北京大学
PEKING UNIVERSITY

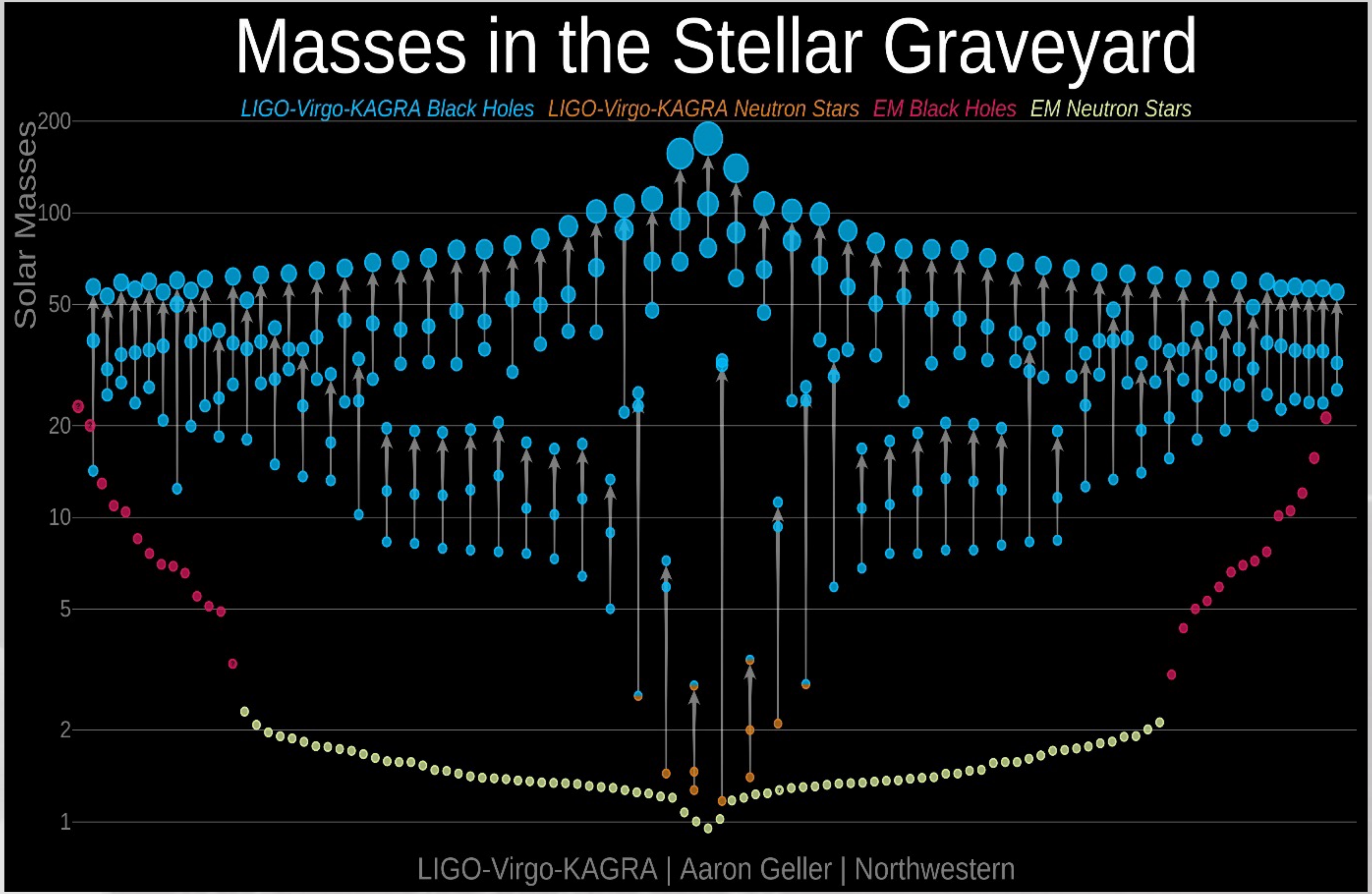
物理学院天文学系
Department of Astronomy, School of Physics

Susceptible gravitational wave sources in the active galactic nucleus

Peng Peng (彭朋)

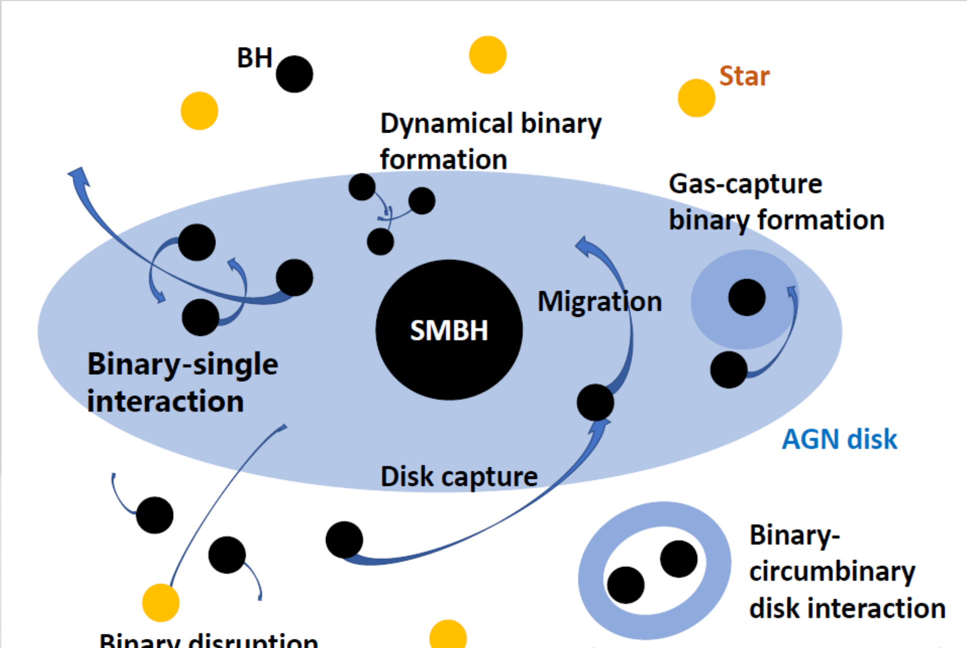
Advisor: Xian Chen (陈弦)

Massive LIGO sources indicates that the Astrophysical Environment of the GW source formation is not 'clean'



GW source in the active galactic nuclei can suffer from many kinds of environmental effect, which will bias the parameter estimation

GW sources in the AGN disk:
BBH embedded in AGN disk; Wet EMRI…
(e.g. Tagawa+2019, Pan&Yang 2021)



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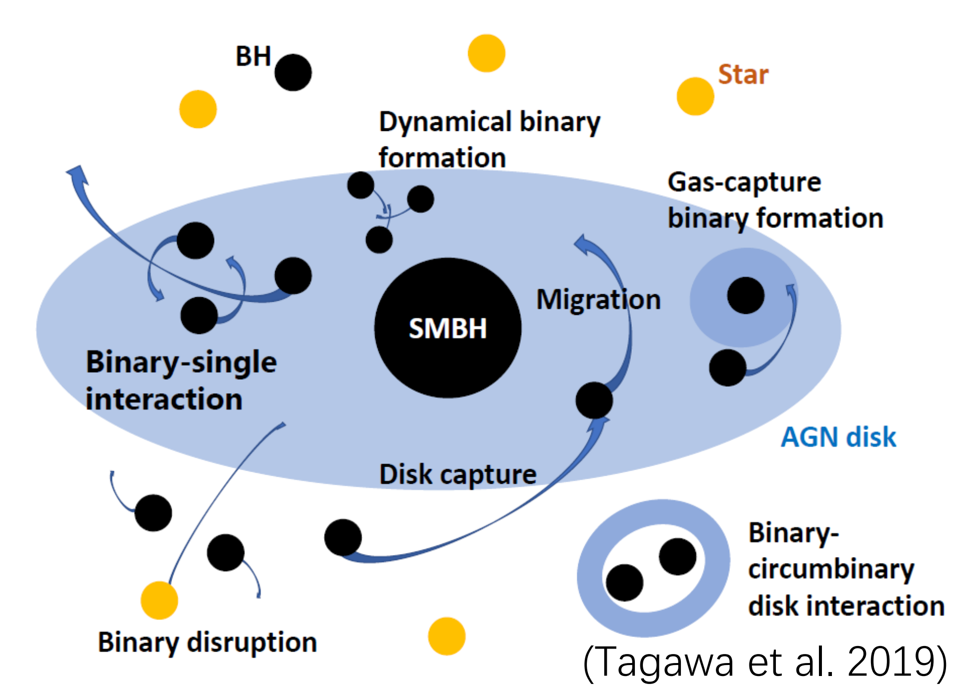

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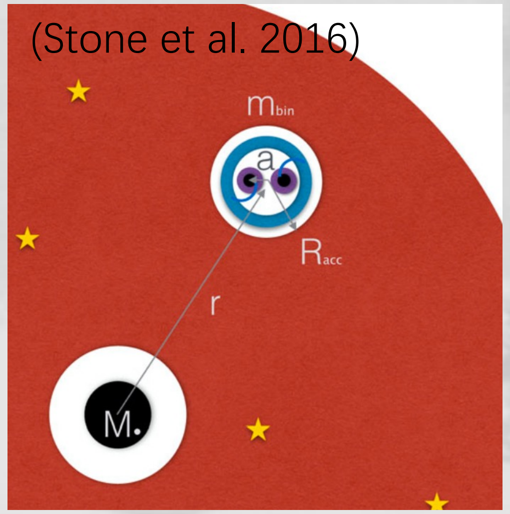
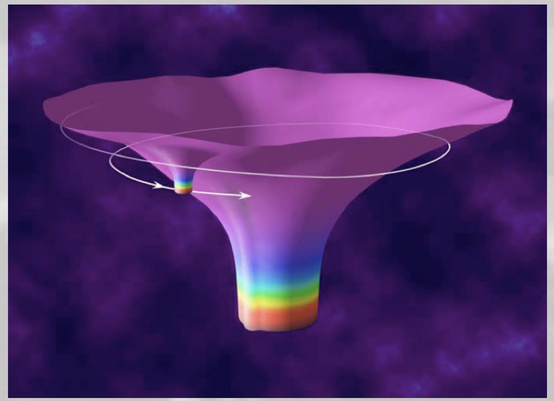


(Stone et al. 2016)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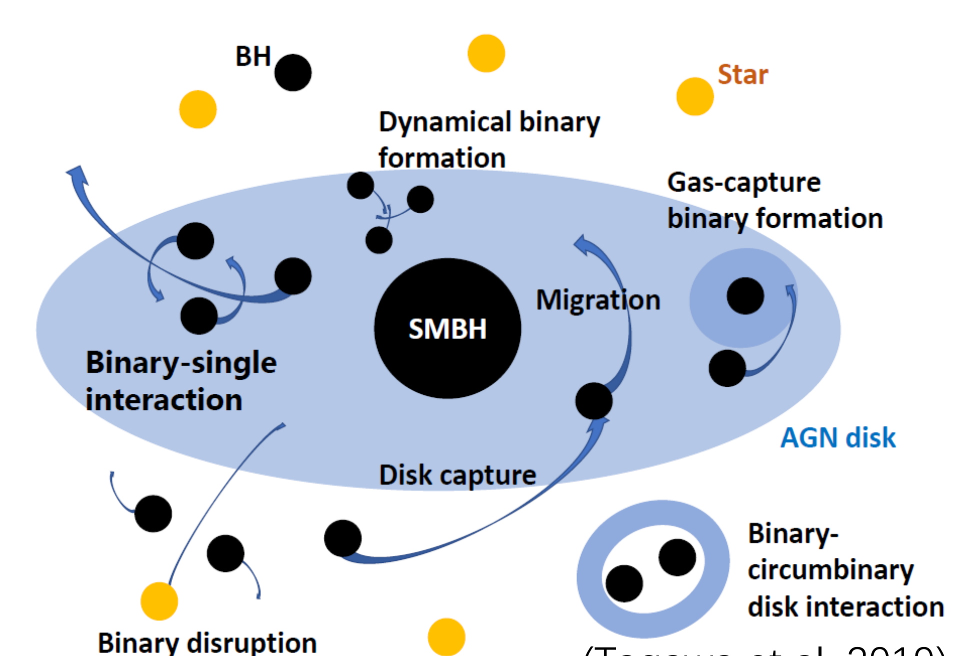

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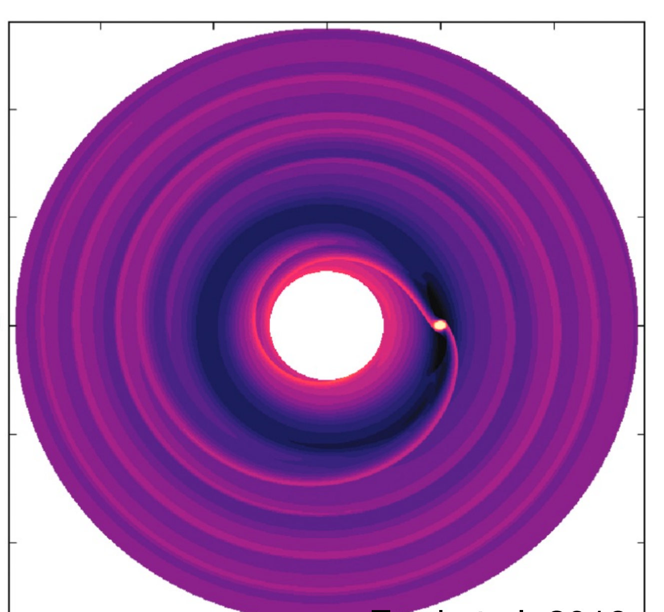
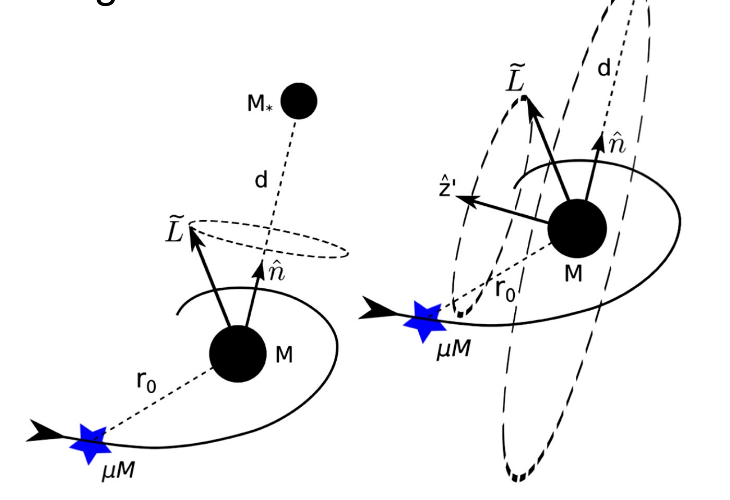
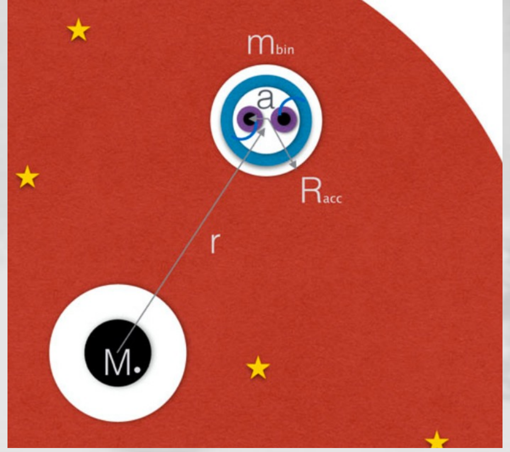

Ford et al. 2019





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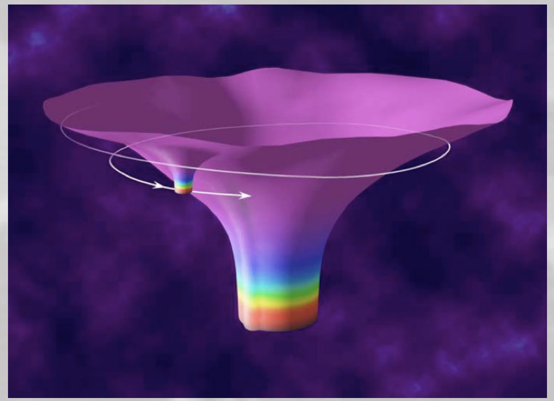
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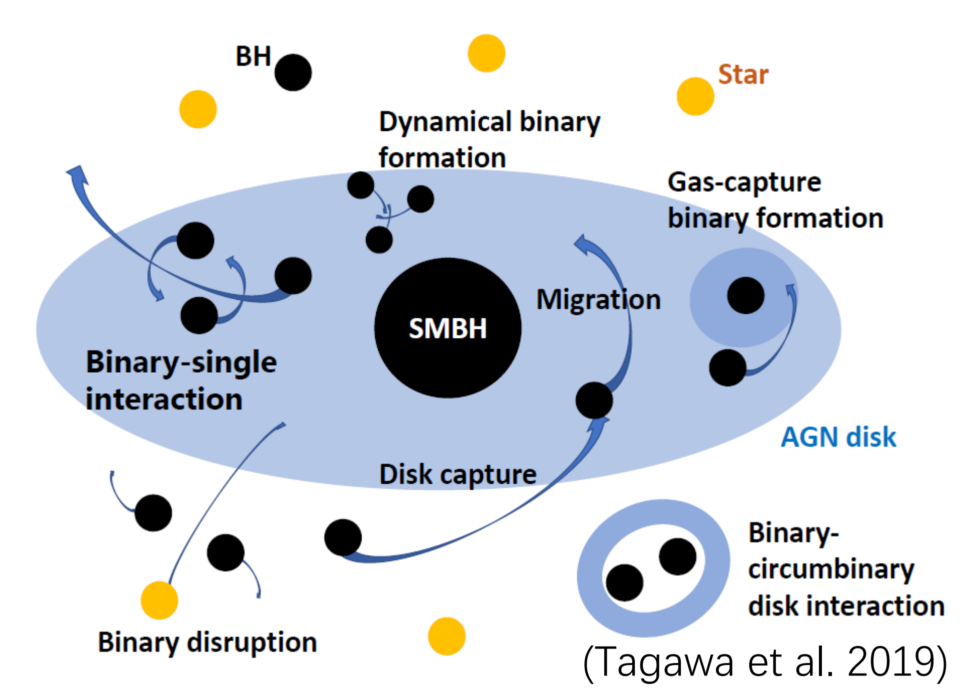

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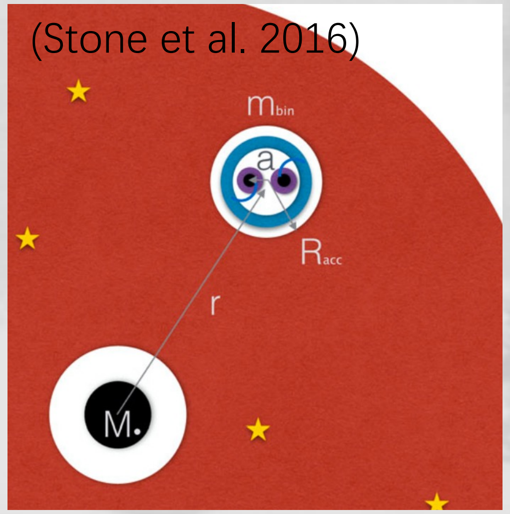

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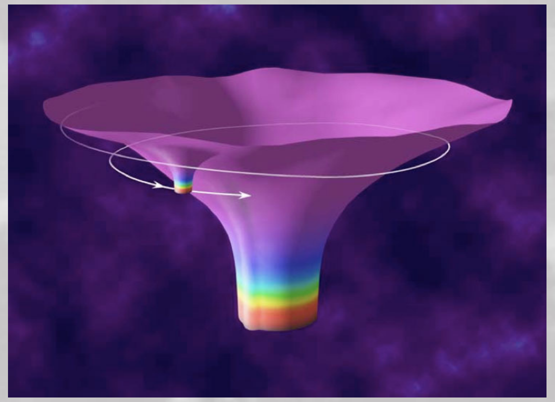
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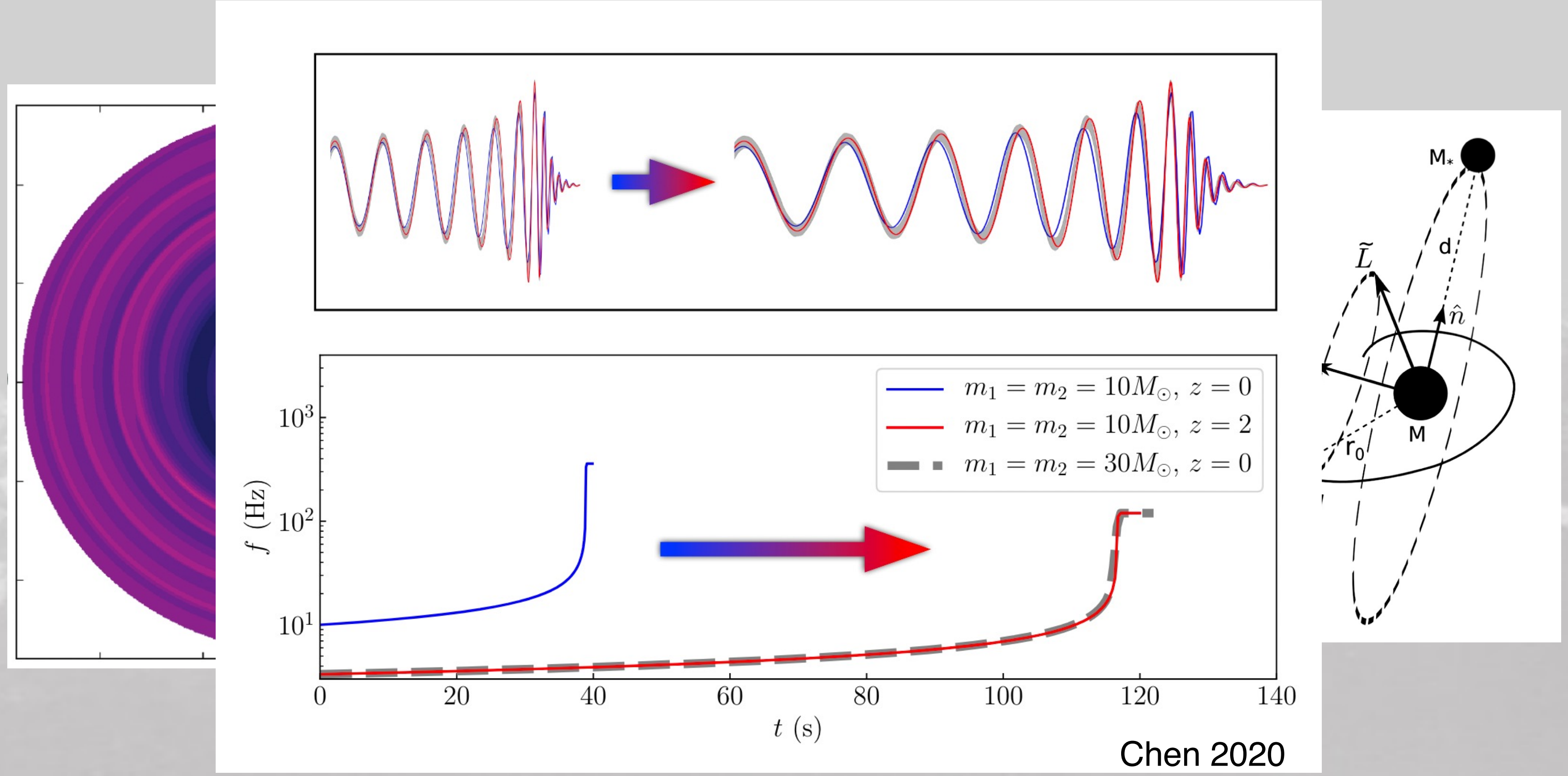

Chen 2020

The environmental effect on the GW sources is important for our understanding about how the Astrophysical BHs form and evolve

Migration of the small BHs in the disk is important for analyzing the astrophysical environmental effect of the GW sources

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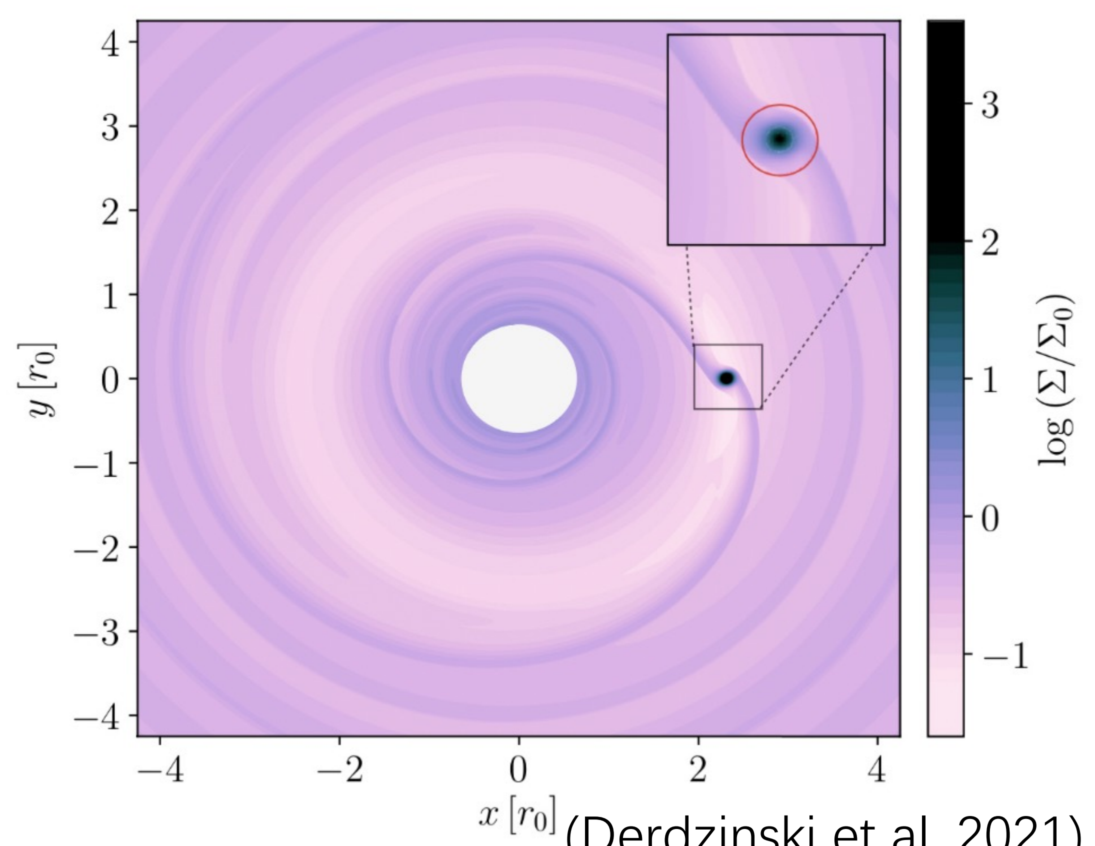

(Derdzinski et al. 2021)

Type-I migration torque:
Energy and Angular-momentum transported by the density wave
(Goldreich & Tremaine 1979, Artymowicz 1993; Ward 1997)

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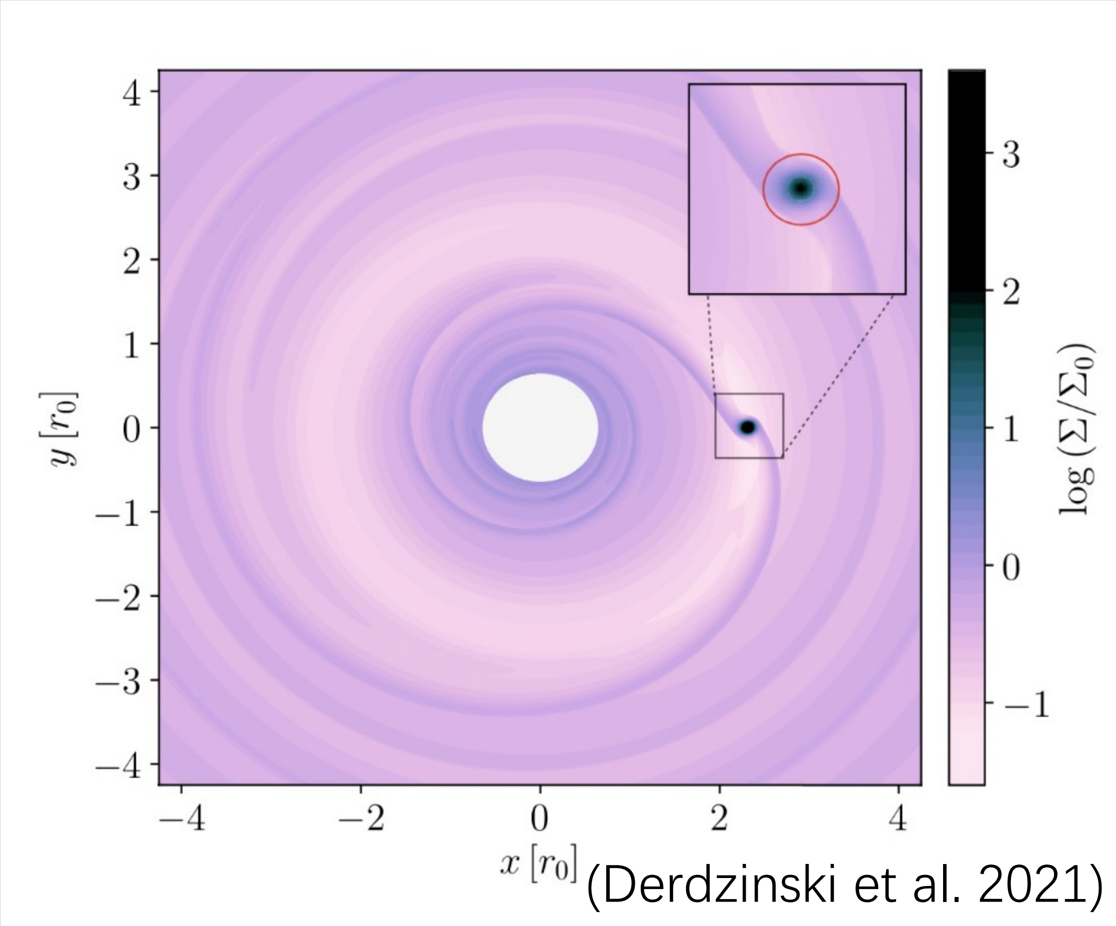

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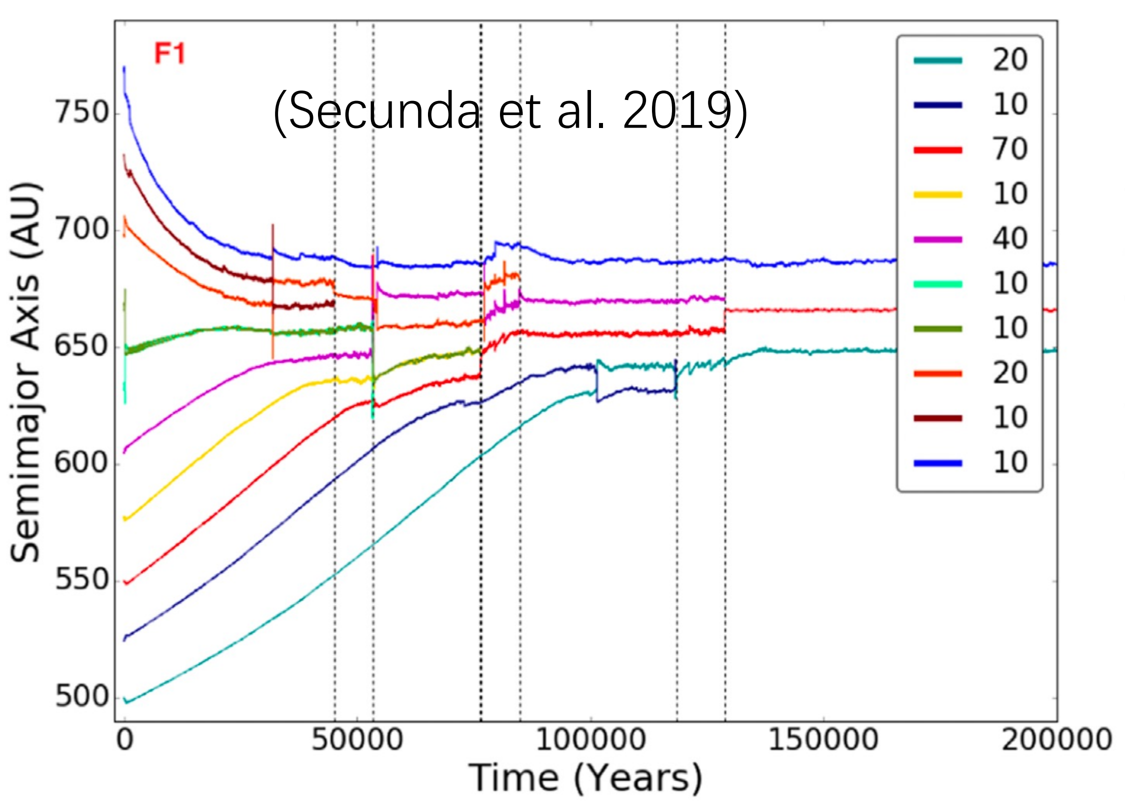

Type-I migration trap
($\sim 100 - 10000 R_s$)

The Type-I migration torque can drive the stellar-mass BHs to migrate to the inner region of the disk ($r \sim 100 - 10000\ R_s$), these BHs will form binaries and merge around these radii. **(e.g. Bellovary 2016)**

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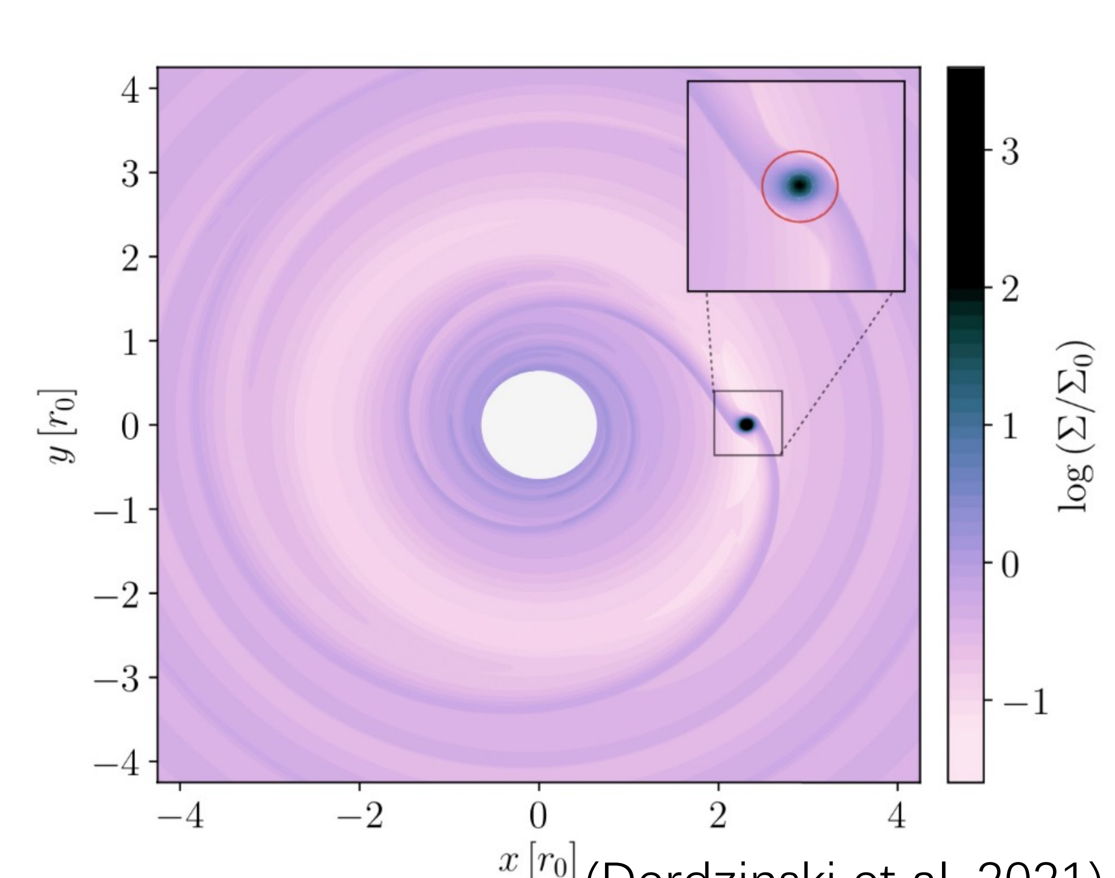

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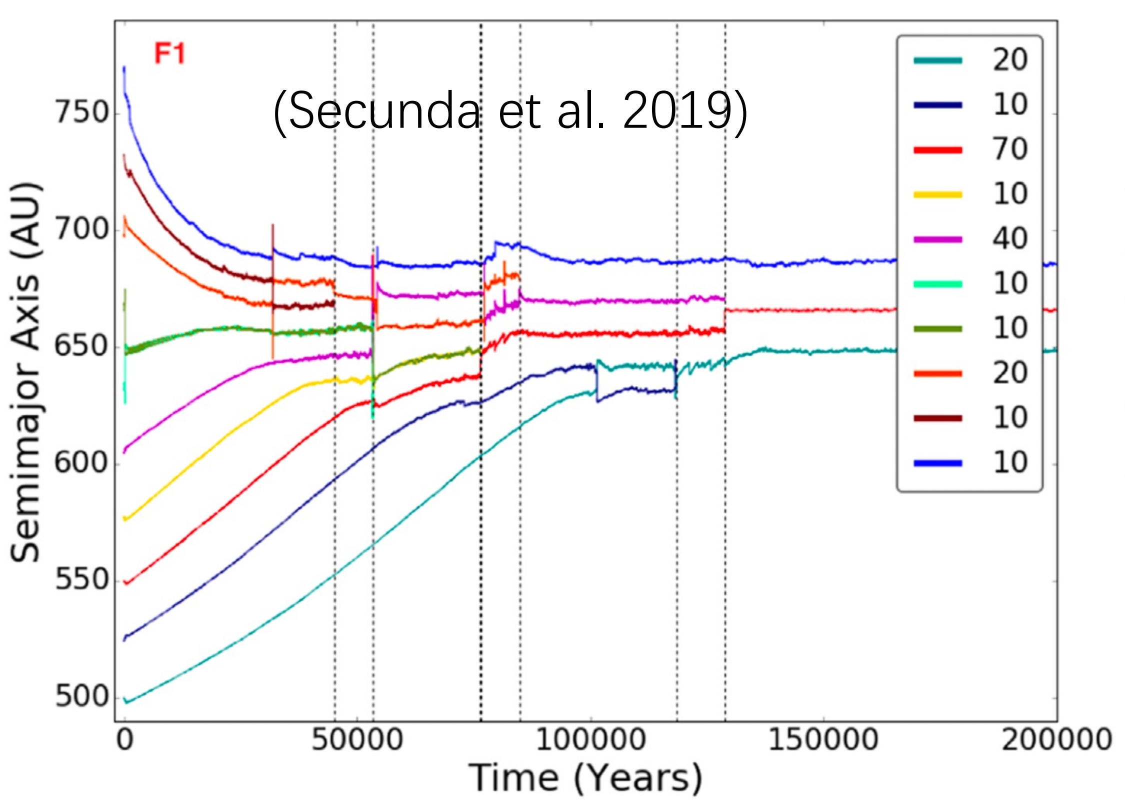

(Secunda et al. 2019)

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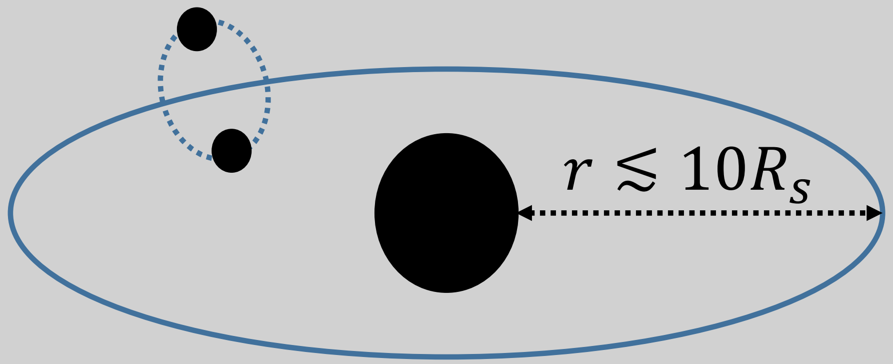

$$\mathcal{M}_o := \left(\frac{5 f_o^{-11/3} \dot{f}_o}{96\pi^{8/3}}\right)^{3/5} = \mathcal{M}(1+z).$$

(Chen 2020)

$$1 + z = 2 \sim 3$$

Can migration help to produce stellar-mass BH binary with $\mathbf{r} < 10\, R_s$?

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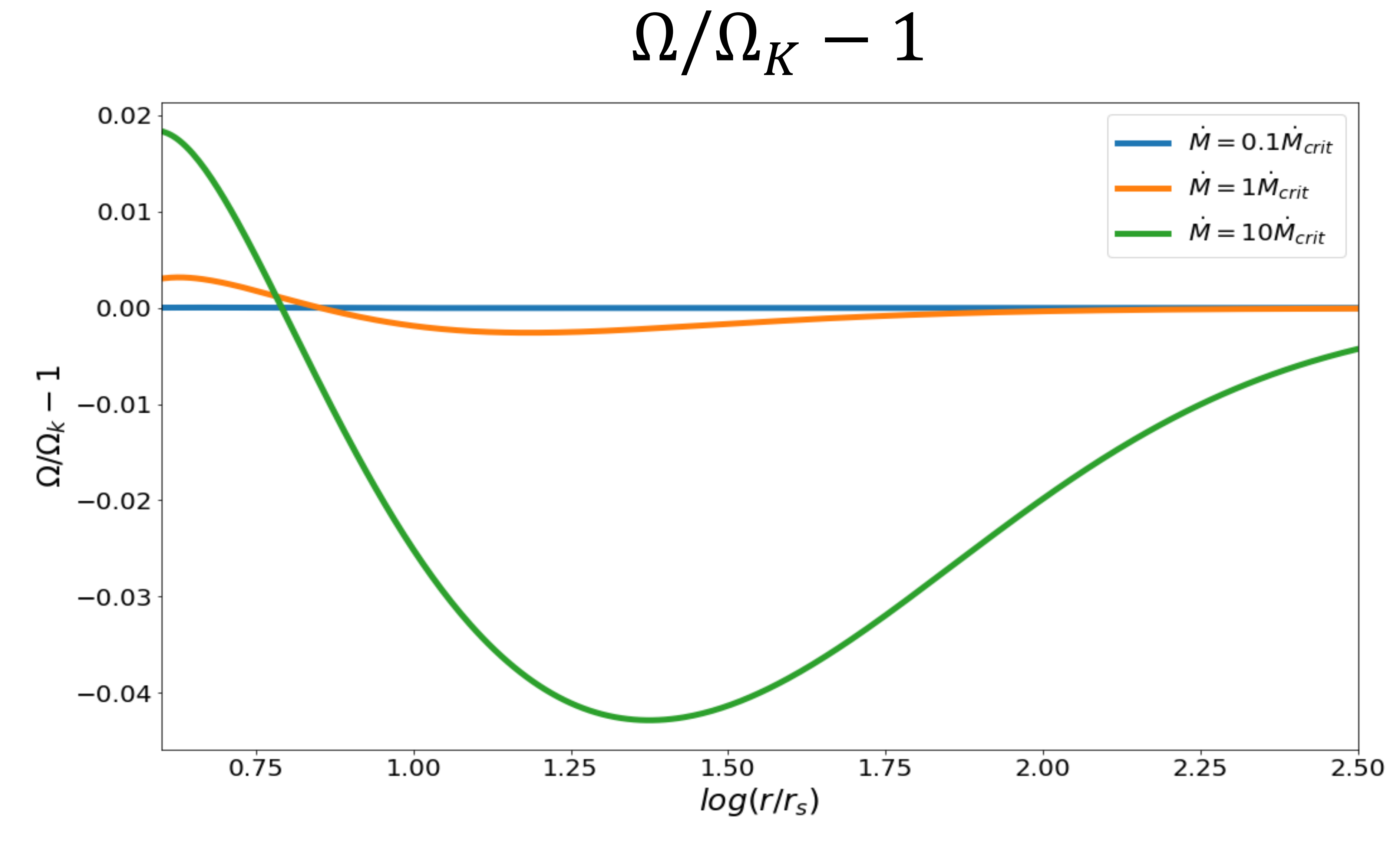
Result (Peng&Chen 2021)

Gaseous torque caused by different orbital velocity of the Gas and the BH



Gas rotational velocity profile in the slim disk

Result (Peng&Chen 2021)

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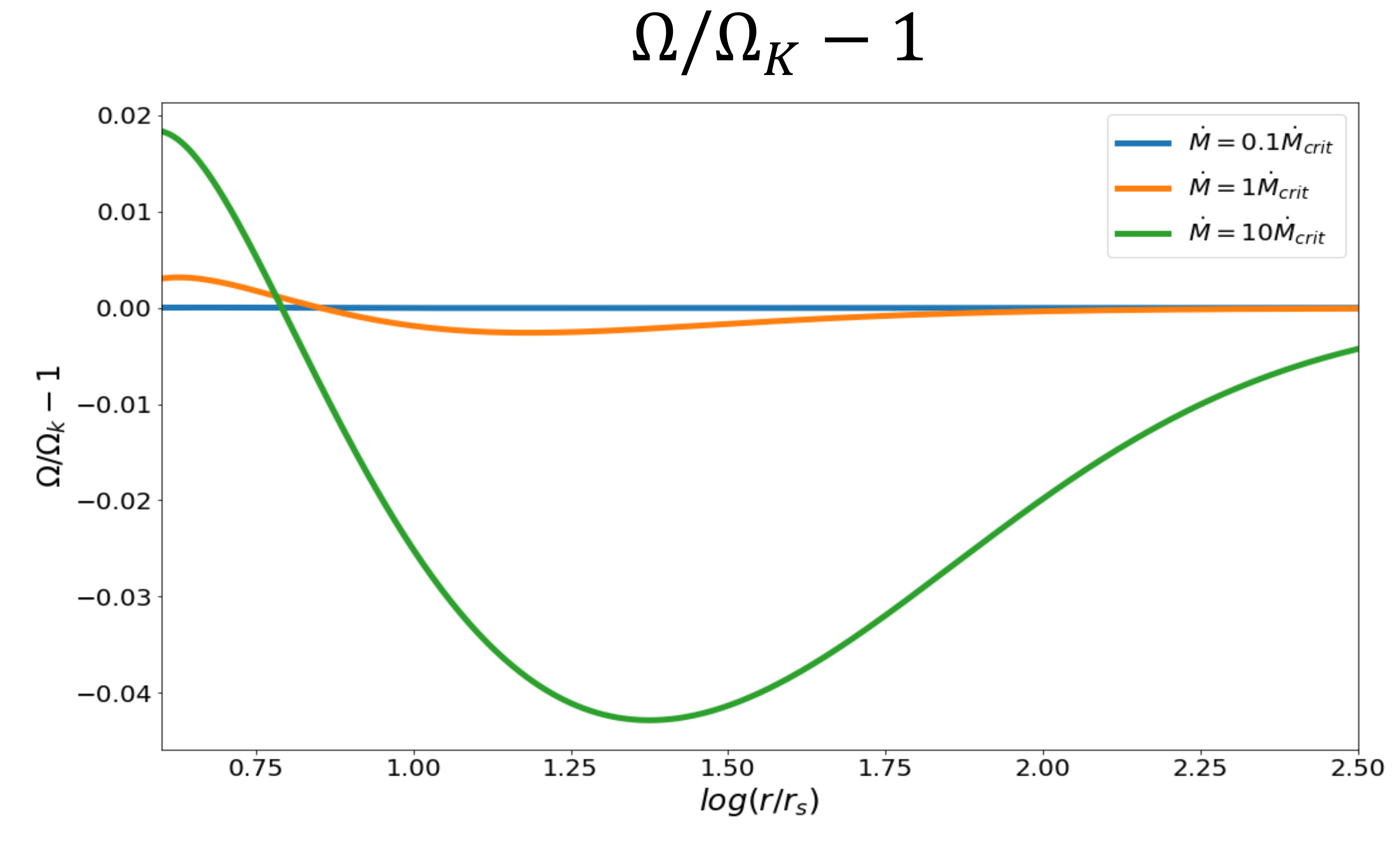

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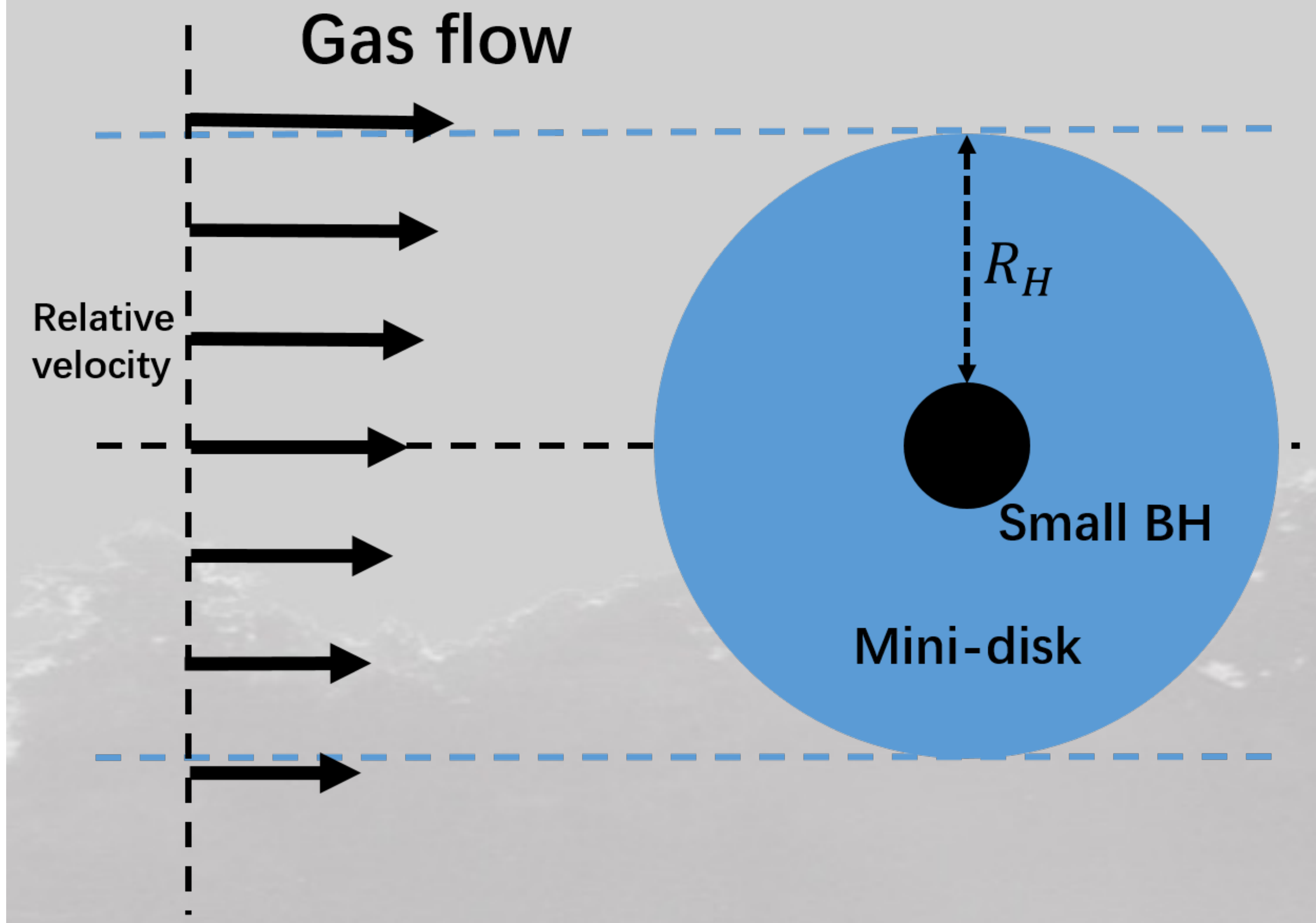


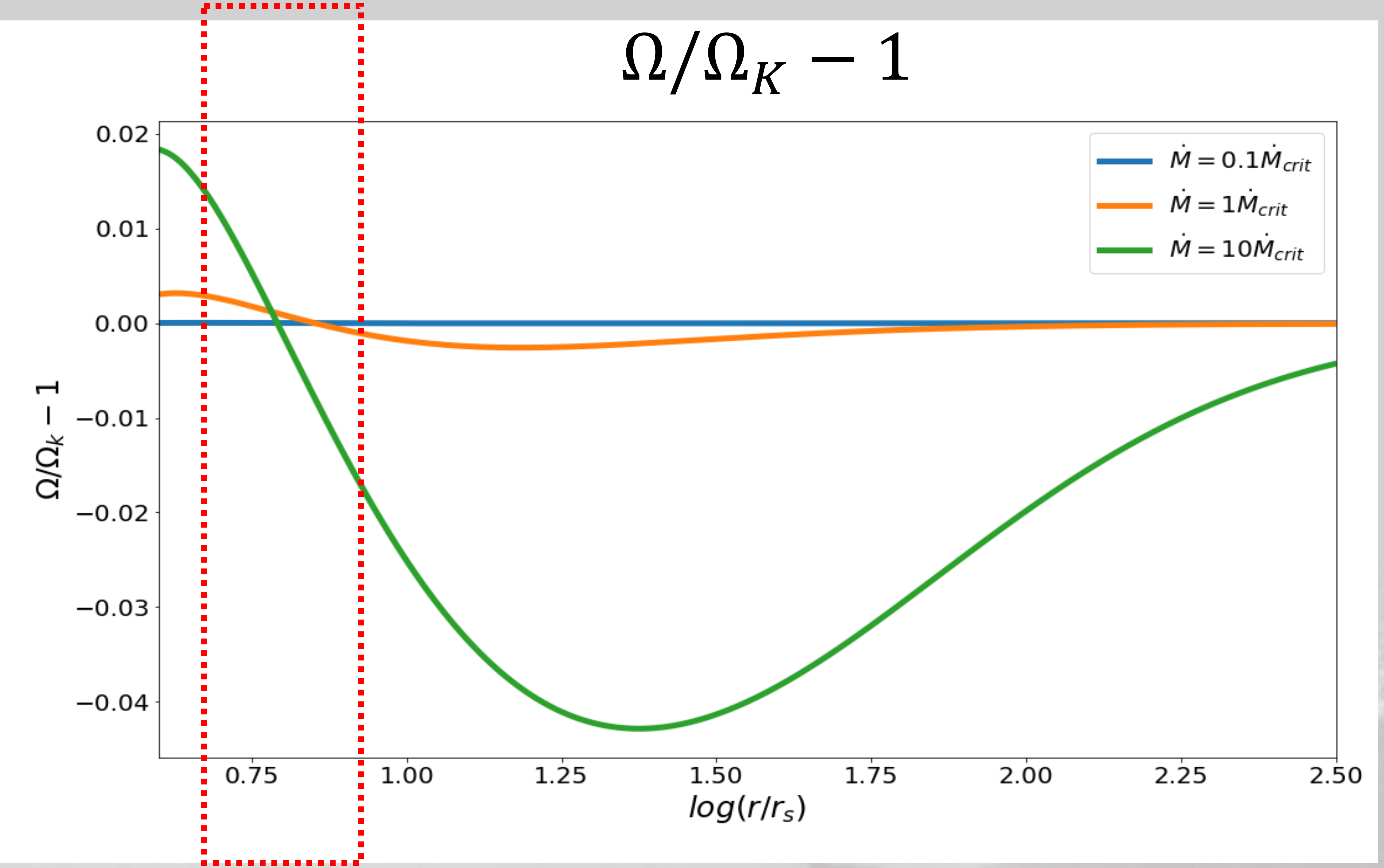
Gas with $v_\phi > v_K$ tend to drive outwards migration

Gas with $v_\phi < v_K$ tend to drive inwards migration

Result (Peng&Chen 2021)

Gaseous torque caused by different orbital velocity of the Gas and the BH

The BH may stop here !!



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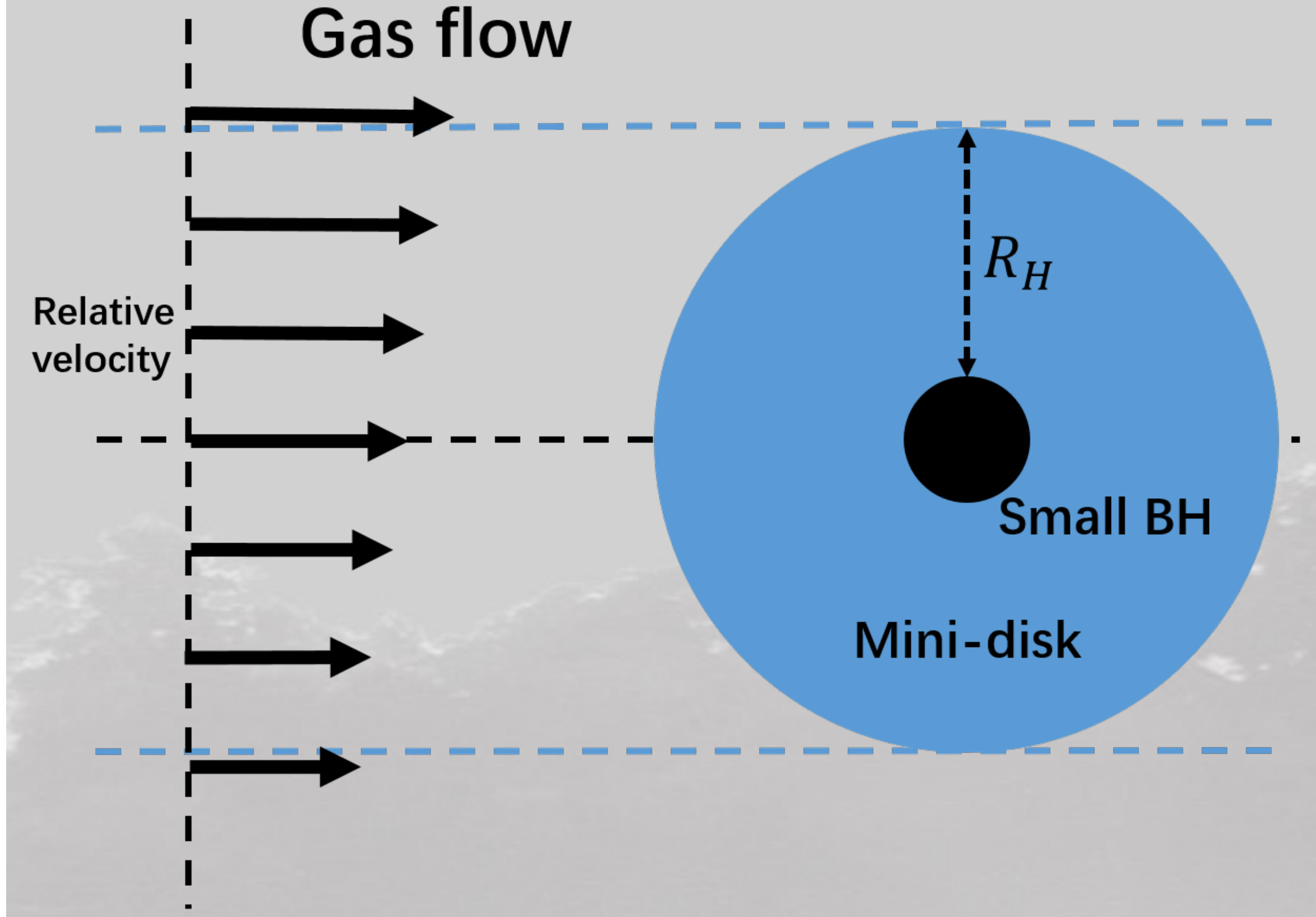

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Result (Peng&Chen 2021)

Existence of the 'last migration trap'

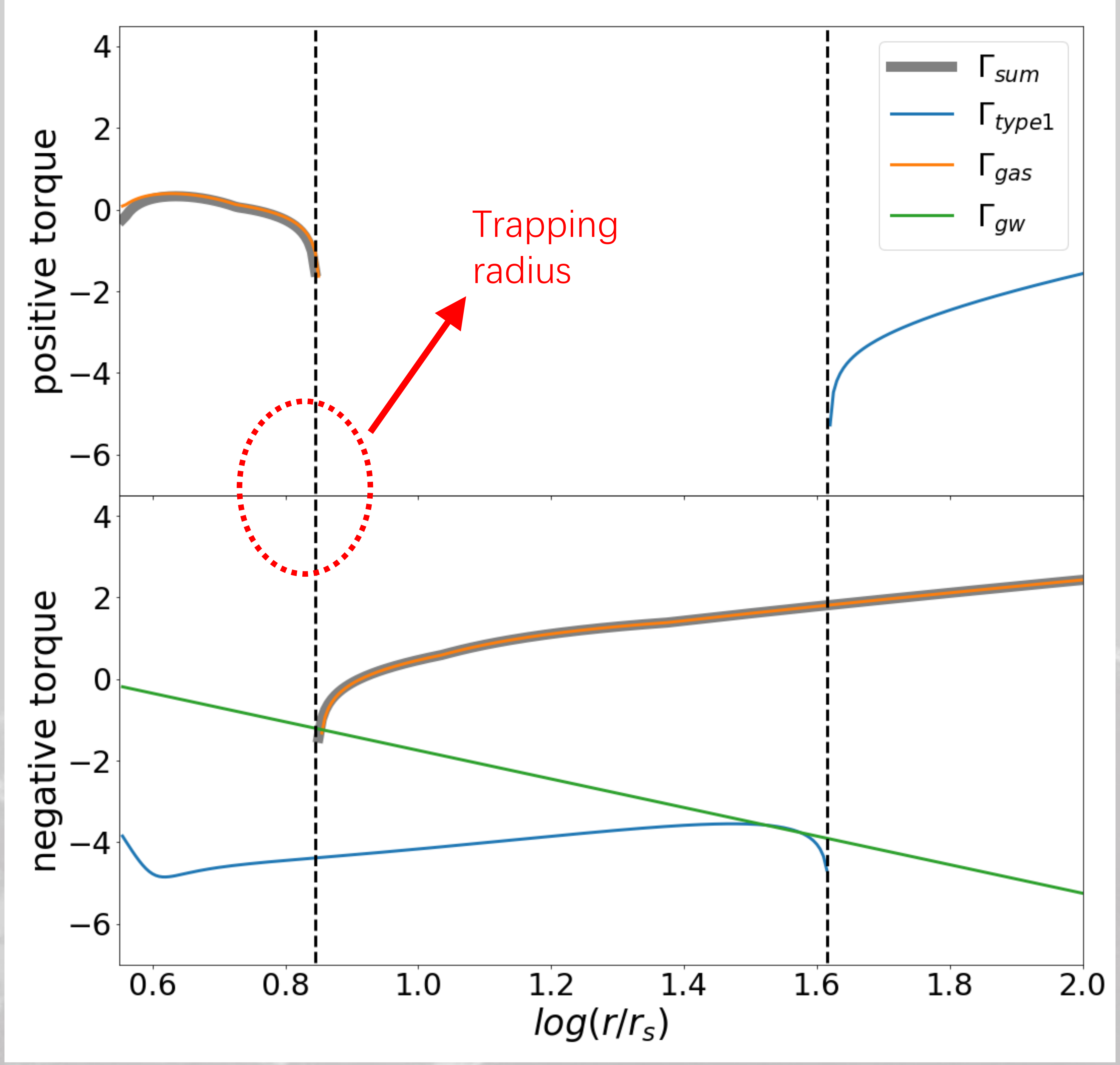
Orange line:
Head wind/ Tail wind

Blue line:
Type-I migration torque

Green line:
Gravitational wave radiation

Grey line: whole torque

The wind dominates and trap the small BH ~ 7 R_s



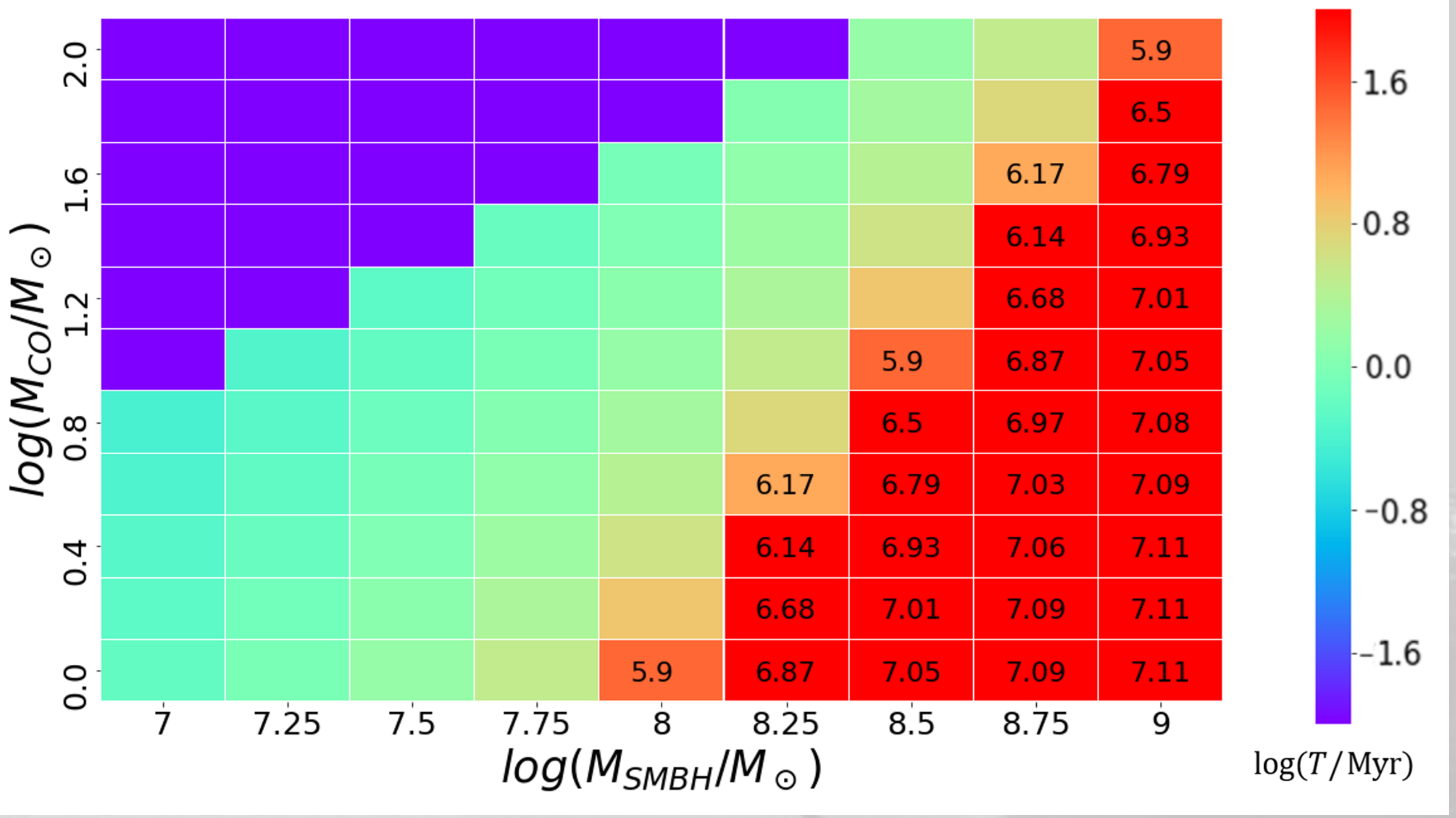
$$M_{SMBH} = 10^9 M_\odot, M_{BH} = 10 M_\odot, \dot{M} = \dot{M}_{Edd}$$

Positive torque
(y-axis in logarithmic coordinate)

Negative torque
(y-axis in logarithmic coordinate)

Result (Peng&Chen 2021)

Parameter spaces where the last migration trap works



$$\dot{M} = \dot{M}_{Edd}, \quad \alpha = 0.01$$

Estimated event rate

$$R = \frac{\frac{1}{2} n_{quasars} N_{BH}}{T_{AGN}}$$

$$\sim 0.4\ Gpc^{-3}\ yr^{-1}$$

- GW bursts and echoes: lensing (e.g. Kocsis 2013, Orazio and Loeb 2020), Penrose process (Gong et al. 2021), Shapiro delay (Sberna et al. 2022)
- Multiband observation: constraint GW dispersion (Han & Chen 2019), SMBH resonates with the binary (Cardoso et al. 2021)

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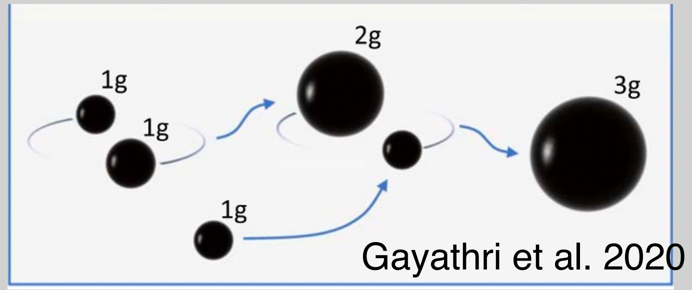
Intermediate-mass BH can be common in the AGN disk (Mckernan+2012)

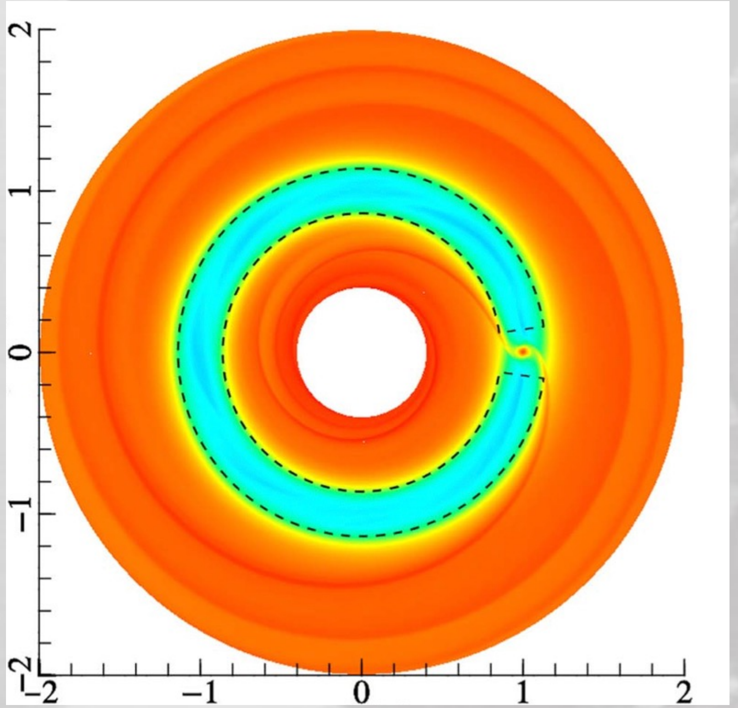
Mass increase:

$$\sim 10\ M_{\odot} \longrightarrow \sim 100 - 1000\ M_{\odot}$$



Gayathri et al. 2020

Gap-opening intermediate-mass BH



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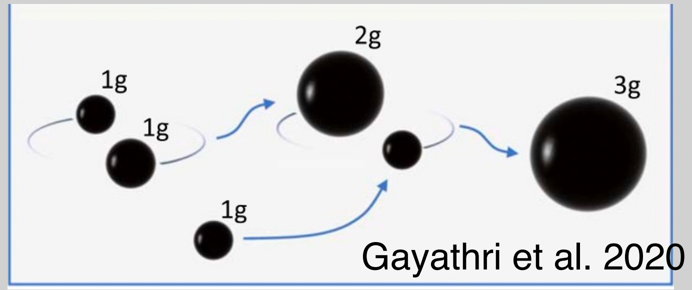

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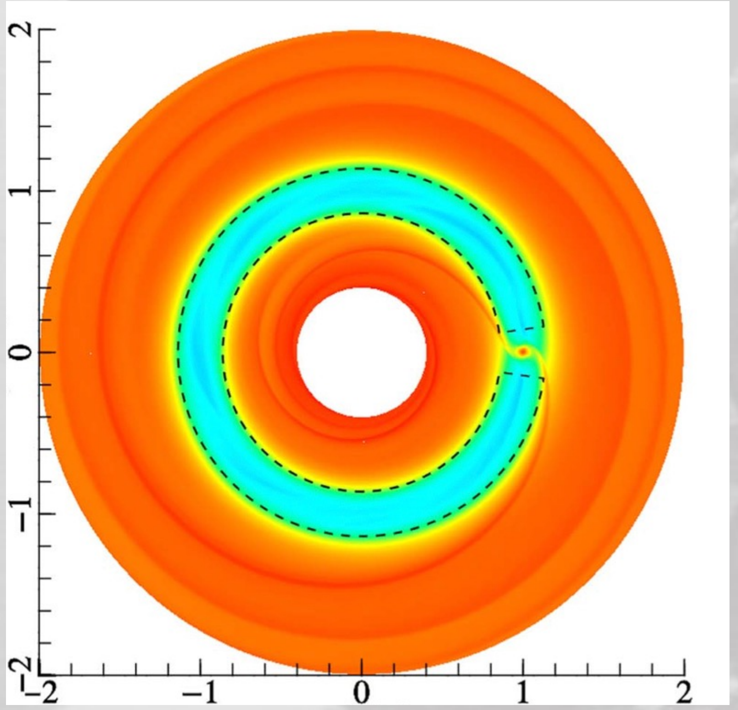

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Gap-opening object: Type-II migration
(Lin & Papaloizou 1986a,b)

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

Sub-gap-opening object: Type-I migration
(Goldreich & Tremaine 1979, Artymowicz 1993; Ward 1997)

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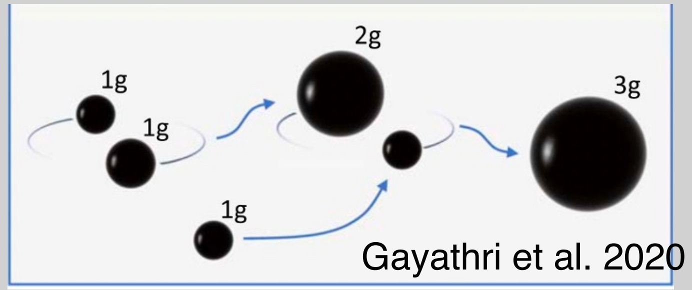

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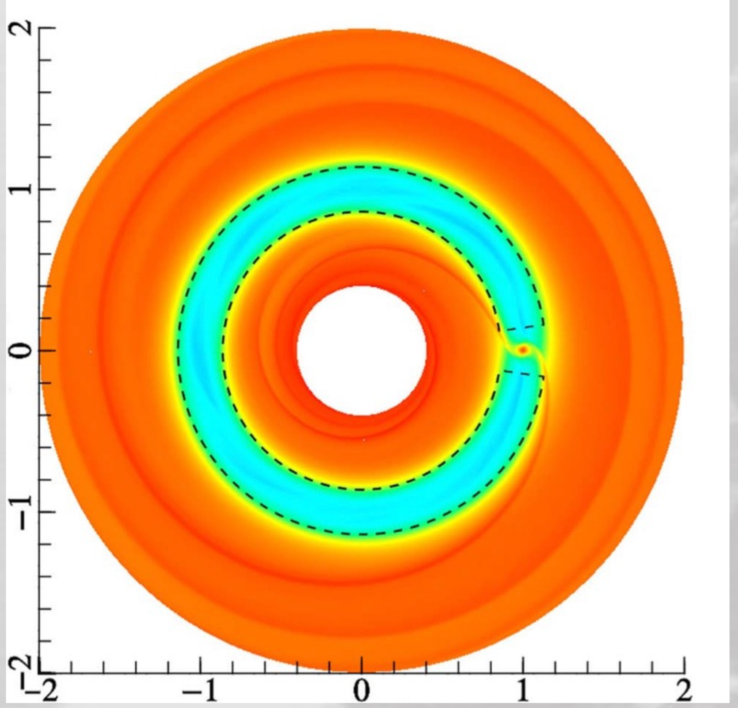

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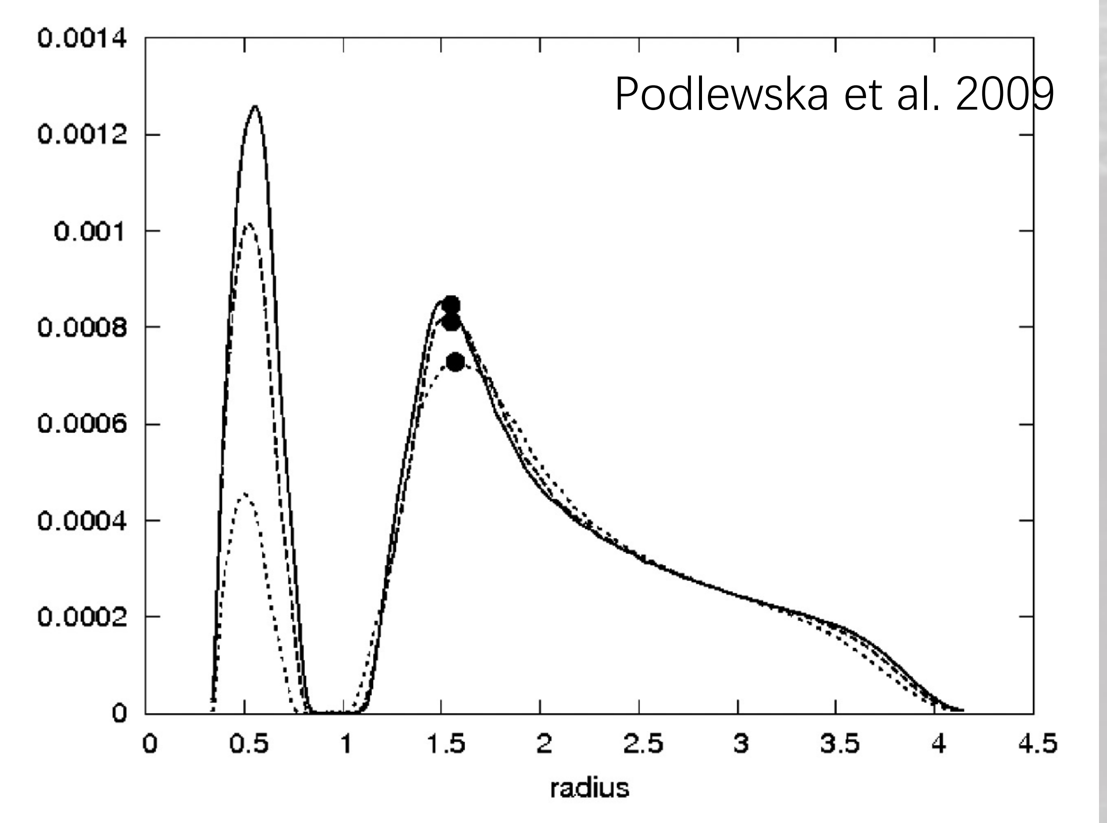
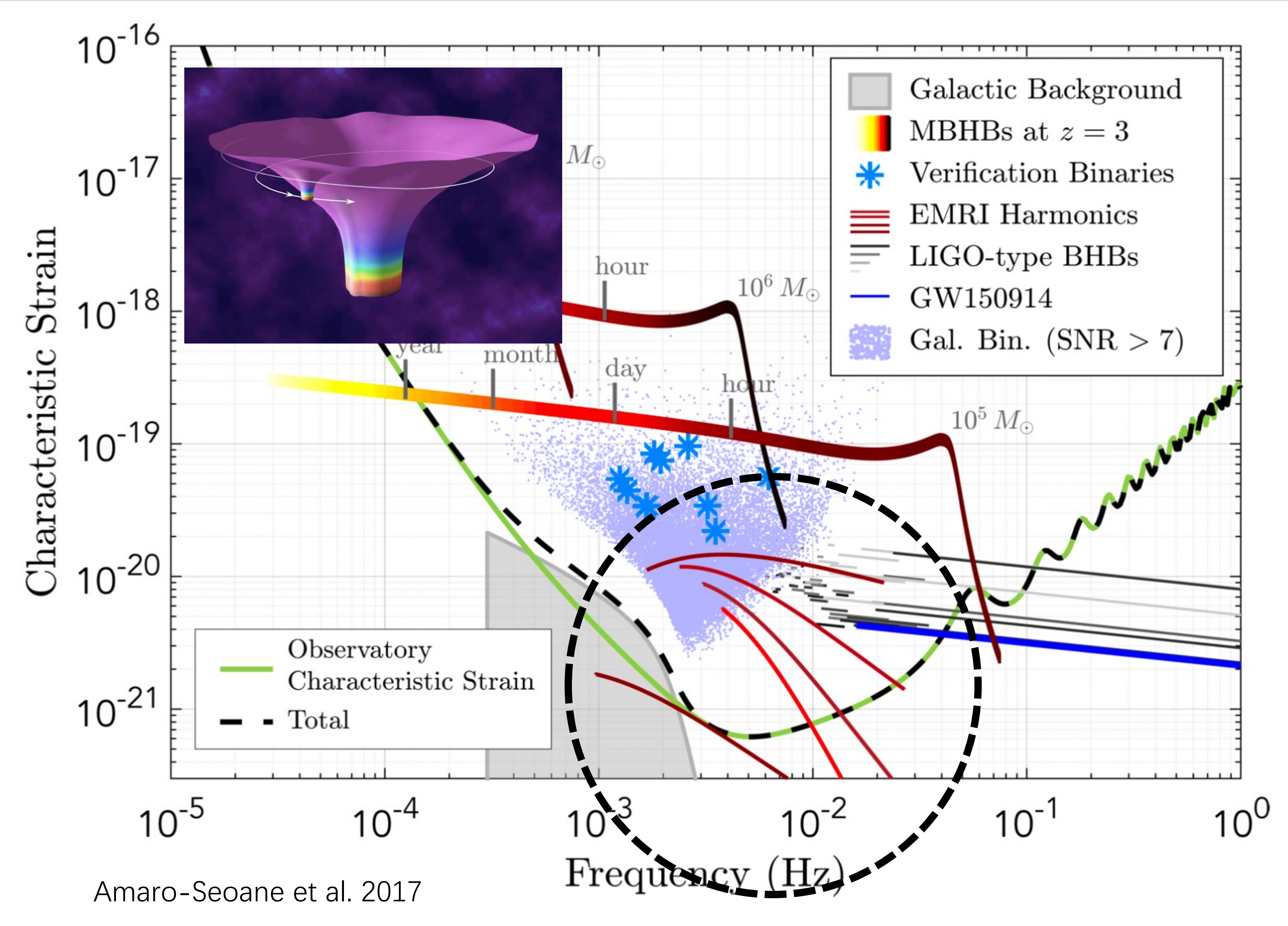
Encounter of the Gap-opening and Sub-gap-opening object. The migration of the small object is totally changed by the gap



Podlewska et al. 2009

Will interaction between the stellar BH and the gap-opening IMBH affects GW of the extreme-mass ratio inspirals and intermediate-mass ratio inspirals?



Amaro-Seoane et al. 2017

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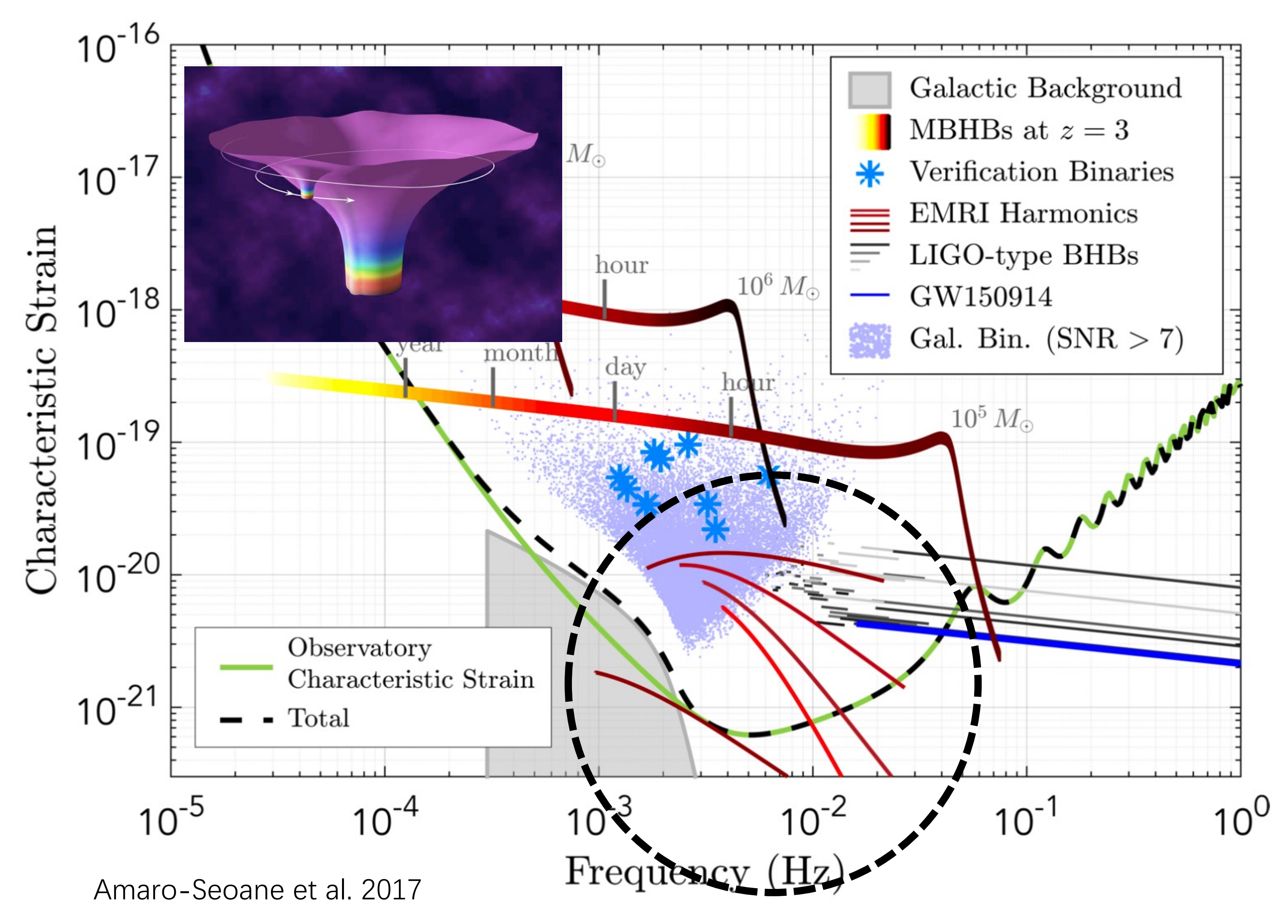

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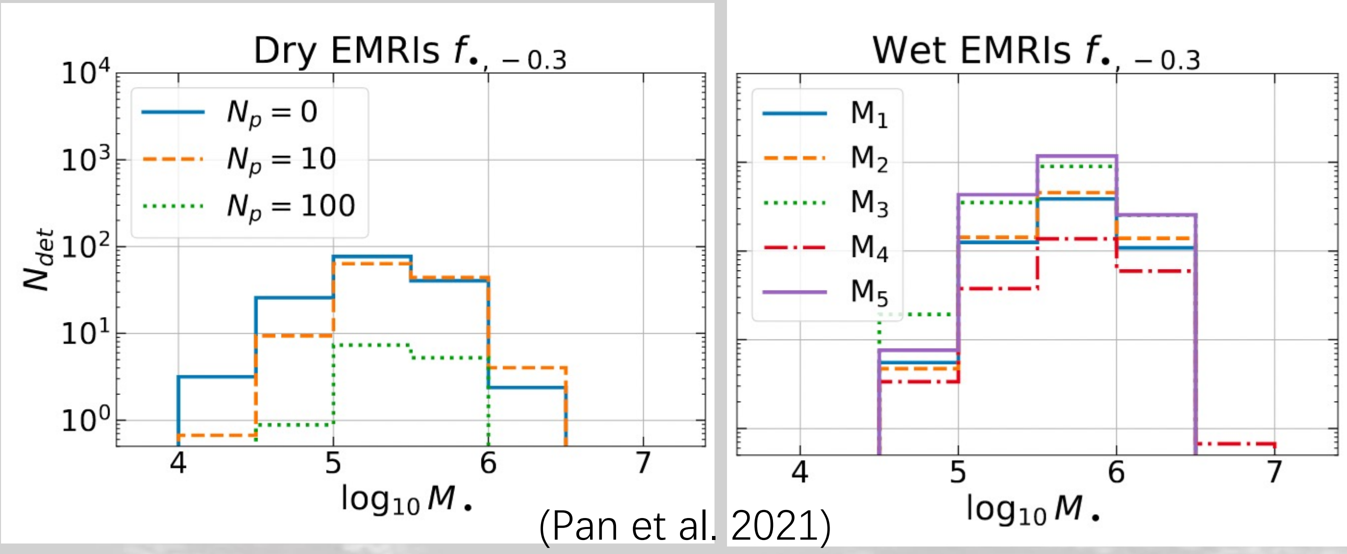


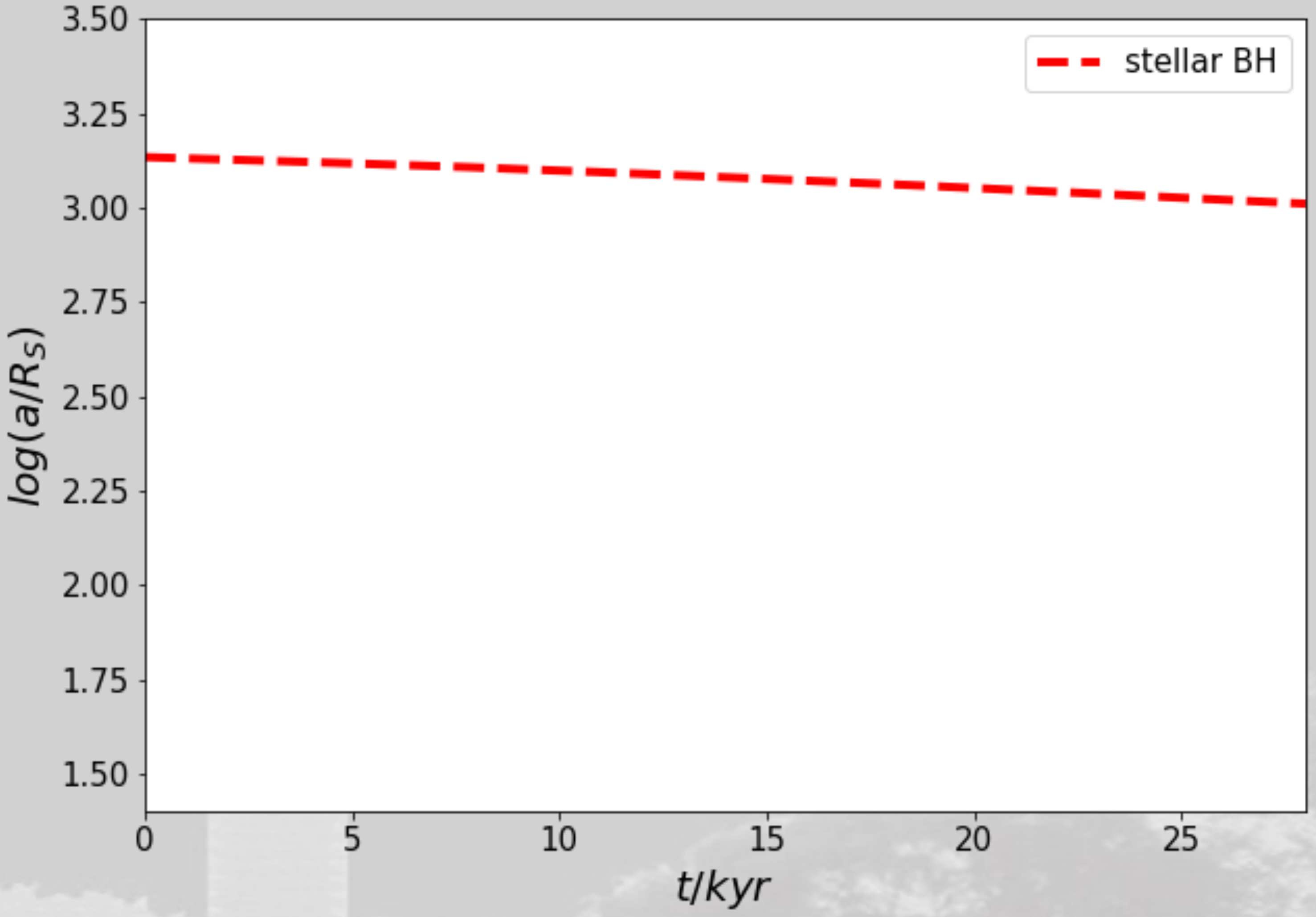
(Pan et al. 2021)

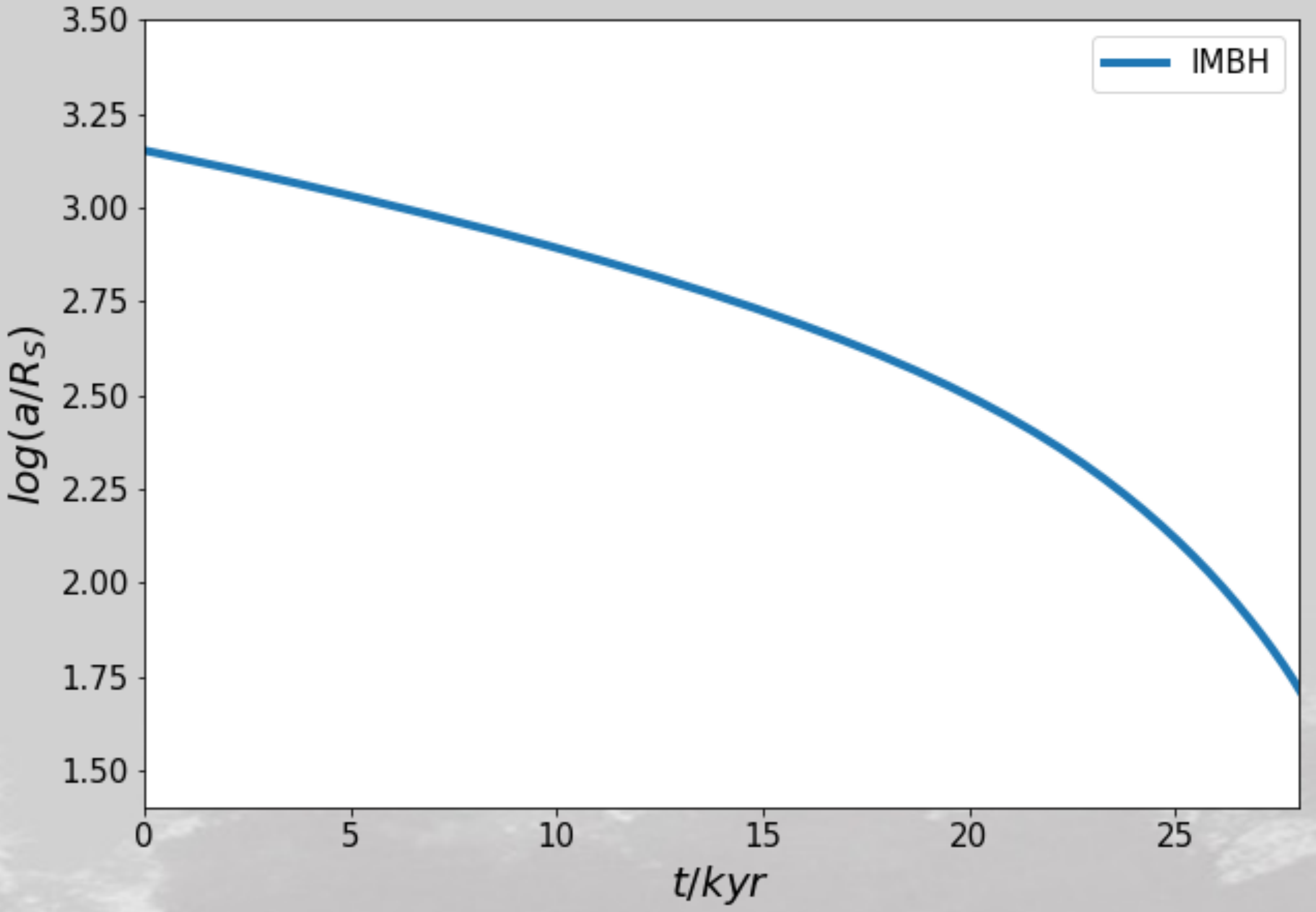
Wet EMRIs can dominate in the future mHz GW detection

Due to the large number of GW phase cycles (> 1000), EMRI and IMRI can provide rich information on the spacetime geometry near the SMBH

Result (Peng&Chen 2023)

Differential migration of the stellar-mass BH and the IMBH





$$T_I = 10^4 f_1 \left(\frac{m_{\rm sBH}}{10 M_\odot}\right)^{-1} \left(\frac{M_{\rm SMBH}}{10^6 M_\odot}\right)^{3/2} \left(\frac{h}{10^{-2}}\right)^2 \times \left(\frac{\Sigma}{10^6\,{\rm g\,cm^{-2}}}\right)^2 \left(\frac{a_s}{1000 R_s}\right)^{-1/2} {\rm yrs},$$

$$T_{II} = 10^4 \left(\frac{M_{\rm SMBH}}{10^6 M_\odot}\right)^{-1/2} \times \left(\frac{h}{10^{-2}}\right)^{-2} \left(\frac{\alpha}{10^{-2}}\right)^{-1} \left(\frac{a_I}{1000 R_s}\right)^{3/2} {\rm yrs}$$

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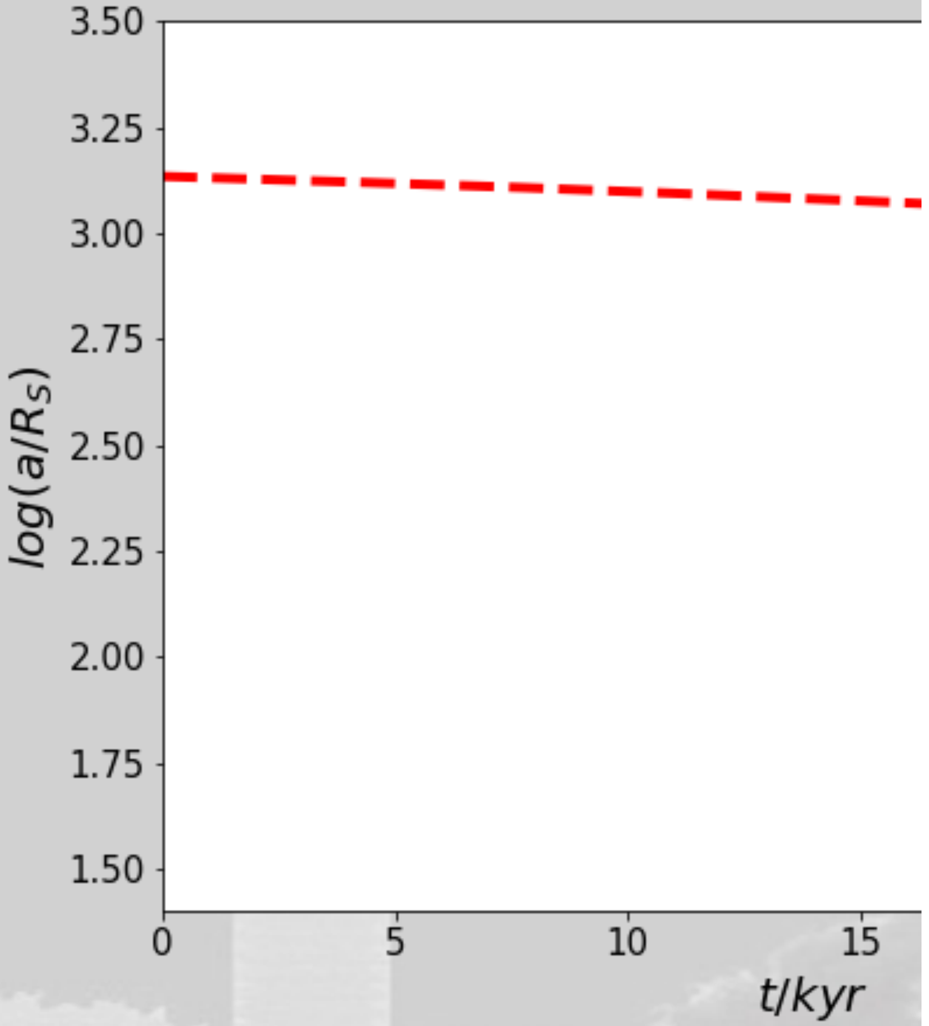
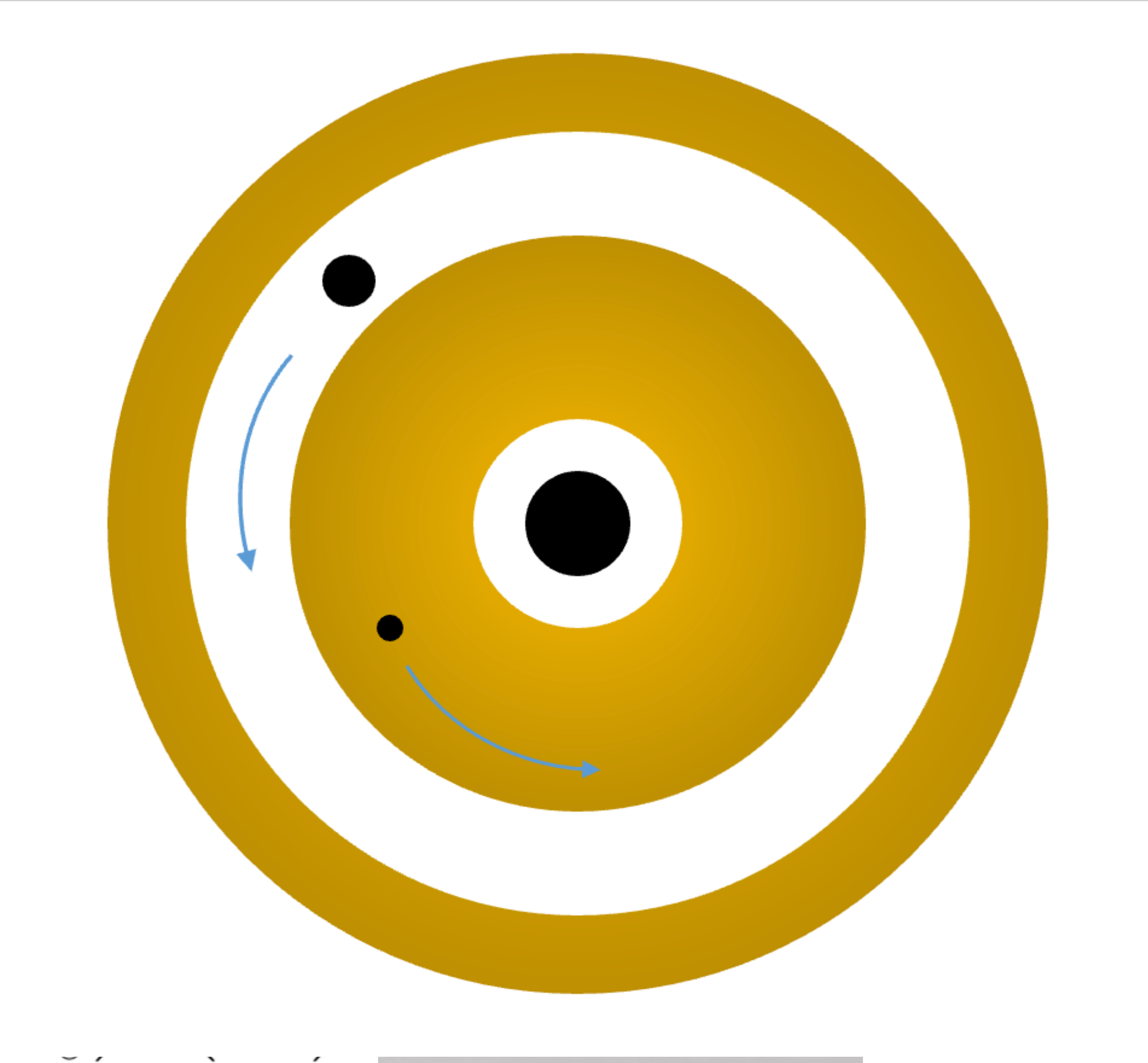
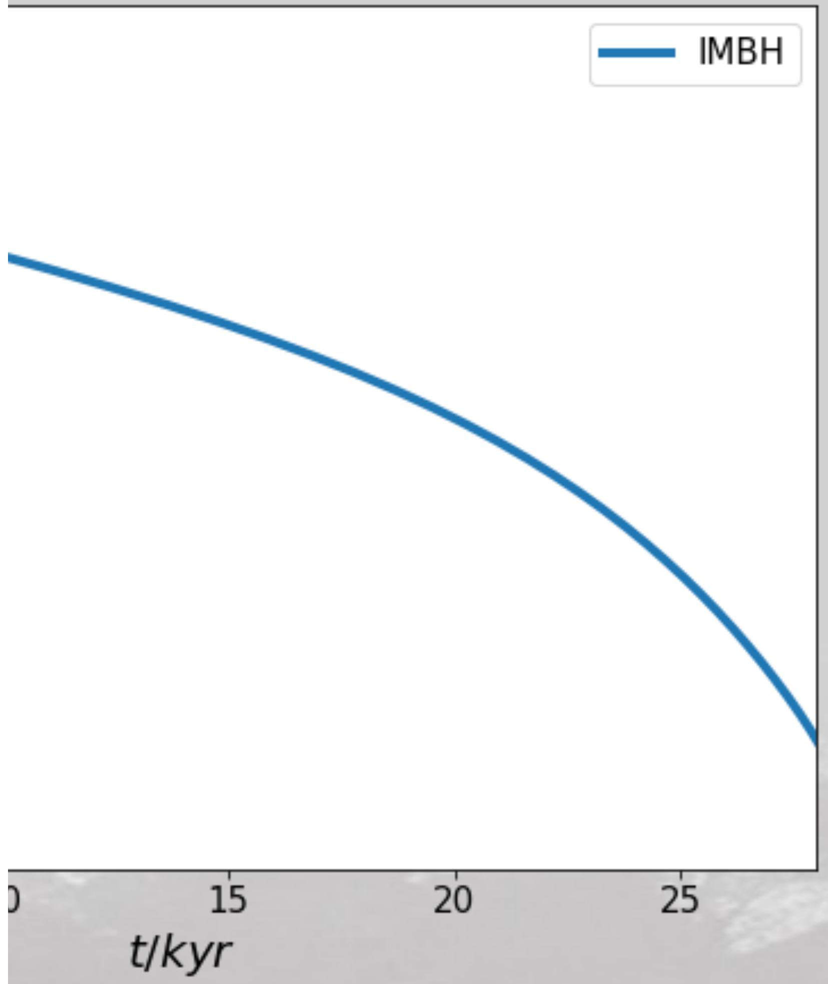






$$T_I = 10^4 f_1 \left(\frac{m_{\rm sBH}}{10M_\odot}\right)^{-1} \left(\frac{M_{\rm S}}{10}\right.$$

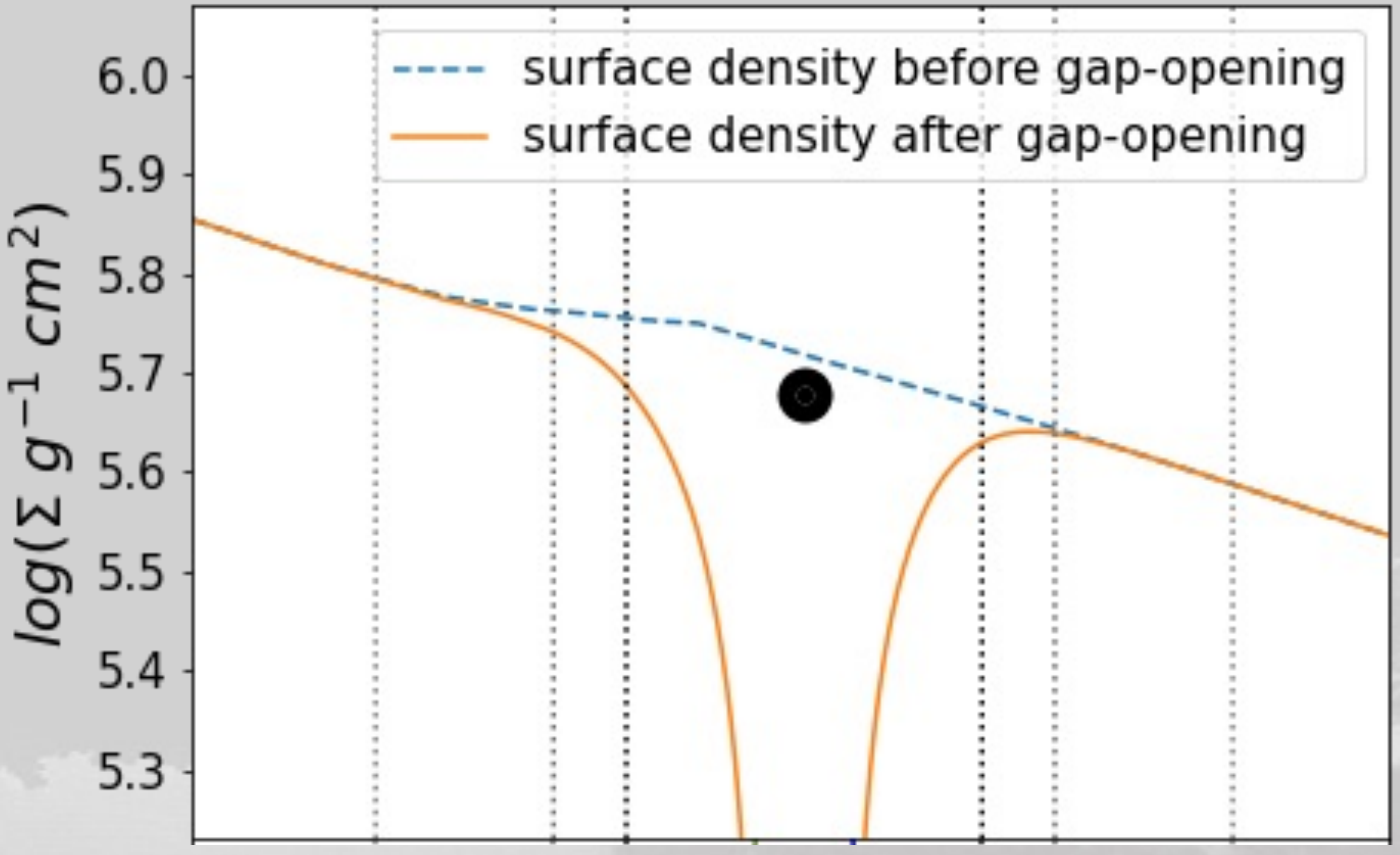
$$\times \left(\frac{\Sigma}{10^6\,{\rm g\,cm^{-2}}}\right)^2 \left(\frac{a_s}{1000R_s}\right)^{-1/2} {\rm yrs},$$

$$= 10^4 \left(\frac{M_{\rm SMBH}}{10^6 M_\odot}\right)^{-1/2}$$

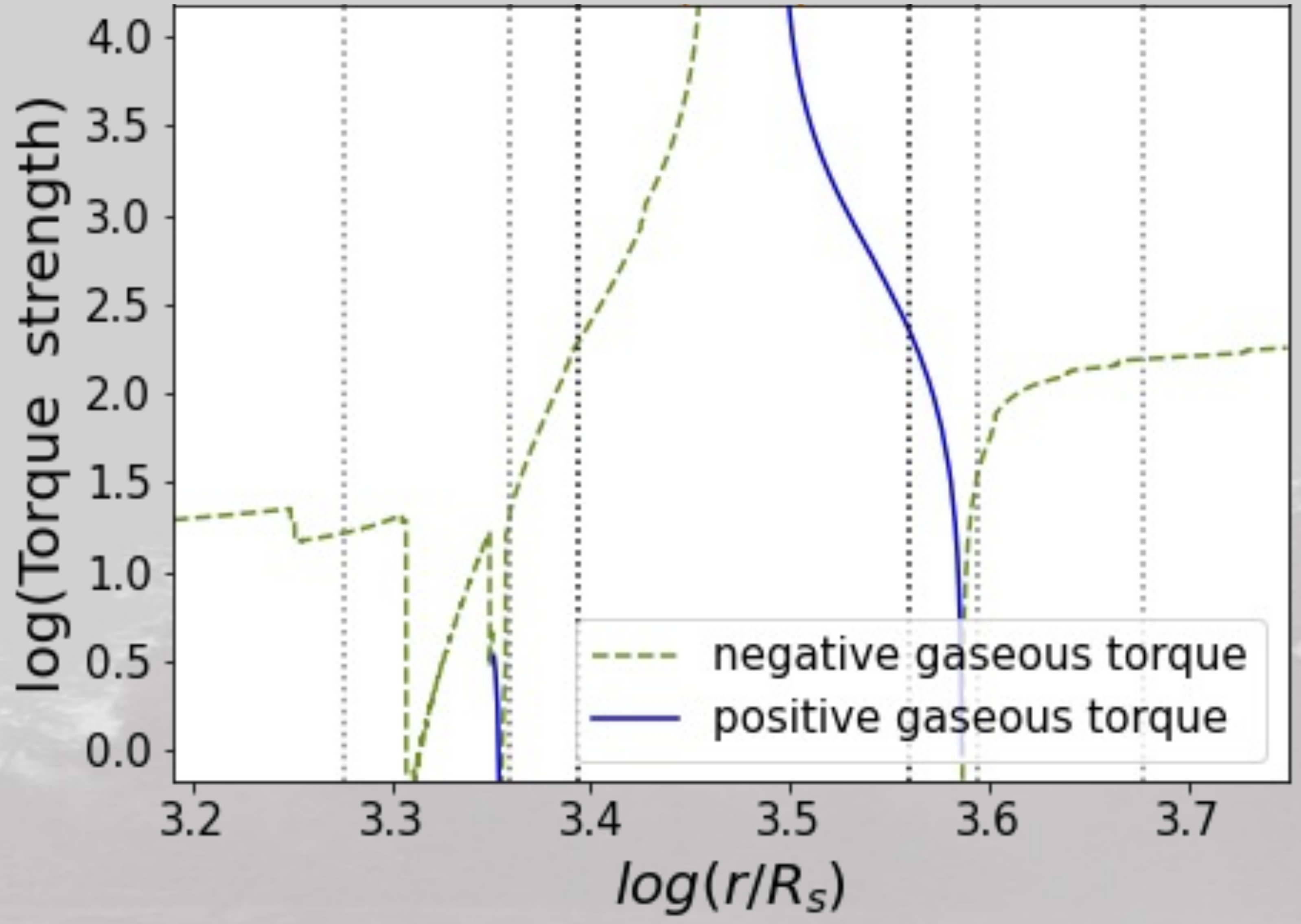
$$\times \left(\frac{h}{10^{-2}}\right)^{-2} \left(\frac{\alpha}{10^{-2}}\right)^{-1} \left(\frac{a_I}{1000R_s}\right)^{3/2} {\rm yrs}$$

Result (Peng&Chen 2023)

The stellar-mass BH near the gap tends to be “pushed away” by the hydrodynamical and gravitational torque



Ω_s/Ω_I= 2:1 3:2 4:3 3:4 2:3 1:2



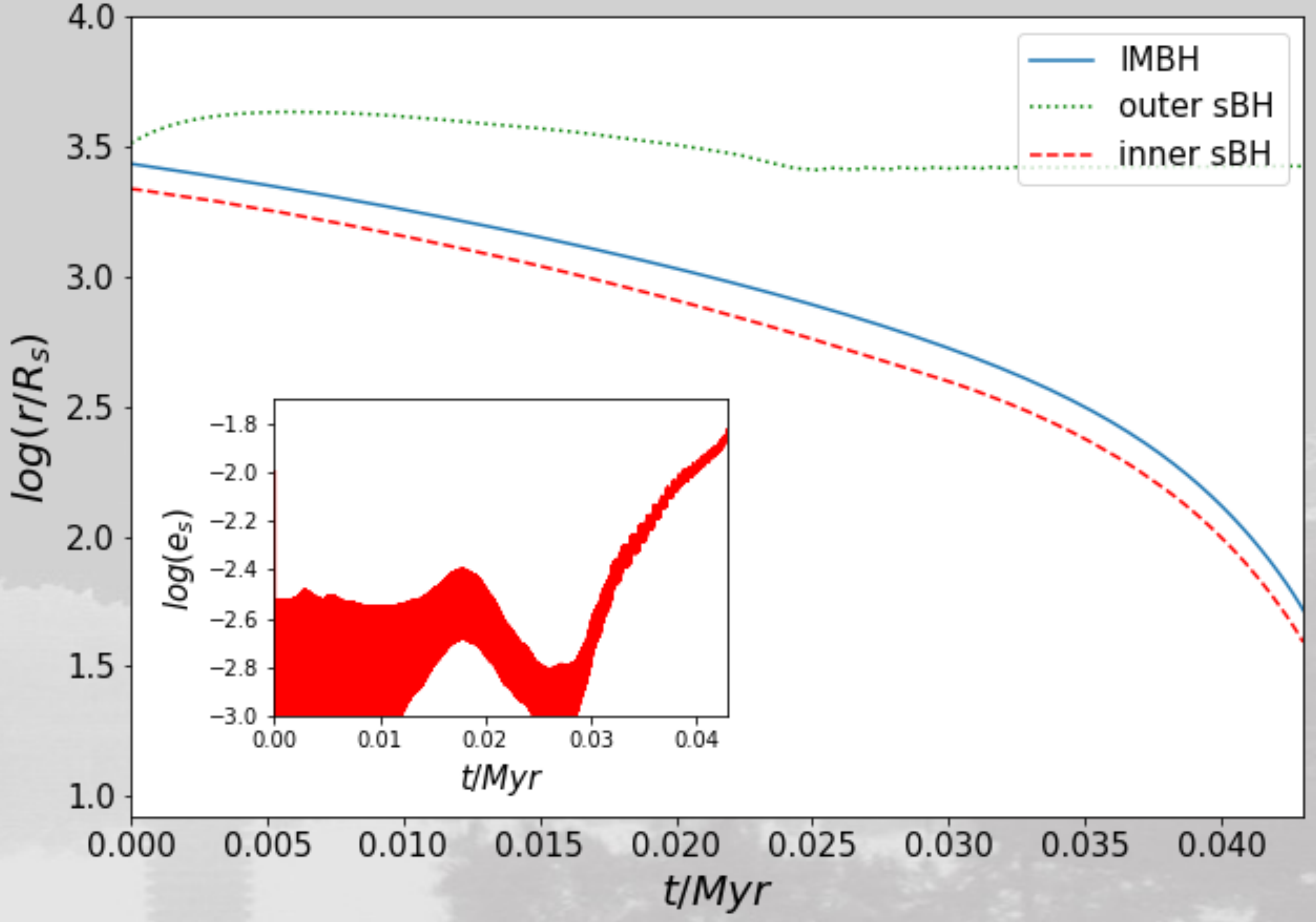
$$\frac{\dot{a}_s}{a_s} = -4\,\mathrm{sgn}(\Omega_s - \Omega_I)\,|f_d| e_s \Omega_s \frac{m_{IMBH}}{M_{IMBH}} \sin(\varphi)$$

Vertical dashed line: locations of mean-motion resonances

$$\gamma\Gamma_{\rm ad}/\Gamma_0 = -0.85 - \alpha - 1.7\beta + 7.9\xi/\gamma.$$

Result (Peng&Chen 2023)

Formation and early evolution of stellar-mass BH —— IMBH pair

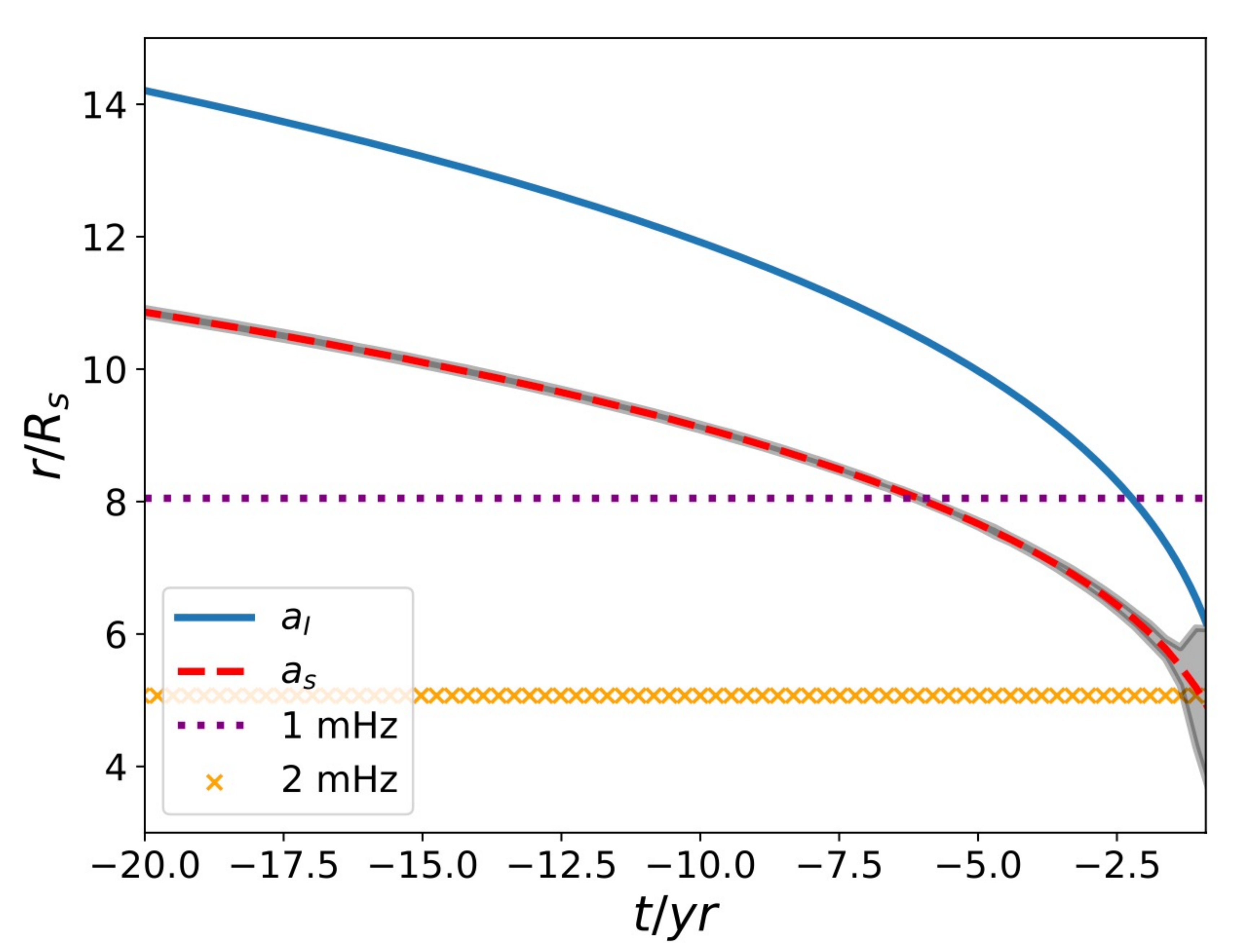


IMBH 'pushes' the stellar BH to migrate inward with the same migration timescale.

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

Result (Peng&Chen 2023)

Later evolution in the GW regime: EMRI-IMRI pair



The EMRI and IMRI can be detected simultaneously

- If ignored in the waveform model, it may induce non-negligible biases in the estimated parameters (e.g. Gupta 2022)
- 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. (e.g. Speri&Gair 2021, Gupta 2022)
- Rich information about the formation and evolution of sBHs and IMBHs in AGNs.

Summary

- The stellar-mass BHs migrate inwards and get trapped to $r \lesssim 10R_s$, driven by the gas in high accretion rate AGN disks or a gap-opening compact object. **1%** the LIGO/Virgo sources can possibly merge in the last migration trap.

- A gap-opening IMBH can trap the stellar BHs inside its orbit, push it to migrate inward and form a stellar BH-IMBH pair. The subsequent migration of the two BHs is synchronized until they reach a distance of about $\sim 10\ R_s$ from the central SMBH, form the EMRI-IMRI pair.

- The GW signals of the BBH forming in the last migration trap and the EMRI-IMRI pair can be very different from the clean BBH and EMRIs, which can provide rich information about the formation and evolution of stellar-mass BHs and IMBHs in AGNs.