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Department of Astronomy, School of Physics

Synchronizing EMRIs and IMRIs in AGN accretion disks

Peng Peng

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Based on: *Peng & Chen 2023; Peng et al. 2024, in prep.*

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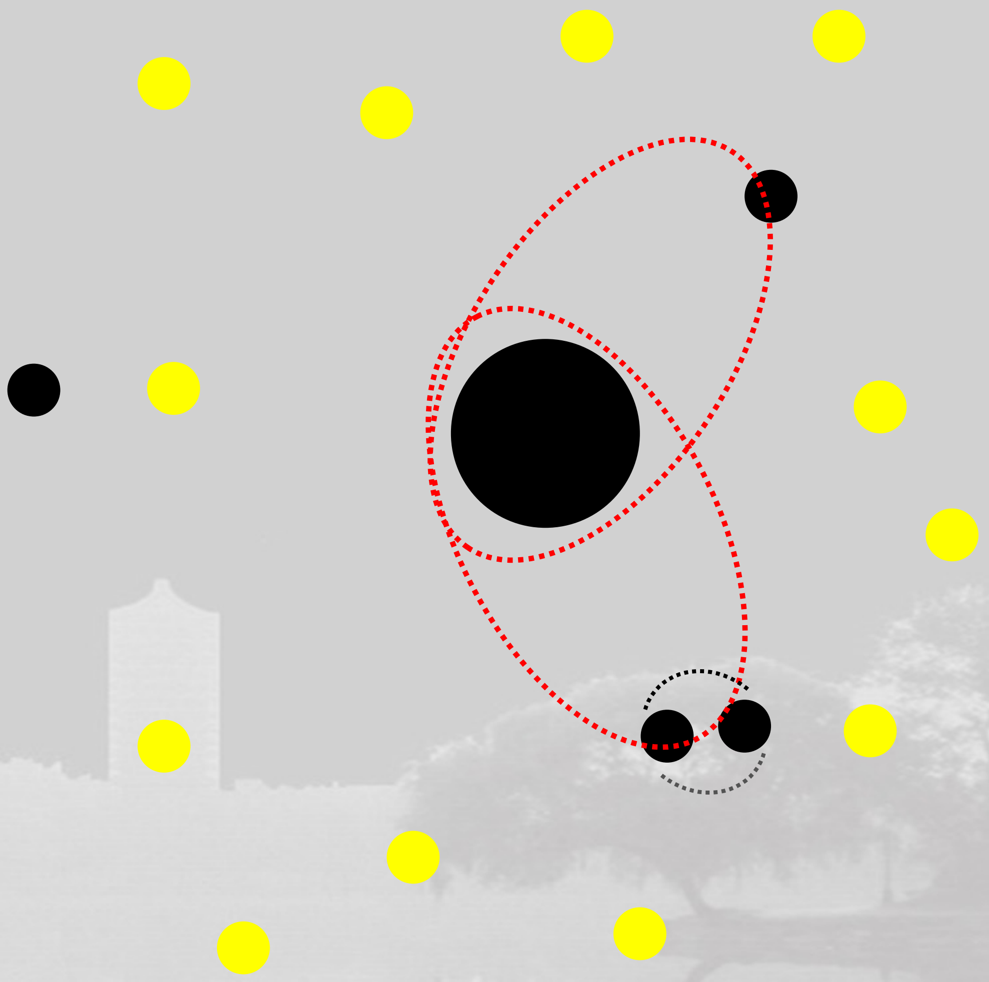
EMRIs in AGN disks could contribute overall event rate significantly



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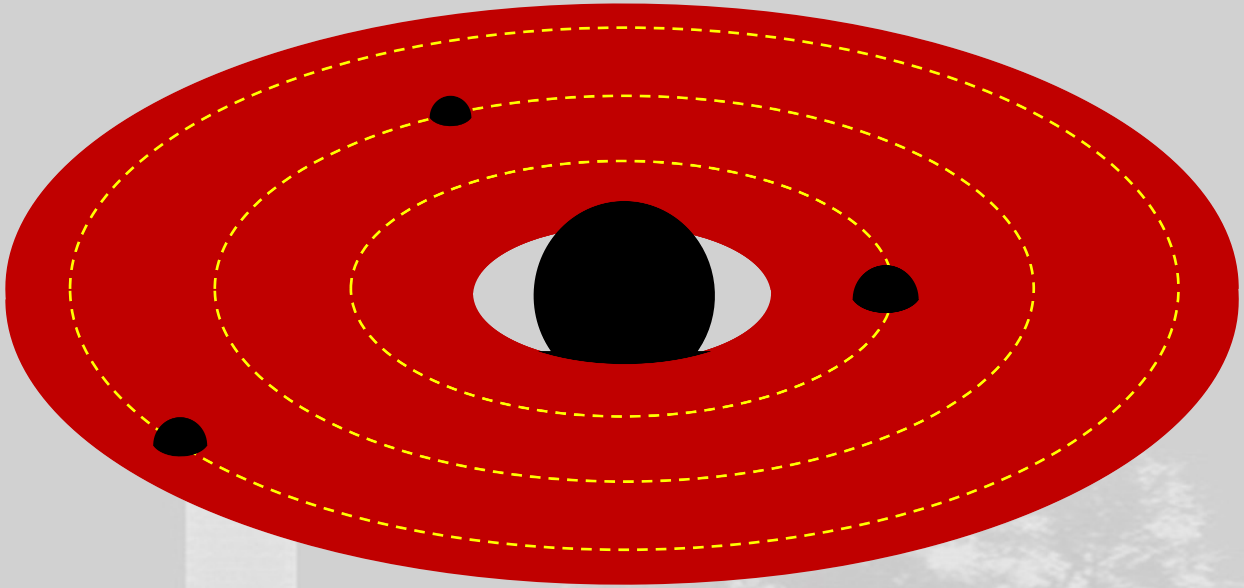

AGN disk is known to be a possible breeding ground of sBHs.
sBHs can either form from massive stars in the disk outskirt
or be captured from the nuclear star cluster
(Syer et al. 1991; Artymowicz et al. 1993; Subr & Karas 1999;
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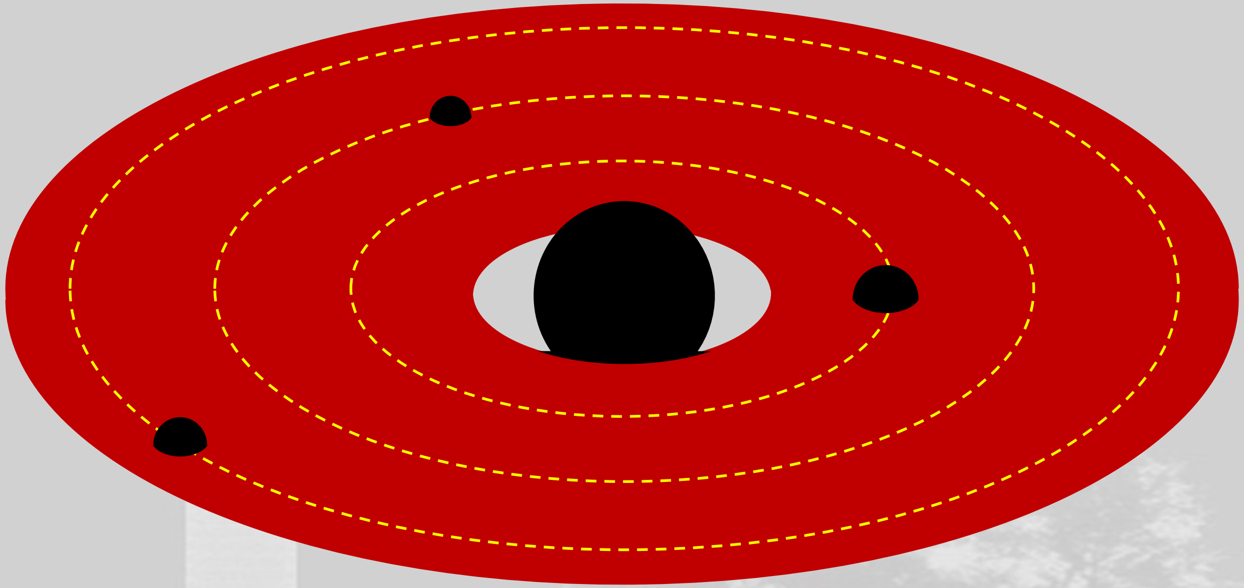

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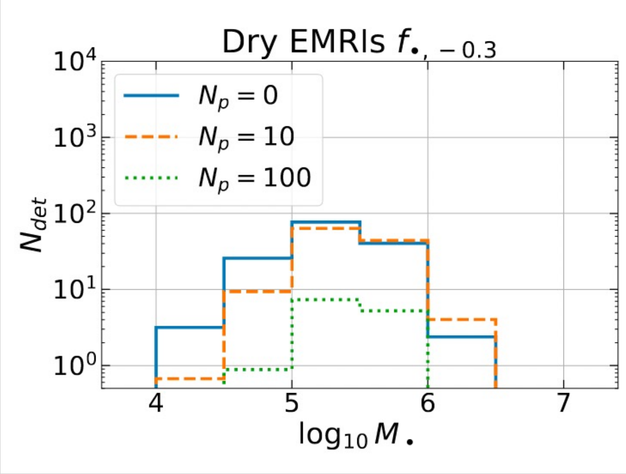
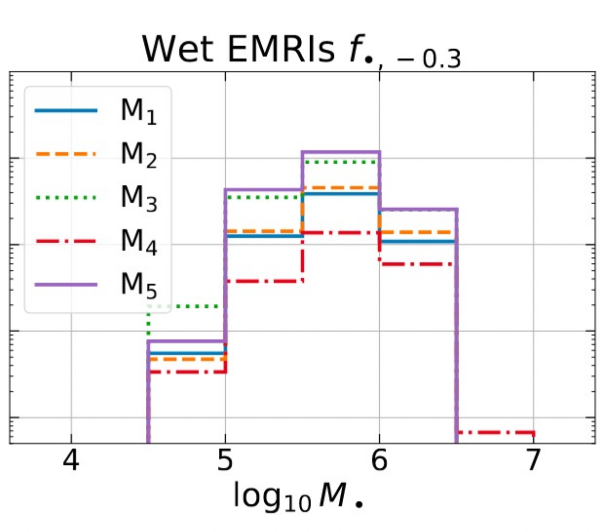
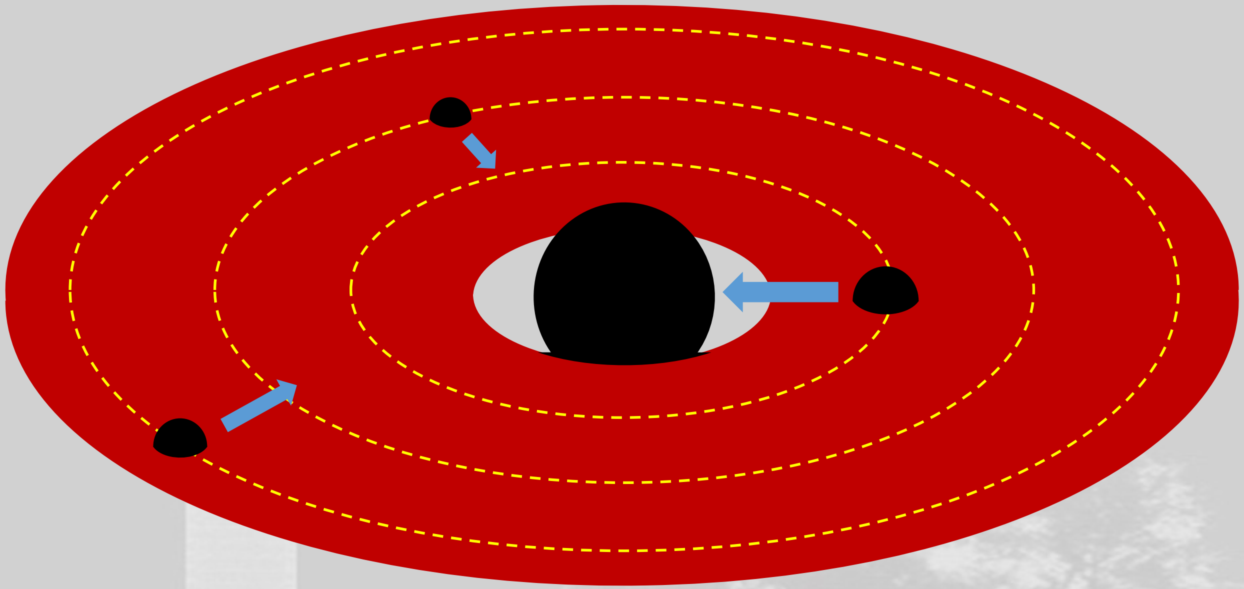




Pan et al. 2021b

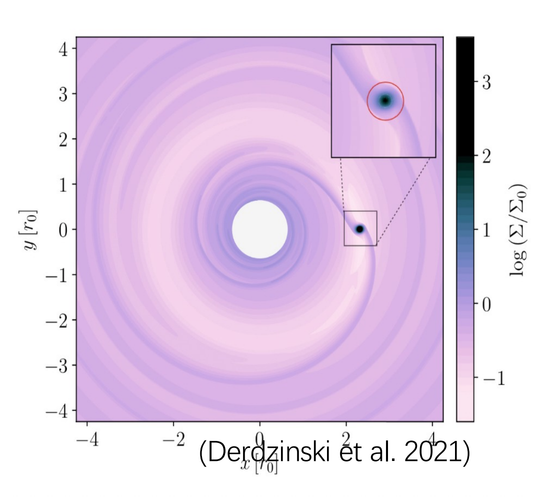
Recent calculations suggesting that these wet EMRIs can significantly contribute to the overall cosmic EMRI rates

Migration of small black holes in AGN disks



Type-I migration
(Goldreich & Tremaine 1979, Artymowicz 1993; Ward 1997)

$$T_I = \frac{f_1 h^2 M_{\rm SMBH}^2}{m_{\rm sBH} \Sigma a_s^2 \Omega_s}$$



(Derdzinski et al. 2021)

Small BHs migrate toward and form EMRIs the central SMBH, driven by e.g. Type-I migration torque, head wind… (e.g. Levin et al. 2007, Yune et al. 2011, Pan et al. 2021a, Derdzinski et al. 2023 …)

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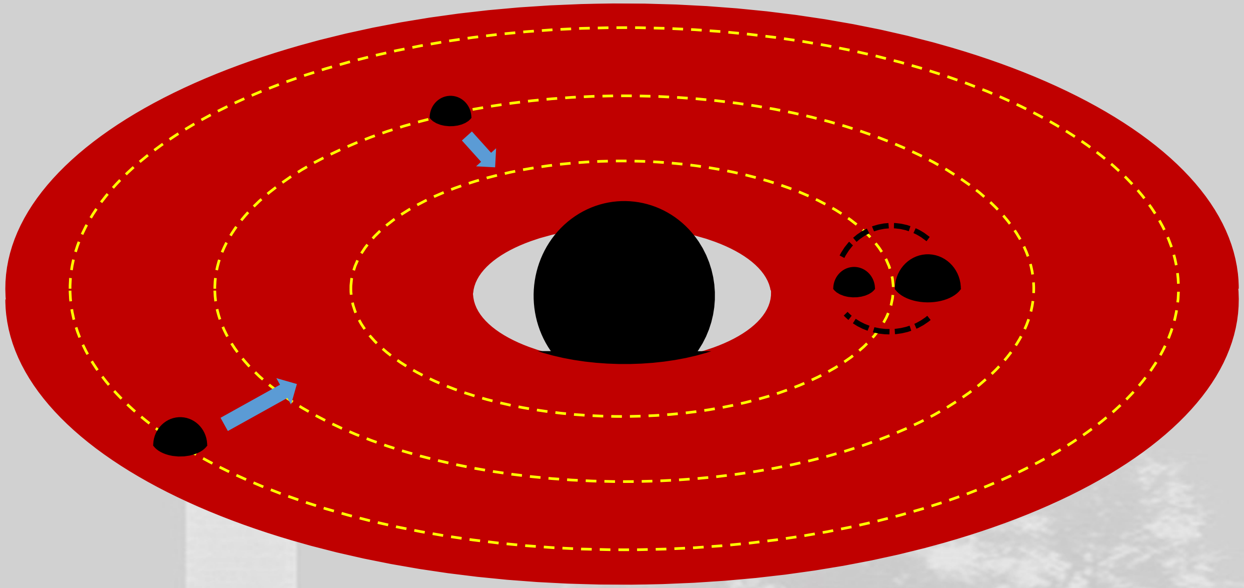

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The disk could be crowded with small BHs

The BH with different mass migrate with different velocity in the AGN disk.

During the migration inward, the small BHs could encounter and interact with each other, affect the following GW source formation. (e.g. Tagawa et al. 2020, Yang et al. 2019)

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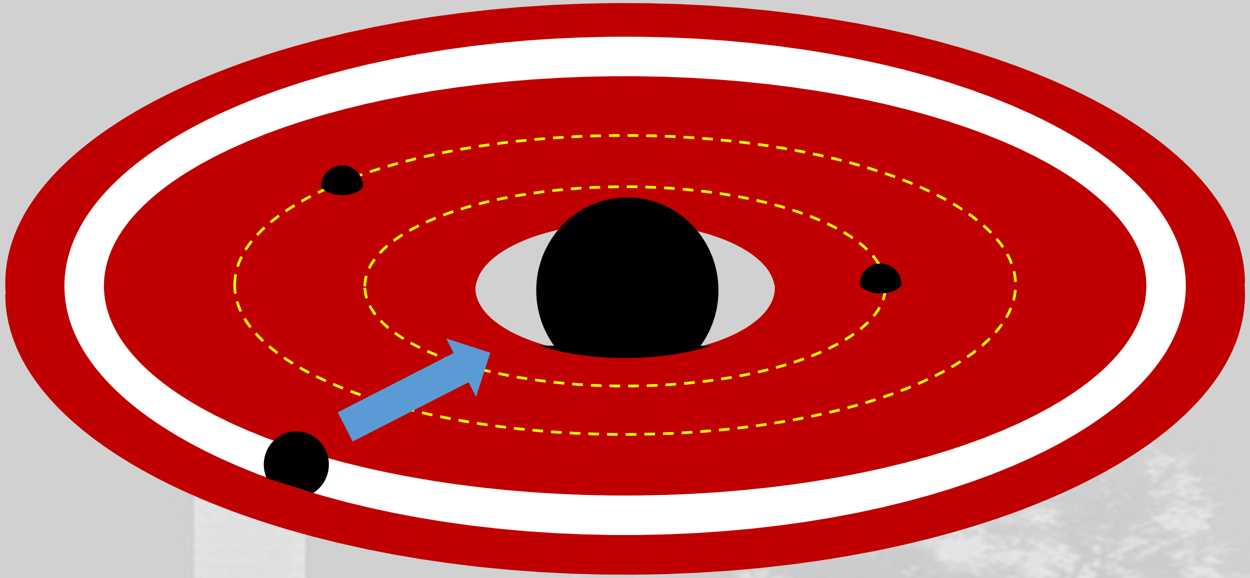
Gap-opening IMBH can form in the AGN disk, migrate inward and encounter with the stellar-mass BH

Intermediate-mass BH can naturally form in the AGN disk
(e.g. Mckernan et al. 2012, 2014; Secunda et al. 2019, 2020 ···)



BH mass increase in AGN disk: $10\ M_{\odot} \longrightarrow 10^2{\sim}10^3\ M_{\odot}$

due to hierarchical merger (e.g. Yang et al. 2019, Gerosa&Fishbach 2020)

and accretion (e.g. Mckernan 2011, Chen & Lin 2023)

IMBH could explain transients in galactic nuclei, e.g. QPO (Tombesi et al. 2024), QPE (Franchini et al. 2023)

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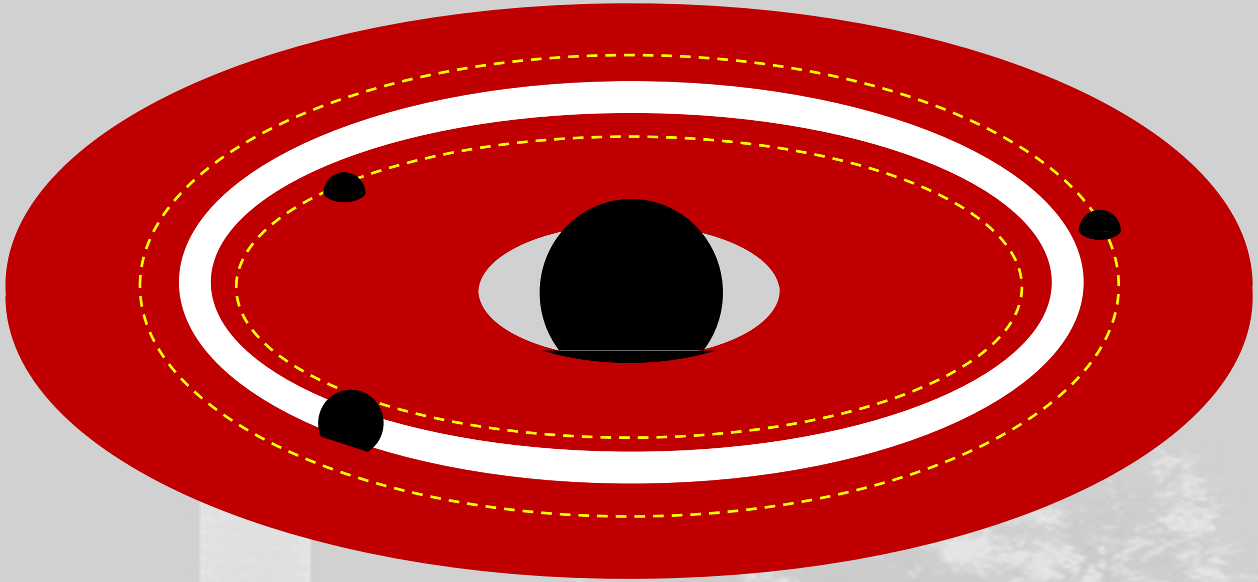

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Encounter between IMBH and stellar-mass BH, due to differential migration and migration trap

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Gap-opening object: Type-II migration
(Lin & Papaloizou 1986a,b)

$$T_{II} = \frac{1}{\alpha h^2 \Omega_I}$$

How the migration of stellar-mass BH affected after the encounter?

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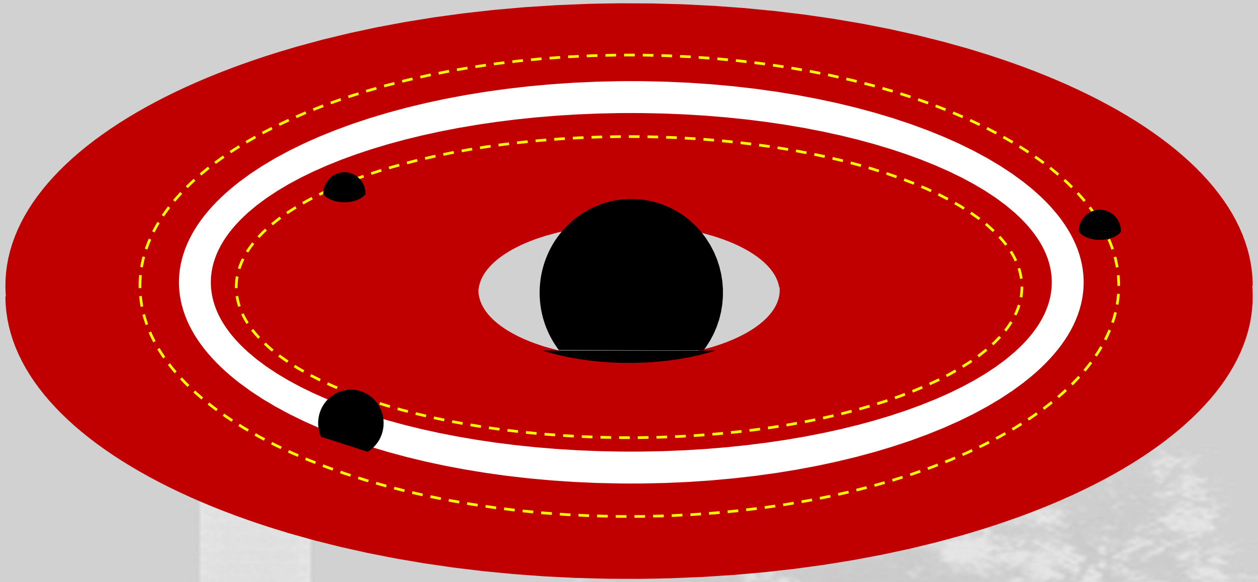

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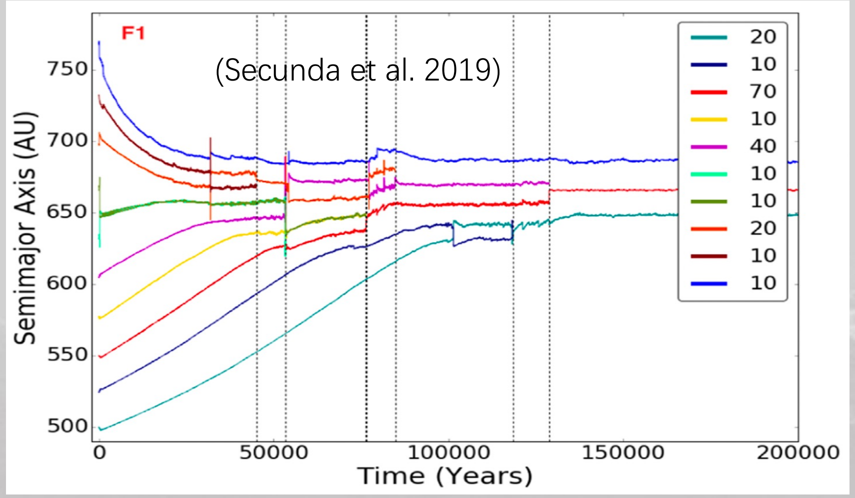
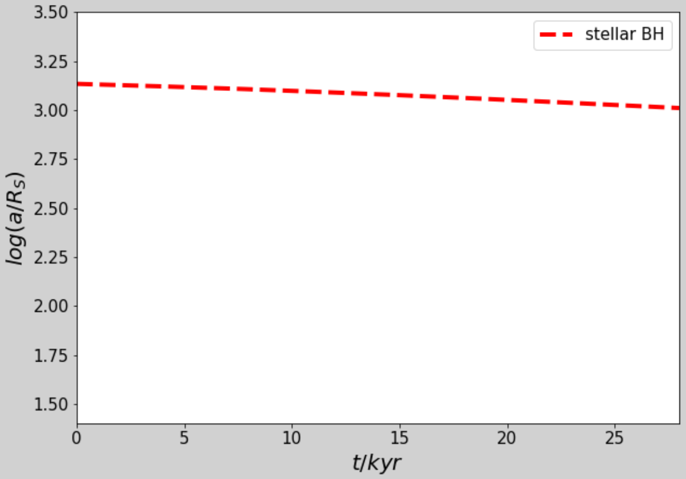
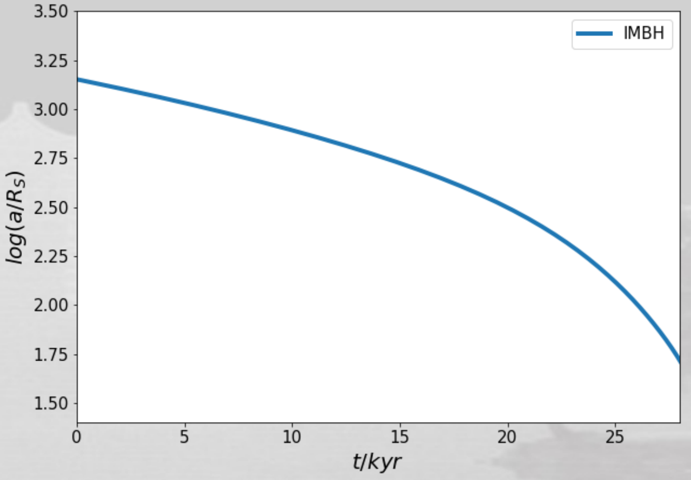


BHs accumulate, merge and grow around the migration trap

How the migration of stellar-mass BH affected after the encounter?

IMBH encounters with sBH





Analytical formula indicates the IMBH migrates faster than the sBH in inner region of the disk

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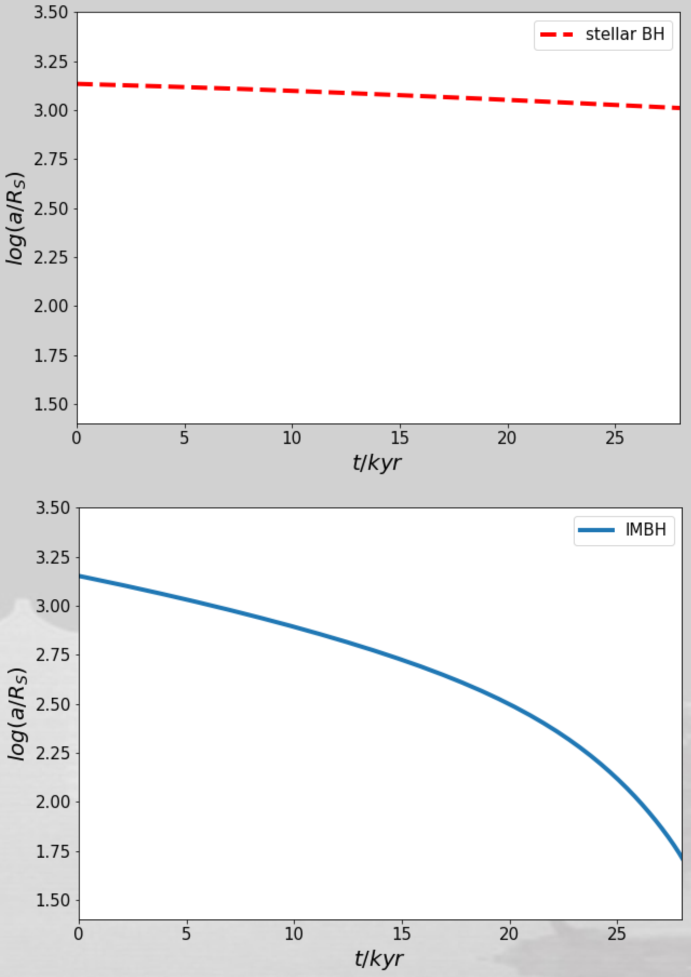

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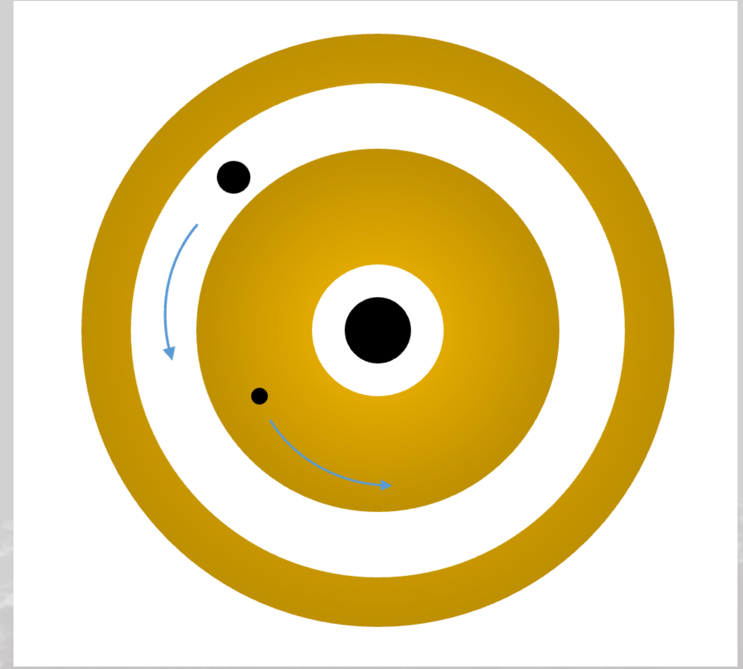
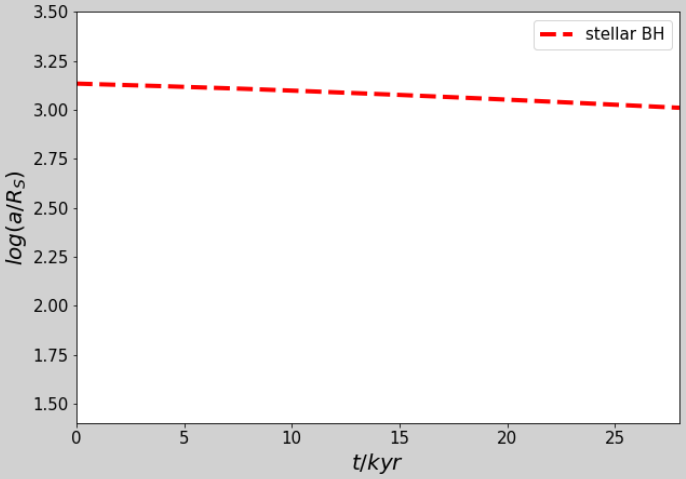
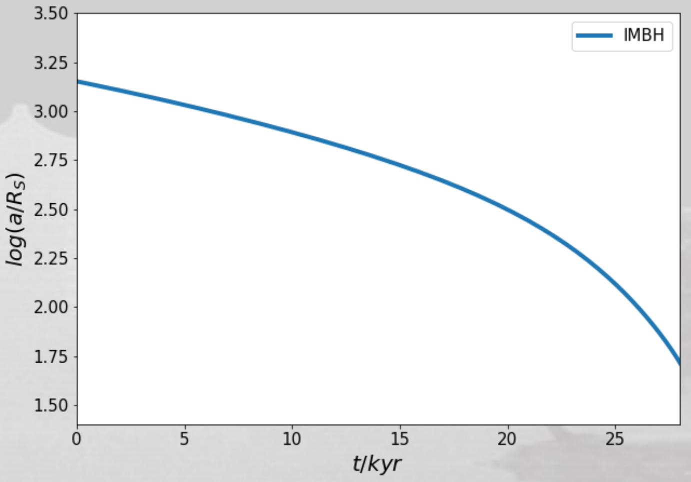


The sBH is put near the inner egde of the gap, with migration torque and disk evolution calculated with semi-analytical formula

IMBH encounters with sBH





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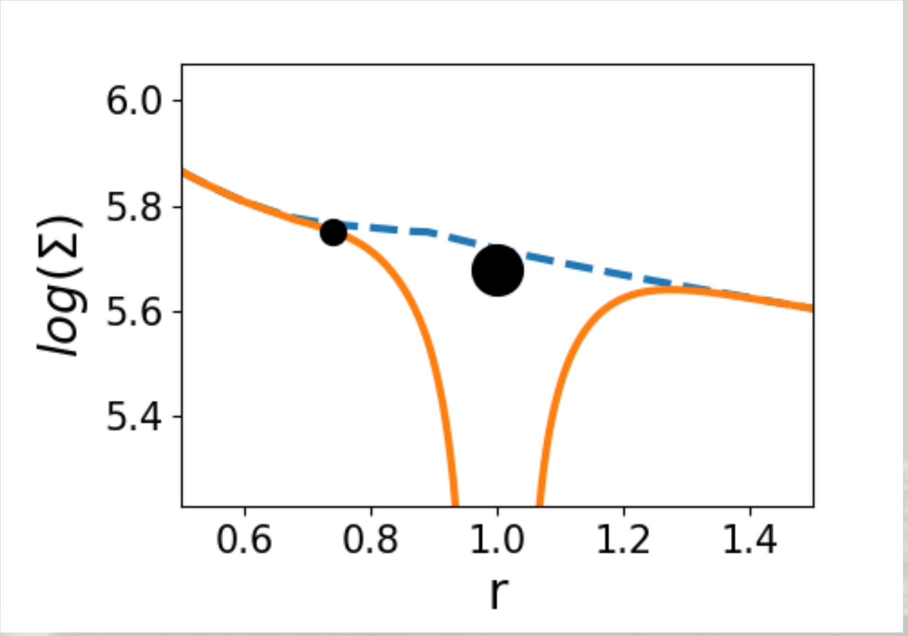
Initial location of sBH, r=0.75



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Accelerated migration of sBH with the presence of IMBH

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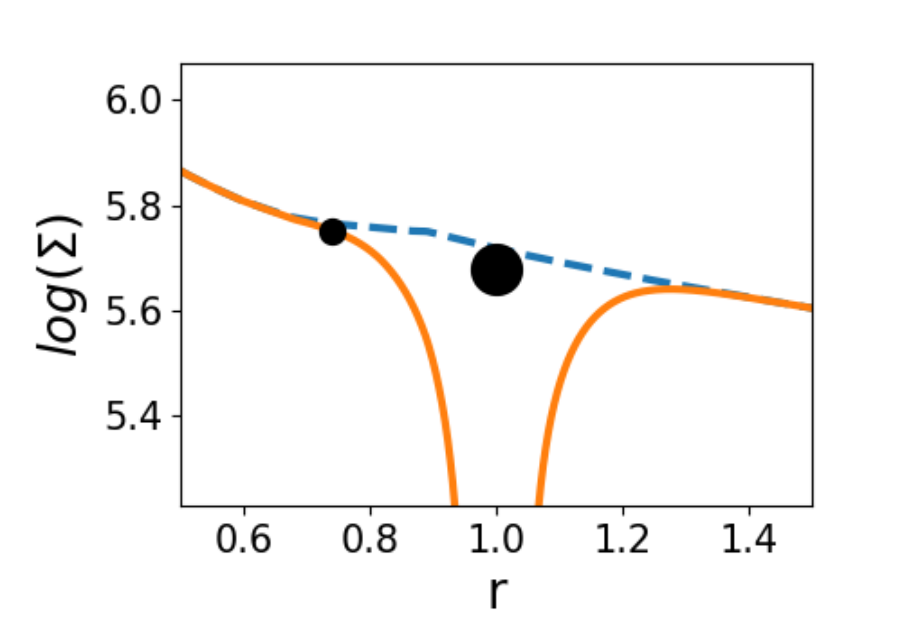

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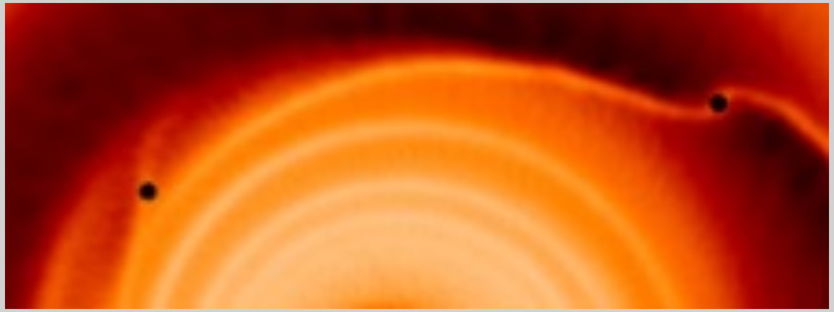


$$\frac{\dot{a}}{a} = -f_{dw}\, q_{sBH}\, q_{disk}\, h^{-2}\, \Omega_s - f_d\, e_s\, q_{IMBH} \sin(\phi)\, \Omega_s - f_{Idw} e_s\, q_{IMBH}\, q_{disk}\, h^{-2} \cos(\phi)\, \Omega_s$$

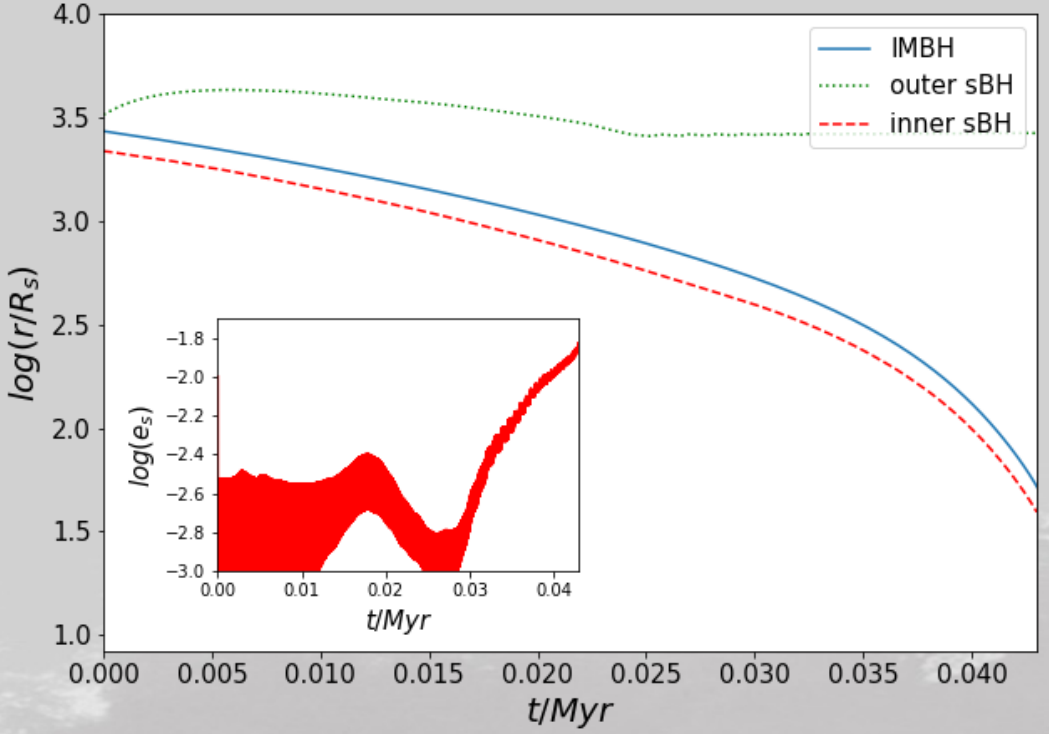
- Strengthened Type-I torque (see Paardekooper et al. 2010)
- Tidal torque of IMBH (see Murray & Dermott 1999)
- Density wave excited by the IMBH (See Yang & Li 2024)

Mechanism to accelerate the sBH migration

Synchronized migration of the sBH and the IMBH

$$\frac{\dot{a}}{a} = -f_{dw}\, q_{sBH}\, q_{disk}\, h^{-2}\, \Omega_s$$
$$-f_d\, e_s\, q_{IMBH} \sin(\phi)\, \Omega_s$$
$$-f_{Idw} e_s\, q_{IMBH}\, q_{disk}\, h^{-2} \cos(\phi)\ \Omega_s$$

$$\dot{e} = -f_{dw,e}\, e_s\, q_{sBH}\, q_{disk}\, h^{-4}\, \Omega_s$$
$$+ f_{d,e}\, q_{IMBH} \sin(\phi)\, \Omega_s$$
$$-f_{Idw,e}\, q_{IMBH}\, q_{disk}\, h^{-2} \cos(\phi)\ \Omega_s$$



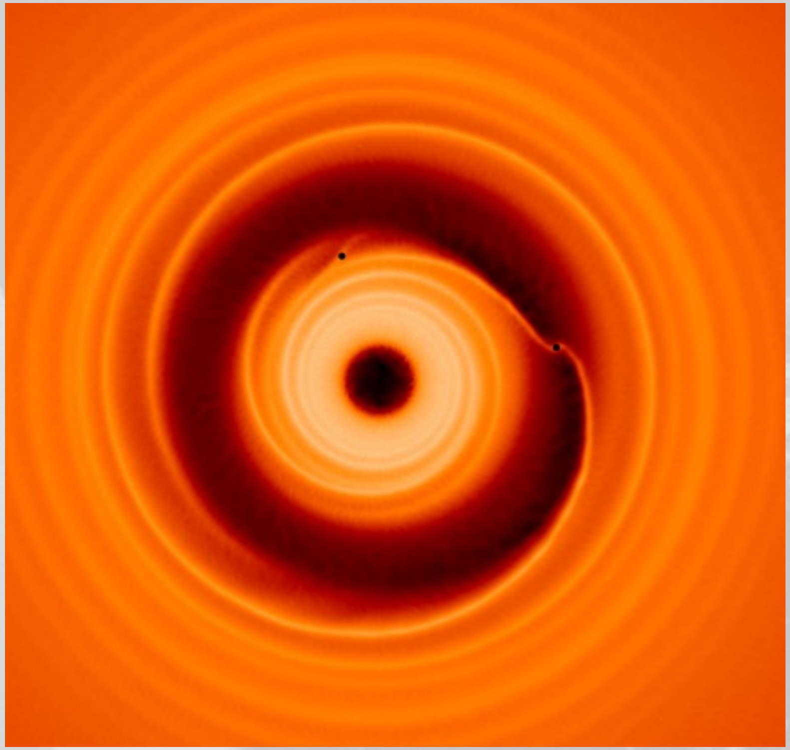
IMBH ‘pushes’ the stellar-mass BH to migrate inward with the same migration timescale, while the orbit of the sBH kept circular.

The pair will migrate to ~10 R_g almost the same time

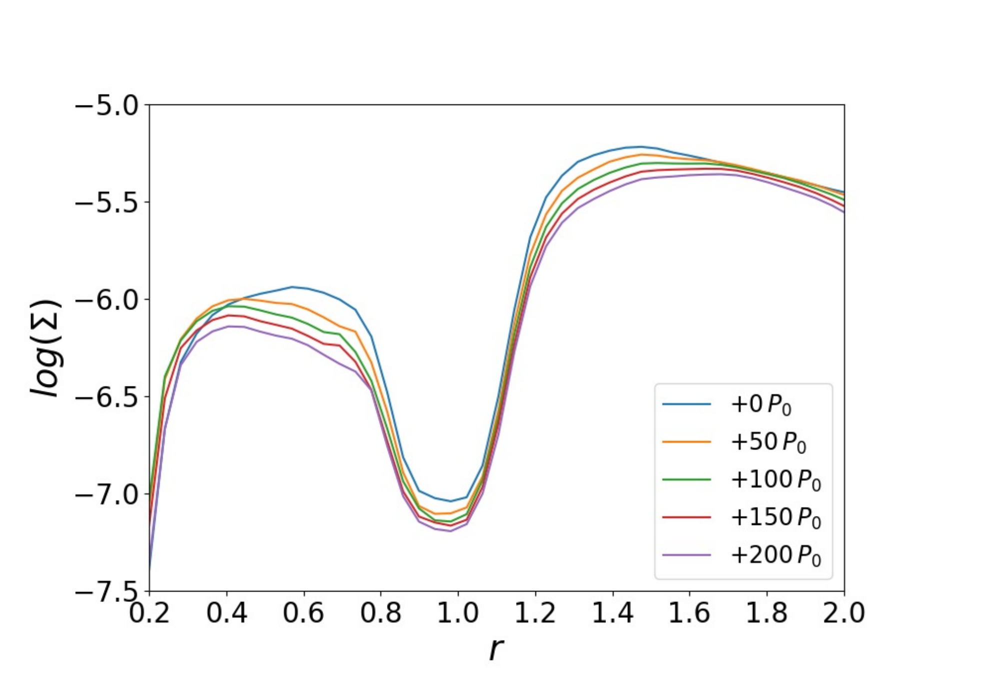
3D Hydrodynamical simulation

(Price et al. 2018)

Snapshot of the disk with a gap opened by the IMBH and a nearby stellar-mass BH, while the GW emission is not strong.



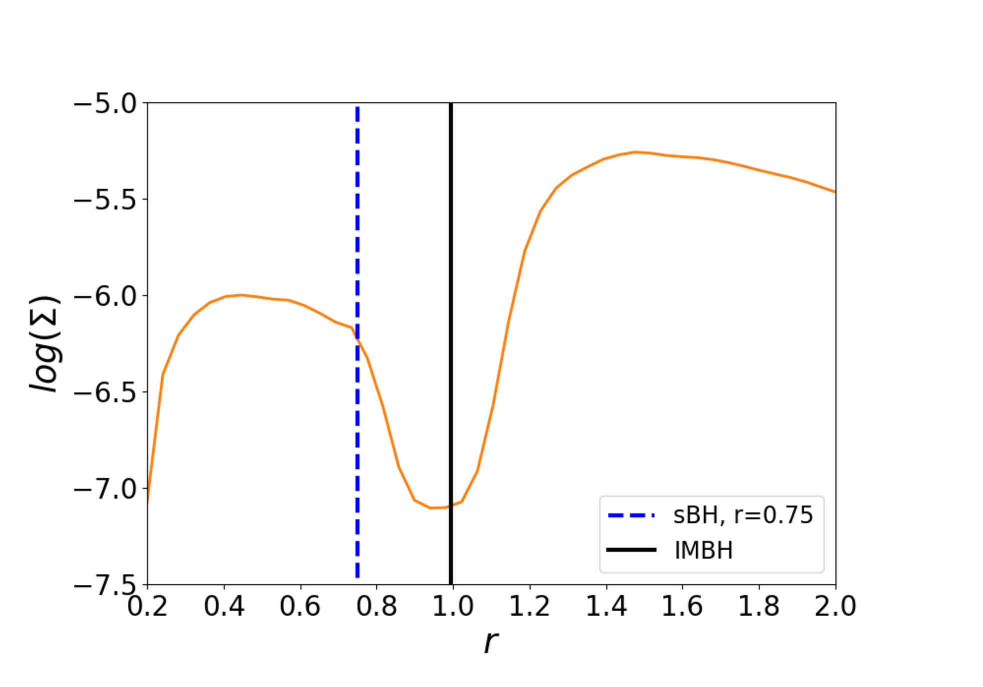
Gap opening and disk shape convergence



The inner disk is partially accreted by SMBH, with gas inflow partially blocked by the tidal barrier produced by the IMBH

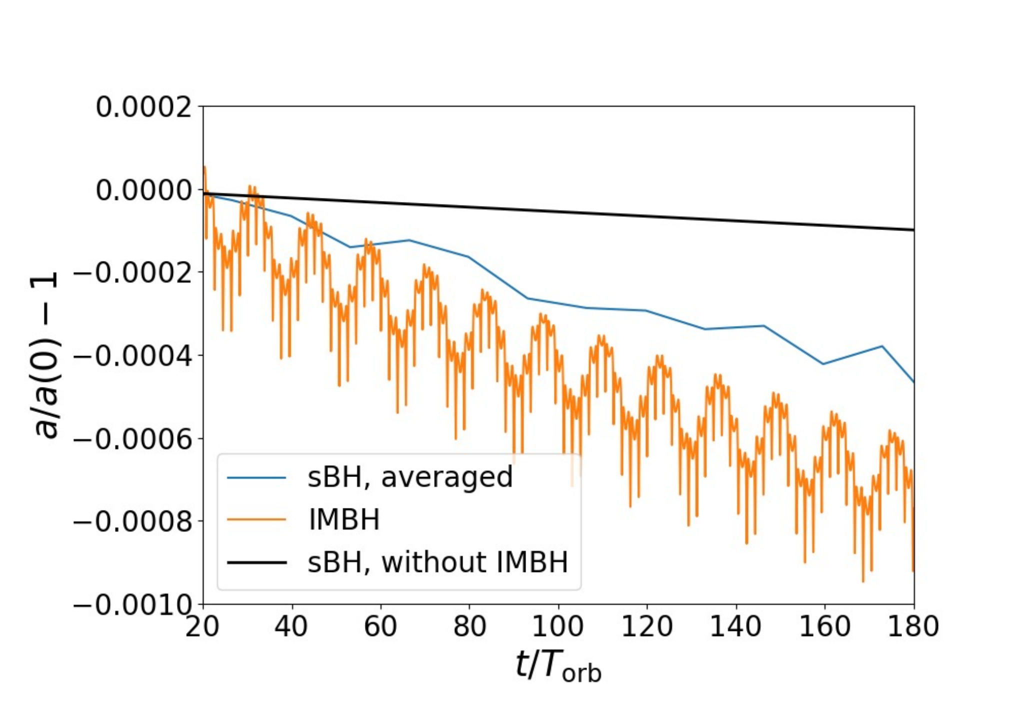
Synchronized migration of the sBH and the IMBH, with the inner disk partially accreted

The sBH is inserted into the simulation after disk profile converging



Initial location of sBH, r=0.75

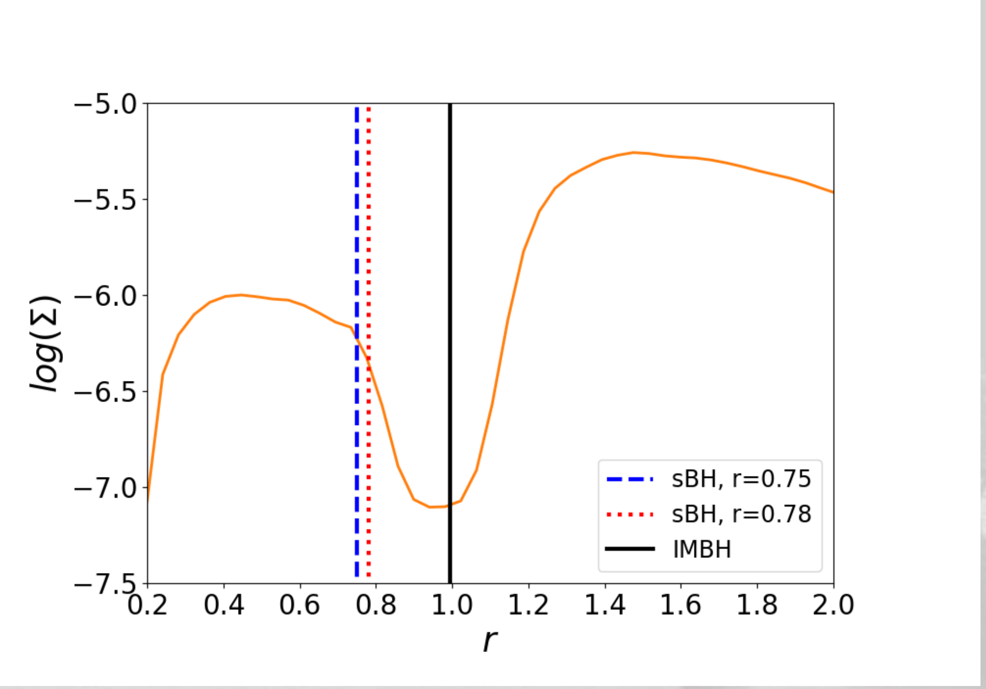
Migration of the IMBH and the sBH



The migration of the sBH is accelerated with the presence of the IMBH

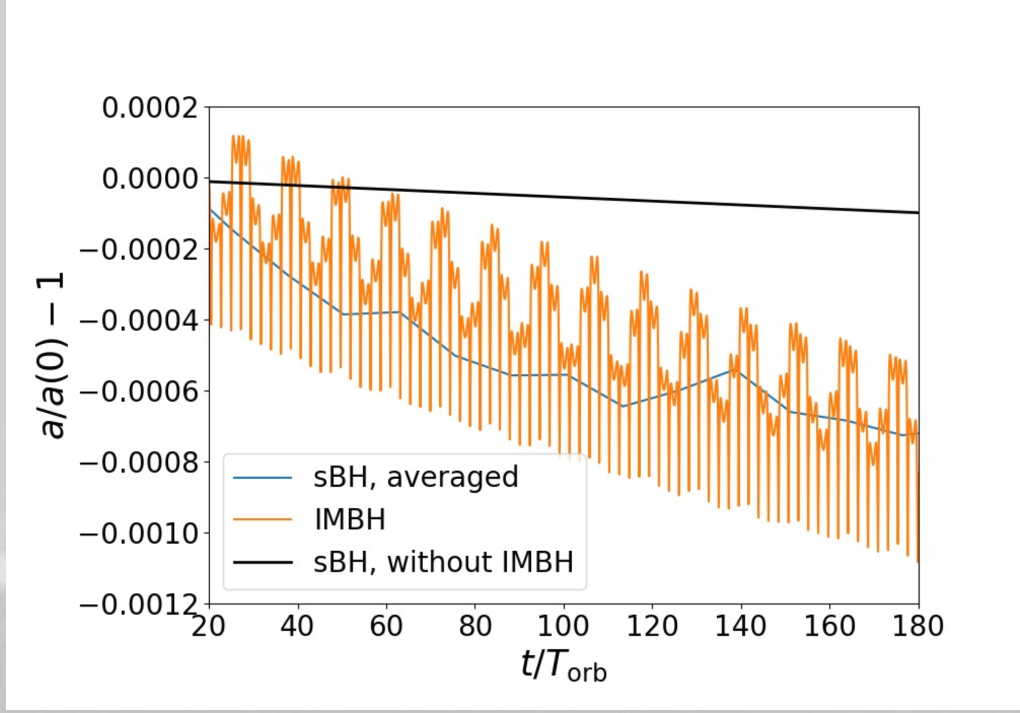
Synchronized migration of the sBH and the IMBH, with the inner disk partially accreted

As the IMBH migrate faster than sBH, sBH goes deeper into the gap



Initial location of sBH, r=0.78

Migration of the IMBH and the sBH



As the sBH goes deeper into the gap, the torque is stronger.

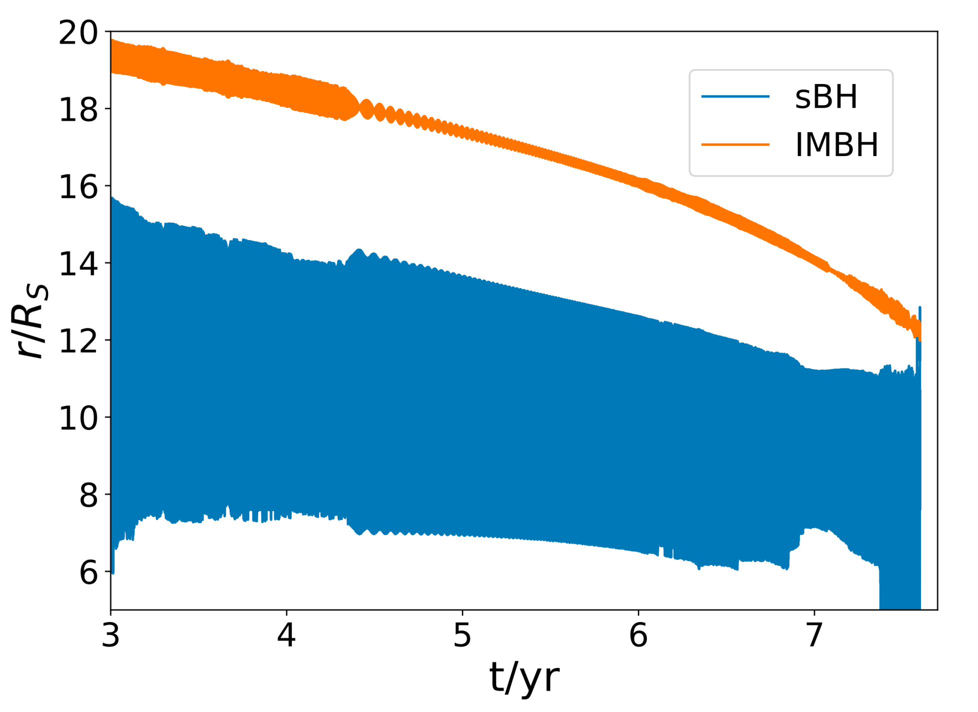
A sBH located at r=0.78 **migrates synchronously** with the IMBH

Evolution in GW dominated regime

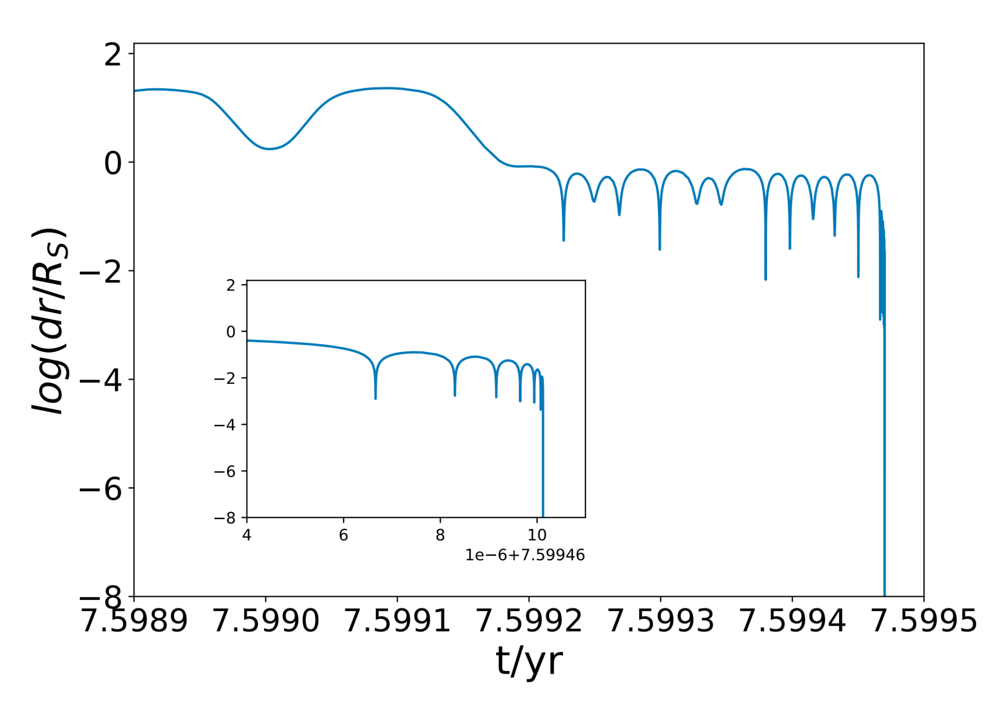
(Simulated with N-body code implemented with PN2.5 terms, also with mock gas force calibrated based on the result in the SPH simulation)

Case 1: Binary formation between the sBH and the IMBH, ~50% of all cases

sBH-IMBH merger followed by an IMRI, with the first event suffers from the environmental effect caused by the nearby SMBH



Distance of the sBH and the IMBH to the central SMBH



Distance between the sBH and the IMBH, normalized with Rg of SMBH, in logarithmic coordinate

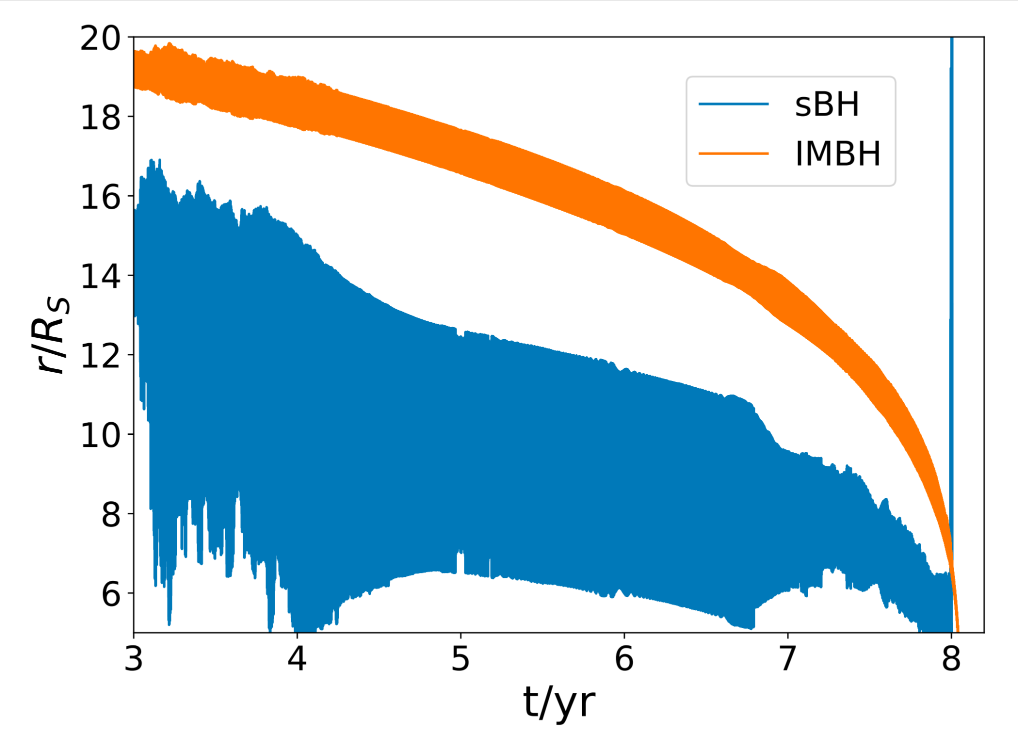
Evolution in GW dominated regime

(Simulated with N-body code implemented with PN2.5 terms, also with mock gas force calibrated based on the result in the SPH simulation)

Case 2: sBH ejected by the IMBH, ~50% of all cases

A temporary EMRI with lifetime ~1 yr, followed by and IMRI event

The GW waveform will be affected by each other



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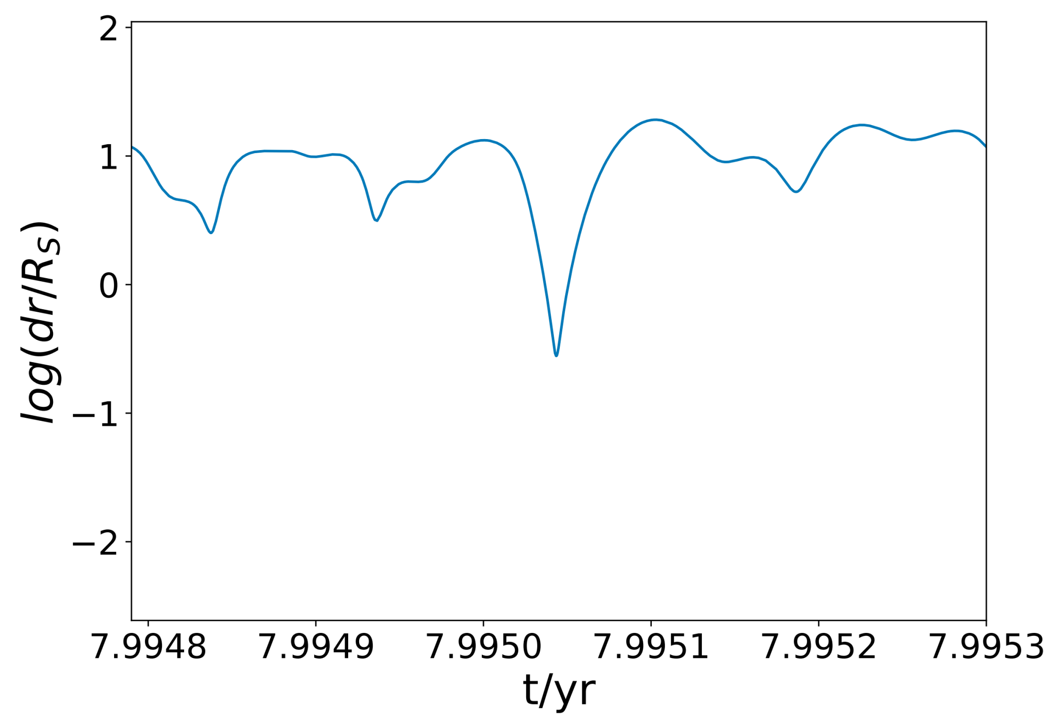

Distance between the sBH and the IMBH, normalized with Rg of SMBH, in logarithmic coordinate

Summary

- During its Type-II migration the IMBH could capture a stellar-mass BH inside its orbit and form a sBH-IMBH pair.
- The migration of the sBH-IMBH pair is synchronized until they reach a distance of about $\sim 10\ R_s$ from the central SMBH.
- Finally the stellar-mass BH can be either captured by the IMBH or ejected, forming successive GW events, very different from the single EMRI/IMRIs

Event rate?

Many theoretical uncertainties! Mostly dependent on IMBH formation rate. If the IMBHs are produced by successive mergers of the stellar-mass BHs, the formation rate of the EMRI-IMRI pairs would be about 0.01-0.1 times the EMRI rate.

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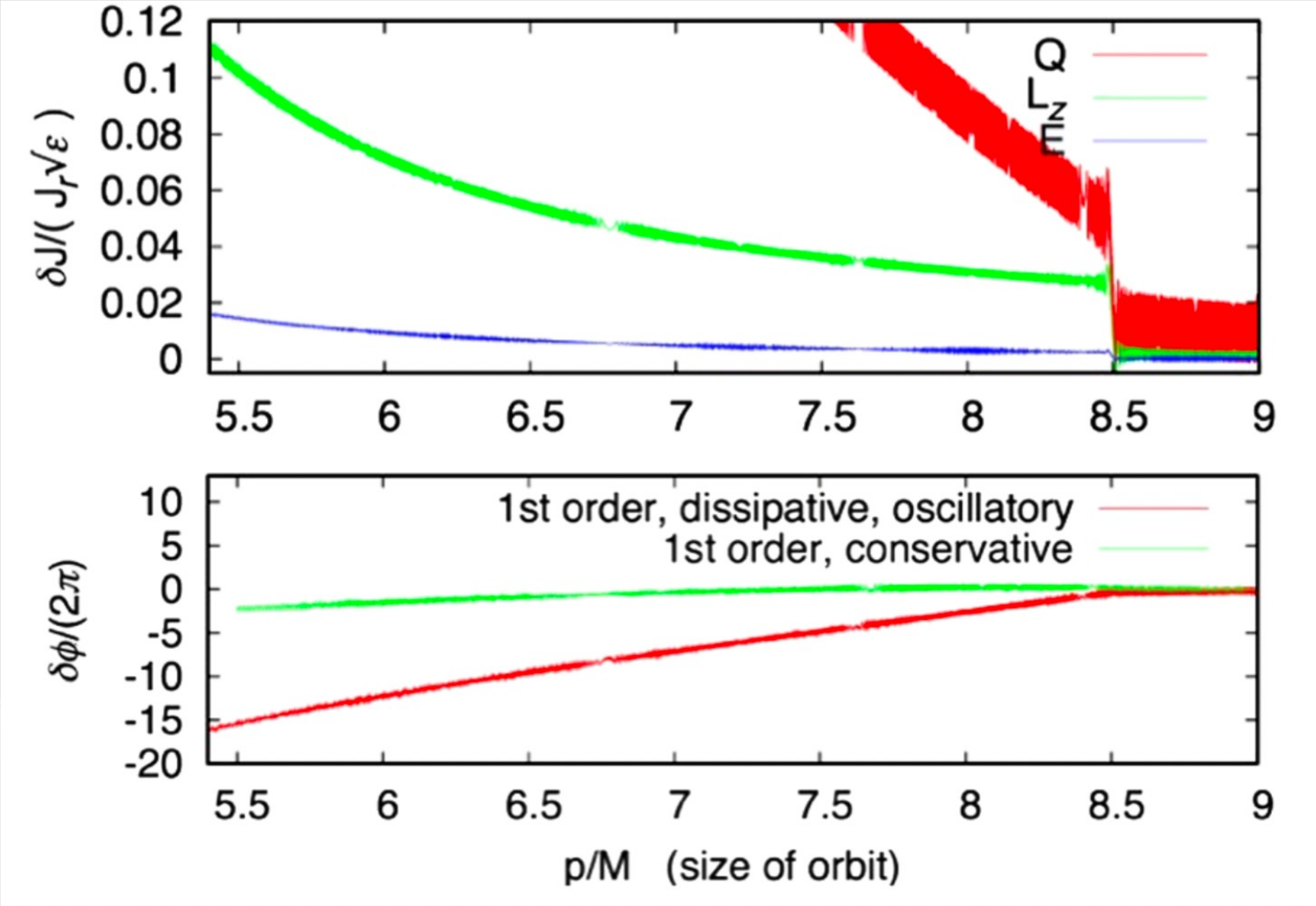
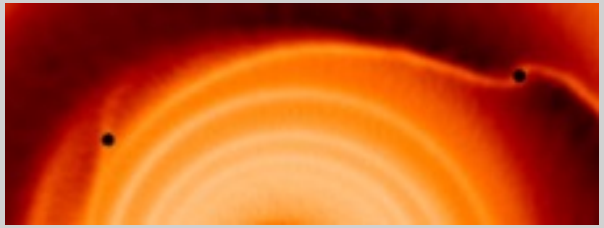
Detection?

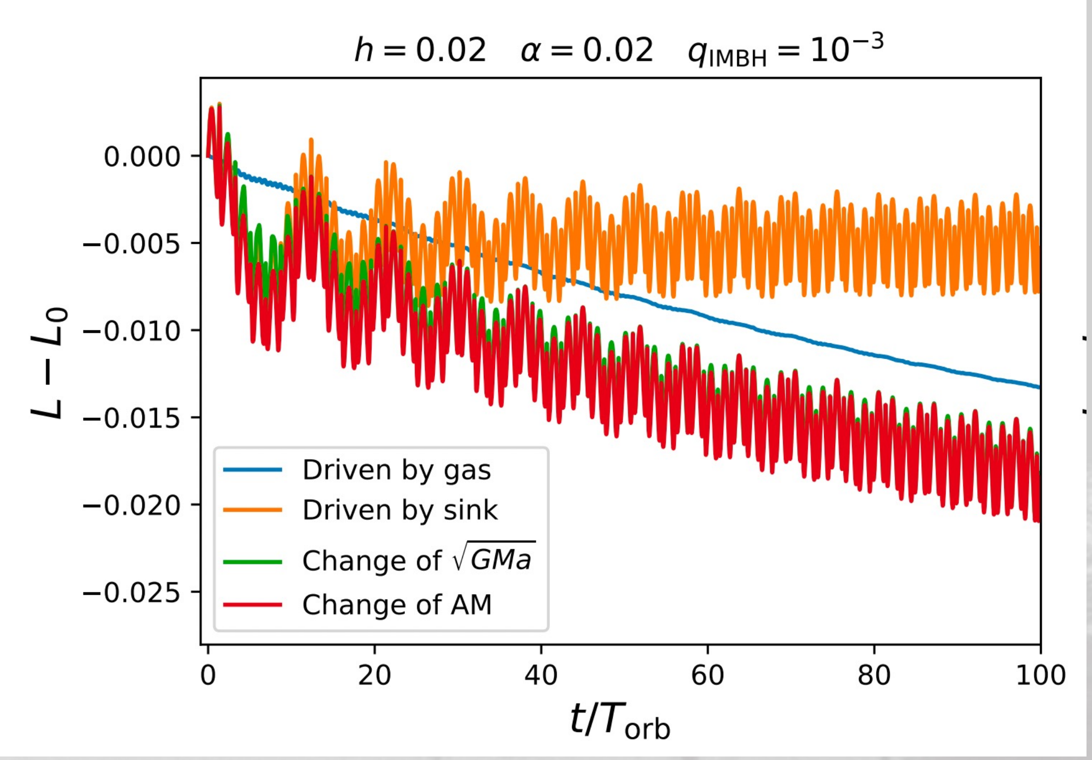


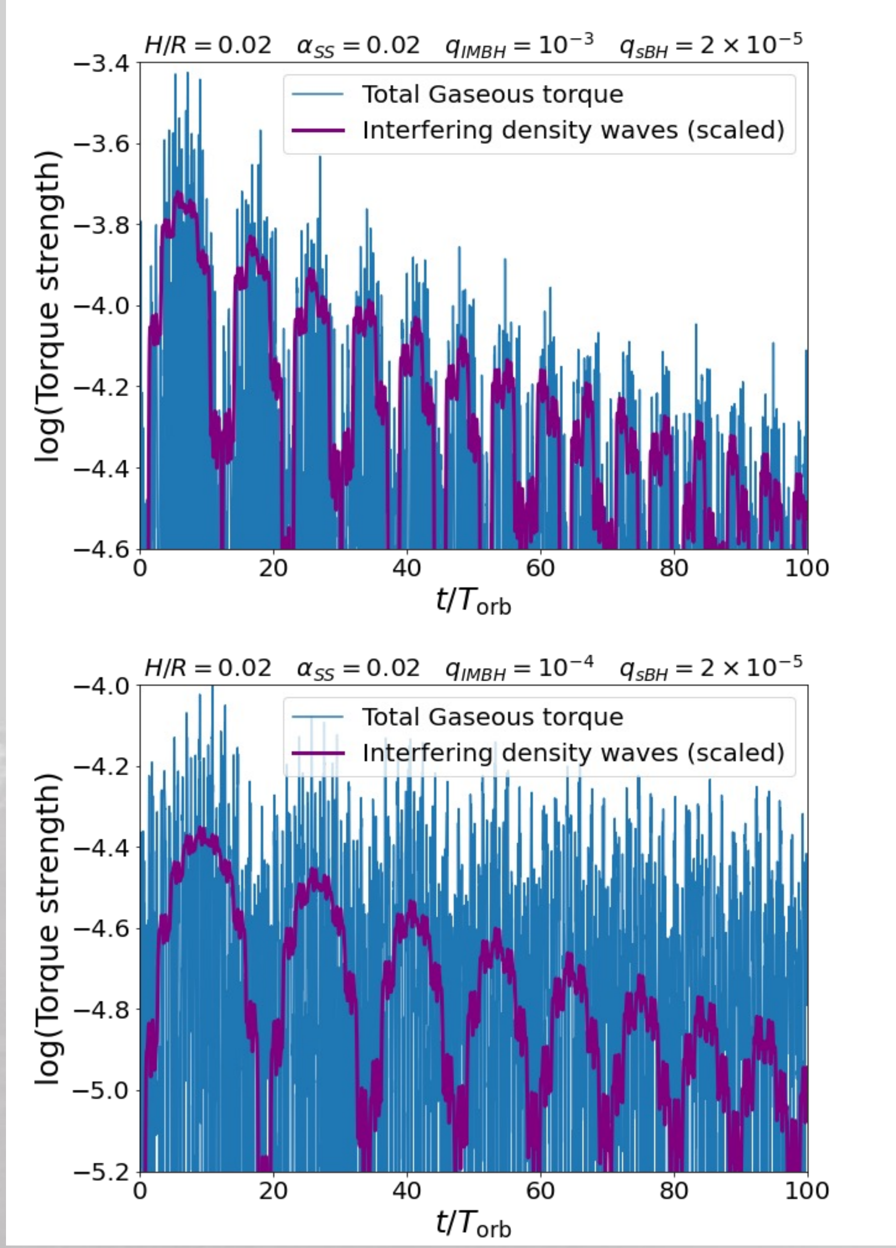
Flanagan et al. 2012

- If ignored in the waveform model, it may induce non-negligible biases in the estimated parameters
- If properly accounted for, the perturbed signal may reveal the mass and orbital parameters of the perturber
- the EMRI signals could reveal the outer IMBHs even before the IMRIs enter the LISA band.

GW signal Phase shift induced by transient resonance







Type-I torque

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Interfering density wave (Yang&Li 2023)