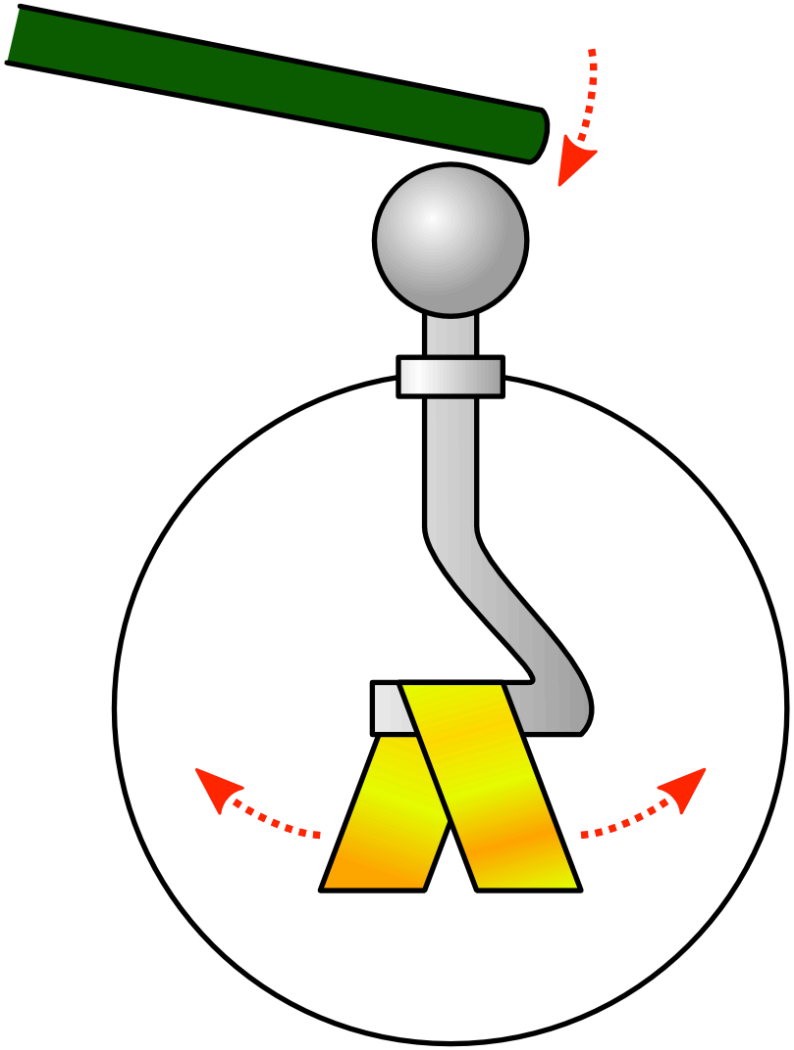
Cosmic Rays and Gamma Rays in the InterStellar Medium

www.cnrs.fr

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 baloon 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

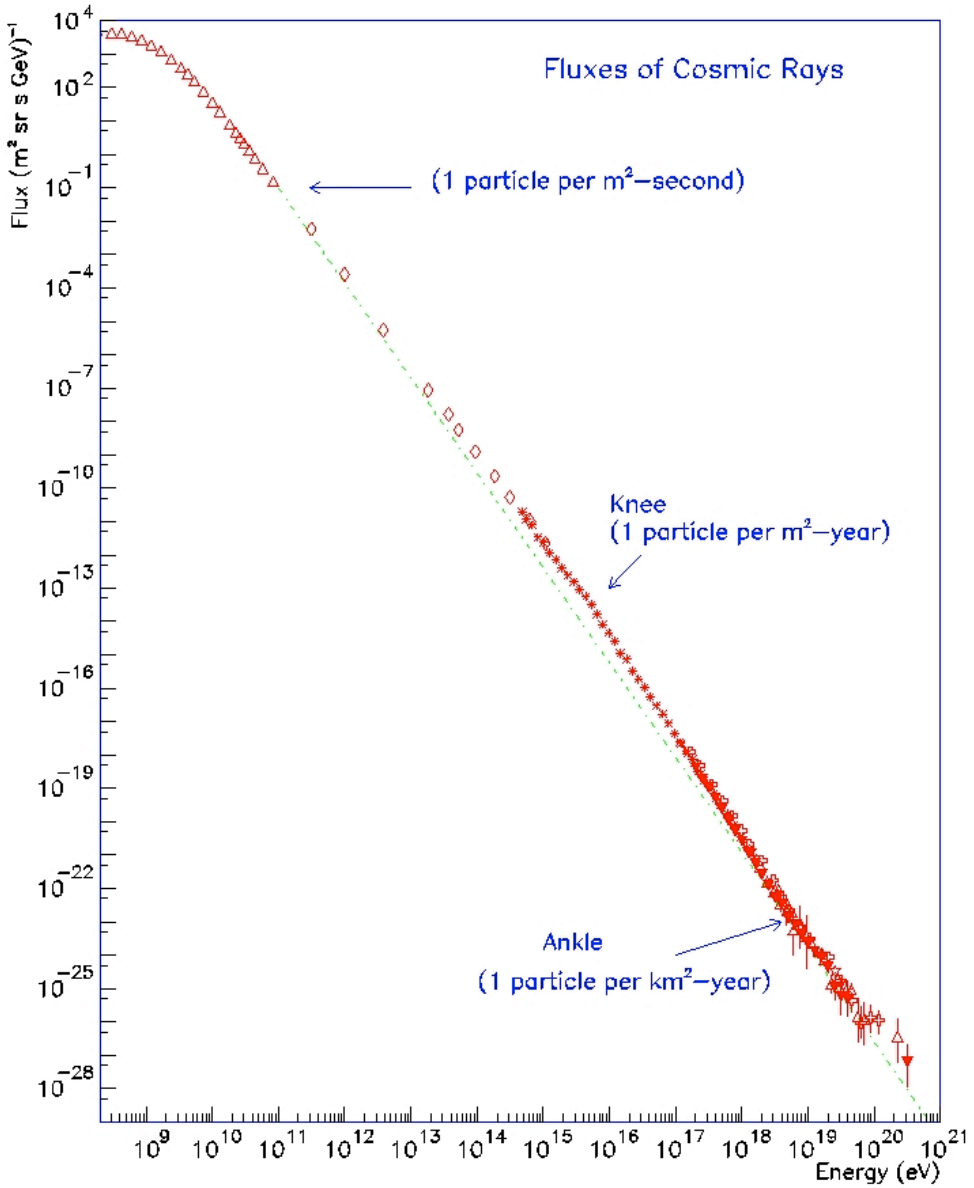
What are Cosmic Rays?

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?"**.

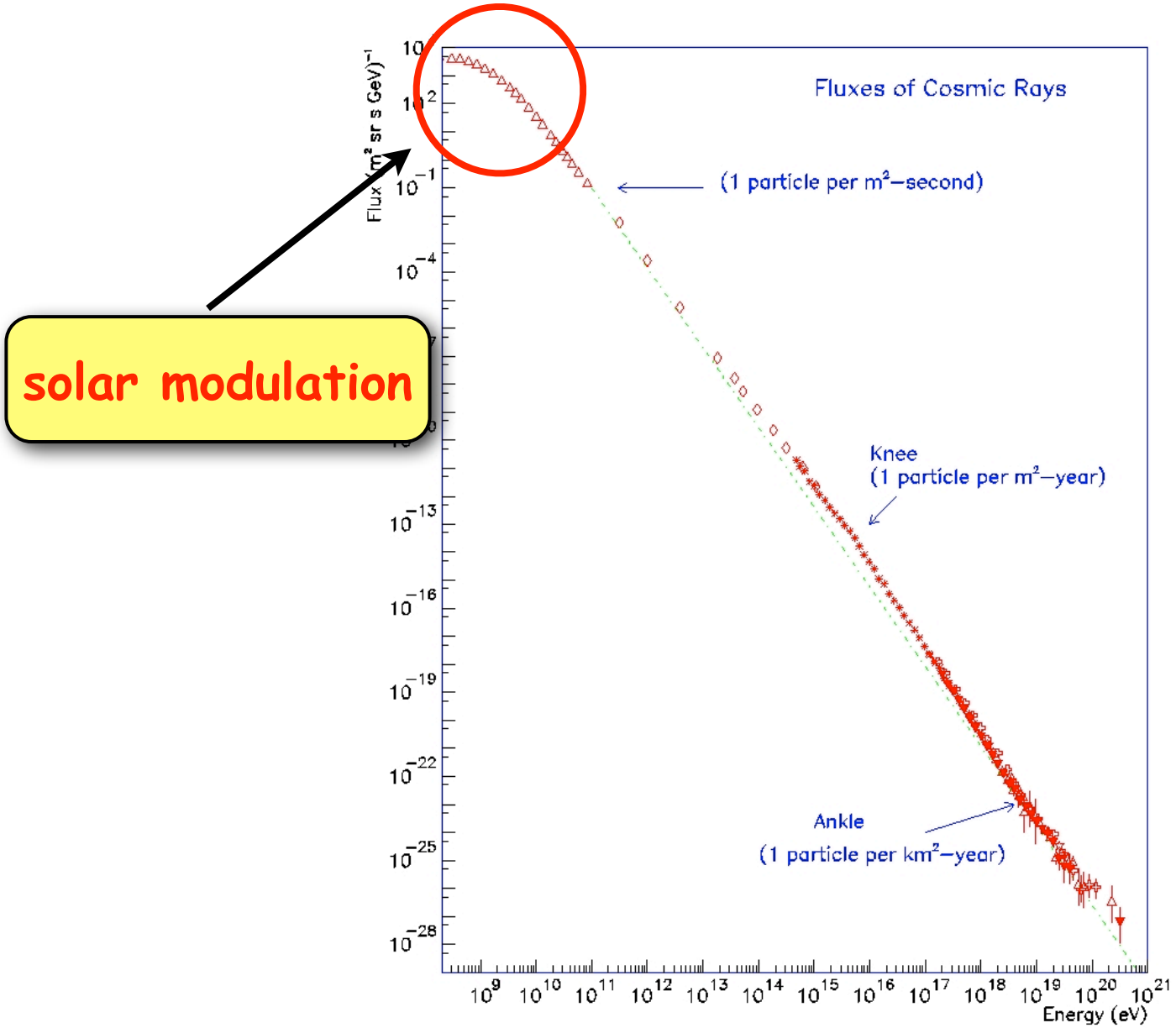
T. Gaisser "Cosmic Rays and Particle Physics"

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

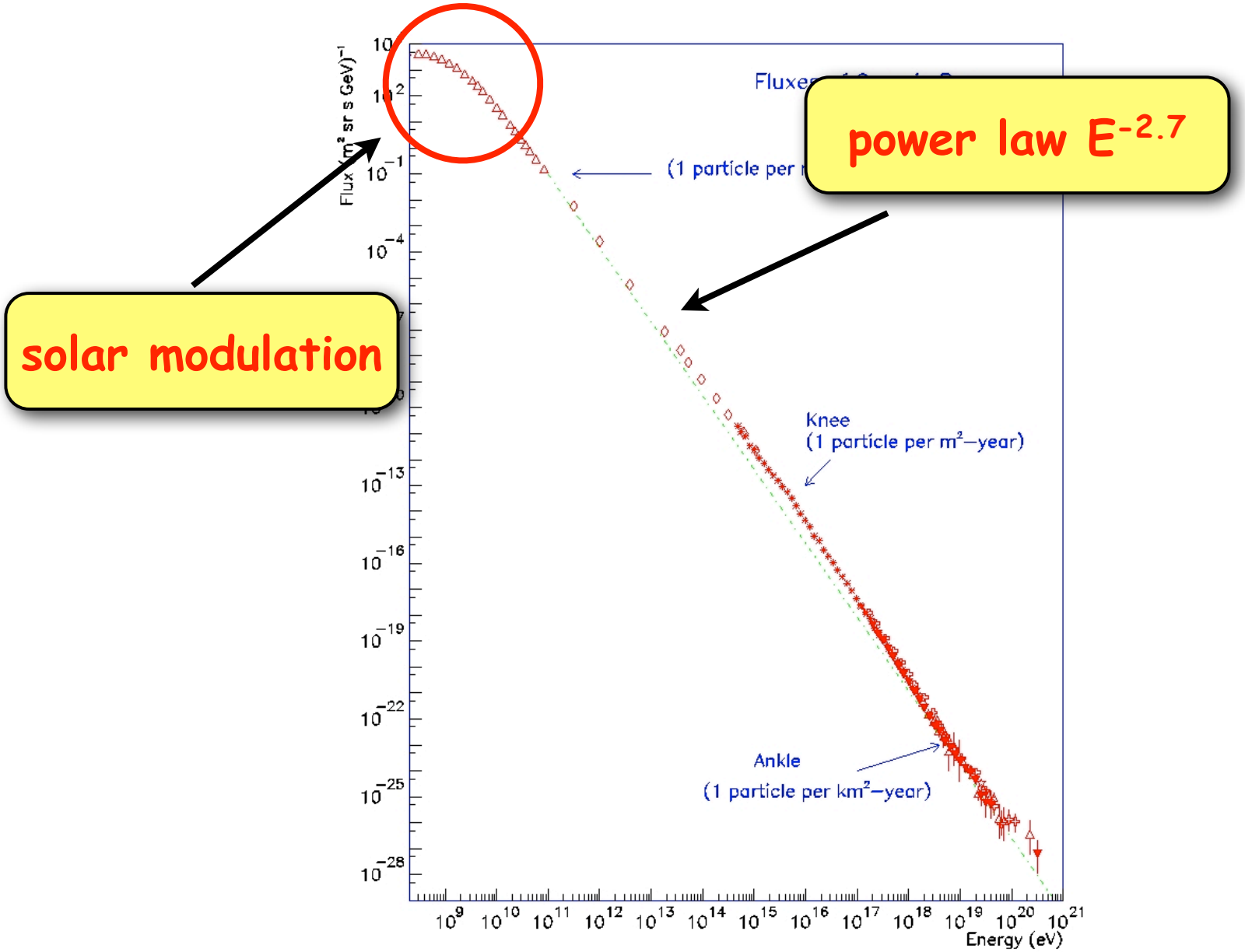
The (local) Cosmic Ray spectrum



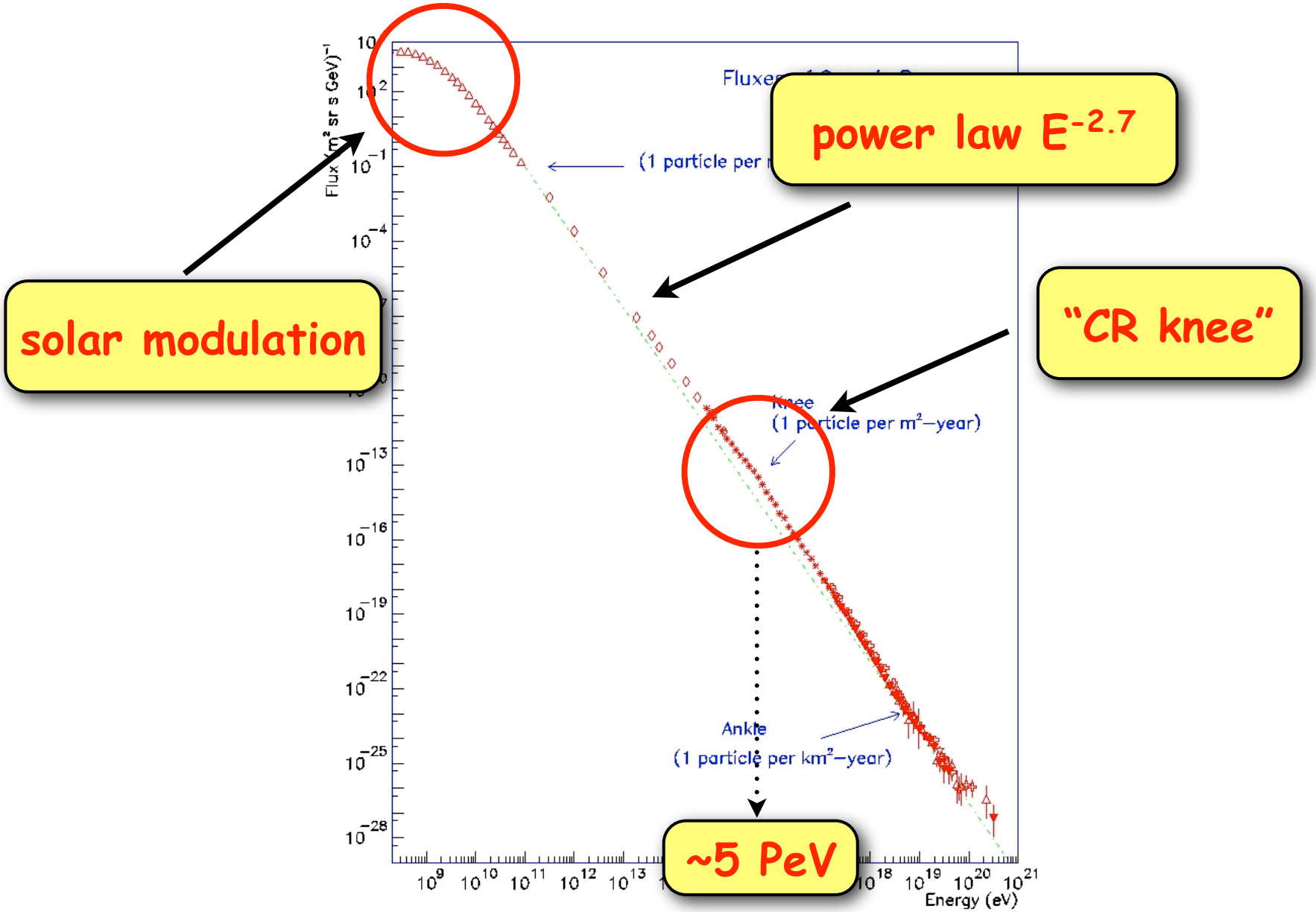
The (local) Cosmic Ray spectrum



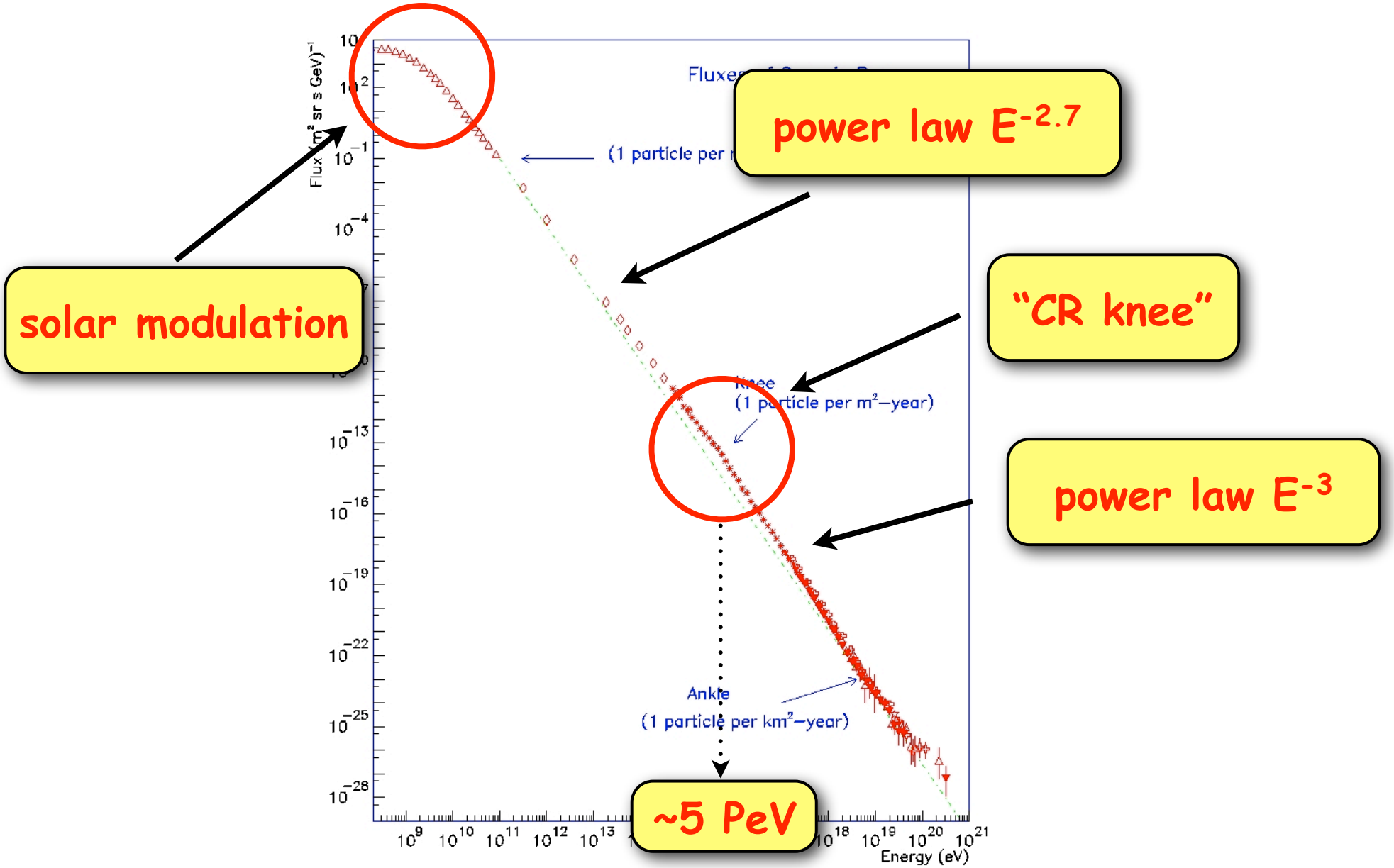
The (local) Cosmic Ray spectrum



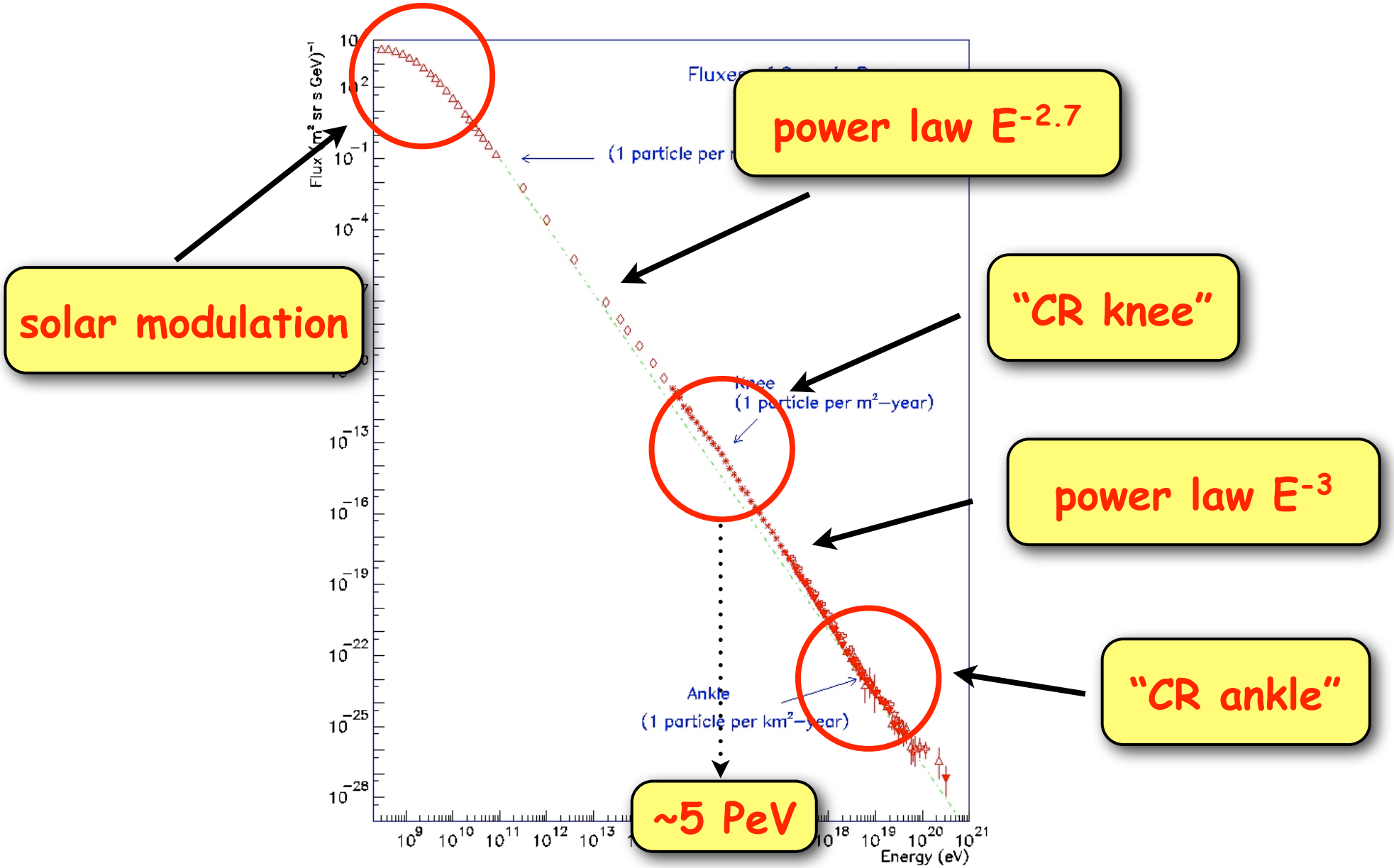
The (local) Cosmic Ray spectrum



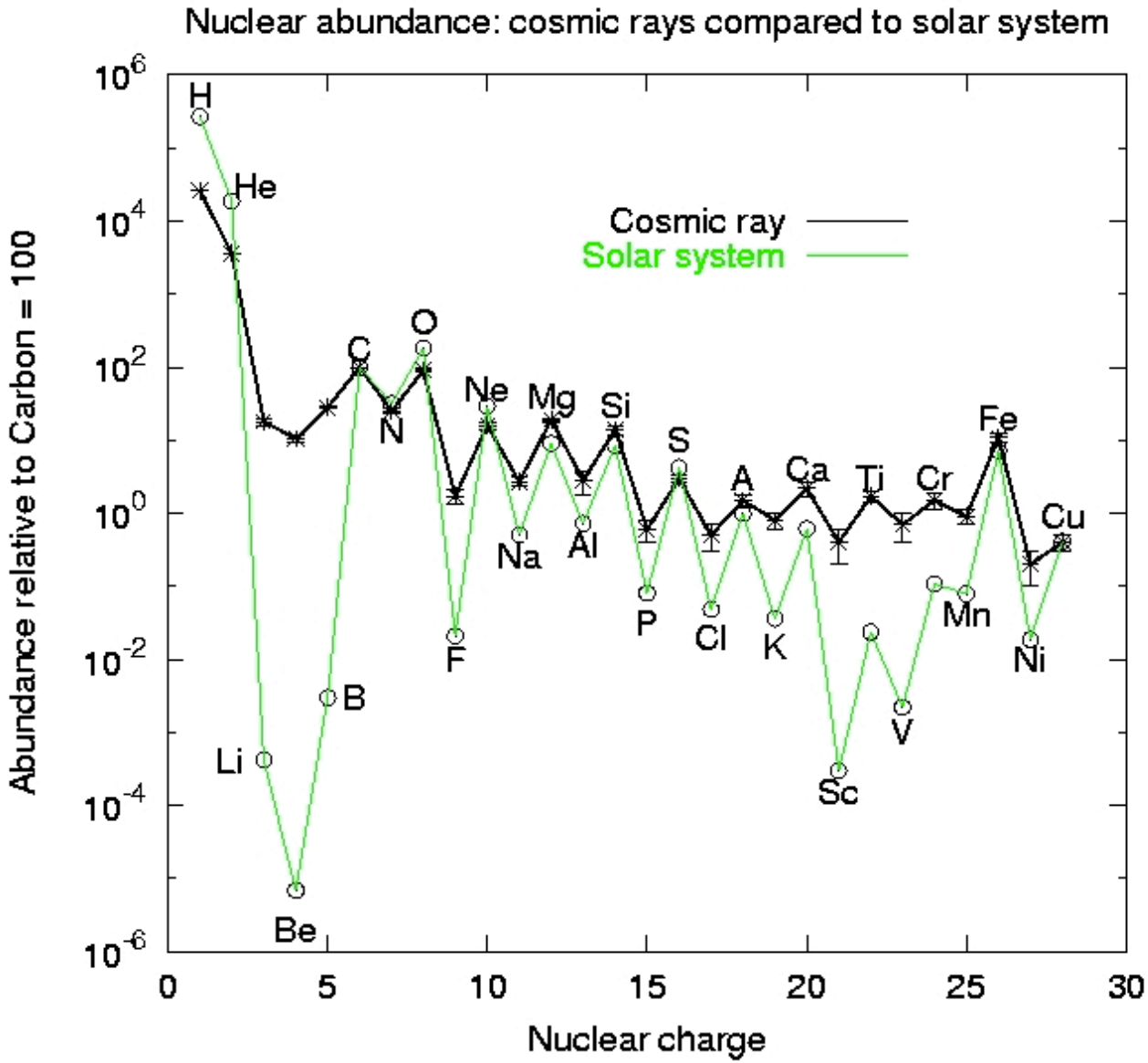
The (local) Cosmic Ray spectrum



The (local) Cosmic Ray spectrum

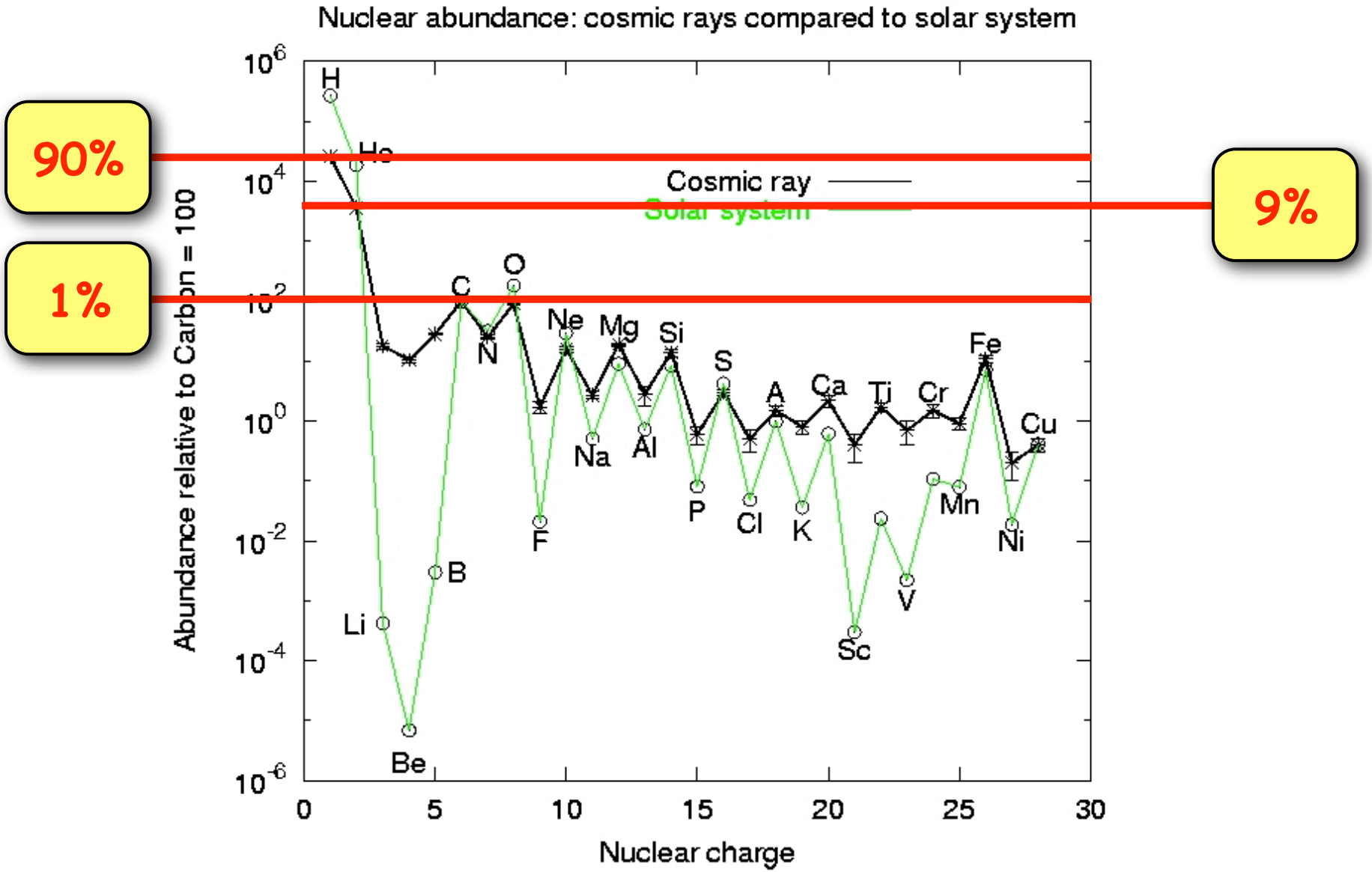


Cosmic Ray composition



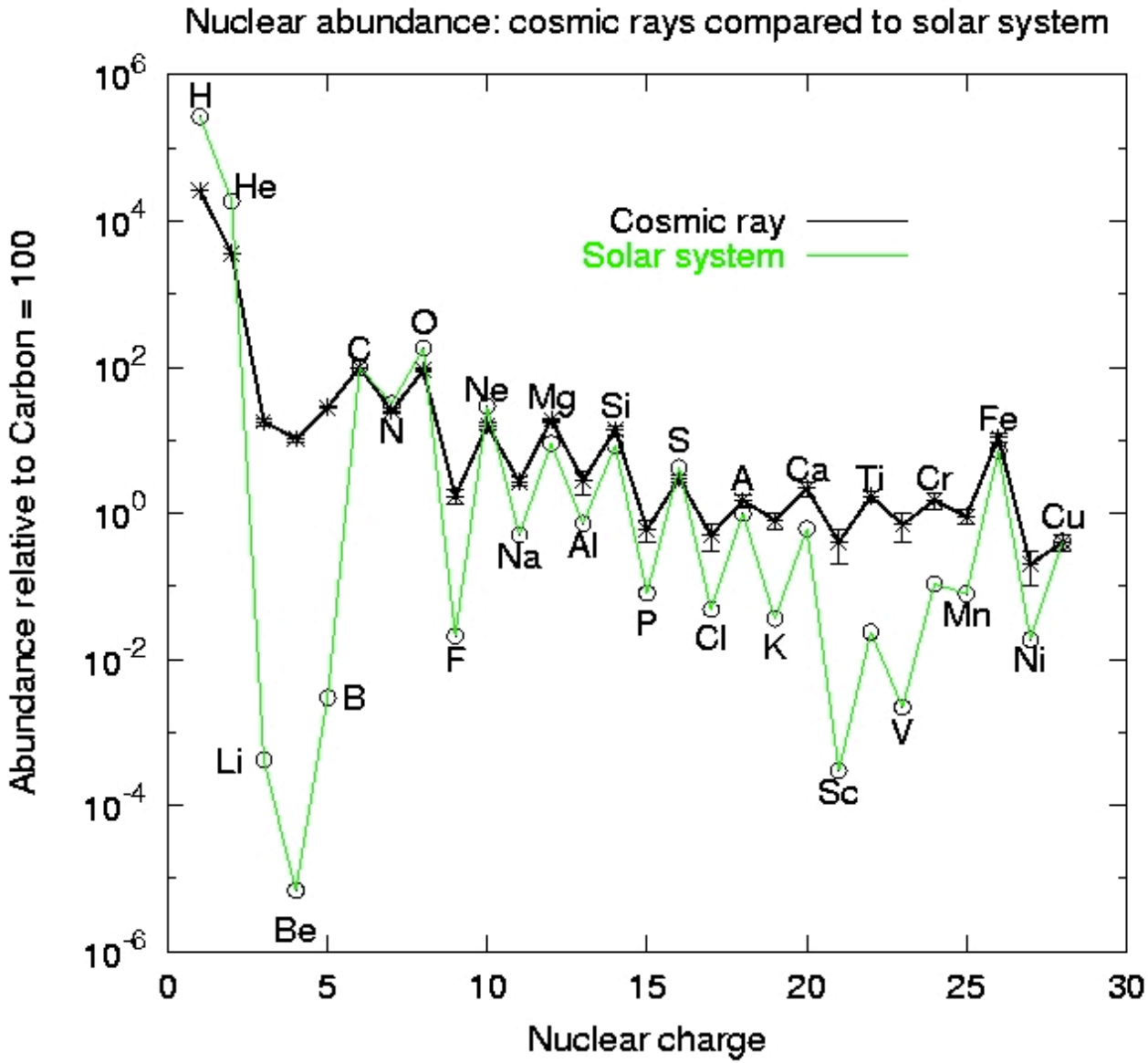
Gaisser & Stanev, 2005

Cosmic Ray composition



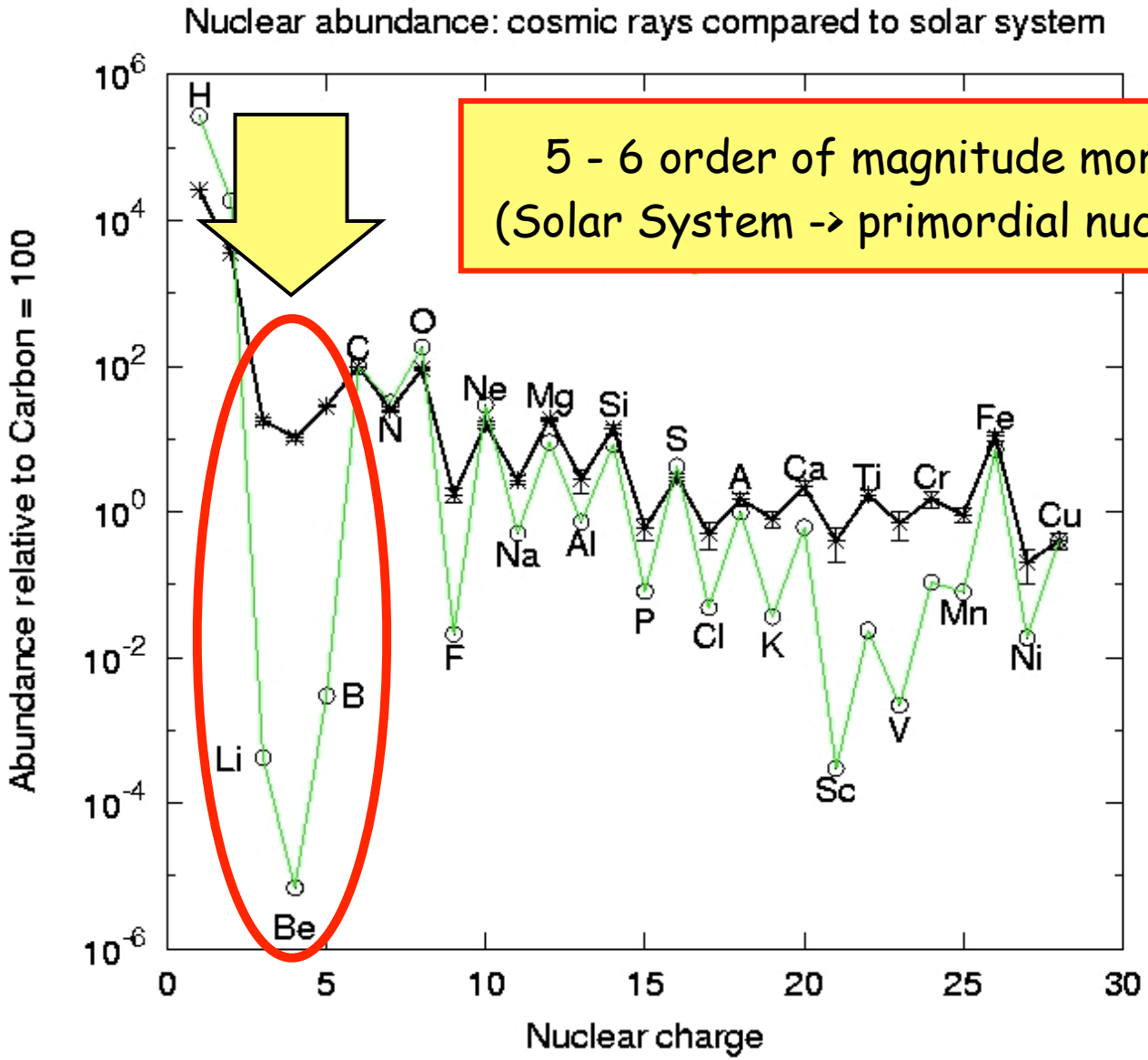
Gaisser & Stanev, 2005

Cosmic Ray composition



Gaisser & Stanev, 2005

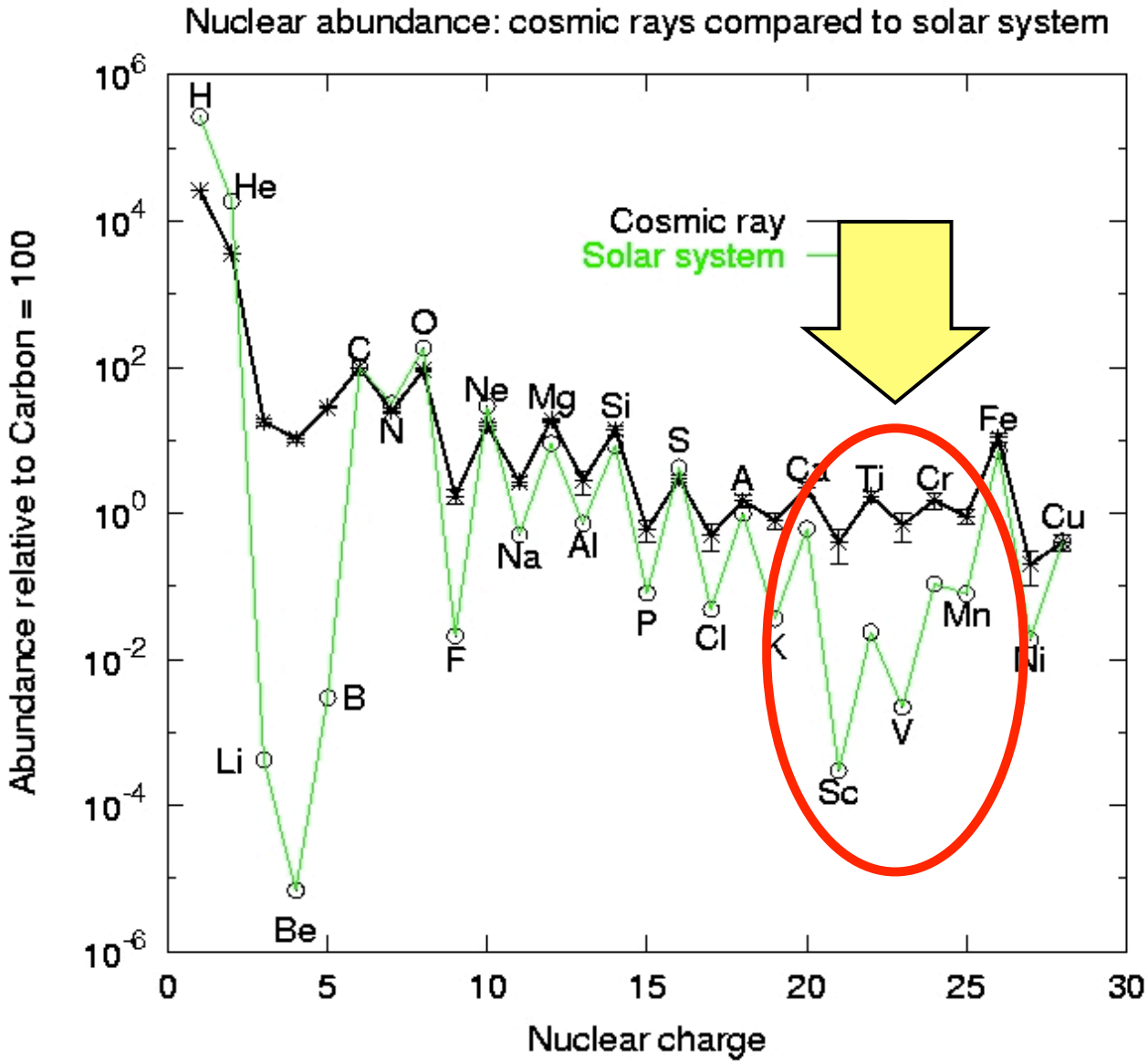
Cosmic Ray composition



5 - 6 order of magnitude more Li, Be, B!
(Solar System -> primordial nucleosynthesis)

Gaisser & Stanev, 2005

Cosmic Ray composition



Gaisser & Stanev, 2005

Cosmic Ray electrons

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

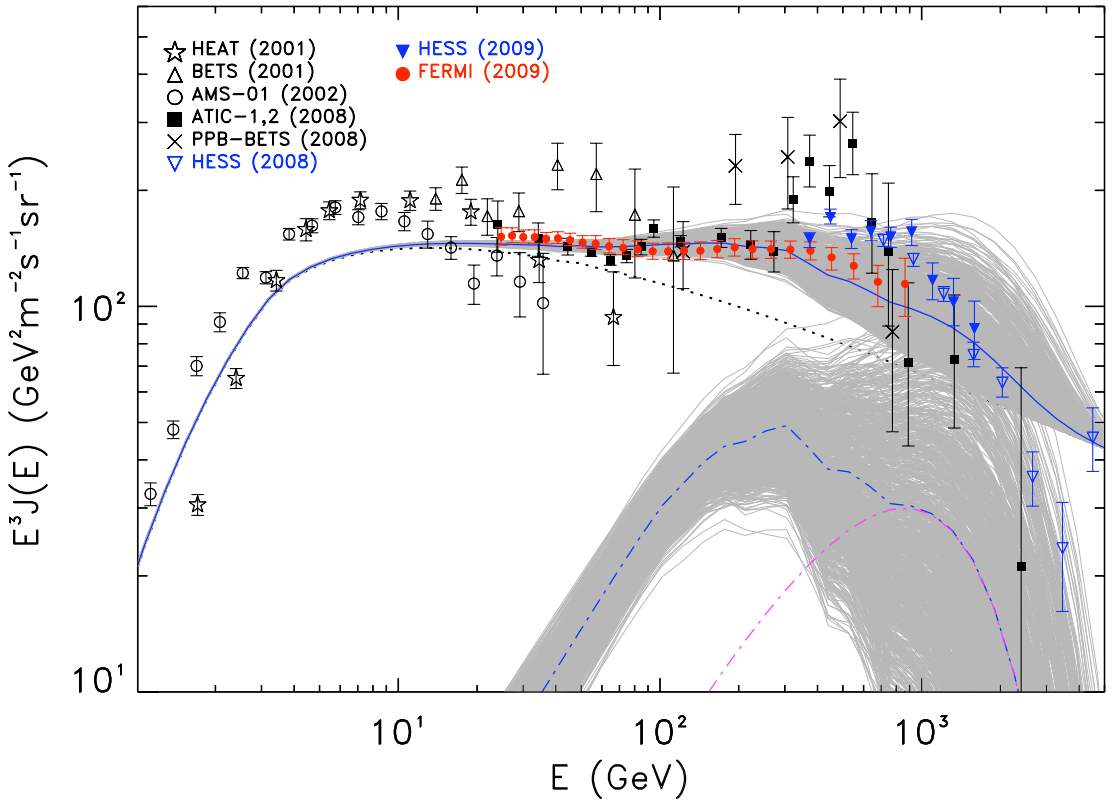


figure from
Grasso et al, 2009

Cosmic Ray electrons

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

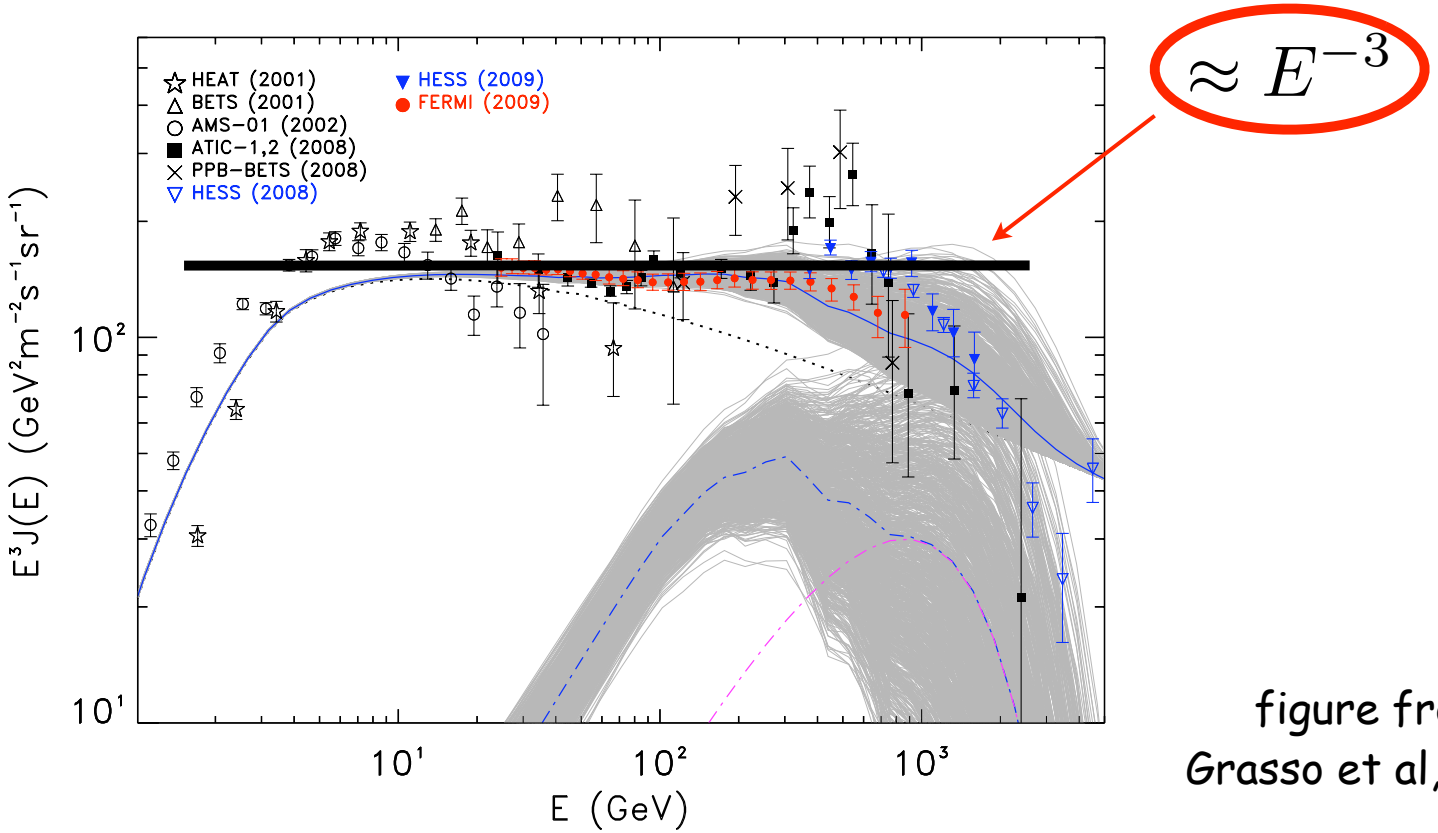
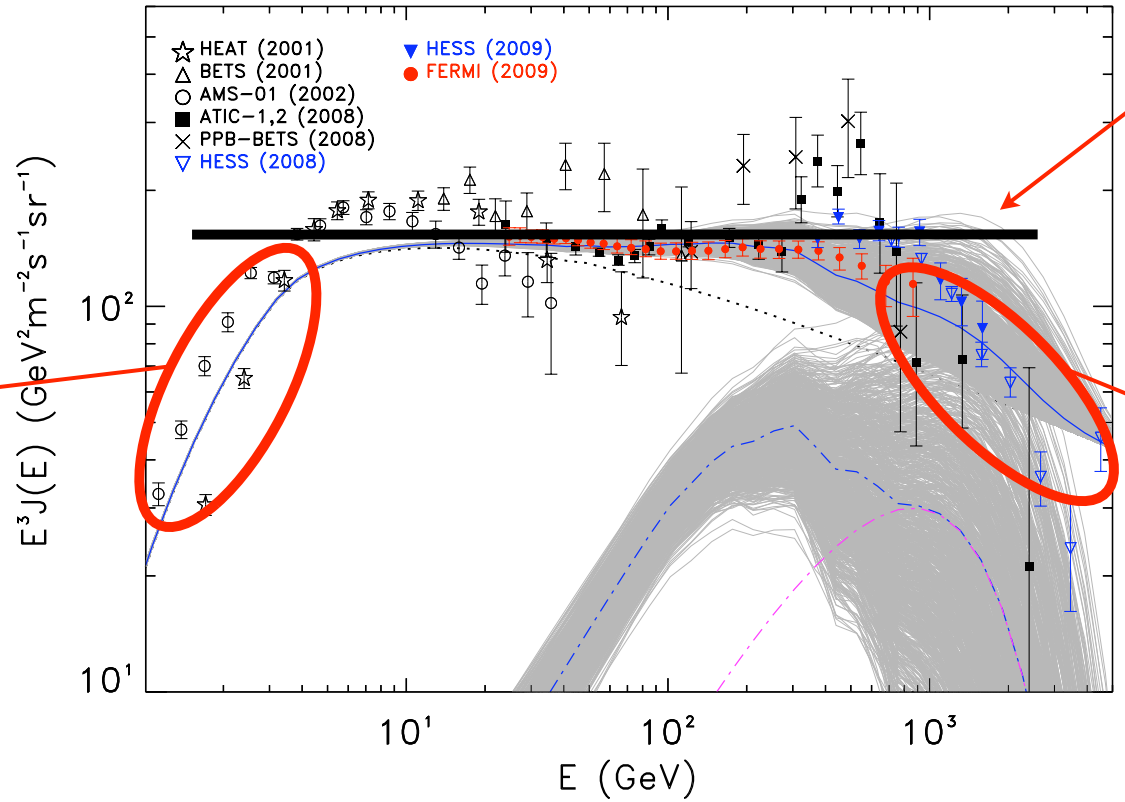


figure from Grasso et al, 2009

Cosmic Ray electrons

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



$\approx E^{-3}$

harder

softer

figure from
Grasso et al, 2009

Cosmic Ray electrons

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

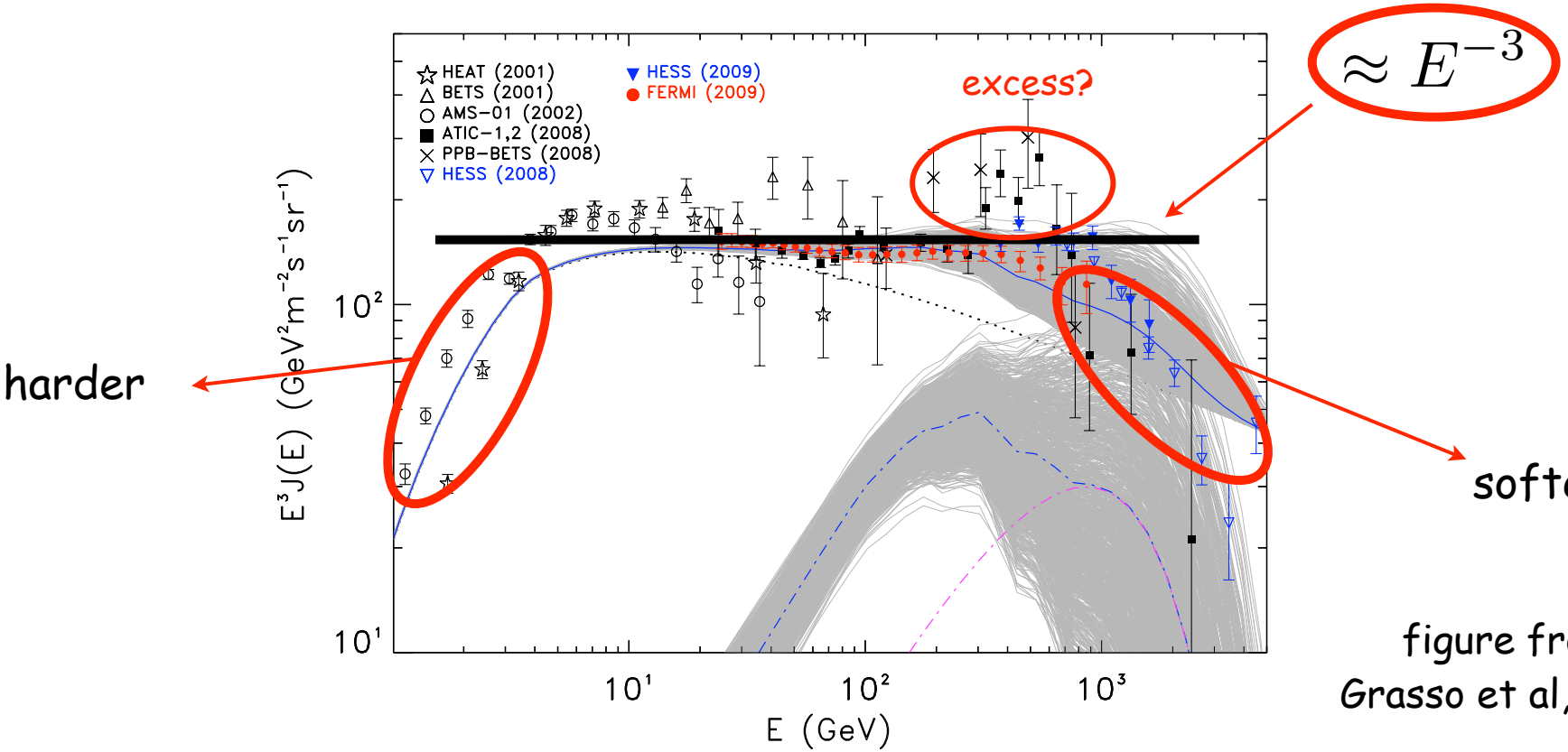
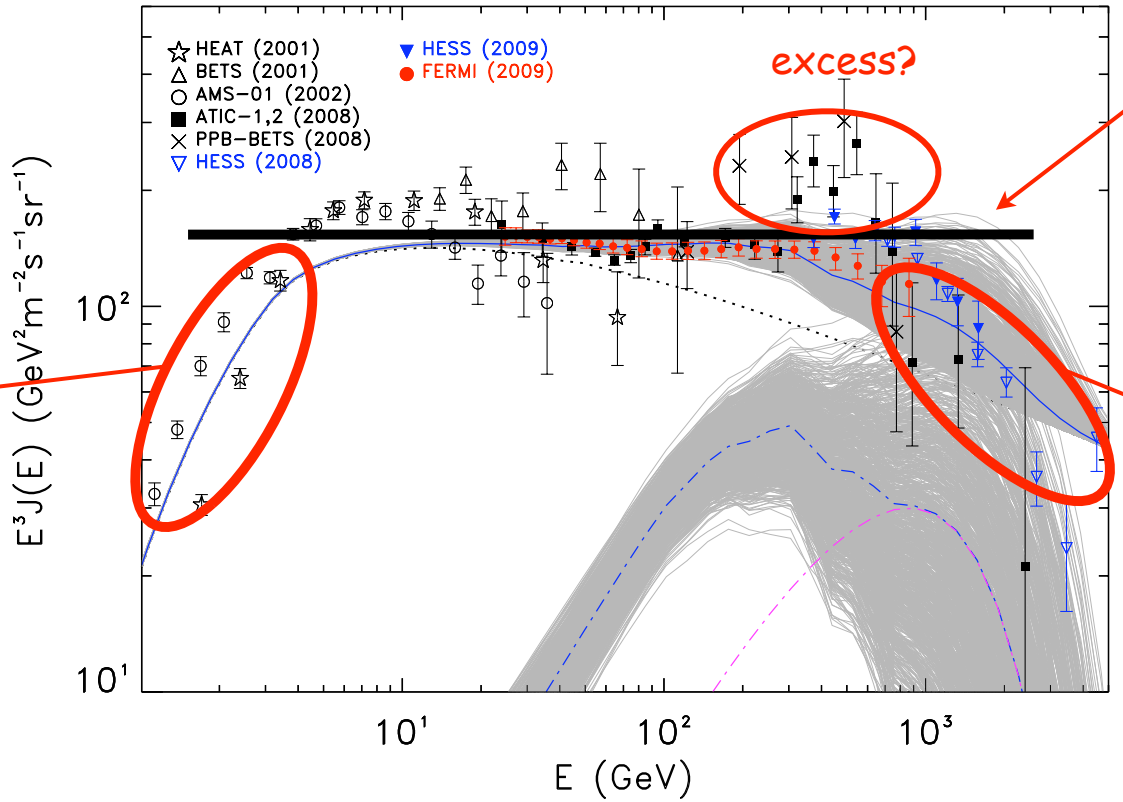


figure from Grasso et al, 2009

Cosmic Ray electrons

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



$\approx E^{-3}$

harder

softer

figure from Grasso et al, 2009

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

Cosmic Ray isotropy

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

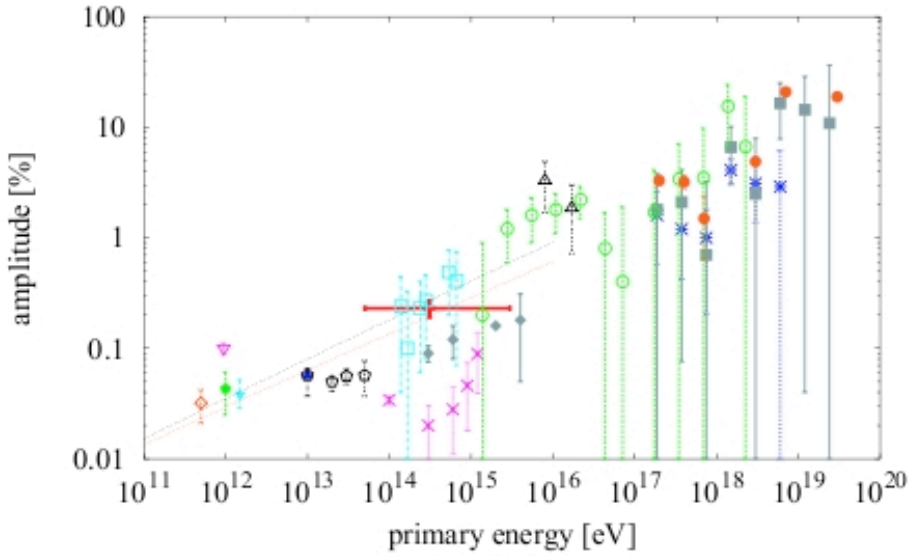


figure from
Iyono et al, 2005

Cosmic Ray isotropy

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

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

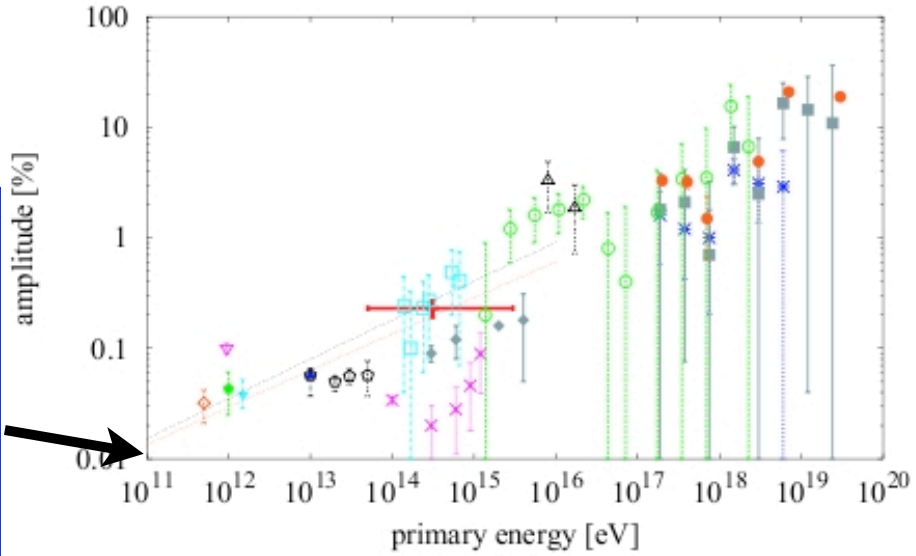
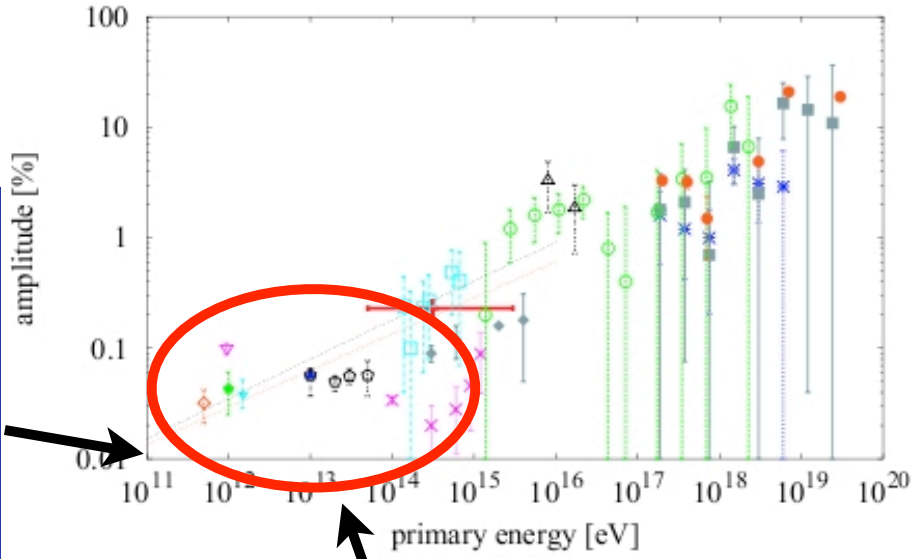


figure from
Iyono et al, 2005

Cosmic Ray isotropy

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

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



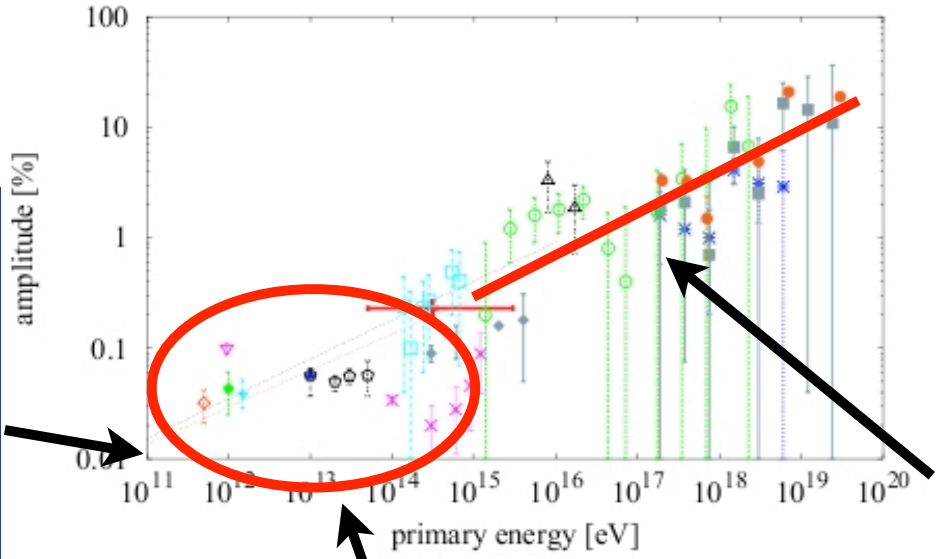
δ ~ 10^{-3}

figure from Iyono et al, 2005

Cosmic Ray isotropy

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

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



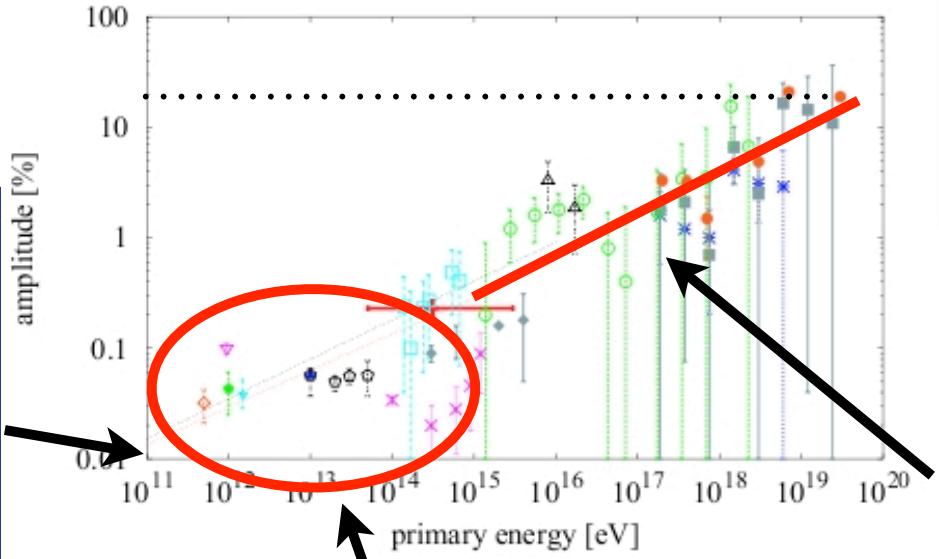
the anisotropy increases with particle energy

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

figure from Iyono et al, 2005

Cosmic Ray isotropy

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



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

CRs are very isotropic in the sky

the anisotropy increases with particle energy

δ ~ 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: $w_{CR} \sim 1 \text{ eV cm}^{-3}$

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

Thermal gas energy density: $w_{gas} = \frac{3}{2} n_{gas} kT \sim 1 \text{ eV cm}^{-3}$

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)

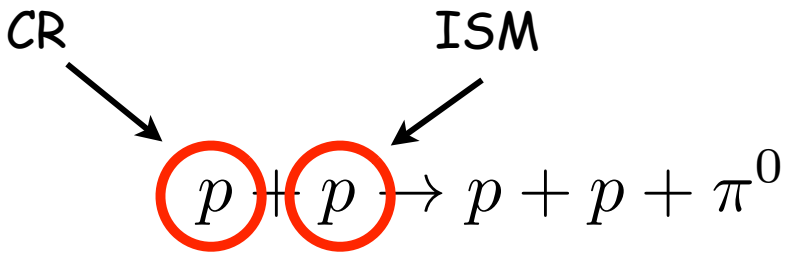
Stability in time and (hints for) spatial homogeneity

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

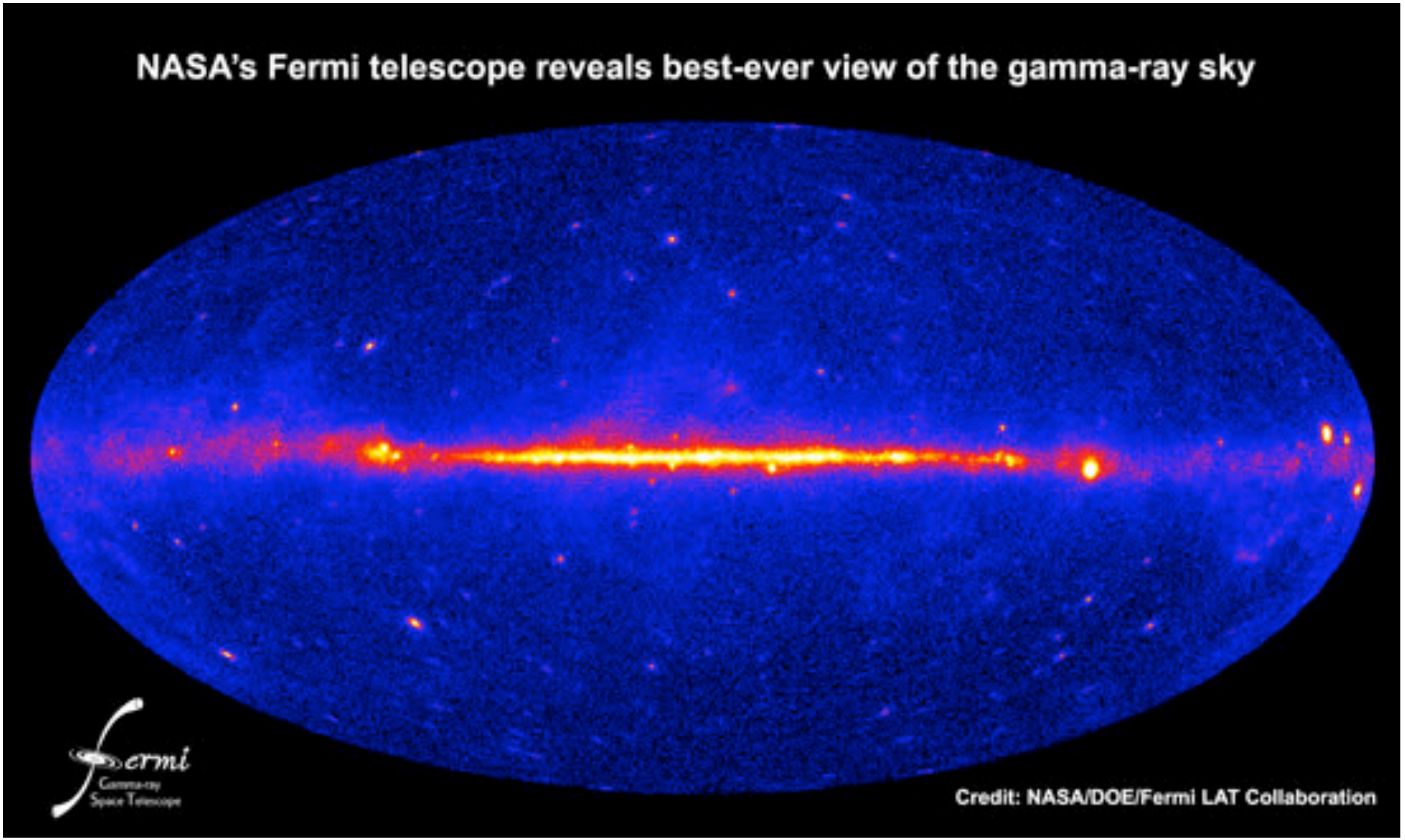
Cosmic Rays undergo hadronic interactions in the InterStellar Medium:



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

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

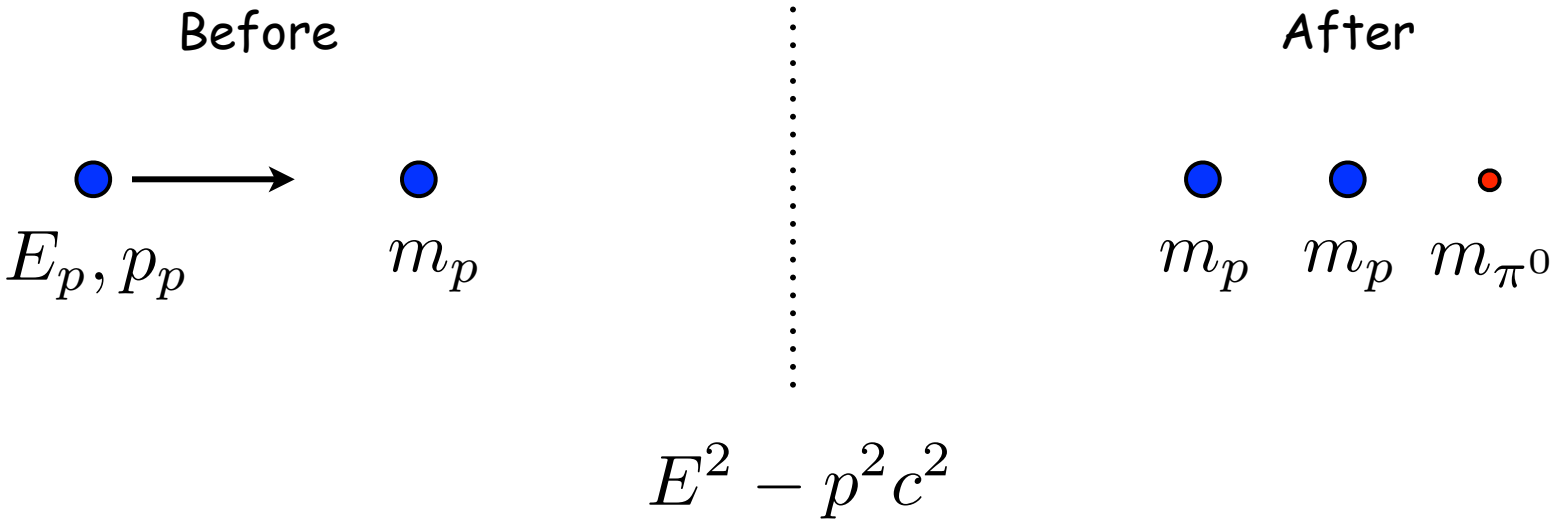
Cosmic Rays and Gamma-Ray Astronomy



Gamma-Ray Astronomy: p-p interactions

Energy threshold for neutral pion production:

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

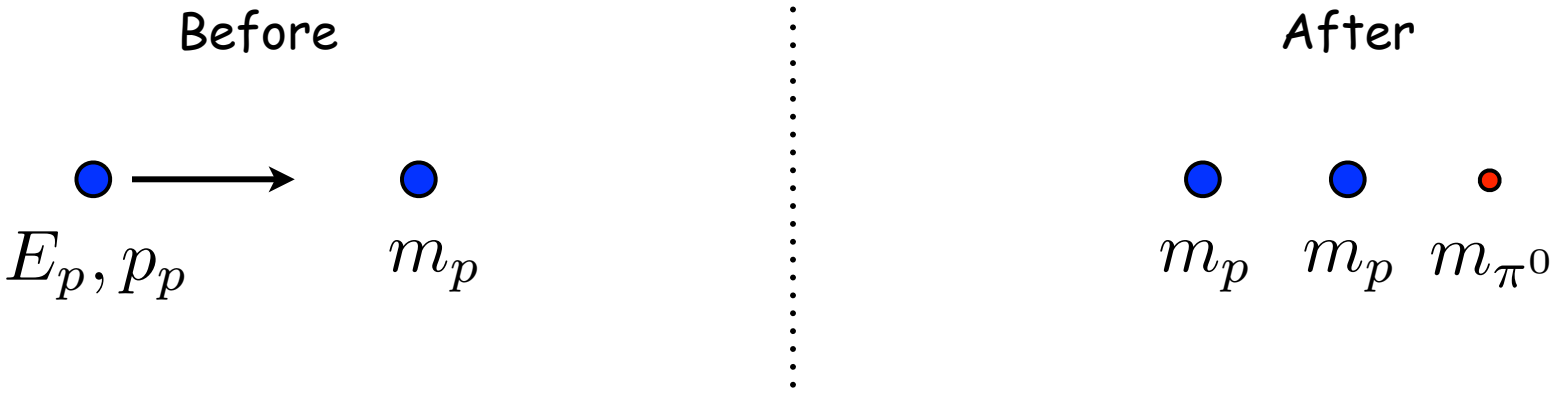


$$E^2 - p^2c^2$$

Gamma-Ray Astronomy: p-p interactions

Energy threshold for neutral pion production:

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

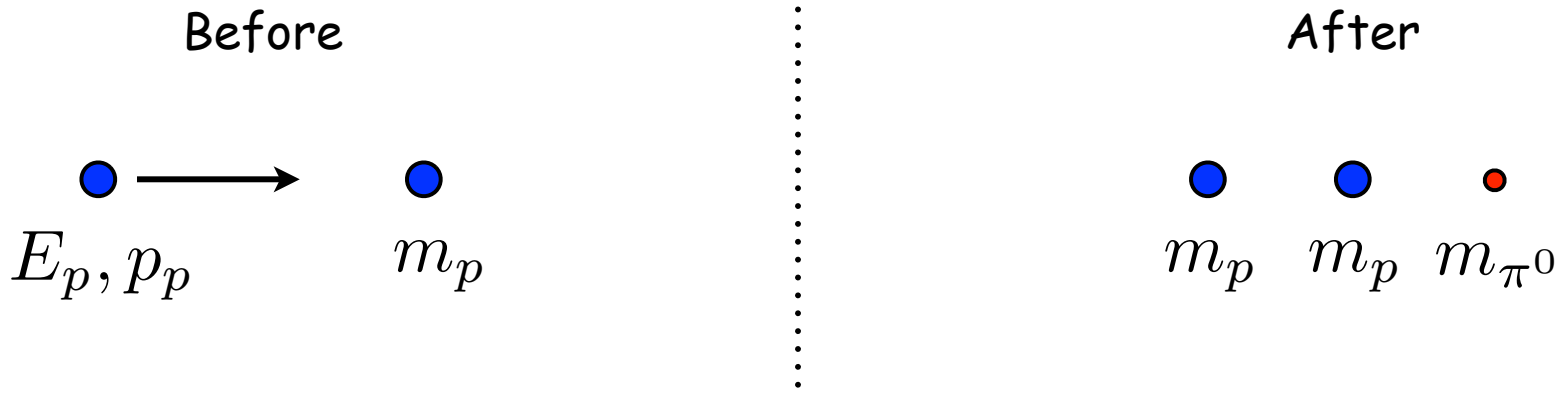


$$E^2 - p^2c^2 = \left(2m_pc^2 + m_{\pi^0}c^2\right)^2$$

Gamma-Ray Astronomy: p-p interactions

Energy threshold for neutral pion production:

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

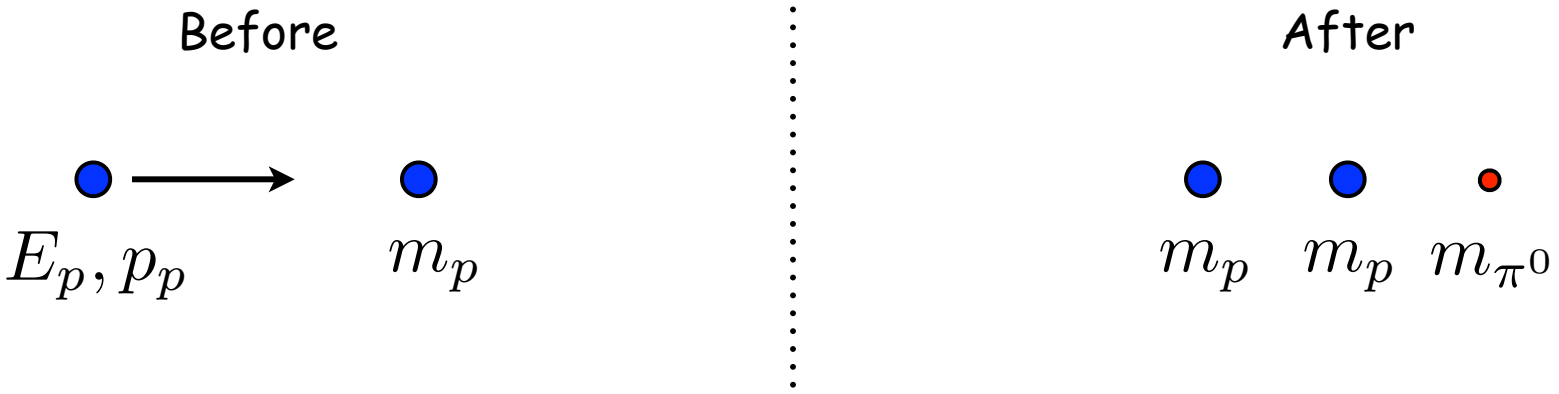


$$\left(E_p + m_p c^2\right)^2 - p_p^2 c^2 = E^2 - p^2 c^2 = \left(2m_p c^2 + m_{\pi^0} c^2\right)^2$$

Gamma-Ray Astronomy: p-p interactions

Energy threshold for neutral pion production:

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



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

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

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

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

Gamma-Ray Astronomy: p-p interactions

Let's calculate the spectrum of neutral pions:

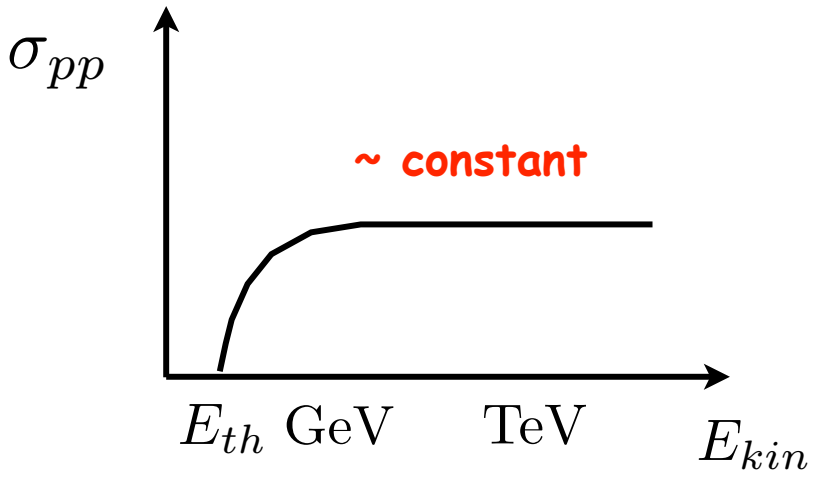
We assume a power law spectrum for CRs: $N_p(E_p) \propto E_p^{-\delta}$

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

production rate

total cross section

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



Gamma-Ray Astronomy: p-p interactions

Let's calculate the spectrum of neutral pions:

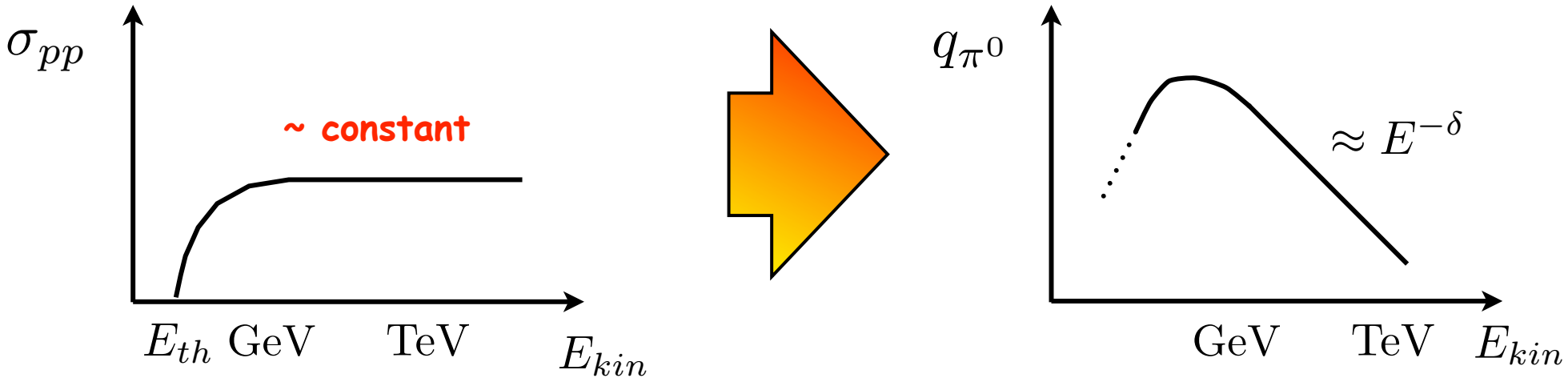
We assume a power law spectrum for CRs: $N_p(E_p) \propto E_p^{-\delta}$

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

production rate

total cross section

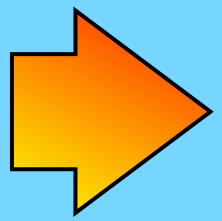
$$q_{\pi^0} = \int \mathrm{d}E_p \; N_p(E_p) \; \delta(E_{\pi^0} - f_{\pi^0} E_{p,kin}) \; \sigma_{pp}(E_p) \; n_{gas} \; c$$



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)

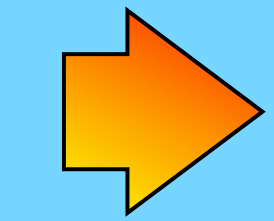


The photon spectrum MUST exhibit a feature at an energy relate to the pion mass

Gamma-Ray Astronomy: p-p interactions

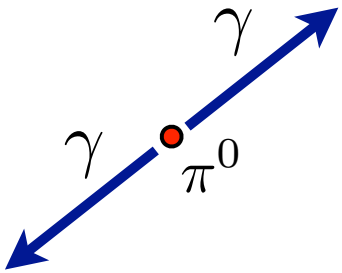
Let's now calculate the spectrum of photons from pion decay - I

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

Pion rest frame:



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

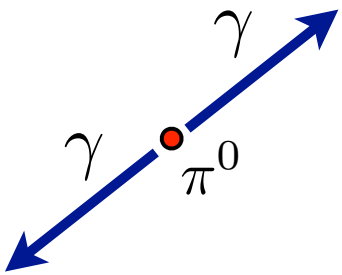
Gamma-Ray Astronomy: p-p interactions

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

Pion rest frame:



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

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

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

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

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

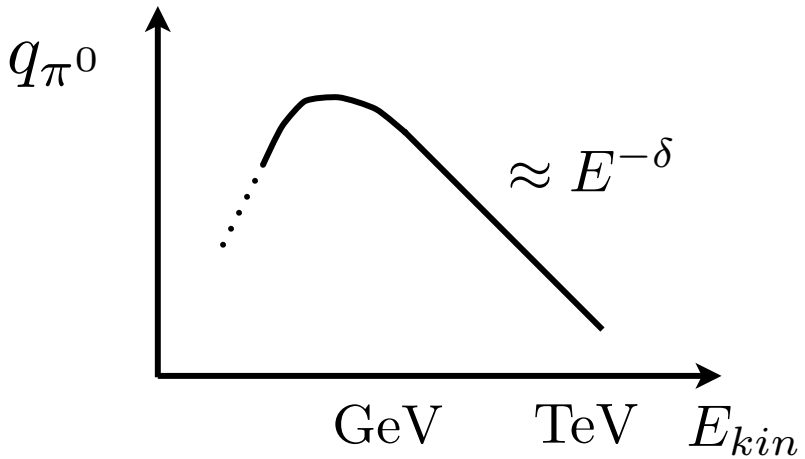
$$E_\gamma = \gamma\left(E_\gamma^* + v p_\gamma^* \cos\theta^*\right) \rightarrow \mathrm{d}E_\gamma \propto \mathrm{d}(\cos\theta^*)$$

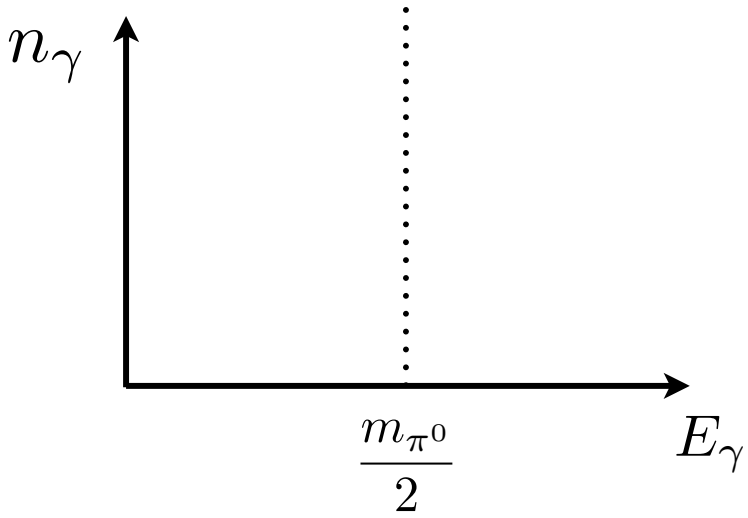
$$\frac{\mathrm{d}n_\gamma}{\mathrm{d}E_\gamma} = const$$

The spectrum is flat!

Gamma-Ray Astronomy: p-p interactions

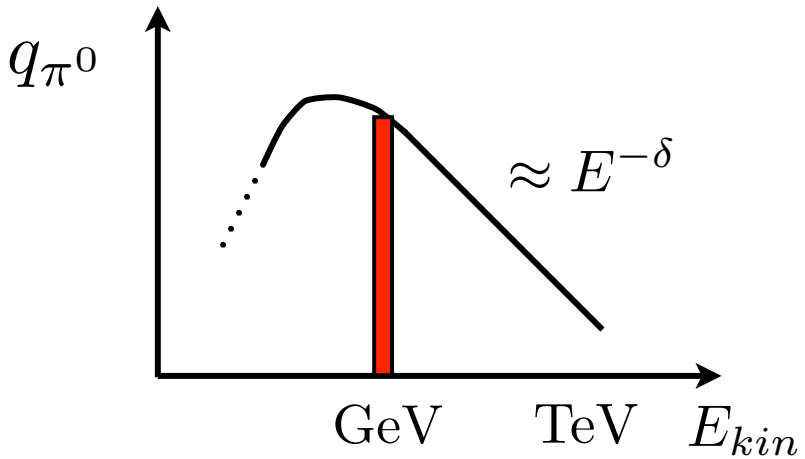
Let's now calculate the spectrum of photons from pion decay - III

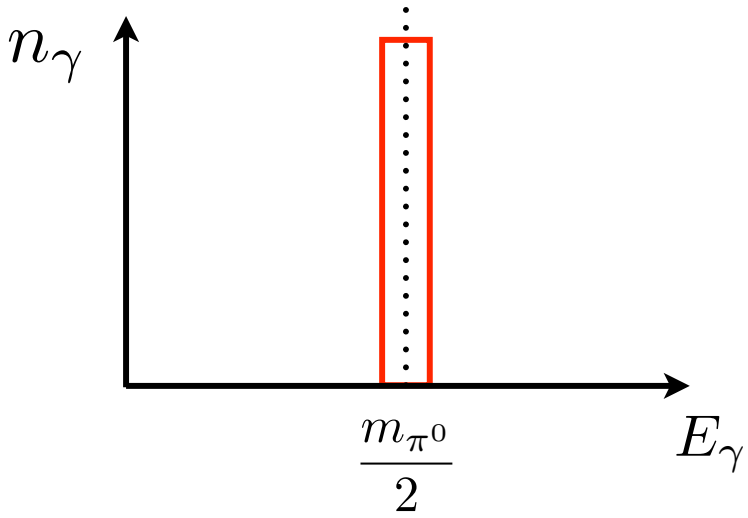




Gamma-Ray Astronomy: p-p interactions

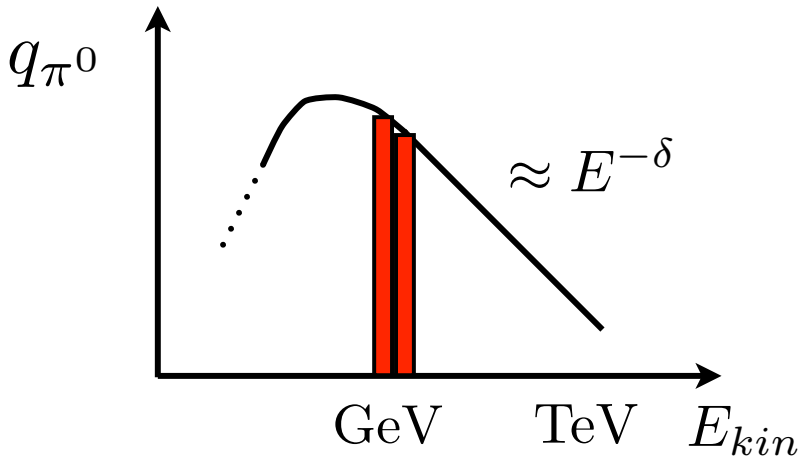
Let's now calculate the spectrum of photons from pion decay - III

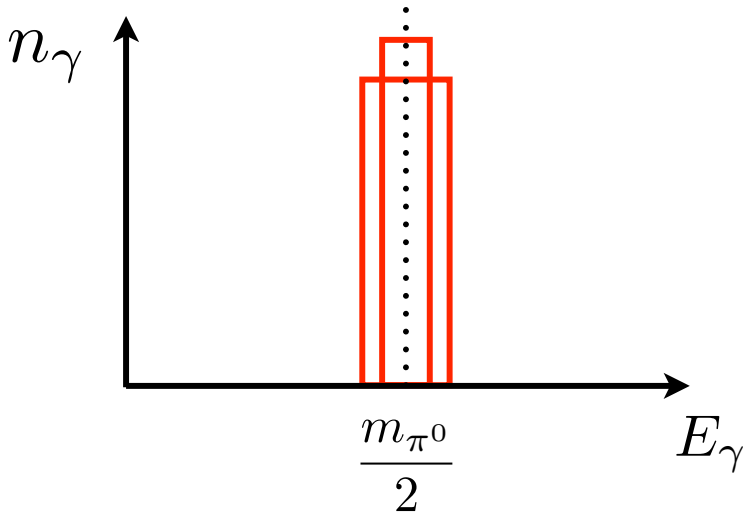




Gamma-Ray Astronomy: p-p interactions

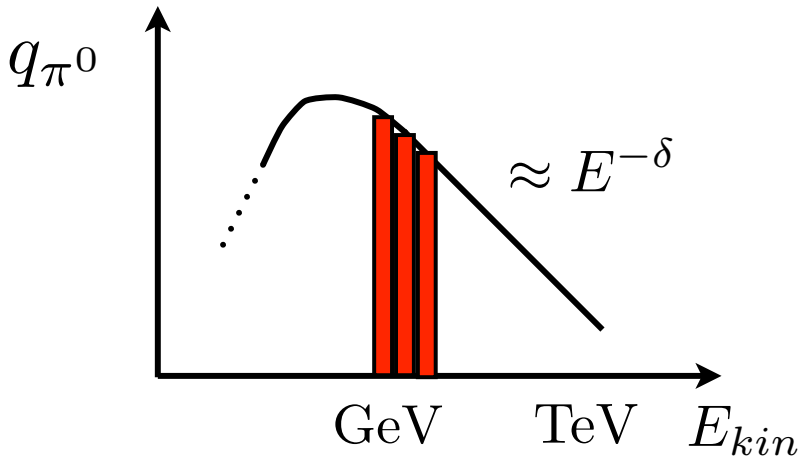
Let's now calculate the spectrum of photons from pion decay - III

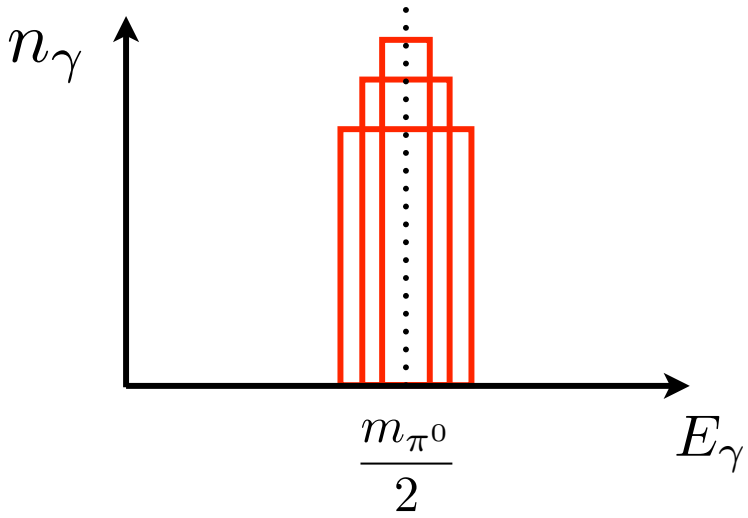




Gamma-Ray Astronomy: p-p interactions

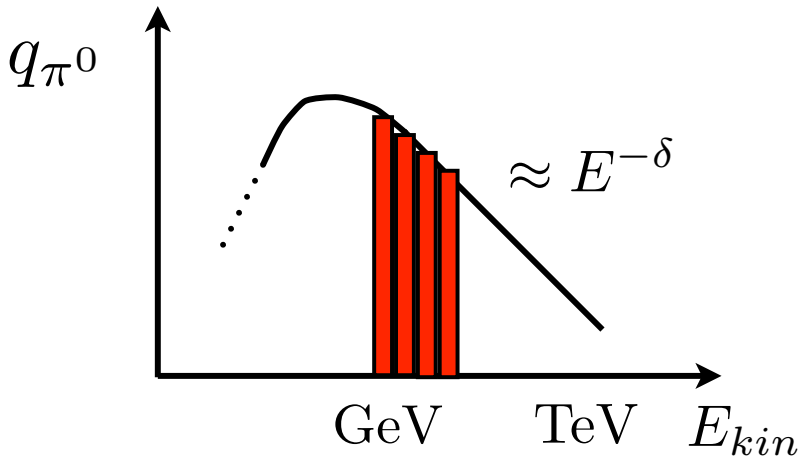
Let's now calculate the spectrum of photons from pion decay - III

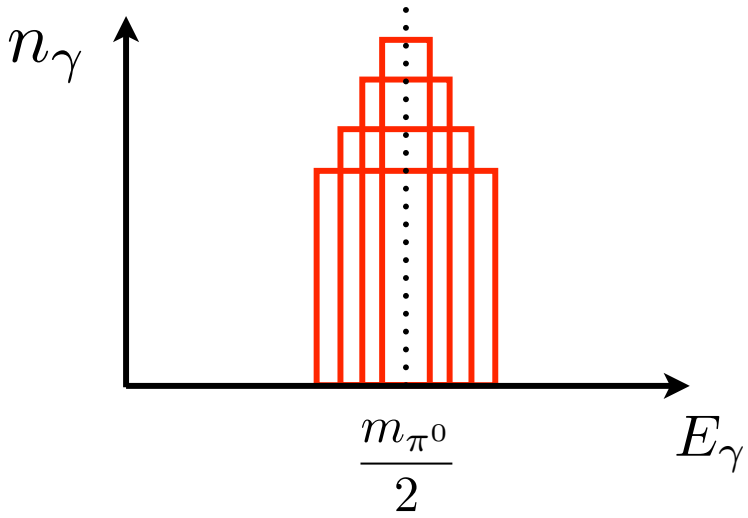




Gamma-Ray Astronomy: p-p interactions

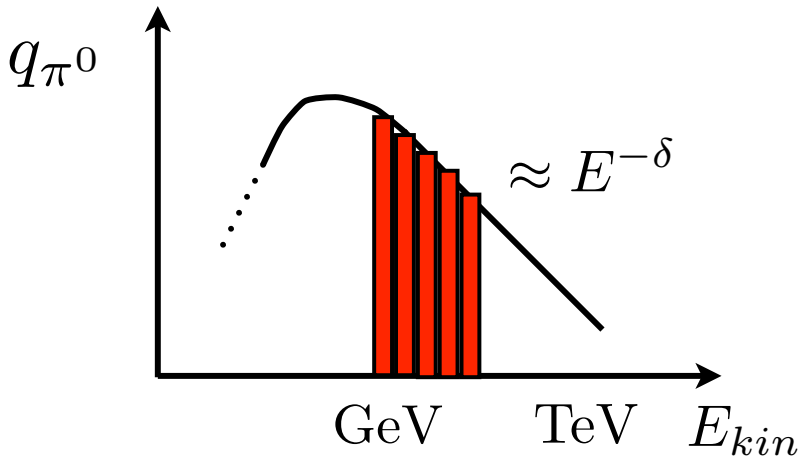
Let's now calculate the spectrum of photons from pion decay - III

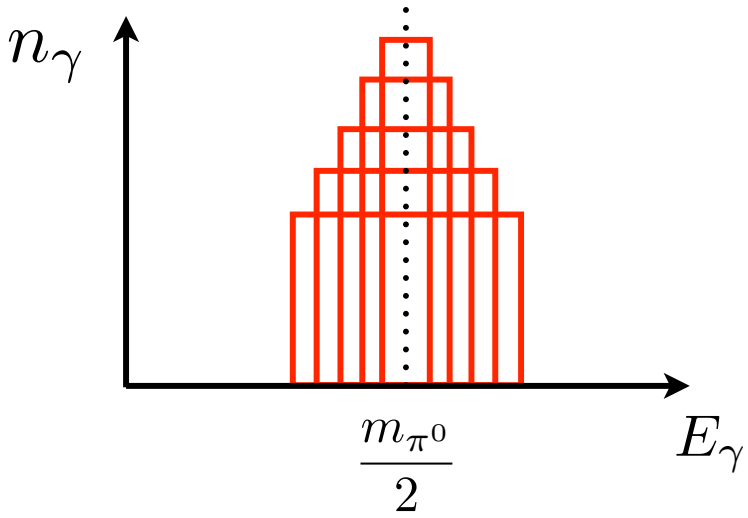




Gamma-Ray Astronomy: p-p interactions

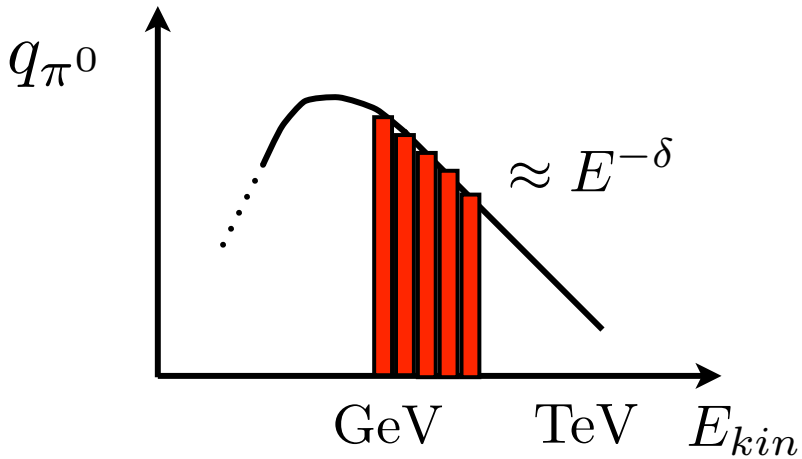
Let's now calculate the spectrum of photons from pion decay - III

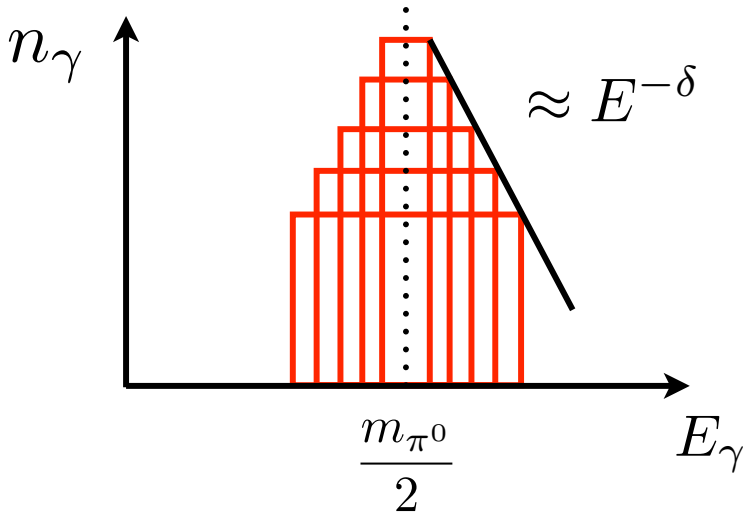




Gamma-Ray Astronomy: p-p interactions

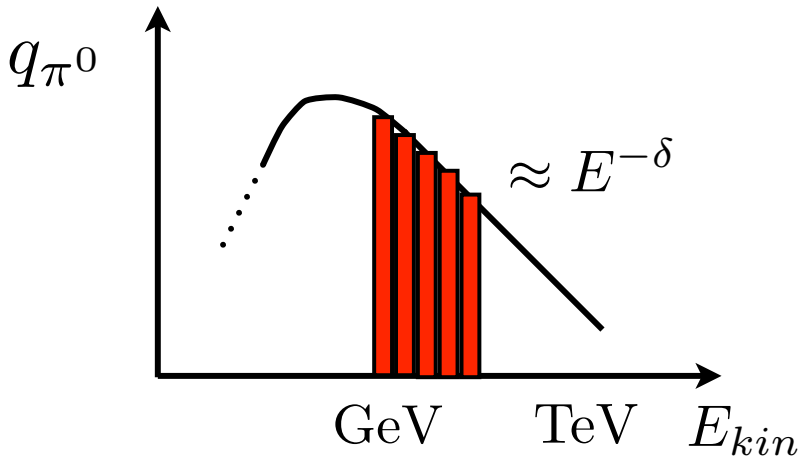
Let's now calculate the spectrum of photons from pion decay - III

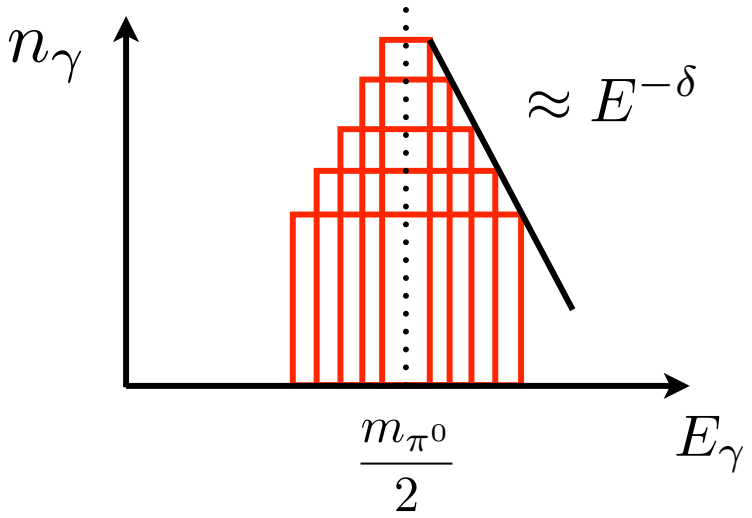




Gamma-Ray Astronomy: p-p interactions

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

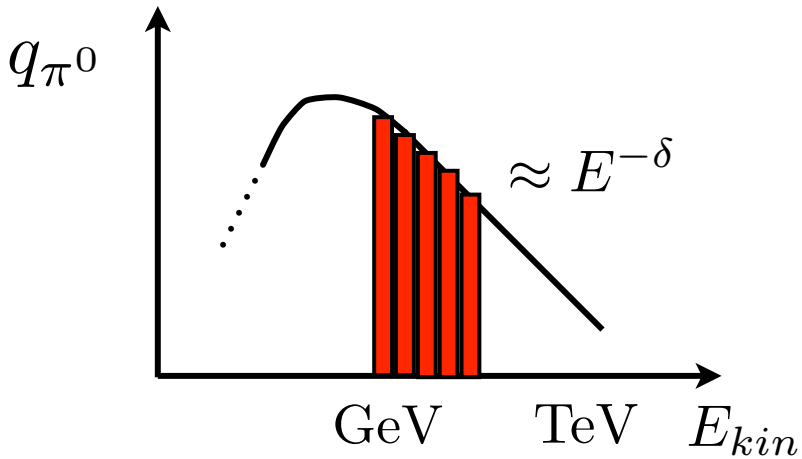


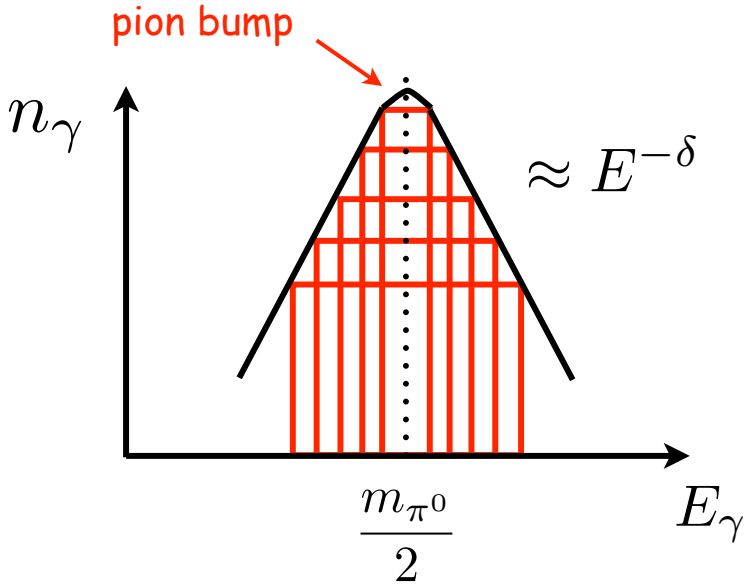


- the gamma ray spectrum is symmetric (in log-log) with respect to: $\frac{m_{\pi^0}}{2} \sim 70$ MeV
- at high energy the spectrum mimic the CR spectrum, with (roughly): $E_\gamma \approx \frac{E_{CR}}{10}$

Gamma-Ray Astronomy: p-p interactions

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





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

Gamma-Ray Astronomy: p-p interactions

Detectability condition for a Cherenkov Telescope

HESS sensitivity: $F^{min}_{HESS}(> 1\ \mathrm{TeV}) \approx 10^{-12}\ \mathrm{ph\ cm^{-2}\ s^{-1}} \rightarrow 10^{-11}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$

Depends a bit on the spectrum

Gamma-Ray Astronomy: p-p interactions

Detectability condition for a Cherenkov Telescope

HESS sensitivity: $F^{min}_{HESS}(> 1\ \mathrm{TeV}) \approx 10^{-12}\ \mathrm{ph\ cm^{-2}\ s^{-1}} \rightarrow 10^{-11}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$

Depends a bit on the spectrum

which corresponds to a luminosity: $L^{min}_{HESS}(> 1\ \mathrm{TeV}) = F^{min}_{HESS}(> 1\ \mathrm{TeV})\ 4\pi d^2 = 10^{33}\ d^2_{kpc}\ \mathrm{erg/s}$

Gamma-Ray Astronomy: p-p interactions

Detectability condition for a Cherenkov Telescope

HESS sensitivity: $F^{min}_{HESS}(> 1\ \mathrm{TeV}) \approx 10^{-12}\ \mathrm{ph\ cm^{-2}\ s^{-1}} \rightarrow 10^{-11}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$

Depends a bit on the spectrum

which corresponds to a luminosity: $L^{min}_{HESS}(> 1\ \mathrm{TeV}) = F^{min}_{HESS}(> 1\ \mathrm{TeV})\ 4\pi d^2 = 10^{33}\ d^2_{kpc}\ \mathrm{erg/s}$

p-p energy loss time

fraction of CR energy transferred to photon

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

Gamma-Ray Astronomy: p-p interactions

Detectability condition for a Cherenkov Telescope

HESS sensitivity: $F^{min}_{HESS}(> 1\ \mathrm{TeV}) \approx 10^{-12}\ \mathrm{ph\ cm^{-2}\ s^{-1}} \rightarrow 10^{-11}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$

Depends a bit on the spectrum

which corresponds to a luminosity: $L^{min}_{HESS}(> 1\ \mathrm{TeV}) = F^{min}_{HESS}(> 1\ \mathrm{TeV})\ 4\pi d^2 = 10^{33}\ d^2_{kpc}\ \mathrm{erg/s}$

$$t_{pp} = (n_{gas}\ \sigma_{pp}\ c\ k)^{-1}$$

inelasticity

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

p-p energy loss time

fraction of CR energy transferred to photon

Gamma-Ray Astronomy: p-p interactions

Detectability condition for a Cherenkov Telescope

HESS sensitivity: $F^{min}_{HESS}(> 1\ \mathrm{TeV}) \approx 10^{-12}\ \mathrm{ph\ cm^{-2}\ s^{-1}} \rightarrow 10^{-11}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$

Depends a bit on the spectrum

which corresponds to a luminosity: $L^{min}_{HESS}(> 1\ \mathrm{TeV}) = F^{min}_{HESS}(> 1\ \mathrm{TeV})\ 4\pi d^2 = 10^{33}\ d^2_{kpc}\ \mathrm{erg/s}$

$$t_{pp} = (n_{gas}\ \sigma_{pp}\ c\ k)^{-1}$$

inelasticity

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

p-p energy loss time

fraction of CR energy transferred to photon

$$= \left(\frac{10^{15}}{n_{gas}}\ \mathrm{s}\right)\ (10)\ \left(10^{33}\ d^2_{kpc}\ \mathrm{erg/s}\right)$$

Gamma-Ray Astronomy: p-p interactions

Detectability condition for a Cherenkov Telescope

HESS sensitivity: $F^{min}_{HESS}(>1\ \mathrm{TeV}) \approx 10^{-12}\ \mathrm{ph\ cm^{-2}\ s^{-1}} \rightarrow 10^{-11}\ \mathrm{erg\ cm^{-2}\ s^{-1}}$

Depends a bit on the spectrum

which corresponds to a luminosity: $L^{min}_{HESS}(>1\ \mathrm{TeV}) = F^{min}_{HESS}(>1\ \mathrm{TeV})\ 4\pi d^2 = 10^{33}\ d^2_{kpc}\ \mathrm{erg/s}$

$$t_{pp} = (n_{gas}\ \sigma_{pp}\ c\ k)^{-1}$$

inelasticity

p-p energy loss time

fraction of CR energy transferred to photon

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

$$= \left(\frac{10^{15}}{n_{gas}}\ \mathrm{s}\right)\ (10)\ (10^{33}\ d^2_{kpc}\ \mathrm{erg/s}) = 10^{49}\ n^{-1}_{gas}\ d^2_{kpc}\ \mathrm{erg}$$

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:

$$W_{CR} > 10^{49} \, n_{gas}^{-1} \, d_{kpc}^2 \text{ erg}$$

↑

above ~ 10 TeV

Gamma-Ray Astronomy: p-p interactions

Secondary electrons and positrons:

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

Gamma-Ray Astronomy: p-p interactions

Secondary electrons and positrons:

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

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

Gamma-Ray Astronomy: p-p interactions

Secondary electrons and positrons:

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

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

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

Gamma-Ray Astronomy: p-p interactions

Secondary electrons and positrons:

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

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

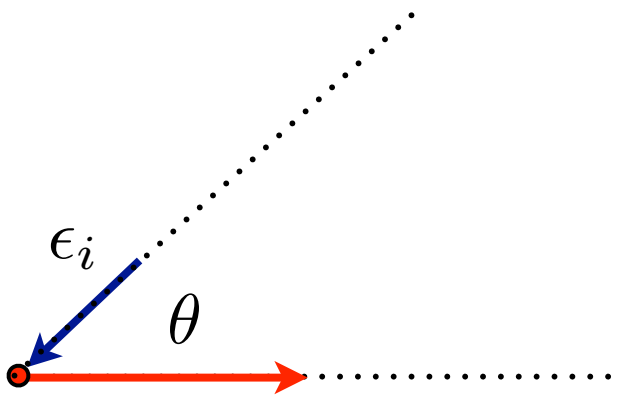
$$\left\{ \begin{array}{l} \pi^{\pm} \rightarrow \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu) \\ \mu^{\pm} \rightarrow e^{\pm} + \bar{\nu}_\mu(\nu_\mu) + \nu_e(\bar{\nu}_e) \end{array} \right.$$

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

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

Leptonic Gamma-Rays: Inverse Compton

Relativistic electrons can interact with soft background photons
(Cosmic Microwave Background, IR and Optical galactic background...)



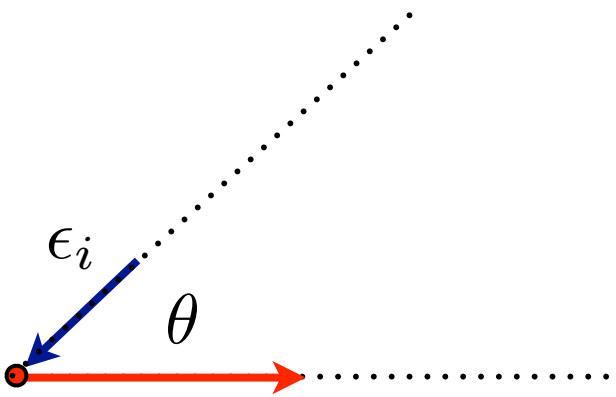
Leptonic Gamma-Rays: Inverse Compton

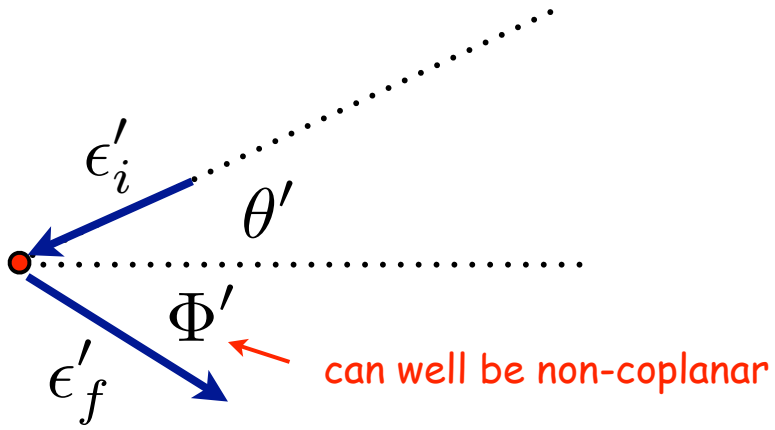
Relativistic electrons can interact with soft background photons
(Cosmic Microwave Background, IR and Optical galactic background...)

In the electron rest frame (e.r.f.) the photon energy is: $\epsilon_i' = \epsilon_i \, \gamma \, (1 - \beta \cos\theta)$

Leptonic Gamma-Rays: Inverse Compton

Relativistic electrons can interact with soft background photons
(Cosmic Microwave Background, IR and Optical galactic background...)



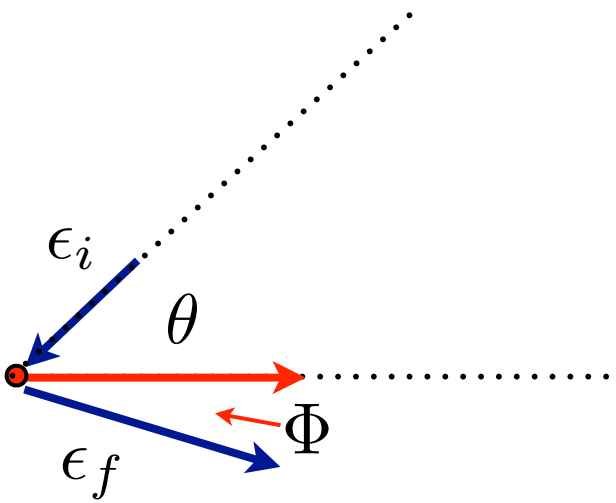


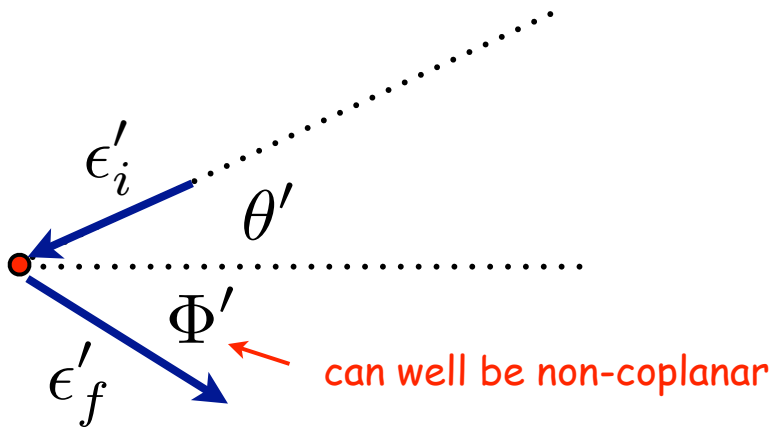
In the electron rest frame (e.r.f.) the photon energy is: $\epsilon'_i = \epsilon_i \, \gamma \, (1 - \beta \cos\theta)$

Assumption: in the e.r.f the scattering is Thomson: $\epsilon'_f = \epsilon'_i$

Leptonic Gamma-Rays: Inverse Compton

Relativistic electrons can interact with soft background photons
(Cosmic Microwave Background, IR and Optical galactic background...)





In the electron rest frame (e.r.f.) the photon energy is: $\epsilon'_i = \epsilon_i \, \gamma \, (1 - \beta \cos\theta)$

Assumption: in the e.r.f the scattering is Thomson: $\epsilon'_f = \epsilon'_i$

In the lab rest frame the (final) photon energy is: $\epsilon_f = \epsilon'_f \, \gamma \, (1 + \beta \cos\Phi)$

Leptonic Gamma-Rays: Inverse Compton

$$\epsilon_f \;=\; \gamma^2 \; \epsilon_i \; G(\theta, \Phi)$$

After averaging over angles (tedious...):

$$\epsilon_f = \frac{4}{3} \gamma^2 \epsilon_i$$

Leptonic Gamma-Rays: Inverse Compton

$$\epsilon_f \;=\; \gamma^2 \; \epsilon_i \; G(\theta, \Phi)$$

After averaging over angles (tedious...):

$$\epsilon_f = \frac{4}{3} \gamma^2 \epsilon_i$$

Example:

Cosmic Microwave Background -> $T \sim 3 \text{ K}$ $kT \approx 3 \times 10^{-4} \text{eV}$

- $E_e = 1 \text{ GeV} \;\rightarrow\; \epsilon_\gamma = 1,5 \text{ keV}$ X-rays
- $E_e = 1 \text{ TeV} \;\rightarrow\; \epsilon_\gamma = 1,5 \text{ GeV}$ gamma rays (FERMI)
- $E_e = 25 \text{ TeV} \;\rightarrow\; \epsilon_\gamma = 1 \text{ TeV}$ gamma rays (Cherenkov Telescopes)

Leptonic Gamma-Rays: Inverse Compton

is there a maximum energy for the up-scattered photons?

$$\epsilon_f = \frac{4}{3}\gamma^2\epsilon_i$$

Leptonic Gamma-Rays: Inverse Compton

is there a maximum energy for the up-scattered photons?

$$\epsilon_f = \frac{4}{3}\gamma^2 \epsilon_i \quad < \gamma\ m\ c^2$$

energy conservation...

above a given energy Inverse Compton scattering becomes ineffective

Leptonic Gamma-Rays: Inverse Compton

is there a maximum energy for the up-scattered photons?

$$\epsilon_f = \frac{4}{3}\gamma^2 \epsilon_i \quad < \gamma\ m\ c^2$$

energy conservation...

above a given energy Inverse Compton scattering becomes ineffective

☑ let's check the assumption of Thomson scattering in the e.r.f.:

photon energy in the e.r.f: $\epsilon_i' \approx \gamma\ \epsilon_i$

Leptonic Gamma-Rays: Inverse Compton

is there a maximum energy for the up-scattered photons?

$$\epsilon_f = \frac{4}{3}\gamma^2 \epsilon_i \quad < \gamma\ m\ c^2$$

energy conservation...

above a given energy Inverse Compton scattering becomes ineffective

☑ let's check the assumption of Thomson scattering in the e.r.f.:

photon energy in the e.r.f: $\epsilon_i' \approx \gamma\ \epsilon_i$

Thomson scattering ONLY if: $\boxed{\gamma\ \epsilon_i < mc^2}$

if $\gamma\ \epsilon_i \sim mc^2$ we must use the quantum relativistic (Klein-Nishina) cross section

Leptonic Gamma-Rays: Inverse Compton

is there a maximum energy for the up-scattered photons?

$$\epsilon_f = \frac{4}{3}\gamma^2 \epsilon_i \quad < \gamma\ m\ c^2$$

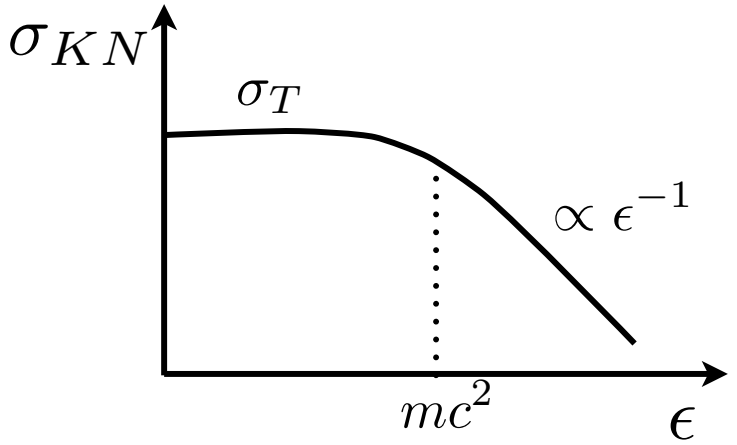
energy conservation...

above a given energy Inverse Compton scattering becomes ineffective

☑ let's check the assumption of Thomson scattering in the e.r.f.:

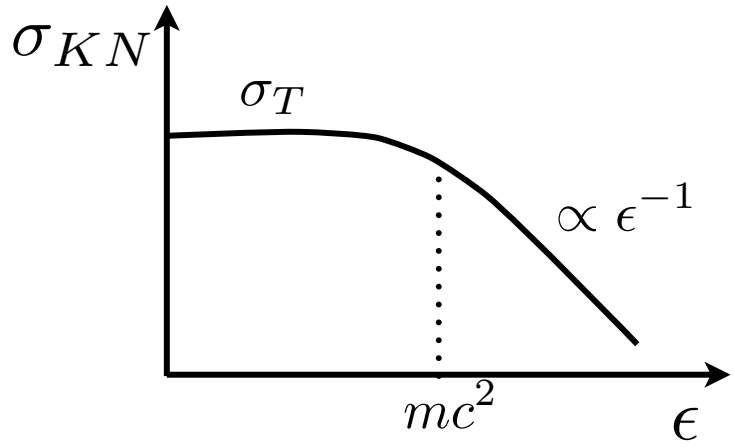
photon energy in the e.r.f: $\epsilon_i' \approx \gamma\ \epsilon_i$

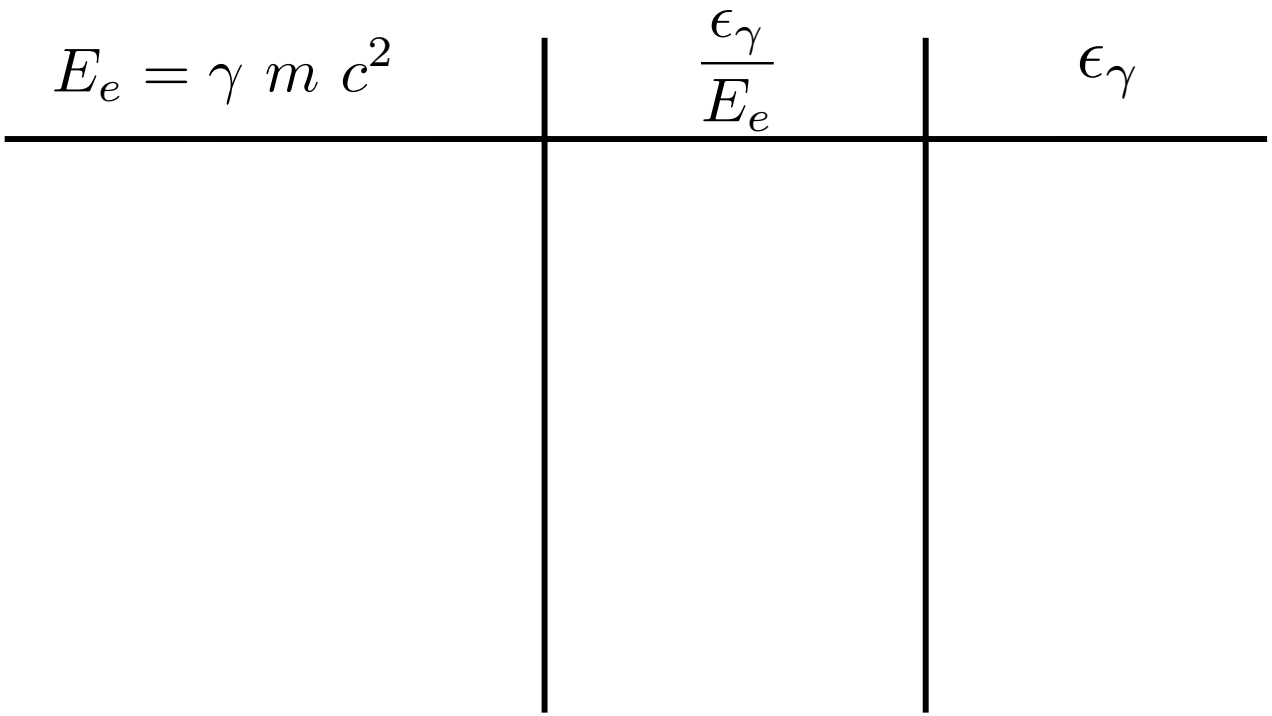
Thomson scattering ONLY if: $\boxed{\gamma\ \epsilon_i < mc^2}$



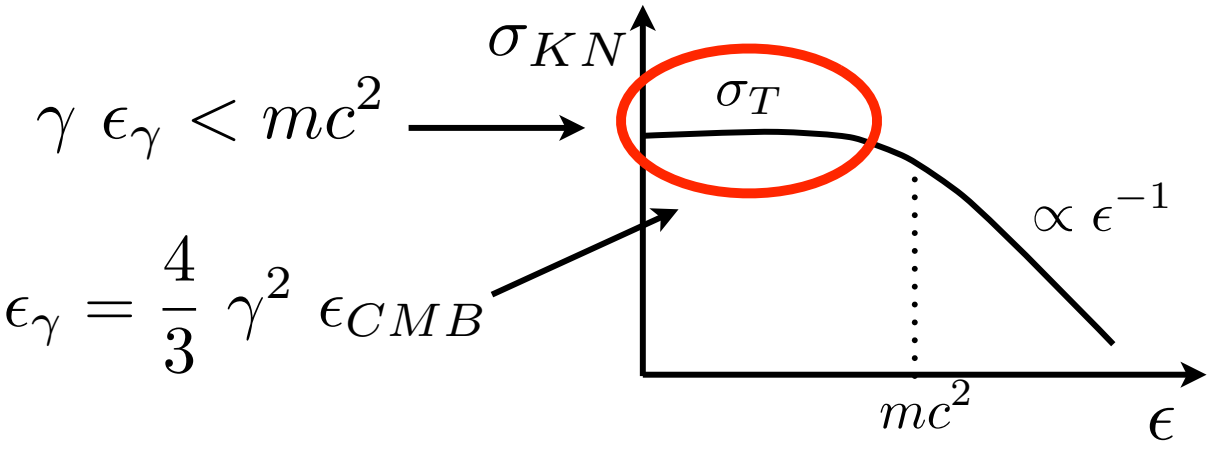
if $\gamma\ \epsilon_i \sim mc^2$ we must use the quantum relativistic (Klein-Nishina) cross section

Leptonic Gamma-Rays: Inverse Compton





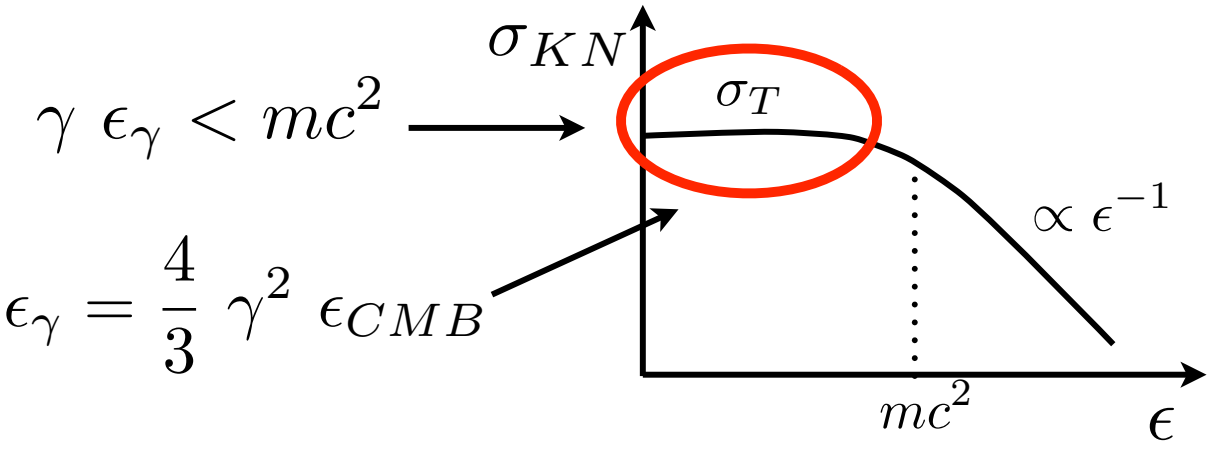
Leptonic Gamma-Rays: Inverse Compton



$E_e = \gamma\ m\ c^2$	$\frac{\epsilon_\gamma}{E_e}$	ϵ_γ
1 TeV	~0.2%	~1.5 GeV
25 TeV	~4%	~1 TeV
100 TeV	~15%	~15 TeV

Thomson

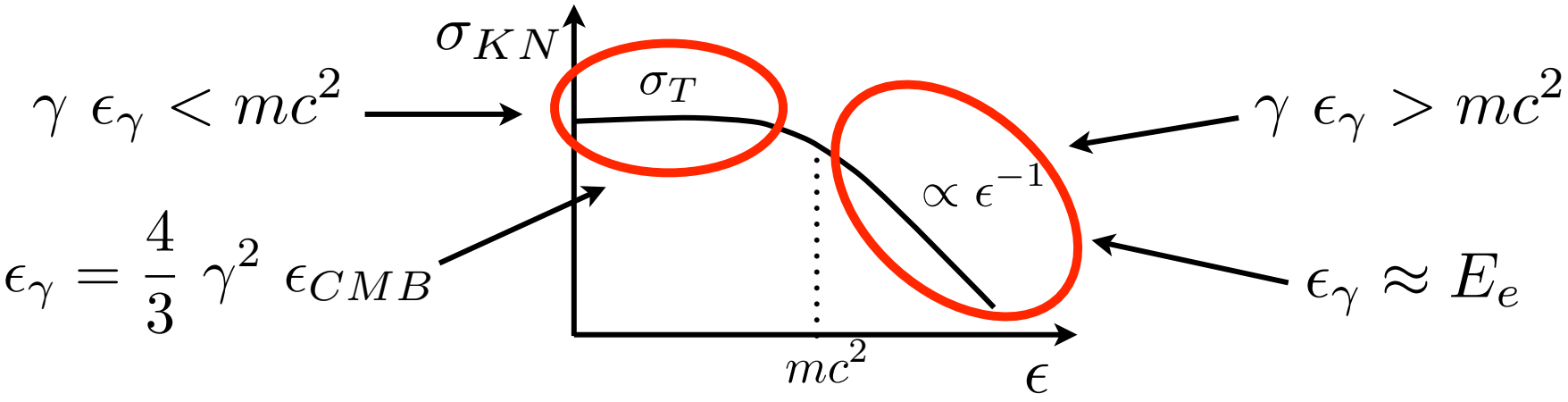
Leptonic Gamma-Rays: Inverse Compton



$E_e = \gamma\ m\ c^2$	$\frac{\epsilon_\gamma}{E_e}$	ϵ_γ
1 TeV	~0.2%	~1.5 GeV
25 TeV	~4%	~1 TeV
100 TeV	~15%	~15 TeV
200 TeV	~30%	~60 TeV
.....	.....	.....

Thomson

Leptonic Gamma-Rays: Inverse Compton

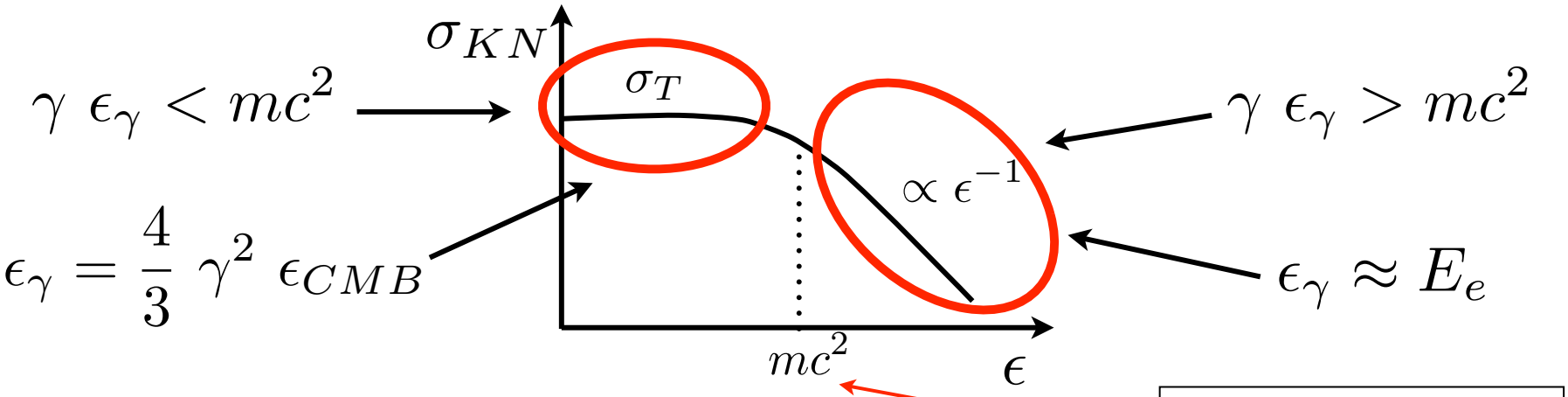


$E_e = \gamma\ m\ c^2$	$\frac{\epsilon_\gamma}{E_e}$	ϵ_γ
1 TeV	~0.2%	~1.5 GeV
25 TeV	~4%	~1 TeV
100 TeV	~15%	~15 TeV
200 TeV	~30%	~60 TeV
.....	.....	.....
E_e >> 200 TeV	~100%	$E_e \sim E_\gamma$

Thomson

Klein-Nishina

Leptonic Gamma-Rays: Inverse Compton



cutoff in the photon spectrum

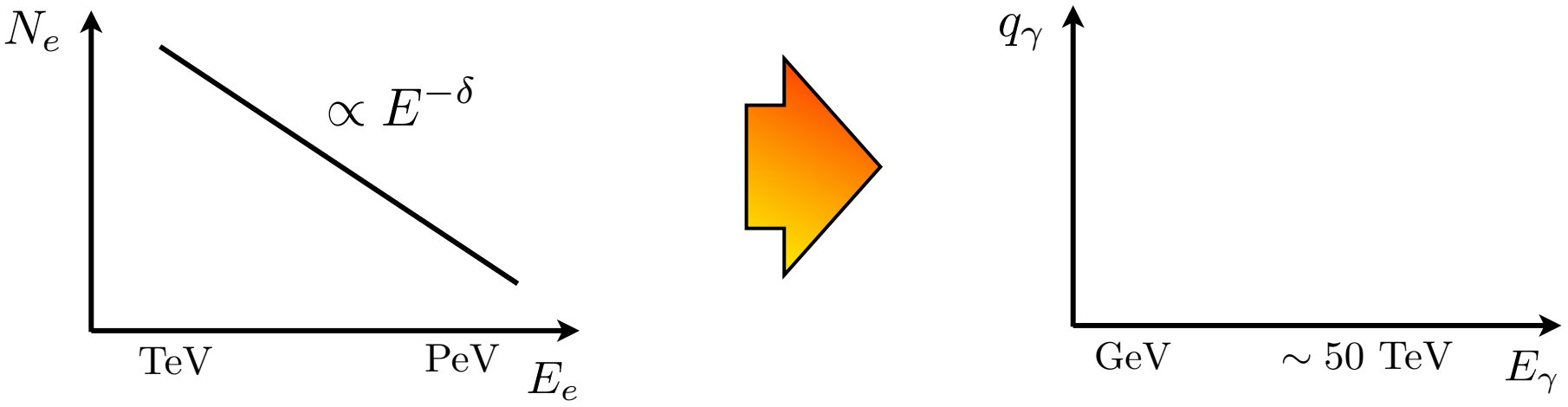
$E_e = \gamma\ m\ c^2$	$\frac{\epsilon_\gamma}{E_e}$	ϵ_γ
1 TeV	~0.2%	~1.5 GeV
25 TeV	~4%	~1 TeV
100 TeV	~15%	~15 TeV
200 TeV	~30%	~60 TeV
.....	.....	.....
E_e >> 200 TeV	~100%	$E_e \sim E_\gamma$

Thomson

Klein-Nishina

Leptonic Gamma-Rays: Inverse Compton

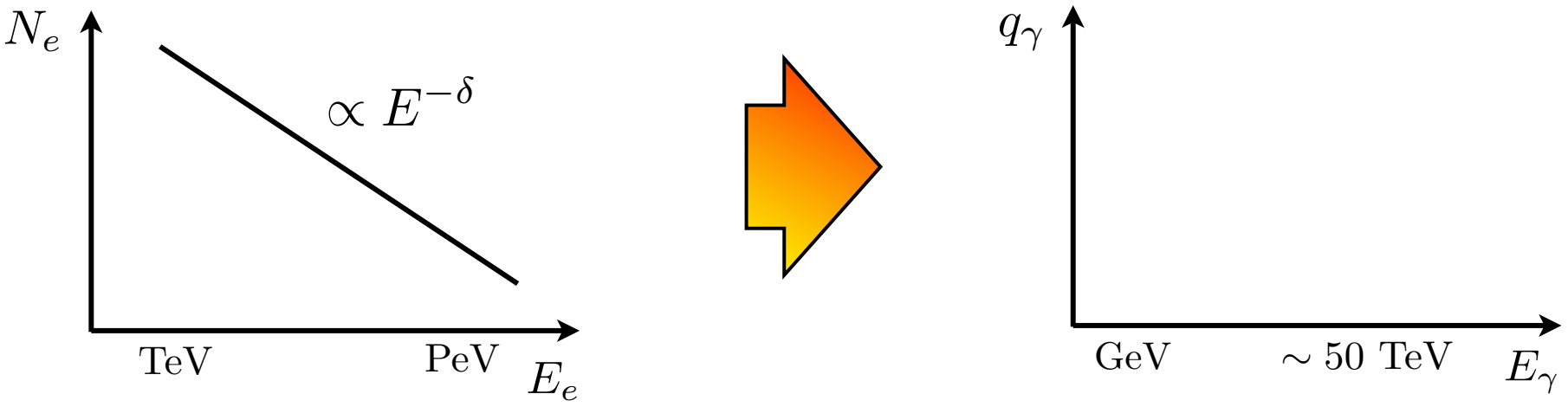
Photon spectrum:



$$q_\gamma(E_\gamma) = \int \mathrm{d}E_e N_e(E_e)\delta(E_\gamma - \frac{4}{3}\gamma^2\epsilon_{CMB})(n_{CMB}\sigma_T c)$$

Leptonic Gamma-Rays: Inverse Compton

Photon spectrum:



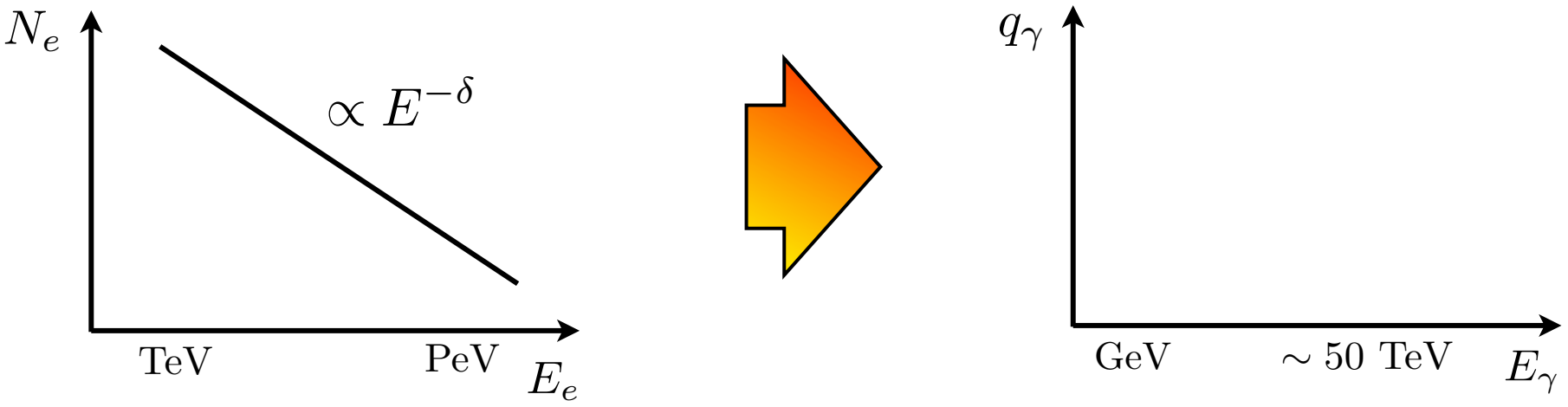
$$q_\gamma(E_\gamma) = \int \mathrm{d}E_e N_e(E_e)\delta(E_\gamma - \frac{4}{3}\gamma^2\epsilon_{CMB})(n_{CMB}\sigma_T c)$$

$$\delta(g(x)) = \frac{\delta(x - x_0)}{|g'(x_0)|}$$

$$g(x_0) = 0$$

Leptonic Gamma-Rays: Inverse Compton

Photon spectrum:



$$q_\gamma(E_\gamma) = \int \mathrm{d}E_e N_e(E_e)\delta(E_\gamma - \frac{4}{3}\gamma^2\epsilon_{CMB})(n_{CMB}\sigma_T c)$$

$$\delta(g(x)) = \frac{\delta(x - x_0)}{|g'(x_0)|}$$

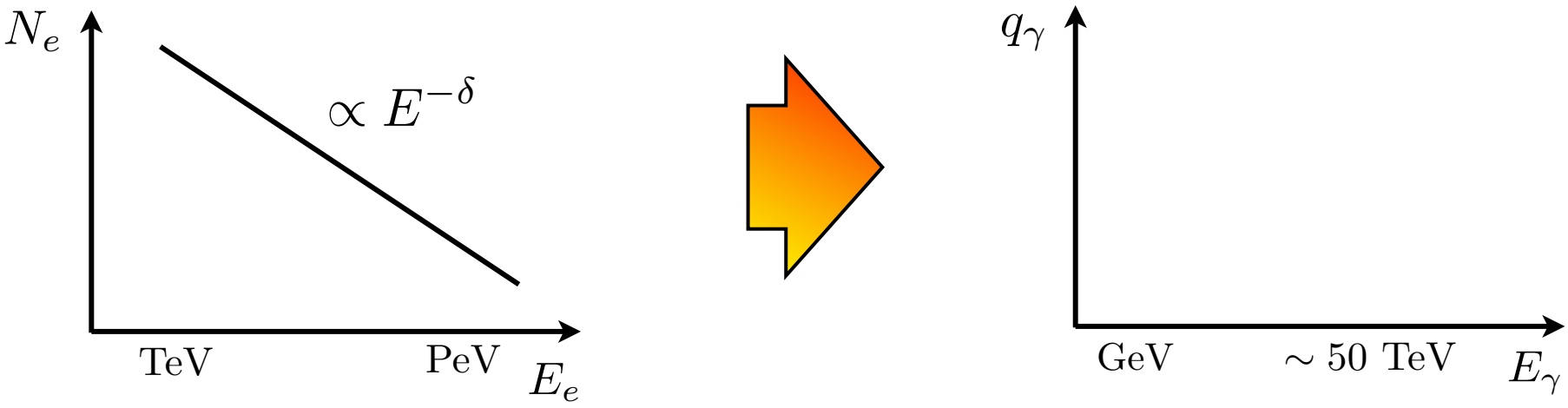
$$g(x_0) = 0$$

$$\delta\left(\overbrace{E_\gamma - \frac{4}{3}\left(\frac{E_e}{mc^2}\right)^2 \epsilon_{CMB}}^{g(x)}\right)$$

$$x_0 \propto E_\gamma^{1/2} \qquad g' \propto E_e$$

Leptonic Gamma-Rays: Inverse Compton

Photon spectrum:



$$q_\gamma(E_\gamma) = \int \mathrm{d}E_e N_e(E_e)\delta(E_\gamma - \frac{4}{3}\gamma^2\epsilon_{CMB})(n_{CMB}\sigma_T c)$$

$$\delta(g(x)) = \frac{\delta(x - x_0)}{|g'(x_0)|}$$

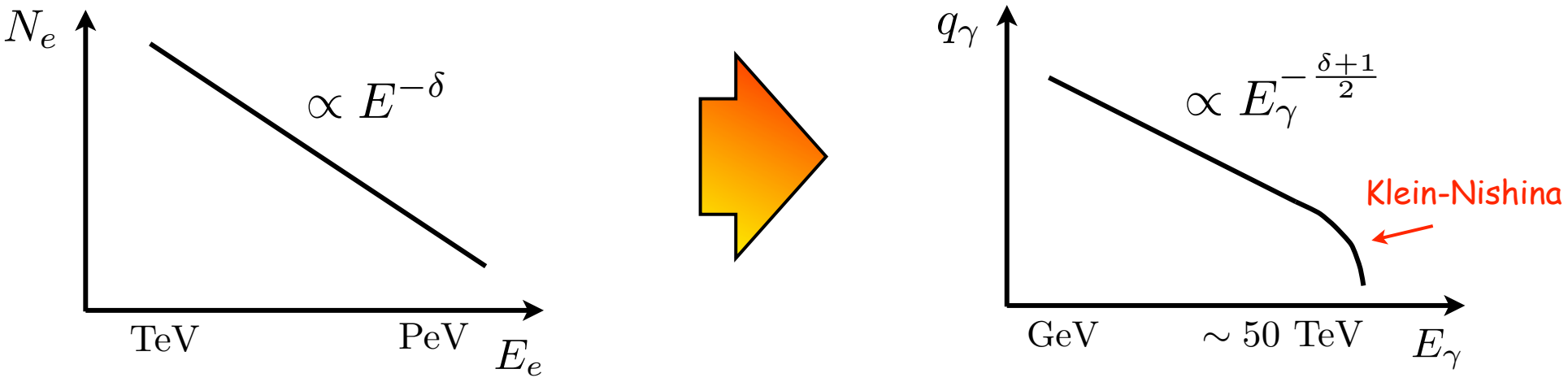
$$g(x_0) = 0$$

$$\delta\left(\overbrace{E_\gamma - \frac{4}{3}\left(\frac{E_e}{mc^2}\right)^2 \epsilon_{CMB}}^{g(x)}\right) = \frac{\delta(E_e - aE_\gamma^{1/2})}{\frac{2}{a}E_\gamma^{1/2}}$$

$x_0 \propto E_\gamma^{1/2}$ $\quad$ $g' \propto E_e$

Leptonic Gamma-Rays: Inverse Compton

Photon spectrum:



$$q_\gamma(E_\gamma) = \int \mathrm{d}E_e N_e(E_e)\delta(E_\gamma - \frac{4}{3}\gamma^2\epsilon_{CMB})(n_{CMB}\sigma_T c) \propto E_\gamma^{-\frac{\delta+1}{2}}$$

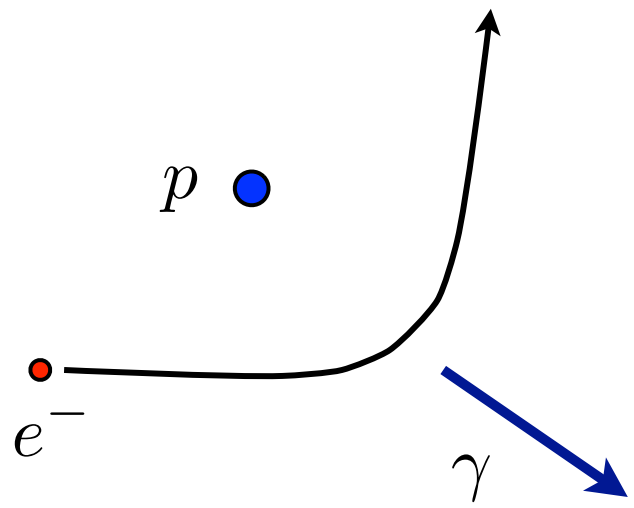
$$\delta(g(x)) = \frac{\delta(x-x_0)}{|g'(x_0)|}$$

$$g(x_0) = 0$$

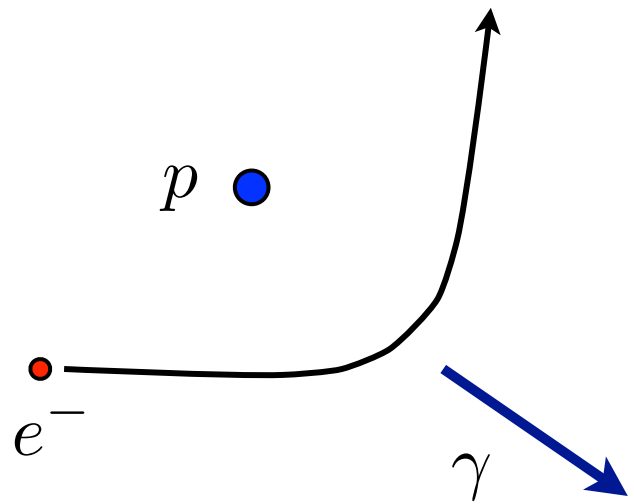
$$\delta\left(\overbrace{E_\gamma - \frac{4}{3}\left(\frac{E_e}{mc^2}\right)^2\epsilon_{CMB}}^{g(x)}\right) = \frac{\delta(E_e - aE_\gamma^{1/2})}{\frac{2}{a}E_\gamma^{1/2}}$$

$x_0 \propto E_\gamma^{1/2}$ $\quad$ $g' \propto E_e$

Leptonic Gamma-Rays: Bremsstrahlung



Leptonic Gamma-Rays: Bremsstrahlung



"catastrophic" process

$$E_e \longrightarrow \epsilon_\gamma$$

$$n_e \propto E_e^{-\delta} \longrightarrow n_\gamma \propto \epsilon_\gamma^{-\delta}$$

(power law -> power law)

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)

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)

(2) inverse Compton scattering: $(\alpha = \frac{\delta + 1}{2})$

CR electron spectrum: $N_e \propto E^{-3}$ ⇨ gamma ray spectrum: $q_\gamma \propto E^{-2}$

(plus the Klein-Nishina cutoff at ~50 TeV)

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)

(2) inverse Compton scattering: $(\alpha = \frac{\delta + 1}{2})$

CR electron spectrum: $N_e \propto E^{-3}$ ⇨ gamma ray spectrum: $q_\gamma \propto E^{-2}$

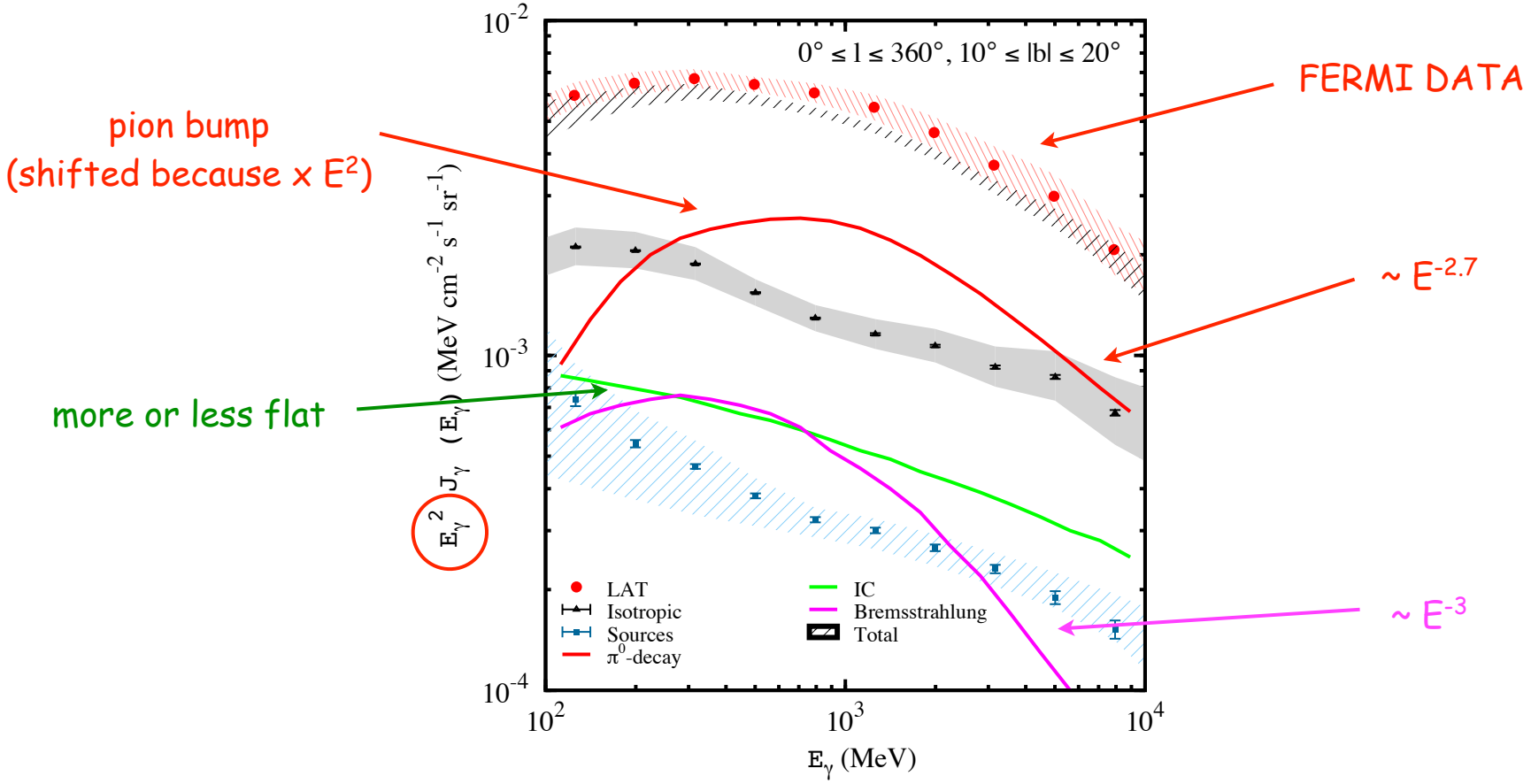
(plus the Klein-Nishina cutoff at ~50 TeV)

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

CR electron spectrum: $N_e \propto E^{-3}$ ⇨ gamma ray spectrum: $q_\gamma \propto E^{-3}$

The gamma ray emission from the Galaxy

FERMI observation of the galactic diffuse emission



p-p interactions dominate the diffuse emission

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.