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Evidence of Neutrino Emission from X-ray Bright Seyfert Galaxies with IceCube

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The IceCube Neutrino Observatory has detected evidence for TeV neutrinos from NGC 1068, a nearby Seyfert galaxy. This discovery suggests that active galactic nuclei may play a significant role as sources of high-energy astrophysical neutrinos. Interestingly, the absence of the expected TeV gamma-ray flux indicates that these gamma-rays could be effectively obscured at their production site, with the hot coronal environment near the Seyfert galaxy's core being a plausible location for this attenuation. Theoretical models suggest that the properties of the corona—and thus the production of neutrinos—can be inferred from the galaxy's intrinsic X-ray luminosity. In this presentation, we report our search for neutrino emission from a sample of X-ray bright Seyfert galaxies selected from the BASS survey. We have employed a disc-corona model to predict the neutrino flux, improving the sensitivity of our search, and compared this model to the more traditional power-law flux assumption. Our stacking analysis shows a 3σ neutrino emission signal from the catalog's collective sources.

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1. Introduction

IceCube recently identified TeV neutrino emission from a nearby Seyfert galaxy, NGC 1068 [1], which suggests that active galactic nuclei (AGN) could be potential sources of high-energy neutrinos. With 9.5 years of neutrino data from the Northern Hemisphere collected and analyzed by IceCube, NGC 1068 has been identified with an excess of 79 muon neutrino candidates, which corresponds to a flux of $5 \times 10^{-9}\,\mathrm{GeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ at 1 TeV with the best-fitted spectral index of $\hat{\gamma} = 3.2$. Such a flux of neutrinos is much higher than the reported GeV-scale γ-ray flux by the *Fermi* Large Area Telescope (LAT) [2] or the TeV-scale flux upper limits reported by MAGIC [3] for this source.

Neutrinos produced by the interaction of CRs should be accompanied by γ-ray productions. Therefore, the absence of GeV-TeV gamma-ray detections of NGC 1068 suggests that the environment near the production site of high-energy neutrinos must be optically opaque to the accompanying γ-rays in such an energy range. A Compton-thick environment near the supermassive black hole (SMBH) host of AGNs would sufficiently support this hypothesis. In this case, Seyfert galaxies (a subcalass of AGN) become ideal candidates for their hot, highly magnetized, and turbulent coronae near the disks [4] that are formed by accretion dynamics and magnetic dissipation. There have been models attempting to use the disk-corona scenario to describe the observed neutrino and obscured γ-ray spectrum for NGC 1068 [5–8]. The model employed in this study [7] estimates the neutrino flux by modeling stochastic acceleration in the corona and the subsequent interaction of CRs with gas or radiation in the inner region of the AGN, in this way, builds a connection between neutrino flux and intrinsic soft X-ray flux. At the same time, the observed neutrino flux in the direction of NGC 1068 suggests that a high level of CR pressure is needed to explain the observed neutrino energy spectra.

2. Source Catalog and Dataset

The BAT AGN Spectroscopic Survey (BASS) [9], an all-sky study of bright X-ray detected AGN, is used to select the catalog used in this search. From the 70-month and 105-month $Swift$-BAT classifications [10, 11], we rank the Seyfert galaxies by their neutrino expectations as predicted by the disk-corona model. The expectations are computed by employing the source coordinates, distances, and intrinsic X-ray luminosity in the 2–10 keV range. The top 14 brightest sources in the Southern Hemisphere are selected, and the sources with signal neutrino expectations less than 0.1 are dropped from our studies. As shown in Figure 1, where the X-ray bright Seyfert galaxy Circinus Galaxy is also one of the brightest sources predicted by the disk-corona model (see Table 1).

Among all the selected sources, Centaurus A gives the highest neutrino expectation based on the intrinsic luminosity and distance reported in BASS. However, the X-ray flux measured from Centaurus A could originate from its bright jets instead of the core, which may not necessarily contribute to the coronal emission. Hence, the most promising source in our catalog is the Circinus Galaxy. Consequently, to avoid biasing the stacking analyses by including Centaurus A, where the disk-corona model may not apply, it is excluded from the stacking analysis to be conservative and only included in the catalog search.

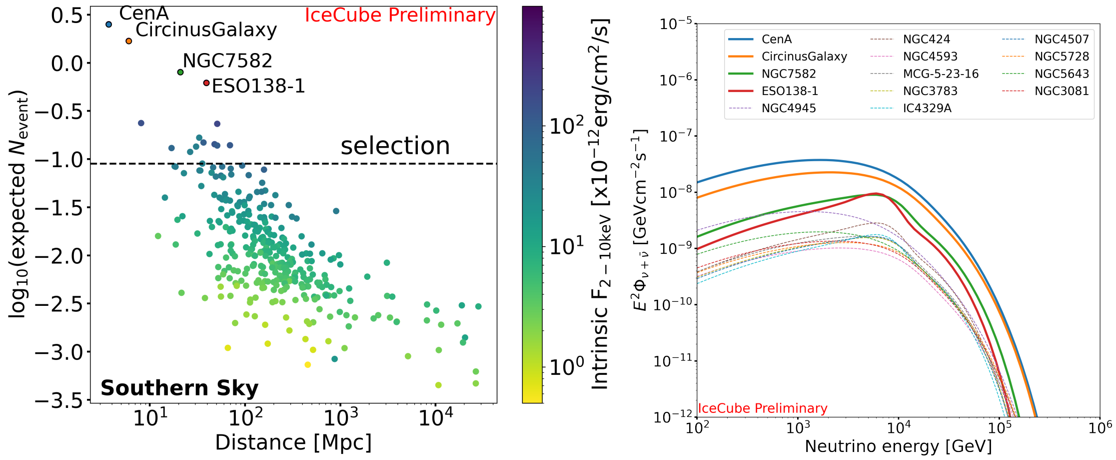

Figure 1: Left: intrinsic fluxes at 2–10 keV of Seyfert galaxies in the Southern Hemisphere plotted against neutrino expectations by using disk-corona model flux vs. distance of source from Earth, where selected sources above the dashed line. Right: disk-corona model predicted neutrino spectral flux of selected catalog sources with the top four predicted brightest sources highlighted as solid curves.

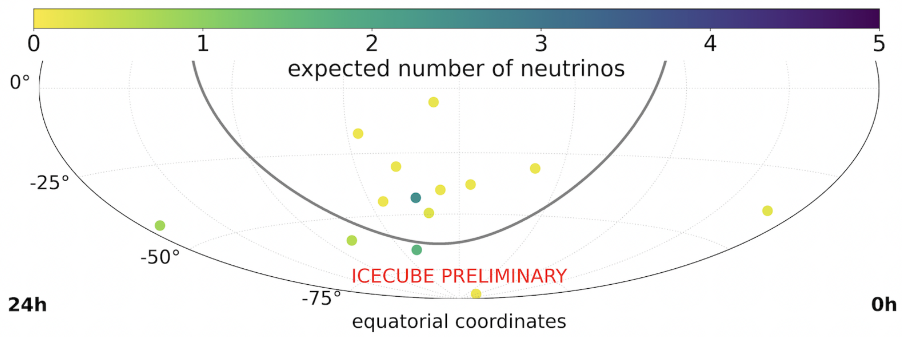

Figure 2: The skymap of catalog sources with color representing the expected number of neutrinos using the disk-corona flux model.

The dataset we used to study the selected Seyfert galaxies in the Southern sky is a sample of events collected by IceCube from 2011 to 2021. The dataset was selected with the enhanced starting track event selection (ESTES) [12–14], which uses a state-of-the-art reconstruction algorithm with improved angular resolution and background rejection in the Southern Hemisphere.

3. Analysis Methodology

For this analysis, we search for potential neutrino excesses from the direction of the selected sources by scrambling observed data by their reconstructed right ascension to represent the underlying isotropic backgrounds on the sky. As shown in Figure 2, some of our catalog sources are close to the GP from which IceCube observes neutrino emission [15]. Therefore, we developed analysis techniques to handle the potential neutrino emissions from the GP. To avoid scrambling the potential neutrino emissions from astrophysical sources into the background representation, we mask the regions within ±10° along the GP and 7° around the hottest four galaxies (Centaurus A, Circinus, NGC 7582, and ESO 138-1) in the selected catalog to be conservative. This helps us avoid over-estimating the background by accidentally scrambling potential neutrino emissions from the possible sources in the Southern Hemisphere. After masking and scrambling, we have a representation of the isotropic backgrounds from the diffuse astrophysical flux and from atmospheric muons and neutrinos. However, with the knowledge of GP's presence near the regions where some of our hottest catalog sources are located, we carefully draw MC events following the conservative π^0 template [16]. This is inferred from the γ-ray emissions and follows a power law in photon energy (E) of $E^{-2.7}$ to represent the potential neutrino candidates from the GP. Then, we add them to the masked-then-scrambled background events. The normalization of the π^0 template is from [15], which is consistent with a similar GP study using ESTES [12].

4. Result and Discussion

	spectral model	n_{exp}	TS	$\hat{n}_{\mathrm{s}}$	$\hat{\gamma}$	p_{local}	$n_{90\%\mathrm{C.L.}}$
Circinus Galaxy	disk-corona	1.7	6.7	3.6	-	0.003 (2.7 σ)	10.0
	power law	-	10.4	3.1	2.5	0.001 (3.1 σ)	63.8×10^{-11}
NGC 7582	disk-corona	0.8	1.4	1.1	-	0.05 (1.6 σ)	5.1
	power law	-	1.7	1.7	4.0	0.05 (1.6 σ)	25.6×10^{-11}
ESO 138-1	disk-corona	0.6	3.0	1.7	-	0.03 (1.9 σ)	5.7
	power law	-	3.0	1.9	3.6	0.06 (1.6 σ)	29.7×10^{-11}
Stacking	disk-corona	4.7	7.8	6.7	-	0.0013 (3.0 σ)	14.3

Table 1: Results of the three hottest sources in the catalog and stacking of catalog excluding Centaurus A, with expected neutrino emissions computed using disk-corona model (n_{exp}); fitted test-statistic values (TS); fitted number of neutrinos ($\hat{n}_{\mathrm{s}}$) and power law spectral index ($\hat{\gamma}$); and pre-trial p-value (p_{local}). $n_{90\%\mathrm{C.L.}}$ is the estimated 90% C.L. upper limit on $\hat{n}_{\mathrm{s}}$, where with disk-corona model we report number of events and with power-law flux we report fluxes in unit of $\mathrm{TeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ at 1 TeV assuming a spectral index of 3.

Using 10.3 years of starting track events in the Southern Hemisphere, the results of the hottest four sources from the catalog search and stacking are summarized in Table 1, and the full catalog results are plotted in Figure 3. The stacking result is compared to the model expectations of the individual sources in Figure 4. The global post-trial p-value of the catalog search is 0.033, corresponding to 1.8σ with Circinus Galaxy, and the significance of stacking is 3.0 σ from a p-value of 0.0013. The 1 σ interval, and 90%C.L. upper limit of the stacking result are estimated using the splined distribution of the TS differences between the scanned list of n_s and the best-fitted value, as shown in Figure 5. The stacking result shows good agreement between the fitted number of neutrinos and the disk-corona model predictions, contributed by the top three brightest sources in the stacking catalog: Circinus Galaxy, NGC 7582, and ESO 138-1. No emission was observed from Centaurus A in the catalog search, as hypothesized for the reasons discussed in Section 2. The local p-values near the hottest spot, Circinus Galaxy, are scanned and shown in Figure 6. The local scanned p-value using a power law flux (left plot in Figure 6) shows higher significance than using the disk-corona model flux (right plot in Figure 6), which is due to the very high energy events having more significant contributions to the TS using a power law to fit the flux whereas the

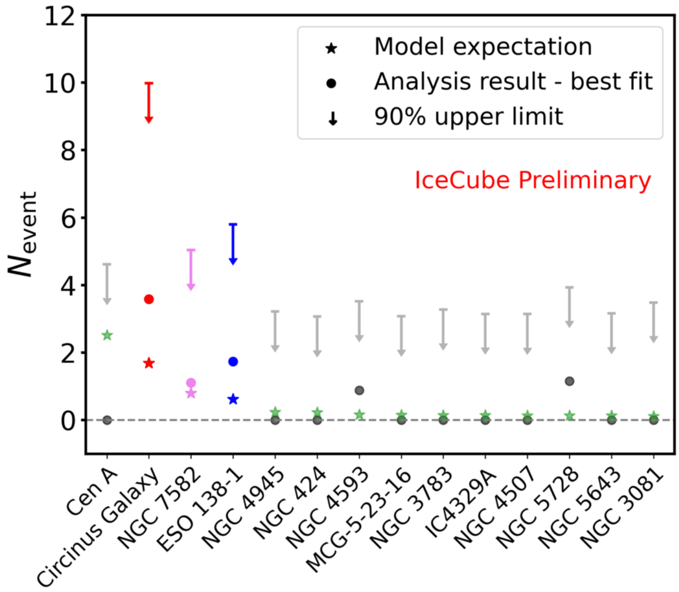

Figure 3: Expected number of events (green star) calculated using the disk-corona model, fitted number of neutrinos (black spots) and corresponding 90% C.L. upper limit (black arrows) of catalog sources plotted along their declination angles.

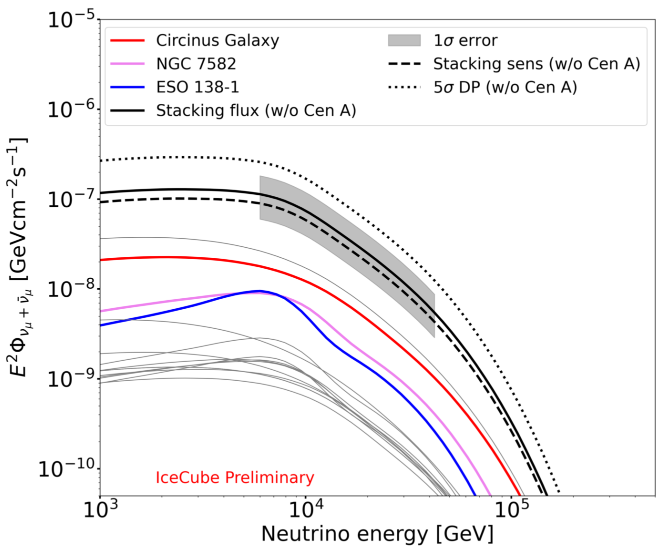

Figure 4: Stacking flux (black) with 1 σ interval (gray band), sensitivity (dashed), and 5 σ discovery potential (dotted), compared to the disk-corona model predicted neutrino spectra of individual sources (gray solid) with the hottest three sources in stacking color highlighted.

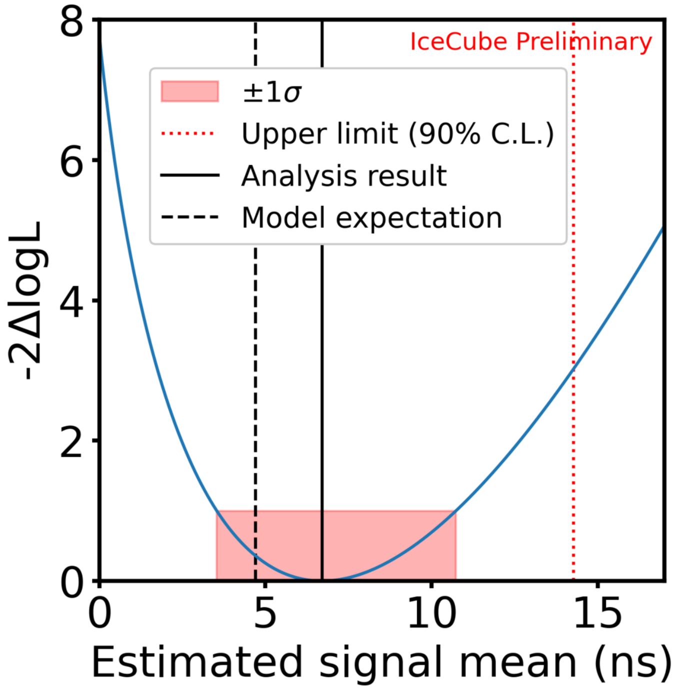

Figure 5: Splined TS differences between list of scanned n_s and best-fit n_s of stacking search, with $1\,\sigma$ interval, [4.5, 10.7], on fitted n_s of stacking search in red and 90% C.L. upper limit ($n_{90\%\ \mathrm{C.L.}}$=14.3) as the dashed line.

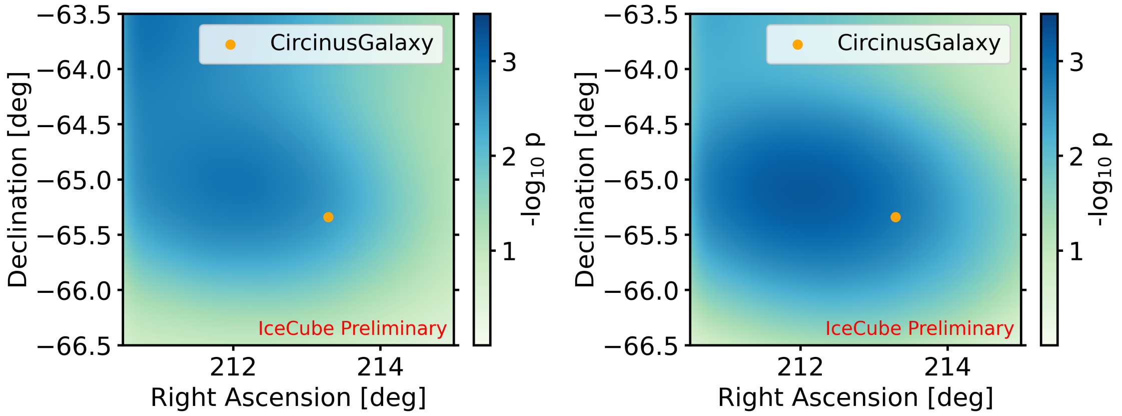

Figure 6: Local pre-trial p-value maps scanned assuming disk-corona model (left) and power law (right) fluxes around Circinus Galaxy, the hottest spots in the catalog search, with color representing p-values and orange spot showing source locations.

disk-corona model is more focused on the med-energy range (~ 30 TeV) but has a lower expectation in the very high energy regime.

The expected stacking n_s is within the $1\,\sigma$ uncertainty of [4.5, 10.7] and well below the 90% C.L. upper limit of 14.3. This outcome is also consistent with IceCube's diffuse astrophysical neutrino limits at intermediate energies (~ 30 TeV), leaving plenty of room to accommodate contributions from other potential astrophysical neutrino sources.

5. Summary and Future

We analyzed selected Seyfert galaxies in the Southern Hemisphere, focusing on sources expected to emit neutrinos based on predictions from the disk-corona model. The individual catalog search reports the three hot spots near Circinus Galaxy, NGC 7582, and ESO138-1, with the hottest spots near the region of the predicted most promising source, Circinus Galaxy, with a local p-value of 0.001 (3.1σ) which corresponds to a global p-value of 0.033 (1.8σ) after accounting for the 14 sources in the catalog and 2 flux models being tested. The stacking result using the selected catalog–excluding Centaurus A–yields a significance of $3.0\,\sigma$, corresponding to a p-value of 0.0013. While the expected number of signal events was 4.7, the fit returned 6.7 events. A similar study has investigated Seyfert galaxies in the Northern Hemisphere [17]. The disk-corona model in that context faces challenges due to uncertainties in the intrinsic soft X-ray flux and its impact on the assumed cosmic-ray pressure. In the Southern Hemisphere, an ongoing analysis incorporates astrophysical electron and tau neutrinos alongside starting-track events from muon neutrinos to enhance the dataset's statistics. This approach may increase the sensitivity to a potential neutrino excess from our Seyfert galaxy catalog.

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