Formation of Black Hole Binaries in AGN disks through Close Encounters

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Collaborators of this project:
Dong Lai and Laetitia Rodet (Cornell)
Hui Li, Adam Dempsey and Shengtai Li (LANL)

Why do we care about BH binaries in AGN disks?

- Mergers in AGN disks may have distinct observable distribution of mass, spin, and eccentricity (e.g., *McKernan+ 2018; Yang+ 2019; Gerosa & Fishbach 2021; **Li**+2022*).

- Mergers may also produce electromagnetic counterparts (e.g., *Stone+ 2017; McKernan+ 2019; Graham+ 2020*).

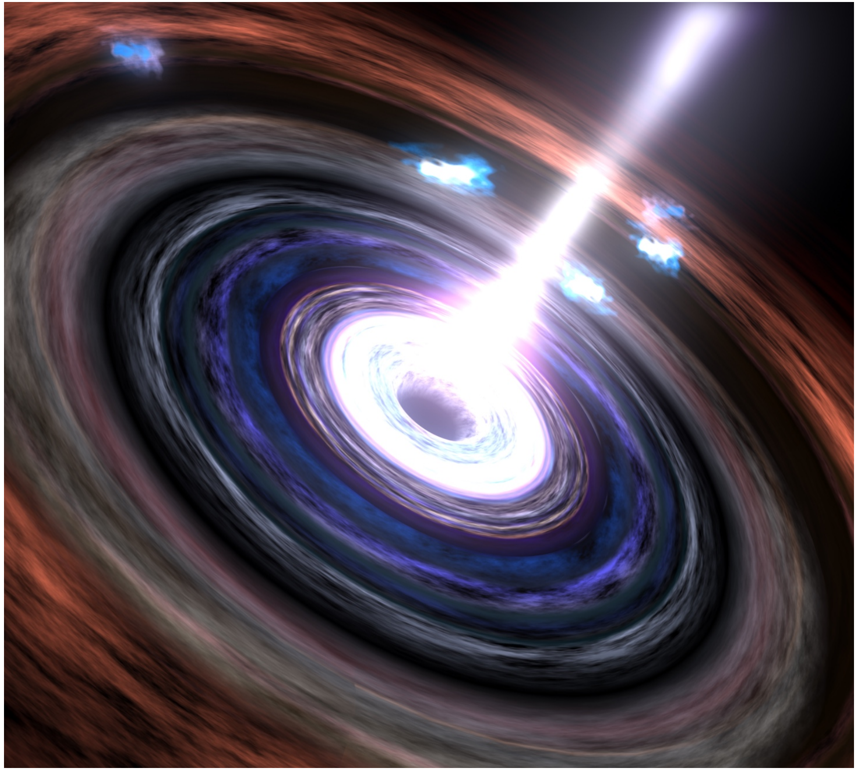
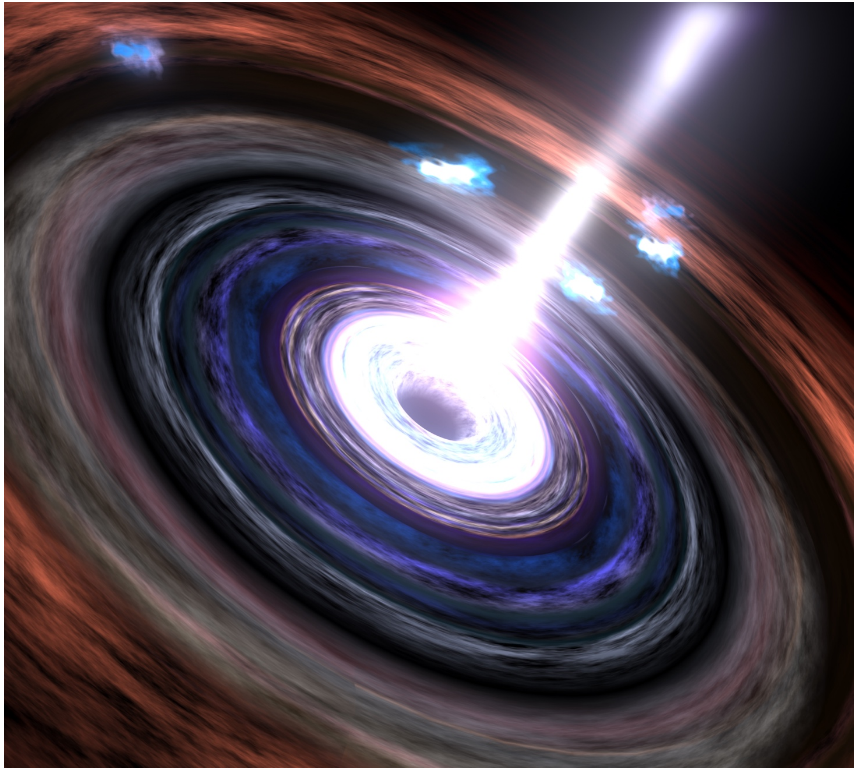


Image Credits: NASA/GSFC Conceptual Image Lab

Why do we care about BH binaries in AGN disks?

- AGN disks may **assist** the BH binaries to evolve toward their mergers.



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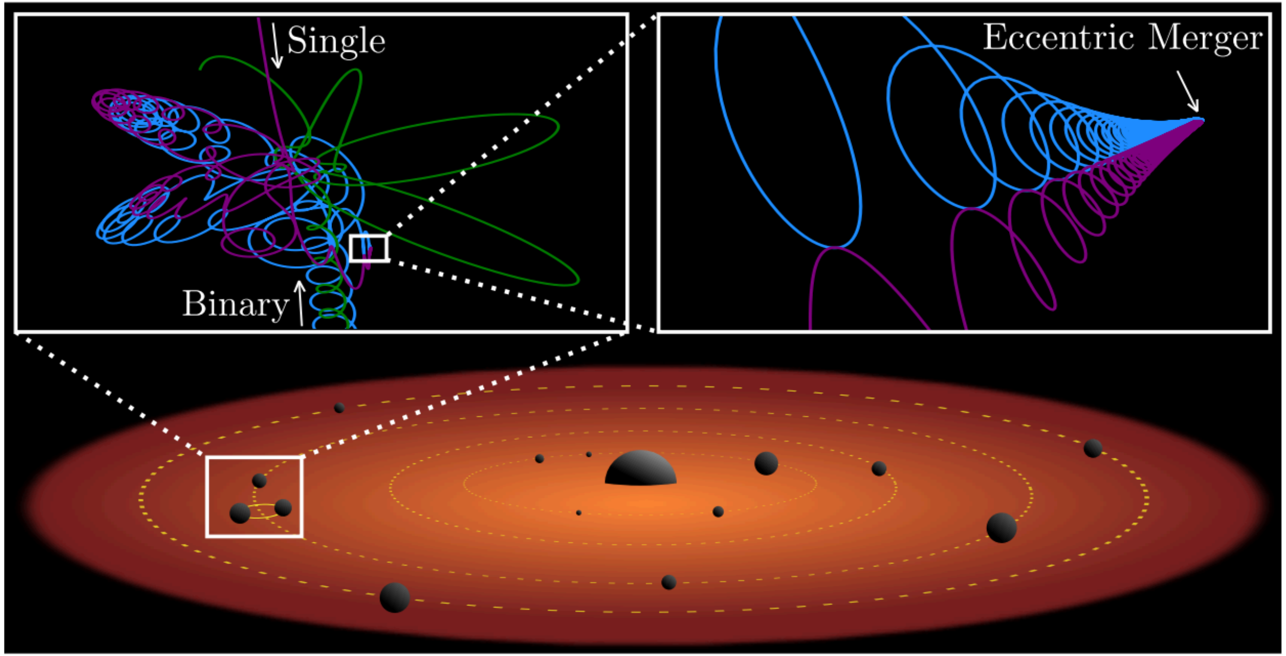
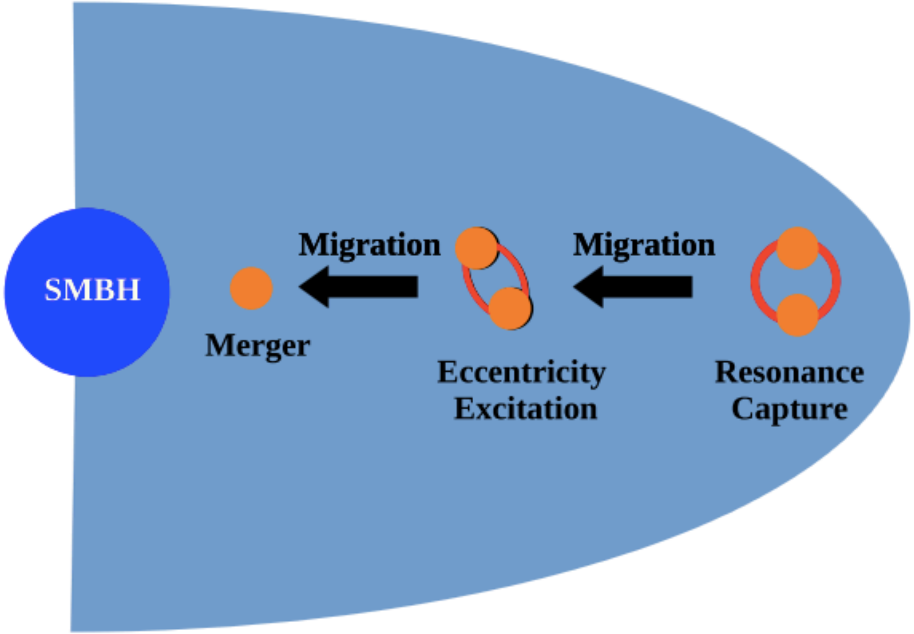
Mechanisms to merge an embedded binary..



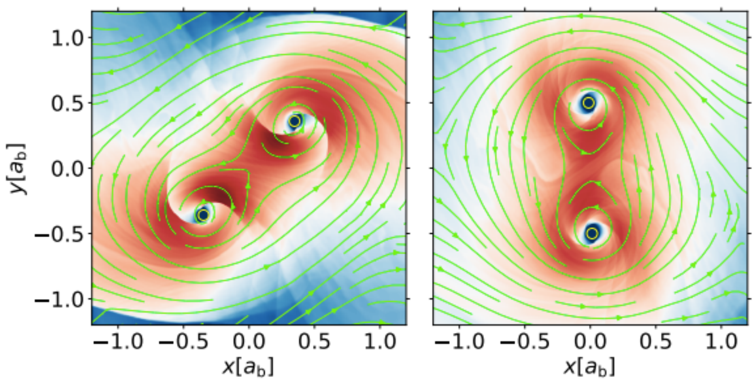
Contraction of BH binaries due to scatterings
(e.g., *Leigh+ 2018; Samsing+ 2022*).

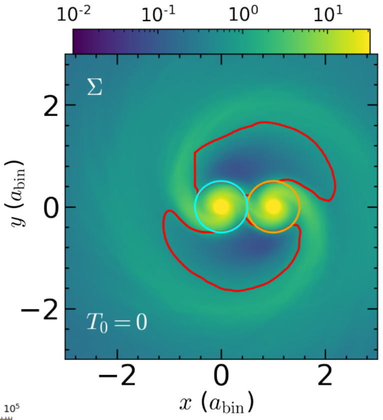
Mechanisms to merge an embedded binary..

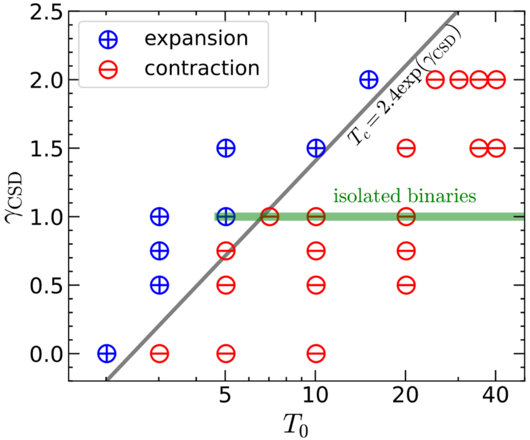


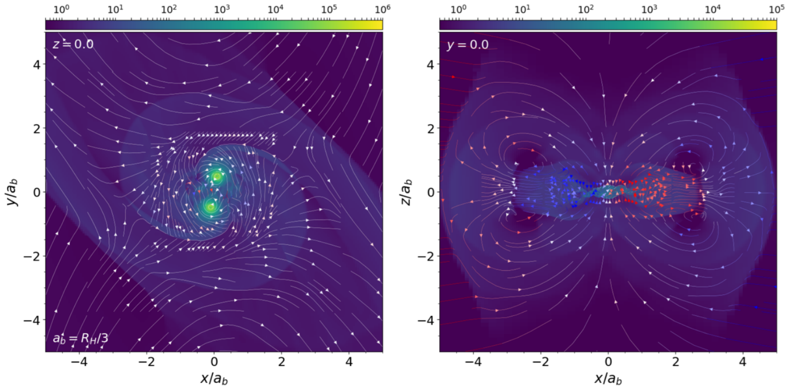
Eccentricity excitation due to evection resonances
(e.g., *Bhaskar+ 2022; Muñoz+ 2022*).

Mechanisms to merge an embedded binary..









Contraction of BH binaries due to the surrounding gas
(e.g., *Li+ incl.* ***JL*** *2021, 2022; Dempsey+ 2022; Li and Lai 2022a, b*).

about BH binaries in AGN disks…

- They may merge! (e.g., *Baruteau+ 2011; Stone+ 2017; Leigh+ 2018; Li+ incl.* ***JL*** *2021, 2022; Dempsey et al. 2022; Li & Lai 2022a,b; Samsing et al. 2022*)

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- However, almost all previous studies consider pre-existing binaries.

- **Q: How to form these BH binaries in AGN disks?**

about BH binaries in AGN disks…

- They may merge! (e.g., *Baruteau+ 2011; Stone+ 2017; Leigh+ 2018; Li+ incl.* ***JL*** *2021, 2022; Dempsey et al. 2022; Li & Lai 2022a,b; Samsing et al. 2022*)

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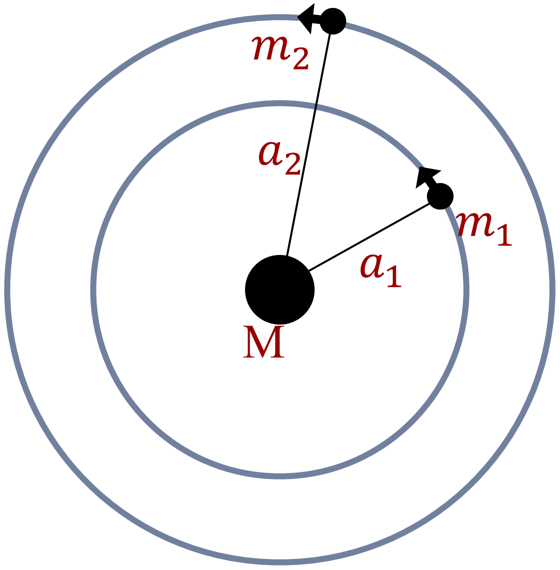
- **Q: How to form these BH binaries in AGN disks?**
  A (in this talk): Close encounters between embedded single BHs.

Formation of BH binaries: long-term N-body simulations

(*Li, Lai, and Rodet 2022*)



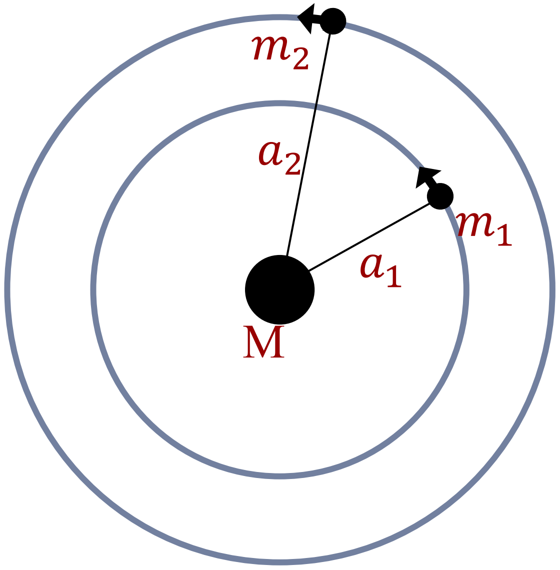
- Initial condition:

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

(Dynamical instability will occur!)

- Reasons for using closely-packed orbits:
  – Large BH population in an AGN disk
  – Differential migration
  – Focus on the close encounters

Formation of BH binaries: long-term N-body simulations

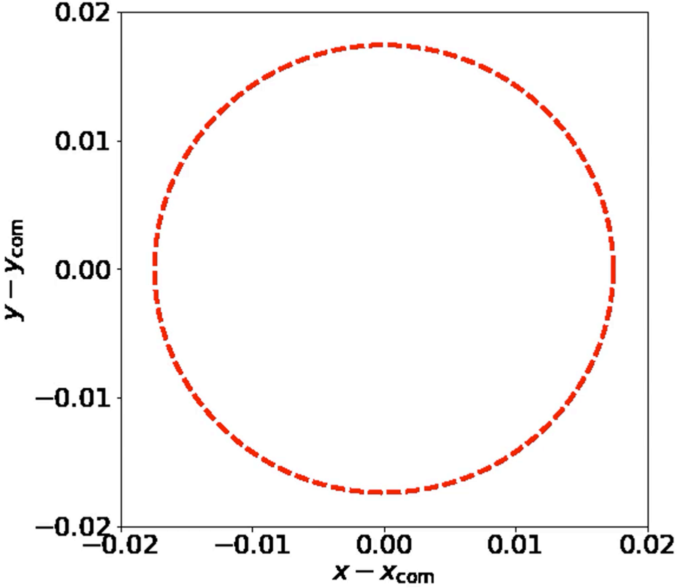


- Simulations:
  - Run for at least $10^5 P_1$ (orbits around the SMBH)
  - Pure N-body and no gas effect for now

- Outcomes of this instability:
  - BH collisions? -- unlikely
  - BH ejections? -- requires very long time
  - **Recurring close encounters** -- will be a lot!
    (we can study this stochastic process statistically)

Formation of BH binaries: long-term N-body simulations

Radius R_H at the BH COM



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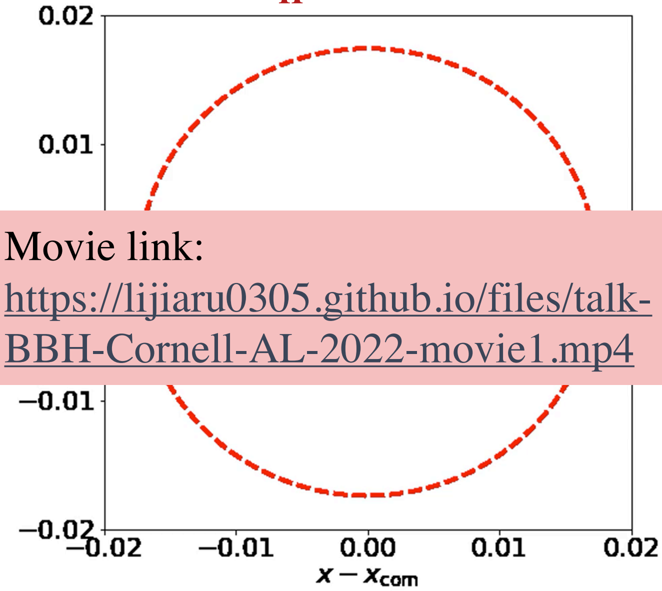

Movie link:
https://lijiaru0305.github.io/files/talk-BBH-Cornell-AL-2022-movie1.mp4

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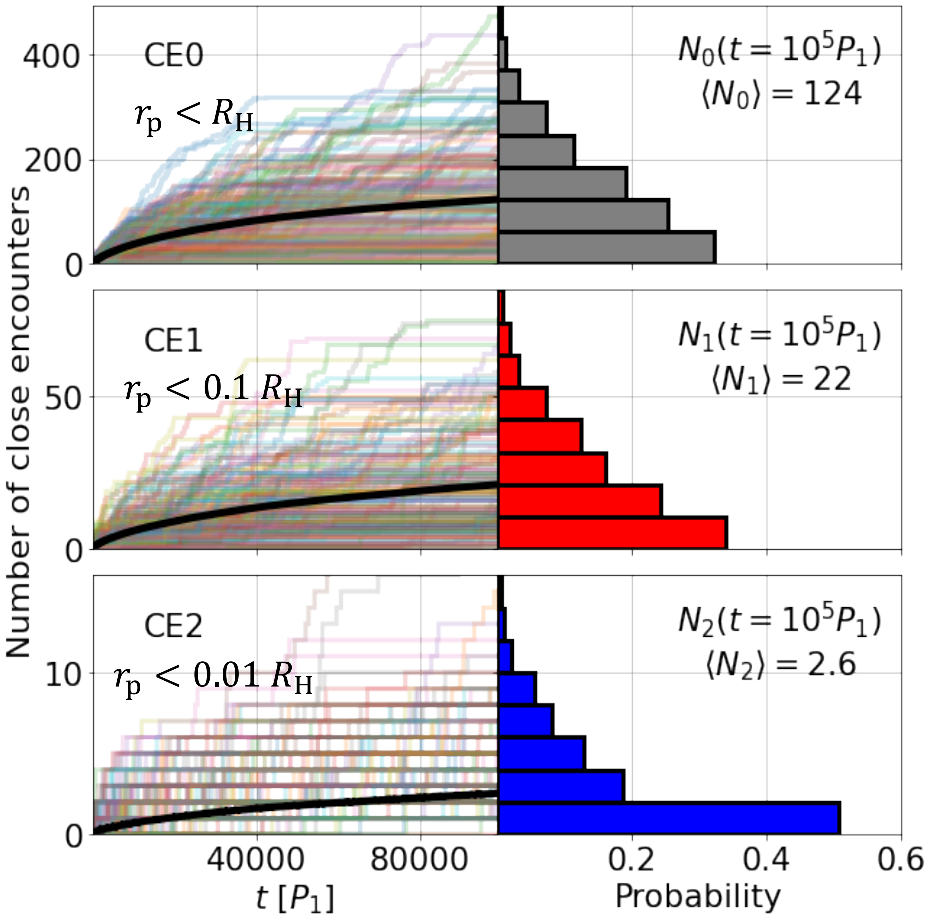
N-body results

Number of close encounters (CE)

***r_p*: minimum BH separation during a CE**

***P_1*: orbital period around the SMBH**



N-body results

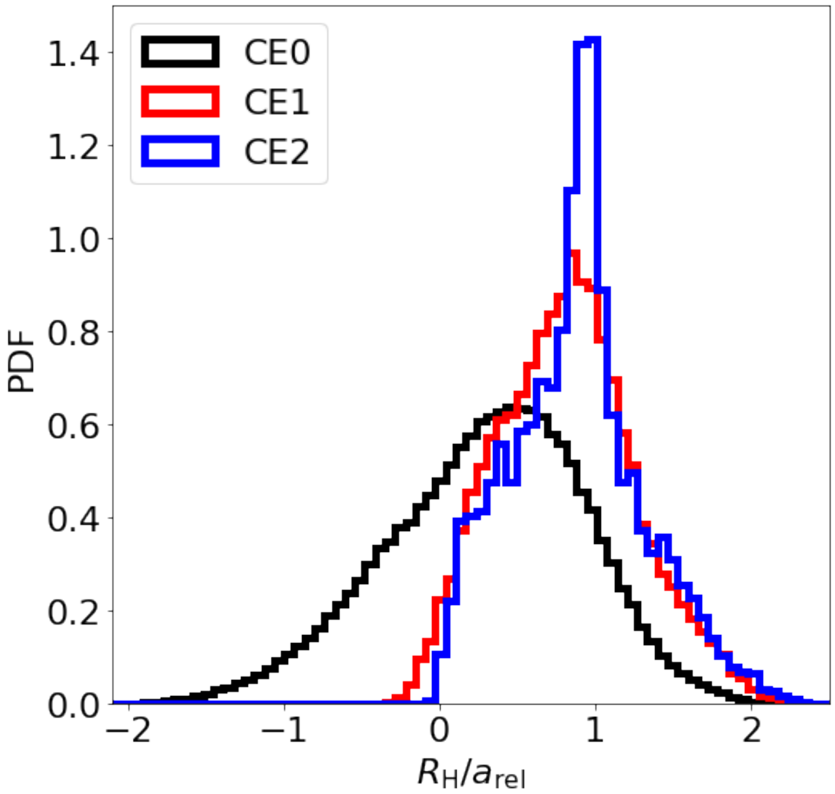
Energy of a CE:

$$\boldsymbol{E} = -\frac{Gm_1m_2}{2\boldsymbol{a}_{\mathbf{rel}}} = \frac{1}{2}\mu v_{\mathrm{rel}}^2 - \frac{Gm_1m_2}{r_{\mathrm{rel}}}$$

’Stability’ of a CE:

$$\boldsymbol{R}_{\mathbf{H}}/\boldsymbol{a}_{\mathbf{rel}} = \frac{Gm_1m_2}{2a_{\mathrm{rel}}} \Big/ \frac{Gm_1m_2}{2R_{\mathrm{H}}}$$

Most encountering BH pairs are disrupted by the **SMBH tidal force** within 1 P_1.



Reduce CE energy through 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:

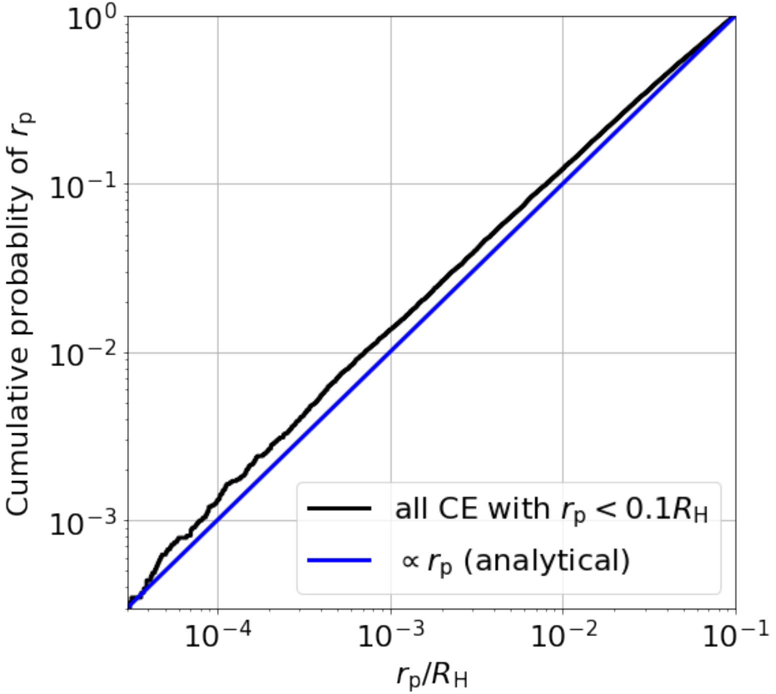
$$\frac{r_{\rm p}}{R_{\rm H}} < \frac{r_{\rm cap}}{R_{\rm H}} \simeq 10^{-4} \left(\frac{4\mu}{m_{12}}\right)^{\frac{2}{7}} \left(\frac{10^6 m_{12}}{M}\right)^{\frac{10}{21}} \left(\frac{a_{\rm SMBH}}{100GM/c^2}\right)^{-5/7}$$

Reduce CE energy through GW radiation

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

$$\frac{r_p}{R_H} < \frac{r_{cap}}{R_H} \simeq 10^{-4}$$

- 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.

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

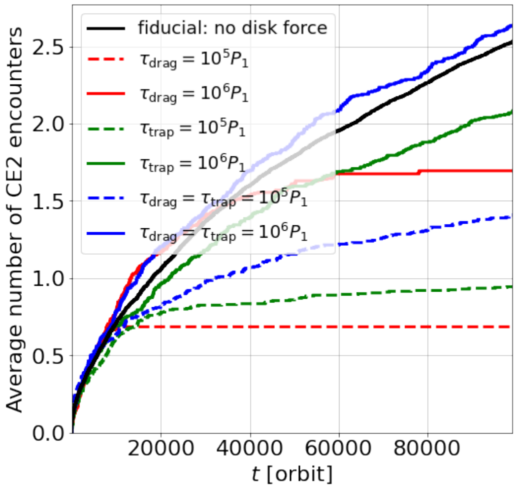
Dissipation through disk gas

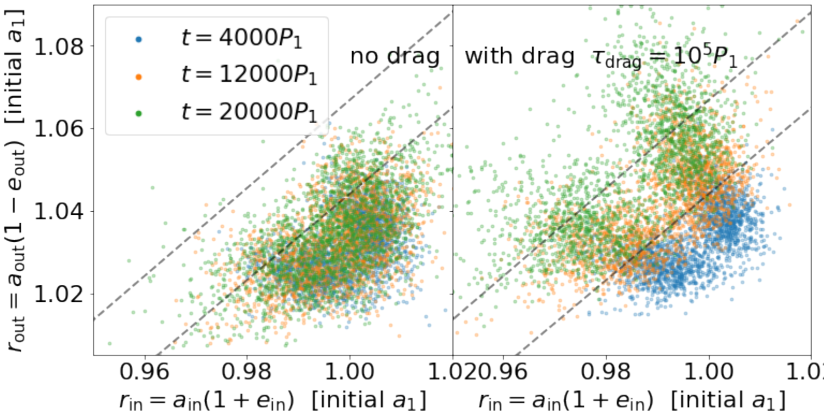
- **Drag force and torque from the AGN disk:**
  - Considered in our paper:

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

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

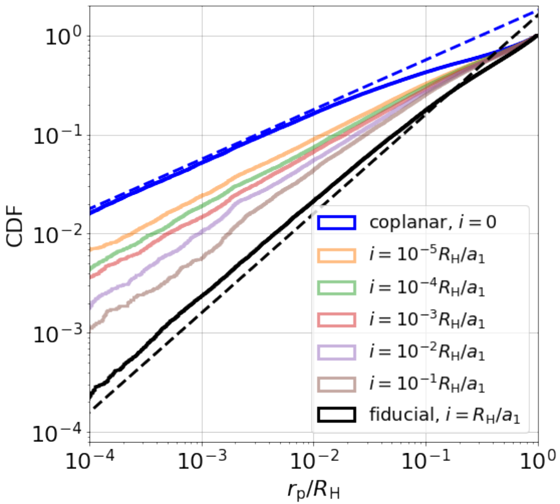
  - They **do not** increase the GW capture rate.



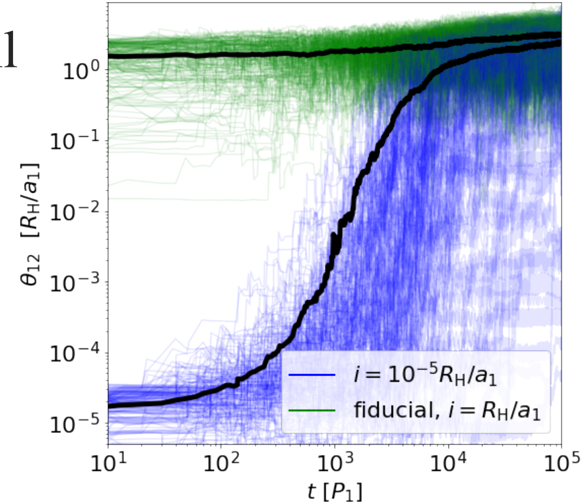


Inclinations

- Exactly co-planar systems have the highest GW capture rate:
  $\sim 10^4 P_1$ per capture
- However, exact co-planarity is not realistic because any non-zero small mutual inclination can grow.



Prob(r_p) changes with the mutual inclination.



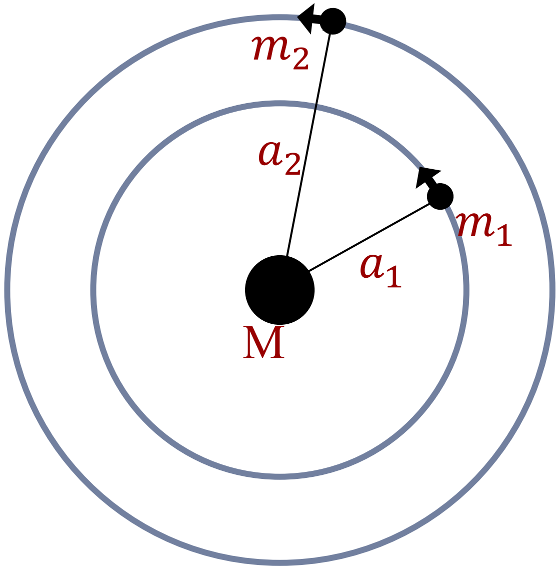
Small mutual inclination converges to our fiducial inclination.

Takeaways from N-body results

- 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:
  - With a small probability $\sim \frac{r_{\mathrm{cap}}}{R_{\mathrm{H}}} \ll 1$.
  - Number of binaries formed = (Probability of $r_{\mathrm{p}} < r_{\mathrm{cap}}$ for one CE) × (Number of CEs)

Formation of BH binaries: hydrodynamics simulations



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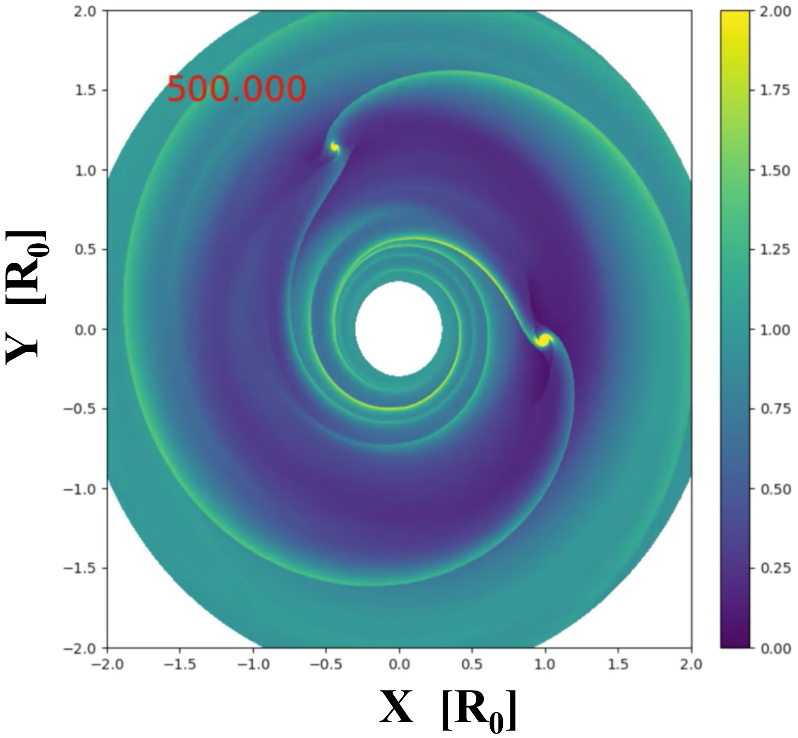
Formation of BH binaries: hydrodynamics simulations



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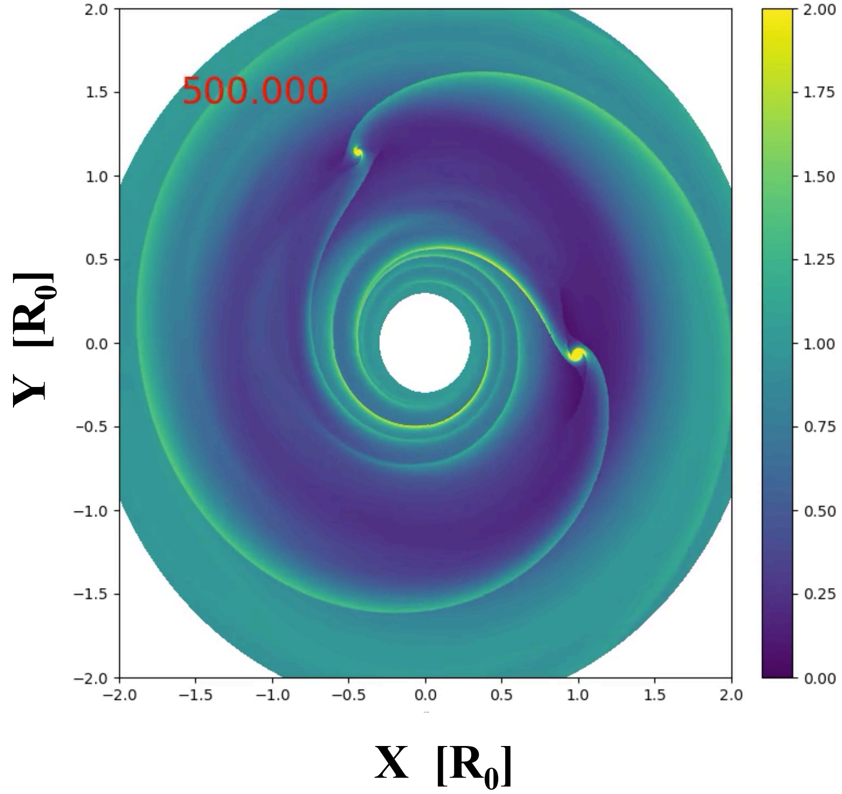


(***Li***+ *to be submitted*)

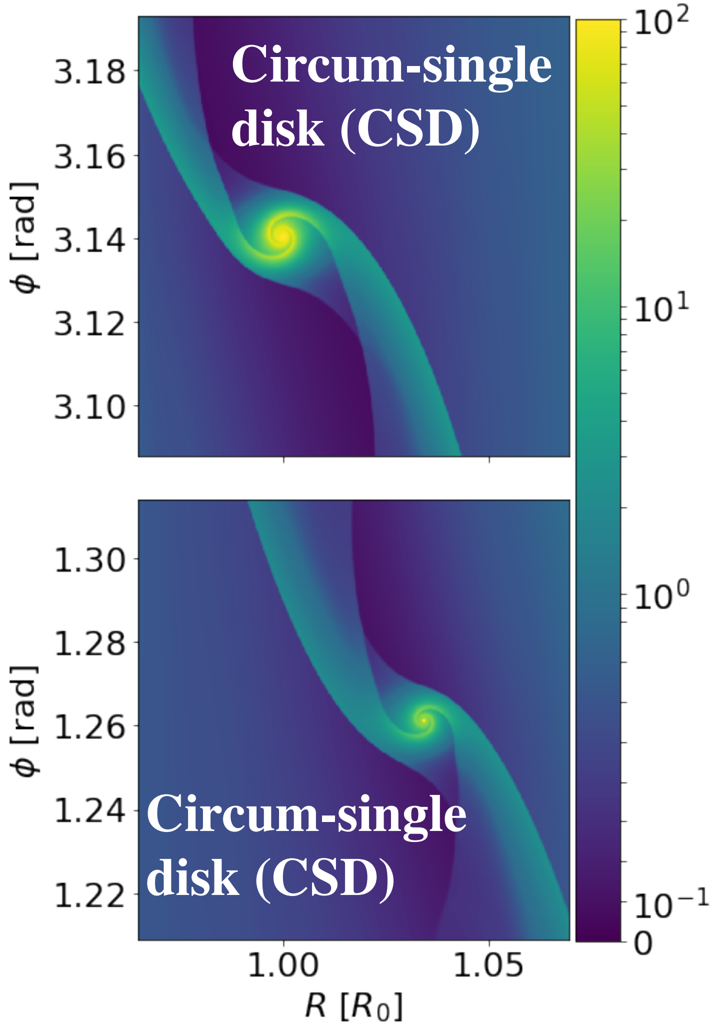
- Initial condition:

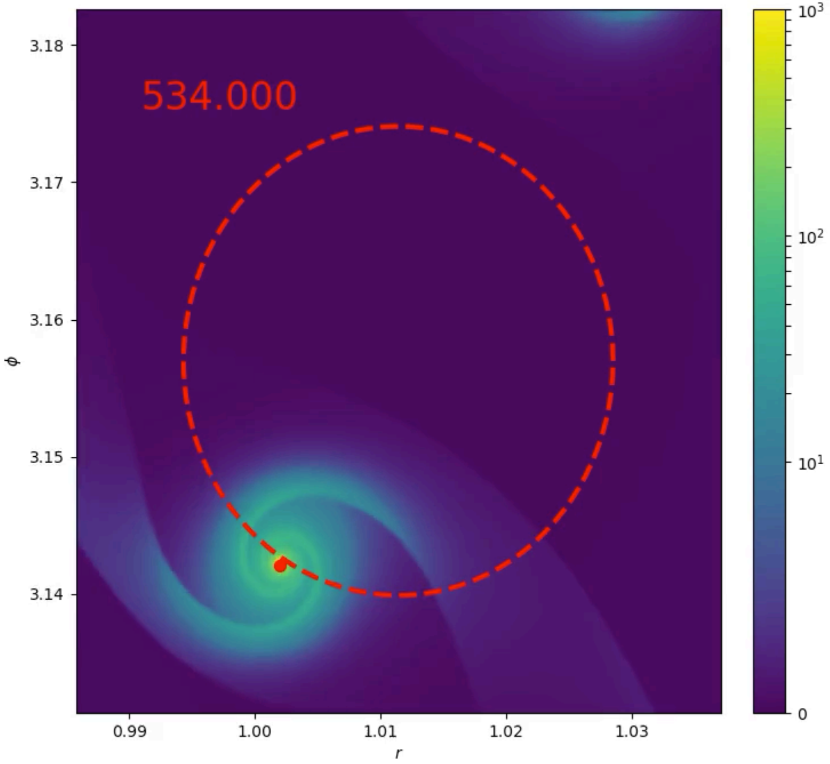
$$a_2 - a_1 = 2R_\mathrm{H}$$

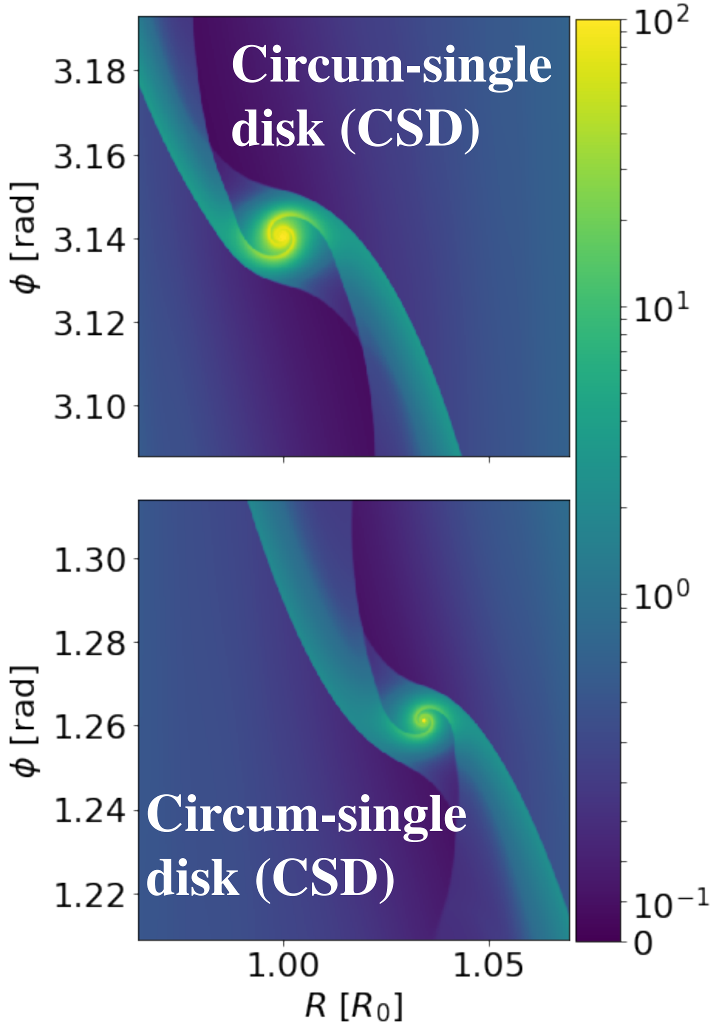
(Close encounter at the first conjunction)

- Simulation setup:
  - $M_\mathrm{SMBH} = 1,\ \ m_1 = 10^{-5},\ \ m_2 = 5\times10^{-6}$
  - Thin disk $H/R = 0.01$, low viscosity $\alpha = 0.01$.
  - Isothermal disk.
  - High resolution with 50→100 grid cells per R_H, where $R_\mathrm{H} = 0.017R_0$

Formation of a binary







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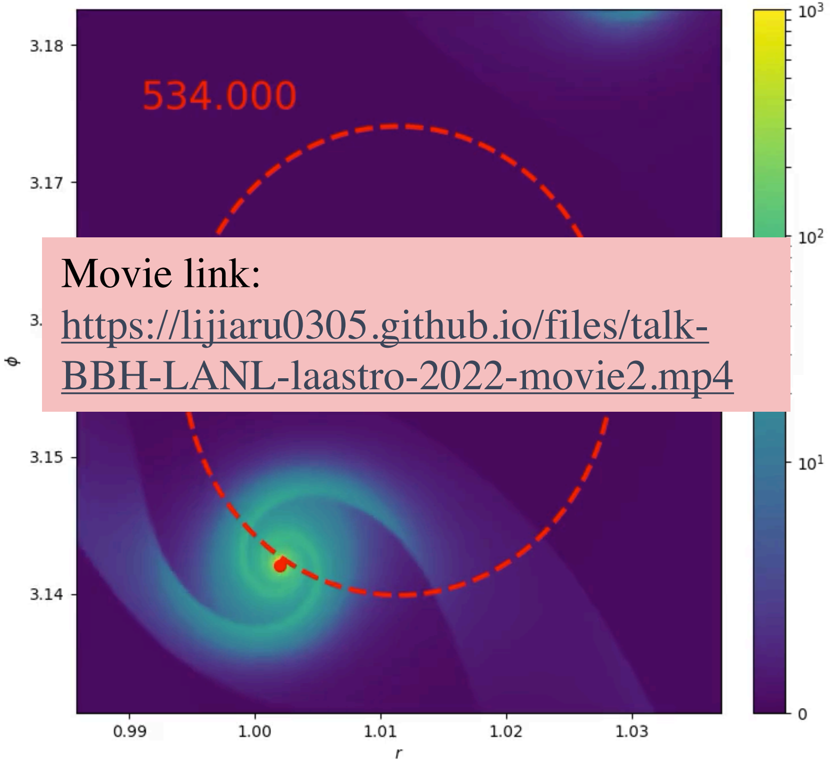
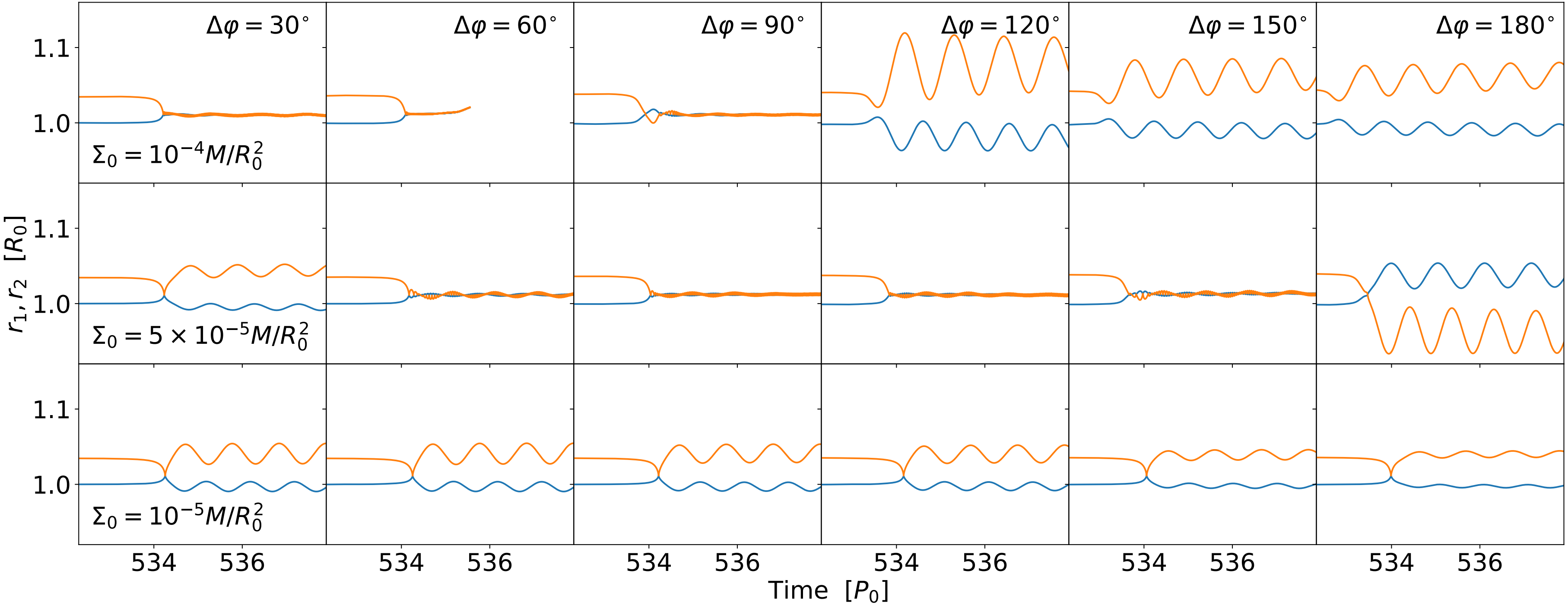


Movie link:
https://lijiaru0305.github.io/files/talk-BBH-LANL-laastro-2022-movie2.mp4

Simulation outcomes



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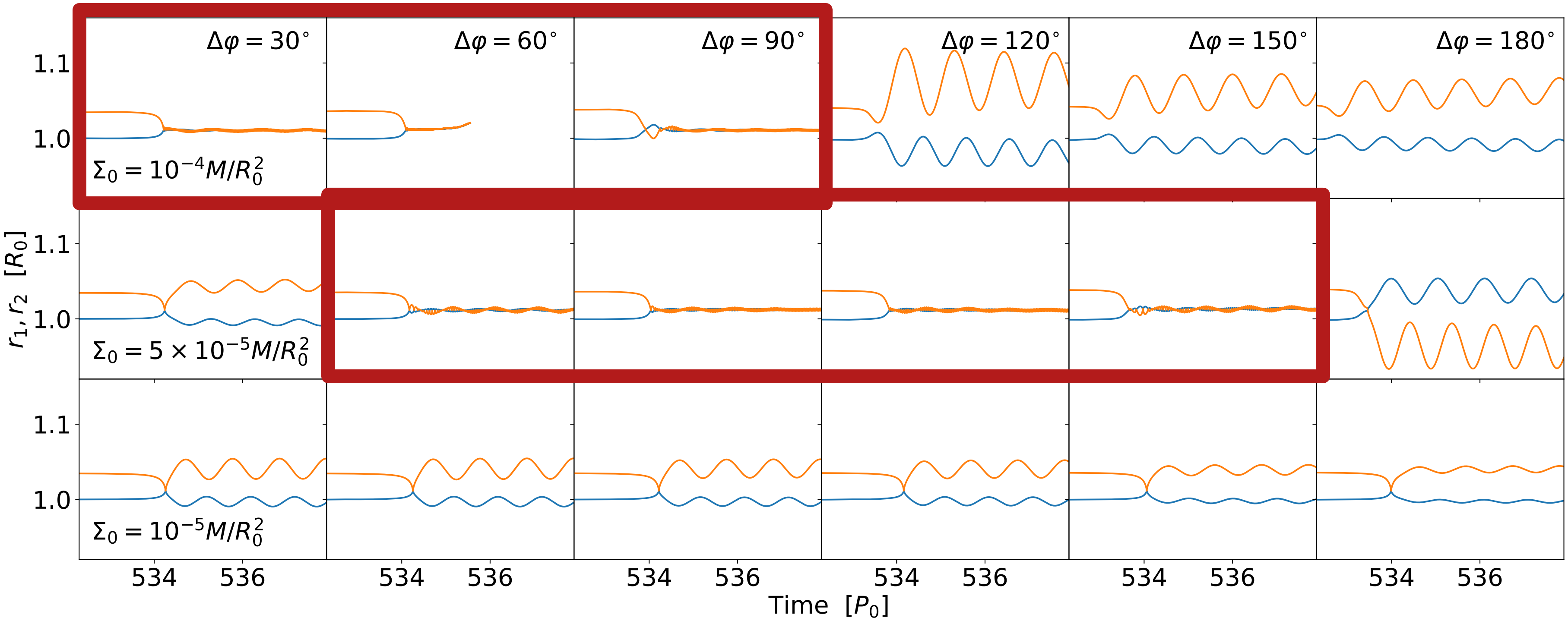
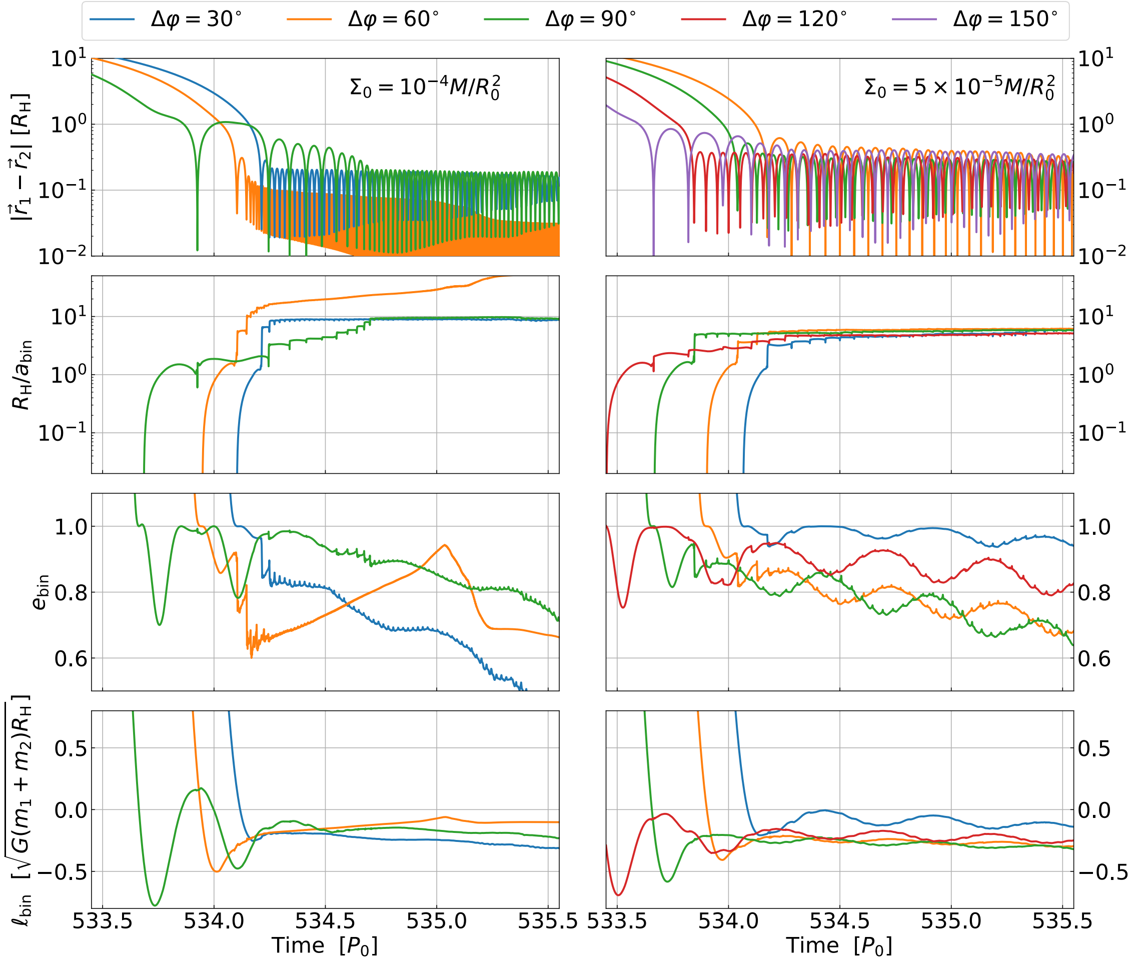
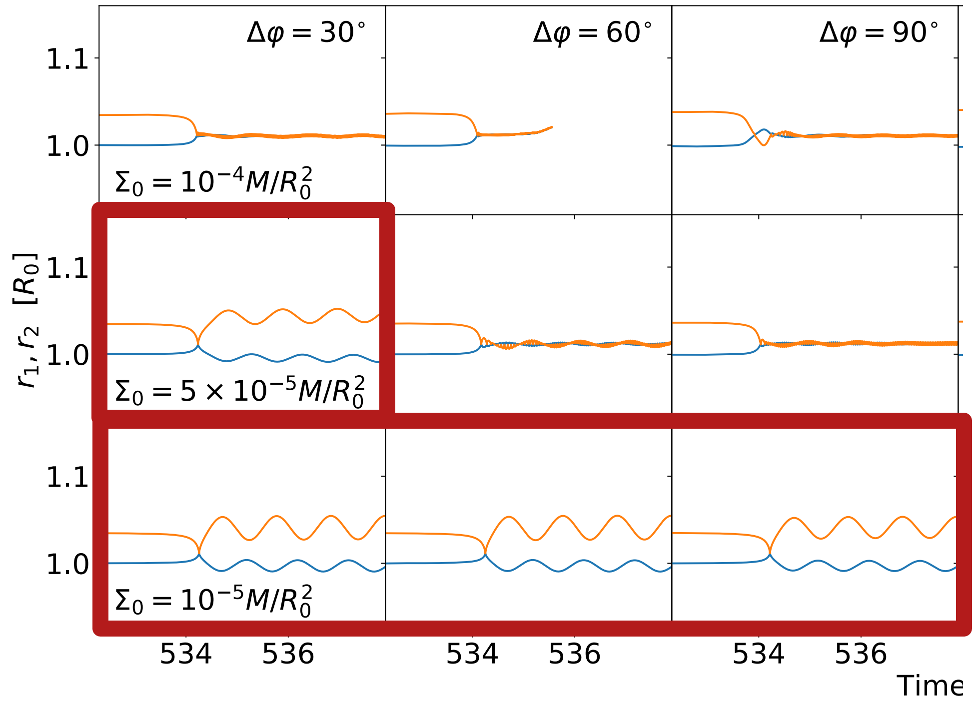


Resulting binary orbit after formation

- small semi-major axis: $\frac{a_{\mathrm{bin}}}{R_{\mathrm{H}}} \sim 0.1$
- large eccentricity: $e_{\mathrm{bin}} > 0.5$
- retrograde rotation: $\ell_{\mathrm{bin}} < 0$



(for those are interested..) No-formation cases…

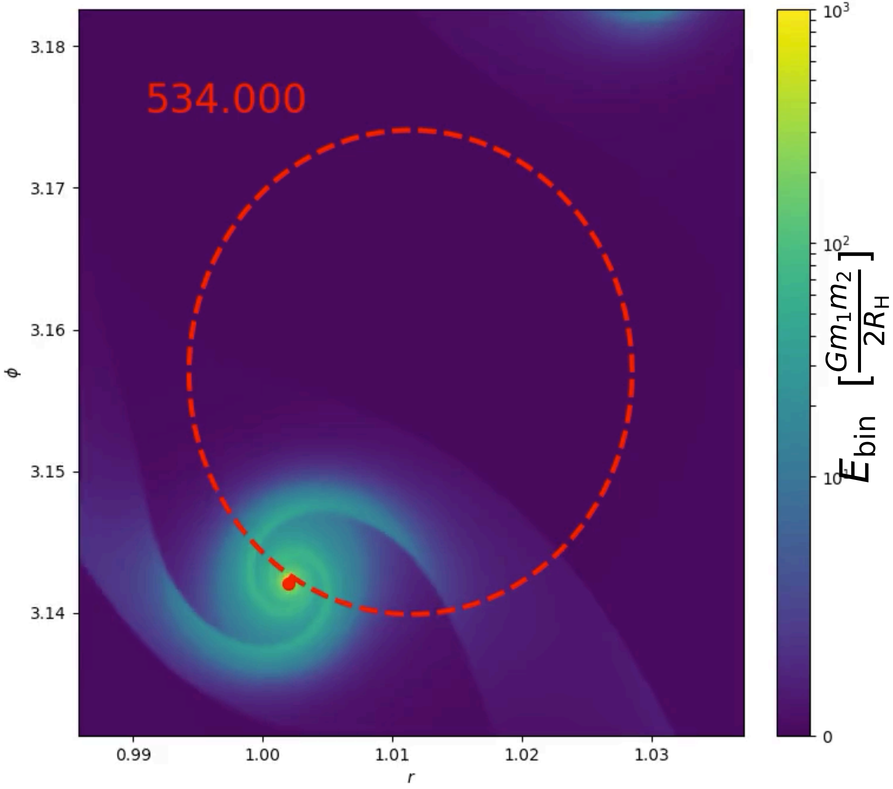


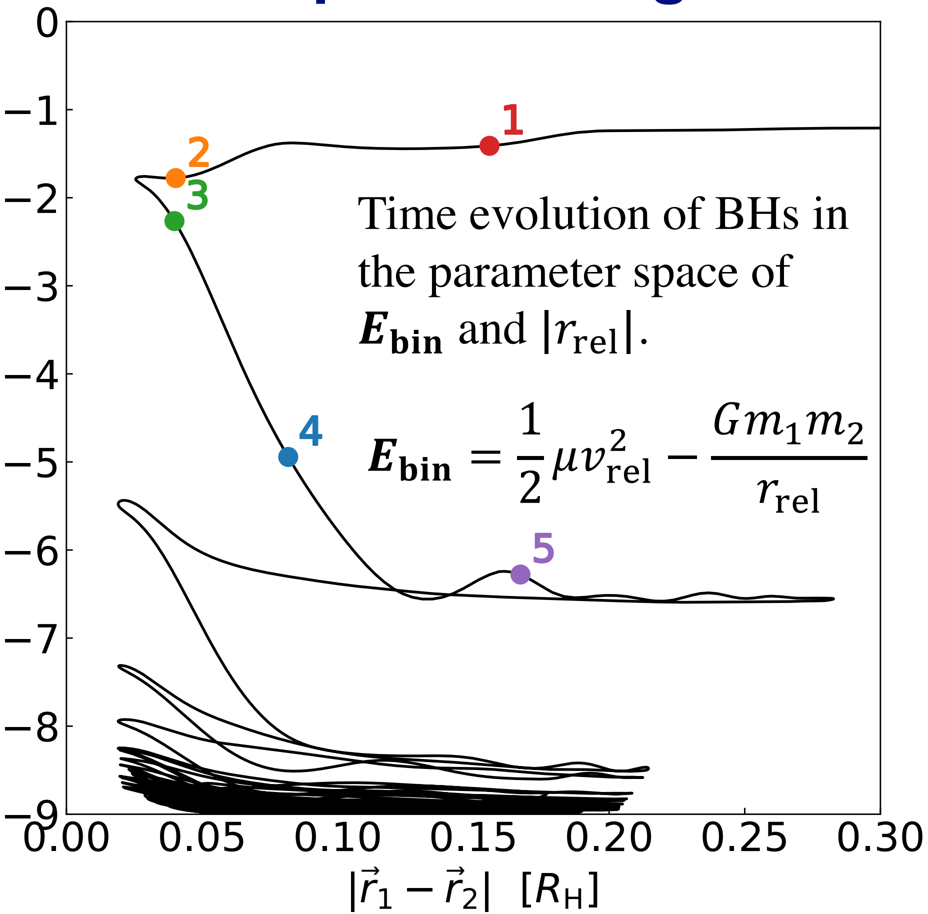
We focus on the outcome of the first close encounters.

But, just to point out the following considerations:

- eccentricity damping
- orbital migration
- …

Analysis: formation mechanism -- a departure drag





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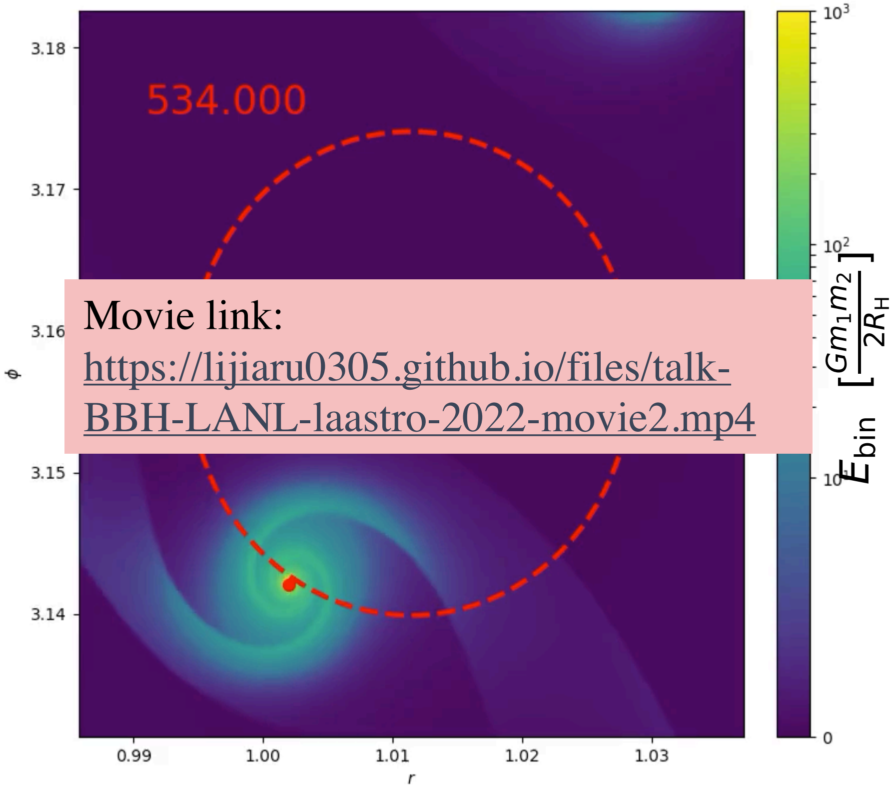

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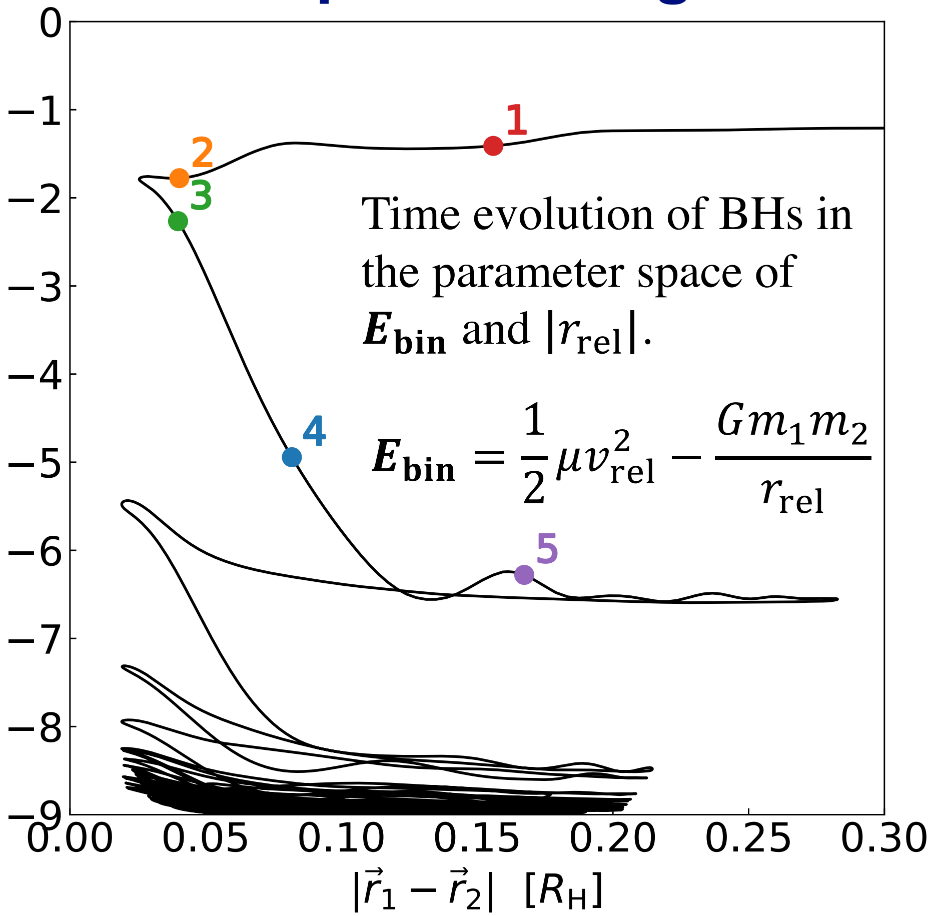
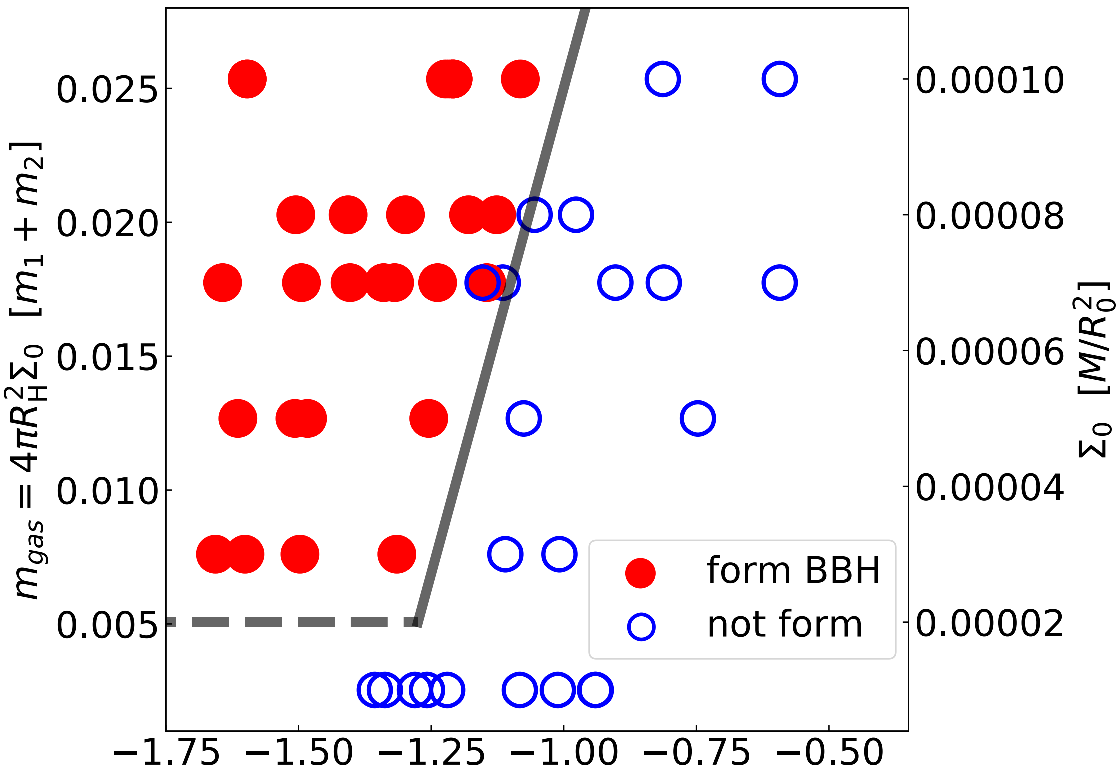


Time evolution of BHs in the parameter space of $\boldsymbol{E}_{\mathbf{bin}}$ and $|r_{\rm rel}|$.

$$\boldsymbol{E}_{\mathbf{bin}} = \frac{1}{2}\mu v_{\rm rel}^2 - \frac{Gm_1m_2}{r_{\rm rel}}$$

Analysis: criteria for binary formation



$$\boldsymbol{E}_{\mathbf{in}} := \frac{1}{2}\mu v_{\mathrm{rel}}^2 - \frac{G m_1 m_2}{r_{\mathrm{rel}}} \text{ when } r_{\mathrm{rel}} = 0.3 R_{\mathrm{H}}$$

Forming binary requires:

- sufficiently large gas mass
- sufficiently small initial binary energy

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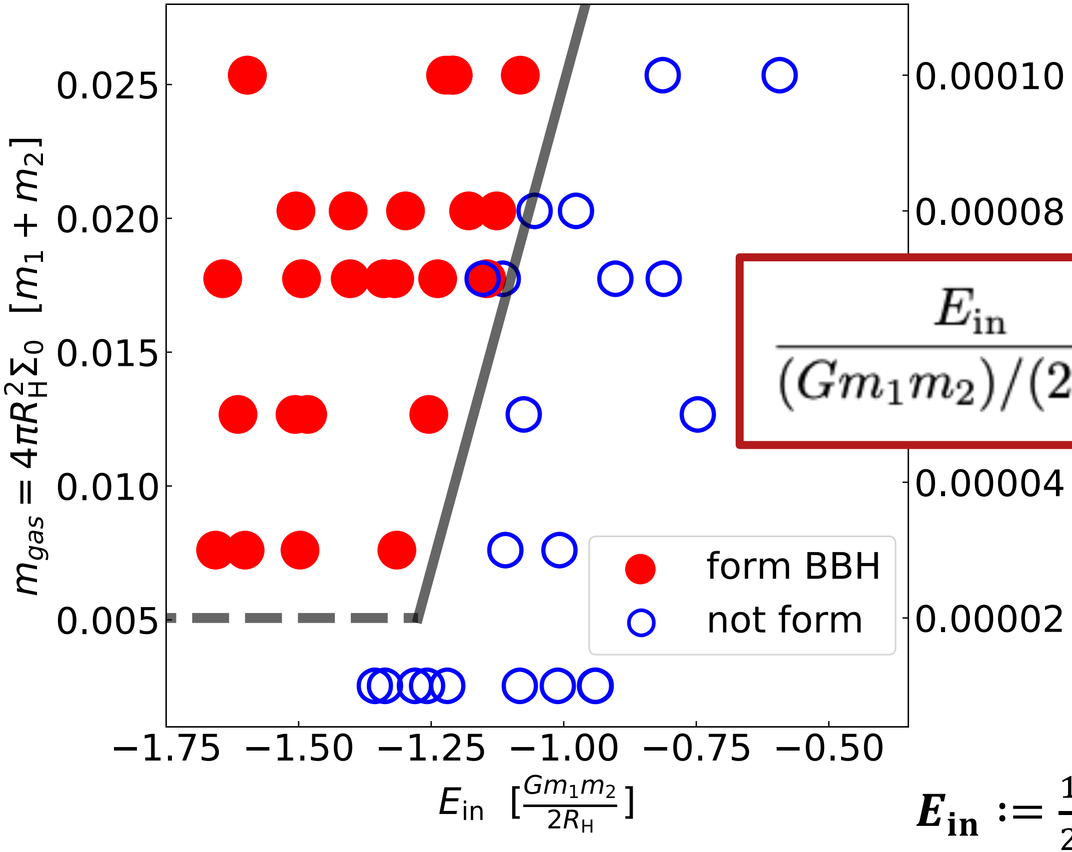

$$\frac{E_{\rm in}}{(Gm_1m_2)/(2R_{\rm H})} < 13.78\frac{m_{\rm gas}}{(m_1+m_2)} - 1.344$$

$$\boldsymbol{E}_{\mathbf{in}} := \frac{1}{2}\mu v_{\rm rel}^2 - \frac{Gm_1m_2}{r_{\rm rel}} \ \text{when } r_{\rm rel} = 0.3R_{\rm H}$$

Summary

- Mergers of BH binaries embedded in AGN disks are considered important sources of gravitational wave.

- When the gas effect is negligible, dynamical instability produces lots of close encounters. → In rare events of every deep encounters, with a certain probability, very tightly-bounded captured binaries can form.

- When the gas density is sufficiently high, close encounters can form bound binaries due to the collision between the two CSDs. → Increases the formation-per-encounter ratio.

- The resulting BH binary orbits can be highly eccentric, compact, and retrograde. → May be considered as the “initial configuration” of the “pre-existing” binaries.