University of Zurich[UZH]

# What solves the 'final parsec' problem for LISA Massive Black Hole Binaries?

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Final year PhD student


Garg+2022

Garg+2024a

Garg+2024b

Garg+2024c

Garg+2024d

Garg+2024e

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LISA AstroWG, Garching

5th November, 2024

# Formation of MBHBs



- Galaxies co-evolve with their central MBHs
- MBHs mainly manifest themselves as Active Galactic Nuclei (AGN)
- From AGN's bolometric luminosity, we can approximately infer **MBH's mass** and accretion rate in terms of the **Eddington ratio** $f_{Edd}$

Kormendy&Ho 2013, Padovani+2017, Lusso+2012

~100 kpc

Photo: NASA/ACS Science team

Galaxy merger

Begelman+1980

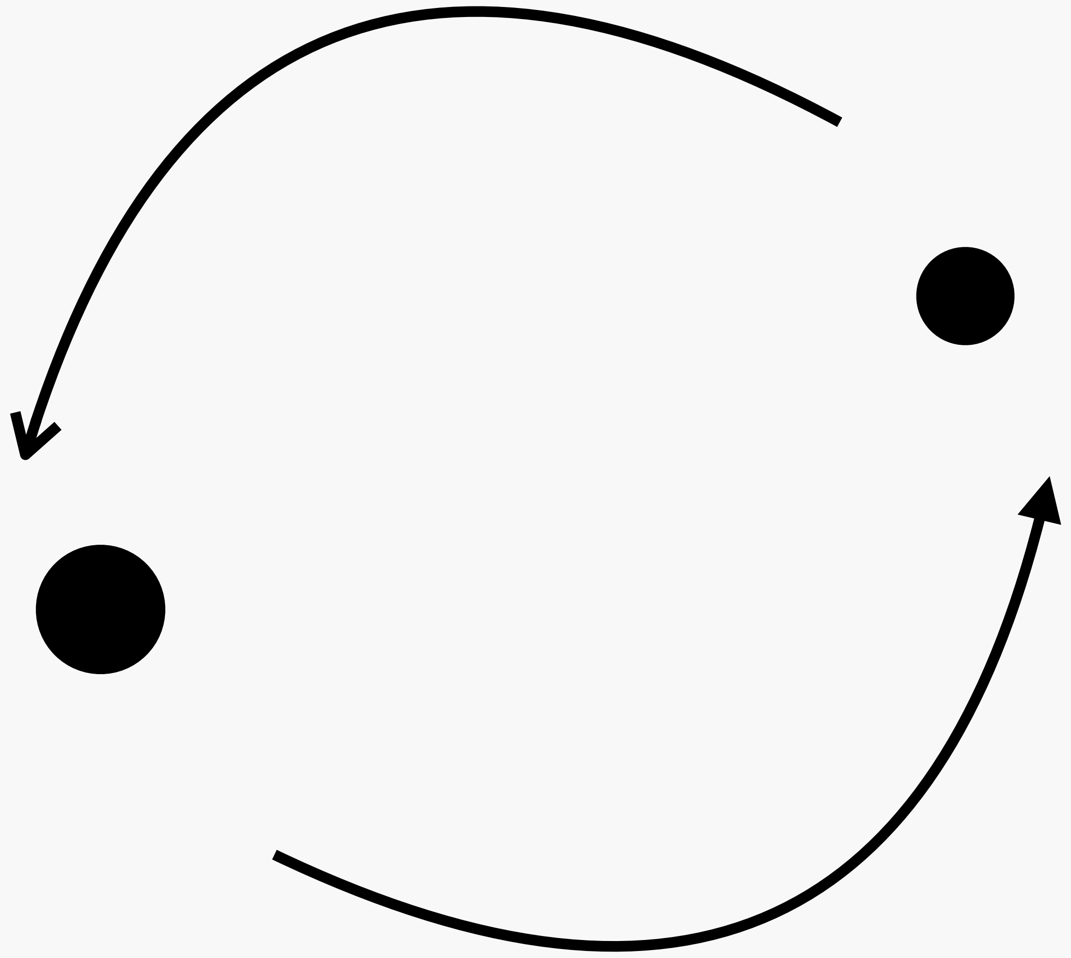
Few Gyrs

Dynamical Friction

Dark matter/stars/gas

Chandrasekhar 1943, Ostriker 1999, Mayer 2013, Amaro-Seoane+2022

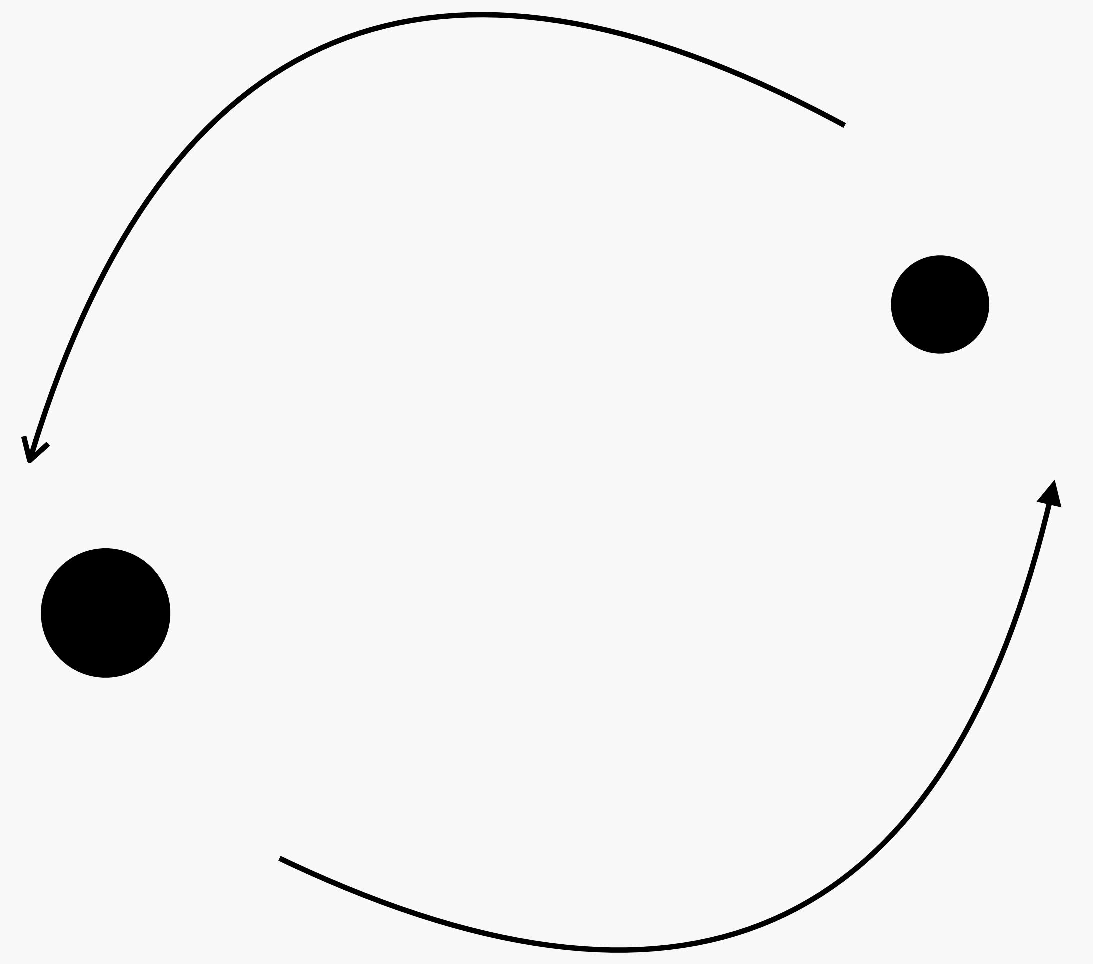
~pc



MBHB

# Evolution of MBHBs in the final parsec

~pc



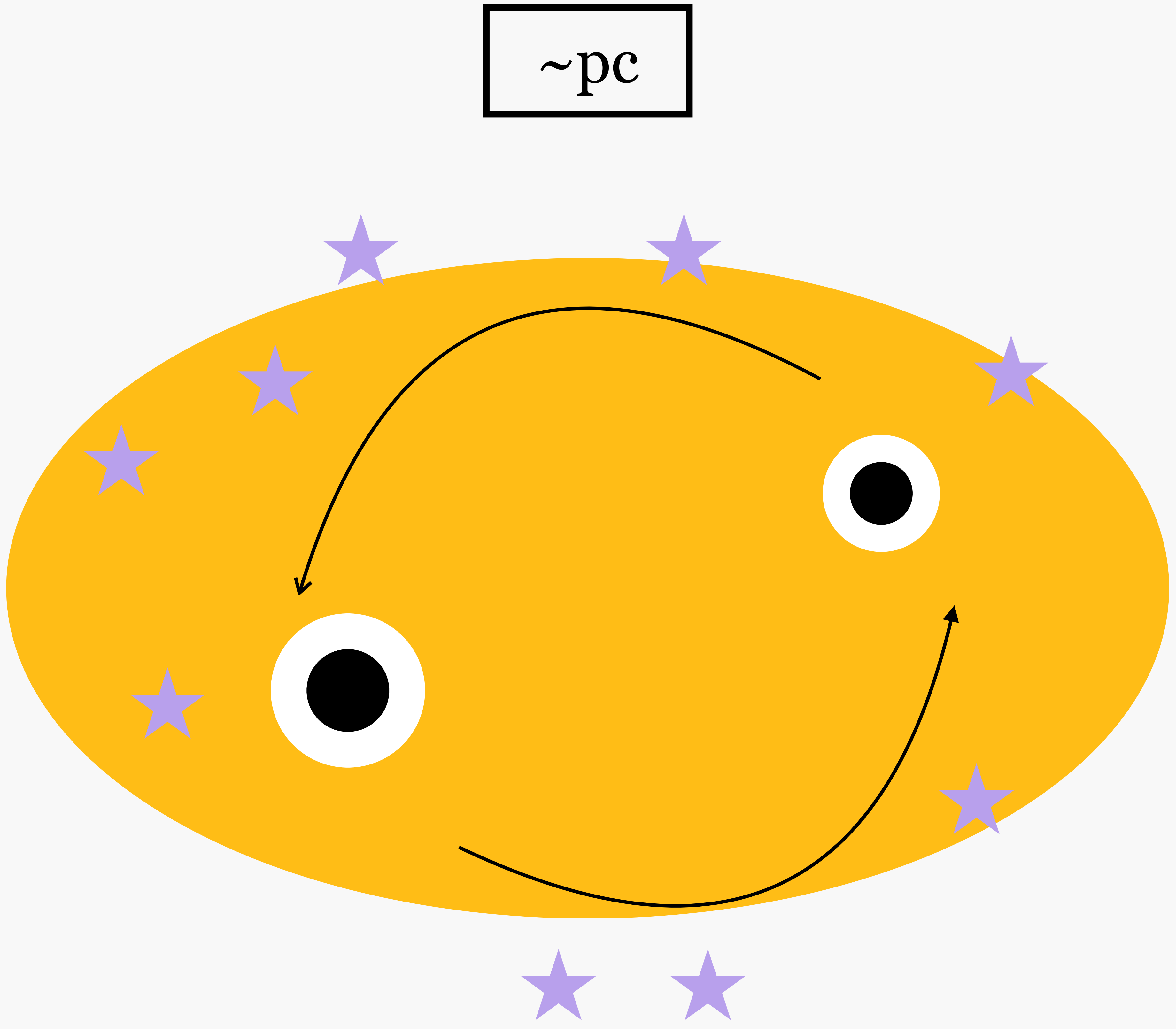
Dynamical Friction inefficient

Two-body relaxation time > Hubble time

**How do we go beyond this stage?**

# Different formation channels of MBHBs






Dynamical Friction inefficient

Two-body relaxation time > Hubble time

**How do we go beyond this stage?**

De Rosa+2019, Amaro-Seoane+2023

**An environment**

Gas torque | ~ 10 – 100 Myr

Escala+2005, Haiman+2009, Mayer 2013

Or

Tri-axial stellar potential | ~ 0.1 – 1 Gyr

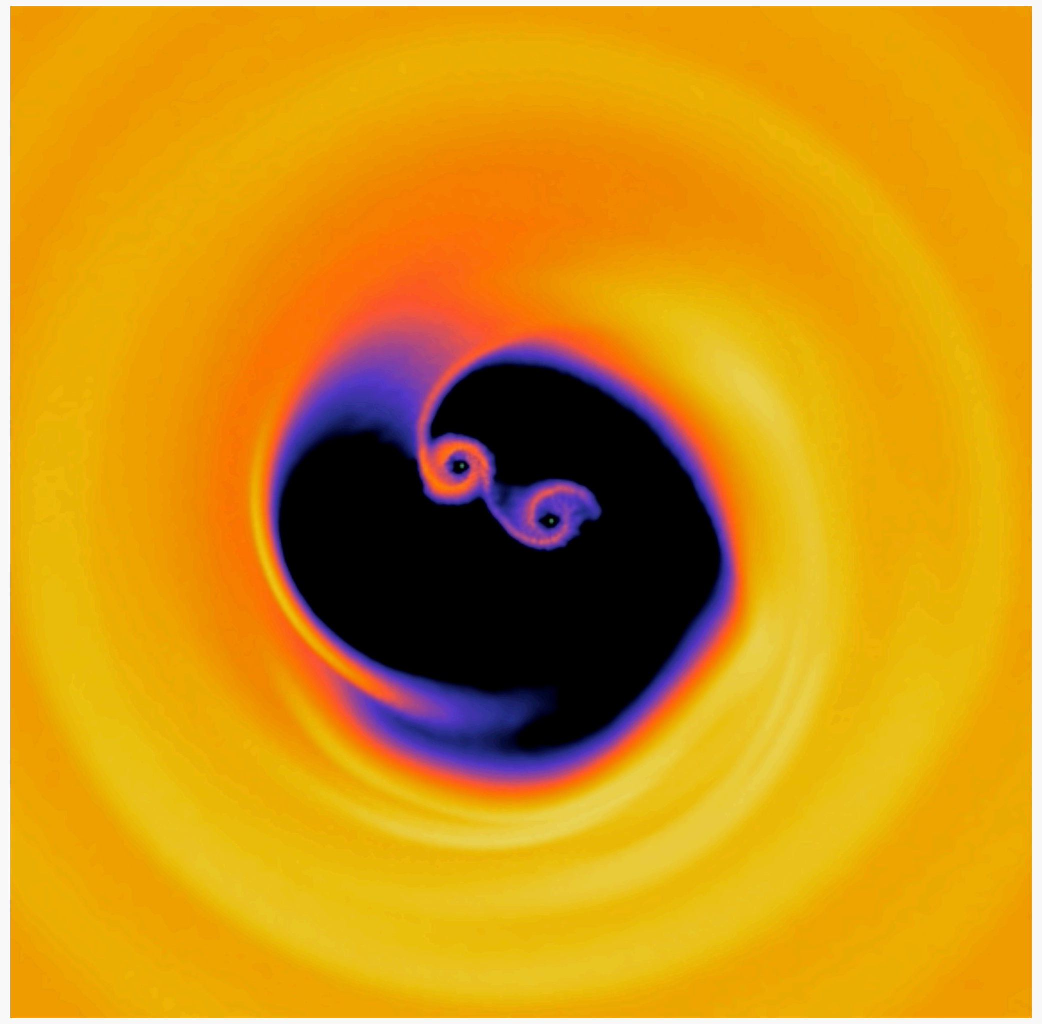
Preto+2011, Khan+2011, Vasiliev+2015

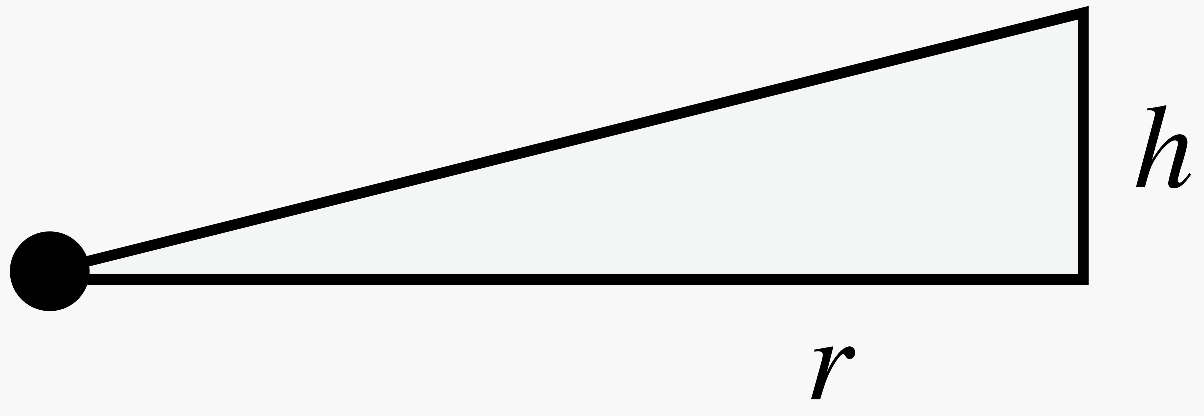
# MBHB interaction with gas

- A radiatively efficient gas can settle into a co-planar geometrically thin accretion disc Shakura&Sunyaev 1973
- Most observed AGN properties could be explained by fitting the thin disc model Padovani+2017

$q \lesssim 25 \implies$ **Cavity** D'Orazio+2016

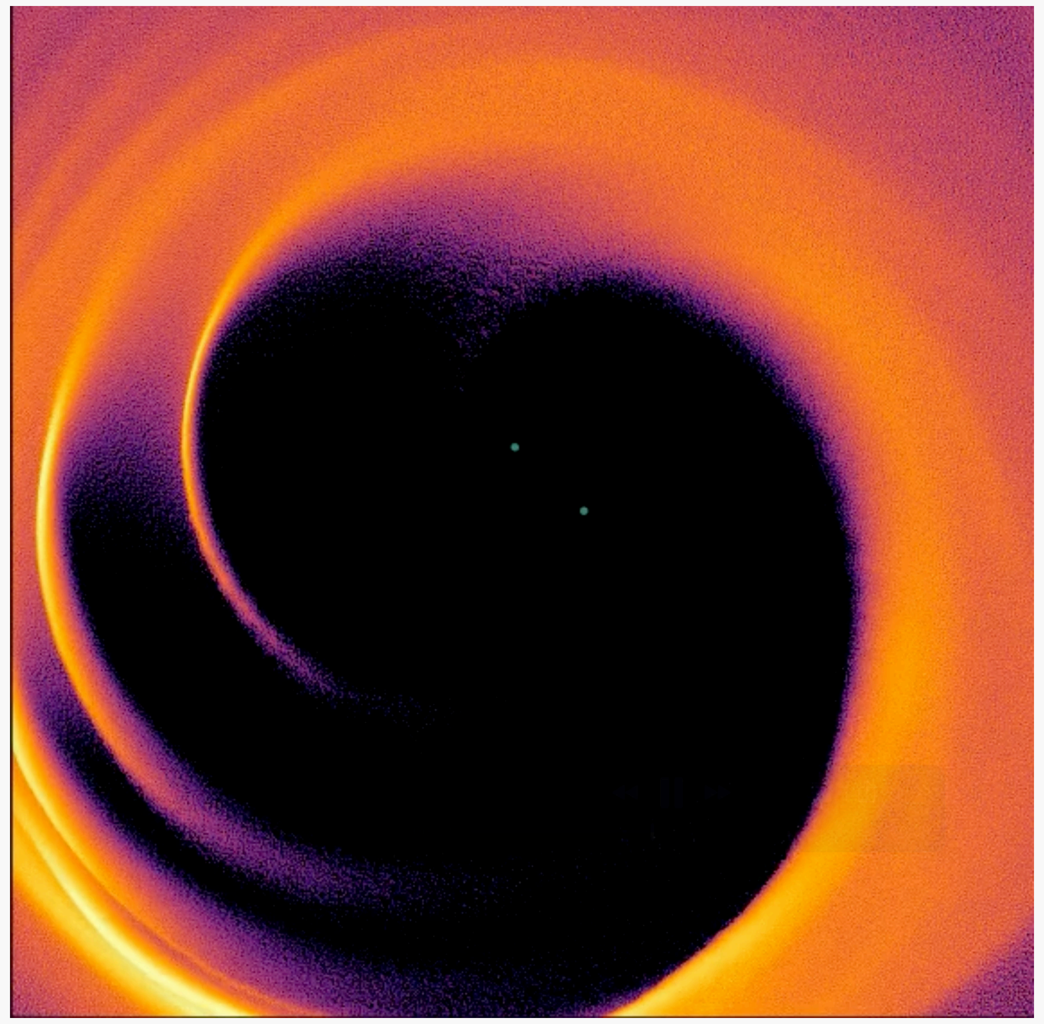
$h/r \gtrsim 0.05$ Franchini+2024a






Both simulations done with concurrent GWs and at $\sim 50\ r_s$

$h/r \lesssim 0.05$ **Garg+2024e**



# LISA will observe GWs from $\sim 10^4$-$10^7$ $M_\odot$ MBHBs



$\sim 10^{-3}$ pc $\Longrightarrow \sim 10^{-5}$ pc

**LISA**

Colpi+2024

- LISA will observe MBHBs up to redshift $z \sim 20$
- LISA will localized the source in the sky to $\sim$ 0.01-10 deg$^2$
- MBHBs can spend up to a few years of inspiral in the LISA band just before merger

LISA-observable MBHBs at $z = 1$

with uniformly distributed

eccentricities and spins

**Prograde or Retrograde CBDs**

→

$\sim$pc $\Longrightarrow \sim 10^{-5}$ pc

| One year before merger | Prograde | Retrograde |
|---|---|---|
| **Effective Spin** | $\sim 1$ | $\sim -0.5$ |
| **Orbital Eccentricty** | $\sim 10^{-2.75}$ | $\sim 10^{-1.25}$ |

**Garg+2024c, MNRAS, 534, 5705**

# Modeling gas torque onto a binary in the GW waveform

Garg+2022, MNRAS, 517, 1339

Simulation-calibrated $\xi = \frac{\text{Gas torque}}{\text{Viscous torque}}$

Farris+2014, Duffell+2014,2020,2024, D'Orazio&Duffell2021, Dittmann & Ryan 2022, Siwek+2023, Tiede&D'Orazio 2024

Semi-major axis $a$

$\dot{M}a^2\Omega$ Lin&Papaloizou 1986

Mostly 2D with fixed Newtonian orbit

Sub-parsec/scale-free so no GWs

Simulations → $\xi$

Observations → $f_{\rm Edd}$

$$\frac{\dot{a}_{\rm gas}}{a} = \xi \frac{2(1+q)^2}{q} \frac{f_{\rm Edd}}{50\rm Myr} \frac{0.1}{\epsilon}$$

- $\xi > 0$ : slow down
- $\xi < 0$ : speed up

$\dot{a} = \dot{a}_{\rm GW} + \dot{a}_{\rm gas}$

No cross-term* $|\dot{a}_{\rm gas}| \ll |\dot{a}_{\rm GW}|$

Encompass secular effects: migration and accretion

# Modeling gas torque onto a binary in the GW waveform

Garg+2022, MNRAS, 517, 1339

Simulation-calibrated $\xi = \frac{\text{Gas torque}}{\text{Viscous torque}}$

$\xi \sim -36$

Semi-major axis $a$

$\dot{M}a^2\Omega$ Lin&Papaloizou 1986

First time in the LISA band with GWs

3D live-orbit PN

Garg+2024e, arXiv:2410.17305

Simulations

Observations

Also, a novel GW-gas cross-term $\propto \dot{a}_{\rm GW}\dot{a}_{\rm gas}$

$$\frac{\dot{a}_{\rm gas}}{a} = \xi \frac{2(1+q)^2}{q} \frac{f_{\rm Edd}}{50\rm Myr} \frac{0.1}{\epsilon}$$

- $\xi > 0$ : slow down
- $\xi < 0$ : speed up

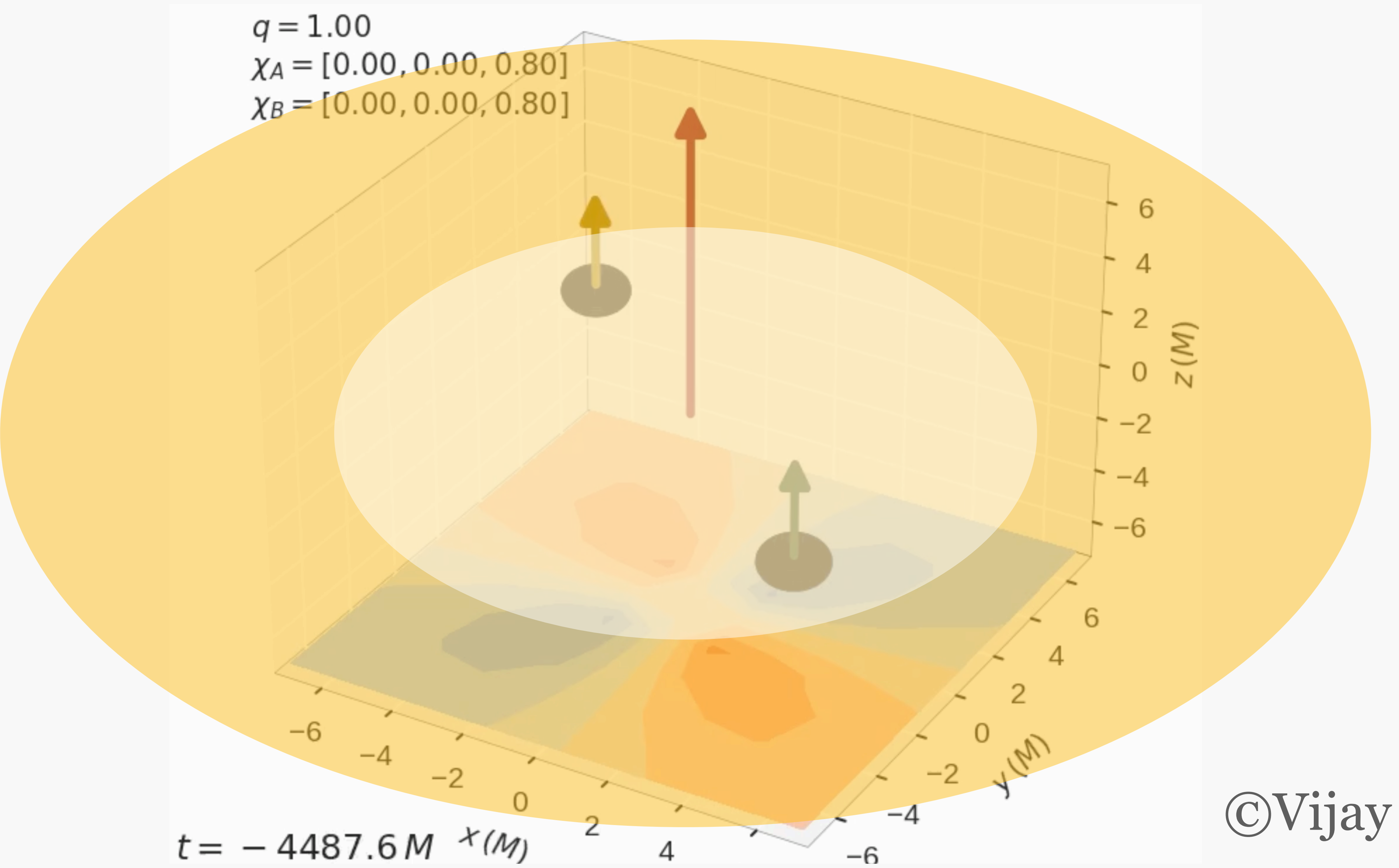
$\dot{a} = \dot{a}_{\rm GW} + \dot{a}_{\rm gas}$

No cross-term considered for now

Encompass secular effects: migration and accretion

# Dephasing in the LISA band

Garg+2022, MNRAS, 517, 1339

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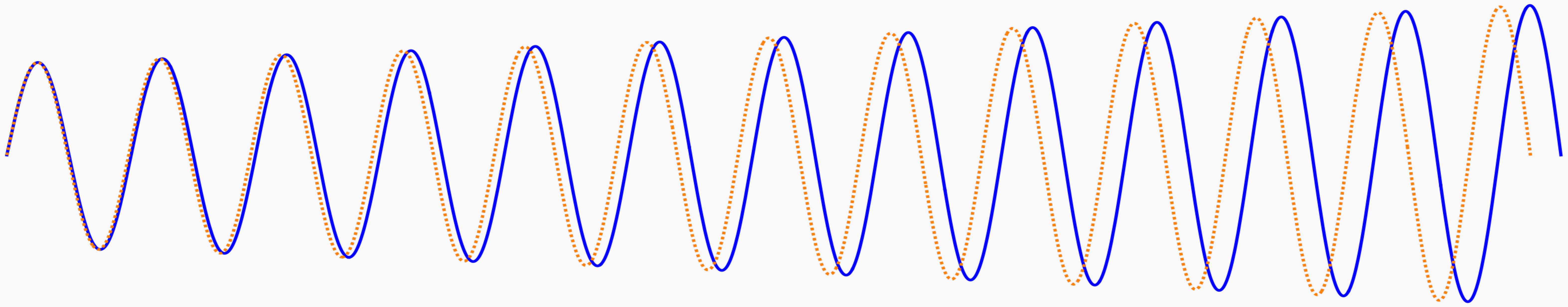
GWs in vacuum vs in gas



# Going beyond cumulative dephasing for GWs of MBHBs



Garg+2024a, MNRAS, 528, 4176; Garg+2024b, MNRAS, 532, 4060

$\Delta\psi_{\rm gas} \sim 10^{-15}\ \xi \times {\rm f}_{\rm Edd}\ \epsilon_{0.1}^{-1}\ f_{\rm GW}^{-13/3}$

$-4$PN relative order

3.5 relative PN order waveforms valid for aligned spins and $e \lesssim 0.1$

Buonanno+2009; Arun+2009; Mishra+2016; Moore+2016

Employ lisabeta to consider a complete LISA response

Marsat+2021

Use Bayesian inference

# Measuring eccentricity and gas imprints from GWs of MBHBs

Garg+2024a, MNRAS, 528, 4176; Garg+2024b, MNRAS, 532, 4060

For free $M_z = 10^5\ \mathrm{M_\odot}$, $q = 8$, $\chi_{1,2} = 0.9$, $t_c = 4$ years

$z = 1$, and all angles set to 0.5 radians

- In vacuum $e_0 \gtrsim 10^{-2.75}$ measurable
- In gas $e_0 \gtrsim 10^{-2}$ measurable

Look up the papers for a wider parameter exploration

Gas-excited eccentricities should be observable

- For $|\xi| \sim 100$
  - For circular system $f_{\mathrm{Edd}} \gtrsim 0.1$ measurable
  - For eccentric system $f_{\mathrm{Edd}} \gtrsim 1.0$ measurable

Constraints on gas disc only using GWs

# Conclusion

- The **minimum measurable eccentricity** for MBHBs is **Garg+2024a,b**
  - $e_0 \sim 10^{-2.75}$ in vacuum or $10^{-2}$ in gas

    Gas-excited eccentricities should be observable
- The minimum measurable Eddington ratio **only using GWs**: **Garg+2022,2024b**
  - $f_{Edd} \sim 0.1$ for a circular MBHB or $f_{Edd} \sim 1.0$ for an eccentric MBHB
- Population-based inference could hint towards a specific formation channel **Garg+2024c**
- **For the first time**, we have a measurement of gas torques on MBHBs in the LISA band
  - Also, a novel GW-gas coupling **Garg+2024e**
- Ignoring small gas effects ($f_{Edd} \sim 0.1$) or eccentricity ($e_0 \sim 10^{-2.5}$) can cause false violations of GR

  **Garg+2024d, arXiv:2410.02910**
- Improving astrophysical and waveform modelling is required for understanding MBHBs' evolution

# Back up slides

# Can ignoring gas perturbations or eccentricity violate GR?

Garg+2024d, arXiv:2410.02910

Only affect inspiral

$$\text{Model} \in \{\text{GR}, \text{GR} + \text{Env}, \text{GR} + \text{Ecc}\}$$

Introduce test of GR parameters at each PN order

$$\psi_{\text{Model+TGR}} = \psi_{\text{Model}} + \frac{3}{128\eta v^5} \sum_k \delta\psi_k \psi_k^{\text{GR}} v^k$$

Li+2012

$$k \in \{-2, 0, 1, 2, 3, 4, 5^{(l)}, 6, 6^{(l)}, 7\}$$

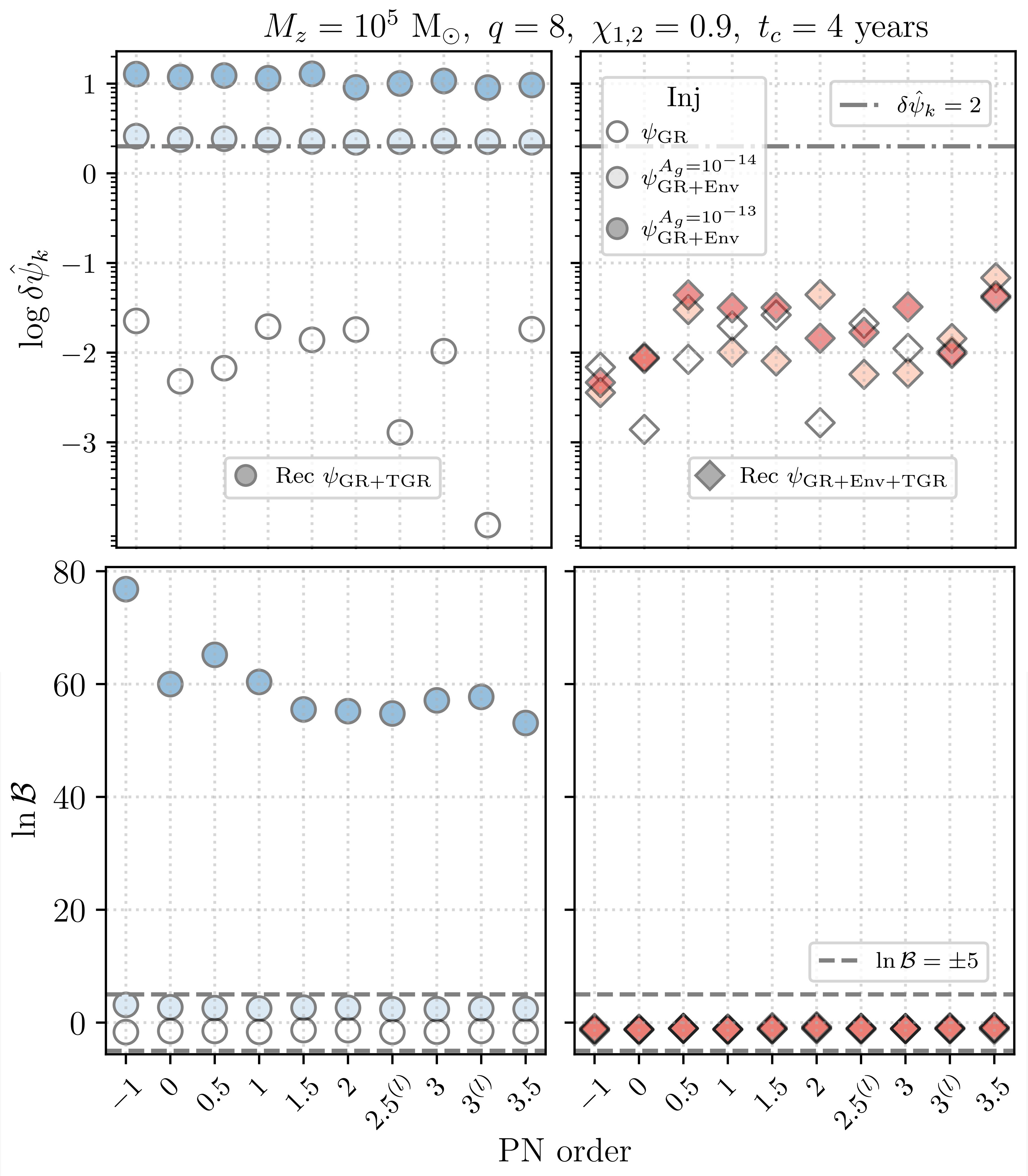
$$\delta\hat{\psi}_k = \frac{\Delta\delta\psi_k}{\sigma_{\delta\psi_k}} > 2$$

$$\ln \mathcal{B} = \frac{Z_{\text{Model+TGR}}}{Z_{\text{Model}}} > 5$$

# How ignoring gas perturbations or eccentricity violate GR?

Garg+2024d, arXiv:2410.02910

Gas-rich circular MBHBs




Vacuum Eccentric MBHBs