Cosmic Rays and Neutrinos in the Multi-Messenger Era

RESERVOIR SOURCES
Implications for High-Energy Neutrinos

ArXiv:2011.02483, AA, Marco Chianese, Damiano Fiorillo, AM, Gennaro Miele, Ofelia Pisanti

Antonio Ambrosone in collaboration with **Antonio Marinelli**

Structure of the Presentation

The presentation is divided in three parts:

First

Overview of the main astrophysical components responsible for EGB and VHE neutrino emission

Second

Starburst Galaxies contribution to diffuse neutrino flux (ArXiv:2011.02483)

Third

observational expectations for Starburst Galaxies with neutrino telescopes

Astrophysical Mystery

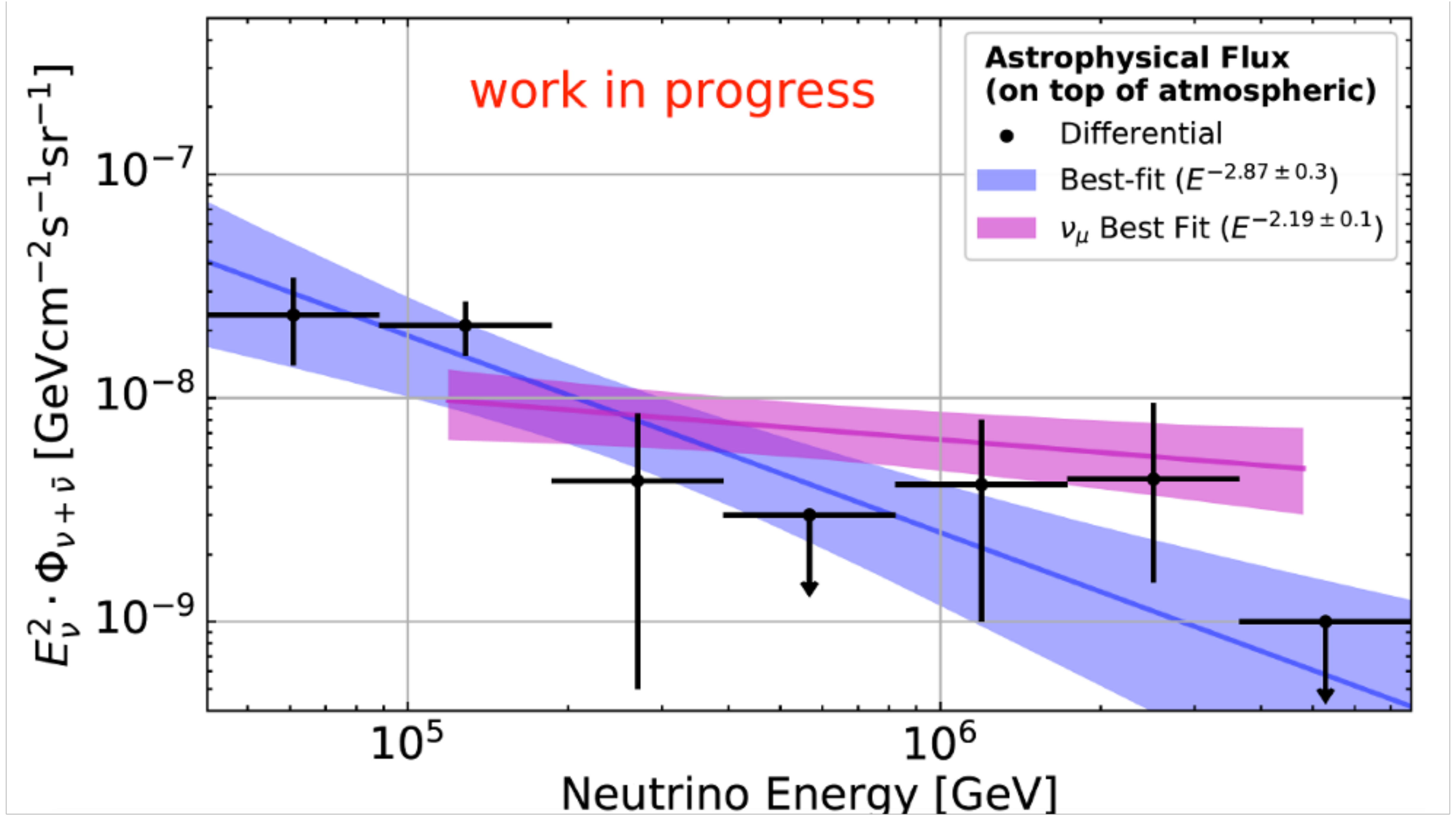
Which Sources are responsible for IceCube observations?

The diffuse Galactic component is completely subdominant
At most ~8% of the flux. **(Arxiv:1707.03416)** ***Apj*, 815:L25 (*2015*)**

Its Origin is still unknown

Reservoirs:
Starforming and Starburst Galaxies

Accelerators:
Blazars, Radio Galaxies



Taboada I., 2018, A View of the Universe with the IceCube and ANTARES Neutrino Telescopes, doi:10.5281/zenodo.1286919

The SED of new HESE data remains almost unaltered

arXiv:2011.03545

Neutrino production mechanisms

Hadronic interactions

dust, gas, …

$$p + p \to \pi^+ \, \pi^- \, \pi^0 \ldots$$

Prevalent on *reservoirs*, where CRs are confined in magnetized environments for a long time

Photo-hadronic interactions

CMB, EBL, …

$$p + \gamma \to \Delta \to \begin{cases} \pi^+ & 1/3 \text{ of cases} \\ \pi^0 & 2/3 \text{ of cases} \end{cases}$$

Prevalent on *accelerators*, for which CRs escape the source environment rapidly

- Neutrinos and gamma-rays from pions decays:

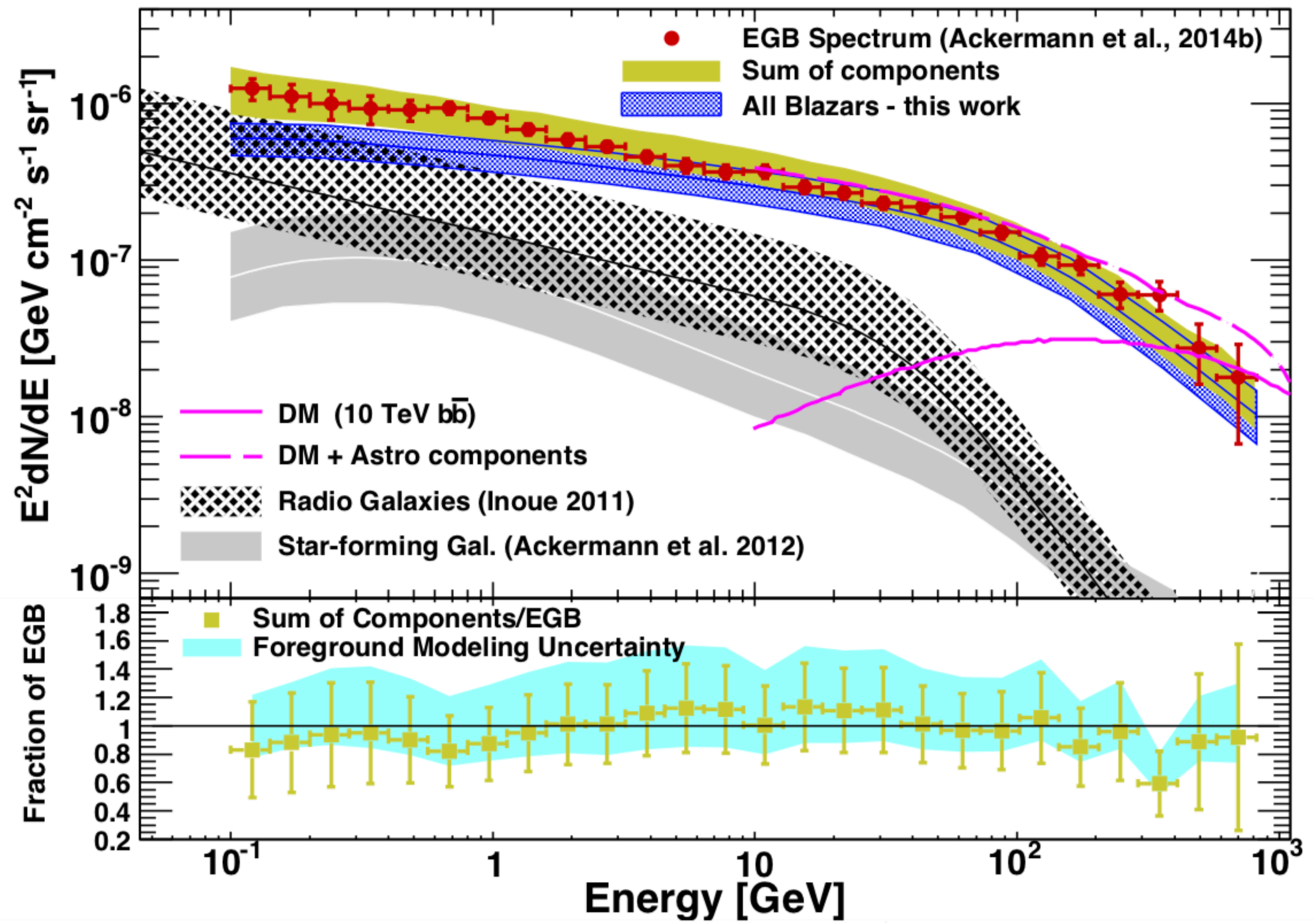
$$\pi^\pm \to e^\pm \, \nu_e \, \nu_\mu \, \overline{\nu}_\mu$$
$$\pi^0 \to \gamma \, \gamma$$

- Power-law behaviors due to CRs seed:

$$\phi_\nu(E_\nu) \sim E_\nu^{-\alpha}$$

Extragalactic gamma-ray background

*Ajello et al., **ApJL 800** (2015)*

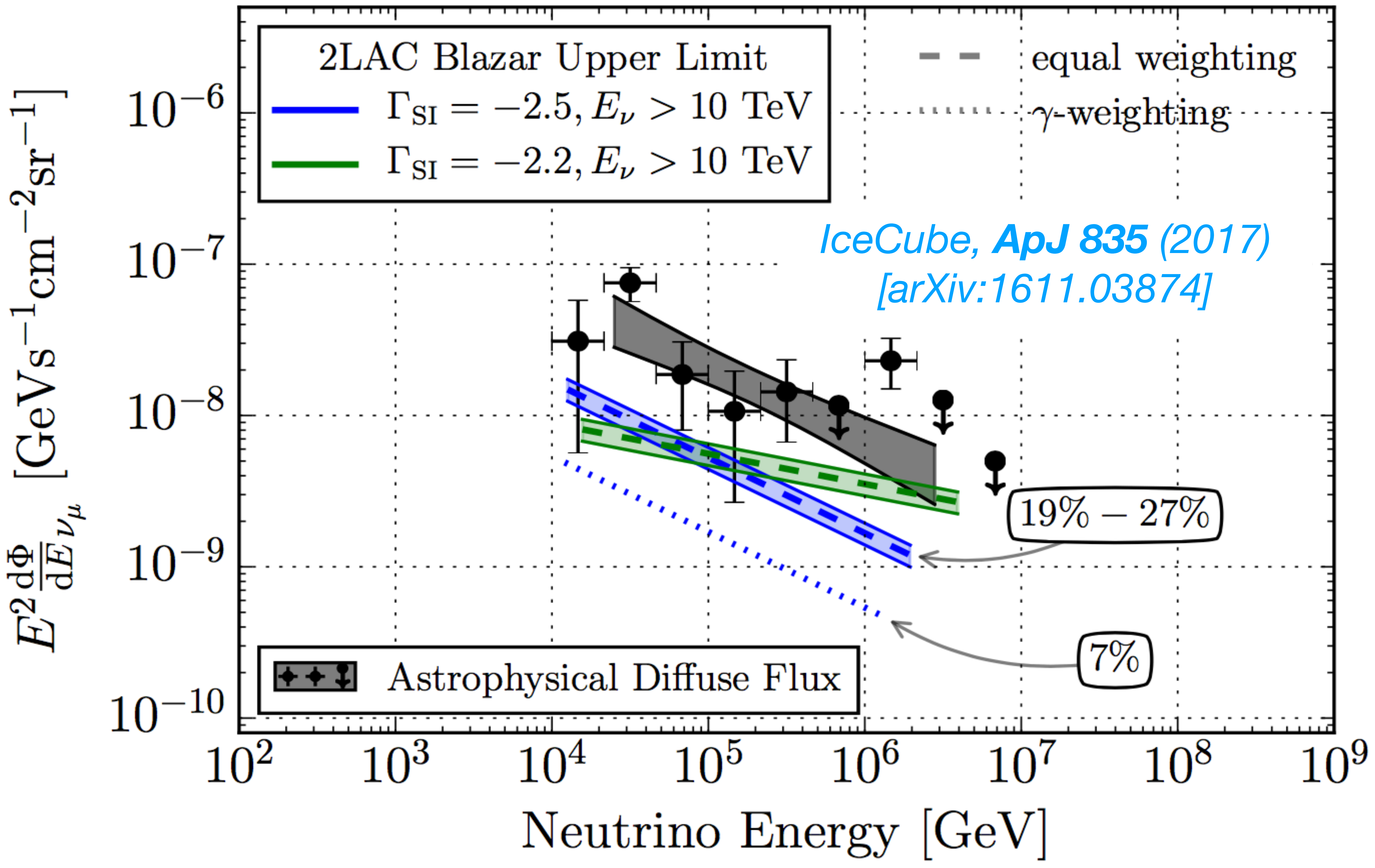


- Fermi-LAT is observing many individual sources belonging to different classes (gamma-ray bursts, active galactic nuclei, star-forming galaxies, …)
- However, **about 80%** of the EGB (diffuse + point sources) above 50 GeV is powered by **blazars.**

after the case of TXS 0506+056, we can expect Blazars to be also important high-energy neutrino factories

May blazars explain IceCube Observations?

Apart a few cases, there are still no significant excess in the point-like analysis when considering resolved blazars.

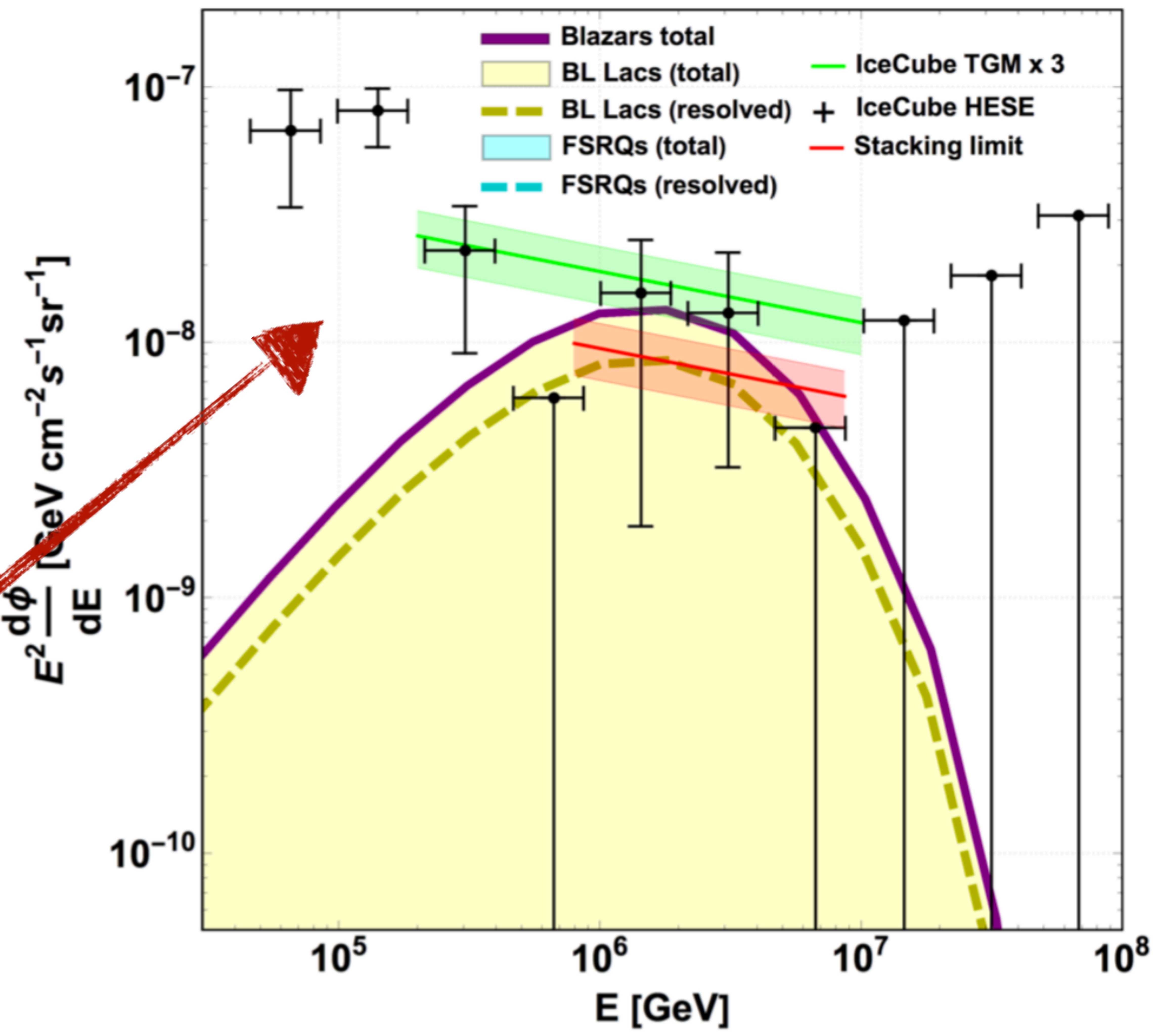


IceCube stacking limit: blazars can contribute at most 19% - 27% of the diffuse neutrino flux ($E_\nu > 10\,TeV$)!

Multi-component neutrino flux

- A possible description of **photo-hadronic** neutrino production of blazars calibrated with TXS 0506+056 observations.

Palladino et al., ***ApJ 871*** *(2019) [arXiv:1806.04769]*



Additional component required to explain events at lower energies!

Hadronic production in the SBGs

https://hubblesite.org/image/3898/printshop

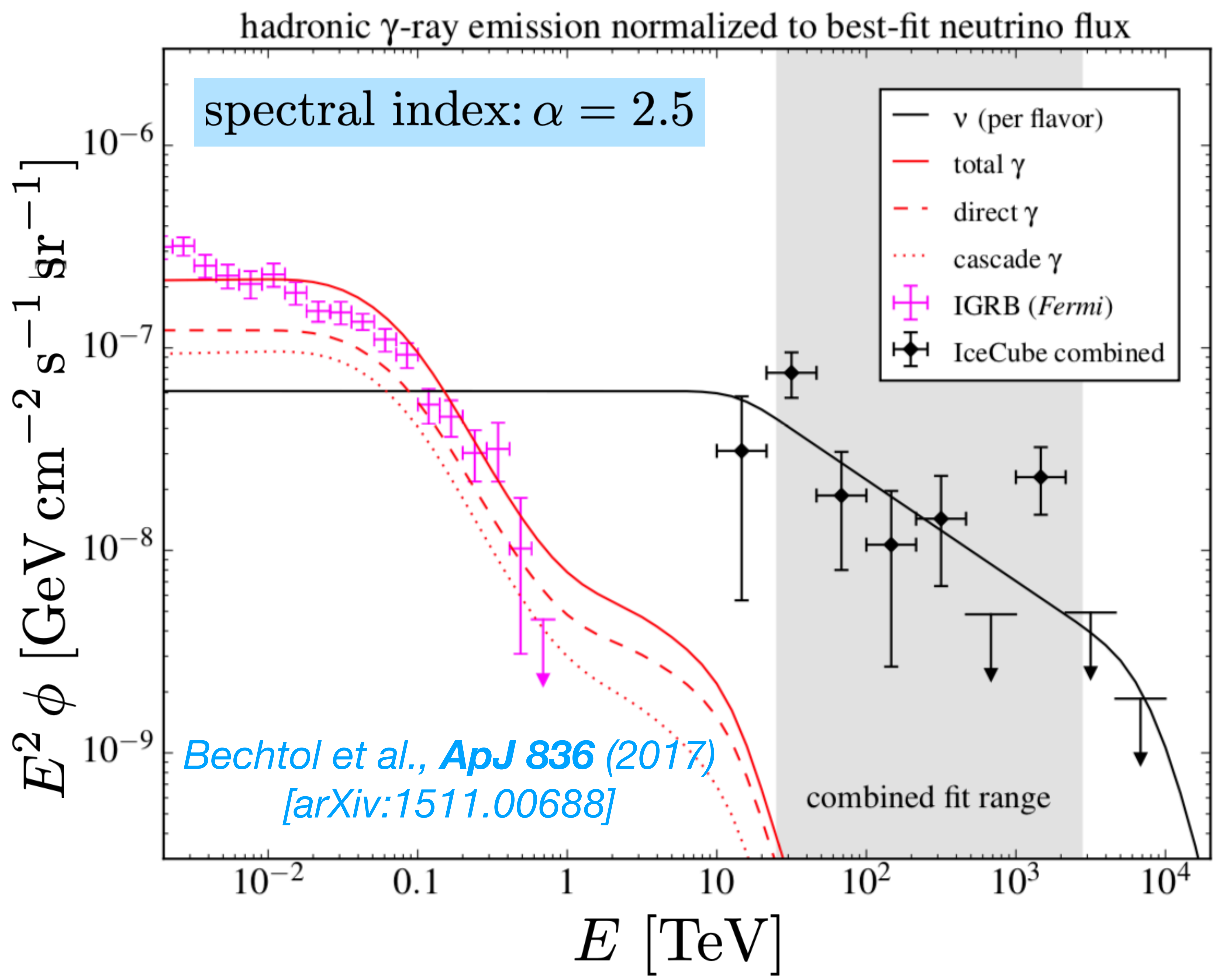
The Starburst Galaxy M82

p-p interaction is likely to occur when *density of gas higher than density of radiation* (for example in Starburst Galaxies)

Properties of SBGs

- High Star Formation Rate **(10-100 times higher than Milky Way)**
- They are abundant **(∽10^4 — 10^5 Gpc^{-3})**
- Not very brilliant in gamma-rays **(only a few currently observed)**

Constraints on p-p Sources

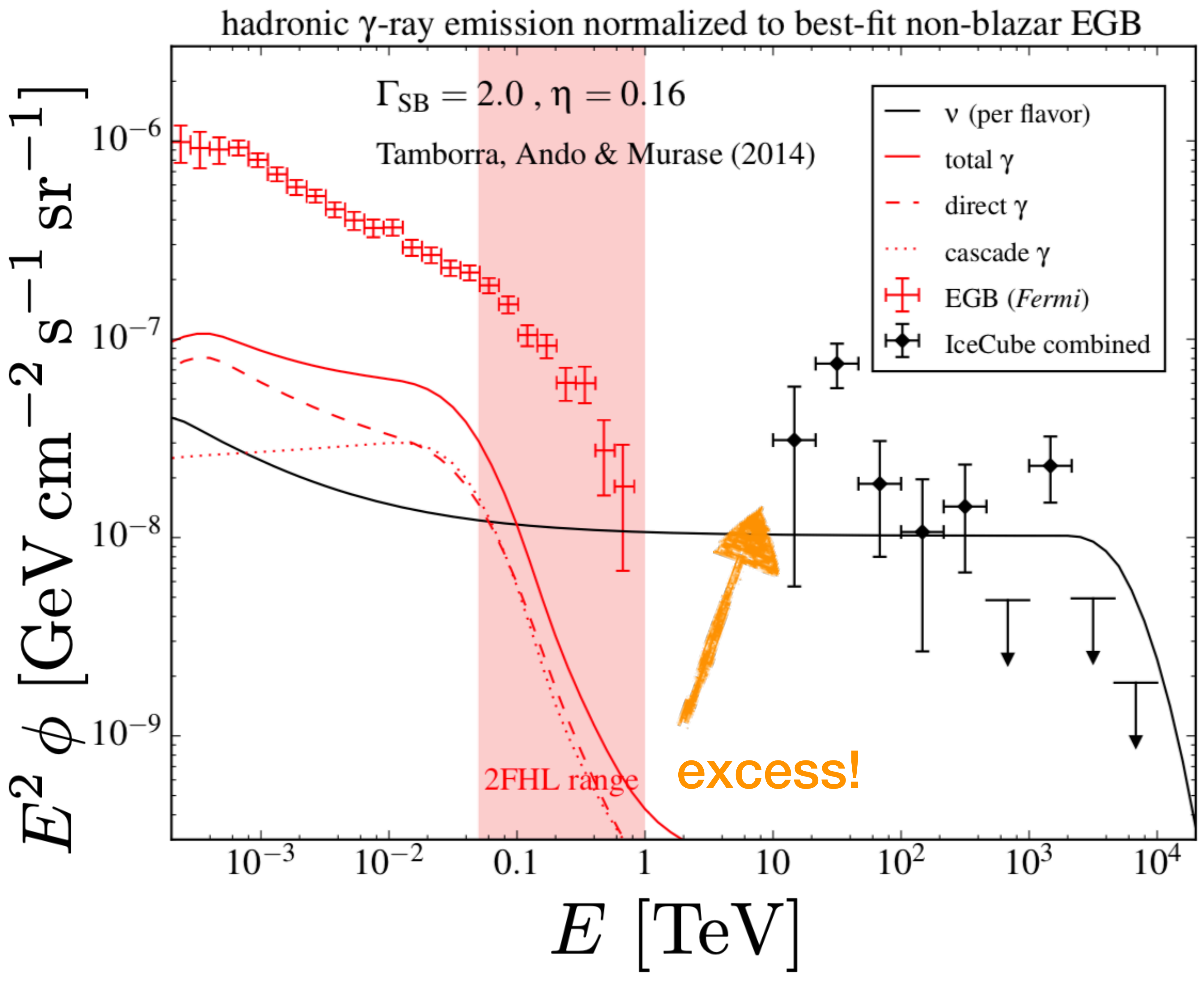


Bechtol et al., ***ApJ 836*** (2017)
[arXiv:1511.00688]

Starburst galaxies (p-p sources) cannot explain entirely IceCube data without over-producing gamma-rays!

Tension between neutrino and gamma-ray data Interpretation

Explaining the **very high neutrino flux at 100 TeV** with p-p sources would oversaturate the EGB.



Possible Solutions

- going beyond the standard modeling based on a fixed power-law flux
- Considering the hypothesis of several components

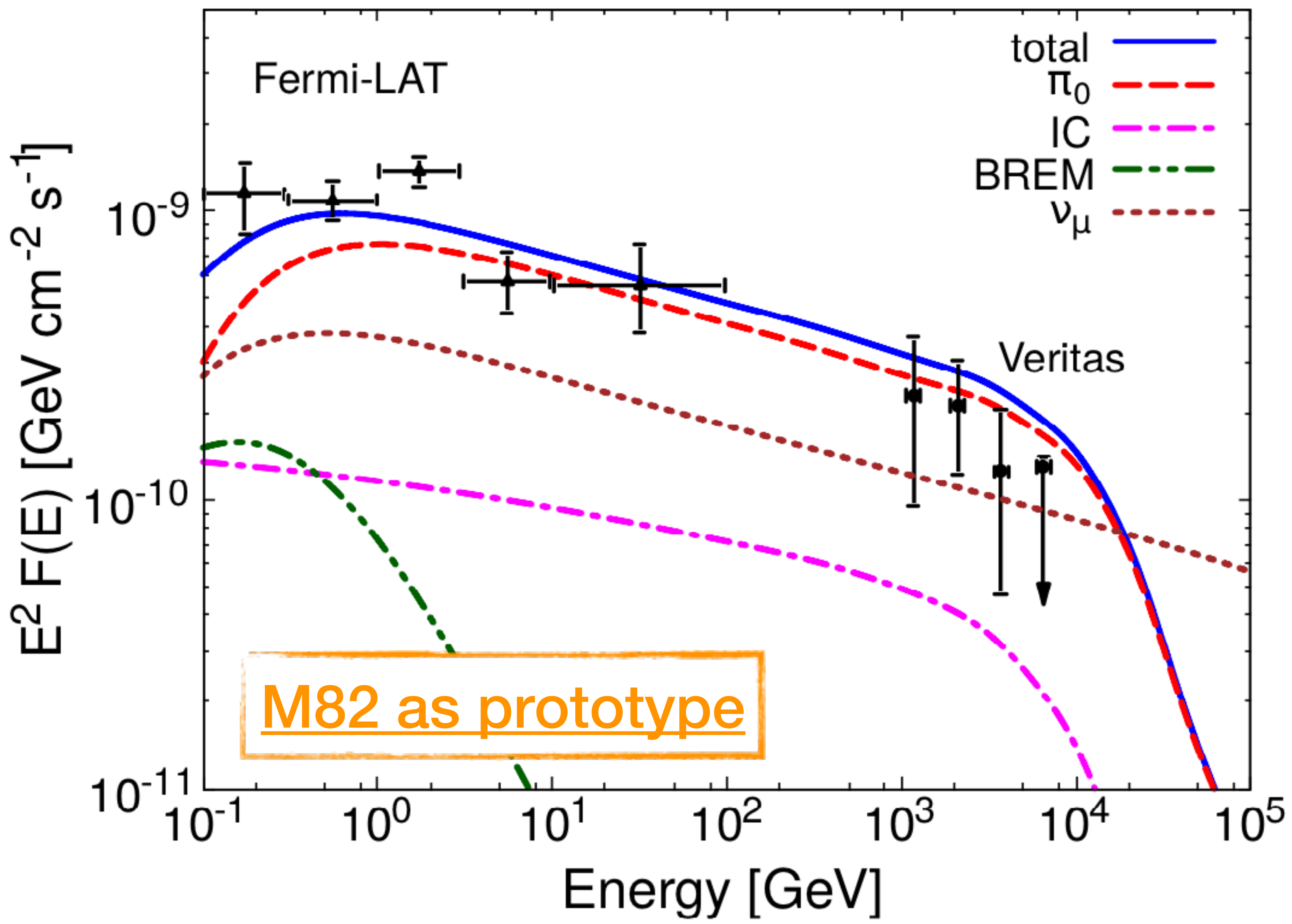
AA, M. Chianese, D. Fiorillo,AM, G: Miele, O. Pisanti,
arXiv:2011.02483

How are SBGs modeled? Semi-analytic parametrization

- ***All*** the SBGs are considered with the same properties of a ***prototype*** galaxy with "known" parameters

parameter	value
$p_{p,\max}$	10^2 PeV
α	4.2
R	0.25 kpc
D_L	3.9 Mpc
$\xi_{\rm CR}$	0.1
$\mathcal{R}_{\rm SN}$	0.06 yr^{-1}
B	200 μG
$n_{\rm ISM}$	100 cm^{-3}
$v_{\rm wind}$	700 km/s
$U_{\rm rad}$	2500 eV/cm^3

fit ⟷



Leaky-box-like model for CR transport

$$f(p)\left(\frac{1}{\tau_{\rm loss}(p)}+\frac{1}{\tau_{\rm adv}(p)}+\frac{1}{\tau_{\rm diff}(p)}\right)=Q(p)$$

injected CR from SN explosion

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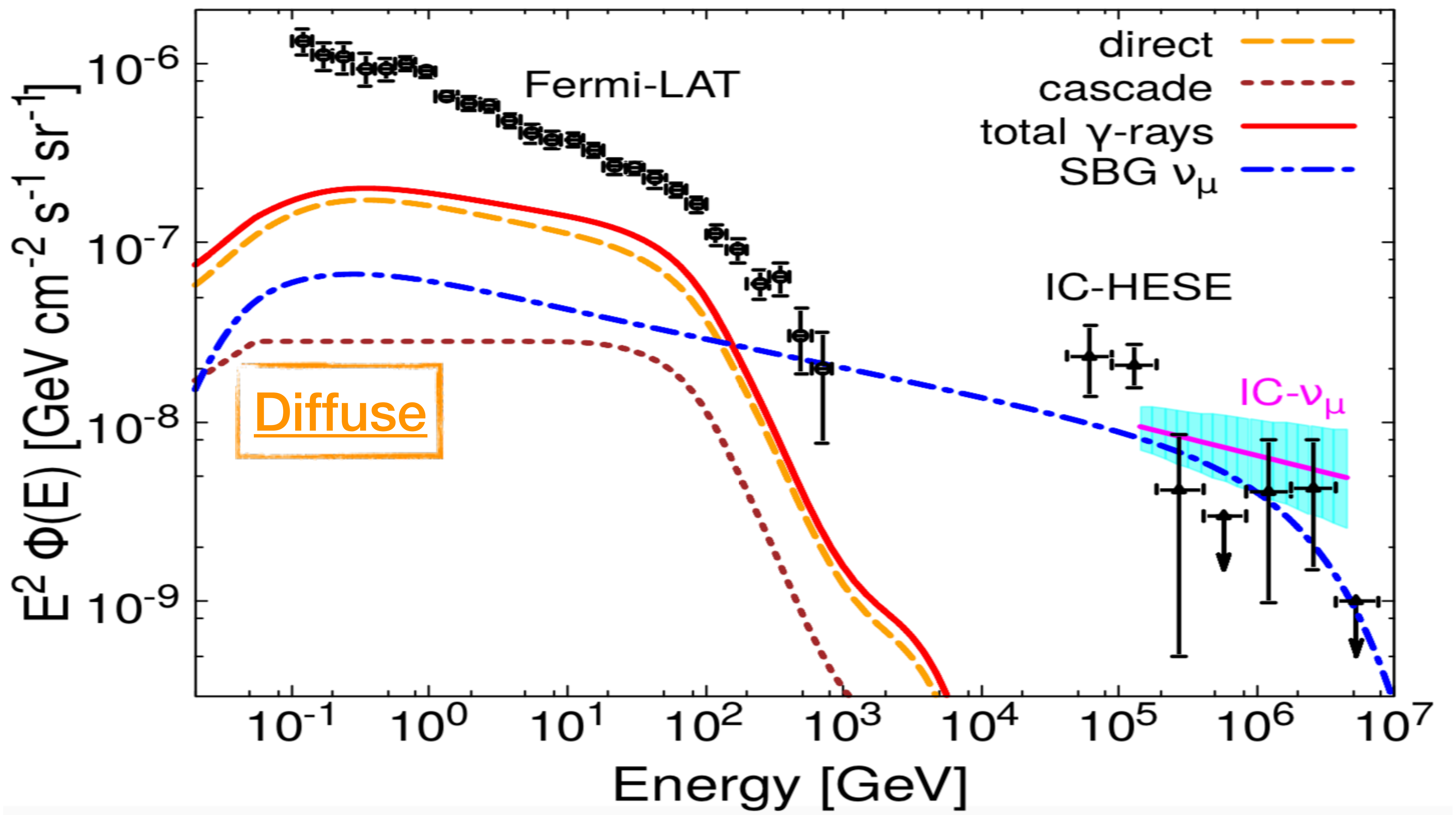
- In the calorimeter scenario, three main parameters:
  - Cut-off energy
  - Spectral index
  - Rate of SuperNovae explosions → **The Star Formation Rate**

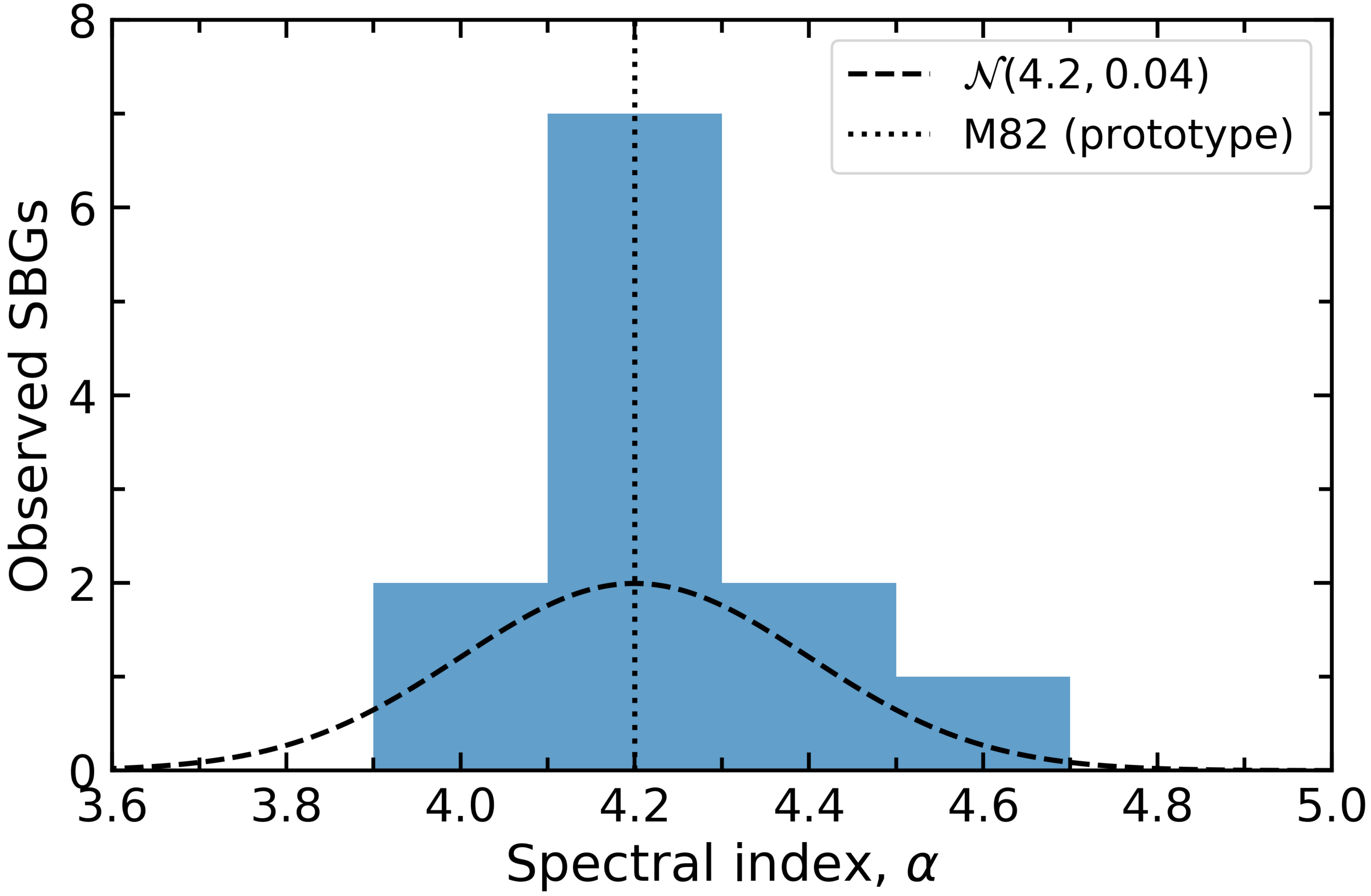


Our approach: blending of spectral indexes

- We allow each starburst galaxy to have different a different spectral index

$$\left\langle \phi_{\nu,\gamma}(E|p^{\max},\alpha)\right\rangle_\alpha = \int \mathrm{d}\alpha\, \phi_{\nu,\gamma}(E|p^{\max},\alpha)\, p(\alpha)$$

ArXiv:2011.02483



- 12 SFGs and SBGs have been resolved in gamma-rays

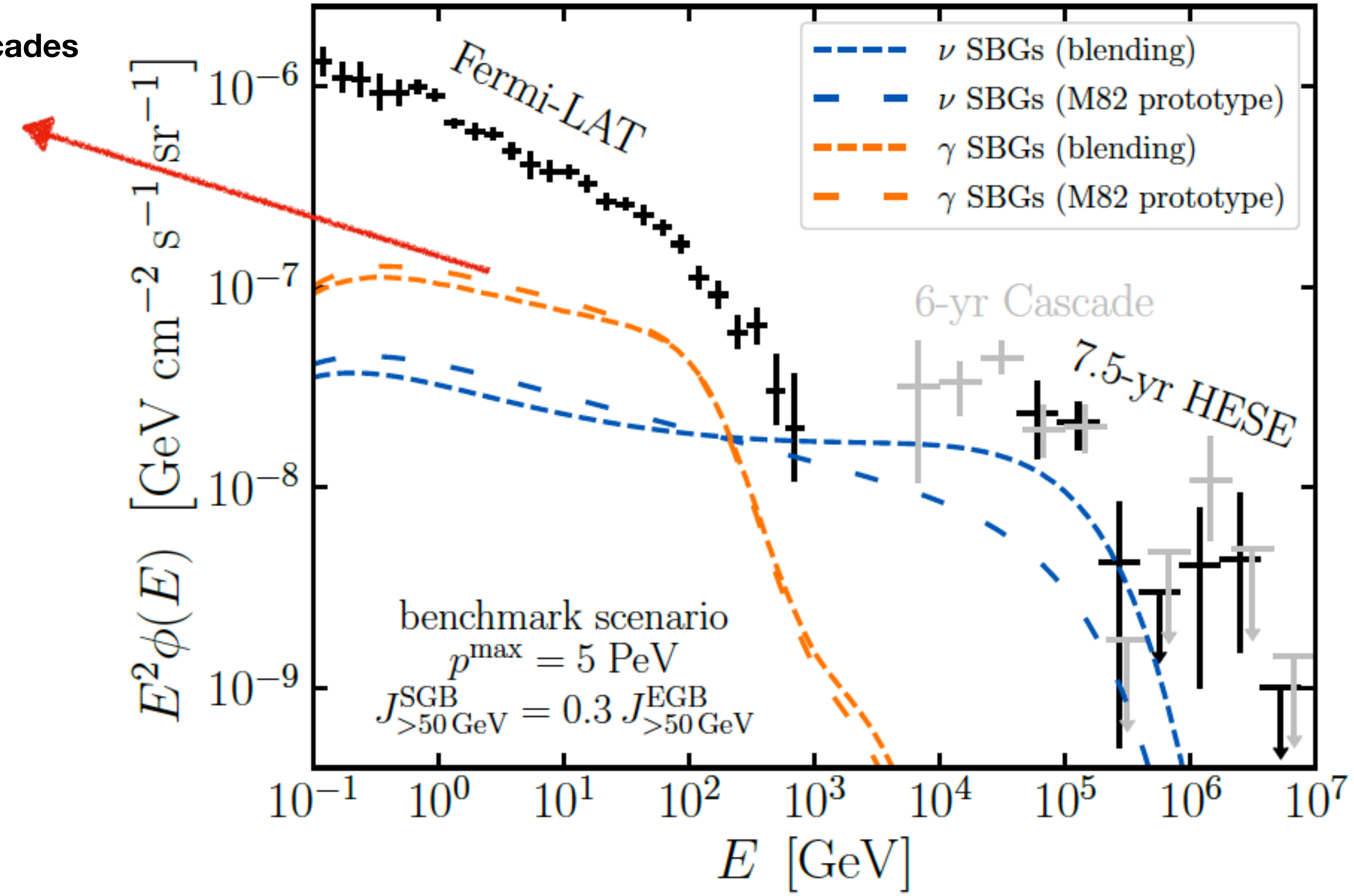
*Ajello et al., **arXiv:2003.05493***

$$p(\alpha) = \mathcal{N}(\alpha|4.2, 0.04)$$

“Blending” Versus “Prototype”

ArXiv:2011.02483

Direct + electromagnetic cascades gamma-ray flux



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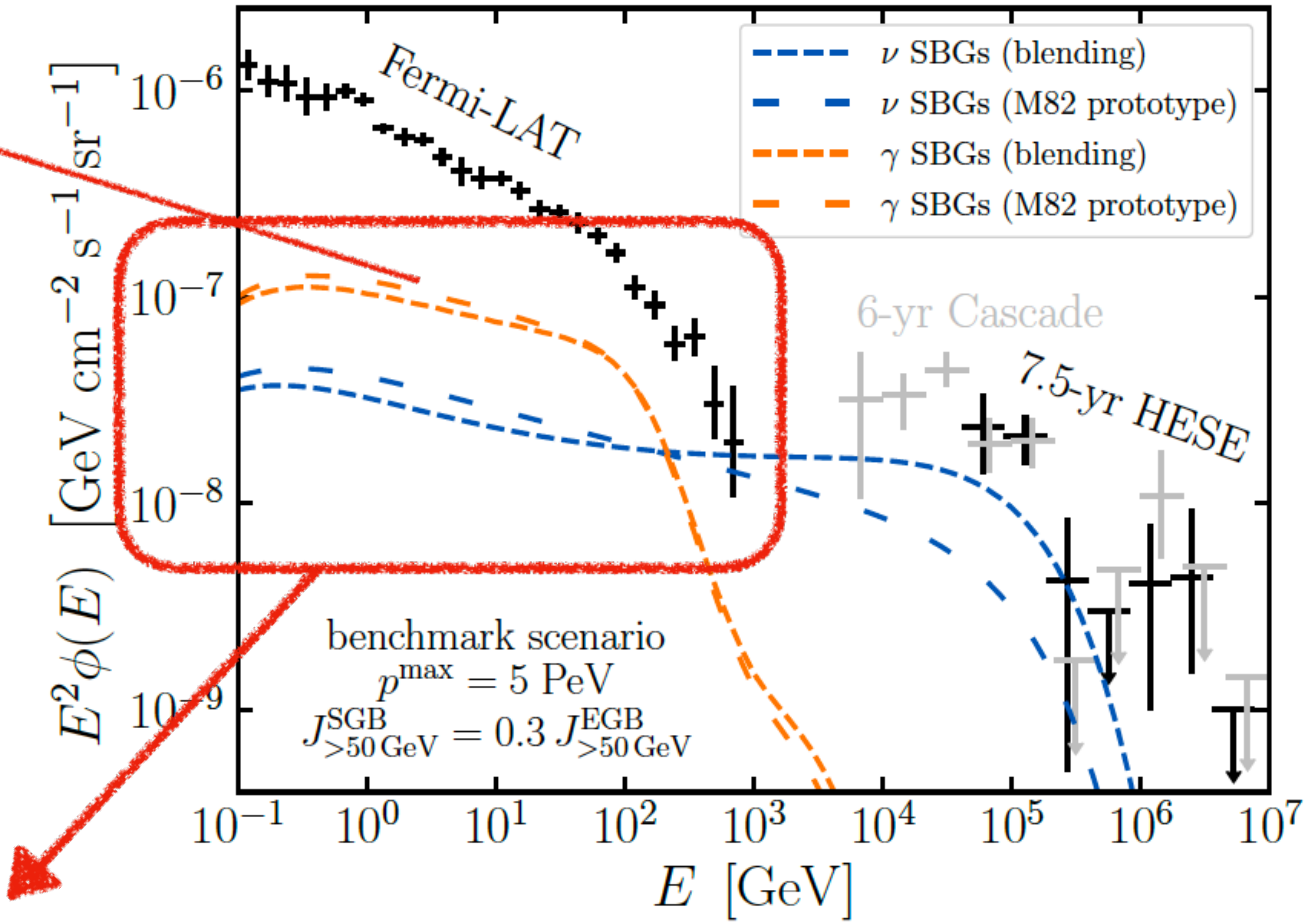
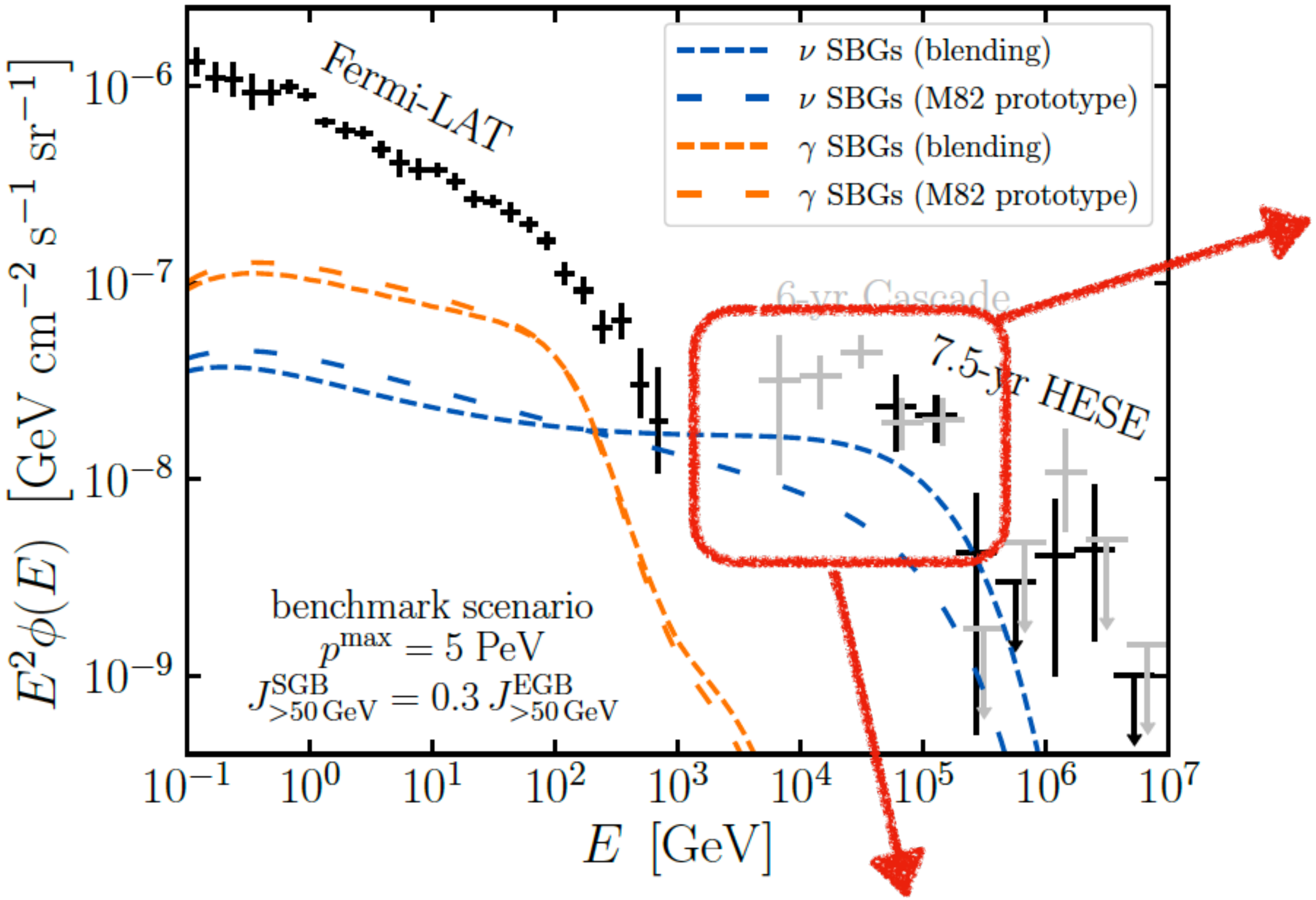


The diffuse gamma contributions are almost the same!

"Blending" Versus "Prototype"

ArXiv:2011.02483

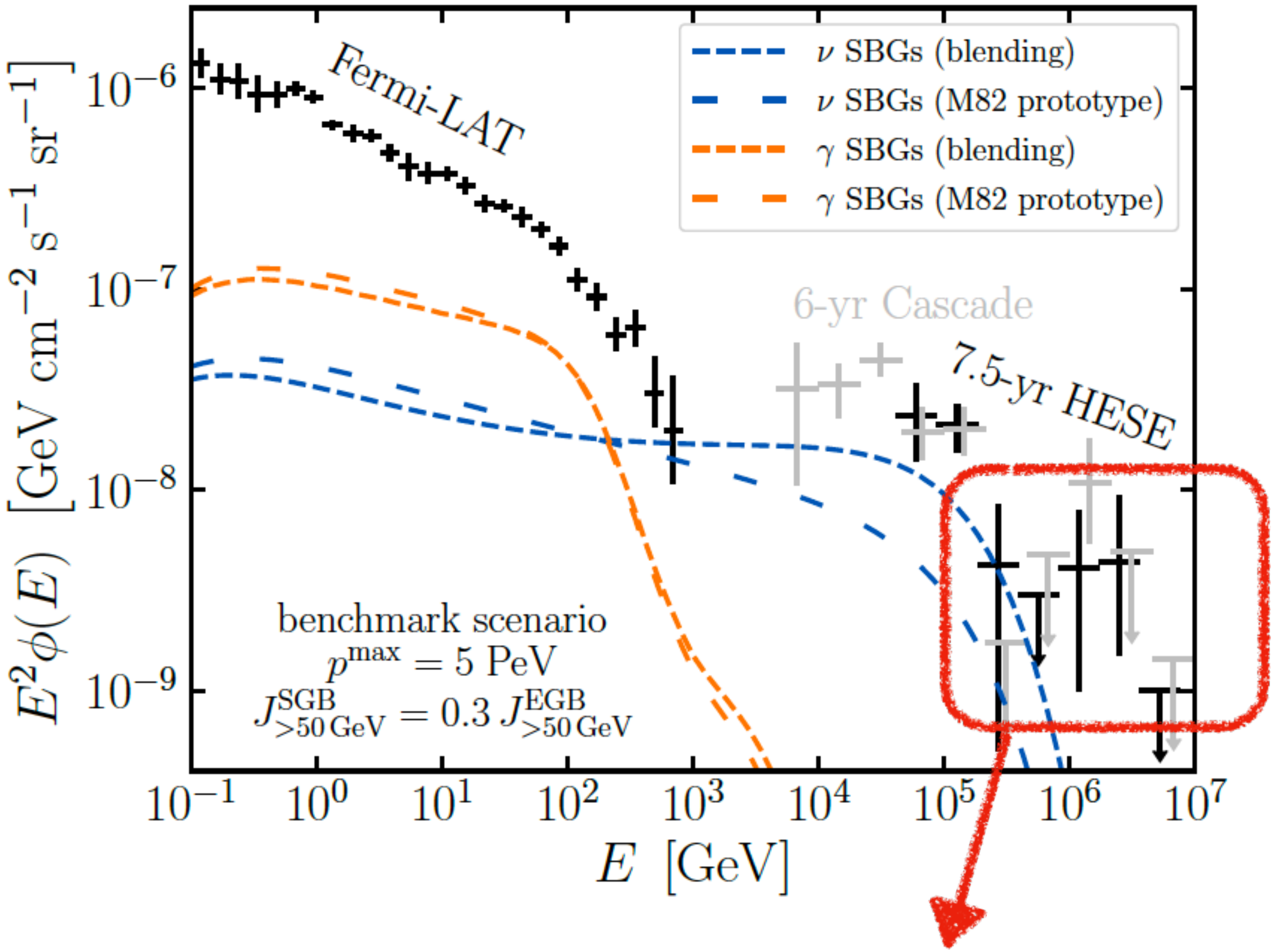


With $p^{\max} = \mathcal{O}(\text{PeV})$ it is possible to give a significant contribution at around 100 TeV

Larger contribution around 100 TeV! Potentially, It could alleviate the Tension between neutrino and gamma-ray data when using hadronic model to explain IceCube observations.

“Blending” Versus “Prototype”

ArXiv:2011.02483



A possible contribution from Blazar? A possible interplay between reservoirs and accelerators?

The proposed Multi-Messenger Fit

The Gamma-Ray Contributions:

1. **SBGs**
2. **Blazar + Electromagnetic Cascades**
3. **Radio Galaxies**

For Blazars and Radio Galaxies, we used the estimations given by Ajello et al. 2015 **(ArXiv: 1501.05301)**

The Neutrino Contributions:

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Observational Samples Used

Extragalactic gamma-ray Background (EGB)

1. **7.5 year HESE**
2. **6 year Cascades**

$$\chi^2_{\nu+\gamma}(N_{SBG}, N_{RG}, N_{Blazars}, p^{max}) = \chi^2_{\nu} + \chi^2_{\gamma} + \left(\frac{N_{Blazars} - 1}{0.26}\right)^2 + \left(\frac{N_{RG} - 1}{0.65}\right)^2 + \left(\frac{N_{Blazars} - 0.80}{0.11}\right)^2$$

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They come from uncertainties of the Non-SBG components

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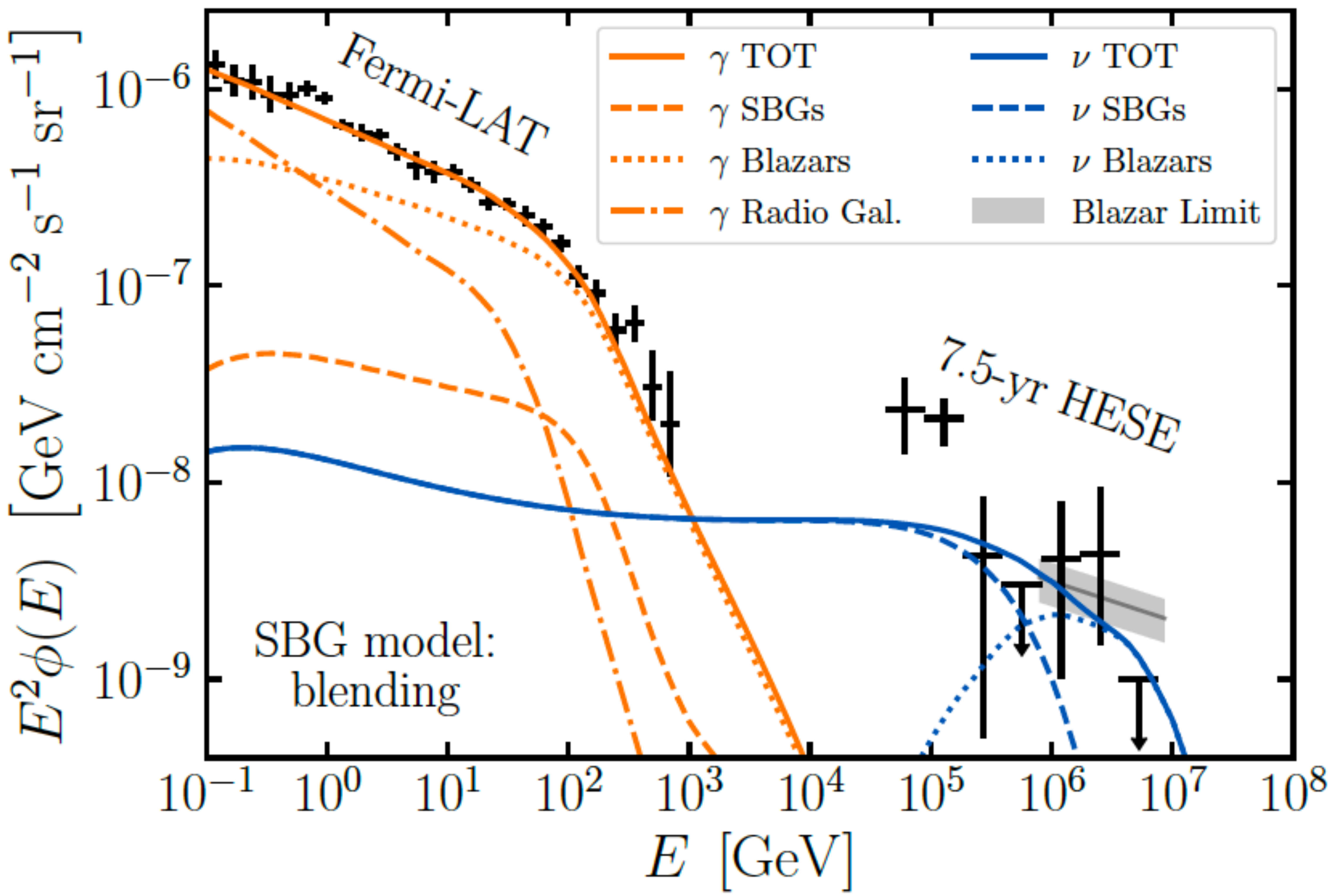
It comes from the positional limit of Point Sources above 50 GeV (Lisanti et al. 2016)

Results: Comparison between “Blending” and “Prototype”

ArXiv:2011.02483



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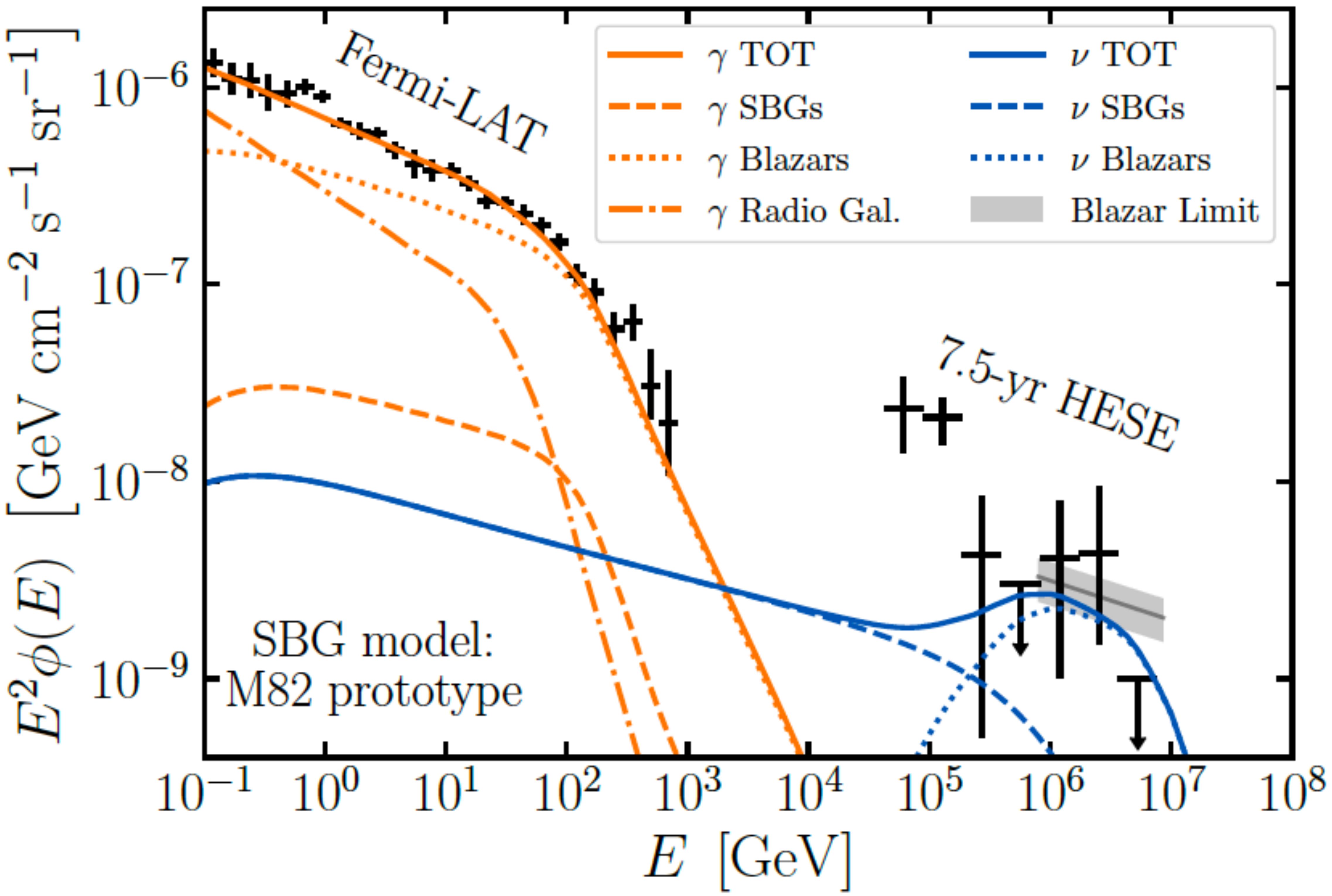

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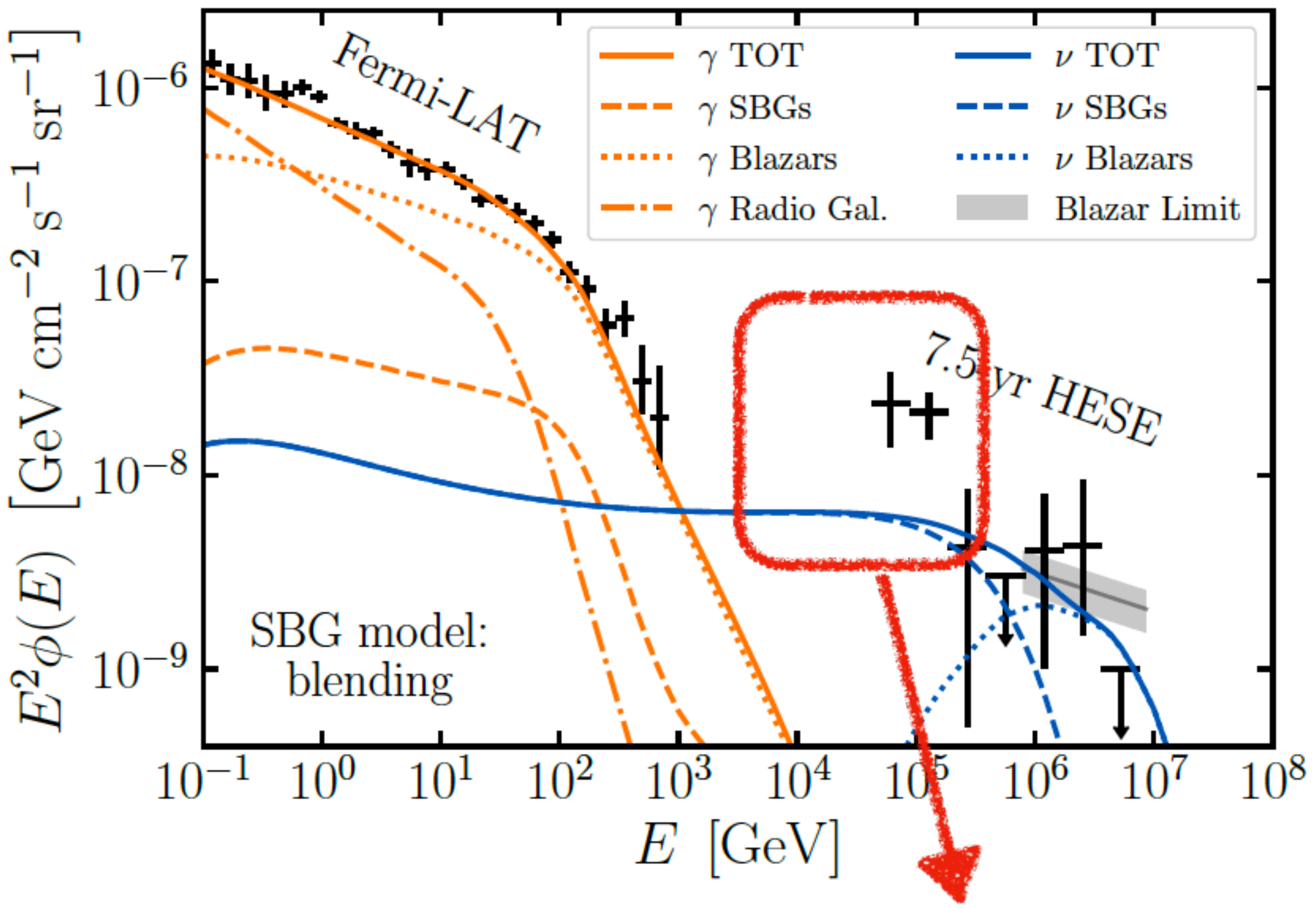

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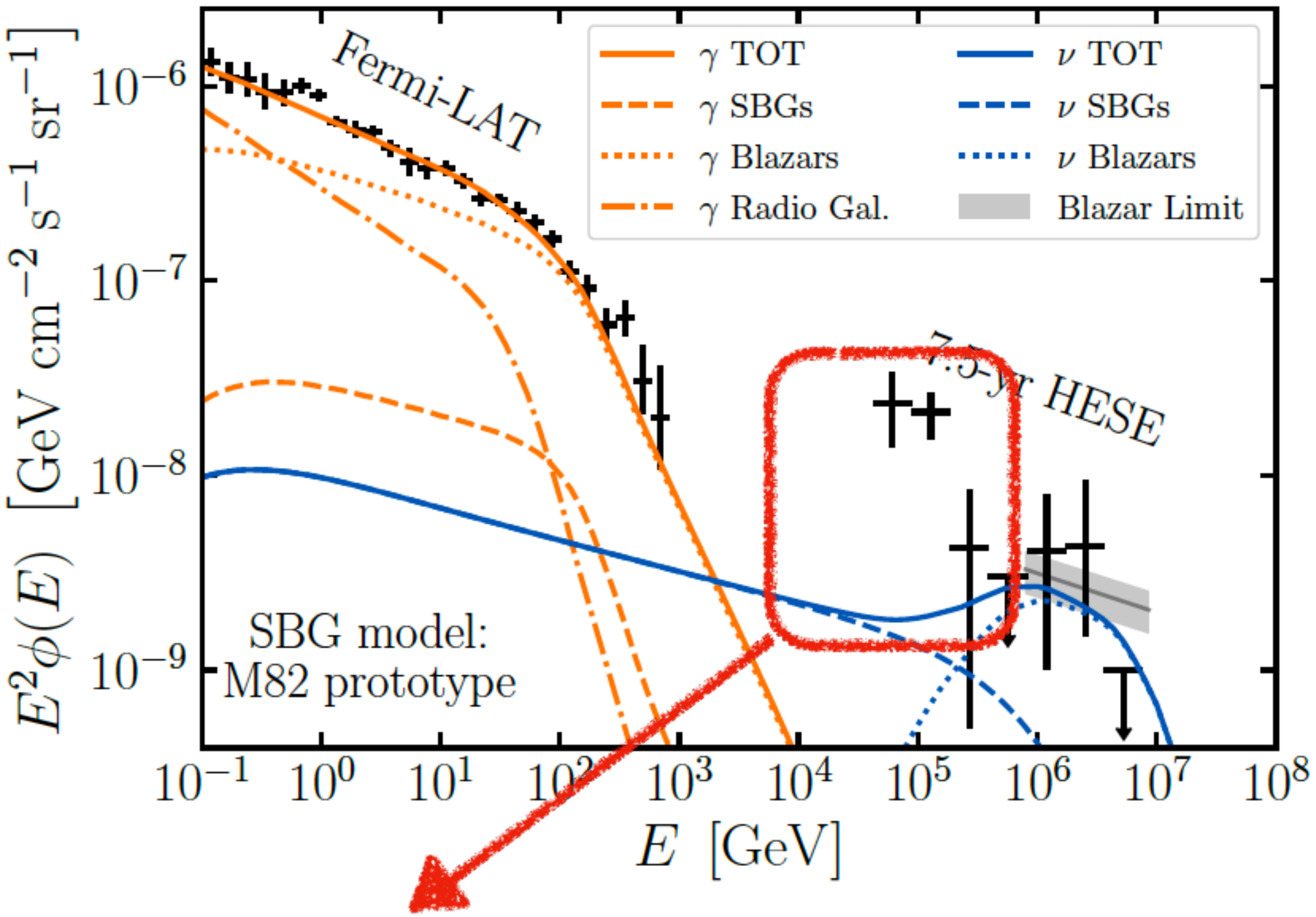

The Blending Scenario is ***allowed*** *to give a greater contribution than the prototype scenario…but it is* ***not enough****…* ***Other Contributions?***

Results: Comparison between “Blending” and “Prototype”

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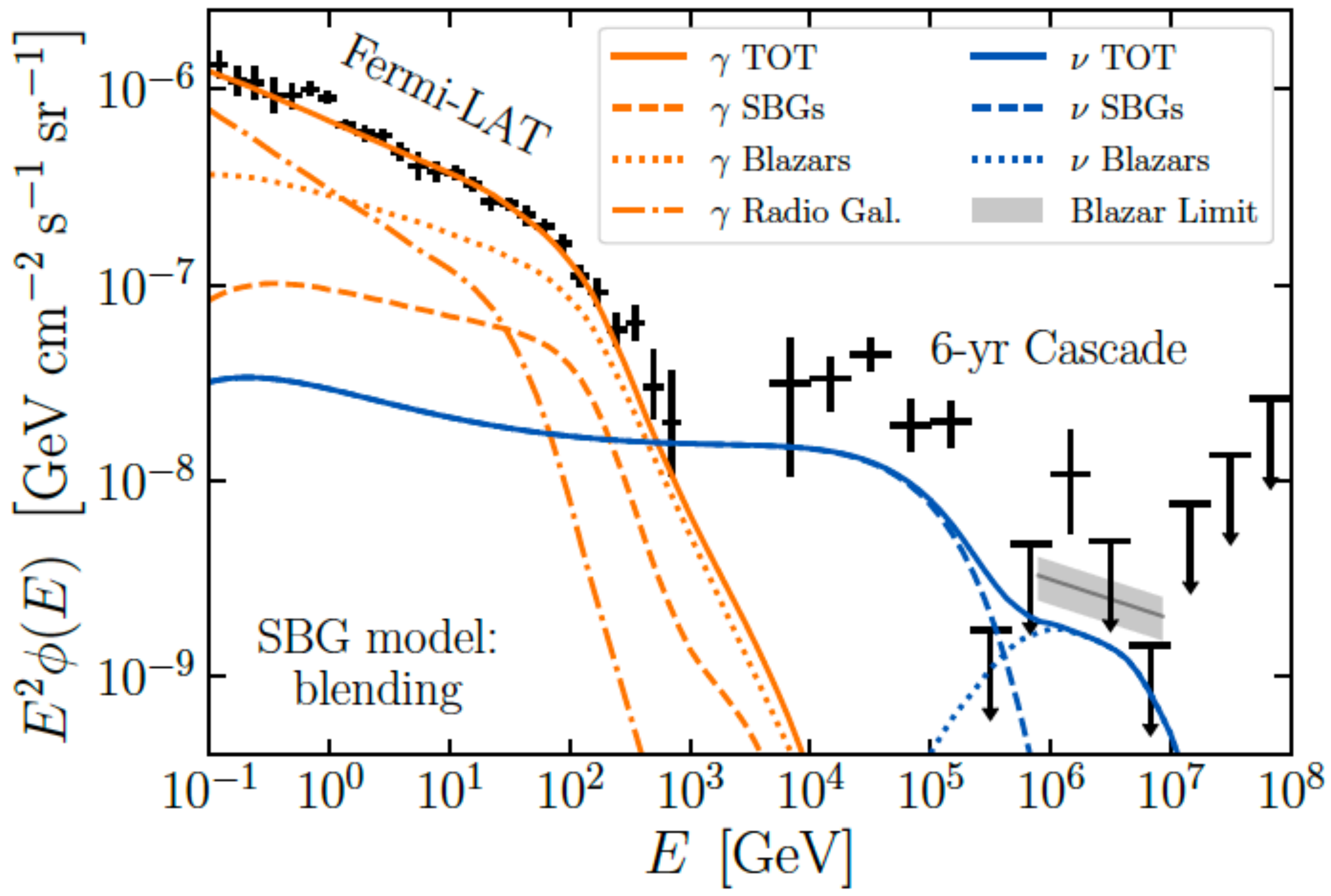

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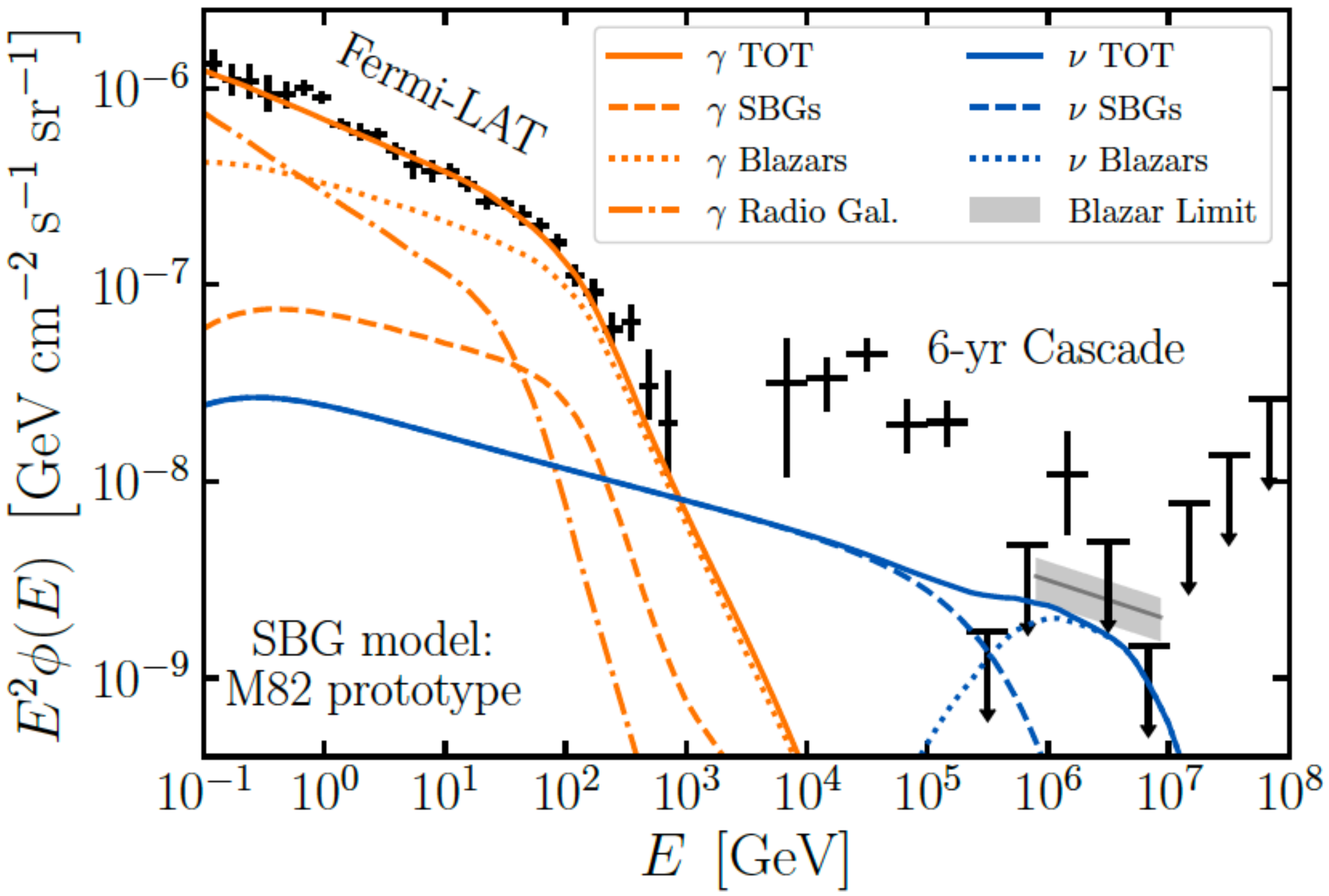
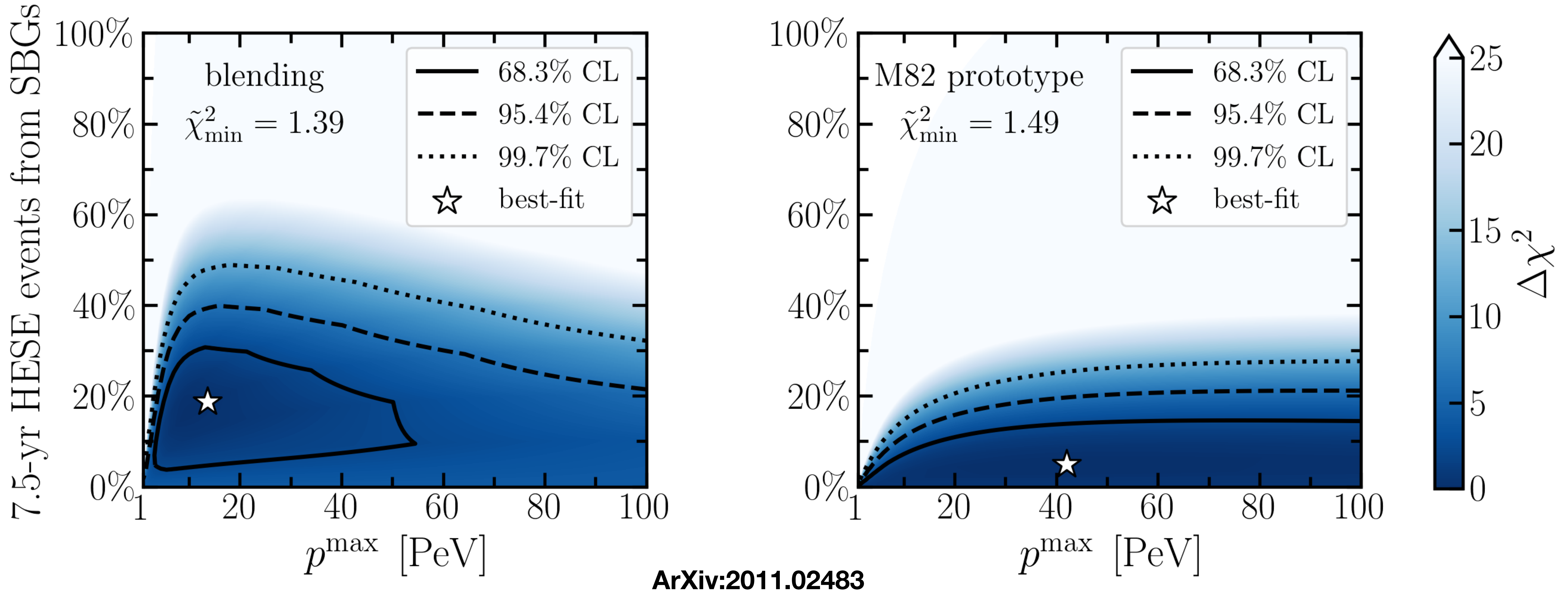


The blending scenario provides also an important contribution whenever we compare the expectation with the IceCube cascade SED between tens to hundreds TeVs

Comparison 2.0: Number of Events in the Detector (HESE)

Redshift interval: $0 \leq z \leq 4.2$



ArXiv:2011.02483

Main Results:

1. **Non-Zero SBG component at 68% Confidence Level**
2. **Preferred smaller values of the maximum energies for injected CRs:** $p^{max} < 50$ **PeV**

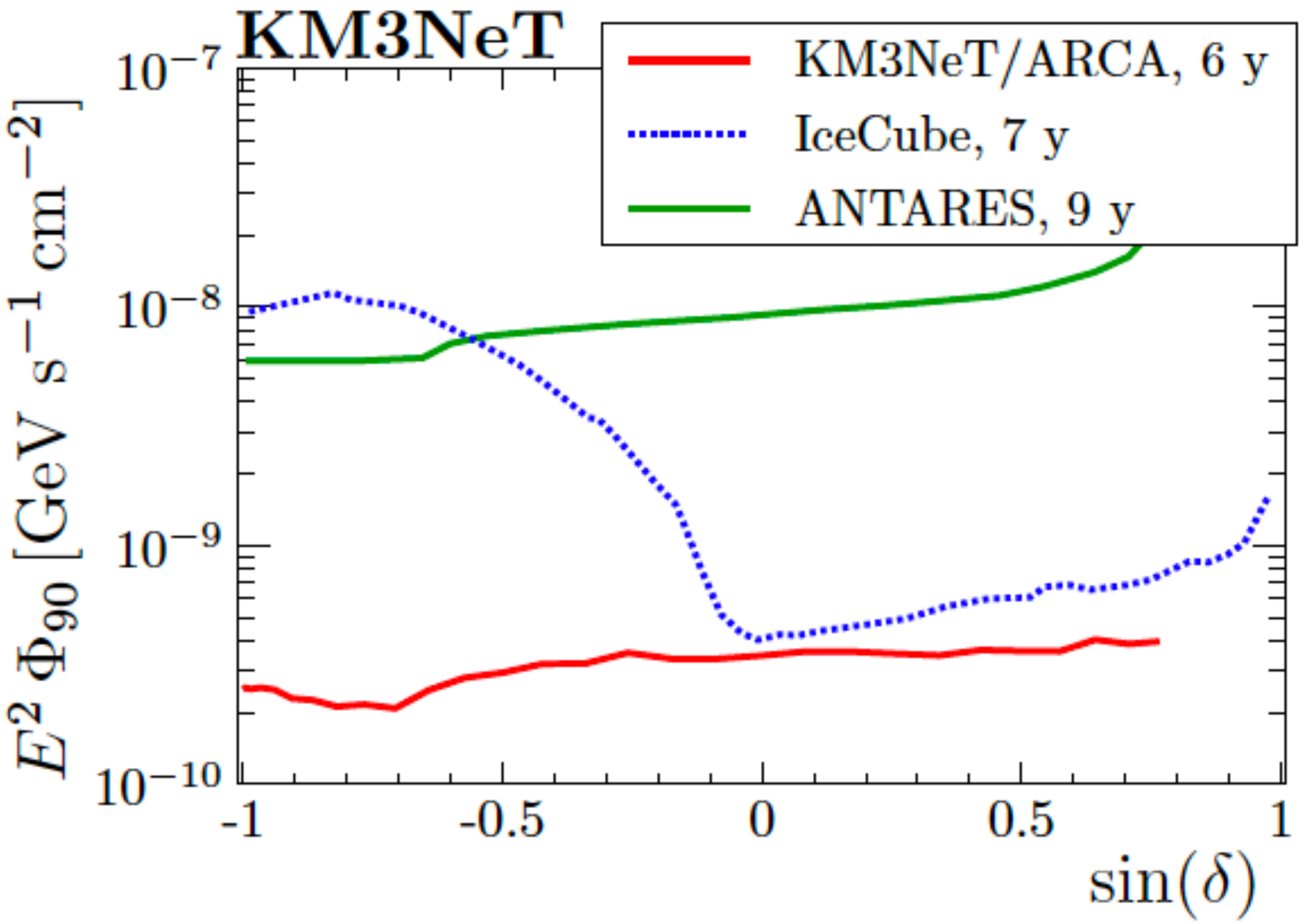
Observational Challenges

With CTA, we expect to increase the gamma-ray sample of observed SBG obtaining more infos about physical parameters

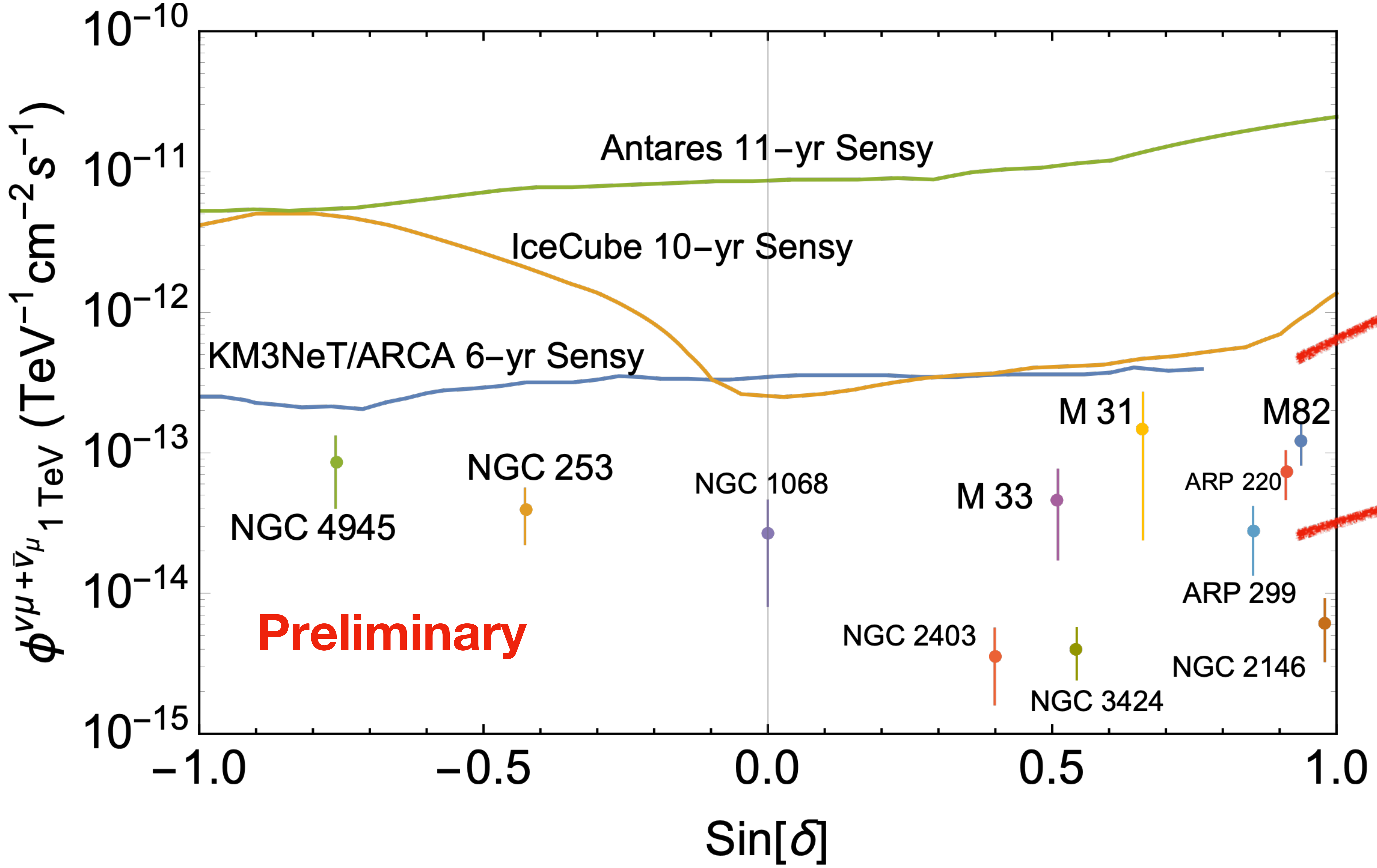
We expect **ARCA Phase 2.0** and **IceCube Gen 2** to increase the sensitivity to astrophysical signal at 100 TeV, which may allow to distinguish between the **Blending** and the **Prototype** Scenario.

Even for this new generation of neutrino telescopes, the **real** challenge will be to observe them as point-like neutrino sources

ArXiv: 1810.08499



Comparison with Known SBGs



We used the list of **Ajello et. Al 2020** and the normalizations are obtained using the calorimetric scenario put forward by Peretti et al., **arXiv:1812.01996**, **arXiv:1911.06163**

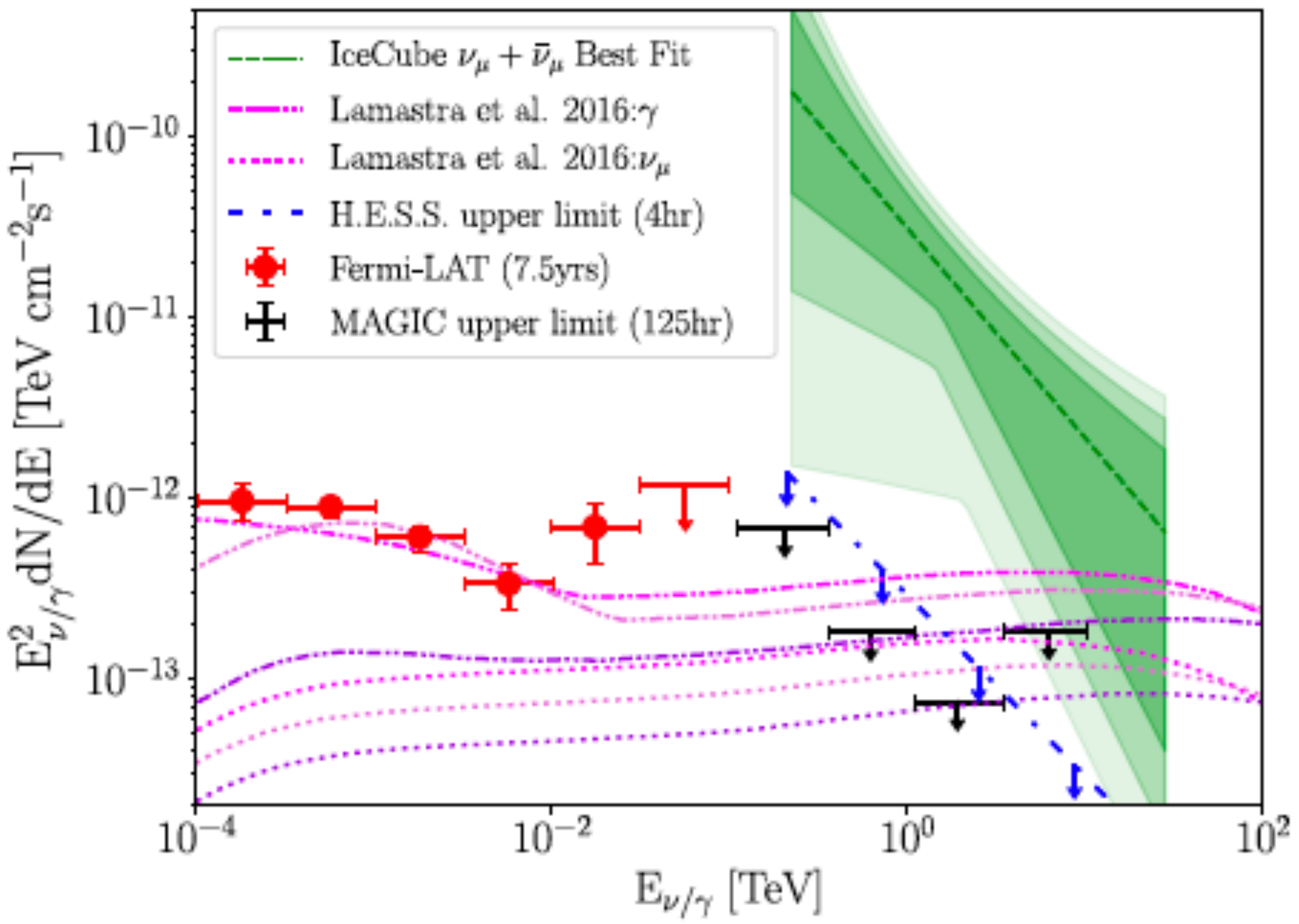
The normalizations shown take only into account the expected SBG activity. However, some of these sources may also have AGN activity that would allow them to reach the detector sensitivity.

With the assumptions made, they currently cannot be observed singularly!

The Case of NGC 1068

Galactic catalog searches. The most significant point in the Northern hemisphere from scanning the sky is coincident with the Seyfert II galaxy NGC 1068, which was included in the source catalog search. The excess at the coordinates of NGC 1068 is inconsistent with background expectations at the level of $2.9\,\sigma$ after accounting for statistical trials. The combination of this result along with excesses observed at the coordinates of three other sources, including TXS 0506+056, suggests that, collectively, correlations with sources in the Northern catalog are inconsistent with background at $3.3\,\sigma$ significance. These results, all based on searches for a cumulative neutrino signal integrated over the ten years of available data, motivate further study of these and similar sources, including time-dependent analyses, multimessenger correlations, and the possibility of stronger evidence with coming upgrades to the detector.

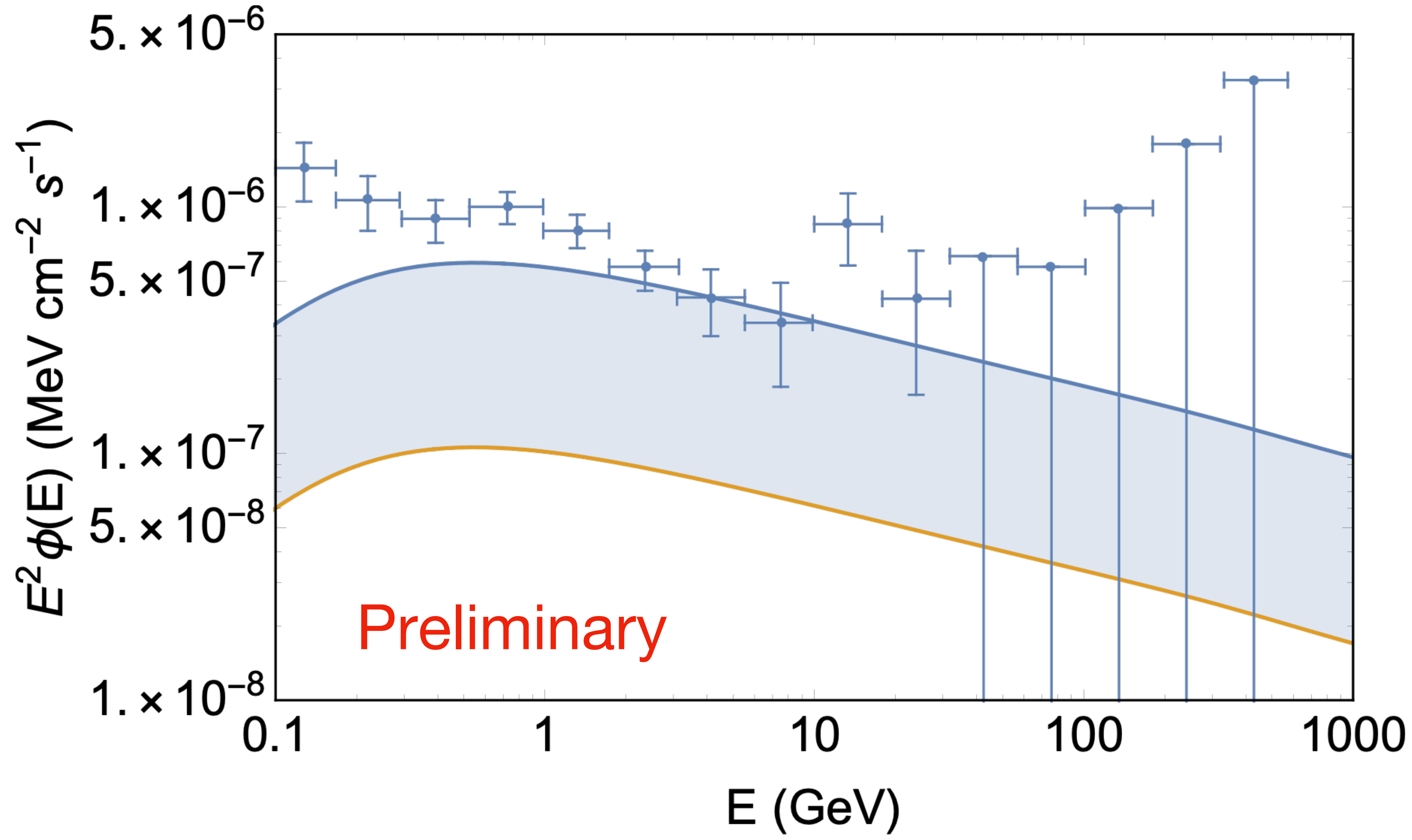
ArXiv: 1910.08488



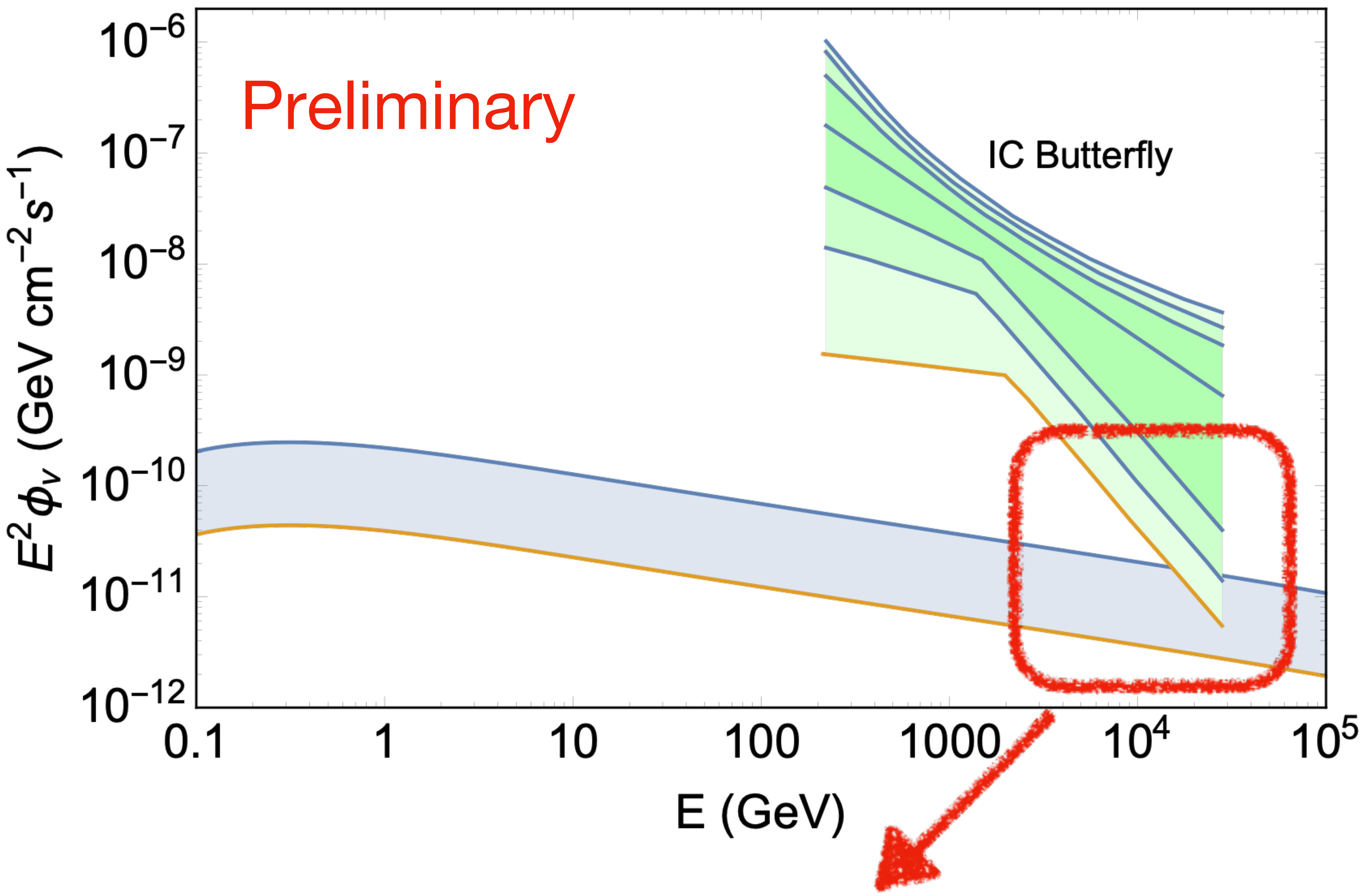
The Case of NGC 1068: Preliminary Prediction

Considering the calorimetric approximation, $f_{\nu,\gamma} \propto \frac{\psi}{\psi_{M82}} f_{M82}$

*Peretti et al., **arXiv:1812.01996, arXiv:1911.06163***



Data Taken from Ajello et al. 2020, arXiv:2003.05493



It is unlikely that the hot-spot excess was caused by the star forming activity. Murase at al. 2020 (ArXiv: 1904.04226) suggested it could be caused by AGN activity

Conclusions and Future Scenarios

★ **SBGs could play an important role for explaining the measured Astrophysical Neutrino Flux.**

★**We show how using the spectral behaviour of a new sample of Fermi-LAT SBGs increases the full-sky neutrino expectation at 100 TeV.**

★ **The reported multi-messenger study that considers gamma-ray EGB and neutrino HESE and cascades samples suggests a Pmax below tens of PeVs.**

★**A new VHE catalogue of SBGs with the incoming CTA will constrain better the calorimetric parameters of these sources.**

★**Even if we highlight the potential neutrino contribution of SBGs overall the sky, the observation of a point-like excess from each of them could take more than a decade of KM3NeT or IceCube observatory.**