Long-term Evolution of Tightly-Packed Stellar Black Holes in AGN Disks: Formation of Merging Black-Hole Binaries via Close Encounters

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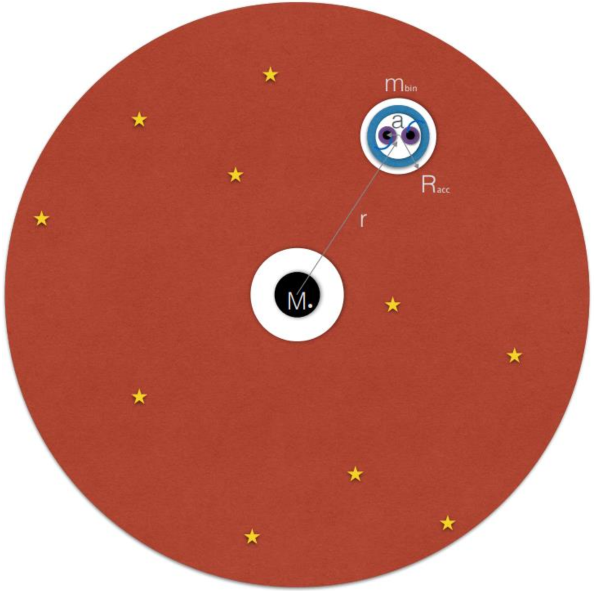
Why do we care about black hole binaries in AGN disks?

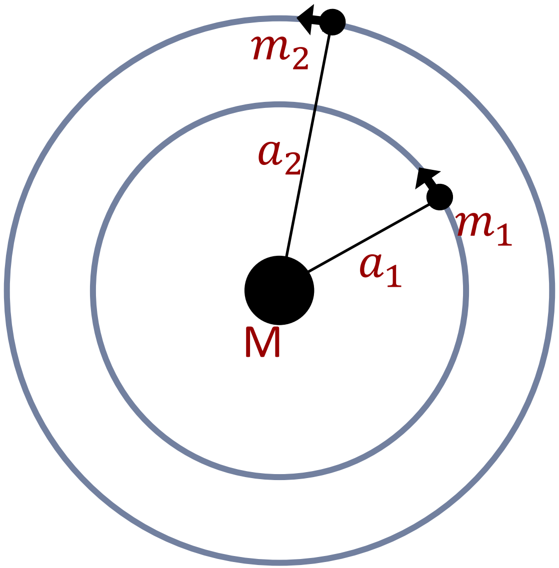


Stone et al. 2017

- Because they may merge! (e.g., Baruteau et al. 2011; Stone et al. 2017; Leigh et al. 2018; Samsing et al. 2020; Li et al. 2021, 2022; Li & Lai 2022)

- **Q: How to form BH binaries in AGN disks? ------ Close encounters between embedded single BHs.**

Our study: long-term **N-body simulations** of SMBH + embedded BHs



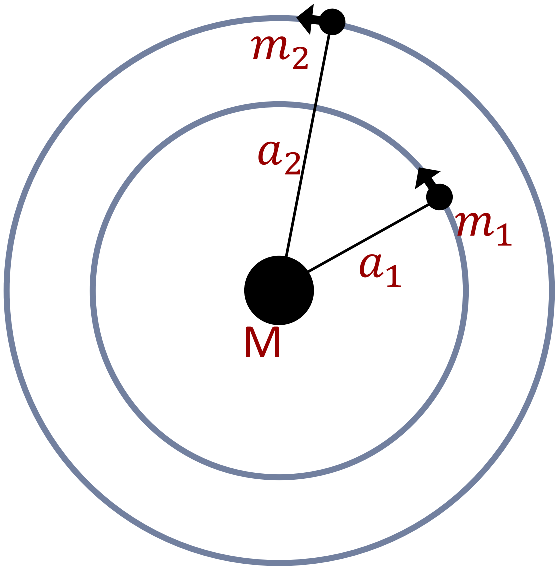
- Initial condition:

  $$\boldsymbol{a_2 - a_1 = 2R_{\mathrm{H}}} \quad \text{where} \quad R_{\mathrm{H}} = \frac{a_1 + a_2}{2}\left(\frac{m_1 + m_2}{3M}\right)^{1/3}$$

  (Dynamical instability will occur!)

- Reasons for using closely-packed orbits:
  - Large BH population in an AGN disk
  - Differential migration

Our study: long-term **N-body simulations** of SMBH + embedded BHs



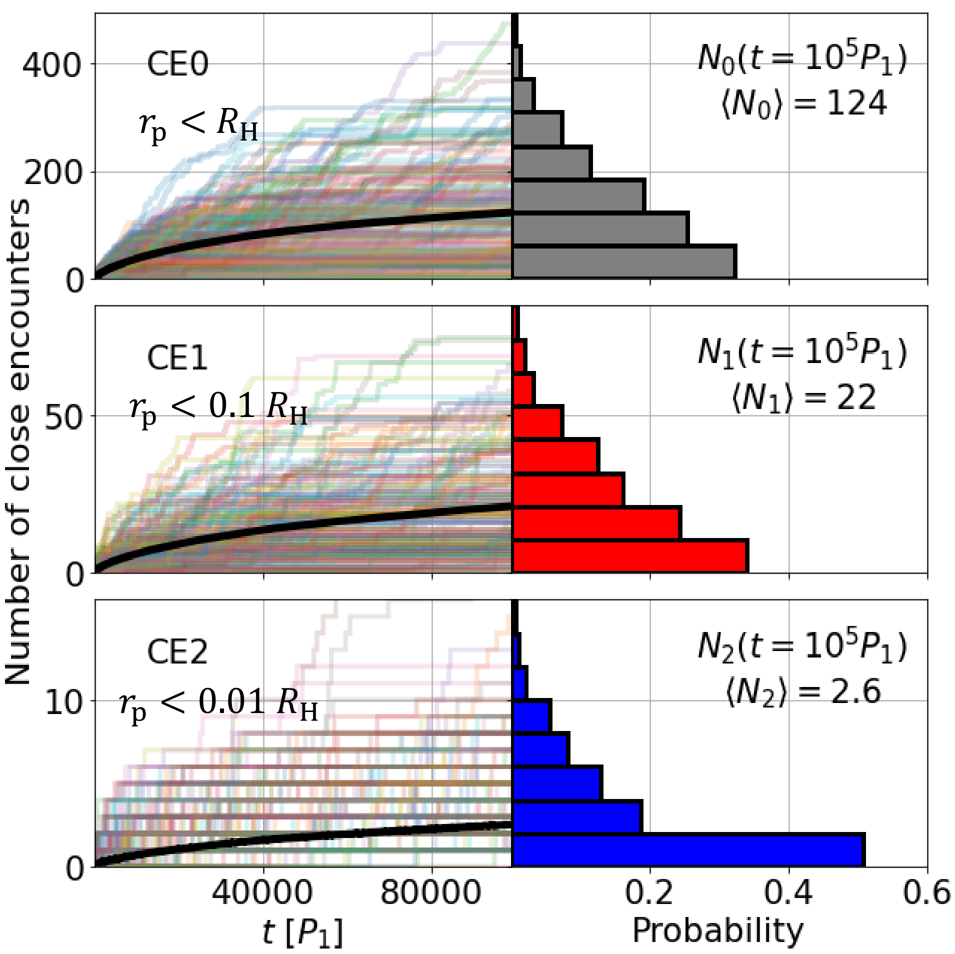
- Simulations:
  - Run for at least $10^5 P_1$ (orbits around the SMBH)
  - Pure N-body and no gas effect for now (gas effect is discussed in the paper).
- Outcomes of this instability:
  - BH collisions? -- unlikely
  - BH ejections? -- requires very long time
  - **Recurring close encounters** -- will be many! (we can study this stochastic process statistically)

Pure N-body results

Number of close encounters (CE)

r_p: minimum BH separation during a CE

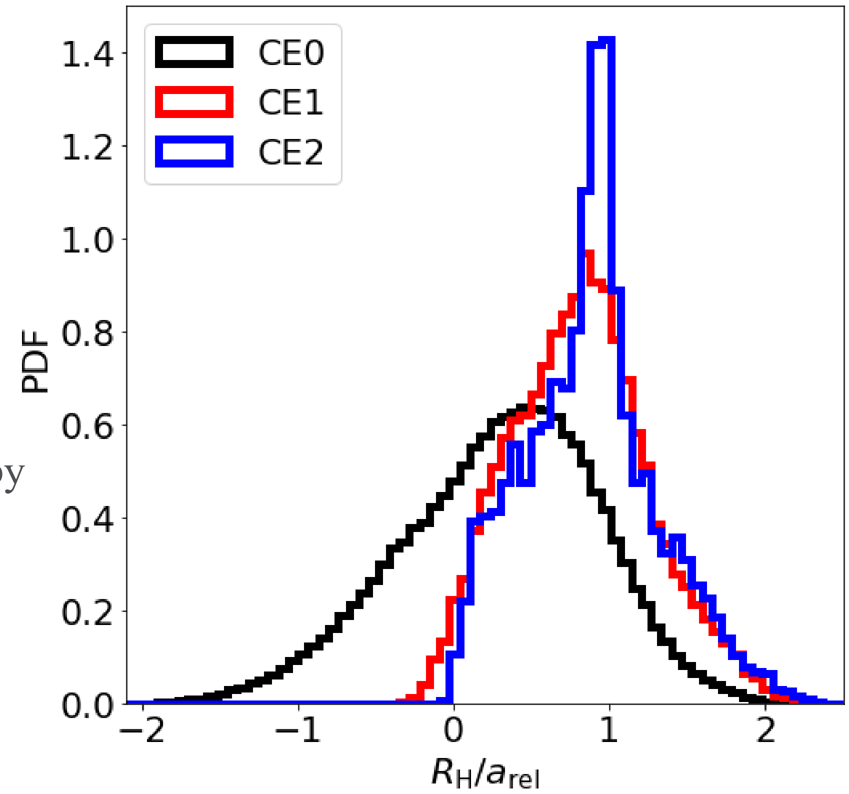
P_1: orbital period around the SMBH



Pure N-body results

$$R_H/a_{rel} = \frac{Gm_1m_2}{2a_{rel}} / \frac{Gm_1m_2}{2R_H}$$

Most BH pairs at close encounters are disrupted by the **SMBH tidal force** within 1 P_1.



Hardening BH encounters with GW radiation

- BHs can be captured into long-lived binary if enough energy is radiated **at once**:

$$\Delta E_{\rm GW} = \frac{85\pi}{12\sqrt{2}} \frac{G^{7/2}\mu^2 m_{12}^{5/2}}{c^5 r_{\rm p}^{7/2}} \gtrsim \eta \frac{G m_1 m_2}{R_{\rm H12}}$$

energy radiated by GW (Quinlan & Shapiro 1989)

energy needs to be removed for binding

- $r_{\rm p}$ needs to be smaller than a critical capture radius:

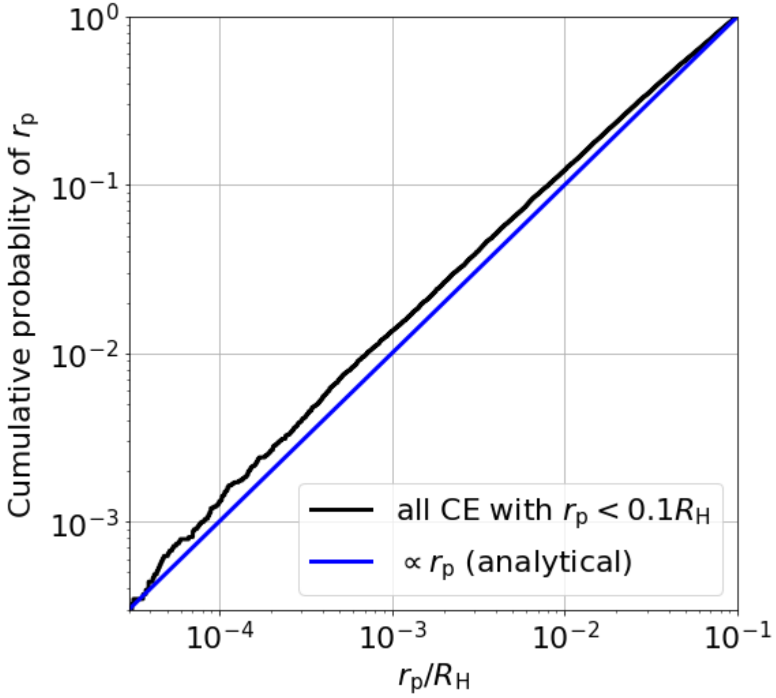
$$\frac{r_{\rm p}}{R_{\rm H}} < \frac{r_{\rm cap}}{R_{\rm H}} \simeq 10^{-4} \left(\frac{4\mu}{m_{12}}\right)^{\frac{2}{7}} \left(\frac{10^6 m_{12}}{M}\right)^{\frac{10}{21}} \left(\frac{a_{\rm SMBH}}{100GM/c^2}\right)^{-5/7}$$

Hardening BH encounters with GW radiation

- r_p needs to be smaller than the critical capture radius:

$$\frac{r_\mathrm{p}}{R_\mathrm{H}} < \frac{r_\mathrm{cap}}{R_\mathrm{H}} \simeq 10^{-4}$$

- We show numerically and analytically that **r_p follows a power-law cumulative probability distribution**, which allows r_p to be arbitrarily small.



Calculate the GW capture rate:

Number of binaries formed = (Probability of $r_p < r_{cap}$ for one CE) × (Number of CEs)

$$\langle N_{\rm capture}\rangle \simeq 6\times10^{-5}\left(\frac{t}{P_1}\right)^{0.52}\left(\frac{r_{\rm cap}}{10^{-4}R_{\rm H}}\right)$$

Fiducial results: Average systems take $\sim 10^8 P_1$ to get one GW capture.

** We expect these captured binaries to merge quickly. Their mergers will show high eccentricities when entering the LIGO band.*

Dissipation through disk gas

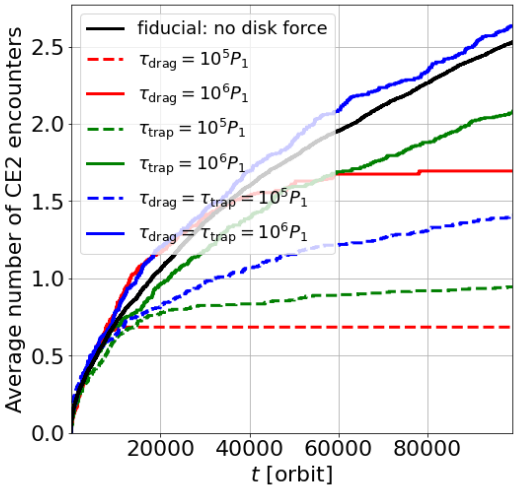
- **Drag force and torque from the AGN disk:**
  - Considered in our paper:

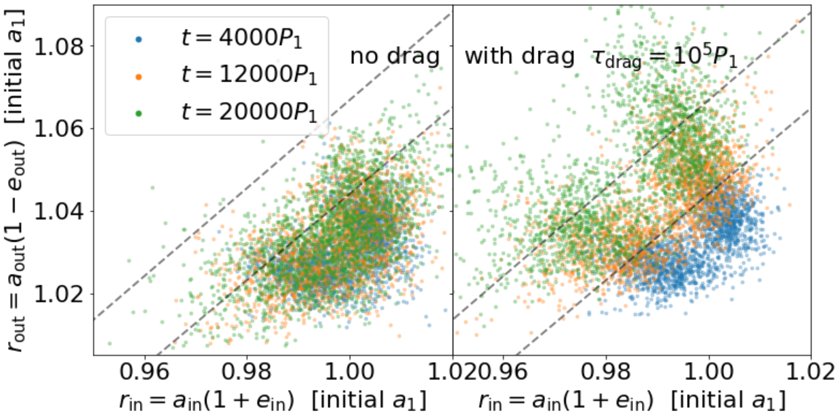
$$\boldsymbol{F}_{\rm drag} = -\frac{\boldsymbol{v} - \boldsymbol{v}_{\rm K}}{\tau_{\rm drag}},$$

$$\boldsymbol{F}_{\rm trap} = -\frac{\Omega_{{\rm K},0}(r - r_0)}{\tau_{\rm trap}}\hat{\boldsymbol{\theta}},$$

  - They **do not** increase the GW capture rate.

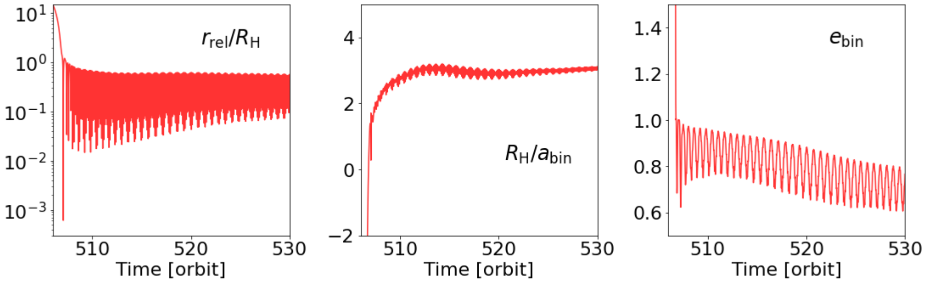
(**Li**, Lai, and Rodet 2022, arxiv:2203.05584)

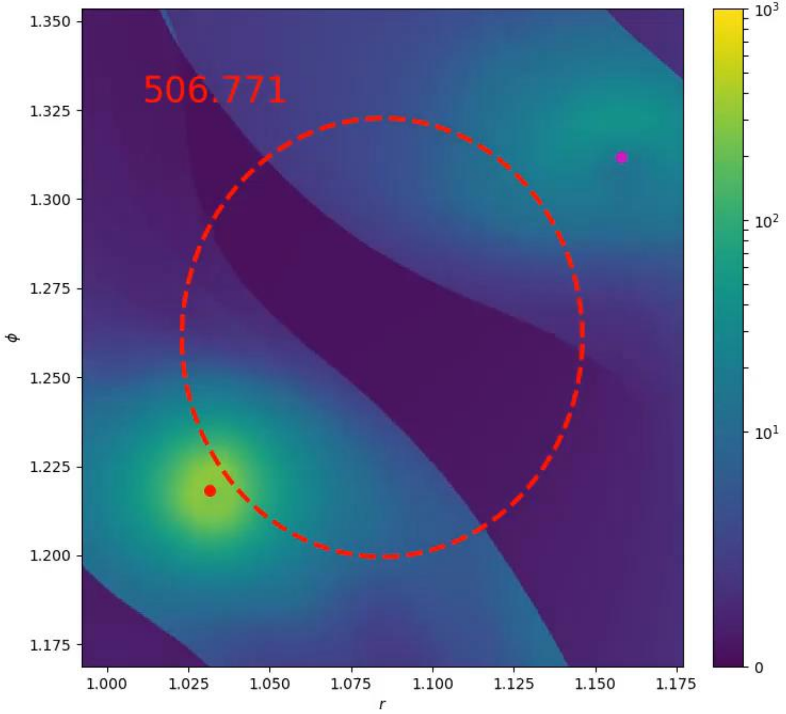




Dissipation through disk gas

- **Collisions** between circum-stellar-BH disk (ongoing work, **Li** et al. 2022 in prep).





Takeaways:

- Dynamical instability in AGN disks produces lots of CEs:
  - Without dissipation, CE pairs are **short-lived**.
  - Separation at CEs can be short enough for GW emission.

- GW radiation can **capture** BHs into binary:
  - Capture efficiency ~ $\boldsymbol{N(t) \times \mathrm{Prob}(r_{\mathrm{p}} < r_{\mathrm{cap}})}$
  - Our average systems take ~ $10^8 P_1$ to get one GW capture.

- Check out our paper for more details (**Li**, Lai, & Rodet 2022, arxiv:2203.05584):
  - Gas effects; Parameter studies (mass, inclination, etc.); More explanations and discussions.

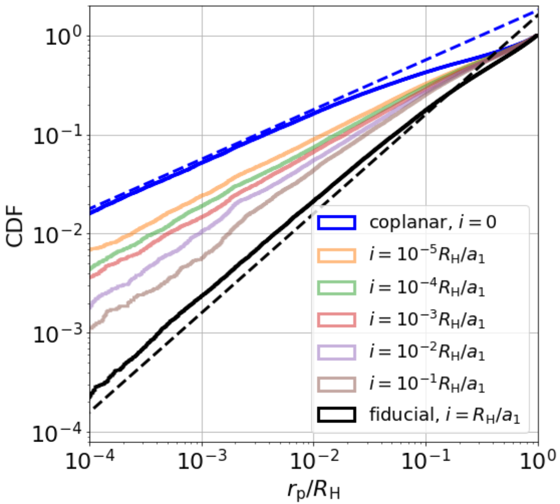
Inclinations

- Exactly co-planar systems have the highest GW capture rate:

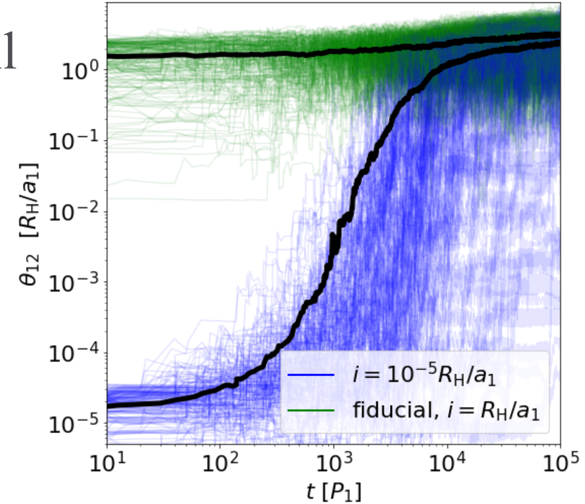
  $\sim 10^8 P_1$ per capture

- However, exact co-planarity is not realistic because any non-zero small mutual inclination can grow.

(**Li**, Lai, and Rodet 2022, arxiv:2203.05584)



Prob(r_p) changes with the mutual inclination.



Small mutual inclination converges to our fiducial inclination.