On the sources of high energy neutrinos

The new era of multi-messenger astrophysics
28.03.19 Groeningen

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Desy, Zeuthen

HESE and Throughgoing muons

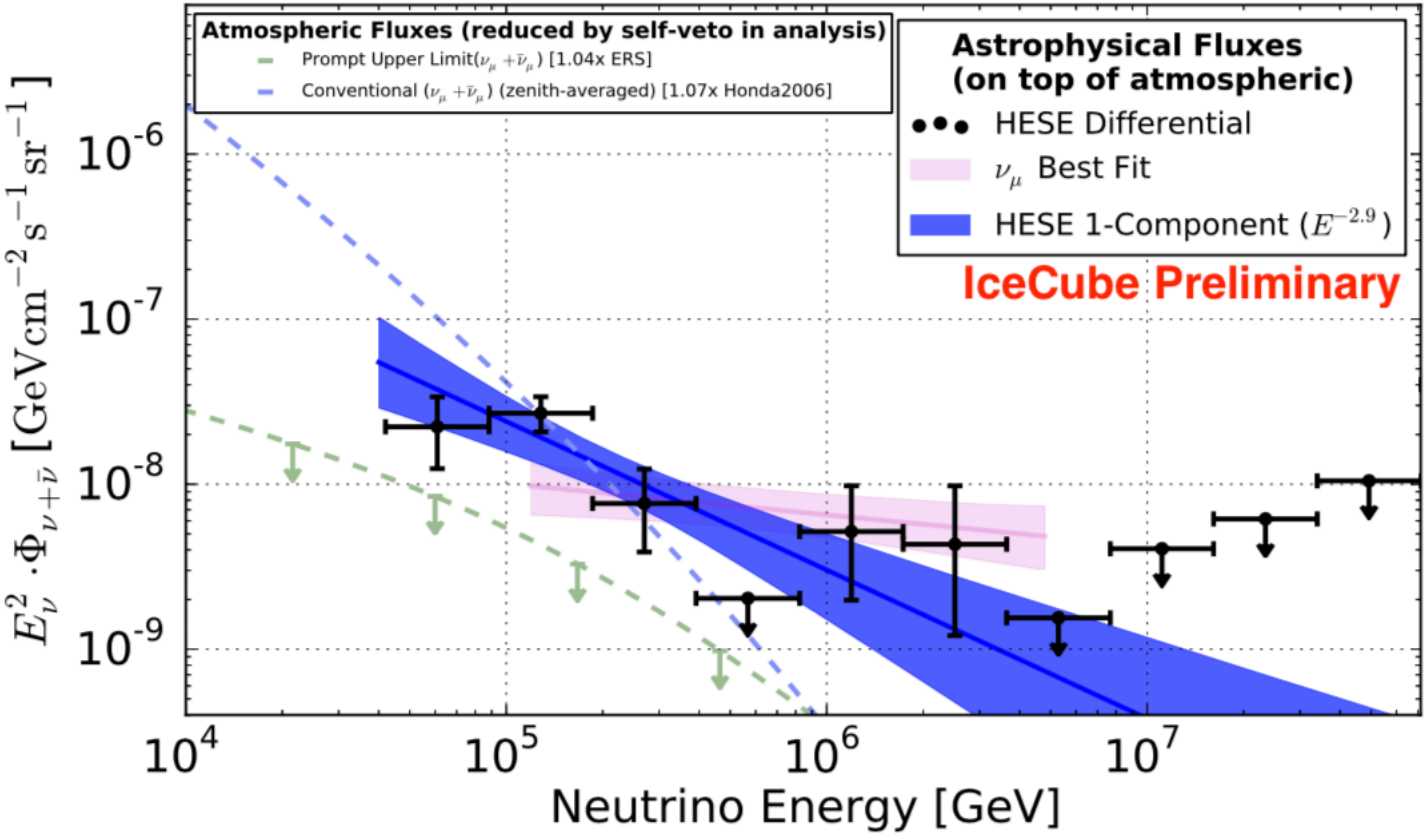

Figure from IceCube, ICRC 2017

6 years of HESE suggests **soft** power law spectrum

$$E^{-\alpha} \text{ with } \alpha = 2.9 \pm 0.3$$

8 years of TGM suggests **hard** power law spectrum

$$E^{-\alpha} \text{ with } \alpha = 2.2 \pm 0.1$$

No clear tension. Above 200 TeV HESE and TGM are in agreement

The shape of the spectrum is crucial for multi-messenger analyses

See E.Bernardini talk for details

DESY.

One identified source

Coincident emission of gamma-rays and one IceCube neutrino from **Blazar TXS0506+056**

This is the first example of multi-messenger astronomy with neutrinos

See S. Britzen talk

RESEARCH

RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†

INTRODUCTION: Neutrinos are tracers of cosmic-ray acceleration: electrically neutral and traveling at nearly the speed of light, they can escape the densest environments and may be traced back to their source of origin. High-energy neutrinos are expected to be produced in blazars: intense extragalactic radio, optical, mic rays. The discovery of an extraterrestrial diffuse flux of high-energy neutrinos, announced by IceCube in 2013, has characteristic properties that hint at contributions from extragalactic sources, although the individual sources remain as yet unidentified. Continuously monitoring the entire sky for astrophysical neutrinos, IceCube provides real-time triggers for observatories around the world measuring γ-rays, x-rays, optical, radio, and gravitational waves, allowing for the potential identification of even rapidly fading sources.

RESULTS: A high-energy neutrino-induced muon track was detected on 22 September 2017, automatically generating an alert that was distributed worldwide within 1 min of detection and prompted follow-up searches by telescopes over a broad range of wavelengths. On 28 September 2017, the *Fermi* Large Area Telescope Collaboration reported that the direction of the neutrino was coincident with a cataloged γ-ray source, 0.1° from the neutrino direction. The source, a blazar known as TXS 0506+056 at a measured redshift of 0.34, was in a flaring state at the time with enhanced γ-ray activity in the GeV range. Follow-up observations by imaging atmospheric Cherenkov telescopes, notably the Major Atmospheric

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Read the full article at http://dx.doi.org/10.1126/science.aat1378

The composition of the extragalactic gamma-ray background

About 80% of the Extragalactic Gamma Ray Background (EGB, diffuse + point sources) is powered by **blazars**

It is natural to consider that blazars are also high energy neutrino emitters

See F.Krauss talk

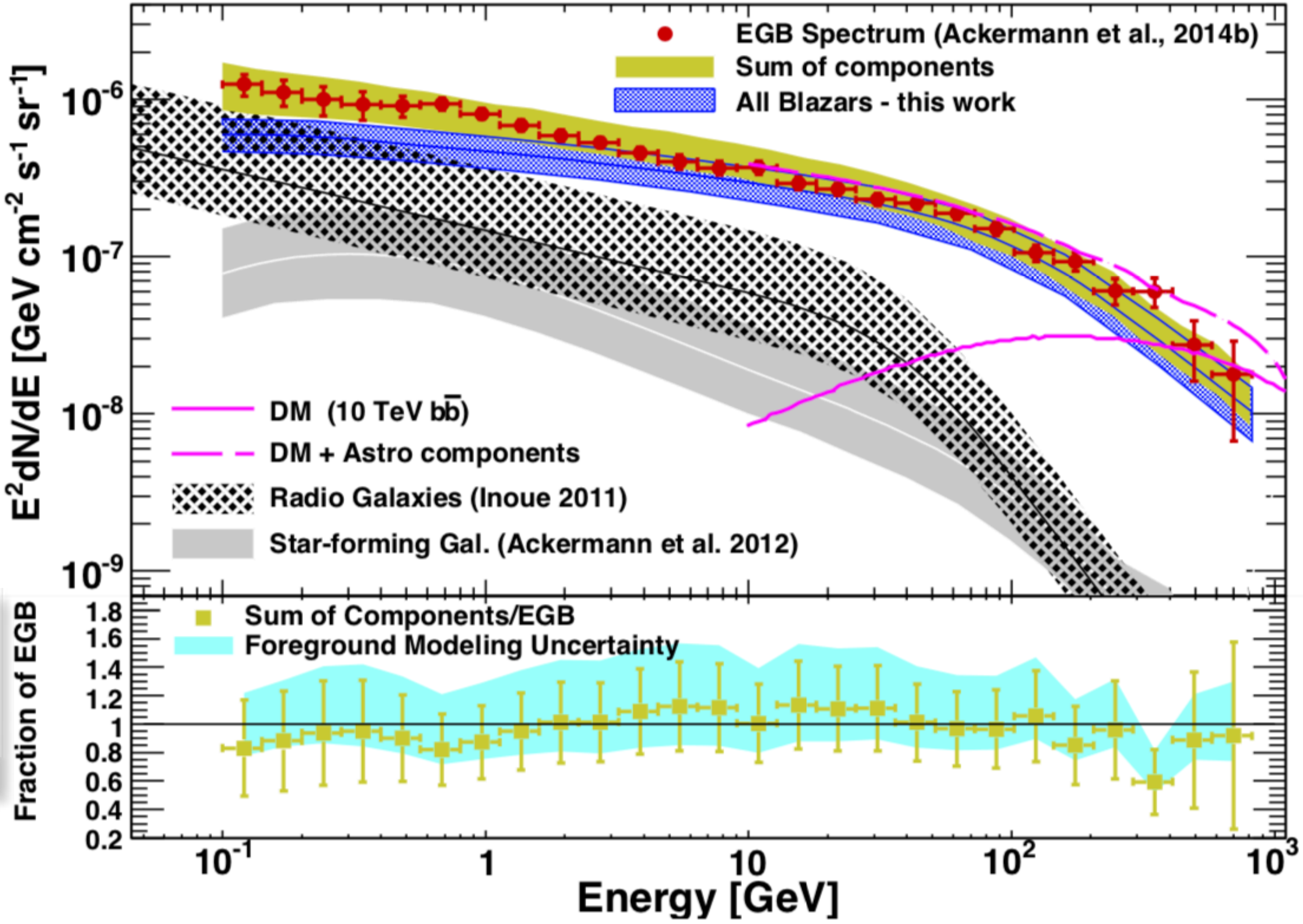
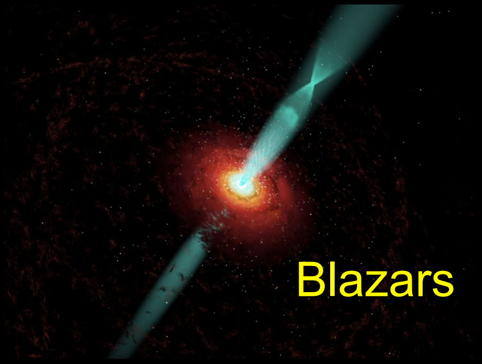
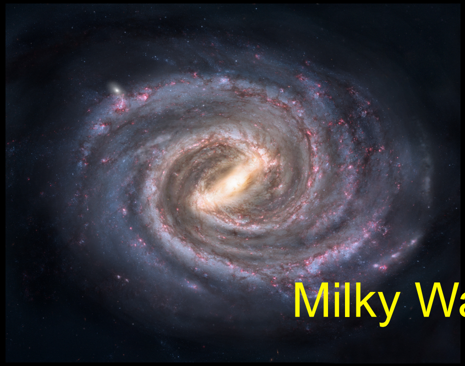


Figure from Ajello et al., APJ 2015

What is the origin ?

4 of the most plausible candidates (Blazars, Starburst Galaxies, GRBs, Milky Way) seem to be already disfavored as sources of high energy neutrinos.





$< 19\% - 27\,\%$ — *IceCube, Astrophys.J. 835 (2017) no.1, 45*

$< 10\,\%$ — *Bechtol et al.,* Astrophys.J. 836 (2017) no.1, 47

$< 10\,\%$ — *IceCube,* Astrophys.J. 868 (2018) no.2, L20

$\sim 1\%$ — *IceCube, Astrophys.J. 824 (2016) no.2, 115*

Most of the IceCube signal still remains without any satisfying counterpart

Why are blazars disfavored as neutrino emitters ?

There are no correlations between the arrival directions of high energy neutrinos and known (resolved) blazars

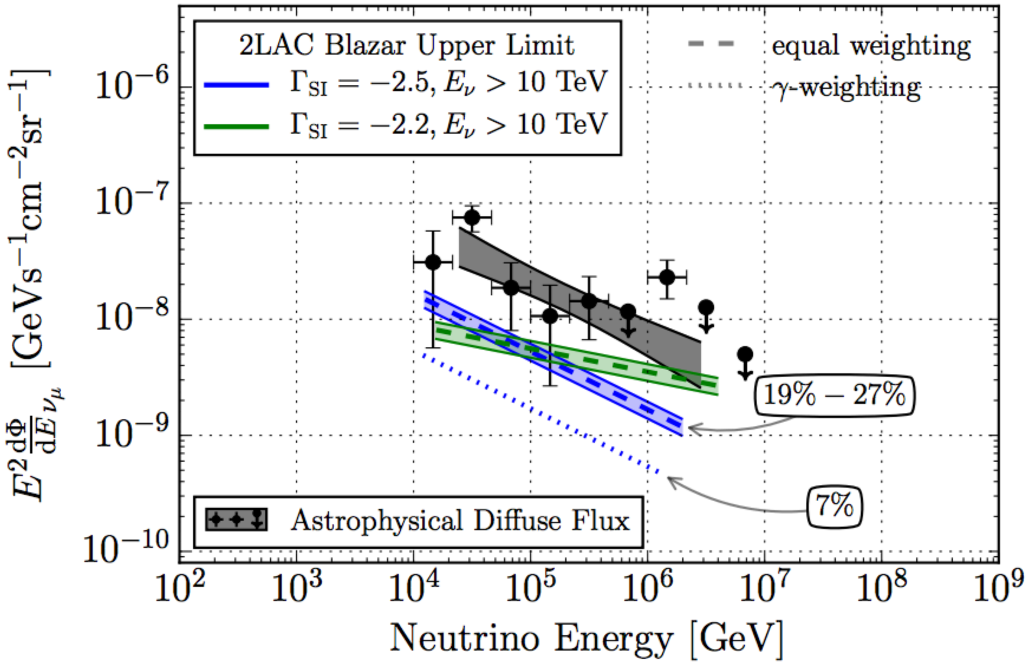


Figure from IceCube, Astrophys.J. 835 (2017) no.1, 45

Resolved blazars **cannot contribute more than 20-25%** to the flux of high energy neutrinos.

If blazars are neutrino emitters, the contribution of not detected (unversolved) blazars has to be relevant

The brightest blazars (high luminosity BL Lacs and FSRQs) cannot power the entire IceCube flux

Cosmic evolution of blazars

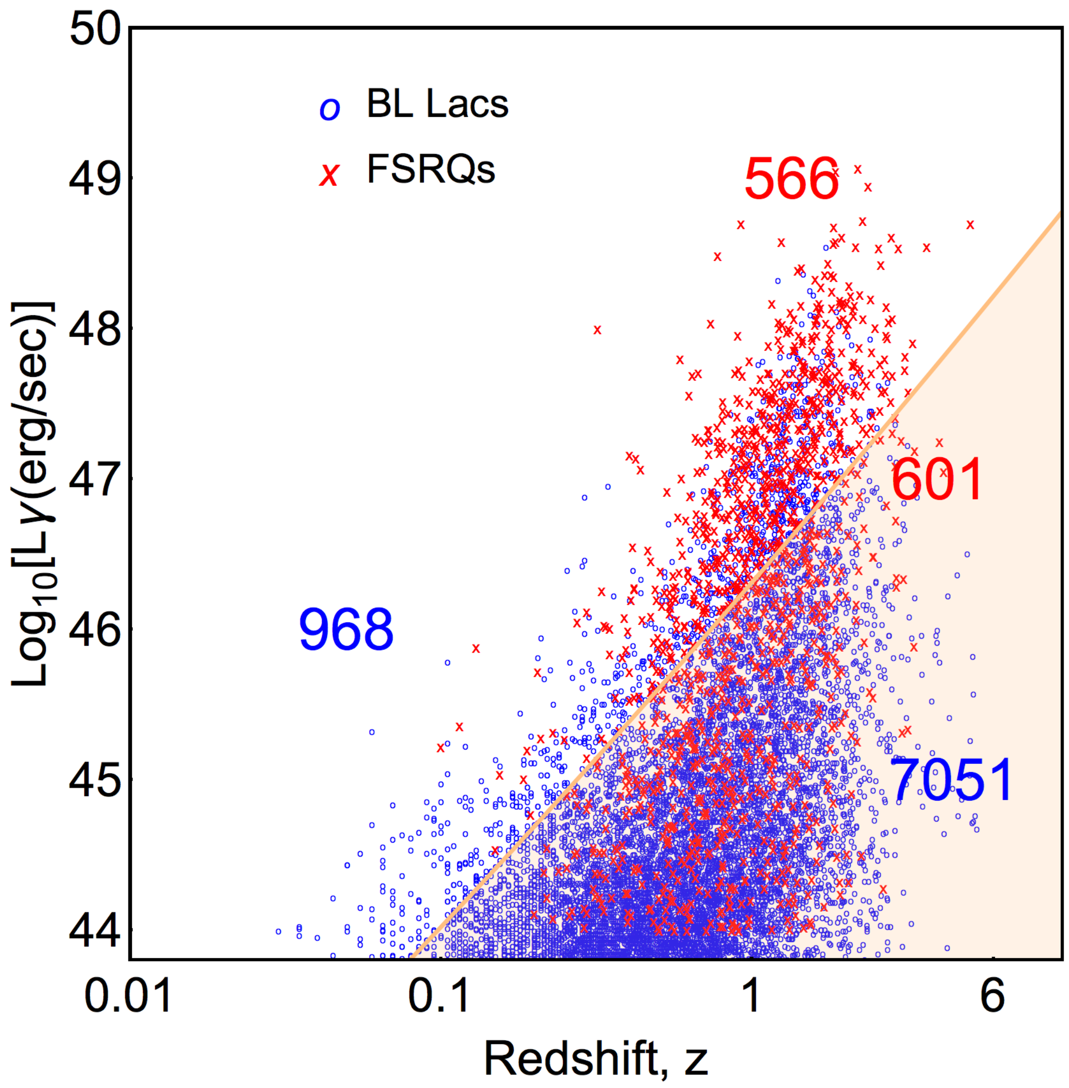


Figure from Palladino et al., APJ 2019

BL Lacs and FSRQs obtained using the cosmic evolution provided in:

- ***Ajello et al., APJ 2014 (BL Lacs)***
- ***Ajello et al., APJ 2012 (FSRQs)***

The luminosity threshold is an average one, chosen to replicate the about 1500 resolved sources contained in the 3LAC catalogue

About 7000 unresolved BL Lacs expected from the distribution

$$\rho_{45} \simeq 10\ \mathrm{Gpc}^{-3}$$

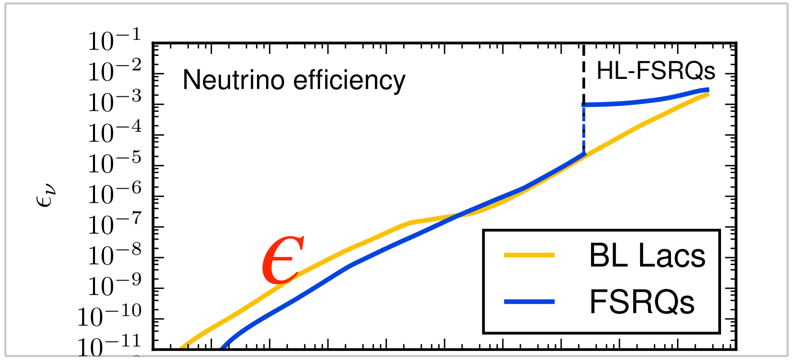
$$\rho_{47} \simeq 0.01\ \mathrm{Gpc}^{-3}$$

	Evolution	Number resolved	Number unresolved	Resolved γ- flux	Unresolved γ- flux
Low luminosity BL Lacs	Negative	359	6070	**64%**	**36%**
High Luminosity BL Lacs	Positive	609	981	90%	10%
FSRQs	Positive	566	601	97%	3%
All blazars	- - -	1534	7652	88%	12%

The IceCube stacking limit (APJ 2017) limits to the contribution of resolved sources

How to produce neutrinos in low luminosity blazars ?

The neutrino efficiency production is small —> We need many protons

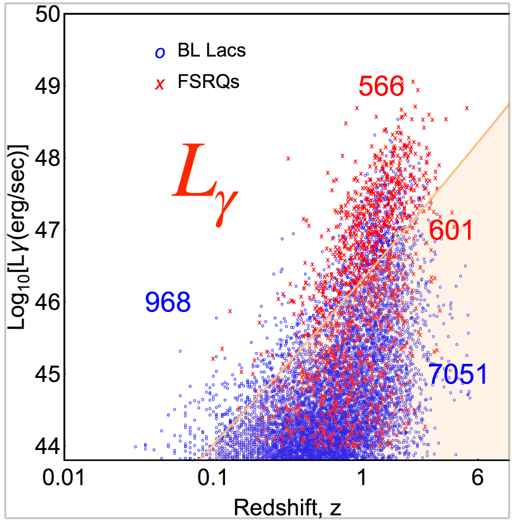


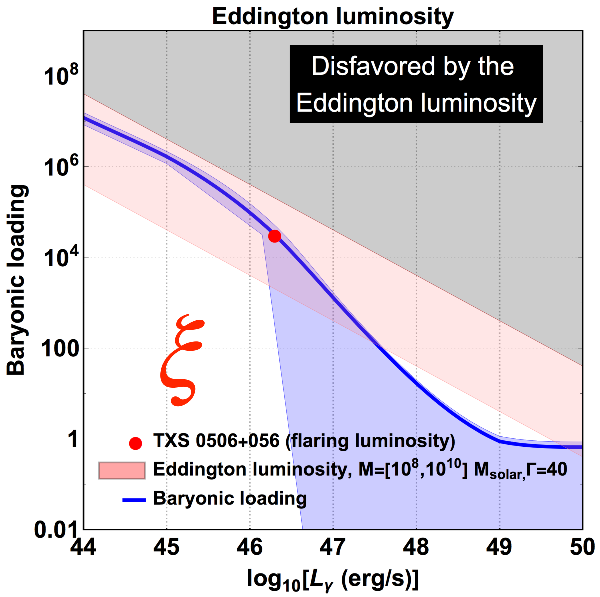
$$L_\nu = \frac{L_\nu}{L_{cr}} \frac{L_{cr}}{L_\gamma} L_\gamma$$

Let us recall that in our model

$$L_\nu = \epsilon \; \xi \; L_\gamma$$

where ϵ the efficiency of neutrino production,
ξ is the baryonic loading

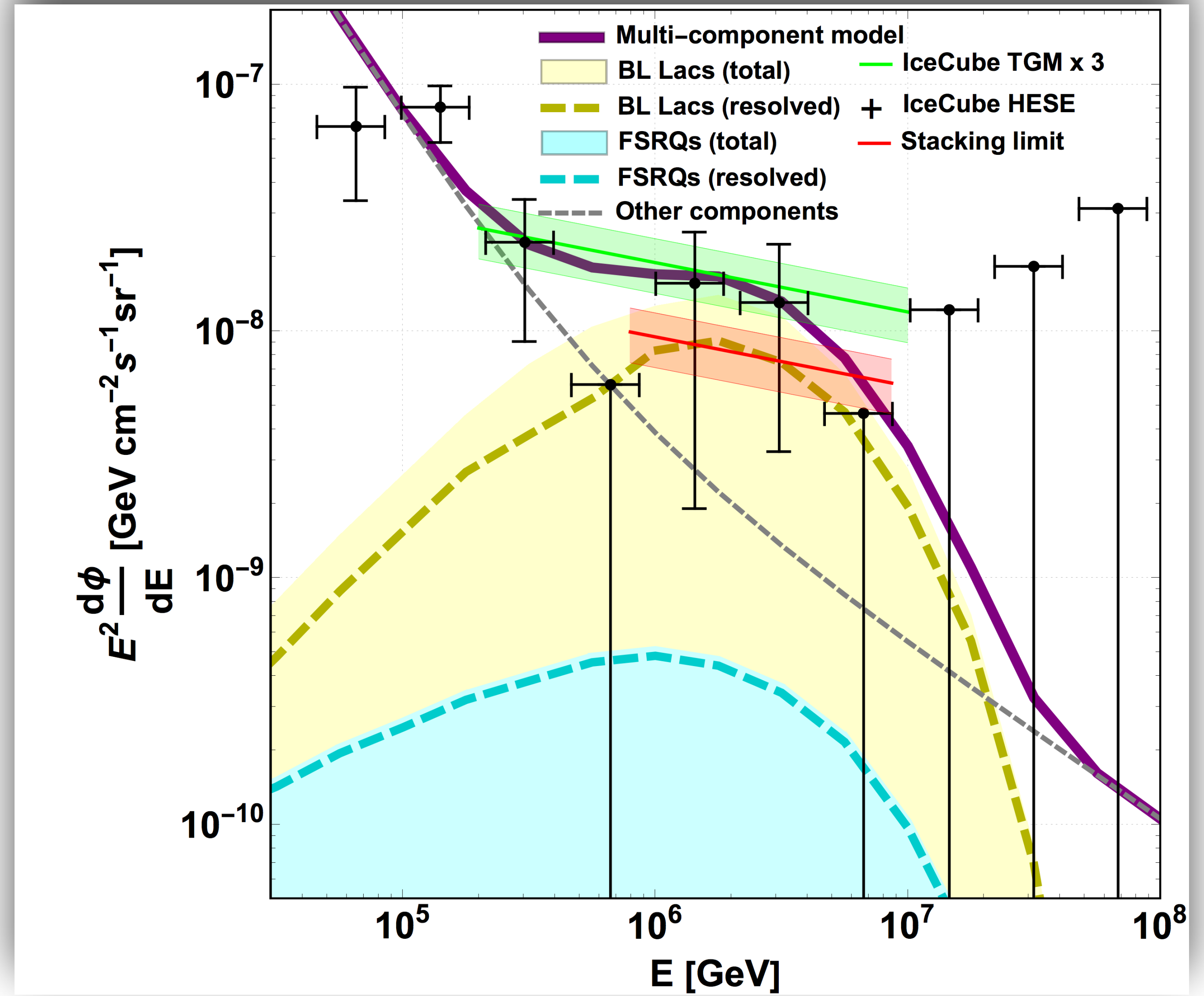




Palladino et al., APJ 2019, Astrophys.J. 871 (2019) 41

DESY.

Results



Low energy flux: residual atmospheric background (conventional, prompt) + galactic neutrinos

Flux above 200 TeV: low luminosity BL Lacs (about half flux from resolved sources and half from unresolved sources)

Negligible contribution from high luminosity sources, to not violate the stacking bound

Figure from Palladino et al., APJ 2019

pp sources instead of pgamma sources ?

The proton-proton collision is a natural way to produce high energy neutrinos

Why pp source are disfavored ?

The argument is contained in Behctol et al. 2015, *“Evidence against Star-Forming Galaxies as the dominant source of IceCube neutrinos”*

Following the shape suggested by HESE, the contribution to the neutrino flux cannot be higher than 10%, otherwise the associated gamma-ray flux is too high

There is a strong hypothesis:

“Following the shape suggested by HESE”

What happens if we follow the shape suggested by throughgoing muons ?

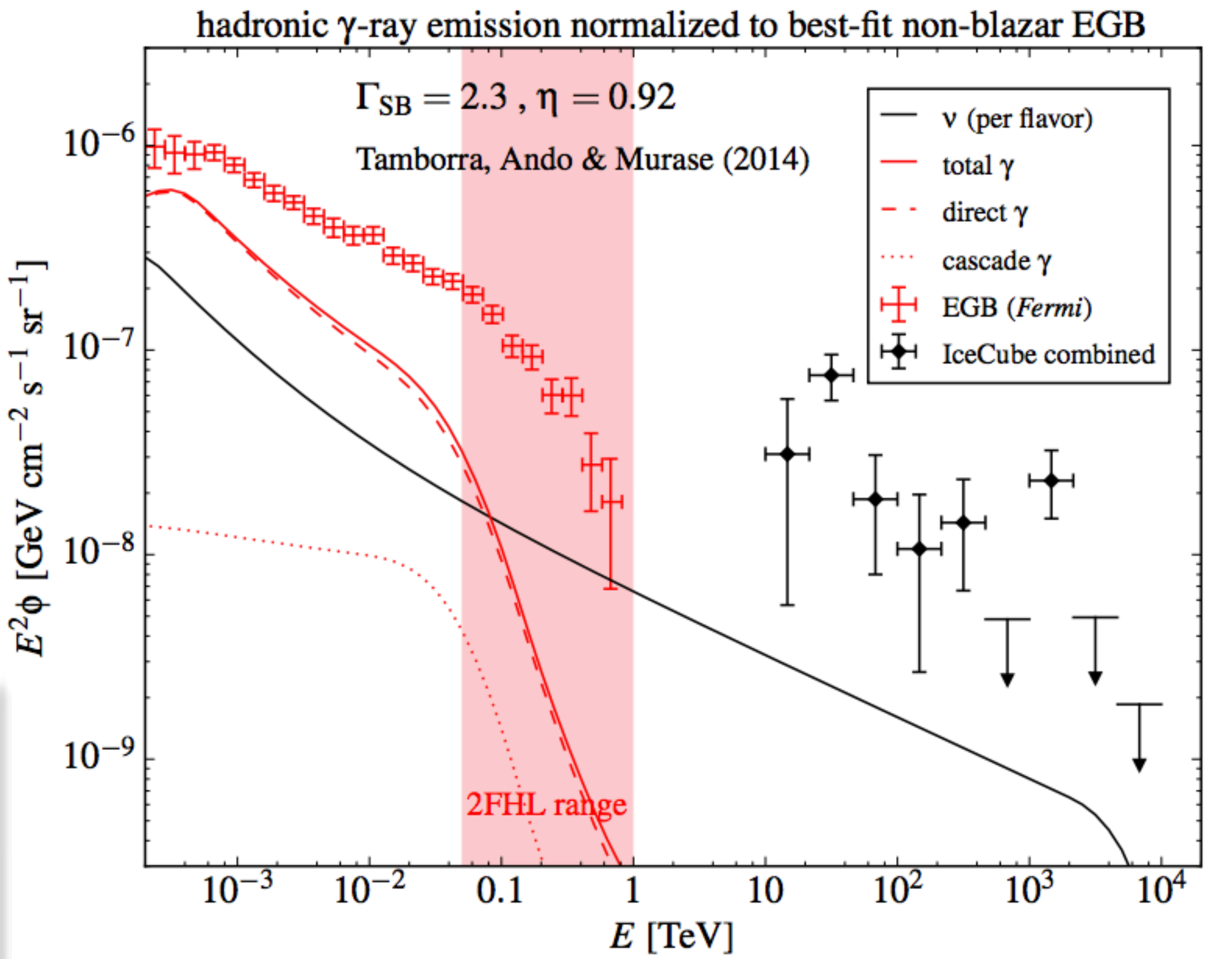


Figure from Bechtol et al., 2015 (published in APJ 2017)

Which pp sources ?

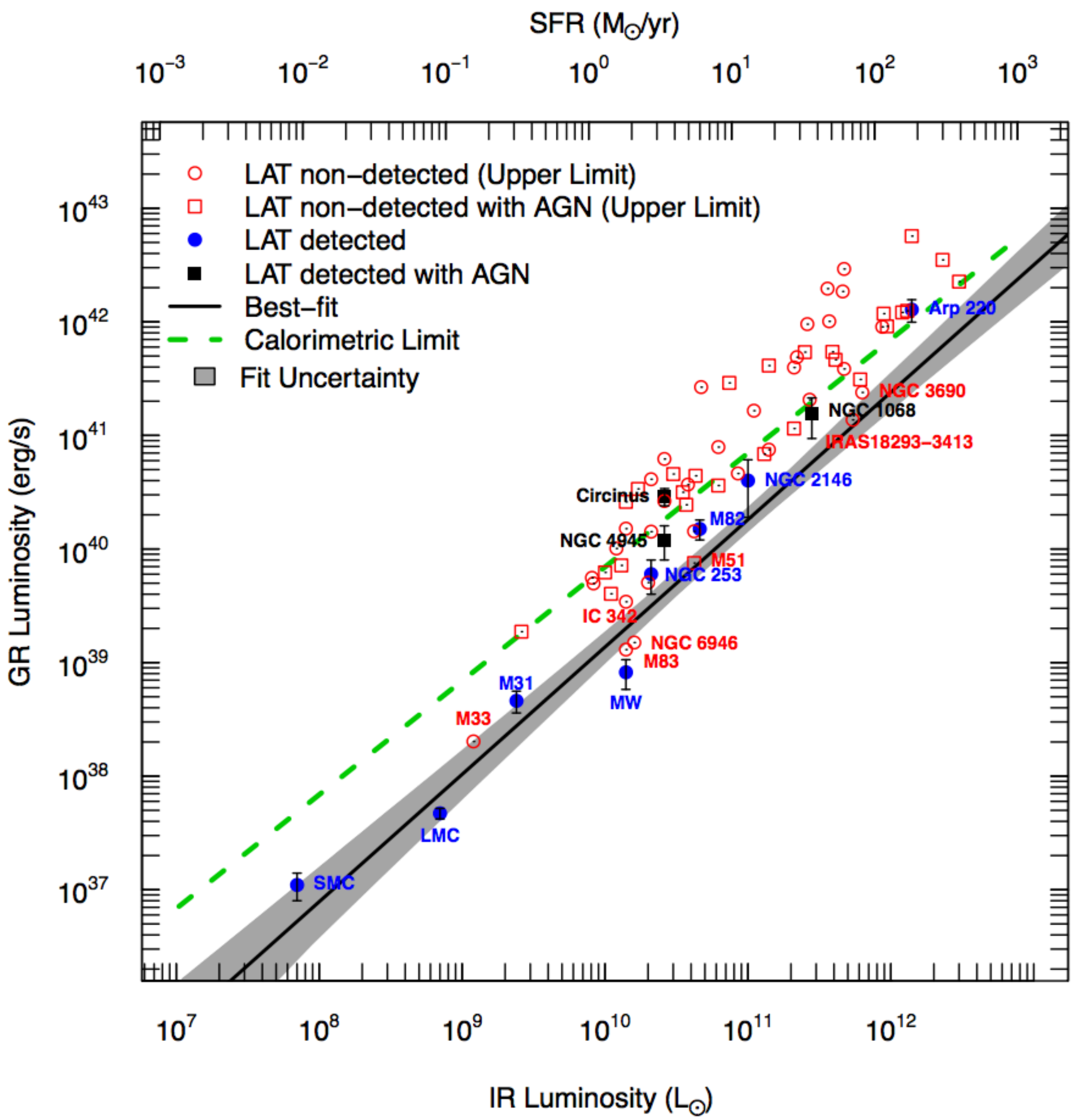


Figure from Royas-Bravo,Araya, MNRAS, 2016

- we consider luminous and very luminous pp sources. As prototype we have chosen **NGC 253, Arp 220**
- in these sources the star formation rate is **10-100** times higher than a normal Galaxy;
- these sources are **rich of gas**. There is the ideal environment for pp interaction and for **neutrino production**

The spectrum of Starburst Galaxy NGC 253

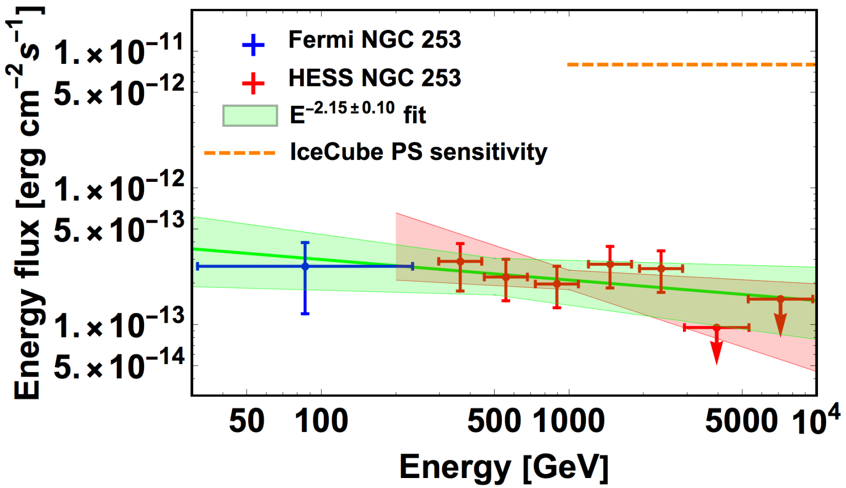


Figure from Palladino et al., arXiv:1812.04685

The multi-messenger result

The associated gamma-ray flux is 25% of EGB, compatible within 1 sigma with Fermi estimated non blazar contribution

Using:

- $E^{-2.1}$ with a multi-PeV cutoff
- the luminosity of NGC 253
- the star formation rate as source evolution
- a source density of $8 \times 10^5\ \mathrm{Gpc}^{-3}$

it is possible to:

- interpret the throughgoing muon flux
- produce 75%-80% of observed HESE
- explain at least 50% of the low energy neutrino flux in the 1 TeV- 100 TeV energy range

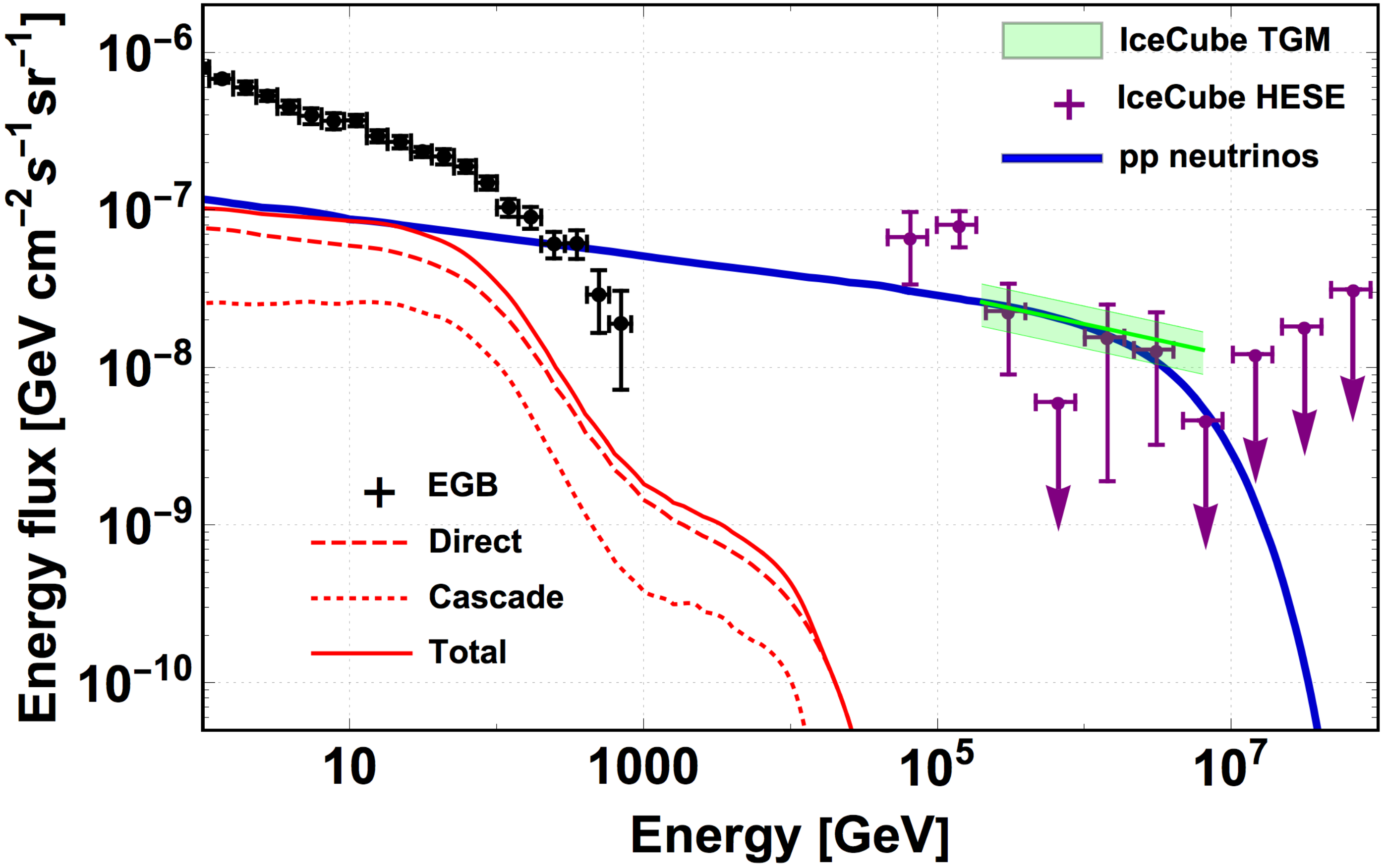


Figure from Palladino et al., arXiv:1812.04685 submitted to JCAP

Conclusion

- The majority of astrophysical neutrinos still remains without any counterpart
- High luminosity BL Lacs and FSRQs cannot power the entire IceCube flux
- Low luminosity BL Lacs are plausible sources of high energy neutrinos, if they are rich of protons
- pp sources (such as Starburst Galaxies) can provide the dominant contribution to astrophysical neutrinos, although they cannot power the entire observed flux