Search for multi-flare neutrino emission from a source catalog with 10 years of IceCube data

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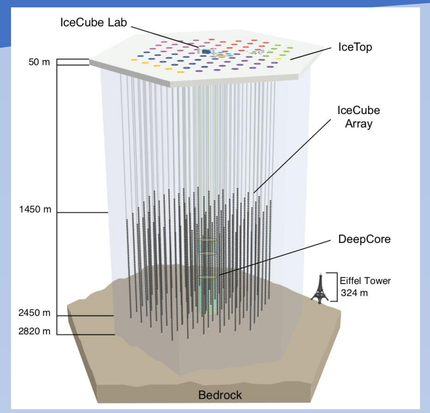


Fig. 1: The IceCube detector

Introduction

IceCube is a cubic-kilometer neutrino telescope located at the South Pole and designed to detect neutrinos from high-energy astrophysical sources. It consists of 86 in-ice vertical stings equipped with digital optical modules from 1,450 to 2,450 meters depth to collect Cherenkov light emitted by secondary charged particles in neutrino interactions.

In a recent investigation, IceCube observed a cumulative excess in the time-integrated flux emitted in the northern sky by four sources from a catalog of astrophysical objects selected on the basis of γ-ray observations. The excess is estimated to have a significance of 3.3σ with respect to the expected background of atmospheric neutrinos and muons and is mainly due to NGC 1068, TXS 0506+056, PKS 1424+240 and GB6 J1542+6129. This poster presents the results of a time-dependent follow-up of that investigation, based on a newly developed multiple flare method.

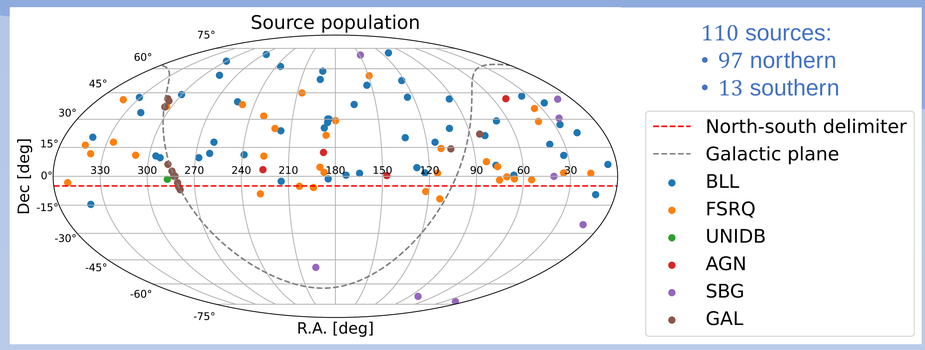


Fig. 2: Sky map with the locations of the sources of the catalog

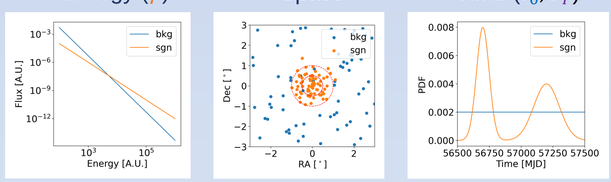
Analysis Method

Multi-flare point-source analysis

It exploits a likelihood $\mathcal{L}$ built from a signal $S_i^{(f)}$ and a background B_i flare probability density function (PDF). These PDFs are the product of an energy, a space and a time PDF (Gaussian for signal). The likelihood is a function of the signal-like neutrinos per flare (n_s^f), the spectral index of each flare (γ^f), the flare time (t_0^f) and the flare duration (σ_T^f). N is the total number of neutrino events.

$$\mathcal{L}(\vec{n}_s, \vec{\gamma}, \vec{t}_0, \vec{\sigma}_T) = \prod_{i=\text{events}} \left[\frac{\sum_{f=\text{flares}} n_s^{(f)} S_i^{(f)}(\gamma^f, t_0^f, \sigma_T^f)}{N} + \left(1 - \frac{\sum_f n_s^{(f)}}{N}\right) B_i \right]$$

Energy ($\vec{\gamma}$) | Space | Time ($\vec{t}_0, \vec{\sigma}_T$)



A test statistic (TS) is defined as the likelihood ratio, with an additional factor (marginalization factor) to correct a bias towards short flares. The marginalization factor is written in terms of the livetime T of the dataset (10 years), the flare duration $\sigma_T^{(f)}$ and the integral of the normalized Gaussian time profile of the flares ($0 < \int G^{(f)}\left(t; t_0^{(f)}, \sigma_T^{(f)}\right) dt \leq 1$).

$$\text{TS} = -2 \log \left[\underbrace{\frac{1}{2}\left(\prod_{f=\text{flares}} \frac{T}{\sigma_T^{(f)} \int G^{(f)}\left(t; t_0^{(f)}, \sigma_T^{(f)}\right) dt} \right)}_{\text{Marginalization term}} \overbrace{\frac{\mathcal{L}(n_s = 0)}{\mathcal{L}(\vec{n}_s, \vec{\gamma}, \vec{t}_0, \vec{\sigma}_T)}}^{\text{Likelihood ratio}} \right]$$

The TS is maximized at the location of each source of the catalog by varying the four likelihood parameters and converted into a pre-trial p-value by comparison with a distribution of TS obtained under the background-only hypothesis.

Binomial test

In each hemisphere, the pre-trial p-values p_k of the N sources are ranked from the most to the least significant and combined in a binomial p-value:

North: $N = 97$
South: $N = 13$

$$P_{bin}(k) = \sum_{m=k}^{N} \binom{N}{m} p_k^m (1 - p_k)^{N-m}$$

The binomial p-value $P_{bin}(k)$ is the probability that the background produces k or more sources with p-values smaller than p_k. The source index k is scanned from 1 to N and the smallest $P_{bin}(k)$ is reported in each hemisphere after correcting for the look-elsewhere effect.

Results

Northern hemisphere ($\delta \geq -5°$)

The binomial test confirms the neutrino excess in the northern hemisphere with a trial-corrected significance of 3.0σ. The contribution is mainly due to four sources: M87, TXS 0506+056, NGC 1068 and GB6 J1542+6129. M87, a galaxy whose core is a known emitter of ultra-relativistic ejecta, is the best source in the northern sky, with a p-value of 4.6×10^{-4} (3.3σ) that becomes 4.3×10^{-2} (1.7σ) after correcting for the look-elsewhere effect. TXS 0506+056 is found to be a multiple flare source, with two notable flares identified.

Southern hemisphere ($\delta < -5°$):

No remarkable results are observed in the southern hemisphere, where the IceCube sensitivity is degraded by the overabundant background of atmospheric muons.

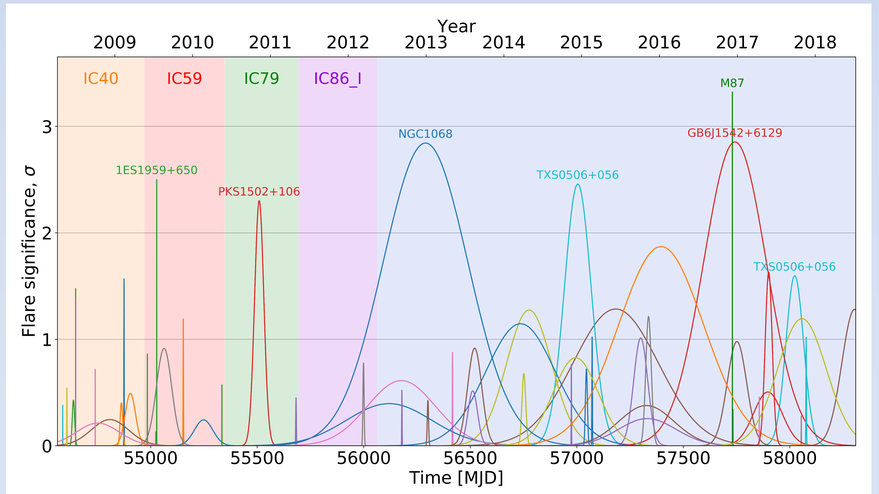


Fig. 3: Best-fit flares of the sources using the multi-flare method described in this poster