A novel multimessenger study of Starburst galaxies: implications for neutrino astronomy

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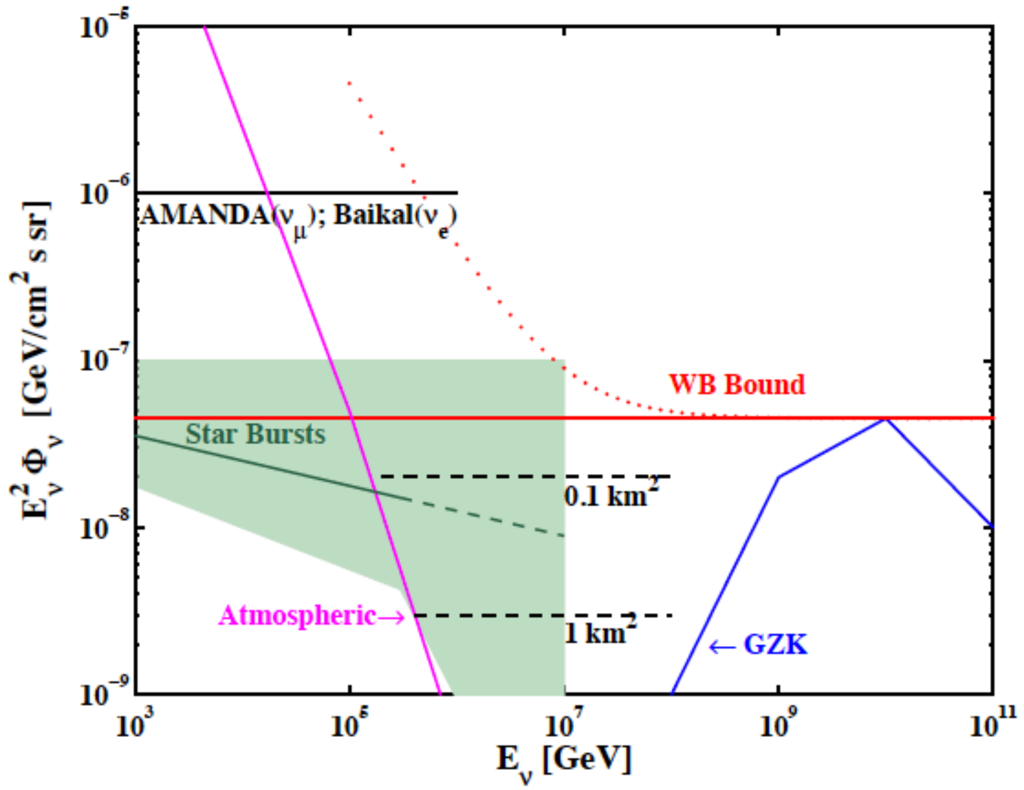
International Workshop on Astronomy and Relativistic Astrophysics

Antigua Guatemala 5-9/09/2022

High star formation rate can trace neutrino production

JCAP (2006)
Loeb & Waxmann



Looking for a preferential environment of neutrino production: a reservoir of high-energy cosmic rays with a region of high-density gas acting as a proton target

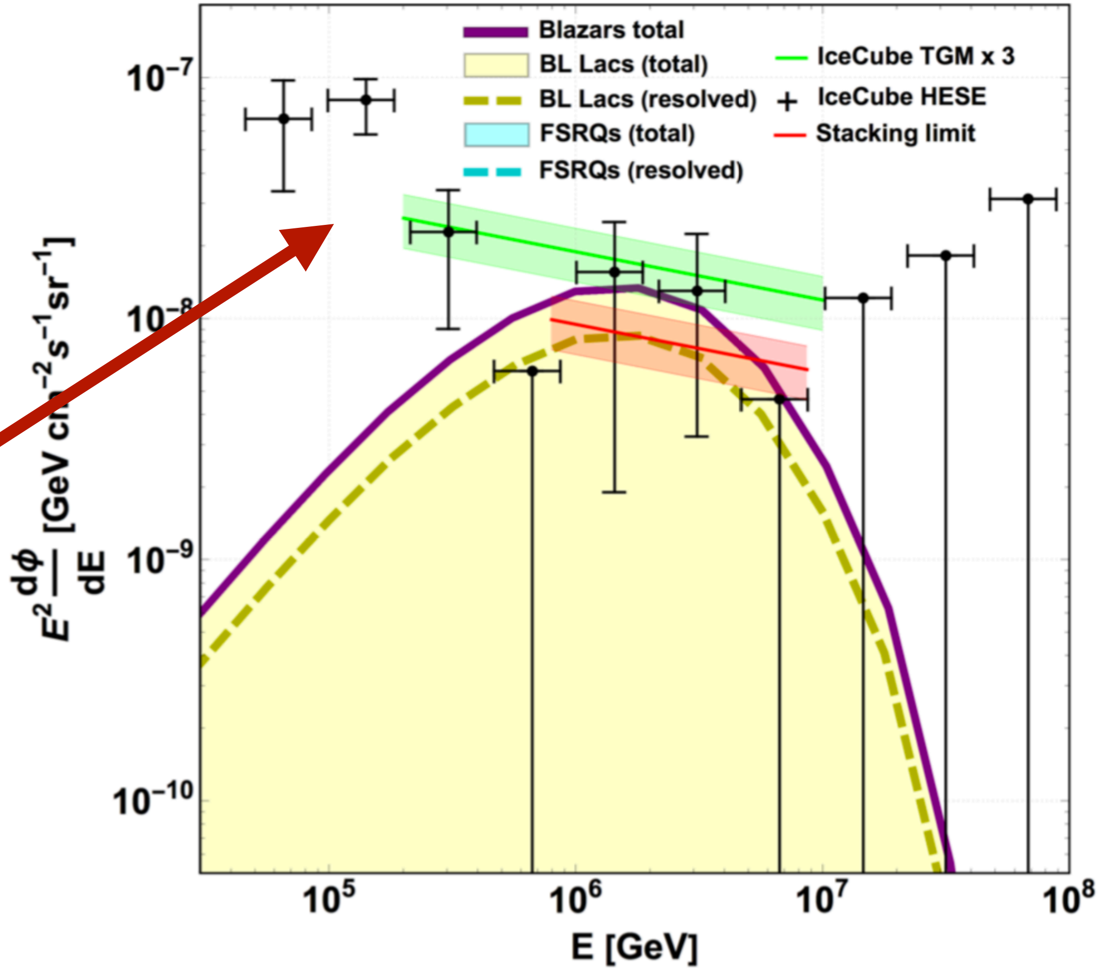
Forecasting scenario obtained for the class of Starburst galaxies 15 years ago, before Fermi-LAT and IceCube

MULTICOMPONENT FIT OF THE ICECUBE DATA

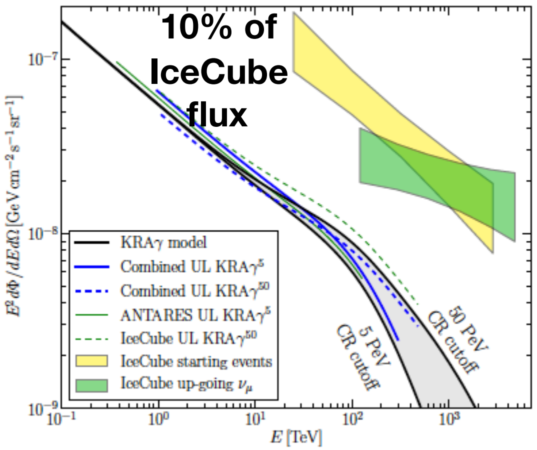
- High energy part of IceCube SED can be described through **photo-hadronic** neutrino production of blazars (in the plot calibrated with TXS 0506+056 observations).

A.M, J.R. Sacahui, A Sharma, M. Osorio-Archila MNRAS2021

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



Gaggero,Grasso, A.M, Urbano, Valli APJL (2015); PRD IceCube +Antares (2017)



+ EG reservoirs

Possible description of "reservoir" components: Starforming + Starburst galaxies

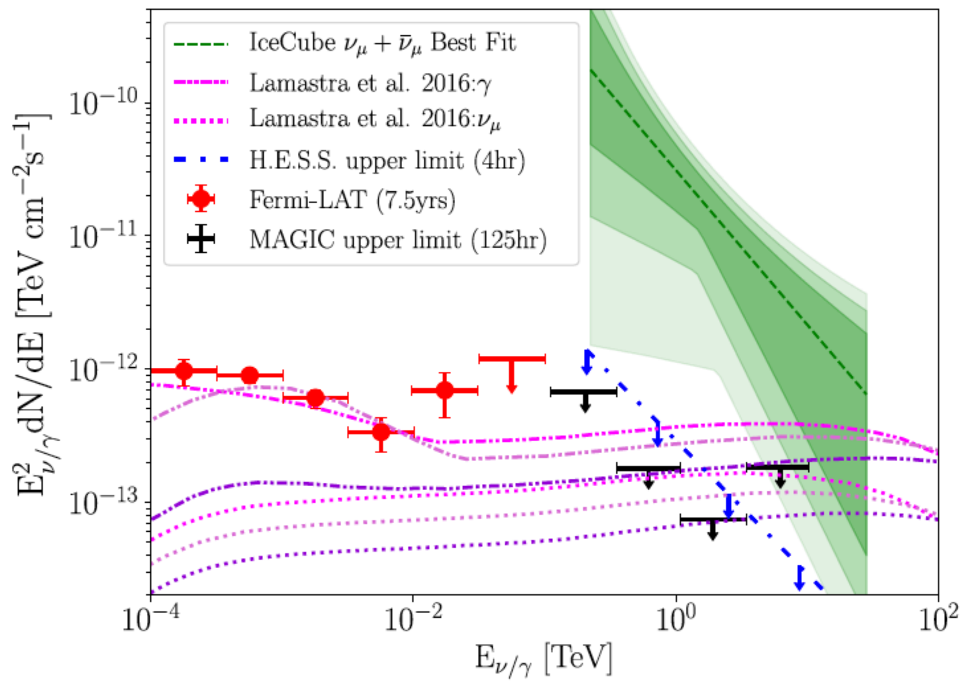
MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

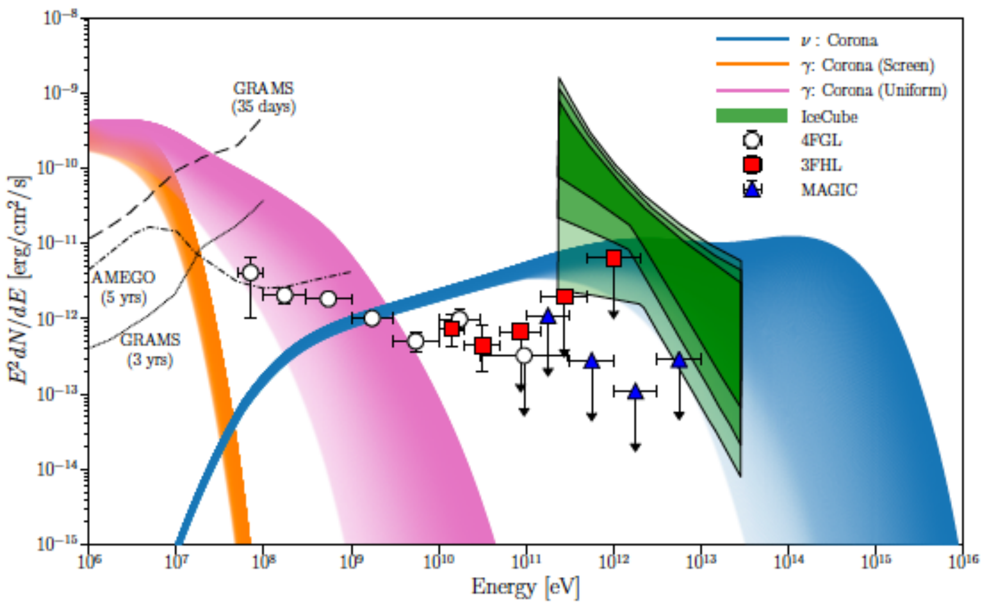
THE CASE OF NGC 1068

PRL 124 (2020) IceCube

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

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

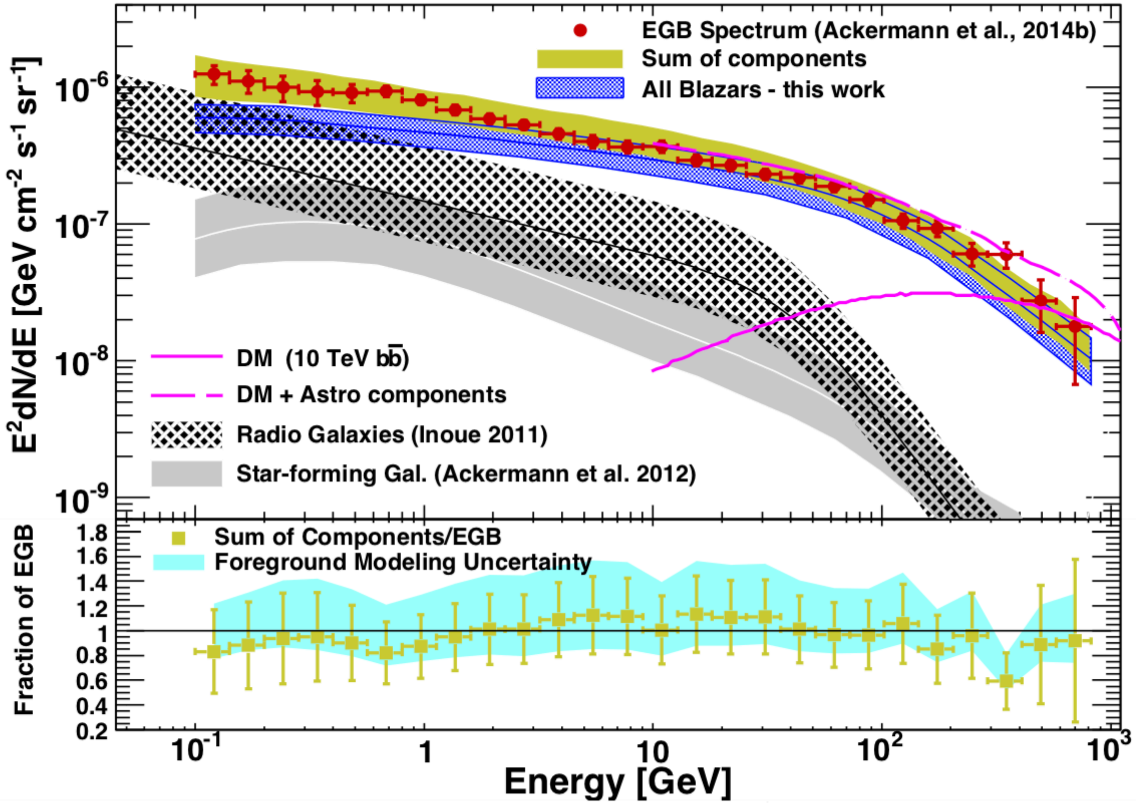




One of the most significant spot in the northern sky observed by IceCube need a better understanding: only starburst emission or additional emission components related to the AGN activity?

EXTRAGALACTIC GAMMA-RAY BACKGROUND

Ajello et al., APJL 800 (2015)



- Fermi-LAT resolved many individual sources belonging to different classes, Blazars dominates the EG samples.
- Limit on PS above 50 GeV varies from 68% (Lisanti et al. 2016) to 86% (Ackermann et al. 2016) of the EGB

Room for Starforming and Starburst galaxies needs a better definition due to the small number of resolved ones at HE

Hadronic production in the SBGs

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

The Starburst Galaxy M82

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)**

Generally, the SBGs are considered with the same properties of a prototype galaxy with “known” parameters (Peretti et al., arXiv:1812.01996, arXiv:1911.06163) see also (Loeb & Waxman 06; Bechtol, Ahlers, Di Mauro & Vandebrouke’15; Murase, Ahlers, Lack’13; Tamborra, Ando & Murase’14; Ando, Tamborra & Zandanel’15; Guetta, Ahlers, Murase’16; Palladino, Fedynitch, Rasmussen and Taylor’19)

SEMI-ANALYTIC PARAMETRIZATION OF SBGs

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

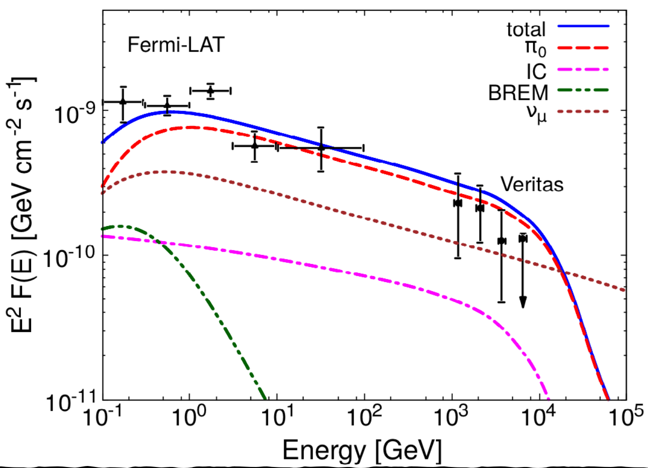
- In the calorimeter scenario, three main parameters:
  - Cut-off energy
  - Spectral index
  - Rate of Supernova explosions ⟶ **The Star Formation Rate**

Tloss > Tesc in the core

Leaky-box-like model for CR transport

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

CR injected and accelerated by SNRs



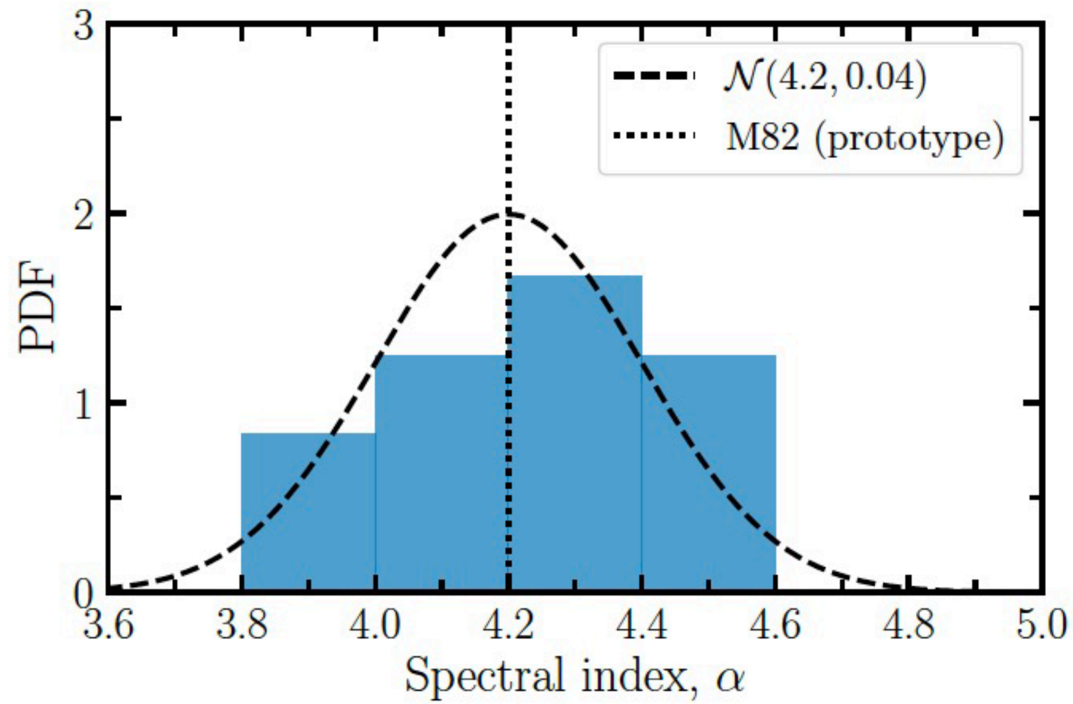
M82 as prototype

BLENDING OF SPECTRAL INDEXES USED

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

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

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti



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

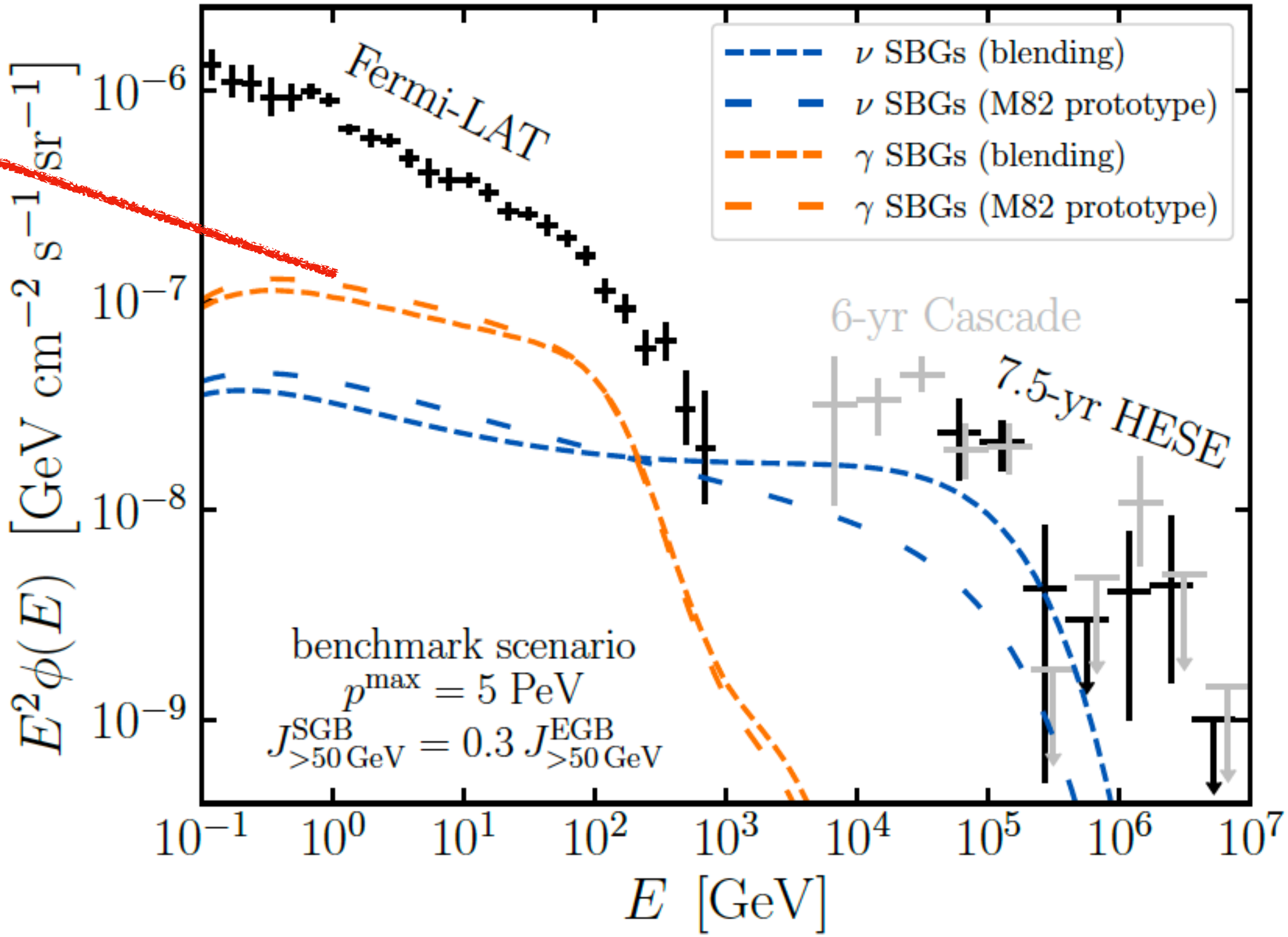
Ajello et al., ***arXiv:2003.05493***

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

BLENDING VERSUS PROTOTYPE SCENARIO

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

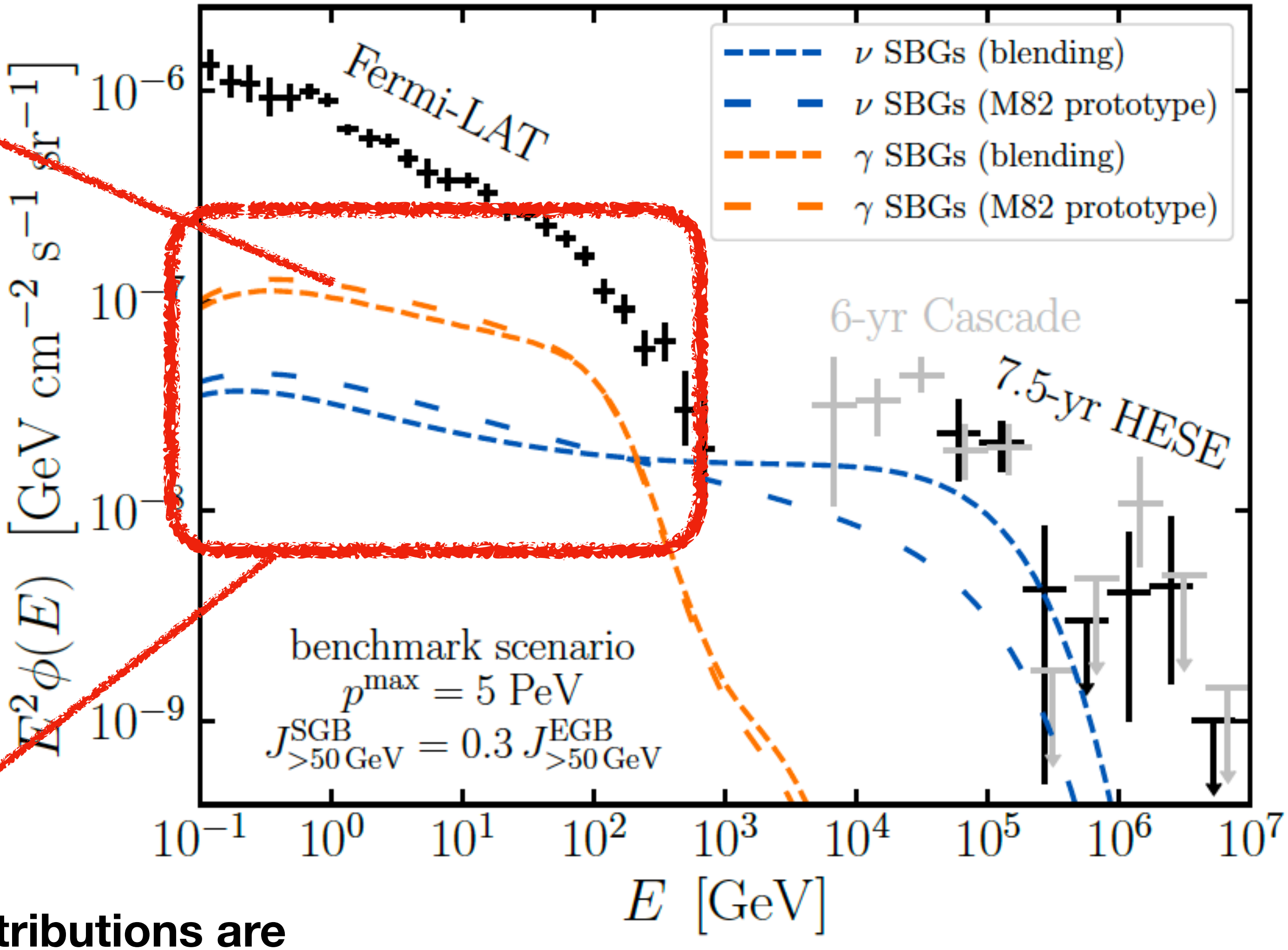
Direct + electromagnetic cascades gamma-ray flux



BLENDING VERSUS PROTOTYPE SCENARIO

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

Direct + electromagnetic cascades gamma-ray flux EBL taken into account

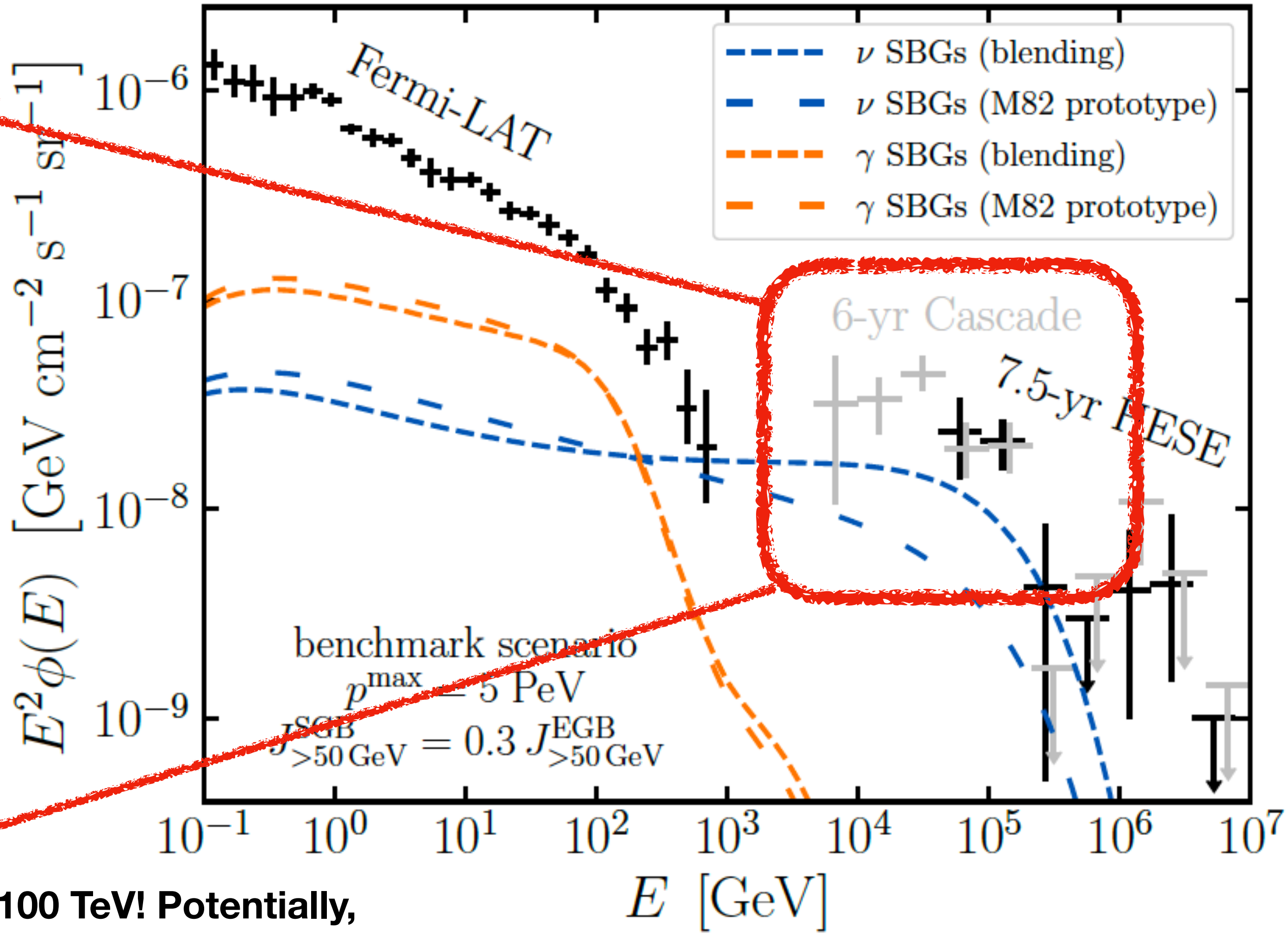


The diffuse gamma contributions are almost the same!

BLENDING VERSUS PROTOTYPE SCENARIO

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

With $p^{\max} = \mathcal{O}(\mathrm{PeV})$ it is possible to obtain a significant nu 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 scenarios to explain IceCube observations.

BLENDING VERSUS PROTOTYPE SCENARIO

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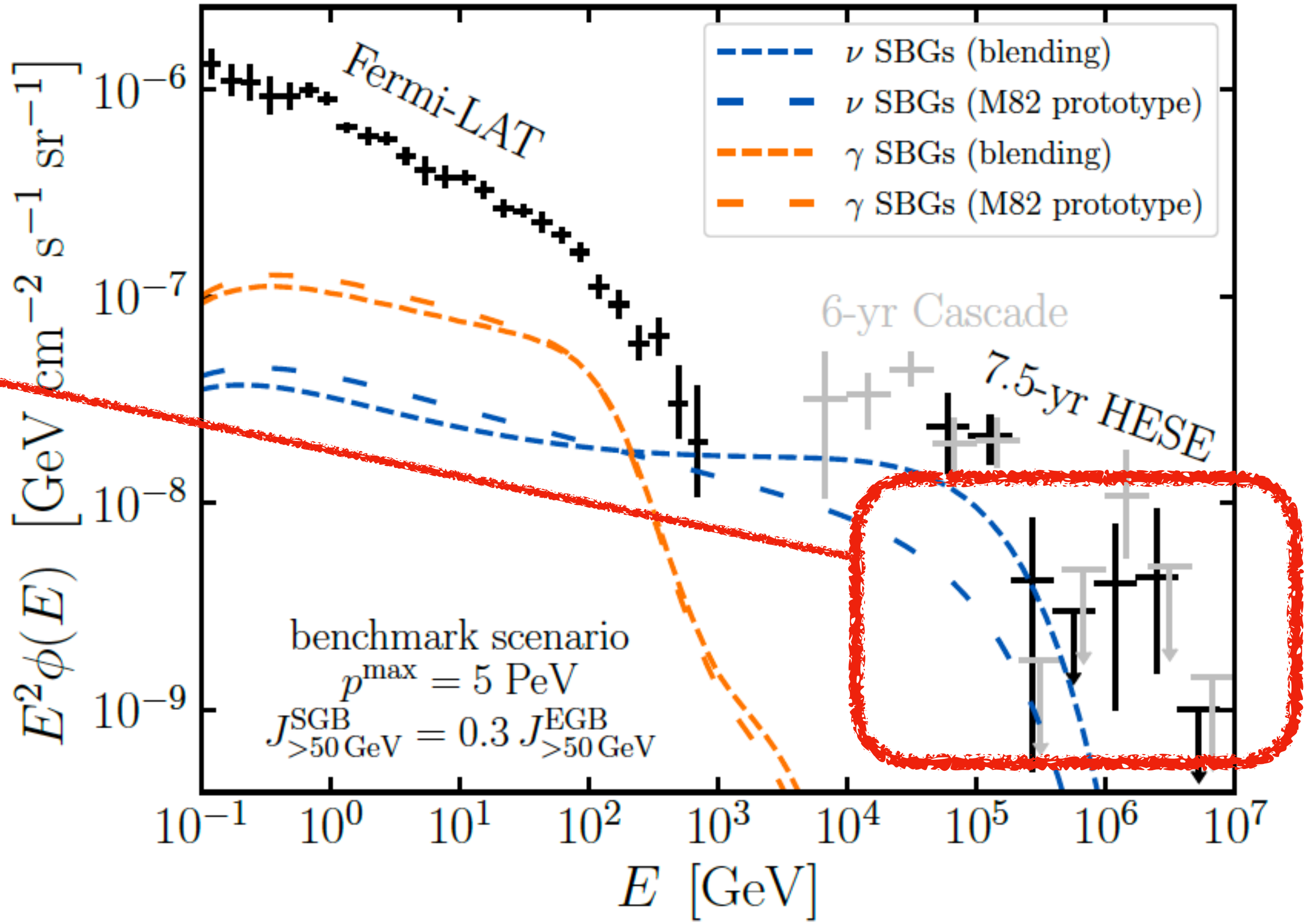
A possible contribution at higher energies from Blazar?
A possible interplay between reservoirs and accelerators can explain the whole IceCube SED



THE PROPOSED MULTIMESSENGER 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:

1. **SBGs**
2. **Blazars**

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

MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

Observational Samples Used

Extragalactic gamma-ray Background (EGB)

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

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

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)

THE PROPOSED MULTIMESSENGER FIT

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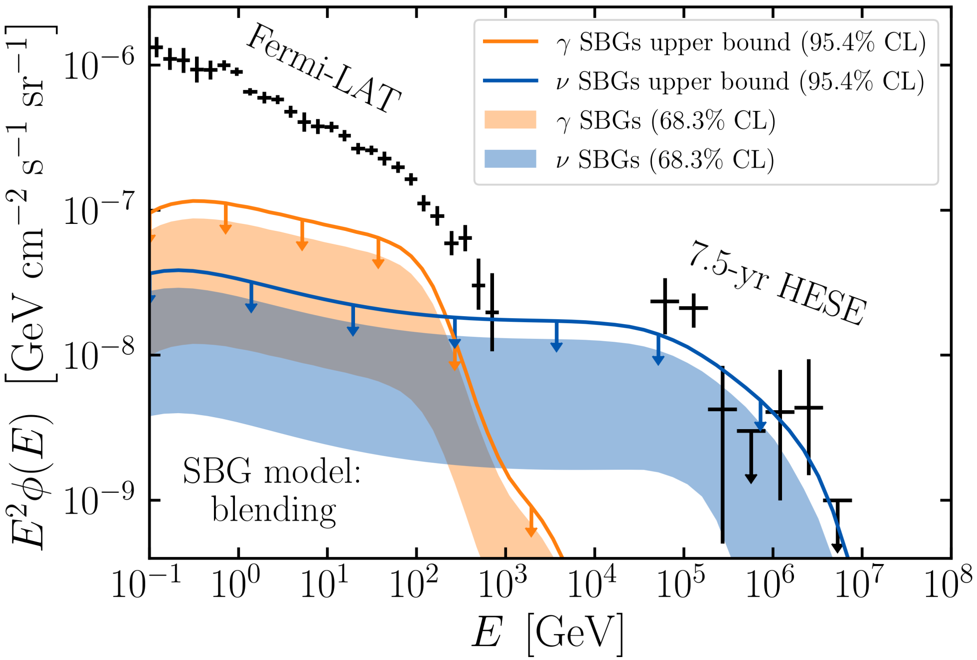

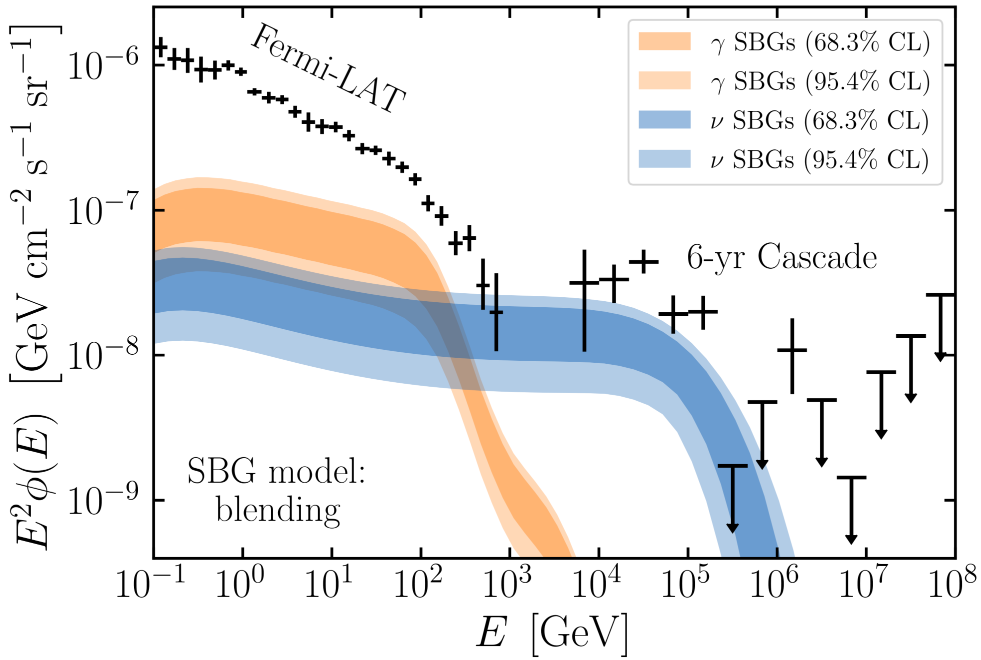

2 sigmas allowed SED considering Fermi-LAT EGB and IceCube HESE data

2 sigmas allowed SED considering Fermi-LAT EGB and IceCube CASCADE data

THE PROPOSED MULTIMESSENGER FIT

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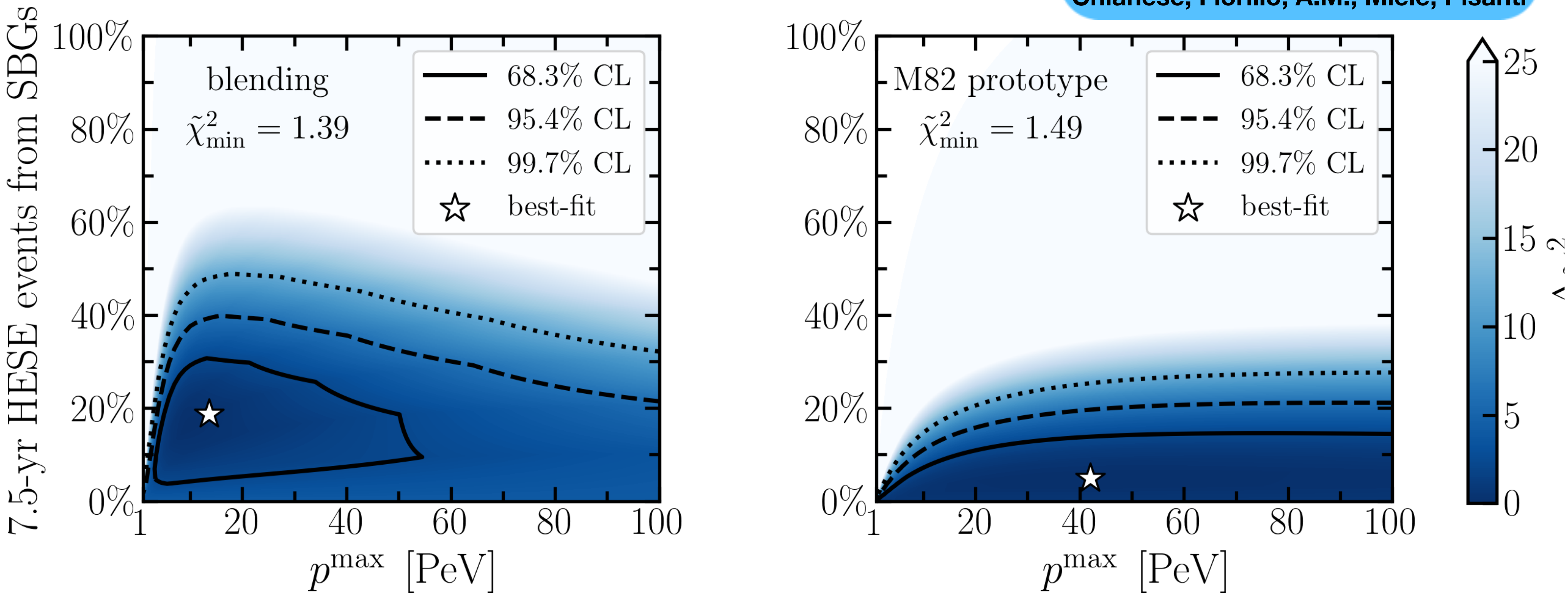
Redshift interval: $0 \leq z \leq 4.2$



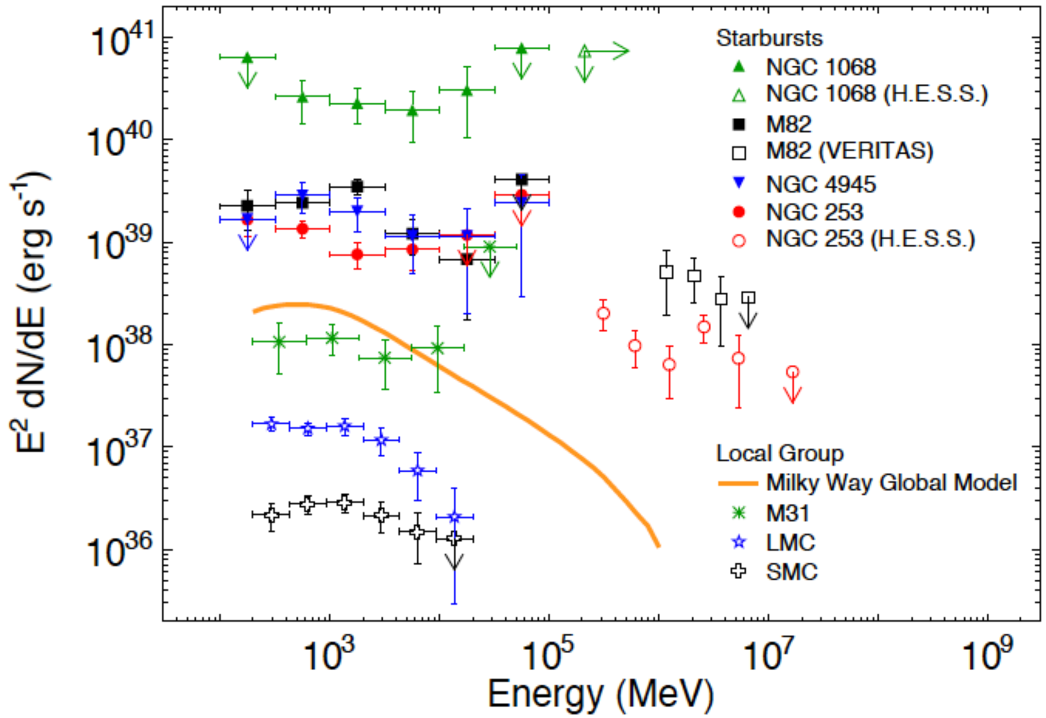
At 2 sigma level the "blending" scenario can account up to 40% of IceCube HESE measured flux, moreover at 1 sigma a Pmax up to 50 PeV is permitted, however a cutoff ~ 10 PeV is favored.

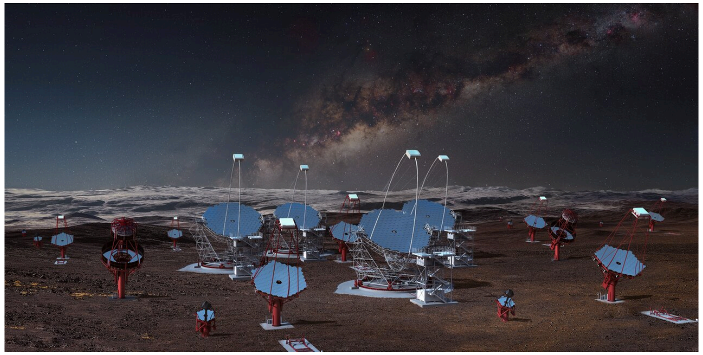
Calorimetric model validation

The calorimetric "prototype" model used needs validation with more resolved SBG at VHE

ApJ 755 (2012)
Fermi-LAT

ApJ 894 (2020)
Ajello et al.





CTA will increase the actuals VHE SBG catalog

The measurements of the single SBG SEDs at more than 1TeV will be crucial to constrain the full sky diffuse neutrino expectations

LOOKING AT NEARBY KNOWN SBGs

The gas density and the star formation rate have been linked trough this relation:

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

(Kennicutt 1998 ; Inoue et al. 2000 ; Hirashita et al. 2003 ; Yuan et al. 2011 ; Kennicutt & Evans 2012 ; Kennicutt & De Los Reyes 2021

While the star formation rate is expected to be proportional to infra red observations through:

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

APJL 919 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele

Source	Uniform prior	Most-likely values	68% credible intervals		χ^2/dof
	$\dot{M}_*$	$(\dot{M}_*, \Gamma)$	$\dot{M}_*$	Γ	
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 star formation rate $\dot{M}_*$ is in units of $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$.

For each SBG we check if the fitting of gamma rays assuming a "calorimetric" scenario does not produce a tension between the gas needed and the IR observations

NEUTRINO EXPECTATIONS FROM KNOWN SBGs

The neutrino normalizations obtained for the 13 SBGs considered have been compared to the expected point-like sensitivities of KM3NeT and IceCube observatories.

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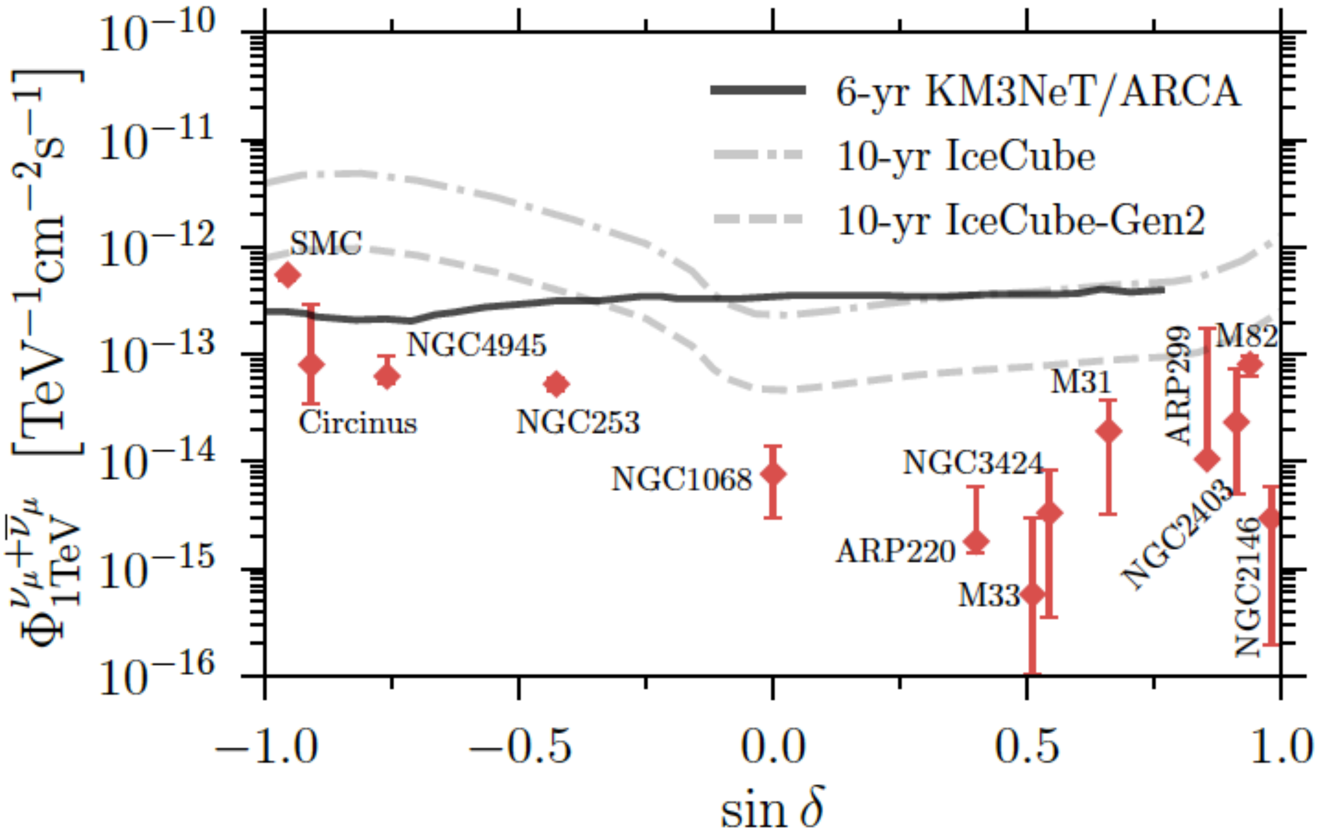

To describe the neutrino excess observed from NCG1068 additional AGN components are needed.

The considered SBGs can be observed with the current and incoming neutrino telescopes only with several years of observation. The most optimistic cases are the Small Magellanic Cloud and Circinus galaxy visible by KM3NeT in 6 years of data taking.

CTA answers at VHE

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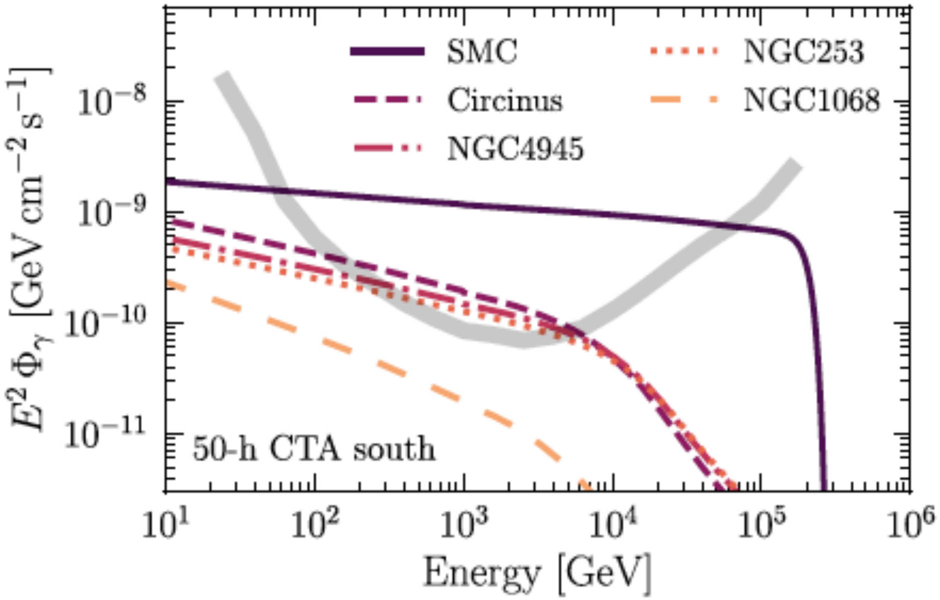
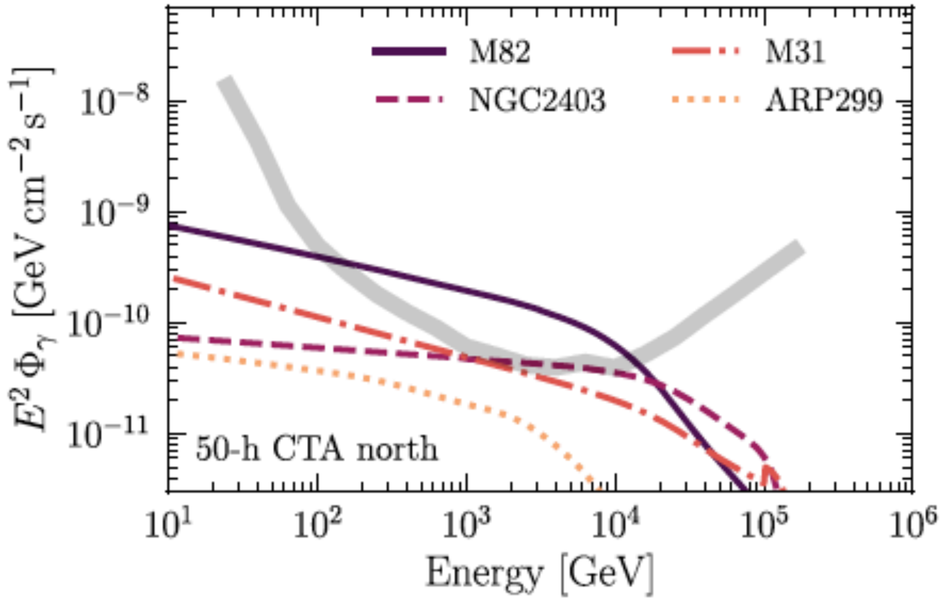
CTA southern sky



CTA northern sky



Both CTA northern and souther hemisphere have the sensitivity to observe the expected gamma-ray spectral features of the known SBGs verifying the calorimetric scenario.

COSMIC-RAY PHYSICS INSIDE SBGN

injection term

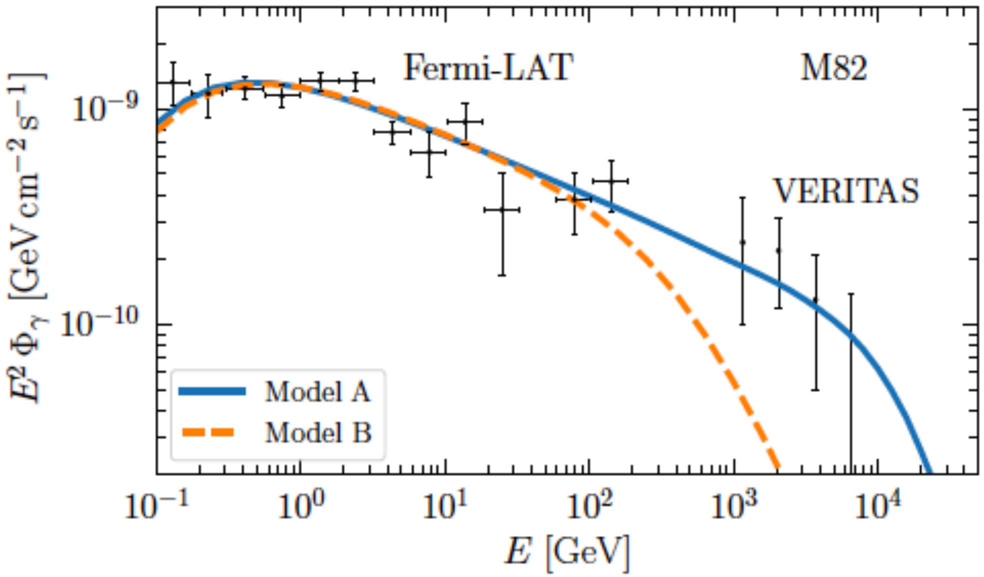
$$\frac{f(p)}{\tau_{\rm loss}(p)} + \frac{f(p)}{\tau_{\rm adv}(p)} + \frac{f(p)}{\tau_{\rm diff}(p)} = Q(p)$$

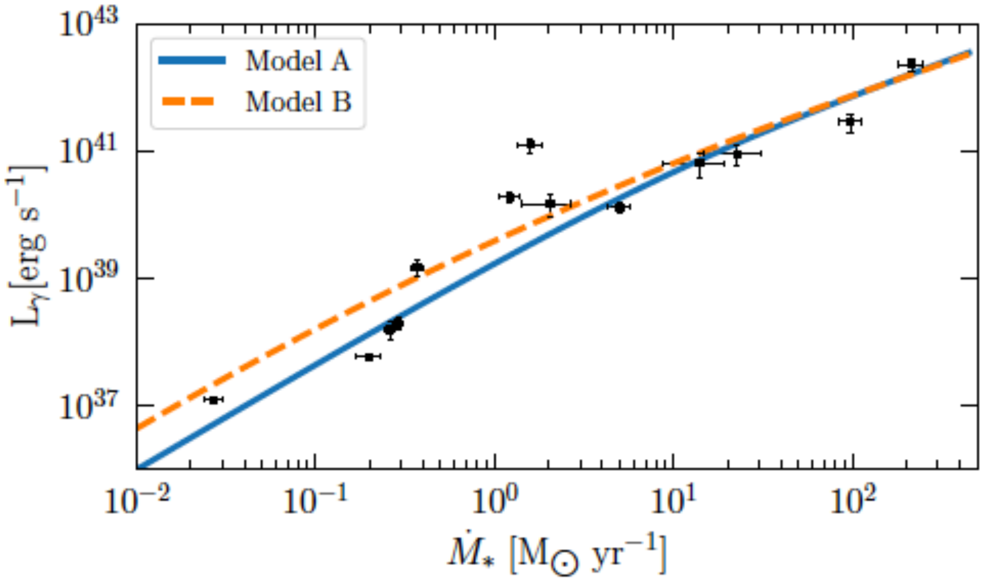
Model A — MNRAS 487,168 (2019) Peretti el al.

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

Model B — MNRAS 493,2817 (2020) Krumoltz el al.

$\tau_{\rm adv} = R_{\rm SBN}/v_{\rm wind}$ $\quad R_{\rm SBN} = 200\,\rm pc$ $\quad v_{\rm wind} = 500\,\rm km/s$

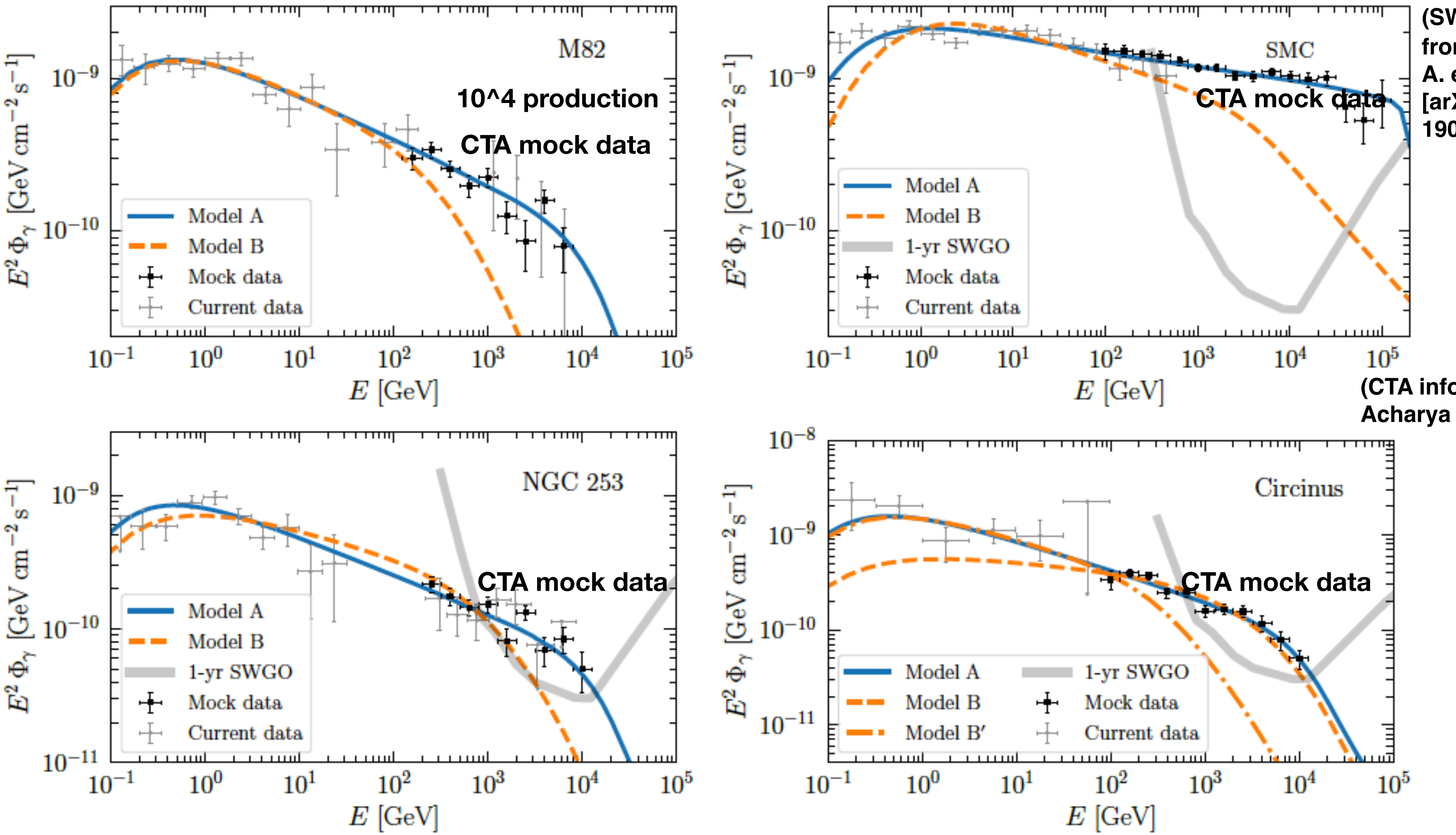




When TeV gamma-ray can be crucial

Arxiv220303 (2022) Ambrosone, Chianese, Fiorillo, A.M., Miele

For most of these known SBG the TeV observation will disentangle the two scenarios



(SWGO info fromAlbert, A. et al. 2019 [arXiv: 1902.08429])

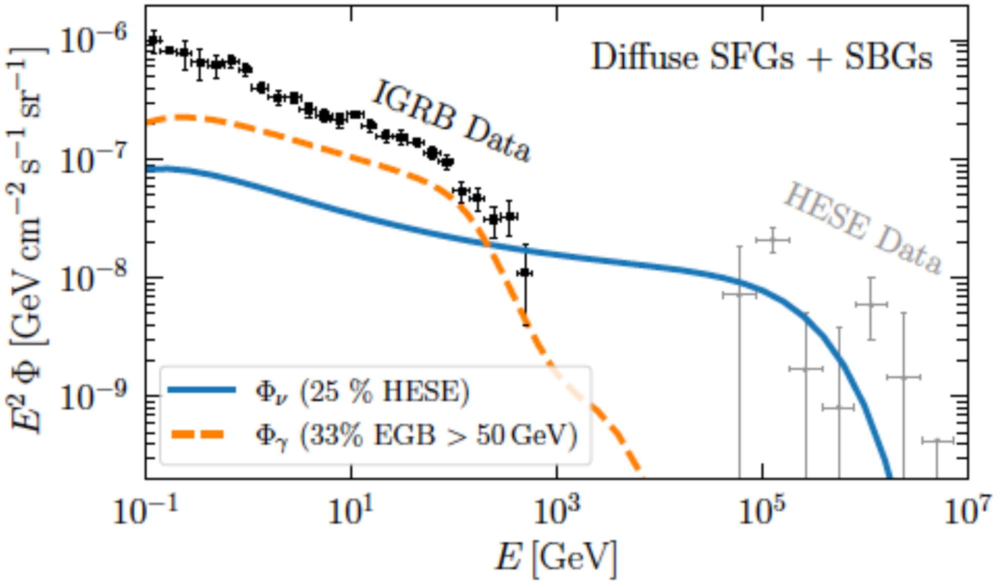
(CTA info from Acharya et al. 2018)

Implication for neutrino expected

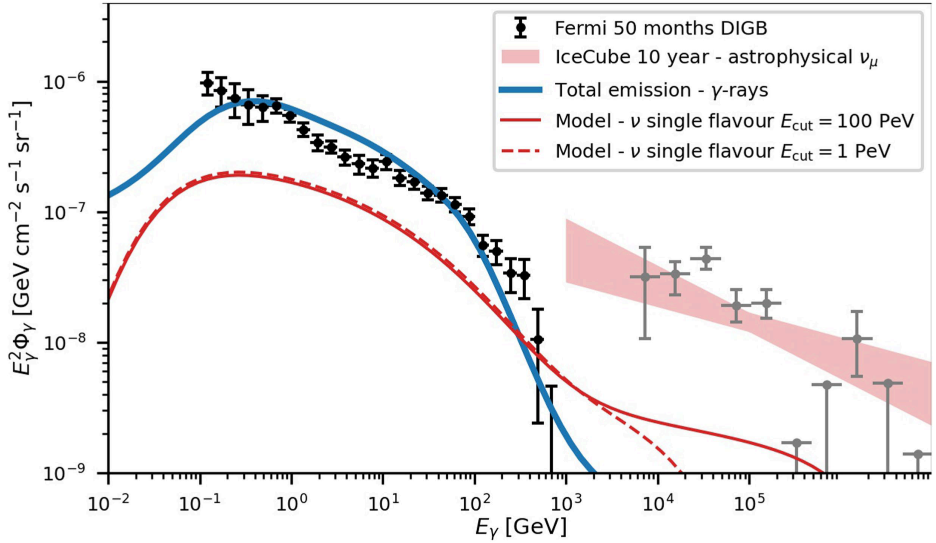
Arxiv220303 (2022) Ambrosone, Chianese, Fiorillo, A.M., Miele

Nature 41586 (2021) M. Roth et al.

Model A



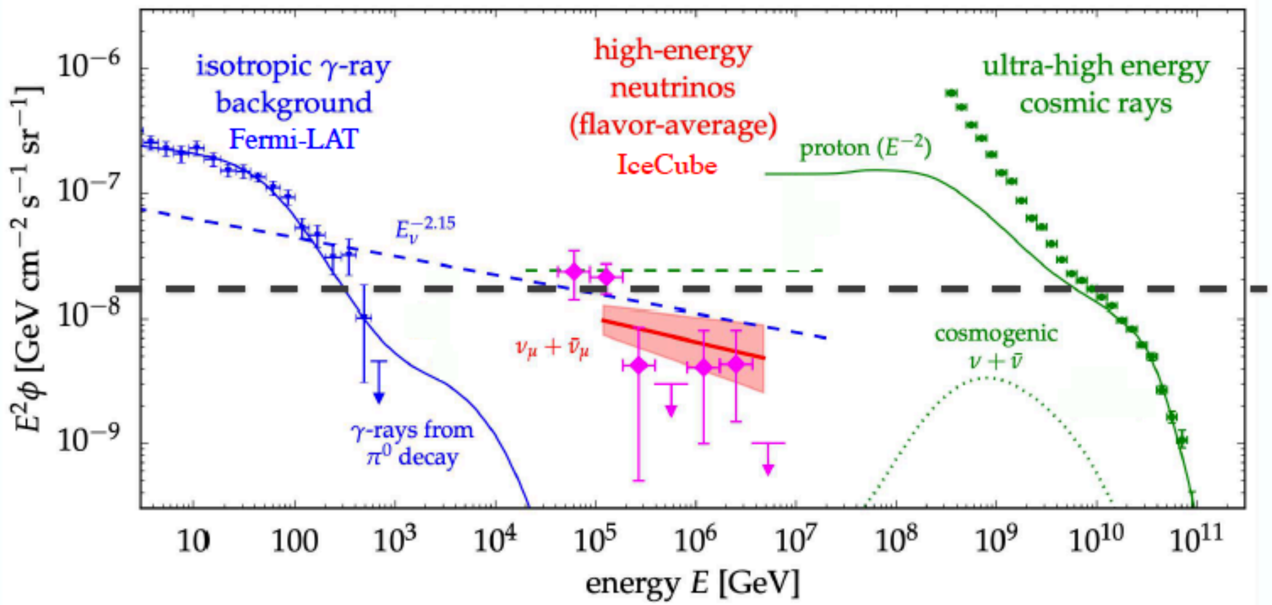
Model B



The two scenarios proposed for the cosmic-ray transport inside the nucleus of Starburst galaxies can produce a quite different prediction for high energy neutrinos

MULTIMESSENGER RECAP

PPNP 102 (2018)
Ahlers & Halzen



APJL 919 (2021)
Ambrosone, Chianese, Fiorillo, A.M., Miele

Diffuse High Energy neutrino

- Starburst galaxies < 40%
- Blazars < 30%
- Diffuse Galactic < 10%
- Radio Galaxies ?

Diffuse High Energy gamma rays

- Starburst galaxies up to 30%
- Blazars up to 70% above 50 GeV
- Radio Galaxies ?

SUMMARY

- The increasing number of catalogued gamma-ray SBGs it's a starting point for a more accurate population study of neutrino emission.

- A considerable contribution (up to 40%) of the astrophysical neutrino signal measured by IceCube can be attributed to this class of sources if we arrive up to z~4.0.

- With incoming gamma-ray telescopes a better constrain of the spectral cutoff and cosmic-ray transport inside these "reservoir" sources will be possible.

- The contribution of the nearby known SGBs to IceCube astrophysical flux is at the level of ~%, however some of them can produce a visible point-like excess within decade of KM3NeT and IceCube/Gen2 data taking. The Small Magellanic Cloud and Circinus galaxy seems very promising.

- Neutrino statistics of a Global Neutrino Network + CTA survey of the close SBGs can solve the puzzle.

Thank you for the attention!