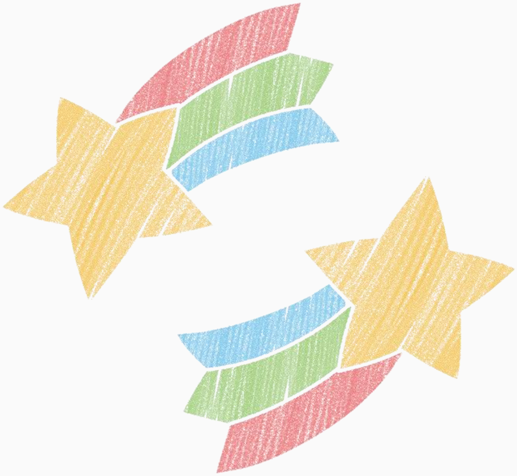
輻射圧を考慮した共通外層期の3次元流体シミュレーション

水谷 耕介（大阪大学）

共同研究者: 高棹 真介

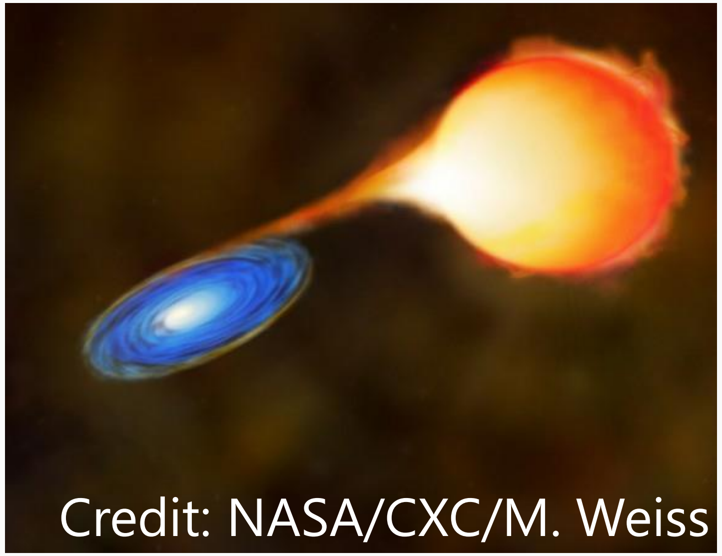


11/13/2024 初代星・初代銀河研究会@信州大学

Introduction

There is a lot of phenomena driven by binary system.

Type Ia SN

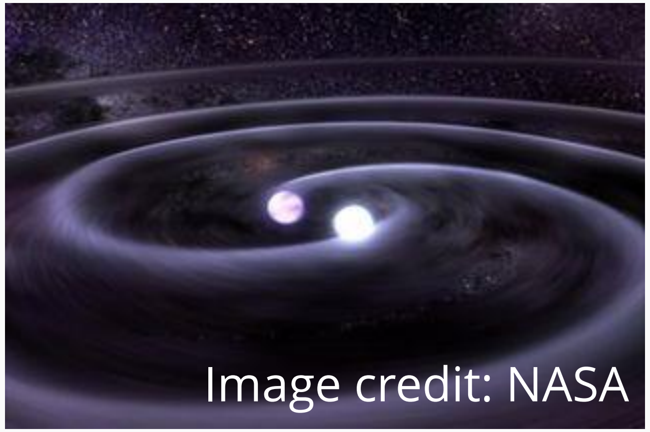


WD+Donor

Gamma Ray Burst

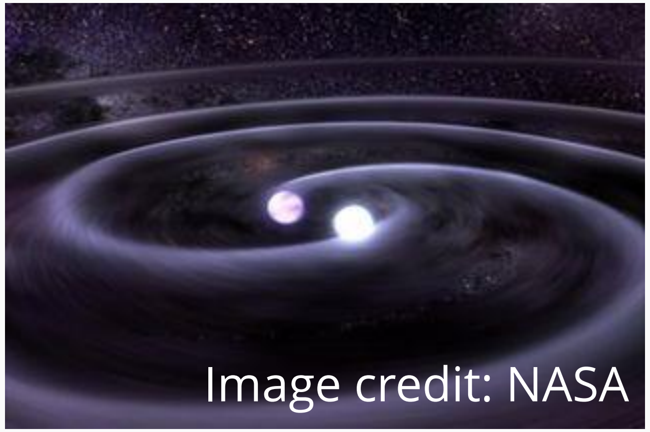
NS+NS

Radiation of GW



BH+BH/BH+NS/...

Introduction



- Merger timescale only by GW radiation

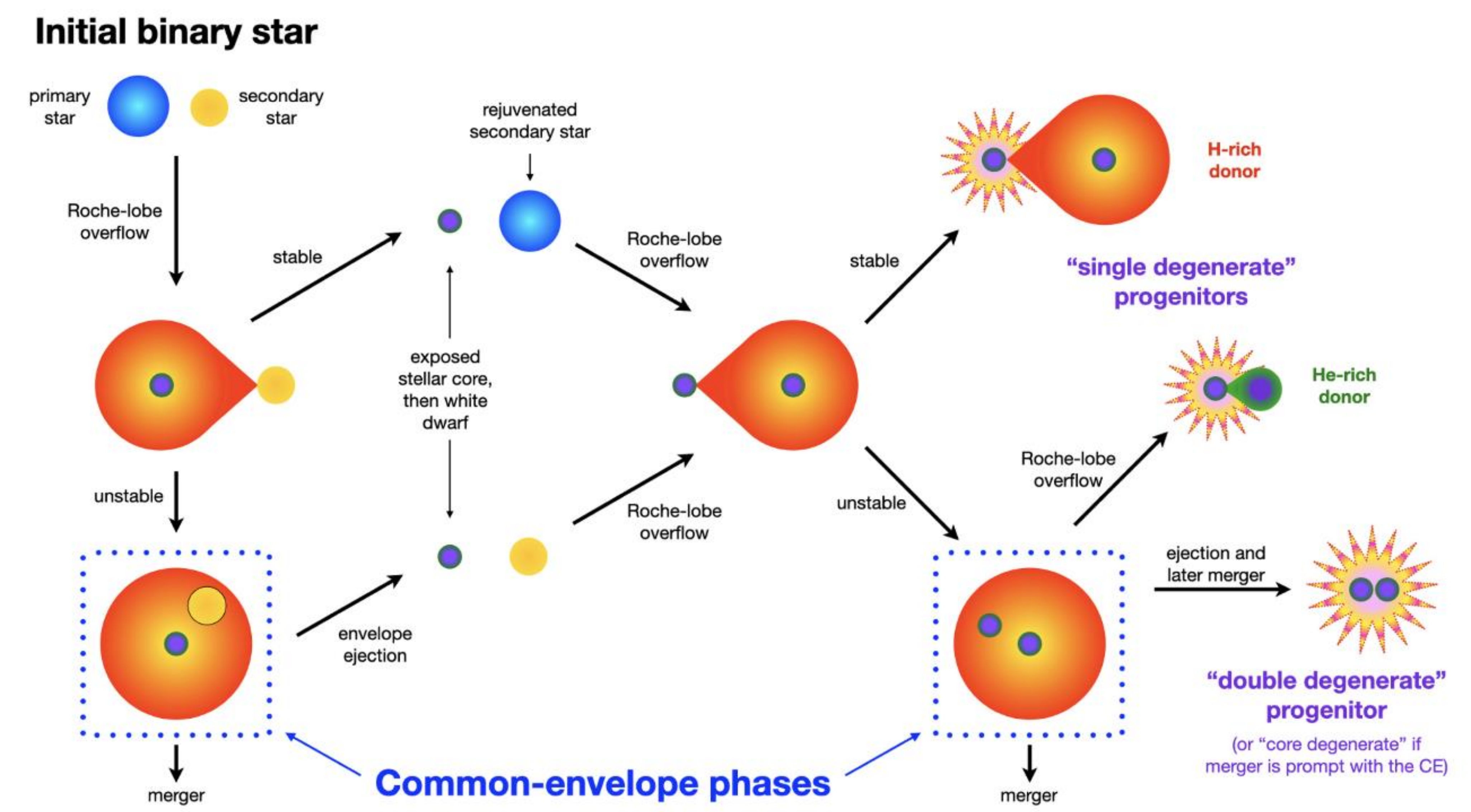
$$t_{\rm GW} = \frac{5}{256}\frac{c^5}{G^3 M_1 M_2 (M_1 + M_2)} a^4$$

$$= 10^{13}\left[\left(\frac{M_1}{30\ M_\odot}\right)\left(\frac{M_2}{30\ M_\odot}\right)\left(\frac{M_1}{30\ M_\odot} + \frac{M_2}{30\ M_\odot}\right)\right]^{-1}\left(\frac{a}{1\ \rm au}\right)^4\ \rm yr$$

→ too long to merge within Hubble time

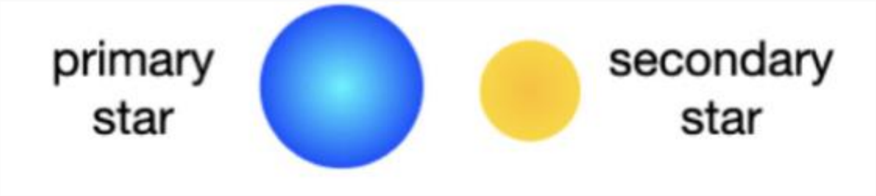
There must be the mechanism
to reduce the separation dramatically.

Common Envelope Evolution (CEE)

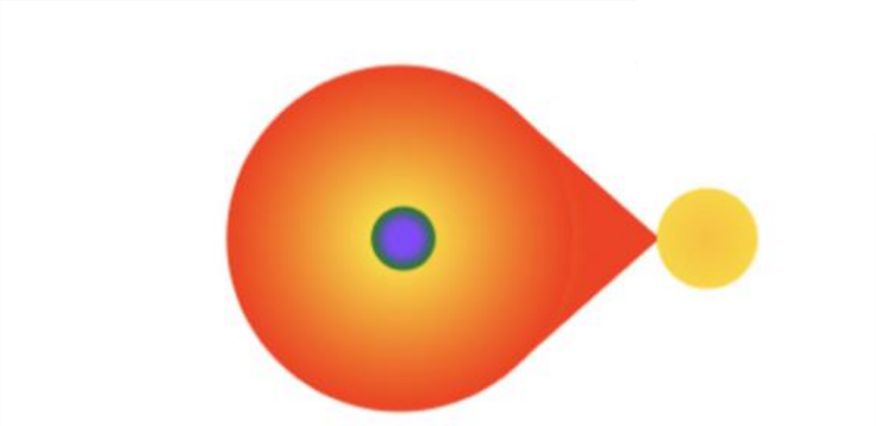


Ivanova et al. 2020

Common Envelope Evolution (CEE)



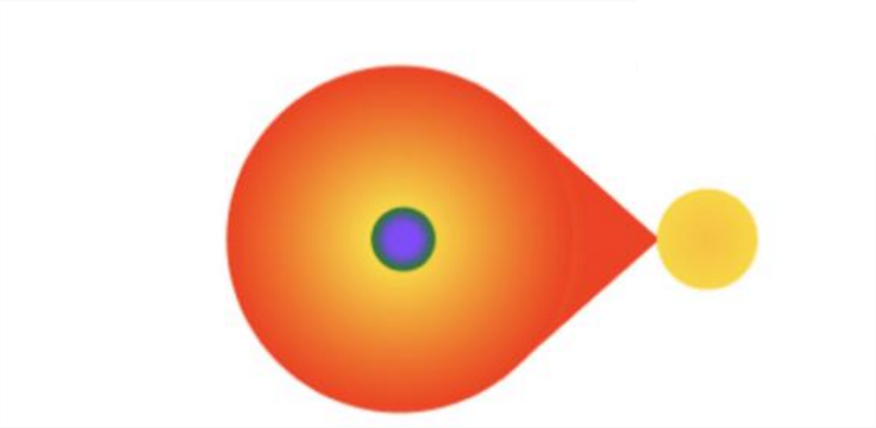
The star expand as it evolve.



Roche-lobe overflow
(RLOF)

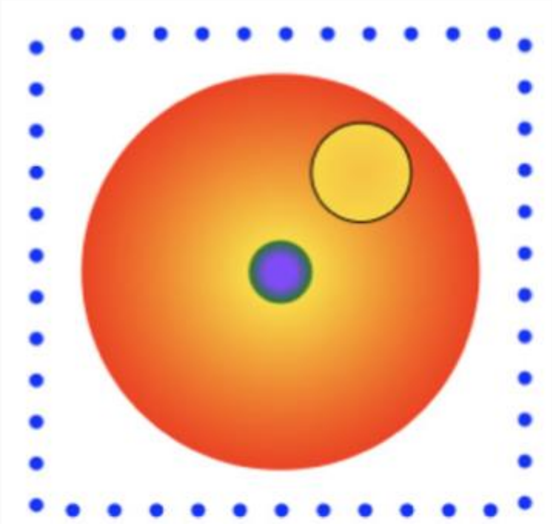
Ivanova et al. 2020

Common Envelope Evolution (CEE)



$$\frac{\dot{a}}{a} = \frac{2}{q_1}\frac{\dot{M}_1}{M_1}(1 - q_1)$$

unstable mass transfer

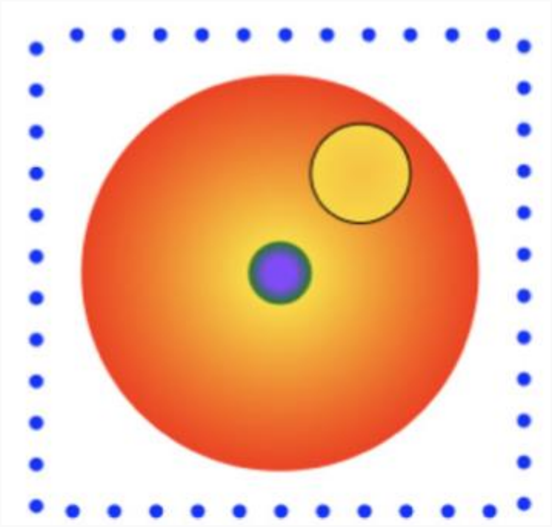


The companion star orbits
inside the envelope of the primary star.

→ <u>Common Envelope phase</u>

Ivanova et al. 2020

Common Envelope Evolution (CEE)

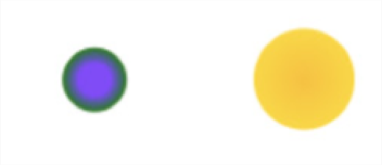


merger

Single star

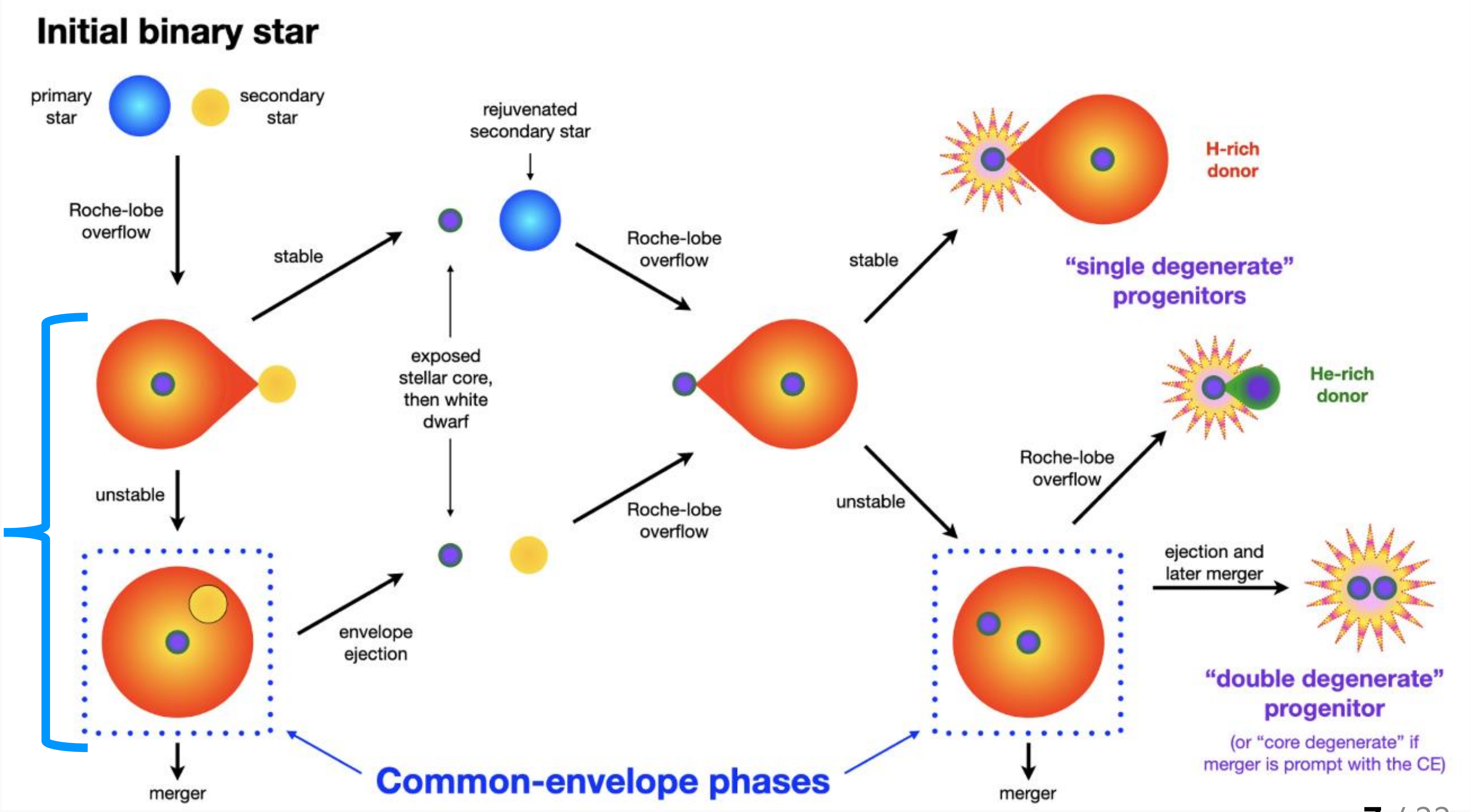
- whose structure would not be expected from single star evolution.

envelope ejection



The initial wide binary is converted into a close binary.

Common Envelope Evolution (CEE)

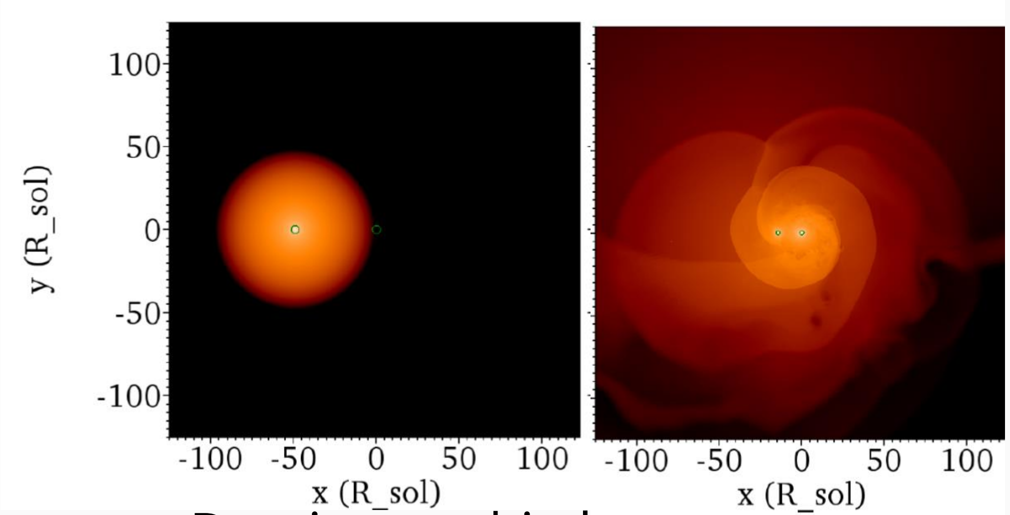


current simulation

Ivanova et al. 2020

3D simulations for Common Envelope phase

Focused on less massive stars

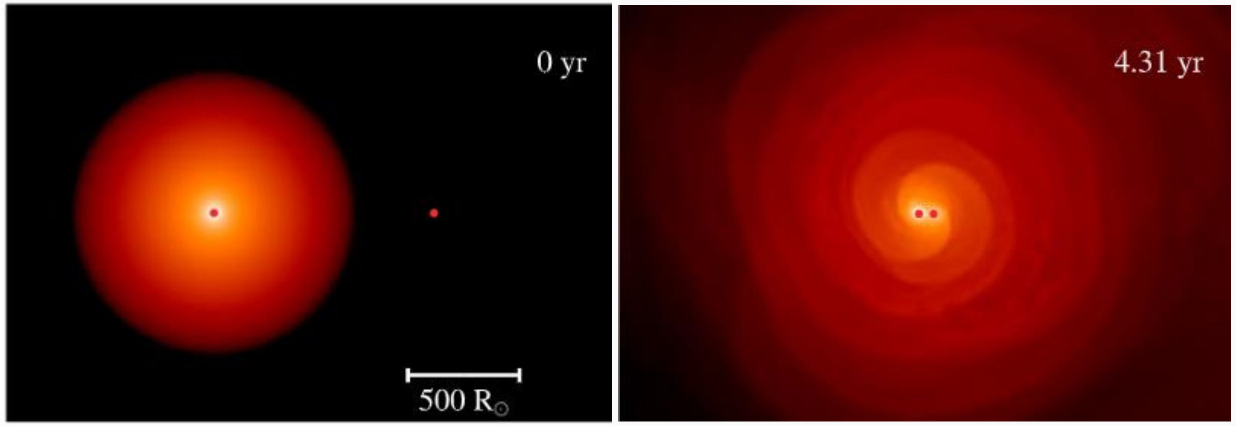


Density at orbital plane Chamandy et al. 2018

Rasio & Livio 1996
Ohlmann et al. 2016
Sand et al. 2020
Calsan et al. 2023

Ricker & Taam 2012
Iaconi et al. 2019
Ondratschek et al. 2022

Focused on massive stars



Density at orbital plane Lau et al. 2022

Ricker et al. 2019

We try to understand the CE in massive stars.

The effect of radiation in massive stars

When compared to the only adiabatic Hydro case,

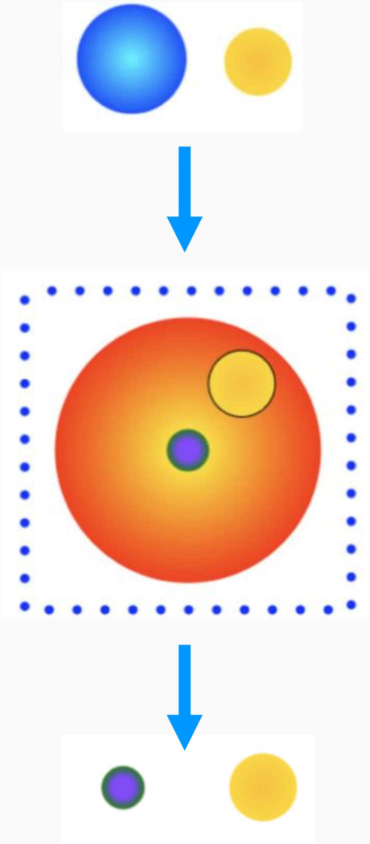
- Provide an additional way to transport the energy
- Make the gas element "softer"

$$P \propto \rho^{\gamma} \qquad \gamma: \frac{5}{3}\,(\mathrm{ad}) \rightarrow \frac{4}{3}\,(\mathrm{rad})$$

Radiation may play an important role in CE phase.

The purpose of this study

- To investigate the influence of the radiation in the Common Envelope (CE) phase
  - We are now implementing the radiative transfer using Flux-Limitted Diffusive approximation.



In ahead of this,

We perform 3D simulation of CE with radiation pressure.

3D simulation for Common Envelope phase

- Code: Public MHD code, Athena++

  Stone et al. 2020

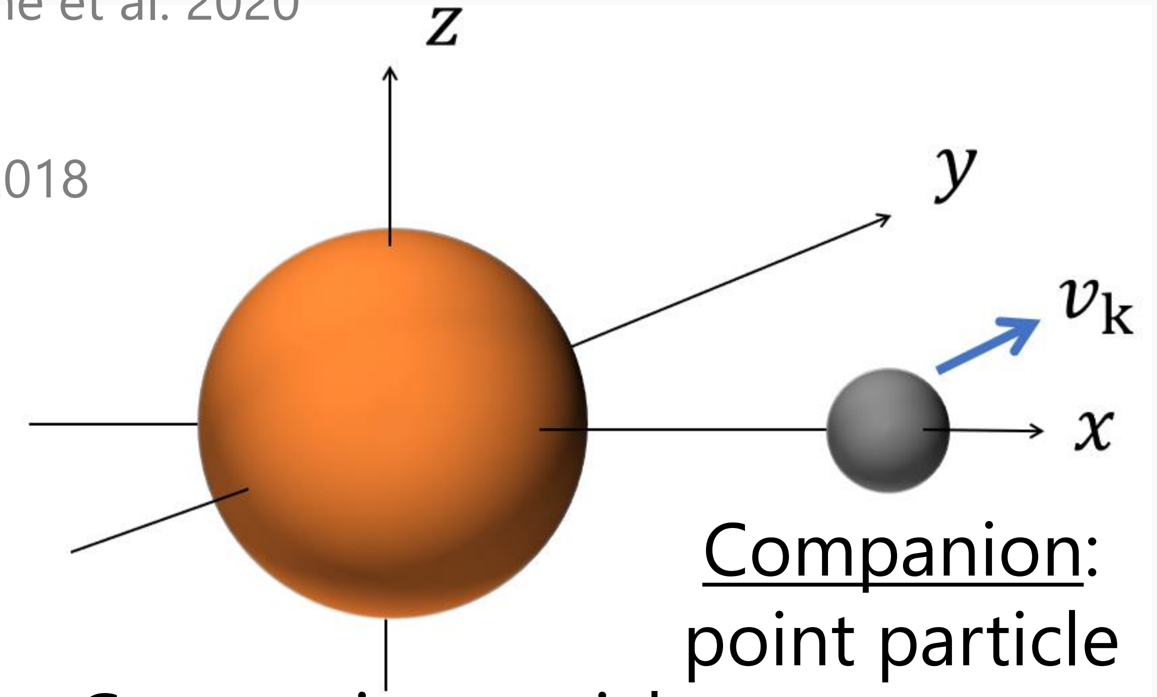
  - Fluid eqs. with fixed gravity
  - Non-inertial frame

    MacLeod et al. 2018

  - Assuming $T_{\rm rad} = T_{\rm gas}$

$$p_{\rm tot} = p_{\rm gas} + p_{\rm rad} = \rho \frac{R_{\rm gas}}{\mu} T + \frac{1}{3} a T^4$$

  - $\Delta x = 0.01\, R_1$ around the orbit



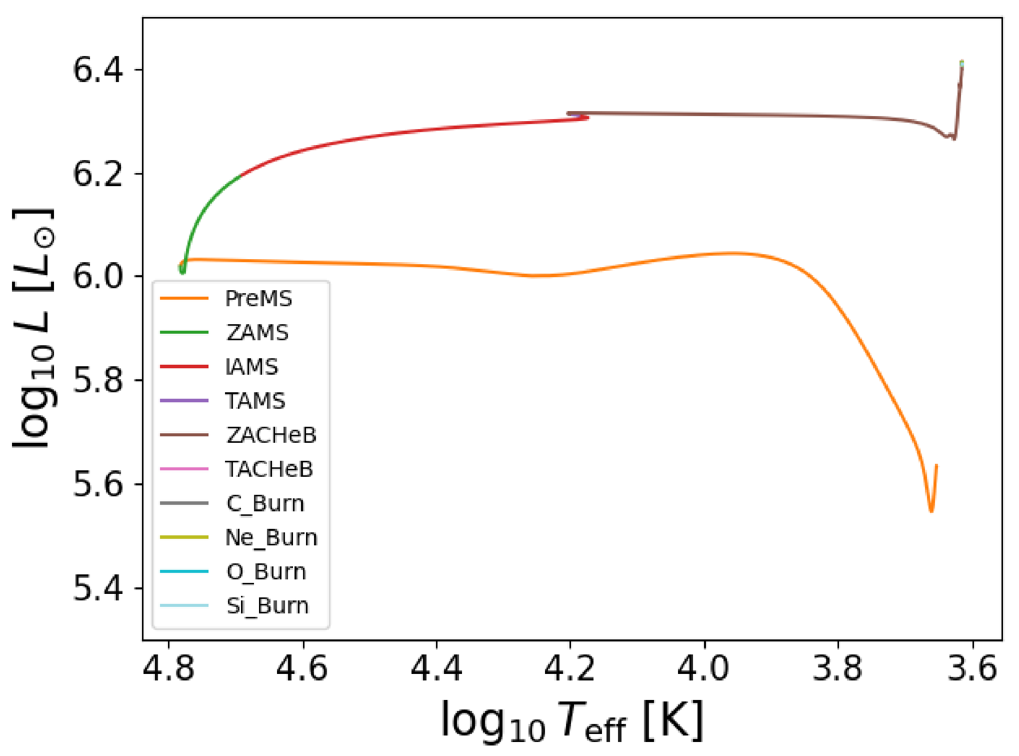
Companion: point particle

Core: point particle

Envelope: fluid

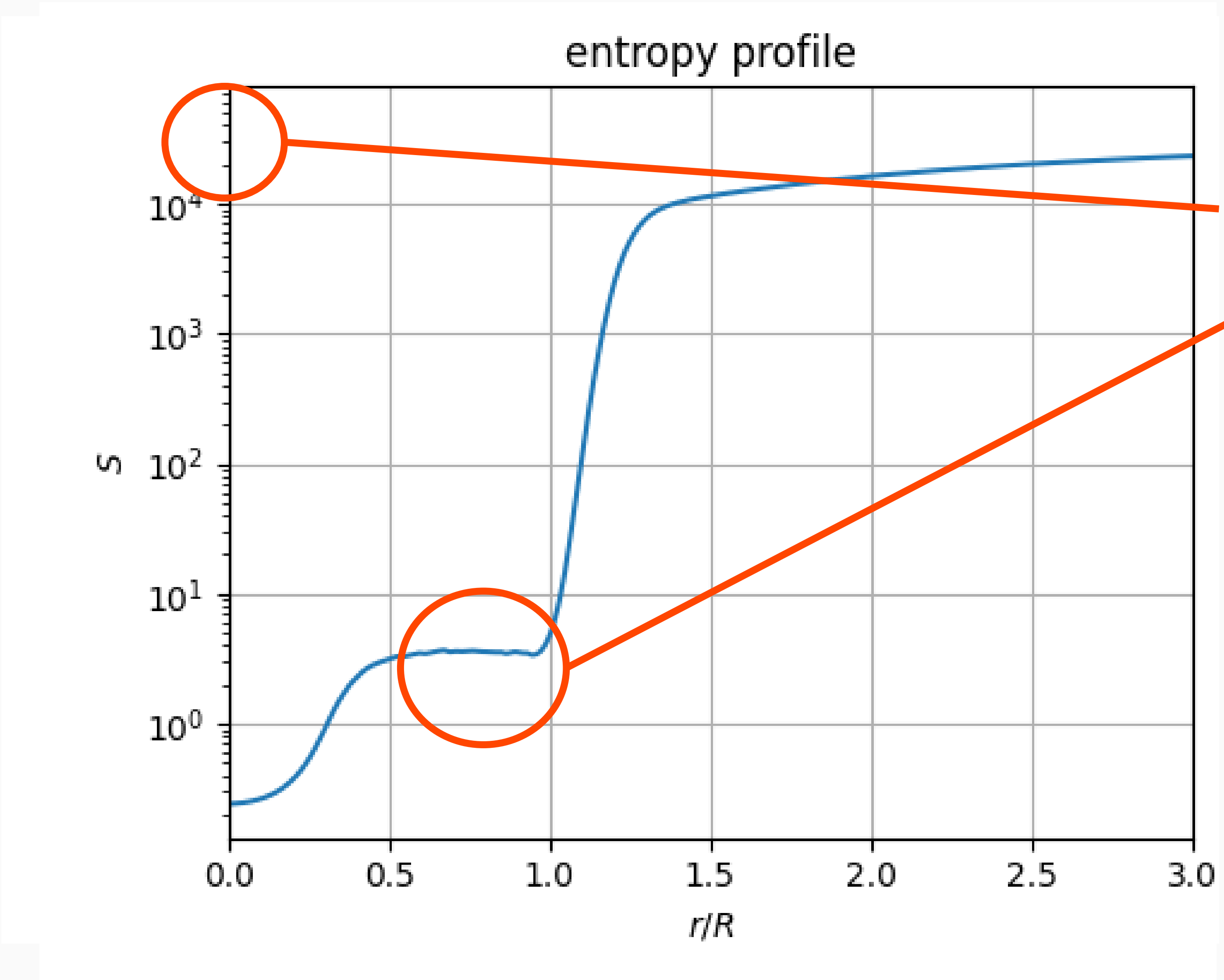
Construction of Initial stellar structure

- Calculate evolution of ZAMS using MESA Paxton et al. 2011
  - $M = 88\ M_{\odot}$ Ricker et al. 2019
  - $Z_{\mathrm{metal}} = 10^{-2}\ Z_{\odot}$
  - to be BH ($M_{\mathrm{BH}} \sim 30\ M_{\odot}$)



- Extract the profile of $\beta = {}^{P_{\mathrm{gas}}}/_{P_{\mathrm{tot}}}$ when its radius ~ $3000\ R_{\odot}$.
  - Reconstruct the stellar profile by solving hydrostatic eq.

Construction of Stellar Structure

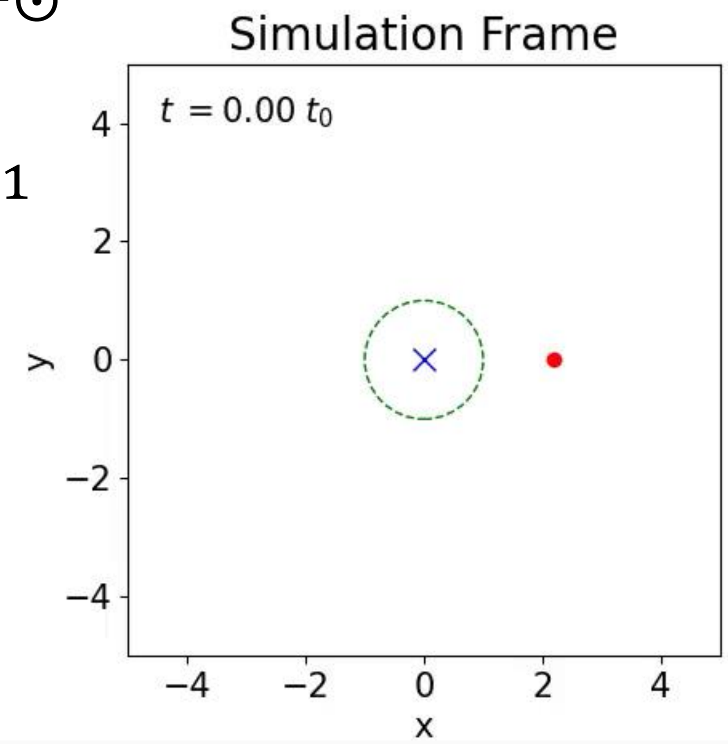


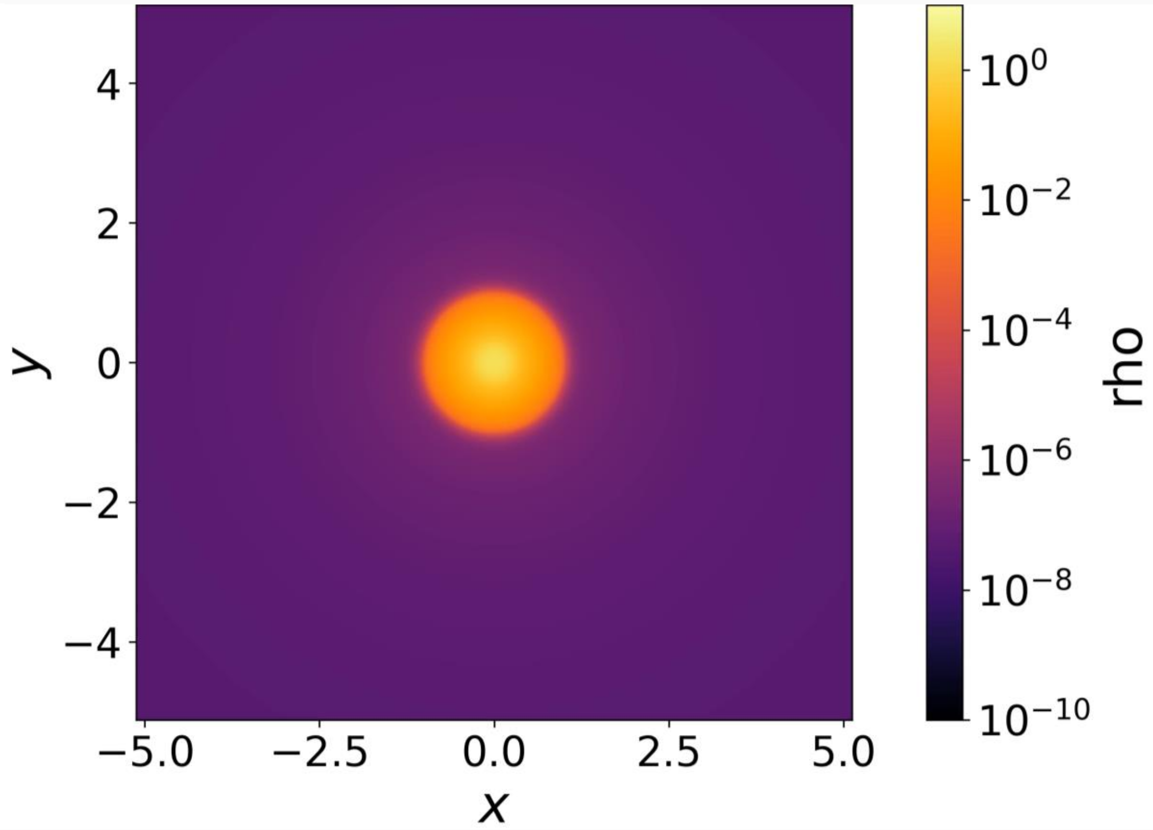
Density enhancement in the center
→ the effect of radiation pressure

Negative slope in entropy
→ convective envelope

3D simulation without radiation pressure

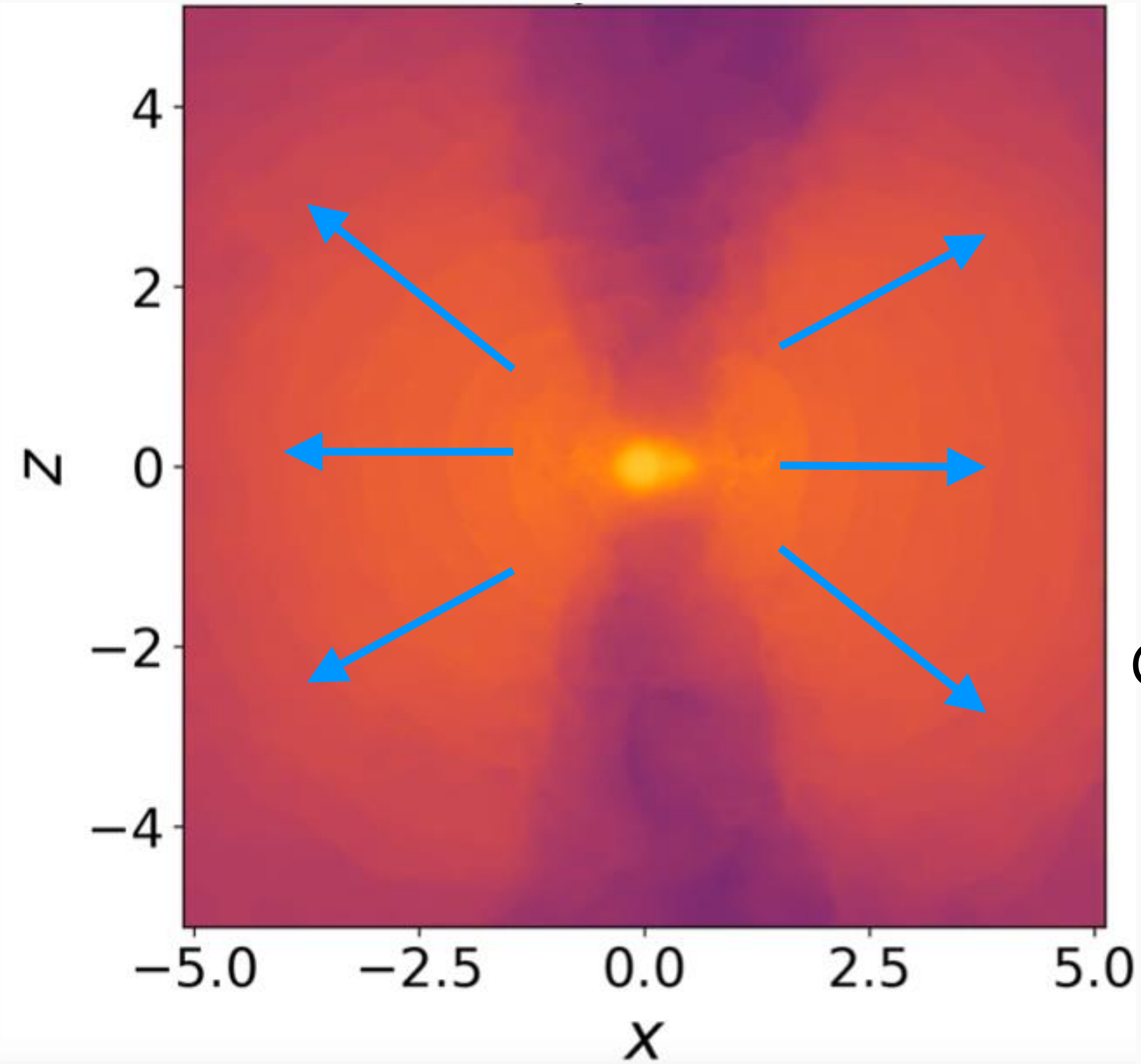
$$M_1 = 82.1\ M_\odot$$
$$R_1 = 2891\ R_\odot$$
$$q = 0.426$$
$$a_i = 2.20\ R_1$$





3D simulation without radiation pressure

Snapshot at spiral-in phase at perpendicular plane



axisymmetric outflow
in the perpendicular plane

Can be linked with Luminous Red Novae?

Matsumoto & Metager 2022

3D simulation with radiation pressure

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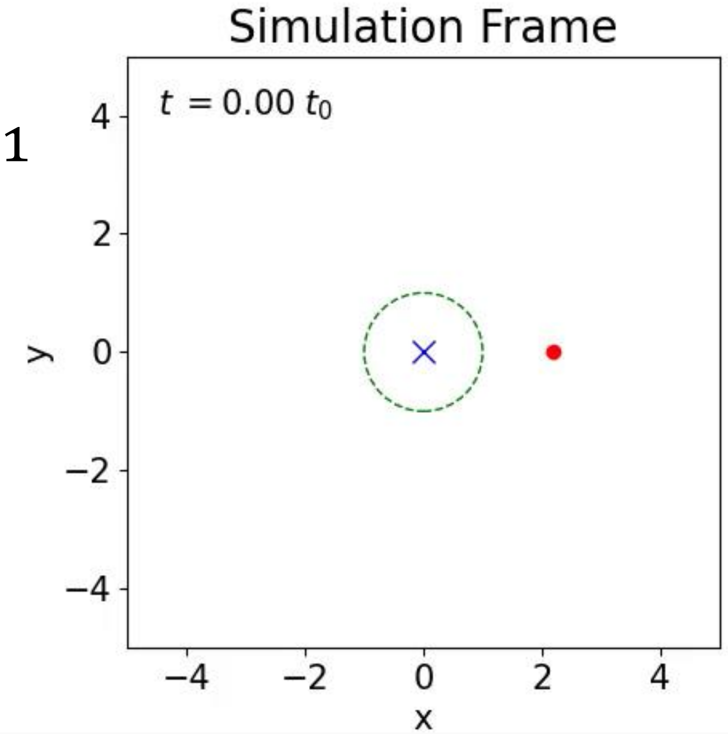
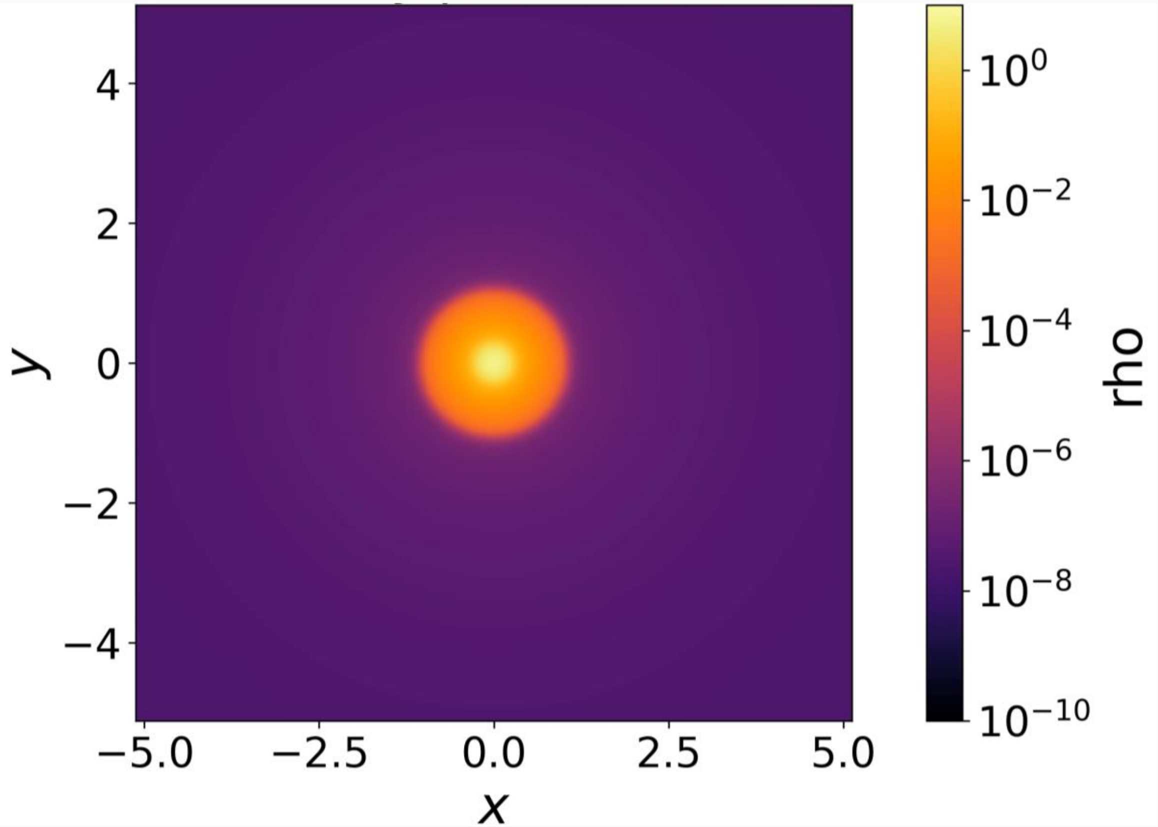
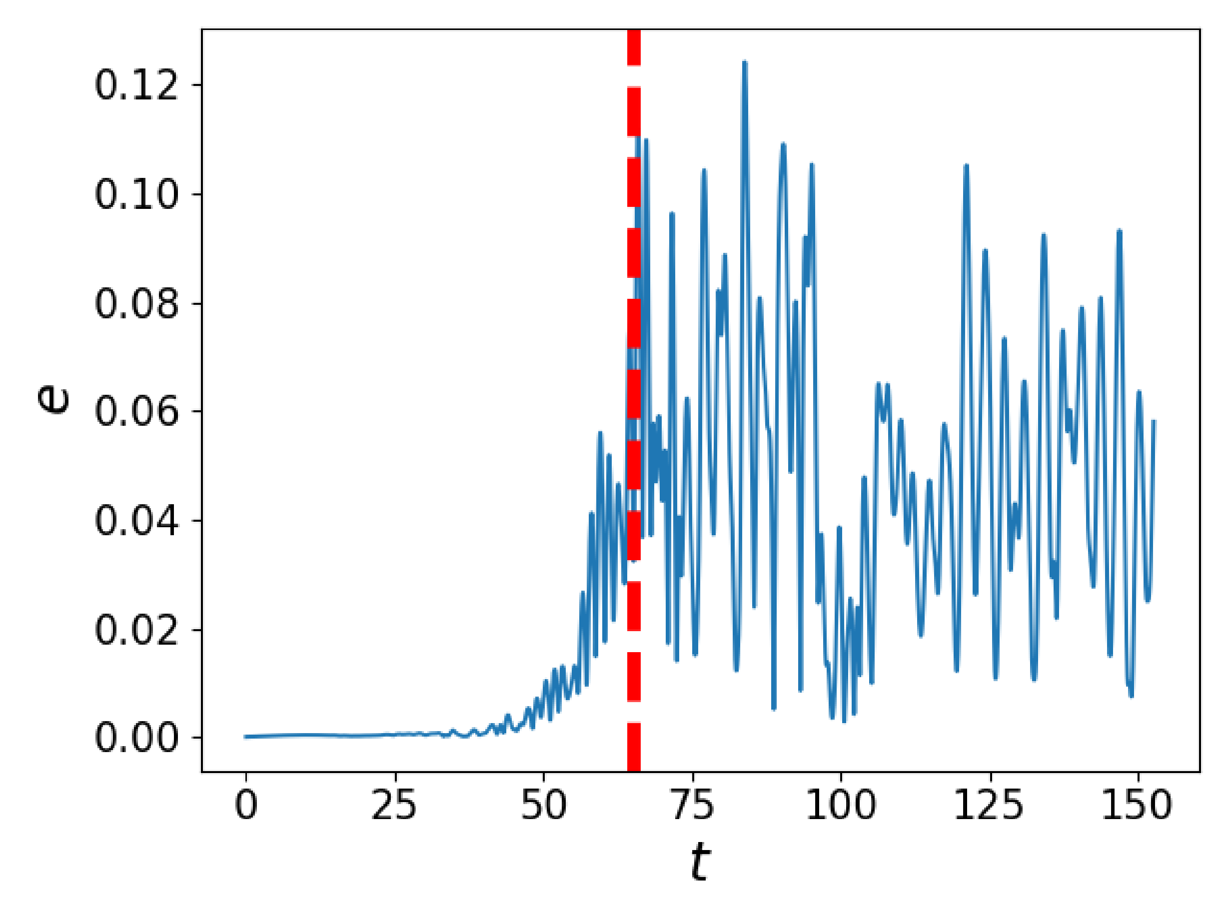
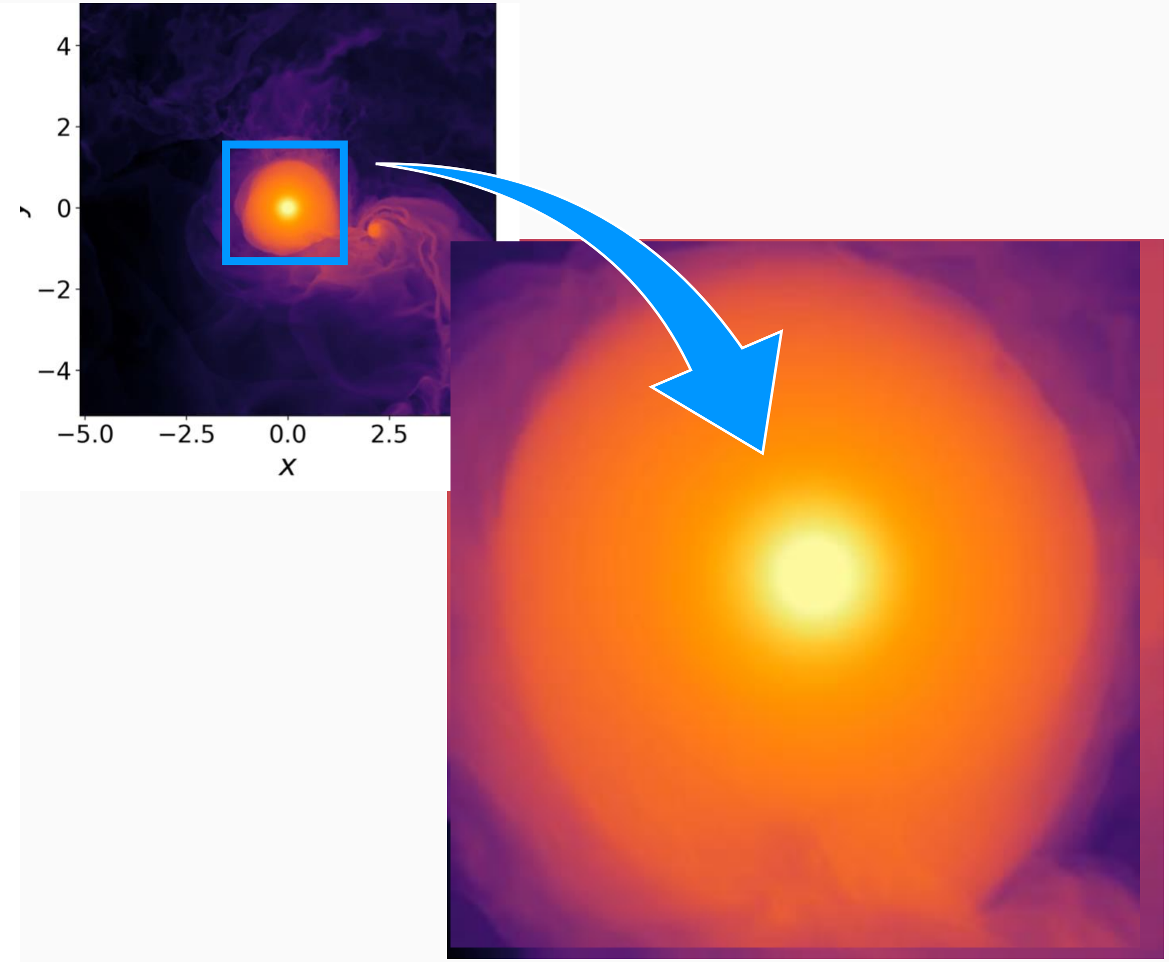




3D simulation with radiation pressure

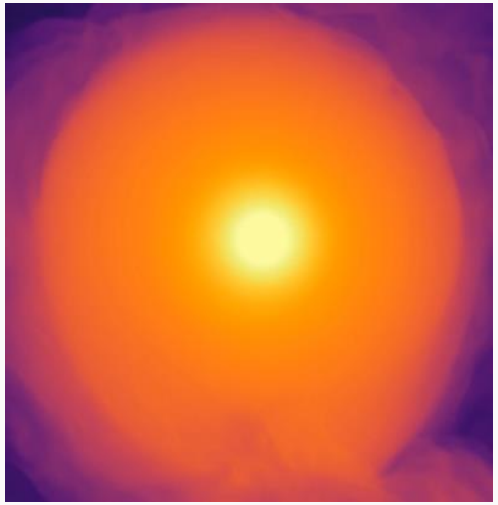
Why orbital motion is changed with $p_{\rm rad}$?





Discussion: What makes the orbit change?

- With p_{rad}, the effective heat ratio is decreased.
  1. The gas is more easily compressed.



$$P \propto \rho^{\gamma}$$

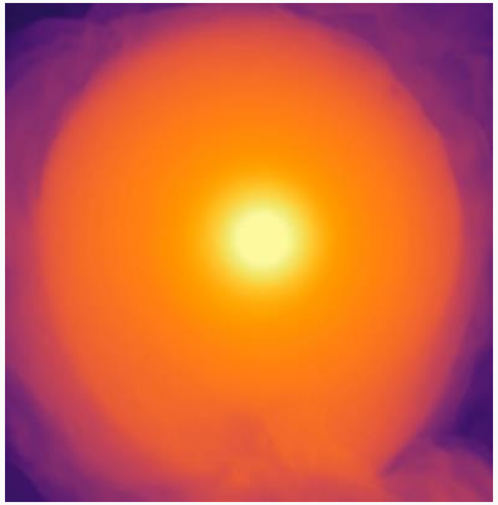
$$\gamma\colon \frac{5}{3}\ (\mathrm{ad}) \rightarrow \frac{4}{3}\ (\mathrm{rad})$$

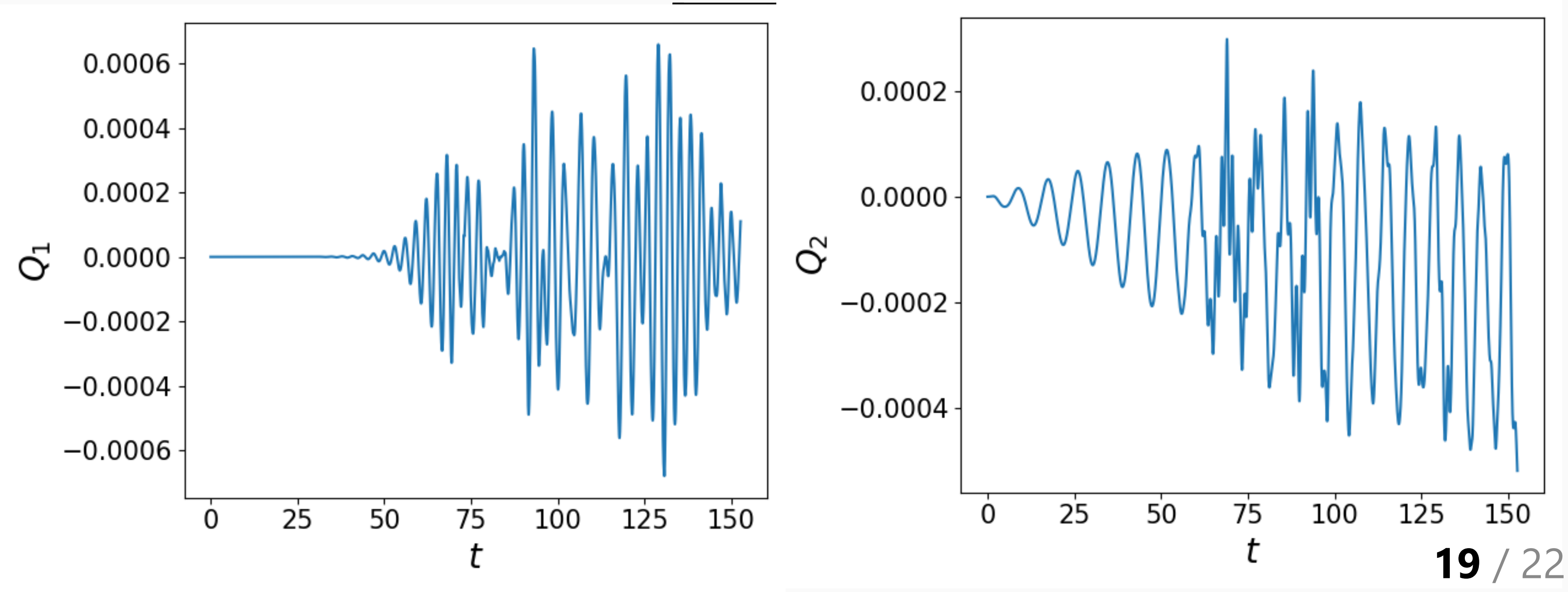
Discussion: What makes the orbit change?

1. The gas is more easily compressed.

- The secondary motion can excite tidal wave.

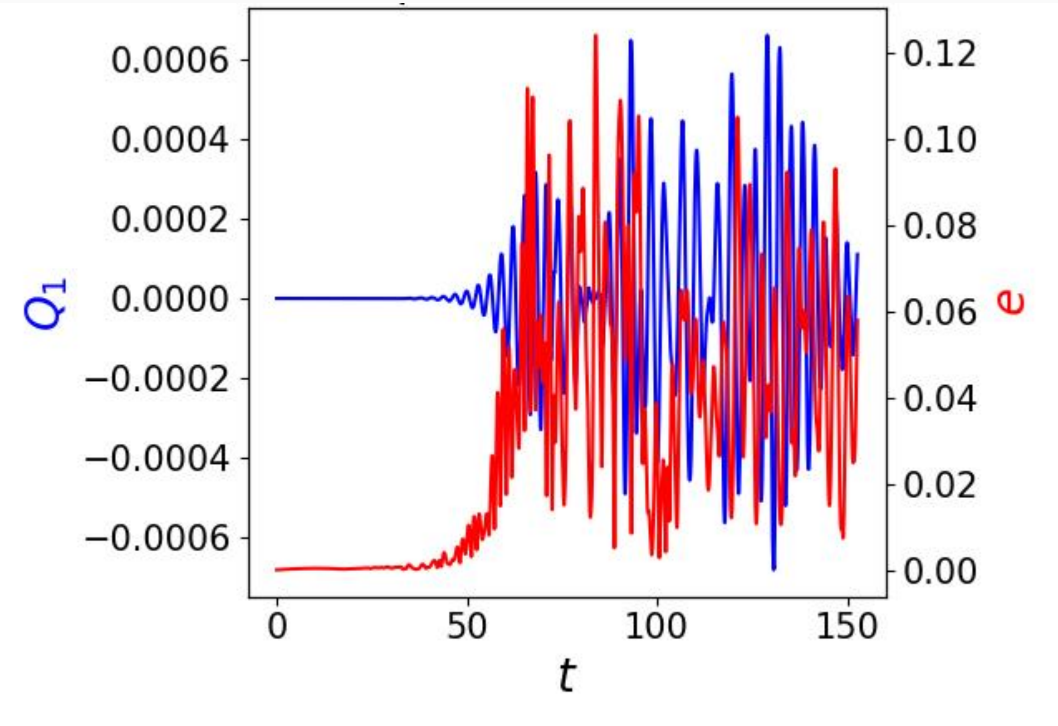
2. The density moment can be non-zero.

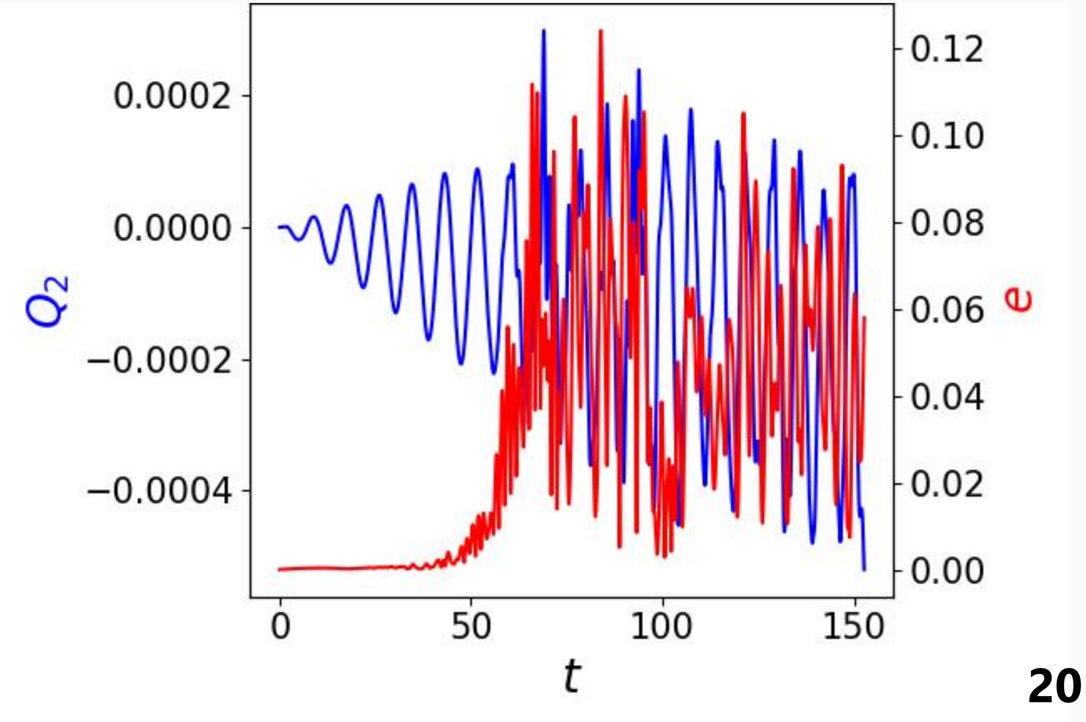




Discussion: What makes the orbit change?

1. The gas is more easily compressed.
2. The density moment can be non-zero.
3. Non-zero Q_l^m can affect orbital evolution.





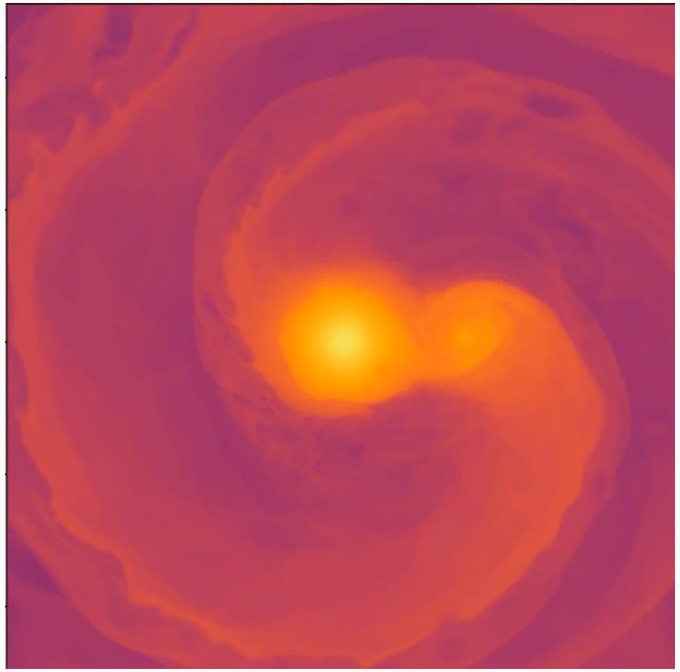
Summary and future work

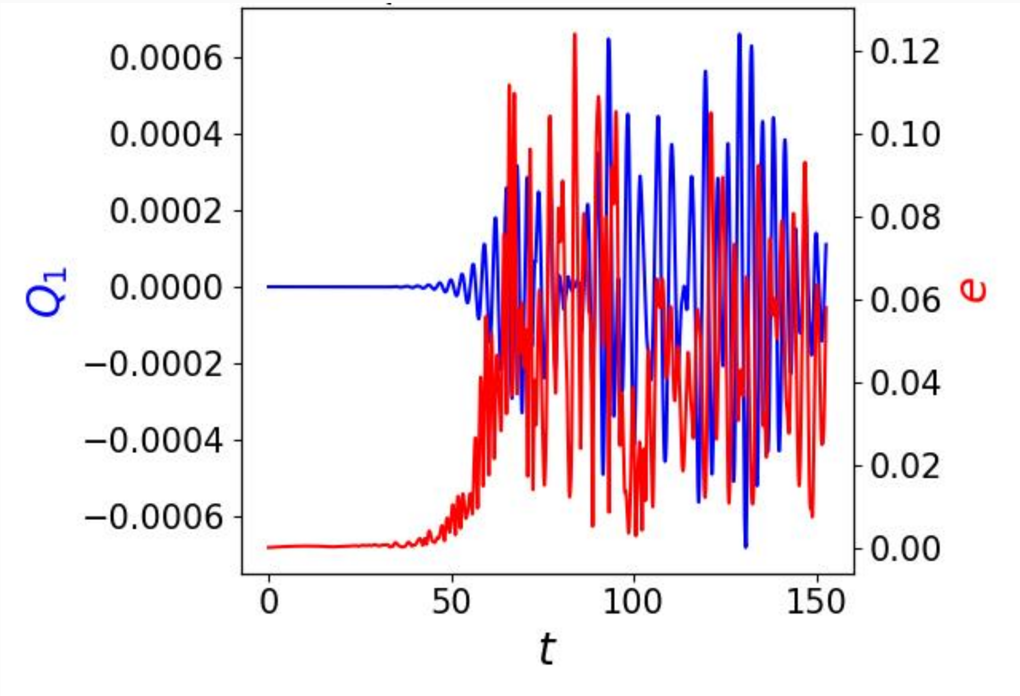
- We perform 3D HD simulation for CE phase

  Confirm orbital shrinkage due to the mass transfer

- With p_{rad}, we get different result from the case without p_{rad}

  Radiation may have an impact on orbital evolution.





Summary and future work

- We perform 3D HD simulation for CE phase

  Confirm orbital shrinkage due to the mass transfer

- With p_{rad}, we get different result from the case without p_{rad}

  Radiation may have an impact on orbital evolution.

- Implementation of …

  Radiative transfer (using Flux-Limitted Diffusion approximation)

  Initial spin of main star, Magnetic field, …

- Focus on the structure of ejecta, compare with observation