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# Evidence for Neutrino Emission from X-Ray Bright Seyfert Galaxies in the Southern Hemisphere Using Enhanced Starting Track Events with IceCube

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**Abstract**

IceCube recently reported the observation of TeV neutrinos from the nearby Seyfert galaxy NGC 1068, and the corresponding neutrino flux is significantly higher than the upper limit implied by observations of GeV–TeV gamma rays. This suggests that neutrinos are produced near the supermassive black hole, where the radiation density is high enough to obscure gamma rays. We use a set of muon neutrinos with interaction vertices inside the detector, which have good sensitivity to sources in the southern sky, from IceCube data recorded between 2011 and 2021. We then search for individual and collective neutrino signals from 14 Seyfert galaxies in the southern sky selected from the Swift Burst Alert Telescope AGN Spectroscopic Survey. Using the correlations between keV X-rays and TeV neutrinos predicted by disk–corona models, and assuming production characteristics similar to NGC 1068, a collective neutrino signal search reveals an excess of $6.7^{+4.0}_{-3.2}$ events, which is inconsistent with background expectations at the $3\sigma$ level of significance. In this Letter, we present new independent evidence that Seyfert galaxies contribute to the extragalactic flux of high-energy neutrinos.

*Unified Astronomy Thesaurus concepts:* Neutrino astronomy (1100); Seyfert galaxies (1447); Active galactic nuclei (16); X-ray active galactic nuclei (2035)

## 1. Introduction

Active galactic nuclei (AGN) have emerged as the leading candidates for the origin of the diffuse high-energy cosmic neutrino flux observed by the IceCube Neutrino Observatory (M. Aartsen et al. 2013). IceCube's observation of this neutrino flux in the TeV to a few PeV energy range demonstrates that hadronic interactions contribute considerably to the nonthermal Universe. The high intensity of the neutrino flux at ∼30 TeV, observed in two independent detection channels, indicates that high-energy neutrinos originate in dense environments that are opaque to gamma rays (N. Senno et al. 2015; K. Murase et al. 2016; K. Bechtol et al. 2017; A. Capanema et al. 2020; K. Fang et al. 2022); otherwise, the contribution of the cosmic neutrino sources to the extragalactic gamma-ray background would exceed measurements by the Fermi Large Area Telescope (LAT; M. Ackermann et al. 2015). This picture was reinforced by the observation of neutrino emission from NGC 1068, a nearby Seyfert galaxy (R. Abbasi et al. 2022). NGC 1068 was identified in an IceCube point source search using 8.7 yr of muon neutrinos from the northern hemisphere. NGC 1068 emerged as the most significant source in the list of sources searched, with a post-trial significance of $4.2\sigma$. A follow-up analysis with an additional 1.5 yr of data found a slightly steeper spectrum ($\gamma = 3.3$) and a post-trial significance of $4.3\sigma$ (R. Abbasi et al. 2025a). The measured flux of high-energy neutrinos from NGC 1068 was found to be much higher than the gamma-ray flux reported by Fermi-LAT (S. Abdollahi et al. 2020; J. Ballet et al. 2020) in the GeV regime, and exceeds the upper limits reported by MAGIC (V. A. Acciari et al. 2019) in the TeV band. The absence of very-high-energy gamma rays from NGC 1068 indicates that the neutrinos are produced in an environment where gamma rays are strongly obscured.

The dense central region of an AGN provides a suitable environment for the efficient production of neutrinos and the suppression of the accompanying gamma-ray signature. Obscuration can also occur at lower photon energies, from the infrared to X-ray bands, due to the dense gas and dust surrounding the AGN (P. Padovani et al. 2017). In the case of NGC 1068, the line of sight passes directly through the dense torus, causing severe X-ray attenuation, which qualifies it as a Compton-thick AGN—a class of objects where even high-energy X-rays are strongly suppressed.

The AGN corona, a matter-dense and radiation-rich region near the central supermassive black hole, is formed by accretion dynamics and magnetic dissipation (K. Miller & J. Stone 2000). The corona is composed of highly magnetized and turbulent plasma (Y. Inoue et al. 2019, 2020; K. Murase et al. 2020; B. Eichmann et al. 2022) and is a candidate for a site of cosmic-ray acceleration. In the disk–corona model, cosmic-ray acceleration occurs via stochastic acceleration (D. F. G. Fiorillo et al. 2024a; R. Mbarek et al. 2024; D. Walter & B. Eichmann 2025) and/or magnetic reconnection (D. F. G. Fiorillo et al. 2024b). Cosmic rays interact with the dense gas and intense ambient radiation to produce mesons, among which the charged mesons decay into neutrinos. Motivated by the identification of NGC 1068 as a neutrino source candidate, we focus on the disk–corona model considering stochastic acceleration in the high-cosmic-ray-pressure scenario (A. Kheirandish et al. 2021). NGC 1068 is among the brightest AGN in terms of intrinsic X-ray flux (A. Marinucci et al. 2016) and has been modeled to be one of the top candidate Seyfert galaxies that can produce neutrinos detectable by IceCube (A. Kheirandish et al. 2021; K. Murase 2022). We adapt model parameters such that the predicted neutrino flux matches the measured flux from NGC 1068.

In this work, we search for neutrinos from X-ray bright Seyfert galaxies in the southern sky, performing two types of analyses. First, we probe for neutrino emission from each candidate source individually. We consider two scenarios: a generic power-law spectrum and the spectral shape predicted by the disk–corona model. Second, we search for cumulative neutrino emission from the selected sources in a stacking search. For the stacking analysis, we test only the disk–corona model.

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**Table 1**
Candidate Source List

| Source | Decl. (deg) | R.A. (deg) | $\log_{10}(L^{\rm intr}_{2-10\,\rm keV})$ | $n_{\rm exp}$ |
|---|---|---|---|---|
| Centaurus A | −43.0 | 201.4 | 42.4 | 2.5 |
| Circinus Galaxy | −65.3 | 213.3 | 42.6 | 1.7 |
| NGC 7582 | −42.4 | 349.6 | 43.5 | 0.8 |
| ESO 138-1 | −59.2 | 252.8 | 44.1 | 0.6 |
| NGC 4945 | −49.5 | 196.4 | 42.1 | 0.2 |
| NGC 424 | −38.1 | 17.9 | 43.8 | 0.2 |
| NGC 4593 | −5.3 | 189.9 | 42.8 | 0.2 |
| MCG-5-23-16 | −30.9 | 146.9 | 43.2 | 0.1 |
| NGC 3783 | −37.7 | 174.8 | 43.4 | 0.1 |
| IC 4329A | −30.3 | 207.3 | 43.8 | 0.1 |
| NGC 4507 | −39.9 | 188.9 | 43.5 | 0.1 |
| NGC 5728 | −17.3 | 220.6 | 42.9 | 0.1 |
| NGC 5643 | −44.2 | 218.2 | 42.4 | 0.1 |
| NGC 3081 | −22.8 | 149.9 | 42.7 | 0.1 |

**Note.** Details of the candidate source list. Logarithm of intrinsic deabsorbed 2–10 keV X-ray luminosity, $\log_{10}(L^{\rm intr}_{2-10\,\rm keV}/{\rm erg\,cm^{-2}\,s^{-1}})$ are from BASS. Numbers of expected signal events ($n_{\rm exp}$) are predicted by the disk–corona model.

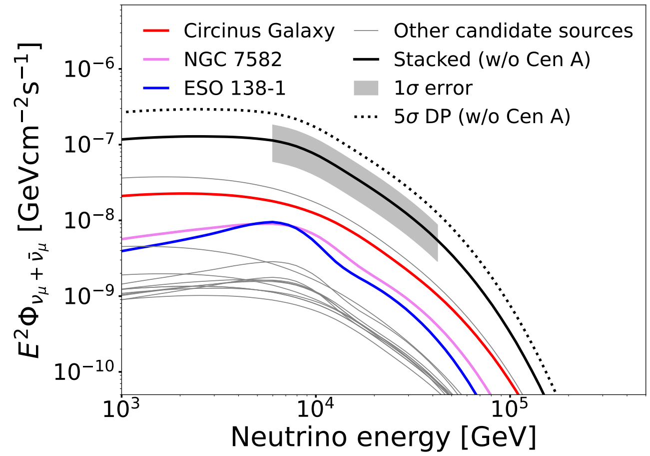


**Figure 1.** Stacked spectrum according to the best-fit normalization (solid black), with 1$\sigma$ statistical uncertainty (shaded gray) and the 5$\sigma$ discovery potential (dotted). The energy range of the gray band is computed from the central 68% of events contributing to the total test statistic (TS) values. Model predictions of neutrino spectra for the 14 candidate sources (A. Kheirandish et al. 2021) are shown as well. The 11 subdominant candidates are shown in gray (see Table 1); Centaurus A appears as the highest gray line due to its strong but ambiguous X-ray emission (see Section 2). The Circinus Galaxy (red), NGC 7582 (light pink), and ESO 138-1 (blue) are the candidates with the largest expected number of signal events, excluding Centaurus A.

## 2. Source Candidate Selection

We select southern hemisphere Seyfert galaxies ($\delta < -5°$) from the 105 month Swift-Burst Alert Telescope (BAT) catalog (K. Oh et al. 2018), avoiding the horizontal region—which is dominated by atmospheric background contamination—to optimize neutrino sensitivity for our candidate sources.

Given the 2–10 keV absorption-corrected fluxes and distances reported in BASS, we compute the expected neutrino flux from each source using the disk–corona model (K. Murase et al. 2020; A. Kheirandish et al. 2021). Combined with IceCube's effective area, we can predict the corresponding number of signal events in the data. For comprehensive coverage, we include candidate sources with expected fluxes slightly below IceCube's single-source sensitivity threshold, using a threshold of 0.1 predicted signal events per source. These sources and their properties are listed in Table 1, ranked by the expected number of signal events, with Centaurus A and the Circinus Galaxy at the top. An overview of the predicted spectra is given in Figure 1. Centaurus A differs from typical Seyfert galaxies because it has a radio-bright jet, and it is known to be a very-high-energy (VHE) gamma-ray emitter (H. Abdalla et al. 2018). Seyfert galaxies are generally radio-quiet and do not show VHE gamma-ray emission (M. Ackermann et al. 2012a). Therefore, the origin of the X-ray emission of Centaurus A is still under debate, leading to large uncertainties in the neutrino flux modeling. Hence, this source is analyzed only in isolation, as described in Section 4.

## 3. IceCube Detector and Data Sample

The IceCube Neutrino Observatory, located deep under the ice at the South Pole, is a cubic-kilometer Cherenkov neutrino telescope. The detector is composed of an array of 5160 digital optical modules (DOMs), each equipped with a photomultiplier tube (PMT) and on-board read-out electronics (M. G. Aartsen et al. 2017). Interactions of neutrinos with nucleons and electrons in the ice or underlying bedrock produce relativistic charged particles, which emit Cherenkov photons collected by the PMTs. The photon arrival times recorded by each DOM are used to reconstruct the energy and direction of each event. The flavor of neutrino and the type of neutrino interaction determine the event morphology in the detector. Muon tracks from $\nu_\mu/\bar{\nu}_\mu$ charged-current interactions provide the best angular resolution and thus are commonly chosen in our searches for pointlike neutrino emission (M. G. Aartsen et al. 2017).

However, cosmic-ray interactions in Earth's atmosphere also produce large numbers of muons and neutrinos. Because of their track-like signature, they pose a background in searches for astrophysical neutrinos. Atmospheric muons trigger the detector at a rate of 3 kHz (M. G. Aartsen et al. 2016). They mostly impact the southern sky, since the muons produced in the northern sky are effectively blocked by the Earth. For the analysis presented here, we rely on an event selection technique that suppresses the atmospheric backgrounds for down-going track events originating from the Southern Hemisphere. The method relies on selecting tracks that start in the detector ("starting tracks"), i.e., the neutrino interacts inside the detector. A dedicated vetoing technique separates neutrino candidate events from atmospheric muons. By efficiently rejecting atmospheric muons, the selection also benefits from a self-veto effect (T. K. Gaisser et al. 2014), which results in a suppression of atmospheric neutrinos, since they are accompanied by muons from the same cosmic-ray air shower. The corresponding dataset, Enhanced Starting Track Event Selection (ESTES), contains events collected by IceCube over ∼10 yr from 2011 May to 2022 January. This enhanced selection employs a dynamic veto and machine learning to significantly improve the retention of starting track events in the southern sky, achieving a median angular resolution of 1°.4 and targeting neutrino energies of 1–500 TeV. More details about the reconstruction and selection techniques used to create the ESTES sample can be found in R. Abbasi et al. (2024, 2026). In total, 10,350 events pass all selection criteria, of which 2091 are down-going and therefore contribute to this analysis.

## 4. Analysis Techniques

We perform two analysis approaches on the selected candidate sources (see Section 2): an individual candidate source search and a stacking search. In the individual source search, we search for an excess of neutrinos from the direction of each candidate source. This is done separately for two model tests: the disk–corona model and the generic power-law spectrum. In the stacking search, we study the accumulated emission from the selected sources. Each source is weighted by the expected number of signal events in the detector, where the expectation is computed using the disk–corona model and the distance of the source. We do not include Centaurus A in the stacking search because of the large uncertainties in the model prediction due to the ambiguous origin of its X-ray emission (see Section 2). Centaurus A would otherwise receive the strongest weight and dominate this stacking analysis (see Figure 1). To test a possible astrophysical neutrino signal against the background-only hypothesis, we rely on an unbinned likelihood ratio test (J. Braun et al. 2008). The test incorporates the energy, direction, and the directional uncertainty of each event in the data sample.

Our modeling of the predominant background components (atmospheric muons, atmospheric neutrinos, and the isotropic contribution from unresolved sources) relies on the experimental data, which is dominated by these backgrounds. Following established IceCube methods (R. Abbasi et al. 2026), we construct the background probability density function (PDF) by randomizing the R.A. of the events. This provides a good approximation for these background events since, due to IceCube's location, they are uniform in R.A. However, IceCube recently reported evidence of neutrino emission from the Galactic plane (R. Abbasi et al. 2023). This adds a new background component to our search. Without modifications, the standard randomizing method would overestimate the background for Seyfert galaxies far from the Galactic plane and underestimate the background for Seyfert galaxies close to the Galactic plane due to this background contamination. For a similar reason, to prevent potential signal events from the brightest candidate sources from being randomized into the background, we remove events near their locations. Hence, in the randomization process, we modified the standard scrambling method as follows. Events in the vicinity of the brightest (according to model expectation) Seyfert galaxies (Centaurus A, Circinus, NGC 7582, and ESO 138-1, radius 7°) or the Galactic plane (absolute value of Galactic latitude $<10°$) are removed from the dataset. The remaining events are then randomized in R.A. Since some background events are removed in the previous step, we randomly resample from the remaining events to compensate for those missing due to masking, thereby preserving the total number of background events. This oversampling step approximates the atmospheric flux and the isotropic astrophysical background, uniform in R.A., as before. However, by construction, it does not account for the contribution from the Galactic plane. To model the Galactic plane, we use Monte Carlo (MC)-generated events. Here we assume IceCube's best estimate of the Galactic neutrino flux, using Fermi-LAT gamma-ray measurements based on the $\pi^0$ template (M. Ackermann et al. 2012b) for the spatial distribution of neutrinos, and a power-law with a spectral index of 2.7 and normalization of $21.8 \times 10^{-12}$ TeV cm$^{-2}$ s$^{-1}$ at 100 TeV for the flavor-averaged flux of neutrinos multiplied by energy squared (R. Abbasi et al. 2023). This technique results in hybrid data + MC background-only datasets that represent the known properties of all relevant background components. Using these datasets, we compute the background PDFs used in the likelihood calculation. The hybrid datasets are also used to derive the distributions of the maximum likelihood test statistic under the background-only hypothesis, a crucial ingredient for the likelihood ratio test.

We tested the performance of the analysis by simulating neutrino emission from the selected Seyfert galaxies in addition to the backgrounds. We find that the stacking analysis, using neutrino expectations calculated from the disk–corona model, would yield a $\geqslant 5\sigma$ discovery in 50% of the simulations (discovery potential) if a total of 15.3 signal neutrinos are distributed across the sources. The disk–corona model with our choice of parameters predicts 4.7 events, corresponding to an expected significance of $2.1\sigma$. Figure 1 compares the modeled energy spectrum to the $5\sigma$ discovery potential based on the disk–corona model.

## 5. Results

Assuming the disk–corona model spectrum, the stacking analysis results in a combined best-fit excess of $6.7^{+4.0}_{-3.2}$ signal events over background and yields a significance of $3.0\sigma$ (single-sided $p$-value $= 1.3 \times 10^{-3}$); see Table 2 for details. This is consistent with the model prediction of 4.7 events. We determine the 68% central confidence interval for the number of signal events $n_s$ from the likelihood function assuming Wilks' theorem (S. S. Wilks 1938). The shaded gray band in Figure 1 shows the measured flux for the stacking search with uncertainties, compared with the $5\sigma$ discovery potential. We also show the predicted spectra of the individual candidate sources.

We also studied each candidate source individually, testing both spectral hypotheses. We find a nonzero, albeit not statistically significant, number of signal neutrinos from the locations of the Circinus Galaxy, ESO 138-1, and NGC 7582. The most significant result is obtained in the direction of the Circinus Galaxy, corresponding to a local (pretrial) significance of $3.1\sigma$ with a best-fit spectral index of 2.5, assuming the neutrino spectrum follows a power-law function. After accounting for the number of candidate sources in the list, which is 14, and the two spectral assumptions, the post-trial significance of the single brightest candidate source is $1.8\sigma$ ($p$-value $= 0.033$). The number of 3.1 best-fit signal neutrinos identified in our analysis is not statistically significant, so we place an upper limit on the neutrino flux from both the Circinus Galaxy and the other sources in this study. For each limit, we assume a power-law with spectral index of $\gamma = 3$. A summary of these results can be found in Table 2. We performed a spatial scan of the local $p$-value around the direction of the Circinus Galaxy. The result is shown in Figure 2. The best-fit and 90% confidence level upper-limit fluxes of both disk–corona and power-law assumptions are shown in Figure 3 along with the expected spectrum of the model. Assuming the disk–corona model, Figure 4 summarizes the expected number of neutrinos, the best-fit number of signal neutrinos ($n_s$), and the upper limits (90% confidence level) for all the candidate sources. It demonstrates that the $3.0\sigma$ result obtained in the stacking search is due to the combined excess of the Circinus Galaxy, ESO 138-1, and NGC 7582, for which the best-fit neutrino counts are correlated with predictions from the disk–corona model. Finally, more details about the individual results for all 14 candidate sources in our list, including flux upper limits, can be found in Table 4 in the Appendix.

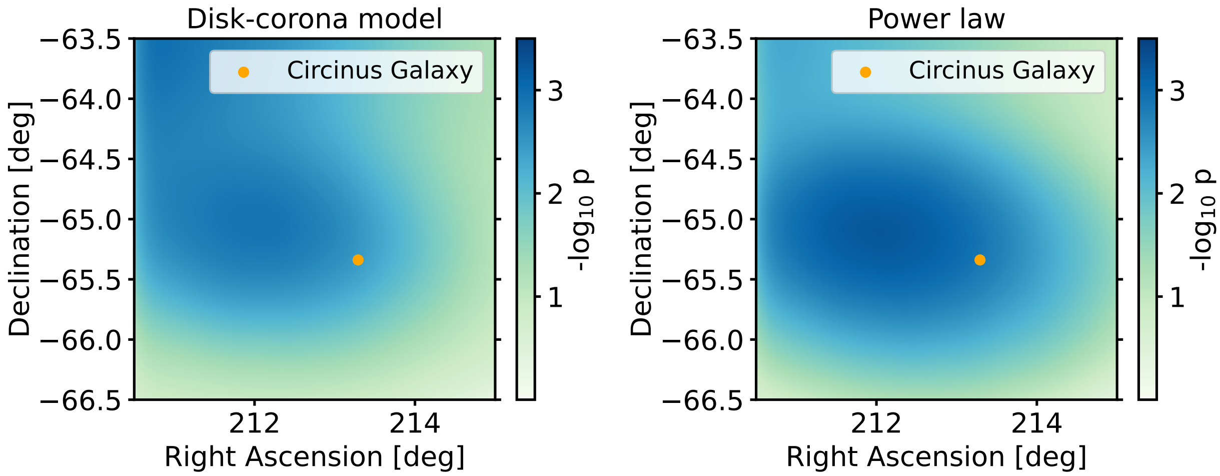


**Figure 2.** Local (pretrial) $p$-value maps near the most significant source—the Circinus Galaxy (orange), assuming the disk–corona model spectrum (left) and the power-law spectrum (right).

**Table 2**
Summary of Brightest Individual Sources and Stacking Analysis Results

| | $n_{\mathrm{exp}}$ | TS | $\hat{n}_s$ | $\hat{\gamma}$ | $p_{\mathrm{pre}}$ | $p_{\mathrm{post}}$ | 90% U.L. |
|---|---|---|---|---|---|---|---|
| Disk–corona | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | $n_s$ |
| Circinus Galaxy | 1.7 | 6.7 | 3.6 | ⋯ | 0.003 ($2.7\sigma$) | ⋯ | 10.0 |
| ESO 138-1 | 0.6 | 3.0 | 1.7 | ⋯ | 0.03 ($1.9\sigma$) | ⋯ | 5.7 |
| NGC 7582 | 0.8 | 1.4 | 1.1 | ⋯ | 0.05 ($1.6\sigma$) | ⋯ | 5.1 |
| Power-law | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | $\phi(\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$at 1 TeV) |
| Circinus Galaxy | ⋯ | 10.4 | 3.1 | 2.5 | 0.001 ($3.1\sigma$) | 0.033 ($1.8\sigma$) | $6.38 \times 10^{-10}$ |
| NGC 7582 | ⋯ | 1.7 | 1.7 | 4.0 | 0.05 ($1.6\sigma$) | ⋯ | $2.56 \times 10^{-10}$ |
| ESO 138-1 | ⋯ | 3.0 | 1.9 | 3.6 | 0.06 ($1.6\sigma$) | ⋯ | $2.97 \times 10^{-10}$ |
| Stacked sources | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | ⋯ | $n_s$ |
| 13 sources w/o CenA | 4.7 | 7.8 | 6.7 | ⋯ | 0.0013 ($3.0\sigma$) | ⋯ | 14.3 |

**Note.** Summary of stacking search results with disk–corona model assumptions and individual source search results for the three most significant sources: Circinus Galaxy, NGC 7582, and ES 138-1, with both disk–corona model and power-law spectral assumptions. The best-fit test statistic (TS), number of signal events ($\hat{n}_s$), pretrial $p$-value ($p_{\mathrm{pre}}$), post-trial $p$-value ($p_{\mathrm{post}}$), and 90% confidence level upper limit (U.L.) are listed for both analyses ($E^{-3}$ flux for power-law analysis and number of signal neutrinos for the model analysis). For the model analysis, the number of expected signal neutrinos ($n_{\mathrm{exp}}$) is listed, while for the power-law analysis, the best-fit spectral index ($\hat{\gamma}$) is shown.

Before unblinding the experimental data, we performed extensive validation of all methods, in particular the improved background estimation and background sampling techniques. We verified postunblinding that the traditional method, which leads to a small overestimation of the background in our stacking search, would have yielded a similar result. Specifically, had we not used the source masking and Galactic plane modeling techniques, we would have obtained a slightly reduced significance of $2.8\sigma$, consistent with the corresponding reduction in the analysis's sensitivity.

## 6. Summary and Discussion

In the southern sky, even though our studies do not identify significant neutrino emission from individual sources, the stacking result is inconsistent with the background hypothesis at $3.0\sigma$ significance, driven by five galaxies, led by three nearby AGNs in the Circinus Galaxy, NGC 7582, and ESO 138-1. Within statistical fluctuations, our findings are consistent with the predictions of the disk–corona model. This work provides evidence independent of NGC 1068 that some X-ray bright Seyfert galaxies are sources of high-energy neutrinos. Table 3 summarizes the searches in both hemispheres.

In this work, we studied 14 candidate sources, selected from the BASS AGN survey, for which the models of neutrino production in the AGN coronae predict the strongest neutrino signal. Our study benefits from the new event selection techniques (ESTES) optimized for isolating starting track events (R. Abbasi et al. 2024, 2026), thereby efficiently suppressing the large background from atmospheric muons, which traditionally limit searches for neutrino sources below 100 TeV in the southern sky. In addition to the generic power-law spectrum, we analyzed each candidate source assuming the spectrum follows the prediction of the disk–corona model. We also searched for the aggregated neutrino signal using a stacking analysis (excluding Centaurus A) based on the same model. The latter analysis identified a total excess of $6.7^{+4.0}_{-3.2}$ events, consistent with the model prediction of 4.7 events. This result is inconsistent with the background hypothesis at $3.0\sigma$ significance.

**Table 3**
Summary of Searches of X-Ray Bright Seyfert Galaxies and Hard X-Ray Bright AGNs using IceCube Data

| Source | $\sigma_{post}$ | $n_s$ | Flux ($\times 10^{-11}$ TeV$^{-1}$cm$^{-2}$s$^{-1}$) | Data Sample |
|---|---|---|---|---|
| (R. Abbasi et al. 2022) | | | | |
| NGC 1068 | 4.2$\sigma$ | ⋯ | $5.0^{+1.5}_{-1.5}$ (best-fit) | 2011 May to 2020 May (NT) |
| (A. Neronov et al. 2024) | | | | |
| NGC 3079 | $\sim$3$\sigma$ | ⋯ | $3.2^{+4.0}_{-2.5}$ (best-fit) | 2008 Apr to 2018 Jul (PS) |
| (R. Abbasi et al. 2025b) | | | | |
| NGC 4151 | 2.9$\sigma$ | ⋯ | $1.51^{+0.99}_{-0.81}$ (UL) | 2008 Apr to 2020 May (PS) |
| (R. Abbasi et al. 2025a) | | | | |
| CGCG 420-015 | 2.3$\sigma$ | 46.4 (UL) | ⋯ | 2011 May to 2022 Feb (NT) |
| binomial test | 2.7$\sigma$ | ⋯ | ⋯ | |
| (R. Abbasi et al. 2025c) | | | | |
| binomial test | 3.3$\sigma$ | ⋯ | ⋯ | 2011 May to 2023 Nov (NT) |
| (This work) | | | | |
| Circinus Galaxy | 1.8$\sigma$ | ⋯ | 63.8 (UL) | 2011 May to 2022 Jan (ST) |
| stacking w/o CenA | 3.0$\sigma$ | 14.3 (best-fit) | ⋯ | |

**Note.** A summary of the datasets and the key results from the searches for hard X-ray bright AGNs (R. Abbasi et al. 2025b), X-ray bright Seyfert galaxies (A. Neronov et al. 2024; R. Abbasi et al. 2025a, 2025c) using the all-sky point source data (PS) (M. G. Aartsen et al. 2020) or the northern sky through-going tracks (NT) (R. Abbasi et al. 2022), and this work, using the southern sky starting tracks (ST) (R. Abbasi et al. 2024). The post-trial significance ($\sigma_{post}$) for each search is listed. The 90% confidence level upper limits (UL) are reported for an $E^{-3}$ spectrum for the power-law results, and as the number of signal (ns) neutrinos for the results assuming the disk–corona model. The most significant individual sources identified in each search are NGC 3079, NGC 4151, CGCG 420-015, and the Circinus Galaxy. The results of the collective searches for neutrino emission—assuming the disk–corona model spectrum for each candidate source—are also included, both with (stacking analysis) and without (binomial test) assumptions about the relative contributions of the sources.

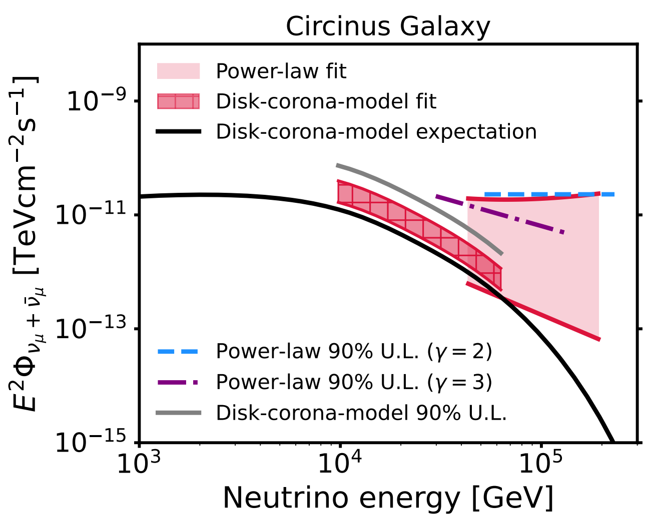


**Figure 3.** The predicted neutrino spectrum for the Circinus Galaxy from the disk–corona model (solid black) is compared to the 68% uncertainty regions of the best-fit spectra assuming the disk–corona scenario (hatched) and a power law (shaded). The energy range corresponds to the central 68% of events contributing to the total TS values. The 90% confidence level upper limits of power-law analysis for $E^{-2}$ (dashed blue) and $E^{-3}$ (dashed–dotted purple) fluxes, as well as the model analysis (solid gray), are shown. The post-trial statistical significance for the Circinus Galaxy is 1.8$\sigma$.

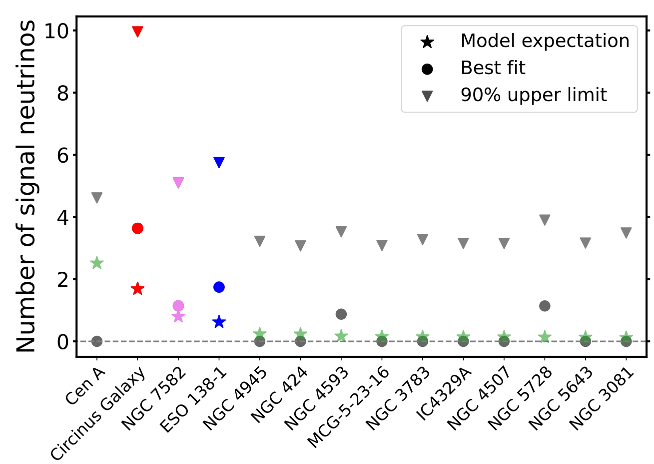


**Figure 4.** Expected (star), best-fit (dot), and 90% confidence level upper limit (triangle) number of signal neutrinos assuming disk–corona model spectra, with the three most significant sources—Circinus galaxy (red), NGC 7582 (pink), and ESO 138-1 (blue)—highlighted. Sources from left to right have a decreasing number of expected signal neutrinos. The ambiguous origin of the X-ray emission from Centaurus A introduces large uncertainties in the expected neutrino flux; therefore, we include it in the individual source search but not in the weighted stacking analysis.

In the northern sky, motivated by the identification of neutrino emission from the Seyfert galaxy NGC 1068 (R. Abbasi et al. 2022), IceCube has searched for neutrinos from X-ray bright Seyfert galaxies (R. Abbasi et al. 2025a) using the same event selection but improved calibration and reconstruction and an additional 1.7 yr of data. A total of 28 sources were selected from the BASS catalog, requiring their 2–10 keV intrinsic X-ray flux to be at least 10% of that of NGC 1068. Although the stacking search in the northern sky did not find statistically significant collective emission from the candidate sources, a binomial test—assuming disk–corona model spectra for the stacked sources (excluding NGC 1068) and no assumption about their relative contributions—yielded a post-trial significance of 2.7$\sigma$. Another analysis, using the same dataset described in R. Abbasi et al. (2022) along with two additional years of data, was conducted around the same time as R. Abbasi et al. (2025a). Similar to

R. Abbasi et al. (2025a, 2025c) reported no significant collective emission from the stacking search. In the individual source search, R. Abbasi et al. (2025b) selected the top-ranked AGNs from the BASS catalog by comparing the ratio of their intrinsic 14–195 keV X-ray flux to the neutrino sensitivity, retaining sources with a ratio no more than 10 times smaller than that of the top-ranked source. In total, 43 candidates were selected. Most of the candidates are located in the northern sky due to better sensitivity with the chosen through-going track dataset. In this search, NGC 4151 was the most significant source, with a post-trial significance of $2.9\sigma$. More recently, IceCube reported observing a $3.3\sigma$ excess from 11 sources out of 47 selected X-ray bright Seyfert galaxies that were not included in the list of gamma-ray emitters (excluding NGC 1068) using 13.1 yr of through-going track events. In addition to these IceCube Collaboration results, we note that independent researchers analyzing 10 yr of publicly available IceCube data (M. G. Aartsen et al. 2020) have reported a $\sim 3\sigma$ excess associated with NGC 3079 (A. Neronov et al. 2024).

The current analysis can be improved in the future by including a sample of cascade-type events (mostly from high-energy electron neutrino interactions) detected by IceCube (R. Abbasi et al. 2023) that provide competitive sensitivity to these interesting sources. However, a firm discovery of this potential class of neutrino emitters will benefit from future neutrino detectors with larger effective areas and improved angular resolution, such as Baikal-GVD, KM3NeT, P-ONE, NEON, TRIDENT, HUNT, and IceCube-Gen2 (A. Avrorin et al. 2014; S. Adrian-Martinez et al. 2016; M. Agostini et al. 2020; M. G. Aartsen et al. 2021; T.-Q. Huang et al. 2023; Z. P. Ye et al. 2023; H. Zhang et al. 2025).

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## Appendix

Table 4 shows the full results of all sources for the catalog search.

**Table 4**
Results of Individual Candidate Source Searches

| Source | Disk–Corona Model | | | | Power Law | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | $n_{\rm exp}$ | $\hat{n}_s$ | $-\log_{10}p$ | $n_{\rm UL}$ | $\hat{n}_s$ | $\hat{\gamma}$ | $-\log_{10}p$ | $\phi_{90\%}^{E^{-2}}$ | $\phi_{90\%}^{E^{-3}}$ |
| Centaurus A | 2.5 | 0.0 | 0.0 | 4.6 | 0.0 | 4.0 | 0.0 | 1.0 | 22.1 |
| Circinus Galaxy | 1.7 | 3.6 | 2.5 | 10.0 | 3.1 | 2.5 | 2.9 | 2.3 | 63.8 |
| NGC 7582 | 0.8 | 1.1 | 1.3 | 5.1 | 1.7 | 4.0 | 1.3 | 1.1 | 25.6 |
| ESO 138-1 | 0.6 | 1.7 | 1.5 | 5.7 | 1.9 | 3.6 | 1.2 | 1.1 | 29.7 |
| NGC 4945 | 0.2 | 0.0 | 0.0 | 3.2 | 0.0 | 4.0 | 0.0 | 0.6 | 15.8 |
| NGC 424 | 0.2 | 0.0 | 0.0 | 3.1 | 0.0 | 2.2 | 0.0 | 0.6 | 14.8 |
| NGC 4593 | 0.2 | 0.9 | 0.6 | 3.5 | 0.6 | 2.9 | 0.4 | 0.6 | 8.9 |
| MCG-5-23-16 | 0.1 | 0.0 | 0.0 | 3.1 | 1.0 | 1.7 | 1.0 | 1.0 | 22.6 |
| NGC 3783 | 0.1 | 0.0 | 0.0 | 3.3 | 0.0 | 4.0 | 0.0 | 0.7 | 15.8 |
| IC 4329A | 0.1 | 0.0 | 0.0 | 3.1 | 0.0 | 3.8 | 0.0 | 0.7 | 15.3 |
| NGC 4507 | 0.1 | 0.0 | 0.0 | 3.1 | 0.0 | 3.8 | 0.0 | 0.7 | 15.1 |
| NGC 5728 | 0.1 | 1.1 | 0.9 | 3.9 | 1.9 | 4.0 | 0.9 | 0.9 | 16.9 |
| NGC 5643 | 0.1 | 0.0 | 0.0 | 3.2 | 0.0 | 4.0 | 0.0 | 0.6 | 15.2 |
| NGC 3081 | 0.1 | 0.0 | 0.0 | 3.5 | 0.0 | 4.0 | 0.0 | 0.8 | 16.1 |

**Note.** Details of the candidate source list and results. Values of best-fit $\hat{n}_s$ (and $\hat{\gamma}$) and pretrial $p$-values using the disk–corona model (power law) spectral assumption are shown. Numbers of expected signal events ($n_{\rm exp}$) and 90% upper limit ($n_{\rm UL}$) are listed for results using model assumptions. For the power-law analysis, 90% upper limit fluxes are listed, parameterized as $\phi_{90\%}^{E^{-\gamma}}(E/1\,{\rm TeV})^{-\gamma}\times 10^{-11}\,{\rm TeV^{-1}\,cm^{-2}\,s^{-1}}$, where $\gamma = 2$ or 3.

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