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The effects of star-gas interactions on binary evolution in open clusters

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Open clusters (OCs)

Pleiades
Credit: Digitized Sky Survey

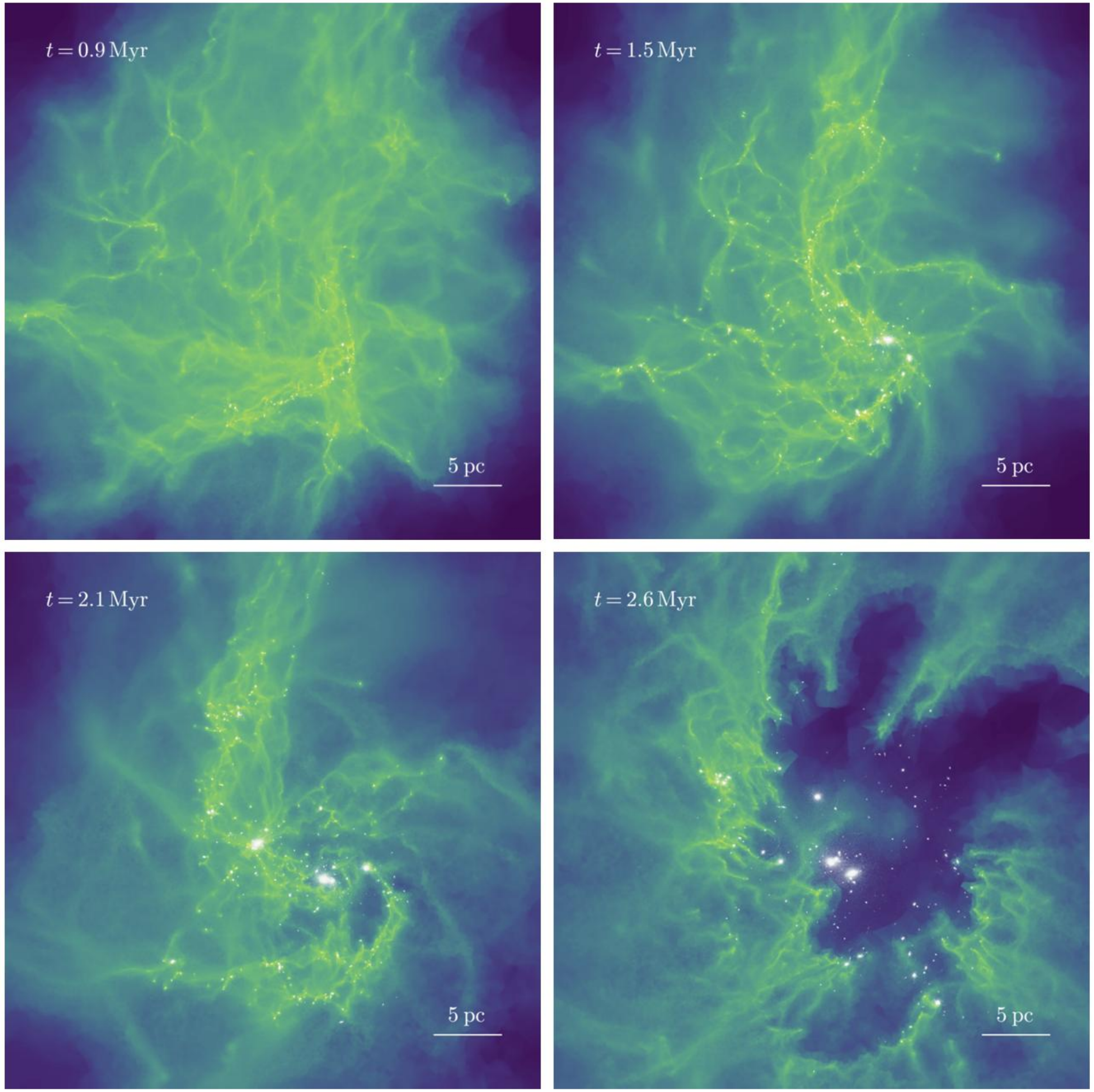
NGC 2164
Credit: ESA/Hubble & NASA, J. Kalirai, A. Milone

NGC 1755
Credit: ESA/Hubble & NASA, A. Milone, G. Gilmore

- Open clusters are loosely bound groups of a few tens to a few thousand stars. They are found in spiral and irregular galaxies. Open clusters are significantly smaller and less densely populated than globular clusters.
- Over 7000 OCs have been found in the Milky Way.

Open clusters (OCs)

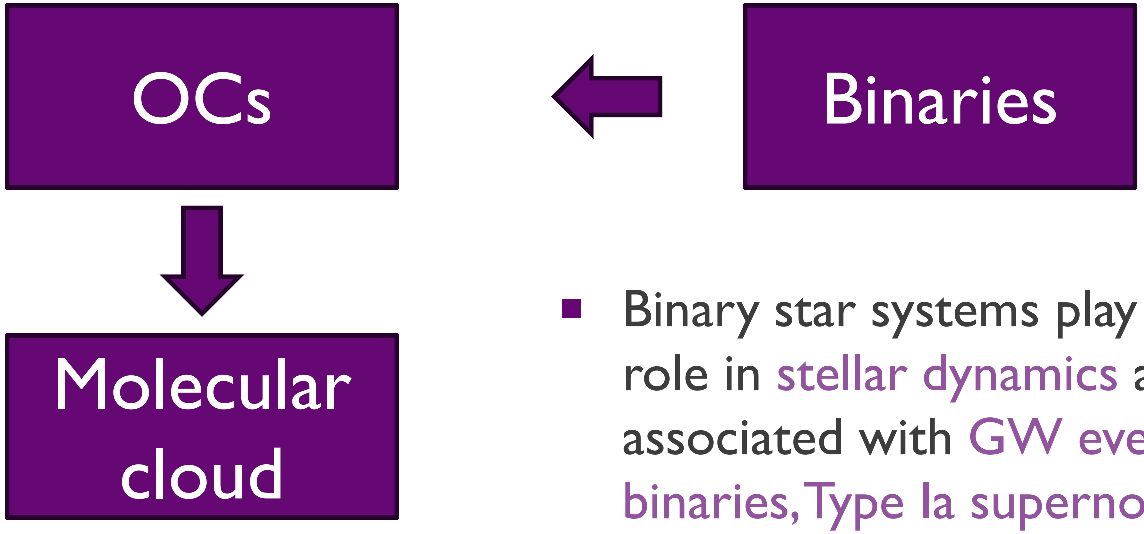
- Stars in the same OC are formed from the same giant molecular cloud and have roughly the same age.
- Young open clusters may be contained within the molecular cloud from which they formed, illuminating it to create an H II region. Over time, radiation pressure from the cluster will disperse the molecular cloud.
- A cluster may have many encounters with GMCs. The tidal field of GMC will accelerate the dissolution of the cluster.



Credit: Li et al. 2019

Background

- OCs form from giant molecular clouds and typically remain embedded in residual gas for $\sim 10^8$ years. They are ideal environments for studying binary evolution.

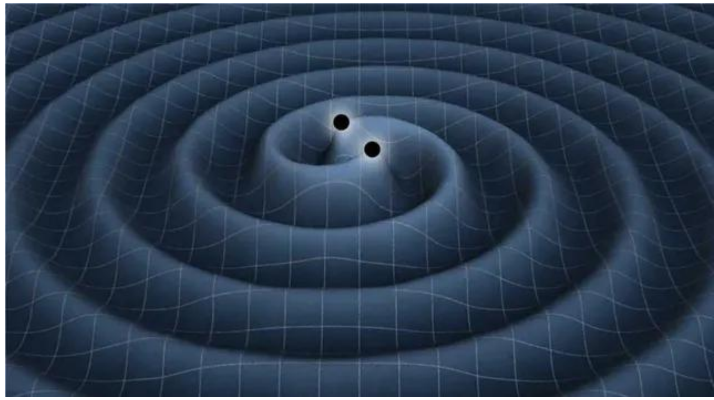


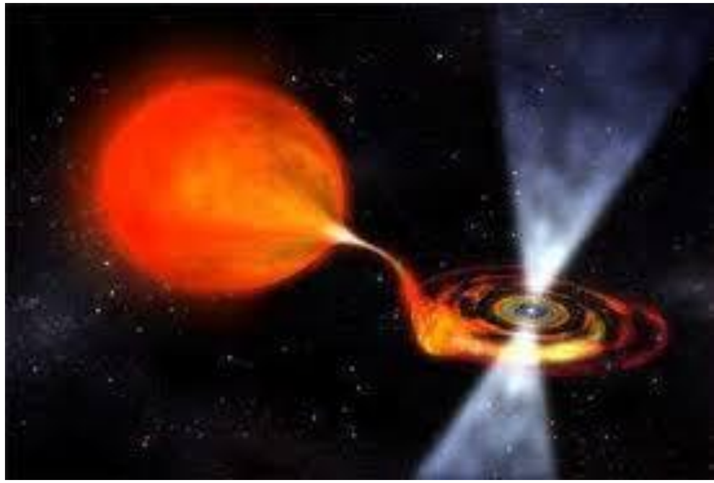
OCs

Binaries

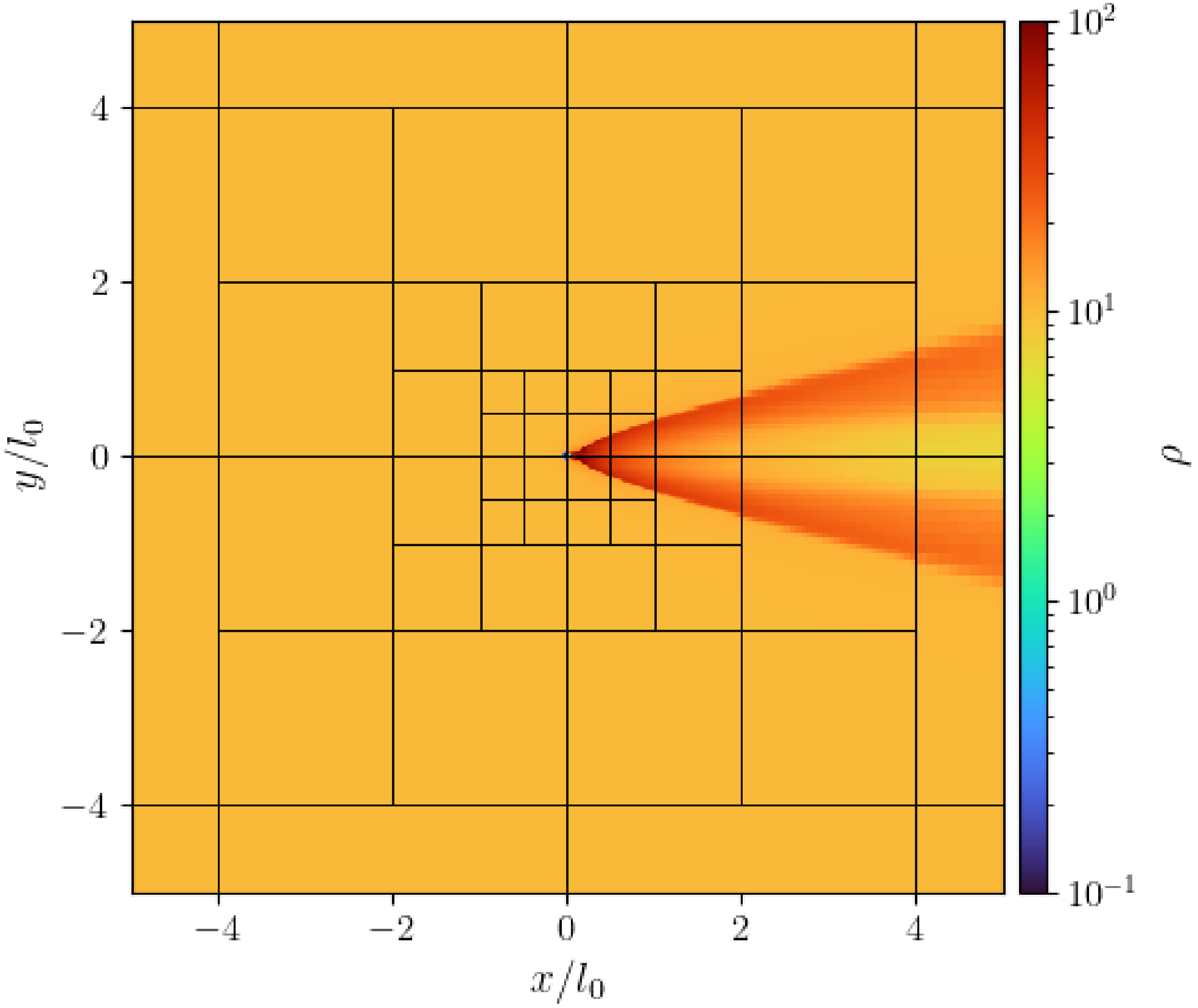
Molecular cloud

- Binary star systems play a fundamental role in stellar dynamics and are closely associated with GW events, X-ray binaries, Type Ia supernovae, etc.





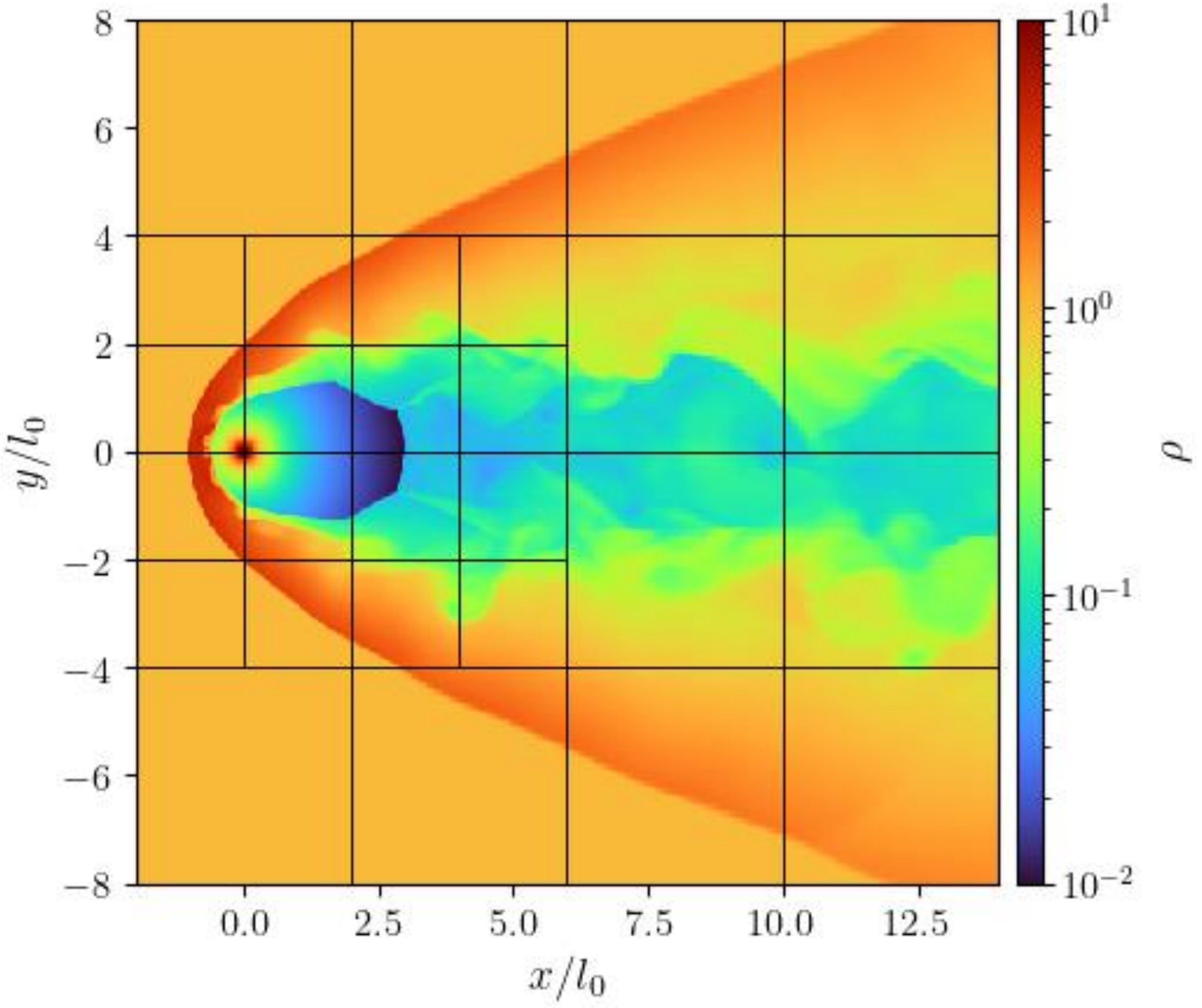
Star-gas interaction



- Chandrasekhar (1943) established the theoretical foundation for dynamical friction (DF).
- Ostriker (1999) gave the analytic approximations:

$$F = -\frac{4\pi\left(GM_p\right)^2\rho_0}{v^2} \times \begin{cases} \frac{1}{2}\ln\left(\frac{1+\mathcal{M}}{1-\mathcal{M}}\right) - \mathcal{M}\,, & \mathcal{M} < 1, \\ \frac{1}{2}\ln\left(1-\frac{1}{\mathcal{M}^2}\right) + \ln\frac{vt}{r_{\min}}\,, & \mathcal{M} > 1. \end{cases}$$

Star-gas interaction



- Theoretical advances by Gruzinov et al. (2020) and numerical simulations by Li et al. (2020) have revealed that stars with strong outflows can generate negative dynamical friction (NDF).

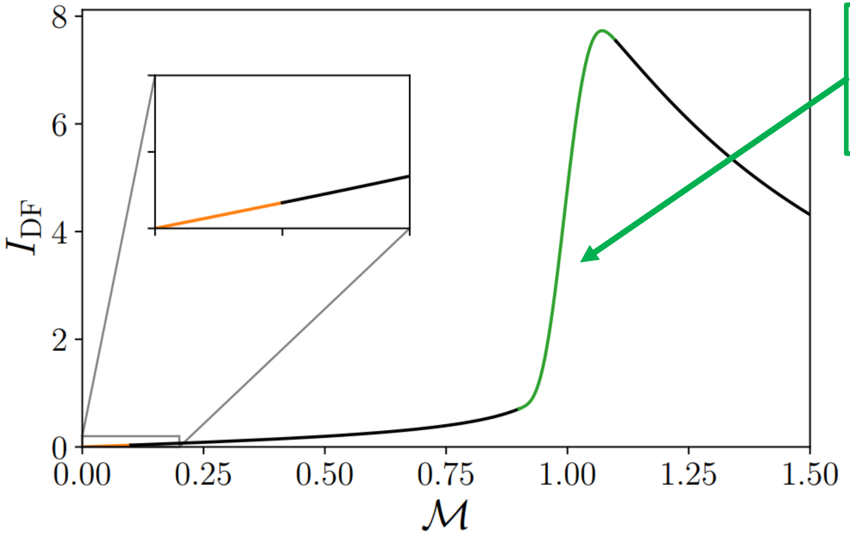
- For isotropic winds:
  - Low-speed stars: $v \ll v_{wind}$,

$$F \approx 8.18 G M_p \rho_0 R_0, R_0 = \left[\frac{\dot{m}_w v_w}{4\pi \rho_0 v_*^2}\right]^{\frac{1}{2}}$$

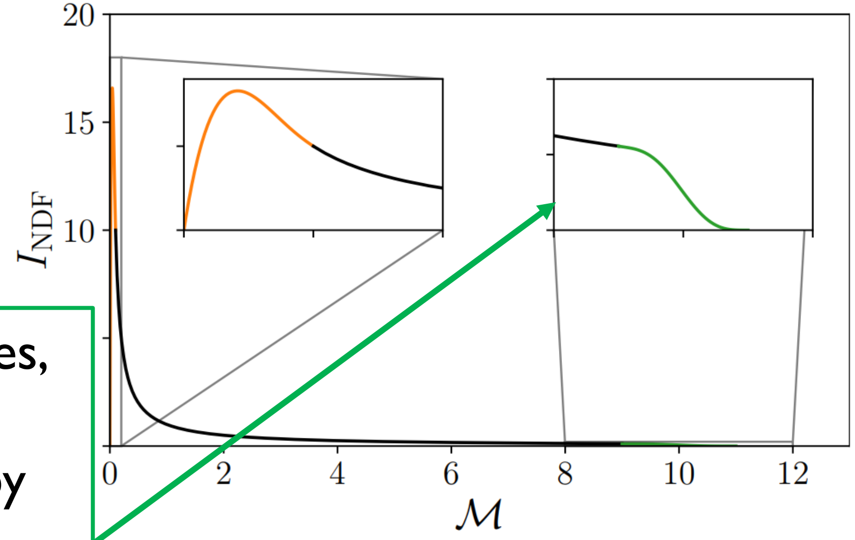
Method

- Initial condition: use McLuster generate initial OC
  - 10000 stars, IMF by Kroupa 2002 ($0.2\ M_\odot \sim 100 M_\odot$)
  - Half-mass radius: $3\ \mathrm{pc}$
  - Density profile: King (1966) with $W_0 = 5$
  - Binary fraction: 40%
- Simulation: use N-body code PeTar
- Binary counting:
  - Binding energy > local average kinetic energy: hard binaries
  - 0 < Binding energy < local average kinetic energy: soft binaries

Method: external force in PeTar



Smooth transition across Mach number = 1



At sufficiently high stellar velocities, NDF can be suppressed.
The critical point is determined by comparing the ambient gas ram pressure $p_0 \sim \rho_0 v_*^2$ with the stellar wind pressure evaluated at the sonic point.

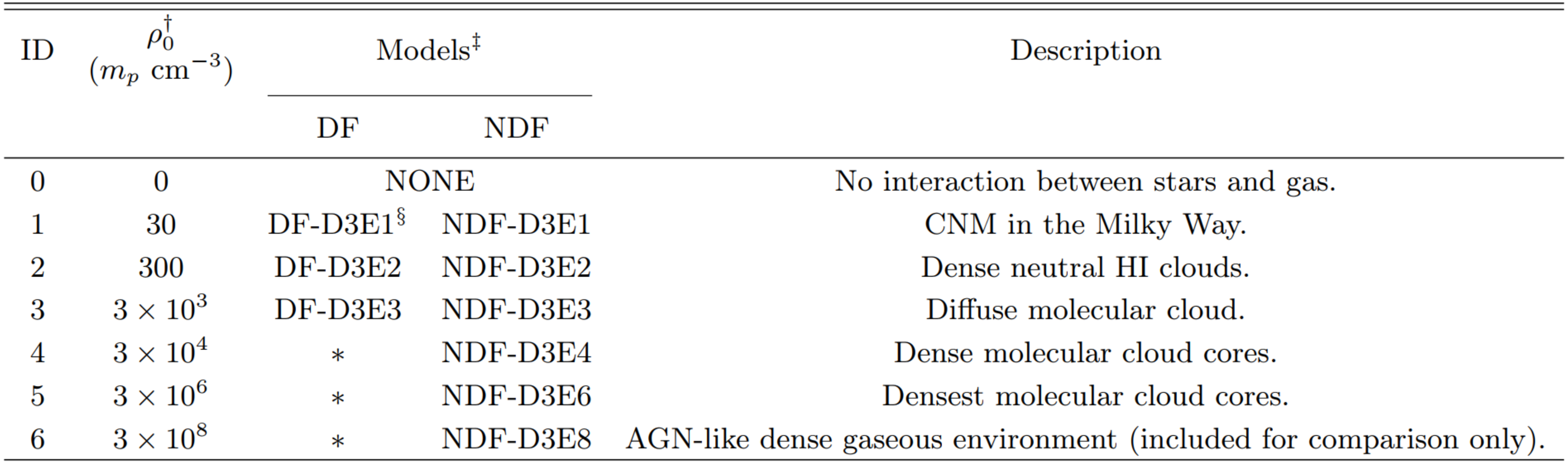
$$a_{DF} = \frac{4\pi G^2 \rho_0 M}{c_s^2} I_{DF}$$

$$I_{\mathrm{DF}}(\mathcal{M}) = \frac{1}{\mathcal{M}^2} \times \begin{cases} \ln\left[\Lambda\left(1 - \frac{1}{\mathcal{M}^2}\right)^{1/2}\right], & \mathcal{M} > 1 \\ \frac{1}{2}\ln\left(\frac{1+\mathcal{M}}{1-\mathcal{M}}\right) - \mathcal{M}, & \mathcal{M} < 1 \end{cases}$$

$$a_{NDF} = 8.18G\sqrt{\frac{\dot{m}_w v_w \rho_0}{4\pi}}\frac{1}{c_s} I_{NDF}$$

$$I_{\mathrm{NDF}}(\mathcal{M}) = \frac{1}{\mathcal{M}}$$

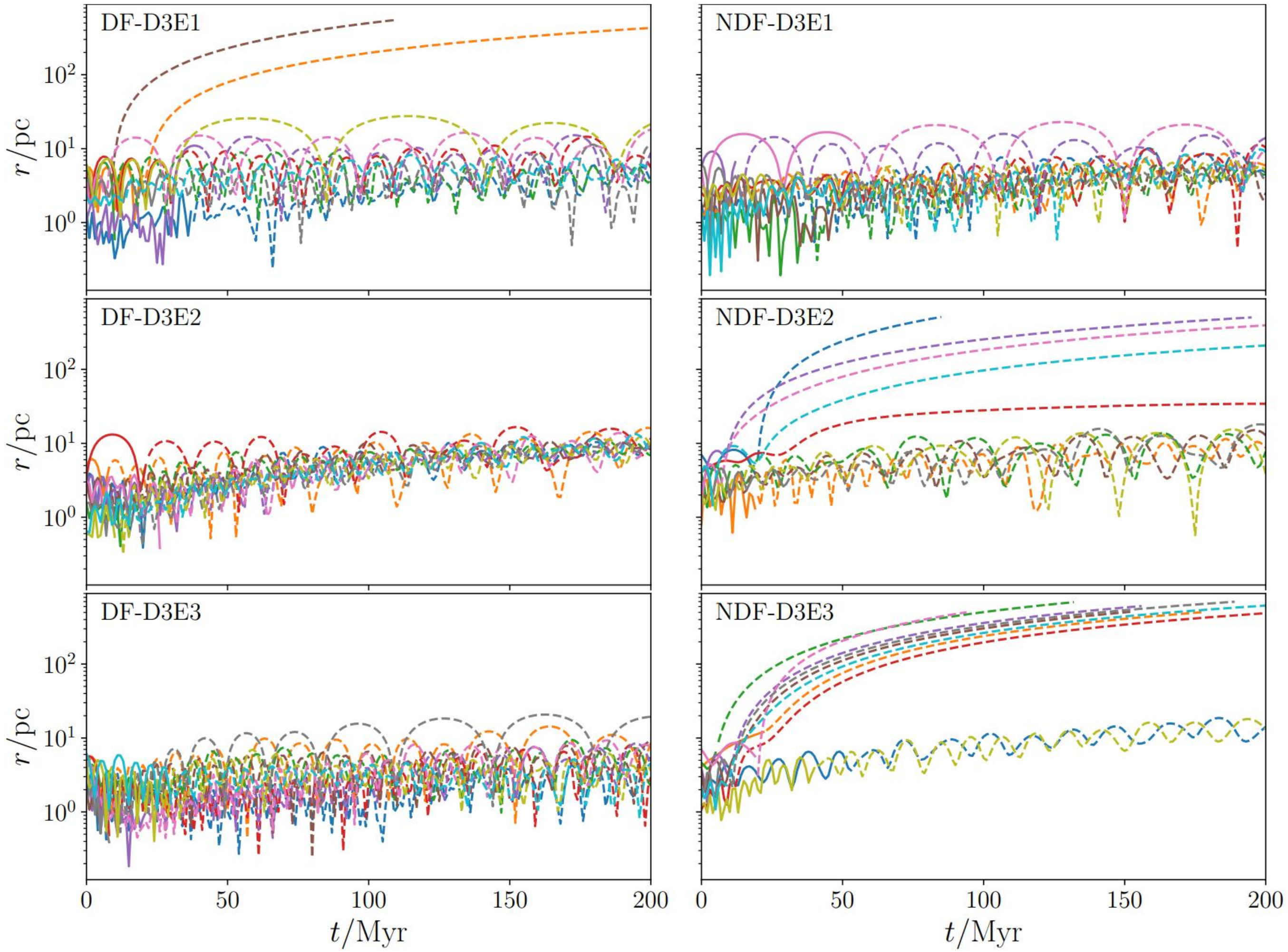
Method



ID	$\rho_0^\dagger$ (m_p cm^{-3})	Models[‡]		Description
		DF	NDF	
0	0	NONE		No interaction between stars and gas.
1	30	DF-D3E1[§]	NDF-D3E1	CNM in the Milky Way.
2	300	DF-D3E2	NDF-D3E2	Dense neutral HI clouds.
3	3×10^3	DF-D3E3	NDF-D3E3	Diffuse molecular cloud.
4	3×10^4	*	NDF-D3E4	Dense molecular cloud cores.
5	3×10^6	*	NDF-D3E6	Densest molecular cloud cores.
6	3×10^8	*	NDF-D3E8	AGN-like dense gaseous environment (included for comparison only).

- Other parameters:
  - lbox=$500\ \mathrm{pc}$
  - Runtime=$200\ \mathrm{Myr}$
  - Milky way CNM $T_{gas} = 100\ \mathrm{K}$

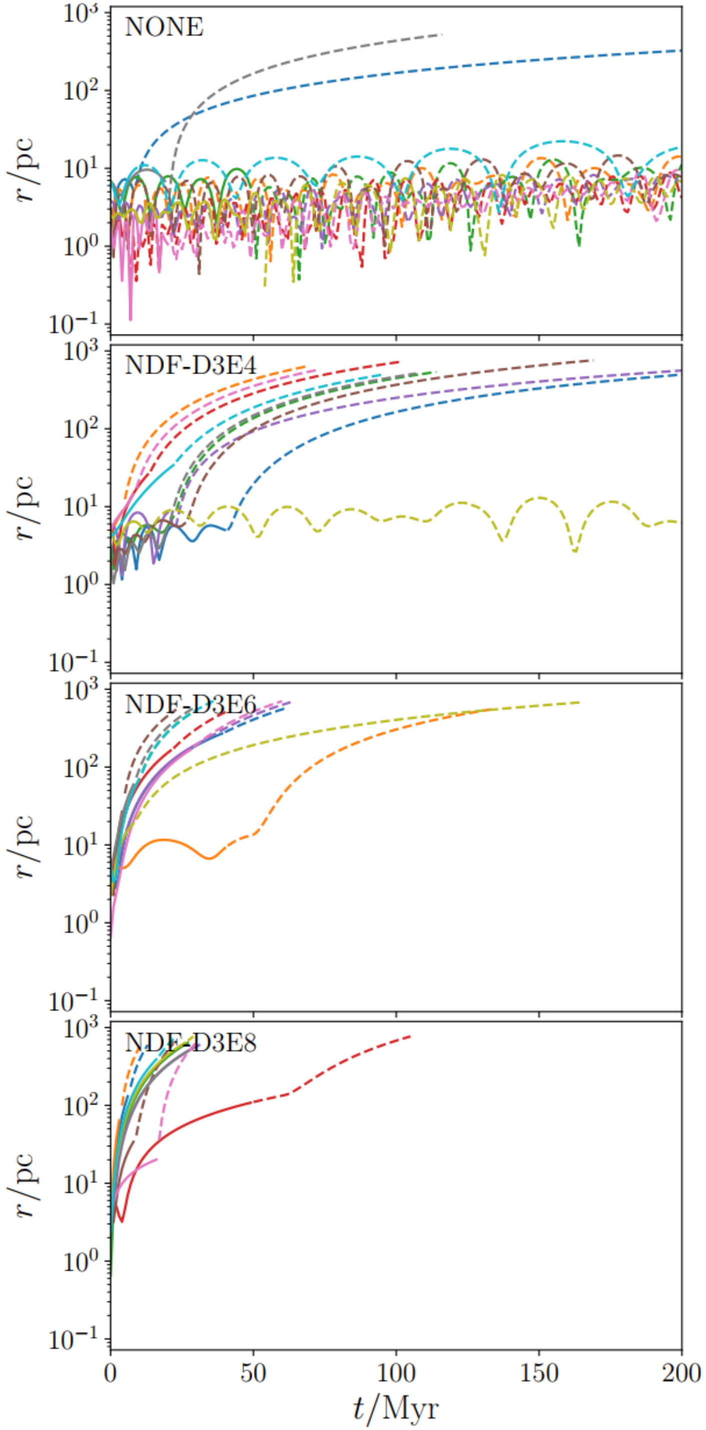
Results: NS expulsion via NDF



The track of stars evolving from MS to NS

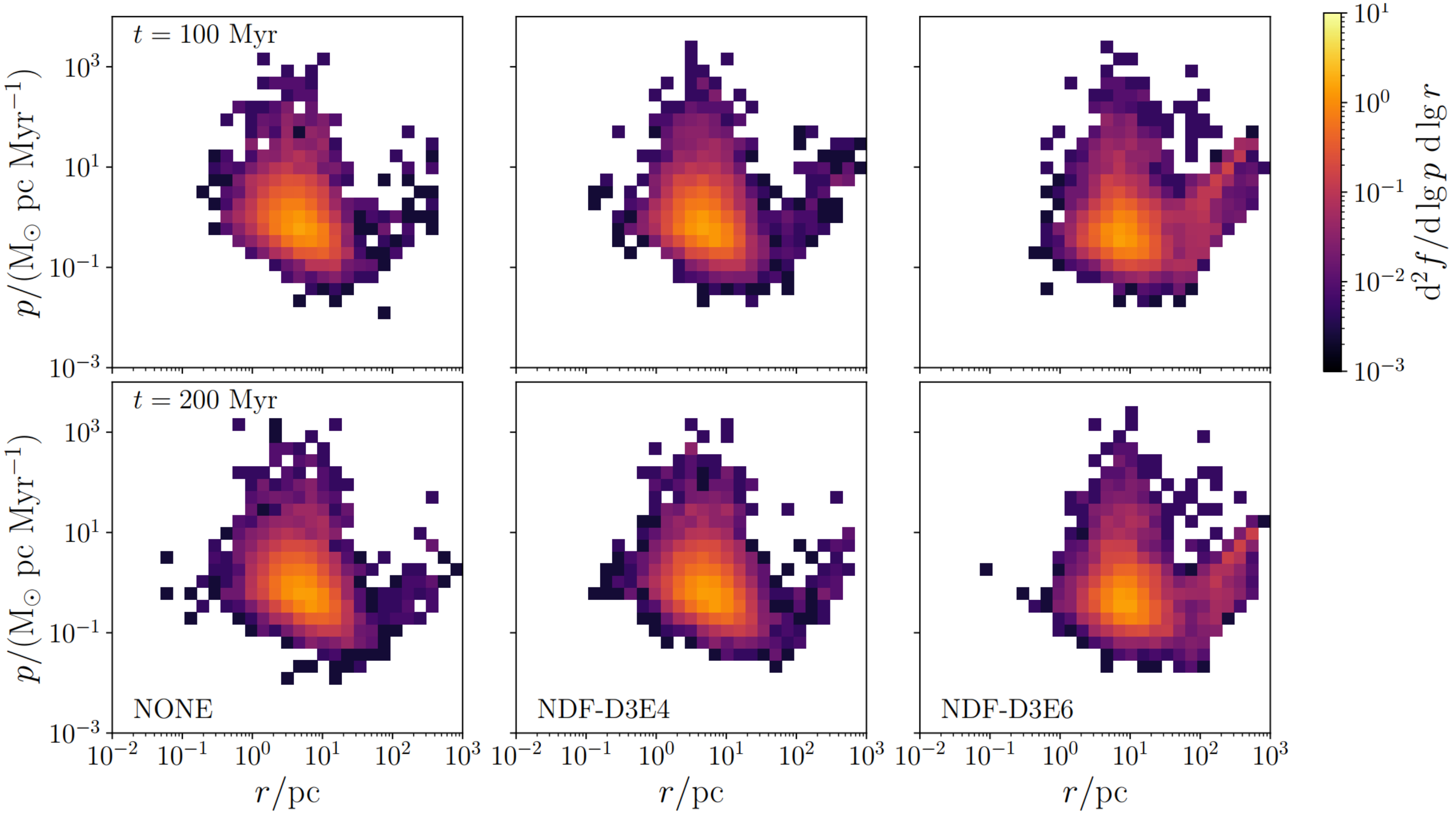
- All of outflow stars are eventually thrown out of the OC by NDF, while most of stars in DF mode and NONE mode keep orbiting the center of the cluster.

Results: NS expulsion via NDF



- The efficiency of NS removal via NDF depends strongly on the ambient gas density.
- In higher-density gas environments, NSs escape from the cluster more rapidly.

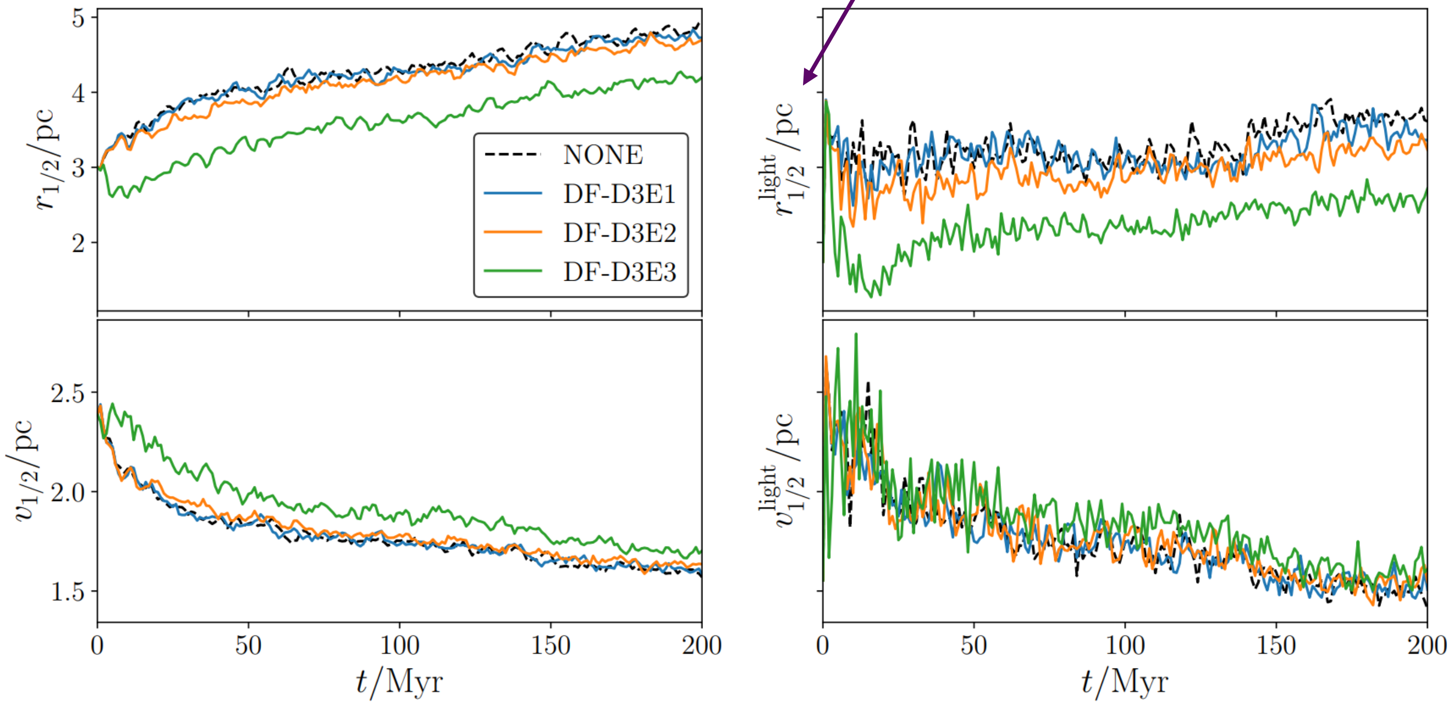
Results: distribution of stars in momentum-radius phase space



Two-dimensional histograms in momentum–radius phase space

- NDF develop a distinct population of stars at large radii that retain substantial radial momentum.
- NDF supplies a sustained outward acceleration, preventing efficient deceleration by the cluster potential.

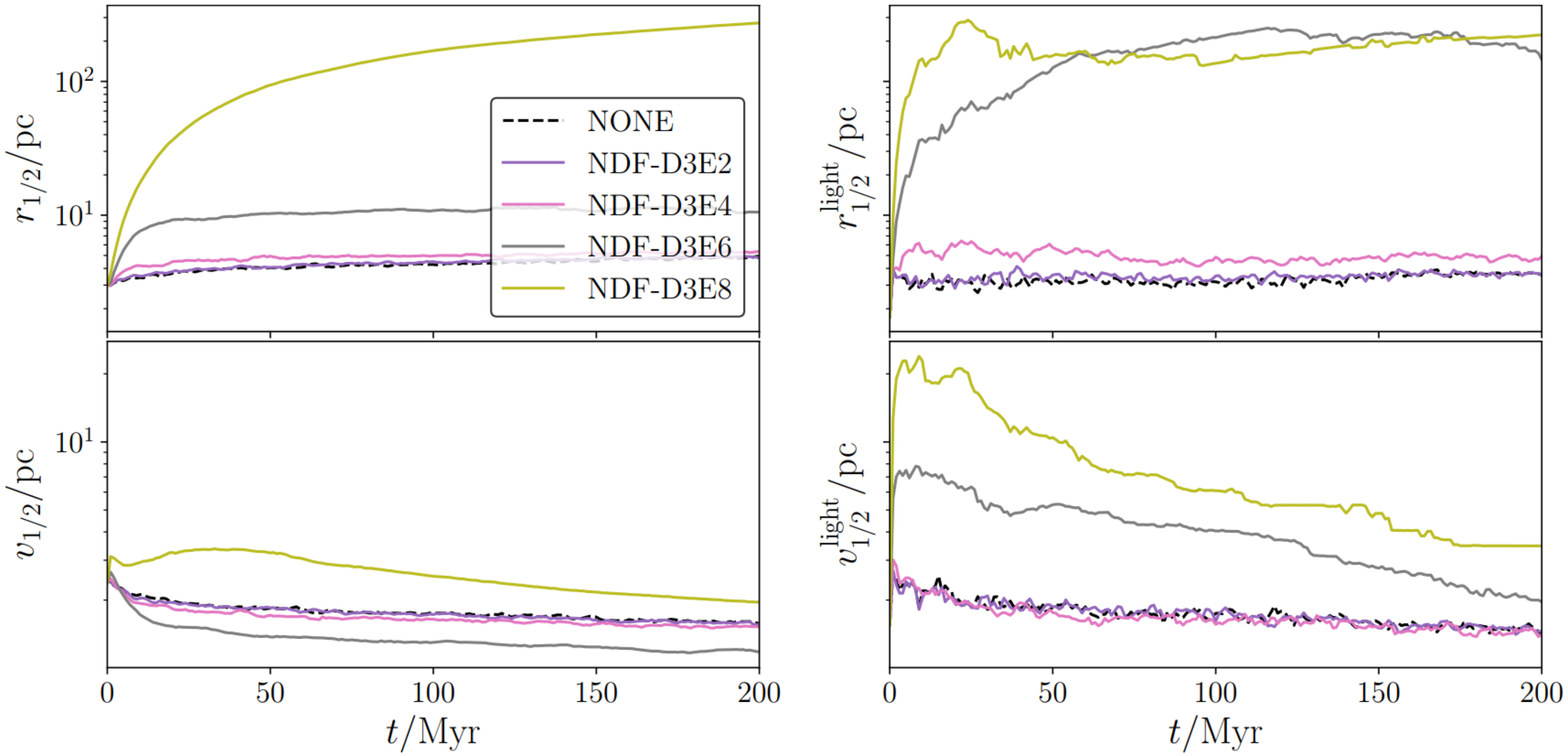
Results: evolution of cluster scale parameters



$L \propto M^{3.5}$

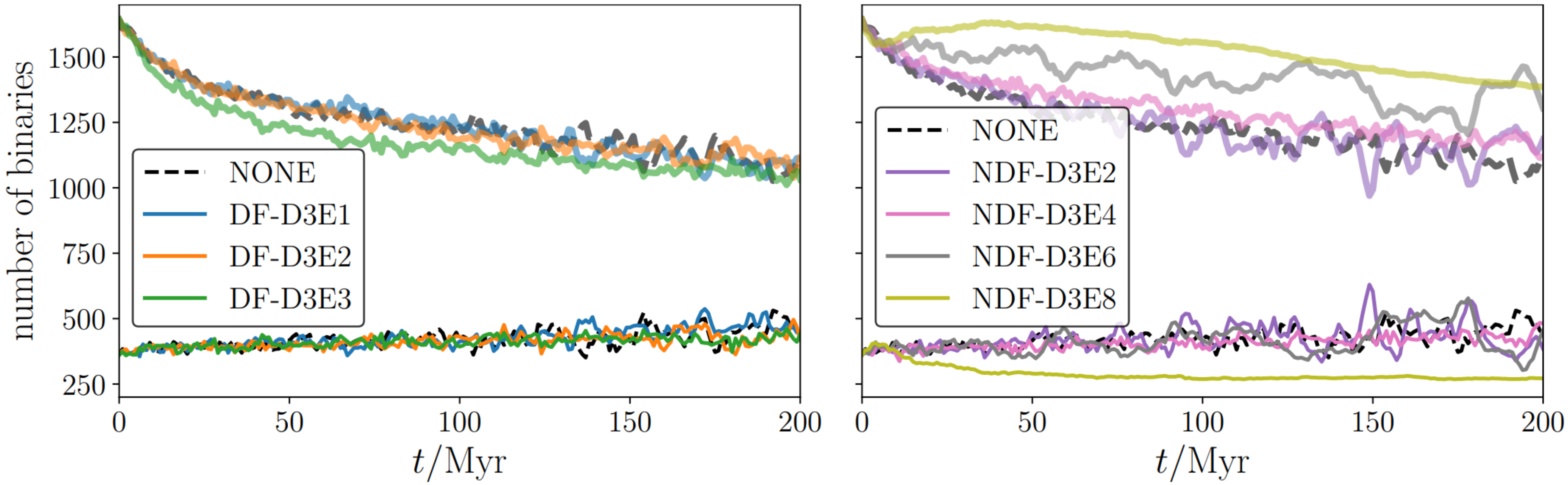
- In DF mode, smaller half-mass radii and larger velocity scales → DF extracts orbital energy from stars and suppresses cluster expansion.

Results: evolution of cluster scale parameters



- In NDF-D3E8, at early times, an expansion in both the half-mass and half-light radii → massive MS stars and their strong wind.

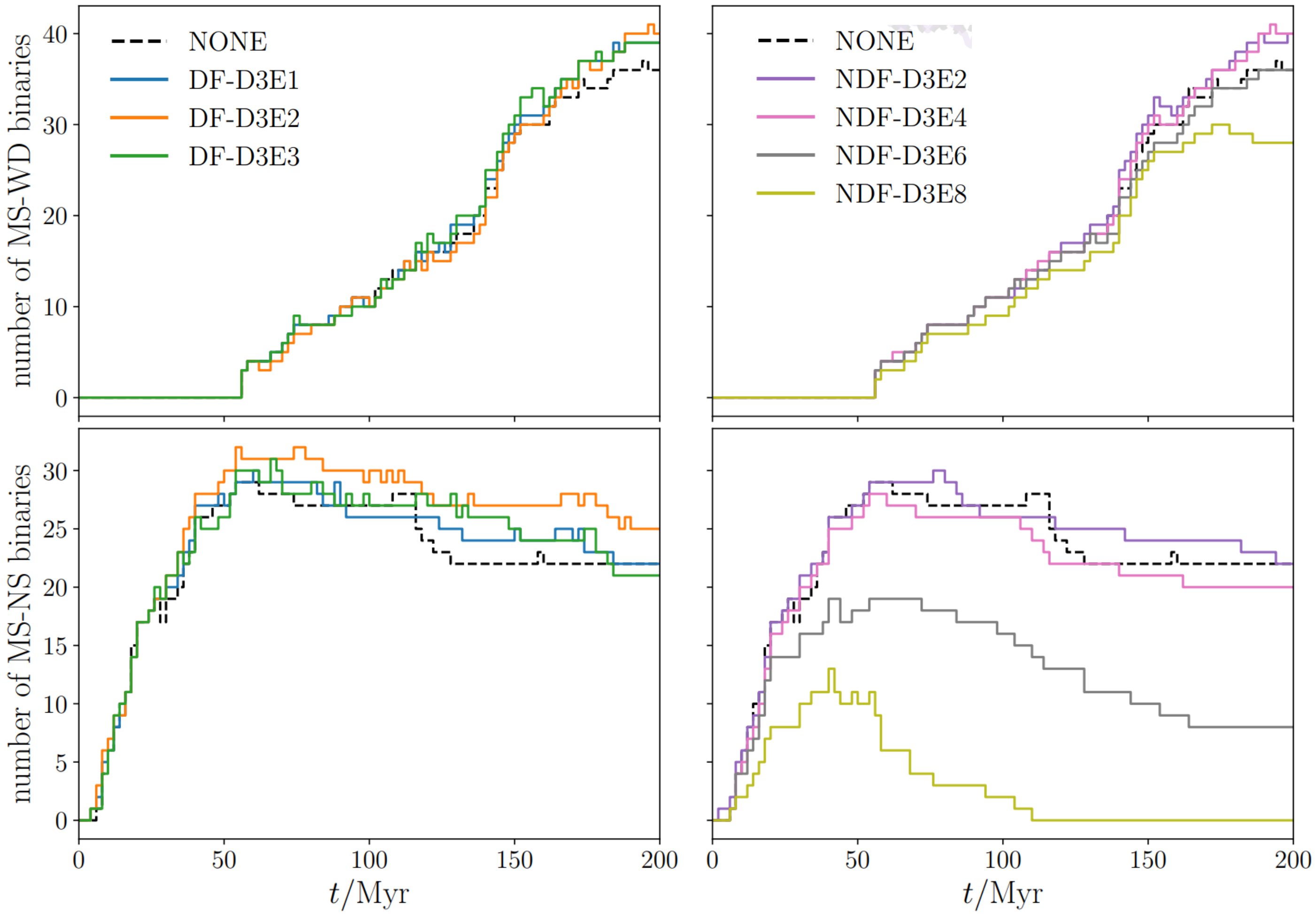
Results: binary dynamics



In the DF-D3E3 models, the binary population exhibits a significantly smaller number of soft binaries than both the no-gas case and DF models at lower gas densities.

In NDF mode, the number of soft binaries increases with increasing gas density because of less collisions.

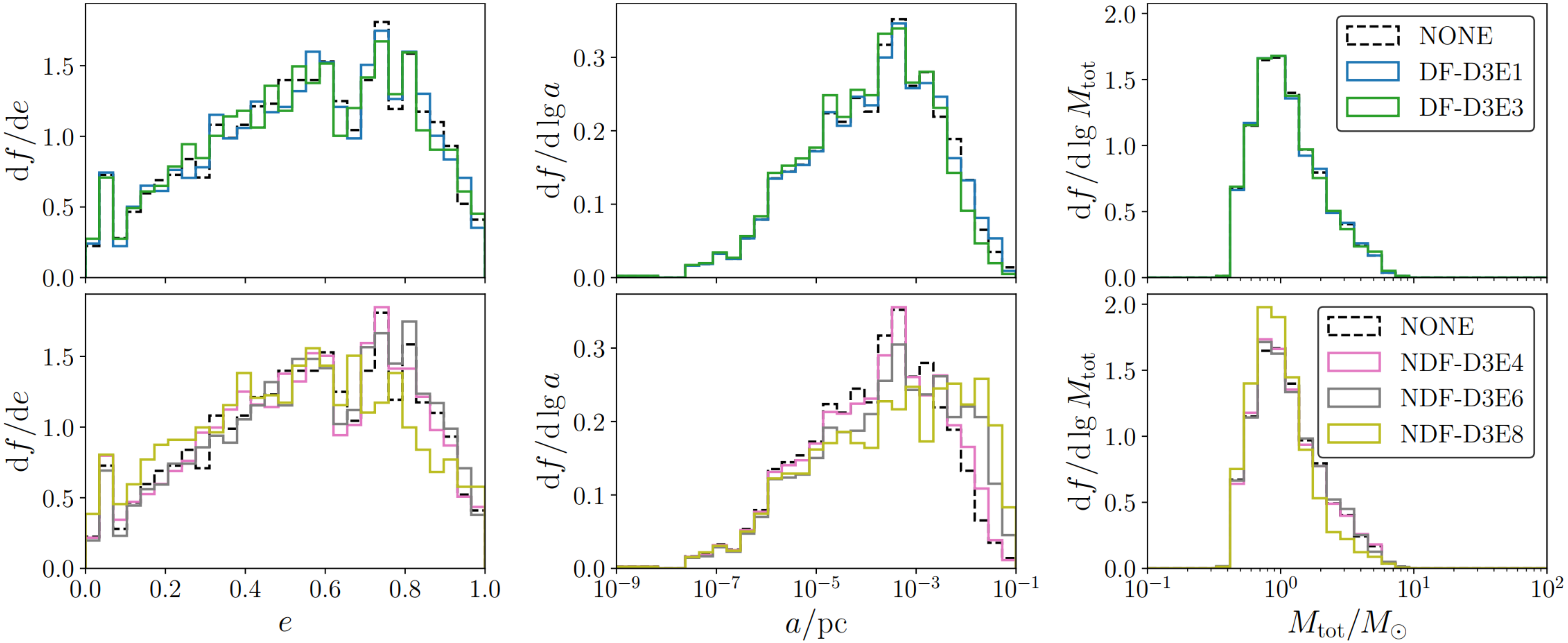
Results: binary dynamics



- NSs are assigned a strong NDF contribution by pulsar winds → When $\rho = 3 \times 10^6, 3 \times 10^8\ m_p\ \mathrm{cm}^{-3}$, the number of MS-NS binaries is much lower than in the DF or no-gas models.

Results: binary dynamics

- NDF tends to keep binaries which have large a, smaller eccentricity e and smaller M_{tot}.



Observation: Cyg OB2

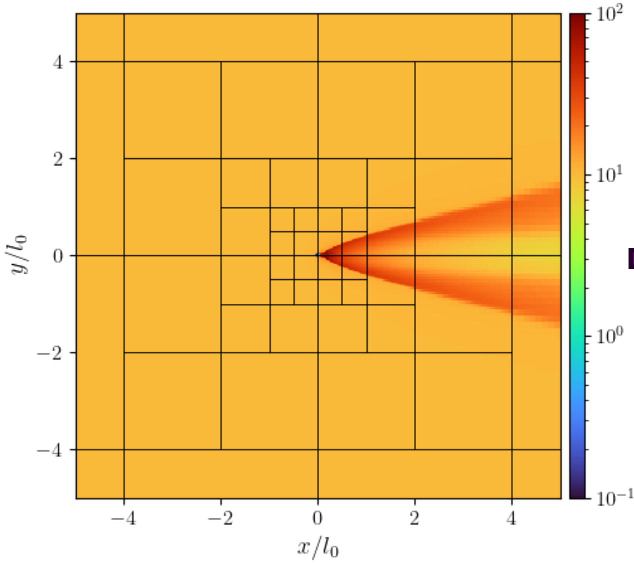
- Cyg OB2 is a young OB cluster. The age is estimated to be in the range $1 - 10\ \mathrm{Myr}$.
- Massive stars have short evolution timescales and dominate the dynamics of OB clusters.

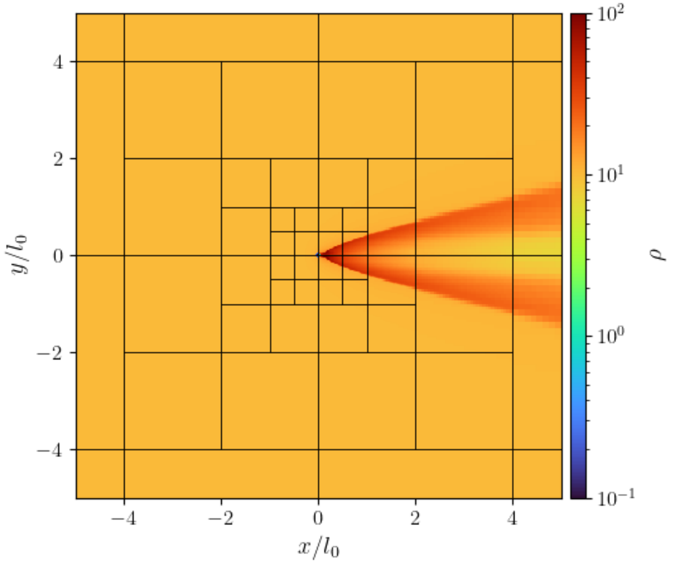
- High-angular-resolution imaging surveys have revealed the presence of massive companions at separations up to $10^3 - 10^4\mathrm{AU}$ in Cyg OB2.

Credit: NASA

How about those close binaries?

➡ A hydrodynamic simulation





Background

- There are many previous works to simulate the gas near the binary system.

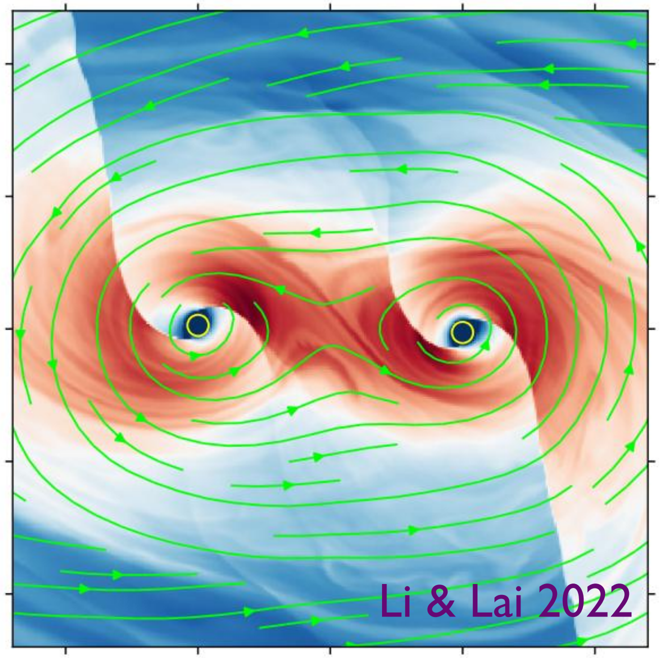
In the late evolutionary stages of the binary system, most of previous works suggest that star-gas interaction will reduce the angular momentum of binary black hole (BBH) and promote the merger.

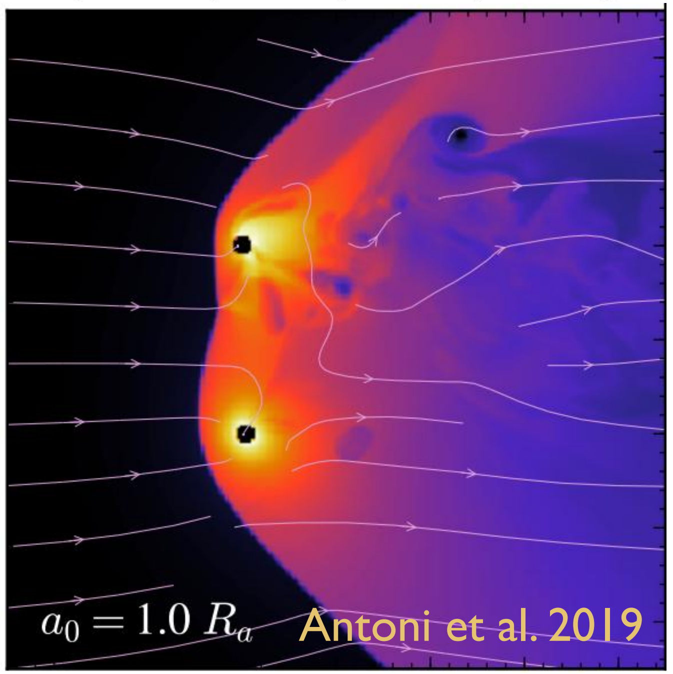
Background

Before gravitational wave radiation dominates the inspiral, star–gas interactions cause the binary orbit to decelerate and the two components to move closer together.

- If the binary center of mass orbits the cluster center or the central SMBH in an AGN, it may have a high velocity relative to the ambient gas.

Inspiral → *Negative* inspiral

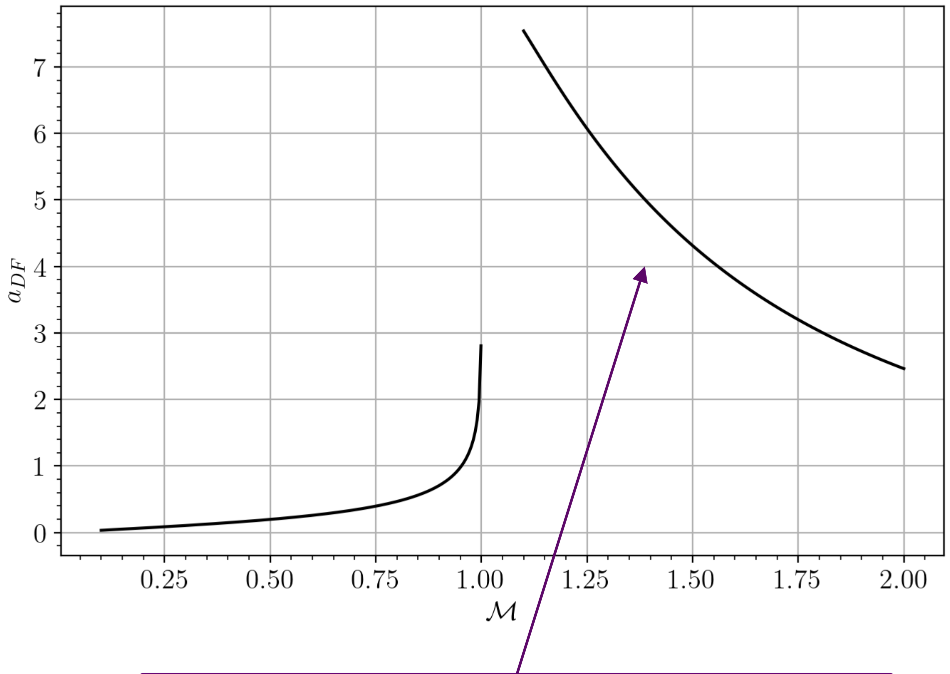

Li & Lai 2022



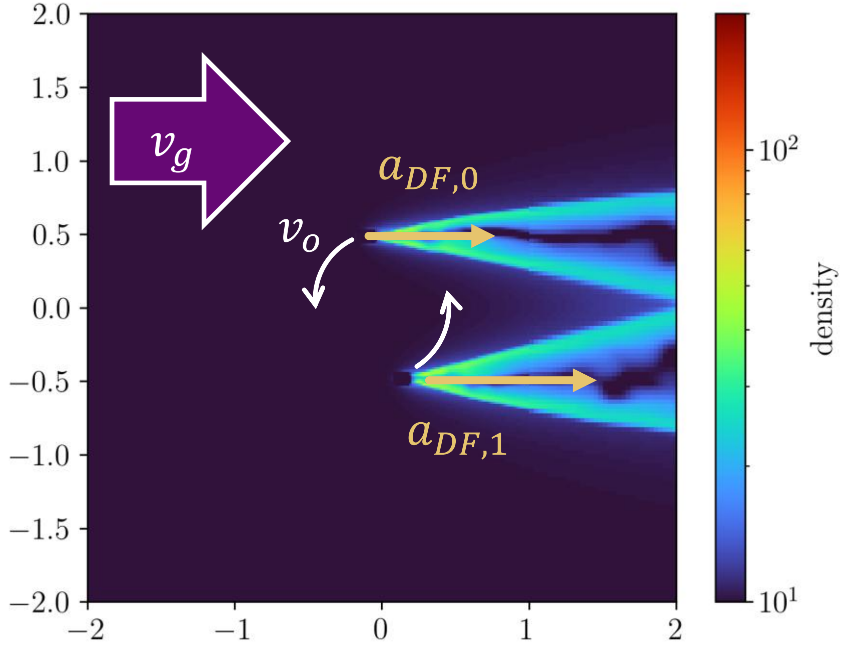
Antoni et al. 2019

Analytical consideration

- Dynamical friction given by Ostriker (1999):



In supersonic case, higher velocity means lower drag force.



Consider binaries (mass ratio $q = 1$) that mass center moving in the uniform ambient gas, $v_g - v_o \geq c_s$.

In the binary center of mass frame, $a_{DF,0} < a_{DF,1}$. The torque about the center of mass will increase the angular momentum of BBH.

Numerical Setup and Method

- In code unit:
  - $c_s = 0.5, v_o = 0.5, v_g = 1, \gamma = \frac{5}{3}, GM = 0.5, \rho = 10$
  - Bondi radius: $R_B \sim \frac{2GM}{v_g^2} = 1$
  - Bondi timescale: $t_B \sim \frac{2GM}{v_g^3} = 1$
  - Box size: 32^3
  - Run the simulations to $t = 50$, which is 18 beyond the box-crossing time of the wind ($L_{box}/v_g = 32$).
- Fixed circular binary orbit.
- Code: Kratos, a GPU-based 3D MHD code.

Results

Define dimsionless parameter $\eta = v_g/v_o$.

The ratio of the binary separation to the Bondi radius

$$\frac{d}{r_B} = \frac{GM/v_o^2}{2GM/(v_g^2 + c_s^2)} = \frac{v_g^2 + c_s^2}{2v_o^2}$$

In the limit of highly supersonic motion ($v_g \gg c_s$),

$$d/r_B \approx v_g^2/2v_o^2 = \eta^2/2$$

- We repeat the results in Antoni et al. 2019 ($\eta = 2$).
- Consider a binary 0.1 pc from the center SMBH ($10^6\ M_\odot$):
  - $\rho = 3 \times 10^{11} m_p\ \mathrm{cm}^{-3}, v_g = 207\ \mathrm{km/s}, d = 2\ \mathrm{AU}, M = 20 M_\odot$
- Time-average torque is ~ -7.46 (in code unit)
  - Inspiral timescale is ~ 1×10^5 yr
  - Orbit period ~ 0.3 yr

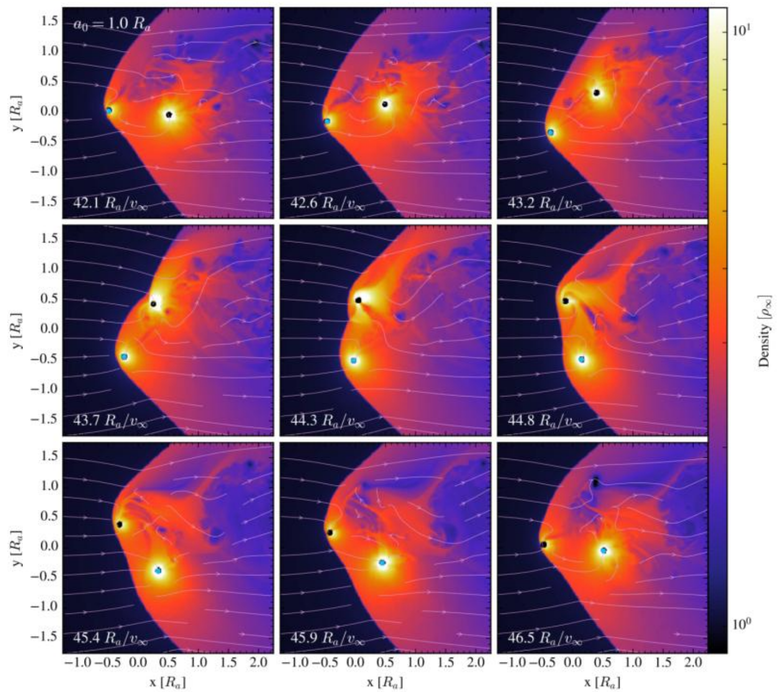
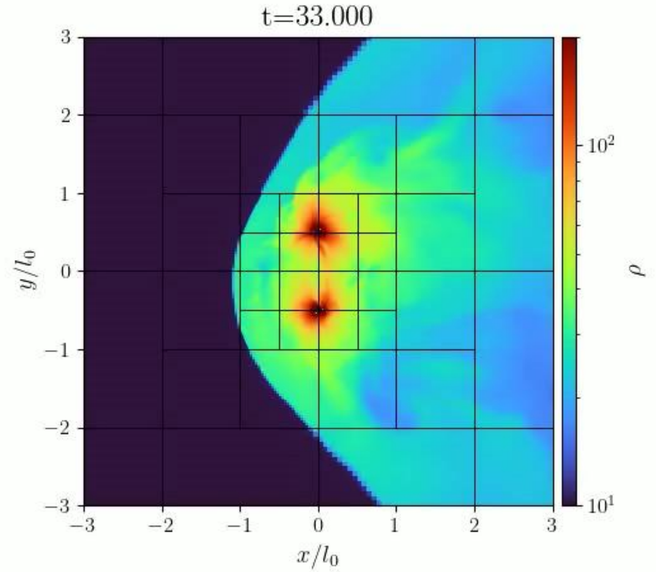
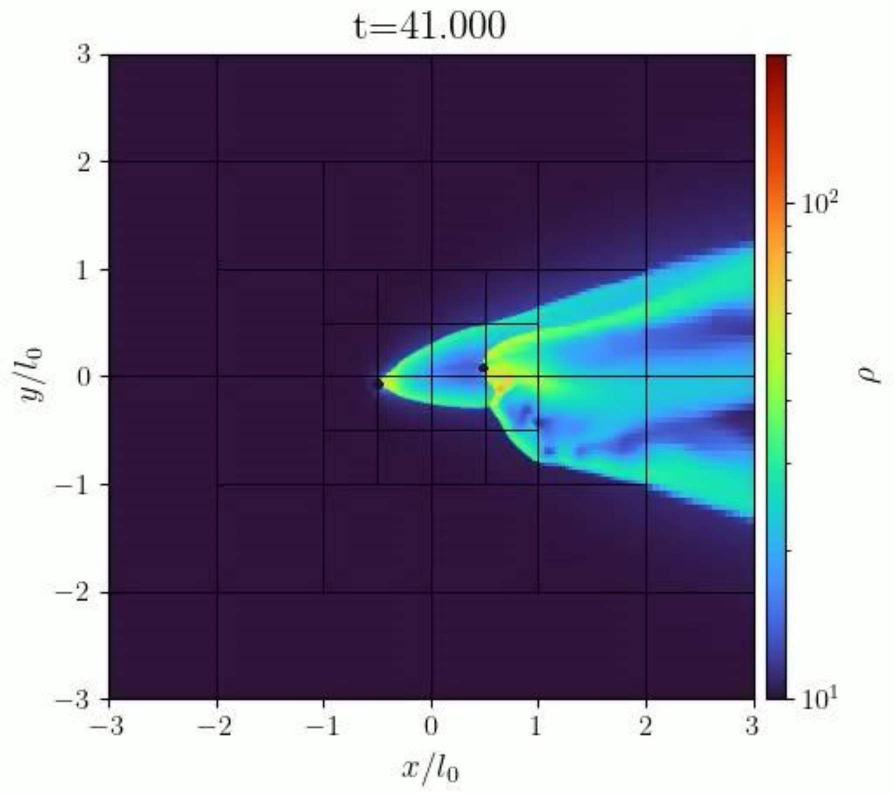


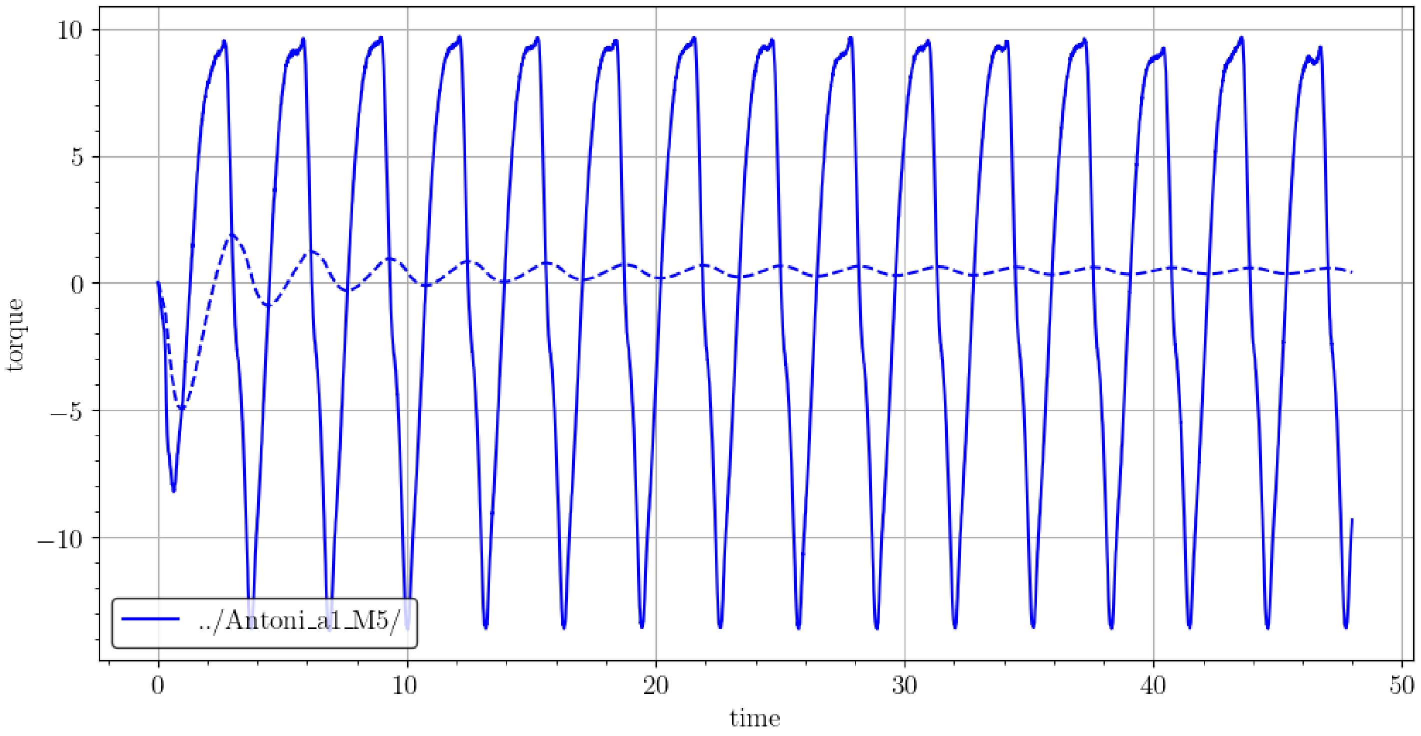
Figure 3 of Antoni et al. 2019



Results

- Increase v_g from 1 to 2.5 ($\eta = 5$).





Time-average torque is ~ +0.42 (in code unit)

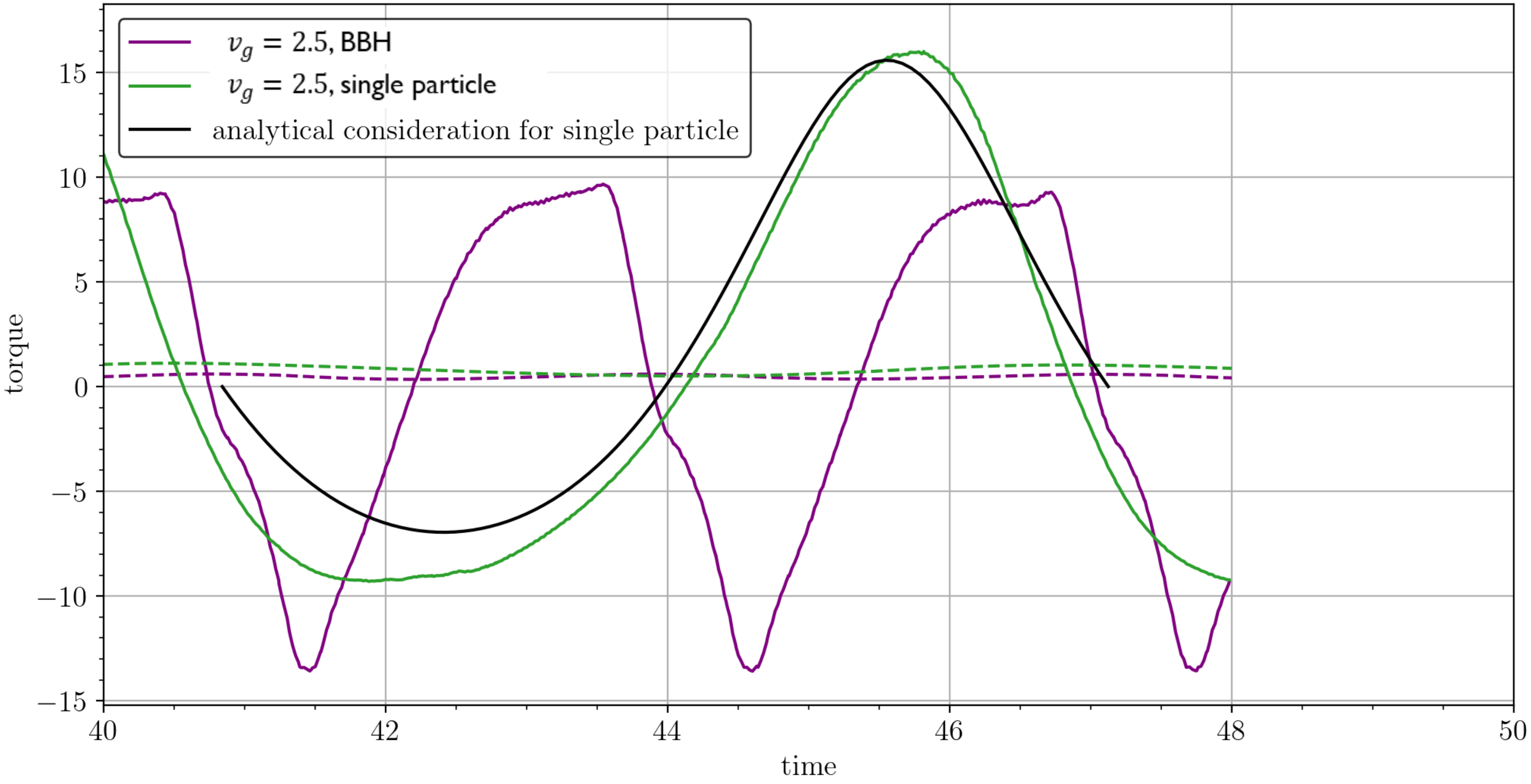
Inspiral timescale ($\eta = 5$) ~ 1.6×10^6 yr

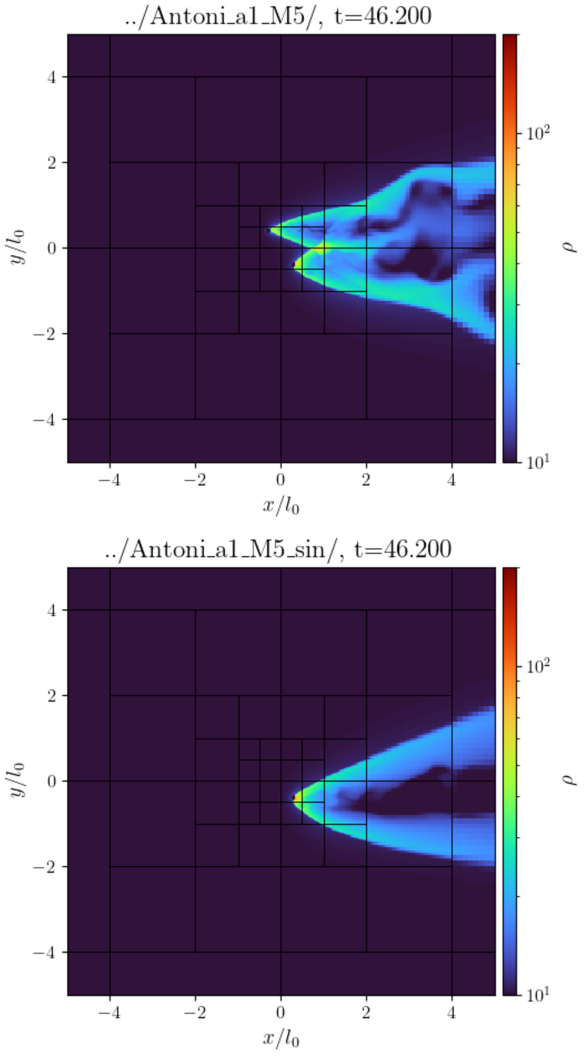
Inspiral timescale ($\eta = 2$) ~ 1×10^5 yr

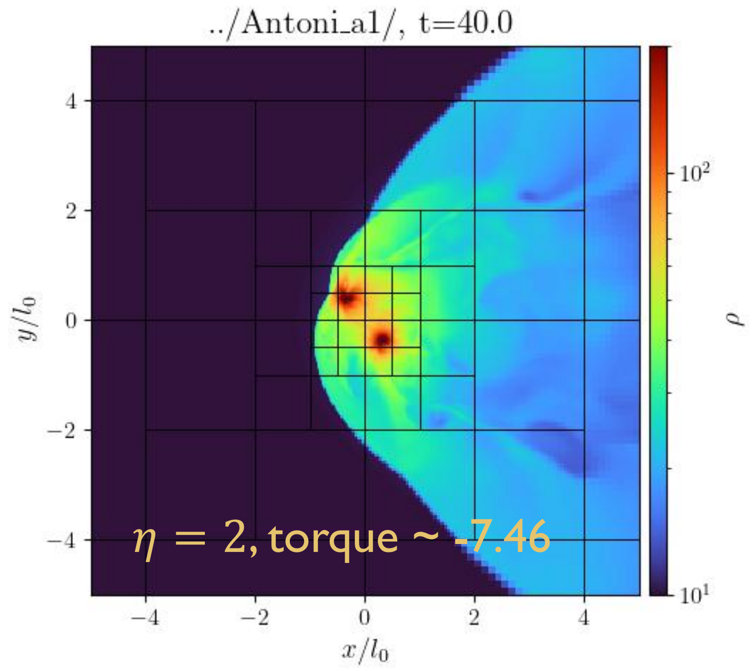
Orbit period ~ 0.3 yr

Results

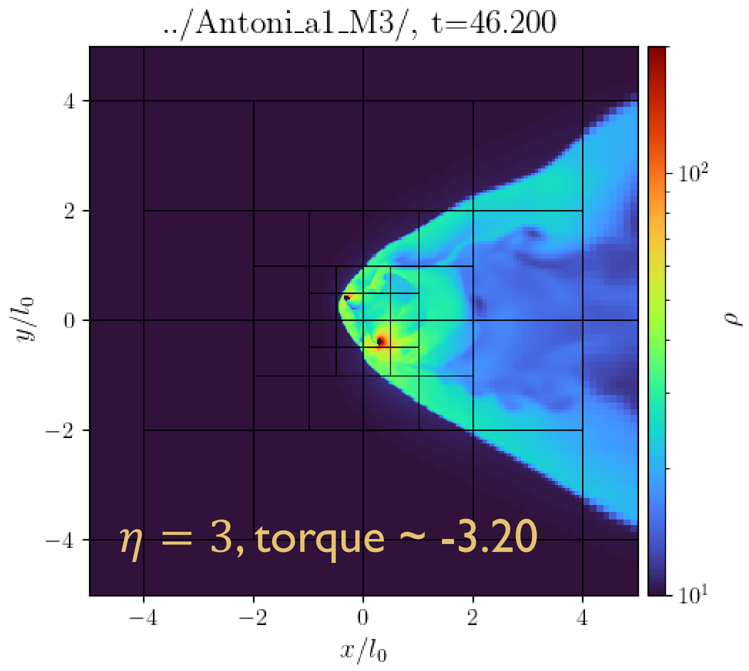
- Compare analytical consideration and simulation.



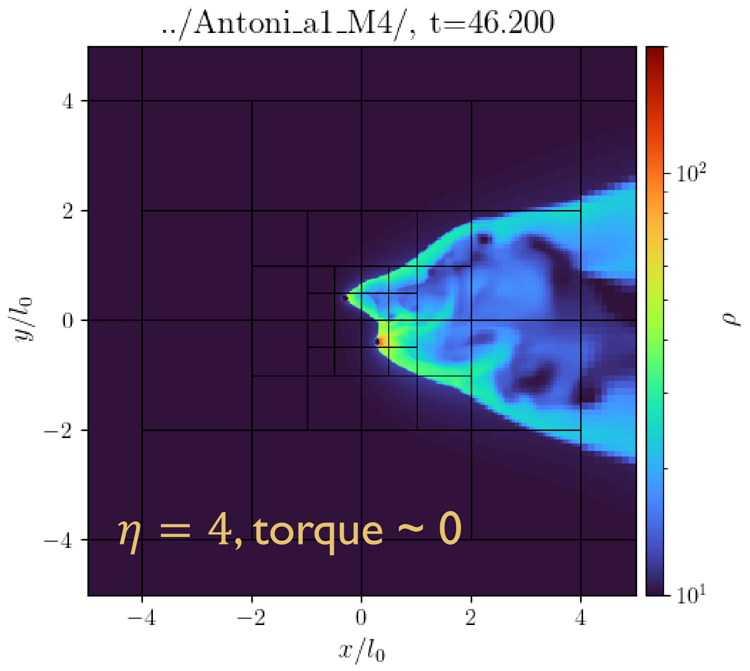




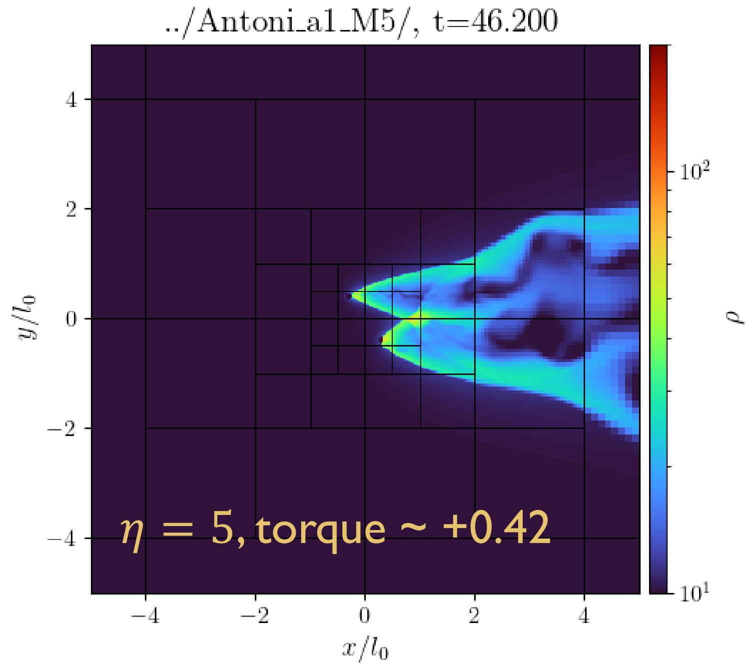
η = 2, torque ~ -7.46



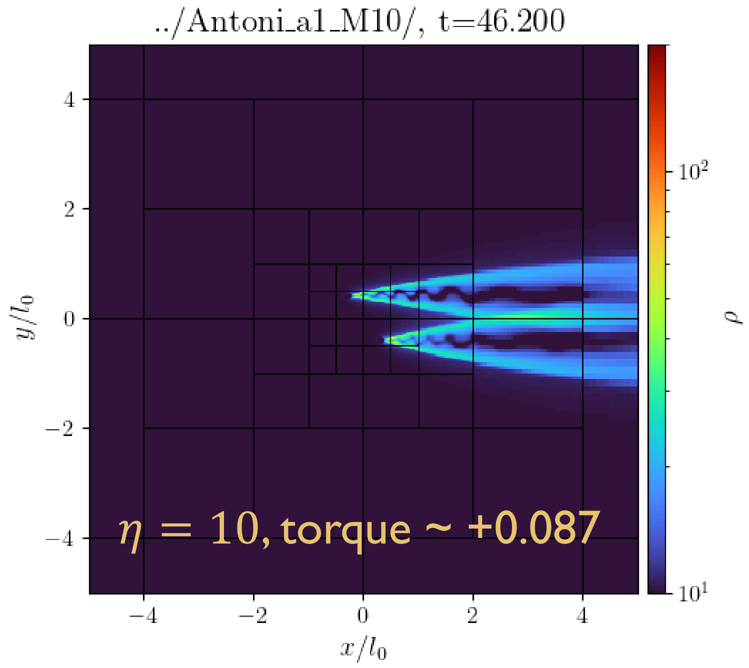
η = 3, torque ~ -3.20



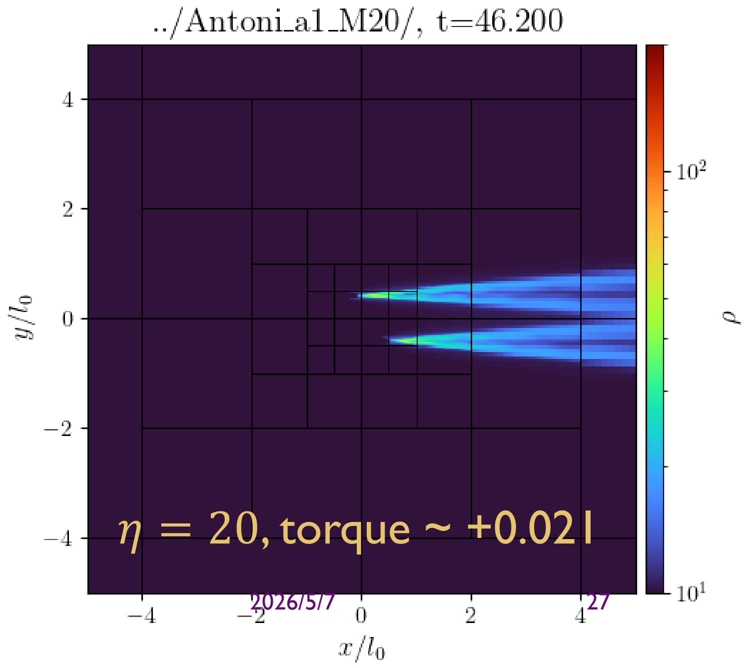
η = 4, torque ~ 0



η = 5, torque ~ +0.42



η = 10, torque ~ +0.087

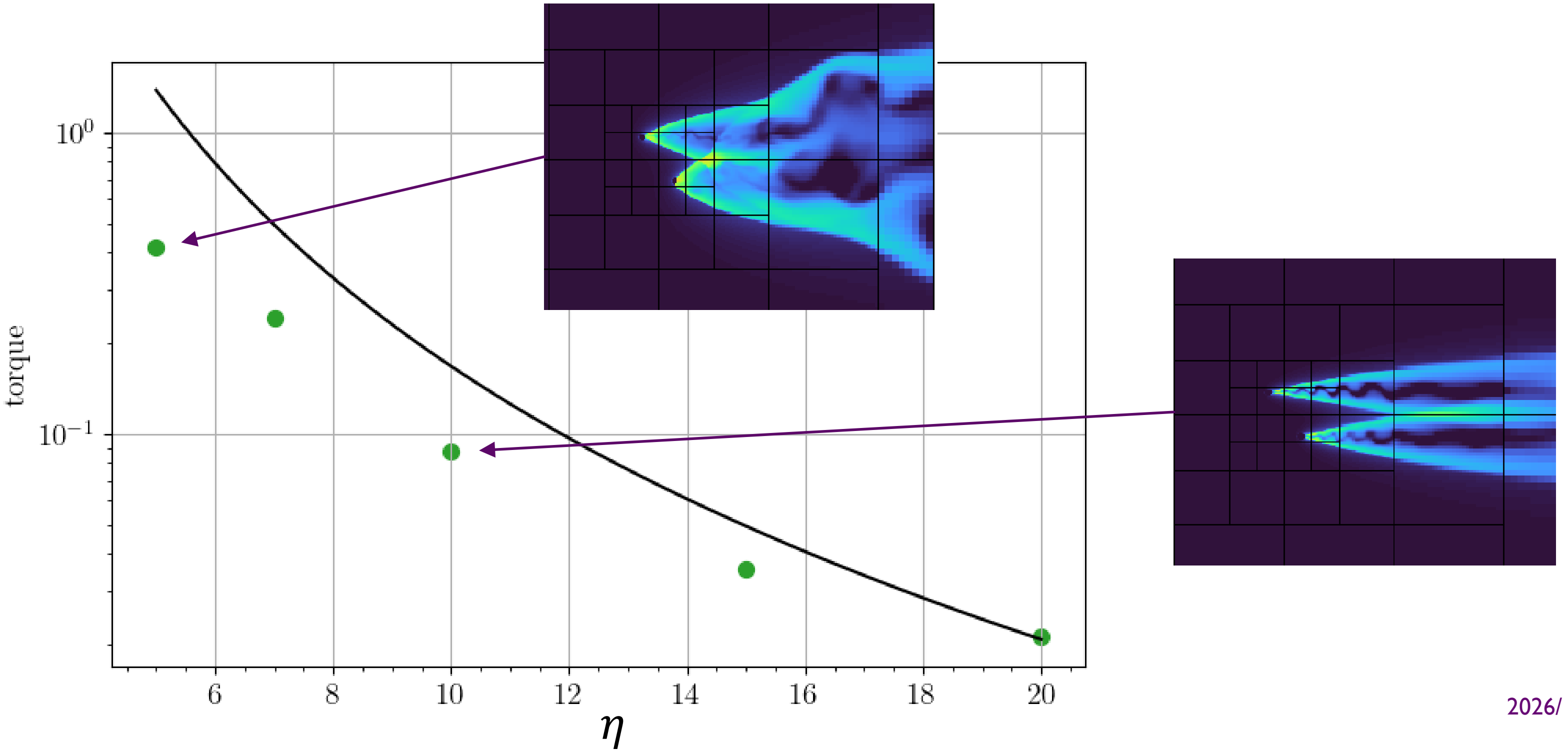


η = 20, torque ~ +0.021

Results

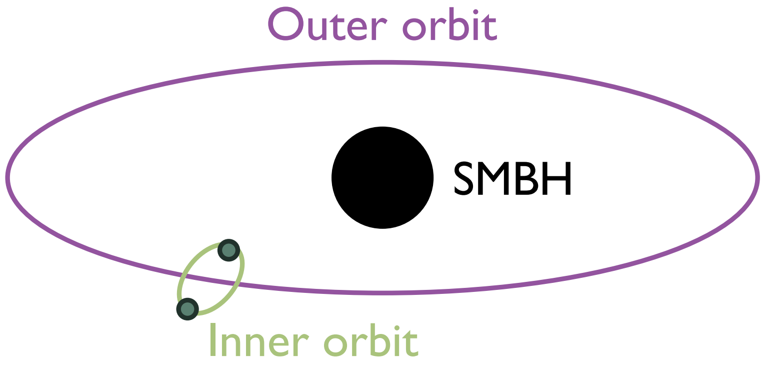
- v_g varies, other parameters are constant. Average torque is proportional to $\frac{1}{\eta^3-\eta}$:

$$\bar{T} = \frac{4\pi G^2 M^2 \rho d I}{v_o^2} \frac{1}{\eta^3 - \eta}$$



Discussion

- Discussion
  - Positive torque need $\eta \geq 4$.
  - The orbit of BBH mass center in the AGN disk:
    - The angle between outer orbit and inner orbit $\neq 0$
    - Outer orbit $e \neq 0$
  - At $5000 r_s$ from center SMBH, $v_k \sim 6000\ \mathrm{km/s}$, in $10^5\ \mathrm{K}$, sound speed is $c_s \sim 50\ \mathrm{km/s}$.



Summary

- Employ PeTar to simulate the dynamical evolution of a massive open cluster initially comprising 10,000 stars.
- Negative dynamical friction (NDF) associated with stellar outflows interacting with the surrounding gas can enhance the rate of cluster expansion.
- A more rapid decline is observed in the number of MS-NS binaries.
- Compared to DF-dominated evolution, NDF tends to retain systems with larger semi-major axes and lower eccentricities.

Through both semi-quantitative analysis and numerical simulations, we find that close binary BH moving at high speeds in the gas will gain angular momentum, preventing the merger.