Dynamical Formation of BH Binaries in AGN Disks

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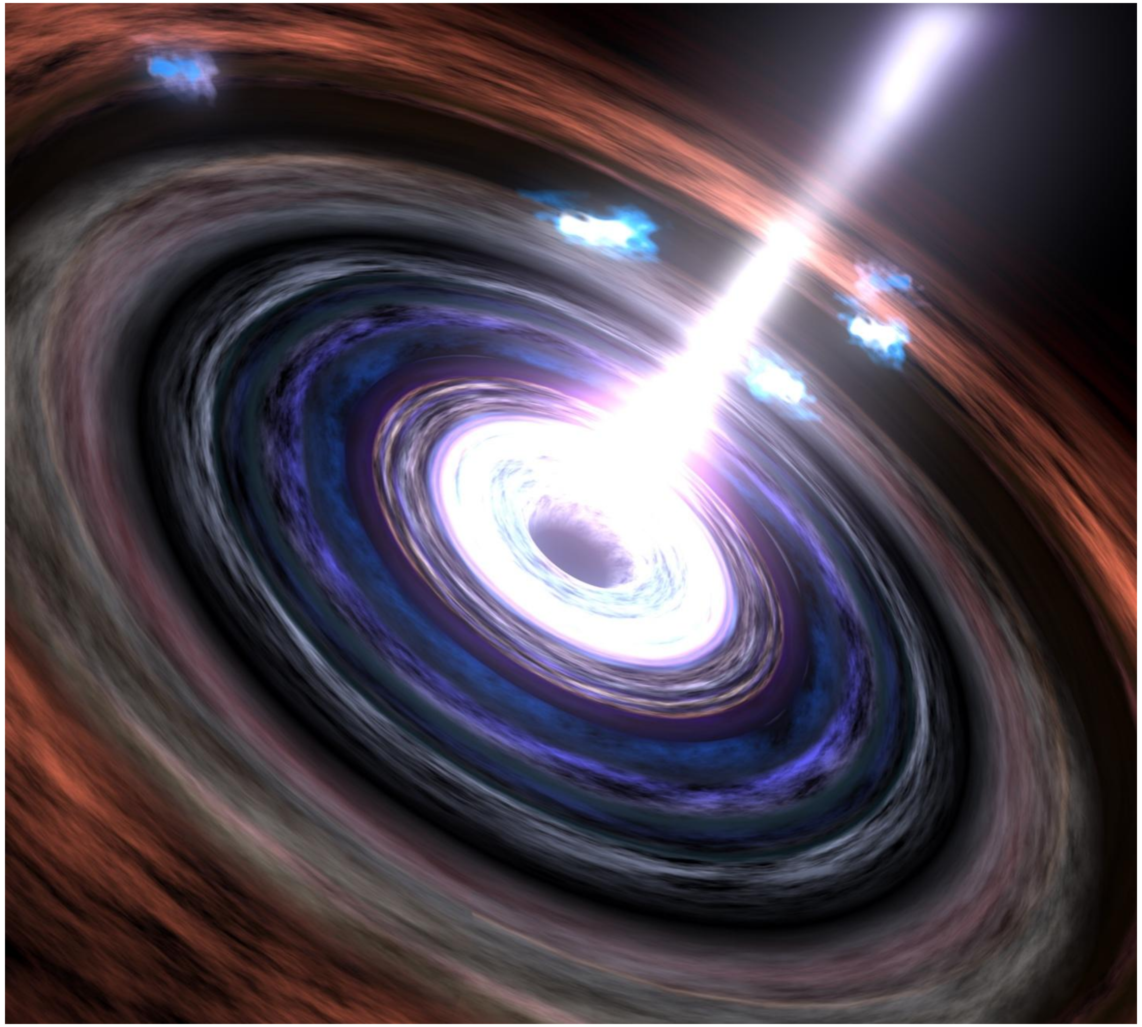
In collaboration with:
Dong Lai, Laetitia Rodet, Kecheng Qian (Cornell)
Hui Li, Adam Dempsey and Shengtai Li (LANL)

Why do we care about BH binaries in AGN disks?

- viable GW progenitors
- possible EM counterparts



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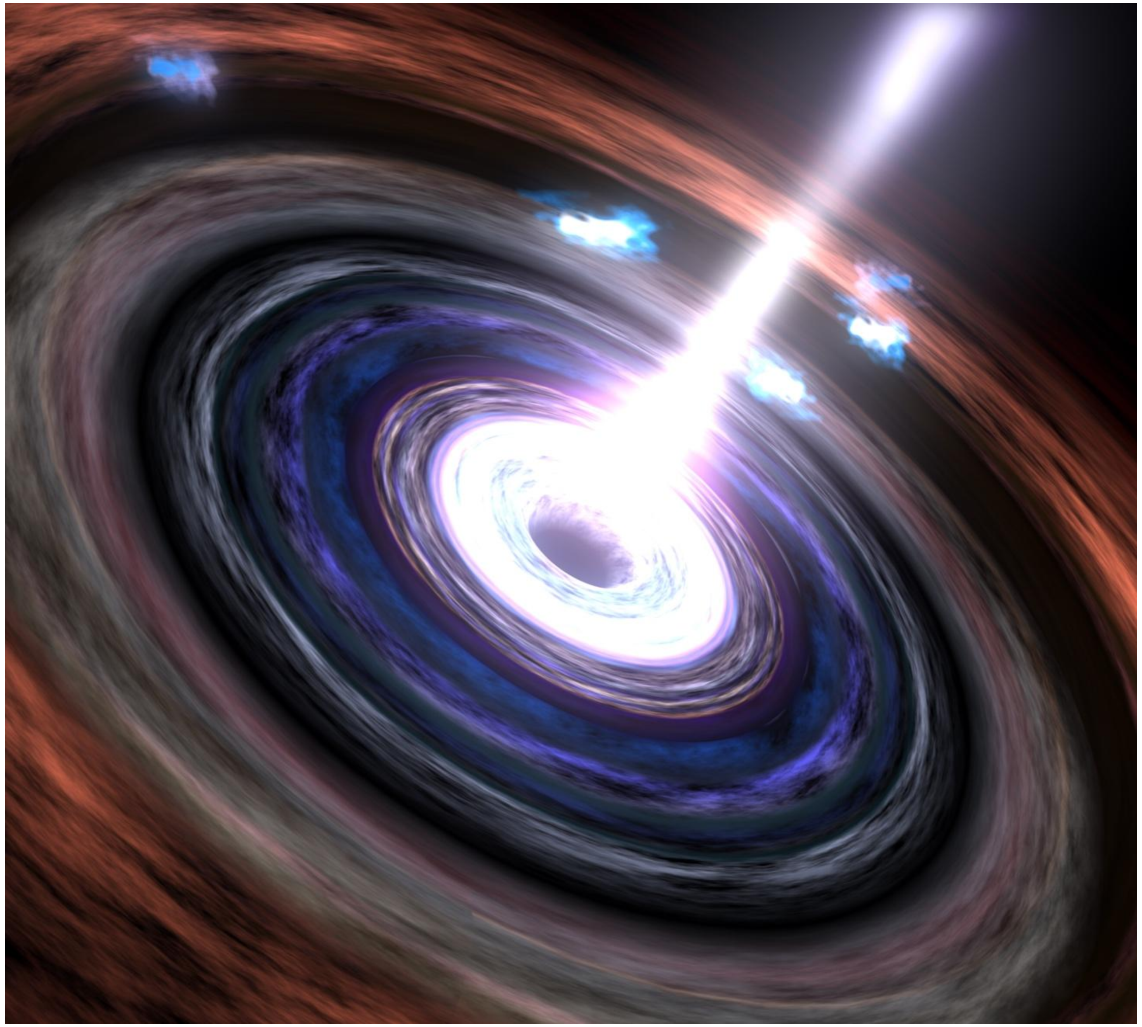
Topics to cover

- Dynamical formation of BH binaries in AGN disks - through close encounters
  - GW Bremsstrahlung
  - Gas dynamical friction
  - Post-collision drag
- A potential new mechanism to form **eccentric extreme-mass ratio binaries**
  - Resonant eccentricity excitation for BH around a SMBH caused by an eccentric AGN disk.
  - NB: Initially developed for exoplanets. Very very preliminary for GW.



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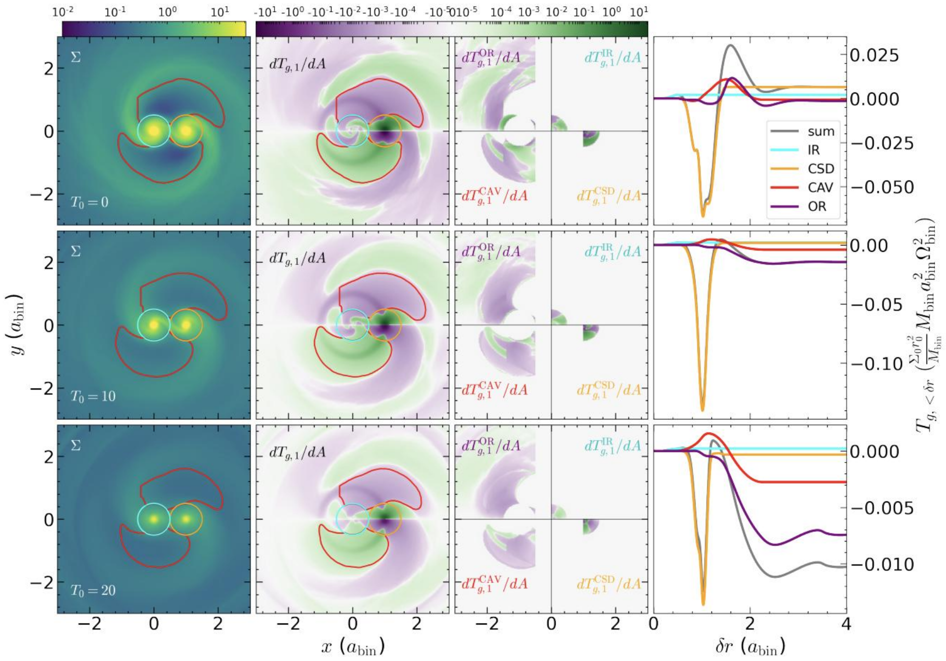
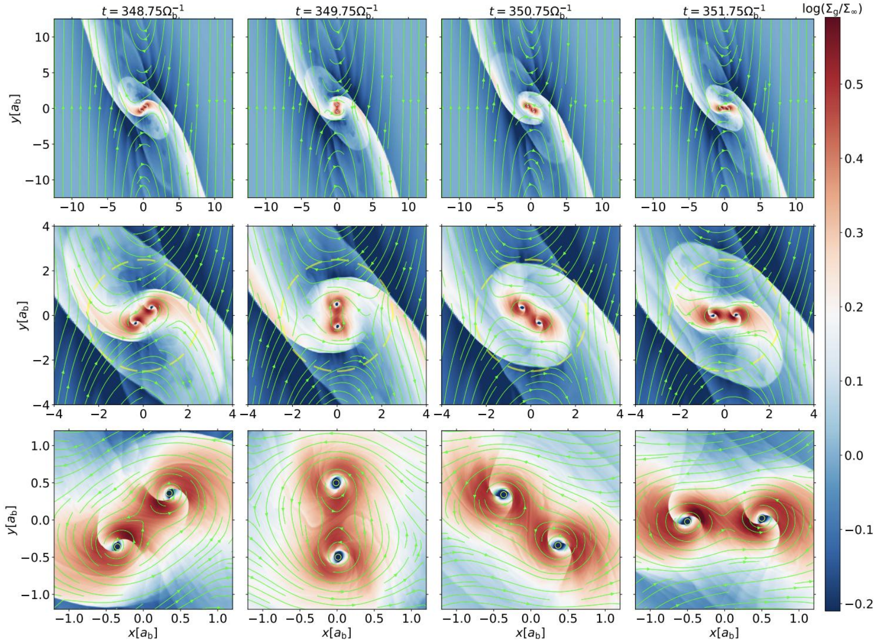
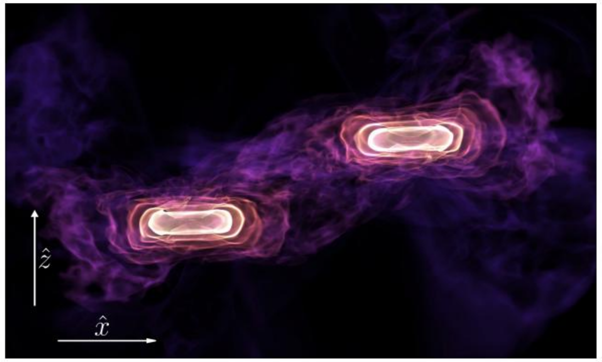
Why care about BBH formation mechanisms?

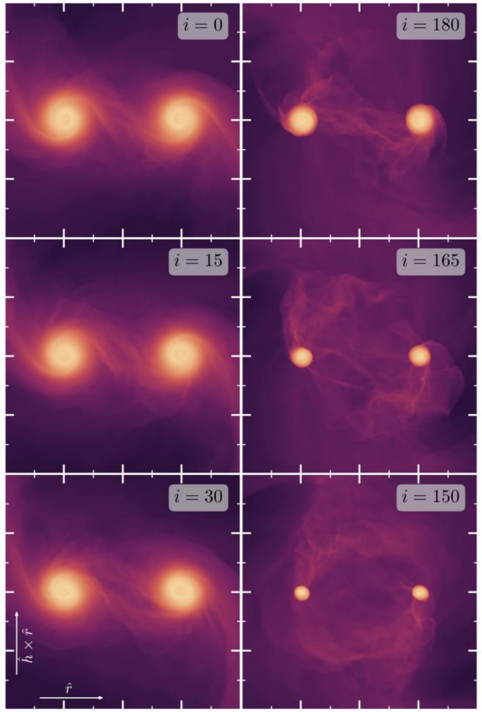


Li+ incl. **J. Li** (2021, 2022)



Li & Lai (2022, 2023, 2024)



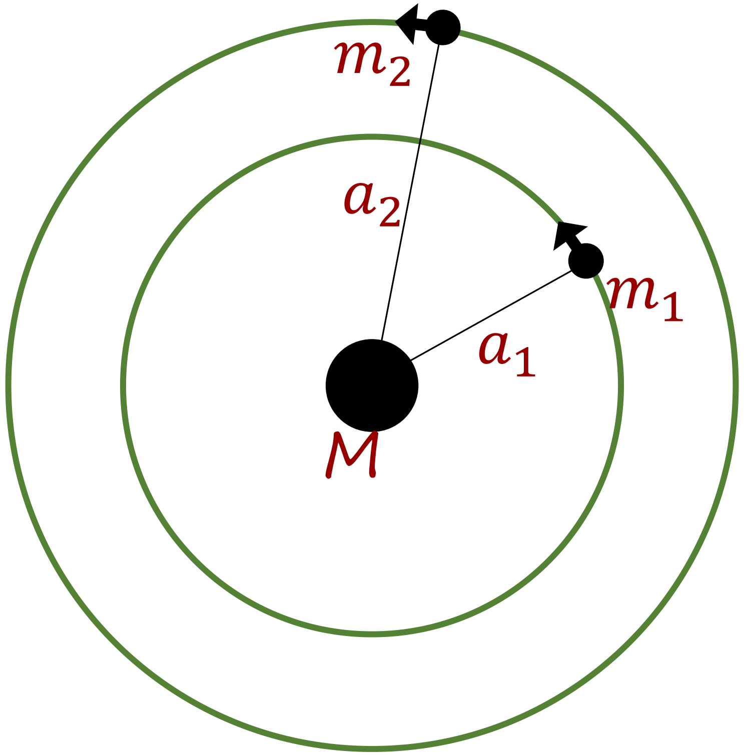


Dittmann+ (2023)
and Calcino+ (2024)

Evolution of BH binaries depends on the disk and **binary** parameters:

Formation mechanism of BBH in AGN disks ←→ Properties of newly formed binaries

Basic picture for the formation of BBH through close encounters



- Consider two BHs on closely-packed orbits.. (see left)

$$\boldsymbol{a_2} - \boldsymbol{a_1} \sim \text{a few } \boldsymbol{R_{\mathrm{H}}}$$

- Possibly due to:
  - Differential migration or migration trap (?)
  - In-situ disk capture
  - and so on..

➢ **Dynamical instability will occur..**

➢ **BHs will undergo scatterings and close encounters.**

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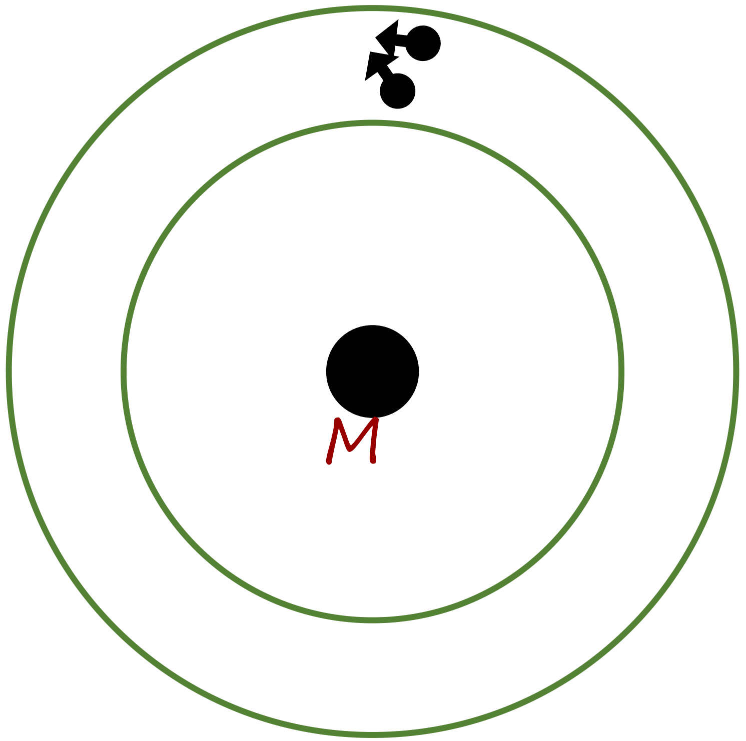

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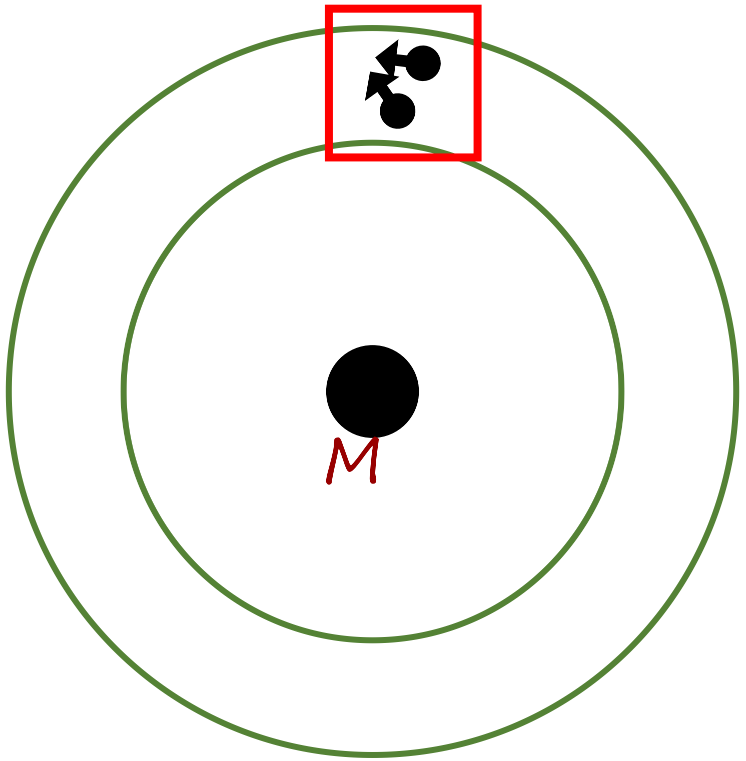
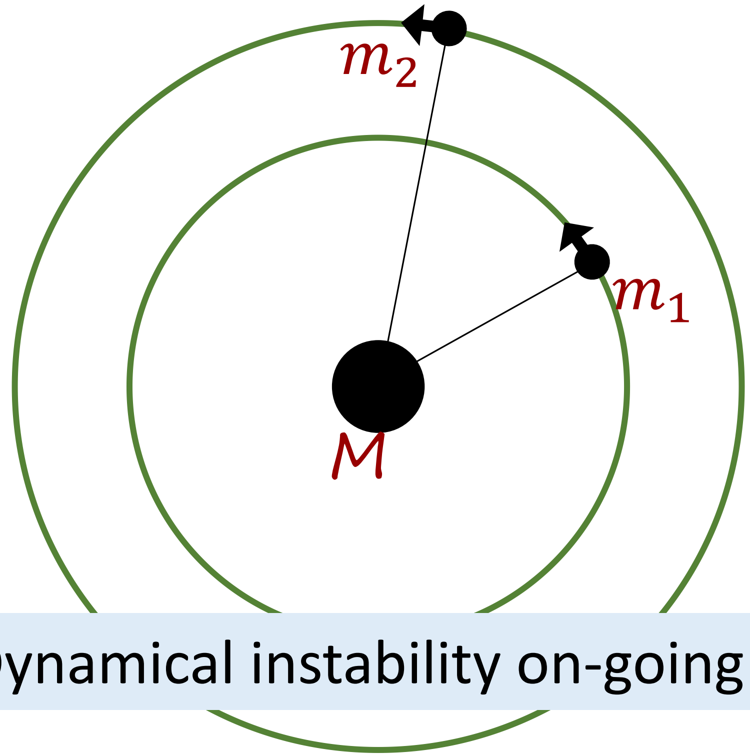


Mechanisms to capture BHs into bound binaries:

- **GW bremsstrahlung (low/negligible gas density)**
  (***J. Li****, Lai, and Rodet 2022*)

- **Gas-assisted capture (high gas density)**
  - Gas dynamical friction
  (*Qian, **J. Li**, and Lai 2024*)
  - Post-collision gas drag
  (***J. Li****+ 2023;* ***J. Li****+ in prep*)

Formation via *GW bremsstrahlung*: basic picture



- If the gas force is weak:
  - **Recurring close encounters** -- will be a lot close encounters!

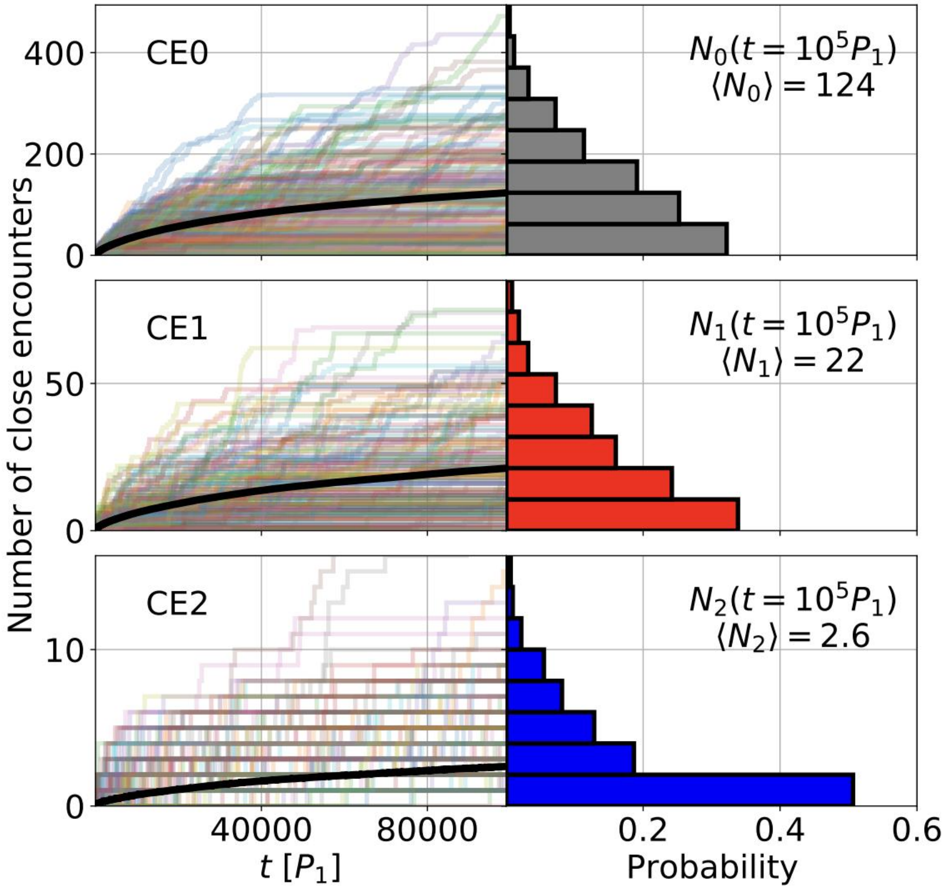
- BHs can form tightly bound binaries during **very** close encounters that radiate enough GW.

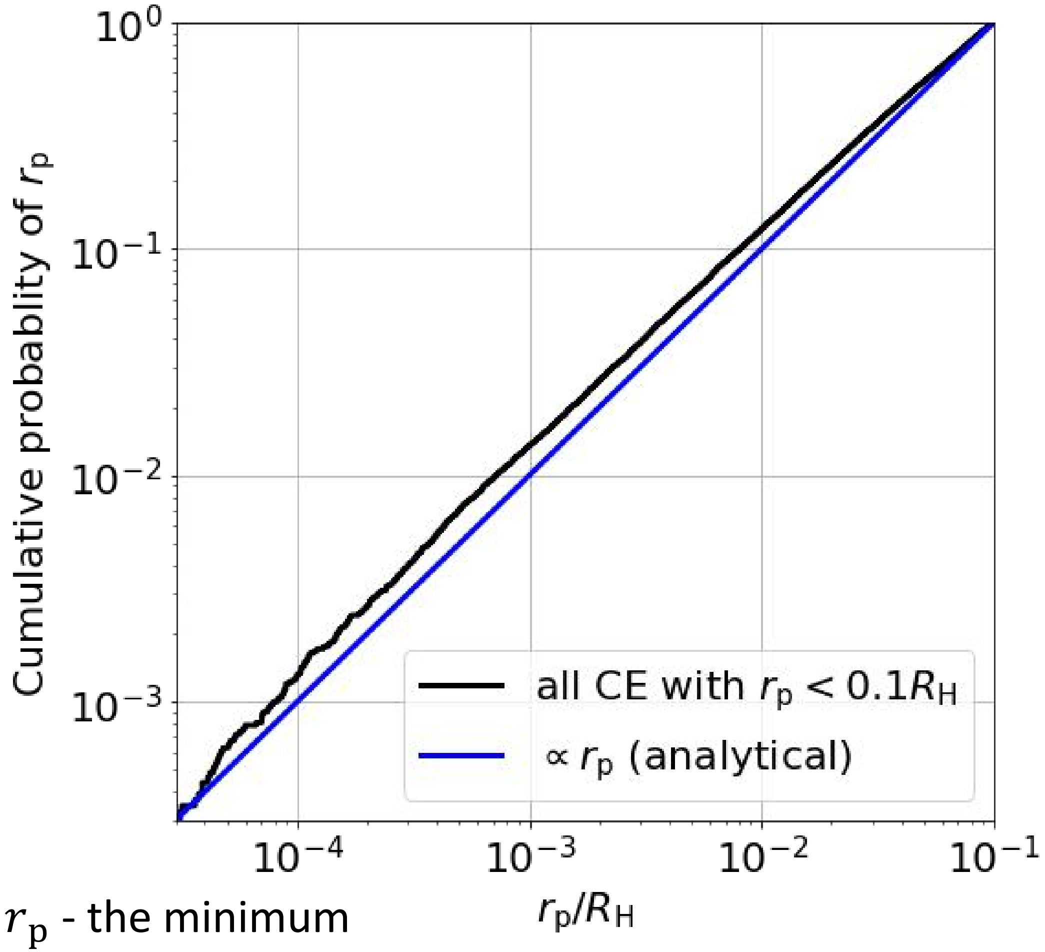
$$\Delta E_{\rm GW} = \frac{85\pi}{12\sqrt{2}} \frac{G^{7/2}\mu^2 m_{12}^{5/2}}{c^5 r_{\rm p}^{7/2}} \quad \gtrsim \eta \frac{G m_1 m_2}{R_{\rm H12}}$$

energy radiated by GW (*Peters 1964, Quinlan & Shapiro 1989*)

energy needs to be removed for binding

Formation via *GW bremsstrahlung*: N-body results

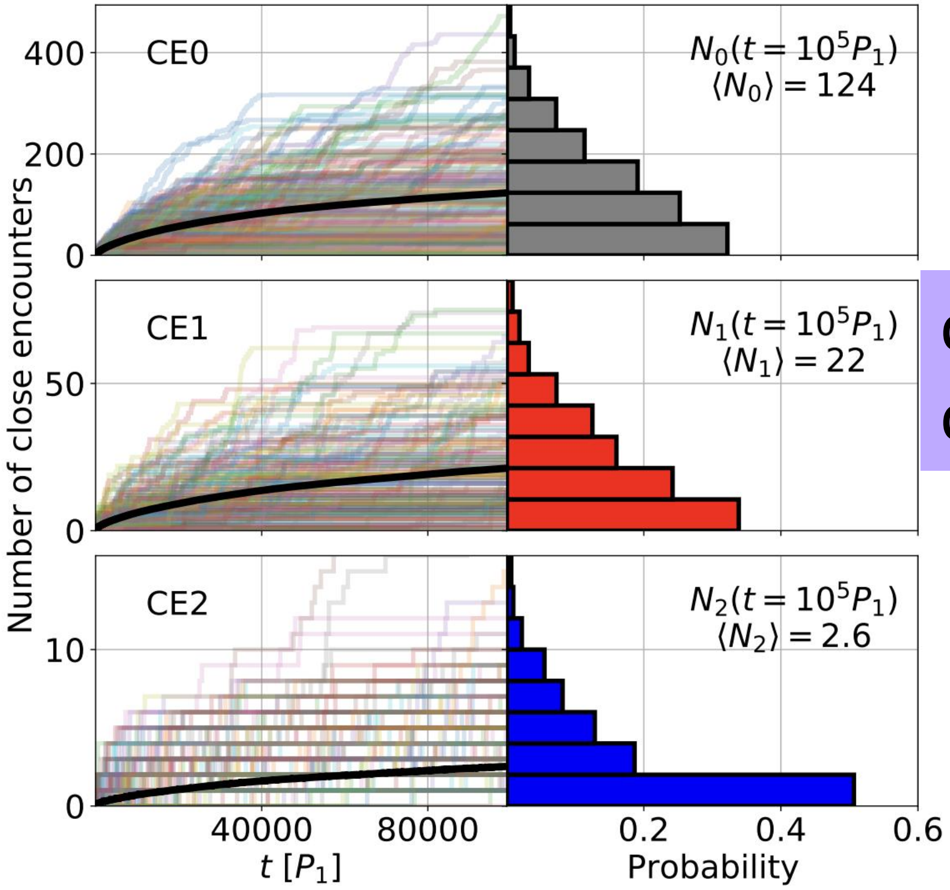


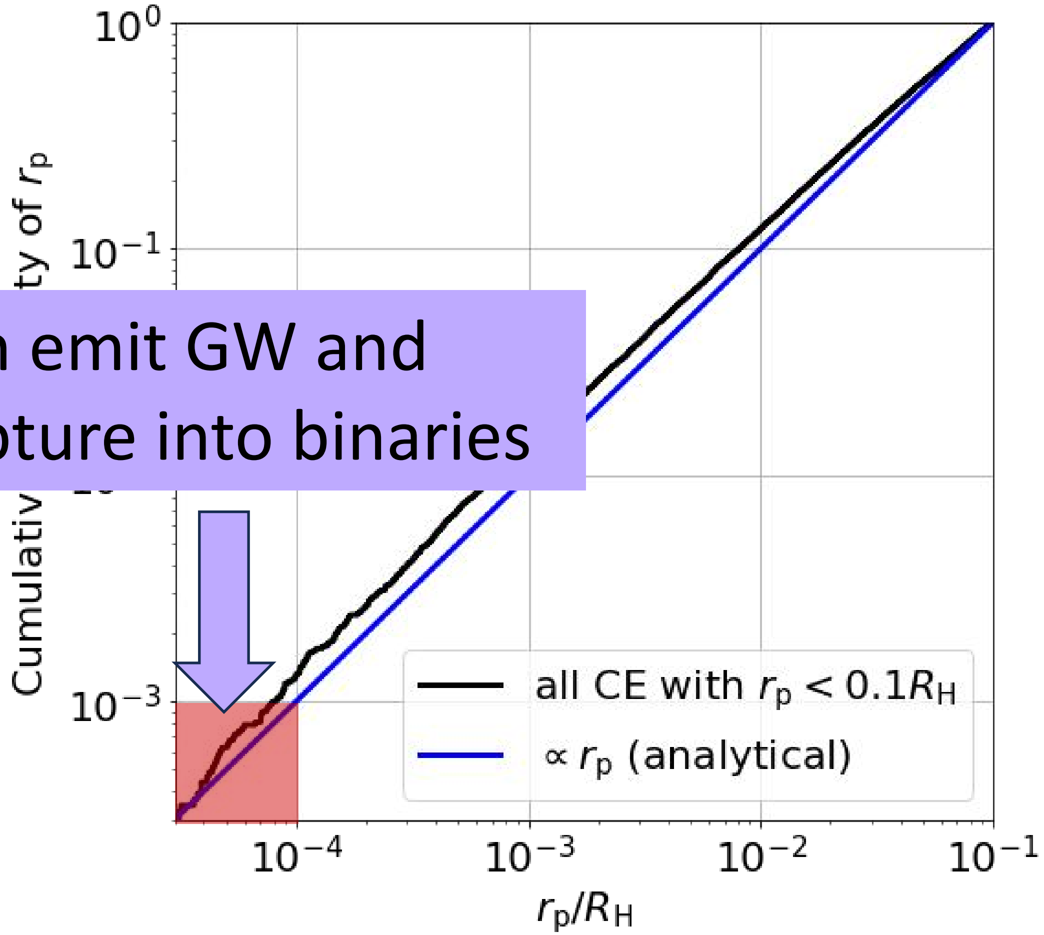


r_p - the minimum passage between the BHs

(***Li***, *Lai, and Rodet 2022*)

Formation via *GW bremsstrahlung*: N-body results





(***Li***, *Lai, and Rodet 2022*)

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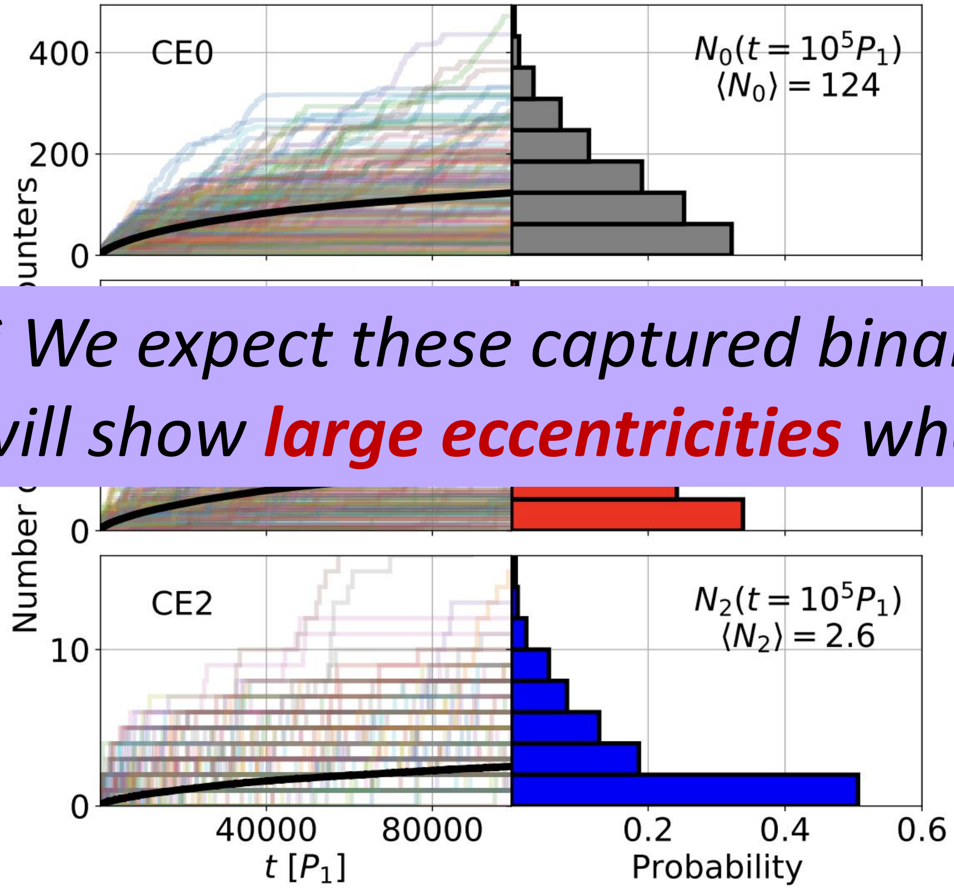
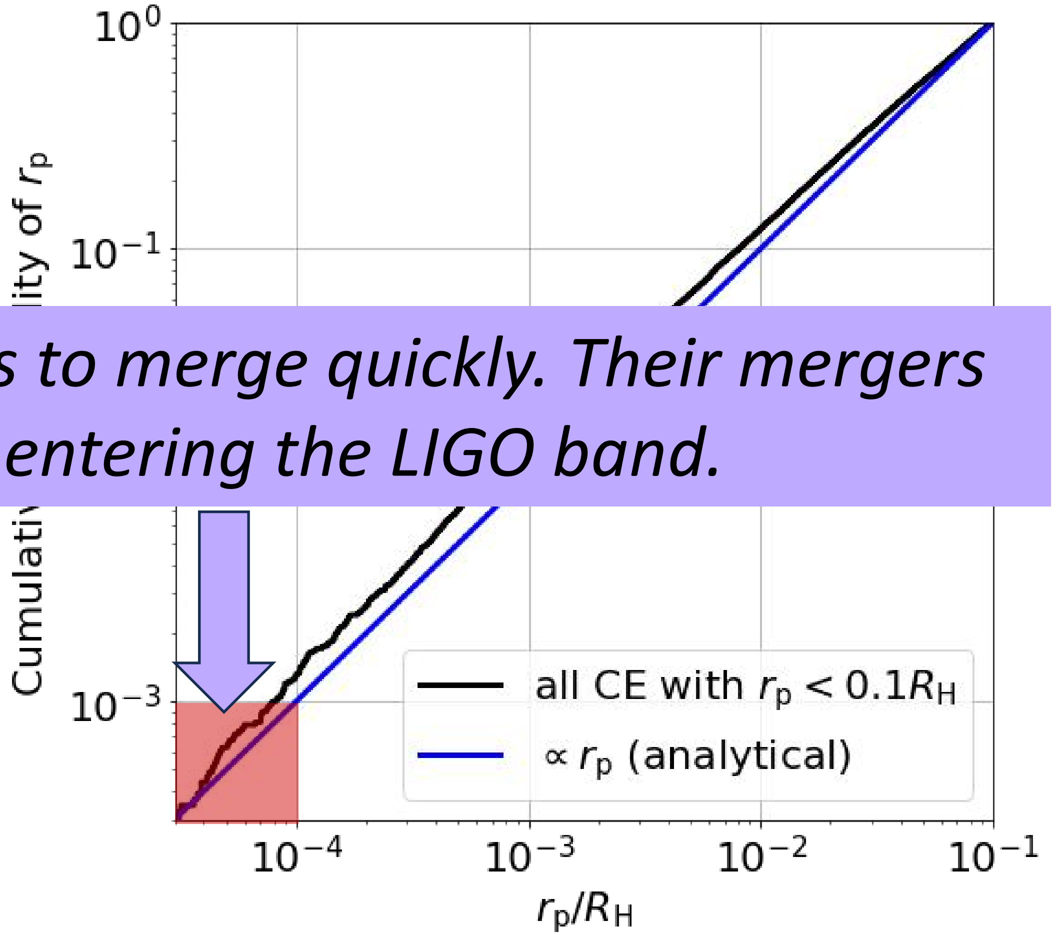
Formation via *GW bremsstrahlung*: N-body results

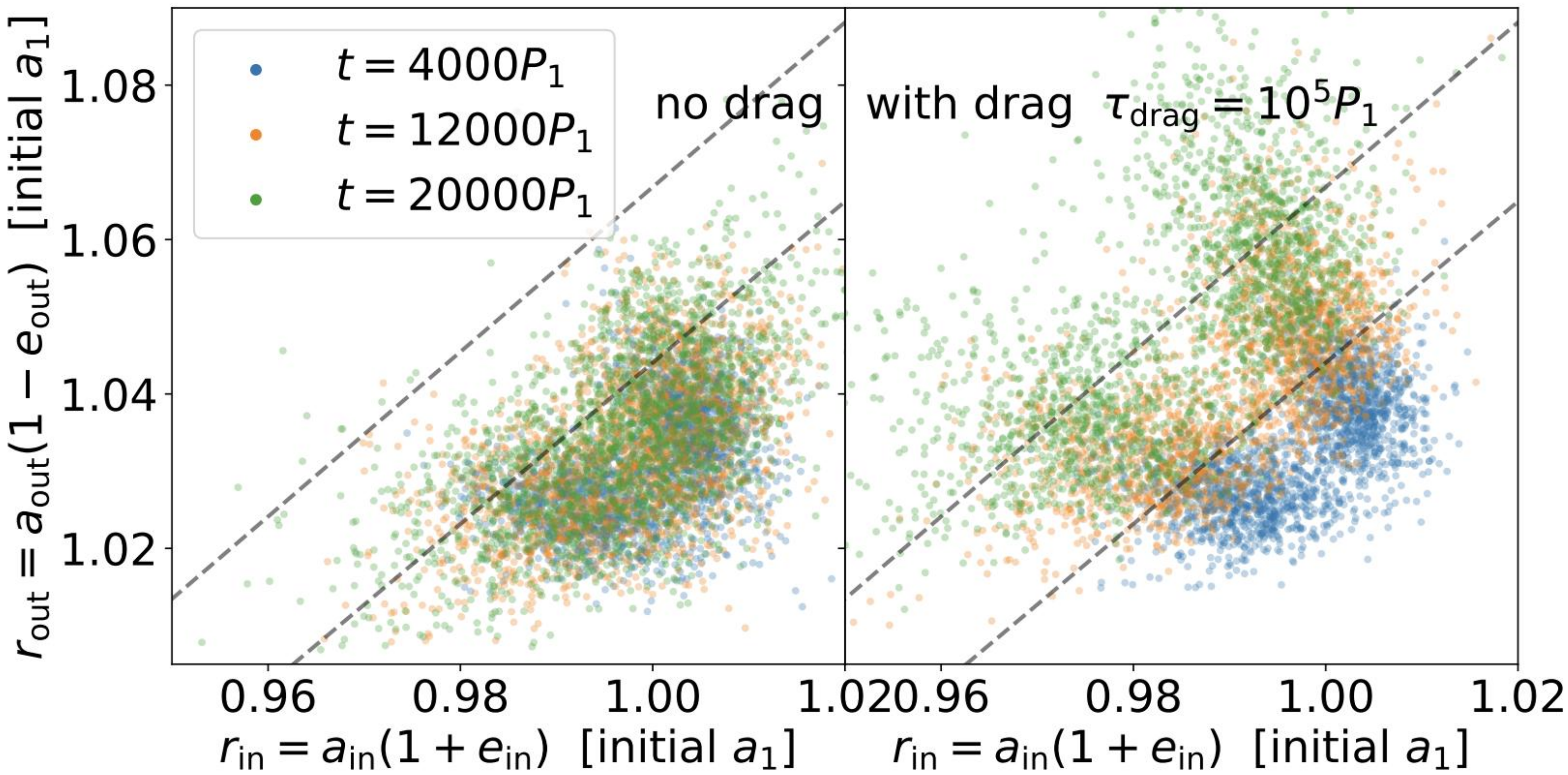




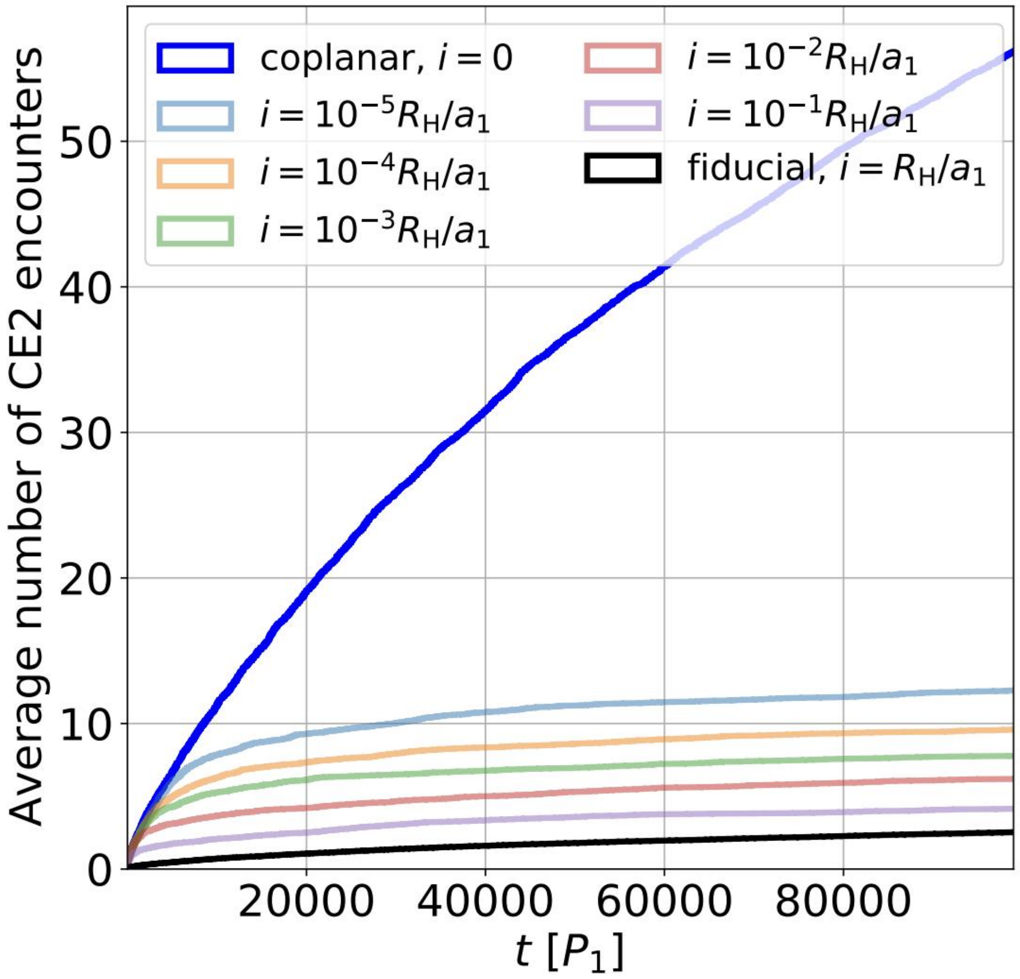
** We expect these captured binaries to merge quickly. Their mergers will show **large eccentricities** when entering the LIGO band.*

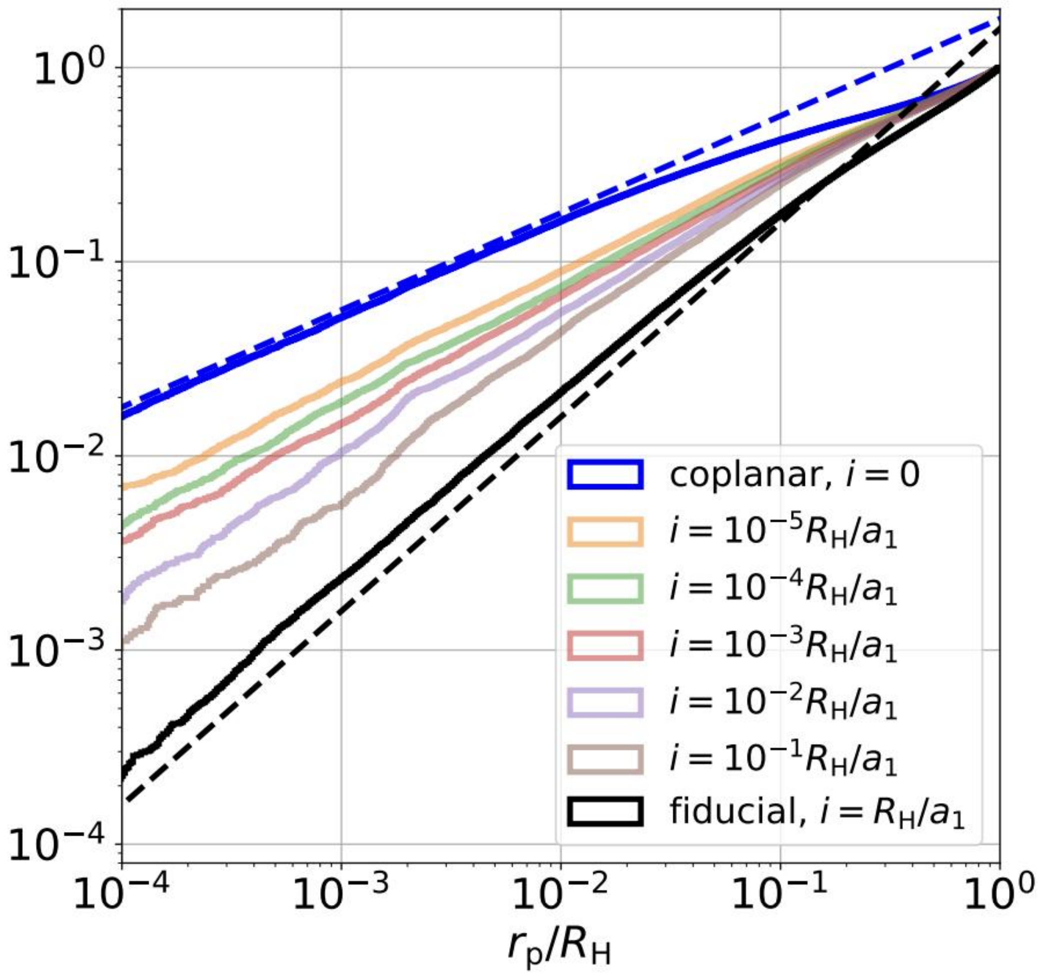
(*__Li__, Lai, and Rodet 2022*)

Formation via *GW bremsstrahlung*: low gas density



Formation via *GW bremsstrahlung*: inclination and rate





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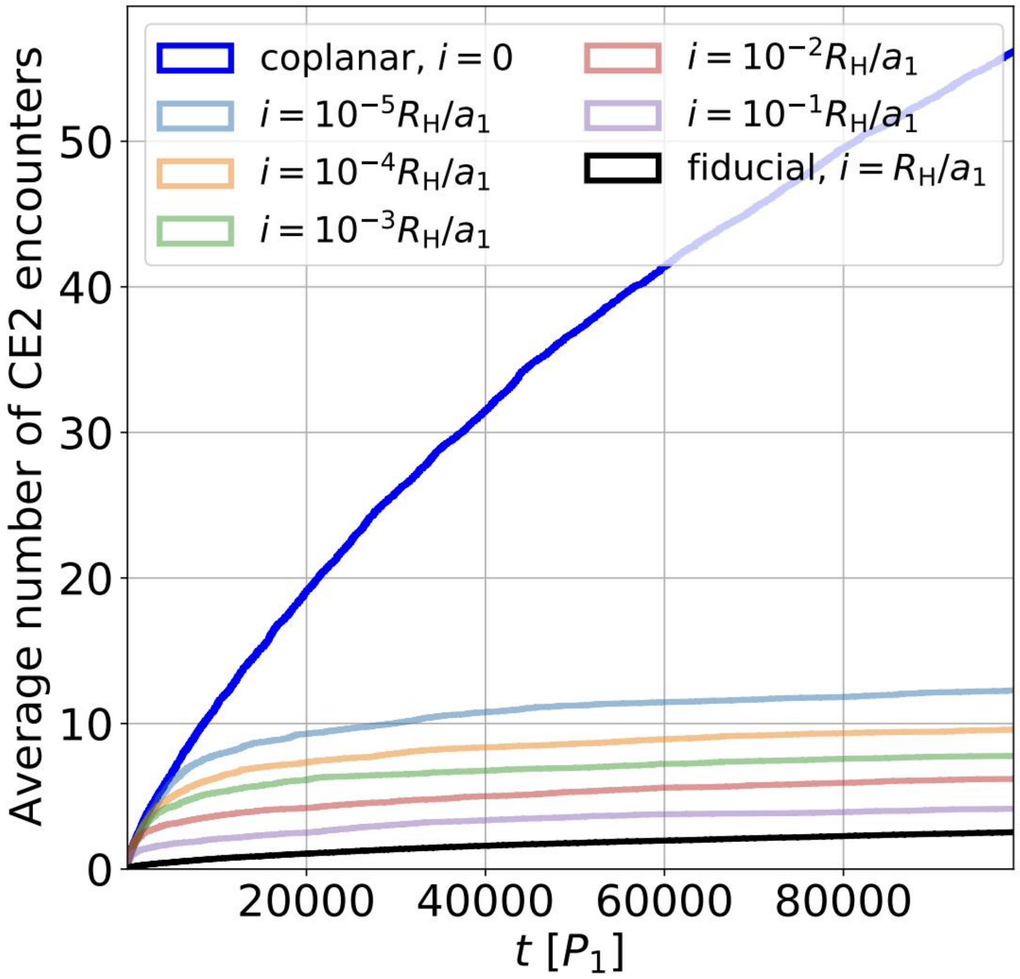
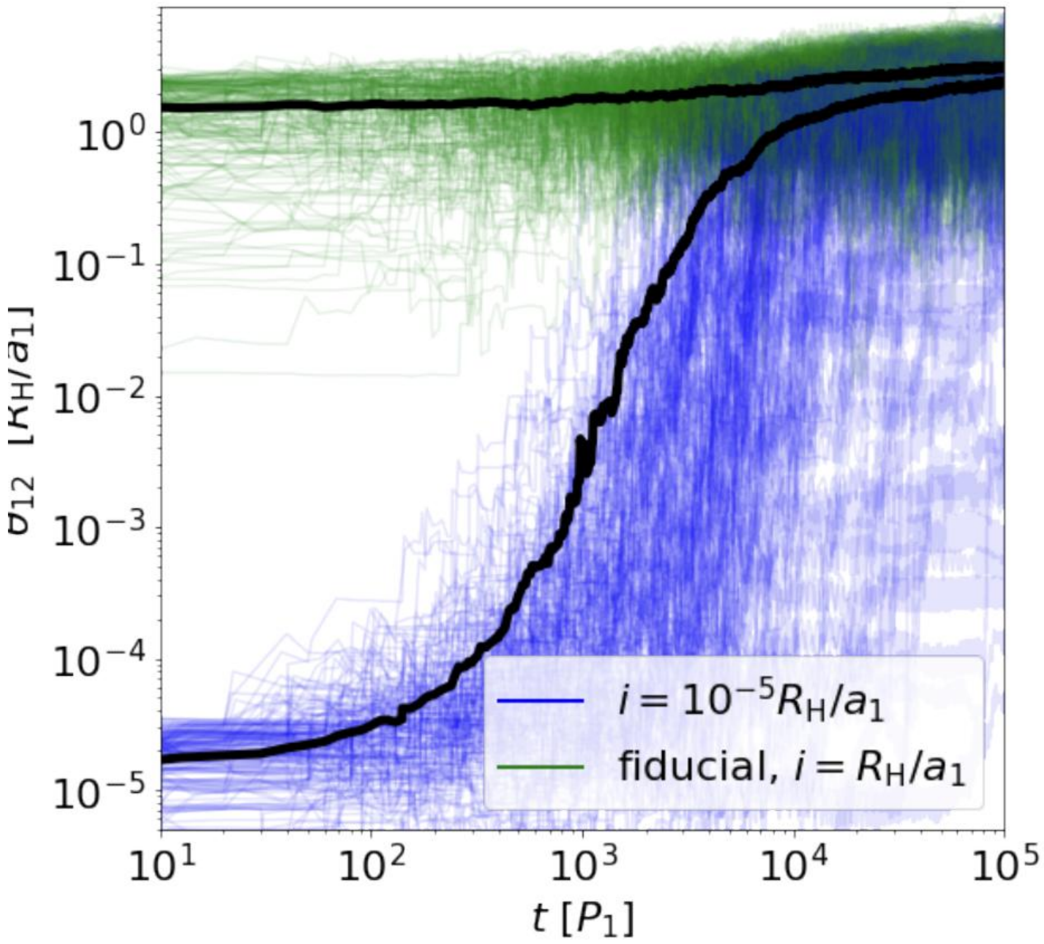
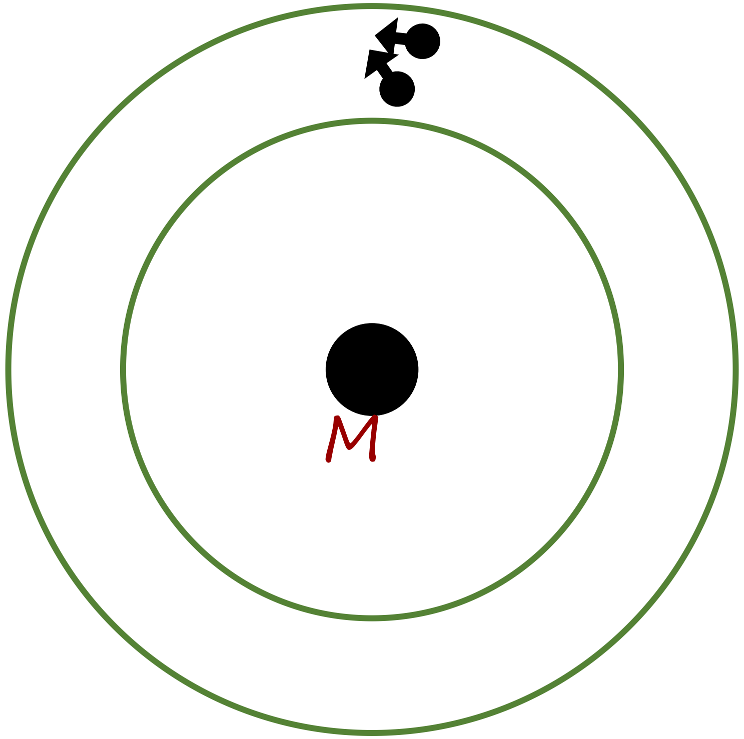


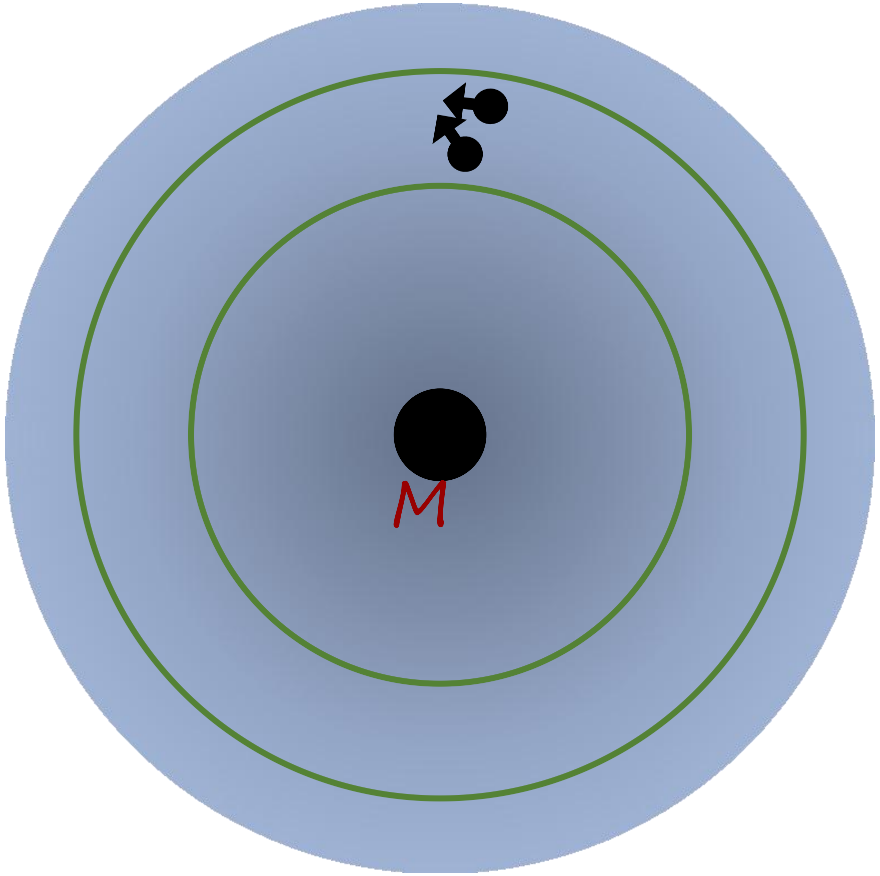


Formation of BBH through close encounters



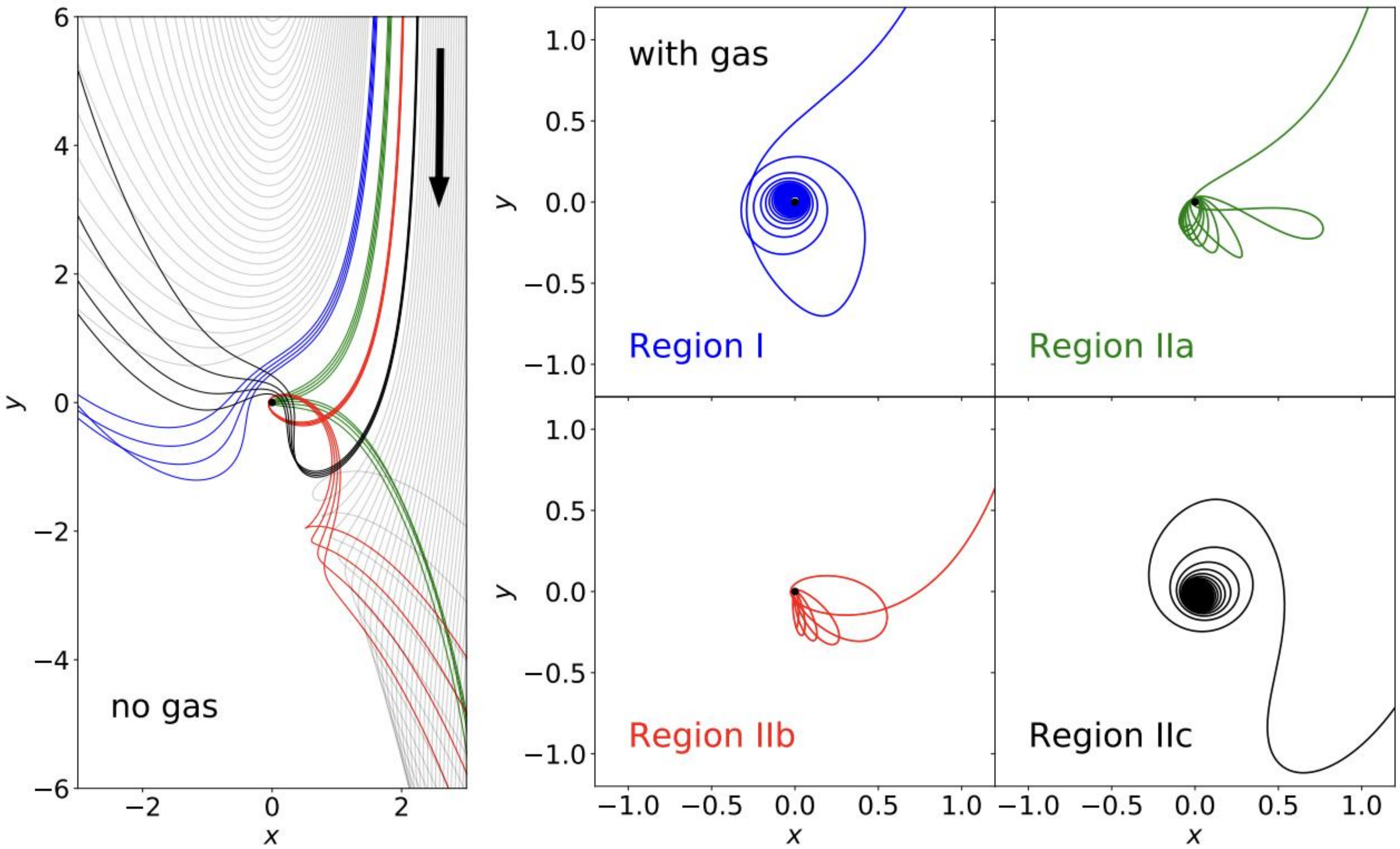
- GW Bremsstrahlung (very low gas density)
  - Lots of encounters..
  - Each encounter has a finite chance

Formation of BBH through close encounters

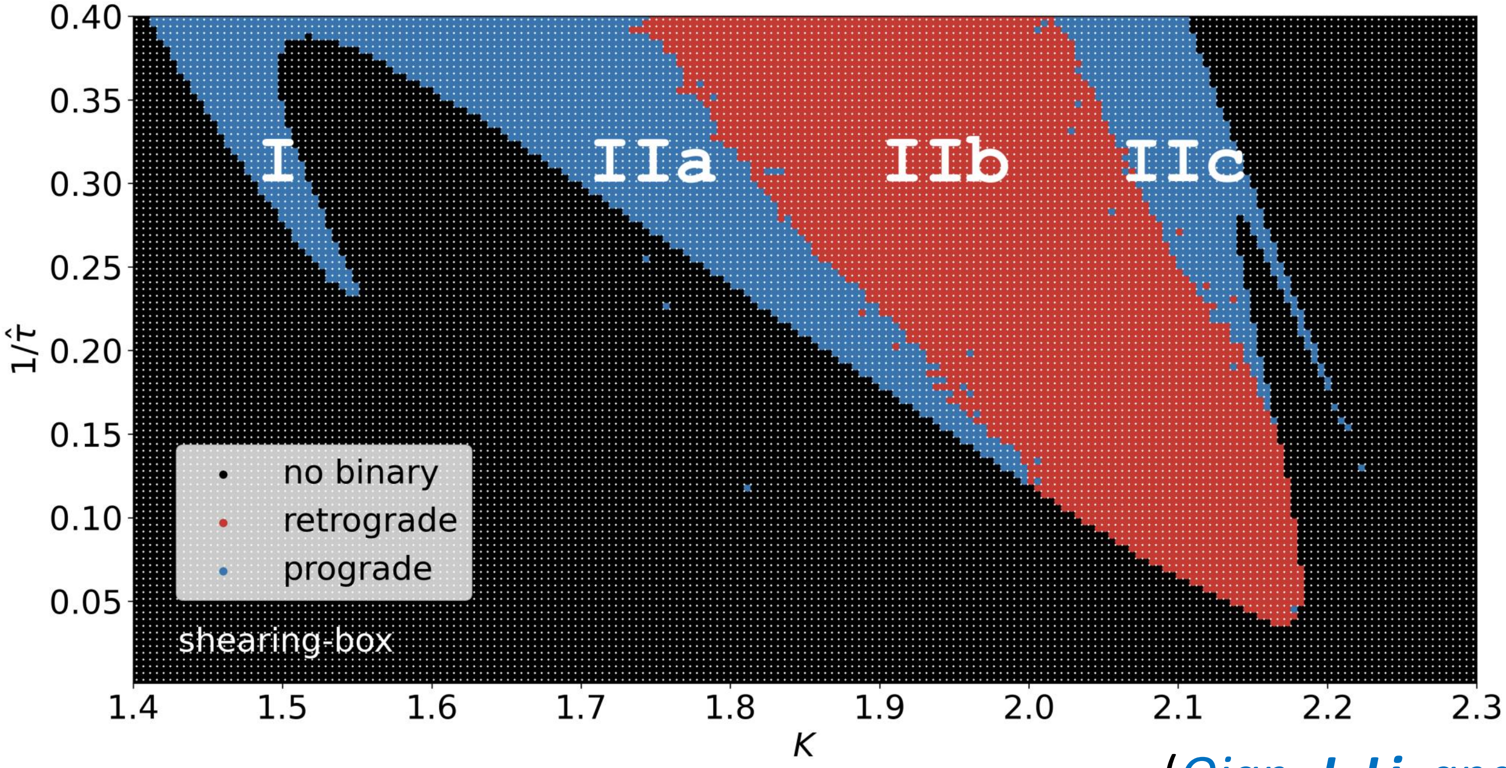


- Gas-assisted capture (high gas density)
  - fewer number of encounters
  - need to form binaries in one-shot

Formation via *frictional damping*: basic picture



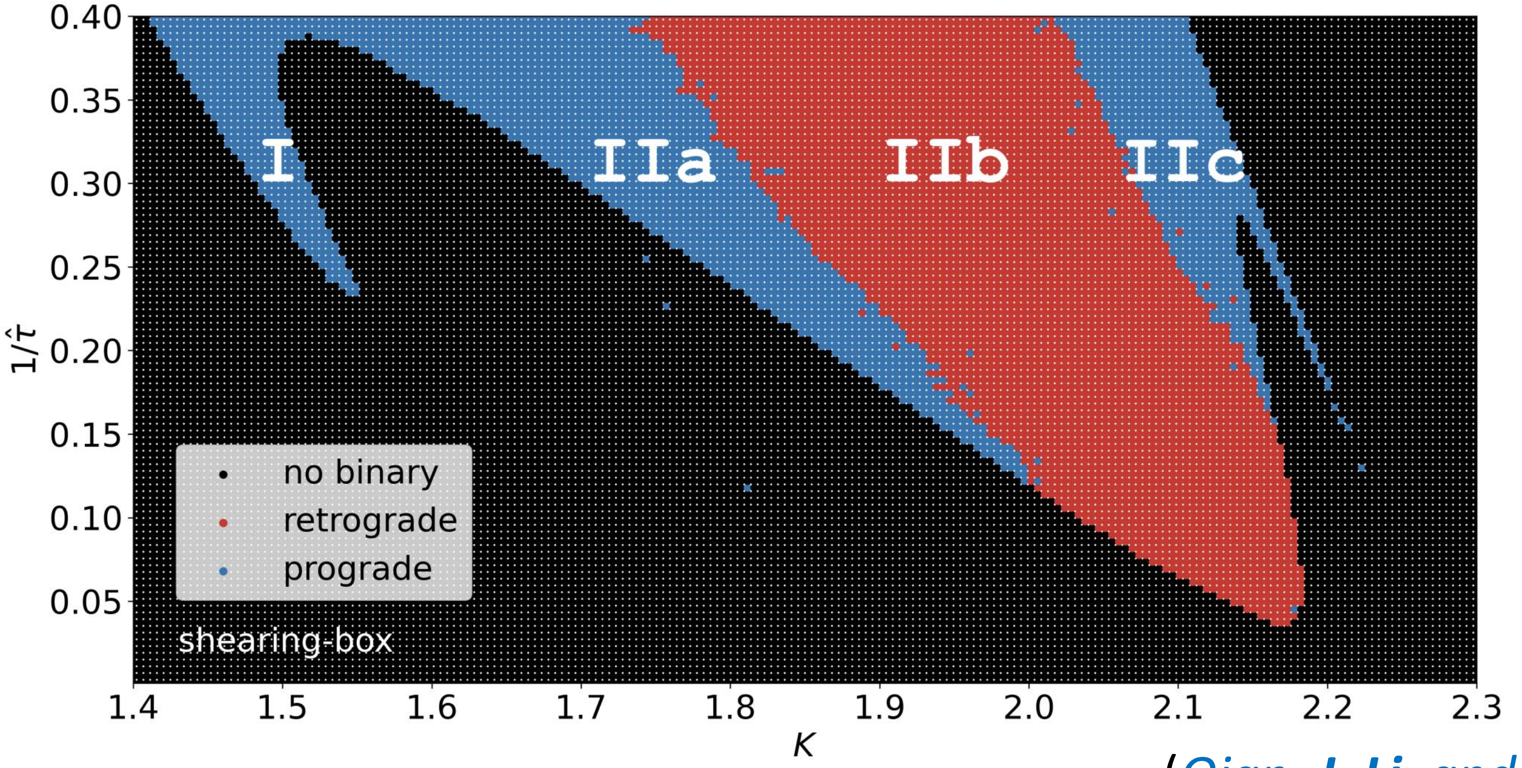
Formation via *frictional damping*: parameter study

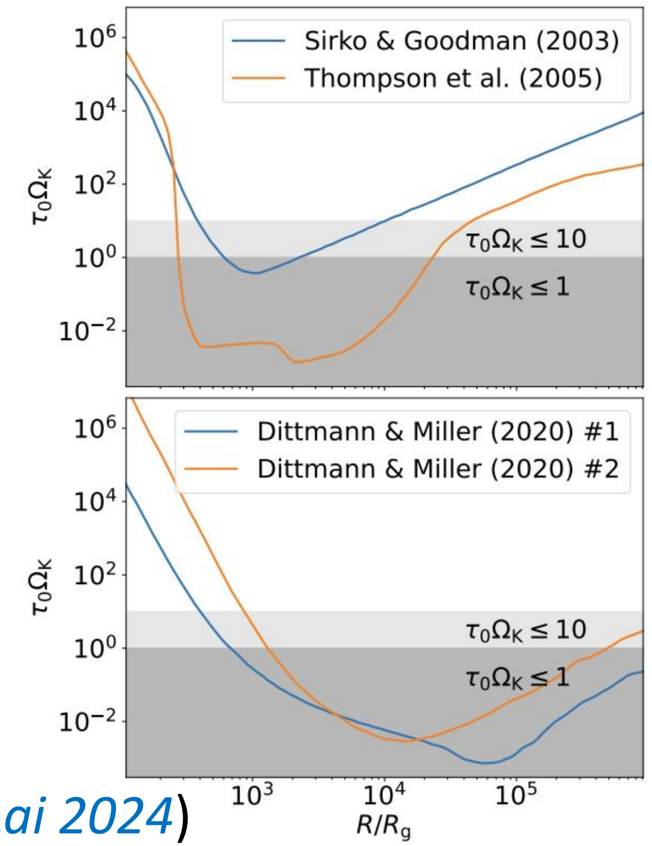


(*Qian, **J. Li**, and Lai 2024*)

Work done by
Kecheng Qian
(Cornell -> Berkeley)

Formation via *frictional damping*: parameter study





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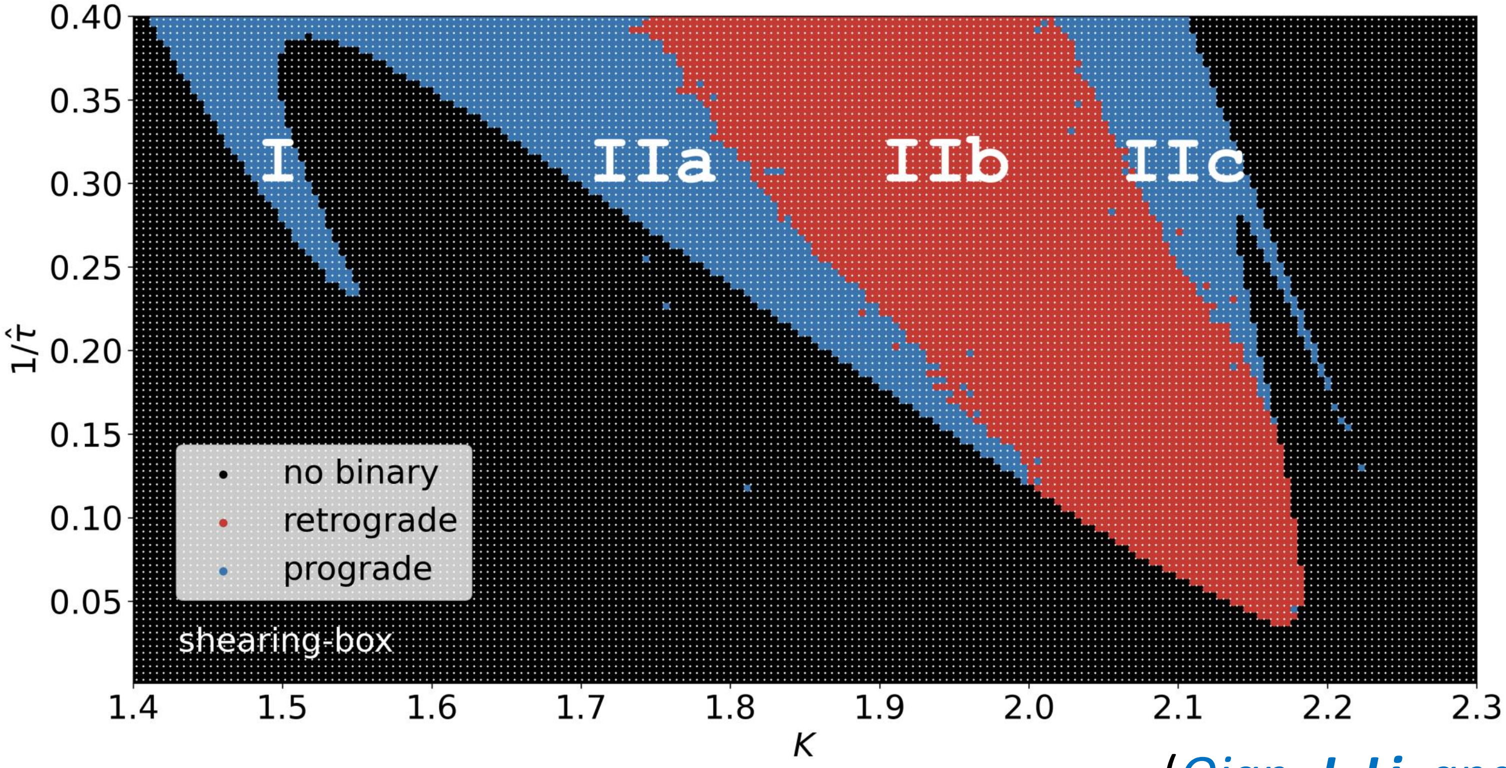

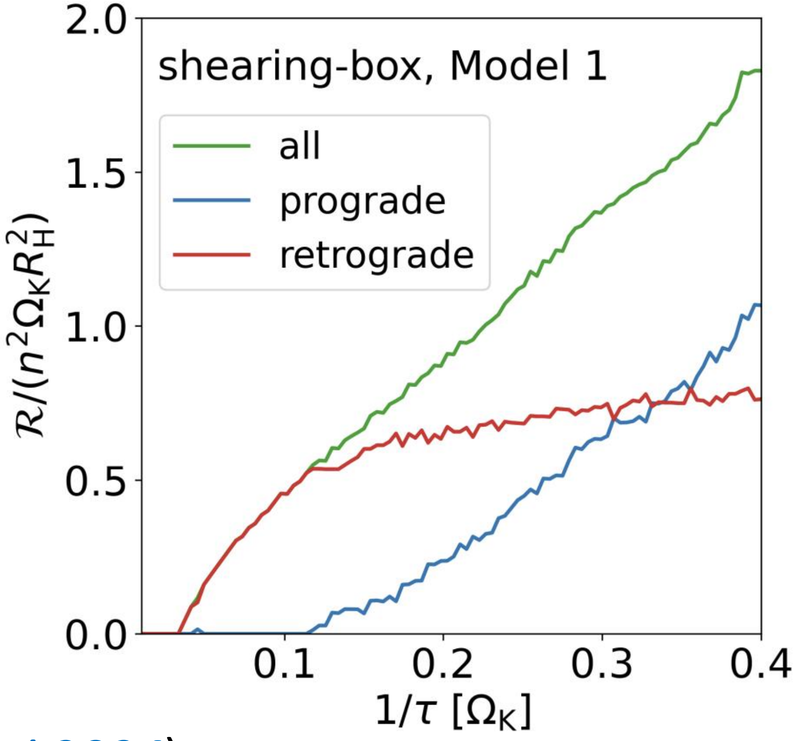

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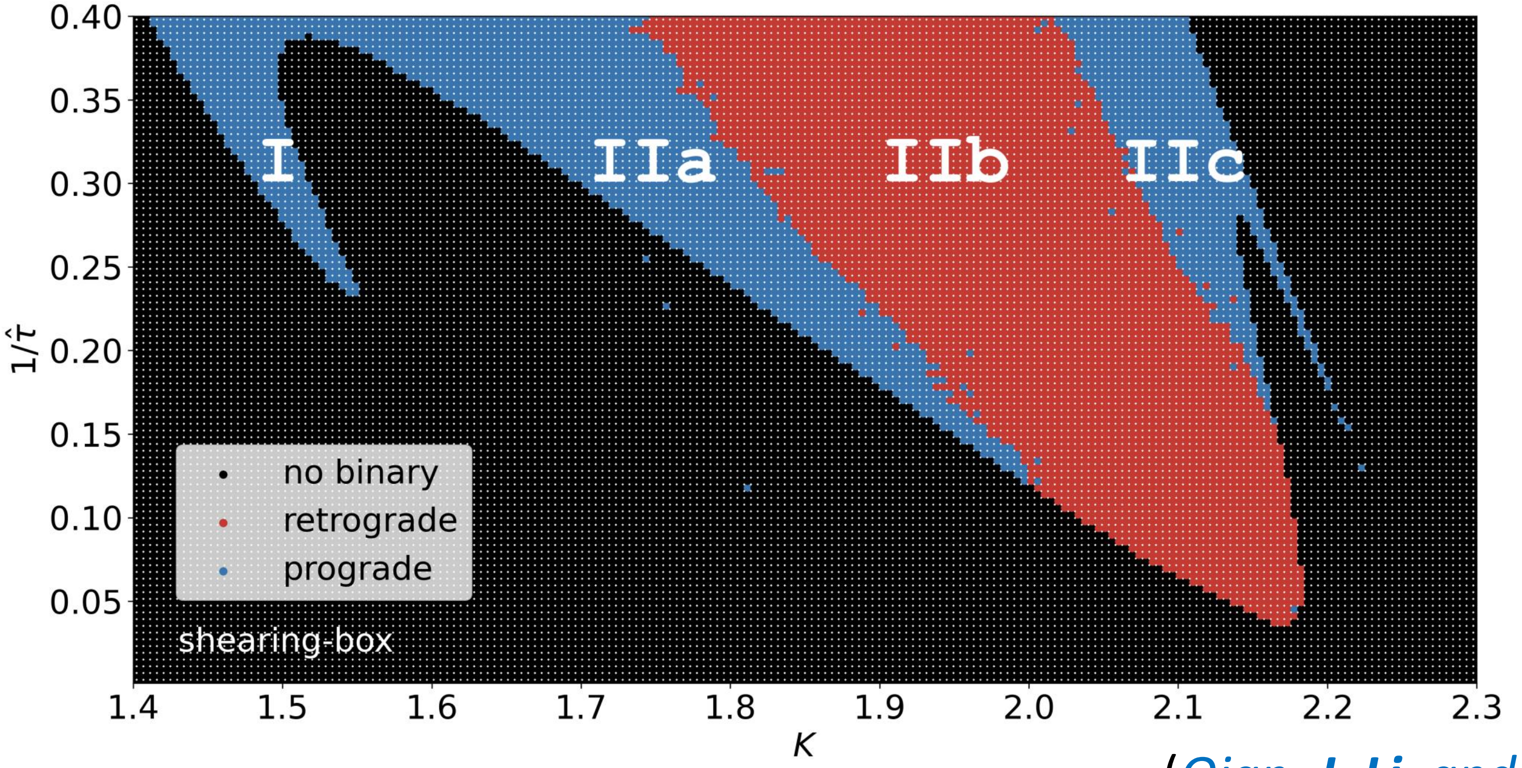

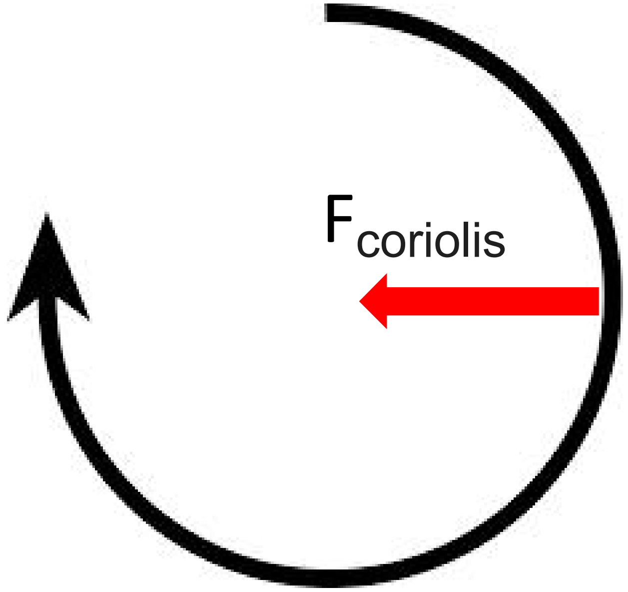

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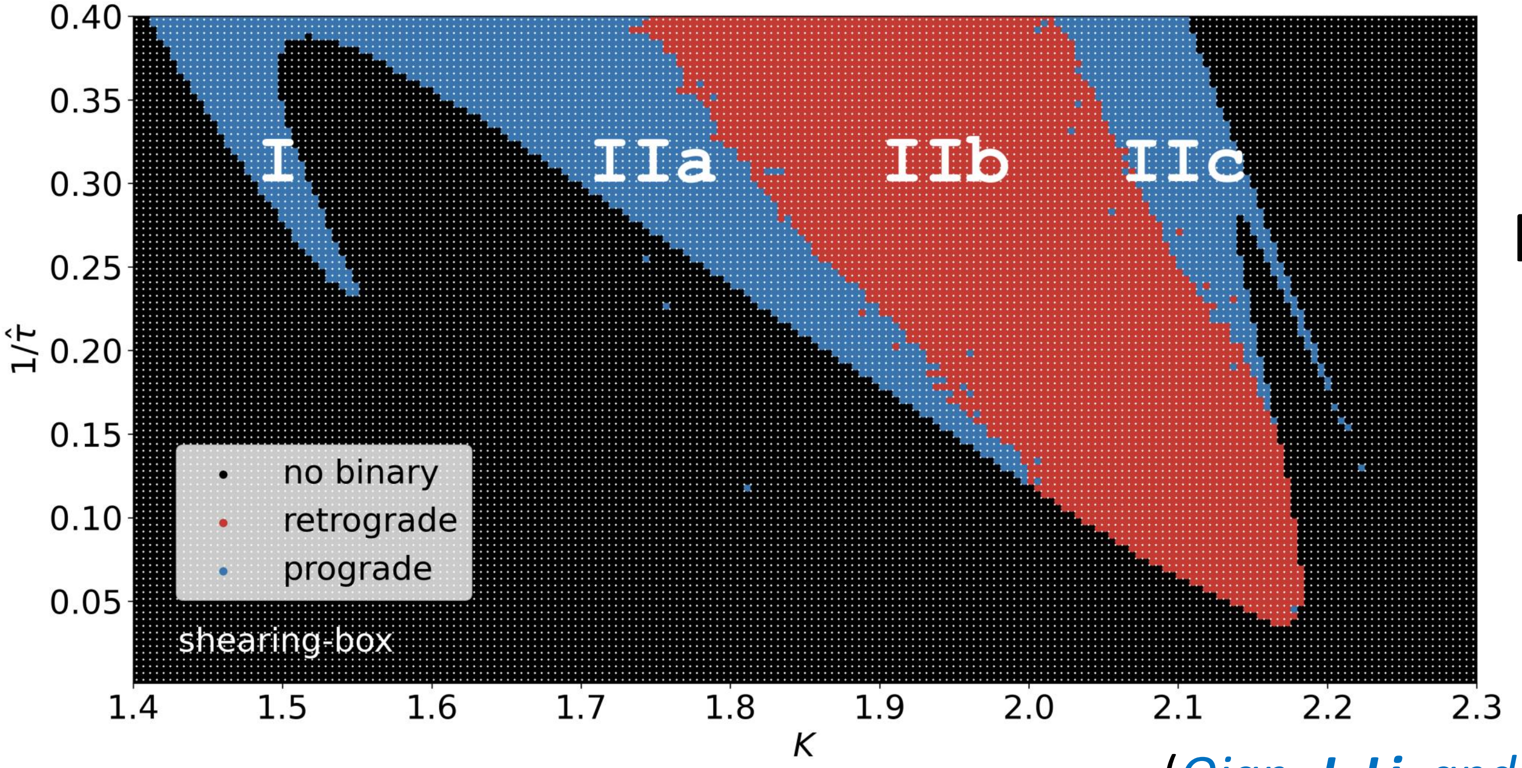

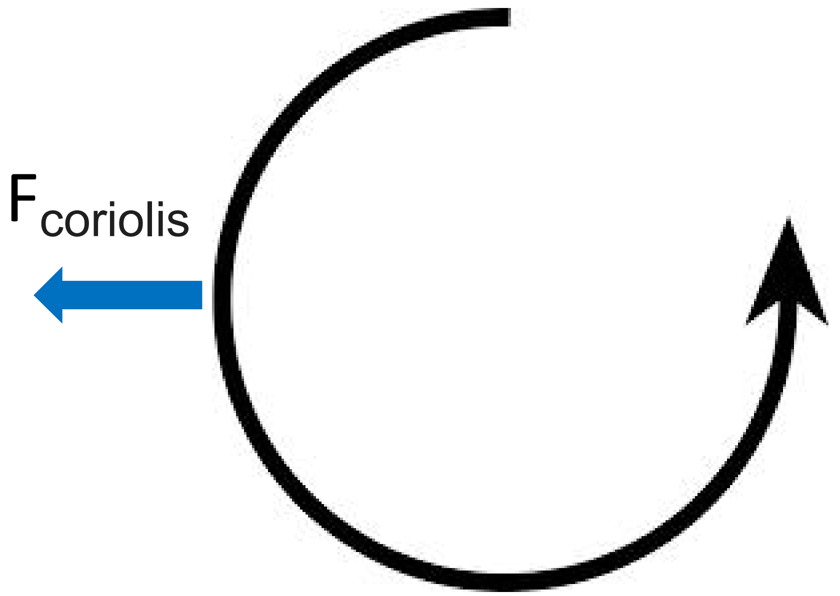

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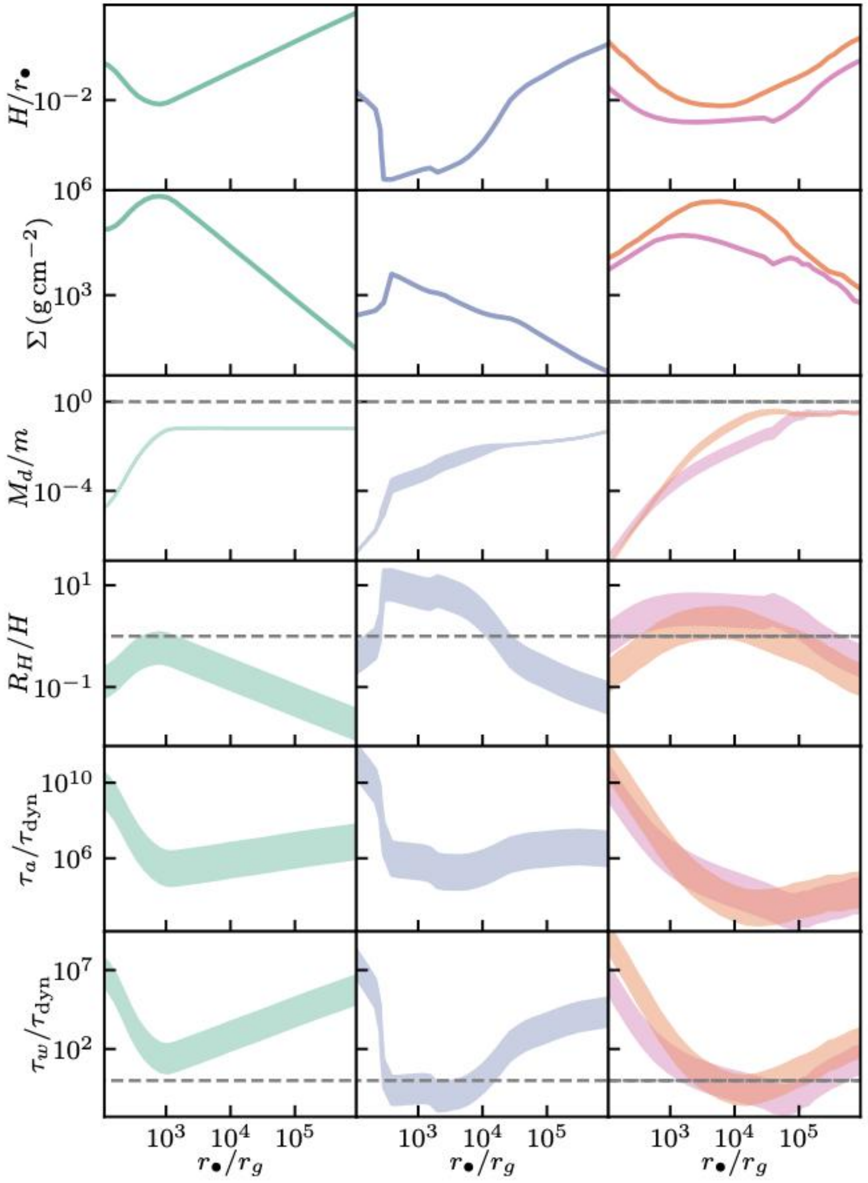
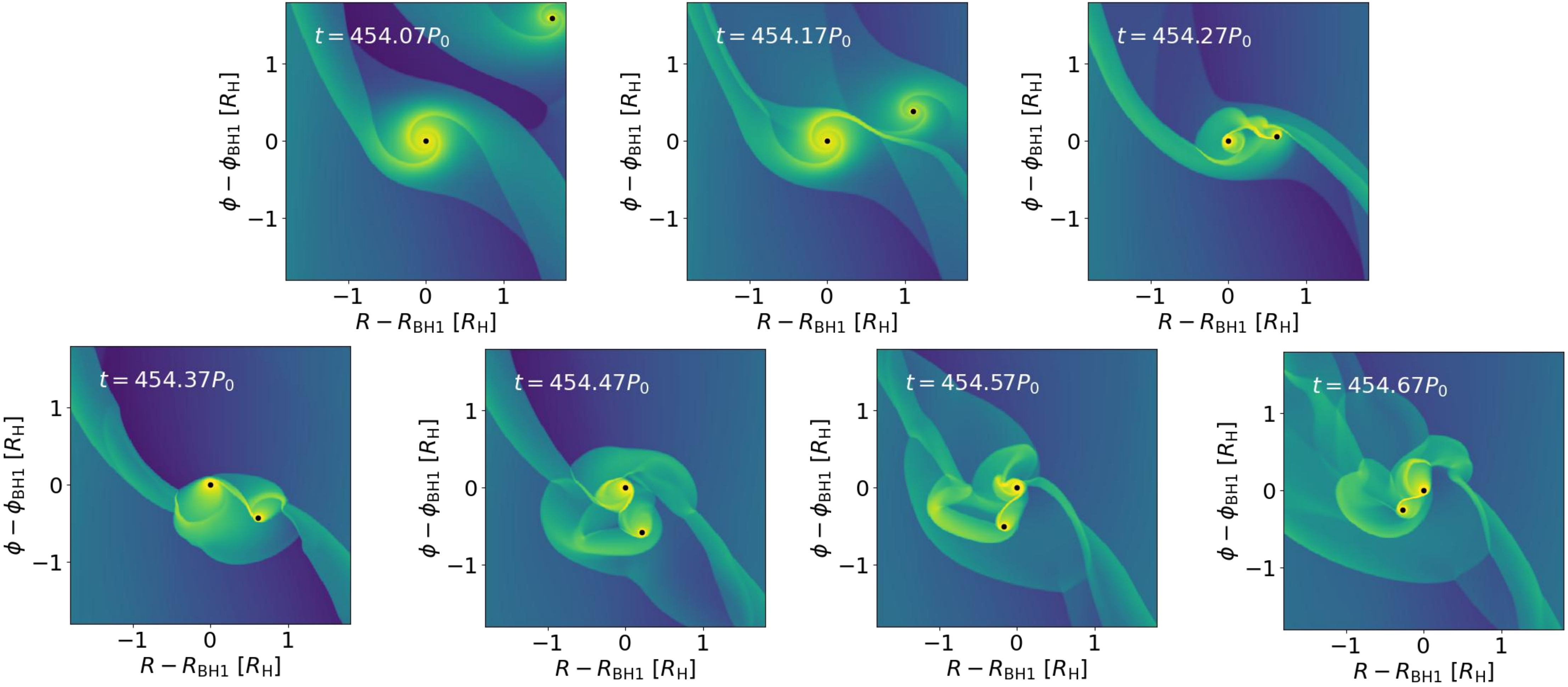


- AGN disk models:
  - Sirko & Goodman (2003),
  - Thompson+ (2005),
  - and Dittmann & Miller (2020).

  - Figure adopted from Dittmann+ (2024)

Formation via *post-collision drag*: hydro simulations



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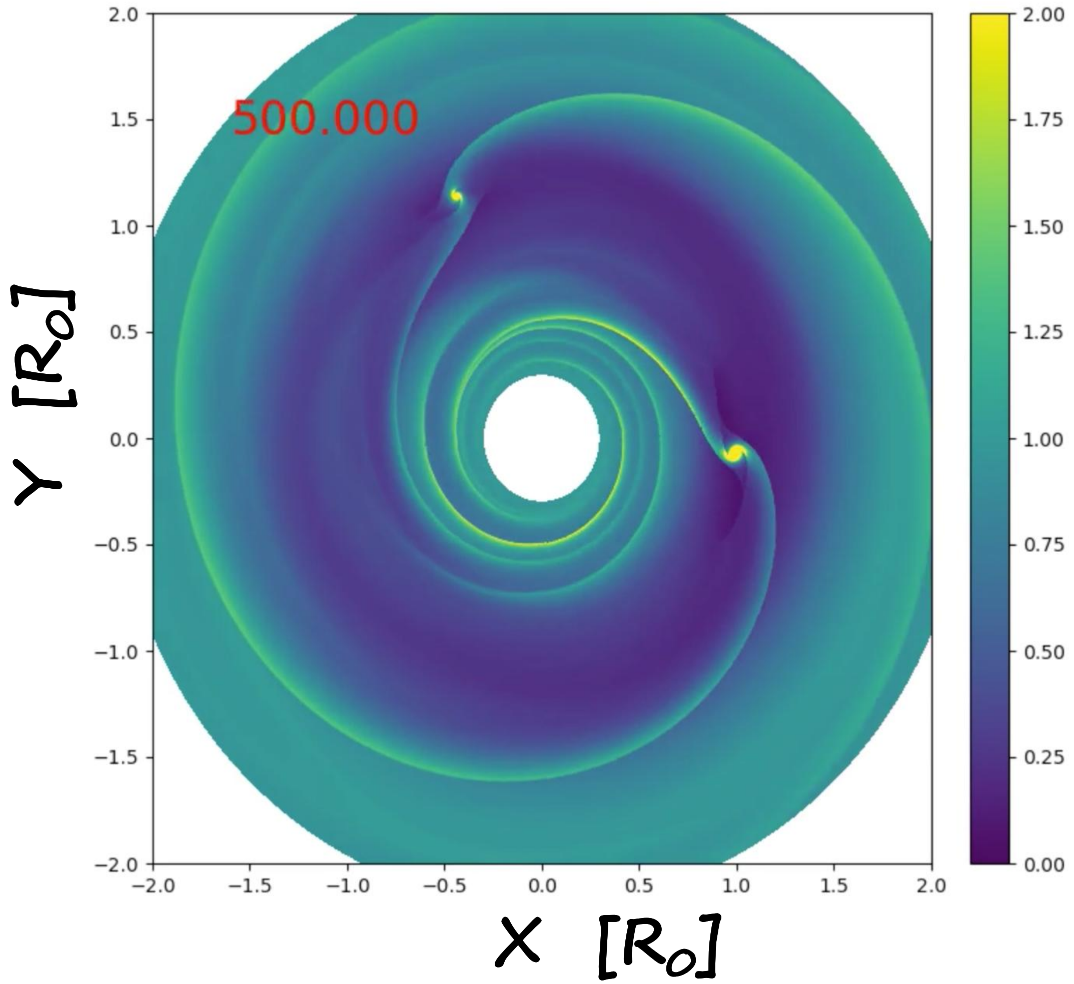


- Initial condition:

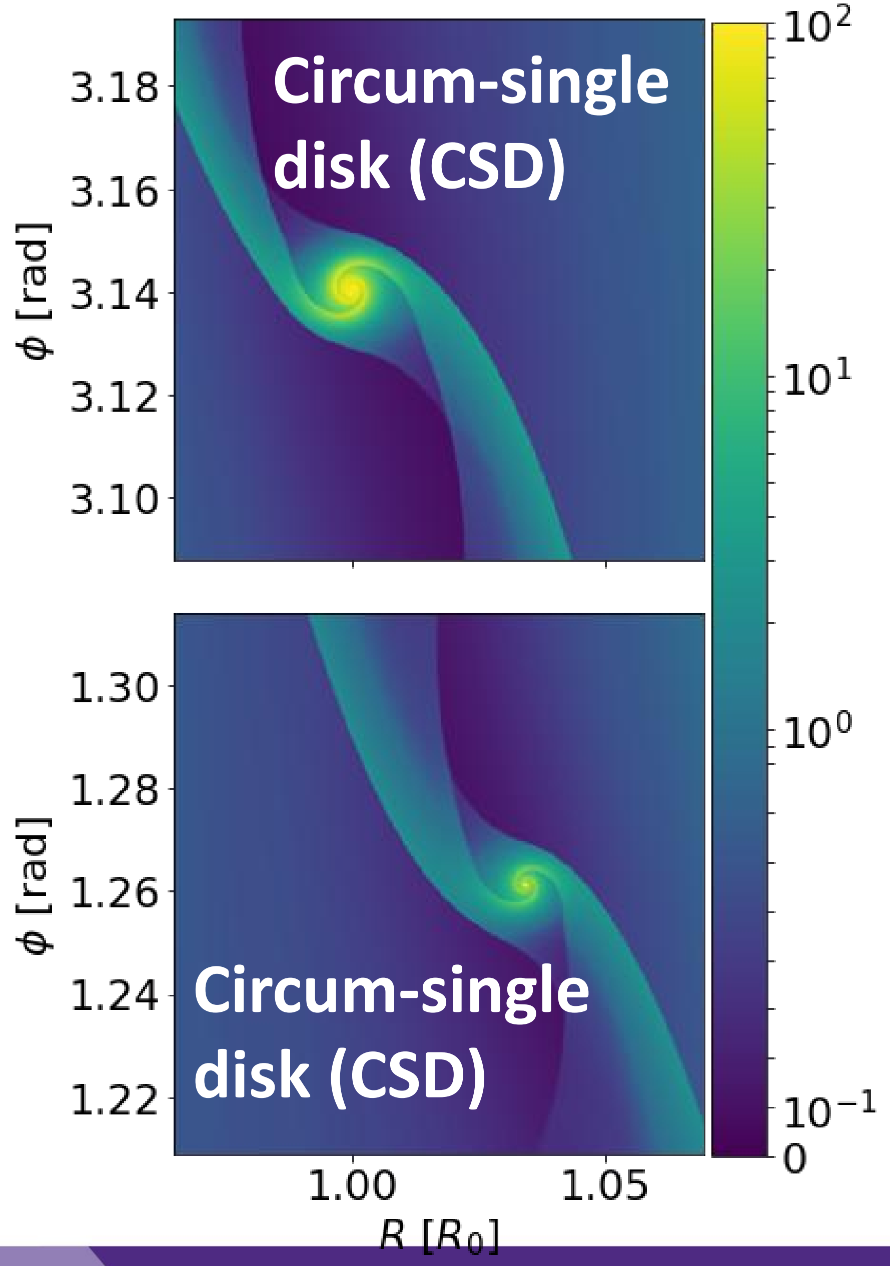
$$a_2 - a_1 = 2R_\mathrm{H}$$

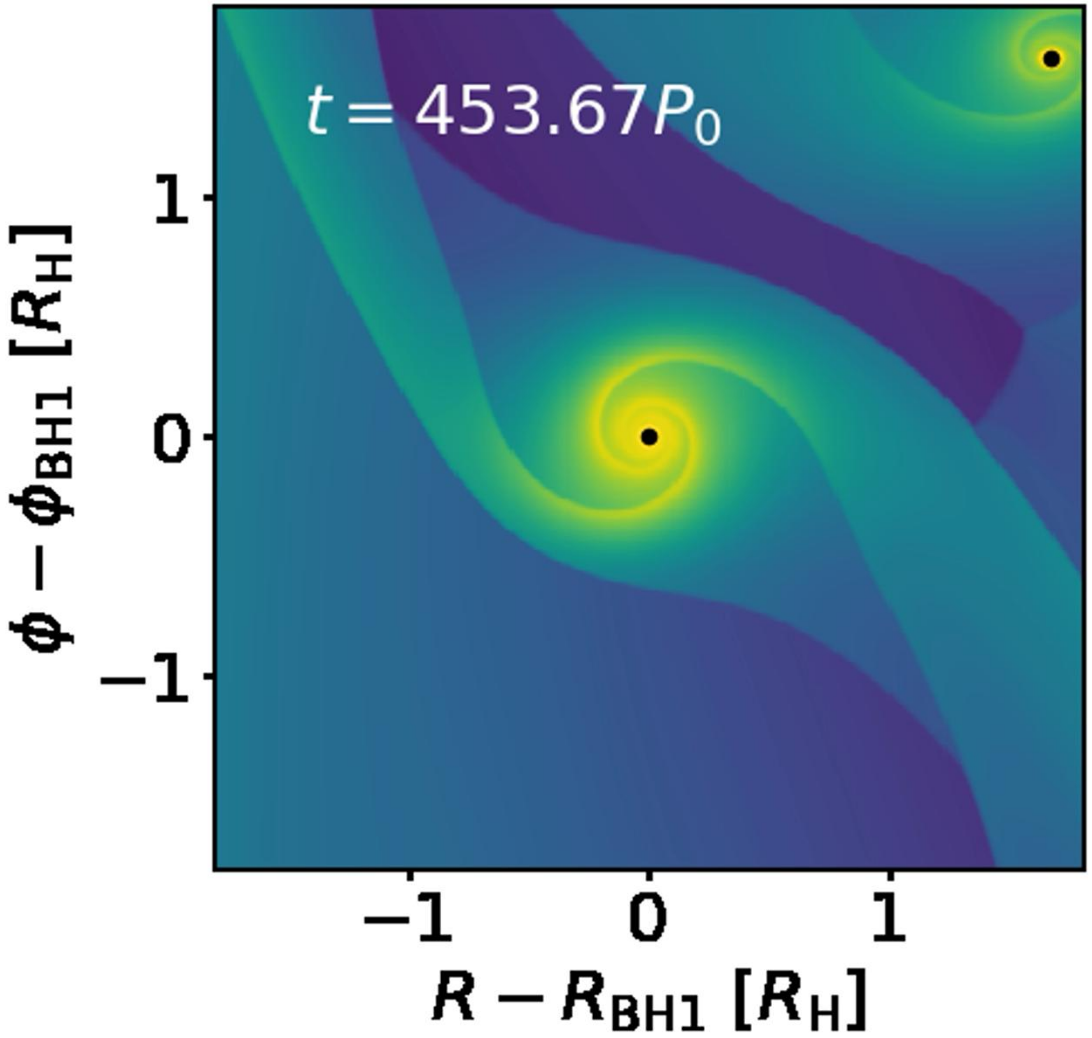
(Close encounter at the first conjunction)

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

(***J. Li***, *Dempsey, Li, Lai, and Li 2023*)

Formation of a binary





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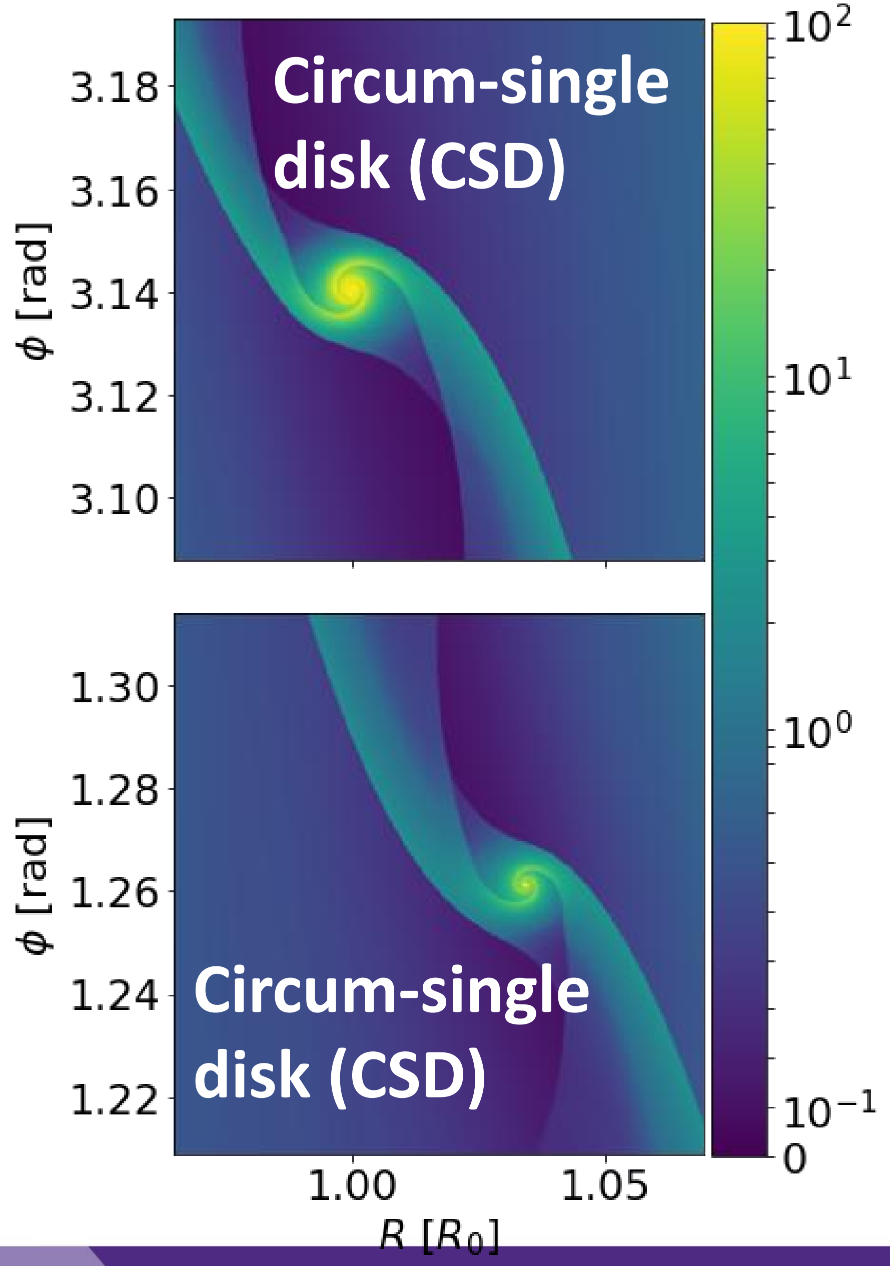

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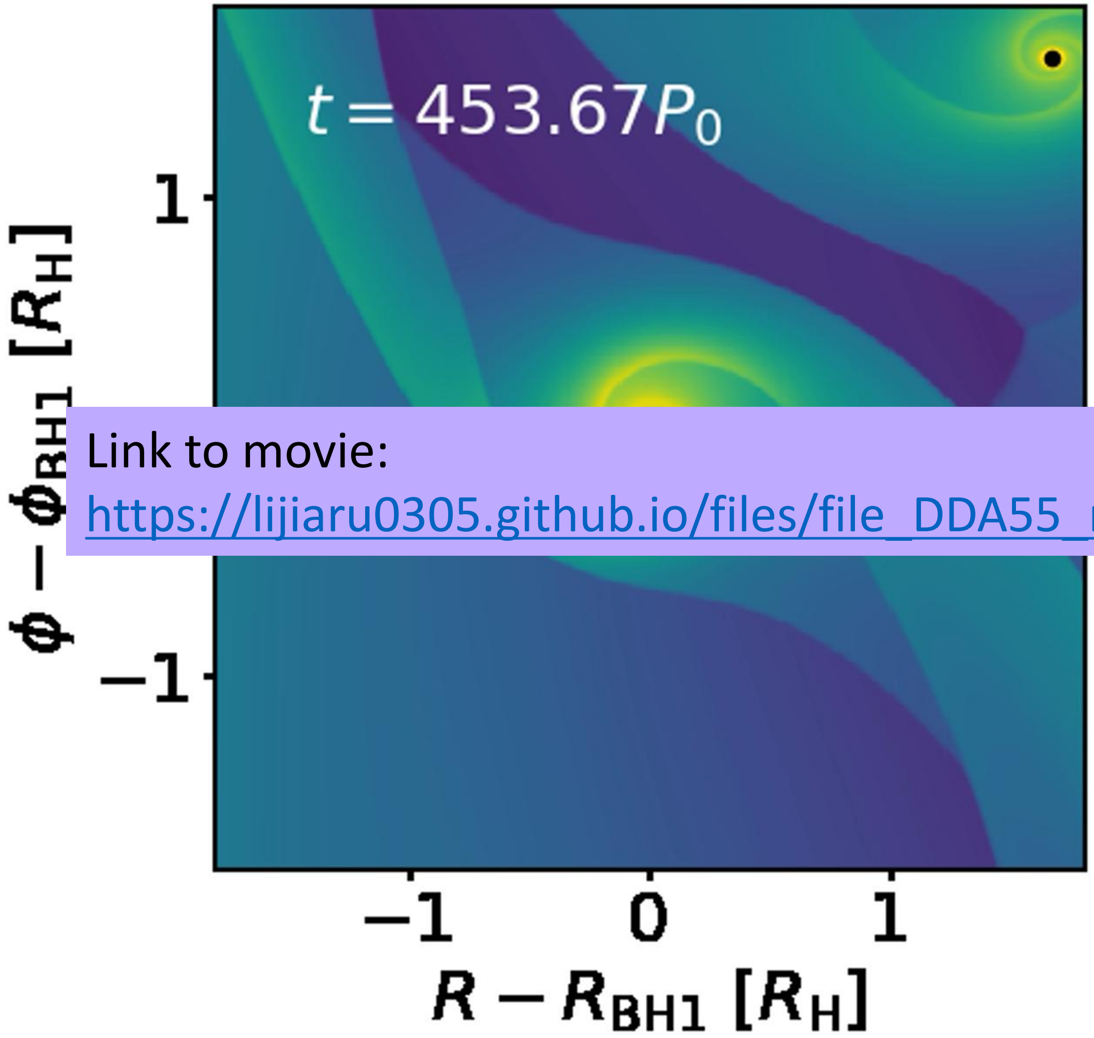
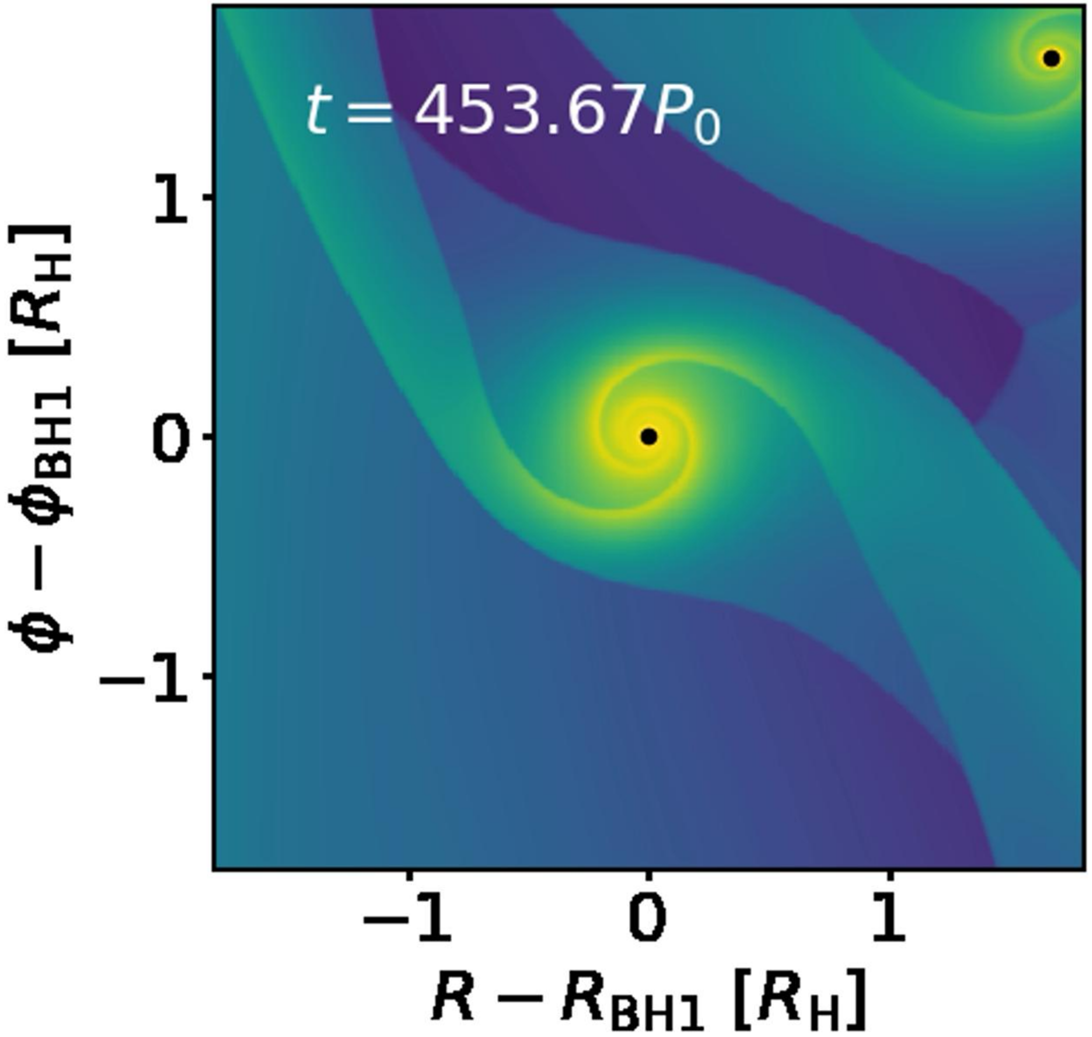
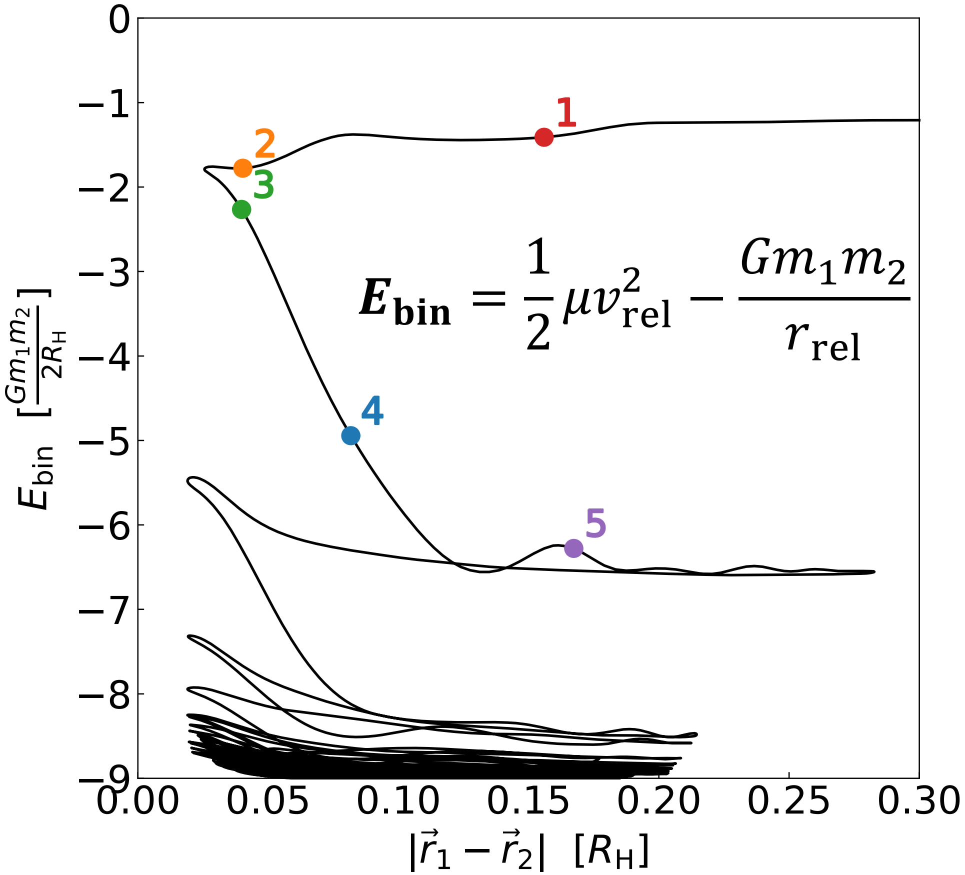


Link to movie:
https://lijiaru0305.github.io/files/file_DDA55_movie.mp4

(*J. Li, Dempsey, Li, Lai, and Li 2023*)

Formation via *post-collision drag*: analysis

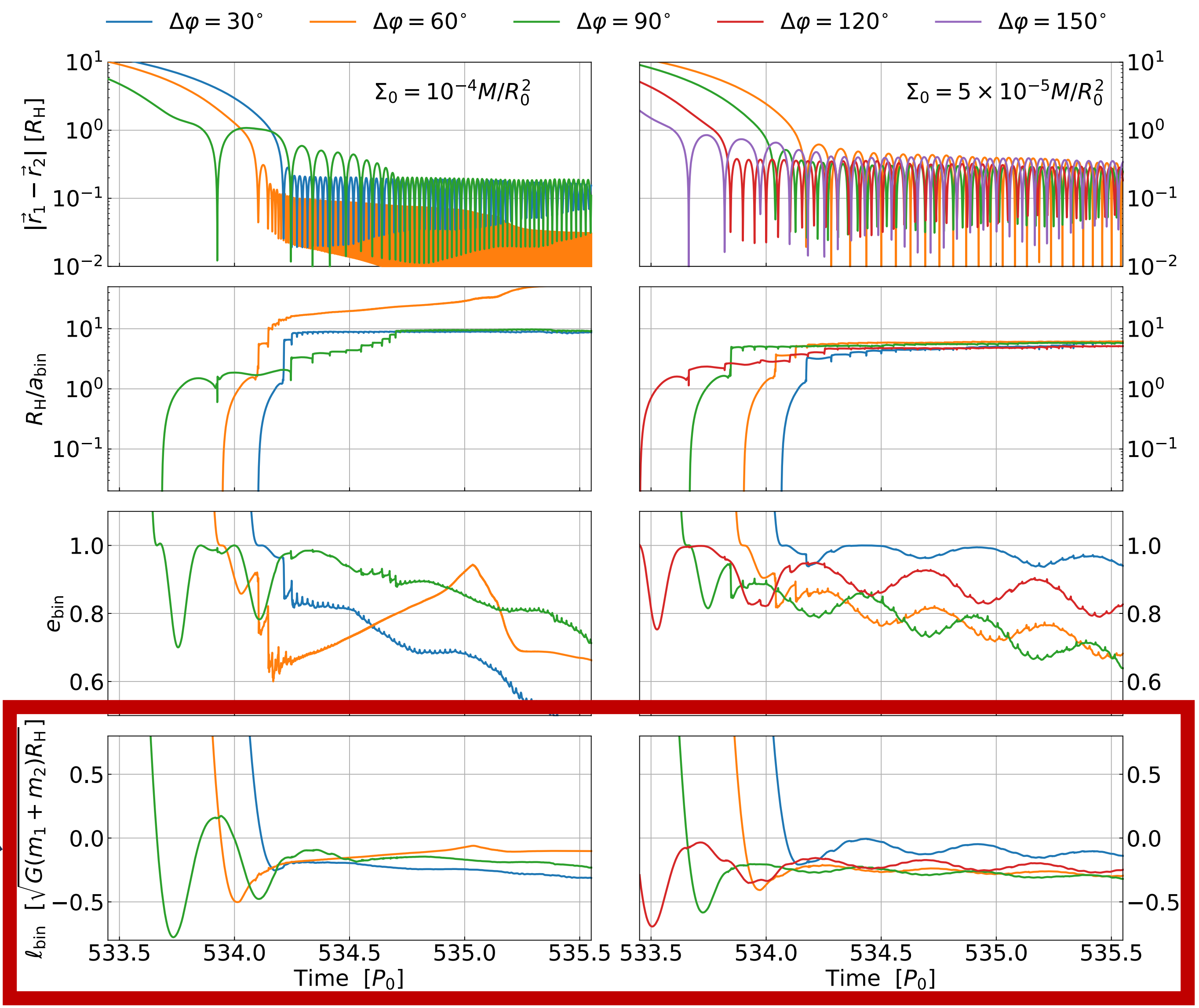




(***J. Li***, *Dempsey, Li, Lai, and Li 2023*)

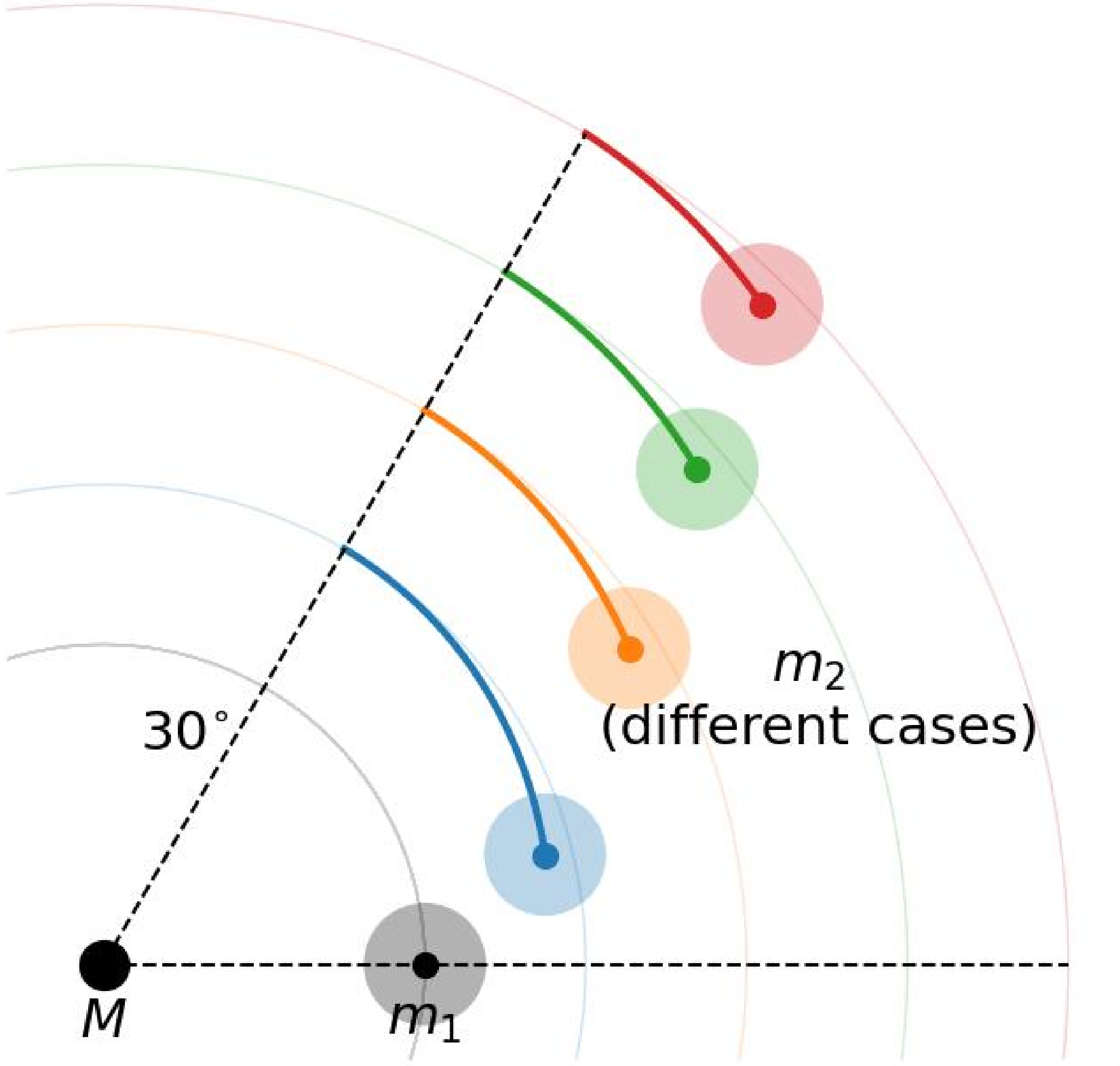
Resulting binary orbit after formation

- small semi-major axis: $\frac{a_{\rm bin}}{R_{\rm H}} \sim 0.1$
- large eccentricity: $e_{\rm bin} > 0.5$
- **(mostly: 26/28) retrograde rotation: $\ell_{bin} < 0$**



Formation via *post-collision drag*: parameter study

(*J. Li+ in prep*)

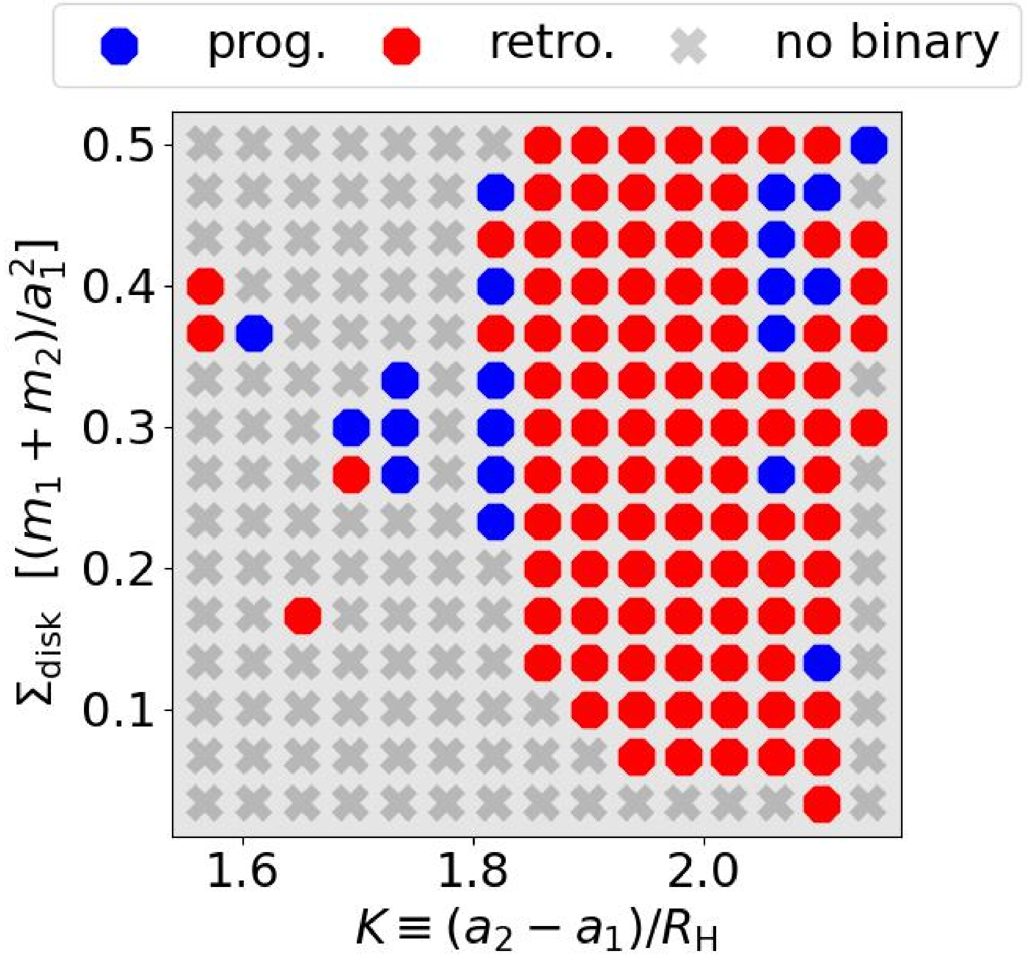


Parameter study setup:

- SMBH + 2 BHs + AGN disk
  (m_1, m_2 ~ 10^{-3} M, H/R = 0.05 for speed)
- BHs are held on their initial orbits for 450 orbital period to form CSDs.
- When their angular separation research 30^o, the BHs are released.

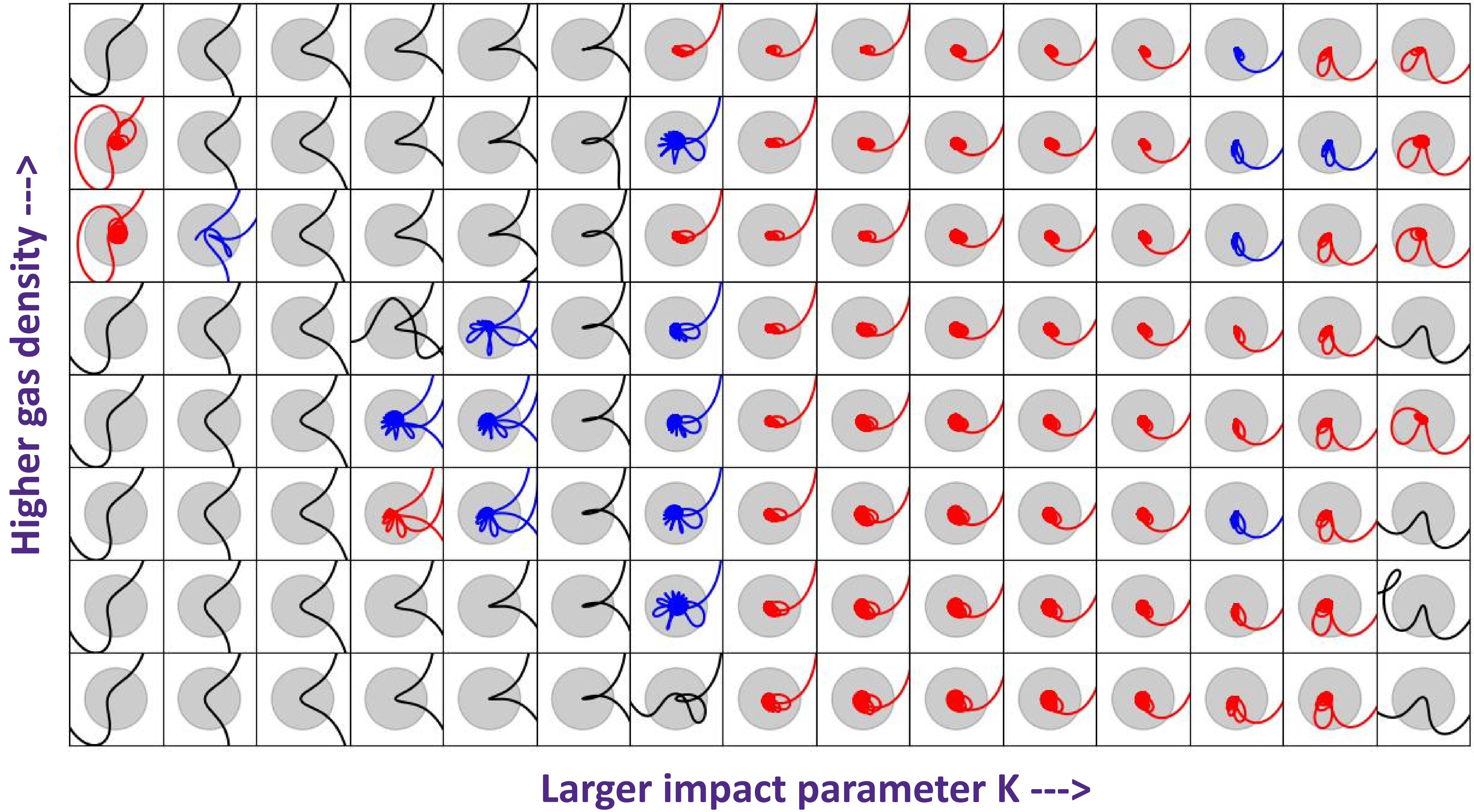
(Left: not-to-scale diagram of our setup in the co-rotating frame of m_1)

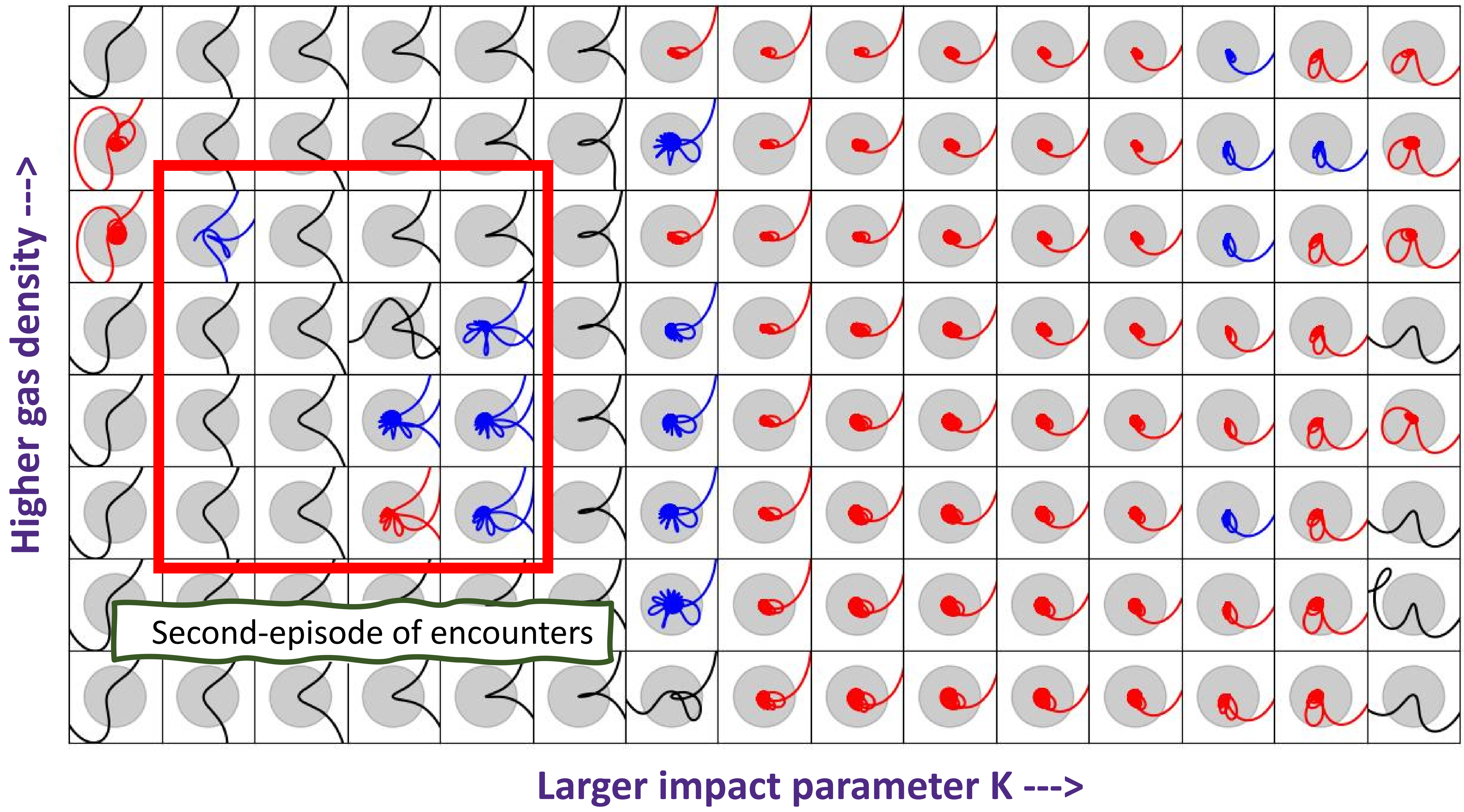
Formation via *post-collision drag*: parameter study (*J. Li+ in prep*)

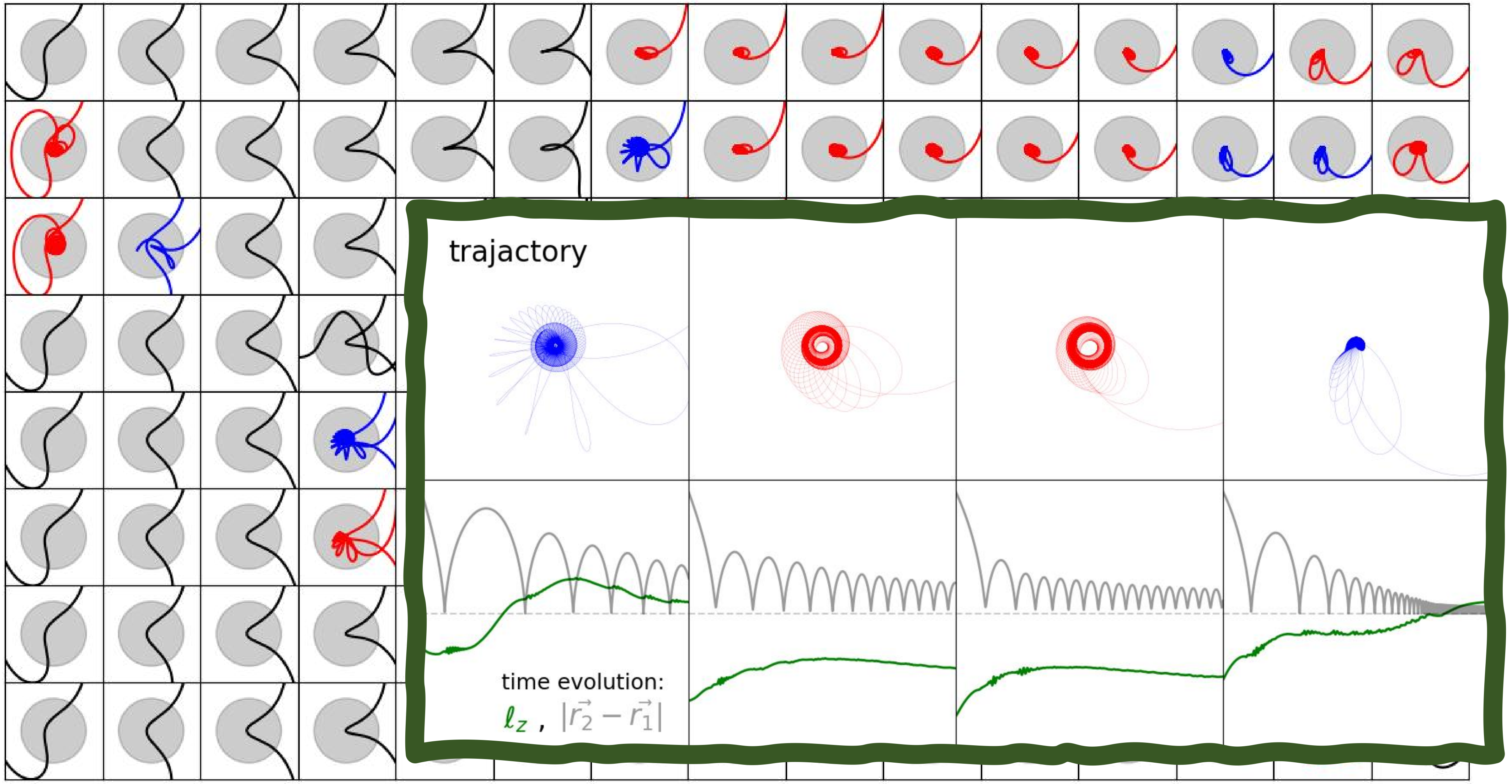


Two key results:

- Most binary formation happens at **K between 1.80 and 2.13**.
- The nearly all binaries are retrograde.

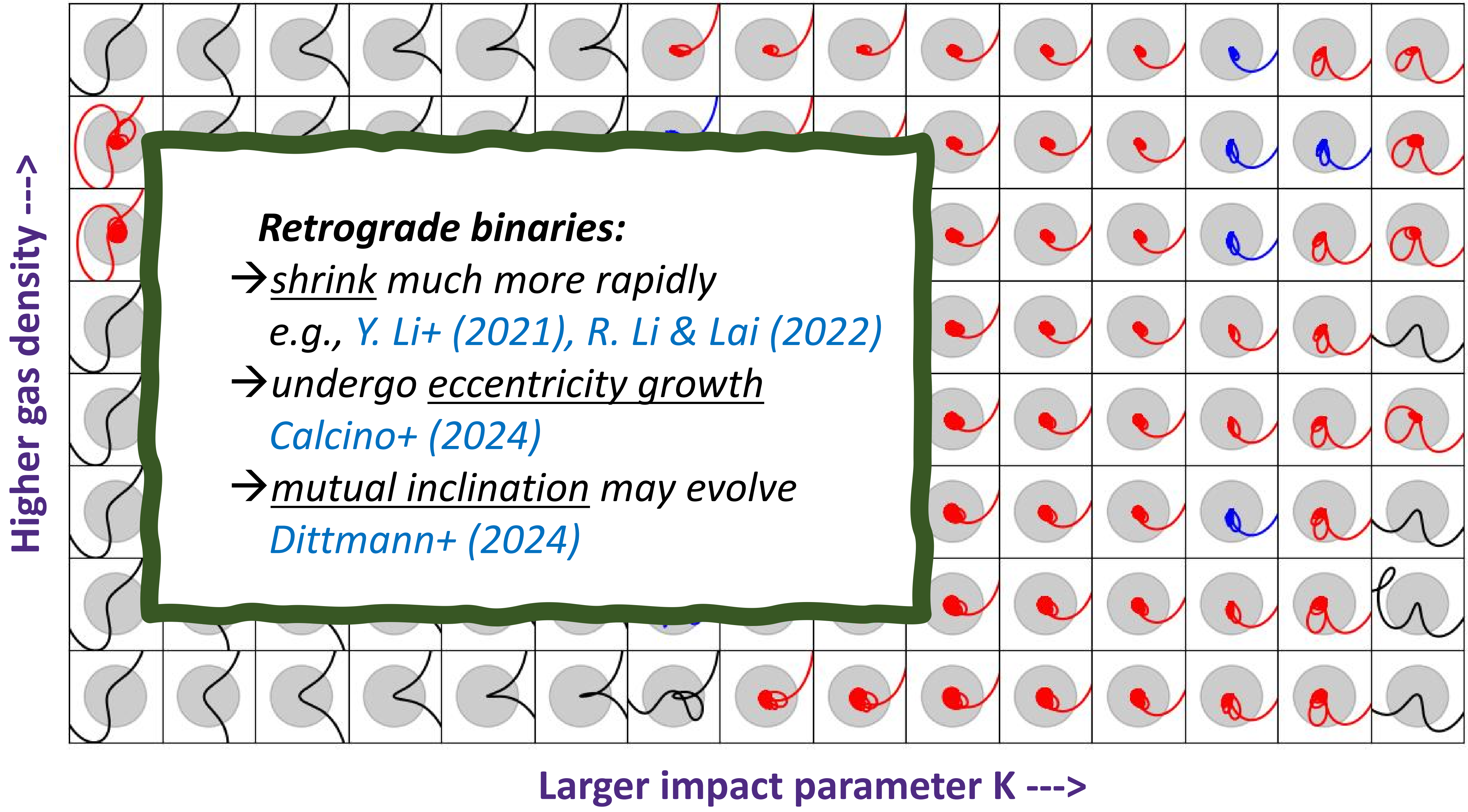

Higher gas density --->
Larger impact parameter K --->


Higher gas density --->
Second-episode of encounters
Larger impact parameter K --->



Higher gas density --->

Larger impact parameter K --->



Retrograde binaries:

→*shrink much more rapidly*
e.g., Y. Li+ (2021), R. Li & Lai (2022)

→*undergo eccentricity growth*
Calcino+ (2024)

→*mutual inclination may evolve*
Dittmann+ (2024)

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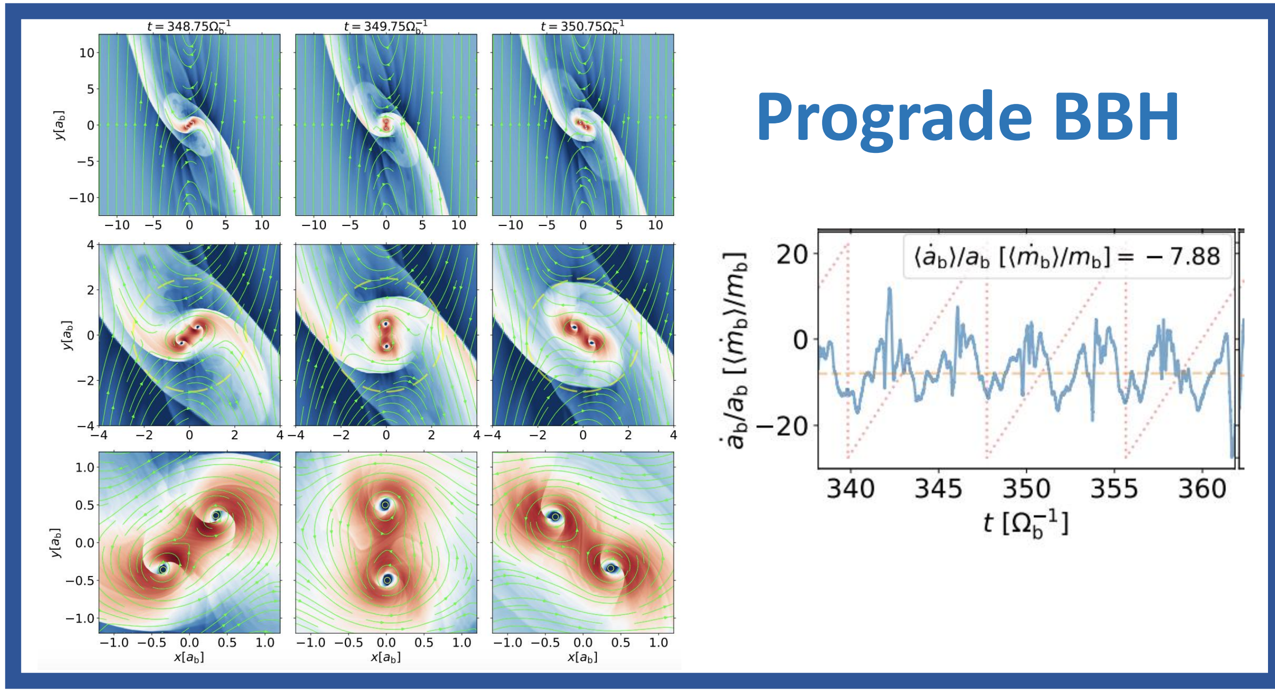

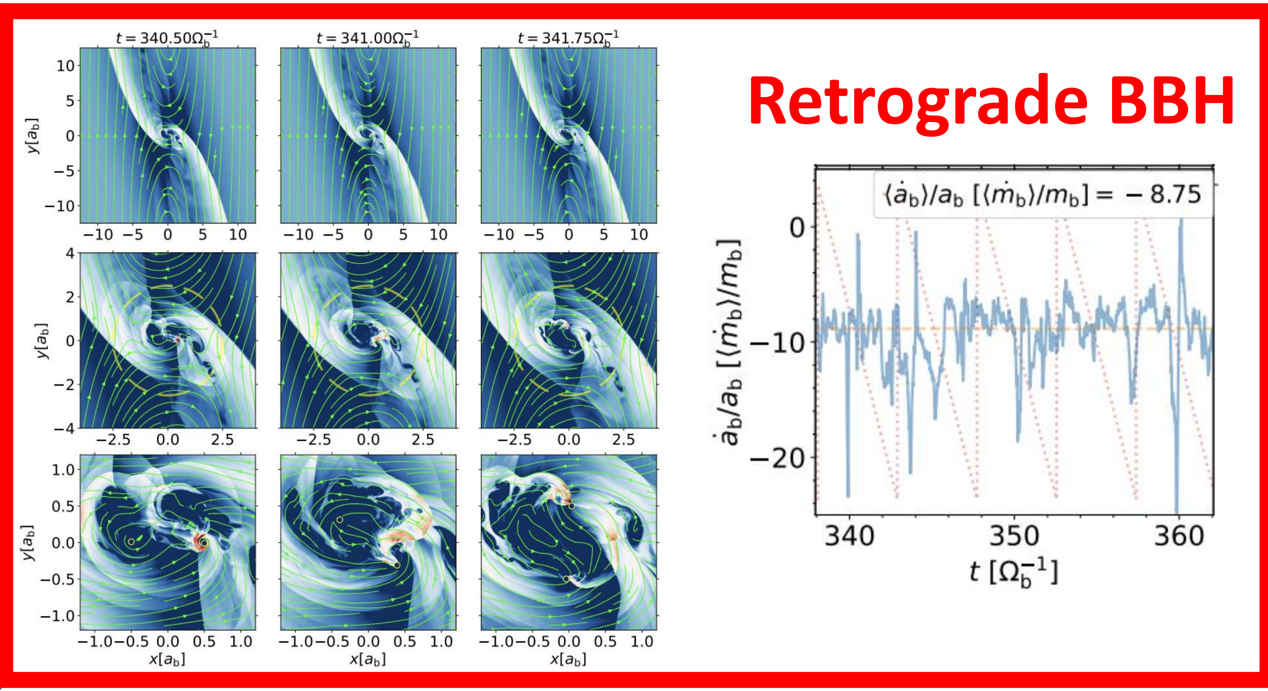

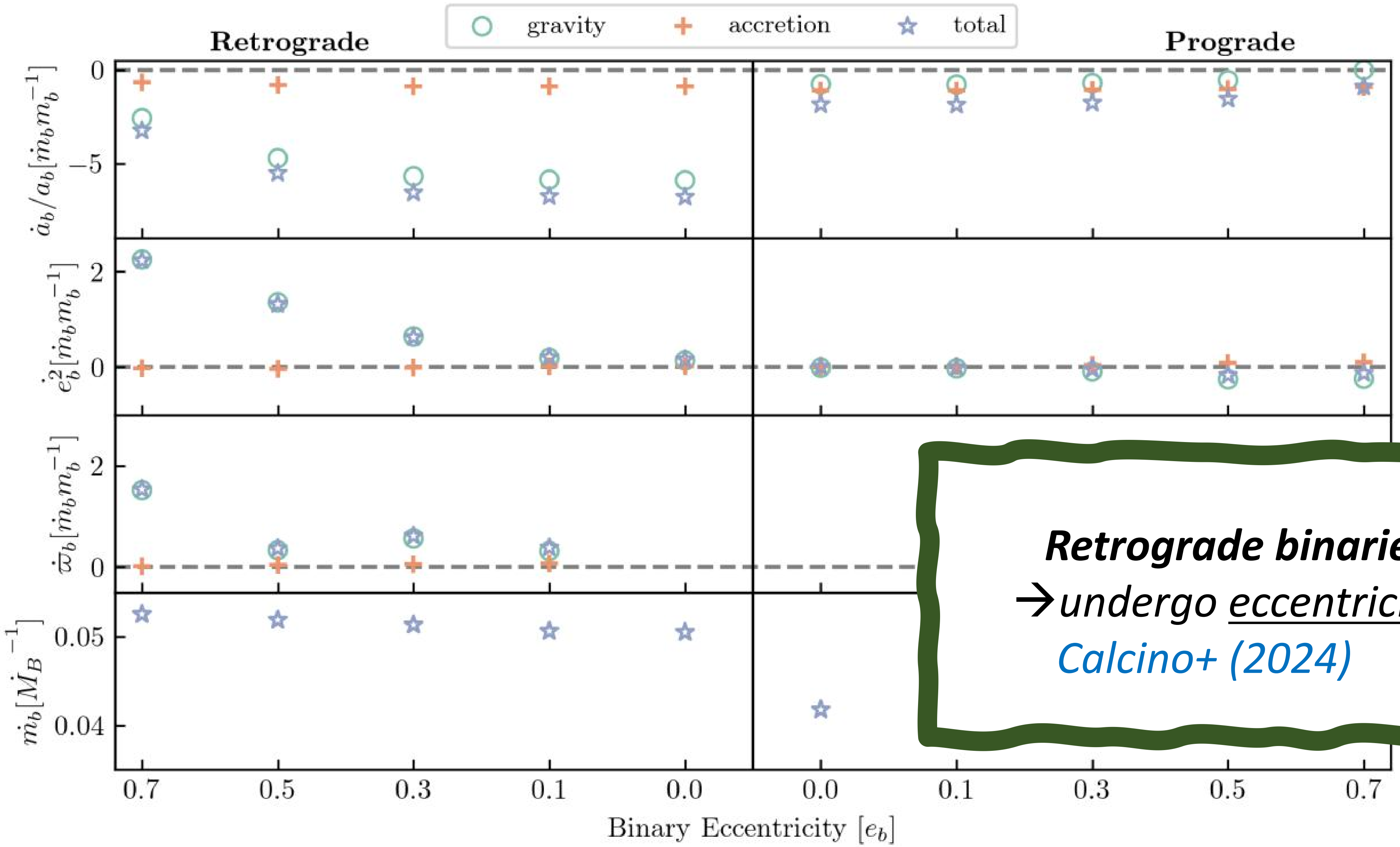

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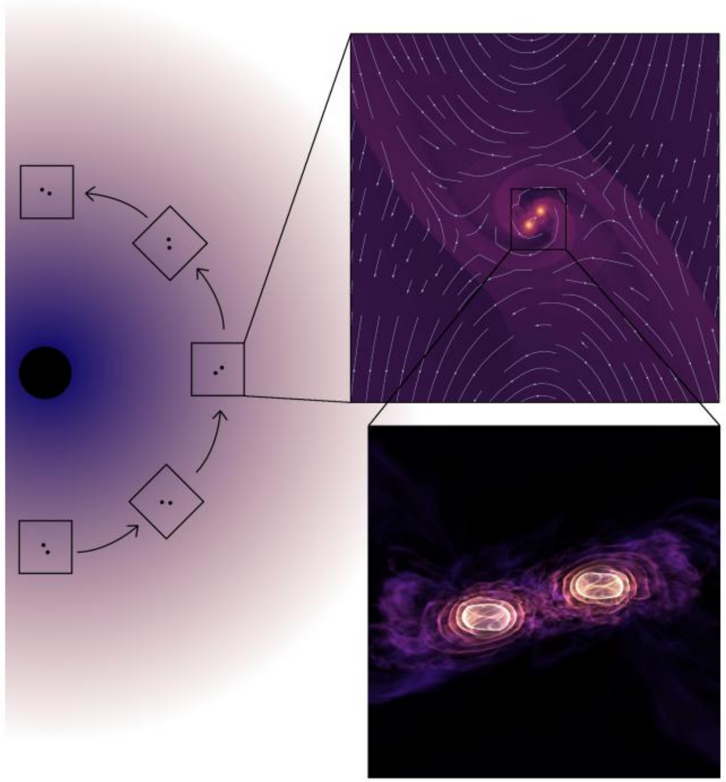
→*undergo <u>eccentricity growth</u>*

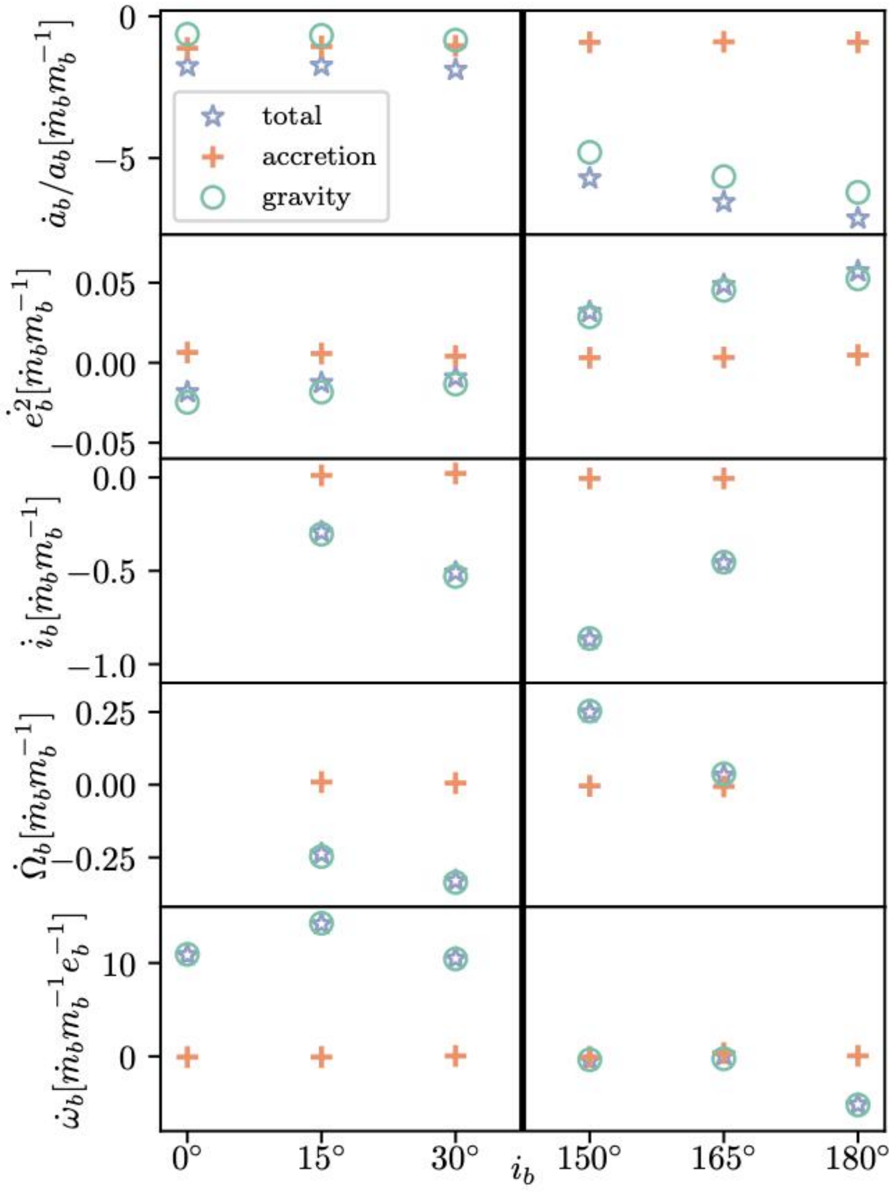
Calcino+ (2024)

Retrograde binaries:

→<u>mutual inclination</u> may evolve

Dittmann+ (2024)





Summary

- ***GW Bremsstrahlung:*** Long-lasting dynamical instability triggers lots of BH-BH encounters, which all have a small chance of forming tight and highly eccentricity binaries.

- ***Gas-assisted binary formation:*** Two types of gas effects are studied, i.e. **frictional effects** and ***post-collision drag***.
  → Both are one-shot (or few-shot) and require sufficiently high gas density.
  → The resulting BH binary orbits can be eccentric, compact, and (most likely to be) retrograde.

- Our results suggest a dynamical channel for BH mergers in AGN disks (which prefers high-mass, eccentric, potentially with $\chi_{eff} < 0$).

- **Three are still many many uncertainties → room for interpretation.**