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Constraining the contribution of Seyfert galaxies to the astrophysical diffuse neutrino flux using source population simulations

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Abstract. Recently, the IceCube collaboration reported evidence for TeV neutrino emission from several nearby Seyfert galaxies that are intrinsically bright in X-rays, with the highest significance found for NGC 1068. The fact that no gamma rays in the TeV energy range are observed from NGC 1068 indicates that these neutrinos are likely to be produced in the AGN corona, which is opaque to high-energy gamma rays. Based on this assumption, we model the neutrino emission of Seyfert galaxies with different X-ray properties. We fit the resulting spectrum for NGC 1068 to public IceCube data and find that our model fits the data well. Using the result of this fit as a benchmark, we apply our model to a selection of nearby Seyfert galaxies and a simulated population of sources. Considering the uncertainties in the cosmological evolution of Seyfert galaxies, this allows us to derive constraints on both the contribution of these sources to the astrophysical diffuse neutrino flux and the underlying source modelling parameters. In particular, we explore a possible correlation between the intrinsic X-ray luminosity of a source and its neutrino emission. Connecting the knowledge of individual nearby Seyfert galaxies to the source population as a whole, this approach provides a realistic picture of the contribution of Seyfert galaxies to astrophysical neutrino observations.

1 Introduction

In 2022, the IceCube collaboration reported evidence of neutrino emission from the nearby Seyfert galaxy NGC 1068 [1]. Analysing 10 years of observational data, they found an excess of 79 neutrinos at TeV energies associated with NGC 1068 with a significance of 4.2σ. NGC 1068 is a well-studied Seyfert II galaxy that is located at a distance of $d_L = 11.14$ Mpc [2] and has an intrinsic 2-10 keV X-ray luminosity of $L_X = 4.2 \times 10^{43}$ erg s^{-1} [3][1]. This makes it the Seyfert galaxy with the highest intrinsic X-ray flux in the Northern Hemisphere. Recently, the IceCube collaboration has also published results for other Seyfert galaxies, with NGC 4151 and CGCG 420-015 as the most significant source candidates besides NGC 1068 [4, 5].

Interestingly, the MAGIC telescopes have not detected any TeV γ-ray emission associated with NGC 1068 [6]. This suggests that the γ-rays produced in the same hadronic interactions

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[1] Value from [3] rescaled for a distance of 11.14 Mpc.

as the neutrinos are absorbed within the source environment. One possible neutrino production site that is opaque to high-energy γ-rays is the AGN corona, a hot plasma of electrons surrounding the central region of the accretion disk. The corona is very luminous in X-rays produced by multiple inverse Compton scattering of optical and UV disk photons. Neutrino emission models proposed in [7, 8] suggest that protons are accelerated to PeV energies inside the corona. These protons can then undergo pp interactions with ambient gas and $p\gamma$ interactions with X-rays, which lead to the production of neutrinos and γ-rays. While the neutrinos escape unhindered, the simultaneously produced γ-rays are attenuated in $\gamma\gamma$ interactions with X-rays and instead contribute to the emission at MeV energies via electromagnetic cascades.

In this contribution, we investigate the extent to which Seyfert galaxies can contribute to the astrophysical neutrino flux. In addition, we aim to constrain the neutrino emission properties of Seyfert galaxies as a source class. To achieve this, we model the neutrino emission of a single Seyfert galaxy based on what is known about NGC 1068 and subsequently apply this model to entire source populations.

2 Neutrino emission model for a single source

Based on the disk-corona model described in [7], we calculate the neutrino spectrum of a single Seyfert galaxy as a function of its intrinsic 2-10 keV X-ray luminosity L_X. We assume that inside a spherical corona, cosmic-ray (CR) protons are accelerated via stochastic acceleration in magnetic turbulence. These protons interact with their environment inside the corona via pp and $p\gamma$ interactions producing neutrinos and γ-rays. In addition, we consider cooling via Bethe-Heitler pair production and proton synchrotron radiation as well as escape via infall onto the SMBH and diffusion. The target photon spectrum relevant for $p\gamma$ and Bethe-Heitler interactions consists of the intrinsic X-ray spectrum of the corona and the optical/UV spectrum of the accretion disk. The neutrino spectrum of a source with a given X-ray luminosity is then computed using the multi-messenger simulation code AM^3 [9].

Besides the X-ray luminosity of the source, our model has two additional free parameters: the normalisation of the injected proton spectrum, which is determined by the ratio of the CR pressure to the thermal gas pressure inside the corona, $P_{\mathrm{CR}}/P_{\mathrm{th}}$, and the inverse turbulence strength $\eta = B^2/\delta B^2$ of the magnetic field. To determine these remaining free parameters, we fit our model neutrino spectrum for NGC 1068 to the public 10-year IceCube dataset of track-like events for point-source searches [10] by performing a likelihood-ratio test using the Python software `SkyLLH` [11]. We impose an upper limit on the normalisation of the injected proton spectrum by requiring that $P_{\mathrm{CR}}/P_{\mathrm{th}} \leq 0.5$ [12].

The fit yields an inverse turbulence strength of $\hat{\eta} = 17$ and $\hat{n}_s = 40$ signal events. This corresponds to a total injected proton luminosity of $L_p = 0.63 L_X$, equivalent to a pressure ratio of $P_{\mathrm{CR}}/P_{\mathrm{th}} = 0.5$. As shown in the left panel of Fig. 1, setting an upper limit on the pressure ratio does not lead to a significantly worse fit to the data since the result of the fit with $P_{\mathrm{CR}}/P_{\mathrm{th}} \leq 0.5$ lies just outside the 68% confidence region of the fit without an upper limit on $P_{\mathrm{CR}}/P_{\mathrm{th}}$. The right panel of Fig. 1 shows our best-fit model neutrino spectrum for NGC 1068 (red line) and the 68% uncertainty band obtained using Wilks' theorem. The result of a standard power-law fit, also performed with `SkyLLH`, is shown for comparison (blue line).

3 Diffuse neutrino flux

Next, we extend our neutrino emission model to an entire population of Seyfert galaxies to calculate the resulting diffuse neutrino flux. The cosmological evolution of this population is described by its X-ray luminosity function (XLF), which gives the differential number

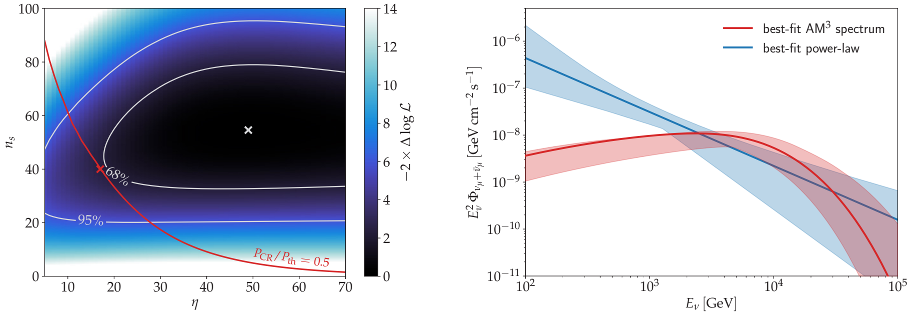

Figure 1. Results of the fit for NGC 1068. Left: Best-fit model parameters obtained with $P_{\rm CR}/P_{\rm th} \leq 0.5$ (red cross) and without an upper limit on $P_{\rm CR}/P_{\rm th}$ (grey cross). The region above the red line corresponds to $P_{\rm CR}/P_{\rm th} > 0.5$ and is therefore excluded. The grey contours represent the 68% and 95% confidence levels for the fit without an upper limit on $P_{\rm CR}/P_{\rm th}$. Right: Our best-fit model neutrino spectrum for NGC 1068 (red line) and the best-fit power-law spectrum (blue line). The shaded regions correspond to the 68% uncertainty bands determined using Wilks' theorem.

density of AGNs per comoving volume as a function of X-ray luminosity and redshift. For our calculation, we consider the XLF from [13] and two XLFs derived in [14] for different priors on the shape of the luminosity function.

For each of these XLFs, we simulate a population of Seyfert galaxies up to a redshift of 5 using the Python package `popsynth` [15]. This results in three populations comprising between 340 million and 1.3 billion sources, for each of which we know the position in the sky, the redshift and the X-ray luminosity. From each population, we remove all sources with an intrinsic 2-10 keV X-ray flux higher than $10^{-11}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ and replace them with 99 nearby sources from the BAT AGN Spectroscopic Survey (BASS) catalogue [16].

Using our best-fit result for NGC 1068 as a benchmark, we apply the neutrino emission model described in Section 2 to all sources to calculate the resulting diffuse neutrino flux for each population. We perform this calculation using two different assumptions on the scaling of the injected proton luminosity with the X-ray luminosity of a source. The left panel of Fig. 2 shows the diffuse neutrino flux spectra for the three different source populations for the case where $P_{\rm CR}/P_{\rm th} = 0.5$ for all sources. For the spectra shown in the right panel of Fig. 2, we assume that $L_p = 0.63 L_X$ for sources with $L_X \leq L_X^{\rm NGC\,1068}$ and $P_{\rm CR}/P_{\rm th} = 0.5$ for sources with $L_X > L_X^{\rm NGC\,1068}$. This ensures that no source exceeds $P_{\rm CR}/P_{\rm th} = 0.5$.

In all cases, the spectra agree well with the observed diffuse flux above $E \gtrsim 5\,\mathrm{TeV}$, but exceed the upper limit at $\sim 2\,\mathrm{TeV}$. This suggests that NGC 1068 might be a particularly powerful Seyfert galaxy and that it is unlikely that all other Seyfert galaxies in the Universe have the same neutrino emission properties as NGC 1068. However, this conclusion is based only on a first visual comparison of our results with the IceCube data points, and we plan to quantify the agreement of our diffuse flux predictions with observational data in more detail.

4 Conclusion

We model the neutrino emission of Seyfert galaxies based on a disk-corona model with two free parameters: the inverse turbulence strength of the magnetic field inside the AGN corona and the normalisation of the primary proton spectrum. Using a likelihood-ratio test, we fit this model to observational data and show that it provides a good fit for NGC 1068. Based on the result of this fit, we apply the model to three populations of Seyfert galaxies simulated based

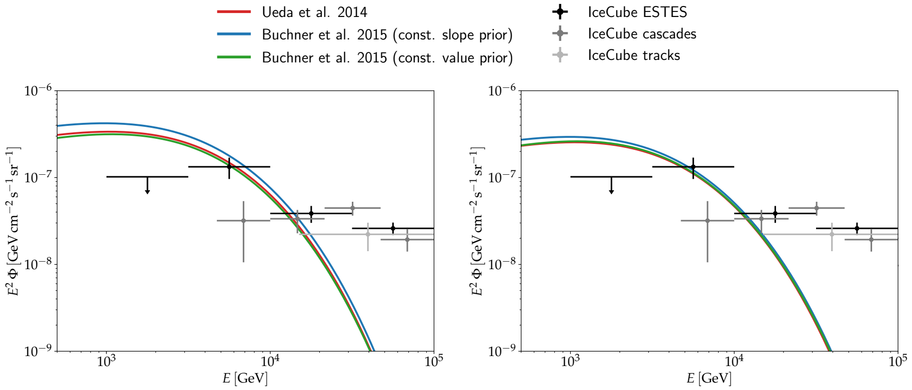

Figure 2. Diffuse neutrino flux spectra (per flavour) obtained by applying the neutrino emission model described in Section 2 to source populations based on the XLFs from [13] (red) and [14] (blue and green). The black, dark grey and light grey data points show the diffuse flux from different IceCube analyses [17–19]. Left: $P_{\mathrm{CR}}/P_{\mathrm{th}} = 0.5$ for all sources. Right: $L_p = 0.63 L_X$ for sources with $L_X \leq L_X^{\mathrm{NGC\,1068}}$ and $P_{\mathrm{CR}}/P_{\mathrm{th}} = 0.5$ for sources with $L_X > L_X^{\mathrm{NGC\,1068}}$.

on different XLFs and calculate the diffuse neutrino flux. We obtain similar results for all three XLFs, suggesting that Seyfert galaxies could be the main sources of the astrophysical neutrino flux at TeV energies. However, if all sources were similar to NGC 1068, their cumulative neutrino emission would exceed the observed neutrino flux below ∼ 5 TeV. This indicates that NGC 1068 might be a particularly powerful Seyfert galaxy.

References

[1] R. Abbasi et al., Science **378**, 538–543 (2022)
[2] N.A. Tikhonov, O.A. Galazutdinova, Astrophys. Bull. **76**, 255–268 (2021)
[3] A. Marinucci et al., MNRAS **456**, L94 (2016), `1511.03503`
[4] R. Abbasi et al., arXiv (2024), `2406.06684`
[5] R. Abbasi et al., arXiv (2024), `2406.07601`
[6] V.A. Acciari et al., Astrophys. J. **883**, 135 (2019), `1906.10954`
[7] K. Murase et al., Phys. Rev. Lett. **125**, 011101 (2020), `1904.04226`
[8] Y. Inoue et al., Astrophys. J. Lett. **891**, L33 (2020), `1909.02239`
[9] M. Klinger et al., Astrophys. J. Suppl. **275**, 4 (2024), `2312.13371`
[10] IceCube Collaboration, All-sky point-source IceCube data: years 2008-2018 (2021), DOI: 10.21234/sxvs-mt83
[11] C. Bellenghi et al., PoS **ICRC2023**, 1061 (2023), `2308.12733`
[12] A. Kheirandish et al., Astrophys. J. **922**, 45 (2021), `2102.04475`
[13] Y. Ueda et al., Astrophys. J. **786**, 104 (2014), `1402.1836`
[14] J. Buchner et al., Astrophys. J. **802**, 89 (2015), `1501.02805`
[15] J. Burgess, F. Capel, JOSS **6**, 3257 (2021), `2107.08407`
[16] C. Ricci et al., Astrophys. J. Suppl. **233**, 17 (2017), `1709.03989`
[17] R. Abbasi et al., Phys. Rev. D **110**, 022001 (2024), `2402.18026`
[18] M.G. Aartsen et al., Phys. Rev. Lett. **125**, 121104 (2020), `2001.09520`
[19] R. Abbasi et al., Astrophys. J. **928**, 50 (2022), `2111.10299`