Production mechanisms of high energy neutrinos and multi-messenger connections

Neutrini fotoni e onde gravitazionali:
nuove prospettive per l'astrofisica di alte energie

27.11.2019, Catania (Italy)

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Desy, Zeuthen

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Outline

- Production mechanisms of neutrinos
- The observed flux of high energy neutrinos
- The Blazar TXS 0506+056
- Neutrinos from Blazars and multi-messenger connections
- Neutrinos from Starburst Galaxies and multi-messenger connections

Mechanisms of production of high energy neutrinos

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

$$pp \to \pi^+\pi^-\pi^0\dots$$

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

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

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

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 $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$

The reality is not so trivial (1)

1 neutrino is produced in 2 body decay

2 neutrinos are produced in 3 body decay

This has an impact on the flavor composition, if the proton spectrum is very different from E^{-2}

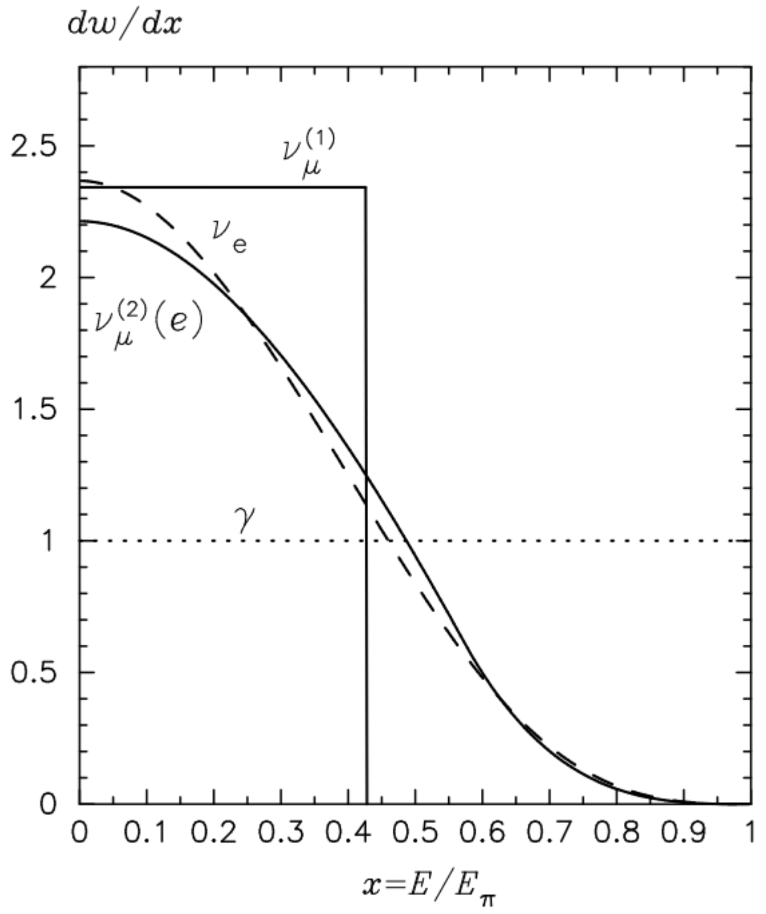


Figure 4: Energy distributions of the secondary products (photons, electrons, muonic and electronic neutrinos) of decays of monoenergetic ultrarelativistic neutral and charged pions. All distributions are normalized, $\int_0^1 dw = 1$.

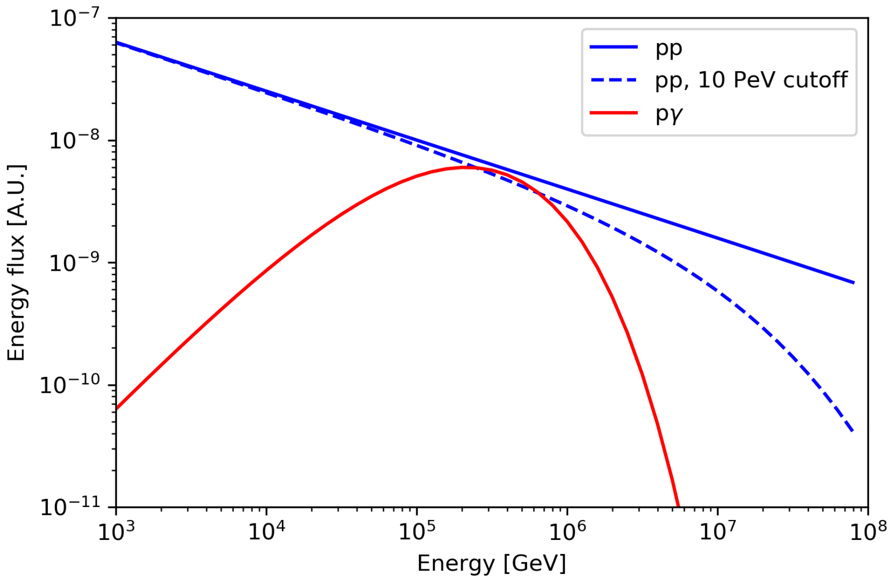
see P. Lipari works on atmospheric neutrinos

From Kelner et al., PRD 2006

The reality is not so trivial (2)

Assuming a power law spectrum for primary protons, the neutrino spectrum will be:

	pp interaction	pgamma interaction
Shape	Power law	Not power law
Cutoff	$\sqrt{E_{cut}^{proton}}$	Depending of the photon spectrum
Energy	$\sim 3/2\ E_{\gamma}^{hadronic}$	$\sim 3/8\ E_{\gamma}^{hadronic}$
Electron antineutrinos	1/6 of the total	0



The **shape** of the spectrum and the **amount of $\bar{\nu}_e$** give important information on the production mechanism

The reality is not so trivial (3)

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

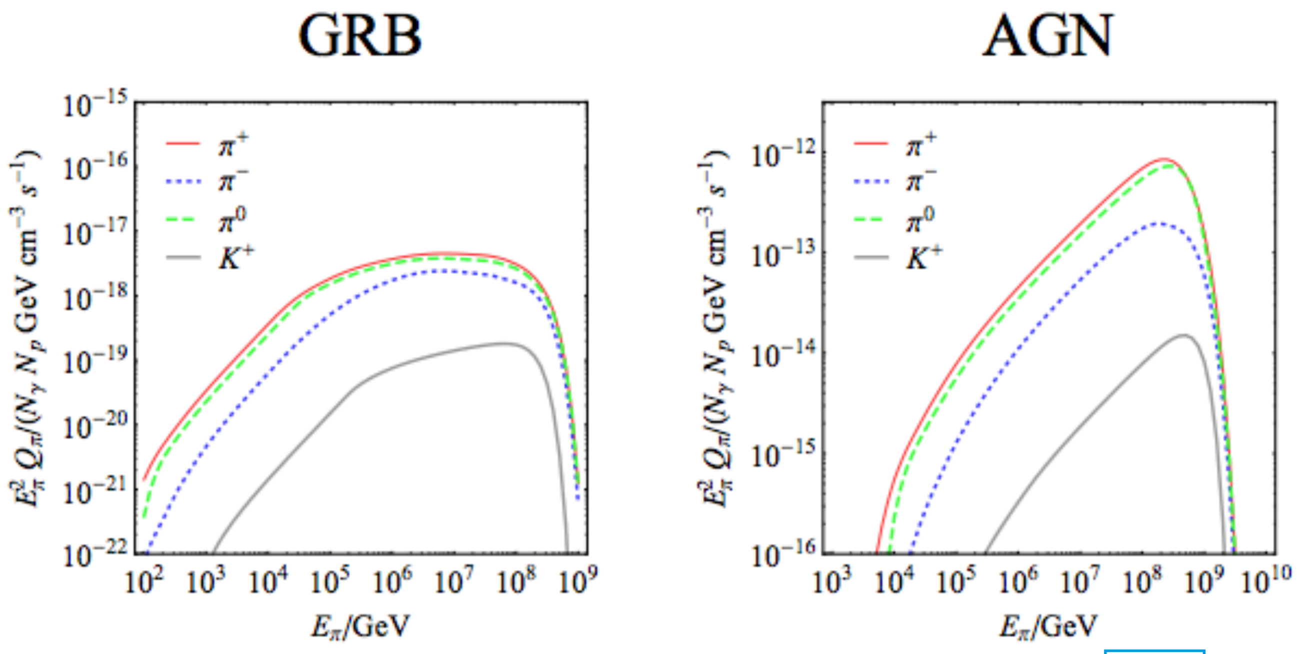
$$\pi^+ \rightarrow e^+\nu_e\nu_\mu\bar{\nu}_\mu$$

$$\pi^0 \rightarrow \gamma\gamma$$

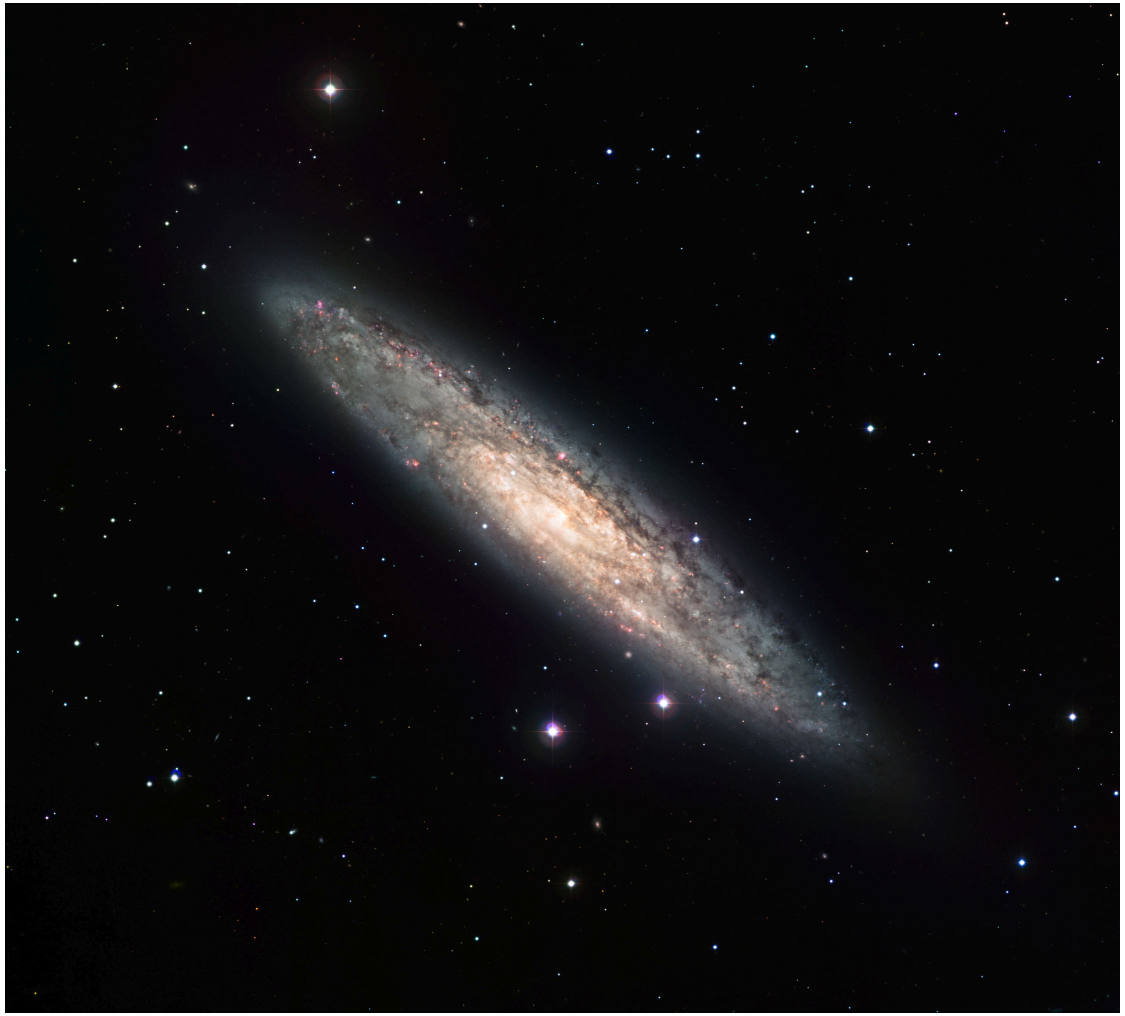
This is an ideal case. A certain amount of negative pions can be produced also in the proton-gamma interaction

Realistic scenarios,
also negative pions are produced

Hummer et al., APJ 2010



proton-proton interaction



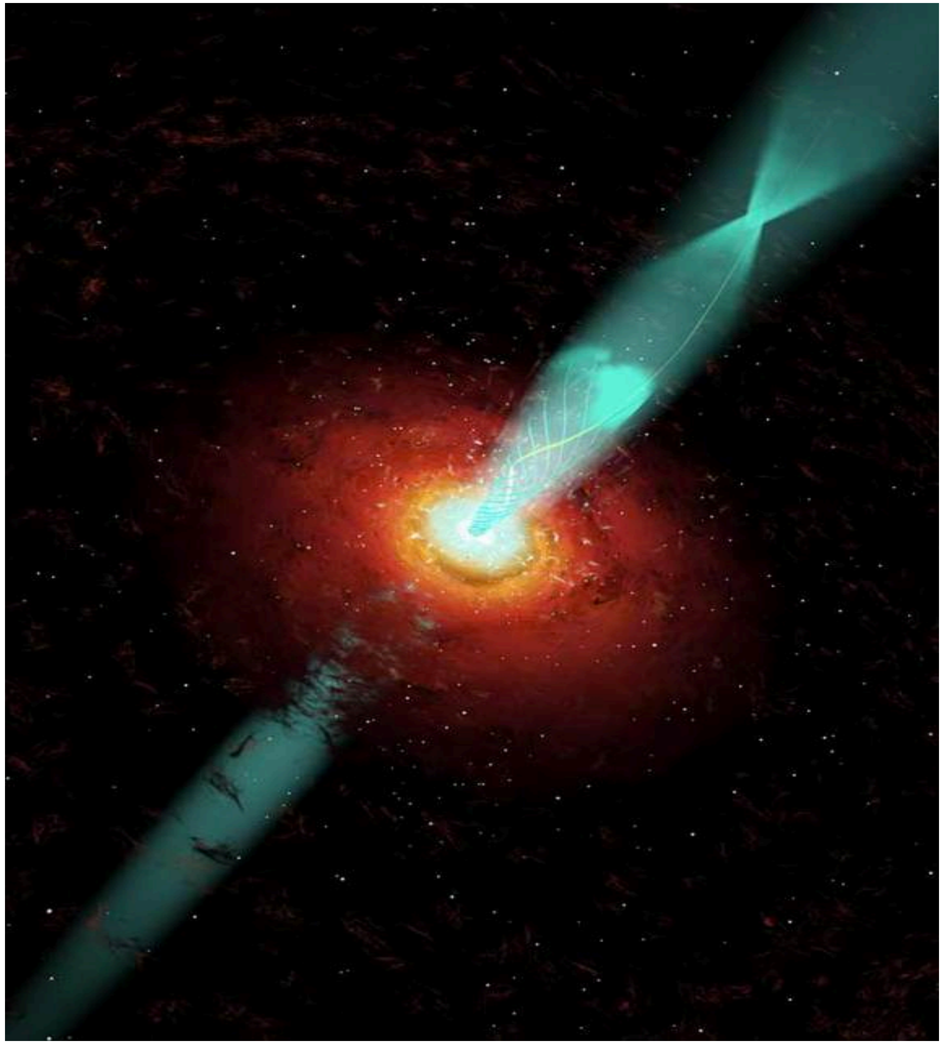
The Starburst Galaxy NGC 253, Credit: ESO Italia

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

Characteristics of a Starburst Galaxy:

- High Star Formation Rate (10-100 times higher than Milky Way)
- They are abundant ($\sim 10^4 - 10^5$ Gpc^{-3})
- Not very brilliant in the $\gamma-$rays band

proton-gamma interaction



Representation of a blazar. Credit: phys.org

pgamma interaction is likely to occur when *Density of radiation higher than density of gas* (for example in Blazars)

A Blazar is an Active Galactic Nuclei (AGN) with the emitted jet pointing to Earth

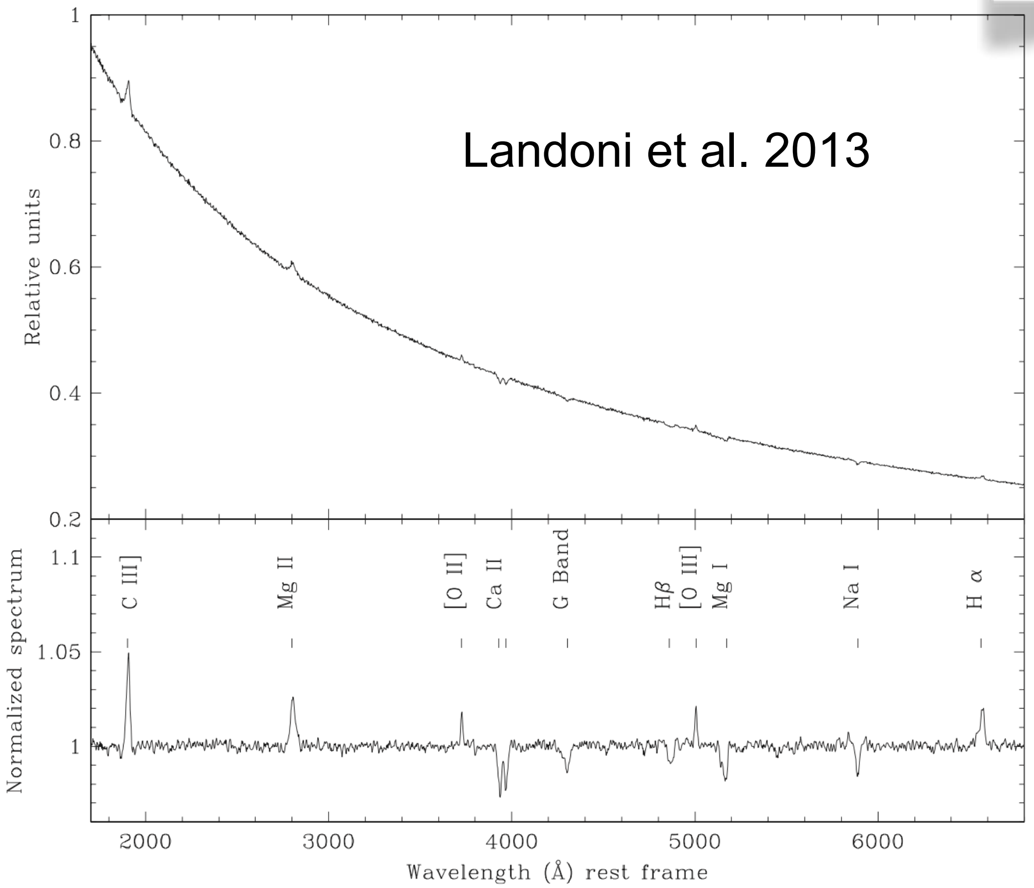
Characteristics of a Blazars:

- Not abundant sources
  (~ 10 Gpc^{-3} for $10^{45} L_\gamma < 10^{46}$ erg/s)
- Very brilliant in the $\gamma-$ray band
- 80% of the Extragalactic Gamma-ray Background (EGB) above 50 GeV is provided by Blazars

Two types of Blazars

BL Lac = BL Lacertae

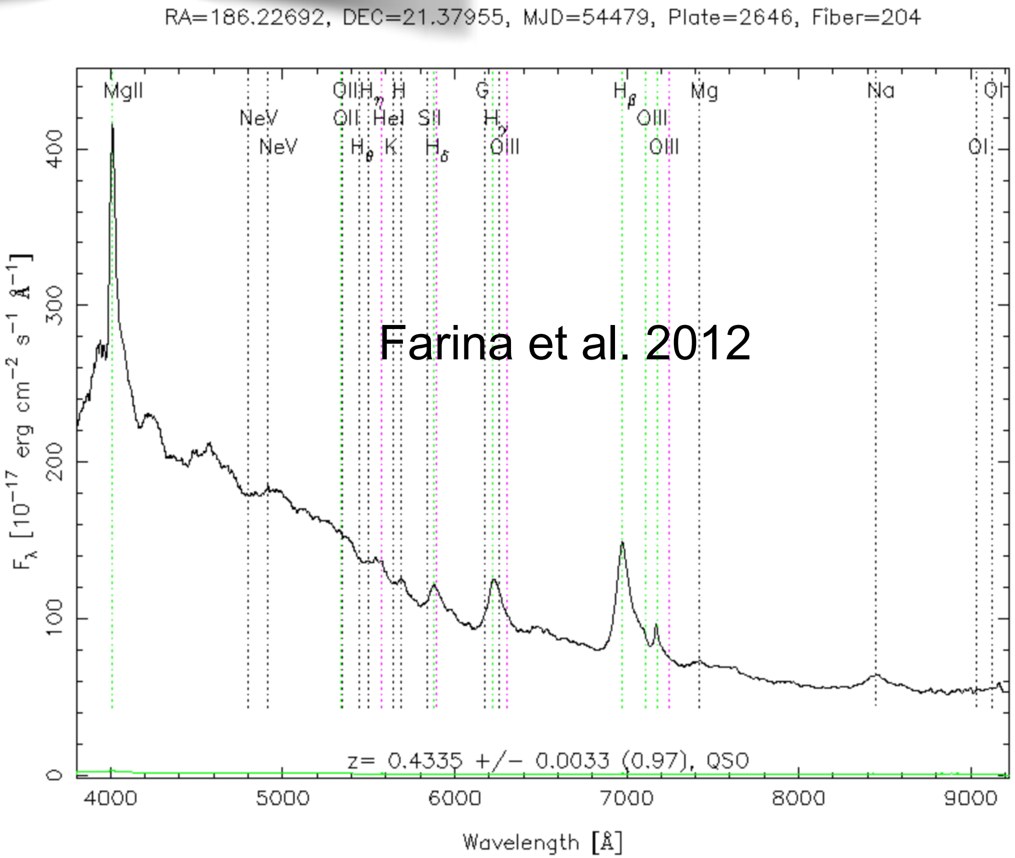
- typically the less luminous blazars
- featureless optical spectrum



FSRQ = Flat Spectrum Radio Quasars

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

See Fabrizio Tavecchio talk



The observed flux 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

For comparison the Thomson cross section is 6.65×10^{-25} *cm*^{2}

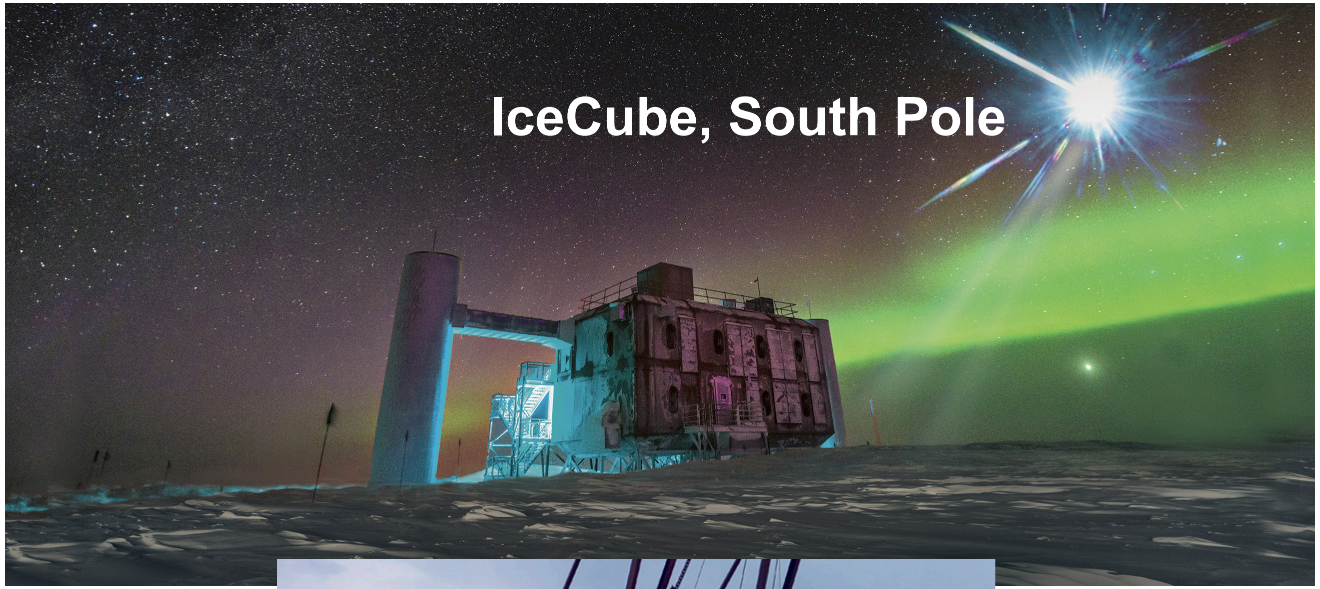
— Astrophysical neutrinos can be detected only using huge detectors

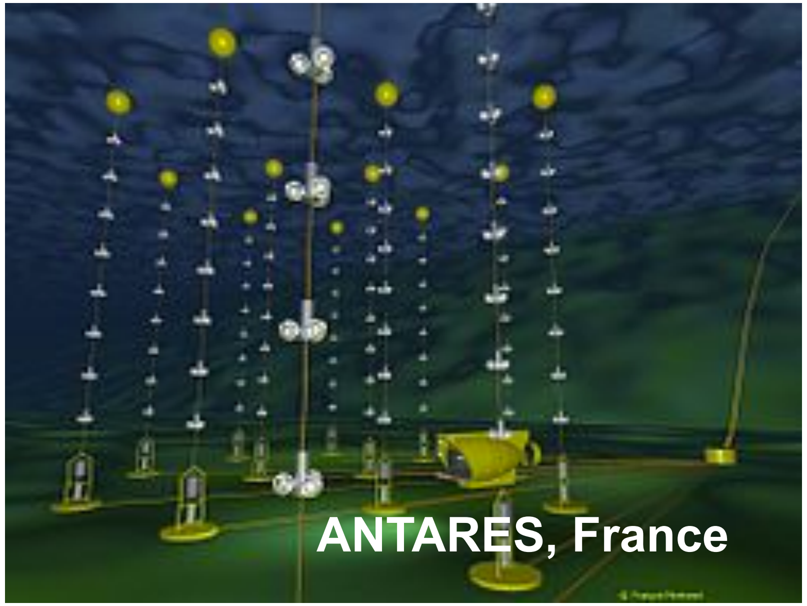
With a 1 km^3 detector less than 10 astrophysical events above 100 TeV per year are expected

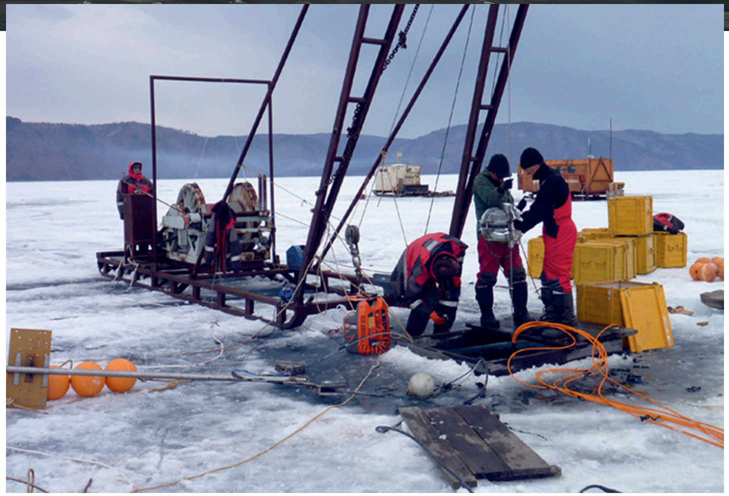
Neutrino telescopes

See the talk of Luigi Fusco

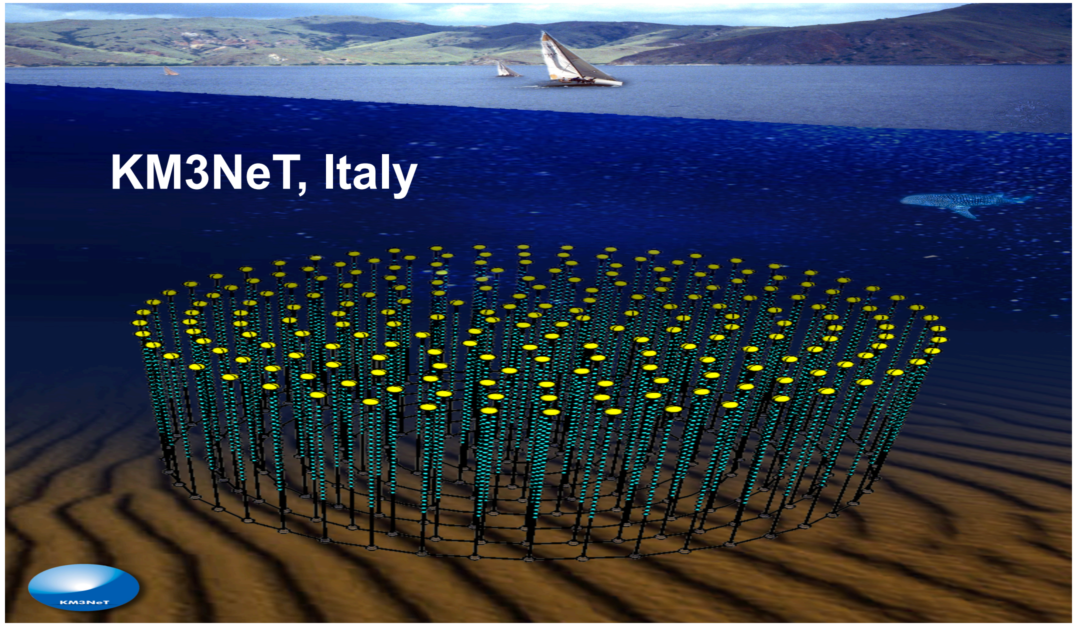
Different neutrino telescopes are operating nowadays







Baikal GVD, Siberia



HESE and Throughgoing muons

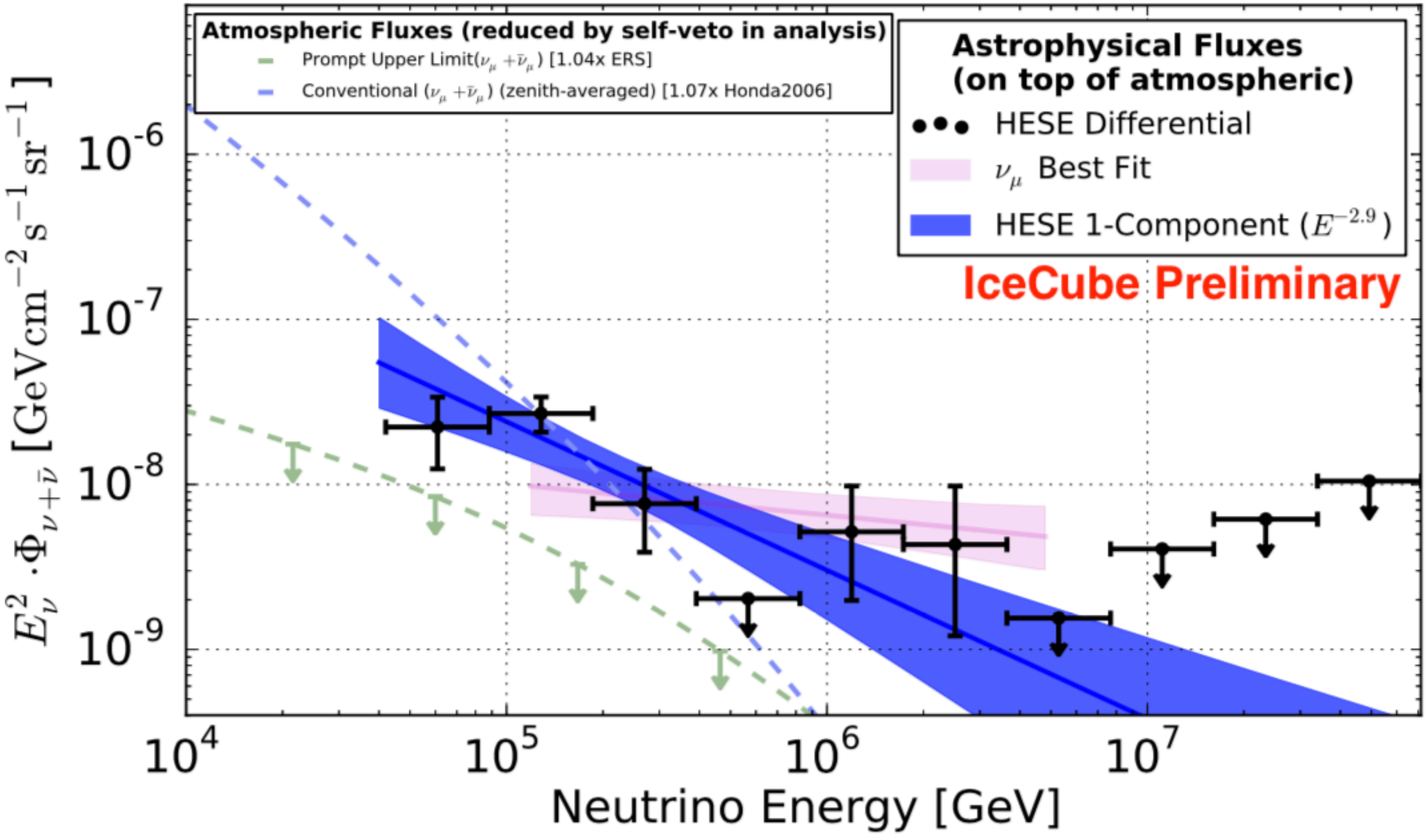


Figure from IceCube, ICRC 2017

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

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

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

See Elisa Bernardini talk
for more details

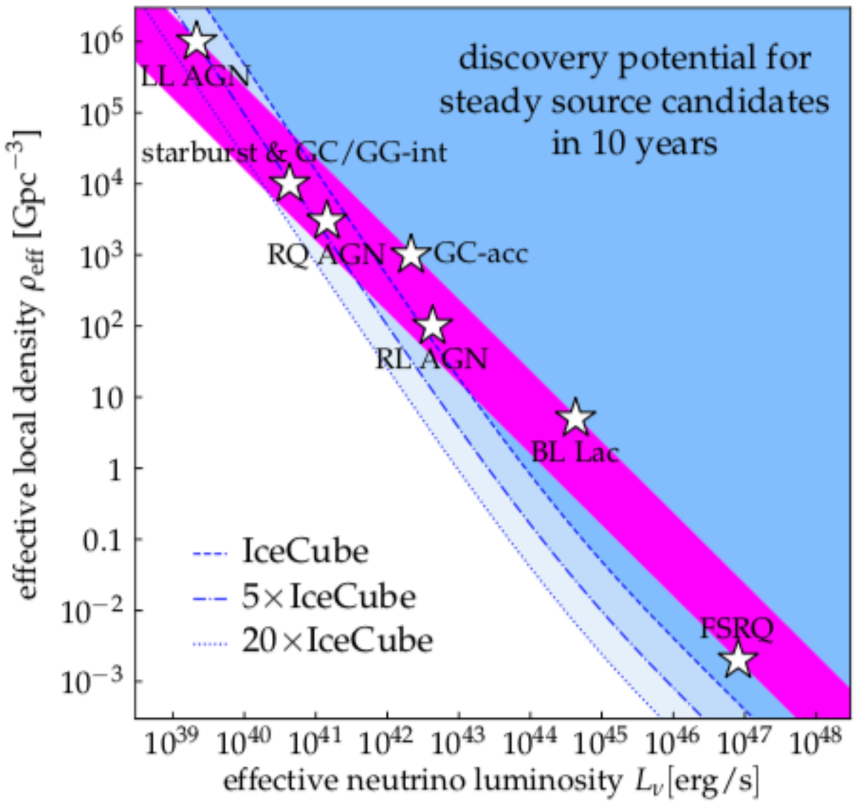
Is there any tension ?

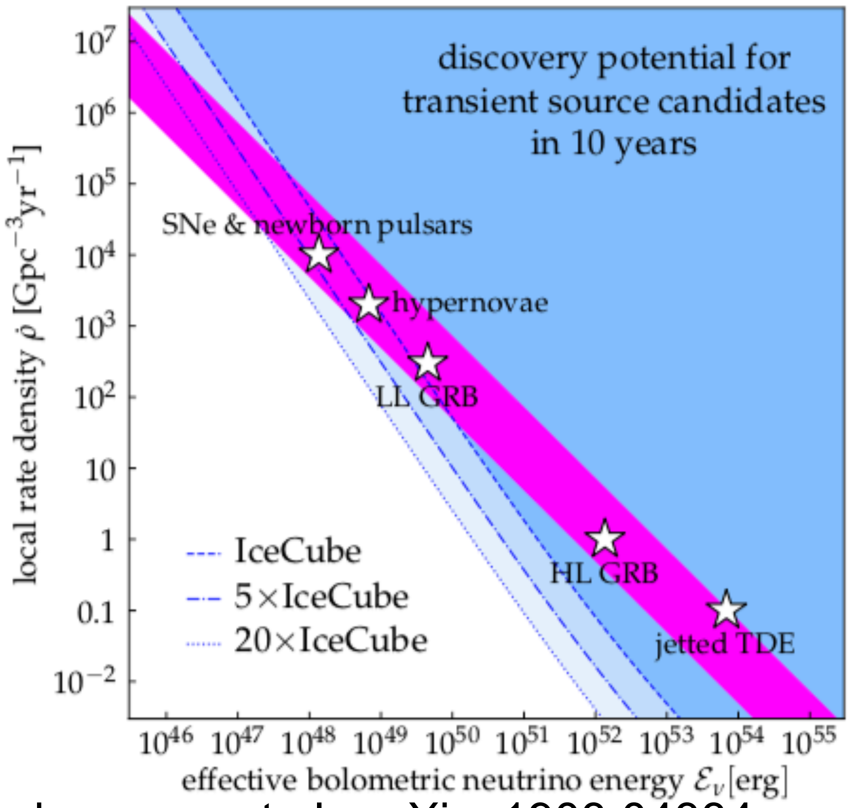
HESE
- mostly showers
- mostly from the Southern hemisphere
- above 30 TeV

THROUGHGOING MUONS
- only tracks
- only from the Northern hemisphere
- above 200 TeV

There is $\sim 3\sigma$ of tension between the measured spectral indices.
However **different hemisphere** are observed and **different energy threshold** are used

What about the origin ?





Ackermann et al., arXiv: 1903.04334

- **The absence of multiplets in neutrino data favors abundant and faint sources**
- **Up to now only 1 neutrino has a (confirmed ?) counterpart, the Blazar TXS 0506+056**

The Blazar TXS 0506+056

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*†

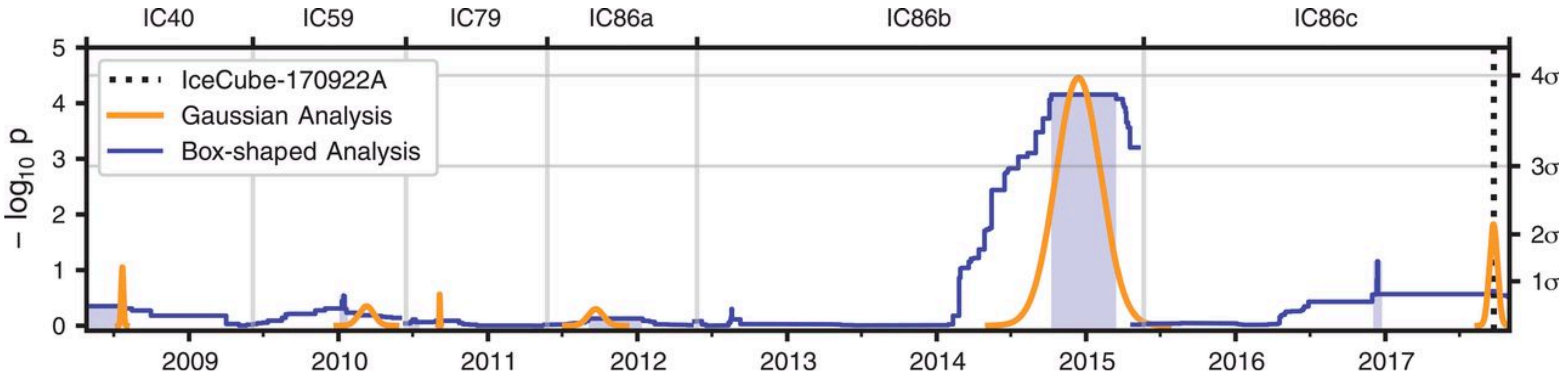
INTRODUCTION: Neutrinos are tracers of cosmic-ray acceleration: electrically neutral and traveling at nearly the speed of light, they can escape the densest environments and may be traced back to their source of origin. High-energy neutrinos are expected to be produced in blazars: intense extragalactic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

The two flares

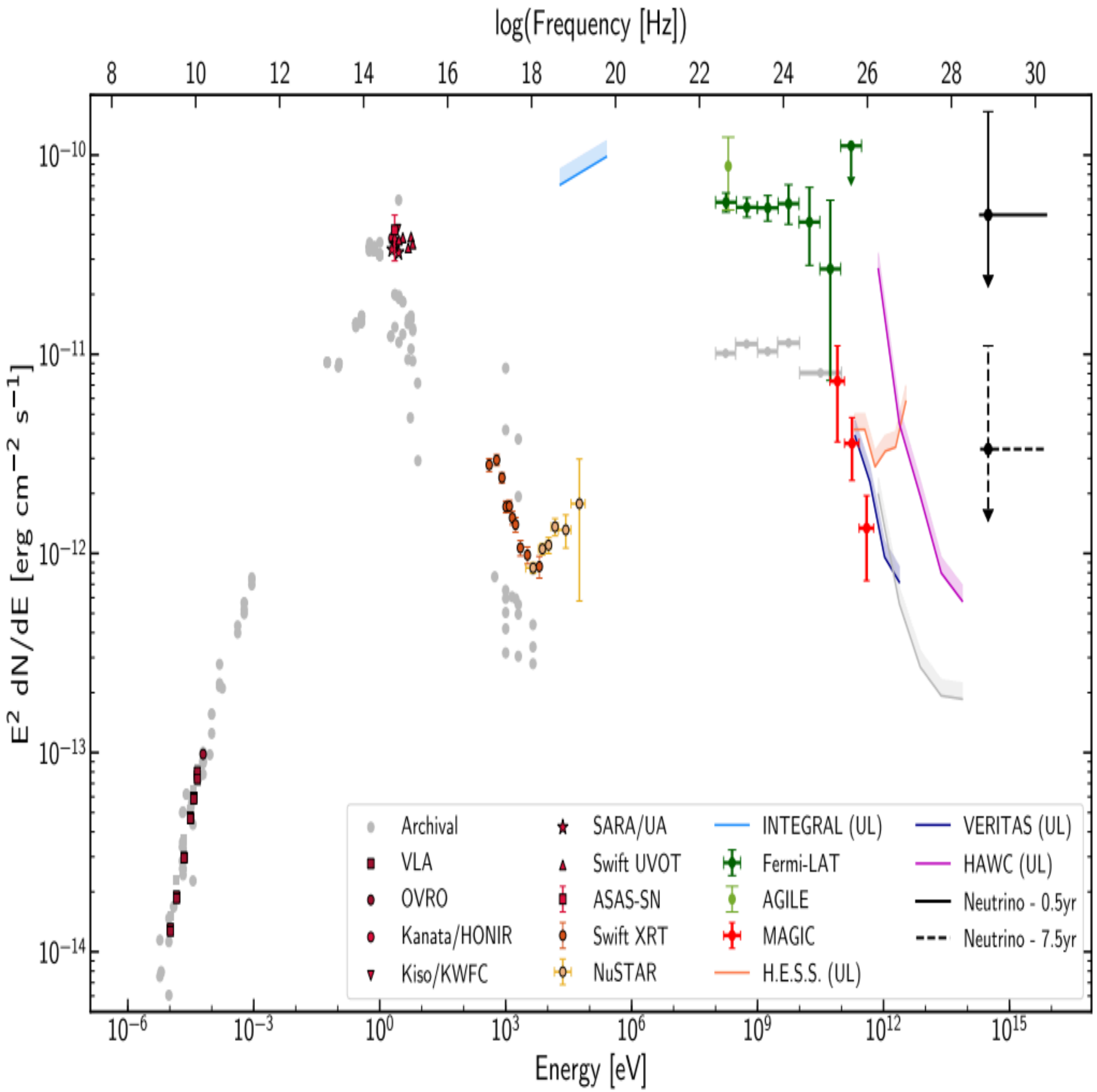


1 Neutrino with associated gamma-ray flare, in September 2017, **IceCube Science 2018**

13 ± 5 signal neutrinos (without gamma-rays) in 2014-2015, **IceCube Science 2018**

Characteristics of TXS 0506+056 and of the 2017 flare

- is a BL Lac for most of the community
- is an FSRQ for **Padovani et al. MNRAS 2018**
- is located at z = 0.3365
- $< L_\gamma > = 2.8 \times 10^{46}$ erg/s
- $L_\gamma^{flare} = 1.3 \times 10^{47}$ erg/s
- Muon track energy 23.7±2.8 TeV
- Most probable neutrino energy 290 TeV
- Significance: 3.5 sigma



IceCube, Science 2018

Interpretation of the 2017

After the IceCube science paper, tens of theoretical papers have been written

Paper with 10+ citations

Sahakyan, APJ 2018
Reimer et al, arXiv:1812.05654
Gao et al., Nature Astronomy 2019
Halzen et al, APJ 2019
Cerrutti et al., MNRAS 2019
Keivani et al., APJ 2019
Rodrigues, Palladino et al., APJ 2019
Padovani et al., MNRAS 2019

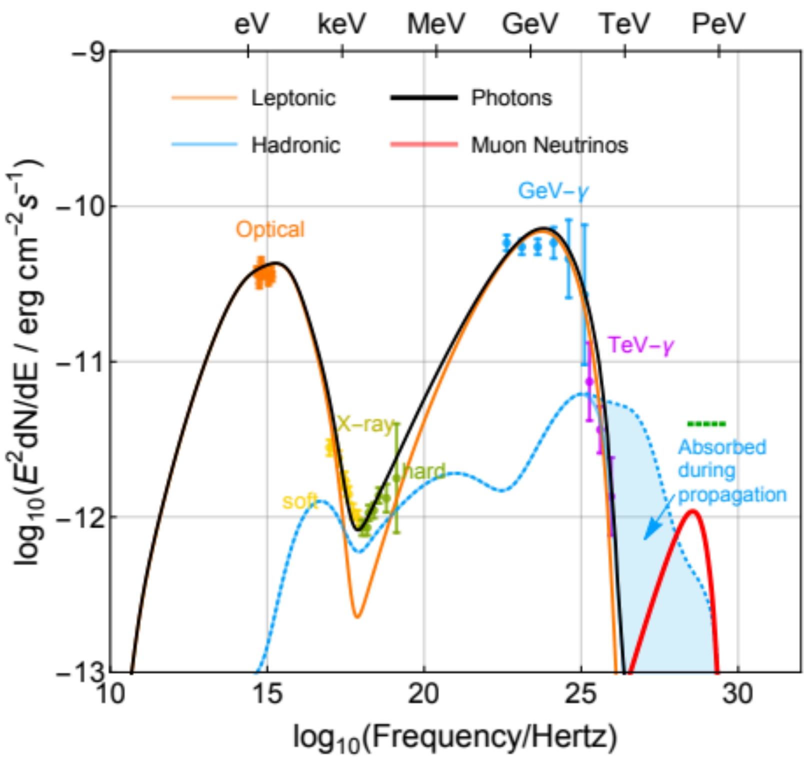


Figure 3: **Energy flux from TXS0506+056 across the electromagnetic spectrum and for neutrinos.** Here the energy spectrum is modeled in our hybrid scenario with both leptonic and hadronic contributions. High-energy photons are absorbed during propagation by extragalactic background light, here indicated by the blue shaded region and modeled as in (*13*). Data points reflect the observed flux and spectrum during the flare (*2*). The dashed horizontal green line corresponds to the expected level and energy range of the incident neutrino flux to produce one muon neutrino in IceCube in 180 days.

The Gao et al. is a lepto-hadronic model that predicts 0.27 muon neutrinos per year above 120 TeV.

The Eddington bias

Strotijohann et al, A&A 2019

We observed in September 2017 1 neutrino from TXS 0506+056. Is it TXS 0506+056 a special source ?

YES

- The TXS 0506+056 is very efficient in neutrino production
- During the flaring state, we expect 1 neutrino per year
- The contribution from other BL Lacs is negligible

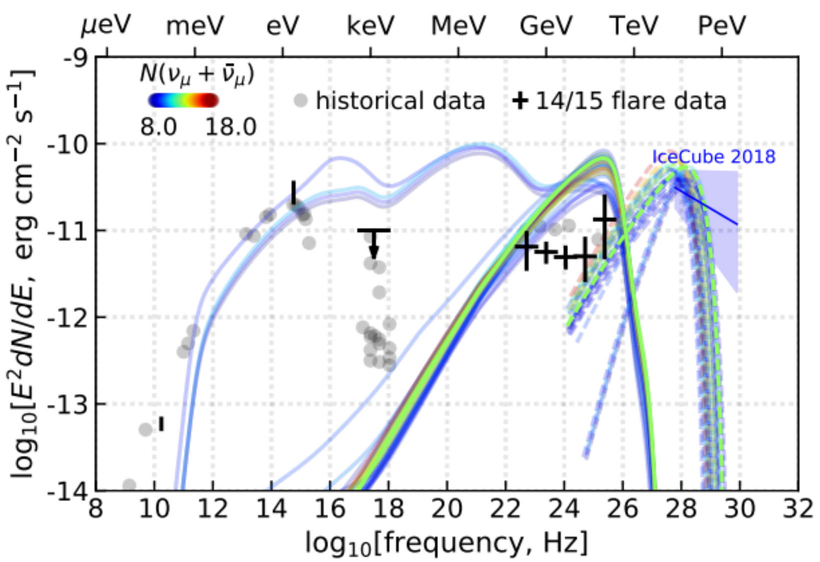
NO

- There are hundred of unresolved blazars (N_s) contributing to the neutrino flux
- The expected number of neutrinos is very small, at level of $1/N_s$
- We observe 1 neutrino from TXS 0506+056 by chance

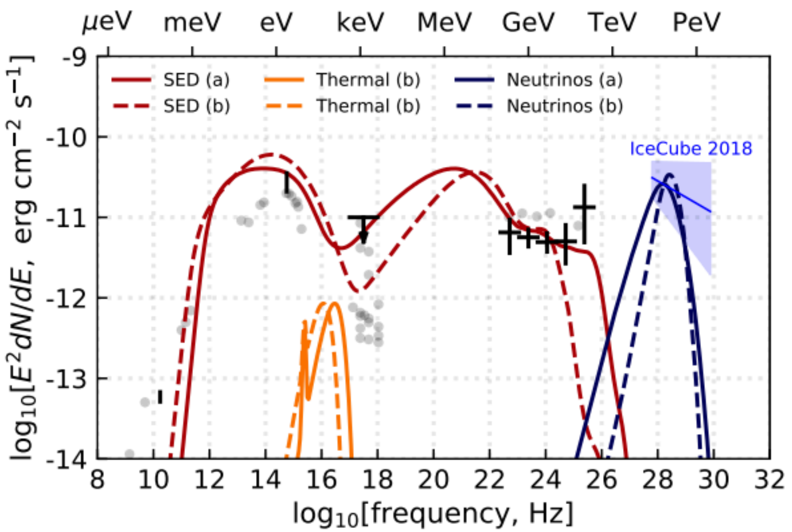
Take home message: the 2017 flare can be explained with several theoretical models

The 2014-2015 flare

13 ± 5 signal events, with no gamma-ray flare associated



- The flux of neutrinos is well measured (not just 1 event)
- The flux of neutrinos is high, requiring a high associated gamma-ray flux from π^o decay (upper panel)
- The flux of gamma-rays constrains the flux of astrophysical neutrinos (lower panel)



We obtain roughly 5 events in the most optimistic case

Take home messages:
- the 2014-15 flare is hard to explain
- The two flares cannot be explain by the same mechanism

Figures from Rodrigues, Palladino et al., APJ 2019

Neutrinos from Blazars and multi-messenger connections

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

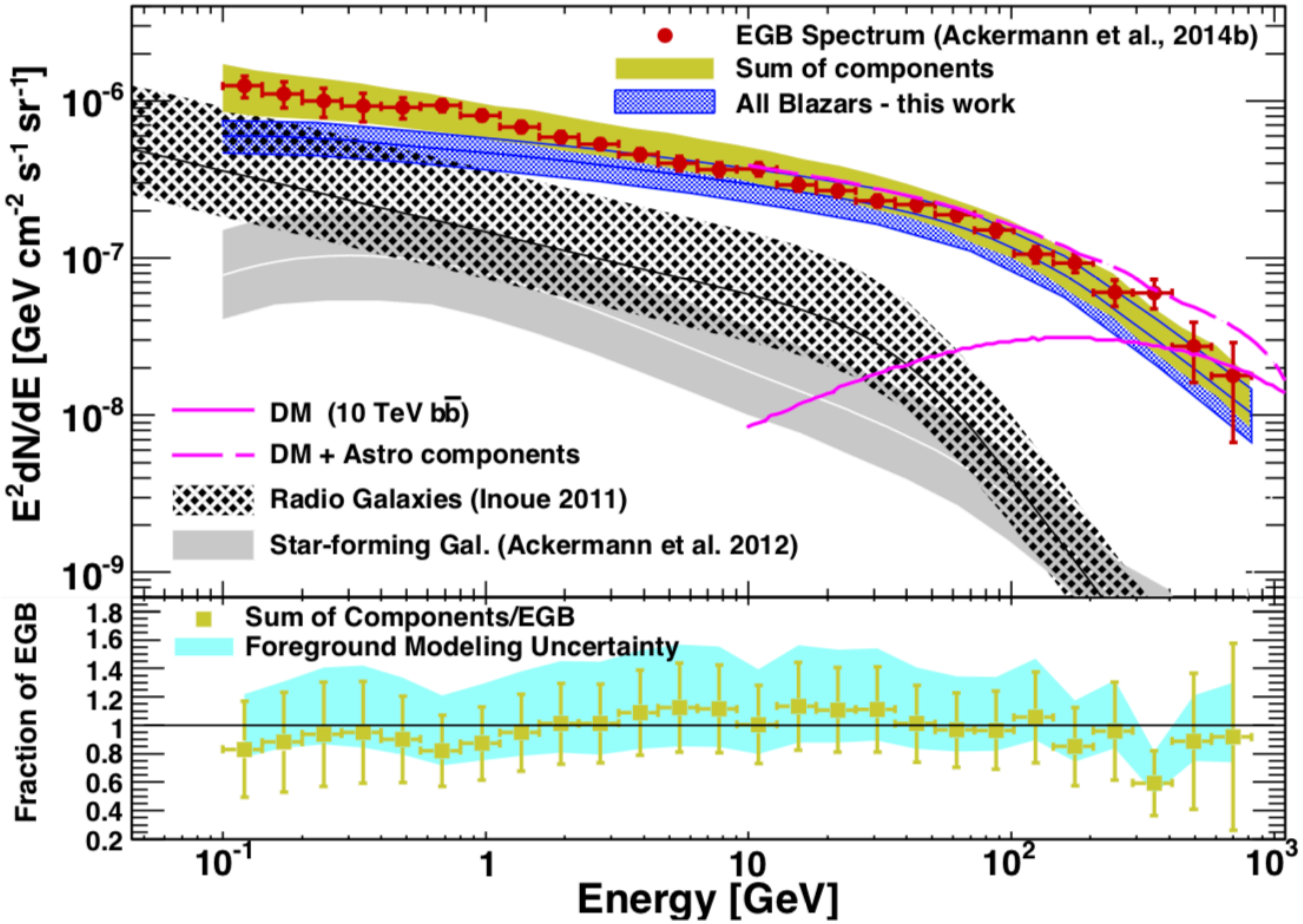


Figure from Ajello et al., APJ 2015

Why are blazars disfavored as neutrino emitters ?

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

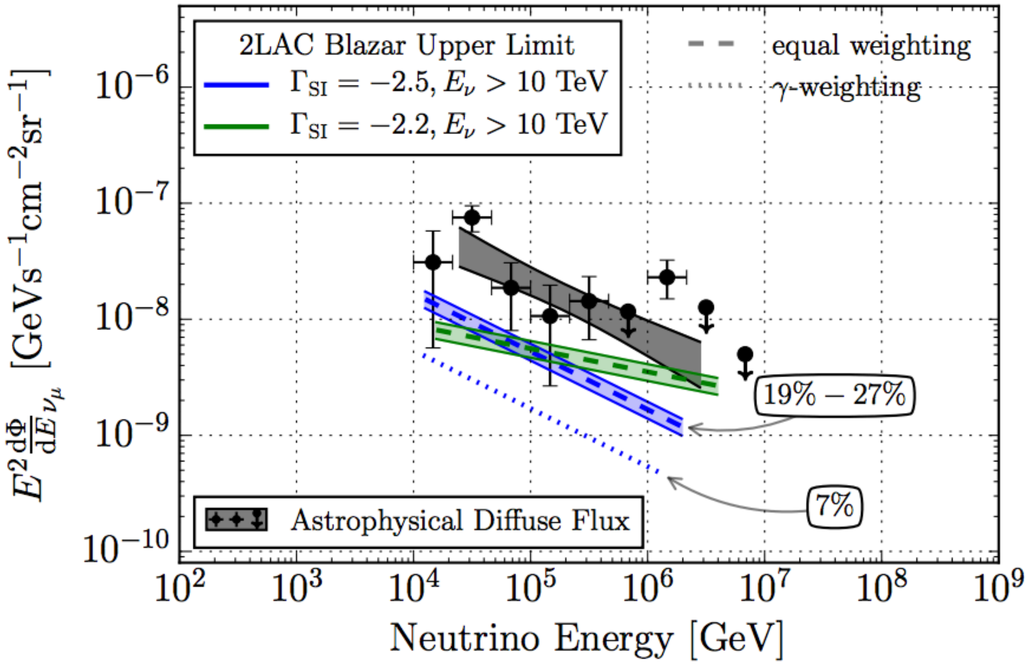


Figure from IceCube, APJ 2017

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

Cosmic evolution of blazars

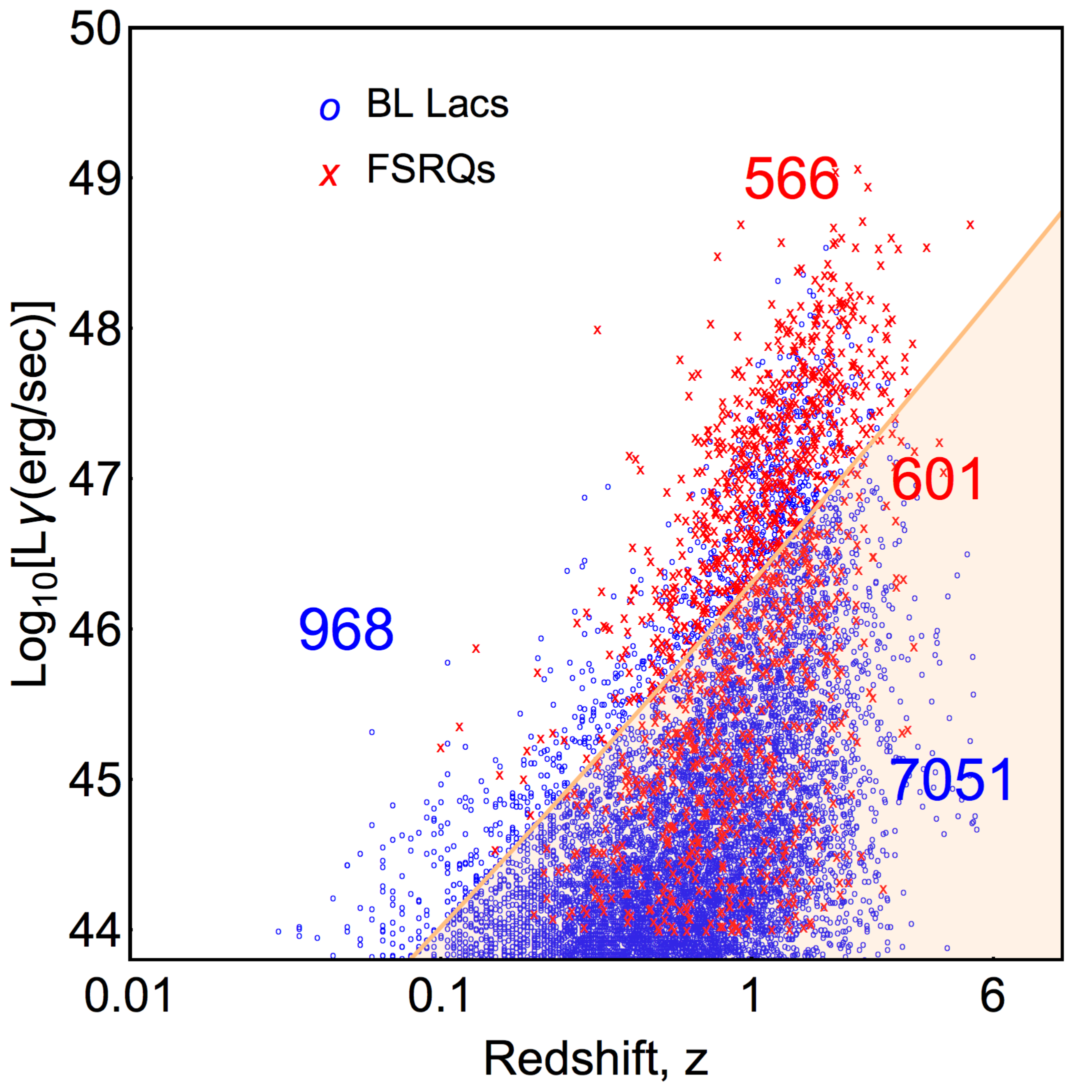


Figure from Palladino et al., APJ 2019

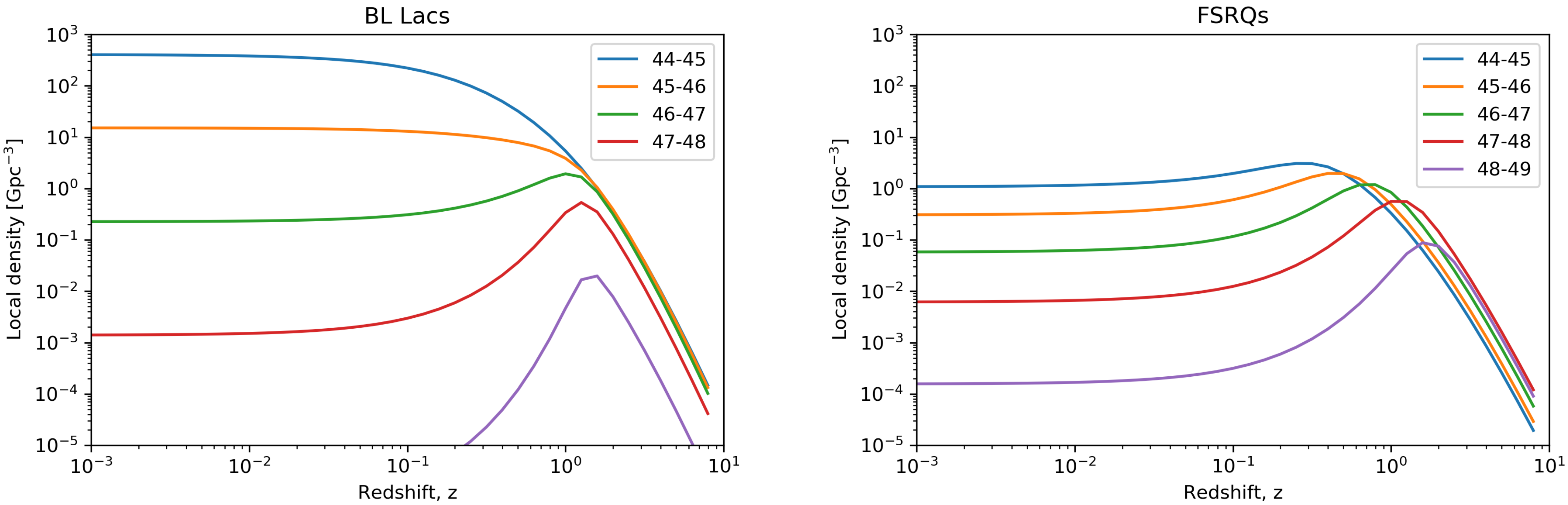
BL Lacs and FSRQs obtained using the cosmic evolution provided in:

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

There thousands of unresolved BL Lacs, expected from the theoretical distribution

DESY.

Source evolutions

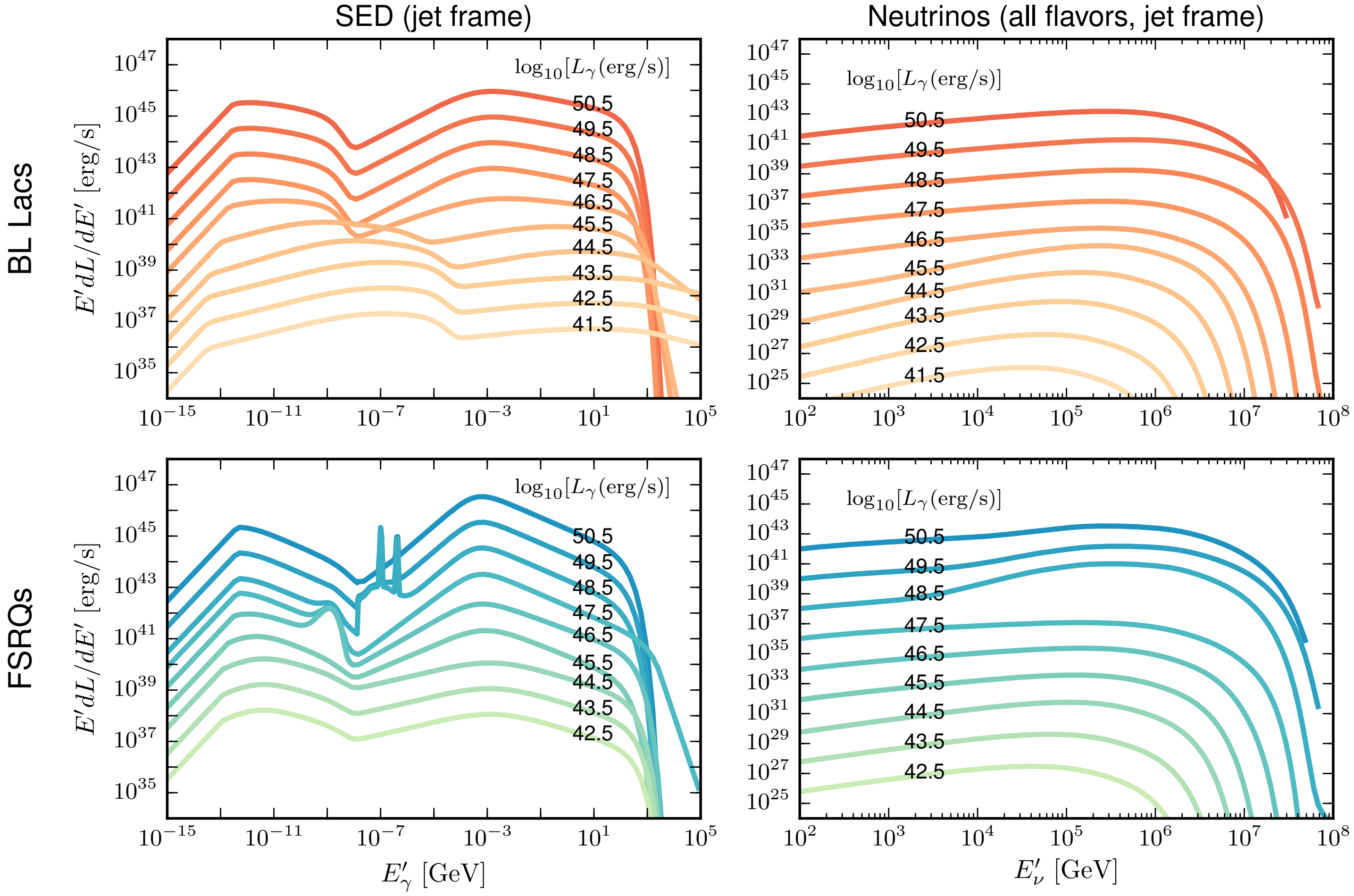


High luminosity objects have positive evolution

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

Neutrino spectra from blazars

Figure from Palladino et al., APJ 2019



Blazar sequence
Ghisellini et al., Mon.Not.Roy.Astron.Soc. 469 (2017)

The peak of the neutrino spectrum moves to higher energy with the increasing of the luminosity of the object.

In Palladino et al., APJ 2019 we use an acceleration efficiency of 1% of the maximum possible efficiency. UHECR-neutrinos are not connected

See Fabrizio Tavecchio talk for AGN emission

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

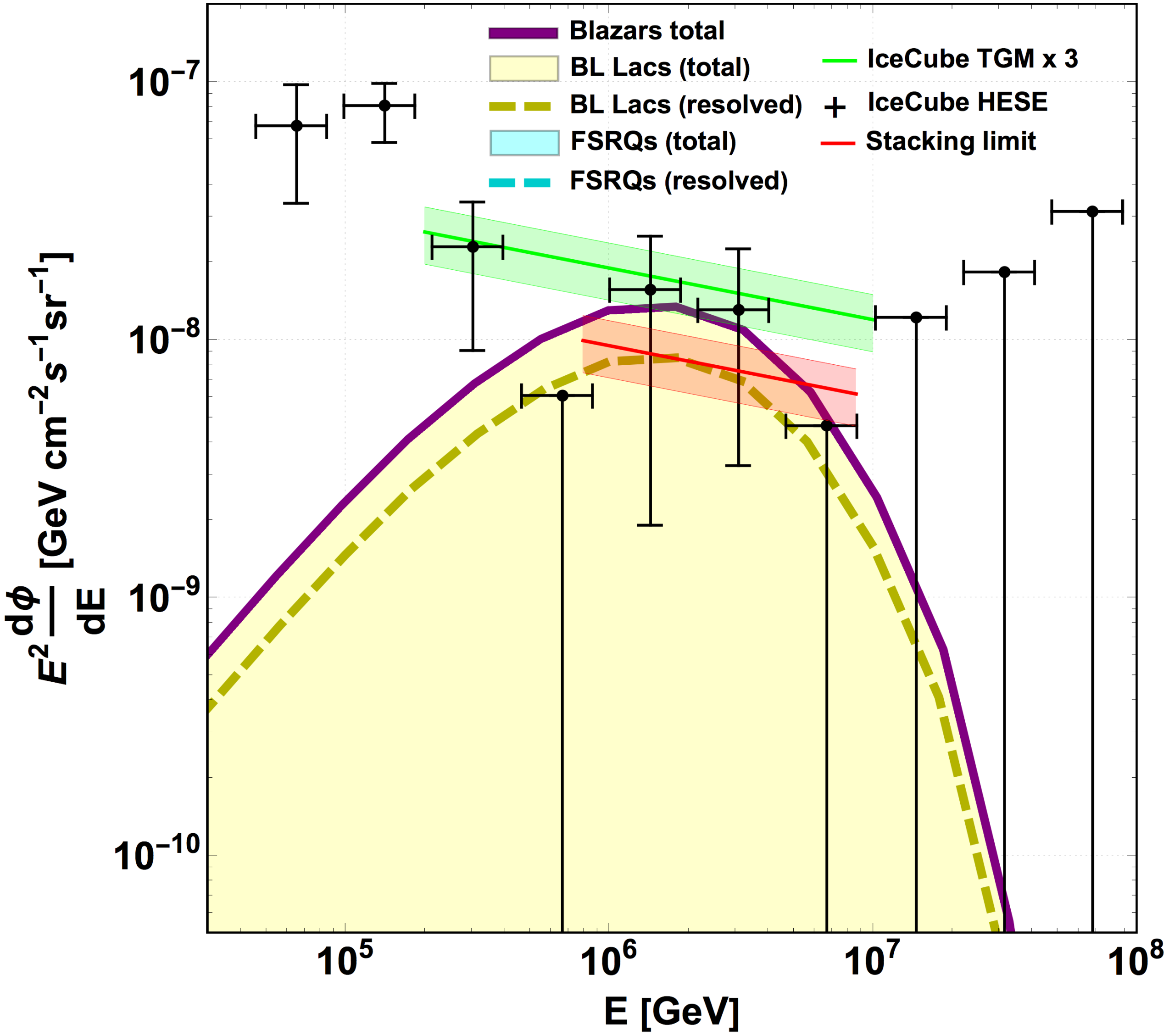


Figure from Palladino et al., APJ 2019

Continuous function for the baryonic loading

The baryonic loading changes roughly as follows:

- at low luminosity we replicate $L_\nu \simeq 10\,\%\,L_\gamma$
- at high luminosity we use the upper limit $L_\nu \leq 0.5\,\%$

- at the TXS flaring luminosity we use the baryonic loading estimated in Gao et al. arXiv:1807.04275

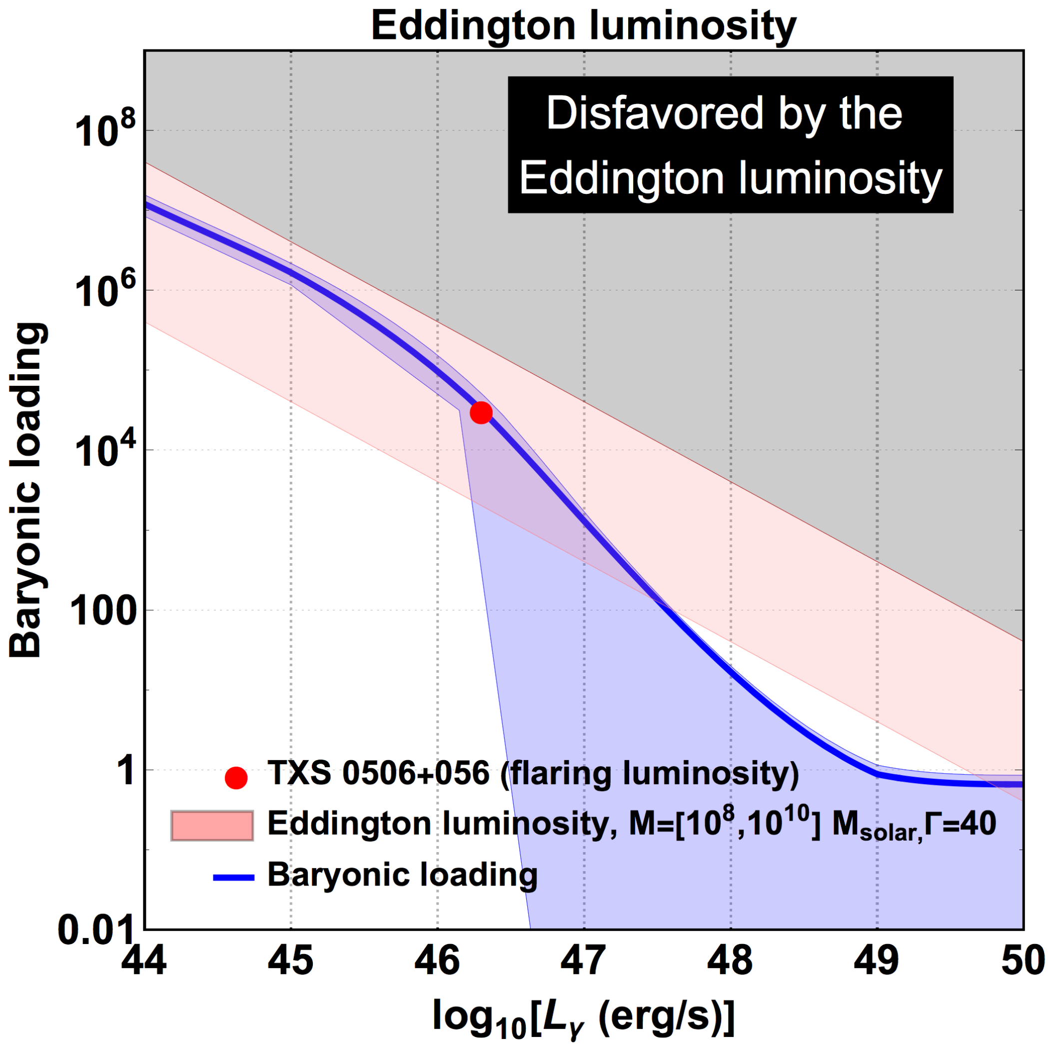


Figure from Palladino et al., APJ 2019

Efficiency of neutrino production

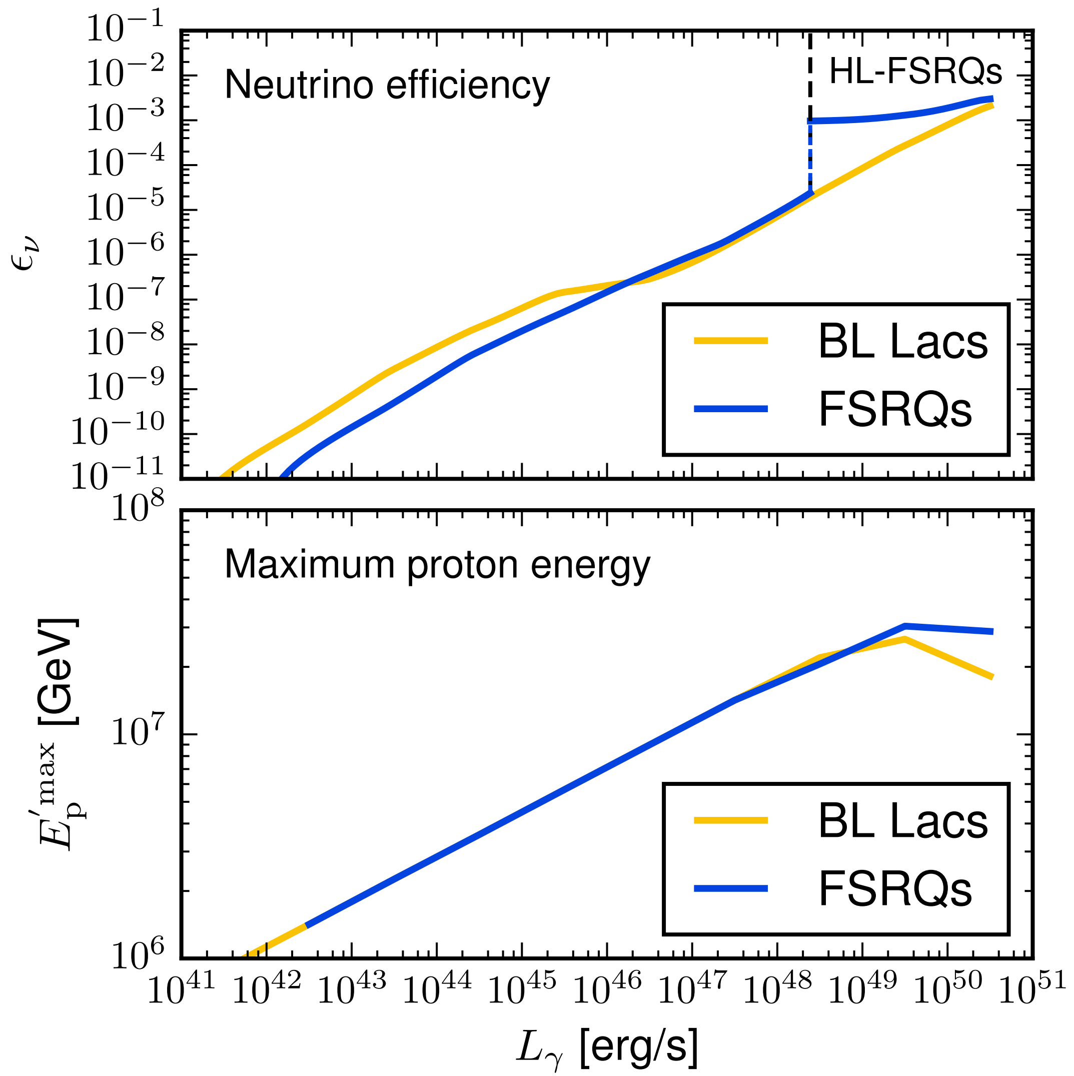
Figure from Palladino et al., APJ 2019

Neutrino efficiencies in terms of $\xi_\nu = \frac{L_\nu}{L_{cr}}$

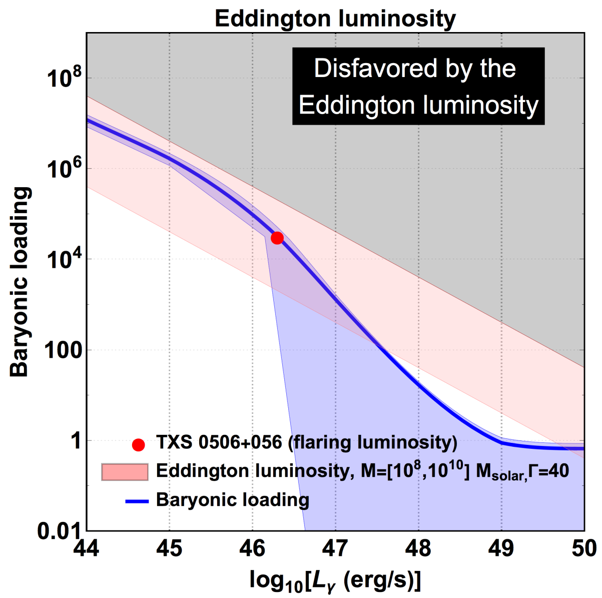
- High luminosity objects are efficient in neutrino production, while low luminosity objects are not efficient
- The jump in the efficiency of FSRQs is due to the interaction of the jet with the external photon field, when

$$L_\gamma > 3 \times 10^{48} \text{ erg/s}$$

Is the baryonic loading the same for all sources ?
Does it change as a function of luminosity ?



The neutrino luminosity



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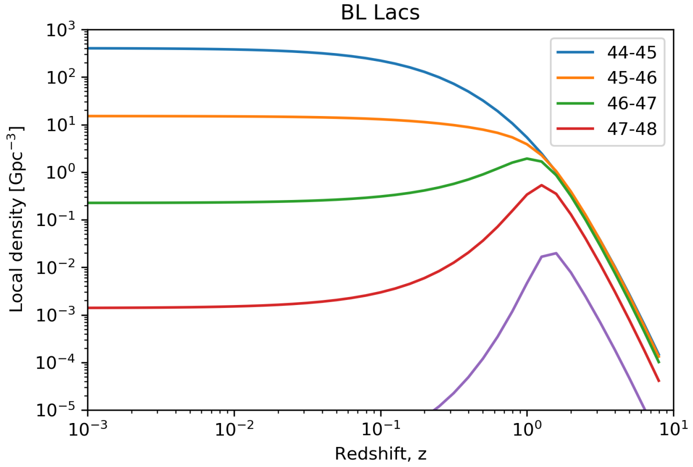

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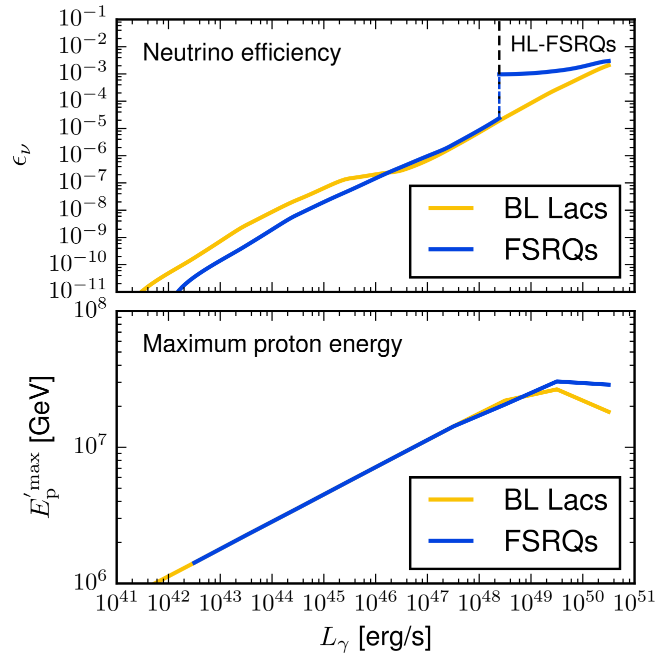


$$\frac{L_p}{L_\gamma} \times L_\gamma \times \frac{L_\nu}{L_p}$$

DESY.

Blazar and Multicomponent model

In ***Palladino-Winter A&A 2018*** a multi-component model for the high energy neutrinos interpretation has been discussed.

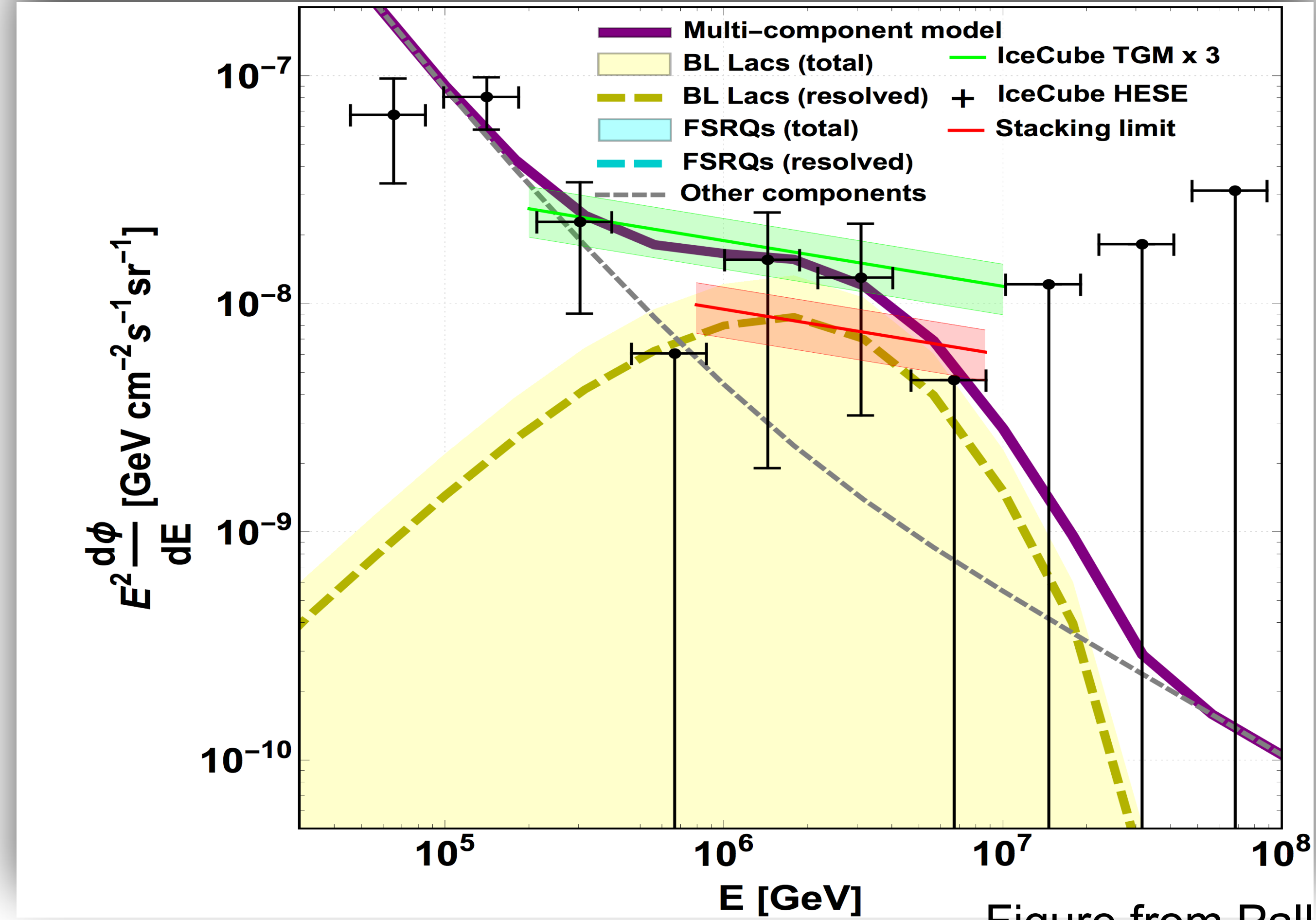


Figure from Palladino et al., APJ 2019

At lower energies the flux may be dominated by:

i) a residual atmospheric component;

ii) a Galactic component, especially seen from the Southern hemisphere;

Comparison with a recent work

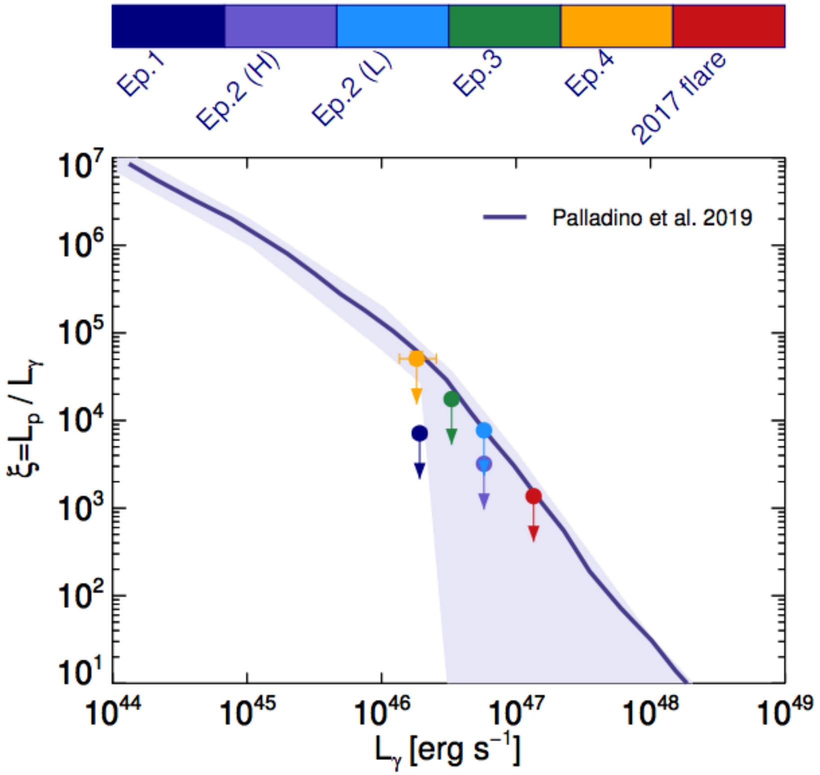


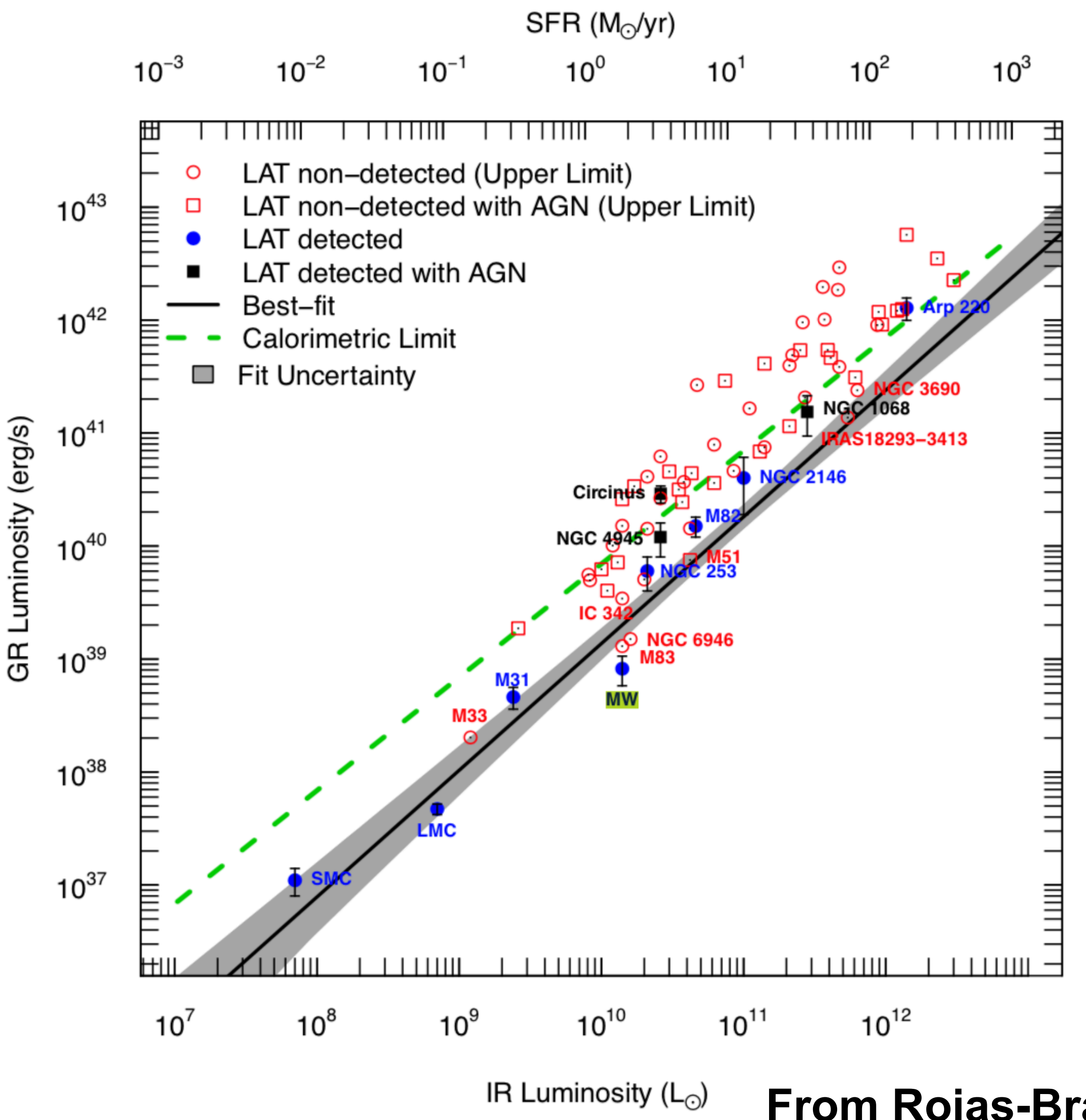
Figure 6. Maximal baryon loading factor ξ of TXS 0506+056 (filled symbols with arrows) as a function of the *Fermi*-LAT (0.1–300 GeV) gamma-ray luminosity for different epochs (see colorbar). For comparison, we show the baryon loading factor (solid blue line) with its uncertainty (shaded region) obtained from a model for the diffuse astrophysical neutrino flux at energies $\gtrsim 1$ PeV from blazars (see scenario 3 in Palladino et al. 2019).

In Petropoulou et al. arXiv:1911.04010 the baryonic loading of TXS 0506+056 in multi-epoch is computed

- Petropoulou et al. is focused on the TXS 0506+056
- Palladino et al. 2019 is focused on the entire blazar population
- However there is a very good agreement between the estimated baryonic loadings

Neutrinos from Starburst Galaxies and multi-messenger connections

Starburst Galaxies



From Rojas-Bravo and Araya, MNRAS 2016

Typical $\gamma-$ray luminosity:

$$10^{39} < L_\gamma < 10^{42} \text{ erg/s}$$

- Starburst Galaxies are easier to observe in the infrared band
- The infrared luminosity and the $\gamma-$ray luminosity seems to be connected

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

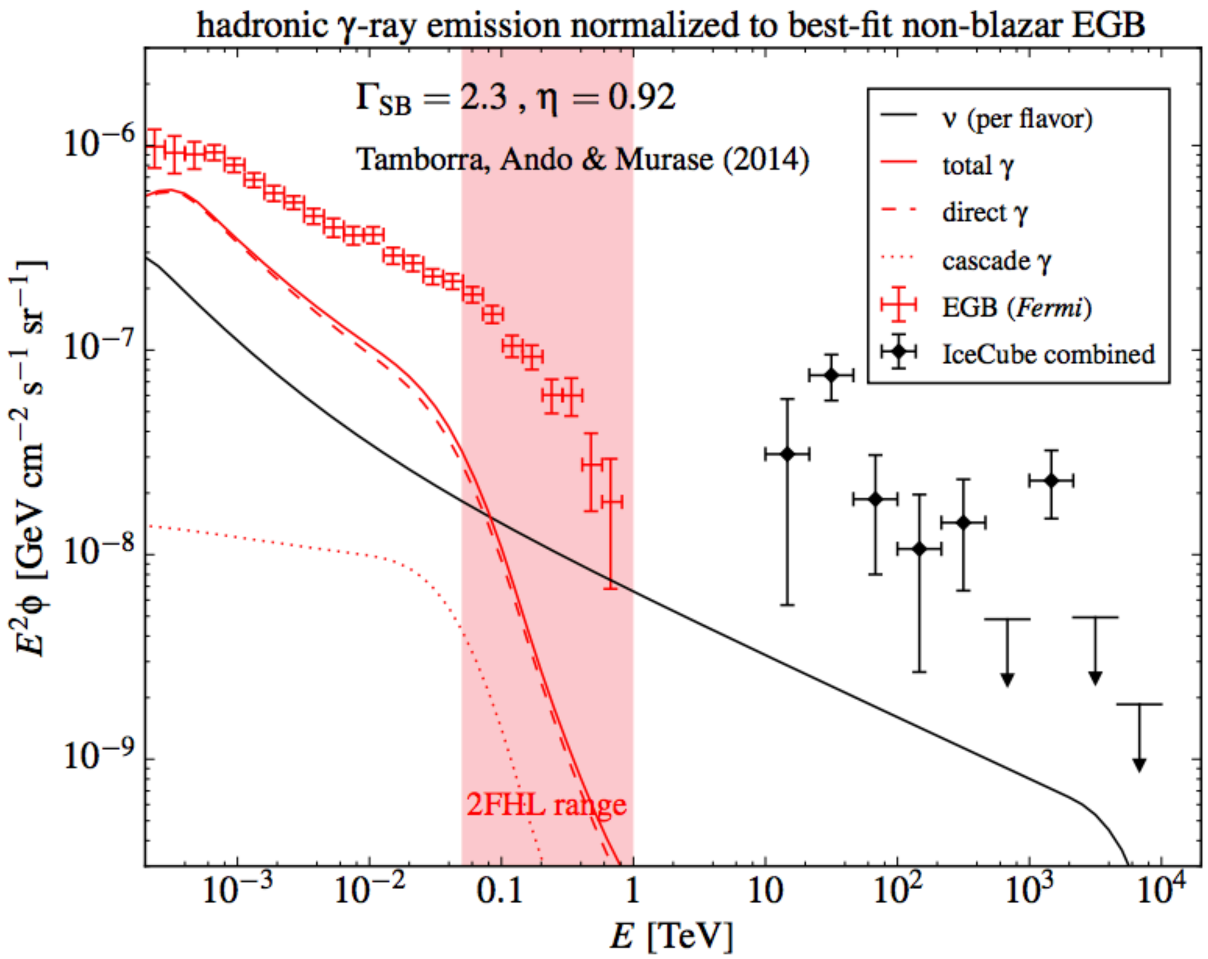


Figure from Bechtol, Ahlers et al., 2015 (published in APJ 2017)

The spectrum of NGC 253

NGC 253 (figure credit, Wikipedia)

Distance= 2.7 Mpc

$L_\gamma \sim 7 \times 10^{39}$ erg/s

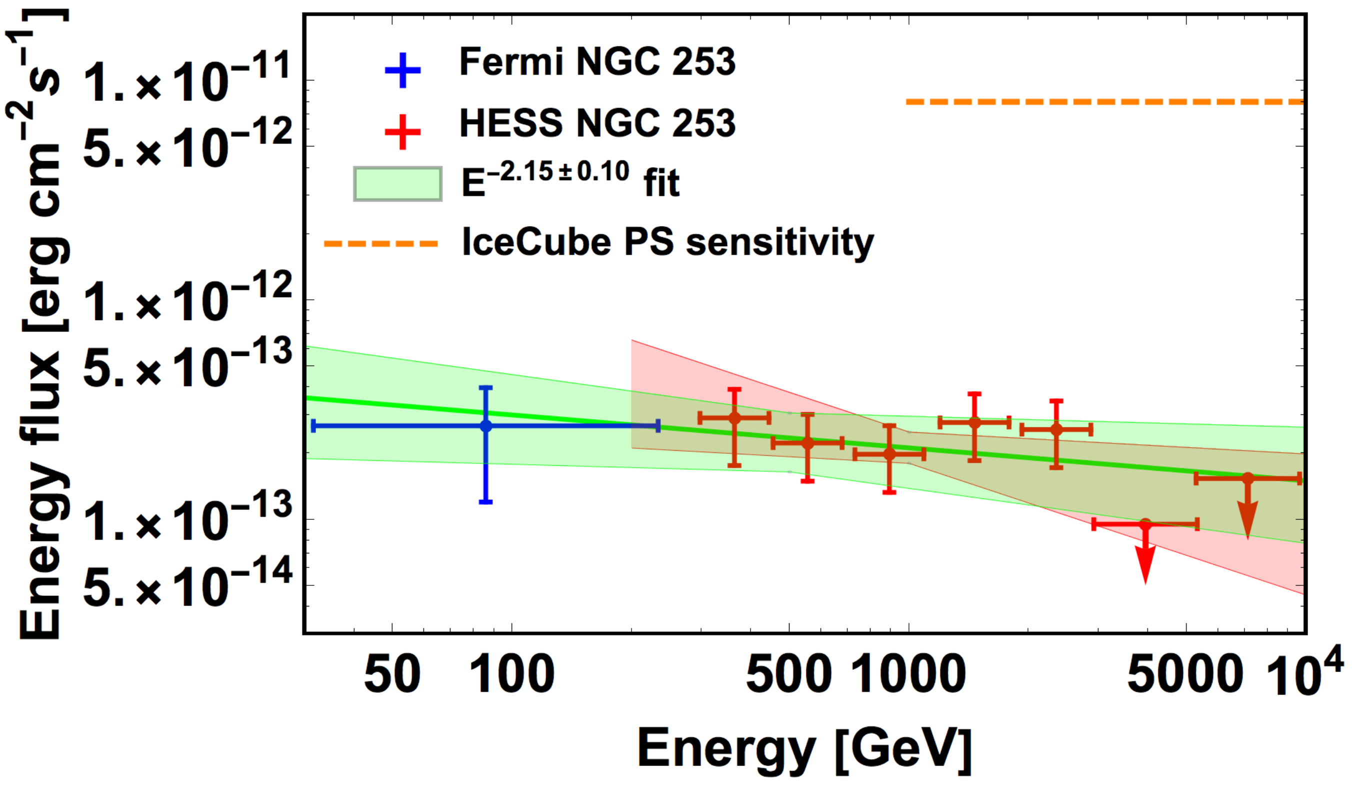


Figure from Palladino et al., arXiv:1812.04685

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 $\sim 10^{-3}$ Mpc^{-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 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

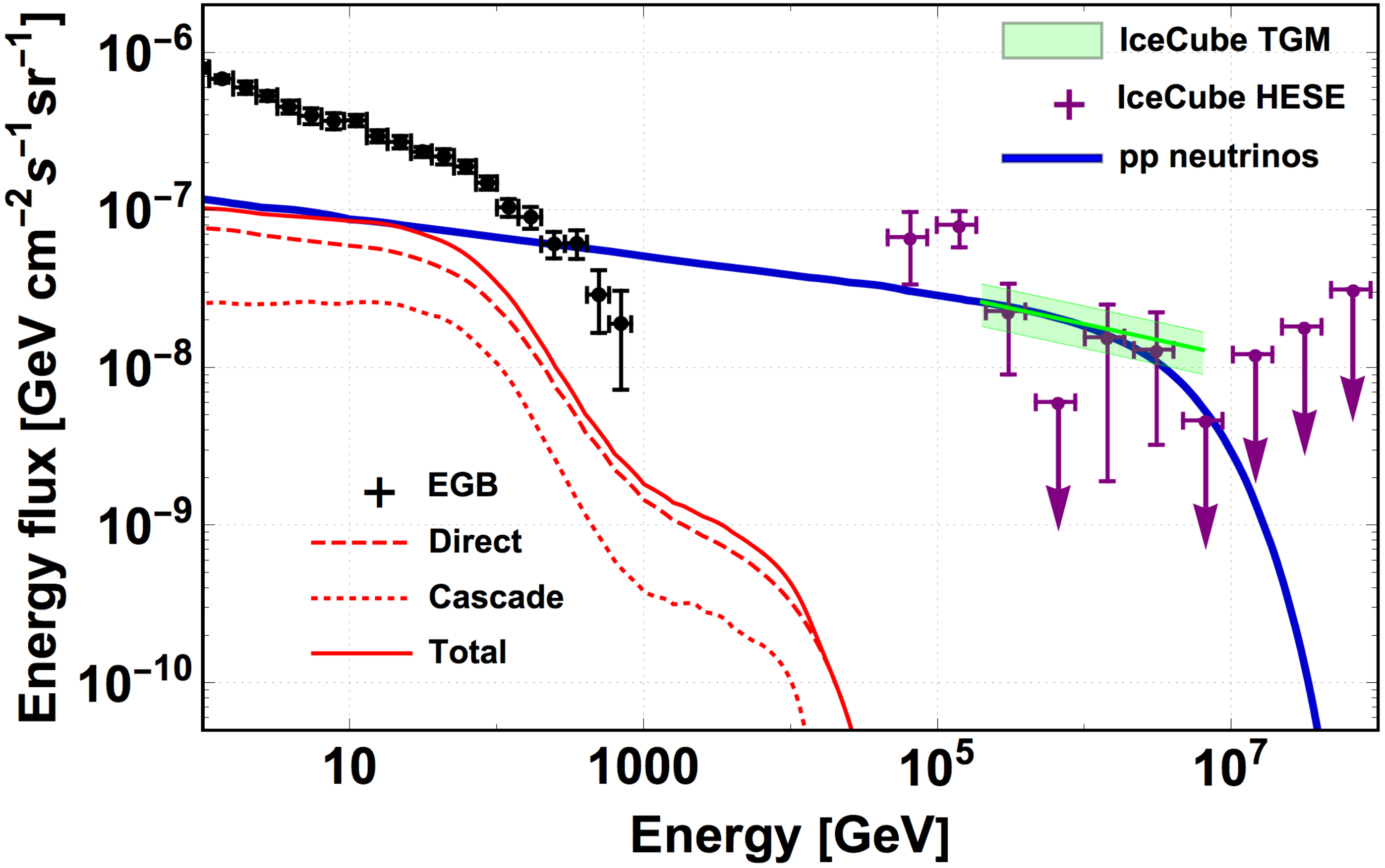


Figure from Palladino et al., JCAP 2019

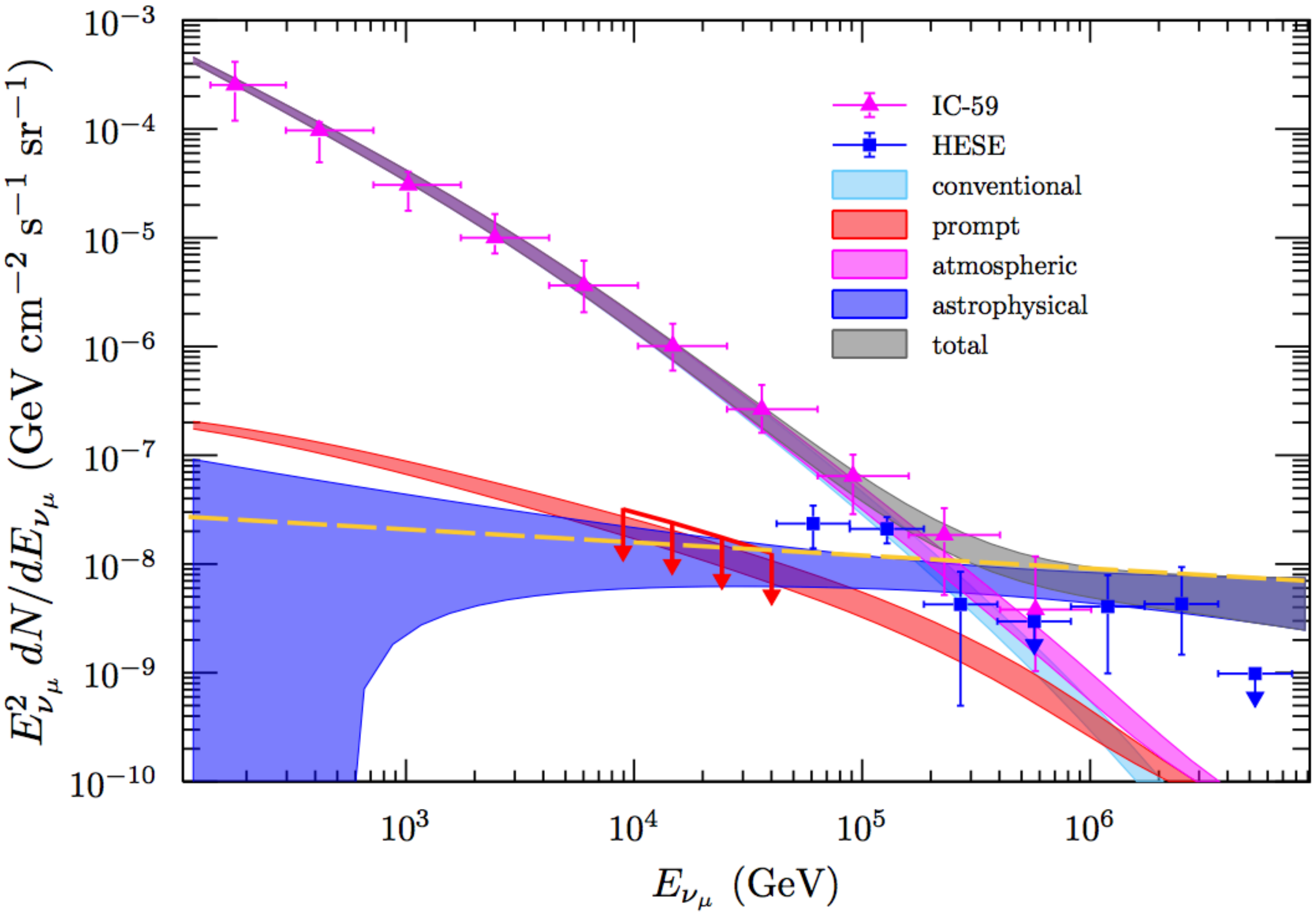
What about lower energies ?

Mascaretti- Vissani, JCAP 2019

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



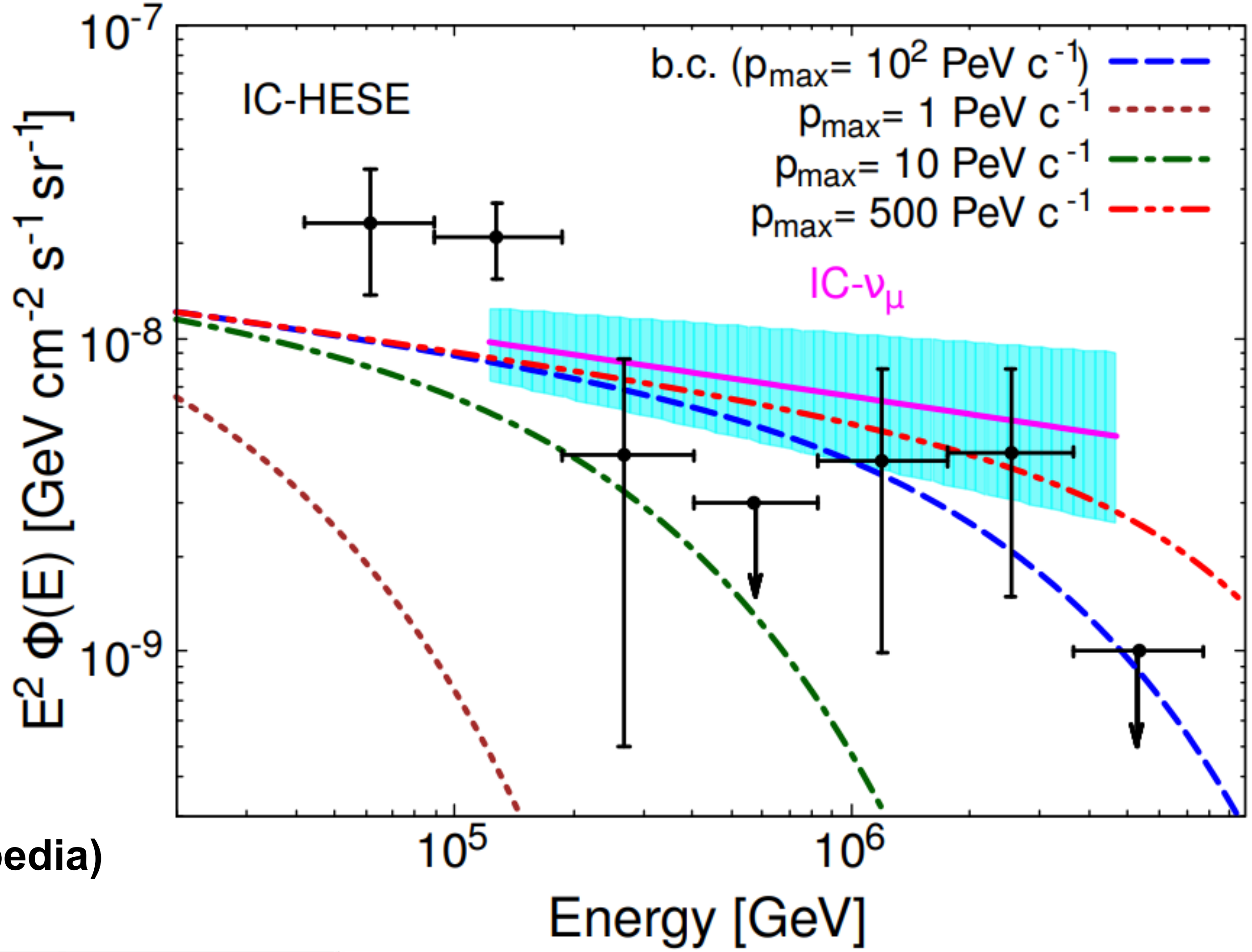
A recent work

In the recent Peretti et al., arXiv:1911:06163 the diffuse neutrino flux is computed using the Starburst Galaxy M82 as prototype

M82, the Cigar Galaxy (figure credit, Wikipedia)

Distance= 3.6 Mpc

$L_\gamma \sim 10^{40}$ erg/s



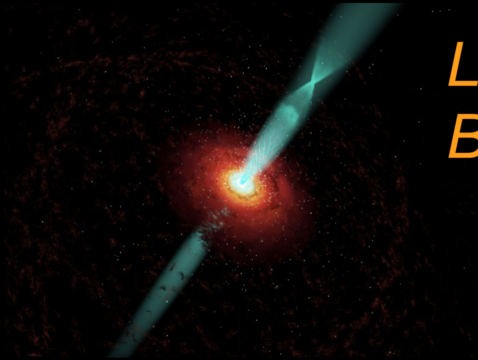
Peretti et al., arXiv:1911:06163

See Giovanni Morlino talk

Conclusion

pp sources

between $50\,\%$ and $100\,\%$

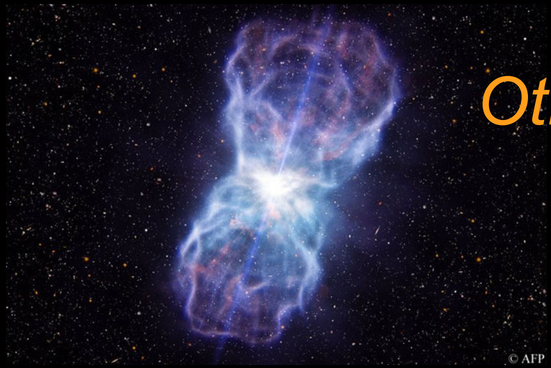


Low luminosity BL Lacs

$\gg 25\,\%$ but $< 100\,\%$

Galactic neutrinos

$\sim 10 - 15\,\%$



Other sources ?

$\sim 1\,\%$

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

Backup slides

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)

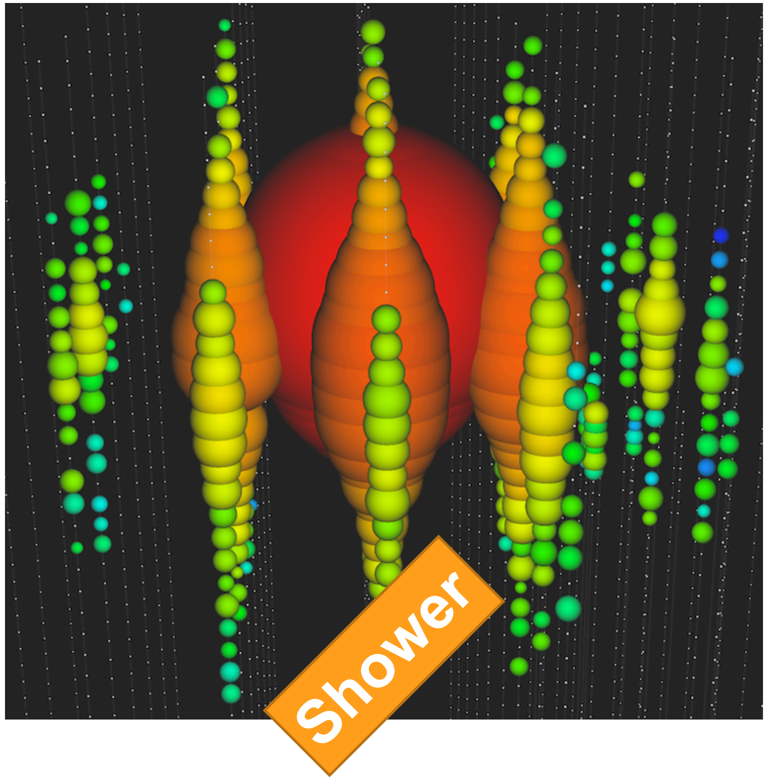
Throughgoing muons

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

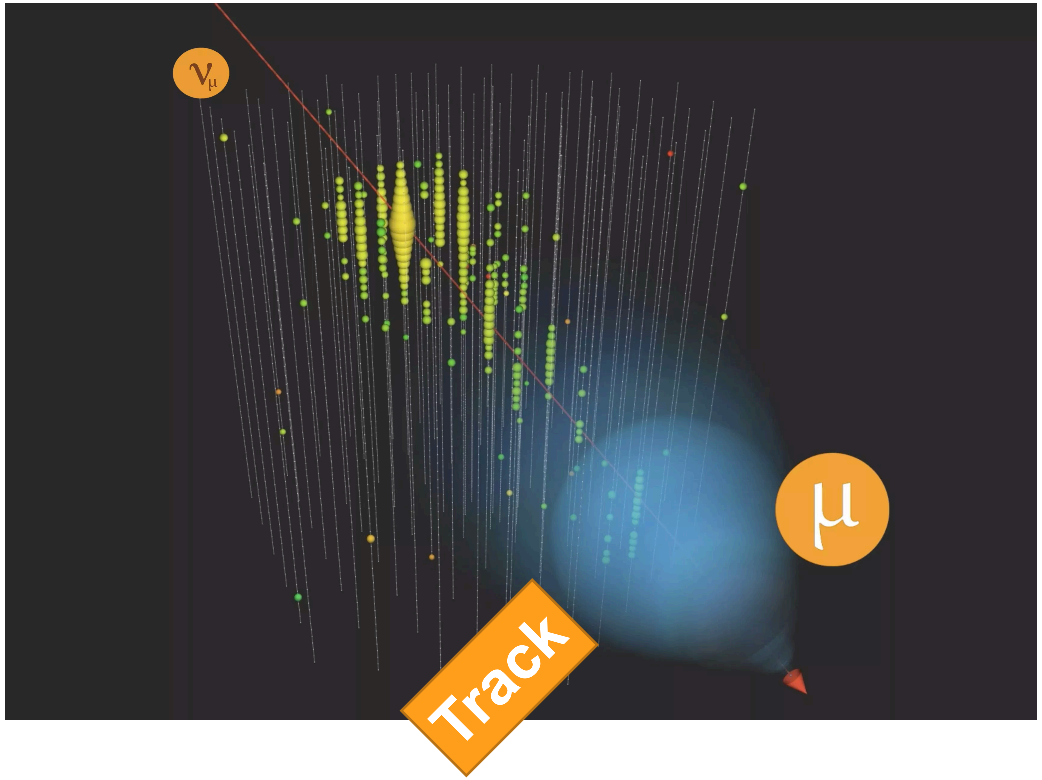
Showers and tracks

- 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



Other event topologies

Where are **resonant events** and **tau neutrinos** ?

Glashow resonance

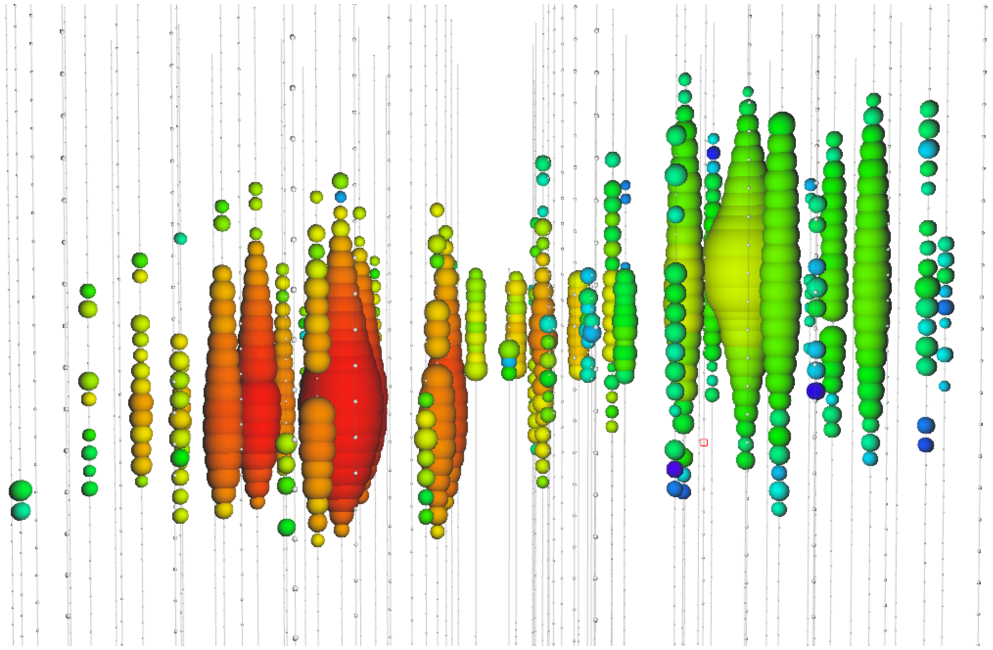
$$\bar{\nu}_e + e^- \to W^- \to \text{hadrons}$$

A shower of 6.3 PeV is a clear hint of a resonant event

ν_τ not expected from atmospheric neutrinos

They **must be observed soon** in IceCube

Palladino-Mascaretti-Vissani, JCAP 2018



Simulated double bang. Credit: IceCube

	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

Consequences for blazars

Following the previous result:

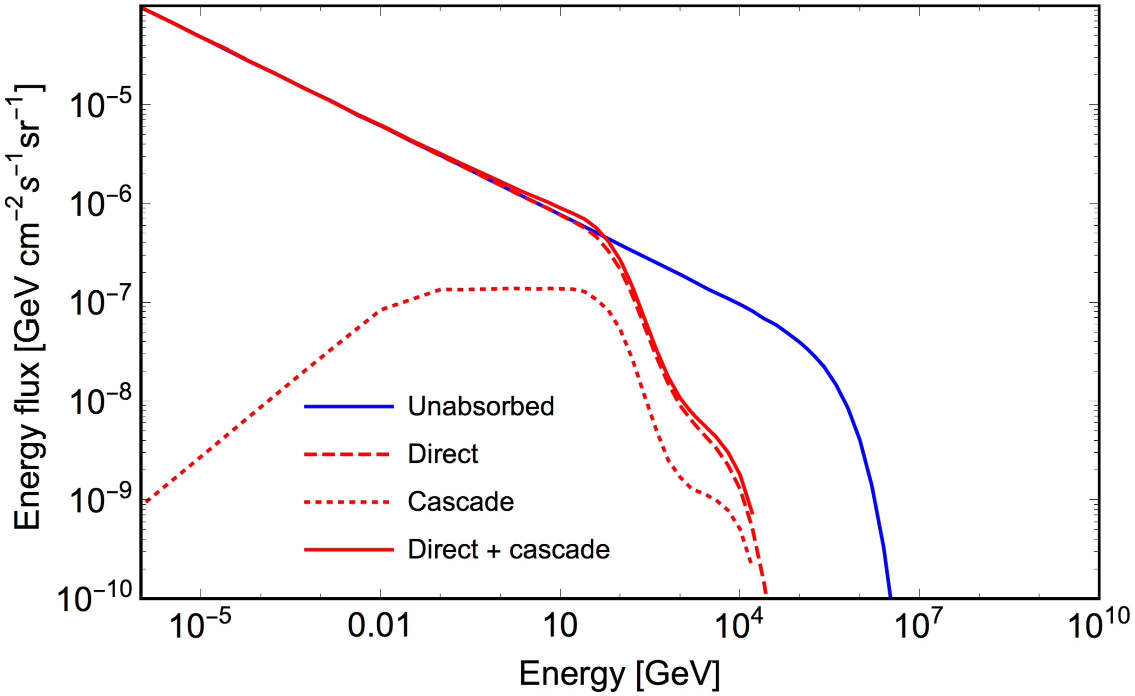
in order to reconcile the throughgoing muon flux with the blazar hypothesis,

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

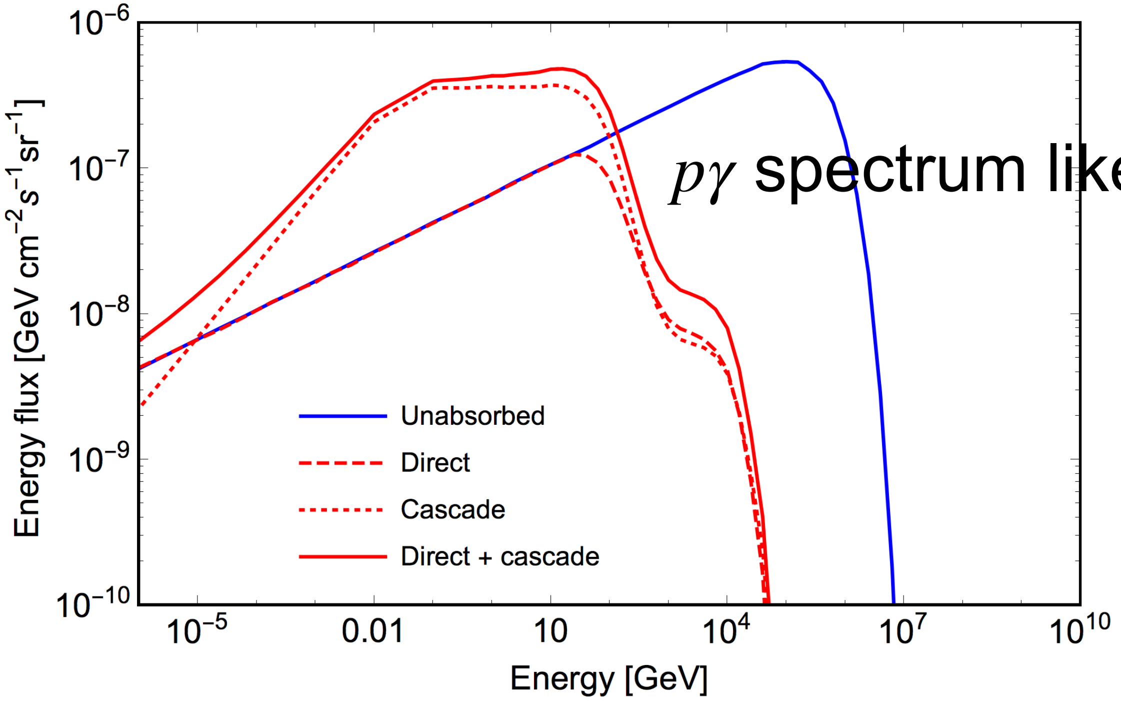
Propagation using other spectral indices

Two examples, using a spectrum softer (left) and harder (right) than E^{-2}

The gamma-ray spectrum at low energy is dominated by the direct flux



The gamma-ray spectrum at low energy is dominated by the cascade flux



$p\gamma$ spectrum like

Sources dominated by pp interaction

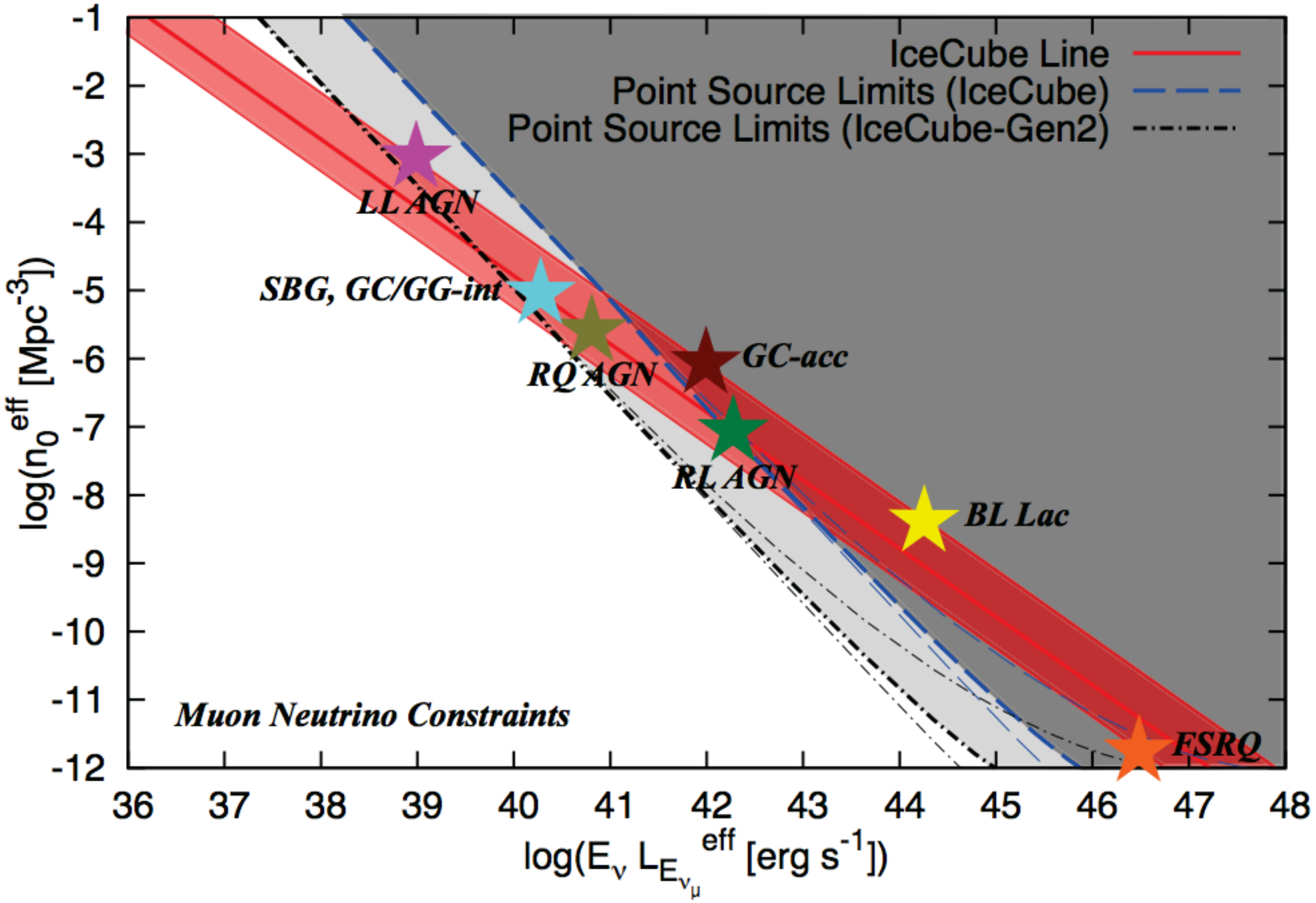
$$\boxed{pp \rightarrow \pi^+\pi^-\pi^0 \ldots}$$

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

- 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

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 detected by IceCube