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Pontifícia Universidade Católica do Rio de Janeiro

The Role of Electromagnetic Cascades in High-Energy Neutrino Astrophysics

NBIA International PhD Summer School on Neutrinos: *Here, There & Everywhere*

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Ph.D. Advisor: Arman Esmaili

ν Here, There & Everywhere

July 20 2023

The High-Energy Multimessenger Picture

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The High-Energy Multimessenger Picture

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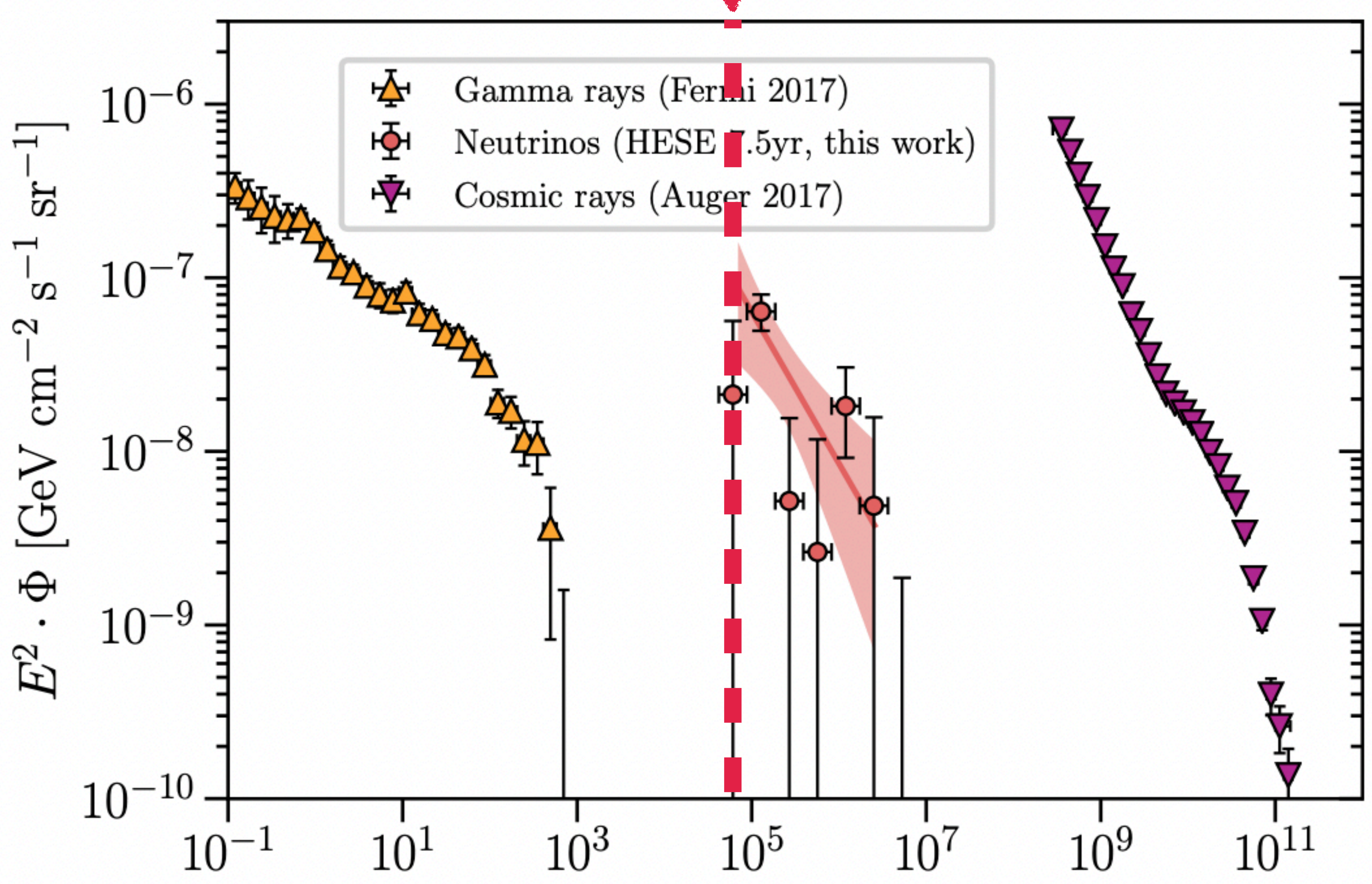
IceCube Observations

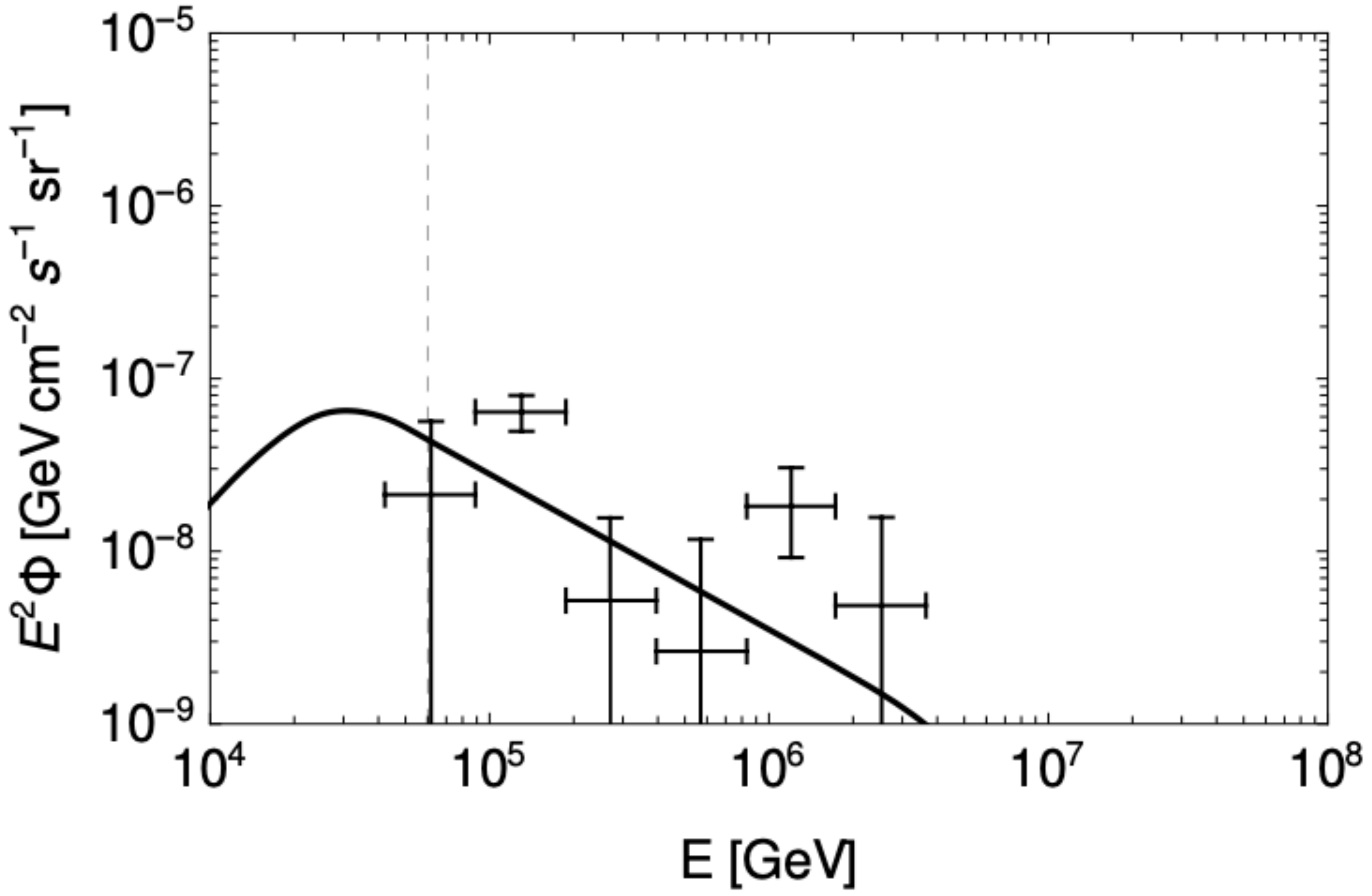
$$\Phi(E_\nu) = \Phi_{\rm astro} \times 10^{-18} \left(\frac{E_\nu}{100\ \rm TeV} \right)^{-\gamma_{\rm astro}}, \quad E_\nu \geq E_{\rm th}$$

	$\Phi_{\rm astro}$ [GeV^{-1} cm^{-2} s^{-1} sr^{-1}]	$\gamma_{\rm astro}$	$E_{\rm th}$ [TeV]
HESE 7.5y	2.15	2.89	60
Cascades 6y	1.66	2.53	16
TG 9.5y	1.44	2.28	40



[IceCube Collaboration (2021)]

Spectral break should exist below $E_{\rm th}$



Minimal injection spectrum:

$$\frac{dN_\nu}{d\varepsilon_\nu}(\varepsilon_\nu) = \begin{cases} A\varepsilon_{\rm br}^{-\gamma}, & \varepsilon_\nu < \varepsilon_{\rm br} \\ A\,\varepsilon_\nu^{-\gamma}, & \varepsilon_{\rm br} < \varepsilon_\nu < 10\ \rm PeV \\ 0, & 10\ \rm PeV < \varepsilon_\nu \end{cases}$$

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Astrophysical Neutrino Production

...and why it should necessarily be accompanied a comparable gamma-ray yield

2 main scenarios: *pp* or *p*γ

$p + p$

$p + \gamma$ $\quad \Delta^+$

π^+, π^-, π^0

γ Undergoes EM cascade

ν

Detected by IceCube

$(\nu_e, \nu_\mu, \nu_\tau) = (1,2,0)_S \approx (1,1,1)_\oplus$

$$\varepsilon_\gamma^2 \frac{\mathrm{d}N_\gamma}{\mathrm{d}\varepsilon_\gamma}(\varepsilon_\gamma) \simeq \frac{2}{3K_\pi} \varepsilon_\nu^2 \frac{\mathrm{d}N_\nu}{\mathrm{d}\varepsilon_\nu}(\varepsilon_\nu)\Big|_{\varepsilon_\nu = \varepsilon_\gamma/2}$$

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The Extragalactic Gamma-ray Background

Contributions

- ✦ Blazars
- ✦ Radio Galaxies
- ✦ Star-Forming Galaxies

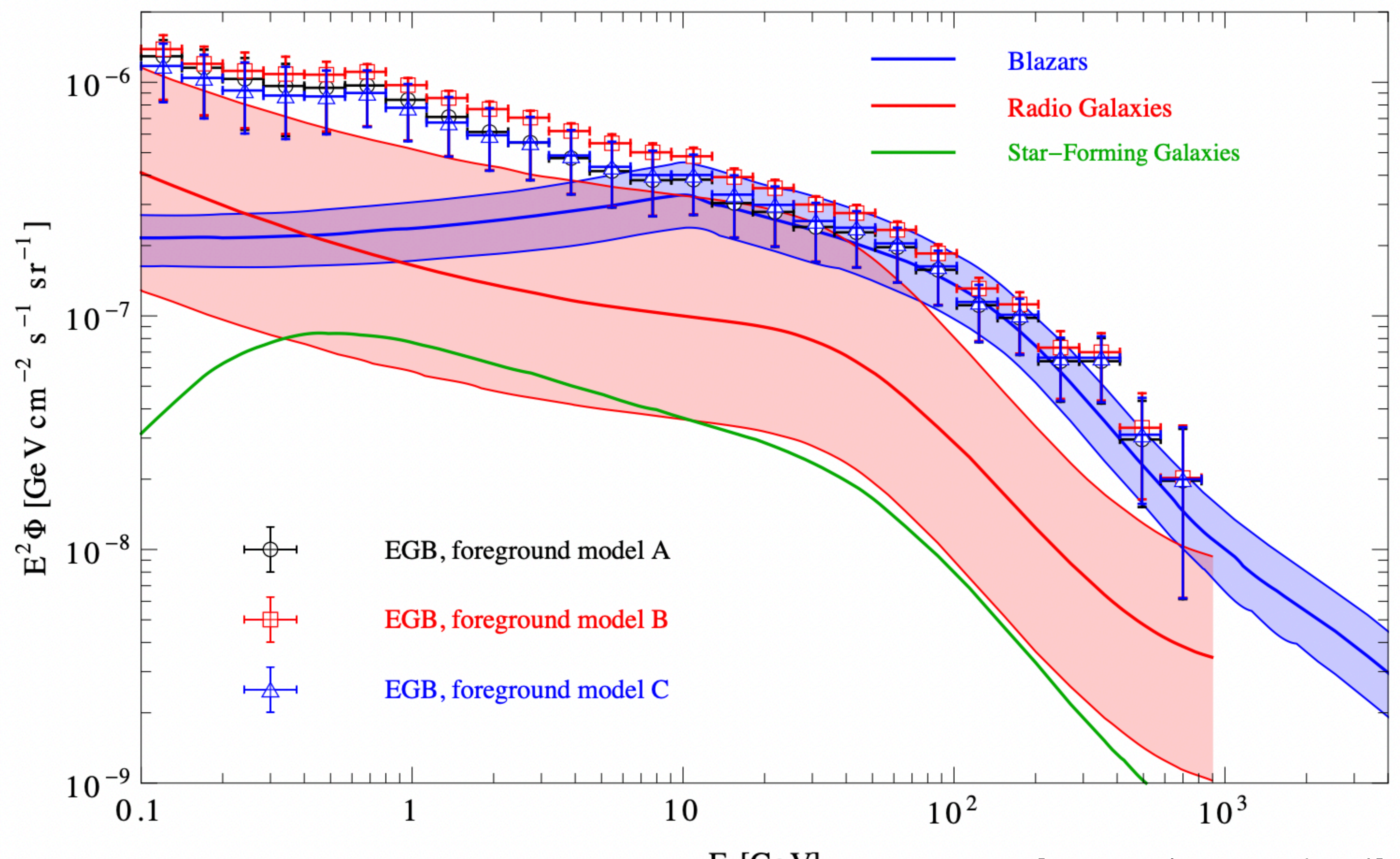
"Conventional"

+

- ✦ Gamma-rays from the IceCube neutrino sources

"Cascaded IceCube"

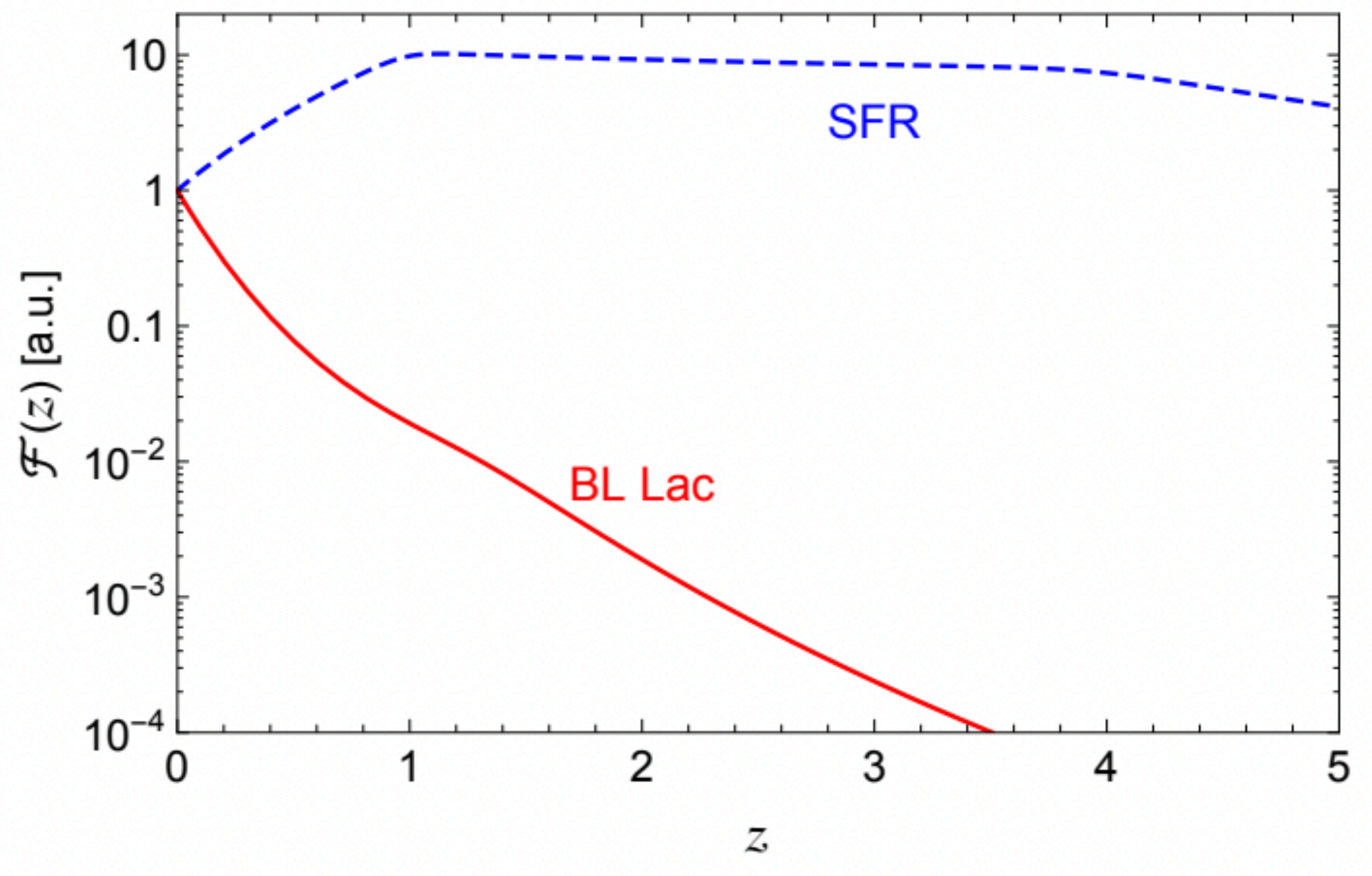
The EGB measured by Fermi-LAT

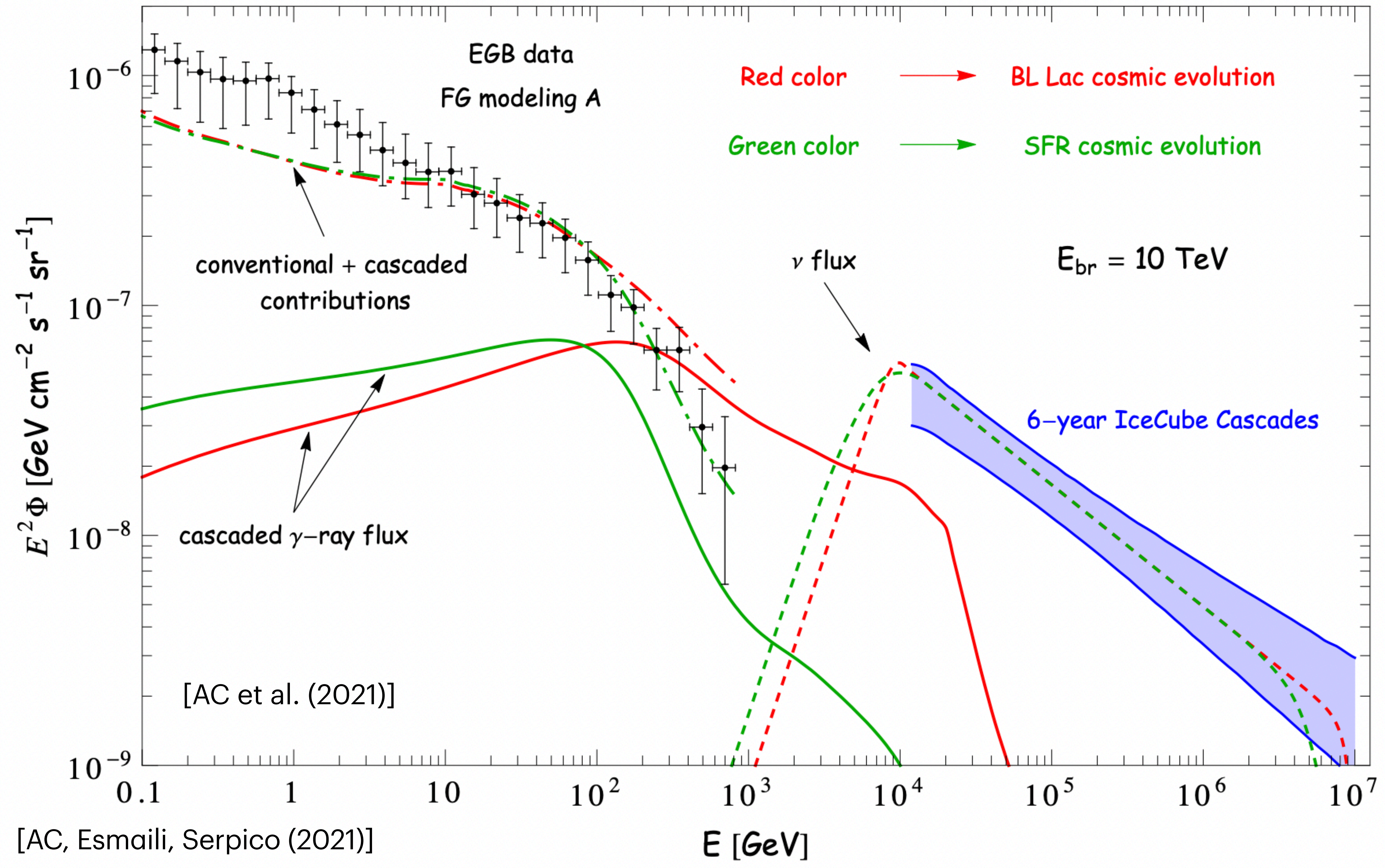


[AC, Esmaili, Serpico (2021)]

An Example

$$\frac{dN_\nu}{d\varepsilon_\nu}(\varepsilon_\nu) = \begin{cases} A\varepsilon_{br}^{-\gamma}\,, & \varepsilon_\nu < \varepsilon_{br} \\ A\,\varepsilon_\nu^{-\gamma}\,, & \varepsilon_{br} < \varepsilon_\nu < 10\text{ PeV} \\ 0\,, & 10\text{ PeV} < \varepsilon_\nu \end{cases} \longrightarrow \varepsilon_\gamma^2 \frac{dN_\gamma}{d\varepsilon_\gamma}(\varepsilon_\gamma) \simeq \frac{2}{3K_\pi}\varepsilon_\nu^2 \frac{dN_\nu}{d\varepsilon_\nu}(\varepsilon_\nu)\Big|_{\varepsilon_\nu=\varepsilon_\gamma/2}$$





[AC, Esmaili, Serpico (2021)]

@ Earth:

$$E_\nu^2\,\Phi(E_\nu) = \frac{1}{4\pi}\int_0^\infty dz\,\frac{d\mathcal{V}_c}{dz}\,\mathcal{F}(z)\,\frac{\left[\varepsilon_\nu^2\frac{dN_\nu}{d\varepsilon_\nu}(\varepsilon_\nu)\right]_{\varepsilon_\nu=(1+z)E_\nu}}{4\pi d_L^2}$$

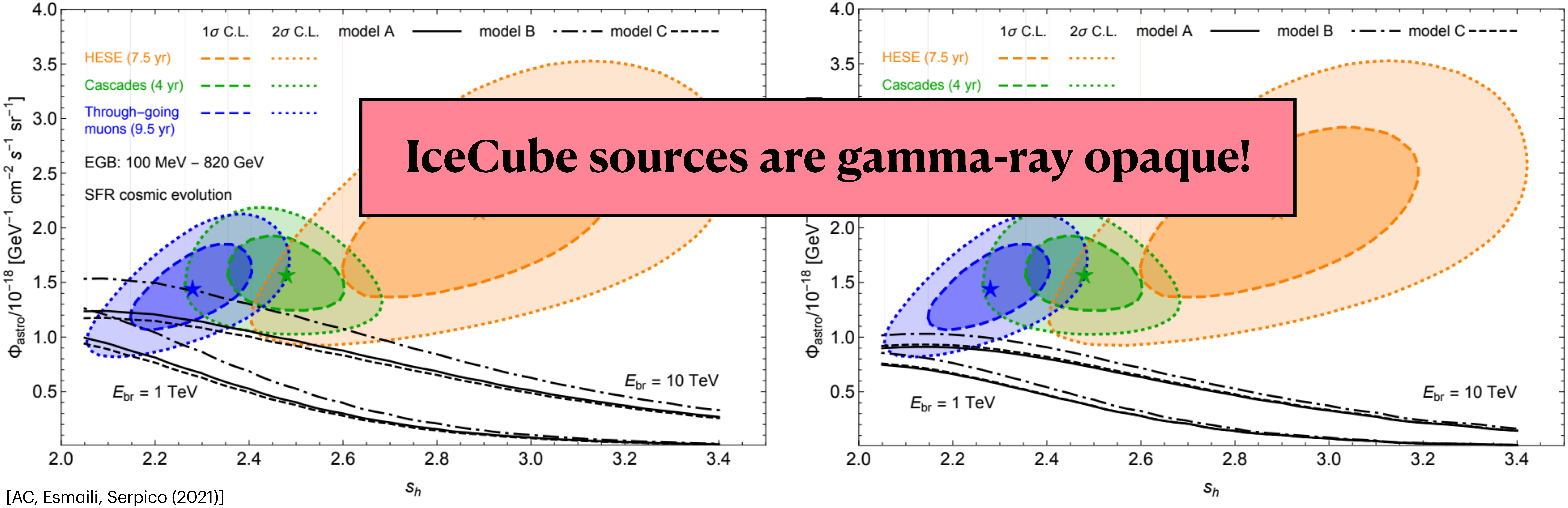
$E_\gamma^2\,\Phi(E_\gamma)$ → Simulations γ-Cascade [Blanco 2019]

Redshift distribution

Is there any choice of $(A, \gamma, \varepsilon_{br}, \mathcal{F})$ that can interpret IceCube and Fermi simultaneously?

Multimessenger Constraints

Chi-square fit to the EGB data: $$\chi^2 = \min_{\alpha_j} \left\{ \left[\sum_i \frac{\left(F_i^{\rm EGB} - F_i^{\rm casc} - \sum_j \alpha_j F_i^j\right)^2}{\sigma_i^2} \right] + \sum_j \left[\frac{(\alpha_j - 1)^2}{\zeta_j^2} \right] \right\}$$



IceCube sources are gamma-ray opaque!

[AC, Esmaili, Serpico (2021)]

CMB PP threshold
~ 100 TeV
EBL PP threshold
~ 100 GeV
EM Cascades:
A closer look
Leading particle
regime
Multiplication
regime
Low energy regime
CMB
CMB
EBL
CMB
CMB
γ
$e^{\pm}$
PP threshold:
$E_{\rm th} = m_e^2/\epsilon_{\rm bkg}$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PP threshold:
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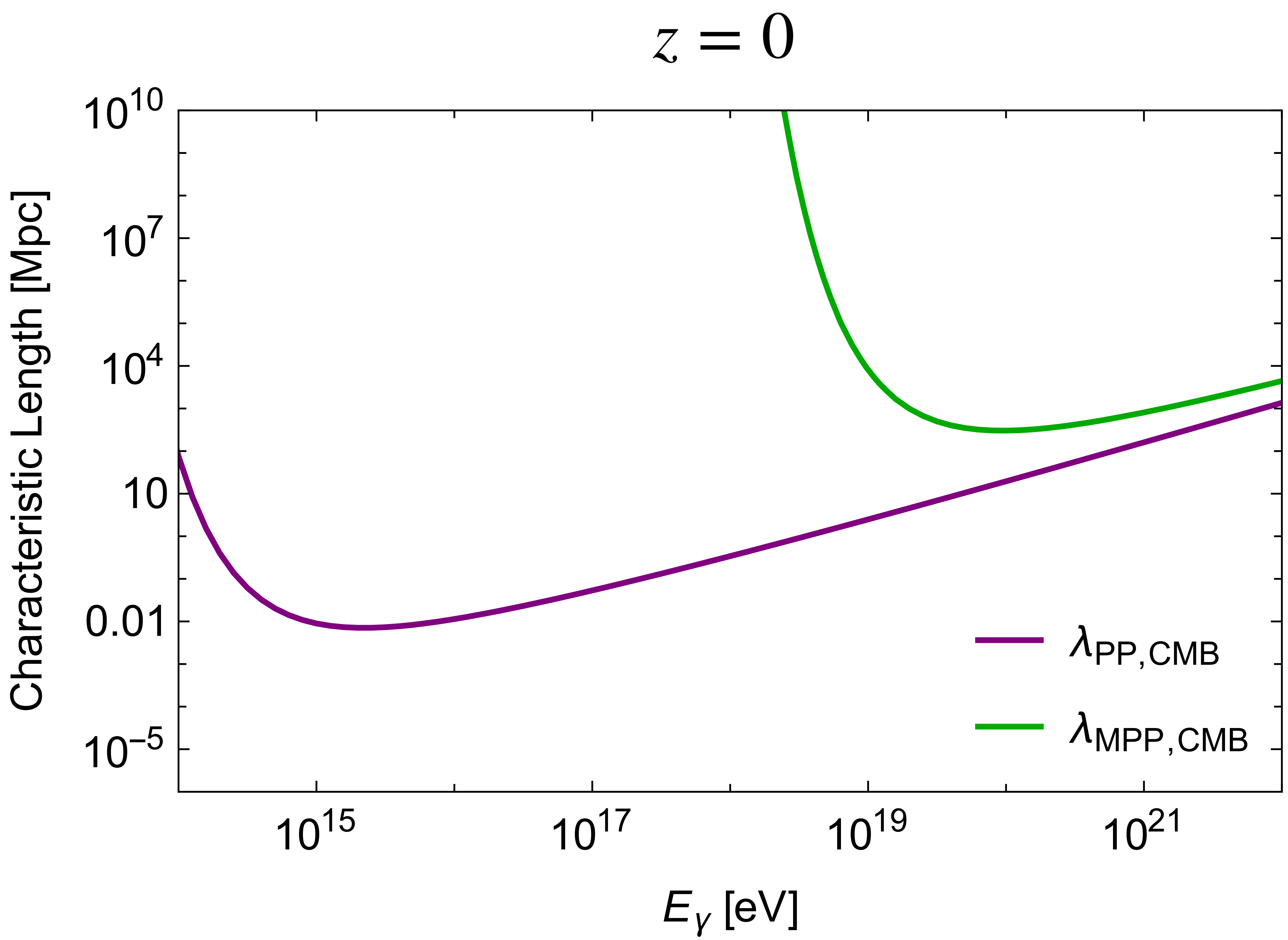
Can cascades produce HE neutrinos?

Muon Pair Production: $\gamma\gamma \to \mu^+\mu^-$ $(E\epsilon \geq m_\mu^2)$



$$\lambda^{-1}(E) = \int_0^\infty d\epsilon\, n(\epsilon) \int_{-1}^{1-\frac{2m^2}{E\epsilon}} d\mu\, \frac{1-\mu}{2}\, \sigma$$

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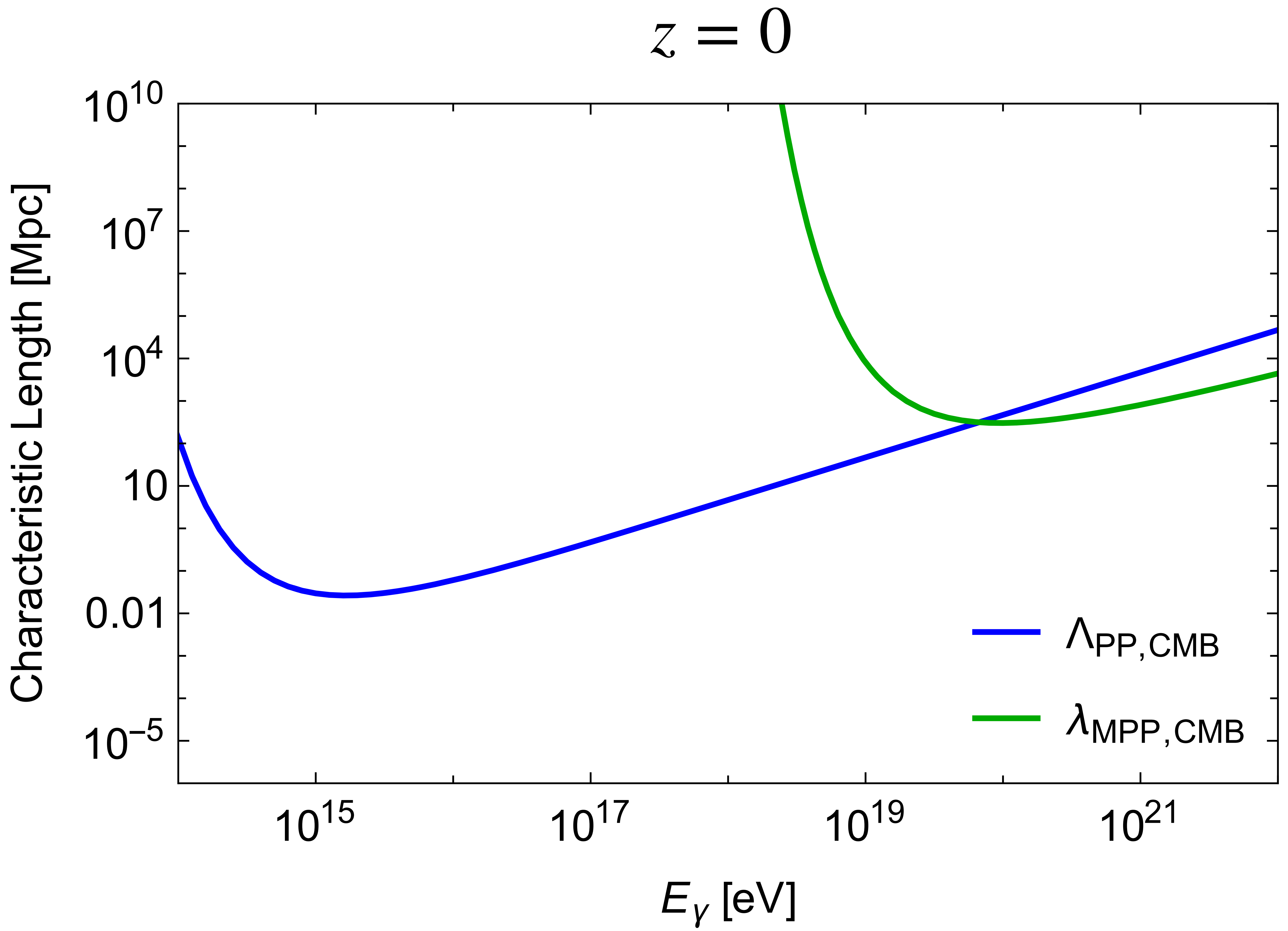

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$$\Lambda^{-1}(E) = \int_0^\infty d\epsilon\, n(\epsilon) \int_{-1}^{1-\frac{2m^2}{E\epsilon}} d\mu\, \frac{1-\mu}{2}\, \sigma(1-\eta)$$

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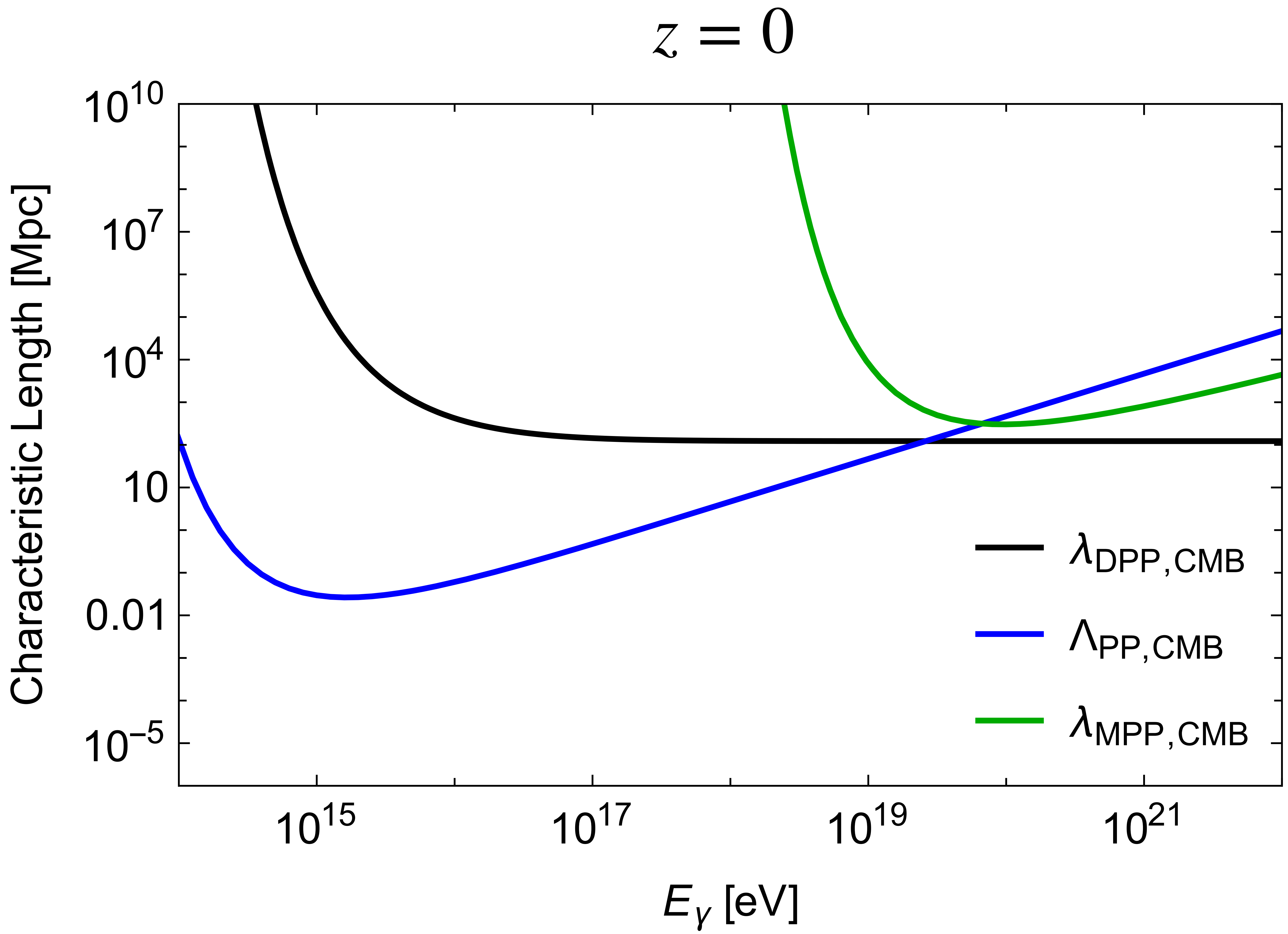

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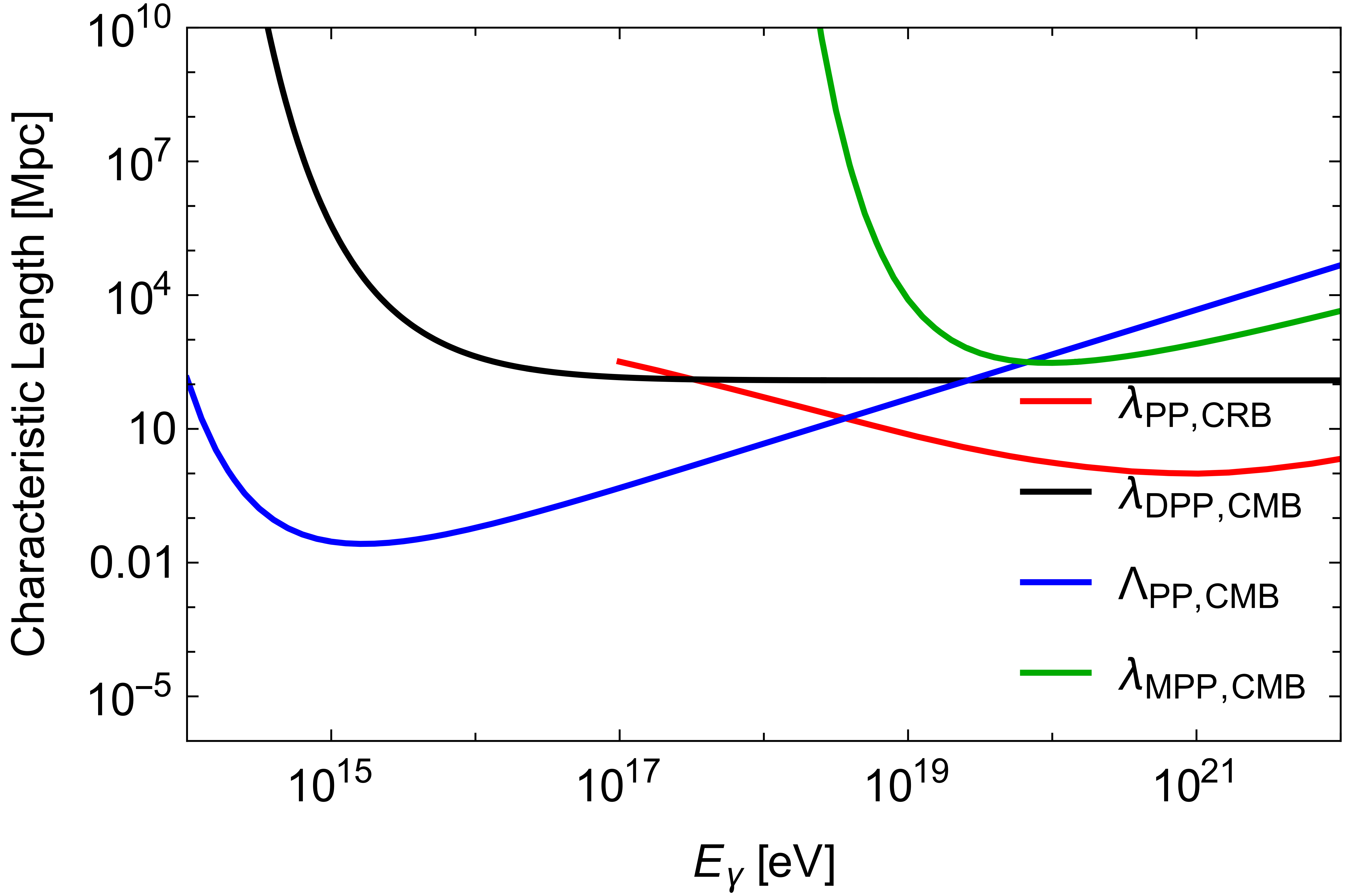
Muon Pair Production: $\gamma\gamma \to \mu^+\mu^-$ $(E\epsilon \geq m_\mu^2)$

$z = 0$



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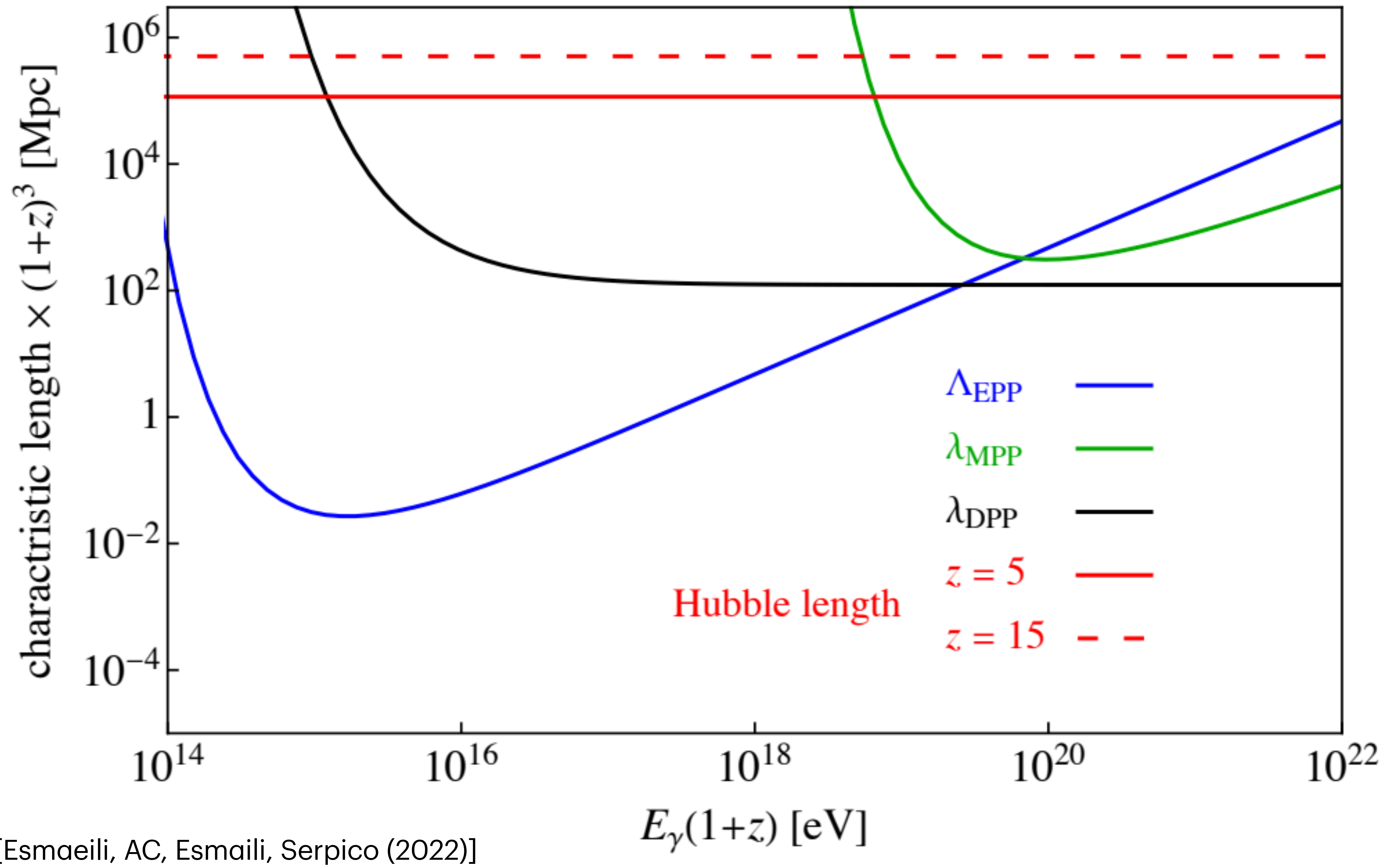
Muon Pair Production: $\gamma\gamma \to \mu^+\mu^-$ $(E\epsilon \geq m_\mu^2)$

High-z



[Esmaeili, AC, Esmaili, Serpico (2022)]

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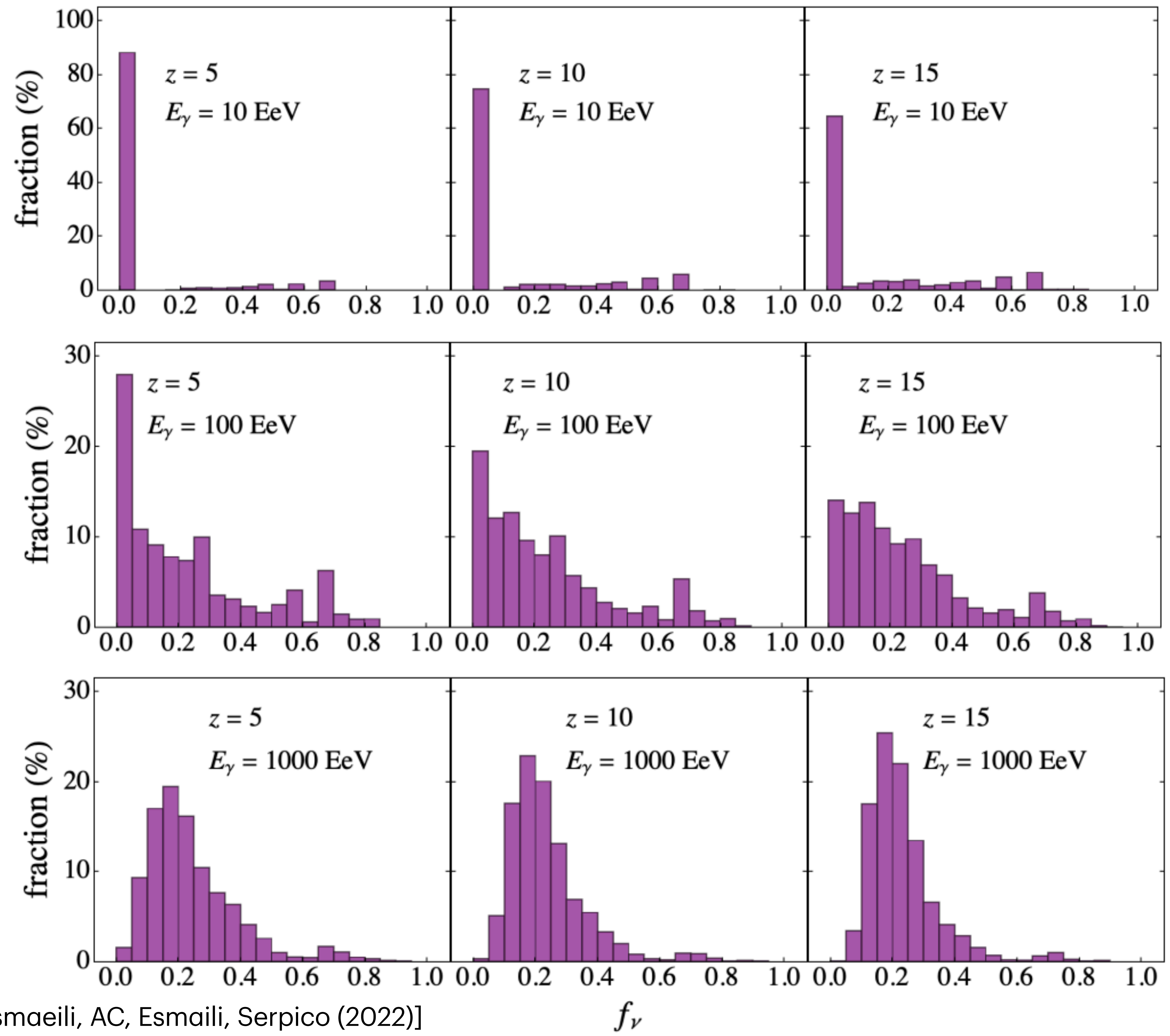
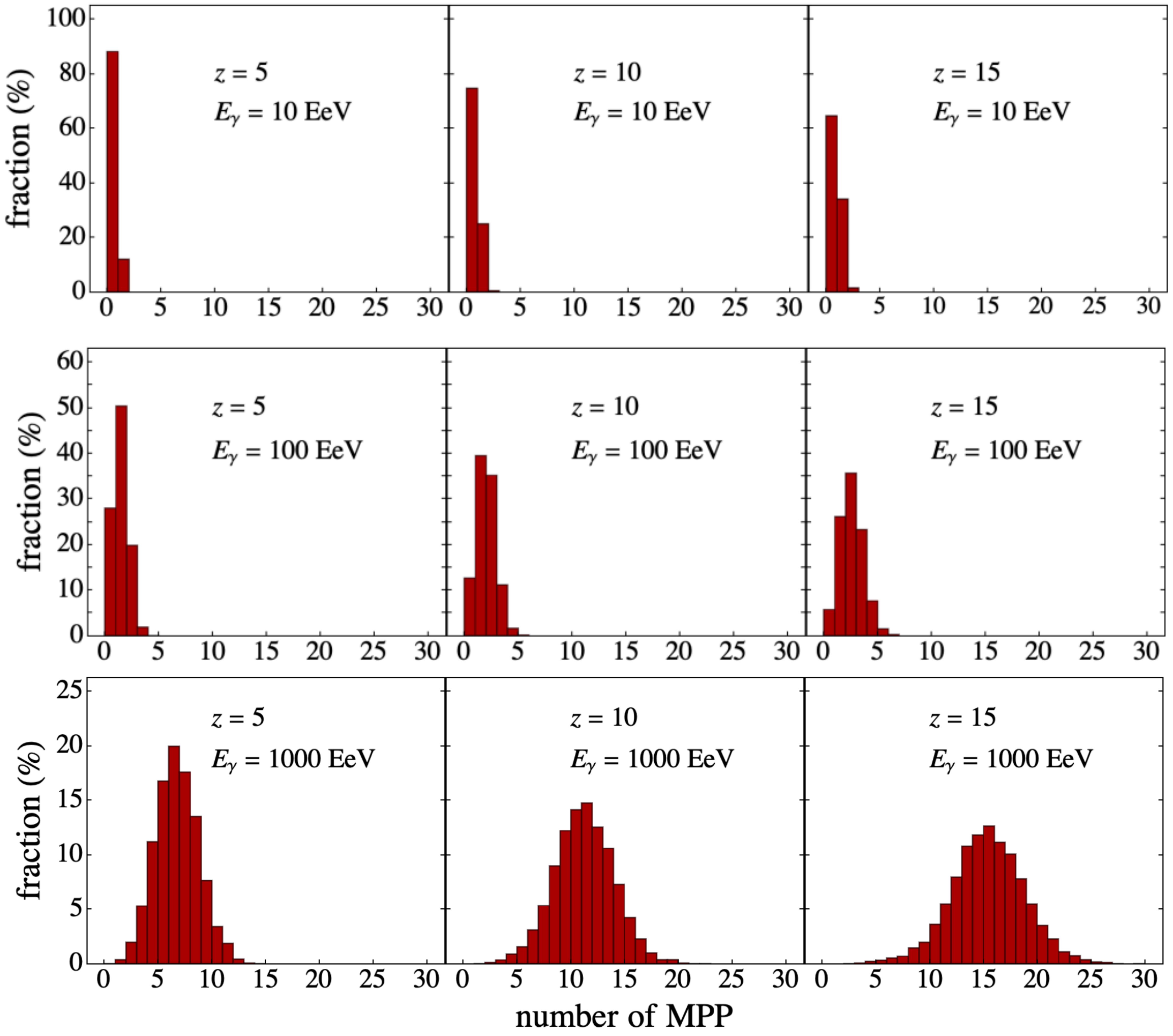
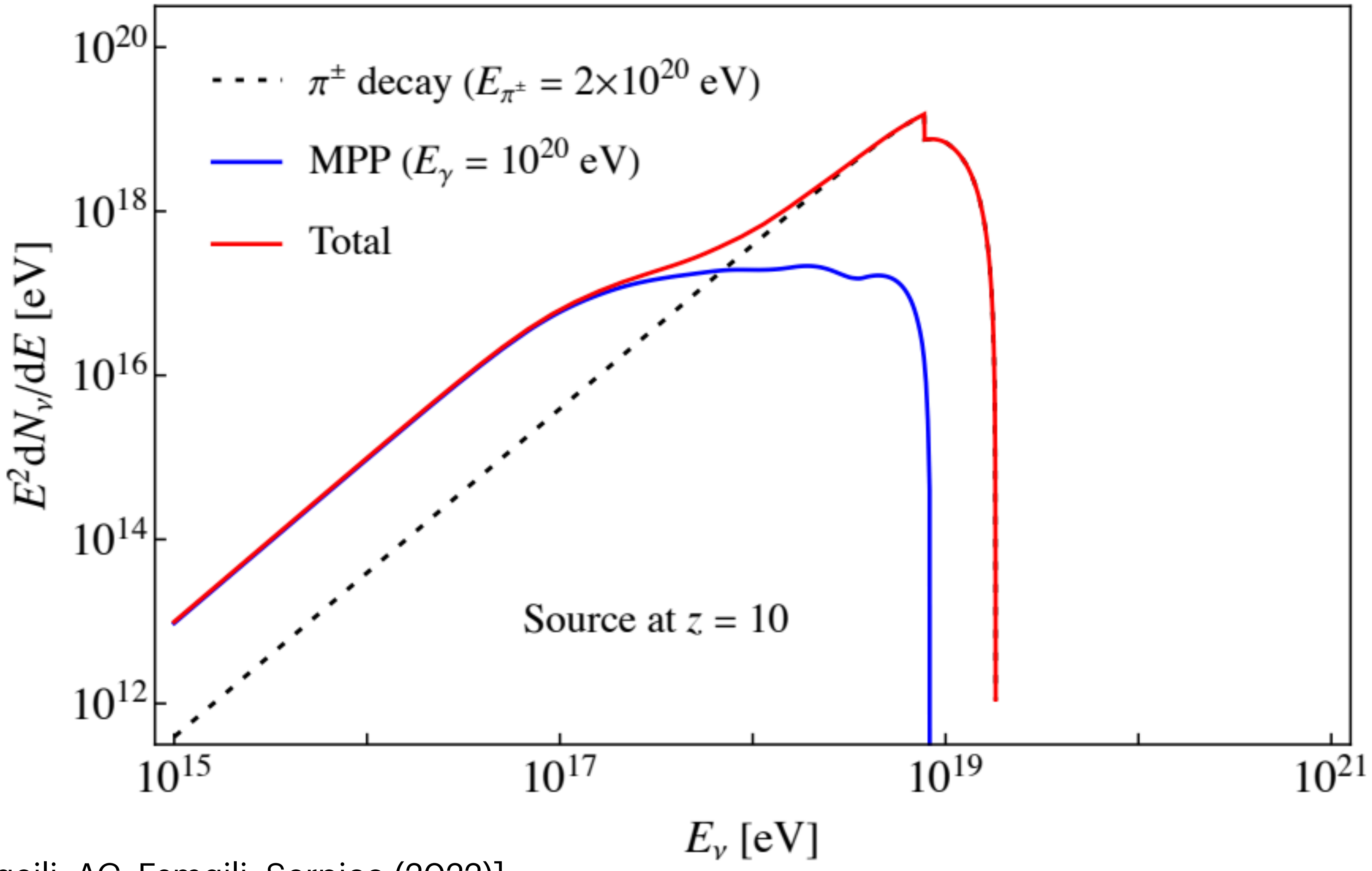
UHE Neutrinos from Cascades at High-Redshifts

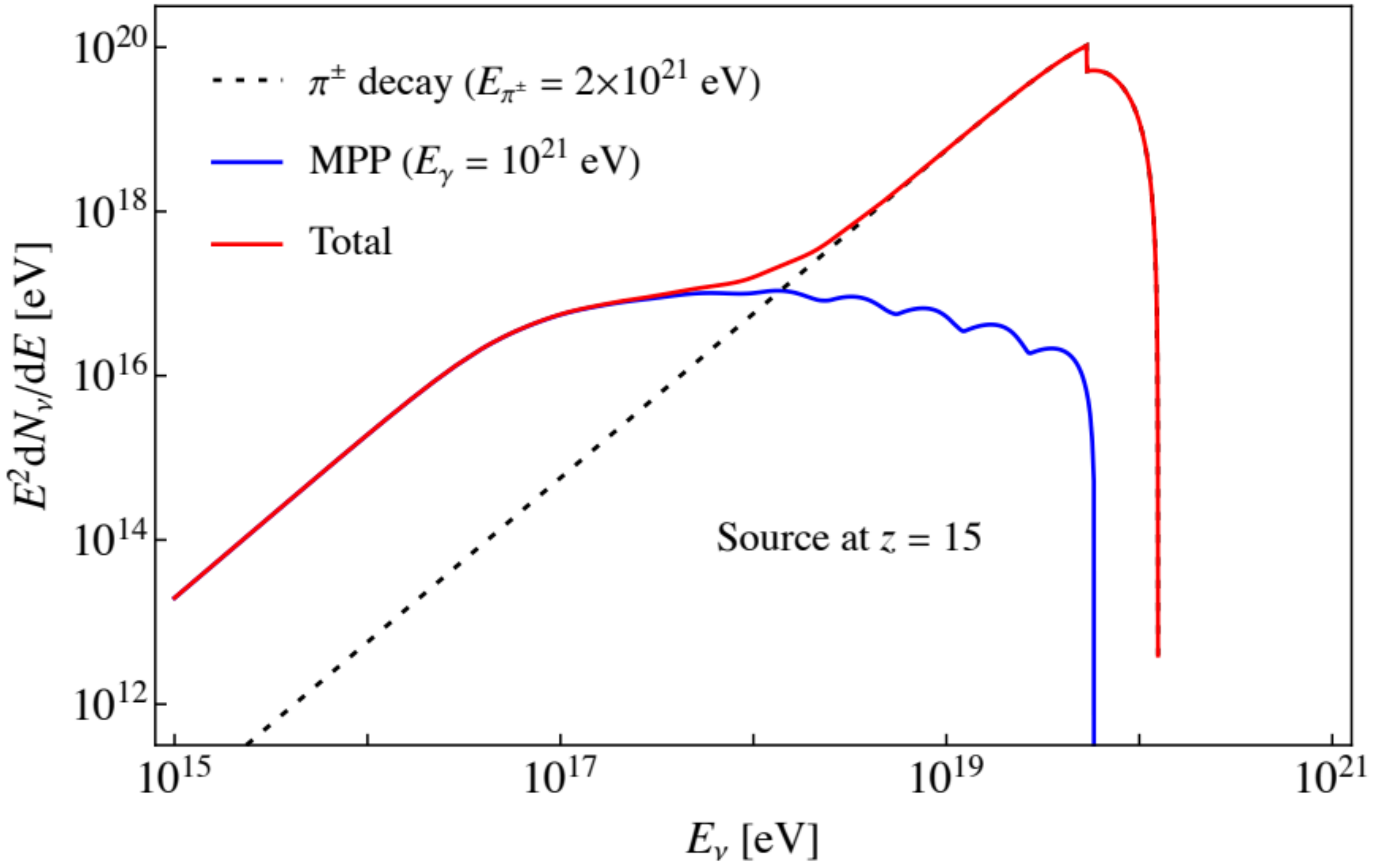




[Esmaeili, AC, Esmaili, Serpico (2022)]

Fluxes @ Earth





[Esmaeili, AC, Esmaili, Serpico (2022)]

$$\varepsilon_\gamma^2 \frac{\mathrm{d}N_\gamma}{\mathrm{d}\varepsilon_\gamma}(\varepsilon_\gamma) \simeq \frac{2}{3K_\pi}\, \varepsilon_\nu^2 \frac{\mathrm{d}N_\nu}{\mathrm{d}\varepsilon_\nu}(\varepsilon_\nu)\bigg|_{\varepsilon_\nu=\varepsilon_\gamma/2} \quad \Rightarrow \quad \mathscr{E}_\gamma/\mathscr{E}_\nu \simeq \begin{cases} \cancel{2/3}, & pp \\ \cancel{4/3}, & p\gamma \end{cases} \begin{cases} 0.44, & pp \\ 0.77, & p\gamma \end{cases}$$

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Thank you!

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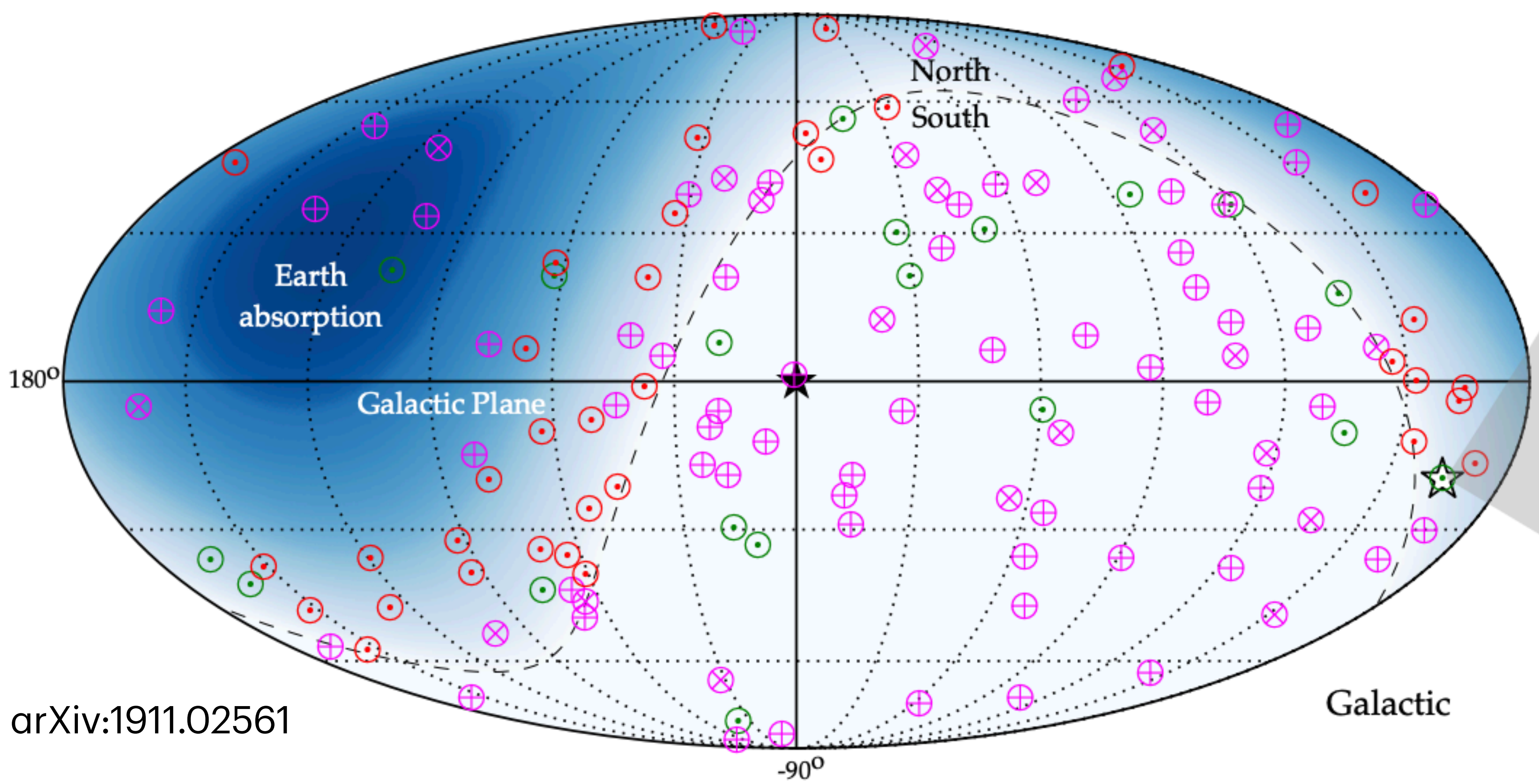
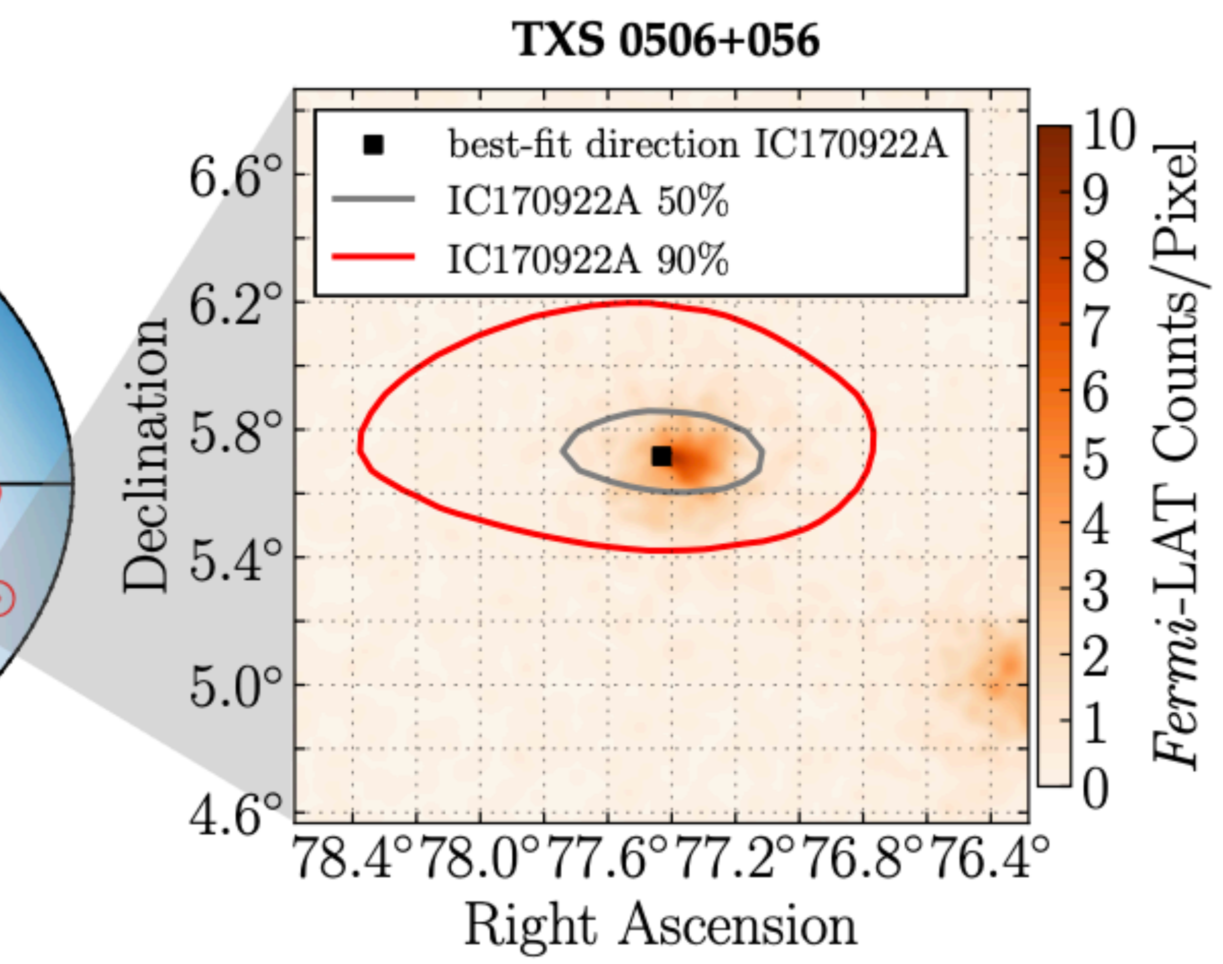
Backup Slides

Astrophysical Neutrinos: Current Status

- ✦ Diffuse flux from ~10 TeV to ~few PeV
- ✦ Quasi-equal flavors ⇒ pp or $p\gamma$
- ✦ Quasi-isotropic ⇒ extragalactic
- ✦ Point-source searches cannot account for bulk of events





arXiv:1911.02561

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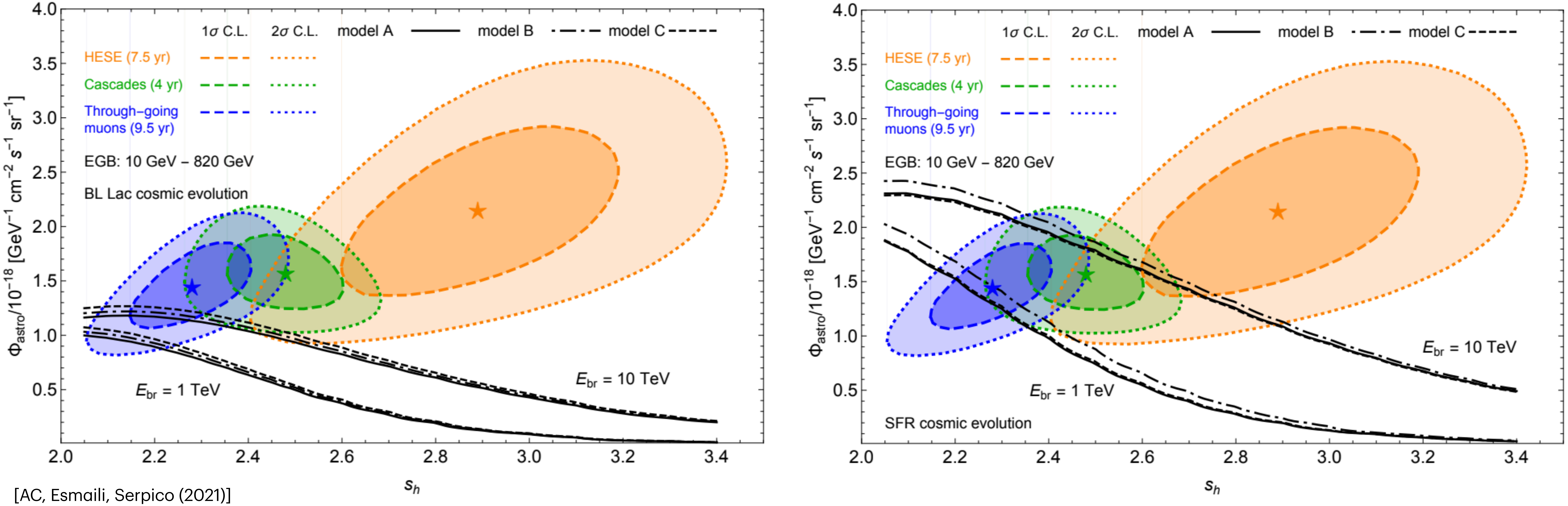
Multimessenger Constraints

Chi-square fit to the EGB data: $\chi^2 = \min_{\alpha_j} \left\{ \left[\sum_i \frac{\left(F_i^{\rm EGB} - \sum_j \alpha_j F_i^j\right)^2}{\sigma_i^2} \right] + \sum_j \left[\frac{(\alpha_j - 1)^2}{\zeta_j^2} \right] \right\}$



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Multimessenger Constraints

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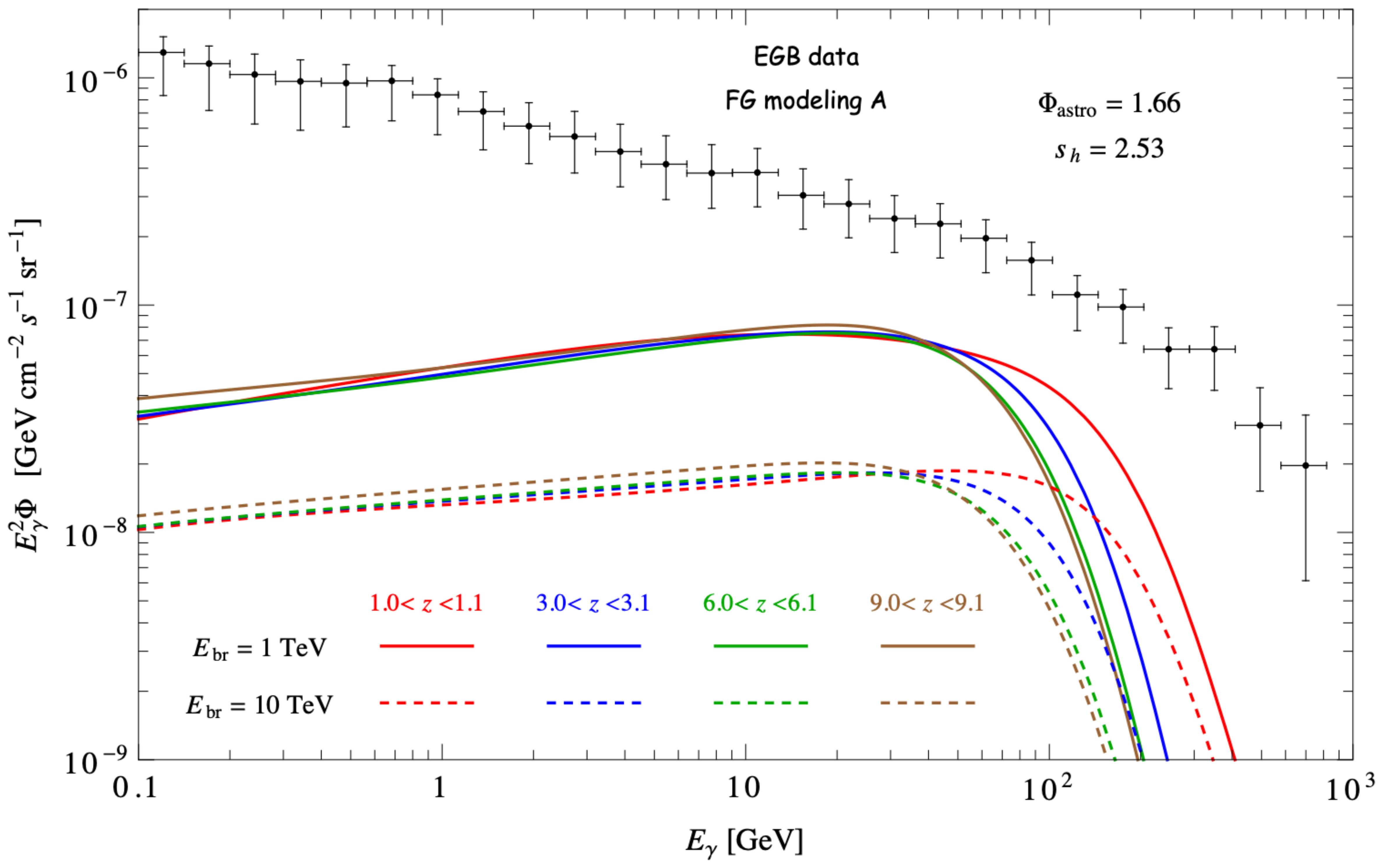

High-z sources: challenging energy budgets

E.g.: SMBHs at $6 < z < 6.1$ and $E_{br} = 10$ TeV

Required: $L_\nu \approx 2 \times 10^{51}$ erg/s

SMBH birth via SN/GRB: $L_{tot} \sim 10^{44}$ erg/s

Eddington accretion: $L_{tot} \approx 4.4 \times 10^{51}$ erg/s

		SFR	BL LAC	$z \gtrsim 3$	$0 \leq z \leq 10^{-2}$	$0 \leq z \leq 10^{-3}$
$E_{br} = 1$ TeV	EGB > 100 MeV	47	137	35	232	110
	EGB > 10 GeV	37	113	29	211	103
$E_{br} = 10$ TeV	EGB > 100 MeV	19	39	4.5	49	5.1
	EGB > 10 GeV	6	26	3.5	40	4.1

$\Delta\chi^2$	C.L.
4.61	1σ
6.18	2σ
11.83	3σ

Low-z sources