Circumbinary accretion onto Supermassive Black hole Binaries with the presence of a Dark Matter Spike

The many tones of accretion – To the memory of Tomaso Belloni
Cefalù, Italy
September 10th, 2026

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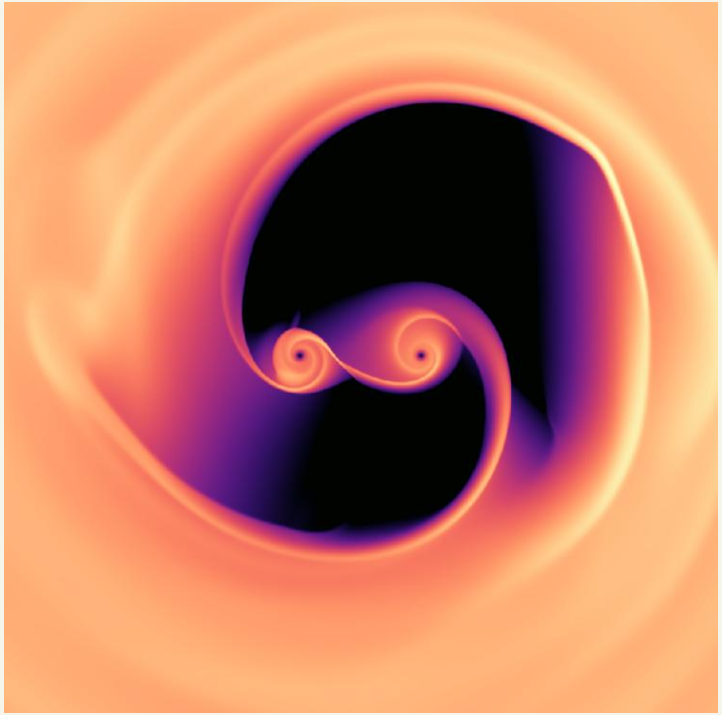
Why study circumbinary disks?

- **Circumbinary disks (CDs)** are important because they would be possible sources of electromagnetic signals (e.g. spectral signatures) of SMBHBs due to the dynamical interactions between the binary system and the disk.

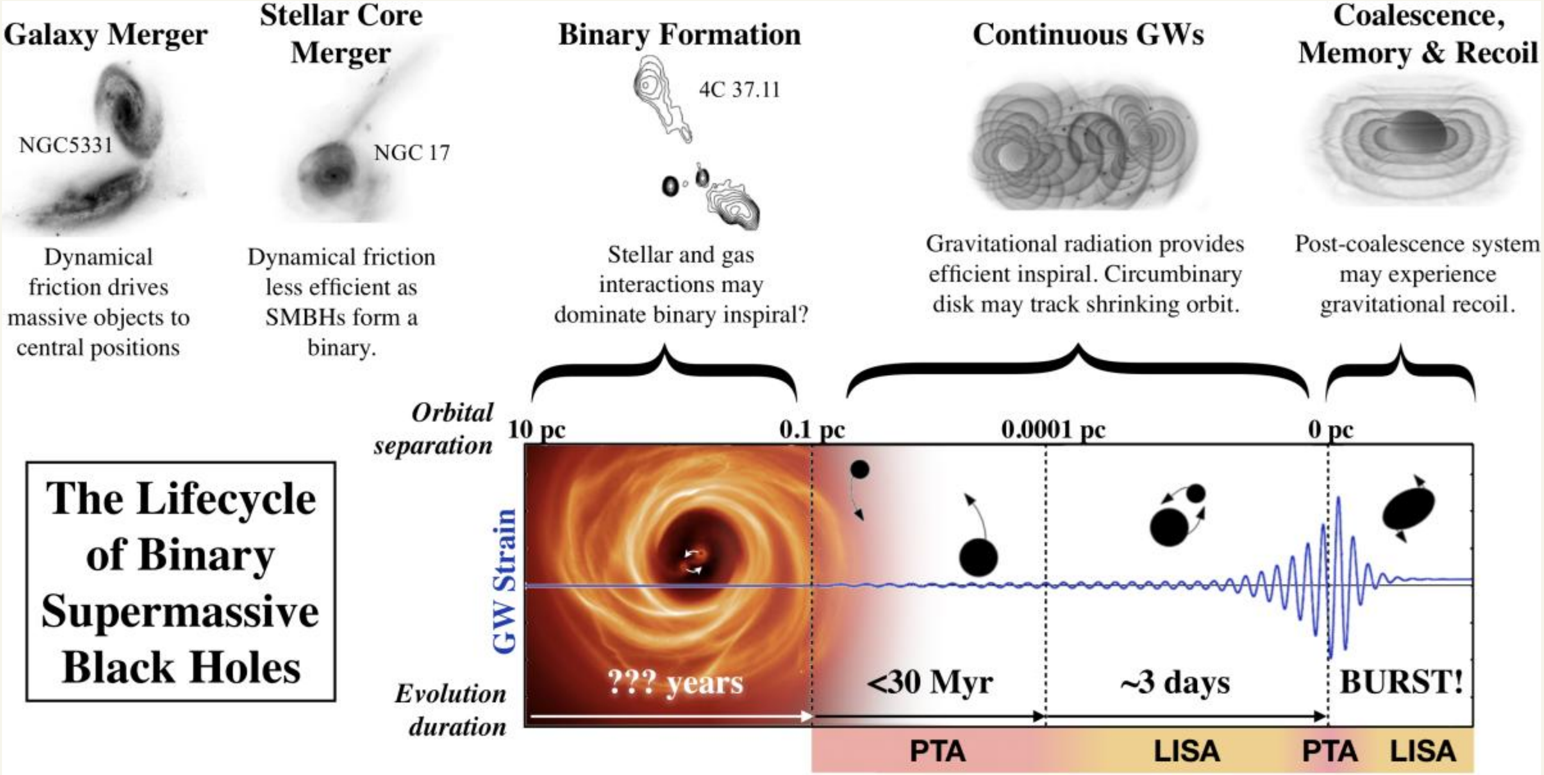
- They have also been proposed as a way to facilitate the merger of SMBHBs in a region where gravitational radiation may not be enough. (e.g. Tiede et al. 2020)

- With the development of the **Laser Interferometer Space Antenna (LISA)**, planned for ~2035+, there is a growing interest in having reliable modelling of the interactions and electronmagnetic signatures of CDs around SMBHBs.



Duffell et al. 2024

Where do these systems come from?



Designed by Sarah Spolaor.

Do we observe them?

Many SMBHBs candidates have been identified via signatures of periodic or nearly periodic variability in the light curves of quasars, which are interpreted as a manifestation of binary orbital motion.

Bogdanović et al. 2022

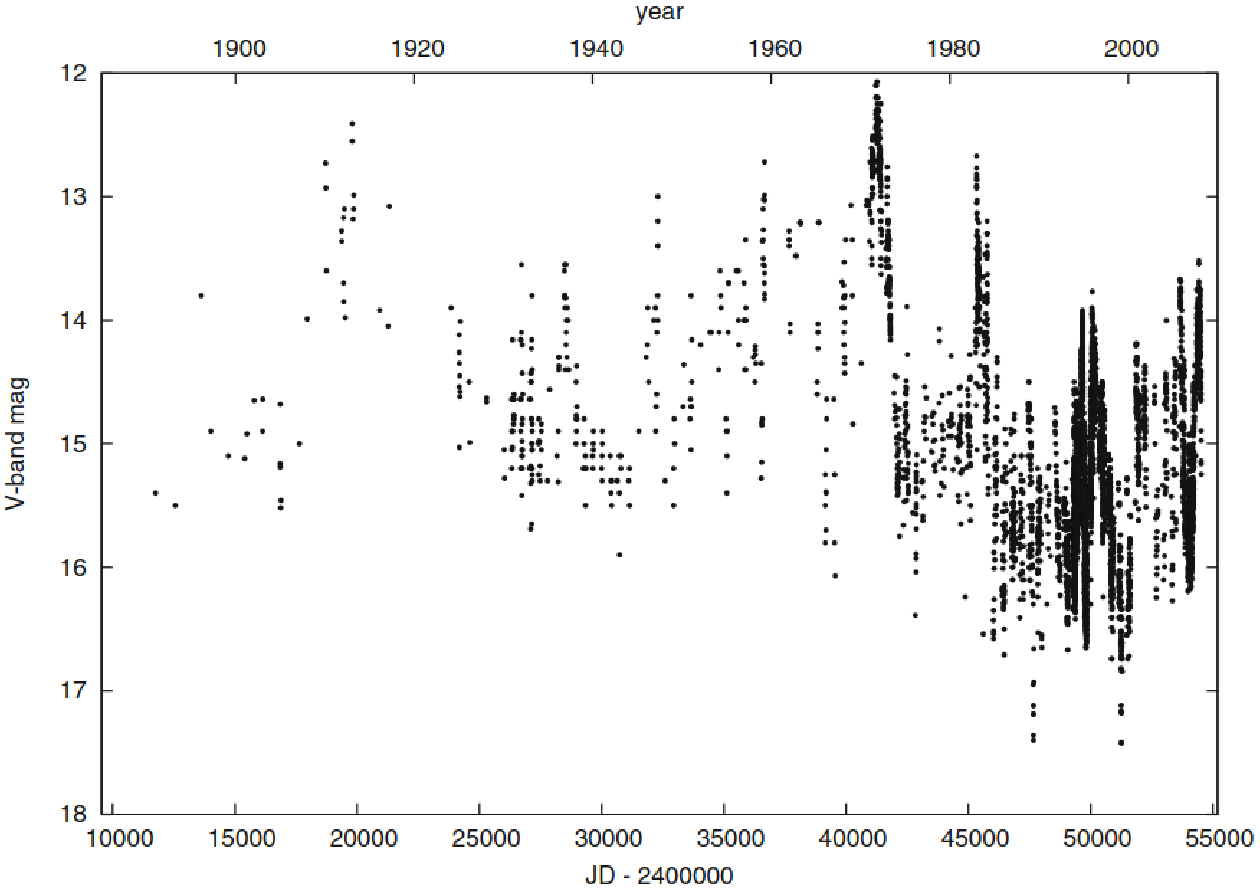


Fig. 6 Historical light curve of OJ 287 in V-magnitude recorded over more than 100 years. Quasi-periodic outbursts with an observed period of ∼12 yr in the light curve of this object have been interpreted as a signature of the MBHB orbital motion. Image reproduced with permisson from Valtonen et al. (2008), copyright by NPG

Takeaway from this slide ☺

D'Orazio & Charisi 2023

Pros and Cons: Periodic Lightcurves

Pros:

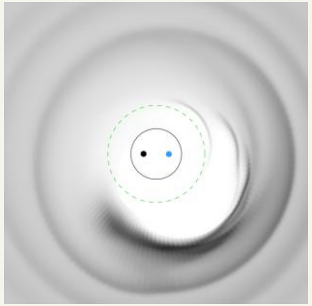
- The expectation for periodic brightness modulation in binaries is simple and intuitive – the two body problem is periodic. Many mechanisms can produce periodicity, as shown in a variety of analytical and numerical studies.
- Some signatures (*e.g.*, the relativistic Doppler boost) are unique containing testable multi-wavelength predictions and possible reverberation signatures.
- This method has been applied in large samples of AGN from past or ongoing time-domain surveys revealing hundreds of promising candidates.
- Upcoming time-domain surveys like LSST will provide even bigger samples, which are required for the detection of rare short-period binaries.

Cons:

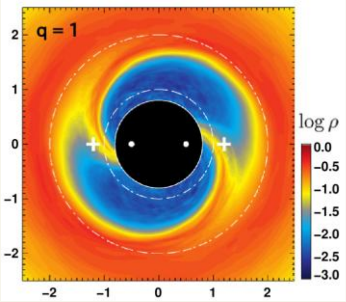
- AGN variability is stochastic and can mimic periodicity. Therefore, the samples of candidates are likely contaminated with false detections.
- Not all signatures are unique, making them hard to distinguish from typical quasar variability, especially in the limit of sparse data.
- Building confidence in the candidates requires observations of many cycles of periodicity, which for periodicities of a few years requires time (decades).
- The multi-wavelength Doppler boost test requires spectra and multi-epoch photometry in two observing bands, while lensing requires relatively high cadence over long temporal baselines.
- Application of IR reverberation models require high-cadence IR all-sky surveys (*e.g.*, to build a large sample and systematically search for binaries) or long-term follow-up of individual candidates.
- Polarization signatures are at the limit of detection and can be confused by scattering from intervening gas in the AGN host galaxy.
- Models of binary accretion are still young.

What has been done?

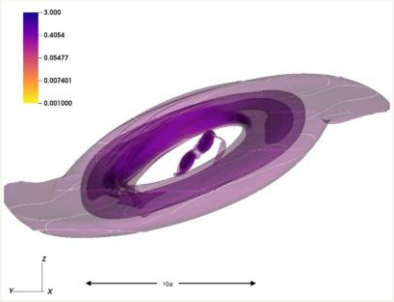
- Circumbinary accretion and morphology has been studied over a wide range of codes and physical setups.
- The majority of works (even recently) have been done as 2D viscous hydrodynamical simulations, which allows to explore a wide range of parameters.
- More RMHD are needed!



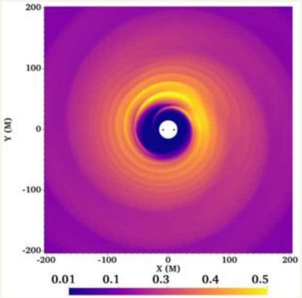
D'Orazio et al. 2013 (2D hydro)



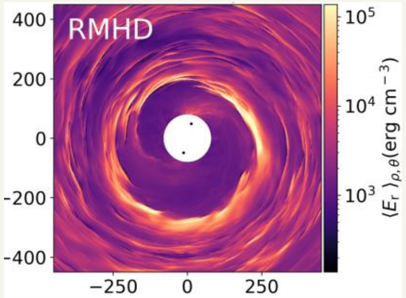
Shi & Krolik 2015 (3D MHD)



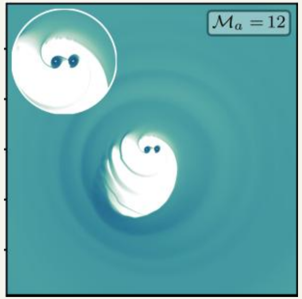
Moody et al. 2019 (3D hydro)



Mignon-Risse et al. 2023 (GR-hydro)



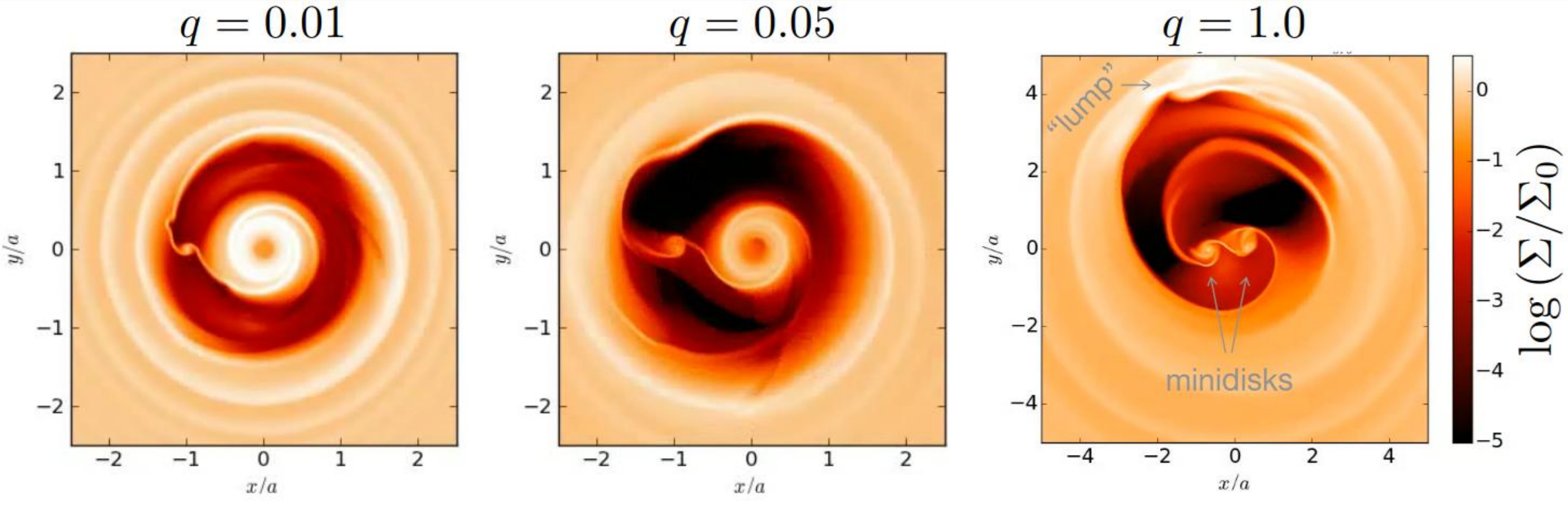
Tiwari et al. 2025 (3D RMHD)



Tiede et al. 2026 (2D hydro)

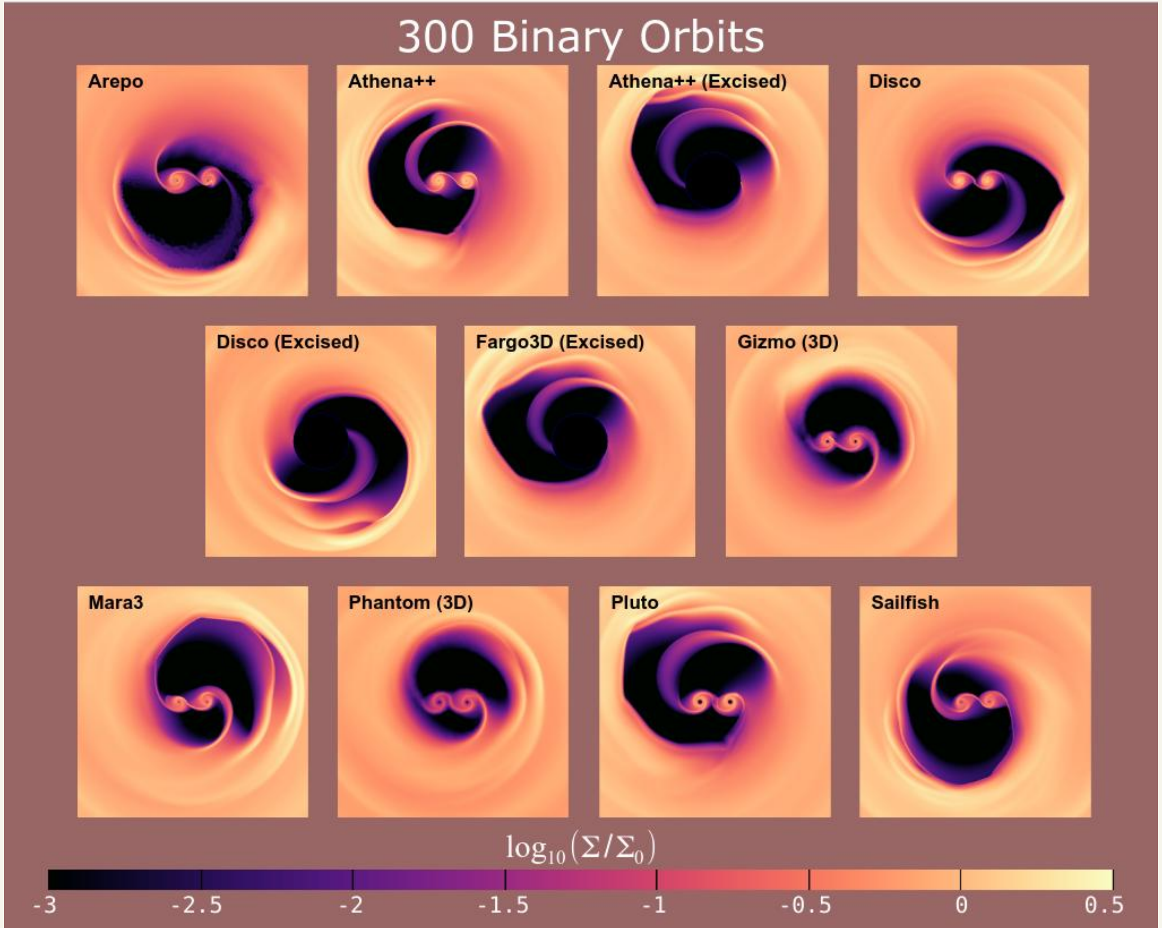
Disk Morphology

- Depending on the mass ratio of the SMBHBs, different morphology arises.
- For systems of similar masses, an eccentric cavity can be formed, alongside an overdensity called “lump”.
- All systems seem to show minidisk formation around each individual **Black Hole (BH)**.



D’Orazio & Charisi 2023

The Santa Barbara Binary-Disk Code Comparison



Duffel et al. 2024

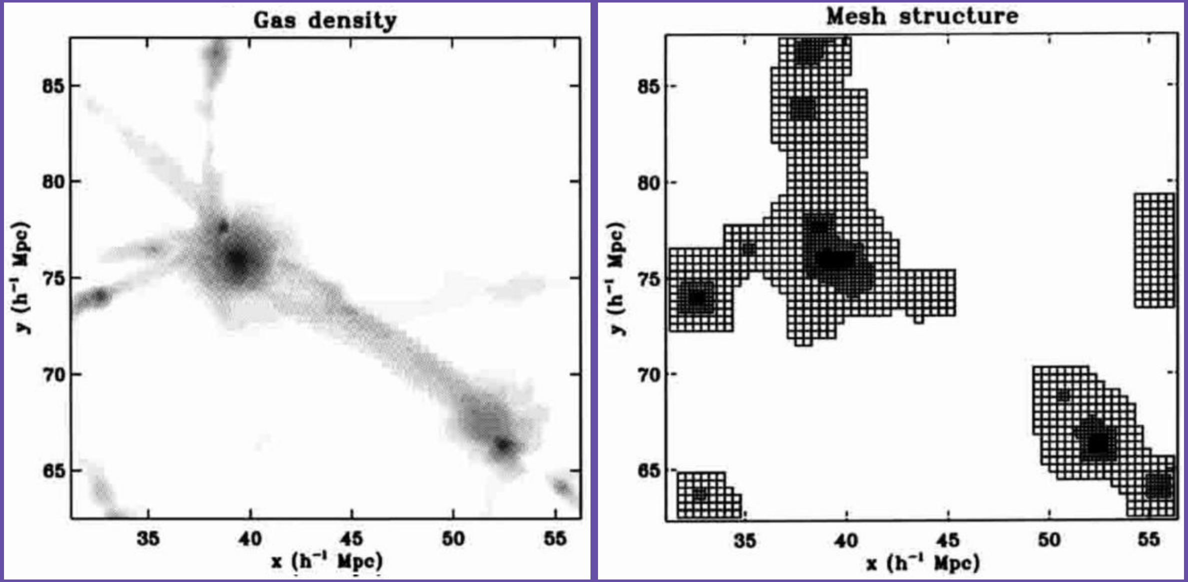
RAMSES

- RAMSES is an N body and hydrodynamical AMR code which divides its calculations in different levels of refinement.

- RAMSES uses a second order Godunov method to solve the hydrodynamics equations, which allows to capture shocks with the help of a Riemann solver.

- It has been used for star formation up to cosmological simulations. It also benefits from a large community (~100 users).

- Since its initial paper in 2002, it has gained a number of implementations, including magnetic fields and radiation.

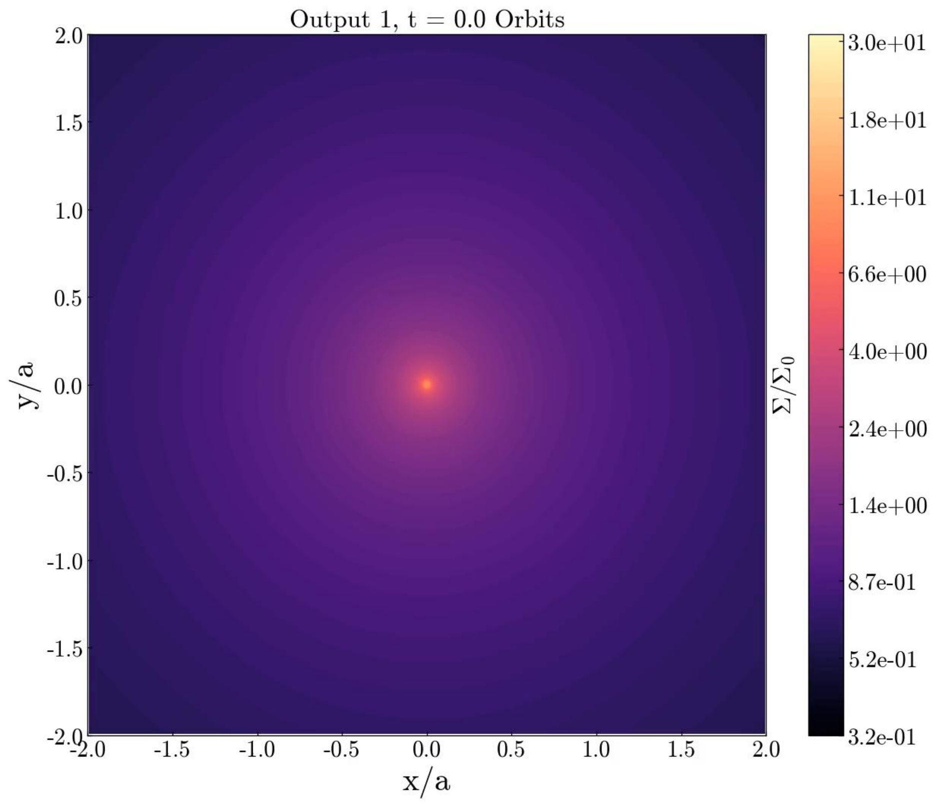


Teyssier 2002

Results:
Low mass ratio regime

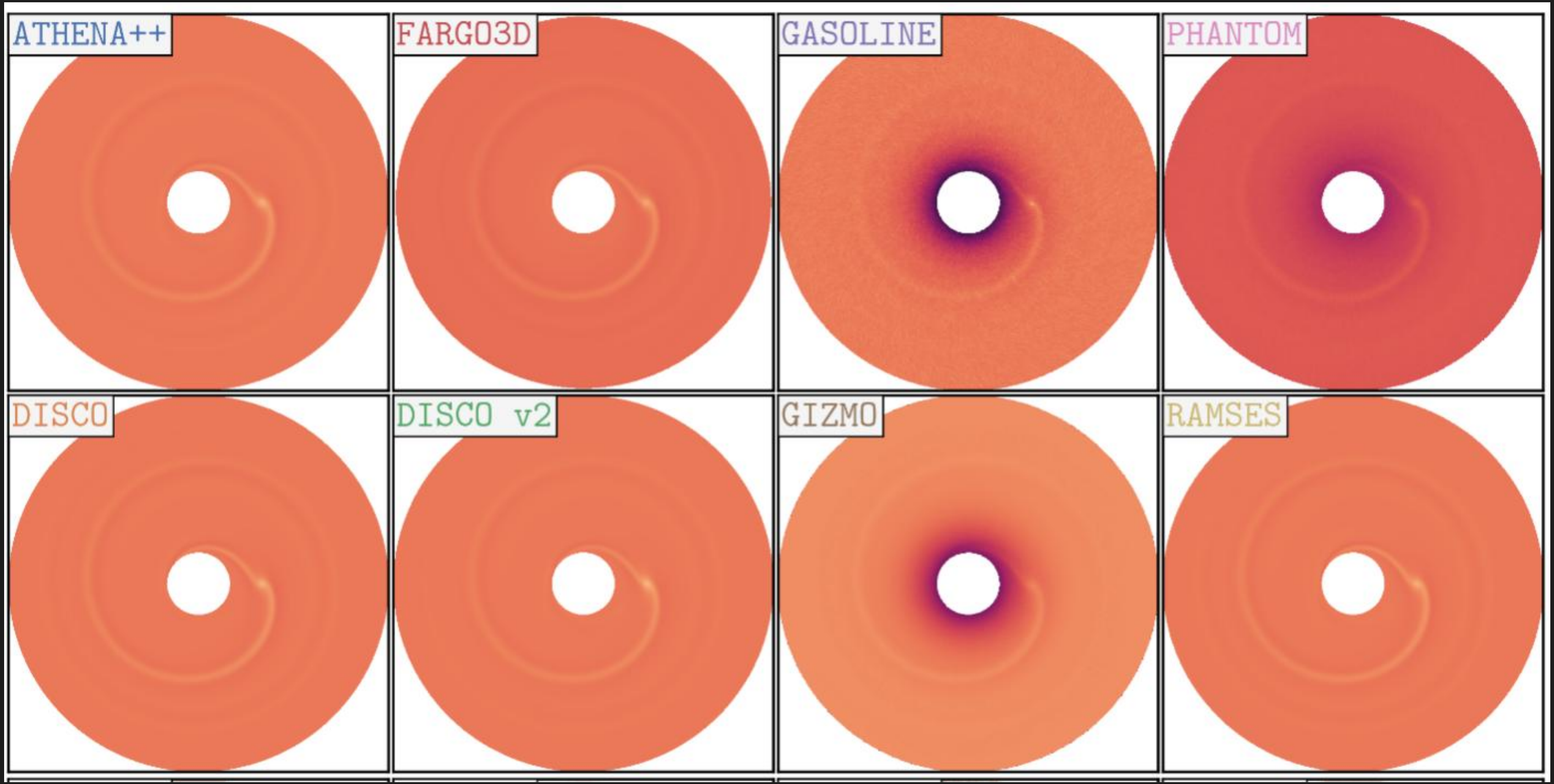
The LISA Astrophysics “DISC-IMRI” Code Comparison Project

- LISA is expected to detect up to hundreds of intermediate-mass-ratio inspirals (IMRIs) per year.
- As part of the LISA Astrophysics Working Group, there is a new code comparison project to explore these systems.
- The runs are made for a “thick disk” (H/r = 0.1) and a “thin disk” (H/r = 0.03).



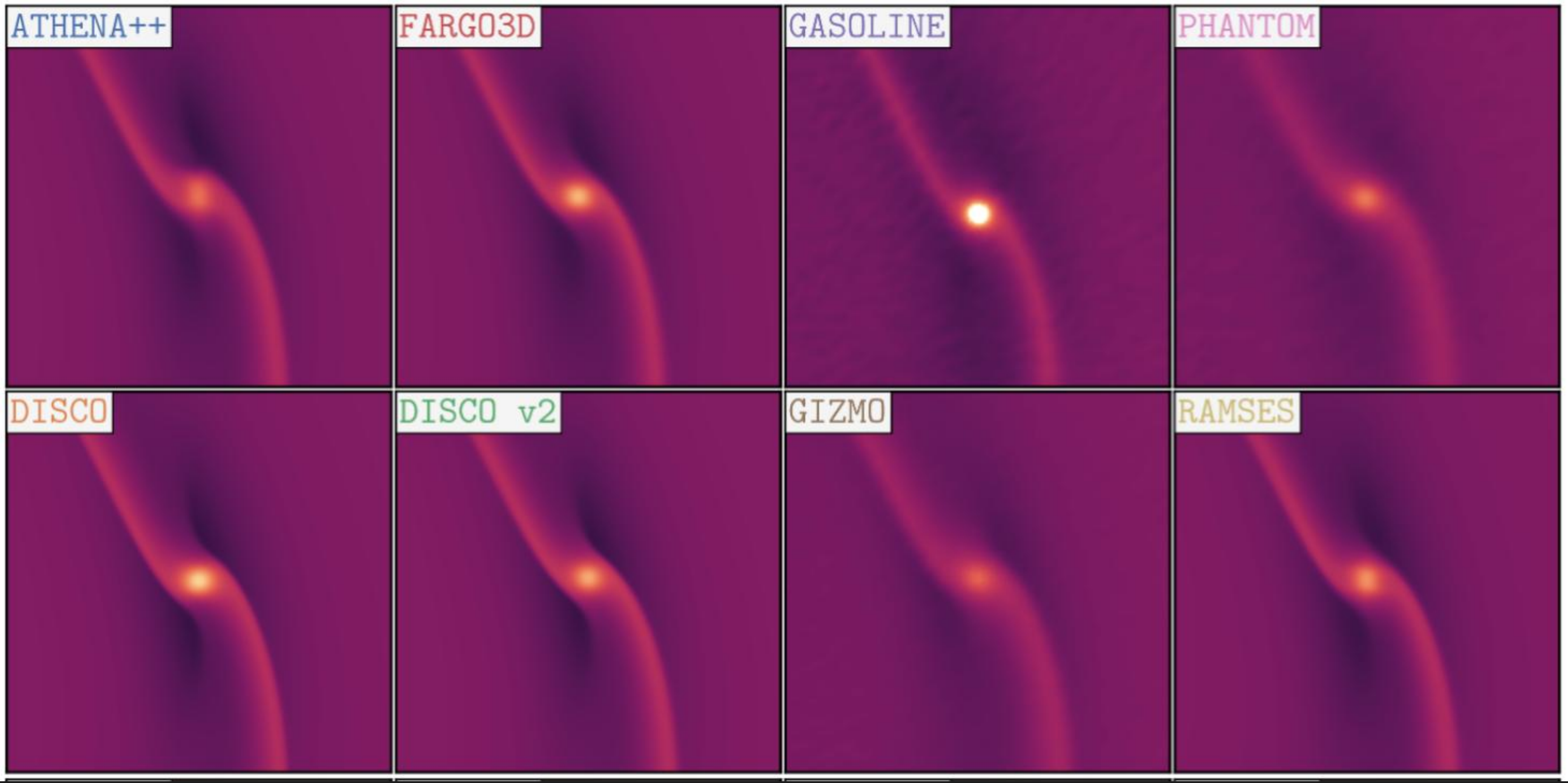
H/r=0.03

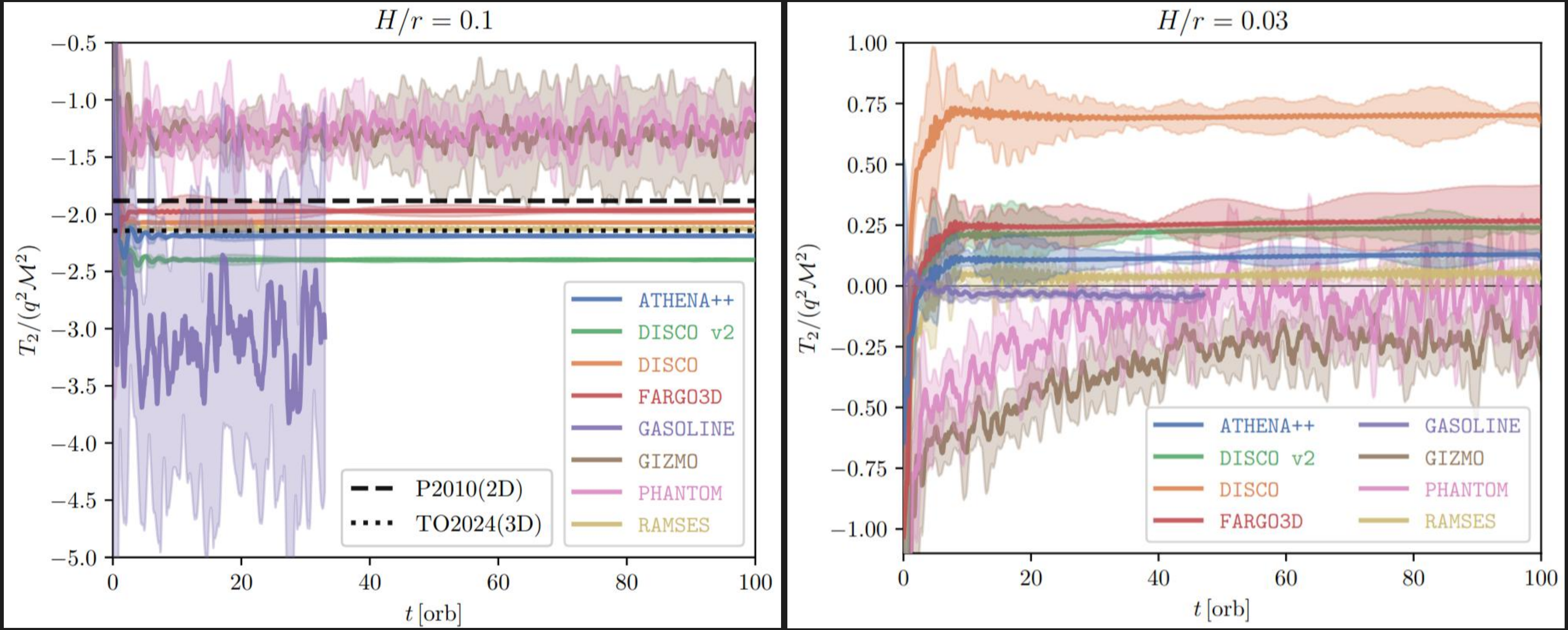
2D Density comparison plot (H/r=0.1)



2D Density comparison plot (H/r=0.03)

2D Density comparison plot (Zoomed in, H/r=0.03)





THE LISA ASTROPHYSICS “DISC-IMRI” CODE COMPARISON PROJECT

Link to the paper:

Derdzinski et al. 2025

THE LISA ASTROPHYSICS "DISC-IMRI" CODE COMPARISON PROJECT: INTERMEDIATE-MASS-RATIO BINARIES IN AGN-LIKE DISCS

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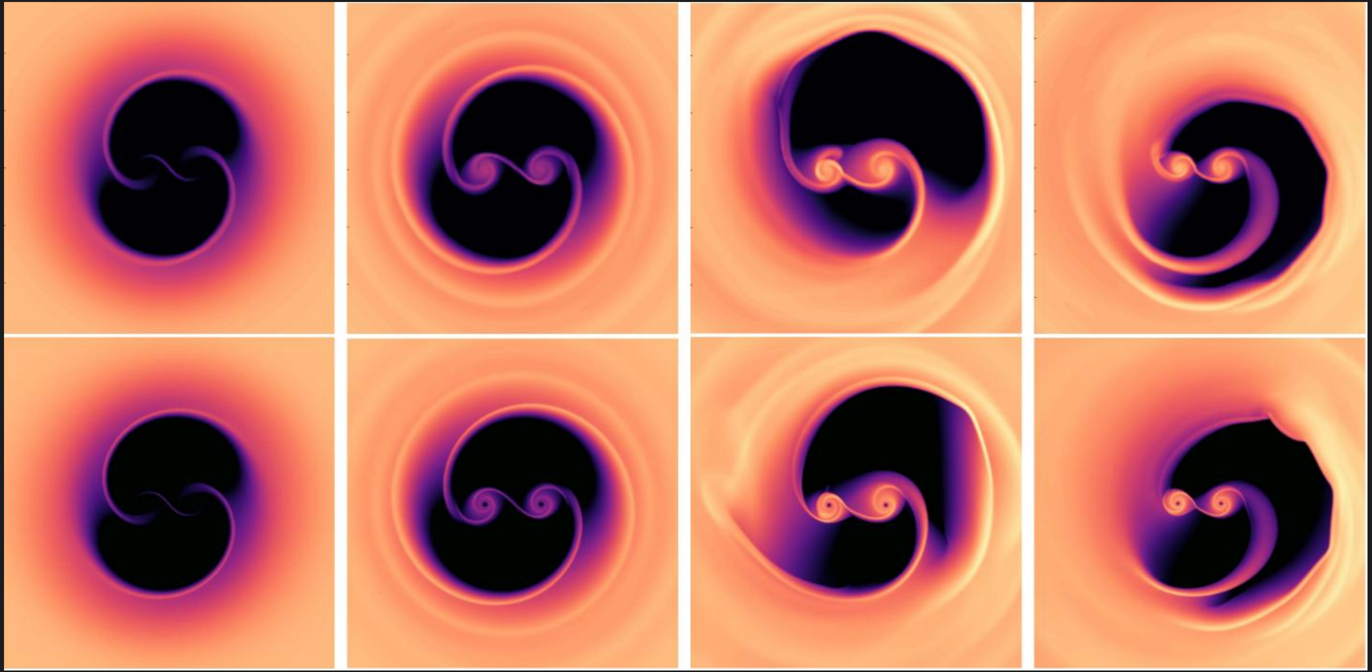
Version December 7, 2025

Results:
Equal mass ratio regime

Santa Barbara Binary Disk-Code Comparison Project

For the equal mass RAMSES Setup we will contrast with The Santa Barbara Binary-Disk Code Comparison



RAMSES implementation

Duffel et al. 2024

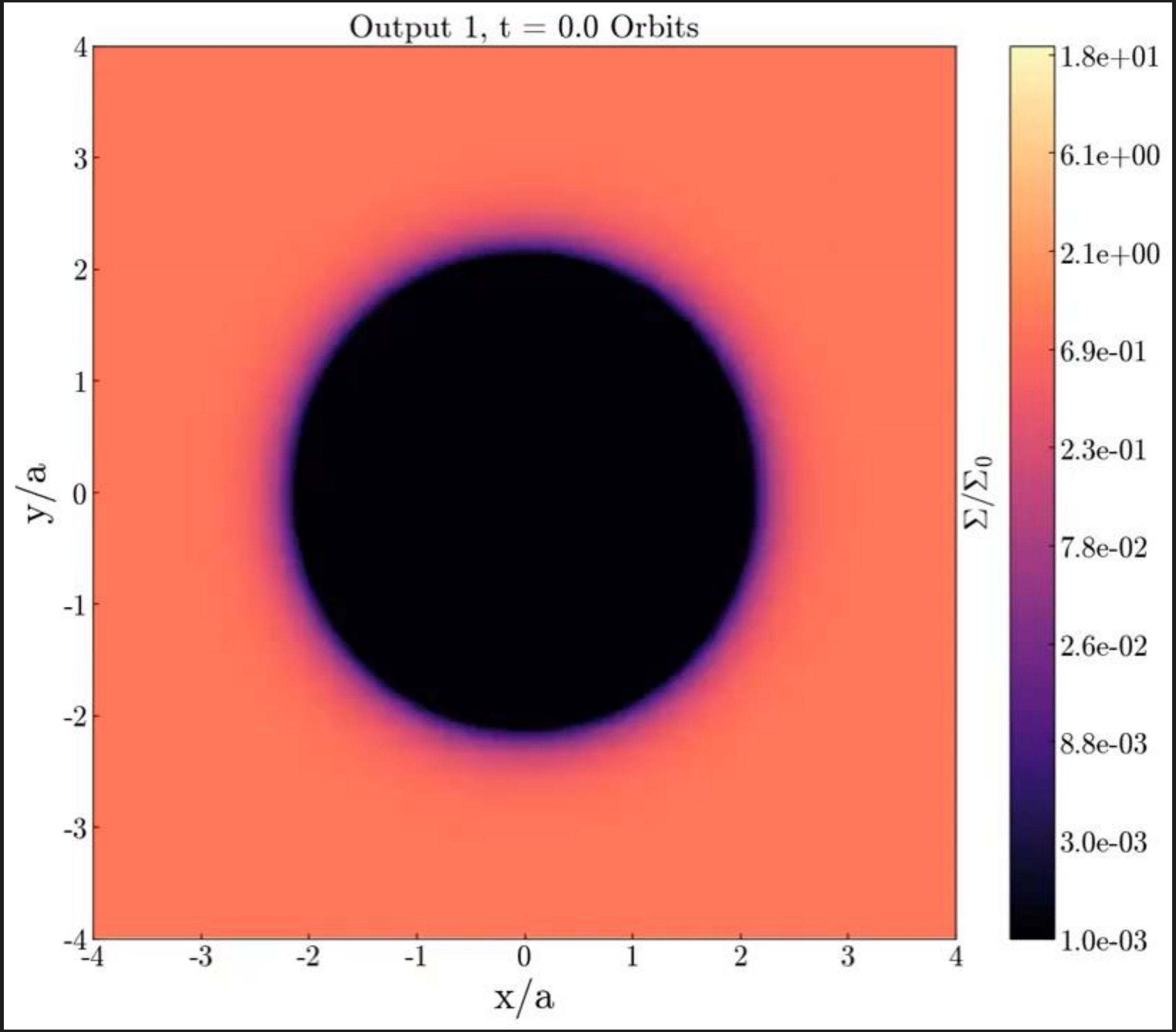
1 Orbit

10 Orbits

100 Orbits

300 Orbits

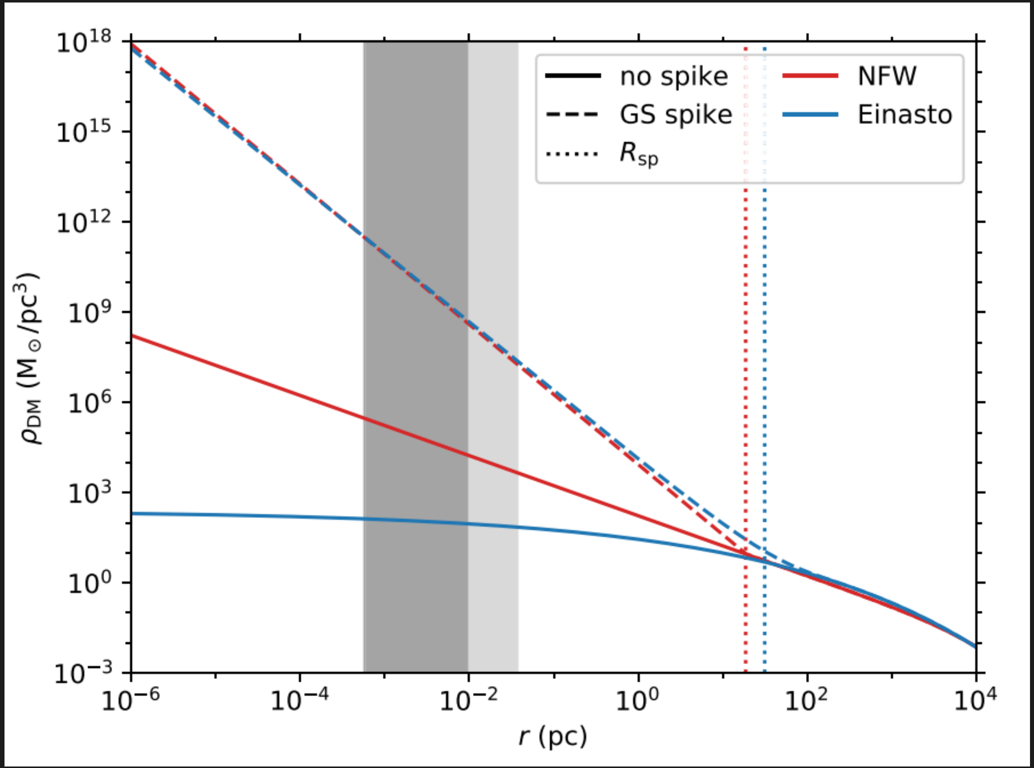
2D Density Map 300 Orbits



DM Spike

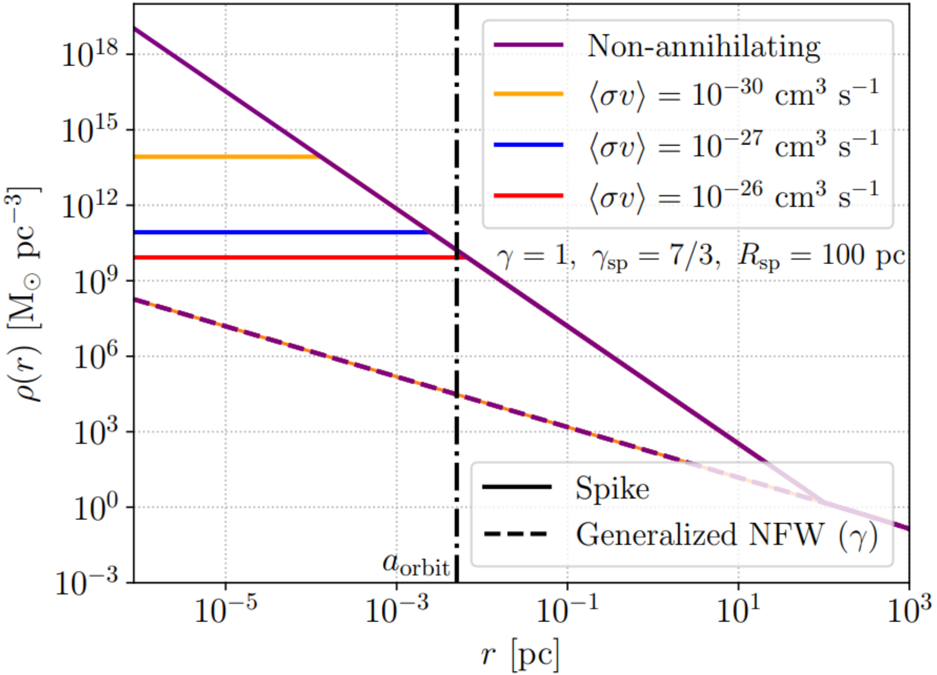
- Some people theorize that at sub parsec scales, dark matter density around the sphere of influence of the SMBH would be significantly enhanced.
- This is called in the literature a Dark Matter Spike
- Something that hasn't been properly explored is the effect a halo potential would have in circumbinary accretion, and the torque exerted to the system.

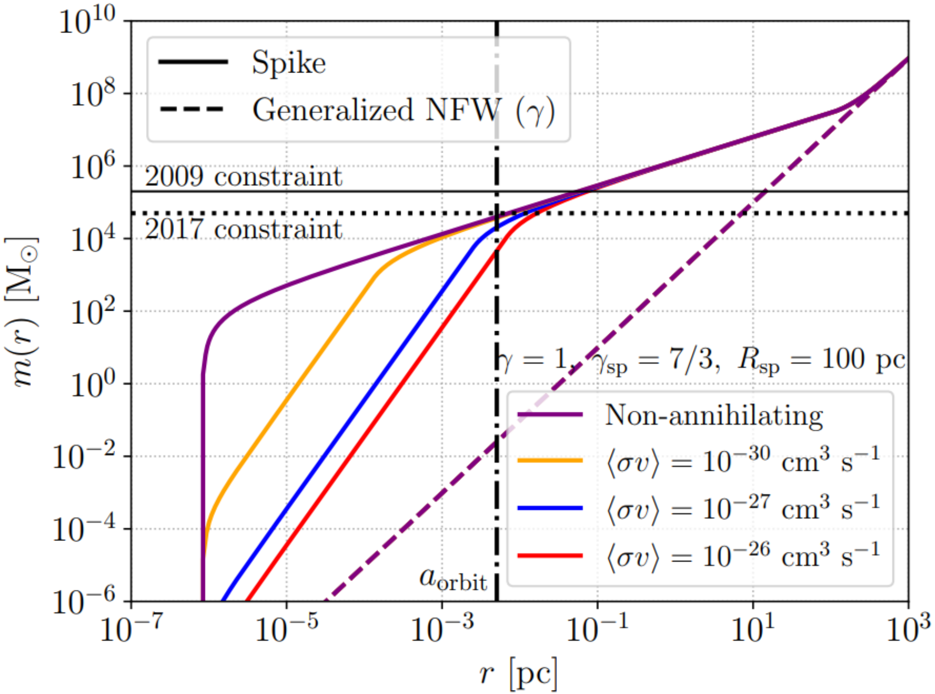
The possible DM density profile in the Milky Way for different models



Zhao-Qiang Shen 2023

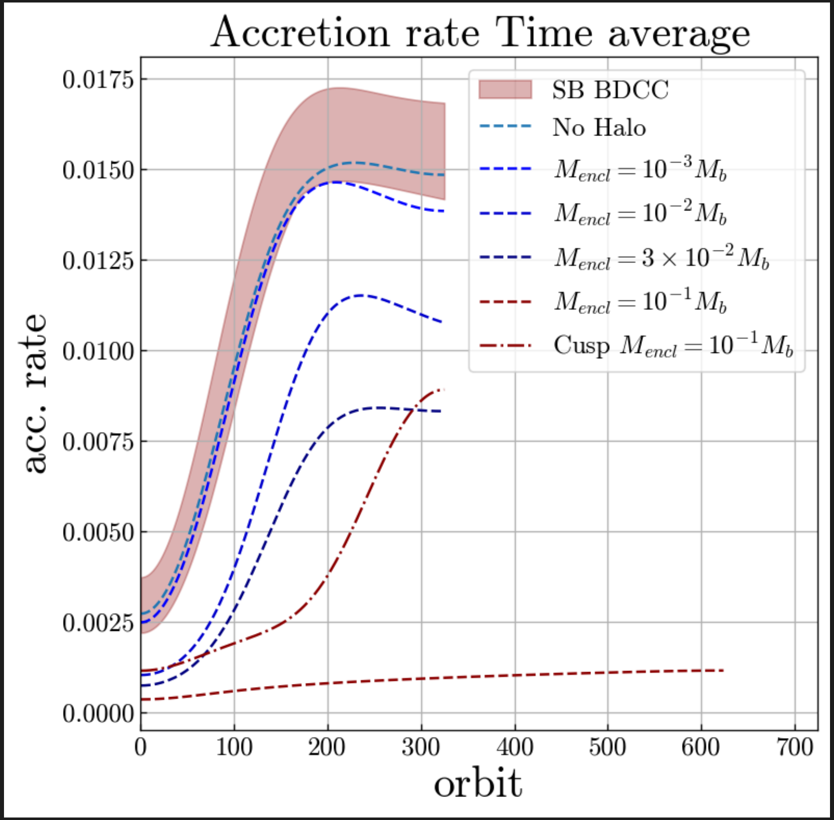
Dark Matter Spike

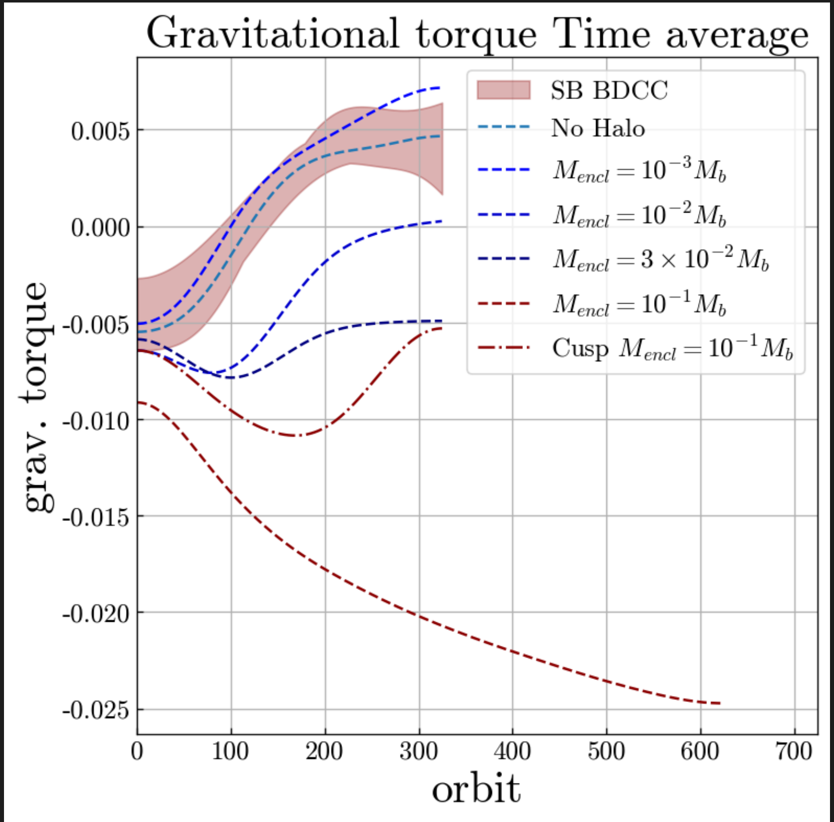




Thomas Lacroix 2018

CB disk inside DM Halo (Preliminary)





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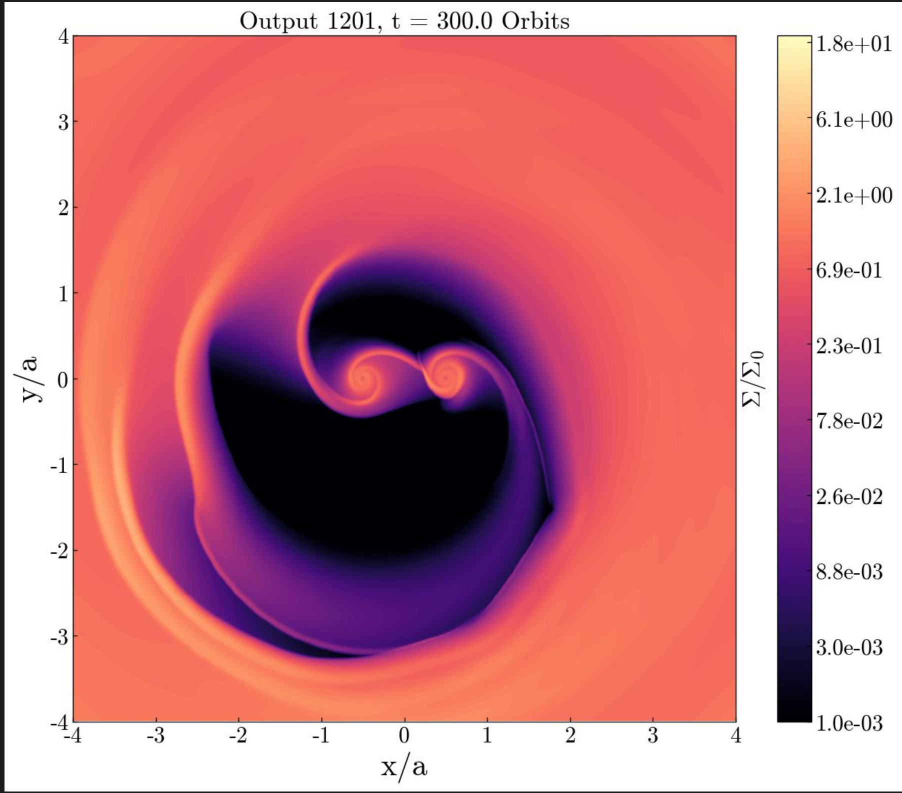
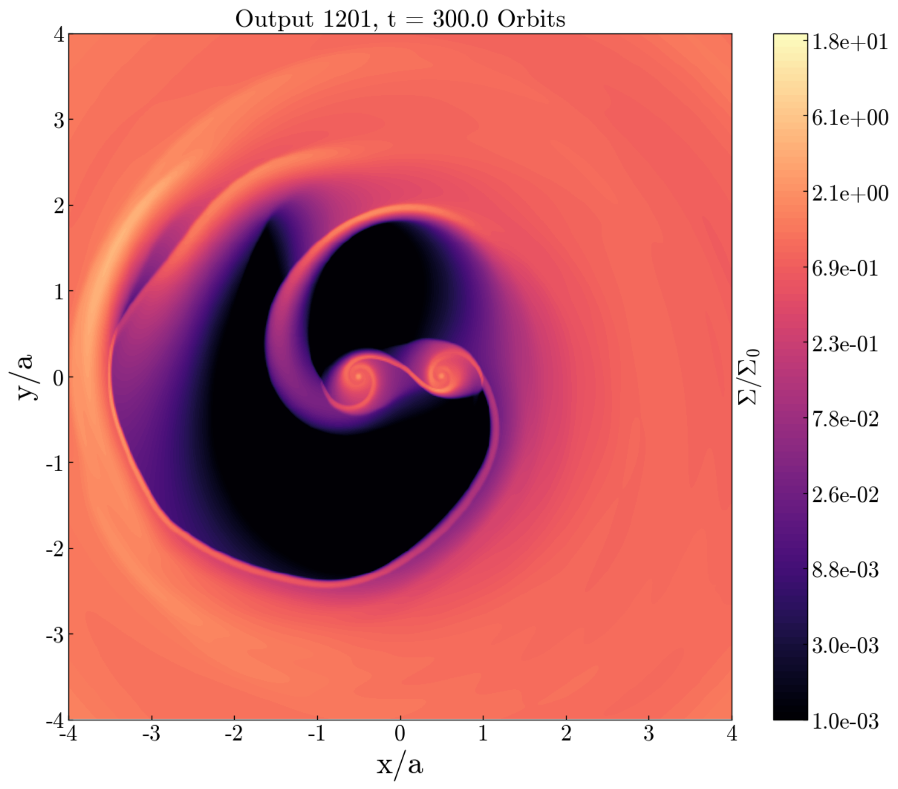
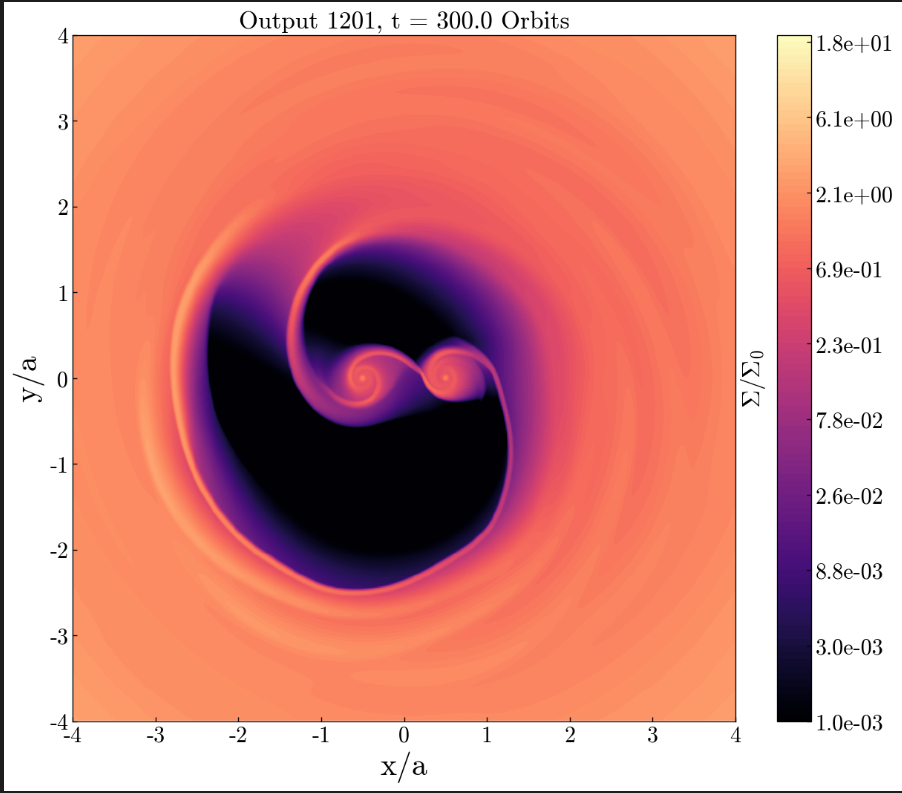


No Halo

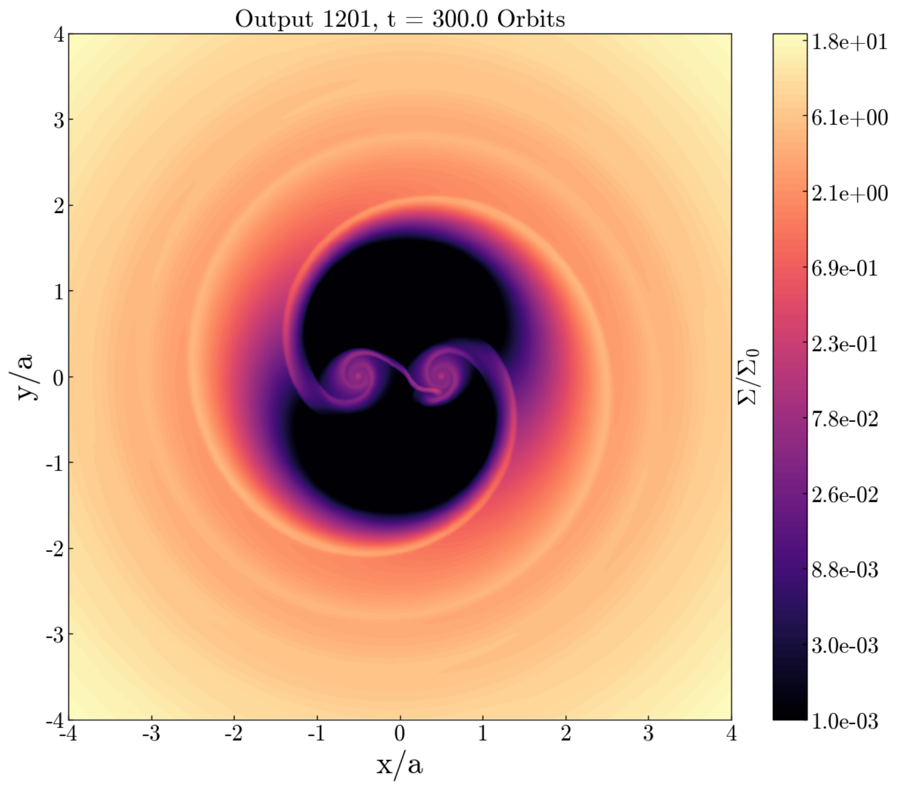


Enclosed mass of 10^{-3} Mb

CB disk inside DM Halo (Preliminary)

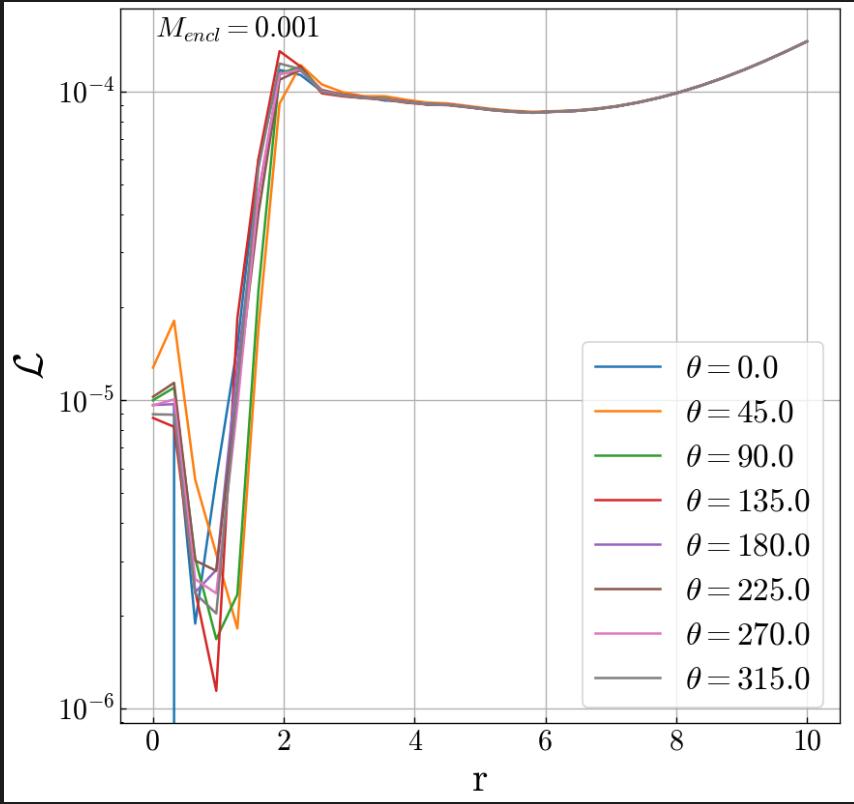


Enclosed mass of 10^{-2} Mb

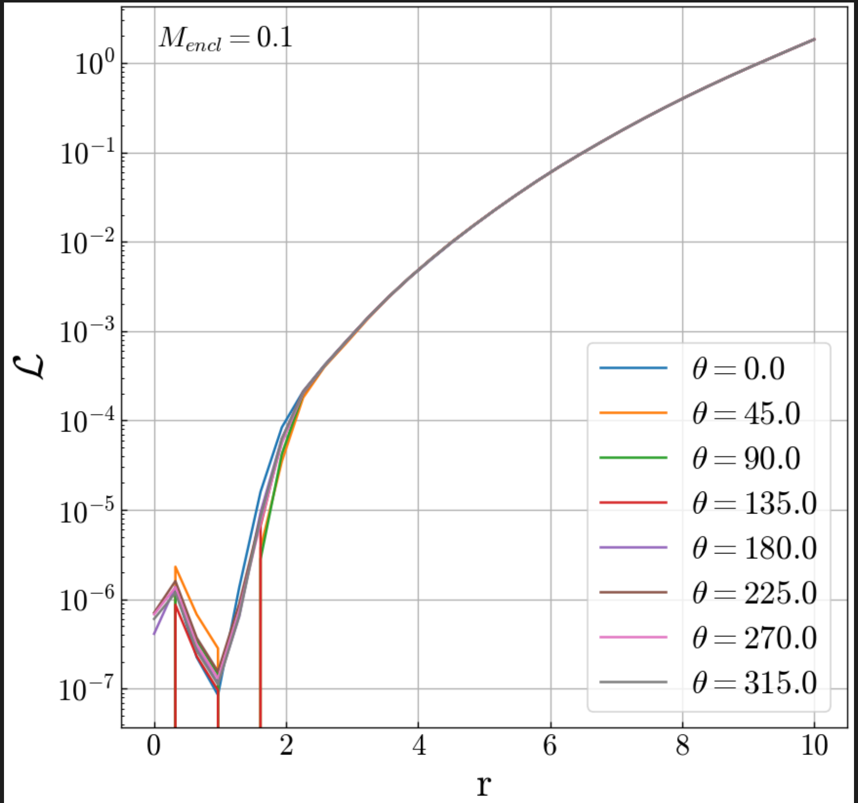


Enclosed mass of 10^{-1} Mb

RWI Instability Profiles (Preliminary)



Enclosed mass of $10^{-3}M_b$



Enclosed mass of $10^{-1}M_b$

Thank you to:

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Ciencia y Tecnología

LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

For making this visit possible

Thank you!

email: esantiago@inaoep.mx

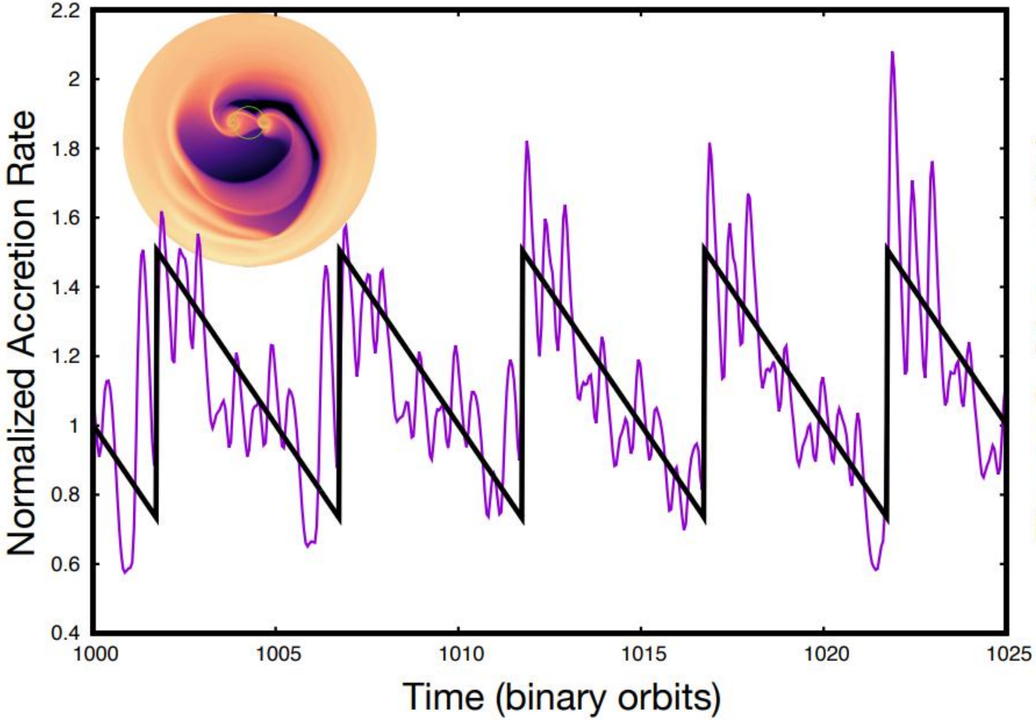
Reviews on the subject:

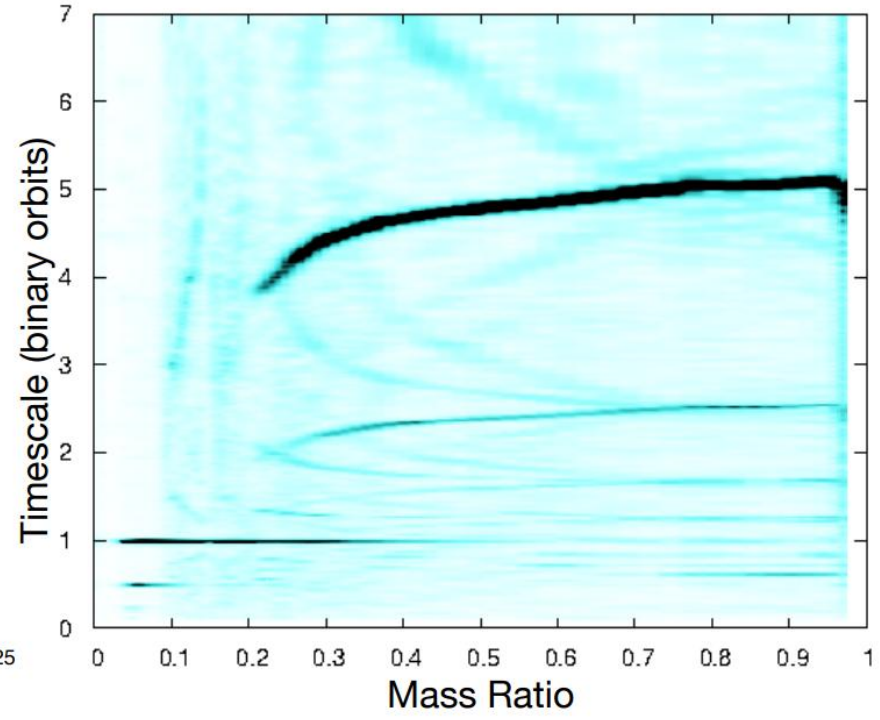
D’Orazio and Charisi 2023

Bogdanović et al. 2022

Accretion rate

The lump at higher mass ratios has an effect over how often the accretion rate has an increase.





D’Orazio & Charisi 2023

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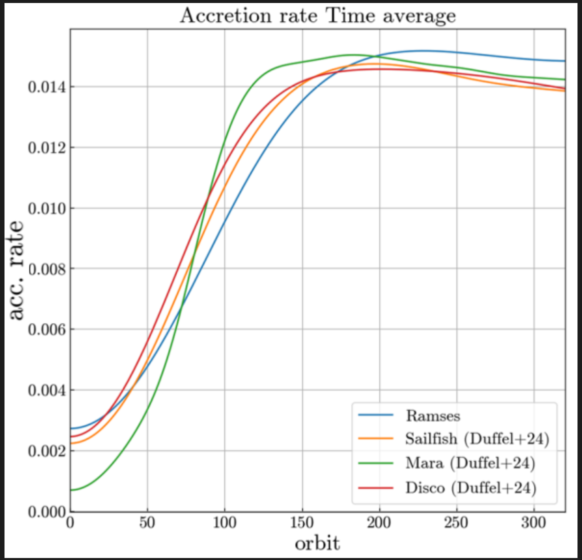
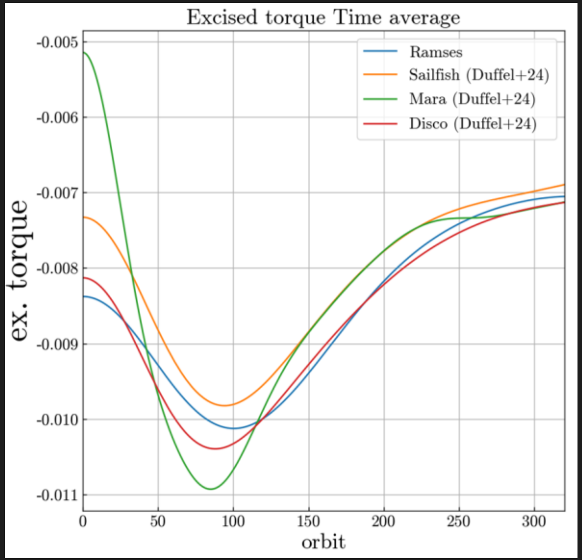
Santa Barbara Binary Disk-Code Comparison Project

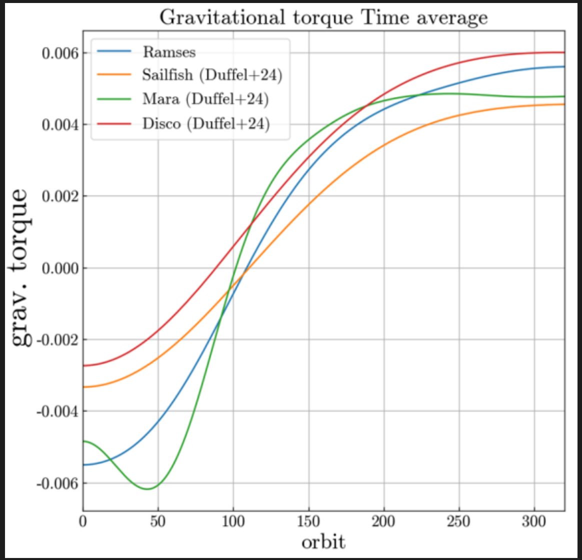
Our results are consistent with the Santa Barbara Binary-Disk Code Comparison.



Accretion Rate



Excised Torque

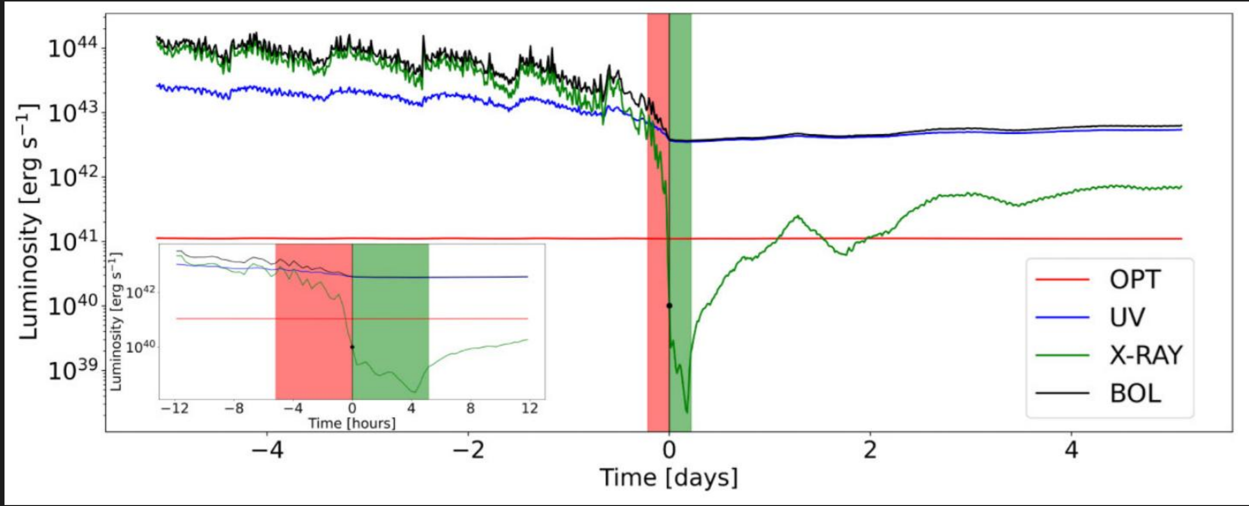


Gravitational Torque

Possible Future Work:

Study of X-ray emission disappearance near merger under pseudo newtonian potential

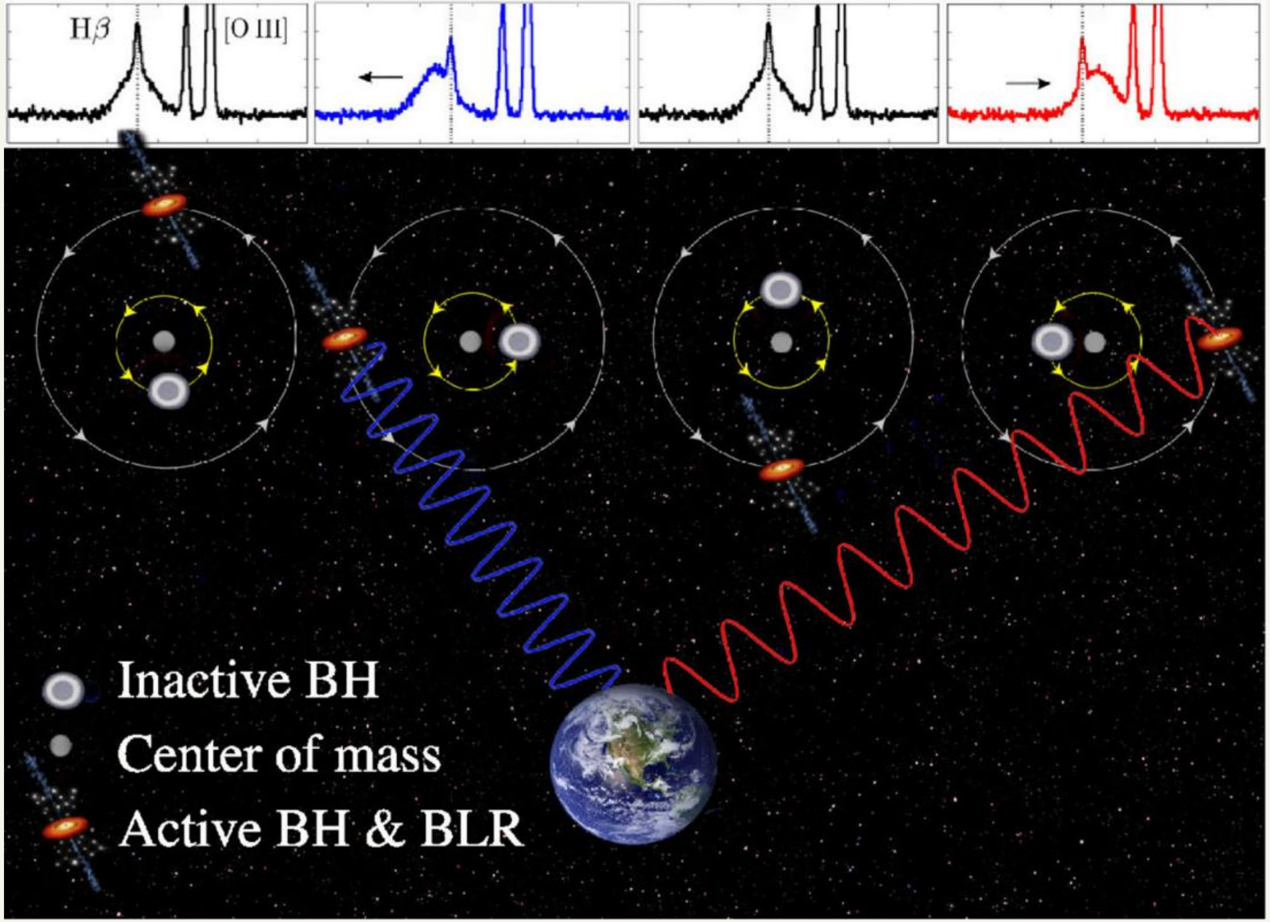
- X ray emission disappearance has been proposed as a possible signature of merging massive BHs.
- The disappearance with a newtonian potential was calculated to happen very close to the merger.
- We would like to investigate this same mechanism under a pseudo newtonian potential that would allow an Innermost Stable Circular Orbit (ISCO) to form.



Krauth et al. 2023

Spectroscopic measurements of offset broad emission lines

Offsets of ~ 103km/s (up to 5,000km/s) in redshift between broad and narrow line centers could suggest that the broad line region is coherently moving, because it is bound to a component of a binary and so red- or blue-shifted by the SMBHB orbital velocity.



Bogdanović et al. 2022

Rossby Wave Instability

Lovelace et al. 1998 found that there is an instability in a Keplerian disk whenever there is an extremum on the function

$$\mathcal{L}(r) \equiv \mathcal{F}(r) S^{2/\Gamma}(r)$$

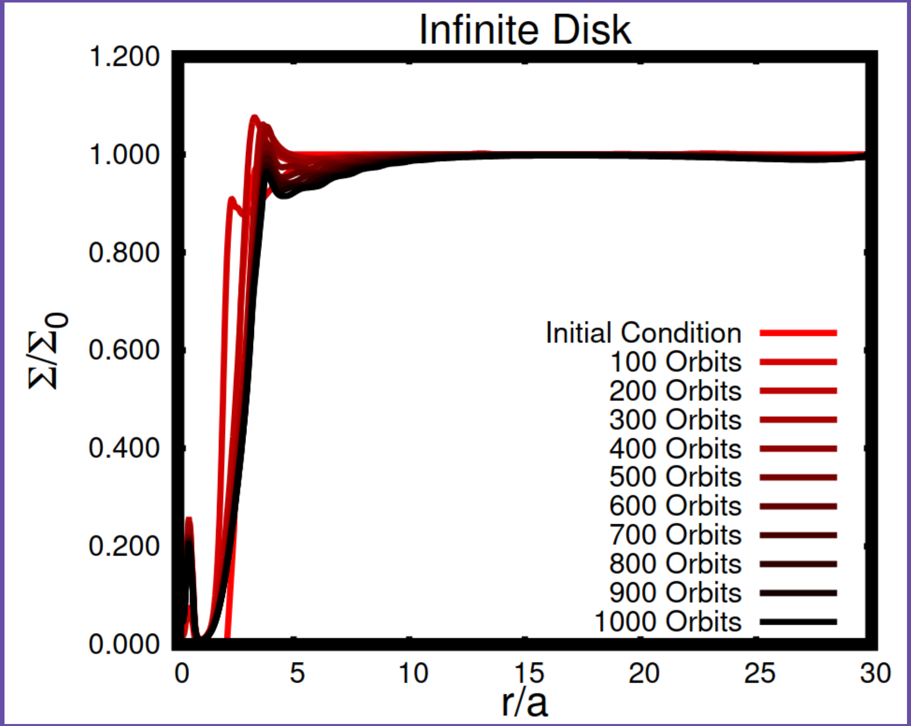
where

$$\mathcal{F}^{-1} = \hat{\mathbf{z}} \cdot (\nabla \times \mathbf{v})/\Sigma$$

It is still a topic of debate whether this is the cause of the transition in CB disks towards an eccentric cavity. We will investigate if we find evidence of this instability disappearing with the presence of the DM halo.

Boundary Conditions

- The outer boundary conditions will give a constant inflow of material to mimic an infinite disk.
- An "infinite disk" model allows the density profile to achieve a more stable state in comparison to the finite disk.
- An infinite disk model is also intended to emulate the very gas rich environments one would expect after a galaxy merger.



Duffel et al. 2024

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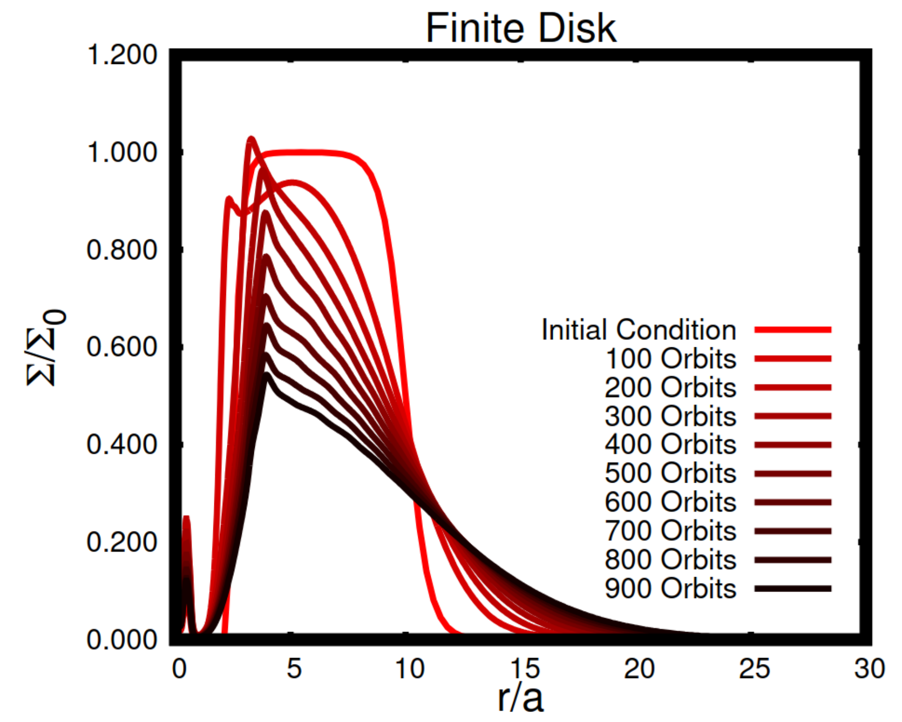


Duffel et al. 2024

Viscosity prescription

We take the same viscosity tensor Tiede et al. 2020 utilized:

$$T_{\text{vis}}^{ij} = \nu\Sigma\left(\frac{\partial v^i}{\partial x^j} + \frac{\partial v^j}{\partial x^i} - \frac{\partial v^k}{\partial x^k}\delta^{ij}\right)$$

And the viscous force would be

$$F_j^{vis} = (\nabla \cdot T_{vis})_j = \partial_k T_{\text{vis}}^{kj}$$

Density Source term

The source terms for accretion follow closely the setup done by Dittmann et al. 2022. The density source term is

$$S_{\Sigma} = -\gamma \Omega_b \Sigma \sum_i s_i(|\mathbf{x} - \mathbf{x}_i|),$$

Where γ is the sink rate and Ω_b is the binary angular frequency. The sink rate is chosen so that the viscous time scale and the sink time scale have a specific ratio (In Dittman et al. 2022, the ratio is 5/3).

The sink is defined by the profiles

$$s_i = \exp\left(-\frac{|\boldsymbol{x} - \boldsymbol{x}_i|^4}{r_s^4}\right)$$

Momentum Source term

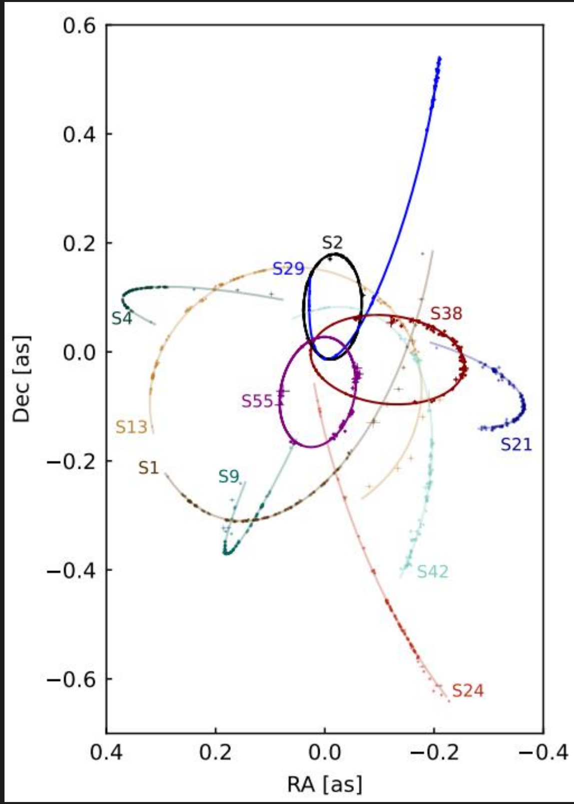
There is an additional source term to remove momentum defined as

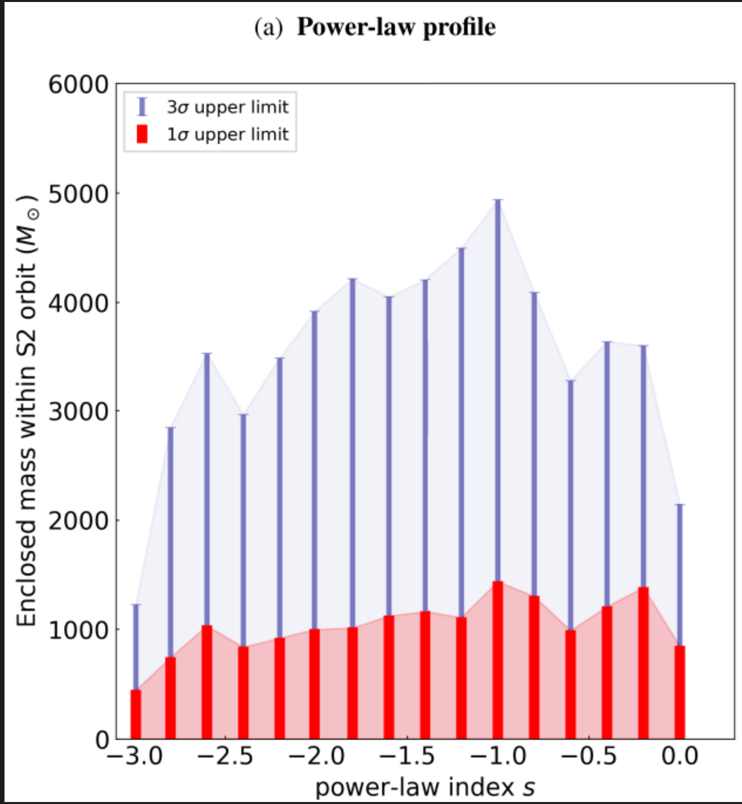
$$\mathbf{S}_p = -\gamma \Omega_b \Sigma \sum_i s_i(|\mathbf{x} - \mathbf{x}_i|)\mathbf{v}_i^*$$

$$\mathbf{v}_i^* = (\mathbf{v} - \mathbf{v}_i) \cdot \left(\hat{\mathbf{r}}_i \hat{\mathbf{r}}_i + \delta \hat{\boldsymbol{\phi}}_i \hat{\boldsymbol{\phi}}_i\right) + \mathbf{v}_i$$

Where the SBBDCC chooses $\delta=0$ to avoid the sink term to exert a torque on the disk (this is known as a “torque-free” sink).

Observational constraints on SgrA*





GRAVITY Collaboration 2024

Spectroscopic measurements of offset broad emission lines

The broad emission lines of particular interest are Hα, Hβ and Mg II, because they are prominent in AGN spectra and are commonly used as tracers of dense, low-ionization gas in BLRs at low (Hα at z<0.4) and high redshift (Mg II at z>2.5).

Bogdanović et al. 2022

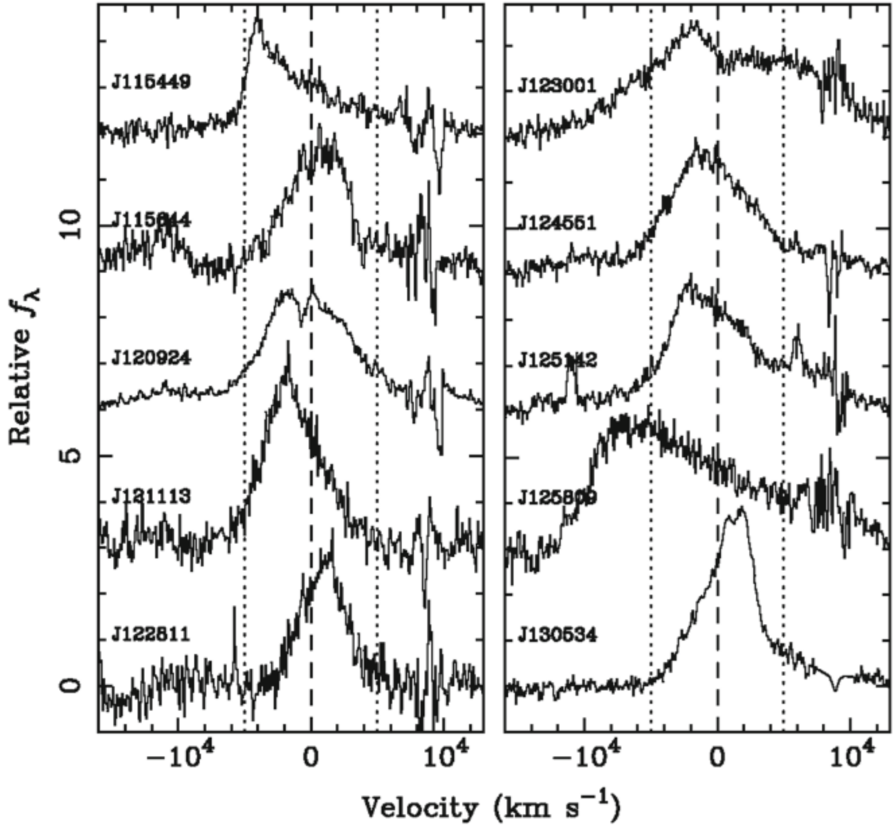


Fig. 8 Hβ emission-line profiles of MBHB candidates selected in a spectroscopic survey by Eracleous et al. (2012). Only the broad emission-line profiles are shown; the narrow line components were removed for clarity. Peaks of the asymmetric profiles are offset from the rest frame of the host galaxy (marked by the dashed vertical line) by $\sim$few $\times 10^3$ km s^{-1}. If measured velocity offsets are associated with the orbital motion of the secondary MBH, they imply orbital periods in the range of $\sim$few $\times$ 10 – few $\times$ 100 yr for MBH mass ratios larger than 0.1. The dotted lines mark velocity offsets of $\pm$5000 km s^{-1}

Pros and Cons: Spectral Signatures

Pros:

- Spectroscopic databases like SDSS have provided large samples of quasars allowing for systematic searches, which have revealed many promising candidates.
- The time-domain component of SDSS-V, Black Hole Mapper, is well suited to uncover more candidates.
- The most widely separated binaries detected with this method can be resolved with VLBI if both components are radio loud (See §'s 3.2.1 and §3.6).
- Long term monitoring can provide stringent constraints on the binary parameters and potentially exclude the binary hypothesis.

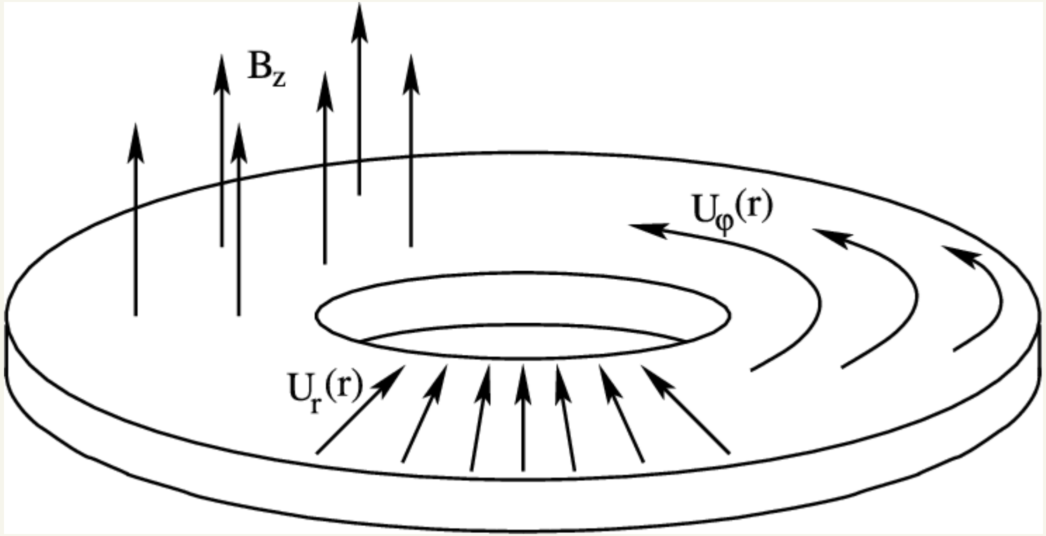
Cons:

- The signatures are not unique to SMBHBs.
- The more unique, Fe K-α signatures are much harder to observe for any but the brightest AGN.
- For the traditional (optical) broad line signatures in the beginning of §3.3.1, binary periods are long (decades to centuries) and thus observing a full orbit is hard and confirmation of binarity challenging.
- This signature likely probes a small part of SMBHB orbital parameter space (Figure 1).

D'Orazio & Charisi 2023

Accretion disk simple prescription

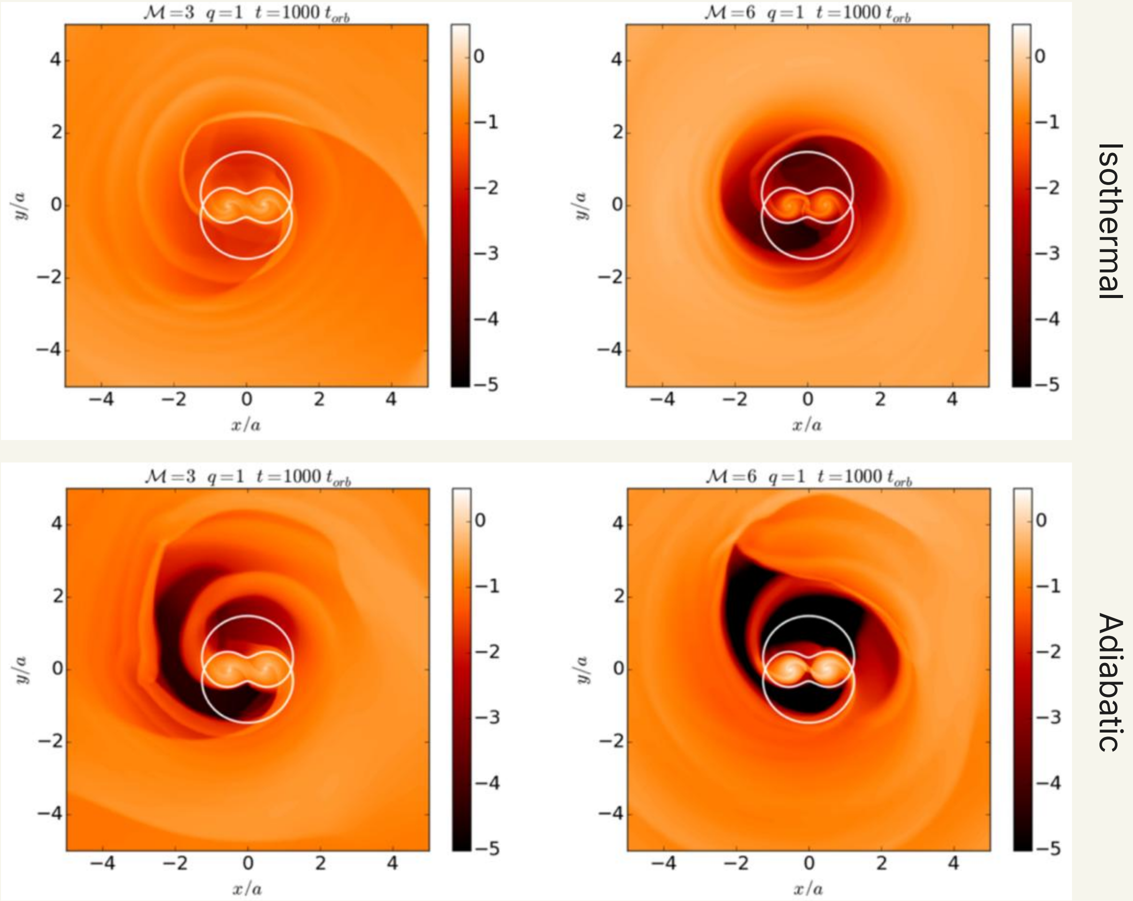
- A thin accretion disk can broadly be thought of as material orbiting the center in circles, with an additional radial speed inward, that balances out an accretion process.
- Its usual to think of the inward speed as a kinematic viscosity.
- In order for an accretion disk to reach steady state, the density profile, the kinematic viscosity and the accretion process should be in equilibrium.



Evy Kersalé et al. 2024

How important is the equation of state?

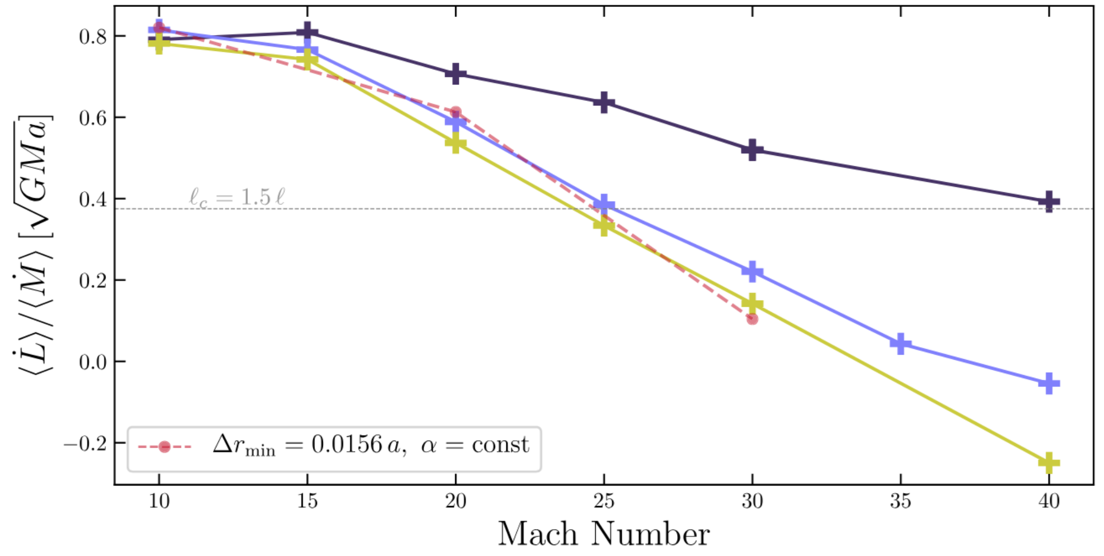
Depending on the equation of state, there are instances where the morphology changes. The cavity can even disappear for some mass ratios.



D'Orazio et al. 2016

How important is the equation of state?

- An important question of SMBHB mergers is whether the CD would help the SMBHBs merge faster.
- Even whether the CD leads to an inspiral or outspiral depends on parameters in the equation of state.
- It is very important to investigate these questions with a more careful treatment of the thermodynamics and radiation.

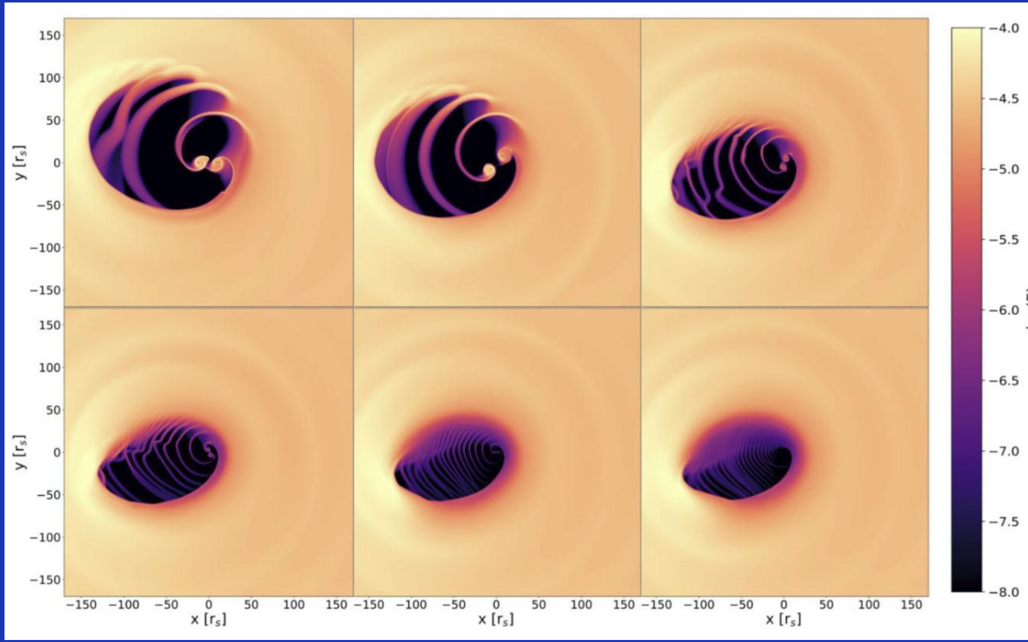


Tiede et al. 2020

Possible Future Work:

Study of X-ray emission disappearance near merger under pseudo newtonian potential

- We consider the ISCO to be relevant because the X-ray emission disappearance was associated with the disappearance of the minidisks.
- However, under a newtonian potential the minidisks were allowed to form even at very small separations.
- It would be possible that with an ISCO the X-ray disappearance would happen much earlier than calculated in Krauth et al. 2023.



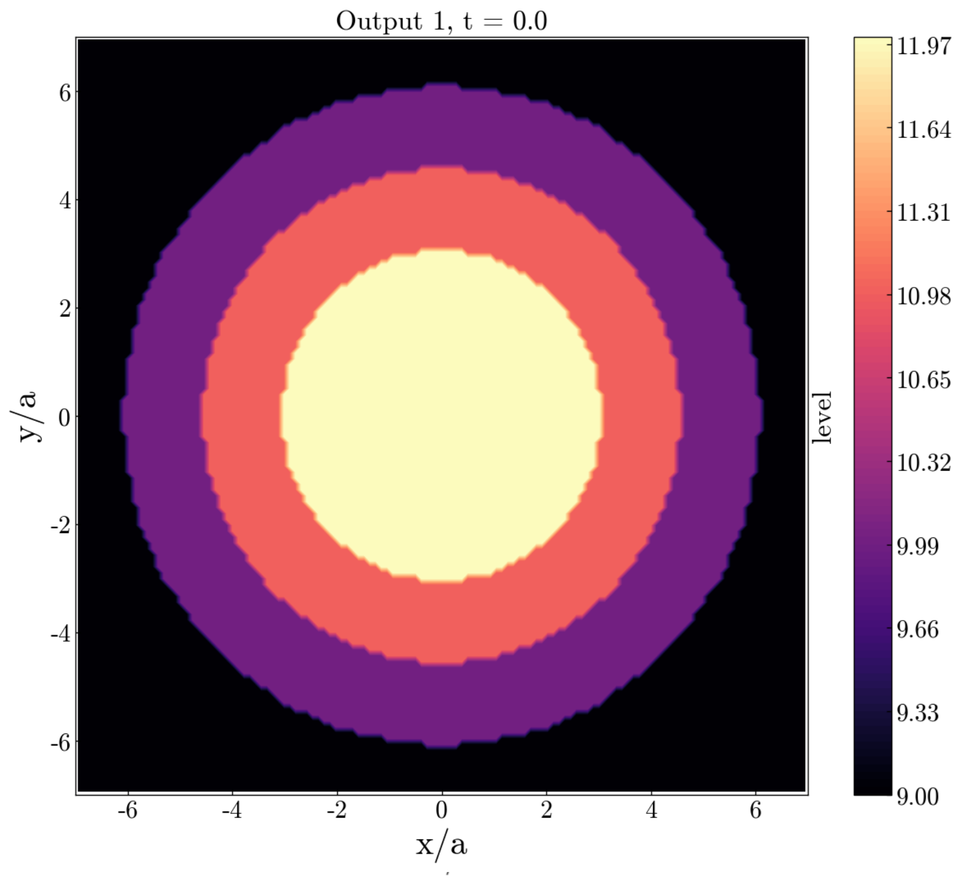
Krauth et al. 2023

Grid setup

- Due to the nature of the simulation, where we know the areas we need greater resolution, the adaptive mesh refinement is omitted.

- The grid is designed to have a greater resolution inside the cavity and lower resolution outside of it.

- Far from the binary, the level of refinement is at its lowest.

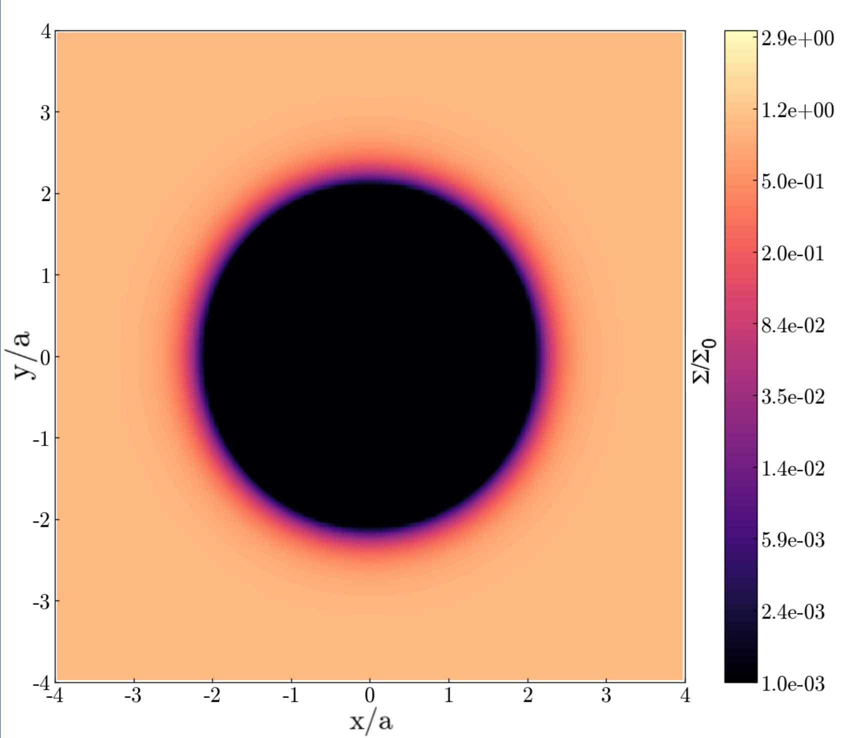


Initial Conditions

- In our first work, the initial conditions will follow the SB BDCC as close as possible.
- The equation of state will be locally isothermal.
- The initial density of the disk begins with a central cavity already formed in the center to allow consistency between codes. δ_0 allows to have a minimum density in the cavity.
- $\Sigma_0 = 1$, $\delta_0 = 1e-5$ and $R_{cav} = 2.5$ separations.

Initial Density:

$$\Sigma(r) = \Sigma_0 \left[(1-\delta_0) e^{-(R_{\rm cav}/r)^{12}} + \delta_0 \right]$$



Initial Conditions

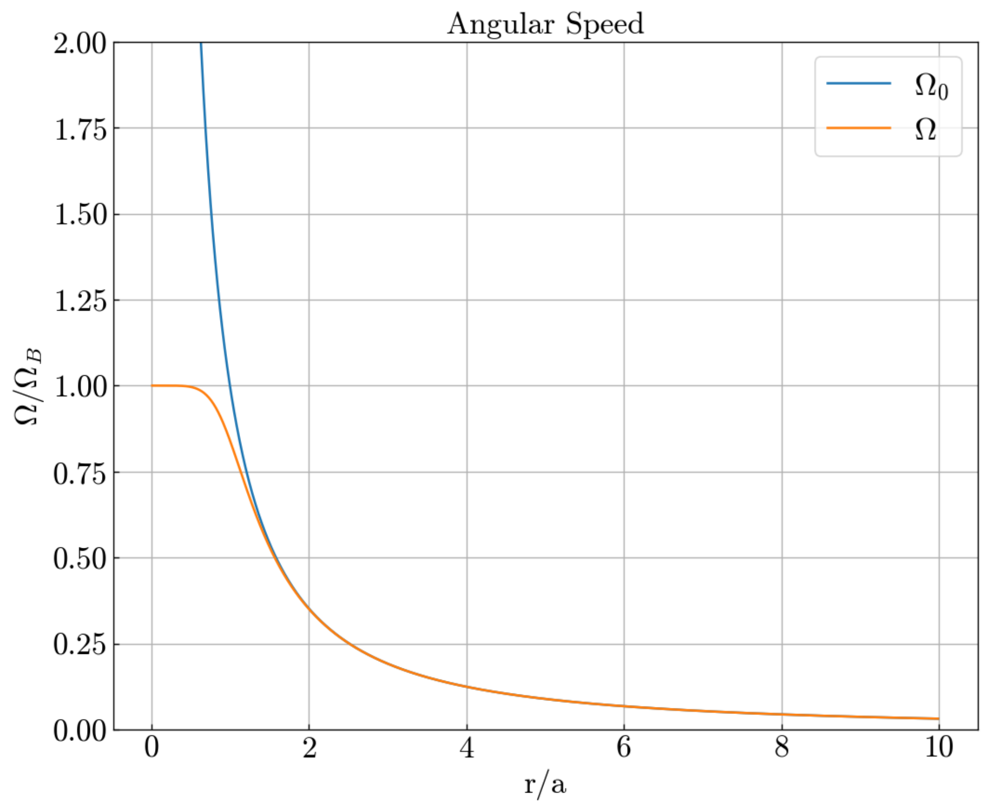
- The initial angular speed is at equilibrium far from the binary but flattened near the binary:

$$\Omega_0^2(r) = \frac{GM}{r^3}\left(1 - h^2\right)$$

$$\Omega(r) = \left[\Omega_0(r)^{-4} + \Omega_B^{-4}\right]^{-1/4}$$

h=0.1 is the disk aspect ratio, and Ω_B is the angular speed of the binary.

Initial angular speed:



Simulation parameters

Min. level of refinement	10
Max. level of refinement	13
Box size	26.0
Refinement radii	22., 18., 12.
Outer boundary radius	30.
Density floor	1e-9

Simulation parameters

$G(M_1+M_2)$	1.0
M_1/M_2	1.0
(x_0, y_0, z_0)	(31., 31., 31.)
a	1.0
ν viscosity constant	1e-3
h/r	0.1

Hydrodynamical solver

The equations of motion are:

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

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) + \nabla p = -\rho \nabla \phi$$

$$\frac{\partial}{\partial t}(\rho e) + \nabla \cdot [\rho \mathbf{u}\,(e + p/\rho)] = -\rho \mathbf{u} \cdot \nabla \phi$$

If we let $U_i^n = (\rho, \rho u, \rho e)$ at time t^n in the i^{th} cell, then the discretization is

$$\frac{U_i^{n+1} - U_i^n}{\Delta t} + \frac{F_{i+1/2}^{n+1/2} - F_{i-1/2}^{n+1/2}}{\Delta x} = S_i^{n+1/2}$$

Hydrodynamical solver

The fluxes are computed with a second order Godunov method. The source term is computed as

$$S_i^{n+1/2} = \left(0, \frac{\rho_i^n \nabla \phi_i^n + \rho_i^{n+1} \nabla \phi_i^{n+1}}{2}, \frac{(\rho u)_i^n \nabla \phi_i^n + (\rho u)_i^{n+1} \nabla \phi_i^{n+1}}{2}\right)$$

This is the setup in its original form in RAMSES. We added 2 additional prescriptions:

- A source term of accretion
- A viscosity prescription