



Astroparticles

Cosmic rays, Neutrinos and Gamma rays

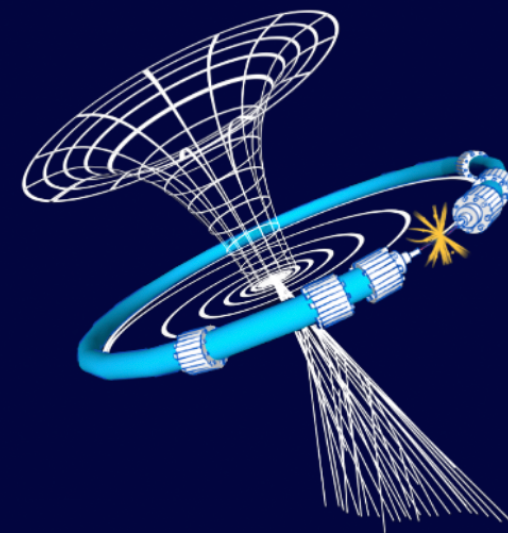
Arman Esmaili

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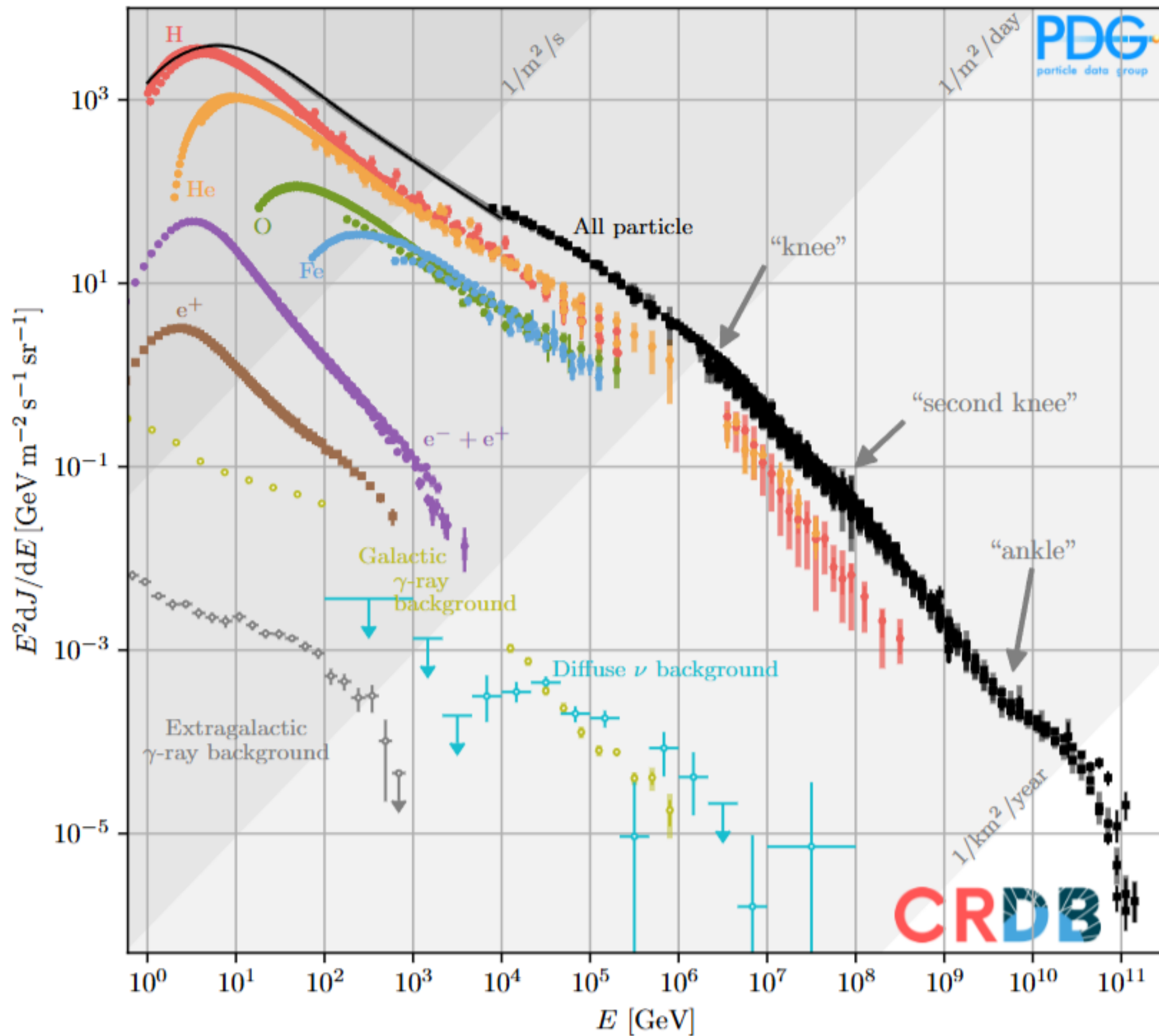
15th IDPASC Summer School

20 - 29 July 2026

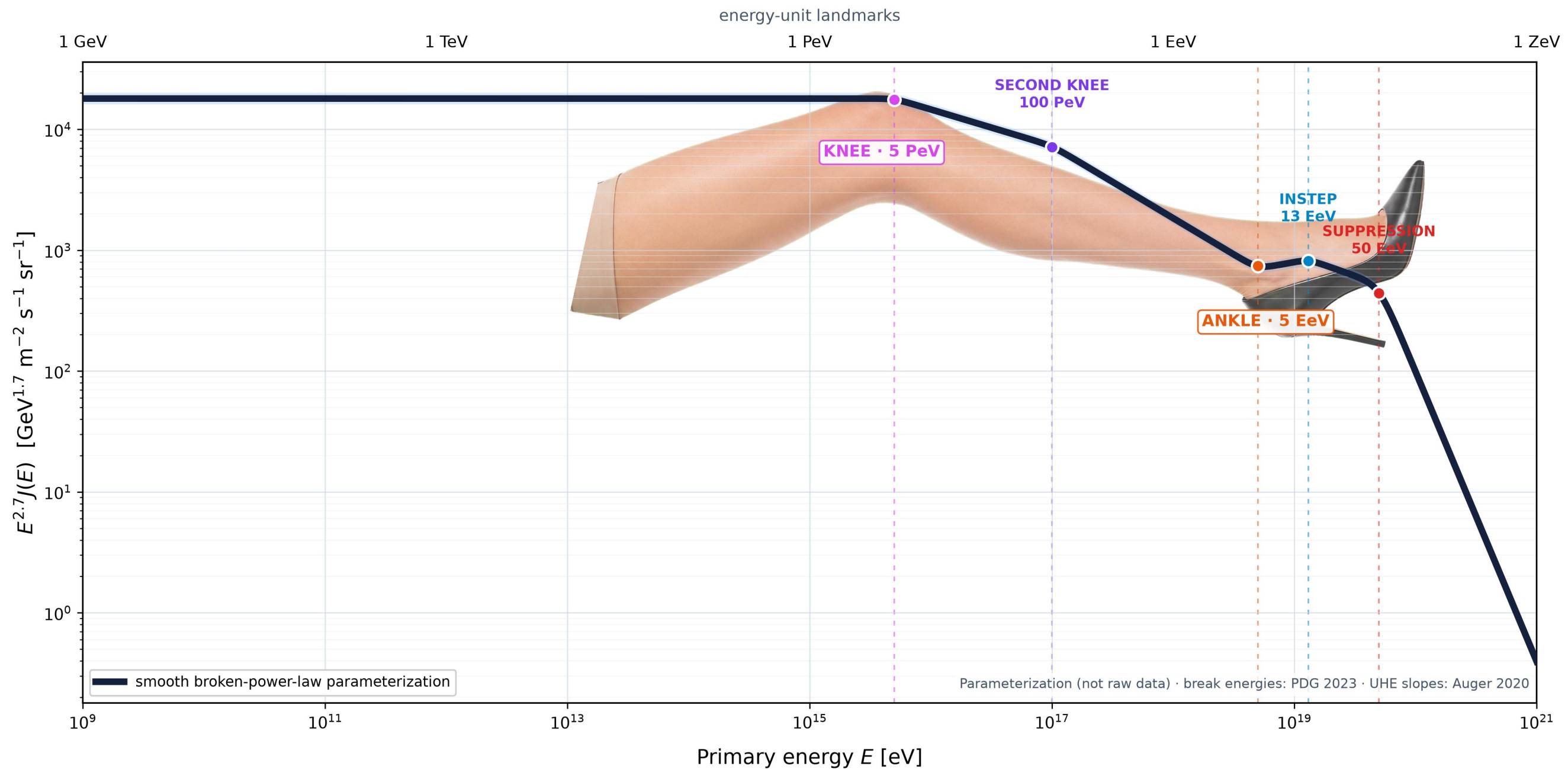
Natal, Brazil



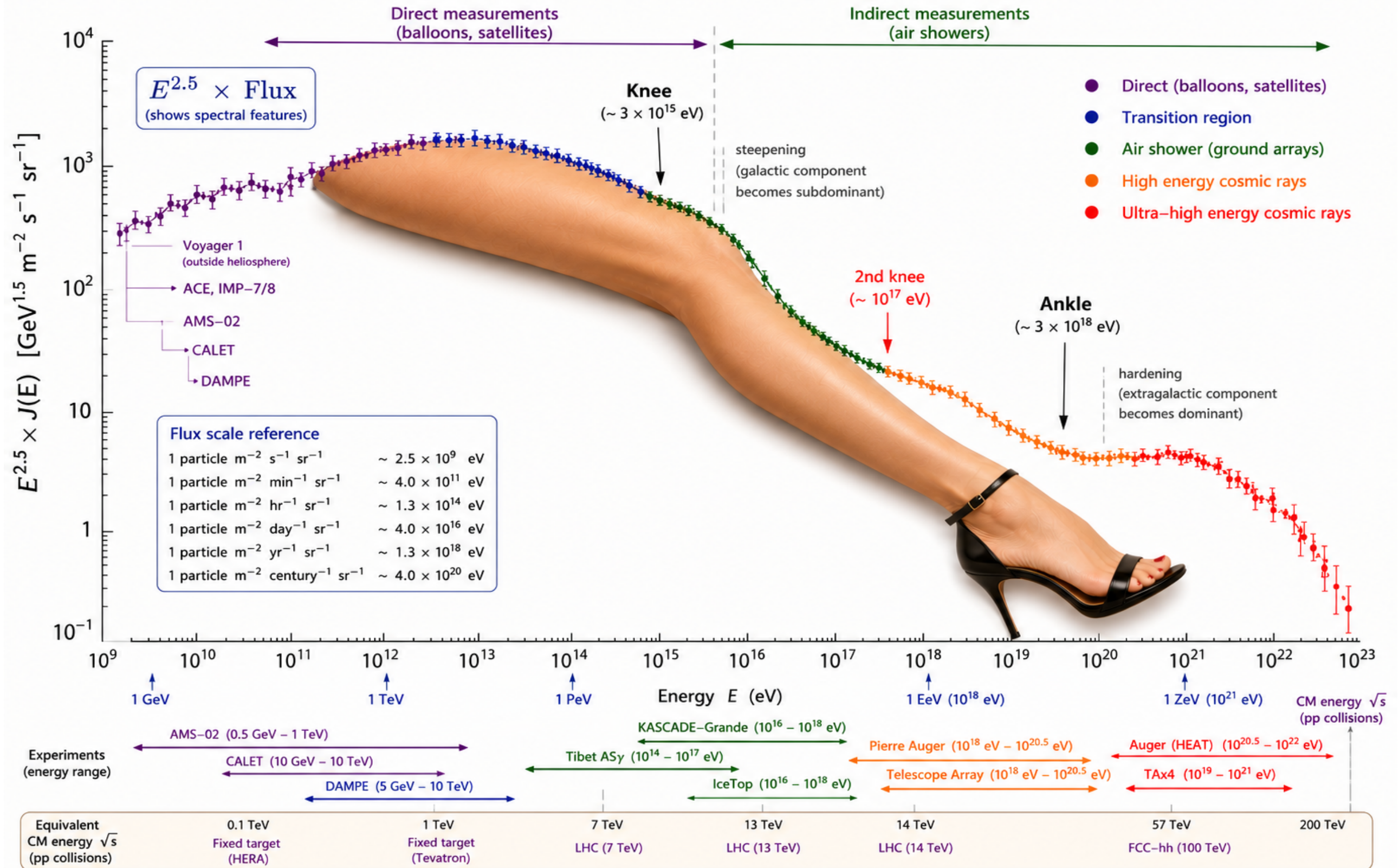
Cosmic Rays



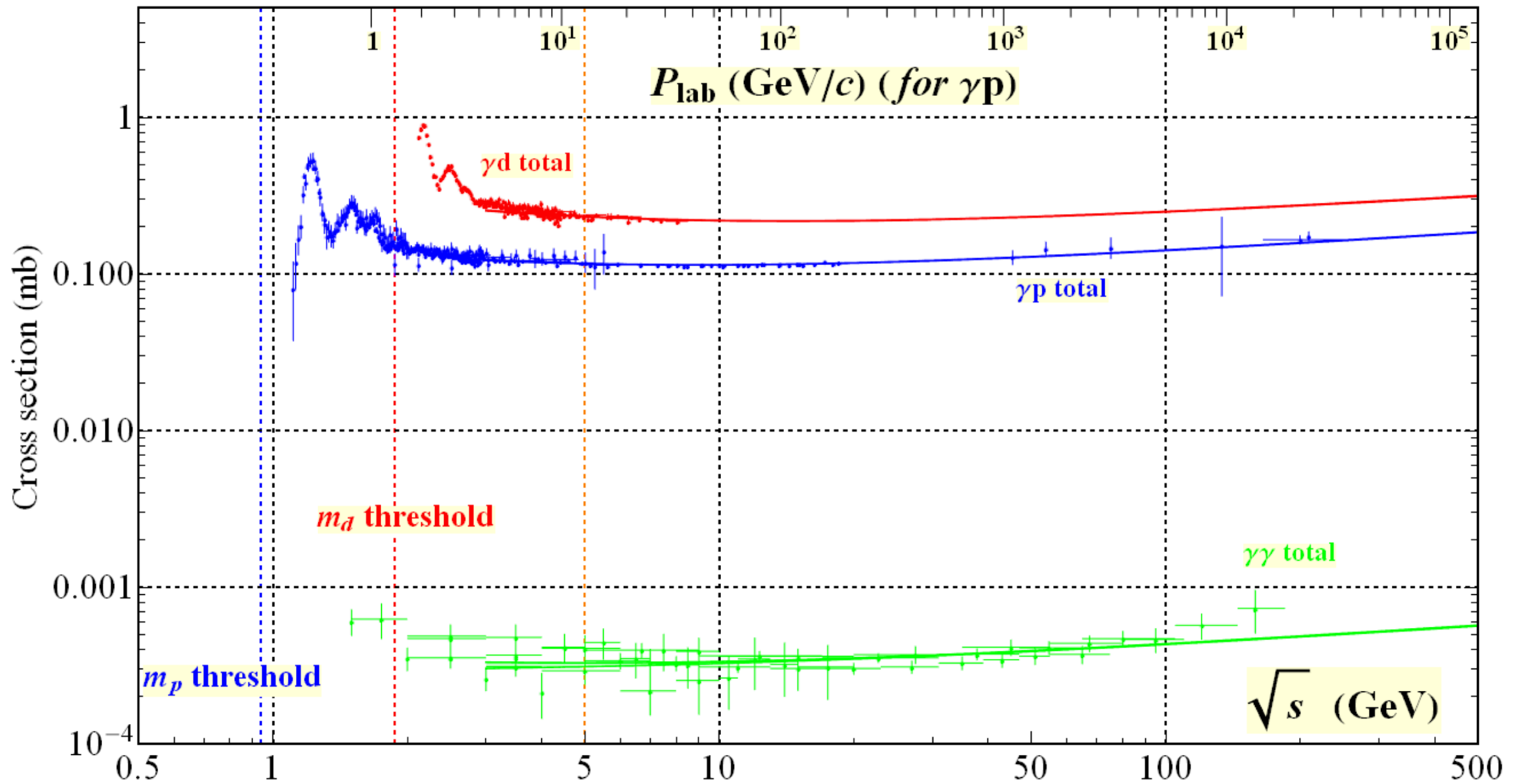
Cosmic Rays



All-particle cosmic-ray spectrum

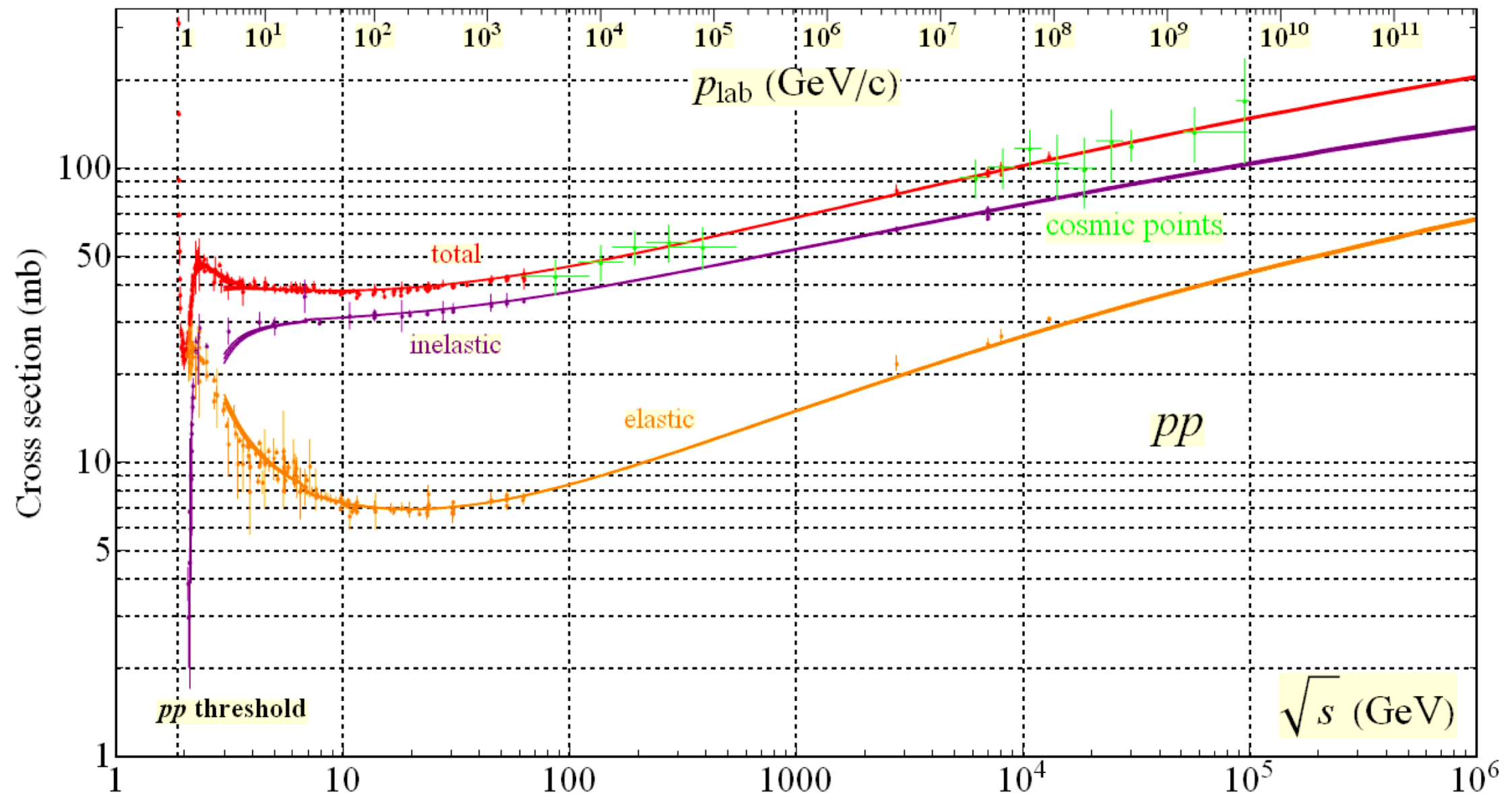


Cosmic Rays



$\gamma\gamma$ cross section, PDG

Cosmic Rays

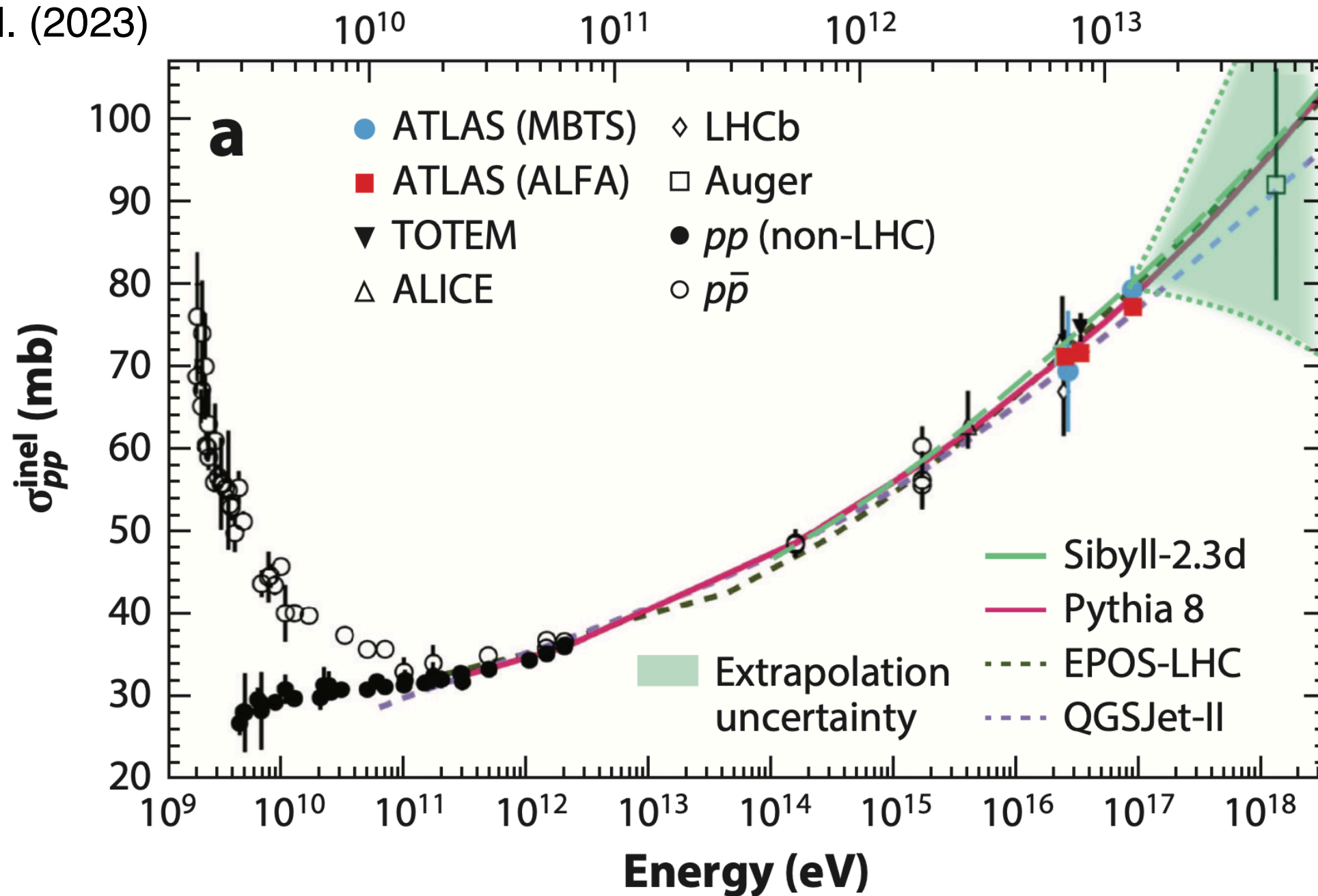


pp cross section, PDG

Cosmic Rays

Equivalent center-of-mass energy (eV) $\sqrt{s_{pp}}$ (eV)

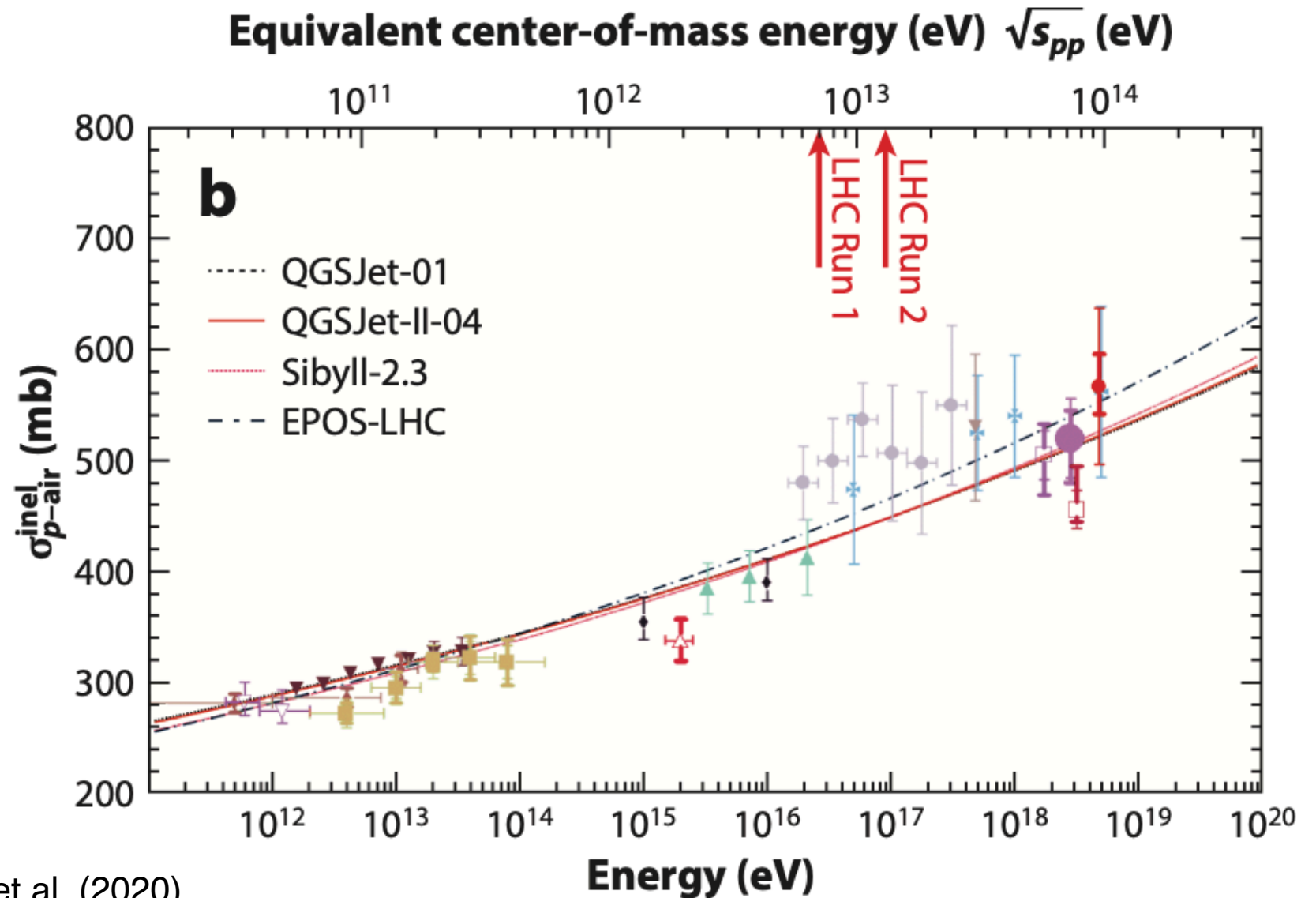
Aad et al. (2023)



Inelastic cross-section measurements and model predictions for pp interactions as a function of energy.

Cosmic Rays

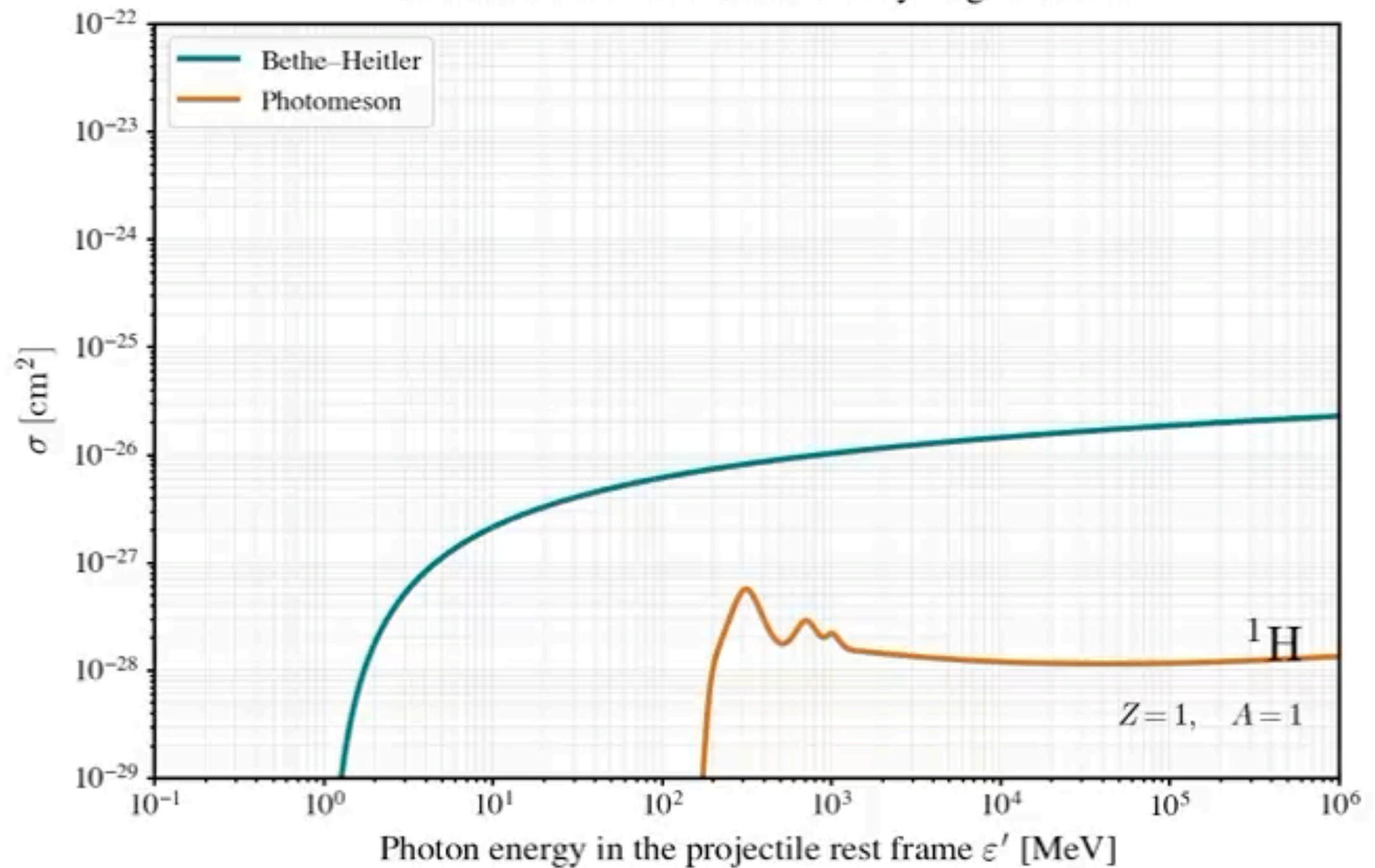
proton–air interaction



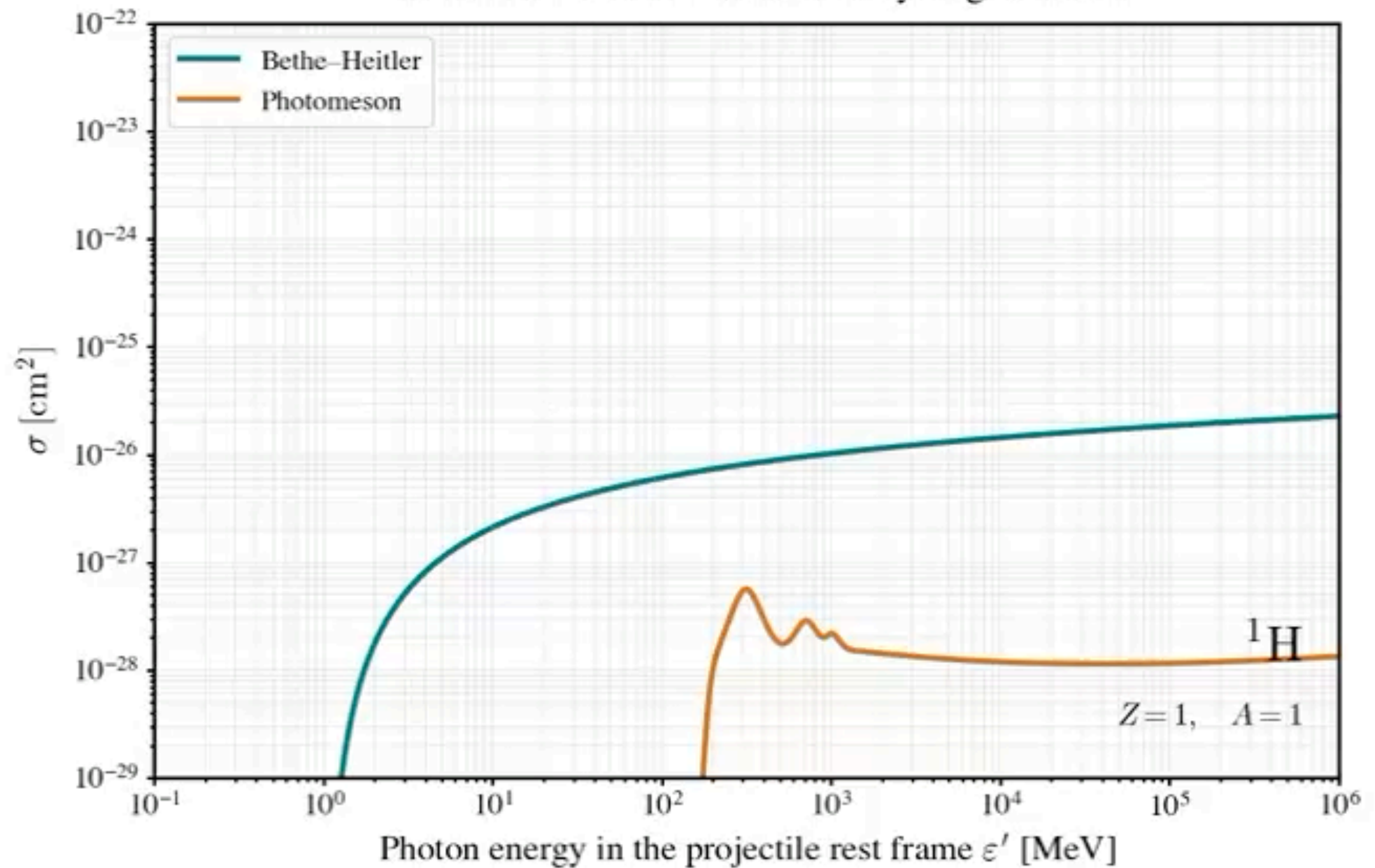
Abbasi et al. (2020).

- ♦ KASCADE prototype (1994)
- ▽ SRCRL (1978)
- ▼ Tien Shan (1975)
- ARGO-YBJ (2009)
- ♦ Tien Shan (2017)
- △ EAS-TOP (2009)
- * Yakutsk (1999)
- ▲ Yakutsk (2013)
- Akeno (1993)
- ▼ Fly's Eye (1984)
- Auger (2012)
- HiRes (2006)
- Telescopic Array BR/LR hybrid (2020)
- Telescopic Array MD hybrid (2015)

Photonuclear cross sections from hydrogen to iron



Photonuclear cross sections from hydrogen to iron



Cosmic Rays

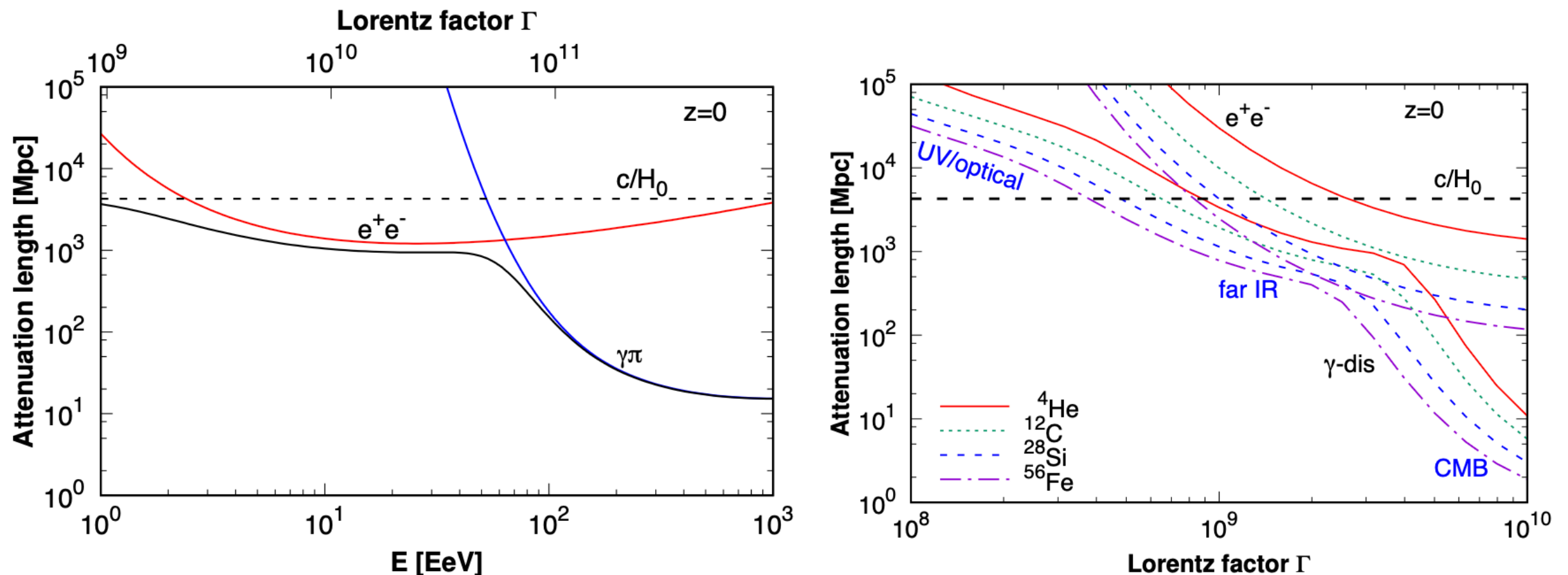


Figure 8: Energy loss length for protons (left panel, as a function of energy) and heavier nuclei (right panel, as a function of the Lorentz factor), computed for redshift $z = 0$ (from [62]). The separate contributions from pair production (e^+e^-) and from photo-disintegration (γ -dis), as well as the dominant photon background responsible for these last, are indicated.

S. Mollerach and E. Roulet, arXiv:1710.11155

GZK

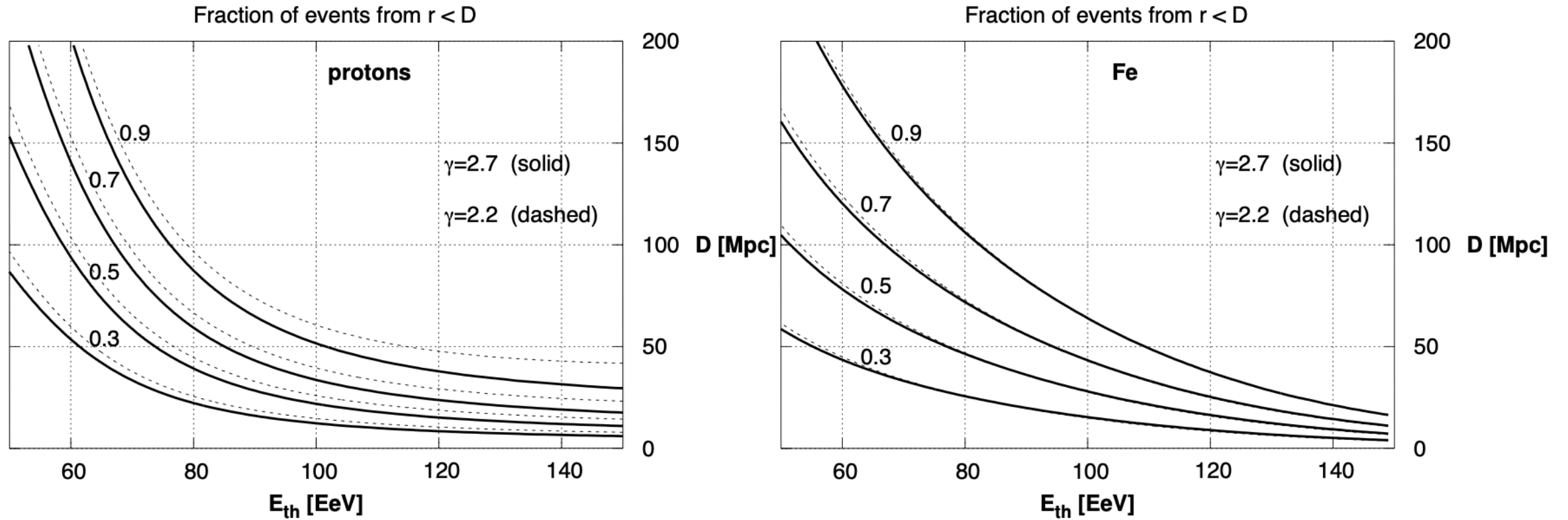
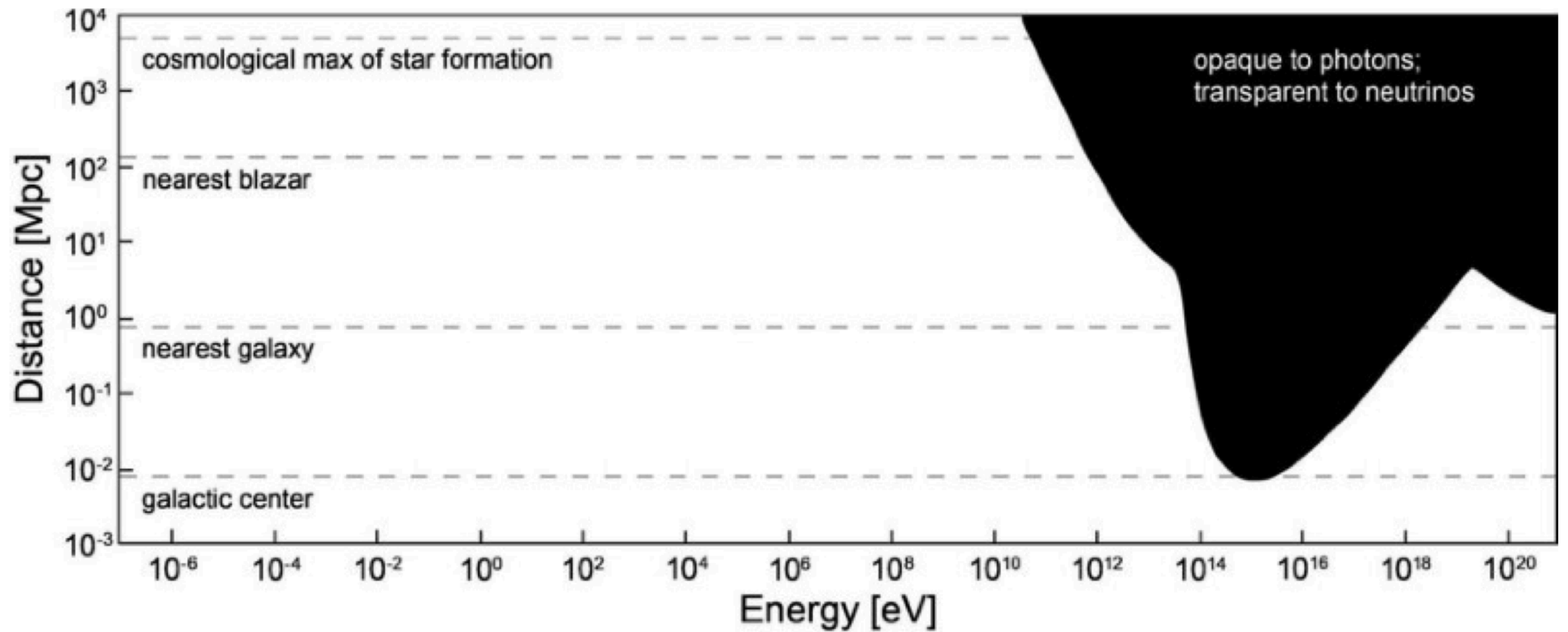


Figure 9: Fraction of the flux observed above a threshold energy E_{th} originating from sources within a distance D . Sources are assumed uniformly distributed and with power law spectra ($\gamma = 2.2$ and 2.7 are shown). The curve labeled as 0.9 would correspond the the GZK horizon defined as the distance within which 90% of the flux observed above a given threshold was produced (adapted from [63]). Left panel is for proton sources and right panel for Fe sources.

S. Mollerach and E. Roulet, arXiv:1710.11155

Opacity of Universe to gamma rays



Cosmic Rays

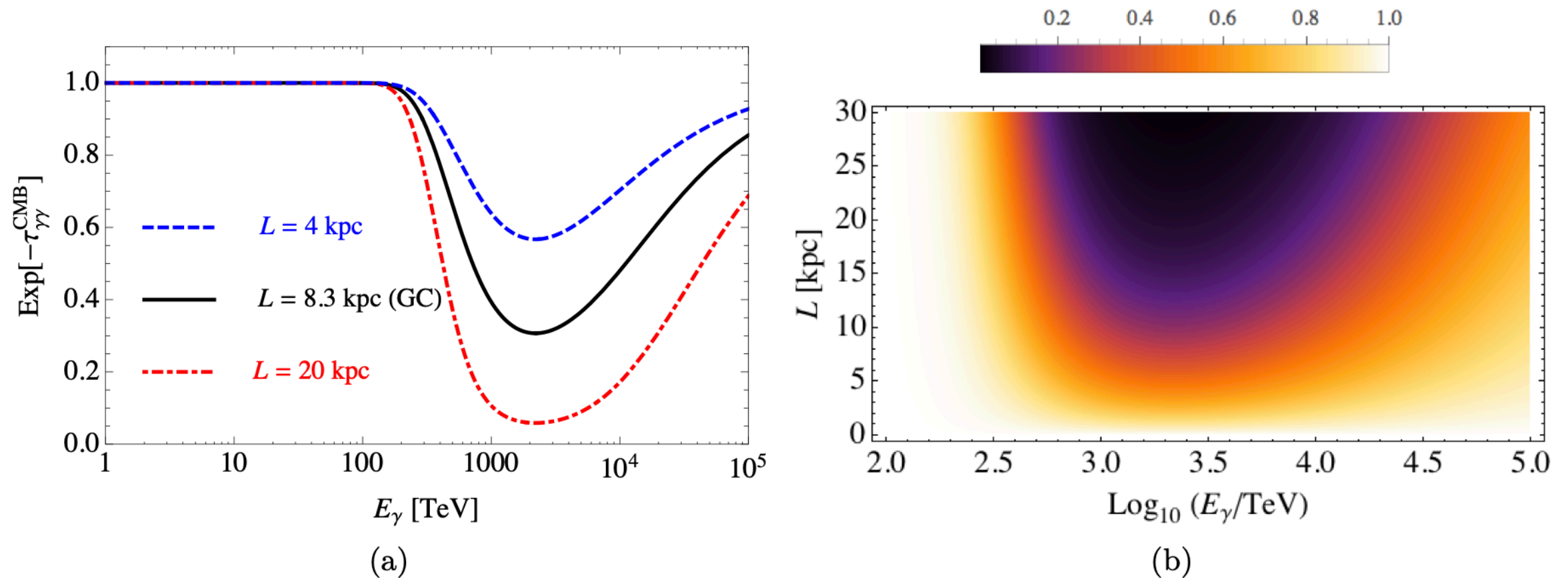


Figure 1. Plot of the absorption of γ -rays on CMB photons. Panel (a): for a source at distance $L = 4$ kpc, 8.3 kpc and 20 kpc. Panel (b): 2D density plot of $\exp[-\tau_{\gamma\gamma}^{\text{CMB}}]$ as function of L and E_γ .

A.E., P. Serpico, arXiv:1505.06486

Cosmic Rays

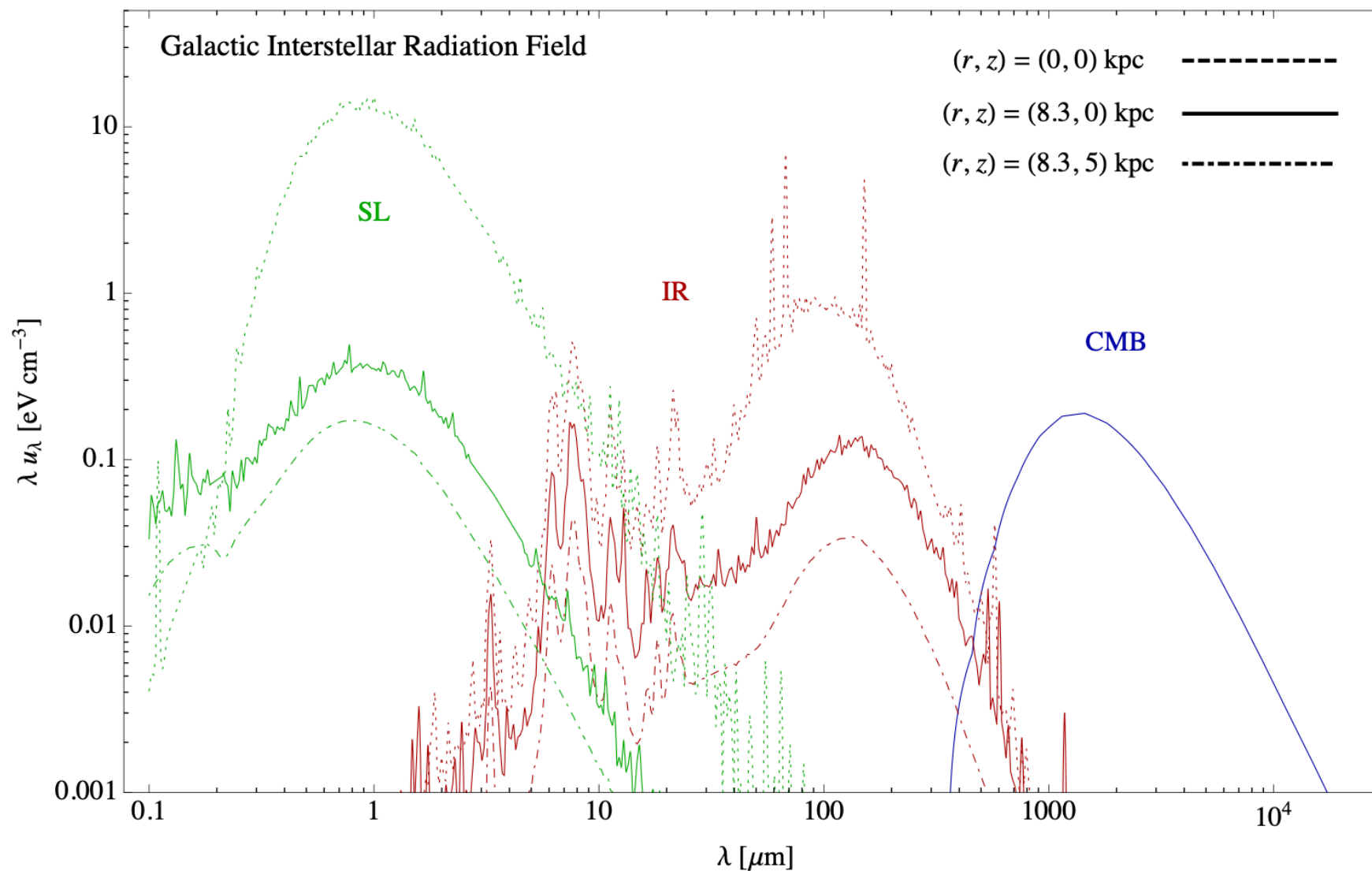


Figure 2. The energy density of ISRF (including starlight, IR and CMB), extracted from GALPROP [28], at three different positions in our Galaxy: the dotted curves are for $(r, z) = (0, 0)$, that is GC; the solid curves are for $(r, z) = (8.3, 0)$ kpc, that is the Sun position, and the dot-dashed curves are for $(r, z) = (8.3, 5)$ kpc.

A.E., P. Serpico, arXiv:1505.06486

Cosmic Rays

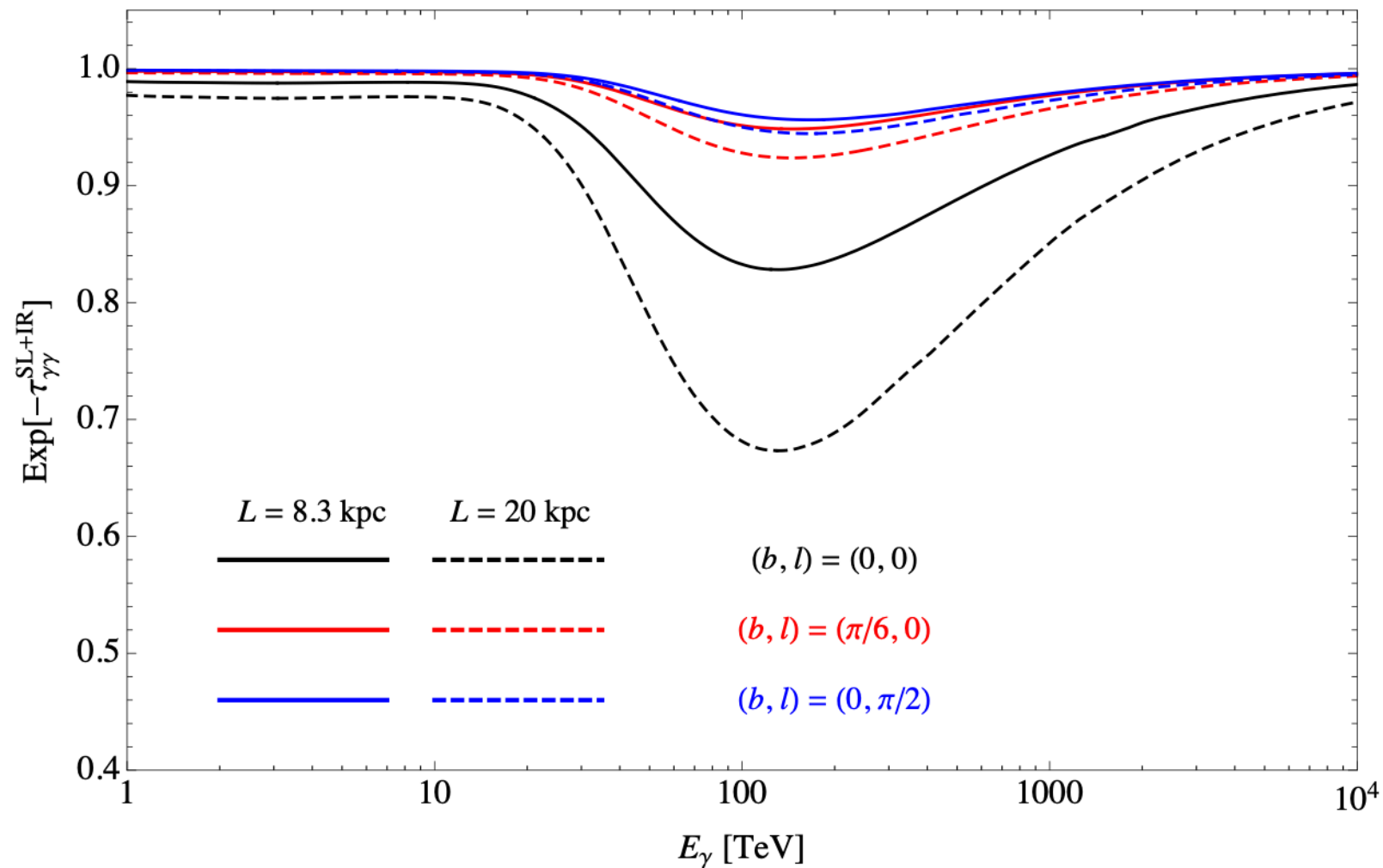
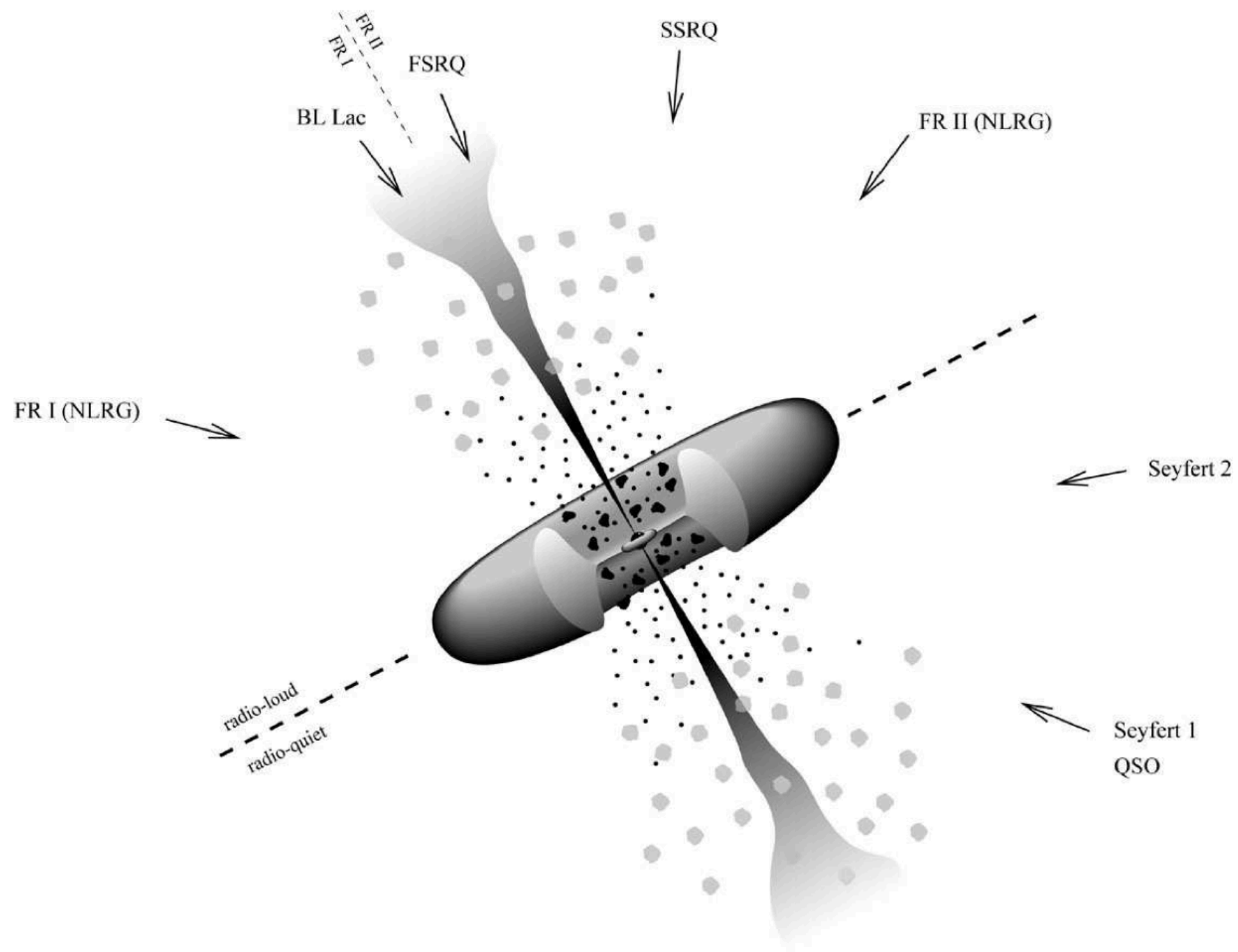


Figure 3. Plot of the absorption of γ -rays on SL+IR photons, for a source at distance $L = 8.3$ kpc (solid curves) and 20 kpc (dashed curves) for various directions.

A.E., P. Serpico, arXiv:1505.06486

Unified picture of AGN



EM cascade

A cascade develops due to:

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

Pair production

Inverse-Compton scattering

$$e + \gamma_t \rightarrow \gamma' + e$$

EM cascade:

$$pp \rightarrow IC \rightarrow pp \rightarrow IC \rightarrow \dots$$

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✓ The cascading process has been elaborated and used by Berezhinsky and Smirnov 75' to constrain the cosmogenic neutrino flux (the idea was proposed earlier by Berezhinsky and Zatsepin 69'). The first analytical calculation was performed in this paper.

Idea: the cosmogenic neutrinos are produced in $p\gamma_{\text{CMB}}$ interaction through the Δ^+ resonance. The same process produces e and γ . So, the energy density of the neutrinos and diffuse gammas are related by a ratio of 1/3. The recent Fermi observation: $w_{\text{cas}} = 5.8 \times 10^{-7} \text{ eV/cm}^3$.

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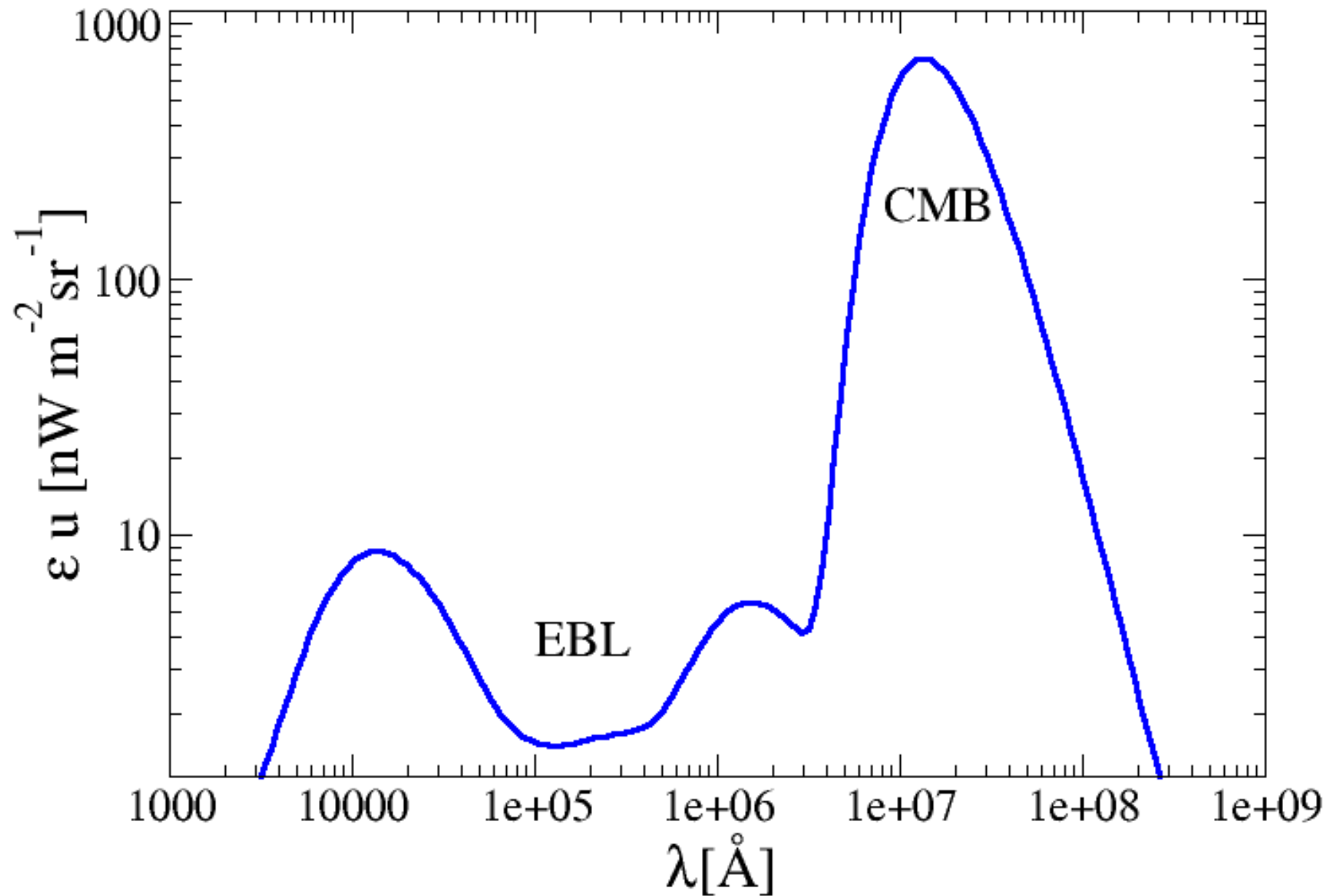
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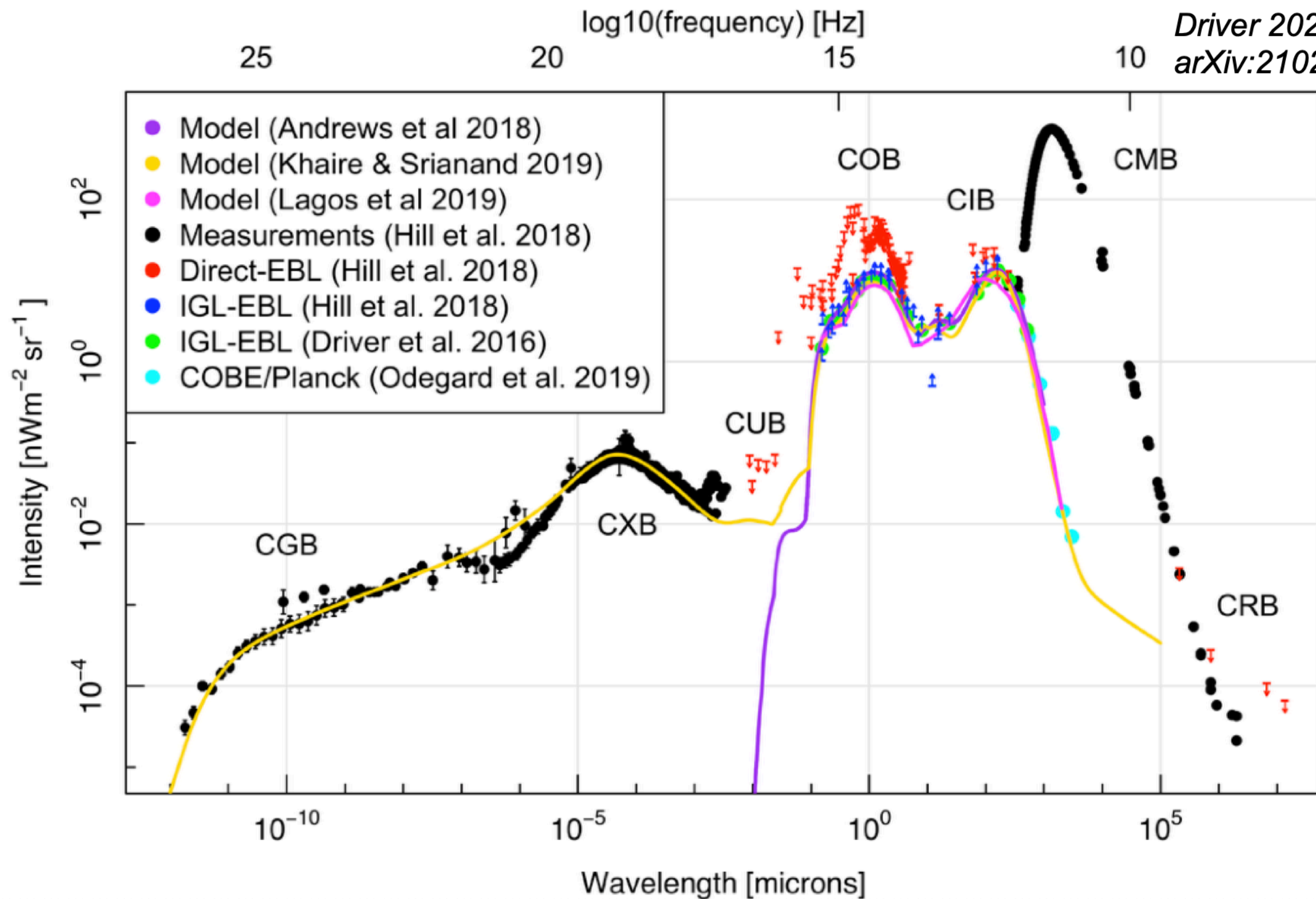
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- ✓ The idea applied to discrete sources by Gould and Schreder 66'. The cascade process proposed to search for extragalactic magnetic field (halo component) by Aharonian et al at 94'.

EM cascade

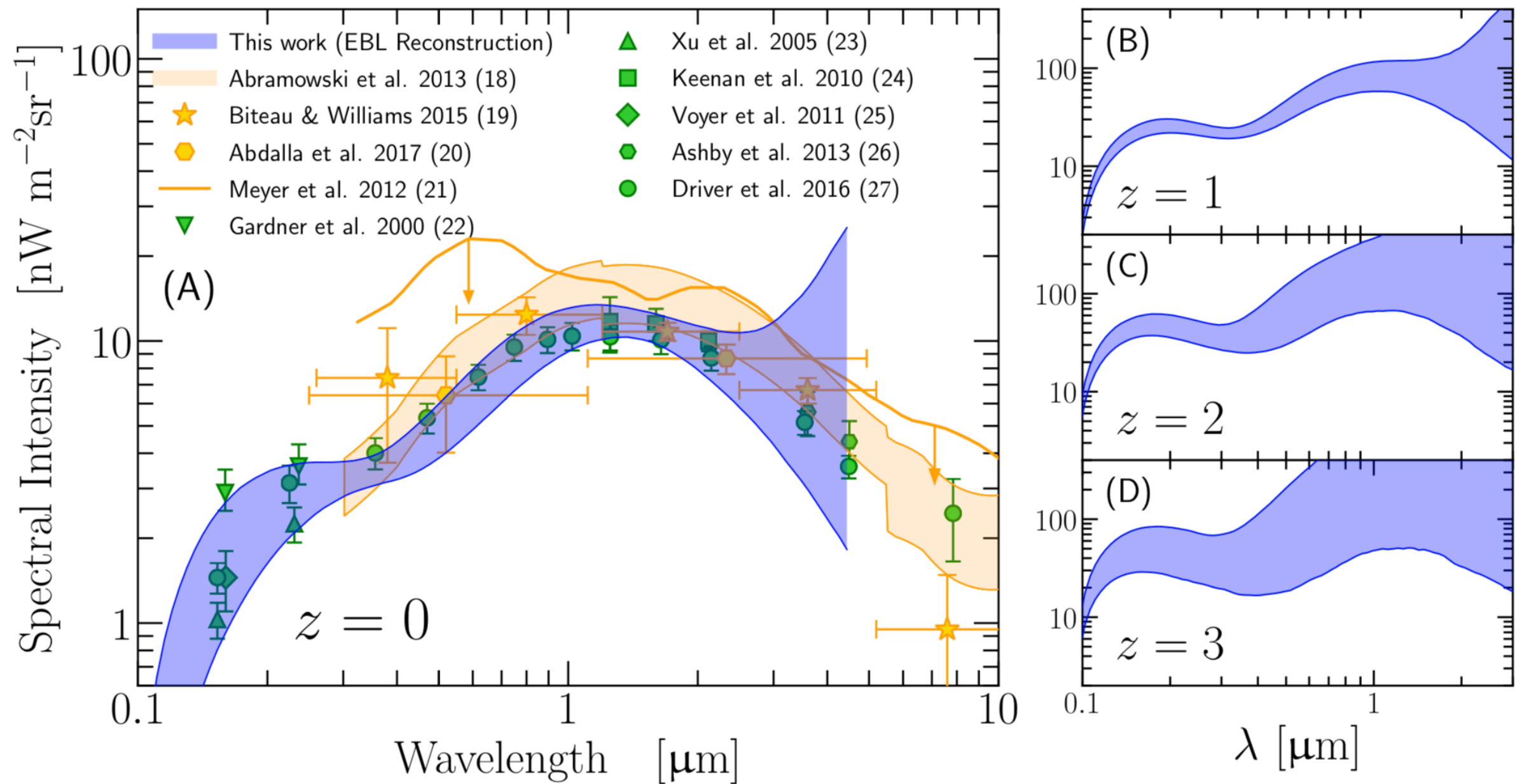
Target photons:





EM cascade

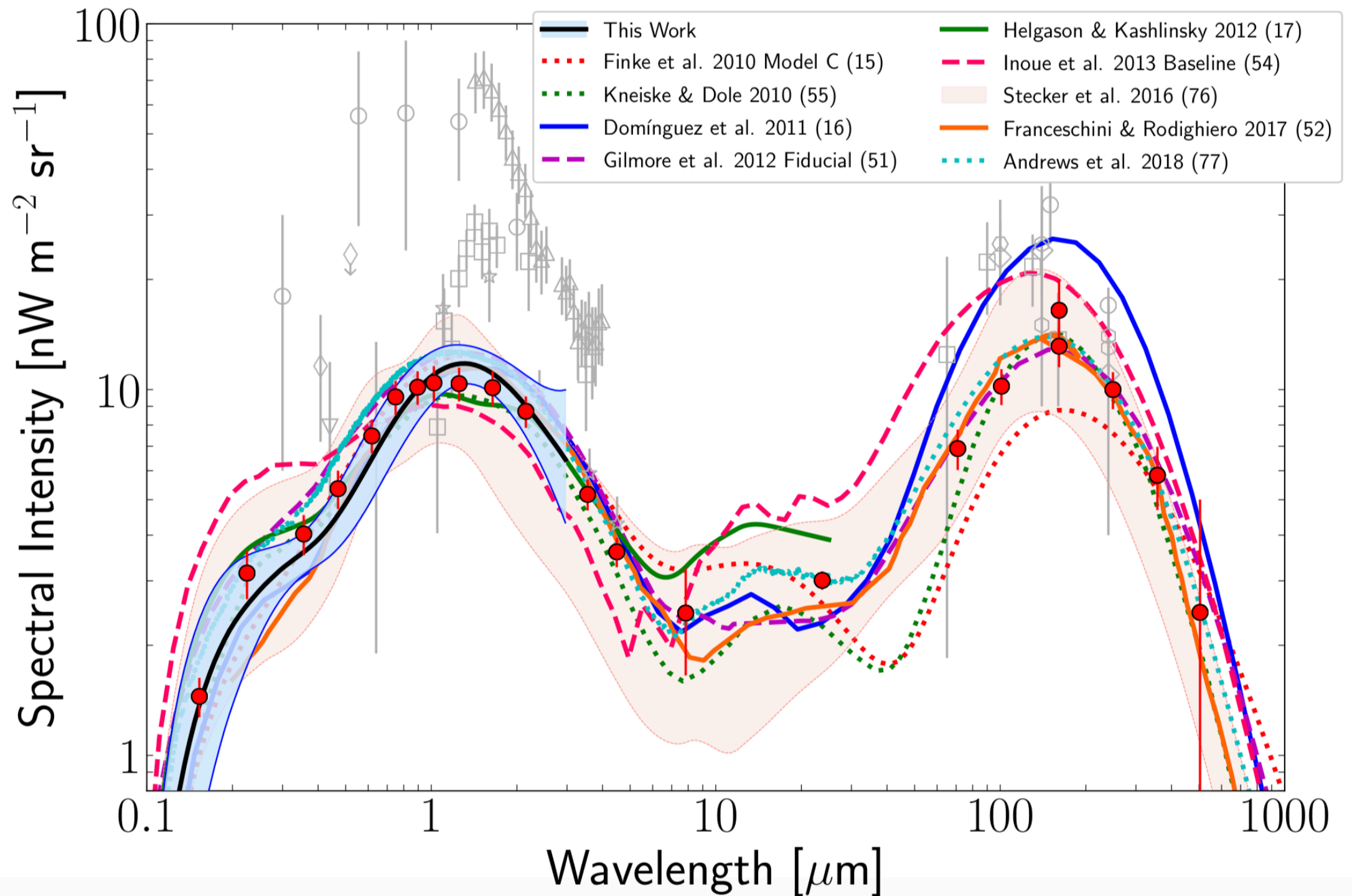
EBL: The light emitted by all galaxies over the history of the Universe at ultraviolet, optical, and infrared wavelengths



arXiv:1812.01031,
Fermi coll.

EM cascade

EBL:



arXiv:1812.01031,
Fermi coll.

EM cascade

Characteristic energies (monochromatic photon gas with energy ϵ):

(Berezinsky and Smirnov 75' estimation)

characteristic energy of
the initial photon/electron

$$\epsilon_0 \sim 0.1 \frac{m_\pi m_p}{\epsilon} \sim \frac{E_p}{10}$$

EM cascade

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critical energy of gamma
(transparency)

$$\epsilon_\gamma \sim \frac{m_e^2}{\epsilon}$$



$$E_\gamma > \epsilon_\gamma$$

absorption
due to p-p

$$E_\gamma < \epsilon_\gamma$$

free escape

EM cascade

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free escape

min energy of e in p-p
(cascade multiplication)

$$\epsilon_e = \frac{\epsilon_\gamma}{2} \sim \frac{m_e^2}{2\epsilon}$$



$$E < \epsilon_e$$

e decelerates by
emitting Compton
photons. No new e

EM cascade

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$E_\gamma > \epsilon_\gamma$ absorption
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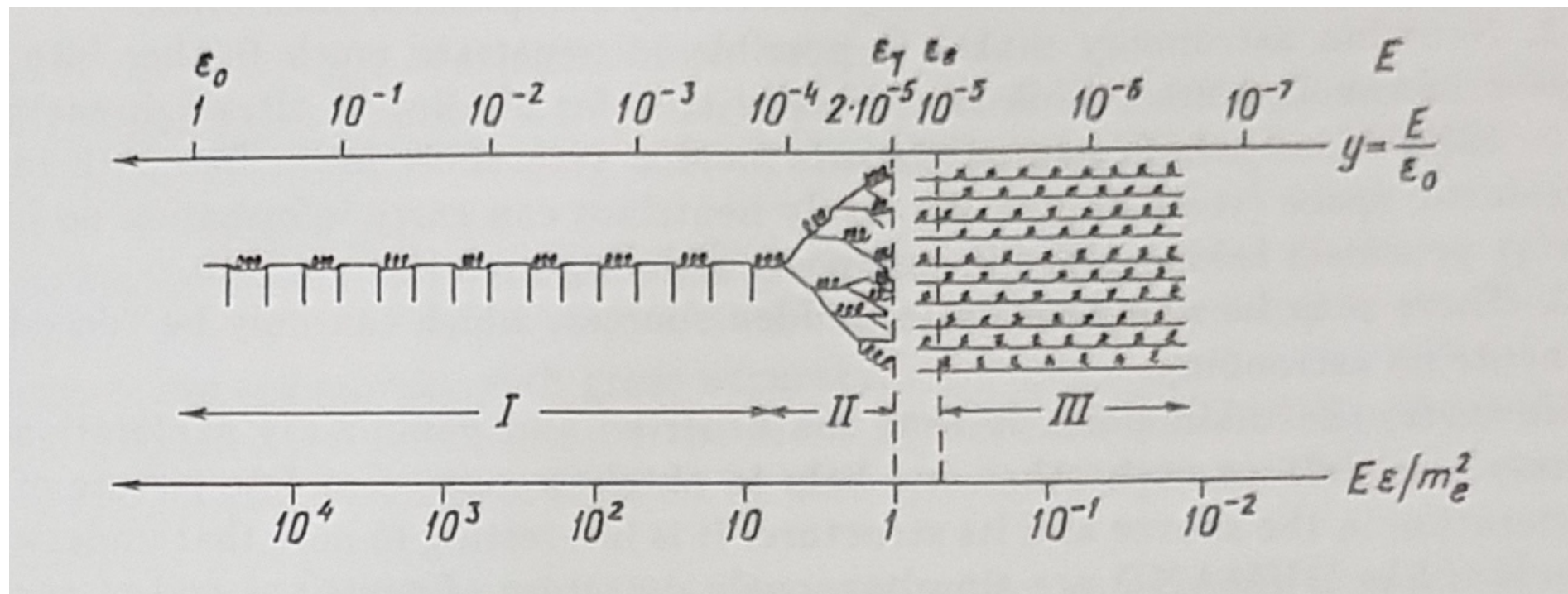
Compton photons
(end of multi. phase)

$$\epsilon_X \sim \frac{4}{3} \frac{\epsilon_e^2 \epsilon}{m_e^2} \sim \frac{\epsilon_\gamma}{3}$$

the highest energy
of photons emitted
by e when $E_e \sim \epsilon_e$

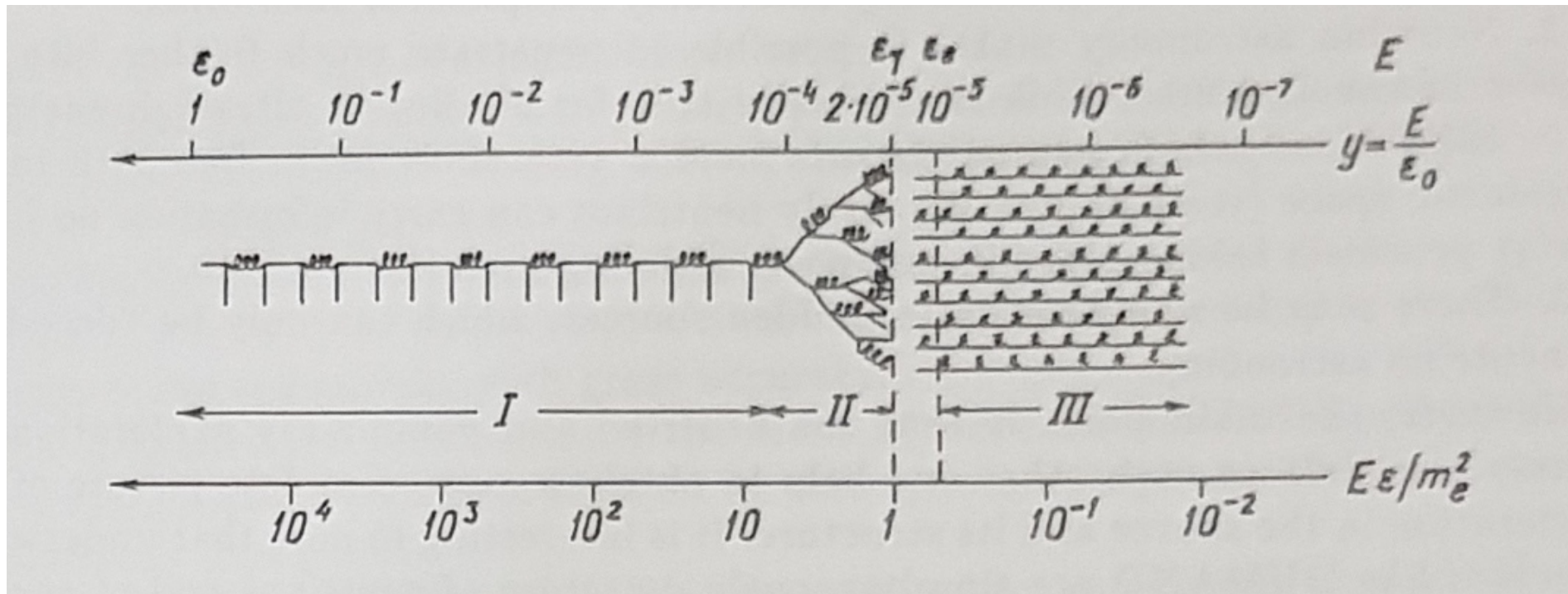
EM cascade

Qualitative description (monochromatic photon gas):



EM cascade

Qualitative description (monochromatic photon gas):



$$n_{\gamma}(E_{\gamma}) = \begin{cases} \left(\frac{K}{\epsilon_X} \right) \left(\frac{E_{\gamma}}{\epsilon_X} \right)^{-3/2} & \text{if } E_{\gamma} \leq \epsilon_X \\ \left(\frac{K}{\epsilon_X} \right) \left(\frac{E_{\gamma}}{\epsilon_X} \right)^{-2} & \text{if } \epsilon_X \leq E_{\gamma} \leq \epsilon_{\gamma} \\ 0 & \text{if } E_{\gamma} \geq \epsilon_{\gamma} \end{cases}$$

$$K = \frac{\epsilon_0}{\epsilon_X (2 + \ln 3)} = \frac{m_e^2}{10 m_p m_{\pi} (2 + \ln 3)} \approx 1.8 \times 10^4$$

EM cascade

The dichromatic photon gas approximation:

The photon gas consists of two populations

(EBL = Extragalactic Background Light ; CMB = Cosmic Microwave Background)

$$\epsilon_{\text{ebl}} \gg \epsilon_{\text{cmb}} \quad \text{and} \quad n_{\text{cmb}} \gg n_{\text{ebl}}$$

Approximation: $\epsilon_{\text{ebl}} \sim 1 \text{ eV} \quad \text{and} \quad \epsilon_{\text{cmb}} \sim 6.3 \times 10^{-4} \text{ eV}$

EM cascade

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Due to these inequalities, the cascade develops in two stages:

1) p-p on CMB and IC on CMB

2) p-p on EBL and IC on CMB

Incident Particle	Process	Target Density [cm^{-3}]	Cross Section [σ_T]	λ [Mpc]
Gamma Rays				
	$\gamma\gamma \rightarrow e^+e^-$ on CIB (TeV)	0.5	3/16	10
	$\gamma\gamma \rightarrow e^+e^-$ on CMB (PeV)	410.5	3/16	10^{-2}
	$\gamma e \rightarrow \gamma e$	10^{-7}	10^{-3}	10^{10}
Electrons and Positrons				
	$e\gamma \rightarrow e\gamma$ on CIB (TeV)	0.5	1	1
	$e\gamma \rightarrow e\gamma$ on CMB (PeV)	410.5	1	10^{-2}

p-p on EBL has a lower threshold than the p-p on CMB

EM cascade

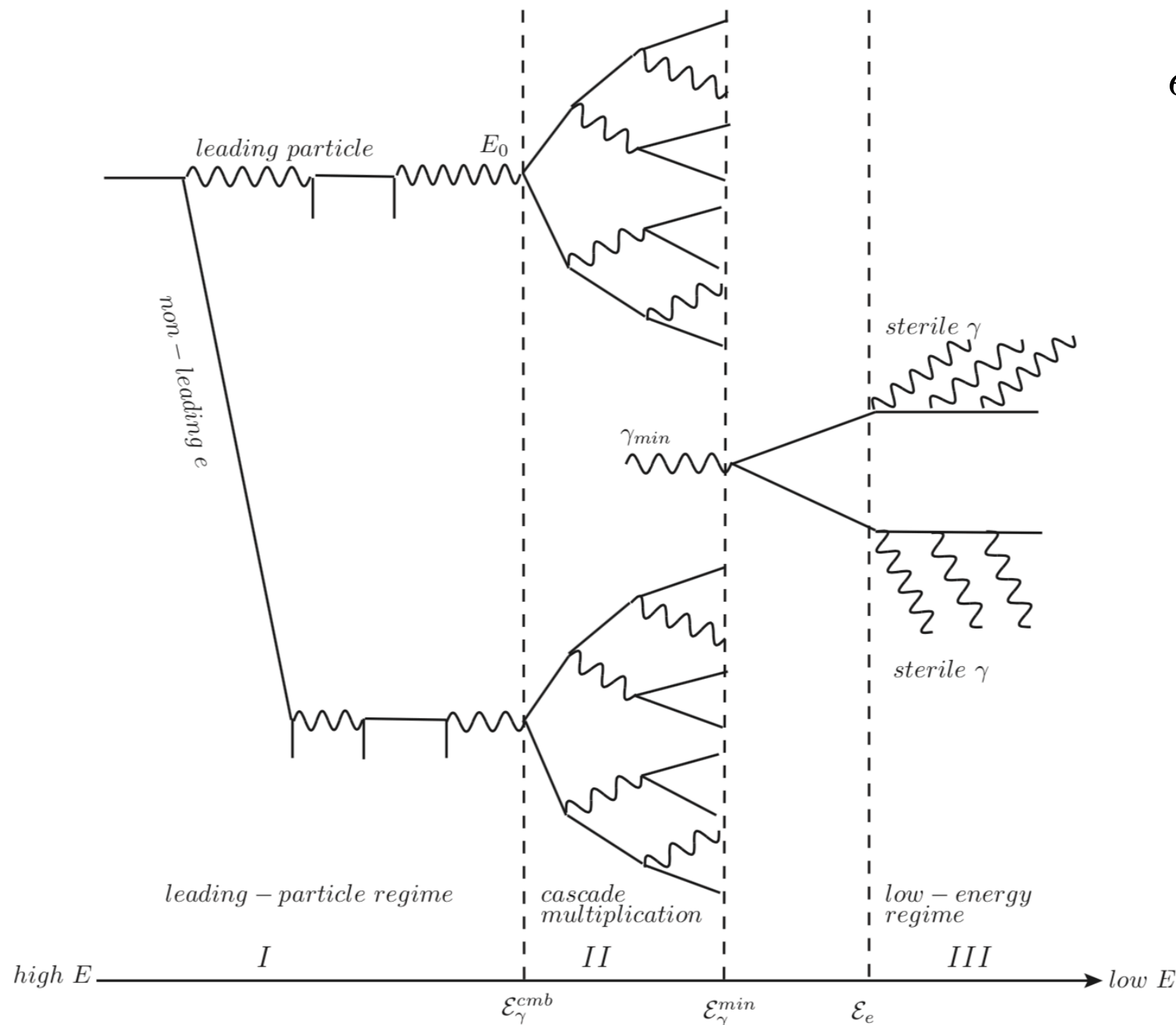
Characteristic energies

$$\epsilon_{\gamma}^{\min} = \epsilon_{\gamma, \text{ebl}} = \frac{m_e^2}{\epsilon_{\text{ebl}}} \approx 400 \text{ GeV}$$

$$\epsilon_{\gamma, \text{cmb}} = \frac{m_e^2}{\epsilon_{\text{cmb}}} \approx 400 \text{ TeV}$$

$$\epsilon_e = \frac{1}{2} \epsilon_{\gamma}^{\min} \approx 200 \text{ GeV}$$

$$\epsilon_X = \frac{1}{3} \epsilon_{\gamma}^{\min} \frac{\epsilon_{\text{cmb}}}{\epsilon_{\text{ebl}}} \approx 120 \text{ MeV}$$



EM cascade

Numerical solution:

The problem is a general Boltzmann process:

$$\dot{N}_e = -\dot{N}_{e,\text{IC}} + \dot{N}_{e,\text{pp}} + \dot{N}_{e,\text{inj}}$$

$$\dot{n}_\gamma = \dot{n}_{\gamma,\text{IC}} - \dot{n}_{\gamma,\text{pp}} - c \frac{dn_\gamma}{dx} + \dot{n}_{\gamma,\text{inj}}$$

$$\frac{dE_e}{dt} \approx \frac{4}{3} \sigma_T c \beta^2 \gamma^2 \frac{\vec{B}^2}{8\pi}$$

Where the production rate [$\text{cm}^{-3} \text{s}^{-1}$] is:

$$\dot{N} = c \int_{\epsilon_{\min}}^{\epsilon_{\max}} d\epsilon n_T(\epsilon) \int_{-1}^1 d\mu \frac{1 - \beta\mu}{2} \int_{E_{\text{I},\min}}^{E_{\text{I},\max}} dE_{\text{I}} n_{\text{I}}(E_{\text{I}}) \int_{E_{\min}}^{E_{\max}} dE' \frac{d\sigma}{dE}(E', E)$$

The flux can be calculated by:

$$\Phi = \frac{c}{4\pi} \int_{E_{\min}}^{E_{\max}} dE \frac{dN}{dE}$$

EM cascade

Example of IC:

$$\dot{N}_{e,IC} = c \int_0^\infty d\epsilon n_T(\epsilon) \int_{2\gamma(1-\beta)\omega}^{2\gamma(1+\beta)\omega} d\kappa N_e(\kappa) \frac{d\sigma_{IC}}{d\kappa}$$

$$\frac{d\sigma_{IC}}{d\kappa} = \frac{3\sigma_T}{32\gamma^2\beta\omega^2} \left[\left(1 - \frac{4}{\kappa} - \frac{8}{\kappa^2}\right) \ln(1 + \kappa) + \frac{1}{2} + \frac{8}{\kappa} - \frac{1}{2(1 + \kappa)^2} \right] \quad \text{Klein-Nishina limit}$$

where $n_{T=CMB}(\epsilon) = \frac{1}{\pi^2(\hbar c)^3} \frac{\epsilon^2}{\exp\left(\frac{\epsilon}{k_b T}\right) - 1}$, $E_\gamma = \gamma m_e c^2$, $E_e = \omega m_e c^2$, $\kappa = 2\gamma(1 - \beta\mu)\omega$

Example of p-p:

$$\dot{N}_{e,pp} = c \int_0^\infty d\epsilon n_T(\epsilon) \int_{-1}^{\mu_{\max}} d\mu \frac{1 - \mu}{2} \int_{E_{\min}}^{E_{\max}} dE_\gamma \frac{d\sigma_{pp}}{dE}(E_\gamma, E) \left(n_{\gamma, \text{inj}}(E_\gamma) + \int_{E_{IC, \min}}^{E_{IC, \max}} dE' N_e(E') \frac{d\sigma_{IC}}{dE}(E, E' - E_\gamma) \right)$$

$$\frac{d\sigma_{pp}}{dE} = \frac{3c\sigma_T(1 - \beta'^2)}{16} \left[(3 - \beta'^4) \ln \left(\frac{1 + \beta'}{1 - \beta'} \right) - 2\beta'(2 - \beta'^2) \right]$$

where $\beta' = \sqrt{1 - 2/\omega_1\omega_2(1 - \mu)}$, $\omega_1 = \epsilon/m_e c^2$, $\omega_2 = E_\gamma/m_e c^2$

EM cascade

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where

ELMAG, M. Kachelrieß et al,

DINT,

EleCa,

Example

GCascade, C. Blanco (Boltzmann eq. approach)

$$\dot{N}_{e,pp} = c \int_0^\infty d\epsilon n_T(\epsilon) \int_{-1}^{\mu_{\max}} d\mu \frac{1-\mu}{2} \int_{E_{\min}}^{E_{\max}} dE_\gamma \frac{d\sigma_{pp}}{dE}(E_\gamma, E) \left(n_{\gamma, \text{inj}}(E_\gamma) + \int_{E_{IC, \min}}^{E_{IC, \max}} dE' N_e(E') \frac{d\sigma_{IC}}{dE}(E, E' - E_\gamma) \right)$$

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where

$$\beta' = \sqrt{1 - 2/\omega_1\omega_2(1 - \mu)} \quad , \quad \omega_1 = \epsilon/m_e c^2 \quad , \quad \omega_2 = E_\gamma/m_e c^2$$

Cascade development in very high energy

The cascade development we considered:

$$\text{EPP} \quad \gamma\gamma_b \rightarrow e^+e^- \quad \text{and} \quad \text{ICS} \quad e\gamma_b \rightarrow e\gamma$$

However, above the threshold of muon pair production we have:

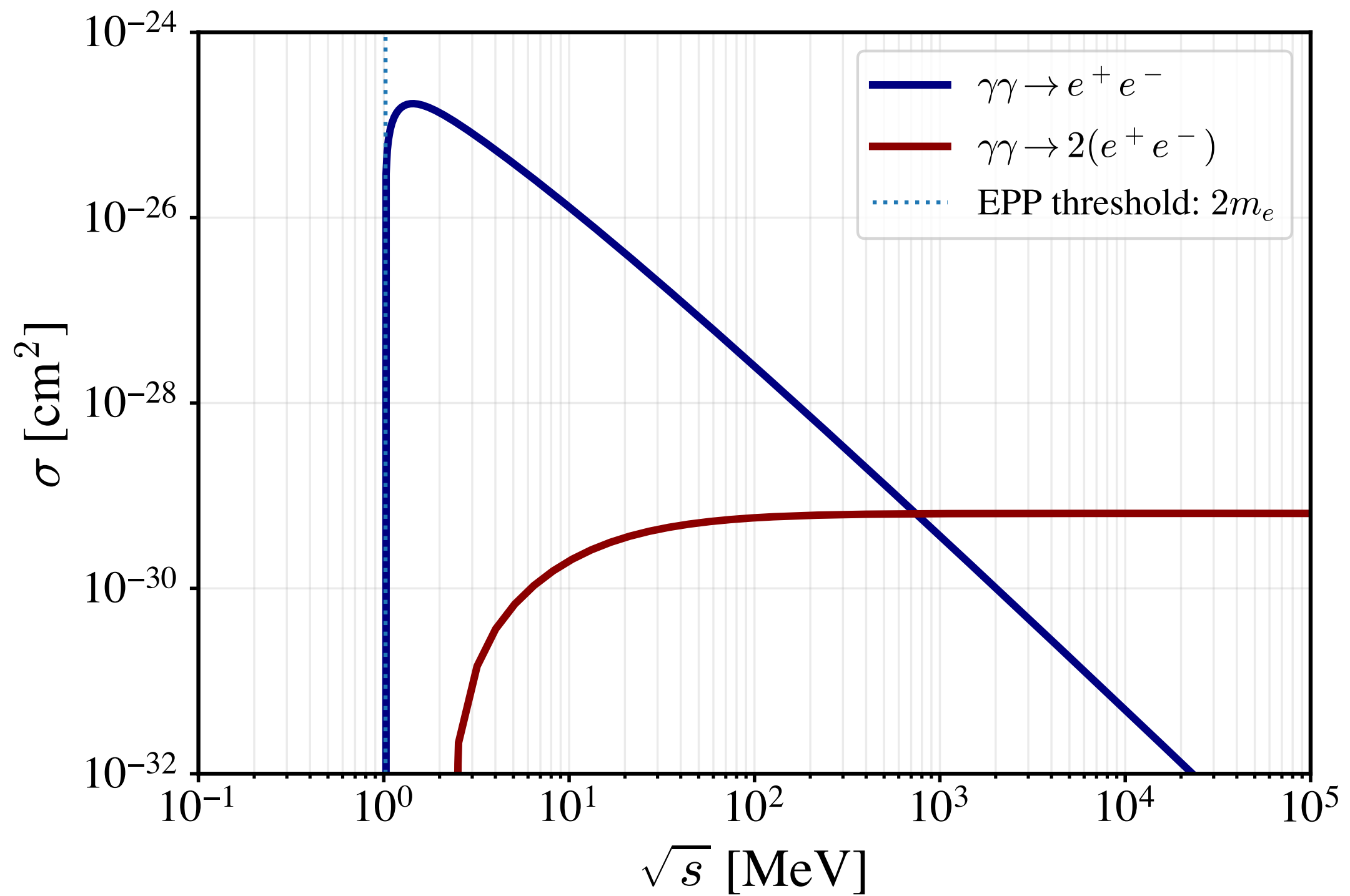
$$\text{MPP} \quad \gamma\gamma_b \rightarrow \mu^+\mu^-$$

$$\sigma_{\text{MPP}} = \sigma_{\text{EPP}}(m_e \rightarrow m_\mu) \quad , \text{for} \quad s \geq 4m_\mu^2$$

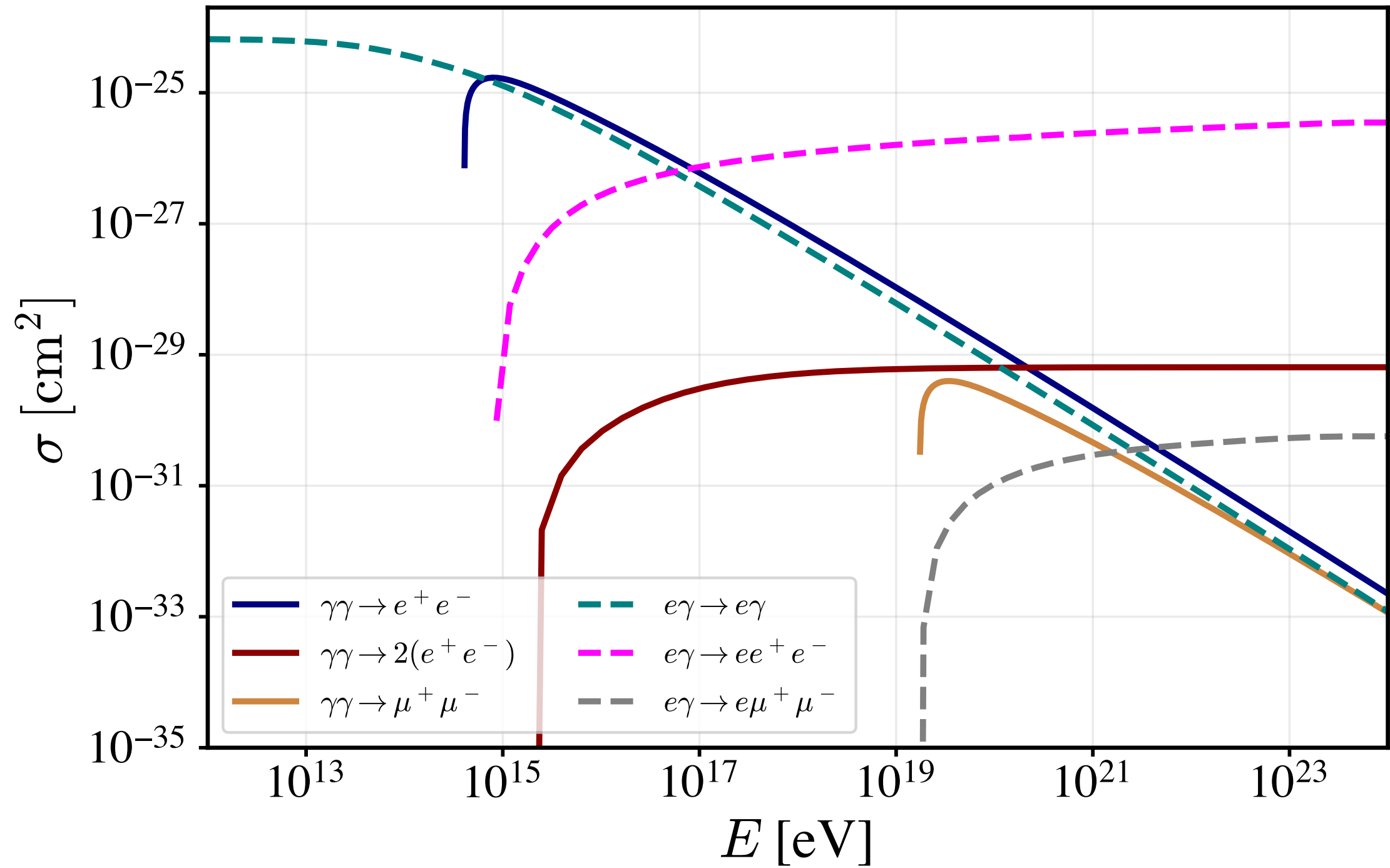
And also the double pair production

$$\text{DPP} \quad \gamma\gamma_b \rightarrow e^+e^-e^+e^- \quad , \text{for} \quad s \geq 16m_e^2$$

$$\sigma_{\text{DPP}} \approx 6.45 \mu\text{b} \left(1 - \frac{4m_e^2}{E_\gamma \epsilon}\right)^6$$



EM cross sections for head-on collisions with $\epsilon = 6.4 \times 10^{-4}$ eV photons



Cascade development in very high energy

Although the MPP cross section is smaller than the EPP: $\left. \frac{\sigma_{\text{MPP}}}{\sigma_{\text{EPP}}} \right|_{s=10^{18} \text{ eV}^2} \approx 0.26$

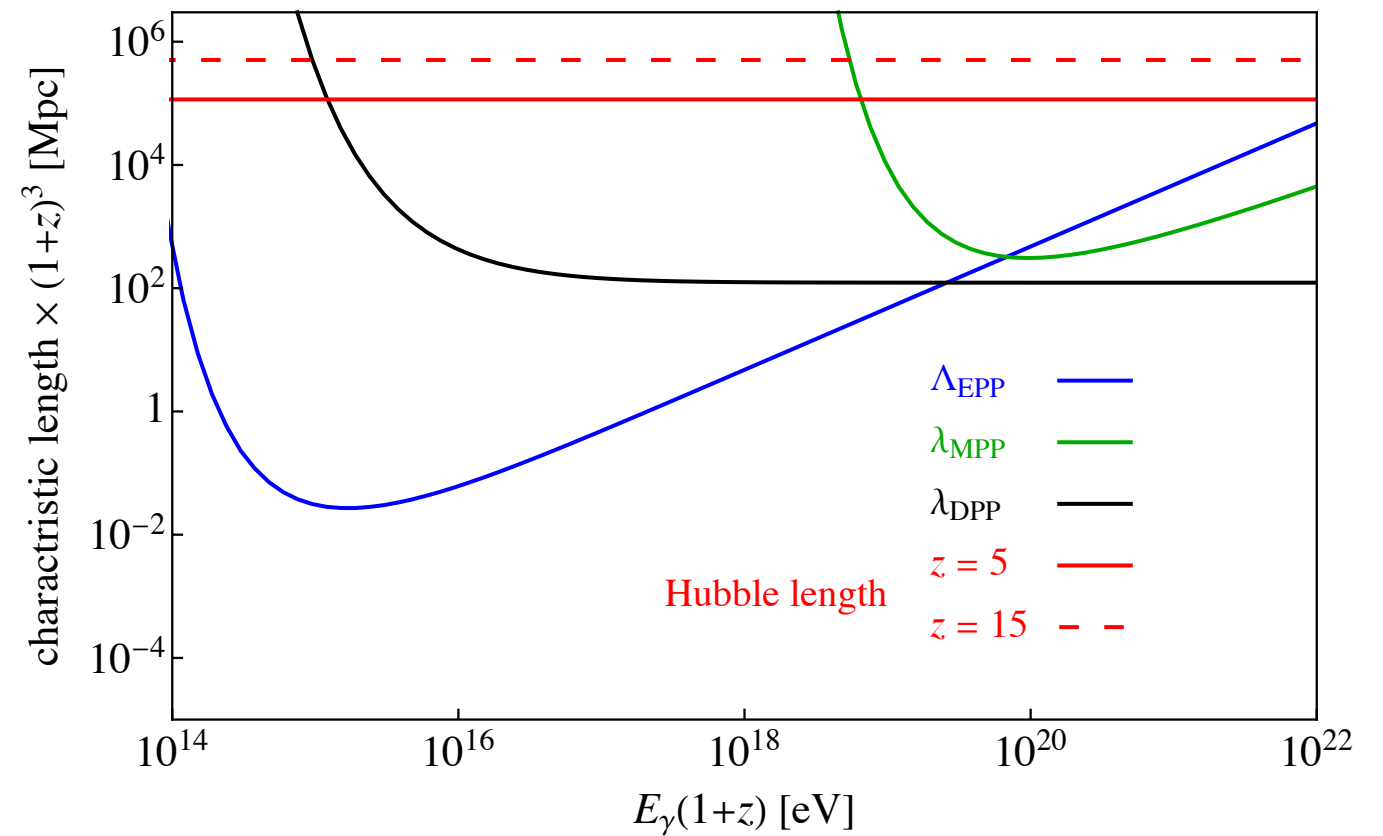
the interaction length Λ_{MPP} is smaller than the energy loss length λ_{EPP} at high-redshifts

Interaction length

$$\lambda_p(E) = \frac{1}{\int d\epsilon \int d\mu \frac{1-\mu}{2} n_{\text{CMB}}(\epsilon) \sigma_p(s)}$$

Energy loss length

$$\Lambda_p(E) = \frac{1}{\int d\epsilon \int d\mu \frac{1-\mu}{2} n_{\text{CMB}}(\epsilon) \sigma_p(s) [1 - \eta_p(s)]}$$



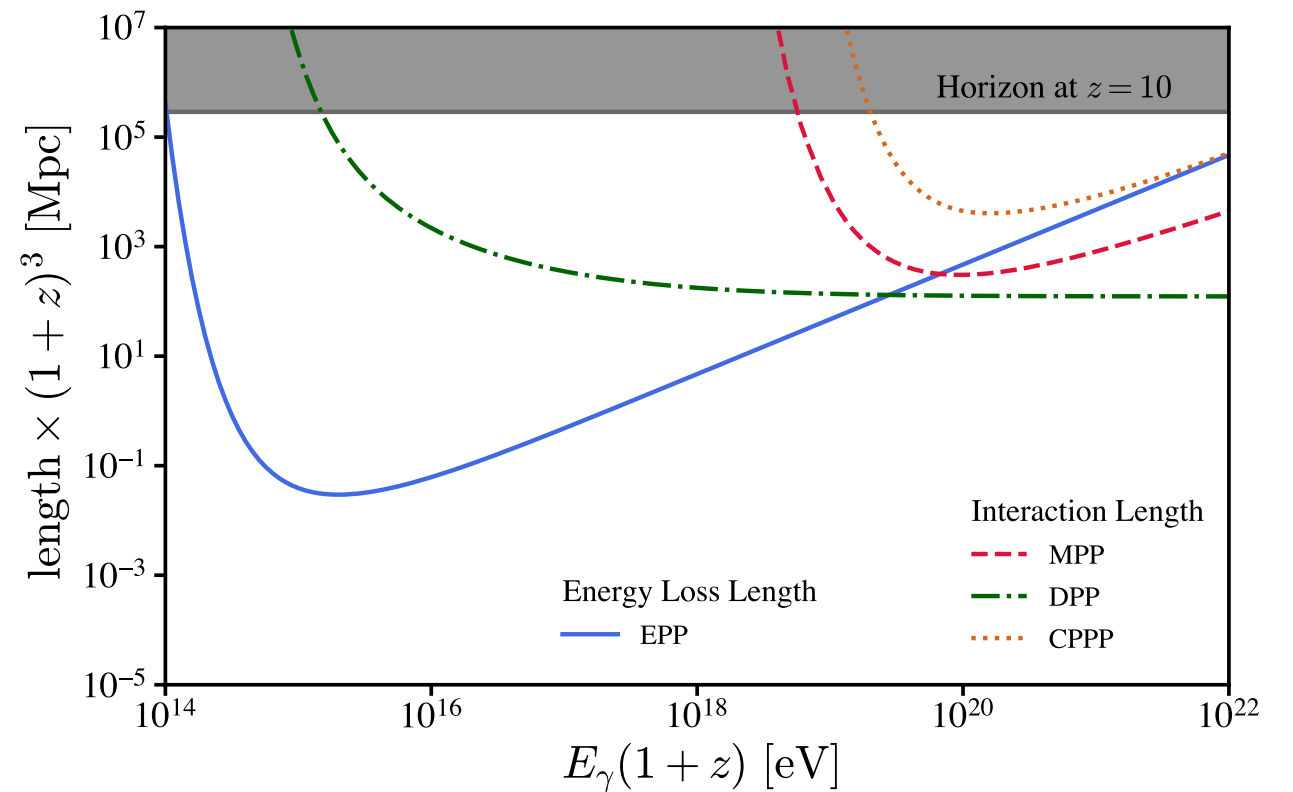
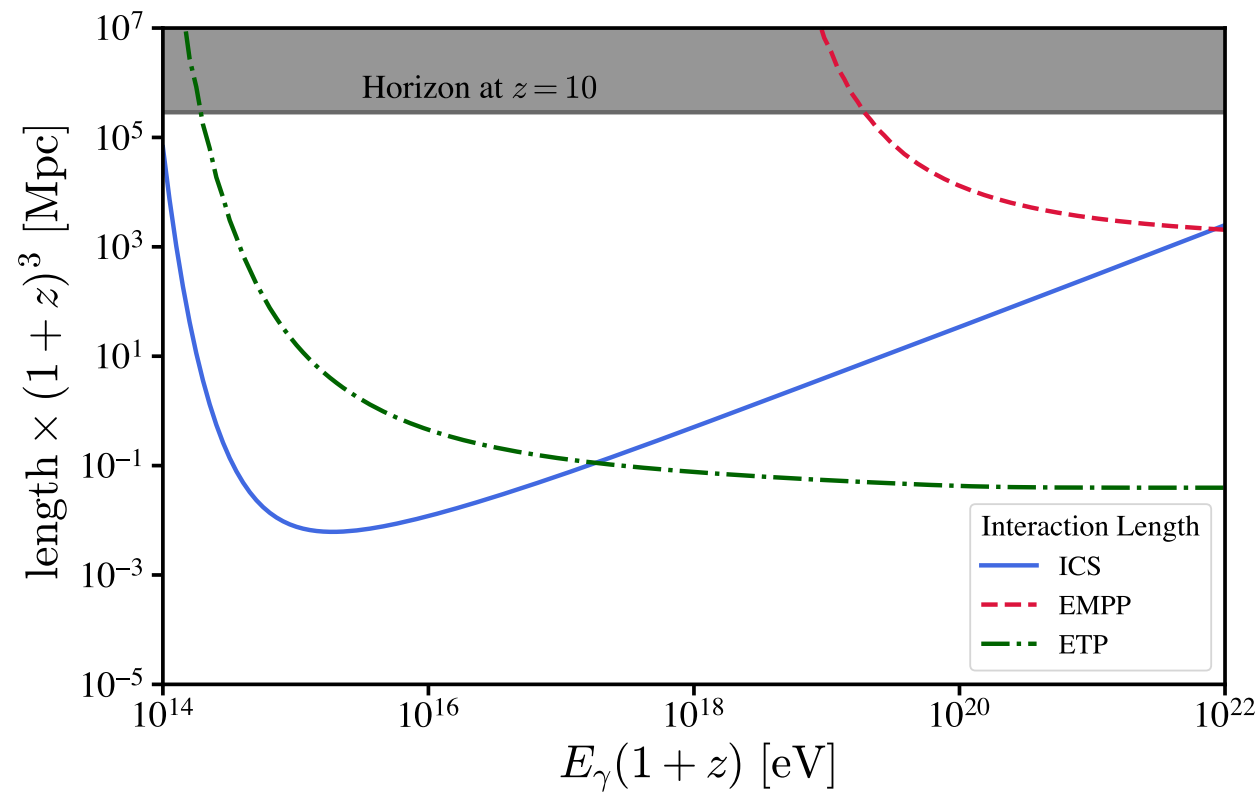
Inelasticity

$$\eta(s) = \frac{1}{\sigma(s)} \int dE' \frac{E'}{E_0} \frac{d\sigma}{dE'}(E', s)$$

Cascade development in very high energy

Other subleasing processes also are important (at ~ 10% level)

Process	Name	Acronym
$\gamma\gamma \rightarrow e^+e^-$	Electron Pair Production	EPP
$\gamma\gamma \rightarrow \mu^+\mu^-$	Muon Pair Production	MPP
$\gamma\gamma \rightarrow e^+e^-e^+e^-$	Double Pair Production	DPP
$\gamma\gamma \rightarrow \pi^+\pi^-$	Charged Pion Pair Production	CPPP
$e\gamma \rightarrow e\gamma$	Inverse Compton Scattering	ICS
$e\gamma \rightarrow e\mu^+\mu^-$	Electron Muon-Pair Production	EMPP
$e\gamma \rightarrow ee^+e^-$	Electron Triplet Production	ETP



EM cascade

MPP: ON
DPP: ON
EMPP: ON
CPPP: ON
Source: CMB
Redshift: 10
INJ_Spectrum: Monochrome
E_gamma: 1e+21
Number_of_photons: 5000
BREAK_Energy: 1.1e+17

