

**GR MHD simulations of post-merger disks, collapsars,
and jet central engines**

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GR MHD simulations: HARM



- Based on HARM by Gammie (2003)
- Basic version: adiabatic Equation of State for gas; various inversion schemes.
- Complex problem of recovery, when EOS is tabulated (2-parameter, 3-parameter)
- Developed in **series of papers** (Janiuk et al. 2013; AJ 2017, 2019; Sapountzis & Janiuk 2019; Janiuk et al. (2023; 2026)
- Evolves chemical composition, neutrino cooling/heating, leakage scheme. Tracers for outflows and jets. Separate modules for Kerr metric evolution and Self-Gravity

$$(\rho u_\mu)_{;\nu} = 0$$

$$T_{\nu;\mu}^\mu = 0.$$

$$T_{(m)}^{\mu\nu} = \rho \xi u^\mu u^\nu + p g^{\mu\nu}$$

$$T_{(em)}^{\mu\nu} = b^\kappa b_\kappa u^\mu u^\nu + \frac{1}{2} b^\kappa b_\kappa g^{\mu\nu} - b^\mu b^\nu$$

$$T^{\mu\nu} = T_{(m)}^{\mu\nu} + T_{(em)}^{\mu\nu},$$

$$F^{*\mu\nu}{}_{;\nu} = 0. \quad F^{*\mu\nu} = b^\mu u^\nu - b^\nu u^\mu$$

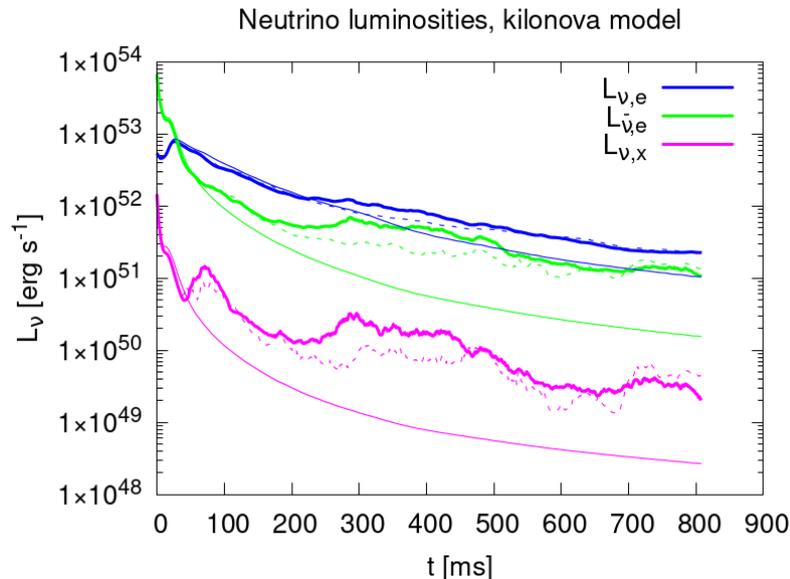
$$\partial_t \mathbf{U}(\mathbf{P}) = -\partial_i \mathbf{F}^i(\mathbf{P}) + \mathbf{S}(\mathbf{P})$$

https://github.com/agnieszkajaniuk/HARM_COOL
3D; CPU only; parallelized with MPI and Open-MP

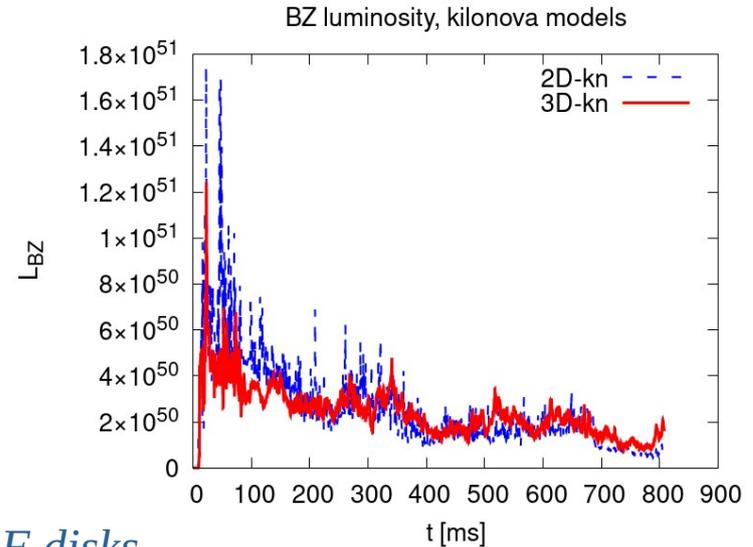
What powers the jet in sGRB?

- Neutrinos?
- BH rotation?

*SANE setup.
Can post-merger disk go
MAD?*

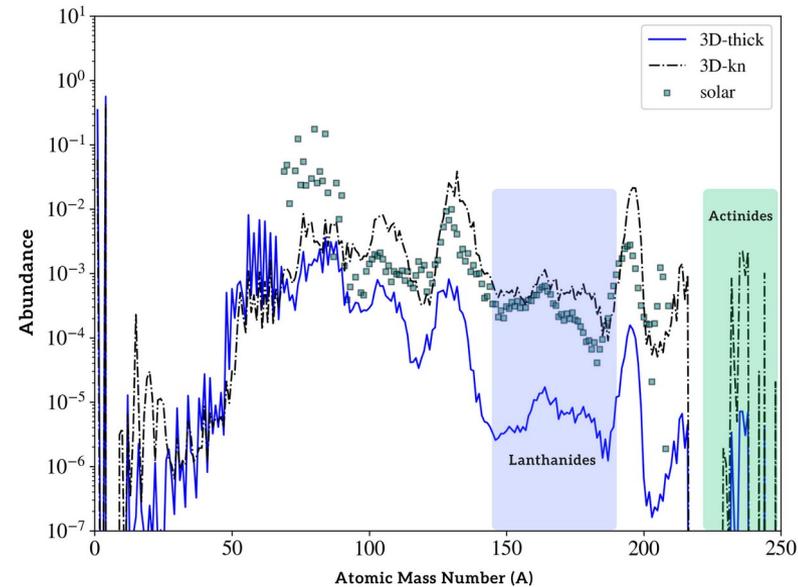
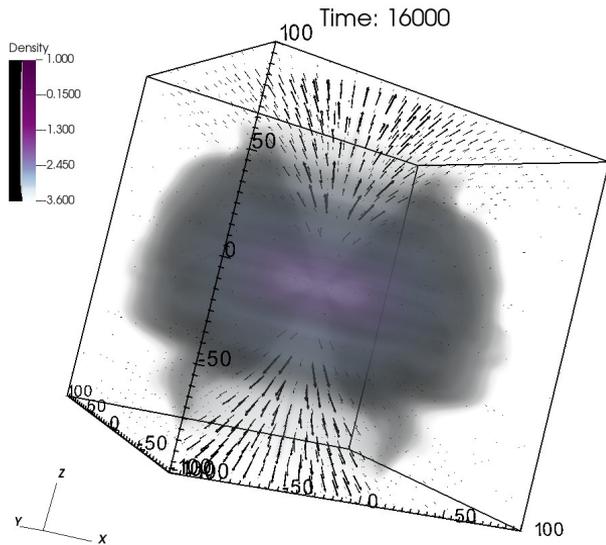


A. Janiuk, J. Saji, G. Urrutia (2026)



cf. NDAF disks...

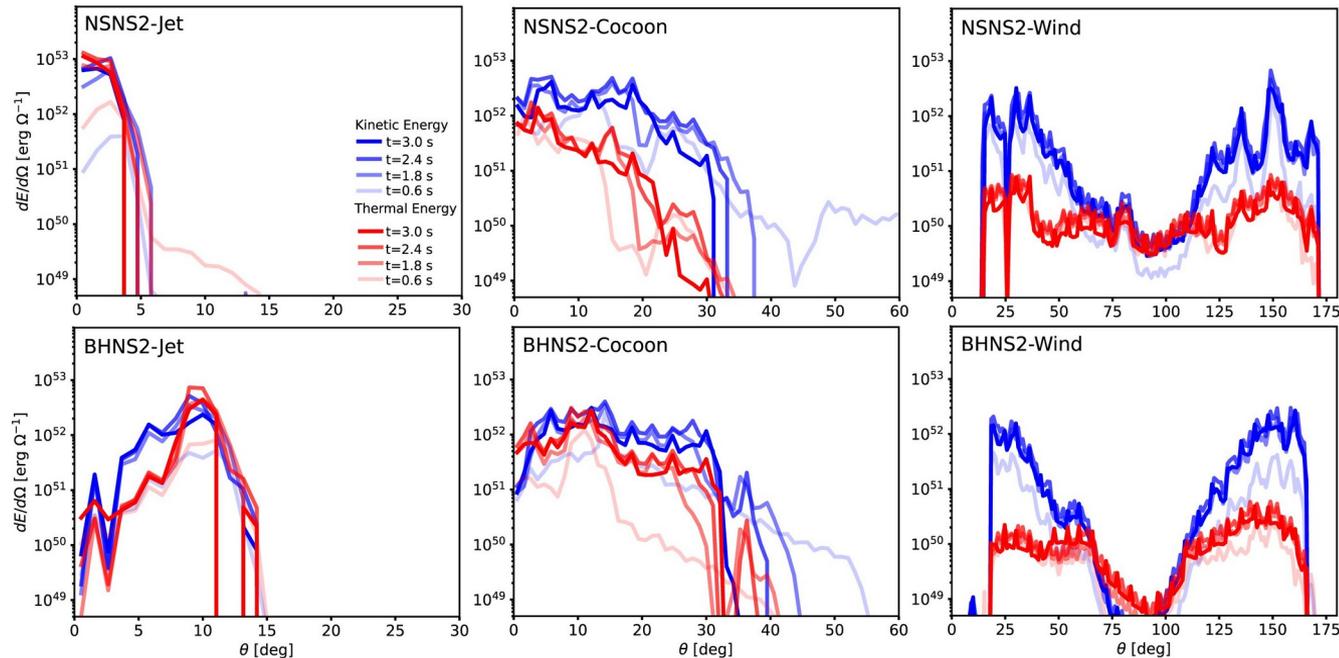
Nucleosynthesis in post-merger disk winds



- 2D and 3D models, for post-merger disks
- „Helmholtz EOS”, recovery cf. Siegel et al. (2018)
- Wind tracers, followed up to 800 rg
- Ejecta masses 0.01 – 0.1 M_{sun}
- Broad range of Ye, velocities up to 0.2 c

**Details: See poster
#14 by Joseph Saji**

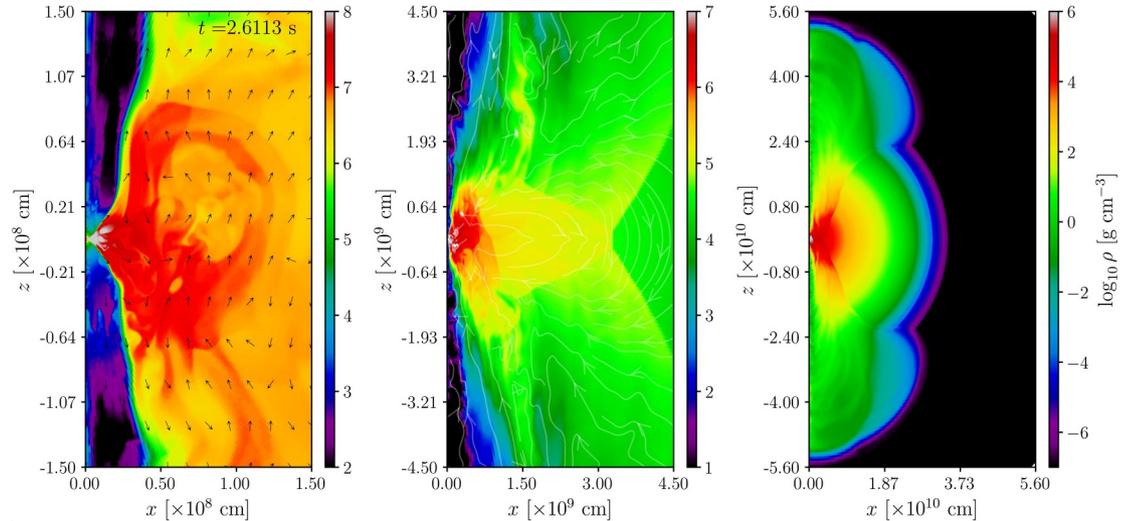
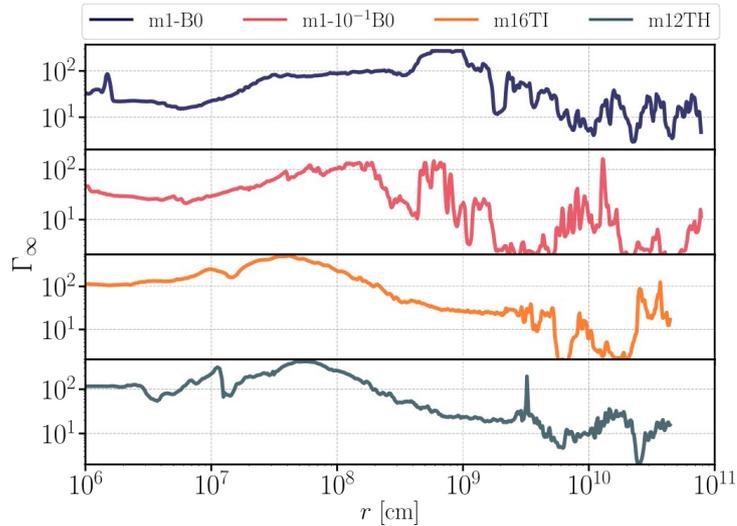
Jet propagation through disk winds



- 2D models, for post-merger disks
- Some contain DE
- Jet injected in the disk wind environment
- Collimation observed: from 15 down to 3.6 or 13.2, deg, for NS-NS and BH-NS

G. Urrutia, AJ, F.H. Nouri, (2025)

Jet breakout from collapsars

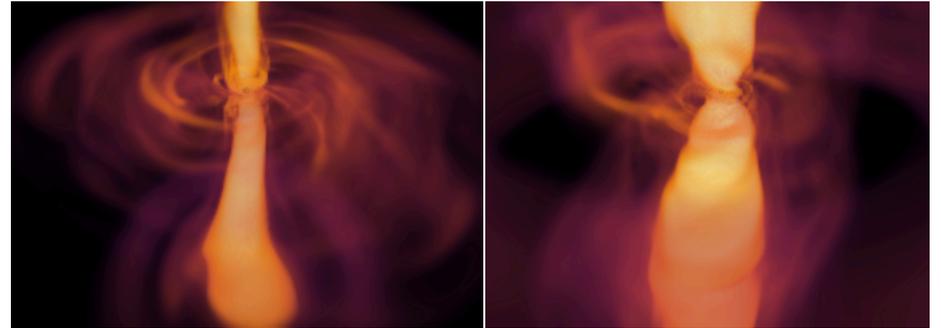


- 2D models, BHAC simulations (AMR)
- Initial stars: MESA, pre-SN stars
- Successful jet breakout, can power long GRB for strong B fields (eg. dipole-like, $\sim 10^{14}$ G)
- Efficient conversion of magnetic+thermal energy to bulk kinetic. Short jet breakout time!

Urrutia, AJ, Olivares (2026)

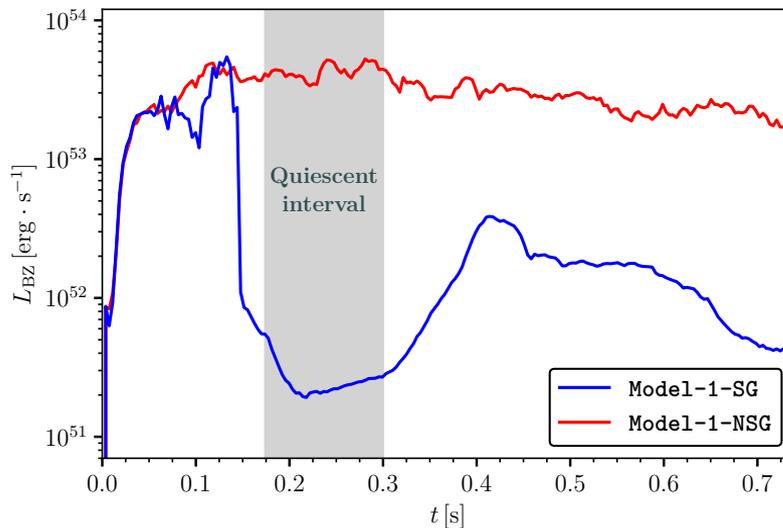
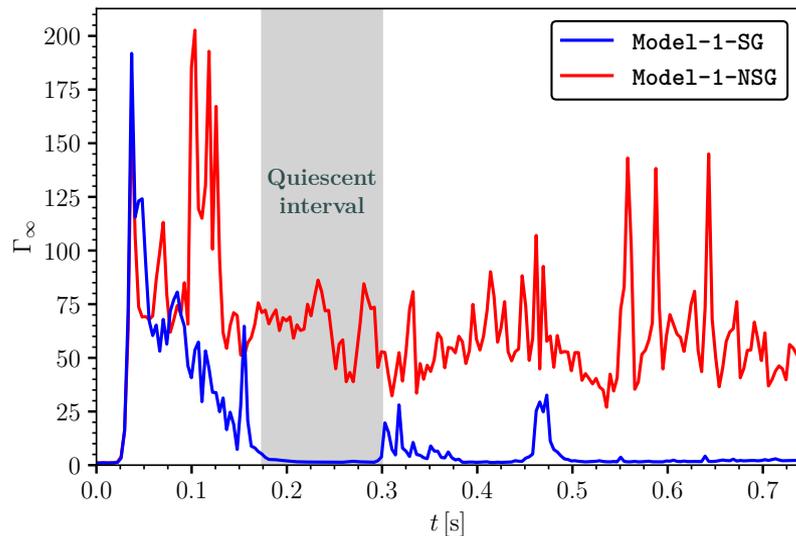
Self gravitating collapsars

- 3D simulations
- code HARM-SELFG (Kerr metric evolution, selfgravity)
- Initial star: spherical cloud with low angular momentum
- Uniform magnetic field



Details: See poster
#13 by Piotr Płonka

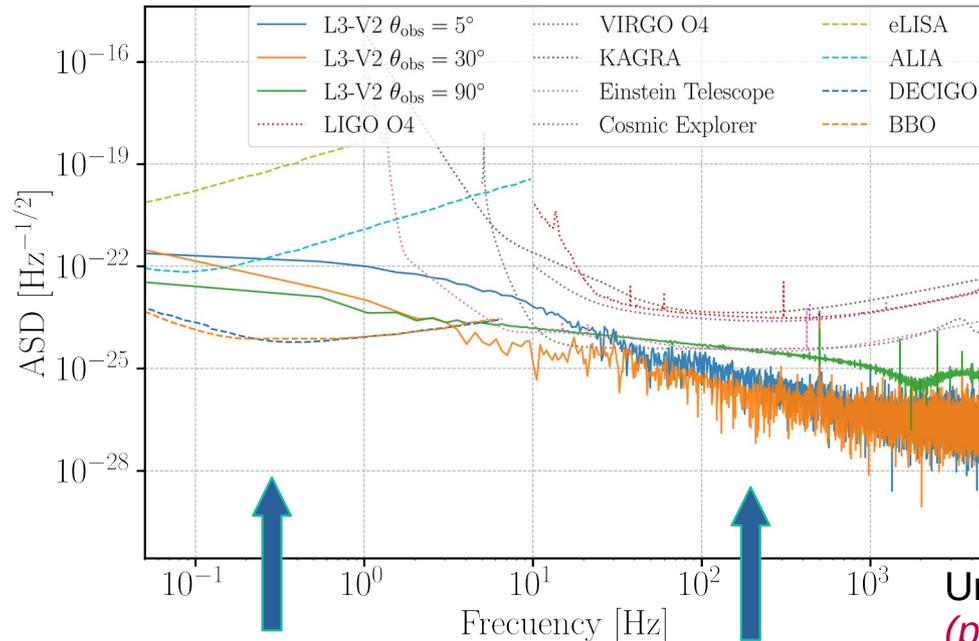
Jet quenching in SG collapsar



- Jets are produced, can power long GRBs
- Large Lorentz factors and jet efficiency above 10%.
- Self-gravity reduces jet luminosity!

*Fast drop of BH spin \rightarrow
Magnetically arrested (MAD)
state quenched \rightarrow jet production
efficiency decrease*

Gravitational waves from jet



Exceeds the minimum sensitivity of DECIGO and BBO. More energetic jets would be detected at higher freq. by Einstein Telescope

- **Amplitude spectral density of GWs from expanding jet.**
- **2D SRHydro jet, Mezcal code**
- **Jet launched from WR-star progenitor**
- **GW signal computed from retarded solution to the wave equation, given the energy-momentum tensor**
- **3 different observing angles**
- **Detectability estimates for $D = 1$ Mpc**

Urrutia, de Colle, AJ, et al.
(preliminary results)

Collapsar disks: may be GW source as well, in ~100 Hz range

MAD thin disk, AGN case

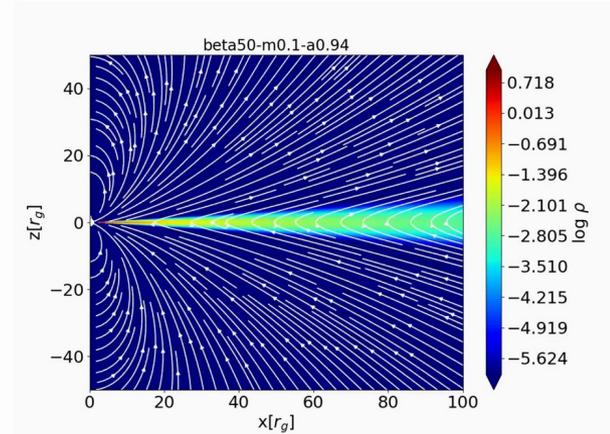
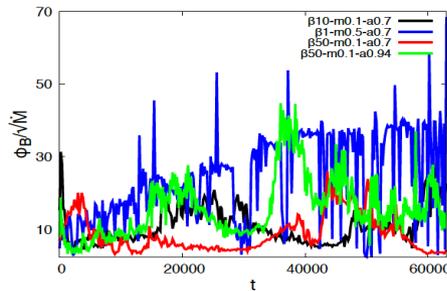
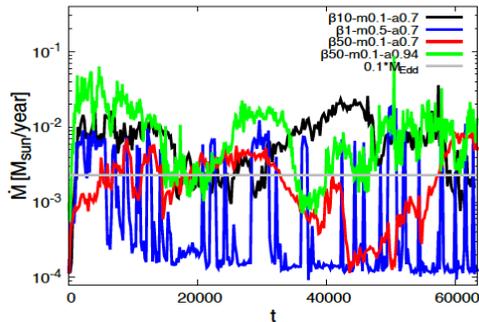


- Initial NT-like disk. Polytropic EOS, $\gamma = 4/3$. Poloidal magnetic field.
- 2D models, 1056×528 , $R_{\text{out}} = 1000 r_g$, $t_{\text{end}} \sim 60000$,
- A 3D sim ($288 \times 256 \times 96$)

$$\rho_e = \left(\frac{\Theta_0}{\kappa} \right)^{\frac{1}{\alpha-1}} \left(\frac{f(x)}{x^2} \right)^{\frac{1}{4(\alpha-1)}}$$

$$A_\phi = r^{3/4} \frac{m^{5/4}}{(m^2 + \cos^2\theta)^{5/8}}$$

cf. Dihinigia et al. (2021)



F.Hosseini- Nouri, AJ, 2024

Comparison of viscous and GW torques

$$T_{GW} = \frac{1}{2} q M_p r \dot{r}_{GW} \Omega_2,$$

$$T_{v,GR} = \dot{M}_{GR} r^2 \Omega_2$$

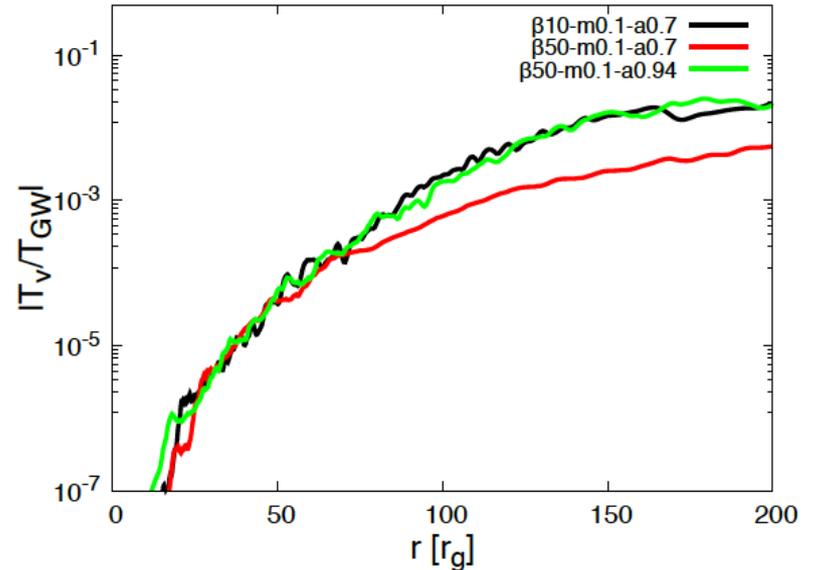
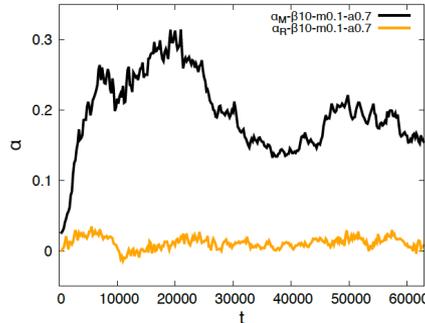
$$\dot{M}_{GR} = 2\pi \left[\frac{\Gamma}{Q} 3r^{1/2} \frac{\partial}{\partial r} \left(r^{1/2} v \Sigma_{GR} \frac{D^2}{C} \right) \right],$$

$$v = \alpha c_s h$$

$$\alpha = \alpha_R + \alpha_M,$$

$$\alpha_R \approx \frac{\rho_0 \delta u_r \delta u_\phi \sqrt{g^{\phi\phi}}}{P_{tot}},$$

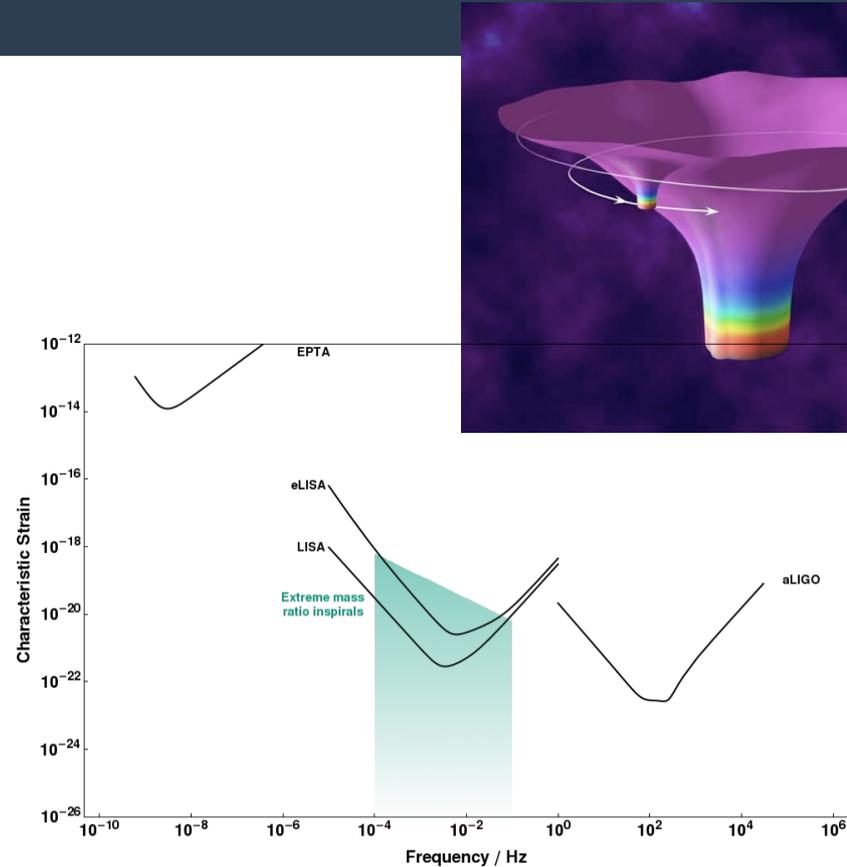
$$\alpha_M \approx -\frac{b_r b_\phi \sqrt{g^{\phi\phi}}}{P_{tot}}.$$



Primary BH mass $10^6 M_\odot$ mass ratio $q = 0.001$ (F.H. Nouri & AJ, 2024)

Dephasing GW signal

- Viscous torque from accretion disk can reach few % of GW torque around 100 rg, for EMRI of $q=0.001$.
- The extra torque from disk environment appears as phase shift in GW (~ 10 radians in 10^5 orbits)
- Effect comparable with modified gravity predictions. Which makes more sense?





EuroHPC
Joint Undertaking

Conference: Polish Society of Relativity, August 2-7 2026

Invited: Campanelli, Levin, Kiefer,
Vitzany, Henry, ...



F. Hossein Nouri, A. Janiuk, 2024, A&A, 687, 184
G. Urrutia, AJ, F. H. Nouri, 2025, MNRAS, 538, 1247
A. Janiuk, J. Saji, G. Urrutia, 2026, A&A, in press
P. Płonka, A. Janiuk, 2026, A&A, subm.
G. Urrutia, AJ, H. Olivares, 2026, JHEA, subm.



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See activities of CTP PAS relativistic astrophysics group
at our website: <http://ra.cft.edu.pl>



Warsaw is a nice city



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