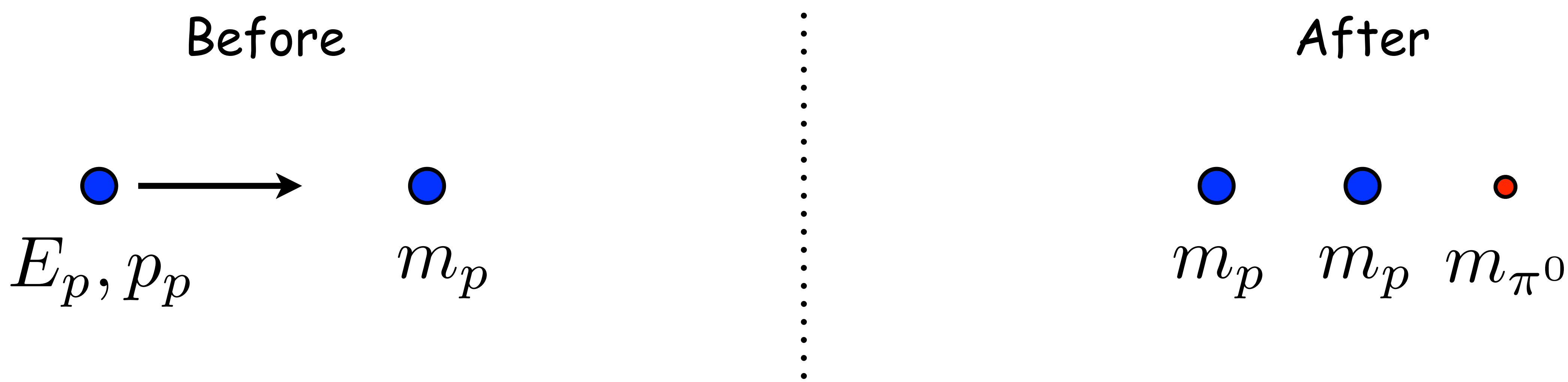
$$P_{SN} = 10^{42} \mathrm{erg/s}$$

SuperNovae alone could maintain the CR population provided that about 10% of their kinetic energy is somehow converted into CRs

Gamma-Ray Astronomy: p-p interactions

Energy threshold for neutral pion production:

$$p + p \rightarrow p + p + \pi^0$$



$$E^2 - p^2c^2$$

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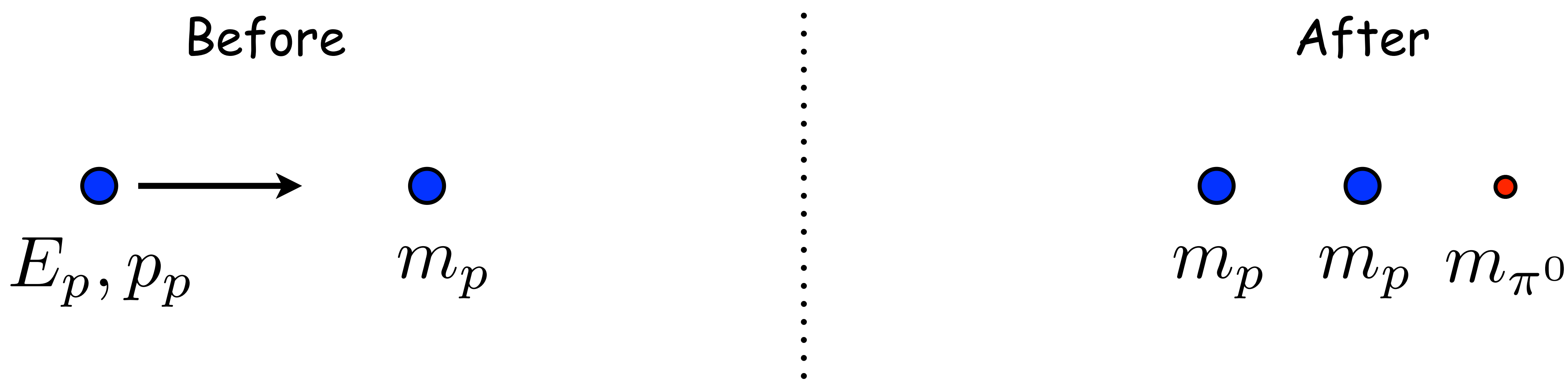

$$E^2 - p^2c^2 = \left(2m_pc^2 + m_{\pi^0}c^2\right)^2$$

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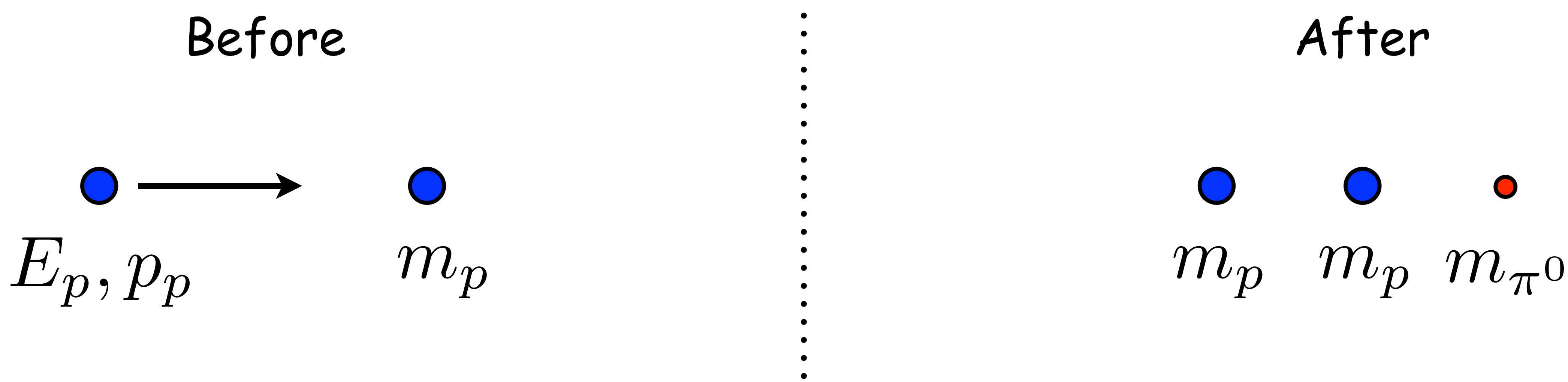

$$\left(E_p + m_p c^2\right)^2 - p_p^2 c^2 = E^2 - p^2 c^2 = \left(2 m_p c^2 + m_{\pi^0} c^2\right)^2$$

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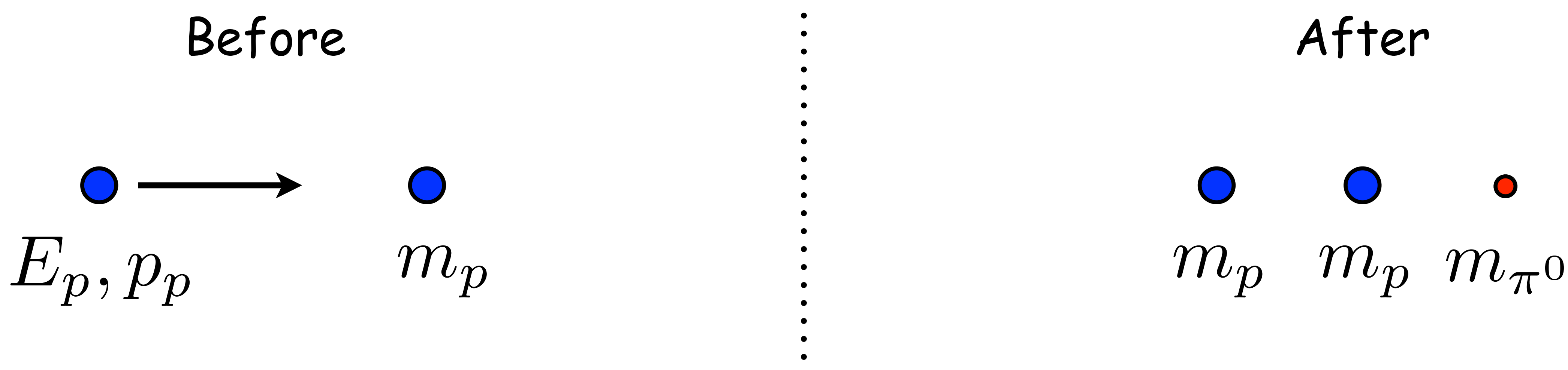

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$$E_p - m_p c^2 > 2m_{\pi^0} c^2 + \left(\frac{m_{\pi^0}}{2m_p}\right) m_{\pi^0} c^2 \approx 280 \text{ MeV}$$

energy threshold

Gamma-Ray Astronomy: p-p interactions

Let's calculate the spectrum of neutral pions:

We assume a power law spectrum for CRs: $N_p(E_p) \propto E_p^{-\delta}$

Fraction of proton kinetic energy transferred to pion (from data): $f_{\pi^0} \approx 0.17$

....

production rate

total cross section

$$q_{\pi^0} = \int \mathrm{d}E_p \; N_p(E_p) \; \delta(E_{\pi^0} - f_{\pi^0} E_{p,kin}) \; \sigma_{pp}(E_p) \; n_{gas} \; c$$

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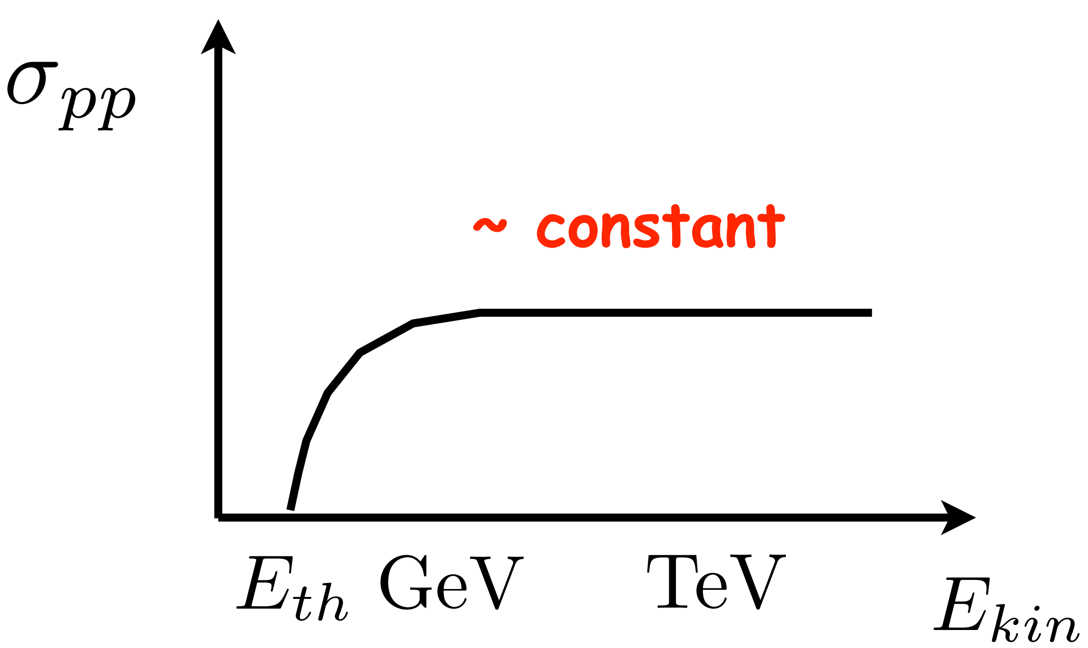

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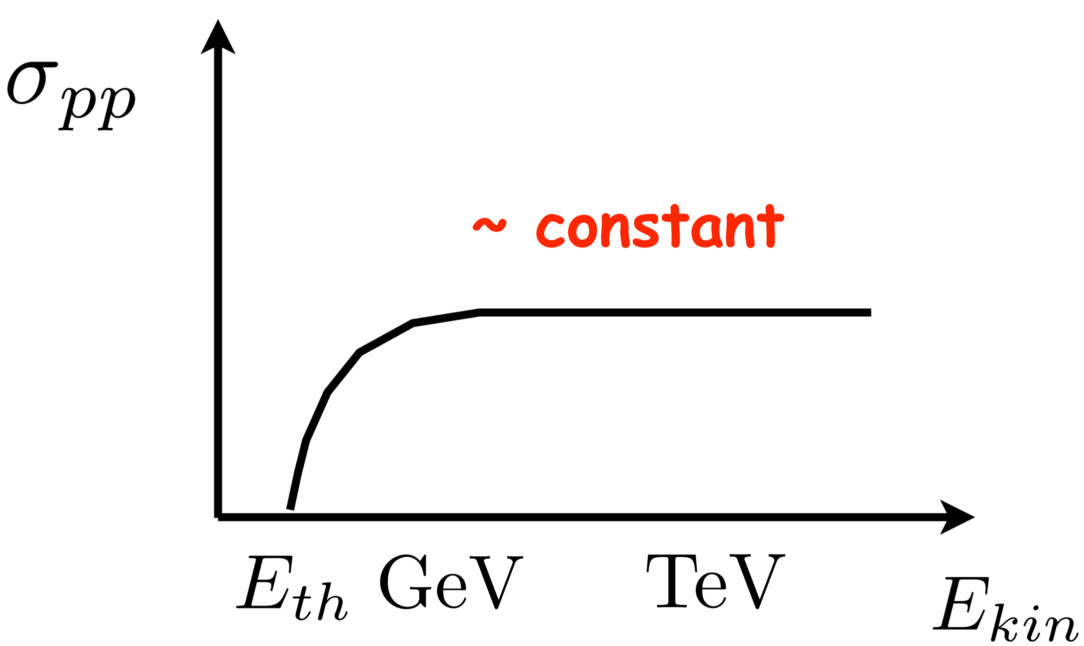

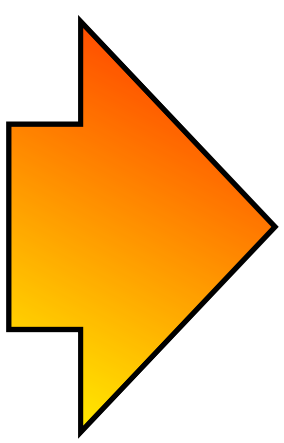

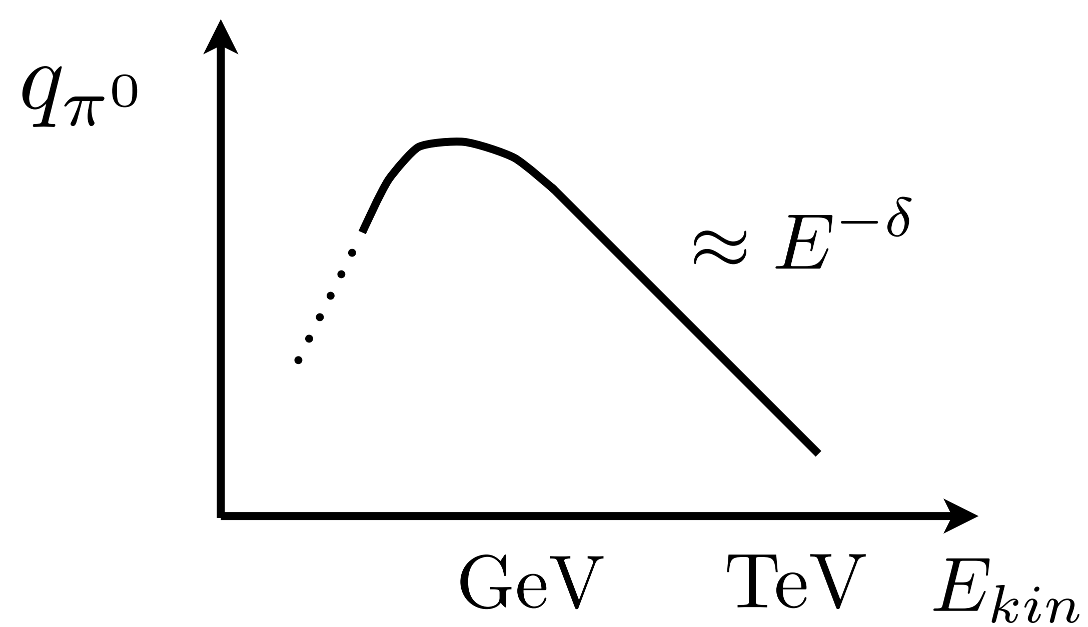

Gamma-Ray Astronomy: p-p interactions

Let's now calculate the spectrum of photons from pion decay - I

The photon spectrum is the result of a "one-body-decay" (neutral pion) → The photon spectrum MUST exhibit a feature at an energy relate to the pion mass

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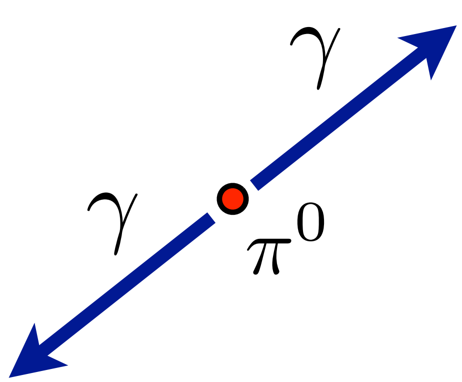
Pion rest frame:



$$E_\gamma^* = \frac{m_{\pi^0}}{2}$$

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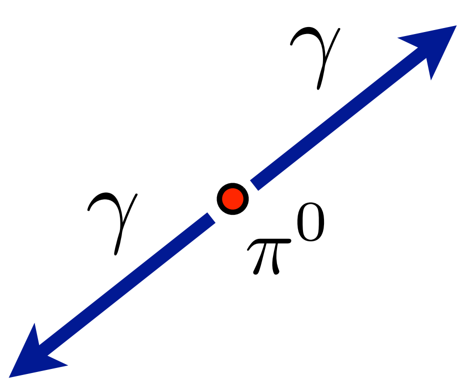

$$E^*_\gamma = \frac{m_{\pi^0}}{2}$$

Lab frame:

$$E_\gamma = \gamma\left(E^*_\gamma + v p^*_\gamma \cos\theta^*\right)$$

max and min energies -> $\cos\theta^* = \pm 1$

$$\frac{m_{\pi^0}}{2}\sqrt{\frac{1-\beta}{1+\beta}} \le E_\gamma \le \frac{m_{\pi^0}}{2}\sqrt{\frac{1+\beta}{1-\beta}}$$

Gamma-Ray Astronomy: p-p interactions

Let's now calculate the spectrum of photons from pion decay - II

$$E_\gamma^{min} = \frac{m_{\pi^0}}{2}\sqrt{\frac{1-\beta}{1+\beta}} \leq E_\gamma \leq \frac{m_{\pi^0}}{2}\sqrt{\frac{1+\beta}{1-\beta}} = E_\gamma^{max}$$

(1) $$\frac{\log E_\gamma^{max} + \log E_\gamma^{min}}{2} = \log\left(\frac{m_{\pi^0}}{2}\right)$$

in log-scale, the centre of the interval is half the pion mass

Gamma-Ray Astronomy: p-p interactions

Let's now calculate the spectrum of photons from pion decay - II

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in log-scale, the centre of the interval is half the pion mass

(2) in the pion rest frame the photon distribution is isotropic $$\frac{\mathrm{d}n_\gamma}{\mathrm{d}\Omega^*} = \frac{1}{4\pi}$$

$$\mathrm{d}\Omega^* \propto \mathrm{d}(\cos\theta^*)$$

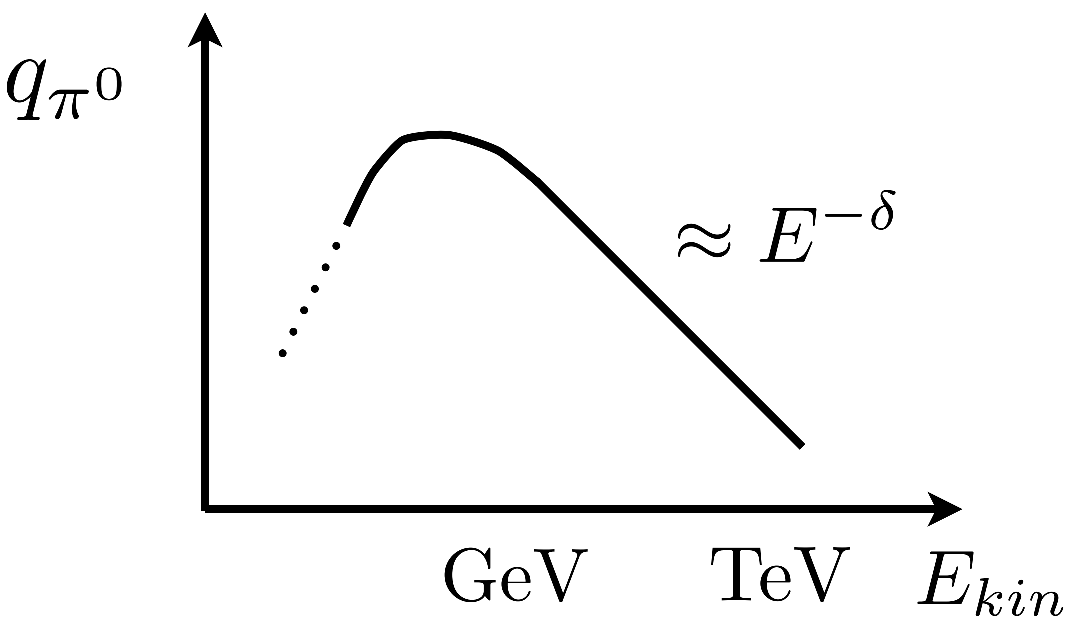
$$E_\gamma = \gamma\left(E_\gamma^* + v p_\gamma^* \cos\theta^*\right) \rightarrow \mathrm{d}E_\gamma \propto \mathrm{d}(\cos\theta^*)$$

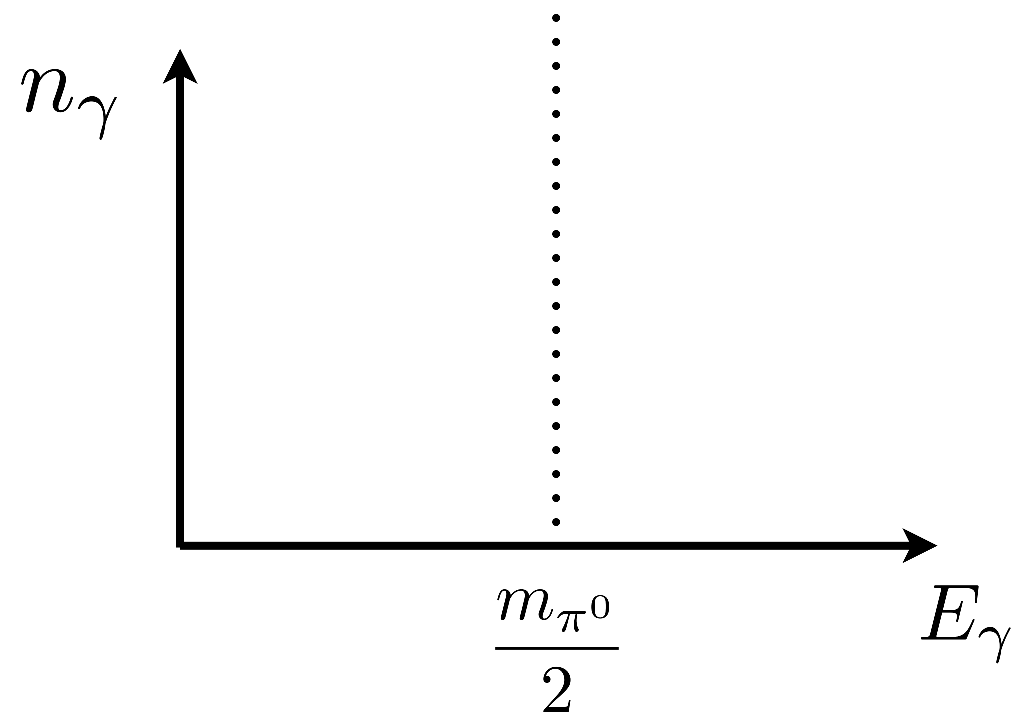
$$\frac{\mathrm{d}n_\gamma}{\mathrm{d}E_\gamma} = const$$

The spectrum is flat!

Gamma-Ray Astronomy: p-p interactions

Let's now calculate the spectrum of photons from pion decay - III





Gamma-Ray Astronomy: p-p interactions

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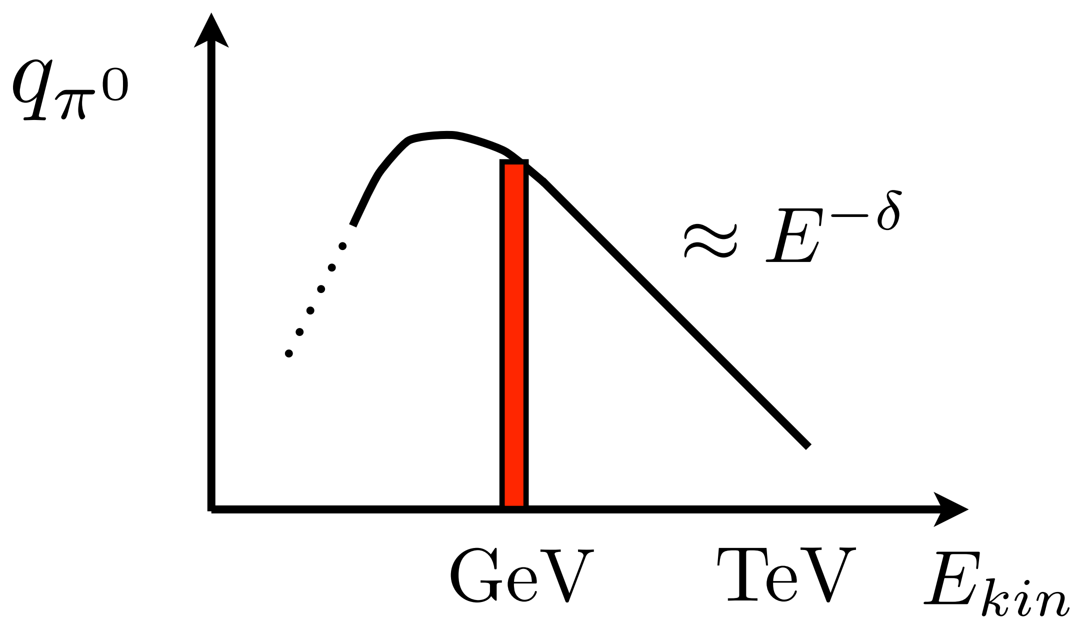

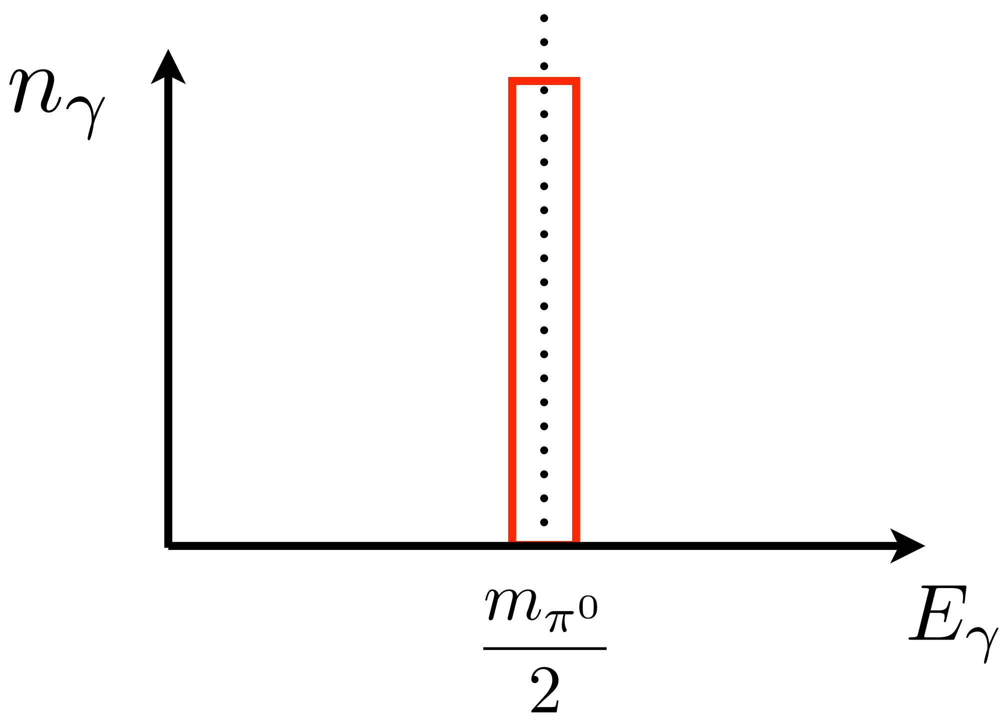

Gamma-Ray Astronomy: p-p interactions

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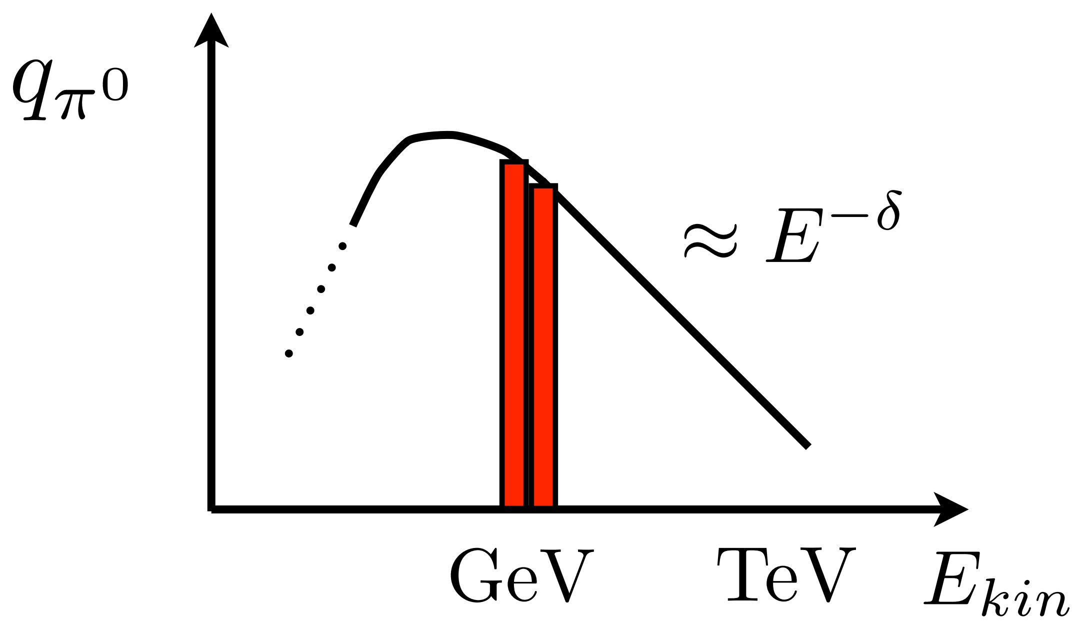

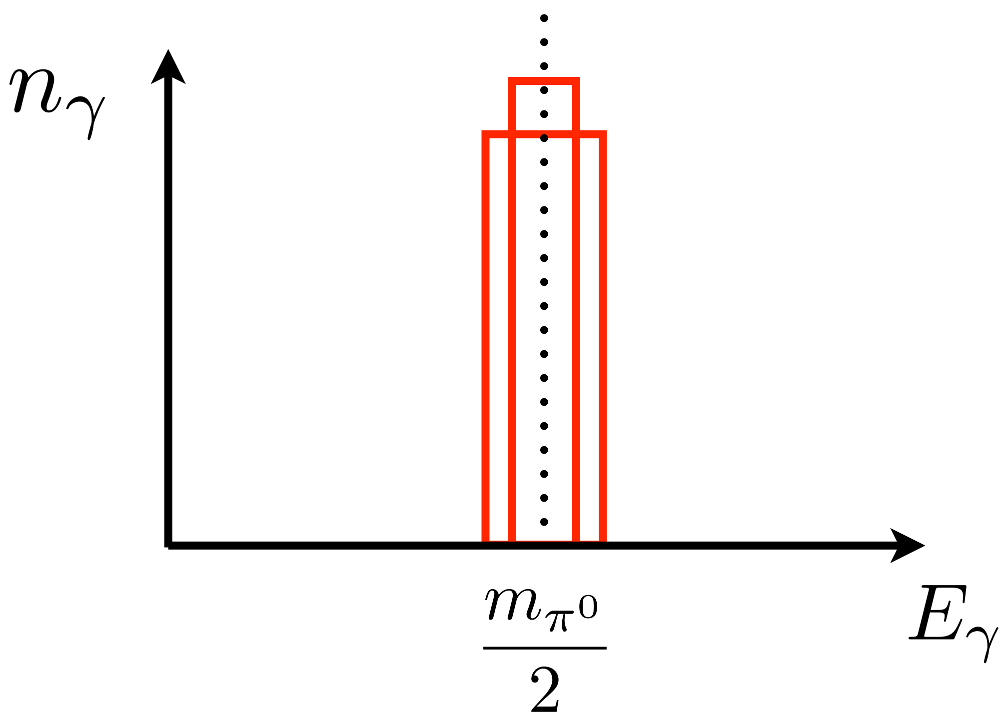

Gamma-Ray Astronomy: p-p interactions

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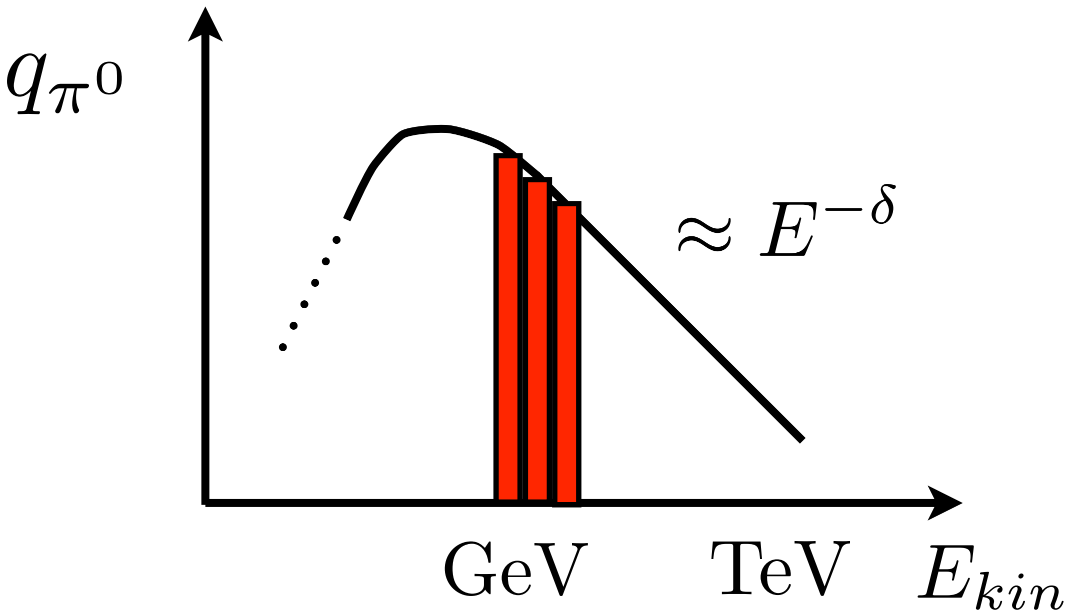

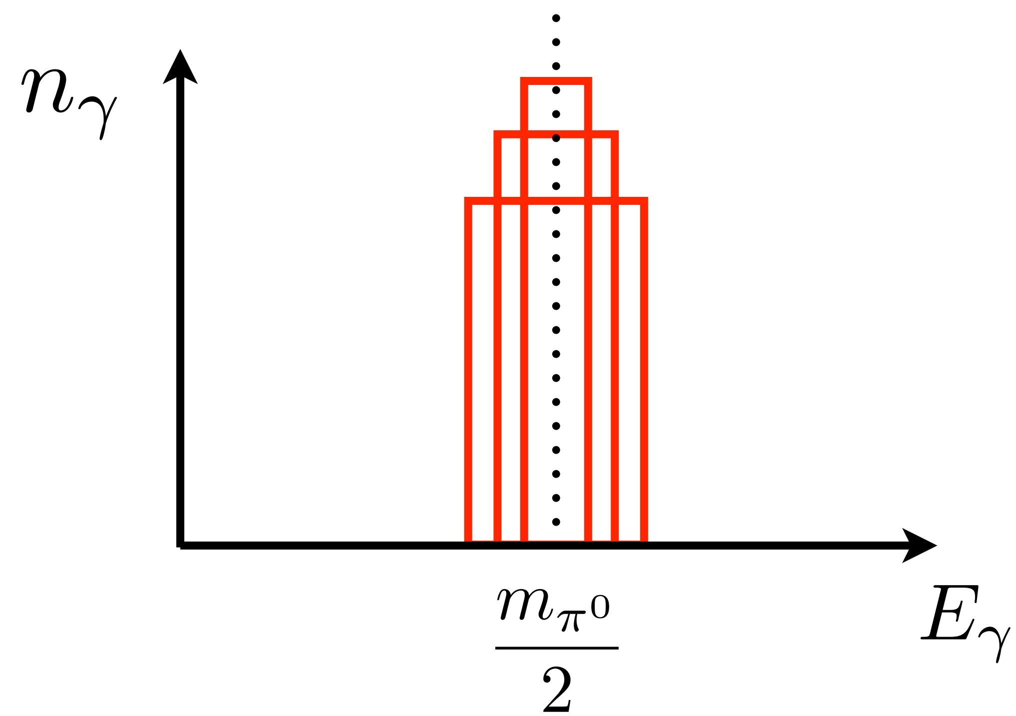

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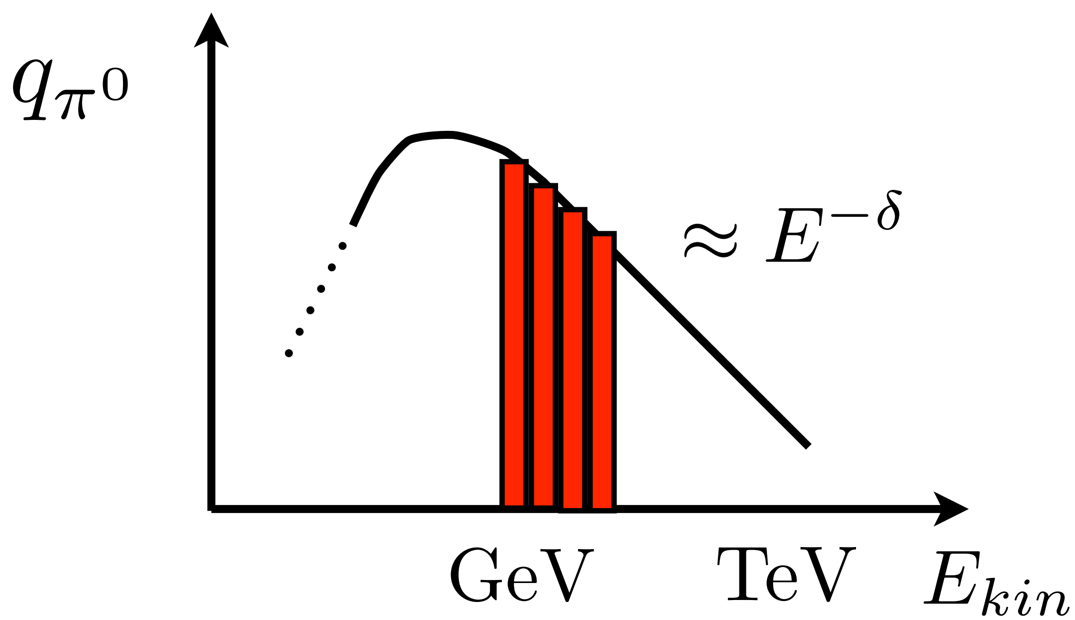

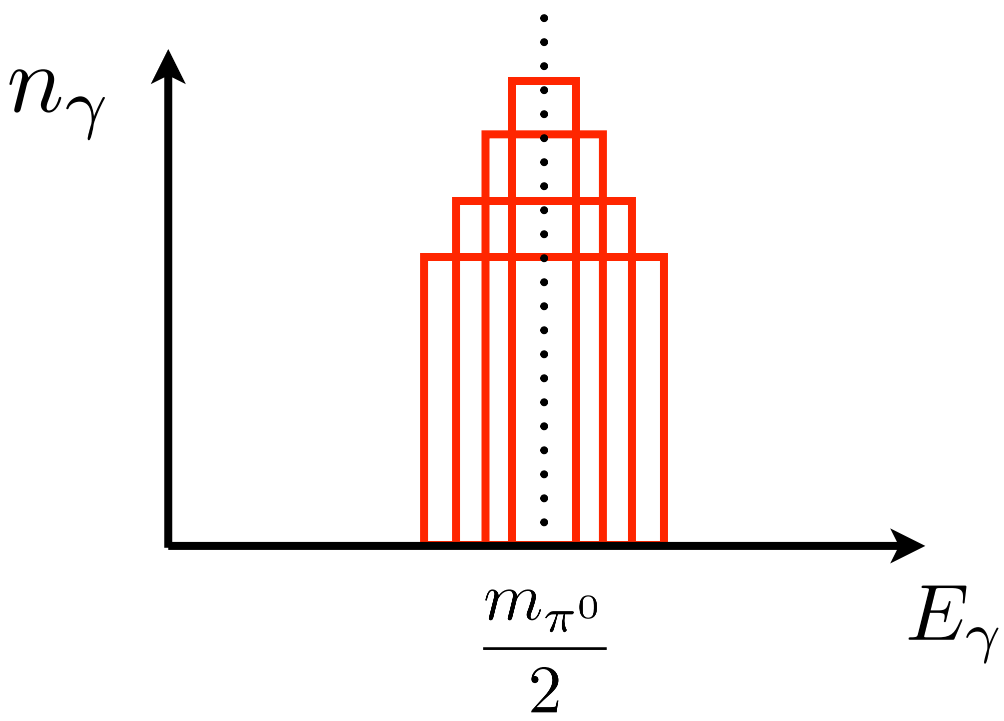

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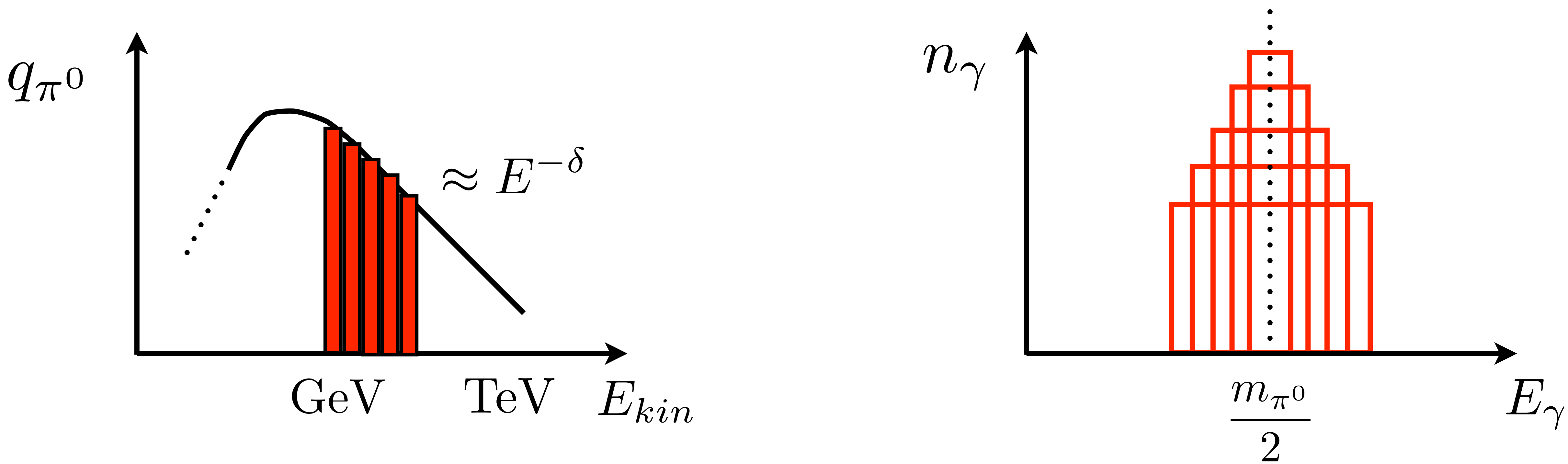

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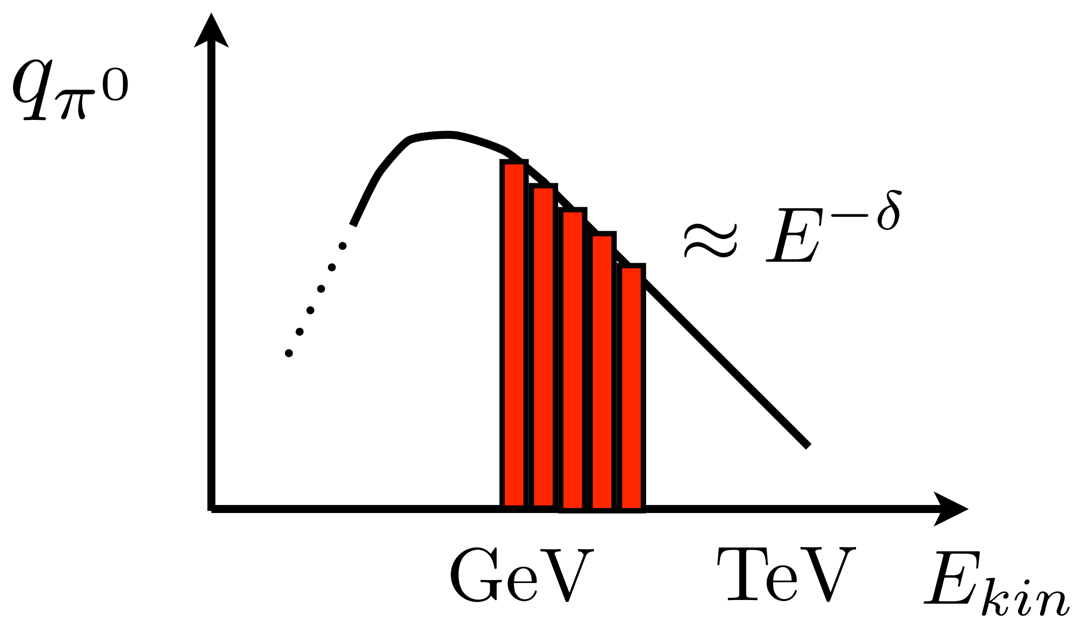

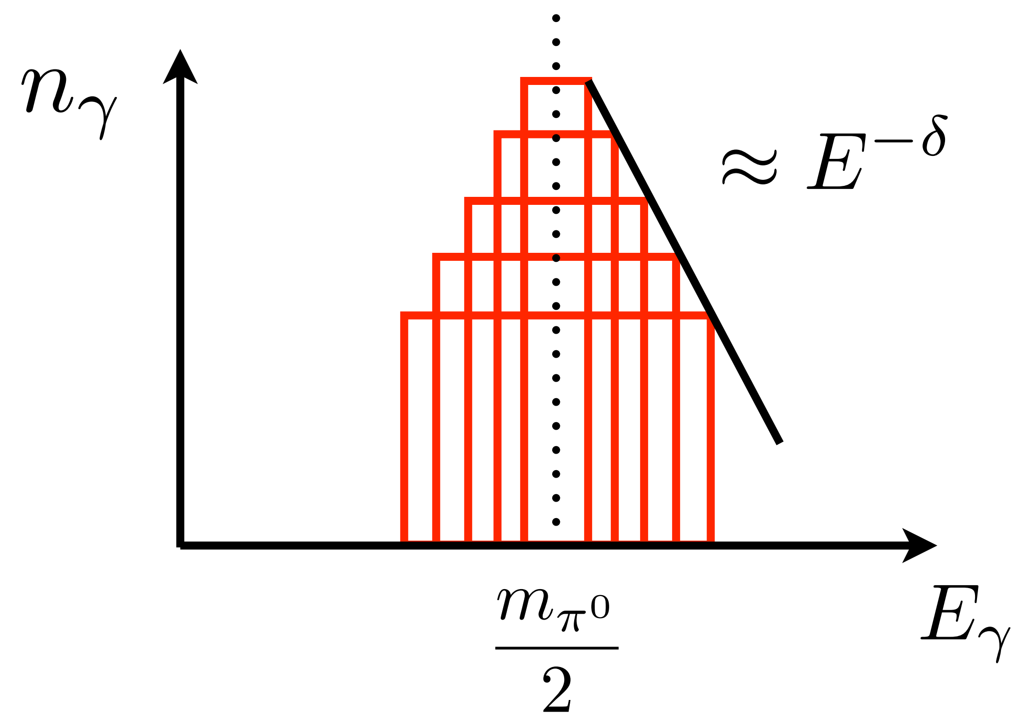

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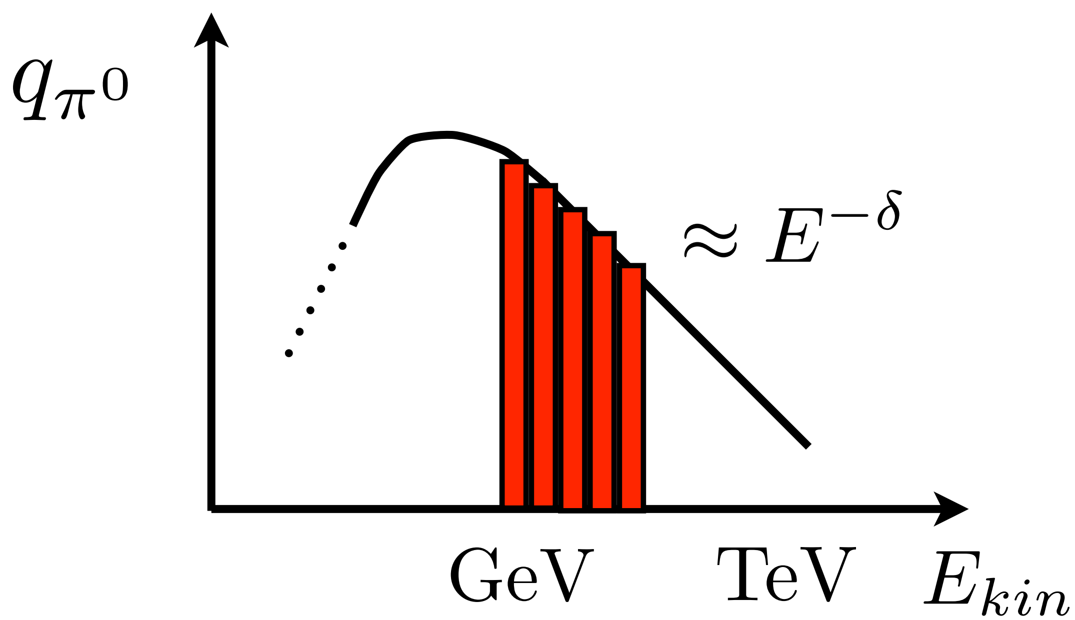

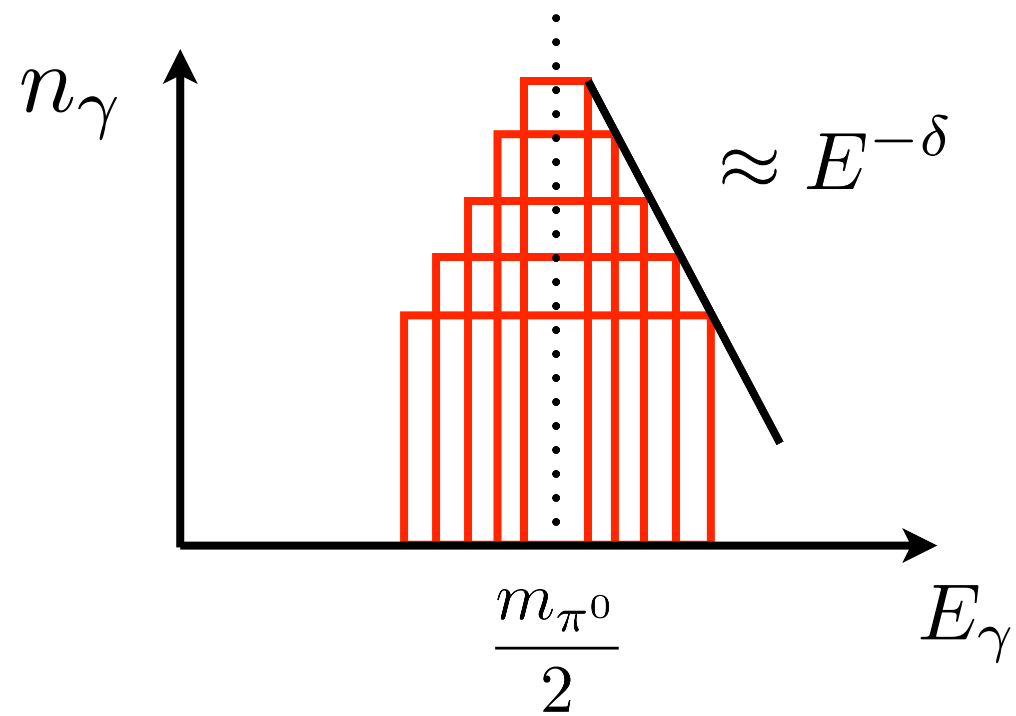

- the gamma ray spectrum is symmetric (in log-log) with respect to: $\frac{m_{\pi^0}}{2} \sim 70 \text{ MeV}$
- at high energy the spectrum mimic the CR spectrum, with (roughly): $E_\gamma \approx \frac{E_{CR}}{10}$

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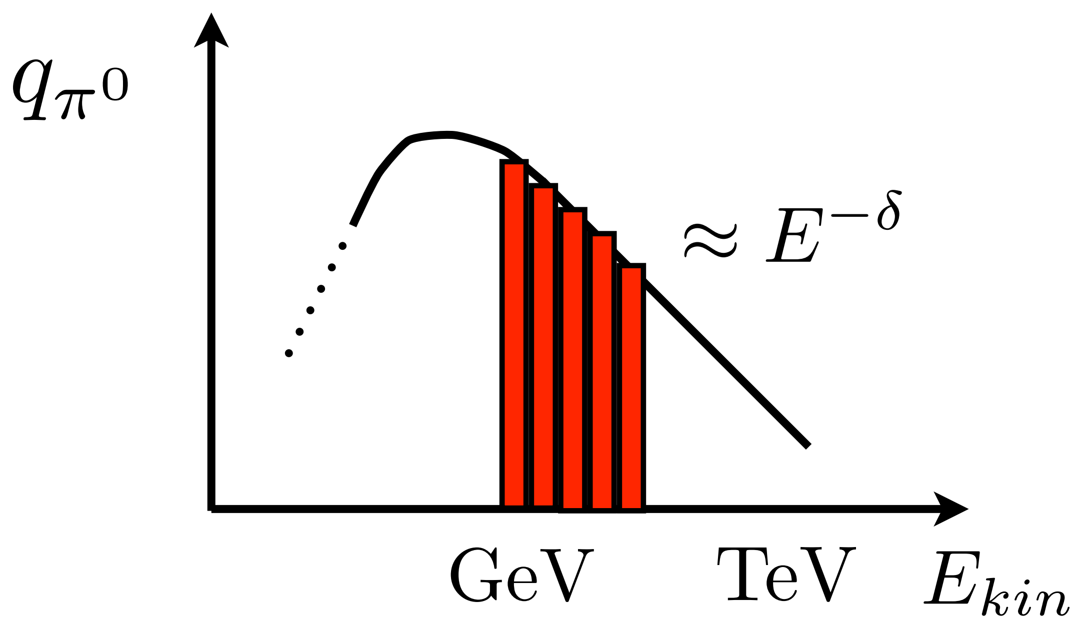

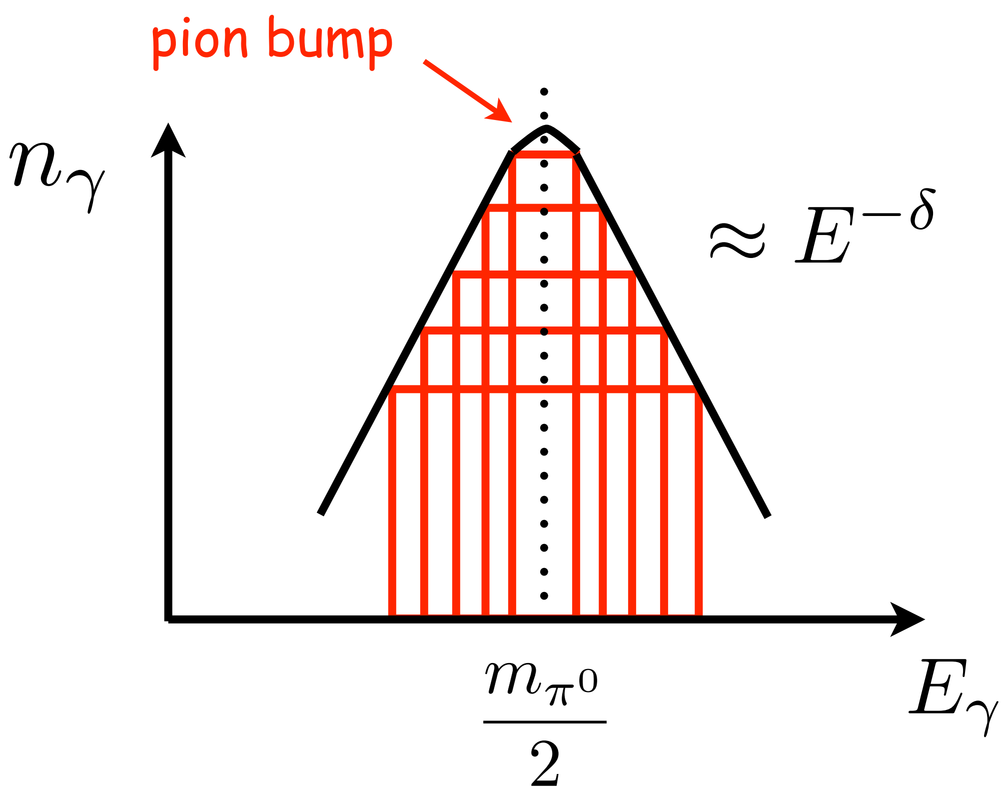

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Why the same power law?

large Lorentz factor

$$E_\gamma^{max} = \frac{m_{\pi^0}}{2}\sqrt{\frac{1+\beta}{1-\beta}} = \frac{m_{\pi^0}}{2}(1+\beta)\gamma \longrightarrow m_{\pi^0}\gamma$$

$$E_\gamma^{min} = \frac{m_{\pi^0}}{2}\sqrt{\frac{1-\beta}{1+\beta}} = \frac{m_{\pi^0}}{2}\left[(1+\beta)\gamma\right]^{-1} \longrightarrow \frac{m_{\pi^0}}{4}\gamma^{-1}$$

very large Lorentz factor

$$0 \lesssim E_\gamma \lesssim m_{\pi^0}\gamma \propto E_p$$

to produce a photon of energy E_γ we need: $E_p \gtrsim \frac{m_p}{m_{\pi^0}} E_\gamma$

$$N_\gamma(E_\gamma) \propto \int_{\frac{m_p}{m_{\pi^0}}E_\gamma}^{\infty} \mathrm{d}E_p \frac{N_p(E_p)}{E_\gamma^{max} - E_\gamma^{min}} \propto \int_{\frac{m_p}{m_{\pi^0}}E_\gamma}^{\infty} \mathrm{d}E_p \frac{E_p^{-\delta}}{E_p} \propto E_\gamma^{-\delta}$$

Not only gammas: neutrinos & electrons

Neutrinos/antineutrinos & electrons/positrons are also produced in pp interactions

$$p + p \rightarrow p + p + \pi^0 + \pi^+ + \pi^-$$

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Final products of proton-proton interactions are not only **gamma ray photons** but also **neutrinos**, **anti-neutrinos**, **electrons** and **positrons**

$$\boxed{E_e \approx E_\nu \approx \frac{E_p}{20}}$$

Not only gammas: neutrinos & electrons

Neutrinos/antineutrinos & electrons/positrons are also produced in pp interactions

$$p + p \rightarrow p + p + \pi^0 + \pi^+ + \pi^-$$

neutral and charged pions produced with the same probability (1/3,1/3,1/3)

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\begin{cases} \pi^\pm \rightarrow \mu^\pm + \nu_\mu(\bar{\nu}_\mu) \\ \mu^\pm \rightarrow e^\pm + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e) \end{cases}$$

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Simple order-of-magnitude calculations

gamma rays

valid at large energies

number of protons of energy E_p produced per s

$$Q_p(E_p)$$

Simple order-of-magnitude calculations

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number of protons of energy E_p produced per s

$$\underbrace{Q_p(E_p)\,E_p^2}$$

power (energy per unit time)

Simple order-of-magnitude calculations

gamma rays

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fraction of the energy converted into pions...

number of protons of energy E_p produced per s

$$\eta_\pi \underbrace{Q_p(E_p)\,E_p^2}_{\text{power (energy per unit time)}}$$

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$$\eta_\pi \underbrace{Q_p(E_p)E_p^2}$$

power (energy per unit time)

$$\eta_\pi = 1 - e^{-\left(\frac{\tau_{res}}{\tau_{pp}}\right)} \longrightarrow \frac{\tau_{res}}{\tau_{pp}} \qquad \tau_{pp} \gg \tau_{res}$$

$$\longrightarrow 1 \qquad \tau_{pp} \ll \tau_{res}$$

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fraction of the energy converted into pions...

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$$f_\gamma \eta_\pi \underbrace{Q_p(E_p) E_p^2}$$

...and into gamma rays (1/3 -> π^0)

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gamma rays

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emitted power in gamma rays

fraction of the energy converted into pions…

number of protons of energy E_p produced per s

$$\overbrace{Q_\gamma(E_\gamma)E_\gamma^2}^{\text{emitted power in gamma rays}} = f_\gamma \eta_\pi \underbrace{Q_p(E_p)E_p^2}_{\text{power (energy per unit time)}}$$

…and into gamma rays (1/3 -> π^0)

power (energy per unit time)

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power (energy per unit time)

$$E_\gamma \sim E_p/10$$

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$$\longrightarrow 1 \qquad \tau_{pp} \ll \tau_{res}$$

Simple order-of-magnitude calculations

neutrinos

valid at large energies

The same as for gammas but:

$$f_\gamma \longrightarrow f_\nu = \frac{2}{3} \times \frac{3}{4} \times \frac{1}{3}$$

fraction of charged pions

fraction of pion energy -> neutrinos

per flavour (after oscillations)

$$E_\gamma \longrightarrow E_\nu \sim 0.05 \times E_p$$

Simple order-of-magnitude calculations

valid at large energies

gamma rays

$$Q_\gamma(E_\gamma)E_\gamma^2 = \frac{\eta_\pi}{3} Q_p(E_p)E_p^2$$

neutrinos (per flavour)

$$Q_\nu(E_\nu)E_\nu^2 = \frac{1}{2} Q_\gamma(E_\gamma)E_\gamma^2$$