Photo-hadronic pair creation and neutrino production in magnetospheric current sheets of accreting black holes

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Abstract

Non-jetted AGN exhibit hard X-ray emission with a power law spectrum above 2 keV, which is thought to be produced through Comptonization of soft photons by electrons and positrons (pairs) in the corona. We study the role of relativistic protons accelerated in black-hole magnetospheric current sheets in the pair enrichment and neutrino production of AGN coronae. We present a model that has two free parameters, namely the proton plasma magnetization, which controls the peak energy of the neutrino spectrum, and the Eddington ratio (defined with respect to the broadband X-ray luminosity), which controls the amount of energy transferred to secondary particles. Our results indicate a strong dependence of the secondary pair density on the Eddington ratio. We also present our model predictions about neutrino emission from individual Seyfert galaxies and 677 non-blazar AGN from the *Swift*-BAT 70-month catalog.

The model

We consider a reconnection layer, forming in the black hole magnetospheric region, with a typical size R of a few gravitational radii (see sketch in figure 1). X-ray photons are produced through Comptonization of soft photons by pairs in the corona. Protons are accelerated by magnetic reconnection to Lorentz factors of the order of magnitude of the proton magnetization σ_p [2] that usually correspond to energies of tens of TeV. The subsequent $p\gamma$ interactions with the coronal X-ray photons trigger an electromagnetic cascade. The latter results in a production of *secondary* pairs and high-energy *neutrinos*.

The model has essentially two free parameters: the Eddington ratio defined as $\lambda_{\rm X,Edd} = L_X/L_{\rm Edd}$ (L_X is the broadband X-ray luminosity), and the proton magnetization σ_p.

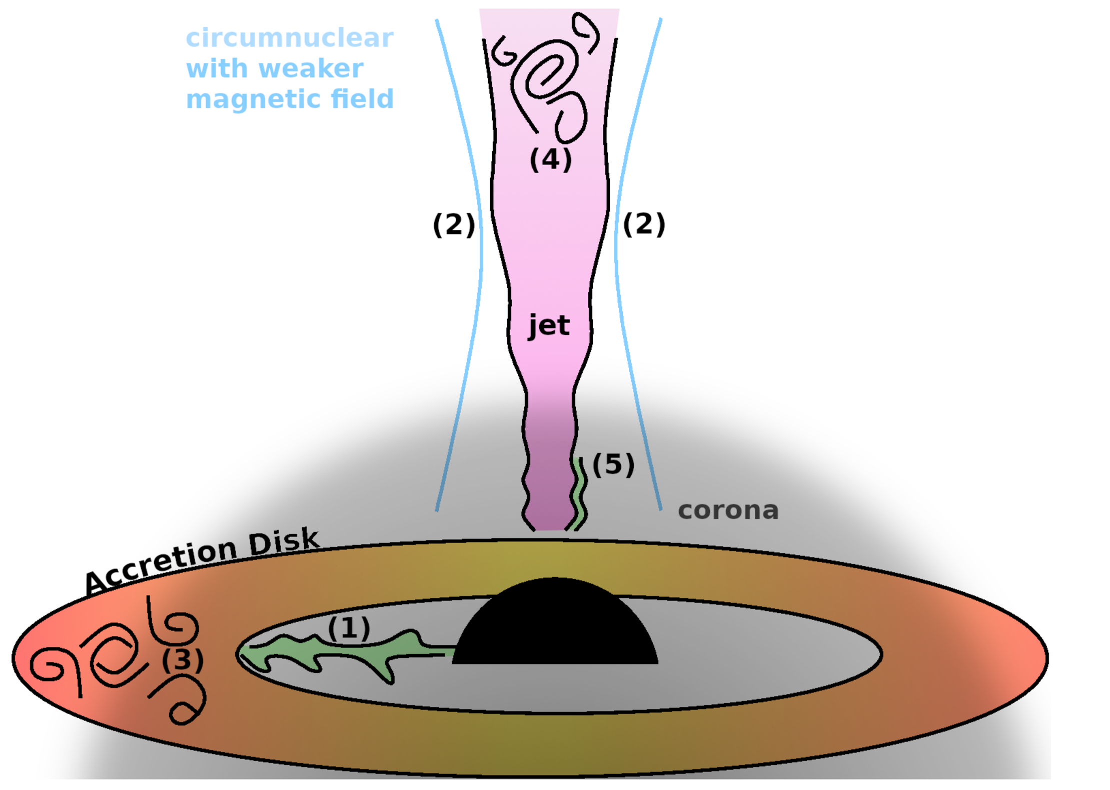

Figure 1: Sketch of a corona that is powered by magnetic reconnection.

We derived an analytical expression for the neutrino luminosity expected from a corona powered by magnetic reconnection:

$$E_\nu L_{\nu+\bar\nu}(E_\nu) \approx \frac{3\eta_{\rm p}}{16\eta_{\rm X}} L_{\rm X} \min\left[1, 1.2\frac{\lambda_{\rm X,Edd,-2}}{\tilde R}\frac{\min(E_\nu, E_{\nu,*})}{5\,{\rm TeV}}\right] \begin{cases} \dfrac{E_\nu}{E_{\nu,{\rm br}}} & , E_\nu \le E_{\nu,{\rm br}} \\ \left(\dfrac{E_\nu}{E_{\nu,{\rm br}}}\right)^{-1} & , E_\nu > E_{\nu,{\rm br}} \end{cases} \quad (1)$$

where $E_{\rm p} \approx 20E_\nu$, $E_{{\rm p},*} \approx 20E_{\nu,*}$ and $E_{\nu,{\rm br}} \approx 5\ \sigma_{{\rm p},5}$ TeV. When evaluated at $E_\nu = E_{\nu,{\rm br}}$, the equation provides an approximation for the bolometric neutrino luminosity.

Neutrino Luminosity and Pair Density

We used the radiative code ATHEνA [3] to calculate the neutrino luminosity and secondary pair density for AGN coronae with different black hole masses and X-ray luminosities (Figs. 2–3).

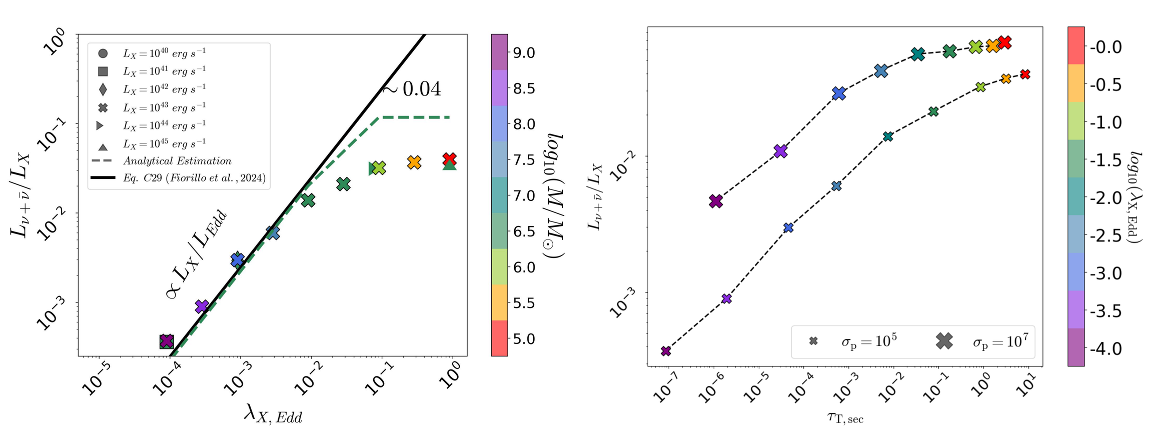

Figure 2: *Left panel:* Ratio of bolometric neutrino luminosity and X-ray luminosity as a function of the source Eddington ratio. The dashed green line shows the analytical expectation of Eq. (1). *Right panel:* All-flavor neutrino luminosity over corona X-ray luminosity as a function of Thomson optical depth due to secondary pairs for cases with $L_{\rm X} = 10^{43}$ erg s^{-1} and varying black hole mass (see colorbar), for two values of $\sigma_{\rm p}$.

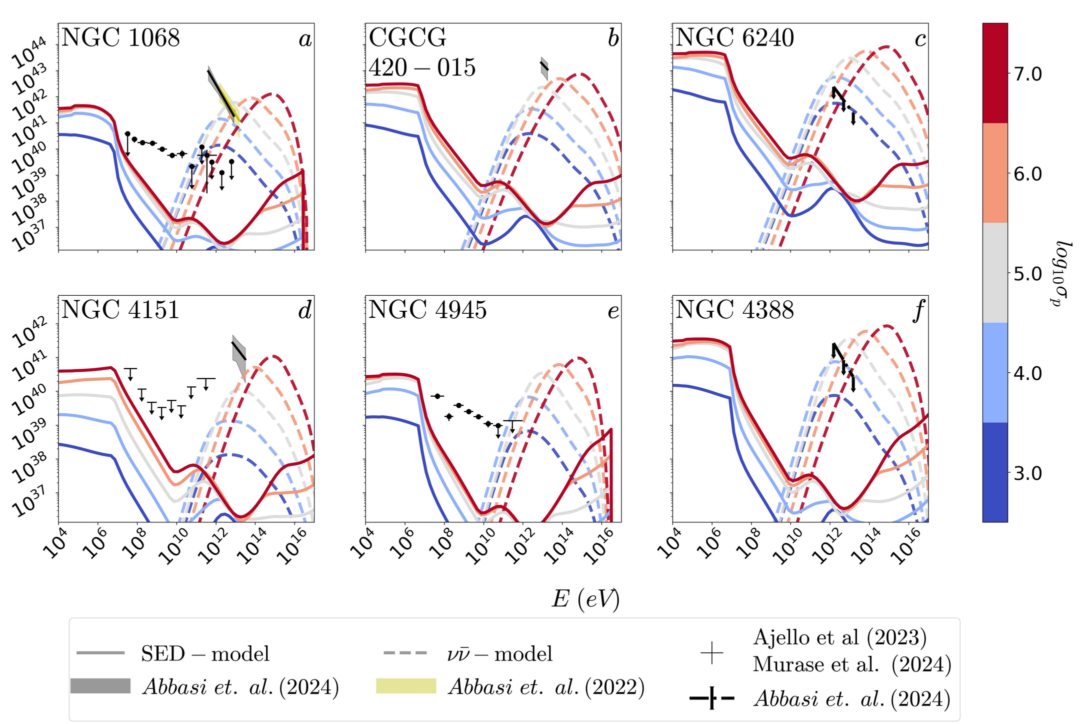

Figure 3: Photon cascade (solid lines) and neutrino (dashed lines) spectra of individual Seyferts calculated for different values of $\sigma_{\rm p}$ (colorbar).

Our main findings are:

- For $\lambda_{\rm X,Edd} \lesssim 10^{-2}$, $L_{\nu+\bar\nu}/L_{\rm X} \propto \lambda_{\rm X,Edd}$, while it saturates to a constant value otherwise in agreement with Eq. 1.
- As $\lambda_{\rm X,Edd}$ increases, Thomson optical depth of the coronal environment increases, as well, meaning that more secondary leptons are produced. The latter results in a more opaque corona which also correlates with a more luminous neutrino spectrum.
- The cascade spectrum of the corona depends on σ_p only in terms of luminosity, not shape. The neutrino energy spectrum strongly depends on σ_p.
- All coronae are opaque in GeV-TeV γ rays due to pair production on the X-ray photons.
- Model predictions for $\sigma_p \sim 10^4 - 10^5$ are closer to IceCube data for the Seyferts shown in Fig. 3.

Contribution is based on [4] (under review in JCAP).

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Stacked ν Spectrum

We estimate the total neutrino flux expected from the 677 non-blazar AGN from the *Swift*-BAT 70-month catalog [5] based on our corona model. We assume that the neutrino spectrum for each source has the same shape as the one of NGC 1068, but scaled as

$$\nu F_{\nu,i} = \nu L_{\nu,1068}\frac{L_{X,i}}{L_{X,1068}}\frac{\nu L_{\nu,i}}{L_{X,i}}(4\pi D_i)^{-2} \quad (2)$$

where D is the source distance from the catalog, and the subscripts i and 1068 are used to indicate the $i-$th galaxy from the sample and NGC 1068, respectively.

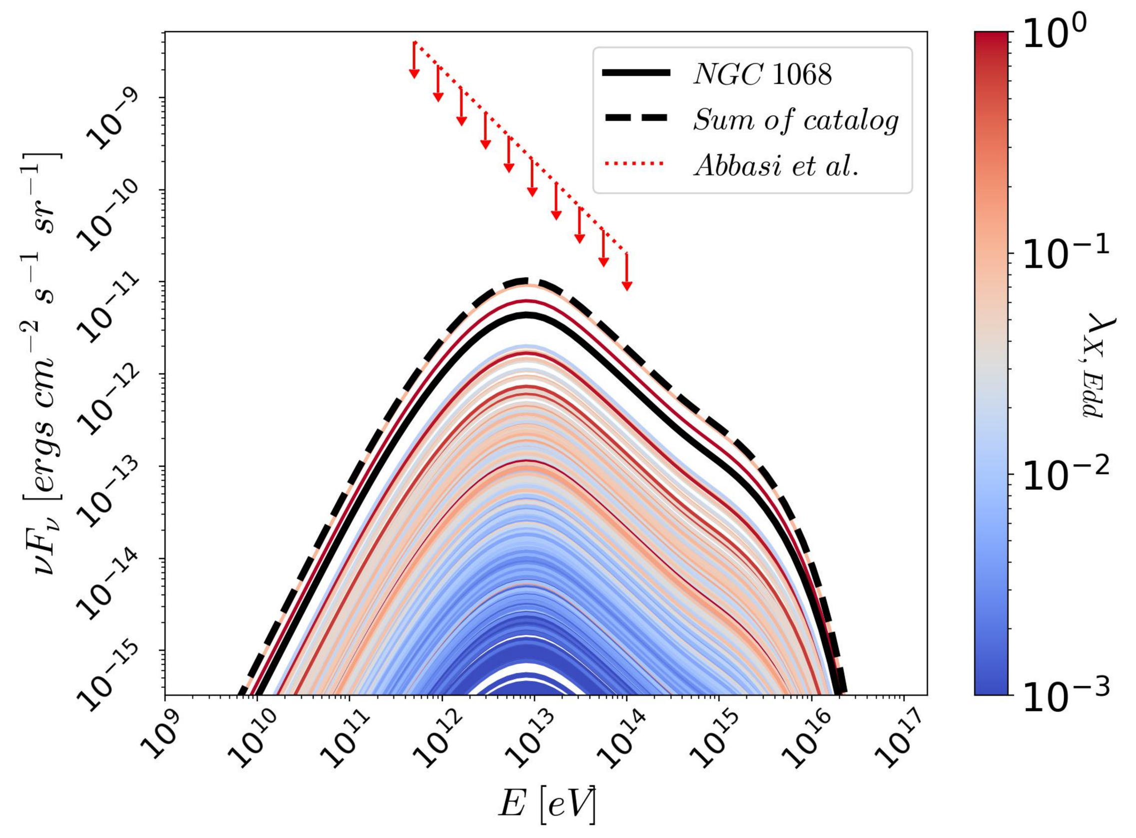

Figure 4: All-flavor neutrino flux of non-blazar AGN in the catalog of [5] with colors representing $\lambda_{\rm X,Edd}$. The dashed black line shows the sum of all sources and the solid black line shows our prediction for NGC 1068. The red dotted line with downward pointing arrows represents the neutrino flux upper limits for non-blazar sources from Table 1 of [1].

We see that NGC 1068 is among the brightest contributors to the stacked neutrino flux. The total flux predicted by our model, assuming that all the non-blazar sources produce an NGC 1068 like spectrum, is consistent with the upper limits calculated in [1].

Conclusions & Future Work

- The model introduced in this study favors astrophysical sources with $\lambda_{\rm X,Edd} \gtrsim 10^{-2}$ in which photohadronic interactions can sufficiently sustain an environment with $0.1 \le \tau_T \le 10$.
- The peak energy of the neutrino spectrum and the peak neutrino luminosity are proportional to the proton magnetization σ_p.
- The fraction of the neutrino to the coronal X-ray luminosity will ultimately reach a saturation value, when pγ interactions become significant in the coronal environment which translates to $\lambda_{X,Edd} \sim 10^{-2}$.
- We plan on making a more detailed calculation of the diffuse neutrino flux by combining our model with a luminosity function for non-blazar sources. We will also consider an intrinsic distribution of corona magnetizations, resulting in the creation of morphologically different individual spectra.

References

[1] Abbasi R. et al., 2024, Search for neutrino emission from hard X-ray AGN with IceCube. ArXiv:2406.06684 [astro-ph]
[2] Comisso L., 2024, ApJ, 972, 9
[3] Dimitrakoudis S., Mastichiadis A., Protheroe R. J., Reimer A., 2012, A&A, 546, A120
[4] Karavola D., Petropoulou M., Fiorillo D. F. G., Comisso L., Sironi L., 2024, Neutrino and pair creation in reconnection-powered coronae of accreting black holes
[5] Ricci C. et al., 2017, The Astrophysical Journal Supplement Series, 233, 17

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