Gamma-ray and neutrino emissions from star-forming and starburst galaxies

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

with **A. Ambrosone**, **D.F.G. Fiorillo**, **A. Marinelli**, **G. Miele**, and **O. Pisanti**

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NAP Theory

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Starburst galaxies (SBGs)

The Starburst Galaxy M82

Properties of SBGs

- ✦ Galaxies with high star-formation rate (~100 $M_\odot$/yr, to be compared with ~3 $M_\odot$/yr in the Milky Way)
- ✦ Dense interstellar gas ($n_{\rm ISM}$ > 100 cm^{-3})
- ✦ Not very brilliant in γ-rays (only a few currently observed)
- ✦ **Cosmic reservoirs:** protons confined for about ~10^5 yr
- ✦ **Hadronic production:**

Interstellar gas as the target

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

Injected CRs with power-law spectrum $Q(p) \propto p^{-\alpha} e^{-p/p_{p,\max}}$

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

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

Modelling SBGs point-like emission

In the calorimeter scenario, three main parameters:

- ✦ Cut-off energy
- ✦ Spectral index
- ✦ Rate of SuperNovae explosions

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

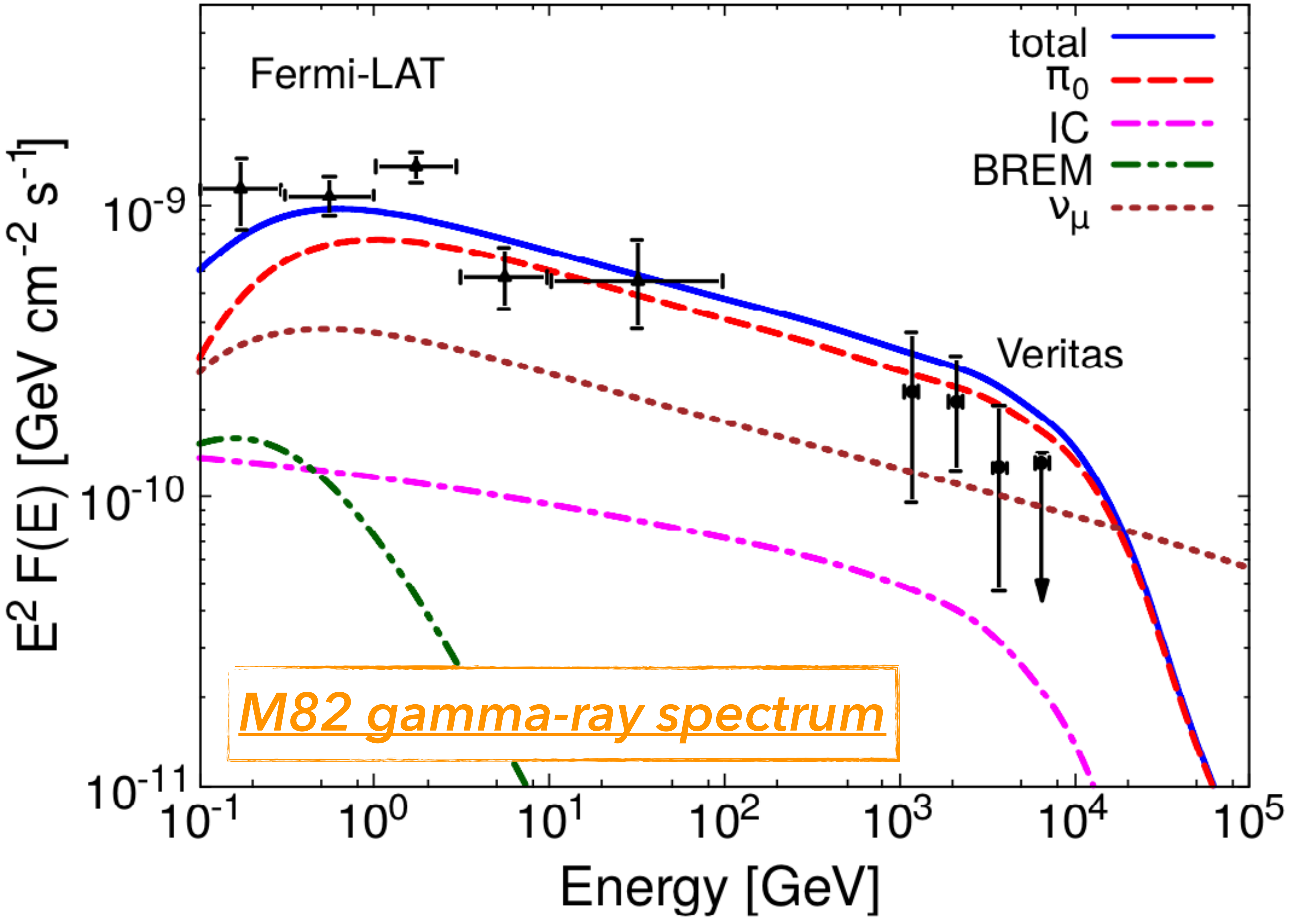
parameter	value
$\mathcal{R}_{\rm SN}$	0.06 yr^{-1}
B	200 μG
$n_{\rm ISM}$	100 cm^{-3}
$v_{\rm wind}$	700 km/s
$U_{\rm rad}$	2500 eV/cm^3

Peretti+, MNRAS 487 (2019), MNRAS 493 (2020)

Leaky-box-like model for CR transport

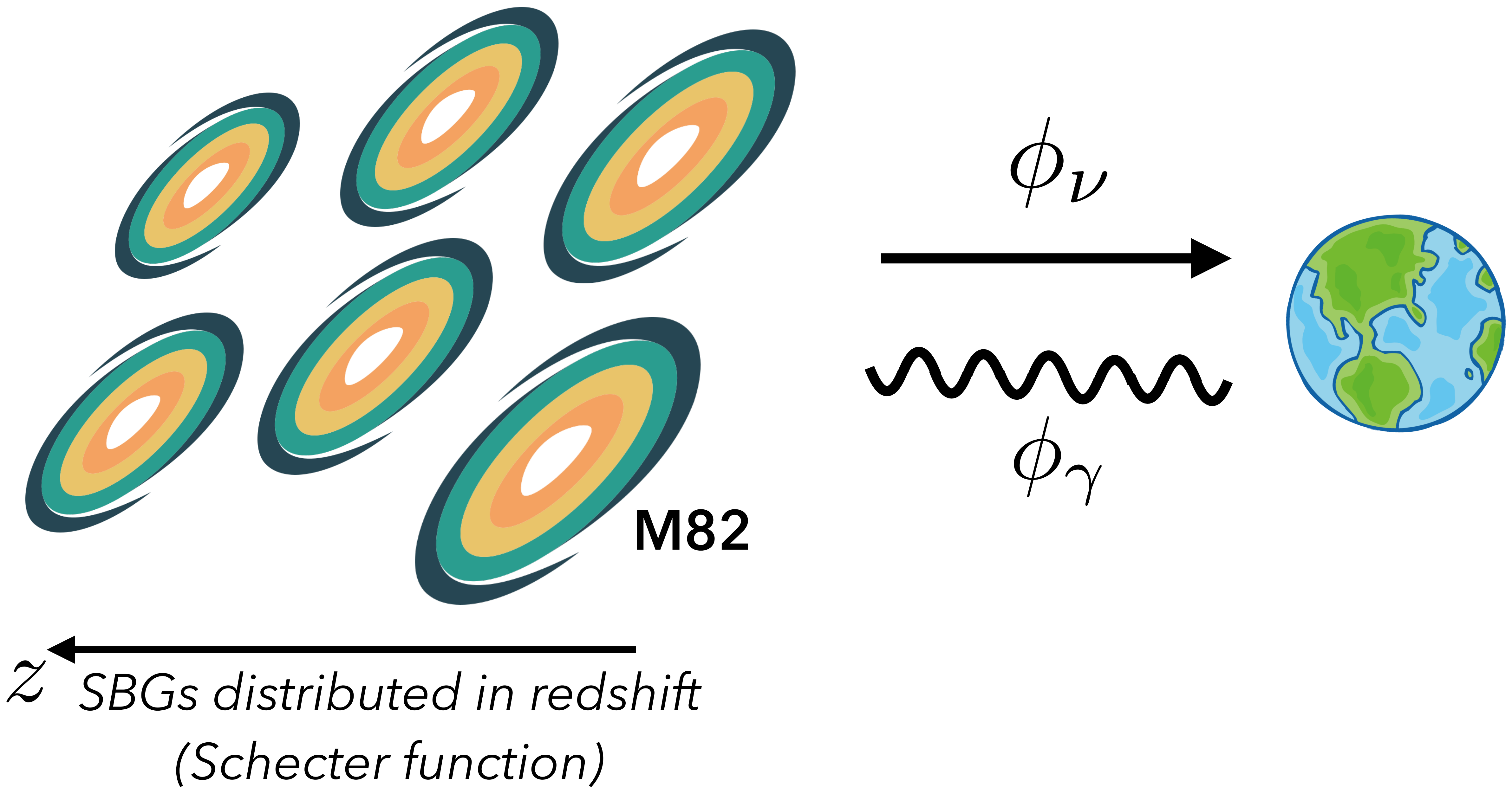
$$f(p)\left(\frac{1}{\tau_{\rm loss}(p)}+\frac{1}{\tau_{\rm adv}(p)}+\frac{1}{\tau_{\rm diff}(p)}\right)=Q(p)$$

injected CR from SN explosion



Modelling SBGs diffuse emission

✦ **Prototype model:** all the SBGs are equal to a galaxy with "known" parameters (e.g. M82)

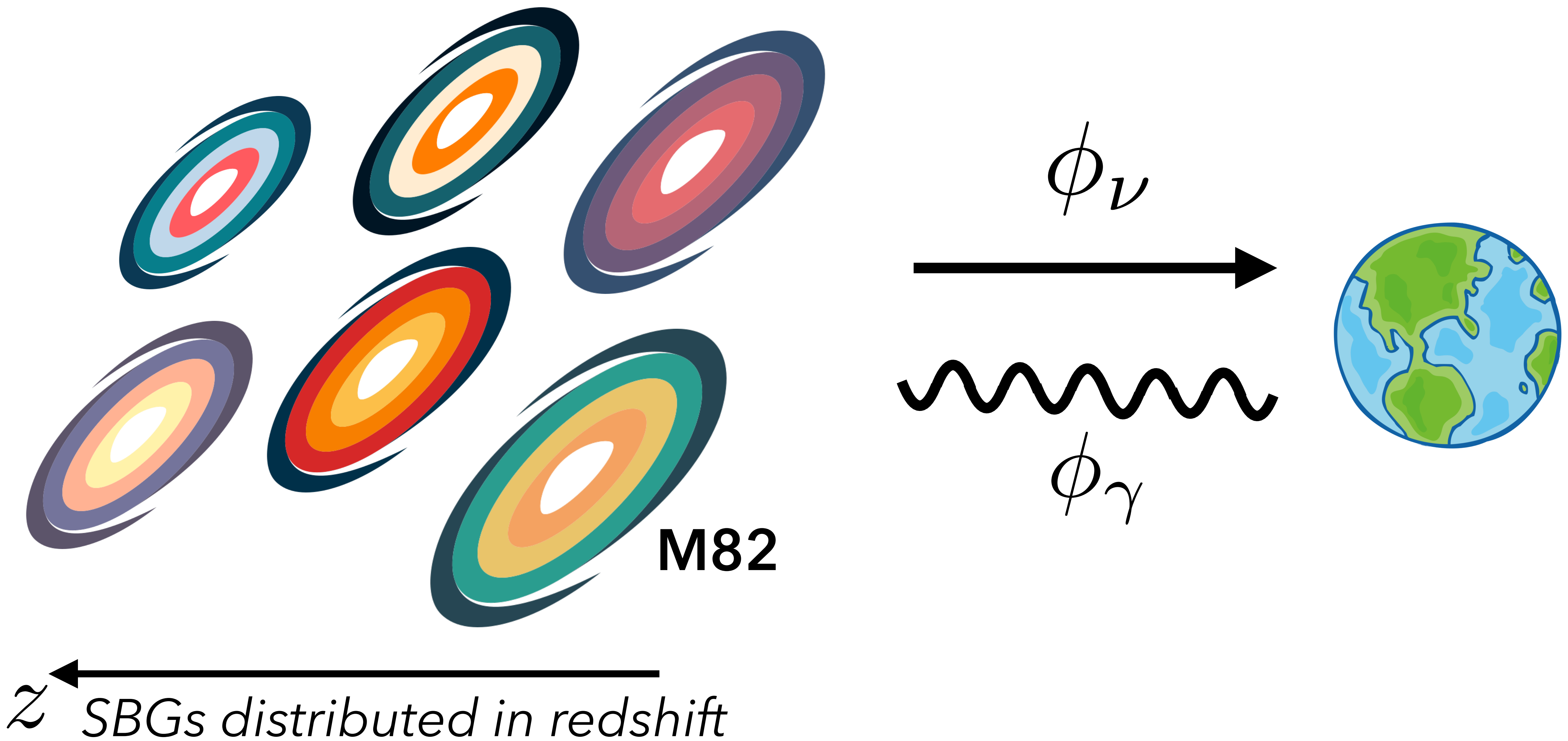


Modelling SBGs diffuse emission

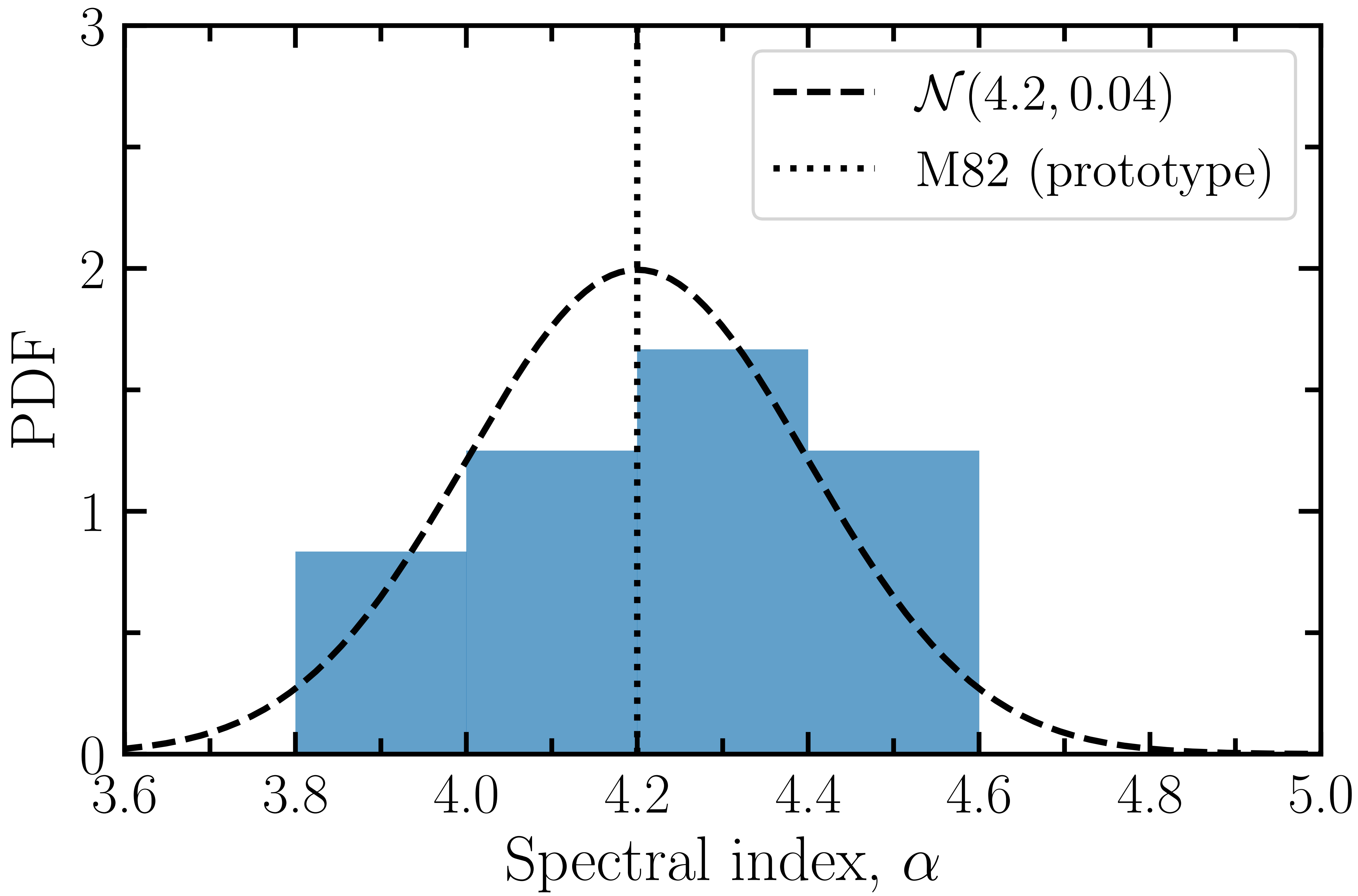
Ambrosone+, 2011.02483

✦ **Prototype model:** all the SBGs are equal to a galaxy with "known" parameters (e.g. M82)

✦ **Blending model:** each SBGs have its own parameters (e.g different spectral indexes)



SBGs distributed in redshift (Schecter function)



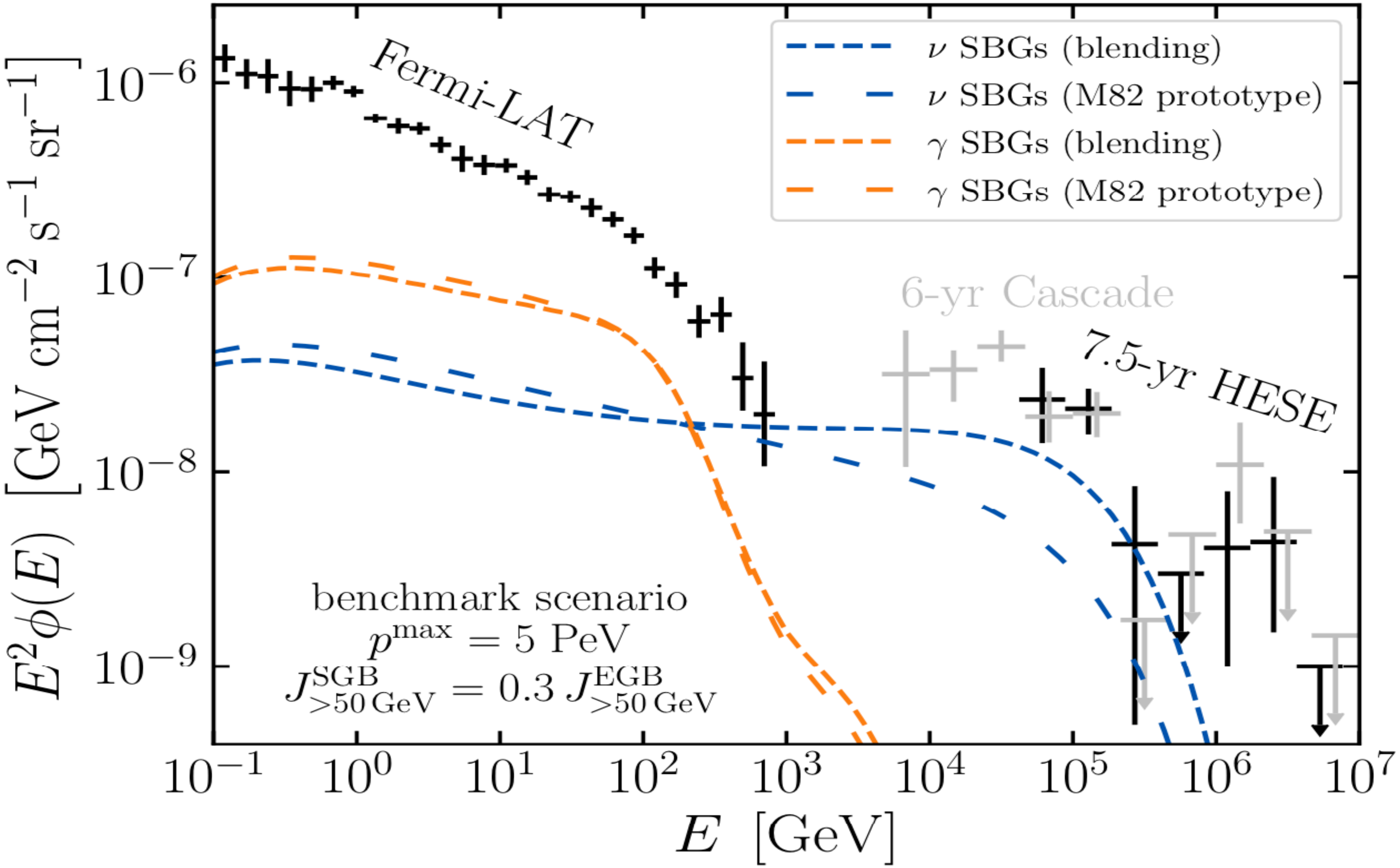
$$\left\langle \phi_{\nu,\gamma}(E|p^{\max},\alpha) \right\rangle_\alpha = \int \mathrm{d}\alpha\, \phi_{\nu,\gamma}(E|p^{\max},\alpha)\, p(\alpha)$$

Empirical distribution from 12 SFGs/SBGs resolved in γ-ray

Ajello+, ApJ 894 (2020)

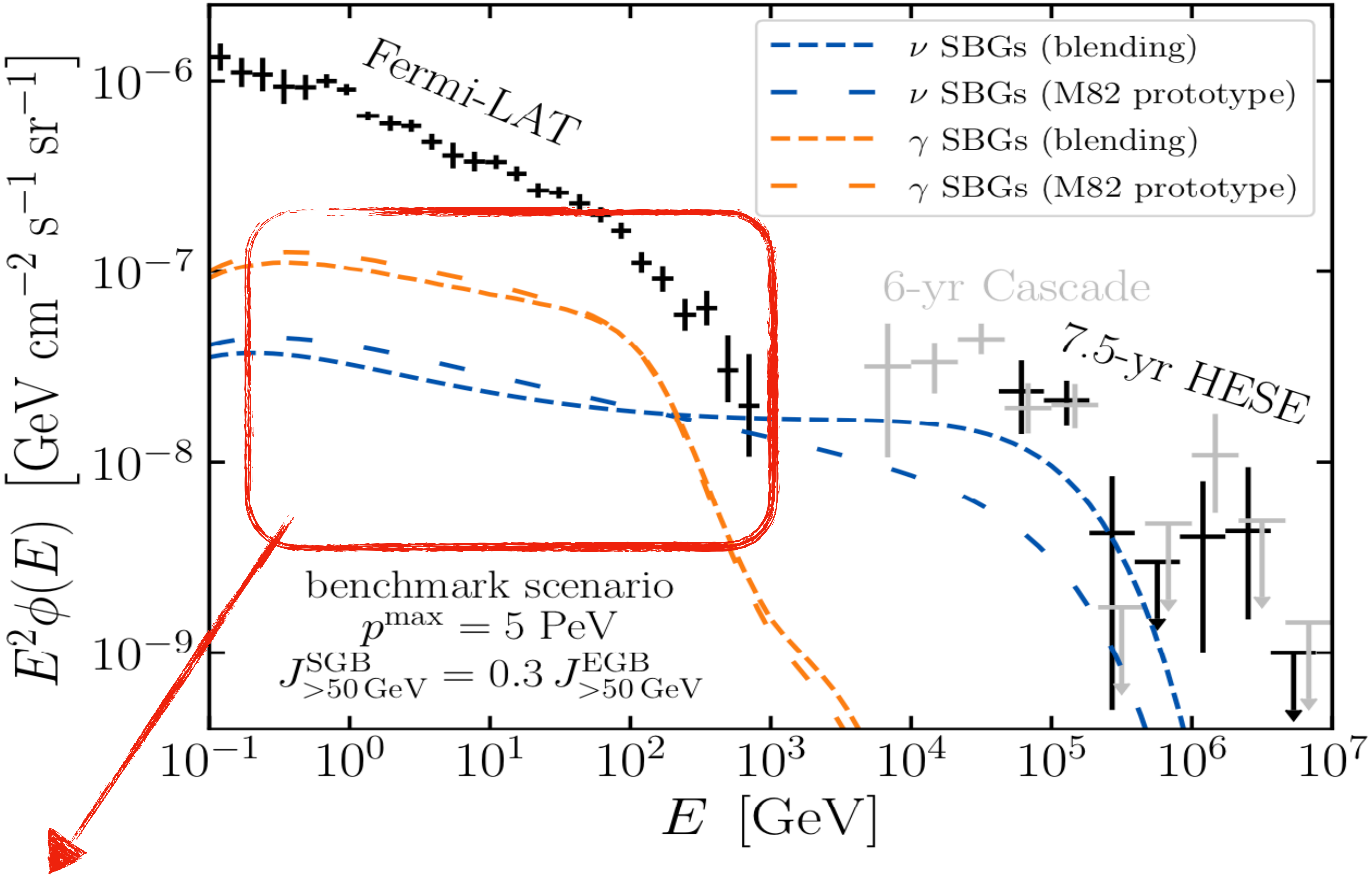
Blending *versus* prototype

Ambrosone+, [2011.02483]



Blending *versus* prototype

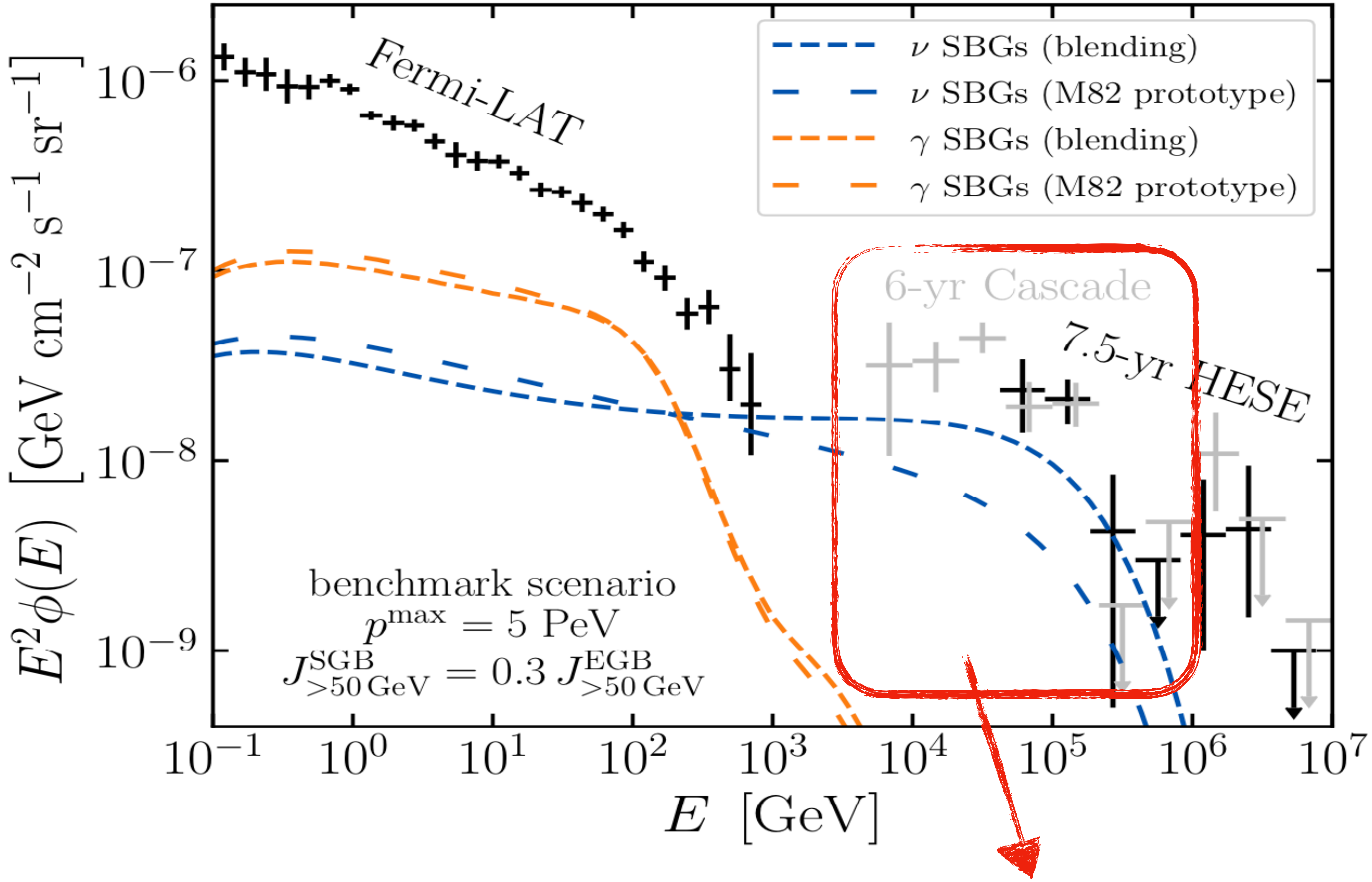
Ambrosone+, 2011.02483



The diffuse gamma contributions (prompt + EM cascades) are almost the same!

Blending *versus* prototype

Ambrosone+, 2011.02483



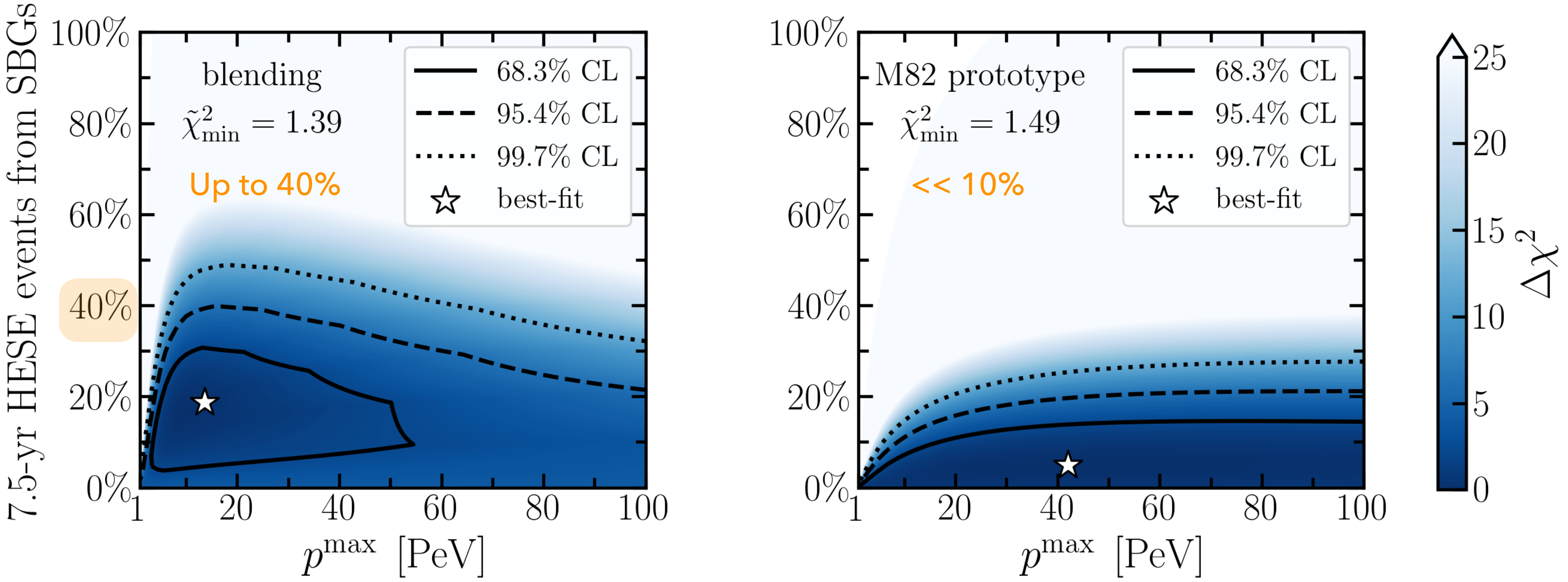
Up to 40% of IceCube HESE neutrinos from SBGs

Larger contribution to diffuse neutrinos at ~100 TeV, alleviating the neutrino-gamma tension

Diffuse multi-messenger analysis

Ambrosone+, [2011.02483]

SBGs contribution to the neutrino flux obtained by analyzing **Fermi-LAT+IceCube** diffuse data (including the emission from blazars and radio galaxies)



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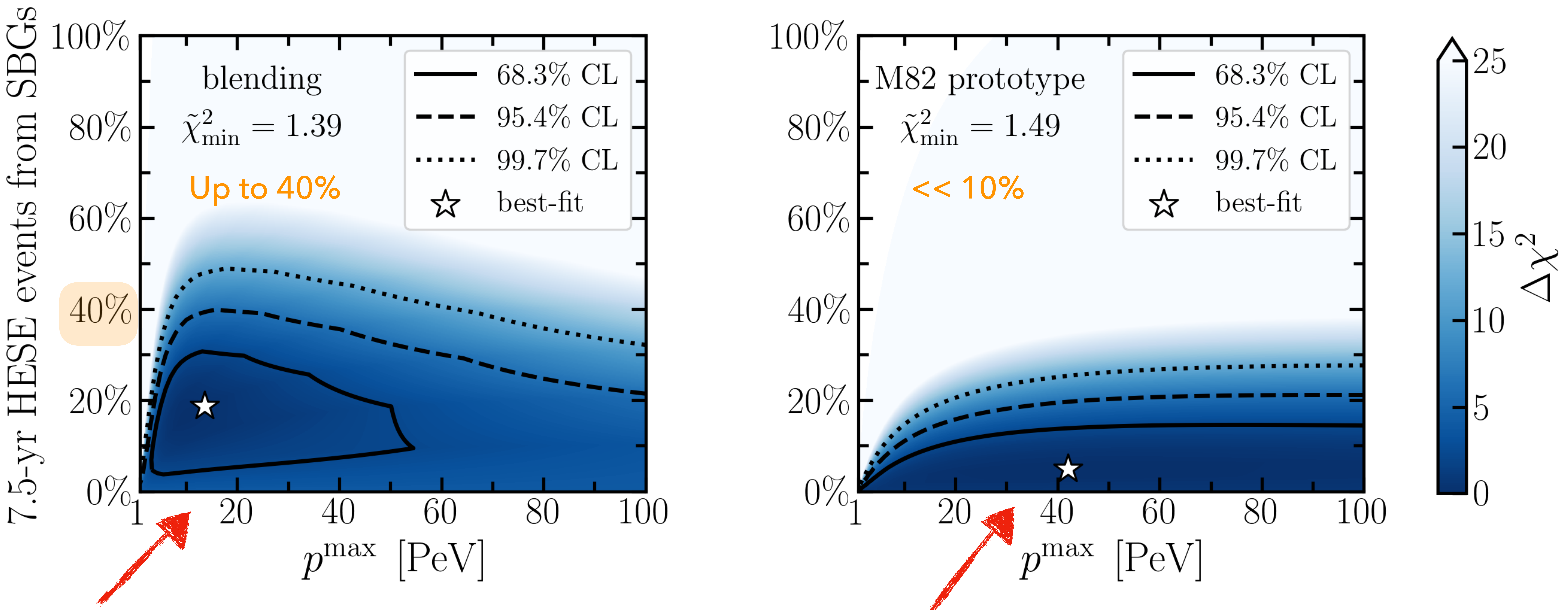


1σ contour closed: preference for a non-zero SBG component

Higher maximal energies

Point-like emission from nearby galaxies

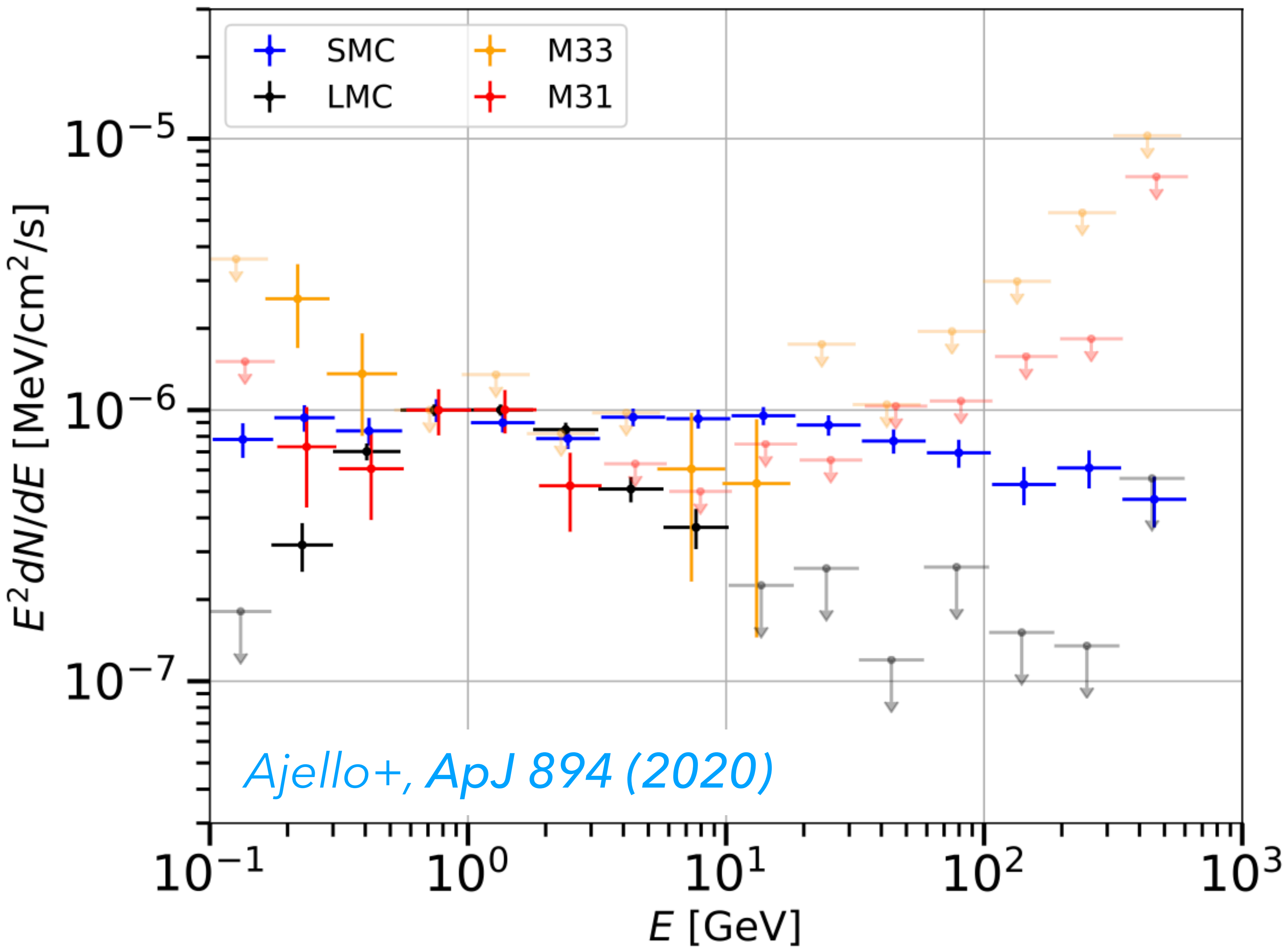
Ambrosone+, 2106.12348

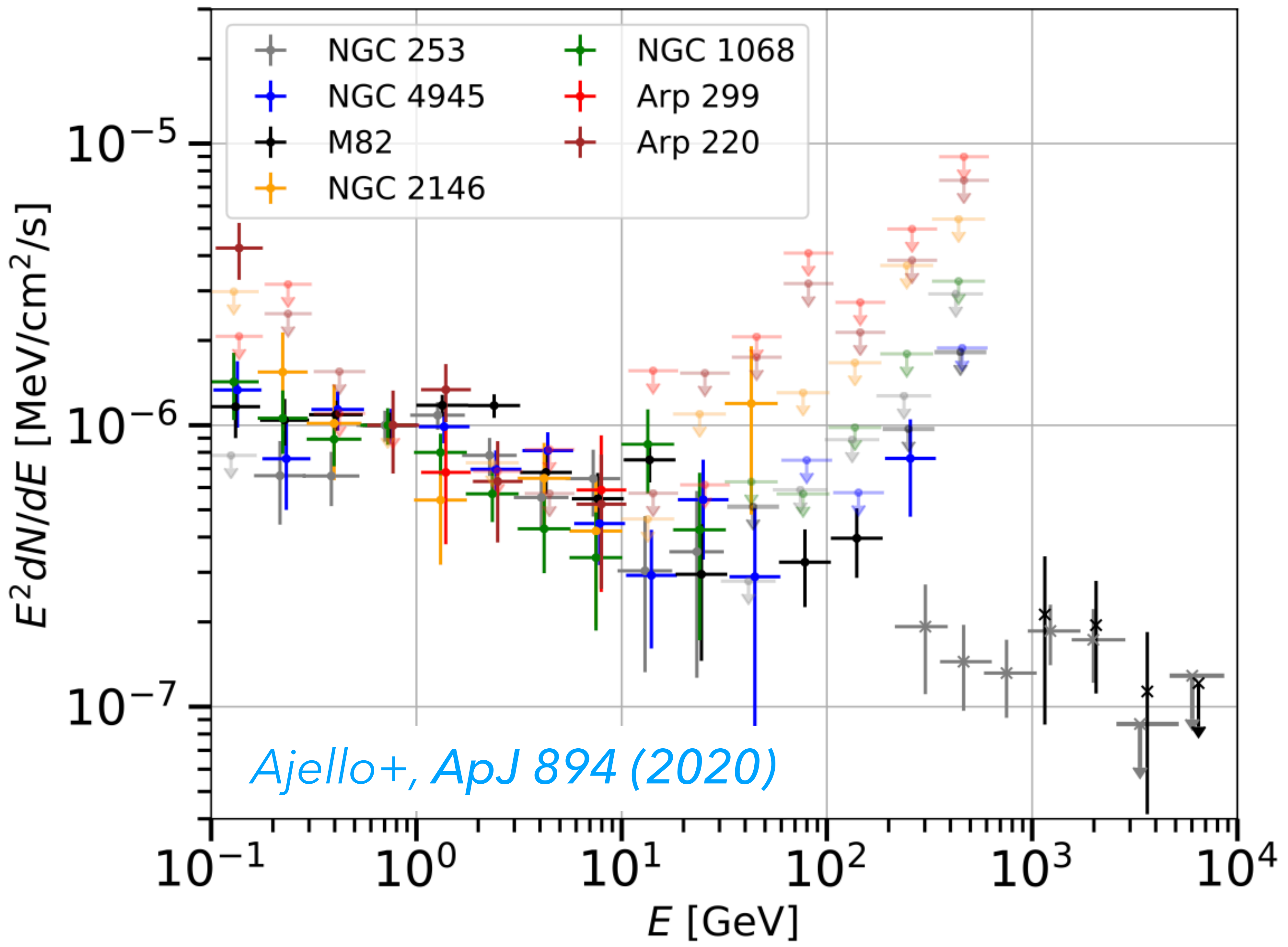
Can we probe the calorimetric model with high-energy point-like observations?

Source
M82
NGC 253
ARP 220
NGC 4945
NGC 1068
NGC 2146
ARP 299
M31
M33
NGC 3424
NGC 2403
SMC
Circinus Galaxy

Analyzing the spectral energy distributions (SEDs)

✦ **HE gamma-rays:** Fermi-LAT and IACTs data





Point-like emission from nearby galaxies

Ambrosone+, 2106.12348

Can we probe the calorimetric model with high-energy point-like observations?

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

Analyzing the spectral energy distributions (SEDs)

- ✦ **HE gamma-rays:** Fermi-LAT and IACTs data
- ✦ IR+UV data: prior on the star-formation rate $\dot{M}_* \simeq 100\,\mathrm{M}_\odot\,\mathcal{R}_{\mathrm{SN}}$

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Analyzing the spectral energy distributions (SEDs)

- ✦ **HE gamma-rays:** Fermi-LAT and IACTs data
- ✦ IR+UV data: prior on the star-formation rate $\dot{M}_* \simeq 100\,\mathrm{M}_\odot\,\mathcal{R}_{\mathrm{SN}}$
- ✦ Scaling Kennicutt's relations:

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

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)

Bayesian analysis

Ambrosone+, 2106.12348

Results of the Likelihood Analysis of Current Gamma-Ray Data

Source	Uniform Prior $\dot{M}_*$	Most Likely Values $(\dot{M}_*, \Gamma)$	68% Credible Intervals $\dot{M}_*$	68% Credible Intervals Γ	χ^2/dof
M82	3.0–30	(4.5, 2.30)	[4.3, 4.6]	[2.27, 2.33]	1.24
NGC 253	1.4–17	(3.3, 2.30)	[3.14, 3.40]	[2.28, 2.32]	1.32
ARP 220	60–740	(740, 2.66)	[492, 740]	[2.51, 2.68]	1.52
NGC 4945	0.35–4.15	(4.15, 2.30)	[4.05, 4.15]	[2.23, 2.32]	1.52
NGC 1068	5–93	(16, 2.52)	[13, 20]	[2.45, 2.65]	0.65
NGC 2146	3–57	(15, 2.50)	[9, 27]	[2.44, 2.88]	0.50
ARP 299	28–333	(28, 2.15)	[28, 200]	[1.40, 1.90] ∪ [2.77, 3.00]	0.18
M31	0.09–0.90	(0.34, 2.40)	[0.31, 0.40]	[2.29, 2.61]	0.52
M33	0.09–0.90	(0.44, 2.76)	[0.19, 0.56]	[2.57, 2.96]	0.44
NGC 3424	0.4–5.4	(5.4, 2.22)	[2.5, 5.4]	[1.92, 2.67]	1.63
NGC 2403	0.1–1.2	(0.75, 2.12)	[0.58, 0.96]	[1.92, 2.36]	0.38
SMC	0.008–0.090	(0.038, 2.14)	[0.037, 0.039]	[2.13, 2.16]	1.90
Circinus Galaxy	0.1–8.1	(6.6, 2.32)	[6.2, 7.8]	[2.15, 2.45]	0.92

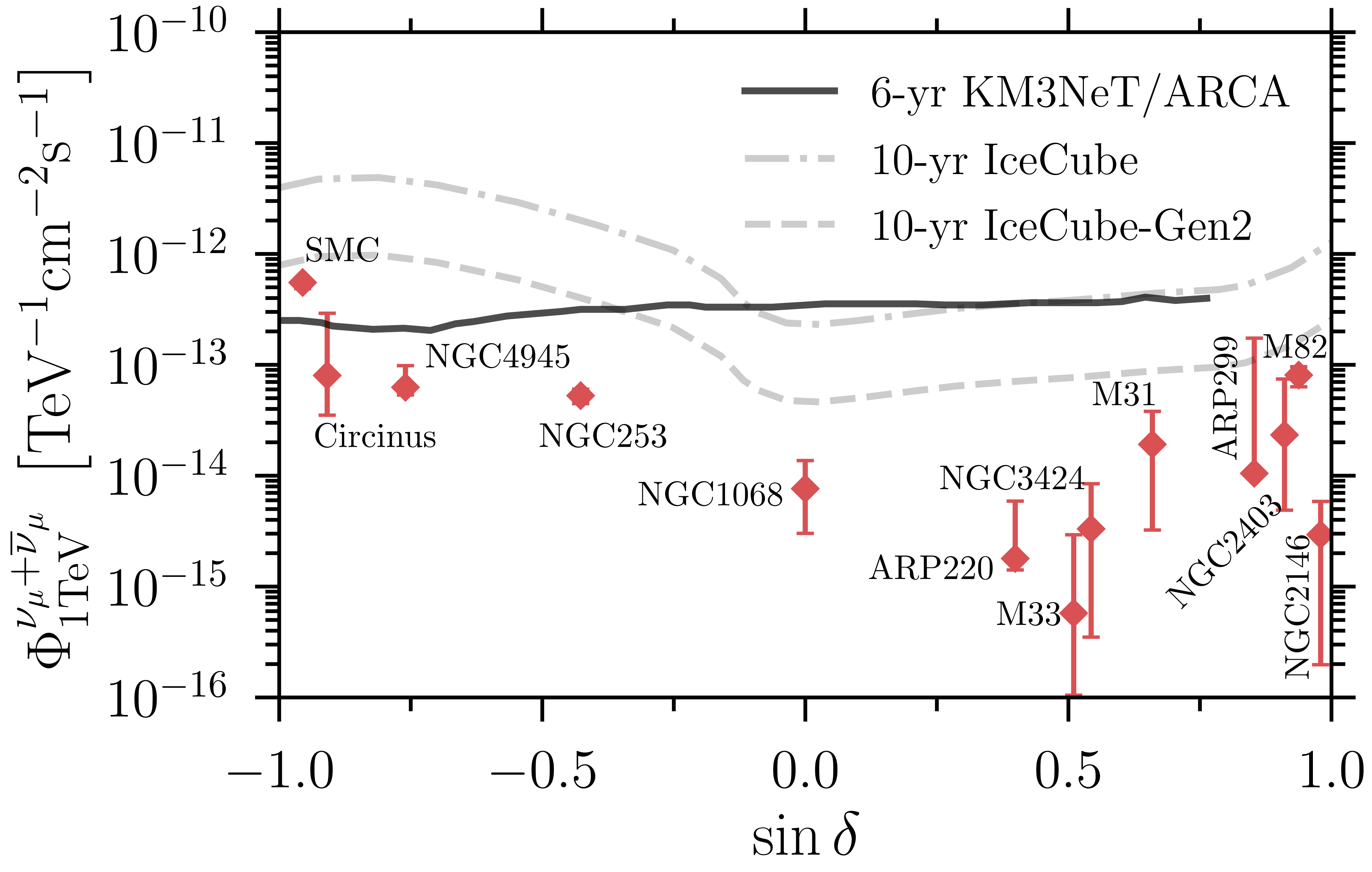
Note. The columns report the source name, the SFR prior, the most likely values of the two parameters, the 68% maximum posterior density credible intervals of the marginal distributions, and the reduced chi-squared values considered as an estimate of the goodness of the fit. The star formation rate $\dot{M}_*$ is in units of $M_\odot$ yr^{-1}.

This allows us to predict the neutrino and VHE gamma-rays emission from these sources!

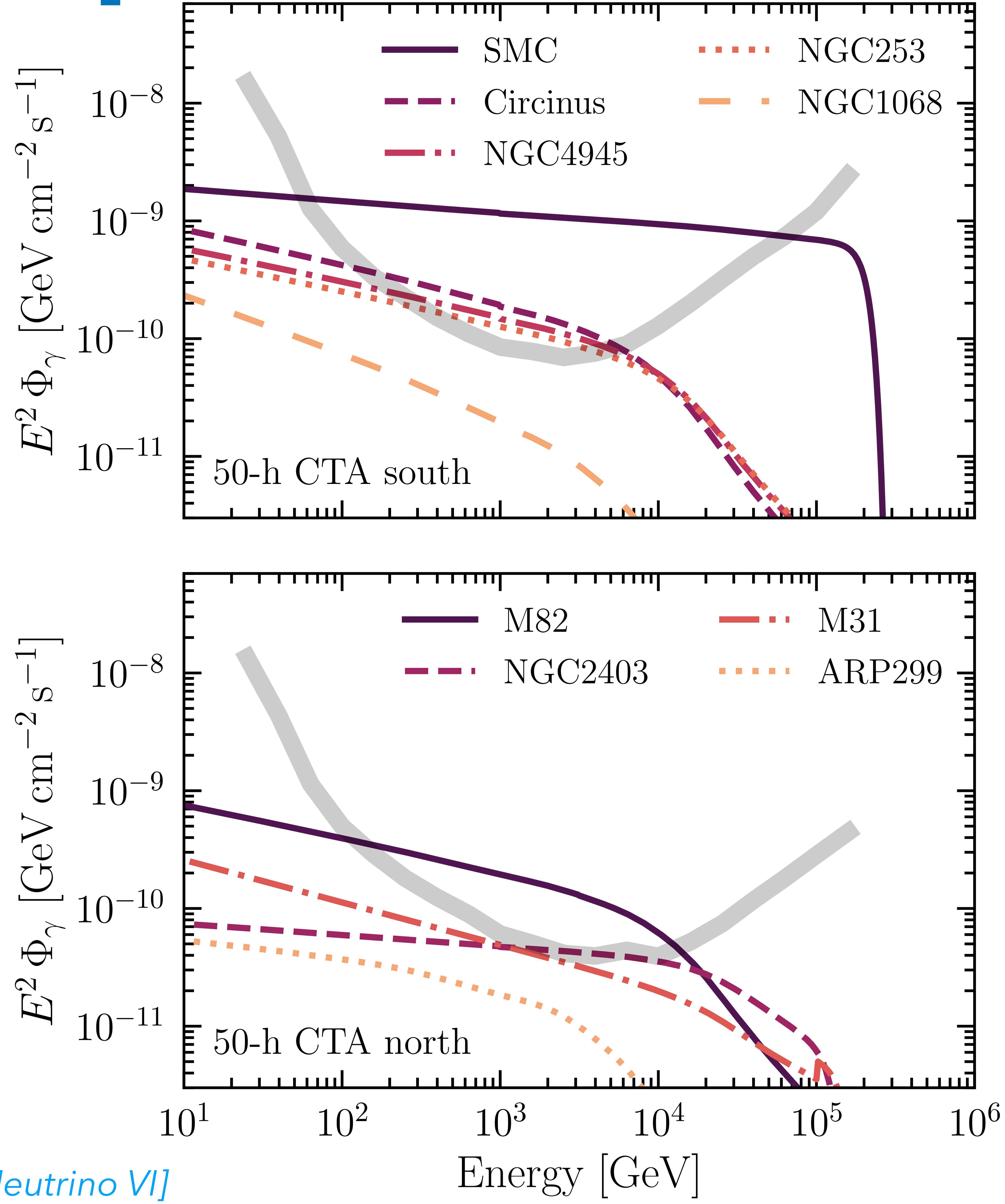
Point-like forecast

Ambrosone+, 2106.12348

NEUTRINOS



VHE GAMMA-RAYS



Future joint ν-γ observations

- ✦ Objective test for the calorimetric model
- ✦ Compelling evidence of star-forming activity as a tracer of neutrino production.

[see also Mancina's talk - Neutrino VI]

Cosmic-ray physics inside SBGs

Ambrosone+, 2203.03642

The relation between neutrino and gamma-ray emissions is however model-dependent!

MODEL A: ADVECTION-DOMINATED

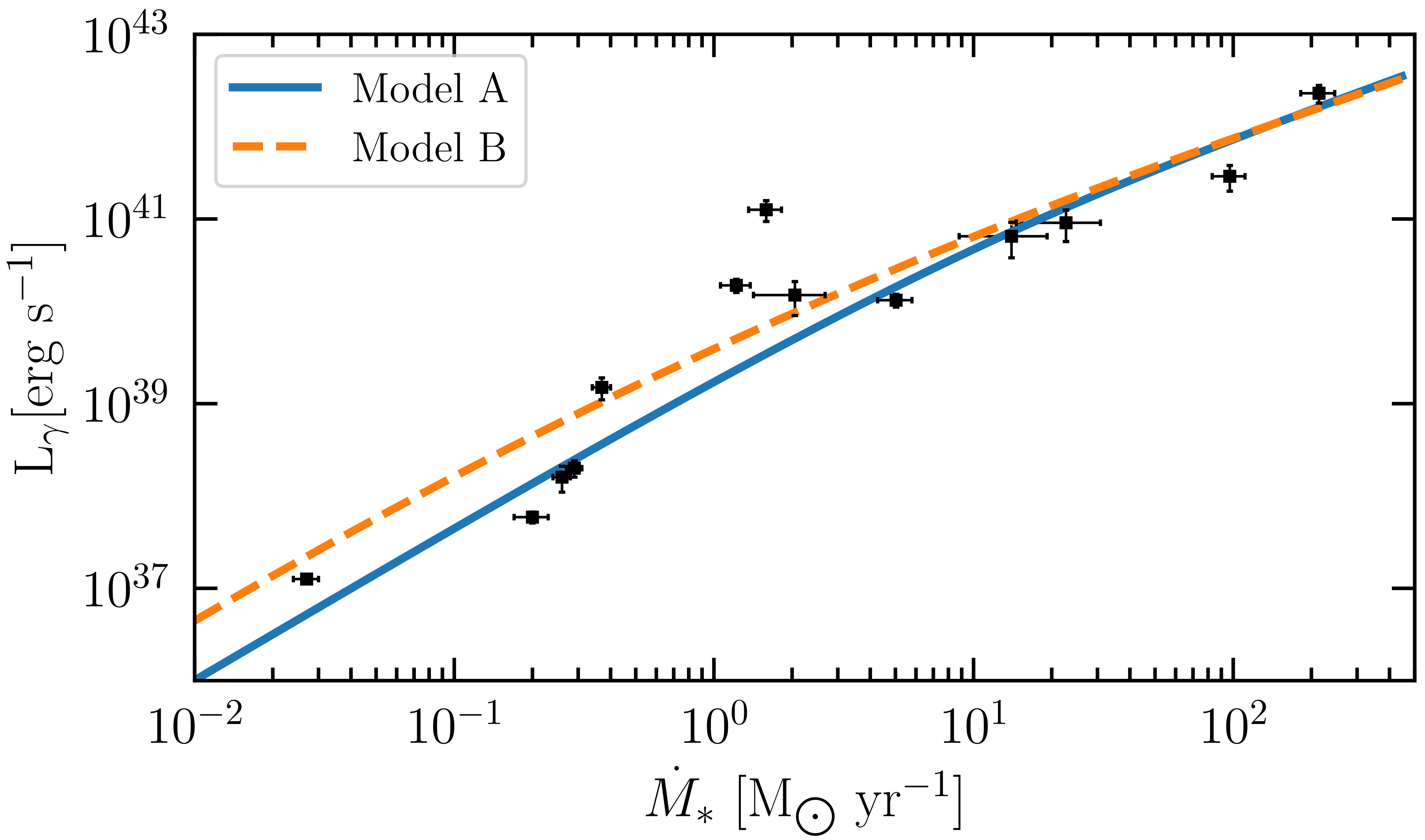
$$f(p)\left(\frac{1}{\tau_{\rm loss}(p)}+\frac{1}{\tau_{\rm adv}(p)}+\frac{1}{\tau^{\rm A}_{\rm diff}(p)}\right)=Q(p)$$

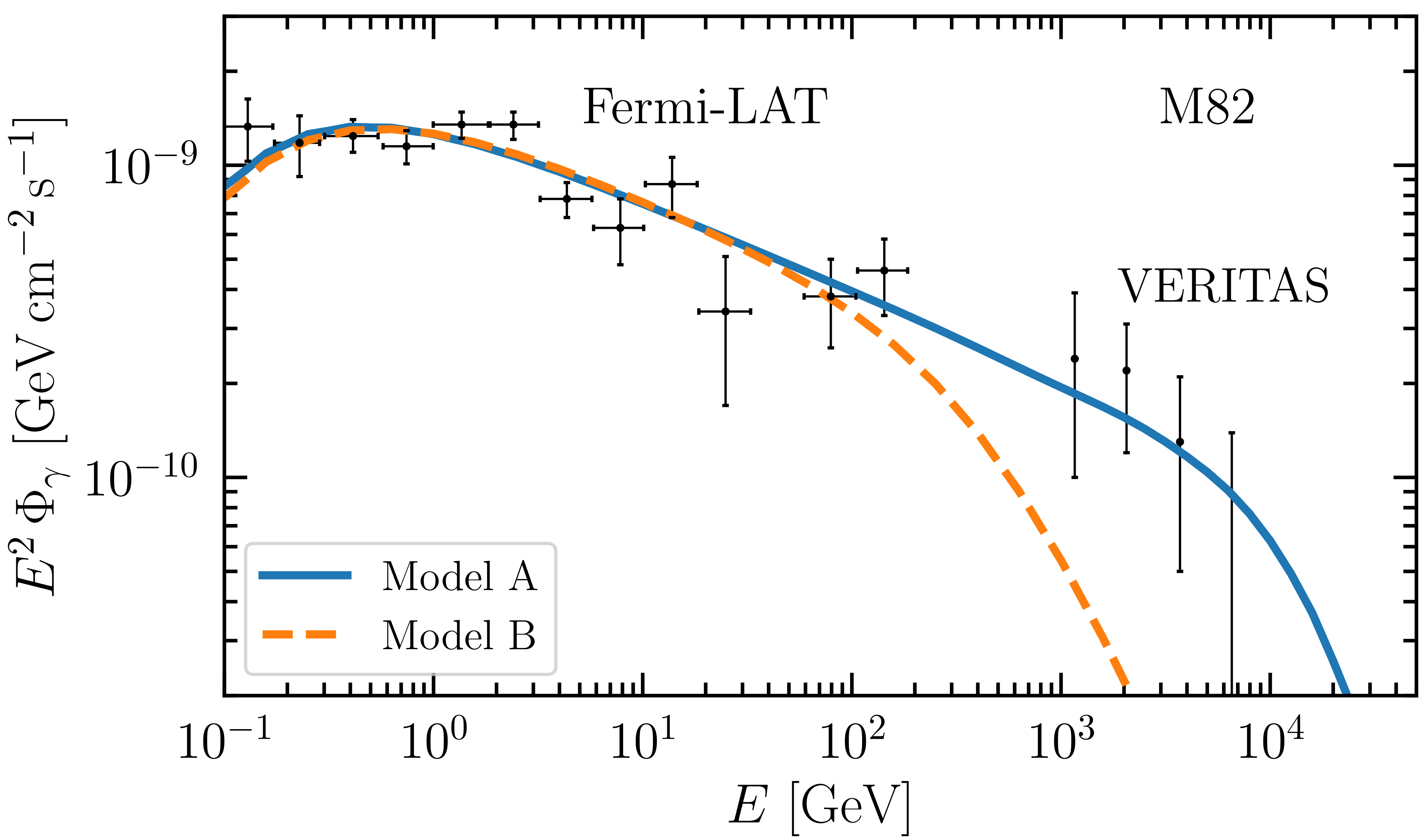
Peretti+, MNRAS 487 (2019)

MODEL B: DIFFUSION-DOMINATED

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

Krumholz+, MNRAS 493 (2020)





When TeV gamma-rays are crucial

Ambrosone+, 2203.03642

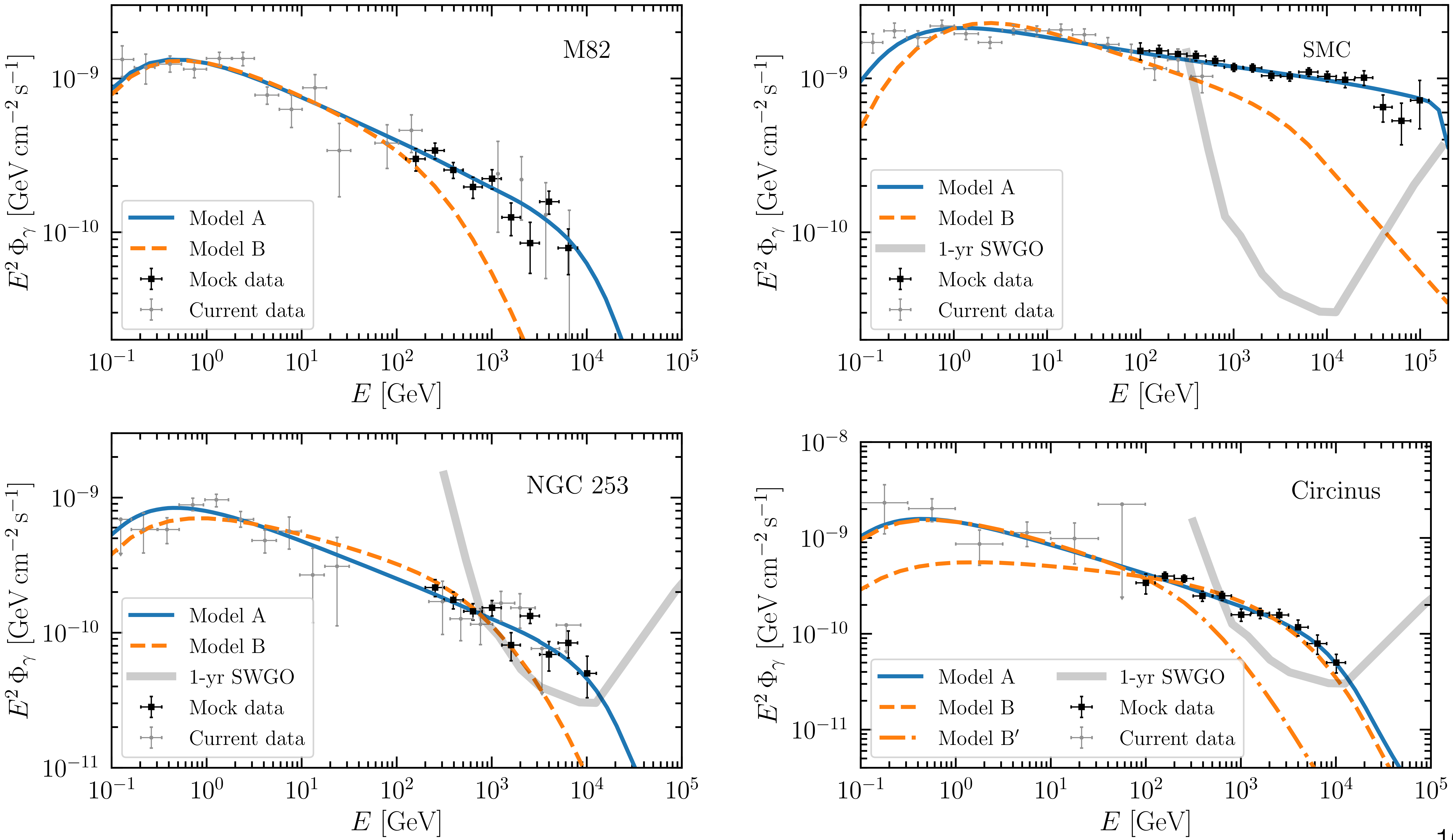
We test *Krumholz+* **model (B)** by means of CTA mock data simulations assuming *Peretti+* **model (A)**

- ✦ Generation of 10^4 mock data sets for the CTA telescope
- ✦ CTA info from:

  Acharya+, 1709.07997
- ✦ SWGO info from:

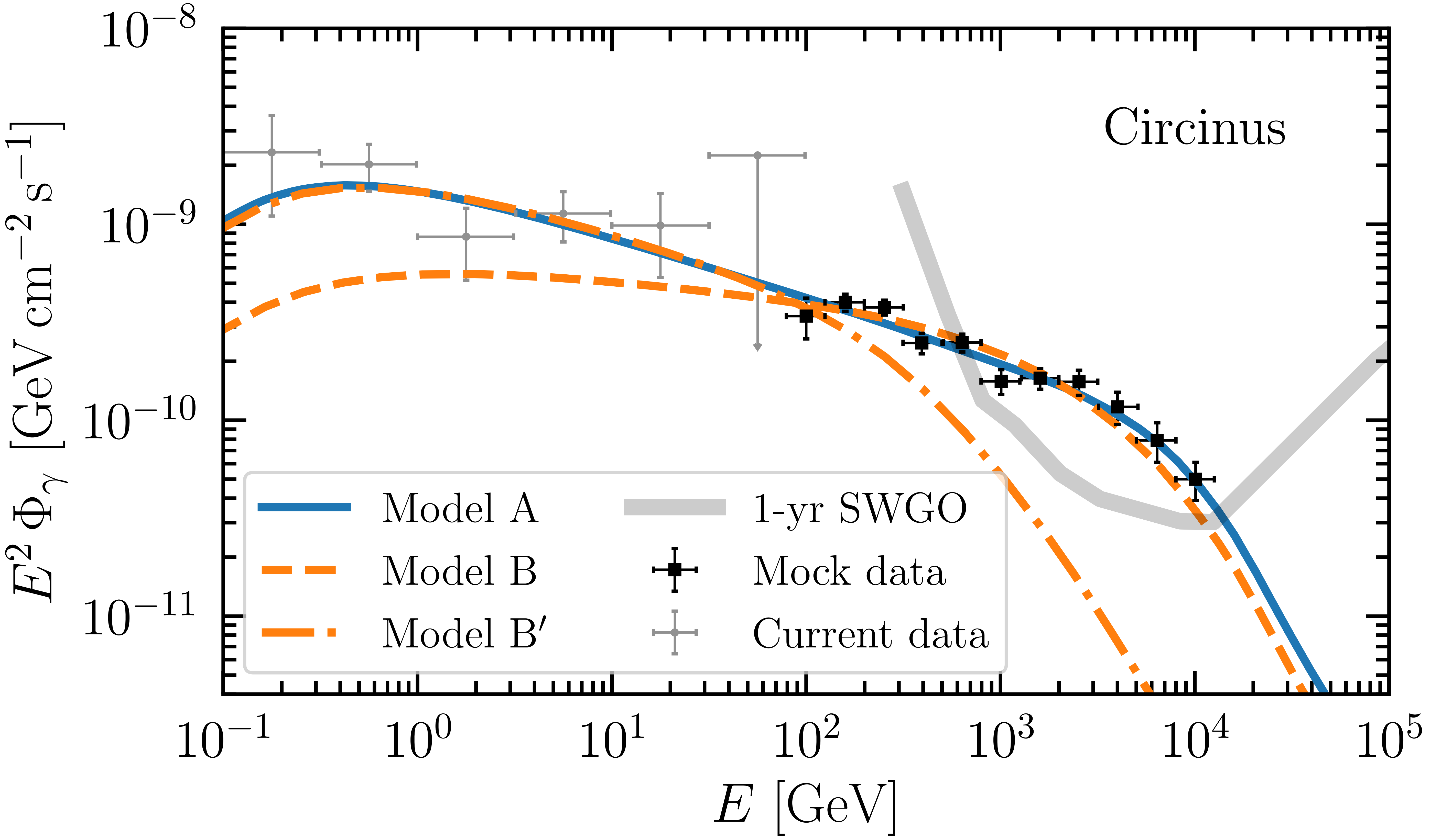
  Albert+, 1902.08429

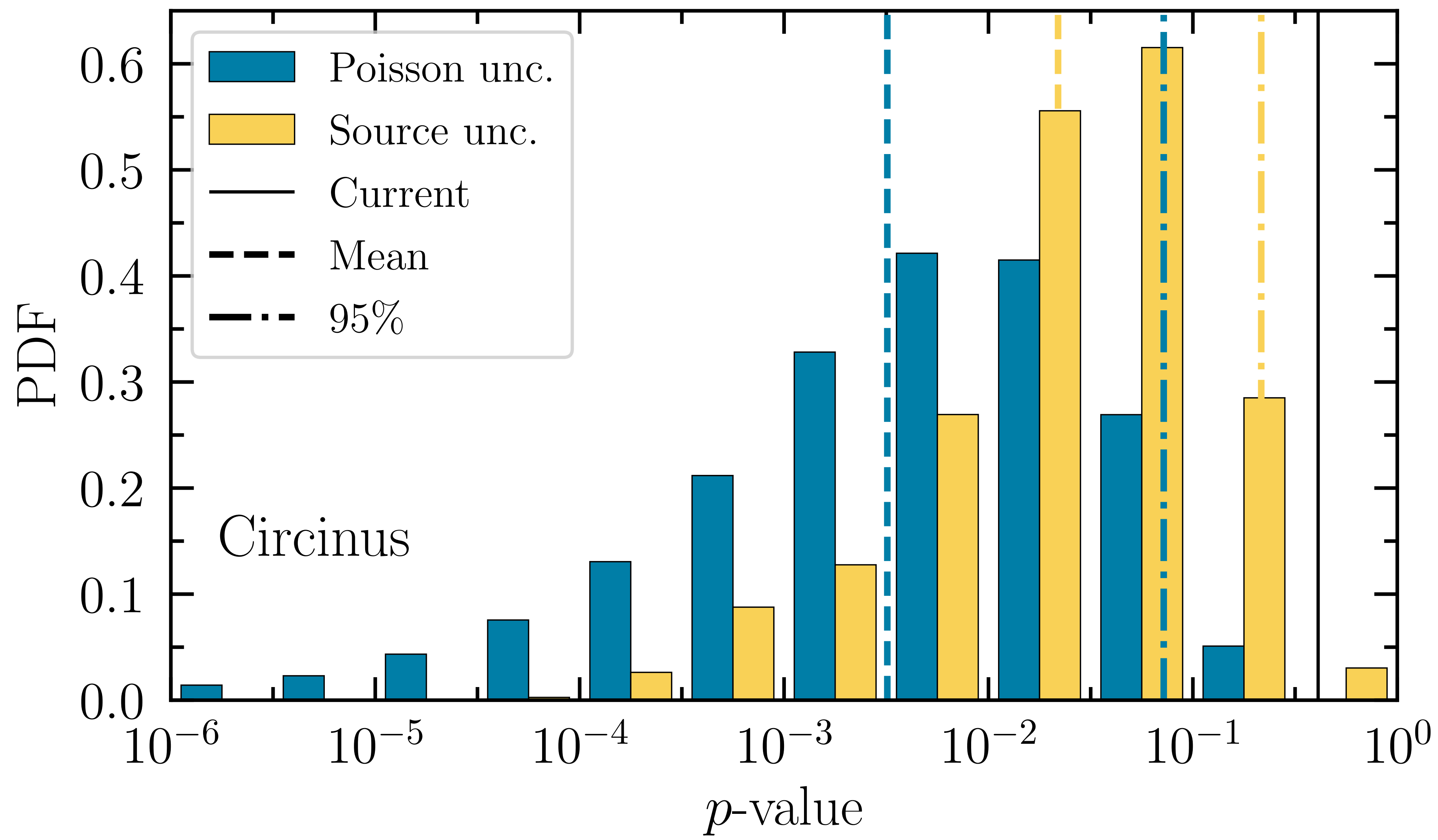
  Hinton, PoS ICRC2021 023

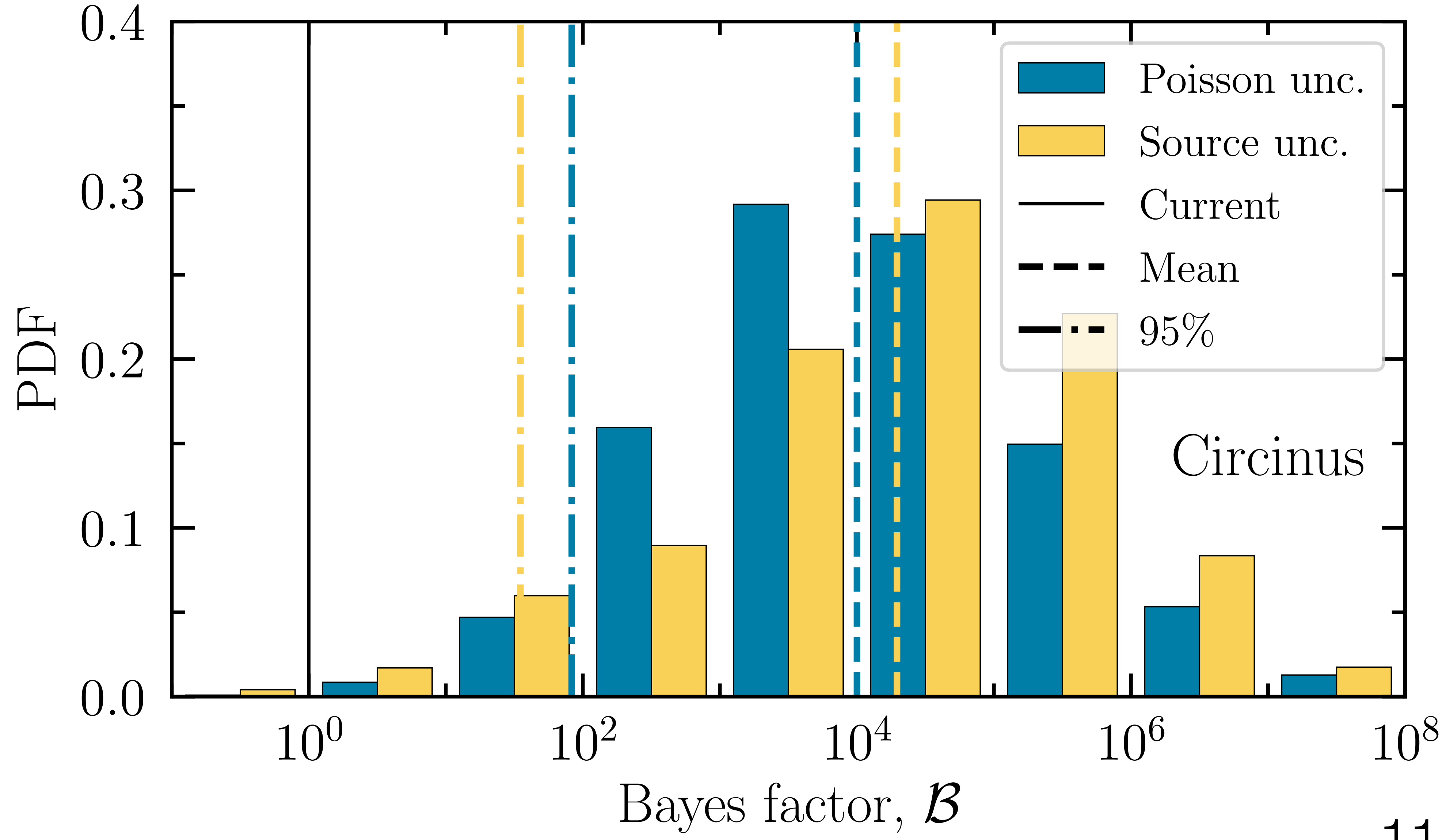


CTA forecast: Circinus

Ambrosone+, [2203.03642]





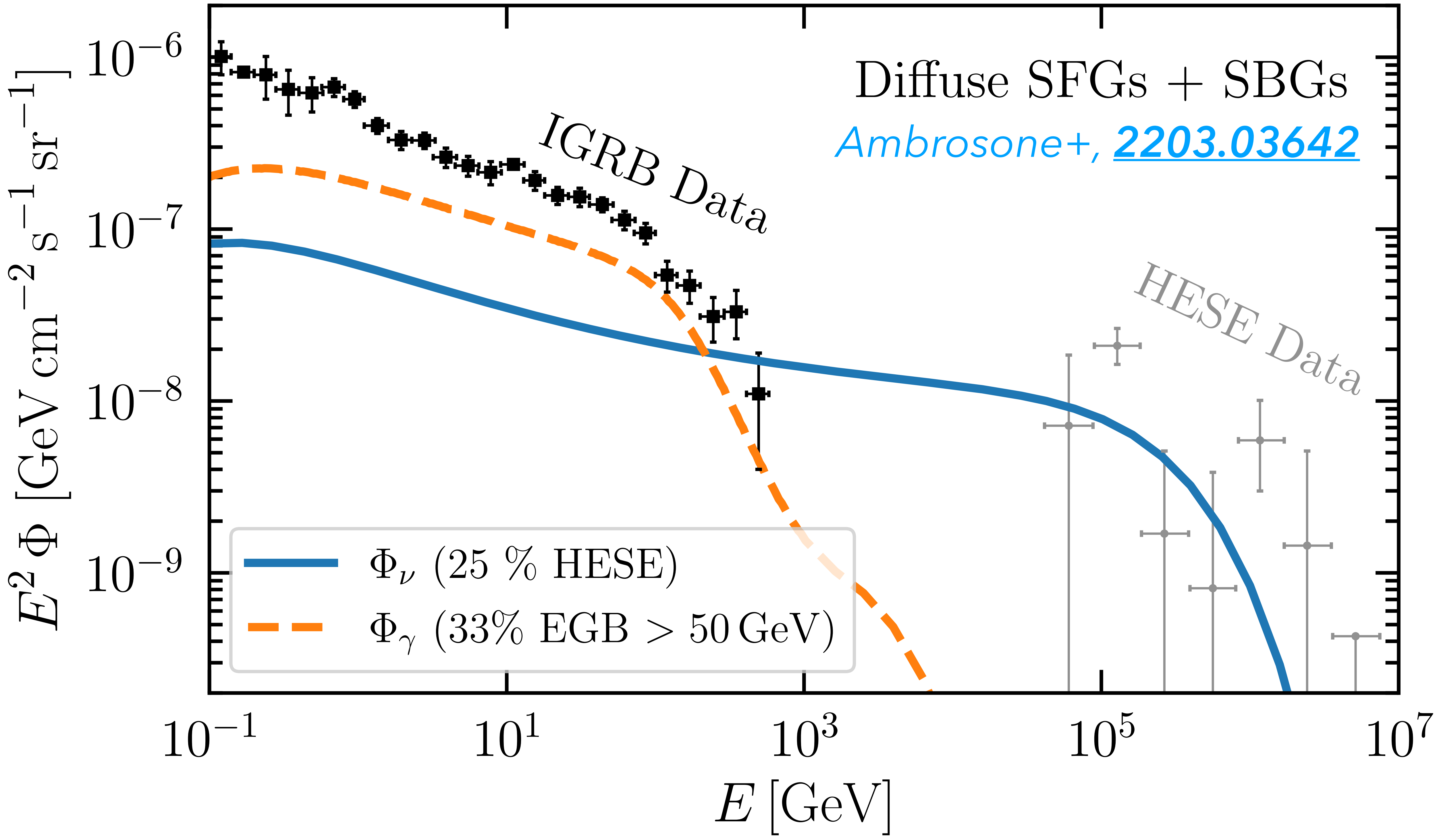


p-value $\leq 7.2 \times 10^{-2}$ & $\mathcal{B} \geq 8.3 \times 10^{1}$ *at 95 % CL*

Implications for the diffuse emission

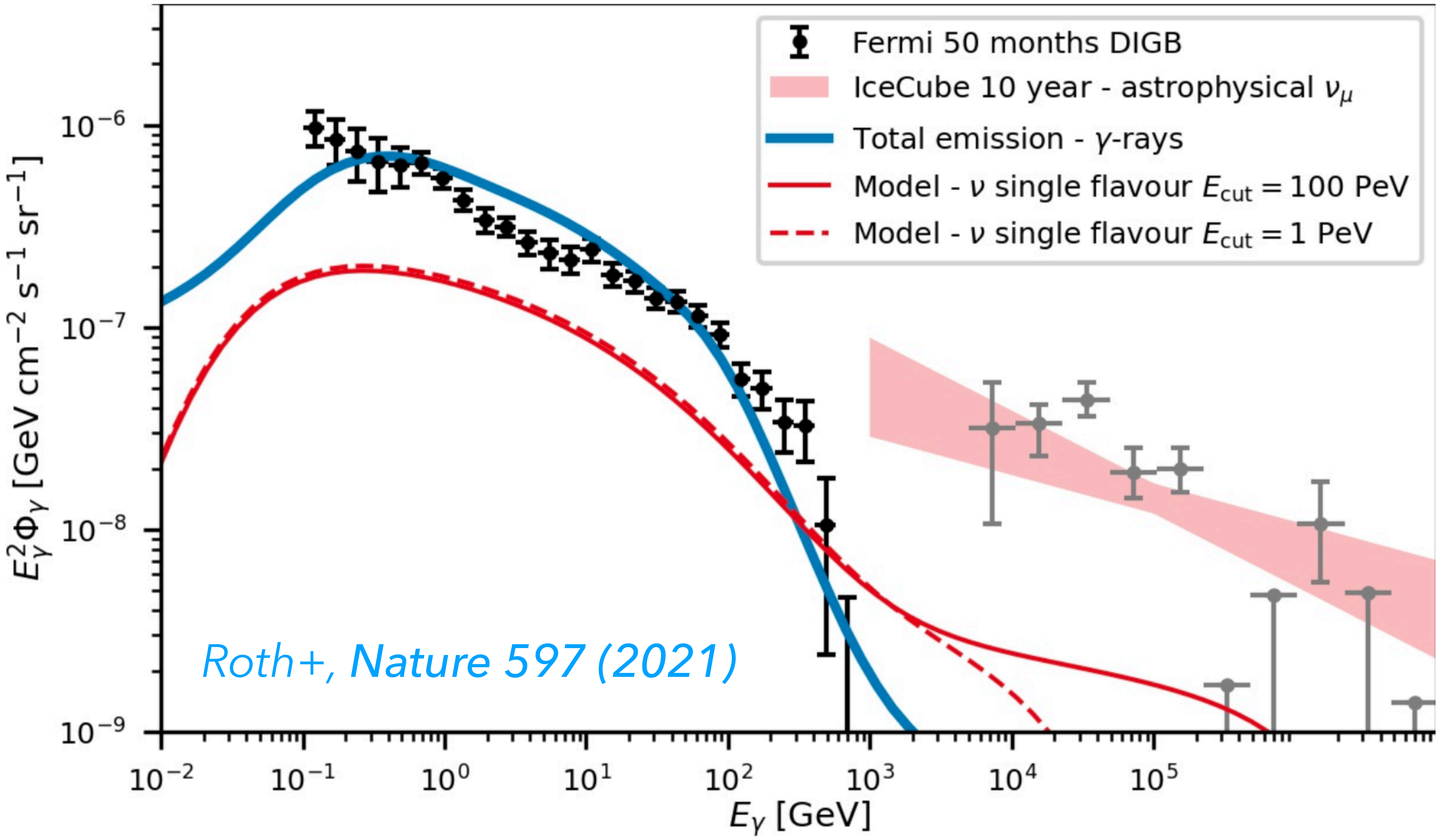
The two models for the CRs transport inside the SBGs lead to very different scenarios.

MODEL A: ADVECTION-DOMINATED



- ✦ 33% EGB gamma-ray above 50 GeV
- ✦ 25% of HESE neutrino

MODEL B: DIFFUSION-DOMINATED



- ✦ Large gamma-ray emission saturating DIGB
- ✦ Negligible contribution to HESE neutrino

Conclusions

- **SBGs are promising high-energy emitters**: they contribute up to 40% to the IceCube astrophysical neutrino signal.
- Upcoming gamma-ray telescopes will allow for a better constrain of the spectral cut-off and cosmic-ray transport inside these sources.
- Global Neutrino Network + CTA/SWGO surveys of the closer SBGs can solve the puzzle.


Antonio Ambrosone


Damiano F.G. Fiorillo


Antonio Marinelli


Gennaro Miele


Ofelia Pisanti

Thanks for listening

BACKUP SLIDES

Multi-messenger analysis

Ambrosone+, 2011.02483

Gamma-ray contributions

- ✦ Starburst Galaxies
- ✦ Blazars (prompt + EM cascades)
- ✦ Radio Galaxies

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

↓

Extragalactic Gamma-ray Background

Neutrino contributions

- ✦ Starburst Galaxies
- ✦ Blazars (resolved and unresolved)

Palladino et al., **ApJ 871 (2019)**

↓

7.5-yr HESE *and* 6-yr cascades

uncertainties affecting theoretical estimations

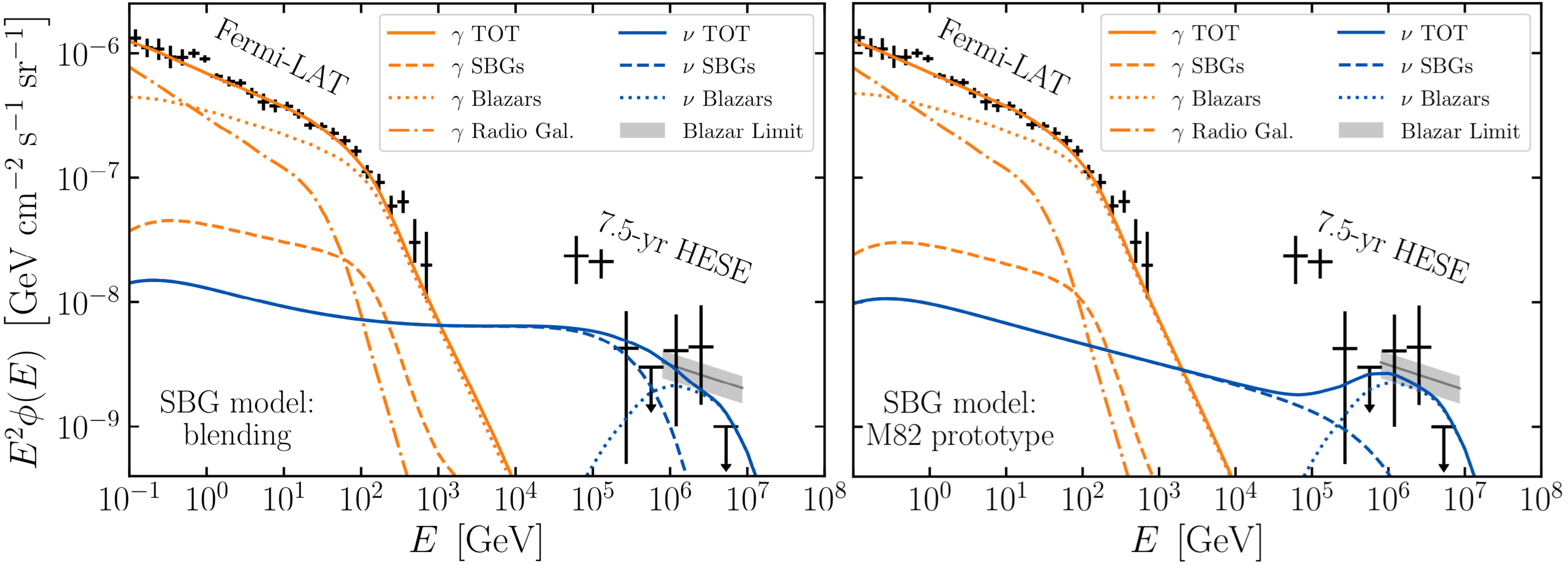
$$\chi^2_{\nu+\gamma}(N_{SBG}, N_{RG}, N_{Blazars}, p^{max}) = \chi^2_\nu + \chi^2_\gamma + \left(\frac{N_{Blazars} - 1}{0.26}\right)^2 + \left(\frac{N_{RG} - 1}{0.65}\right)^2 + \left(\frac{N_{Blazars} - 0.80}{0.11}\right)^2$$

joint γ-ν chi-square
with 4 free parameters

Positional limit of resolved point sources above 50 GeV
(see Lisanti et al., ApJ 832 2016)

Comparison between best-fit scenarios

Ambrosone+, 2011.02483



*The blending scenario is **allowed** to give a greater contribution than the prototype scenario…but it is not enough…**other contributions at 100 TeV?***

Upper limit on the SBG component

Ambrosone+, 2011.02483