Multimessenger approach in probing the high energy universe: the case of neutrinos and gamma-rays

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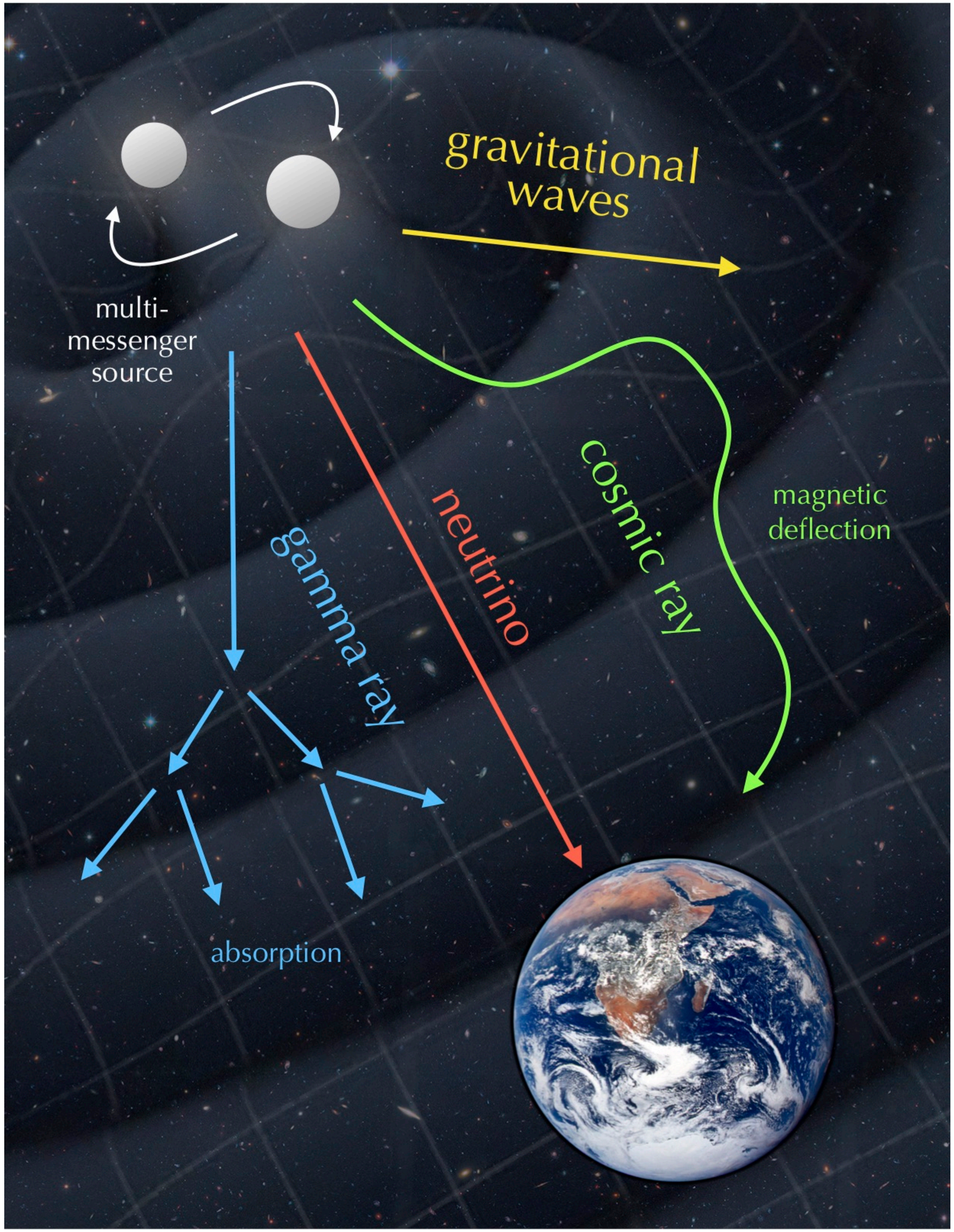

gravitational
waves
multi-
messenger
source
cosmic ray
magnetic
deflection
neutrino
gamma ray
absorption

EM cascade

A cascade develops due to:

$$\gamma + \gamma_t \to e^- + e^+$$ Pair production

Inverse-Compton scattering $$e + \gamma_t \to \gamma' + e$$

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

Idea: the cosmogenic neutrinos are produced in $p\gamma_{CMB}$ interaction through the Δ^+ resonance. The same process produces e and γ. The energy density of the neutrinos and diffuse gammas are related by a ratio of 1/3. The recent Fermi observation: $\omega_{cas} = 5.8\times10^{-7}$ eV/cm^3.

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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

One thing is common between IC and p-p processes in the **high energy**

In both IC and p-p processes, the original particle transfer almost all its energy to one of the secondary particles (leading particle)

in the high energy: $\frac{E\epsilon}{m_e^2} \gg 1$

$$f \approx \frac{1}{\ln(2E\epsilon/m_e^2)}$$

average fraction of energy lost by the cascade particle

in the intermediate energy: $\frac{E\epsilon}{m_e^2} \sim 1$ → $f \approx 0.5$

in the low energy: $\frac{E\epsilon}{m_e^2} \ll 1$ → $f \approx \frac{4}{3}\frac{E\epsilon}{m_e^2}$

just IC $E'_\gamma = f E_\gamma$

EM cascade

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→ In the high energy, the leading particle decelerates by releasing energy in the form of low-energy electrons (photon always remains as leading particle)

EM cascade

Characteristic energies (monochromatic photon gas):

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

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

e decelerates by emitting Compton photons. No new e

EM cascade

Characteristic energies (monochromatic photon gas):

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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
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 $E_e \sim \varepsilon_e$

EM cascade

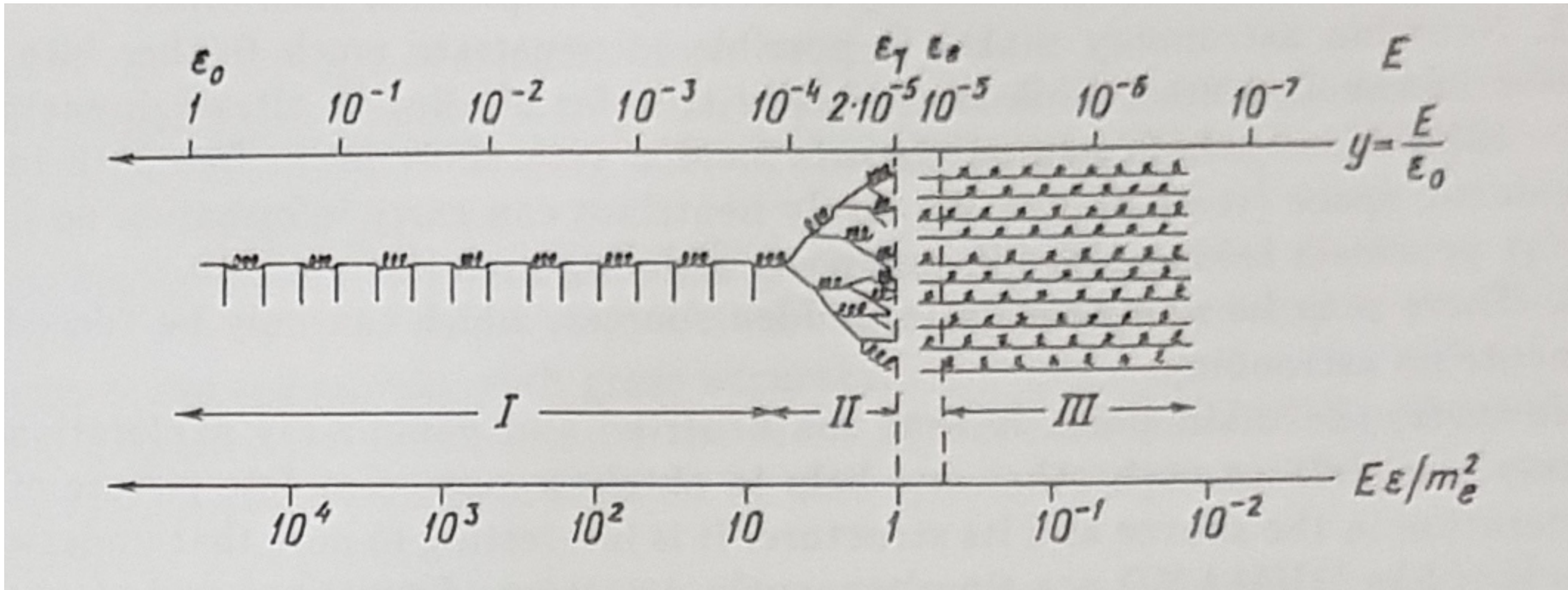
Characteristic energies (monochromatic photon gas):

		scaling
characteristic energy of the initial photon/electron	$\epsilon_0 \sim 0.1 \frac{m_\pi m_p}{\epsilon} \sim \frac{E_p}{10}$	$y_0 \sim 1$
critical energy of gamma (transparency)	$\epsilon_\gamma \sim \frac{m_e^2}{\epsilon}$	$y_\gamma \sim 2 \times 10^{-5}$
min energy of e in p-p (cascade multiplication)	$\epsilon_e = \frac{\epsilon_\gamma}{2} \sim \frac{m_e^2}{2\epsilon}$	$y_e \sim 10^{-5}$
Compton photons (end of multi. phase)	$\epsilon_X \sim \frac{4}{3} \frac{\epsilon_e^2 \epsilon}{m_e^2} \sim \frac{\epsilon_\gamma}{3}$	$y_X \sim 6.7 \times 10^{-6}$

in terms of the scaling parameter y the cascade spectrum is universal

EM cascade

Qualitative description (monochromatic photon gas):



EM cascade

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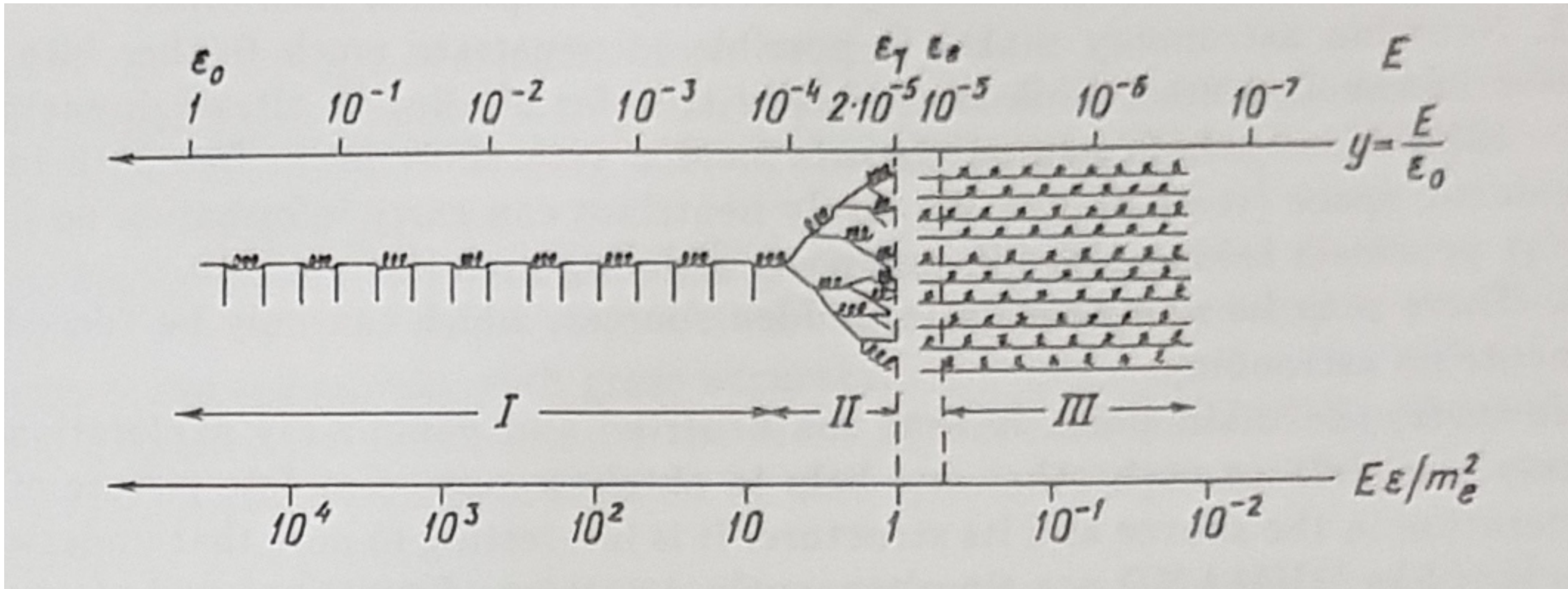

Berezinsky & Smirnov

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

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

EM cascade

The dichromatic photon gas approximation:

The photon gas consists of two populations
(EBL = Extragalactic Background Light ; CMB = Cosmic Microwave Background)

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

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

EM cascade

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

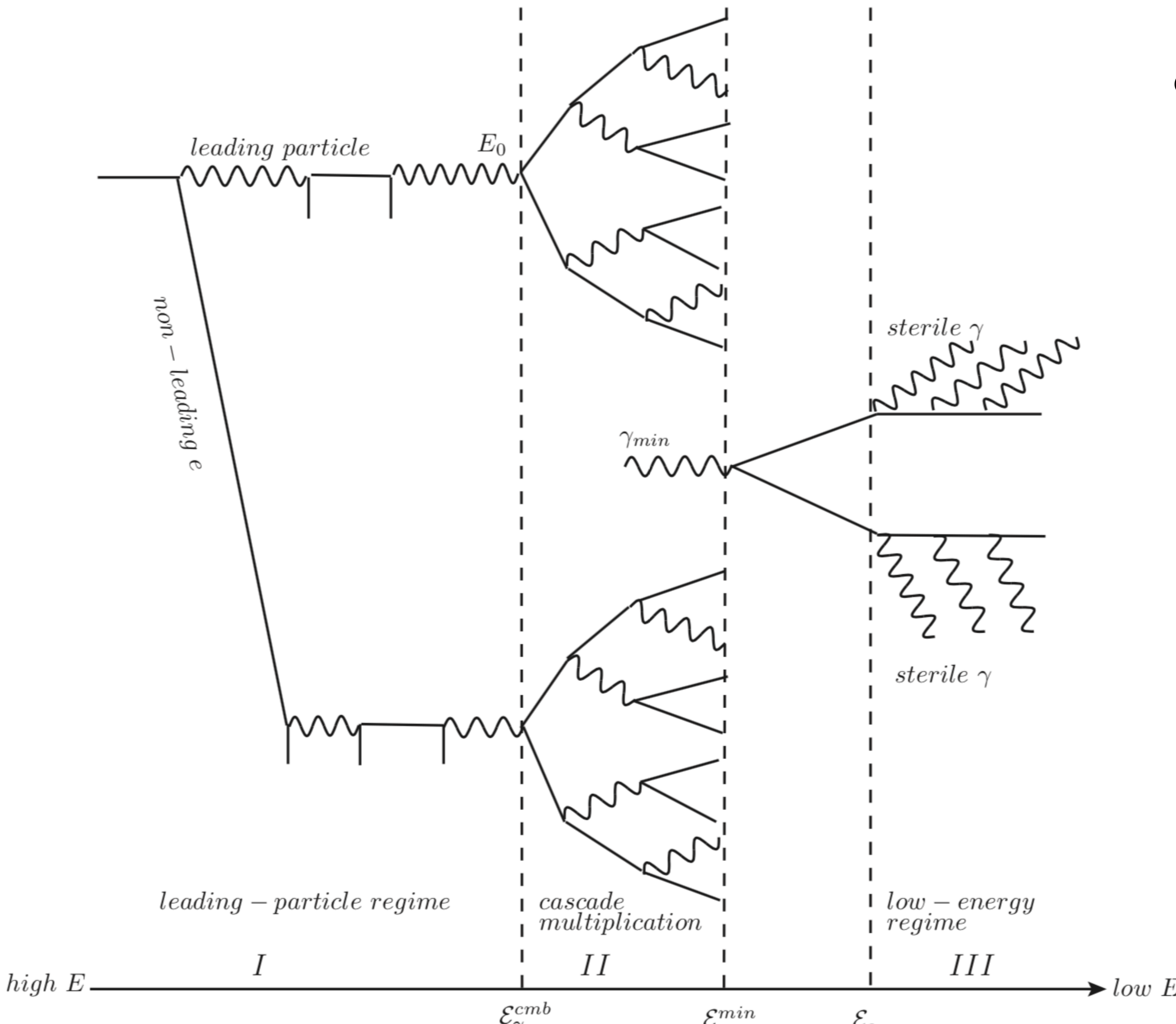
1) p-p on CMB and IC on CMB

2) p-p on EBL and IC on CMB

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

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

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

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

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

EM cascade

$\epsilon_{\gamma,\mathrm{cmb}} \approx 400\,\mathrm{TeV}$ $\epsilon_\gamma^{\mathrm{min}} \approx 400\,\mathrm{GeV}$ $\epsilon_e \approx 200\,\mathrm{GeV}$ $\epsilon_X \approx 120\,\mathrm{MeV}$

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

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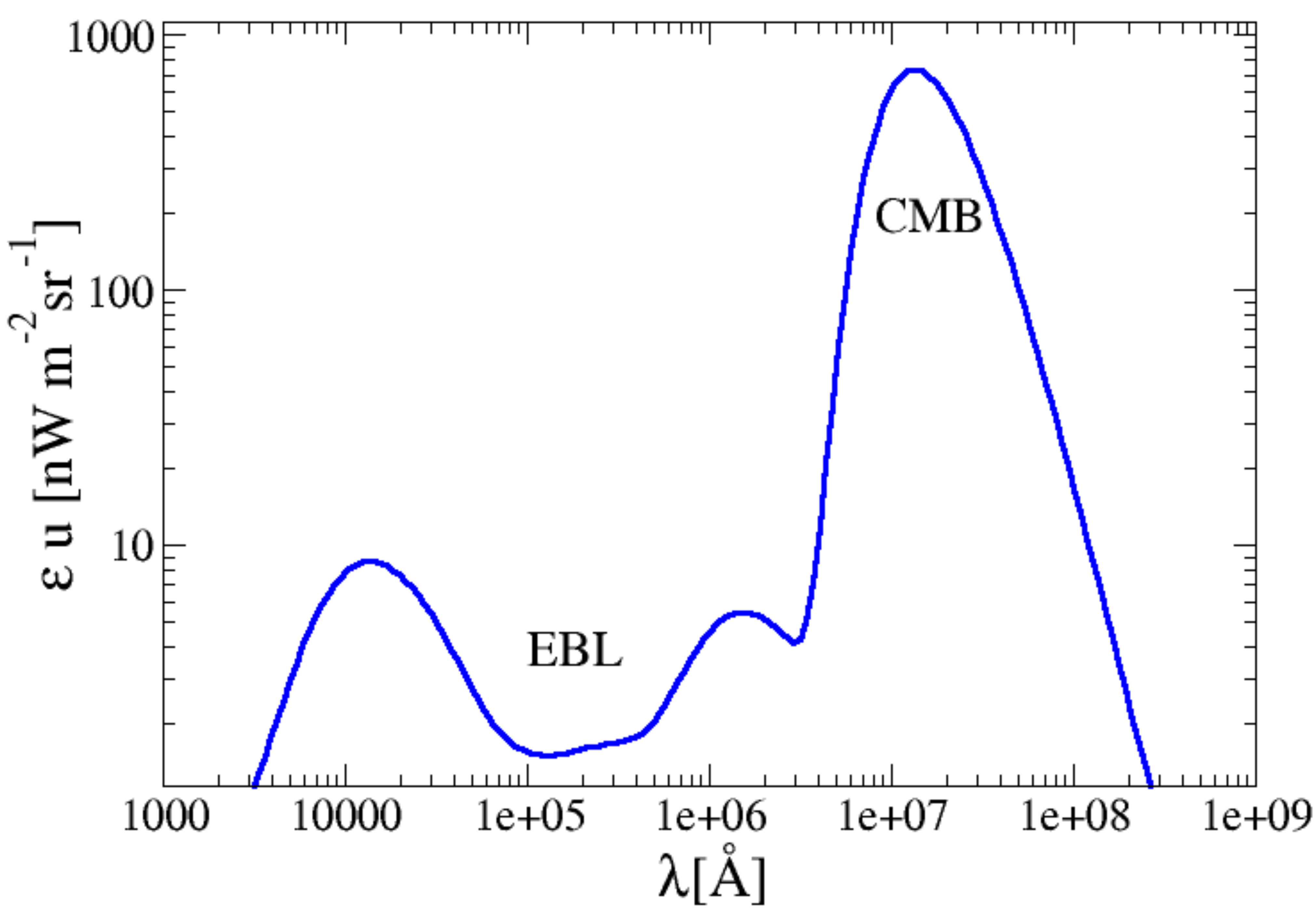
Used approximation:

1) Both the CMB and EBL are continuous distributions, not monochromatic.

EM cascade

$\epsilon_{\gamma,\text{cmb}}$ ... eV

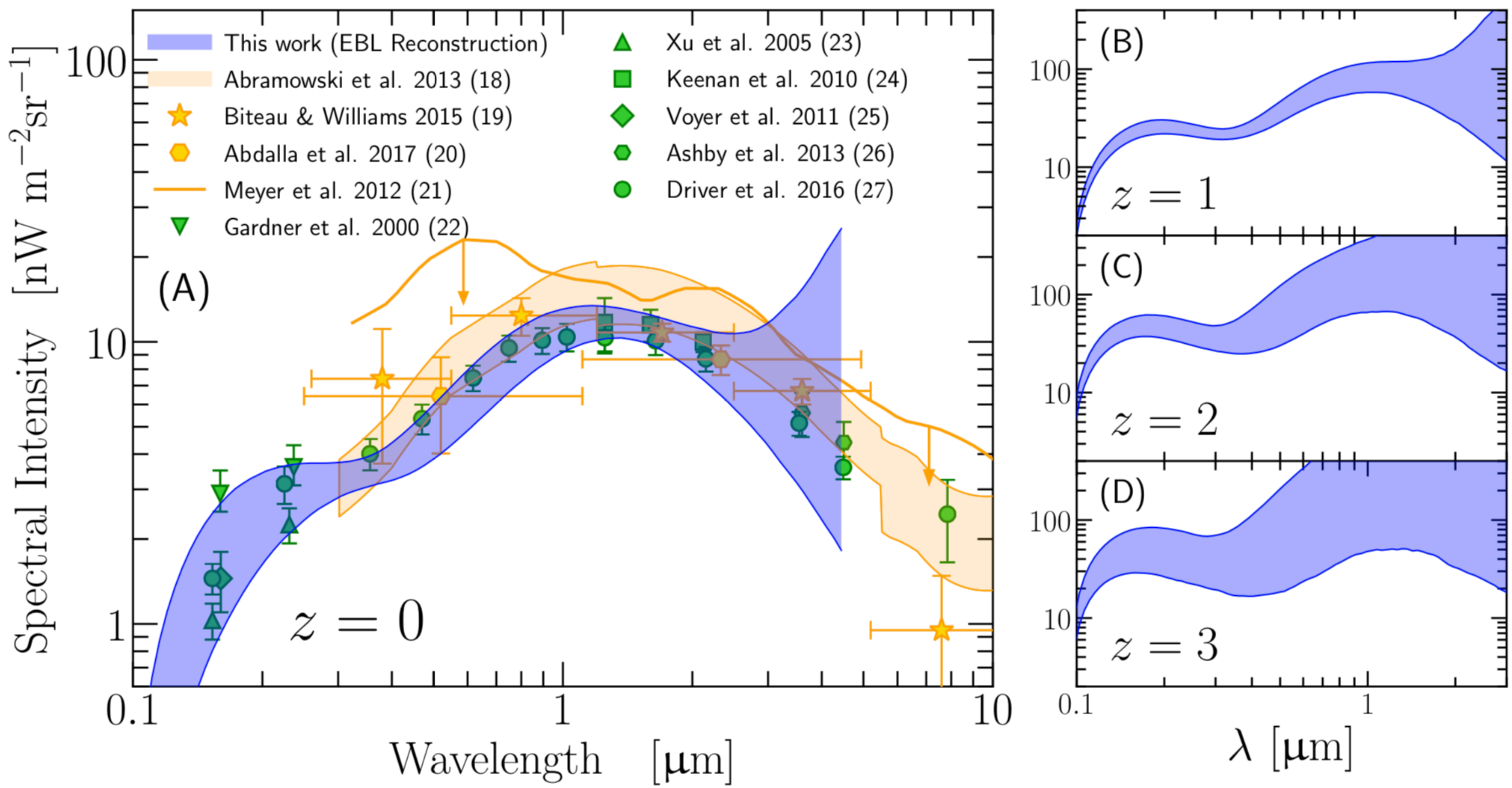


Used

1) Both

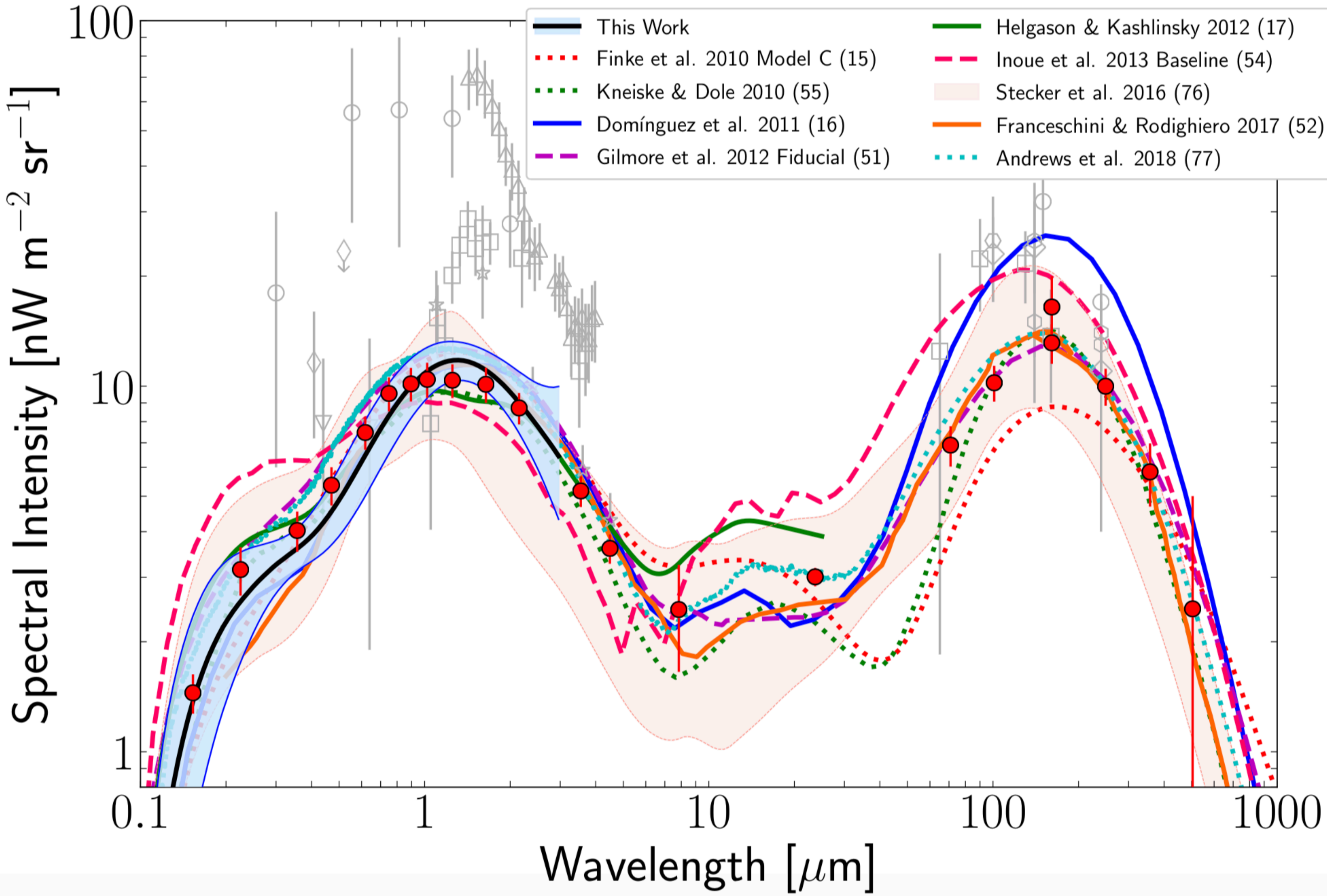
EM cascade

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



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1) Both the CMB and EBL are continuous distributions, not monochromatic.

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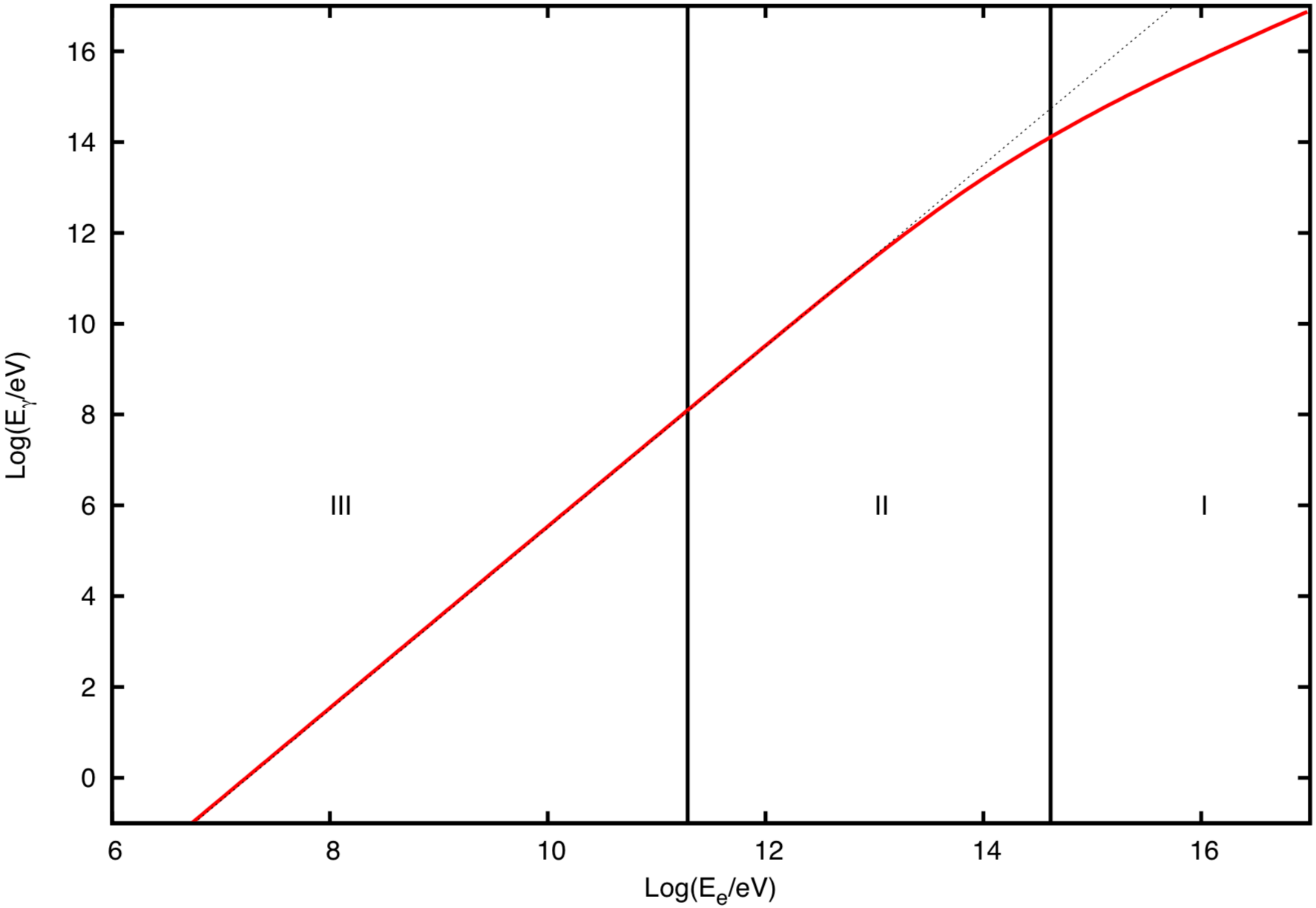
Used

1) Bot

2) Th



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5) Distance of the source: not fully developed cascades.

6) Nearby sources lead to photon flux at $E_\gamma > \varepsilon_\gamma^{\min}$

EM cascade

Numerical solution:

The problem is a general Boltzmann process:

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

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

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

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

$$\dot{N} = c\int_{\epsilon_{\min}}^{\epsilon_{\max}} d\epsilon\, n_{\mathrm{T}}(\epsilon) \int_{-1}^{1} d\mu\, \frac{1-\beta\mu}{2} \int_{E_{\mathrm{I},\min}}^{E_{\mathrm{I},\max}} dE_{\mathrm{I}}\, n_{\mathrm{I}}(E_{\mathrm{I}}) \int_{E_{\min}}^{E_{\max}} dE'\, \frac{d\sigma}{dE}(E', E)$$

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:

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

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

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

EM cascade

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Example of p-p:

$$\dot{N}_{e,\mathrm{pp}} = c \int_0^\infty d\epsilon \, n_\mathrm{T}(\epsilon) \int_{-1}^{\mu_\mathrm{max}} d\mu \, \frac{1-\mu}{2} \int_{E_\mathrm{min}}^{E_\mathrm{max}} dE_\gamma \frac{d\sigma_\mathrm{pp}}{dE}(E_\gamma, E) \left(n_{\gamma,\mathrm{inj}}(E_\gamma) + \int_{E_{\mathrm{IC,min}}}^{E_{\mathrm{IC,max}}} dE' \, N_e(E') \frac{d\sigma_\mathrm{IC}}{dE}(E, E'-E_\gamma) \right)$$

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

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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ELMAG, M. Kachelrieß et al

GCascade, C. Blanco

EleCA, DINT, CRPropa

where $n_{\mathrm{T}=\mathrm{C}}$ … $E_e = \omega m_e c^2$

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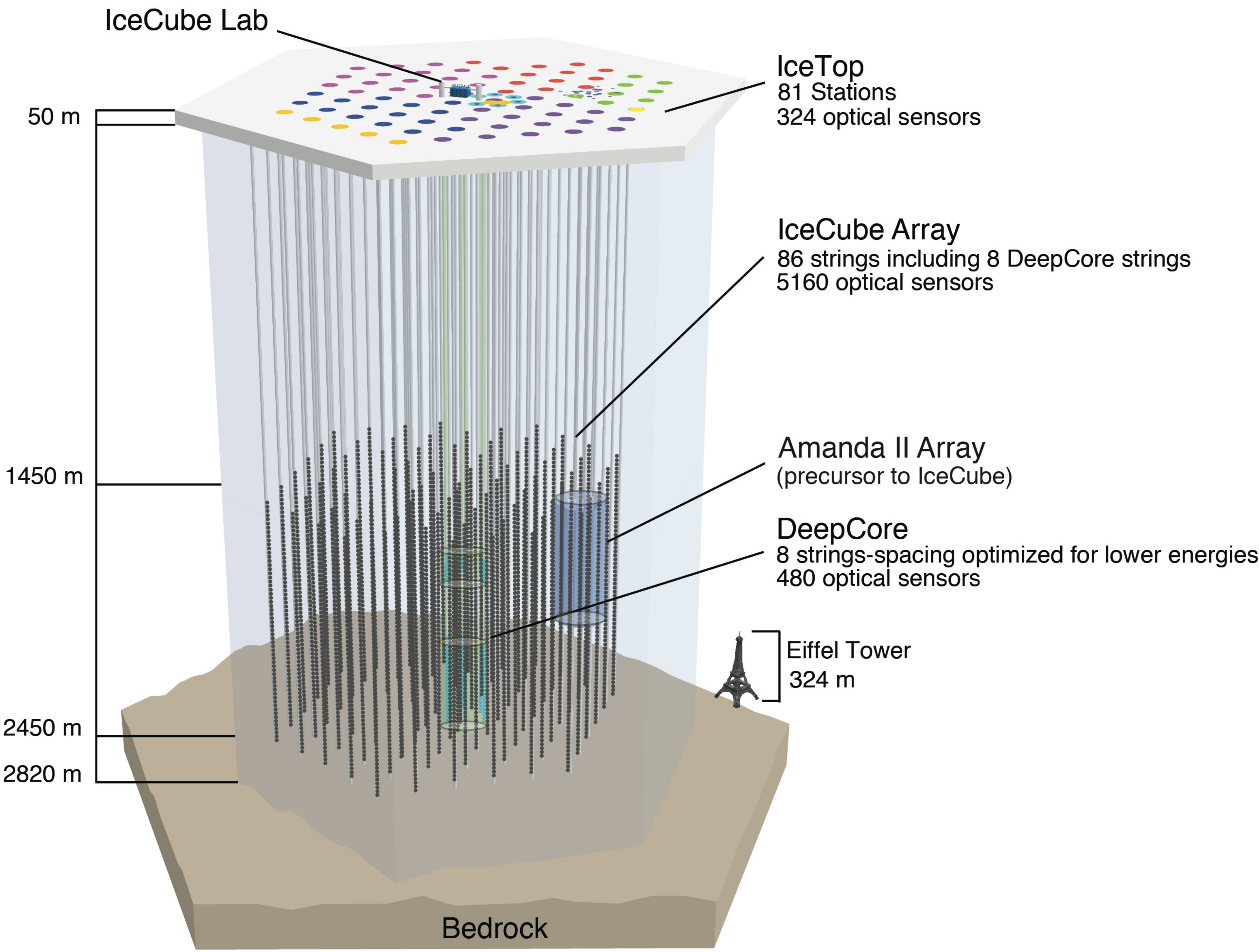
where $\beta' = \sqrt{1-2/\omega_1\omega_2(1-\mu)}$, $\omega_1 = \epsilon/m_e c^2$, $\omega_2 = E_\gamma/m_e c^2$

An example of multi-messenger approach

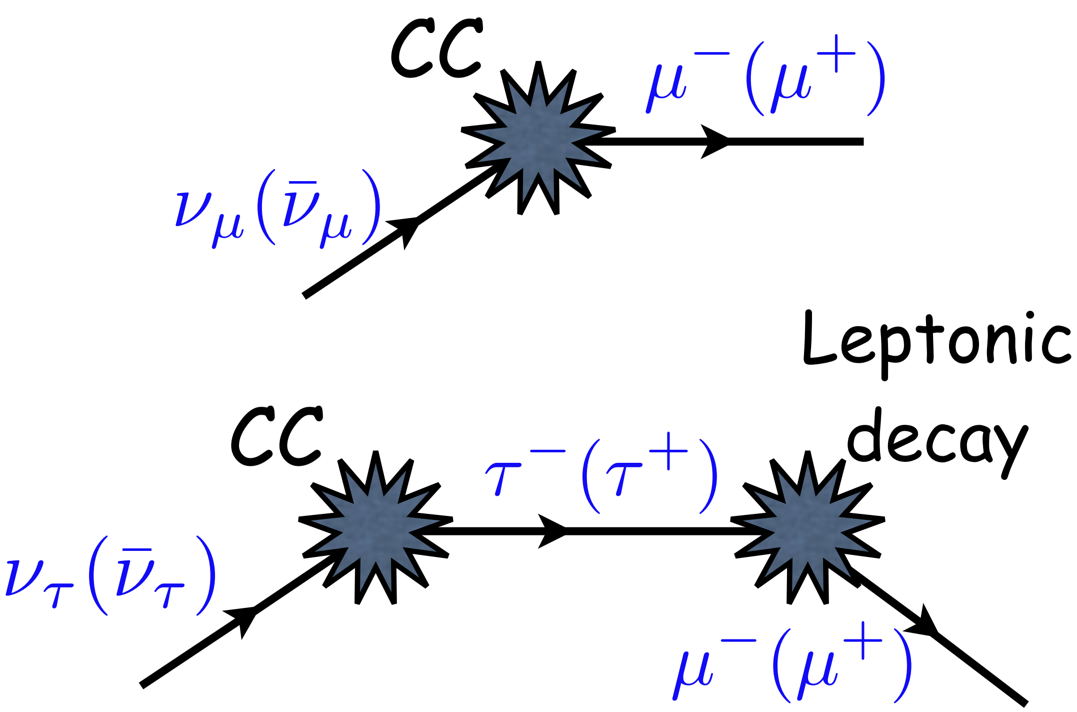
what can we learn about the source(s) of IceCube neutrinos?



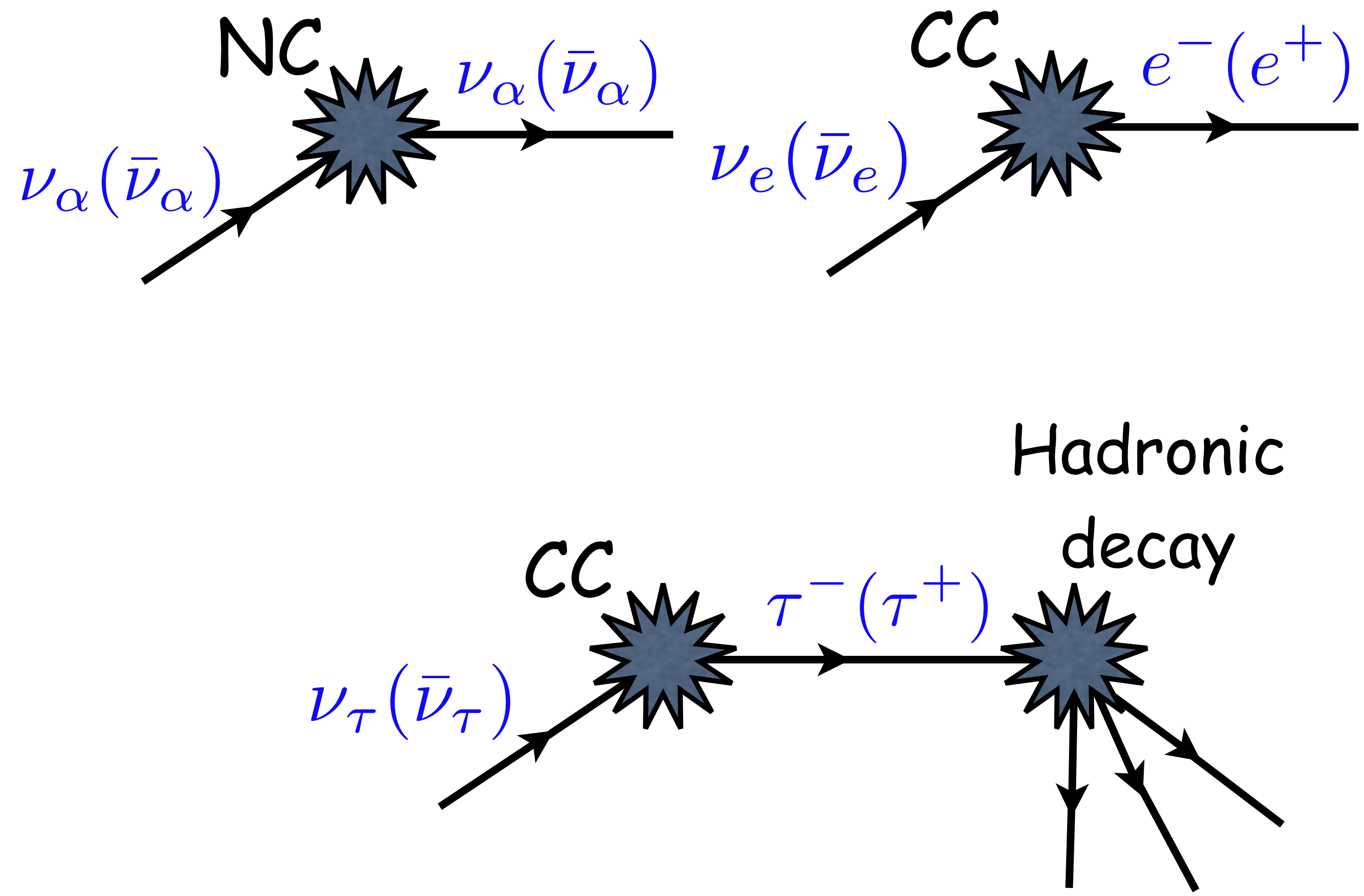
IceCube Lab
IceTop
81 Stations
324 optical sensors
50 m
IceCube Array
86 strings including 8 DeepCore strings
5160 optical sensors
1450 m
Amanda II Array
(precursor to IceCube)
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock

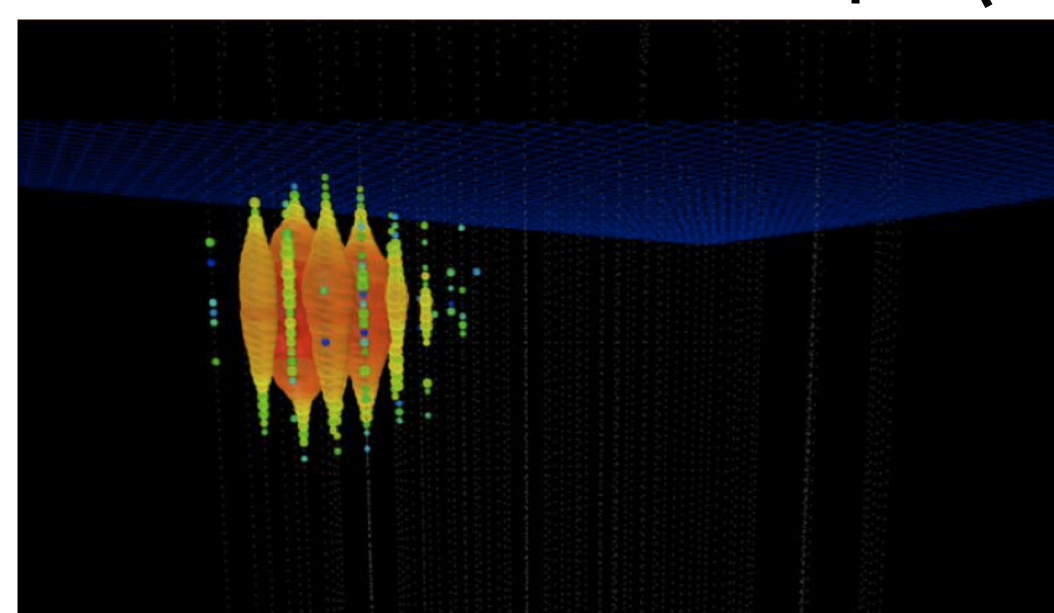
Flavoring at IceCube

muon-track events



cascade events





figures from IceCube website

Flavoring at IceCube

muon-track events

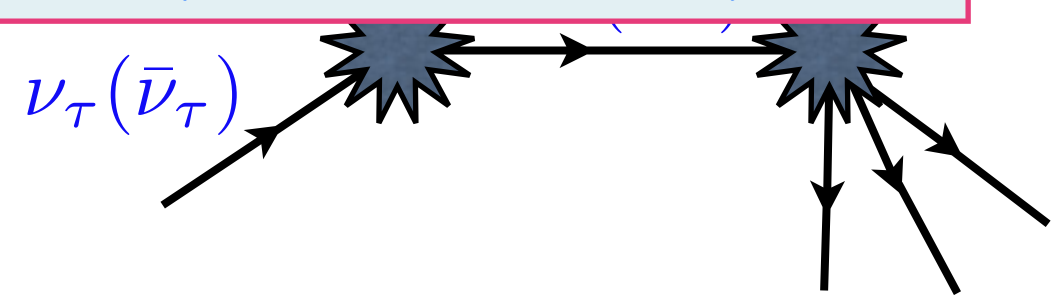
good angular resolution (< 1°)

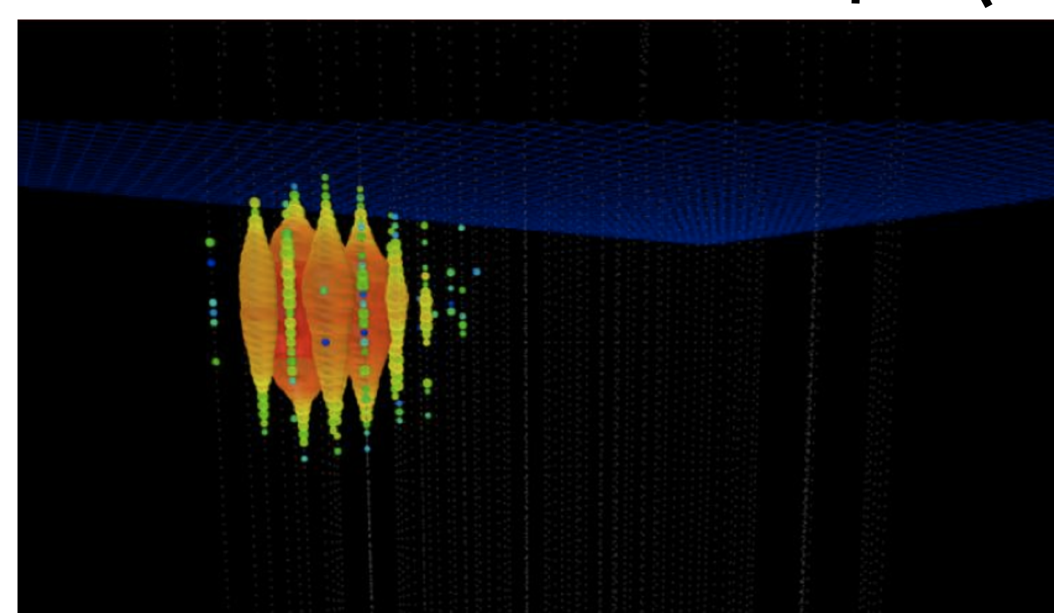
moderate energy resolution (σ_E ~ E)

cascade events

poor angular resolution (< 10° - 20°)

good energy resolution (σ_E ~ 0.15 x E)

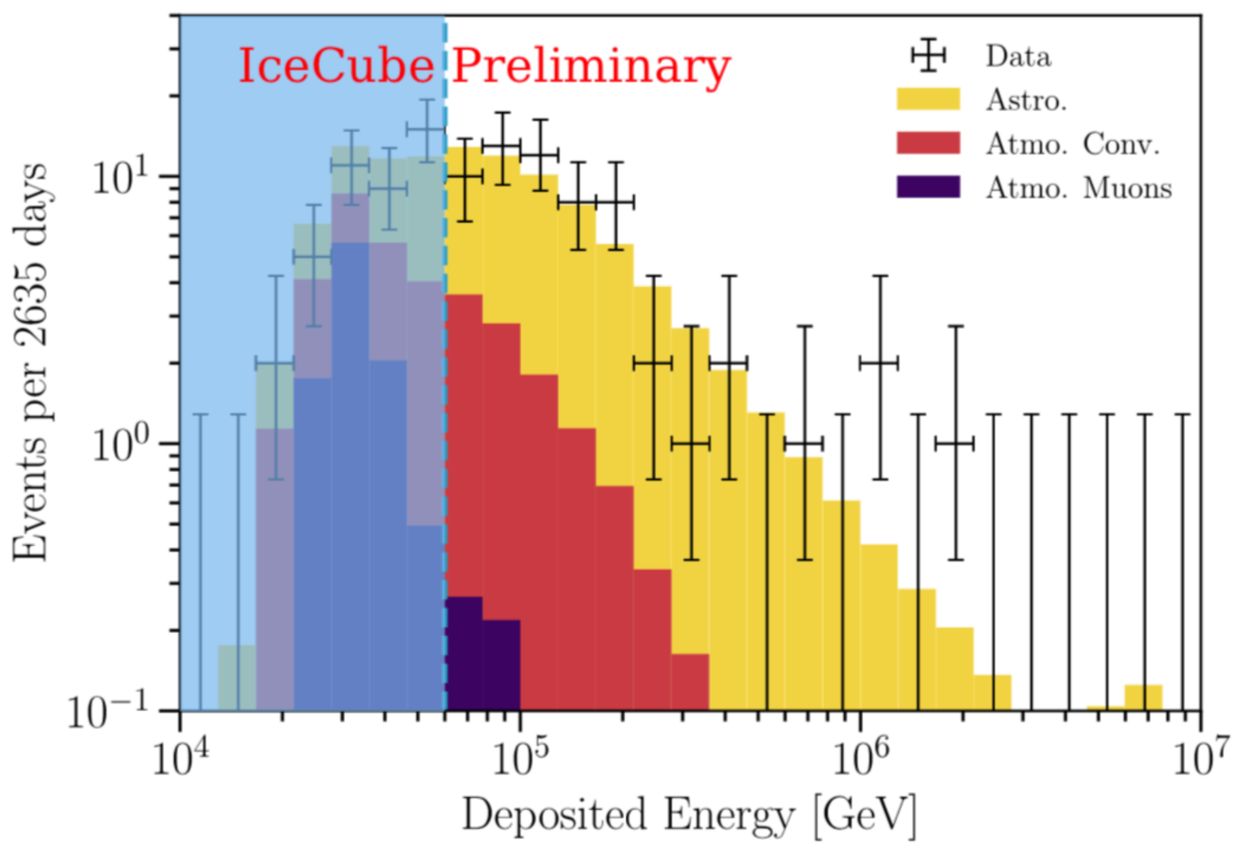


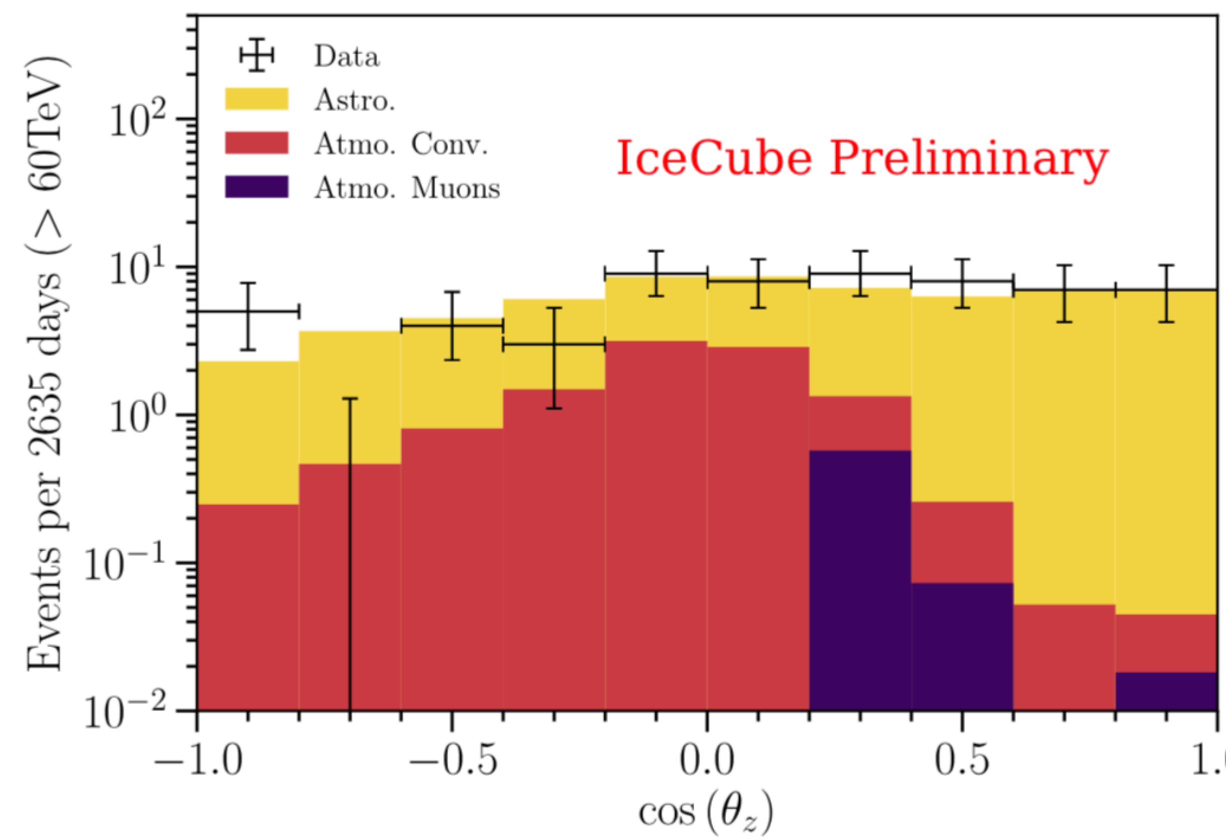


figures from IceCube website

IceCube data

✓ 7.5 years HESE:





$$\frac{d\Phi_\nu}{dE_\nu} = 10^{-18} \cdot \phi_{\rm astro} \left(\frac{E_\nu}{100\ \rm TeV}\right)^{-\gamma_{\rm astro}} \quad [\rm GeV^{-1} cm^{-2} s^{-1} sr^{-1}]$$

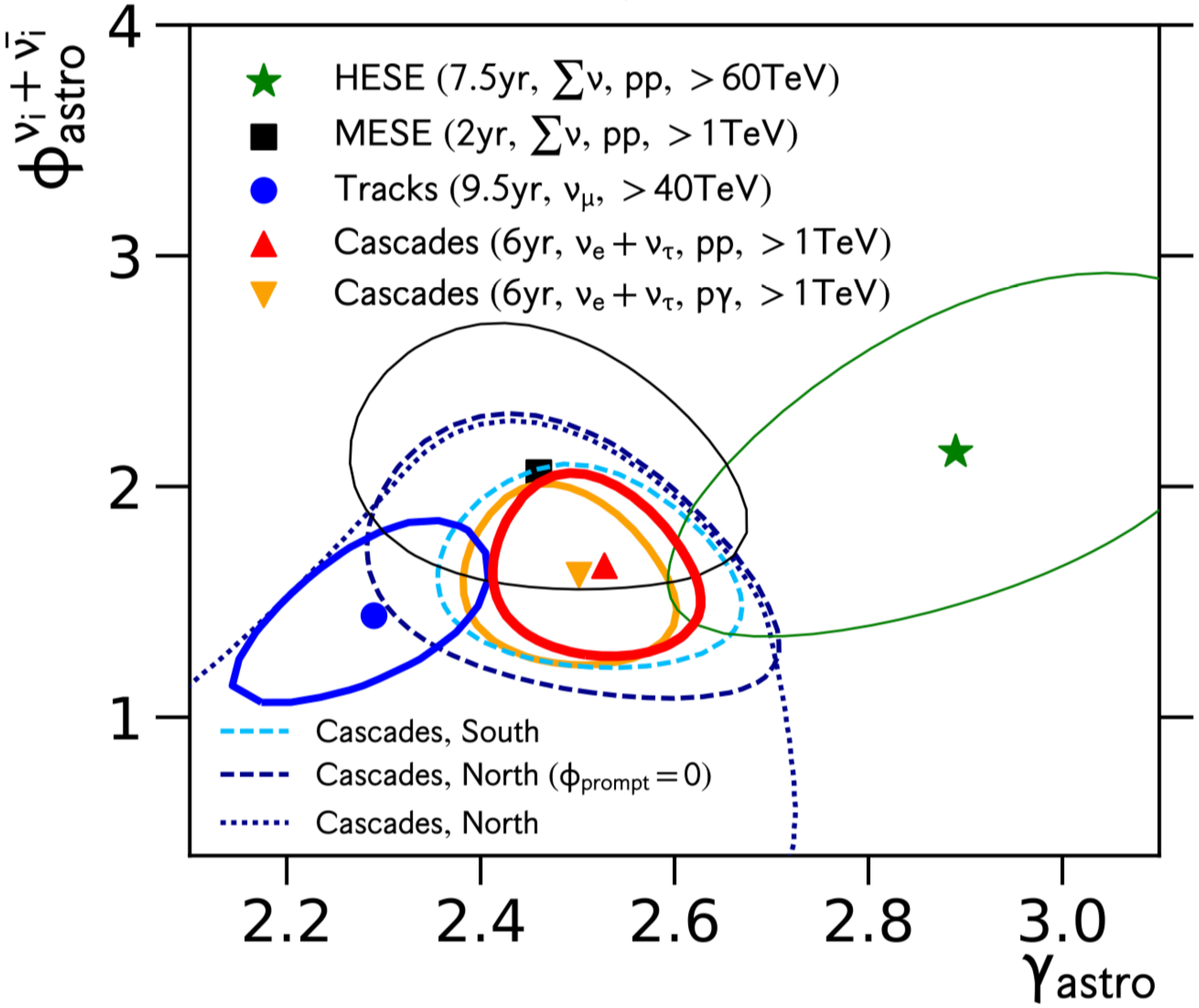
All-flavor

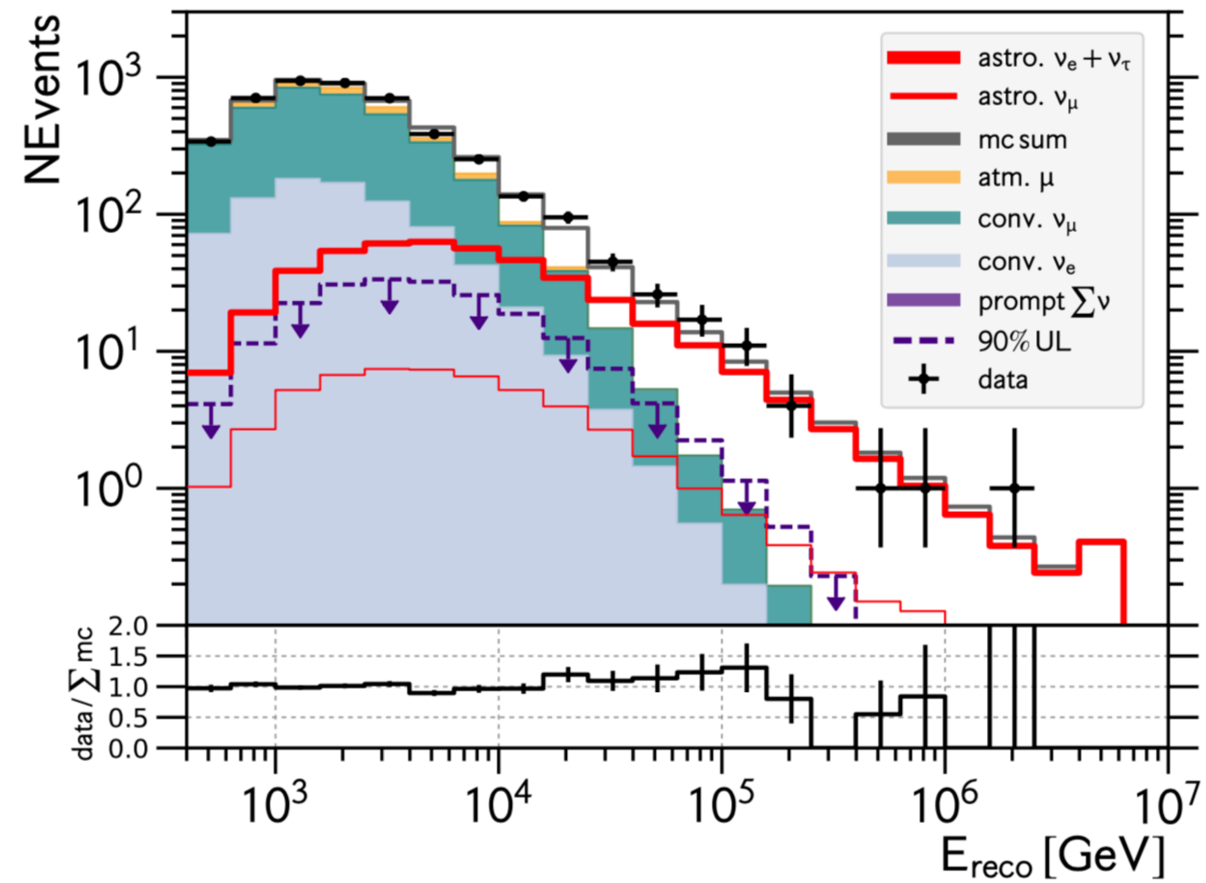
$\phi_{\rm astro} = 6.45^{+1.46}_{-0.46}$ $\gamma_{\rm astro} = 2.89^{+0.2}_{-0.19}$ $E_{\rm thr} = 60\ \rm TeV$

IceCube data

✓ 6 years Cascade events:

IceCube, 2001.09520





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$$[\rm GeV^{-1} cm^{-2} s^{-1} sr^{-1}]$$

One-flavor

$$\phi_{\rm astro} = 1.66^{+0.25}_{-0.27}$$

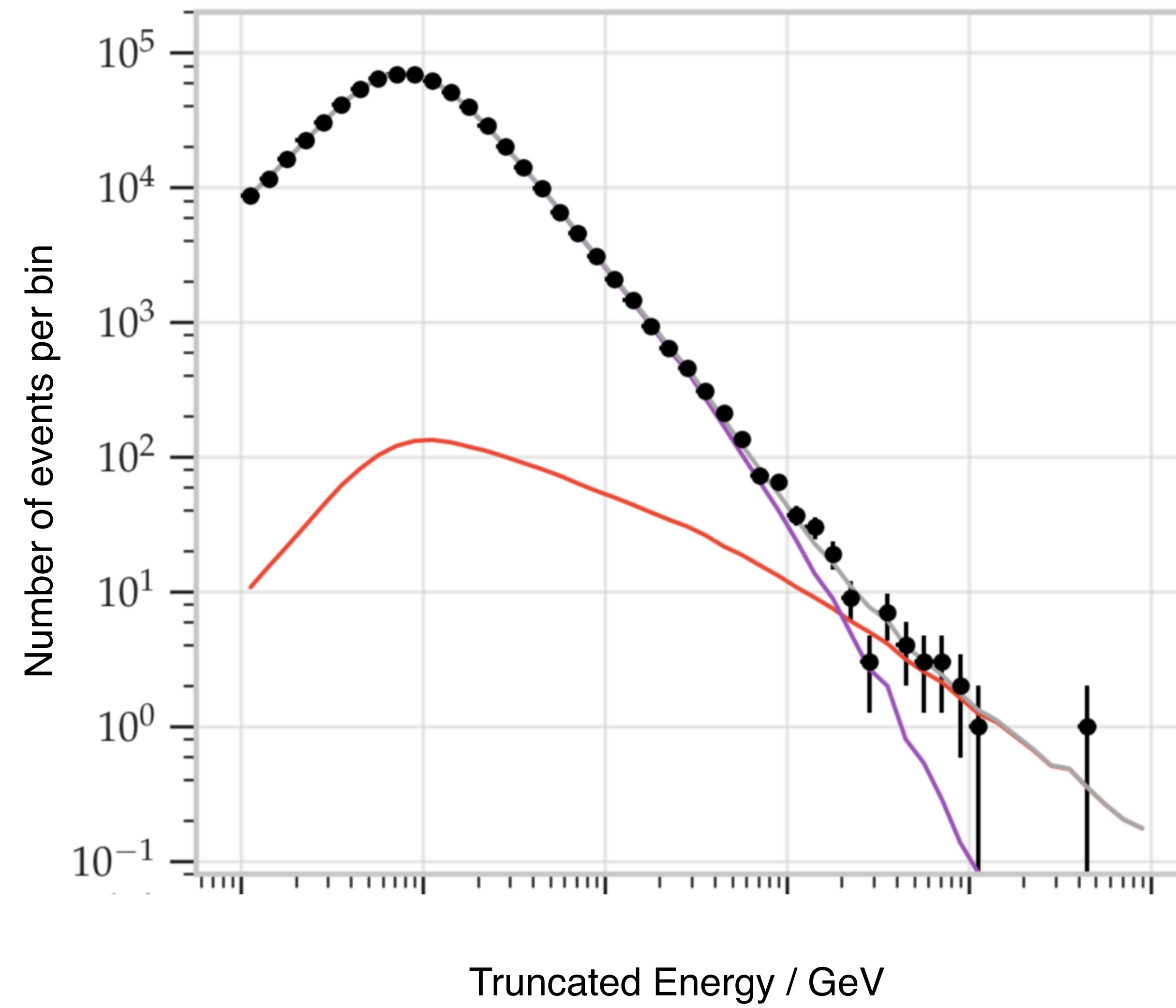
$$\gamma_{\rm astro} = 2.53 \pm 0.07$$

$$E_{\rm thr} = 16\ \rm TeV$$

IceCube data

✓ 9.5 years Through-going Muon Tracks:

IceCube, 1908.09551



$$\frac{d\Phi_\nu}{dE_\nu} = 10^{-18} \cdot \phi_{\rm astro} \left(\frac{E_\nu}{100 \text{ TeV}}\right)^{-\gamma_{\rm astro}}$$

$$[\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]$$

One-flavor

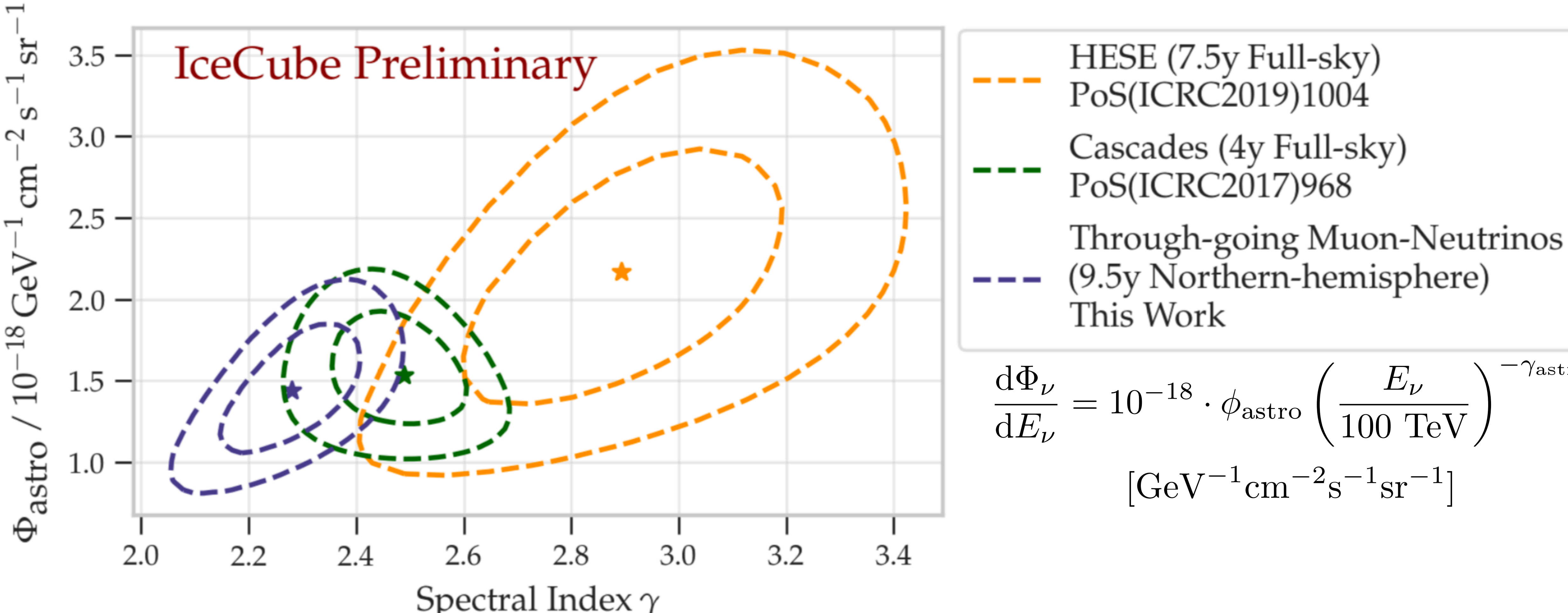
$$\phi_{\rm astro} = 1.44^{+0.25}_{-0.24}$$

$$\gamma_{\rm astro} = 2.28^{+0.08}_{-0.09}$$

$$E_{\rm thr} = 119 \text{ TeV}$$

IceCube data

✔ Summary of the three data sets:



$$\frac{d\Phi_\nu}{dE_\nu} = 10^{-18} \cdot \phi_{\rm astro} \left(\frac{E_\nu}{100\ {\rm TeV}}\right)^{-\gamma_{\rm astro}}$$

$[\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$

HESE	Cascades	Through-going muons
$E_{\rm thr} = 60$ TeV	$E_{\rm thr} = 16$ TeV	$E_{\rm thr} = 119$ TeV

NOTICE: the E_{thr} does not show the lowest available energy in data! it comes from optimization of the fit (considering the background rejection efficiency). There are events with energy below E_{thr}.

IceCube data

✓ Some candidate sources:

GRBs

Active Galactic Nuclei (Blazars, BL Lacs, Radio galaxies)

Starburst Galaxies

Supernova Remnants

Tidal Disruption Events

Up to now, all the searches yielded null result!

Neutrino and gamma-ray connection

Any source that produces neutrinos, should produce gamma-rays also:

$$p + p \to \pi^{\pm} + X \quad (\pi^{\pm} \to \mu + \nu,\ \mu \to e + \nu + \bar{\nu})$$

$$p + \gamma \to \pi^{\pm} + X \quad (\pi^{\pm} \to \mu + \nu,\ \mu \to e + \nu + \bar{\nu})$$

$$\pi^0 \to 2\gamma$$

More precisely
(conservative assumption)

$$\frac{1}{3}\sum_{\alpha} E_\nu Q_{\nu_\alpha}(E_\nu)\Big|_{E_\nu = E_\gamma/2} = \frac{K_\pi}{4} E_\gamma Q_\gamma(E_\gamma)$$

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$$\frac{1}{3}\sum_{\alpha} E_\nu Q_{\nu_\alpha}(E_\nu)\Big|_{E_\nu = E_\gamma/2} = \frac{K_\pi}{4} E_\gamma Q_\gamma(E_\gamma)$$

While it is straightforward to calculate the neutrino flux at Earth, gamma-rays initiate EM cascade

$$\phi_\nu^{\rm diff}(E_\nu) = \frac{1}{4\pi}\int {\rm d}z \, \frac{{\rm d}\mathcal{V}}{{\rm d}z}\, \mathcal{H}(z)\, \frac{Q_\nu((1+z)E_\nu)}{4\pi d_c^2}$$

Neutrino and gamma-ray connection

SFR

Observed at IceCube:

$$\phi_\nu^{\rm diff}(E_\nu) = \frac{1}{4\pi}\int {\rm d}z\,\frac{{\rm d}\mathcal{V}}{{\rm d}z}\,\mathcal{H}(z)\,\frac{Q_\nu((1+z)E_\nu)}{4\pi d_c^2}$$

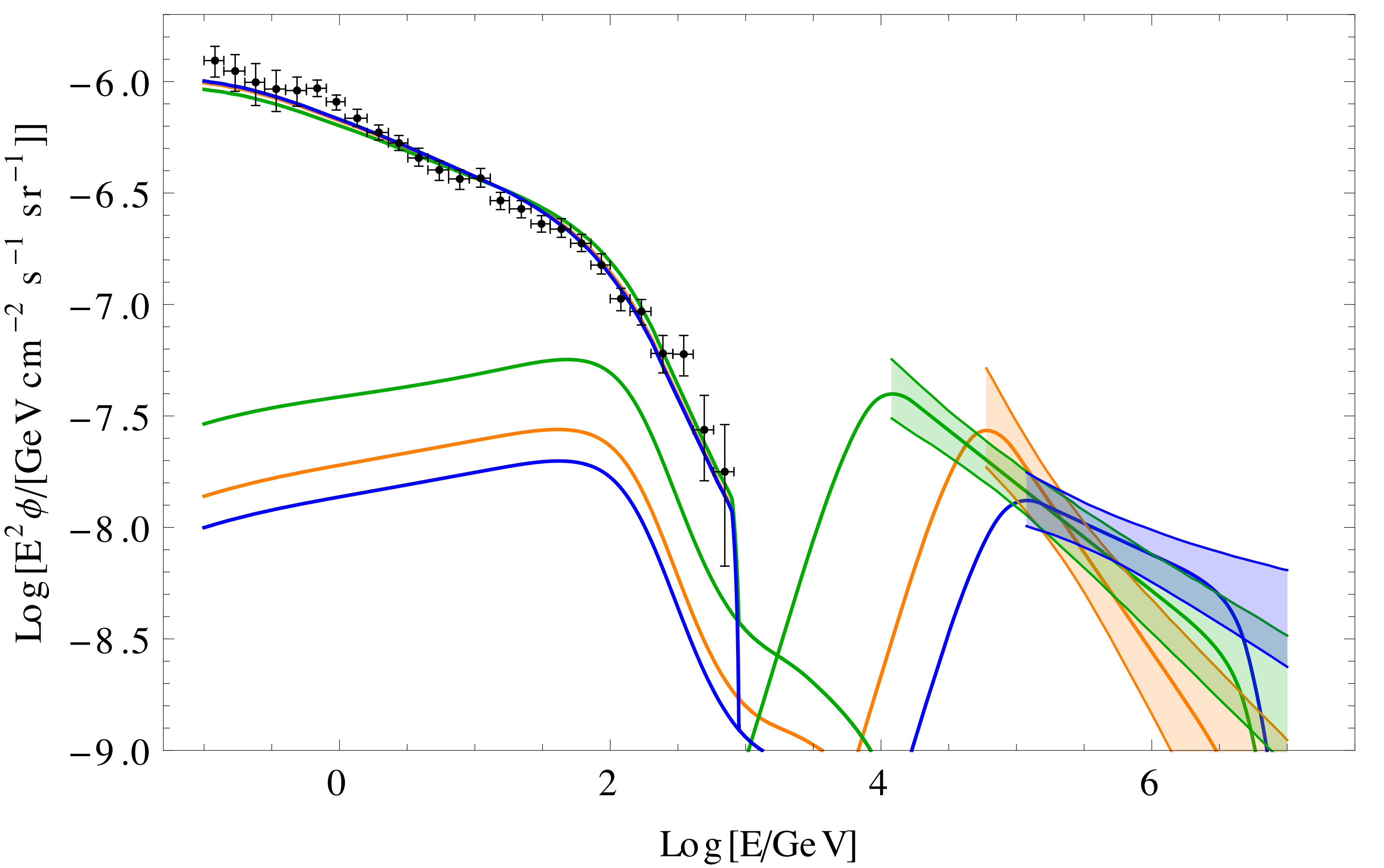
p-gamma scenario for neutrino production: A minimalistic assumption

$$\varepsilon_\nu Q_\nu(\varepsilon_\nu) \propto \begin{cases} \varepsilon_\nu & \varepsilon_\nu < \varepsilon_{\rm br} \\ \varepsilon_\nu^{1-s_h} & \varepsilon_{\rm br} \le \varepsilon_\nu \le 10\,{\rm PeV} \\ 0 & \varepsilon_\nu > 10\,{\rm PeV} \end{cases}$$

There is a natural threshold in p-gamma scenario

$$\sim 4\times 10^{-2} m_\pi m_p/\varepsilon_t$$

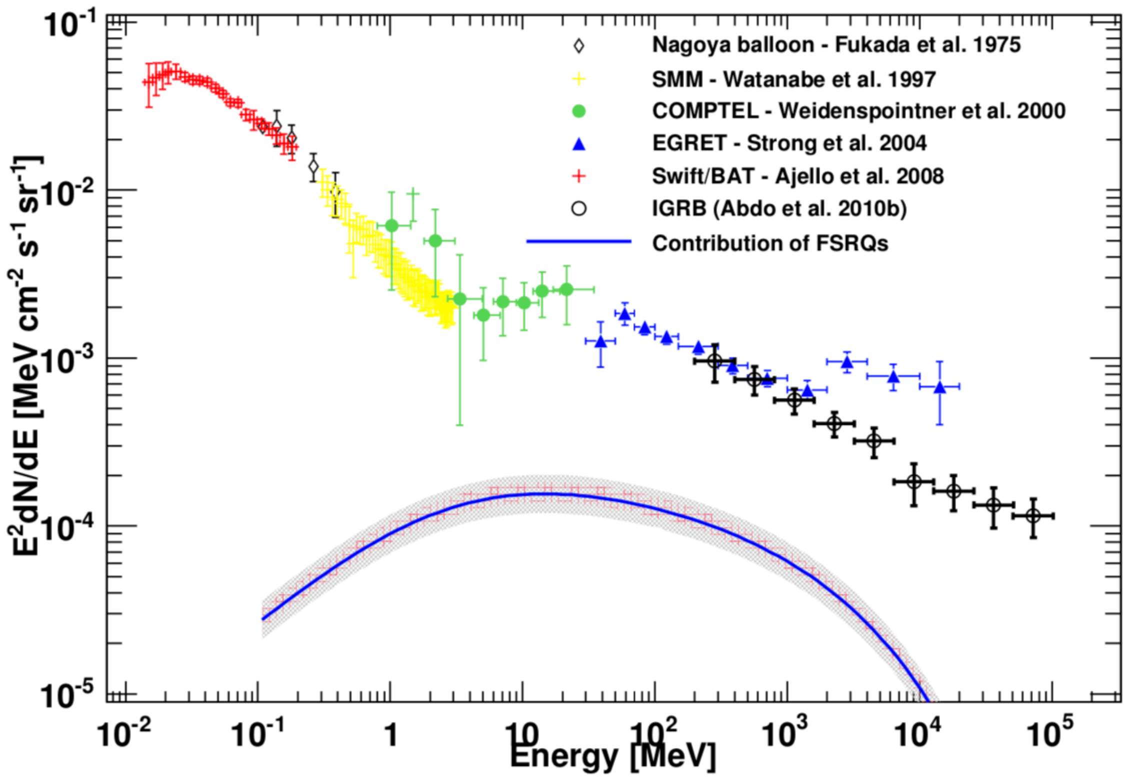
$$\sim 6\times 10^{6}\,{\rm GeV}\,({\rm eV}/\varepsilon_t)$$



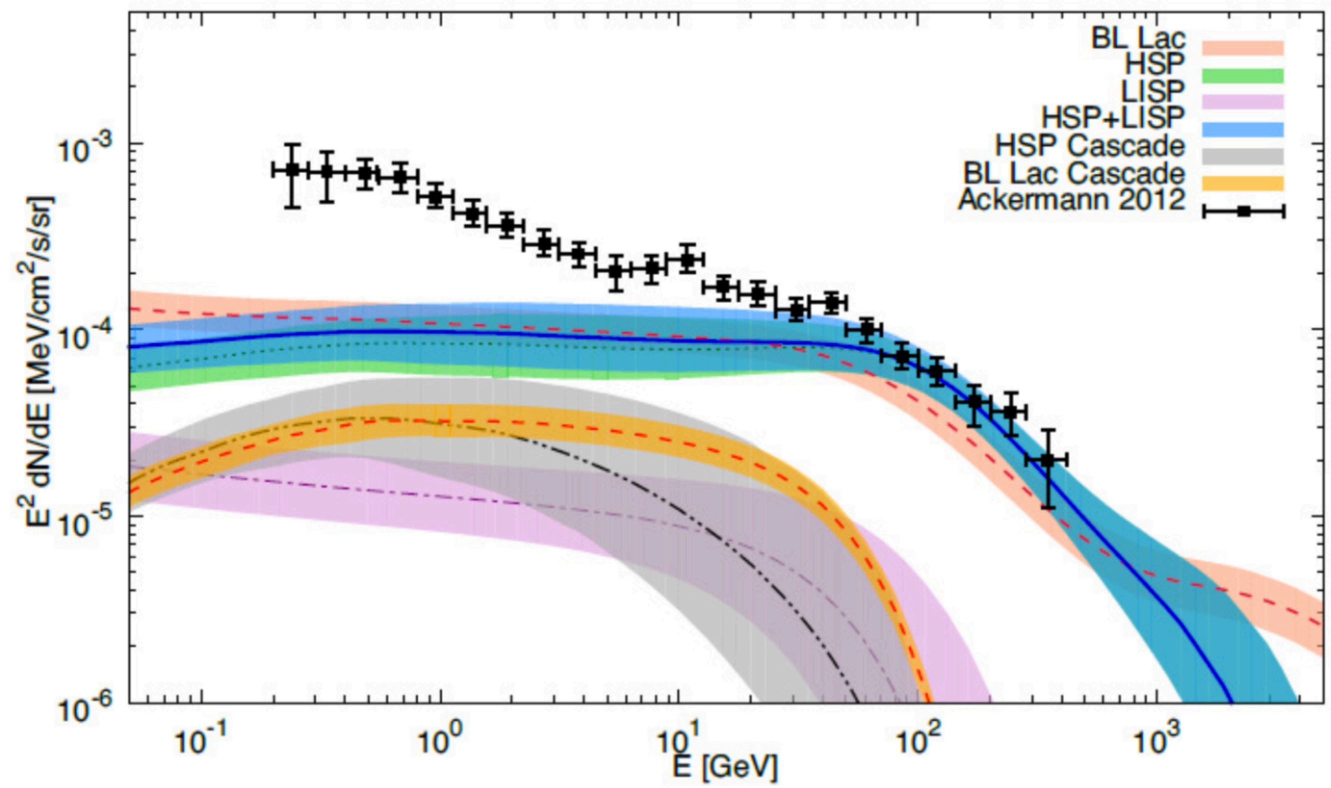
Various contributions to IGRB

DI MAURO, DONATO, LAMANNA, SANCHEZ, SERPICO, arXiv:1311.5708

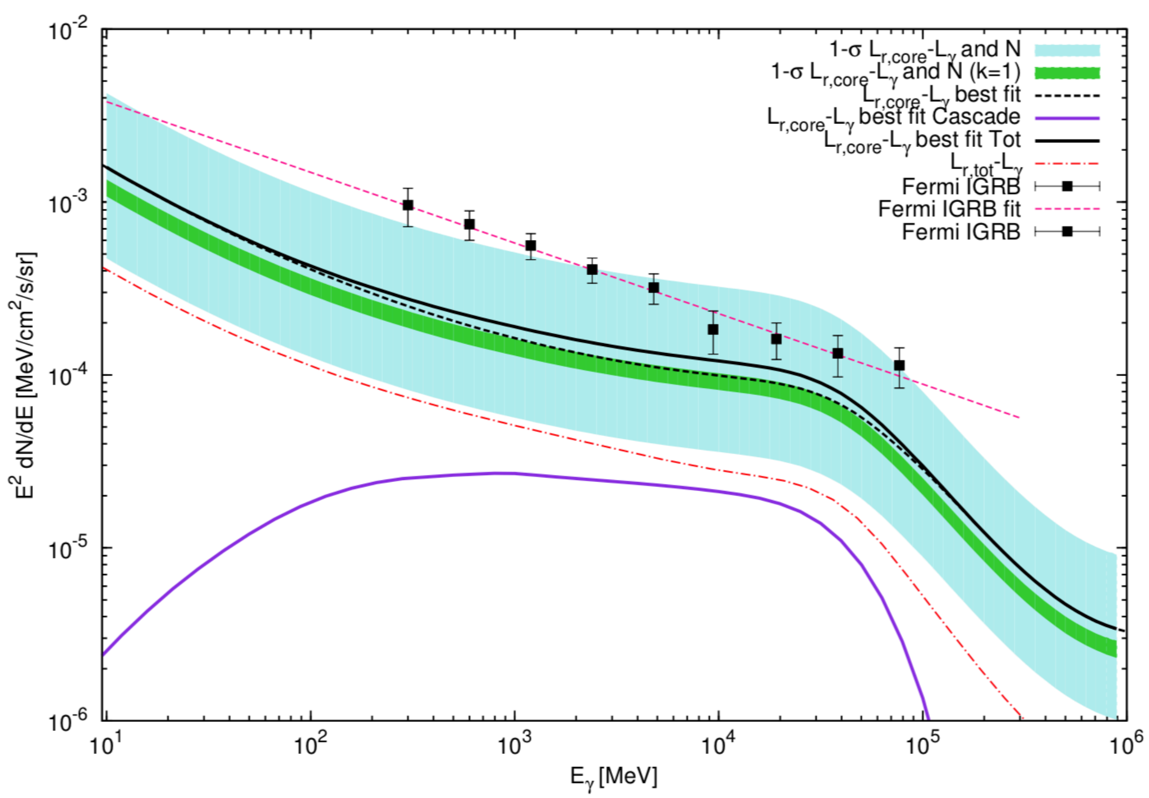
Flat Spectrum Radio Quasars (FSRQ)



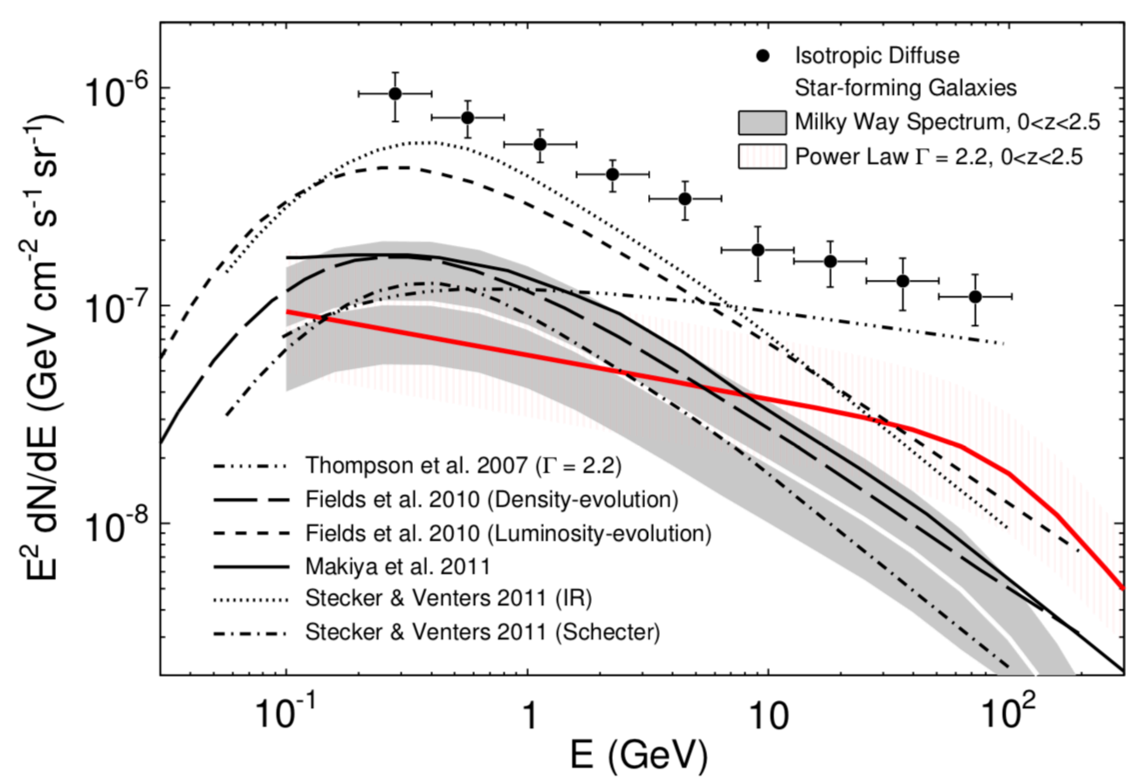
BL Lacs



Misaligned Active Galactic Nuclei (MAGN)



Star-Forming Galaxies (SFG)

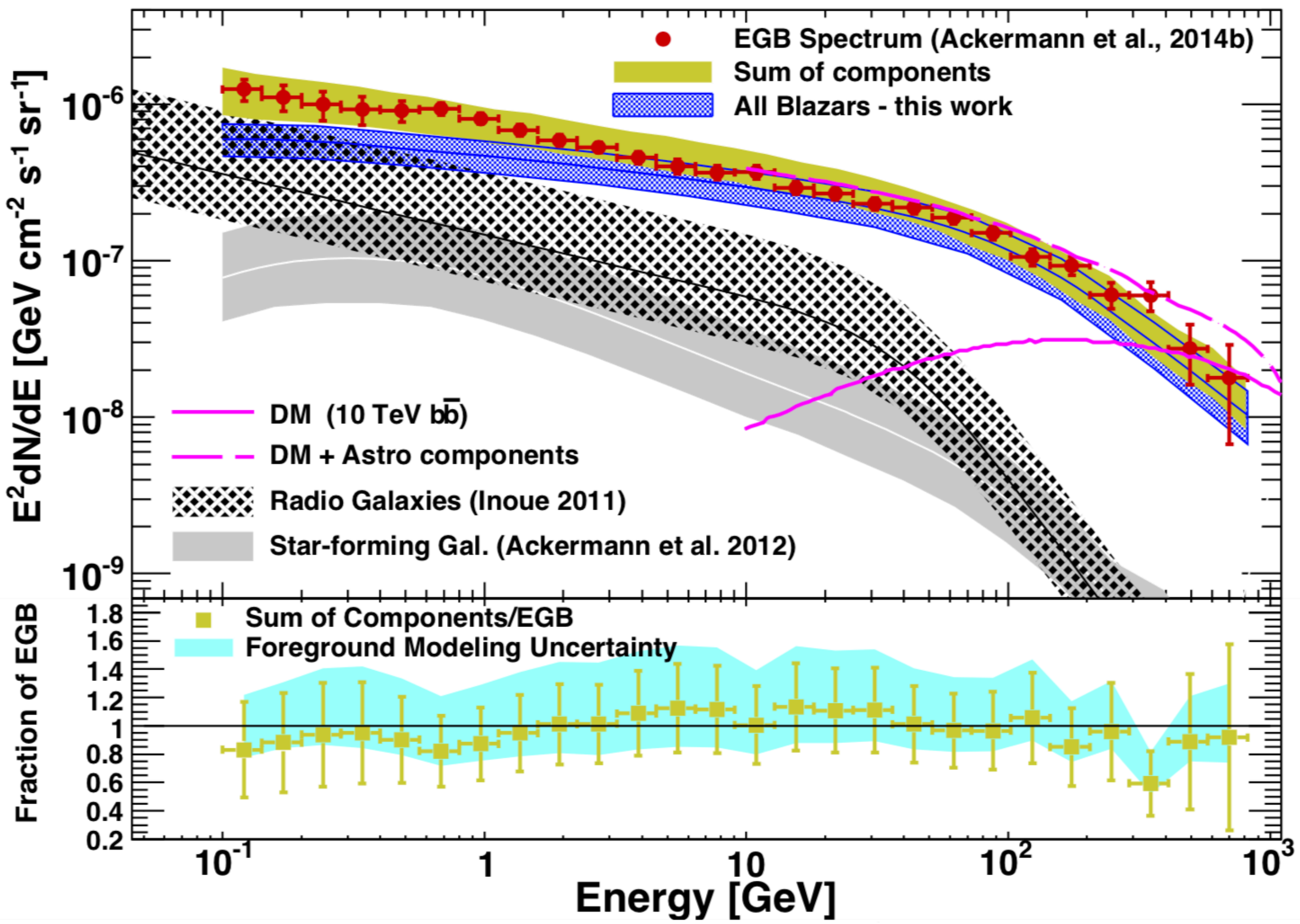


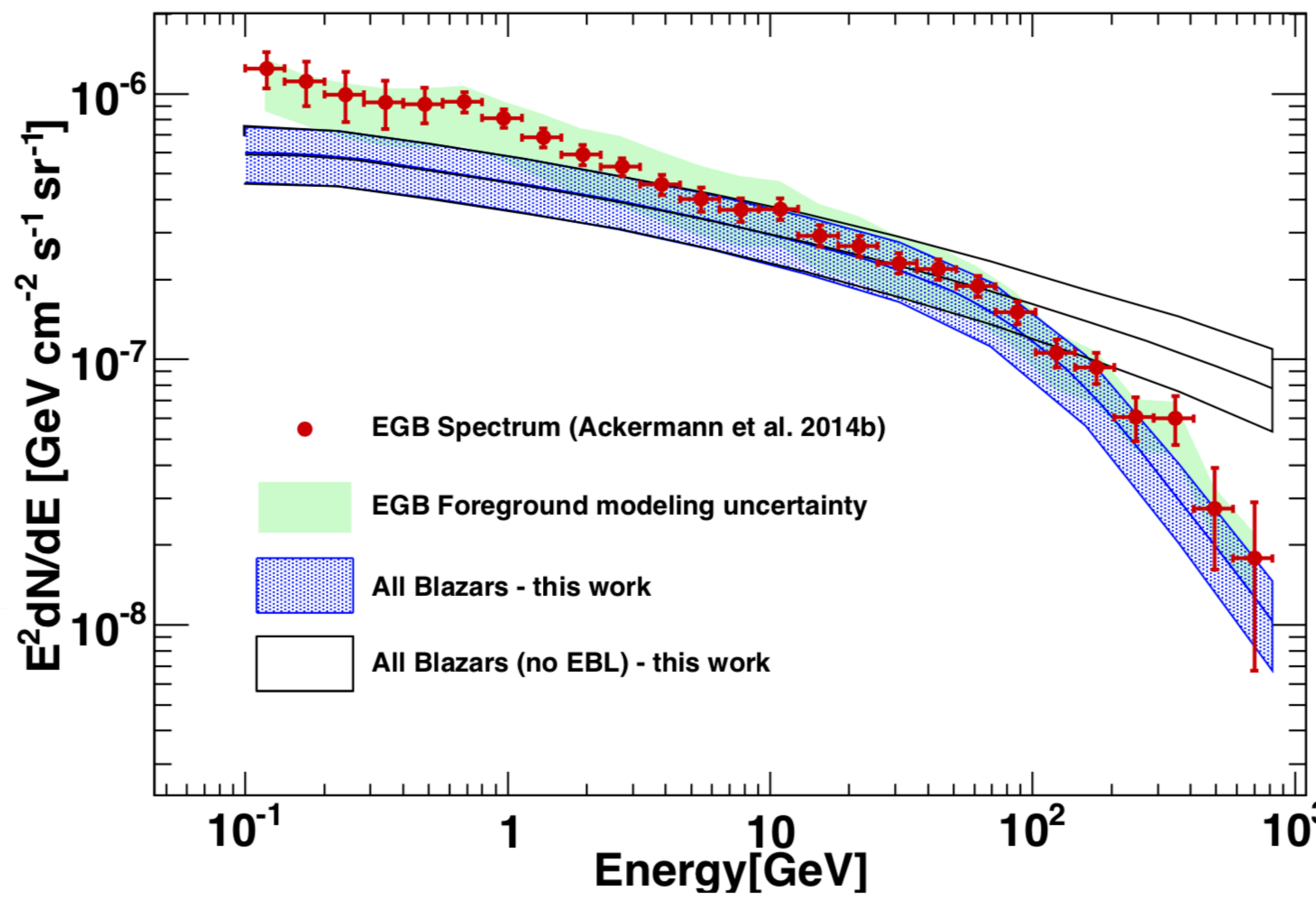
Analysis

Analyzing the EGB data: χ^2 analysis

$$\chi^2 = \min_{\mathcal{A}} \left[\sum_i \frac{(F_{i,\mathrm{EGB}} - \mathcal{A} F_{i,\mathrm{a}} - F_{i,\mathrm{Cas}})^2}{\sigma_i^2} + \frac{(\mathcal{A}-1)^2}{\sigma_{\mathcal{A}}^2} \right]$$

Ajello et al, 1501.05301





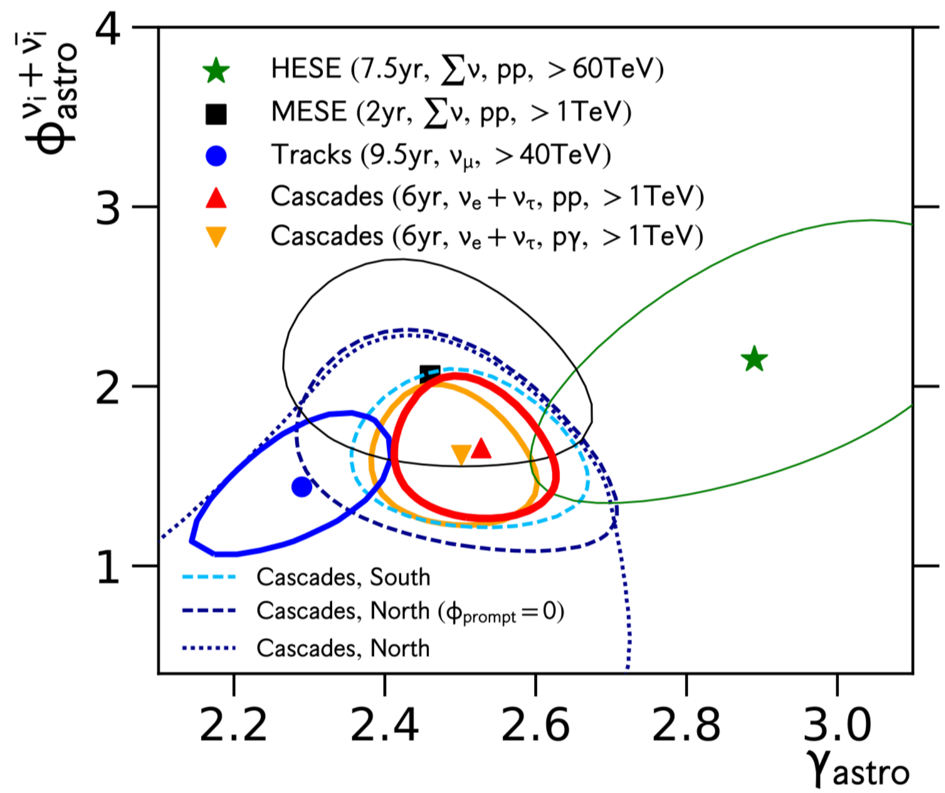
Results

Analyzing the EGB data: χ^2 analysis

$E_{\rm thr} = 60$ TeV — HESE

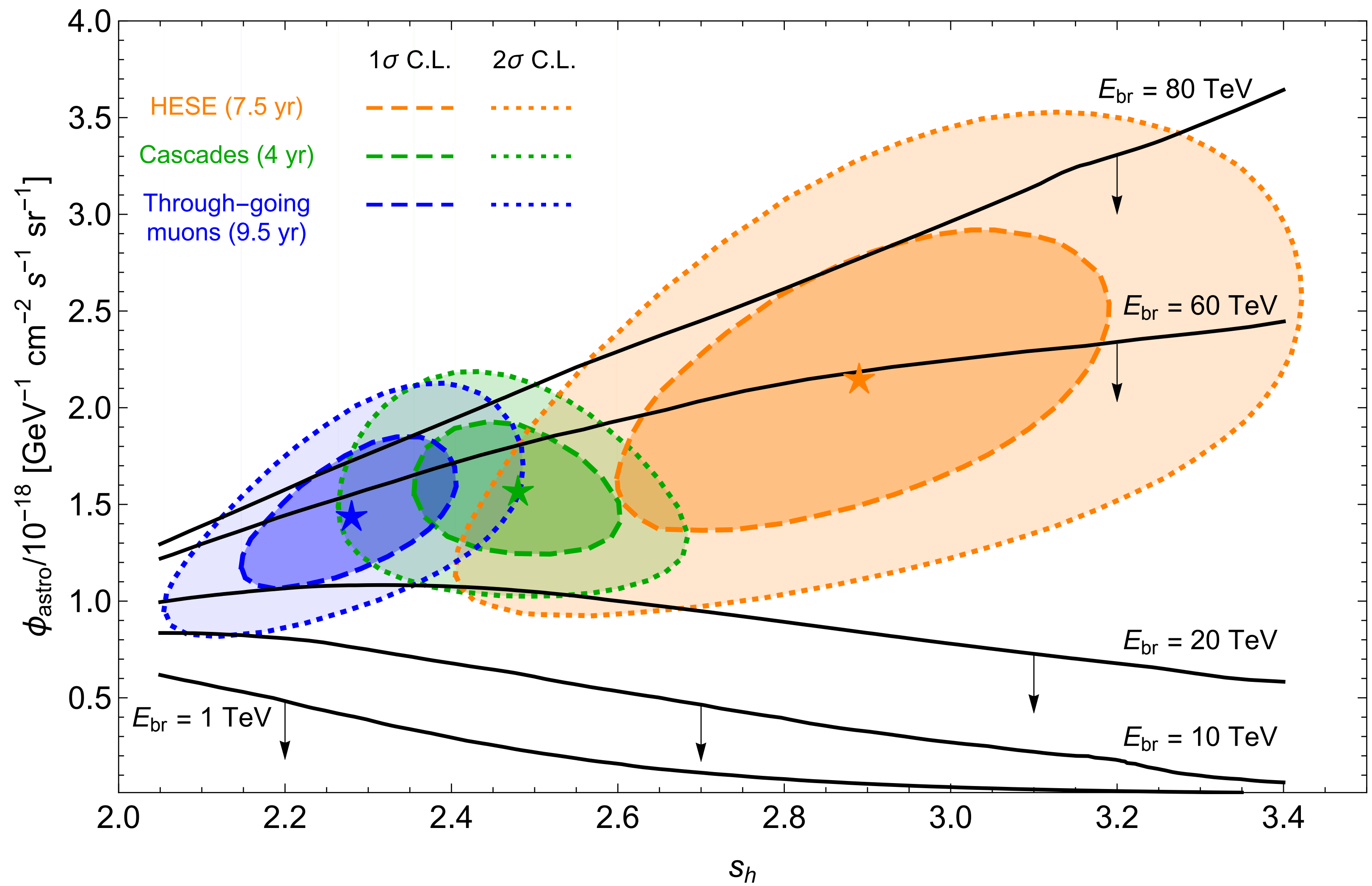
$E_{\rm thr} = 12$ TeV — Cascades

$E_{\rm thr} = 119$ TeV — Through-going muons



~ 3σ tension for E_{br} = 10 TeV

~ (4-5)σ tension for E_{br} = 1 TeV

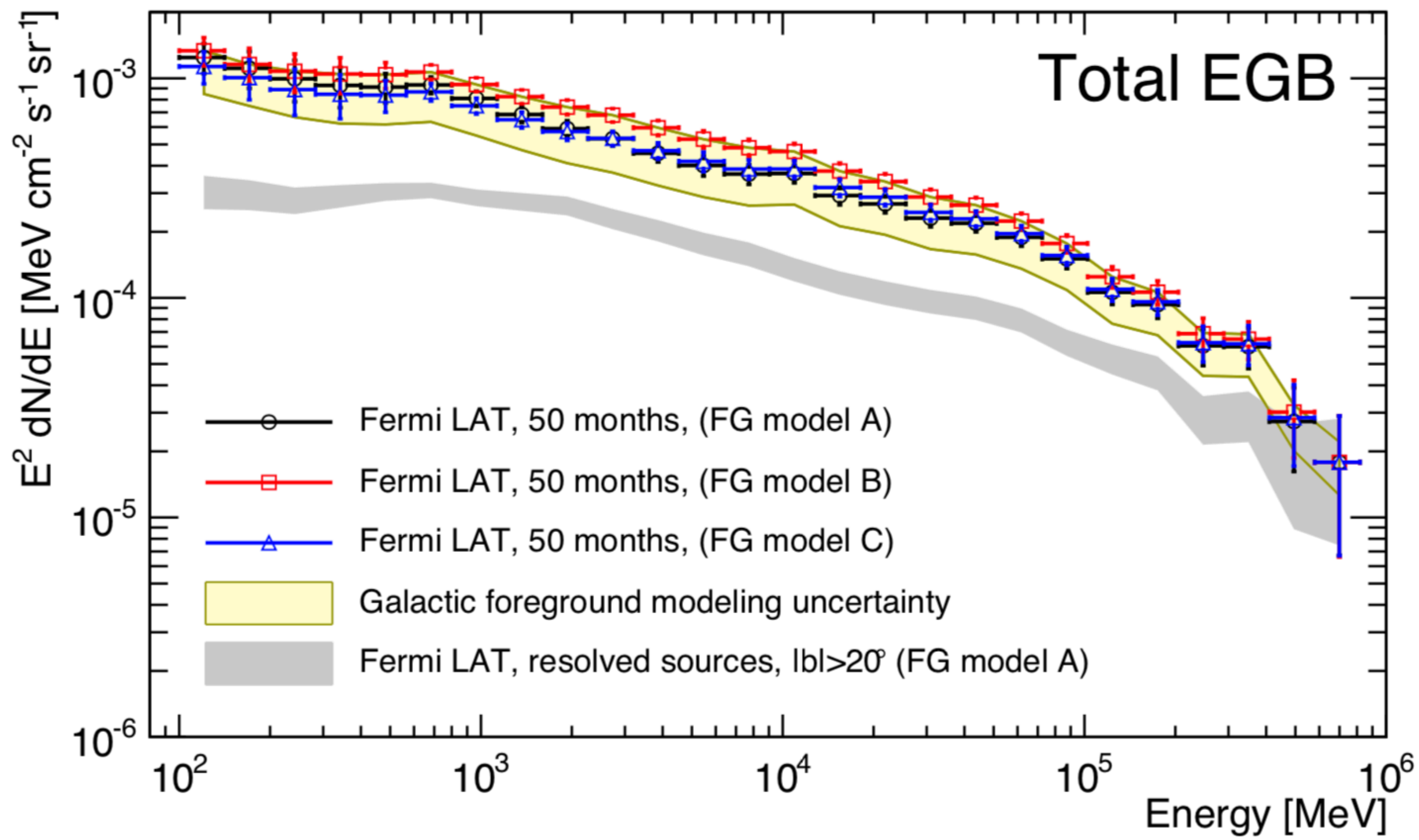


Results

✓ How robust are these results (tension)?

The EGB data depends on the foreground rejection (three models: A, B and C)

A bit of details on the analysis method and assumptions



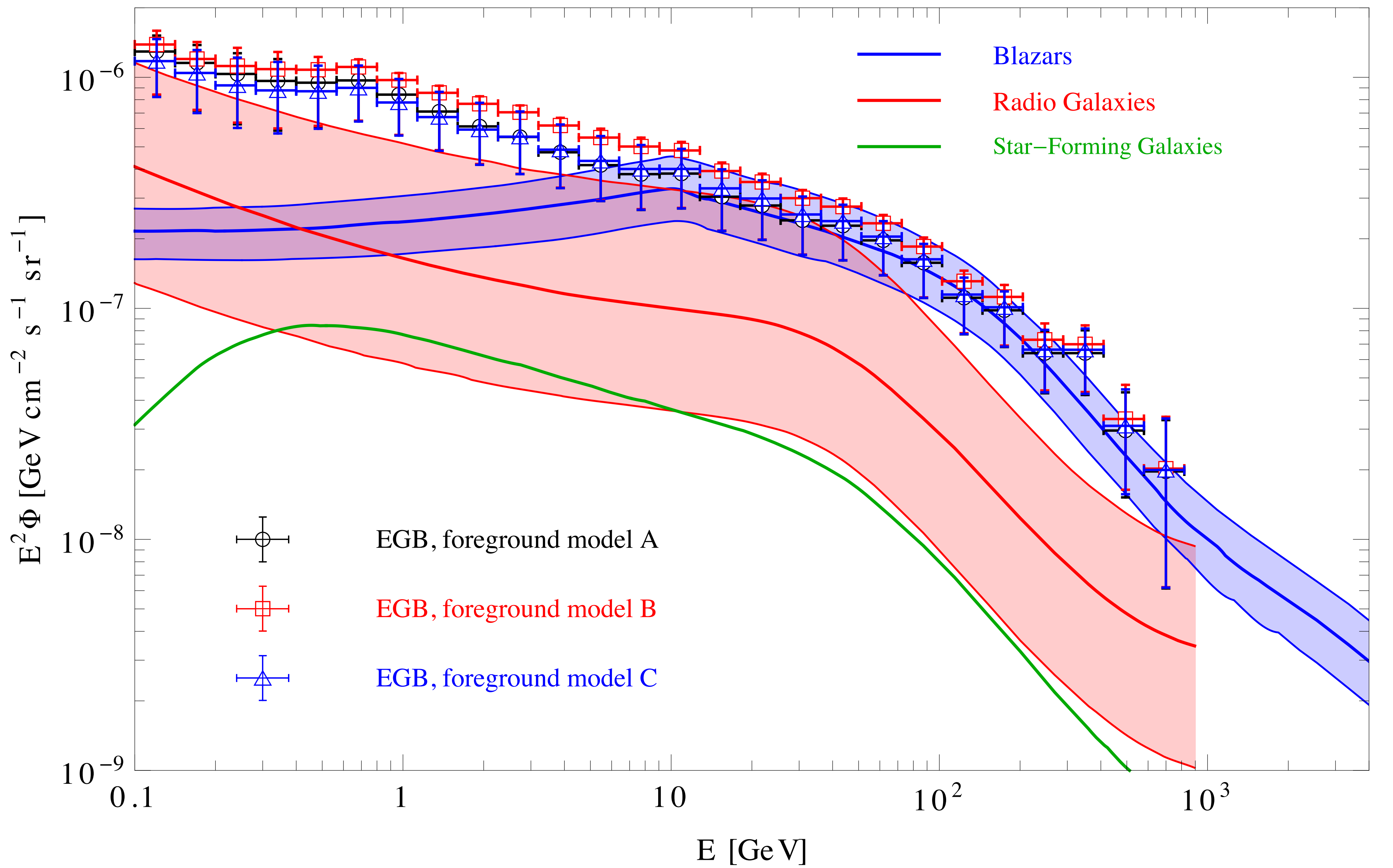
Foreground	Main features and differences with respect to other DGE models
Model A	Sources of CR nuclei and electrons trace pulsar distribution; constant CR diffusion coefficient and re-acceleration strength through Galaxy
Model B	Additional electron-only source population near Galactic center, these electrons are responsible for majority of IC emission; local source of soft CR electrons needed to explain CR electron spectrum at Earth below 20 GV
Model C	Sources of CR nuclei and electrons more centrally peaked than pulsar distribution; CR diffusion coefficient and re-acceleration strength vary with Galactocentric radius and height

Results

✓ How robust are these results (tension)?

A bit of details on the analysis method and assumptions

More conservative conventional contributions to the EGB



Results

✓ How robust are these results (tension)?

A bit of details on the analysis method and assumptions

More conservative analysis method
(independent nuisance parameter for each contribution)

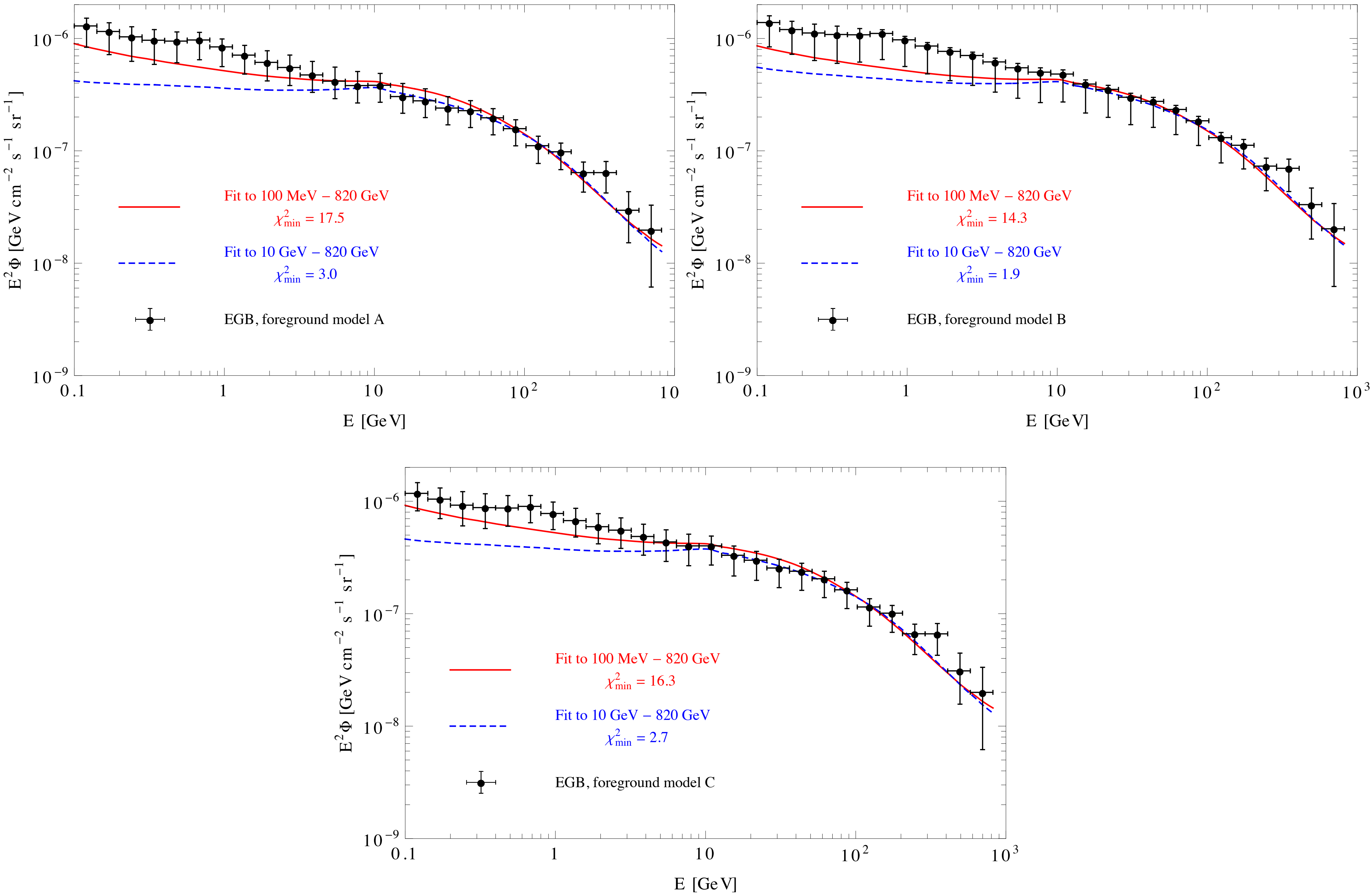
$$\chi^2 = \min_{\alpha_j} \left\{ \left[\sum_i \frac{\left(F_i^{\rm EGB} - \sum_j \alpha_j F_i^j\right)^2}{\sigma_i^2} \right] + \sum_j \left[\frac{(\alpha_j - 1)^2}{\varsigma_j^2} \right] \right\}$$

Results

✓ How robust are these results (tension)?

separate analysis for different energy ranges of EGB data

A bit of details on the analysis method and assumptions

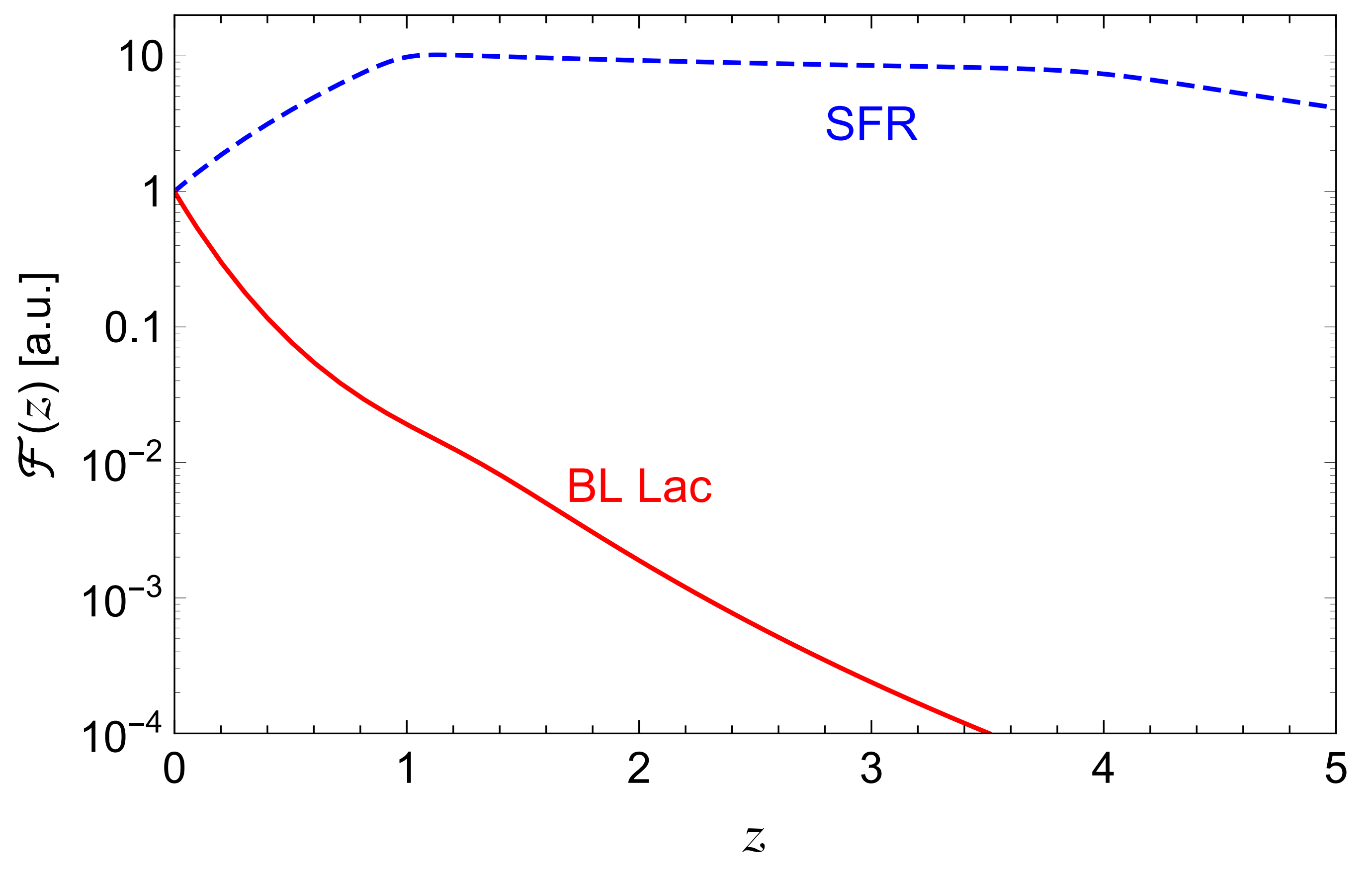


Results

✓ How robust are these results (tension)?

A bit of details on the analysis method and assumptions

Cosmic evolution different from SFR



Results

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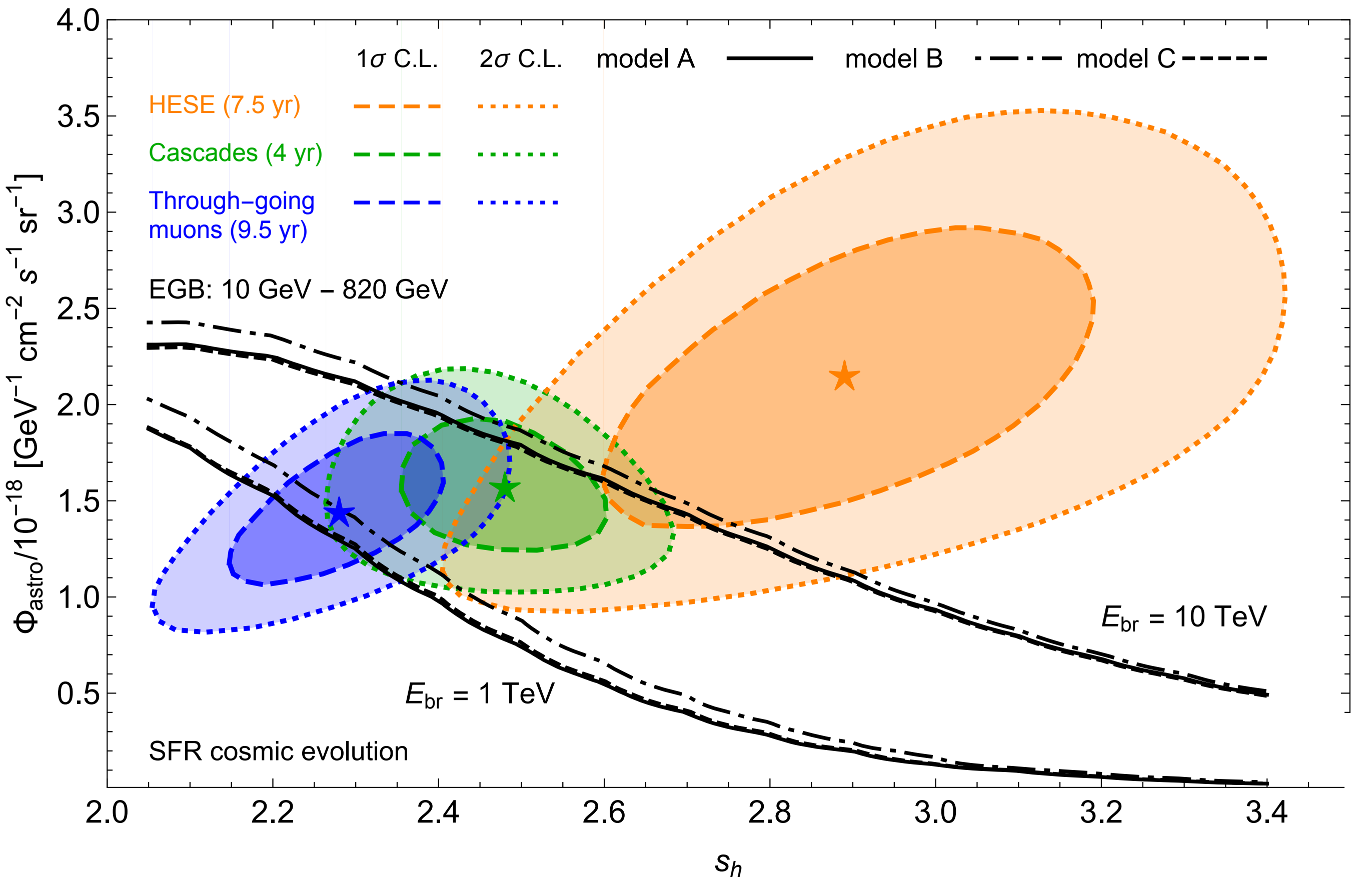
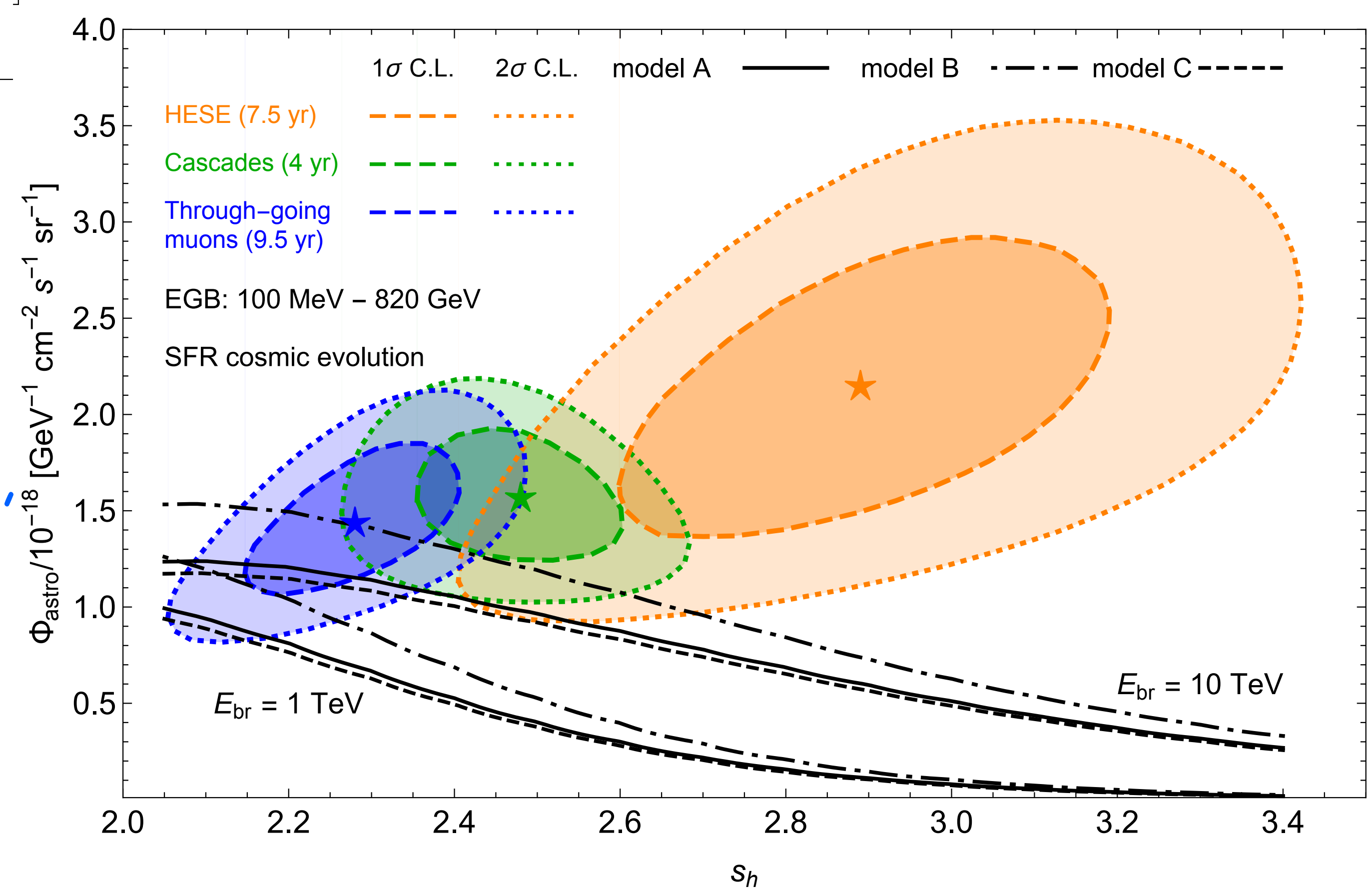


SFR cosmic evolution
two energy ranges of EGB data
three foreground modeling

✓ Tension exist for all the foreground modelings

✓ Considering just the high energy EGB data, for E_{br} = 10 TeV the tension disappears

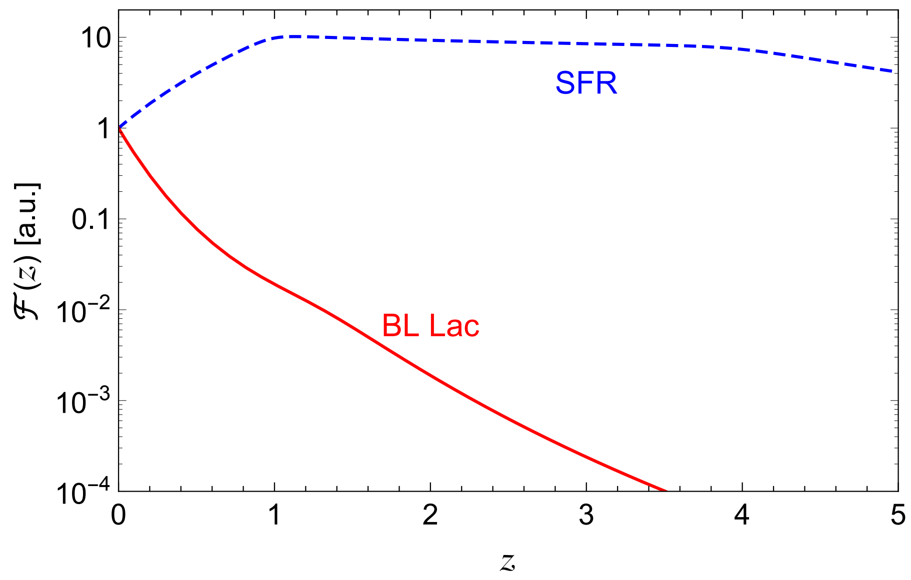
✓ However, in this case we lose the RG interpretation of low energy EGB data



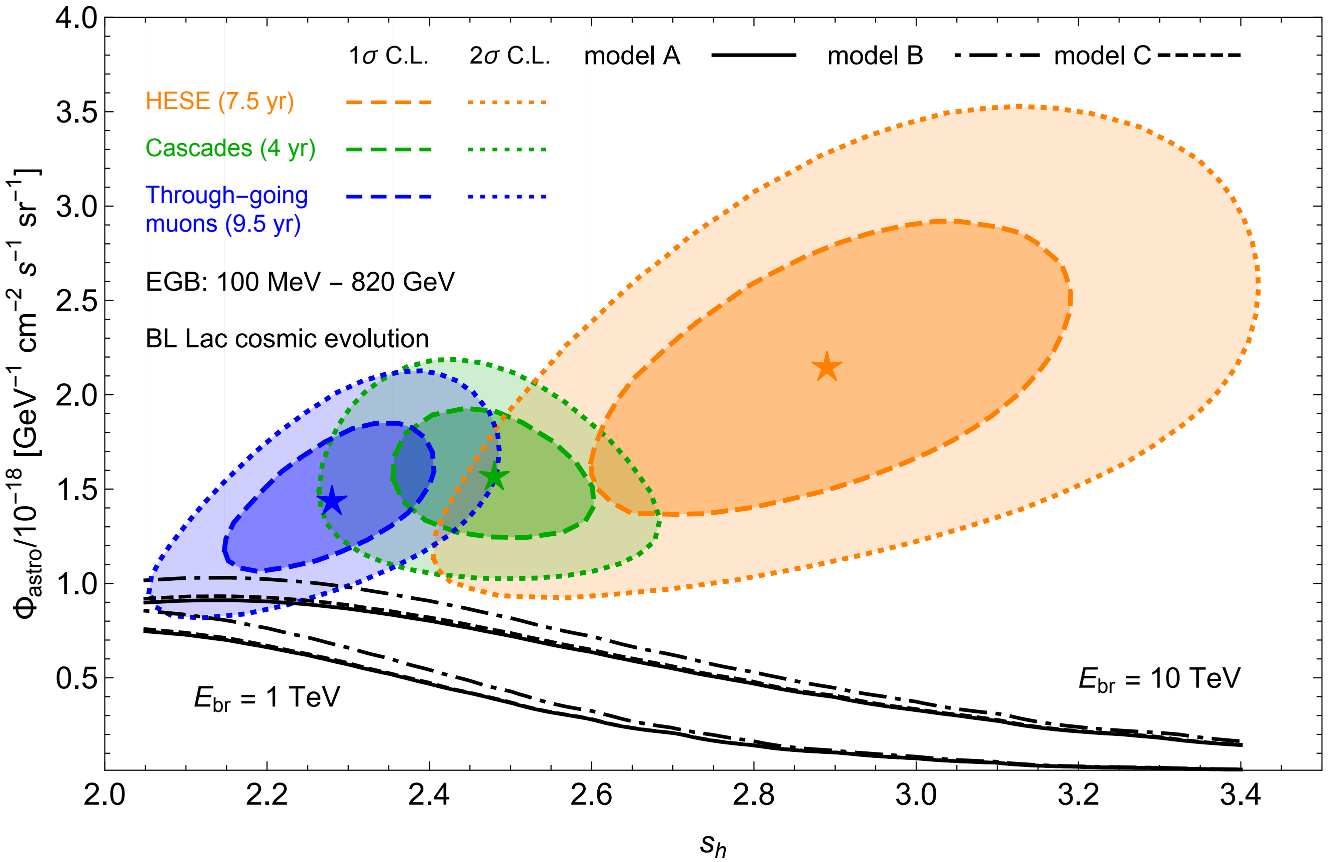
Results

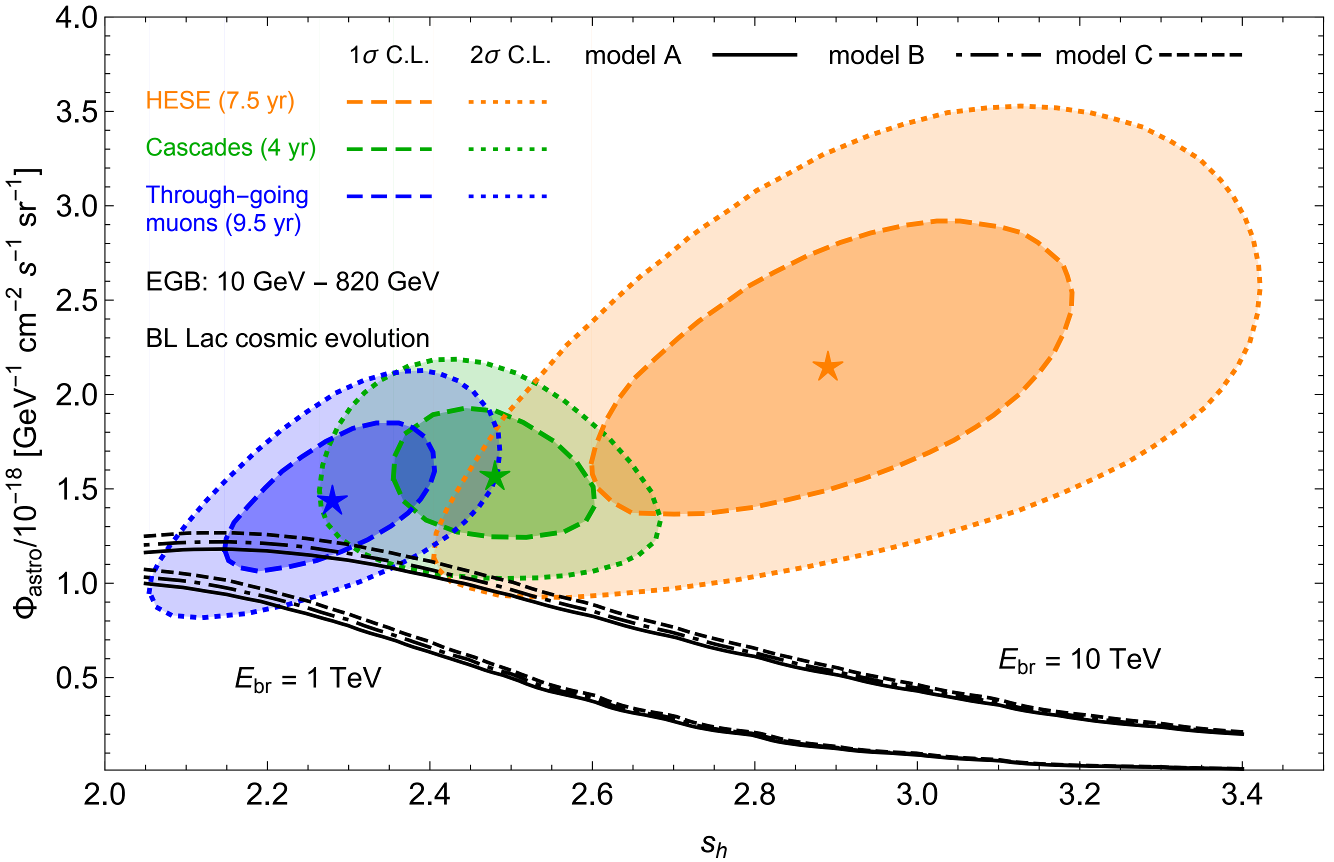
✓ How robust are these results (tension)?

BL Lac cosmic evolution
two energy ranges of EGB data
three foreground modeling



The tension is almost similar to SFR, although the cosmic evolution is very different





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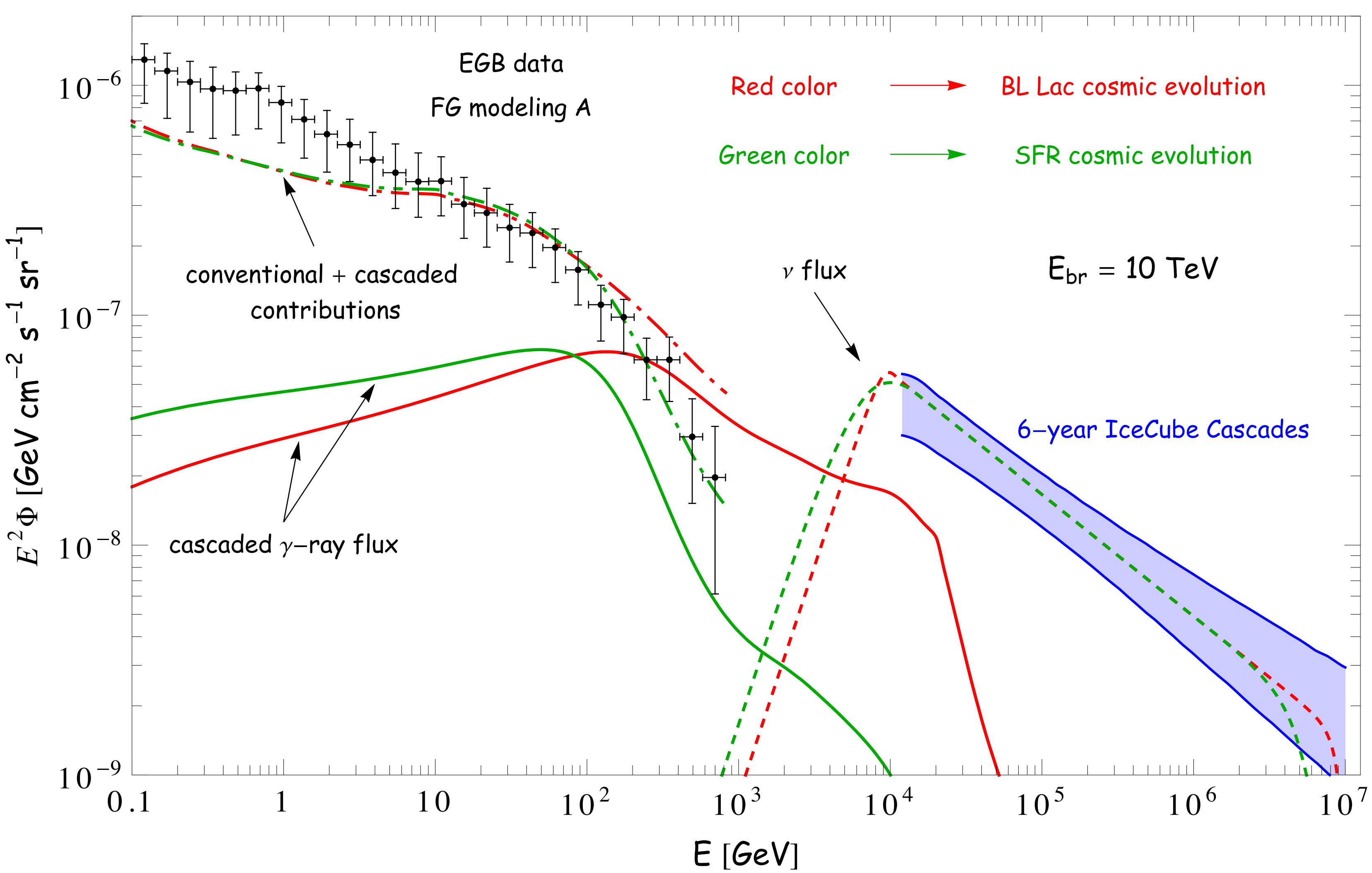

BL Lac cosmic evolution
two energy ranges of EGB data
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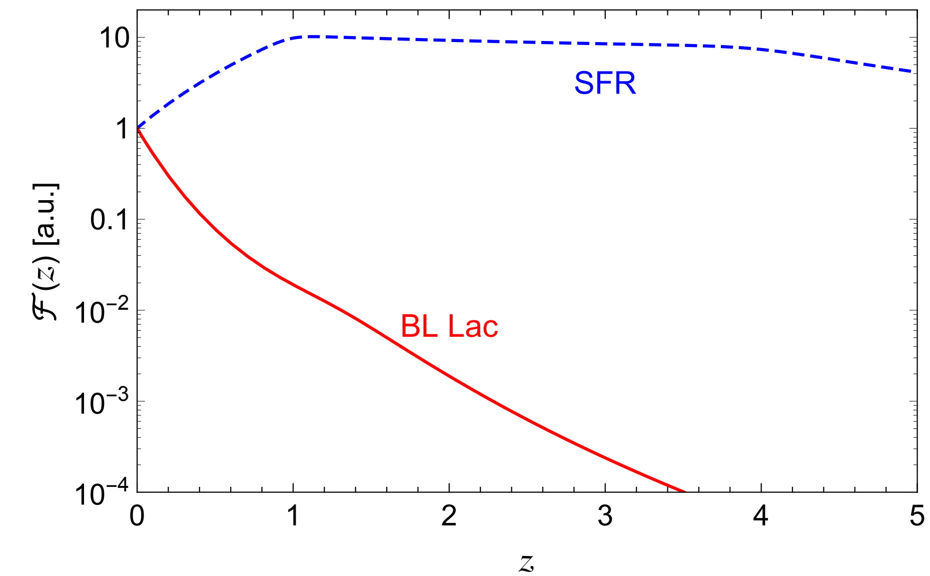


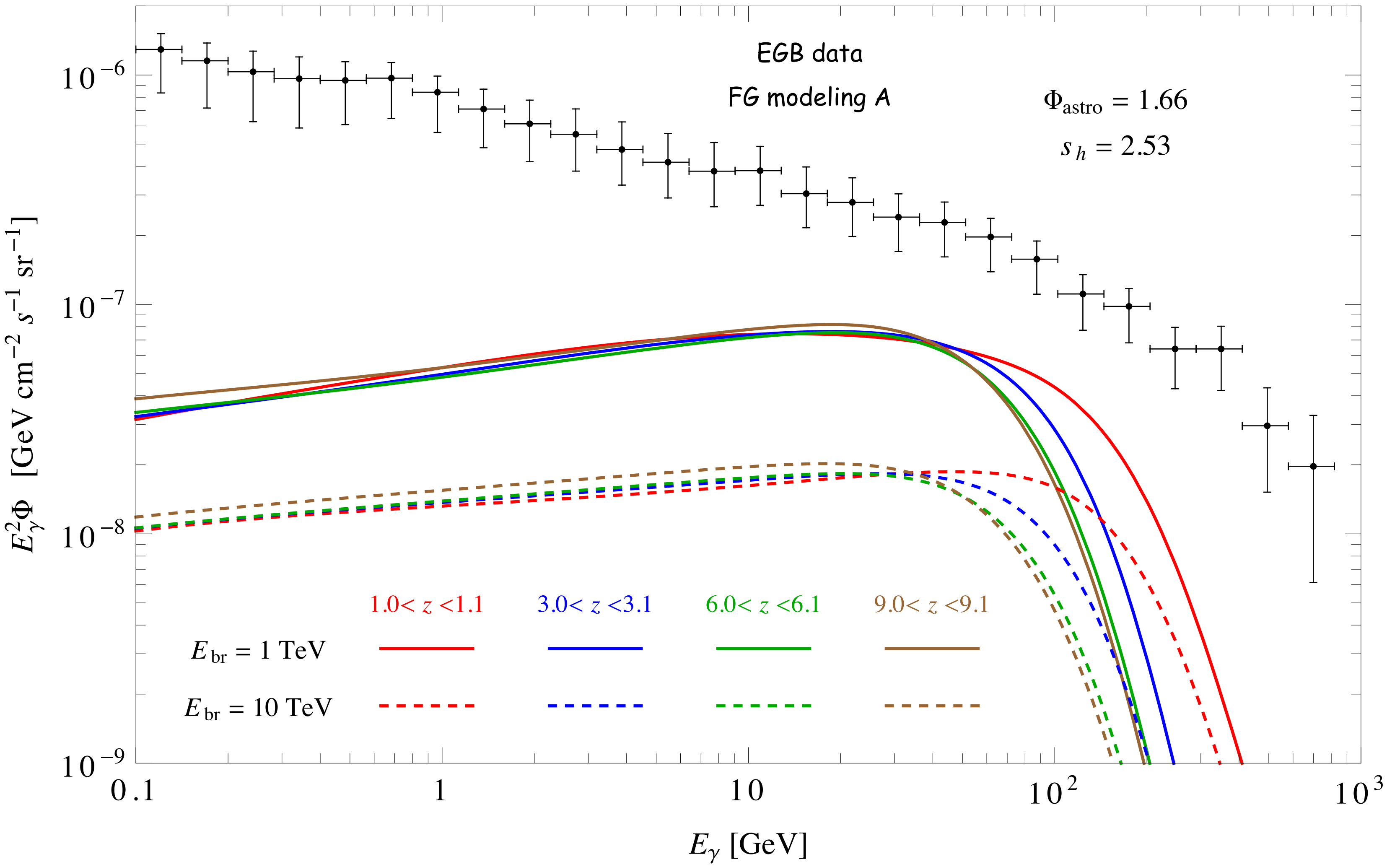
For BL Lac evolution, the tension originates from the highest energy EGB data, while for SFR ~ 100 GeV data are overshot.

Results

✓ How robust are these results (tension)?

A more general approach to cosmic evolution

- ✓ The EM cascade is fully developed for far sources, leading to the universal form
- ✓ High-z sources are completely invisible at > 10 GeV (high z CMB, EBL)
- ✓ E_{br} = 10 TeV compatible with EGB, for z > 3
- ✓ E_{br} = 1 TeV has strong tension, independent of energy range of EGB data



High-z sources can be excluded based on energy considerations.

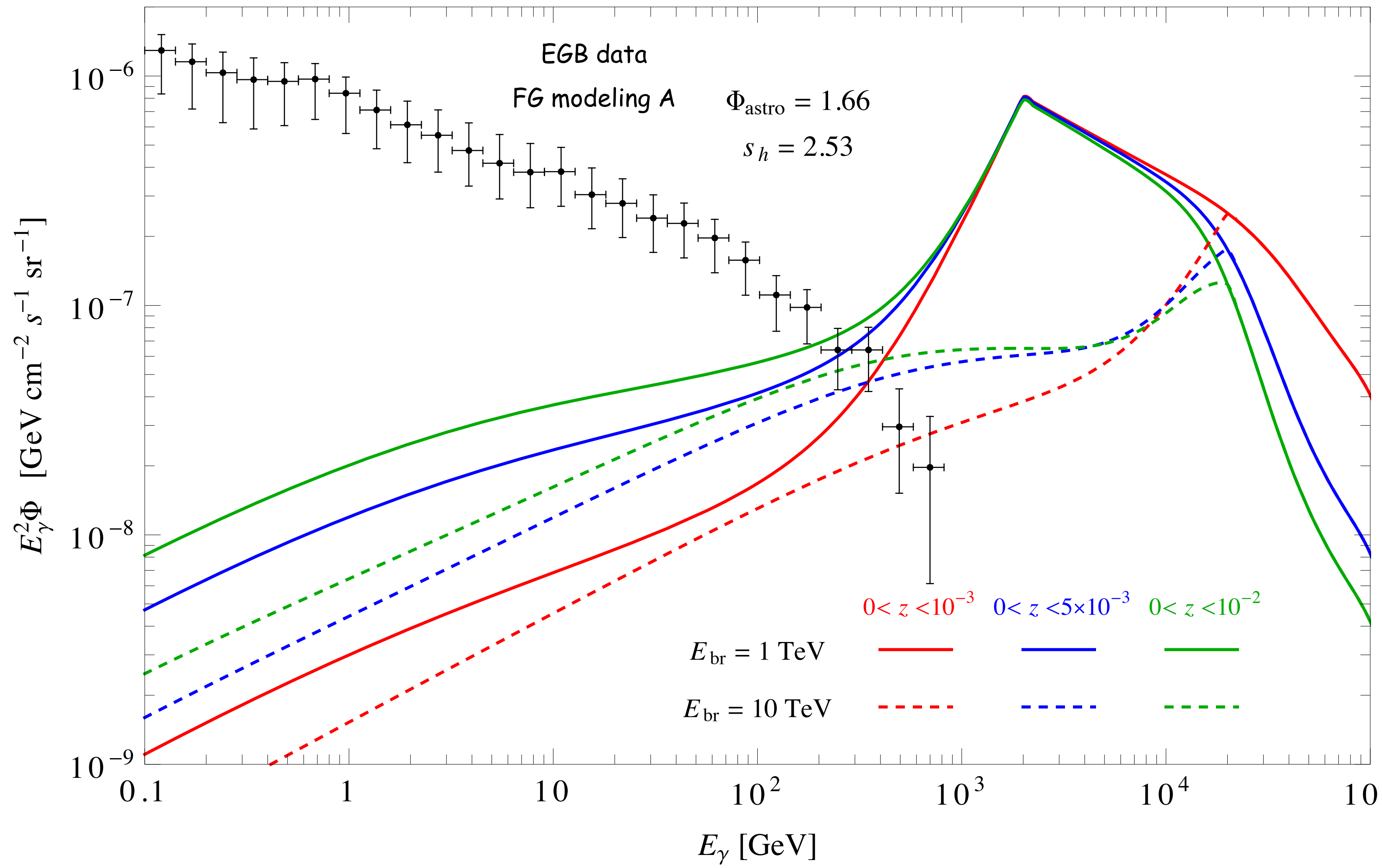
Even the most luminous object at high z, SMBH at the Eddington limit of luminosity, cannot provide the required total luminosity.

Results

✓ How robust are these results (tension)?

A more general approach to cosmic evolution

- ✓ The EM cascade cannot develop. Large high energy photon flux.
- ✓ E_{br} = 1 TeV has strong tension with EGB, independent of EGB energy range.
- ✓ E_{br} = 10 TeV and $z < 10^{-3}$ is compatible with EGB.
- ✓ E_{br} = 10 TeV case enjoys the lack of EGB data > 820 GeV.



The requirement of $z < 10^{-3}$ is quite challenging. The required density of local sources saturates the overall density of galaxies.

By further shrinking of z we arrive to the Galactic halo population; incompatible with HAWC and KASCADE data.

Summary

✓ The multimessenger approach (nu-gamma) provides invaluable information on the source(s) of IceCube neutrinos. There is a tension between EGB and IceCube data (low energy).

The resulted $\Delta\chi^2$ from the fit of EGB data after including the cascaded flux

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

✓ The result is robust. We were very conservative about the assumptions: conservative conventional contributions to EGB, minimalistic nu-gamma relation, neglecting gamma-rays from leptonic processes, UHECR propagation, etc.

Cascade development in very high energy

The cascade development we considered:

EPP $\gamma\gamma_{\rm b} \to e^+e^-$ and **ICS** $e\gamma_{\rm b} \to e\gamma$

Cascade development in very high energy

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

MPP $\gamma\gamma_{\rm b} \to \mu^+\mu^-$

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

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

And also the double pair production

DPP $\gamma\gamma_{\rm b} \to e^+e^-e^+e^-$, for $s \geq 16m_e^2$

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

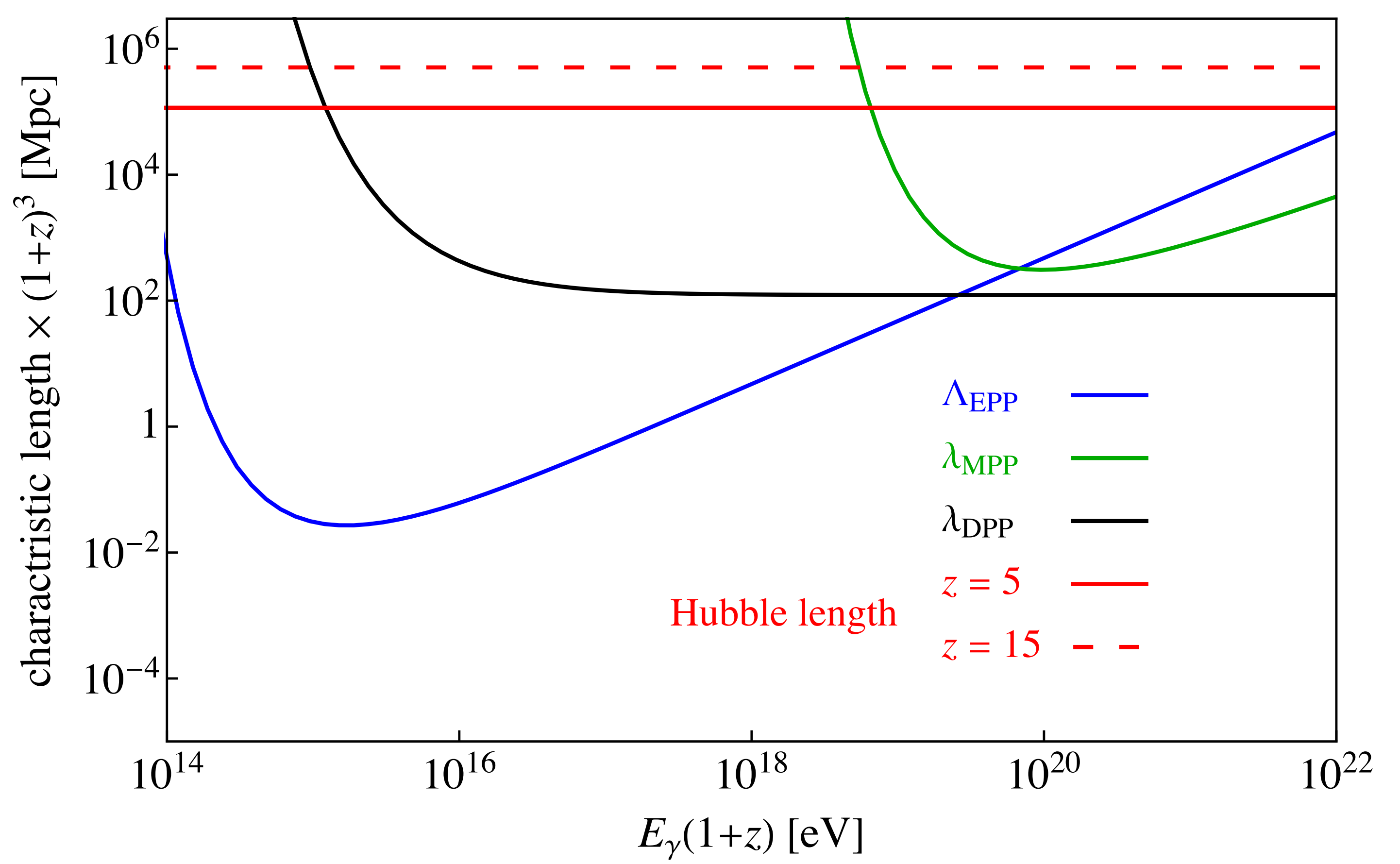
Cascade development in very high energy

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

the interaction length $\Lambda_{\rm MPP}$ is smaller than the energy loss length $\lambda_{\rm EPP}$ at high-redshifts

Interaction length

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



Energy loss length

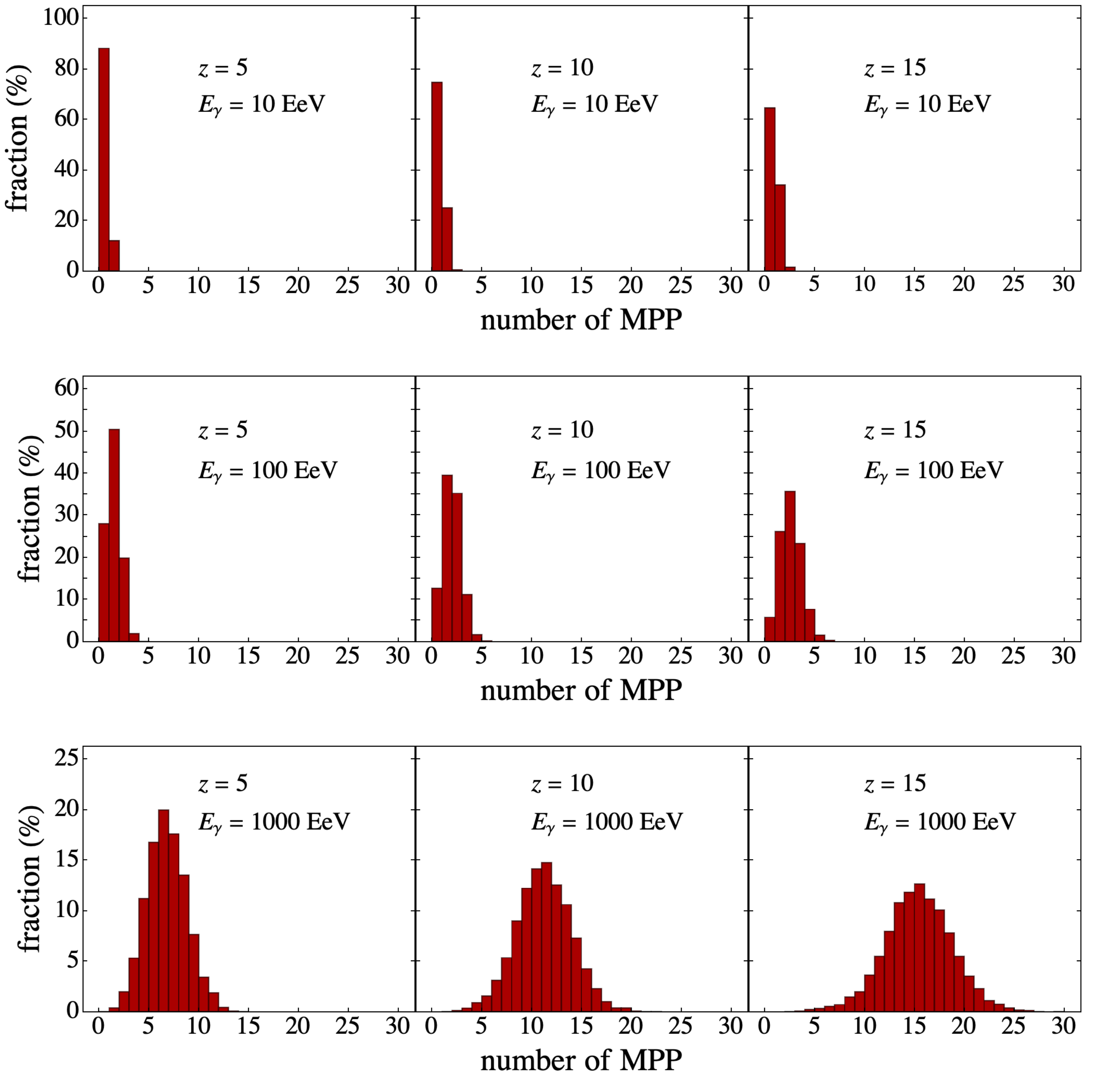
$$\Lambda_p(E) = \frac{1}{\int {\rm d}\epsilon \int {\rm d}\mu \, \frac{1-\mu}{2} \, n_{\rm CMB}(\epsilon) \, \sigma_p(s) \, [1-\eta_p(s)]}$$

Inelasticity

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

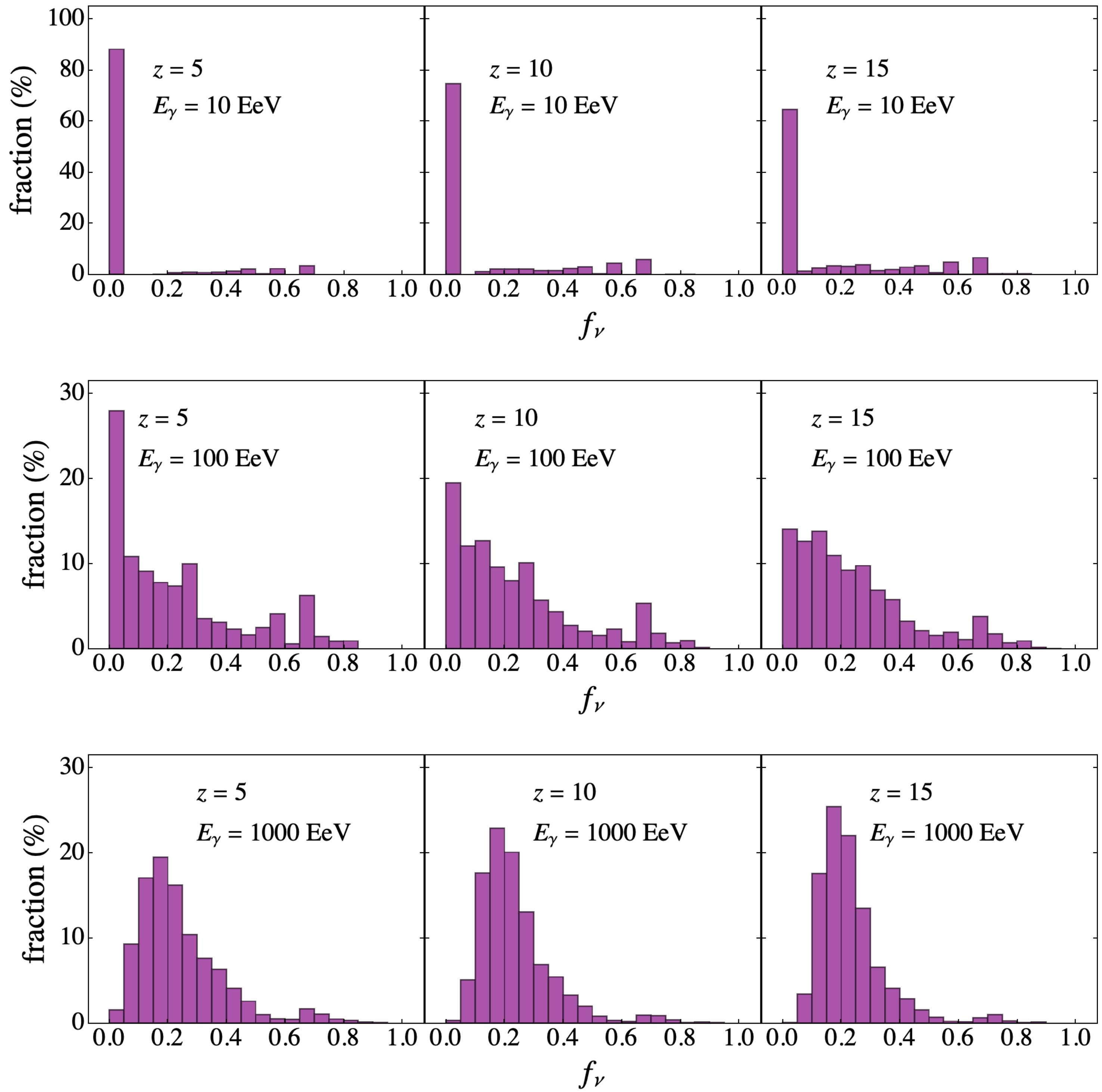
Cascade development in very high energy

✔ The distribution of the number of MPP occurrence



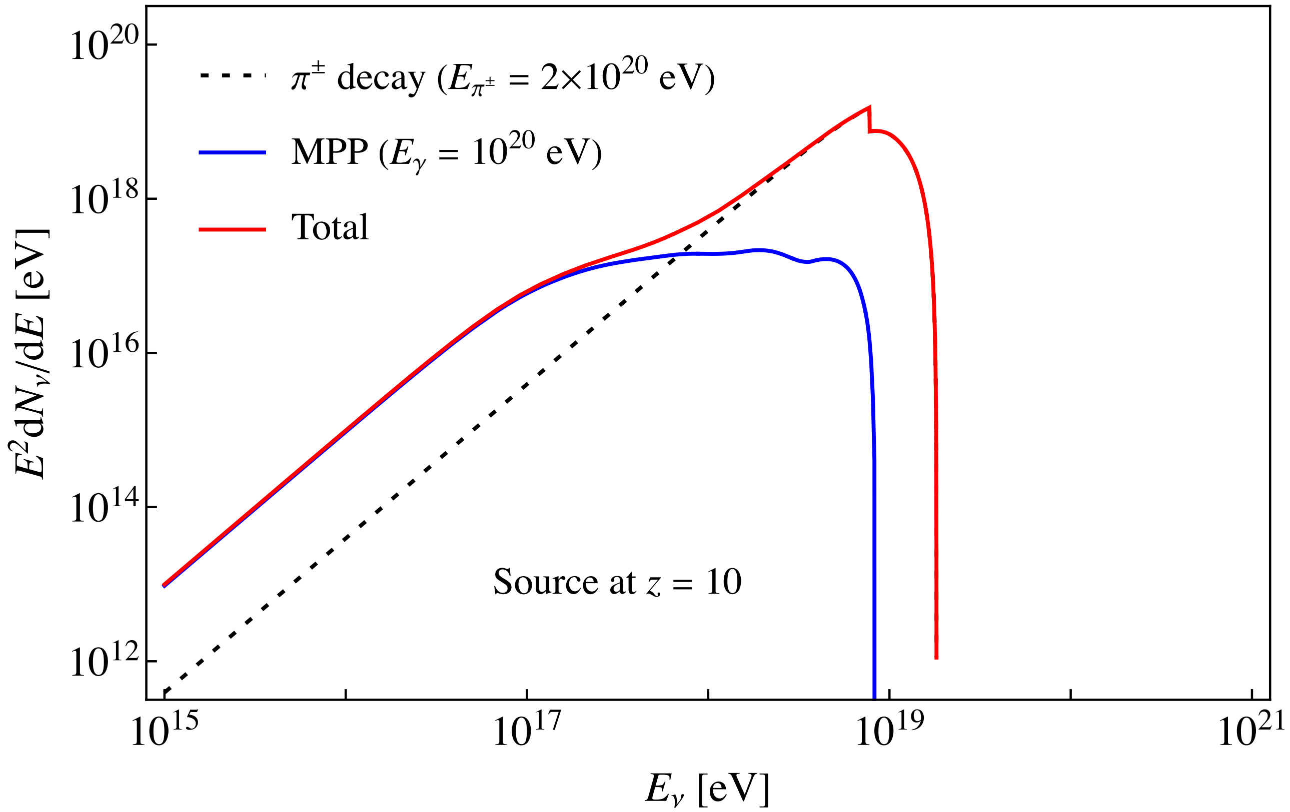
Cascade development in very high energy

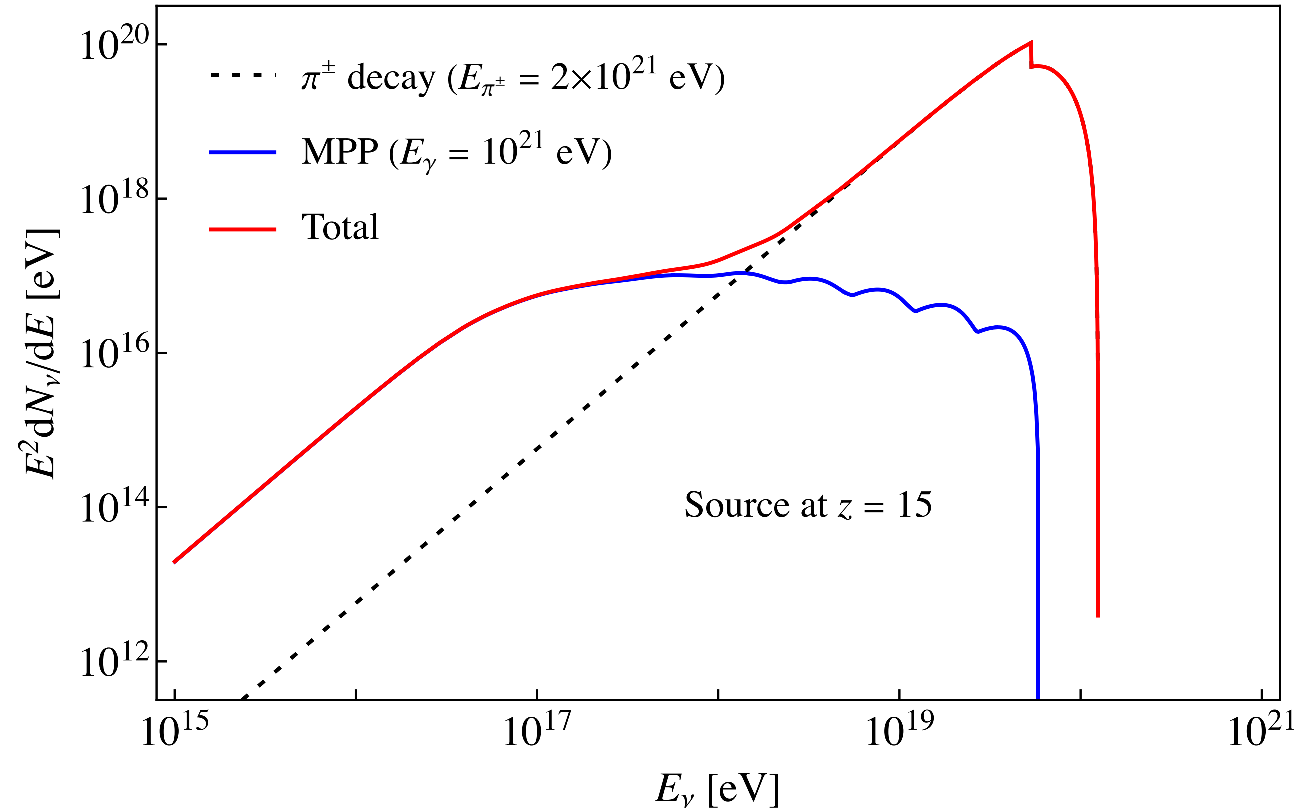
✓ The fraction of photon/electron energy channeling into neutrinos



Cascade development in very high energy

- Neutrino spectrum at the Earth from a source at redshift z injecting photons at energy E_γ





- A unique way to probe high-redshift and high-energy Universe

- The neutrino spectrum is within the range of sensitivity of experiments like GRAND.

Summary

— A lot can be learned from the Electromagnetic Cascades!

— There is a tension between IceCube's neutrino and Fermi-LAT's EGB. The tension points toward "opaque sources".

— Opaque source means a "new class" of objects, yet unknown to us! From model building point of view it is challenging: requires high densities to make the source opaque to gamma-rays, while the protons still can be accelerated to ~ 100 PeV. Directional correlations with X-ray and MeV gamma-ray maps are unavoidable.

— Extension of EGB data to multi-TeV range can further constrain the sources (or pinpoint them). Larger statistics by IceCube-Gen2 can reduce the error on flux normalization and energy index, quantifying better the tension.

— The microphysics of cascade development at high energies is rich. Purely leptonic processes can produce neutrinos!

— Electromagnetic cascades can provide a way to probe high-redshift and high-energy Universe, the dark ages!

Thank you !