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Linking hard X-ray and high-energy neutrino emission from radio-loud and radio-quiet AGN

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High-energy neutrinos, detected by the IceCube Neutrino Observatory, have been linked to both radio-loud and radio-quiet active galactic nuclei (AGN). While jets are often invoked to explain neutrino production in radio-loud AGN, we explore an alternative scenario based on observations: particle production in the gamma-obscured cores near supermassive black holes. We report comparable unabsorbed hard X-ray and neutrino luminosities in six AGNs, including the radio-quiet Seyfert galaxy NGC 1068 and the radio-loud blazar TXS 0506+056. Our findings point to a possible common origin of neutrino emission in diverse AGN classes.

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1. Introduction

The IceCube Neutrino Observatory allowed several groundbreaking discoveries, including the detection of high-energy ($\sim$ 10 GeV–10 PeV) astrophysical flux of cosmic neutrinos of unknown origin [1], and the identification of individual astrophysical sources associated with high-energy neutrino emission, such as a radio-loud [2] and a radio-quiet AGN [3], as well as the Galactic Plane [4].

The first neutrino source confirmed at $> 3\sigma$ significance was the blazar TXS 0506+056 [2], a type of active galactic nuclei (AGN) with one of its relativistic jets aimed toward Earth. These jets are theorized to produce high-energy neutrinos via proton-photon ($p\gamma$) or proton-proton (pp) interactions [see e.g., 5–8], with the latter requiring external material [9] and/or jet structuring [10]. The second confidently associated neutrino source was the Seyfert galaxy NGC 1068 [3], a radio-quiet AGN with weaker jets. Its hard X-ray emission is believed to arise predominantly from the hot corona around the accretion disk of its central black hole. Other sources have also been linked to neutrinos, including two blazars (PKS1502+106 [11], PKS1424−41 [12]) and three Seyfert galaxies (NGC 4151, NGC 3079, and CGCG420-015) [13–15]. Candidate sources also include PKS1424+240 (3.7σ) and GB6 J1542+6129 (2.2σ) [3], potentially masquerading BL Lacs [16].

Neutrinos are accompanied by γ-rays from hadronic processes, but if produced near the AGN core, these γ-rays can be reprocessed into hard X-rays through pair production [14, 17–19]. The absence of γ-rays observed during the neutrino-episode from many candidate neutrino source AGN is consistent with this scenario [e.g., 20, 21]. Even blazars exhibit temporary γ-ray dimming during neutrino events, and diffuse neutrino spectra show signs of γ-absorption [17, 22].

This suggests that the hard X-ray luminosity, arising from reprocessed γ-rays, should match the neutrino luminosity in cosmic particle accelerator AGN. A linear correlation between the unabsorbed hard X-ray and high-energy neutrino fluxes was proposed by [23], and later used to predict promising neutrino source AGNs [17]. AGN such as NGC 1068 [$z = 0.003810$, 24], NGC 3079 [$z = 0.00399$, 25], and NGC 4151 [$z = 0.003152$, 25] were found to have comparable unabsorbed hard X-ray luminosities (15–195 keV) and all-flavor neutrino fluxes [14], reinforcing the proposed X-ray–neutrino link.

In this paper, we show that a similar correlation holds for six AGN, including four Seyferts (NGC 1068, NGC 4151, NGC 3079, and CGCG 420-015) and, most notably, two radio-loud objects of the blazar subtype (TXS 0506+056 and GB6 J1542+6129). This finding is particularly ground-breaking, as radio-loud AGN are thought to produce neutrinos via different mechanisms and different emission sites compared to their radio-quiet counterparts.

2. Cosmic messengers for the radio-quiet and two radio-loud AGN in our sample

2.1 Hard X-ray fluxes

To explore the connection between AGN X-ray and neutrino emission, we investigated the unabsorbed hard X-ray fluxes of four IceCube-detected Seyfert galaxies (NGC 1068, NGC 4151, NGC 3079, and CGCG 420-015) and two blazars (TXS 0506+056 and GB6 J1542+6129). Detailed obscurer models (e.g., `MYTorus`, [26, 27]) were employed for Seyferts in the literature, while for the two blazars with new flux estimates in our work, we did not need such correction.

For NGC 1068, we extrapolated the 10–40 keV NuSTAR luminosity of 1.5×10^{43} erg s^{-1} [28] to the 15–55 keV band using the spectral index $\Gamma = 2.10 \pm 0.07$, obtaining $L_{15-55} \approx (1.36 \pm 0.15) \times 10^{43}$ erg s^{-1}. For NGC 3079, adopting *NuSTAR*-based obscuration models [29, 30], we use $L_{15-55} = (2.63^{+0.61}_{-0.59}) \times 10^{42}$ erg s^{-1}. Considering the line-of-sight column density for NGC 4151 as $N_H \sim 10^{22}$–10^{23} cm^{-2}, we derived $F_{15-55} \approx 3.1 \times 10^{-10}$ erg s^{-1} cm^{-2} using `nthcomp` parameters from [31]. For CGCG 420-015, we assumed $\log(L_{15-55}) = 43.65^{+0.09}_{-0.12}$ erg s^{-1} and $N_H = (7.15^{+0.85}_{-0.97}) \times 10^{23}$ cm^{-2} [29].

In case of TXS 0506+056 ($z = 0.3365$, [32]), we analyzed 18 NuSTAR observations between 2017 and 2021, totaling 371 ks observing time. The 15–55 keV flux varied by a factor ~2, with photon indices between 1.5–1.9. Using `tbabs*zpow` with $N_H = 1.55 \times 10^{21}$ cm^{-2}, we derived an average $L_{15-55} = (9.0 \pm 2.4) \times 10^{44}$ erg s^{-1}. We initiated hard X-ray observations of the blazar GB6 J1542+6129 ($z = 0.507$) with *NuSTAR*, which source was eventually observed with a 36 ks exposure (PI: del Palacio). Using `tbabs*zpow` and $N_H = 0.13 \times 10^{21}$ cm^{-2}, we found a photon index $\Gamma = 1.55 \pm 0.15$ and a 15–55 keV flux of $(6.0 \pm 1.2) \times 10^{-13}$ erg s^{-1} cm^{-2}. The source shows no major X-ray flaring based on Swift measurements, indicating a relatively stable flux over the 10-year observation window of IceCube.

2.2 Neutrino fluxes

We adopted the high-energy neutrino fluxes for NGC 1068, NGC 4151, and NGC 3079 from [14], assuming a power-law spectrum $\phi_\nu(E) = \phi_0(E_\nu/E_0)^{-\gamma}$ with $E_0 = 1$ TeV. All analyses are based on comparable IceCube data sets. For CGCG 420-015, we estimated the 0.3–100 TeV neutrino flux using the best-fit parameters from [15]: $\phi_0 \approx 1.2 \times 10^{-11}$ TeV^{-1} cm^{-2} s^{-1} and $\gamma \approx 2.8$. This yields $F_{\nu_\mu+\bar{\nu}_\mu} = (3.04 \pm 2.08) \times 10^{-11}$ erg cm^{-2} s^{-1}.

For TXS 0506+056, based on [3], we use $\phi_0 \approx 3.57 \times 10^{-13}$ TeV^{-1} cm^{-2} s^{-1} and $\gamma \approx 2.04$, resulting in $F_{\nu_\mu+\bar{\nu}_\mu} = (1.55^{+6.00}_{-1.27}) \times 10^{-12}$ erg cm^{-2} s^{-1}. For GB6 J1542+6129, using the best-fit neutrino number $\hat{n}_s = 16.0$ and spectral index $\gamma = 3.0$ [3], and IceCube effective area data [33], we derive $\phi_0 = 1.5 \times 10^{-12}$ TeV^{-1} cm^{-2} s^{-1} and $F_{\nu_\mu+\bar{\nu}_\mu} = (4.03 \pm 3.02) \times 10^{-12}$ erg cm^{-2} s^{-1}.

We summarize the fluxes in Table 1. and plot the resulting luminosities in Figure 1 with cosmological parameters as $H_0 = 69.6$, $\Omega_m = 0.286$, $\Omega_\Lambda = 0.714$, $T_{\rm cmb} = 2.72548$ K.

Name	**Neutrinos (0.3–100 TeV)**	**Hard X-rays (15–55 keV)**
NGC 1068	$8.99^{+4.16}_{-4.16} \times 10^{-10}$	$4.23^{+0.47}_{-0.47} \times 10^{-10}$
NGC 4151	$1.49^{+1.02}_{-1.02} \times 10^{-10}$	$3.10^{+0.31}_{-0.31} \times 10^{-10}$
NGC 3079	$8.09^{+6.65}_{-6.65} \times 10^{-11}$	$7.57^{+1.74}_{-1.69} \times 10^{-11}$
CGCG 420-015	$3.04^{+2.08}_{-2.08} \times 10^{-11}$	$2.19^{+0.51}_{-0.53} \times 10^{-11}$
TXS 0506+056	$1.55^{+6.00}_{-1.27} \times 10^{-12}$	$2.35^{+0.63}_{-0.63} \times 10^{-12}$
GB6 J1542+6129	$4.03^{+3.02}_{-3.02} \times 10^{-12}$	$6.00^{+1.20}_{-1.20} \times 10^{-13}$

Table 1: High-energy neutrino fluxes and unabsorbed hard X-ray fluxes for selected sources.

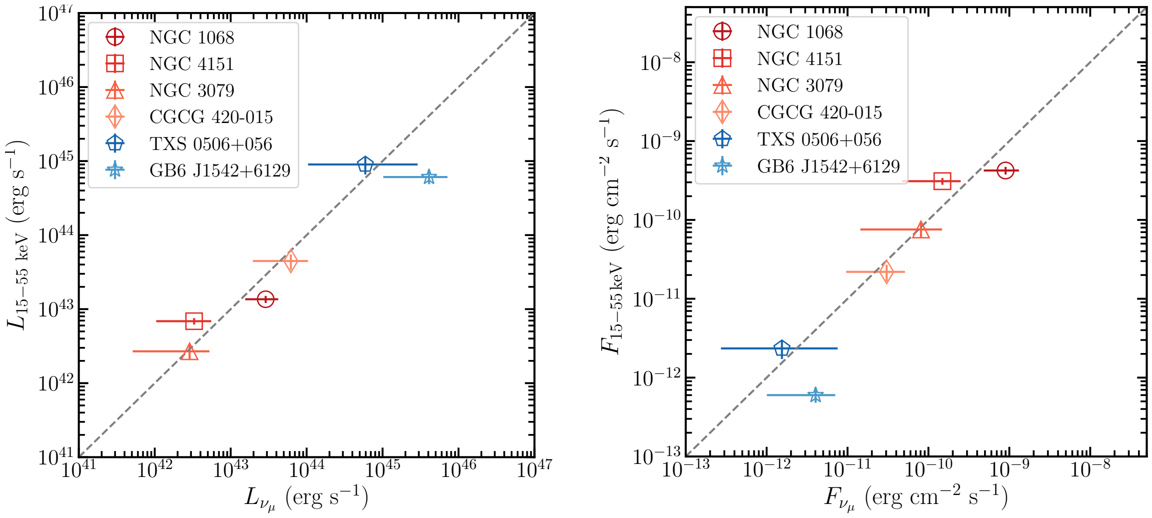

Figure 1: Correlation plot between unabsorbed hard X-rays and neutrinos in radio-loud and radio-quiet AGN in our sample. Left: Luminosity of the main (unabsorbed) hard X-ray continuum as a function of high-energy neutrino luminosity. Four Seyferts (NGC1068, NGC4151, NGC3079, and CGCG 420-015) are shown in red, and the two blazars (TXS 0506+056 and GB6 J1542+6129) in blue. The dashed line indicates $L_X = L_\nu$. Right: Same as left, but showing fluxes instead of luminosities.

3. γ-obscured neutrino sources

Figure 1. shows a potential correlation between unabsorbed hard X-ray and neutrino luminosities of four Seyferts and two blazars. The Pearson coefficient between these luminosities is $R = 0.97$ (all sources), and $R = 0.78$ for Seyferts alone, implying the blazars strengthen the correlation. This suggests a possible common emission mechanism for the radio-quiet and radio-loud sources in our sample. To refine this picture, we plan to initiate further hard X-ray observations, especially of blazars with only upper limits so far.

3.1 Does the jet significantly contribute to the hard X-ray flux of TXS 0506+056?

Two very-high-energy (VHE) phases of TXS 0506+056 following the IceCube neutrino event IC-170922A were reported [34]. The first two *NuSTAR* observations (2017-09-29 and 2017-10-19) overlapped with MAGIC observations, which revealed low VHE-flux. The corresponding hard X-ray luminosity was $(6.6 \pm 0.9) \times 10^{44}$ergs^{-1}, consistent with the overall average of the *NuSTAR* observations covered by our work ($(9.0 \pm 2.4) \times 10^{44}$ erg s^{-1}), suggesting a minimal jet contribution. Comparing *Fermi*-LAT and *NuSTAR* light curves reveals that while γ-ray emission decreases, the hard X-ray flux remains high until 2020, reinforcing the idea of gamma-ray flux reprocessing to hard X-rays (see Figure 2 in [35]). Since jet contribution is expected to be minimal, the observed hard X-rays might have been indeed originated from γ-obscured regions near the cores, rather than the jets.

3.2 Comparable hard X-ray and neutrino luminosity from γ-obscured sources

Protons accelerated near a black hole or in the accretion disk can interact with dense photon fields in the corona region, producing neutrinos and pionic γ-rays. The opacity for proton–photon

($p\gamma$) interactions depends on the inelasticity $\kappa_{p\gamma}$, photon density n_γ, cross section $\sigma_{p\gamma}$, and the size of the target region R_{target} [36]. The corresponding opacity to pionic γ-rays is governed by $\tau_{\gamma\gamma} \sim R_{\text{target}}\sigma_{\gamma\gamma}n_\gamma$. Because $\sigma_{\gamma\gamma} \gg \sigma_{p\gamma}$, the photon opacity is typically two, even three orders of magnitude larger: $\tau_{\gamma\gamma} \sim 10^3\tau_{p\gamma}$. This implies that if neutrinos are produced efficiently ($\tau_{p\gamma} \gtrsim 0.1$), the associated γ-rays are likely absorbed locally. Thus, sources can be bright in neutrinos but faint in γ-rays, which is natural in the γ-obscured AGN scenario.

[37] also showed that a linear L_X–L_ν scaling is expected in such systems when the characteristic timescale $t^\star \approx R/V$ exceeds R/c. In non-relativistic regions like AGN coronae, this leads to enhanced $p\gamma$ optical depth by factors of 10–100. These conditions naturally connect hard X-ray and neutrino luminosities in obscured AGN.

4. Summary and conclusion

We found that the unabsorbed hard X-ray and high-energy neutrino luminosities of blazar TXS 0506+056 are comparable to each other. A similar relation holds for Seyfert galaxies NGC 1068, NGC 4151, NGC 3079, and CGCG 420–015 (see Fig. 1, left). Another blazar, GB6 J1542+6129, also appears to follow this trend. We have recalculated the hard X-ray fluxes based either on more sophisticated obscuration modeling available in the literature or on new *NuSTAR* observations initiated by our team. Importantly, we did not rely on broad-band spectral modeling to attribute the 15–55 keV X-ray emission to any part of in TXS 0506+056. Instead, we based our findings on direct X-ray observations. We found that the blazars follow the same X-ray–neutrino flux relation as the Seyferts, which suggests that similar emission zones, likely coronal regions, may dominate even in blazars, at least in the 15-55keV hard X-ray energy band.

Comparable unabsorbed hard X-ray and neutrino luminosities in our sample are consistent with neutrino production in γ-obscured regions, suggesting that a common astrophysical mechanism can explain neutrino emission in both blazars and Seyfert AGNs. Nevertheless, significant uncertainties remain. The flux measurements are subject to temporal variability and limited photon statistics and to different observational windows,; neutrino events often lack precise timing information,; and modeling the unabsorbed X-ray component requires careful spectral analysis, especially in Seyfert galaxies. Despite these challenges, the observed hard X-ray—high-energy neutrino correlation is compelling. Future works should test whether this relation extends to other neutrino-bright AGNs. A larger and more diverse sample will be crucial to confirm this hypothesis and rule out alternative interpretations.

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