





LETTER TO THE EDITOR

# The neutrino background from non-jetted active galactic nuclei

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## ABSTRACT

**Aims.** We calculate the contribution to the neutrino background from the non-jetted active galactic nuclei (AGN) population following the recent IceCube association of TeV neutrinos with NGC 1068.

**Methods.** We exploited our robust knowledge of the AGN X-ray luminosity function and evolution and converted it to the neutrino band by using NGC 1068 as a benchmark, together with a theoretically motivated neutrino spectrum.

**Results.** The resulting neutrino background up to redshift 5 does not violate either the IceCube diffuse flux or the upper bounds for non-jetted AGN, although barely so. This is consistent with a scenario in which the latter class makes a substantial contribution mostly below 1 PeV, while jetted AGN, that is, blazars, dominate above this energy, in intriguing agreement with the dip in the neutrino data at  $\sim 300$  TeV. More and better IceCube data on Seyfert galaxies will allow us to constrain the fraction of neutrino emitters among non-jetted AGN.

**Key words.** neutrinos – radiation mechanisms: non-thermal – galaxies: Seyfert

## 1. Introduction

IceCube has recently detected an excess of TeV neutrinos with a  $4.2\sigma$  significance from the direction of NGC 1068, the prototype Seyfert II galaxy (IceCube Collaboration 2022). This event was somewhat unexpected. Non-jetted active galactic nuclei (AGN)<sup>1</sup> such as NGC 1068 are usually characterised by thermal emission, in contrast to jetted AGN, which are known for their predominantly non-thermal radiation (e.g. Padovani et al. 2017). Only the latter class was deemed to have the capability to accelerate protons to the energies necessary for neutrino production, as discussed, for example, in the review by Giommi & Padovani (2021, and references therein; but see Berezhinsky 1977; Eichler 1979; Silberberg & Shapiro 1979).

Being so close, NGC 1068 can be spatially resolved into a number of components that might all be relevant to neutrino production (Padovani et al. 2024). These include 1. a starburst region in the spiral arms of its host galaxy; 2. a  $\lesssim$  kiloparsec jet; 3. a sub-kiloparsec molecular outflow; 4. and the vicinity of the supermassive black hole (SMBH). By first using simple order-of-magnitude arguments and then applying specific theoretical models, Padovani et al. (2024, and references therein) have come to the conclusion that only the region close to the accretion disc around the SMBH, most likely the X-ray emitting corona, fulfils the conditions of the right density of photons needed to provide the targets for protons to sustain neutrino production and to absorb the expected but unobserved  $\gamma$  rays.

<sup>1</sup> We follow Padovani (2017) and define as jetted AGN with strong relativistic jets, which is not the case for NGC 1068, as discussed in Padovani et al. (2024).

The question is how unique NGC 1068 is. The extent to which the process that produces neutrinos in NGC 1068 can be generalised to the wider AGN population is currently unknown. Assuming a tight connection between neutrino emission and the plasma in AGN coronae, theoretical studies of Seyfert galaxies that host X-ray bright AGN have been carried out to determine possible new neutrino sources (e.g. Kheirandish et al. 2021).

The purpose of this Letter is to approach this question from an observational and population-wide perspective. We leverage the well-established knowledge of X-ray luminosity functions (XLF) and the evolution of AGN, along with the constraints provided by the cosmic X-ray background (CXB; Gilli et al. 2007). We then translate these findings to the neutrino band by normalising them to NGC 1068. In short, our aim is to use the somewhat limited neutrino information, both on the observational and modelling side, to investigate the implications of an extrapolation from a single non-jetted AGN to the entire population. We assume a distance to this source of 10.1 Mpc, following Padovani et al. (2024).

## 2. Population synthesis of the X-ray background

The spectrum of the CXB records the integrated emission of AGN across all cosmic times (Setti & Woltjer 1989). Several papers (e.g. Comastri et al. 1995; Treister & Urry 2006; Akylas et al. 2012; Ueda et al. 2014; Ananna et al. 2019) demonstrated that the peak around 20–30 keV in the CXB spectrum cannot be reproduced by the emission of unobscured and moderately obscured AGN alone, but that a large population

of heavily obscured Compton-thick AGN<sup>2</sup> is required. To date, population synthesis models of the CXB provide the best inference about the overall abundance of accreting SMBHs. We adopted the model of Gilli et al. (2007). It accurately fits the CXB spectrum and agrees very well with the most recent estimates of the AGN XLFs (Ueda et al. 2014) and number counts in different redshift intervals and X-ray bands (Luo et al. 2017; Nanni et al. 2020; Marchesi et al. 2020). Starting from the 0.5–2 keV XLF of unobscured AGN described in Hasinger et al. (2005), and assuming a distribution of AGN-obscuring column densities in agreement with observational constraints (Risaliti et al. 1999; Tozzi et al. 2006), Gilli et al. (2007) found that moderately obscured Compton-thin AGN ( $N_{\text{H}} = 10^{22-24} \text{ cm}^{-2}$ ) need to outnumber unobscured AGN (by a factor decreasing from 4 to 1 with increasing luminosity) to reproduce the measured 2–10 keV AGN XLF (Ueda et al. 2003; La Franca et al. 2005). Furthermore, a luminosity-dependent space density of Compton-thick AGN equal to that of moderately obscured Compton-thin AGN was required to fit the CXB spectral peak (assuming all populations follow the same cosmological evolution). We remark that the AGN XLF used by Gilli et al. (2007) are largely ( $\geq 90\%$ ) dominated by non-jetted AGN. As discussed below, our computation specifically refers to the contribution to the neutrino background from the non-jetted AGN population alone.

### 3. Predicting the neutrino background

To compute the expected neutrino background using CXB population synthesis models, we first extended the AGN X-ray spectra considered by Gilli et al. (2007) to the neutrino domain.

We first assumed that the  $10^{-4}$ – $10^3$  TeV neutrino spectrum of each non-jetted AGN follows the “minimal  $pp$  scenario” model of Murase (2022, as shown in their Fig. 3, left and middle panels), which provides an X-ray corona-based theoretical fit to the NGC 1068 IceCube data. This spectrum peaks at  $E \sim 1$  TeV, and its slope in the  $\sim 2$ – $15$  TeV energy range is consistent with what IceCube has observed ( $\gamma = 3.2 \pm 0.2$ , where  $n(E) \propto E^{-\gamma}$  and  $n(E)$  is the neutrino particle spectrum: IceCube Collaboration 2022).

As for the relative normalisation between neutrino and X-ray AGN spectra, we resorted to the observed X-ray and neutrino fluxes (or luminosities) of NGC1068, the only non-jetted AGN for which these two crucial parameters are available. We remark that what matters here is the intrinsic, that is, corrected for absorption, AGN X-ray flux (or luminosity), since the total background is obtained by integrating intrinsic AGN luminosity functions. The best estimate of the intrinsic X-ray flux of NGC1068 was arguably presented by Marinucci et al. (2016), who, by means of *NuSTAR* observations, obtained spectra of the target up to  $\sim 60$  keV at different epochs and discovered a transient decrease in the column density along the line of sight from  $\geq 10^{25}$  to  $7 \times 10^{24} \text{ cm}^{-2}$ , which was sufficient to reveal its direct nuclear radiation. The intrinsic flux density at 1 keV was found to be  $f_{1 \text{ keV}} = 1.44 \times 10^{-9} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ . We then derived the all-flavour neutrino flux density at 4 TeV, where it is likely best constrained, by considering the muon-type neutrino spectrum measured by IceCube,  $EF(E) = 5 \times 10^{-11} (E/1 \text{ TeV})^{-1.2} \text{ TeV cm}^{-2} \text{ s}^{-1}$ , and multiplying it by 3 (which assumes vacuum neutrino mixing). This gives a neutrino flux density of  $f_{4 \text{ TeV}} = 1.14 \times 10^{-20} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1}$ , and hence,

<sup>2</sup> These are defined by a column density along our line of sight  $N_{\text{H}} > 1/\sigma_{\text{T}} \sim 10^{24} \text{ cm}^{-2}$ , where  $\sigma_{\text{T}}$  is the Thomson cross-section.

an X-ray to neutrino flux ratio  $\nu f_{\nu}|_{1 \text{ keV}}/\nu f_{\nu}|_{4 \text{ TeV}} = 31.5$ . The uncertainty on this value, taking the errors on the X-ray and neutrino fluxes and those on the photon indices into account, is  $\sim 0.5$  dex. We used this ratio as the relative normalisation between the neutrino and X-ray AGN spectra and computed the expected neutrino background spectrum as

$$F(E) = \frac{1}{4\pi} \int_0^{z_{\text{max}}} \frac{1+z}{4\pi d_L^2} \frac{dV}{dz} \int_{L_{\text{min}}}^{L_{\text{max}}} f[E(1+z)]\Phi[L, z]L dL dz, \quad (1)$$

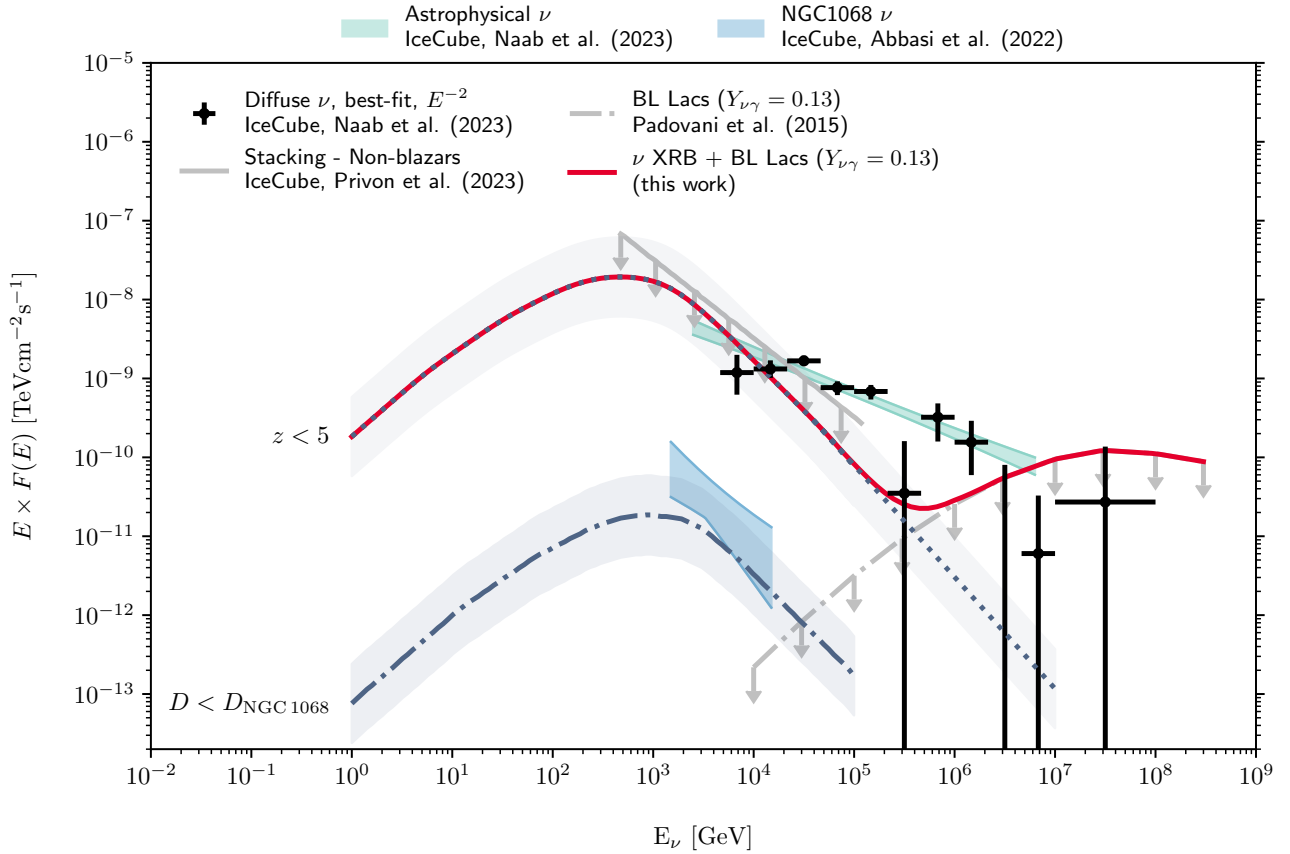
where  $d_L$  is the luminosity distance,  $\frac{dV}{dz}$  is the comoving volume element,  $\Phi[L, z]$  is the total intrinsic comoving AGN XLF (obtained by summing both obscured and unobscured AGN) as per the CXB model of Gilli et al. (2007), and  $f[E(1+z)]$  is the X-ray normalised neutrino flux density at the energy  $E(1+z)$ . We integrated the AGN XLF in the luminosity range  $L_{0.5-2 \text{ keV}} = 10^{42}$ – $10^{48} \text{ erg s}^{-1}$  and in the redshift interval  $z = 0$ – $5$ . We note that the contribution of AGN at  $z > 5$  to the total background flux is negligible and that integrating the AGN XLF down to  $L_{0.5-2 \text{ keV}} = 10^{41} \text{ erg s}^{-1}$  to include the contribution of low-luminosity AGN would increase the total background flux by  $\sim 16\%$  at most. For comparison, we also computed the diffuse neutrino background expected from very local AGN, that is, within the same distance to NGC1068.

### 4. Main results

Figure 1 shows the resulting all-flavour neutrino background integrated up to redshift  $z = 5$  (dotted blue curve). This can be compared with the current best fit for the IceCube astrophysical diffuse neutrino flux as obtained by Naab et al. (2023), derived using a segmented neutrino flux fit with individual energy bins assuming an  $E^{-2}$  energy spectrum in each bin (black points) and a single power-law fit  $\propto E^{-2.52 \pm 0.04}$  (green area). Our integrated non-jetted AGN contribution is consistent with the IceCube diffuse component down to  $\approx 10$  TeV. In other words, the assumption that all non-jetted AGN behave like NGC 1068 in terms of their neutrino properties is consistent with current IceCube data above this energy.

Most likely, different astrophysical populations contribute to the IceCube diffuse component, and hence, this comparison might be not be very constraining. In Fig. 1 we therefore also show upper limits derived by IceCube from a stacking analysis carried out on non-blazar (and therefore, mostly non-jetted) AGN (solid grey line: Privon et al. 2023). The analysis tested the hypothesis of neutrino emission from hard X-ray AGN in the BASS catalogue (Ricci et al. 2017), assuming that the neutrino flux correlates with the de-absorbed X-ray flux. After finding no significant results, Privon et al. (2023) placed upper limits at 90% confidence on the neutrino emission from all non-jetted hard X-ray AGN assuming an energy spectrum  $\propto E_{\nu}^{-3}$ . These limits were corrected for catalogue incompleteness by accounting for the missing neutrino signal from all non-detected non-jetted X-ray AGN in the Universe using the XLF given in Ueda et al. (2014). Our results are consistent even with the estimated maximum emission from non-jetted AGN, although barely so.

Figure 1 also shows the diffuse neutrino background expected from all AGN within 10.1 Mpc, which is the most reliable distance to NGC1068 (Sect. 1: dash-dotted blue curve). At first glance, this is somewhat smaller than the neutrino flux from NGC1068 alone. We note, however, that the 0.5 dex uncertainty on the ratio of the X-ray to neutrino flux assumed



**Fig. 1.** Computed all-flavour neutrino background derived from an X-ray AGN population synthesis. The dark blue curves show the computed neutrino backgrounds for source populations integrated up to the distance of NGC1068 and redshift  $z = 5$  (dash-dotted and dotted, respectively). A high-energy extrapolation up to  $10^7$  GeV is added to the integrated spectrum for  $z = 5$  and combined with the blazar neutrino background model by Padovani et al. (2015; dash-dotted grey curve) to highlight the structure of the combined AGN neutrino background flux (double-humped solid red curve). The estimated uncertainty on the integrated neutrino component from X-ray AGN is assumed to be 0.5 dex (dark blue band). We also show the current best-fit astrophysical diffuse neutrino flux and the segmented neutrino flux fit assuming an  $E^{-2}$  energy spectrum in each bin (green area and black points: Naab et al. 2023), IceCube upper limits from stacking analyses for non-blazar AGN (solid grey line: Privon et al. 2023), and the point-source neutrino flux of NGC1068 (blue area: Abbasi et al. 2022).

for NGC1068 (Sect. 3) significantly alleviates this difference. Moreover, the model predictions may be significantly limited when tiny redshift (distance) intervals are considered, primarily because of statistical fluctuations. The shape and evolution of the AGN XLFs are in fact derived from samples of thousands of objects distributed up to large cosmological distances ( $z \lesssim 5$ ). By contrast, only three AGN with intrinsic  $L_{0.5-2\text{keV}} > 10^{42} \text{ erg s}^{-1}$  (the luminosity limit used in our integrations), including NGC 1068, fall within 10.1 Mpc, as derived from the BASS DR2 catalogue (Koss et al. 2022). The number of sources predicted by the assumed XLFs within this small volume is then bound to be somewhat inaccurate, whereas it becomes more precise, to the level of up to a few percent, when we integrate over the full redshift range (dotted blue curve in Fig. 1).

Our results are model-independent, which is crucial. It means that any model capable of reproducing the IceCube data for NGC 1068 would yield very similar curves in the energy range covered by the current neutrino data. Consequently, our conclusions hold regardless of the specific mechanism driving neutrino emission in this source.

To understand the larger picture, we added a high-energy extrapolation up to  $10^7$  GeV to the whole AGN-integrated spectrum and then combined it with the blazar neutrino background

model by Padovani et al. (2015)<sup>3</sup> (dash-dotted grey curve). Our overall results are shown by the double-humped solid red curve and present a possible scenario in which non-jetted AGN mostly contribute to the low-energy ( $\lesssim 1$  PeV) IceCube diffuse component, whereas blazars dominate the high-energy part. This would be in tantalising agreement with the dip in the data at  $\sim 300$  TeV, which might then be related to the fall of the non-jetted AGN contribution and the rise of the blazar contribution.

The question is whether we can improve on our predictions. Preliminary results indicate that the IceCube data associated with the selection of Seyfert galaxies in the northern sky, in particular, NGC 4151 and CGCG 420-015, are inconsistent with the neutrino background at the  $2.7\sigma$  level of significance (Abbasi et al. 2023). Moreover, the IceCube search for high-energy neutrino emission from hard X-ray AGN has reported NGC 4151 at a significance level of  $2.9\sigma$  (Privon et al. 2023). Using the IceCube fluxes and spectral slopes for these two sources (Qinrui & IceCube Collaboration 2023) and typical X-ray data (powers and spectra) from Wang et al. (2010) and Tanimoto et al. (2022) respectively, we derived X-ray to

<sup>3</sup> As explained in Padovani et al. (2022), the blazar curve is scaled down by a factor  $\sim 6.2$  compared to the original to avoid violating the upper limits of Aartsen et al. (2016).

neutrino flux ratios  $\nu_{f_\nu|1\text{keV}}/\nu_{f_\nu|4\text{TeV}} \sim 5.4$  and  $\sim 0.5$ , that is,  $\sim 6$  and  $\sim 60$  times lower than for NGC 1068. At face value, this would then mean that the neutrino to X-ray ratio of NGC 1068 is lower than average, implying that the dotted blue curve in Fig. 1 should be shifted upwards by  $\sim 1-2$  orders of magnitude. As this would violate the AGN IceCube upper limits from Privon et al. (2023) by the same amount, it would then follow that only  $\sim 1-10\%$  of non-jetted AGN are neutrino emitters. Clearly, more and better IceCube data are of paramount importance, both on the source and population side, to make progress on this issue.

In summary, a population synthesis model that accounts for the CXB from non-jetted AGN, predicts a neutrino background that does not violate current IceCube data and upper limits when NGC 1068 is used to convert from one band to the next. Preliminary results from two more Seyfert galaxies instead appear to imply an over-prediction. Further IceCube observations are clearly needed to determine this issue.

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## References

- Aartsen, M. G., Abraham, K., Ackermann, M., et al. 2016, *Phys. Rev. Lett.*, **117**, 241101
- Abbasi, R., Ackermann, M., Adams, J., et al. 2022, *Science*, **378**, 538
- Abbasi, R., Ackermann, M., Adams, J., et al. 2023, *PoS, ICRC2023*, 1052
- Akylas, A., Georgakakis, A., Georgantopoulos, I., Brightman, M., & Nandra, K. 2012, *A&A*, **546**, A98
- Ananna, T. T., Treister, E., Urry, C. M., et al. 2019, *ApJ*, **871**, 240
- Berezinsky, V. S. 1977, *Proceedings of the International Conference Neutrino '77*, 177
- Comastri, A., Setti, G., Zamorani, G., & Hasinger, G. 1995, *A&A*, **296**, 1
- Eichler, D. 1979, *ApJ*, **232**, 106
- Gilli, R., Comastri, A., & Hasinger, G. 2007, *A&A*, **463**, 79
- Giommi, P., & Padovani, P. 2021, *Universe*, **7**, 492
- Hasinger, G., Miyaji, T., & Schmidt, M. 2005, *A&A*, **441**, 417
- IceCube Collaboration (Abbasi, R., et al.) 2022, *Science*, **378**, 538
- Kheirandish, A., Murase, K., & Kimura, S. S. 2021, *ApJ*, **922**, 45
- Koss, M. J., Ricci, C., Trakhtenbrot, B., et al. 2022, *ApJS*, **261**, 2
- La Franca, F., Fiore, F., Comastri, A., et al. 2005, *ApJ*, **635**, 864
- Luo, B., Brandt, W. N., Xue, Y. Q., et al. 2017, *ApJS*, **228**, 2
- Marchesi, S., Gilli, R., Lanzuisi, G., et al. 2020, *A&A*, **642**, A184
- Marinucci, A., Bianchi, S., Matt, G., et al. 2016, *MNRAS*, **456**, L94
- Murase, K. 2022, *ApJ*, **941**, L17
- Naab, R., Ganster, E., & Zhang, Z. 2023, *PoS, ICRC2023*, 1064
- Nanni, R., Gilli, R., Vignali, C., et al. 2020, *A&A*, **637**, A52
- Padovani, P. 2017, *Nat. Astron.*, **1**, 0194
- Padovani, P., Petropoulou, M., Giommi, P., & Resconi, E. 2015, *MNRAS*, **452**, 1877
- Padovani, P., Alexander, D. M., Assef, R. J., et al. 2017, *A&A Rev.*, **25**, 2
- Padovani, P., Giommi, P., Falomo, R., et al. 2022, *MNRAS*, **510**, 2671
- Padovani, P., Resconi, E., Ajello, M., et al. 2024, *Nat. Astron.*, submitted
- Privon, G. C., Abbasi, R., Ackermann, M., et al. 2023, *PoS, ICRC2023*, 1032
- Qinrui, L., & IceCube Collaboration 2023, in XVIII International Conference on Topics in Astroparticle and Underground Physics (TAUP2023)
- Ricci, C., Trakhtenbrot, B., Koss, M. J., et al. 2017, *ApJS*, **233**, 17
- Risaliti, G., Maiolino, R., & Salvati, M. 1999, *ApJ*, **522**, 157
- Setti, G., & Woltjer, L. 1989, *A&A*, **224**, L21
- Silberberg, R., & Shapiro, M. M. 1979, *Int. Cosmic Ray Conf.*, **10**, 357
- Tanimoto, A., Ueda, Y., Odaka, H., Yamada, S., & Ricci, C. 2022, *ApJS*, **260**, 30
- Tozzi, P., Gilli, R., Mainieri, V., et al. 2006, *A&A*, **451**, 457
- Treister, E., & Urry, C. M. 2006, *ApJ*, **652**, L79
- Ueda, Y., Akiyama, M., Ohta, K., & Miyaji, T. 2003, *ApJ*, **598**, 886
- Ueda, Y., Akiyama, M., Hasinger, G., Miyaji, T., & Watson, M. G. 2014, *ApJ*, **786**, 104
- Wang, J., Risaliti, G., Fabbiano, G., et al. 2010, *ApJ*, **714**, 1497