Viscous torque in turbulent magnetized AGN accretion disks and its effects on EMRI's gravitational wave

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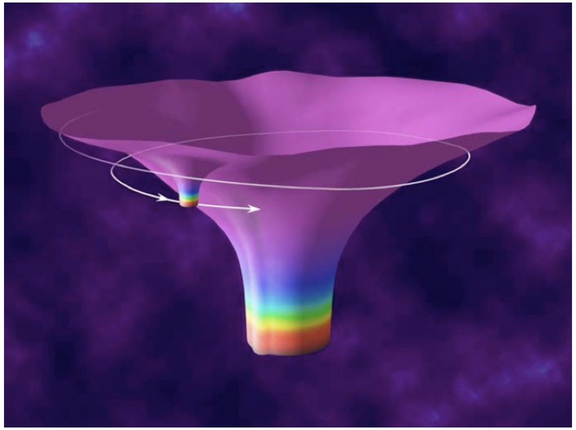
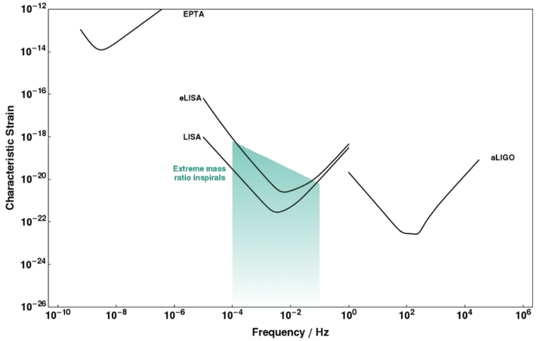
EMRIs : Extreme Mass Ratio Inspirals

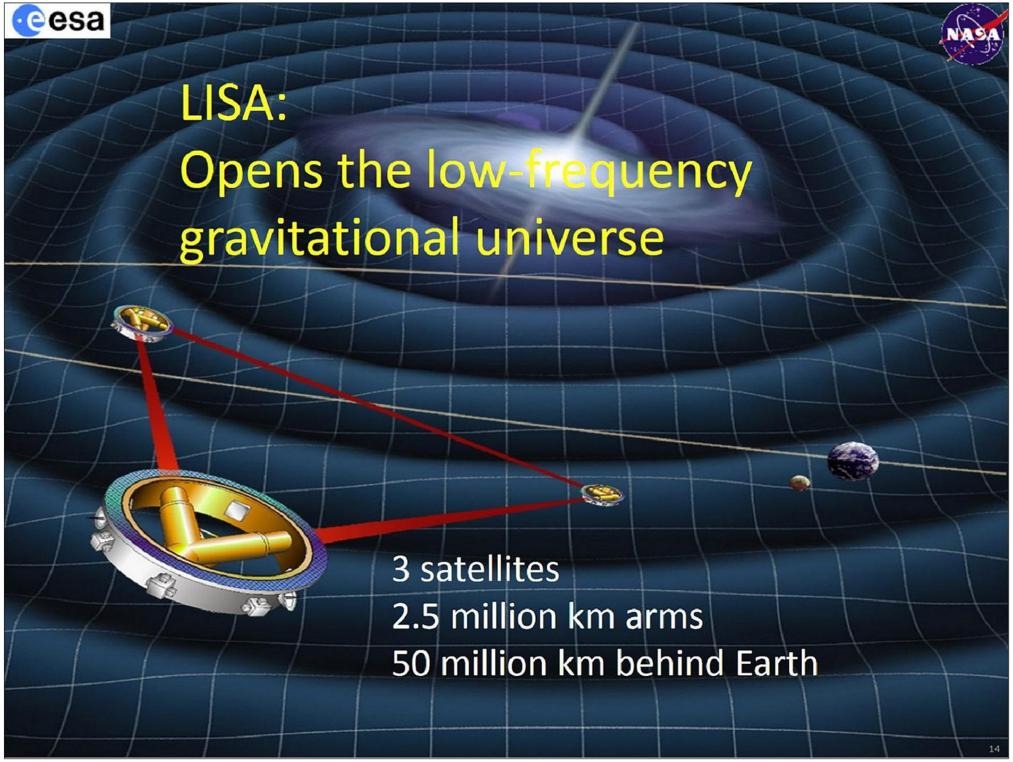
- EMRI is the orbit of a relatively light object around a much heavier (by a factor 10,000 or more), that gradually spirals in due to the emission of gravitational waves.
- They are likely to be found in the centers of galaxies, where stellar mass black holes and neutron stars are orbiting a supermassive black hole.
- EMRIs evolve slowly and complete many (~10,000) cycles before eventually plunging.
- Their characteristic strain lies in the frequency band of space-based detectors.





LISA mission

- Originally planned, LISA would have three identical spacecraft in an orbit around the Sun. Each spacecraft would have targeted the other two with lasers, forming a triangle of light with sides five million kilometers long.
- NASA and ESA dissolved their decade-long LISA partnership in March 2011.
- ESA scaled down LISA's triangle, planned to launch in 2034.
- On 25 January 2024, the LISA Mission was formally adopted by ESA



LISA:

Opens the low-frequency gravitational universe

3 satellites

2.5 million km arms

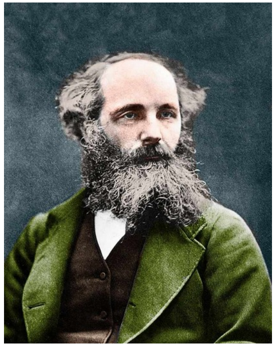
50 million km behind Earth

Mergers in gas-rich environment

- Supermassive binary black holes (SMBBH) merger produces mHz gravitational waves (GW), detectable by future Laser Interferometer Space Antenna (LISA)
- Such binary systems are usually embedded in an accretion disk environment at the center of AGNs (GSN 069, RX J1301.9+2747, NGC 5548).
- Recent studies suggest the plasma environment affects the GW emitted from extreme mass ratio inspiral (EMRI) binary black holes (GW phase shift > 10 radians per year) (Yunes et al. (2011), Kocsis et al. (2011), Derdzinski et al. (2019), Garg et al. (2022))
- The previous works in the literature assume the artificial thin disk alpha prescription as the mechanism for the angular momentum transport (Shakura-Sunyaev disk). In their approach, the α-viscosity is assumed a typical constant value (0.01-0.1).
- In this study, we include the magnetic field evolution to provide the physical mechanism for the angular momentum transport caused by the Magneto-Rotational Instability (MRI) to quantify equivalent α-viscosity based on the disk's evolution. We use the numerical results to estimate the viscous torque.

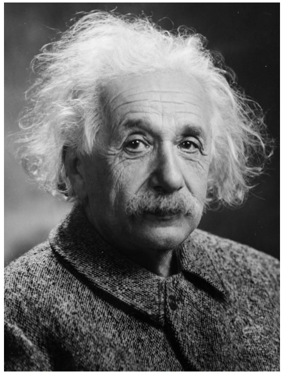
General Relativistic MHD simulations

- **Describe gas motion in gravitational field of a black hole**
- **Use ideal MHD approach (electric field vanishes)**
- **No magnetic monopole constraint**
- **Equation of state for gas (i.e. adiabatic). Needs inversion scheme.**
- **Discretise equations on a grid and solve by finite-volume methods**



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

$$T^\mu_{\nu;\mu} = 0.$$



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

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

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

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

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

https://github.com/agnieszkajaniuk/HARM_COOL
- CPU only; - parallelized with MPI or hybrid with Open-MP
- outputs in ASCII or HDF5
- stationary or evolving Kerr metric (Król & Janiuk 2021)
- analytic or tabulated EOS (Janiuk 2019)

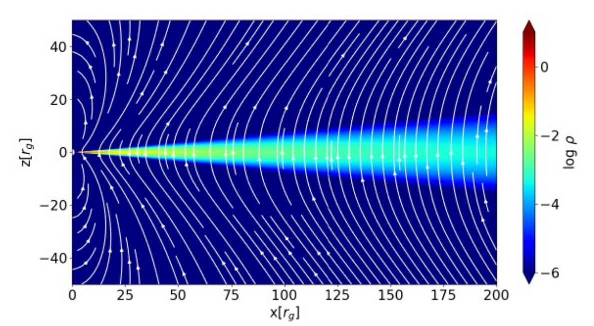
Initial setup

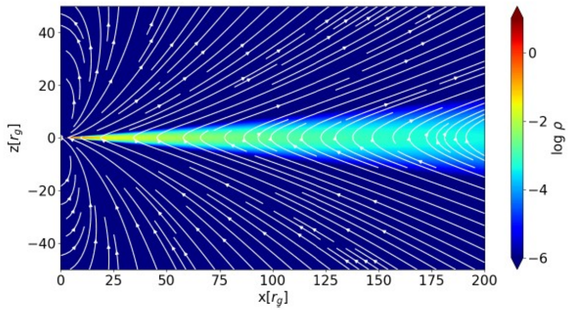
- Initial configuration for thin disk. Density profile from Dihinigia et al. (2021). Polytropic EOS with index 4/3. Poloidal magnetic field.

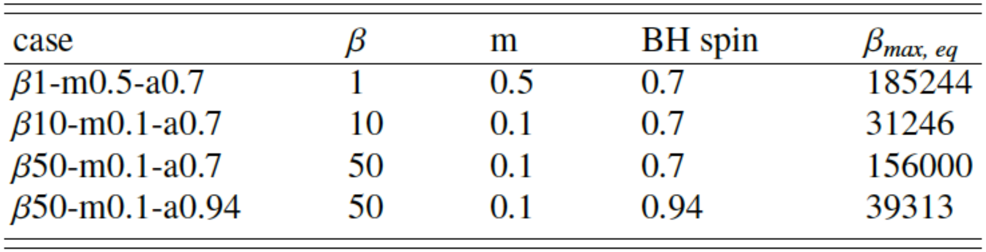
- Results are scaled for the central BH mass $10^6\,M_\odot$ and mass ratio $q=10^{-3}$ (the low-mass secondary BH is not included in hydro simulation)
- 2D models, 1056x528 cells, $r_{out} = 1000\,r_g$ evolved for t ~ 60000,
- 3D model with 288x256x96 cells

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

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



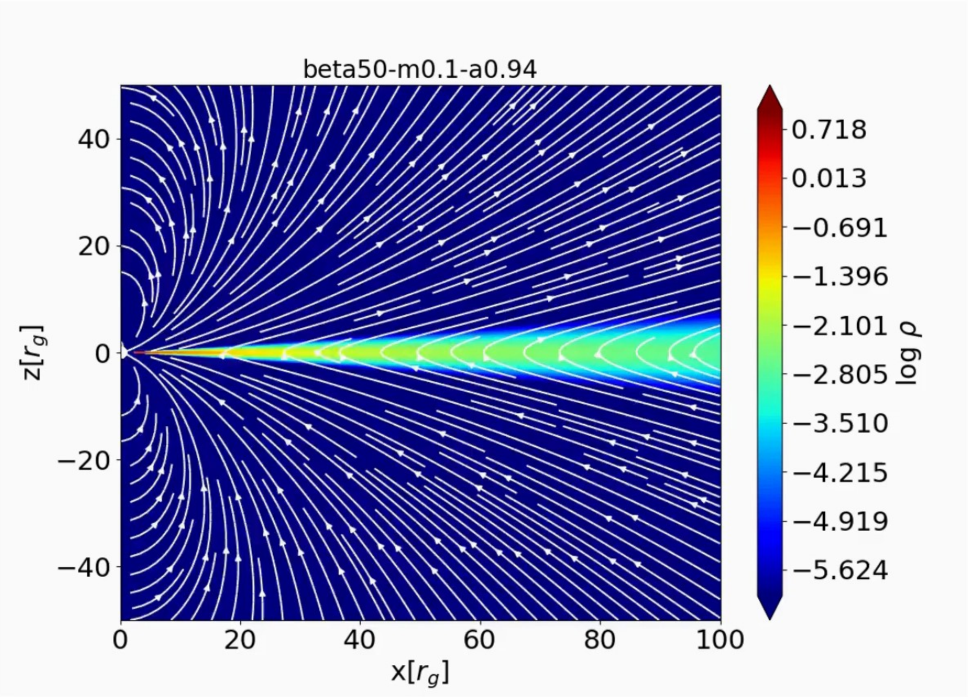




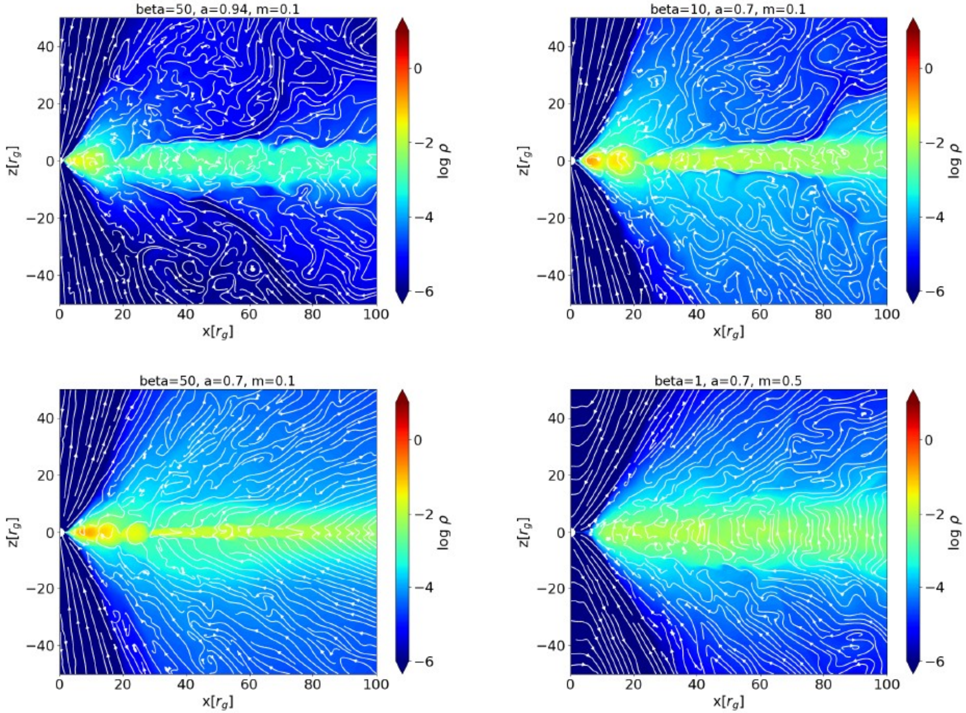
case	β	m	BH spin	$\beta_{max,\,eq}$
β1-m0.5-a0.7	1	0.5	0.7	185244
β10-m0.1-a0.7	10	0.1	0.7	31246
β50-m0.1-a0.7	50	0.1	0.7	156000
β50-m0.1-a0.94	50	0.1	0.94	39313

$\beta = P_{gas,max}/P_{B,max}$

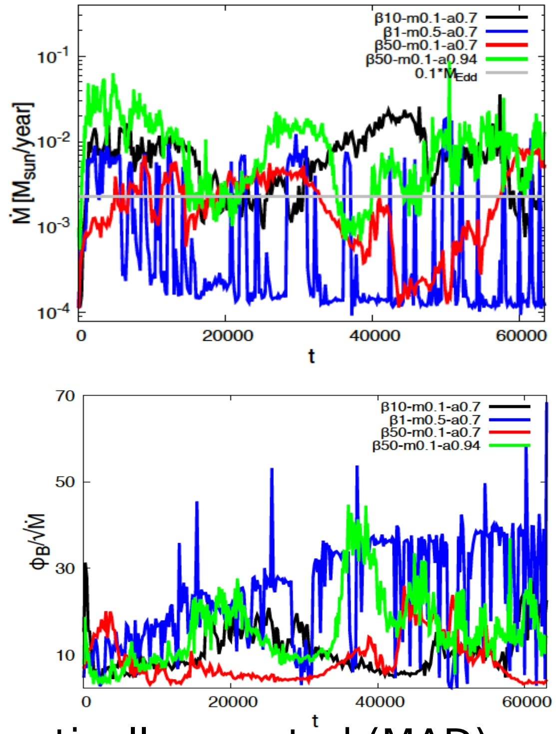
Time evolution



Results



Density and magnetic field distribution at final time



Magnetically arrested (MAD) state → pauses accretion

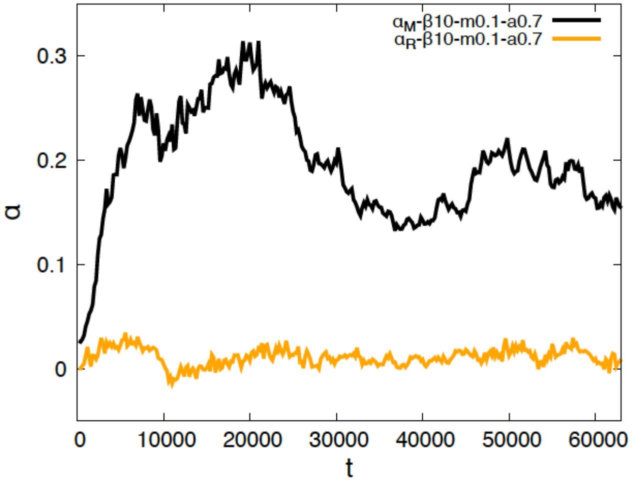
Viscosity magnitude

- Turbulent viscosity dominated by Maxwell stress
- We compute volume average of ‘effective alpha’ over innermost disk part (~150 r$_g$)
- We also check its time average, over second half of evolution

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

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

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



Comparison of viscous and GW torques

- **Gravitational waves**

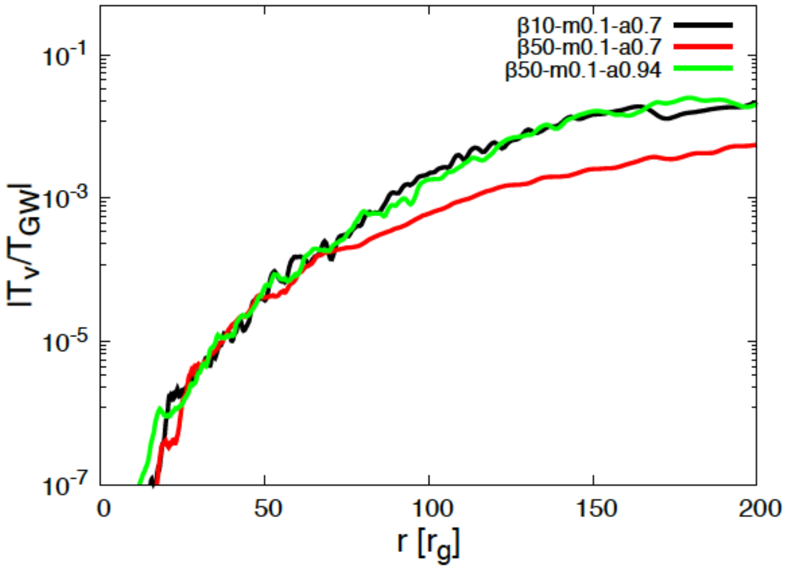
$$T_{GW} = \frac{1}{2} q M_p r \dot{r}_{GW} \Omega_2,$$

- **Viscosity (relativistic)**

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

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

$$\nu = \alpha c_s h$$



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

Dephasing of GW signal due to accretion disk

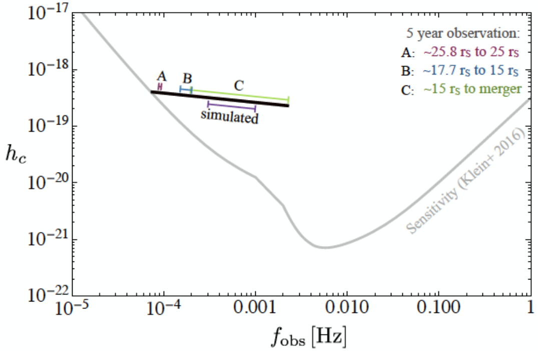
For GW frequency of ~ 1 mHz (primary mass 10^6 M_{Sun}, mass ratio q=0.001)

$$\dot{r} = \dot{r}_{GW} + 2\frac{\dot{L}_T}{Mq}\sqrt{\frac{r}{GM}} \equiv \dot{r}_{GW} + \dot{r}_T .$$

$$\delta\phi = \phi_{vac} - \phi \approx 2\pi \int f_{GW}(r)\frac{\dot{r}_{gas}}{\dot{r}_{GW}^2}dr.$$

$$\dot{L}_T = -\alpha\frac{6\pi r^{7/2} c_s(r)^3 \rho(r)}{\sqrt{GM}},$$

$$\dot{r}_{GW} = -\frac{64}{5}\frac{(GM)^3}{c^5}\frac{1}{1+q^{-1}}\frac{1}{1+q}\frac{1}{r^3}.$$



(Derdzinski et al. 2019)

Resulting phase shift in GW signal is about ~ 10 radians

Conclusions

- Magnetic field triggers MRI instability and turns the accretion disk into MAD state
- From MHD simulations, we measure ‘effective alpha’. Density weighted volume average varies around 0.1-0.25
- We applied this result to measure the viscous torque from accretion disk. It can reach few % of GW torque around 100 rg, for EMRI of mass ratio q=0.001.
- The extra torque from environment appears as phase shift in GW signal (~ 10 radians in 10^5 orbits)

Thank you

F. H. Nouri & A. Janiuk, 2024,
A&A, 687, 184

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