Multimessenger astrophysics with accreting black holes

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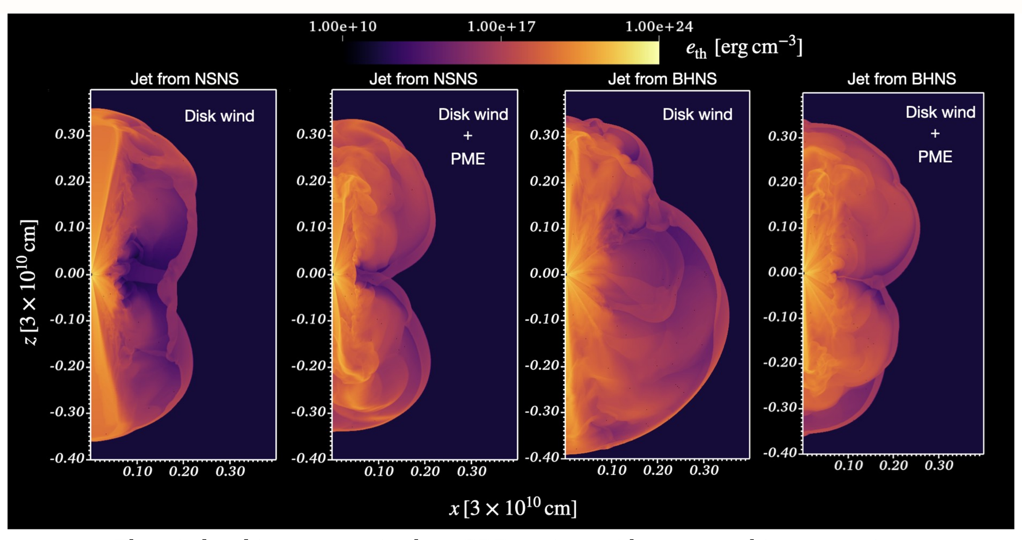
Introduction

Since the discovery of the first detection of gravitational waves coming from neutron star mergers and their electromagnetic counterparts, high-energy astrophysics has been an intensive research field. Studies of the physics of the central engine, i.e. a plasma accreting onto a black hole and its outflows, have a strong impact on the interpretation of electromagnetic signals in high-energy transients such as kilonova and GRBs. On the other hand, the low frequency GW signal from merging supermassive black holes (SMBH) may be affected by the environment of the accretion disk surrounding the primary companion. Our relativistic astrophysics group at CTP PAS has been studying the accretion of plasma around black holes by numerical simulations. The results presented in this poster, have been applied to the understanding of kilonovae, GRB jet launching, equatorial outflows from our Galaxy center, and thin disk accretion in SMBHs.

Postmerger Outflows from Magnetized Neutrino-cooled Tori

Kilonovae are transient emissions in the optical or near-infrared band, powered by the radioactive decay of the elements produced through r-process nucleosynthesis from binary neutron star (NSNS) or black hole-neutron star (BHNS) mergers [1]. Two different sources are suggested to explain kilonova emissions: 1- High-speed, neutron-rich dynamical ejecta expelled from the tidal tail during the merger; 2- Less neutron-rich material with moderate velocity ejected from the post-merger accretion disk, driven magnetically.

In this project, we focused on the second component. We evolved several magnetized black hole-accretion disk models with different initial setups using the GRMHD HARM-COOL code [2]. We observed our models generate winds with moderate velocity ($v/c \sim 0.1-0.24$) and a broad range of electron fraction ($Y_e \sim 0.01-0.5$). Generally, disks with higher mass and BH spin generate faster, more massive, and more neutron-rich outflows.



The wind and jet structure in short GRB engines with compact object progenitors. Jet is modeled by MEZCAL simulations, with winde re-mapped with HARM_COOL data, postprocessed by nuclear reaction network (G. Urrutia et al 2024)

Figure 1: Four different scenarios of the post-merger wind-jet system for short GRBs

We parameterize our models with jet luminosity, being 1.4×10^{50}, and $2.13 10^{50}$ erg/s, for NSNS and BHNS systems, respectively. We adopt the same opening angle, $\theta_j = 15°$, at launching, and Lorentz factors of $\Gamma_j = 7.4$, and 12, while the jet injection time is either $t_j = 1.57$, or 1.07 s, for respective cases. The engine properties differ with respect to the black hole mass, being $M_{BH} = 2.65 M_\odot$ and $5 M_\odot$ in NSNS and BHNS post-merger systems, respectively. Also, respective masses of the disk are taken to be 0.1 or 0.3 $M_\odot$. The spin of black hole was assumed constant, $a = 0.9$. **We conclude that post-merger accretion disk wind acts as collimation mechanism at larger distance from the engine, and it also shapes the 'cocoon' around the jet.**

Turbulent magnetized AGN accretion disks and its effects on EMRI's gravitational waves

The equal mass binary black holes embedded inside an accretion disk and its possible electromagnetic counterparts have been studied widely in the literature. However, the effect of such a gaseous environment on GW signals is expected to be significant in the case of extreme mass ratio inspirals (EMRI), and more probable to be detected by future interferometers such as LISA.

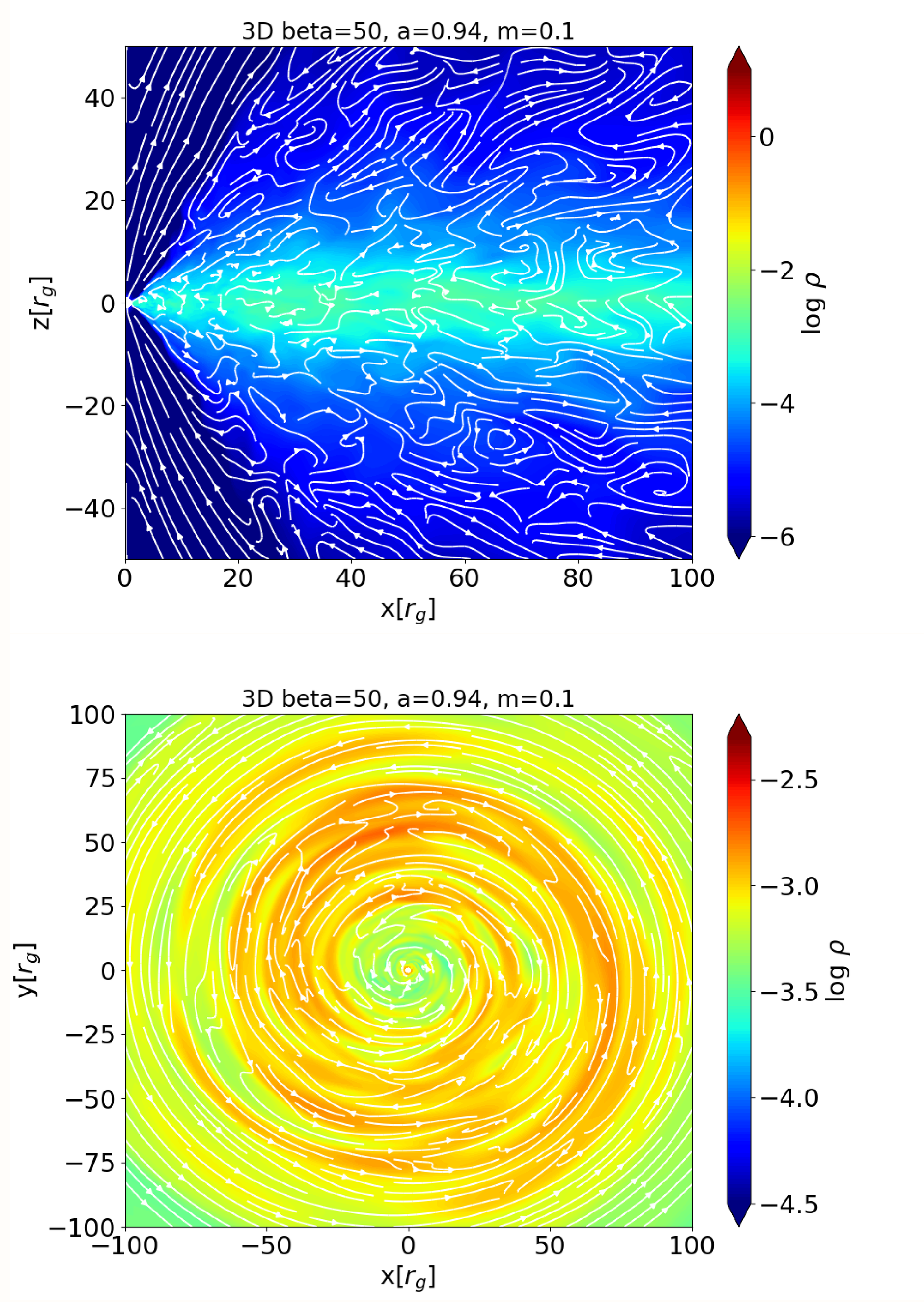


Figure 2: 3D simulation of the thin disk around SMBH. Top: density and magnetic fields in the poloidal cut. Bottom: equatorial cut with the same quantities

We investigated this effect by measuring the viscous torque from the evolution of magnetized tori around the primary SMBH [3]. Using the GR MHD code HARM-COOL , we performed 2D and 3D simulations of weakly magnetized, thin accretion disks, with a possible truncation and transition to advection-dominated accretion flow. We studied the turbulence generated by the magnetorotational instability, quantified the disk's effective alpha viscosity and its evolution over time. We applied our numerical results to estimate the GR viscous torque on a hypothetical secondary black hole and compare it with gravitational wave torque, inside the inner few hundred r_g (late phase of inspiral). **We found that the time-averaged viscous torque can be as large as 1% of the GW torque. This extra torque from the environment appears as phase shift in the GW signal (~ 10 radians in 10^5 orbits).**

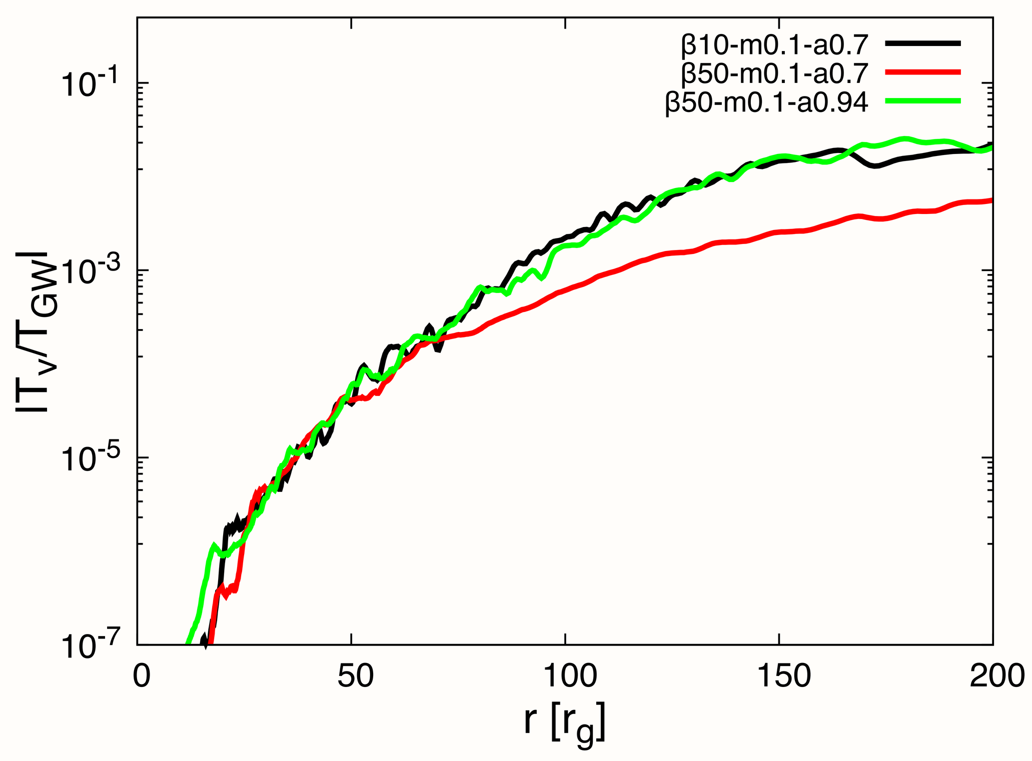


Figure 3: Ratio of the viscous torque to the effective GW torque for all models scaled for a fixed primary BH mass of $M_p = 10^6 M_\odot$ and a mass ratio of $q = 0.001$.

Black hole outflows initiated by accretion of large-scale magnetic field

Various observational studies point to the idea that accreting black holes drive the most energetic astrophysical objects in the Universe, including active galactic nuclei (AGNs) and gamma-ray bursts (GRBs). Accretion onto the central compact object produces various observable effects like relativistic jets and outflows in the form of winds. It is appropriate to assume that plasma at large scales is magnetized due to its environment.

Here we focus on the equatorial outflows in an accreting plasma around a black hole mediated by the presence of large-scale magnetic fields, as discussed in [4]. Such outflows are considered to explain the observed properties of M87*, with an in-fall of matter at a larger radius and an ejection disc at a smaller radius [5]. In this work we are interested in gradually evolving the structure of spherically distributed gas and mass flow in the regions near to the black hole horizon in the presence of a large-scale uniform magnetic field. Its repulsive effect is known as discussed by Wald [6].

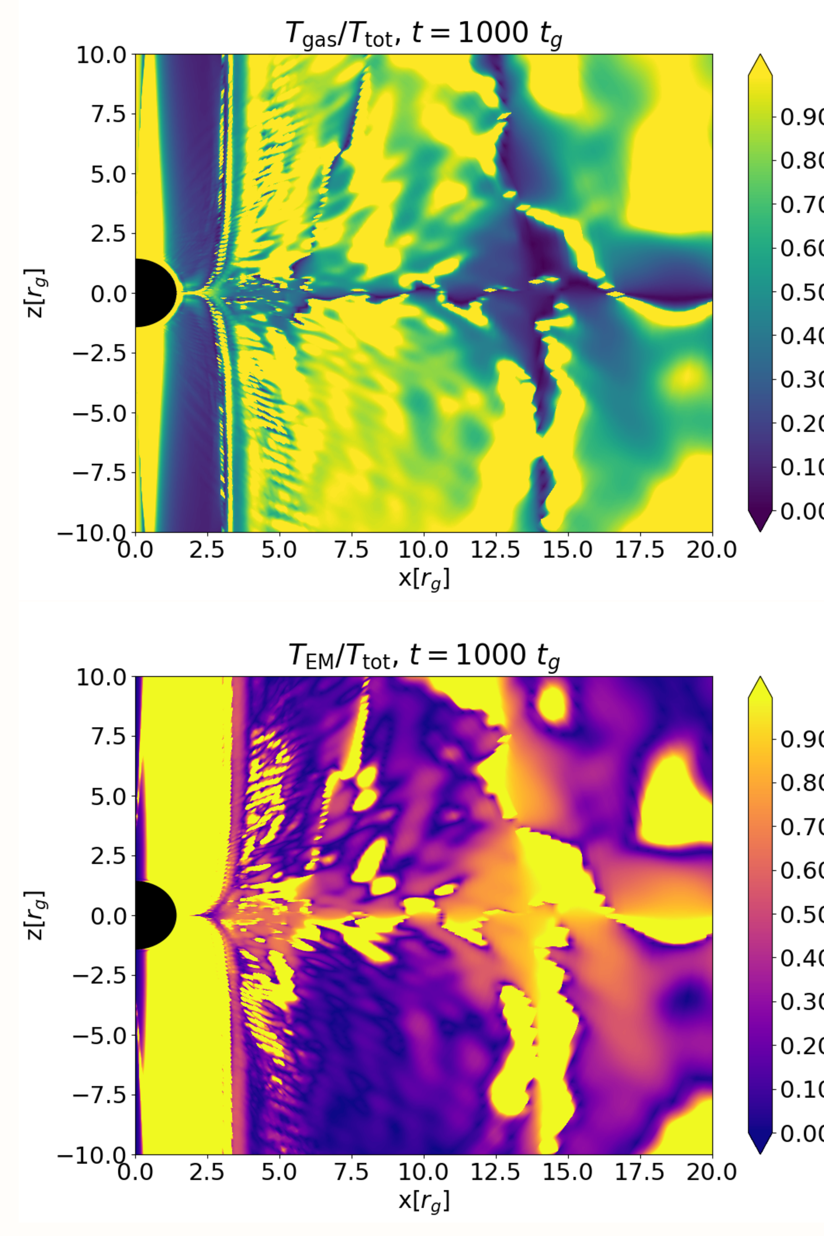


Figure 4: The energy composition of the developed outflows in a 2D model. Plots show the ratio of the matter (top) and electromagnetic energy (bottom) to the total energy, at chosen time instance of 1000 t_g. While the system is relatively organized at the beginning of the evolution, turbulent behaviour gradually prevails in the course of time. Large-scale structures are still seen in the equatorial plane and along the axis, although a well-defined jet does not develop in this simulation.

We follow the flow evolution in a fixed Kerr metric and investigate it for different values of black hole spin and magnetic field strength. We observe equatorial outflows produced in the course of the flow evolution. Our study can be useful to understand the effects of magnetic fields in driving intermittent outflows in weakly active AGNs.

References

[1] Tanvir, N. R., Levan, A. J., Fruchter, A. S., et al. 2013, Nature, 500, 547, doi: 10.1038/nature12505

[2] https://github.com/agnieszkajaniuk/HARM_COOL

[3] Hossein Nouri F., Janiuk, A., 2024, AA, 687, 124

[4] James B., Janiuk, A., Karas V., 2024, AA, 687, 185

[5] Blandford, R. & Globus, N. 2022, MNRAS, 514, 5141. doi:10.1093/mnras/stac1682

[6] Wald, R. M., 1974, PRD, 10, 1680. doi:10.1103/PhysRevD.10.1680