Neutrino Signal from a Population of Seyfert Galaxies

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IceCube Collaboration has previously reported evidence for a neutrino signal from a Seyfert galaxy NGC 1068. This may suggest that all Seyfert galaxies emit neutrinos. To test this hypothesis, we identify the best candidate neutrino sources among nearby Seyfert galaxies, based on their hard x-ray properties. Only two other sources, NGC 4151 and NGC 3079 are expected to be detectable in 10 years of IceCube data. We find evidence ($\sim 3\sigma$) for a neutrino signal from both sources in a publicly available ten-year IceCube dataset. Though neither source alone is above the threshold for discovery, the chance coincidence probability to find the observed neutrino count excesses in the directions of the two out of two expected sources, in addition to the previously reported brightest source, is $p < 2.6 \times 10^{-7}$. This corresponds to a correlation between Seyfert galaxies and neutrino emission.

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Introduction.—Seyfert galaxies form the most abundant type of active galactic nuclei (AGN) in the local Universe [1,2]. Their emission spectra are dominated by the infrared-visible continuum originating from black hole accretion disk emission scattered by a dusty torus and by hard x-ray band emission from a hot corona near the black hole. Most Seyfert galaxies are radio quiet sources, showing no or weak particle acceleration activity. Recent high-resolution imaging of nearby Seyfert galaxies by very large baseline array (VLBA) [3] shows that in most of the sources, weak radio emission originates from extended structures in the host galaxy, rather from the AGN itself. Only several sources show signatures of nonthermal synchrotron emission from the nucleus that may be related to a weak jet. Seyfert type AGN are also not strong γ ray sources. Only two Seyfert galaxies, NGC 1068 and NGC 4945, are detected by the Fermi Large Area Telescope (LAT) in the energy range above 100 MeV [4] and it is probable that the γ ray emission is not related to the activity of the AGN, but may rather originate from starburst activity also found in these sources.

In this respect, a recent report by IceCube Collaboration presenting evidence for the neutrino signal from a Seyfert galaxy NGC 1068 [5] appears surprising and deserves larger scrutiny. Remarkably, the reported neutrino flux from the source in the TeV energy range is 2 orders of magnitude higher than the γ ray flux at the same energy, derived from MAGIC Telescope observations of the source [6]. This may possibly be explained by the compactness of the source. If the signal originates from the vicinity of the black hole, γ rays that are produced together with neutrinos in interactions of high-energy protons would not be able to leave the source because of the pair production on low-energy photons originating from the accretion disk and hot corona.

It is not clear *a priori* if Seyfert galaxies are generically capable to accelerate protons to multi-TeV range and emit neutrinos or NGC 1068 is a peculiar source and neutrino emission from the source is not related to the Seyfert activity powered by the accretion on the supermassive black hole. It is possible that protons are accelerated in the accretion flows of all Seyfert galaxies [7,8] or in the black hole magnetosphere [9,10] and is possibly related to the generation of jet, so that only jet-emitting Seyfert galaxies are neutrino sources. Finally, it may be that a specific event in NGC 1068 that is not typical to the entire Seyfert population is responsible for the neutrino emission.

In what follows, we explore the possibility that Seyfert galaxies are generically sources of high-energy neutrinos. To test this hypothesis, we identify the best neutrino source candidates among nearby Seyfert galaxies and search for the neutrino signal from these best candidates using the publicly available ten-year point source analysis dataset of IceCube [11].

Neutrino—Hard x-ray flux scaling.—We assume that the neutrino signal from NGC 1068 is a template for a typical Seyfert galaxy, and we want to find which other Seyfert galaxies should be detectable under this hypothesis. Neutrinos from high-energy proton interactions are produced together with γ ray s, electrons, and positrons. Total power injected into the electromagnetic channel (electrons, positrons, γ ray s) is comparable to the power injected into neutrinos.

The electromagnetic power can be only dissipated radiatively. This means that the electromagnetic luminosity

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generated by high-energy proton interactions has to be of the same order as the neutrino luminosity of the source. The energies of γ ray s, electrons, and positrons produced in pp and $p\gamma$ interactions are comparable to the energies of neutrinos. The absence of γ-ray emission with the flux comparable to the neutrino flux from NGC 1068 at the energy $E_\gamma \sim 1$ TeV indicates that the source is not transparent to γ ray s [12]. γ ray s produce pairs in interactions with photons of energy $\epsilon_{\rm ph} \simeq 1[E_\gamma/1\ {\rm TeV}]^{-1}$ eV. Such photons are emitted by the accretion flow that in NGC 1068 has the luminosity $L_a \sim 10^{45}$ erg/s [13]. The conventional accretion disk spectrum is $L_a(E) \sim EdL_{\rm acc}/dE \propto E^{4/3}\exp(-E/E_{\rm cut})$ that peaks at $E_{\rm cut} \sim 100$ eV for the disk around a black hole of the mass $M \sim 10^7 M_\odot$ [14]. The strongest opacity for the $\gamma\gamma$ pair production is thus expected for the γ ray s with energies $E_\gamma \sim 10$ GeV, with the optical depth $\tau_a = \sigma_{\gamma\gamma} n_{\rm ph} R \simeq 10^6 [L_a/10^{45}\ {\rm erg/s}][R/3\times 10^{12}\ {\rm cm}]^{-1} [E_\gamma/10\ {\rm GeV}]$ where $\sigma_{\gamma\gamma} \simeq 10^{-25}\ {\rm cm}^2$ is the pair production cross-section, $n_{\rm ph} = L_a/(4\pi R^2 \epsilon_{\rm ph} c)$ is the density of soft photons and R is the source size, comparable to the Schwarzschild radius $R \sim R_{\rm schw} \simeq 3\times 10^{12}[M/10^7 M_\odot]$ cm (for emission at $\epsilon_{\rm ph} \sim 100$ eV). Assuming the radial accretion flow temperature and luminosity dependence $T \propto R^{-4/3}$, $L_a \propto R^{-1}$, one can estimate the energy dependence of the optical depth $\tau_a \sim 10^6 (E/10\ {\rm GeV})^{-3/2}$, so that the source may be opaque to γ ray s with energies up to approximately 100 TeV.

γ ray s with energies below 10 GeV are absorbed in interactions with x-ray photons from hot corona with temperature reaching $T_c \sim 100$ keV. Its optical depth for this process is $\tau_c \simeq 7[L_c/10^{43}\ {\rm erg/s}][R/3\times 10^{12}\ {\rm cm}]^{-1} [E_\gamma/10\ {\rm MeV}]$ where L_c is the luminosity of the corona. Thus, most of the electromagnetic power from pp and $p\gamma$ interactions, comparable to the neutrino luminosity of the source, has to be released in the energy range $E \lesssim 1$ MeV [15]. A linear scaling between the neutrino and secondary hard x-ray–soft γ-ray flux from high-energy proton interactions is expected in this case.

The TeV band muon neutrino luminosity of NGC 1068 is estimated as [5] $L_{\nu_\mu} \sim 4\pi D^2 F_{\nu_\mu} \sim 2\times 10^{42}[F_{\nu_\mu}/5\times 10^{-11}\ {\rm TeV/cm^2\ s}]$ erg/s where $D \simeq 16.3$ Mpc is the distance to the source. This is approximately $L_{\nu_\mu,{\rm TeV}} \sim 0.02 L_{hX0}$ of the intrinsic hard x-ray band source luminosity L_{hX0} in the hard x-ray band. NGC 1068 is a Compton-thick AGN, with x-ray flux attenuated by the Compton scattering through a medium with the column density [16] $N_H \gtrsim 10^{25}\ {\rm cm}^2$. The hard x-ray flux arriving at Earth is $F_{hX} \sim L_{hX0}/(4\pi D^2)\exp(-\tau_C)$ where the optical depth for the Compton scattering is $\tau_C = \sigma_T N_H \simeq 7[N_H/10^{25}\ {\rm cm}^{-2}]$. Apart from the attenuated flux from the corona, the hard x-ray flux has a contribution from Compton reflection that may even dominate the observed flux for heavily obscured sources, like NGC 1068. This introduces large uncertainty in the estimates of the intrinsic luminosity of the corona for such sources [17]. The power released by high-energy proton interactions contributes to the intrinsic hard x-ray luminosity of the source and hence the neutrino luminosity is expected to scale with the intrinsic, rather than observed, hard x-ray luminosity in Compton-thick sources of Seyfert 2 type.

Source selection.—The linear scaling of neutrino and the secondary sub-MeV electromagnetic luminosity from the power released in interactions of high-energy protons suggests that Seyfert galaxies with the highest unabsorbed sub-MeV flux should be the brightest neutrino sources.

To define a predetermined (*a priori*) neutrino source candidate catalog, we follow the approach of Ref. [3] and start from a volume-complete sample of nearby Seyfert galaxies above the luminosity threshold $L_{\rm min} = 10^{42}$ erg/s from the *Swift*-BAT 105 months survey [18]. We consider sources in the declination range $-5° < \delta < 60°$ in which IceCube can observe in the muon neutrino channel at moderate atmospheric background levels and without strong absorption by Earth. We include in our candidate list sources that are confirmed Seyfert galaxies, based on the Turin Seyfert galaxy catalog [2].

This preselects 13 sources in the sky region of interest, listed in Table I of Supplemental Material [19] that includes information on the sources, further description of the selection criteria, and Refs. [20–30]. Apart from NGC 1068, three other sources, NGC 1320, NGC 3079, and NGC 7479 are Compton-thick and two other, NGC 4388 and NGC 5899, have N_H in excess of $10^{23}\ {\rm cm}^2$. For these sources, we find the estimates of the intrinsic hard x-ray luminosity based on the detailed modeling of the spectra measured by the *NuSTAR* Telescope (with higher signal-to-noise compared to *Swift* Burst Alert Telescope (BAT) reported in the literature [17,31,32].

Figure 1 shows the estimates of the muon neutrino fluxes from the preselected sources. The horizontal dashed line shows the sensitivity limit of the ten-year IceCube exposure for the E^{-3} power law neutrino spectrum (with the slope close to the measured slope of the NGC 1068 spectrum [5]). Only two additional sources may be detectable individually in the ten-year IceCube exposure: NGC 4151, a Seyfert 1 galaxy, and a Seyfert 2 galaxy, NGC 3079. NGC 3079 is similar to NGC 1068 in the sense that it is also Compton thick with $N_H > 10^{24}\ {\rm cm}^{-2}$. For NGC 4151 the column density is much lower.

The requirement that the source should be above the sensitivity limit of IceCube reduces the number of sources from 13 to 3. We exclude NGC 1068 from our final source catalog, because this source has been used to formulate the hypothesis on the scaling of the neutrino flux with the hard x-ray intrinsic source luminosity. Thus, the final “neutrino candidate” source catalog consists of only two sources.

IceCube data analysis.—We search for the neutrino signal from these two potentially detectable sources using

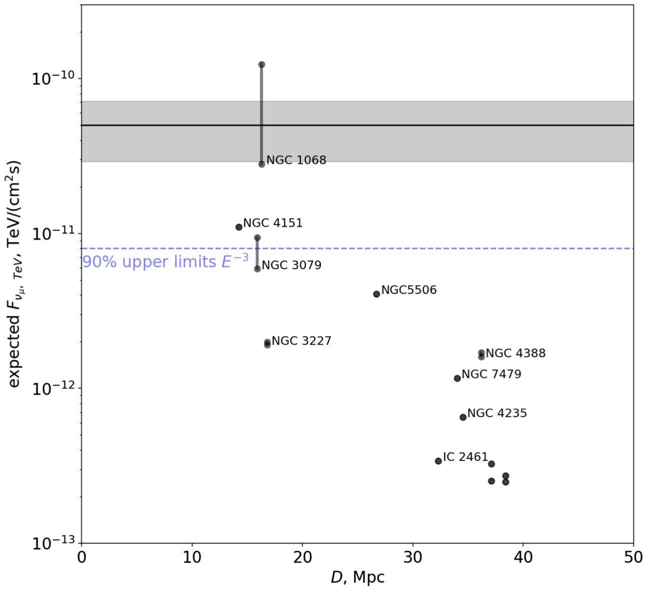

FIG. 1. Expected neutrino fluxes of Seyfert galaxies derived from the hard x-ray data. Vertical lines correspond to the uncertainty of the intrinsic hard x-ray flux estimates for Compton-thick sources. Horizontal black line and gray band show the measured neutrino flux of NGC 1068 [5]. The horizontal dashed line shows the expected level of 90% upper limits on neutrino flux for sources with E^{-3} powerlaw spectra in the declination range $-5° <$ to $< 60°$, attainable with ten-year IceCube exposure [11].

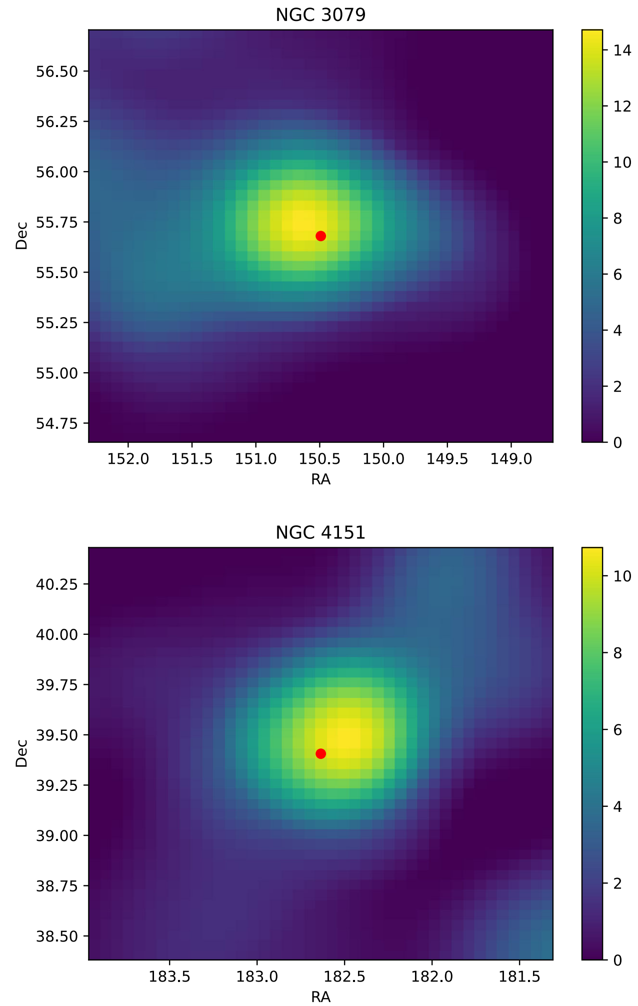

FIG. 2. Maps of test statistic values around the positions of NGC 3079 and NGC 4151. Red dots mark the catalog source positions.

a publicly available ten-year dataset of IceCube [33]. Similar to [5], we consider only the data of the fully assembled 86 string detector that has homogeneous event selection and stable instrument response functions. We perform the unbinned likelihood analysis [34], see Supplemental Material [19] for details.

Figure 2 shows the map of test statistic values around the positions of NGC 3079 and NGC 4151. For each source, evidence for the signal is found in the data. In the case of NGC 3079, the maximal test statistic value is found at the right ascension 150.7°, declination 55.7°. The test statistic value at the catalog source position is 14.1. The probability that this or higher test statistic value is found in a background fluctuation is $p_{3079} = 9.3 \times 10^{-5}$. The 0.3–100 TeV flux is $F_{\nu_\mu,100} = 3.2 + 4.0 - 2.5 \times 10^{-11}$ (TeV/cm^2 s). For NGC 4151, the excess at the source position has the test statistic value 10.0. Such an excess can be found in background fluctuations with probability $p_{4151} = 2.7 \times 10^{-3}$. The highest test statistic is found at the position right ascension 182.5° and declination 39.5°, just 0.1° from the catalog source position. The 0.3–100 TeV flux is estimated to be $F_{\nu_\mu,100} = 2.8 + 2.2 - 2.0 \times 10^{-11}$ (TeV/cm^2 s). Overall, two out of two additional sources show evidence for the signal in the IceCube data. The probability to find random background count fluctuations at the two positions is $p = p_{3079} p_{4151} \simeq 2.6 \times 10^{-7}$. No other Seyfert galaxy from our source sample shows an excess in our analysis. Figure 3 shows a comparison between neutrino flux estimates and upper limits and hard x-ray corona fluxes of the selected sources.

Discussion.—Analysis of the IceCube data presented above reveals a correlation between Seyfert galaxies and neutrino emission. Estimates of the neutrino flux based on the hard x-ray luminosity of the central engines of Seyfert type AGN has suggested that only two additional sources, besides NGC 1068, should have been detected in the ten-year IceCube data sample. We have found excess neutrino counts at the positions of both additional sources, NGC 3079 and NGC 4151. The chance coincidence probability to find the observed excess in both sources is $p \simeq 2.6 \times 10^{-7}$, which corresponds to the 5σ confidence level detection of the correlation.

The spectra of neutrino emission from the three sources are softer than E^{-2} (see Supplemental Material [19]). This means that most of the neutrino power is emitted in the

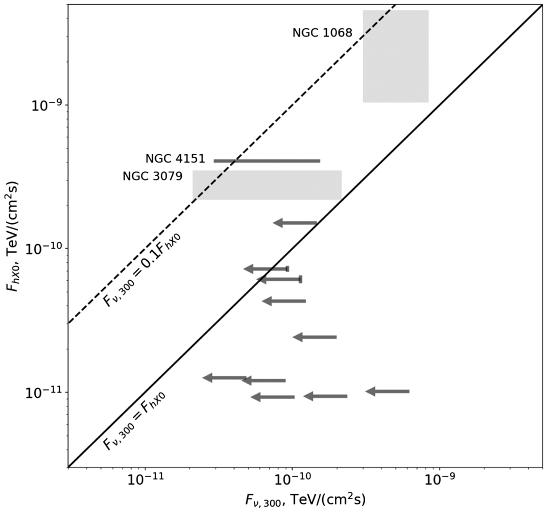

FIG. 3. Comparison of the intrinsic hard x-ray fluxes (15–195 keV range) with the all-flavor neutrino flux measurements or upper limits in the energy range above 300 GeV (see Supplemental Material [19]). Gray boxes correspond to the uncertainties of the flux for detected sources. Black solid line shows the $F_{\nu,300} = F_{hX0}$ scaling, dashed line is for the neutrino flux 10 times smaller than the hard x-ray flux.

energy range close to the energy threshold of IceCube (at several hundred GeV). Figure 3 shows a comparison of the integral all-flavor neutrino flux in the IceCube energy band (we assume equal flux per neutrino flavor) with the hot corona flux in the *Swift* BAT energy range that would be observed if the sources would be Compton thin. One can see that the neutrino source power is comparable to the power emitted by the hot corona. This suggests that interactions of high-energy protons may be an important element of the energy balance of the hot corona around the black hole accretion disk. This fact may call for a revision of the models of the hot coronas [35].

Seyfert galaxies provide a major contribution to the x-ray background that peaks at the energy ~30 keV at the flux level $F_{XRB} \sim 10^{-4.5}$ GeV/(cm^2 s sr) [36]. If all Seyfert galaxies would emit neutrinos with the power at the level of 0.1–1 of their hard x-ray power, and with soft neutrino spectrum with slope $\Gamma > 2$ extending into (or below) the 100 GeV range, the cumulative neutrino flux from the Seyfert galaxy population would be at the level of 0.1–1 of hard x-ray background level. In this case, Seyfert galaxies may also provide a major contribution to the observed astrophysical neutrino flux [37].

The origin of the high-energy protons whose interactions lead to neutrino emission from the cores of Seyfert galaxies is not clear. Difference between the neutrino and γ ray luminosity in the TeV energy range suggests compact size of the neutrino source and locates proton acceleration site close to the black hole. NGC 1068, NGC 3079 and NGC 4151 all have detectable radio flux from the central parsec around the black hole, revealed by the VLBA detections [3]. This radio emission may be associated to particle acceleration activity close to black hole. However, the angular resolution of radio observations is not sufficient for localizing the acceleration site. It may be that the acceleration happens at the base of a weak jet ejected by the black hole. Alternatively, reconnection in the accretion disk or a vacuum gap in the black hole magnetosphere may be considered as candidate proton acceleration sites [9,10].

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