On the sources of high energy neutrinos

WIN 2019,
04.06.2019, Bari (Italy)

Andrea Palladino
Desy, Zeuthen

- A summary of the current observations
- Few words on the production mechanisms of high energy neutrinos
- Blazars as sources of high energy neutrinos
- pp sources (like Starburst Galaxies) as sources of high energy neutrinos

Neutrino telescopes

— Astrophysical neutrinos are detected looking at secondary particles produced in the **deep inelastic scattering** between high energy neutrinos and nucleons

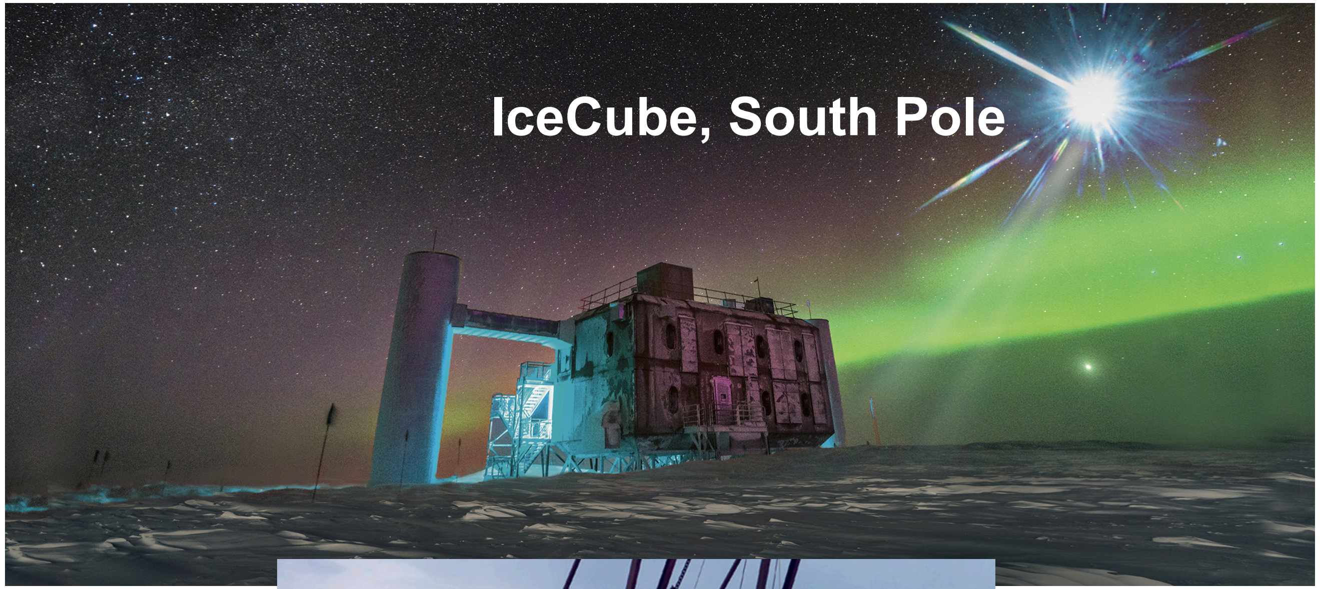
— Very small cross section, $\sigma_{dis} = 10^{-33} cm^2$ at PeV scale

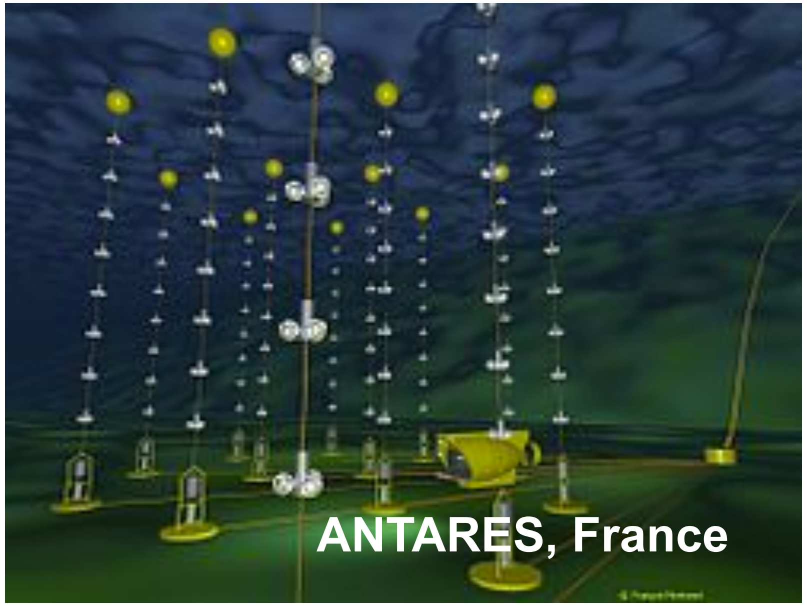
— Astrophysical neutrinos can be detected only using huge detectors

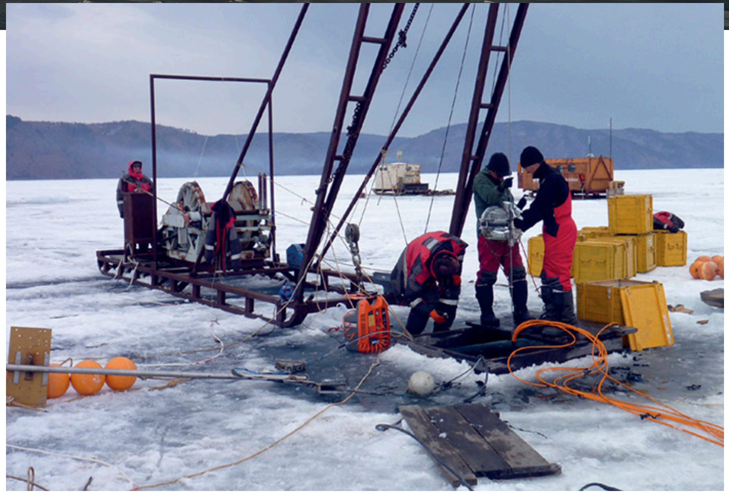
With a 1 km^3 detector less than 10 astrophysical events above 100 TeV per year are expected

Neutrino telescopes

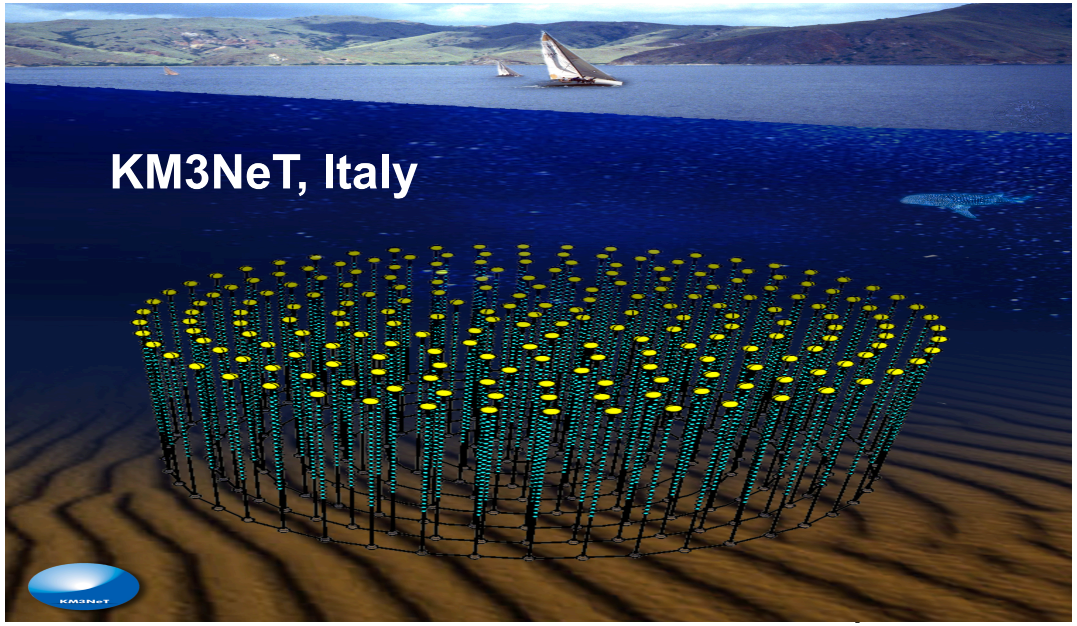
Different neutrino telescopes are operating nowadays







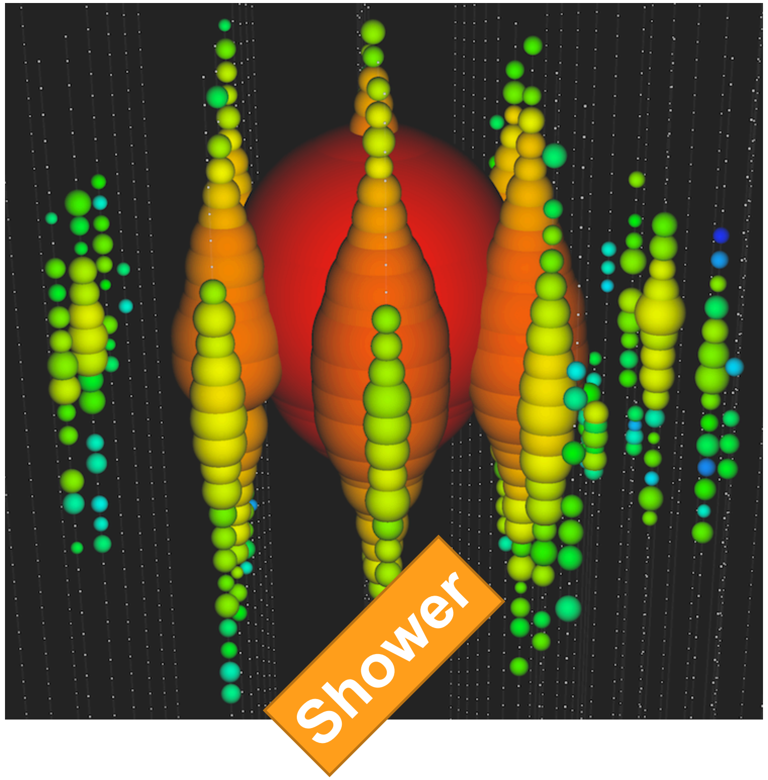
Baikal GVD, Siberia



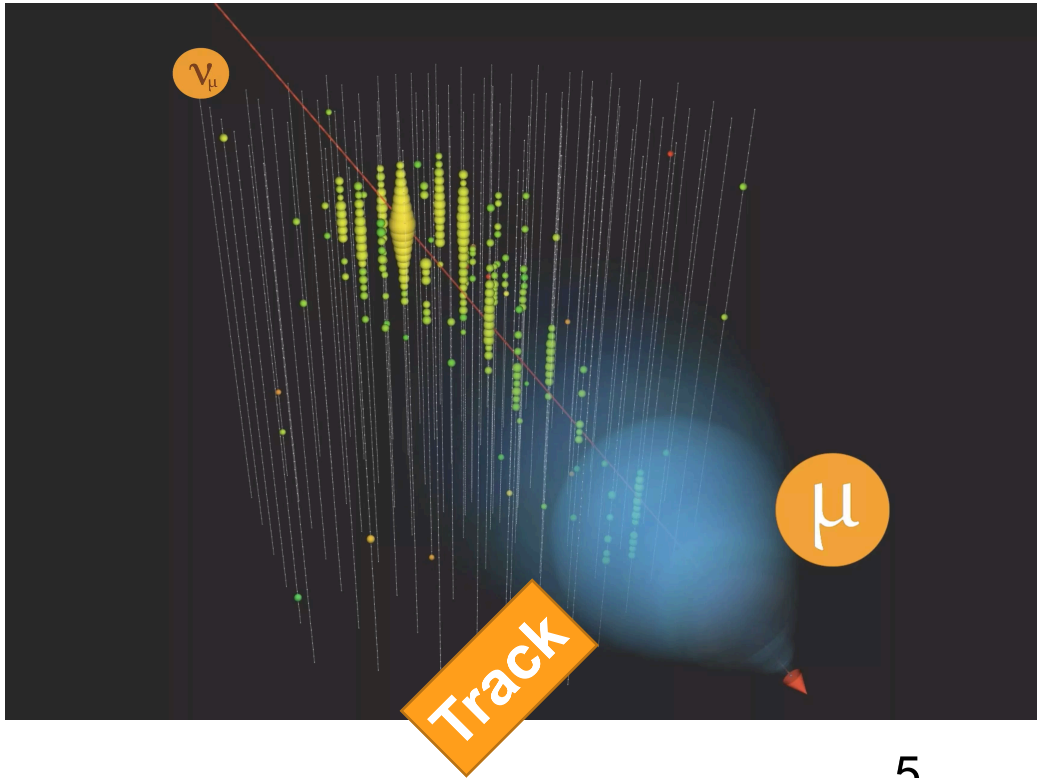
Showers and tracks

- Sensitive to all flavors, ν_e ν_μ ν_τ, CC and NC interaction
- Good energy reconstruction (most of the energy is deposited)
- Angular resolution of 10°-15°

- Only sensitive to muon neutrinos ν_μ, CC interaction
- Only part of the energy is deposited
- Good angular resolution, 1° in ice, sub-degree in water



Credit: figures from IceCube



IceCube, HESE and throughgoing muons

IceCube is the biggest neutrino telescope up to now (**1 cubic kilometer**)

It is taking data since about **10 years**

Two main dataset available

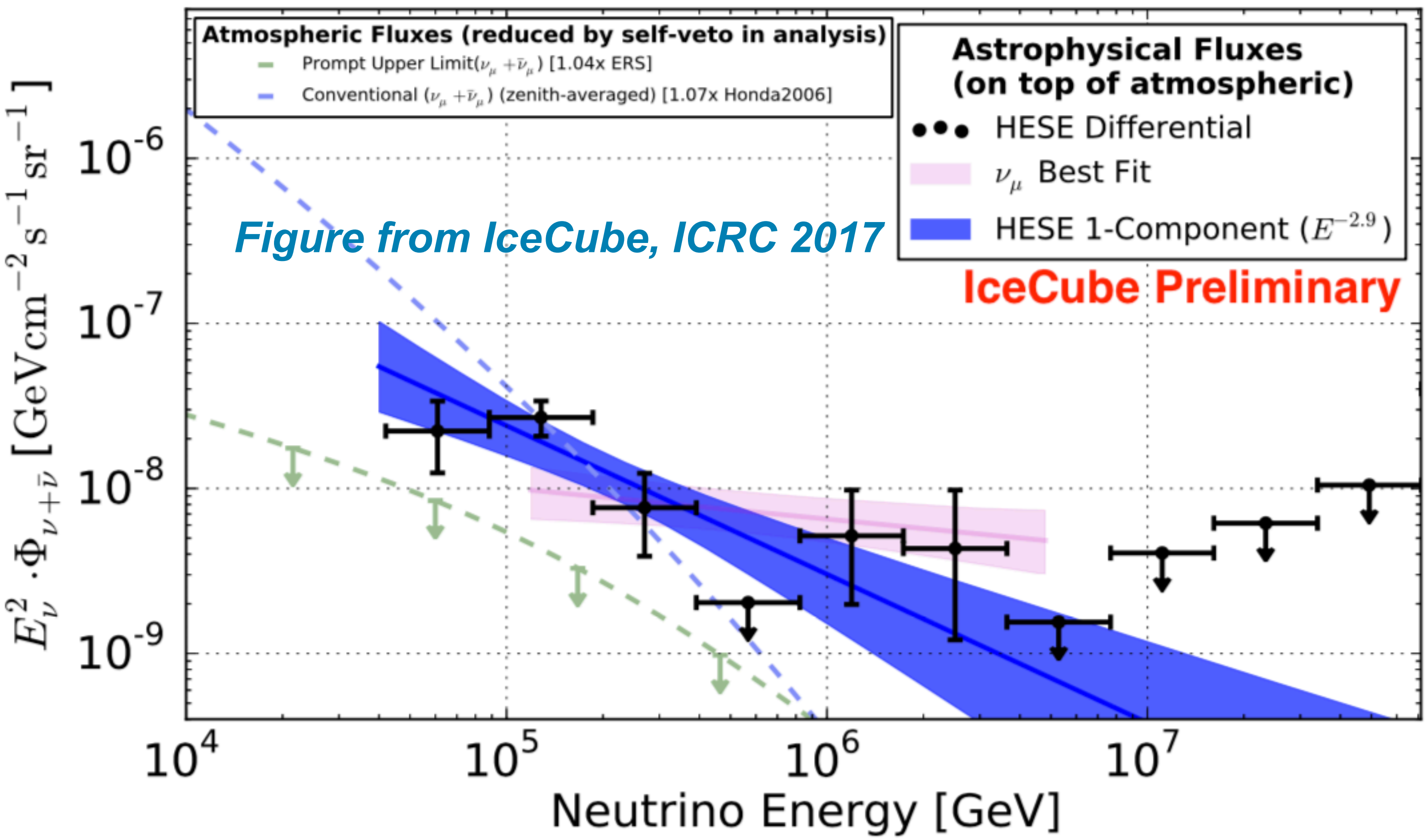
High Energy Starting Events (HESE),

- vertex of interaction inside the detector
- energy threshold of 60 TeV
- more showers than tracks
- more events from the Southern hemisphere than from the Northern one (due to Earth opacity to neutrinos above hundreds of TeV)

Throughgoing muons

- vertex of interaction outside the detector
- energy threshold of 200 TeV
- only tracks
- only from the Northern hemisphere

HESE and Throughgoing muons



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

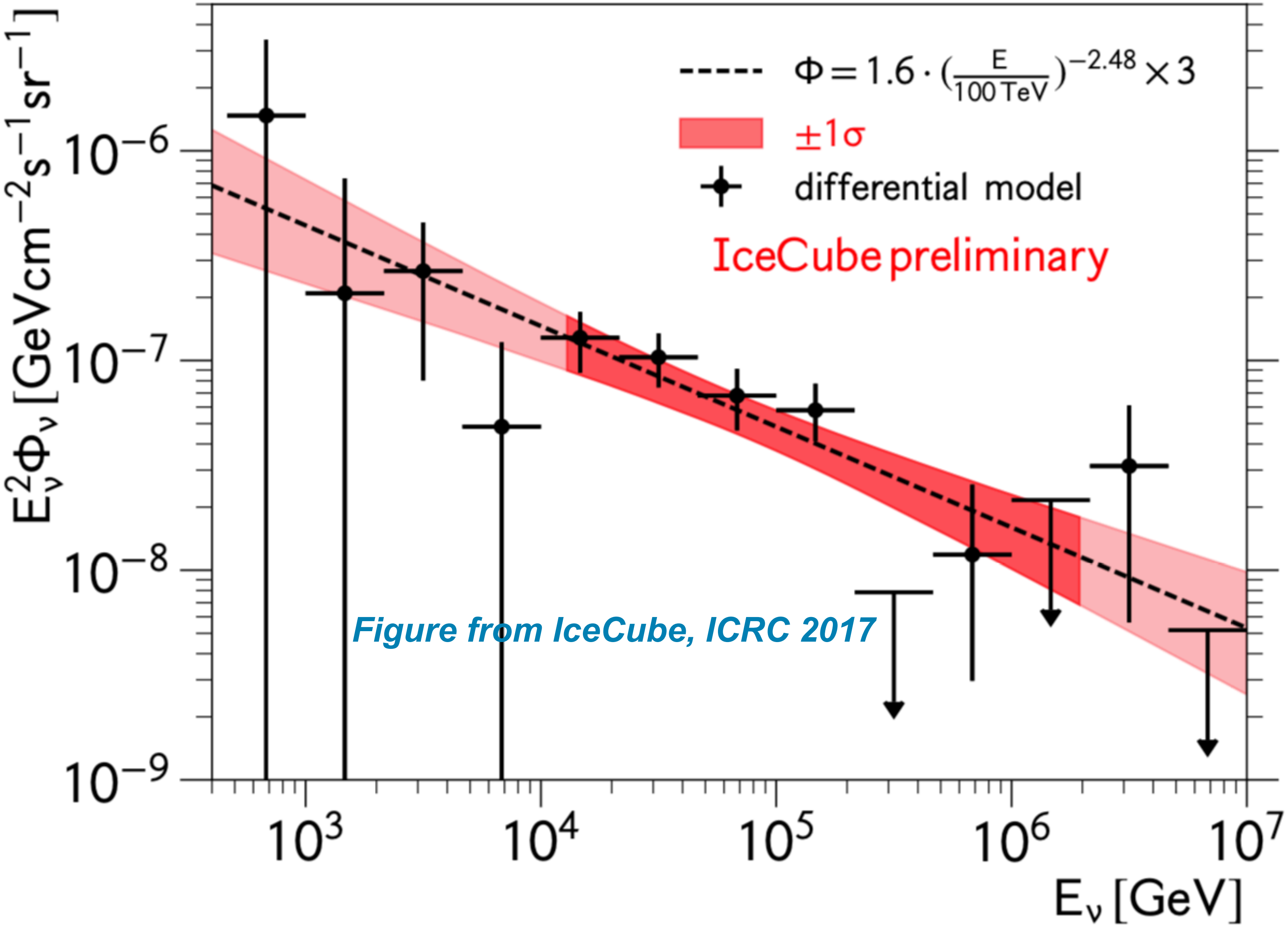
$$E^{-\alpha} \text{ with } \alpha = 2.2 \pm 0.1$$

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

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

Cascade events above 1 TeV

Figure from IceCube, ICRC 2017



6 years of cascade events above 1 TeV suggests an **intermediate** spectrum:

$E^{-\alpha}$ with $\alpha = 2.5 \pm 0.1$

Single power law or broken power law ?

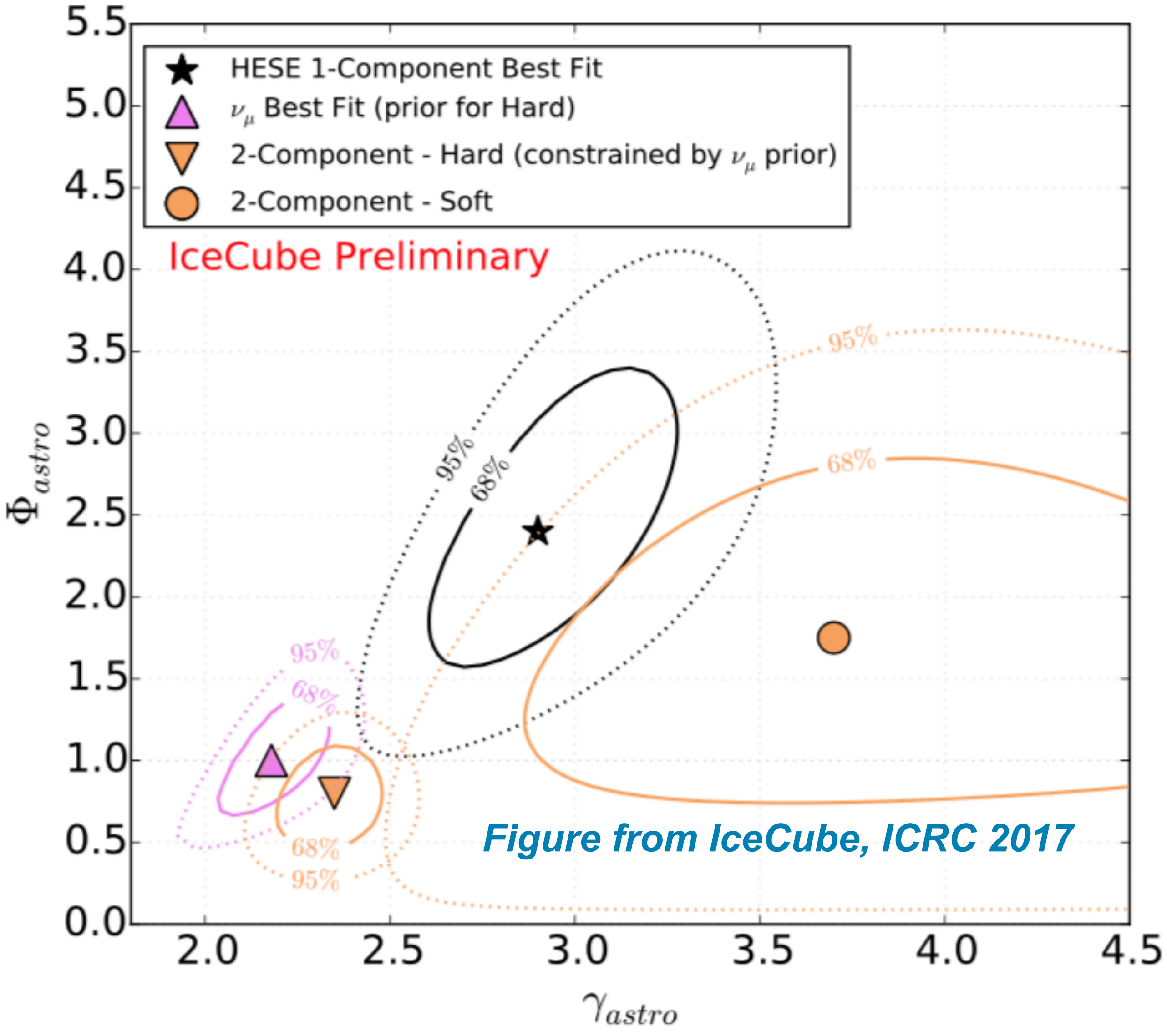


Figure from IceCube, ICRC 2017

Single power law: still compatible with data

Broken power law: improves the agreement

What do we learn from the spectral shape ?

See Ahlers talk (on Thursday) for more details

Mechanisms of production of high energy neutrinos

Two main mechanisms. Proton-proton and proton-gamma collision

$$pp \rightarrow \pi^+\pi^-\pi^0 \ldots$$

$$\begin{aligned} \pi^+ &\rightarrow e^+\nu_e\nu_\mu\bar{\nu}_\mu \\ \pi^- &\rightarrow e^-\bar{\nu}_e\bar{\nu}_\mu\nu_\mu \\ \pi^0 &\rightarrow \gamma\gamma \end{aligned}$$

$$p\gamma \rightarrow \Delta \rightarrow \begin{cases} \pi^+ & 1/3 \text{ of cases} \\ \pi^0 & 2/3 \text{ of cases} \end{cases}$$

$$\begin{aligned} \pi^+ &\rightarrow e^+\nu_e\nu_\mu\bar{\nu}_\mu \\ \pi^0 &\rightarrow \gamma\gamma \end{aligned}$$

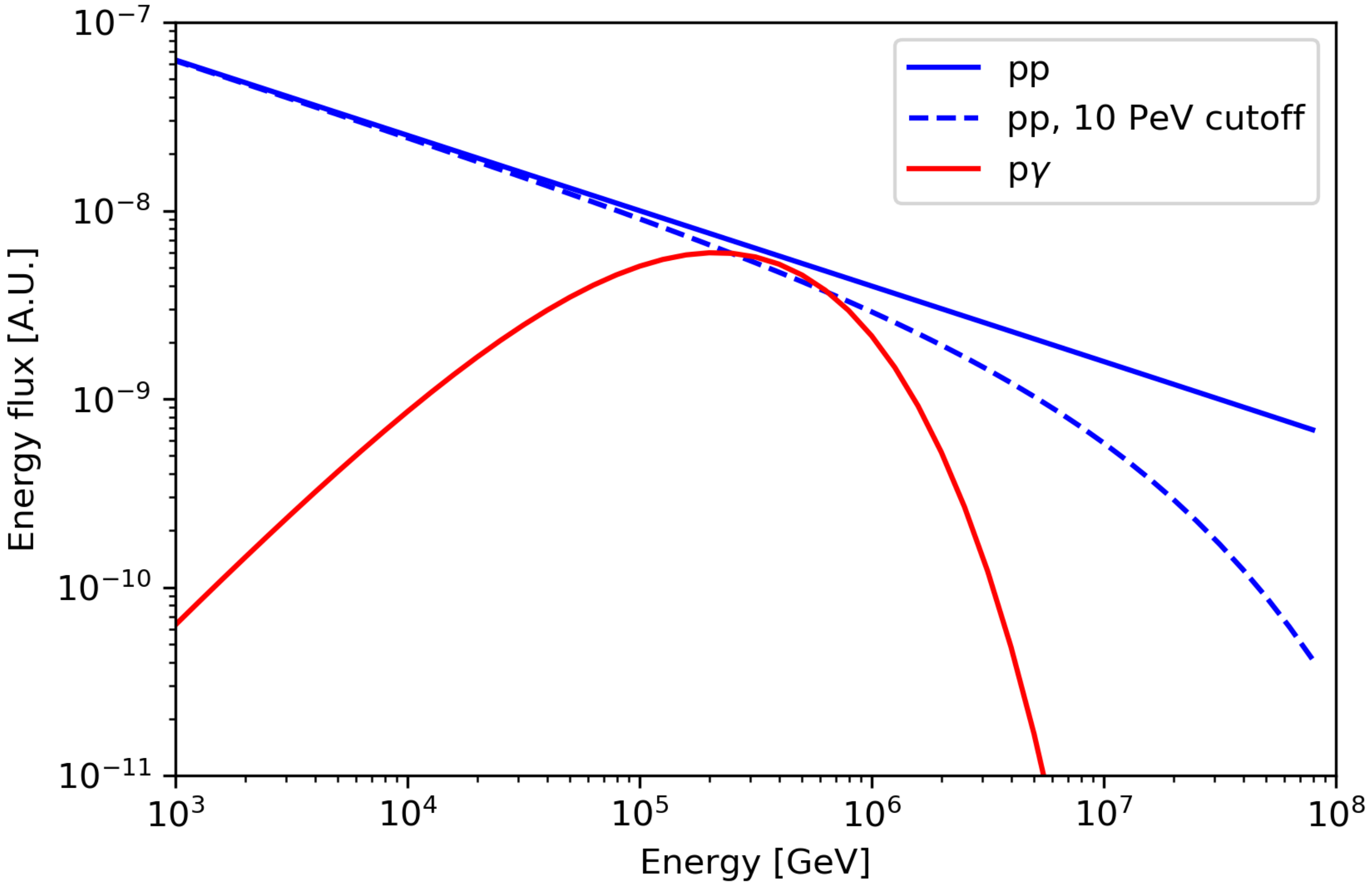
The energy of neutrinos is about 1/20 of the primary proton's energy

Initial flavor composition $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

Flavor composition after oscillations $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

pp versus p-gamma

From proton-proton and proton-gamma interactions different neutrino spectra are expected



pp interaction:
power law remains power law

pg interaction:
power law is distorted

No hint of p-gamma spectrum in the present IceCube data, although more data are required

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

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*†

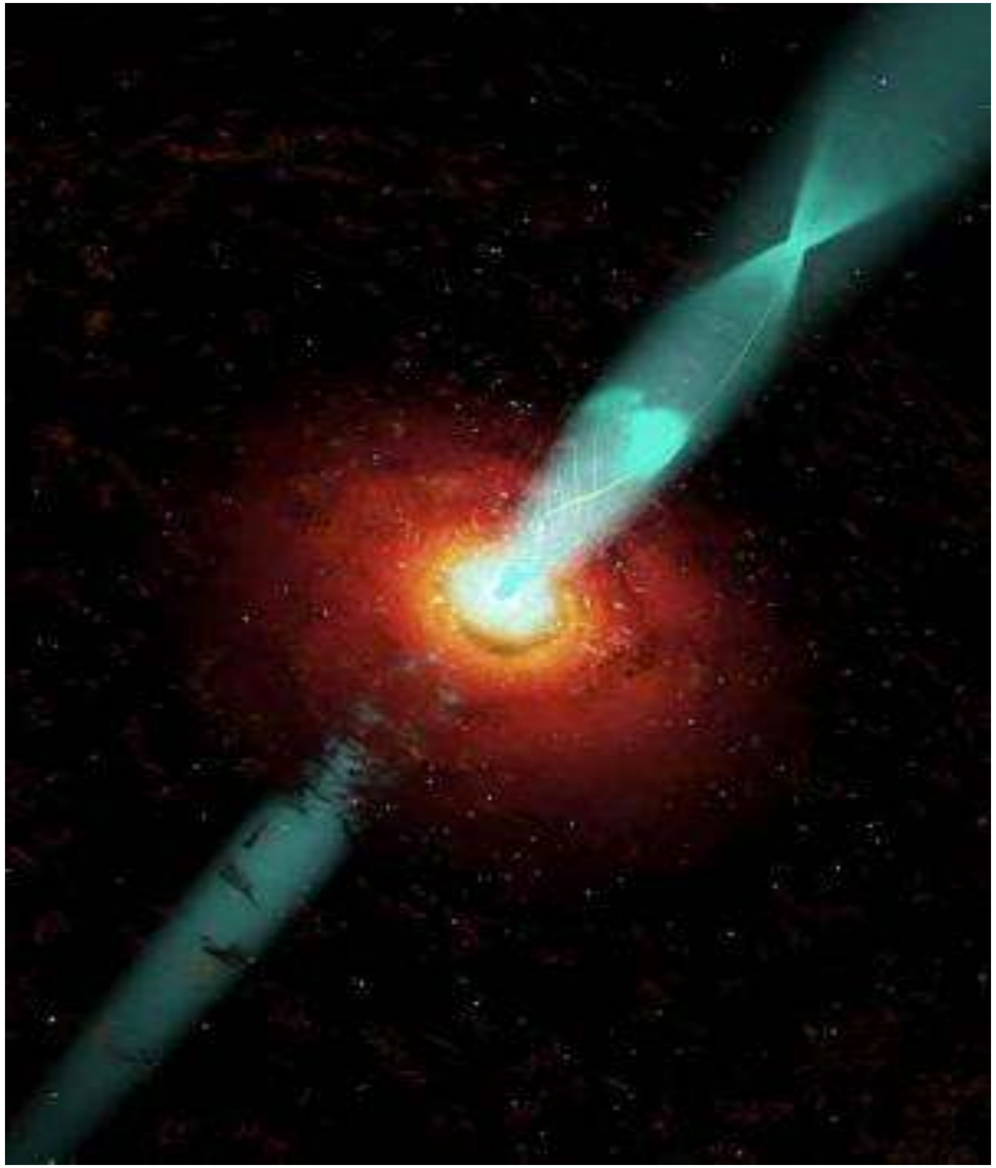
INTRODUCTION: Neutrinos are tracers of cosmic-ray acceleration: electrically neutral and traveling at nearly the speed of light, they can escape the densest environments and may be traced back to their source of origin. High-energy neutrinos are expected to be produced in blazars: intense extragalactic 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

ON OUR WEBSITE

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

What is a blazar ?



- A Blazar is an Active Galactic Nuclei (AGN), with the emitted jet pointing to Earth;
- An AGN is a Galaxy having an active supermassive black hole in the center

Blazars are very bright objects, reaching even

$$L_\gamma = 10^{49}\text{erg/s}$$

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

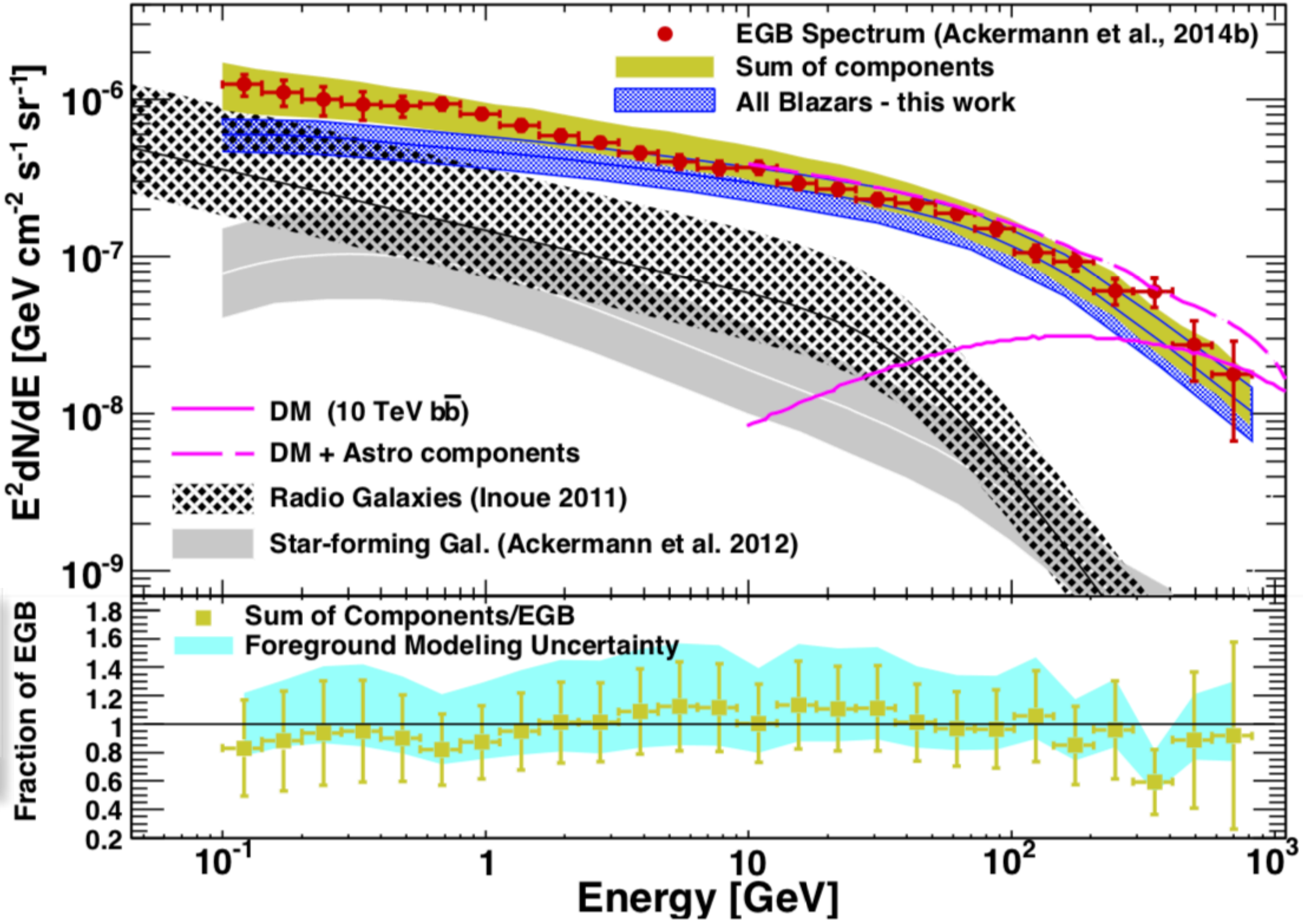


Figure from Ajello et al., APJ 2015

Why are blazars disfavored as neutrino emitters ?

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

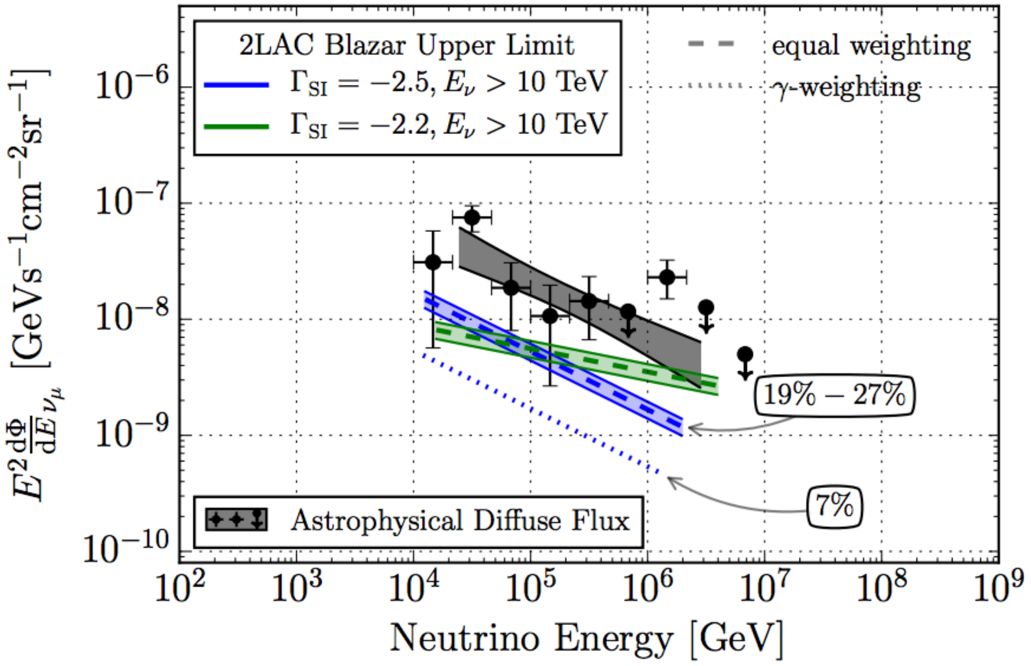


Figure from IceCube, Astrophys.J. 835 (2017) no.1, 45

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

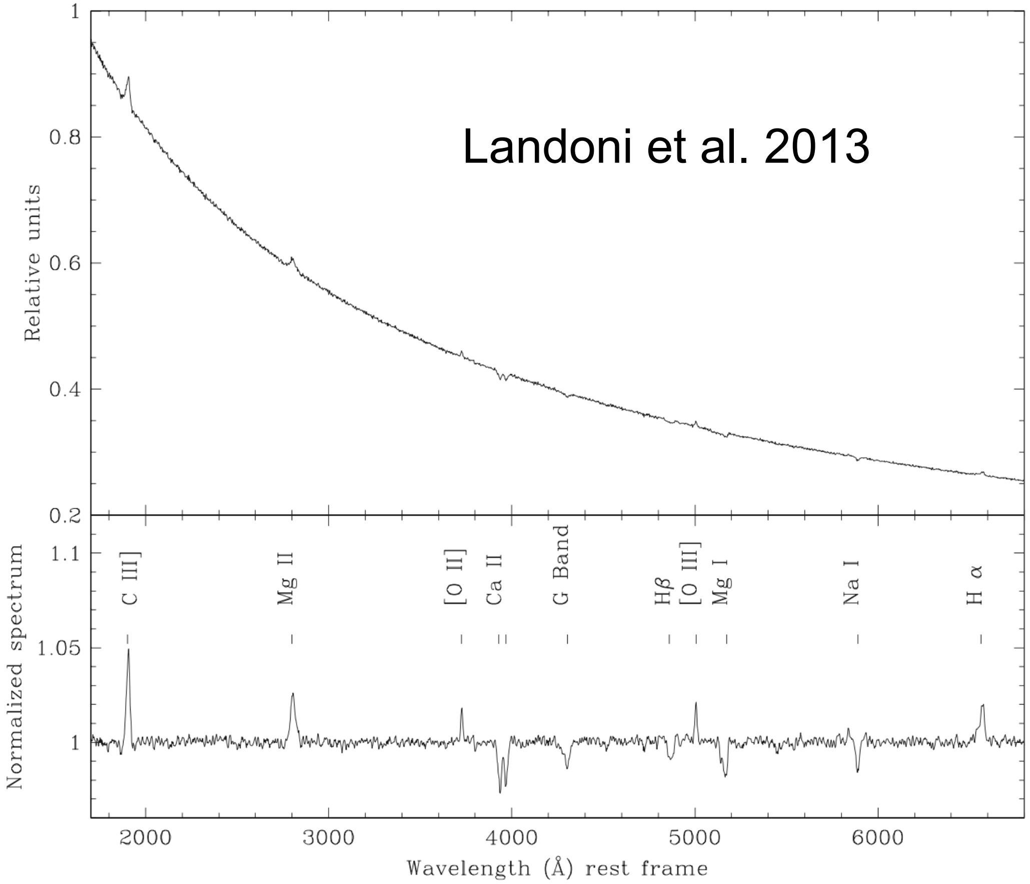
If blazars are neutrino emitters, the contribution of not detected (unversolved) blazars has to be relevant

The brightest blazars cannot be the main sources of high energy neutrinos

Two types of Blazars

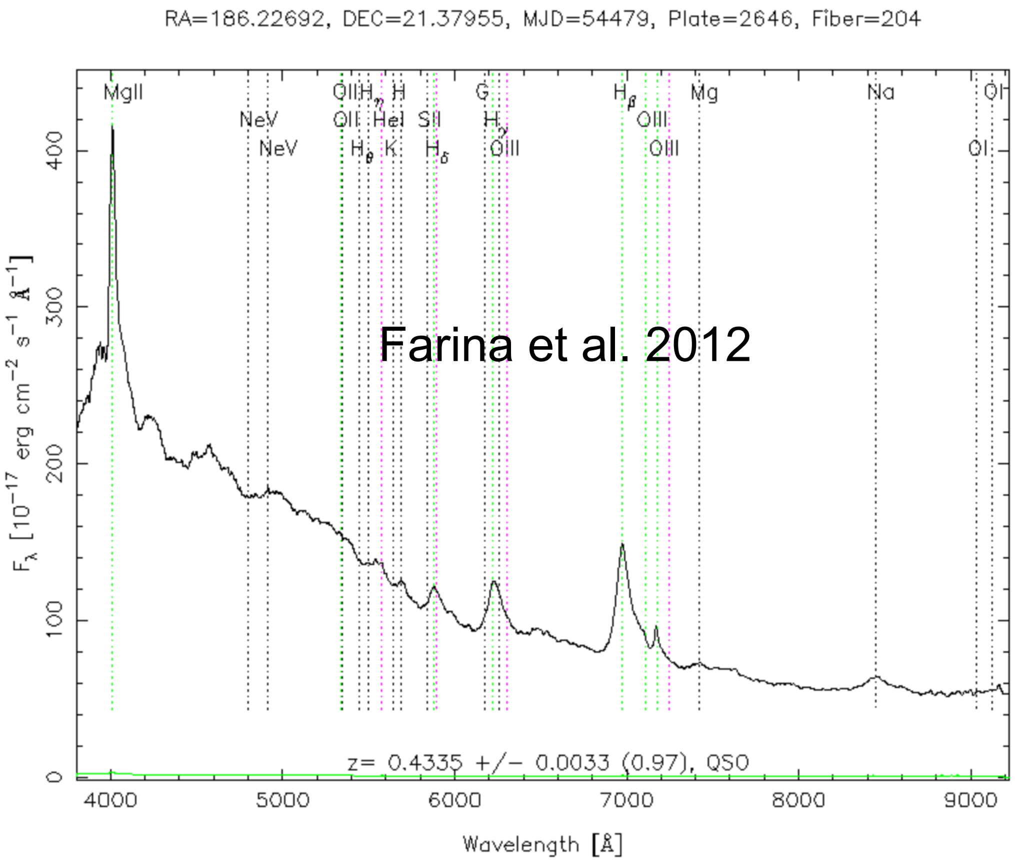
BL Lacs

- typically the less luminous blazars
- featureless optical spectrum



FSRQs

- the most luminous blazars
- optical spectrum with absorption lines, due to interaction with the external region



Cosmic evolution of blazars

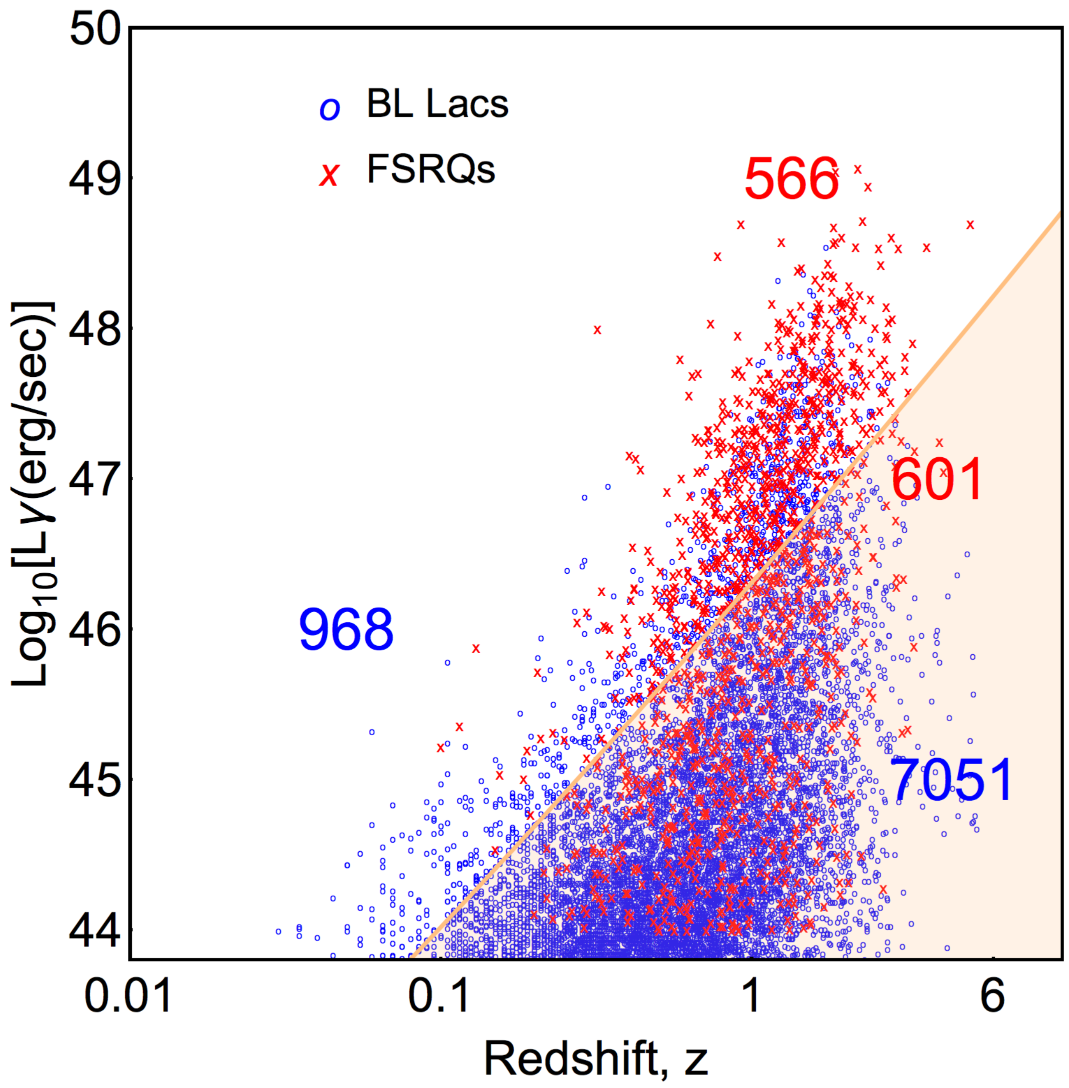


Figure from Palladino et al., APJ 2019

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

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

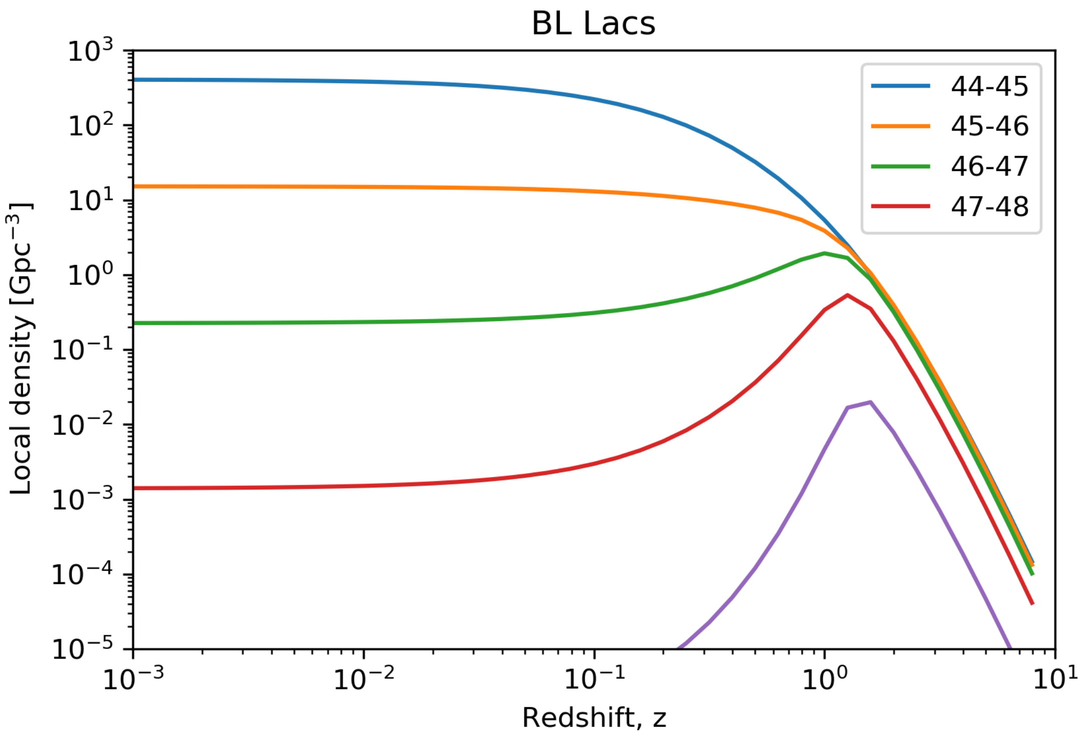
The luminosity threshold is an average one, chosen to replicate the about 1500 resolved sources contained in the 3LAC catalogue

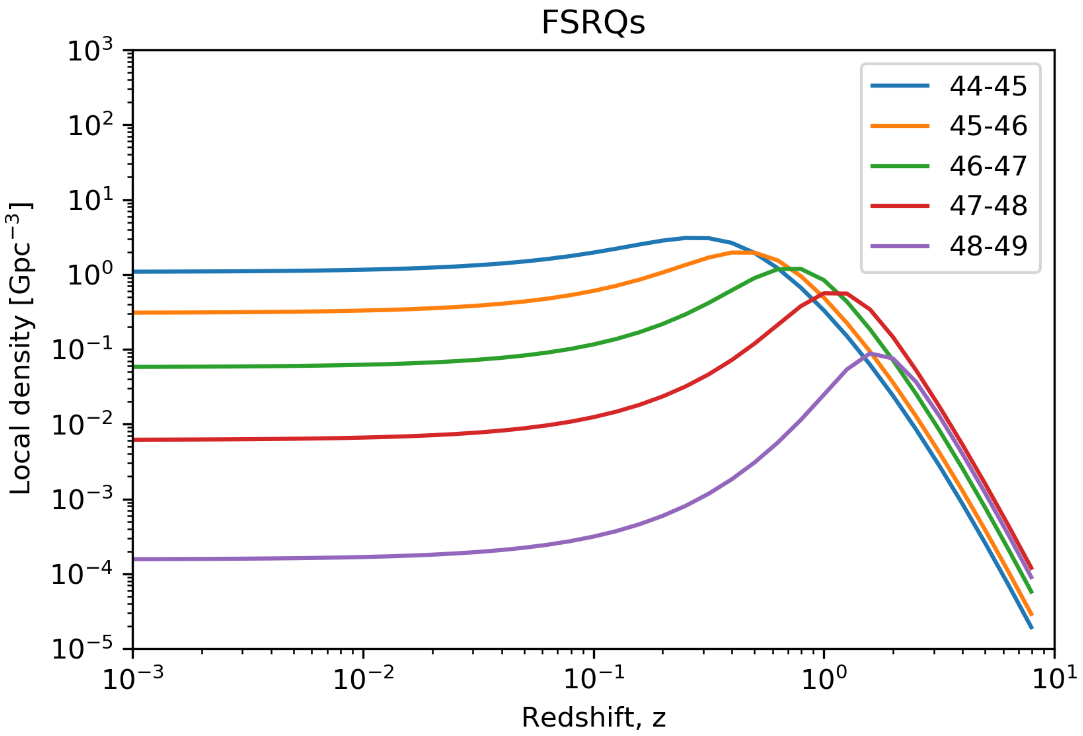
Thousands of unresolved BL Lacs expected from the distribution

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

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

Source evolutions





High luminosity objects have positive evolution

Low luminosity BL Lacs have negative evolution (they are more abundant in the local universe)

DESY.

	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

Different neutrino efficiencies

Assuming:

$$L_\nu = 10\,\%\ L_\gamma$$

for low luminosity BL Lacs and

$$L_\nu < 0.1\,\%\ L_\gamma$$

for high luminosity BL Lacs and FSRQs

we can power partially avoid the IceCube stacking limit, since 50% of the flux is provided by unresolved sources

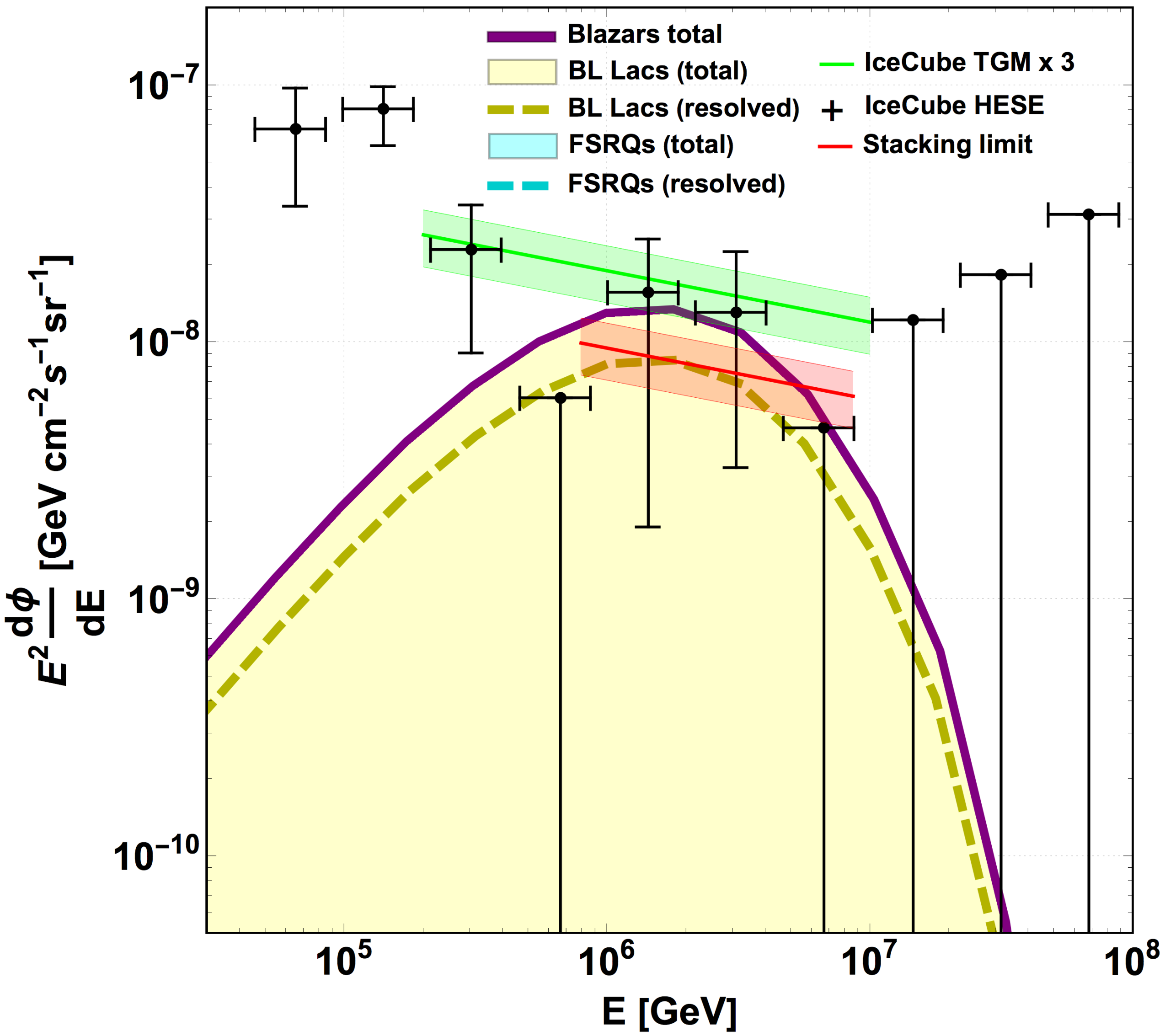


Figure from Palladino et al., APJ 2019

Consequences for blazars

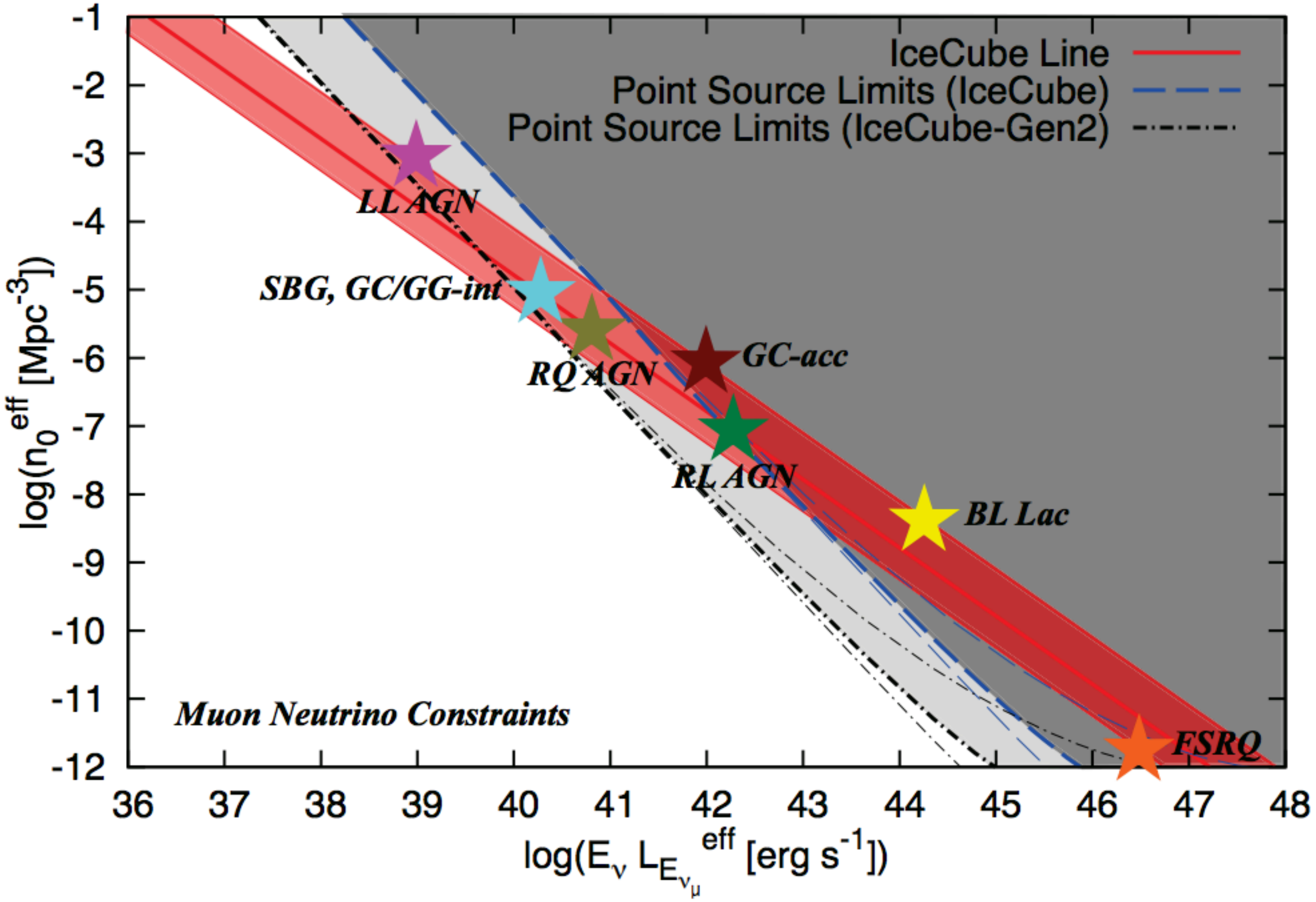
Following the previous result:

in order to reconcile the throughgoing muon flux with the blazar hypothesis,

- **low luminosity BL Lacs** should be **rich of protons**
- **high luminosity BL Lacs and FSRQs** should be (almost) **purely leptonic** sources

Few words on the multiplet problem

See Murase - Waxman, PRD 2016



If sources are not abundant, the probability the observe two neutrinos from the same source is quite high

however, no multiplets are present in the neutrino data !

This is another hint against blazars as dominant sources of high energy neutrinos

pp sources instead of pgamma sources ?

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

Sources dominated by pp interaction

$$
\begin{aligned}
pp &\rightarrow \pi^+\pi^-\pi^0 \\
\pi^+ &\rightarrow e^+\nu_e\nu_\mu\bar{\nu}_\mu \\
\pi^- &\rightarrow e^-\bar{\nu}_e\bar{\nu}_\mu\nu_\mu \\
\pi^0 &\rightarrow \gamma\gamma
\end{aligned}
$$

- The proton-proton interaction is a natural way to produce high energy neutrinos
- Important: the neutrino spectrum replicates the spectrum of primary particles
- The associated gamma-ray flux (produced by pi^0 decay) is almost equal to the all flavor neutrino flux

Can pp sources saturate the IceCube flux ?

No !

Following the shape suggested by HESE, the associated gamma-ray flux would be too high, violating the EGB constraint

We have seen before —-> 80% of EGB above 100 GeV is produced by blazars

Let us try to explain only the thoroughgoing muon flux

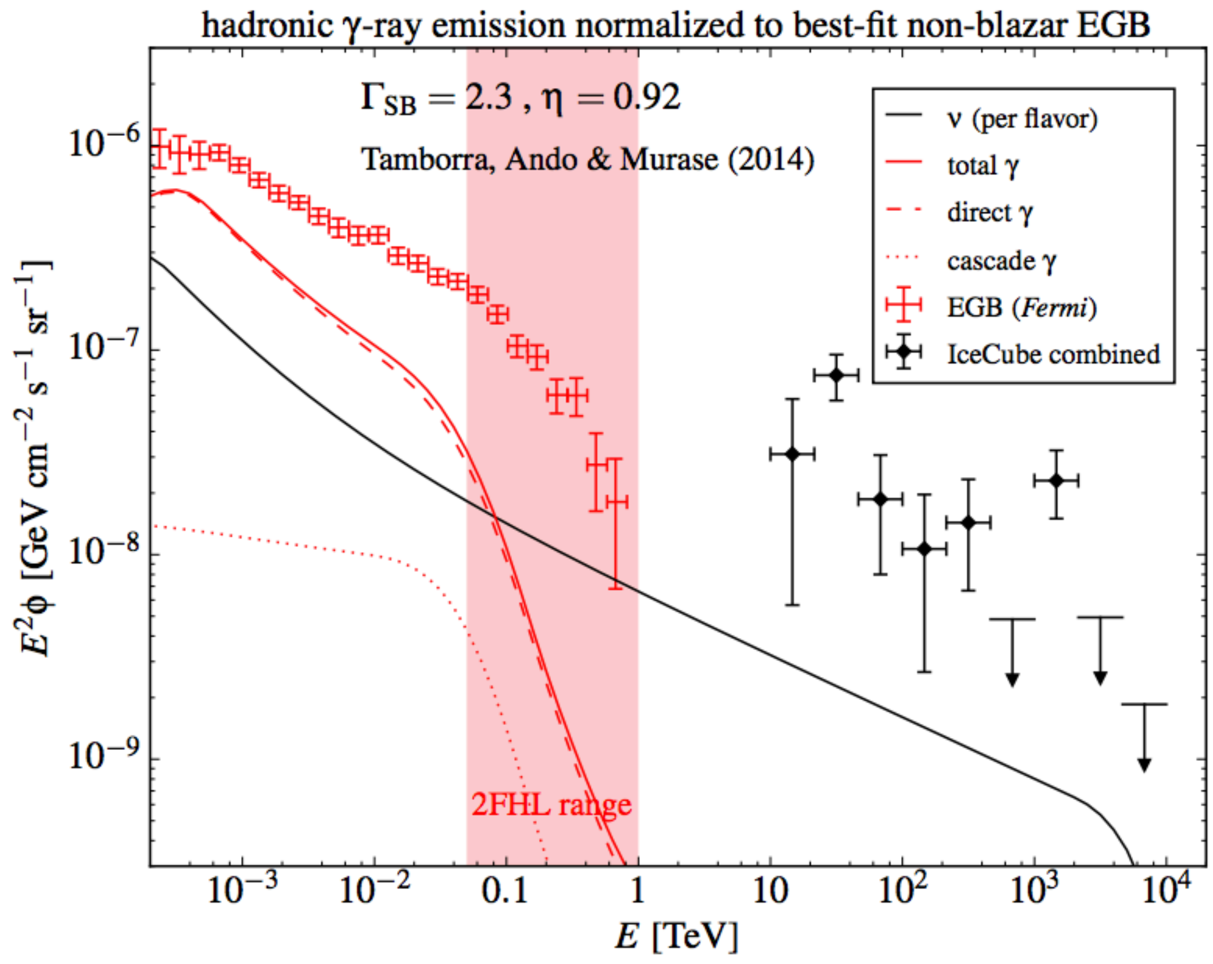


Figure from Bechtol, Ahlers et al., 2015 (published in APJ 2017)

Which pp sources ?

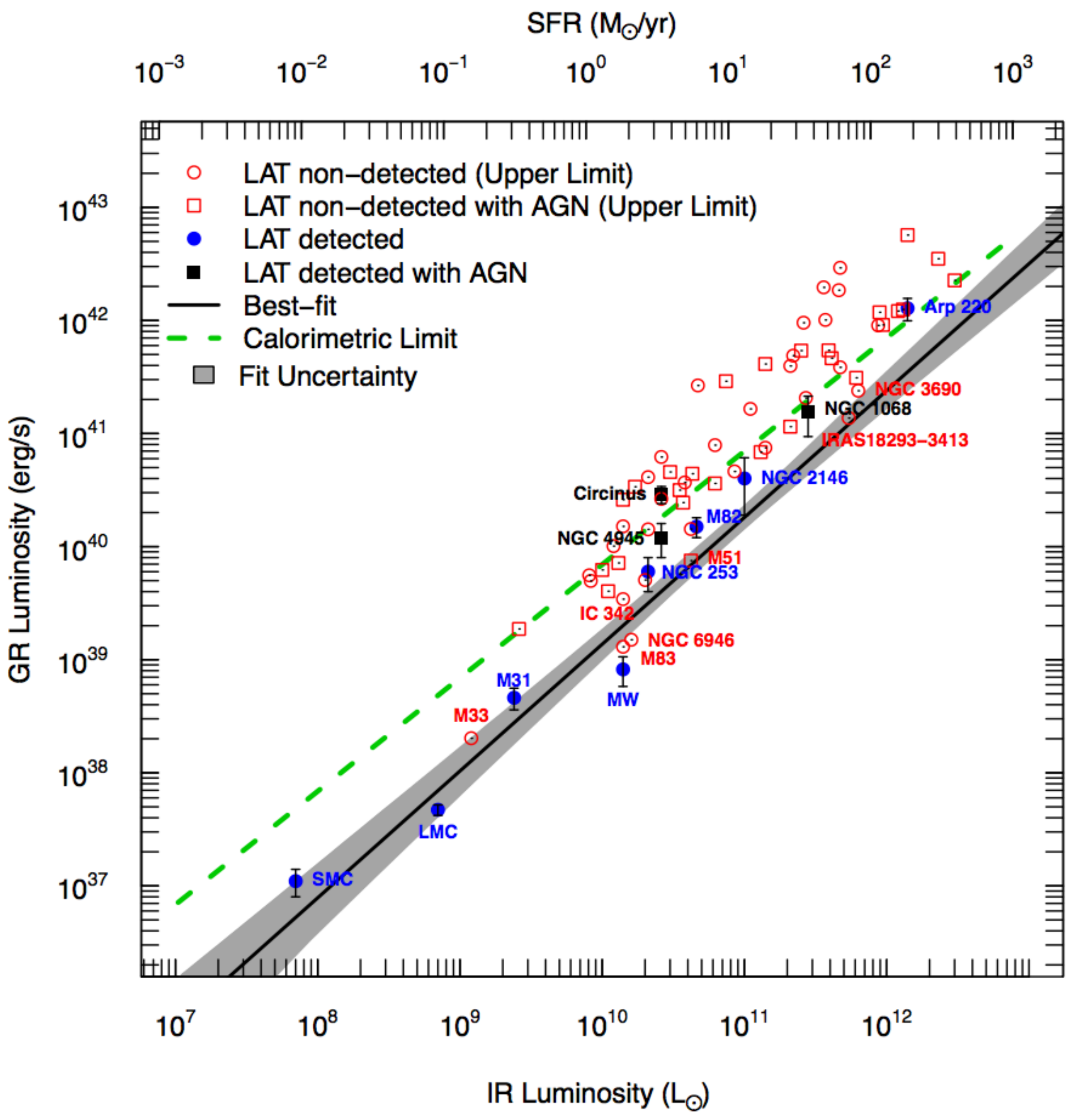


Figure from Royas-Bravo,Araya, MNRAS, 2016

- 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**

DESY.

The spectrum of NGC 253

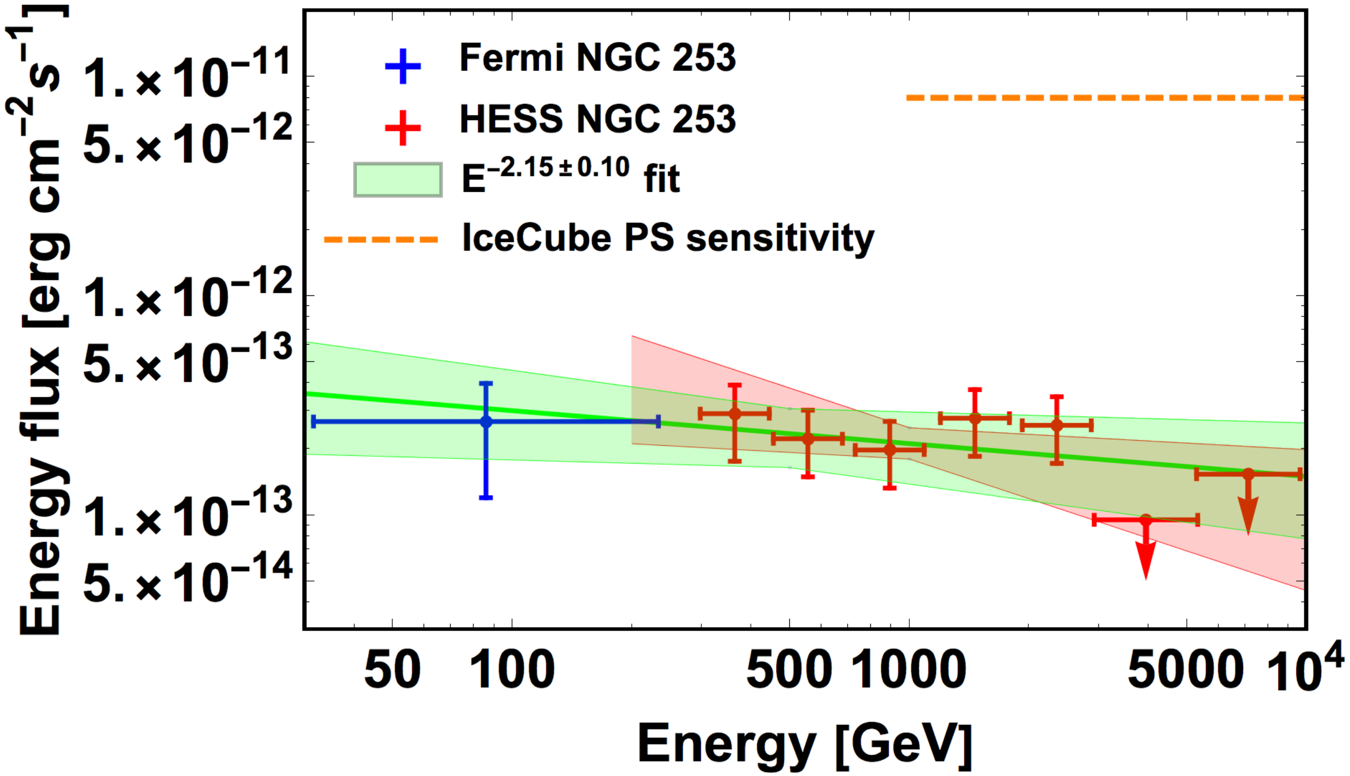


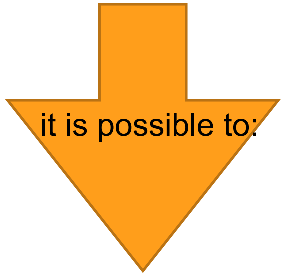
Figure from Palladino et al., arXiv:1812.04685

The NGC 253 is a Starburst Galaxy detected by both Fermi and HESS. It shows a hard spectrum above 100 GeV, the region of interest for the multi-messenger comparison

The multi-messenger result

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 $8 \times 10^5 \ \mathrm{Gpc}^{-3}$



- interpret the throughgoing muon flux
- produce 75%-80% of observed HESE
- explain at least 50% of the low energy neutrino flux in the 10 TeV- 100 TeV energy range

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

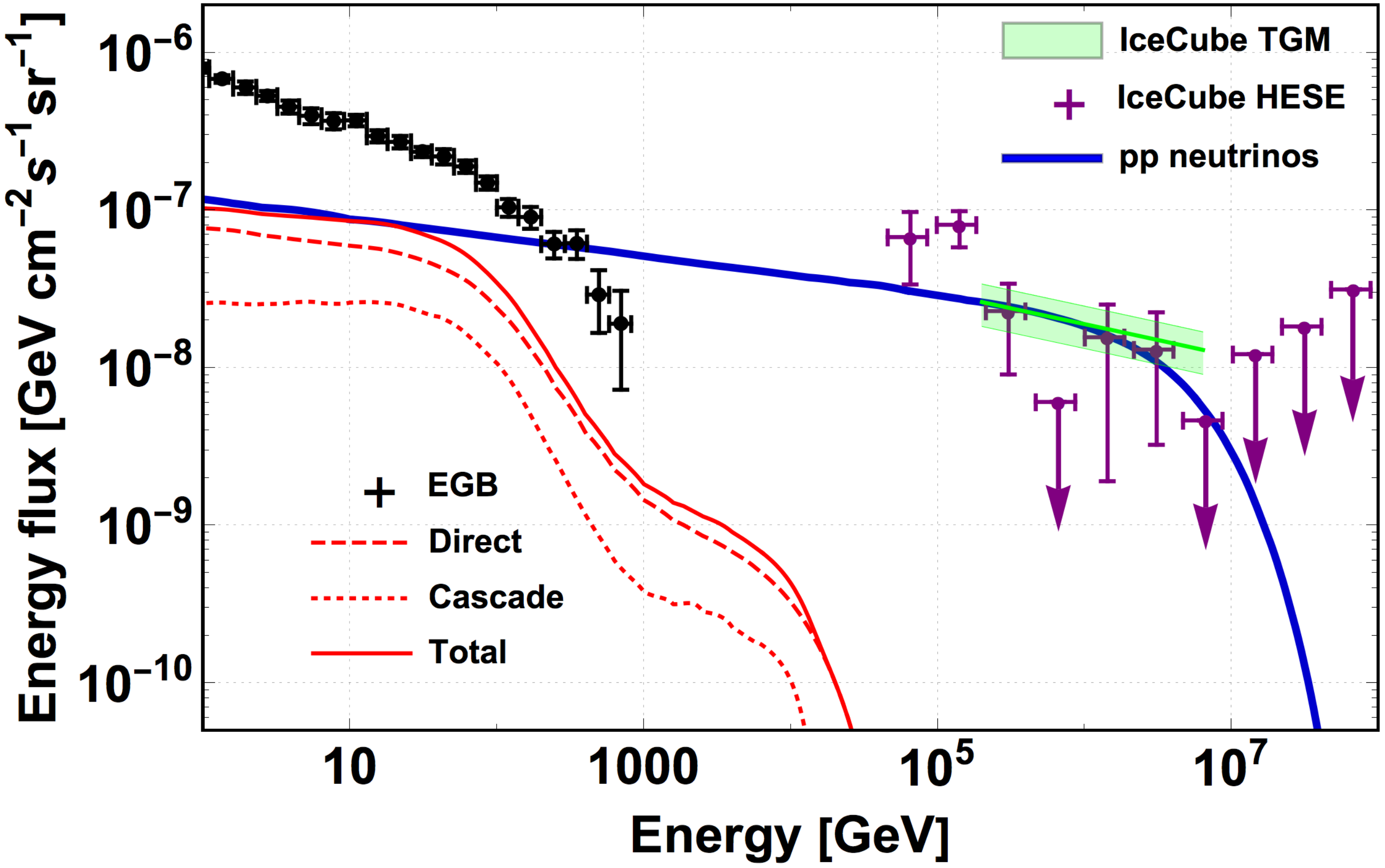


Figure from Palladino et al., arXiv:1812.04685 submitted to JCAP

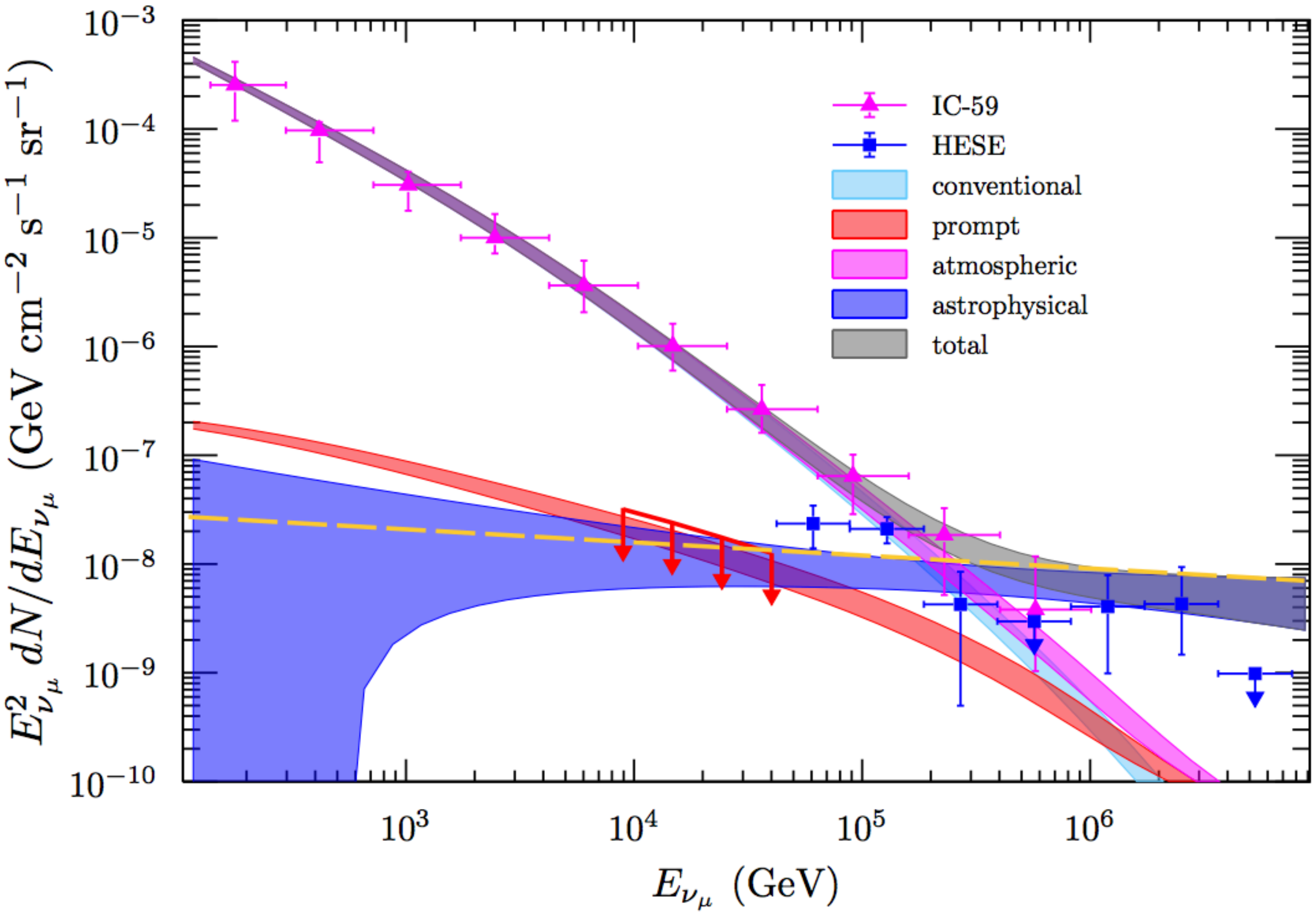
What about lower energies ?

Mascaretti- Vissani, arXiv: 1904.11938

The Authors claim that summing:

- a hard astrophysical spectrum
- prompt neutrinos
- conventional atmospheric neutrinos

the results are in agreement with the IceCube observations at TeV energies



Conclusion

- HESE and thoroughgoing muons indicate different spectral indices
- There is only one confirmed counterpart, the blazar TXS 0506+056
- 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 the throughgoing muon flux, assuming that they are rich of protons
- pp sources (such as Starburst Galaxies) can provide the dominant contribution to astrophysical neutrinos above 100 TeV. Other components are required below this energy