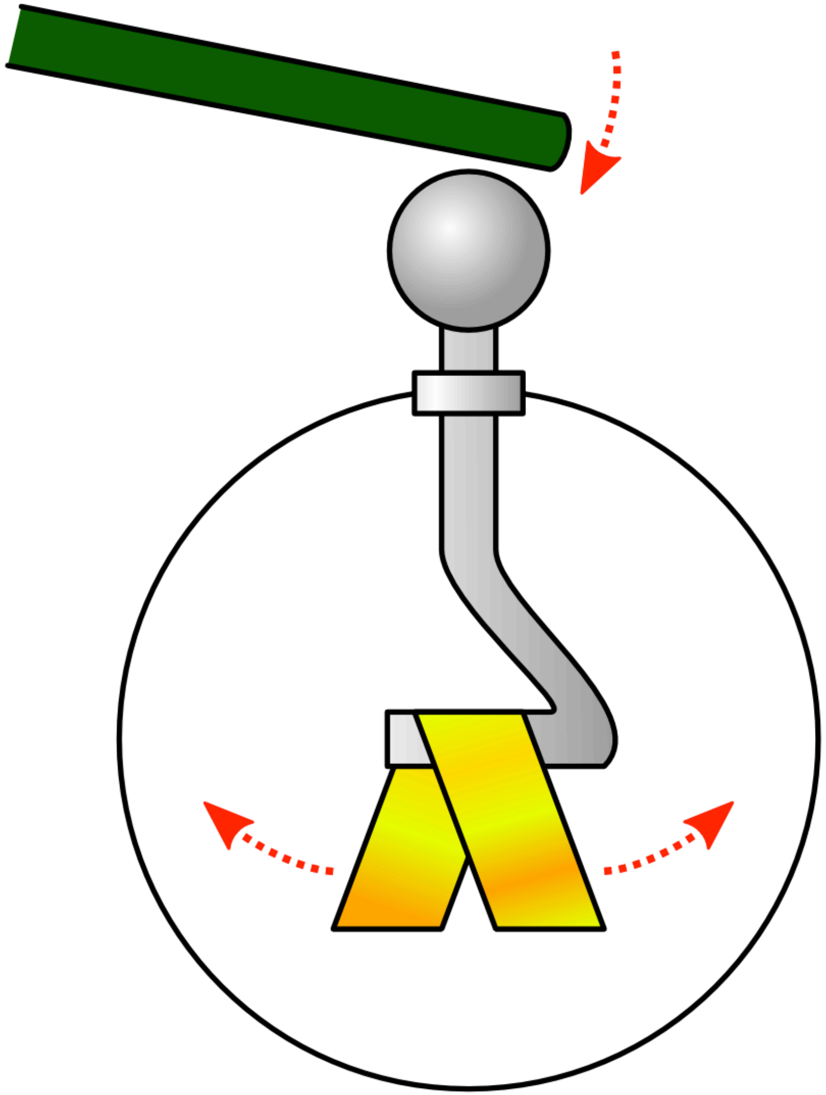
Cosmic Rays and Gamma Rays in the InterStellar Medium

Stefano Gabici
APC, Paris

The discovery of Cosmic Rays

- at the beginning of the 20th century, the discharge rate of an electroscope was used as a measure of the level of radioactivity
- electroscopes discharge slowly even in the absence of a radioactive source -> background radiation
- radiation from radioactive materials in the Earth?



ELECTROSCOPE

The discovery of Cosmic Rays

If due to radioactive materials in the Earth, the effect should diminish with height

In 1912, during a balloon flight Victor Hess discovered that the effect was indeed **increasing with height**, and concluded that:

"a radiation of very high penetrating power enters our atmosphere from above"

V. Hess in 1912

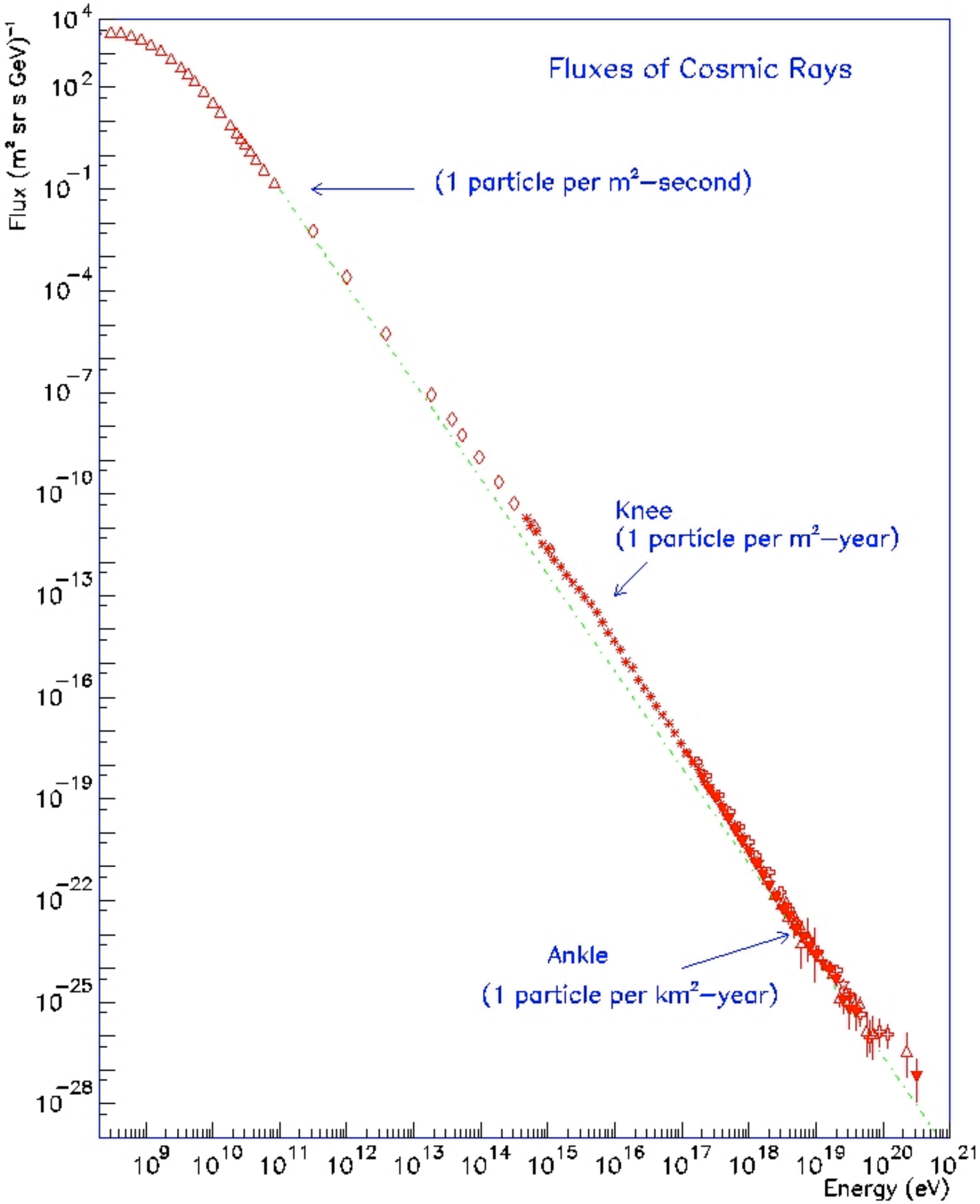
What are Cosmic Rays?

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



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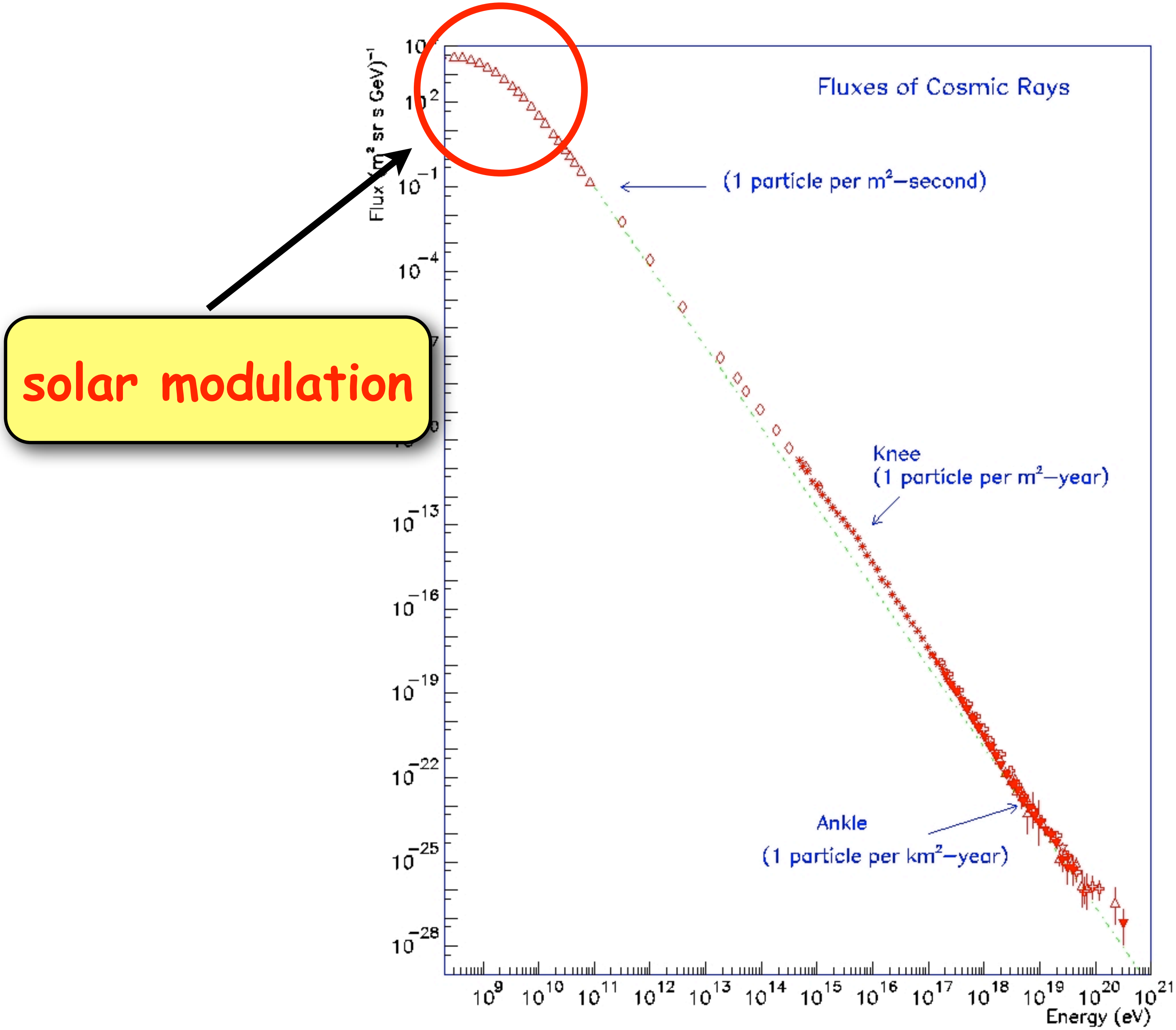

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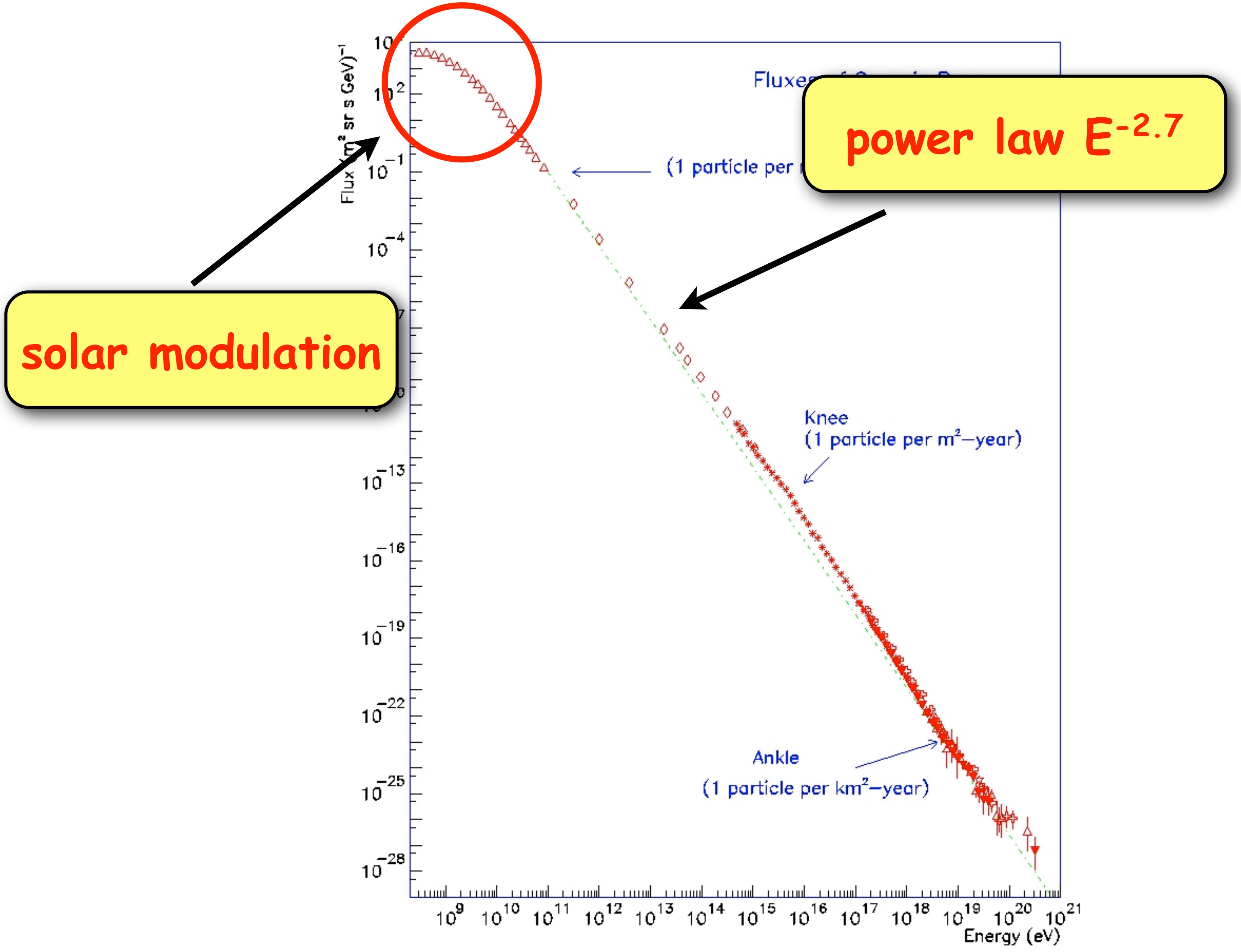

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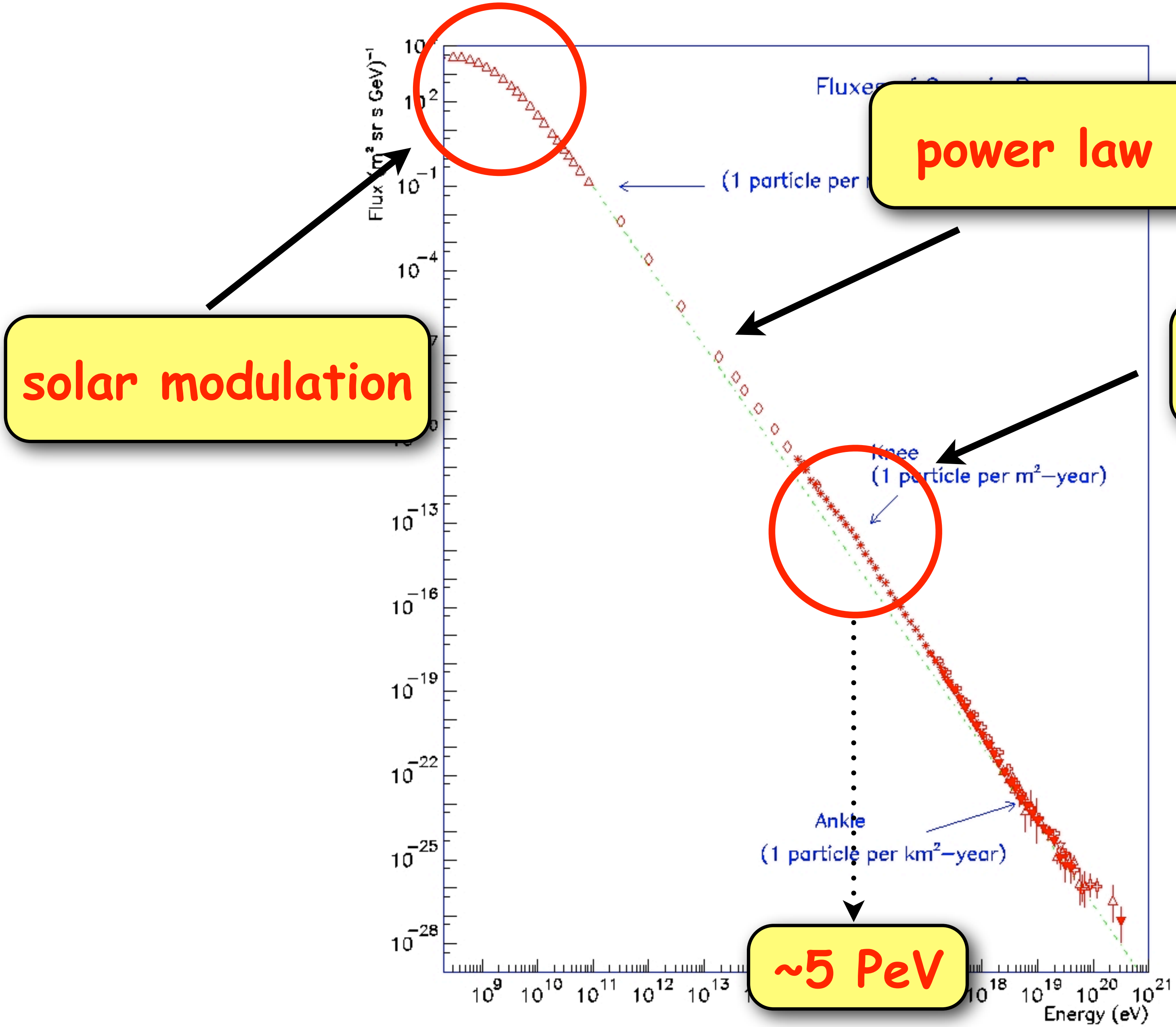

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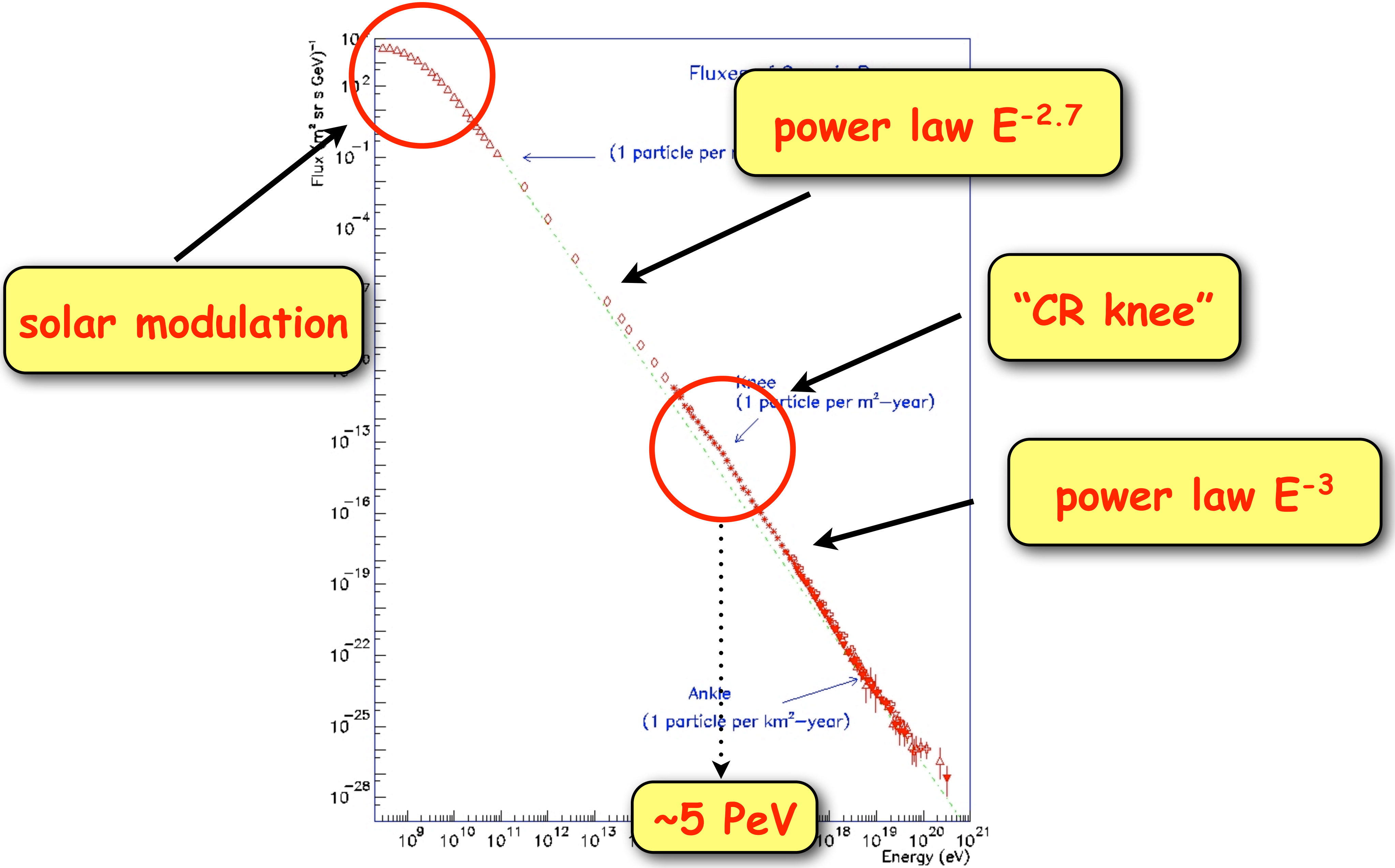

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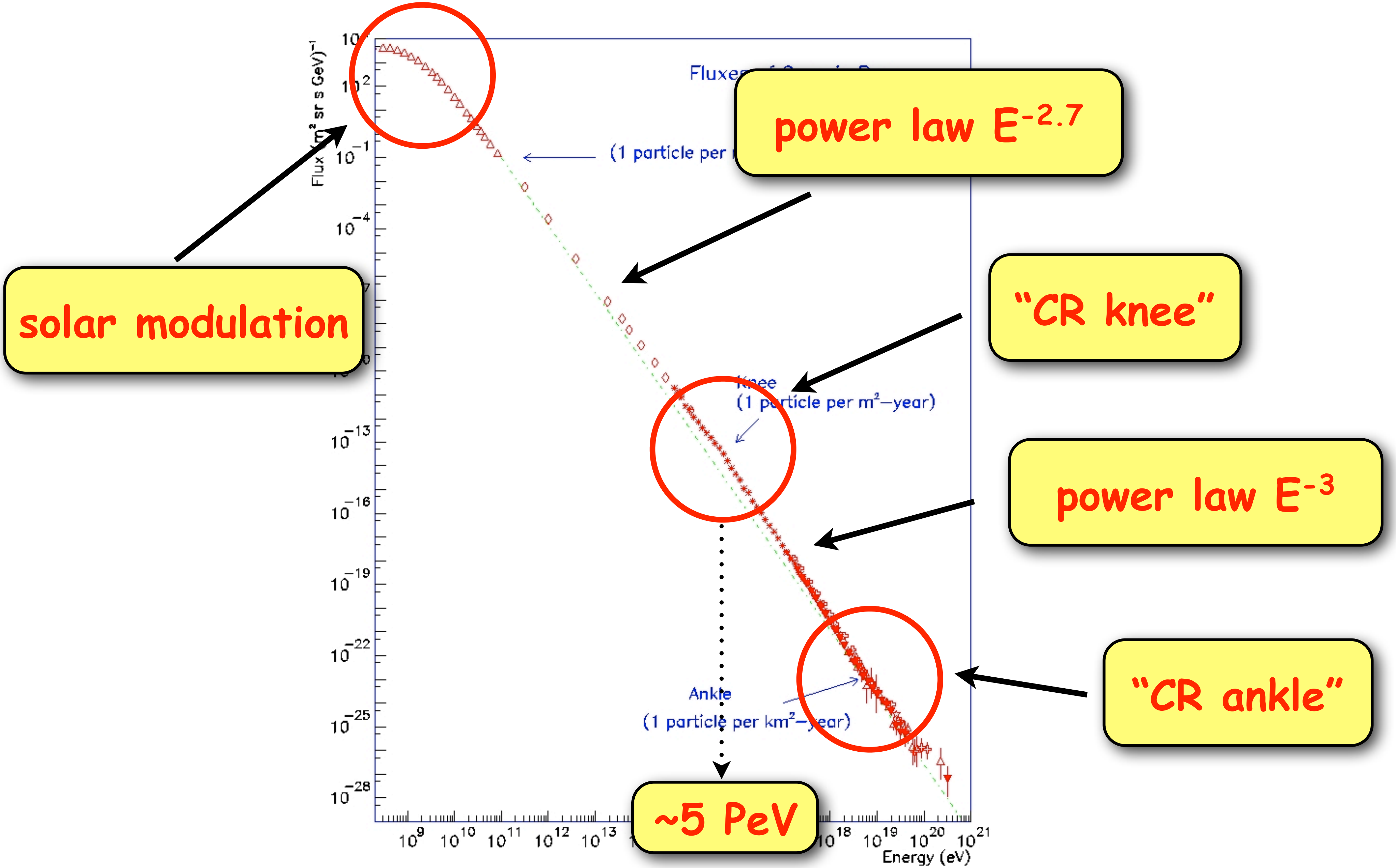
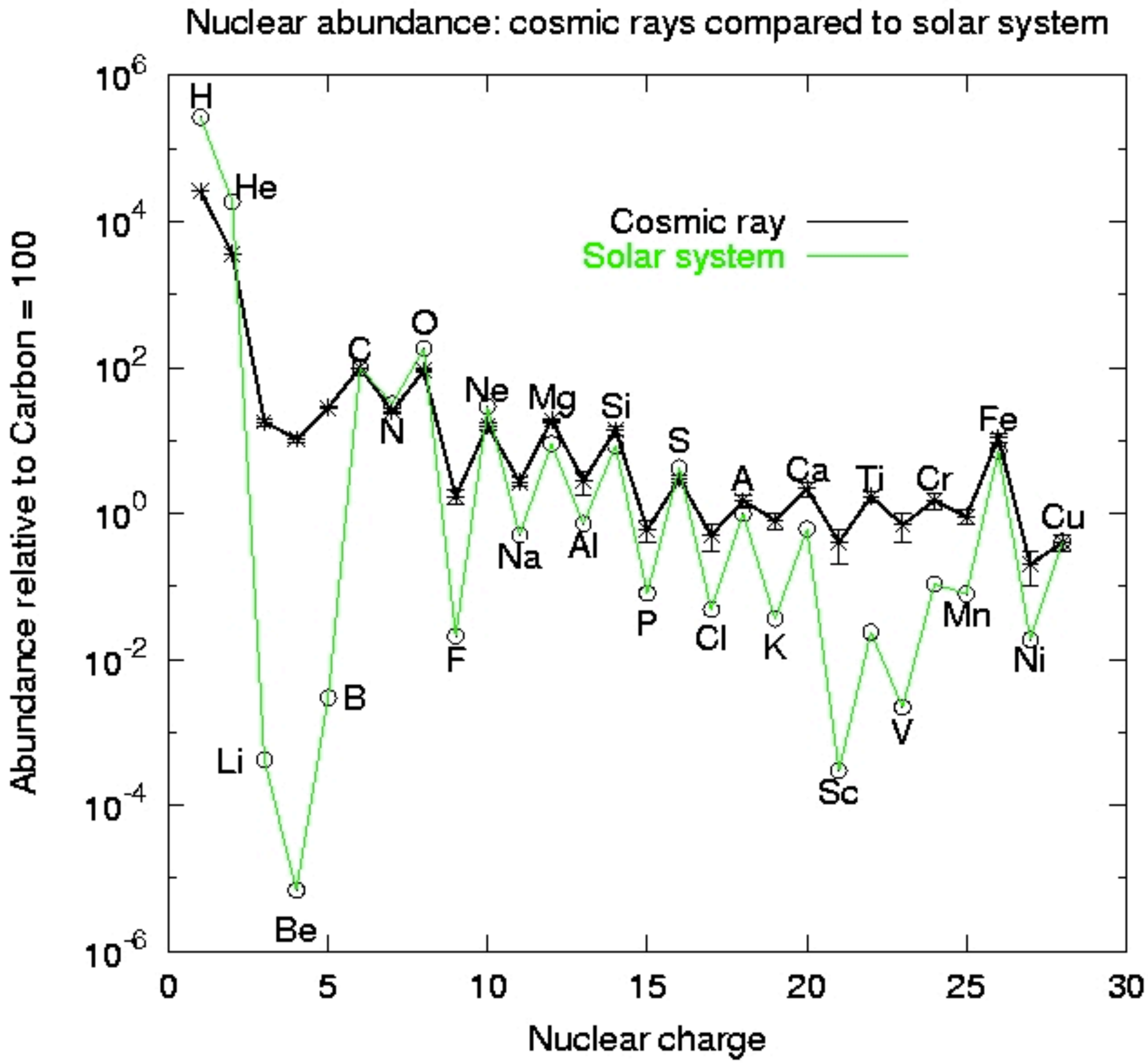


Cosmic Ray composition



Gaisser & Stanev, 2005

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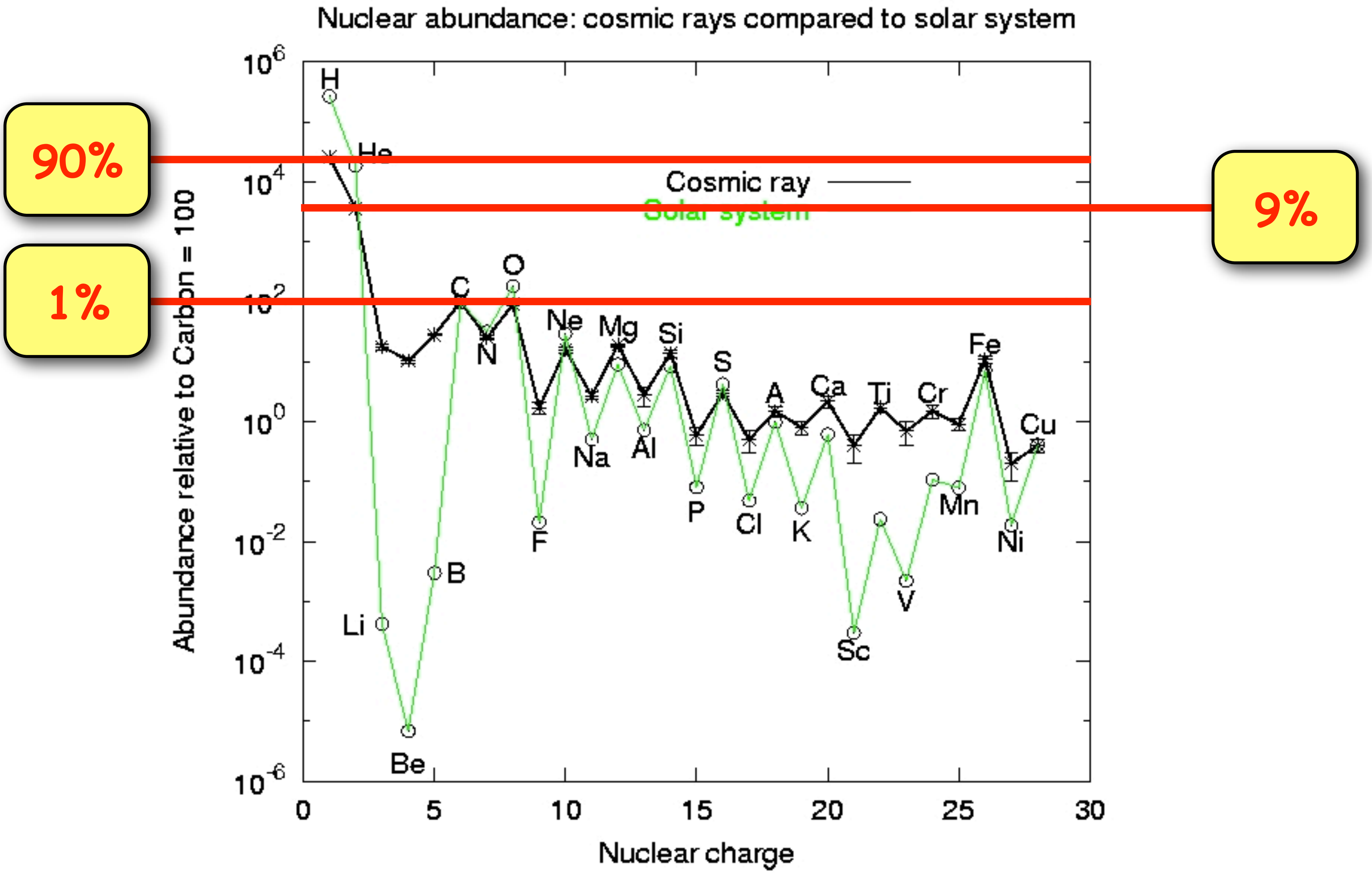

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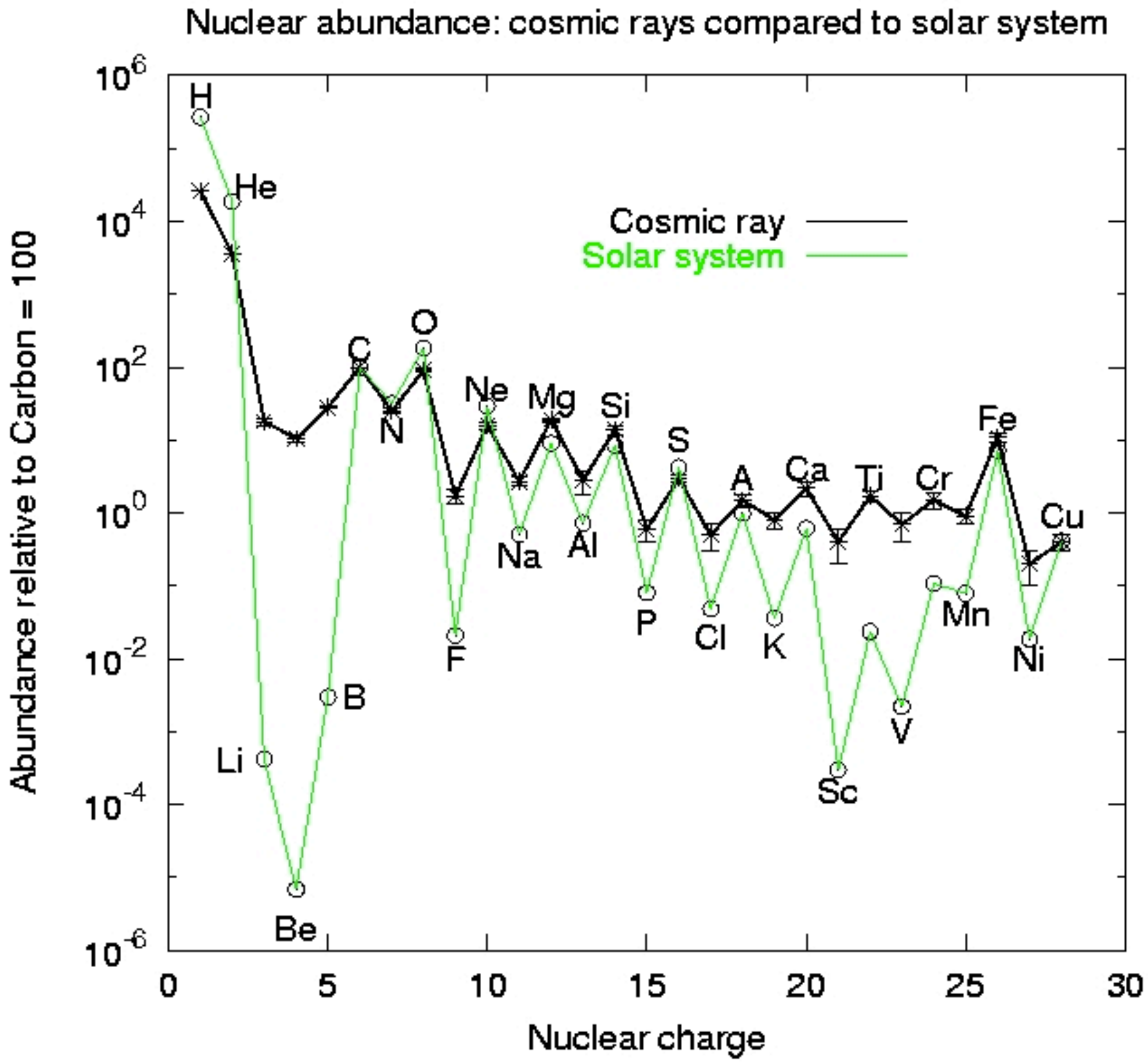

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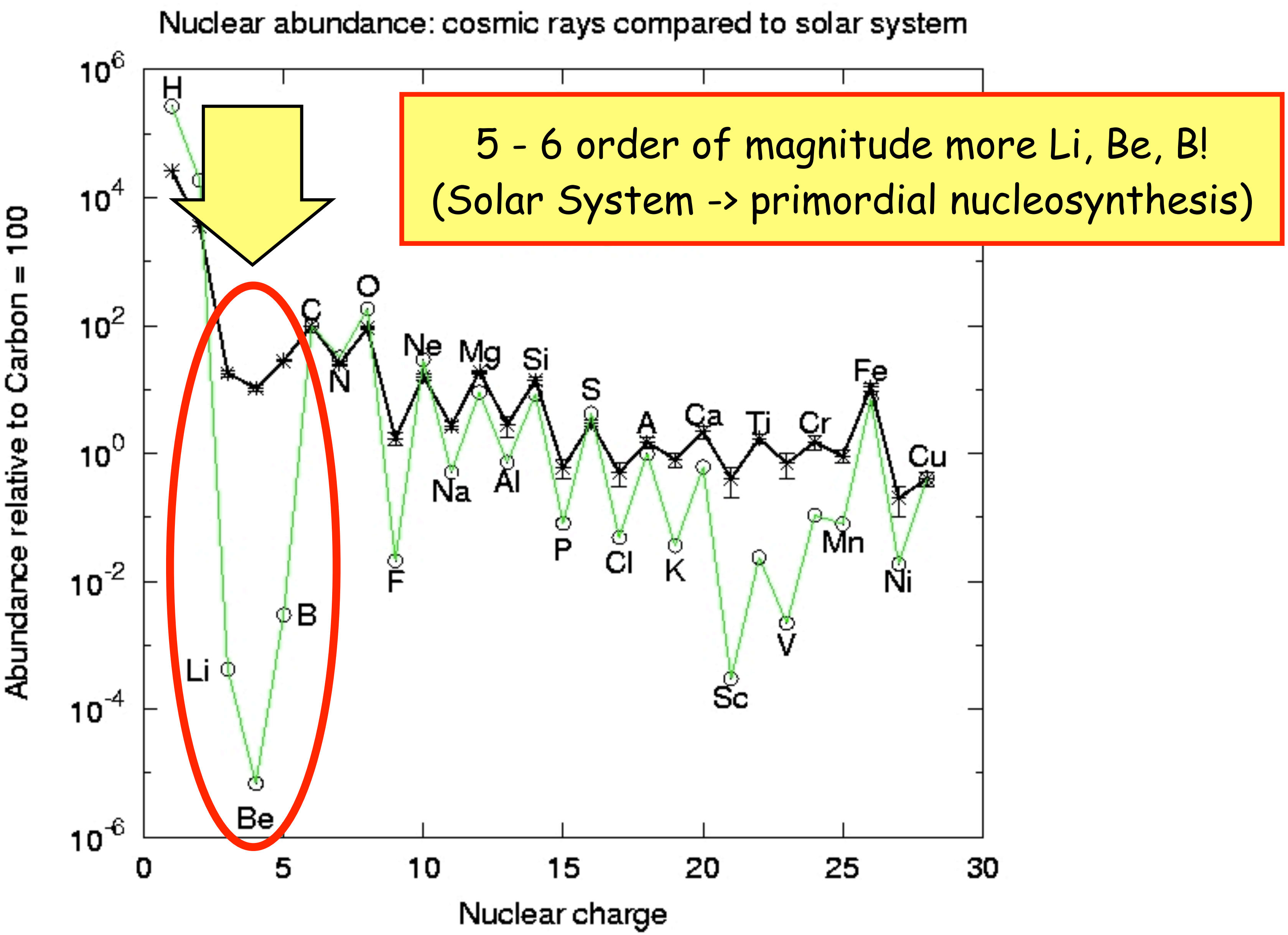

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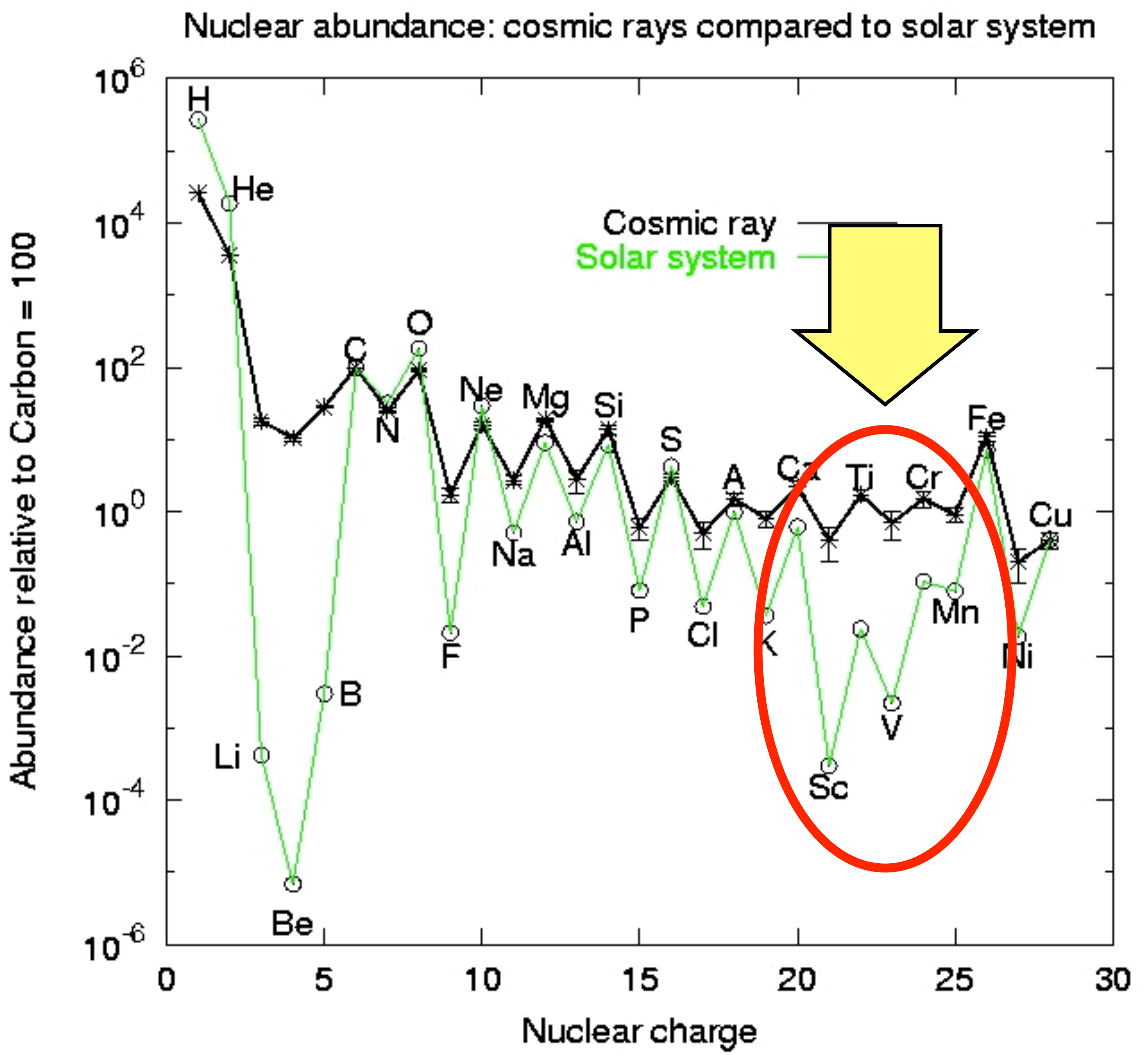

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Cosmic Ray electrons

The CR electron spectrum is more structured (and more difficult to be measured) than the proton one

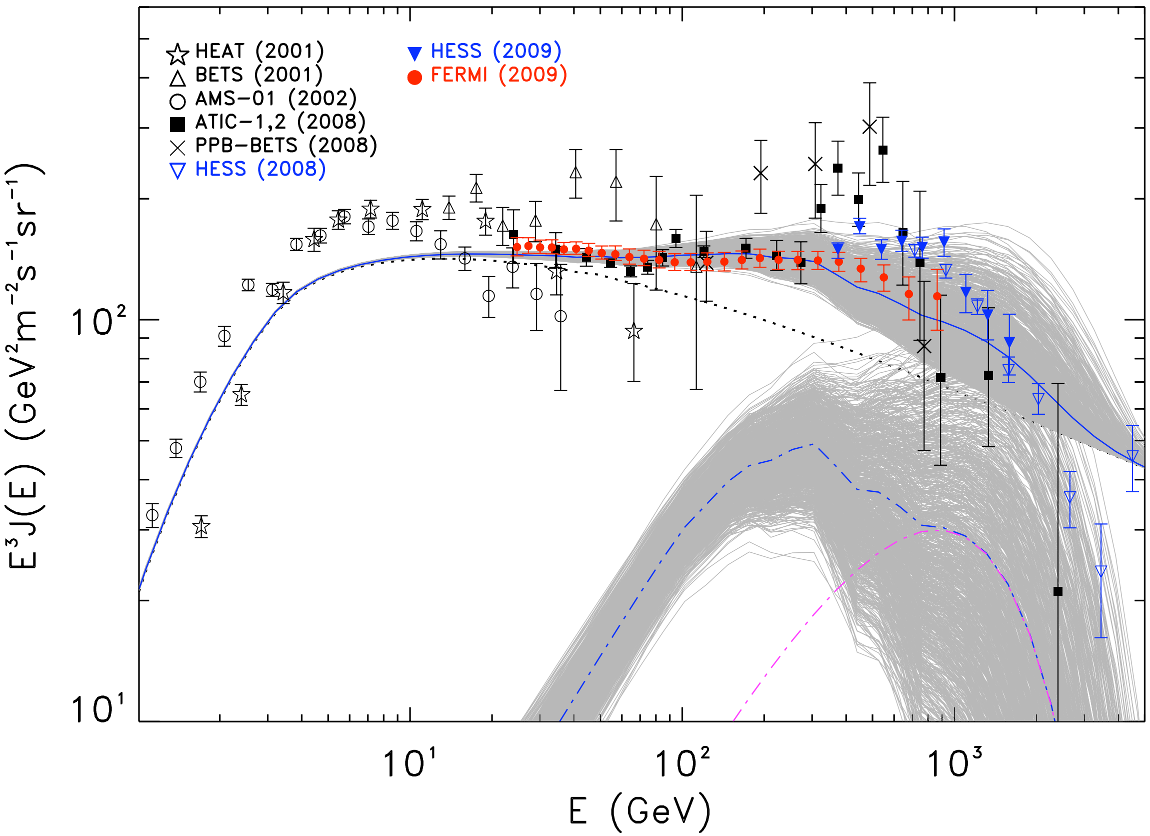

figure from
Grasso et al, 2009

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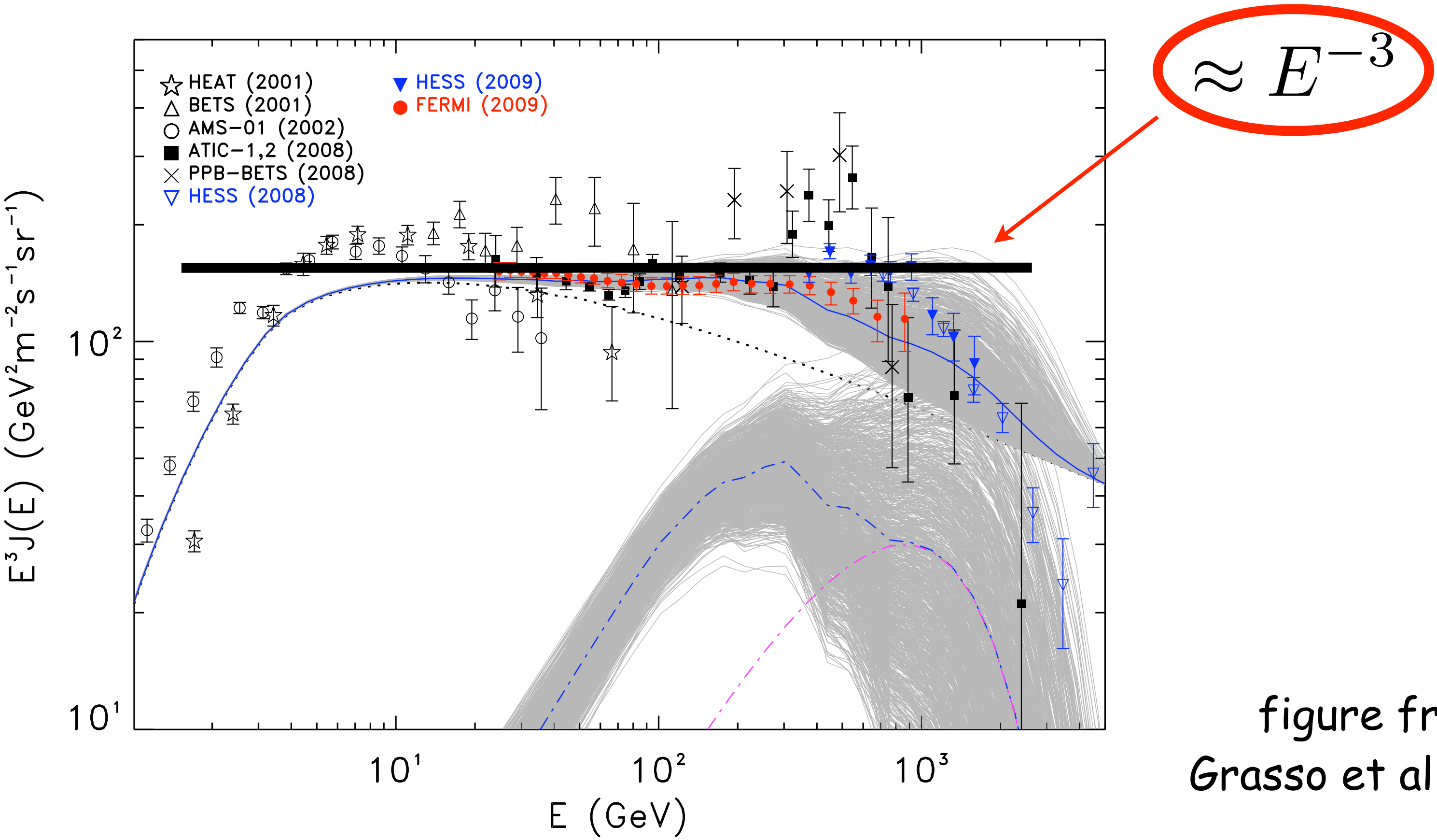

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Cosmic Ray electrons

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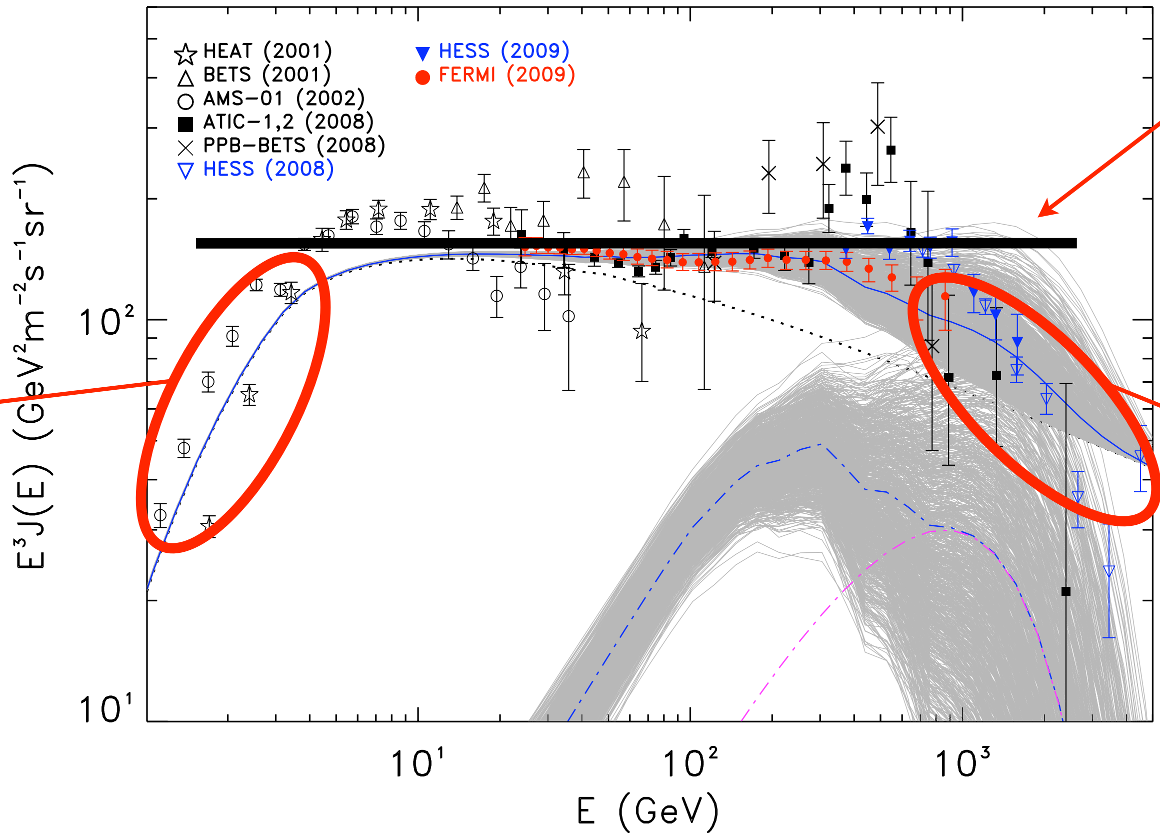
$\approx E^{-3}$

harder



softer

figure from Grasso et al, 2009

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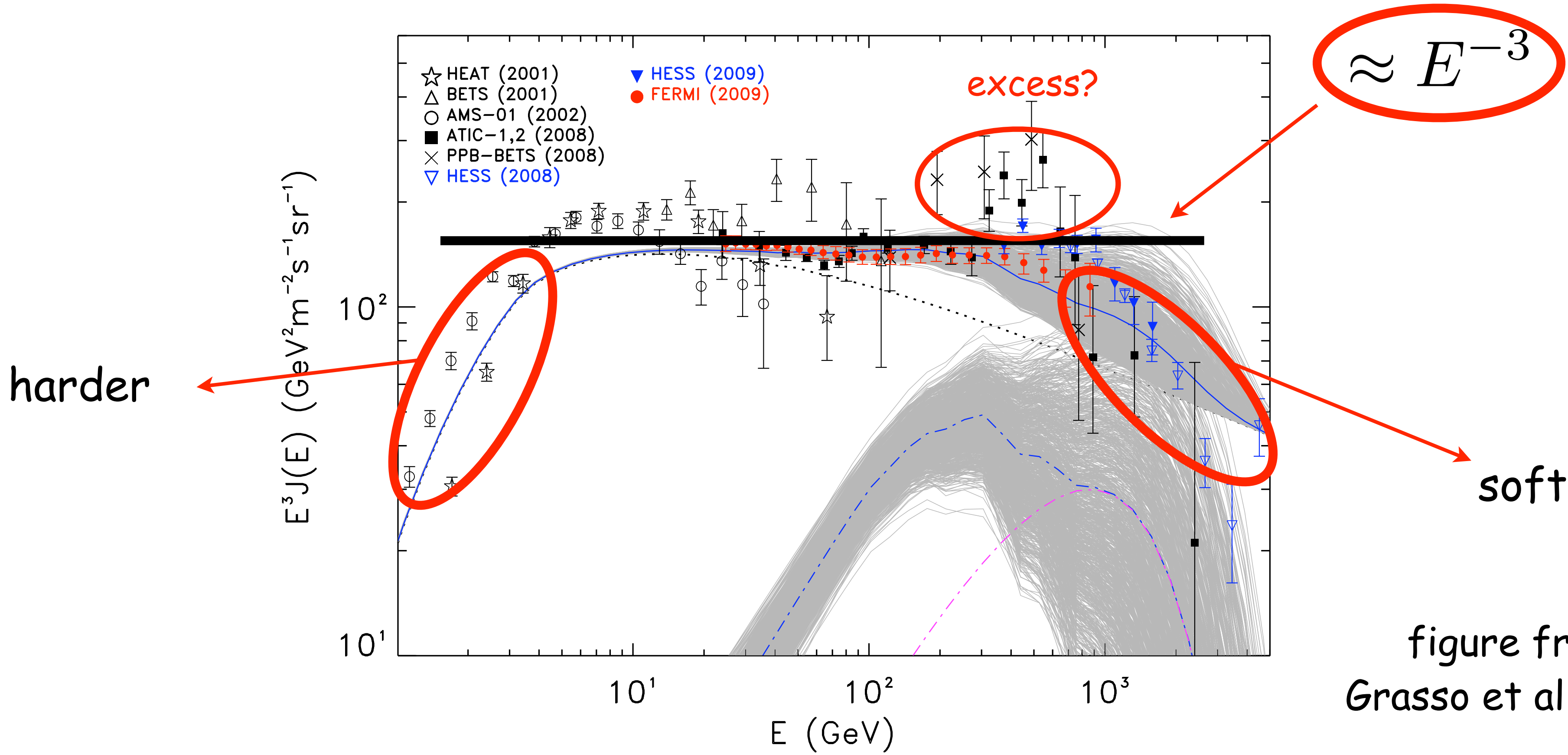

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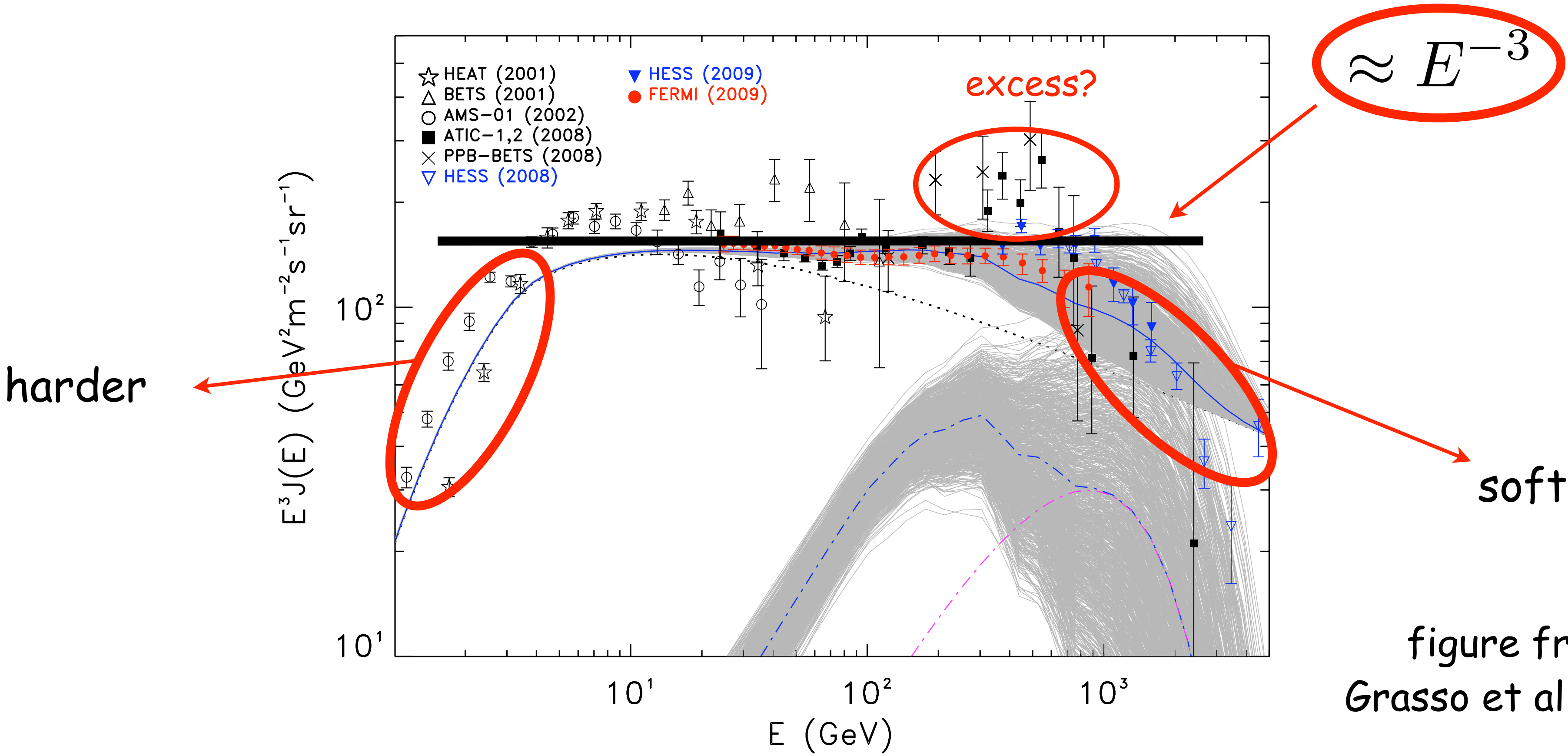

figure from Grasso et al, 2009

@ ~1 GeV --> N_p/N_e ~ 100

Cosmic Ray isotropy

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

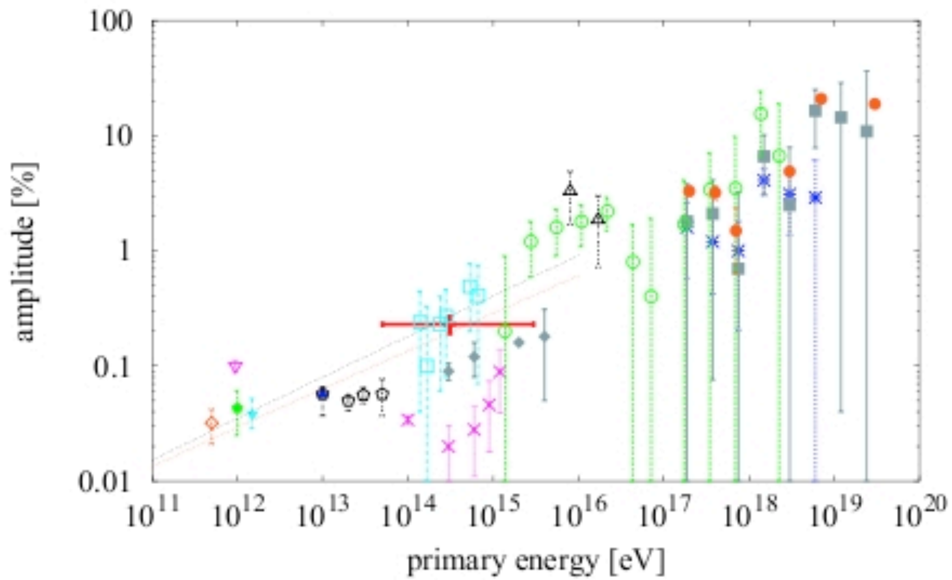

figure from
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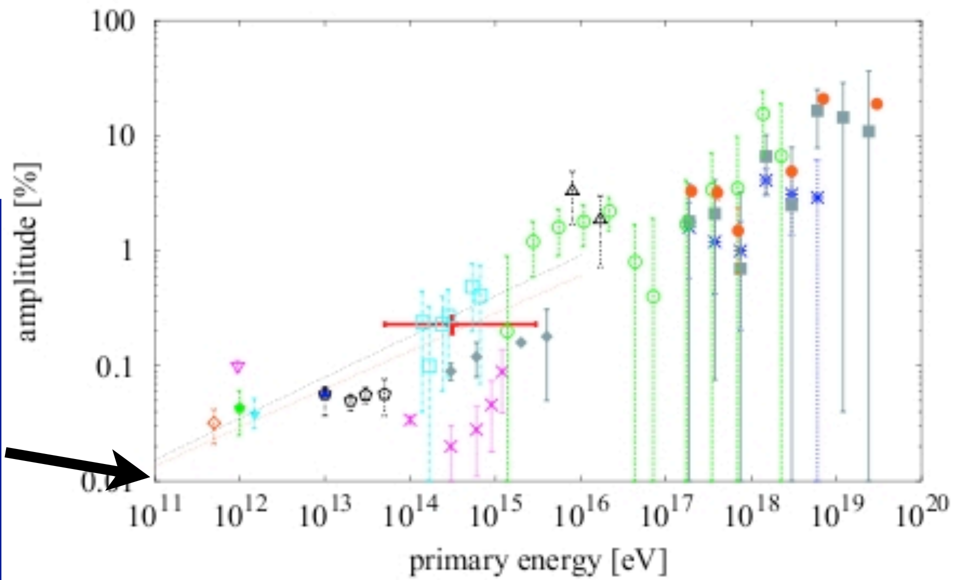
measures available only above ~500 GeV -> magnetic field of the solar system has no effect



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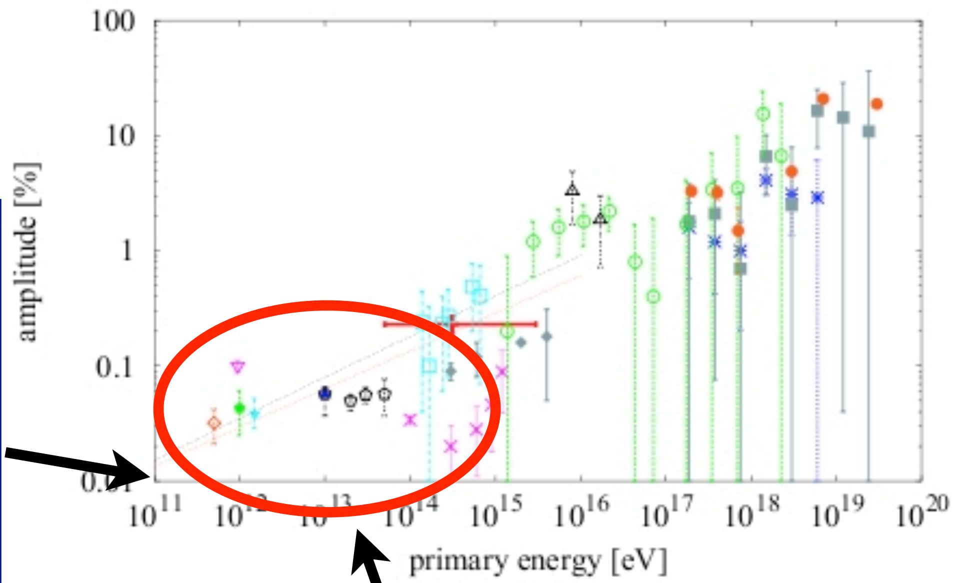

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$\delta \sim 10^{-3}$

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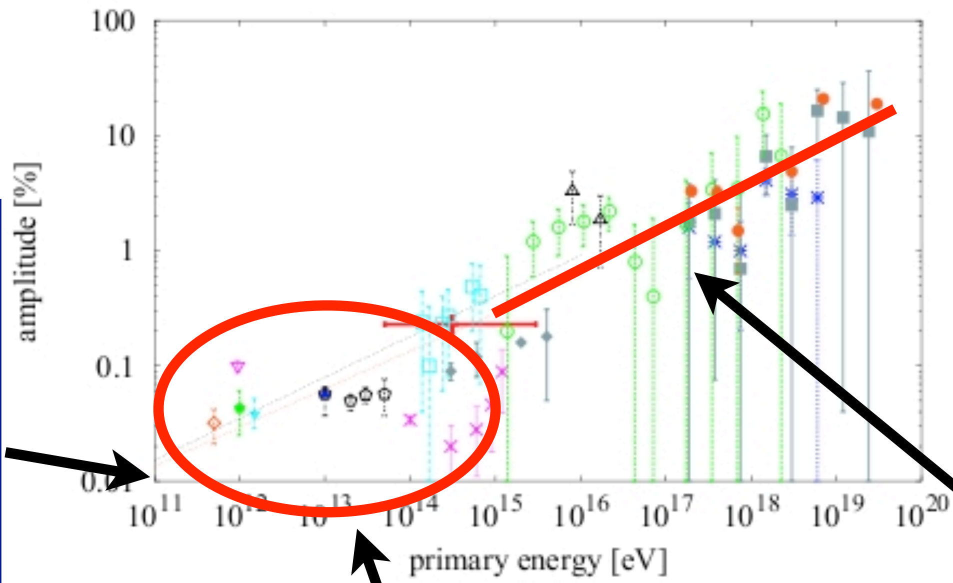

the anisotropy increases with particle energy

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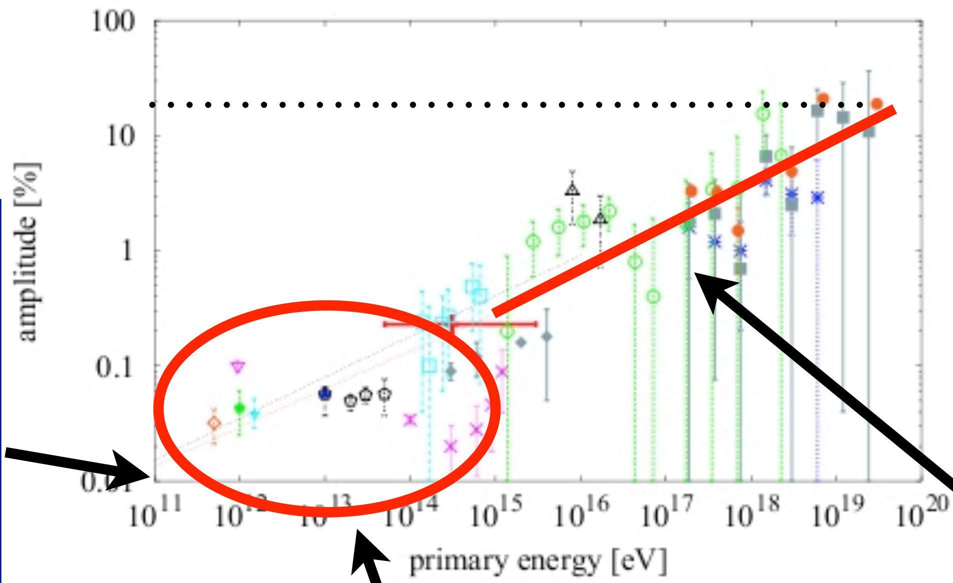


CRs are very isotropic in the sky

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

the anisotropy increases with particle energy

$\delta \sim 10^{-3}$

figure from Iyono et al, 2005

Energy density

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

Energy density

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

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

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

CRs are dynamically important in the Galaxy

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

What we have to explain about CRs:

- Energy density
- Energy spectrum
- Chemical composition
- Isotropy
- Stability in time
- Spatial homogeneity (?)

Cosmic Rays and Gamma-Ray Astronomy

Cosmic Rays undergo hadronic interactions in the InterStellar Medium:

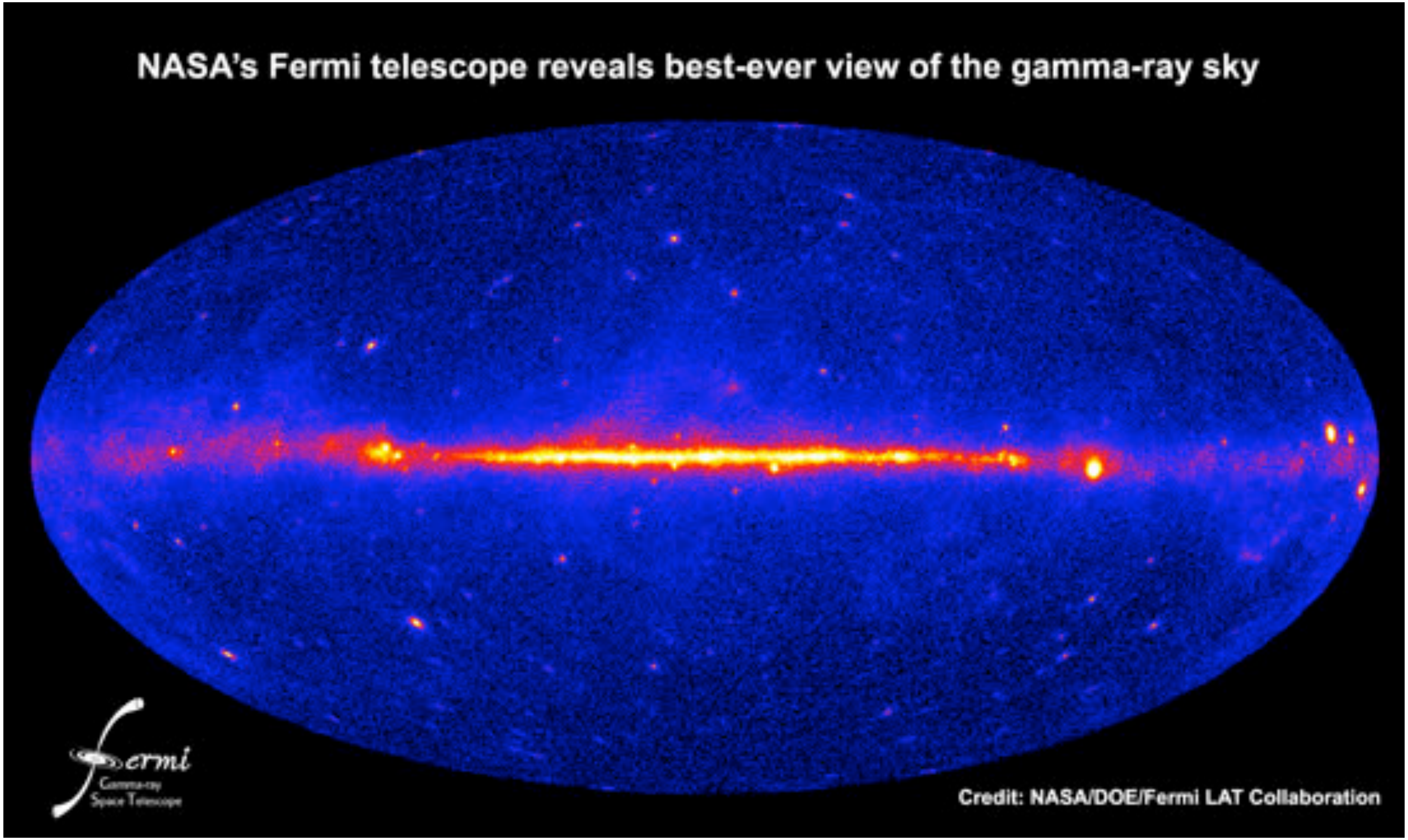
CR ISM

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

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

The gamma ray emission traces the gas distribution (times the CR distribution)

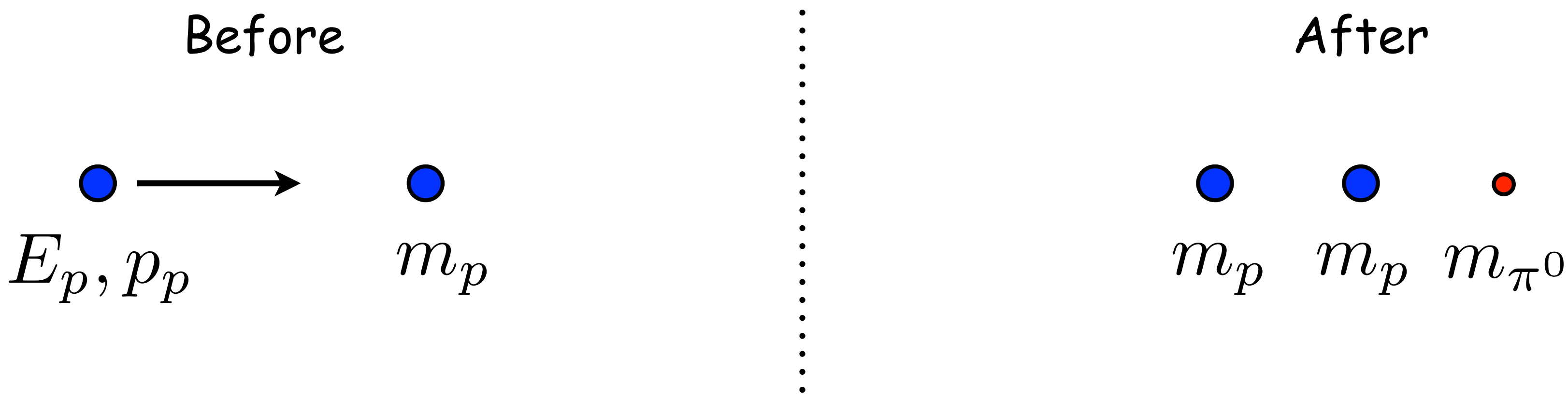
Cosmic Rays and Gamma-Ray Astronomy



Gamma-Ray Astronomy: p-p interactions

Energy threshold for neutral pion production:

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



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

Gamma-Ray Astronomy: p-p interactions

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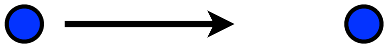
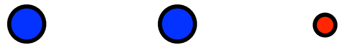
Before



E_p, p_p $\quad$ m_p

After



m_p $\quad$ m_p $\quad$ m_{π^0}

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

Gamma-Ray Astronomy: p-p interactions

Energy threshold for neutral pion production:

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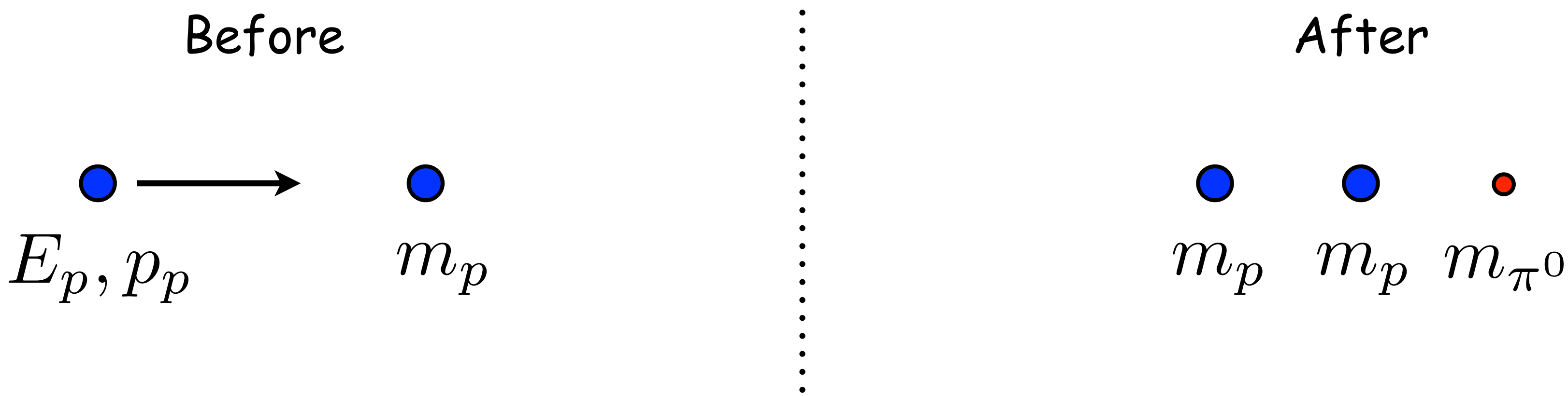

$$\left(E_p + m_p c^2\right)^2 - p_p^2 c^2 = E^2 - p^2 c^2 = \left(2 m_p c^2 + m_{\pi^0} c^2\right)^2$$

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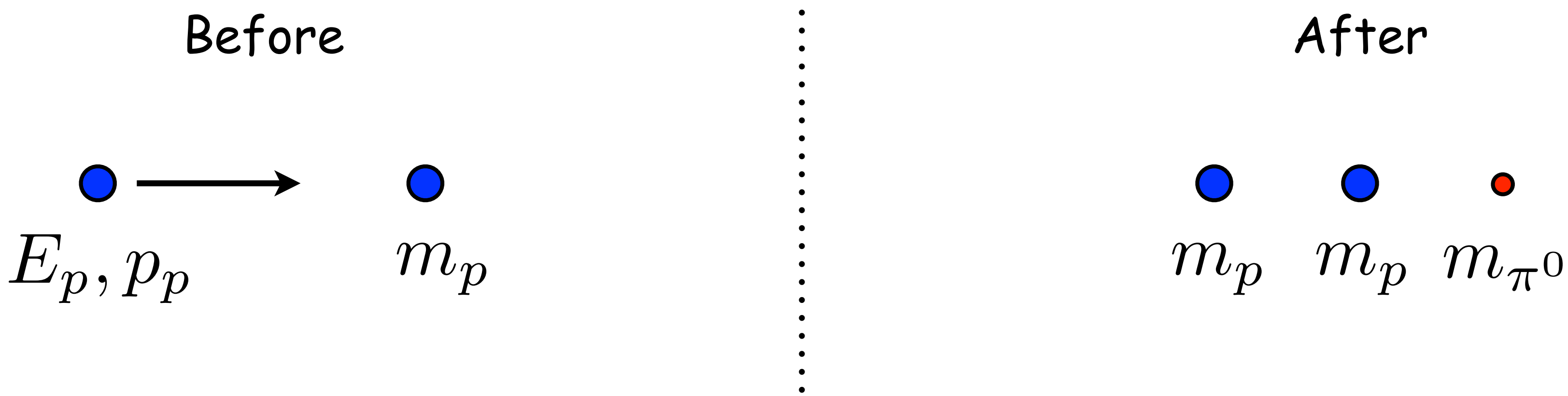

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$$E_p - m_p c^2 > 2m_{\pi^0} c^2 + \left(\frac{m_{\pi^0}}{2m_p}\right) m_{\pi^0} c^2 \approx 280 \text{ MeV}$$

CRs produce gammas

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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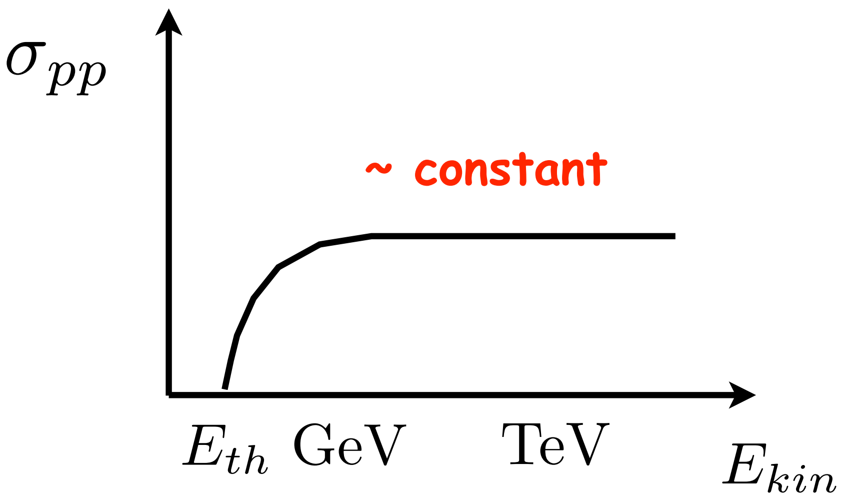

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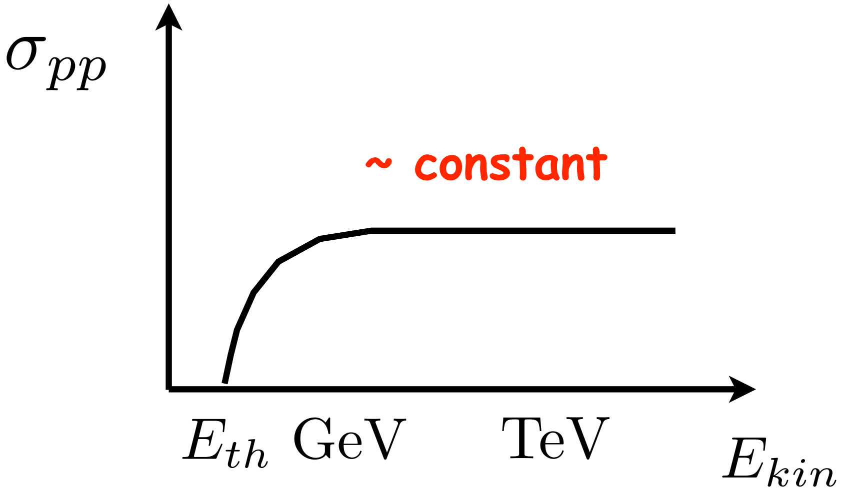

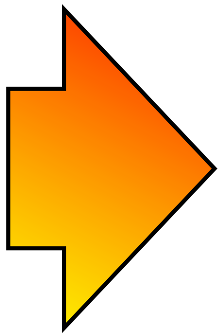

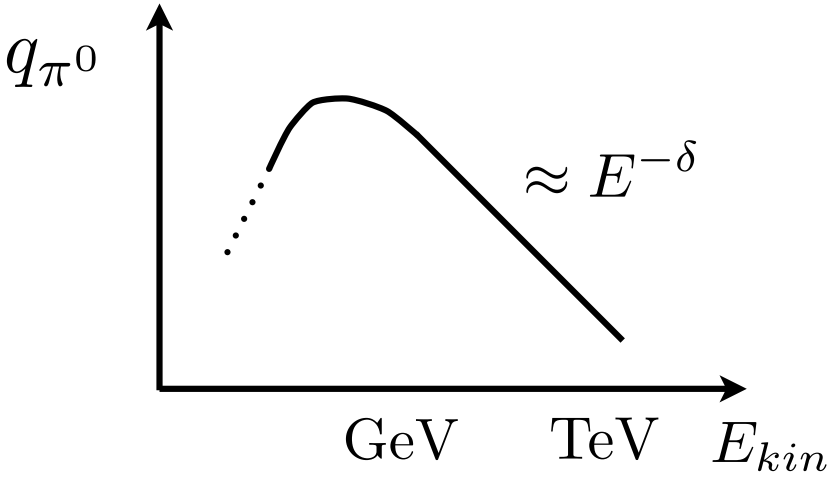

Gamma-Ray Astronomy: p-p interactions

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

Gamma-Ray Astronomy: p-p interactions

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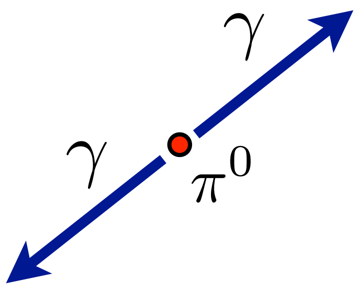
Pion rest frame:



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

Gamma-Ray Astronomy: p-p interactions

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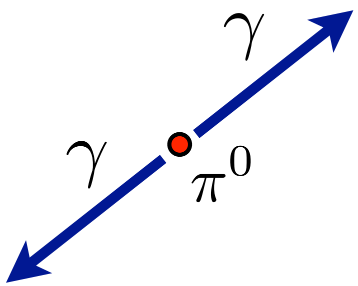

$$E_\gamma^* = \frac{m_{\pi^0}}{2}$$

Lab frame:

$$E_\gamma = \gamma \left(E_\gamma^* + v p_\gamma^* \cos\theta^* \right)$$

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

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

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

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

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

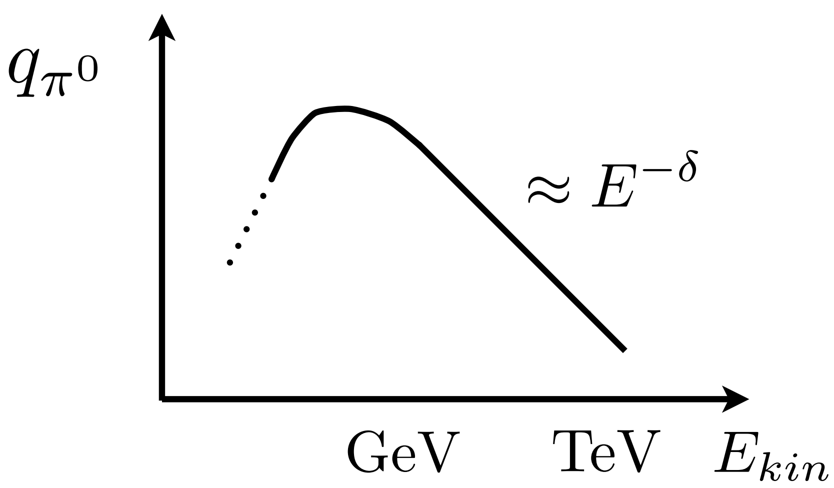
$$E_\gamma = \gamma\left(E_\gamma^* + v p_\gamma^* \cos\theta^*\right) \rightarrow \mathrm{d}E_\gamma \propto \mathrm{d}(\cos\theta^*)$$

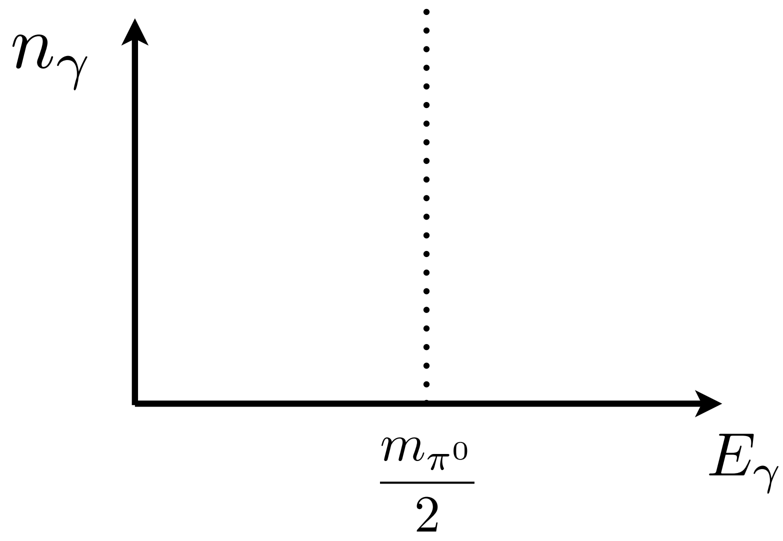
$$\Rightarrow \quad \frac{\mathrm{d}n_\gamma}{\mathrm{d}E_\gamma} = const$$

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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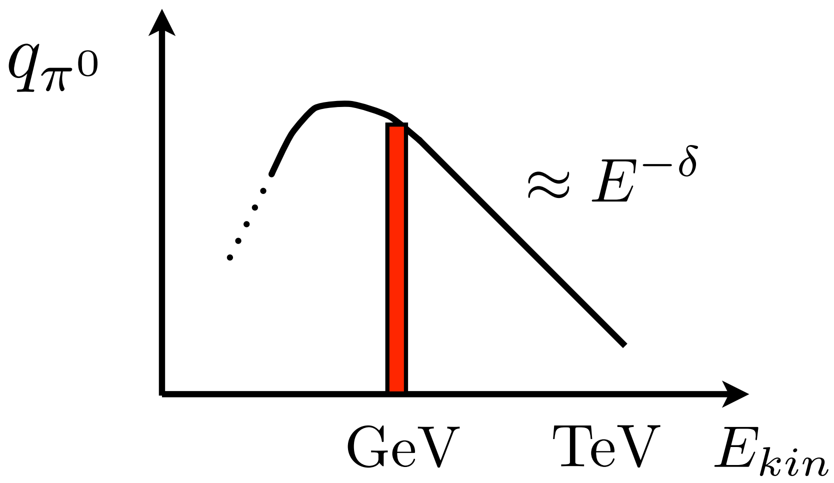

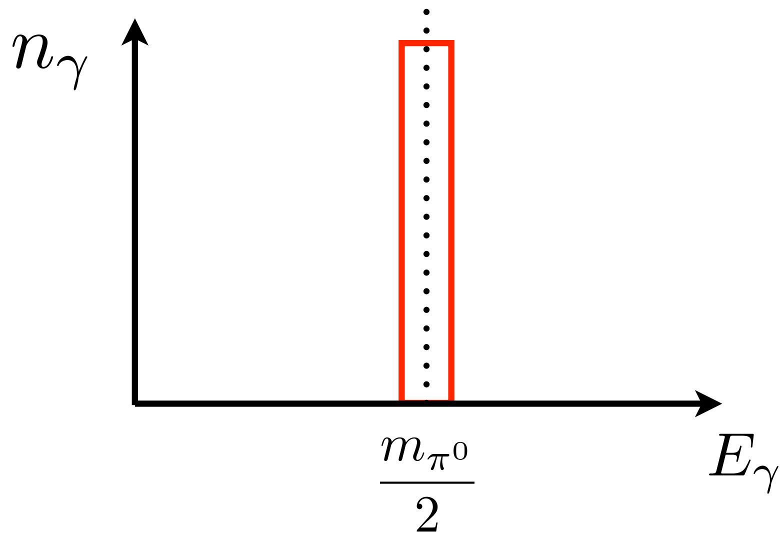

Gamma-Ray Astronomy: p-p interactions

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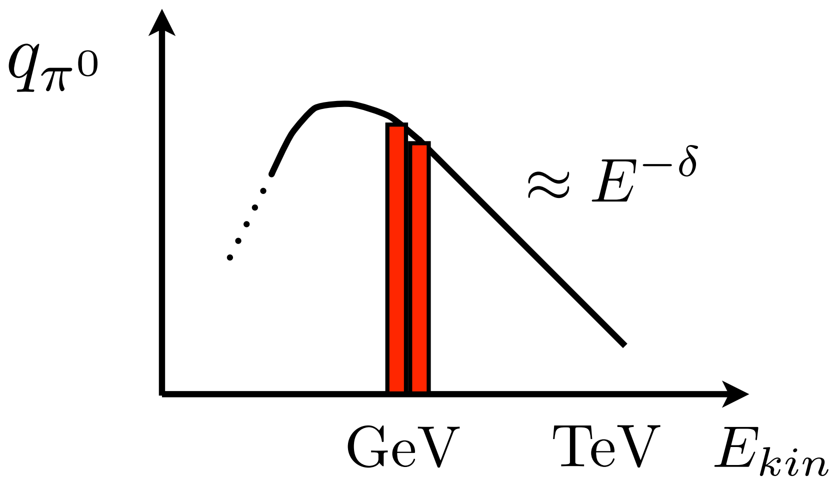

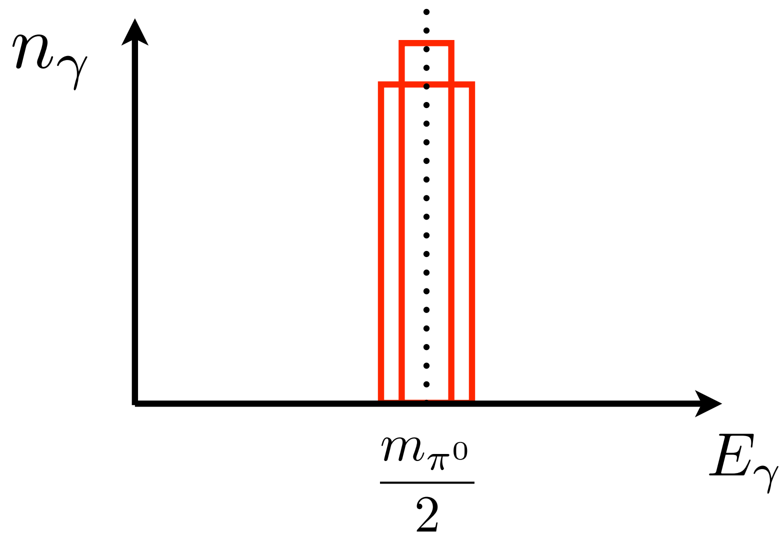

Gamma-Ray Astronomy: p-p interactions

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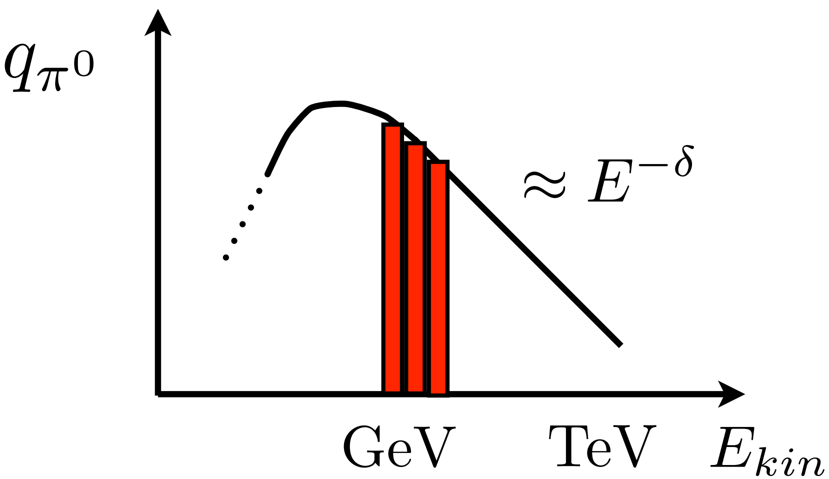

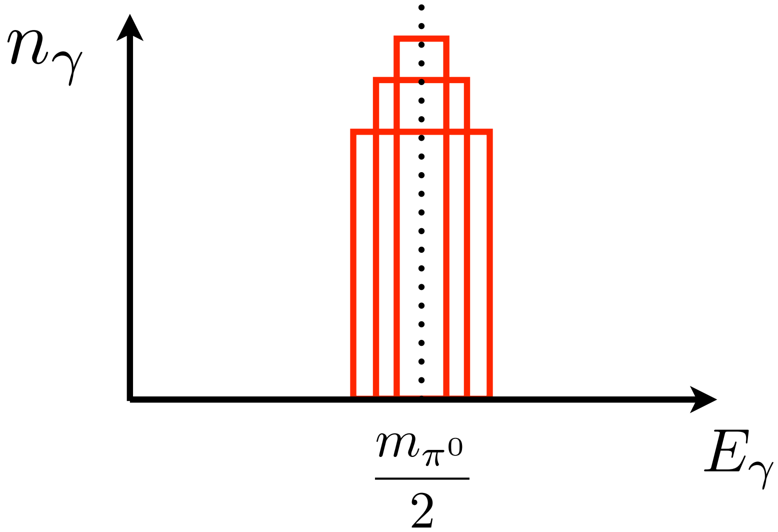

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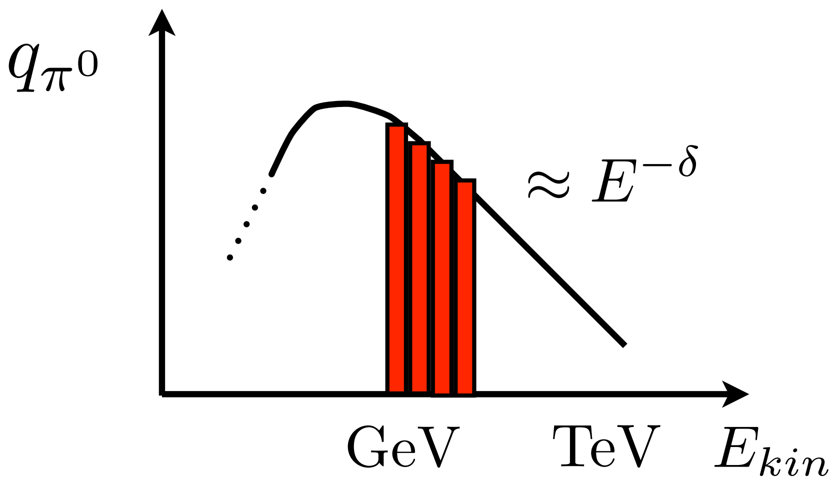

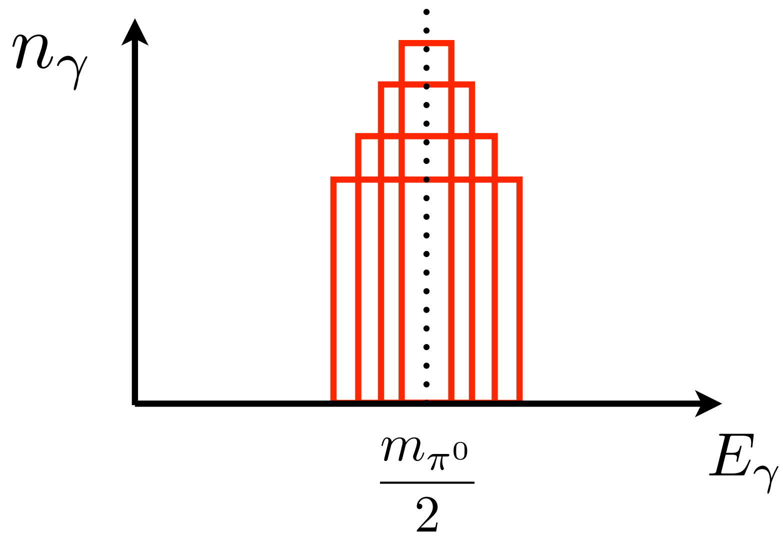

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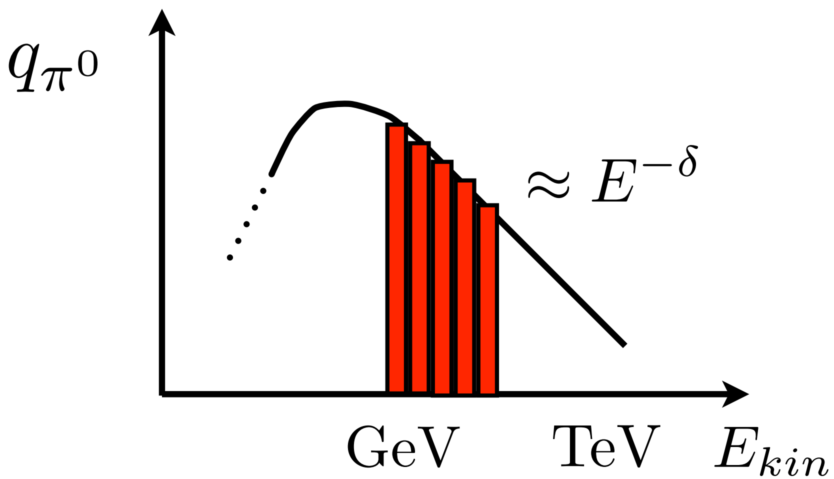
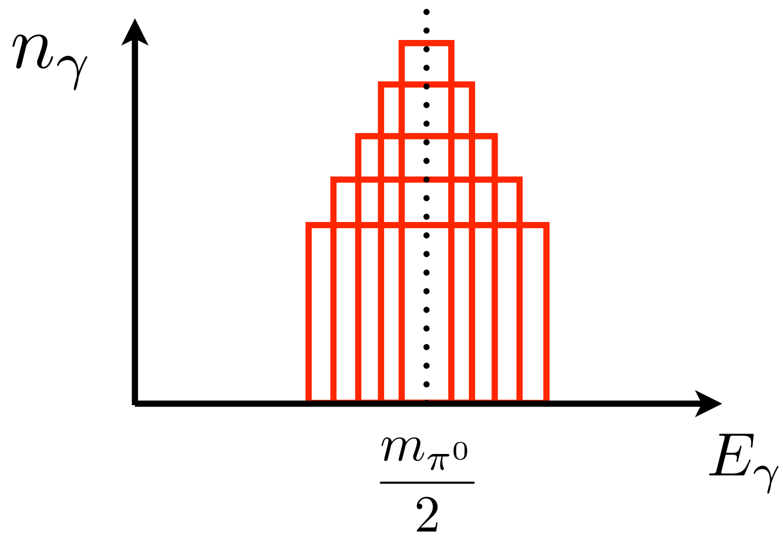
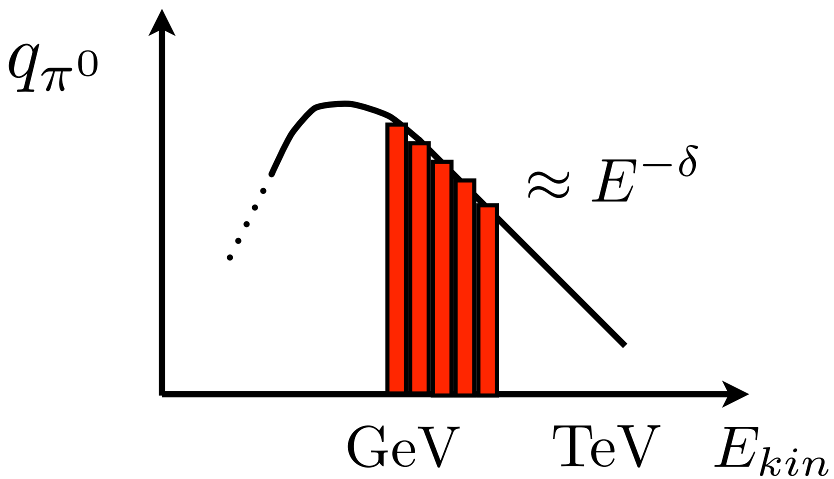
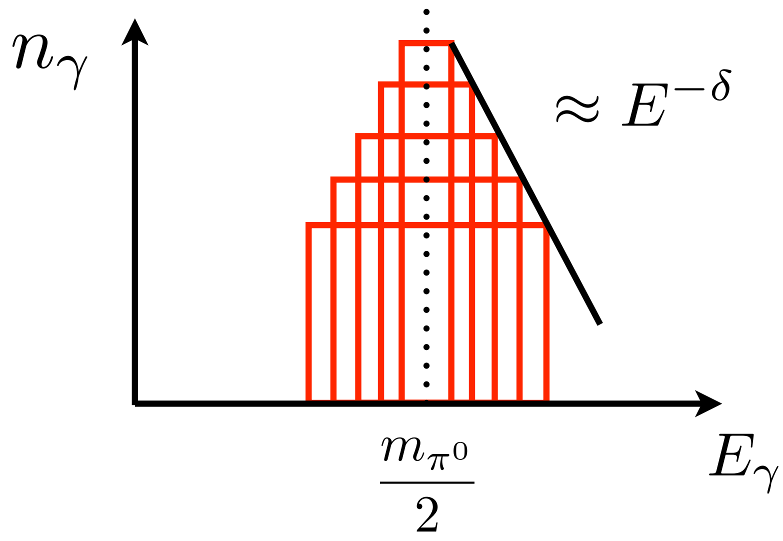




Gamma-Ray Astronomy: p-p interactions

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





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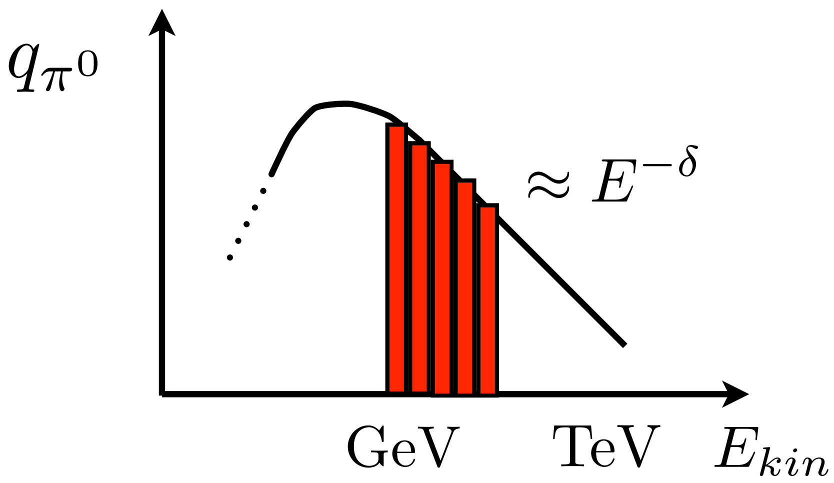

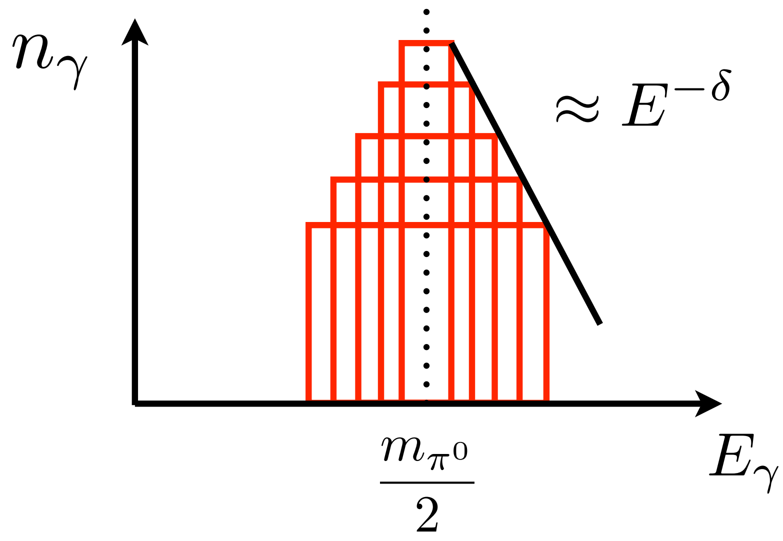

- the gamma ray spectrum is symmetric (in log-log) with respect to: $\frac{m_{\pi^0}}{2} \sim 70\ \mathrm{MeV}$

- at high energy the spectrum mimic the CR spectrum, with (roughly): $E_\gamma \approx \frac{E_{CR}}{10}$

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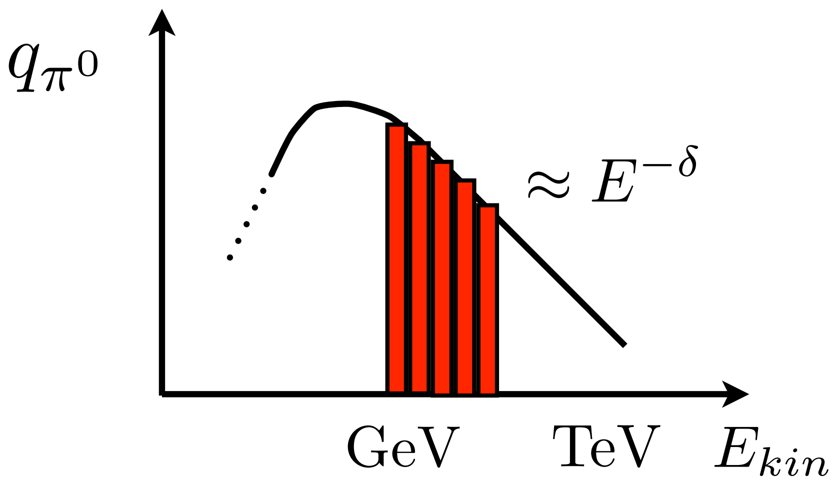

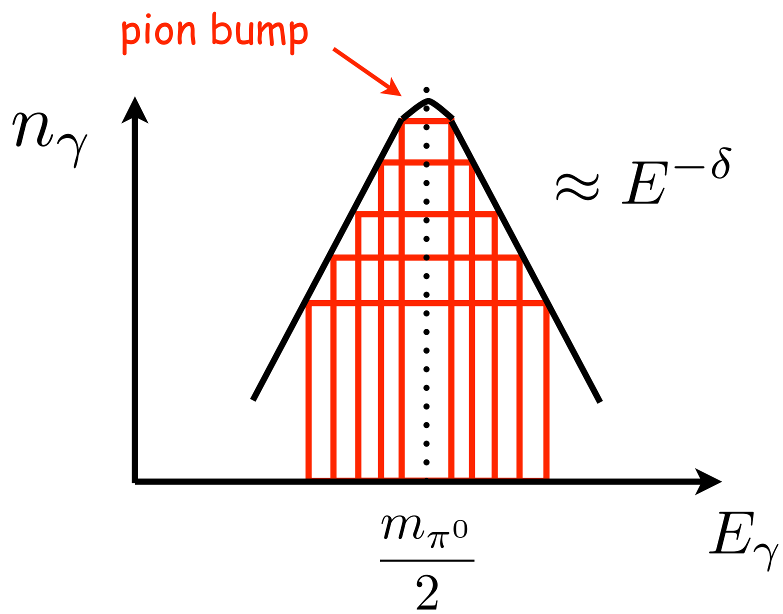

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Detectability condition for a Cherenkov Telescope

HESS sensitivity: $F^{min}_{HESS}(> 1\ \mathrm{TeV}) \approx 10^{-12}\mathrm{ph\ cm^{-2}s^{-1}} \ \rightarrow\ 2\times 10^{-12}\mathrm{erg/cm^2/s}$

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p-p energy loss time

fraction of CR energy transferred to photon

which corresponds to a CR total energy: $W_{CR} \;=\; t_{pp}\; c^{-1}_{p\rightarrow\gamma}\; L^{min}_{HESS} \;=$

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inelasticity

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$$= \left(\frac{10^{15}}{n_{gas}}\ \mathrm{s}\right)\ (10)\ \left(2\times 10^{32} d^2_{kpc}\mathrm{erg/s}\right) = 2\times 10^{48}\ n^{-1}_{gas}\ d^2_{kpc}\ \mathrm{erg}$$

Gamma-Ray Astronomy: p-p interactions

SUMMARY:

- 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 mimics the CR spectrum, with (roughly): $E_\gamma \approx \frac{E_{CR}}{10}$
- detectability condition: $\boxed{W_{CR} \;>\; 2 \times 10^{48} \; n_{gas}^{-1} \; d_{kpc}^2 \text{ erg}}$

above ~ 10 TeV

Gamma-Ray Astronomy: p-p interactions

Secondary electrons and positrons:

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

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$$\left\{ \begin{array}{c} \pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \\ \\ \mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e) \end{array} \right.$$

Gamma-Ray Astronomy: p-p interactions

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

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

Production of gamma rays in the Galaxy

(1) proton-proton interactions: $(\alpha = \delta)$

CR proton spectrum: $N_{CR} \propto E^{-2.7}$ ⇨ gamma ray spectrum: $q_\gamma \propto E^{-2.7}$

(plus the pion bump at ~70 MeV)

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(3) relativistic Bremsstrahlung: $(\alpha = \delta)$

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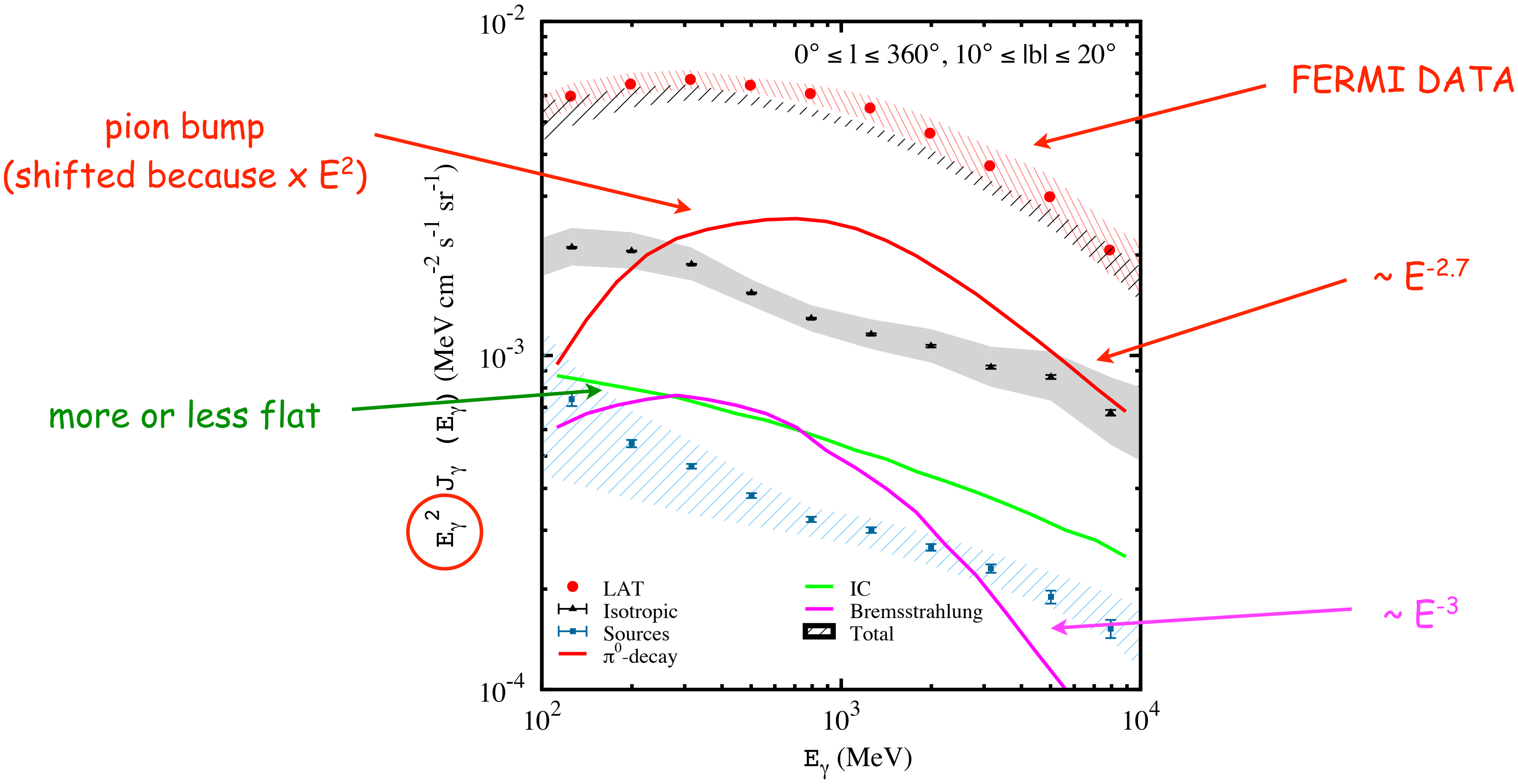
The gamma ray emission from the Galaxy

FERMI observation of the galactic diffuse emission



p-p interactions dominate the diffuse emission

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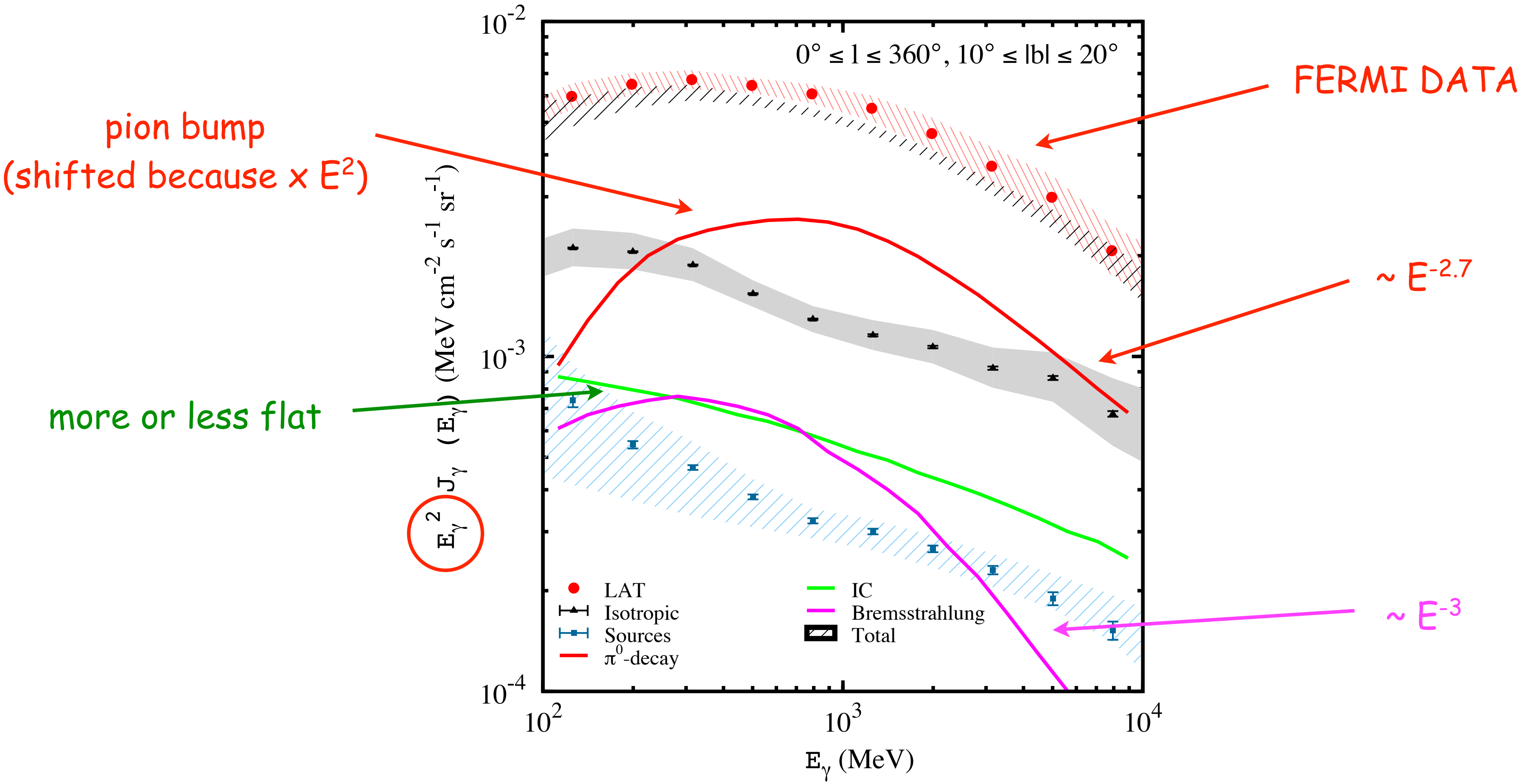

CRs quite homogeneous in the Galaxy!

Take-home message

- We have plenty of data on CRs but we still don't know where they are from;
- A connection exists between CR physics and Gamma Ray Astronomy because CRs produce gamma rays in interactions with matter and radiation fields;
- What we know about CRs seems to explain fairly well the gamma ray diffuse emission we observe from the Milky Way.