Cosmic Reservoirs : the importance of CTA to understand high-energy neutrino observations

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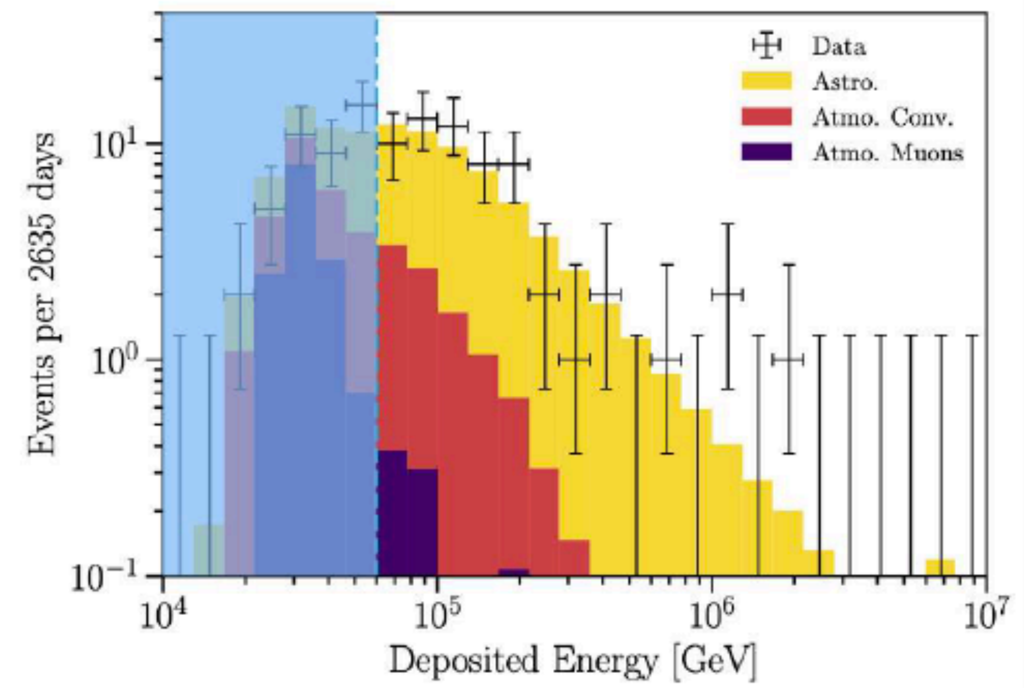
OAS Very High Energy Meeting 8-9/06/2022

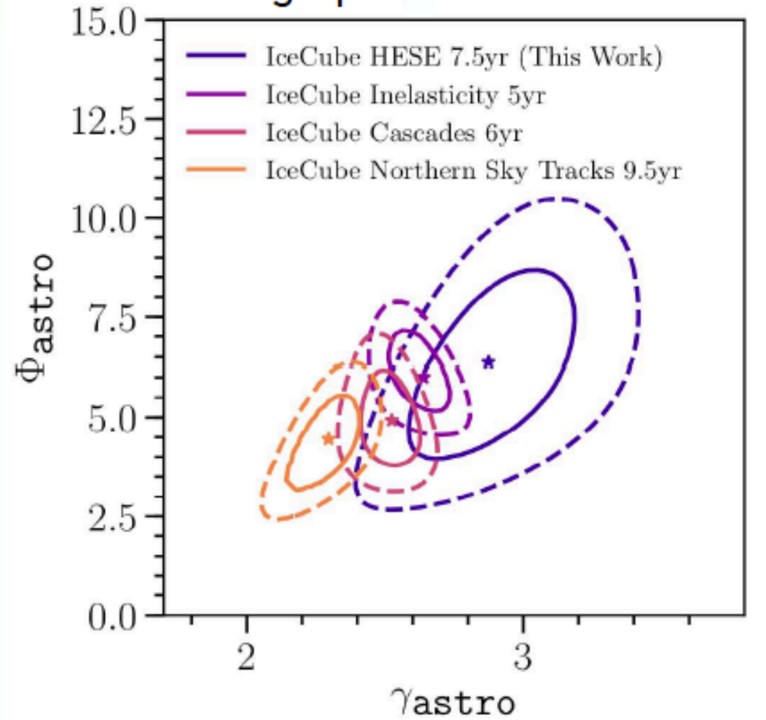
ν Spectral properties

PRD 104 (2021)
IceCube

7.5-year High-Energy Starting Events (HESE)



Single power-law best-fit

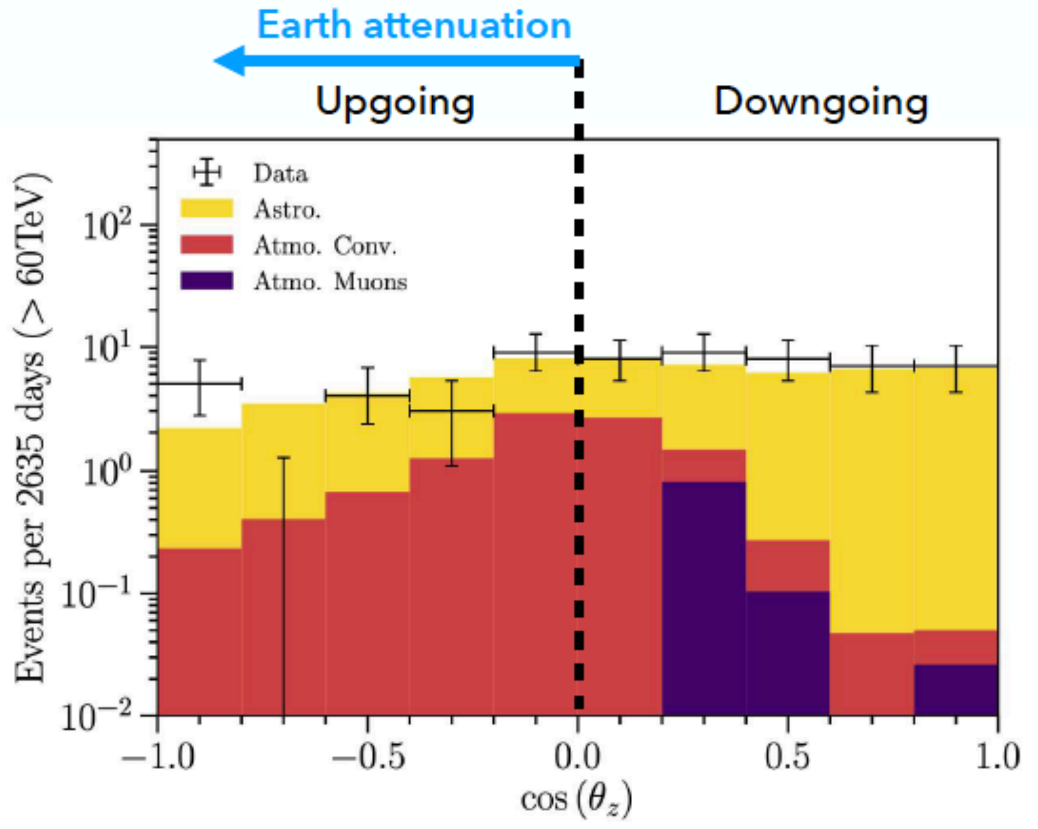


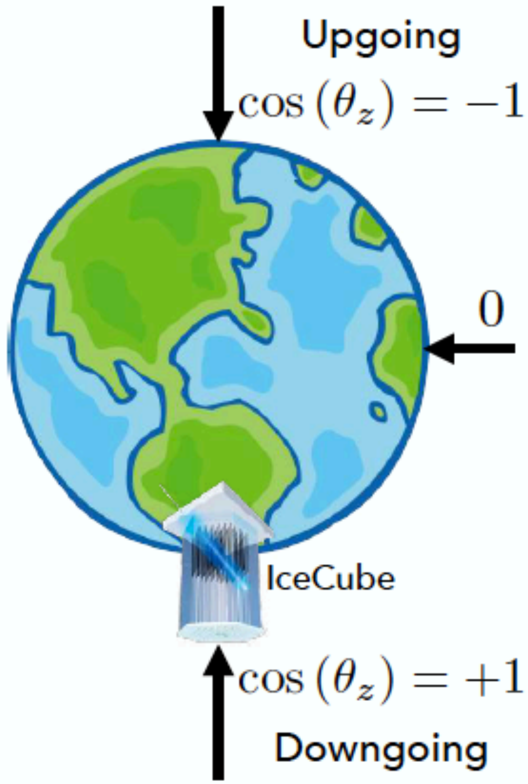
- ✦ 100+ neutrino events above 30 TeV since 2011
- ✦ Bkg-only hypothesis excluded at more than 7σ

$$\frac{d\Phi_{6\nu}}{dE} = \Phi_{\mathrm{astro}} \left(\frac{E_\nu}{100\,\mathrm{TeV}} \right)^{-\gamma_{\mathrm{astro}}} \cdot 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

ν Arrival direction

PRD 104 (2021)
IceCube





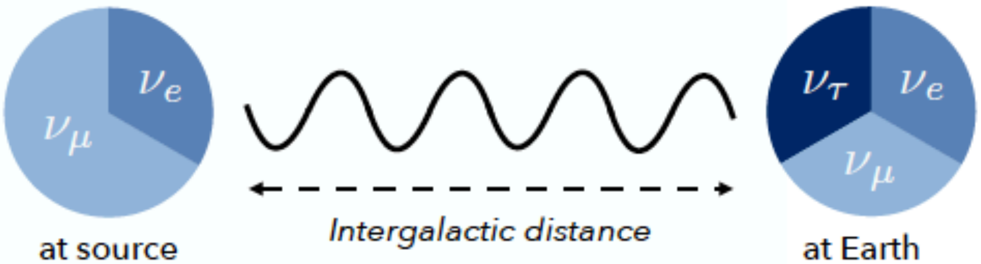
✦ The diffuse flux is isotropic

expected observation: Isotropy

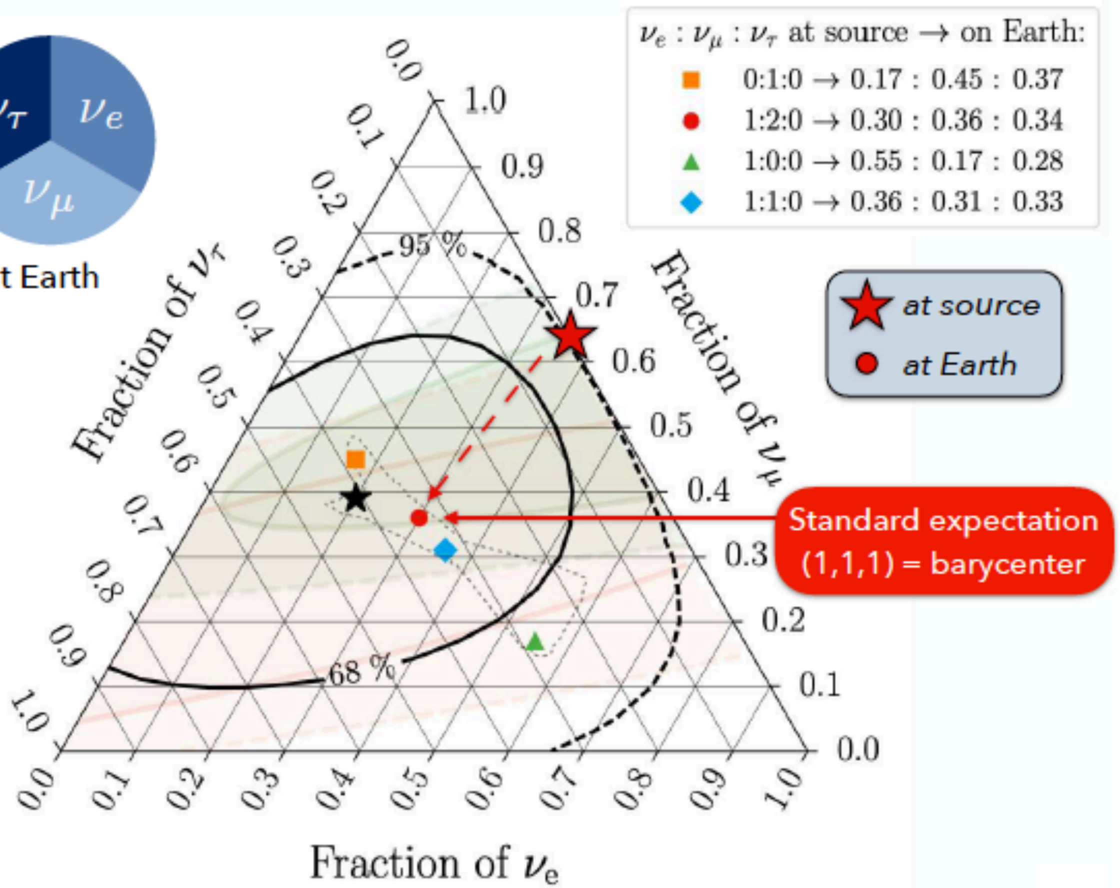
ν FLAVORS: ASTROPHYSICAL ORIGIN

ArXiv 2011:03561
IceCube

The different event topologies (tracks and showers) allow the study of flavor composition and oscillation



$$\nu_\alpha = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} \nu_\beta$$

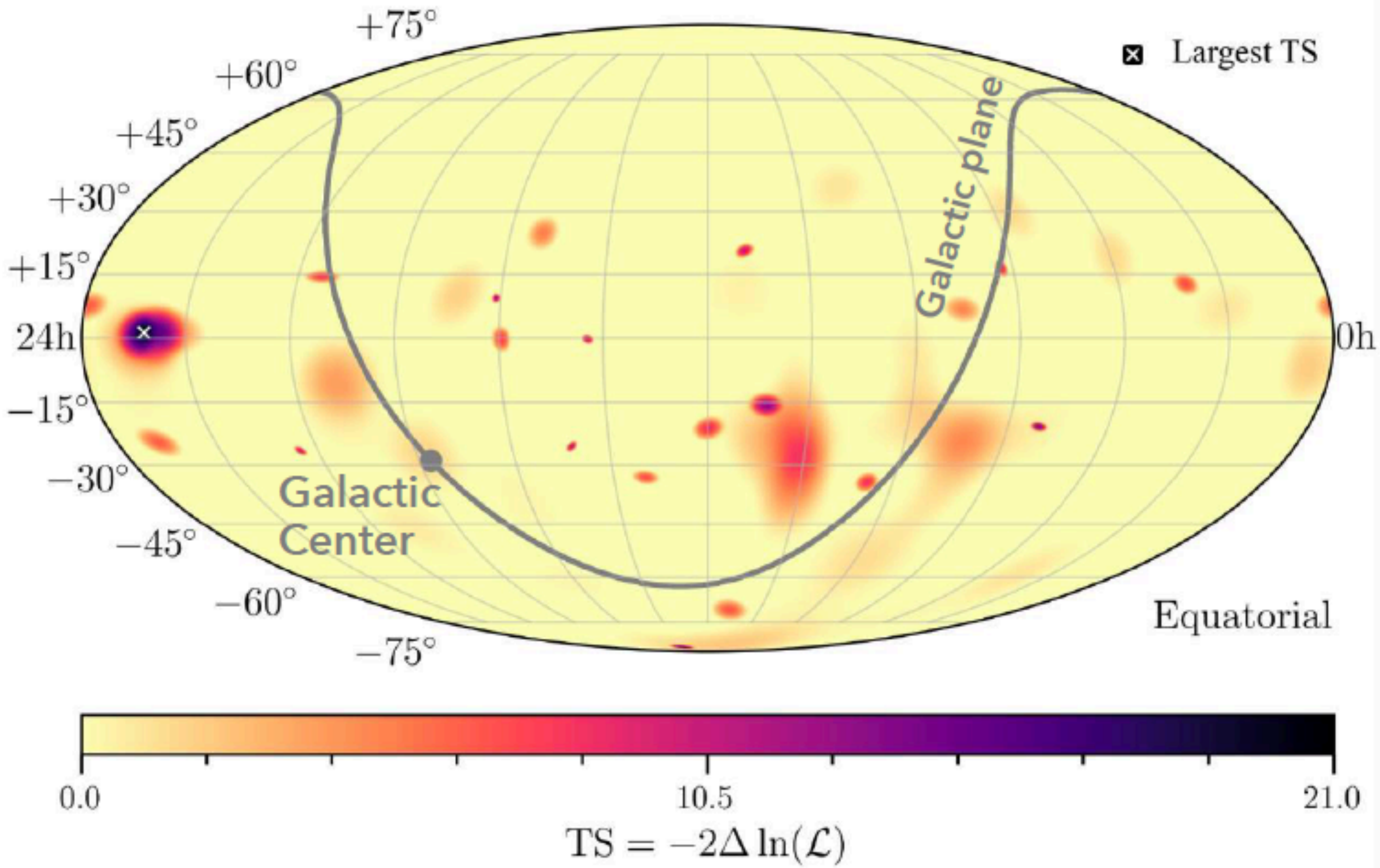


- ✦ Unveiling the astrophysical neutrino production
- ✦ Probing standard and non-standard neutrino oscillation probabilities thanks to high energies and large distances

ν Arrival direction

PRD 104 (2021)
IceCube

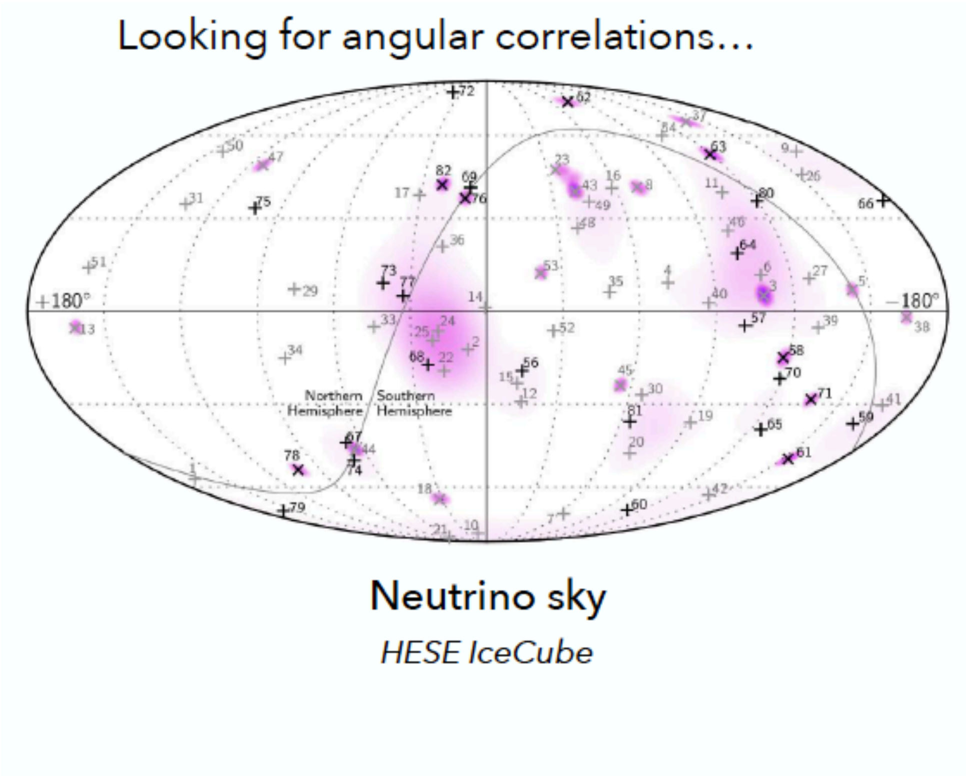
No significant excess in the neutrino sky

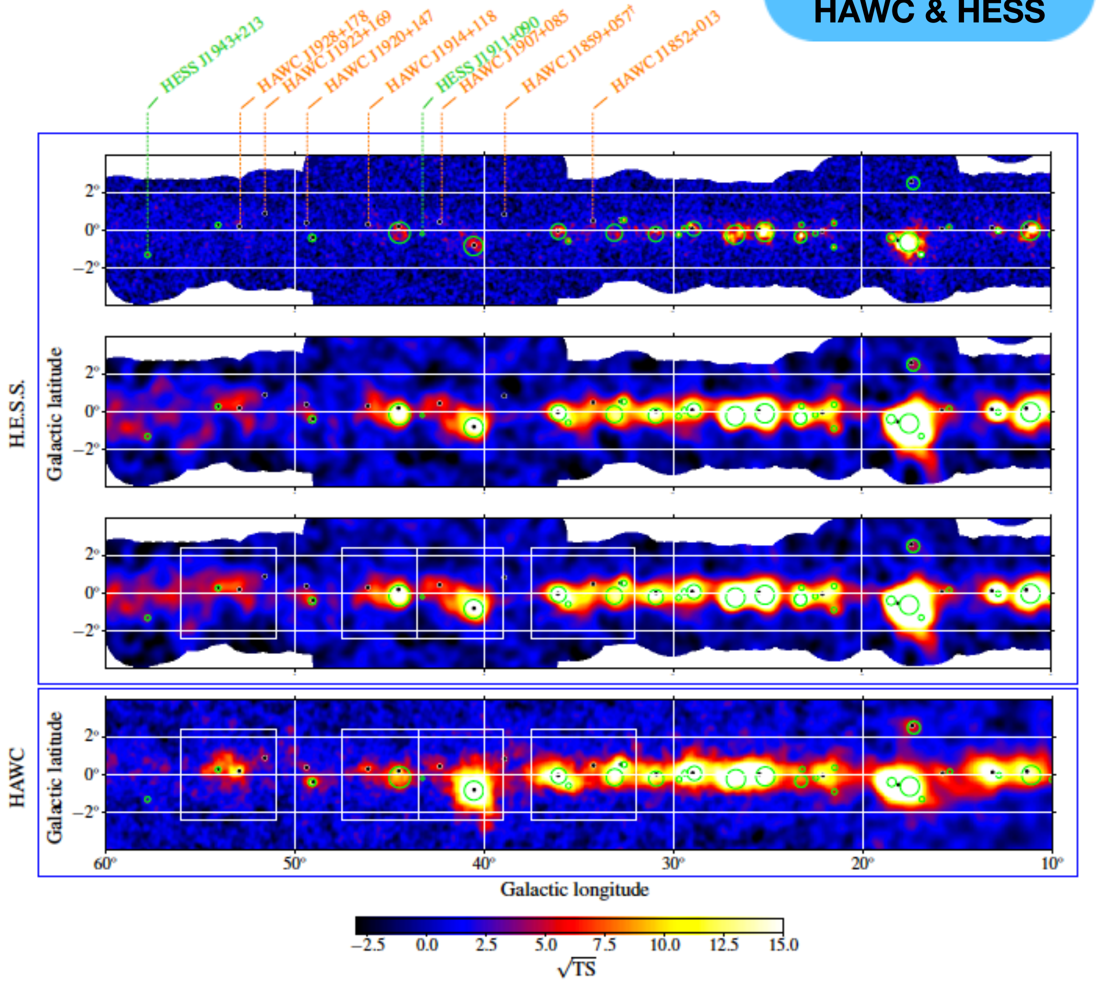


Correlation with galactic sources

ApJ 849 (2017)
IceCube

ApJ 917:6 (2021)
HAWC & HESS



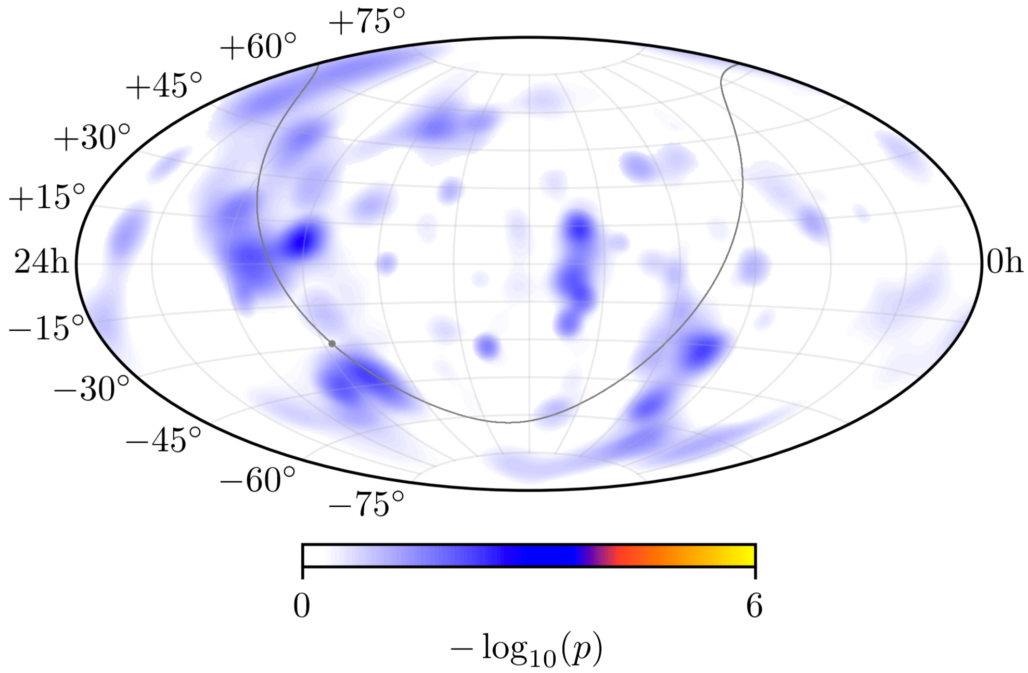


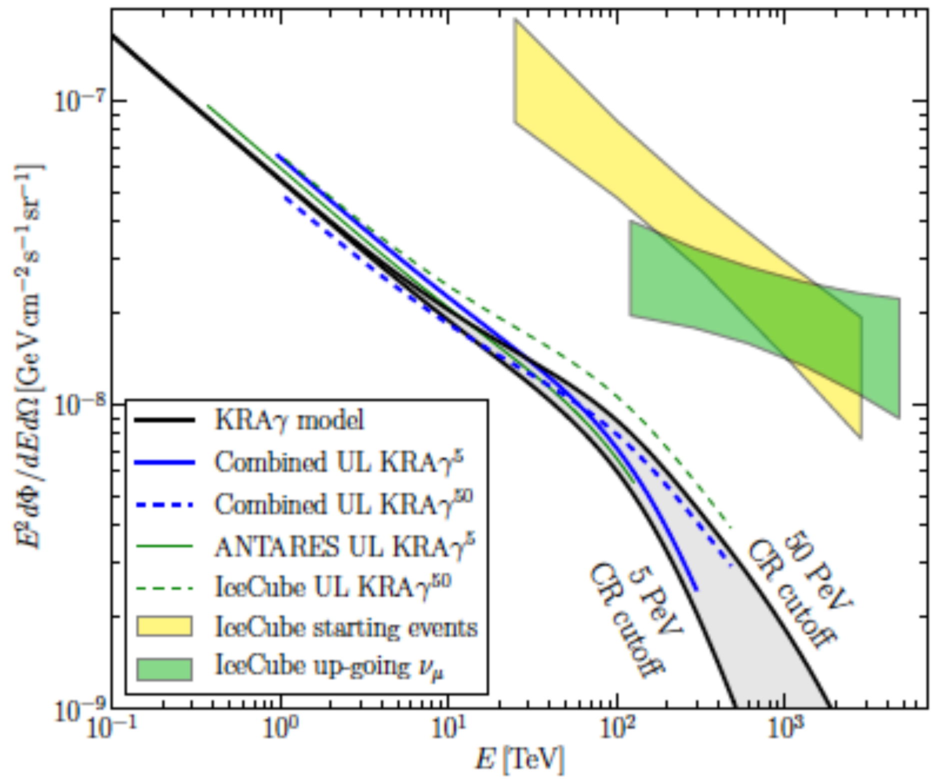
No significant association with the HAWC and H.E.S.S. observed Galactic sources

Galactic diffuse component

ApJ 920 (2019)
IceCube

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



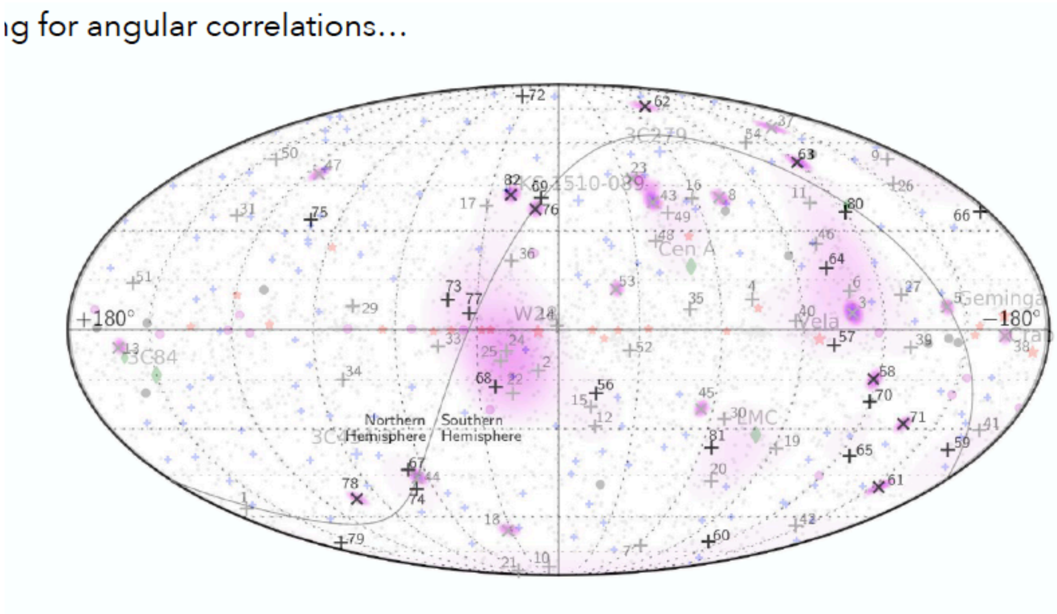


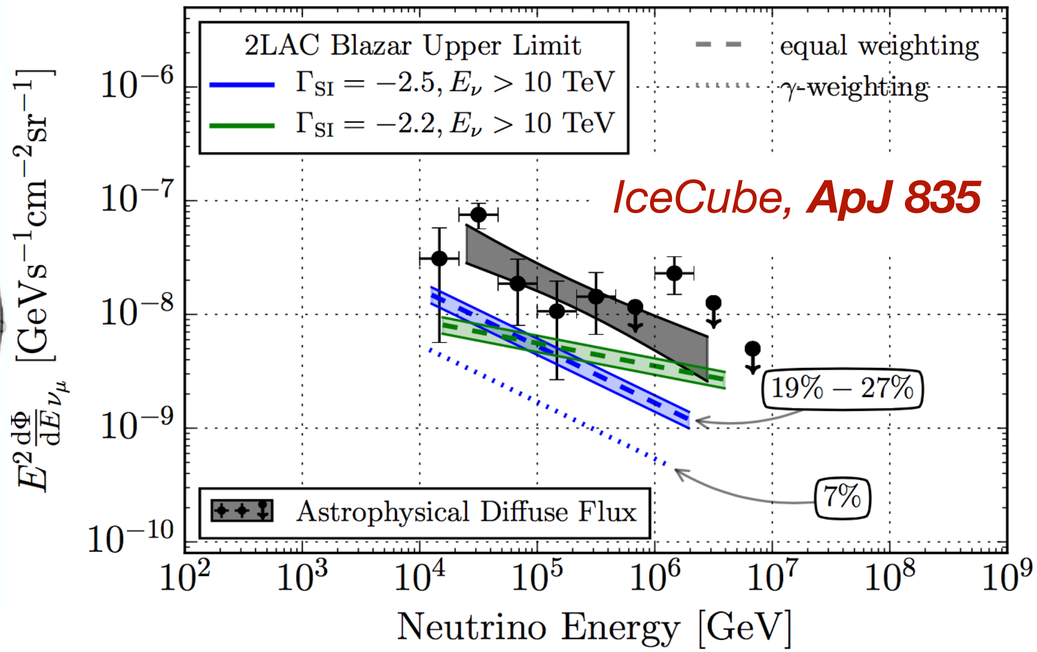
Evidence of galactic diffuse component at 2.2 sigma

Galactic diffuse component less than 10% of total astrophysical flux measured by IceCube

Blazars neutrino stacking limit

ApJ 835 (2017)
IceCube



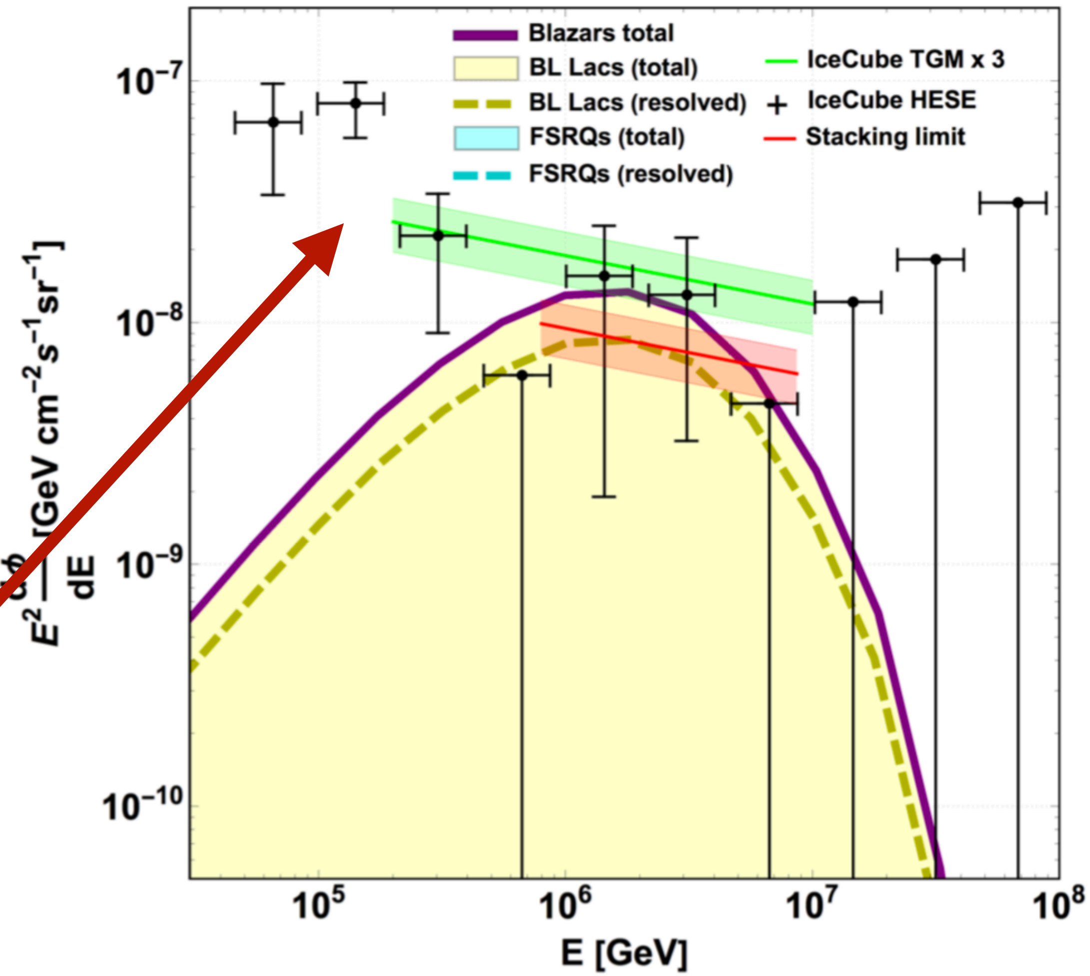


IceCube stacking limit: blazars can contribute at most 19% - 27% of the diffuse neutrino flux ($E_\nu > 10$ **TeV**)

MULTICOMPONENT FIT OF THE ICECUBE DATA

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

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



Additional component required to explain events at lower energies!

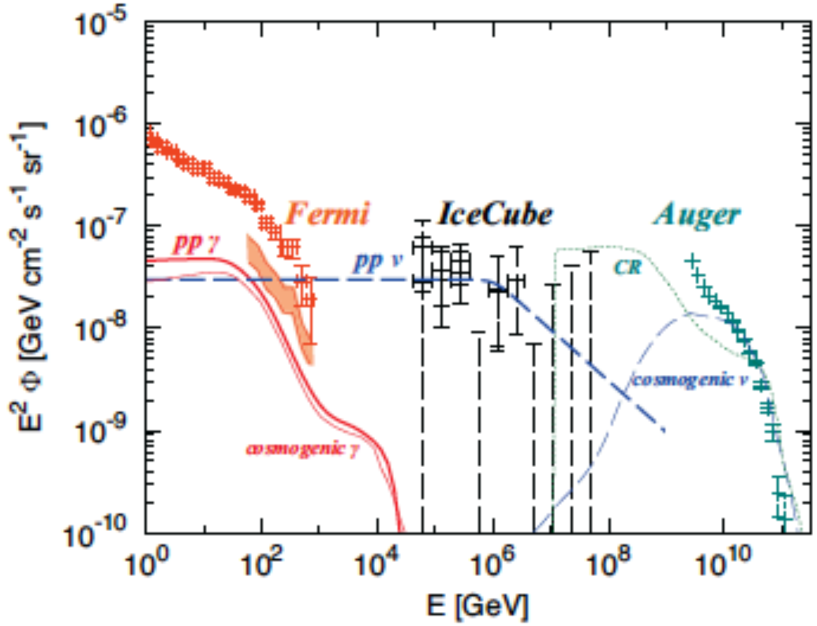
Possible explanation: "reservoir" components: Galactic and SBGs →

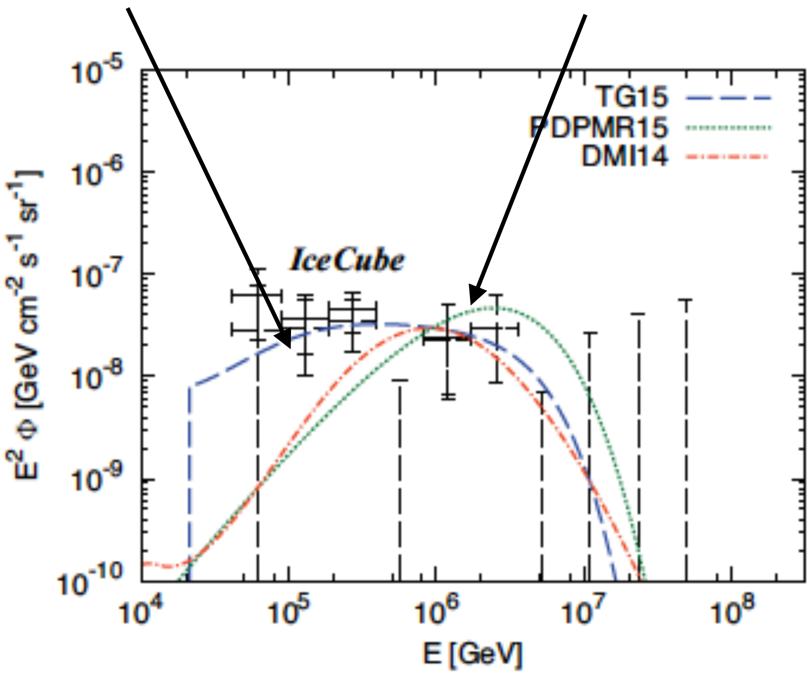
MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti

Explaining the IceCube signal with a multicomponent approach

PRL (2016)
Murase & Waxmann

"Reservoirs" component **"Accelerators" component**





Challenge: A multicomponent description of IceCube signal taking into account the diffuse multimessenger observations

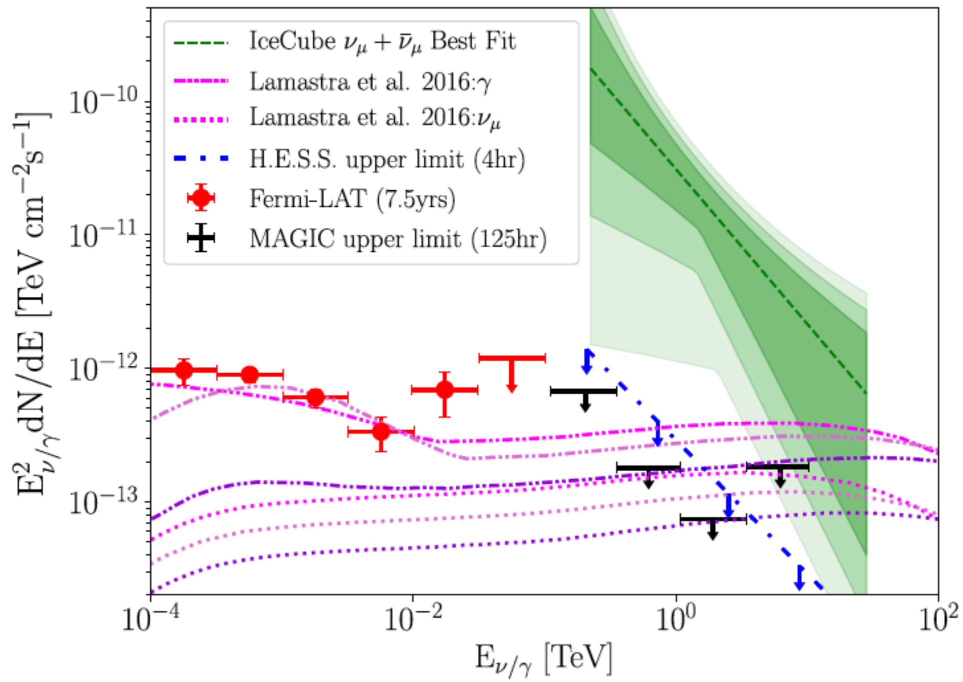
Balance between two actors: Accelerators and Reservoirs

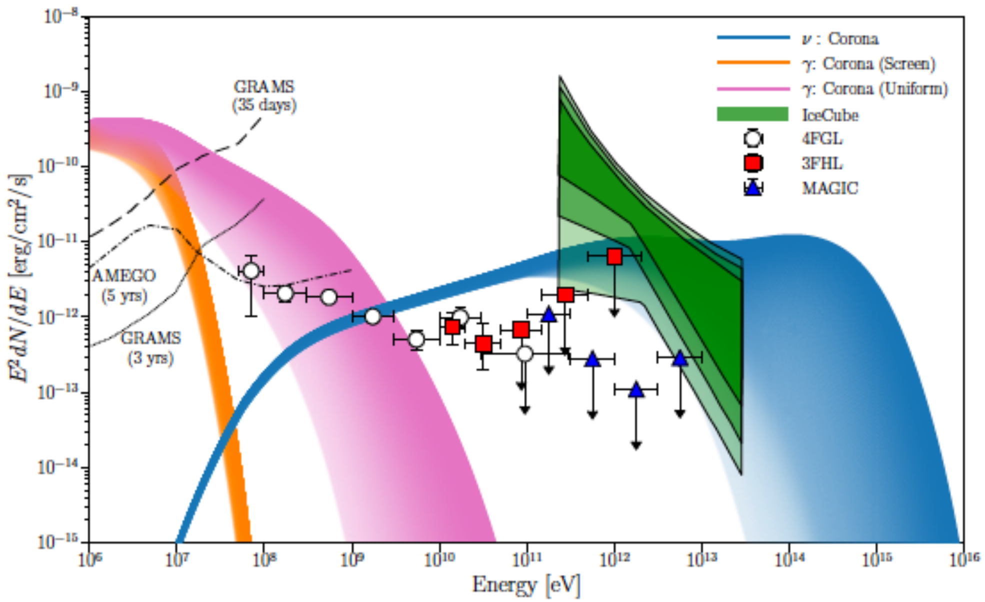
THE CASE OF NGC 1068

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.

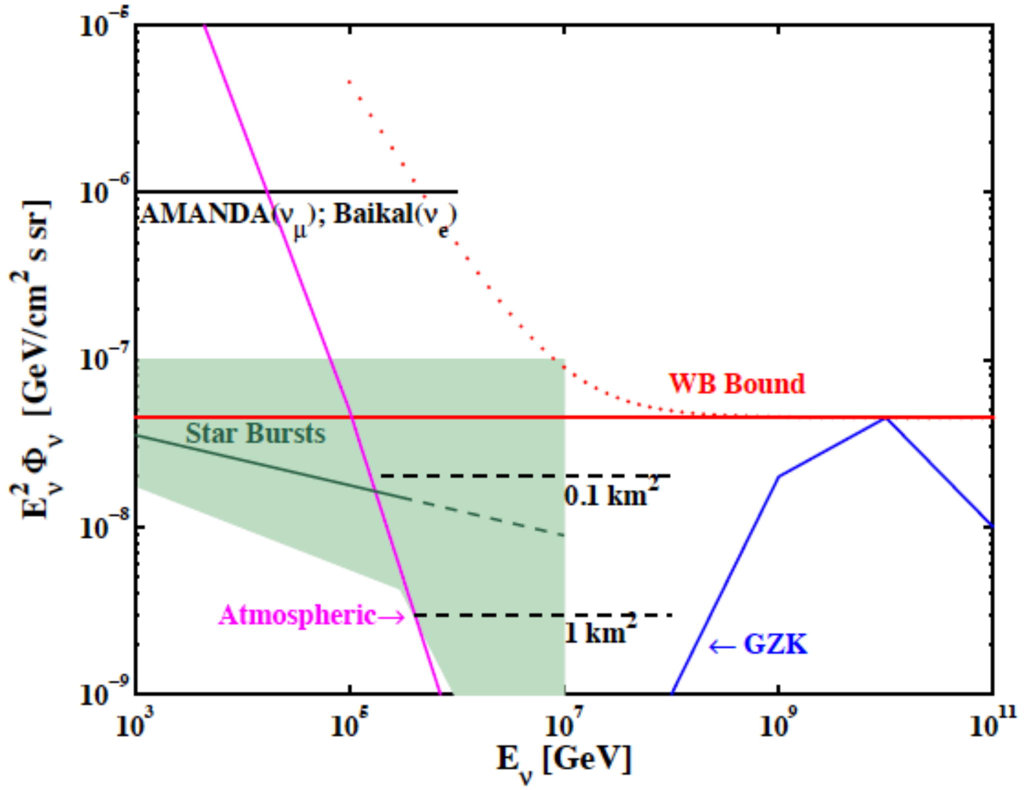




One of the of the most significant spot in the northern sky observed by IceCube need a better understanding: only starburst emission or additional AGN activity?

High star formation rate traces 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, IceCube and ANTARES

Hadronic production in the SBGs

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)**

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

- In the calorimeter scenario, three main parameters:

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

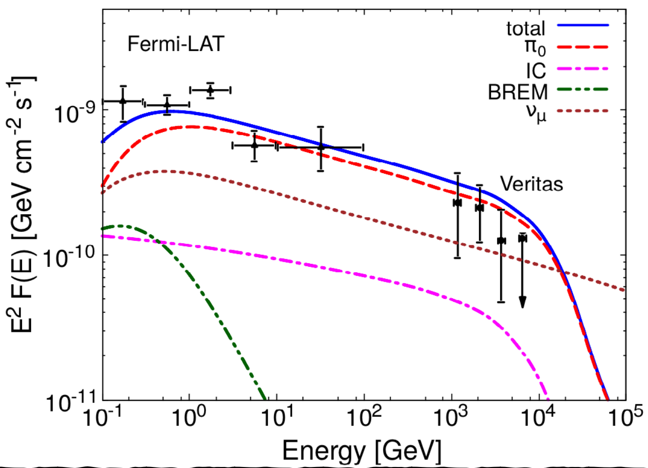
- Cut-off energy
- Spectral index
- Rate of Supernova explosions → **The Star Formation Rate**

Tloss > Tesc in the core

Leaky-box-like model for CR transport

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

CR injected and accelerated by SNRs



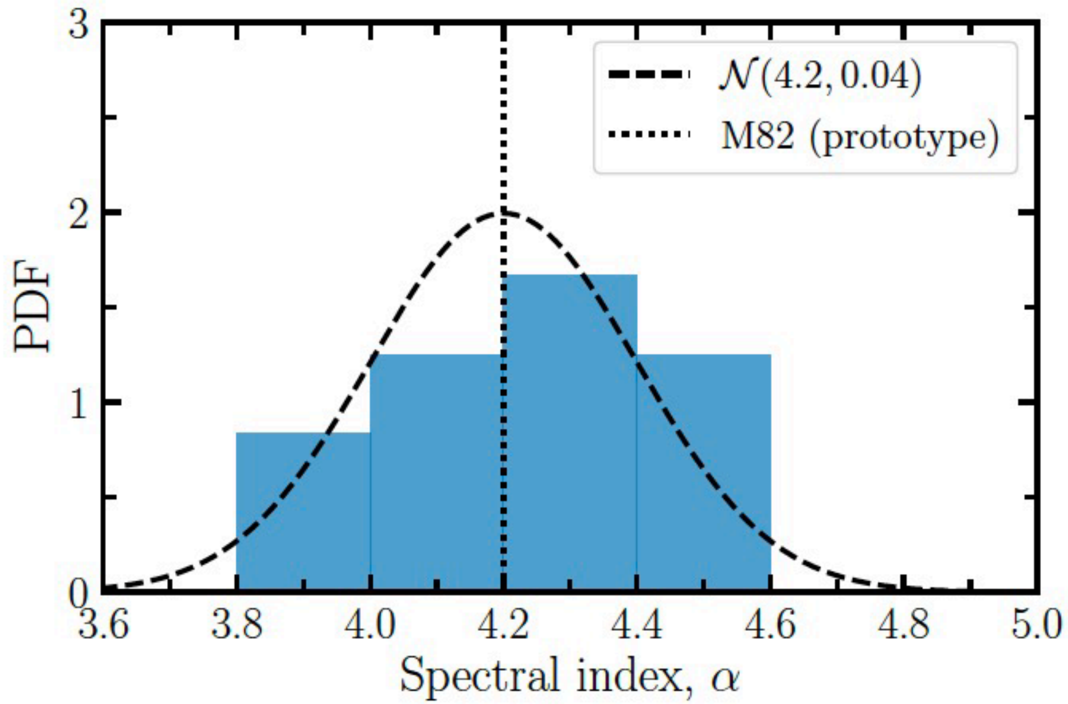
M82 as prototype

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***

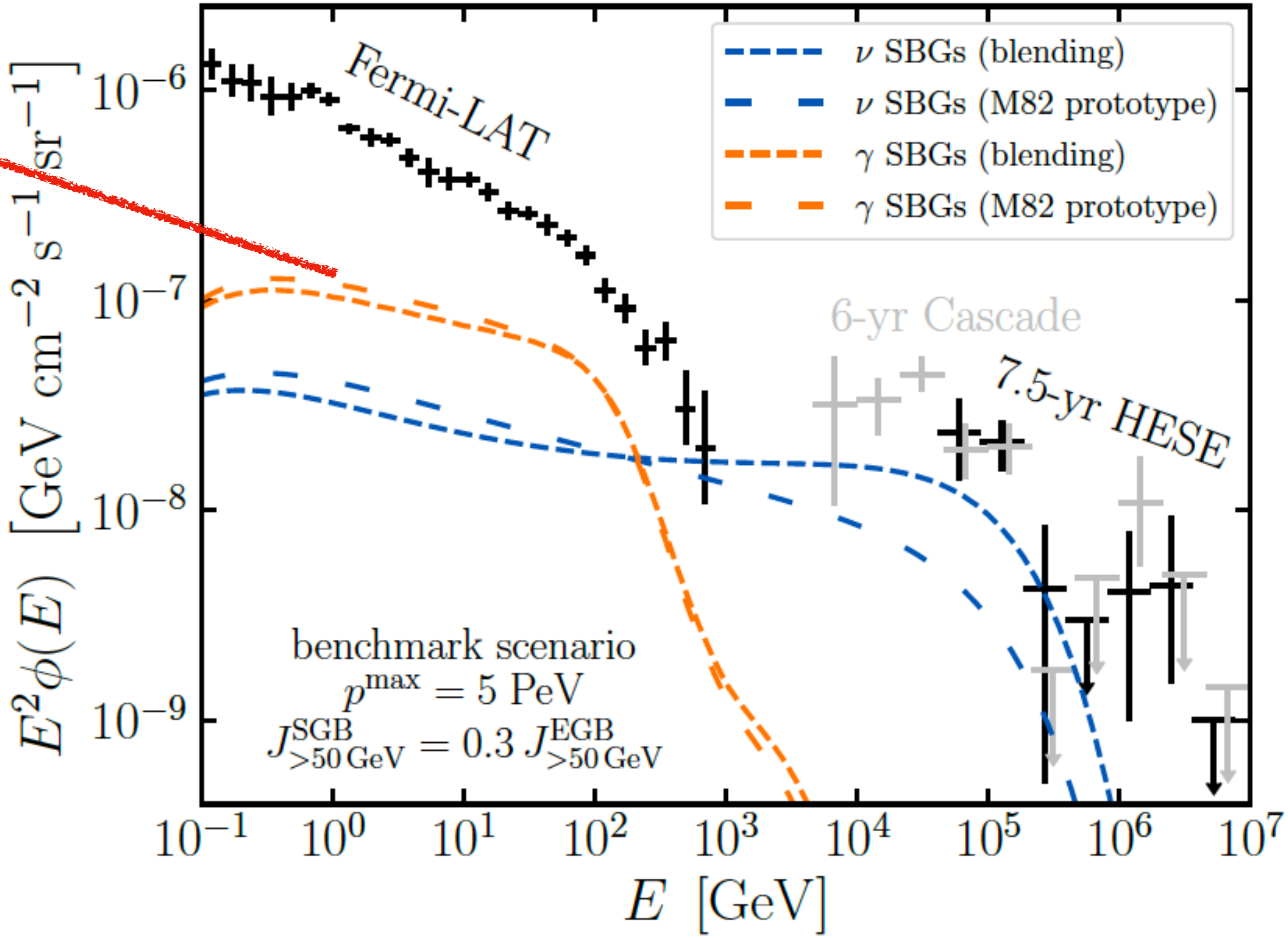
↓

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

BLENDING VERSUS PROTOTYPE SCENARIO

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

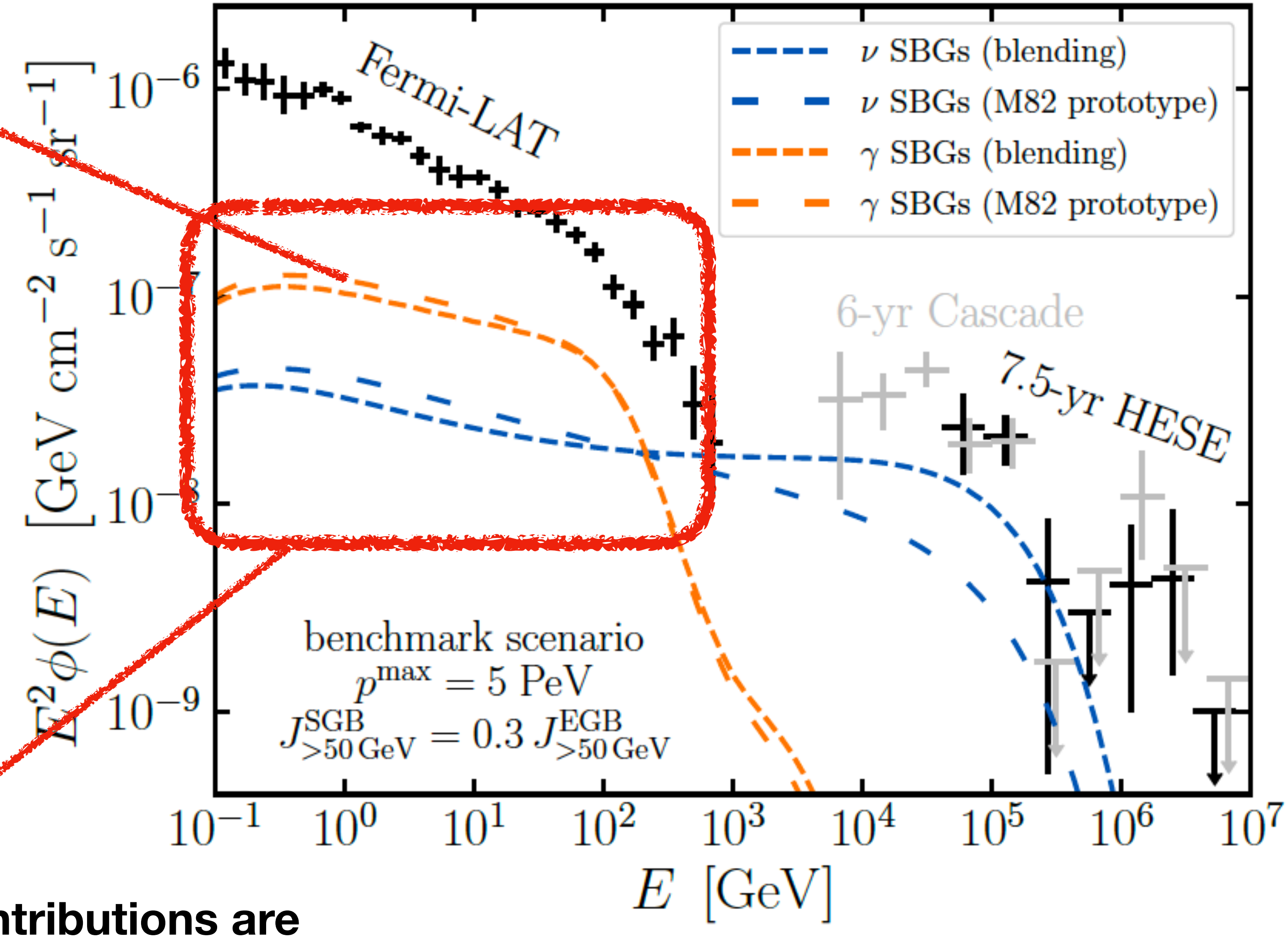
Direct + electromagnetic cascades gamma-ray flux



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

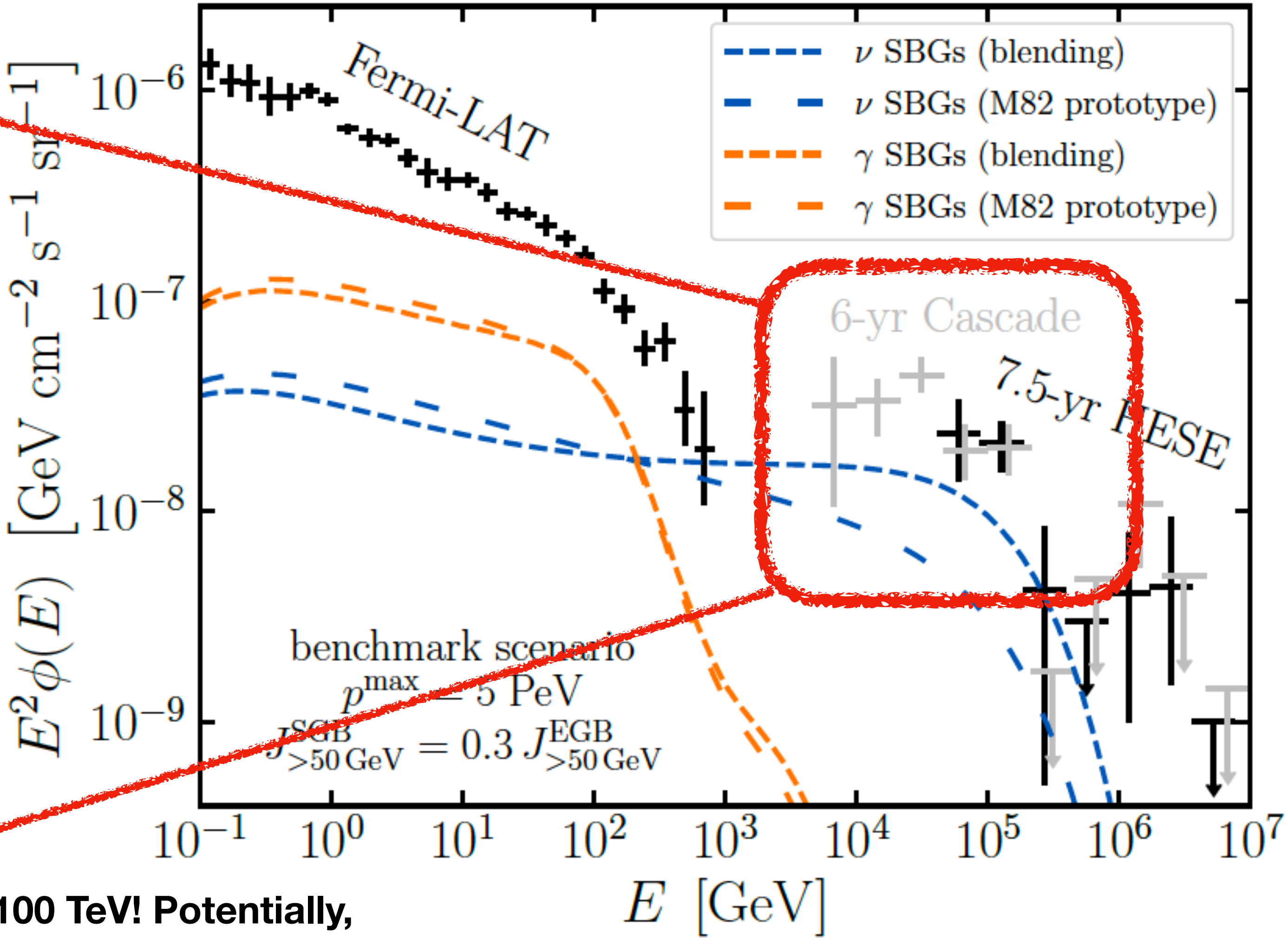


The diffuse gamma contributions are almost the same!

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

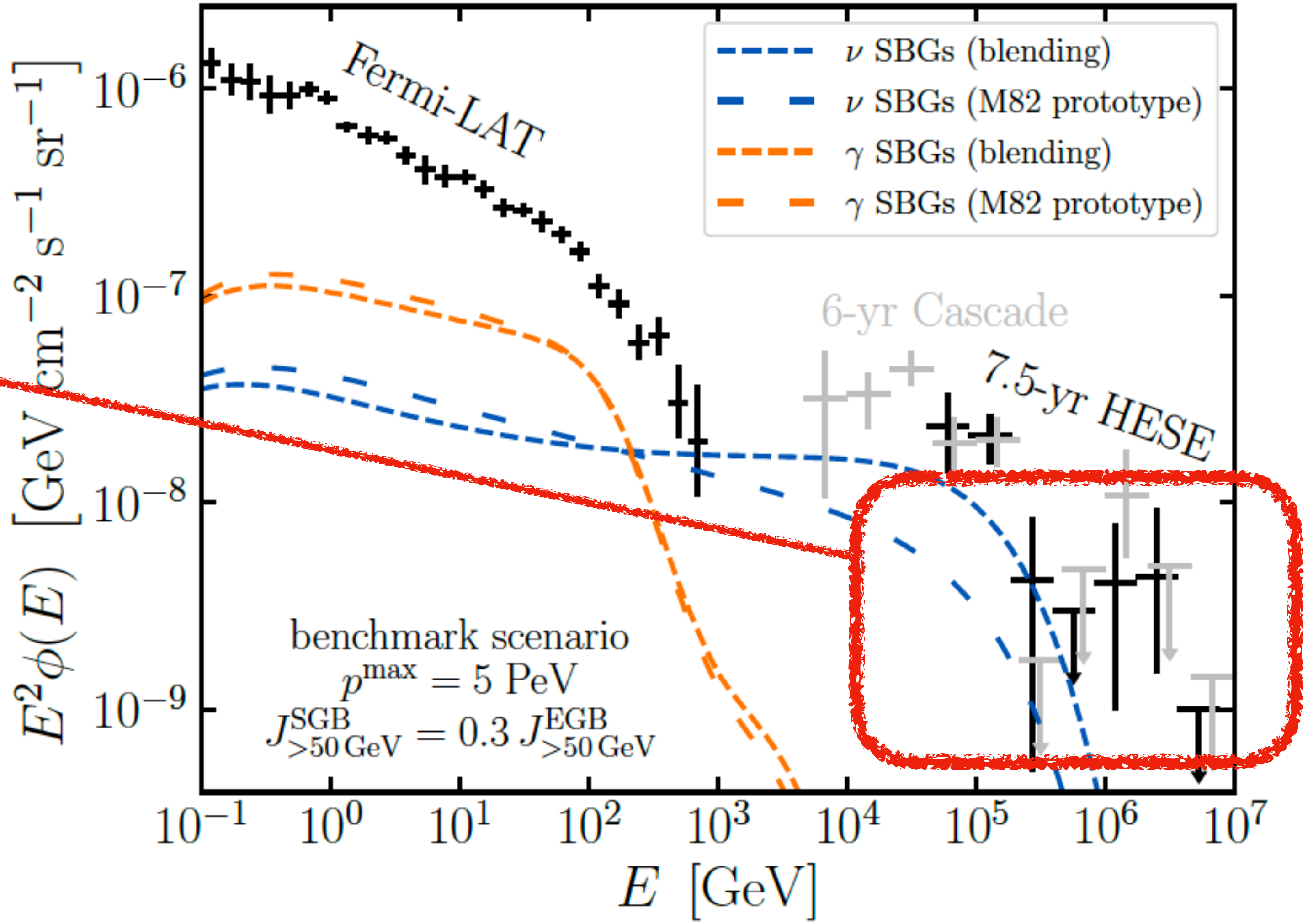


Larger contribution around 100 TeV! Potentially,
It could alleviate the tension between neutrino and gamma-ray data when using hadronic scenarios to explain IceCube observations.

BLENDING VERSUS PROTOTYPE SCENARIO

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

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



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**

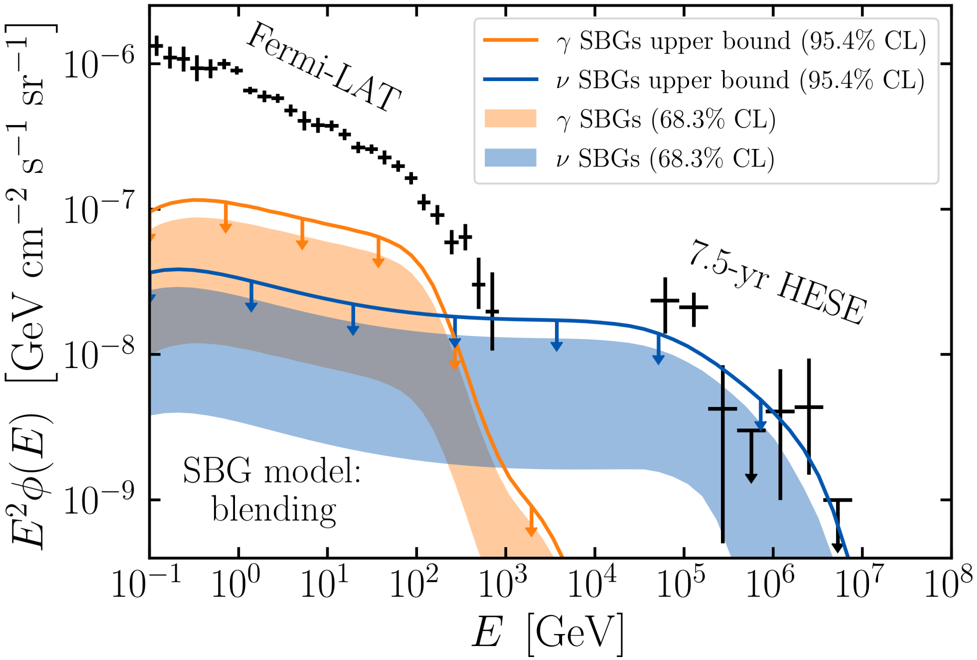
$$\chi^2_{\nu+\gamma}(N_{SBG}, N_{RG}, N_{Blazars}, p^{max}) = \chi^2_\nu + \chi^2_\gamma + \left(\frac{N_{Blazars} - 1}{0.26}\right)^2 + \left(\frac{N_{RG} - 1}{0.65}\right)^2 + \left(\frac{N_{Blazars} - 0.80}{0.11}\right)^2$$

They come from uncertainties of the Non-SBG components

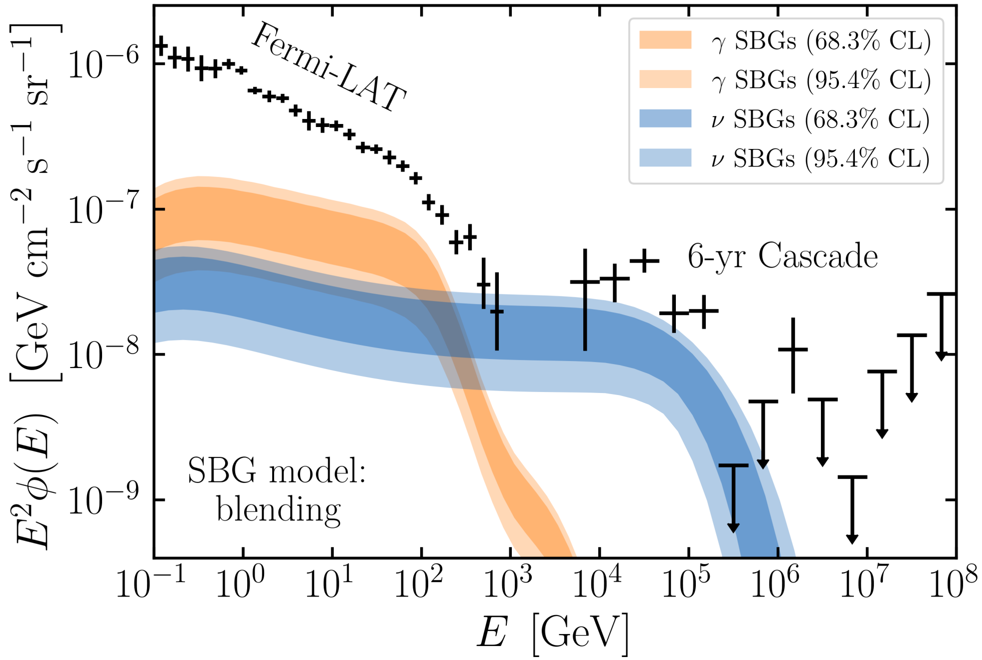
It comes from the positional limit of Point Sources above 50 GeV (Lisanti et al. 2016)

THE PROPOSED MULTIMESSENGER FIT

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



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

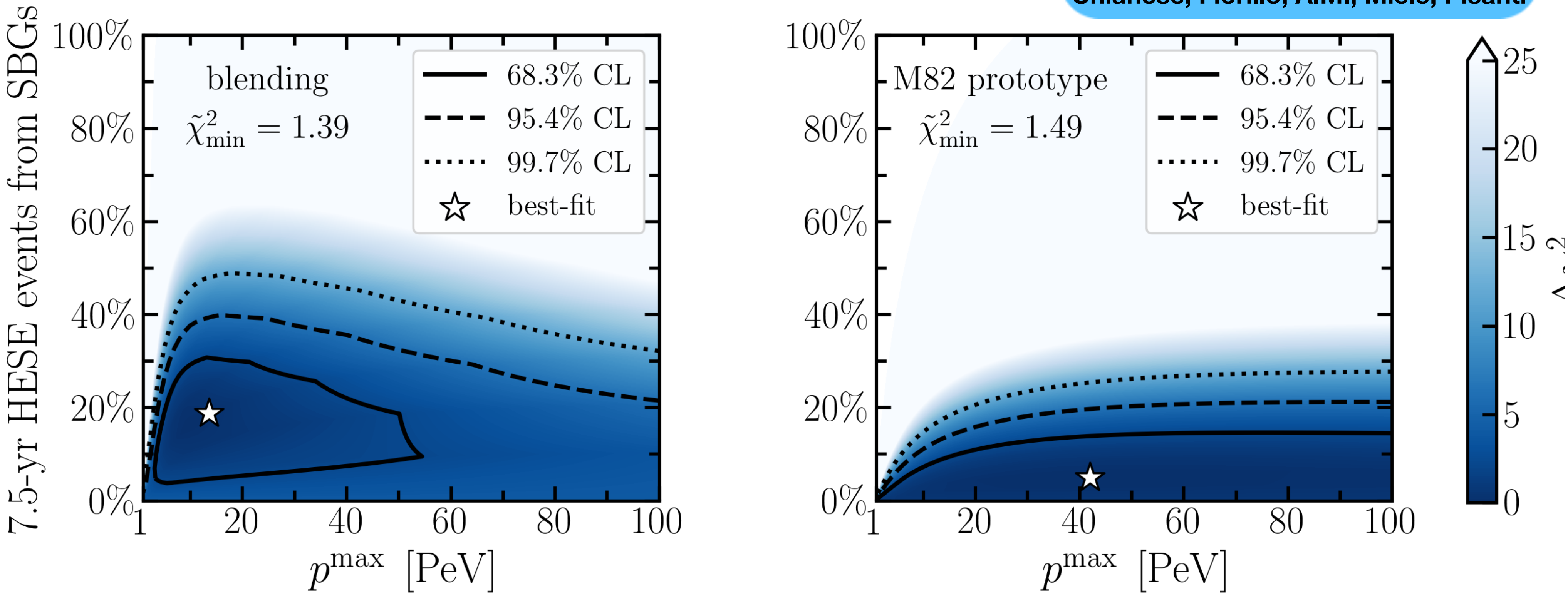


2 sigmas allowed SED considering Fermi-LAT EGB and IceCube CASCADE data

THE PROPOSED MULTIMESSENGER FIT

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

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



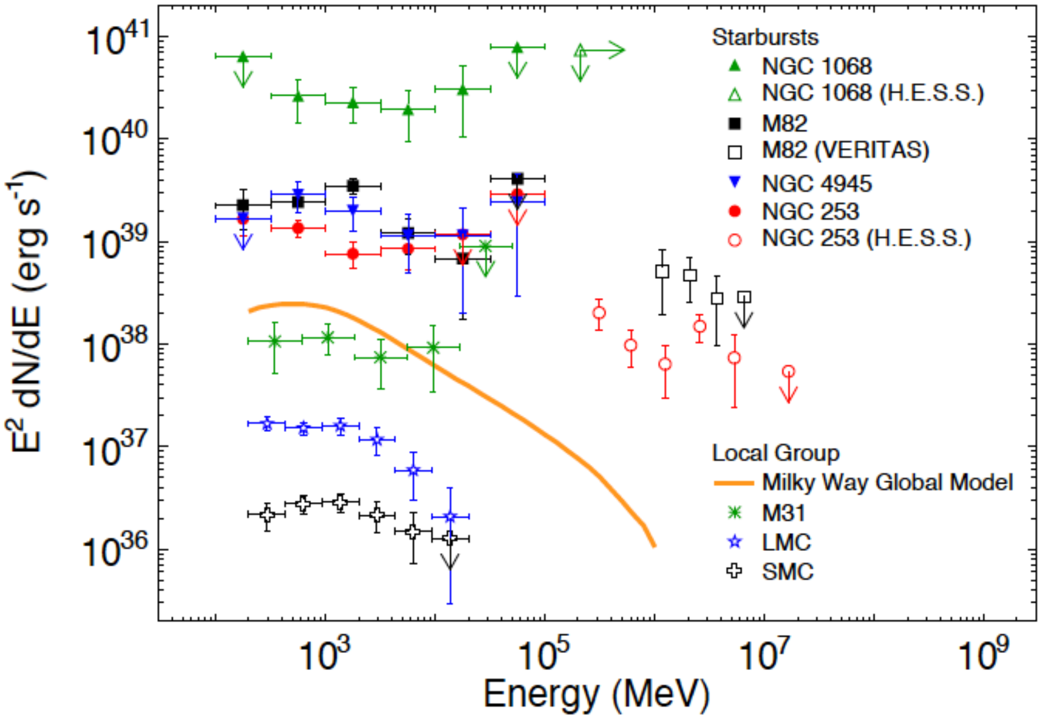
At 2 sigma level the "blending" scenario can account up to 40% of IceCube HESE measured flux, moreover at 1 sigma a Pmax up to 50 PeV is permitted

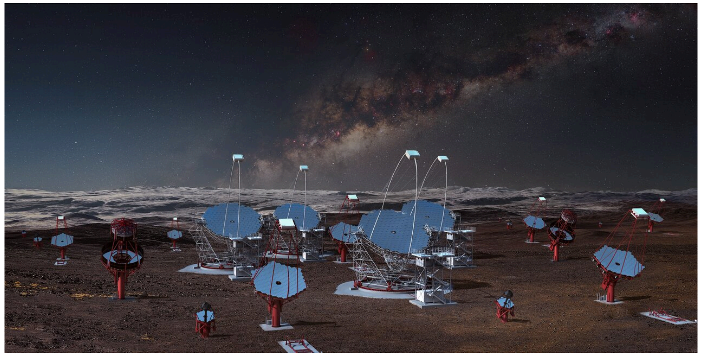
Calorimetric model validation

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 CLOSE KNOWN SBGs

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

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

(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:

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

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

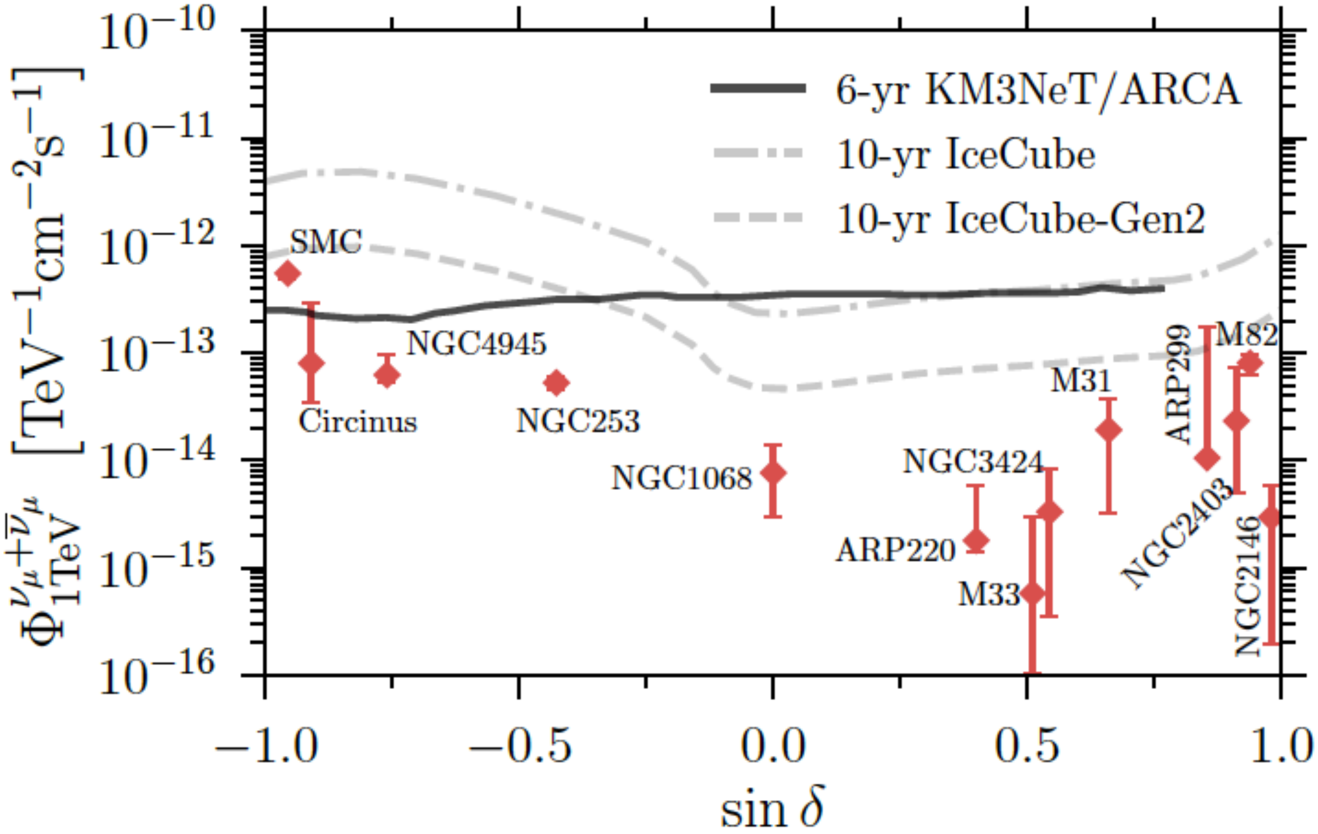
NOTE—The star formation rate $\dot{M}_*$ is in units of $M_\odot\ yr^{-1}$.

<u>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</u>

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.

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



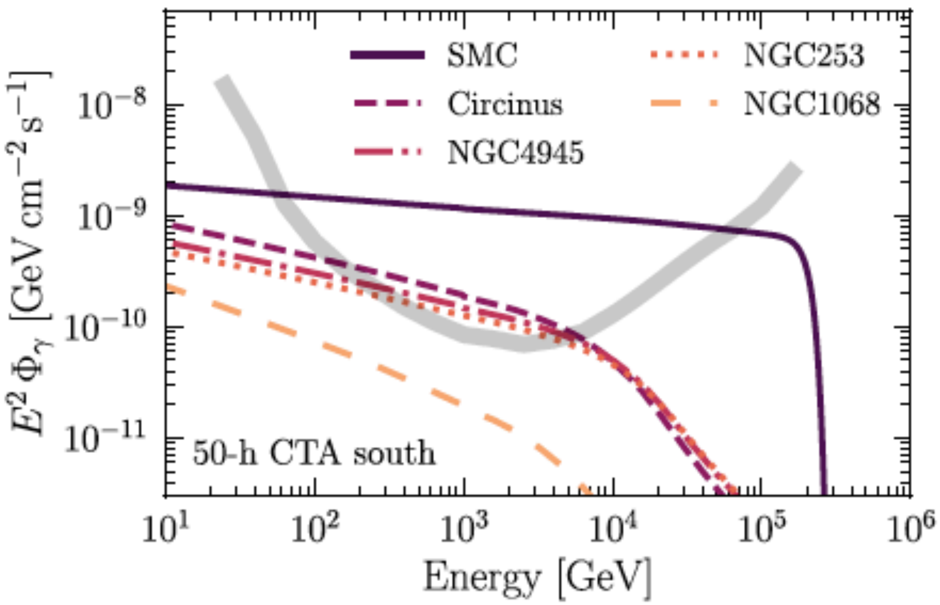
To describe the neutrino excess observed from NCG1068 additional AGN component is needed.

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

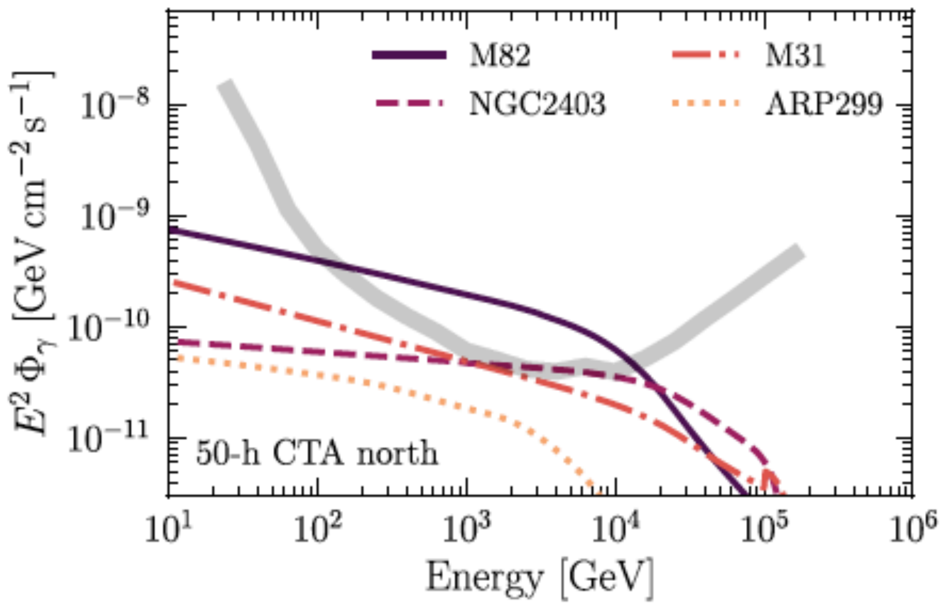
CTA answers at VHE

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

CTA southern sky



CTA northern sky



Both CTA northern and souther hemisphere have the sensitivity to observe the expected SBG gamma-ray spectral features, for some SBG also disentangle the core emission

COSMIC-RAY PHYSICS INSIDE SBGN

injection term

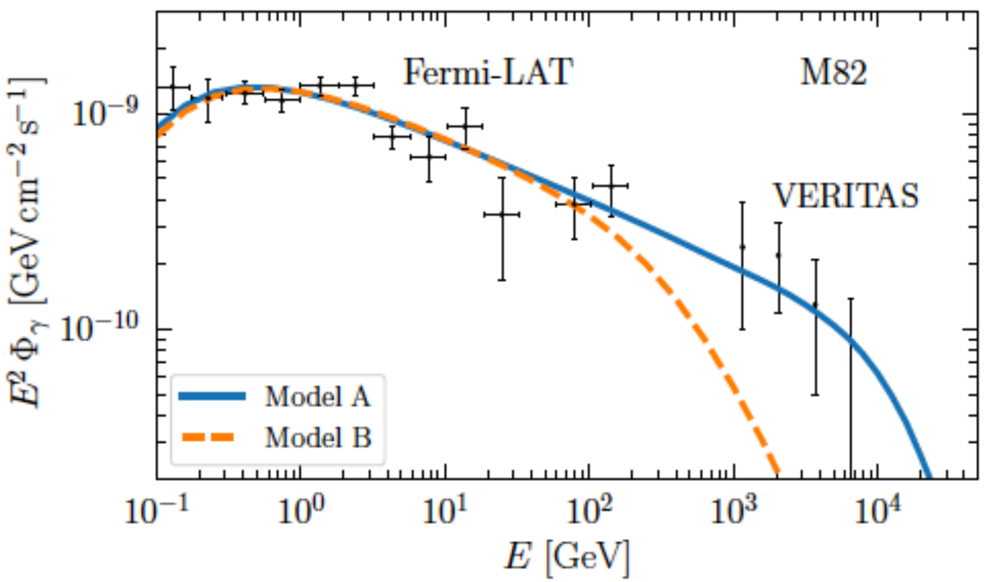
$$\frac{f(p)}{\tau_{\rm loss}(p)} + \frac{f(p)}{\tau_{\rm adv}(p)} + \frac{f(p)}{\tau_{\rm diff}(p)} = Q(p)$$

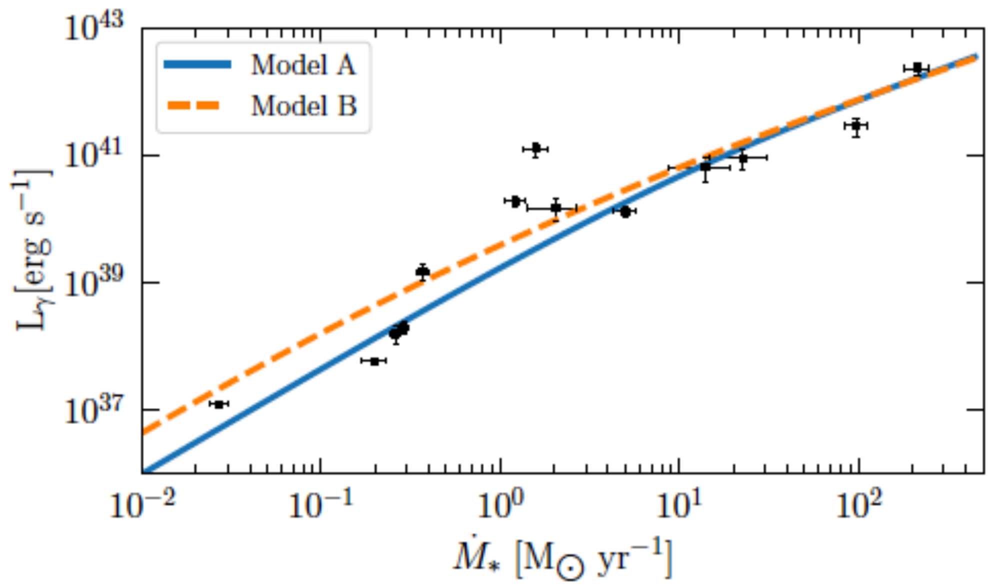
Model A — MNRAS 487,168 (2019) Peretti el al.

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

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

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

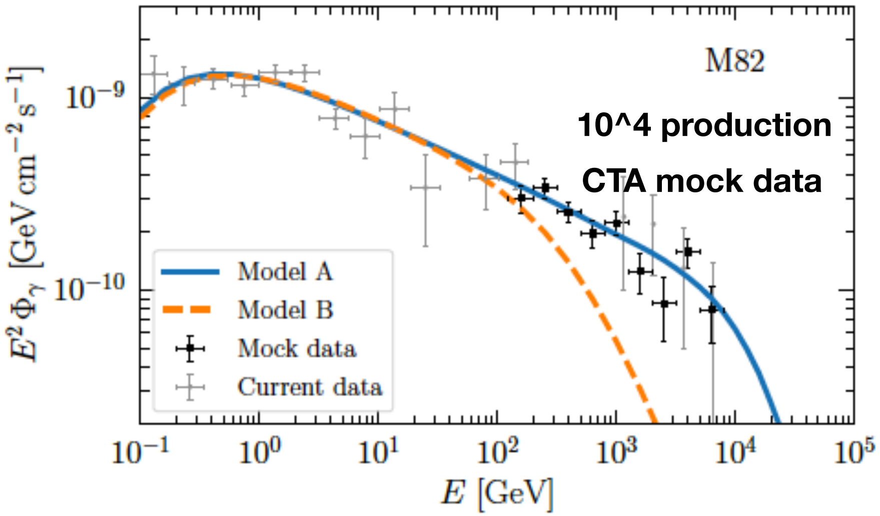


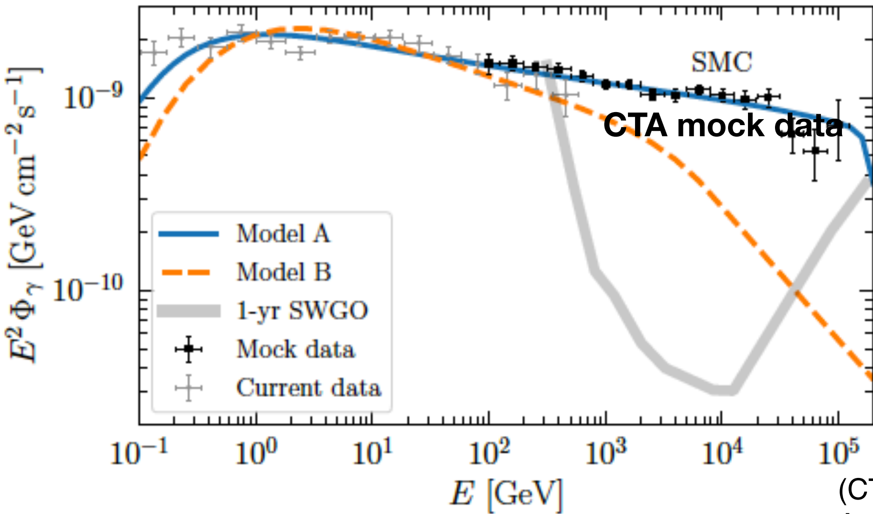


When TeV gamma-ray can be crucial

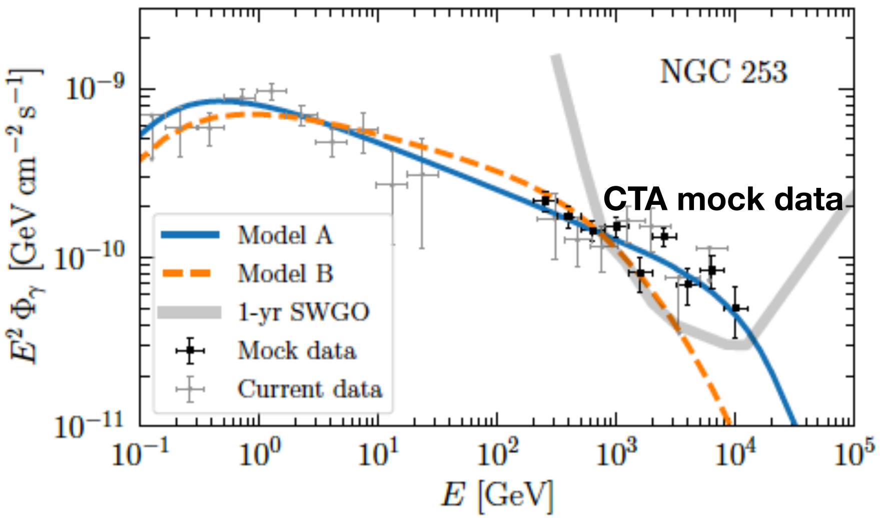
Arxiv220303 (2022) Ambrosone, Chianese, Fiorillo, A.M., Miele

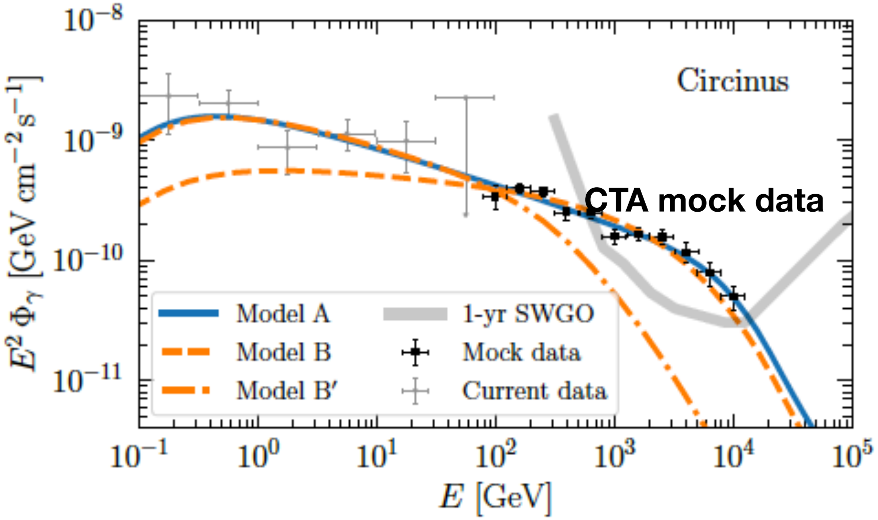
For most of these known SBG the TeV observation will disentangle the two scenarios





(CTA info from Acharya et al. 2018)



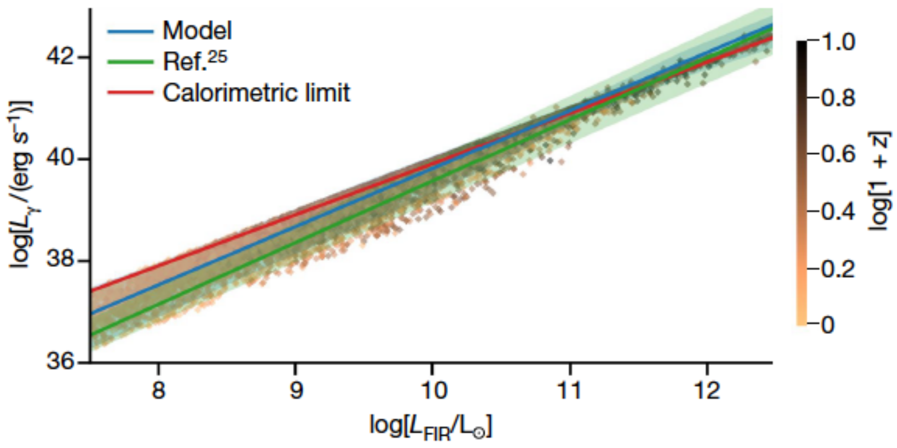


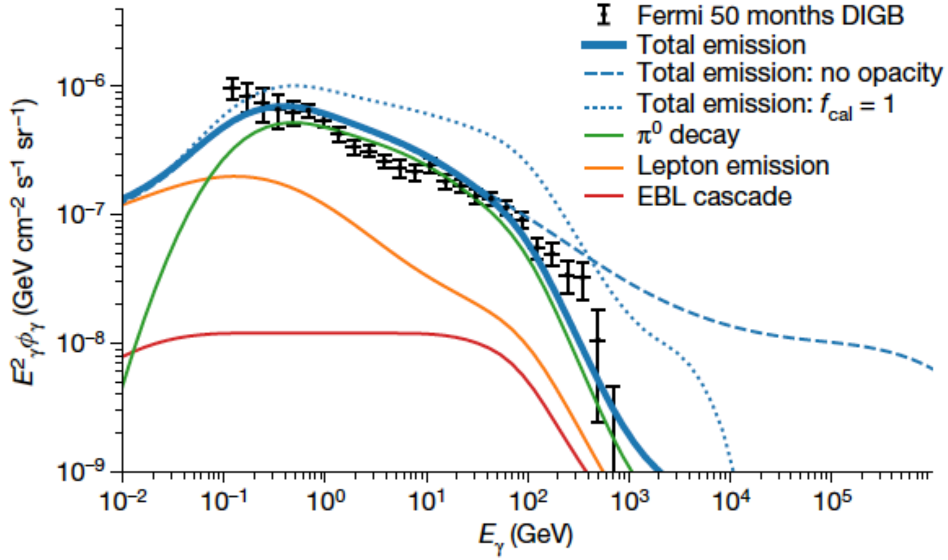
Implication for the EGB description

Nature 41586 (2021)

M. Roth et al.

Model B





Verified on a sample of 35000 galaxies

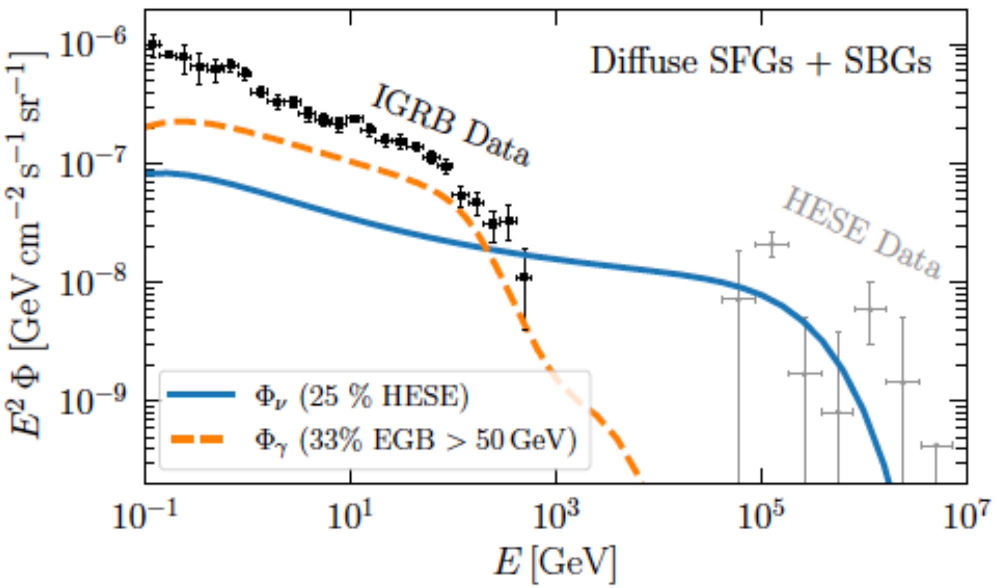
The Fermi-LAT IGRB would be completely described by the Starburst galaxy emission, therefore the limit of Lisanti et al. 2016 for Blazar component would be exceeded

Implication for neutrino expected

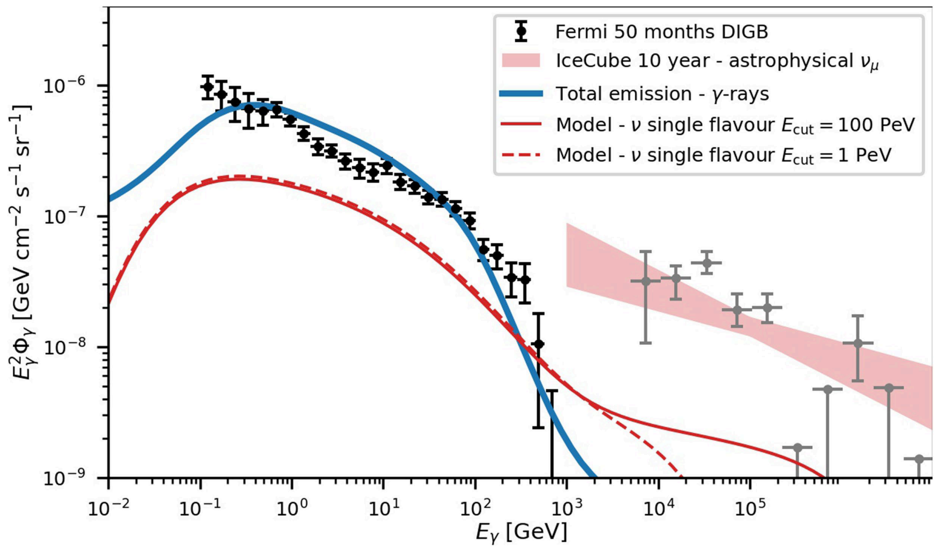
Arxiv220303 (2022) Ambrosone, Chianese, Fiorillo, A.M., Miele

Nature 41586 (2021) M. Roth et al.

Model A



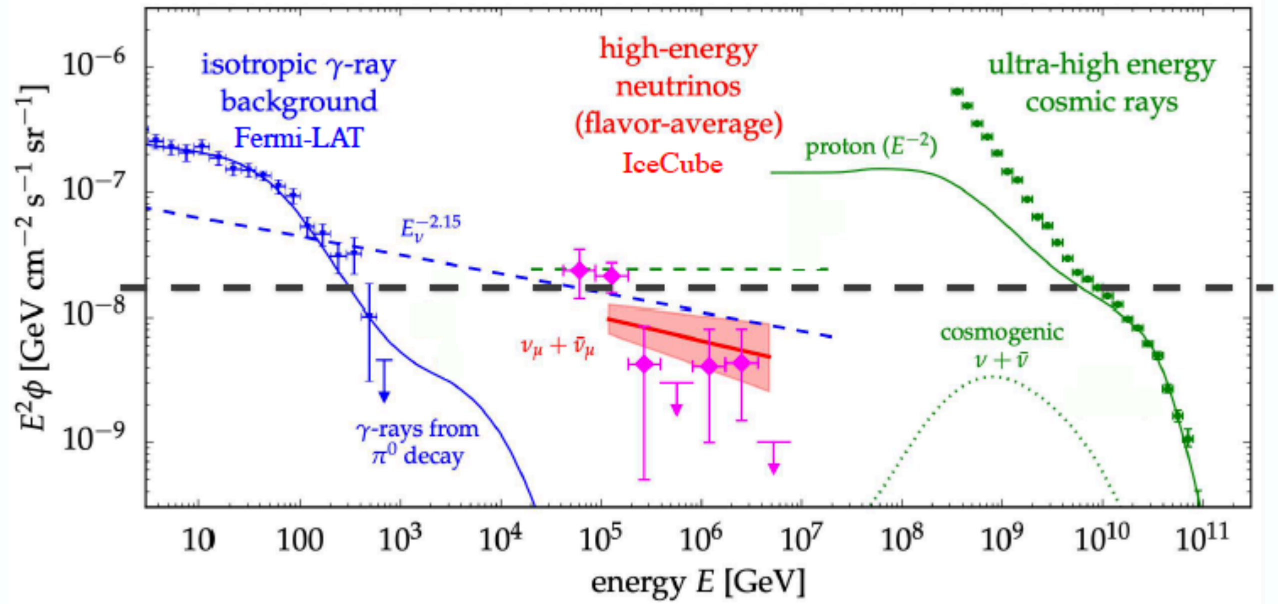
Model B



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%

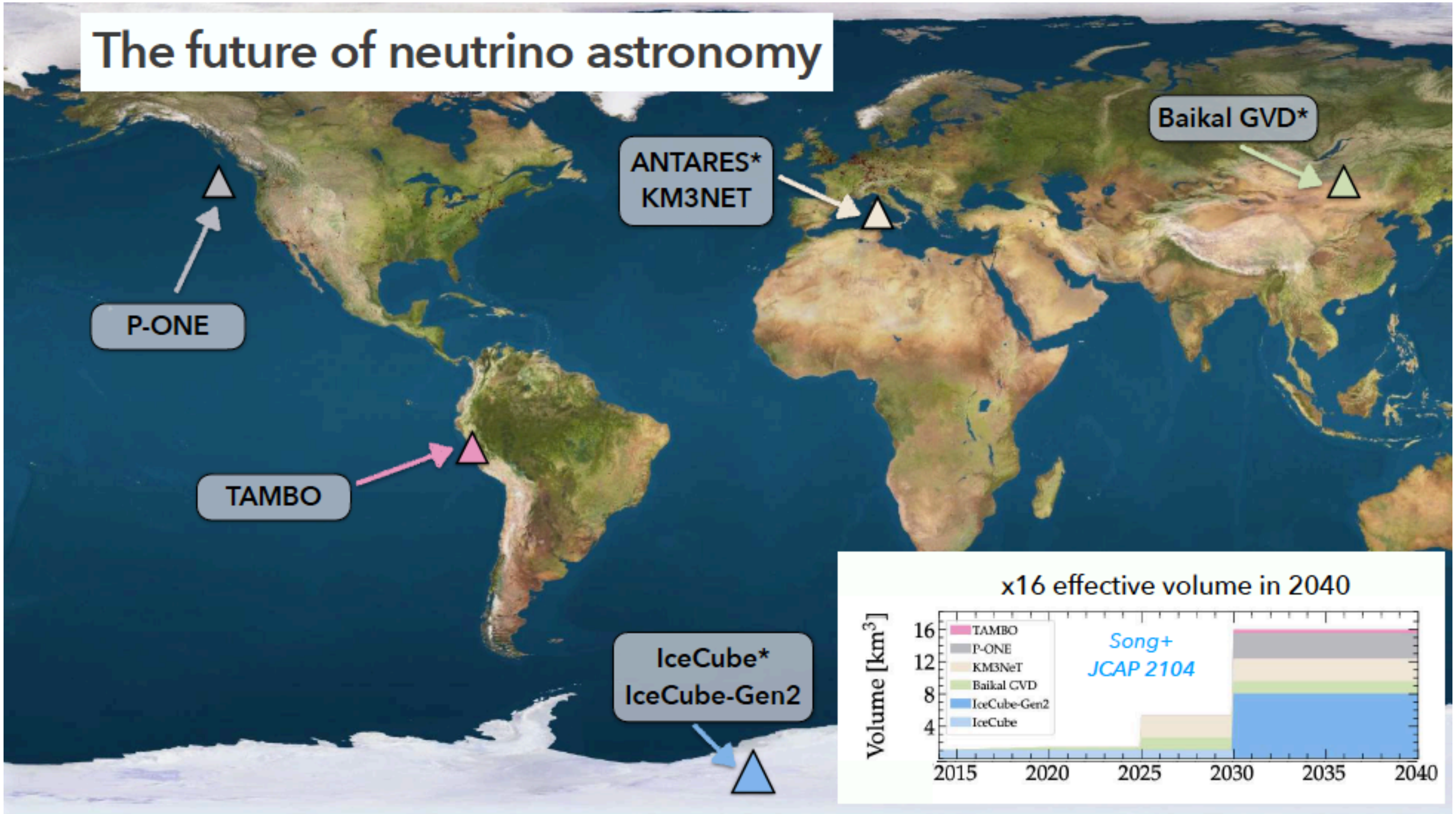
Diffuse High Energy gamma rays

- 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. CTA will be crucial on this.
- 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 CTA a better constrain of the spectral cutoff and cosmic-ray transport for these “reservoir” sources will be possible.
- The contribution of the close 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 the most promising ones.
- Neutrino statistics of a Global Neutrino Network + CTA survey of the close SBGs can solve the puzzle.

What we need for the future



Thank you for the attention

https://www.rankred.com/catalogue-of-star-forming-galaxies/

Backup slides

VHE neutrino observables

Energy spectrum

Standard expectation: power-law energy spectrum

Arrival directions

Standard expectation: isotropy for diffuse flux from extragalactic sources

Arrival times

Standard expectation: ν and γ from transients arrive simultaneously

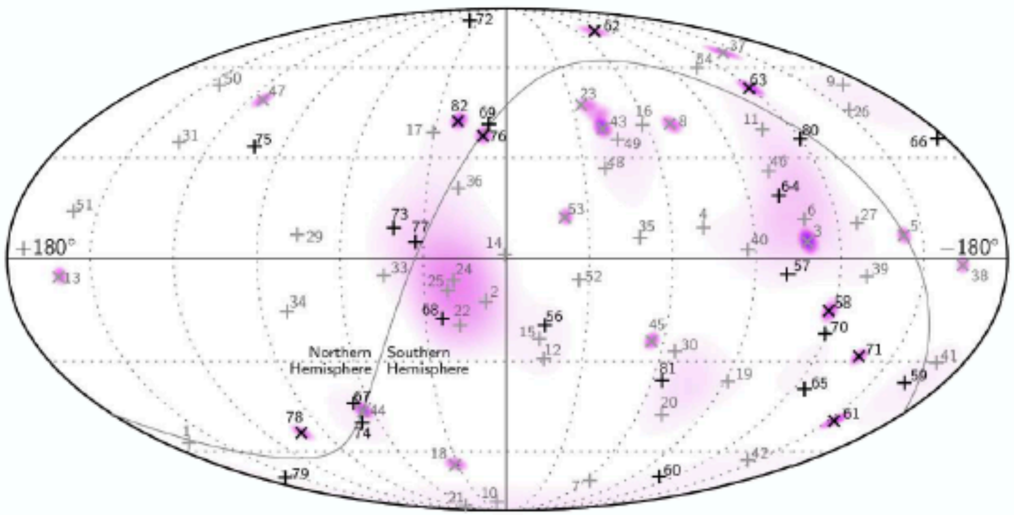
Neutrino flavors

Standard expectation: equal number of ν_e, ν_μ, ν_τ

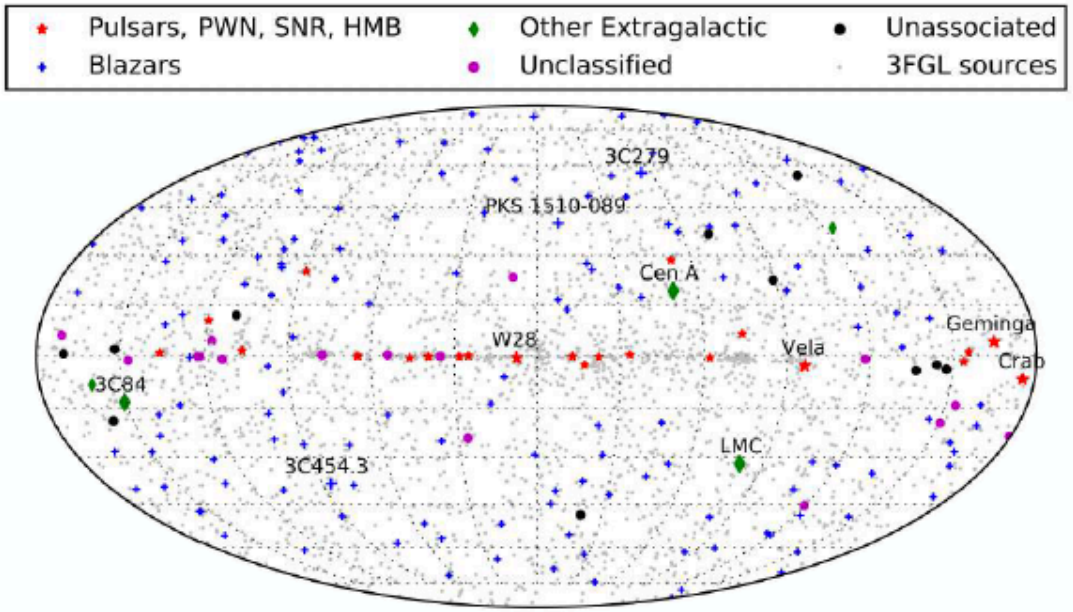
ANGULAR ASSOCIATION WITH FERMI-LAT KNOWN SOURCES

ApJ 835 (2017)
IceCube

Looking for angular correlations…



Neutrino sky



Gamma-ray sky (steady blazars)

Fermi-LAT Source Catalog (3FGL)

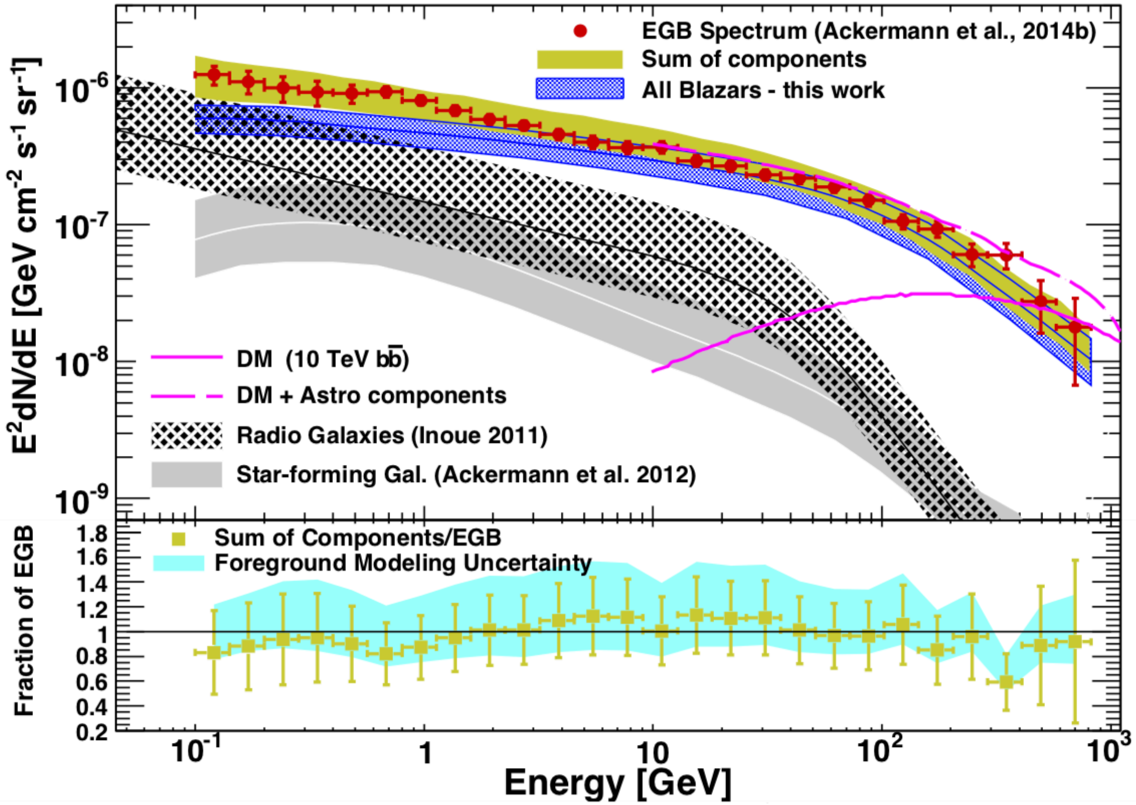
No association at more than 3 sigma

- Blazars comprise **about 70%** of the Extragalactic Gamma-ray Background (EGB) above 50 GeV

Ajello+, ApJL 800 (2015)

EXTRAGALACTIC GAMMA-RAY BACKGROUND

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

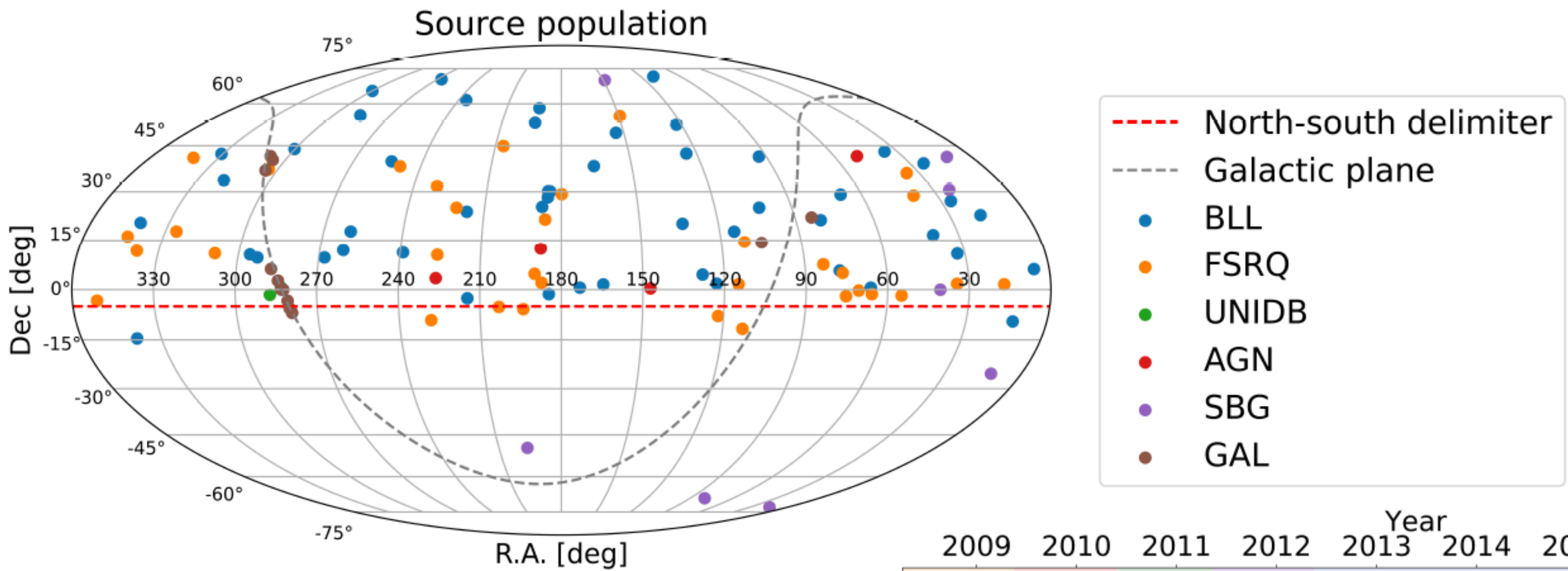


- Fermi-LAT is observing many individual sources belonging to different classes (gamma-ray bursts, active galactic nuclei, star-forming galaxies, …)
- However, **about 80%** of the EGB (diffuse + point sources) above 50 GeV is powered by **blazars.**

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

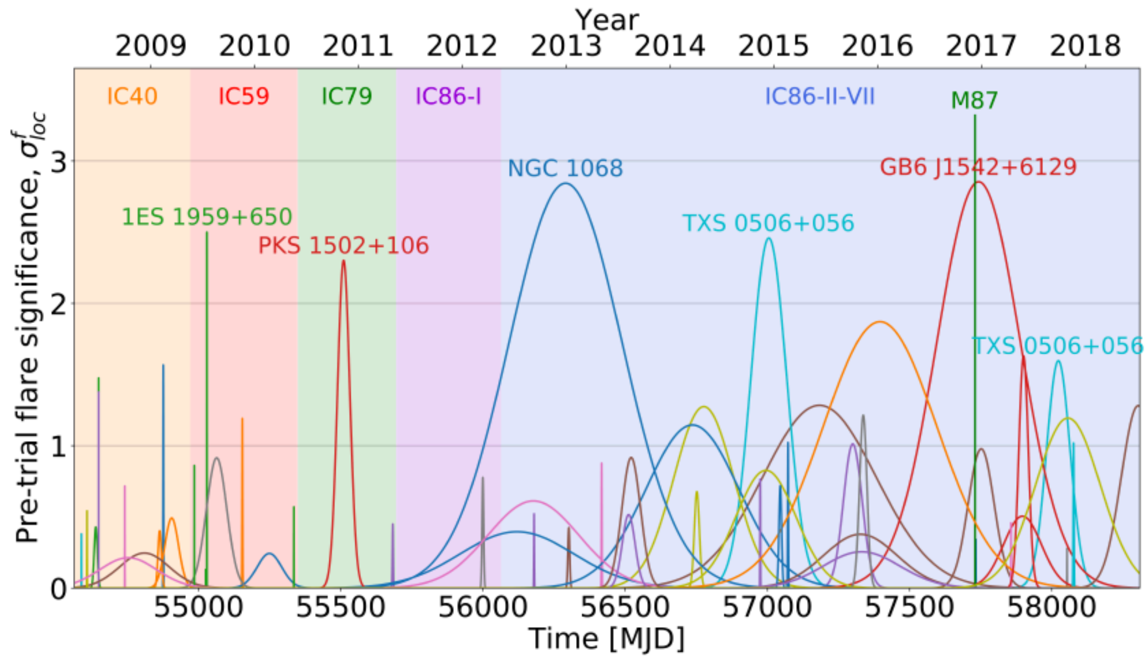
TIME INFORMATION: 10 YEARS OF ICECUBE TEV TRACK-LIKE EVENTS, UNBLIND ANALYSIS

ApJL 920 (2021)
IceCube



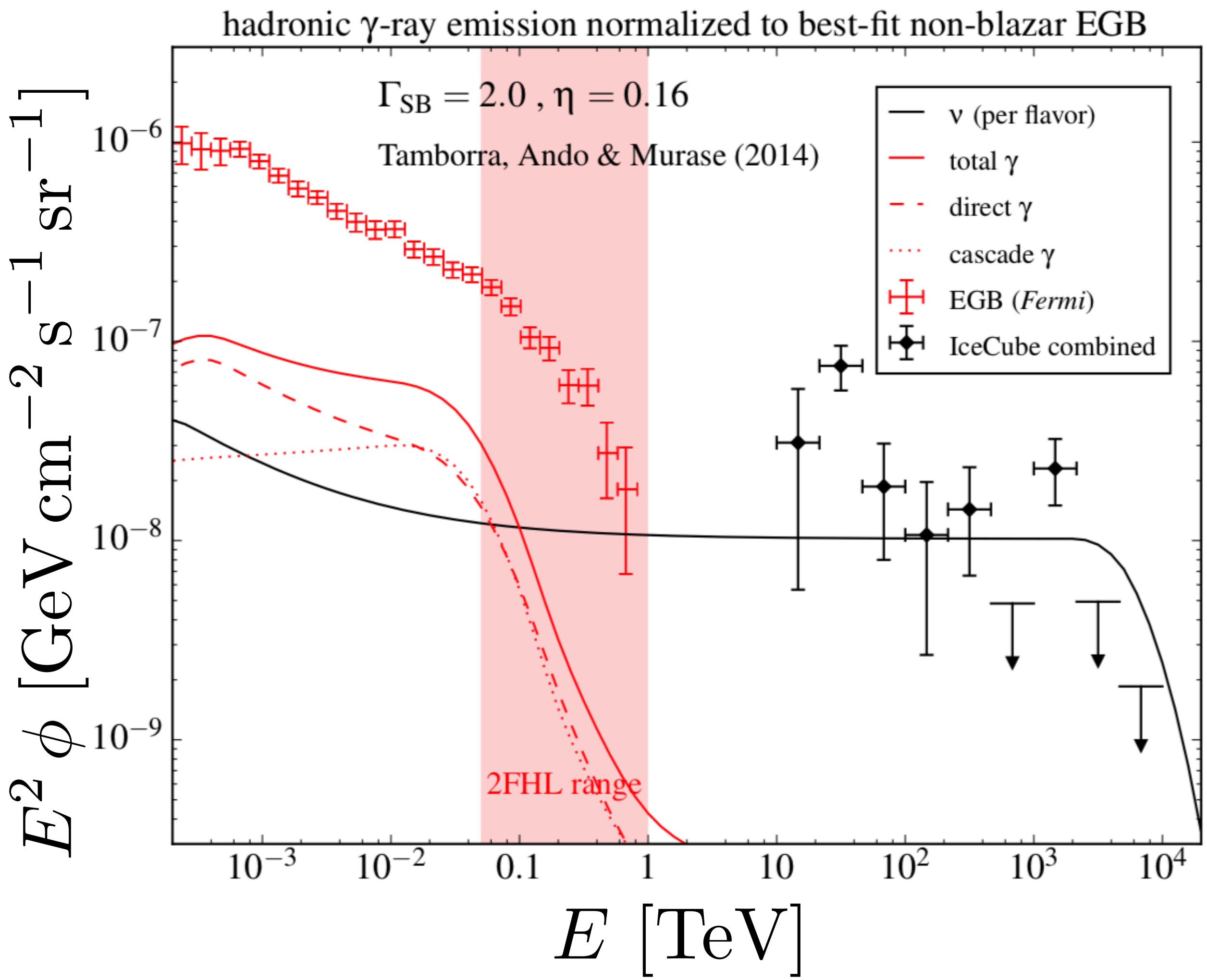
Several classes of TeV sources selected

neutrino "lightcurve" produced for the most significant ones



Tension between neutrino and gamma-ray interpretation

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



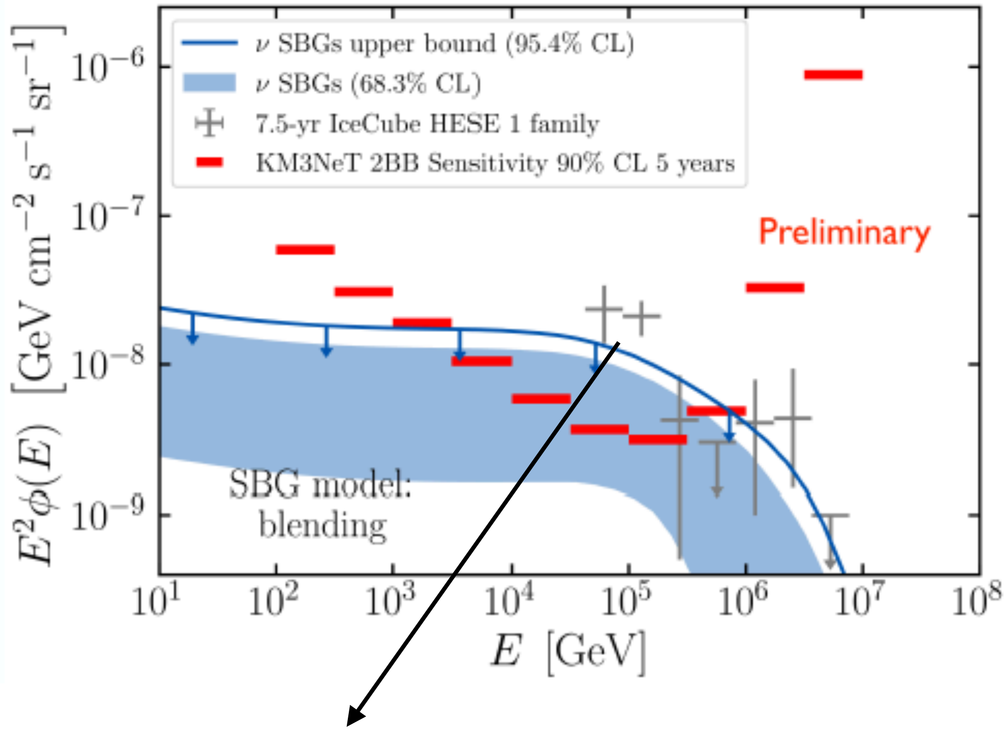
Possible Solution

- going beyond the standard modeling based on a fixed power-law flux
- Considering the hypothesis of multiple components → **MNRAS 503 4032 (2021) Ambrosone, Chianese, Fiorillo, A.M., Miele, Pisanti**

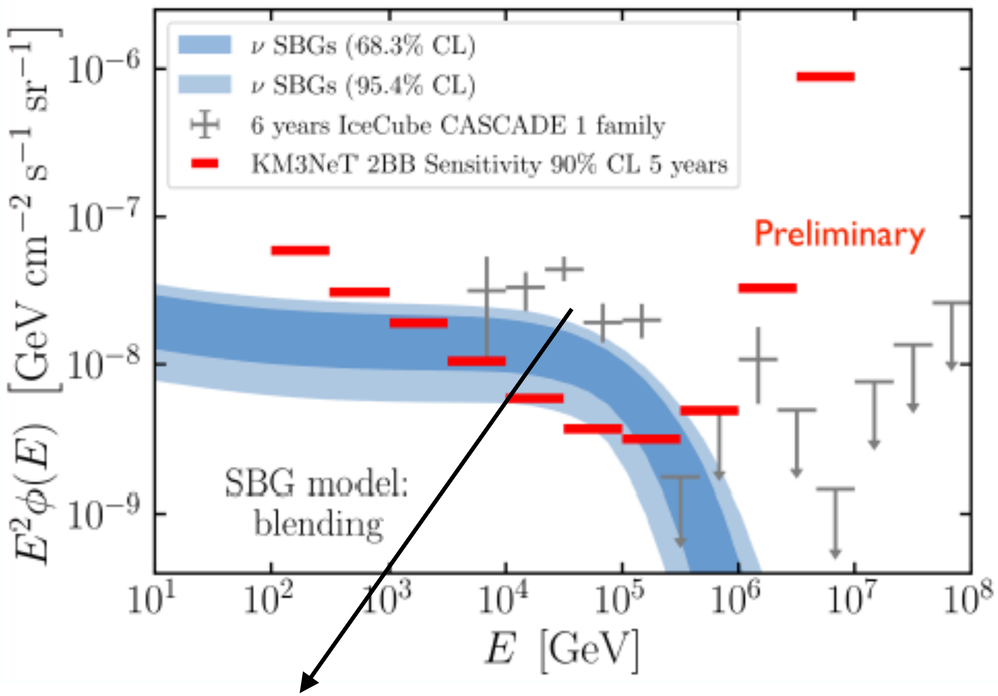
ANSWERS FROM KM3NeT ON RESERVOIRS

JINST 16 (2021)
A.M. et al. for KM3NeT

HESE+ Fermi-LAT modeling



through going + Fermi-LAT modeling



Starburst galaxies neutrino emission + diffuse Galactic component can explain the IceCube signal at 100 TeV, a important answer will come from KM3NeT/ARCA