Binary Black holes in magnetized AGN disks

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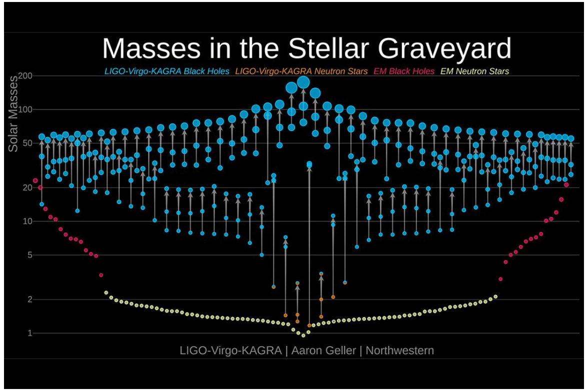
Binary Black Hole Mergers

LIGO/Virgo detection of GW150914 confirmed the existence of BBHs.

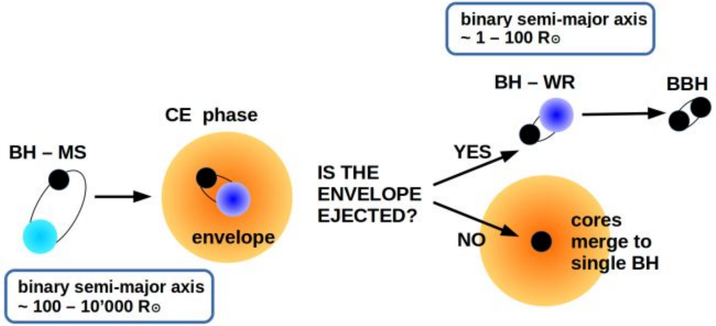
Detected binary black hole (BBH) mergers in the local (z < 1) universe at a rate of about once per week during O3.



Channels for merger

Field binary origin (i.e., from the evolution of a field binary system consisting of two massive stars.

Dynamical origin- Mergers in globular clusters, mergers in the accretion disks of active galaxies.



Binary Black Hole Mergers

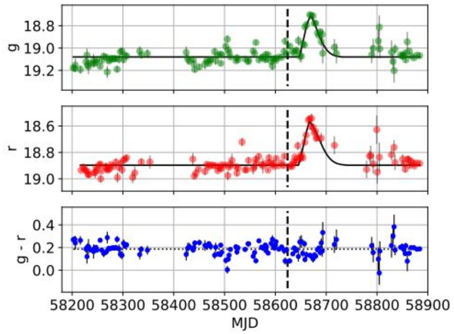
Binary neutron star merger or BH-NS merger - Enough material to generate EM radiation.
BBH- No/Low possibility of EM counterparts.
BBH mergers in AGN disks occur in the presence of gas and must always produce some EM radiation, whether detectable or not.
(EM counterpart of GW190521, Graham 2020 et. al.)

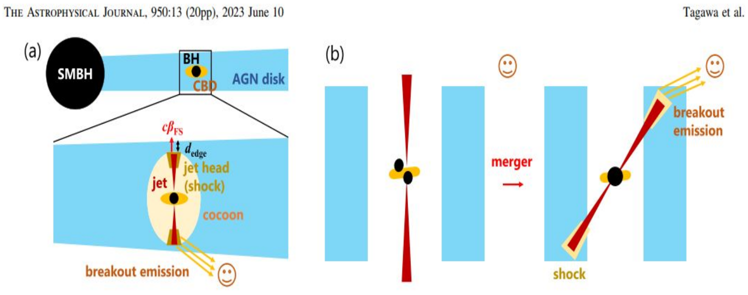
Optimistic scenario- AGN disks have enough material.
Pessimistic scenario- The disk itself.

Optically thick disks.

What if pre-merger dynamics/processes helps in clearing out material.

(Radiation pressure?? Magnetic field???)

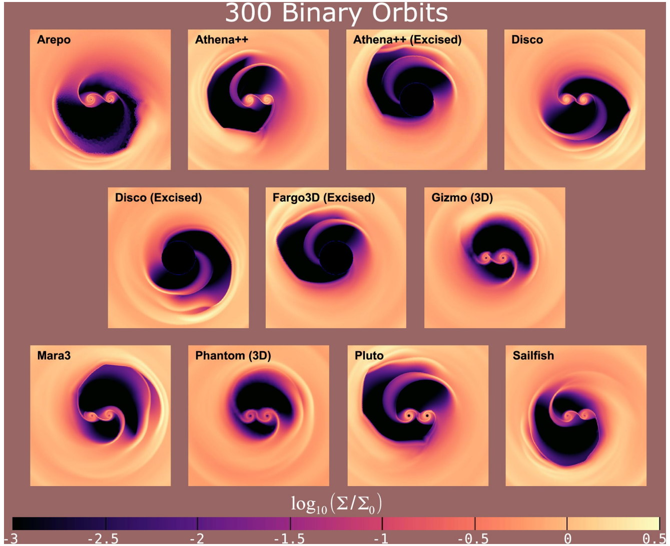




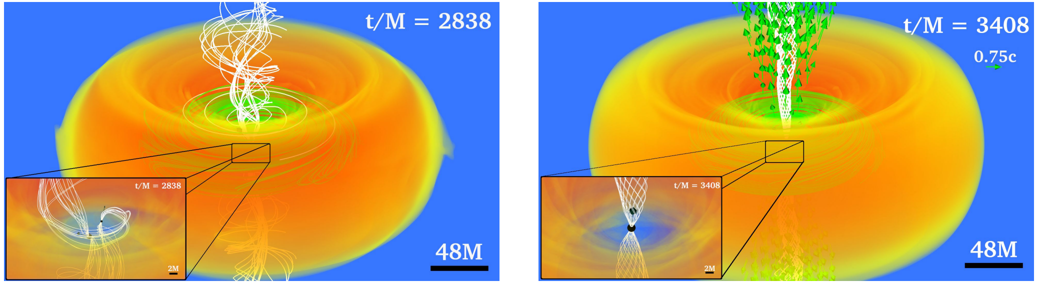
Flare of AGN J124942.3+344929. (GW190521)

Simulations

Disks around Binaries and Binaries in Big Disks

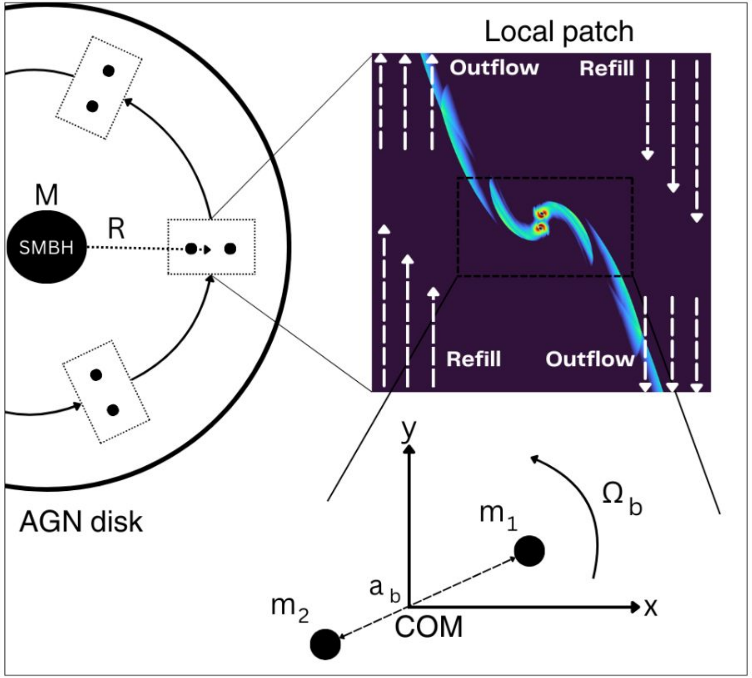


Credits- Duffell et.al 2024
Santa Barbara Binary disk Code Comparison

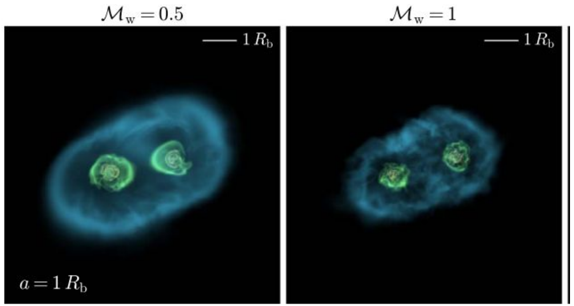


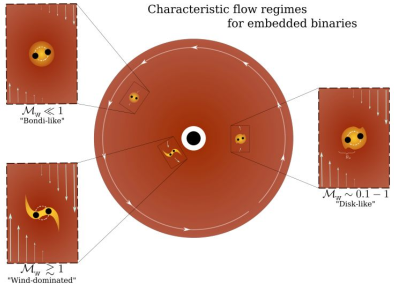
Credits- Ruiz M. et. al, 2023

Binary Black holes in AGN Disks

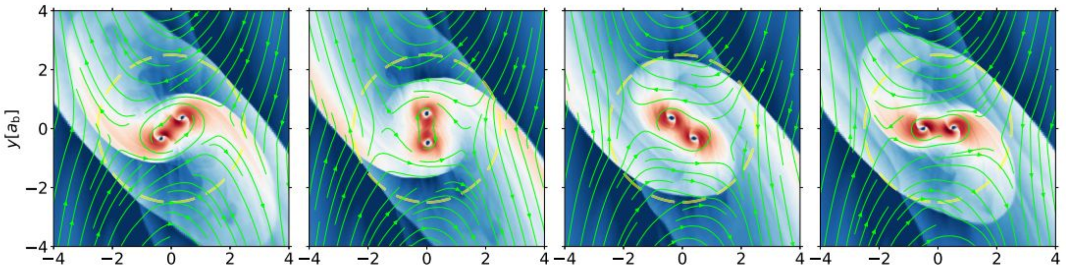


$$\lambda = \frac{R}{a_b}\left(\frac{m_b}{M}\right)^{1/3}, \quad h = \frac{H_g}{R} = \frac{c_s}{V_K}, \quad q_M = \frac{m_b}{M}$$





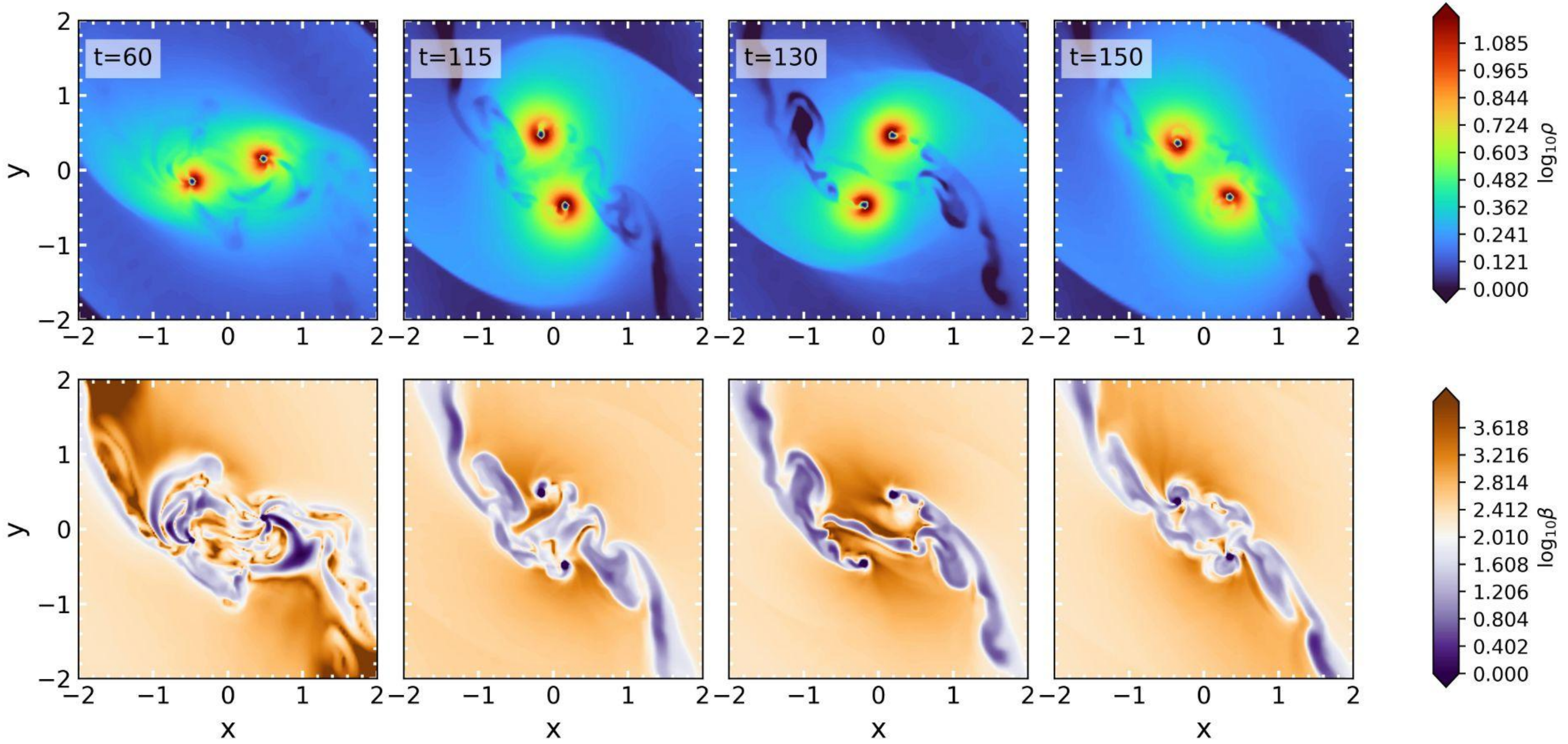
Kaaz et. al 2023



$$\frac{c_s}{v_b} = h q_M^{-1/3} \lambda^{-1/2}, \quad \frac{V_s}{v_b} = q_{sh}\frac{\Omega_K}{\Omega_b} = q_{sh}\lambda^{-3/2}, \quad q_M = 10^{-6}.$$

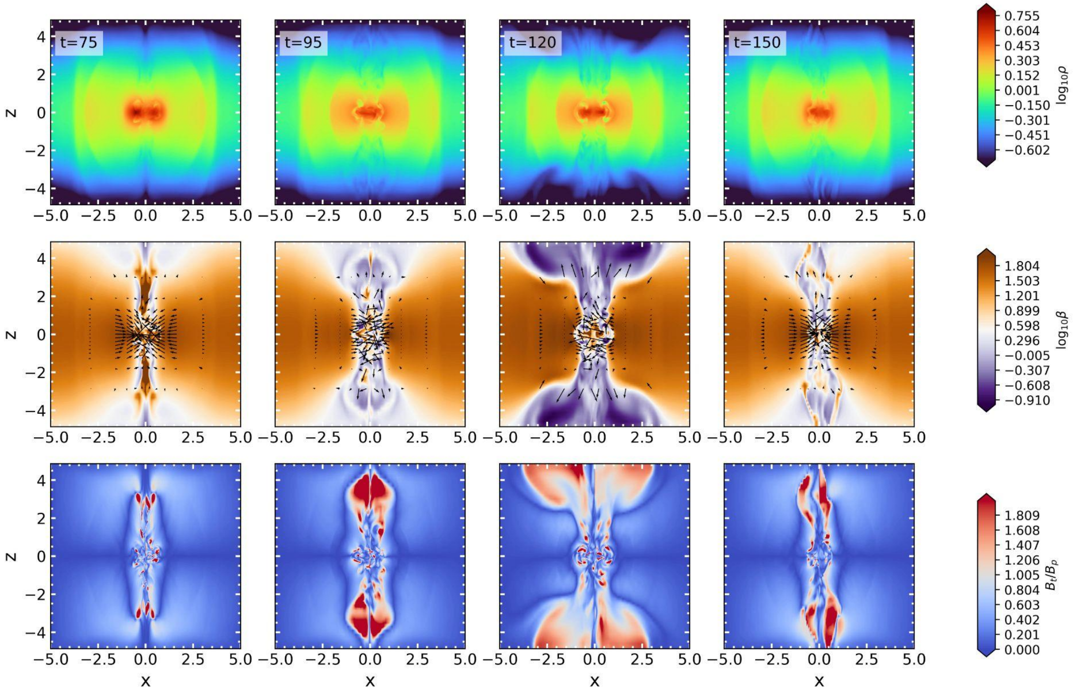
$$h = 0.01$$

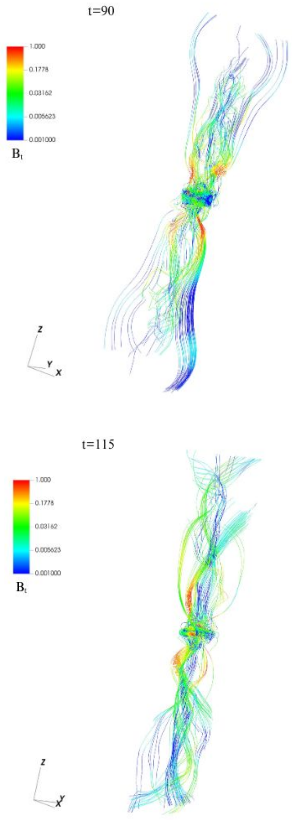
Binary Black holes in AGN Disks



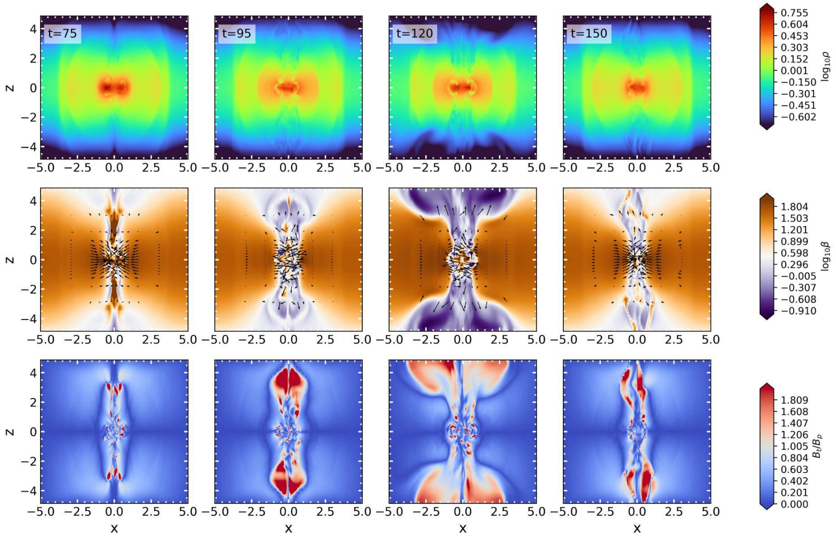
Outflows

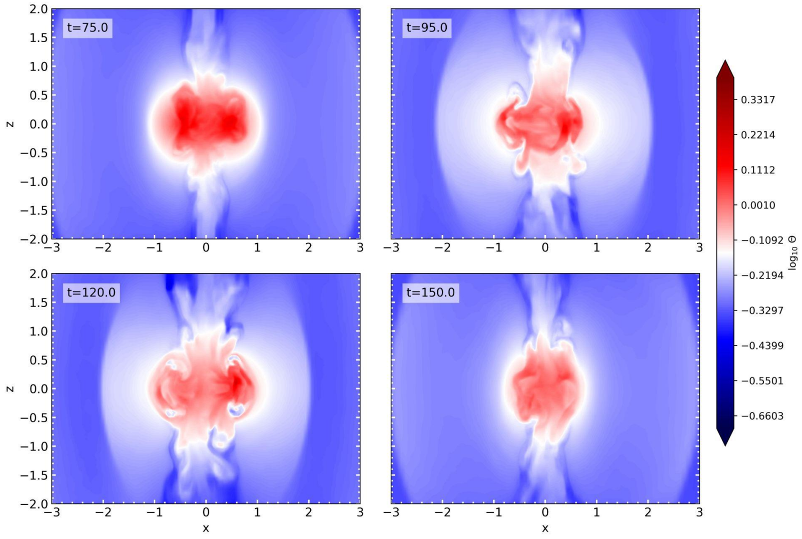
Magnetic tower jets- Nakamura et al. (2006)





Outflows



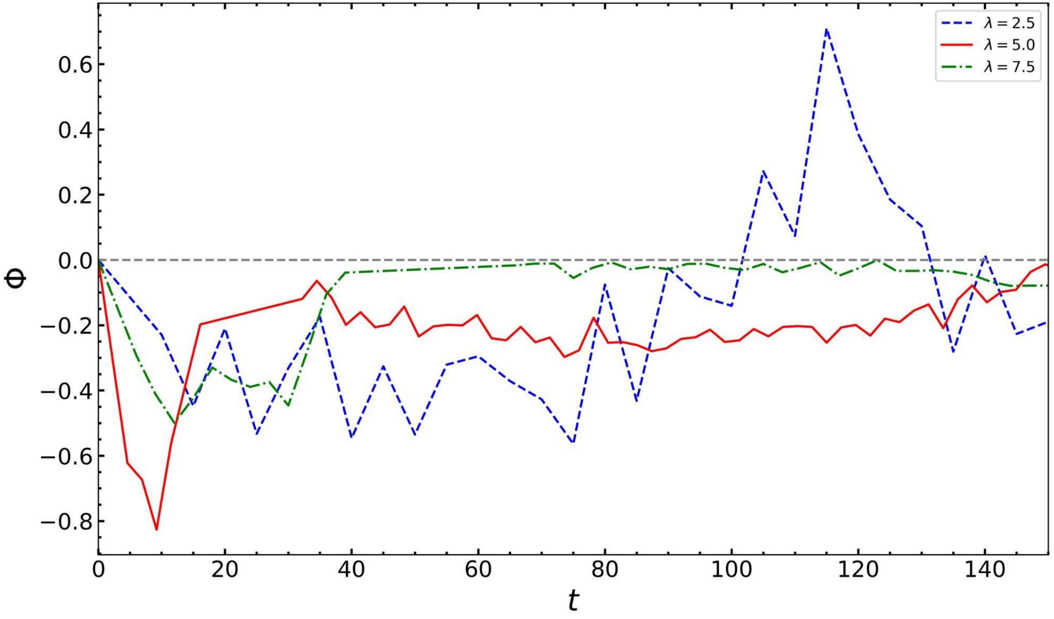


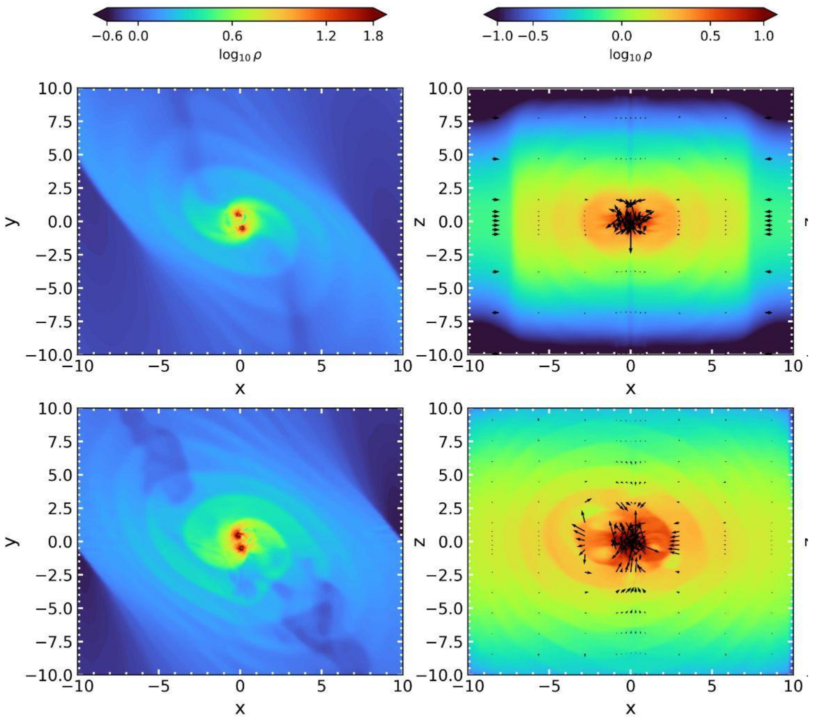
λ	Ω_k	p	c_s
2.5	0.253	0.250	0.632
5.0	0.089	0.125	0.447
7.5	0.048	0.083	0.365

$$\frac{c_s}{v_b} = h q_M^{-1/3} \lambda^{-1/2},$$

Outflows are location dependent

$$\Phi = \sum \rho(\mathbf{v} \cdot \hat{n}) dA / \mathbf{S}$$





Conclusions

Binaries in magnetised accretion disks can generate outflows which clears up a cavity in the disk.

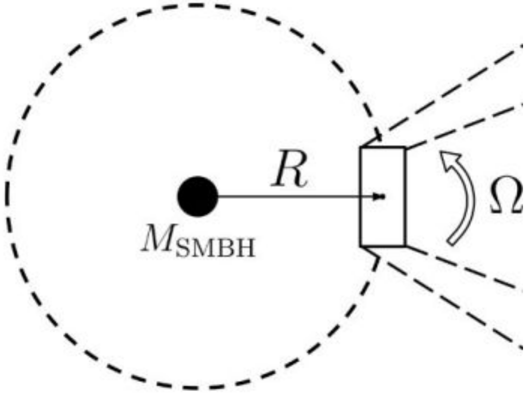
Outflow formation depends on local disk environment.

Outflow activity becomes weaker if BBHs are seeded in outer parts of the disk.

Thank You

Shearing box

x→ Radial direction (points outward)
y→ Azimuthal direction (along the orbital motion)
z→ Vertical direction (perpendicular to the disk plane)



$$v_\phi = \Omega(R)R \qquad \Omega(R) = \sqrt{\frac{GM}{R^3}}.$$

$$\Omega(R) \approx \Omega_0 + (R - R_0)\frac{d\Omega}{dR}.$$

$$v_\phi \approx \Omega_0 R_0 + x\left(-\frac{q\Omega_0}{R_0}R_0 + \Omega_0\right)$$

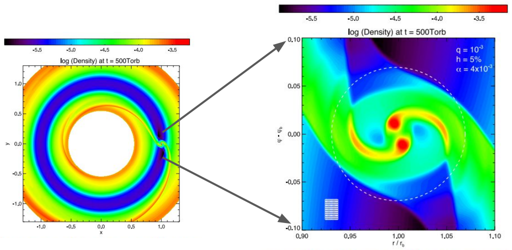
$$v_y = v_\phi - \Omega_0 R_0.$$

As the reference frame is co-rotating.

Similar treatment if followed for the components of gravity (Tidal expansion)

Shearing box in Magnetohydrodynamic Framework

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$



$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v}\mathbf{v} - \mathbf{B}\mathbf{B}) + \nabla p_t = \rho (g)_s - 2\rho\Omega\hat{z} \times \mathbf{v} + \rho \mathbf{f}_b$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0\,,$$

$$\boldsymbol{g}_s = \Omega_0^2 (2qx\hat{\boldsymbol{x}} - z\hat{\boldsymbol{z}})$$

$$q = -\frac{1}{2} \frac{\mathrm{d} \log \Omega^2(R)}{\mathrm{d} \log R}\bigg|_{R_0}$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + p_t)\mathbf{v} - (\mathbf{v}.\mathbf{B})\mathbf{B}] = \rho \mathbf{v}.\mathbf{g}_s + \rho \mathbf{v}.\mathbf{f}_b$$

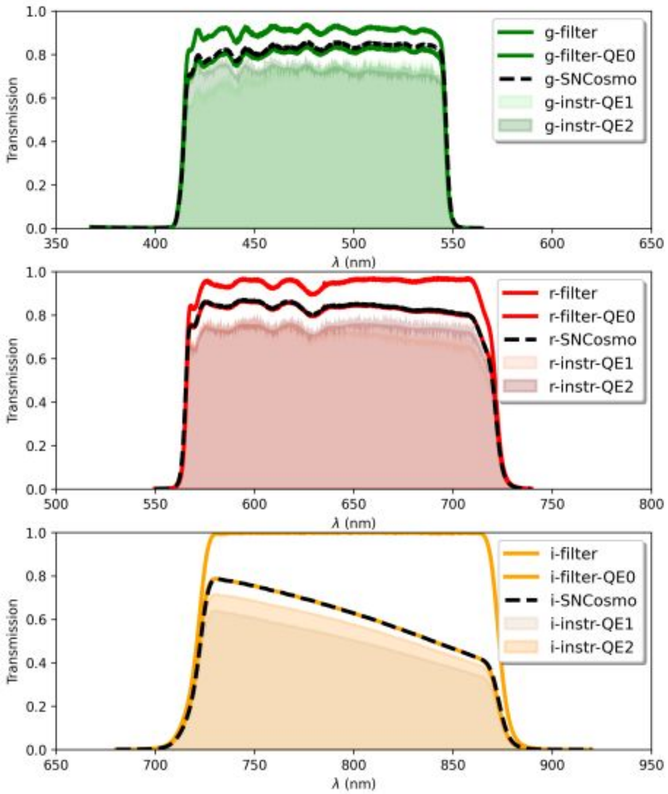
$$E = \frac{p}{\Gamma - 1} + \frac{1}{2}\rho \boldsymbol{v}^2 + \frac{1}{2}\boldsymbol{B}^2,$$

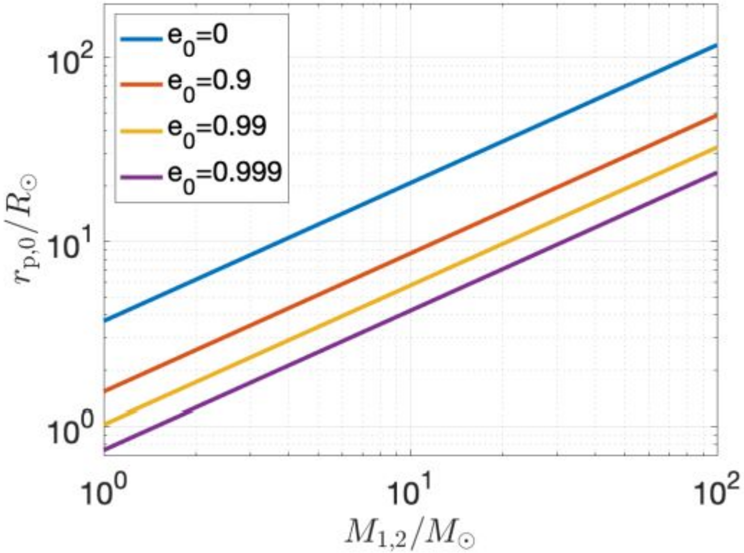
$$p_t = p + \boldsymbol{B}^2/2$$

Conclusions, Caveats and Future aspects

Depending upon the initial separation the binaries may not have sufficient time to reach the magnetically dominated state and the probability of jet formation reduces. So we need a constraint on the initial separation to do a parametric study.

BBH mass distribution





$$T = 1.4 \times 10^4 \alpha^{-1/5} \dot{M}_{16}^{3/10} m_1^{1/4} r_{10}^{-3/4} f^{6/5} \mathrm{K}$$

$$\rho = 3.1 \times 10^{-8} \alpha^{-7/10} \dot{M}_{16}^{11/20} m_1^{5/8} r_{10}^{-15/8} f^{11/5} \mathrm{g/cm^3}$$

Here T and ρ are the mid-plane temperature and density respectively. $\dot{M}_{16}$ is the accretion rate, in units of $10^{16} \mathrm{g/s}$, m_1 is the mass of the central accreting object in units of a solar mass, r_{10} is the radial location in the disc, in units of $10^{10} \mathrm{cm}$, and $f = [1 - (r_0/r)^{1/2}]^{1/4}$, where r_0 is the inner radius of the disc.

disc = $10^6 - 10^{11}$ cm $[M/M_\odot]$