

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



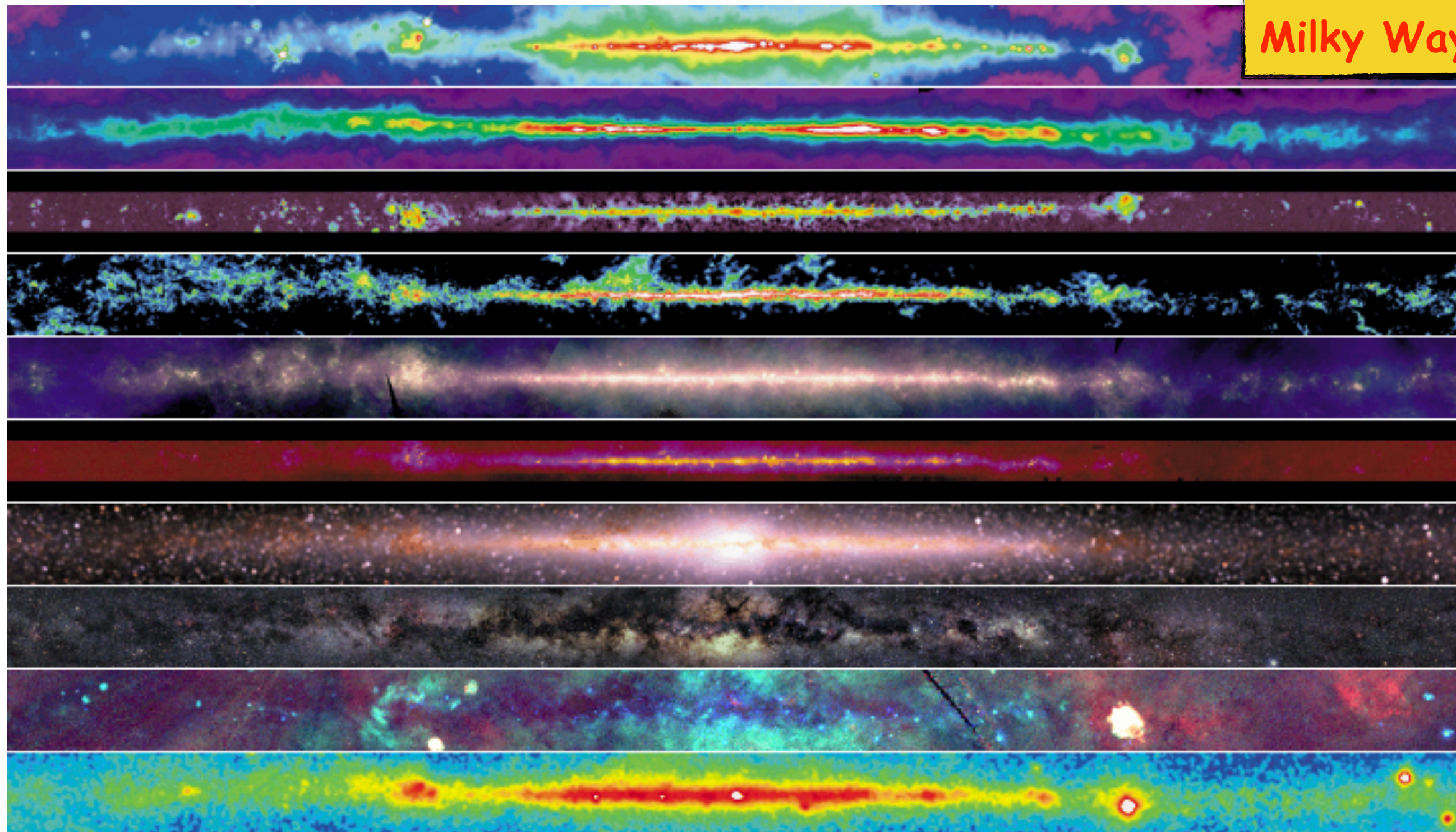
Stefano Gabici
APC, Paris



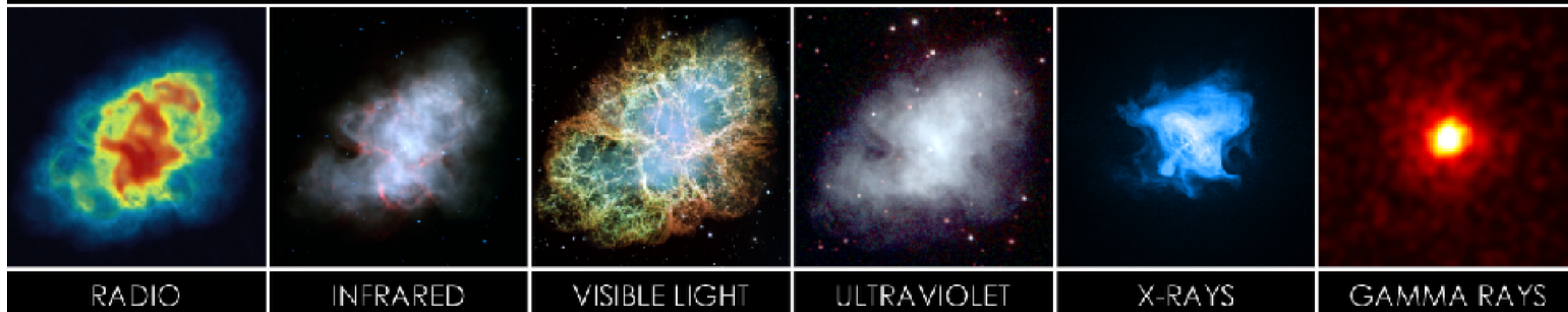
www.cnrs.fr

gamma-rays ----- radio waves

Milky Way



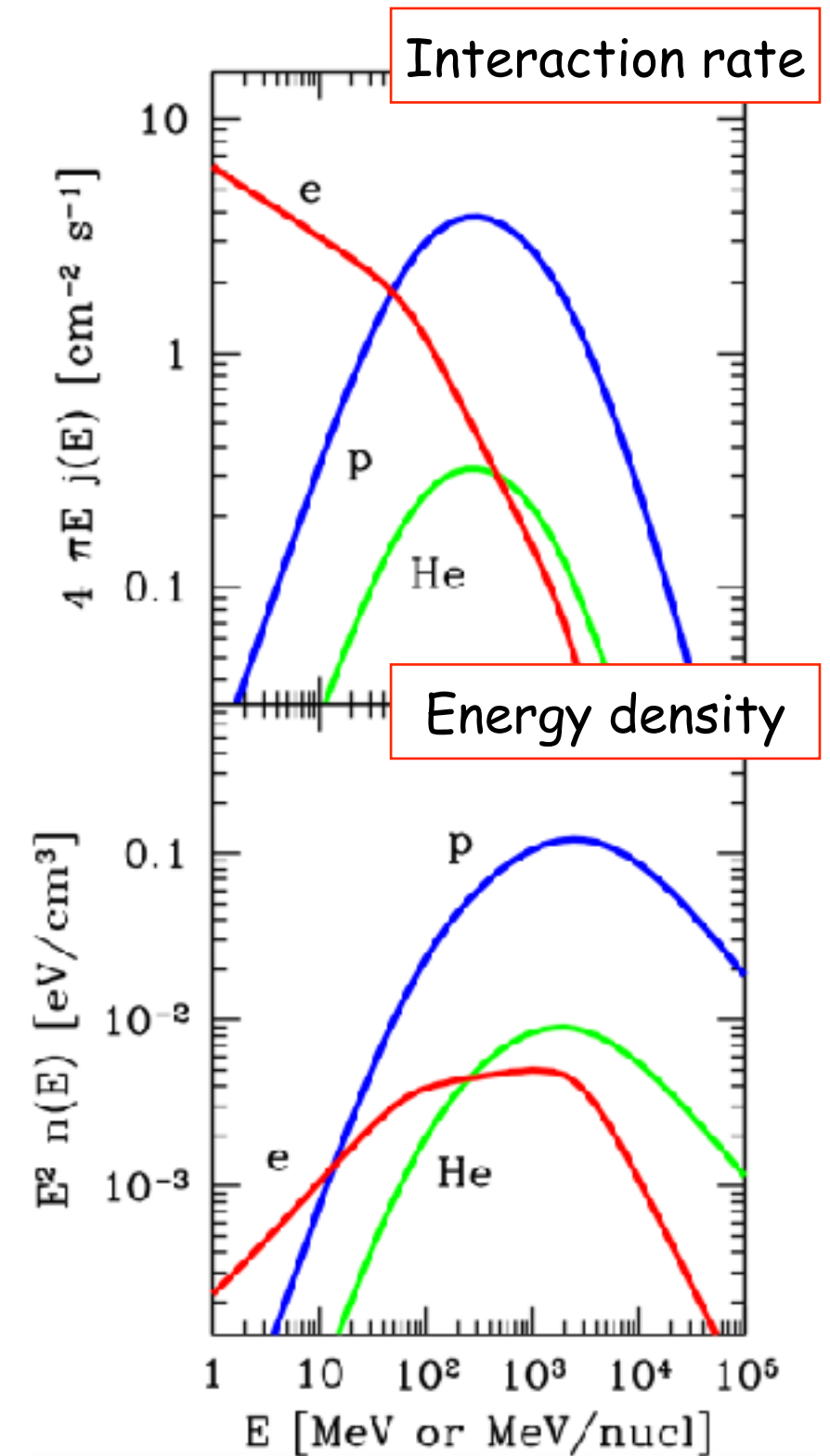
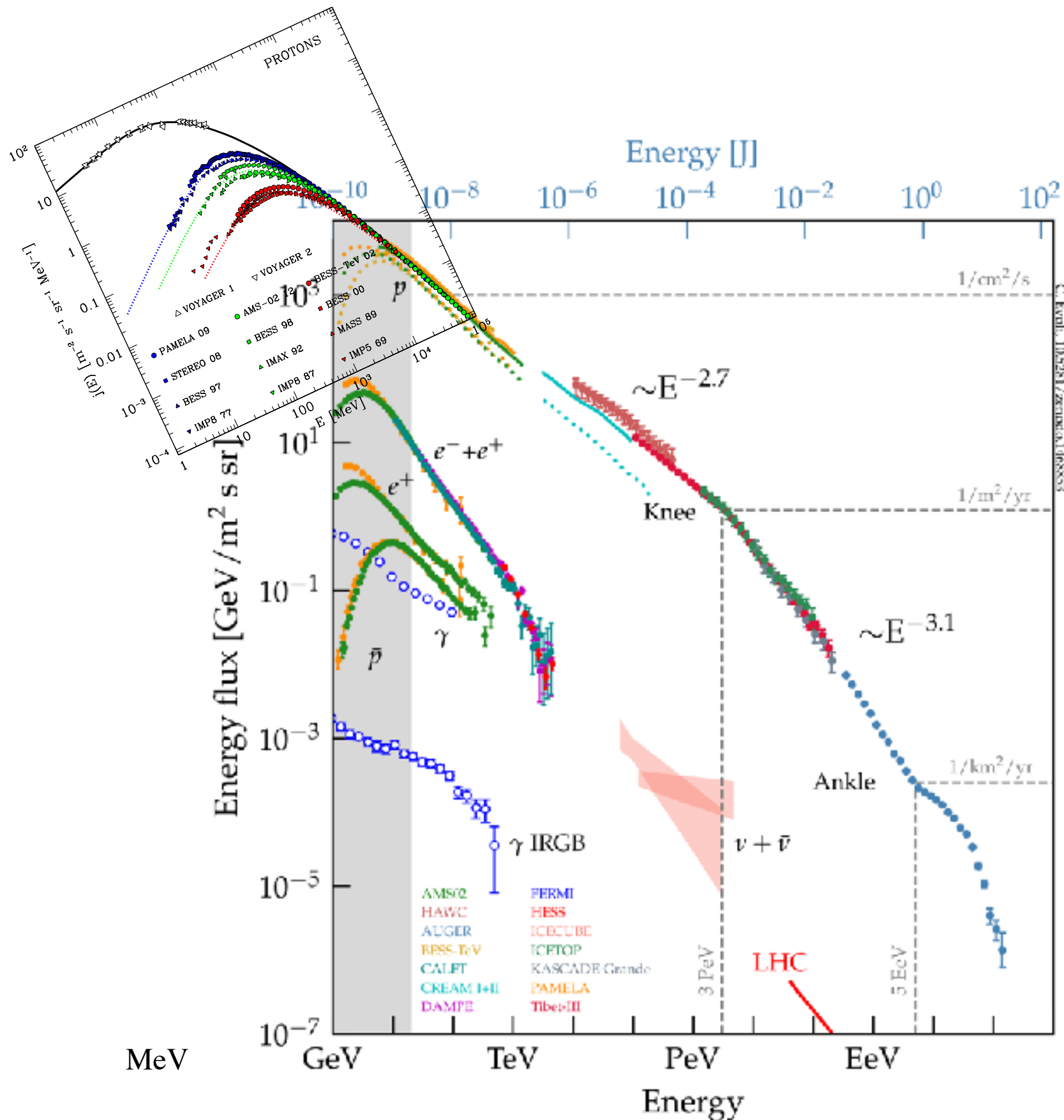
CRAB NEBULA



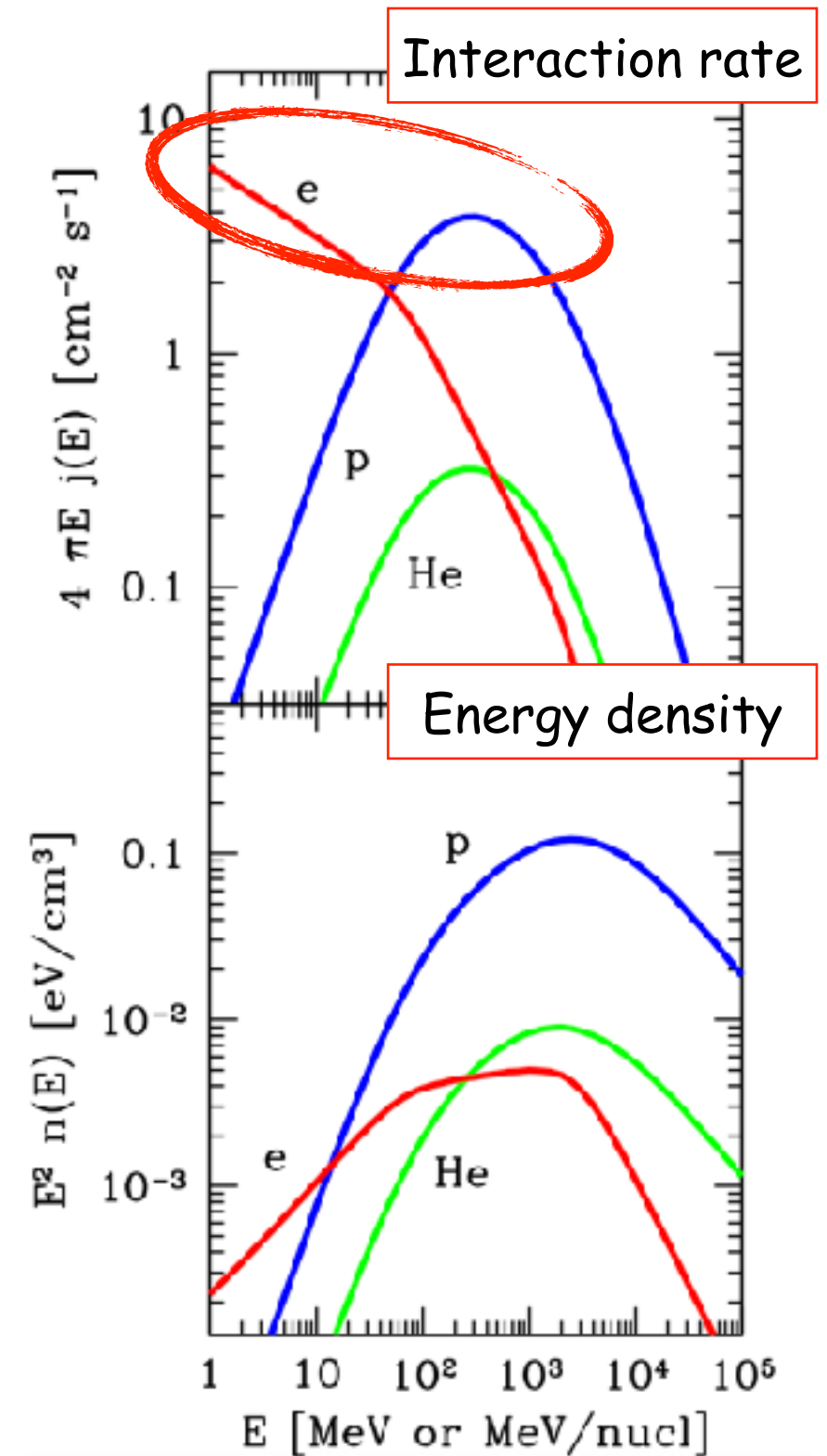
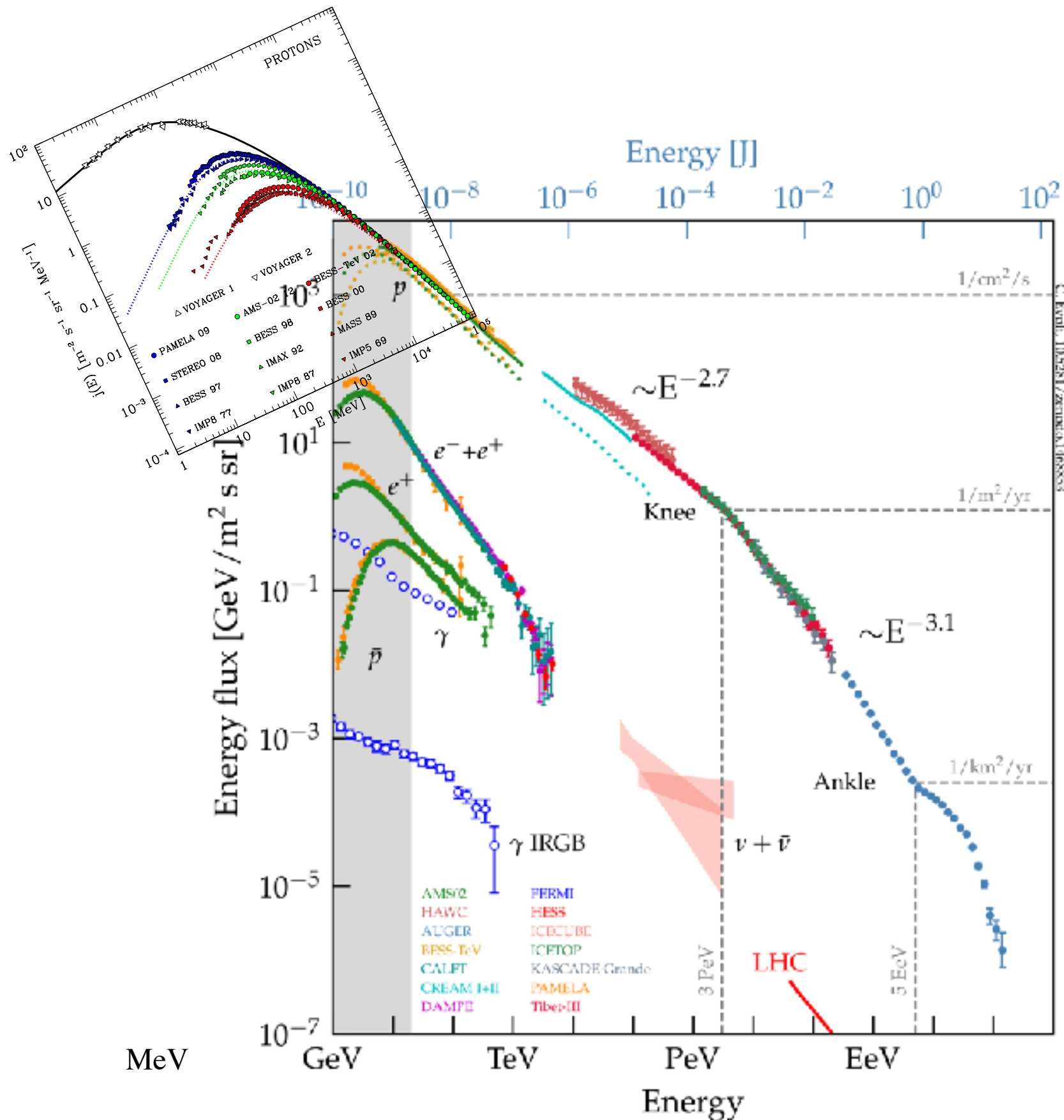
it is impossible to review in a decent way “all” radiative processes in 1.5 h



One question every 3 (energy) decades...

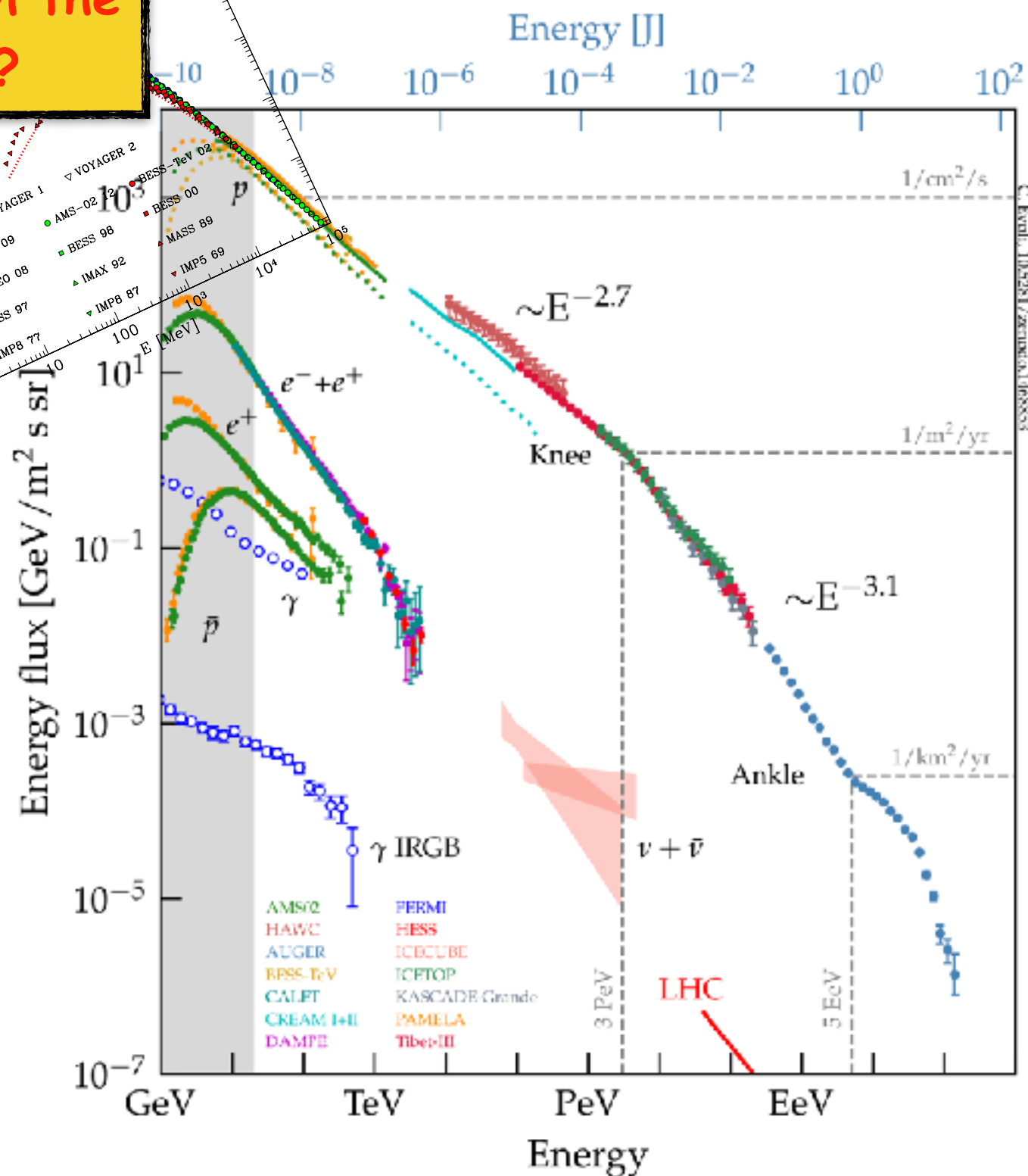


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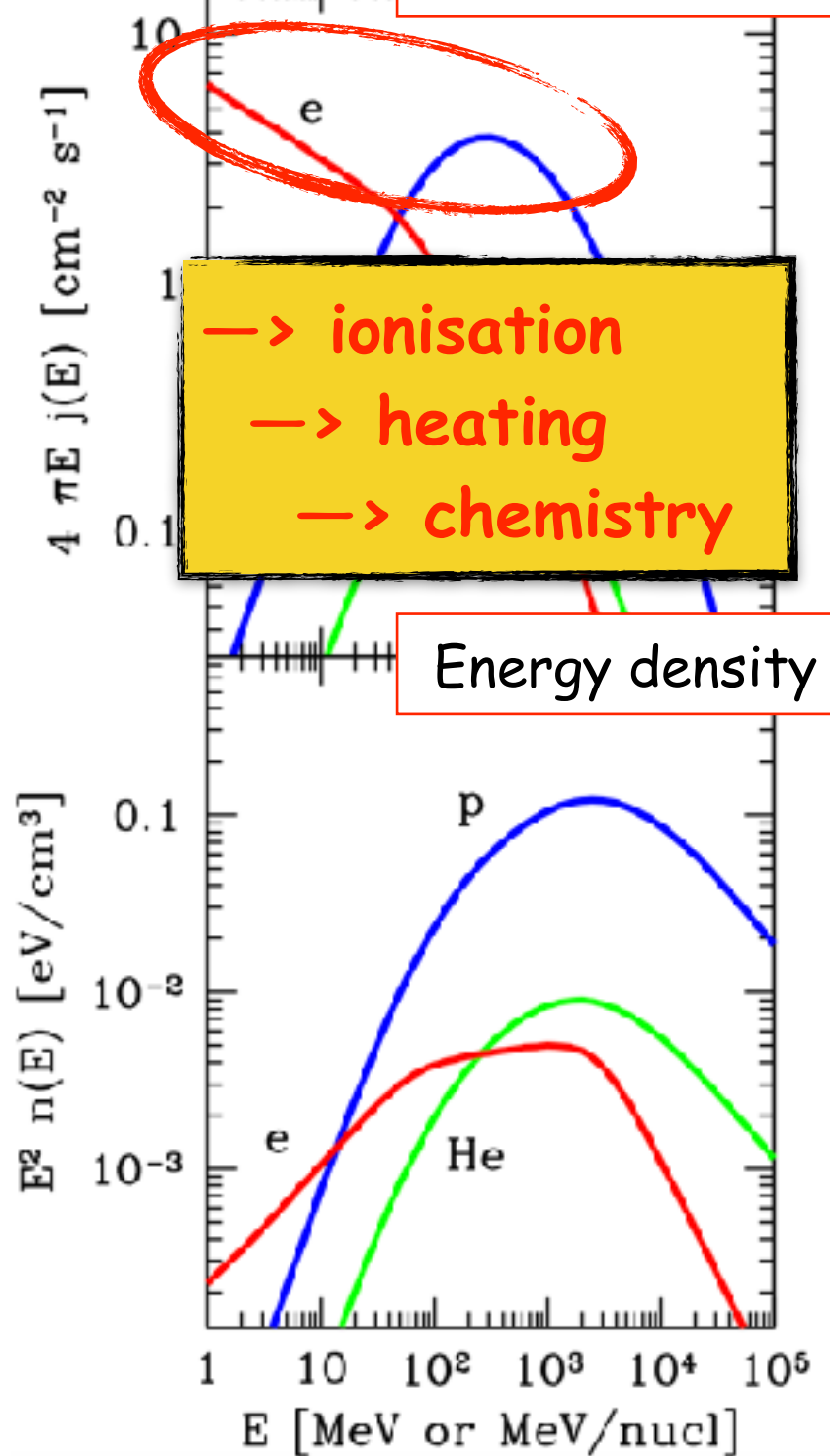


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MeV: which impact on the ISM?

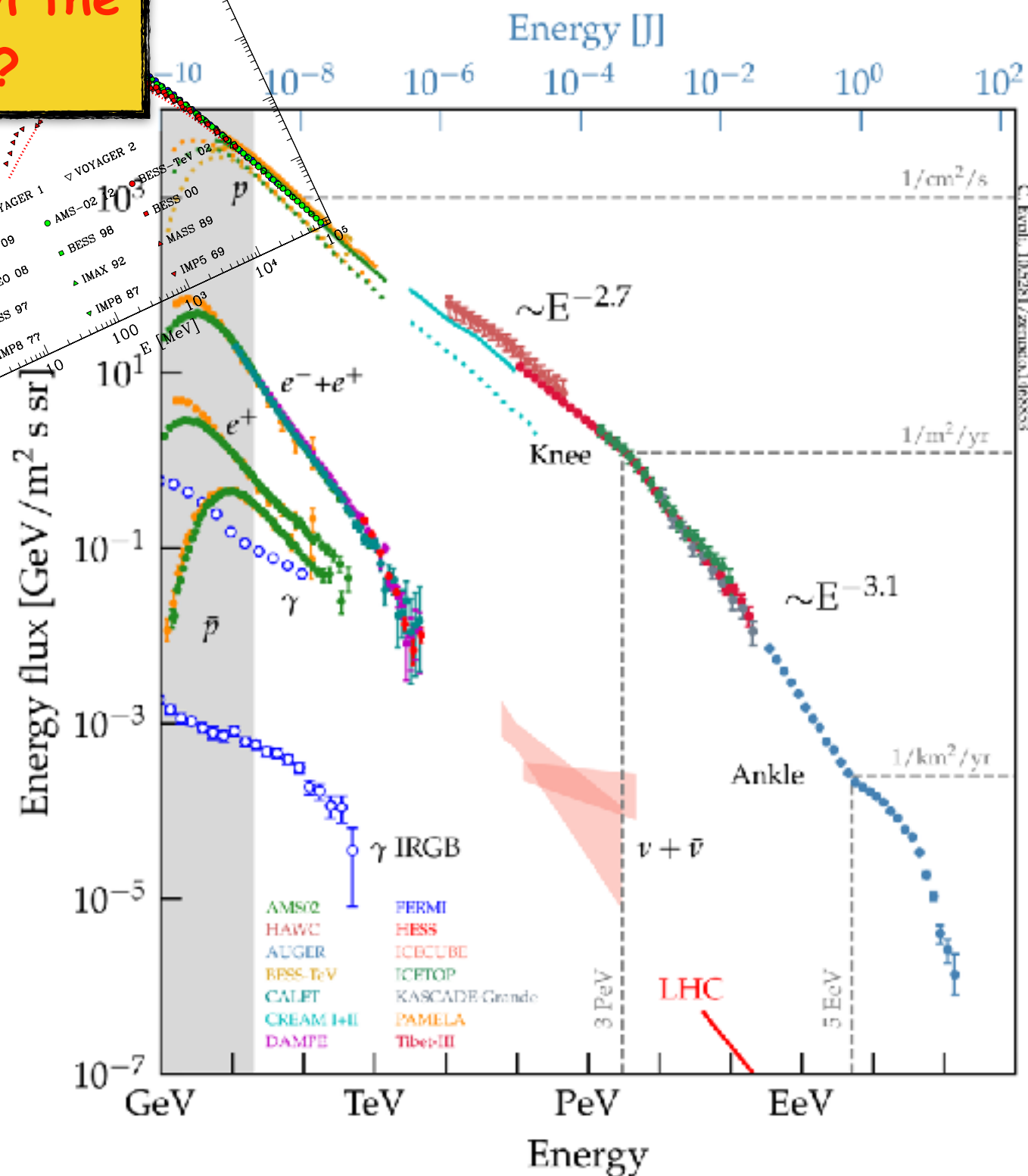


Interaction rate

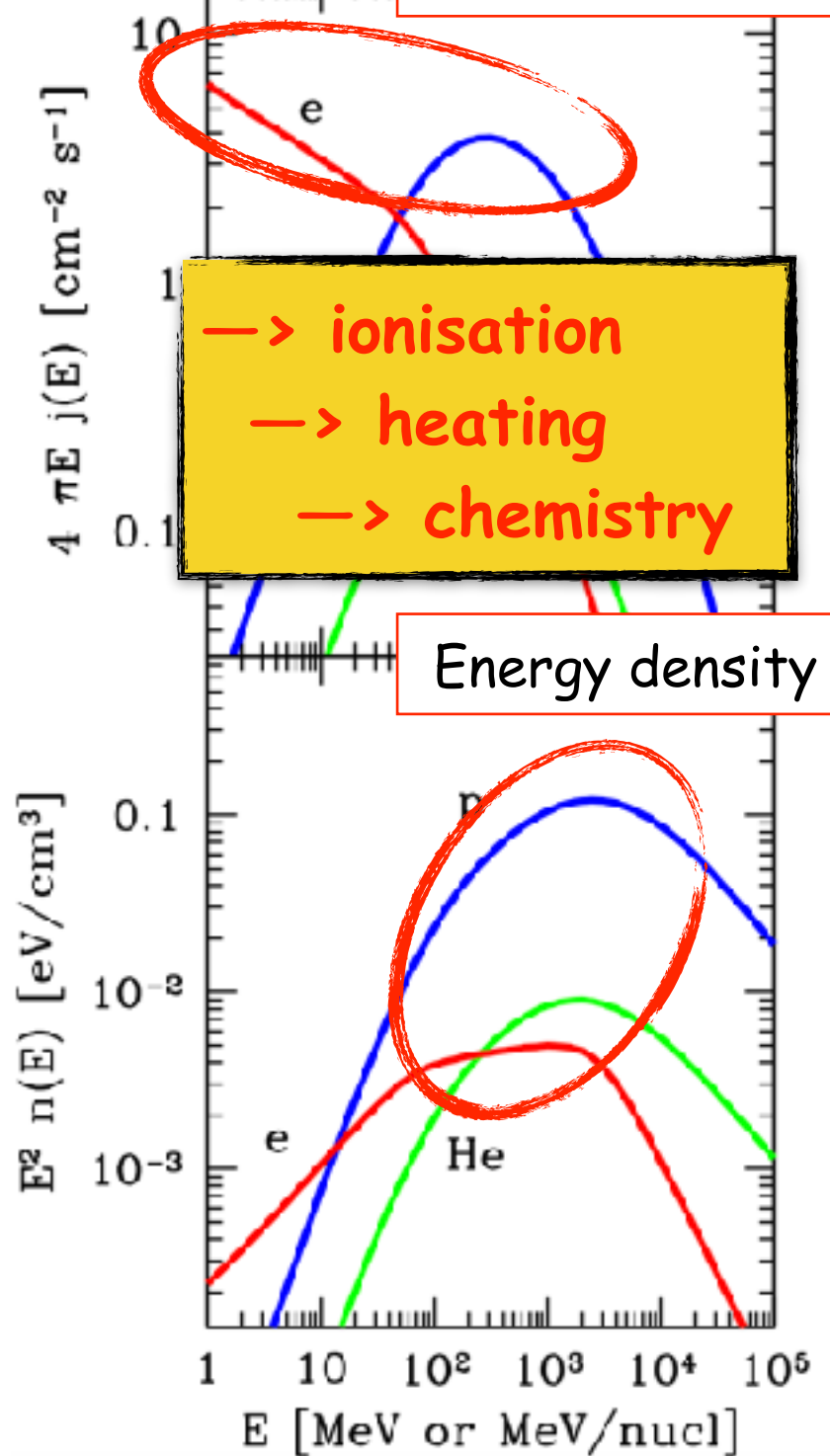


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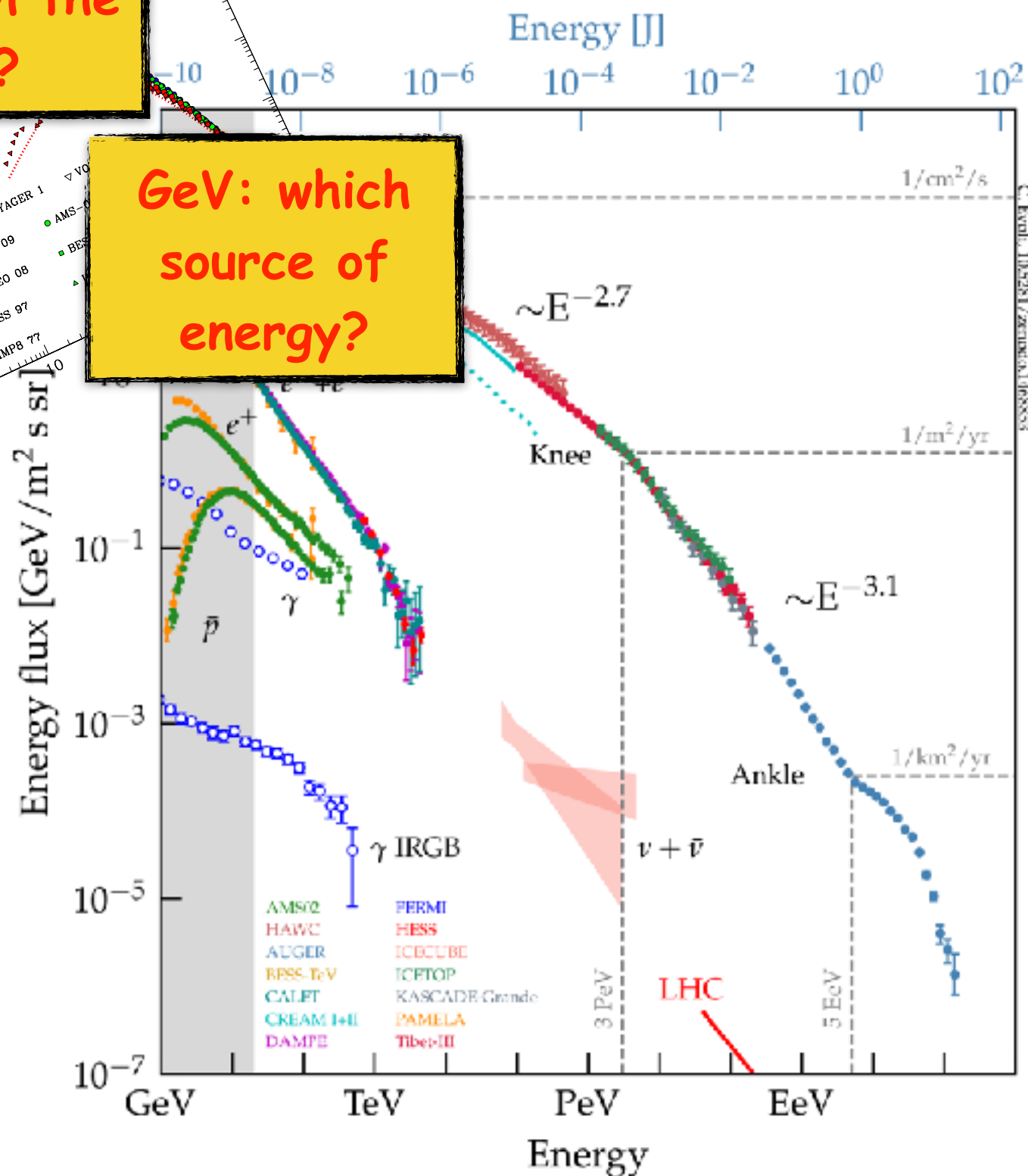
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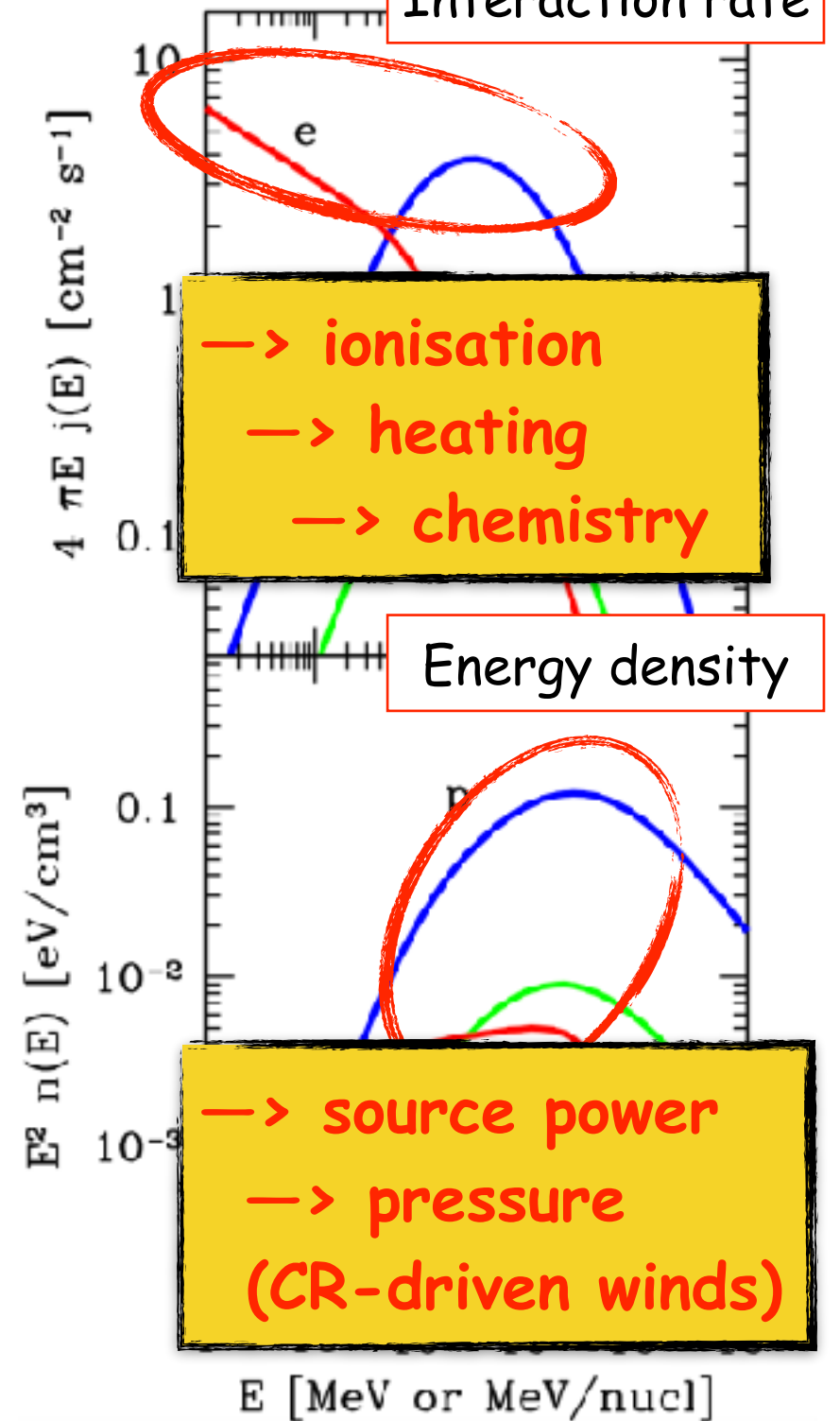
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GeV: which
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Interaction rate



—> ionisation
—> heating
—> chemistry

Energy density

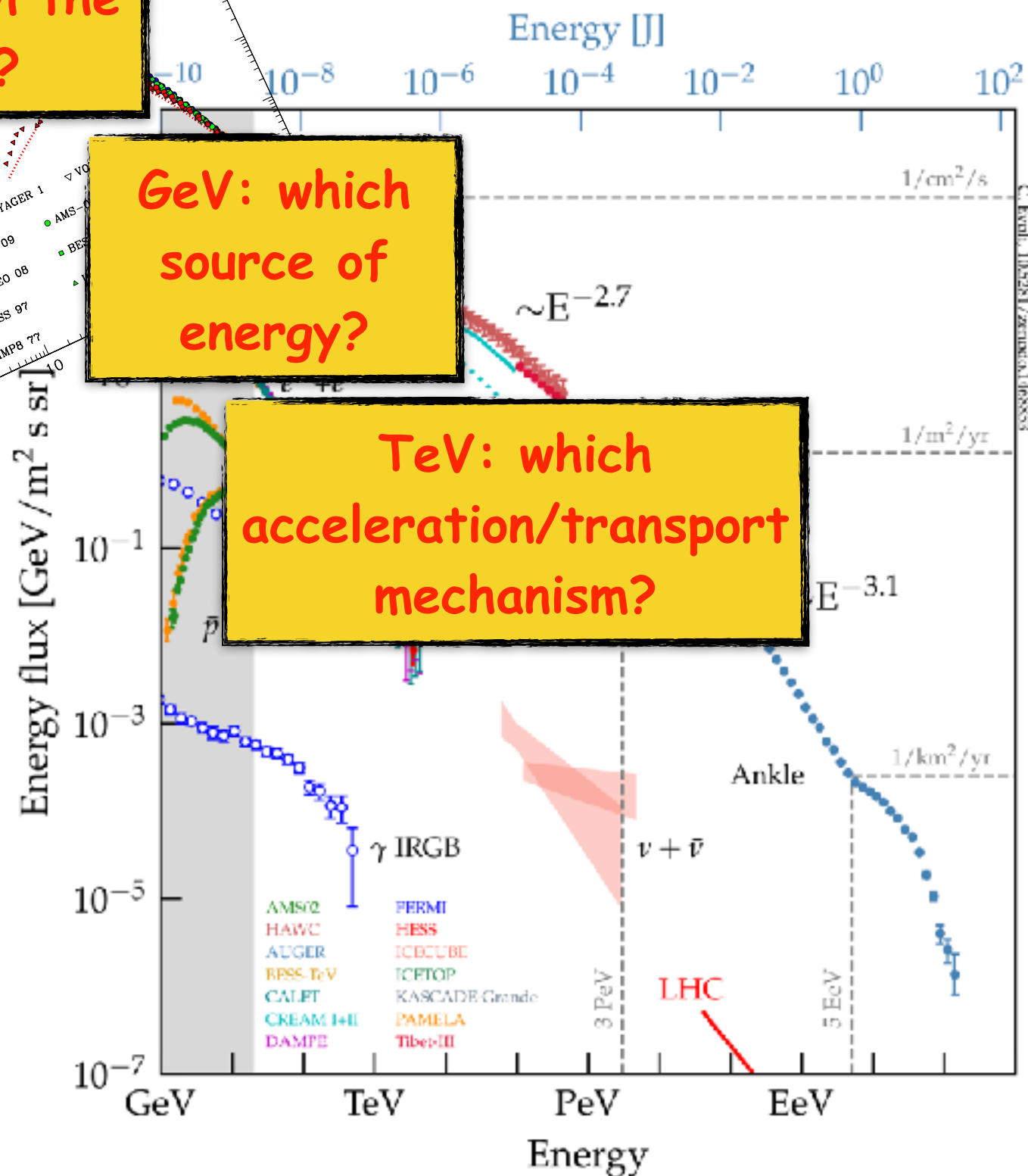
—> source power
—> pressure
(CR-driven winds)

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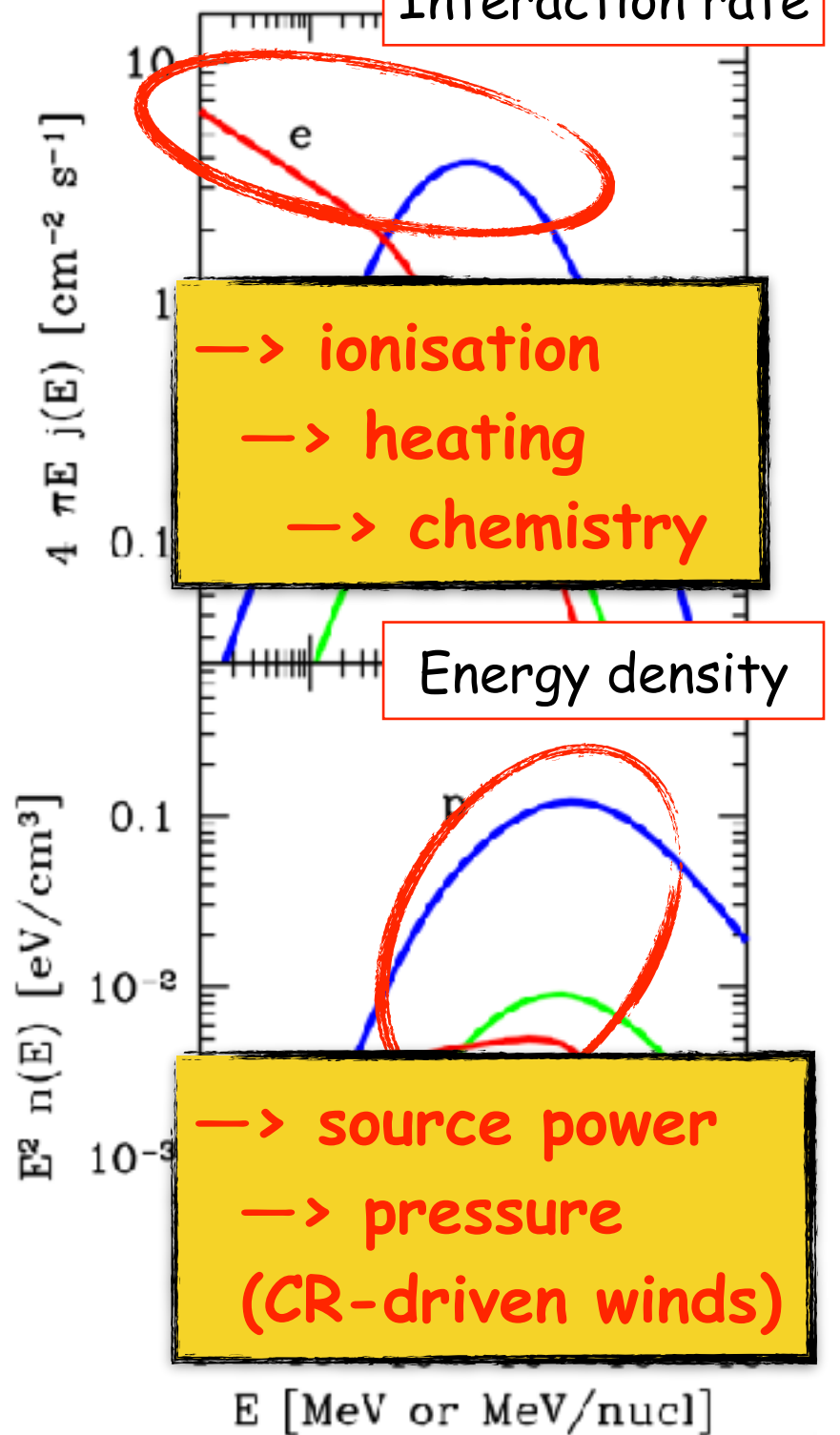
MeV: which impact on the ISM?

GeV: which source of energy?

TeV: which acceleration/transport mechanism?



Interaction rate



→ ionisation
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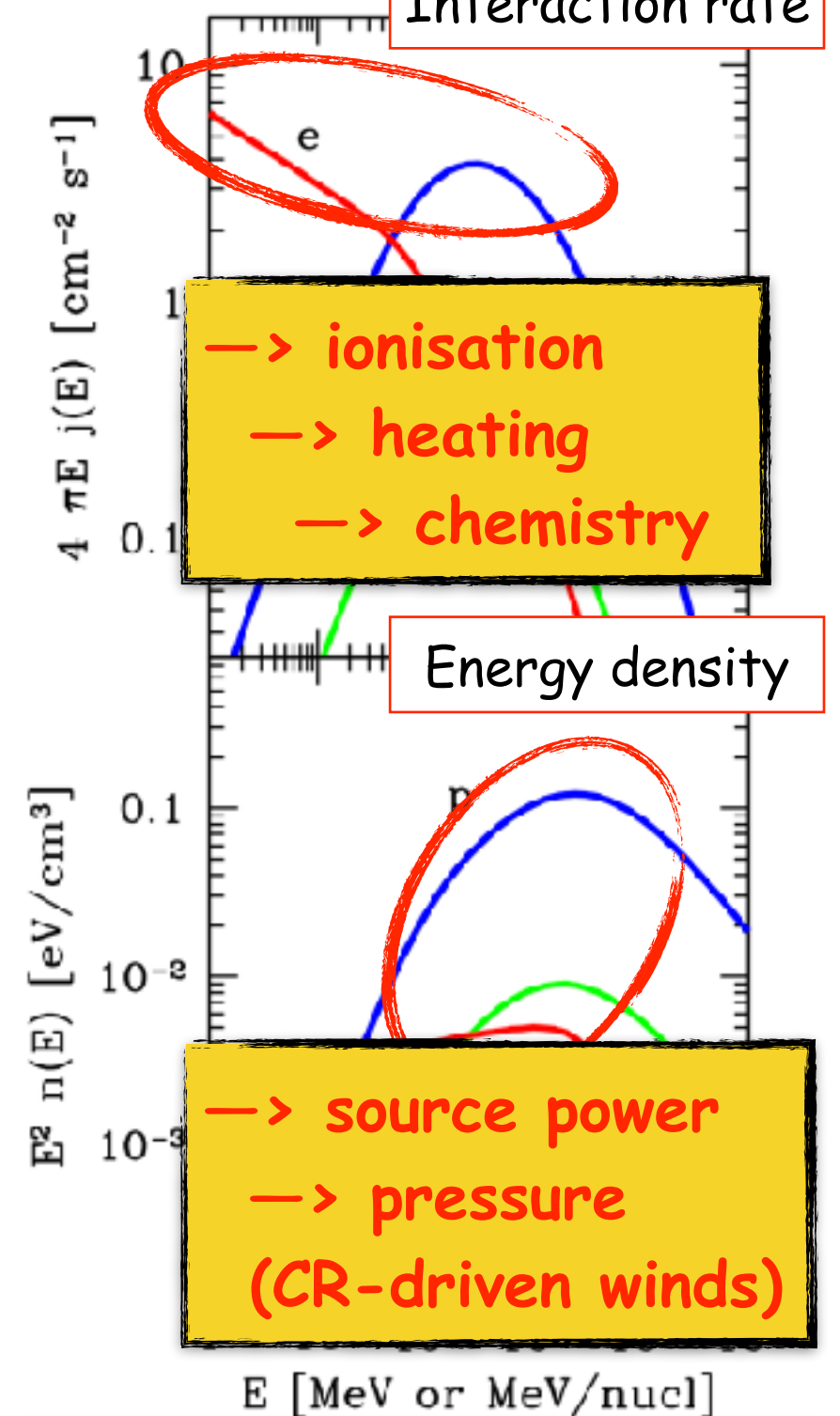
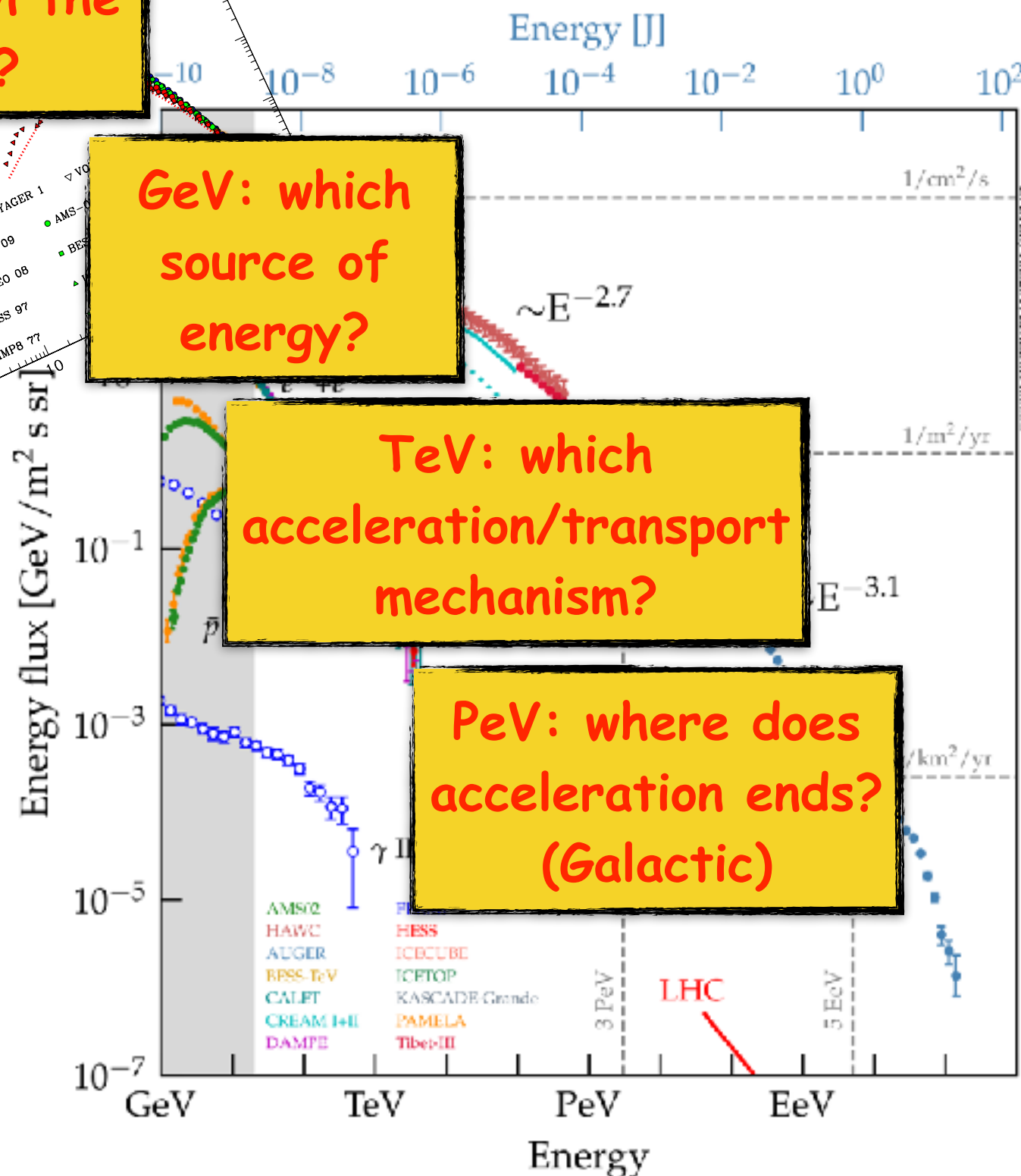
PeV: where does acceleration ends? (Galactic)

Interaction rate

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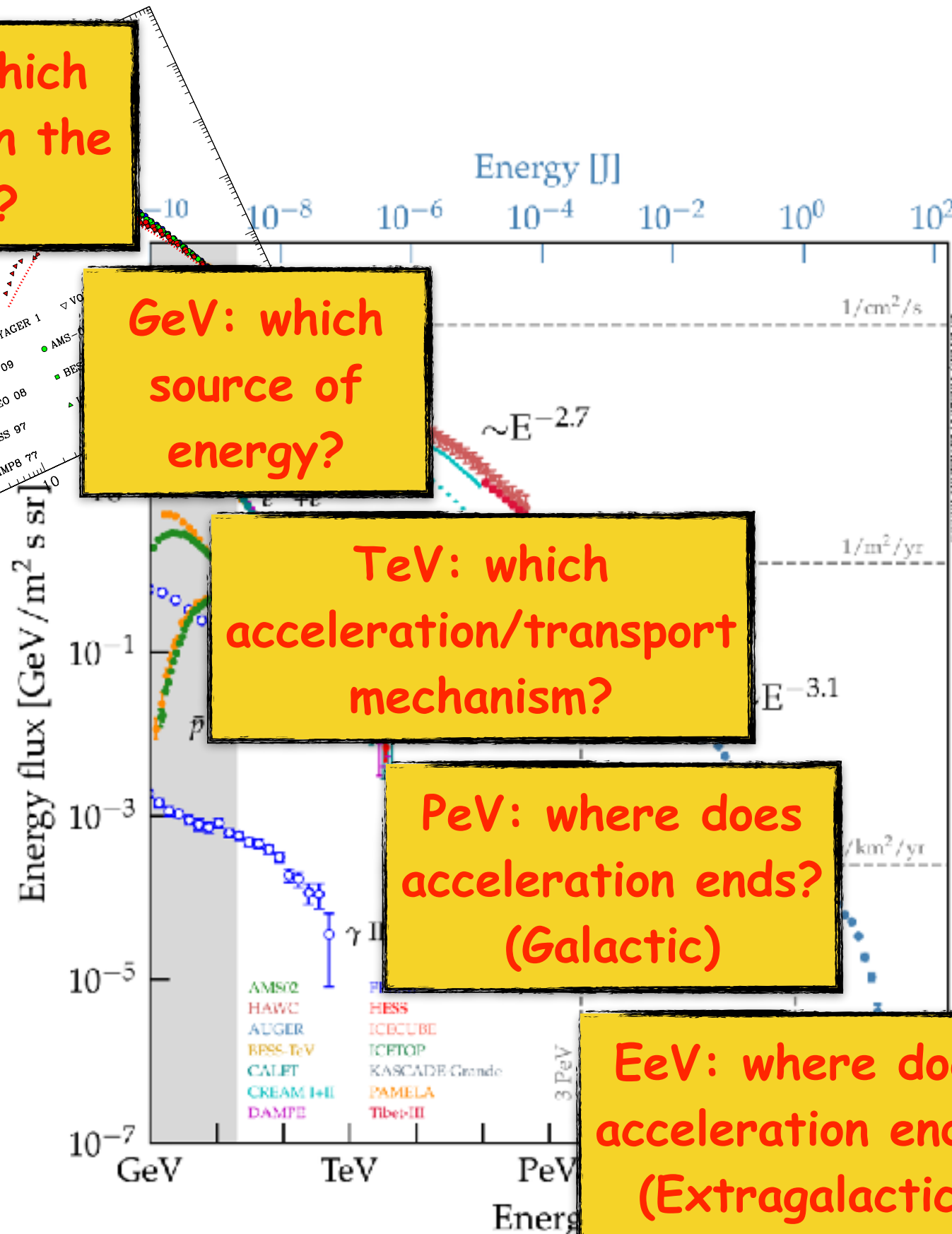
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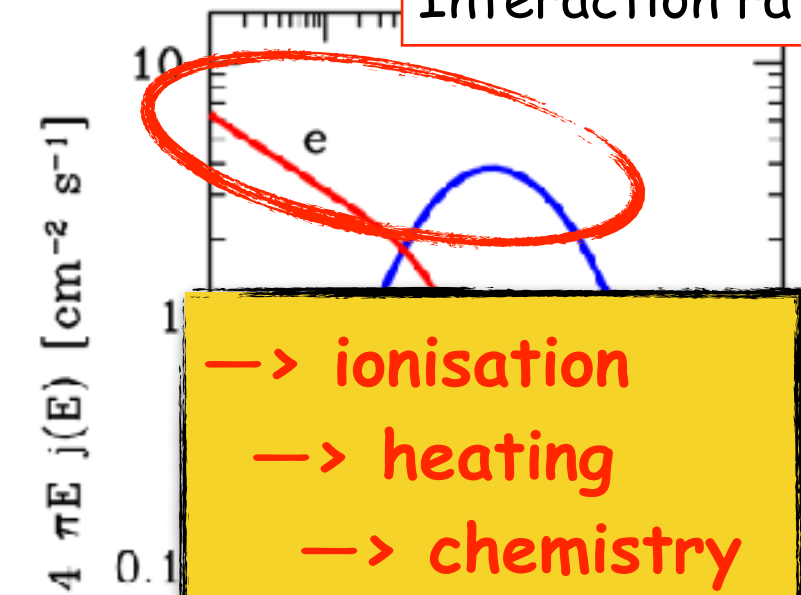
TeV: which acceleration/transport mechanism?

PeV: where does acceleration ends? (Galactic)

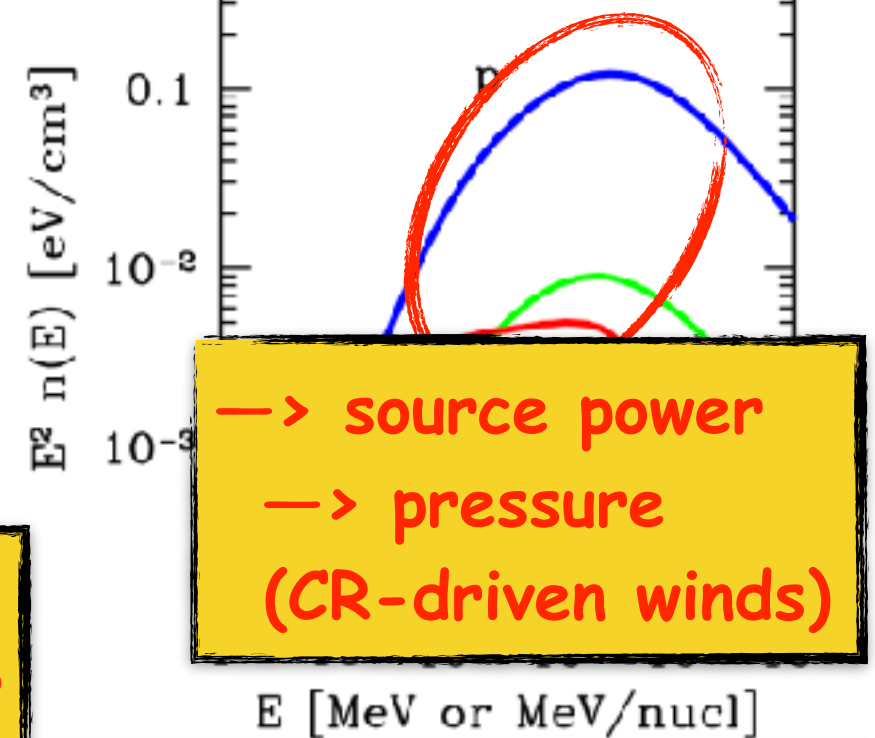
EeV: where does acceleration ends? (Extragalactic)



Interaction rate



Energy density



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
Warm Neutral	0.5	8,000	4.0	0.3
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$$B \sim 3 \mu\text{G}$$

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a remarkable
coincidence (yes,
just a coincidence)

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

Astrophysical environments

we will mostly discuss the interstellar medium (ISM) but not only → high energy radiation without non-thermal particles and matter or radiation/B-fields

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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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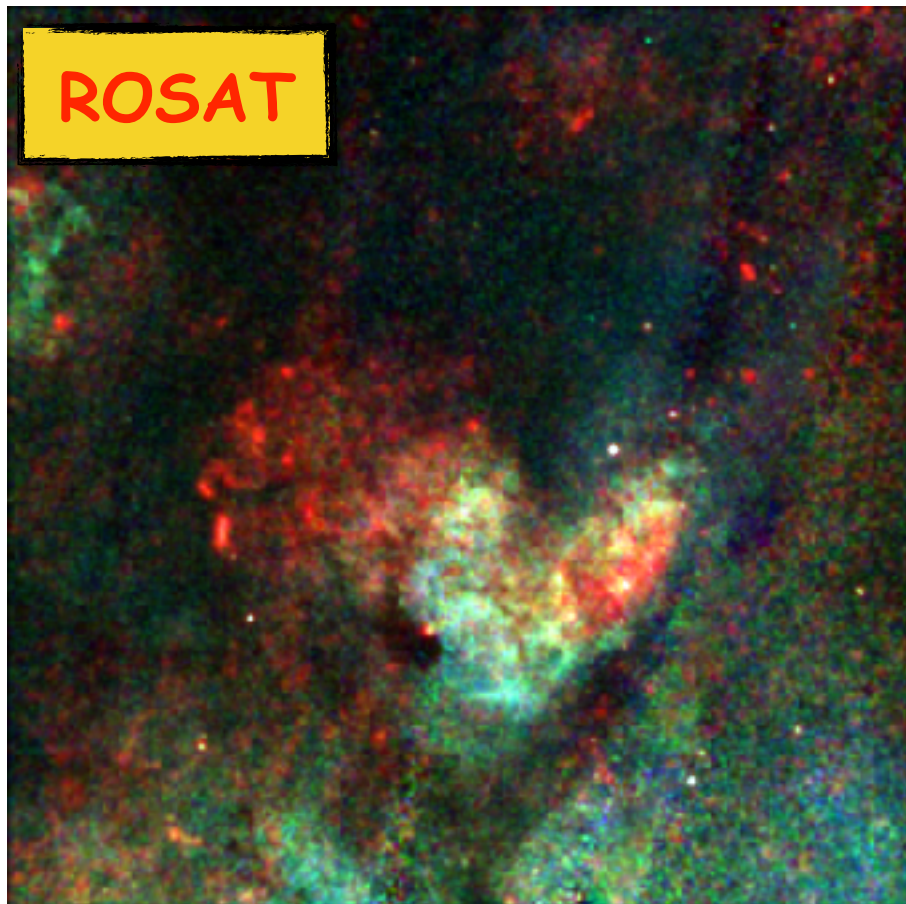
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ROSAT



$\rightarrow$ 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

Emission from hot plasmas: thermal Bremsstrahlung

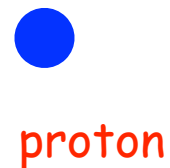
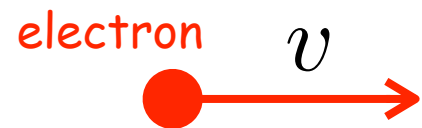
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$$v = \sqrt{\frac{3kT}{m}} \longrightarrow v_e = \left(\frac{m_p}{m_e}\right)^{1/2} v_p \gg v_p$$

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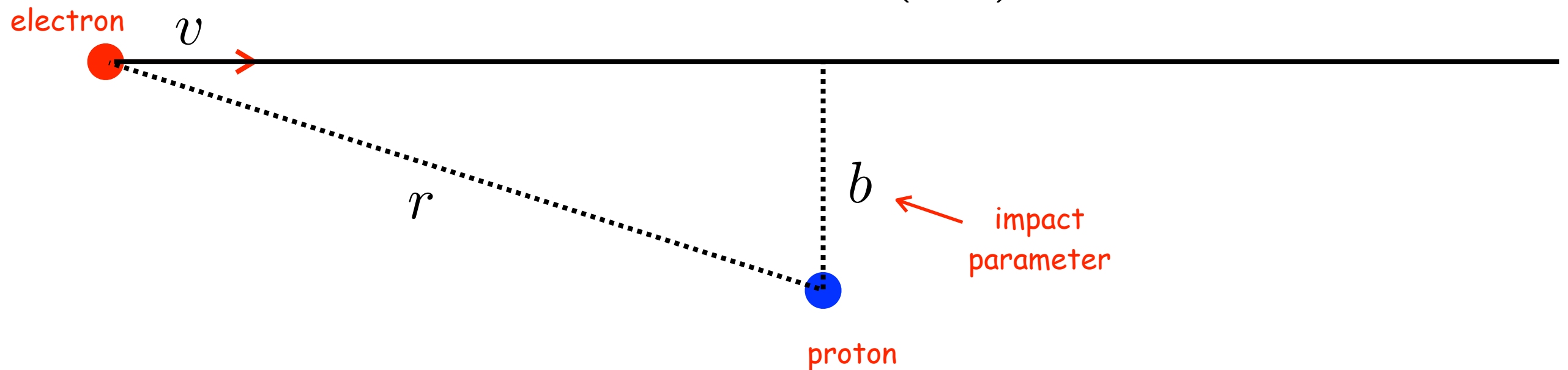
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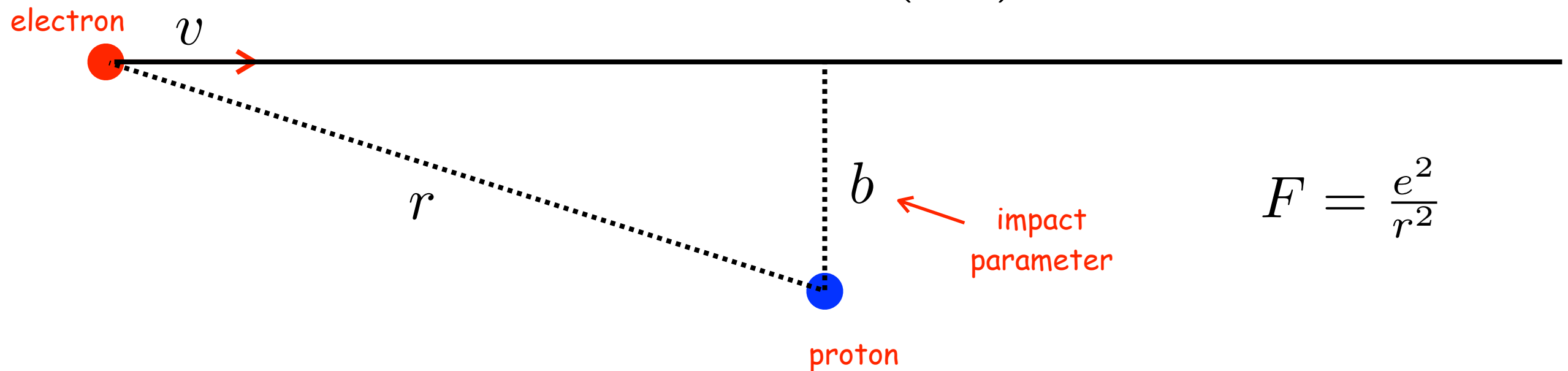
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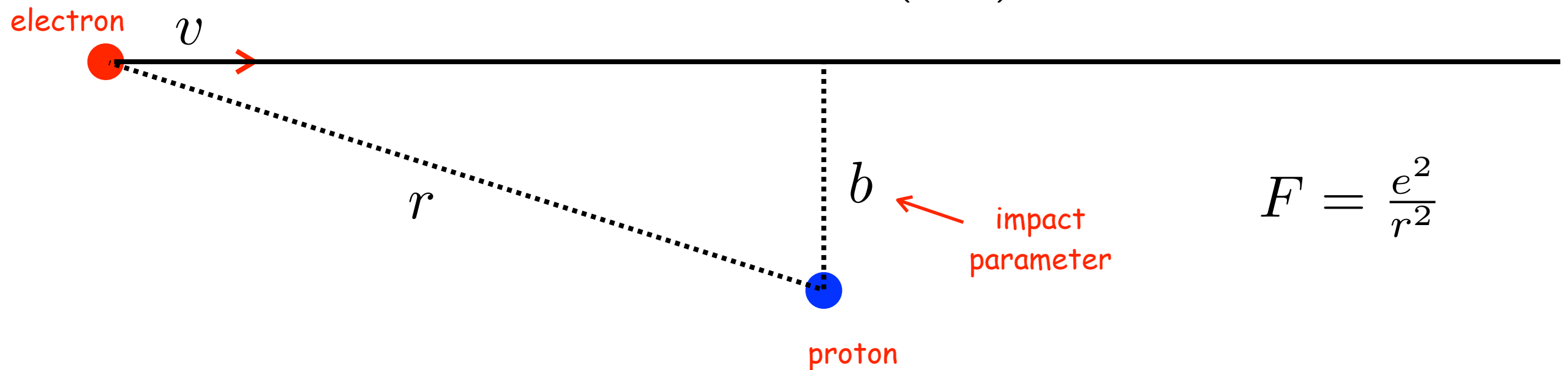
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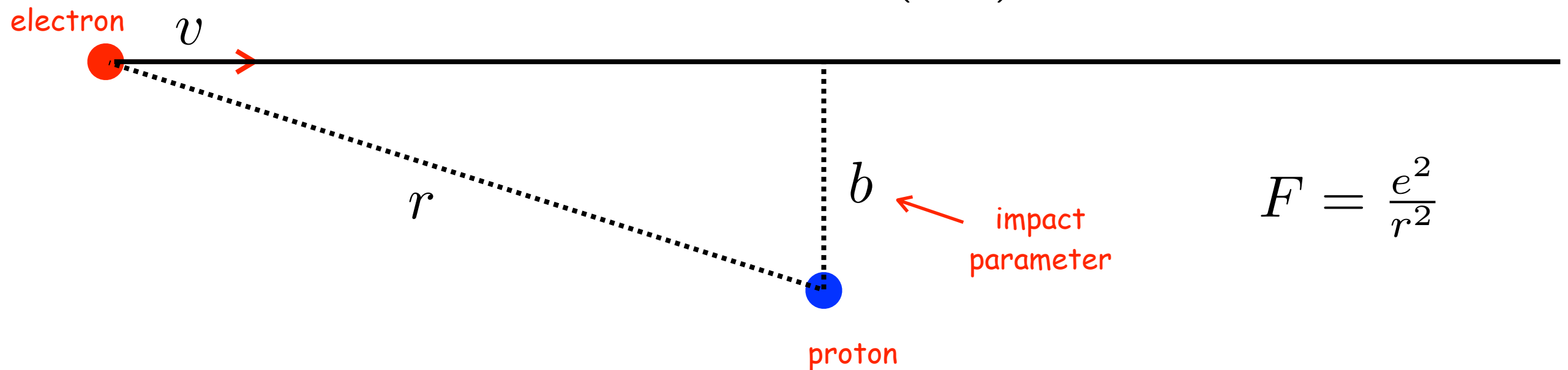
power emitted by an
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$$\begin{cases} r \approx b \rightarrow a \approx \frac{e^2}{m_e b^2} \\ r \gg b \rightarrow a \approx 0 \end{cases}$$

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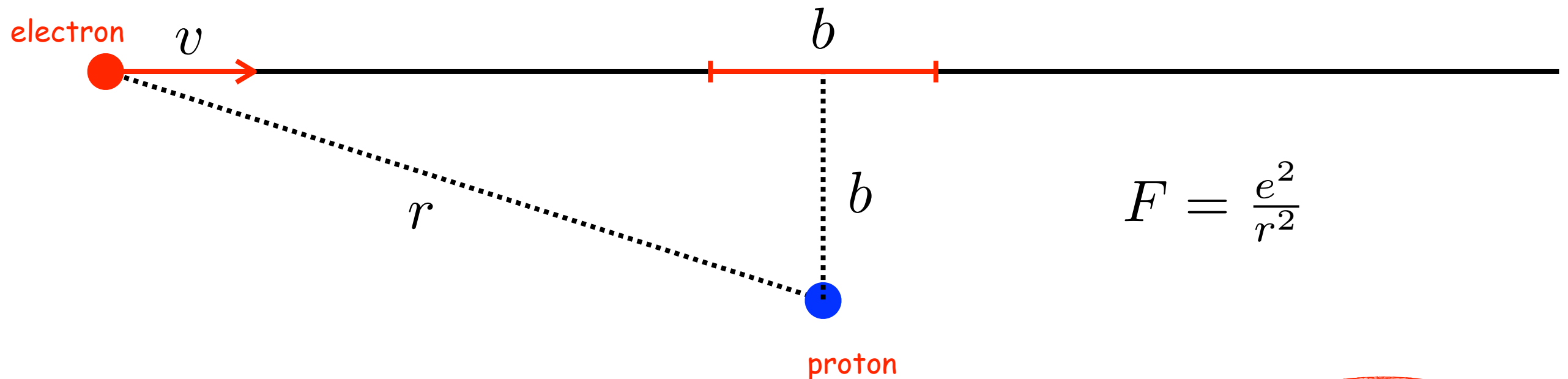
Thermal Bremsstrahlung

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



power emitted by an
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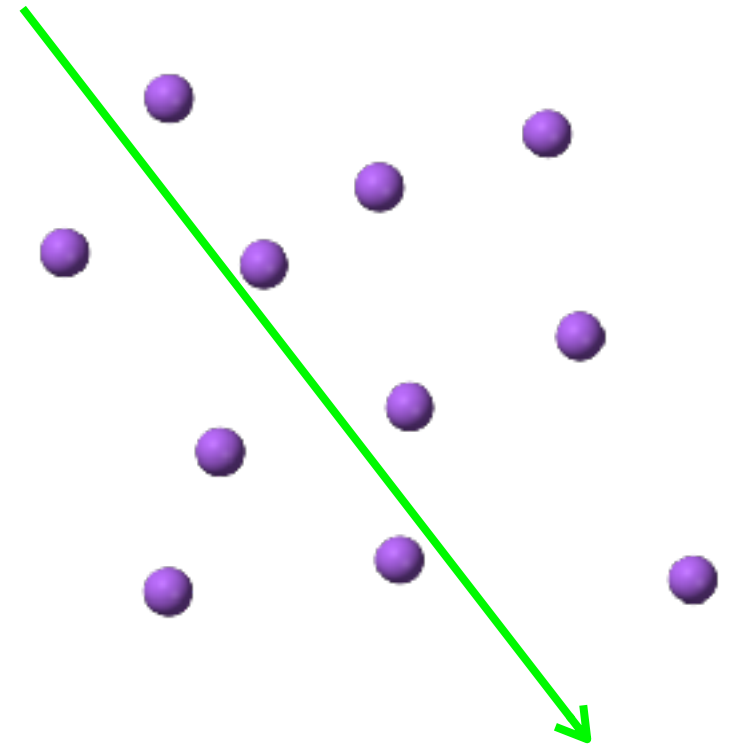
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Thermal Bremsstrahlung

rough estimate of the
impact parameter b

plasma proton density $\rightarrow n_p$

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

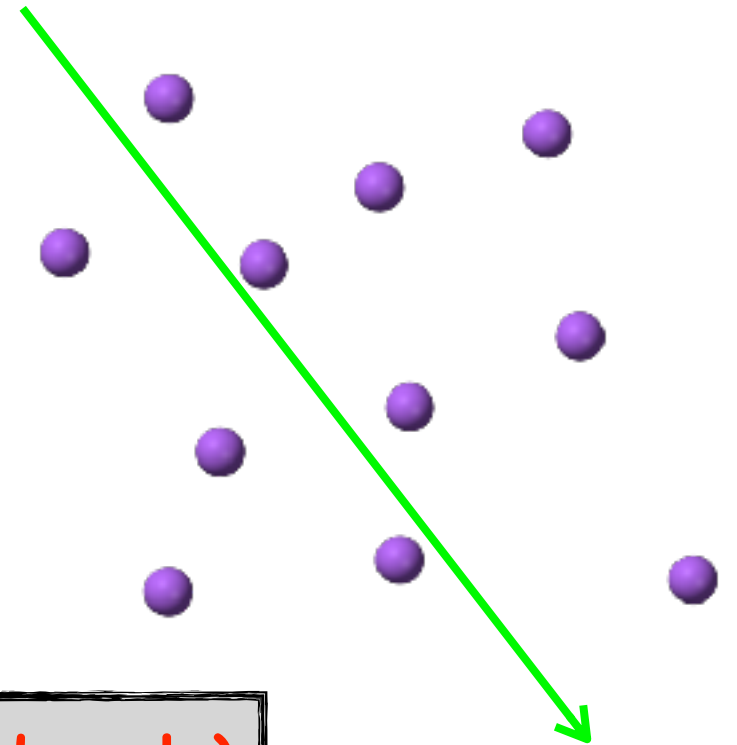


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emissivity (power per unit frequency, volume, and solid angle)

$\omega \rightarrow \nu = \omega/2\pi$

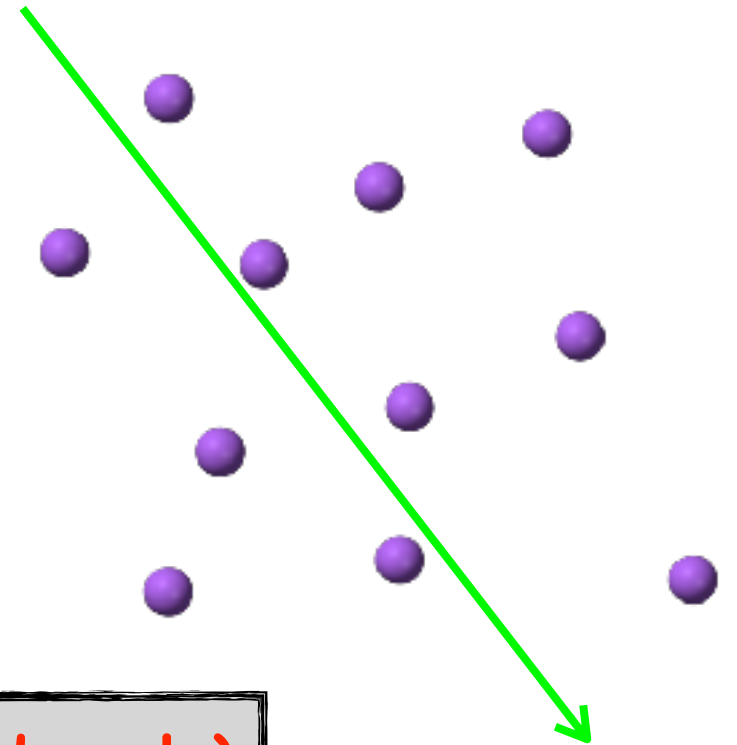
$$j(\nu) \approx \frac{n_e P}{(4\pi)} \frac{2\pi}{\omega} = \frac{n_e n_p e^6}{3c^3 m_e^2} \left(\frac{m_e}{kT} \right)^{1/2}$$

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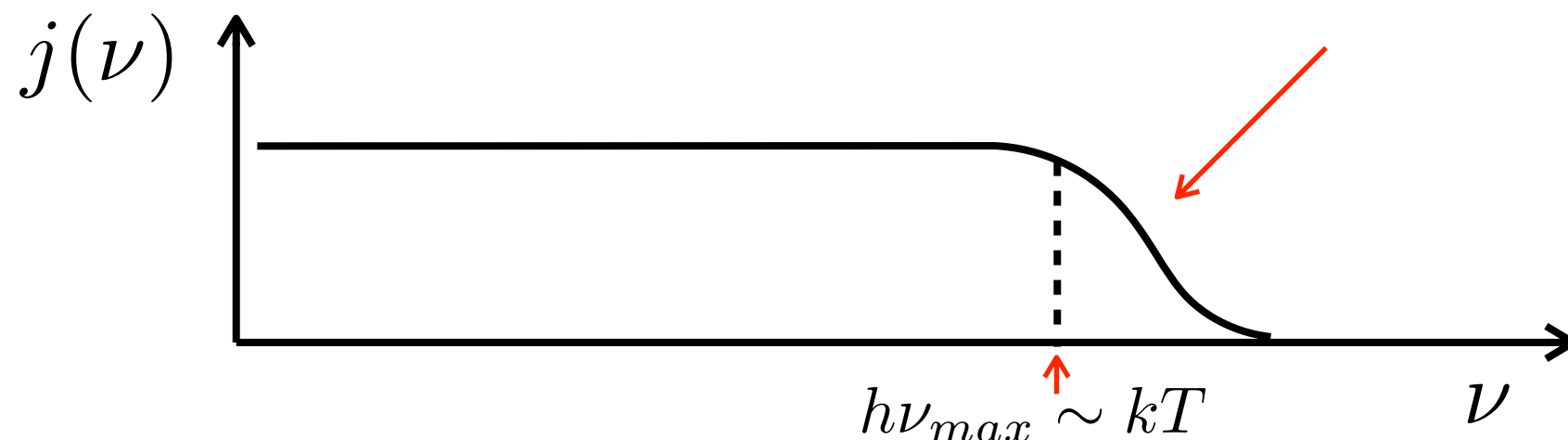


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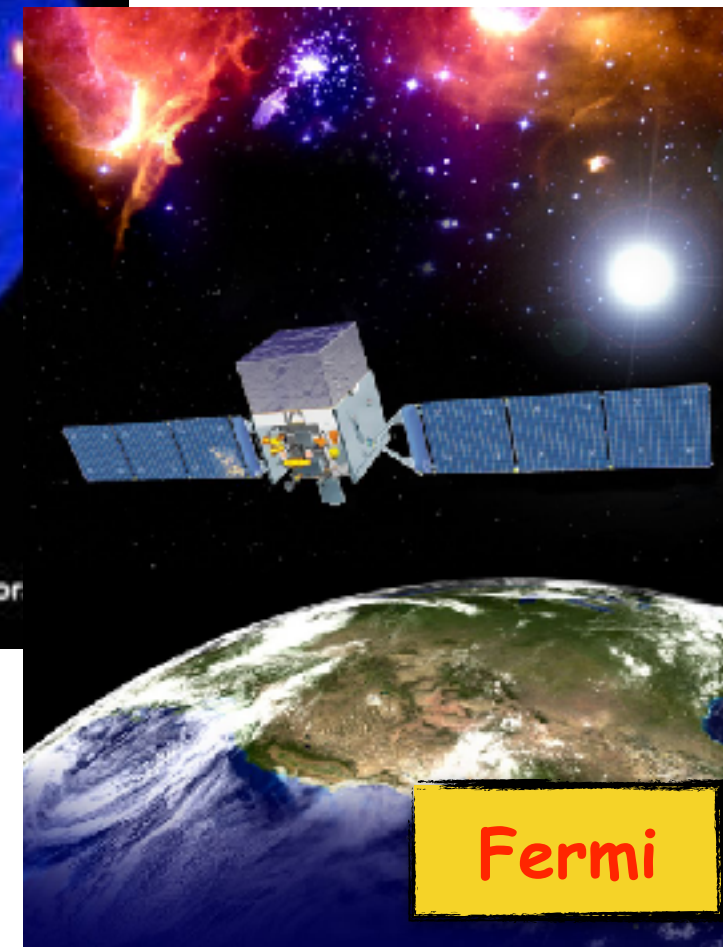
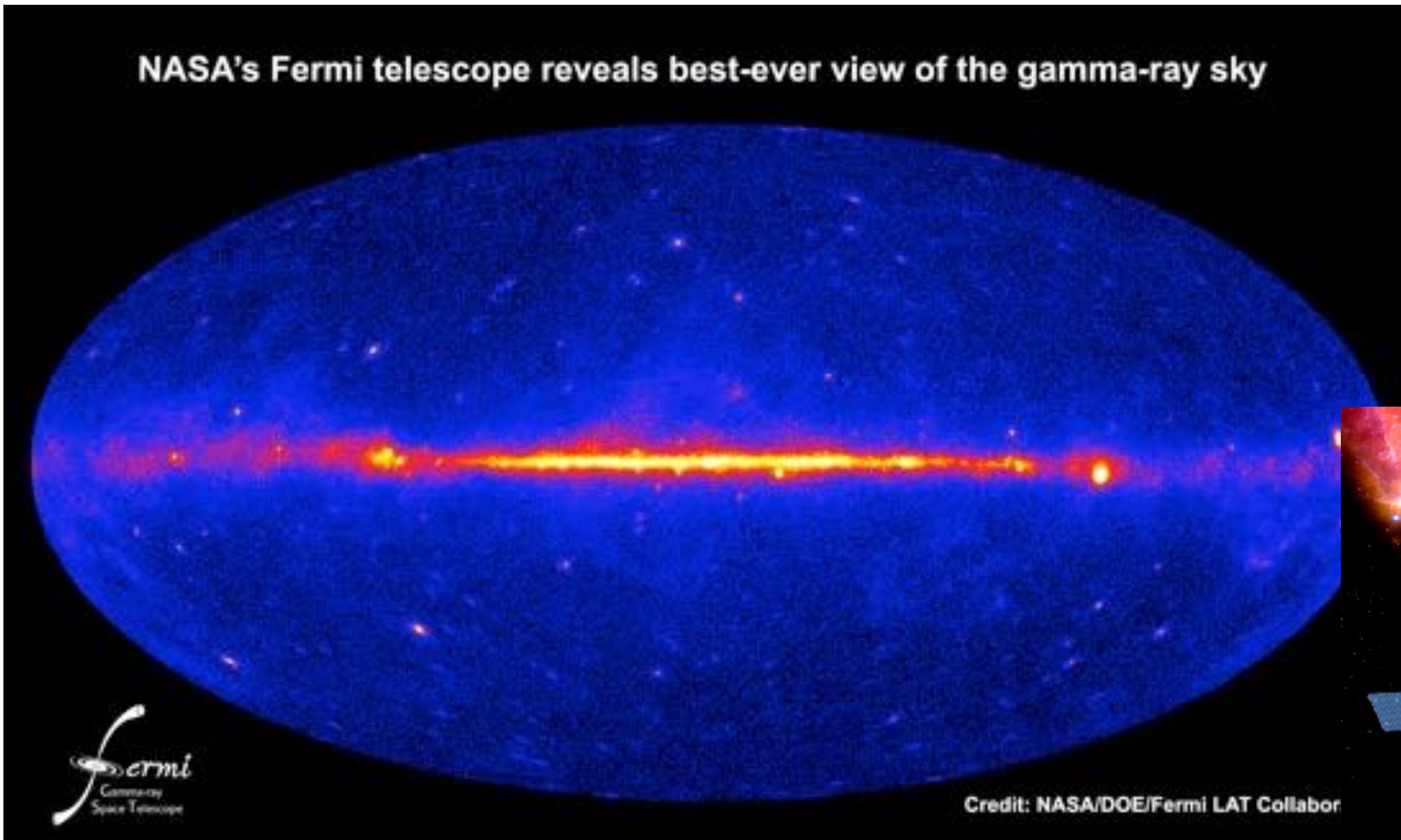
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exponential suppression
 $\rightarrow$ no electrons with energy $\gg kT$

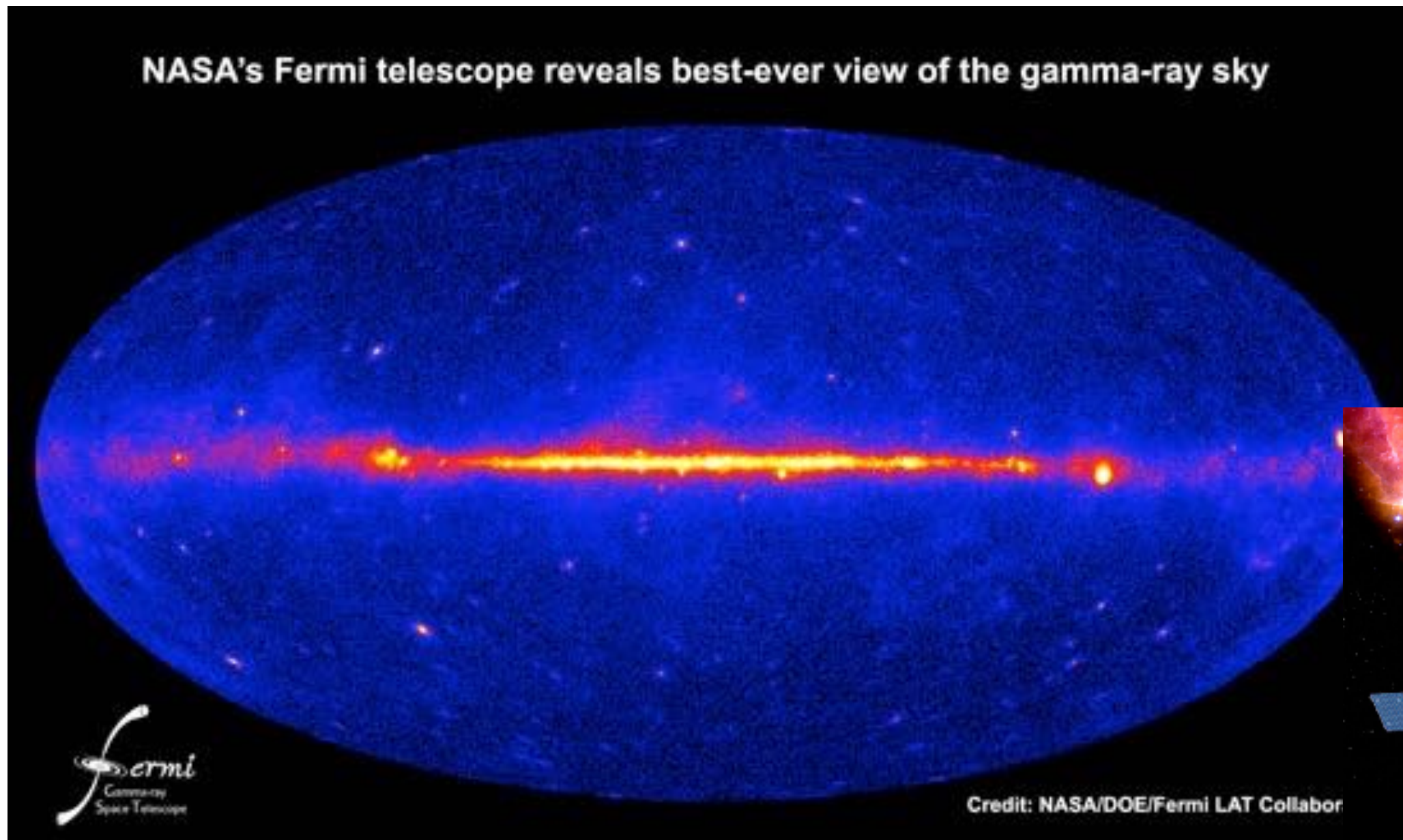


Cosmic ray interactions in the sky

NASA's Fermi telescope reveals best-ever view of the gamma-ray sky



Cosmic ray interactions in the sky



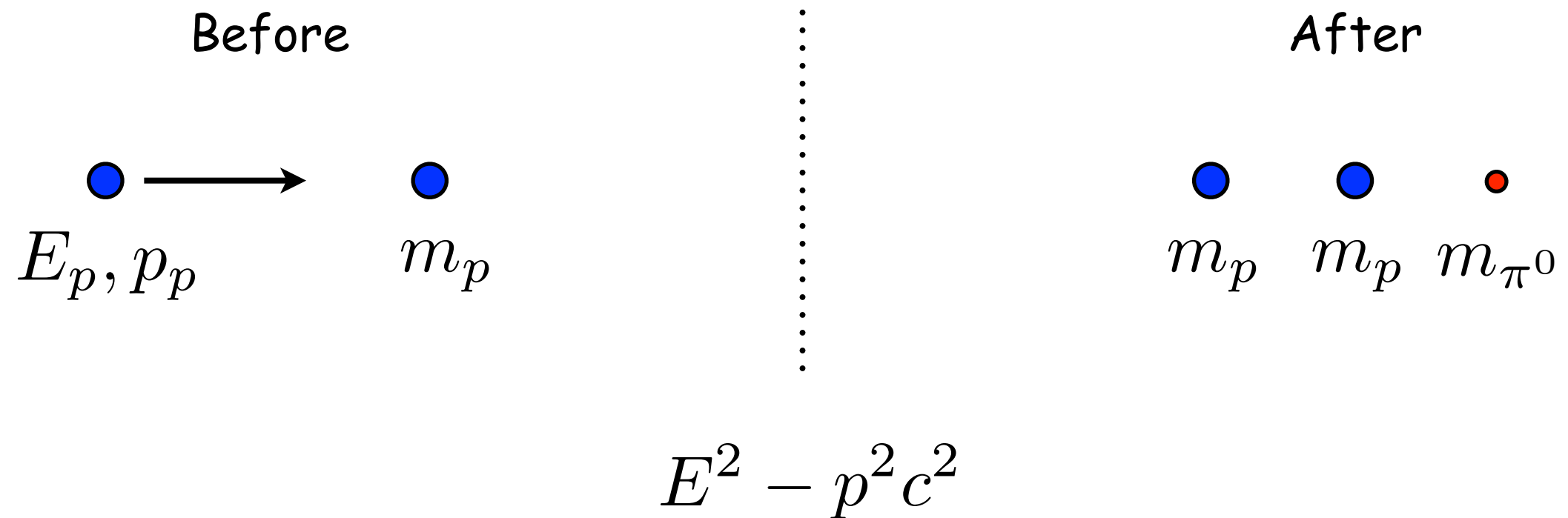
$$p + p \rightarrow p + p + \pi^0$$

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

Gamma-Ray Astronomy: p-p interactions

Energy threshold for neutral pion production:

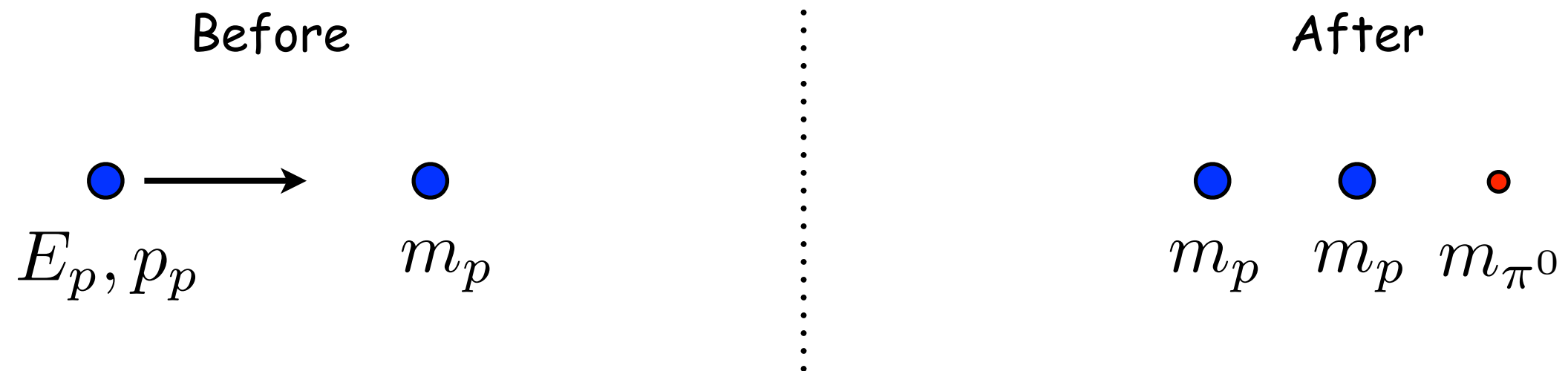
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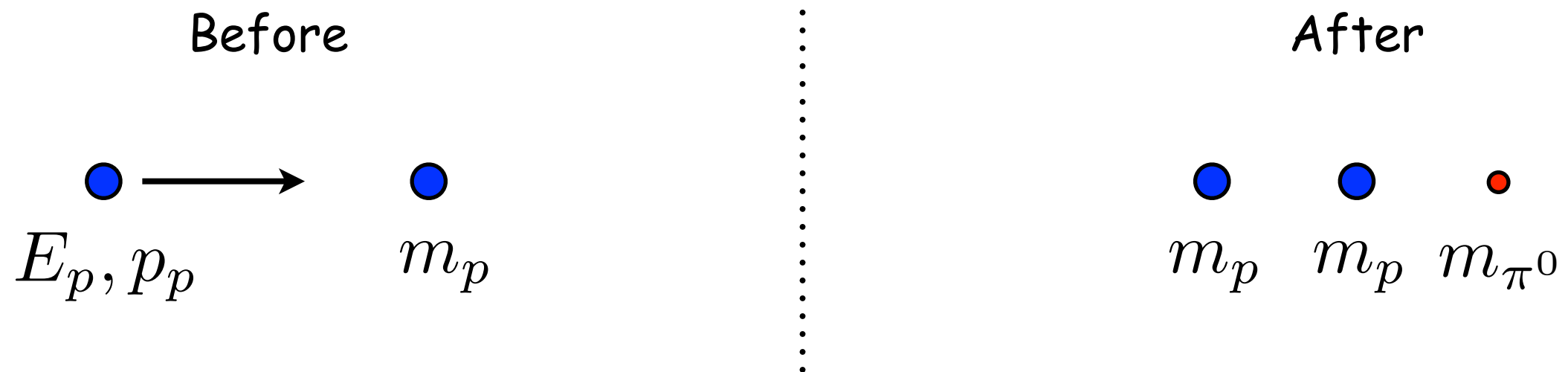


$$E^2 - p^2 c^2 = (2m_p c^2 + m_{\pi^0} c^2)^2$$

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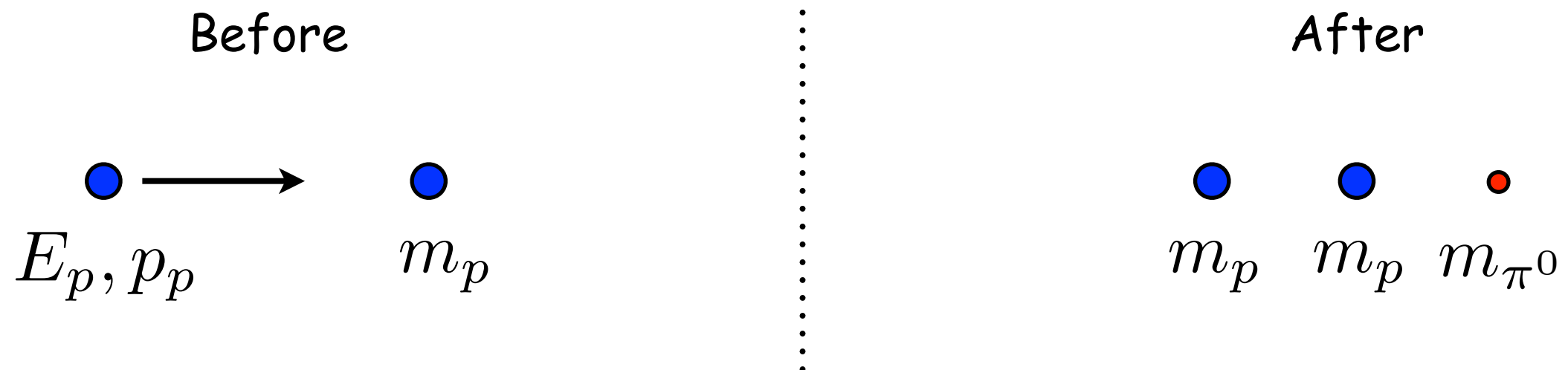
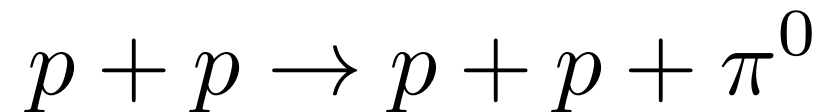
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$$(E_p + m_p c^2)^2 - p_p^2 c^2 = E^2 - p^2 c^2 = (2m_p c^2 + m_{\pi^0} c^2)^2$$

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

energy threshold

Gamma-Ray Astronomy: p-p interactions

Let's calculate the spectrum of neutral pions:

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

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

production
rate

total cross
section

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

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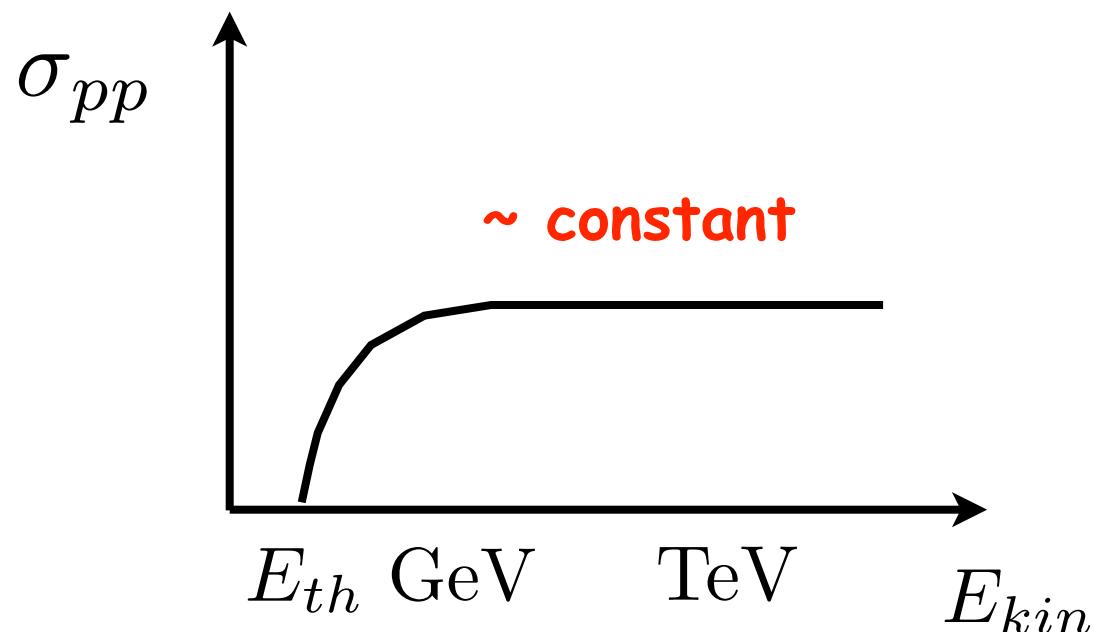
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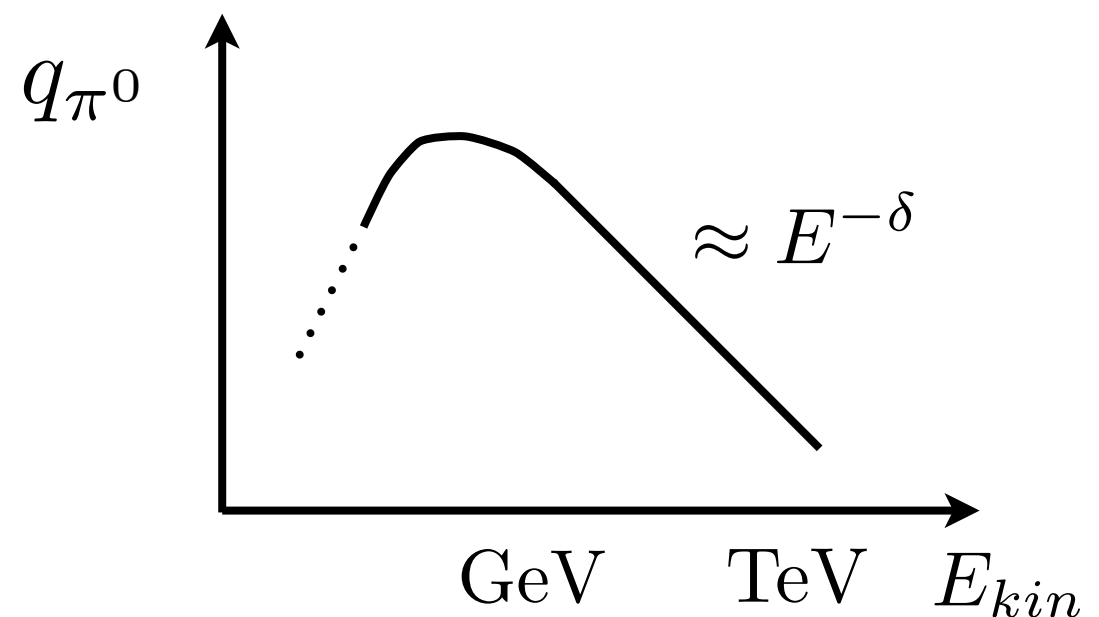
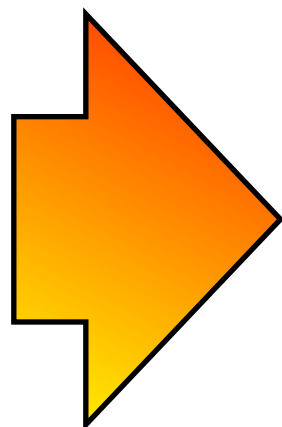
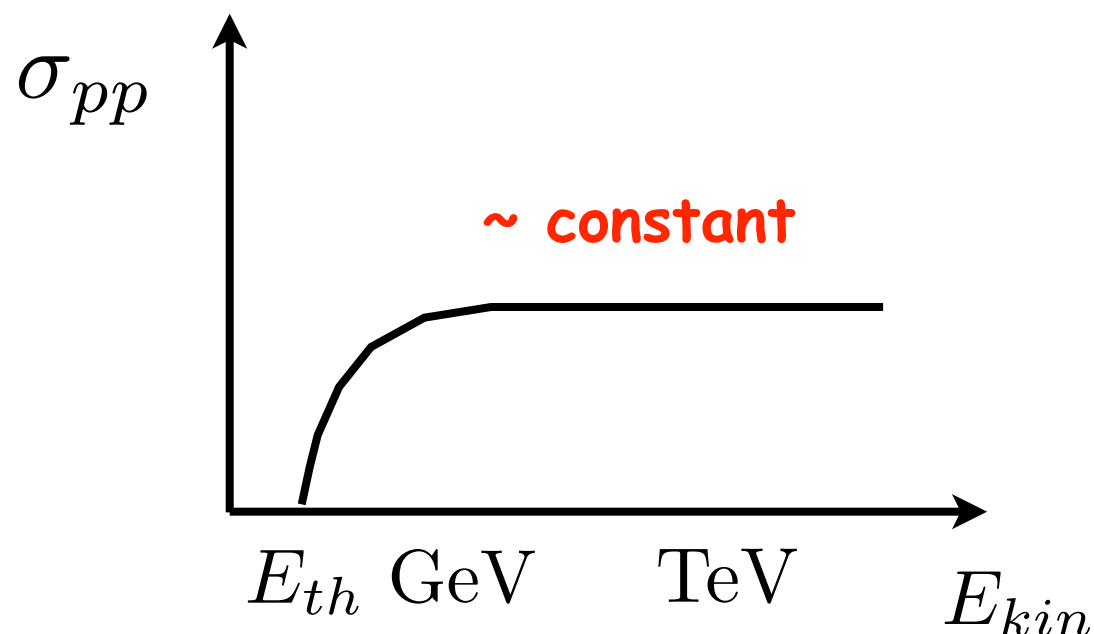
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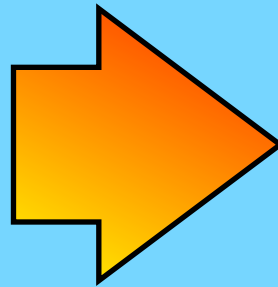
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Gamma-Ray Astronomy: p-p interactions

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

The photon spectrum is the result of a "one-body-decay" (neutral pion)

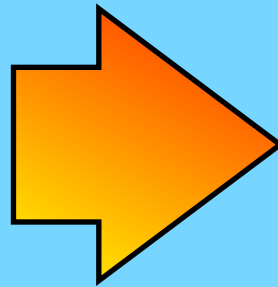


The photon spectrum **MUST** exhibit a feature at an energy relate to the pion mass

Gamma-Ray Astronomy: p-p interactions

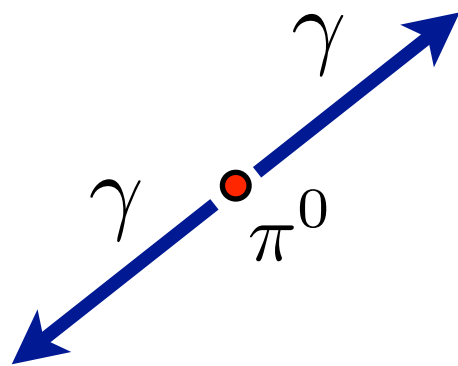
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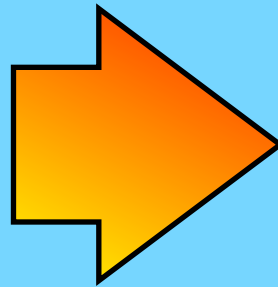


$$E_{\gamma}^* = \frac{m_{\pi^0}}{2}$$

Gamma-Ray Astronomy: p-p interactions

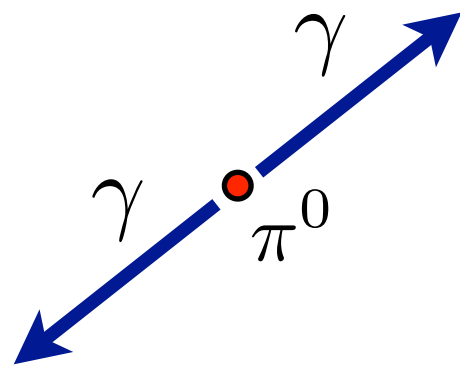
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Pion rest frame:



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

Lab frame:

$$E_{\gamma} = \gamma (E_{\gamma}^* + v p_{\gamma}^* \cos \theta^*)$$

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

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

Gamma-Ray Astronomy: p-p interactions

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

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

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

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

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

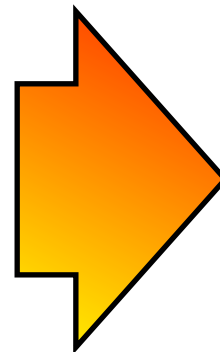
$$(1) \quad \frac{\log E_{\gamma}^{max} + \log E_{\gamma}^{min}}{2} = \log \left(\frac{m_{\pi^0}}{2} \right)$$

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

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

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

$$E_{\gamma} = \gamma (E_{\gamma}^* + vp_{\gamma}^* \cos \theta^*) \rightarrow dE_{\gamma} \propto d(\cos \theta^*)$$

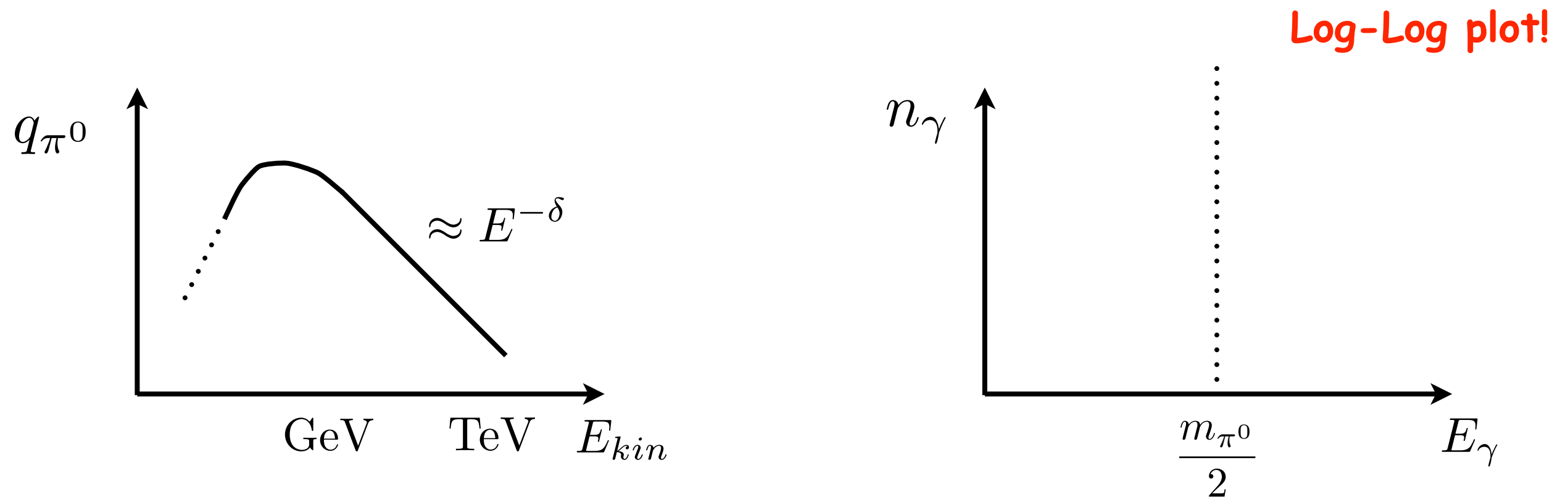


$$\frac{dn_{\gamma}}{dE_{\gamma}} = \text{const}$$

The spectrum is flat!

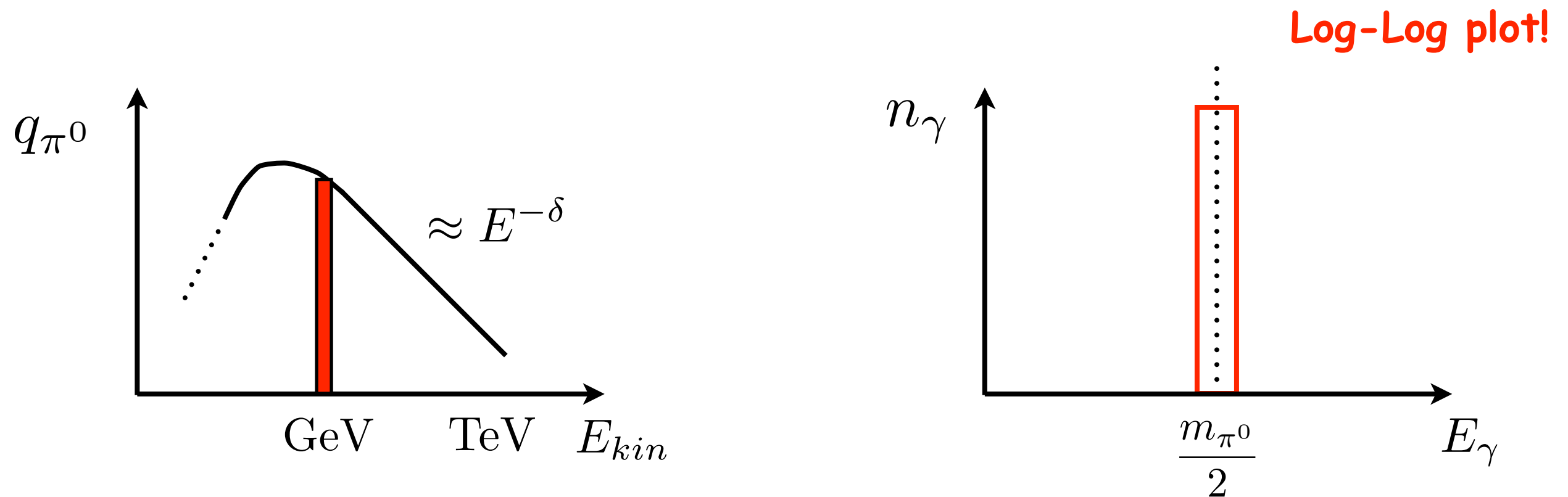
Gamma-Ray Astronomy: p-p interactions

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



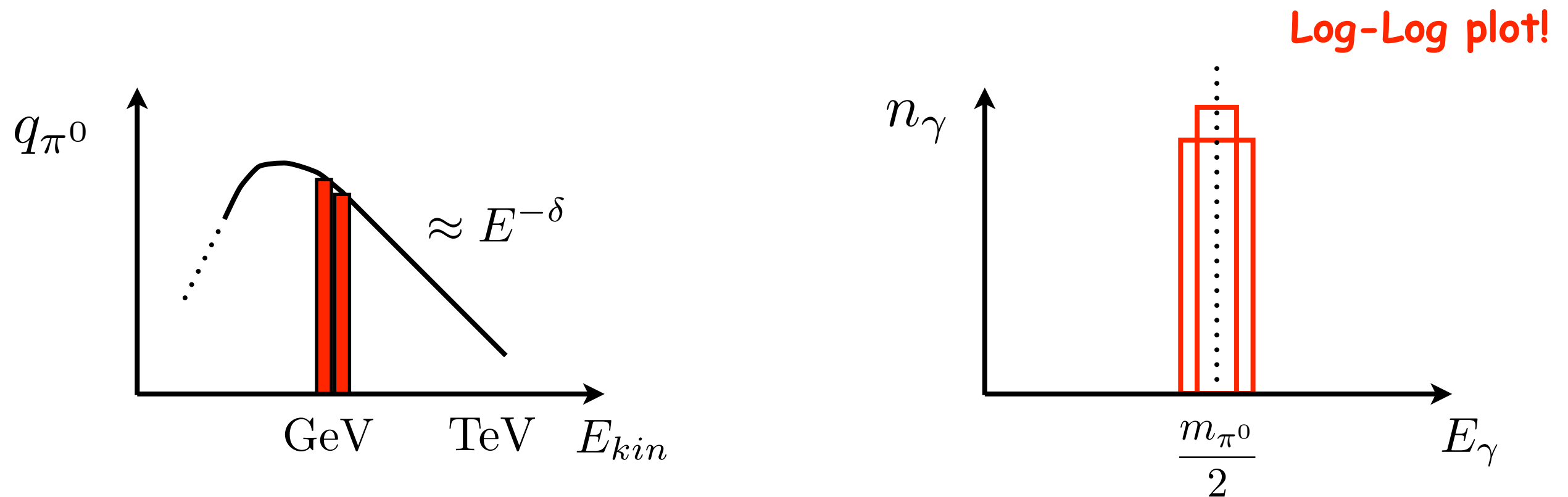
Gamma-Ray Astronomy: p-p interactions

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



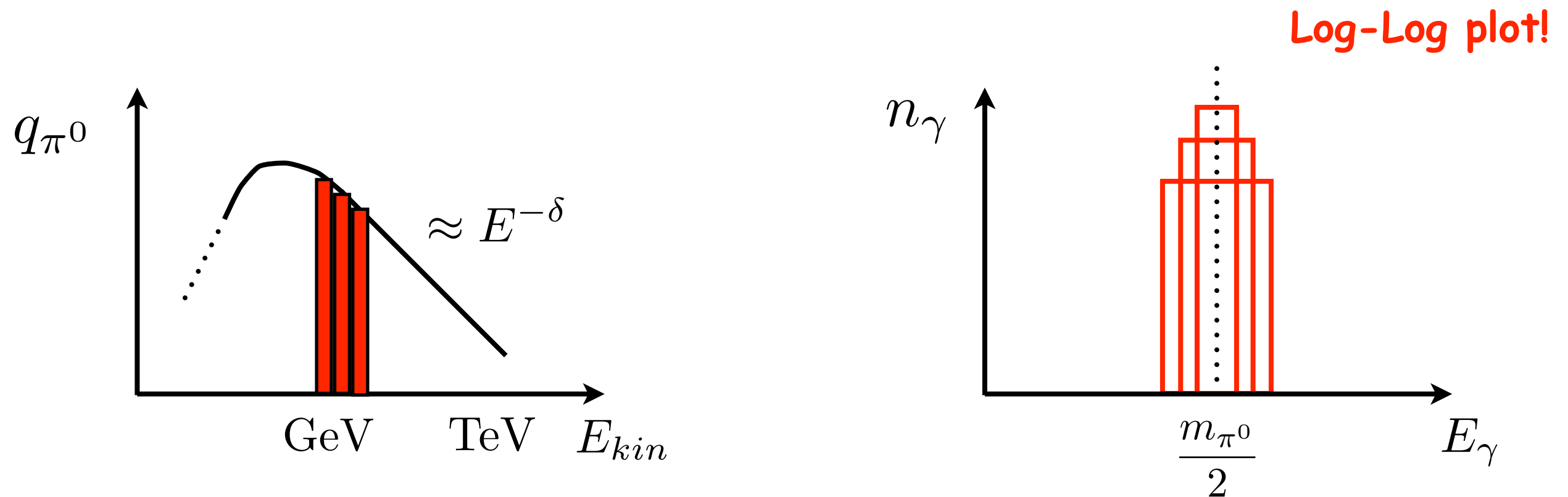
Gamma-Ray Astronomy: p-p interactions

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



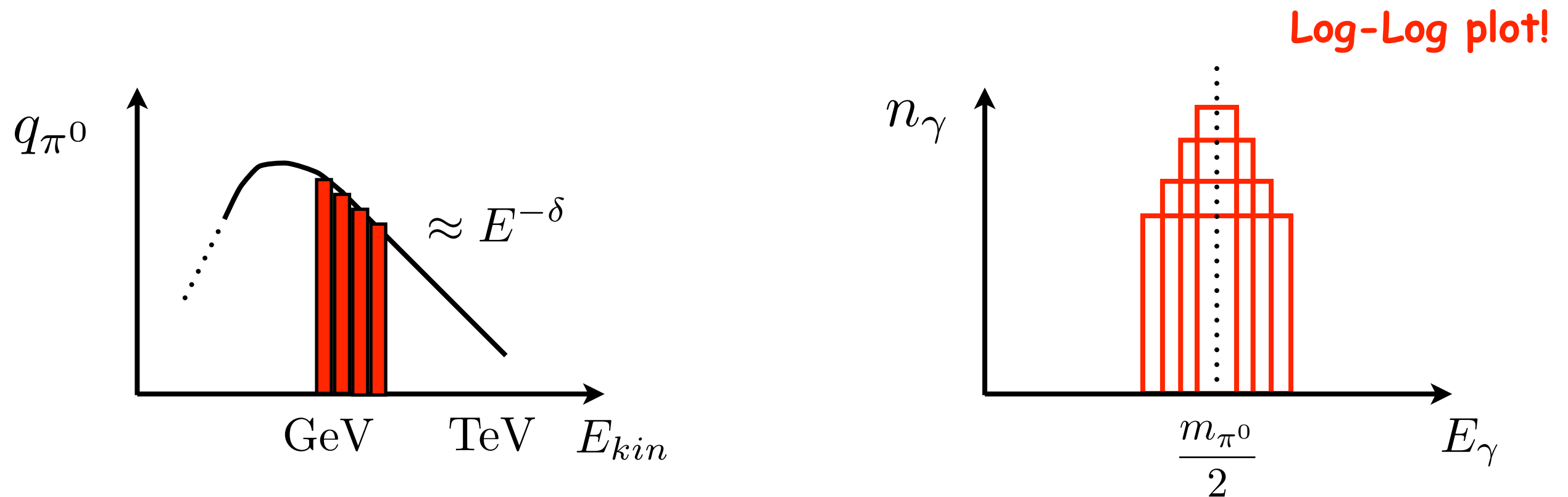
Gamma-Ray Astronomy: p-p interactions

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



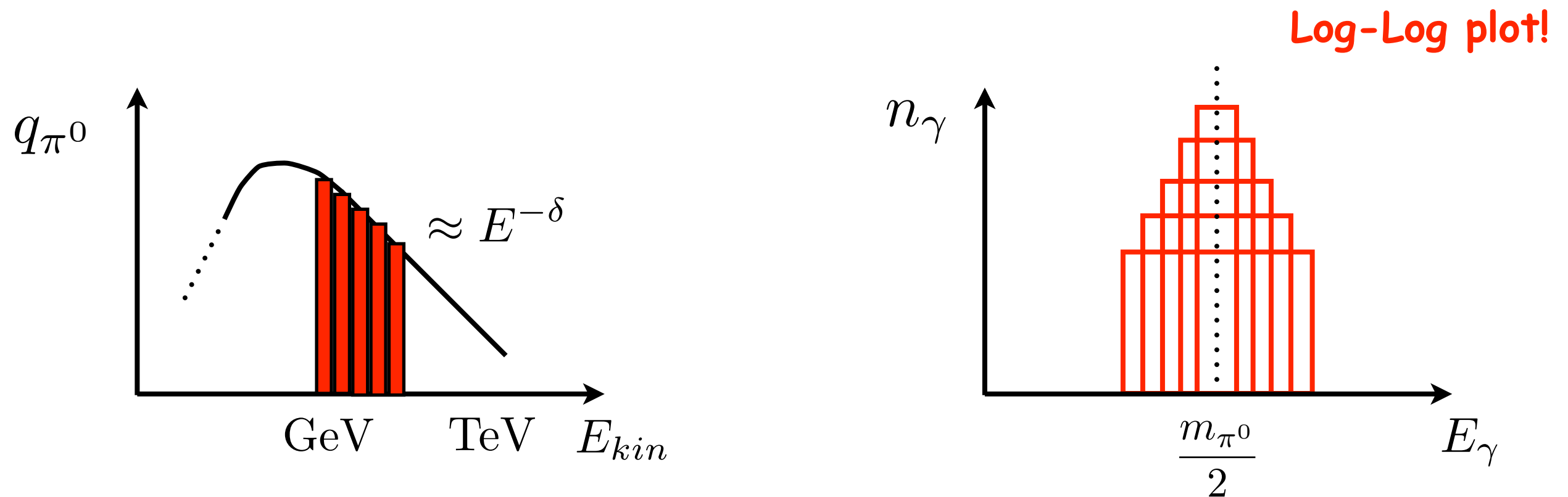
Gamma-Ray Astronomy: p-p interactions

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



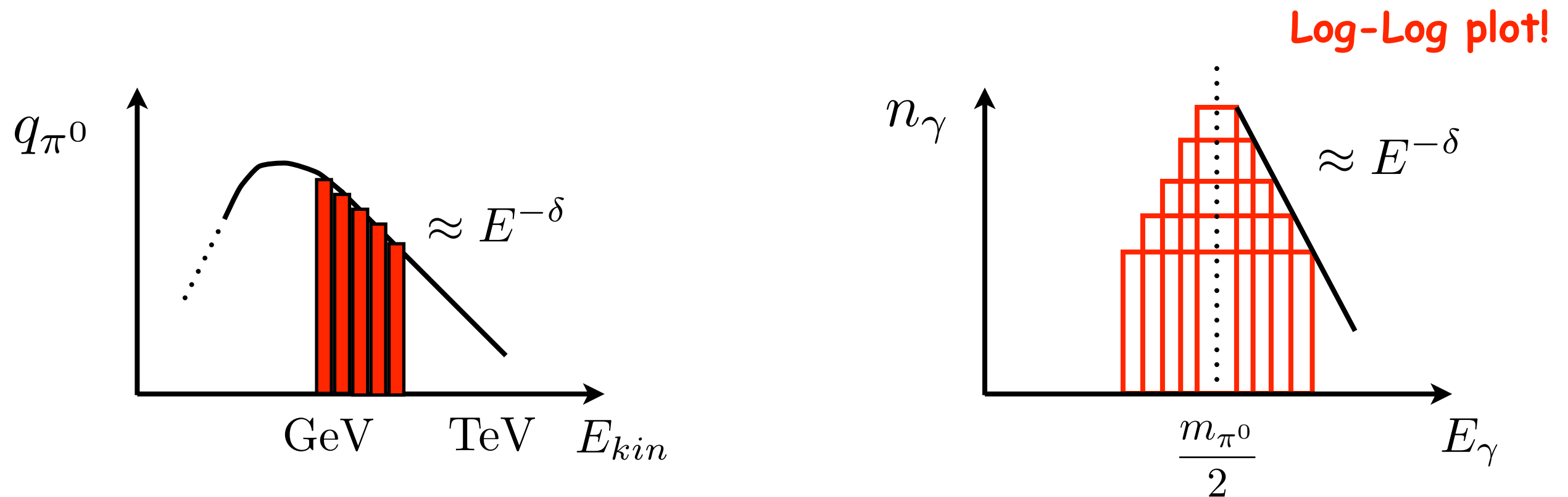
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Let's now calculate the spectrum of photons from pion decay - III



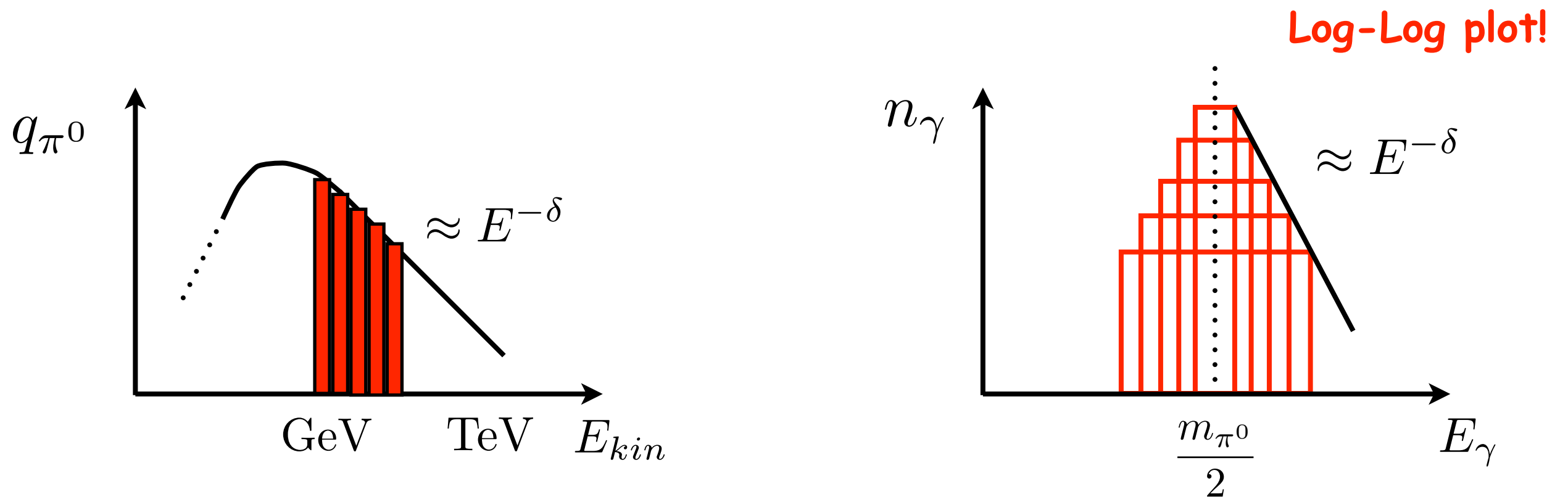
Gamma-Ray Astronomy: p-p interactions

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



Gamma-Ray Astronomy: p-p interactions

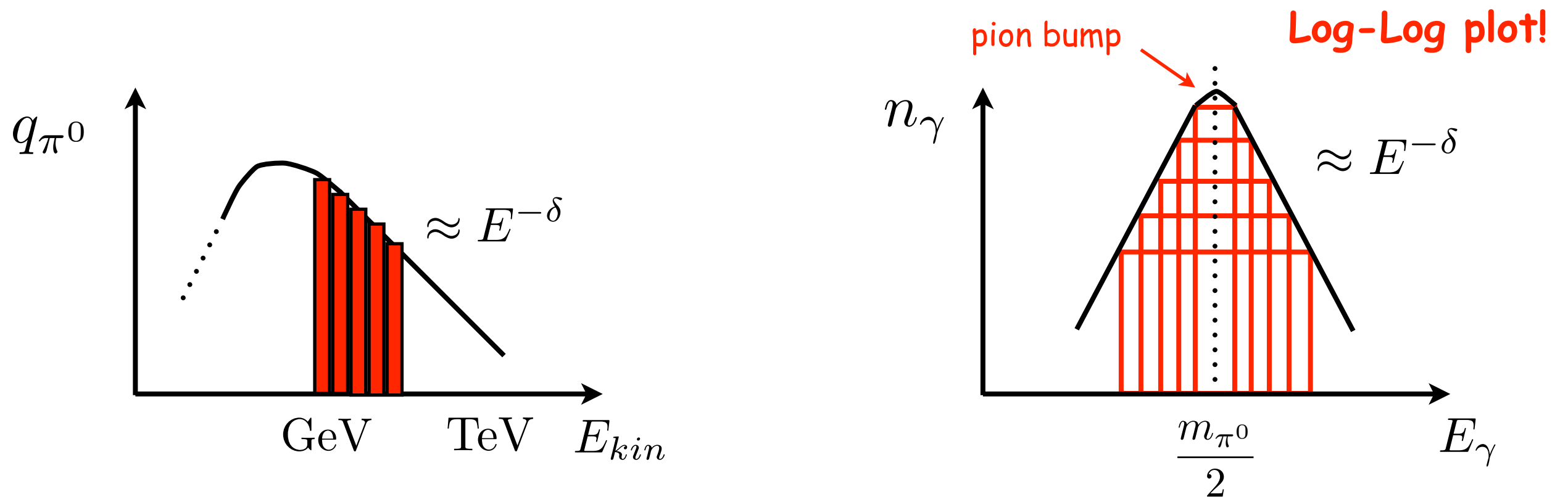
Let's now calculate the spectrum of photons from pion decay - III



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

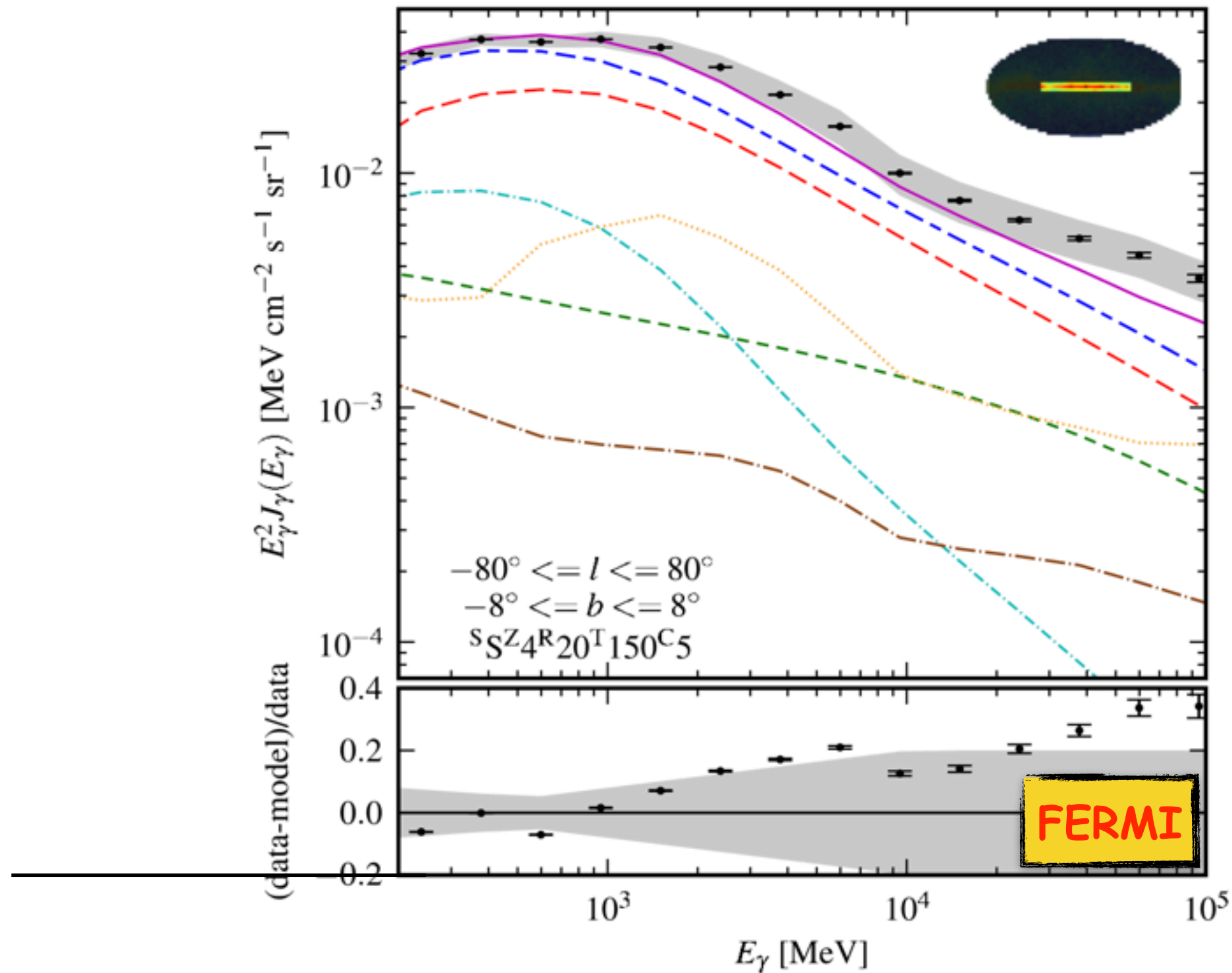
Gamma-Ray Astronomy: p-p interactions

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

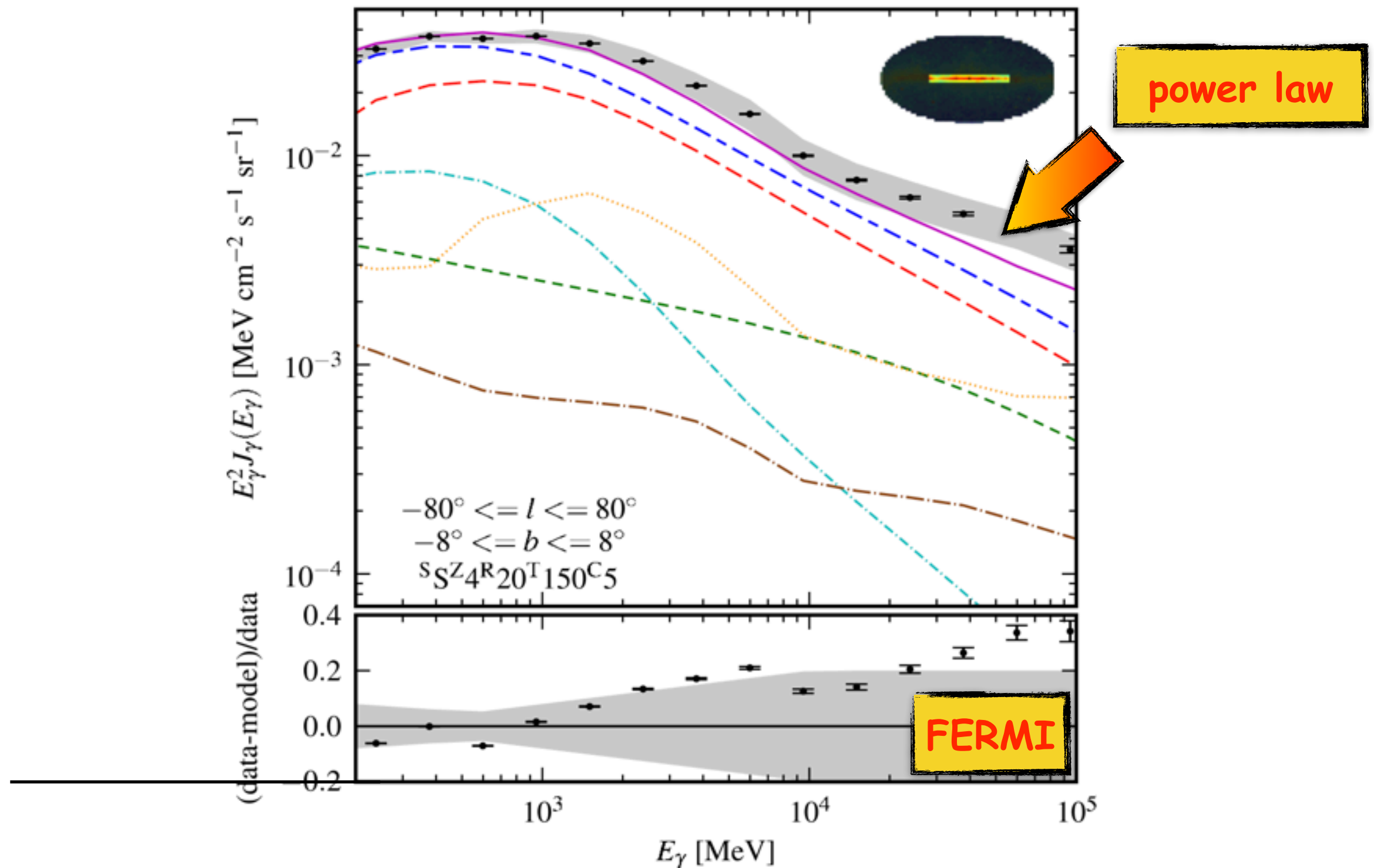


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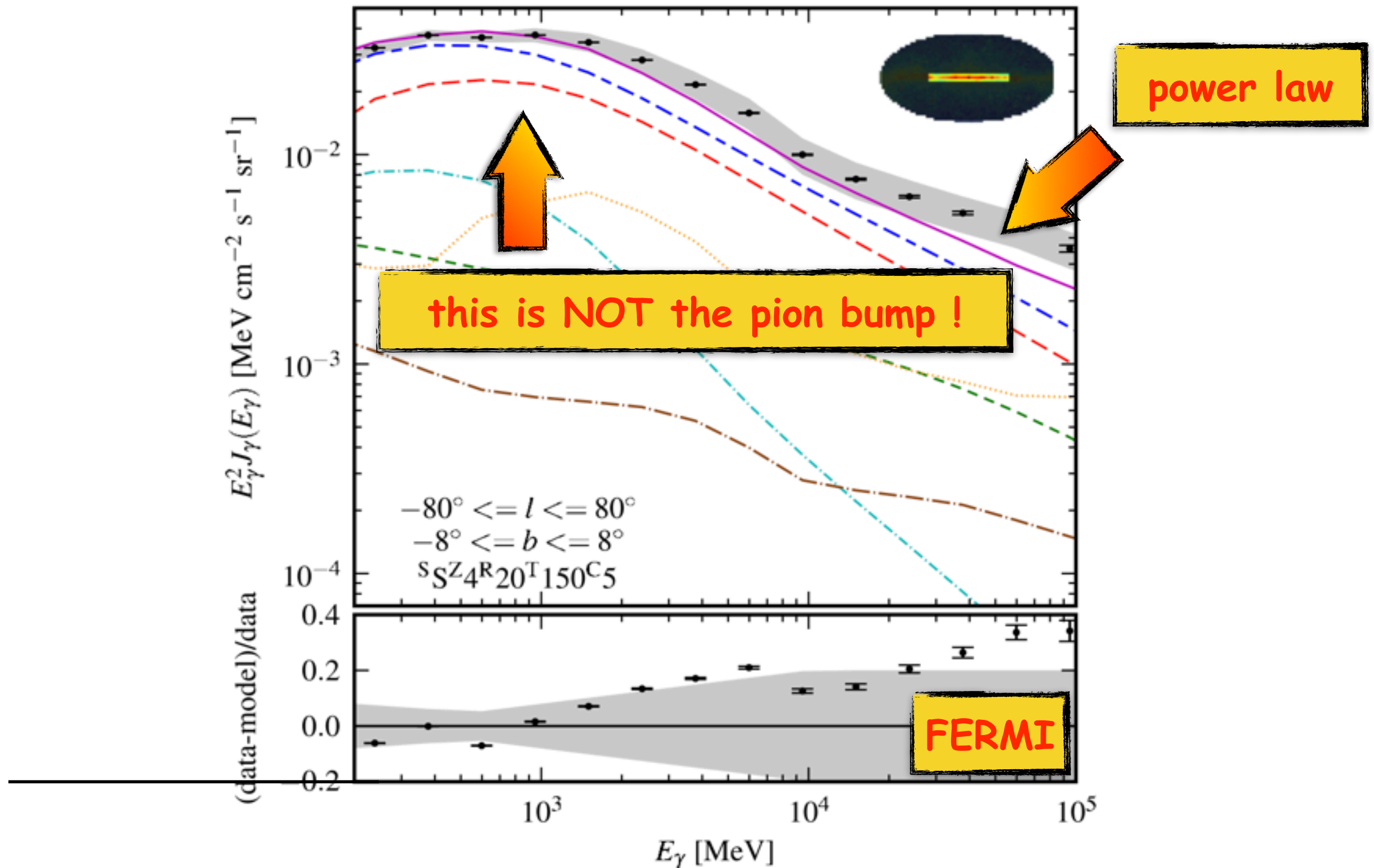
Diffuse emission from the inner Galaxy



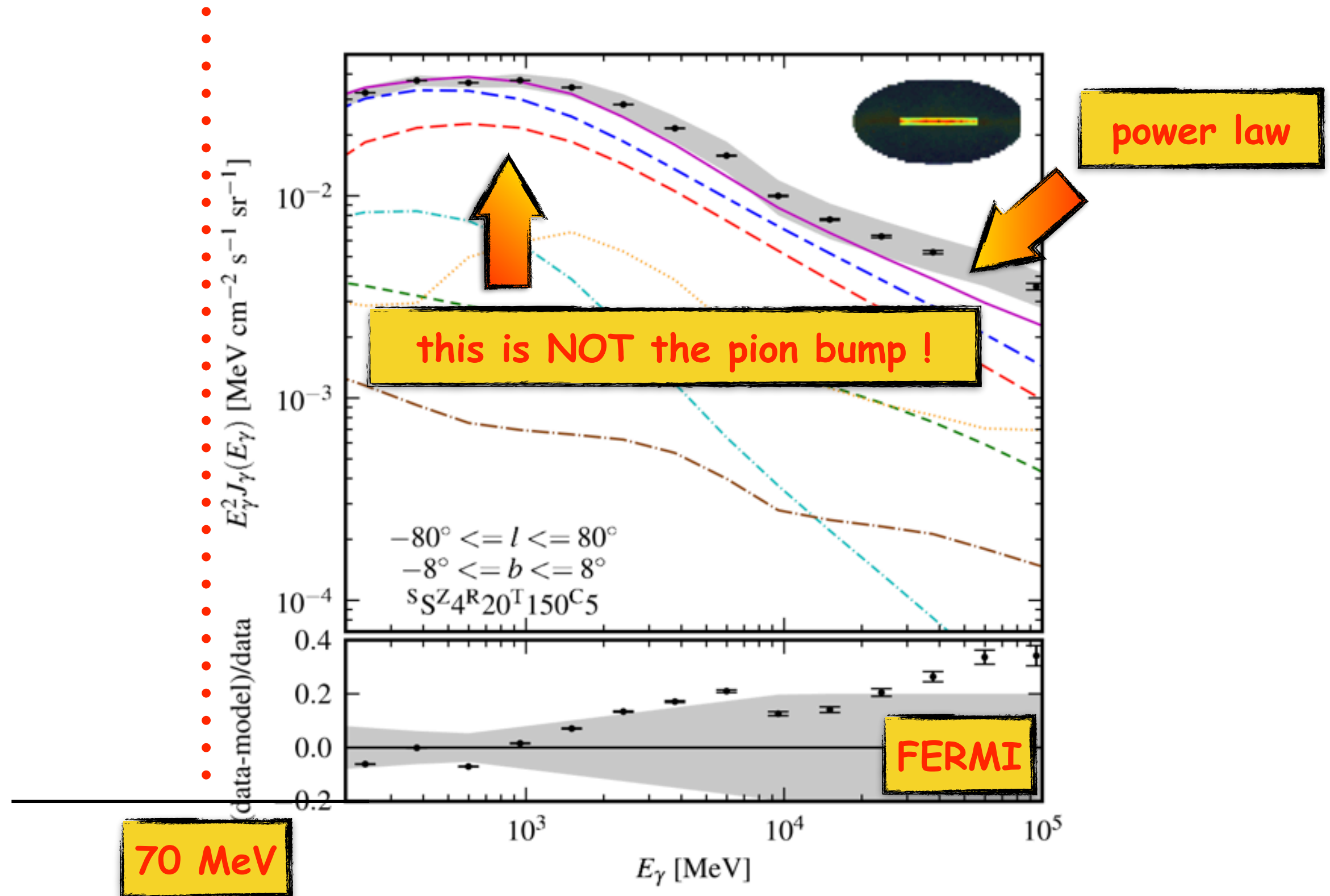
Diffuse emission from the inner Galaxy



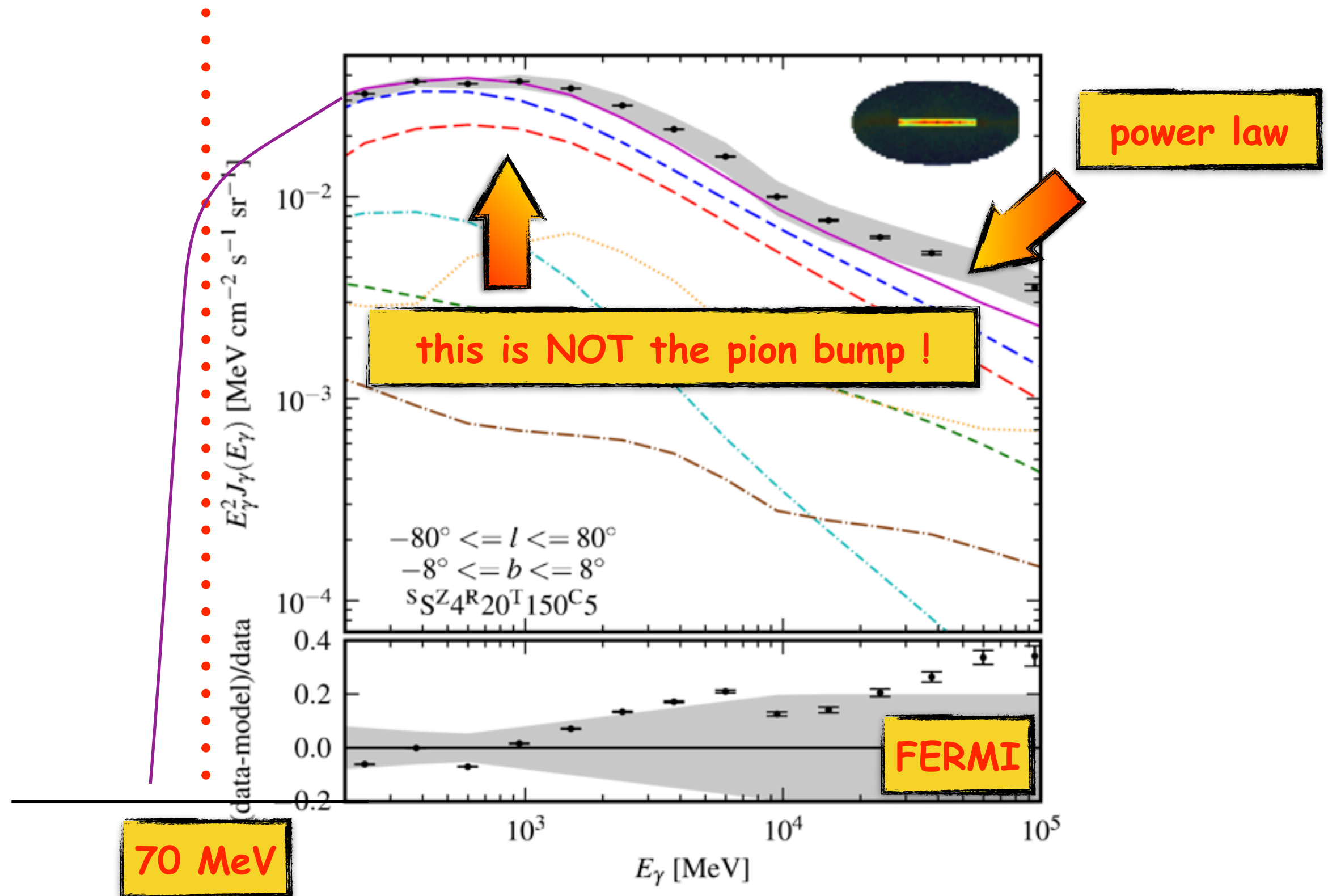
Diffuse emission from the inner Galaxy



Diffuse emission from the inner Galaxy



Diffuse emission from the inner Galaxy



Not only gammas: neutrinos & electrons

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

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

Not only gammas: neutrinos & electrons

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

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

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

Not only gammas: neutrinos & electrons

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

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

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

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

Not only gammas: neutrinos & electrons

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

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

Not only gammas: neutrinos & electrons

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

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

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

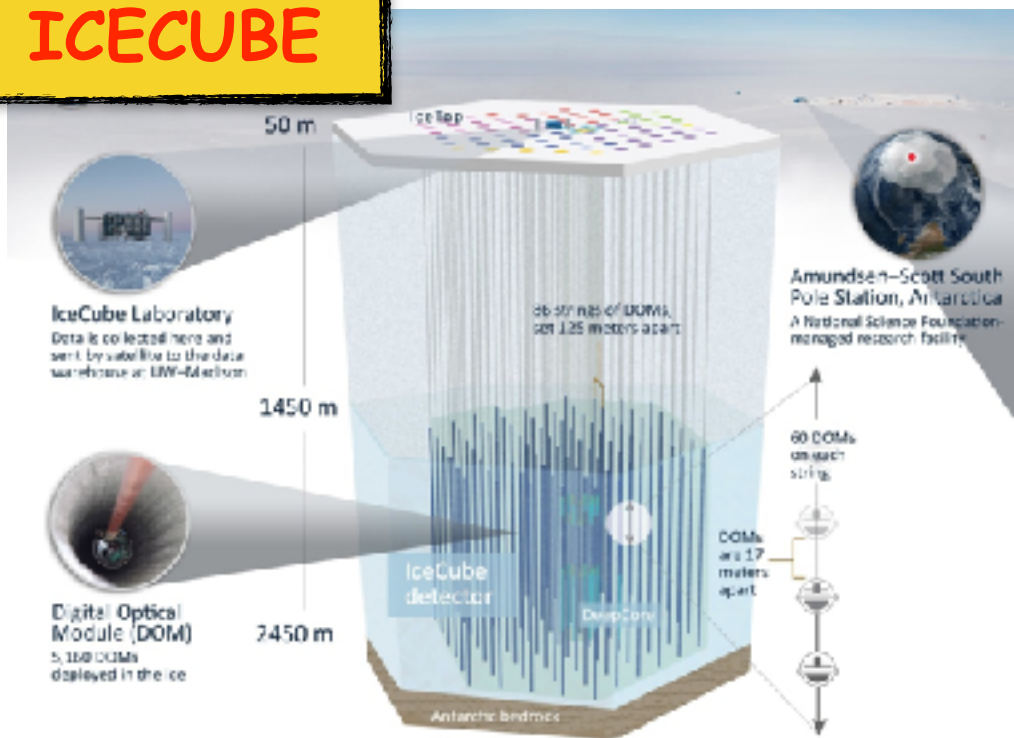
$$\pi^0 \rightarrow \gamma + \gamma$$

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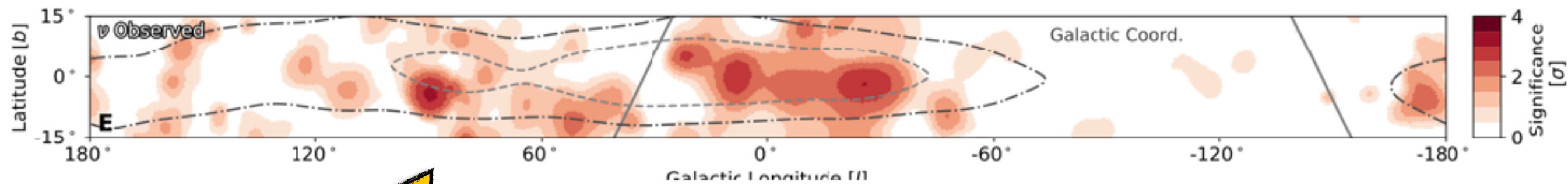
$$E_e \approx E_\nu \approx \frac{E_p}{20}$$

ICECUBE

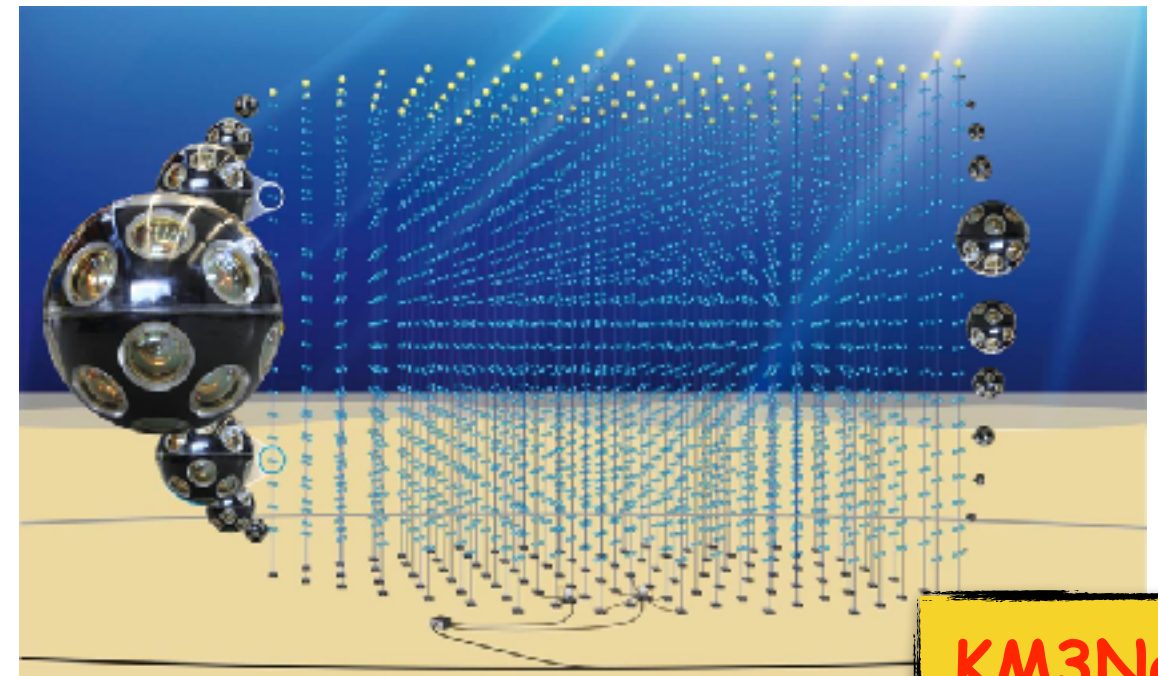


Neutrino telescopes

Baikal



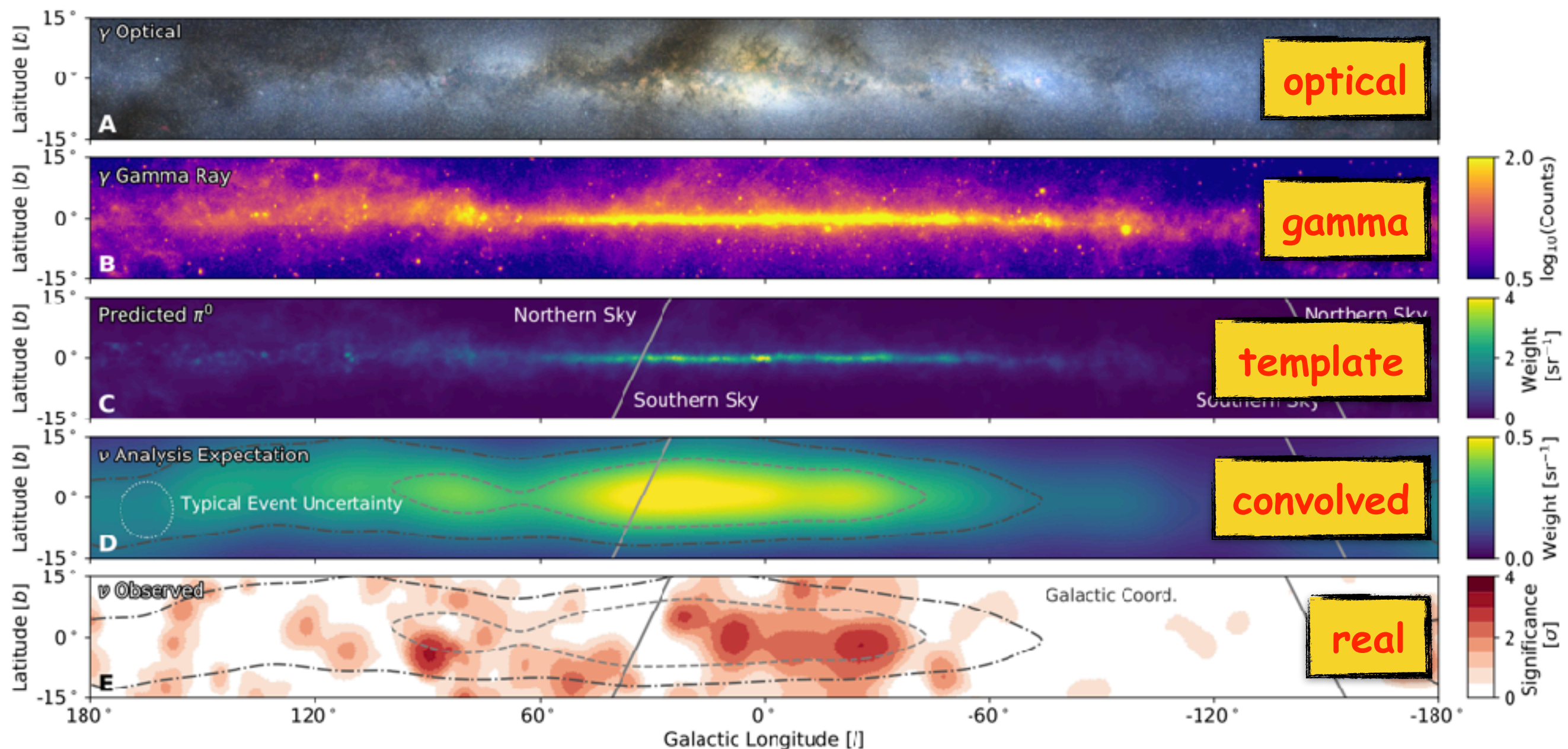
diffuse emission
from Galactic plane!



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

valid at large energies

number of protons of
energy E_p produced per s

$$Q_p(E_p) E_p^2$$

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

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

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

$$\eta_\pi Q_p(E_p) E_p^2$$

power (energy
per unit time)

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

$$\longrightarrow \frac{\tau_{res}}{\tau_{pp}}$$

$$\tau_{pp} \gg \tau_{res}$$

$$\longrightarrow 1$$

$$\tau_{pp} \ll \tau_{res}$$

Simple order-of-magnitude calculations

gamma rays

valid at large energies

fraction of the energy converted into pions... $\rightarrow$

number of protons of energy E_p produced per s $\rightarrow$

...and into gamma rays (1/3 $\rightarrow$ π^0) $\rightarrow$

power (energy per unit time) $\rightarrow$

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

$$\eta_\pi = 1 - e^{-\left(\frac{\tau_{res}}{\tau_{pp}}\right)} \quad \begin{array}{l} \longrightarrow \frac{\tau_{res}}{\tau_{pp}} \quad \tau_{pp} \gg \tau_{res} \\ \longrightarrow 1 \quad \tau_{pp} \ll \tau_{res} \end{array}$$

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

$$Q_\gamma(E_\gamma)E_\gamma^2 = f_\gamma \eta_\pi Q_p(E_p)E_p^2$$

...and into gamma rays (1/3 $\rightarrow \pi^0$)

power (energy per unit time)

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

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...and into gamma rays (1/3 $\rightarrow \pi^0$)

power (energy per unit time)

$E_\gamma \sim E_p/10$

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

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

Simple order-of-magnitude calculations

neutrinos

valid at large energies

The same as for gammas but:

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

fraction of
charged pions

fraction of
pion energy $\rightarrow$
neutrinos

per flavour (after
oscillations)

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

Simple order-of-magnitude calculations

valid at large energies

gamma rays

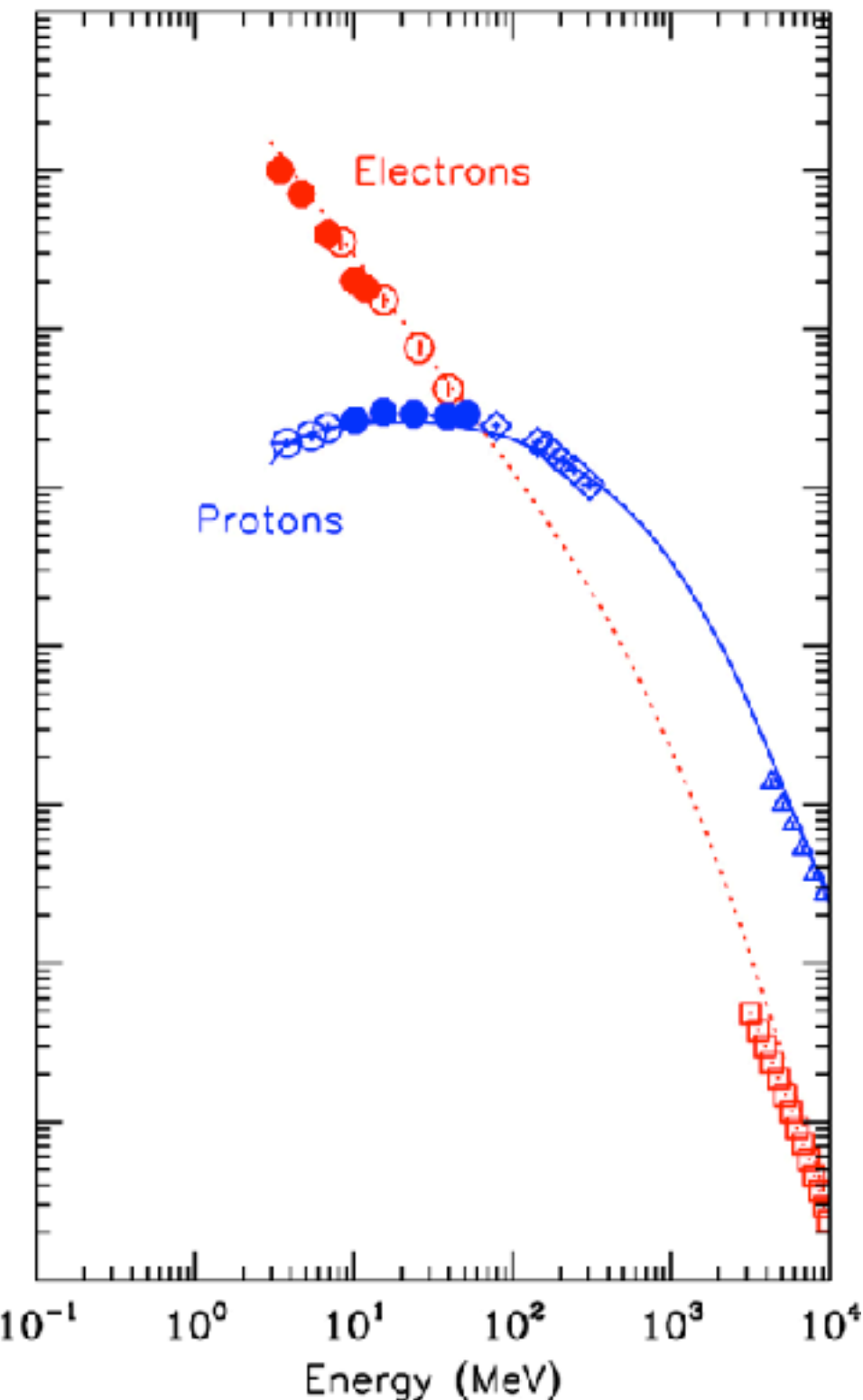
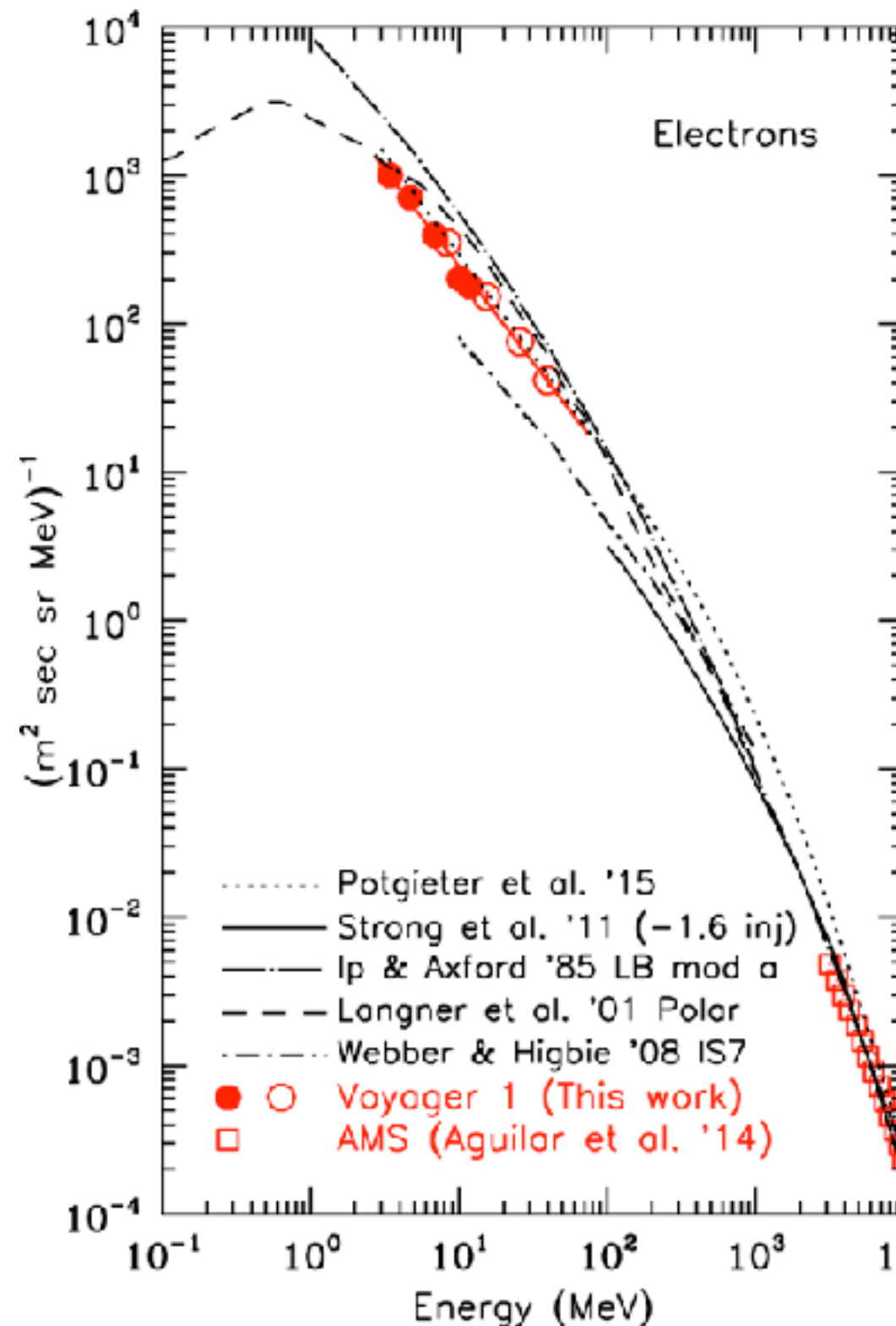
$$Q_{\gamma}(E_{\gamma})E_{\gamma}^2 = \frac{\eta_{\pi}}{3} Q_p(E_p)E_p^2$$

neutrinos
(per flavour)

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

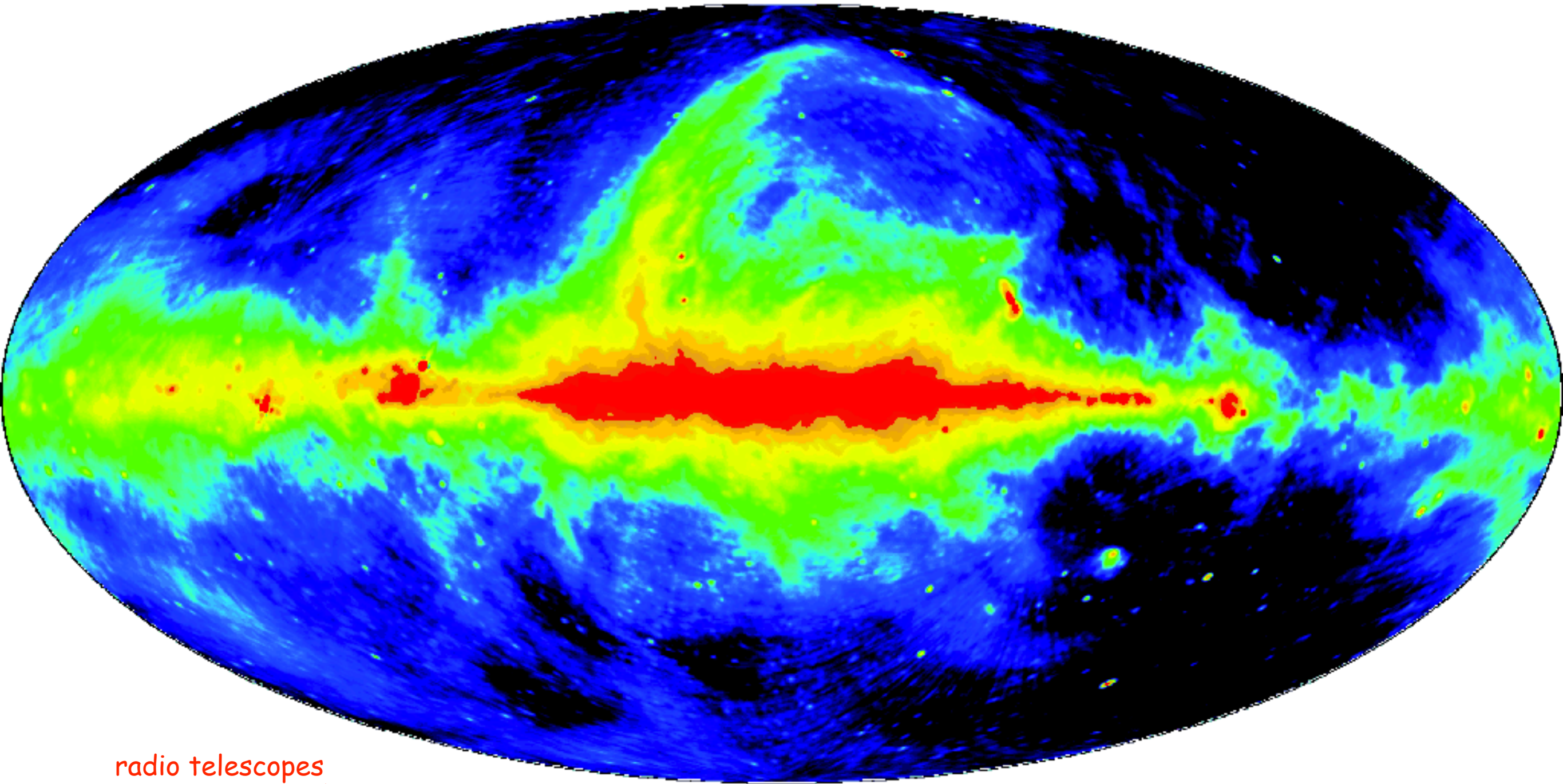
What about electrons?

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



Synchrotron emission from the Milky Way

radio domain $\longrightarrow$ 408 MHz



radio telescopes

$\longrightarrow$ Jodrell-Bank 250-ft + Effelsberg 100-m + Parkes 64-m

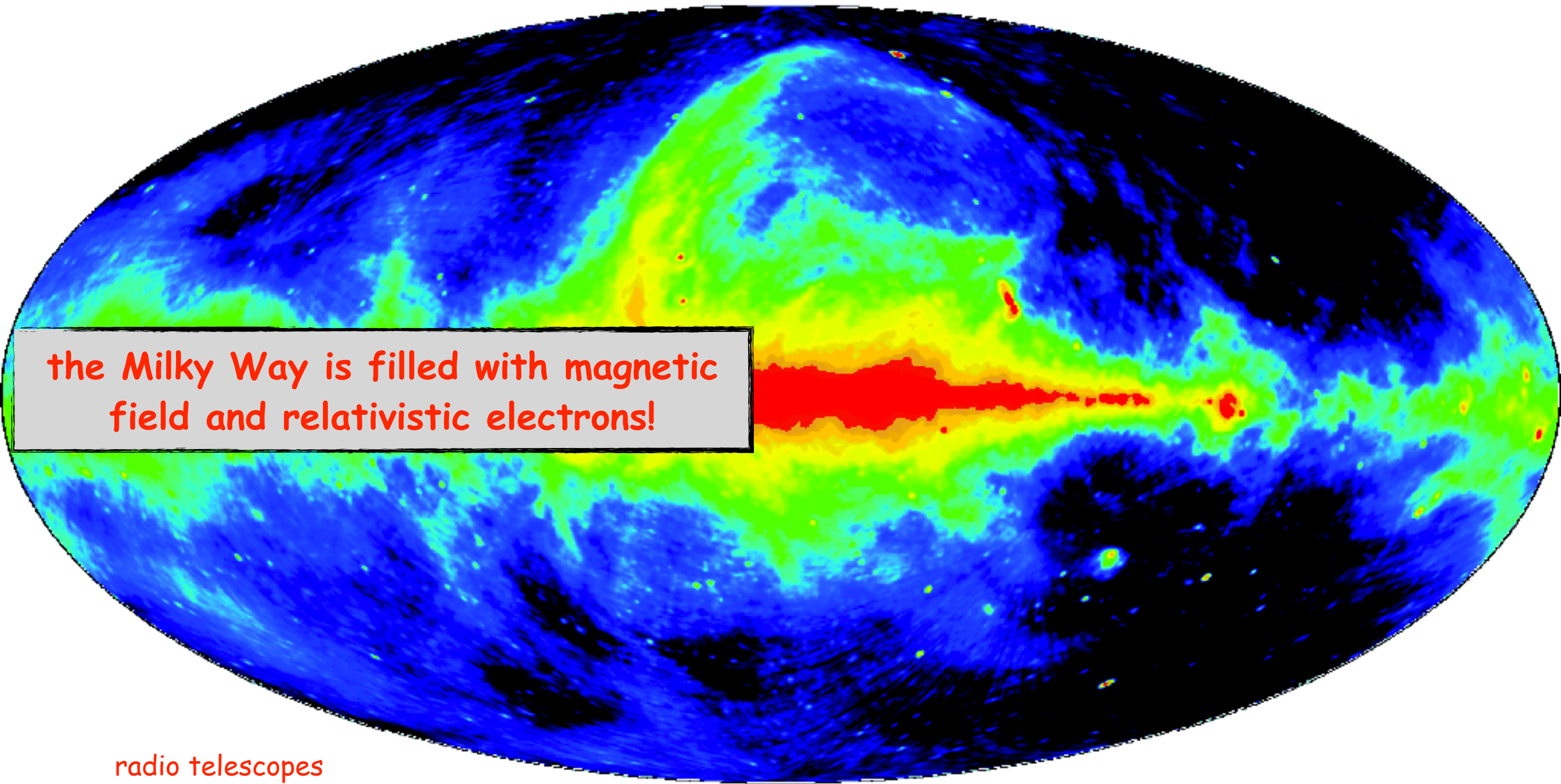
Synchrotron emission from the Milky Way

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the Milky Way is filled with magnetic field and relativistic electrons!

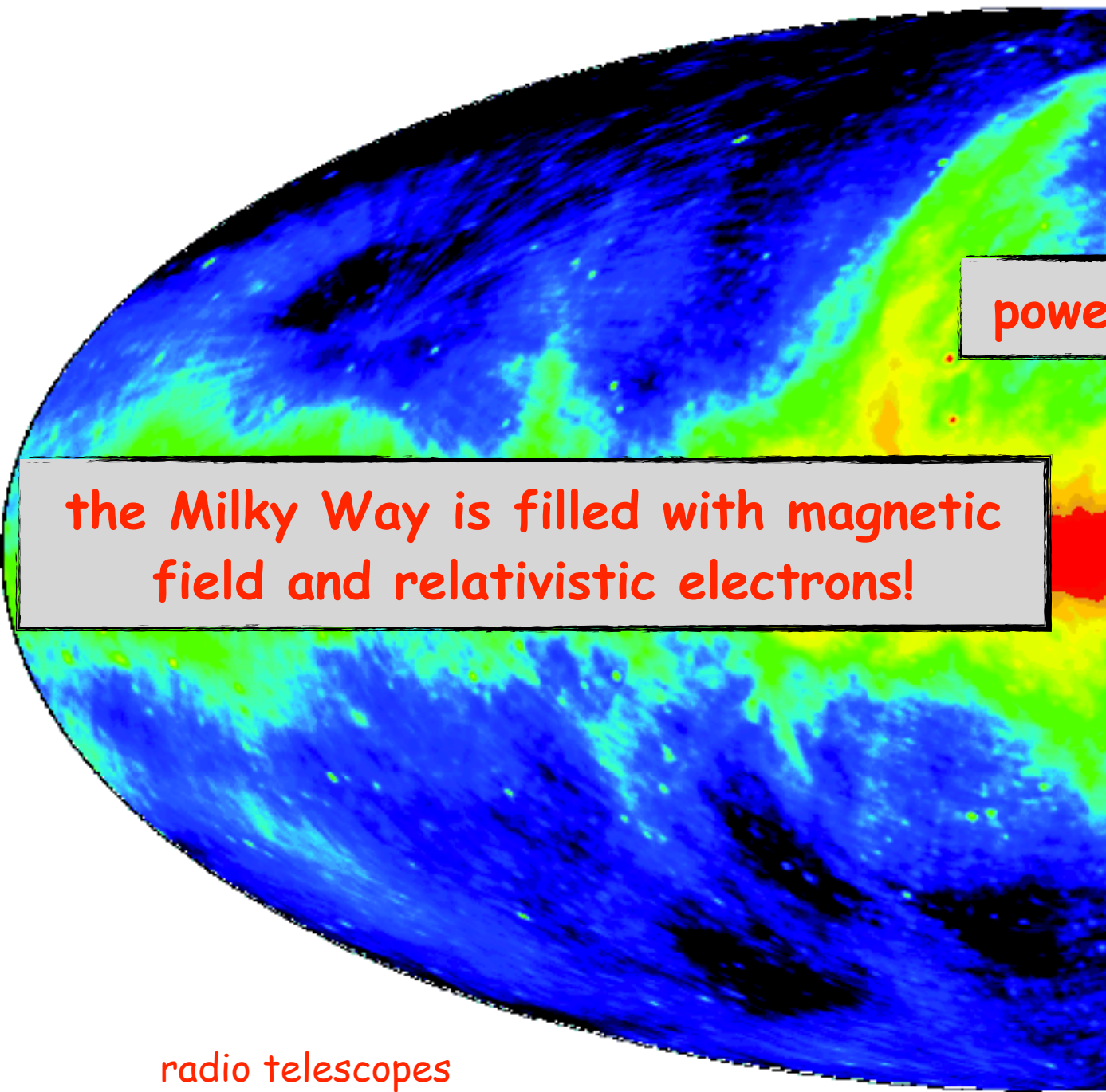
radio telescopes

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



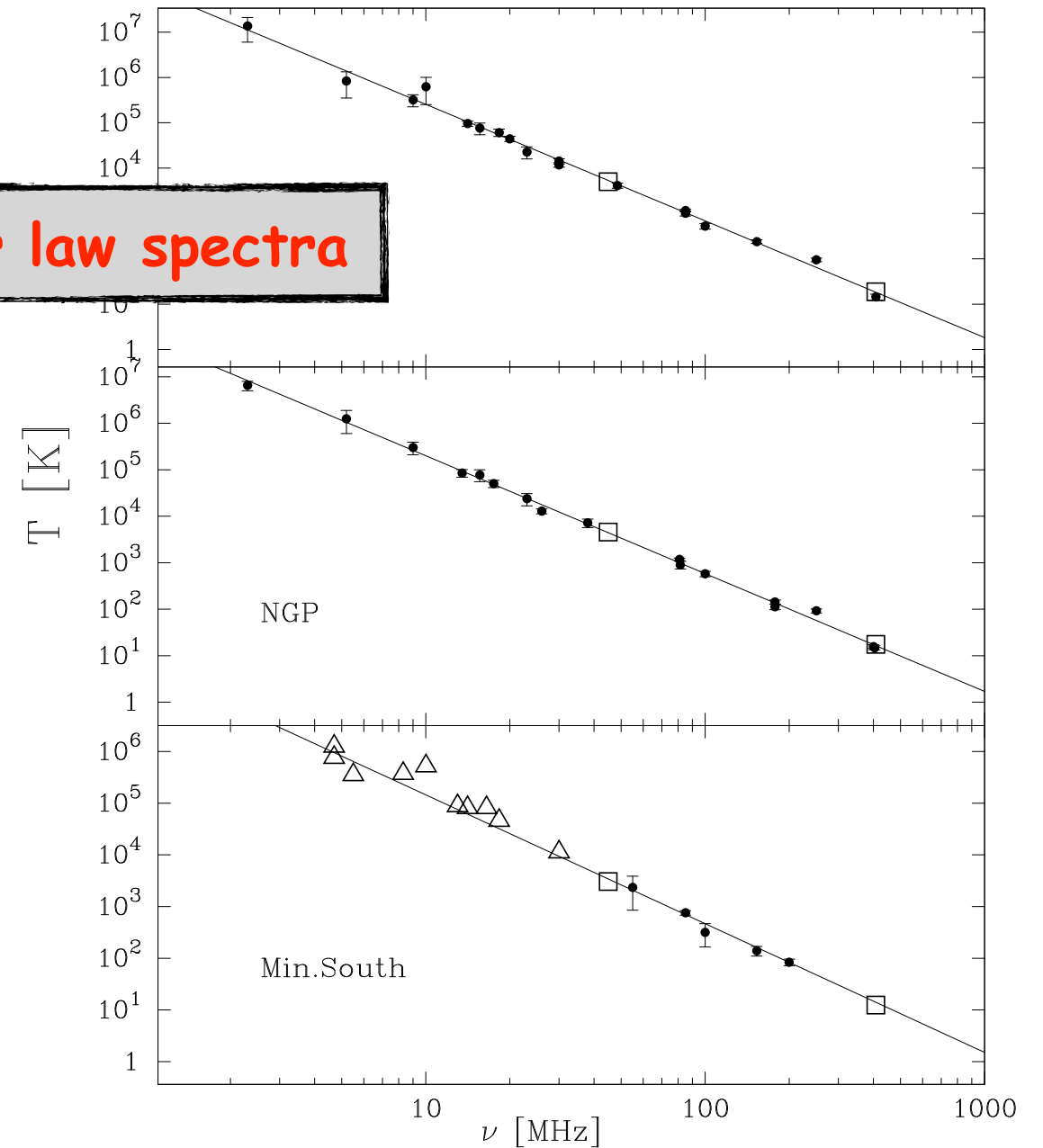
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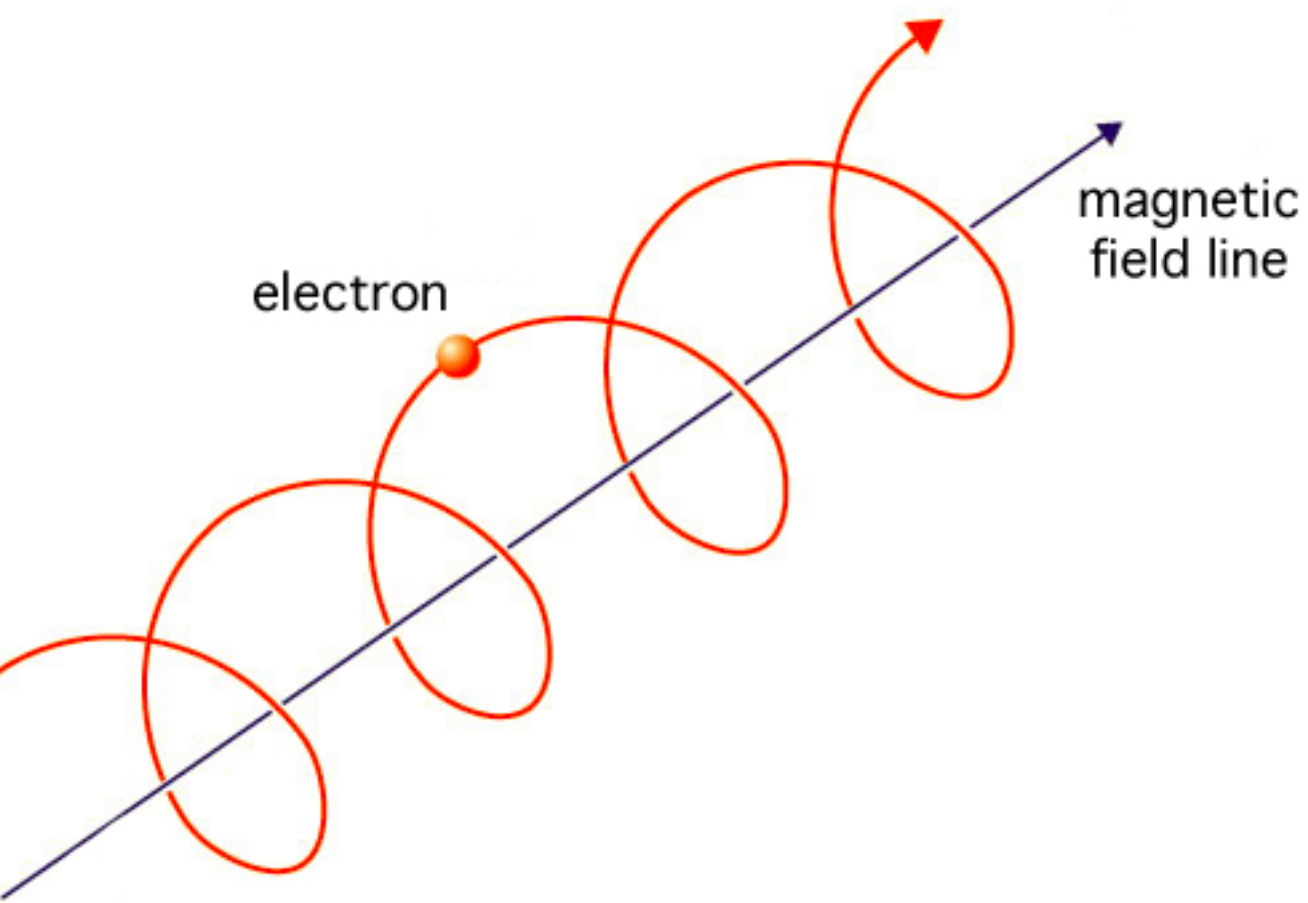
power law spectra



radio telescopes

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

Motion of a particle in a magnetic field

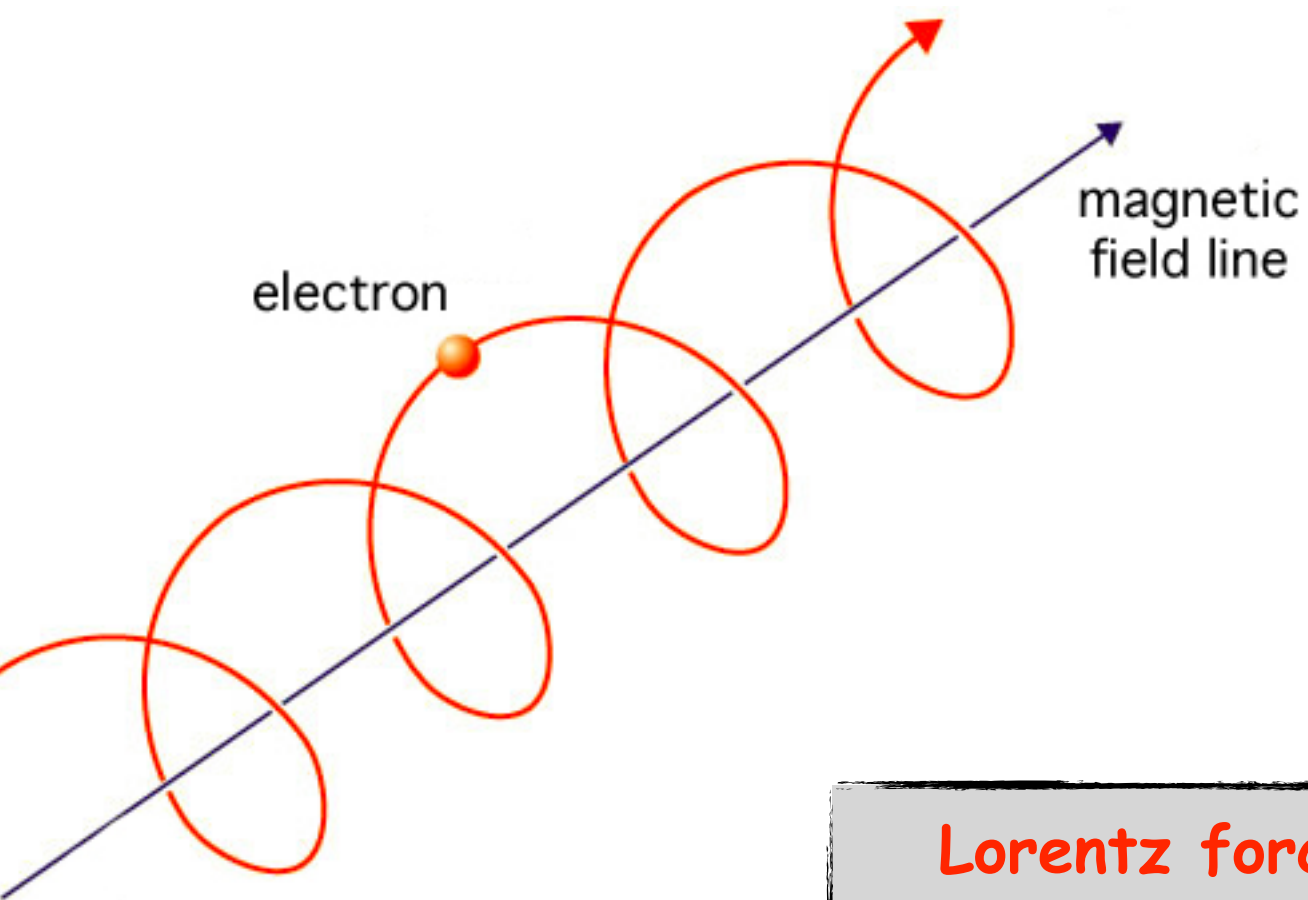


$$\mu = \cos \vartheta$$

pitch angle = angle between v and B

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

Motion of a particle in a magnetic field



$$\mu = \cos \vartheta$$

pitch angle = angle between $\mathbf{v}$ and $\mathbf{B}$

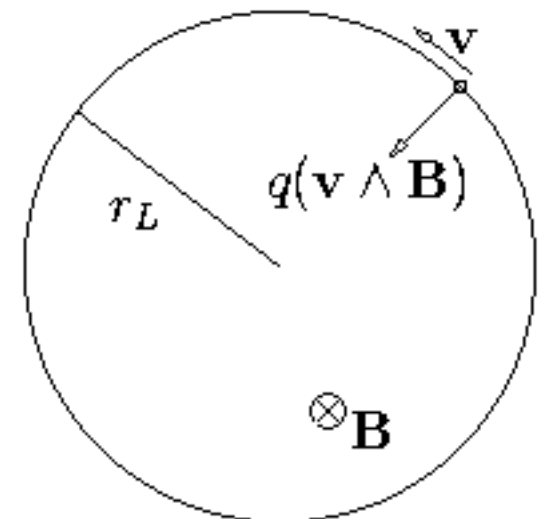
$$\begin{cases} v_{\parallel} &= \mu v \\ v_{\perp} &= (1 - \mu^2)^{1/2} v \end{cases}$$

Lorentz force

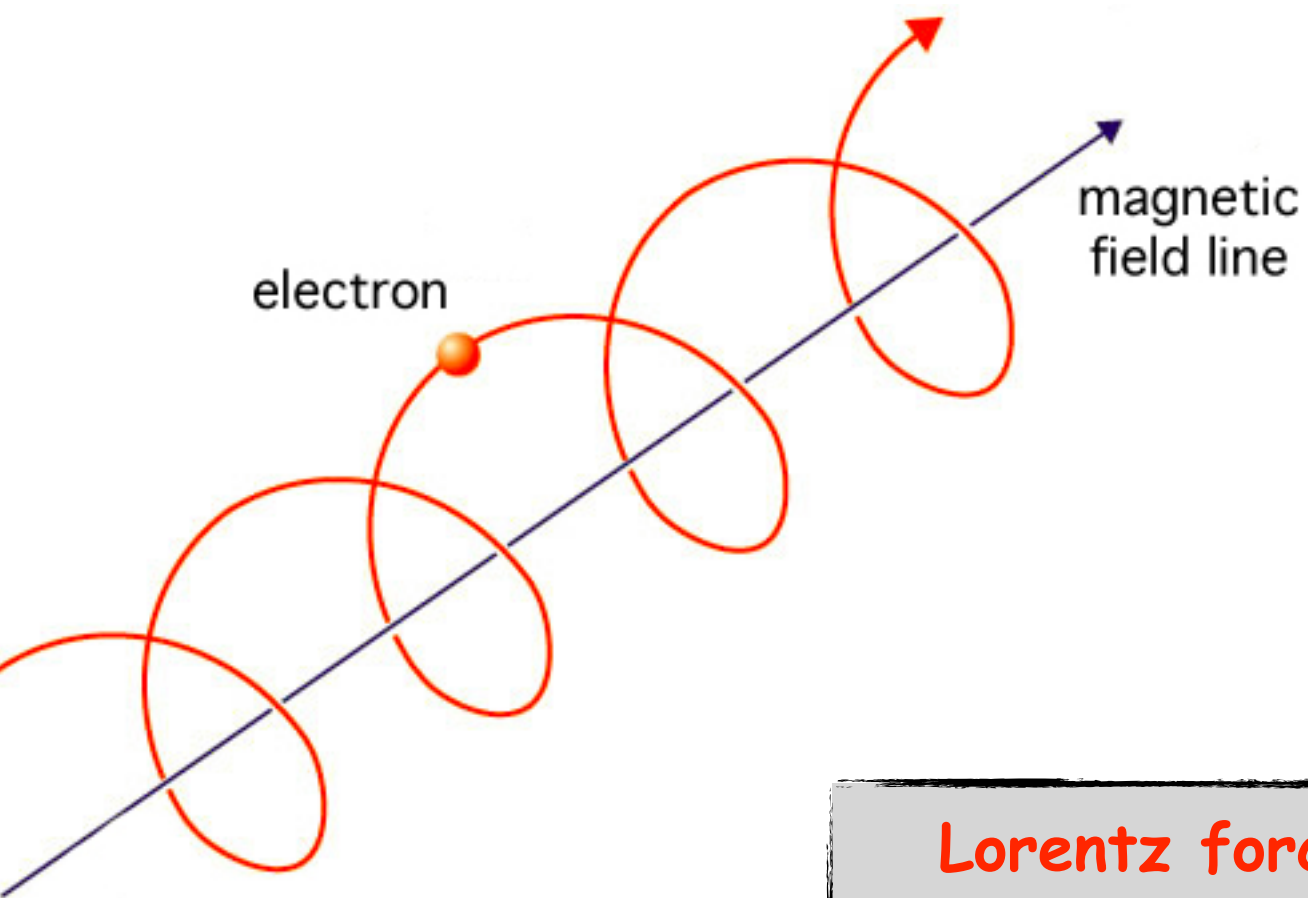
$$\mathbf{F}_L = \frac{q}{c} \vec{v} \times \vec{B}$$

Larmor radius

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



Motion of a particle in a magnetic field



$$\mu = \cos \vartheta$$

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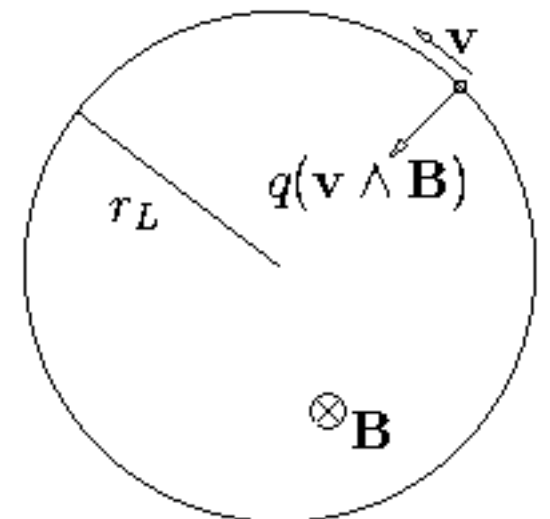
Larmor radius

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

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*

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

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

Power emitted by an electron*

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

Lorentz force is orthogonal to v

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Power emitted by an electron*

non-relativistic

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relativistic

Lorentz force is orthogonal to v

$$F_L = F_{L,\perp} = \frac{ev_{\perp}B}{c} \equiv \gamma m \frac{dv_{\perp}}{dt} \longrightarrow a_{\perp} = \frac{ev_{\perp}B}{\gamma mc}$$

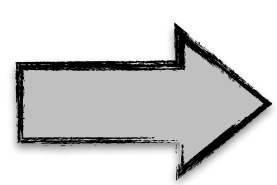
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$$P = \frac{4}{3} \sigma_T c U_B \gamma^2$$

■ Thomson cross section

$$\sigma_T = \frac{8\pi}{3} \left(\frac{e^2}{mc^2} \right)^2 = 6.65 \times 10^{-25} \text{cm}^2$$

■ magnetic field energy density

$$U_B = B^2 / 8\pi$$

■ ultra relativistic electrons

$$\beta \longrightarrow 1$$

■ isotropic distribution of particles

$$\langle \sin^2 \vartheta \rangle = 2/3$$

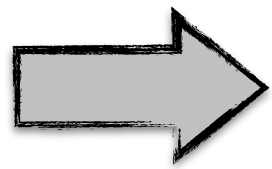
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Lorentz force is orthogonal to v

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Characteristic frequency

as done for Bremsstrahlung: characteristic time $\longrightarrow$ characteristic frequency

gyration frequency?

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

Characteristic frequency

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Beaming

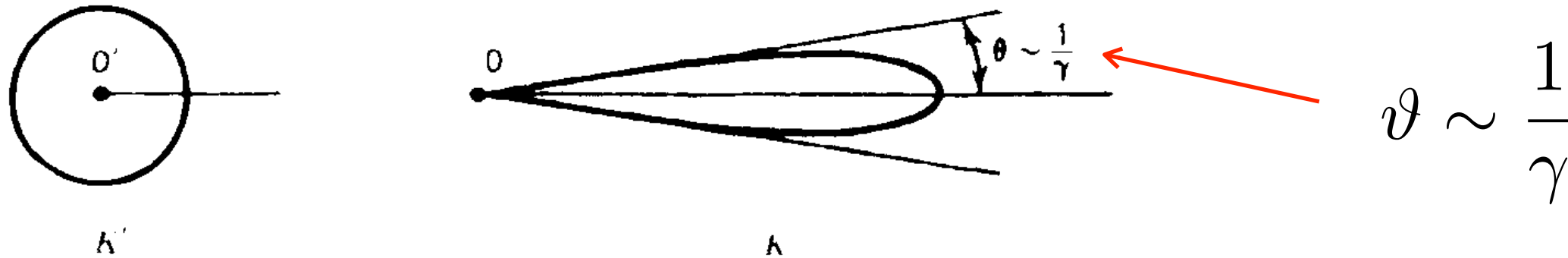


Figure 4.3 *Relativistic beaming of radiation emitted isotropically in the rest frame K' .*

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

Characteristic frequency

as done for Bremsstrahlung: characteristic time $\longrightarrow$ characteristic frequency

gyration frequency?

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

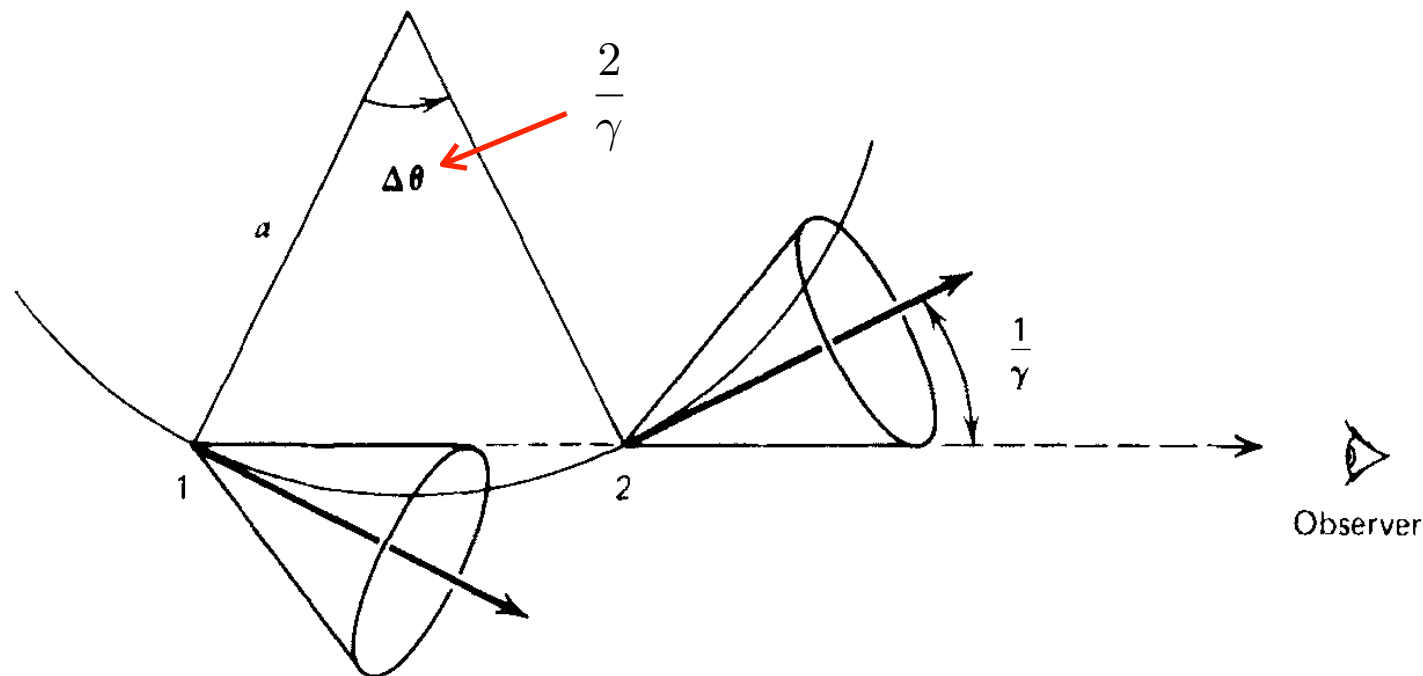


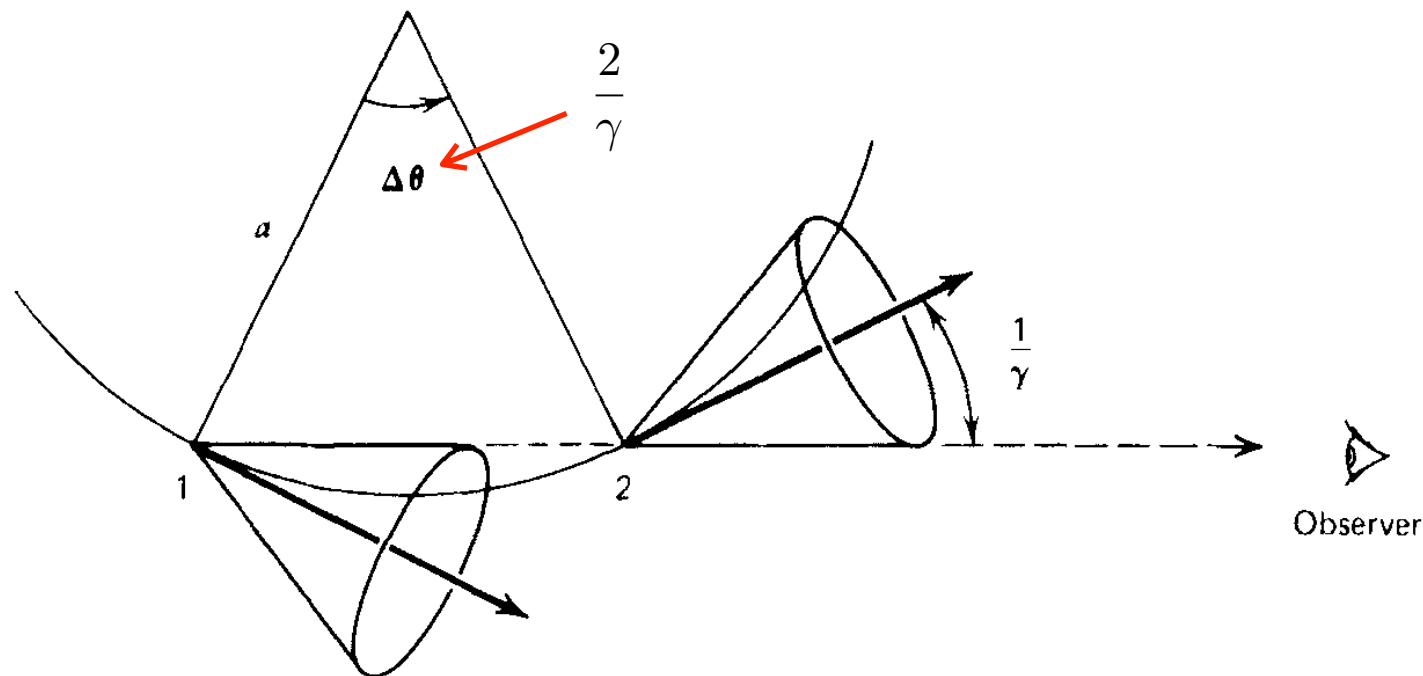
Figure 6.2 Emission cones at various points of an accelerated particle's trajectory.

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as done for Bremsstrahlung: characteristic time $\longrightarrow$ characteristic frequency

gyration frequency?

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



photons that reach us are emitted in the time interval:

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

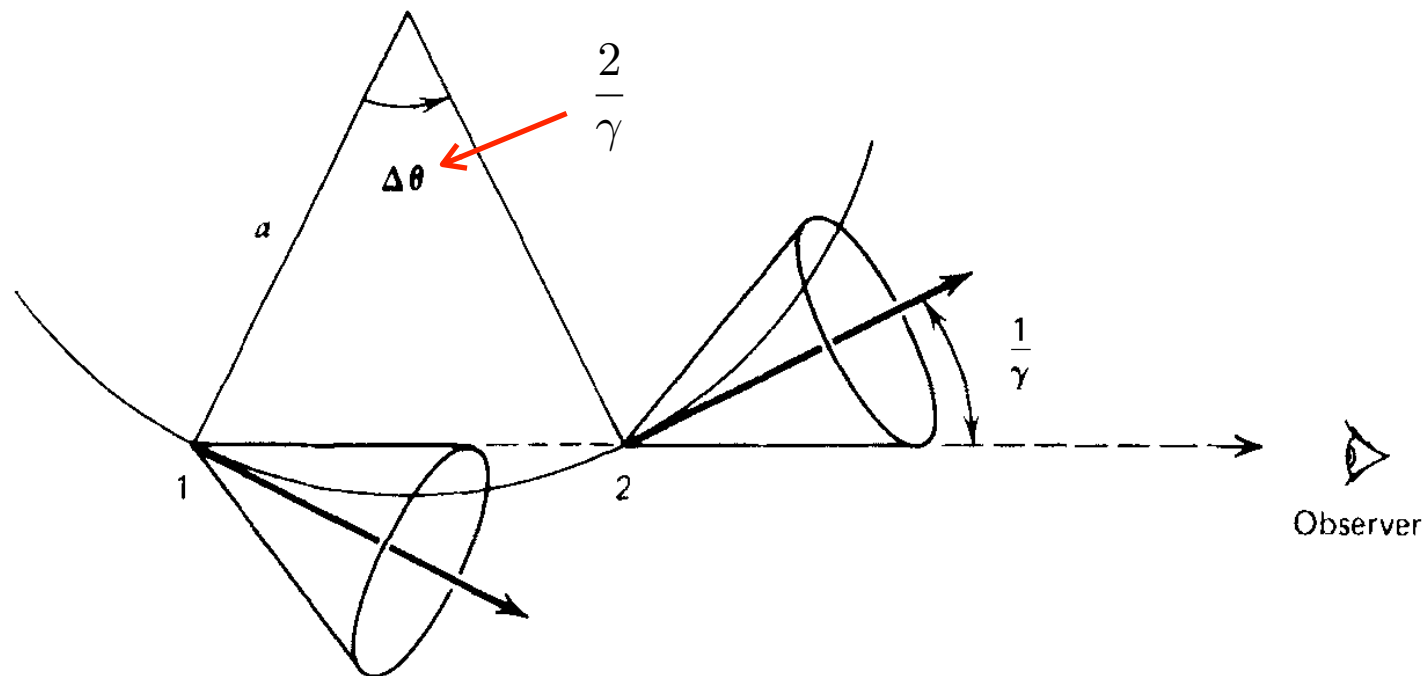
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photons that reach us are emitted in the time interval:

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

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

but the arrival time interval is shorter!

when a photon is emitted in 2, the photon emitted in 1 has traveled a distance: $c \Delta t_e$

Characteristic frequency

as done for Bremsstrahlung: characteristic time $\longrightarrow$ characteristic frequency

gyration frequency?

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

photons that reach us are emitted in the time interval:

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

but the arrival time interval is shorter!

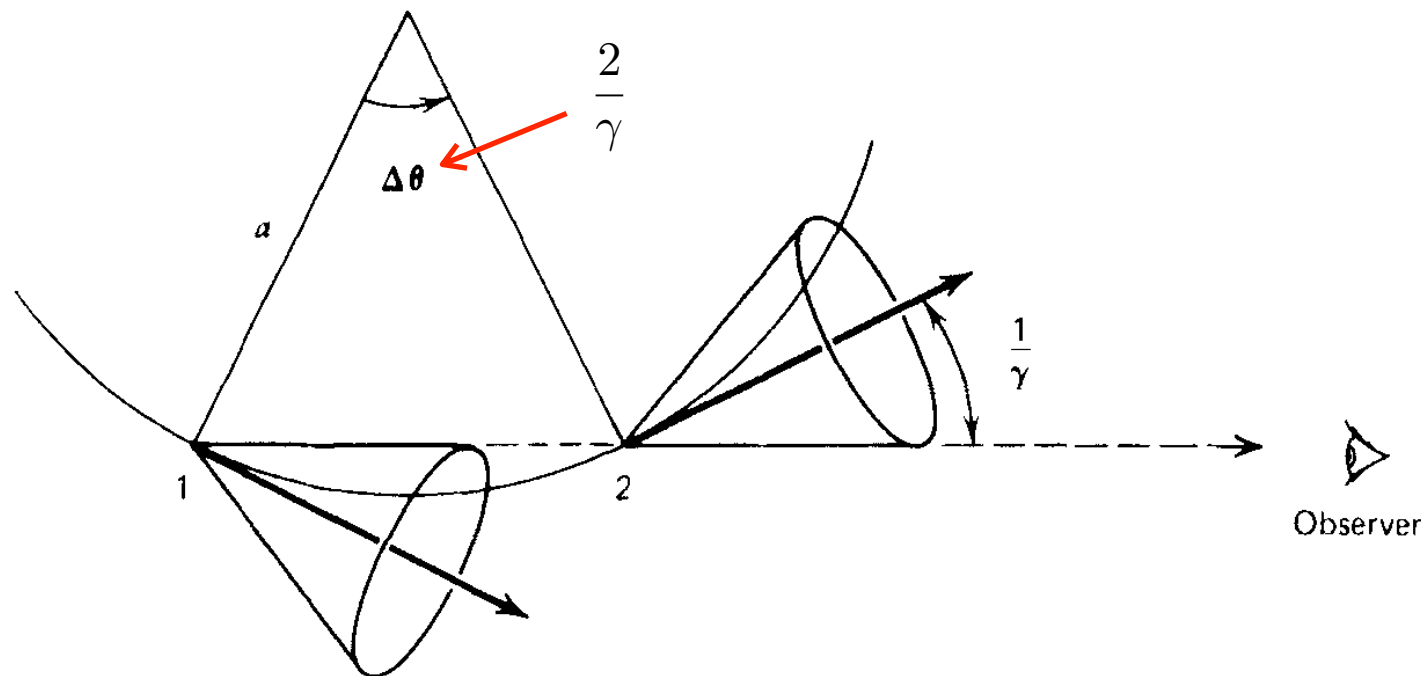


Figure 6.2 Emission cones at various points of an accelerated particle trajectory.

when a photon is emitted in 2, the photon emitted in 1 has traveled a distance: $c \Delta t_e$

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

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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power emitted by one electron

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

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in high energy astrophysics: POWER LAW

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

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delta function approximation

$$L_s(\nu) = \int d\gamma N(\gamma) P(\gamma, B) \delta(\nu - \nu_s(\gamma, B))$$

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

delta function approximation

POWER LAW

$$L_s(\nu) = \int d\gamma N(\gamma) P(\gamma, B) \delta(\nu - \nu_s(\gamma, B)) \propto K B^{\frac{\delta+1}{2}} \nu^{-\frac{\delta-1}{2}}$$

$$\delta(\nu - \nu_s(\gamma, B)) = \delta(f(\gamma)) = \frac{\delta(\gamma - \gamma_0)}{|f'(\gamma_0)|} = \frac{\delta(\gamma - (\nu/\nu_L)^{1/2})}{2(\nu\nu_L)^{1/2}}$$

Synchrotron emission: final considerations

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

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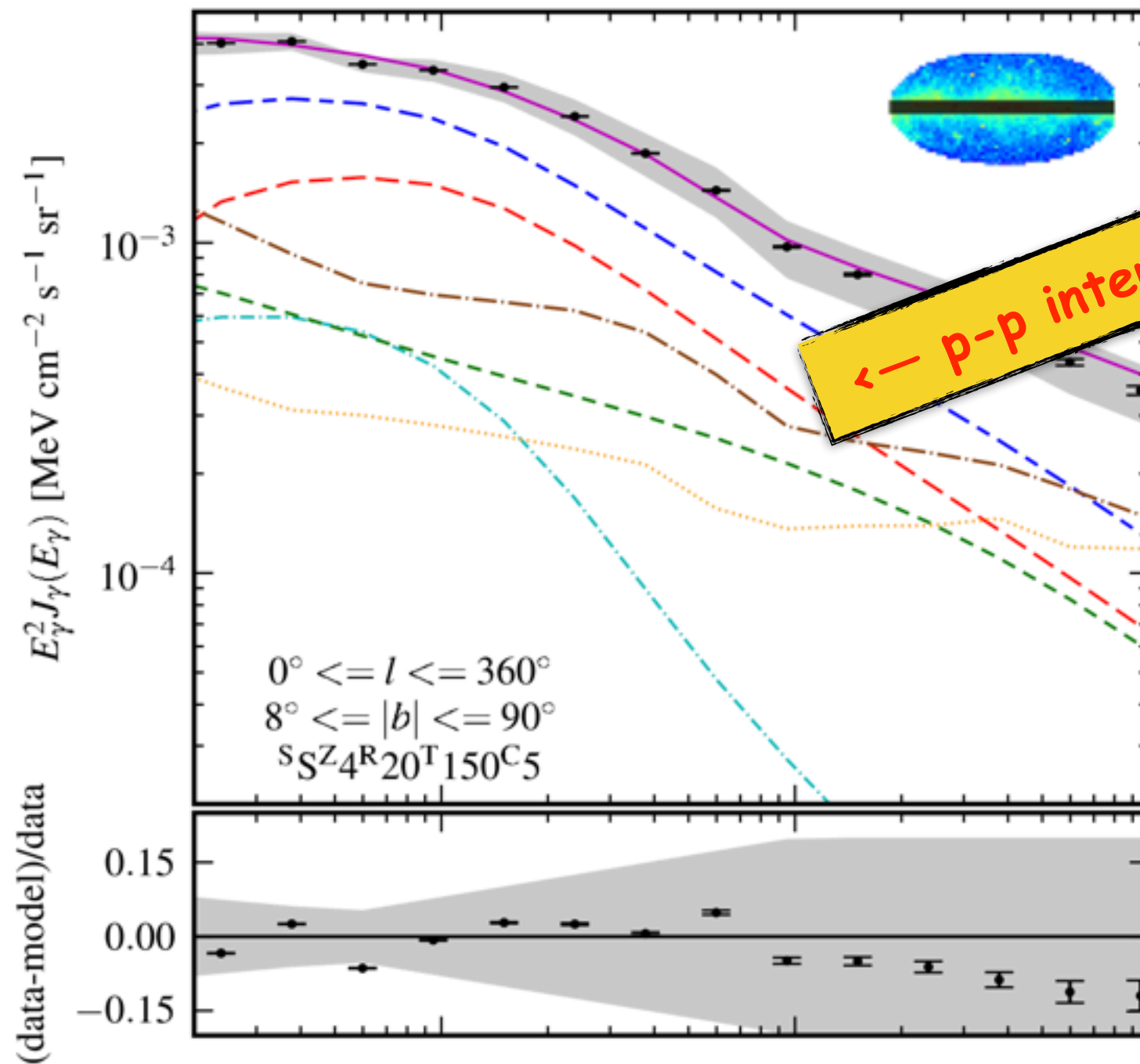
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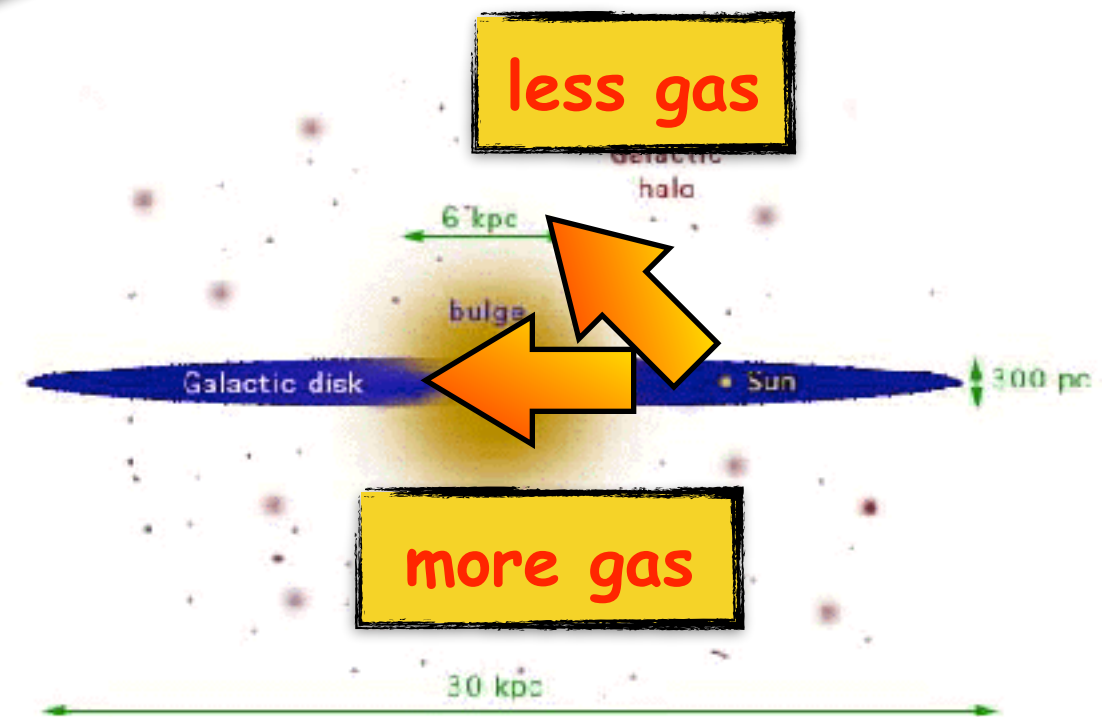
several ways to measure B exist, and they indicate $B \sim 3 \mu\text{G}$ in the Milky Way

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

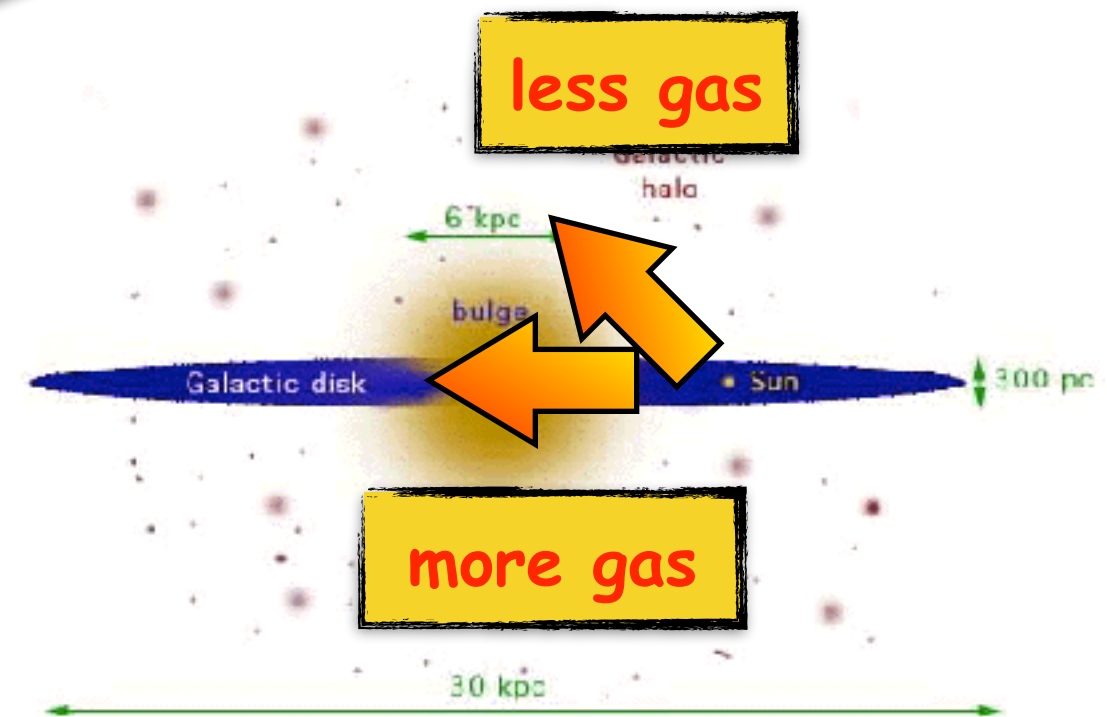
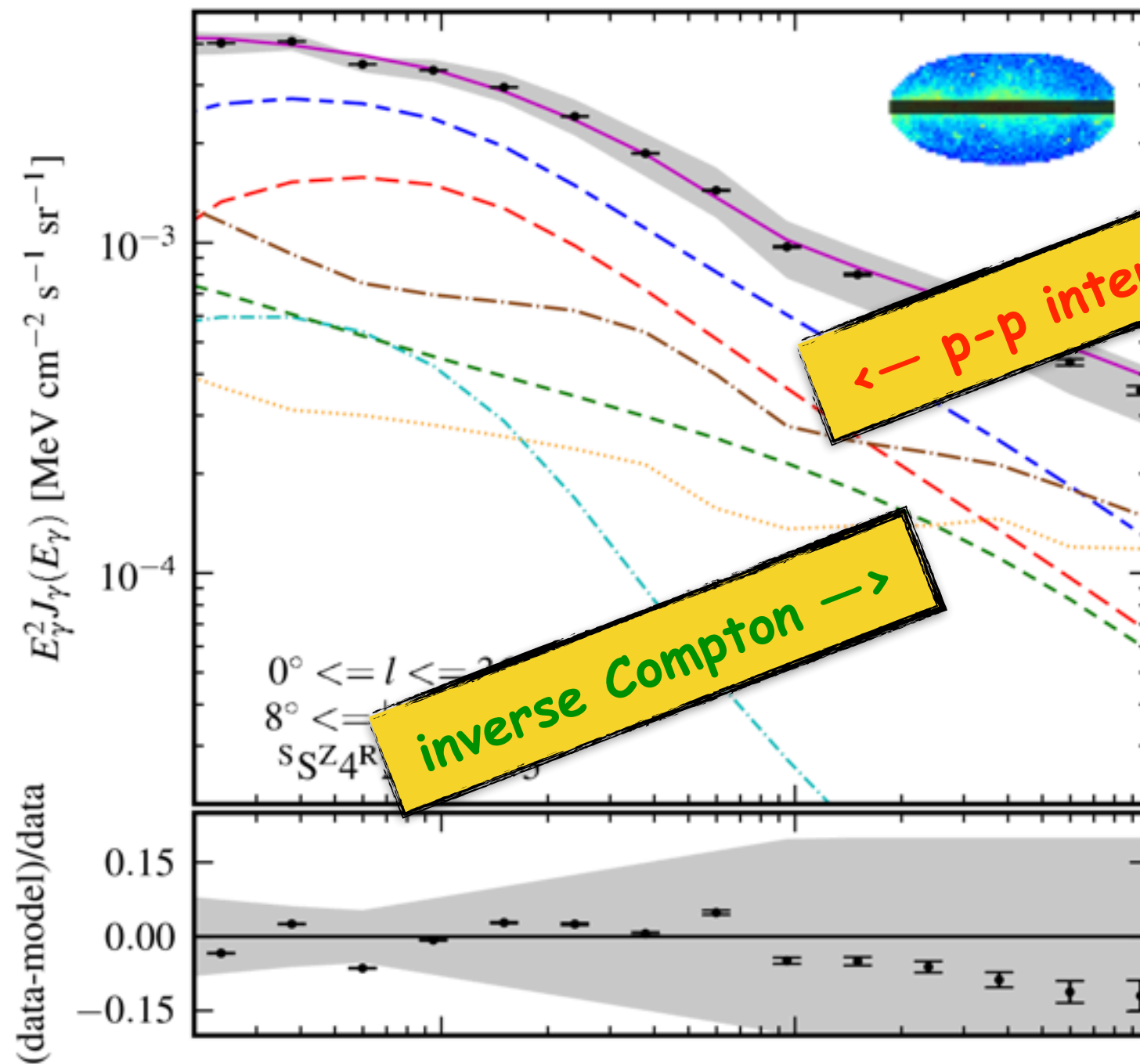
Diffuse emission, large Galactic latitudes



$\leftarrow$ p-p interactions

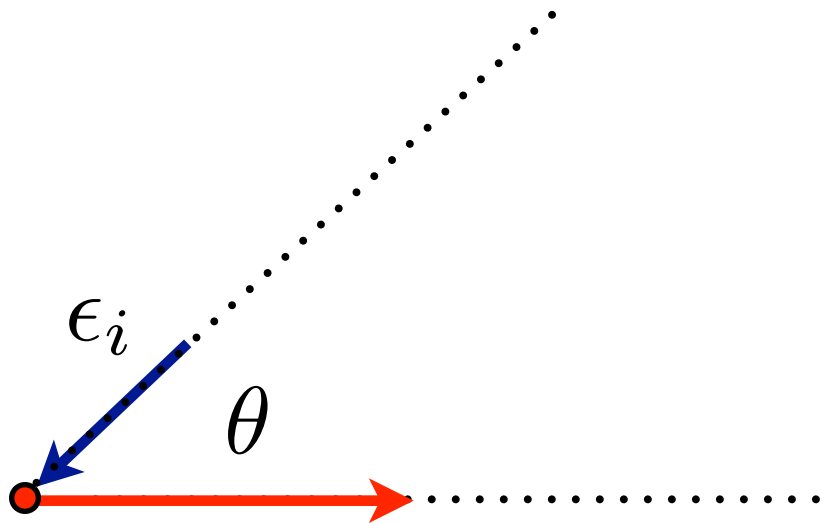


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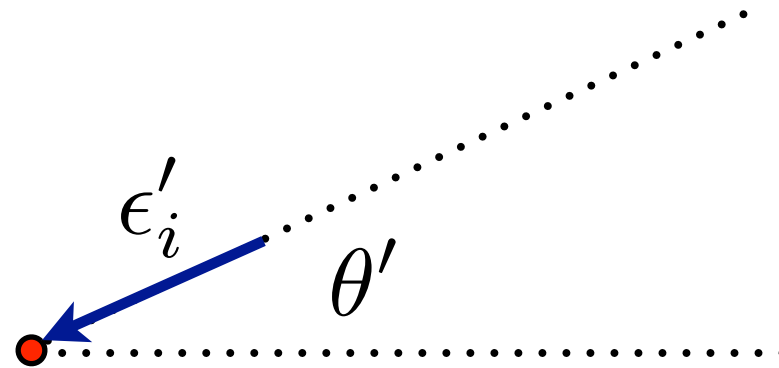
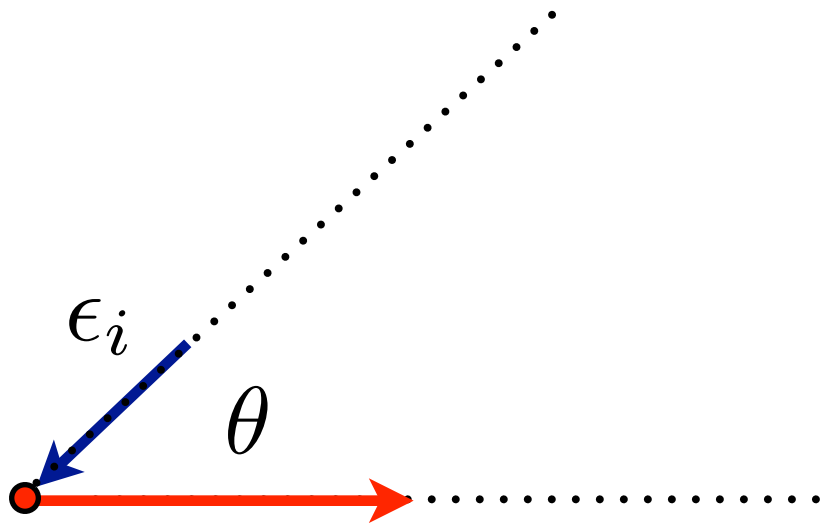
Leptonic Gamma-Rays: Inverse Compton

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



Leptonic Gamma-Rays: Inverse Compton

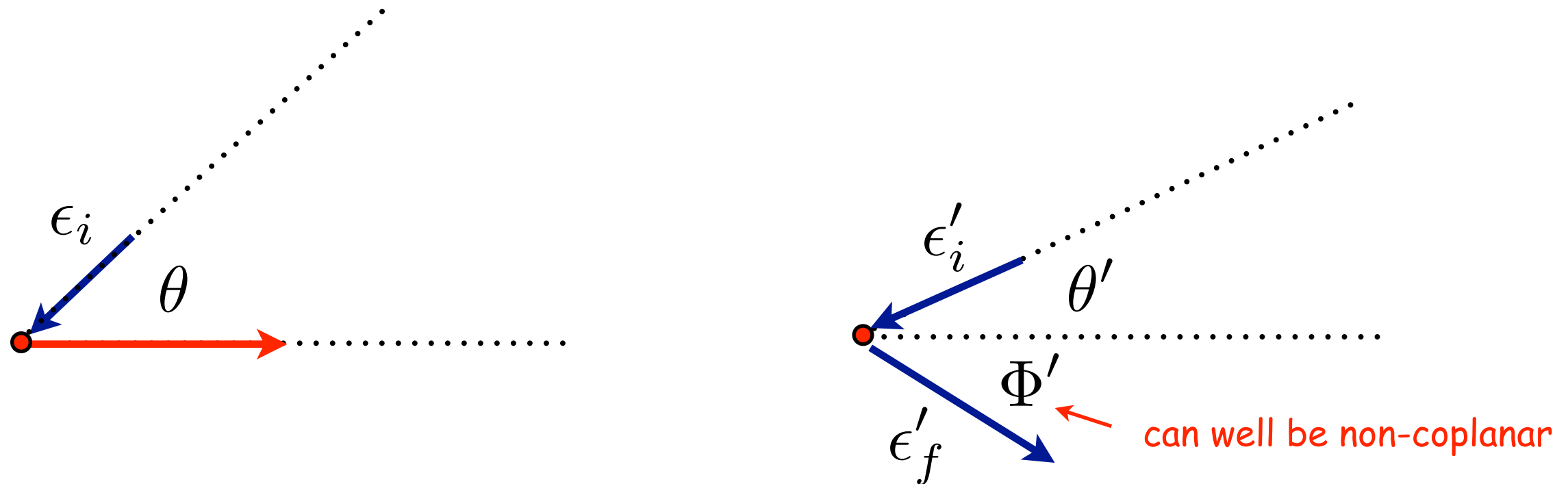
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In the electron rest frame (e.r.f.) the photon energy is: $\epsilon'_i = \epsilon_i \gamma (1 - \beta \cos \theta)$

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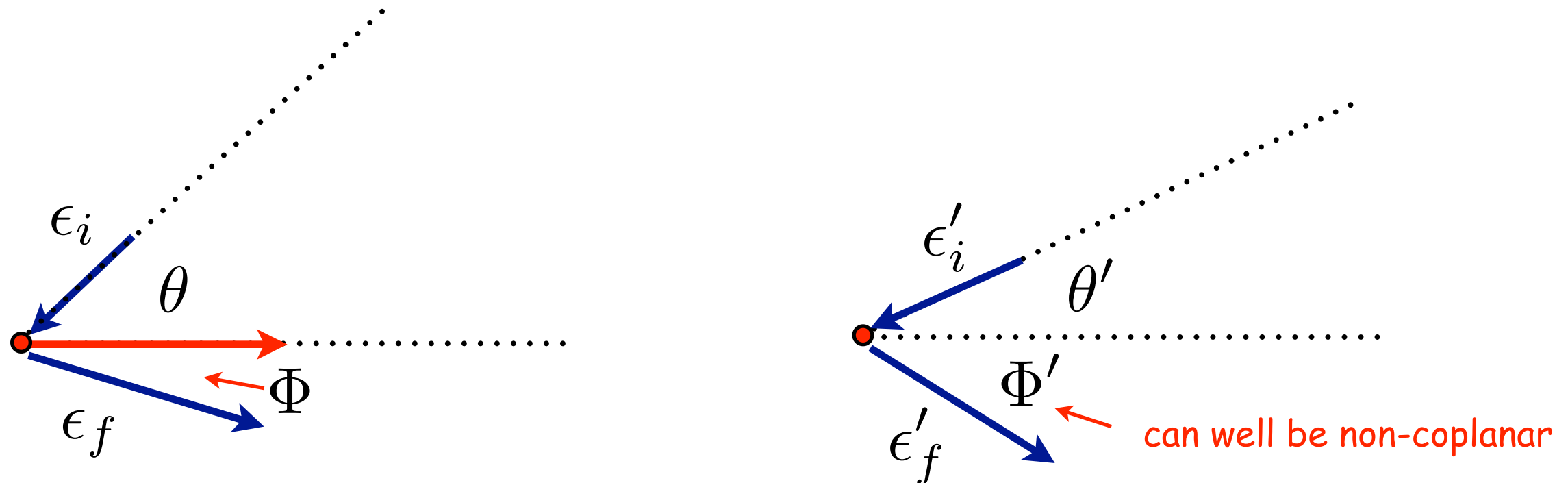


In the electron rest frame (e.r.f.) the photon energy is: $\epsilon'_i = \epsilon_i \gamma (1 - \beta \cos \theta)$

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

Leptonic Gamma-Rays: Inverse Compton

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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

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Example:

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

- $E_e = 1 \text{ GeV} \rightarrow \epsilon_\gamma = 1, 5 \text{ keV}$ 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

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



energy conservation...

above a given energy Inverse Compton scattering becomes ineffective

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

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

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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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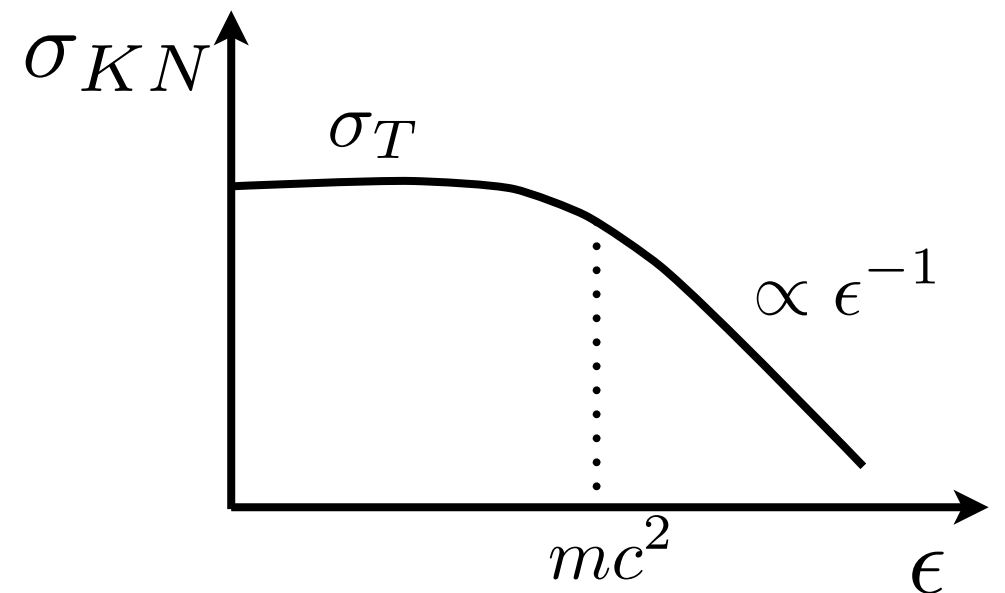
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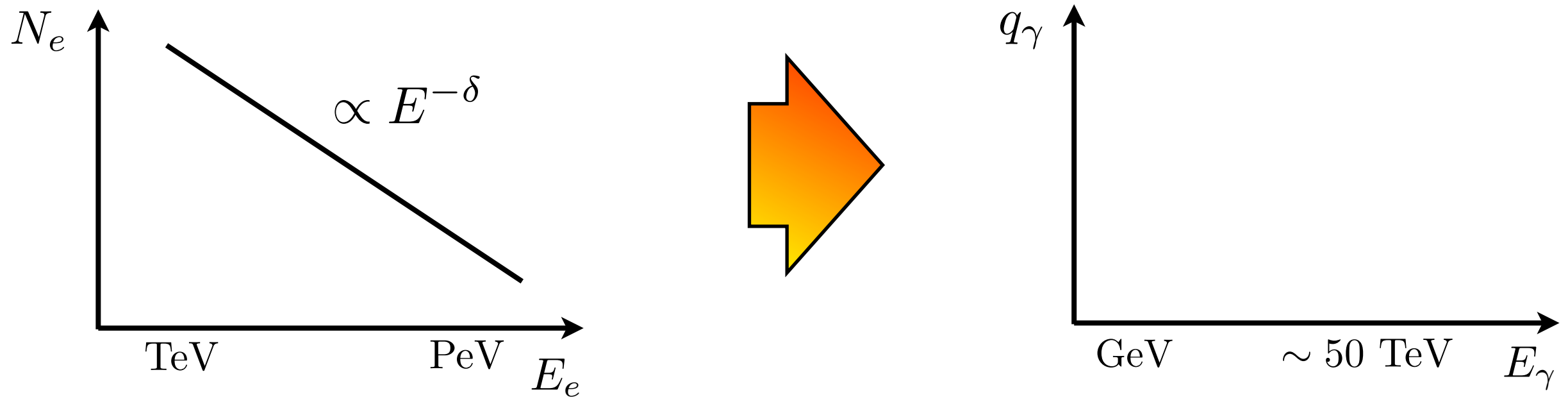
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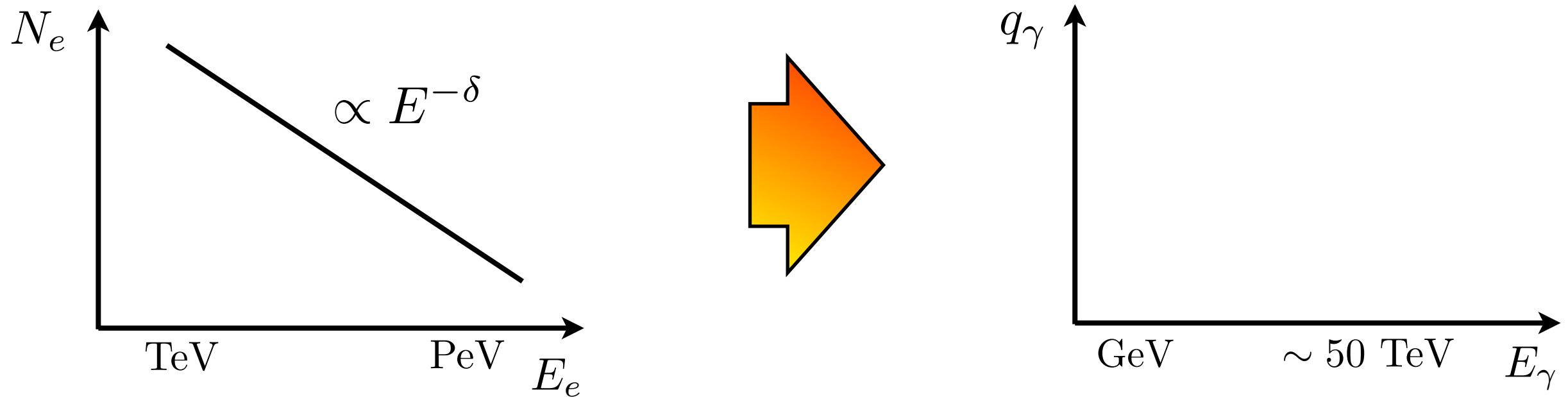
Photon spectrum:



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

Leptonic Gamma-Rays: Inverse Compton

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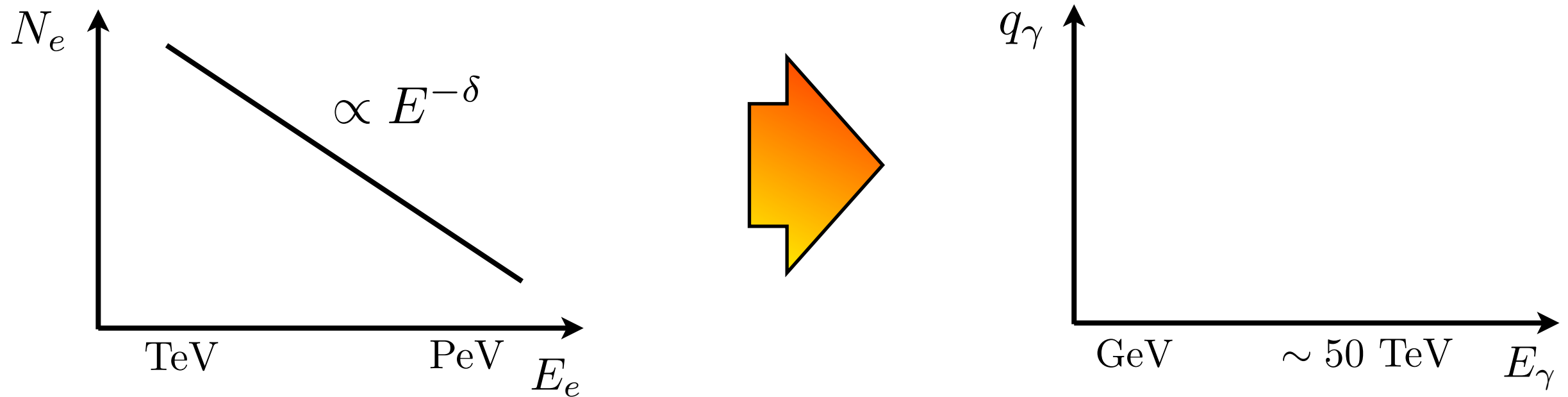
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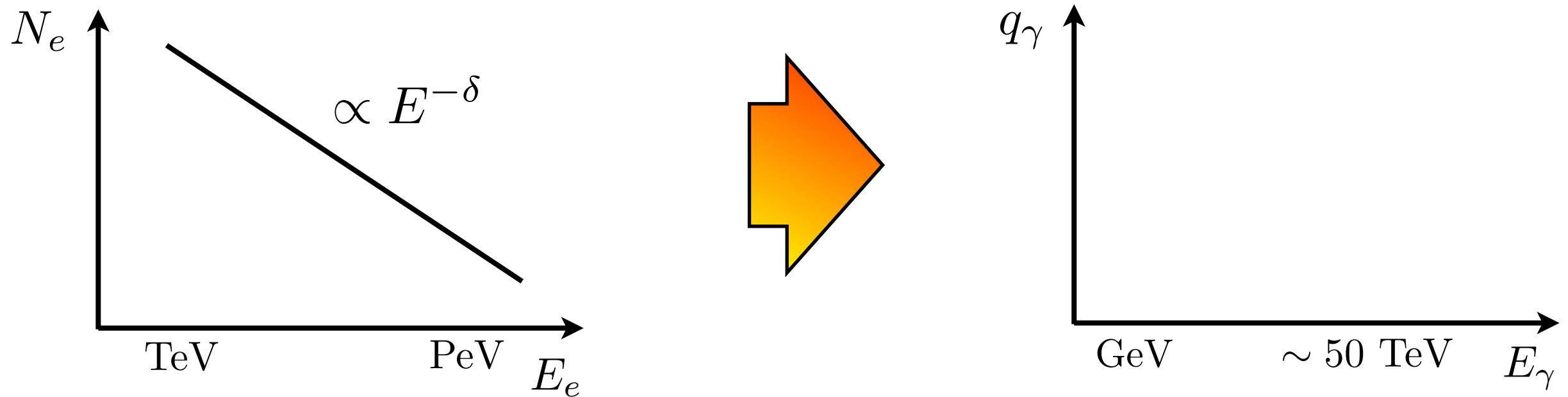
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The diagram shows the application of the delta function identity to the photon spectrum equation. The argument of the delta function is $E_\gamma - \frac{4}{3} \left(\frac{E_e}{mc^2}\right)^2 \epsilon_{CMB}$. A red bracket above this expression is labeled $g(x)$. Red arrows point from the terms $\frac{E_e}{mc^2}$ and ϵ_{CMB} to the relations $x_0 \propto E_\gamma^{1/2}$ and $g' \propto E_e$ respectively.

Leptonic Gamma-Rays: Inverse Compton

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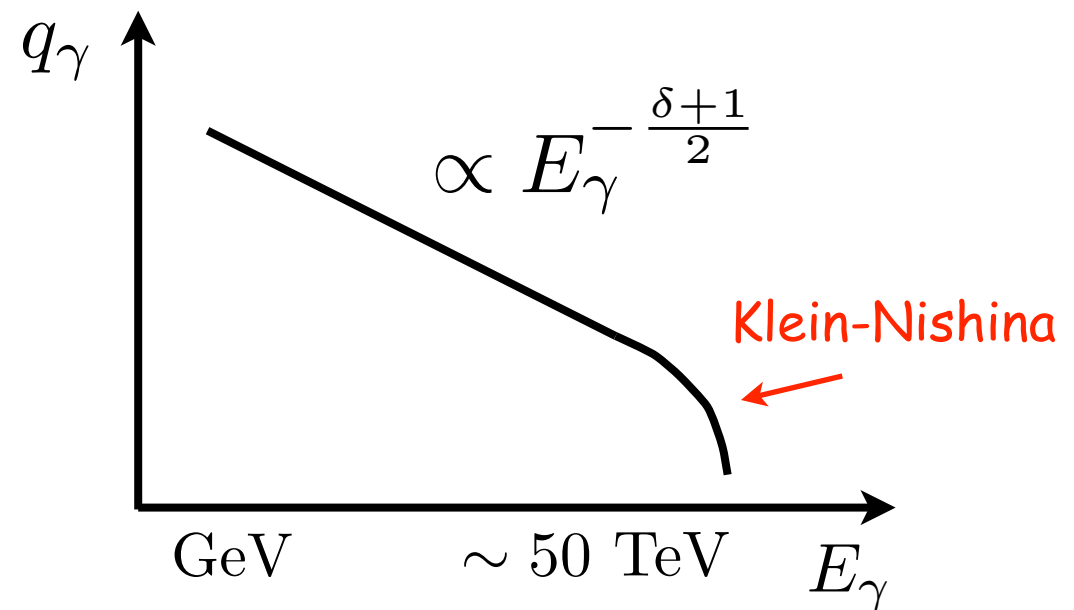
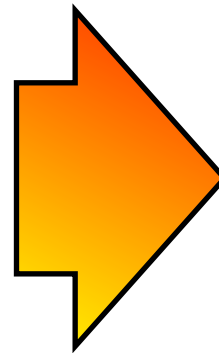
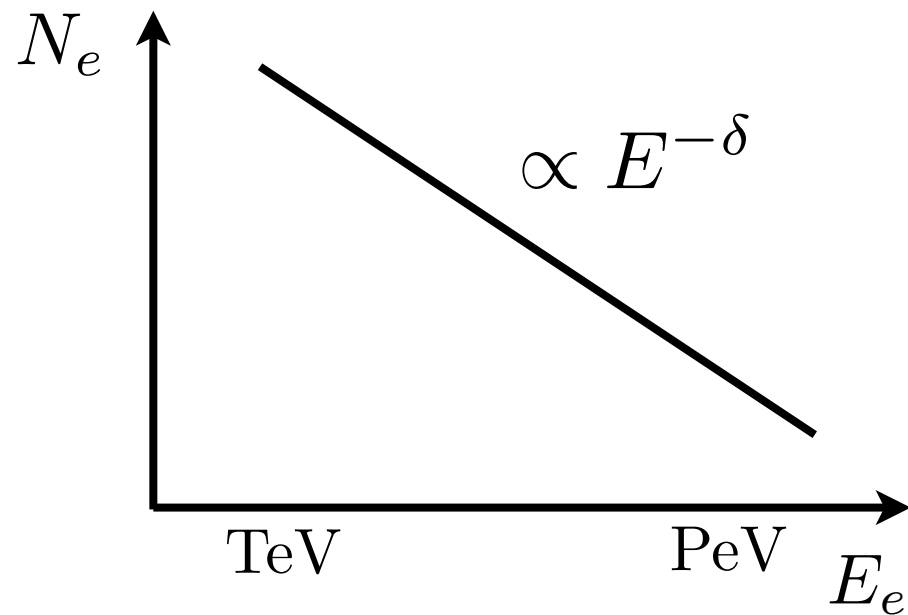
➔

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

$\overbrace{\hspace{10em}}^{g(x)}$
 $\swarrow \quad \searrow$
 $x_0 \propto E_\gamma^{1/2} \quad g' \propto E_e$

Leptonic Gamma-Rays: Inverse Compton

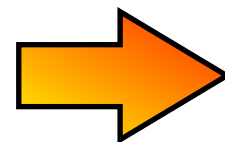
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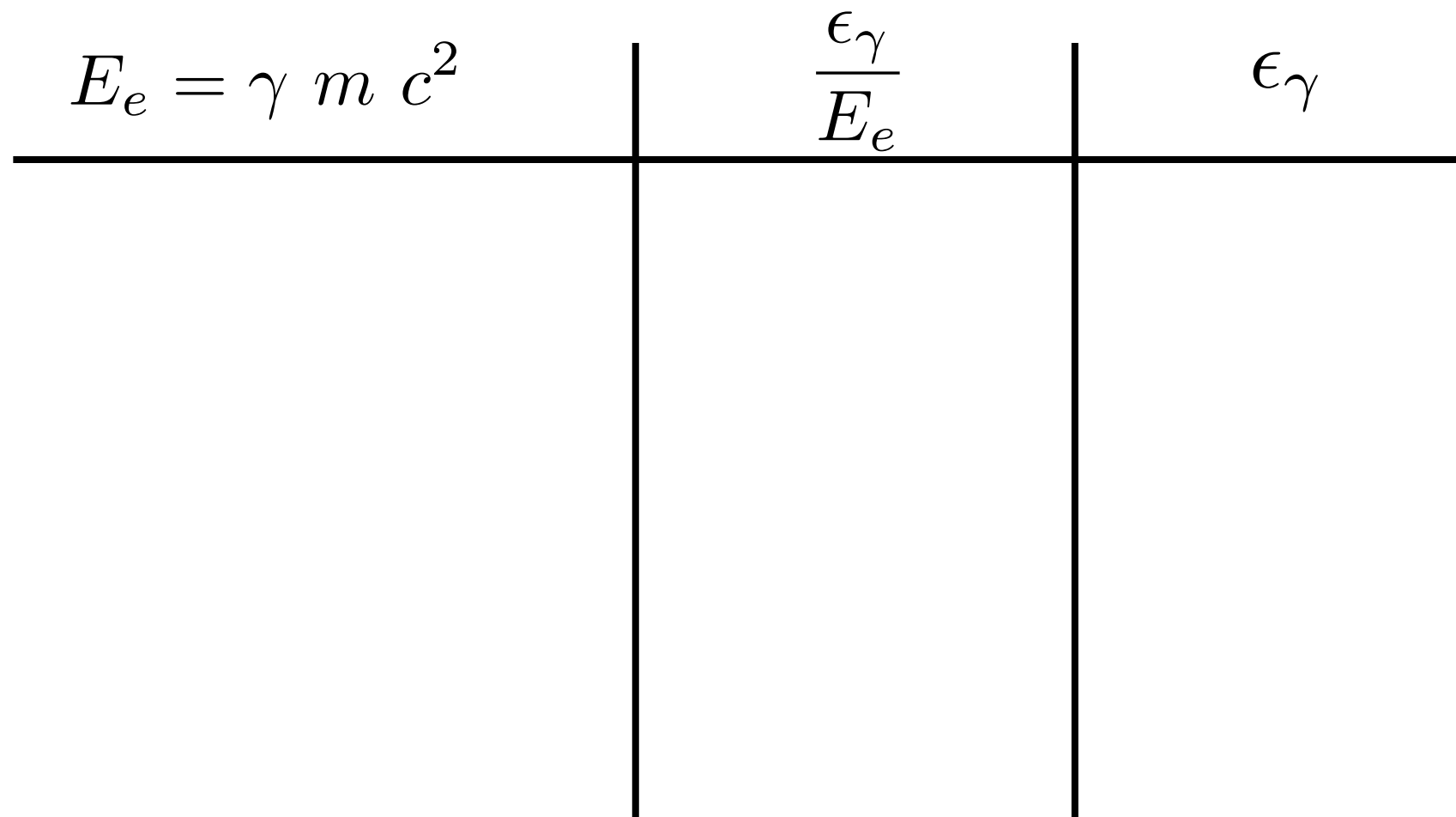
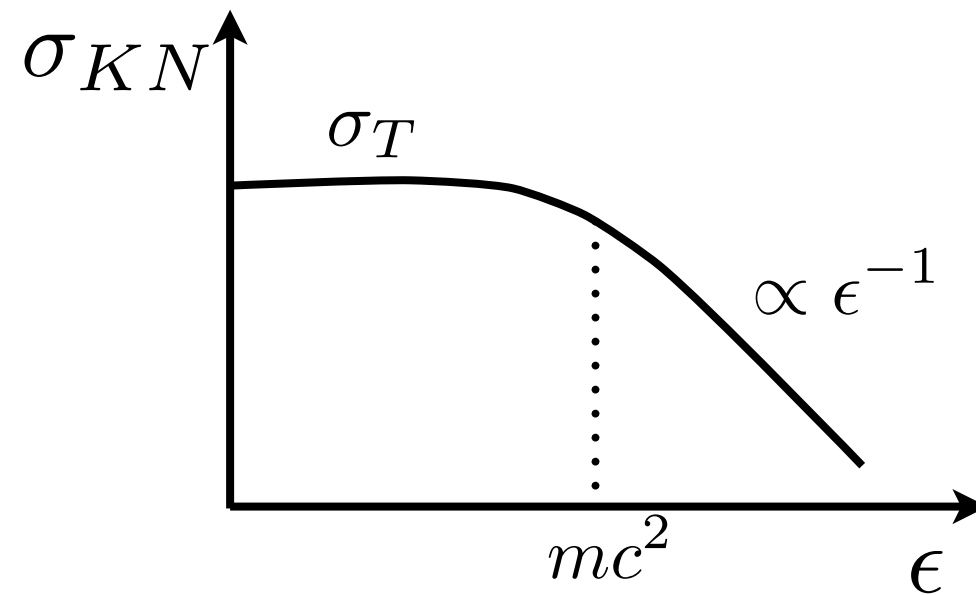
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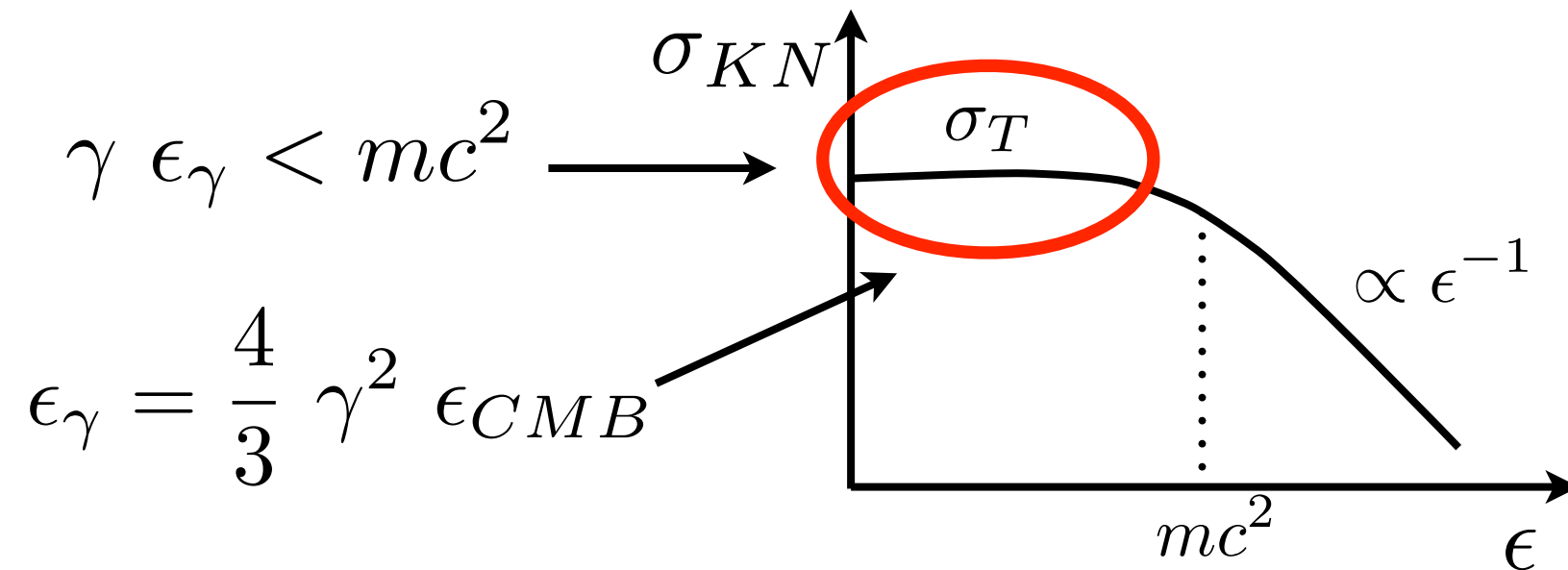
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Leptonic Gamma-Rays: Inverse Compton



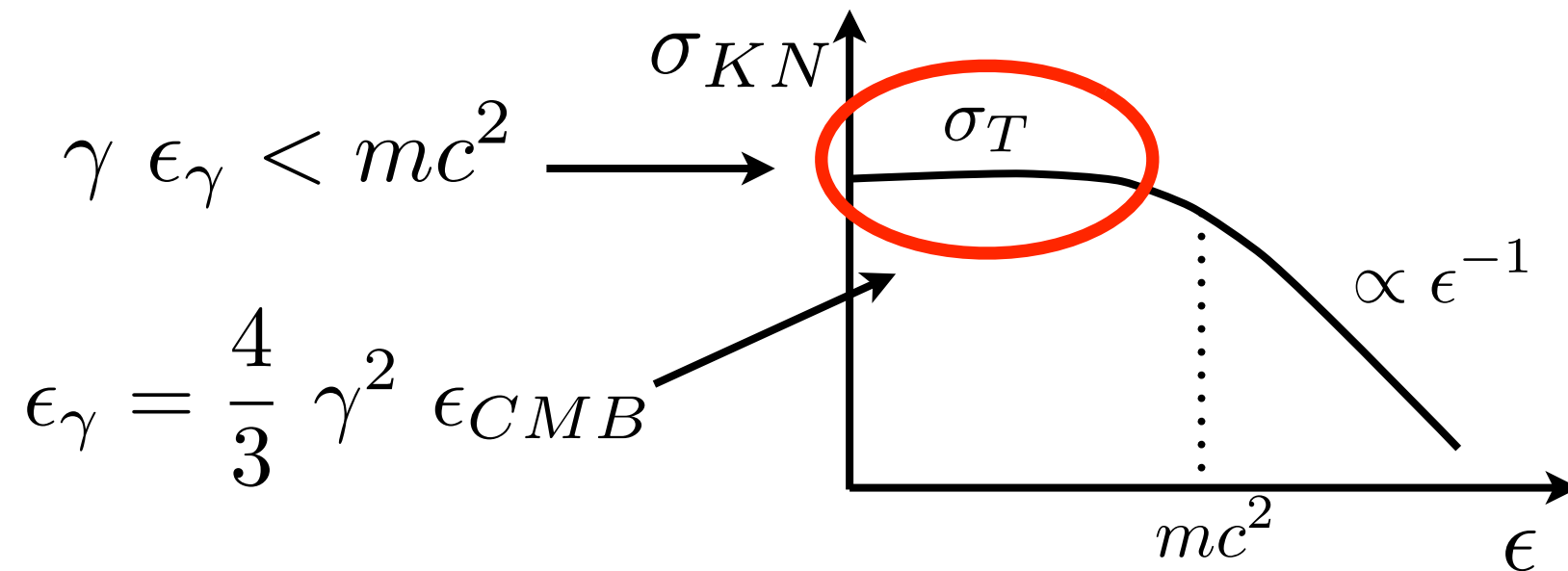
Leptonic Gamma-Rays: Inverse Compton



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

Thomson

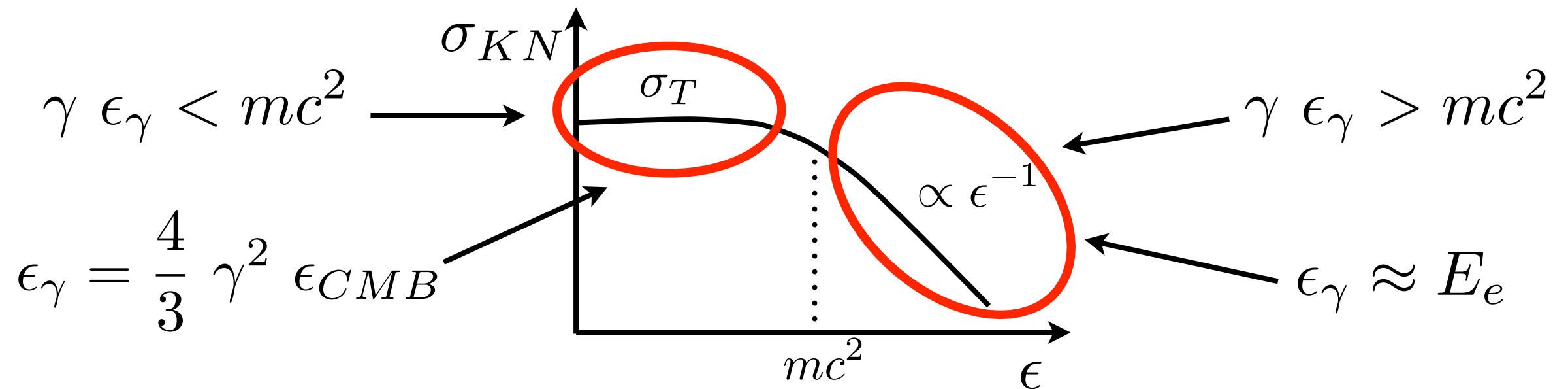
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Leptonic Gamma-Rays: Inverse Compton

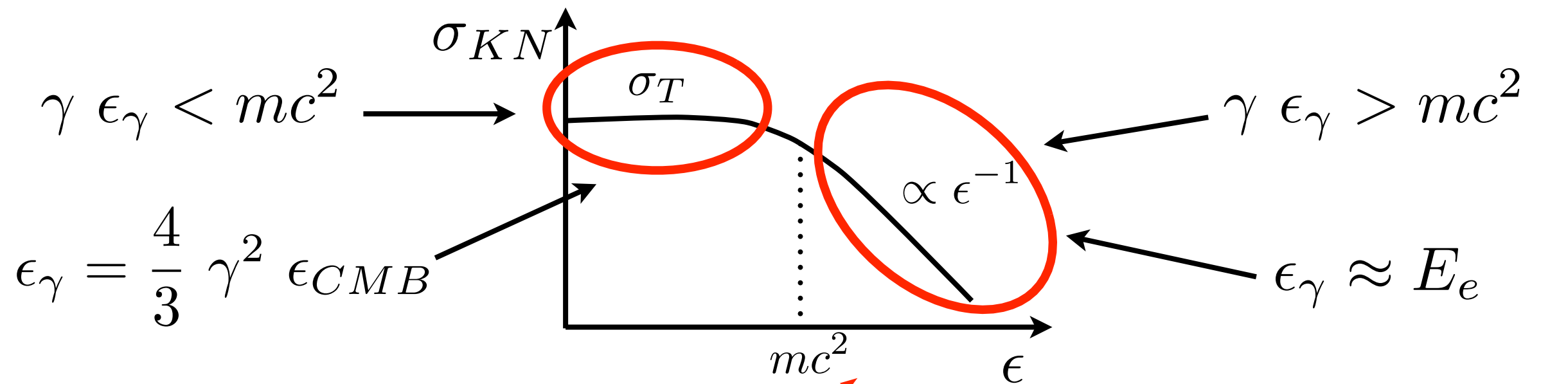


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$E_e \gg 200 \text{ TeV}$	~100%	$E_e \sim E_\gamma$

Thomson

Klein-Nishina

Leptonic Gamma-Rays: Inverse Compton



cutoff in the
photon spectrum

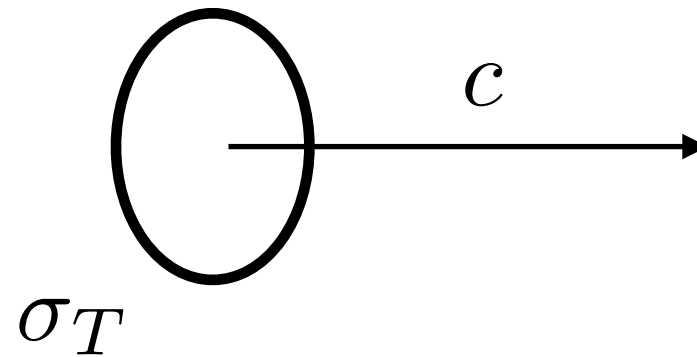
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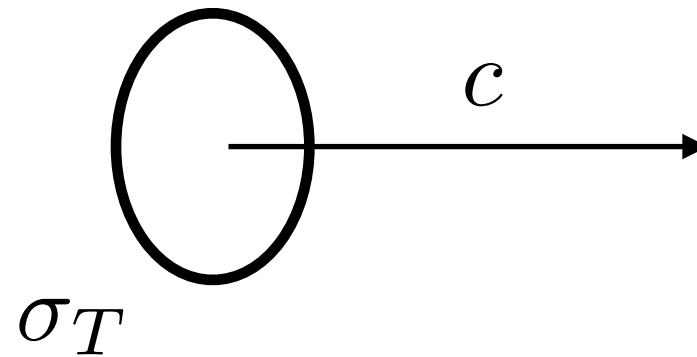
Inverse Compton: energy loss rate

Scattering rate



Inverse Compton: energy loss rate

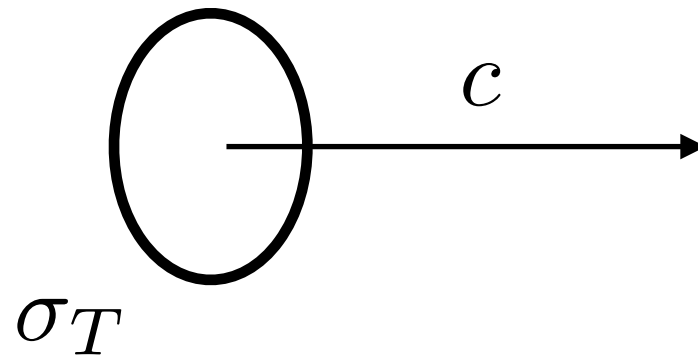
Scattering rate



Volume swept per second $\sigma_T c$

Inverse Compton: energy loss rate

Scattering rate



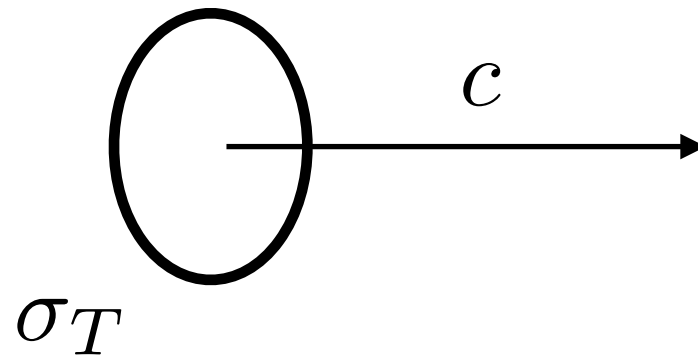
Volume swept per second $\sigma_T c$

Interaction rate $\sigma_T c n_{CMB}$

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

Inverse Compton: energy loss rate

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Volume swept per second $\sigma_T c$

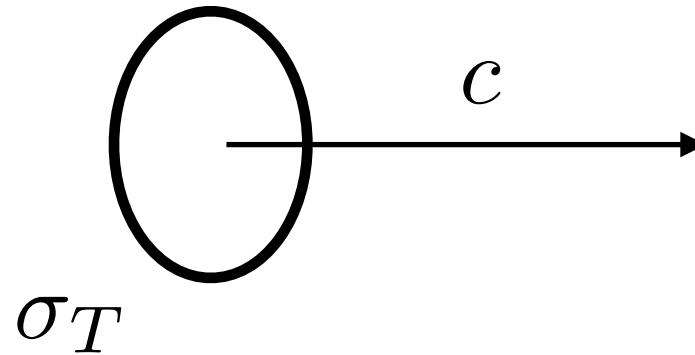
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Radiated power
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Inverse Compton: energy loss rate

Scattering rate



Volume swept per second $\sigma_T c$

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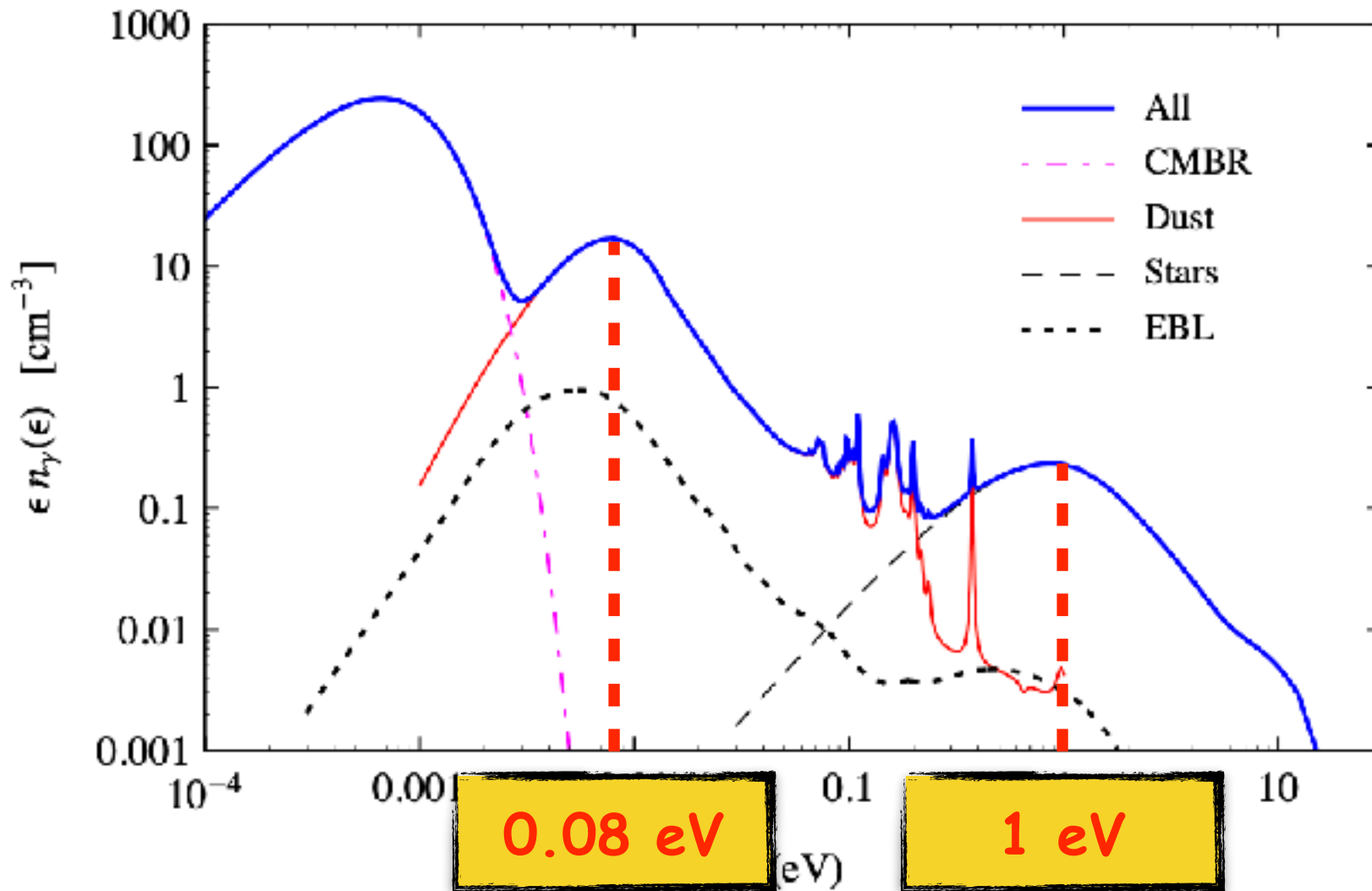
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Same expression as synchrotron!

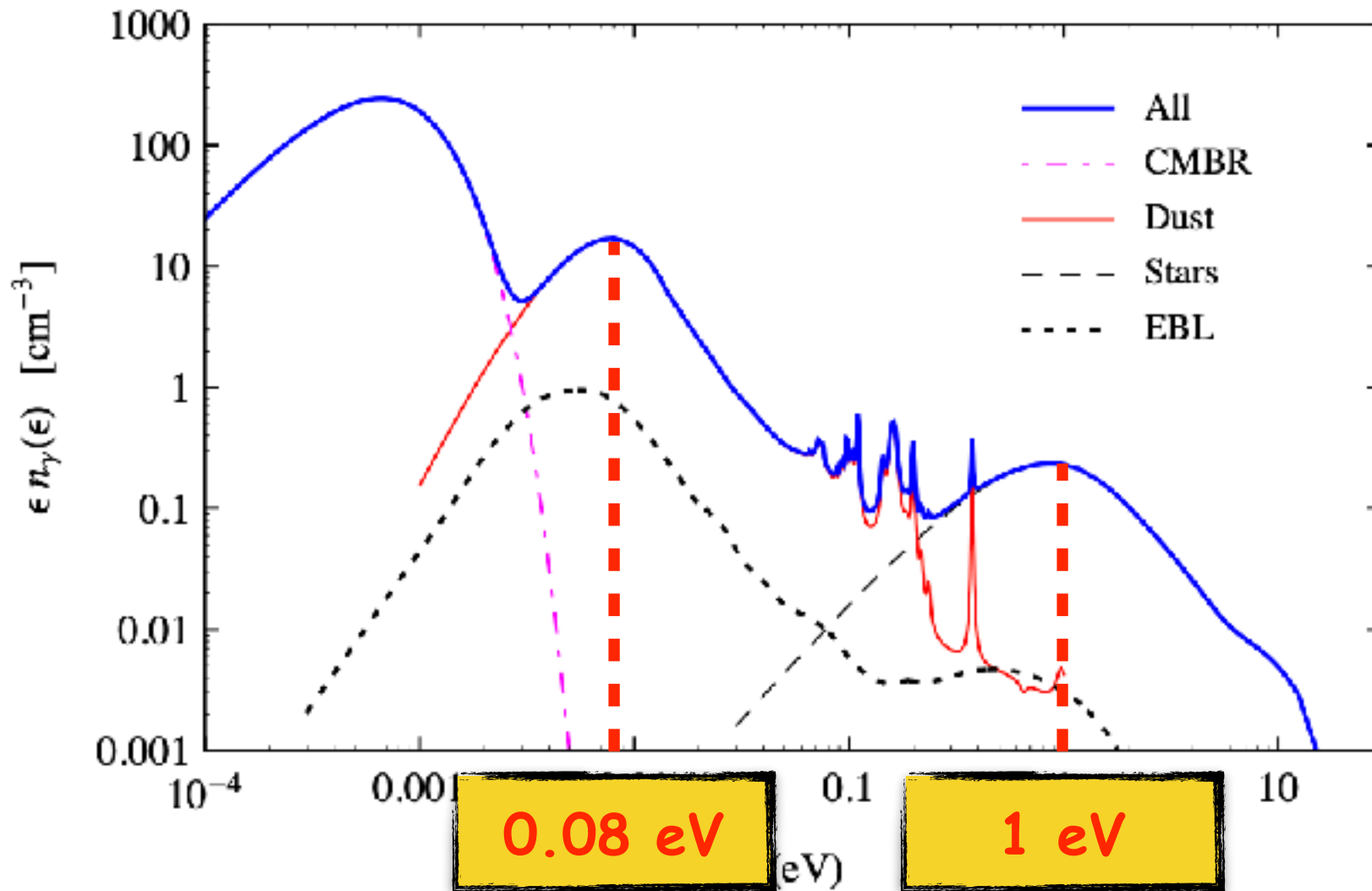
Note on the K-N regime

Lipari & Vernetto 2018



Note on the K-N regime

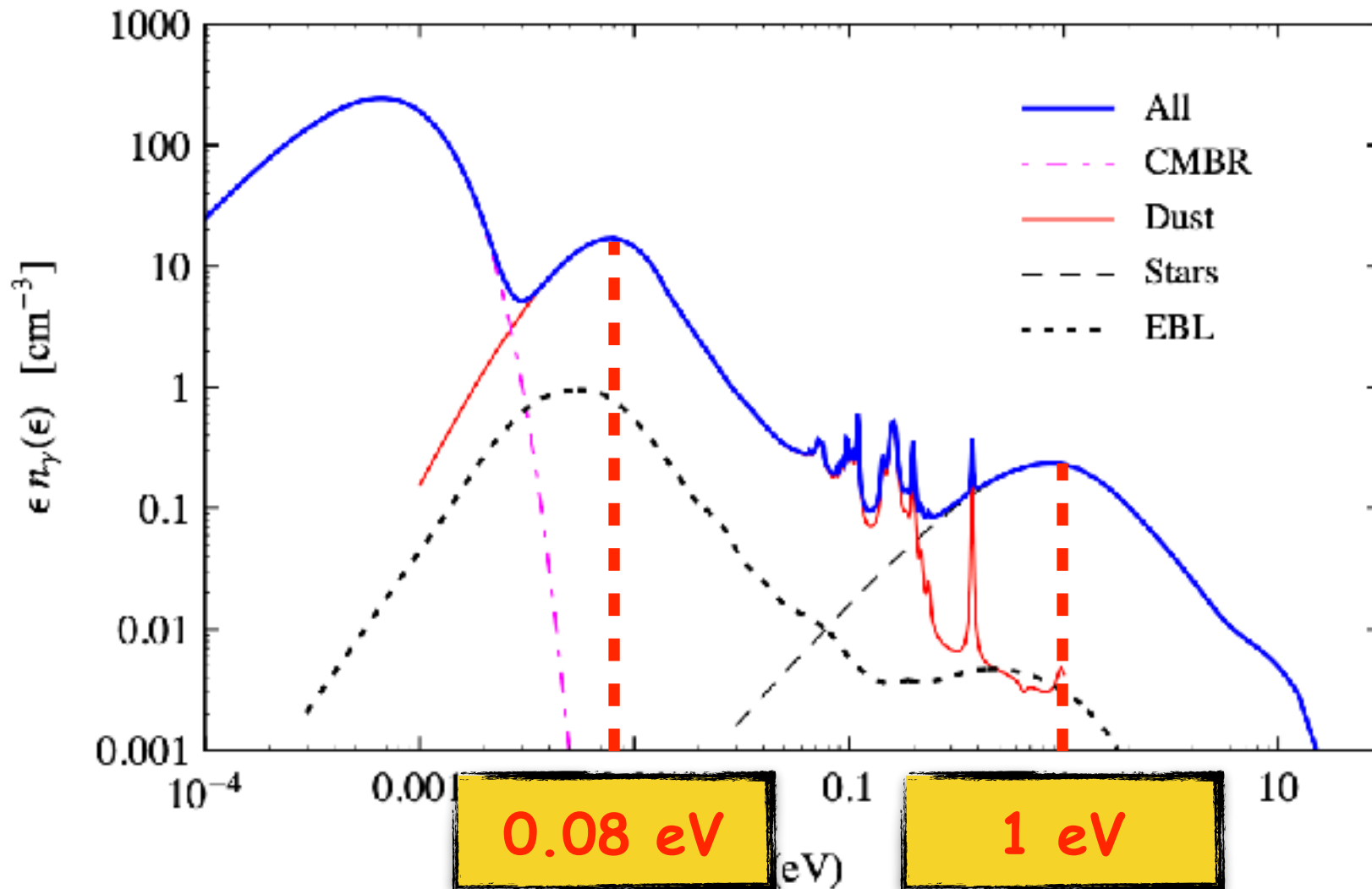
Lipari & Vernetto 2018



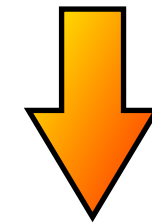
$$\gamma \quad \epsilon_\gamma > mc^2$$

Note on the K-N regime

Lipari & Vernetto 2018



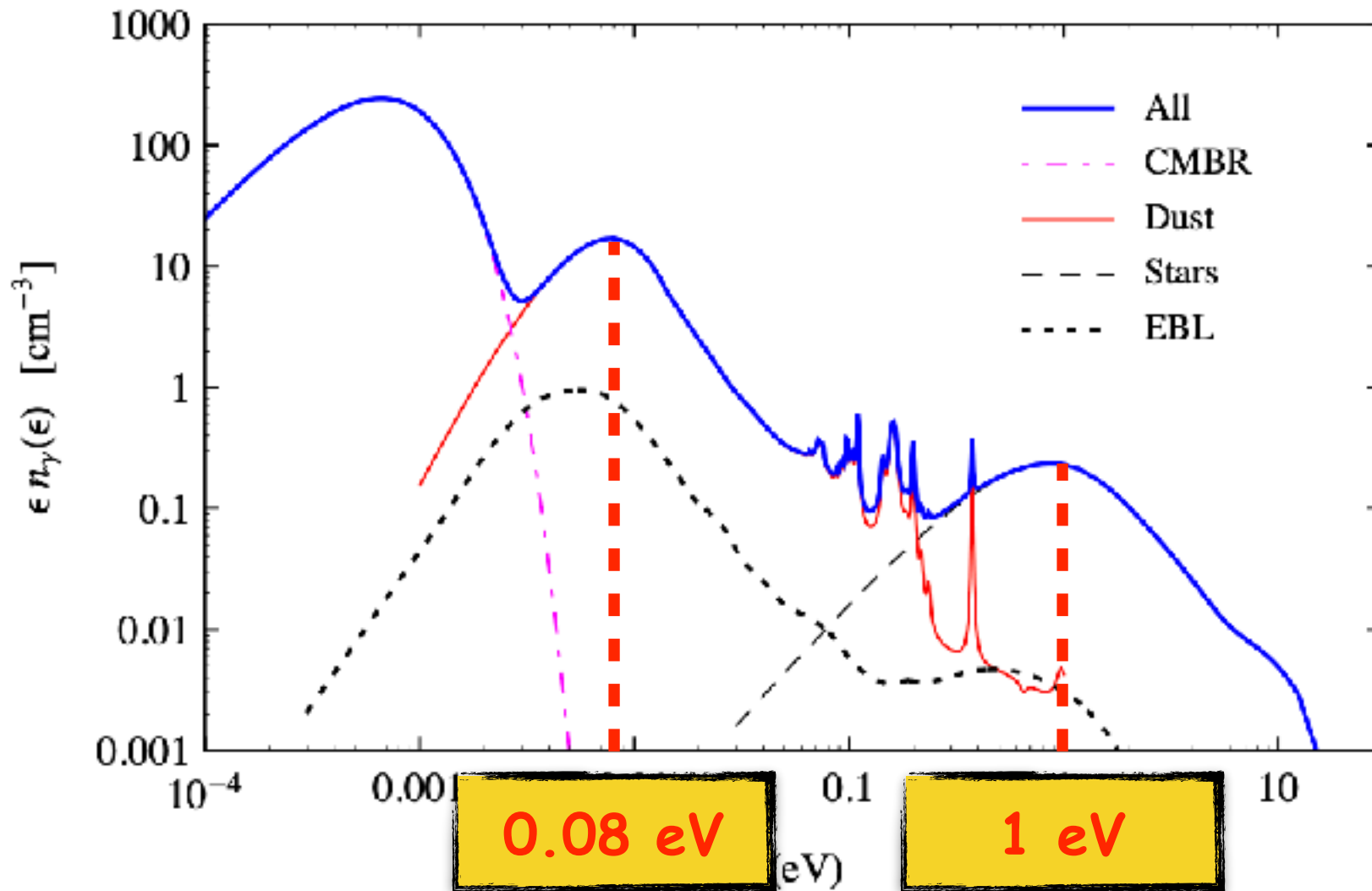
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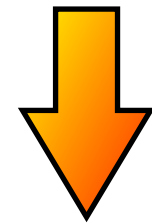
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Lipari & Vernetto 2018



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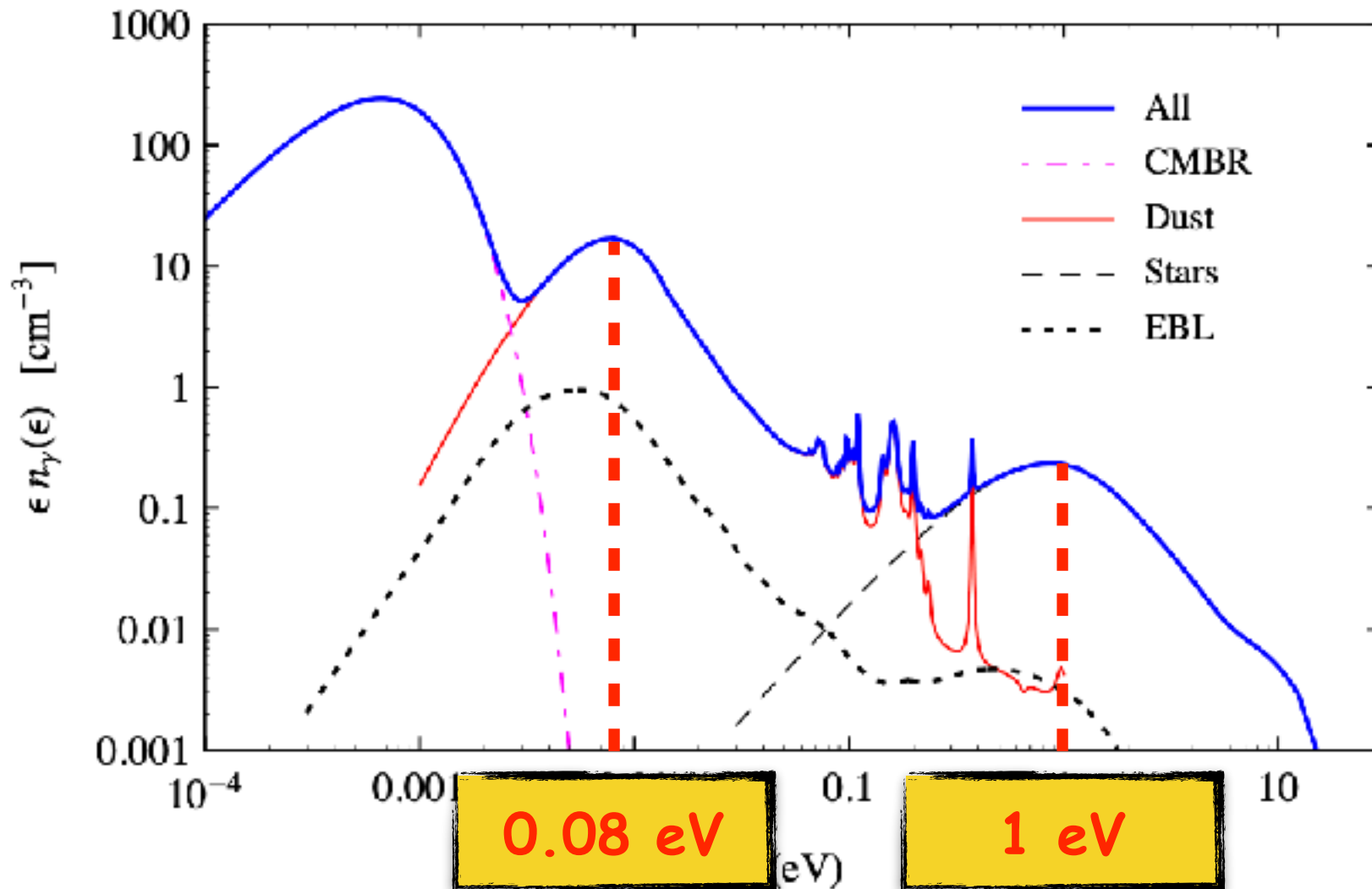
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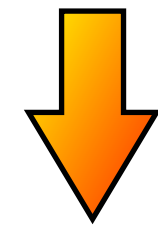
$$E_\gamma = \frac{4}{3} \gamma^2 \epsilon_\gamma \quad \Rightarrow \quad E_\gamma > \frac{4}{3} \frac{(mc^2)^2}{\epsilon_\gamma} \sim 0.3 \left(\frac{\epsilon_\gamma}{\text{eV}} \right) \text{TeV}$$

Note on the K-N regime

Lipari & Vernetto 2018



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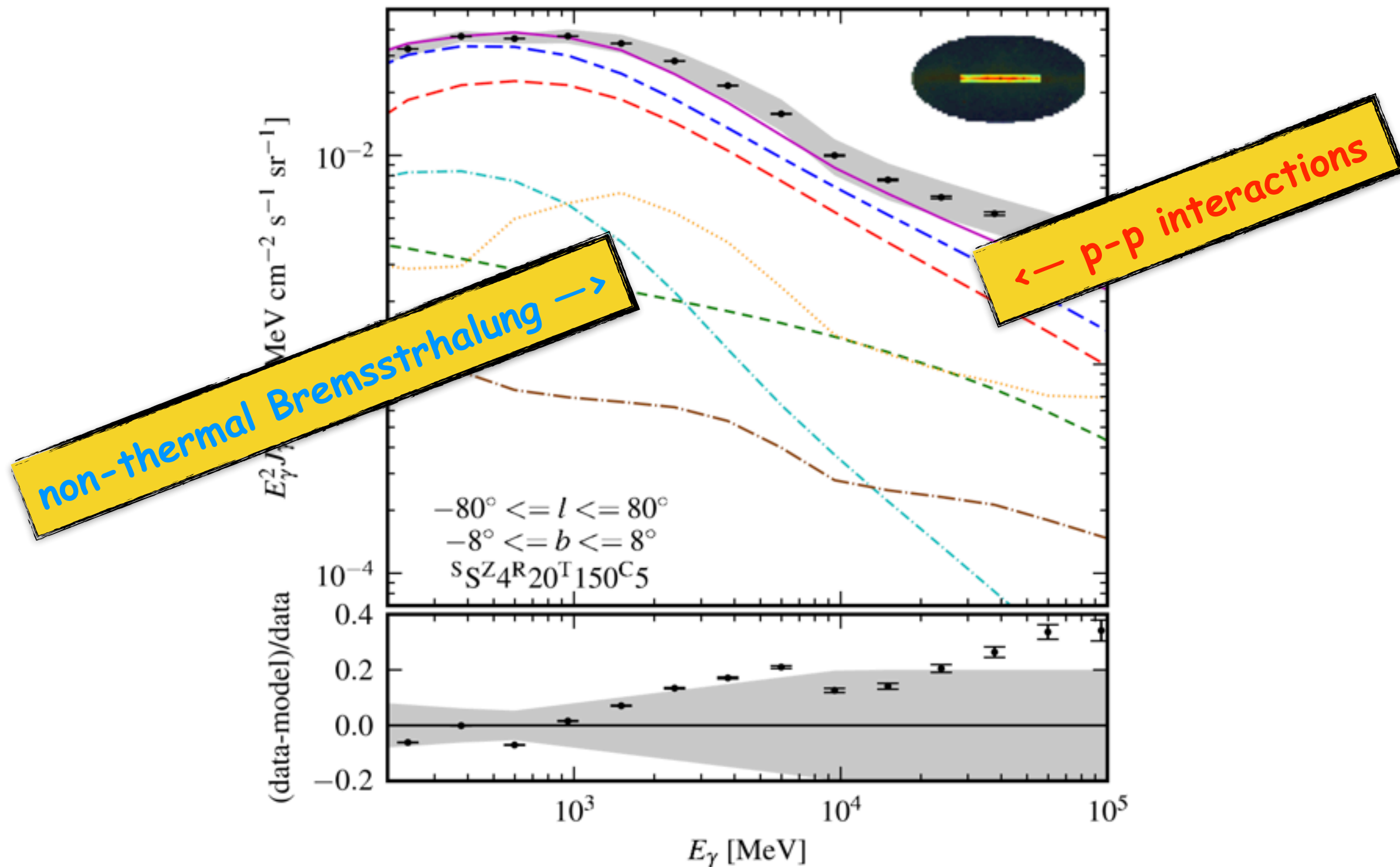
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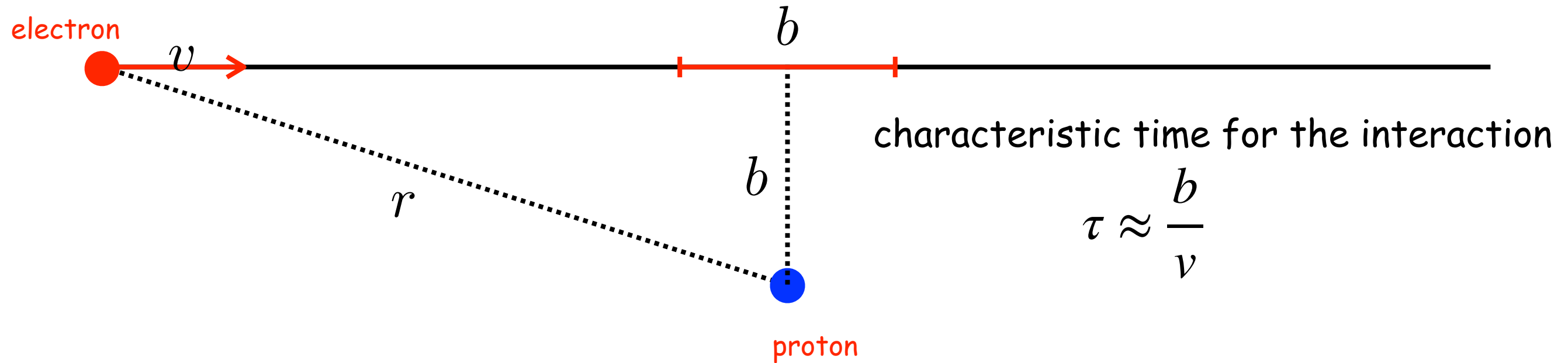
in first approximation: if you are a TeV astronomer just CMB matters for ICS

Non-thermal bremsstrahlung



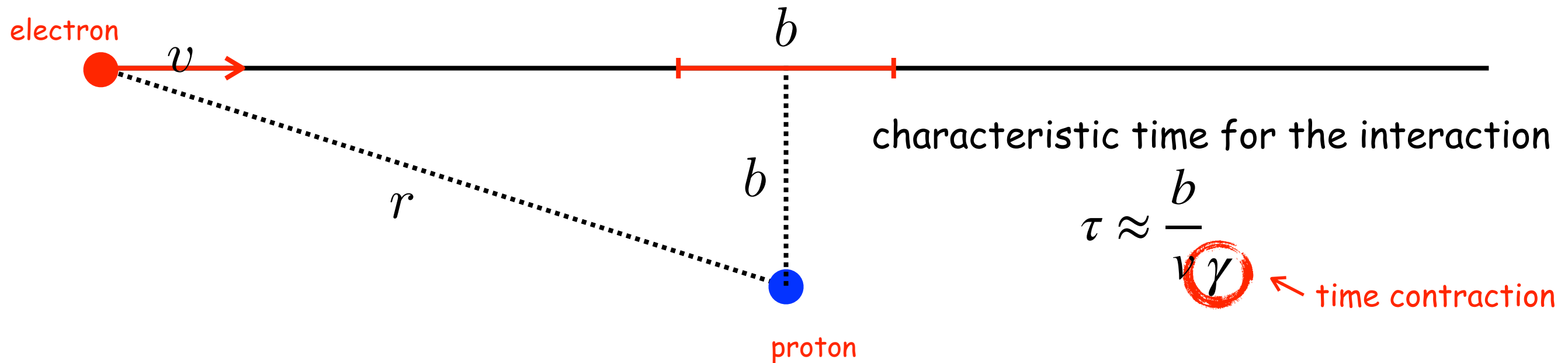
Non-thermal Bremsstrahlung

remember what we did for the thermal Bremsstrahlung



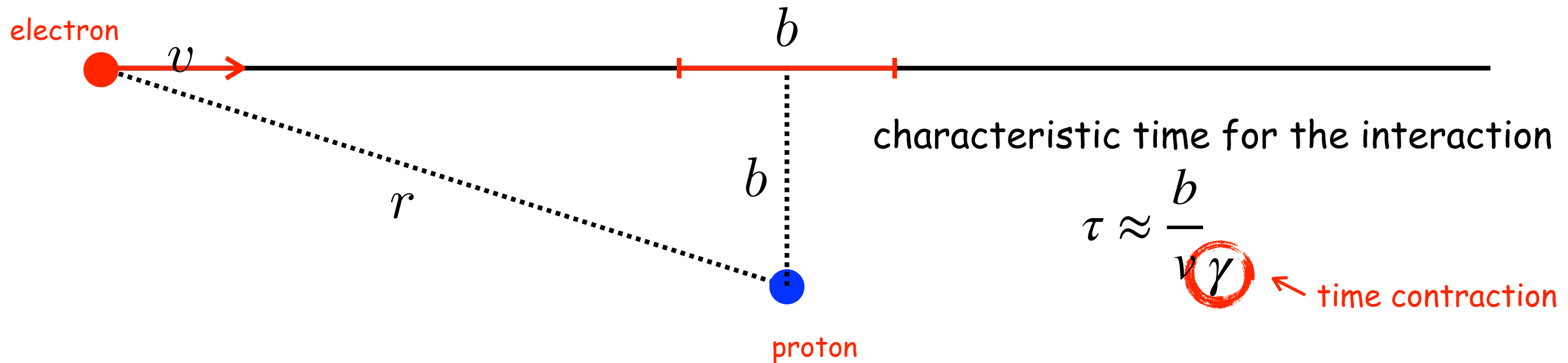
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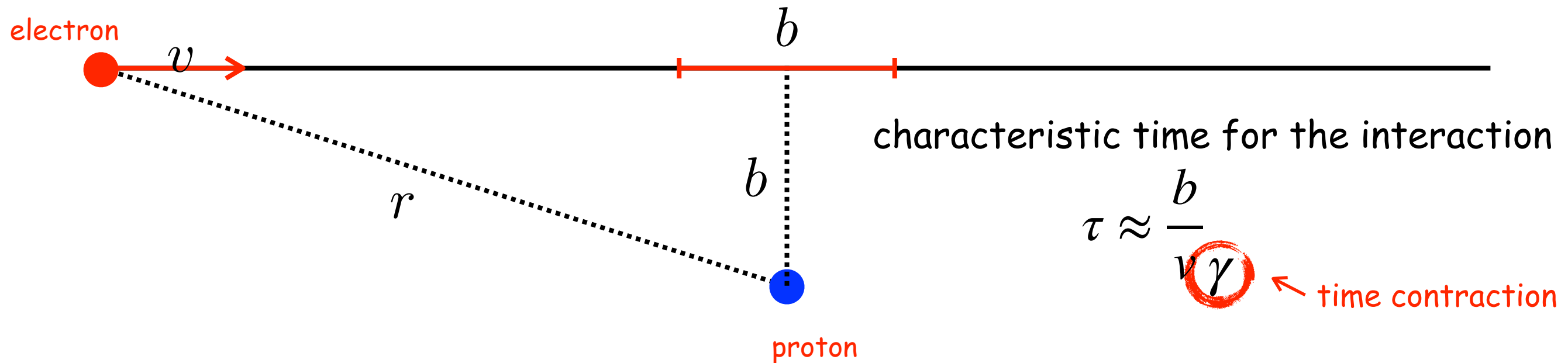
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→ in its rest frame, the e^- sees the proton's E field contracted into a very fast pulse

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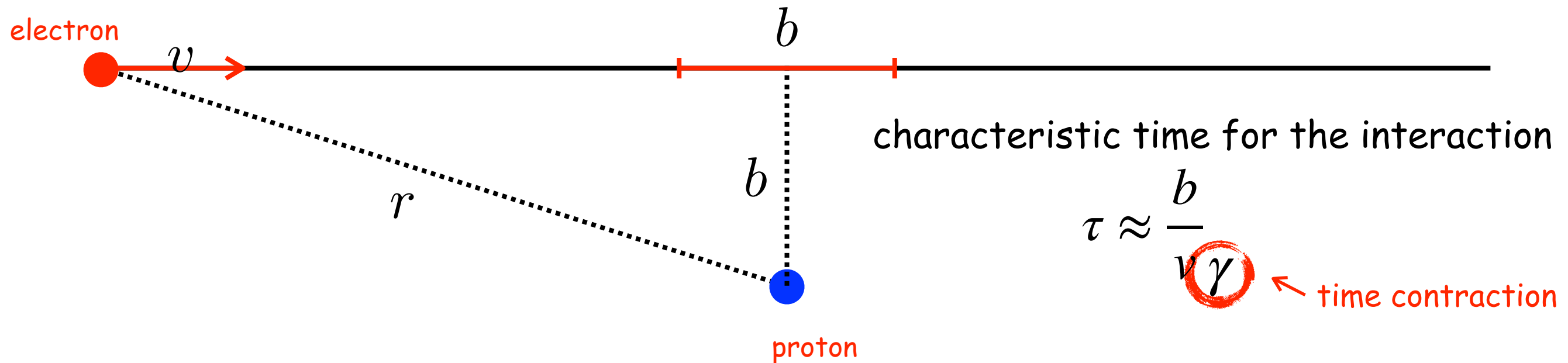
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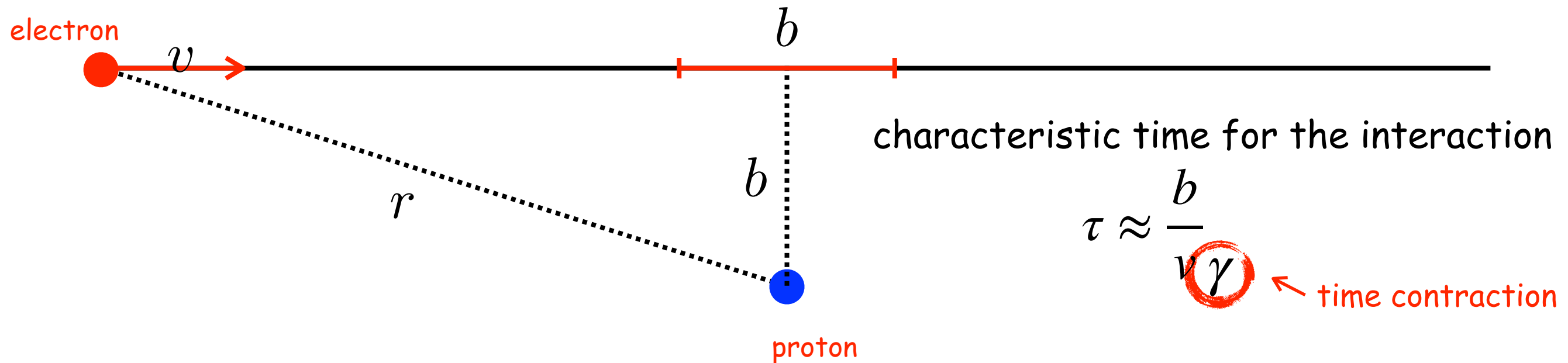
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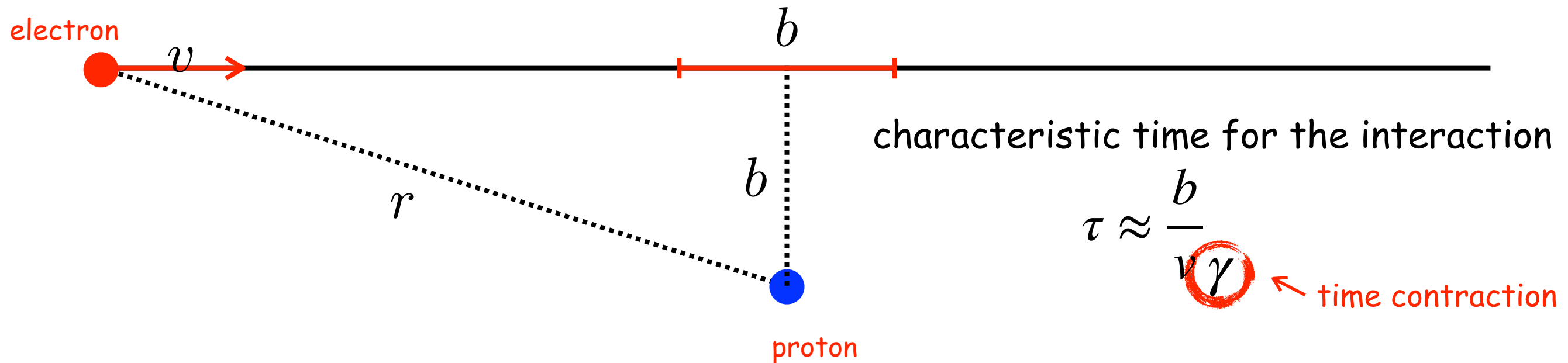
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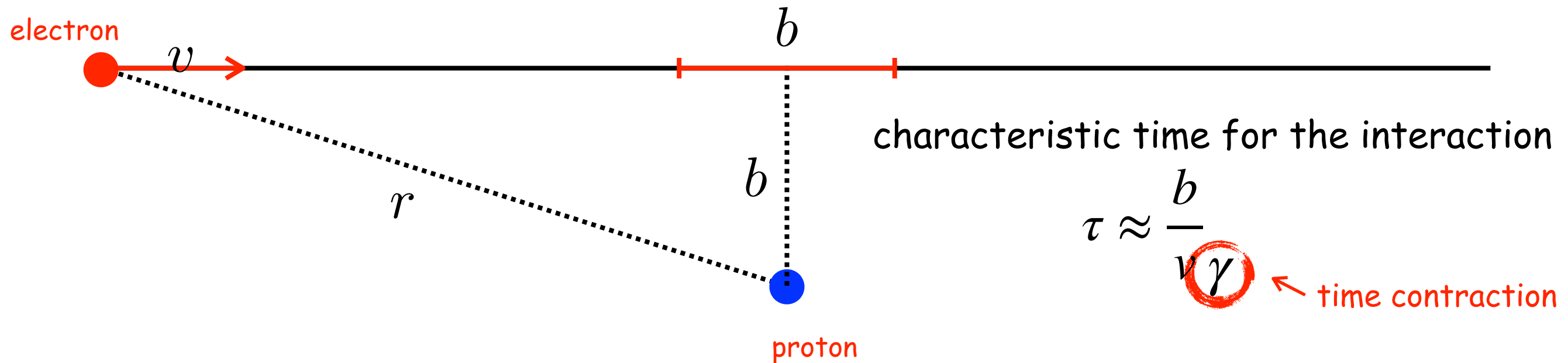
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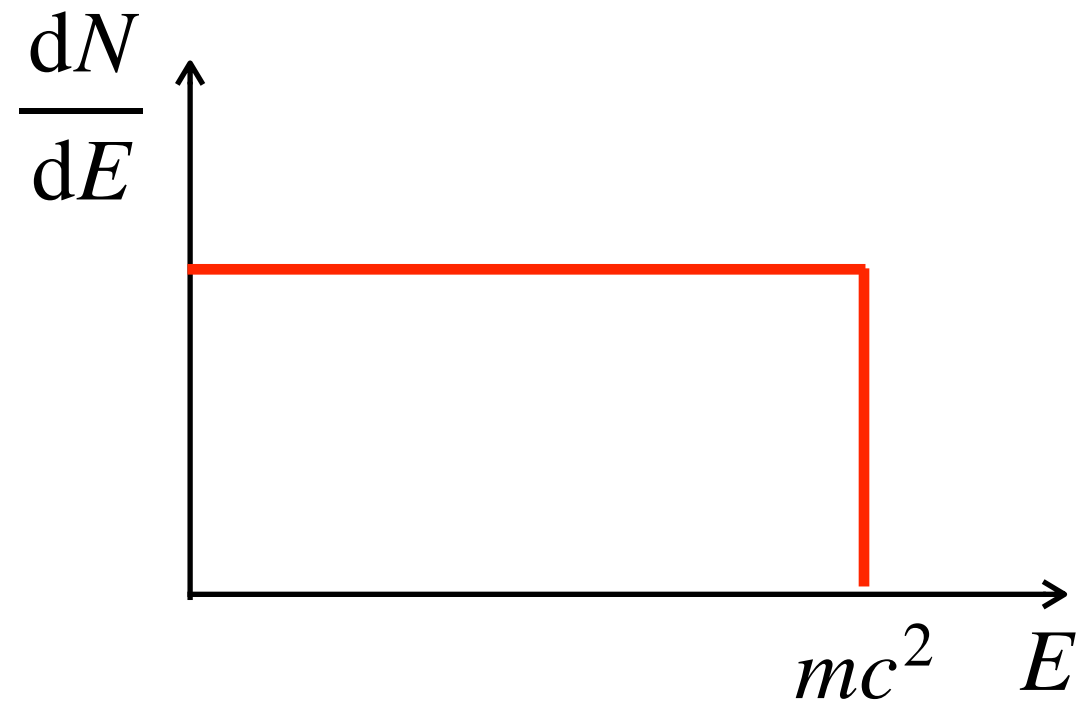
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 - the e^- will Compton scatter the virtual photon
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 - the spectrum of scattered photons (in the e^- rest frame) extends up to mc^2
 - in the lab frame the spectrum extends up to γmc^2 !

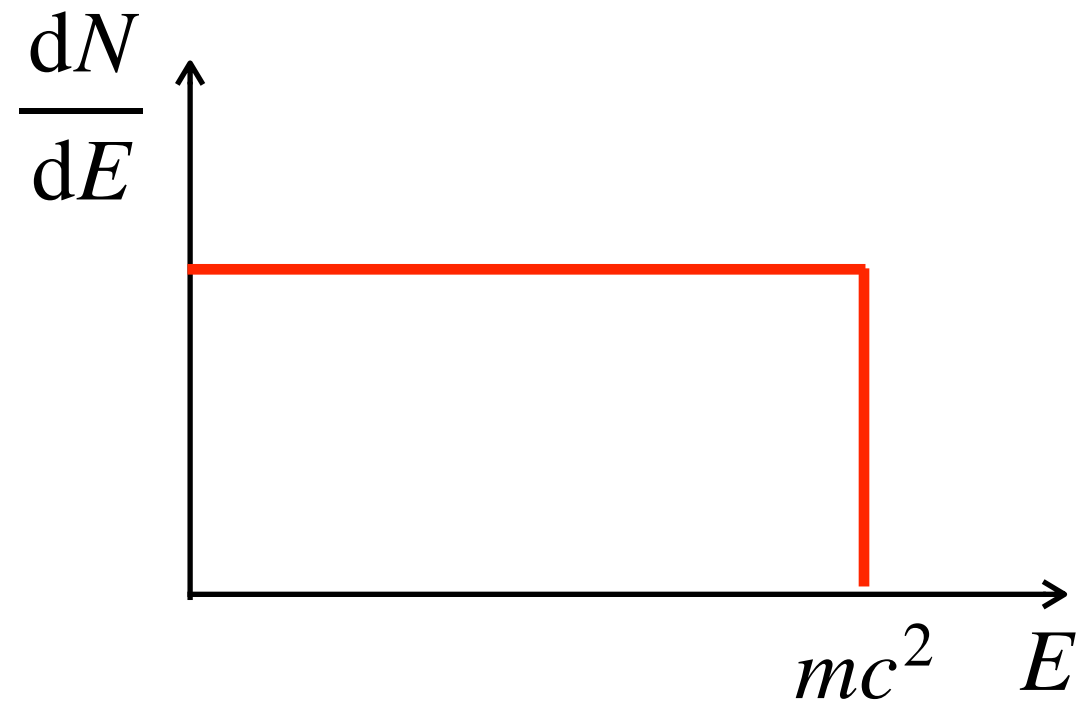
Non-thermal bremsstrahlung

electron frame

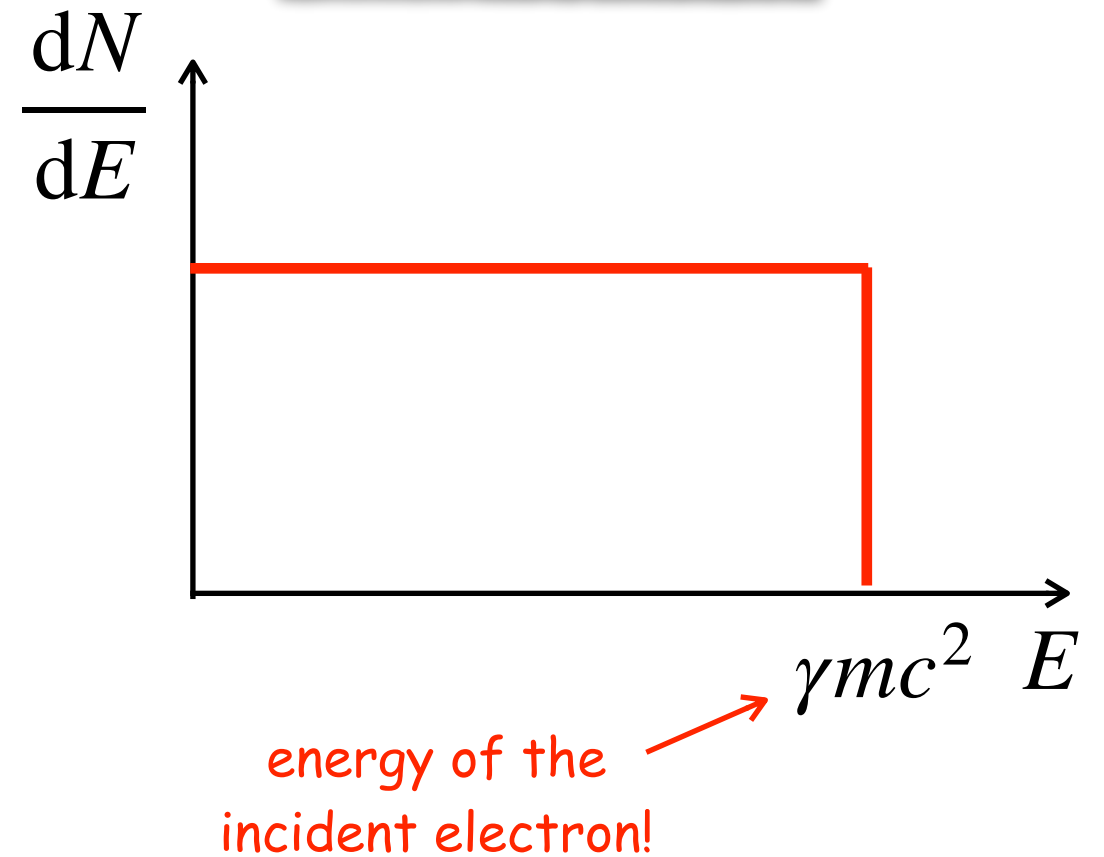


Non-thermal bremsstrahlung

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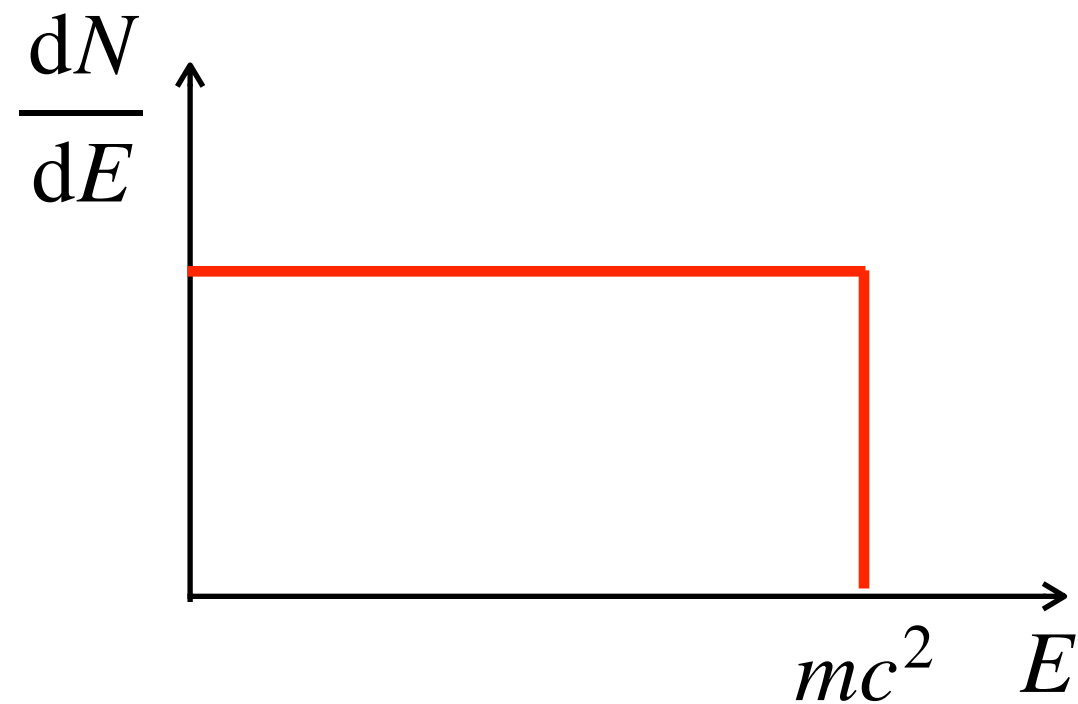


lab frame

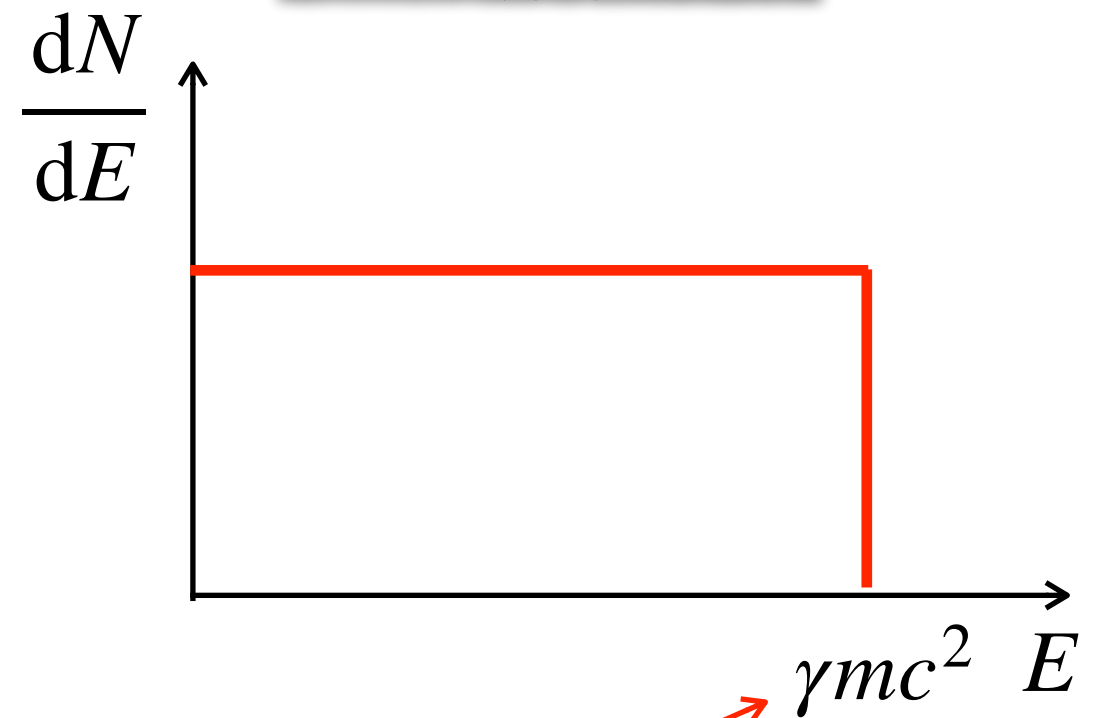


Non-thermal bremsstrahlung

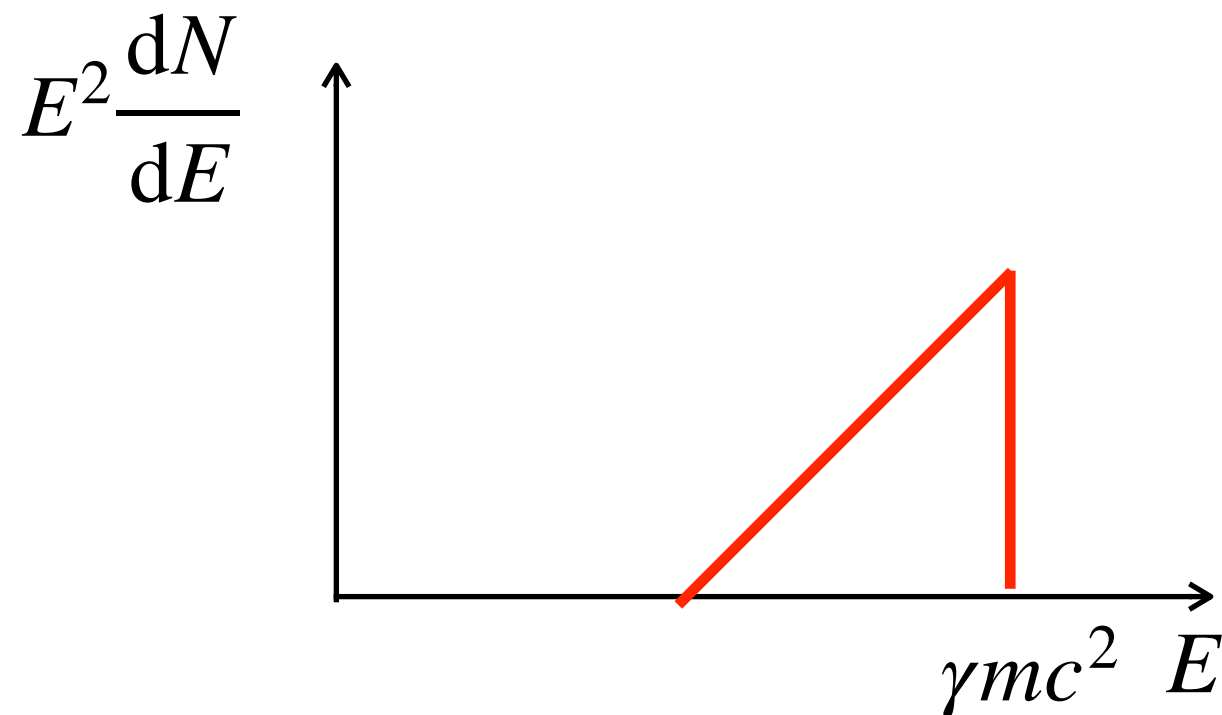
electron frame



lab frame

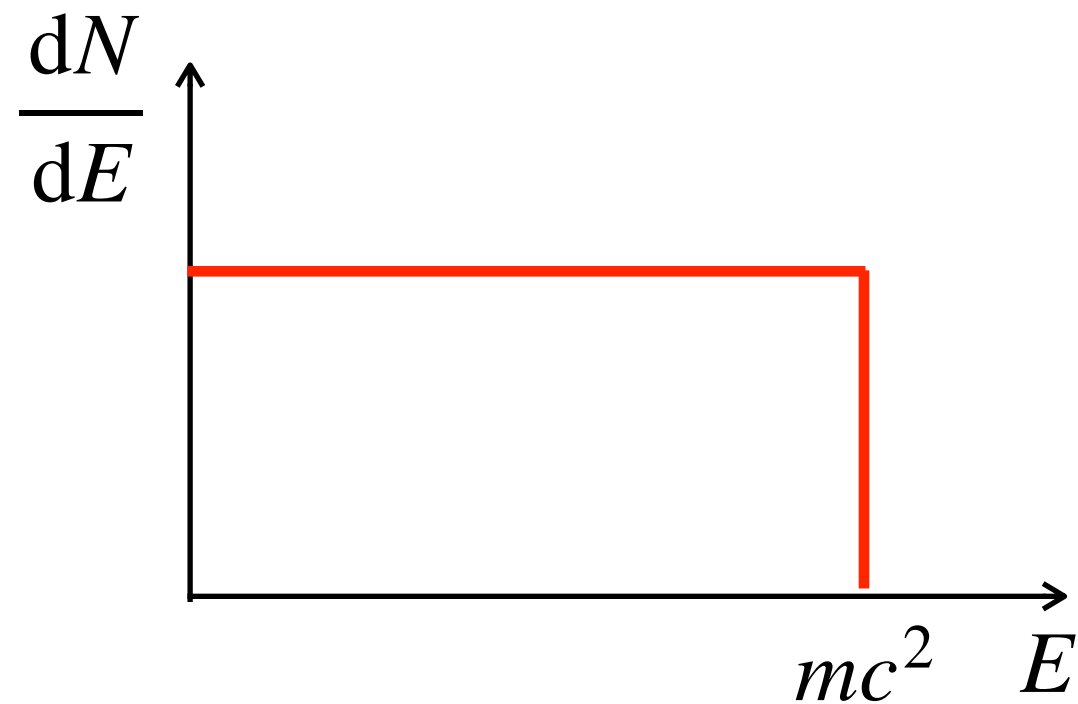


energy of the
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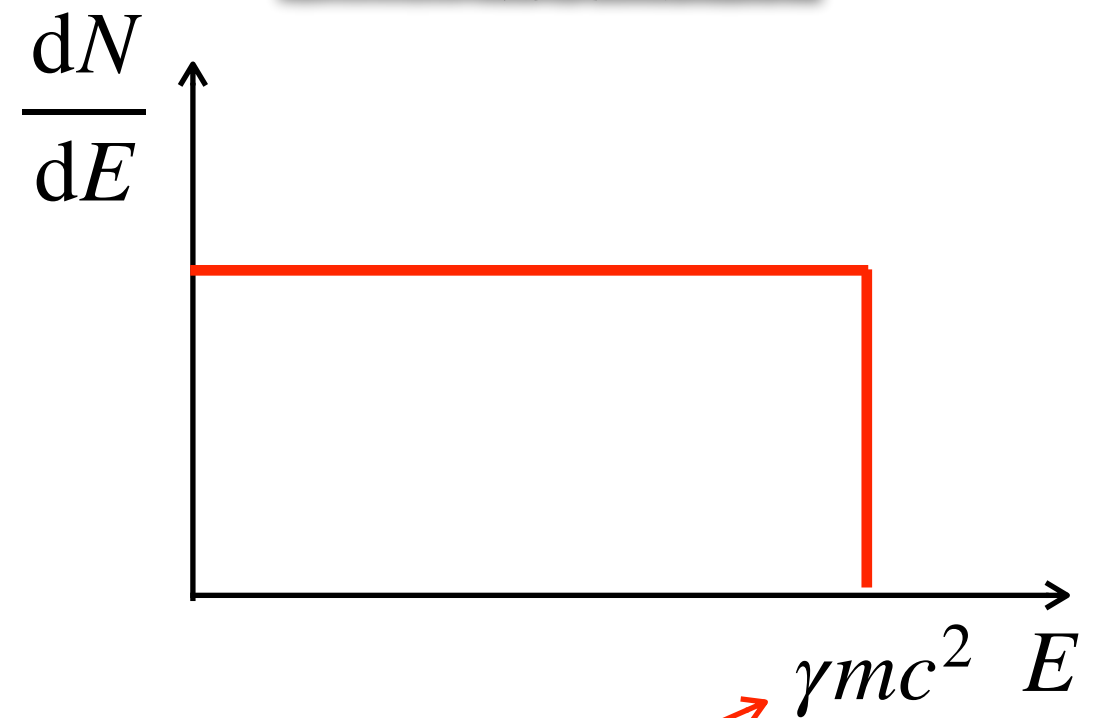


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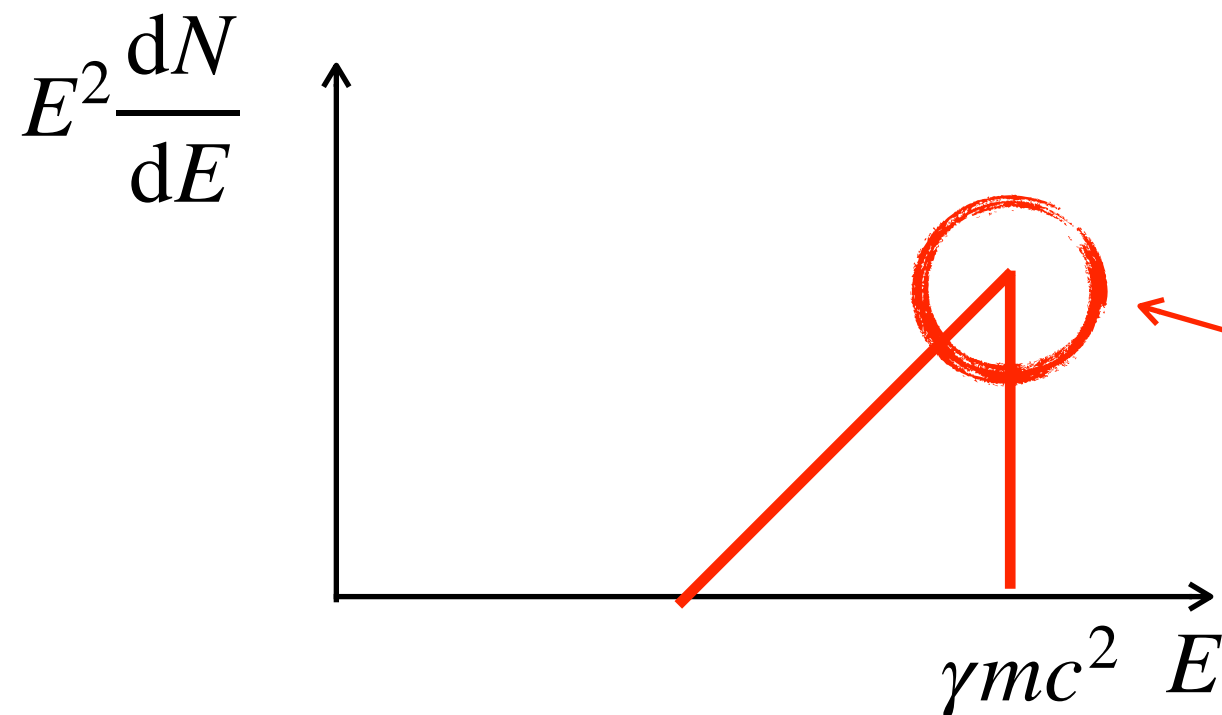
electron frame



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 →

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

same importance
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$$\tau_{syn/IC} \sim \frac{E}{dE/dt} \approx 1 \left(\frac{\omega_{TOT}}{0.25 \text{ eV/cm}^3} \right)^{-1} \left(\frac{E}{\text{TeV}} \right)^{-1} \text{ Myr}$$

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p-p interactions →

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

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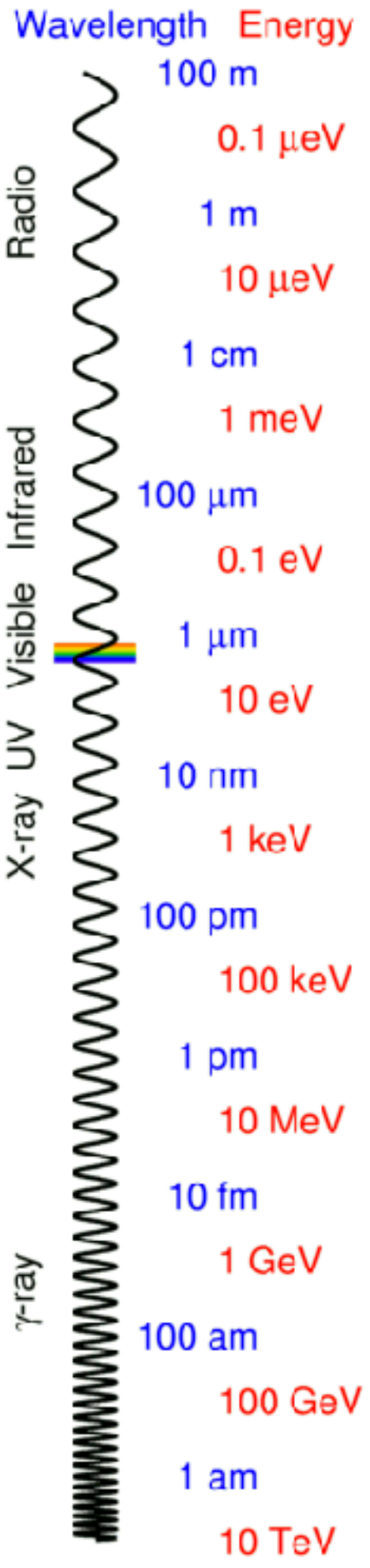
$$\tau_{pp} \sim 60 \left(\frac{n_{gas}}{\text{cm}^{-3}} \right)^{-1} \text{ Myr}$$

relativistic Bremsstrahlung →

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

ICS more effective in the TeV domain

GALACTIC NON-THERMAL EMISSIONS



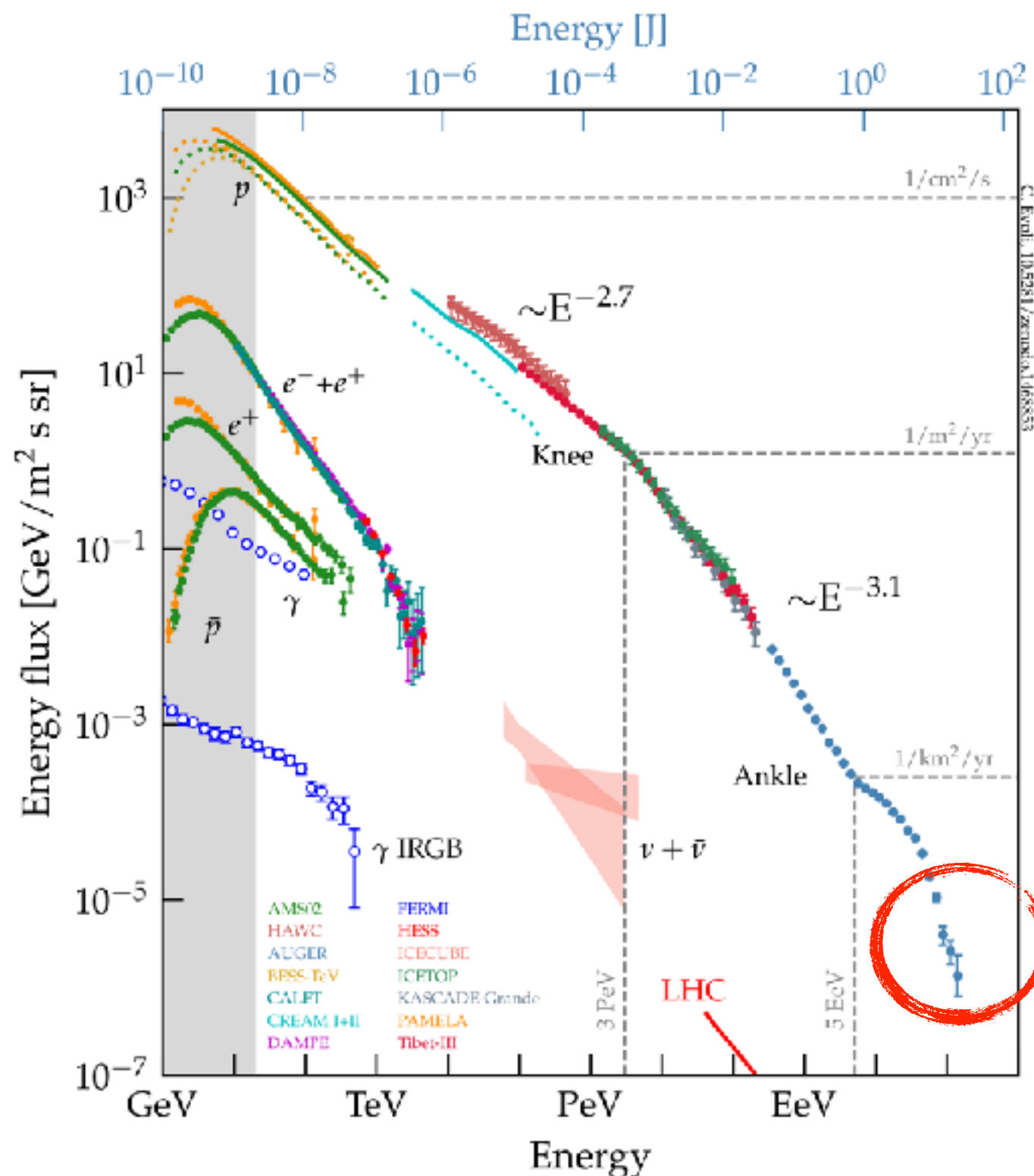
synchrotron emission
electrons in gal. B
 $E \sim 10 \text{ GeV}$ 100 TeV

Bremsstrahlung emission
electrons
 $E \sim \text{keV}$ MeV GeV TeV

inverse Compton scattering
electrons in CMB
 $E \sim \text{GeV}$ TeV 30 TeV

pp interactions
protons
 $E > 280 \text{ MeV}$

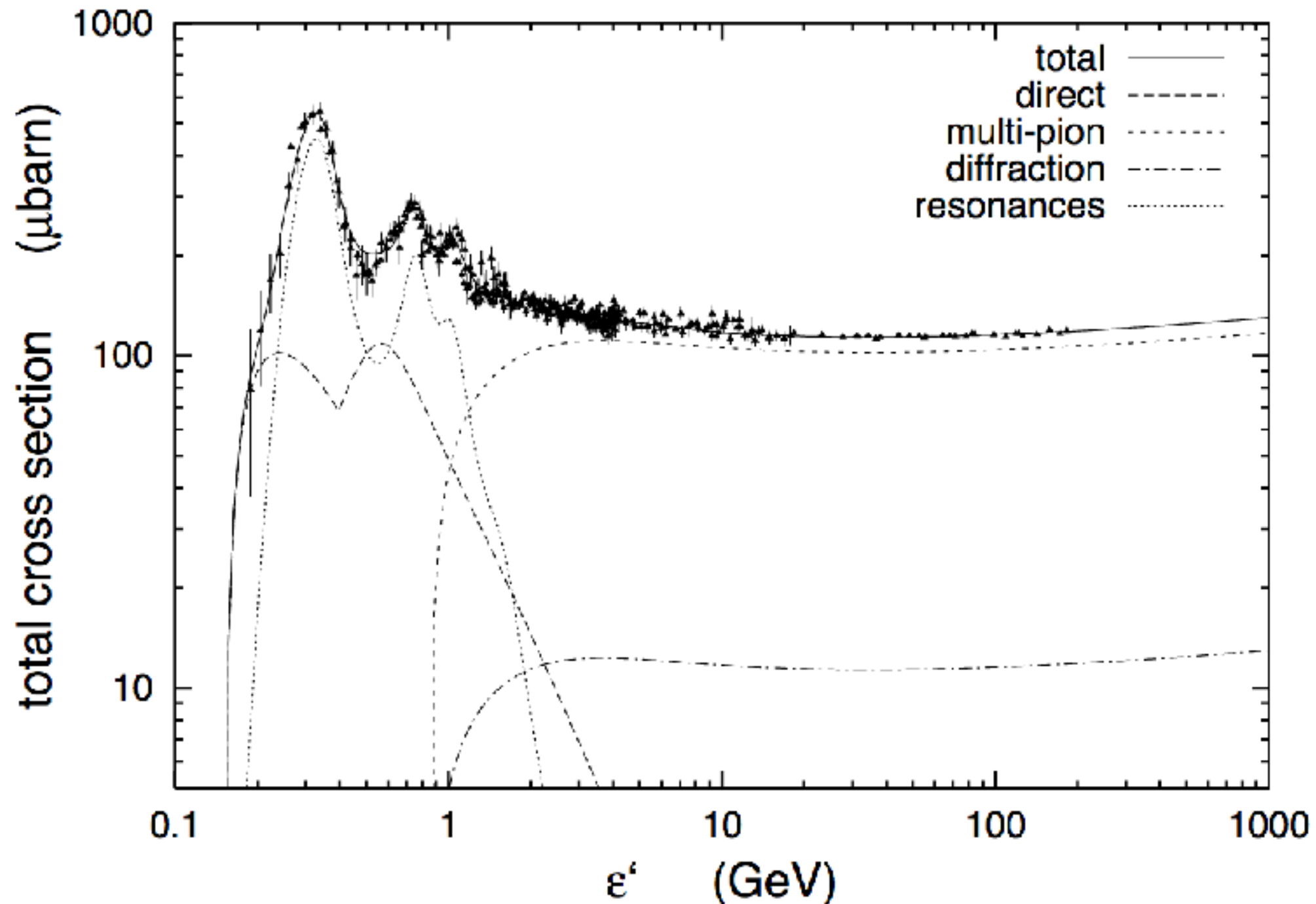
Question: where does the cosmic ray spectrum ends?



$\leftarrow 10^{20} \text{ eV}$

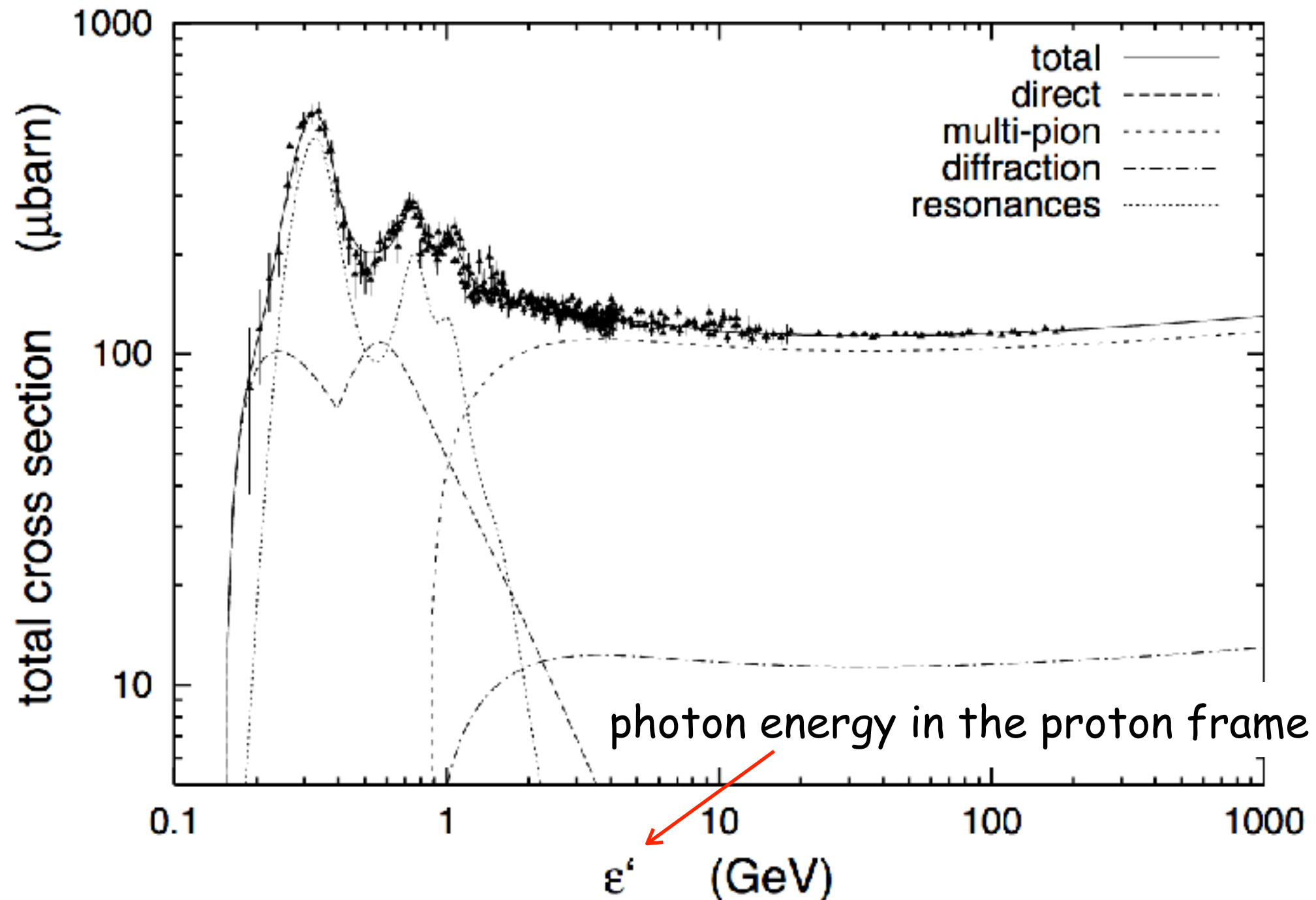
Photomeson production:

$$p\gamma \longrightarrow n\pi^+ \text{ or } p\pi^0$$



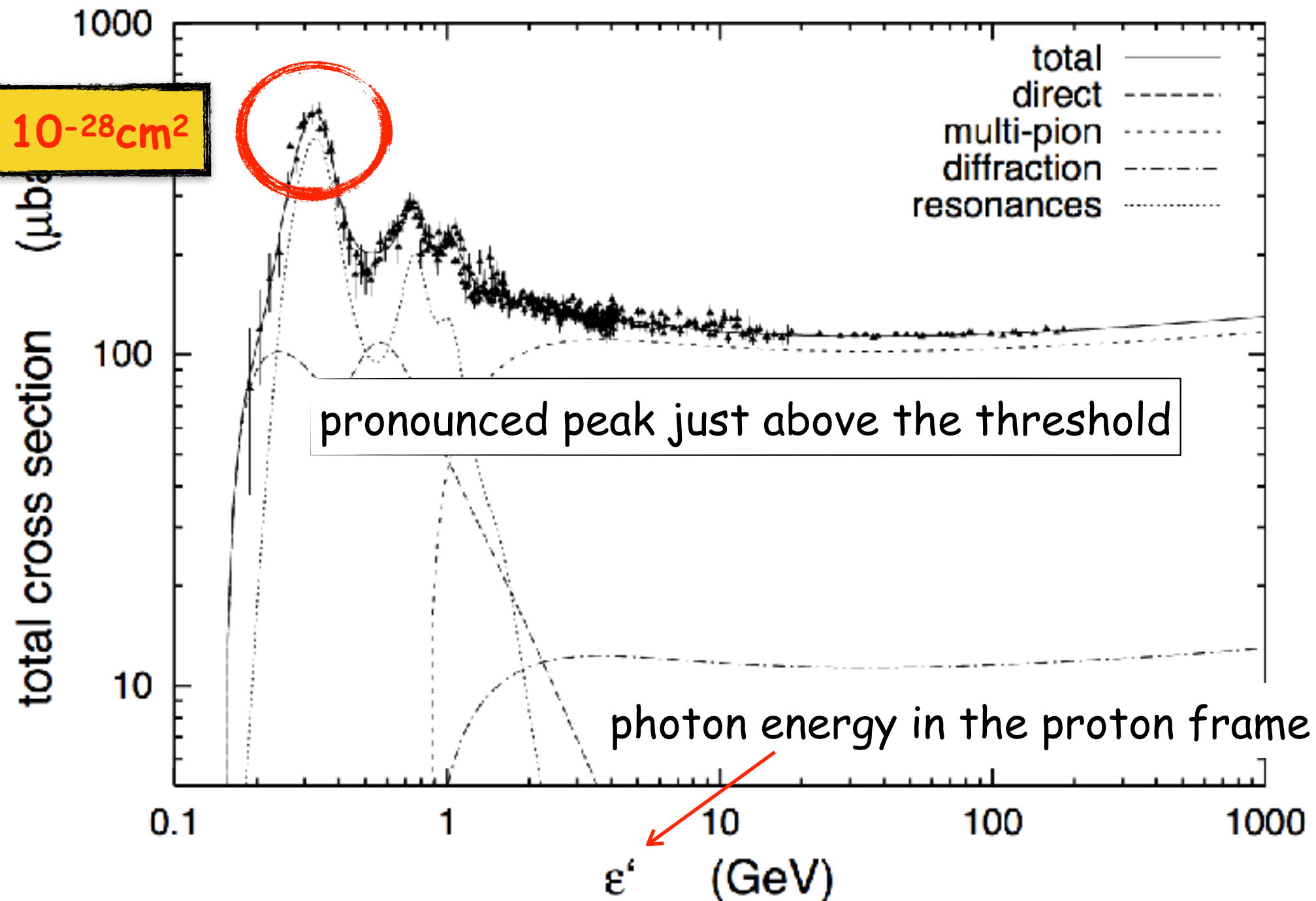
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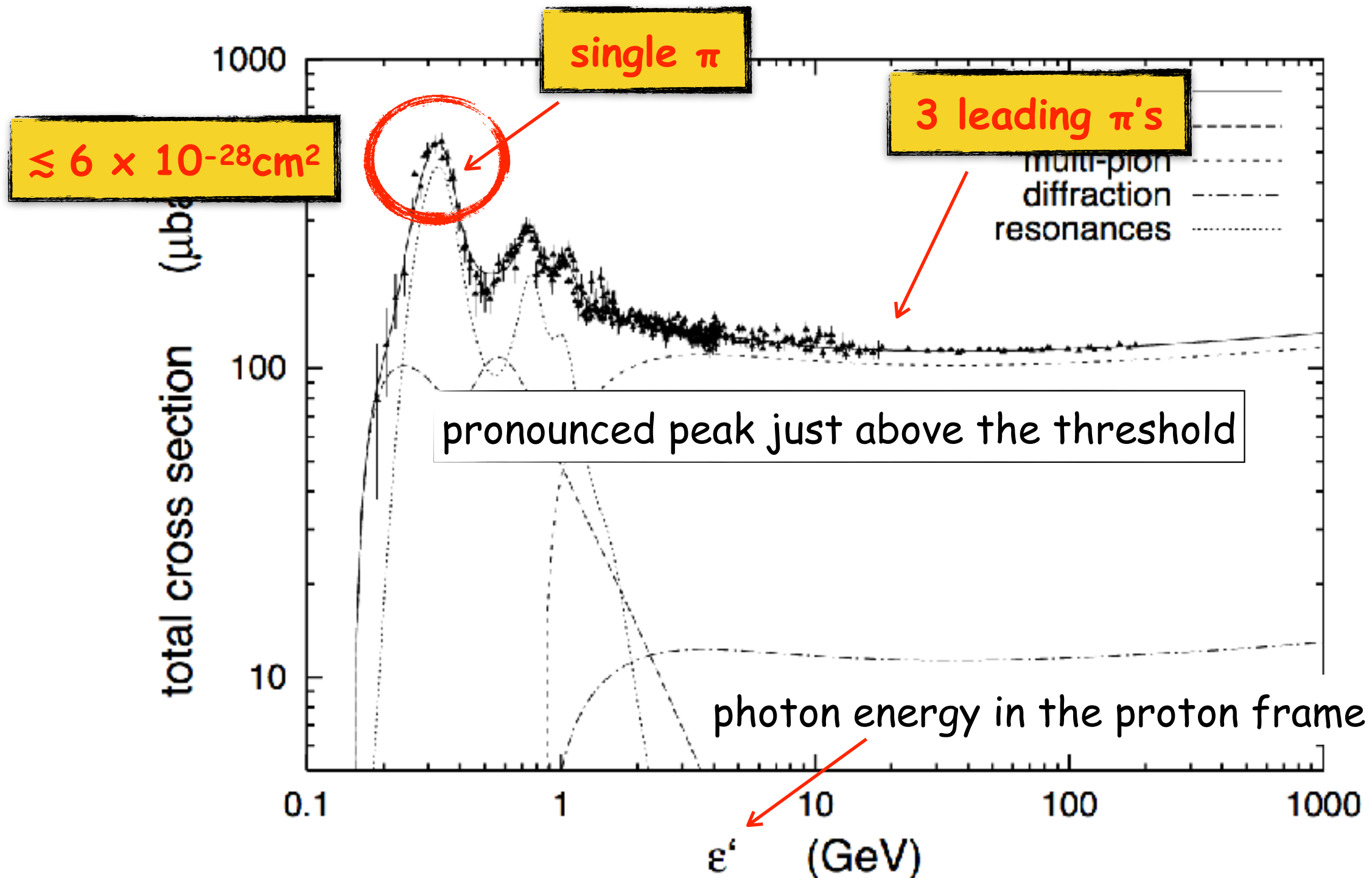
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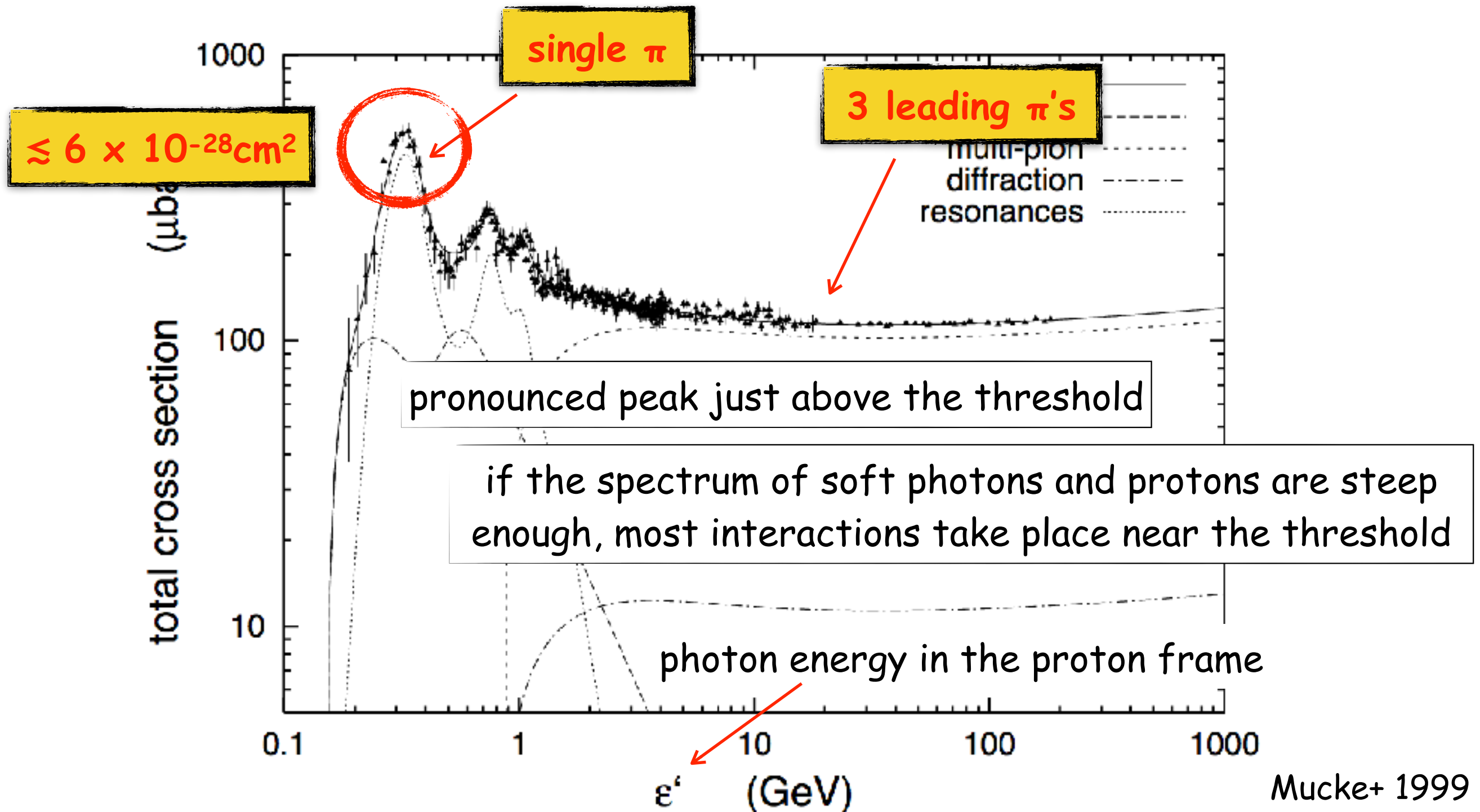
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Photomeson production: threshold

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

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energy in the center of mass frame

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

Photomeson production: threshold

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

energy in the center of mass frame

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

after the collision

and

$$\rightarrow s_{th} = m_p + m_\pi$$

at the threshold

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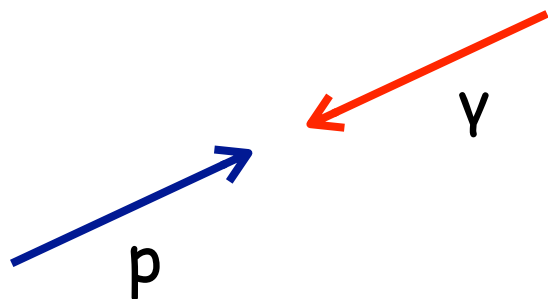
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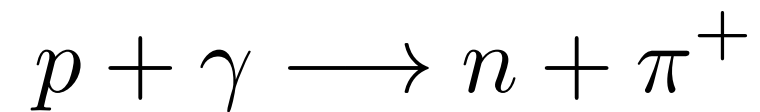
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Photomeson production: threshold



energy in the center of mass frame

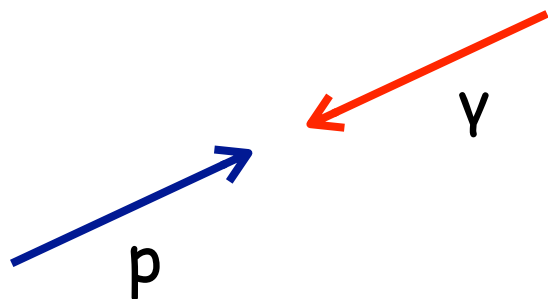
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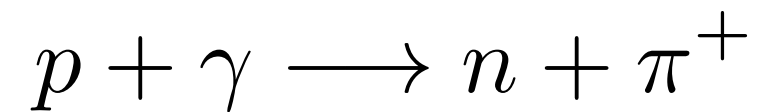
$\rightarrow s_{th} = m_p + m_\pi$

at the threshold



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

Photomeson production: threshold



energy in the center of mass frame

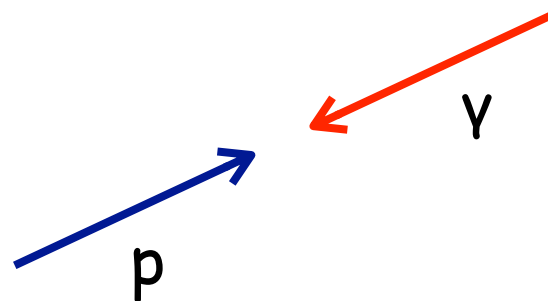
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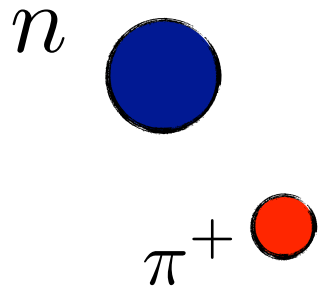
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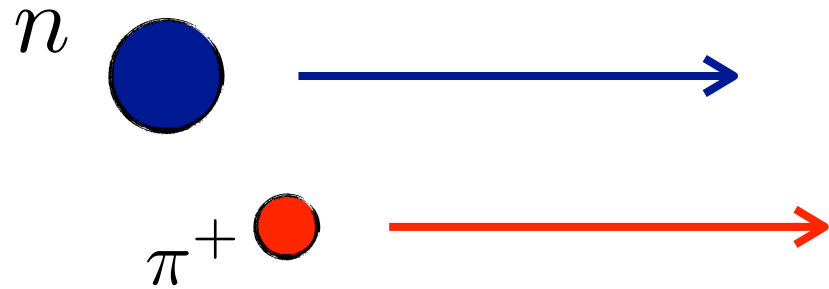
for CMB photons this is $\sim 10^{20}$ eV !

Photomeson production: threshold



produced at
rest in the CMF

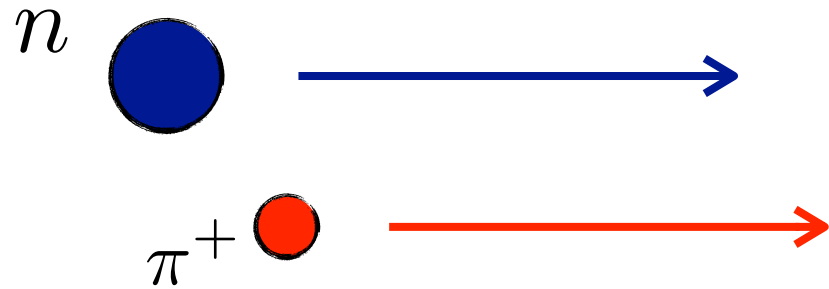
Photomeson production: threshold



produced at
rest in the CMF

boost to the
lab frame

Photomeson production: threshold

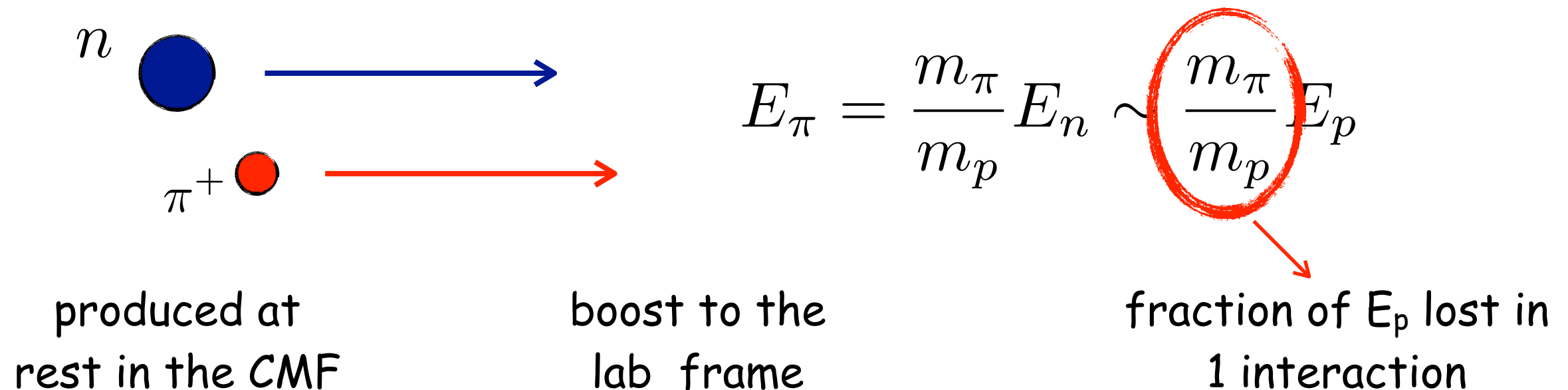


$$E_{\pi} = \frac{m_{\pi}}{m_p} E_n \sim \frac{m_{\pi}}{m_p} E_p$$

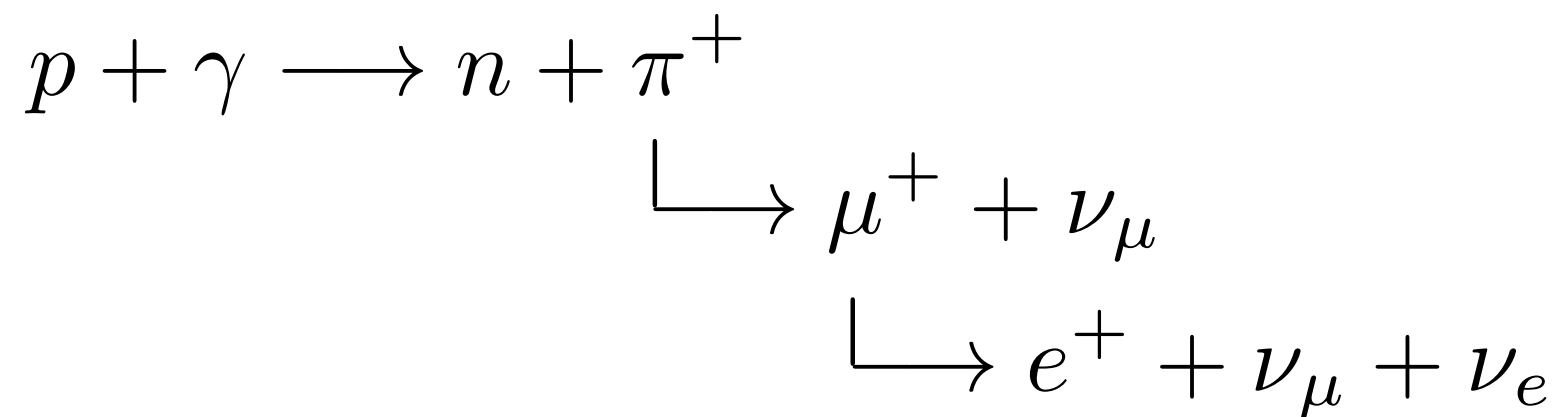
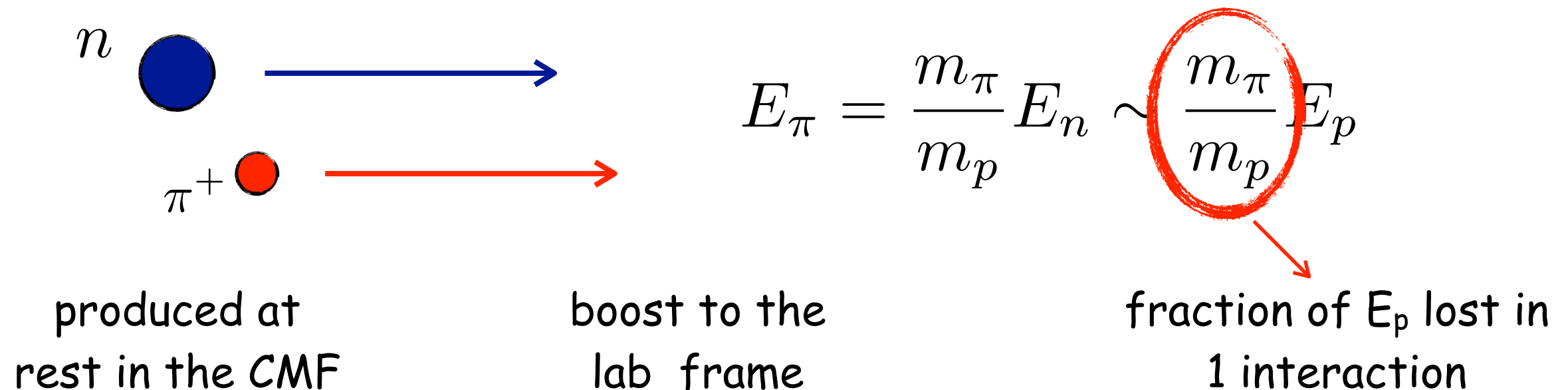
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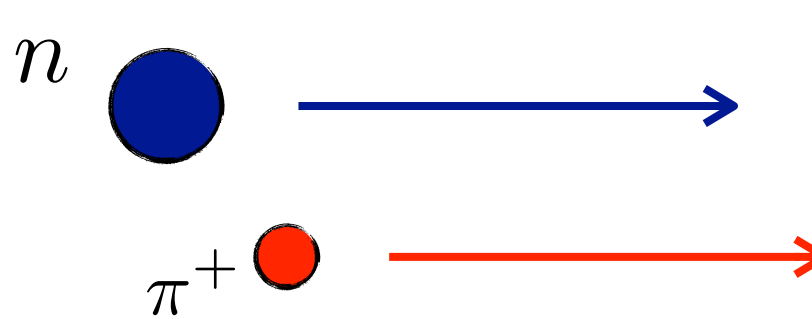
Photomeson production: threshold



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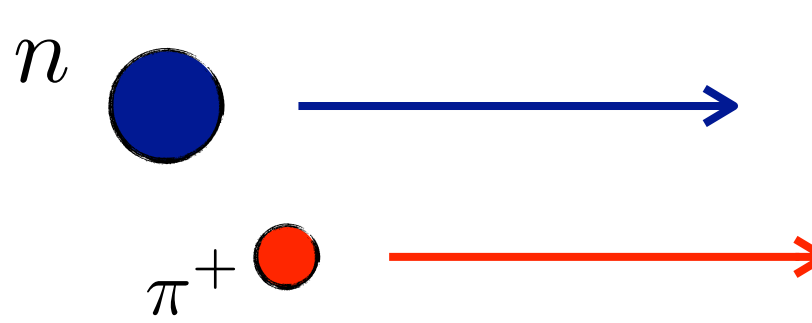
fraction of E_p lost in
1 interaction

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

$$\begin{aligned} &\longrightarrow \mu^+ + \nu_\mu \\ &\quad \longrightarrow e^+ + \nu_\mu + \nu_e \end{aligned}$$

4 stable particles carrying
~the same energy

Photomeson production: threshold



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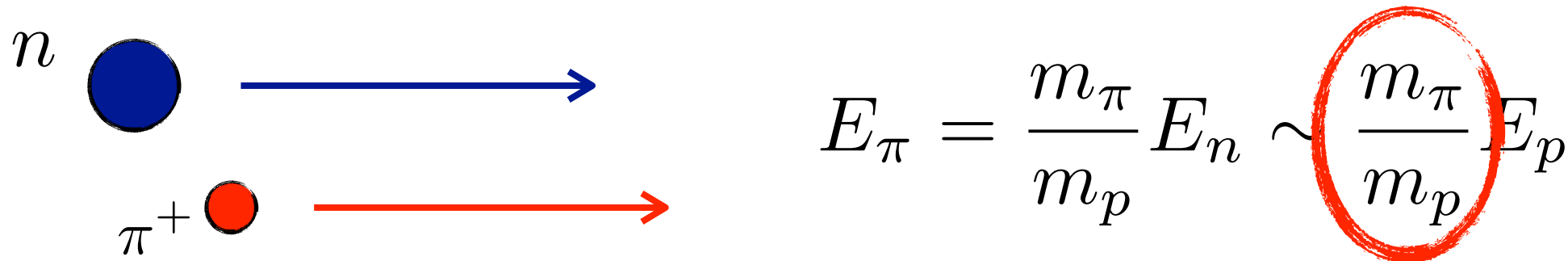
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$$E_\nu \sim \left(\frac{m_\pi}{4m_p} \right) E_p$$

Photomeson production: threshold



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produced at
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boost to the
lab frame

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4 stable particles carrying
~the same energy

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

Absorption of gamma rays

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

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Absorption of gamma rays

50% of the times

$$p + \gamma \longrightarrow p + \pi^0 \\ \quad \searrow \longrightarrow \gamma + \gamma$$

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■ 2 stable particles of average energy

$$E_\gamma \sim \left(\frac{m_\pi}{2m_p} \right) E_p \sim 2 E_\nu$$

Absorption of gamma rays

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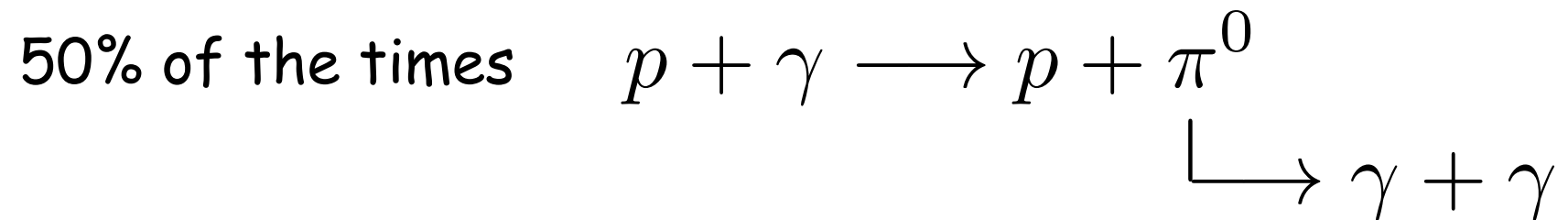
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threshold energy pair production

$$\gamma + \gamma \rightarrow e^+ + e^-$$

$$E_\gamma \epsilon_\gamma (1 - \cos \vartheta) > 2 m_e^2$$

Absorption of gamma rays

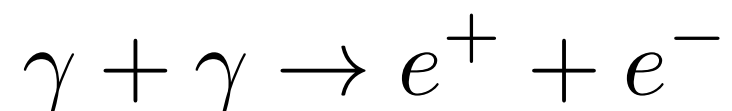


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Absorption of gamma rays

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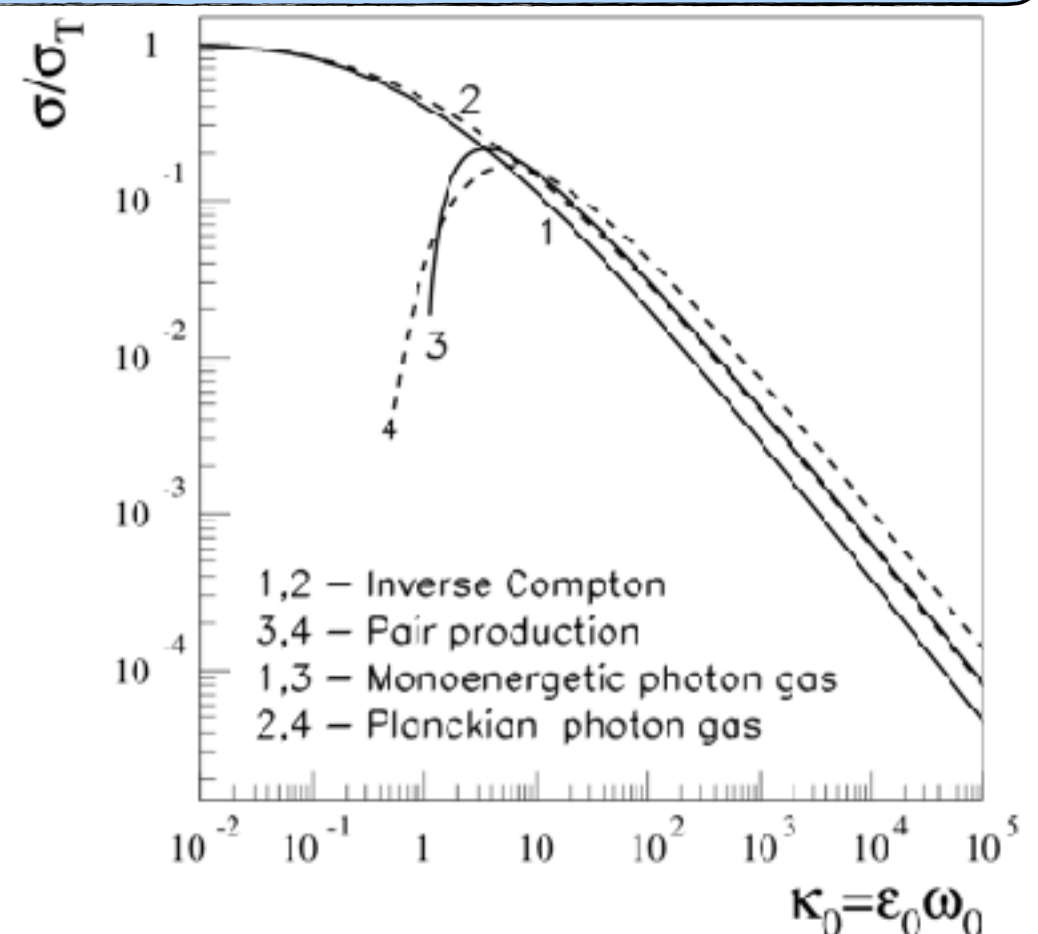
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$$E_\gamma \epsilon_\gamma (1 - \cos \vartheta) > 2 m_e^2$$

$$E_{\gamma}^{min} \approx 0.3 \left(\frac{\epsilon_{\gamma}}{\text{eV}} \right)^{-1} \text{TeV}$$

$$E_\gamma \sim \left(\frac{m_\pi}{2m_p} \right) E_p \sim 2 E_\nu$$



Absorption of gamma rays

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

■ the π^0 carries a fraction of the proton energy equal to $\frac{m_\pi}{m_p}$

■ 2 stable particles of average energy

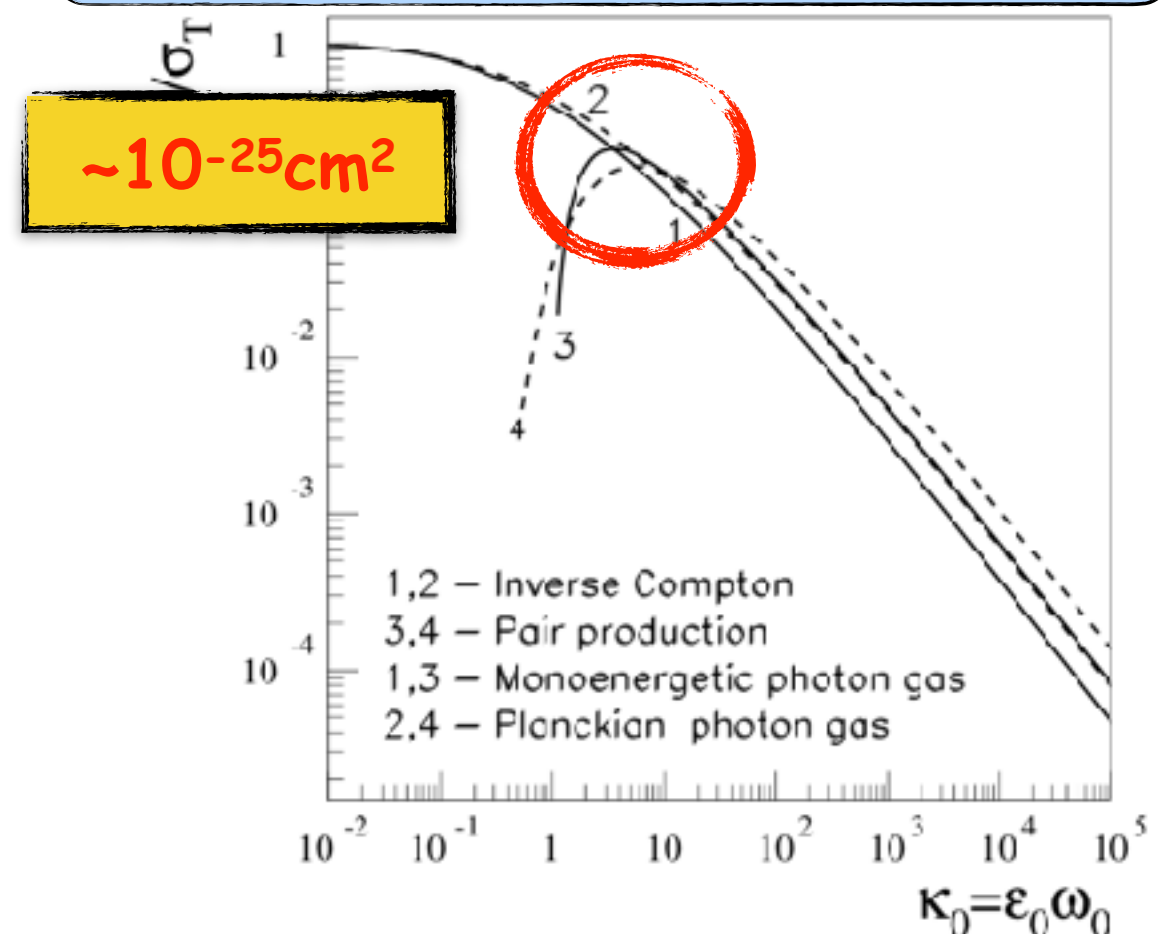
threshold energy pair production

$$\gamma + \gamma \rightarrow e^+ + e^-$$

$$E_\gamma \epsilon_\gamma (1 - \cos \vartheta) > 2 m_e^2$$

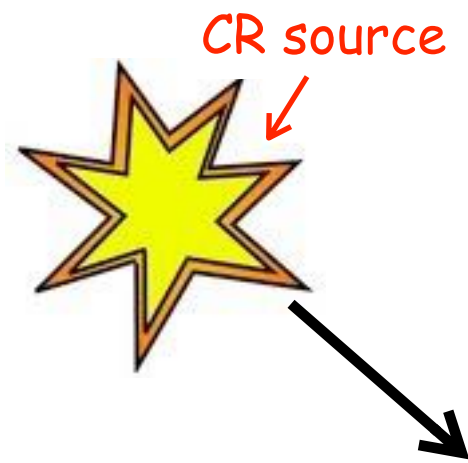
$$E_{\gamma}^{min} \approx 0.3 \left(\frac{\epsilon_{\gamma}}{\text{eV}} \right)^{-1} \text{TeV}$$

$$E_\gamma \sim \left(\frac{m_\pi}{2m_p} \right) E_p \sim 2 E_\nu$$



Where do photons go?

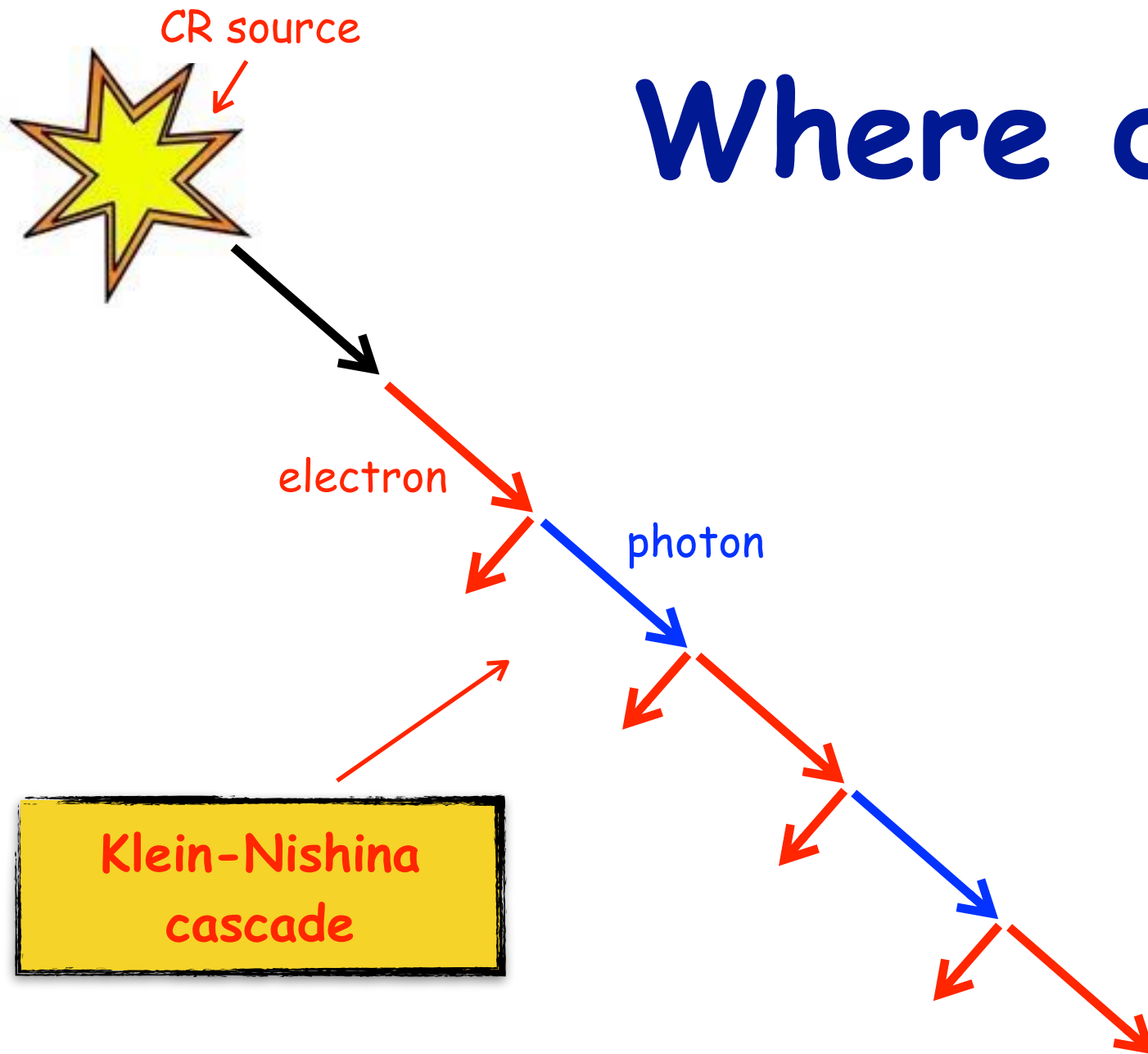




Where do photons go?



Where do photons go?



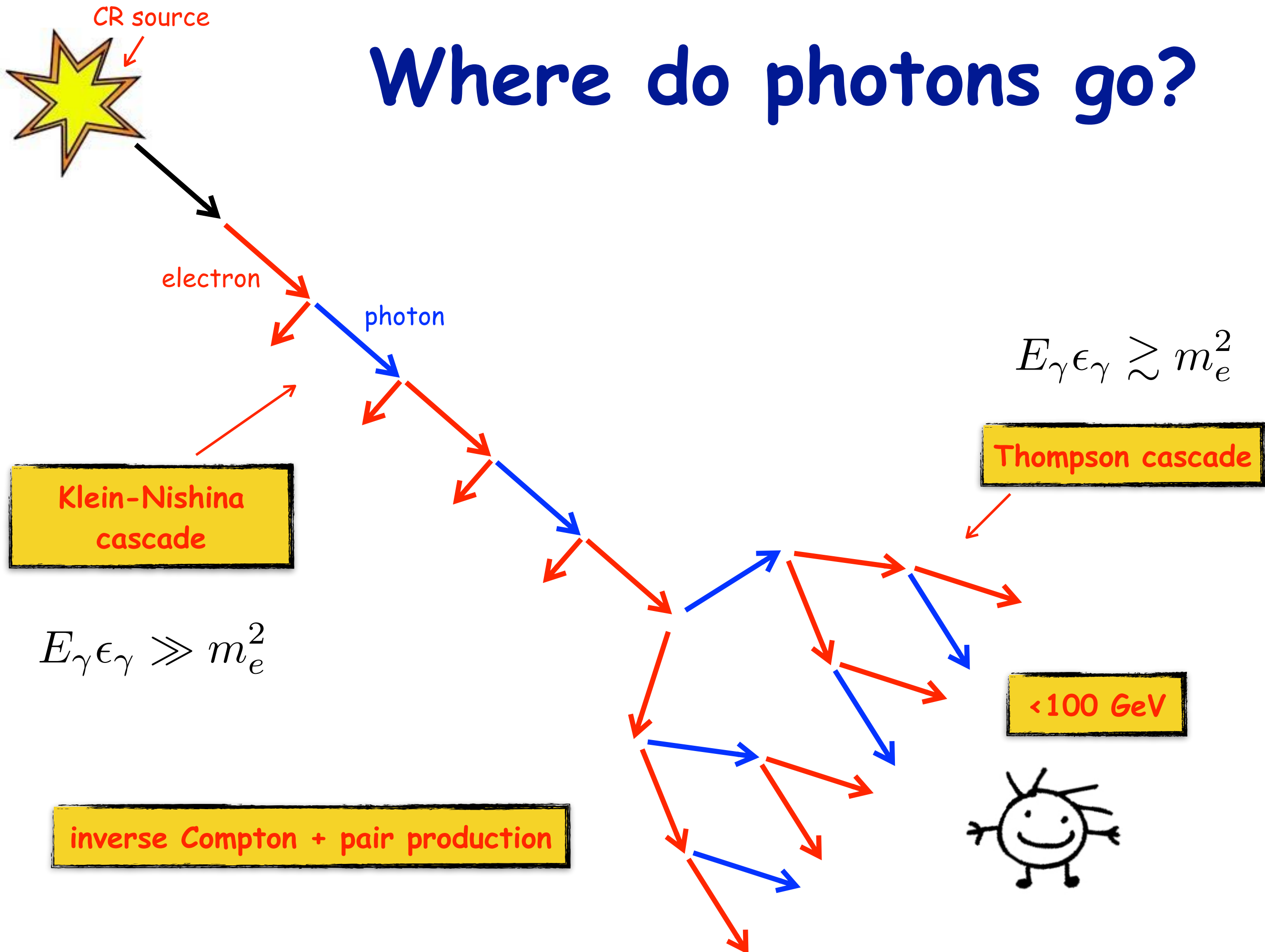
Klein-Nishina
cascade

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

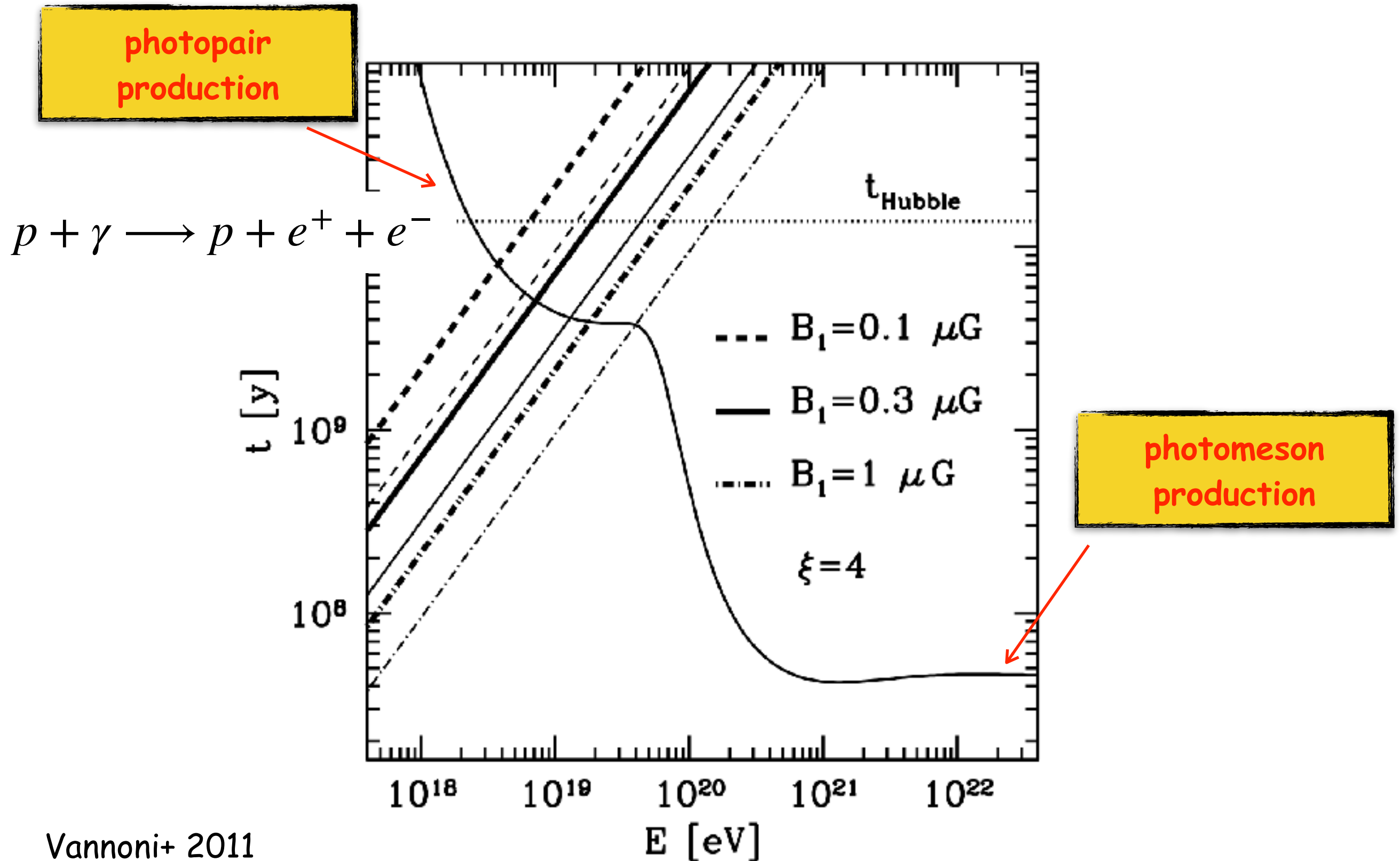
inverse Compton + pair production



Where do photons go?

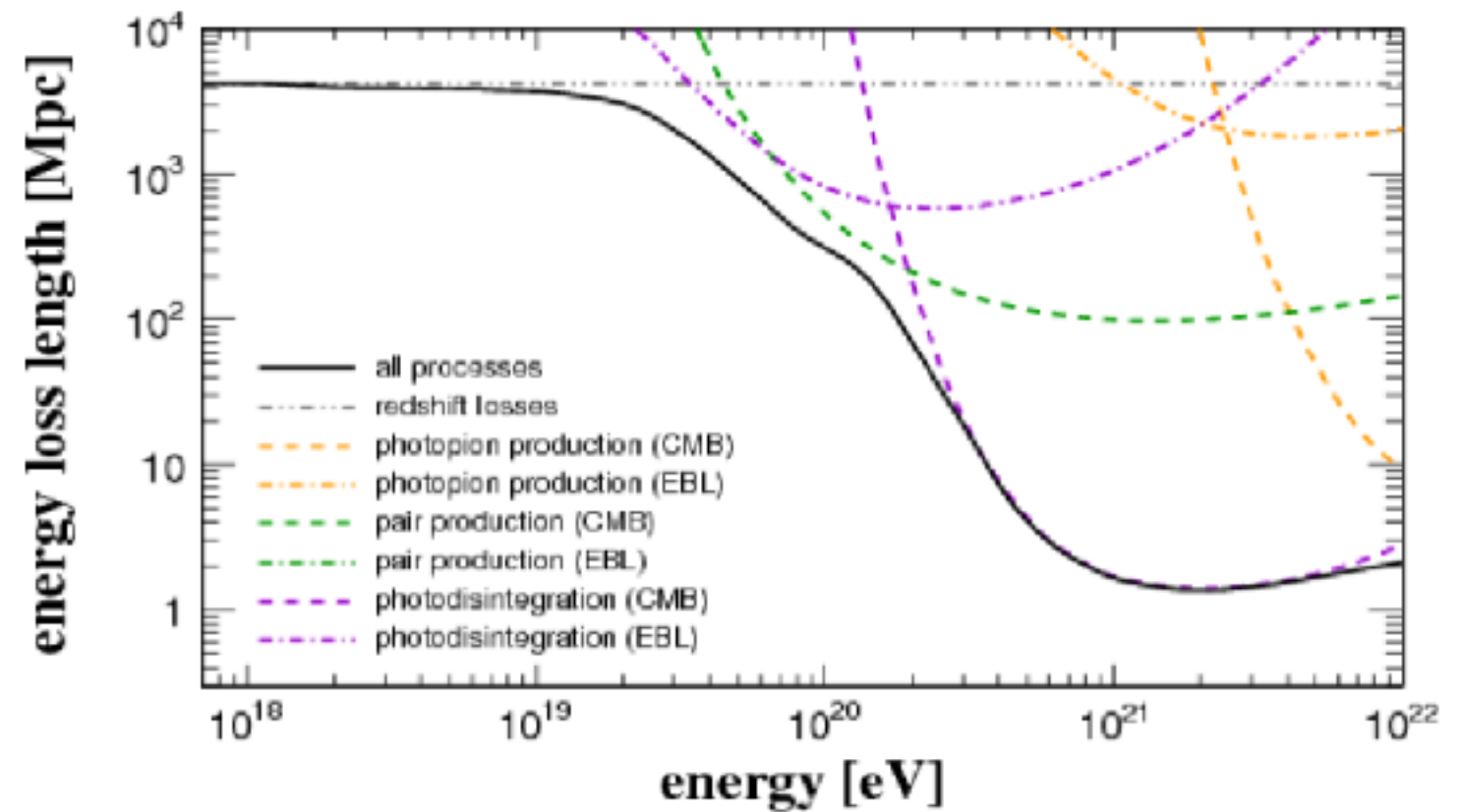
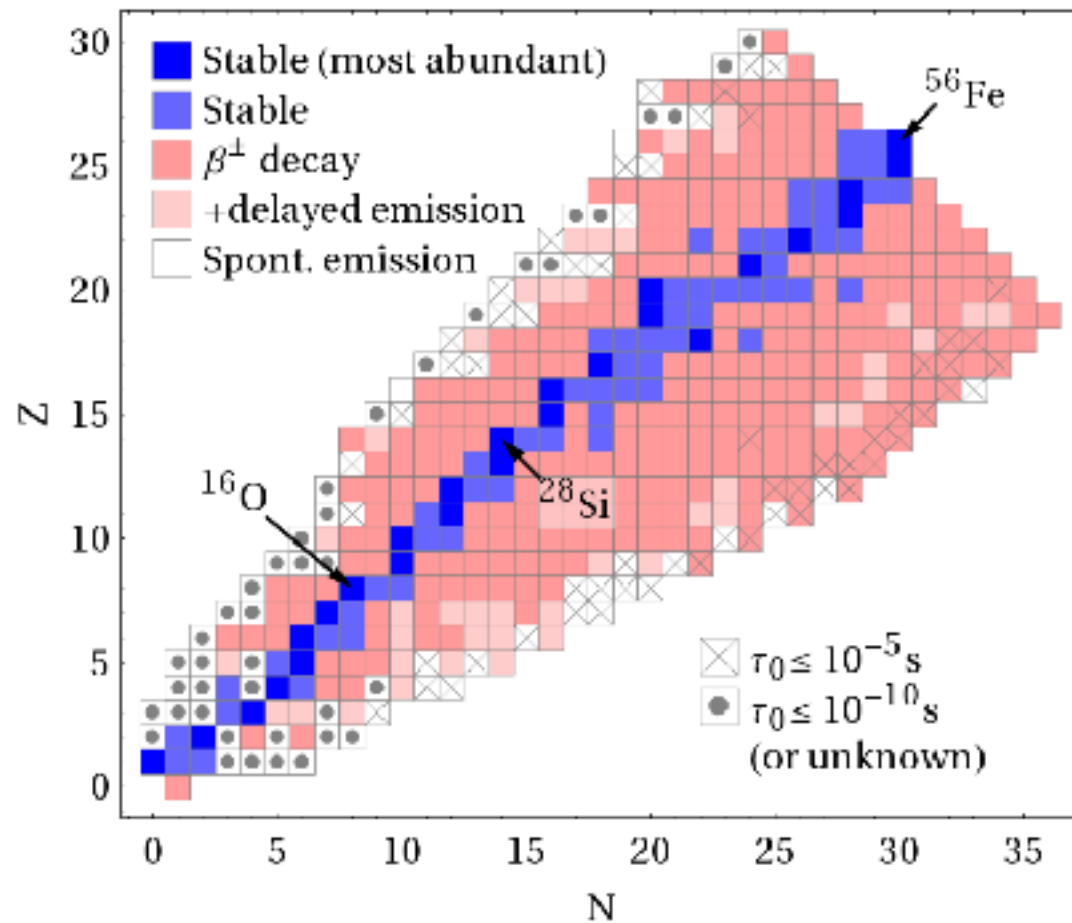


Photopair production



What about heavy nuclei?

Photodisintegration



for a review see Boncioli 2023