Connection between Blazars and IceCube neutrinos

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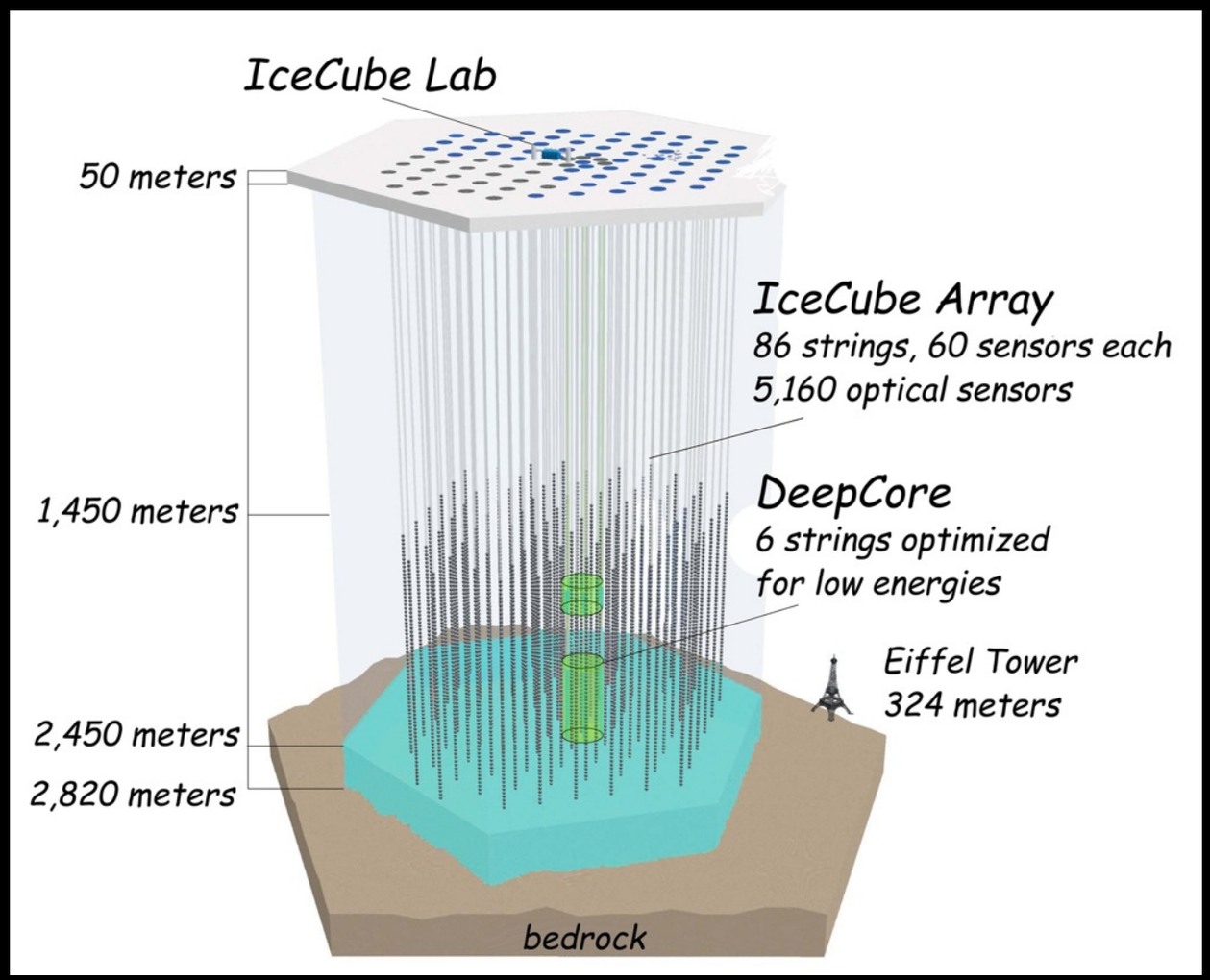
NEUCOS workshop, 29/05/2017

Evidence of cosmic neutrinos

IceCube, a detector of 1 km cube, provided the first evidence of an high energy neutrino flux (from 30 TeV to PeV) with a possible astrophysical origin.



The excess, respect to the atmospheric background, is greater than **5 sigma**.

IceCube coll., Astrophys.J. 809 (2015) no.1, 98

Mechanisms of production of high energy neutrinos

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

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

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

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

Production of π^- can be relevant also in $p\gamma$ mechanism.
See **Hummer et al., Astrophys.J. 721 (2010) 630-652**

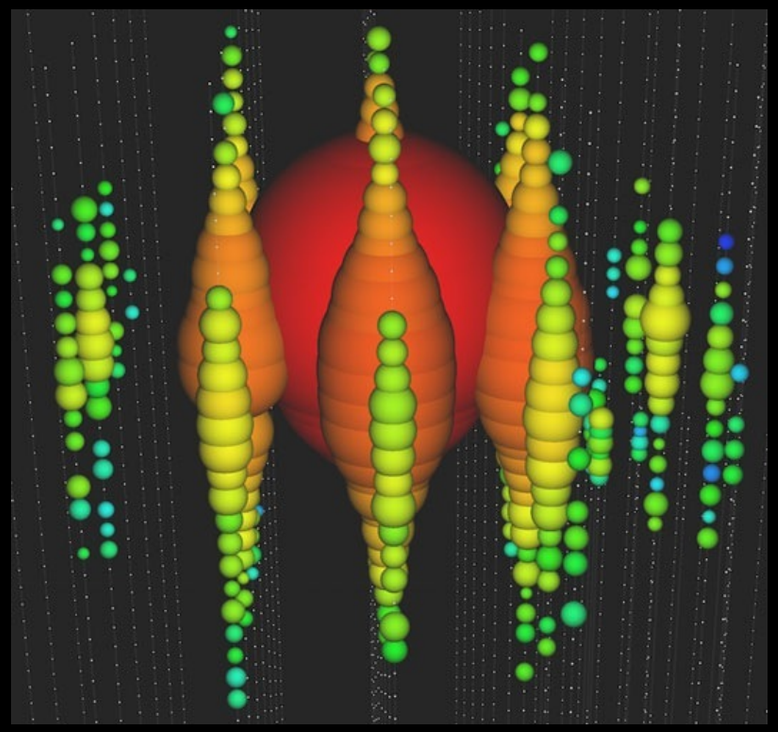
The energy of neutrinos is about 1/20 of the primary proton's energy

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

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

How do we observe neutrinos in IceCube?

Two different ways: HESE e throughgoing muons



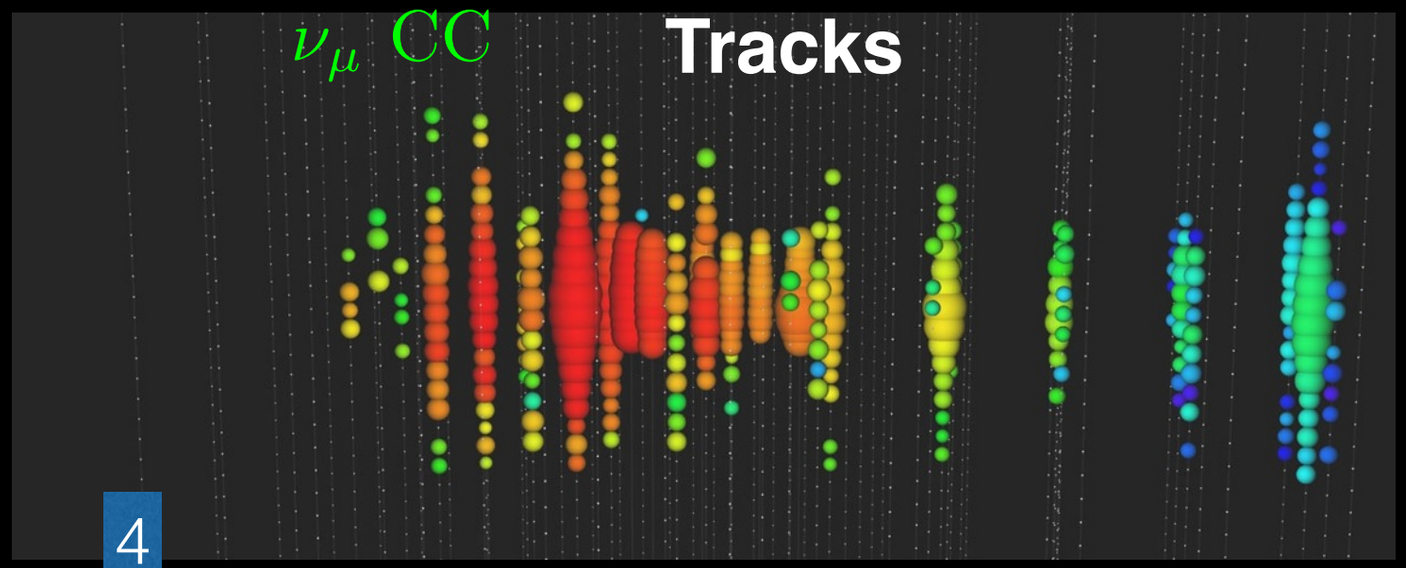
1) **HESE** (High Energy Starting Events) mainly look at showers from Southern sky

Showers (electromagnetic and/or hadronic, not distinguishable each others). The angular resolution is not good, about 10°-15°

$\nu_e,\ \nu_\tau$ CC

$\nu_e,\ \nu_\mu,\ \nu_\tau$ NC

2) The **throughgoing muons** are induced muons from Northern sky. Good angular resolution, about 1°.



The observed spectra

The HESE dataset (all flavor) suggests a soft spectrum

$$\phi = (6.7^{+1.1}_{-1.2}) \times 10^{-18}\ \mathrm{GeV}^{-1}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{cm}^{-2} \left(\frac{\mathrm{E}}{100\mathrm{TeV}}\right)^{-2.50\pm0.09}$$

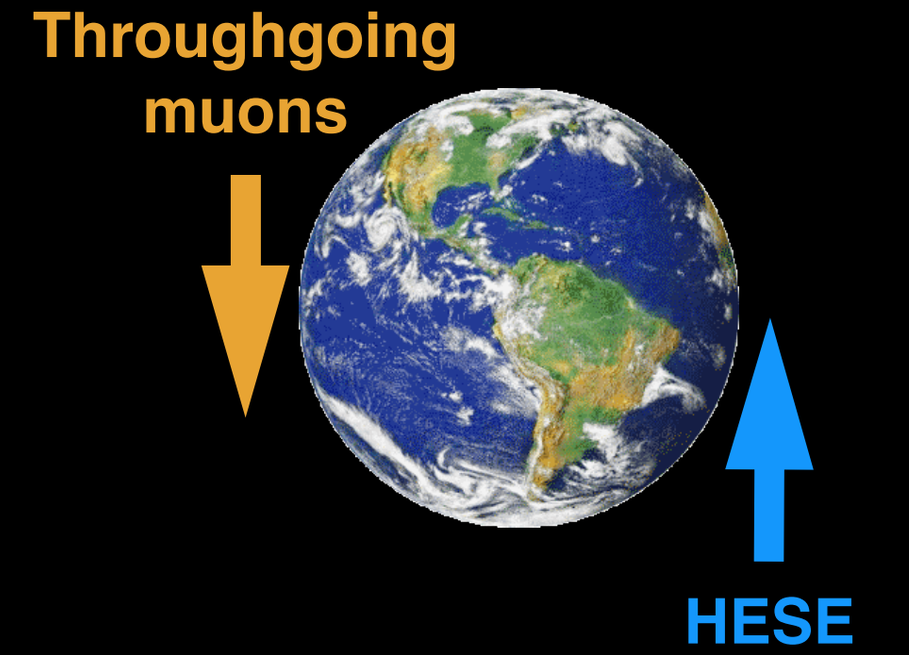
IceCube coll., Astrophys.J. 809 (2015) no.1, 98

The throughgoing muons observes an hard spectrum

$$\phi_{\nu_\mu+\bar{\nu}_\mu} = (0.90^{+0.30}_{-0.27}) \times 10^{-18}\ \mathrm{GeV}^{-1}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{cm}^{-2} \left(\frac{\mathrm{E}}{100\mathrm{TeV}}\right)^{-2.13\pm0.13}$$

IceCube coll., Astrophys.J. 833 (2016) no.1, 3

Tension of 3.6 sigma. Neutrino oscillations, instead, suggests the equipartition of the fluxes.

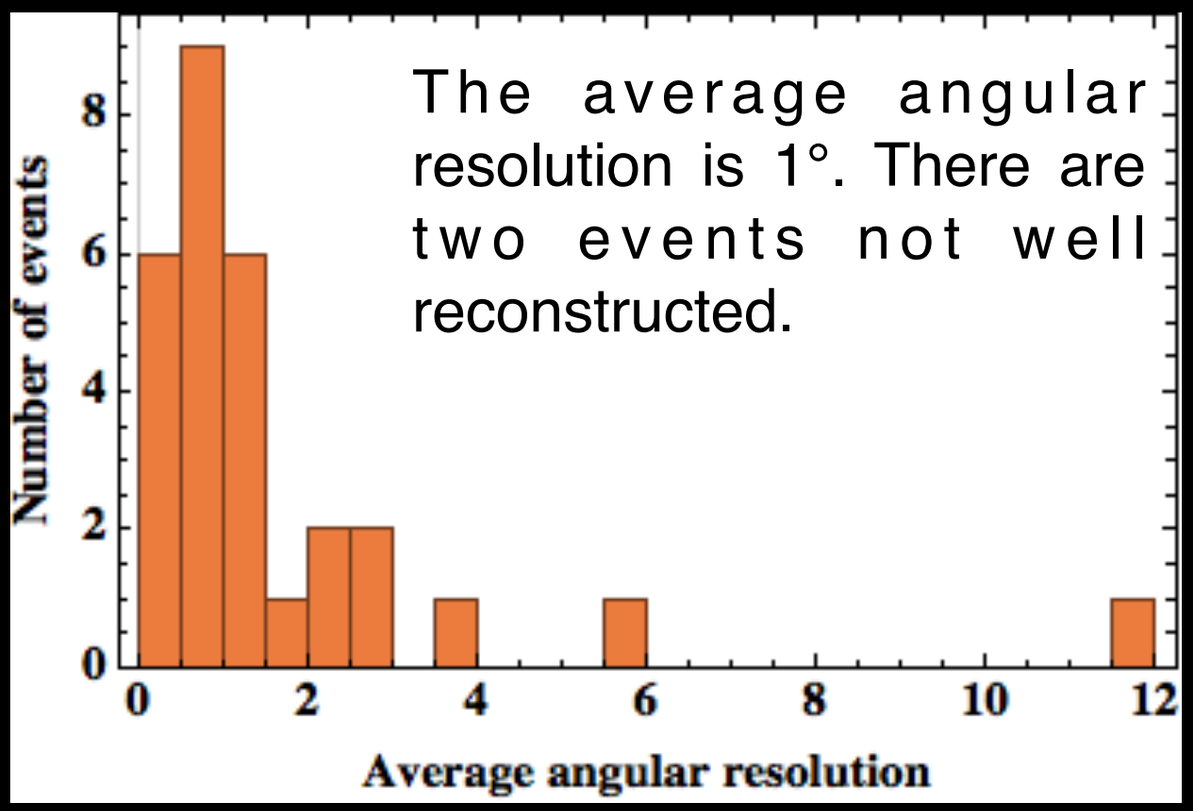


The throughgoing muons

This dataset consists of 29 tracks above 200 TeV. Using the "signalness" provided in **IceCube coll., Astrophys.J. 833 (2016) no.1, 3**, it is possible to estimate the number of signal events (astrophysical):

$$N_s = 20.4 \pm 2.4$$

About 1/3 of events are due to the atmospheric background



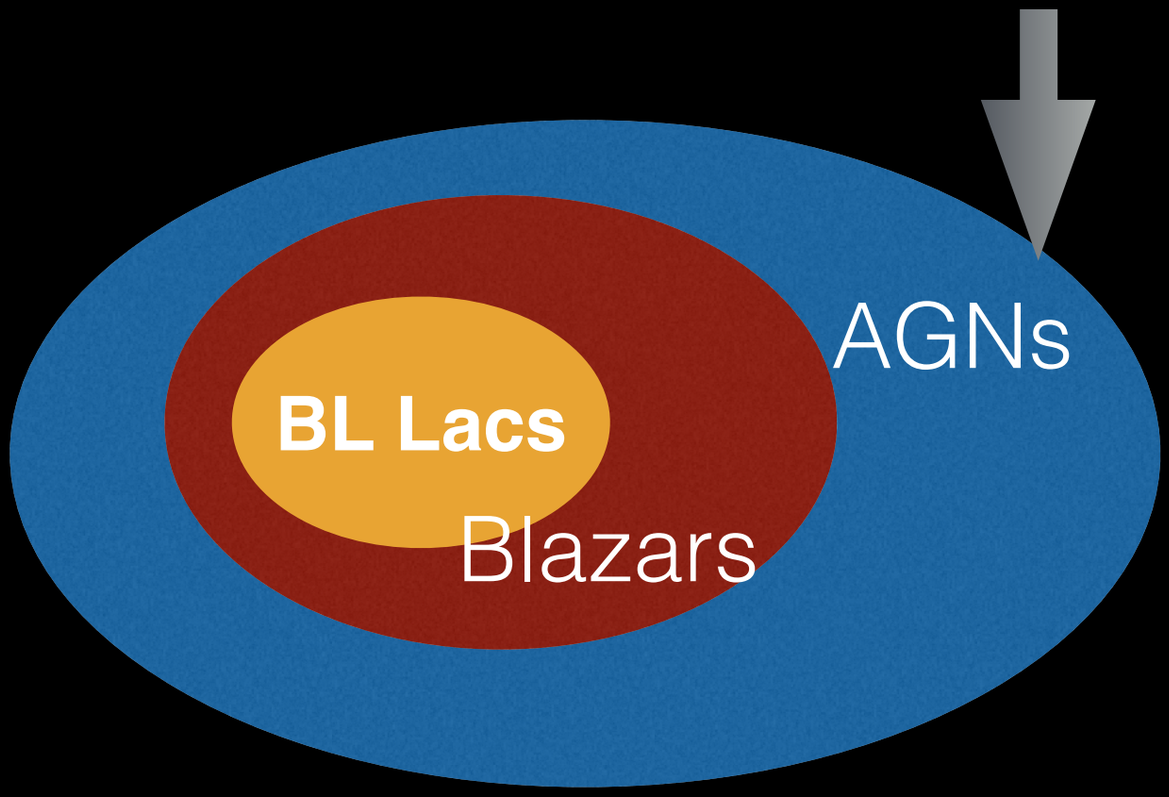
An angular resolution of 1° is sufficient to search spatial correlation with known sources.

What is the source of high energy neutrinos ?

See my talk of Wednesday for an overview of the possible sources, in a multi-component model context.

In this talk I focus on a specific source, called BL Lacertae or BL Lac.

The BL Lac is a sub-class of Blazars, that is a subclass os AGN



Blazars are the brightest objects in the gamma-rays sky above 100 GeV. This motivates the search of correlations with high energy neutrinos.

AGNs and Blazars

An active galactic nucleus (AGN) is a compact region at the center of a galaxy that has a much higher than normal luminosity. A galaxy hosting an AGN is called an active galaxy.

The radiation from an AGN is believed to be the result of accretion of matter by a **supermassive black hole** at the center of its host galaxy.

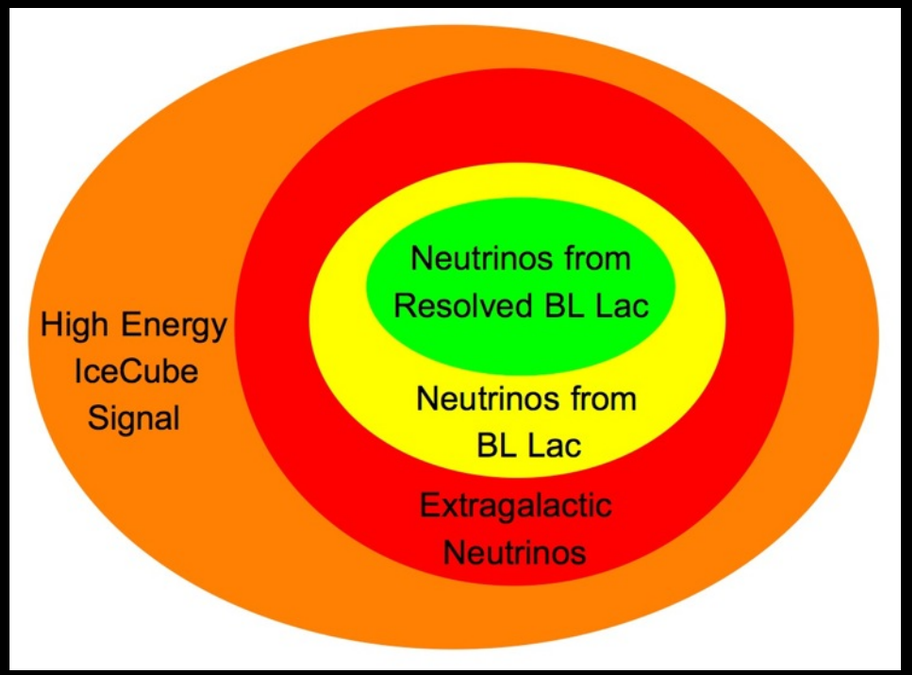
Blazar is a sub-class of AGN that emit a relativistic jet pointing in direction of the Earth

BL Lac and FSRQ

Blazars are classified in:

- Flat Spectrum Radio Quasars (FSRQ).
- BL Lac (namely BL Lacertae). They are characterized by featureless optical spectra (i.e., lacking strong emission/absorption lines)

After **Tavecchio-Ghisellini, Mon.Not.Roy.Astron.Soc. 451 (2015) no.2, 1502-1510** BL Lacs seem to be more promising candidate for the production of high energy neutrinos.



Limit of the IceCube collaboration to the contribution of blazars **Astrophys.J. 835 (2017) no.1, 45**

25% considering a **soft spectrum** of neutrinos
50% considering an **hard spectrum** of neutrinos

The fraction of visible BL Lacs

In Ajello et al. **Astrophys.J. 780 (2014) 73** it is described the "cosmic evolution of BL Lacs", using a distribution on:

$$\frac{\partial^3 N}{\partial L_\gamma \partial z \partial \Gamma}$$

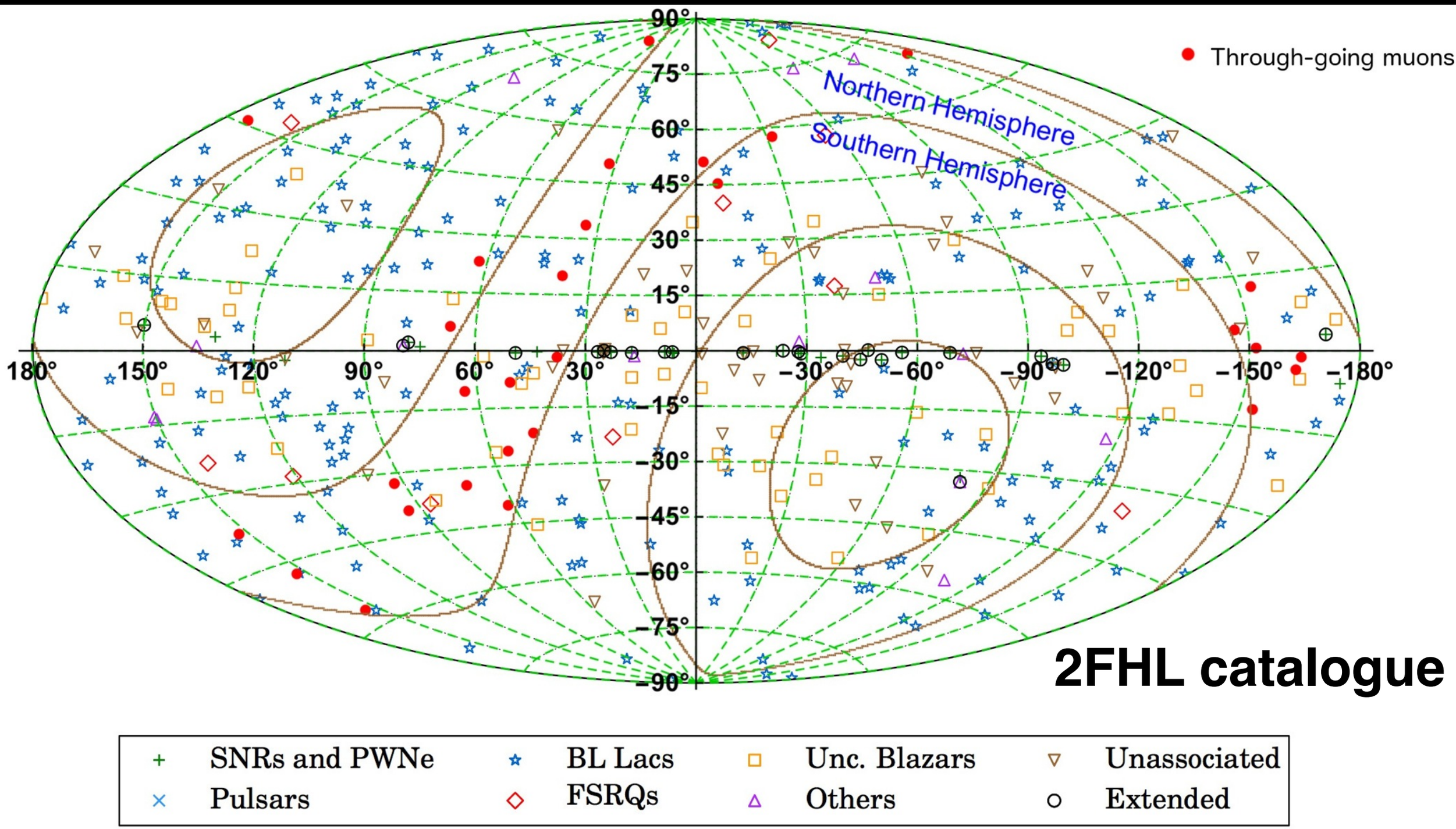
L_γ luminosity
z redshift
Γ spectral index

The distribution can be used to evaluate the number of expected BL Lacs (**see Esmaili-Palladino-Vissani, EPJ Web Conf. 116 (2016) 11002**) and to compare it with the detected ones, finding: $f = 0.5 \pm 0.1$

Therefore —> if high energy neutrinos are produced by BL Lacs we expect the following number of correlations:

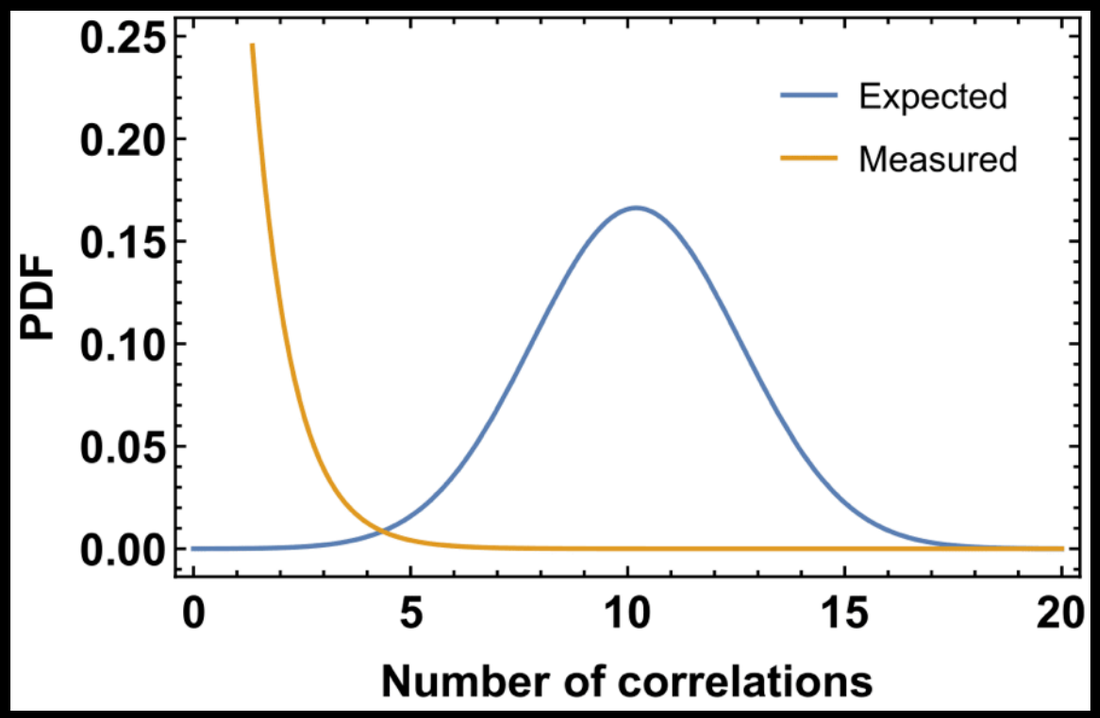
$$N_c = f \times N_s = 10.2 \pm 2.4$$

Map of the correlations



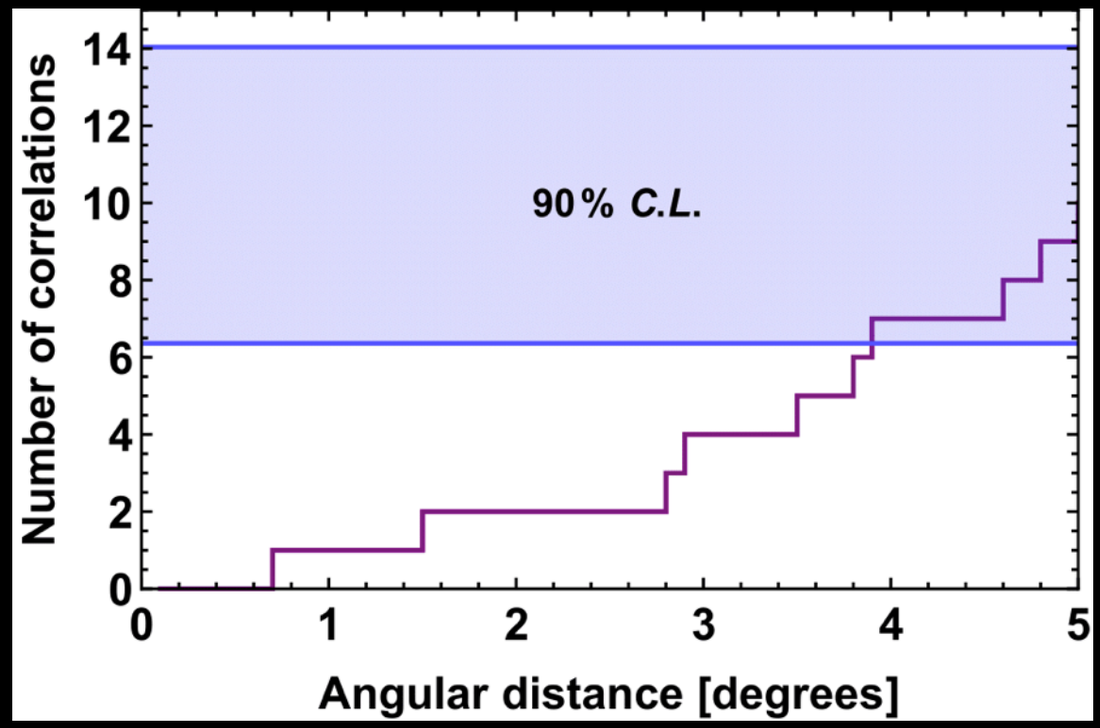
Expectations vs observations

- There is **only 1 correlation** within 81% C.L.
- This correlation is associated to a neutrino events with angular uncertainty > 10°



*There is a tension of **3.7 sigma** between the expectations and the observations*

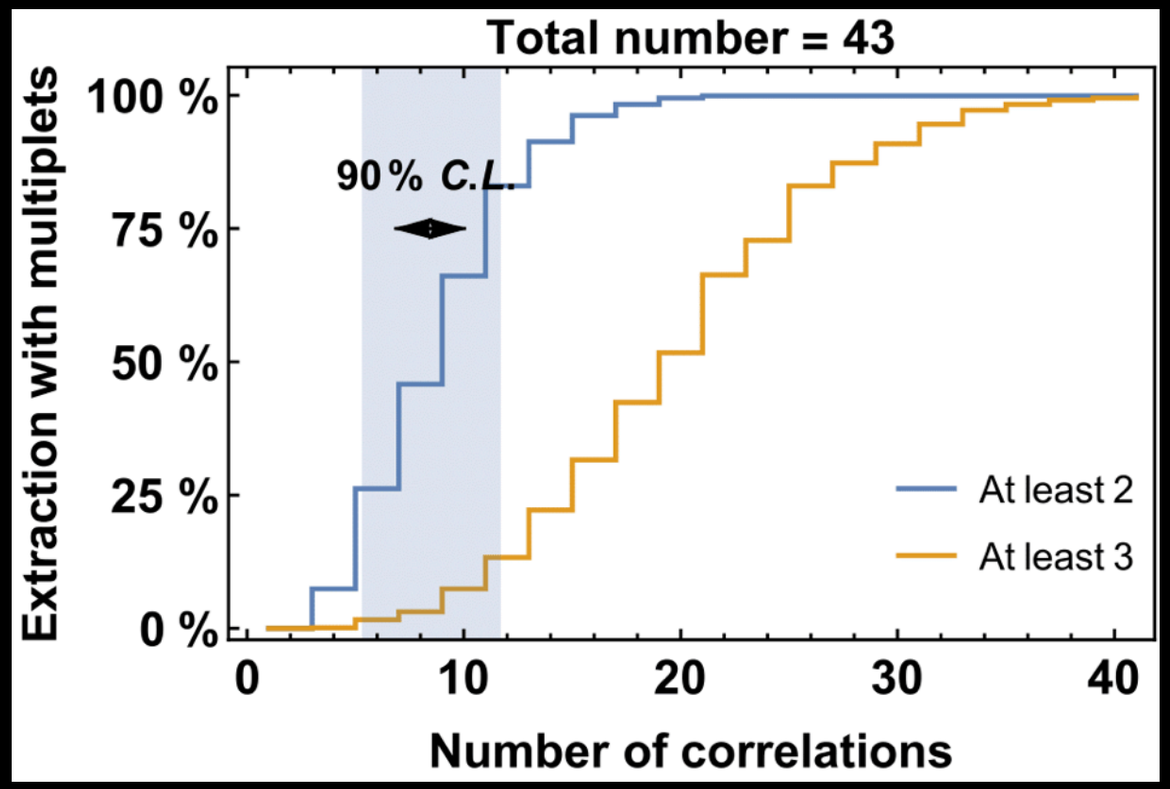
Palladino-Vissani, arXiv 1702:08779, accepted for publication in A&A



*The angular resolution of tracks should be much worse than 1° to be in agreement with the BL Lacs hypothesis, namely **4°***

See Resconi et al., Mon.Not.Roy.Astron.Soc. 468 (2017) 597
Padovani et al., Mon.Not.Roy.Astron.Soc. 457 (2016) no.4, 3582-3592
for complementary discussions on the connection between Blazars and IceCube neutrinos

The multiplets



We focus on BL Lacs in the interval of declination between 0° and 30°, since most of throughgoing muons come from that region.

The non observation of multiplets is not a problem with the present exposure

This analysis strongly depends on the class of objects considered.

See Murase and Waxman **Phys.Rev. D94 (2016) no.10, 103006** for a scenario in which, on the contrary, the absence of multiplets represents an issue even with the present IceCube data.

Open questions

- For the IceCube collaboration the contribution of blazars to the diffuse flux (observed with High Energy Starting Events, HESE) is less than 25%. **IceCube coll., Astrophys.J. 835 (2017) no.1, 45**
- This limit increases up to 50% if an harder spectrum of neutrinos is considered. The throughgoing muons dataset suggest an harder spectrum than HESE.
- What population of AGNs should be included in this kind of analysis ? Blazars ? If blazars, BL Lacs or FSRQ ? Both ?
- Can the computation of a realistic AGN's spectrum help us ?
- Are we sure that the diffuse flux is only produced by extragalactic sources?

Conclusions

- IceCube provided the first evidence of astrophysical neutrinos
- 2/3 of throughgoing muons events can have an astrophysical origin
- The average angular resolution of these tracks is about 1°

- AGNs are promising extragalactic sources of IceCube neutrinos
- Among AGNs we have investigated blazars, particularly BL Lacs
- There are about half BL Lacs tagged and half of them untagged

- No evidence of correlations between neutrinos and BL Lacs has been found
- There is a discrepancy of 3.7 sigma between expectations and observations
- The absence of multiplets is not **yet** an issue

Thanks for the attention