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Investigating the neutrino emission of candidate neutrino-emitter blazars with the `icecubepy` likelihood framework

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Active galactic nuclei are promising candidates for astrophysical neutrino sources, as suggested by the detection of a high-energy neutrino positionally consistent with the flaring blazar TXS 0506+056 [1] and evidence of neutrino emission from the nearby Seyfert galaxy NGC 1068. Our recent studies based on the IceCube time-integrated sky maps provided evidence of a statistically significant correlation between blazars and "hotspots" in the neutrino sky as seen by the IceCube Neutrino Observatory. A small subset of blazars, appearing as promising candidate neutrino point sources, has been highlighted. The neutrino emission properties of these blazars remain largely unexplored. The IceCube Collaboration has publicly released a 10-year muon-track dataset; however, publicly available analysis tools for these data are currently limited. In this contribution, we introduce `icecubepy`, an unbinned maximum likelihood framework designed for the analysis of the public data from the IceCube Neutrino Observatory. We present the analysis performance of `icecubepy`, finding general agreement with results published by the IceCube Collaboration. This demonstrates that the software has reached an adequate level of maturity and reliability suitable for scientific analyses.

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1. Introduction

High-energy neutrinos are a crucial messenger of hadronic acceleration processes in astrophysics, with the unique potential to unveil the origin of ultra-high-energy cosmic rays, the most energetic known particles. Detecting astrophysical neutrinos has been historically challenging, due to the tiny magnitude of the astrophysical flux and the small cross section of weak interactions, which are the primary means of their detection. In over ten years of operation, the IceCube Neutrino Observatory has observed and characterised an astrophysical diffuse flux of neutrinos of all flavours. This flux manifests as a power-law shape from TeV to PeV energies, emerging above the dominant backgrounds of atmospheric muons and neutrinos at $\gtrsim$ 100 TeV. The large majority of neutrinos observed by IceCube appear as track-like emissions of Cherenkov light, induced by muons outgoing charged-current interactions. These events can be reconstructed with a relatively good angular accuracy (below 0.5°) and are hence a primary channel for neutrino astronomy.

The majority of the astrophysical neutrino flux is of unexplained origin. The first candidate point-sources belong to different classes of active galactic nuclei (AGN). NGC 1068 is a Seyfert-II galaxy associated with a neutrino signal in time-integrated point source studies. TXS 0506+056 is a blazar initially associated with a ~290 TeV IceCube neutrino event while flaring in gamma rays. In 2021, the IceCube Collaboration released a dataset of track-like events covering ten years observations of the whole sky [2]. These data have been exploited in several all-sky and catalogue-based searches for point sources. The corresponding sky map, published by the IceCube Collaboration, has not been publicly released in a machine-readable format.

A sample of blazars from the Roma 5th Catalog (5BZCat) has been proposed as associated with anisotropies in the IceCube neutrino data [3–5]. These spatial cross-correlation studies have been conducted on high-level data products released by the IceCube Collaboration in the form of sky maps. The latter are produced with unbinned maximum likelihood analyses of candidate neutrino events, conducted with proprietary tools. For the southern celestial hemisphere (declination interval: $-85° < \delta < -5°$) a neutrino sky map based on 7 years (2008-2015) of data [6] has been considered. For the northern hemisphere ($-3° \leq \delta \leq 81°$), a more recent 10-year map (2011–2020), resulting from the application of improved methods [7], is available. The results of the correlation between the sky regions showing the strongest deviation from the background expectation (hotspots) and the 5BZCat blazars indicated a post-trial chance probability of 2×10^{-6} (4.5σ) for the southern hemisphere and 6.79×10^{-3} (2.47σ) for the northern hemisphere. These findings highlight a statistically significant association between a small subset of blazars and the samples of observed neutrino hotspots. Independent studies [8] confirmed the blazar–neutrino association reported in [3] when using the 7-year southern sky neutrino skymap released by the IceCube Collaboration [6]. However, when extending the test to the 10-year with the SkyLLH software [9], their analysis of the public IceCube dataset yields differing results, putting into question the blazar/neutrino association and/or the reproducibility of previous IceCube results with the public data.

In this contribution, we present the latest updates on `icecubepy`, an open-software framework designed for the analysis of the public IceCube data, which represent a key resource for the astronomy community to build independent studies on astrophysical neutrino sources. The methods, implementation and first applications are introduced here, more details will be available in [10]. As part of the development process of such framework, the open-source tool SkyLLH [8], is used for cross-checking purposes.

2. `icecubepy`: unbinned maximum likelihood analysis

The unbinned maximum likelihood method implemented in `icecubepy` is an analysis method commonly used in the search for point-like neutrino sources. In this, a likelihood function is constructed as a joint probability density evaluated on the observables of all the events in the dataset, for given signal and background hypotheses. The likelihood function for a signal hypothesis where n_s signal neutrinos have an energy distribution characterised by a parameter γ, is defined as:

$$\mathcal{L}(n_{\rm s}, \gamma) = \prod_{\rm i=0}^{\rm N} \left[\frac{n_s}{\rm N} \mathcal{S}(\vec{x}_i, \sigma_i, E_i; \gamma) + \left(1 - \frac{n_{\rm s}}{\rm N}\right) \mathcal{B}(\vec{x}_i, E_i) \right] \tag{1}$$

where N is the number of events in the data sample, $\mathcal{S}$ the probability density function (PDF) describing signal events and $\mathcal{B}$ the probability density function describing background events. The event observables are $x_i = (\alpha, \delta)$, the vector formed by the equatorial coordinates (right ascension, α and declination, δ) of the reconstructed muon; E_i, the reconstructed muon energy, σ_i the angular error estimator of the individual event. In a first approximation, the spatial and energy components are treated as independent. For $n_s = 0$, Equation 1 is the likelihood function for the background hypothesis. Then, the test statistic (TS) is defined from the likelihood ratio between the signal and background hypotheses:

$$\mathrm{TS} = 2 \log \frac{\mathcal{L}(\hat{n}_s, \hat{\gamma})}{\mathcal{L}(n_s = 0)} = 2 \sum_{i=1}^{N} \log \left[1 + \frac{\hat{n}_s}{N} \left(\frac{\mathcal{S}_{\rm spatial}(|\vec{x}_i - \vec{x}_s|)}{\mathcal{B}_{\rm spatial}(\sin\delta_i)} \times \frac{\mathcal{S}_{\rm energy}(\sin\delta_i, E_i; \hat{\gamma})}{\mathcal{B}_{\rm energy}(\sin\delta_i, E_i)} - 1 \right) \right] \tag{2}$$

where $\hat{n_s}$ and $\hat{\gamma}$ are the values of the parameters that maximise the likelihood ratio. The maximum-likelihood test consists of the maximisation of the TS value in the (n_s, γ) space.

2.1 Probability density functions

To define the background hypothesis, the spatial and energy components of the PDFs are purely evaluated from the data. This is possible because the astrophysical component in the data is overall very small. Hence, the spatial PDF of the background is uniform in right ascension (RA), and proportional to the observed event rate as a function of declination. The spatial PDF of signal events is assumed to be a bivariate Gaussian with standard deviation equal to the event angular error estimator in both directions. This is a common approximation used in previous analyses of neutrino data, although it is known to be less than optimal [7]. The energy PDF is estimated from the distribution of the reconstructed energy as a function of energy and declination. For the background, it is once again built from the data. For the signal, it is built by simulating signal events with true energy following a power-law with different values of the spectral index γ. In each case, a two-dimensional histogram of the events as a function of reconstructed muon energy and declination is built, and used as basis for an interpolation in the continuous space of the event energy.

3. `icecubepy` performance: sensitivity and discovery potential

The performance of the `icecubepy` analysis is evaluated by comparing the test statistic distribution obtained under the background hypothesis with the test statistic distributions obtained when simulating a signal. The TS distribution under the background hypothesis is studied from synthetic background data sets. These are realised by assigning random right ascention values to the event data, hence removing any potential spatial correlation potentially arising from the presence of point sources. Repeating the process, many background data sets (*realisations*) are obtained, from which the distribution of TS values can be evaluated. The analysis is repeated $O(10^9)$ times, each time evaluating the maximum likelihood at a random declination δ, sampled from a uniform distribution in $\sin\delta$. With this procedure, the dependence of the background TS distribution on δ is characterised. From the background TS distribution, local (pre-trial) p-values can be estimated. These represent the probability of observing a TS value above an observed one, λ, under the background hypothesis. The p-value for an observed TS, λ, is hence equal to the integral of the background TS distribution over the interval $[\lambda, +\inf]$. Below a local significance of $2.5\,\sigma$, the histogram of the background TS distribution is used as PDF. Above this threshold, the distribution fitted with a gamma distribution, to make the result robust against statistical fluctuations of the histogram at high values of TS. Signal realisations are generated by modelling a point-source as a power-law spectrum. Each realisation is constructed by injecting a simulated source, characterised by a given flux normalization and spectral index, into a background dataset. By fixing the spectral index and varying the flux normalization, key performance metrics such as the *sensitivity* and *discovery potential* are estimated. The sensitivity is the flux level at which 90% of the signal realisations produce a TS greater or equal to the background median. The discovery potential for a given local significance (e.g., $5\,\sigma$, in Gaussian standard equivalent units) is defined as the flux at which 50% of the signal realisations exceeds the TS value that, if observed, would yield the p-value corresponding to the given significance. The sensitivity and discovery potential of the analysis implemented in `icecubepy` are evaluated as a function of declination and shown in Figure 1. The results are overall consistent with those published by the IceCube Collaboration. Observed differences can be attributed to limitations of the instrument response functions released with the public data, that are not as accurate as complete Monte Carlo data sets used in IceCube internal analyses. Such differences are also observed in the SkyLLH analysis of this public dataset [gray points 8], further supporting this interpretation.

4. First applications

4.1 Local p-value maps for candidate neutrino sources

Local p-values are estimated for regions of interest (ROIs) centred on the coordinates of TXS 0506+056 (RA: 77.36°, Dec: 5.69°; J2000) and NGC 1068 (RA: 40.67°, Dec: −0.01°; J2000), the two most promising point-like neutrino sources known to date. For representation purposes, the L-value, $L = -\log_{10}(p)$, is reported. The morphology of the local L-value map is consistent with the IceCube results. The L-values measured with `icecubepy` are of 3.5 for TXS 0506+056 and 5.0 for NGC 1068, compared to values, estimated by IceCube, of 3.72 and 4.74.

4.2 Comparison to IceCube catalogue searches

A catalogue of 110 astrophysical sources, selected based on their γ-ray properties, was investigated by the IceCube Collaboration using the 10-year dataset [11]. This list includes NGC 1068 and TXS 0506+056. We evaluate the L-values for these sources with `icecubepy` and compare them with those published by the IceCube Collaboration, based on the same data (but proprietary detector

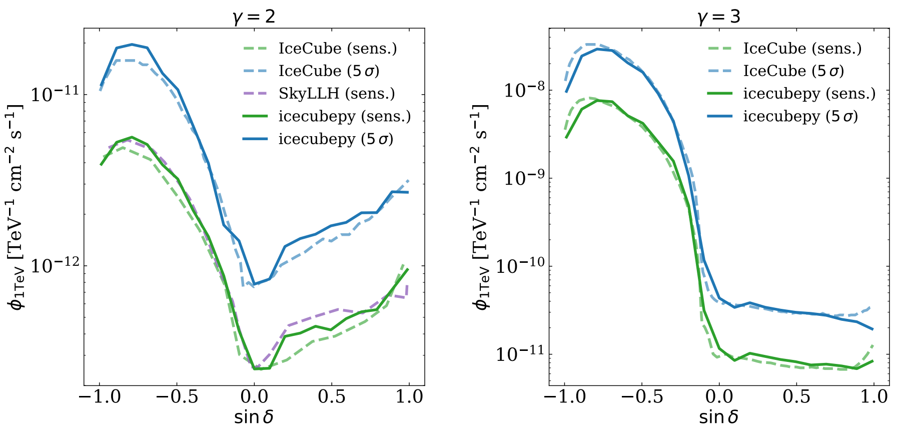

Figure 1: Sensitivity and 5 σ discovery potential of `icecubepy` for an injected source with spectral index $\gamma = 2$ (left) and $\gamma = 3$ (right) as a function of declination. The sensitivity and 5σ discovery potential of the full dataset published by [11] are shown with the "IceCube" label. The sensitivity of the public dataset using SkyLLH is retrieved from [8]. Fluxes (ν_μ+$\bar{\nu}_\mu$) are evaluated at 1 TeV. The black and gray dashed lines indicate declinations where known discontinuities occur in the Instrument Response Functions and the dataset, i.e. $-10°$, $-5°$ and $+10°$. These also coincide with abrupt changes in the analysis performance [10].

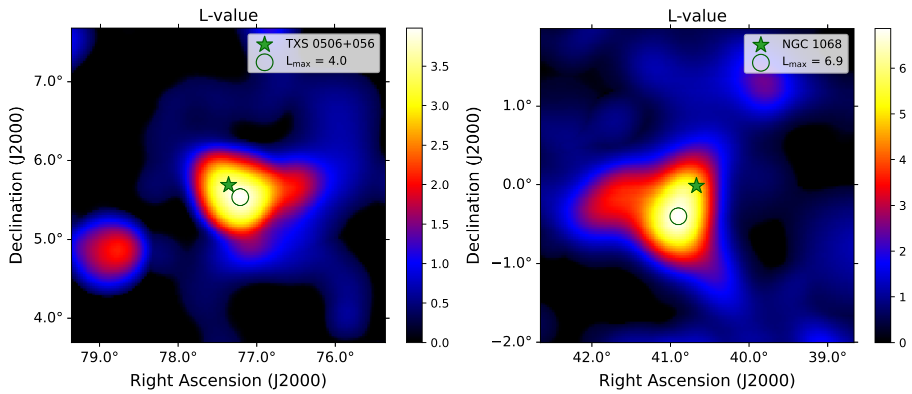

Figure 2: L-value map of a 3-degree radius region of interest centred on the coordinates of TXS 0506+056 (left) and NGC 1068 (right). The astrophysical source is represented by a star-shaped marker. The blue circle indicates the point of maximum L-value in the region (L_{max}).

information). As shown in 3 (left), the L-values obtained with `icecubepy` from the public dataset, are largely consistent with the IceCube results, demonstrating the reliability of our implementation.

4.3 Comparison with hotspots in the IceCube 7-year southern skymap

`icecubepy` provides a framework to independently assess previous results and enables the astrophysical community to carry out studies using the public IceCube muon-track dataset. As a first application presented here, we focus on the 7-year southern hemisphere hotspots considered in [3]. At these sky locations, showing the highest discrepancy from the background expectation, the IceCube Collaboration reported L-values $L \geq 4$. We evaluate the TS and corresponding L-values at the same coordinates, for the hypothesis of a point-source with a power-law spectrum.

The L-values obtained with `icecubepy` are presented in Figure 3 (right panel, green markers) in comparison with those published by the IceCube Collaboration. We find that the L-values are systematically lower than those extracted from the IceCube sky map. A similar trend is observed when analysing the same locations with the SkyLLH software [blue, 9]. While the results from `icecubepy` and SkyLLH are broadly consistent with each other, both differ noticeably from the values published by the IceCube Collaboration. The primary difference between the IceCube 7-year study and our work is the dataset. Besides the through-going muon-track events in the public data [2], the 7-year IceCube southern analysis included starting tracks, i.e. muons-tracks originating within the detector. These have typically relatively poor angular resolution compared to through-going tracks, but a higher purity. The limited accuracy of the instrument response functions accompanying the public data set may as well influence the observed results. While for the northern hemisphere the 7-year sky map used in [3] has been superseded by the improved point-source analysis presented in [7], it still represents the most sensitive analysis of the southern celestial hemisphere made publicly available by the IceCube Collaboration to date.

The consistency of results between `icecubepy` and SkyLLH indicates that the differences with respect to the IceCube published 7-year southern sky map are unlikely to be due to the analysis methods. At the same time, it confirms that `icecubepy` can be reliably used for multimessenger studies. Moreover, the absence of a blazar/neutrino correlation reported by [8] in a southern sky analysis extended to 10 years of public data does not necessarily contradict the original findings [3, 4]. Given that the software used in [8], i.e. SkyLLH, when applied to the public dataset, also does not reproduce the IceCube Collaboration 7-year southern hotspots, it is not expected that the previously observed correlation can be recovered.

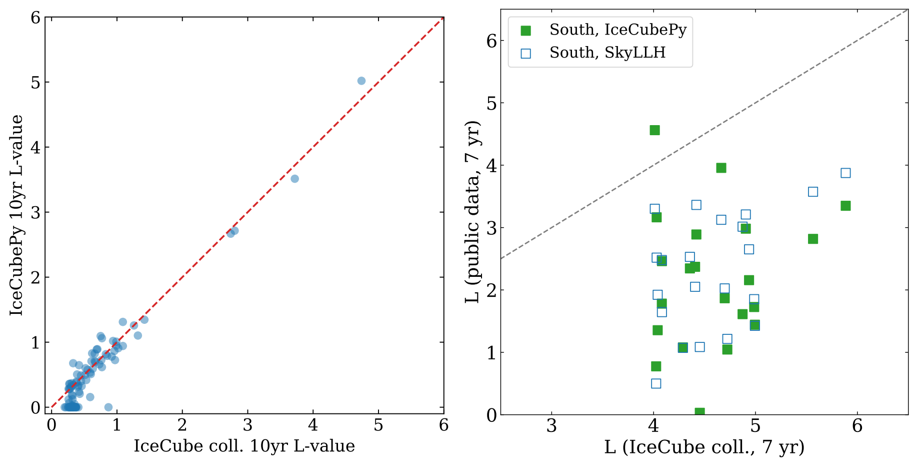

Figure 3: Left: L-value estimated with `icecubepy` as a function of the L-value published by the IceCube Collaboration for a sample of 110 candidate neutrino sources selected on the basis of their gamma-ray properties. Right: L-values ($L = -\log_{10} p$) estimated with `icecubepy` (green, full markers) and SkyLLH (blue, hollow markers) using 7 out of 10 year of the public data release as a function of the L-value extracted from the 7-year sky map published by the IceCube Collaboration [6], for the Southern hemisphere. Only positions with $L \geq 4.0$ in the IceCube skymap are considered.

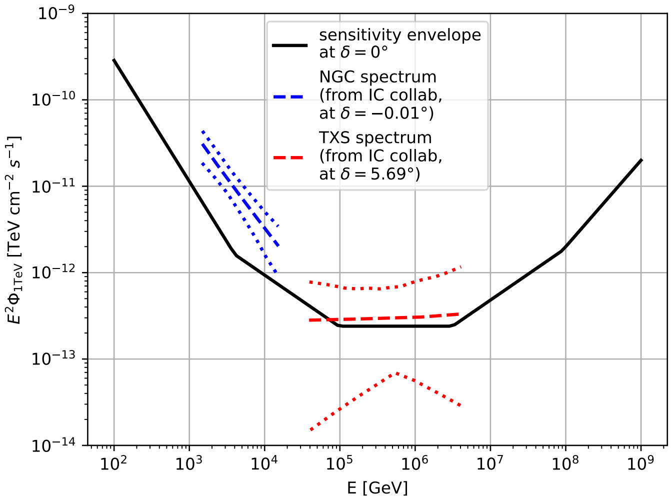

Figure 4: Sensitivity envelope for a source at declination $\delta \simeq 0$ estimated with `icecubepy`. The confidence intervals of the IceCube Collaboration estimates of the TXS 0506+056 ($\delta \simeq +5.7$) and NGC 1068 ($\delta \simeq 0$) fluxes from [7] are plotted as comparison.

5. Constraining the neutrino component in blazar spectral energy distributions

A challenging task for point-source neutrino analyses, beyond the estimation of local significances, is constraining the intrinsic neutrino spectrum of an hypothetical point source, from the observed data. This is a key ingredient in multimessenger astronomy studies, as it can be used to place additional constraints to theoretical models of candidate neutrino sources, such as [12].

For those cases in which the observed value of TS at the source coordinates is consistent with the background expectation, the analysis sensitivity represents the 90% upper limit to the source neutrino flux. However, this relies on the source spectrum having fixed spectral index γ that, a priori, is unknown. To overcome this limitation, an *envelope* of sensitivity fluxes is constructed by evaluating the change in sensitivity, $\phi_s(E)$, as a function of the spectral index, $\phi_s(E;\gamma)$, and taking the maximum flux across the different indices as a function of energy: $\max_\gamma \phi_s(E;\gamma)$. In presence of a null observation, this construction allows to conservatively set the 90% upper limits for a power-law source independently of its spectral index. An example of such sensitivity envelope evaluated at $\delta = 0$ is shown in Figure 4. The qualitative comparison with the IceCube Collaboration flux measurements for TXS 0506+056 and NGC 1068 from [7] show that these fluxes are above the sensitivity flux, which is expected given the tentative observation of neutrino signals from these sources. An extension of the approach used to estimate the sensitivity fluxes can be applied to derive confidence intervals of the neutrino flux parameters for a hypothetical point source, given an observed value of TS. A study of more refined and exhaustive methods is currently ongoing.

6. Conclusion and outlook

We presented `icecubepy`, an open source likelihood framework for conducting point-source analyses of the public data from the IceCube Neutrino Observatory. The preliminary investigations carried out show that `icecubepy` produces results largely consistent with those published by the IceCube Collaboration. When discrepancies are observed, these are at least in part attributed to the use of different datasets. This is the case in the local significance of the 7-year hotspots of the southern hemisphere, for which a correlation with a subset of 5BZcat blazars had been observed.

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