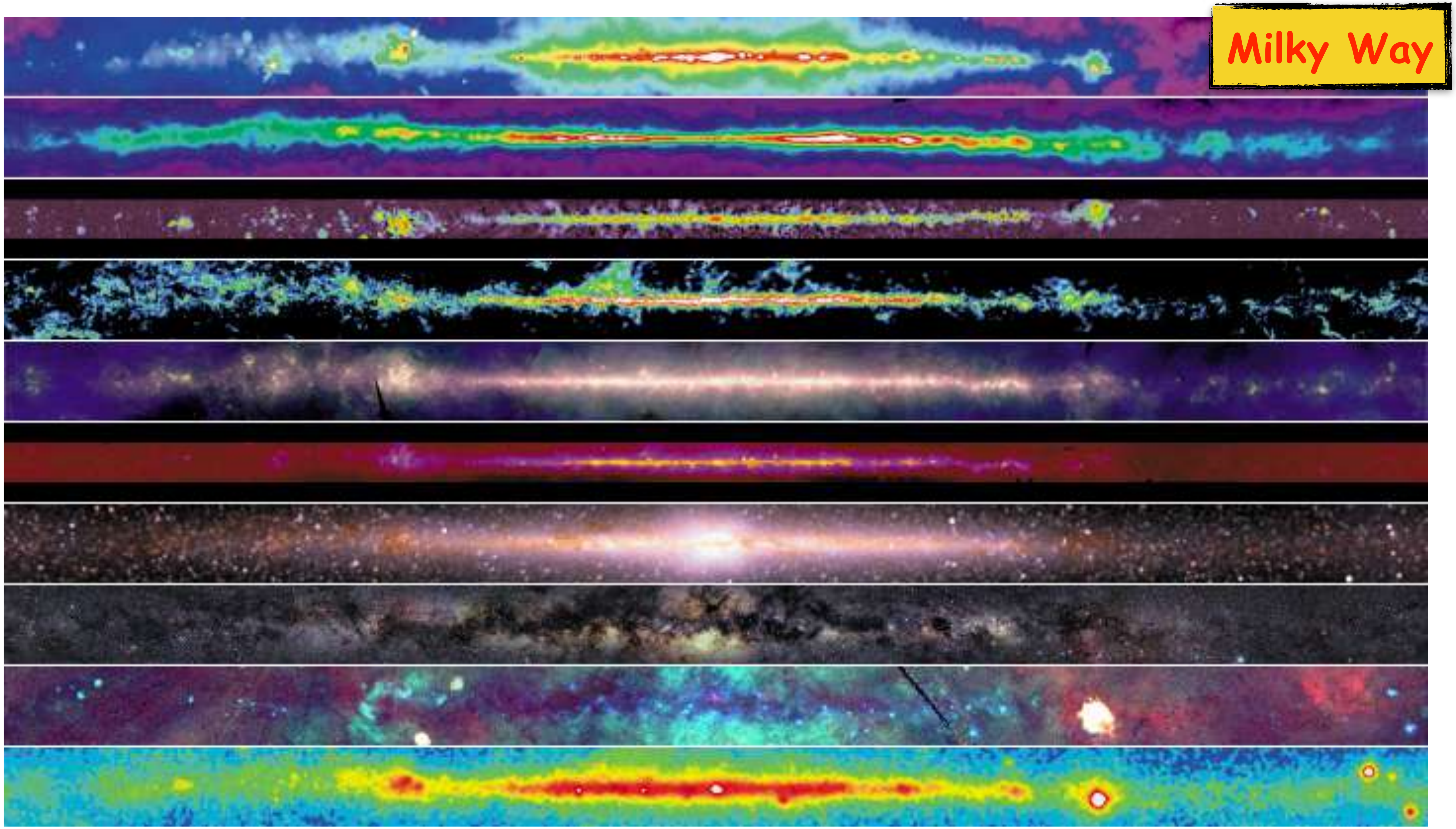
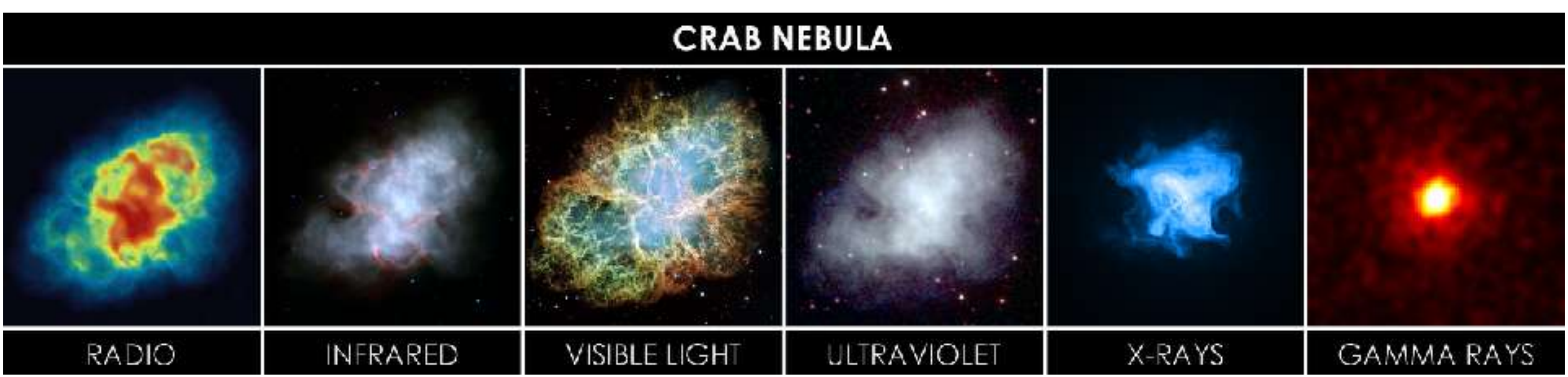
Production of photons (and not only) by high-energy particles (and not only)

Stefano Gabici
APC, Paris

www.cnrs.fr

gamma-rays ———————— radio waves

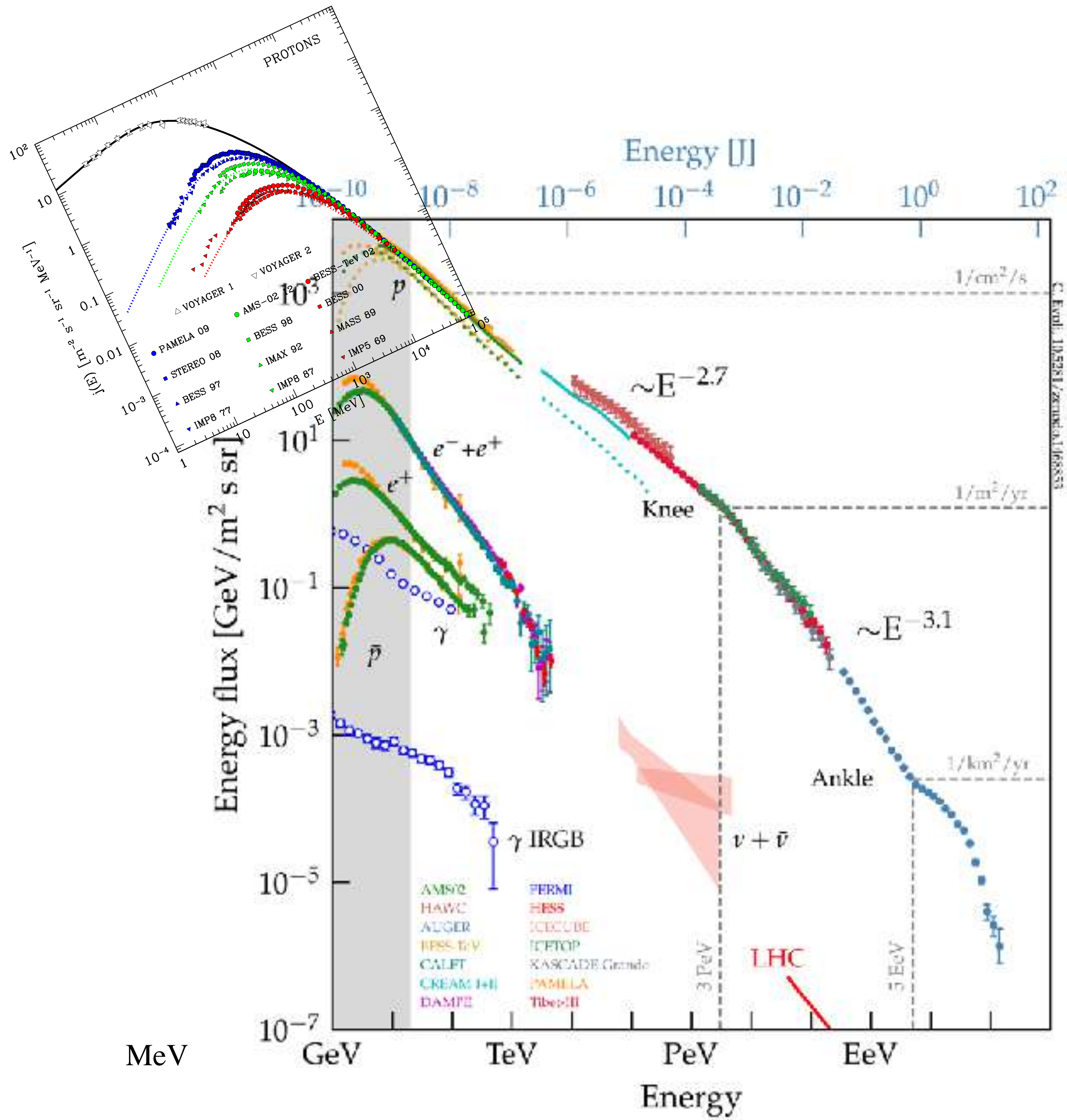


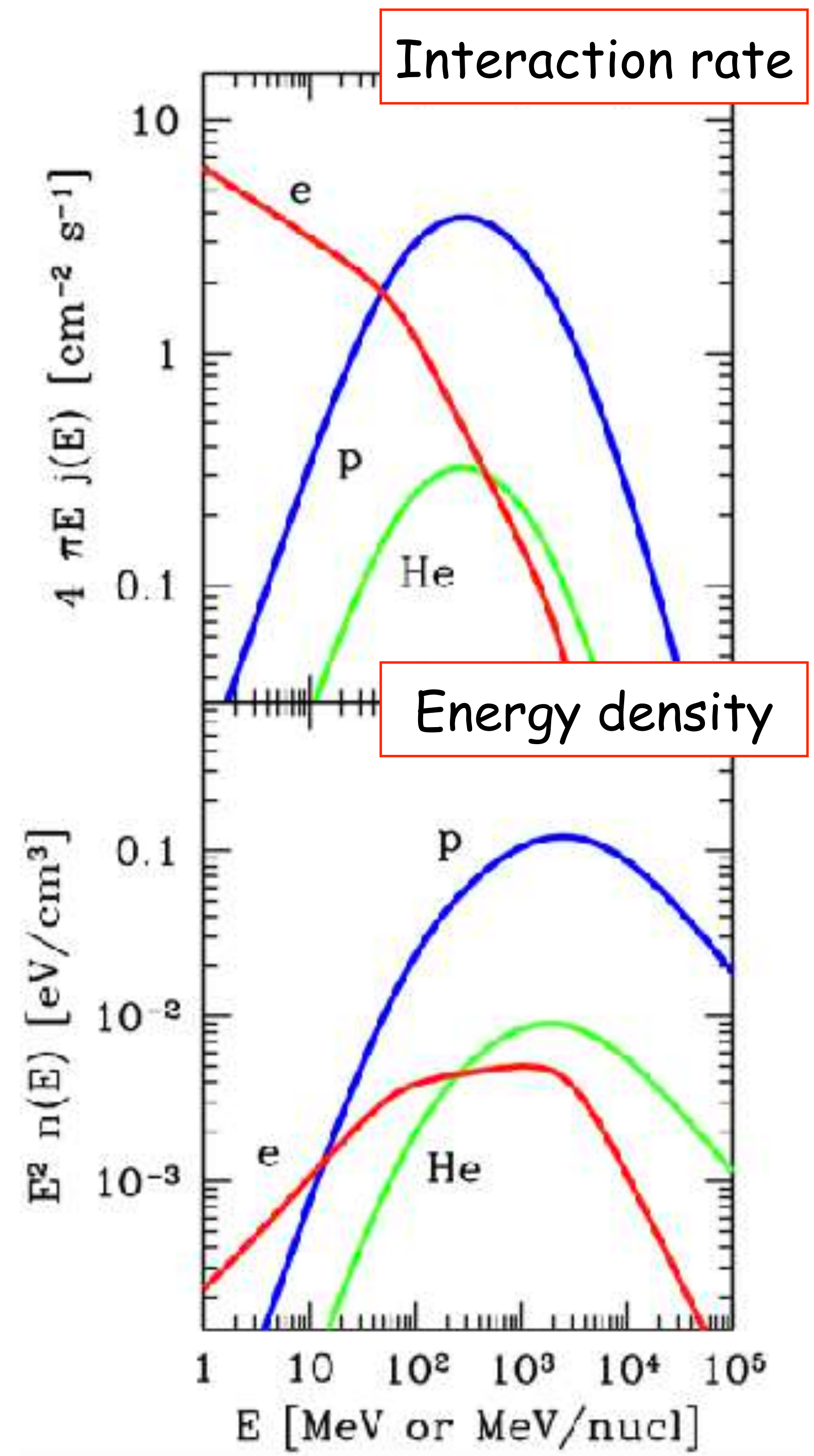


it is impossible to review in a decent way “all” radiative processes in 1.5 h*

* see also Matteo’s classes

One question every 3 (energy) decades…





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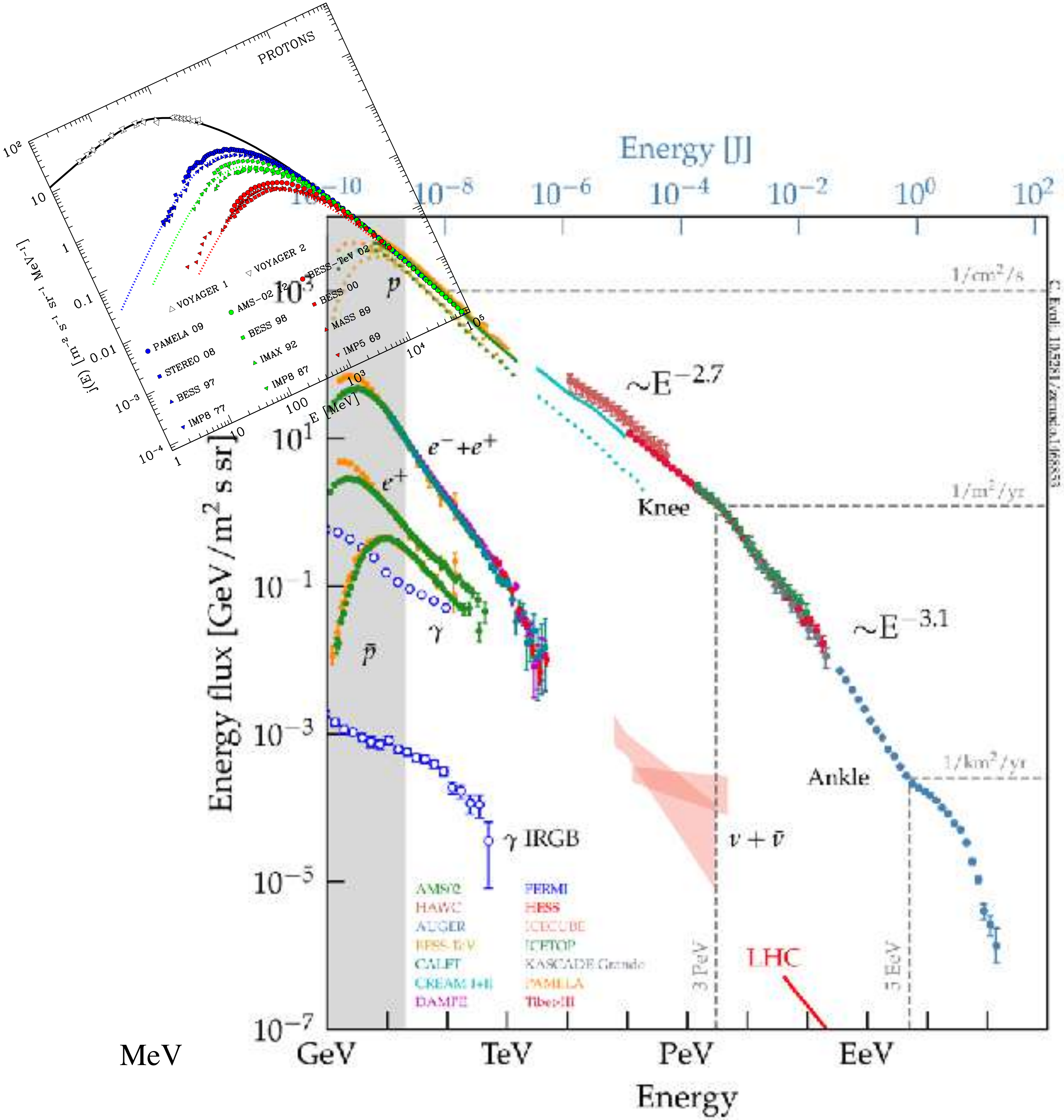

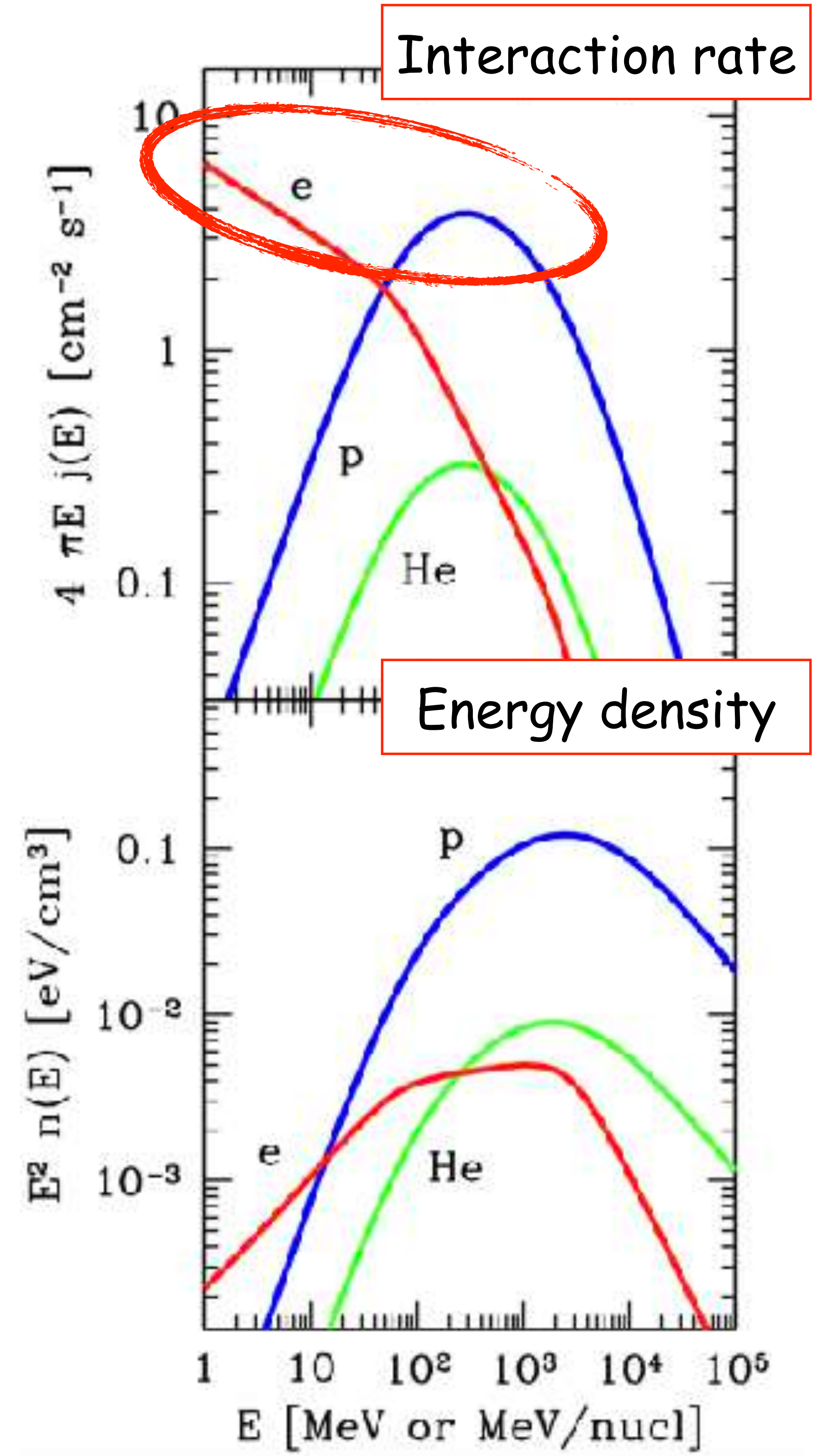

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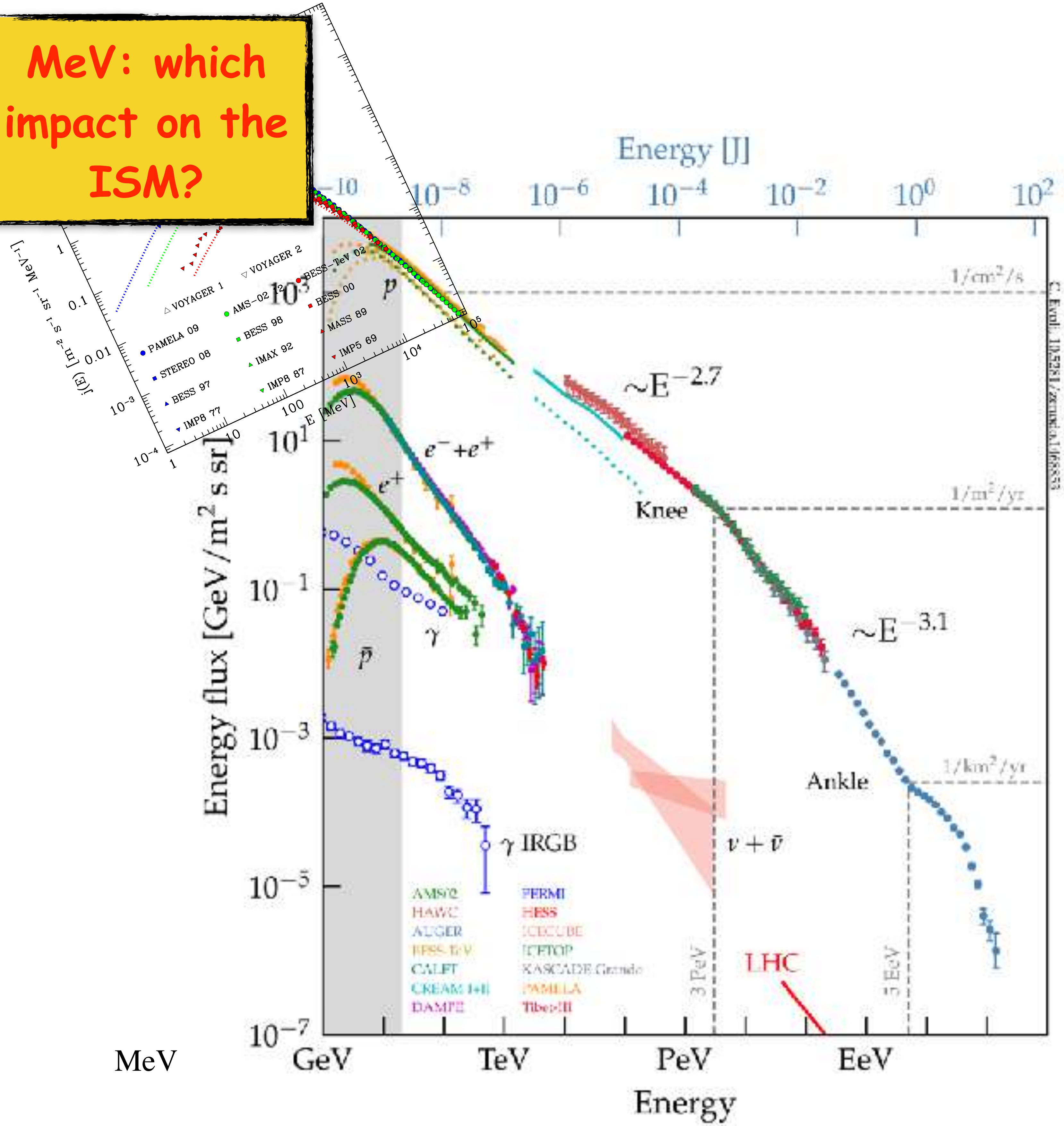
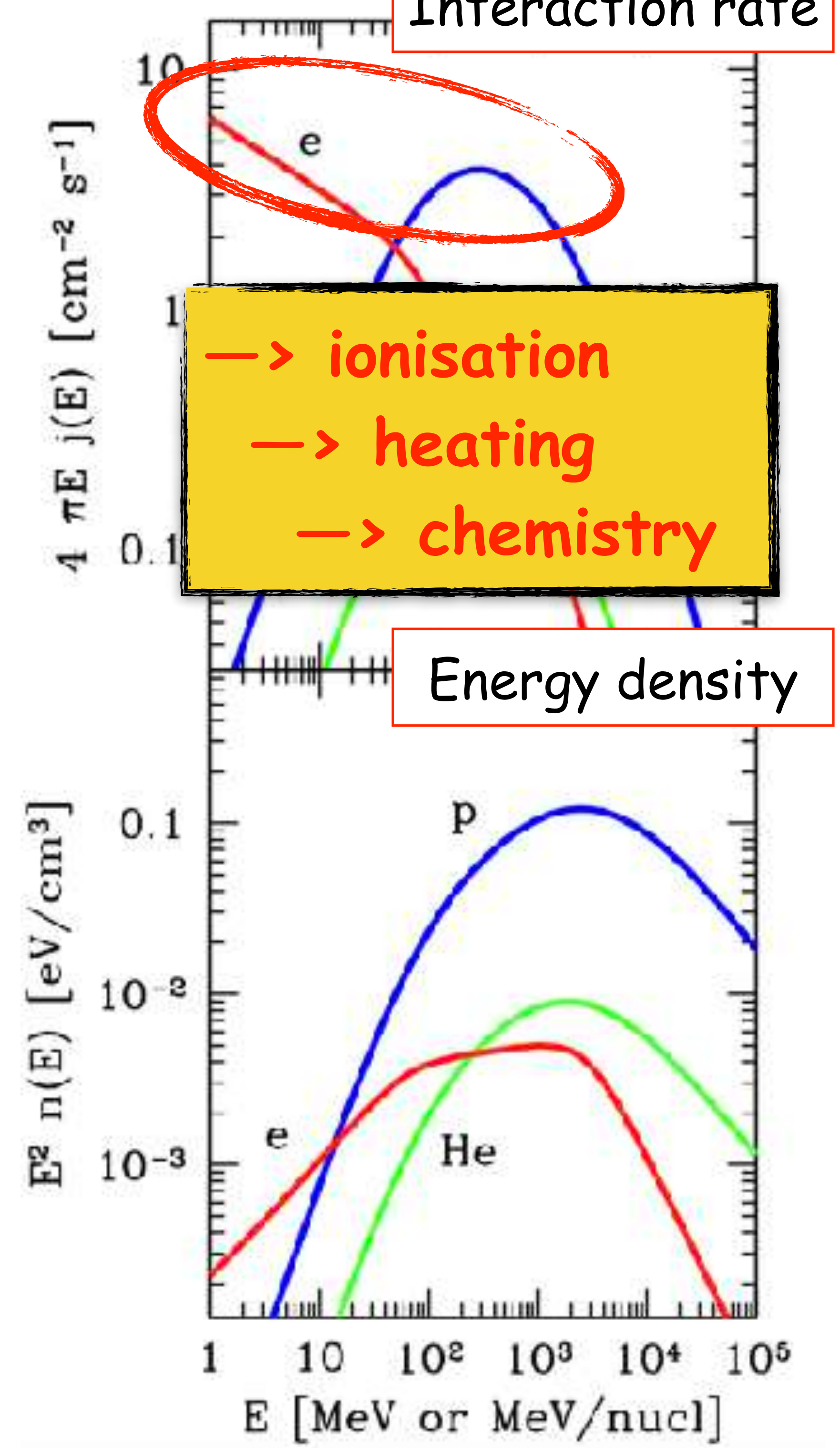
MeV: which impact on the ISM?





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—> heating
—> chemistry

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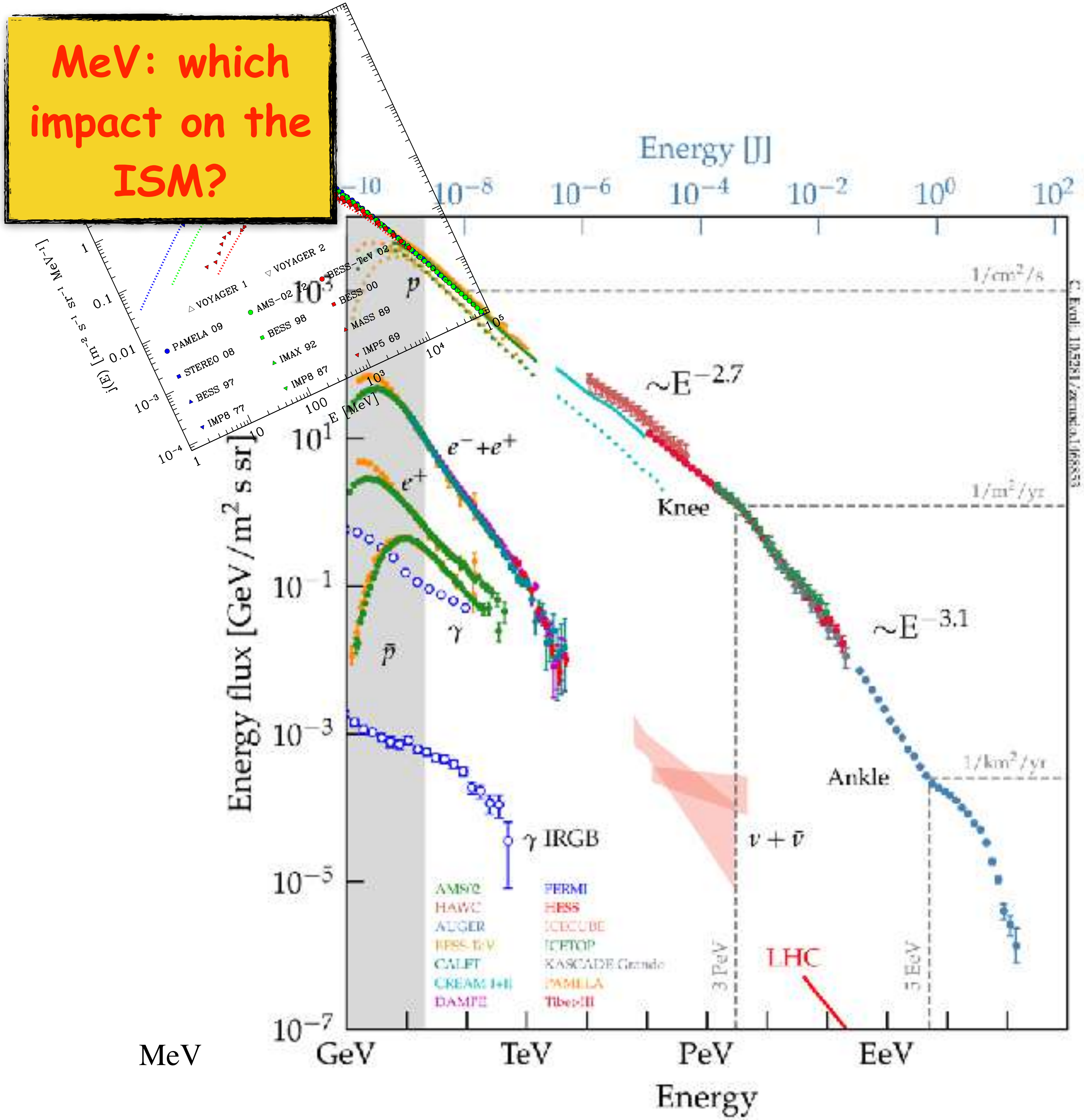

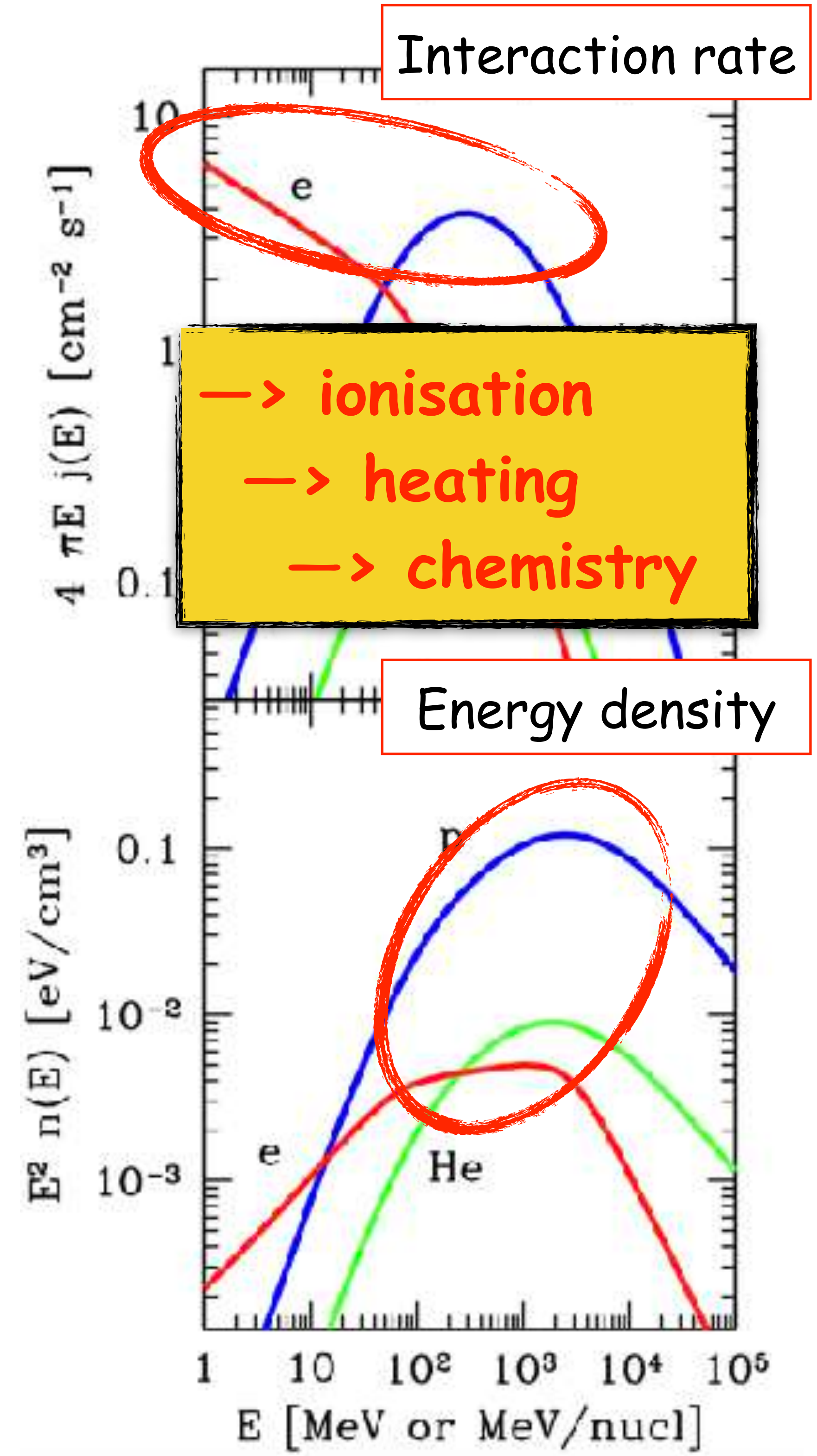

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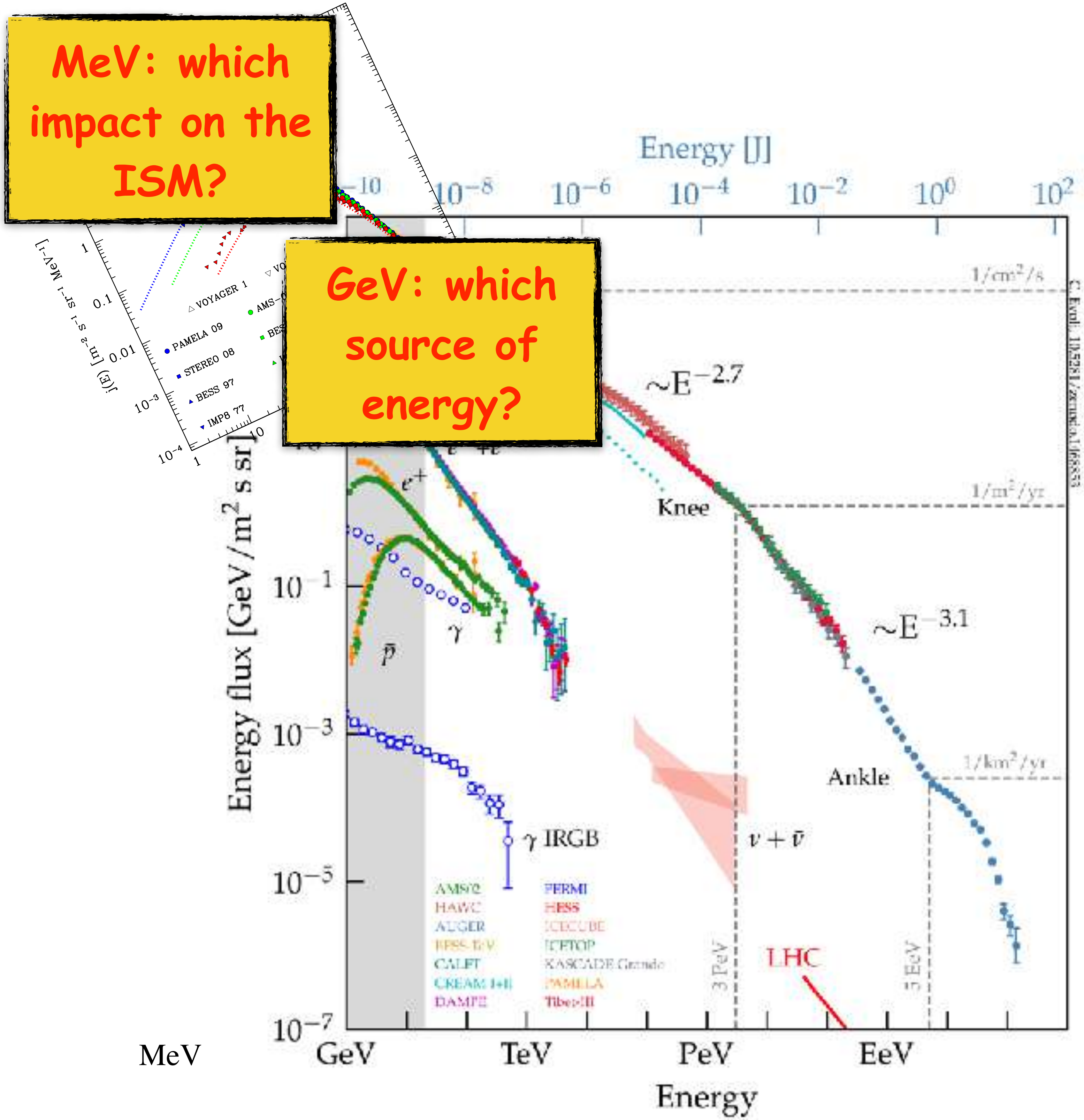

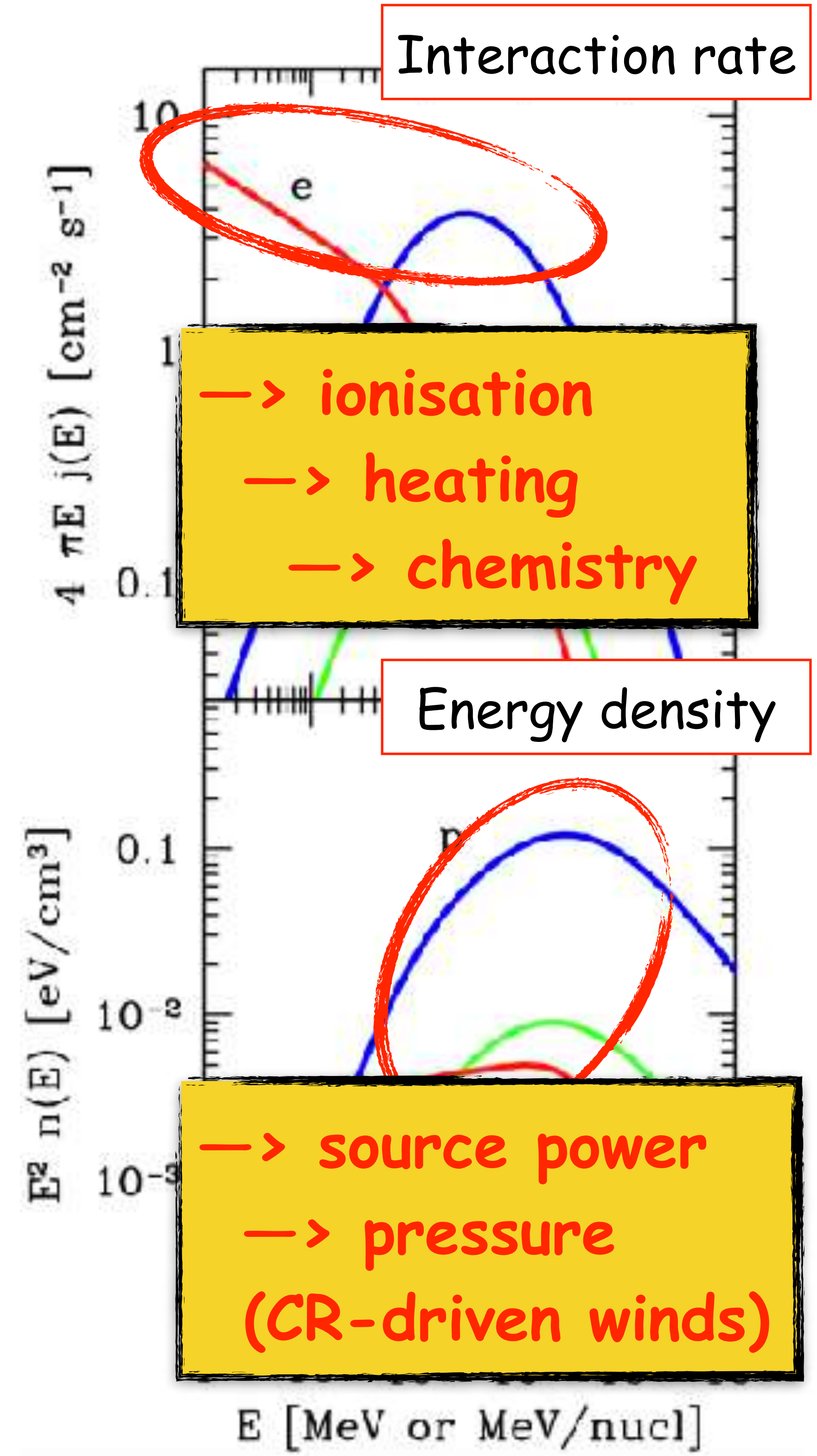

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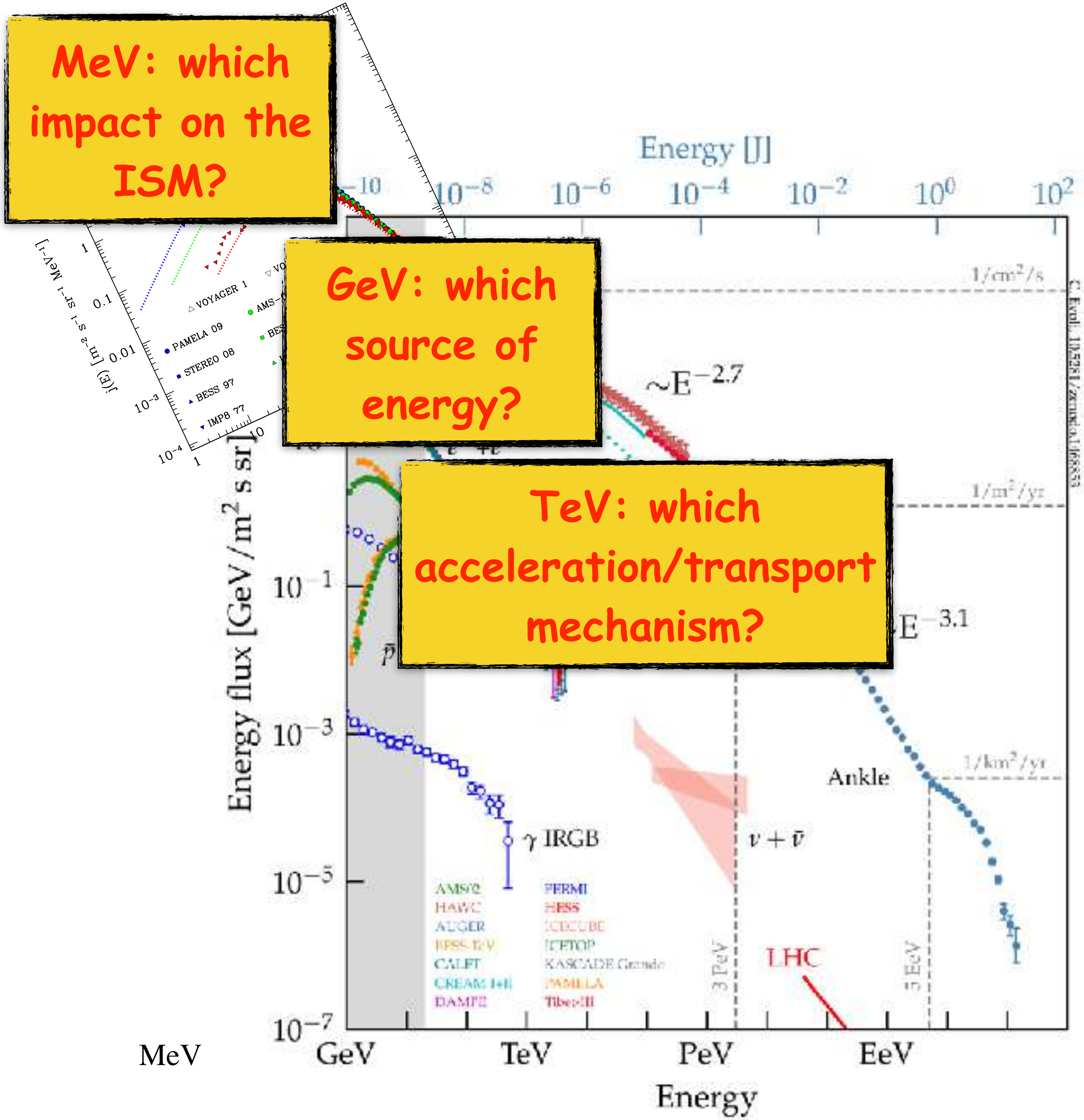
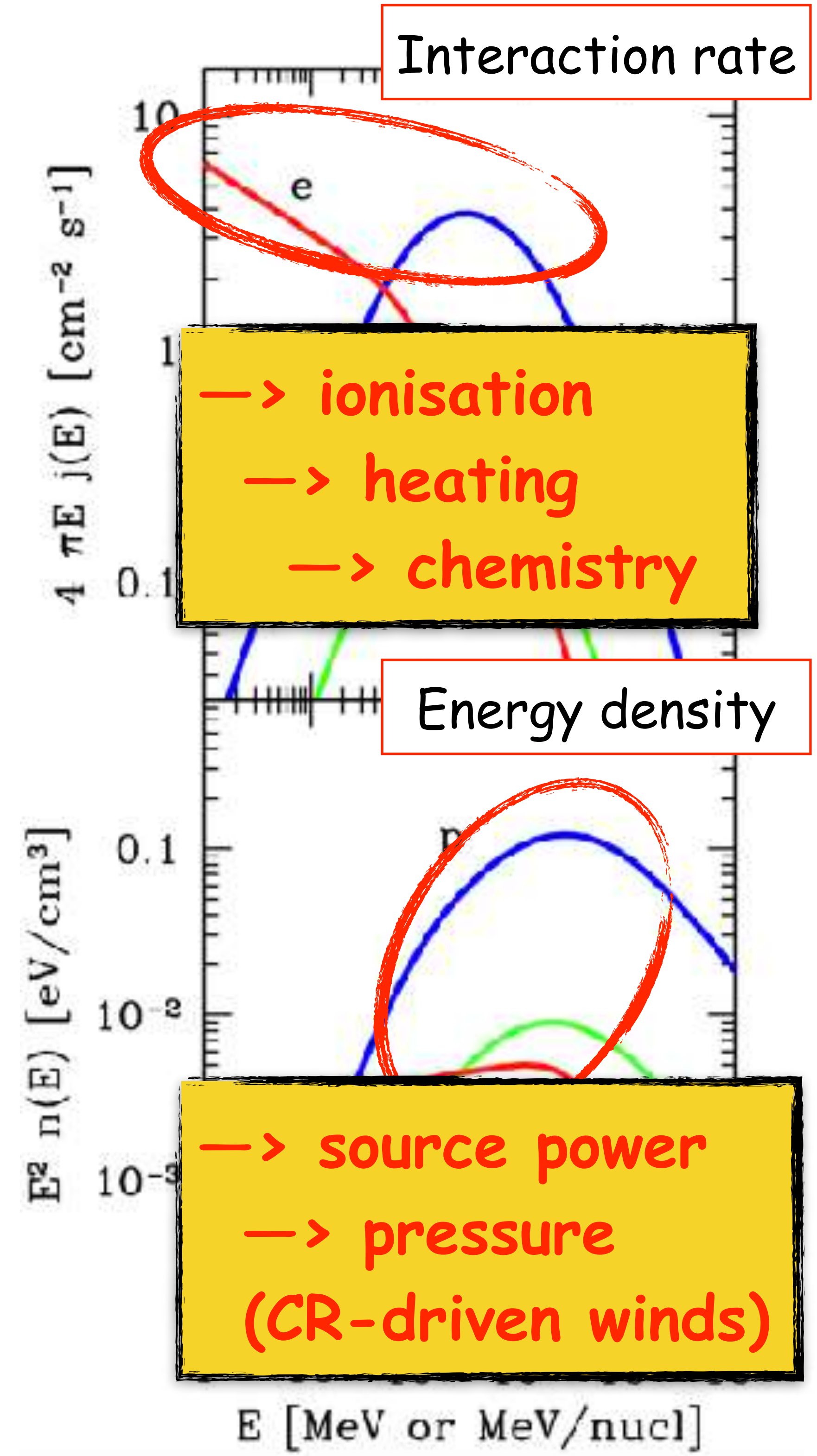
GeV: which source of energy?

TeV: which acceleration/transport mechanism?





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(CR-driven winds)

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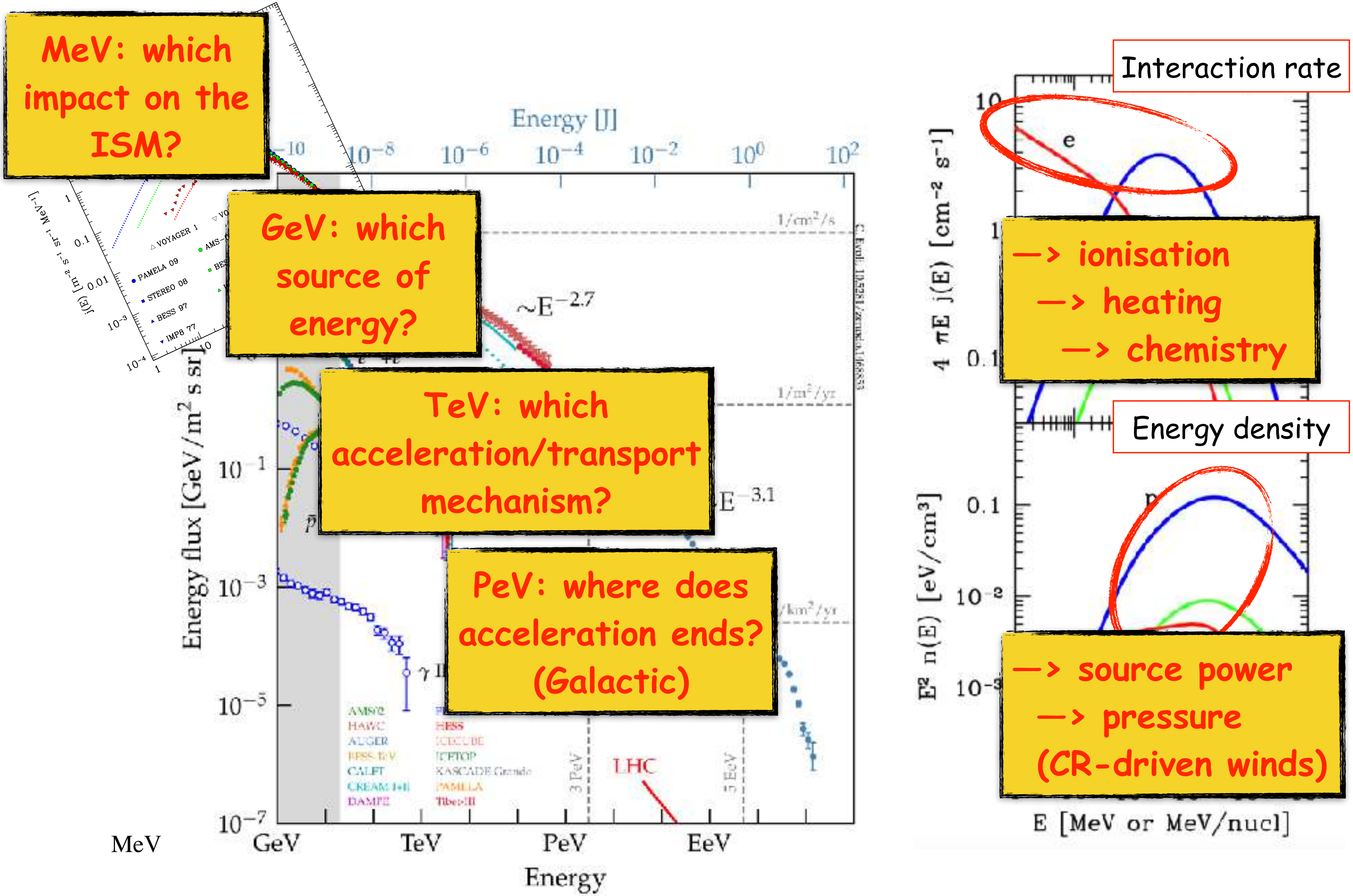

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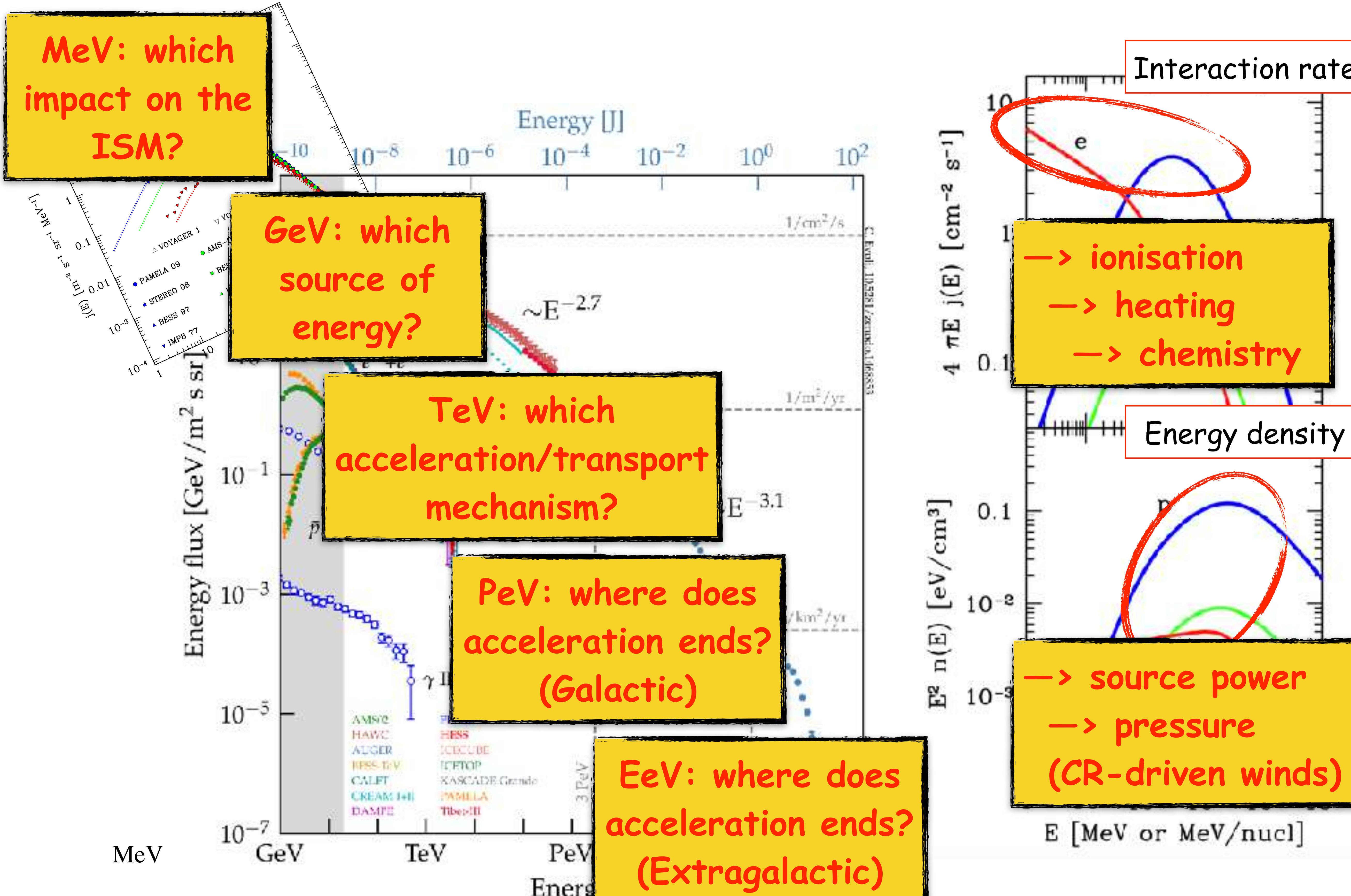

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GeV: which source of energy?

TeV: which acceleration/transport mechanism?

PeV: where does acceleration ends? (Galactic)

EeV: where does acceleration ends? (Extragalactic)

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Astrophysical environments

we will mostly discuss radiation produced
in interactions between energetic particles and matter or radiation/B-fields

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interstellar medium (ISM)

filling factor

Phase	n_{tot} (cm^{-3})	T (K)	M ($10^9\,M_\odot$)	f
Molecular	>300	10	2.0	0.01
Cold neutral	50	80	3.0	0.04
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$$B \sim 3\ \mu G$$

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a remarkable coincidence (yes, just a coincidence)

$$\frac{B^2}{8\pi} \sim \omega_{CMB} \sim 0.25\ \mathrm{eV/cm^3}$$

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but not only —> high energy radiation without non-thermal particles

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let's begin with estimating the emission of a thermal plasma of temperature T

Simplifying assumptions: fully ionised hydrogen plasma ($n_i = n_e$), protons and electrons in thermal equilibrium (same temperature T)

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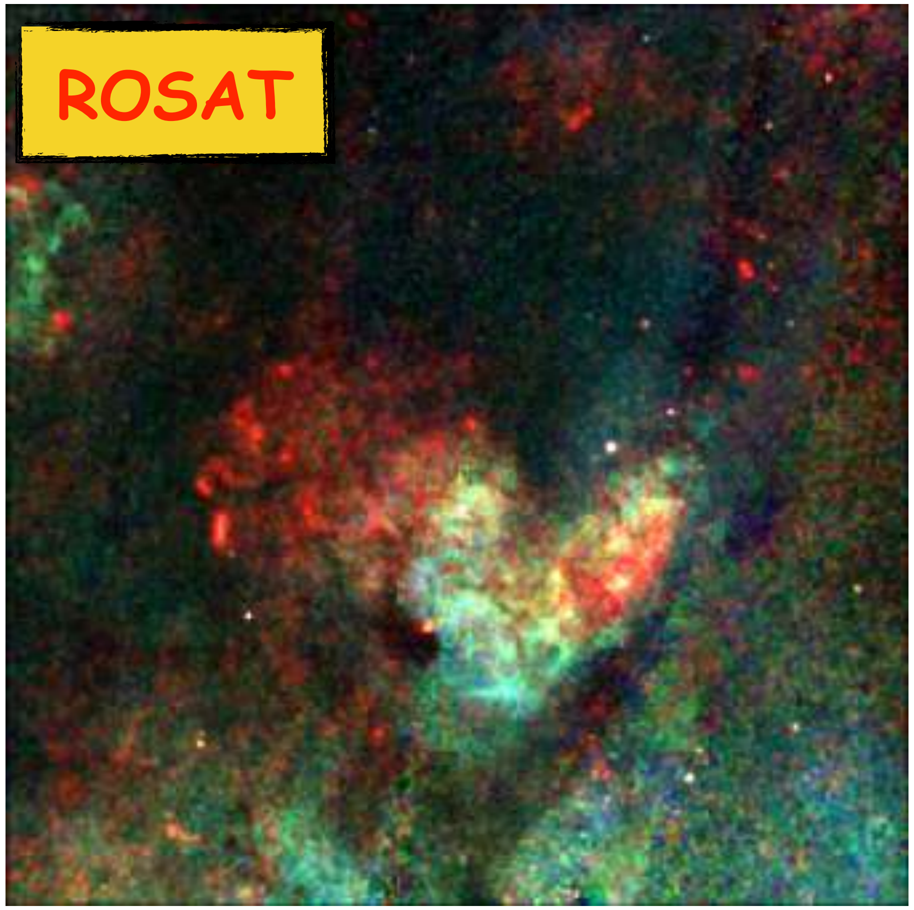

—> the hot phase consists of cavities inflated by stellar winds or generated by supernova remnants and emits thermal X-rays

X-ray telescopes onboard of satellites: XMM, Chandra, NuSTAR, eROSITA, …

Emission from hot plasmas: thermal Bremsstrahlung

Radiation from a thermal electron-proton plasma

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$$v = \sqrt{\frac{3kT}{m}} \longrightarrow v_e = \left(\frac{m_p}{m_e}\right)^{1/2} v_p \gg v_p$$

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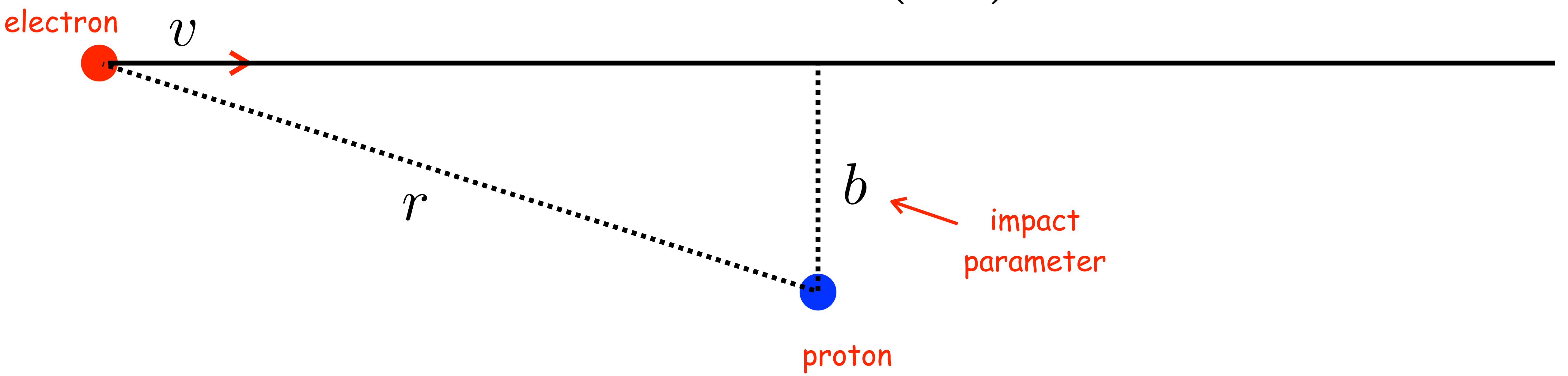

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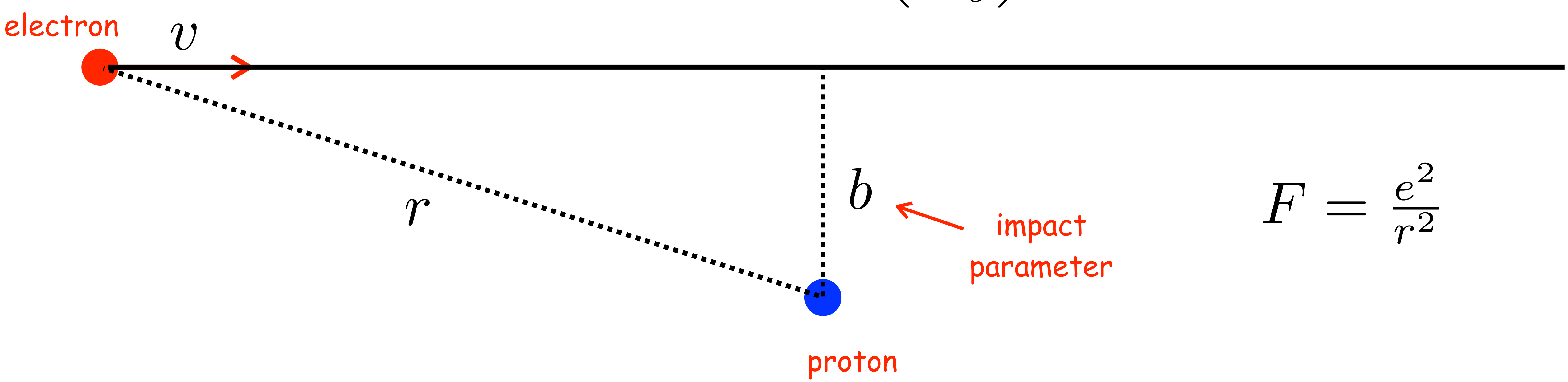

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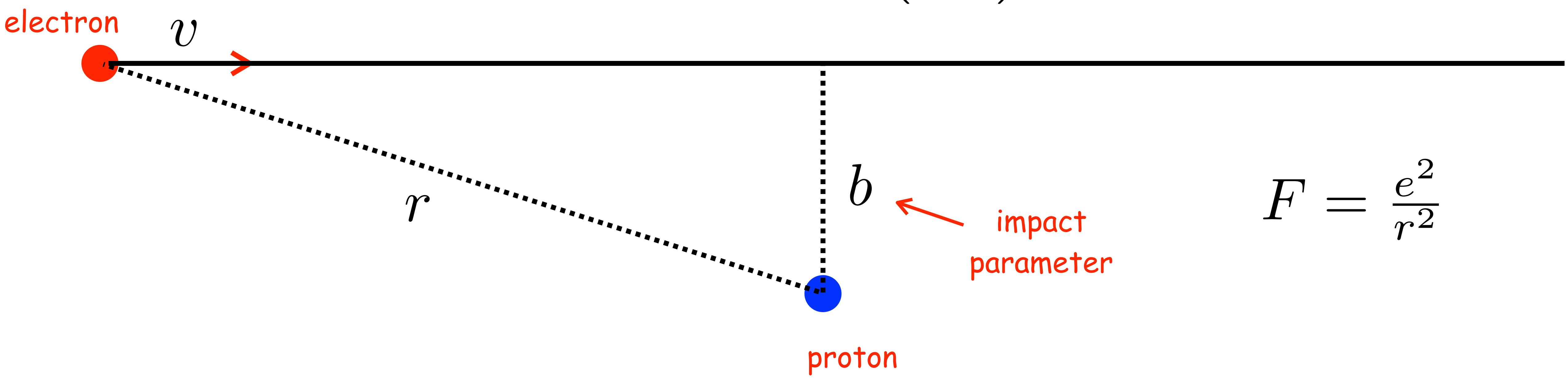

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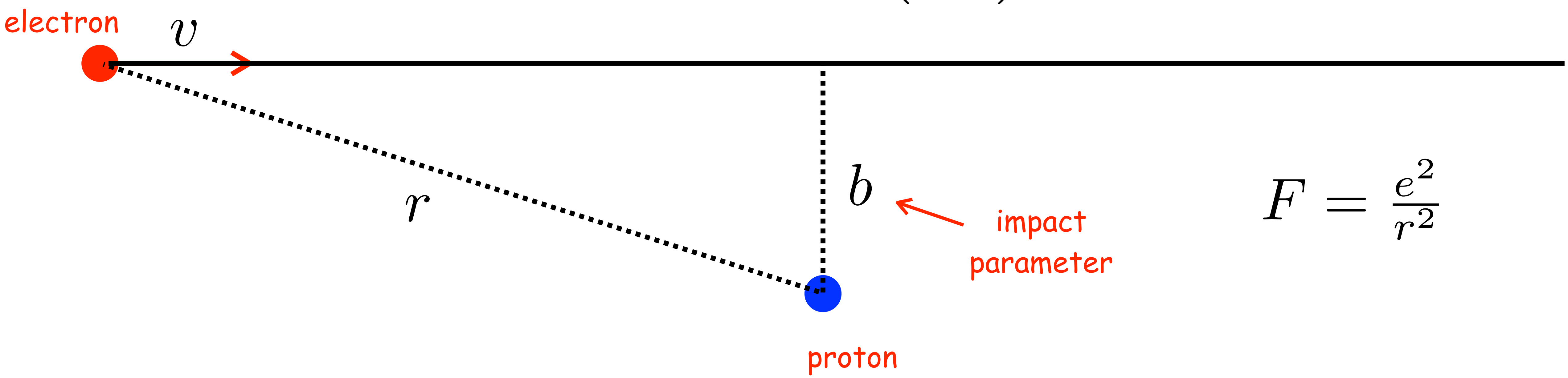

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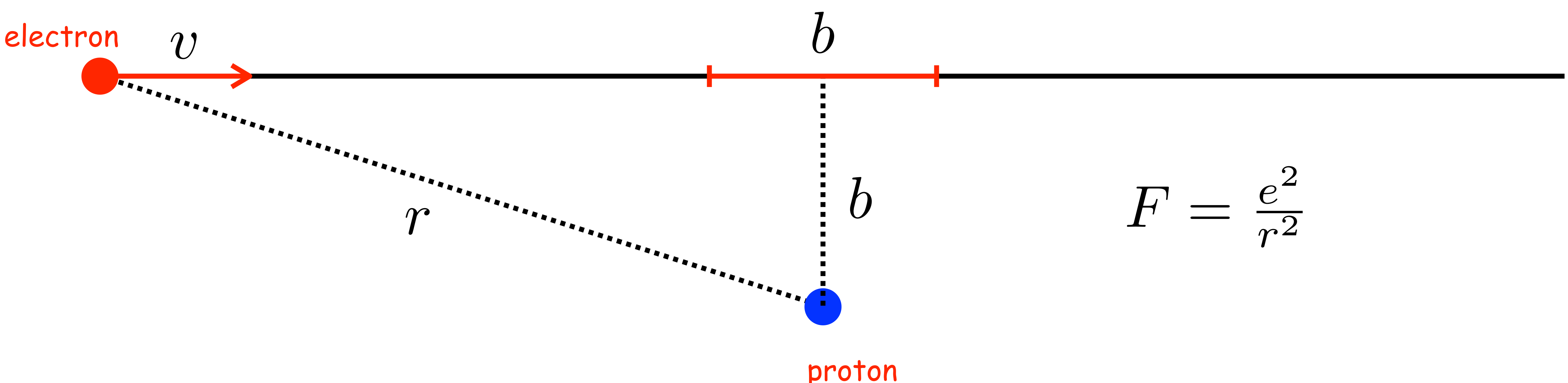
Thermal Bremsstrahlung

very brutal approximations...

characteristic time for the interaction $\tau \approx \frac{b}{v} \longrightarrow \omega \approx \frac{1}{\tau} = \frac{v}{b}$ characteristic frequency of the emitted radiation



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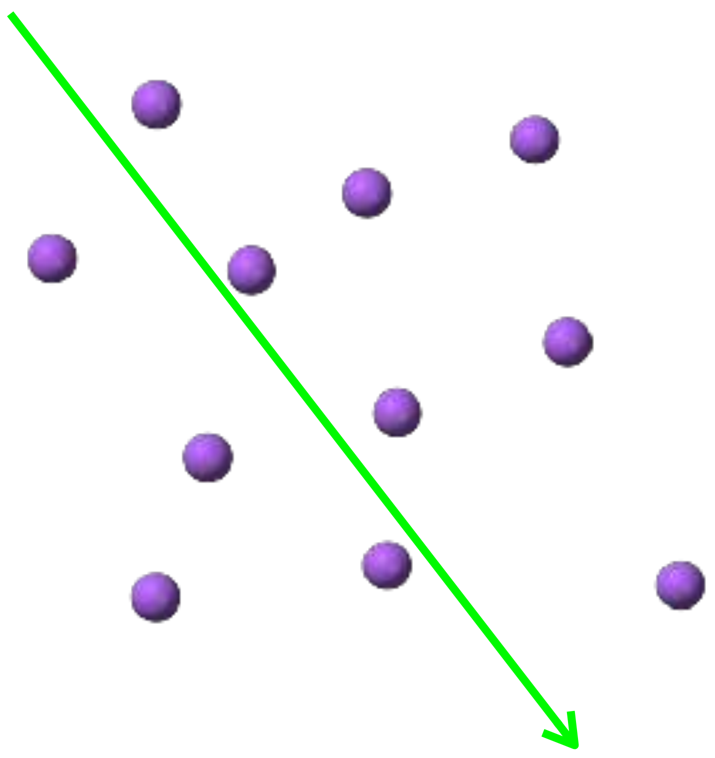
Thermal Bremsstrahlung

rough estimate of the impact parameter b

plasma proton density -> n_p

mean distance between protons -> $l_p \sim n_p^{-1/3} \approx b$



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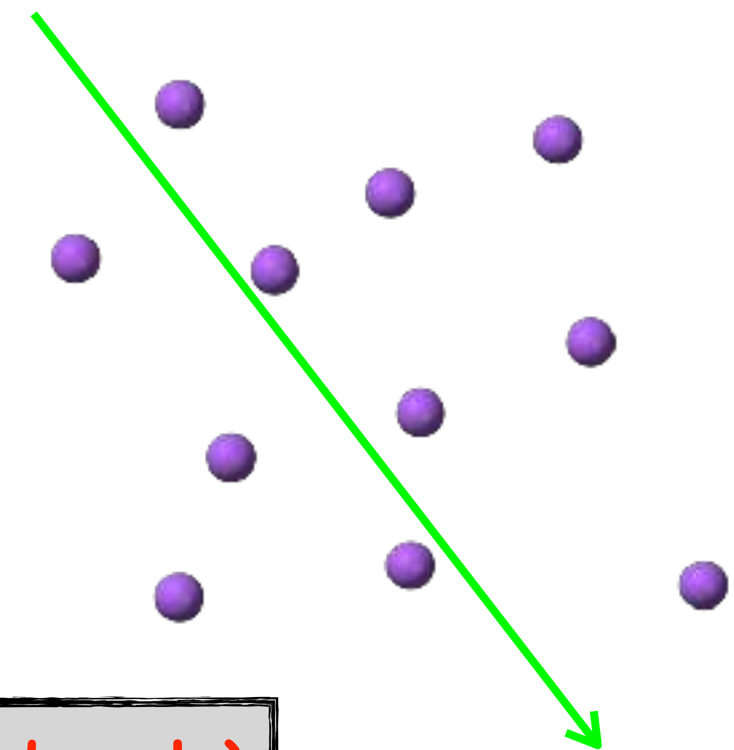

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emissivity (power per unit frequency, volume, and solid angle)

ω -> ν = ω/2π

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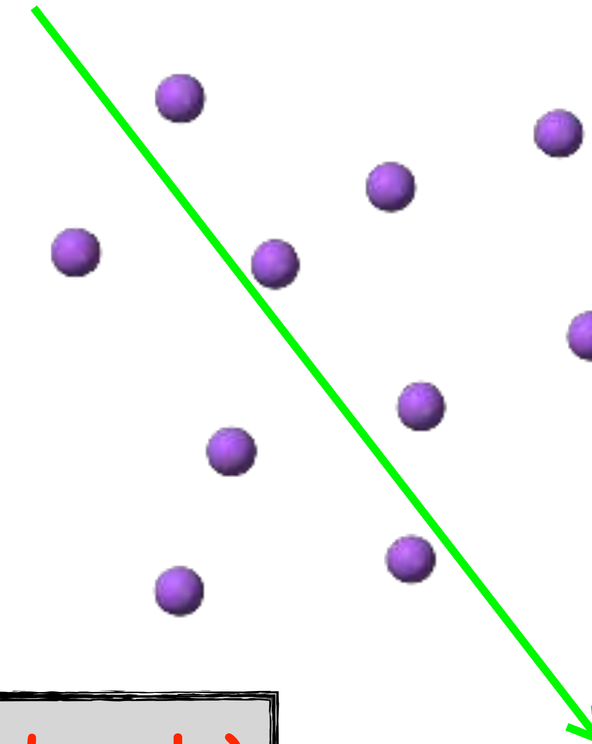

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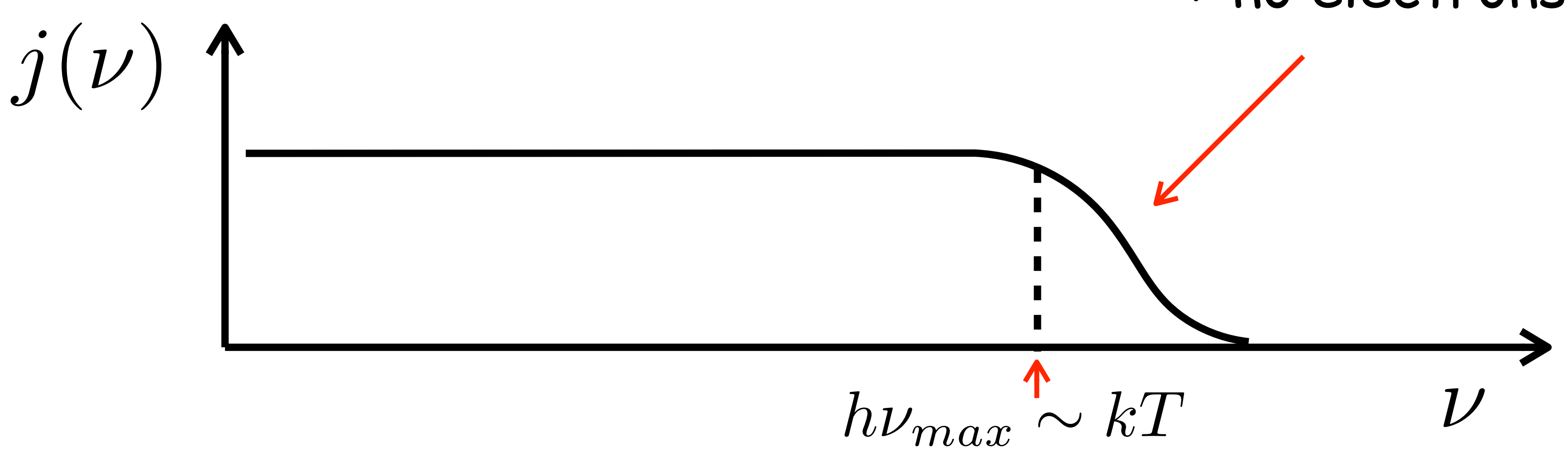
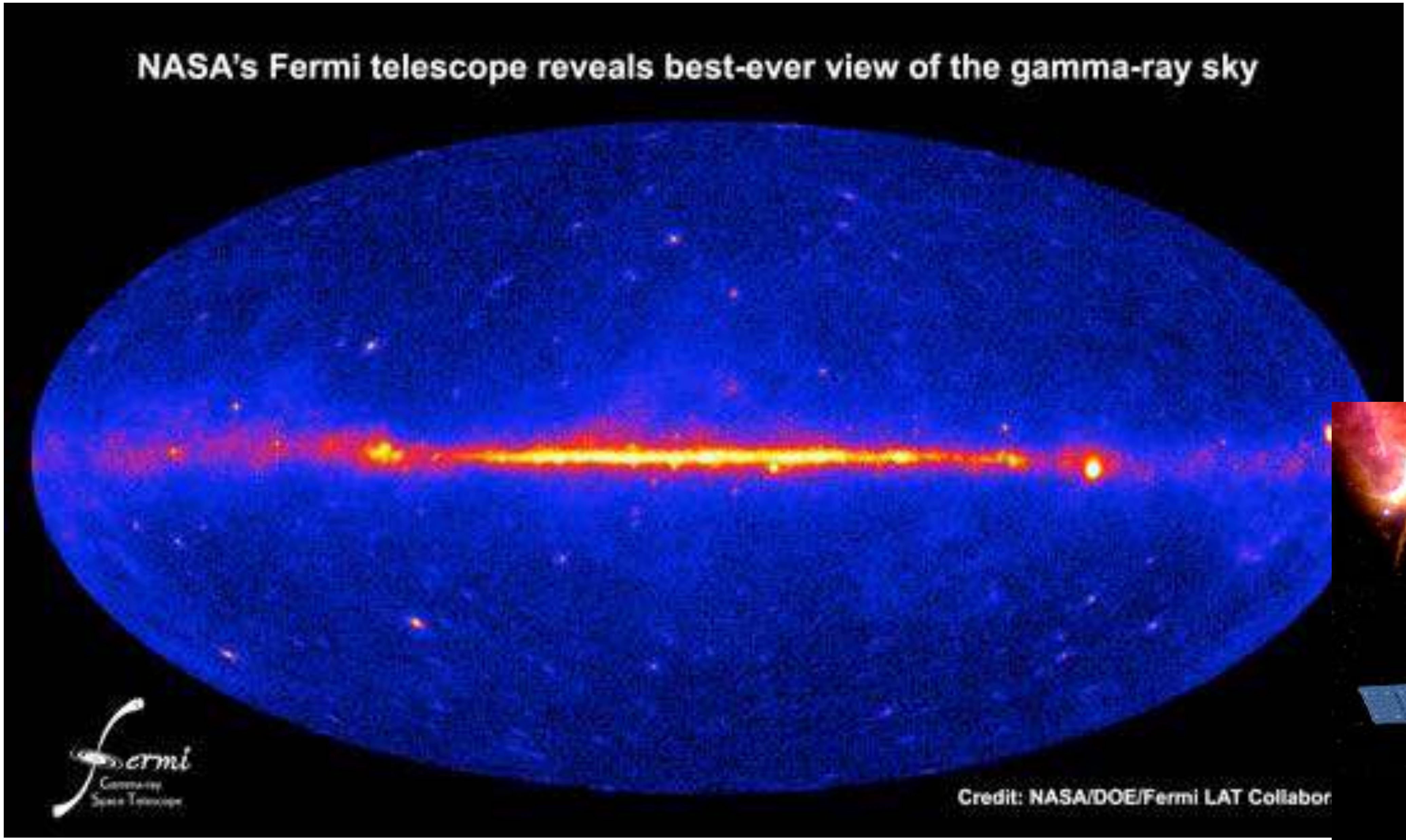
exponential suppression
-> no electrons with energy >> kT



Cosmic ray interactions in the sky



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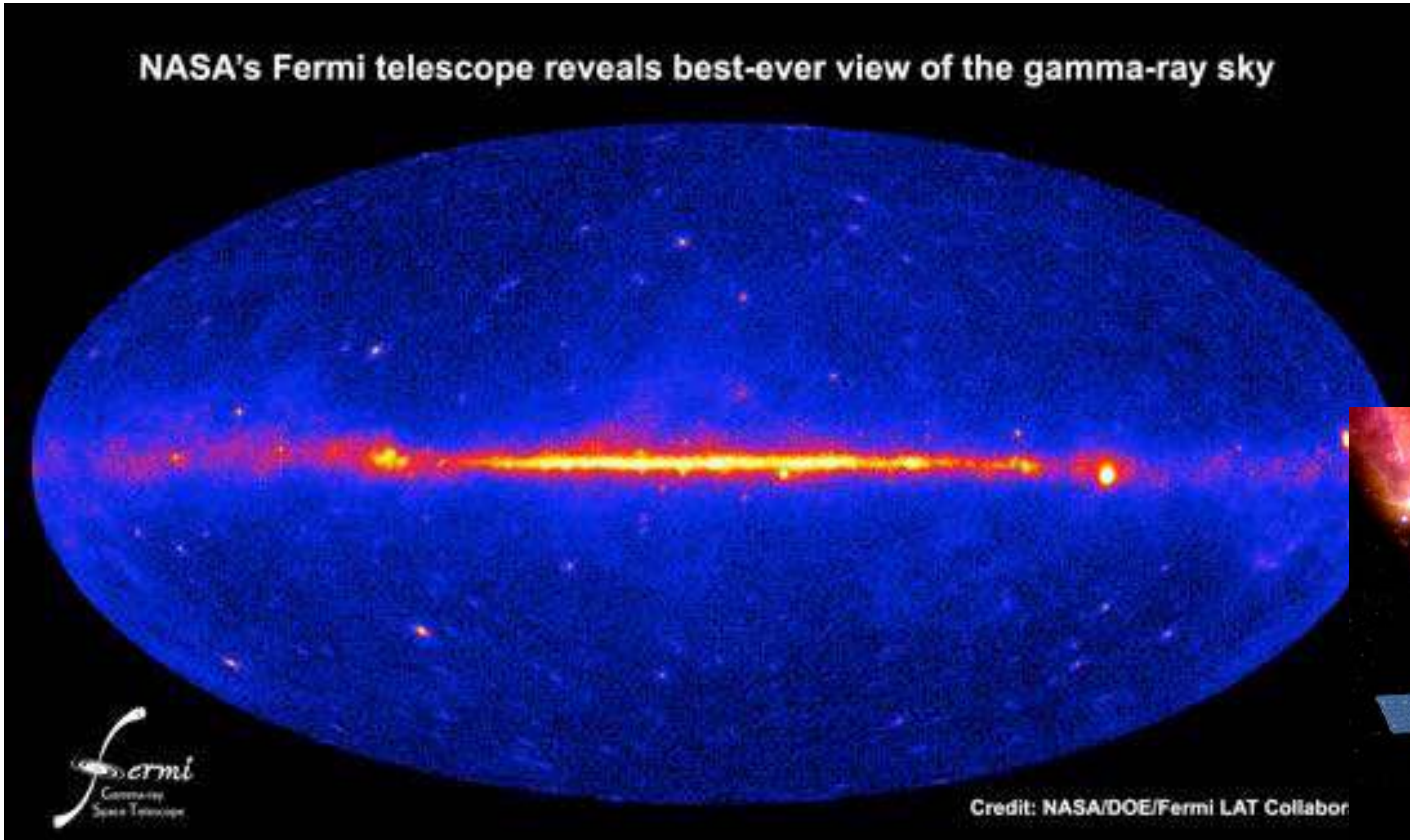

$$p + p \rightarrow p + p + \pi^0$$

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

Gamma-Ray Astronomy: p-p interactions

Energy threshold for neutral pion production:

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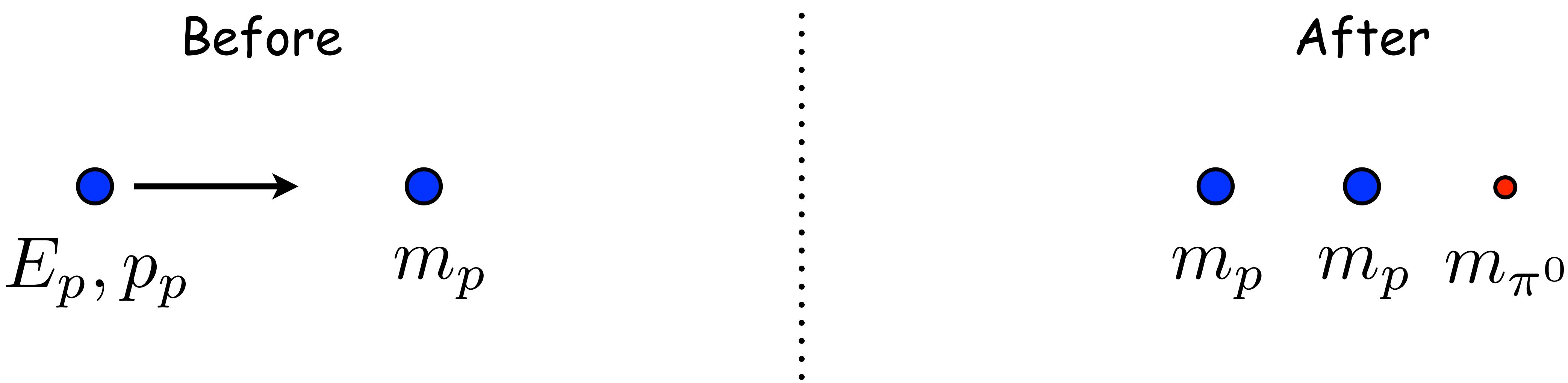

$$E^2 - p^2c^2$$

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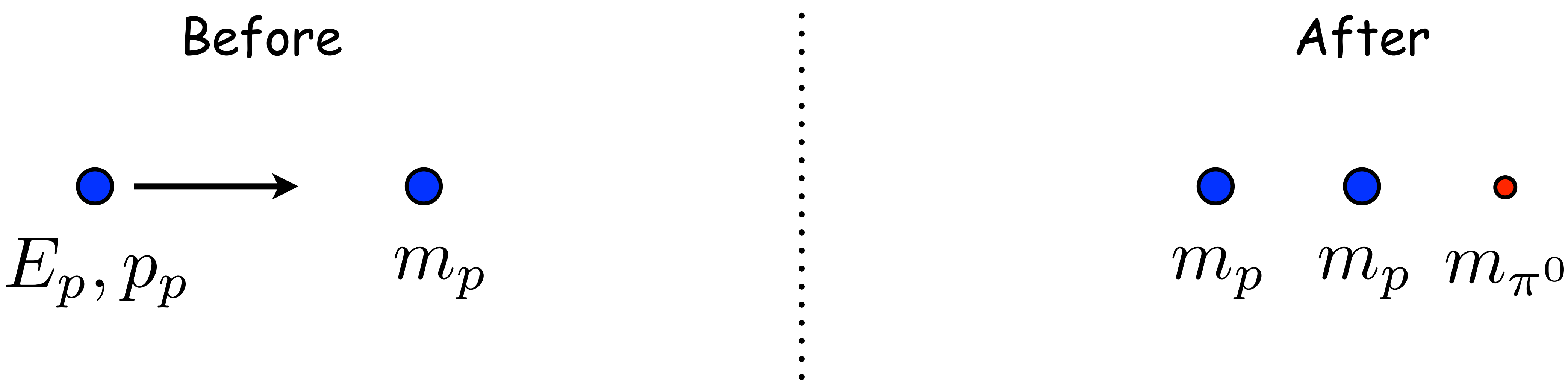

$$E^2 - p^2c^2 = \left(2m_pc^2 + m_{\pi^0}c^2\right)^2$$

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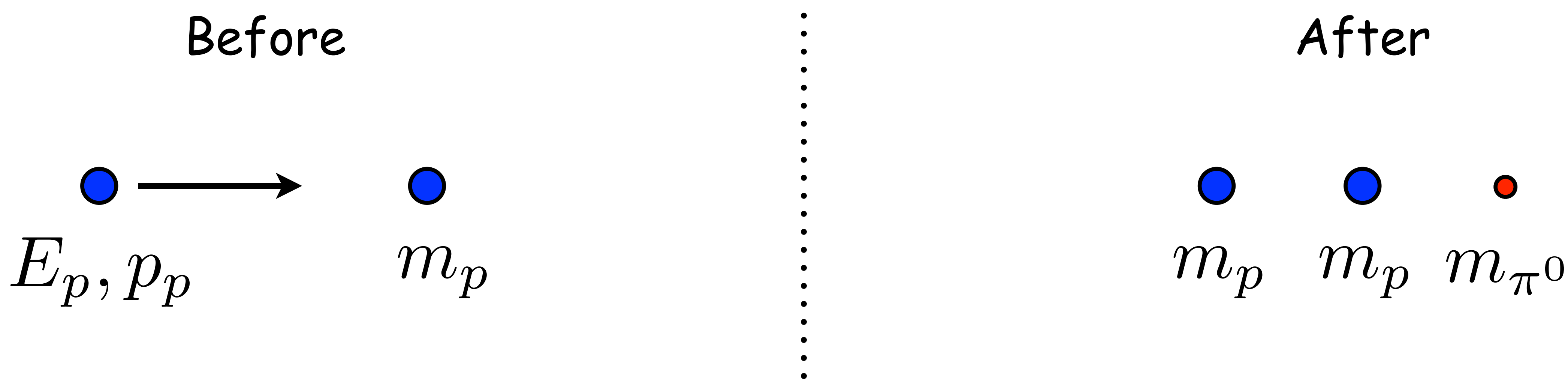

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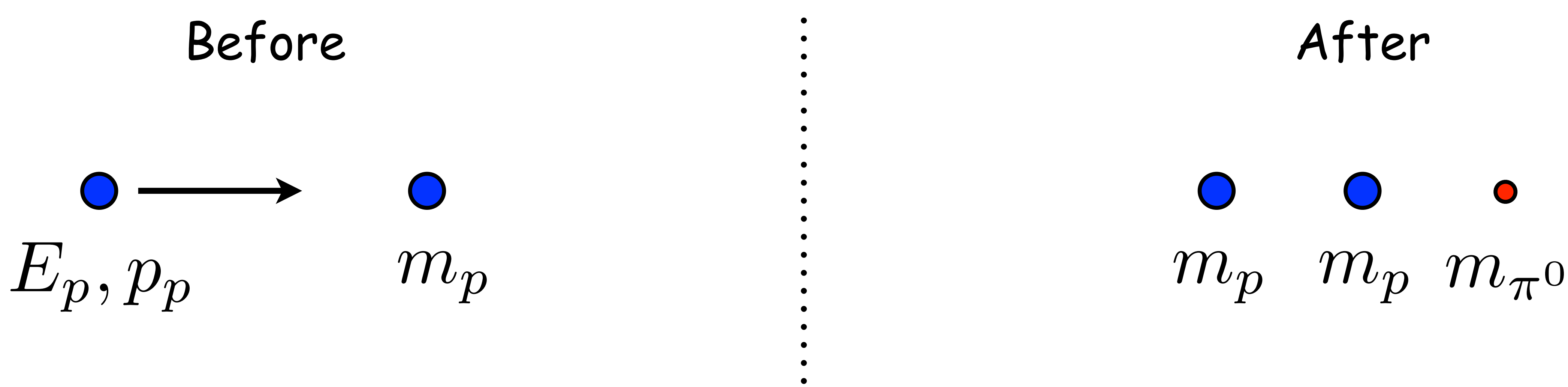

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$$E_p - m_p c^2 > 2m_{\pi^0} c^2 + \left(\frac{m_{\pi^0}}{2m_p}\right) m_{\pi^0} c^2 \approx 280 \text{ MeV}$$

energy threshold

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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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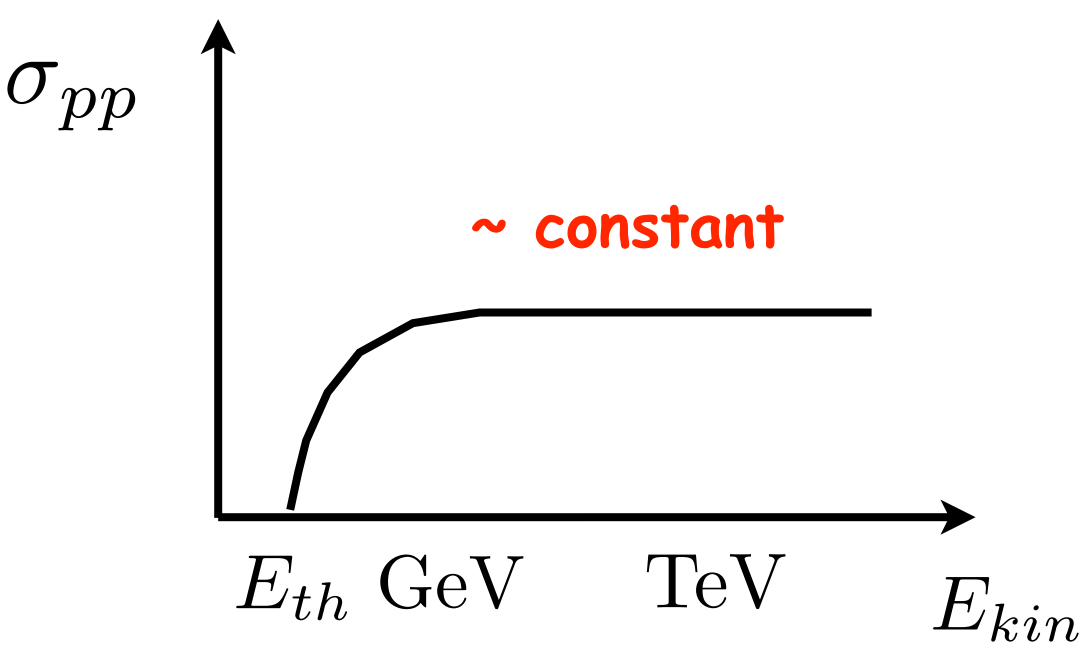

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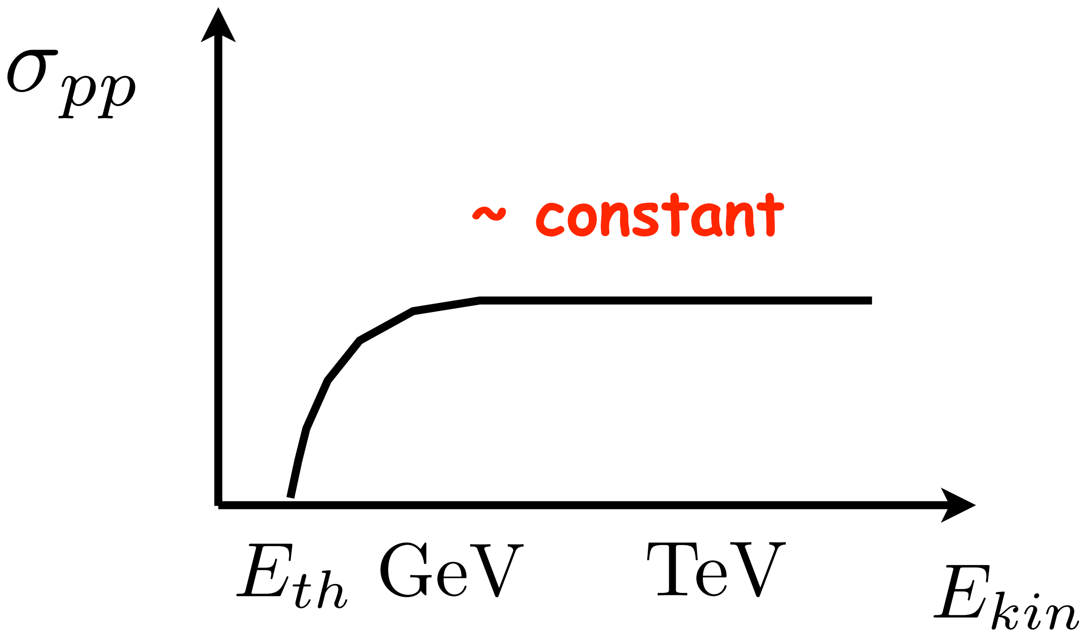

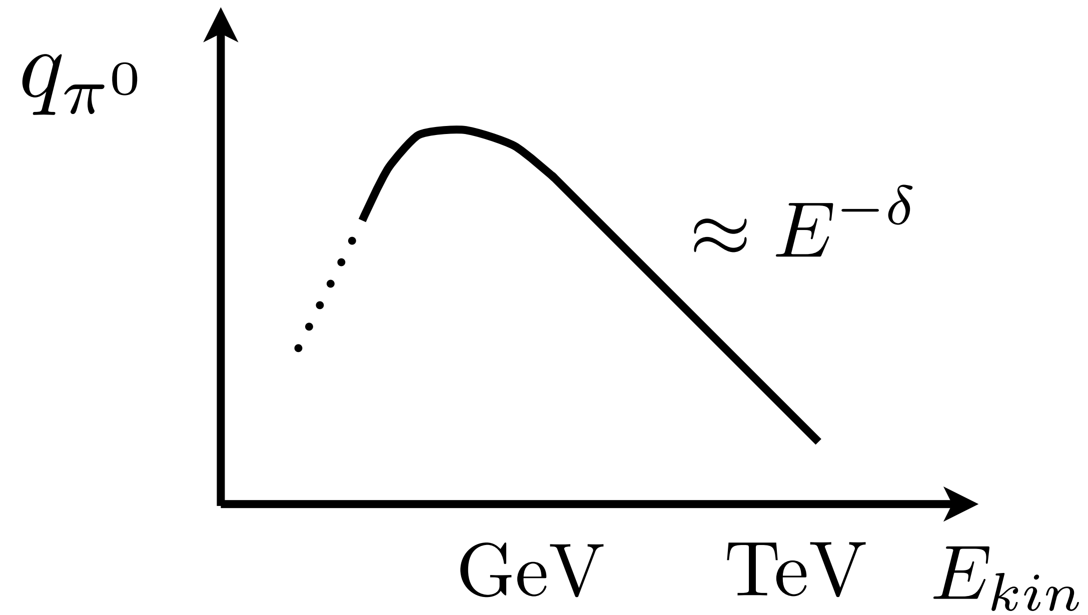

Gamma-Ray Astronomy: p-p interactions

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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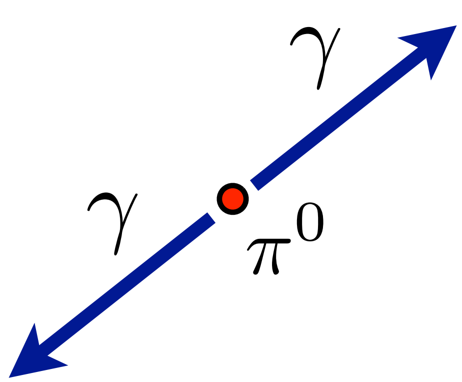

$$E_\gamma^* = \frac{m_{\pi^0}}{2}$$

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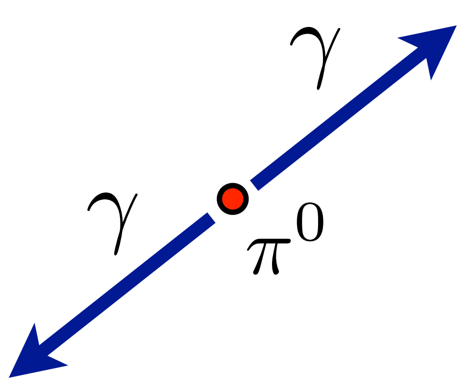

$$E^*_\gamma = \frac{m_{\pi^0}}{2}$$

Lab frame:

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

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

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

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

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(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 $\frac{dn_\gamma}{d\Omega^*} = \frac{1}{4\pi}$

$$d\Omega^* \propto d(\cos\theta^*)$$

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

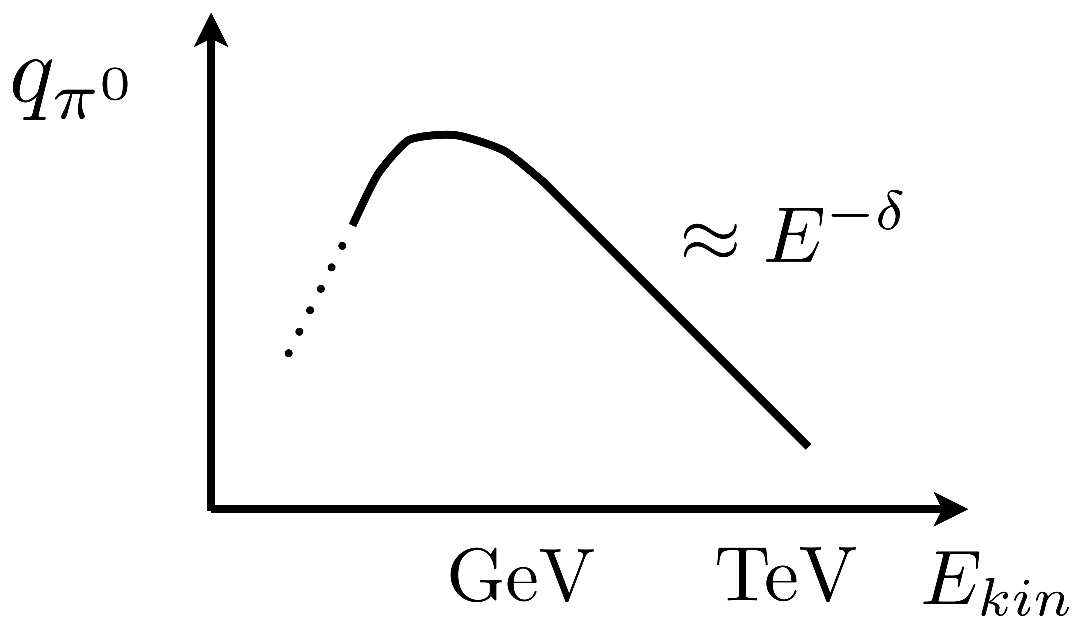
$$\Rightarrow \quad \frac{dn_\gamma}{dE_\gamma} = const$$

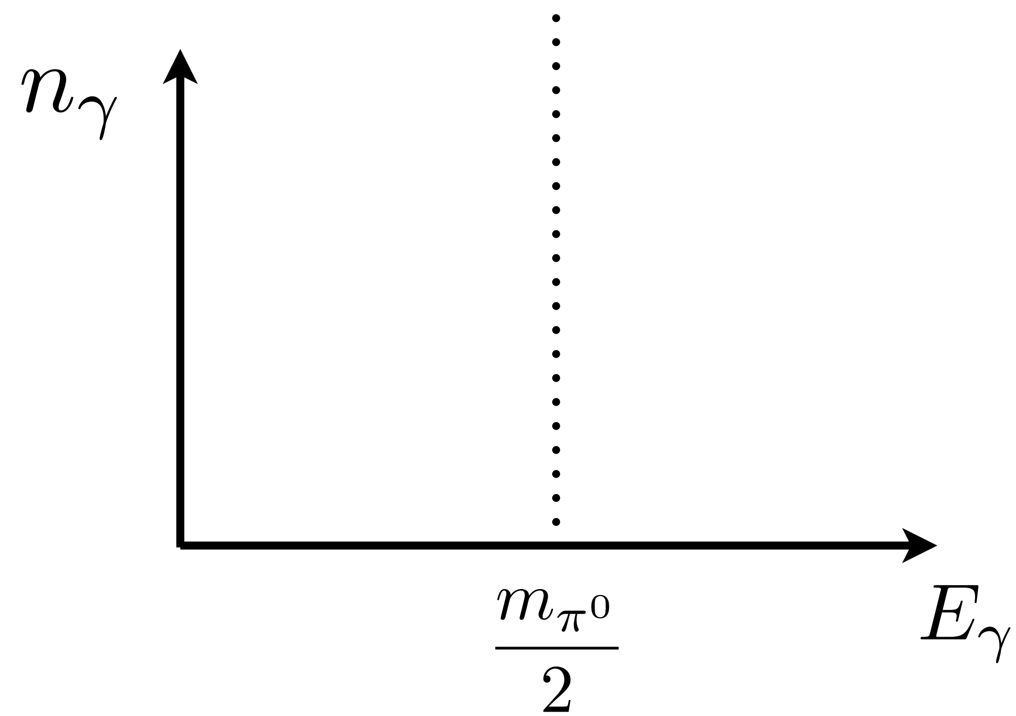
The spectrum is flat!

Gamma-Ray Astronomy: p-p interactions

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

Log-Log plot!





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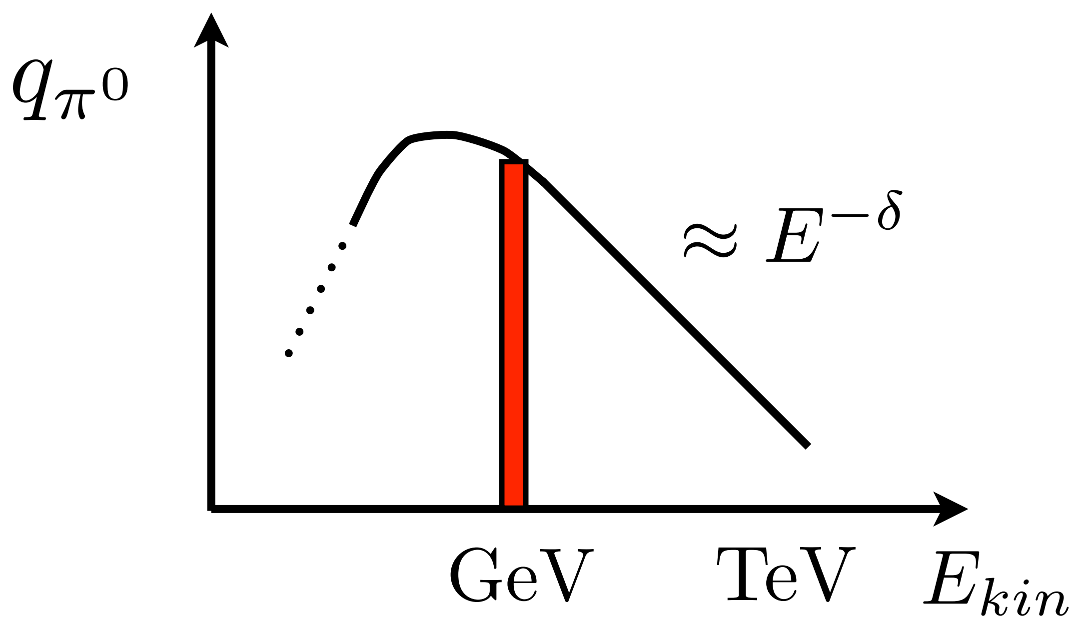

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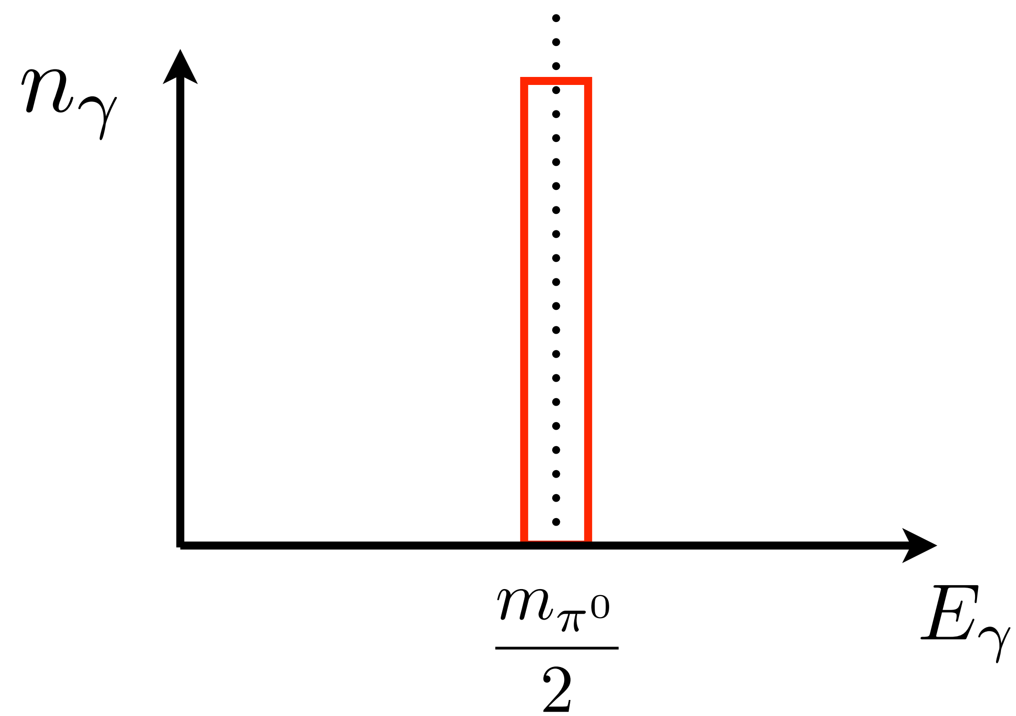

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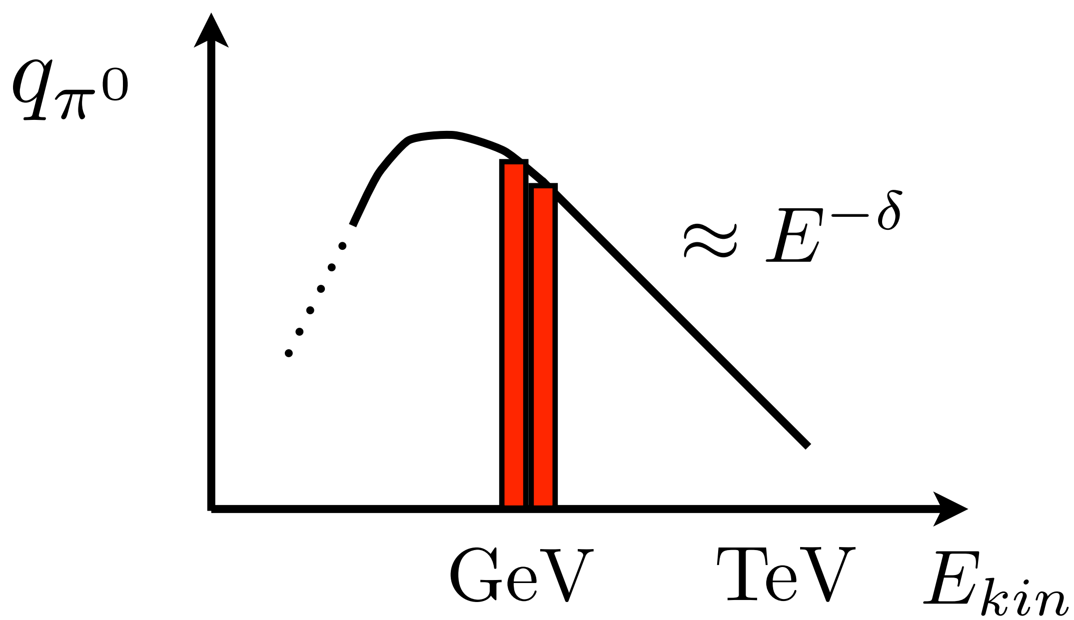

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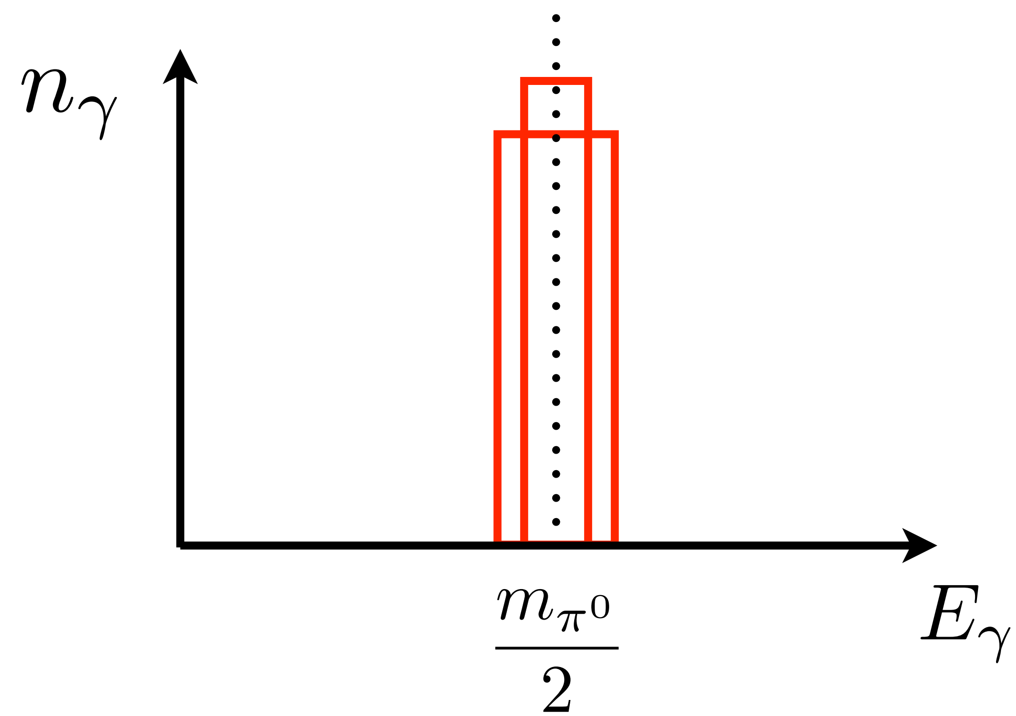

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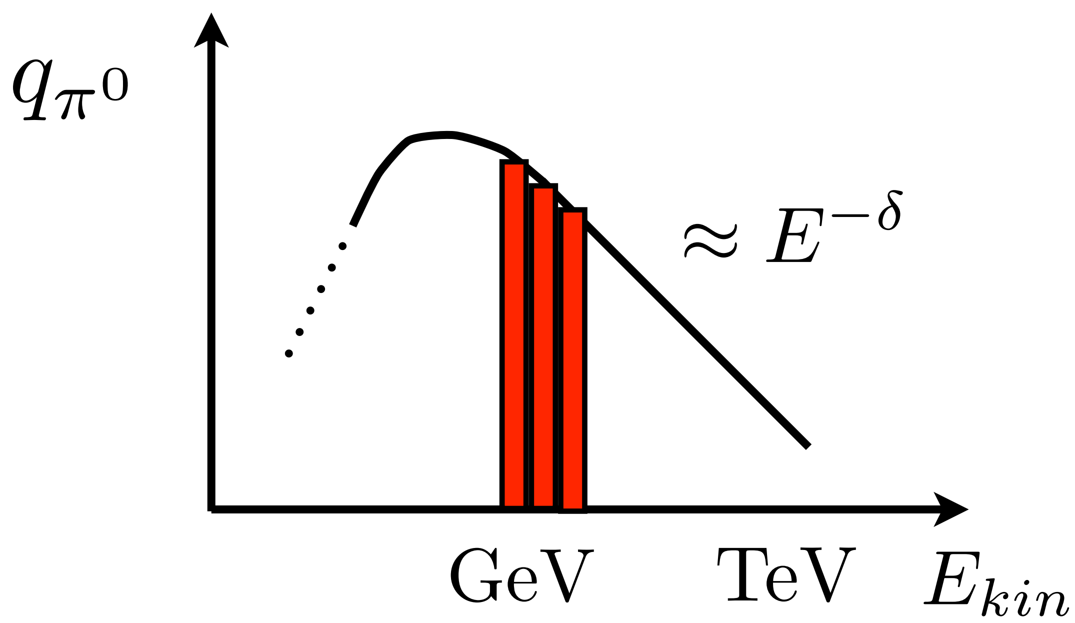

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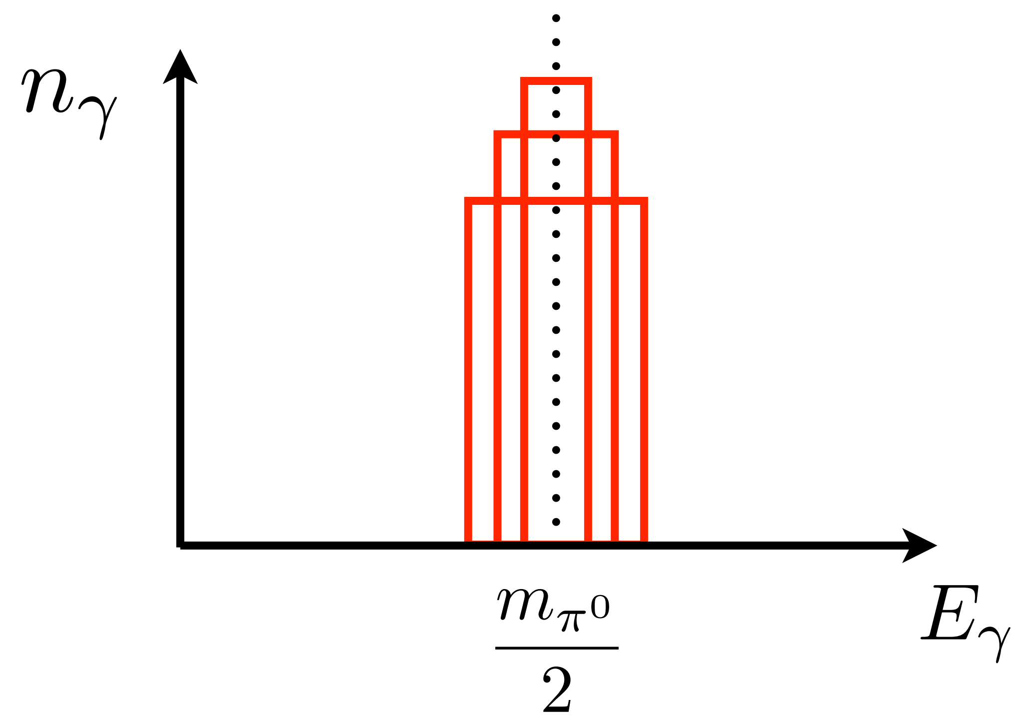

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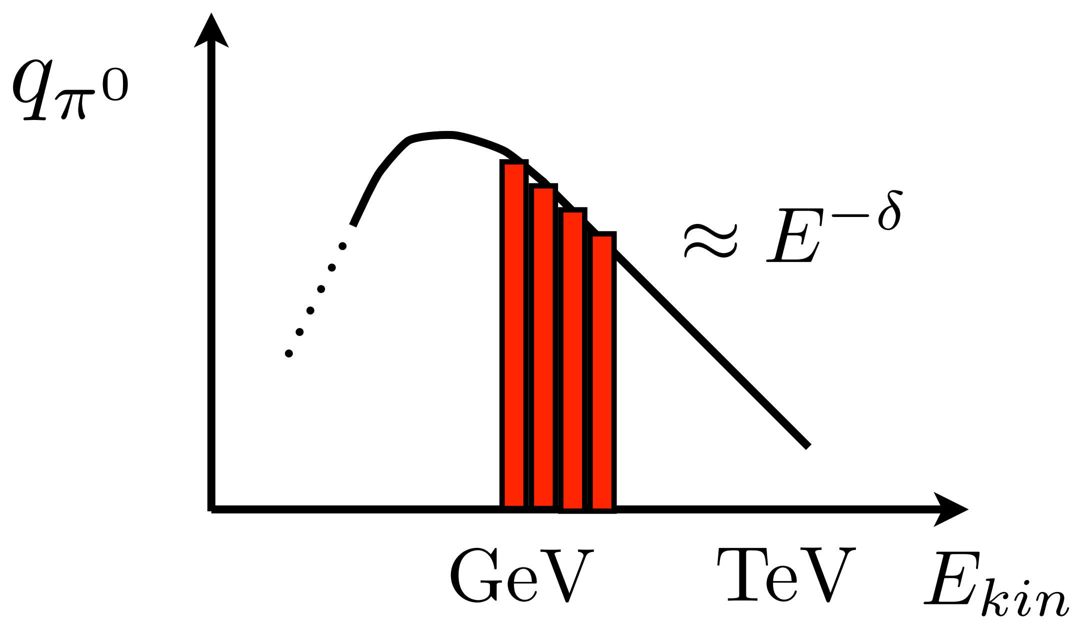

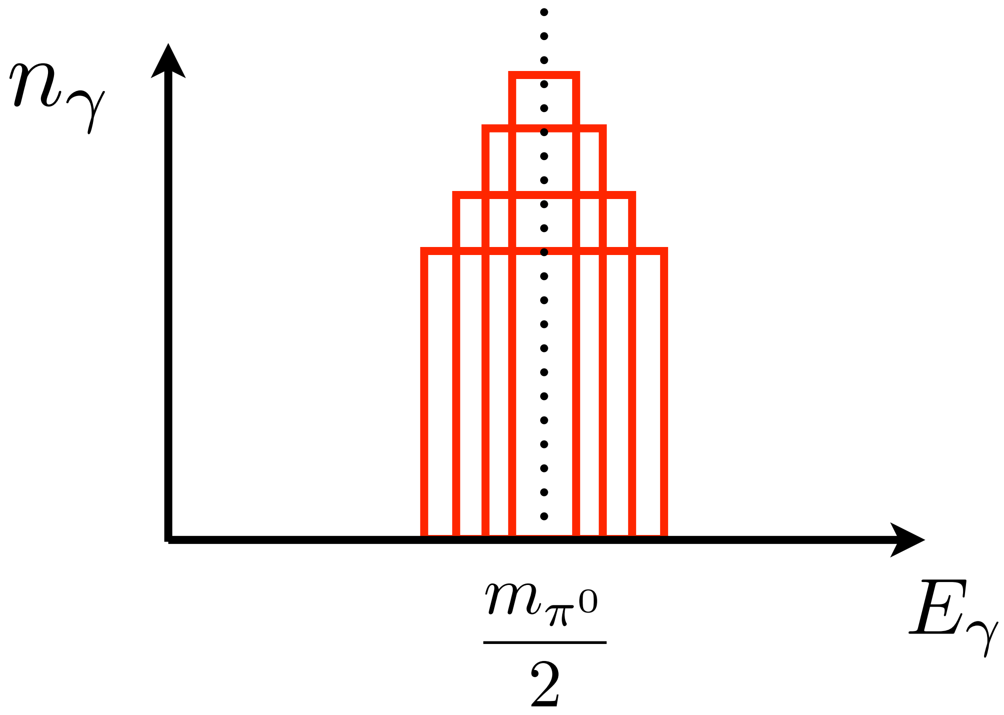

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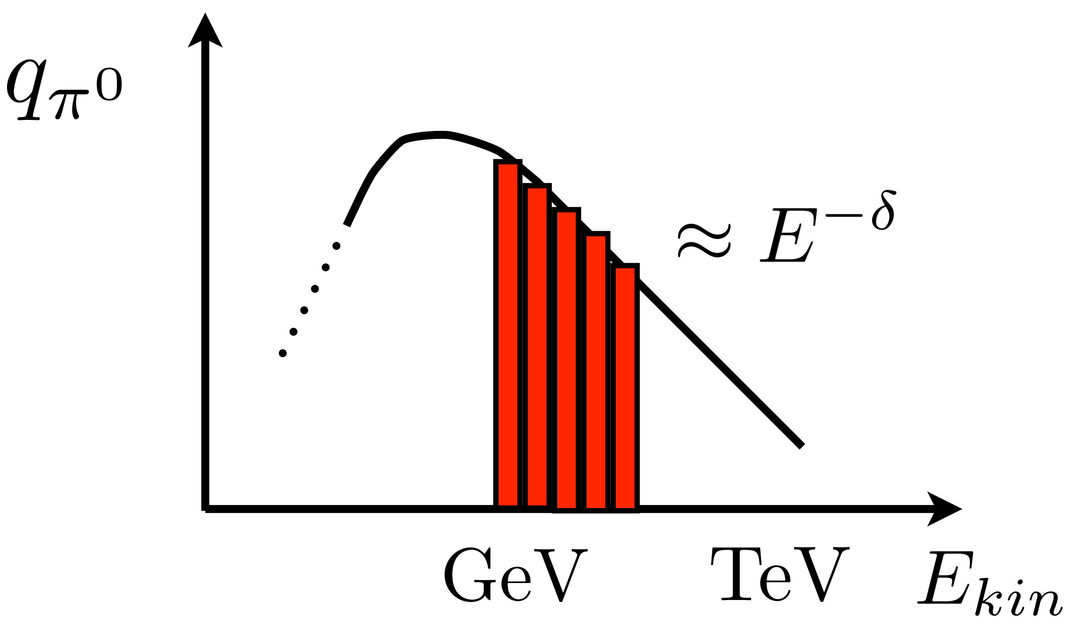

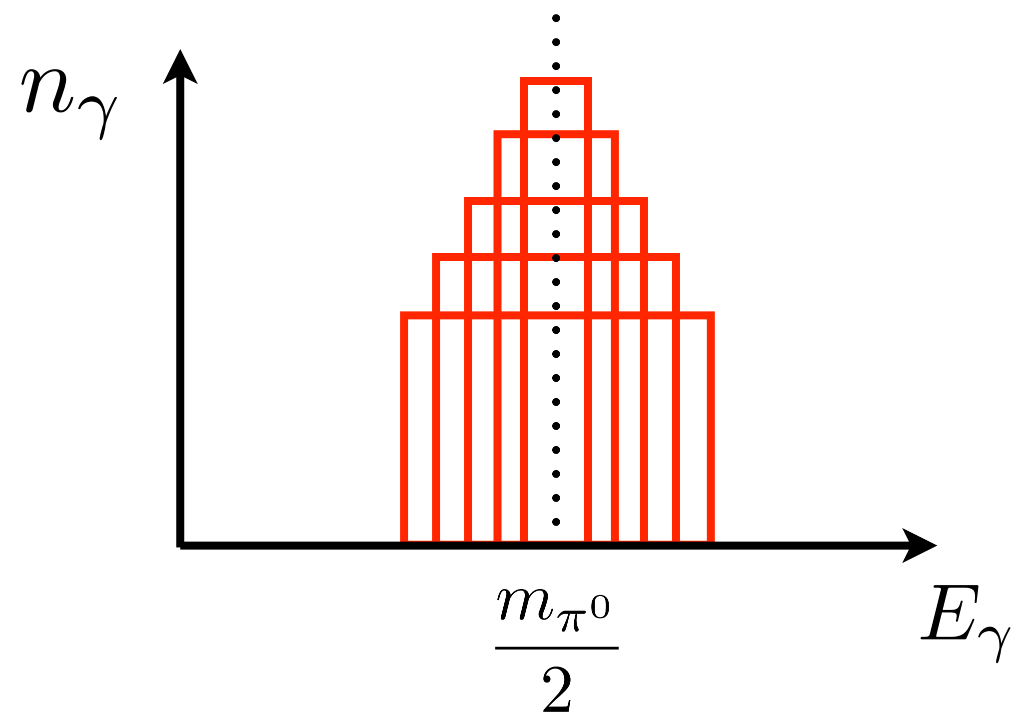

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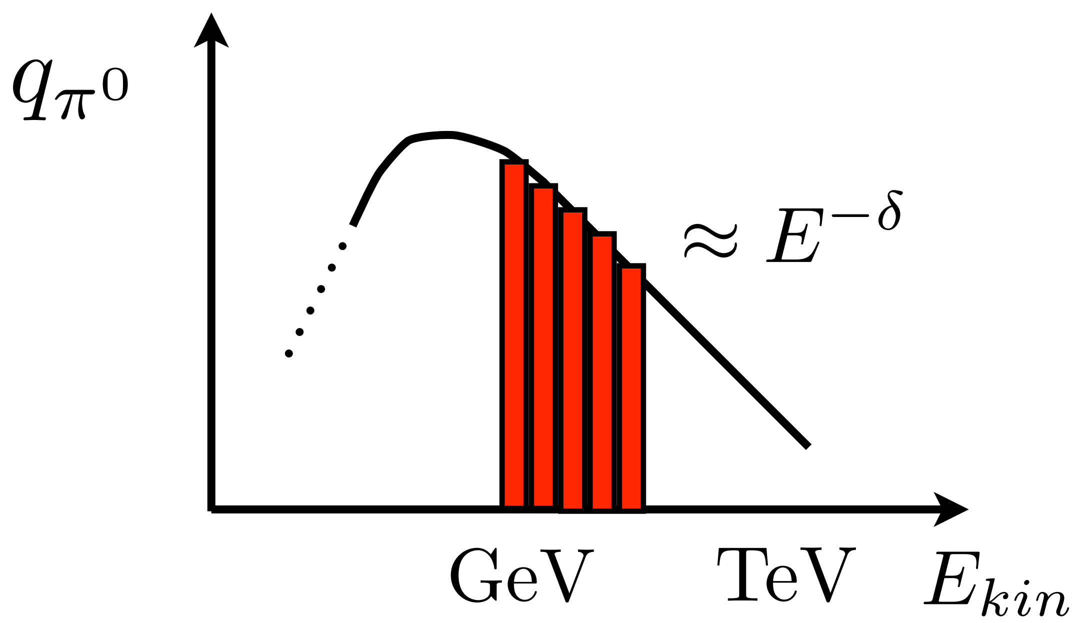

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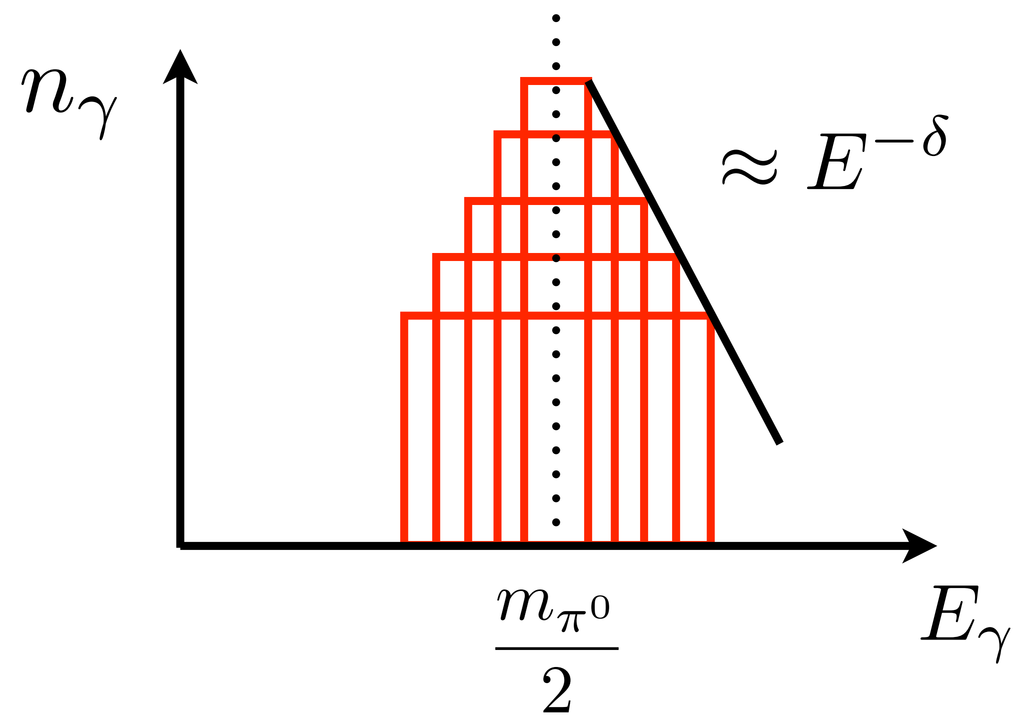

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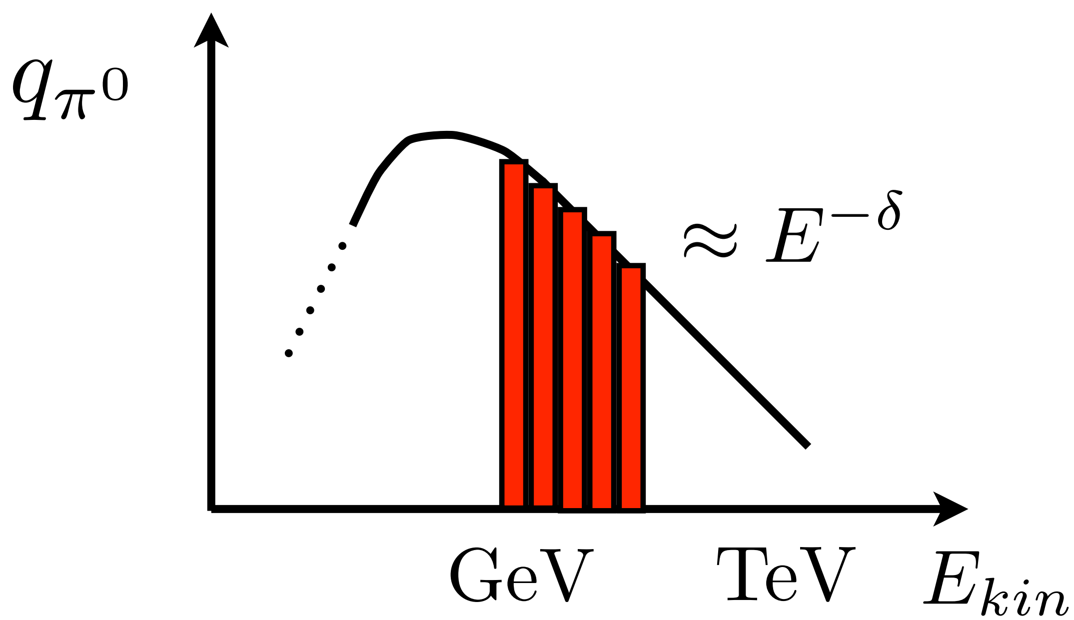

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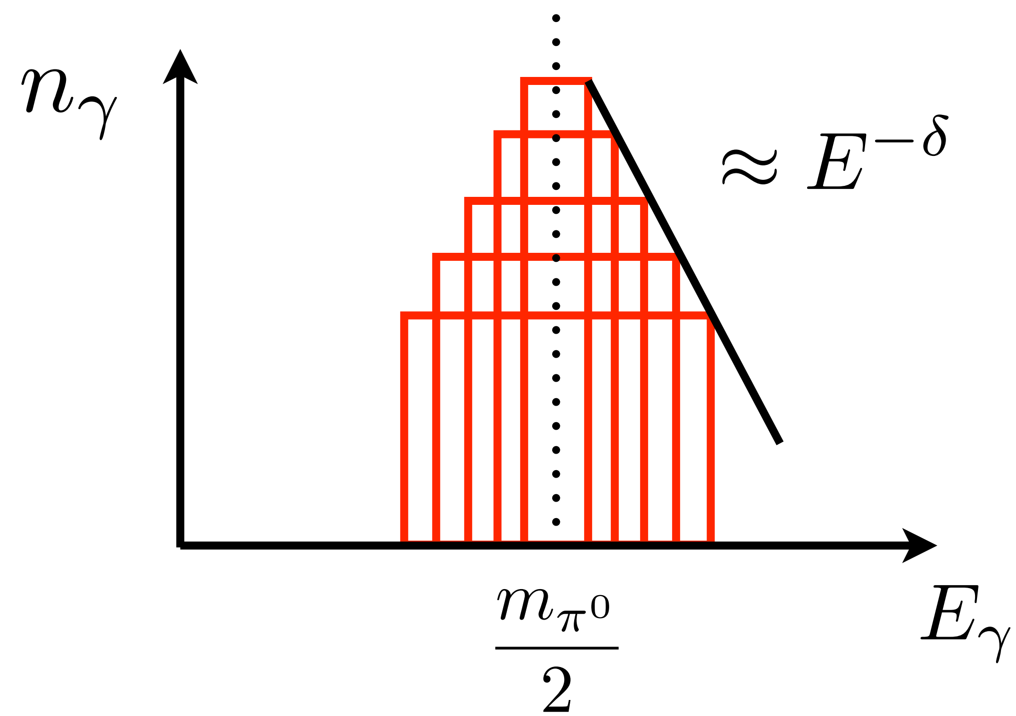

- the gamma ray spectrum is symmetric (in log-log) with respect to: $\frac{m_{\pi^0}}{2} \sim 70 \text{ MeV}$
- at high energy the spectrum mimics the CR spectrum, with (roughly): $E_\gamma \approx \frac{E_{CR}}{10}$

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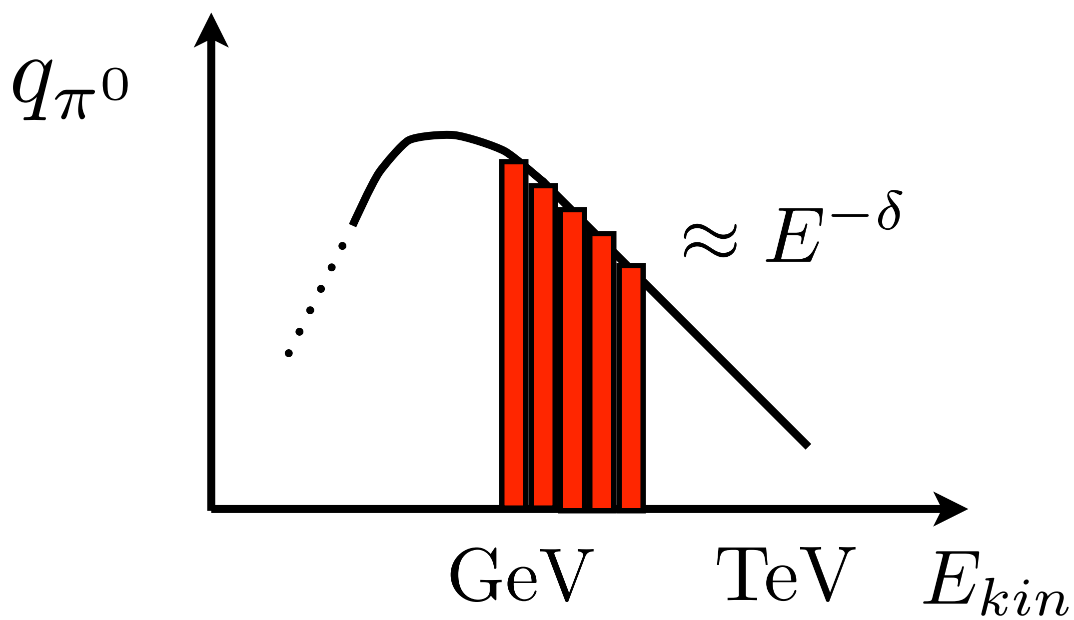

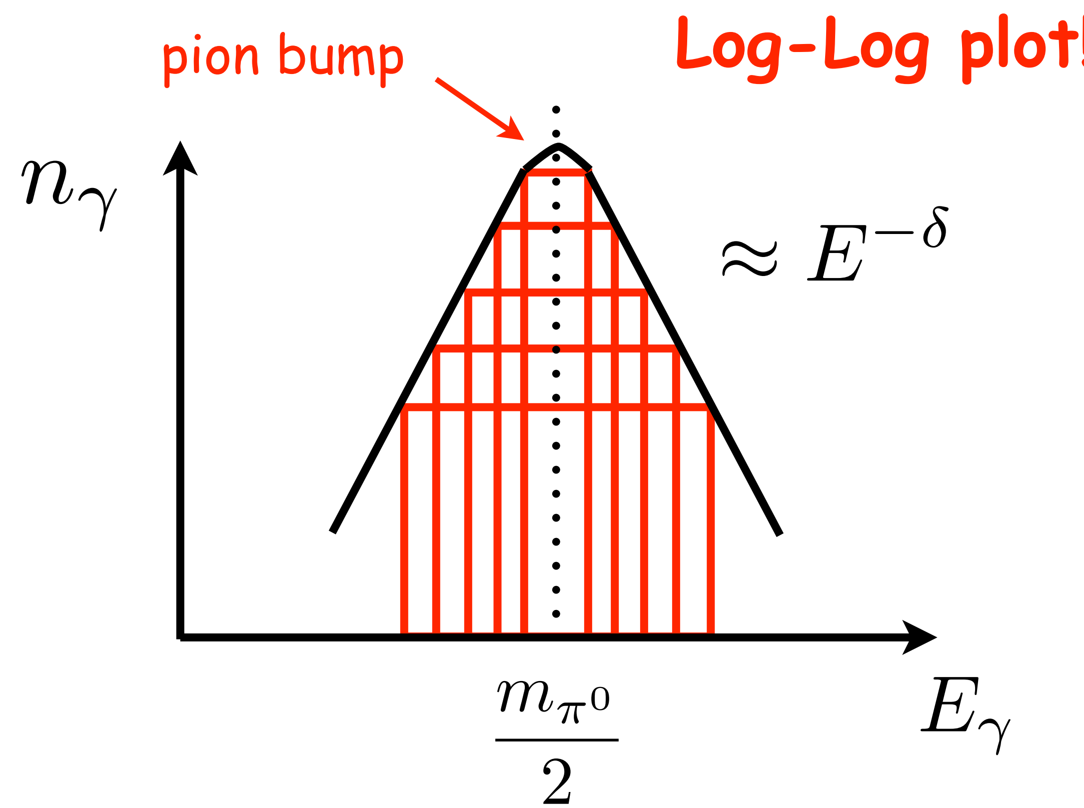

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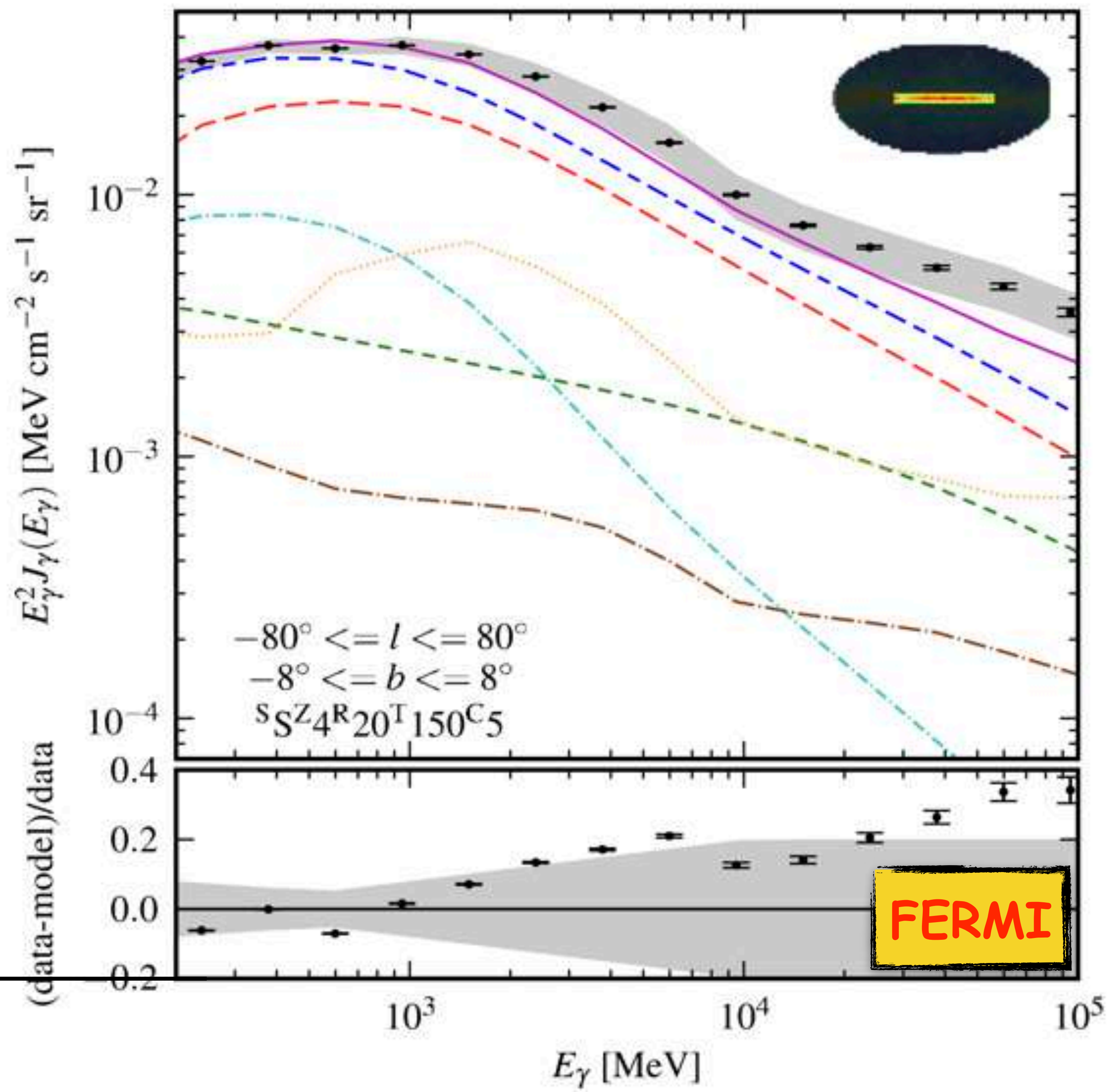
Diffuse emission from the inner Galaxy



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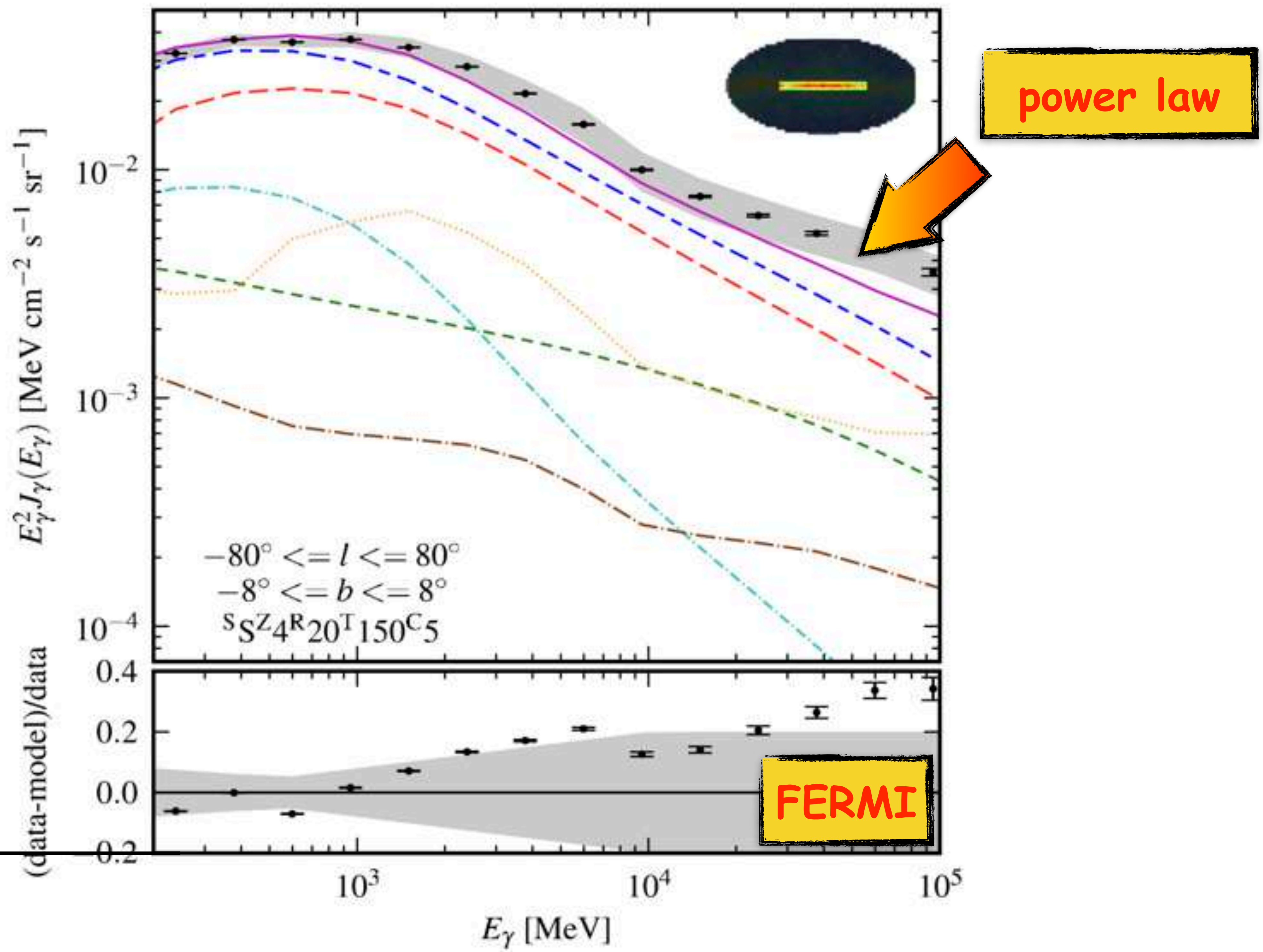

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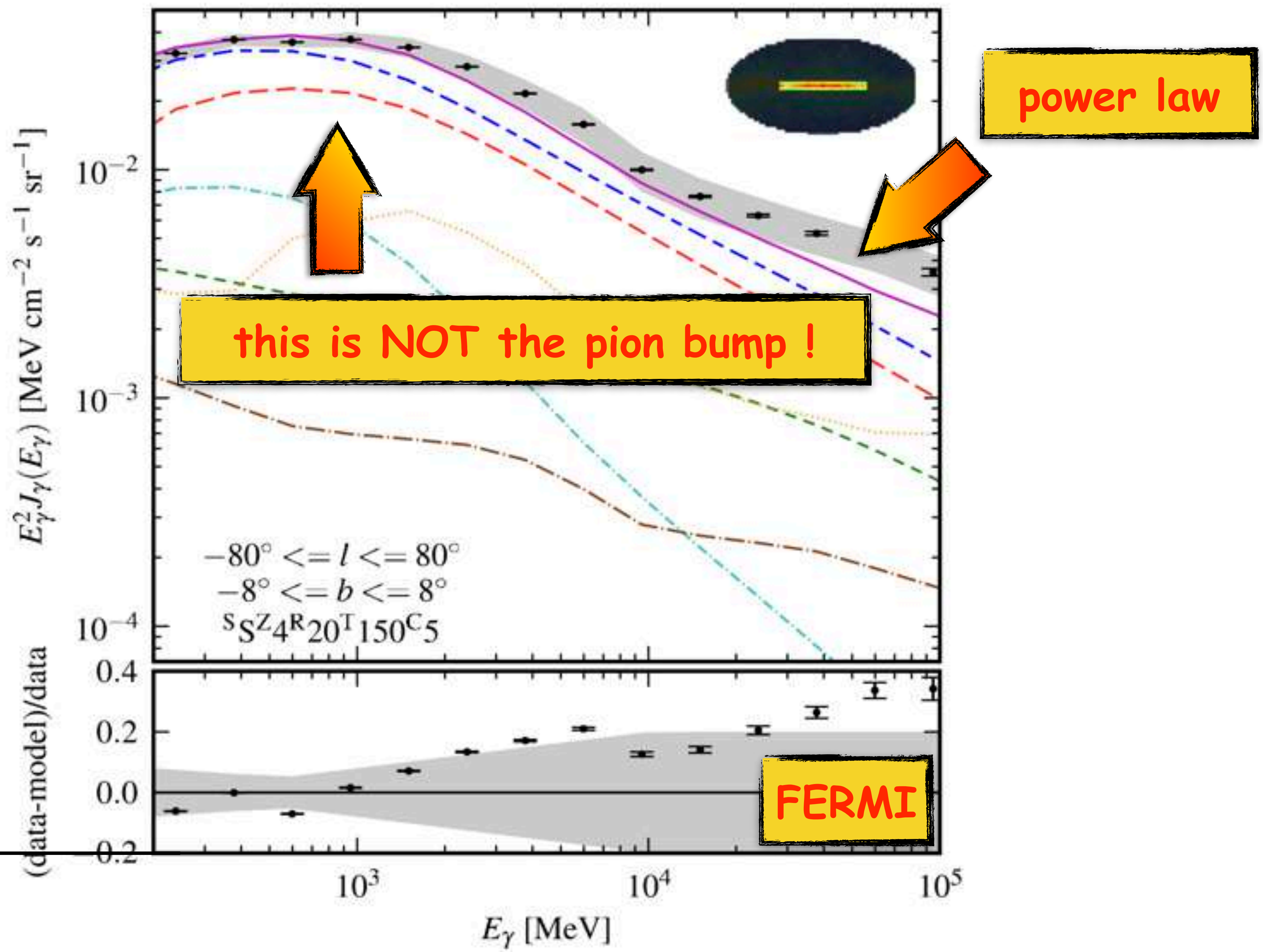

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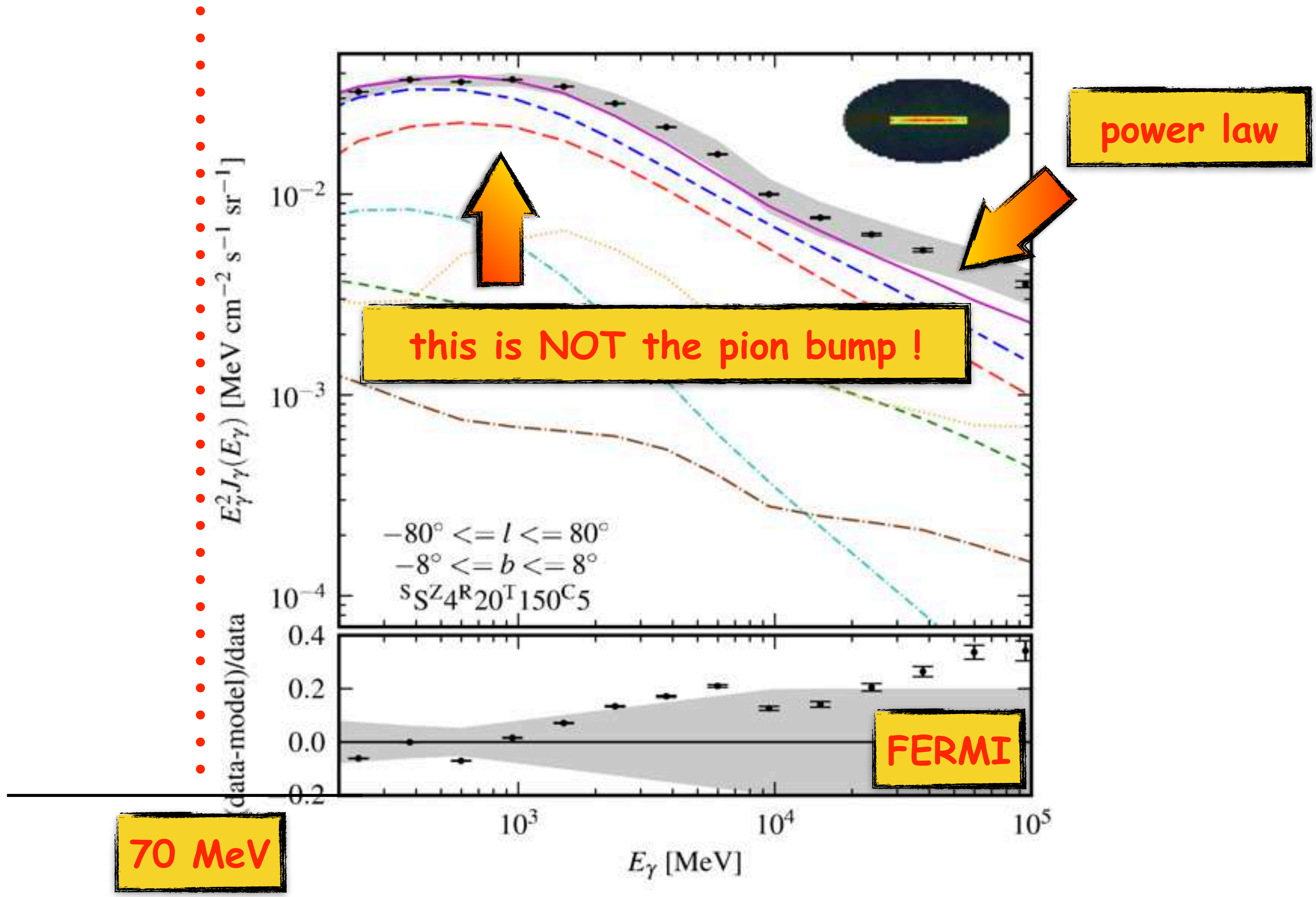

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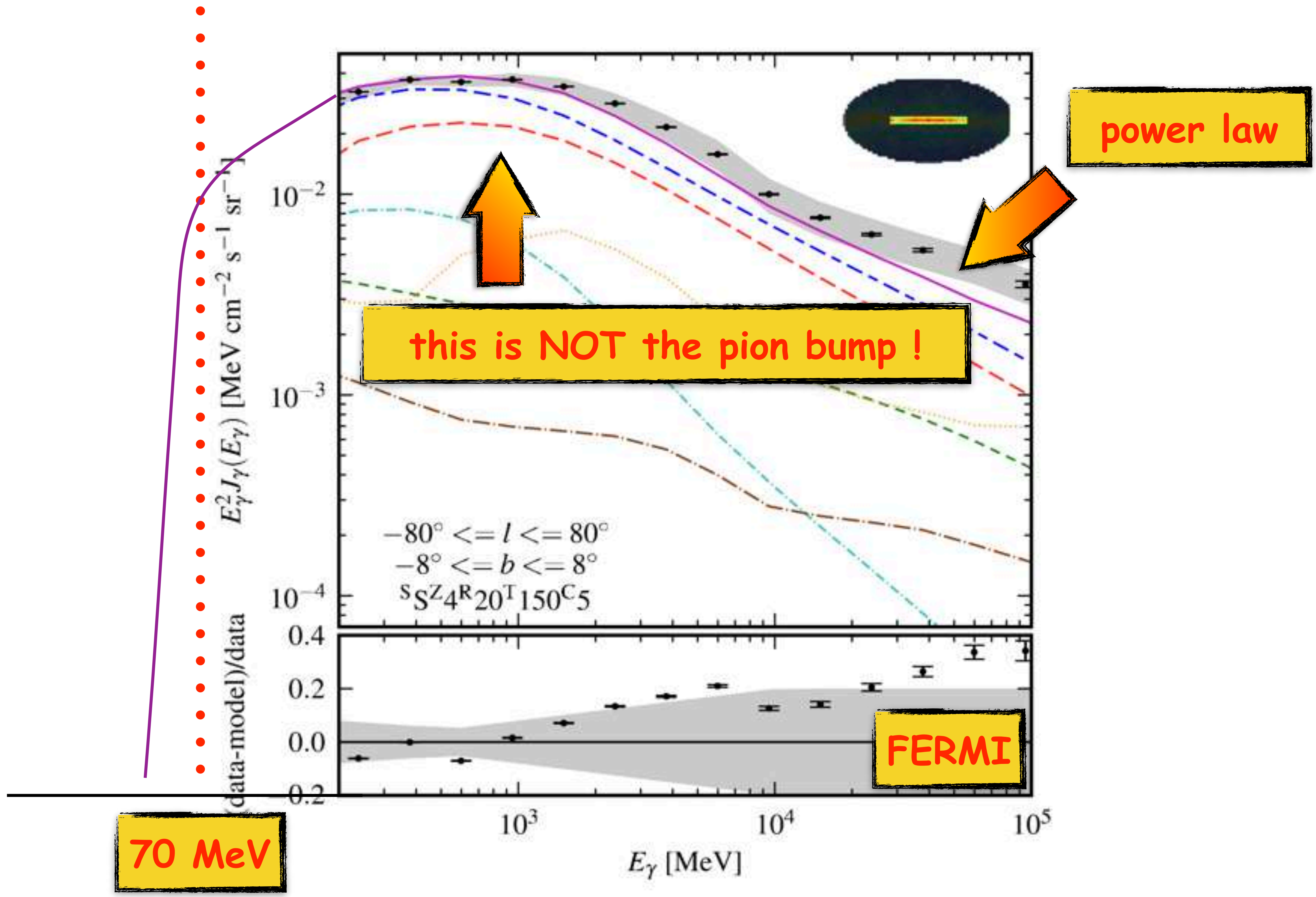

Not only gammas: neutrinos & electrons

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

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

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

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

Not only gammas: neutrinos & electrons

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

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

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

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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

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

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

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

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

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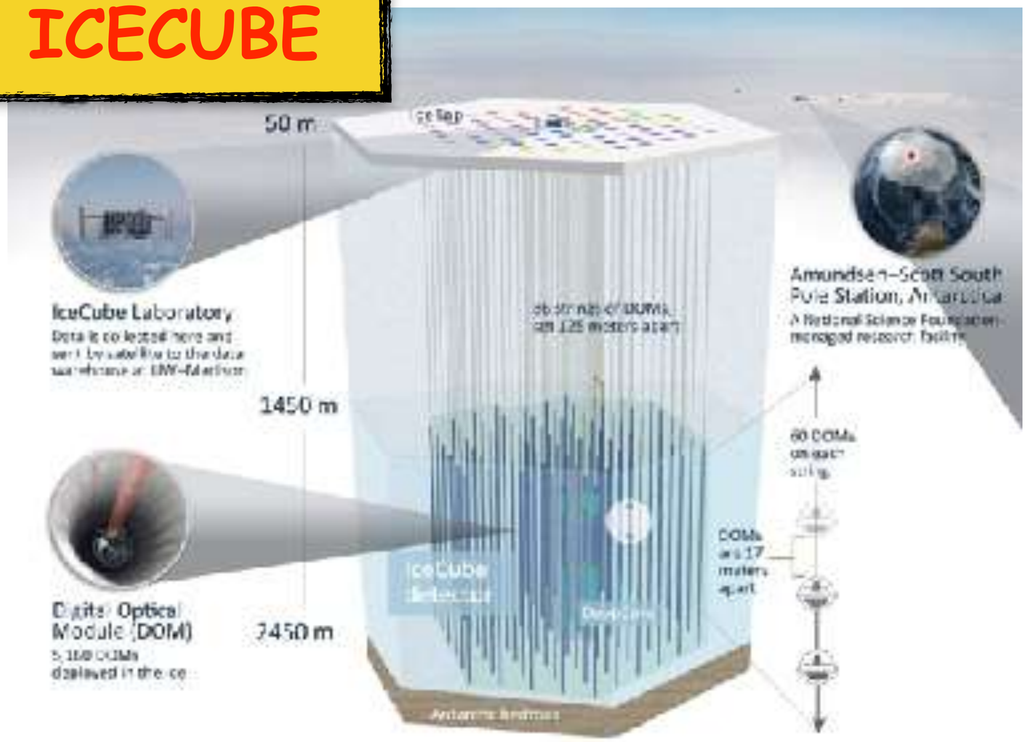
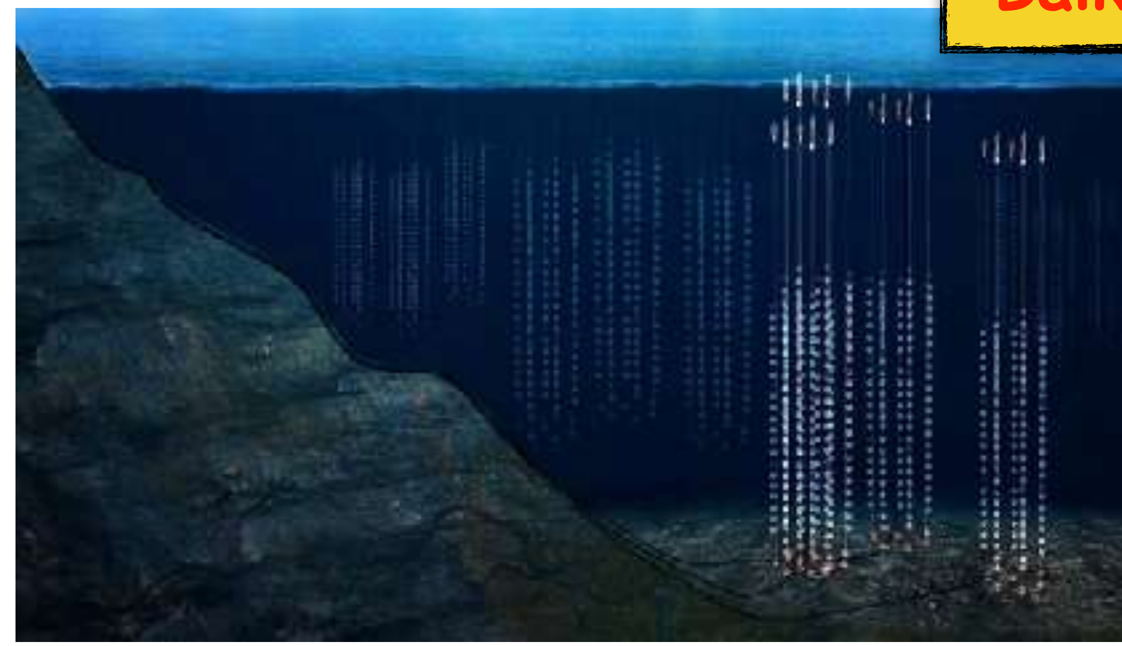
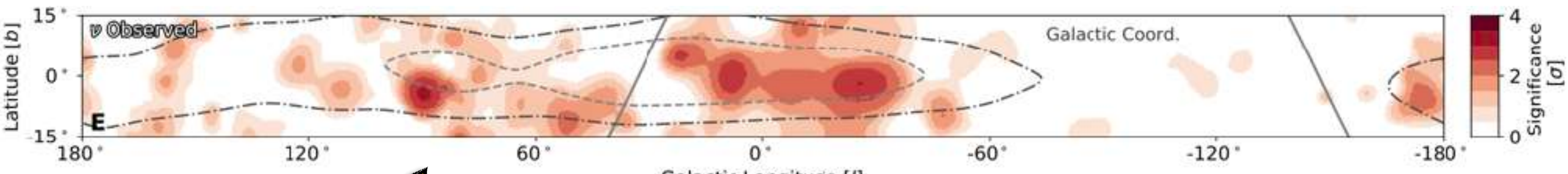
Neutrino telescopes

ICECUBE

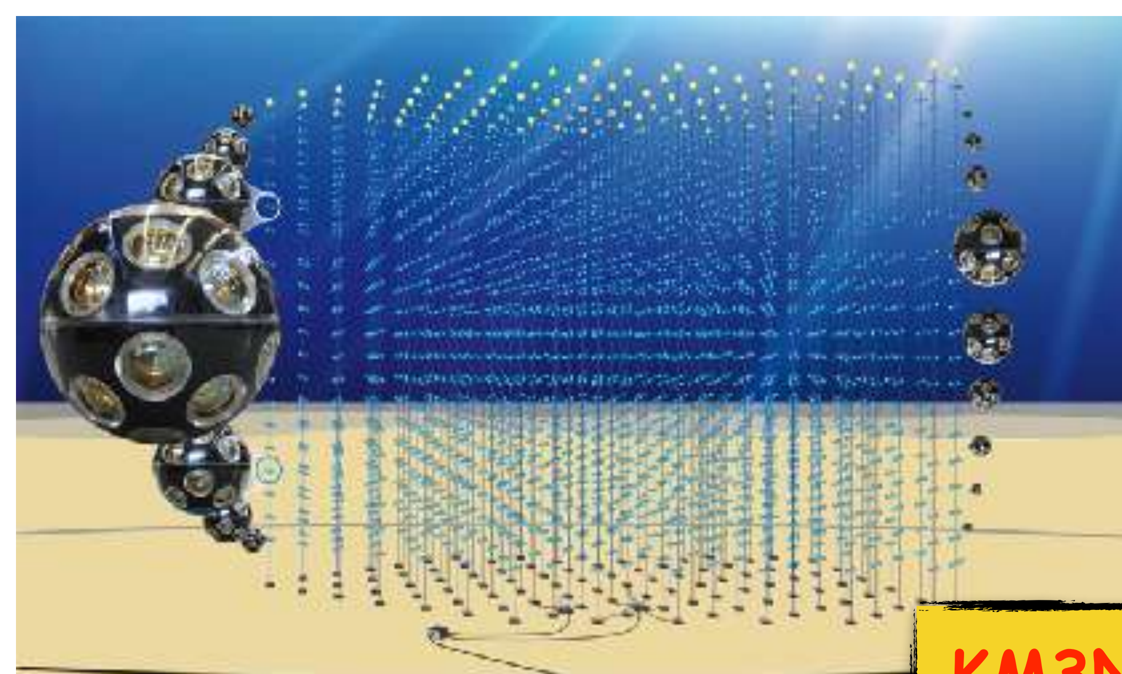


Baikal





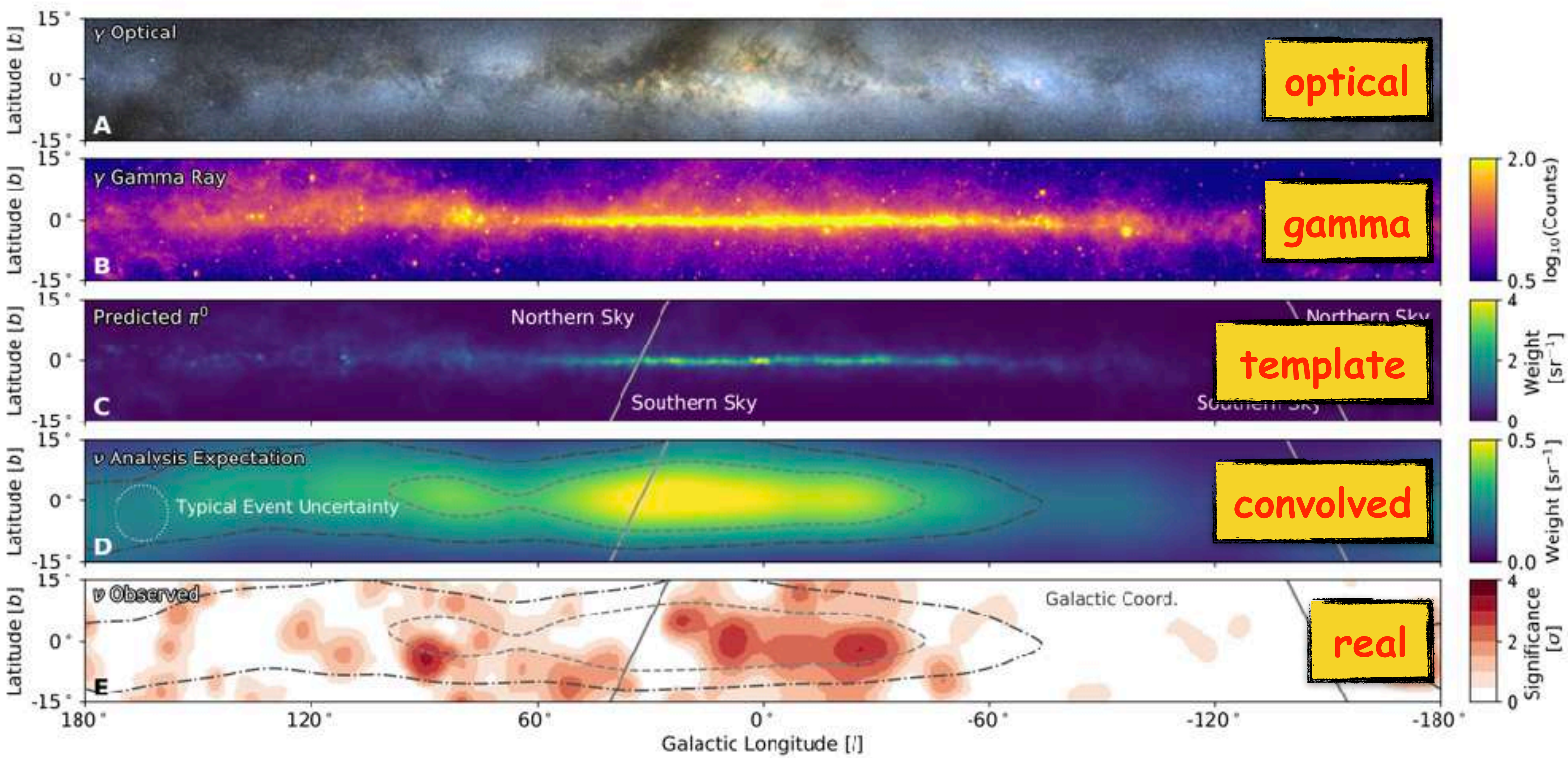
diffuse emission from Galactic plane!



KM3NeT

The gamma-neutrino connection

a neutrino signal from the disk is unavoidable !



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

gamma rays

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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

valid at large energies

fraction of the energy converted into pions...

number of protons of energy E_p produced per s

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

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Simple order-of-magnitude calculations

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power (energy per unit time)

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

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

Simple order-of-magnitude calculations

gamma rays

valid at large energies

fraction of the energy converted into pions...

number of protons of energy E_p produced per s

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

...and into gamma rays (1/3 -> π^0)

power (energy per unit time)

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Simple order-of-magnitude calculations

gamma rays

valid at large energies

emitted power in gamma rays

fraction of the energy converted into pions...

number of protons of energy E_p produced per s

$$\overbrace{Q_\gamma(E_\gamma)E_\gamma^2}^{} = f_\gamma \eta_\pi \underbrace{Q_p(E_p)E_p^2}_{}$$

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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

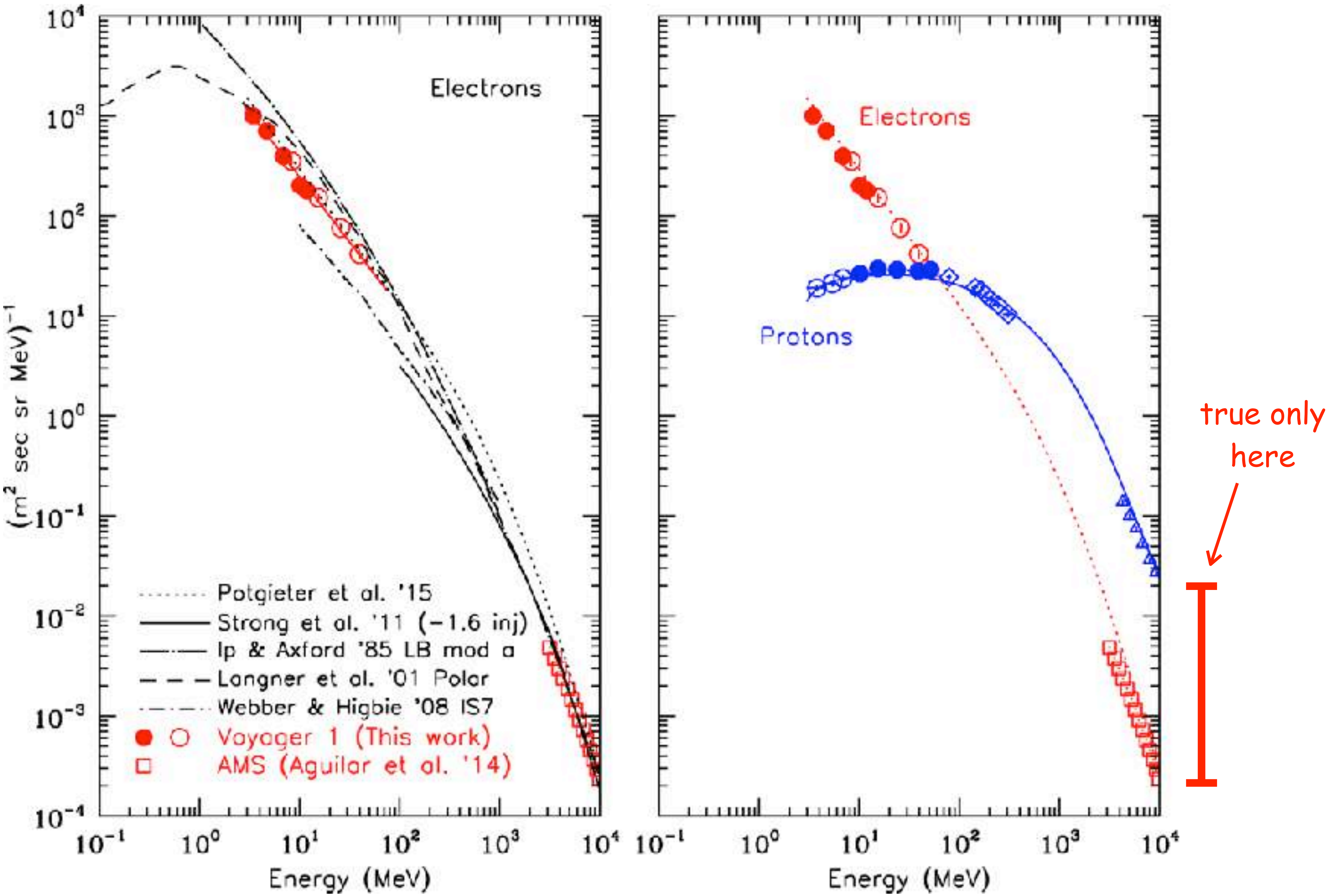
$$Q_\gamma(E_\gamma)E_\gamma^2 = \frac{\eta_\pi}{3} Q_p(E_p)E_p^2$$

neutrinos
(per flavour)

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

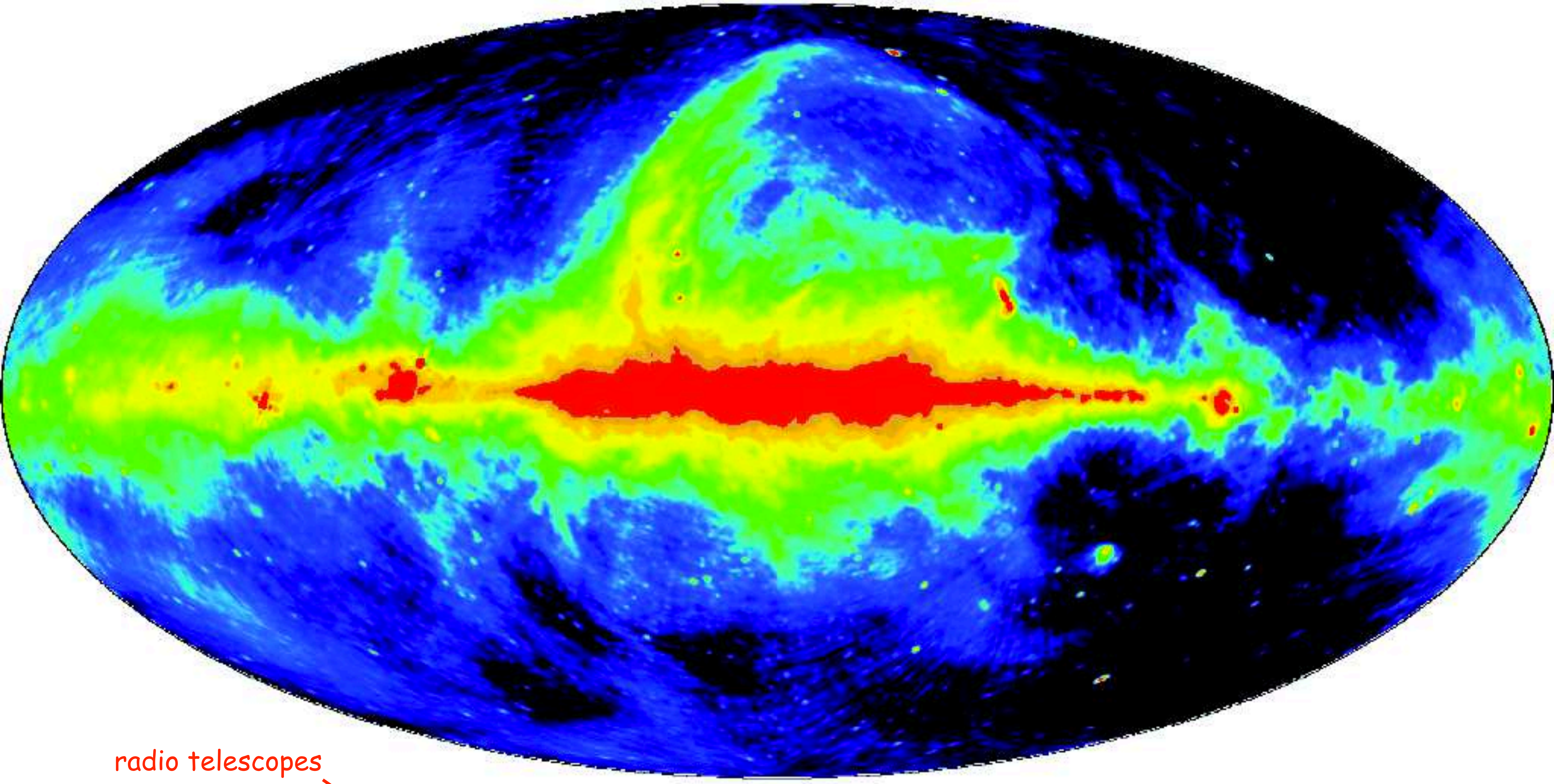
What about electrons?

false myths: the proton-to-electron ratio is ~100 in Galactic cosmic rays



Synchrotron emission from the Milky Way

radio domain → 408 MHz



radio telescopes

Jodrell-Bank 250-ft + Effelsberg 100-m + Parkes 64-m

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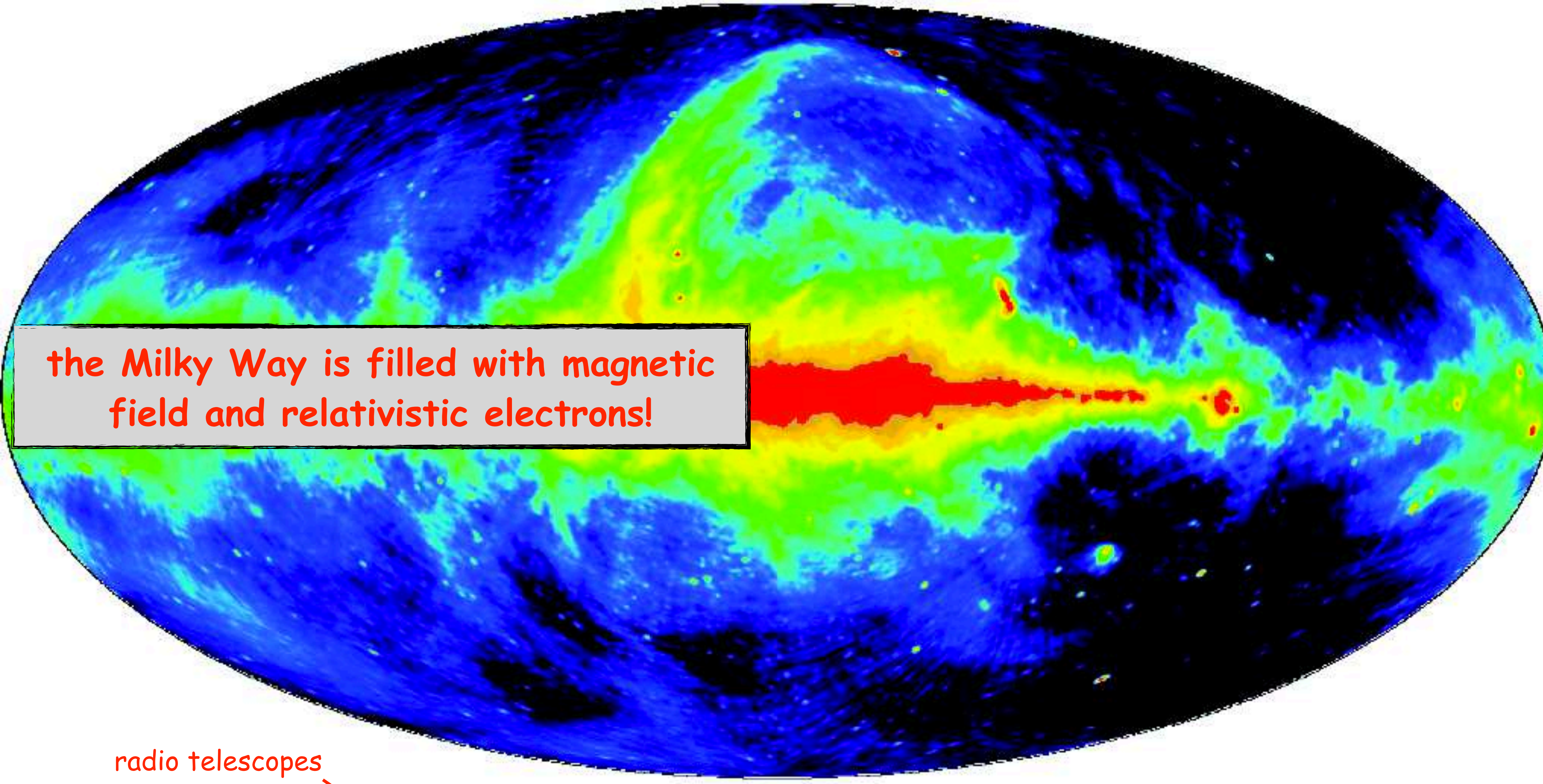

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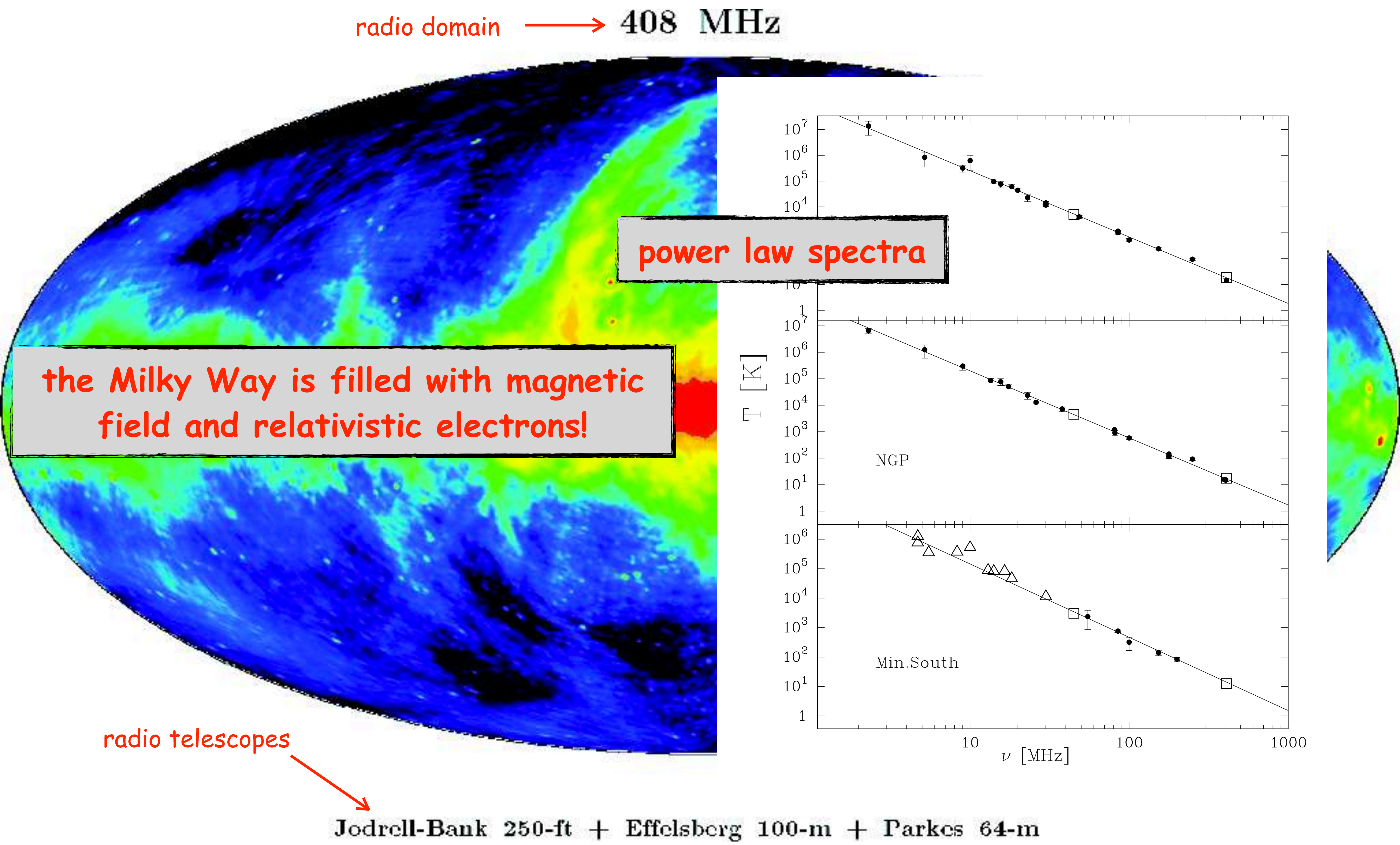
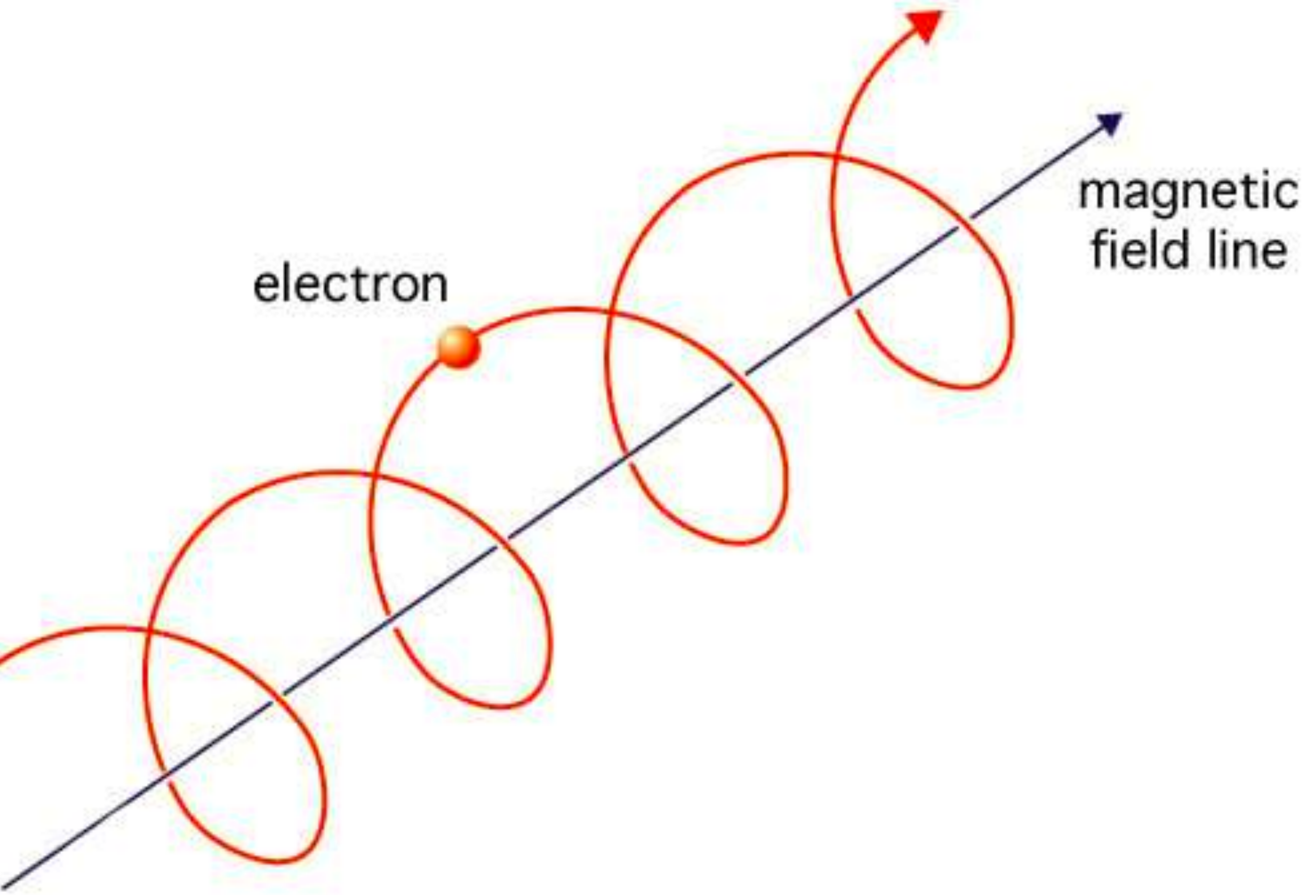


Motion of a particle in a magnetic field



$$\mu = \cos\vartheta$$

pitch angle = angle between v and B

$$\begin{cases} v_{\parallel} & = & \mu\ v \\ v_{\perp} & = & (1-\mu^2)^{1/2} v \end{cases}$$

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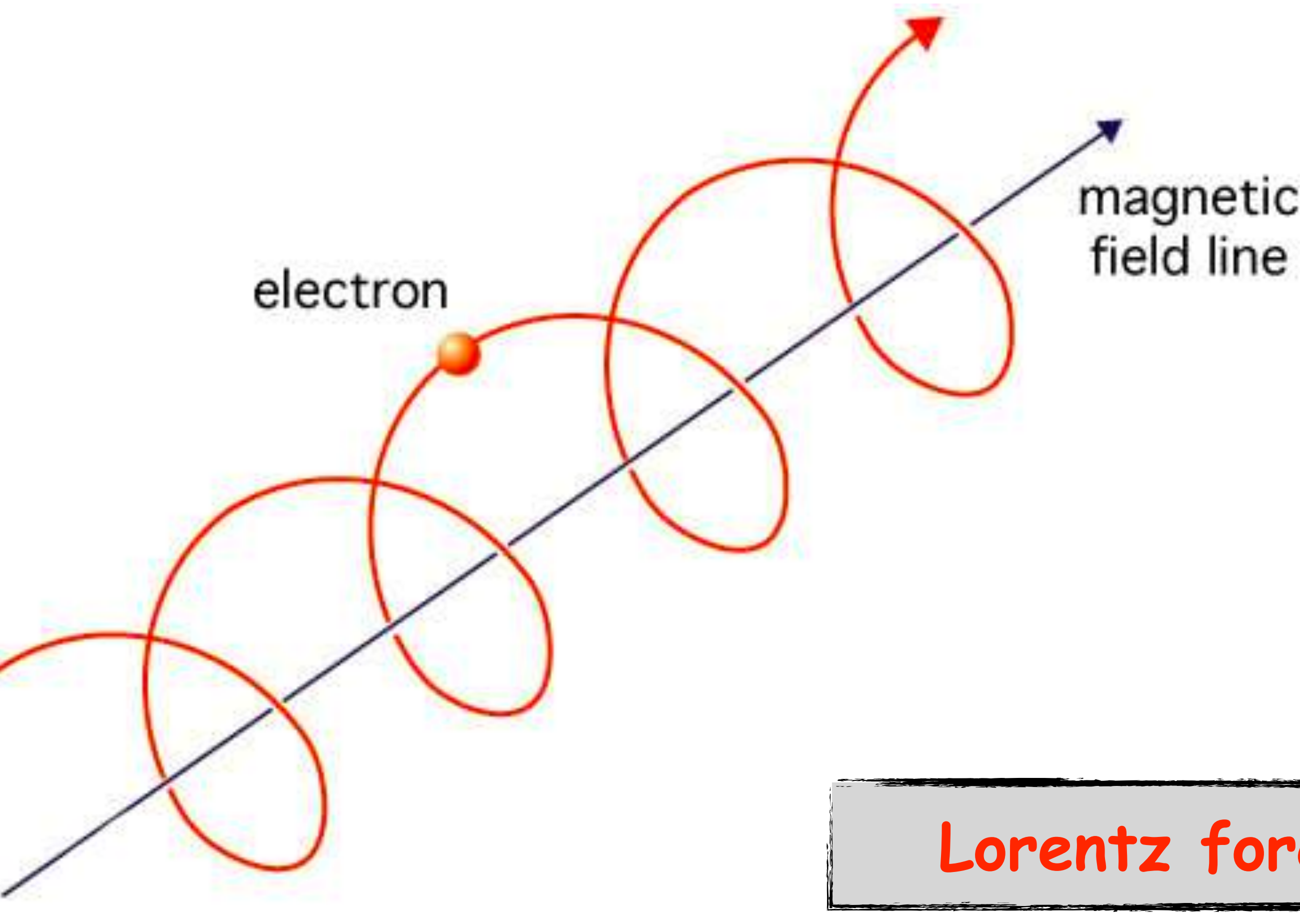

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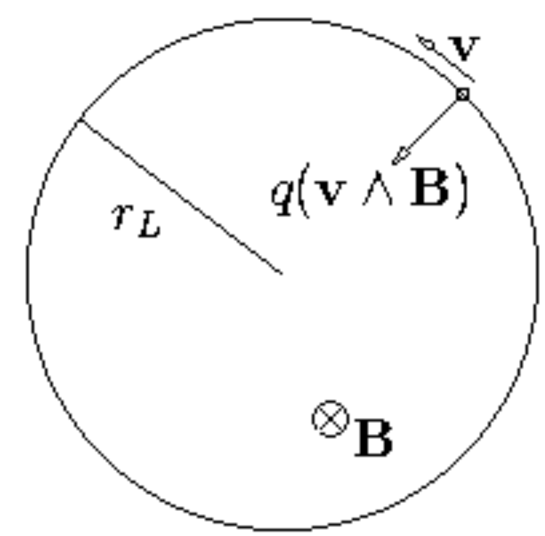
Lorentz force $$F_L = \frac{q}{c}\vec{v} \times \vec{B}$$

Larmor radius $$R_L = \frac{p_{\perp} c}{qB}$$



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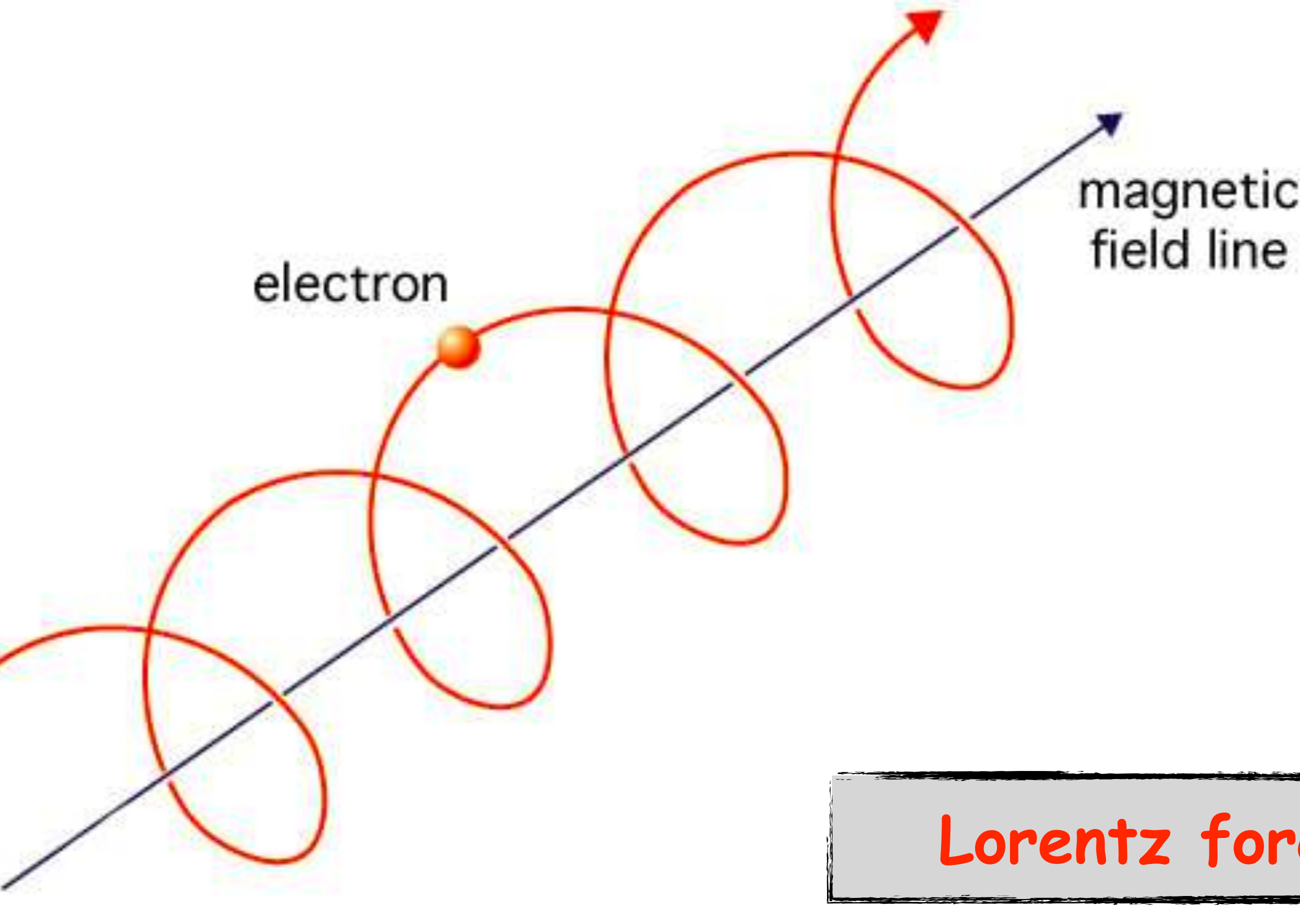

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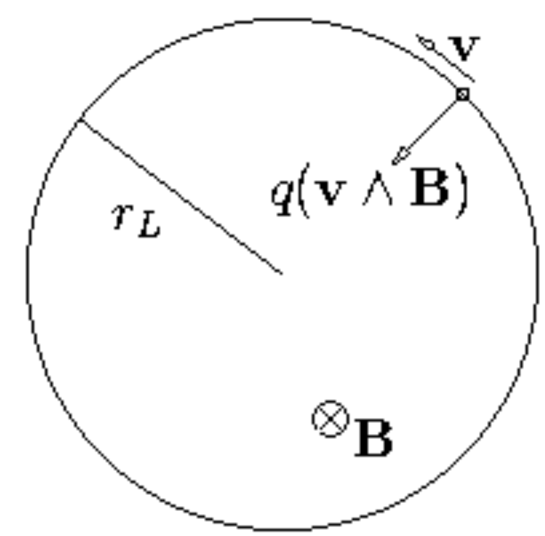
gyration frequency $$\nu_B = \frac{1}{t_g} = \frac{v_{\perp}}{2\pi R_L} = \frac{qB}{2\pi\gamma mc}$$

Lorentz factor



Power emitted by an electron*

non-relativistic $$P = \frac{2e^2}{3c^3} a^2 \longrightarrow P = \frac{2e^2}{3c^3}\gamma^4 \left[\gamma^2 a_{\parallel}^2 + a_{\perp}^2\right]$$ **relativistic**

* implicit assumption: the energy of the electron does not change during one gyration around the B-field

Power emitted by an electron*

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Lorentz force is orthogonal to v

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Lorentz force is orthogonal to v

$$F_L = F_{L,\perp} = \frac{e v_\perp B}{c} \equiv \gamma m \frac{\mathrm{d} v_\perp}{\mathrm{d} t} \longrightarrow a_\perp = \frac{e v_\perp B}{\gamma m c}$$

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$$P = \frac{4}{3} \sigma_T c \, U_B \gamma^2$$

- Thomson cross section $\sigma_T = \frac{8\pi}{3} \left(\frac{e^2}{mc^2} \right)^2 = 6.65 \times 10^{-25} \mathrm{cm}^2$
- magnetic field energy density $U_B = B^2 / 8\pi$
- ultra relativistic electrons $\beta \longrightarrow 1$
- isotropic distribution of particles $\langle \sin^2 \vartheta \rangle = 2/3$

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Characteristic frequency

as done for Bremsstrahlung: characteristic time ———> characteristic frequency

gyration frequency?

$$\nu_B = \frac{1}{t_g} = \frac{v_\perp}{2\pi R_L} = \frac{qB}{2\pi\gamma mc}$$

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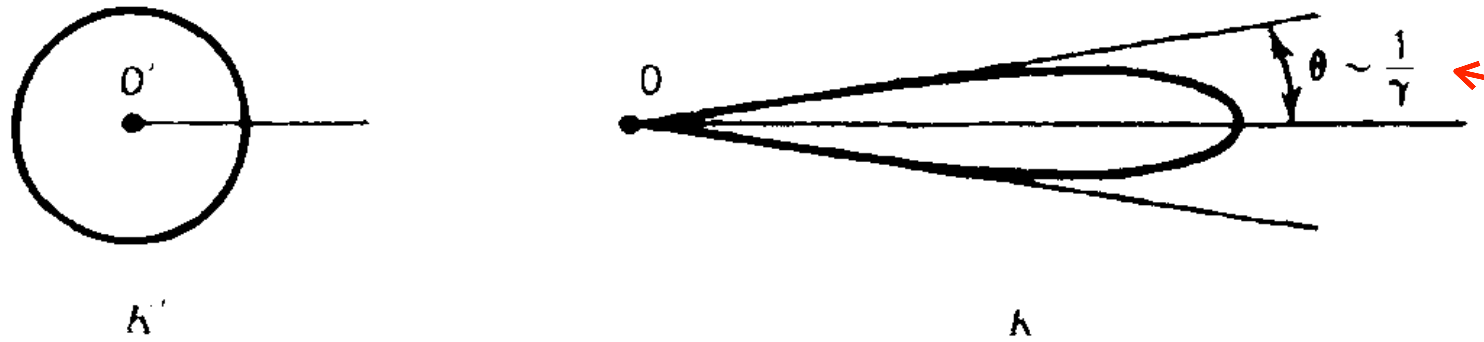
$$\nu_B = \frac{1}{t_g} = \frac{v_\perp}{2\pi R_L} = \cancel{\frac{qB}{2\pi\gamma m c}}$$

Beaming



$$\vartheta \sim \frac{1}{\gamma}$$

Figure 4.3 Relativistic beaming of radiation emitted isotropically in the rest frame K'.

the radiation emitted by a relativistic particle is concentrated within a cone of opening angle 1/γ entered along the particle velocity

Characteristic frequency

as done for Bremsstrahlung: characteristic time ——> characteristic frequency

gyration frequency?

$$\nu_B = \frac{1}{t_g} = \frac{v_\perp}{2\pi R_L} = \cancel{\frac{qB}{2\pi\gamma m c}}$$

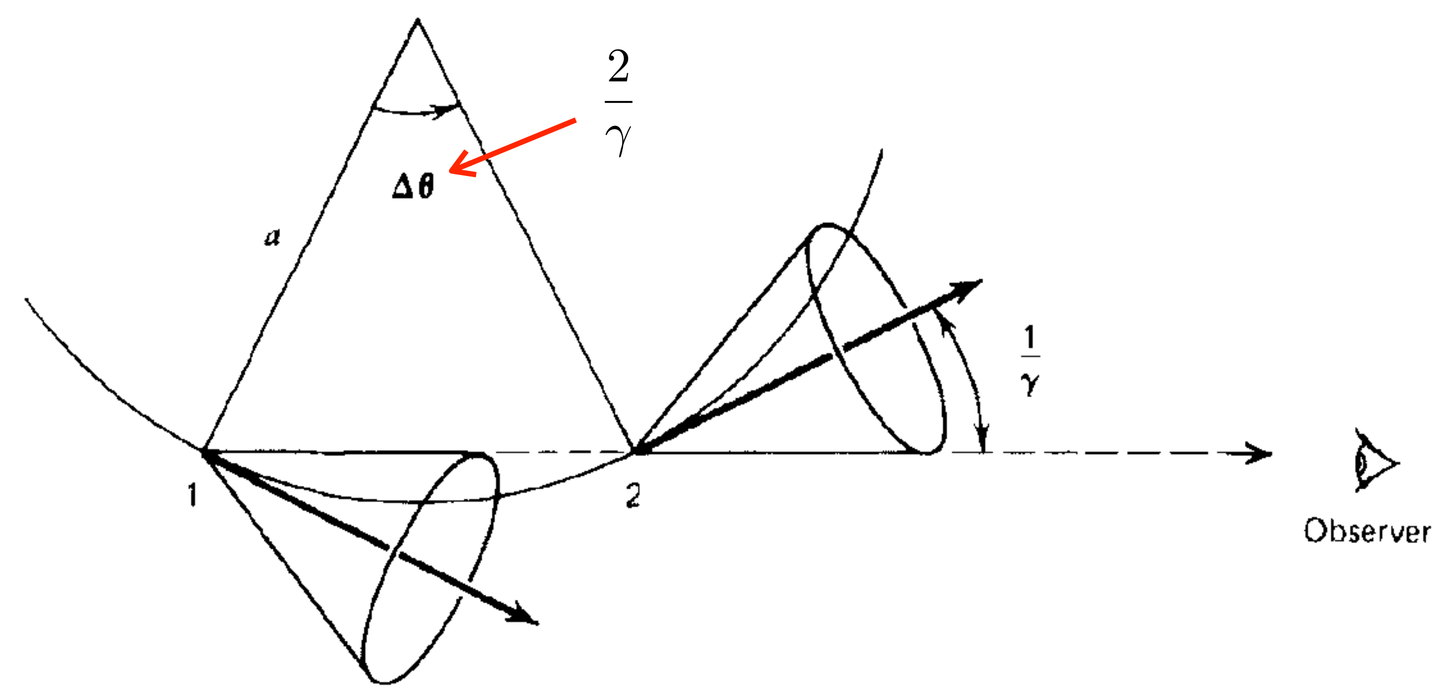


Figure 6.2 Emission cones at various points of an accelerated particle's trajectory.

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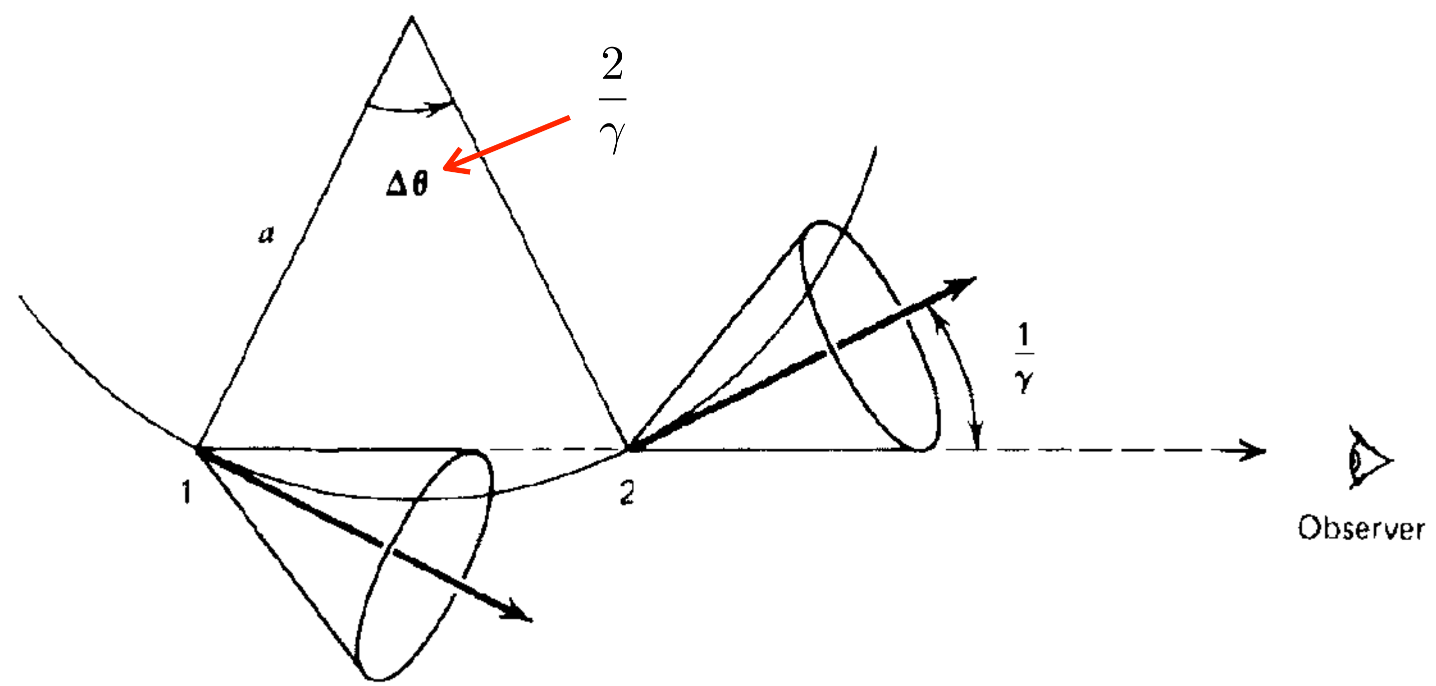

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photons that reach us are emitted in the time interval:

$$\Delta t_e = \frac{R_L \Delta\vartheta}{v_\perp} = \frac{1}{\pi\gamma\nu_B}$$

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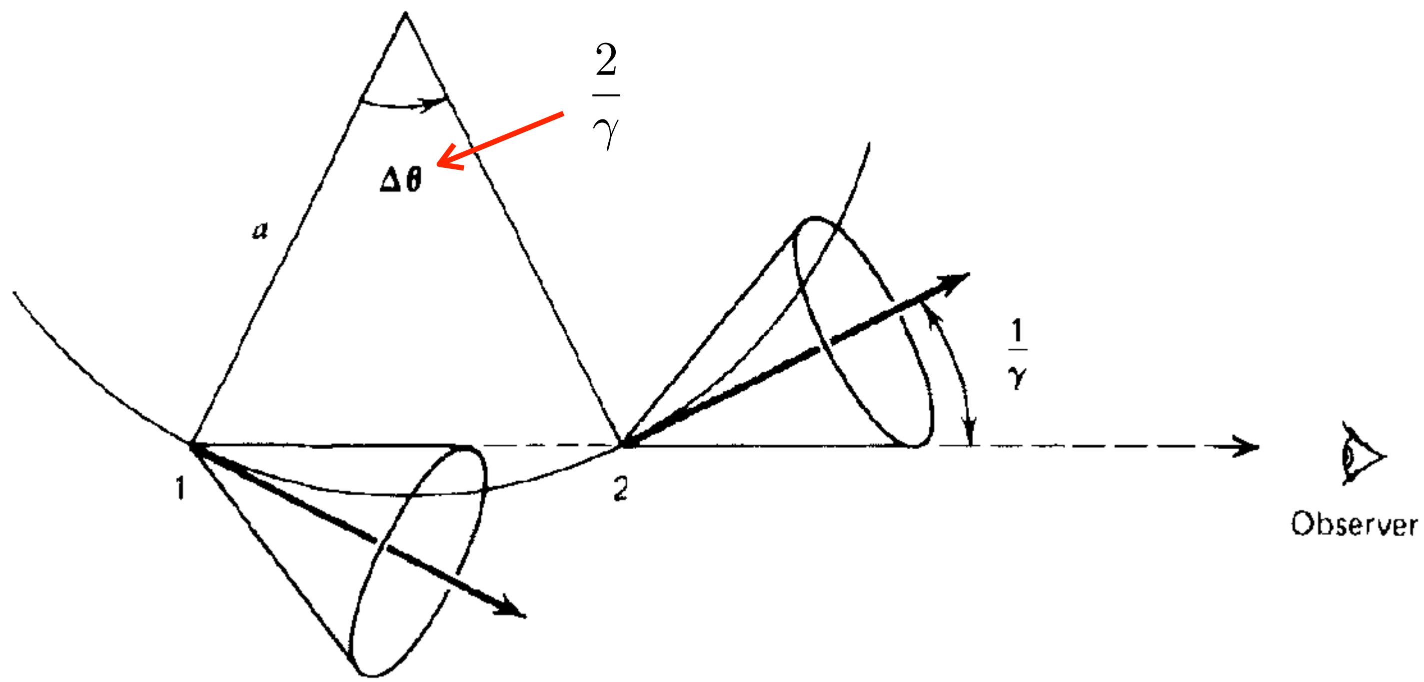

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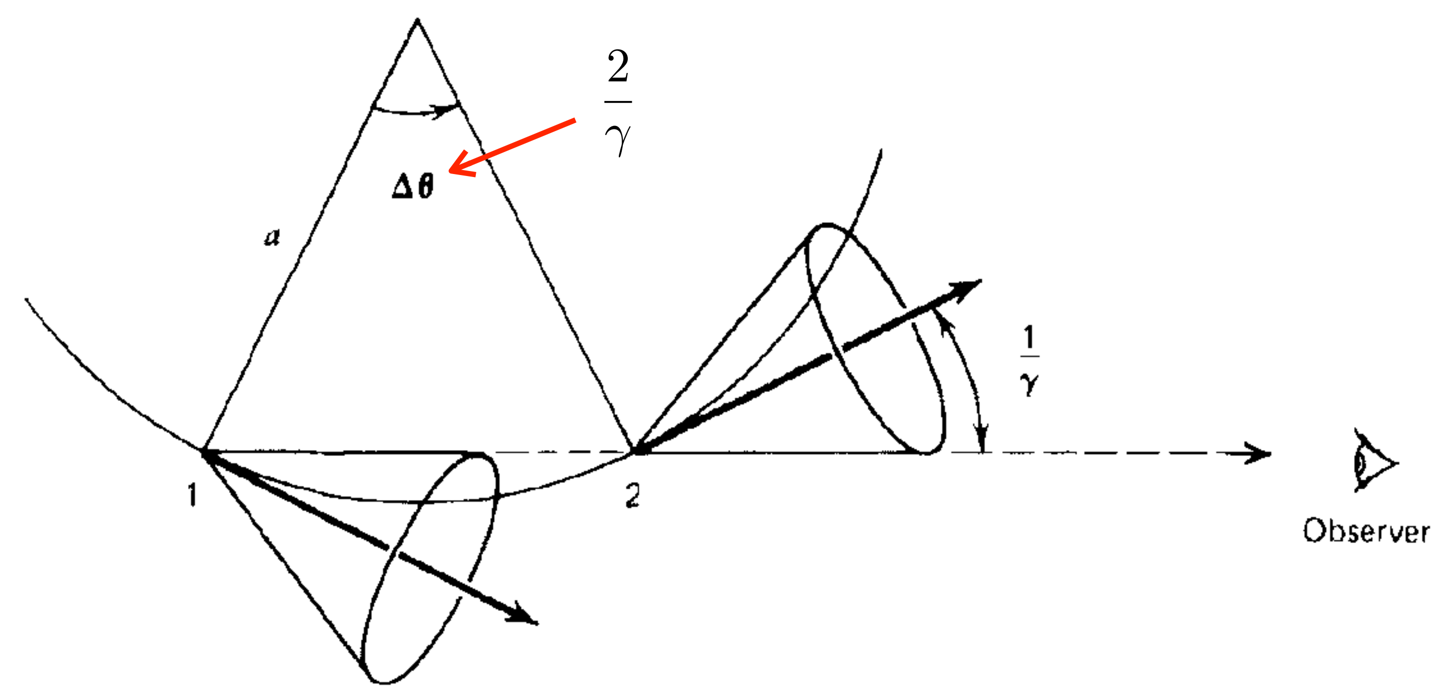

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$$\Delta t_a = \frac{c\Delta t_e - v_\perp \Delta t_e}{c} \approx \Delta t_e\,(1-\beta) = \Delta t_e \frac{1-\beta^2}{1+\beta} \approx \frac{\Delta t_e}{2\gamma^2}$$

Emission from one and many electrons

duration of the received pulse

$$\Delta t_a \approx \frac{\Delta t_e}{2\gamma^2} = \frac{1}{2\pi\gamma^3\nu_B} = \frac{1}{\gamma^2}\frac{mc}{qB}$$

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characteristic synchrotron frequency

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$$P = \frac{4}{3}\,\sigma_T c\, U_B\gamma^2$$

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$$N(\gamma) = K\gamma^{-\delta}$$

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$$L_s(\nu) = \int \mathrm{d}\gamma N(\gamma) P(\gamma, B)\delta\left(\nu - \nu_s(\gamma, B)\right)$$

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$$L(\nu) \propto K B^{\frac{\delta+1}{2}} \nu^{-\frac{\delta-1}{2}}$$

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at a given frequency

we can estimate a combination of K and B, but not the two quantities separately!!!

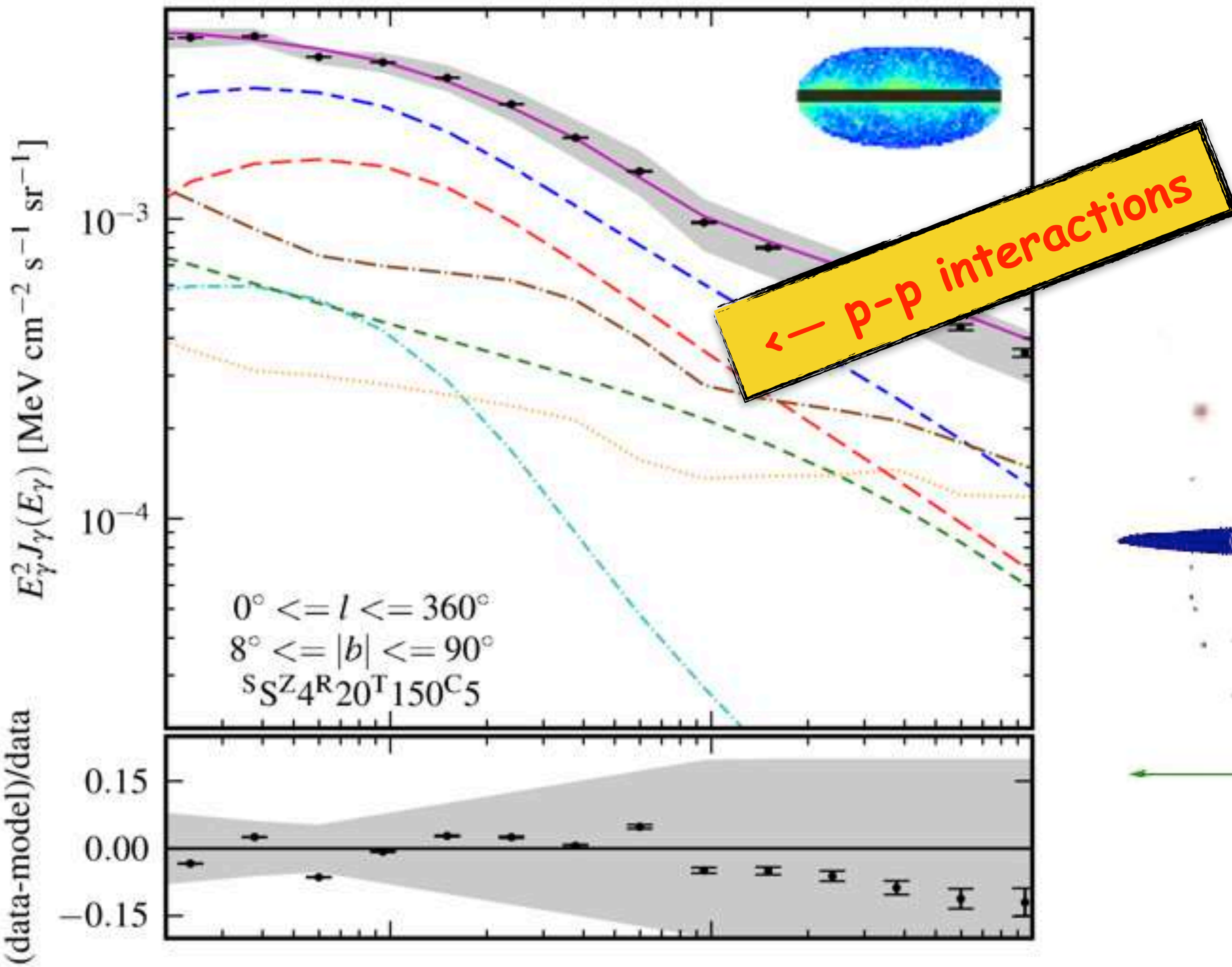
several ways to measure B exist, and they indicate B ~ 3 μG in the Milky Way

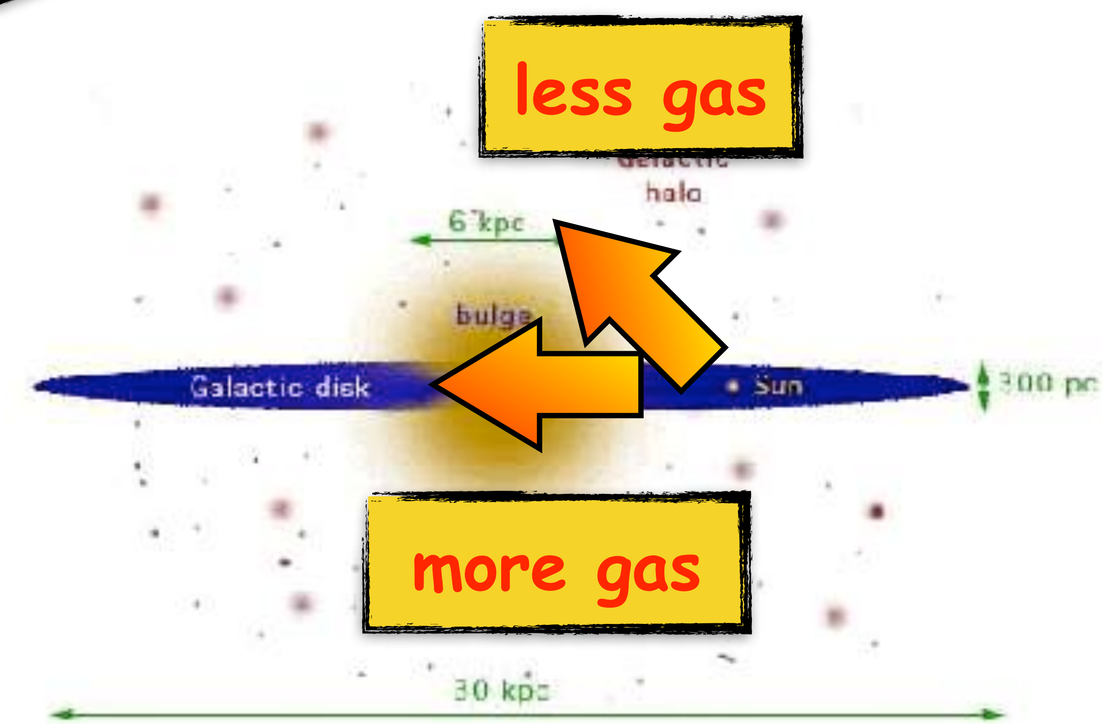
$$\nu_s = \gamma^2 \frac{qB}{2\pi mc} \begin{cases} E_e = 10 \text{ GeV} \longrightarrow \nu_s \sim 3 \text{ GHz} \\ E_e = 100 \text{ TeV} \longrightarrow \nu_s \sim 1 \text{ keV} \end{cases}$$

radio

X-rays

Diffuse emission, large Galactic latitudes





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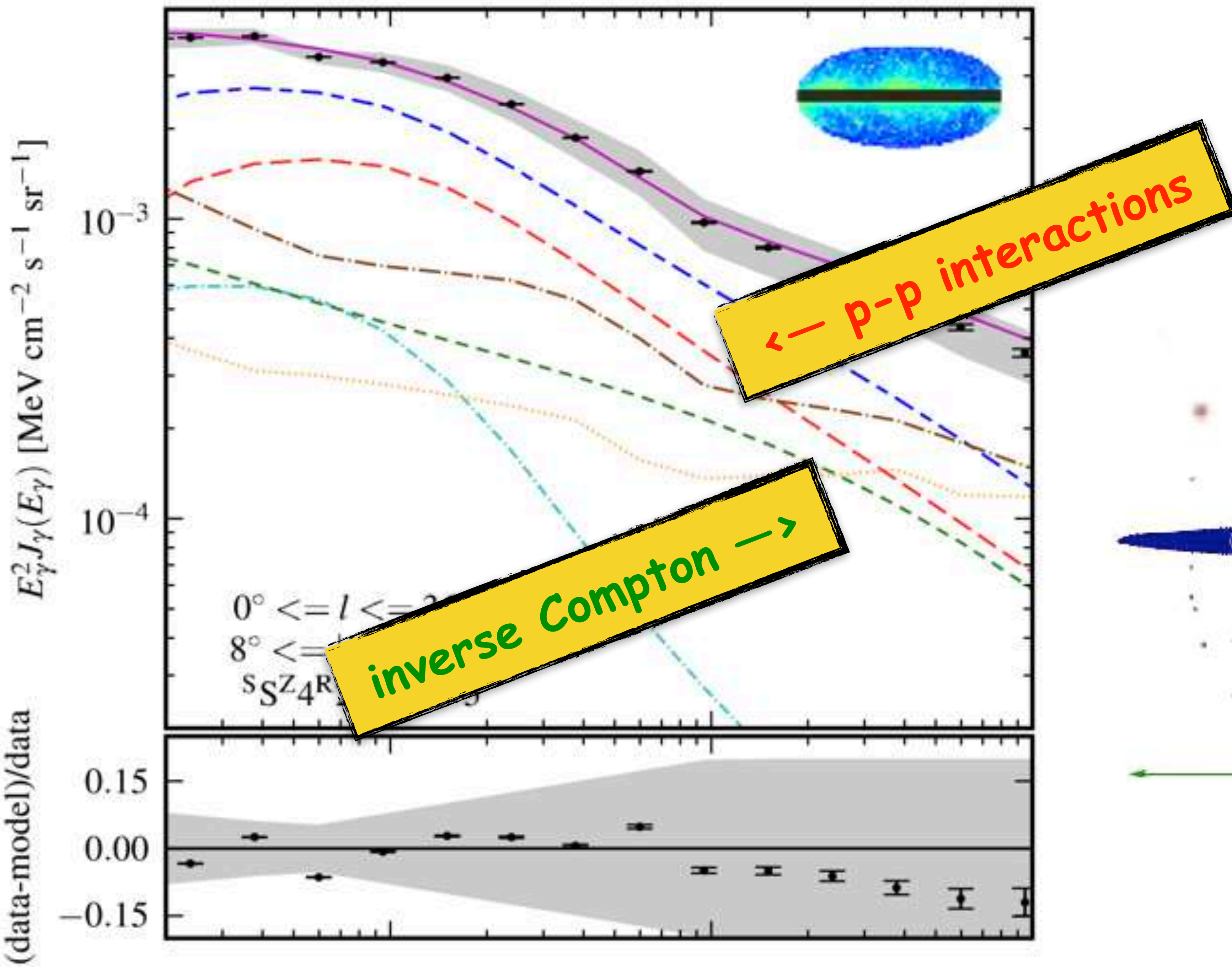
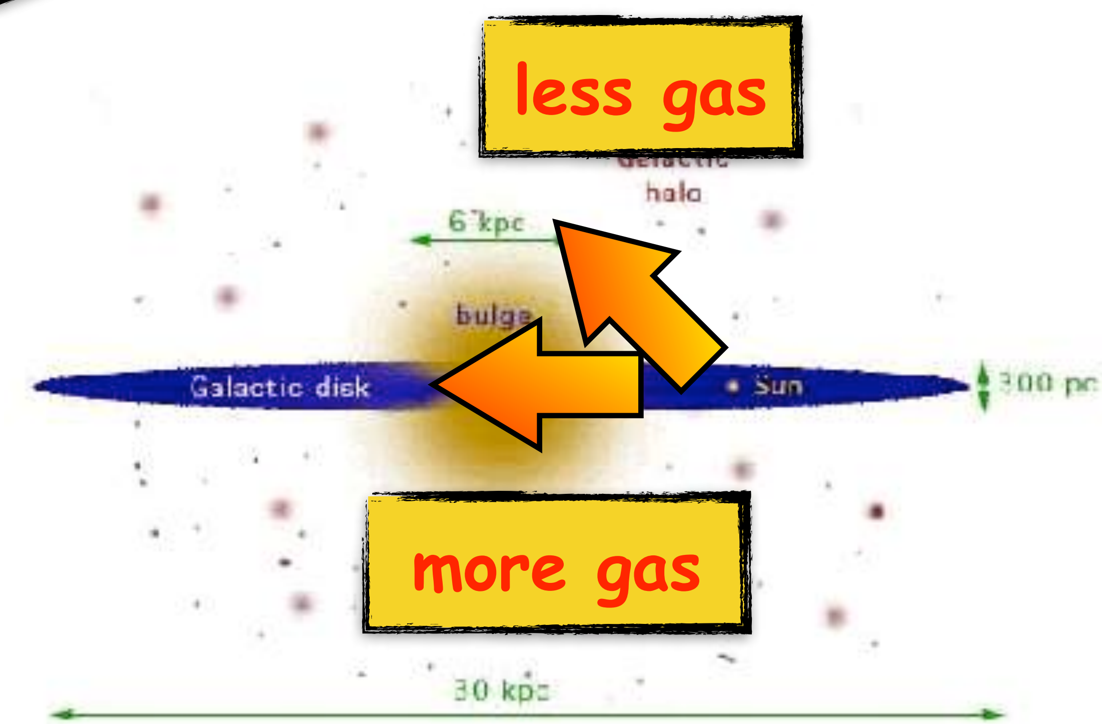
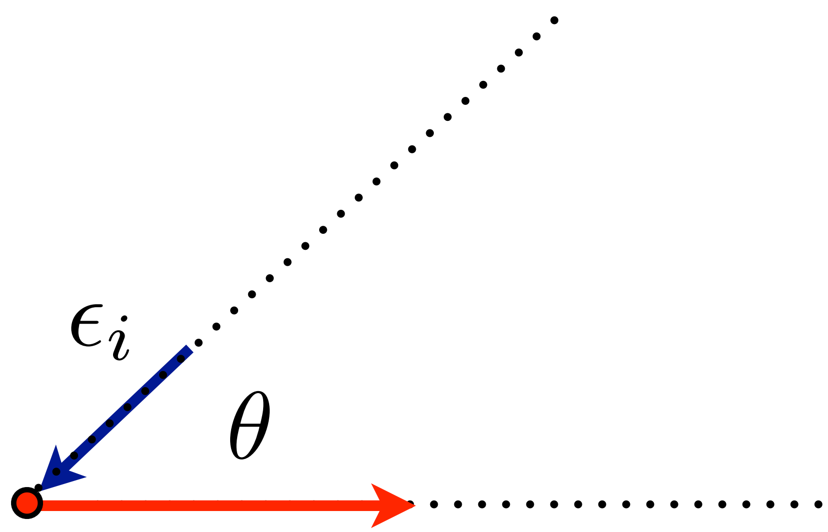




Leptonic Gamma-Rays: Inverse Compton

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



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

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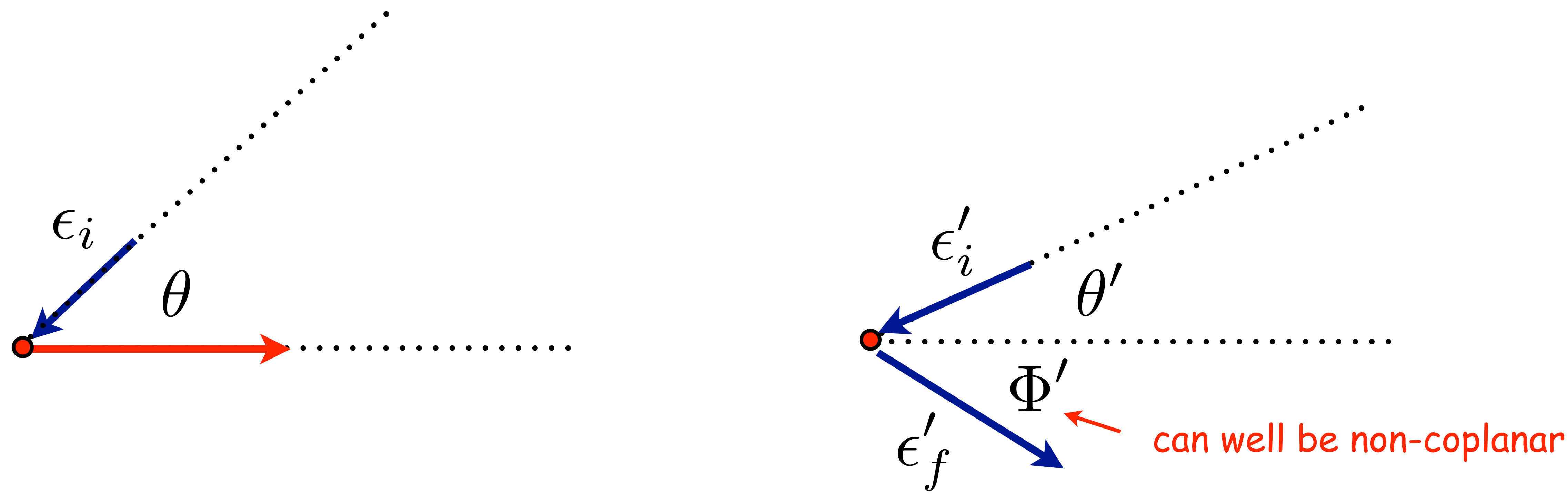

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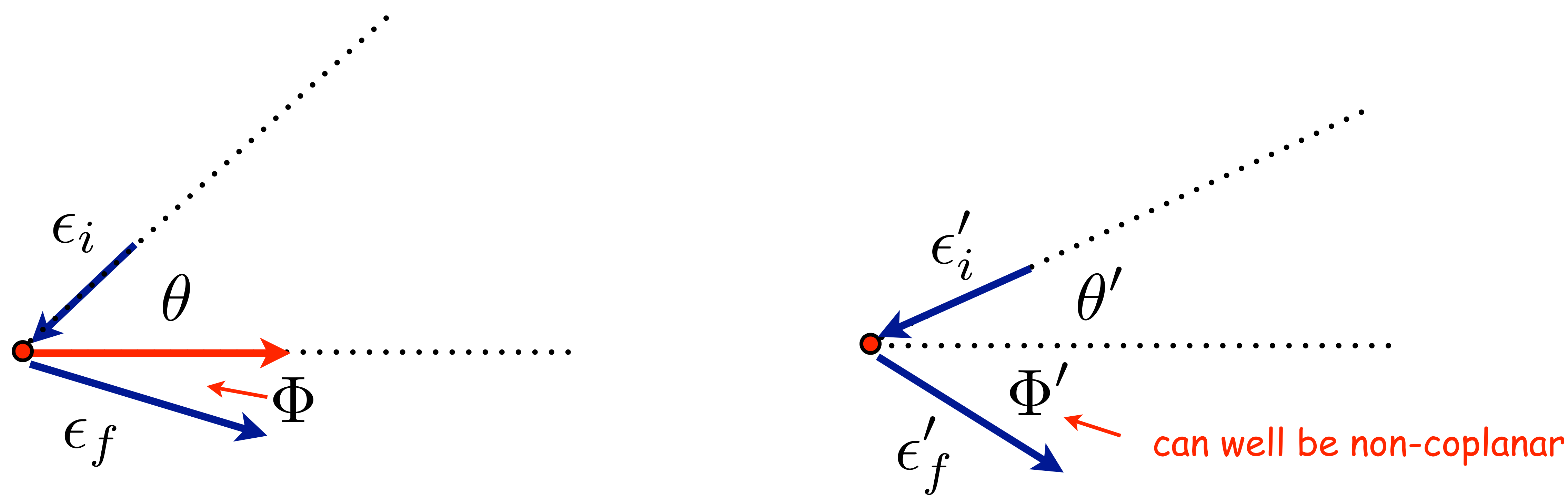

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In the lab rest frame the (final) photon energy is: $\epsilon_f = \epsilon_f' \, \gamma \, (1 + \beta \cos\Phi)$

Leptonic Gamma-Rays: Inverse Compton

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

After averaging over angles (tedious...):

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

Leptonic Gamma-Rays: Inverse Compton

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Example:

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

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

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

energy conservation...

above a given energy Inverse Compton scattering becomes ineffective

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

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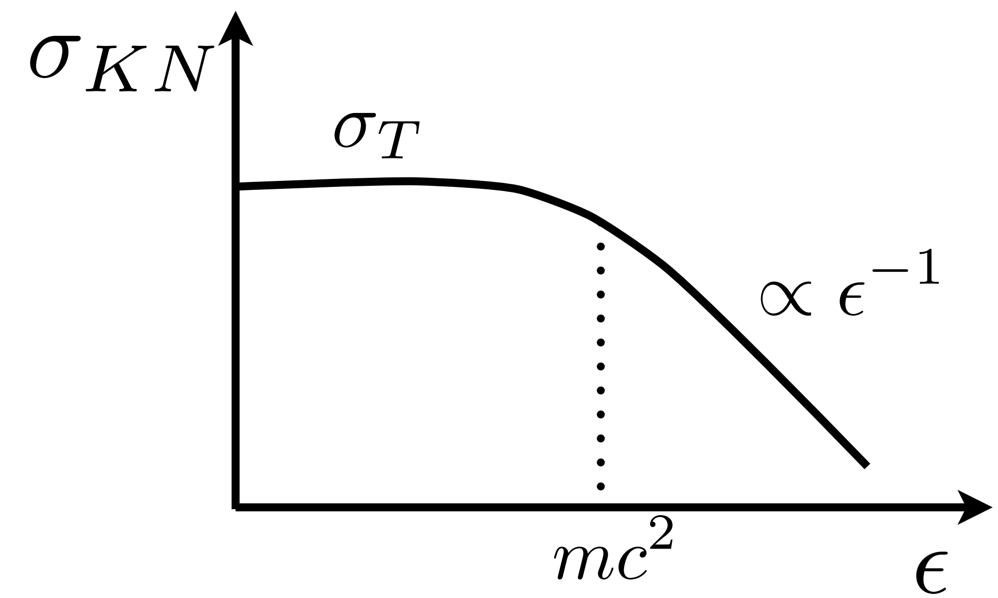

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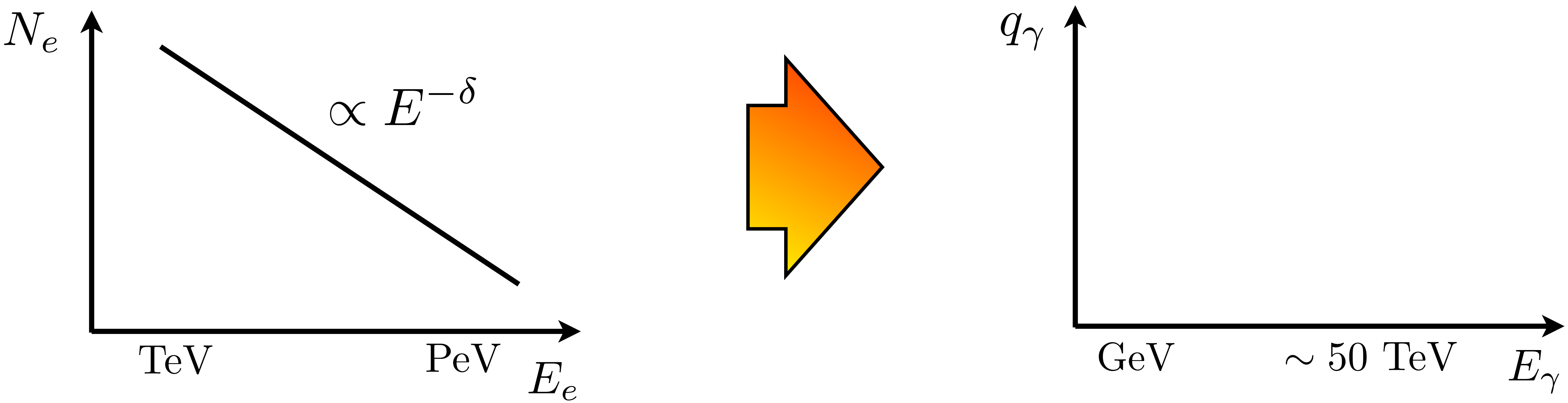
Leptonic Gamma-Rays: Inverse Compton

Photon spectrum:



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

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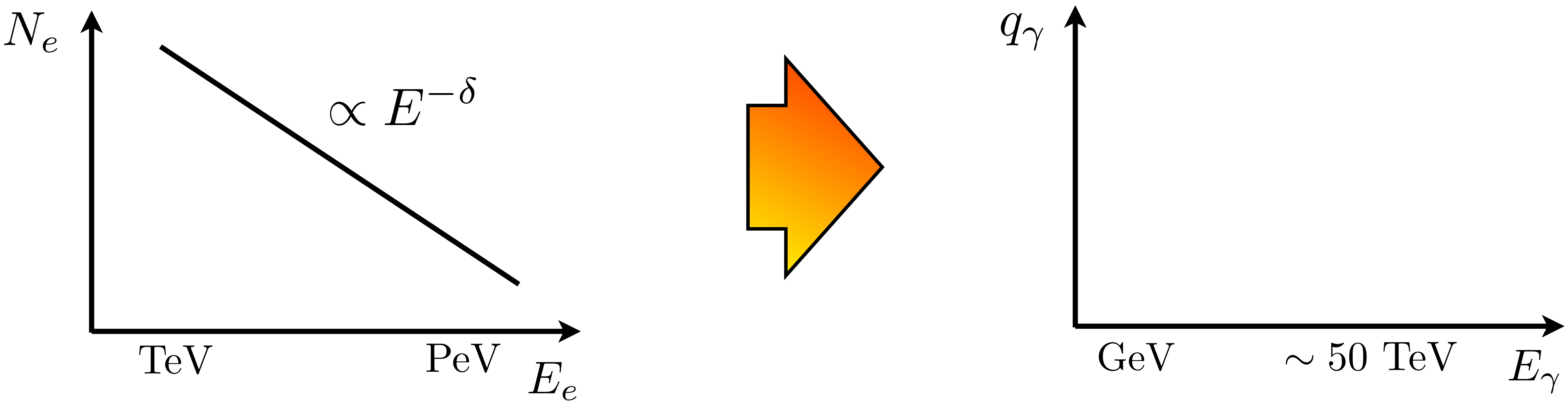

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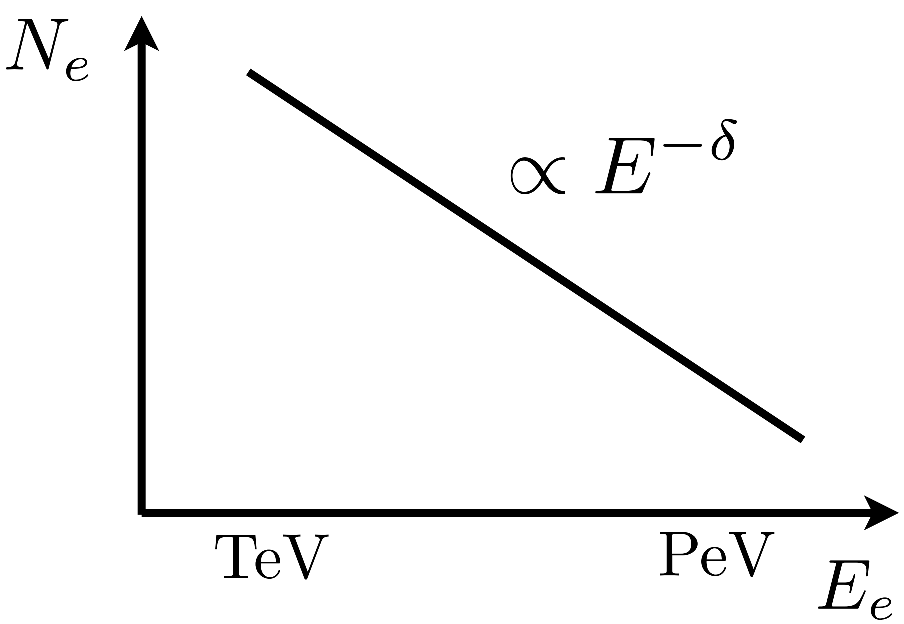

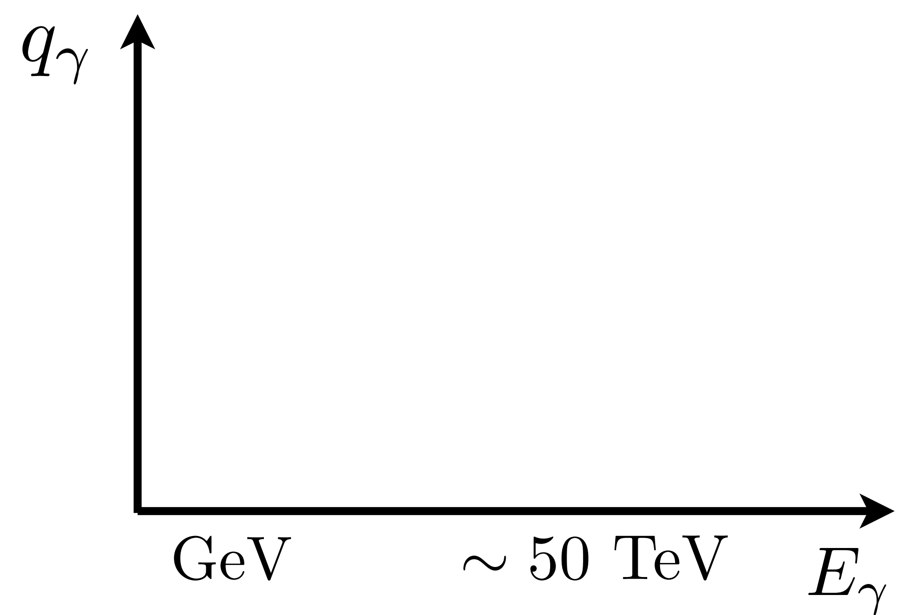

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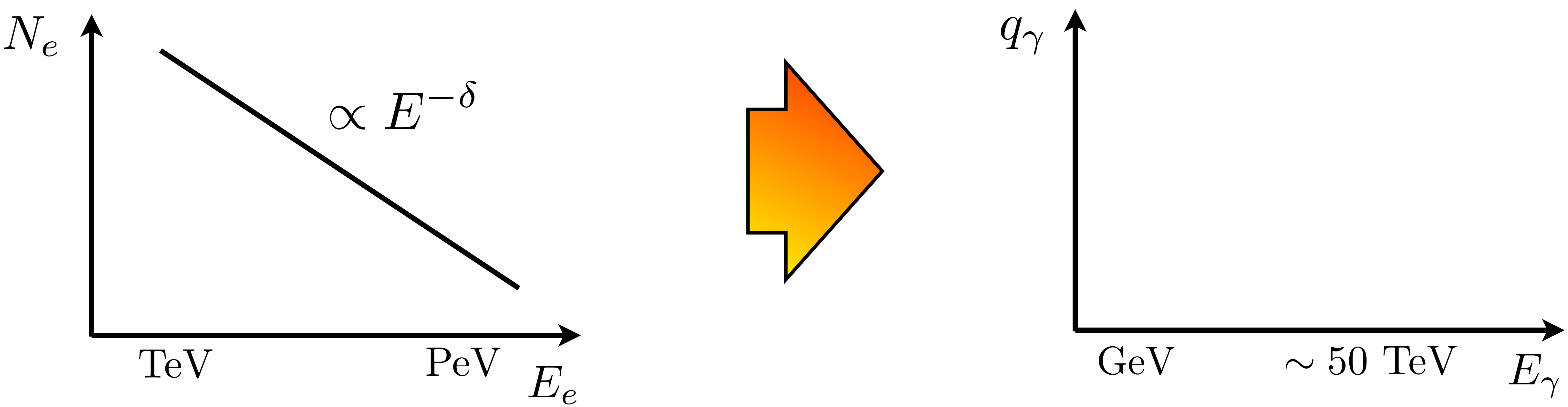

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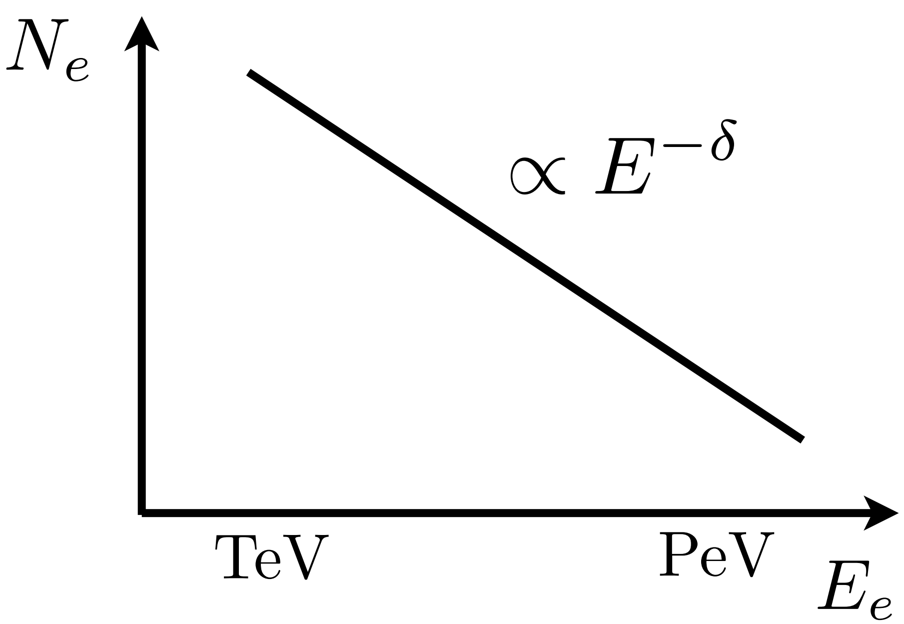

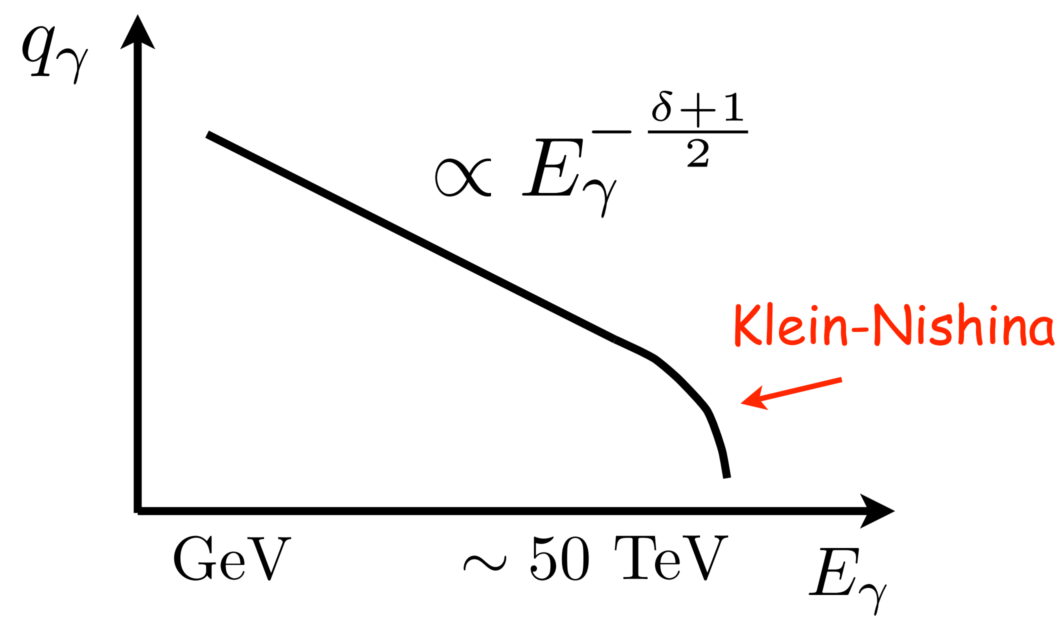

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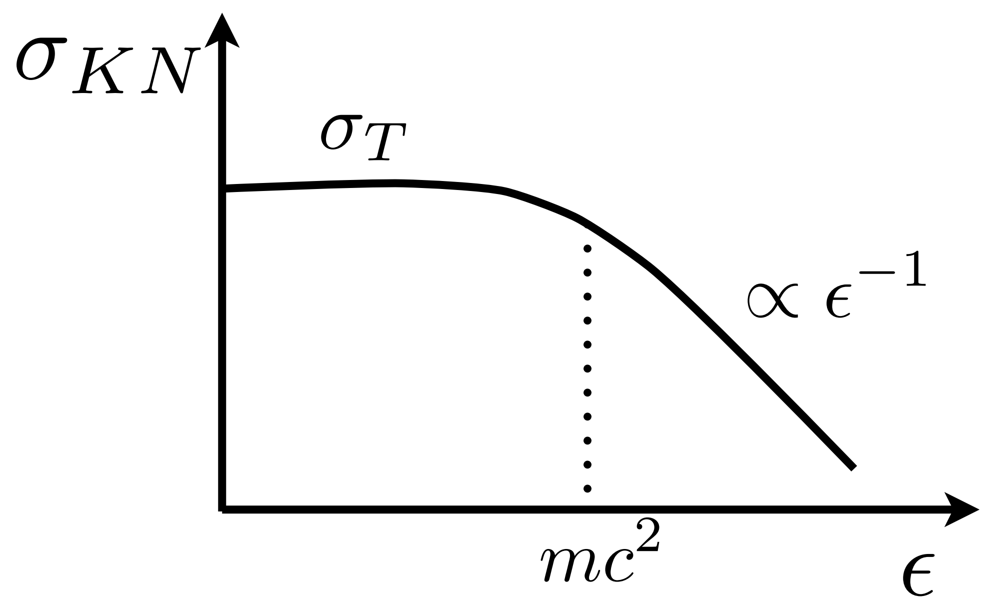
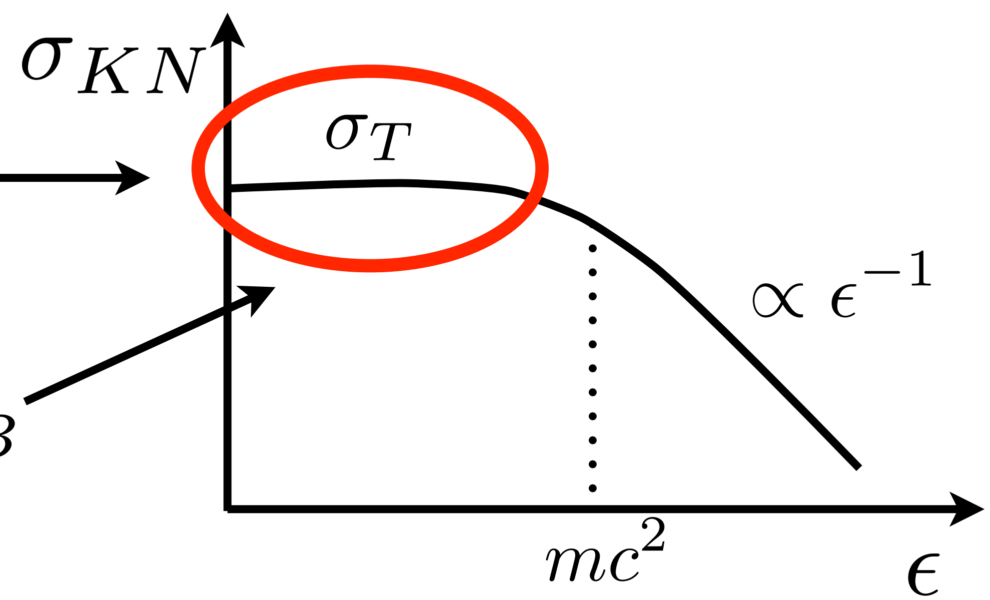


$E_e = \gamma\ m\ c^2$	$\frac{\epsilon_\gamma}{E_e}$	ϵ_γ

Leptonic Gamma-Rays: Inverse Compton

$$\gamma\ \epsilon_\gamma < mc^2$$

$$\epsilon_\gamma = \frac{4}{3}\ \gamma^2\ \epsilon_{CMB}$$



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Thomson

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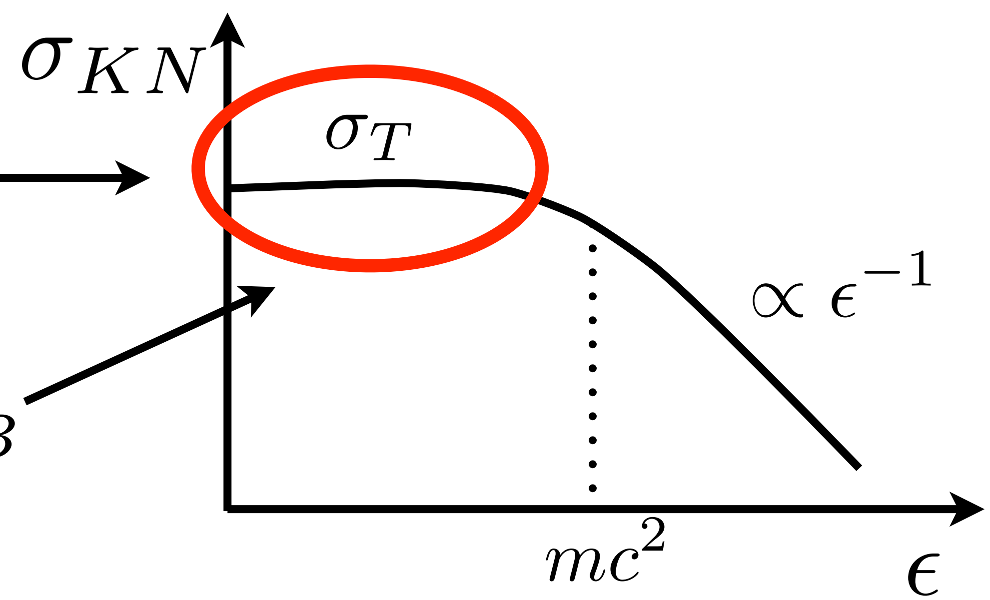

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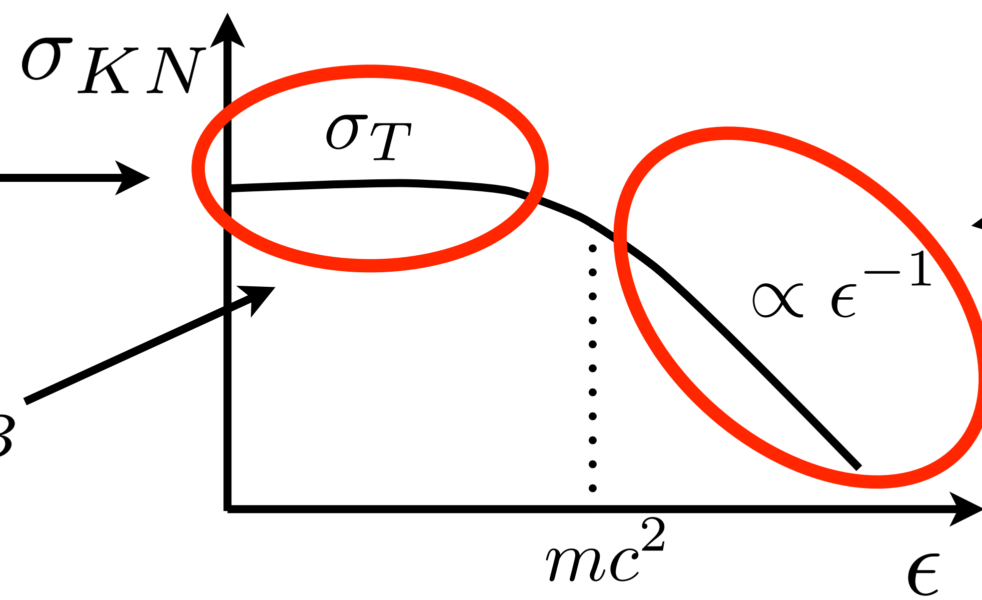

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....	....	....
E_e >> 200 TeV	~100%	E_e ~ E_γ

Thomson

Klein-Nishina

Leptonic Gamma-Rays: Inverse Compton

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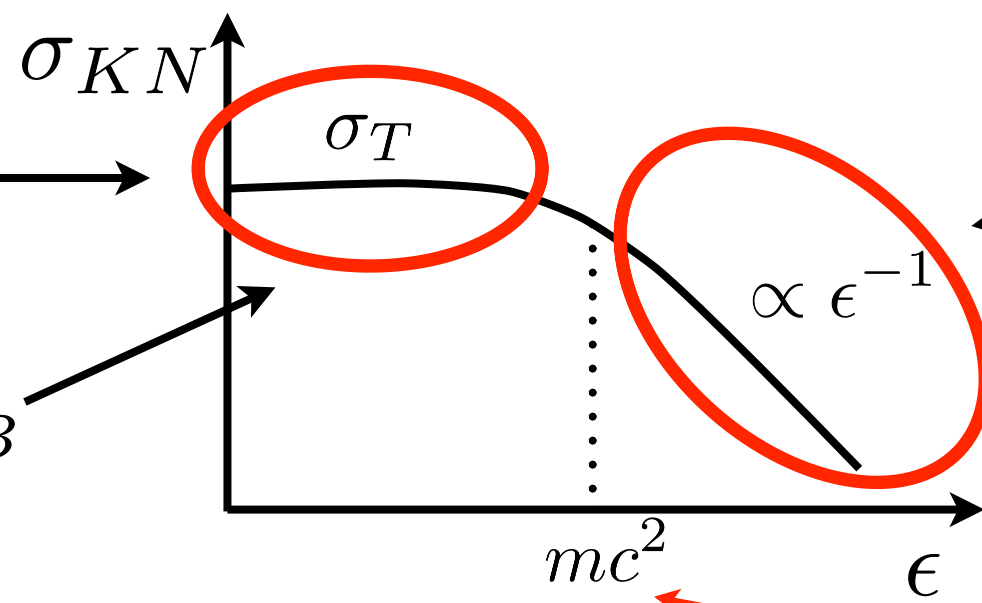

$$\gamma \ \epsilon_\gamma > mc^2$$

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cutoff in the photon spectrum

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1 TeV	~0.2%	~1.5 GeV
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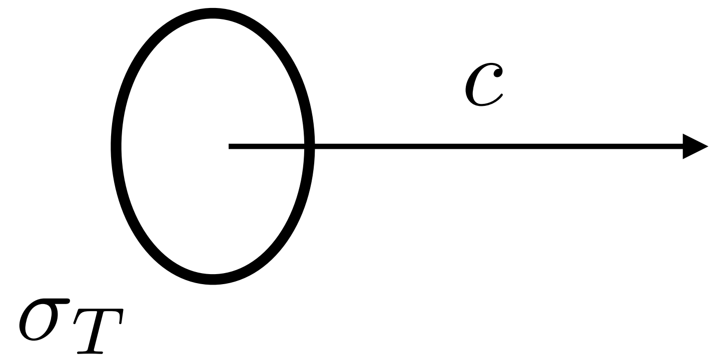
200 TeV	~30%	~60 TeV
....	....	....
E_e >> 200 TeV	~100%	$E_e \sim E_\gamma$

Thomson

Klein-Nishina

Inverse Compton: energy loss rate

Scattering rate



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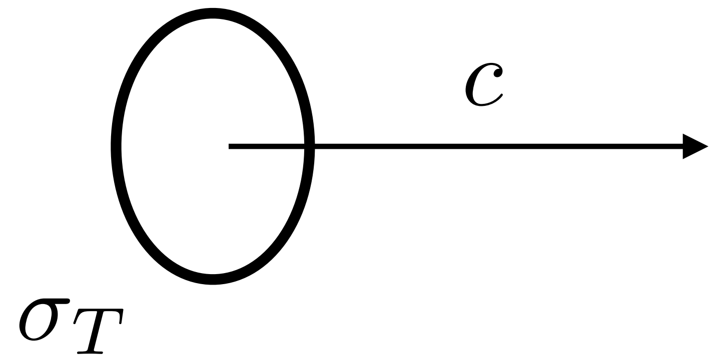
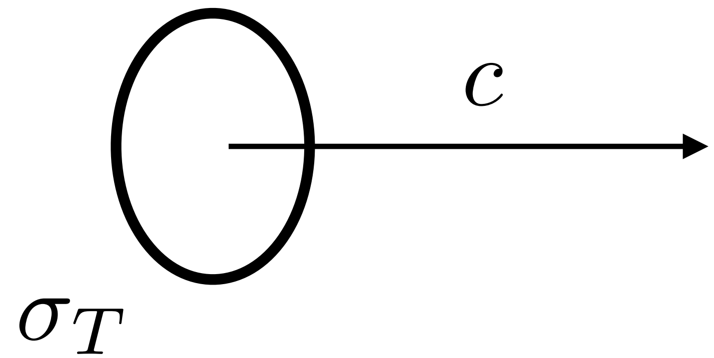


Volume swept per second $\sigma_T c$

Inverse Compton: energy loss rate

Scattering rate



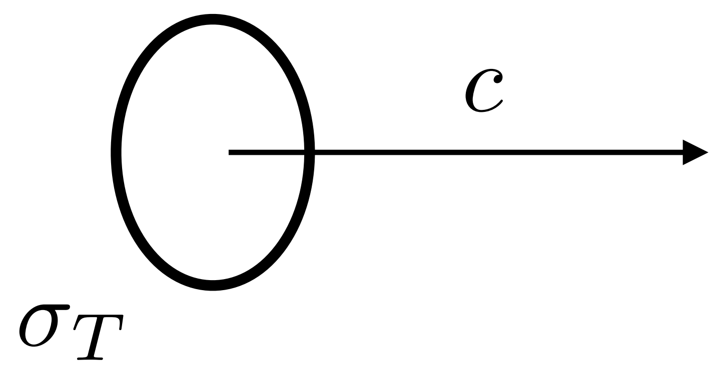
Volume swept per second $\sigma_T c$

Interaction rate $\sigma_T c n_{CMB}$

$$n_{CMB} = \frac{\omega_{CMB}}{\langle \epsilon \rangle}$$

Inverse Compton: energy loss rate

Scattering rate



Volume swept per second $\sigma_T c$

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Radiated power $$P_{IC} = \left(\sigma_T c \frac{\omega_{CMB}}{\langle \epsilon \rangle} \right) \left(\frac{4}{3} \gamma^2 \langle \epsilon \rangle \right) = \frac{4}{3} \sigma_T c \gamma^2 \omega_{CMB}$$

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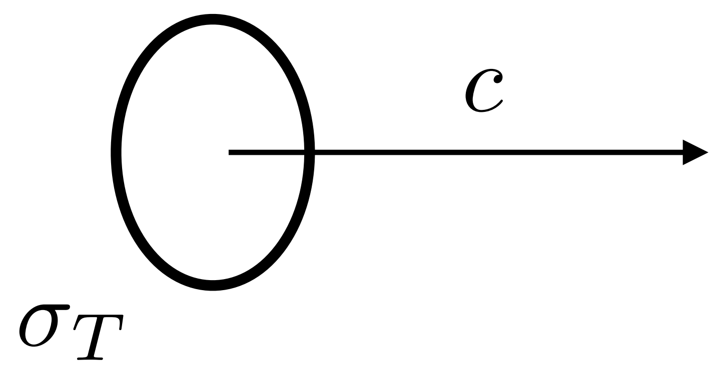
Scattering rate



Volume swept per second $\sigma_T c$

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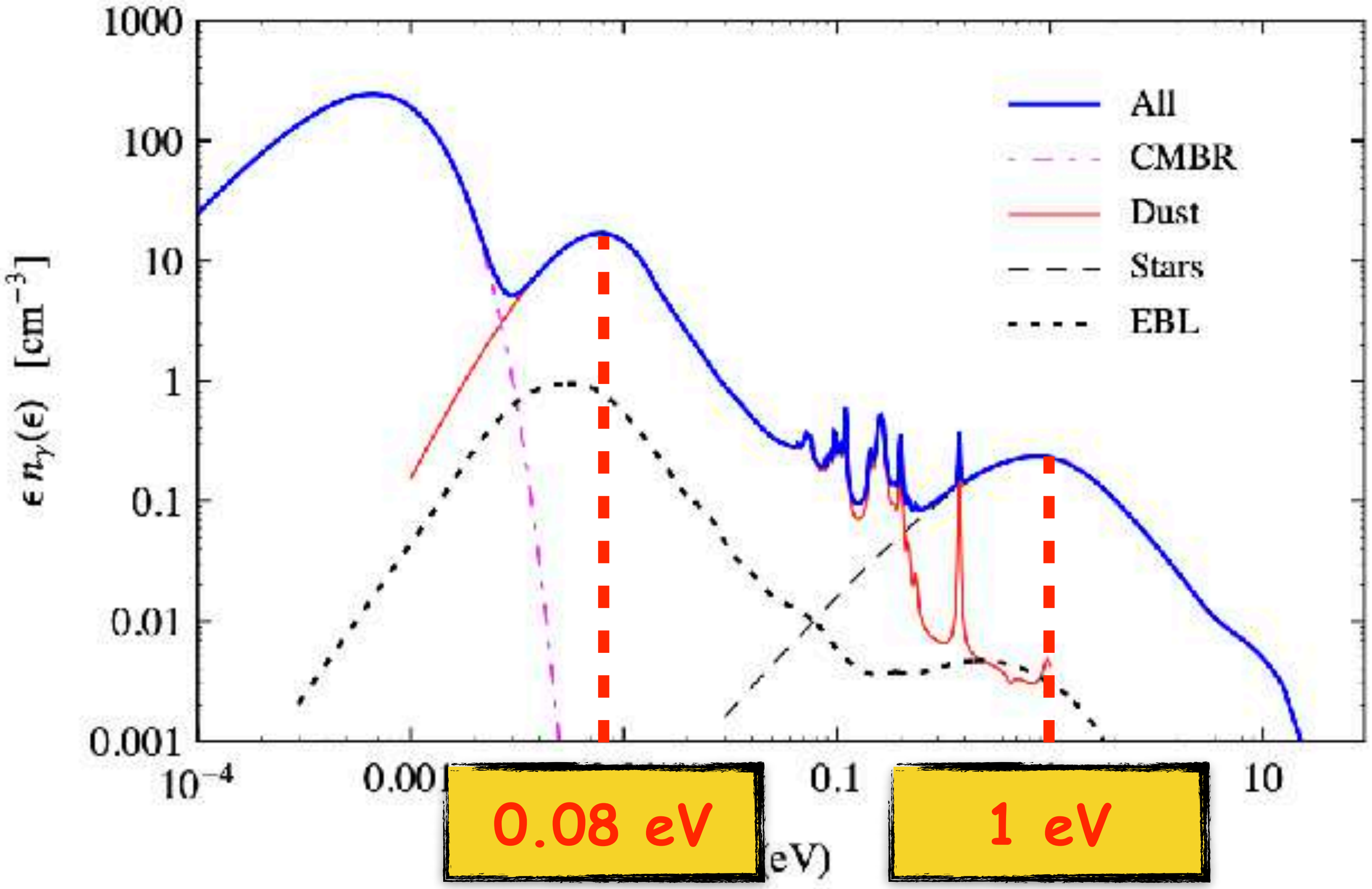
Same expression as synchrotron!

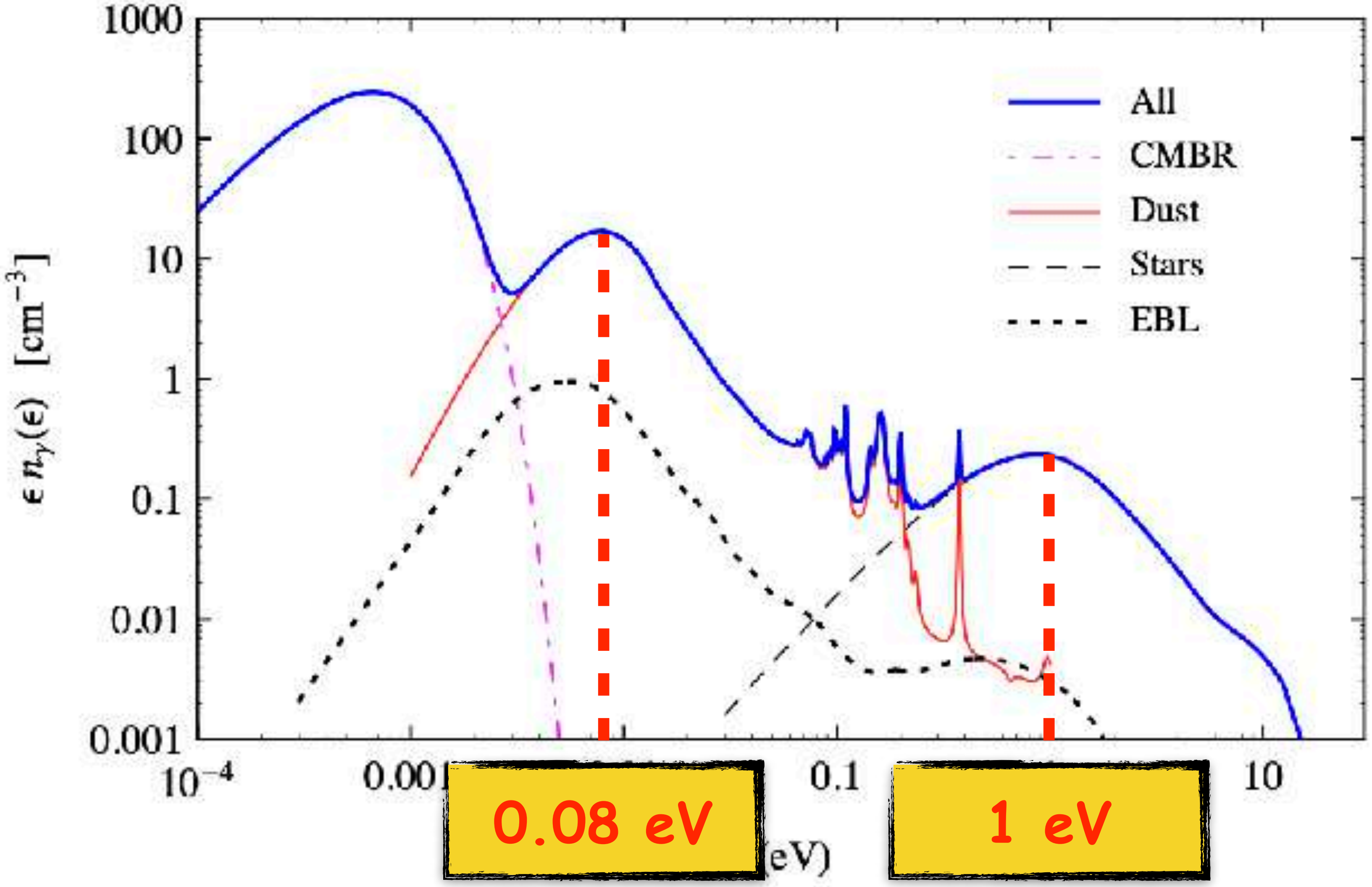
Note on the K-N regime

Lipari & Vernetto 2018



Note on the K-N regime

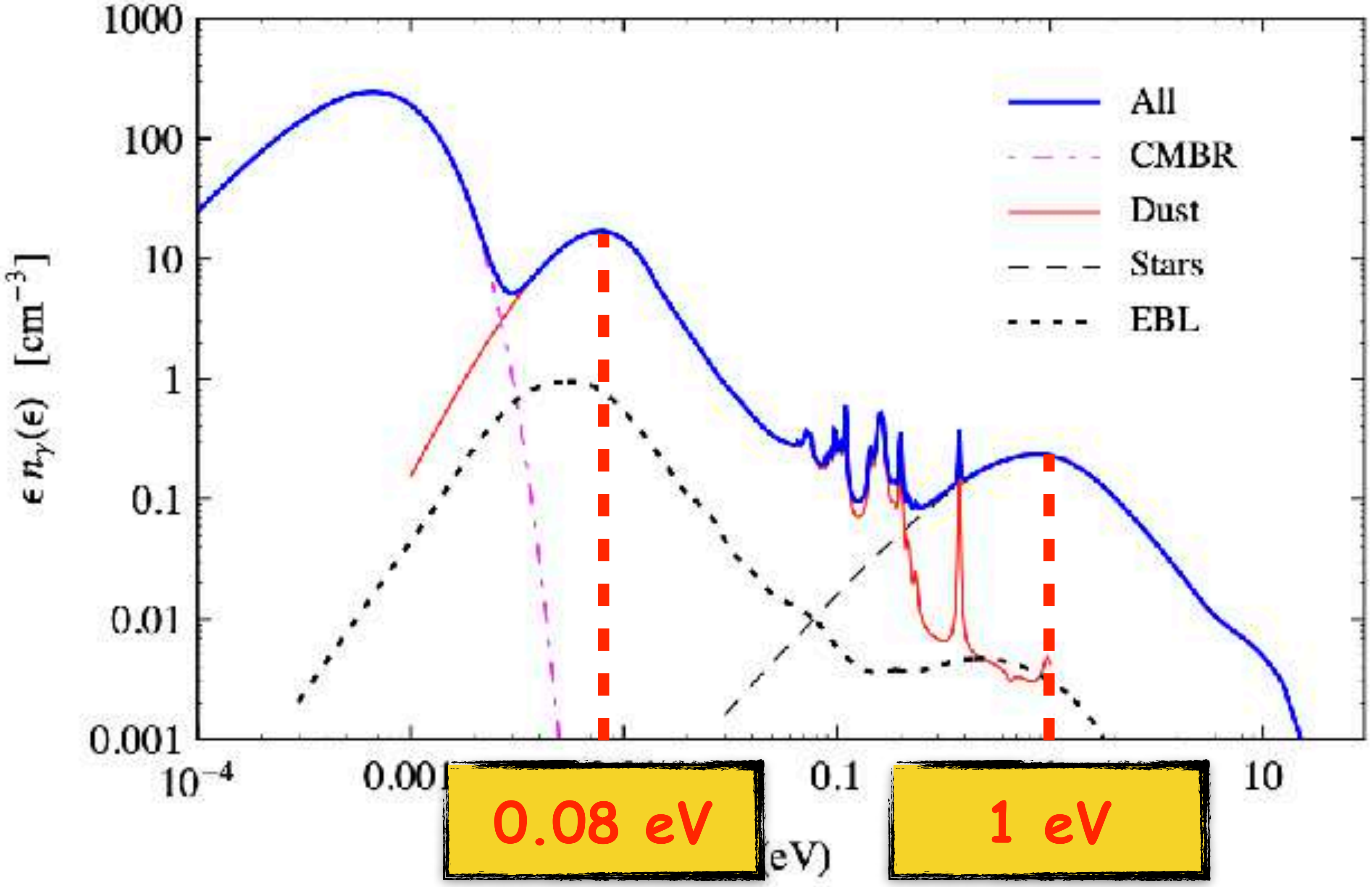
Lipari & Vernetto 2018



$$\gamma\ \epsilon_\gamma > mc^2$$

Note on the K-N regime

Lipari & Vernetto 2018



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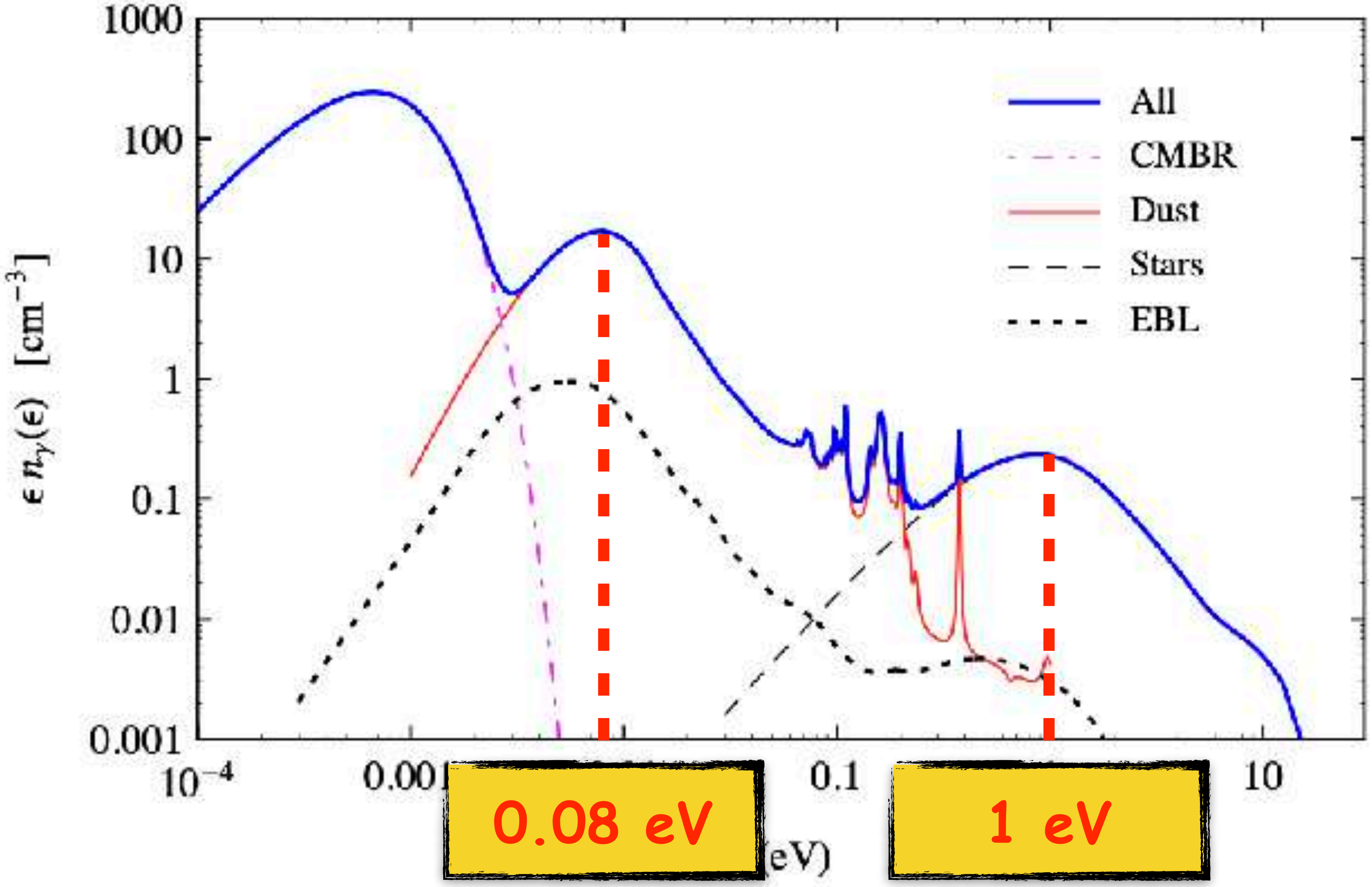

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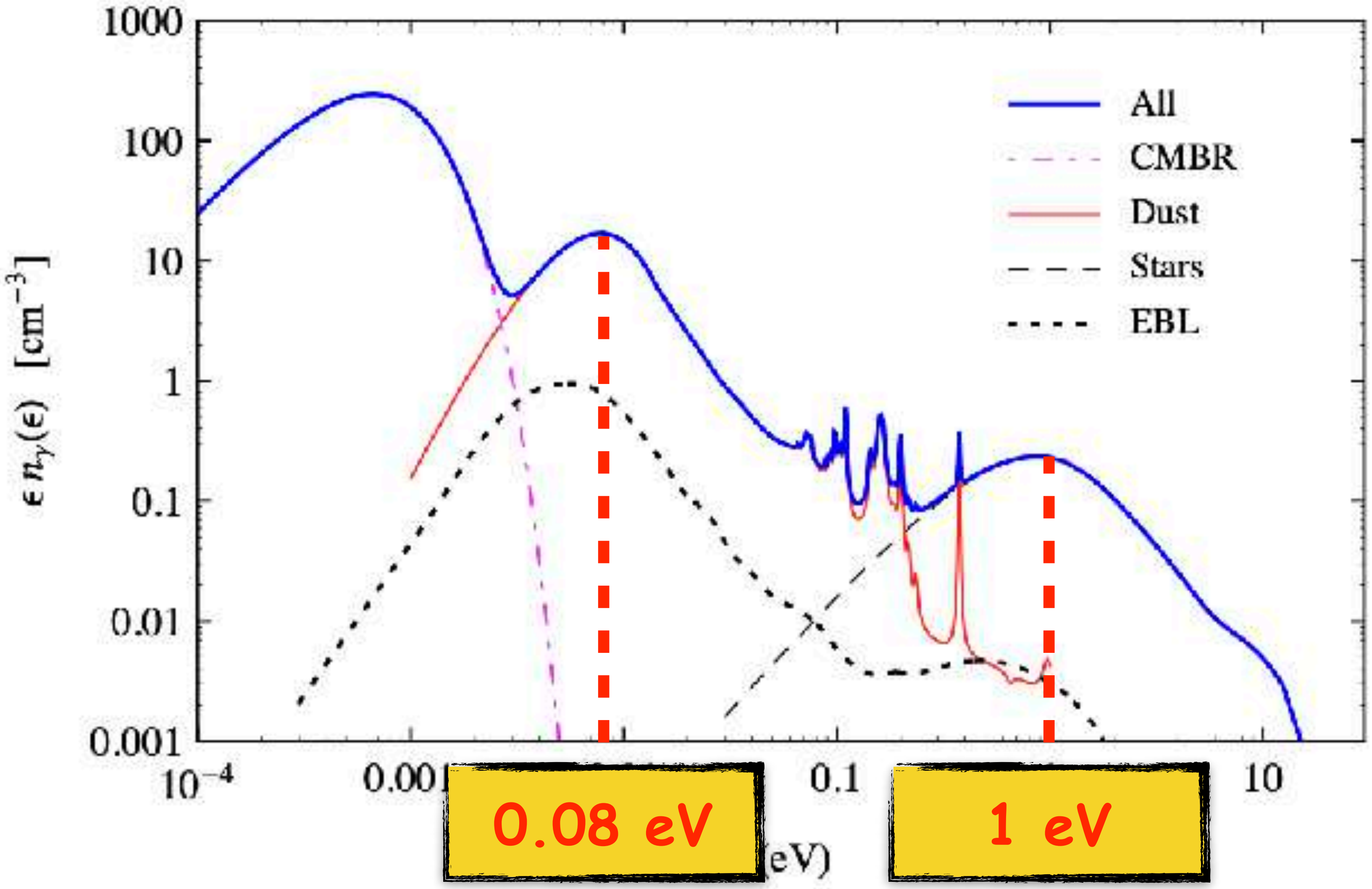
$$E_\gamma = \frac{4}{3}\gamma^2\epsilon_\gamma$$

$$E_\gamma > \frac{4}{3}\frac{(mc^2)^2}{\epsilon_\gamma} \sim 0.3\left(\frac{\epsilon_\gamma}{\text{eV}}\right)\text{TeV}$$

Note on the K-N regime

Lipari & Vernetto 2018



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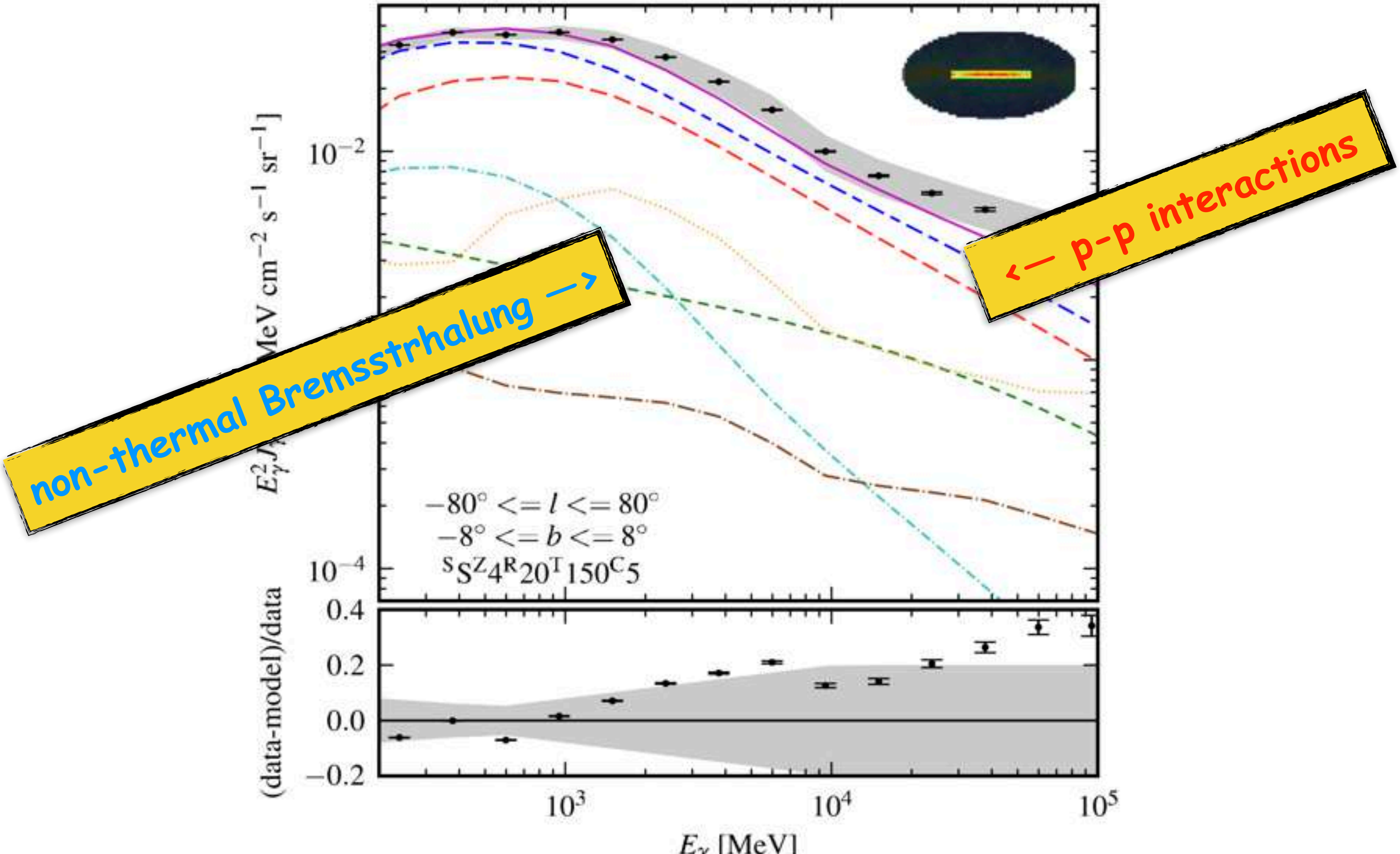
$$E_\gamma = \frac{4}{3}\gamma^2\epsilon_\gamma \quad \Rightarrow \quad E_\gamma > \frac{4}{3}\frac{(mc^2)^2}{\epsilon_\gamma} \sim 0.3\left(\frac{\epsilon_\gamma}{\text{eV}}\right)\text{TeV}$$

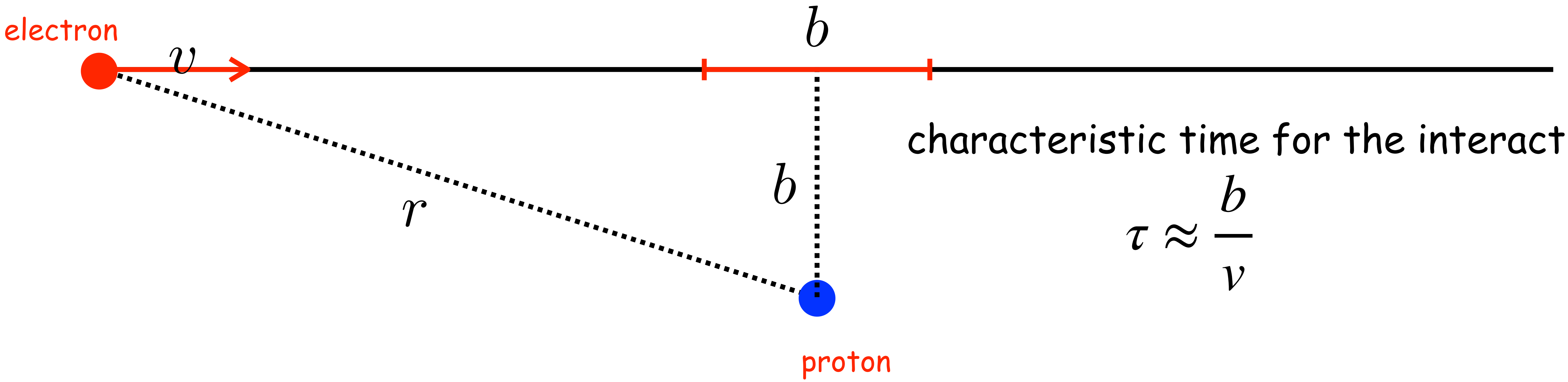
in first approximation: if you are a TeV astronomer just CMB matters for ICS

Non-thermal bremsstrahlung



Non-thermal Bremsstrahlung

remember what we did for the thermal Bremsstrahlung



characteristic time for the interaction

$$\tau \approx \frac{b}{v}$$

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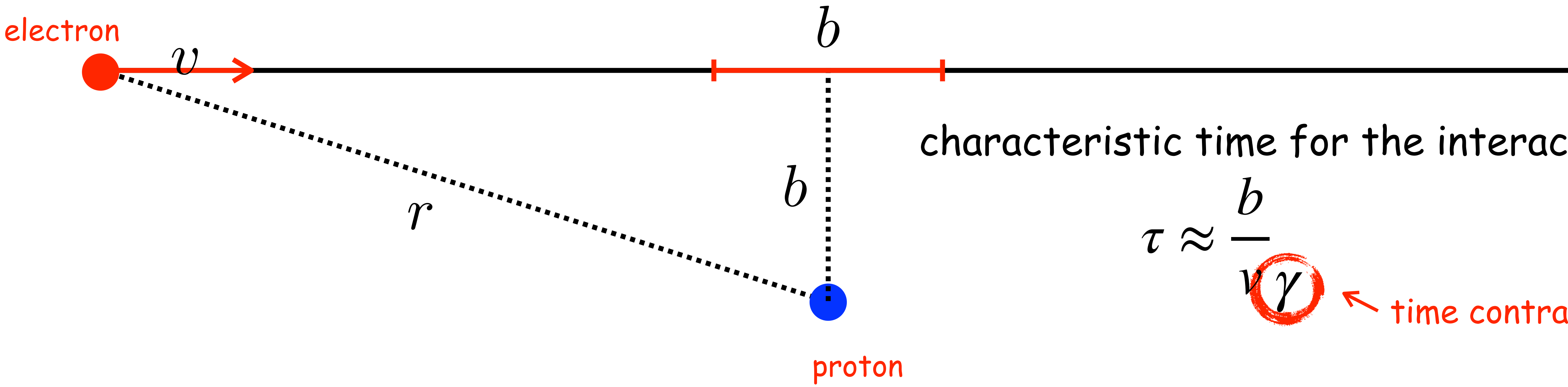

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time contraction

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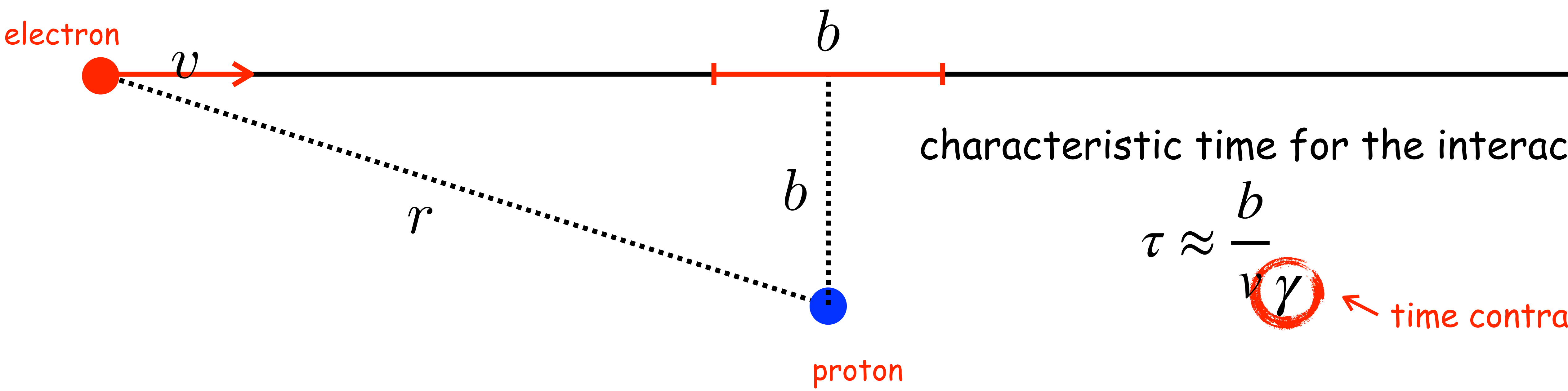

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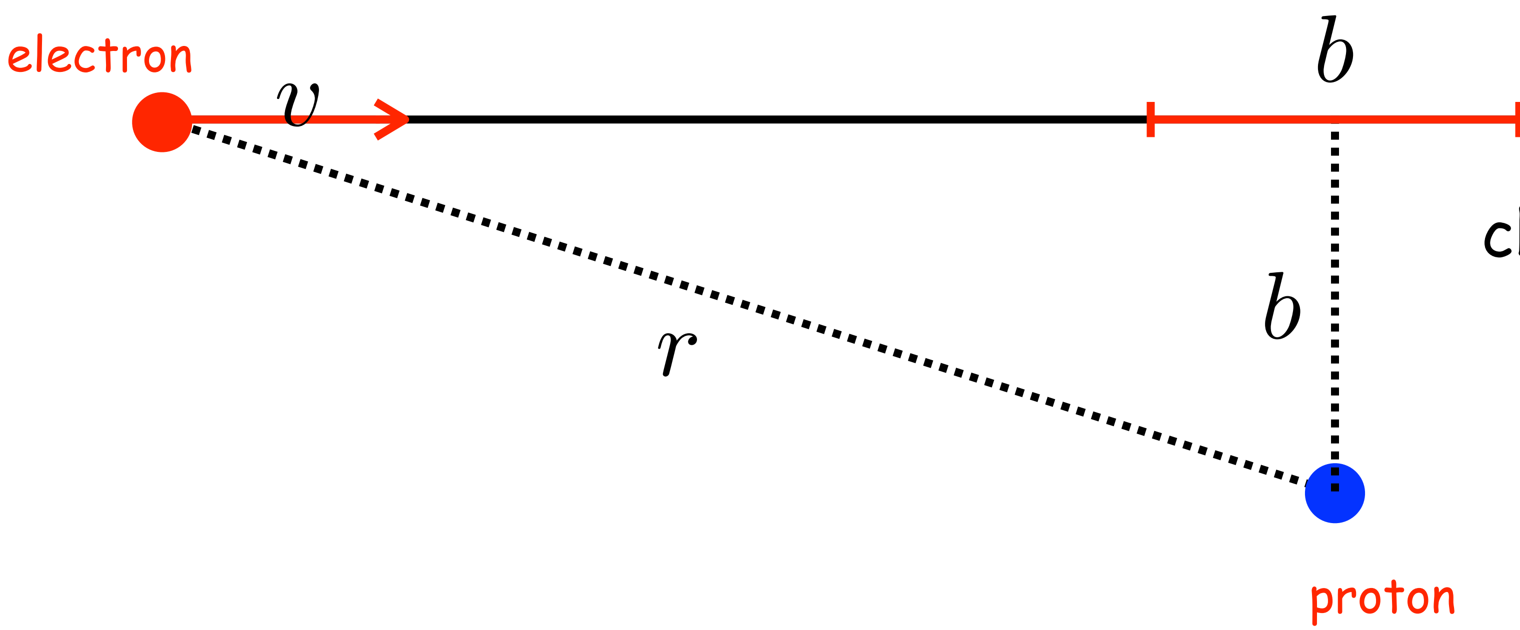

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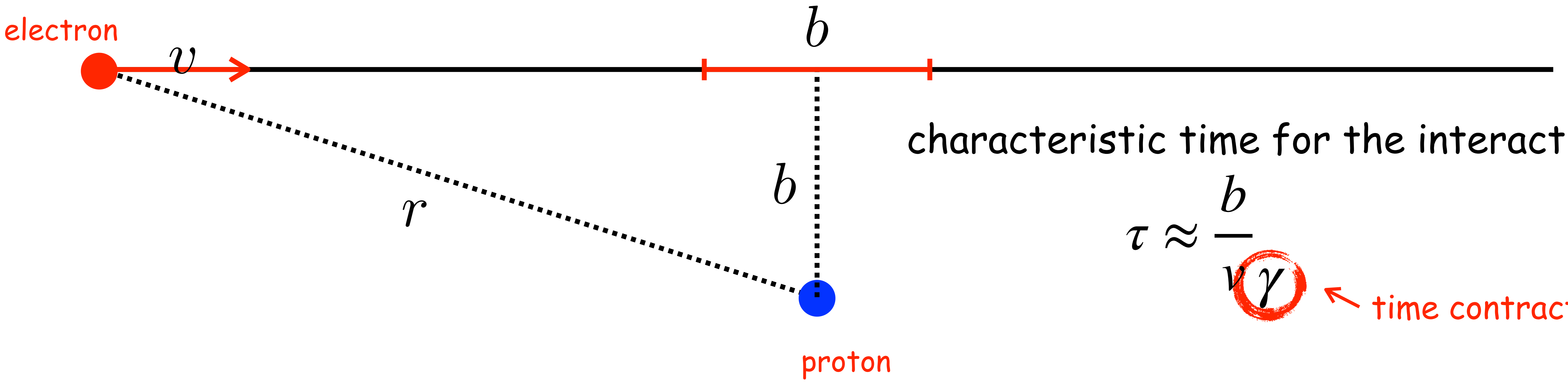


characteristic time for the interaction

$$\tau \approx \frac{b}{v\gamma}$$

time contraction

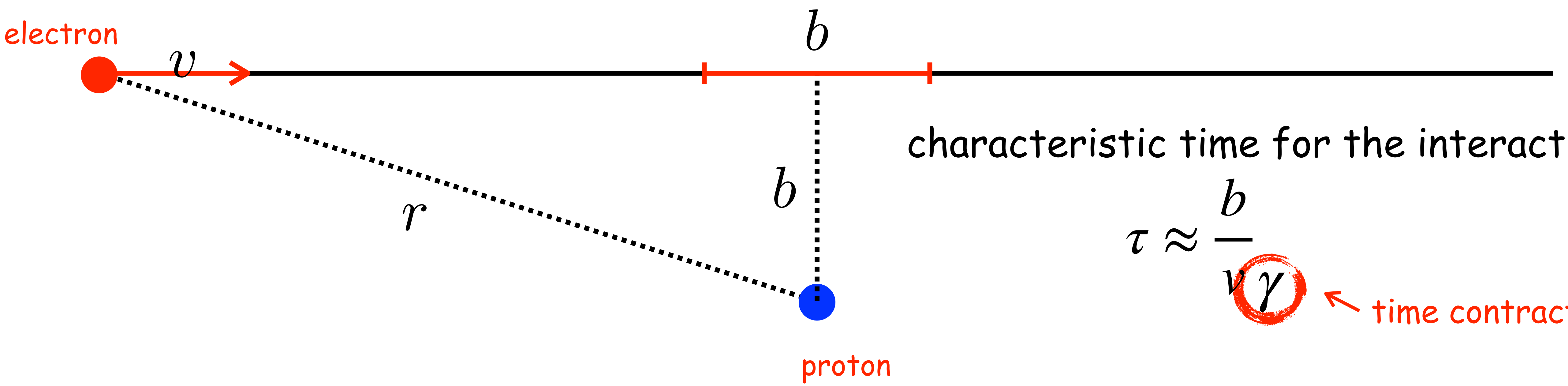
—> in its rest frame, the e^- sees the proton's E field contracted into a very fast pulse

—> the pulse can be approximated as a spectrum of plane waves, i.e., "virtual" photons

—> the e^- will Compton scatter the virtual photon

Non-thermal Bremsstrahlung

remember what we did for the thermal Bremsstrahlung



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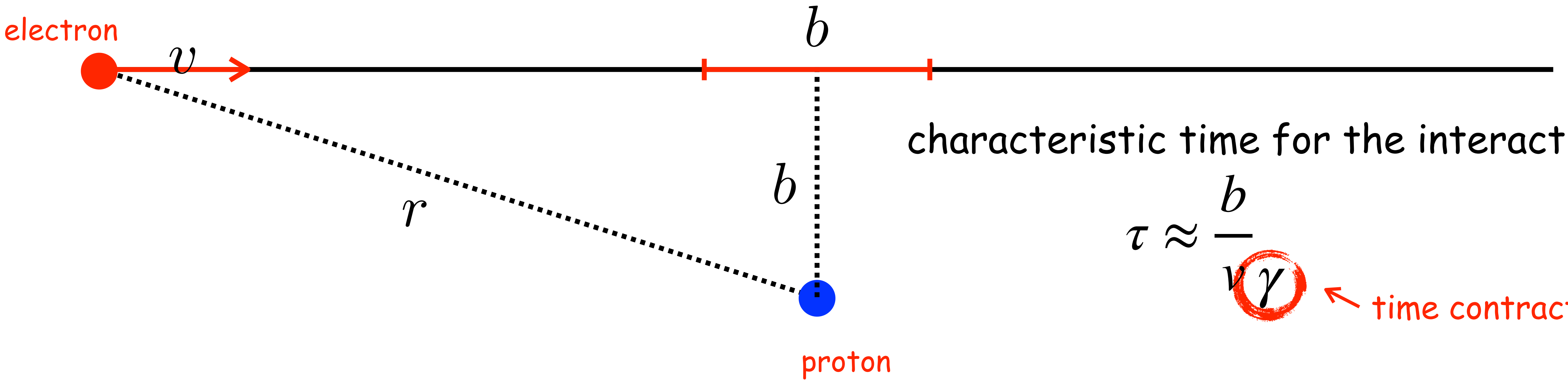

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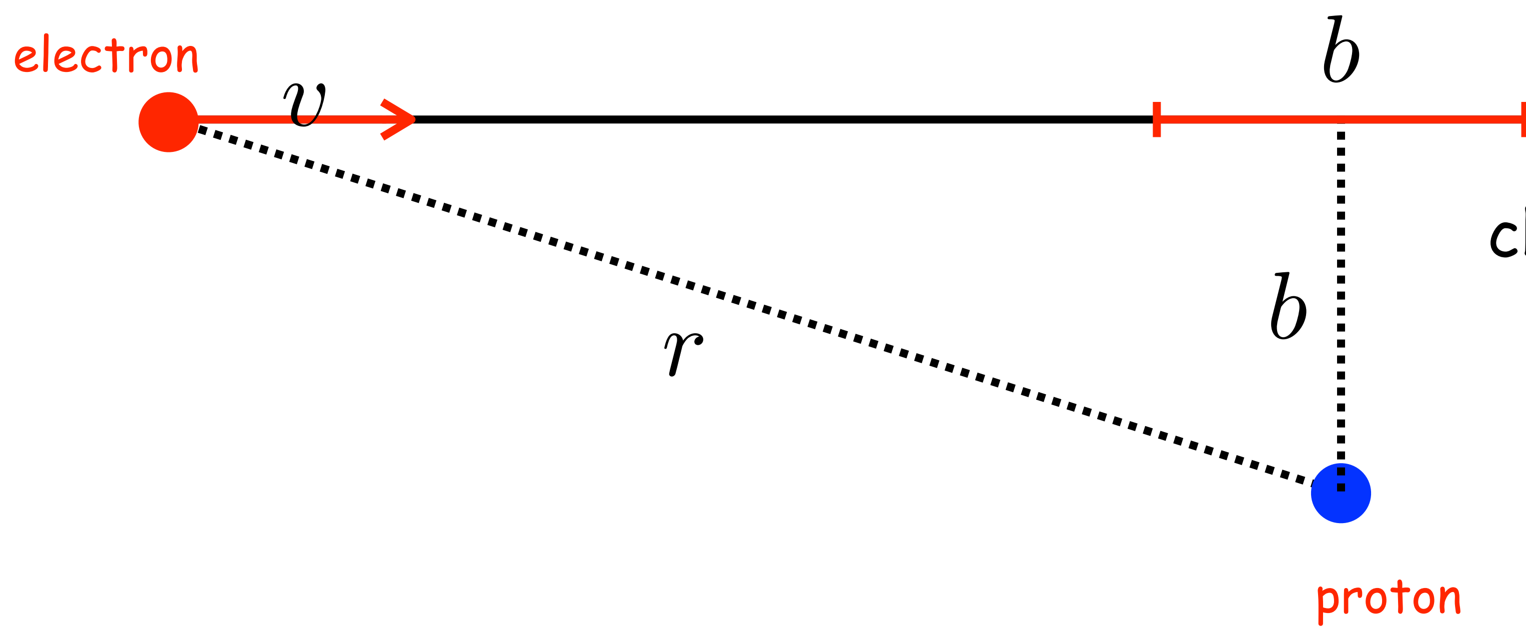

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—> in its rest frame, the e⁻ sees the proton's E field contracted into a very fast pulse

—> the pulse can be approximated as a spectrum of plane waves, i.e., "virtual" photons

—> the e^- will Compton scatter the virtual photon

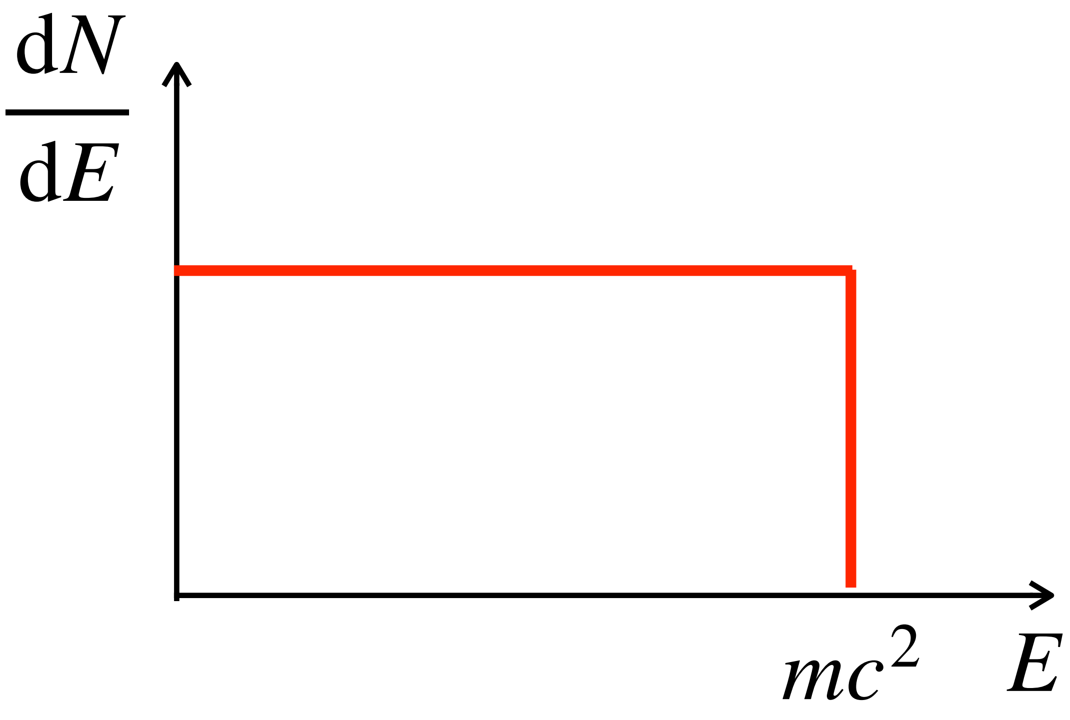
—> Compton cross section drops beyond photon energies equal to mc^2

—> the spectrum of scattered photons (in the e^- rest frame) extends up to mc^2

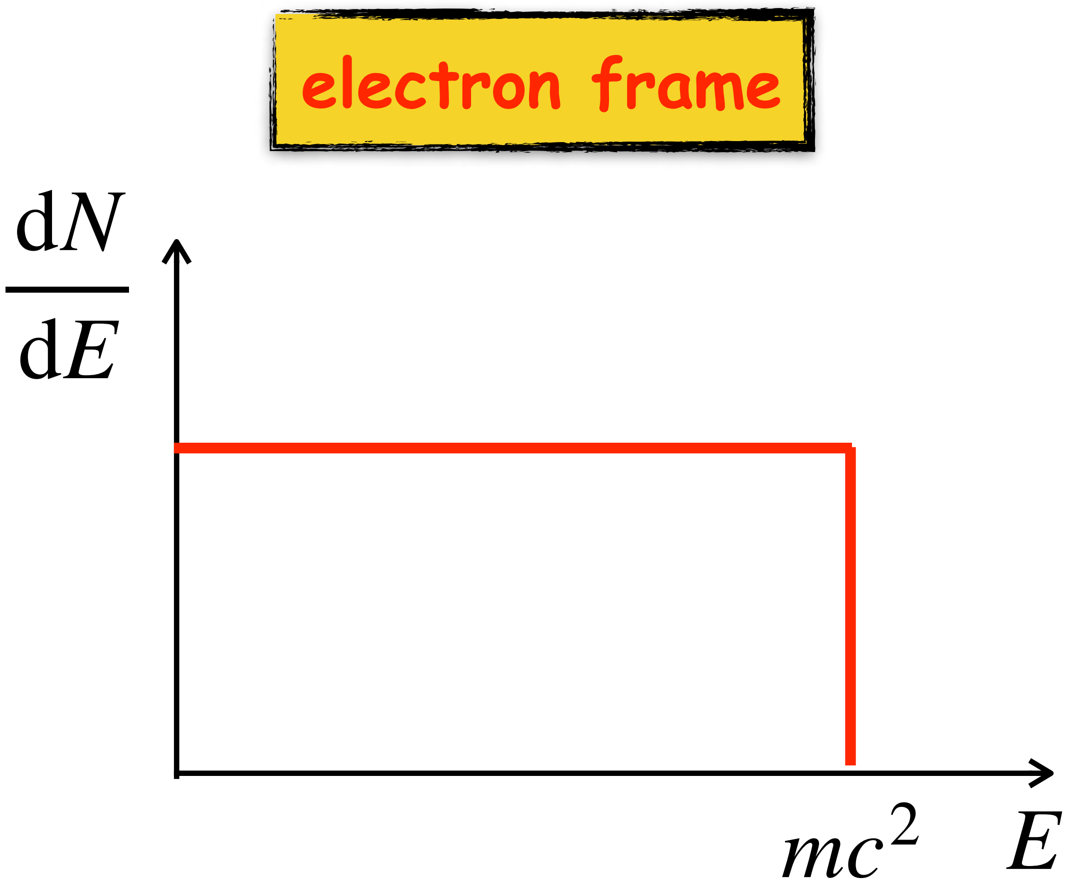
—> in the lab frame the spectrum extends up to $\gamma\, mc^2$!

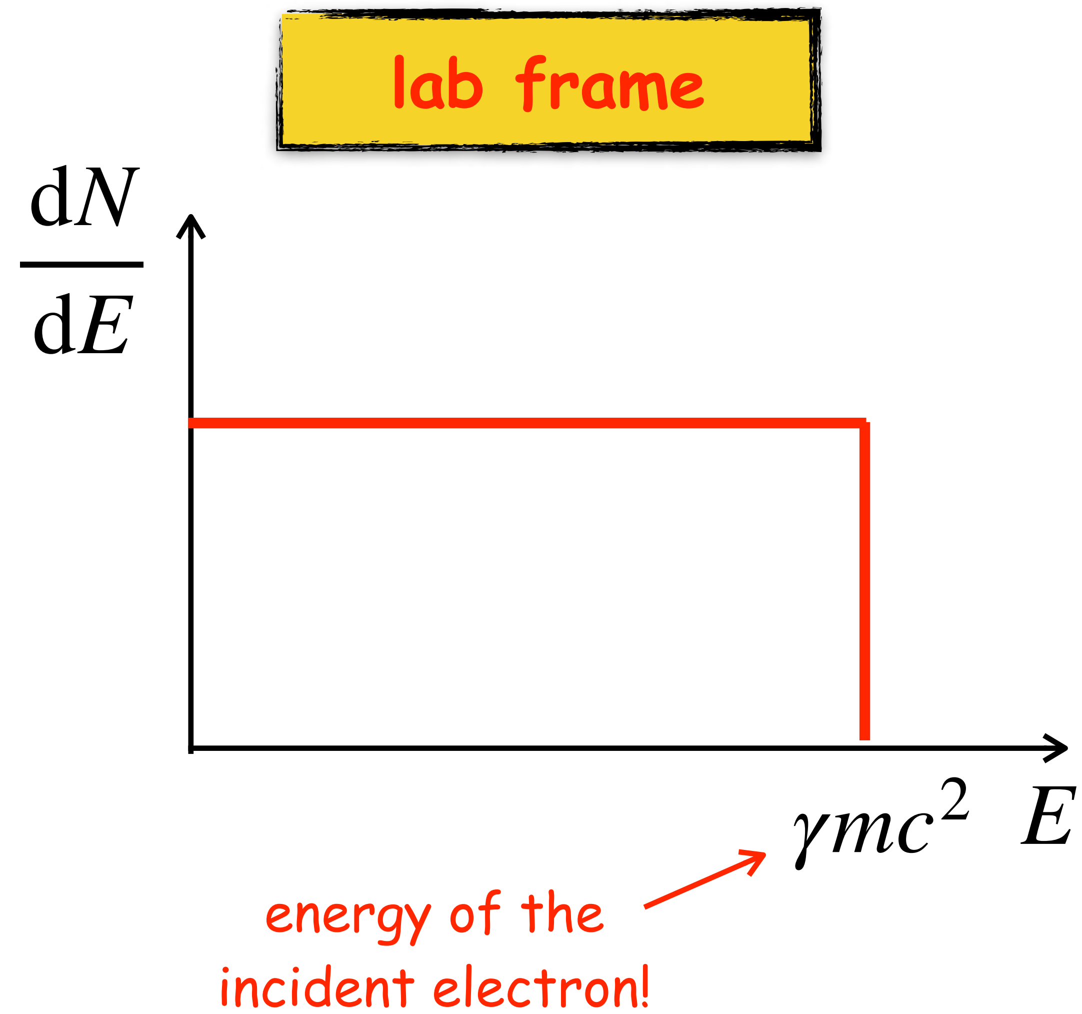
Non-thermal bremsstrahlung

electron frame

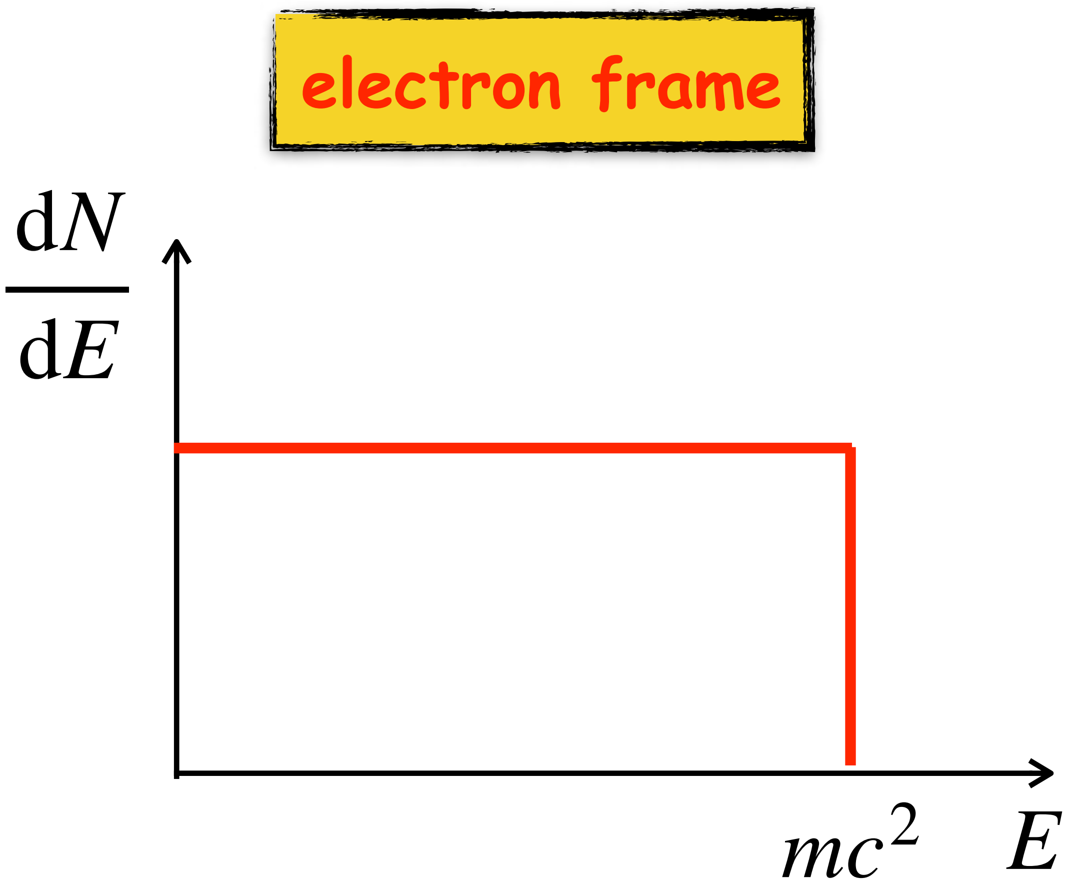


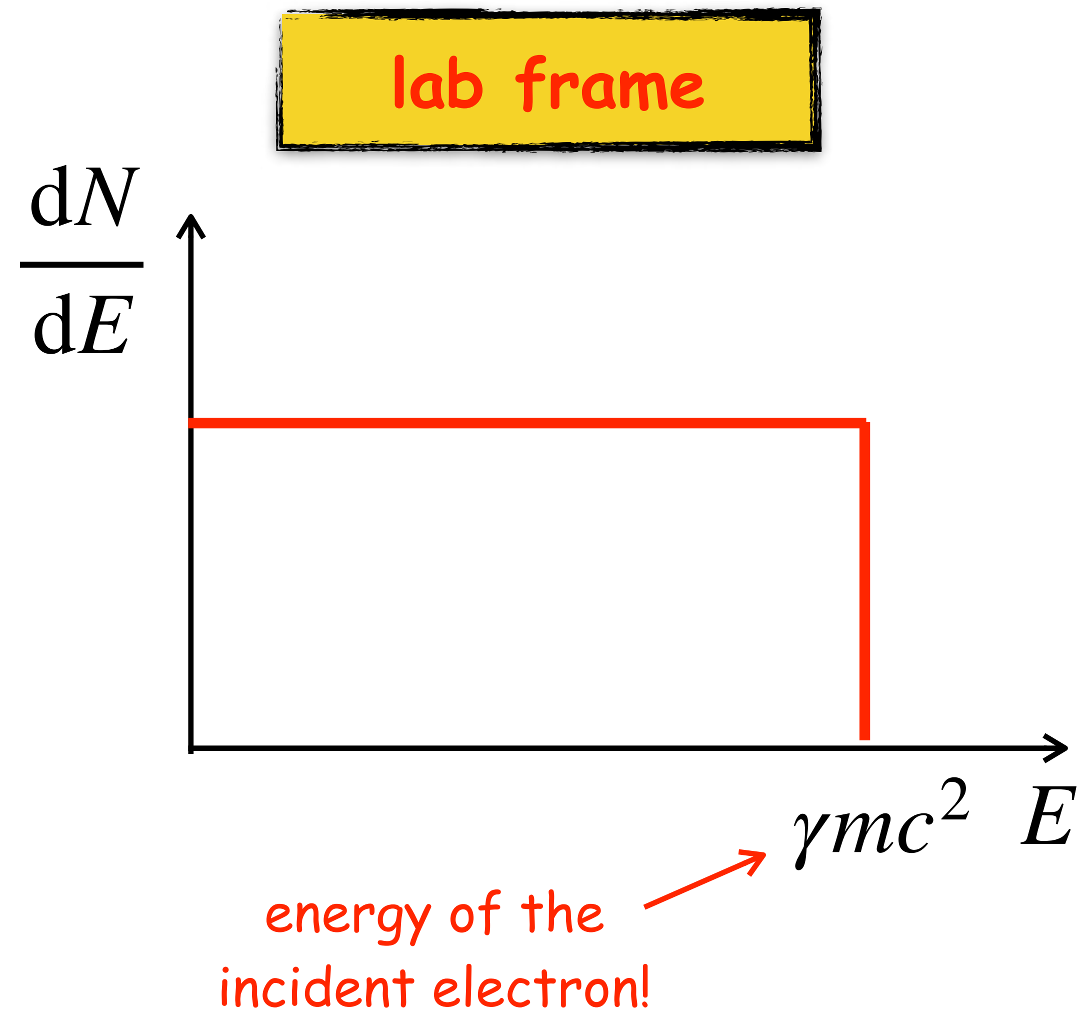
Non-thermal bremsstrahlung

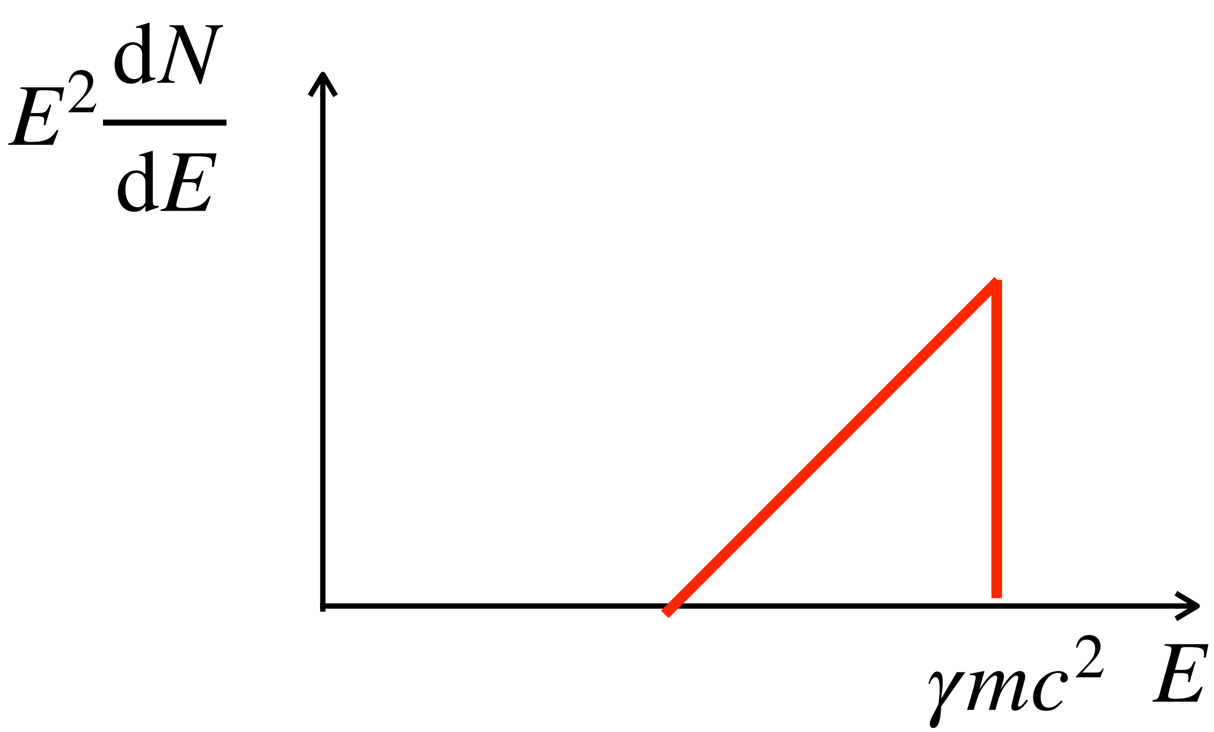




Non-thermal bremsstrahlung

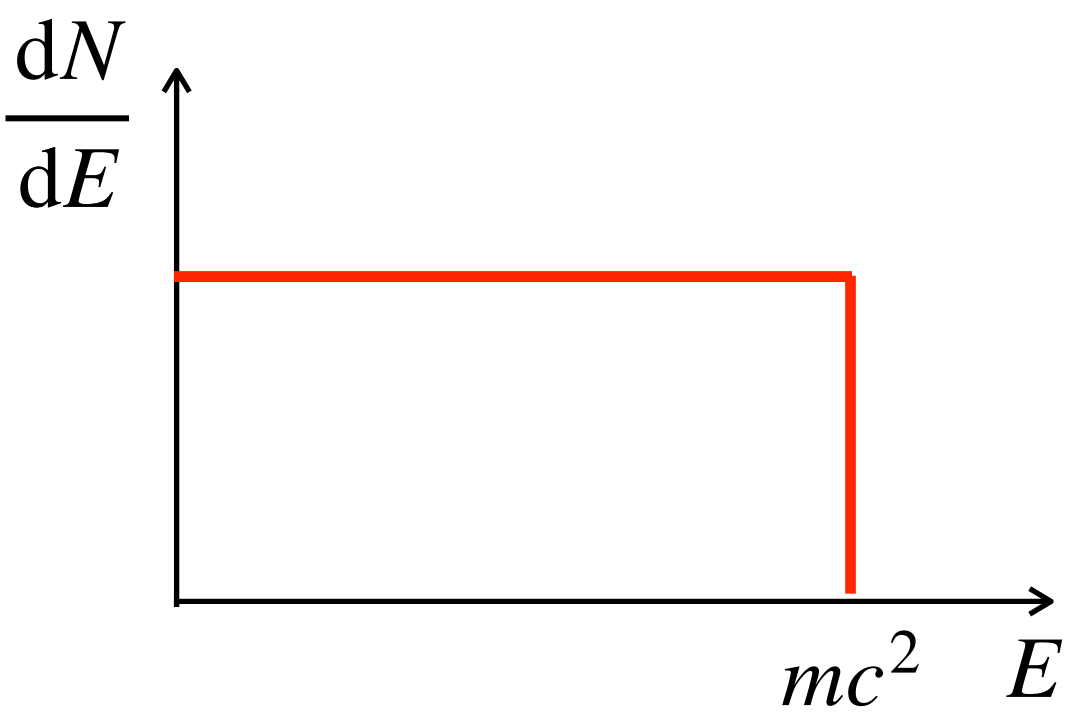




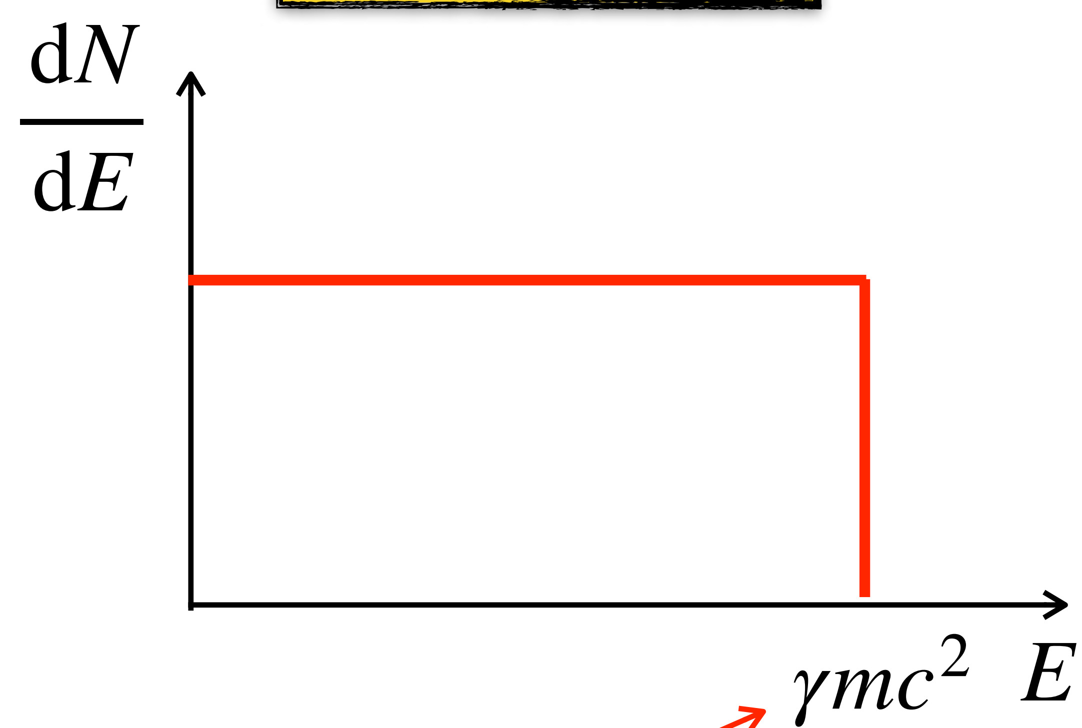


Non-thermal bremsstrahlung

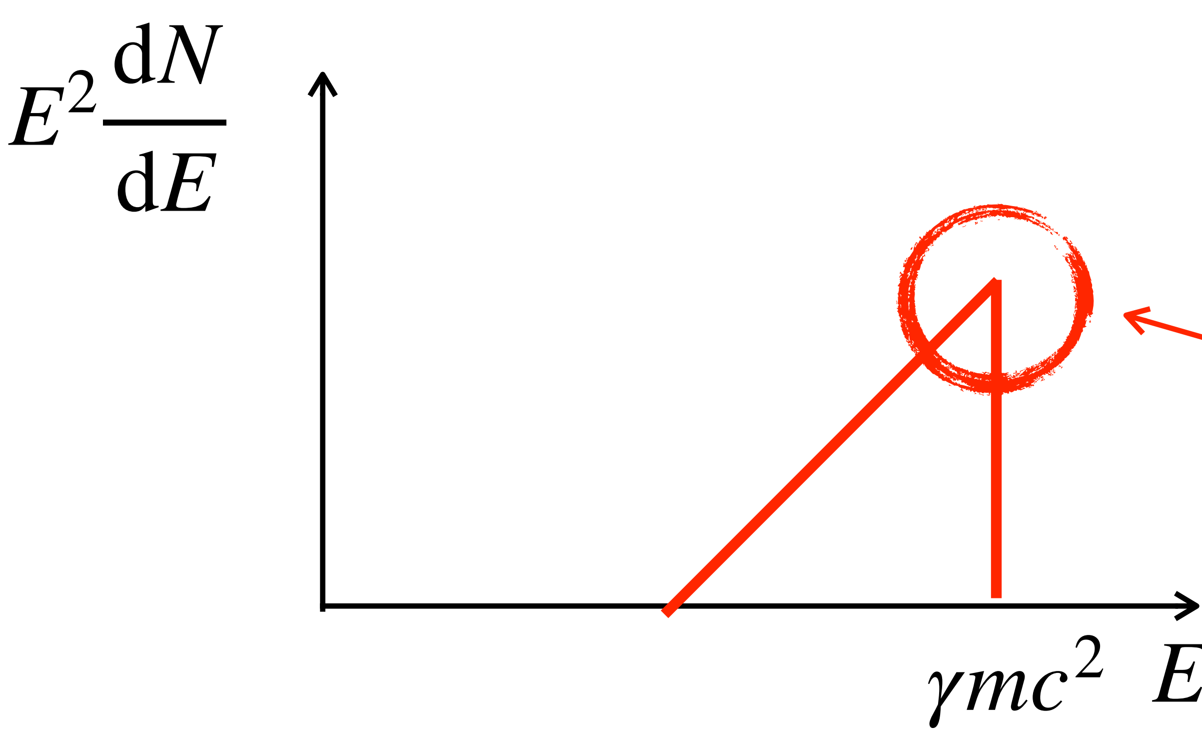
electron frame



lab frame



energy of the incident electron!



$\langle E_\gamma \rangle \lesssim E$

Bremsstrahlung is a catastrophic process

Energy loss times in the ISM...

continuous losses —>

synchrotron

inverse Compton

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{4}{3}\sigma_T c \gamma^2 \left(\omega_B + \omega_{CMB}\right)$$

same importance
in the ISM !

Energy loss times in the ISM...

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same importance in the ISM !

$$\tau_{syn/IC} \sim \frac{E}{\mathrm{d}E/\mathrm{d}t} \approx 1 \left(\frac{\omega_{TOT}}{0.25\ \mathrm{eV/cm^3}}\right)^{-1} \left(\frac{E}{\mathrm{TeV}}\right)^{-1}\ \mathrm{Myr}$$

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catastrophic losses —>

inelasticity

$$\tau_{loss} \sim \left(\kappa n_{gas} \sigma c\right)^{-1}$$

Energy loss times in the ISM...

continuous losses —>

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inverse Compton

$$\frac{dE}{dt} = \frac{4}{3}\sigma_T c \gamma^2 \left(\omega_B + \omega_{CMB}\right)$$

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inelasticity

catastrophic losses —>

$$\tau_{loss} \sim \left(\kappa n_{gas} \sigma c\right)^{-1}$$

p-p interactions —>

$$\tau_{pp} \sim 60 \left(\frac{n_{gas}}{\mathrm{cm^{-3}}}\right)^{-1} \mathrm{Myr}$$

Energy loss times in the ISM…

continuous losses —>

synchrotron, inverse Compton

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \frac{4}{3}\sigma_T c\gamma^2\left(\omega_B + \omega_{CMB}\right)$$

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$$\tau_{syn/IC} \sim \frac{E}{\mathrm{d}E/\mathrm{d}t} \approx 1\left(\frac{\omega_{TOT}}{0.25\ \mathrm{eV/cm^3}}\right)^{-1}\left(\frac{E}{\mathrm{TeV}}\right)^{-1}\ \mathrm{Myr}$$

catastrophic losses —>

inelasticity

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p-p interactions —>

$$\tau_{pp} \sim 60\left(\frac{n_{gas}}{\mathrm{cm^{-3}}}\right)^{-1}\ \mathrm{Myr}$$

relativistic Bremsstrahlung —>

$$\tau_{Brem} \sim 30\left(\frac{n_{gas}}{\mathrm{cm^{-3}}}\right)^{-1}\ \mathrm{Myr}$$

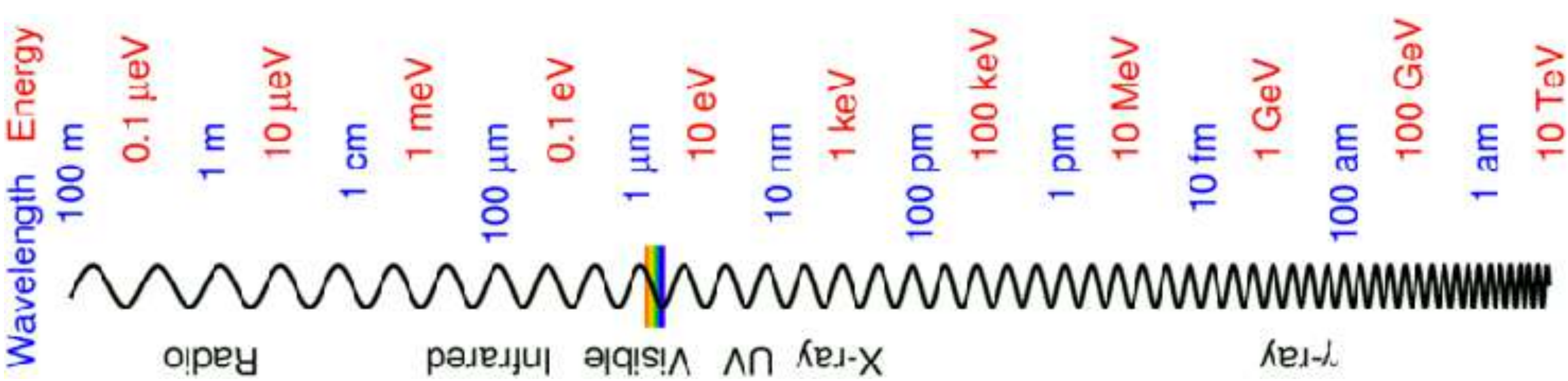
ICS more effective in the TeV domain

inverse Compton scattering
electrons in CMB
E ~ GeV TeV 30 TeV

Bremsstrahlung emission
electrons
E ~ keV MeV GeV TeV

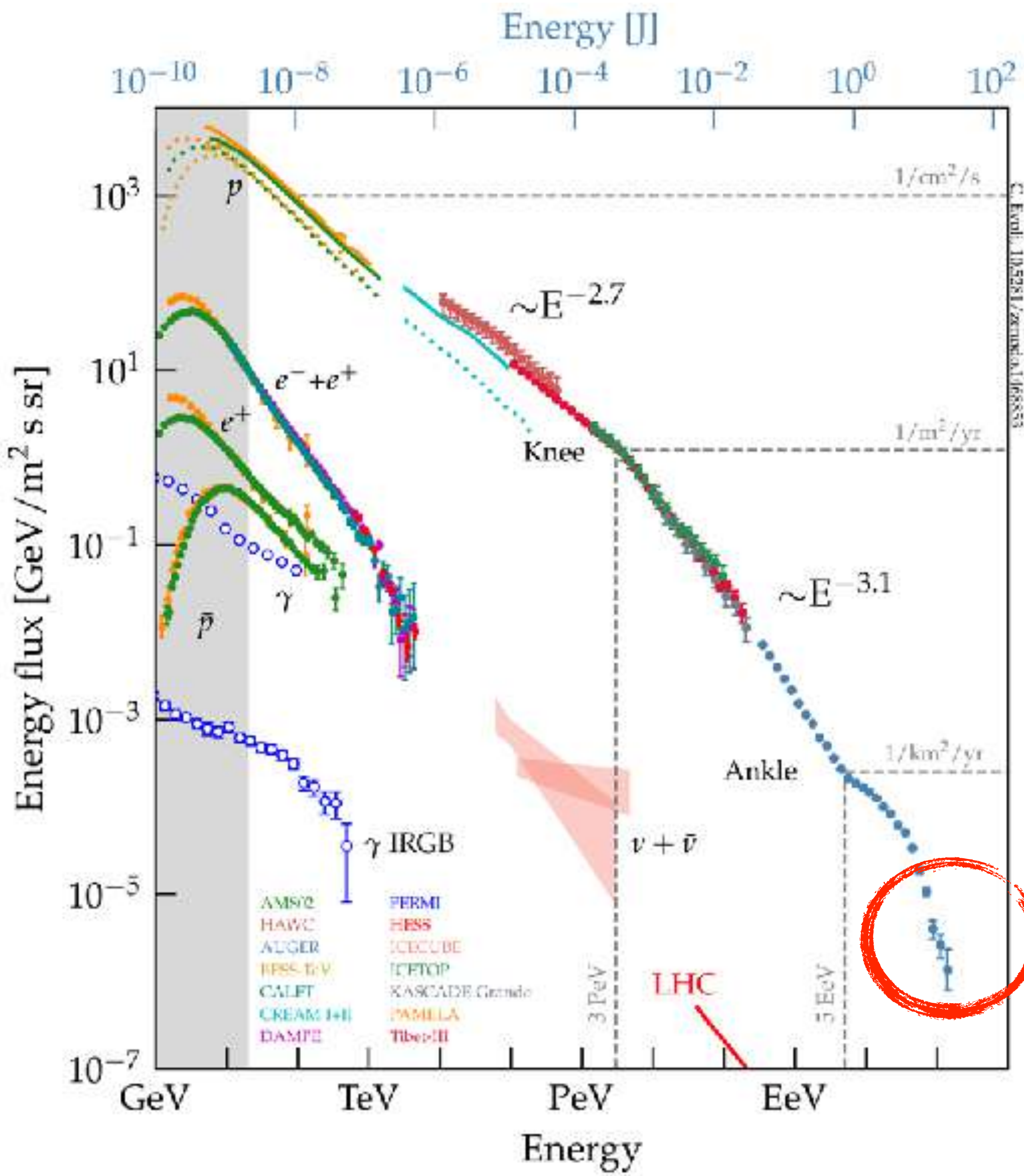
synchrotron emission
electrons in gal. B
E ~ 10 GeV 100 TeV

pp interactions
protons
E > 280 MeV



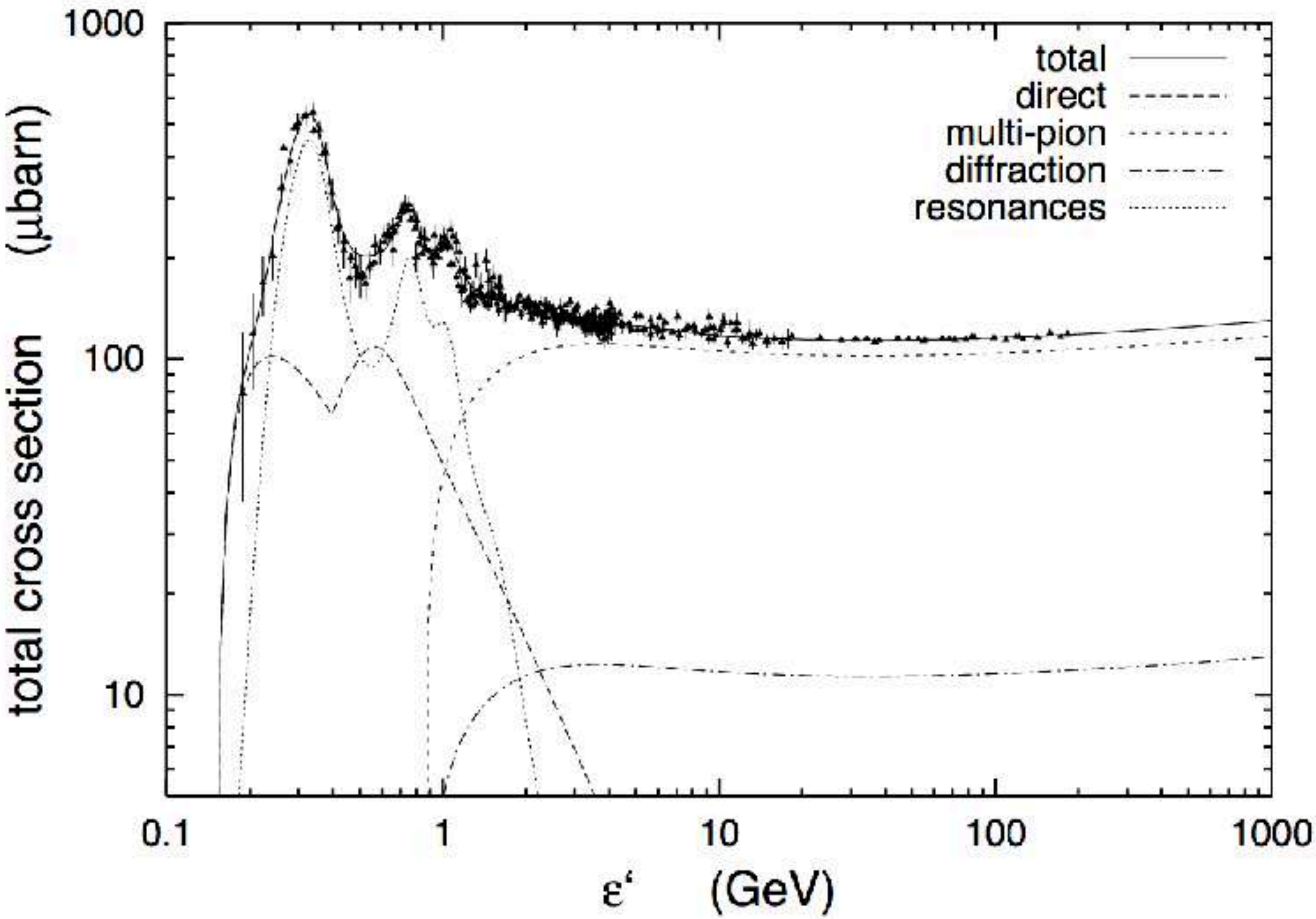
GALACTIC NON-THERMAL EMISSIONS

Question: where does the cosmic ray spectrum ends?



<- 10^20 eV

Photomeson production:
$p\gamma \longrightarrow n\pi^+$ or $p\pi^0$



Mucke+ 1999

Photomeson production:
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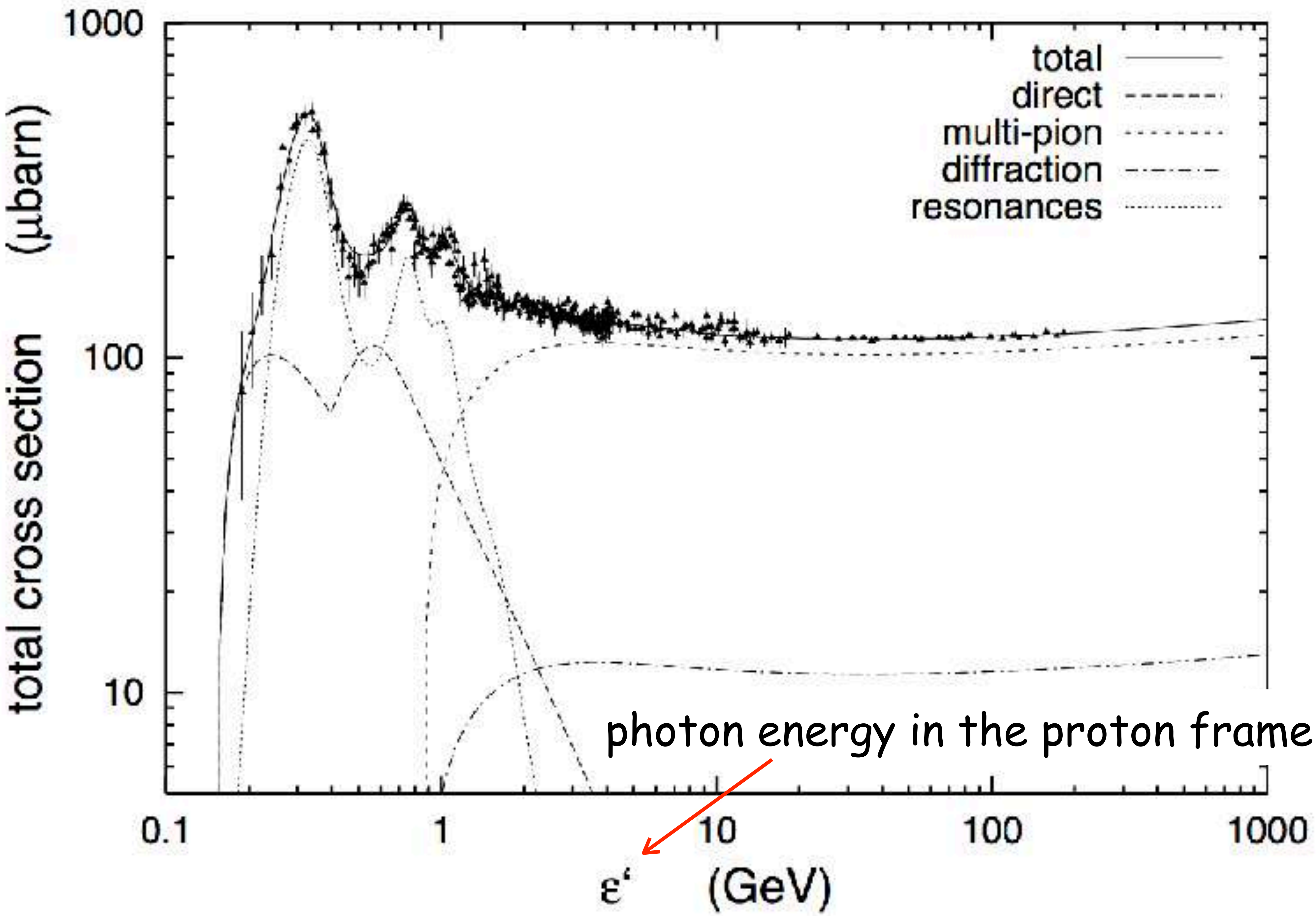

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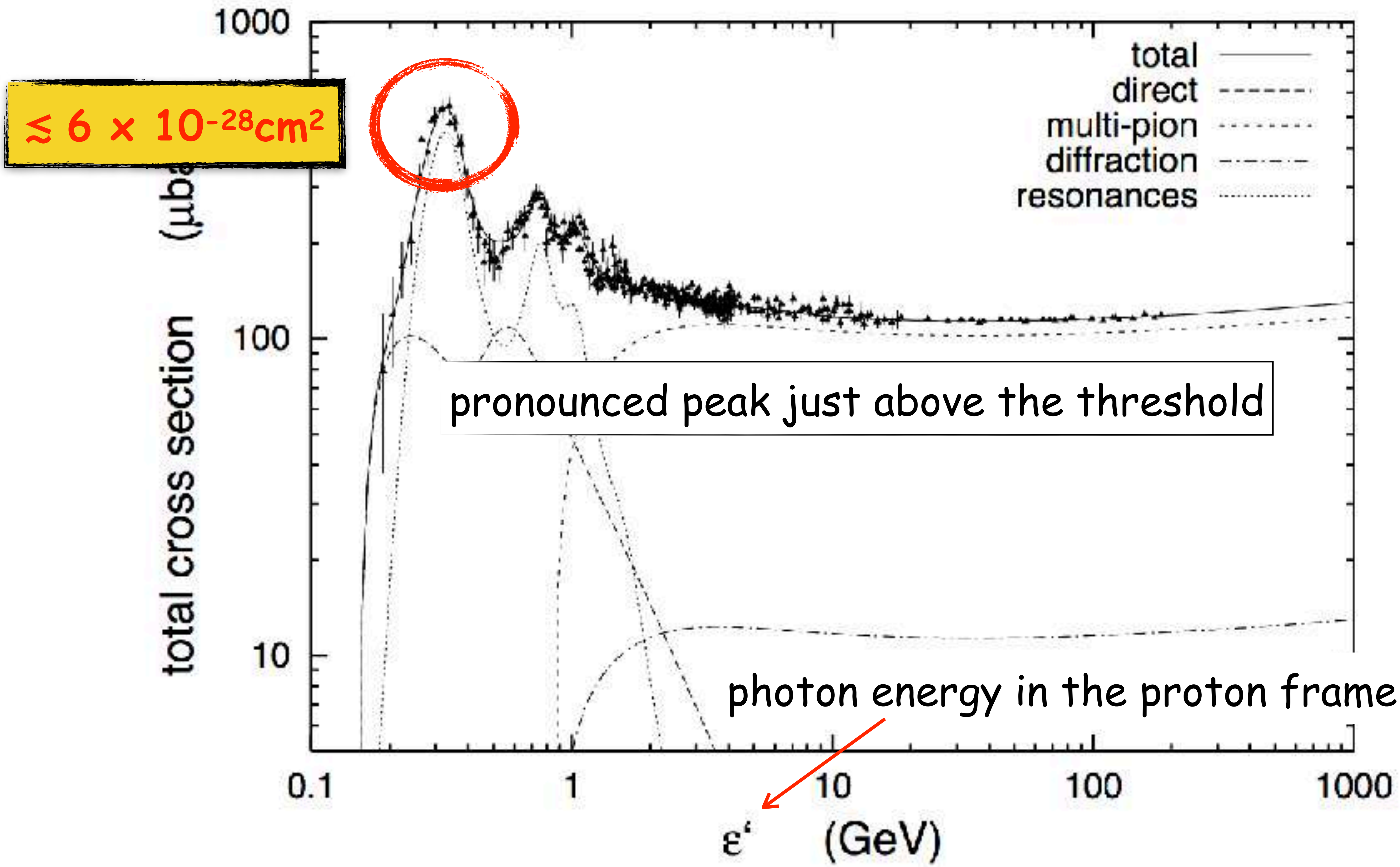

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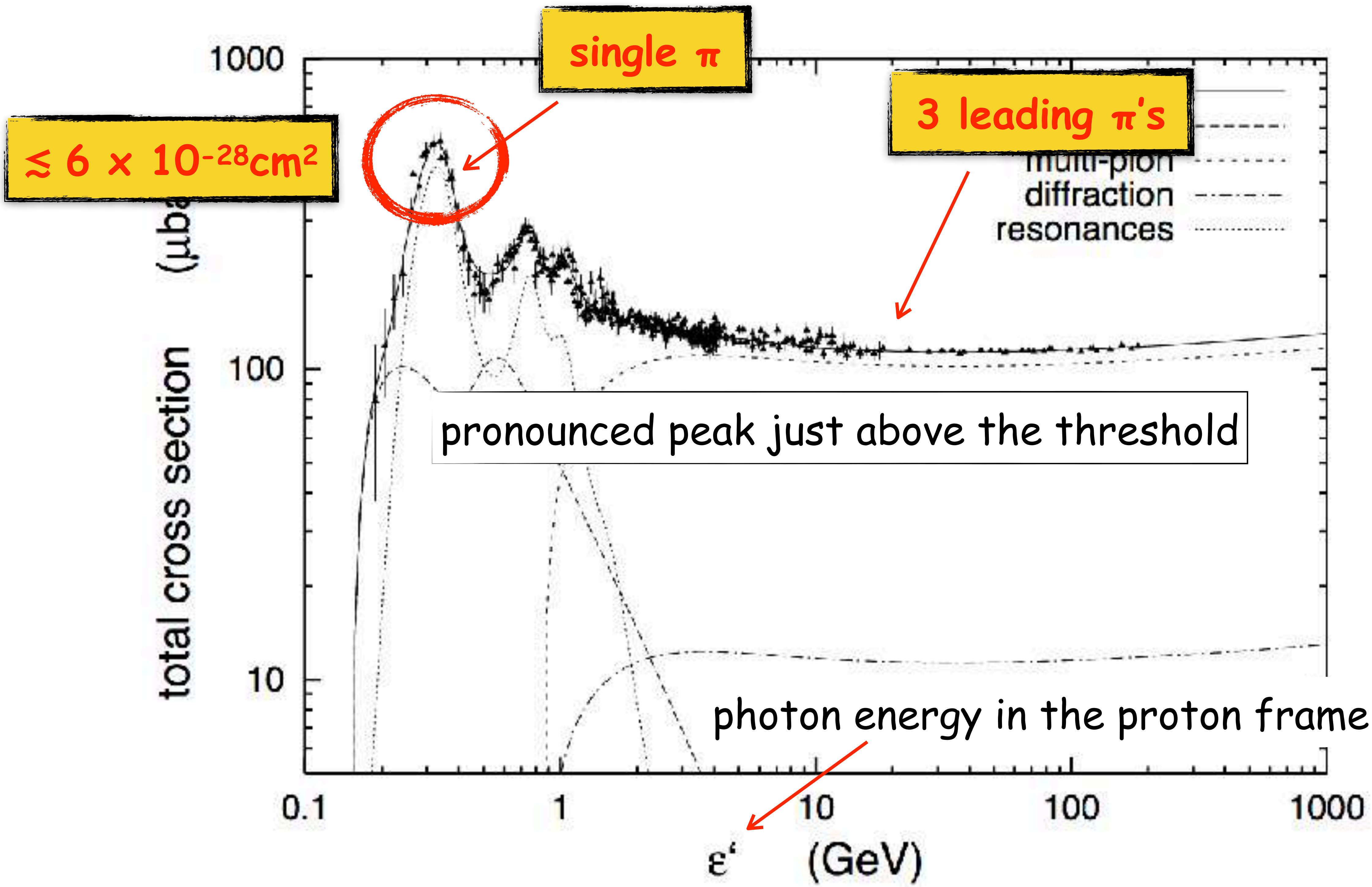

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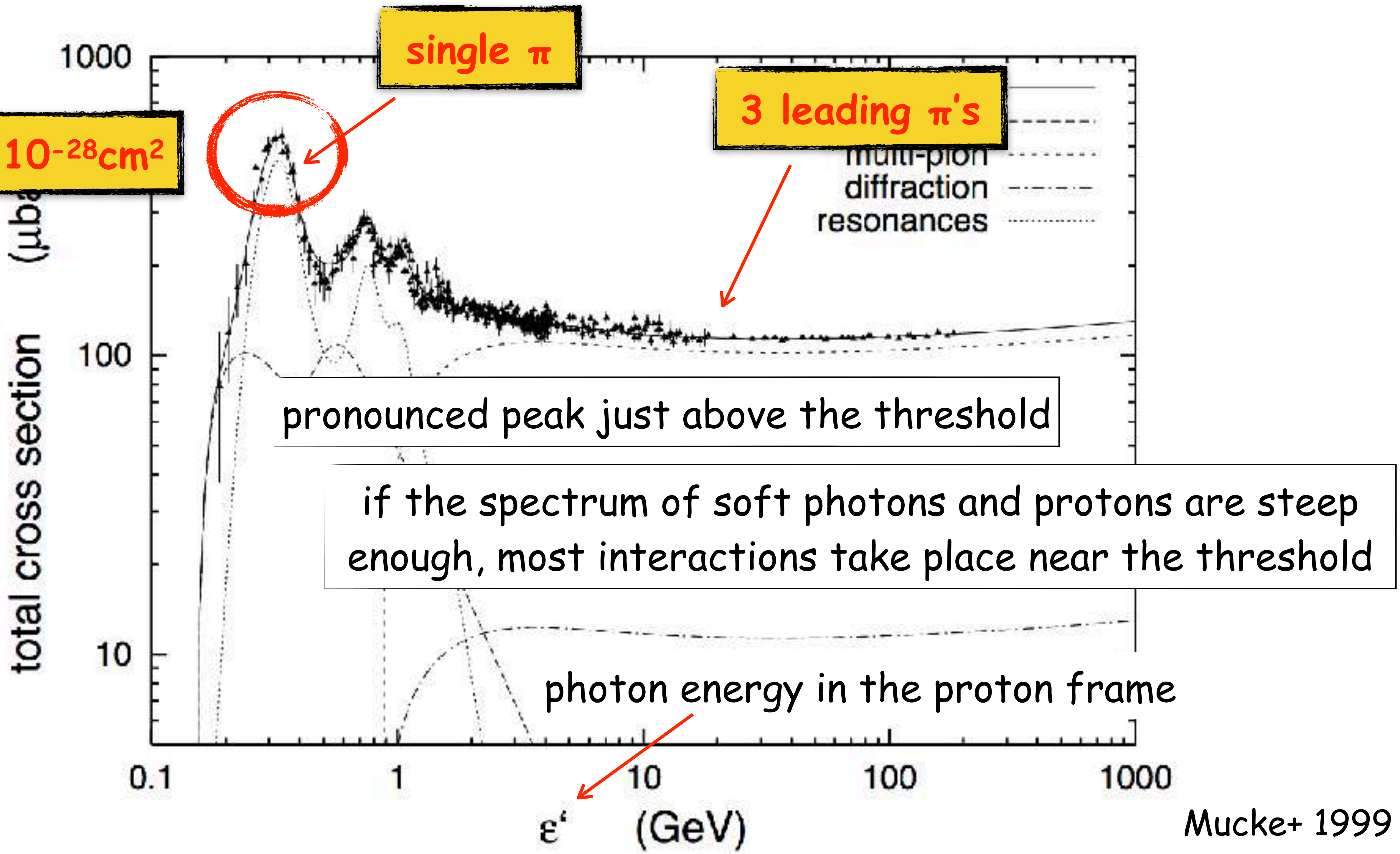

Mucke+ 1999

Photomeson production: threshold

$$p + \gamma \longrightarrow n + \pi^+$$

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energy in the center of mass frame

Photomeson production: threshold

$$p + \gamma \longrightarrow n + \pi^+$$

energy in the center of mass frame

before the collision —> $$s^2 = (E_p + \epsilon_\gamma)^2 - (\vec{p}_p + \vec{p}_\gamma)^2$$

Photomeson production: threshold

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energy in the center of mass frame

before the collision → $$s^2 = (E_p + \epsilon_\gamma)^2 - (\vec{p}_p + \vec{p}_\gamma)^2$$

after the collision **and** at the threshold → $$s_{th} = m_p + m_\pi$$

Photomeson production: threshold

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energy in the center of mass frame

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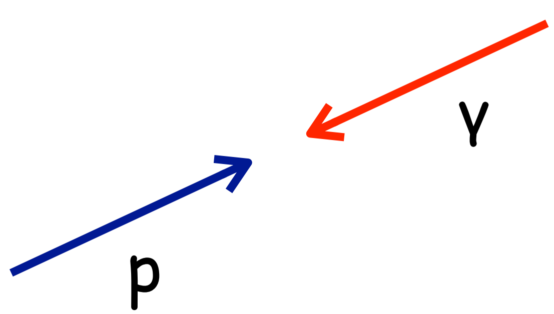
after the collision

and –> $s_{th} = m_p + m_\pi$

at the threshold



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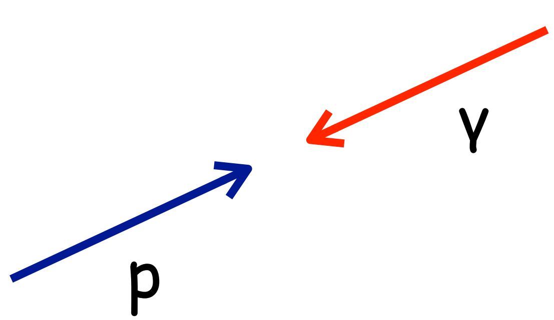

$$E_p^{min} \approx 60 \left(\frac{\epsilon_\gamma}{\mathrm{eV}}\right)^{-1} \mathrm{PeV}$$

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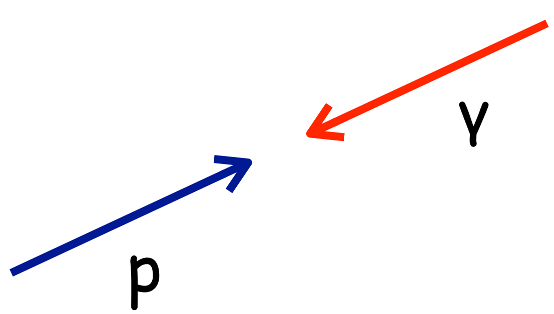

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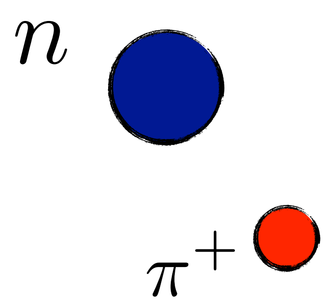
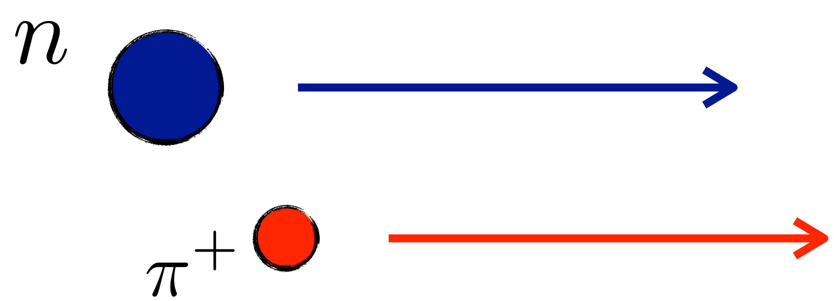
for CMB photons this is ~10^{20} eV !

Photomeson production: threshold



produced at
rest in the CMF

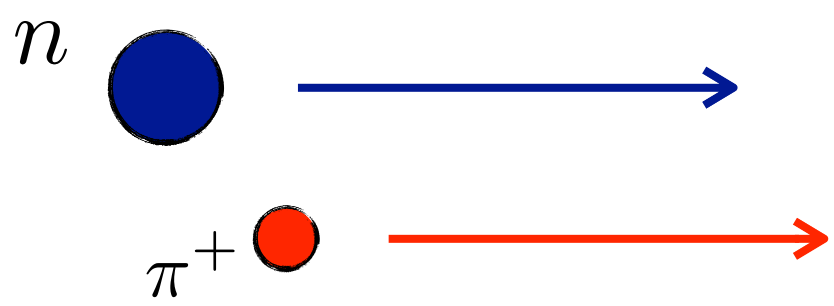
Photomeson production: threshold



produced at
rest in the CMF

boost to the
lab frame

Photomeson production: threshold

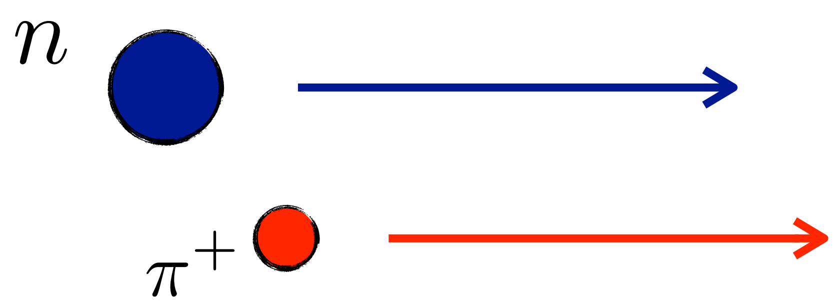


produced at rest in the CMF

boost to the lab frame

$$E_\pi = \frac{m_\pi}{m_p} E_n \sim \frac{m_\pi}{m_p} E_p$$

Photomeson production: threshold



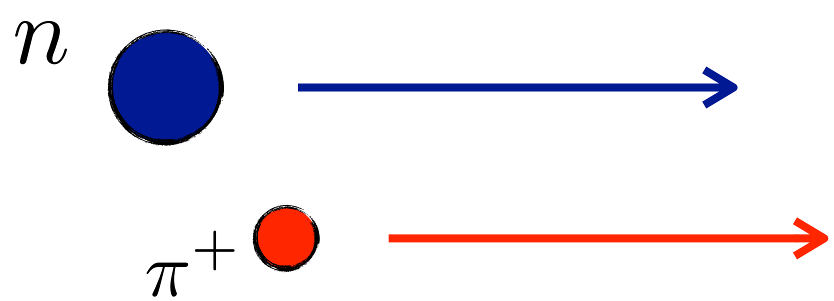
$$E_\pi = \frac{m_\pi}{m_p} E_n \sim \frac{m_\pi}{m_p} E_p$$

produced at
rest in the CMF

boost to the
lab frame

fraction of E_p lost in
1 interaction

Photomeson production: threshold



$$E_\pi = \frac{m_\pi}{m_p} E_n \sim \frac{m_\pi}{m_p} E_p$$

produced at rest in the CMF

boost to the lab frame

fraction of E_p lost in 1 interaction

$$p + \gamma \longrightarrow n + \pi^+$$
$$\hookrightarrow \mu^+ + \nu_\mu$$
$$\hookrightarrow e^+ + \nu_\mu + \nu_e$$

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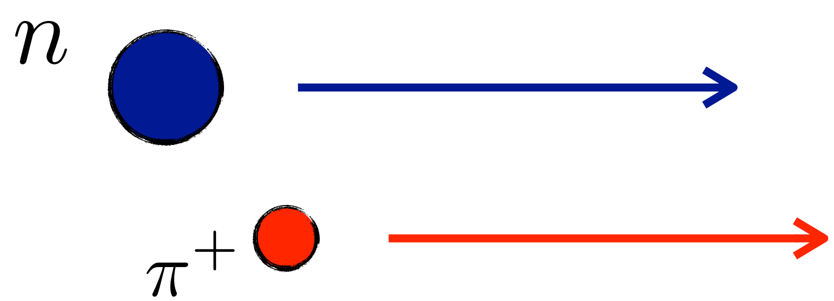

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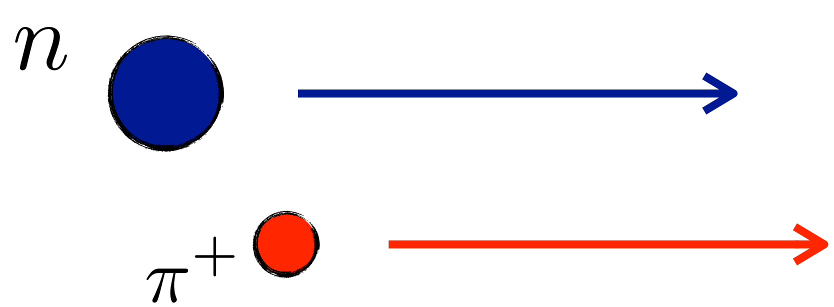

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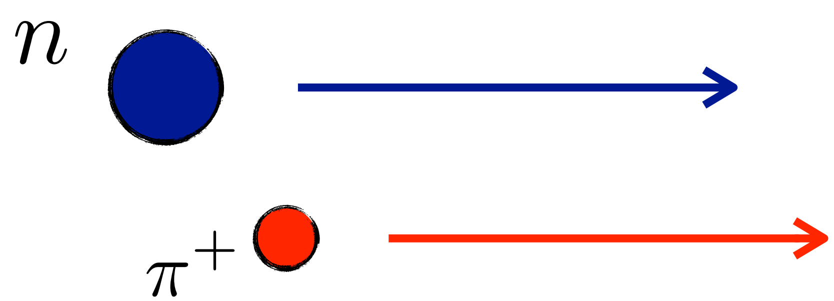

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$$\boxed{E_\nu \sim \left(\frac{m_\pi}{4 m_p}\right) E_p} \approx 0.04 \ E_p$$

Absorption of gamma rays

50% of the times $p + \gamma \longrightarrow p + \pi^0$

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threshold energy pair production

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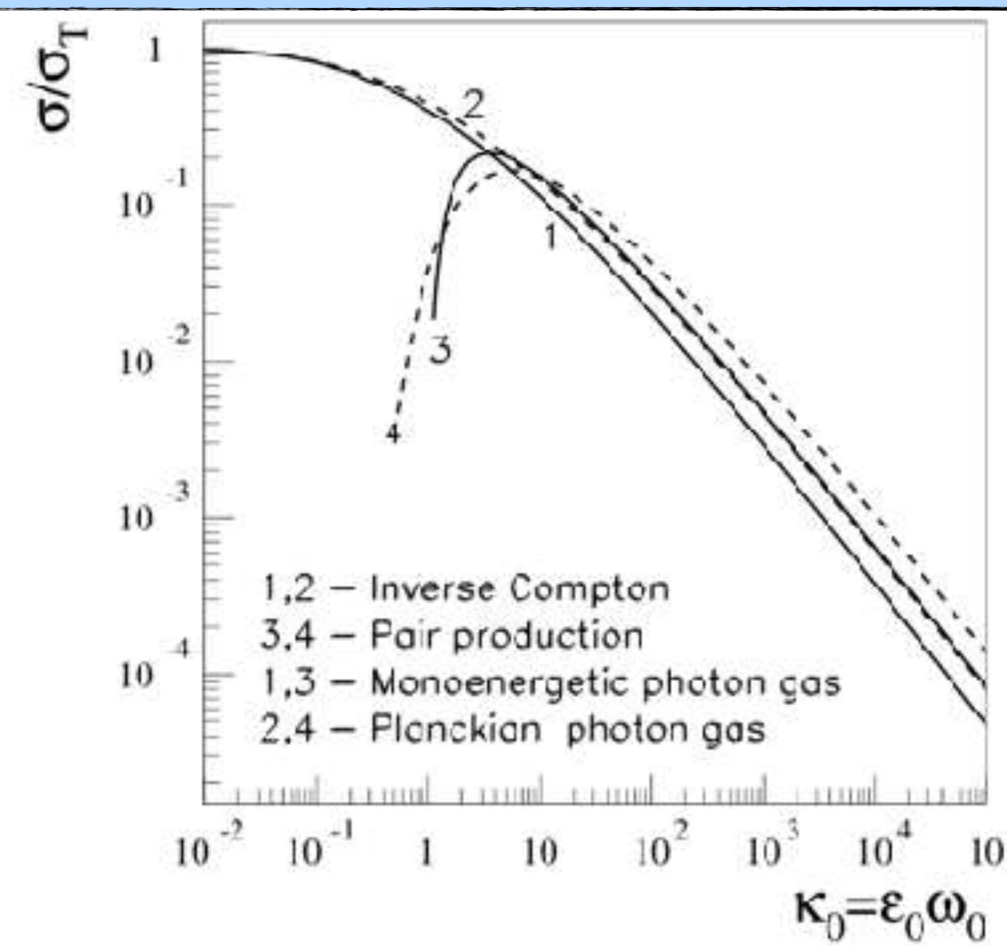

Aharonian's book

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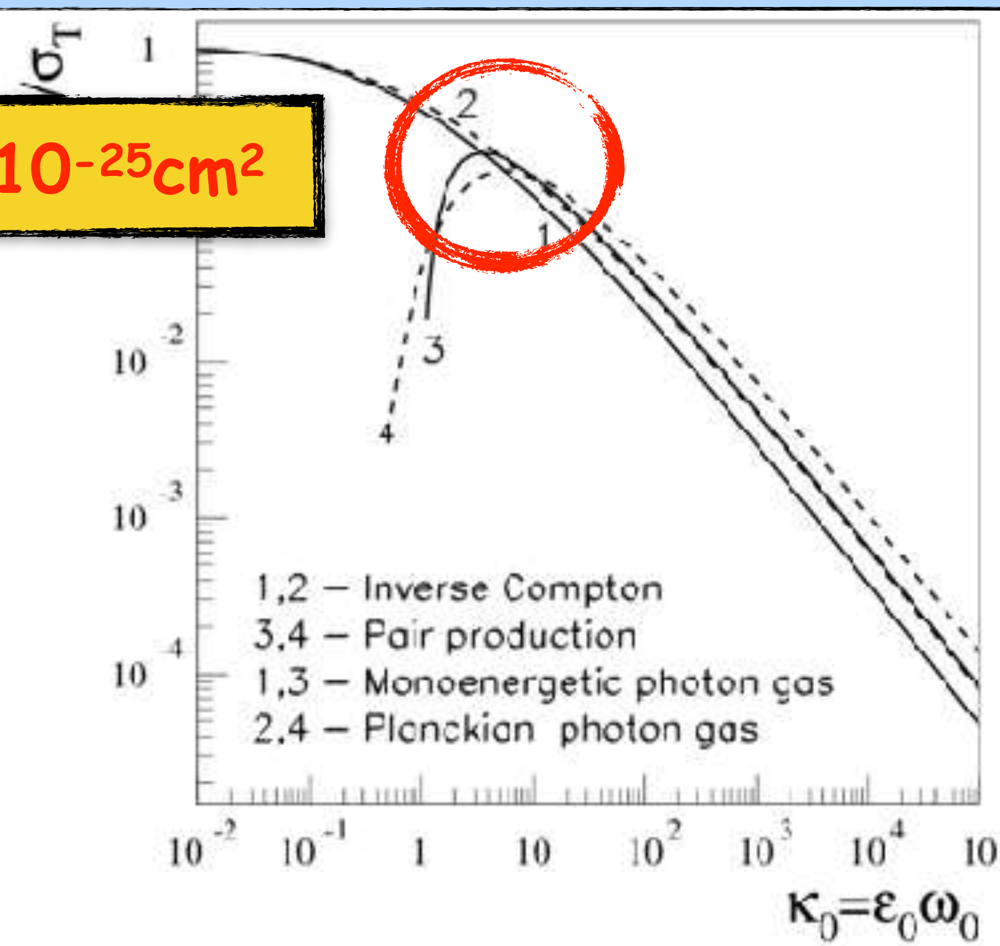
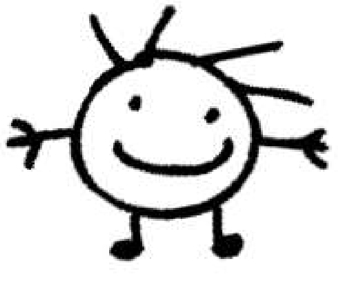
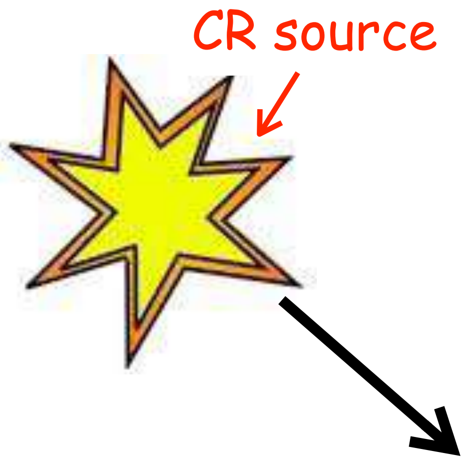


~10^{-25}cm^2

Aharonian's book

Where do photons go?





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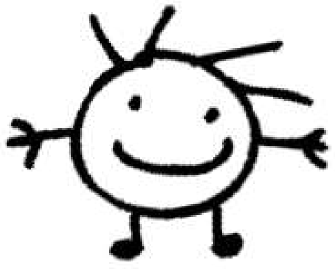

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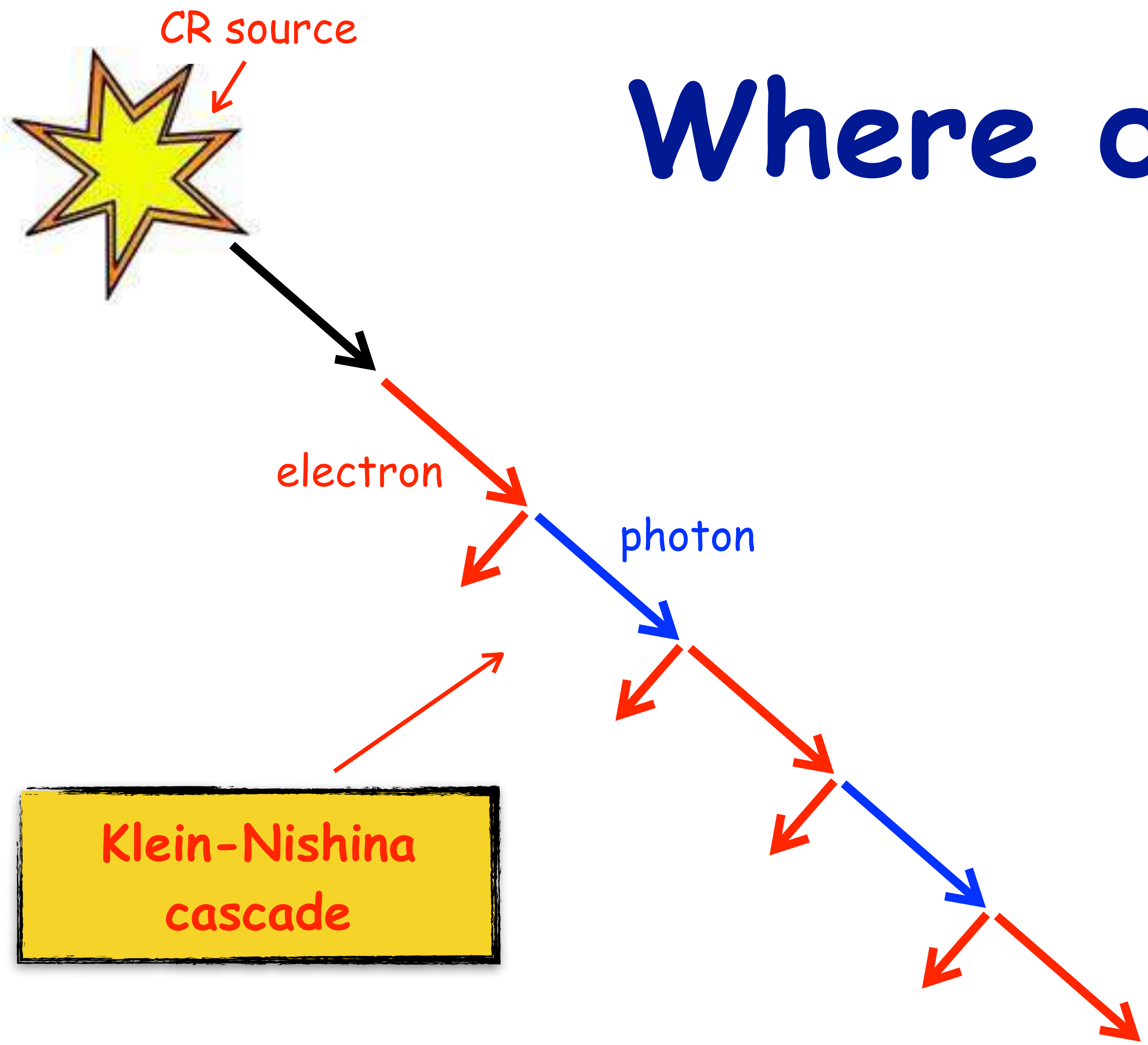
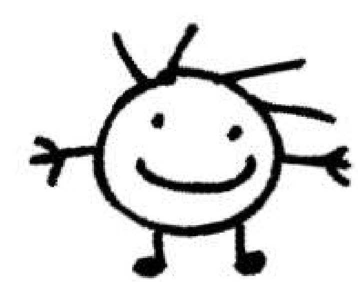


Klein-Nishina cascade

$$E_\gamma \epsilon_\gamma \gg m_e^2$$

inverse Compton + pair production



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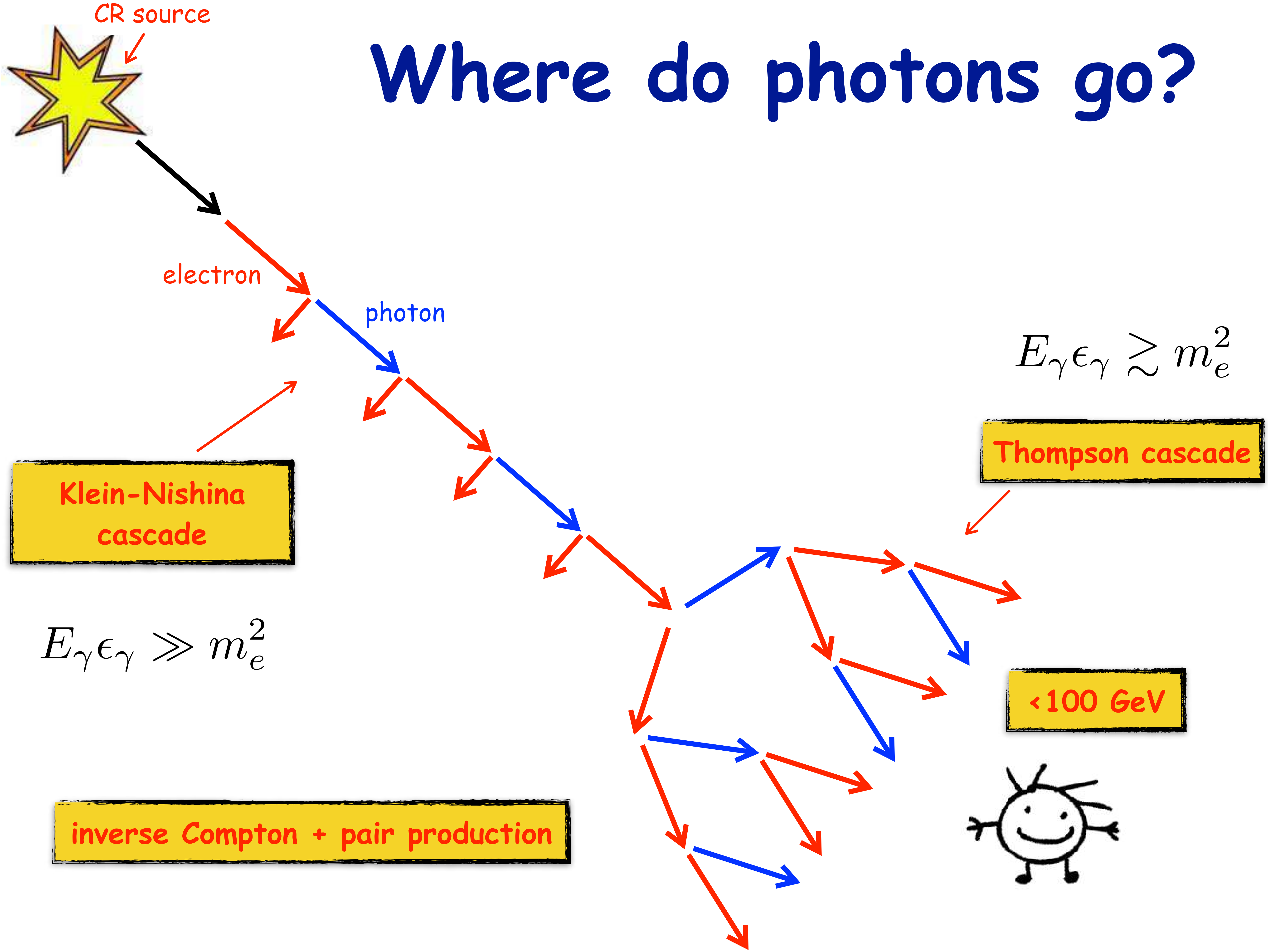
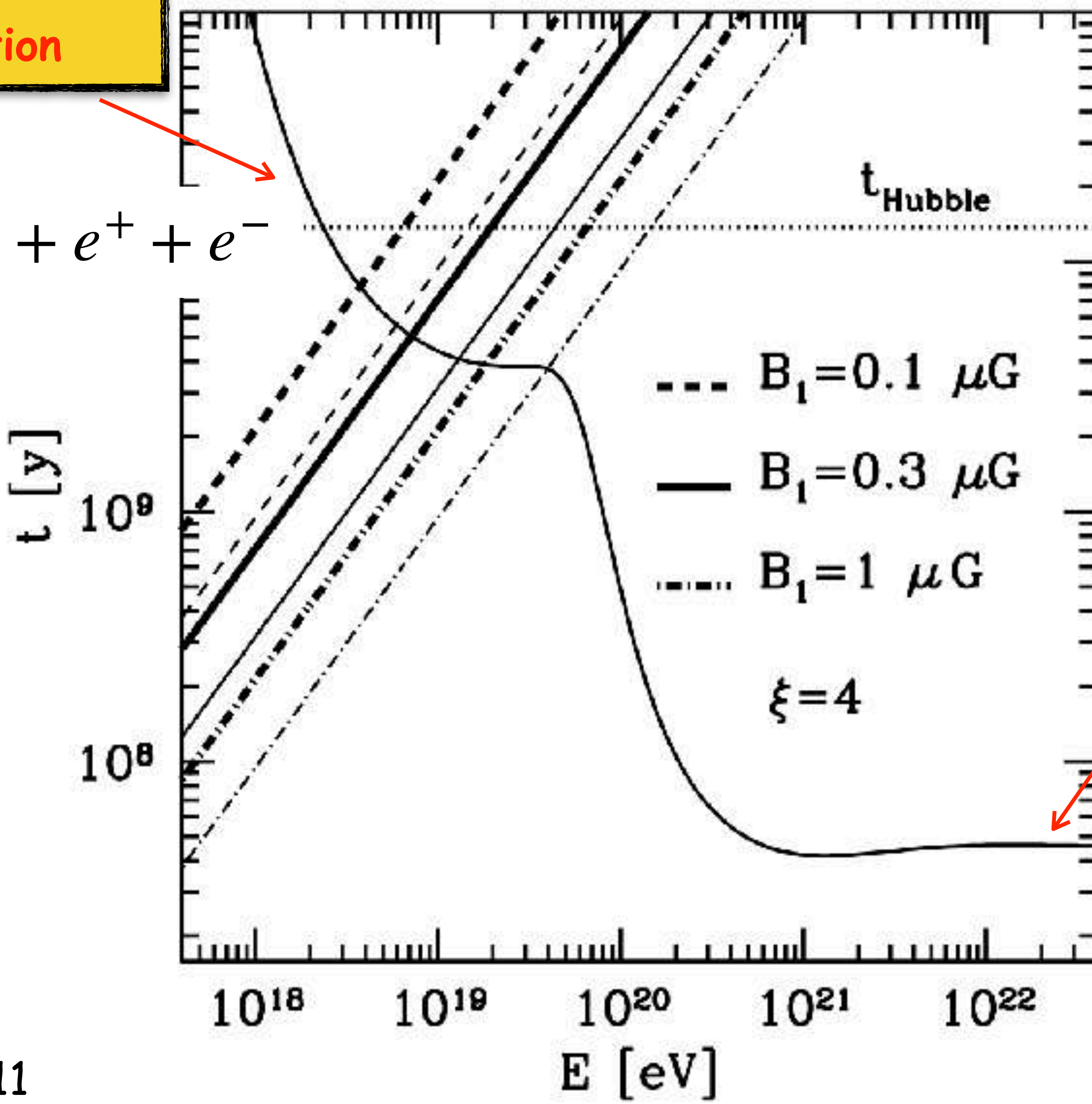


Photopair production

photopair production

$$p + \gamma \longrightarrow p + e^{+} + e^{-}$$



photomeson production

Vannoni+ 2011

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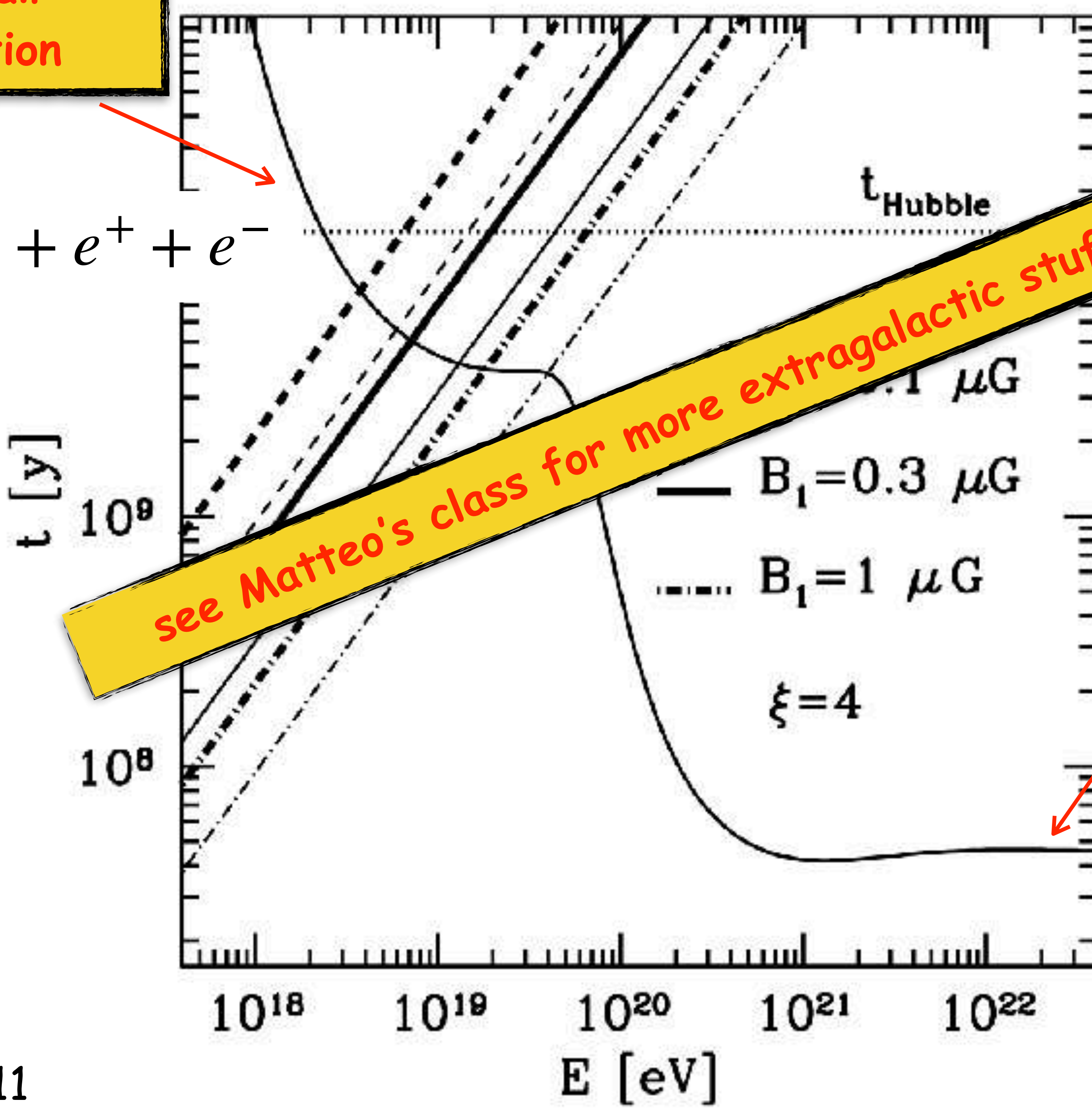

see Matteo's class for more extragalactic stuff!

photomeson production

Vannoni+ 2011

next class: apply all this to “Galactic sources”…