UNIVERSITY OF COPENHAGEN

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Electromagnetic Cascades

as probes of the High and Ultra-High Energy Universe

Antonio Capanema

PhD Advisor: Prof. Arman Esmaili

TeVPA 2023

Napoli, Italy

September 11 2023

The High-Energy Multimessenger Picture

Multimessenger Source

2

The High-Energy Multimessenger Picture

3

The High-Energy Multimessenger Picture

The High-Energy Multimessenger Picture

The High-Energy Multimessenger Picture

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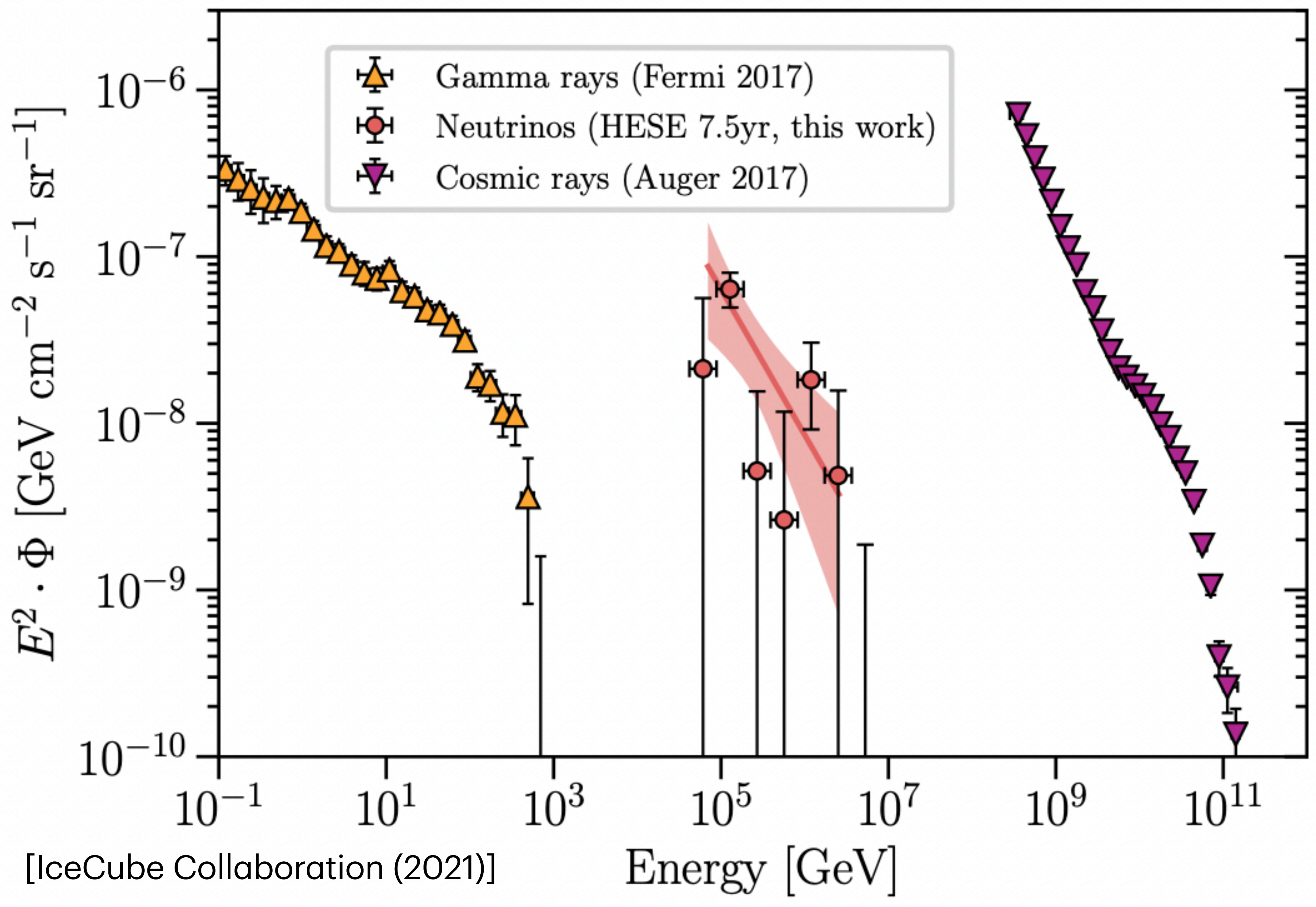
IceCube Observations

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

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



[IceCube Collaboration (2021)]

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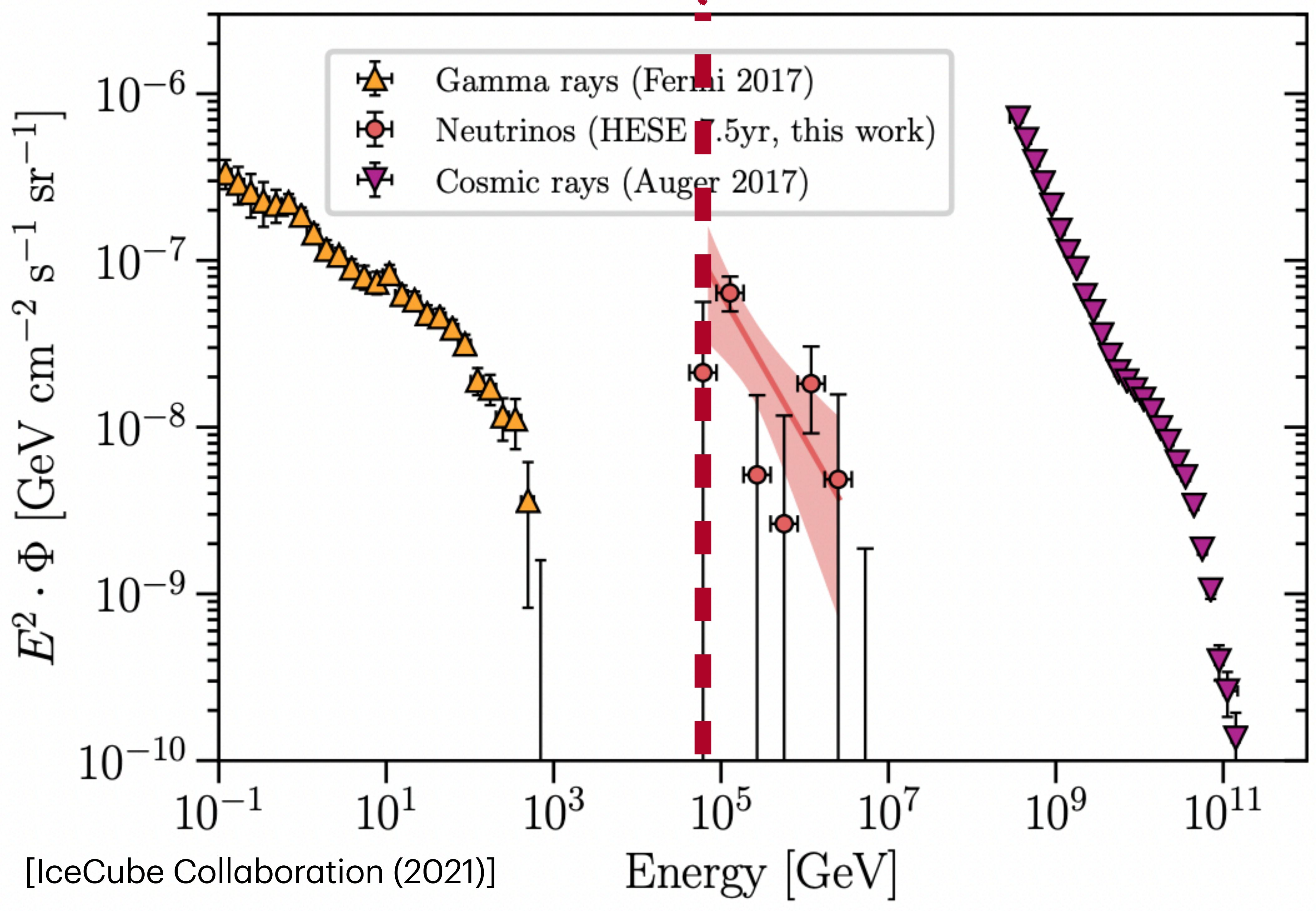

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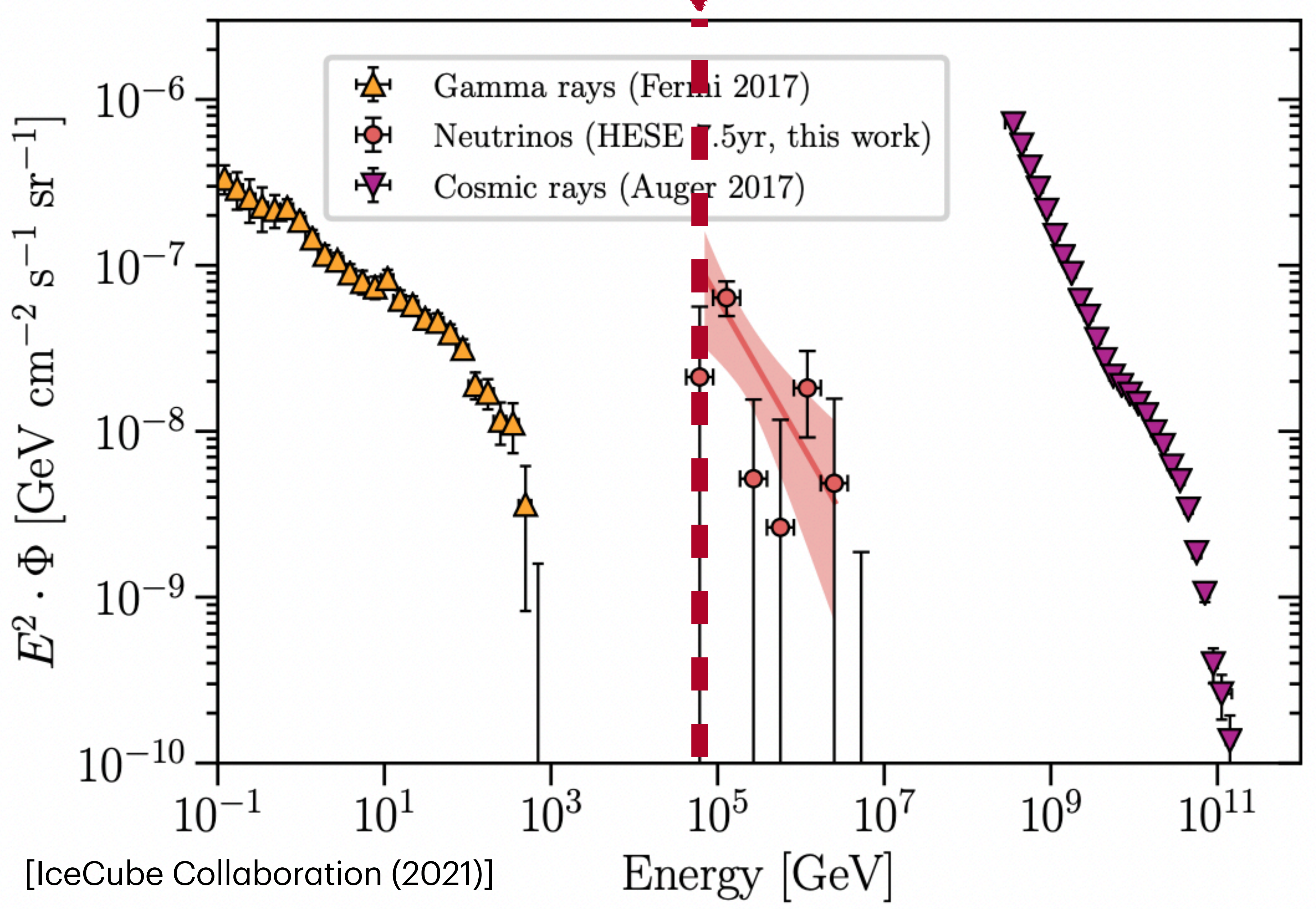
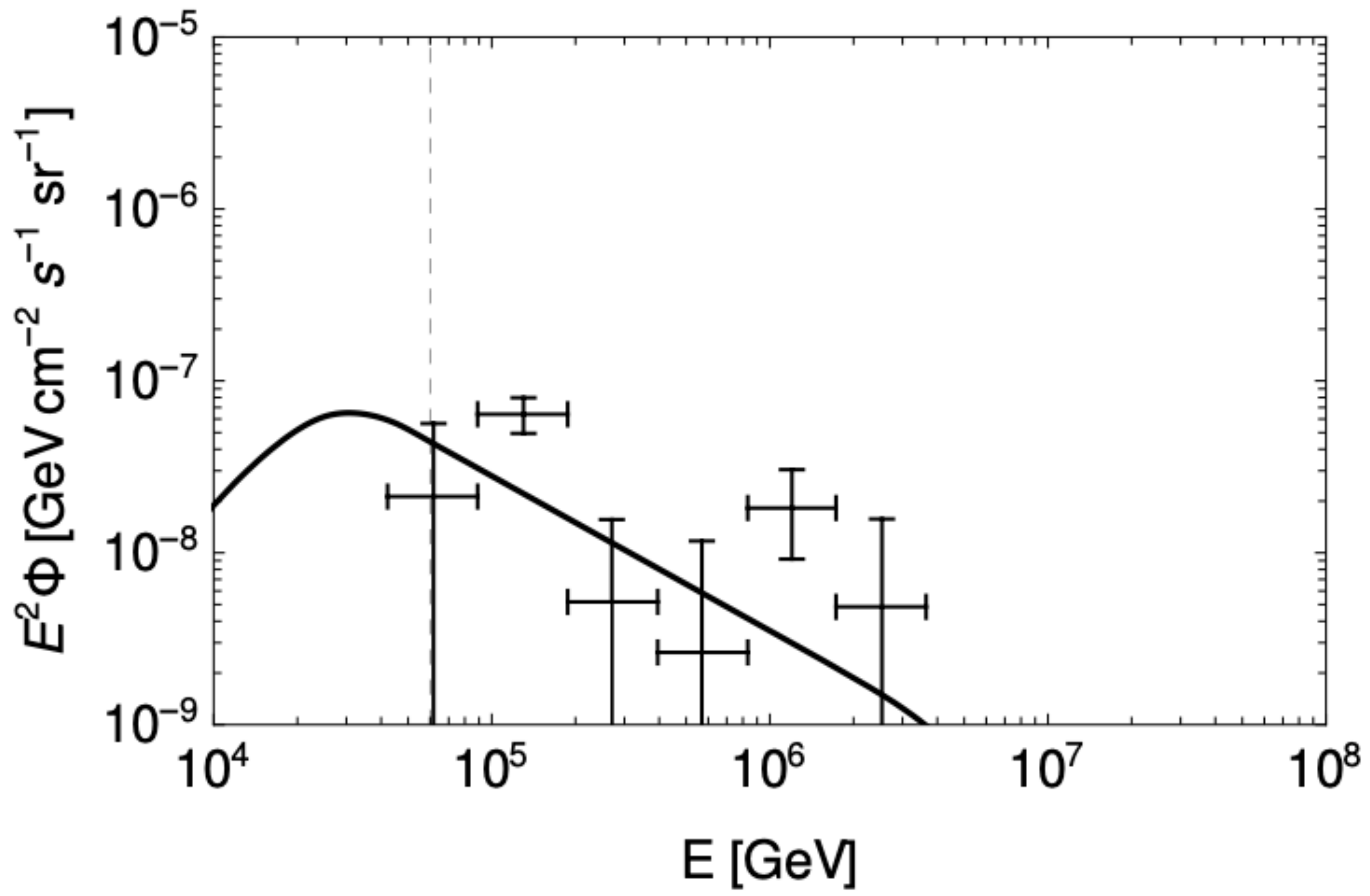


[IceCube Collaboration (2021)]

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



Minimal emission spectrum:

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

Astrophysical Neutrino Production

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

2 main scenarios: pp or $p\gamma$

$$p + p \longrightarrow \pi^+,\ \pi^-,\ \pi^0$$

$$p + \gamma \xrightarrow{\Delta^+} \pi^+,\ \pi^-,\ \pi^0$$

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$$\nu$$

Seen by IceCube

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

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Undergoes EM cascade

ν

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

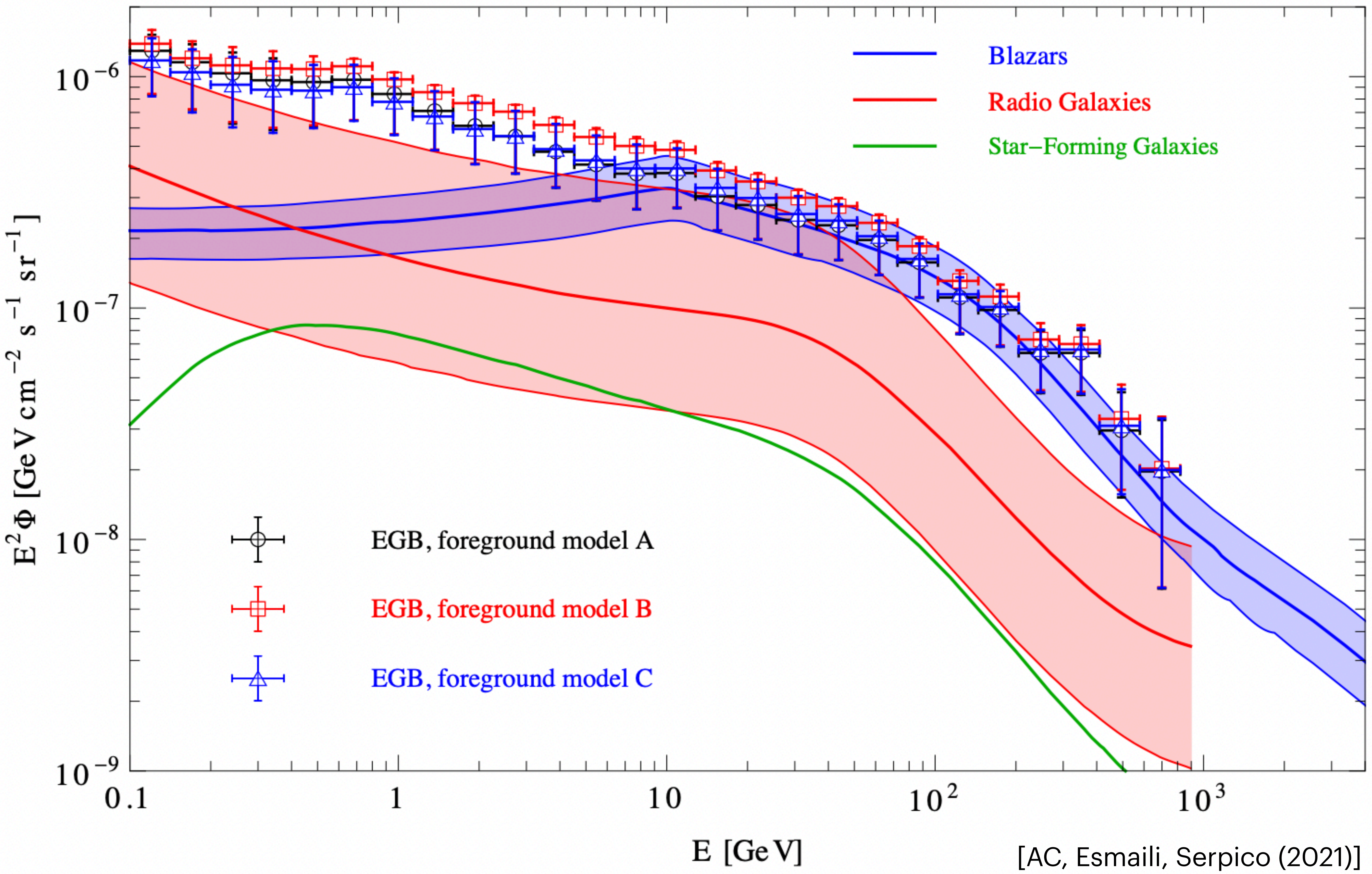
- No leptonic contribution
- No absorption inside source

The Extragalactic Gamma-ray Background (EGB)

Contributions

- Blazars [Qu, Zeng, Yan (2019)]
- Radio Galaxies [Di Mauro et al. (2014)]
- Star-Forming Galaxies [Ajello et al. (2020)]

The EGB measured by Fermi-LAT [Ackermann et al. (2015)]



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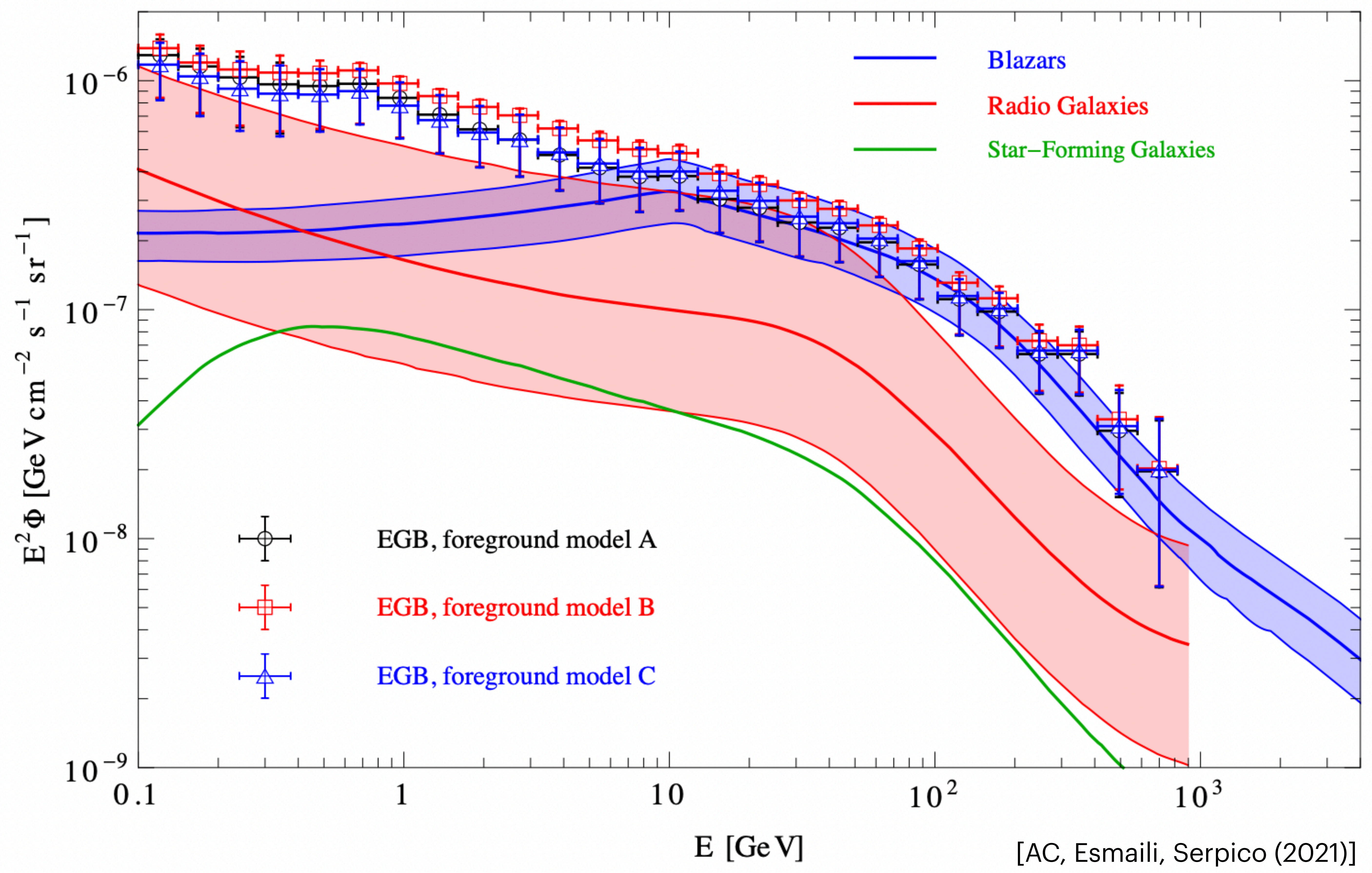

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"Conventional"

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- Gamma-rays from the IceCube neutrino sources

"Cascaded IceCube"

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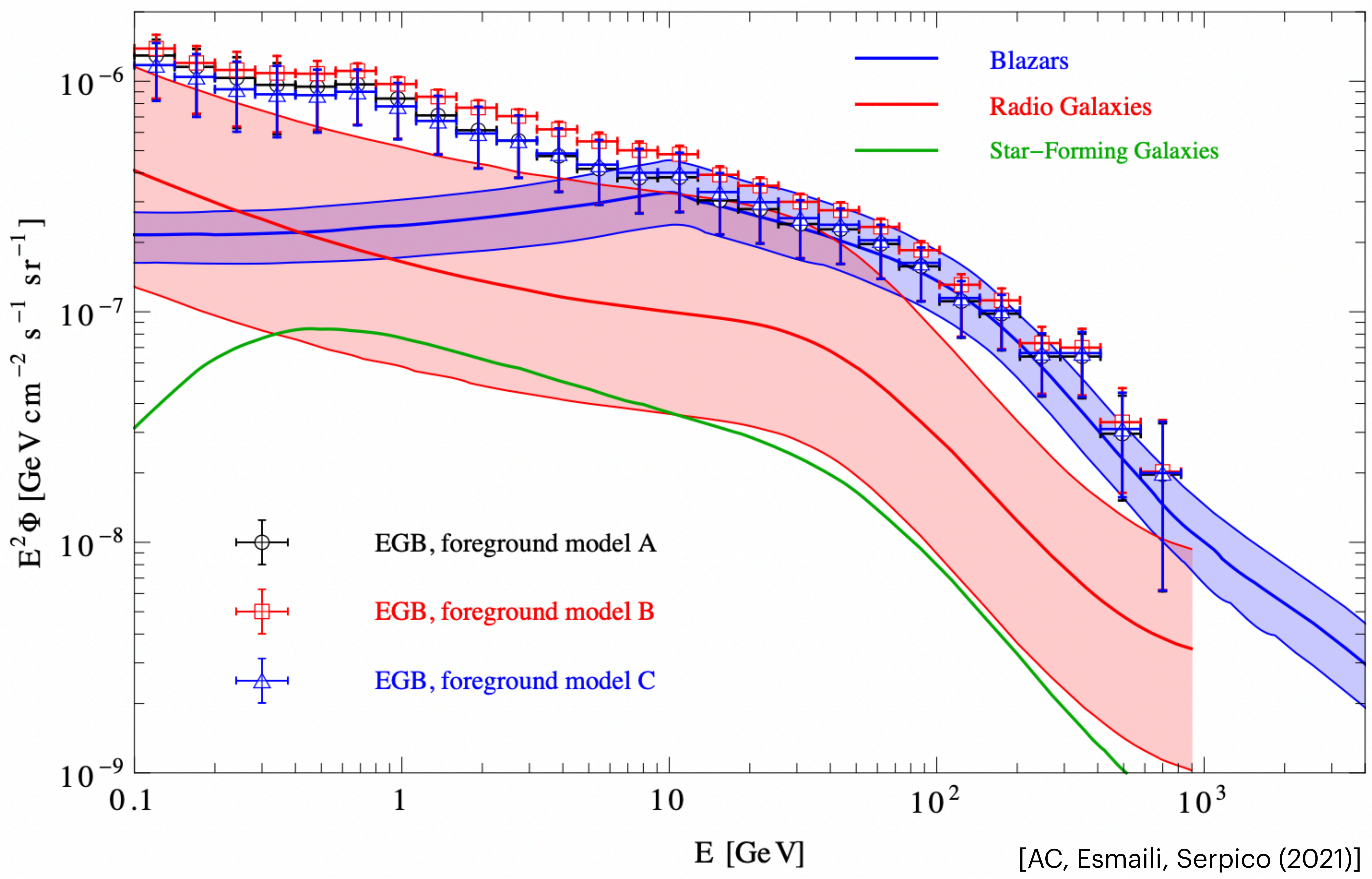

[AC, Esmaili, Serpico (2021)]

An Example

@ Source:

$$\frac{dN_\nu}{d\varepsilon_\nu}(\varepsilon_\nu) = \begin{cases} \text{const}\,, & \varepsilon_\nu < \varepsilon_{\rm br} \\ A\,\varepsilon_\nu^{-\gamma}\,, & \varepsilon_\nu > \varepsilon_{\rm br} \end{cases} \rightarrow \varepsilon_\gamma^2 \frac{dN_\gamma}{d\varepsilon_\gamma}(\varepsilon_\gamma) \simeq \frac{2}{3K_\pi} \varepsilon_\nu^2 \frac{dN_\nu}{d\varepsilon_\nu}(\varepsilon_\nu)\bigg|_{\varepsilon_\nu = \varepsilon_\gamma/2}$$

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@ Earth:

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

Redshift distribution

$$E_\gamma^2\,\Phi(E_\gamma) \longrightarrow$$

Simulations
γ-Cascade
[Blanco (2019)]

An Example

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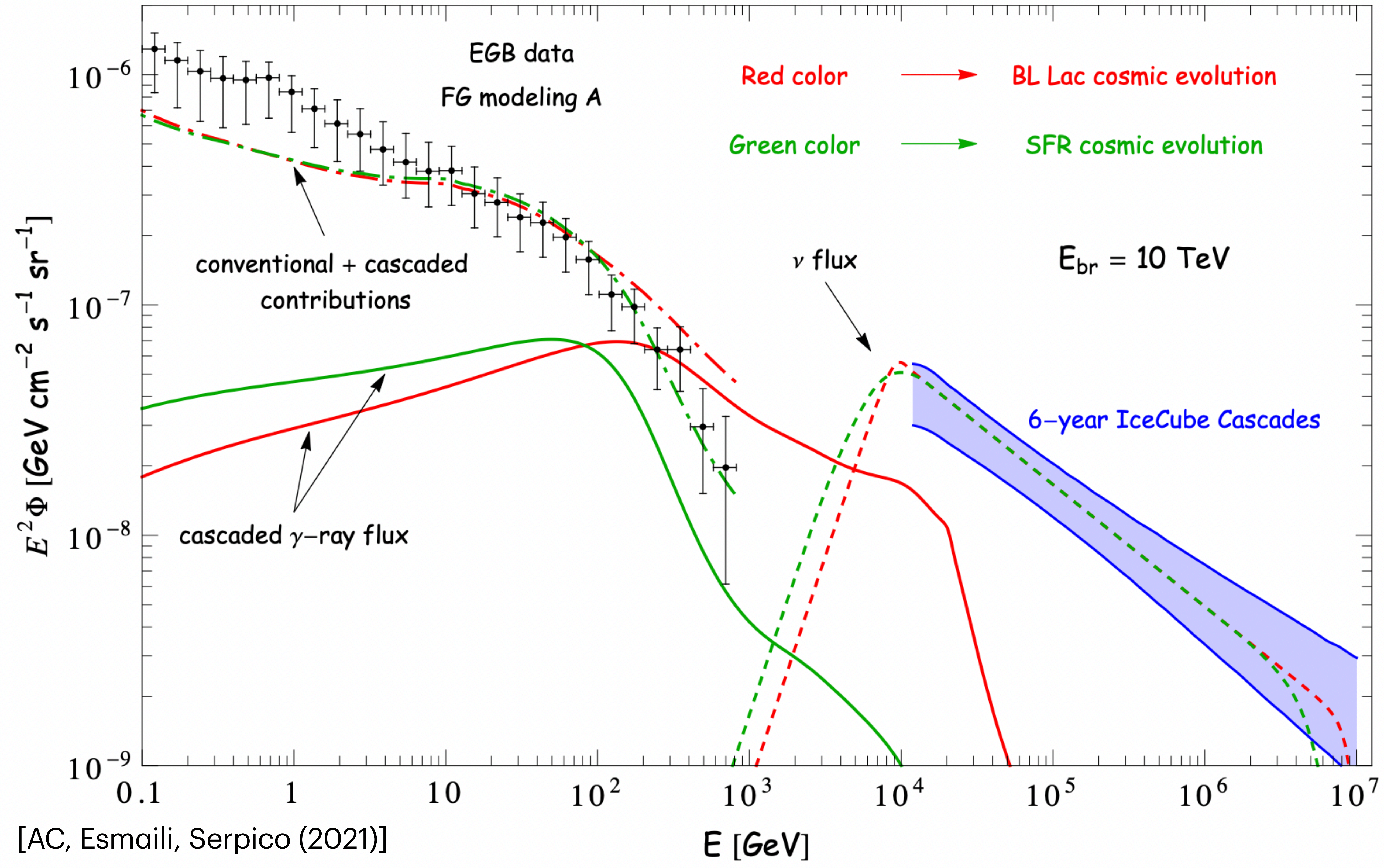
Redshift distribution

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



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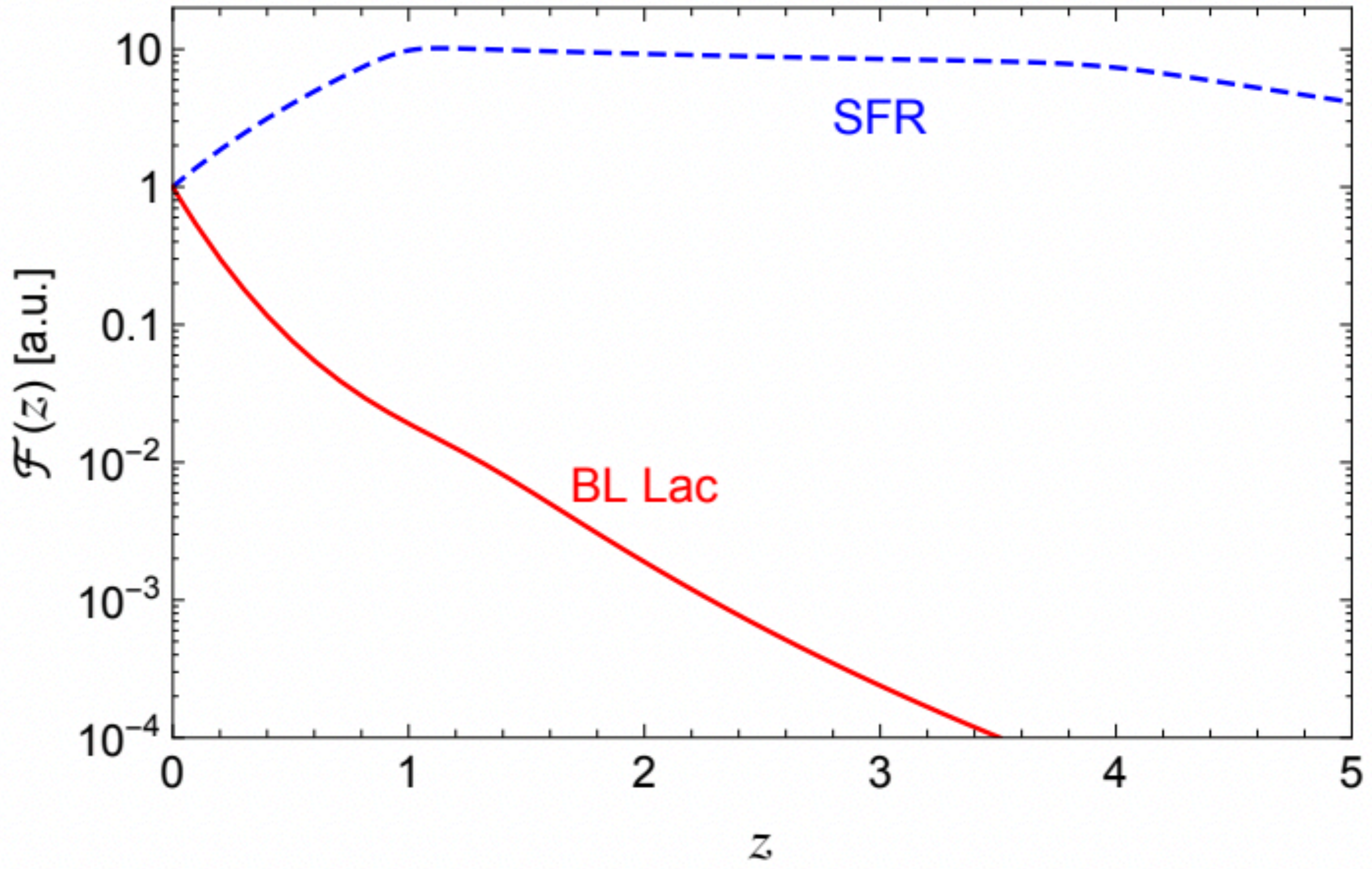

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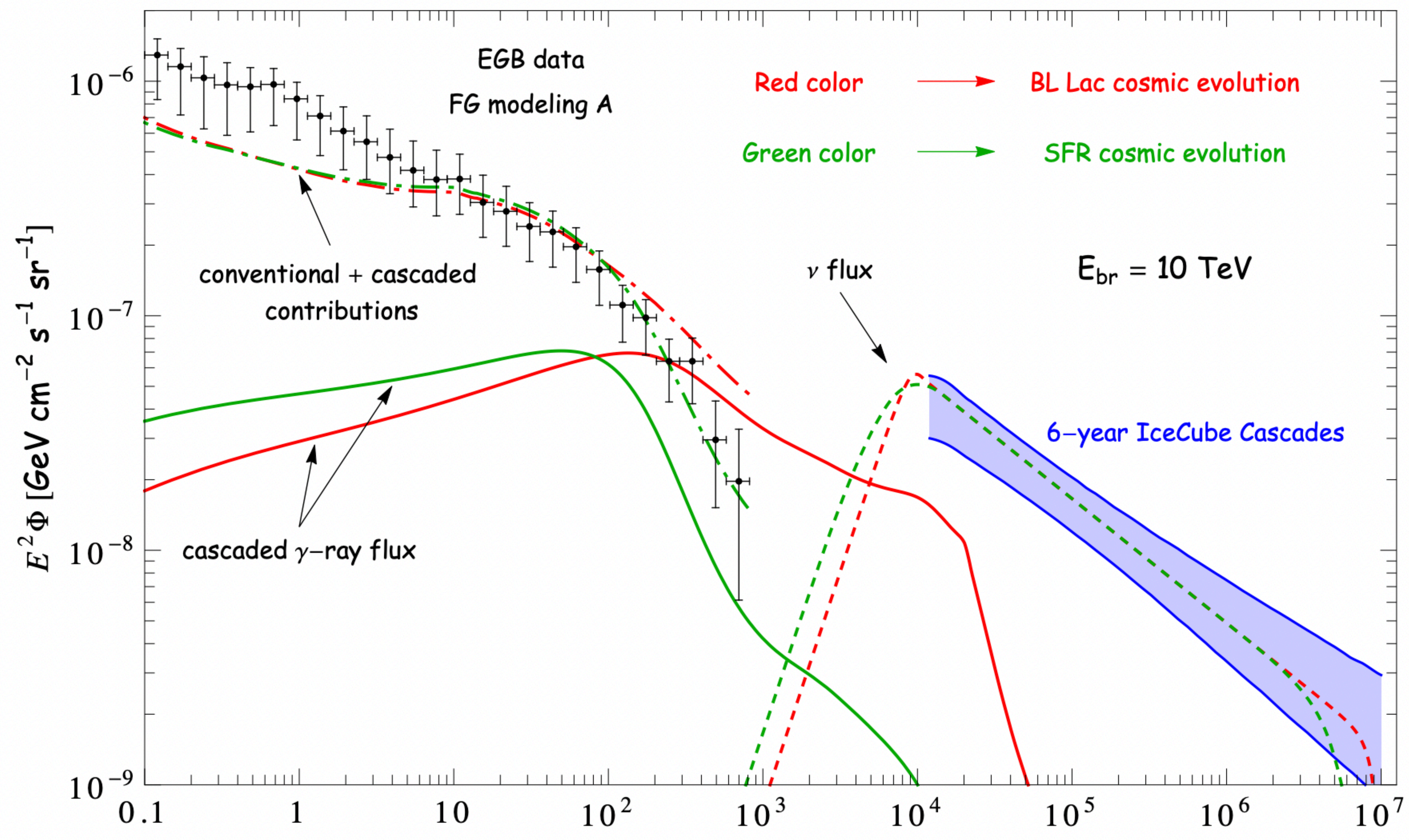

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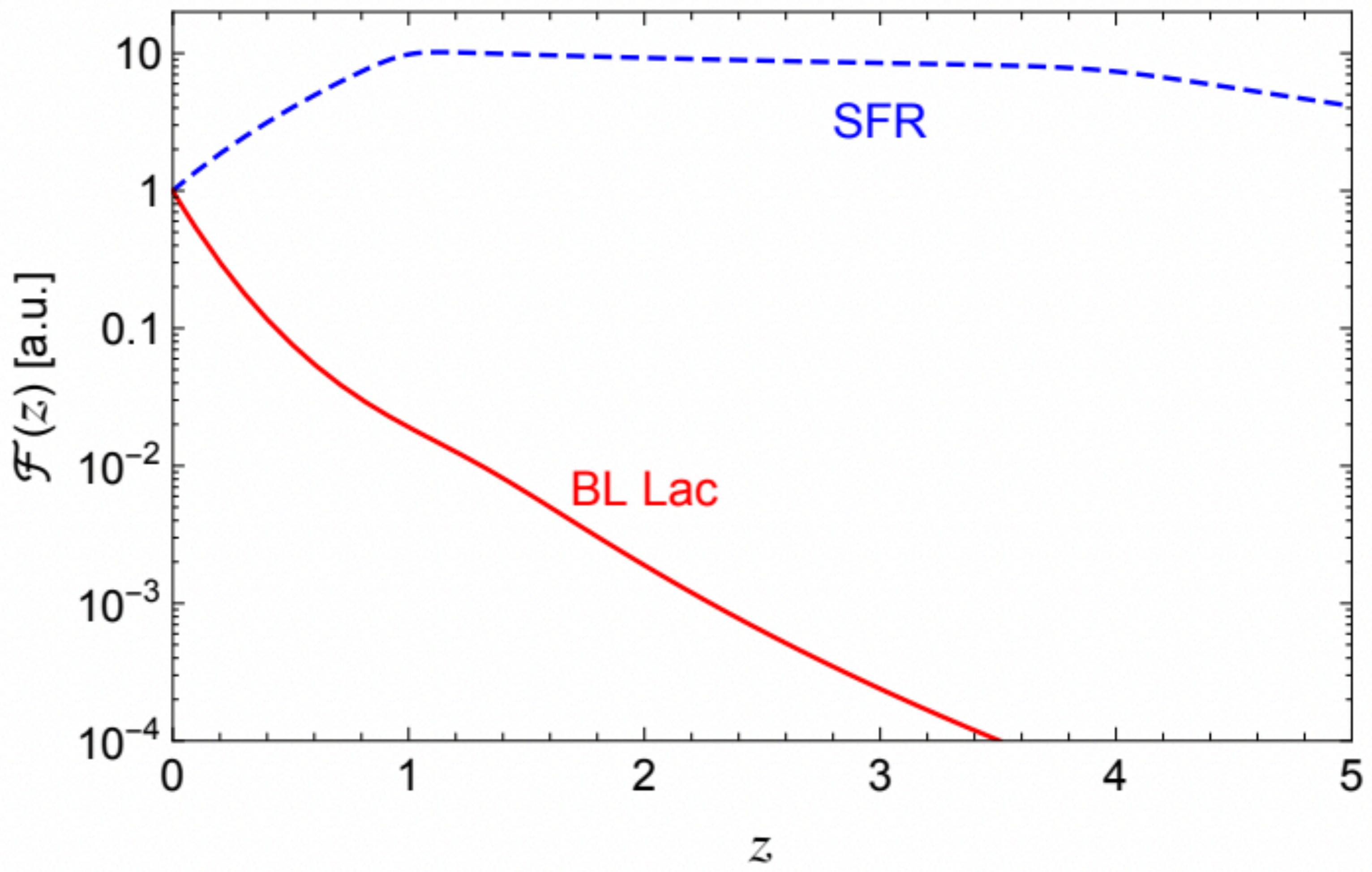
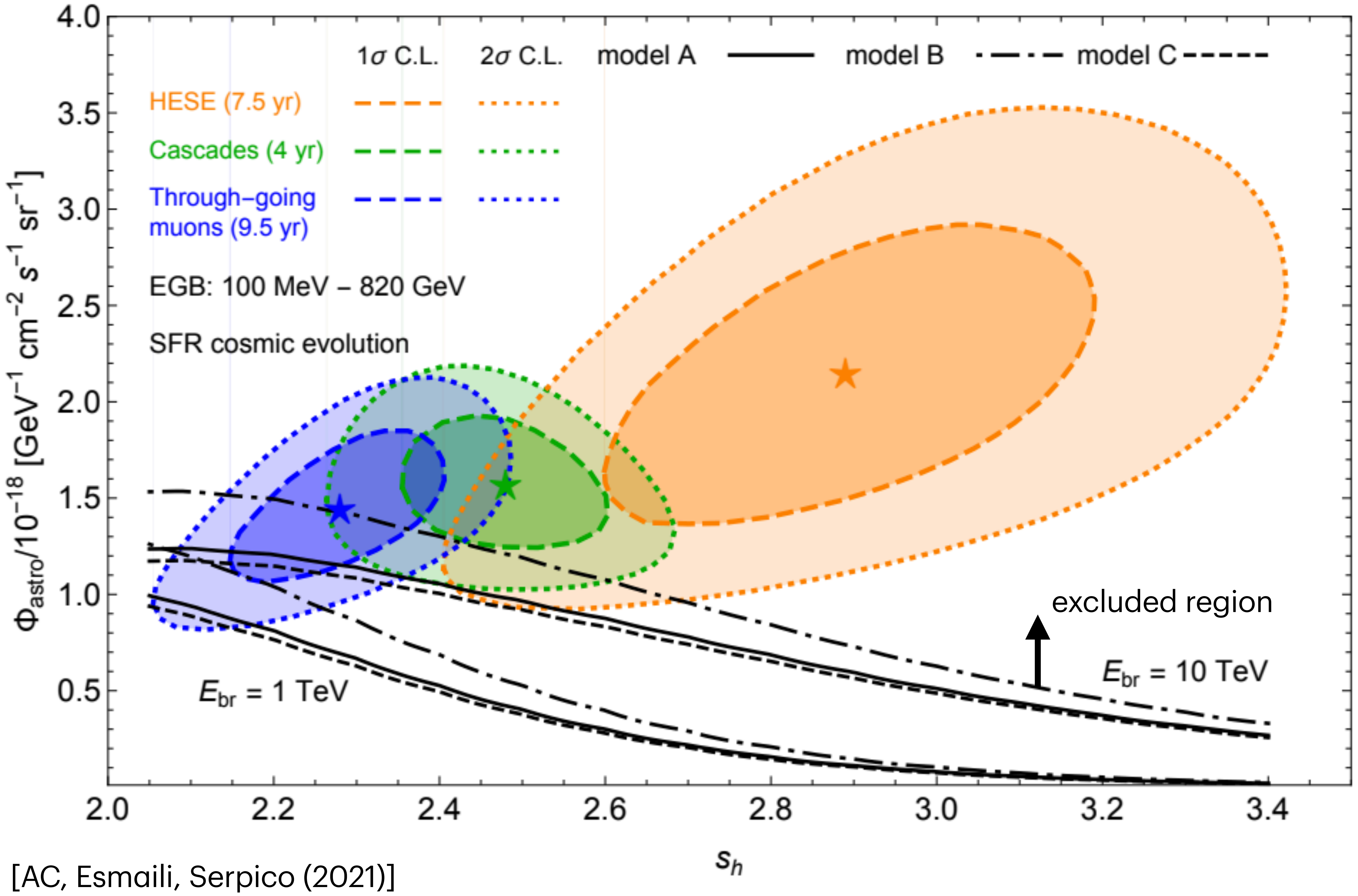


Is there any choice of $(A, \gamma, \varepsilon_{\rm br}, \mathscr{F})$ that can interpret IceCube and Fermi simultaneously?

Multimessenger Constraints

$$\chi^2 = \min_{\alpha_j} \left\{ \left[\sum_i \frac{\left(F_i^{\mathrm{EGB}} - F_i^{\mathrm{casc}} - \sum_j \alpha_j F_i^j\right)^2}{\sigma_i^2} \right] + \sum_j \left[\frac{(\alpha_j - 1)^2}{\zeta_j^2} \right] \right\}$$



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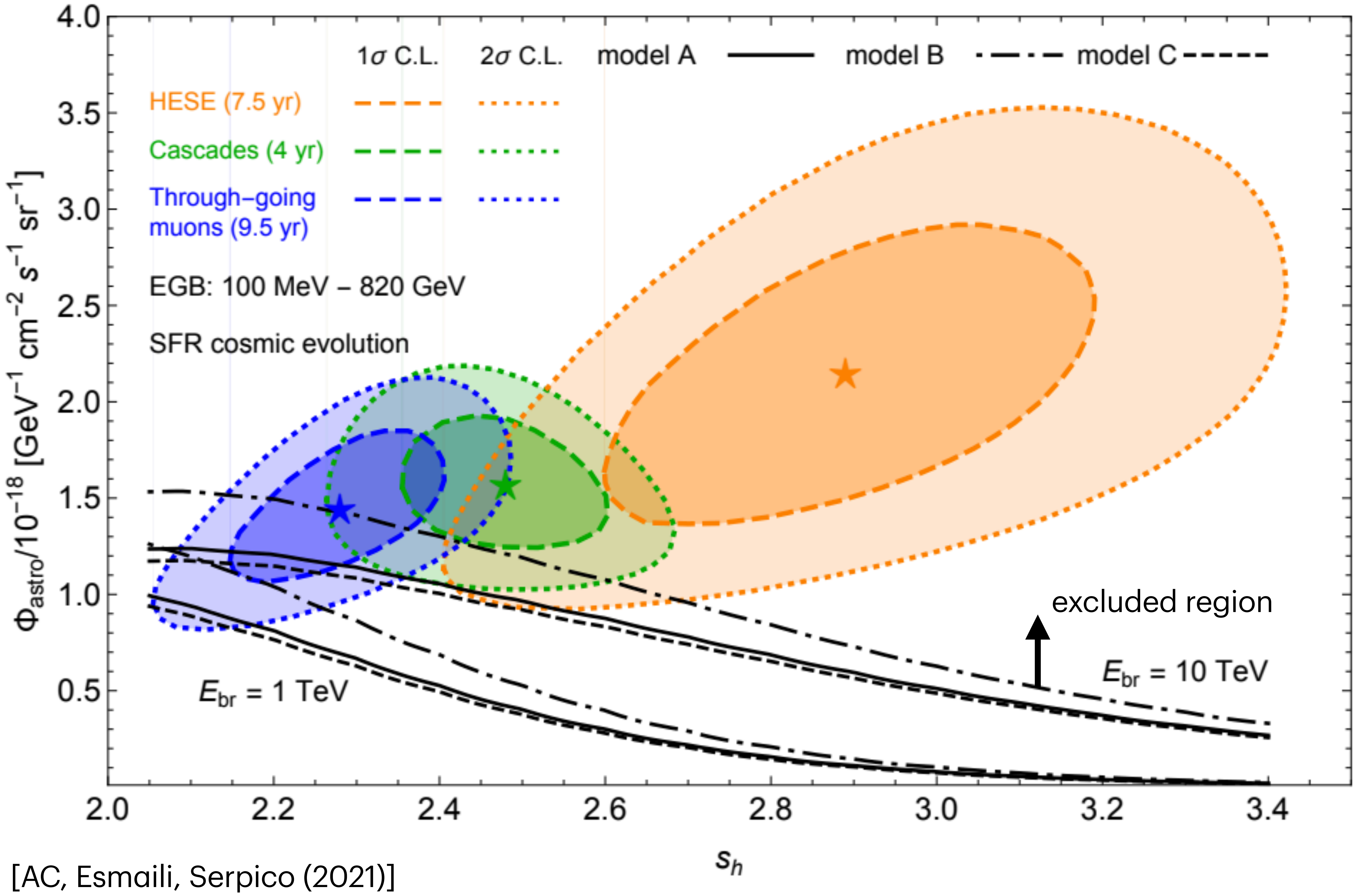

[AC, Esmaili, Serpico (2021)]

$\Delta\chi^2$ values from fit to EGB model A assuming Cascades 6y best-fit $(\Phi_{\text{astro}}, s_h)$

$\mathscr{F}(z)$	SFR	BL Lac	$z \gtrsim 3$	$0 \leq z \leq 10^{-2}$
$E_{\text{br}} = 10$ TeV	19	39	4.5	49
$E_{\text{br}} = 1$ TeV	47	137	35	232

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

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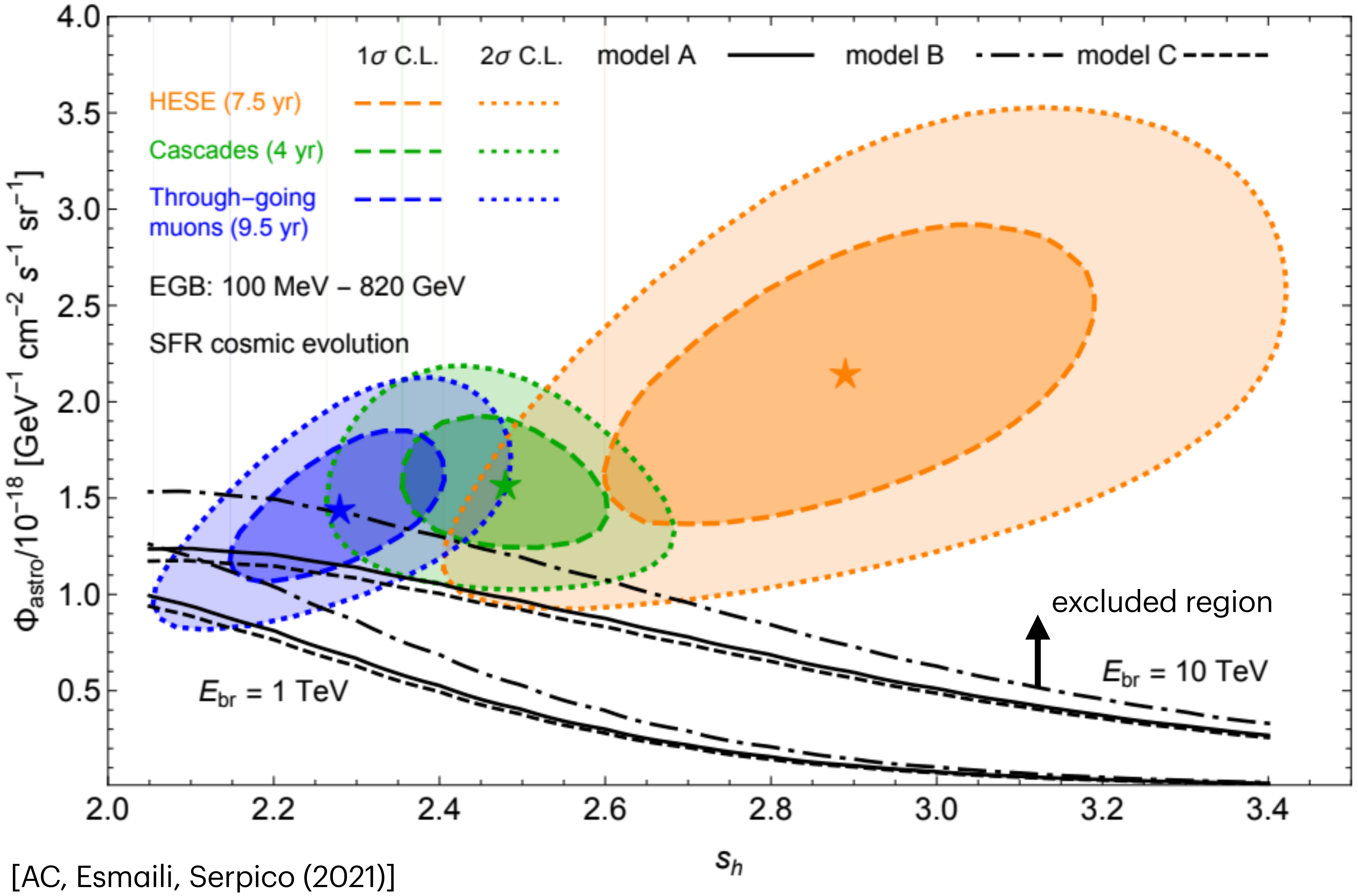

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Requires unreasonably large neutrino energy budgets!

E.g.: SMBHs at $z \approx 6$ accreting @ Eddington luminosity require $L_\nu \approx 0.5\, L_{\mathrm{tot}}$

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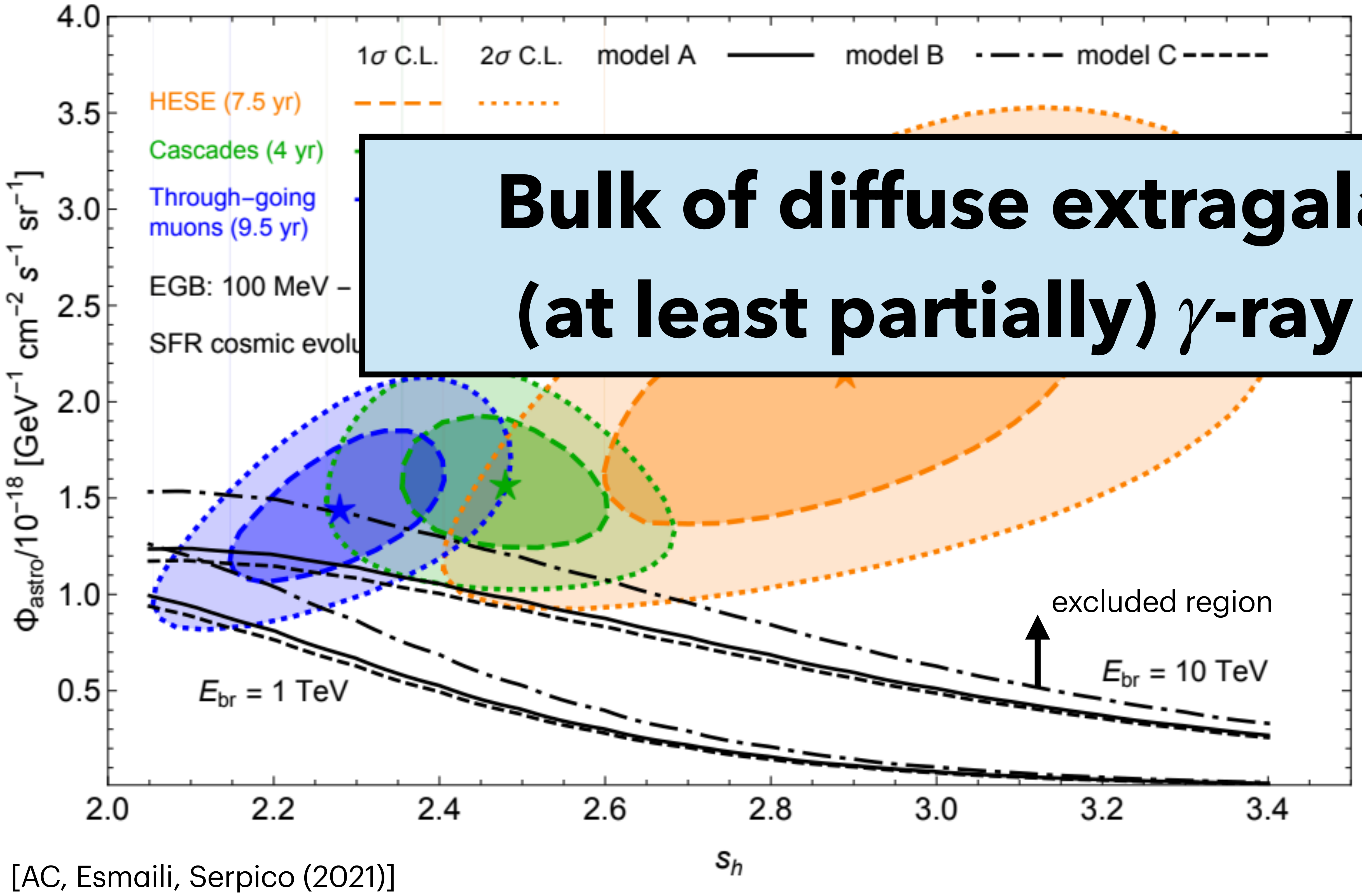

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Bulk of diffuse extragalactic ν sources should be (at least partially) γ-ray opaque above ~10 GeV

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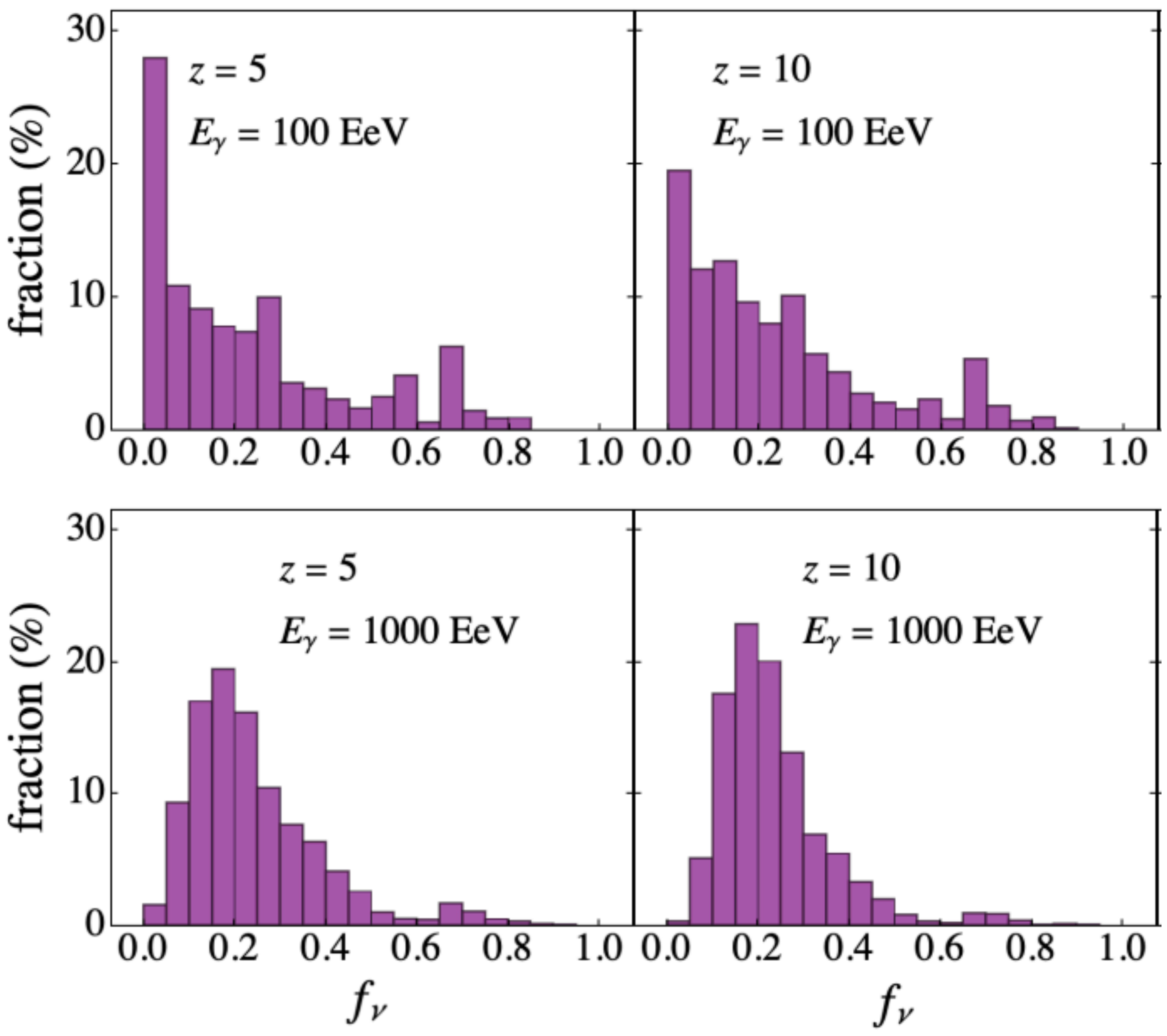
Neutrino Production in UHE Cascades @ High-z

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

Muon Pair Production

$$\gamma\gamma \rightarrow \mu^+\mu^-$$

Threshold condition: $E_\gamma \geq \frac{m_\mu^2}{\epsilon_{\rm bkg}} \approx 10\ \mathrm{EeV}\left(\frac{1\ \mathrm{meV}}{\epsilon_{\rm bkg}}\right)$



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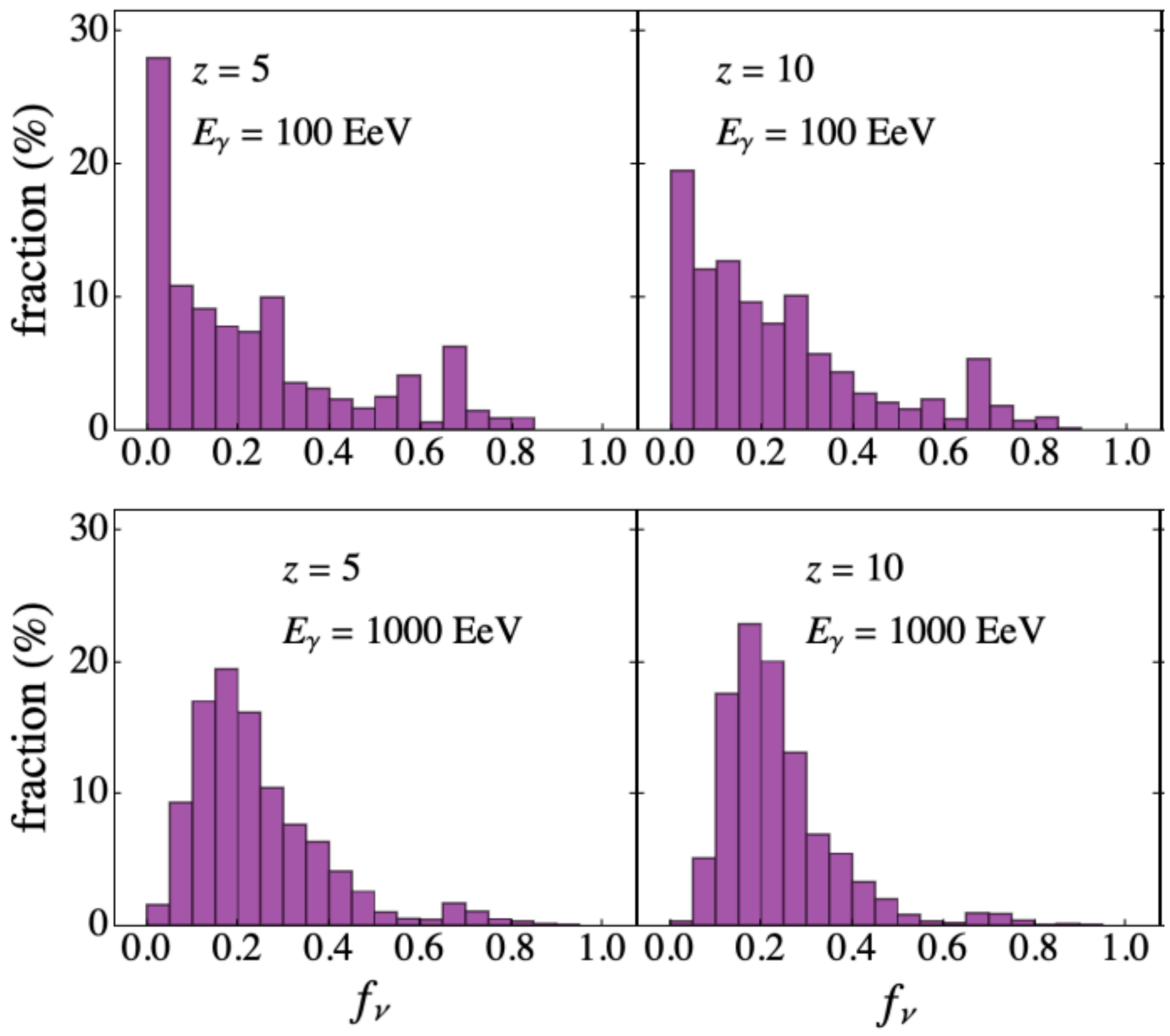
Makes UHE multimessenger sources
gamma-ray **darker** and neutrino **brighter**

$$\mathcal{E}_\gamma/\mathcal{E}_\nu \simeq \begin{cases} \cancel{2/3} & 0.44 \quad (pp) \\ \cancel{4/3} & 0.77 \quad (p\gamma) \end{cases}$$



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Thank you!

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Backup Slides

UHE EM Cascades

PP threshold:

$E_{\text{th}} = m_e^2/\epsilon_{\text{bkg}}$


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

Muon Pair Production: $\gamma\gamma \to \mu^+\mu^-$

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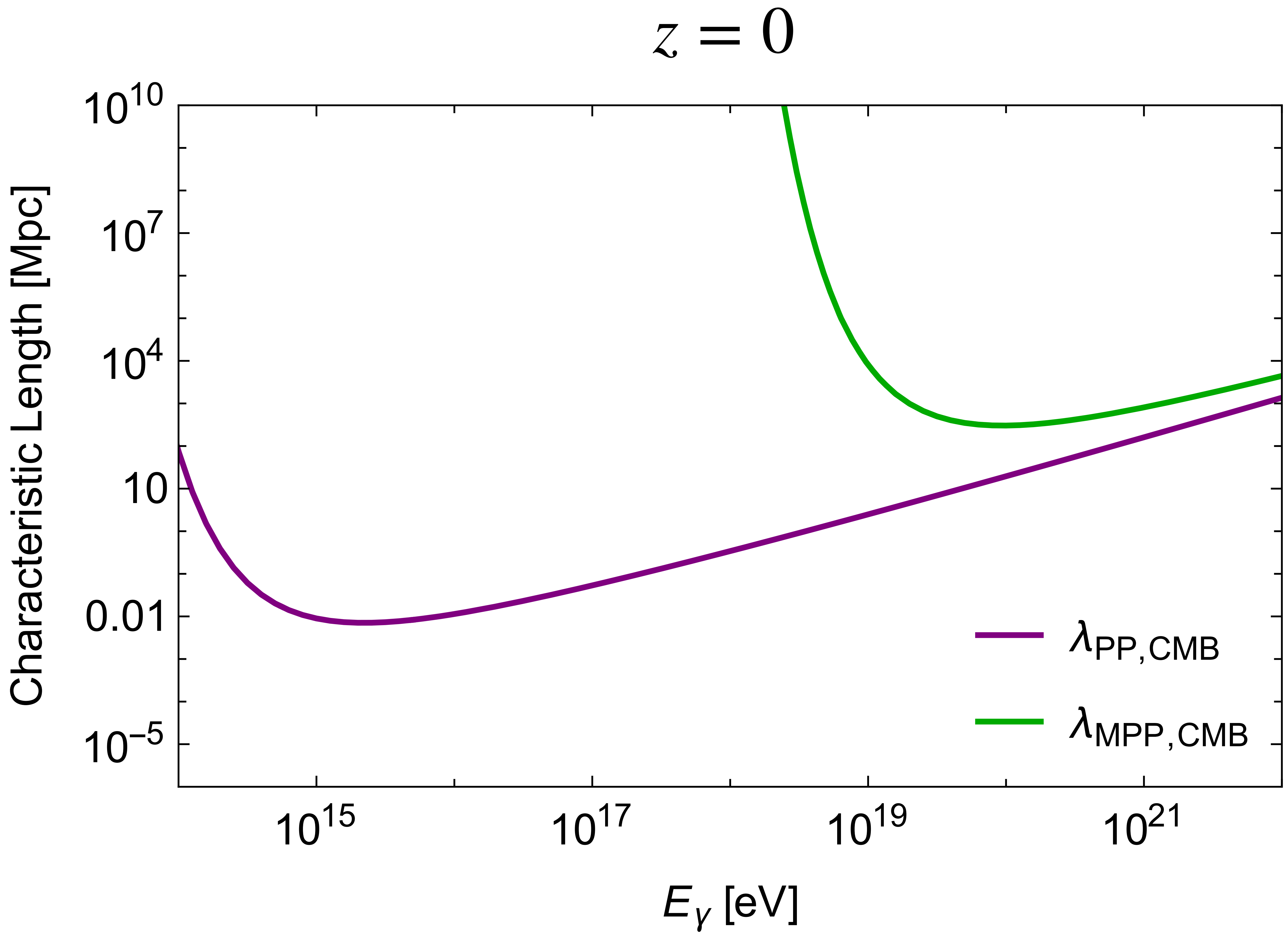

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Mean free path:

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

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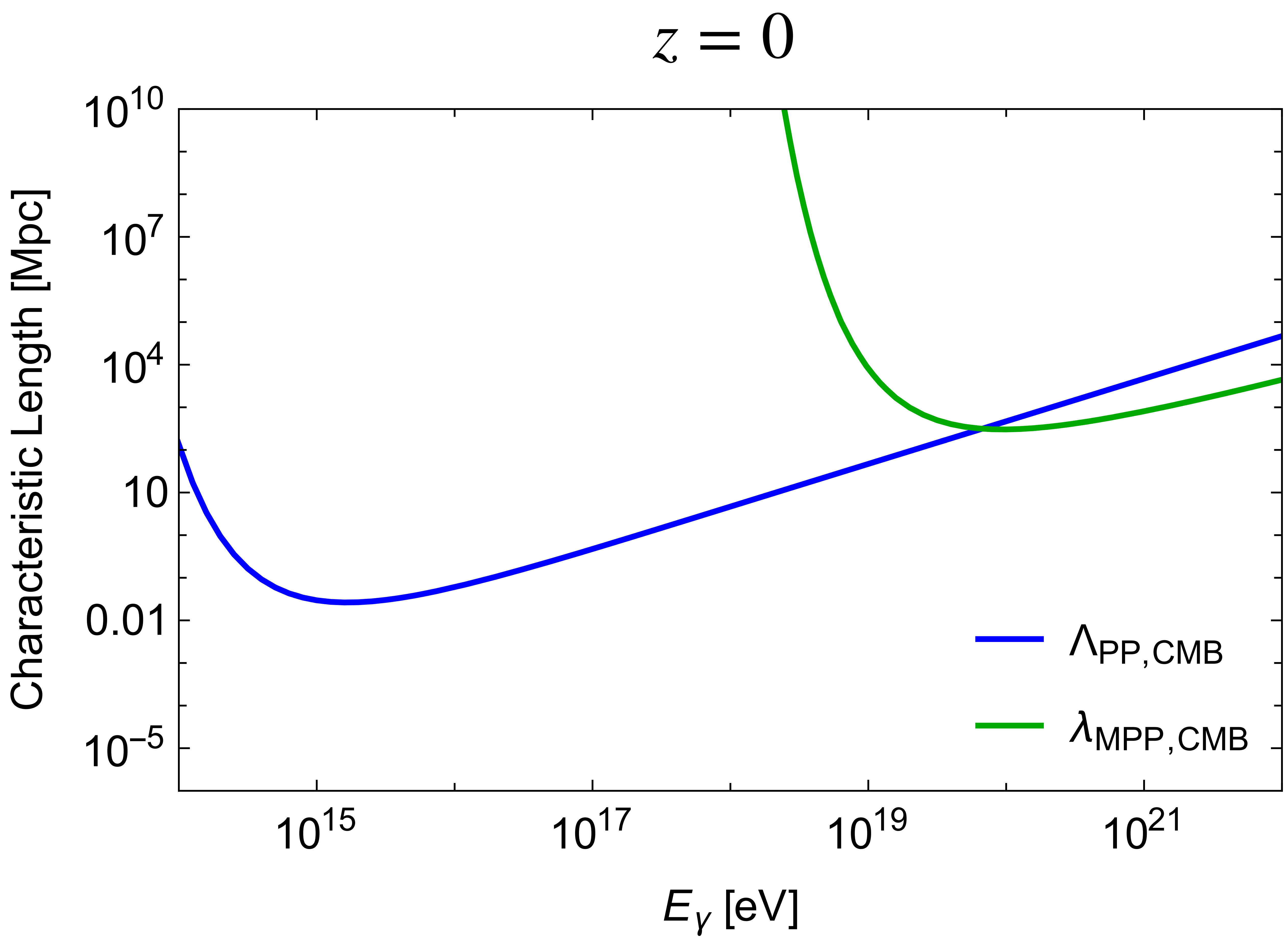

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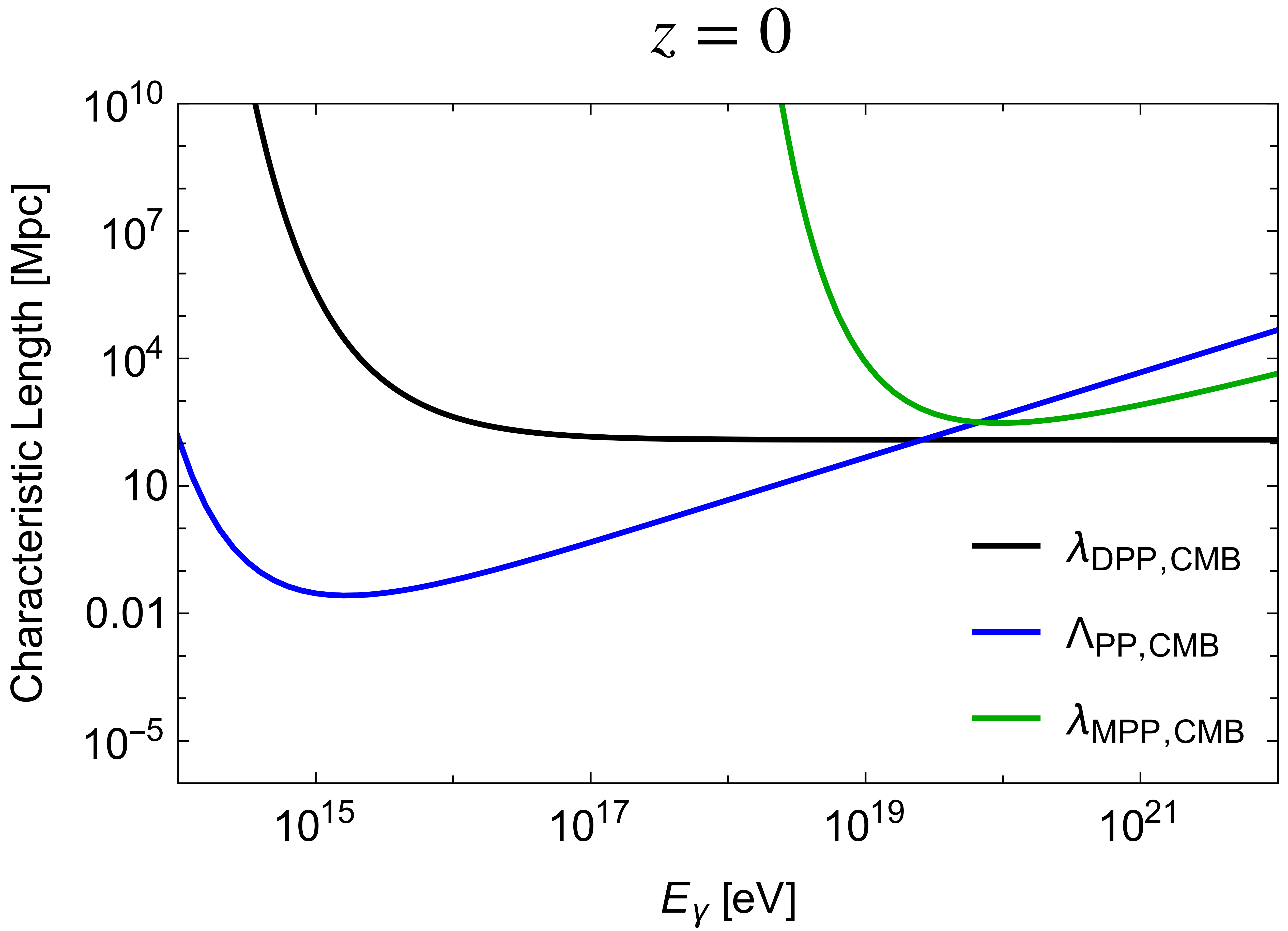

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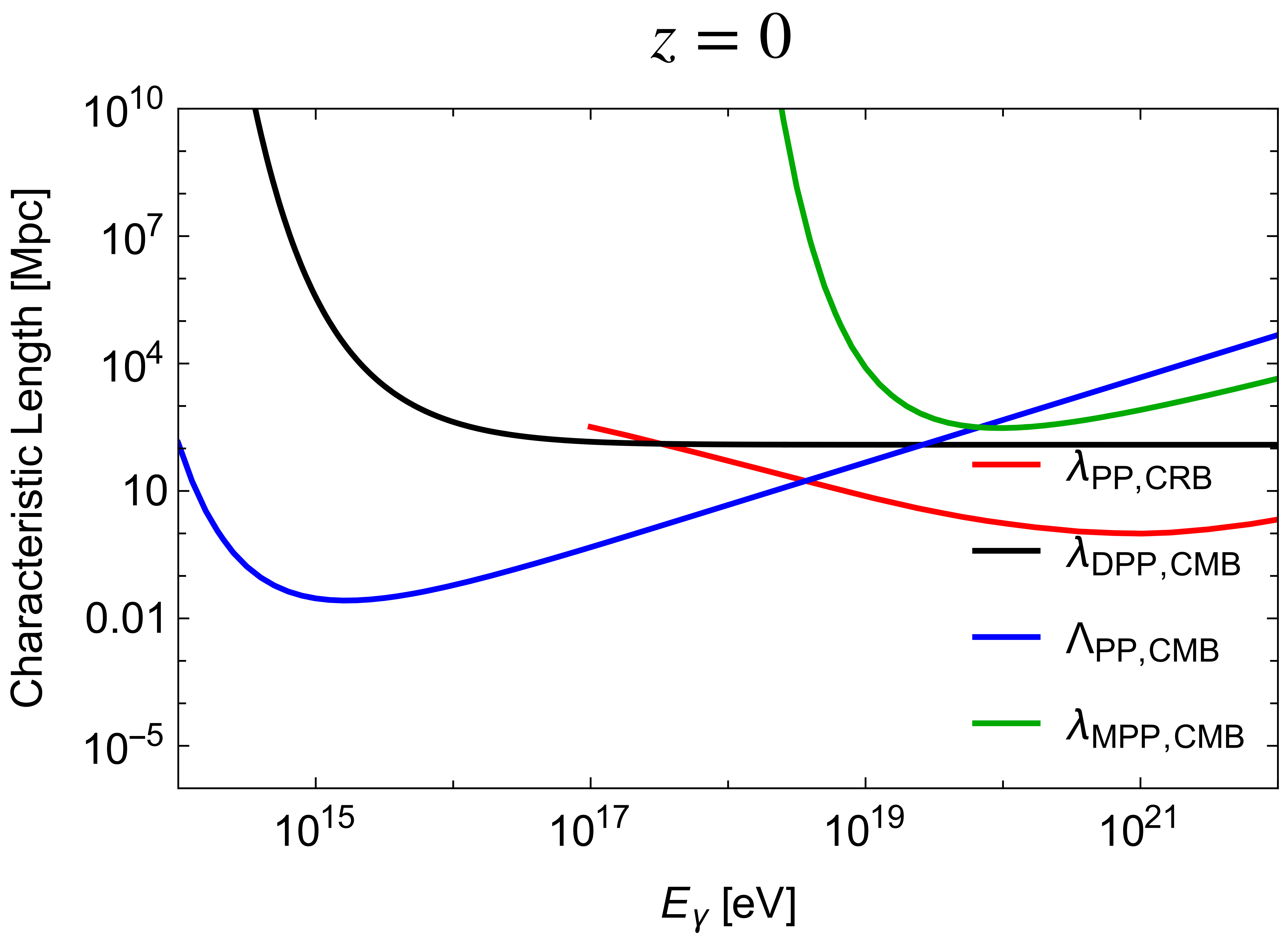

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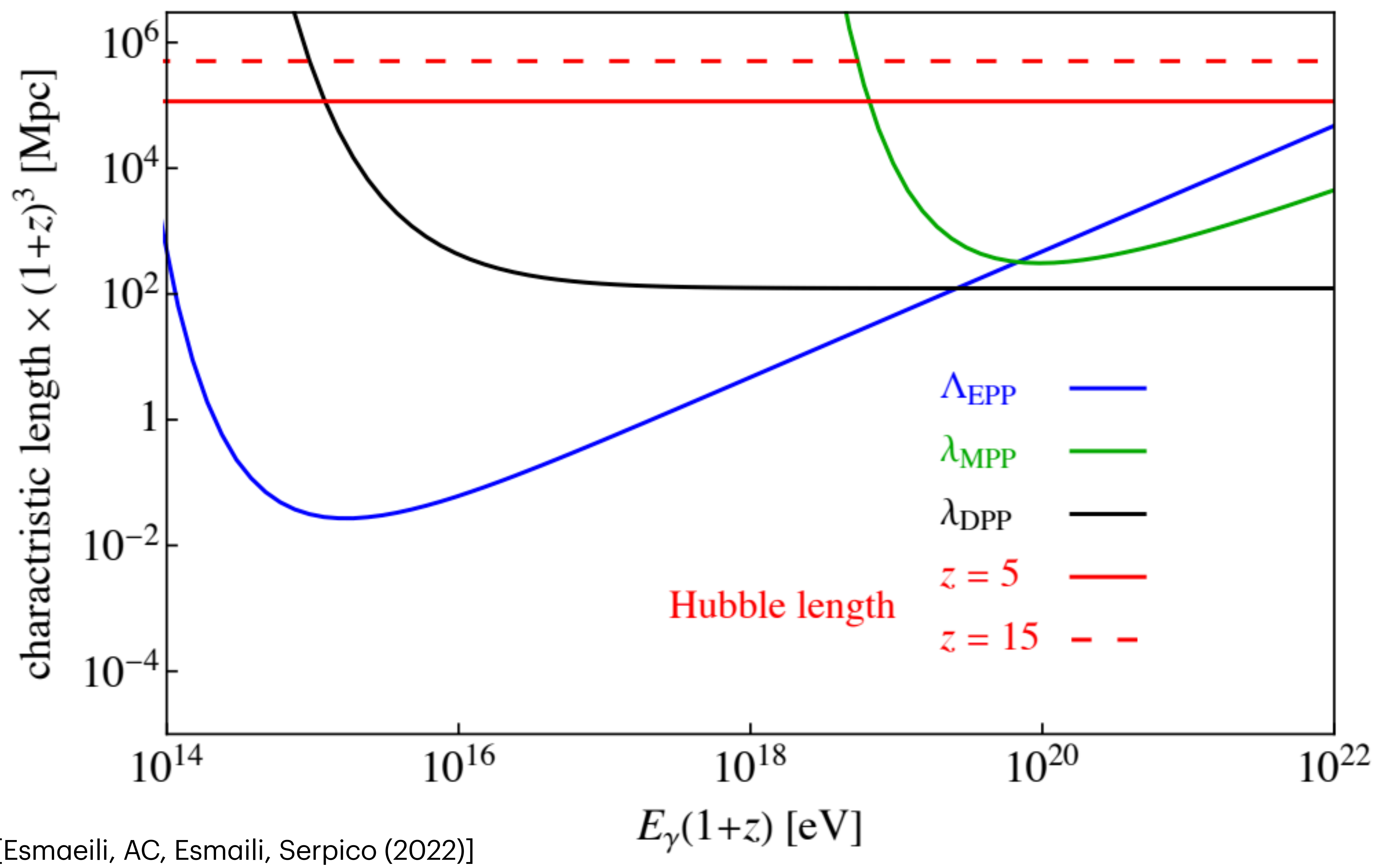
High-z



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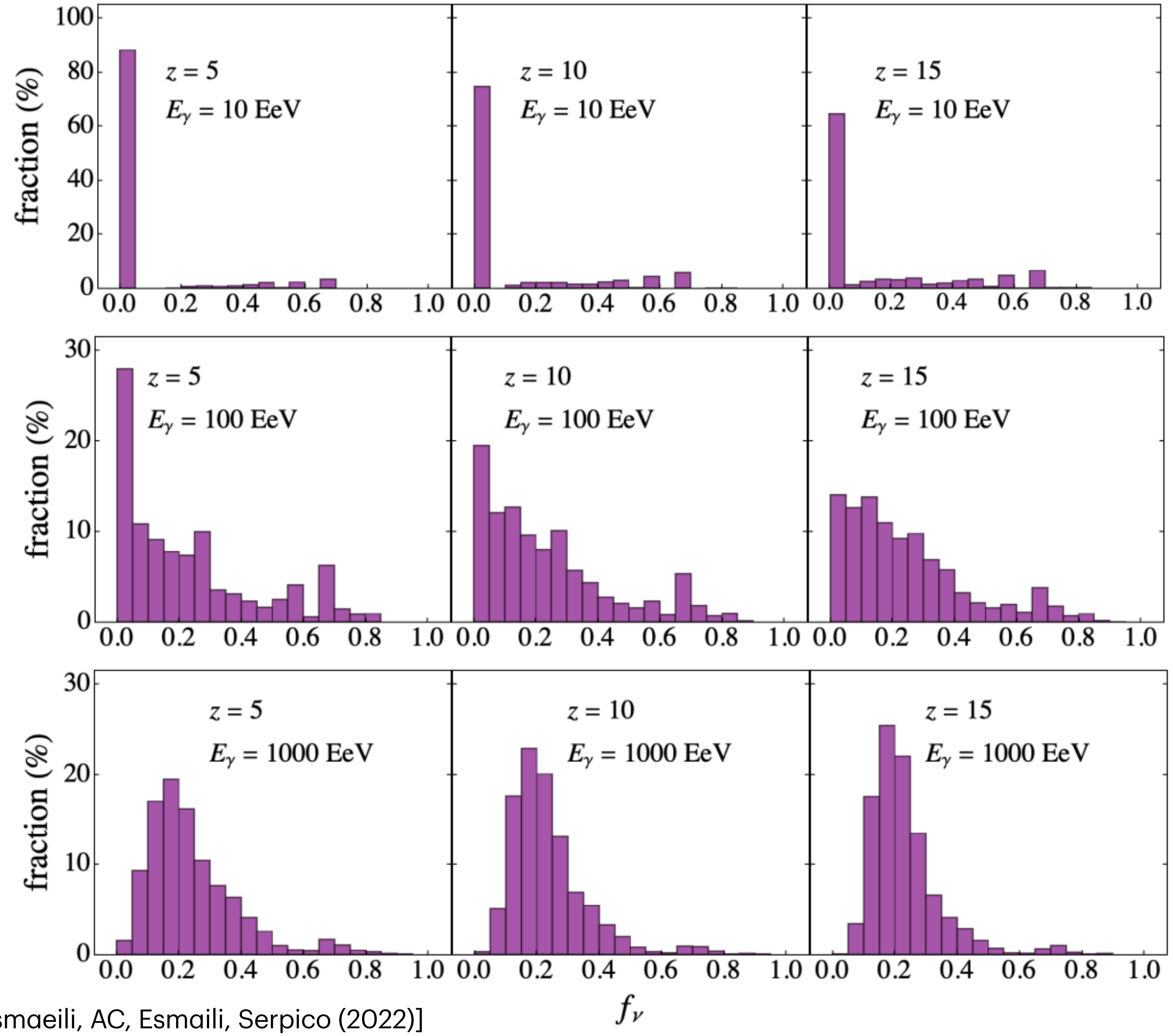
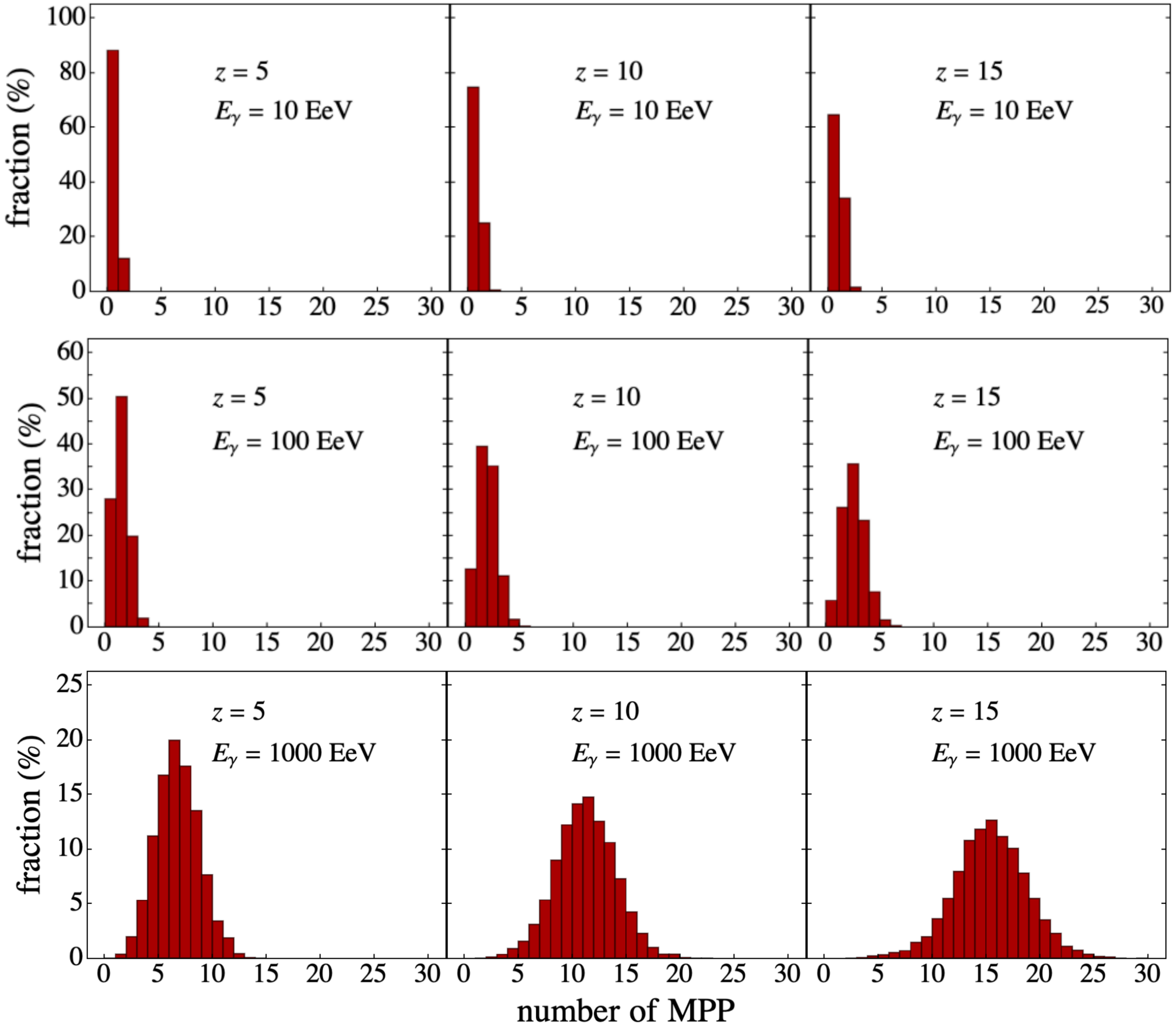
$$\Lambda^{-1}(E) = \int_0^\infty d\epsilon\, n(\epsilon) \int_{-1}^{1-\frac{2m^2}{E\epsilon}} d\mu\, \frac{1-\mu}{2}\sigma(1-\eta)$$

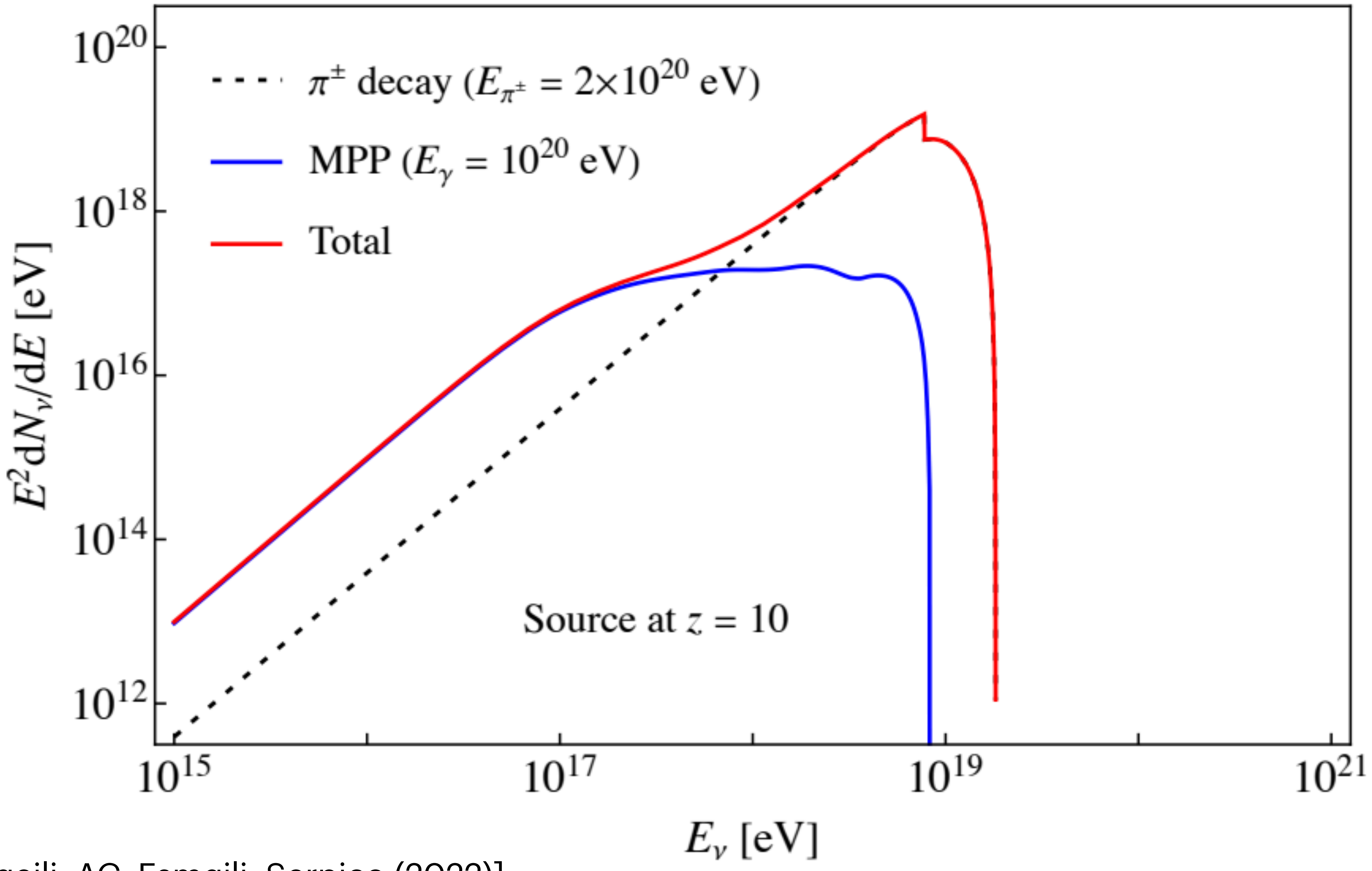
UHE Neutrinos from Cascades at High-Redshifts

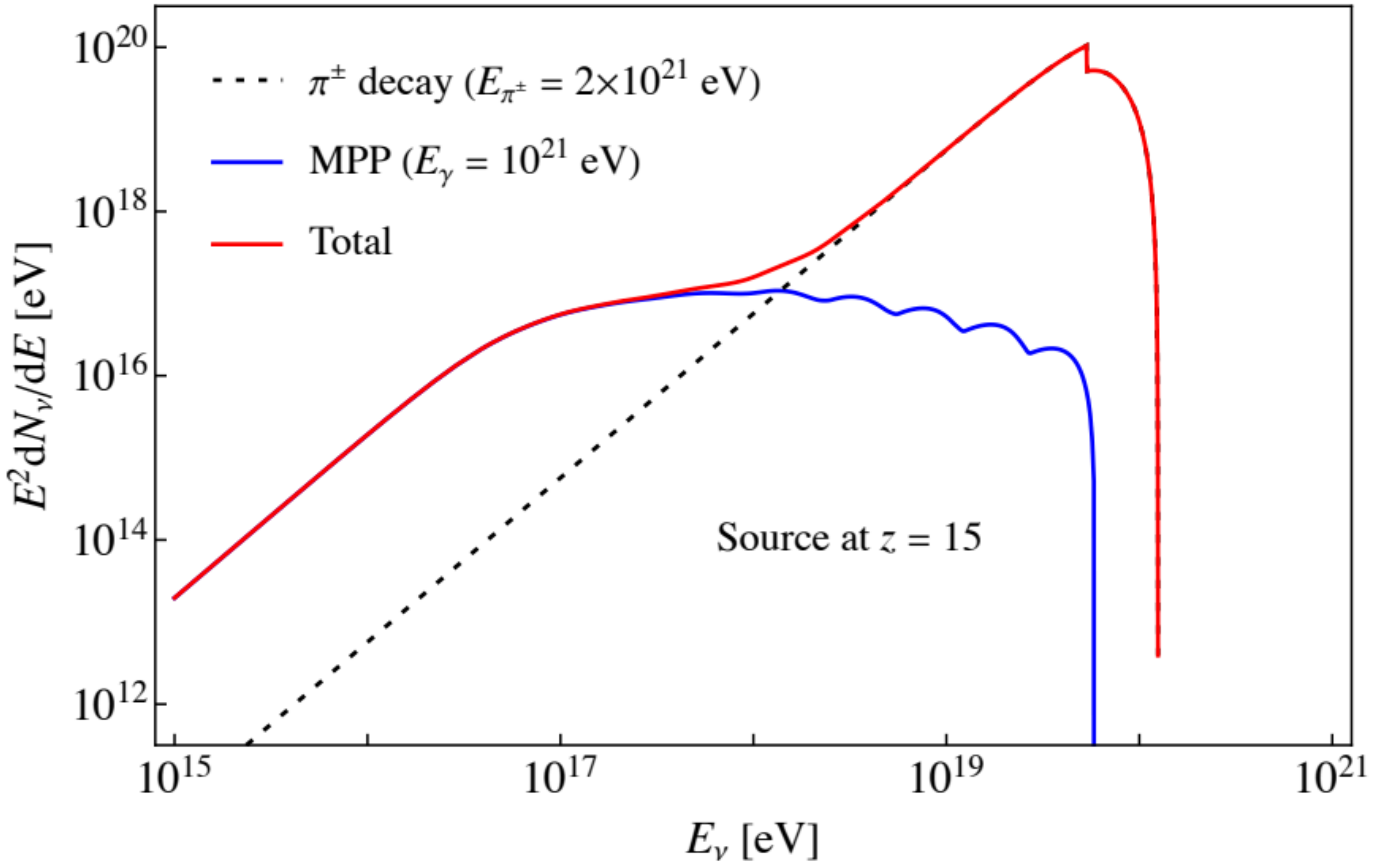




[Esmaeili, AC, Esmaili, Serpico (2022)]

Fluxes @ Earth from Monochromatic Sources





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

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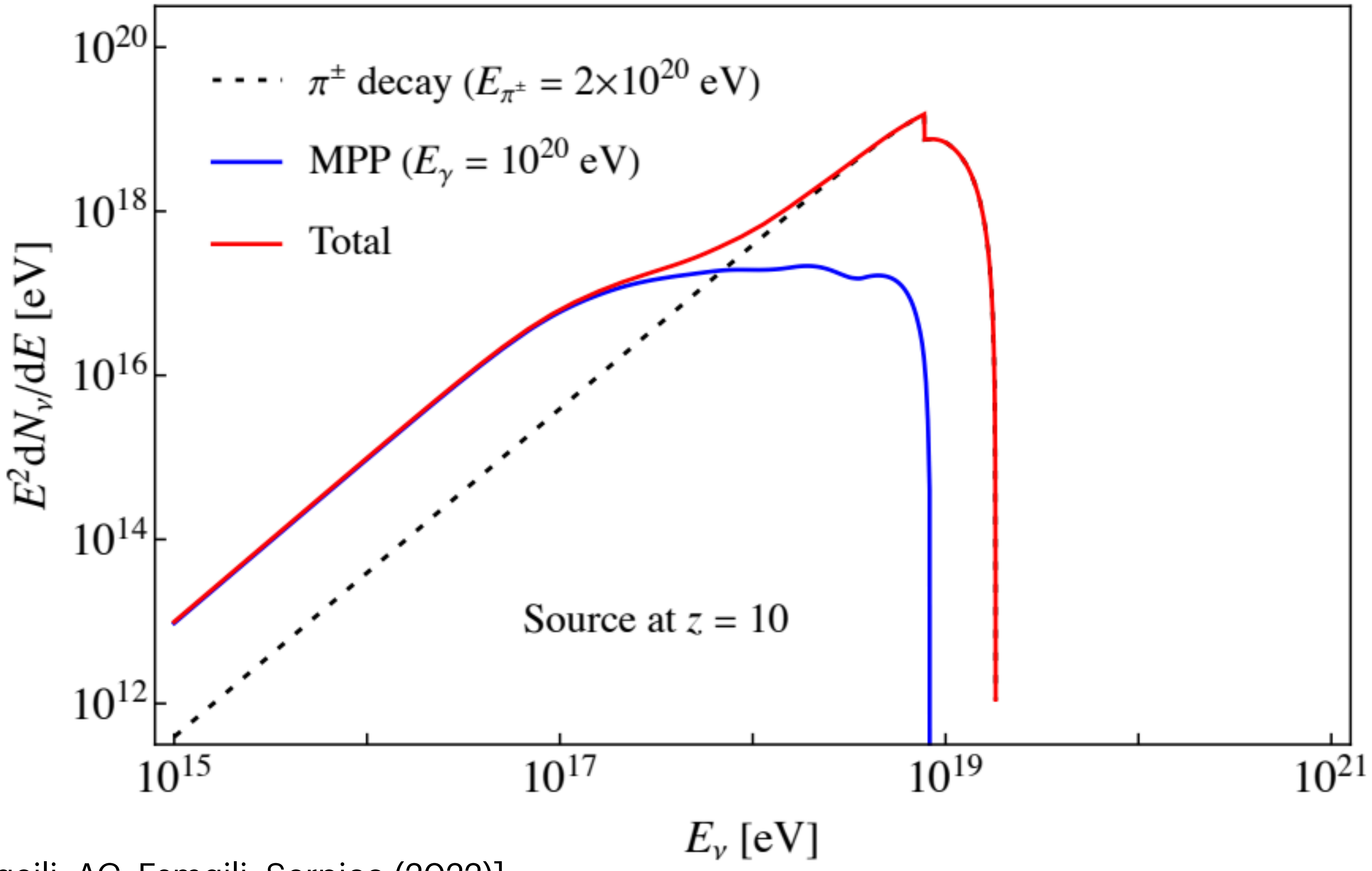
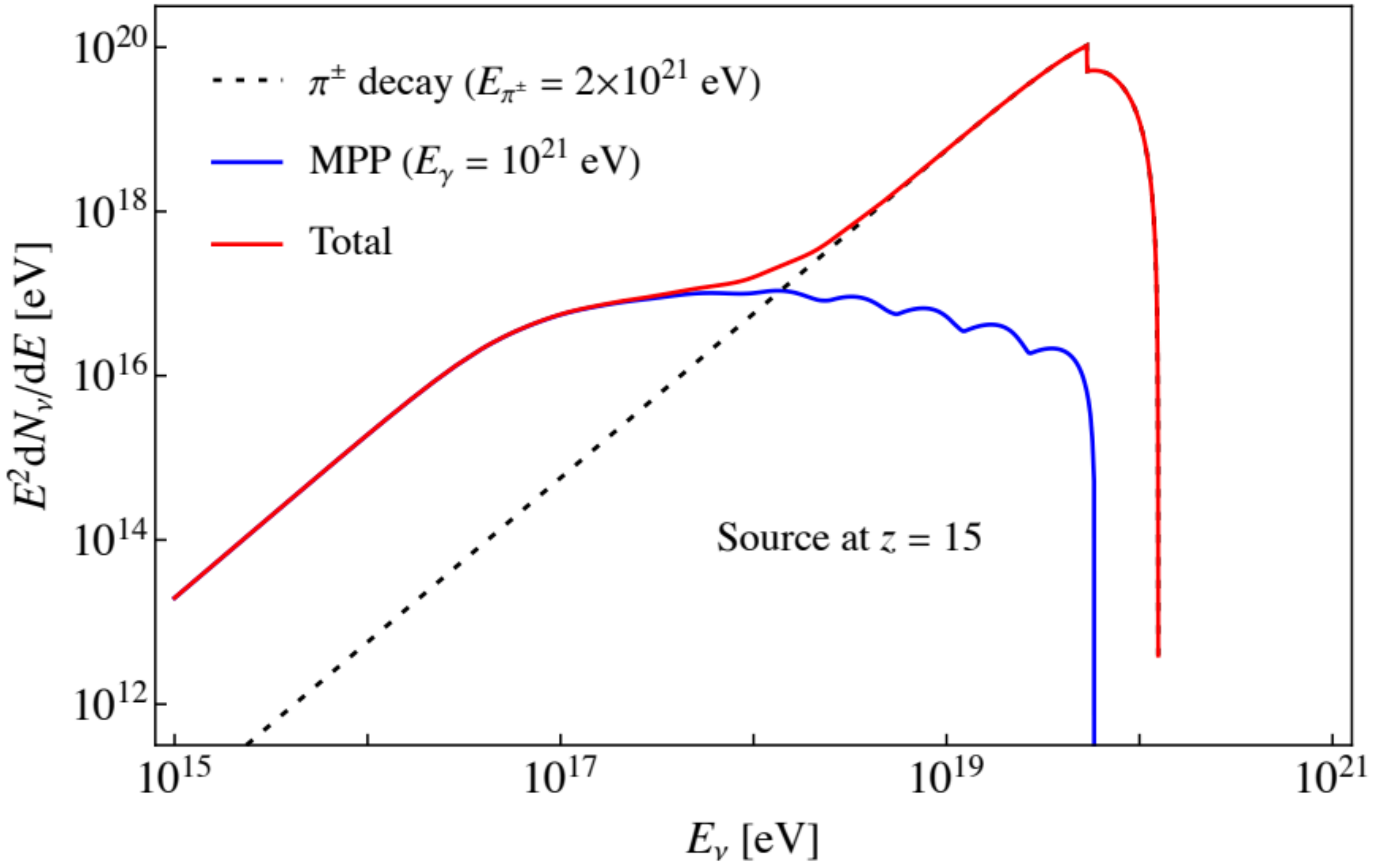
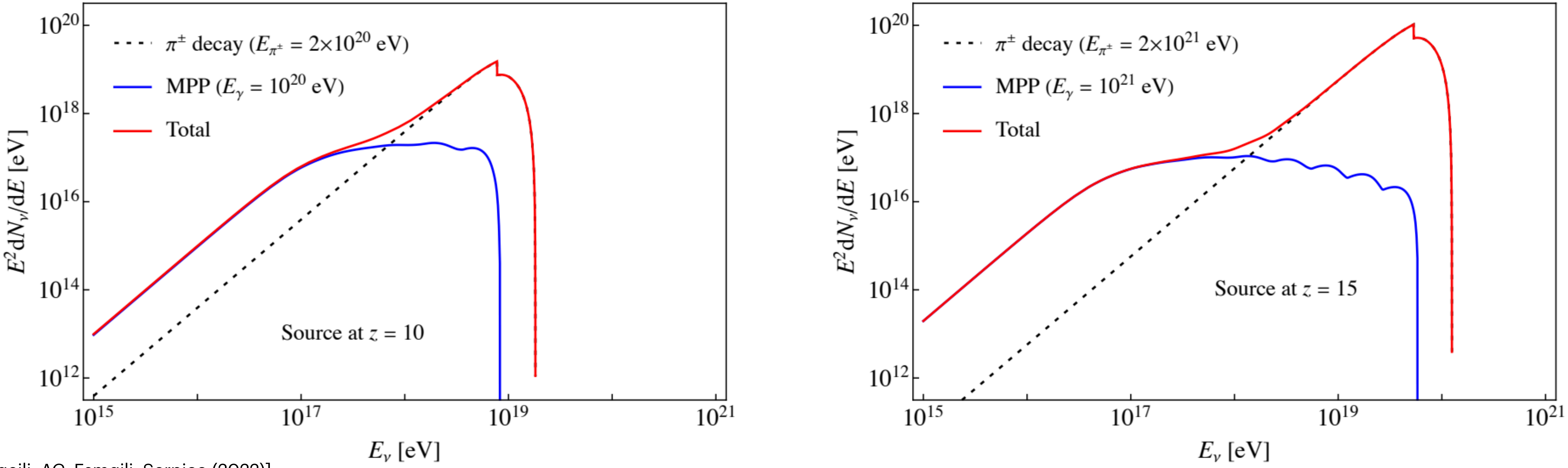




[Esmaeili, AC, Esmaili, Serpico (2022)]

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

Fluxes @ Earth from Monochromatic Sources

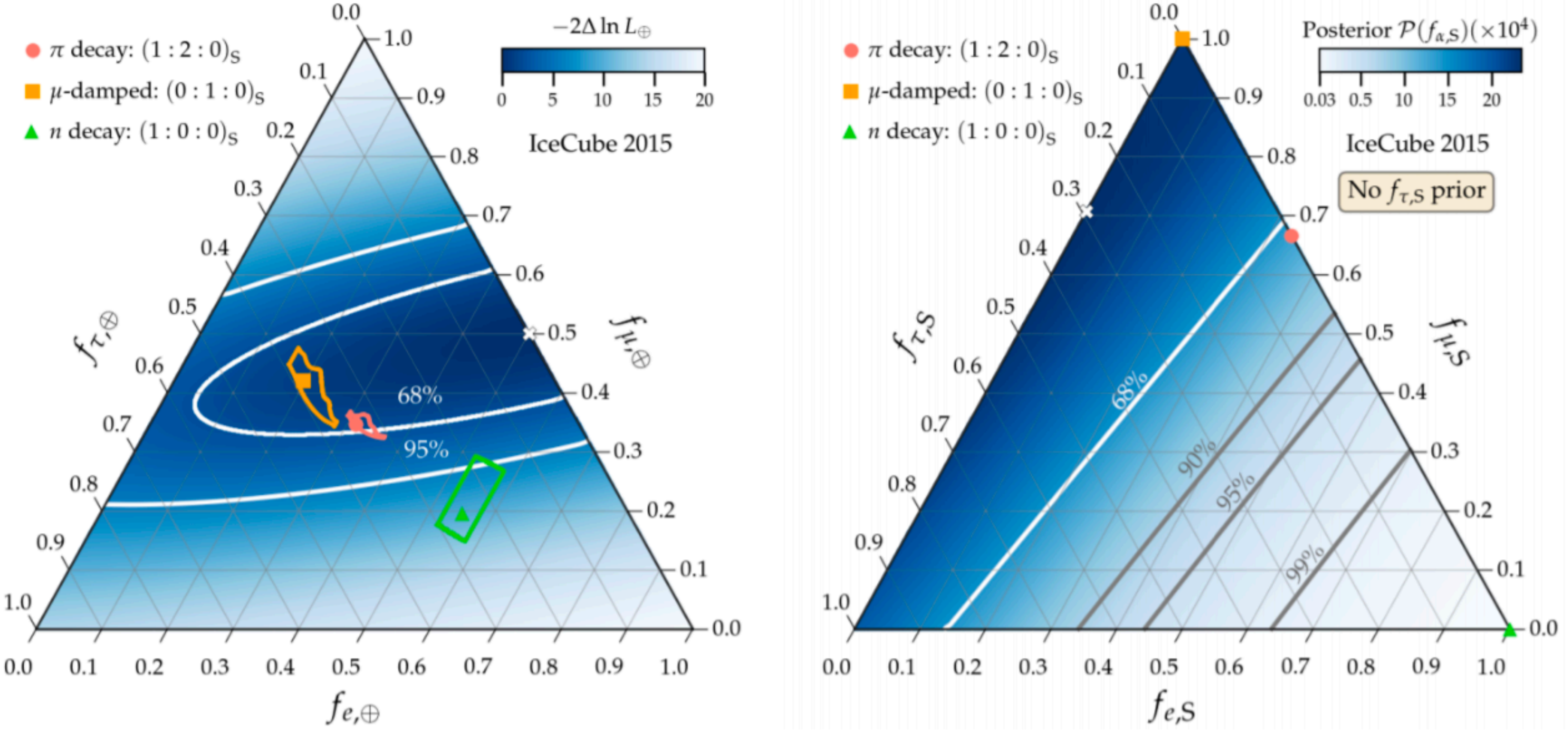


[Esmaeili, AC, Esmaili, Serpico (2022)]

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

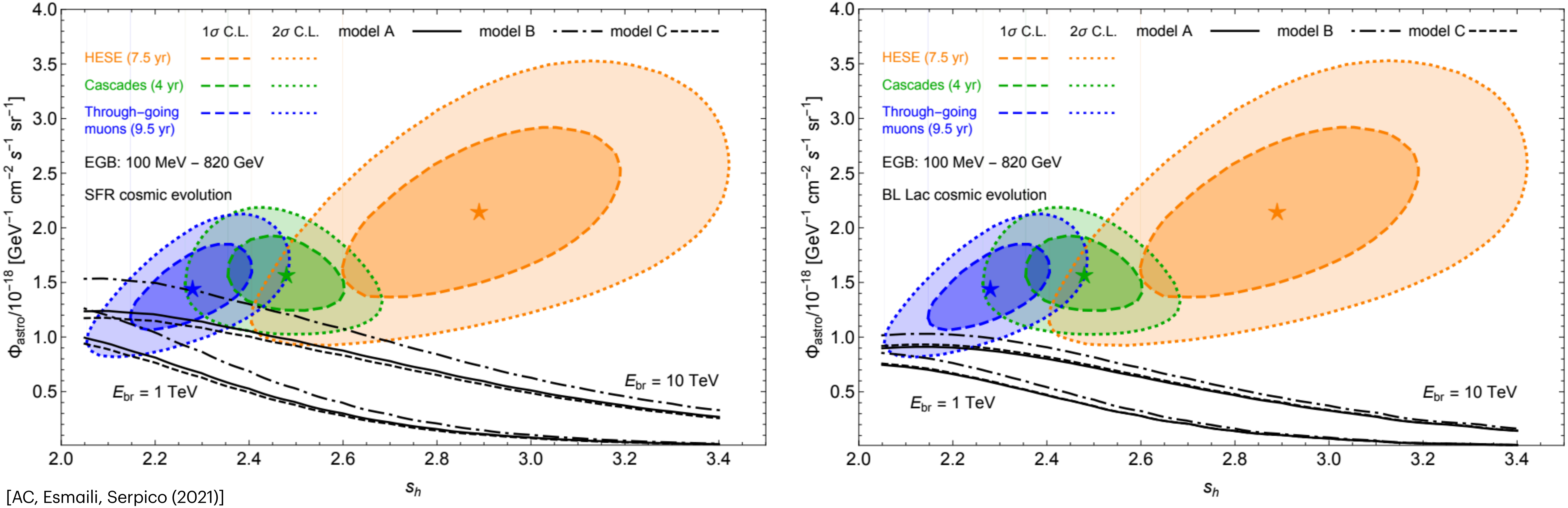
Flavors

[Bustamante, Ahlers (2019)]



Multimessenger Constraints

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



[AC, Esmaili, Serpico (2021)]

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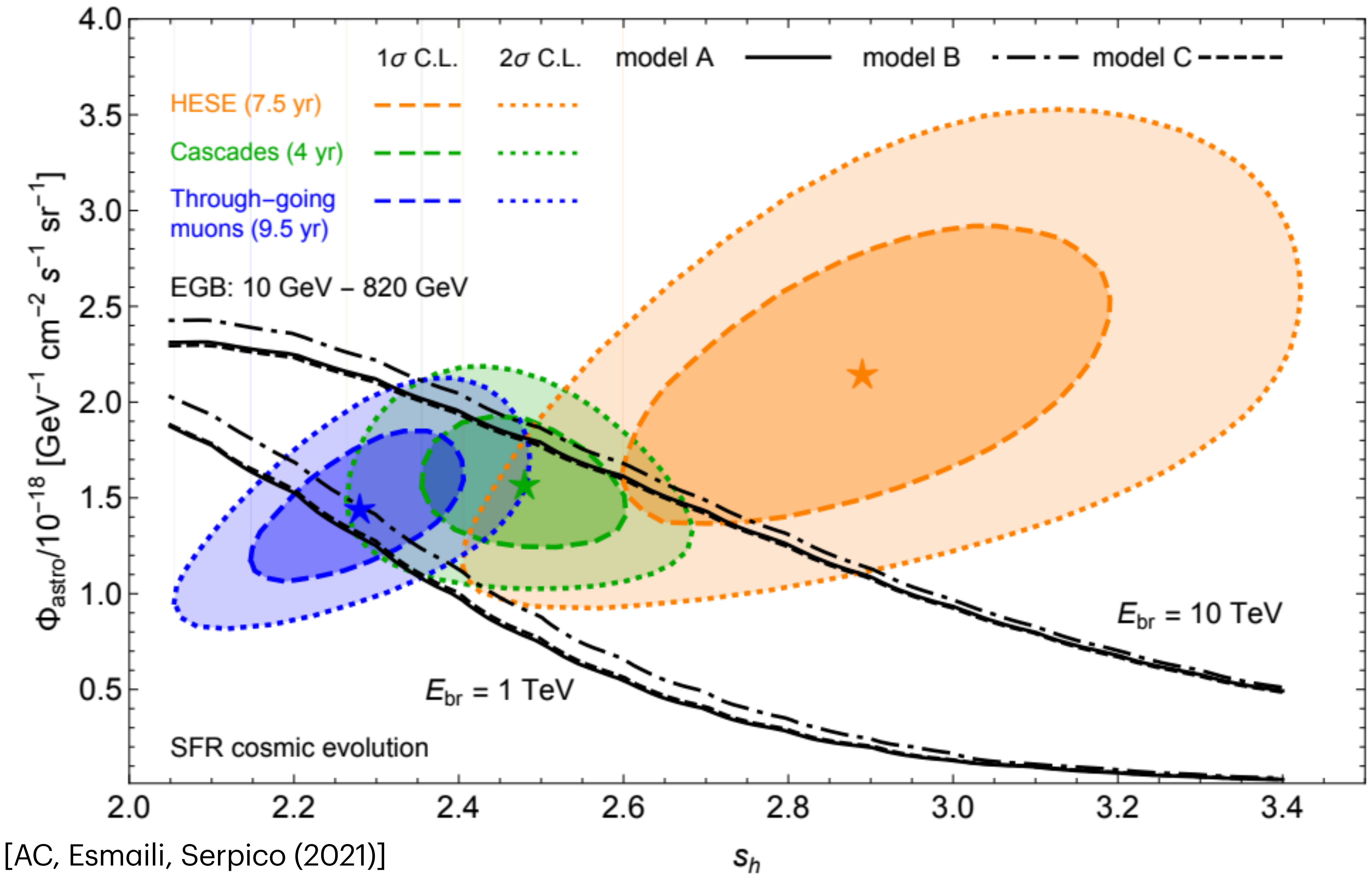
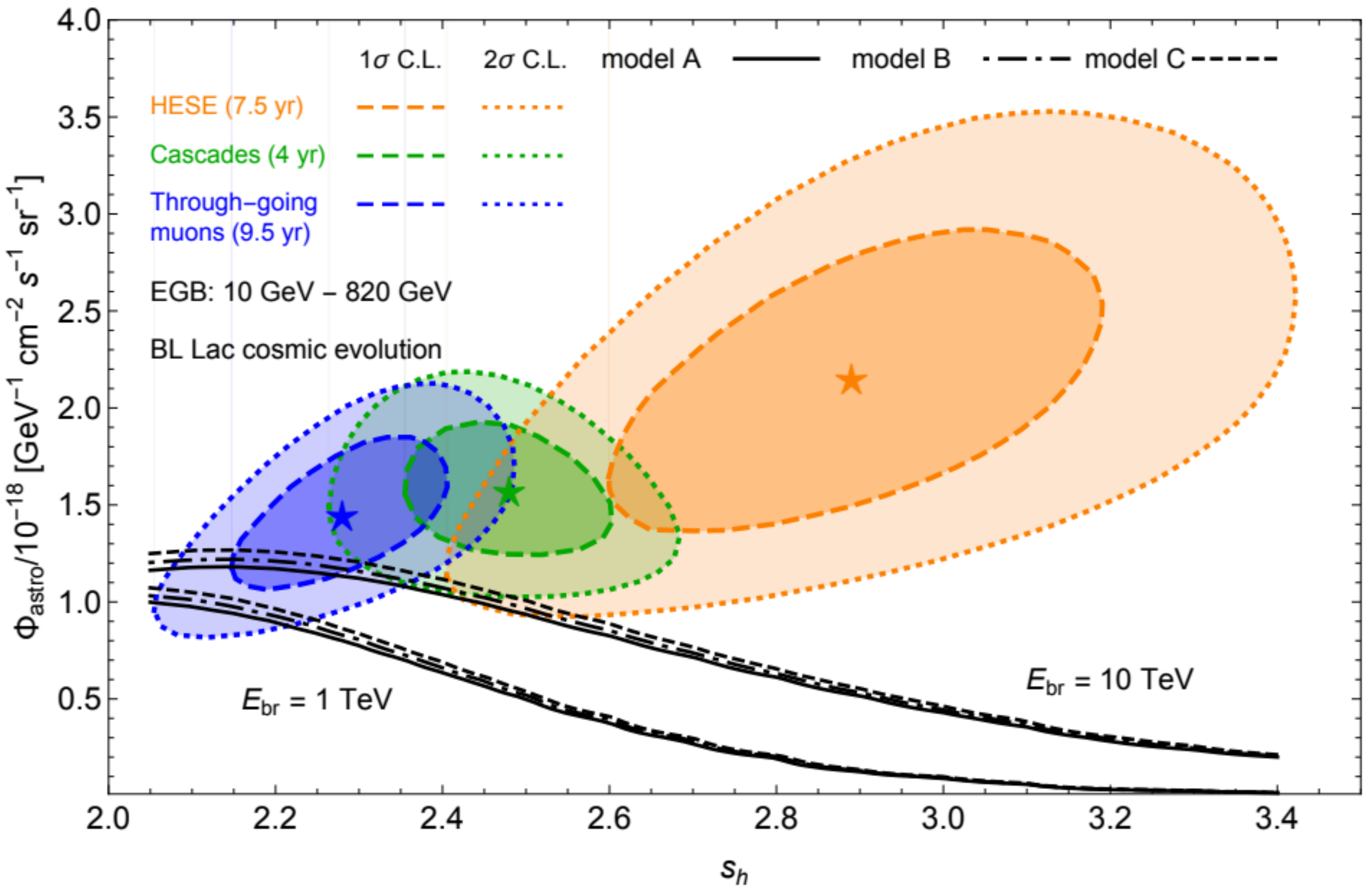
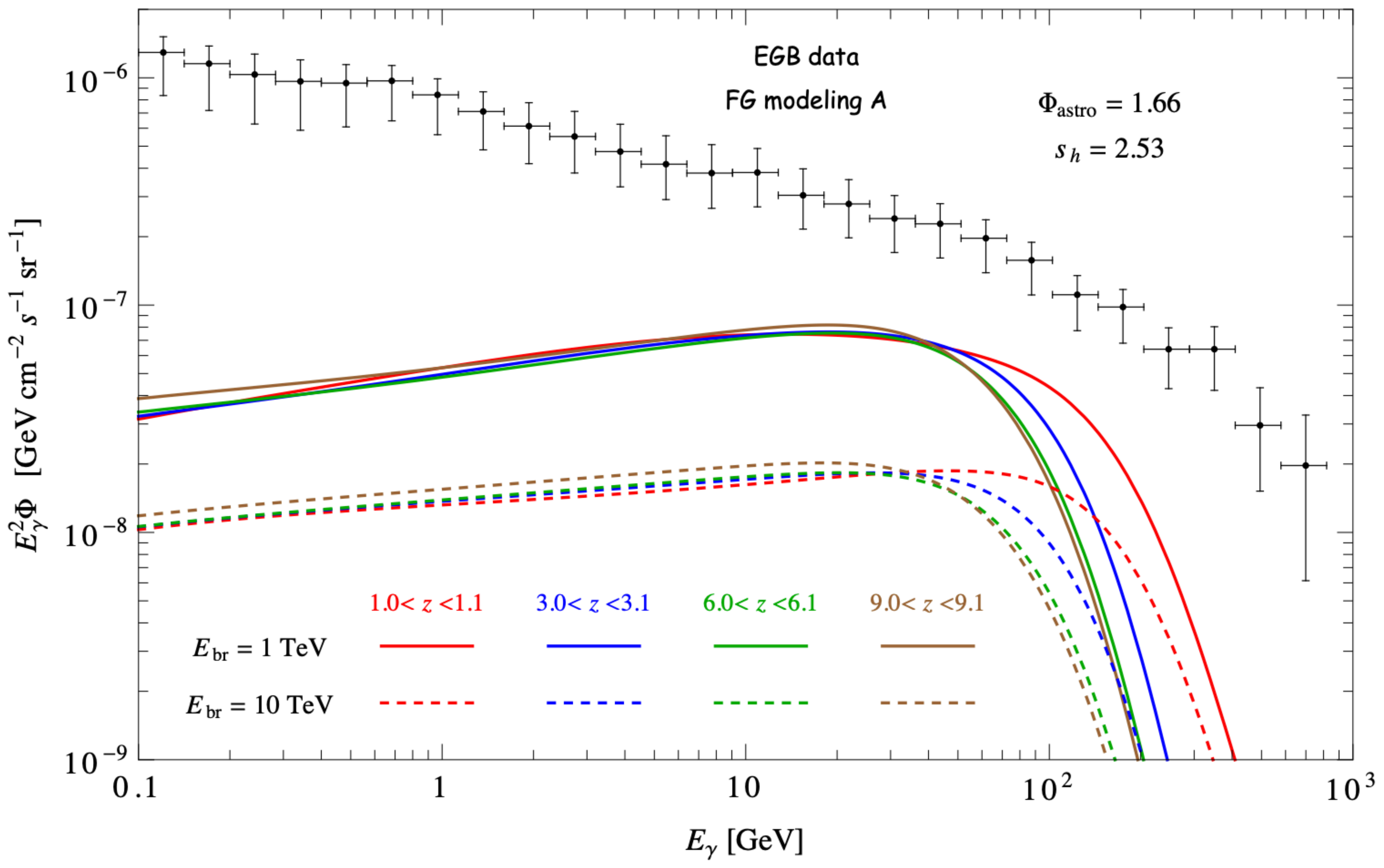


[AC, Esmaili, Serpico (2021)]



High-z Sources

[AC, Esmaili, Serpico (2021)]



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

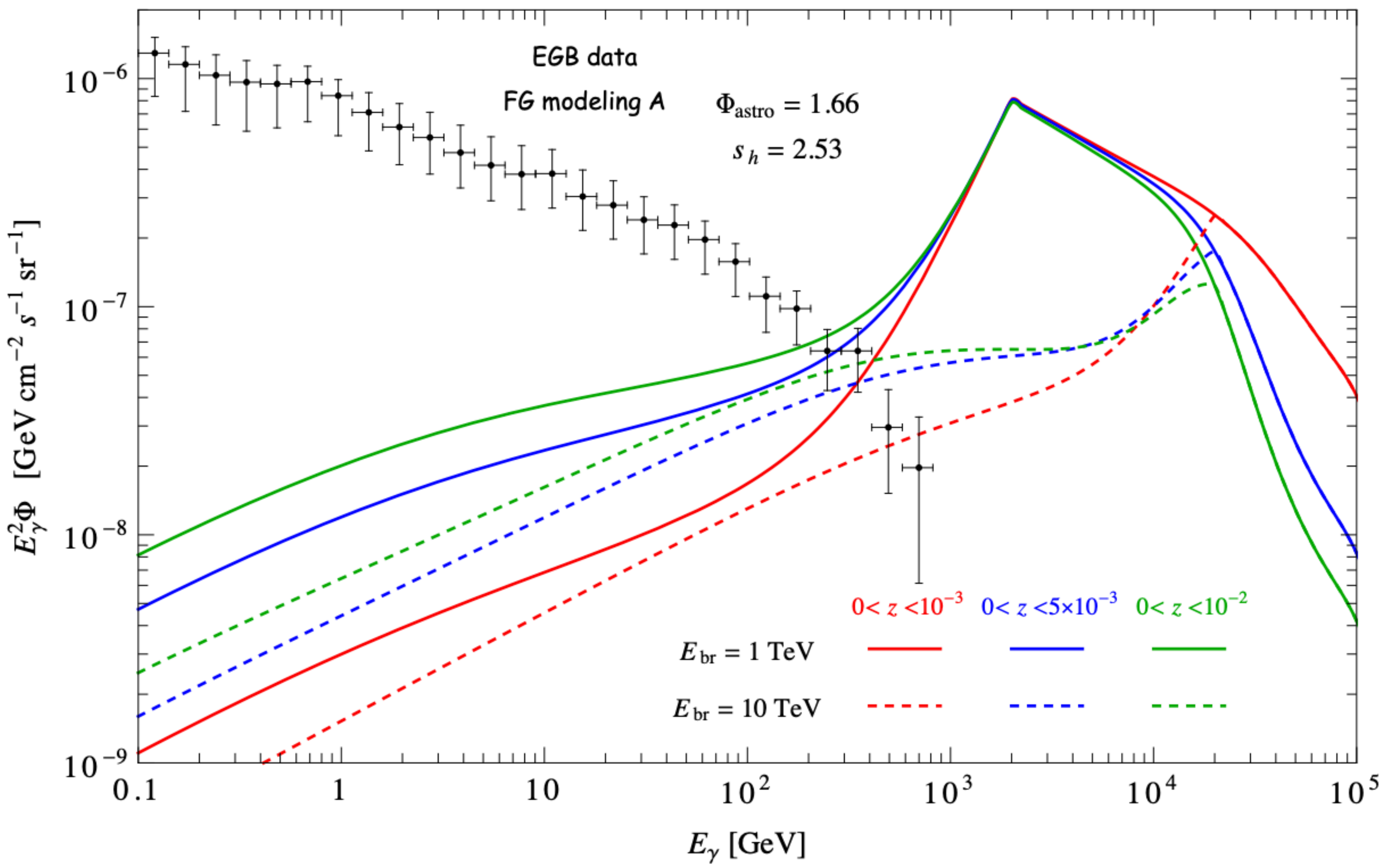
SMBH birth via SN/GRB: $L_{tot} \sim 10^{44}$ erg/s

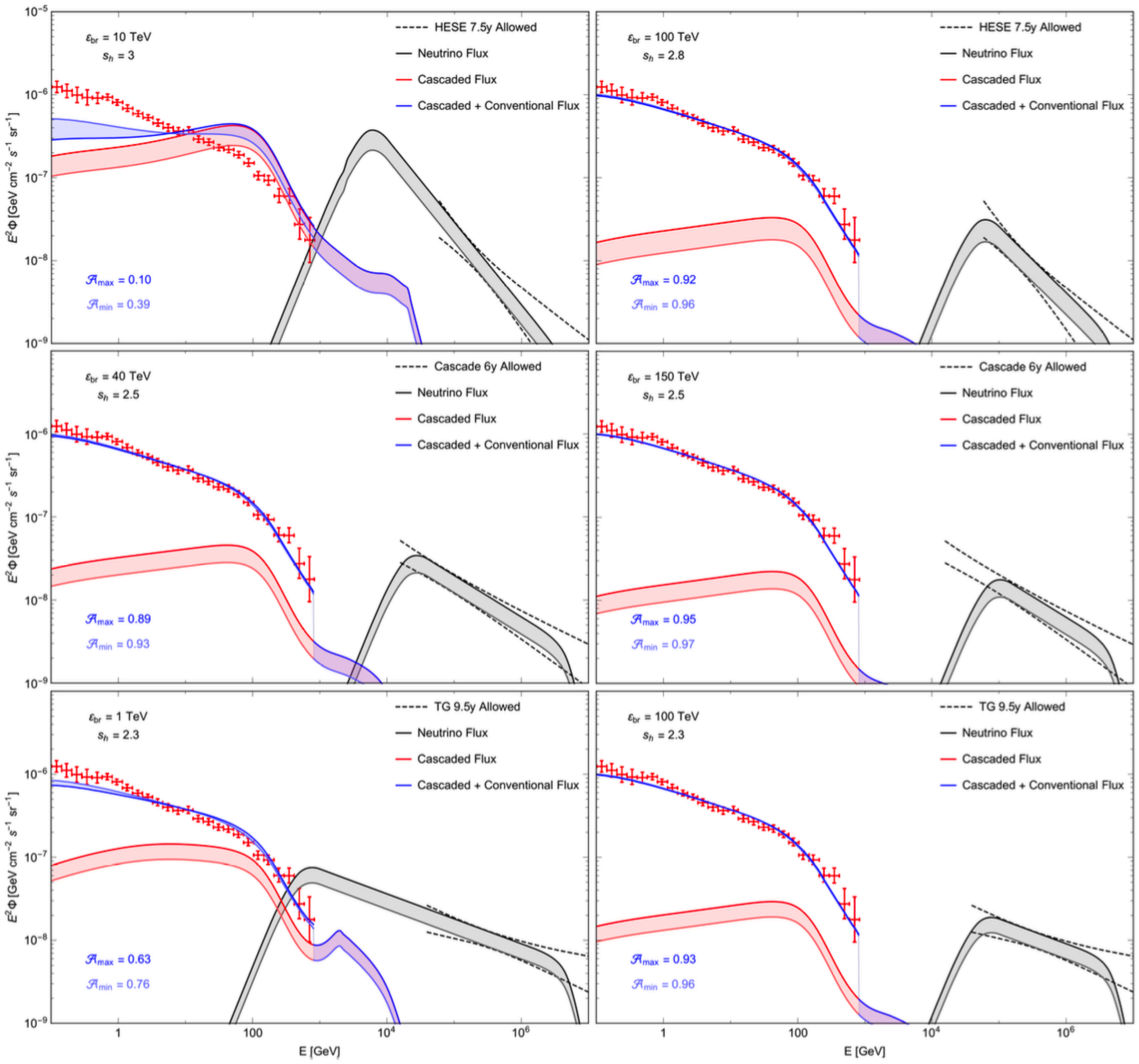
Eddington accretion: $L_{tot} \approx 4.4 \times 10^{51}$ erg/s

		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

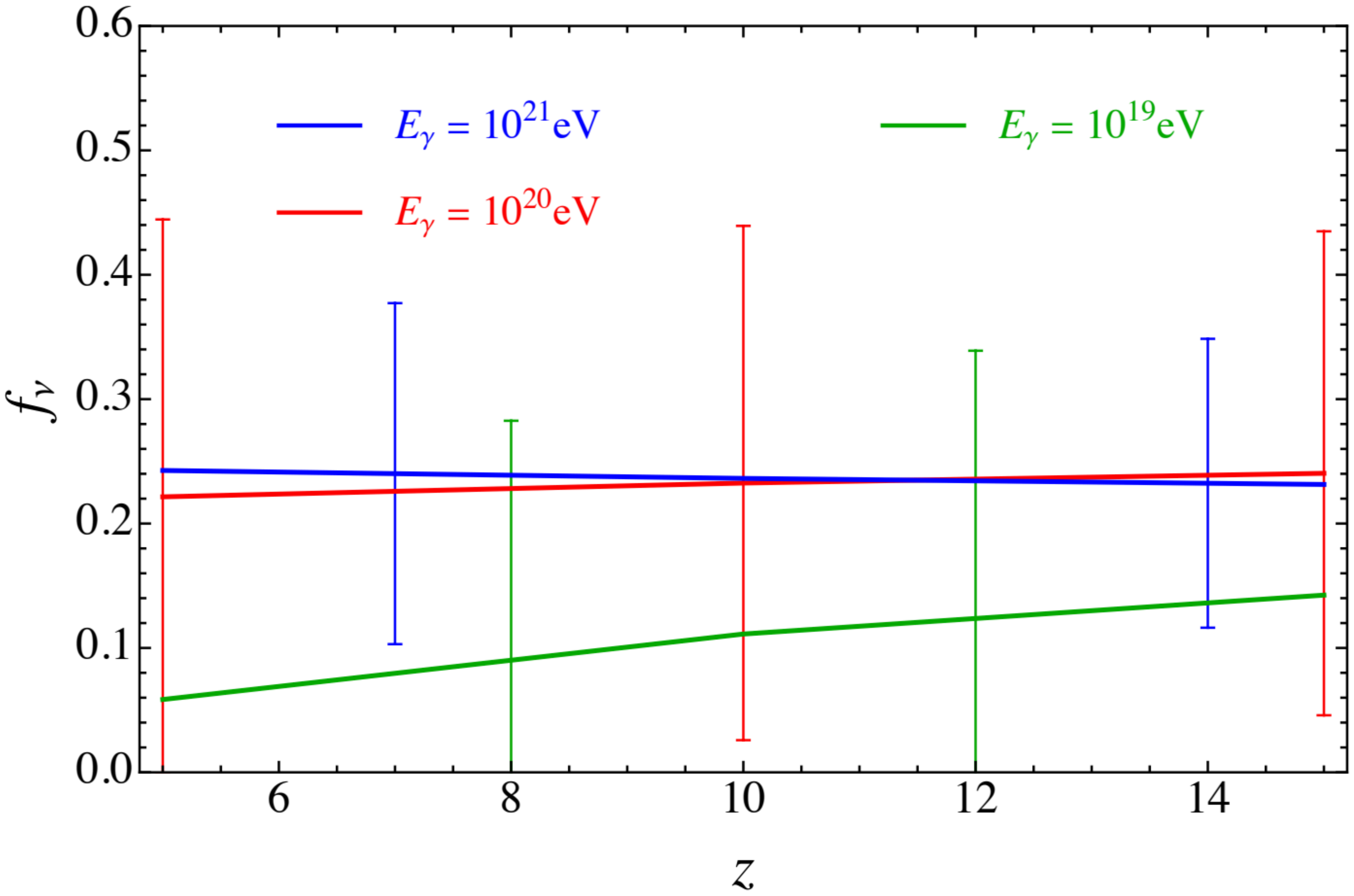
$\Delta\chi^2$	C.L.
4.61	1σ
6.18	2σ
11.83	3σ

Low-z sources





More Examples



Fraction of Energy Given to Neutrinos