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Unveiling the hard X-ray emission of NGC 1068, a possible high energy neutrino source

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CENTRE NATIONAL D'ÉTUDES SPATIALES

I – INTRODUCTION / CONTEXT :

What is an AGN ?

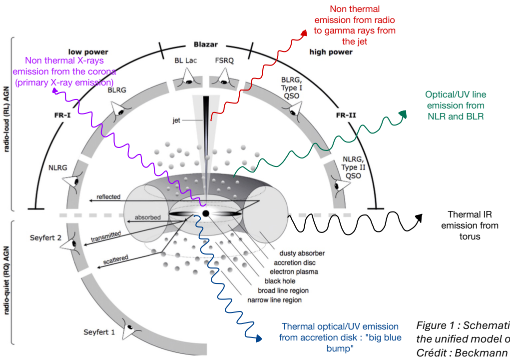


Figure 1 : Schematic view of the unified model of AGNs.
Crédit : Beckmann et al. 2012

AGNs as probable emitters of high energy neutrinos?

The study of Active Galactic Nucleus (AGNs) allows us to better understand the accretion and ejection processes and address the question of the origin of high-energy cosmic rays (HECRs). While **HECRs**, being charged particles, **are deflected by magnetic fields, high-energy neutrinos produced by hadronic interactions near black holes, travel unaffected by such fields.** Unlike gamma-ray photons, these **neutrinos** are also **not absorbed by $\gamma\gamma$ interactions**, making them unique probes for investigating HECR sources. In this context, the IceCube neutrino observatory has identified **the Seyfert 2 galaxy NGC 1068 as one of the most promising candidates** with a significant neutrino excess of **4.2σ** over 10 years of observations [1]. Located at 14.4 Mpc, NGC 1068 is currently the strongest known neutrino source in the northern hemisphere.

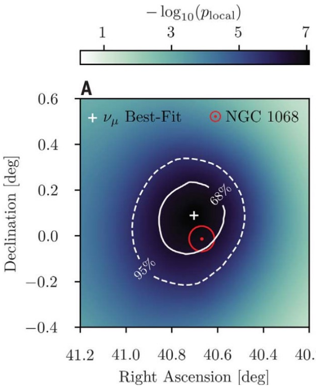
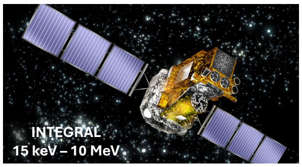
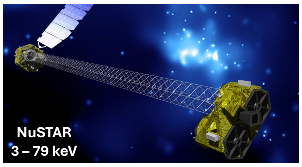


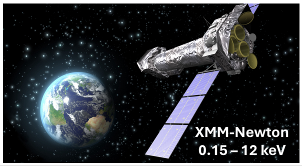
Figure 2 : Clustering map of the neutrinos (white cross). NGC 1068 and its angular size are highlighted with red dot and circle (optical wavelength). Crédit : [1]

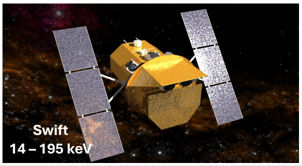
X-rays as a key to understand the emission of AGNs

Astrophysical neutrinos are mainly produced through hadronuclear and photohadronic interactions, which also generate same amount of γ-rays. However, observations of NGC 1068 show that its GeV-TeV γ-ray flux is over ten times weaker than its neutrino flux, suggesting the neutrino production region is highly opaque to GeV-TeV photons. This points to a compact emission region, possibly involving the AGN's disk and corona. Emissions in the X-ray to soft gamma-ray range (~50 keV to ~100 MeV) are key to probing hadronic contributions in NGC 1068. Several studies (e.g. [7, 8]) have proposed that AGNs may appear faint in γ-rays due to gamma-ray interactions, producing secondary particle cascades that re-emit in the keV-MeV range. This signal is expected to be significantly stronger than the usual leptonic coronal emission, which cuts off between 100 and 400 keV. Therefore, detailed X-ray observations are crucial to refining AGN emission models and exploring leptonic and hadronic components. **In this study, we analyze the most up-to-date datasets of NGC 1068 from XMM-Newton, NuSTAR, Swift-BAT, INTEGRAL-IBIS, and INTEGRAL-SPI to search for the hard X-ray signature of a hadronic component.**









MODEL AND RESULTS :

Model :

The hard X-ray flux includes Compton reflection, which can dominate in heavily obscured sources like NGC 1068. This leads to uncertainty in estimating the primary intrinsic luminosity from the black hole environment, potentially linked to hadronic emission. To accurately model the various emission components, we use the approach outlined in [2, 3, and 4]. It consists of a **double reflection emission scenario combined with an additional primary emission originating from the corona**. The **primary X-ray radiation from the corona passes through the dusty torus, resulting in significant absorption in the soft X-ray range (see figure 3)**. We also account for the reflection on the far-side of the dusty torus and for the emission of the host galaxy.

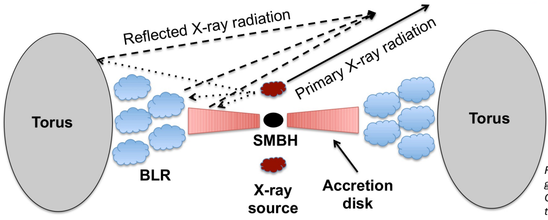


Figure 3: Scheme of the geometry of the model. Crédit : Ricci 2011, PhD thesis

Results :

We fit the model described above to our data following the methodology outlined in [4]. The intrinsic emission of the corona is described by an absorbed cutoff power law leading to : $\Gamma = 2.08^{+0.02}_{-0.03}$, $N_H = 3.67^{+0.36}_{-0.34}\times10^{24}\mathrm{cm}^{-2}$, $E_c = 118.6^{+19.9}_{-15.8}$ keV, and $K = 5.77^{+3.03}_{-1.93}\times10^{-2}$ ph/cm²/s/keV at 1 keV with a $\chi^2_{reduced} = 1.55$. All the parameters are consistent with previous works of [2] and [4] except the normalization which is found weaker than in the previous studies. Computing the intrinsic X-ray luminosity in the range 15-55 keV, we find $L_{X,prim} = 2.25^{+1.75}_{-0.9}\times10^{42}$erg/s which is smaller than the values found in [2] and [3]. While the exact value of $L_{X,prim}$ depends on the complex structure of the reflection components, this result is still **fully compatible with a leptonic scenario** as origin of the observed X-ray emission. Finally, we find that the **primary X-ray emission starts to dominate above a few hundred keV, showing the importance of having data in the range [100 keV - 1 MeV] to constrain further the presence of a hadronic component.**

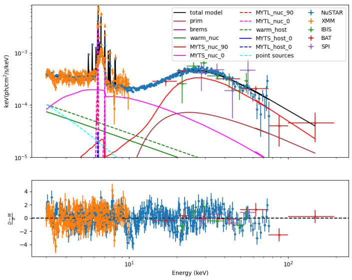


Figure 4 : Spectral energy distribution (SED). Here "MYTS-L" components stands for the reflections at different angles. The term "host" refers to the emission of the host galaxy whereas "nuc" is for the emission of the nucleus. The primary X-ray emission of the corona is represented by "prim" in the legend.

CONCLUSIONS AND DISCUSSIONS :

We present the **most recent spectral fit of NGC 1068 from 3 to 195 keV.** Our results remain **consistent with a leptonic scenario**, indicating a cutoff energy of the primary emission at $E_c = 118.6^{+19.9}_{-15.8}$ keV, compatible with inverse Compton scattering of soft photons. Still, our analysis also confirms that the [15-55] keV luminosity $\boldsymbol{L_{X,prim} = 2.25^{+1.75}_{-0.9}\times10^{42}}$**erg/s is compatible with the neutrino luminosity** $\boldsymbol{L_\nu = (2.9 \pm 1.1)\times10^{42}}$ **erg/s [1].** This result may also be consistent with neutrino production in γ-obscure regions as suggested e.g., by [5, 6] who predict a **correlation between hard X-ray and neutrino luminosities.** The lack of a definitive conclusion highlights the need for MeV-range data, where the primary X-ray emission from the vicinity of the black hole becomes dominant, to conclusively distinguish between hadronic and leptonic processes in the future.

REFERENCES:

[1]: IceCube Collaboration, Abbasi, R., Ackermann, M., et al. 2022, Science, 378, 538. doi:10.1126/science.abg3395
[2]: Bauer, F. E., Arévalo, P., Walton, D. J., et al. 2015, ApJ, 812, 116. doi:10.1088/0004-637X/812/2/116
[3]: Marinucci, A., Bianchi, S., Matt, G., et al. 2016, MNRAS, 456, L94. doi:10.1093/mnrasl/slv178
[4]: Zaino, A., Bianchi, S., Marinucci, A., et al. 2020, MNRAS, 492, 3872. doi:10.1093/mnras/staa107
[5]: Kun, E., Bartos, I., Becker Tjus, J., et al. 2024, arXiv:2404.06867. doi:10.48550/arXiv.2404.06867
[6]: Neronov, A., Savchenko, D., & Semikoz, D. V. 2023, arXiv:2306.09018. doi:10.48550/arXiv.2306.09018
[7]: Kohta Murase, Shigeo S. Kimura, et al. jun 2020, Physical Review Letters, 125, 011101
[8]: Björn Eichmann, Foteini Oikonomou, et al. nov 2022, The Astrophysical Journal, 939, 43
[9]: Yoshiyuki Inoue *et al* 2020 *ApJL* **891** L33