Formation of Black Hole Binaries in AGN disks through Close Encounters

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Why do we care about black hole (BH) binaries?

BH binaries are:

- the simplest systems that can produce significant gravitational wave (GW) signal,
- the main GW sources seen by LIGO (binary inspiral/merger).

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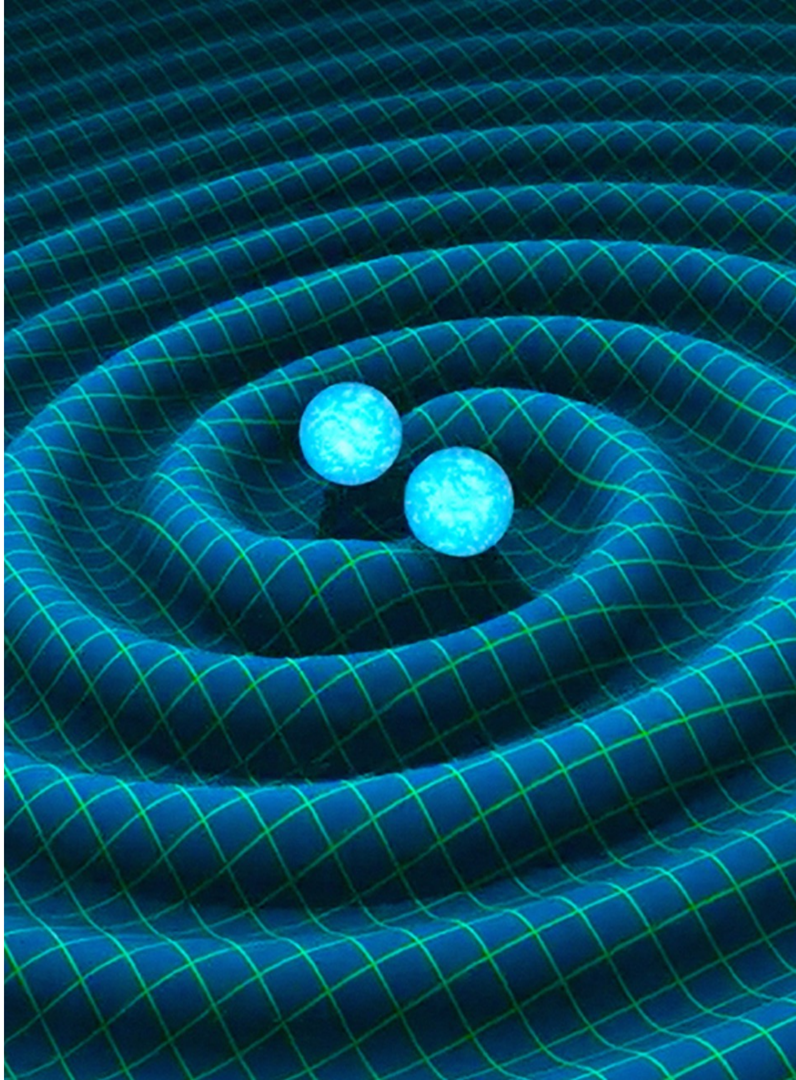
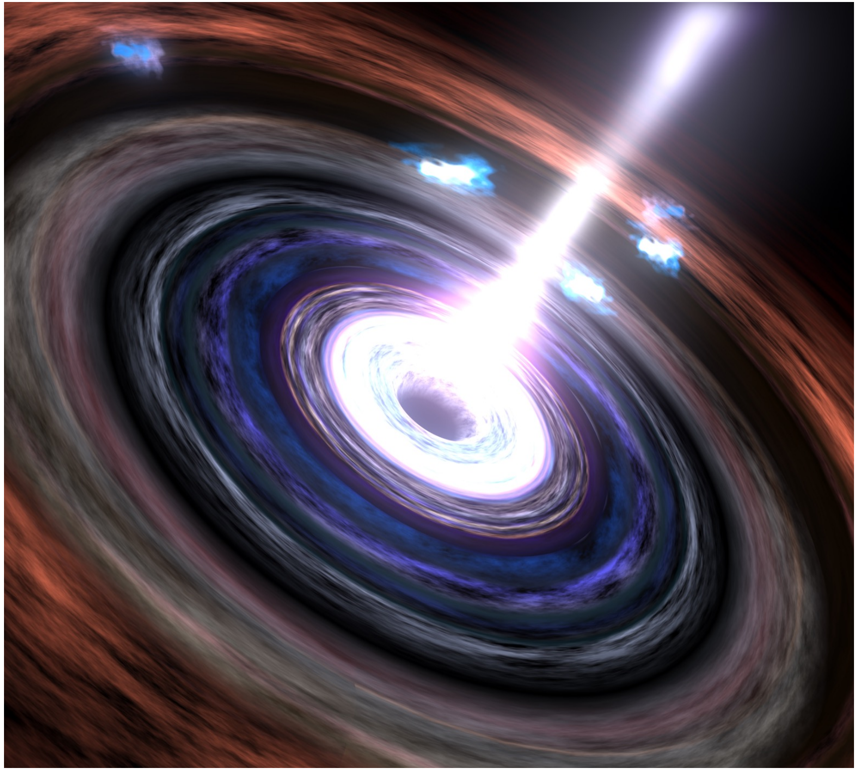


Why do we care about BH binaries in AGN disks?

- GW radiation is weak when BHs are not very close to each other.
  → No inspiral/mergers in Newtonian two-body problem.

- A binary embedded in a gaseous disk
  → May be able to contract.



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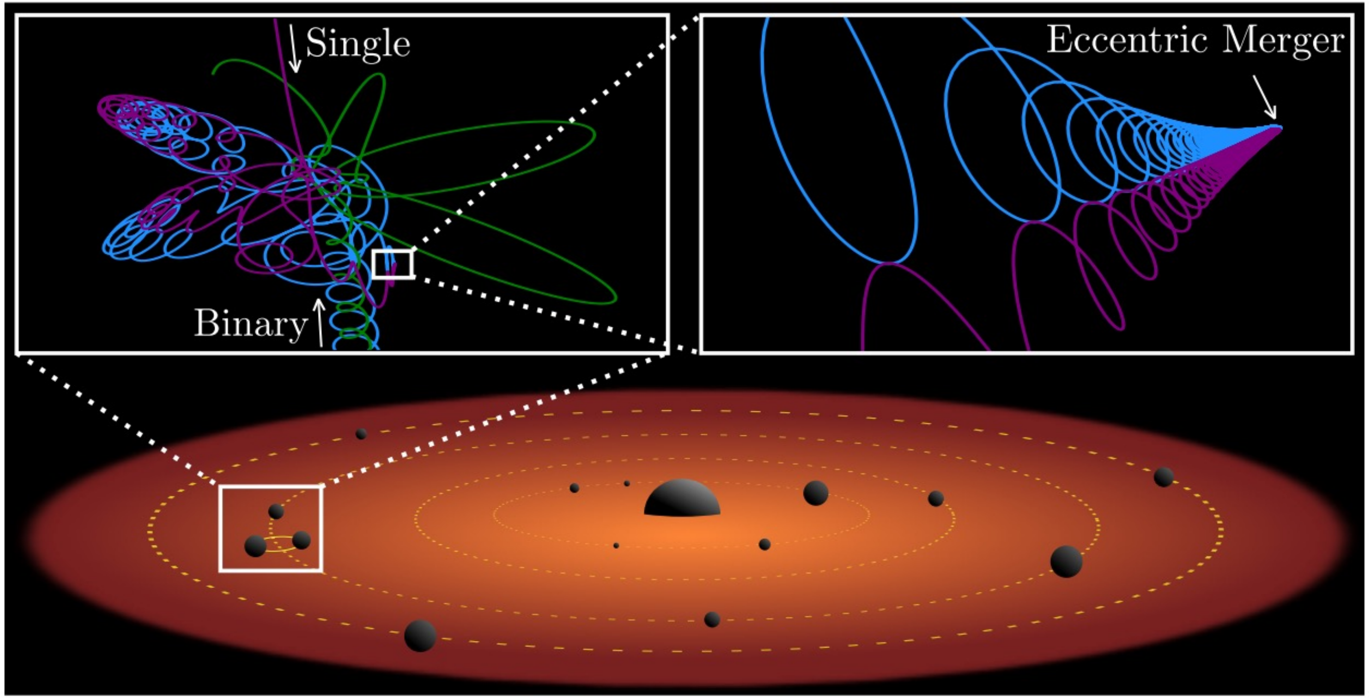
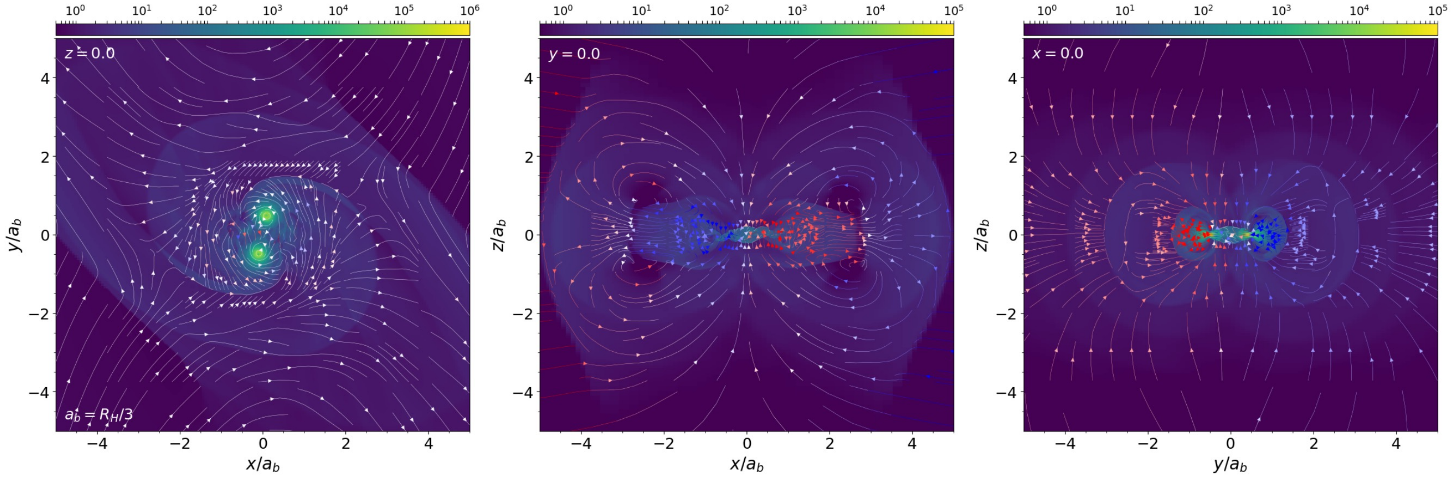
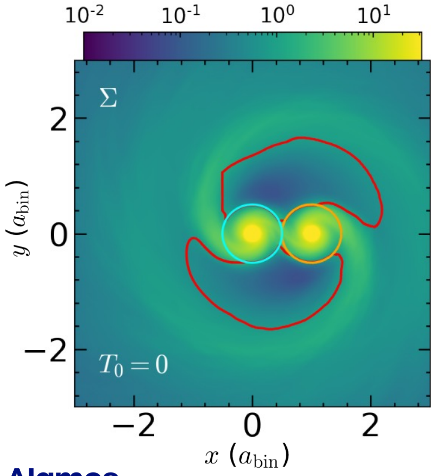
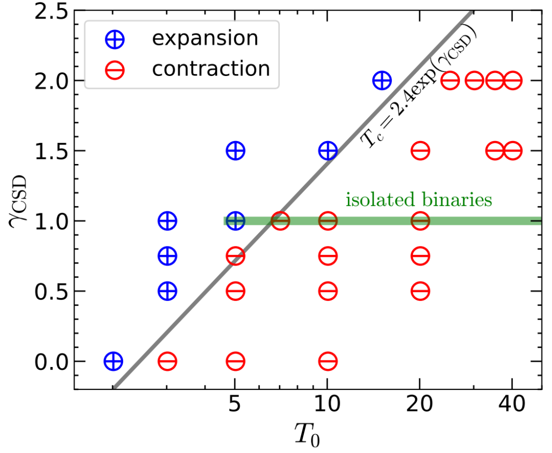


Contraction of BH binaries due to scatterings
(e.g., *Samsing et al. 2022*).







Contraction of BH binaries due to the surrounding gas (e.g., *Dempsey et al. 2022*; *Li et al. incl. **JL** 2022*).

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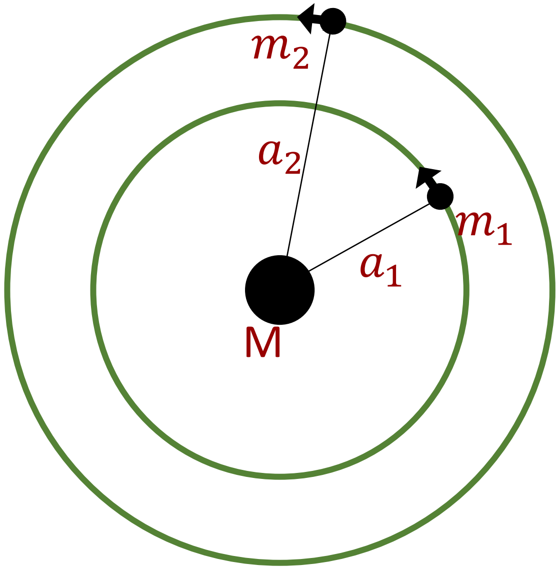
We care about BH binaries in AGN disks..

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

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

- **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



- Initial condition:

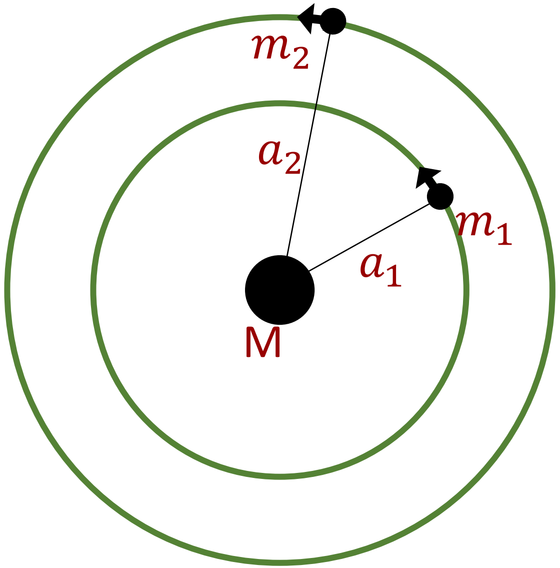
$$a_2 - a_1 = 2R_\mathrm{H} \quad \text{where} \quad R_\mathrm{H} = \frac{a_1 + a_2}{2}\left(\frac{m_1 + m_2}{3M}\right)^{1/3}$$

(Dynamical instability will occur!)

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

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

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)

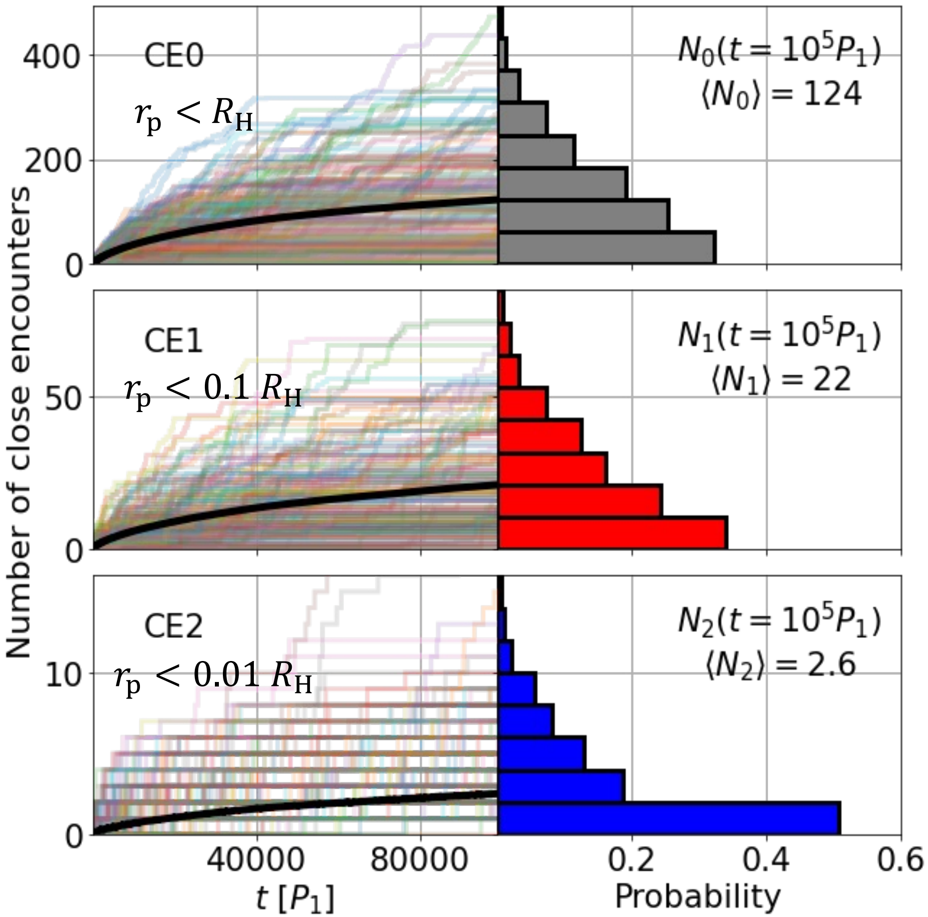
(***Li***, *Lai, and Rodet 2022*, arxiv:2203.05584)

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

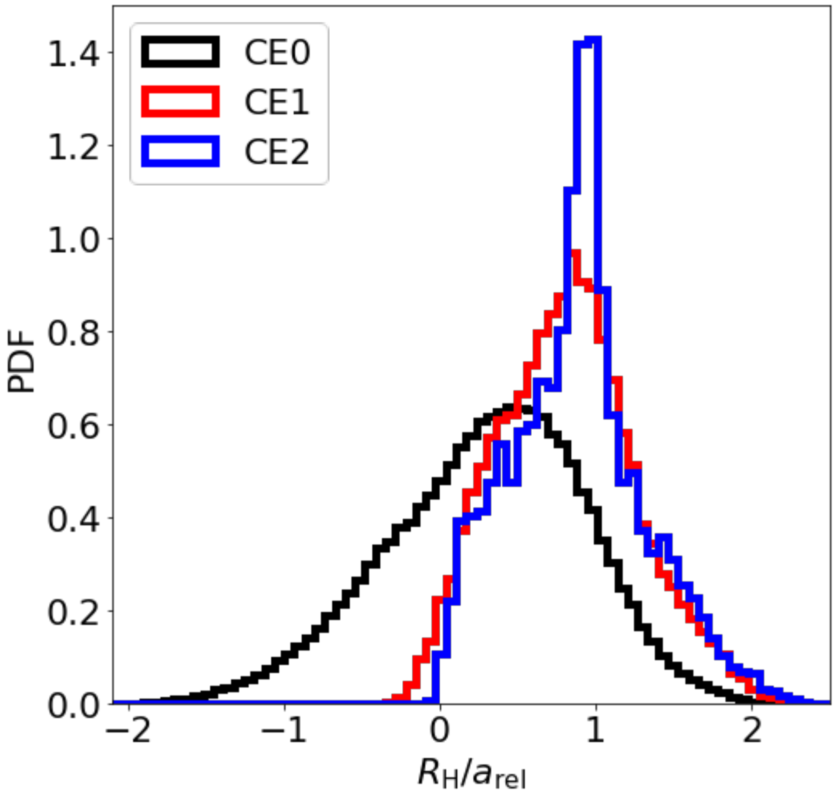
Energy of a CE:

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

'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.



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Reduce CE energy through GW radiation

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

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

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:

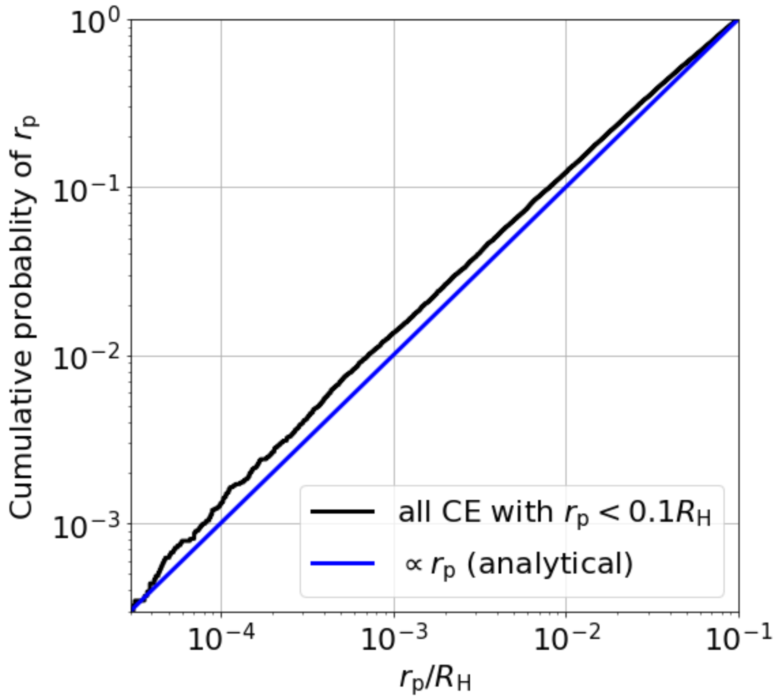
$$\frac{r_{\rm p}}{R_{\rm H}} < \frac{r_{\rm cap}}{R_{\rm H}} \simeq 10^{-4} \left(\frac{4\mu}{m_{12}}\right)^{\frac{2}{7}} \left(\frac{10^6 m_{12}}{M}\right)^{\frac{10}{21}} \left(\frac{a_{\rm SMBH}}{100GM/c^2}\right)^{-5/7}$$

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.



Reduce CE energy through GW radiation

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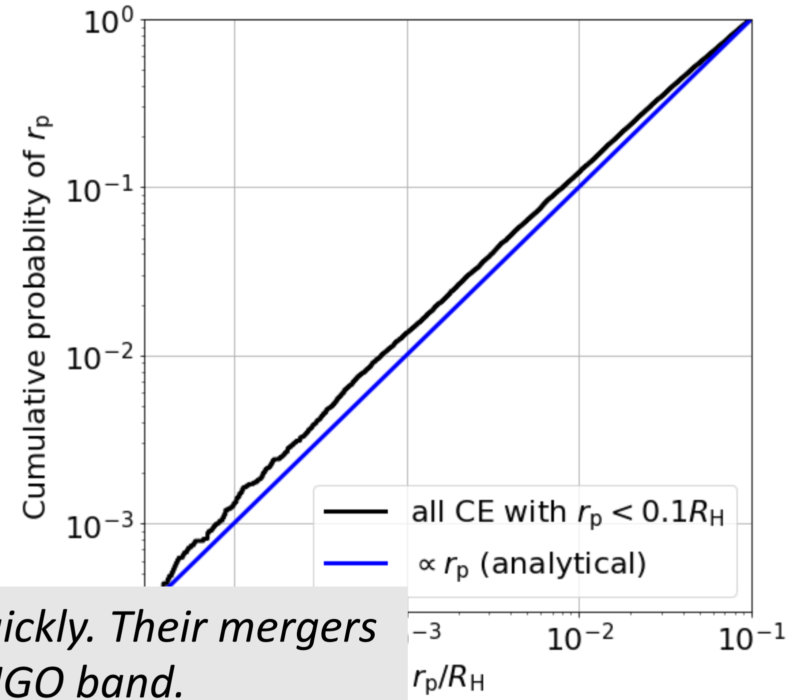

** We expect these captured binaries to merge quickly. Their mergers will show high eccentricities when entering the LIGO band.*

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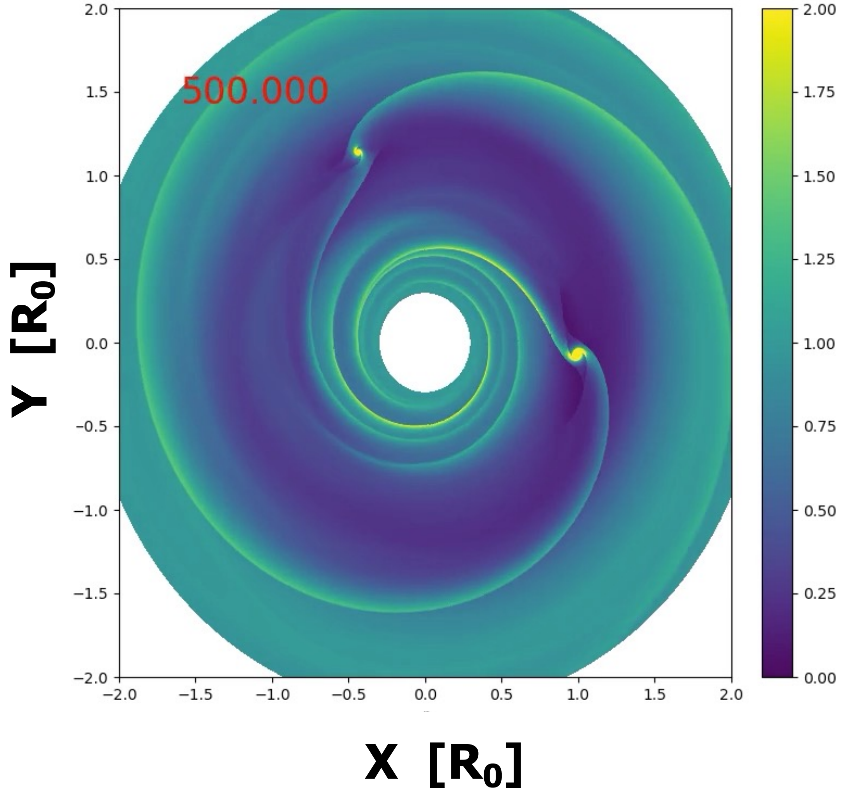
Takeaways from N-body results

- 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 very small probability $\sim \frac{r_{\rm cap}}{R_{\rm H}} \ll 1$.
  - These captured binaries should merge very quickly.

Formation of BH binaries: hydrodynamics simulations



- Initial condition:

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

  (Close encounter at the first conjunction)

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

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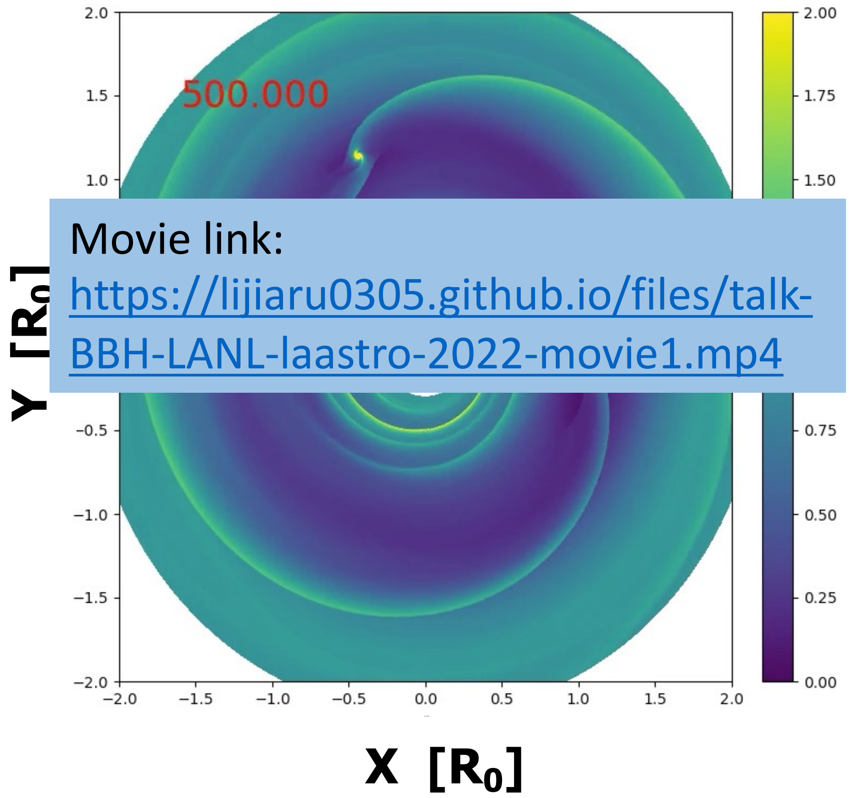

Movie link:
https://lijiaru0305.github.io/files/talk-BBH-LANL-laastro-2022-movie1.mp4

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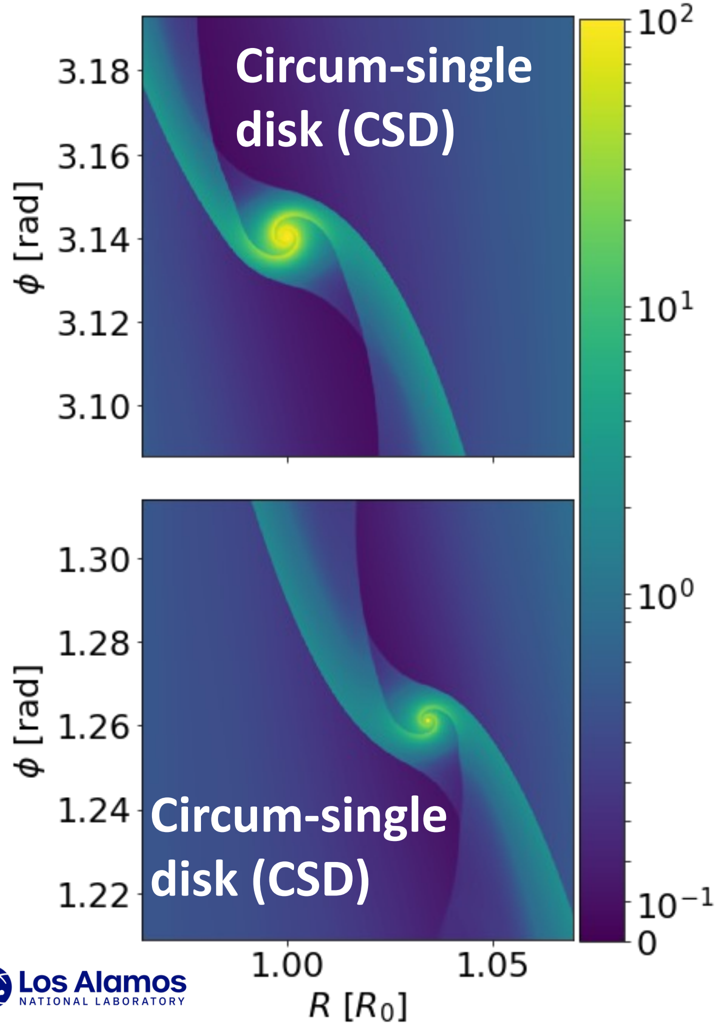
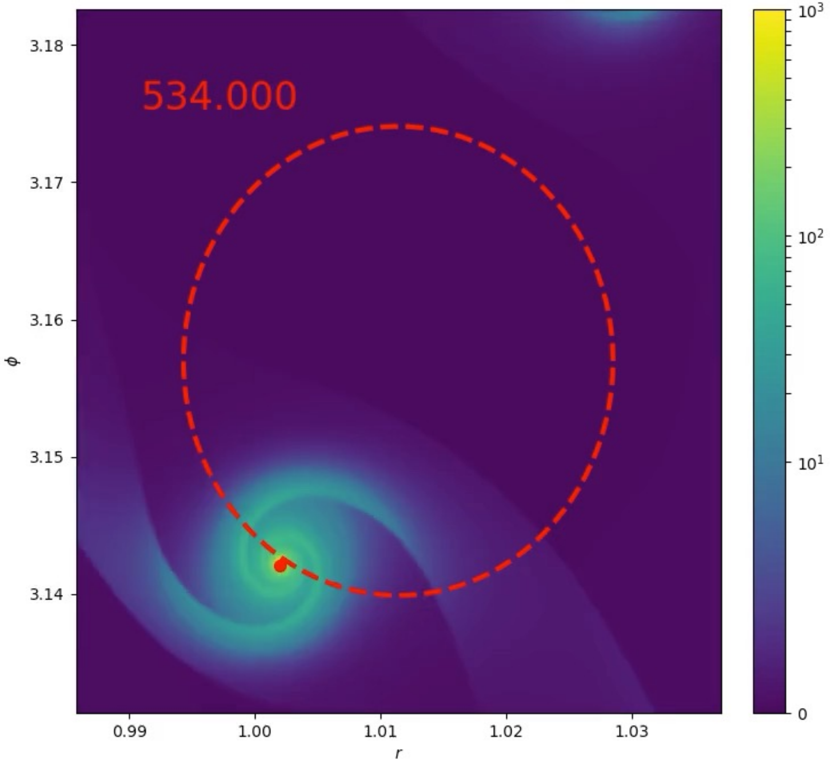
Formation process





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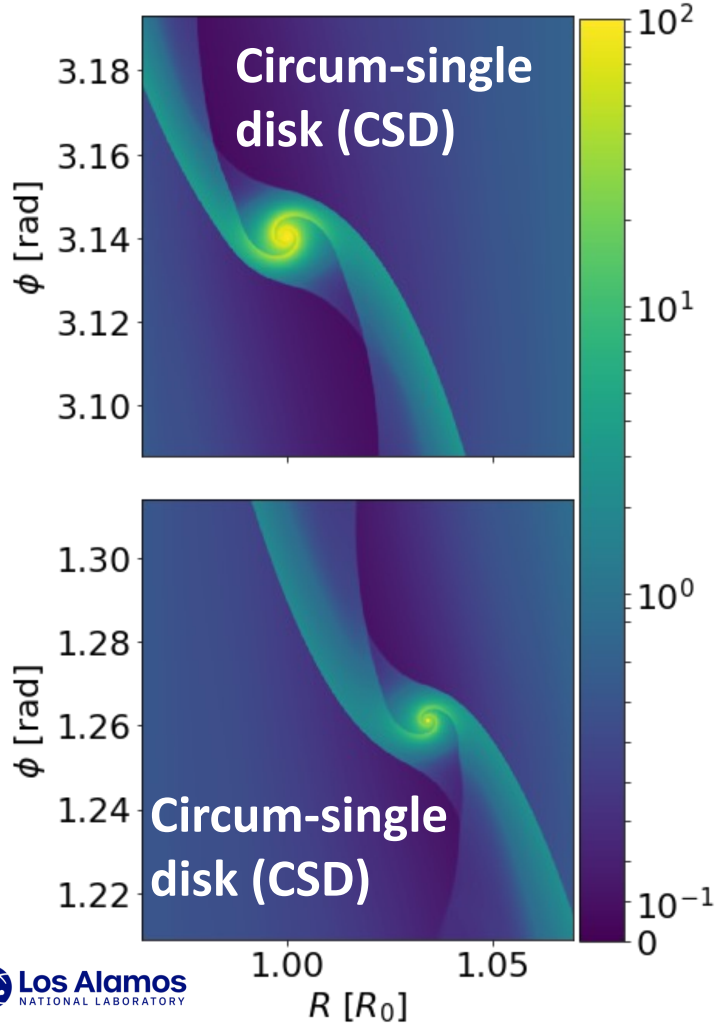
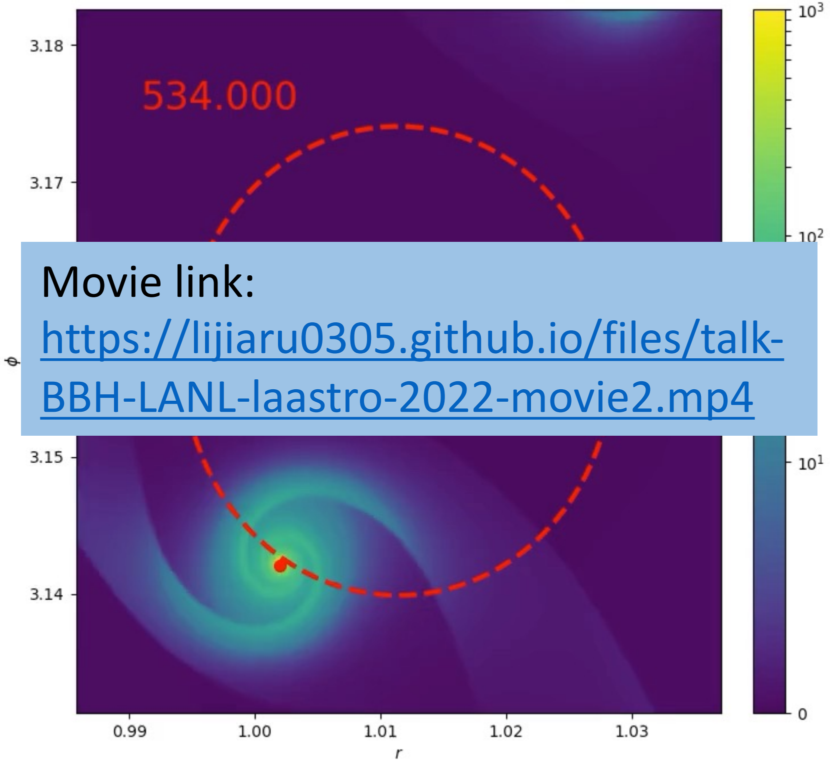
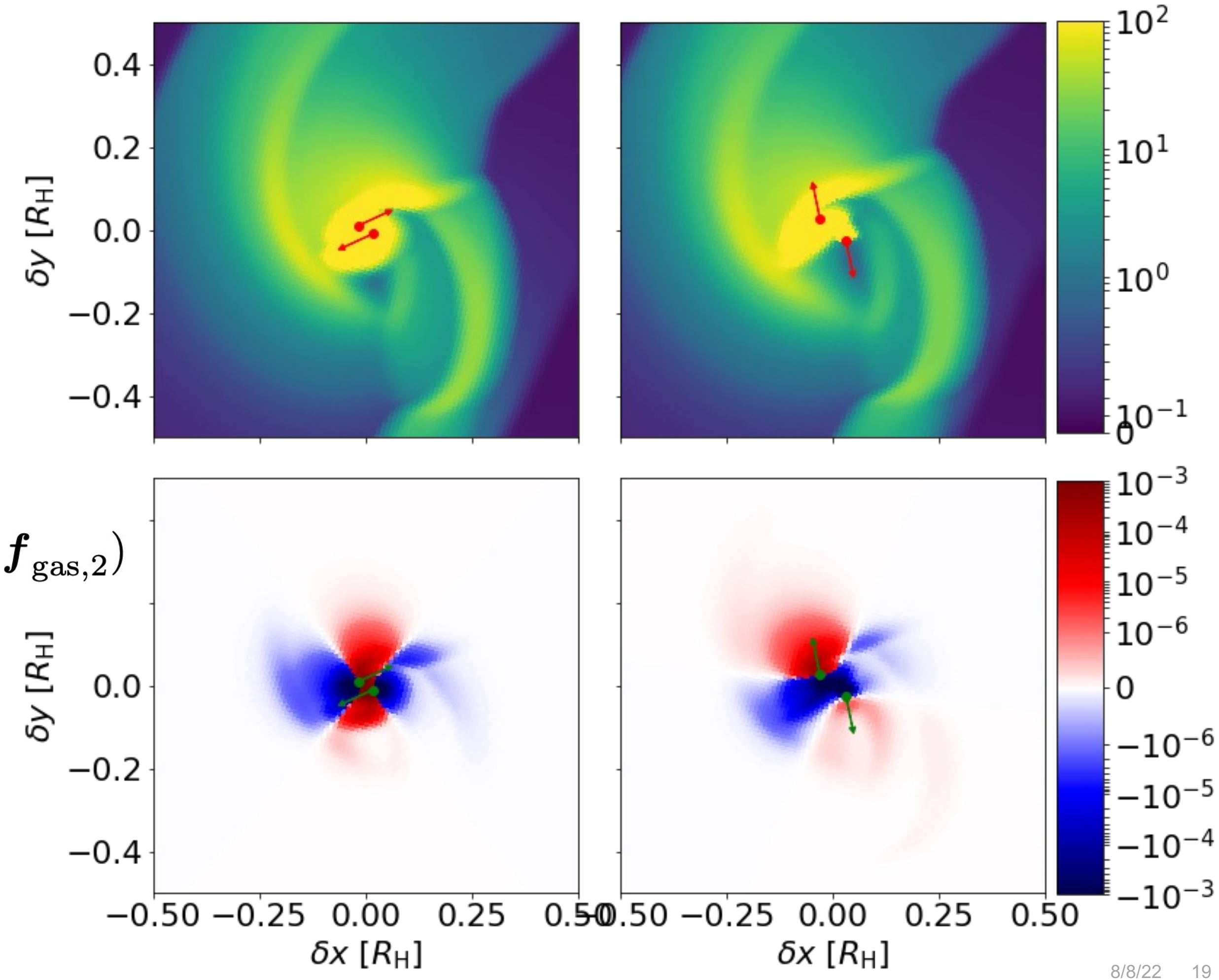




Movie link:
https://lijiaru0305.github.io/files/talk-BBH-LANL-laastro-2022-movie2.mp4

Energy change rate of the binary due to gas gravity

$$\dot{E}_{\rm gas} = \mu(\boldsymbol{v}_1 - \boldsymbol{v}_2) \cdot (\boldsymbol{f}_{\rm gas,1} - \boldsymbol{f}_{\rm gas,2})$$



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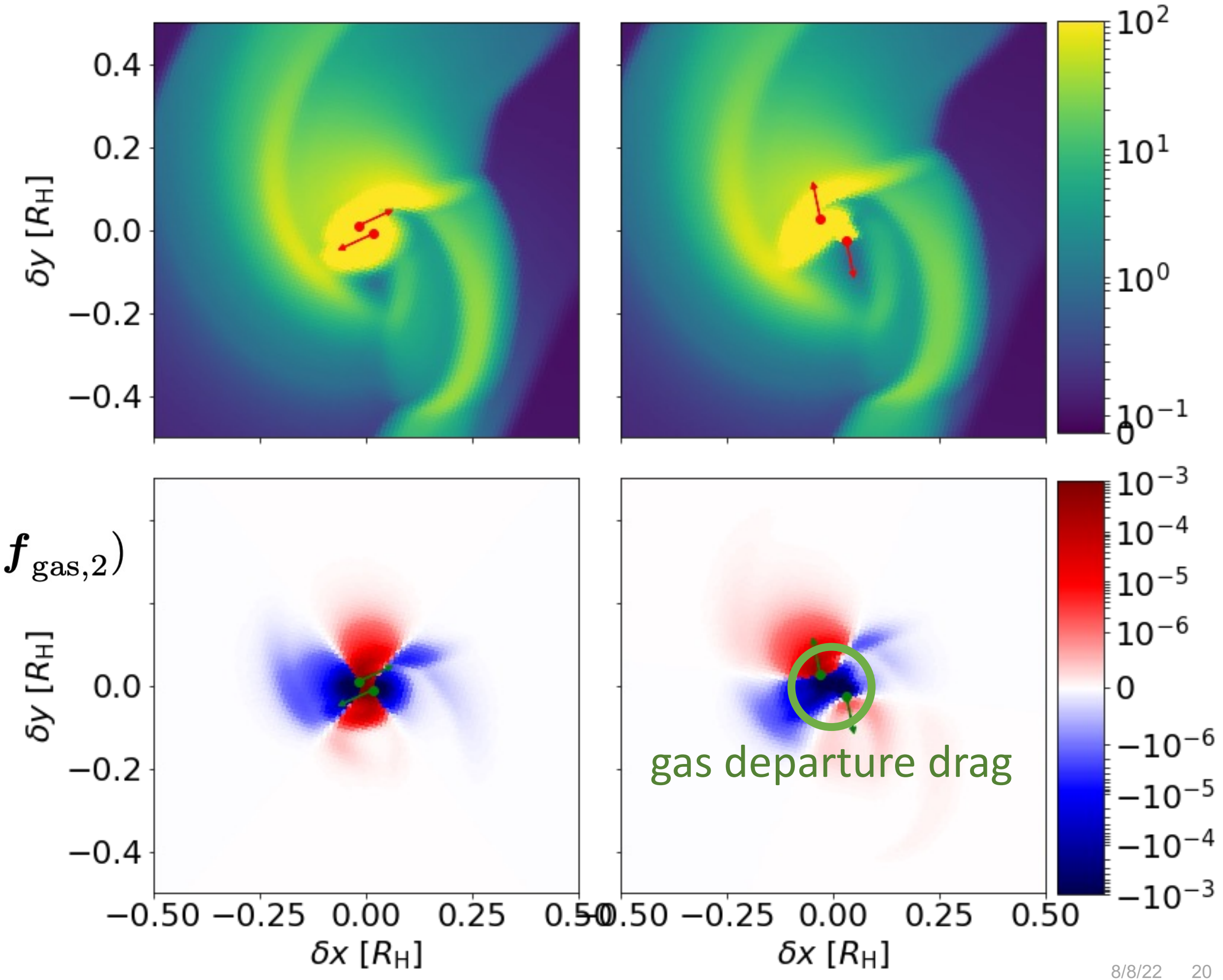
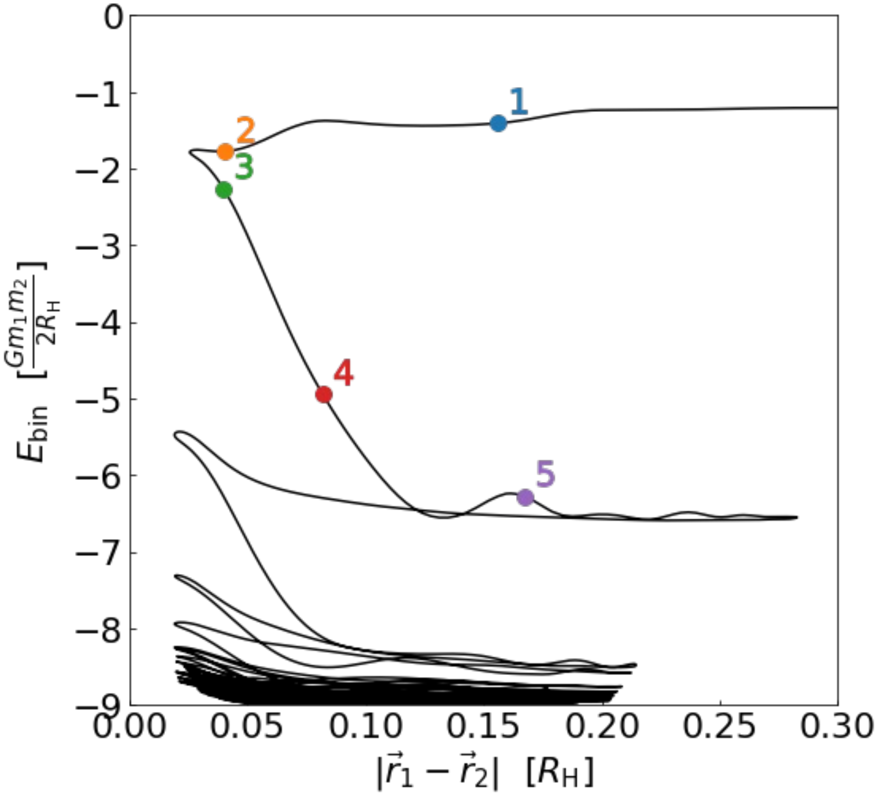


Analysis of the departure drag



Time evolution of BHs in the parameter space of the binary relative energy ($\boldsymbol{E}_{\mathbf{bin}}$) and separation ($|r_{\rm rel}| = |r_1 - r_2|$).

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

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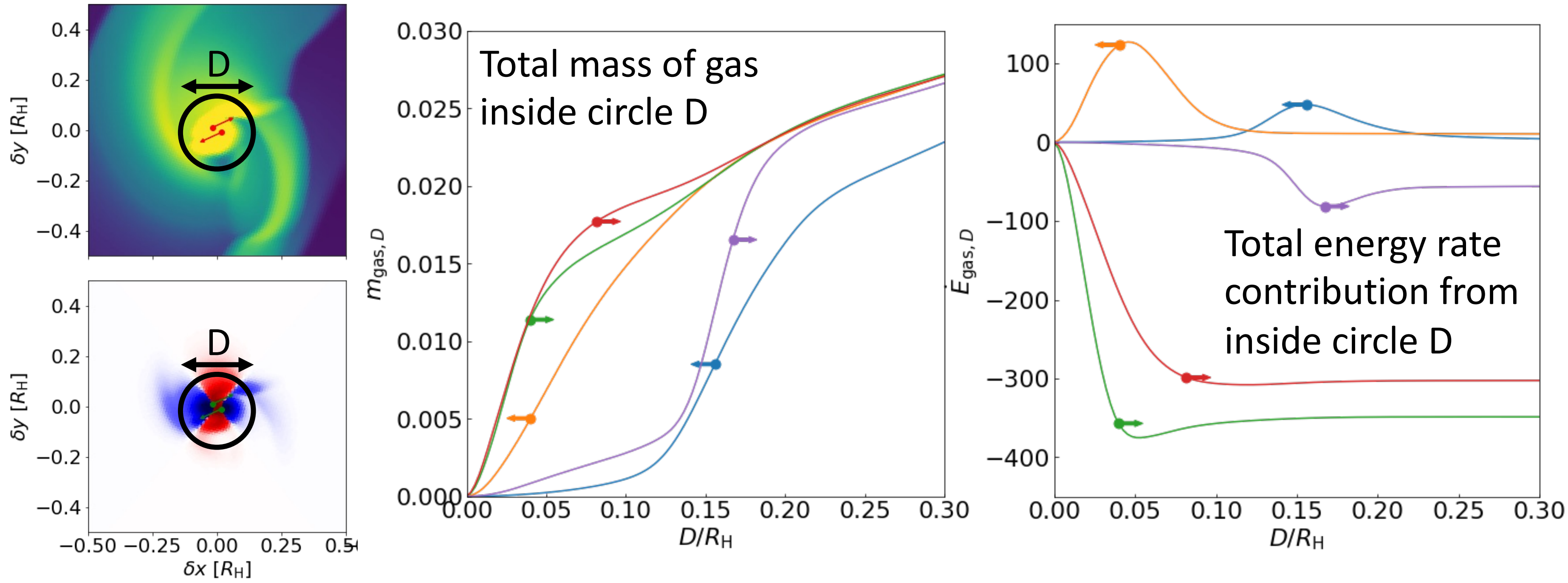
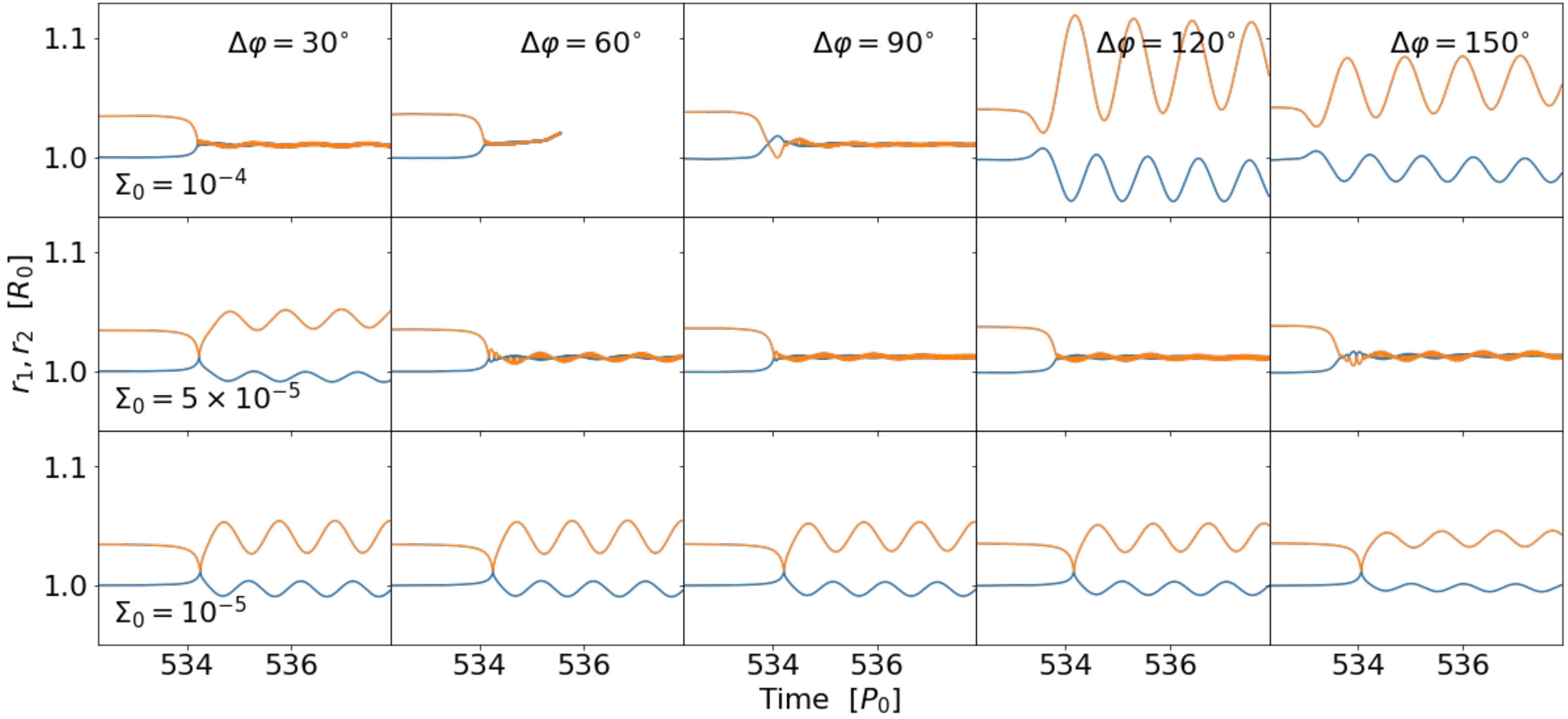


Parameter space for binary formation



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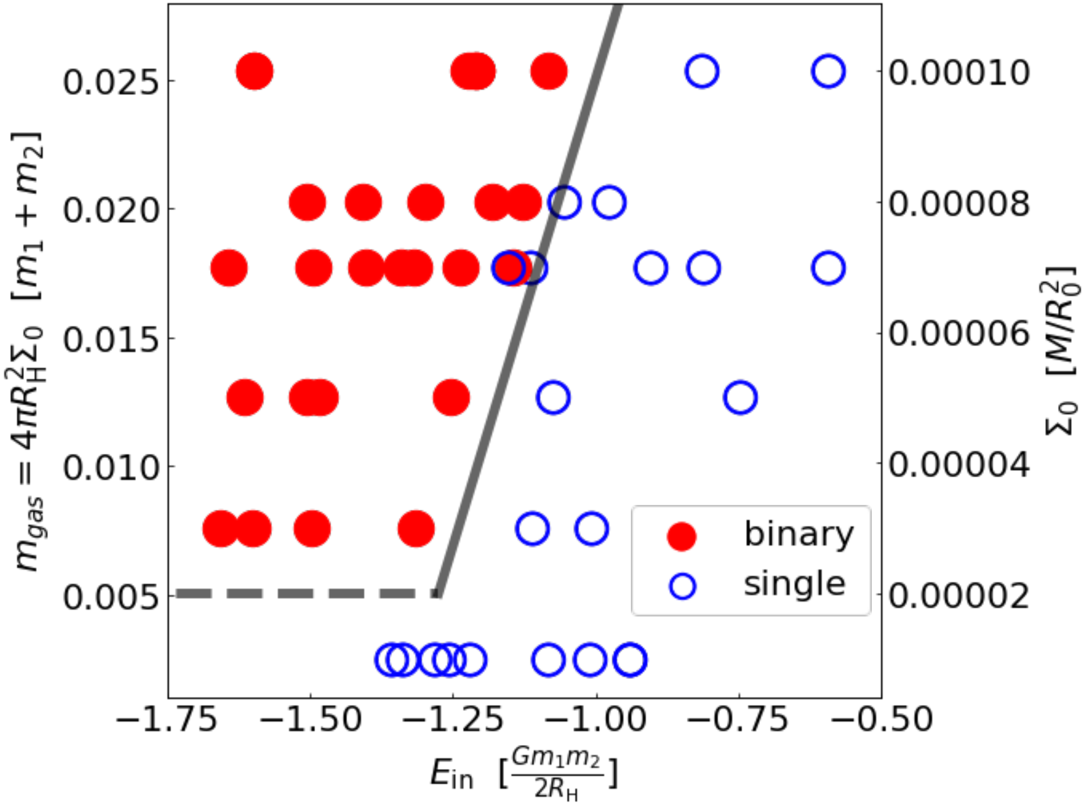


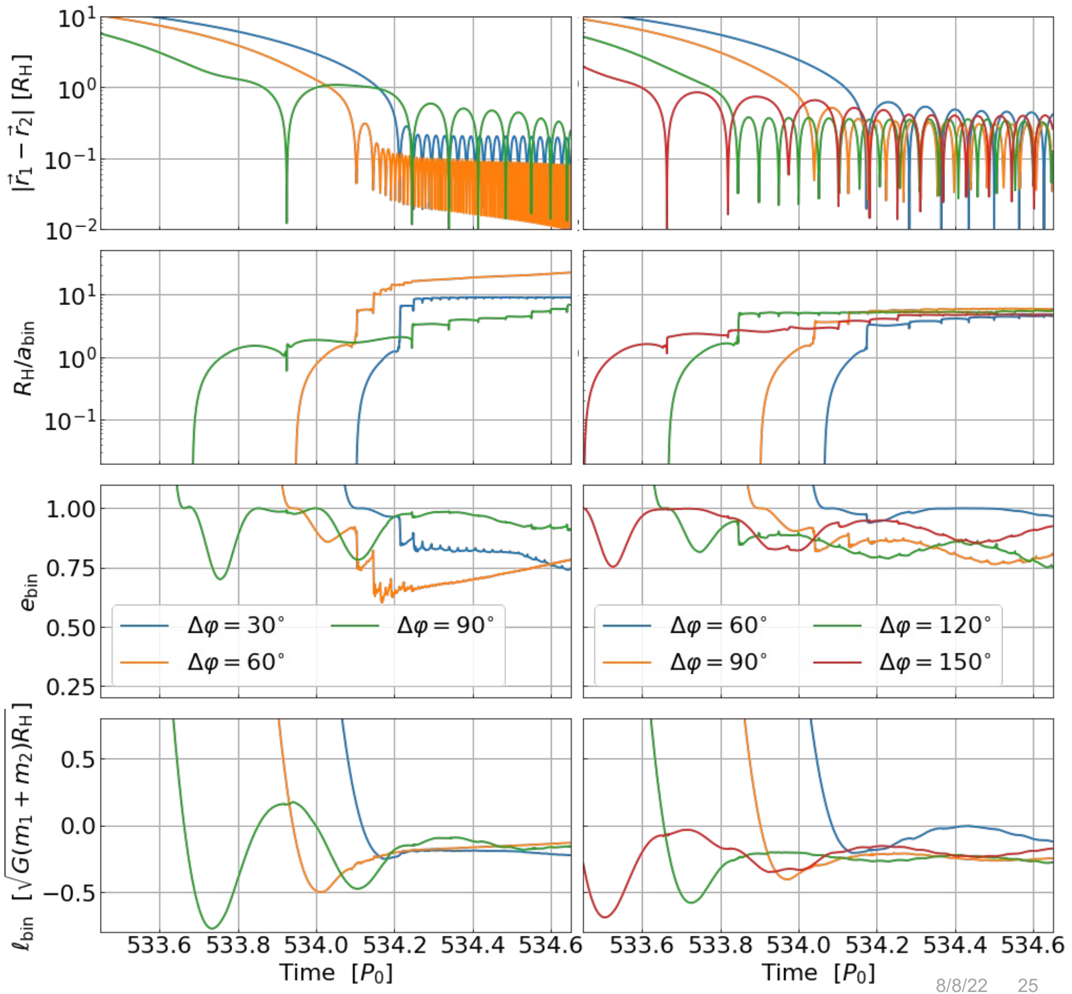
$E_{in} := E_{bin}$ | before pericenter

Forming binary requires:

- sufficiently large gas mass
- sufficiently small initial binary energy

Resulted 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: $\ell_{\mathrm{bin}} < 0$



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Summary

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

- In the low gas density limit, dynamical instability produces lots of close encounters. → In rare events of every deep encounters, very tightly-bounded GW-dominated binaries can form.

- When the gas density is sufficiently high, close encounters can form bound binaries due to the collision between the two CSDs. → Formation-per-encounter ratio is much higher than in the low density limit.

- The resulted BH binary orbits can be highly eccentric, compact, and retrograde.