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High-energy neutrino emission from the Seyfert galaxy NGC 7469

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Abstract. In the recent years we are witnessing the birth of high-energy neutrino astronomy. In 2013, the IceCube collaboration announced the detection of a high-energy astrophysical neutrino flux and in 2022 the highest evidence to date (4.2 sigma) of neutrino emission from a single source, the Seyfert galaxy NGC 1068. Nevertheless, as the great majority of sources is still unidentified, IceCube sends out realtime alerts for neutrinos with a high probability of astrophysical origin to encourage electromagnetic follow-up with the goal to identify new counterparts. The two neutrino alerts IC220424A and IC230416A, with energies around 100 TeV, both coincided with the Seyfert galaxy NGC 7469, 70 Mpc away. To determine whether this coincidence happened by chance, we designed a statistical test to determine the p-value of the background hypothesis. As a result, we get a p-value of 4.4×10^{-4}, disfavoring the background scenario with a significance of 3.3σ. NGC 7469 was undetected in previous IceCube point source searches. To explain the association of the two high-energy neutrinos together with the non-detection, the neutrino spectrum would have to follow a power-law with a hard spectral index. Such a neutrino spectrum would differ greatly from the soft power-law associated with NGC 1068.

1 Introduction

When high-energy protons or heavy nuclei collide with proton or photon targets, charged mesons are produced. In their decay chain, neutrinos are produced. This is the sole way to produce high-energy neutrinos. An astrophysical origin of high-energy neutrinos has been proven by the IceCube Collaboration in 2013 with the detection of a diffuse neutrino flux above 30 TeV (Aartsen et al., 2013). However, it has not been possible to associate this neutrino flux with a known source population. Candidate sources for neutrino production must be capable of accelerating protons or heavy nuclei to high energies and host a target for those to interact with. Active Galactic Nuclei (AGN) belong to the most promising candidates for the production of high-energy neutrinos.

Indeed, all extragalactic source candidates identified so far are accreting supermassive black holes. Among these, we recall the flaring γ-ray blazar TXS 0506+056 (IceCube Collaboration et al., 2018), the tidal disruption events AT2019dsg (Stein et al., 2021) and AT2019fdr (Reusch et al., 2022), and the most significant one, the nearby Seyfert galaxy NGC 1068 with a significance of 4.2 σ (Abbasi et al., 2022). The neutrino production in Seyfert galaxies has been explained by several models involving coronae, shocks, winds, and their interaction with dense material (Eichmann et al., 2022; Inoue et al., 2022; Kheirandish et al., 2021; Inoue et al., 2020; Murase et al., 2020).

In this work, we consider a new candidate source for high-energy ($\sim 100\,\mathrm{TeV}$) neutrino emission, the Seyfert galaxy NGC 7469. Two 100 TeV neutrinos selected by the IceCube realtime system (Blaufuss et al., 2019), IC220424A and IC230416A, were spatially coincident with the Seyfert galaxy, located at a redshift of 0.016 (Koss et al., 2022). The focus of this work is the estimation of the chance probability of a similar coincidence, i.e. of two neutrino realtime alerts with a likely neutrino emitter. In this estimate, we consider two different source catalogs (as likely neutrino emitters), the Million Quasars (Flesch, 2023) and the Turin-SyCAT catalog (Peña-Herazo et al., 2022).

The structure of this proceeding is as follows: In Sec. 2 we briefly outline the main physical properties and differences between NGC 7469 and NGC 1068. Sec. 3 explains the features of the IceCube realtime system and of the neutrinos coincident with NGC 7469. The statistical test which estimates the chance probability is presented in Sec. 4 and its results in Sec. 5. Sec. 6 discusses the results and the features of the possible neutrino emission from NGC 7469.

2 Physical features of NGC 7469 and NGC 1068

The two sources NGC 1068 and NGC 7469 are both Seyfert galaxies, both host starburst activity. NGC 7469 is a Seyfert 1, i.e. with broad emission lines and, according to the unified model (Antonucci, 1993), without an obscuring torus in our line of sight. NGC 1068 is a Seyfert 1.9, so with a weaker broad-line component and with a dust torus partly obscuring our view onto the nucleus. NGC 7469 is five times more distant than NGC 1068, which is located at 14.4 Mpc. Nevertheless, the observed X-ray fluxes of the two sources are comparable (Ricci et al., 2017). This can be expected, taking into account the different viewing angle with respect to the dust torus. Indeed, the intrinsic X-ray flux (also shown in Fig. 3) estimated by Ricci et al. (2017) is ~ 3 times larger for NGC 1068 than for NGC 7469.

3 Neutrino events from IceCube

The IceCube neutrino observatory consists of 5160 digital optical modules (DOMs), sensitive to the single photon, embedded in 1 km^3 of antarctic ice in close proximity to the Amundsen Scott South Pole Station (Aartsen et al., 2017b). When a neutrino interacts with the surrounding ice or the nearby bedrock, secondary charged particles are produced. IceCube detects the Cherenkov light emitted by those secondary particles. The detected light patterns can be classified as “tracks” or “cascades”. If a neutrino interacts through a neutral current (NC) interaction or produces an electron or a tau through a charged current (CC) interaction, the light pattern has a spherical shape, which we refer to as a cascade. Instead, if a muon is produced by a CC or by a cosmic-ray shower and enters the detector, the light pattern is track-like. The direction of cascade-like events is harder to reconstruct, which typically results in angular uncertainties of $\sim 10°$. On the other hand, track-like events offer more directional information and are reconstructed with uncertainties of typically less than $1°$.

3.1 The IceCube realtime alerts

Since 2016, IceCube sends out realtime alerts as soon as track-like events with a high probability of astrophysical origin are detected (Aartsen et al., 2017c). This realtime alert system was then updated in 2019 with the introduction of two streams called “Gold” and “Bronze” with an average signalness (probability of astrophysical origin) of 30% and 50% respectively (Blaufuss et al., 2019). Few seconds after the detection, a Global Coordinate Network (GCN) Notice[1] is sent out reporting a first reconstructed direction and angular uncertainty obtained with the algorithm SplineMPE (Sommani et al., 2023). After a few hours a GCN Circular[2] is sent out with an updated direction and angular error reconstructed with a more time-consuming algorithm referred to as Millipede (Aartsen et al., 2014; Lagunas Gualda et al., 2021; Sommani et al., 2023). SplineMPE is significantly faster and relies on a simplified light-emission model, while Millipede has a more realistic light-emission description, but at the same time requires much more computational resources (Aartsen et al., 2014; Lagunas Gualda et al., 2021; Sommani et al., 2023).

3.2 Neutrino dataset for the chance probability estimation

Although Millipede is a more sophisticated algorithm, Monte Carlo studies indicate that SplineMPE is more precise (Lagunas Gualda et al., 2021; Sommani et al., 2023). Moreover, the areas of the angular uncertainty regions released with the GCN Circular (Millipede) are on average more than 10 times bigger than the ones of the first GCN Notice (SplineMPE).

For the reasons listed above, we use the angular errors from the first GCN Notice in our estimation of the chance probability in Sec. 4. The neutrino dataset used in the test includes the bronze and gold alerts released since June 2019 until October 2023, covering a period of 4 years. The IceCat catalog (Abbasi et al., 2023) contains more neutrino alerts, starting from 2011, but includes only directions and uncertainties based on Millipede.

The GCN Notices released by IceCube report the radius with 50% and 90% containment. Our calculation for the chance probability (Sec. 4) models IceCube’s point-spread function as a bivariate

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[1] `https://gcn.nasa.gov/notices`

[2] `https://gcn.nasa.gov/circulars`

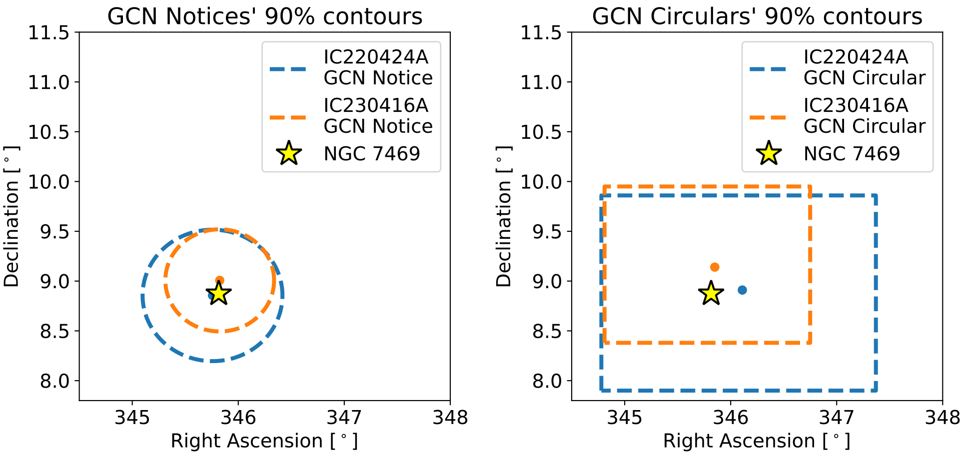

Figure 1: Angular reconstructions reported in the GCN Notices (left) and in the GCN Circulars (right) for the neutrino alerts IC220424A and IC230416A. The figures show the 90% uncertainties, the best-fit directions, and the position of NGC 7469.

Gaussian and makes use of its standard deviation σ. To extrapolate this σ, we take the 50% containment error and re-scale it to the corresponding σ of a bivariate Gaussian.

3.3 IC220424A & IC230416A

Two neutrino alerts, detected on April 24, 2022, and almost a year later on April 16, 2023, were found coincident with the position of the Seyfert galaxy NGC 7469. The two neutrino events are known as IC220424A and IC230416A, respectively. For both events the GCN Notices[3] and GCN Circulars (IceCube Collaboration, 2022; IceCube Collaboration, 2023) are available. The uncertainty contours released in the GCN Notices and GCN Circular are shown in Fig. 1. IC220424A and IC230416A have a most-likely neutrino energy of 184 TeV and 127 TeV, and a signalness of 50% and 34%, respectively.

4 Statistical test

The fact that the reconstructed direction of two neutrinos is consistent with the source NGC 7469 does not prove that this is their source. This coincidence could be there by chance and the origin of the neutrinos could be unrelated to NGC 7469. The goal of this work is to estimate how likely one would find a coincidence with a similar or larger significance by chance. To estimate the chance probability, we generate mock datasets with randomized neutrino alert directions. We count then the cases where we find a neutrino doublet coincident with an *interesting source* with a higher or equal *significance*. The frequency of this corresponds to the chance probability.

Two terms need to be defined before performing this calculation: how do we define an *interesting source* (Sec. 4.2) and how do we define the *significance of the coincidence* (Sec. 4.3).

4.1 Neutrino background datasets

To generate datasets of IceCube realtime alerts with random directions, we take the observed list of realtime alerts and scramble their right ascension. We do not change the declination because IceCube's effective area depends on it (Abbasi et al., 2023).

4.2 Source catalogs

We define a source as an *interesting source*, if it belongs to an inclusive list of potential neutrino emitters. The detection of neutrinos from NGC 1068 (Abbasi et al., 2022) identifies Seyfert galaxies as likely neutrino sources. It is currently unknown if all Seyfert galaxies or only a subset can host neutrino production, if the same mechanism takes place in other types of AGN and which electromagnetic properties trace the

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[3] GCN Notice for IC220424A: `https://gcn.gsfc.nasa.gov/notices_amon_g_b/136565_2186969.amon`
GCN Notice for IC230416A: `https://gcn.gsfc.nasa.gov/notices_amon_g_b/137840_57034692.amon`

neutrino emission. To be agnostic and avoid fine-tuning of our test, we take into account the following two catalogs:

- all the AGN in the Milliquas catalog (Flesch, 2023). In total, made of 50757 sources. This is the most agnostic catalog, as it includes all AGN as interesting sources;
- the Seyfert galaxies from the Turin-SyCAT catalog (Peña-Herazo et al., 2022). The same catalog was studied by (Neronov et al., 2023) and includes 351 sources, selected based on multifrequency observations.

4.3 Test statistic

We define a doublet as *any* pair of neutrinos. We define a coincidence as a pair of a doublet and *any* source in our catalog. Our test is based on a metric which penalizes coincidences based on: the angular distance of the neutrino doublet from the source position (taking into account IceCube's point-spread function) and the distance of the associated source, given by its redshift. This means that a doublet coincident with a distant source should get assigned a smaller significance compared to a coincidence with a close-by source.

This metric will be applied to our mock datasets to generate a distribution for the background-only scenario. This can then be compared to the value of the metric for our observation of the two neutrino alerts coincident with NGC 7469.

We define our metric as a test statistic TS, which is based on a log-likehood ratio λ[4]:

$$TS(A_i, A_j|S) \propto \lambda(A_i, A_j|S) = 2\log\frac{p_1(A_i, A_j|S)}{p_0(A_i, A_j)}\,, \tag{1}$$

where A_i is the i-th neutrino alert, S is a source, p_0 is the probability of having the neutrinos A_i and A_j at their specific energy and direction by considering them as background, and p_1 is the same probability but assuming they were generated by the source S. Sec. 4.3.1 outlines how p_0, the background probability, is defined. p_1, the alternative probability, is explained in Sec. 4.3.2.

The test statistic in Eq. 1 refers to a doublet associated to a specific source S. We can easily define a test statistic per-doublet just by picking the source which maximizes the test statistic:

$$TS(A_i, A_j) = \max_S\left[TS(A_i, A_j|S)\right] \propto 2\log\frac{\max_S\left[p_1(A_i, A_j|S)\right]}{p_0(A_i, A_j)}\,. \tag{2}$$

4.3.1 Background probability If the two neutrinos A_i and A_j are background, the two alerts are independent of each other and therefore also the probabilities of detecting a single neutrino are independent:

$$p_0(A_i, A_j) = p_0(A_i)p_0(A_j)\,. \tag{3}$$

The probability of detecting the single neutrino A_i in case of an isotropic background is determined only by the effective area of IceCube:

$$p_0(A_i) = \frac{1}{2\pi}\cos\theta_i\, a(\theta_i, E_i)\,, \quad \text{where :} \quad a(\theta_i, E_i) = \frac{A_{\rm eff}(\theta_i, E_i)}{\int A_{\rm eff}(\theta, E)\cos\theta d\theta dE}\,, \tag{4}$$

where θ_i is the declination of the i-th alert, E_i is its most-likely neutrino energy, and $A_{\rm eff}$ is the effective area of IceCube for realtime alerts, taken from (Abbasi et al., 2023).

4.3.2 Alternative probability The alternative hypothesis to the background scenario, assumes that a specific source S has produced the two neutrinos. To estimate a probability for this second scenario, we split p_1 into:

- the probability for the source S of producing *at least* two neutrino alerts $p_{2\nu}(S)$;
- the probability for the two neutrinos of being produced at a specific angular distance from the source S $p_{\rm dist}(A_i, A_j|S)$.

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[4] The test statistc is defined without constant factors as they do not change the outcome of the estimations.

Table 1: Statistical test results

Catalog	Best-doublet	Source	p-value	p-value (in σ)
Milliquas	IC220424A & IC230416A	NGC 7469	3.2×10^{-3}	2.73
Turin	IC220424A & IC230416A	NGC 7469	2.2×10^{-4}	3.51

$p_{2\nu}$ consists of the cumulative density function between 2 and $+\infty$ detections of a Poisson distribution:

$$p_{2\nu}(S) = \sum_{k=2}^{+\infty} \frac{\mu_S^k}{k!} e^{-\mu_S} = 1 - \sum_{k=0}^{1} \frac{\mu_S^k}{k!} e^{-\mu_S} = 1 - (1 + \mu_S)\, e^{-\mu_S}\,, \tag{5}$$

where μ_S is the expected number of detected neutrinos from the source S. We assume our sources to be steadily emitting. Under this assumption, μ_S is given by

$$\mu_S = T \int \phi_S(E) A_{\text{eff}}(\theta_S, E) dE\,, \tag{6}$$

where T is the total duration of the experiment and $\phi_S(E)$ is the neutrino differential flux of the source S at Earth. To evaluate this integral, we need to assume a neutrino energy spectrum for the source, which is unknown. To simplify things, we assume the same spectral shape and normalization for all sources. We select a power-law spectrum with spectral index of $\gamma = 2$. The normalization scales with the inverse distance squared, which is given by assuming a linear relation between redshift and distance.

This standard candle assumption is a pragmatic choice, which does most probably not reflect reality. Given the lack of knowledge on possible tracers of the neutrino emission, it is a conservative choice. The metric introduces an ordering scheme for the found neutrino doublet and source coincidences. With these assumptions, by performing the integral in Eq. 6 we get:

$$\mu_S = \frac{H_0^2 T}{4\pi z_S^2 c^2} \phi_0 E_0^2 \sum_k A_{\text{eff}}\left(\theta_S, E_k\right) \frac{E_k^+ - E_k^-}{E_k^+ E_k^-}\,, \tag{7}$$

where H_0 is the Hubble constant, z_S is the redshift of the source S, E_0 is the lowest energy bound for the effective area of IceCube from Abbasi et al. (2023), ϕ_0 is the differential flux at the source at energy E_0 (same for all sources), and E_k^+ and E_k^- are the low and high-energy bounds for the various energy bins in IceCube's effective area. To completely define μ_S for all sources, the value of ϕ_0 has to be defined. By going in the regime of small fluxes, i.e. having ϕ_0 small enough to have $\mu_S \ll 1$, the probability in Eq. 5 becomes $p_{2\nu} \simeq \frac{1}{2}\mu_S^2$. Thereby, in the test statistic in Eq. 1 ϕ_0 is just a constant factor and therefore does not influence the outcome of our calculation. In other words, by choosing a ϕ_0 small enough the outcome becomes independent of the specific value of ϕ_0 and the only factor defining the "significance" of the specific sources will be the redshift. For this reason, we require for our test $\phi_0 < 10^{37}$ s^{-1}GeV^{-1}. This choice indicates that all source have an expectation value smaller than one, which might seem unrealistic. However, due to the Eddington bias (Strotjohann et al., 2019), Poisson fluctuations are not unlikely given the fact that we consider a large list of sources. Furthermore, given the lack of knowledge on the neutrino production in AGN, our goal is not to describe a realistic scenario, but to find a pragmatic weighting scheme for neutrino doublet and source coincidences.

The probability of the two neutrinos to be located at a certain angular distance from the source $p_{\text{dist}}(A_i, A_j|S)$ is described by a Gaussian distribution:

$$p_{\text{dist}}(A_i, A_j \,|\, S) = \frac{1}{4\pi^2 \sigma_i^2 \sigma_j^2} \exp\left[-\left(\frac{\Omega_{Si}^2}{2\sigma_i^2} + \frac{\Omega_{Sj}^2}{2\sigma_j^2}\right)\right], \tag{8}$$

where σ_i is obtained as described in Sect. 3.2 and where $\Omega_{Si}^2 = (\varphi_S - \varphi_i)^2 + (\theta_S - \theta_i)^2$ with right ascension φ_S and declination θ_S of the source. Combining Eq. 5 and Eq. 8 we get the complete alternative probability $p_1(A_i, A_j|S)$.

5 Results

By testing the Milliquas (Flesch, 2023) and the Turin (Peña-Herazo et al., 2022) catalog (Sec. 4.2) we generated 7×10^4 and 3×10^5 background datasets, respectively, as outlined in Sec. 4.1. For each dataset,

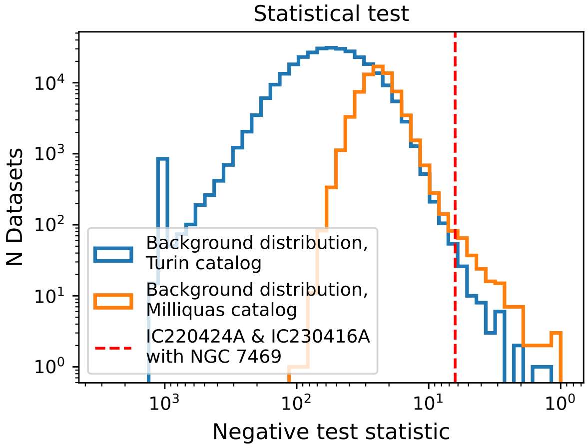

Figure 2: Test statistic distributions under the background hypothesis for the Turin (Peña-Herazo et al., 2022) and Milliquas (Flesch, 2023) catalogs. For the Turin catalog 3×10^5 mock-background datasets were generated, and for the Milliquas catalog 7×10^4 datasets. The red dashed vertical line indicates the test statistic for the neutrino doublet coincident with NGC 7469. The Turin background distribution has a 'bump' at a test statistic of -10^3, which is an artifact of assigning a test statistic value of -10^3 in cases where no source is found close to a neutrino doublet to save computing time. This does not impact the result.

we select the highest test statistic value (Sec. 4.3) and we compare their distribution to the test statistic value for IC220424A & IC230416A with NGC 7469 (see Fig. 2).

Table 1 shows the results for the tests with the two catalogs.

The two catalogs represent two separate trials of our test. The sources in the Turin catalog (Peña-Herazo et al., 2022) are also included in the Milliquas catalog (Flesch, 2023). Therefore, the two tests are not independent. However, we aim to be conservative and multiply the p-value by factor of 2, resulting in a global p-value of 4.4×10^{-4}, which corresponds to a Gaussian one-sided significance of $3.33\,\sigma$.

6 Discussion

Our result disfavors the background-only hypothesis. Assuming that both neutrinos are produced by NGC 7469, we calculate the corresponding neutrino flux assuming a steady neutrino emission for the whole 4 years covered by our neutrino dataset. First, we estimated a confidence interval on the rate of neutrinos from the source detected by IceCube $\lambda_{\nu_\mu+\bar{\nu}_\mu}$ and then converted it to an energy flux through the equation $\Phi_{\nu_\mu+\bar{\nu}_\mu} = \lambda_{\nu_\mu+\bar{\nu}_\mu}/(EA_{\text{eff}}(E))$. This estimation depends strongly on the neutrino energy, which has large uncertainties. We provide an energy uncertainty based on the method used to estimate the energy of IC170922A (IceCube Collaboration et al., 2018). More precisely, IceCube Collaboration et al. (2018) reports a most likely neutrino energy of 290 TeV and a lower limit at 90% confidence level (CL) of 183 TeV. In the same way, we adopt a lower limit at 27 TeV (100 TeV less than the lowest energy of the two neutrino events). We include as well an upper limit at 20 PeV, indicating the highest energies that IceCube should be able to detect. This results in an energy range of 27 TeV to 20 PeV for the two neutrinos from NGC 7469 at 90% confidence (see Fig. 3).

No precedent IceCube analysis ever showed hints of neutrino emission from NGC 7469. For a reference of a typical sensitivity of IceCube's searches, we report in Fig. 3 the sensitivity from an all-sky search for time-integrated neutrino emission from astrophysical sources with 7 years of IceCube data (Aartsen et al., 2017a). The precedent non-detections would be in agreement with the two neutrinos of this work if the neutrino spectrum of NGC 7469 follows a power-law shape with a hard spectral index or peaks at high energies. A hard neutrino spectrum could be explained by magnetized strongly turbulent corona with a non-resonant cosmic ray acceleration (Fiorillo et al., 2024; Murase et al., 2024). Its spectrum would be much harder than the one measured for NGC 1068, which can be explained by substantially different models involving diffusive shock acceleration (Inoue et al., 2022; Inoue et al., 2020) or gyroresonant stochastic acceleration (Kheirandish et al., 2021; Murase et al., 2020). A harder spectrum would point to a spread in spectral properties in the population of neutrino emitting Seyfert galaxies.

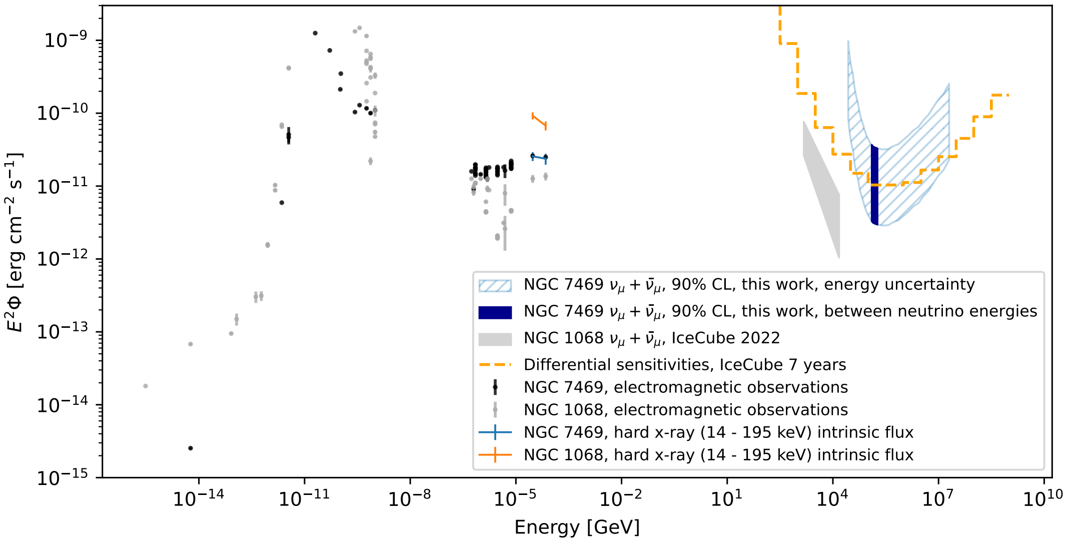

Figure 3: Multimessenger spectral emission distributions (SEDs) of the two sources, NGC 7469 and NGC 1068. Electromagnetic observations from Oh et al. (2018), Webb et al. (2020), Saxton et al. (2008), Boller et al. (2016), Evans et al. (2013), Cutri et al. (2013), Aghanim et al. (2020), Murphy et al. (2010), Skrutskie et al. (2007), Lane et al. (2014), and Condon et al. (1998). Neutrino flux of NGC 1068 from Abbasi et al. (2022). Differential sensitivities from Aartsen et al. (2017a). Intrinsic X-ray fluxes from Ricci et al. (2017). The confidence interval for the emission of NGC 7469 was estimated in this work. The width in energy of the confidence interval spans from 27 TeV to 20 PeV, reflecting the uncertainty on the true neutrino energy. The shape of the confidence interval reflects the dependence of IceCube's effective area for realtime alerts reported in Abbasi et al., 2023 and has nothing to do with the neutrino energy spectrum of the source.

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