Orbital evolution of binary black holes in active galactic nucleus disks: a disk channel for binary black hole mergers?

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BBH mergers

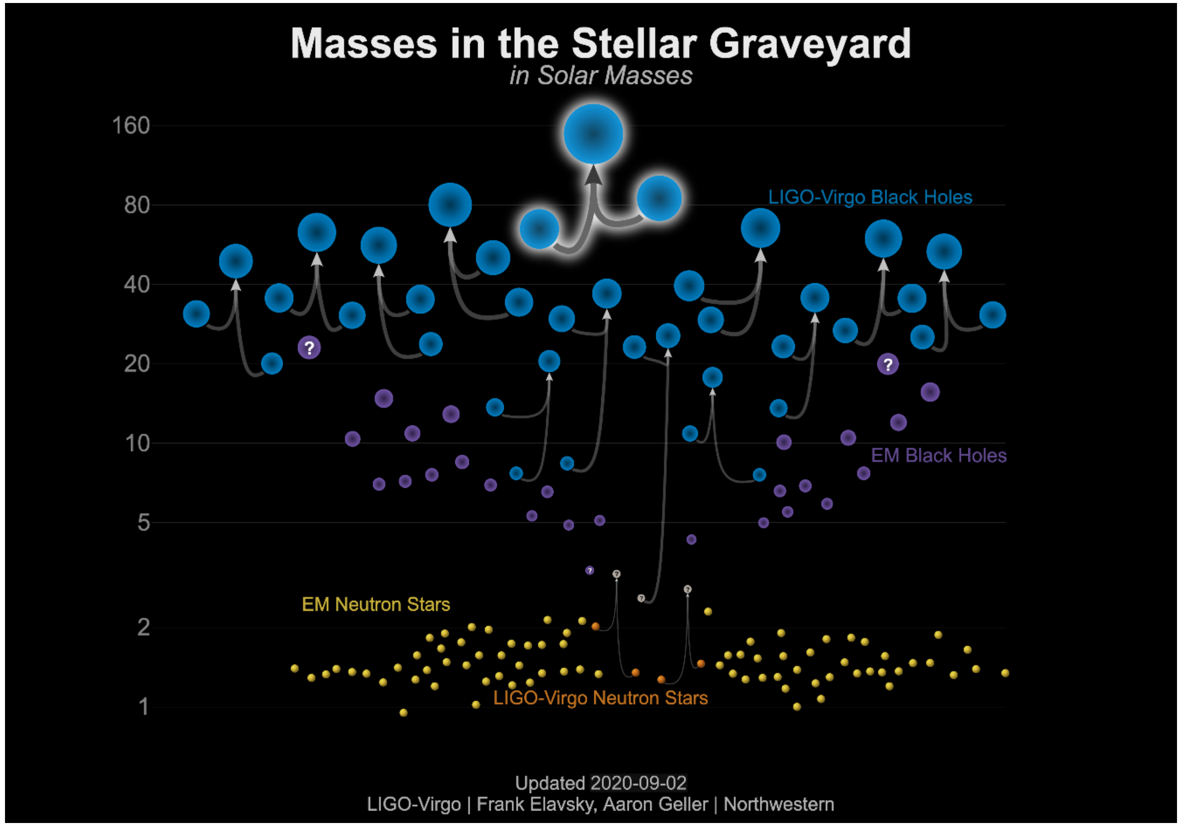


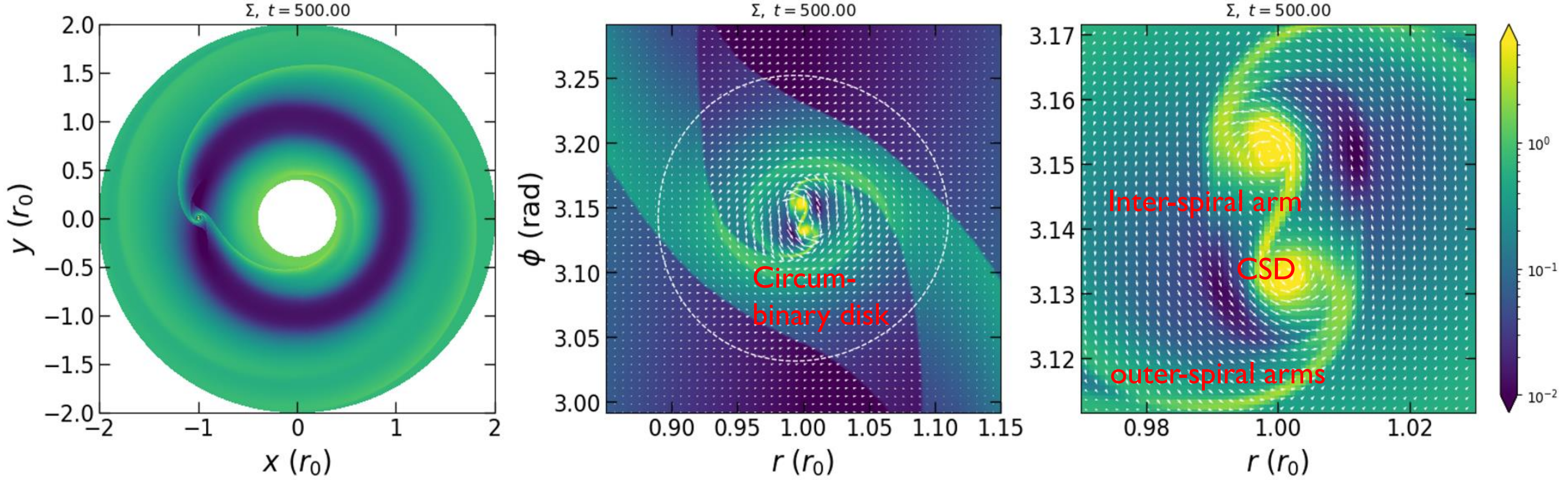
Image credit: LIGO-Virgo/Northwestern U./Frank Elavsky & Aaron Geller

- BBH merger channels
  - ✓AGN disks (McKernan+12, Bartos+17,Stone+17)
  - ✓Isolated binary star evolution (e.g., Belczynski+10)
  - ✓Chance encounter in a dense stellar environment (e.g., O'Leary+09;Wang+16)
- AGN disks channel:
  - ✓Heavier BBH mergers (Yang+19; e.g., GW190521)
  - ✓ Large spin magnitudes (McKernan+12)
  - ✓Electromagnetic counterpart McKernan+19; Graham+20)

Review of BBH Mergers in Disks

- Similar problem: Supermassive binary black holes mergers
  - Similar to planetary migration for a smaller secondary (Armitage&Natarajan 2002; Cuaddra+09)
  - Equal mass ratio (MacFadyen et al. 2008): orbital decay driven by spiral arm in the CBD
- Recent simulations for circum-binary: gap not empty, but with gas streams
  - Orbital expand: Roedig+12; Miranda+17; Moody+19 *(2D+3D);* Muñoz+19; Muñoz+20
  - Orbital contract: Tang+17; *cold disk*(Tiege+20; Heath+20)
  - Duffell+20: inspiral for $q<0.05$; outspiral for $q>\sim0.05$ (see also Derdzinski+20)
- Embedded Binary Simulations in AGN disks (Baruteau, Cuadra & Lin 2011)
  - Binary orbit contract
  - But, did not resolve circum-single disk region appropriately…
- The fate of binary BHs in AGN disks→ Contract or Expand?
  - Properly resolve circum-single disk region: small softening scale with higher resolution?
  - Quasi-steady state?
  - Different accretion scenarios?

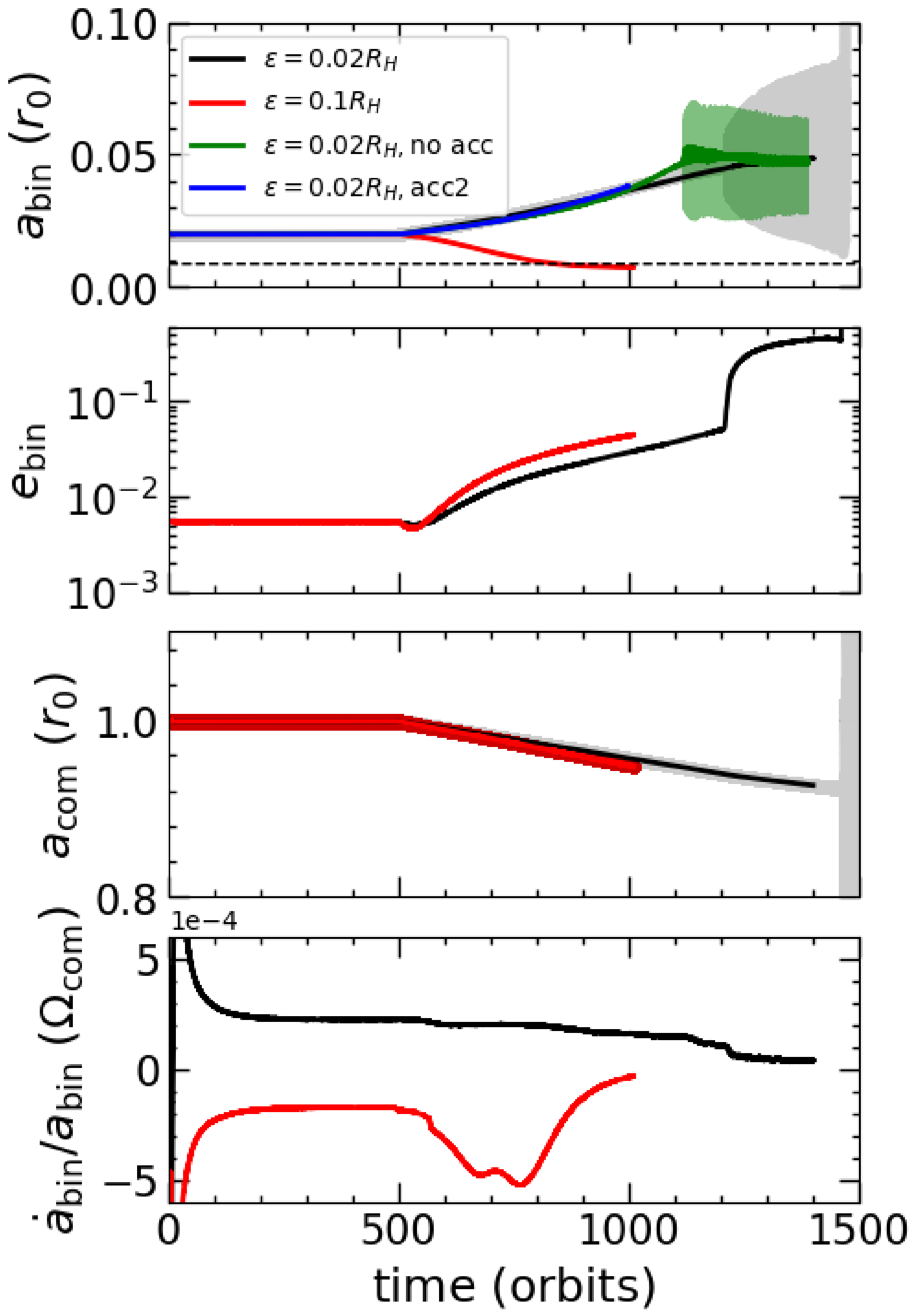
Gas structures



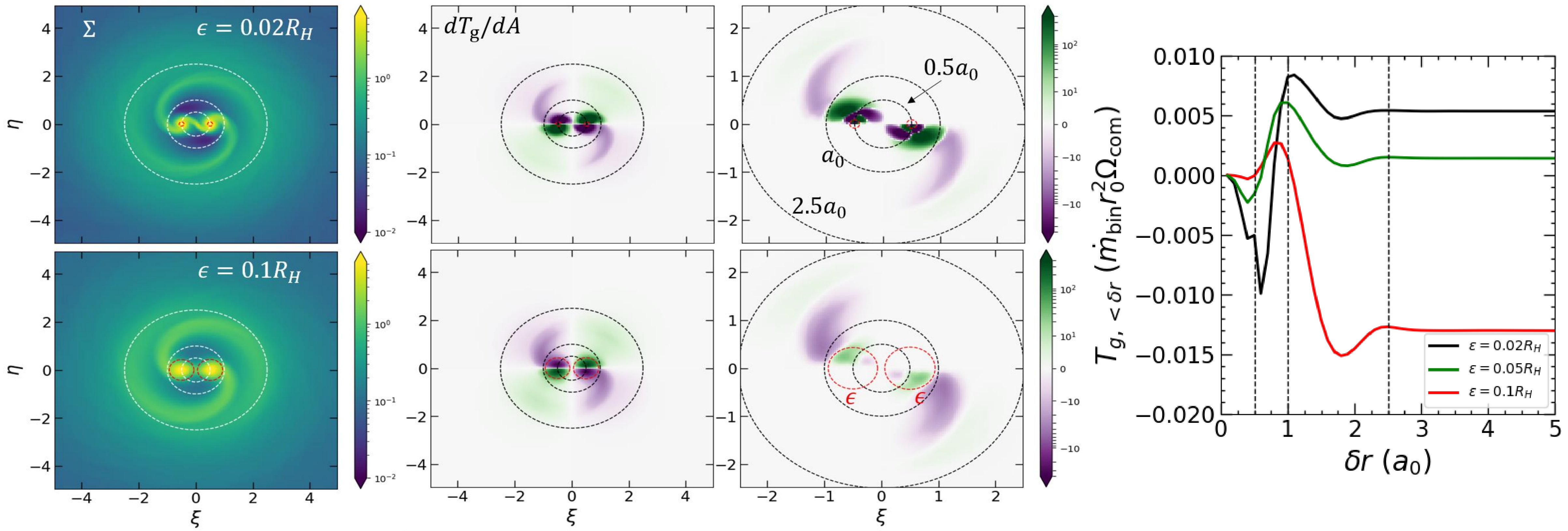
- Binary open gap and induce large scale spiral arms.
- Circum-binary disk inside Hill radius of the binary, and outer-spiral arms feeding the binary.
- Inter-spiral arm connecting two BHs and prominent circum-single disk.

Binary Dynamics

- Small softening: binary expand.
  - Binary eccentricity excitation
- Large softening: binary contract.
- Similar global migration for small and large softening.
- Insensitive to accretion.
- Reach a steady state: Binary semi-major axis a_{bin} evolution smoothly evolve after release.
- a_{bin} is determined fully by disk force.

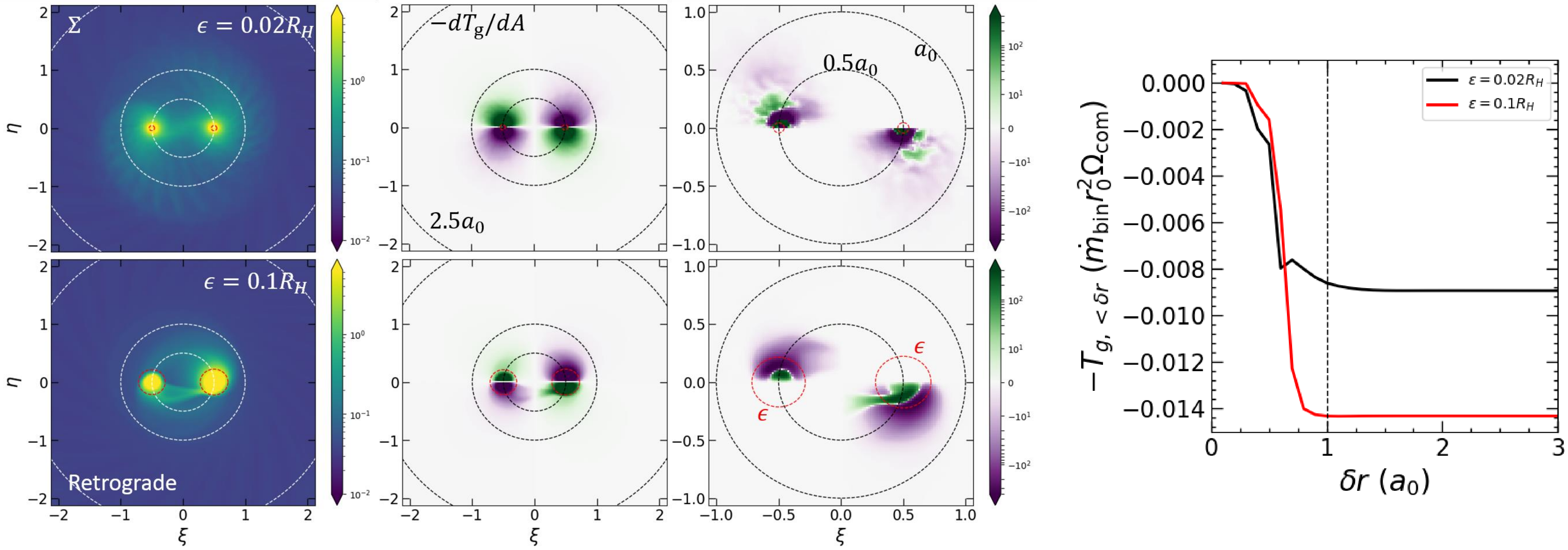


Why BBH expands? →Gravitational torque



- Small softening: the domination of the positive contribution from the CSD region around the binary → BBH expand.
- Large softening: smooth the CSD contribution, dominated by negative torque from outer-spiral arms → BBH contract.

Retrograde BBH



The domination of the positive contribution from the CSD region both for small and large softening→ BBH contracts (Binary angular momentum is negative).

Conclusions

- BBH with a small softening binary to appropriately resolve CSD region will expand, but will contract if a large softening is adopted.
- The expansion of the binary is due to the domination of the positive contribution from the CSD region around the binary.
- Binary eccentricity will be significantly excited rapidly for the expanded binary.
- For retrograde orbits, BBH contracts both for the small and large softening.

Outlook

- Realistic softening (Muller+12): 3D simulation.

- Isothermal EoS: implement radiative cooling/heating, and/or AGN feedback (Yuan+18;Yoon+18;Li+18) or viscosity prescription.

- Other parameter space: disk mass, disk scale height, binary mass ratio……

BBH accretion

- The accretion rate on the short time-scale is highly variable.
- The periodicity is about $\Omega_{\rm bin}$ (early stage or for very high eccentricity) or $2\Omega_{\rm bin}$ (around 900 orbits).