Gamma-Ray and Neutrino Emissions from Starforming and Starburst Galaxies

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In collaboration with

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Based on MNRAS 503 [2011.02483], ApJL 919 [2106.12348] and MNRAS [2203.03642]

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Why Starburst Galaxies?

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

The Starburst Galaxy M82

Phenomenological Properties of SBGs

✦ Galaxies with high star-formation rate (~100 M⊙/yr, to be compared with ~1 M⊙/yr in the Milky Way)

✦ Star forming activity mainly concentrated in the core (nucleus), which lasts for $\sim 10^{7-8}\,\mathrm{yr}$

✦ High dense interstellar gas ($n_{\mathrm{ISM}} \simeq 10^2\,\mathrm{cm}^{-3}$)

✦ High degree of magnetic turbulence which traps high-energy protons for a long time $\sim 10^5\,\mathrm{yr}$:
Cosmic Reservoirs

Expected copious hadronic production:

Interstellar gas as the target

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

✦ **Neutrinos** and **γ-rays** from pions decays:

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

Point-Like SBG Emissions: Semi-Analytical Approach

Benchmark 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

Leaky-box-like model for CR transport

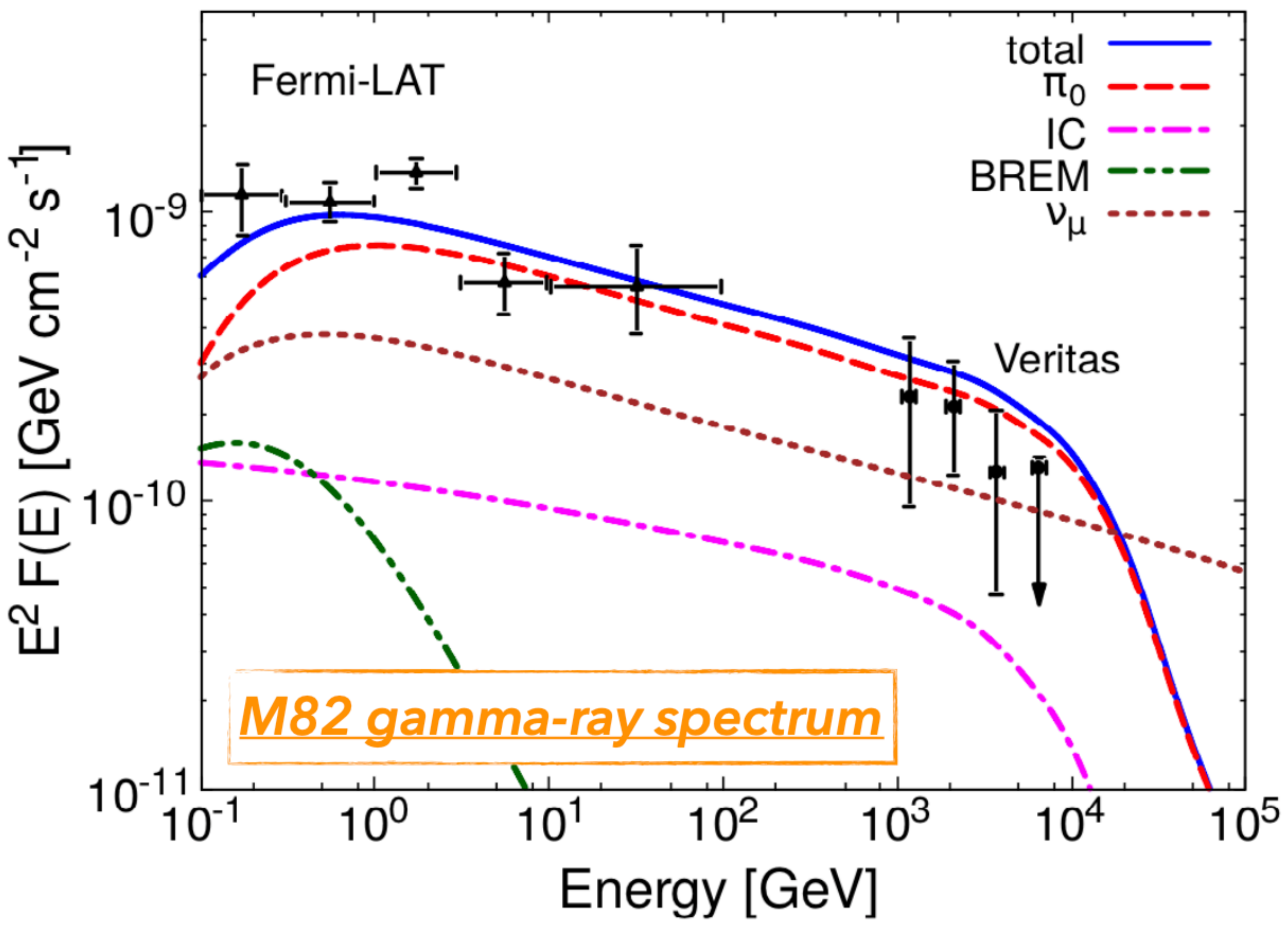
$$f(p)\left(\frac{1}{\tau_{\rm loss}(p)}+\frac{1}{\tau_{\rm adv}(p)}+\frac{1}{\tau_{\rm diff}(p)}\right)=Q(p)$$

$$f(p) = Q(p)\tau_{pp}\cdot F_{\rm cal}(E)$$

In general, the higher the star formation rate, the more $\tau_{\rm pp}$ dominates on the others ($\tau_{\rm loss} < \tau_{\rm adv}, \tau_{\rm diff}$), leading to Fcal = 1

✦In the calorimetric scenario, three fundamental parameters:

- ✦ High-energy cut-off
- ✦ Spectral Index
- ✦ Rate of supernovae explosions ∝ Star formation rate



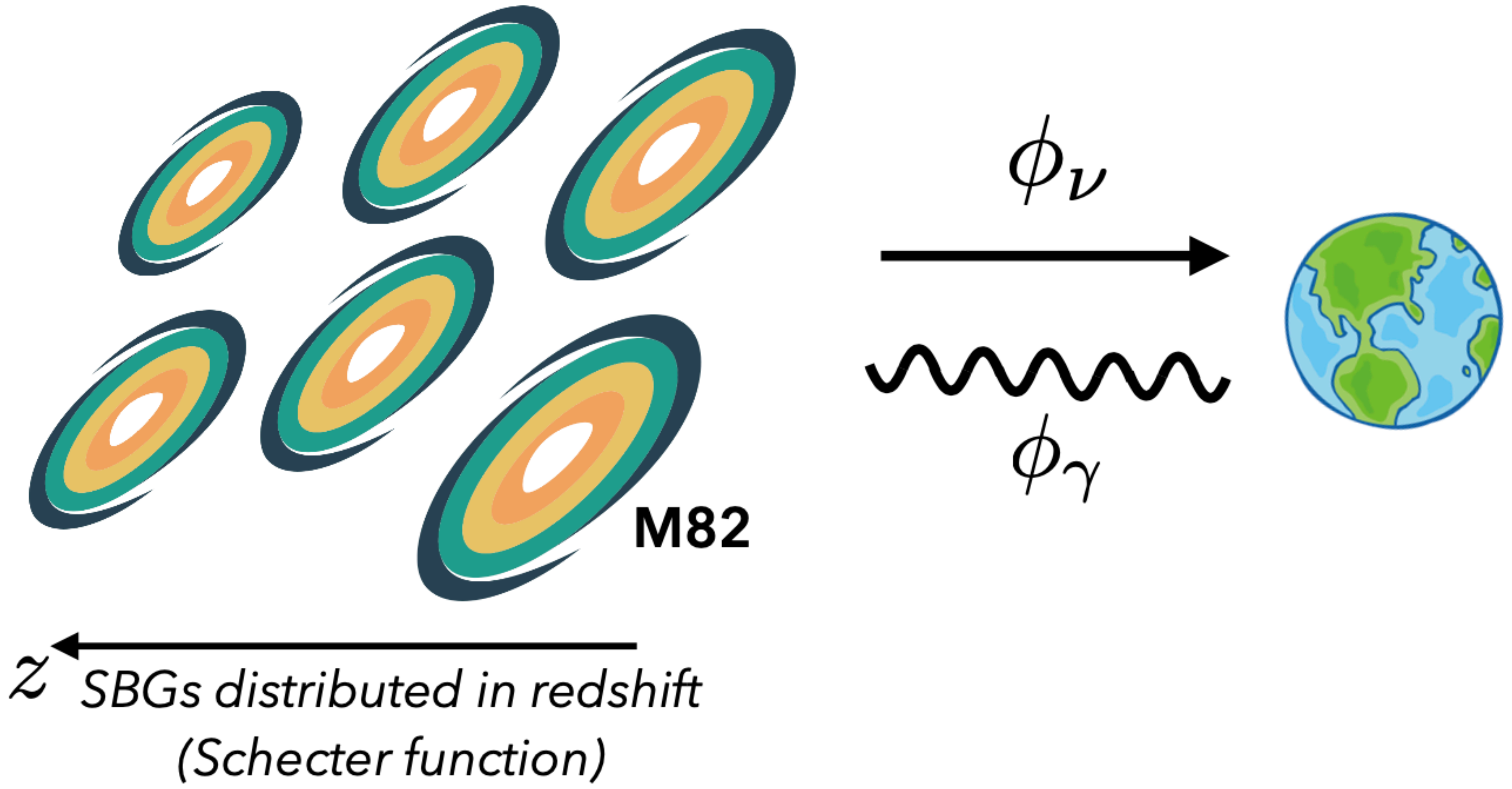
Peretti et al., **arXiv:1812.01996**, **arXiv:1911.06163** (Peretti+, MNRAS 487 (2019), MNRAS 493 (2020))

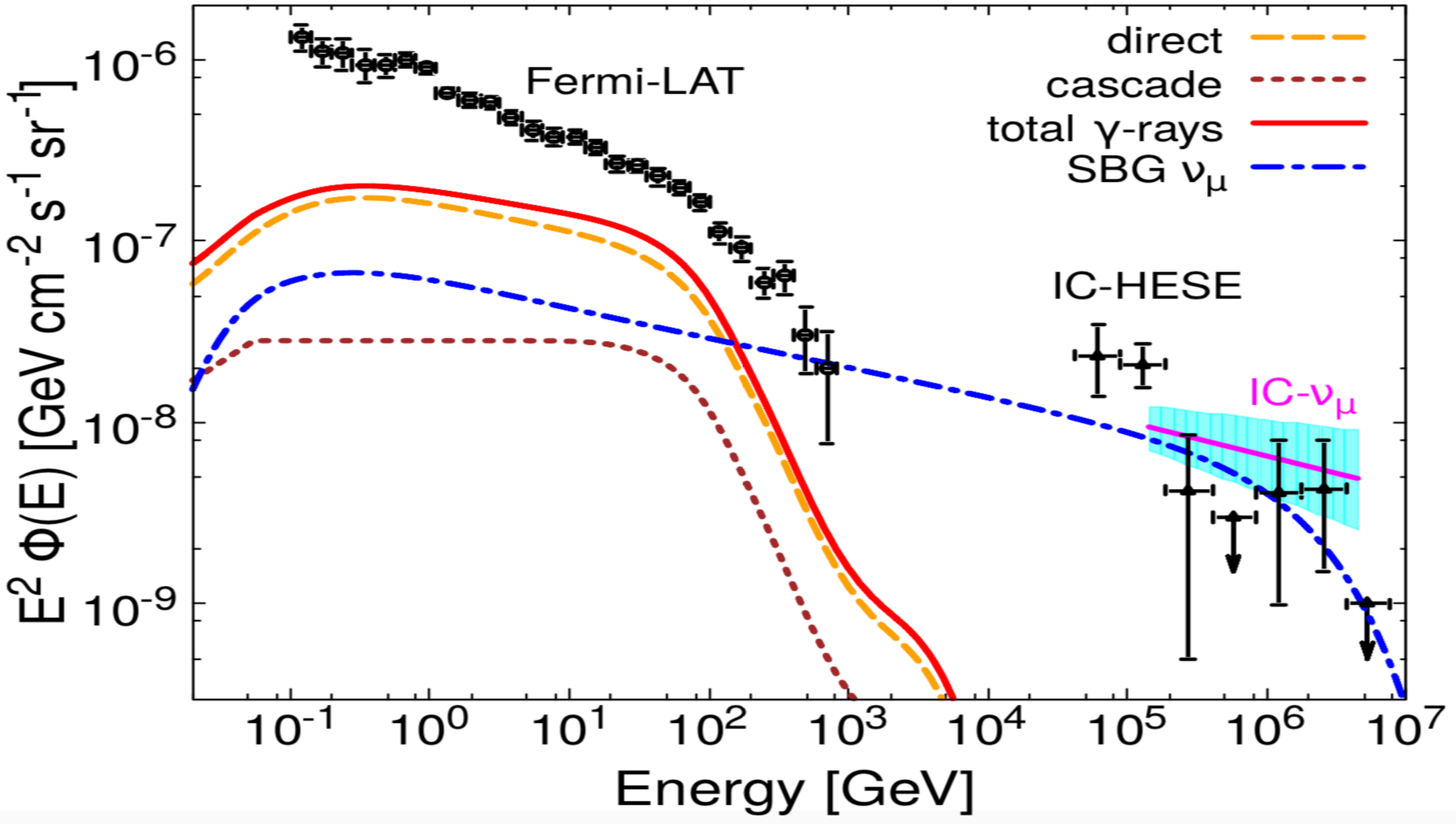
Diffuse Emissions: Prototype Modelling

Peretti et al., ***arXiv:1812.01996***, ***arXiv:1911.06163*** *(Peretti+, MNRAS 487 (2019), MNRAS 493 (2020))*

✦All the sources have the same emission properties **(calorimetric assumptions)**

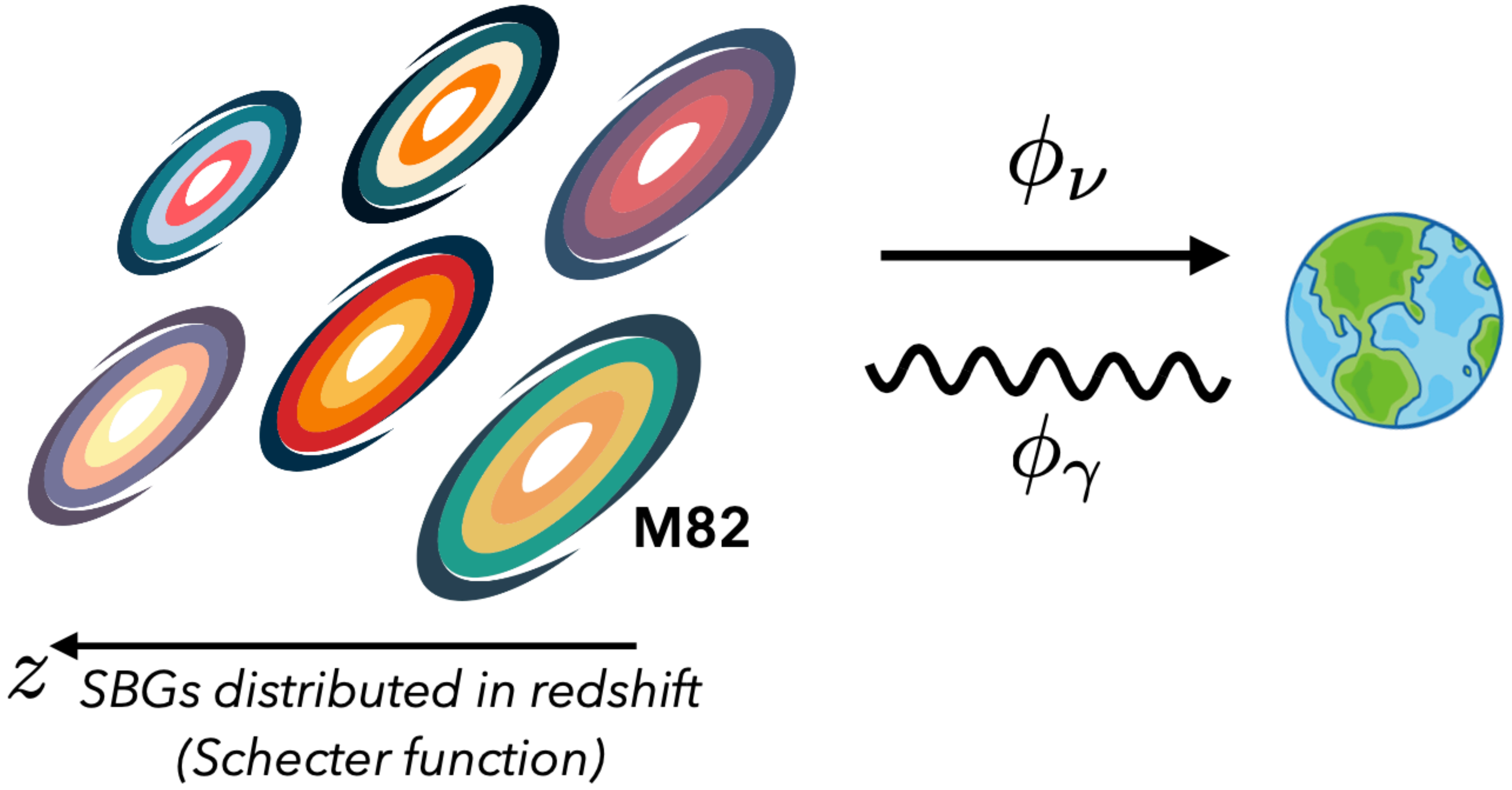
$$f_{\rm SBG} \propto \frac{\dot{M}_*}{\dot{M}_{*\,\rm M82}} f_{\rm M82}$$





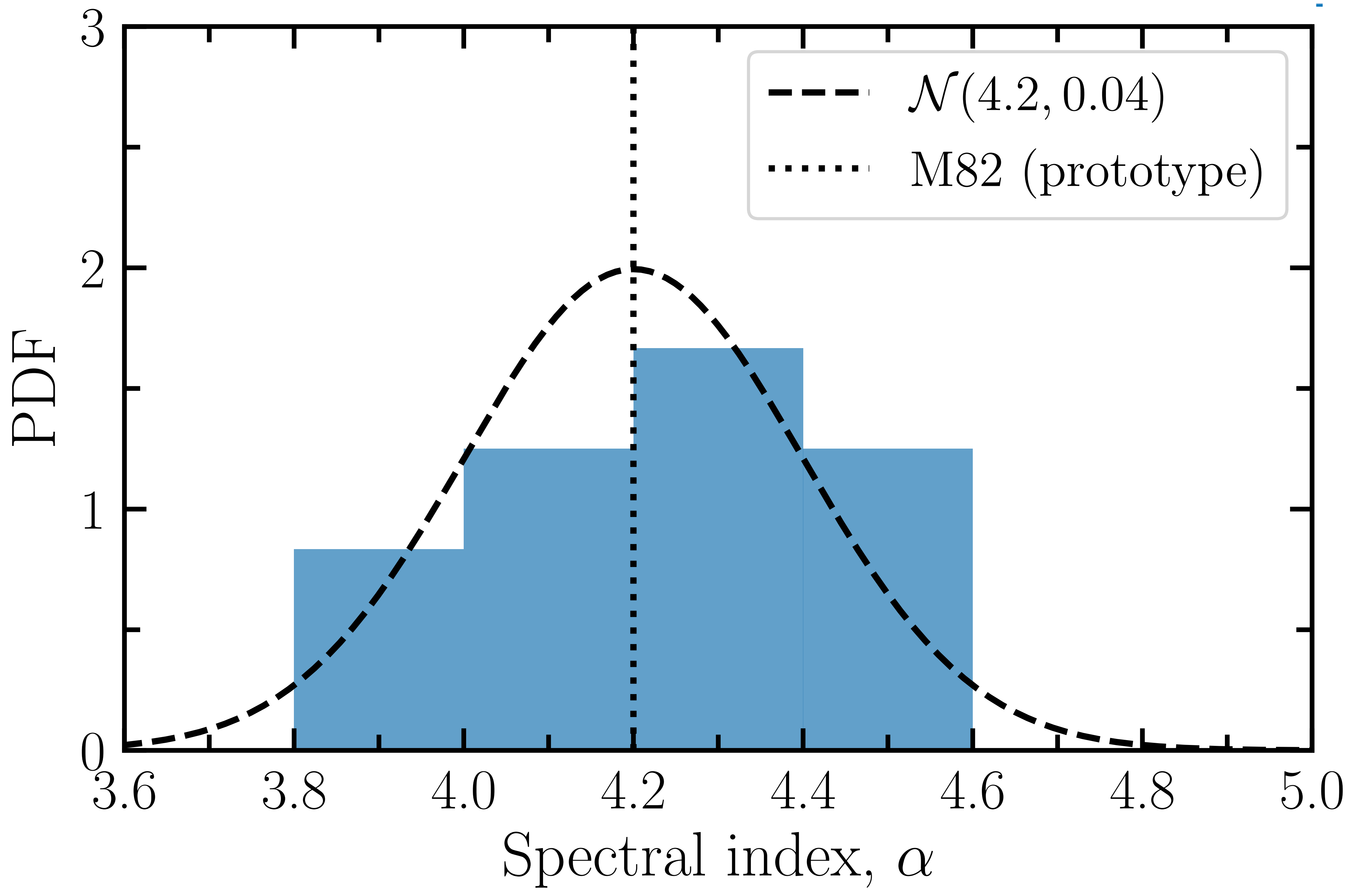
Diffuse Emissions: Blending Modelling

✦Each source has their own parameters (**Spectral index Blending!**)



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

Ambrosone+, [2011.02483]



Distribution of 12 SFGs and SBGs resolved in gamma-rays

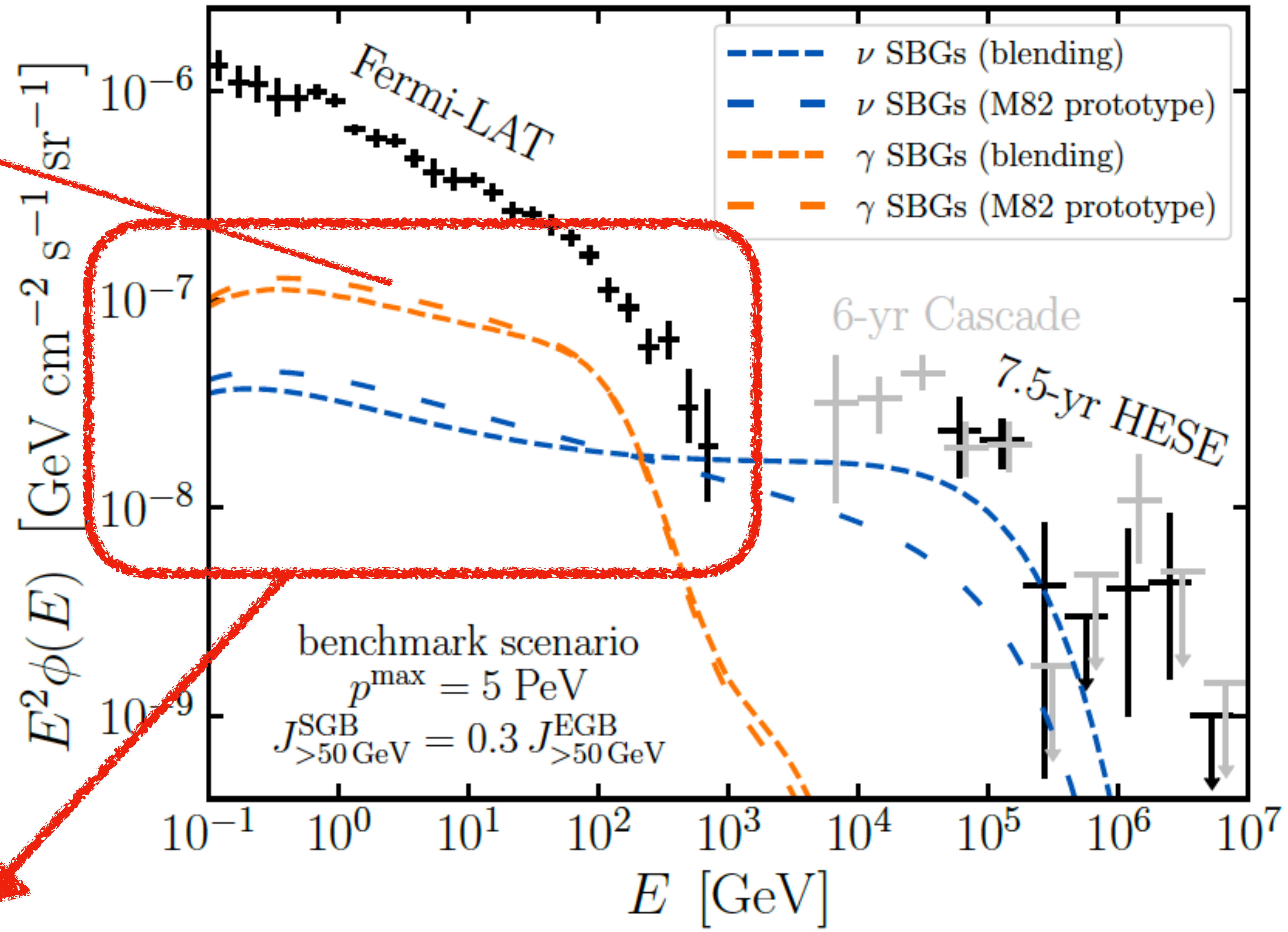
*Ajello+, ApJ 894 (2020) (**arXiv:2003.05493**)*

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

Blending Versus Prototype

Ambrosone+, 2011.02483

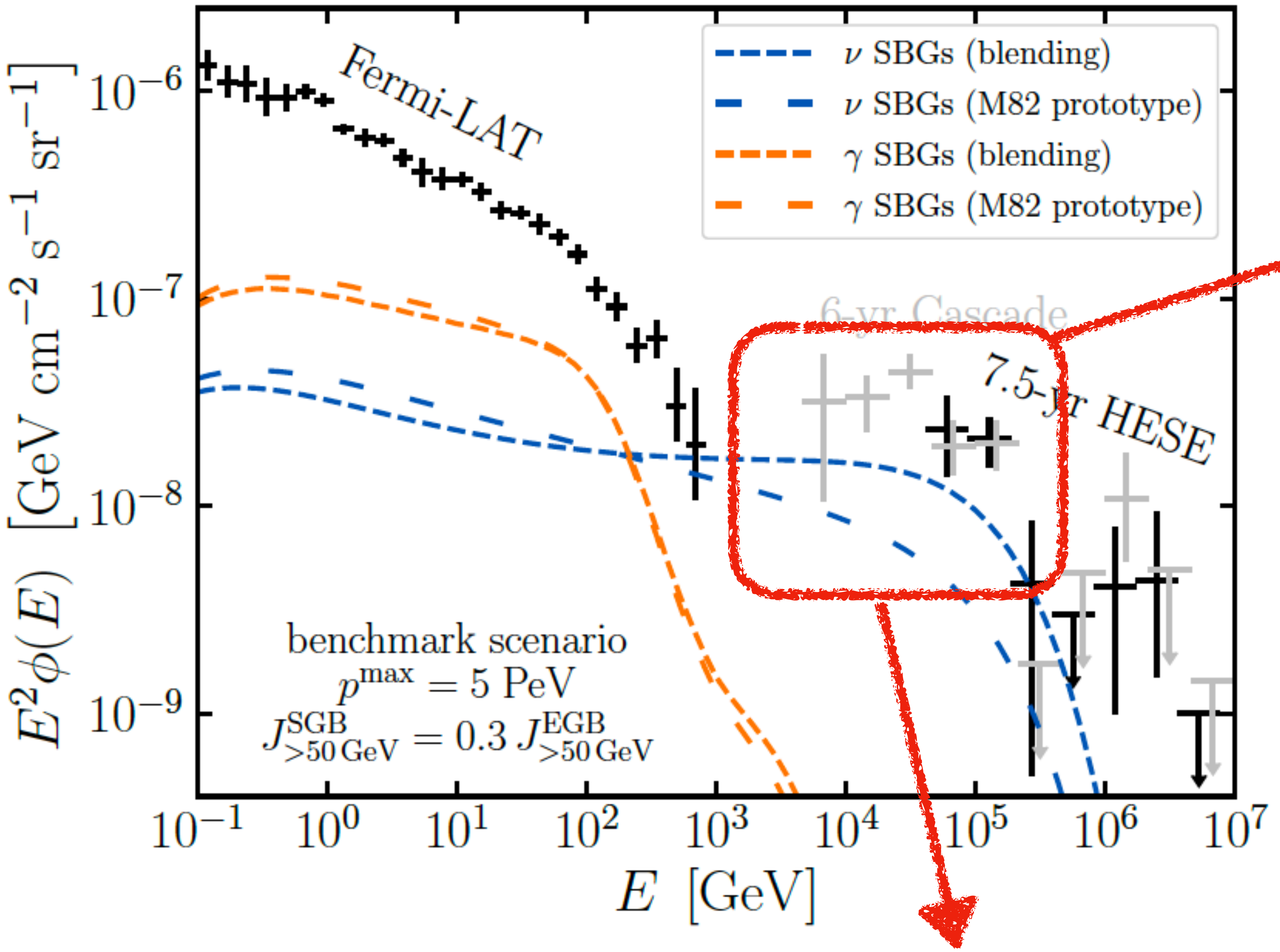
Direct + electromagnetic cascades gamma-ray flux



The diffuse gamma contributions are almost the same!

Blending Versus Prototype

Ambrosone+, [2011.02483](https://arxiv.org/abs/2011.02483)

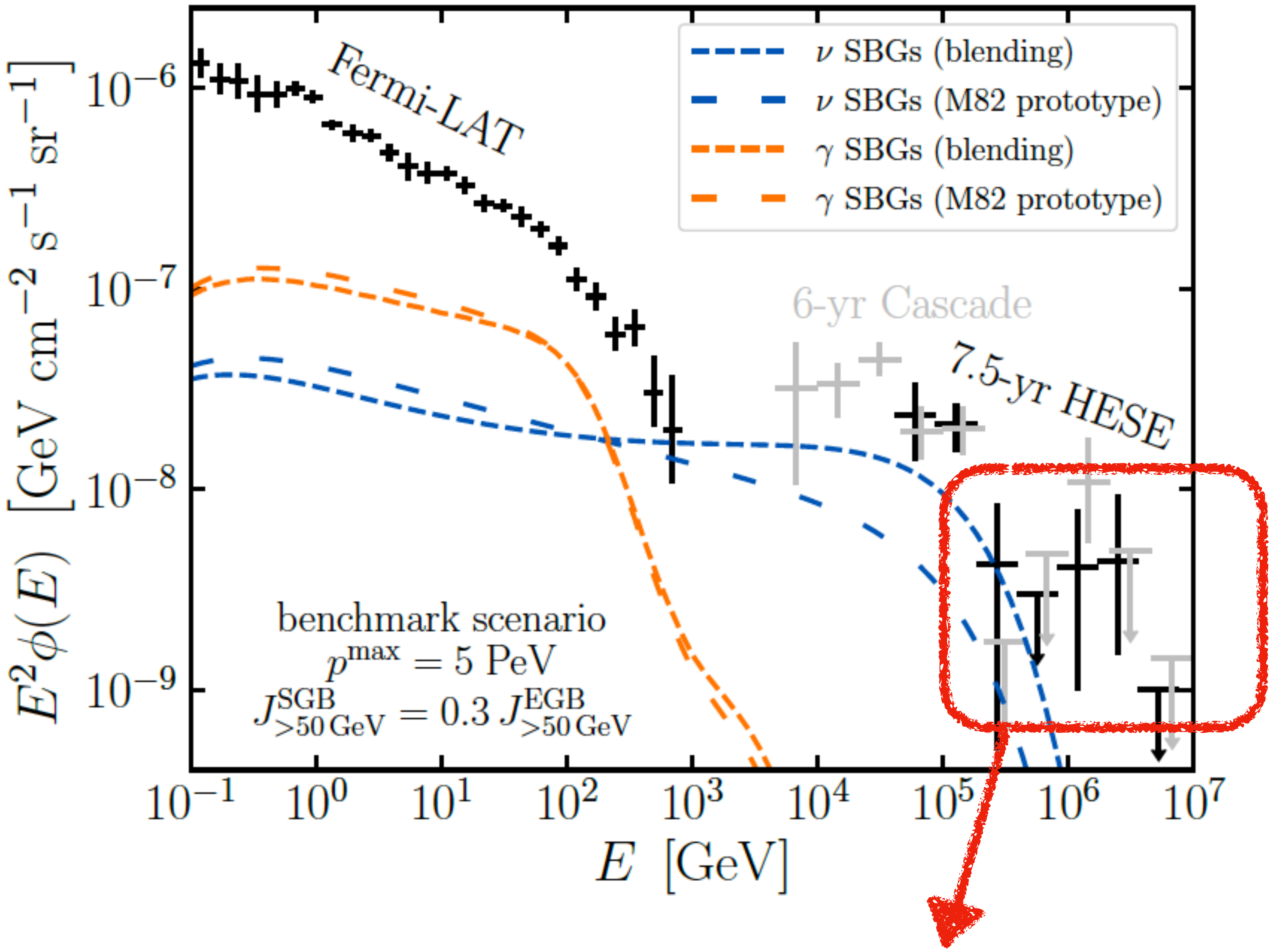


With $p^{\max} = \mathcal{O}(\mathrm{PeV})$ it is possible to give a significant contribution at around 100 TeV

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

Ambrosone+, **2011.02483**



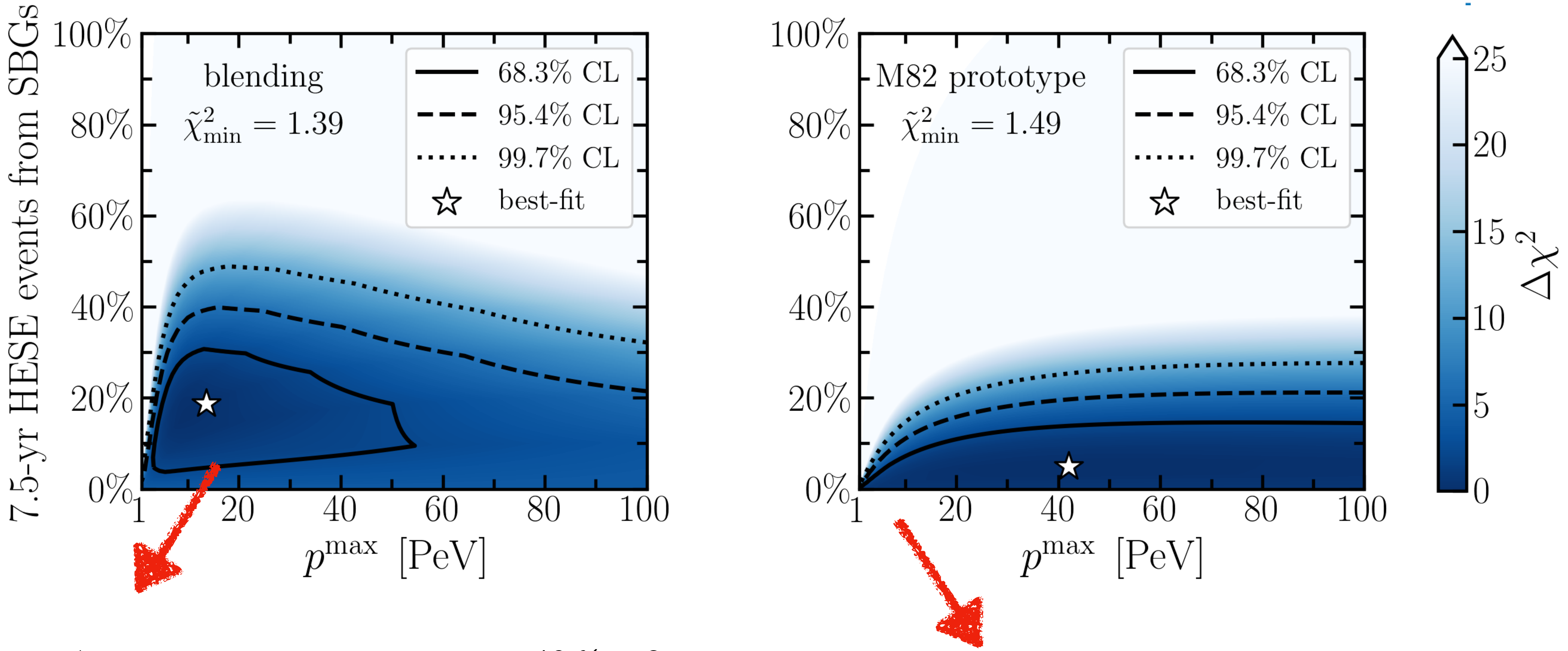
Other Contribution? A possible interplay between reservoirs and accelerators?

Multi-Messenger/Component Fit: The role of SBGs

We analyze **Fermi-LAT + IceCube** diffuse data, including: SBGs, Blazars and Radio Galaxies (Ajello et al. 2015 (ArXiv: 1501.05301), Palladino et. Al 2019 (ArXiv:1806.04769))

Main Result: Number of events produced by SBGs

Ambrosone+, 2011.02483



- Non-zero component at 1σ level. It can explain up to $\simeq 40\,\%$ at 2σ
- The cut-off is a bit constraints at $\sim$ O(PeV), which is consistent with the theoretical expectations

- Strongly constrained by the data. $\ll 10\,\%$
- No constraints no the cut-off

Multi-Messenger/Component Fit: The role of SBGs

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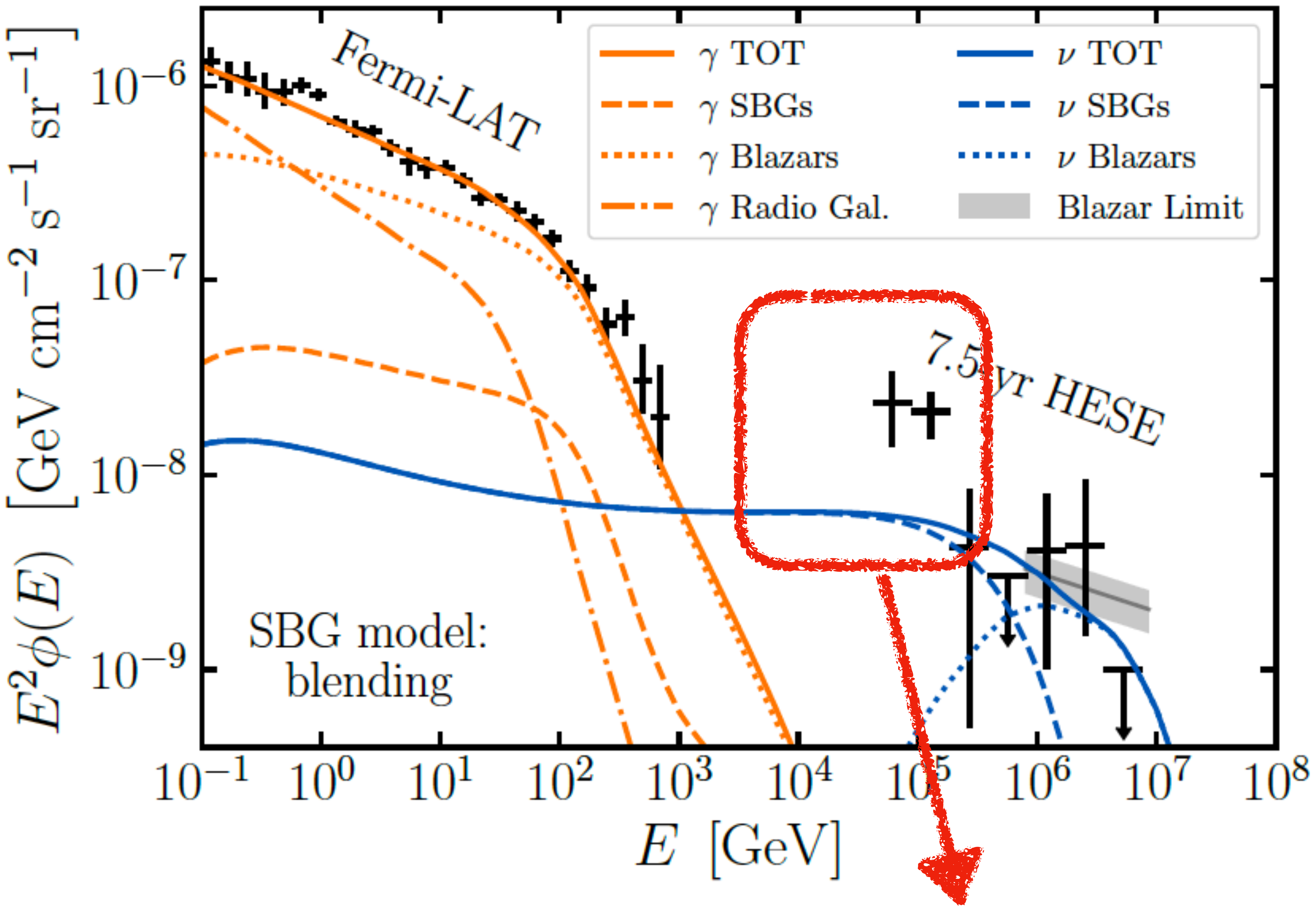
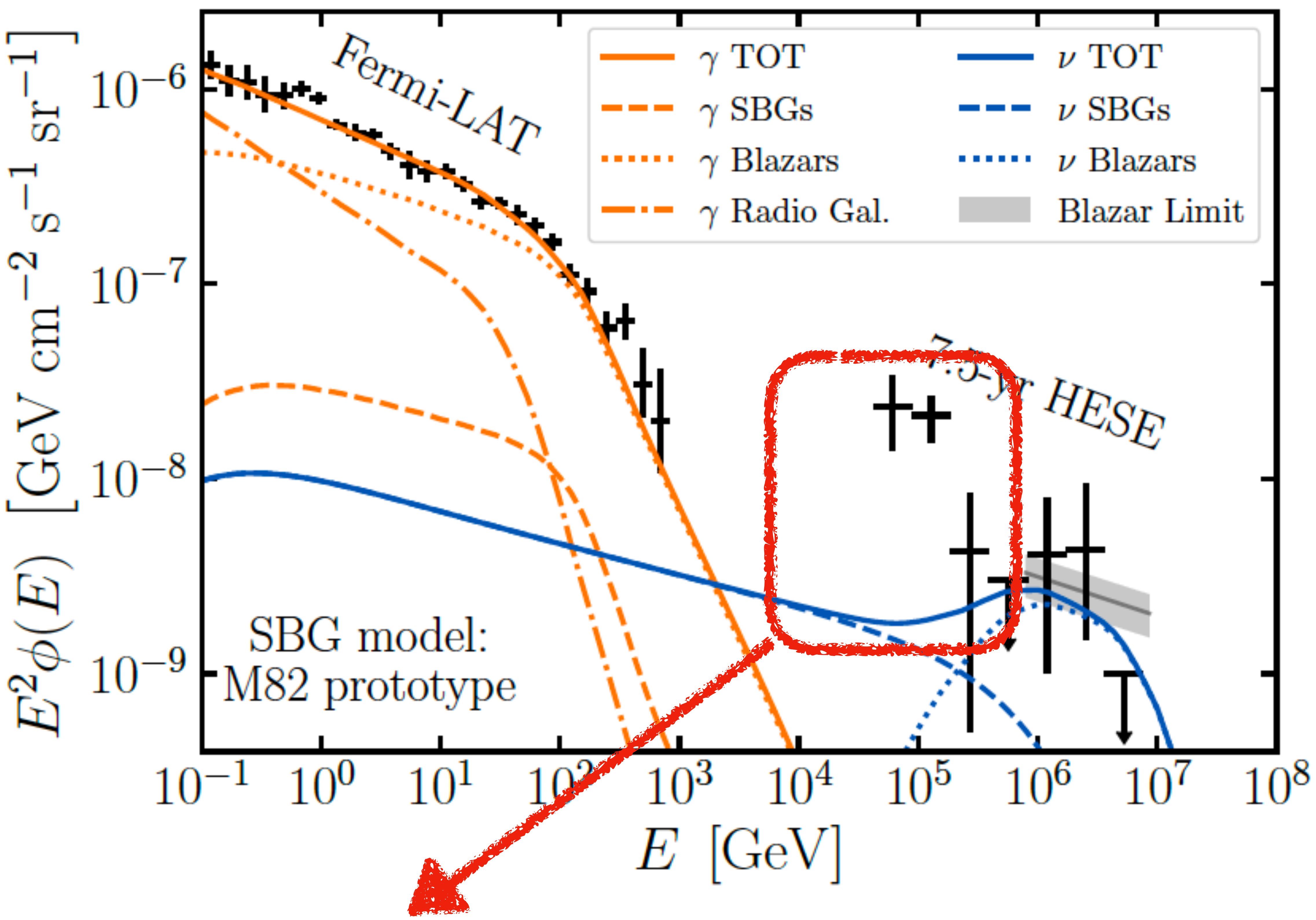
Best-fit SEDs

Ambrosone+, 2011.02483 **Blending Scenario**



Prototype Scenario *Ambrosone+, 2011.02483*

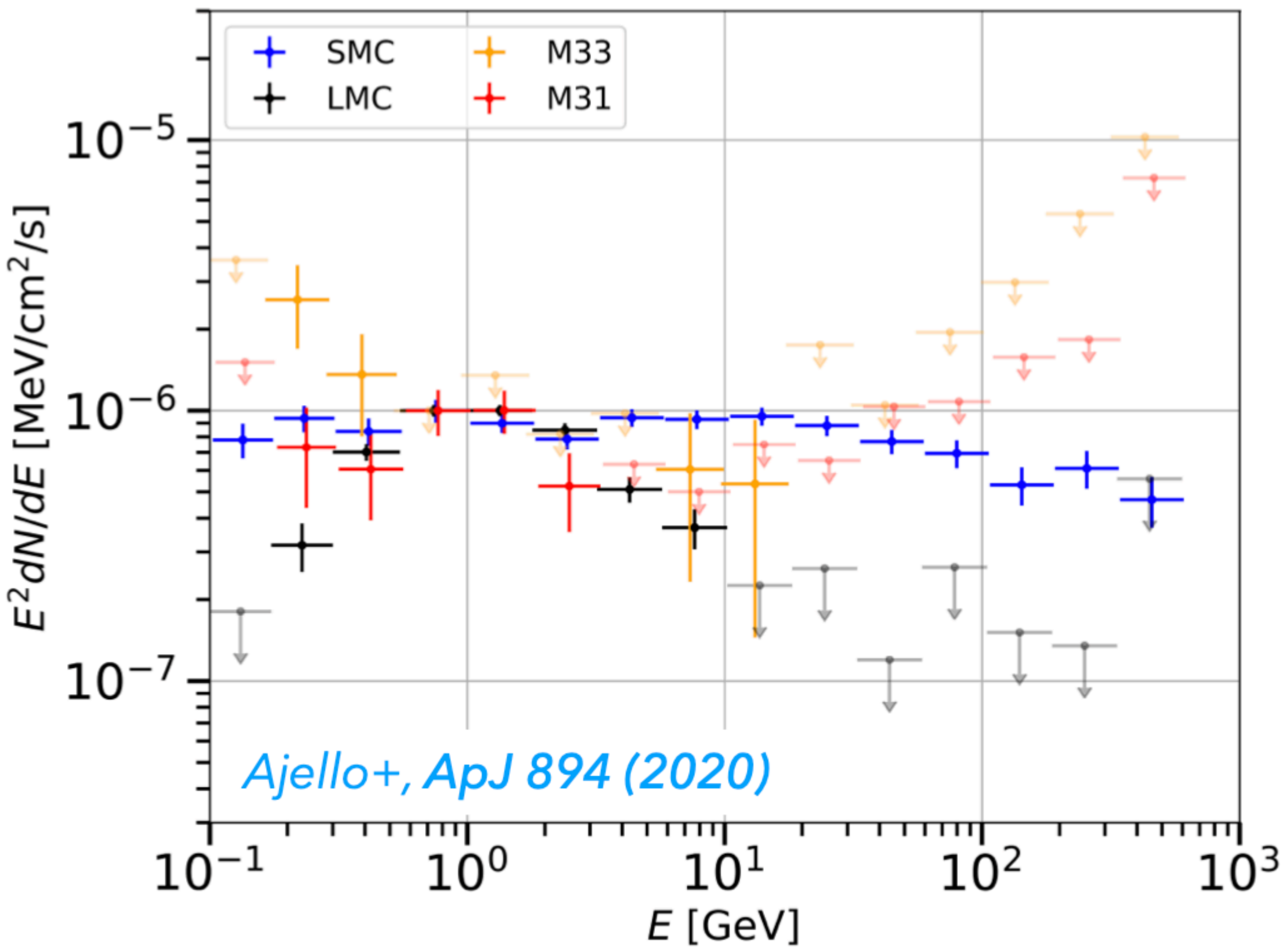


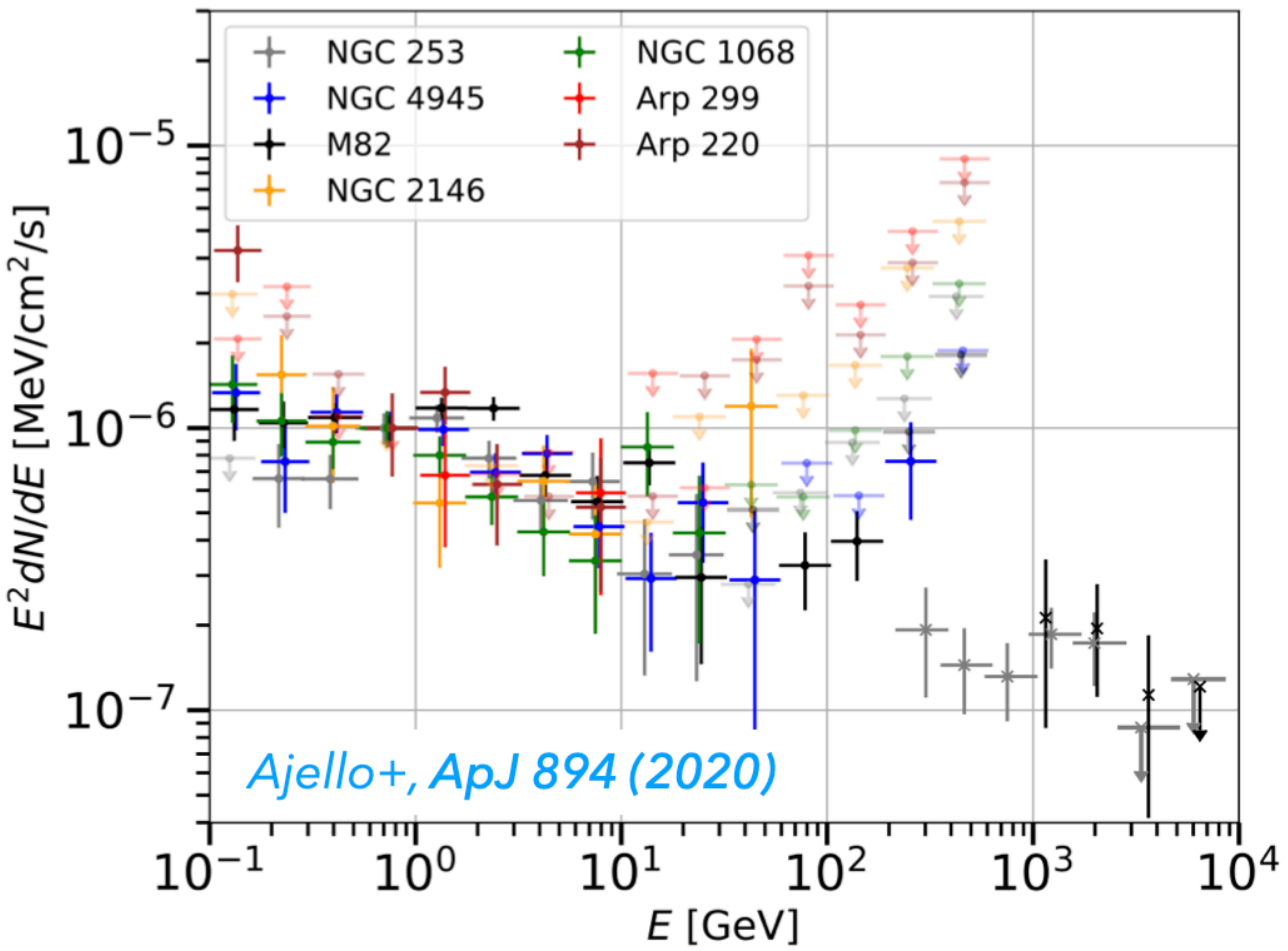
The Blending Scenario is ***expected to give*** *a greater contribution than the prototype scenario…but it is* ***not enough****…****Other Contributions?***

Can we probe either the calorimetric scenario or cosmic-ray transport using local /nearby SBGs?

Nearby SBG Gamma-Ray Emissions

✦ **Fermi-LAT data (GeV energies) + IACTs Telescope (TeV energies)**





✦ Only a dozen of sources have been detected
✦ Only few of them have both GeV and TeV data

For M82 also VERITAS measurements (VERITAS Collaboration et al., 2009, Nature, 462, 770). For NGC 253 also HESS measurements (H. E. S. S. Collaboration et al., 2018, A&A, 617, A73)

Probing the SBG Calorimetric Scenario

Ambrosone+, ApJL 919 [2106.12348]

Source	Uniform prior $\dot{M}_*$
M82	3.0 – 30
NGC 253	1.4 – 17
ARP 220	60 – 740
NGC 4945	0.35 – 4.15
NGC 1068	5 – 93
NGC 2146	3 – 57
ARP 299	28 – 333
M31	0.09 – 0.90
M33	0.09 – 0.90
NGC 3424	0.4 – 5.4
NGC 2403	0.1 – 1.2
SMC	0.008 – 0.090
Circinus Galaxy	0.1 – 8.1

We analyze the observed nearby SBG Gamma-ray SED: Bayesian approach

- ✦ We use both GeV and TeV gamma-ray data (Fermi-LAT + IACTs data)
- ✦ IR + UV data: Prior on the star formation rate
- ✦ Starburst Nucleus of the order of 10^2 pc $\quad f(p) = Q(p)\tau_{pp} \cdot F_{\rm cal}(E)$
- ✦ Escaping phenomena dominated by advection
- ✦ Using Kennicutt's relations:

$$n_{\rm ISM} = 175 \left(\frac{\dot{M}_*}{5\ {\rm M_\odot\ yr^{-1}}} \right)^{2/3} {\rm cm^{-3}} \qquad U_{\rm rad} = 2500 \left(\frac{\dot{M}_*}{5\,{\rm M_\odot\ yr^{-1}}} \right) {\rm eV\ cm^{-3}}$$

Gas density as target for p-p interactions

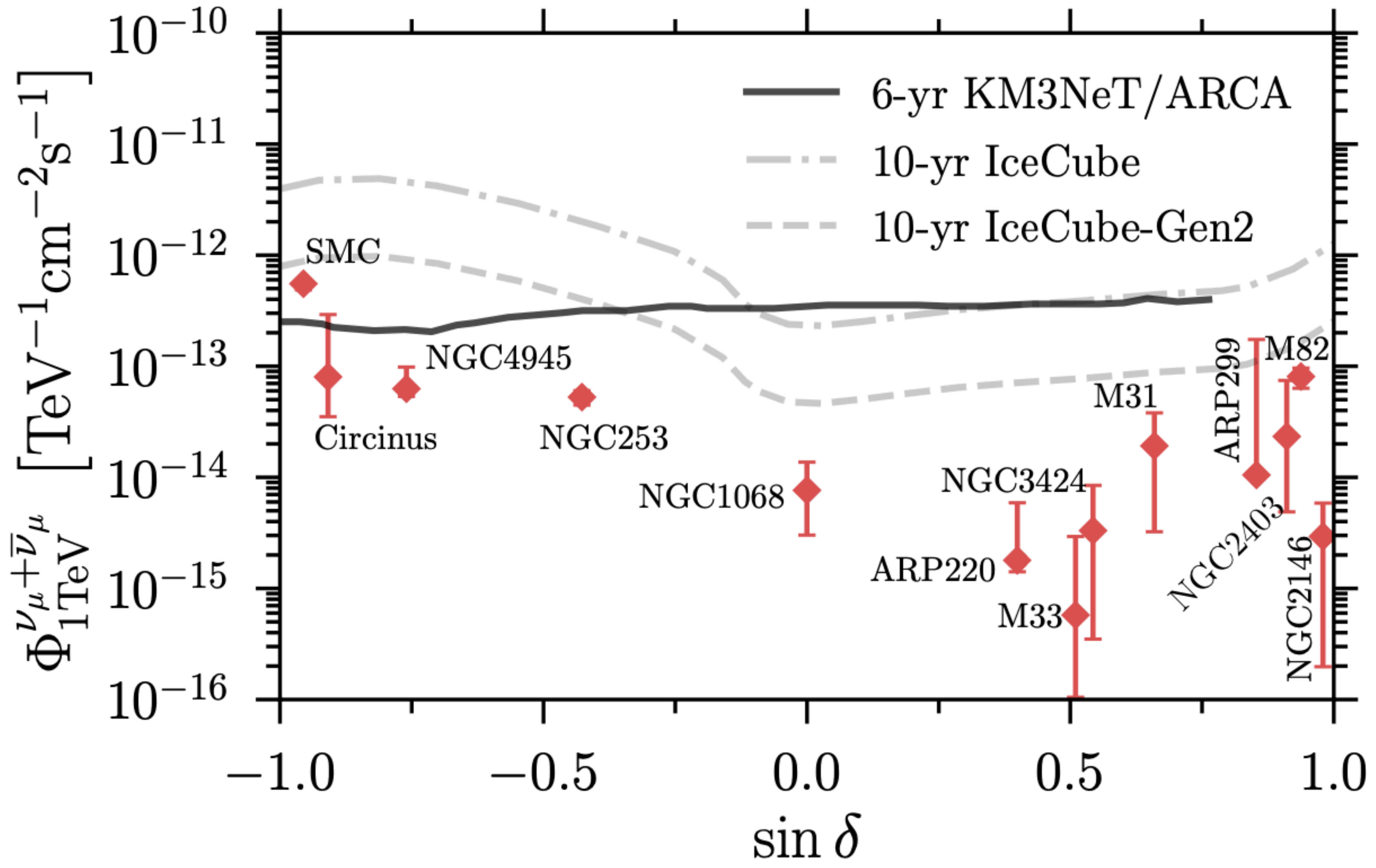
Photon energy density as target for secondary production

Kennicutt, ARA&A 36 (1998); Inoue+, PASJ 52 (2000); Hirashita+, A&A 410 (2003); Yuan+, PASJ 63 (2011); Kennicutt and Evans, ARA&A 50 (2012); Kennicutt & De Los Reyes, ApJ 908 (2021)

Probing the SBG Calorimetric Scenario

Ambrosone+, ApJL 919 [2106.12348]

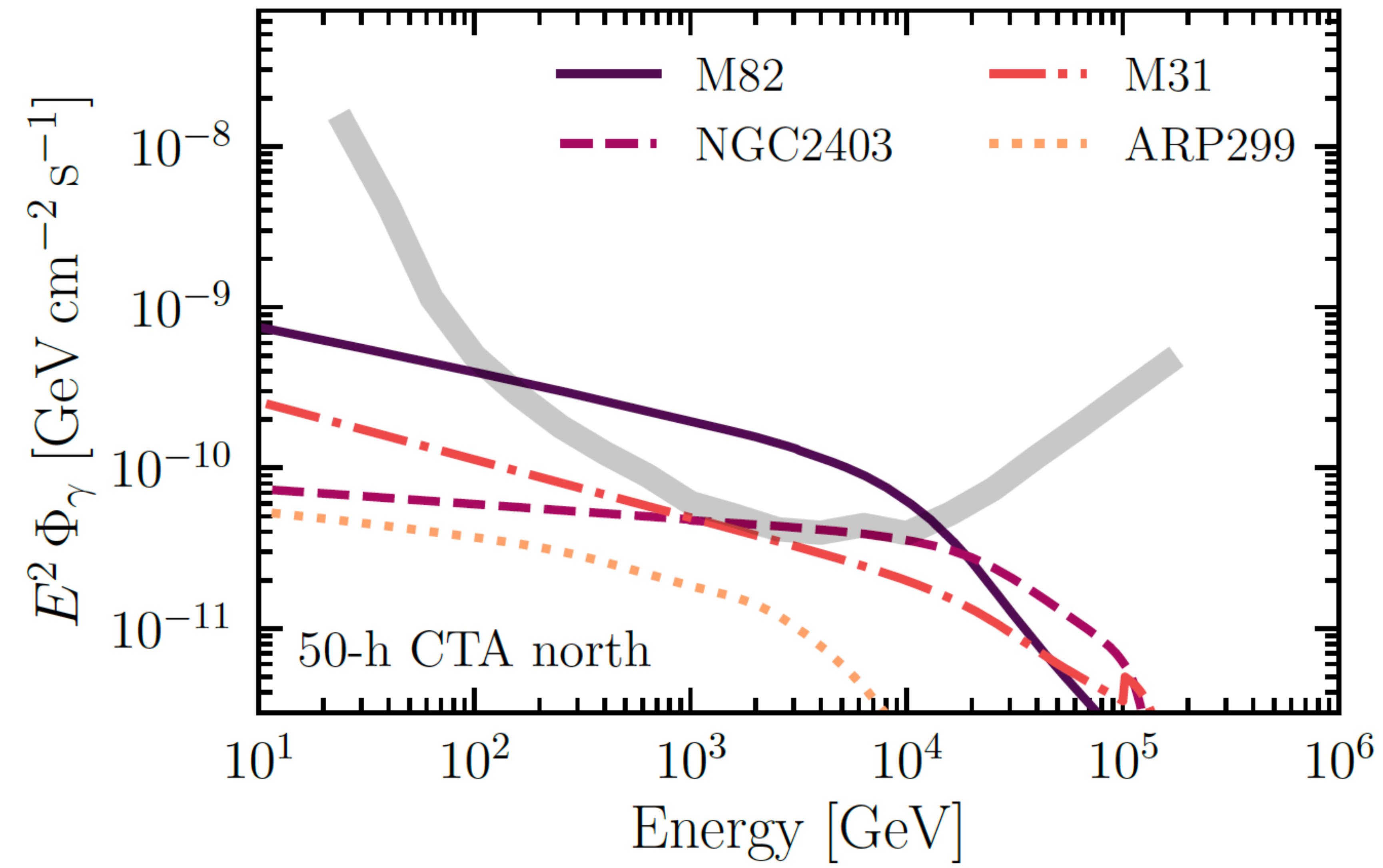
Neutrino Expectations: KM3NeT Forecast

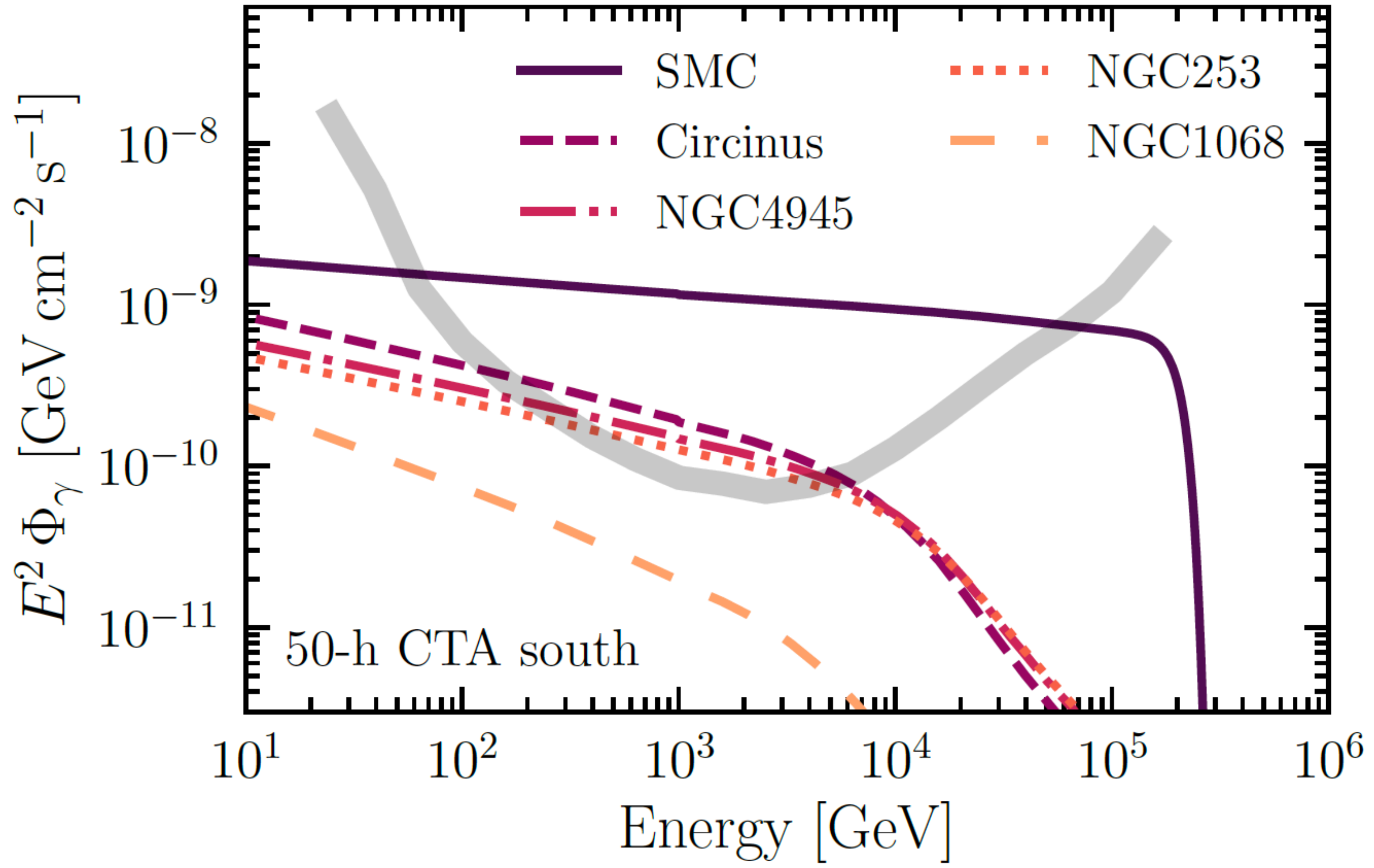


Future γ/ν observations will be fundamental to:

- ✦ Discover if Neutrino Astronomy is a tracer for star-forming activity
- ✦ Probe the calorimetric fraction inside SBG: If there will be no detection, nearby SBGs are dominated by diffusion and not by either p-p collisions or advection.

Gamma-Rays Expectations. CTA Forecast





Probing the Cosmic-Ray Transport inside SBGs

Cosmic- Ray Transport Mechanism inside SBGs are, **however**, model-dependent.

Model A (adopted in the previous results):

$$f(p) = Q(p)\left(\frac{1}{\tau_{\mathrm{loss}}} + \frac{1}{\tau_{\mathrm{adv}}} + \frac{1}{\tau^{A}_{\mathrm{diff}}}\right)^{-1}$$

Peretti+, MNRAS 487 (2019)

- They are global phenomena in SBGs
- The diffusion of CRs occurs along pre-existing (strong) magnetic turbulence. This leads to a small diffusion coefficient

→ Fcal is almost independent of the energy! Protons either get trapped or they escape through advection

Model B

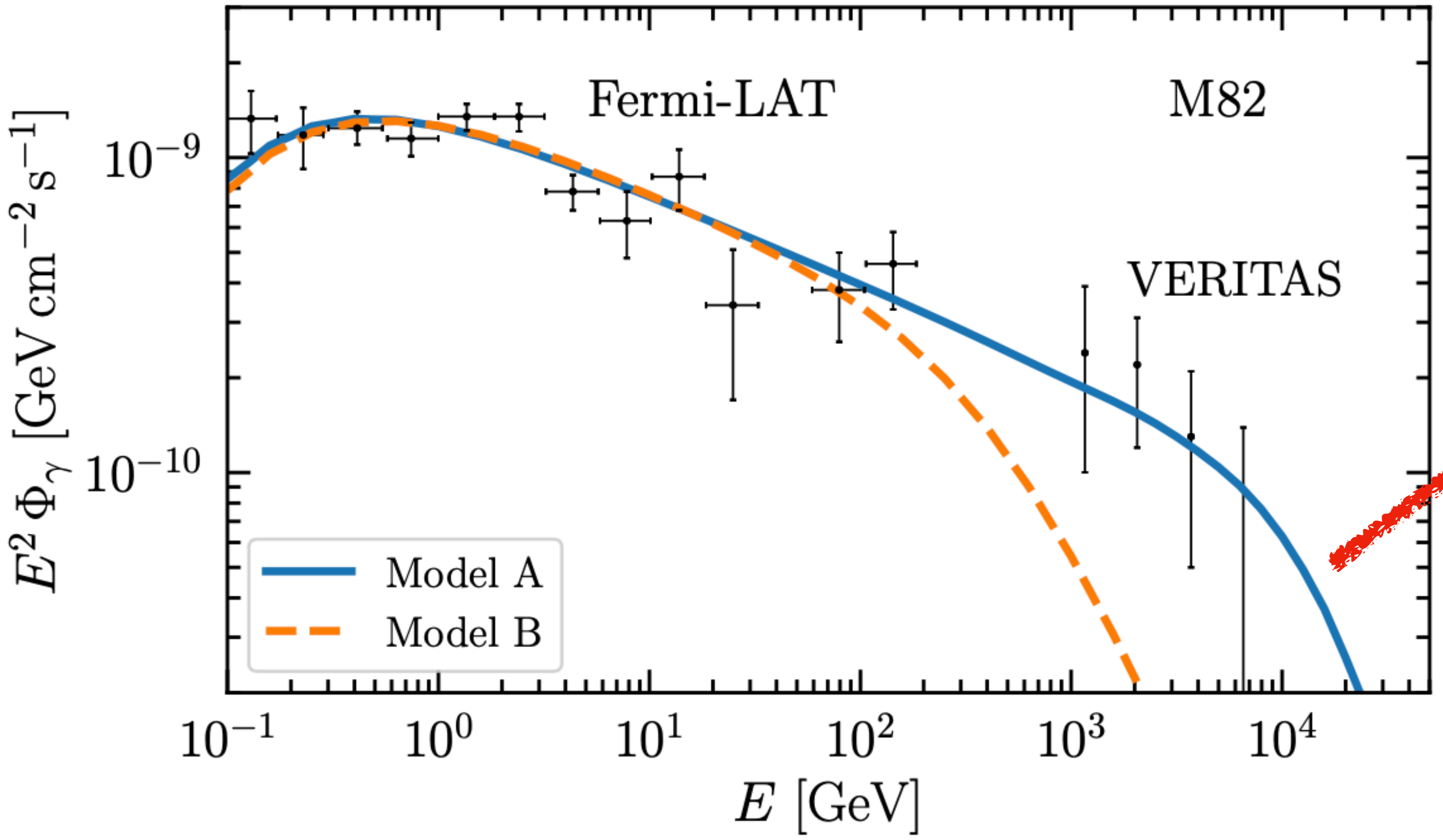
$$f(p) = Q(p)\left(\frac{1}{\tau_{\mathrm{loss}}} + \frac{1}{\tau^{B}_{\mathrm{diff}}}\right)^{-1}$$

Krumholz+, MNRAS 493 (2020)

- Advection is negligible process
- Diffusion of CRs occurs by self-generated streaming instability. This leads to a high diffusion coefficient

→ Fcal strongly depends on the energy above $\sim 50 - 100\,\mathrm{GeV}$

Ambrosone +, MNRAS [2203.03642]



TeV Gamma-rays from Model B are suppressed due to major role of diffusion

TeV Measurements are fundamental: CTA Forecast

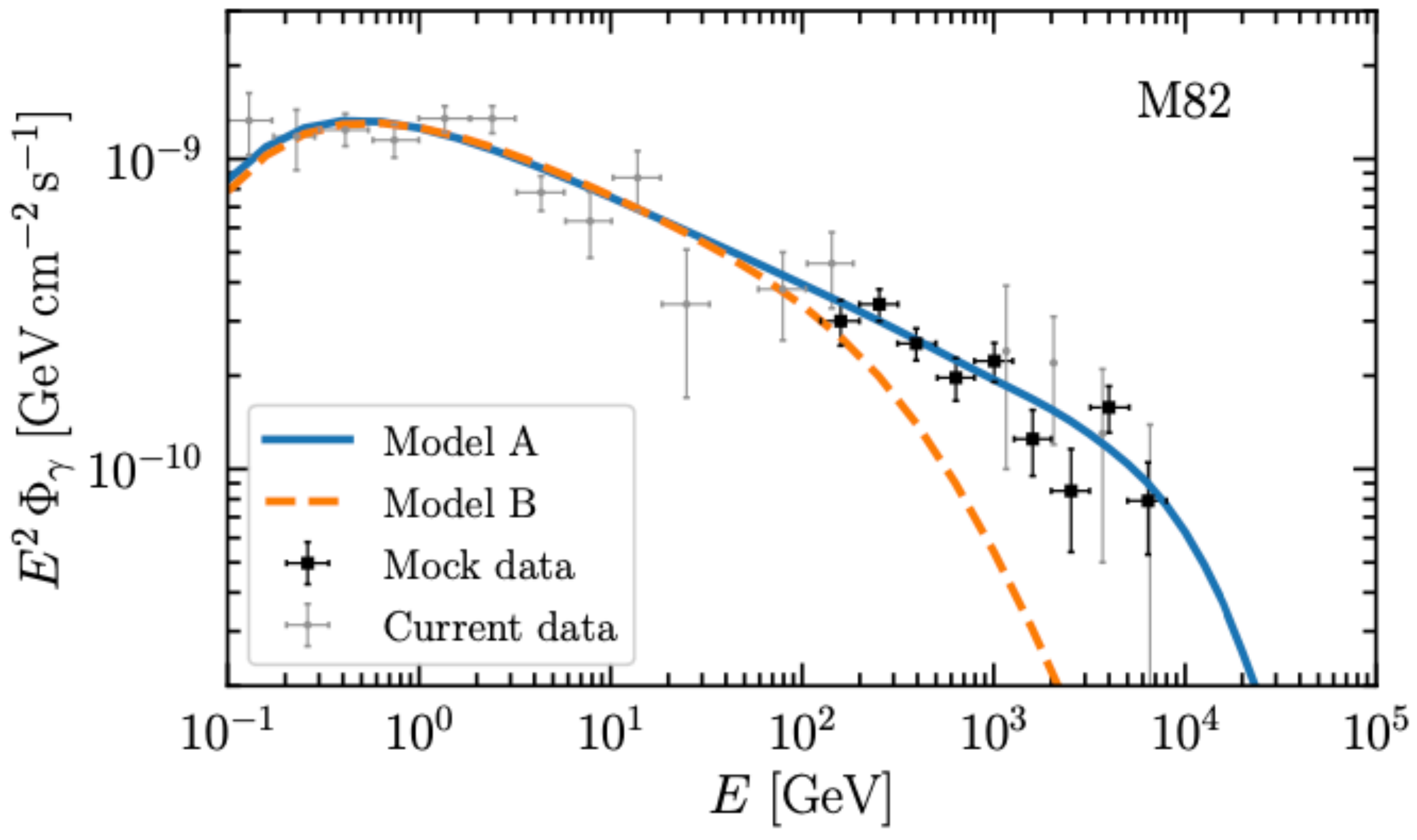
We test Krumohlz + (model B) by means of CTA mock data simulations assuming Peretti + (Model A)

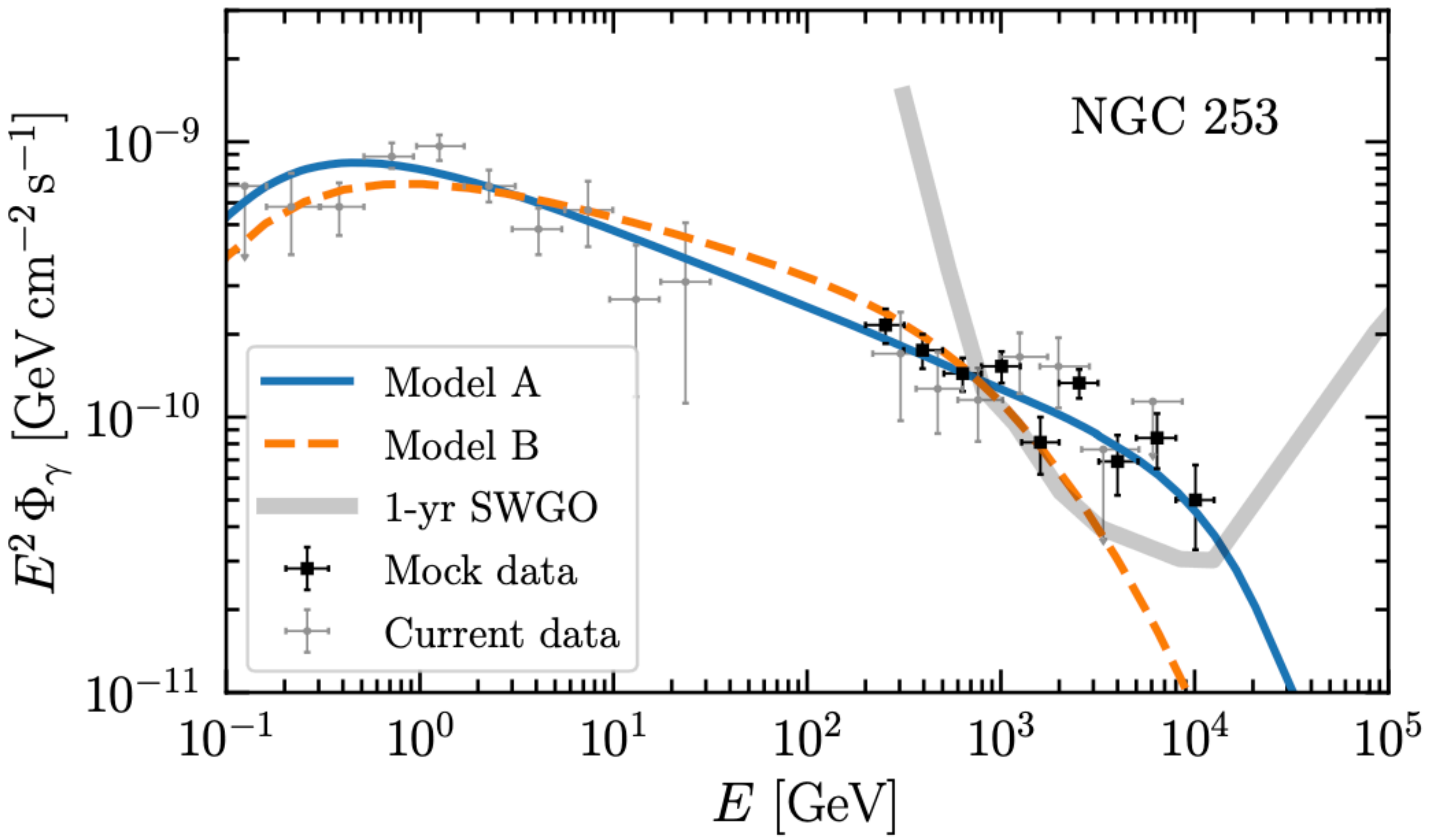
Ambrosone +, MNRAS [2203.03642]

✦Generation of 10^4 sets of mock SED data

✦ CTA Info from: Acharya+, 1709.07997

✦ SWGO Info from: Albert+, 1902.08429 Hinton, PoS ICRC2021 023





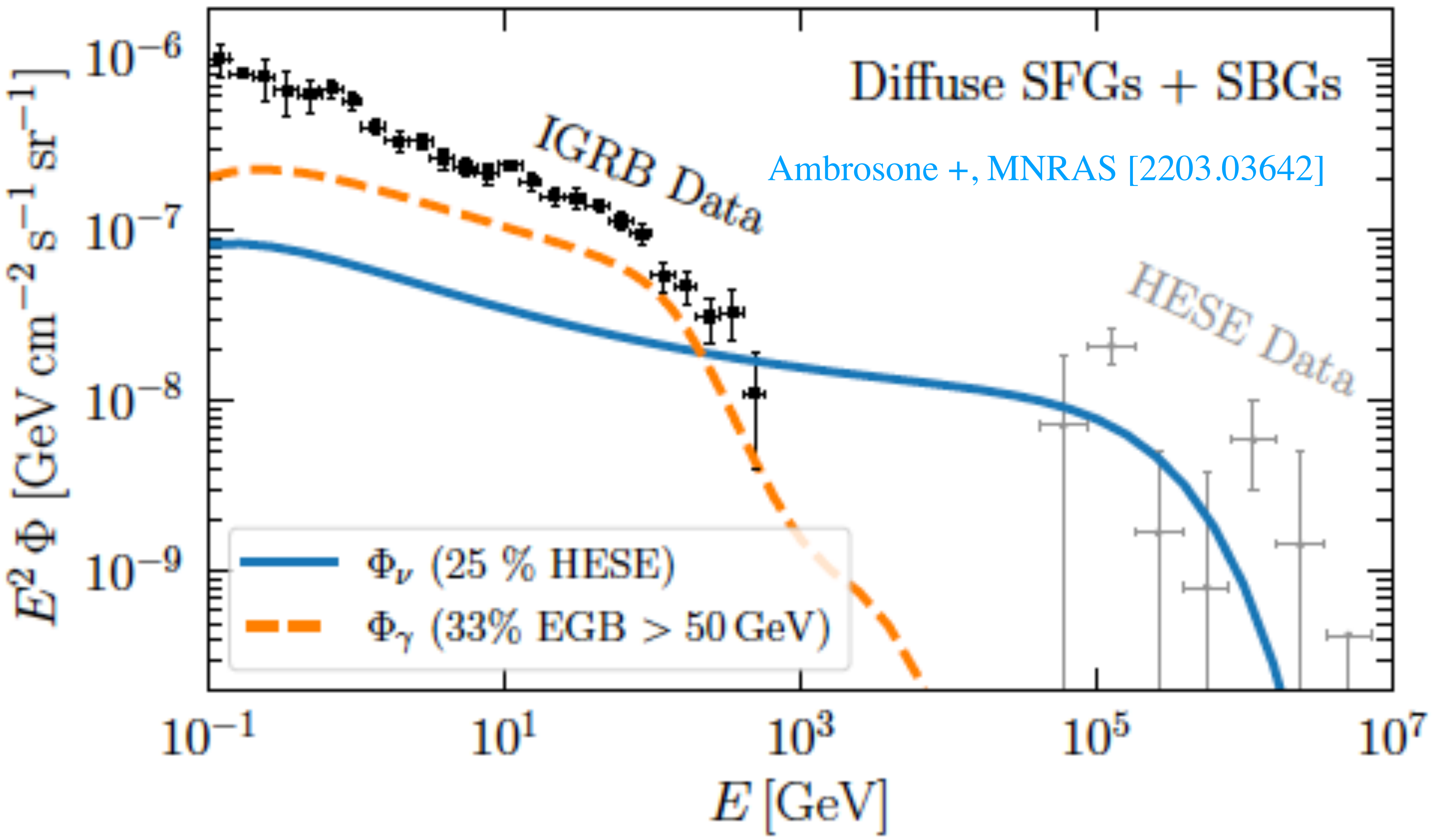
Future Measurements should be able, despite astrophysical uncertainties, to distinguish between the two scenario at more than 2σ level!

This will have significant repercussion on Neutrino Prediction as well!

Implications on Neutrino Astronomy

Different CR mechanism scenarios might well give a different contribution to the diffuse emissions

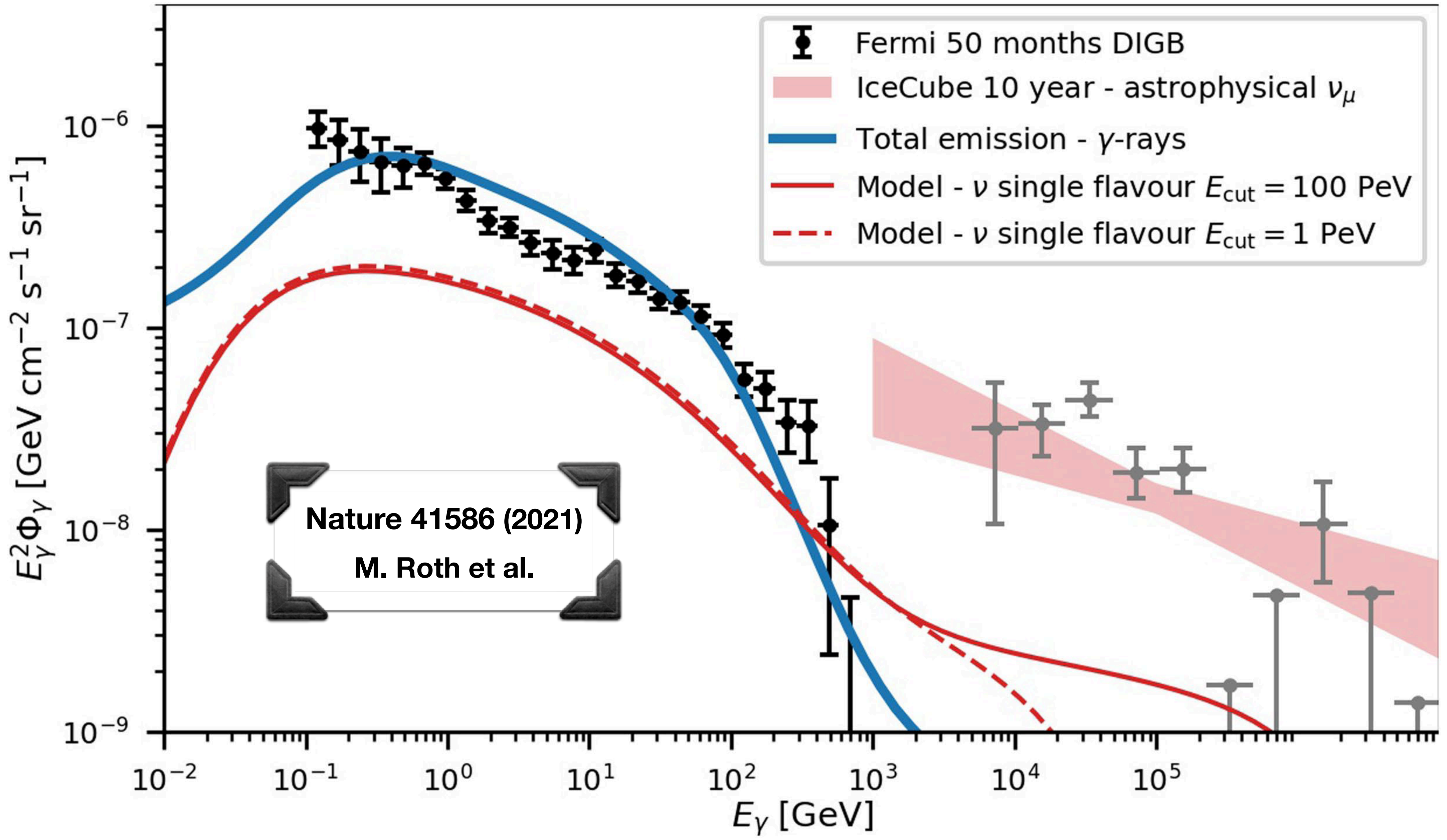
Model A (Peretti+, MNRAS 487 (2019))



Fcal is independent on energy. The calorimetric approach is justified

- ✦ Important contribution to Neutrinos (25% of the HESE)
- ✦ Important Contribution to gamma-rays (33% of the EGB)

Model B (Krumholz+, MNRAS 493 (2020))



Fcal is dependent on the energy above $\sim 100\,\mathrm{GeV} - 1\,\mathrm{TeV}$

- ✦ Negligible contributions to Neutrinos
- ✦ Important Contributions to gamma-rays (which can saturate the DIGB)

Attention: Due to uncertain origin of the diffuse emissions data, we cannot use them to discrminate between the two CR transport models

Conclusions and Outlooks

- ✦ SBGs are promising high-energy emitters: they can contribute up to 40% to the IceCube astrophysical neutrino signal
- ✦ Increasing the number of the gamma-ray catalogued SBGs is fundamental to constrain their diffuse neutrino contribution.
- ✦ Some Nearby SBGs can produce a point-like excess within few years of data taking of the upcoming KM3NeT Telescope
- ✦ Upcoming gamma-ray telescopes will give us a better understanding of the cosmic-ray transport inside SBGs.
- ✦ Global Neutrino Network + CTA/SWGO surveys of the closer SBGs can solve the puzzle

Back-up Slides

About the Multi-Component Fit

Ambrosone+, 2011.02483

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:
1. SBGs
2. Blazars

For Blazars, we used the estimations given by Palladino et. Al 2019 **(ArXiv:1806.04769)**

Observational Data Samples Used

Extragalactic gamma-ray Background (EGB)

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

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

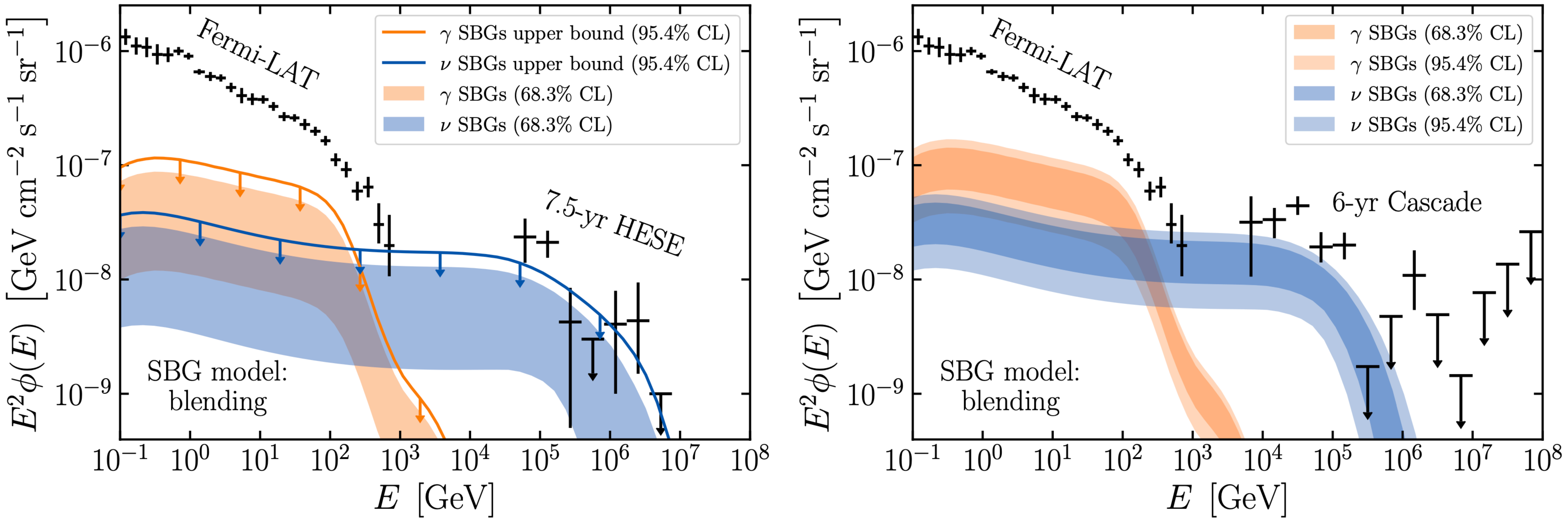
Joint γ/ν fit with 4 free parameters

They come from uncertainties of the Non-SBG components

It comes from the positional limit of Point Sources above 50 GeV (Lisanti et al. 2016) , ApJ 832 2016

Diffuse SBG Contribution Upper Limits

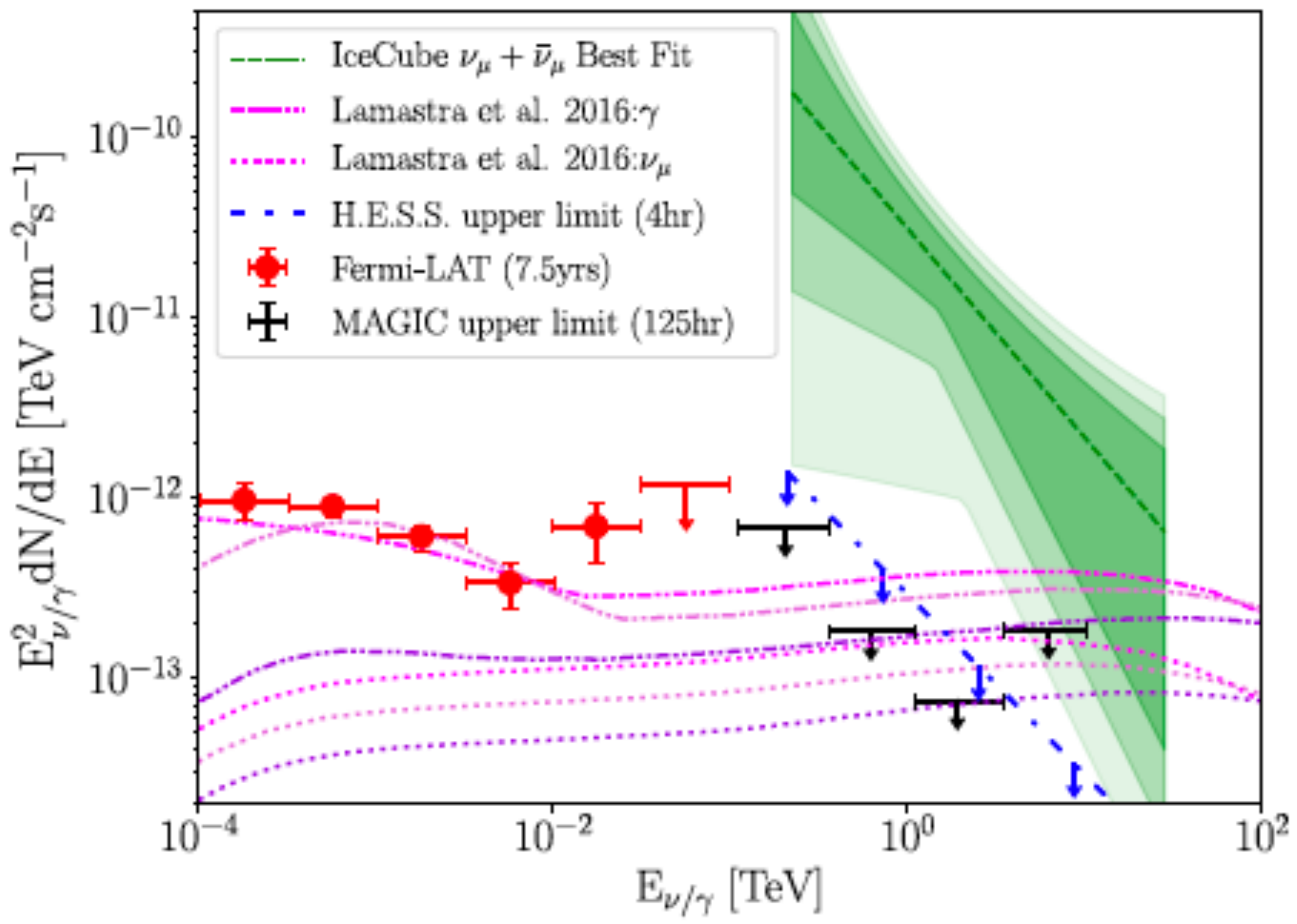
Ambrosone+, **2011.02483**



The Special Case of NGC 1068

PRL 124 (2020) IceCube

May the NGC-1068 star-forming activity explain this excess?



The IceCube Collaboration has found a 2.9σ excess into the 10-year data

The gamma-ray spectrum is much lower than the observed neutrino flux → **SBG activity cannot explain this excess! It is needed AGN activity. Hot Corona Activity?**

APJL 891 (2020) Inoue et al.
PRL 125 (2020) Murase et al.