3D Magnetohydrodynamic Simulations of the Common Envelope Phase in a Massive Binary System

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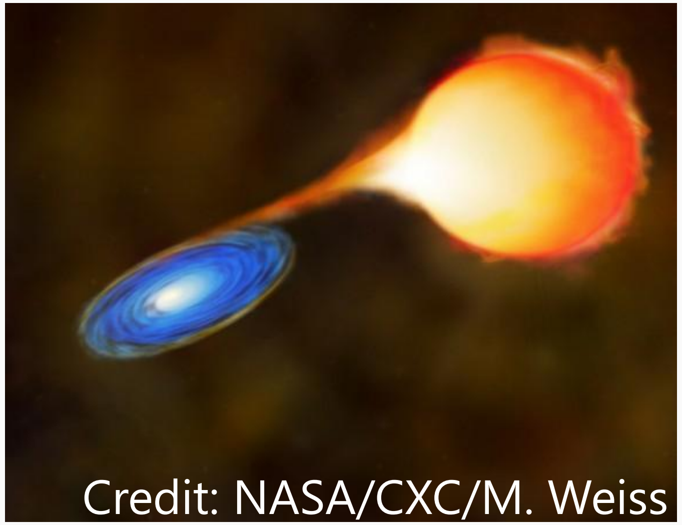
10/01/2025 Keihan meeting @ Panasonic auditorium

The binary system in the universe

Type Ia SN

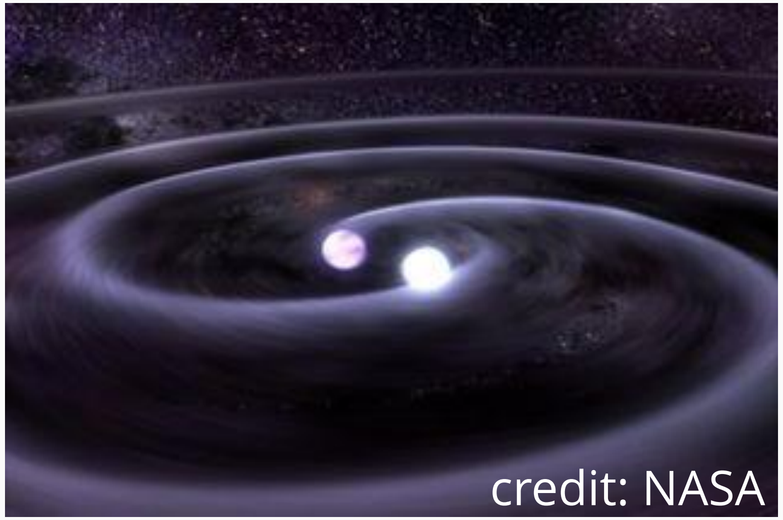


WD+Donor

Gamma Ray Burst

NS+NS

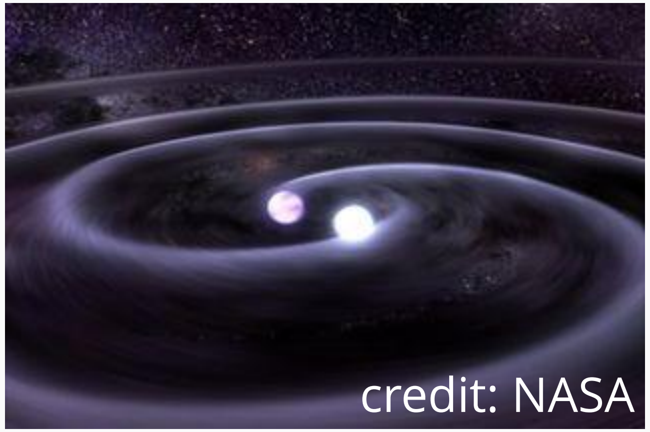
Radiation of GW



BH+BH/BH+NS/...

There are many phenomena driven by **close** binary systems.

Big question: How to make close binary?



- Merger timescale only by GW radiation

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

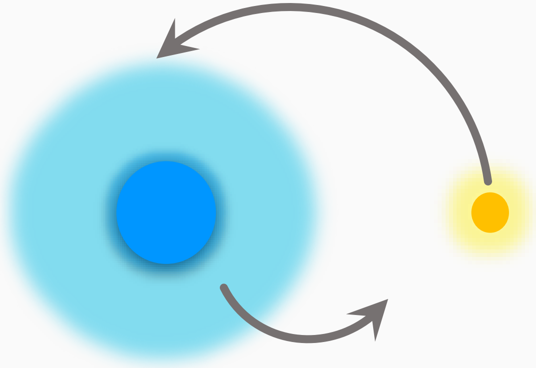
$$= 10^{13} \left[\left(\frac{M_1}{30\ M_\odot}\right)\left(\frac{M_2}{30\ M_\odot}\right)\left(\frac{M_1}{30\ M_\odot} + \frac{M_2}{30\ M_\odot}\right)\right]^{-1} \left(\frac{a}{1\ \mathrm{au}}\right)^4\ \mathrm{yr}$$

→ too long to merge within the Hubble time

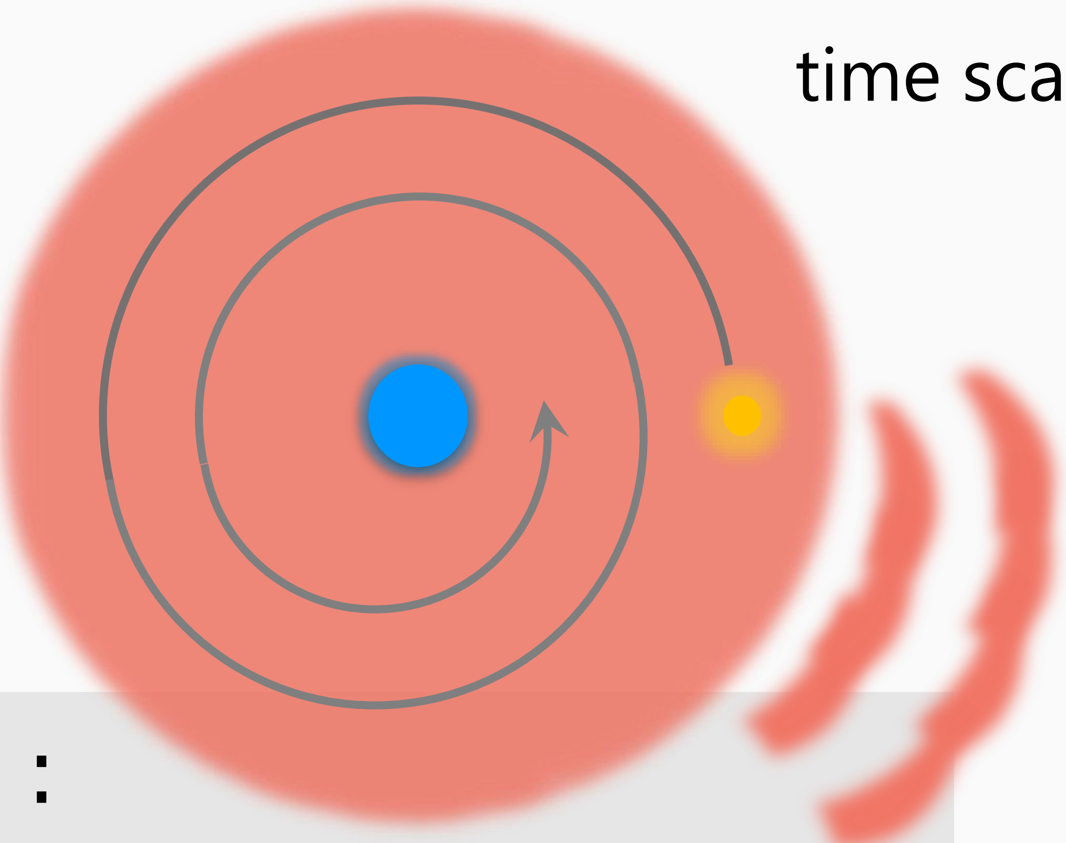
There must be the mechanism
to reduce the separation dramatically.

Common Envelope: pathway to make close binary

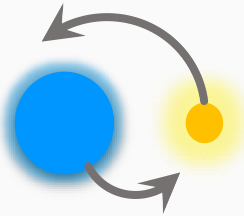
Paczynski 1976, Ivanova et al. 2013, Röpka & De Marco 2023



main sequence binary



time scale ~ several orbits



close binary

<u>Common Envelope</u> :

in which a giant star swallows its companion star
The orbital energy is transferred to the envelope of the giant, efficiently reducing the separation.

Common Envelope: pathway to make close binary

Paczynski 1976, Ivanova et al. 2013, Röpka & De Marco 2023

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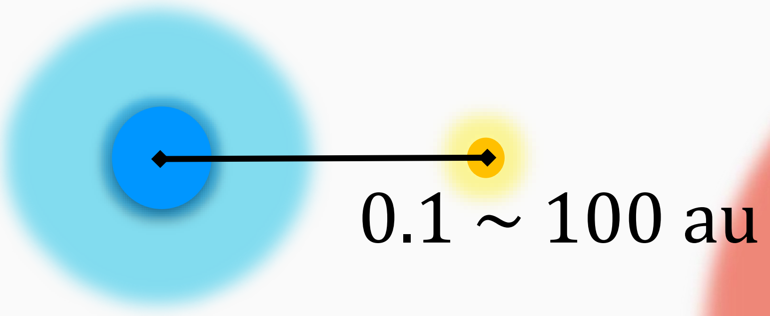
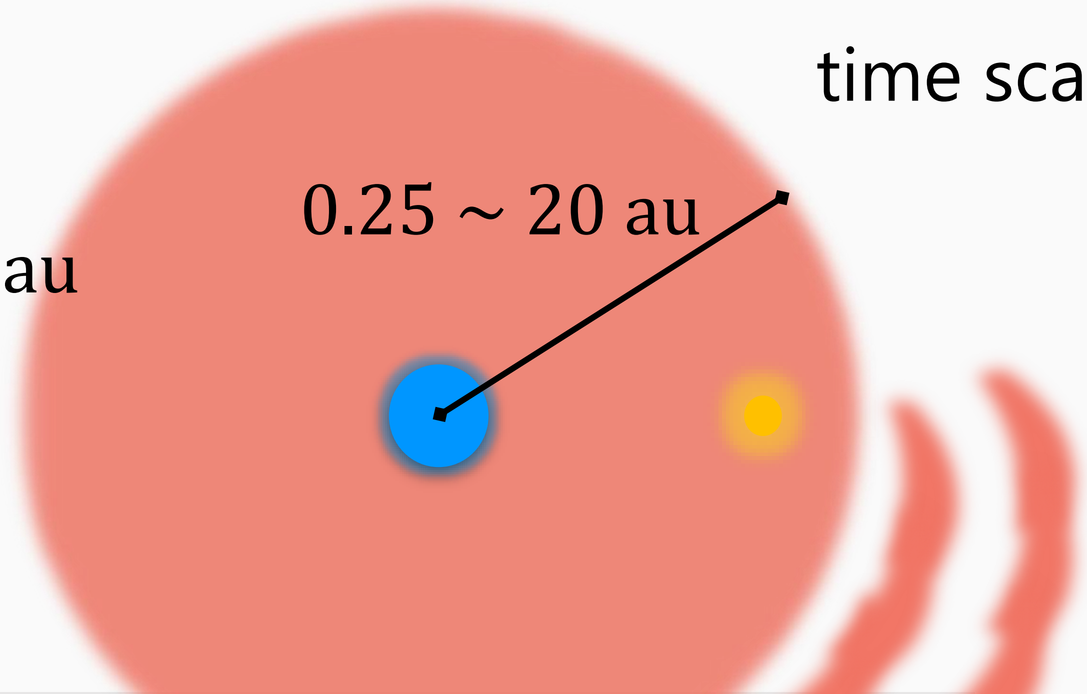
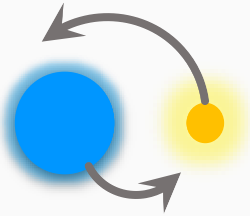


main sequence binary

$1\ \mathrm{au} \sim 200\ R_\odot$





close binary

<u>Common Envelope</u>：

in which a giant star swallows its companion star
The orbital energy is transferred to the envelope of the giant, efficiently reducing the separation.

Open Questions in the Common Envelope Phase

Paczynski 1976, Ivanova et al. 2013, Röpka & De Marco 2023

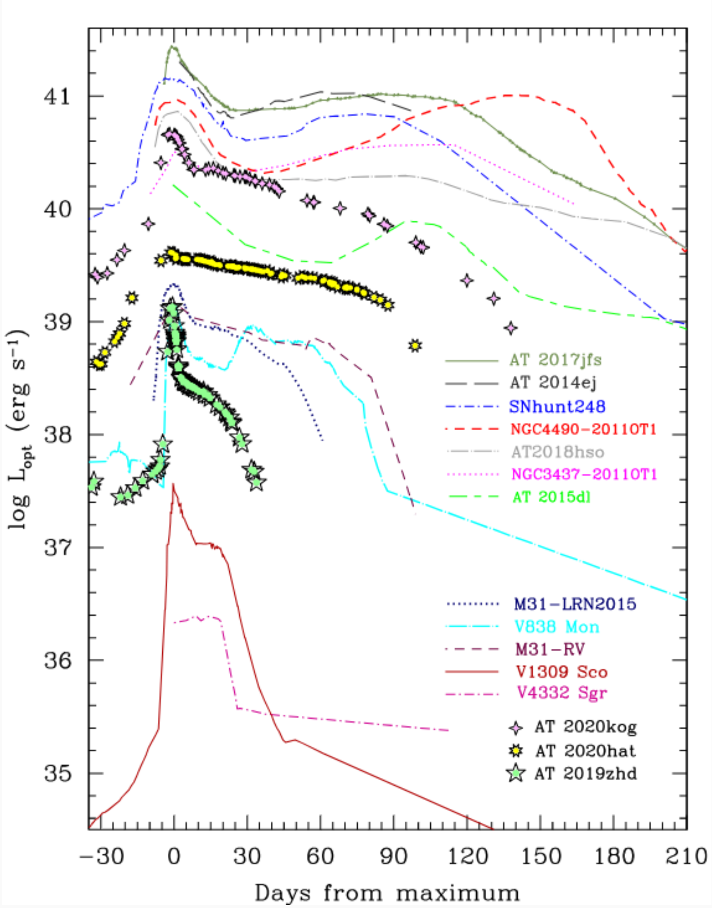
- ❑ Which system/ How the systems enters CE?

  MacLeod et al. 2018, Zhang et al. 2024

- ❑ How much orbital energy (ΔE_{orb}) is lost? De Marco et al. 2011
  - It is not necessarily equal to the binding energy of the envelope.
- ❑ What structure does the stripped envelope take?
  - Interaction with pre-existing Circum Binary Disk? Metzger and Pejcha 2017
  - A significant role of magnetic fields? Ondratschek et al. 2022

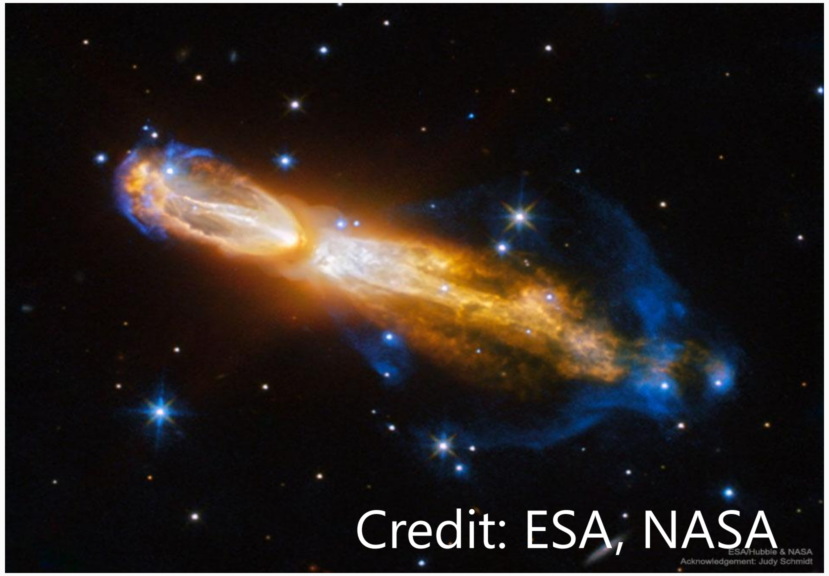
Observations about Common Envelope phase

Luminous Red Novae



Pastorello et al. 2021

Bipolar planetary nebulae



The Calabash nebula

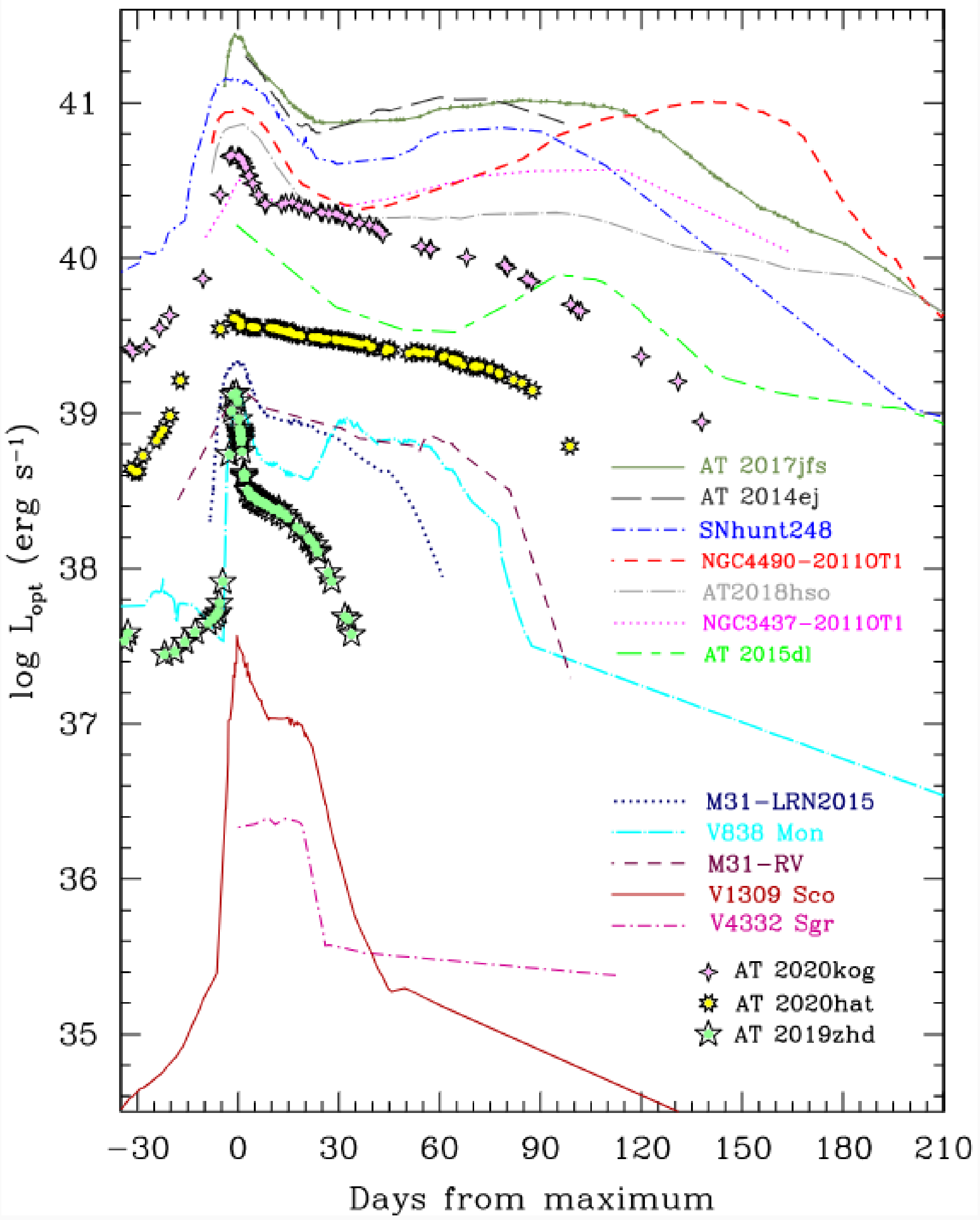
Luminous Red Novae (LRNe)

Optical transients

Rapid brightening followed by peak and (long-lasting) plateau

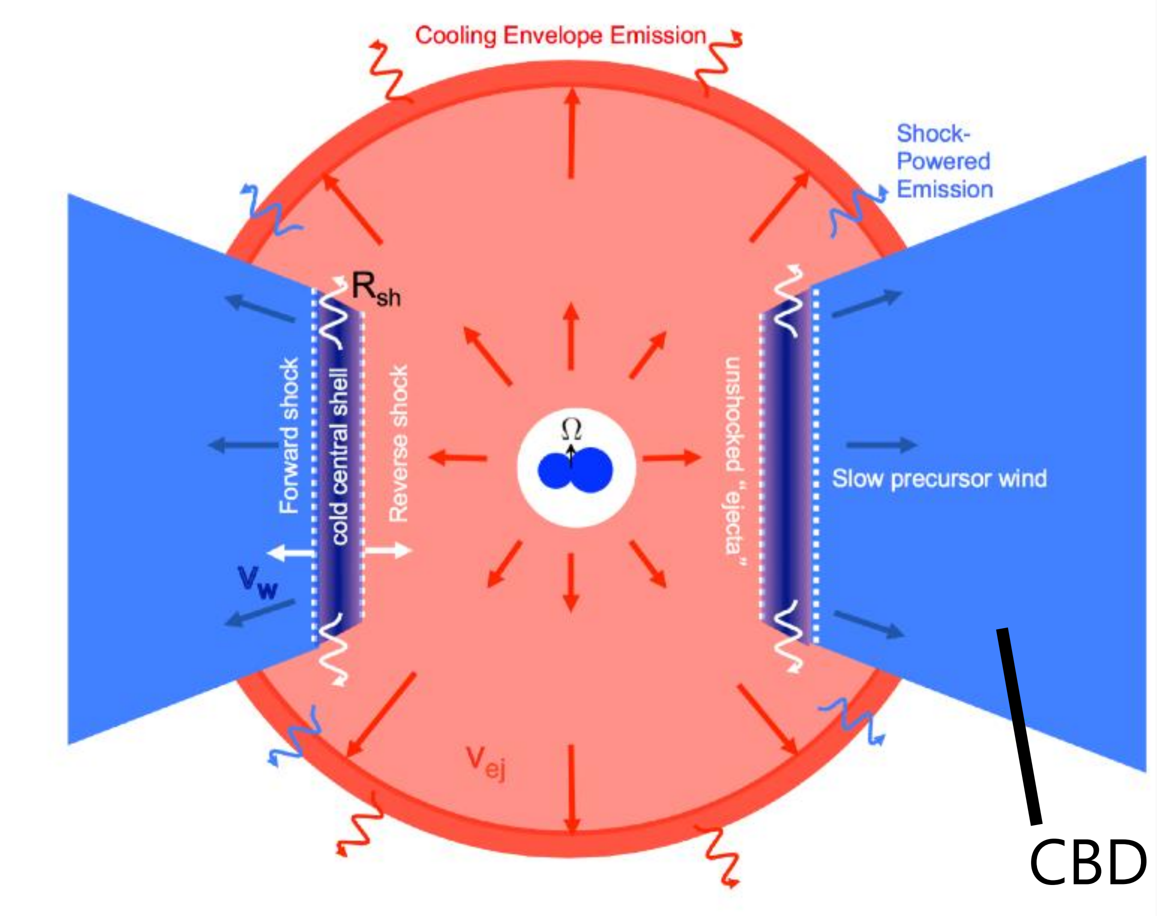
$$L_{\text{opt}} = 10^{37\sim41}\ \text{erg s}^{-1}$$
$$t_{\text{peak-plateau}} = 10\sim200\ \text{days}$$
$$r_{\text{LRN}}(-16 \le M_r \le -11\ \text{mag}) = 7.8 \times 10^{-5}\ \text{Mpc}^{-3}\ \text{yr}^{-1}$$

Karambelker et al. 2023



Pastorello et al. 2021

Luminous Red Novae: possible mechanism



Metzger and Pejcha 2017

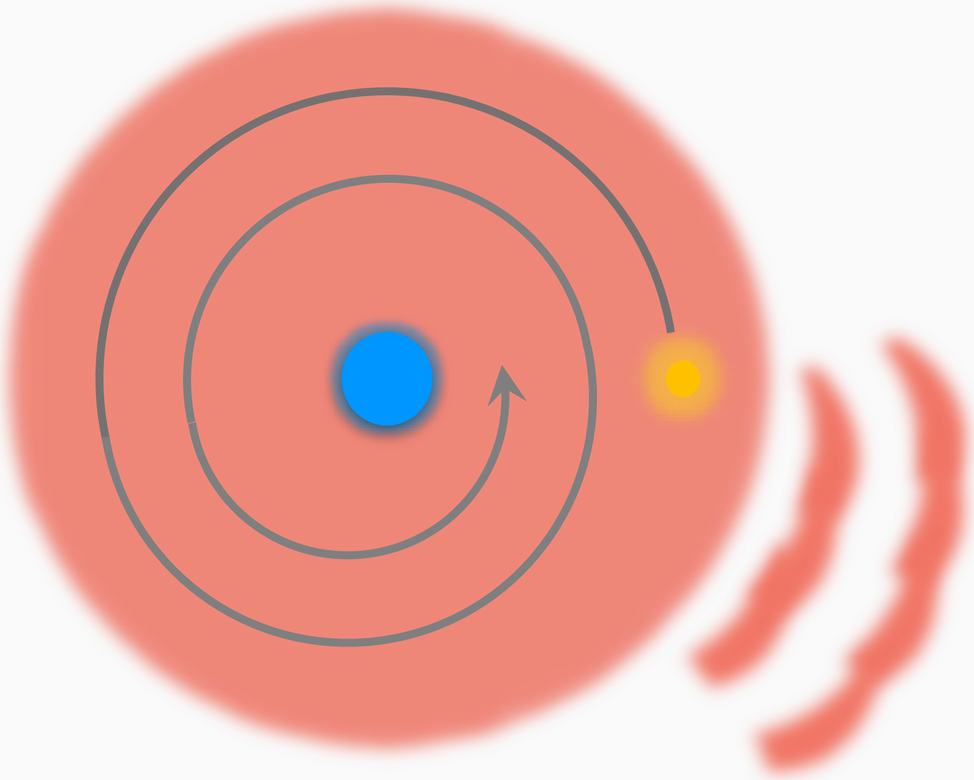
How to make plateau

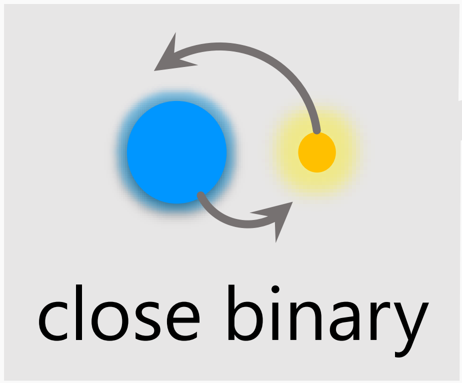
- Higher luminosity LRN
  Shock interaction between ejecta and CBD
  Metzger and Pejcha 2017, Anthony et al. 2025
- Lower luminosity LRN
  Recombination of Hydrogen
  Matsumoto and Metzger 2022
  Chen and Ivanova 2024

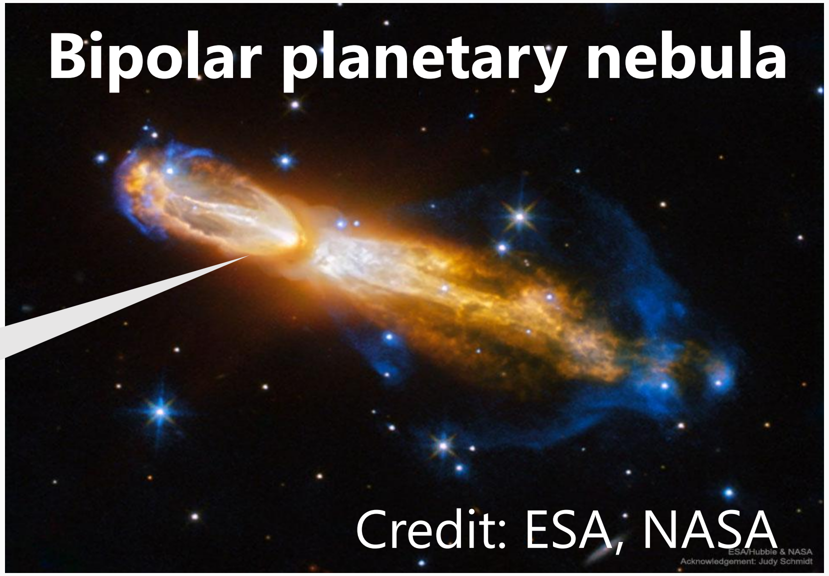
CBD is made via L2 mass loss before CEE

Bipolar planetary nebulae (bipolar PNe)

- Bipolar-shaped object observed in optical
- Possible origin: magnetic field amplified via CEE

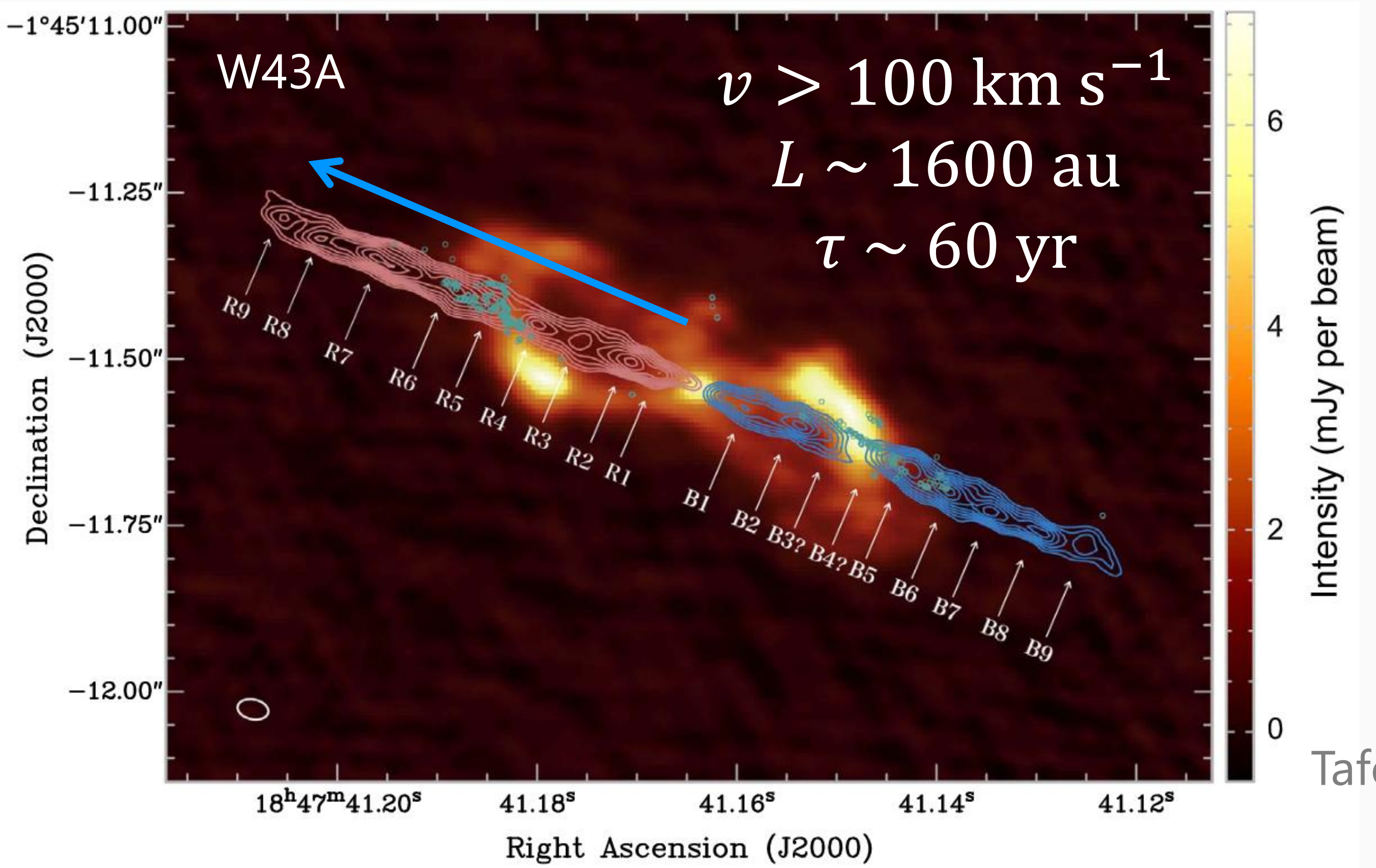


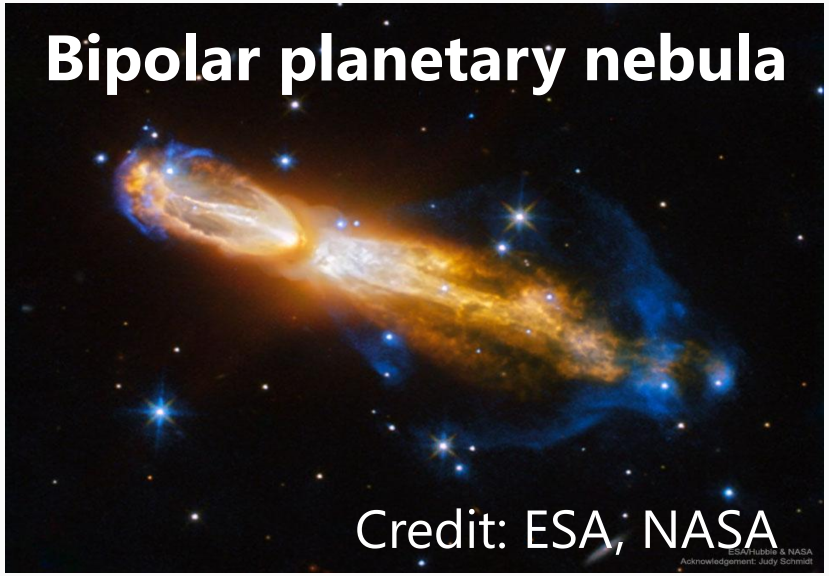




The Calabash nebula

Observations of bipolar PNe: The Presence of Jets



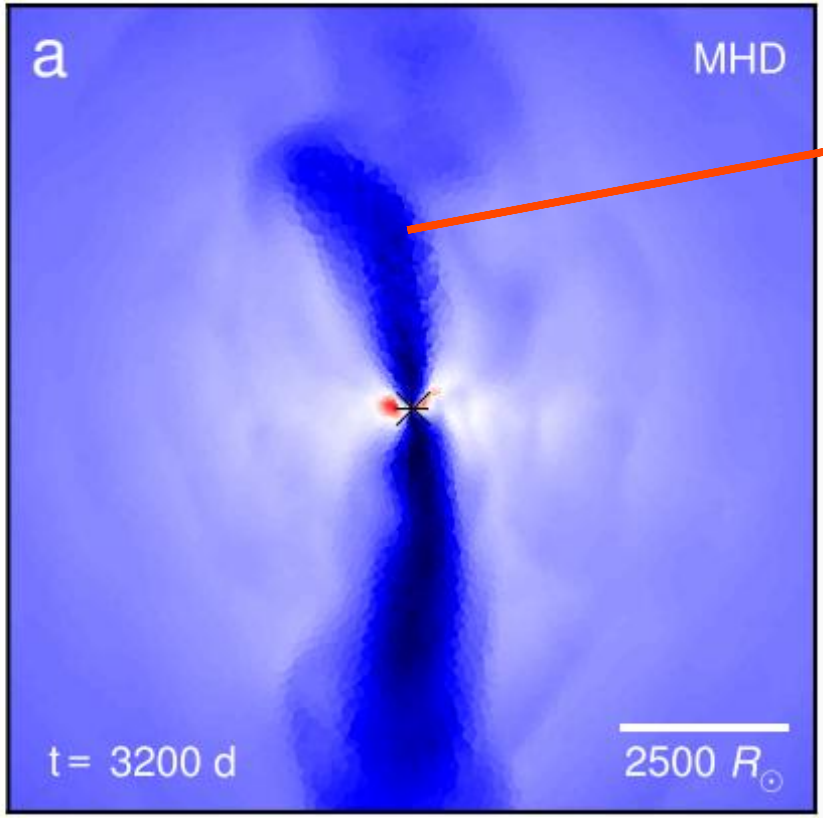


The Calabash nebula

Tafoya et al. 2020

A jet exists along a single axis; binary origin?

CE and polar outflows: Past MHD simulation



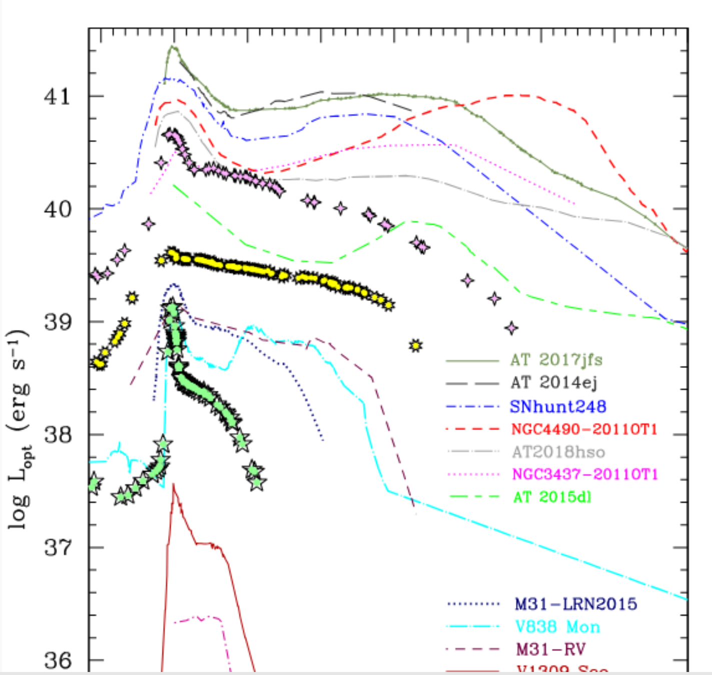
radial velocity
(perpendicular plane)

During the CE phase,
the magnetic field amplifies
and polar outflow are driven.
Ondratschek et al. 2022, Vetter et al. 2025

Method characteristics:
Utilizes Adaptive Mesh Refinement
→ Excellent resolution in high-density regions
Employs the Powell method for magnetic fields
→ Leaves finite $\nabla \cdot B$ residuals
The companion is initially
placed on the surface of the primary

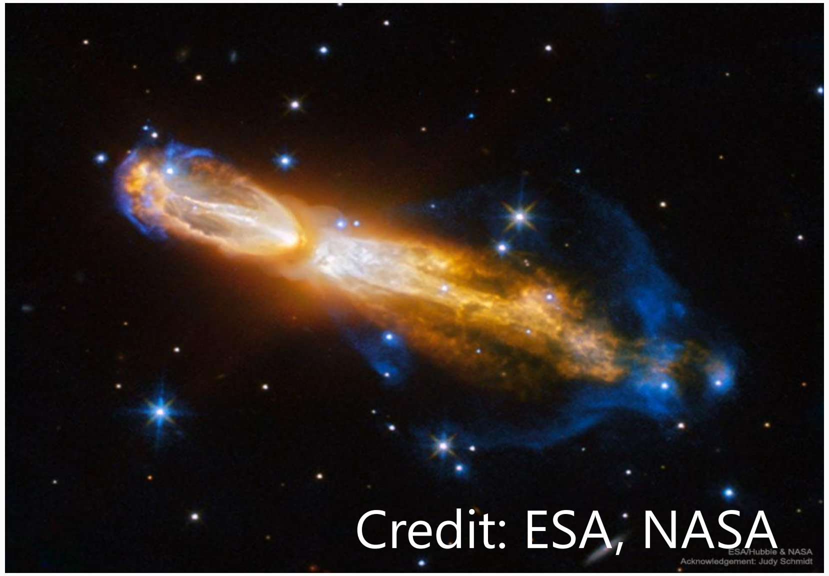
Connection between Observation and Simulation

Luminous Red Novae



Pre-CE mass loss via L2
should be included for CBD.
Radiative transfer is needed.

Bipolar planetary nebulae

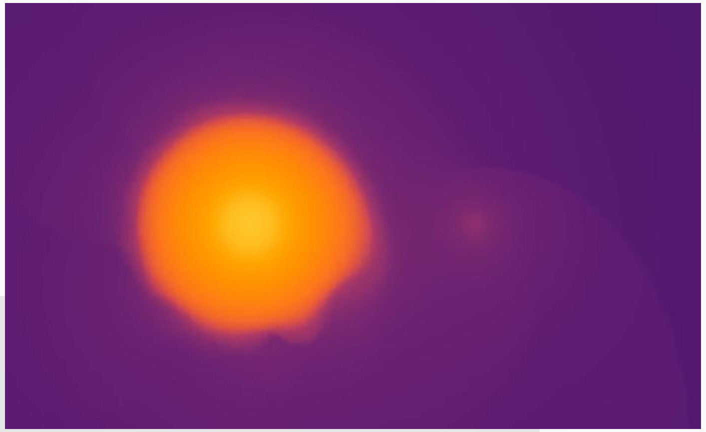


Credit: ESA, NASA

Magnetic field is needed?

The Purpose of This Study

Investigate the influence of magnetic fields
on the ejecta during the CE phase in massive binary systems



Characteristics of the method:

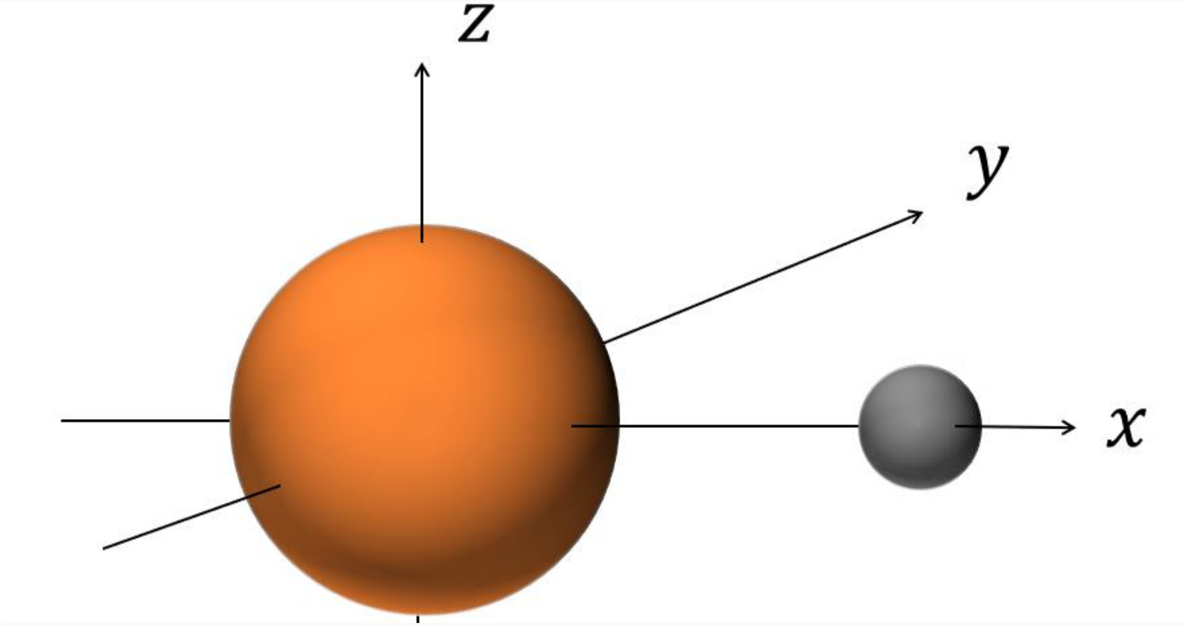
Starting calculations from the Roche lobe overflow
→ Enabling tracking of evolution preceding the CE

Utilizing open-source MHD codes Athena++ Stone et al. 2022
→ Employing Static Mesh Refinement
→ Employing Constrained Transport method

Setup for 3D magnetohydrodynamic calculations

Target system：RSG (82.1 $M_\odot$) and companion (35.0 $M_\odot$)

Ricker et al. 2019

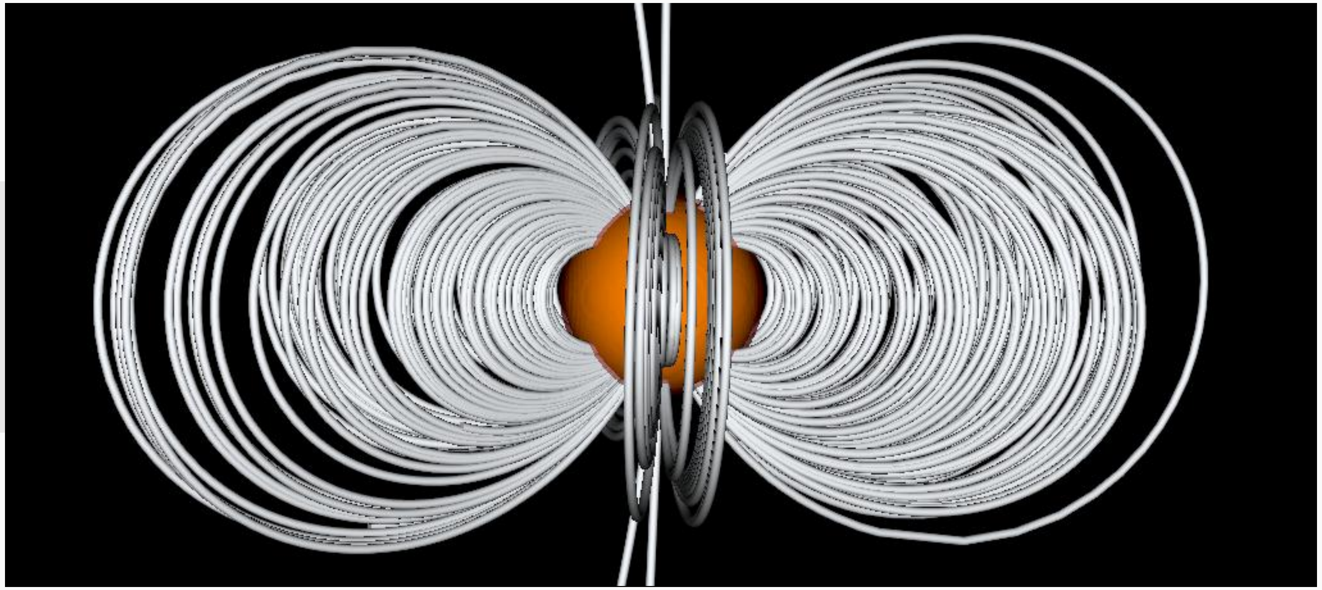


Construction of the initial stellar structure

1. Solve hydrostatic equi. assuming a gravitational acceleration profile
2. Introduce a dipole magnetic field as initial condition

$$\boldsymbol{A} = \frac{\bar{\boldsymbol{m}} \times \boldsymbol{r}}{r_{\mathrm{c}}^3}$$

Zhu et al. 2024



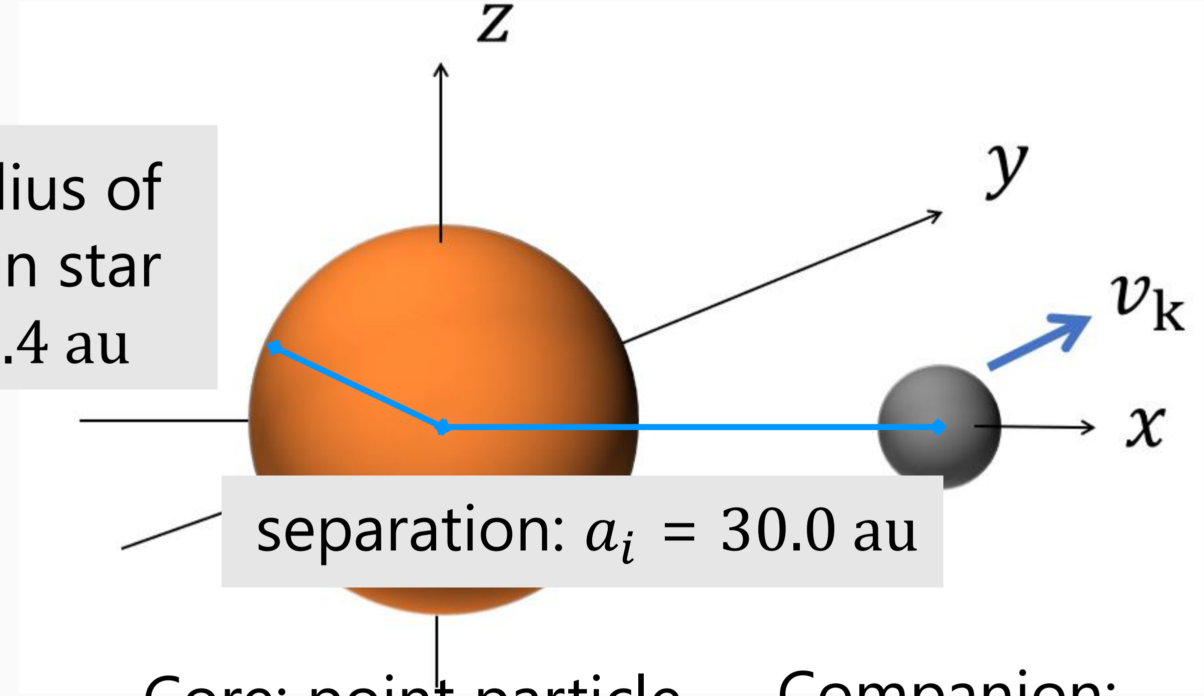
$$\beta = {}^{p_{\mathrm{gas}}}\!/\!_{p_{\mathrm{mag}}} = 1000$$

at surface of main star

As for the main star's structure, magnetic field is negligible.

Overview of calculation setup

Target system : RSG ($82.1\ M_{\odot}$) + companion ($35.0\ M_{\odot}$) Ricker et al. 2019



Radius of main star 13.4 au

v_{k} : to be circular orbit ($e = 0$)

separation: a_i = 30.0 au

Core: point particle
Envelope: fluid

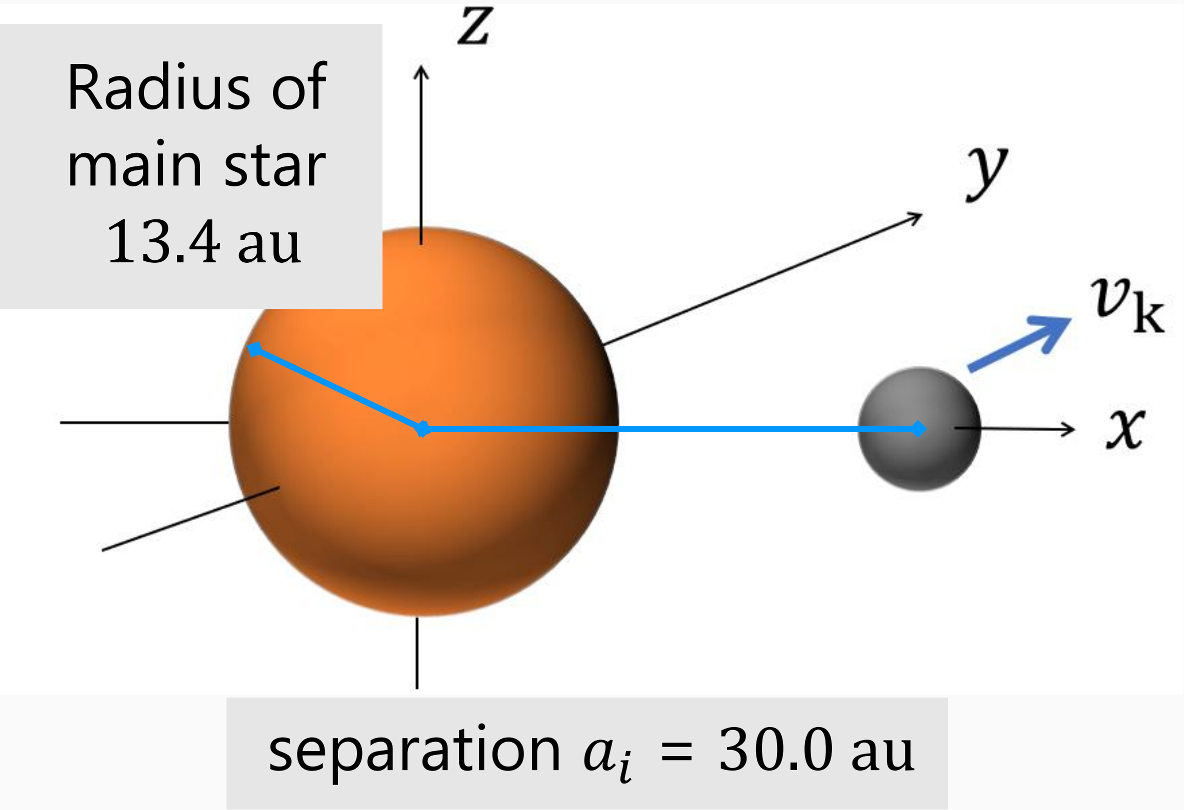
Companion:
point particle

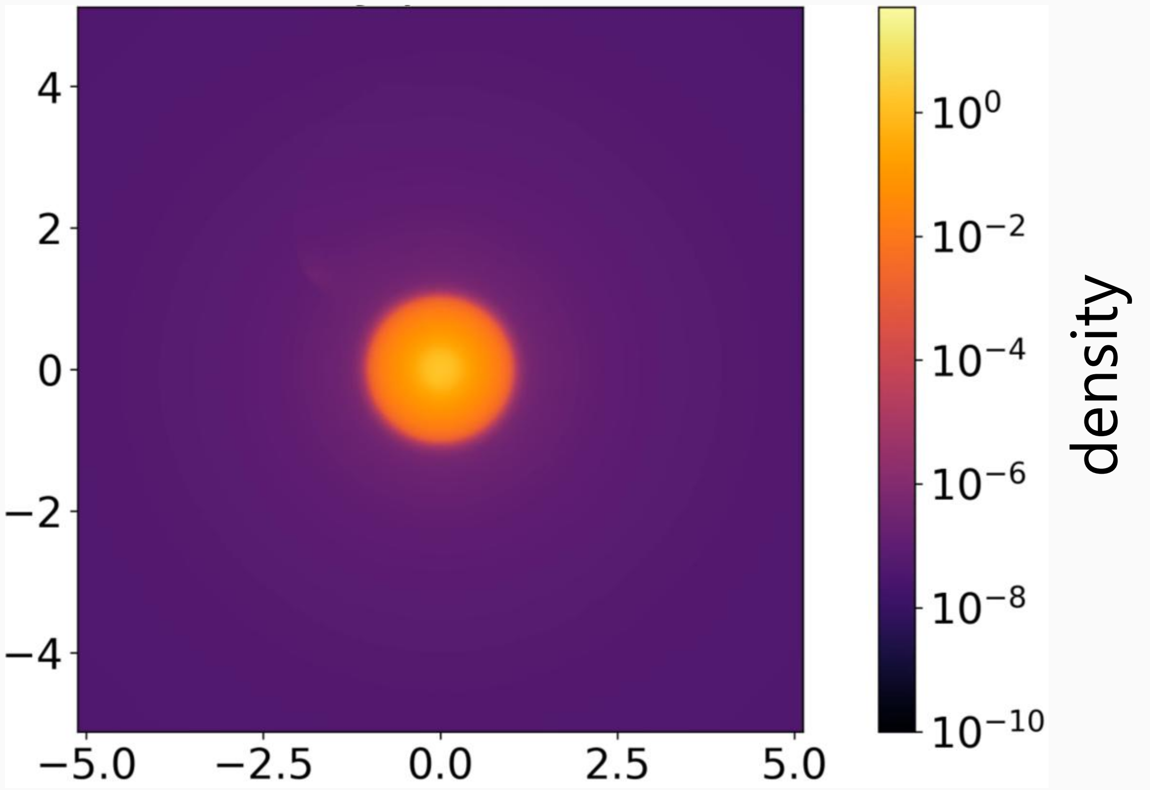
Non-inertial frame MacLeod et al. 2018

Perform calculations with and without a magnetic field

Result : 3D simulation with MHD

Target system : RSG ($82.1\ M_\odot$) + companion ($35.0\ M_\odot$)





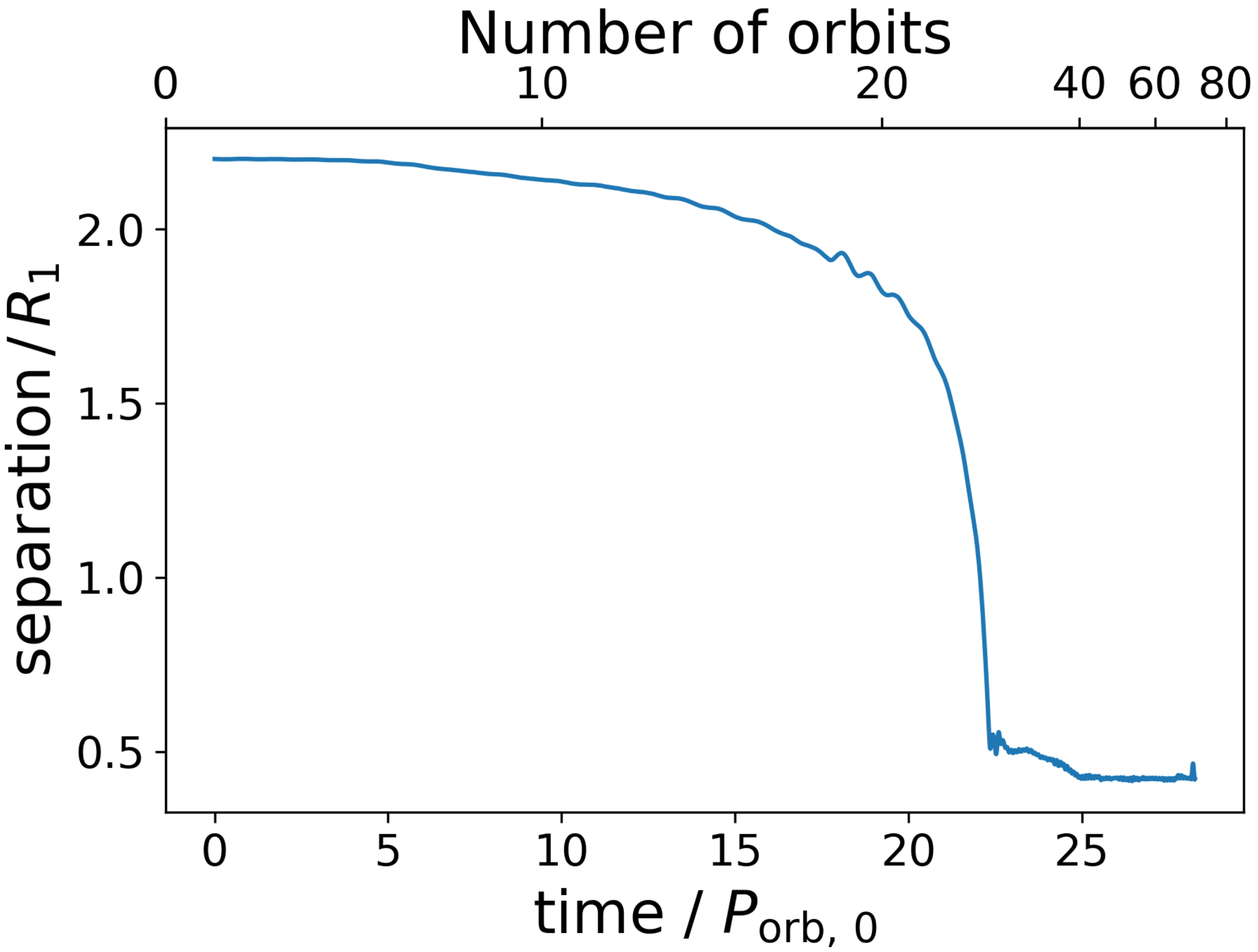
density at orbital plane

Result: Time evolution of separation (MHD)

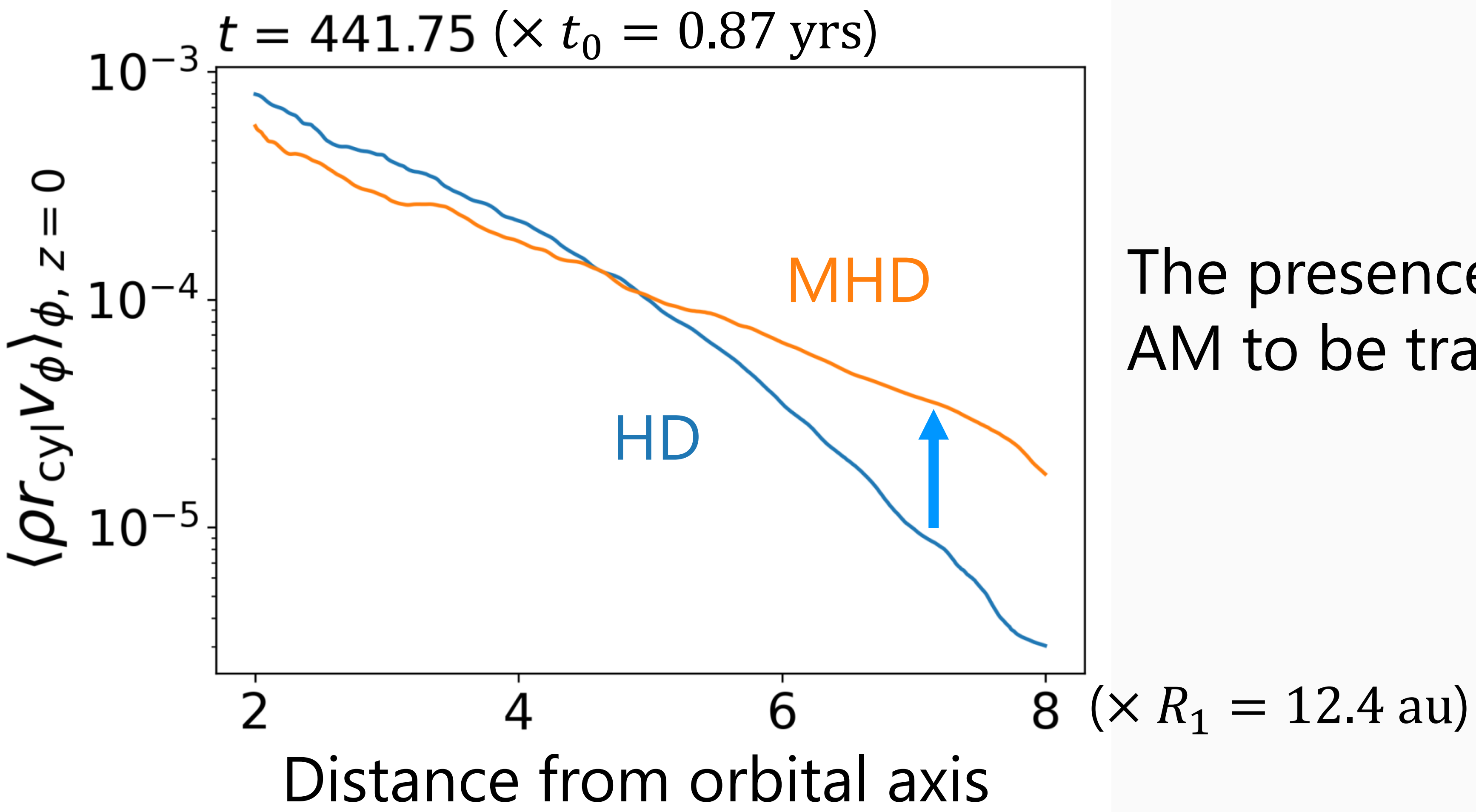
About 25 orbits,
the companion within
initial primary's envelope.

<u>Final separation</u>

HD ： 6.05 au
MHD ： 5.63 au

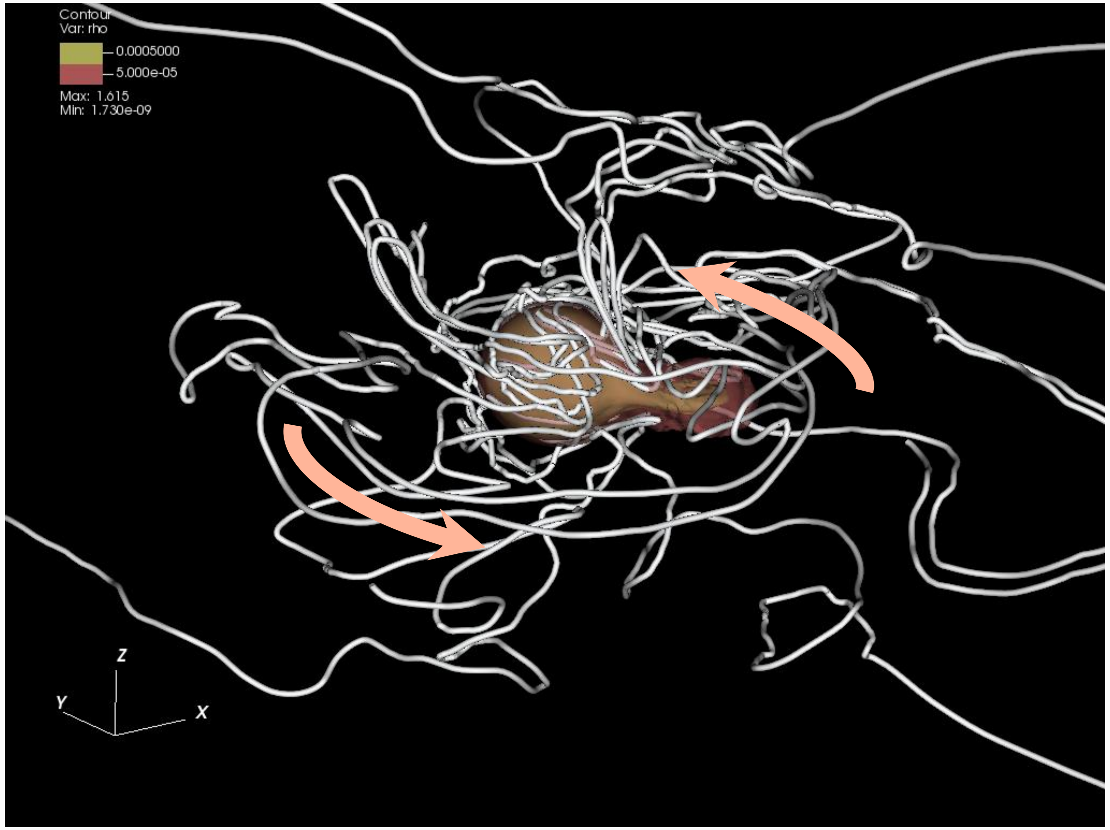


Result: Comparison of angular momentum distributions

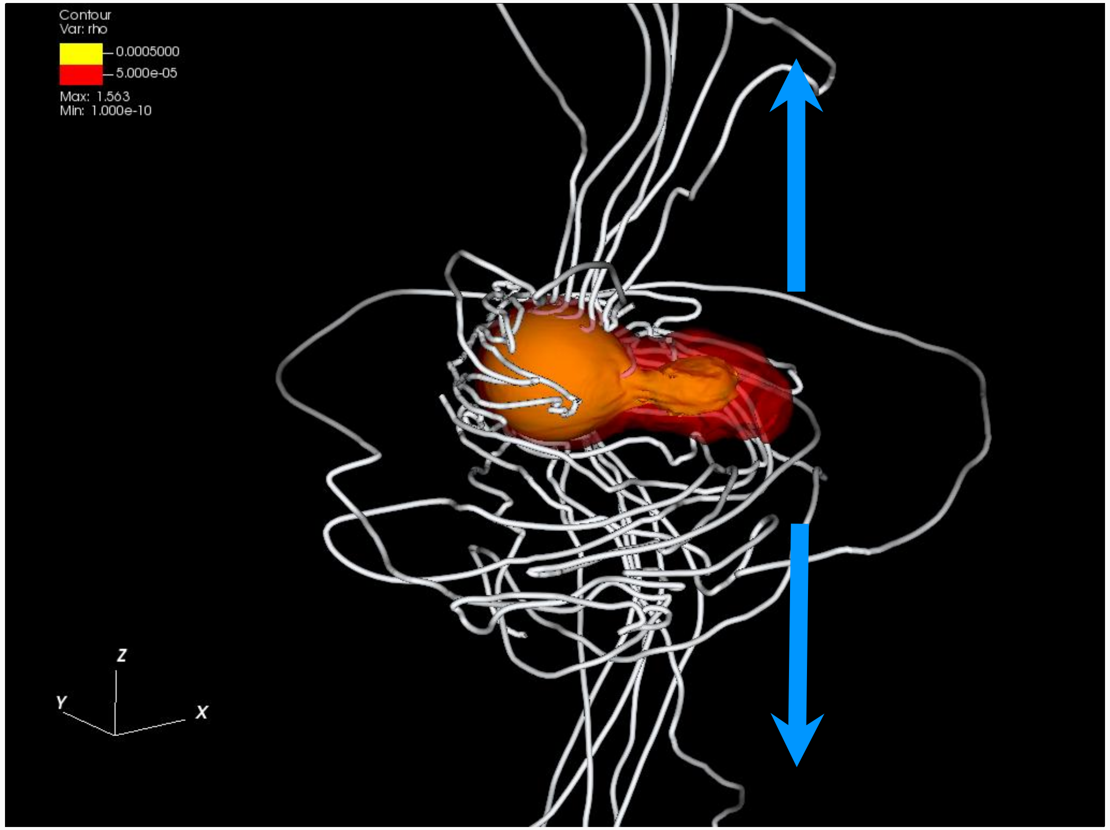


The presence of a B-field causes AM to be transported outwards.

Result: Time evolution of magnetic field line

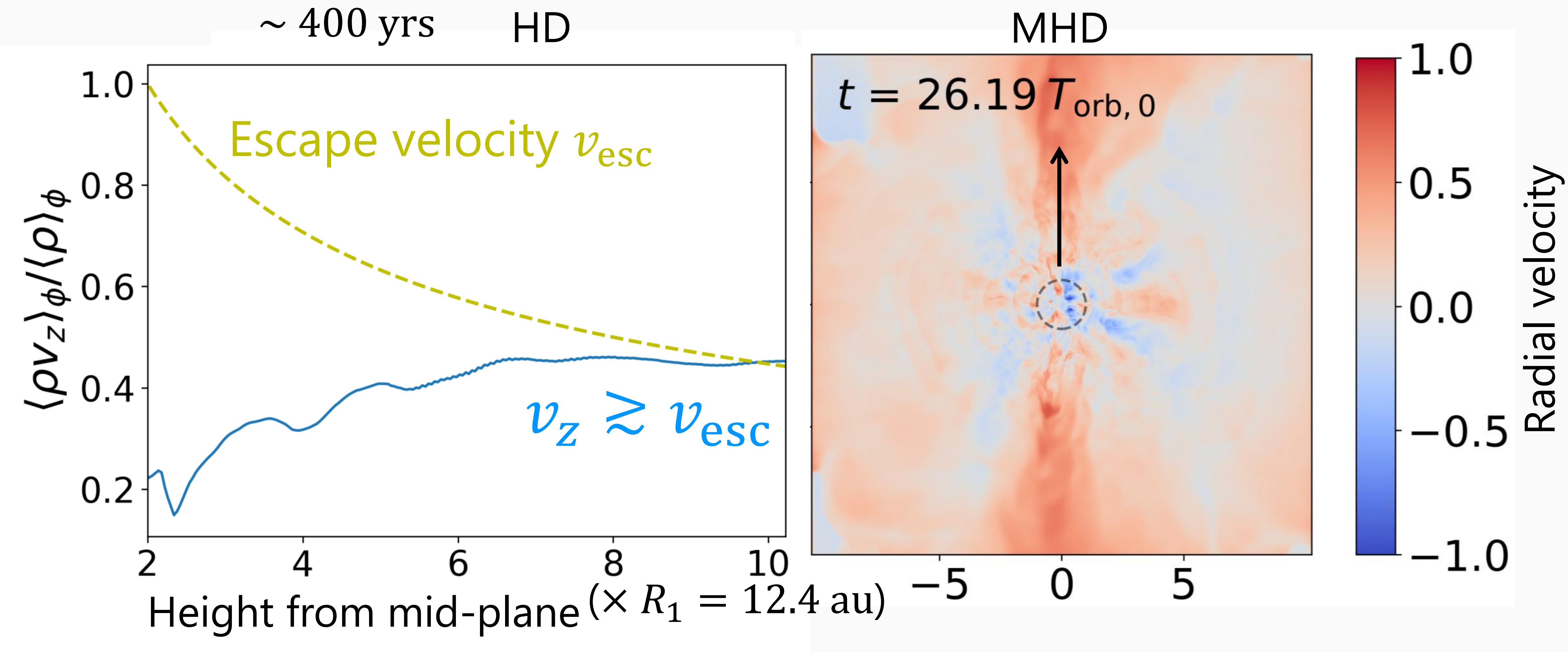


+ 6 oribits



Magnetic pressure concentrates the field lines toward the **polar regions**

Result: Verification of outflow drive



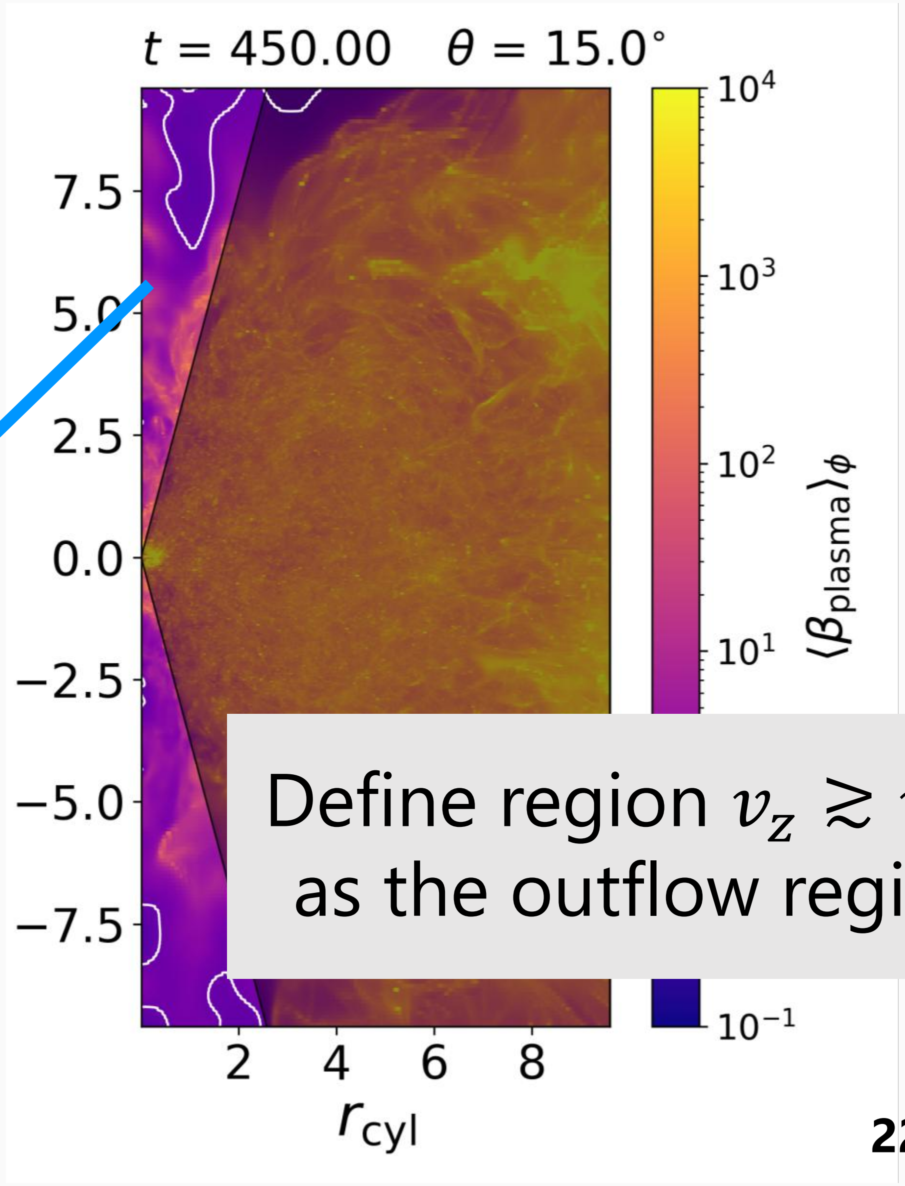
What is the driving mechanism of an outflow?

Discussion: The Drive Mechanism of Outflow

Candidate acceleration mechanisms

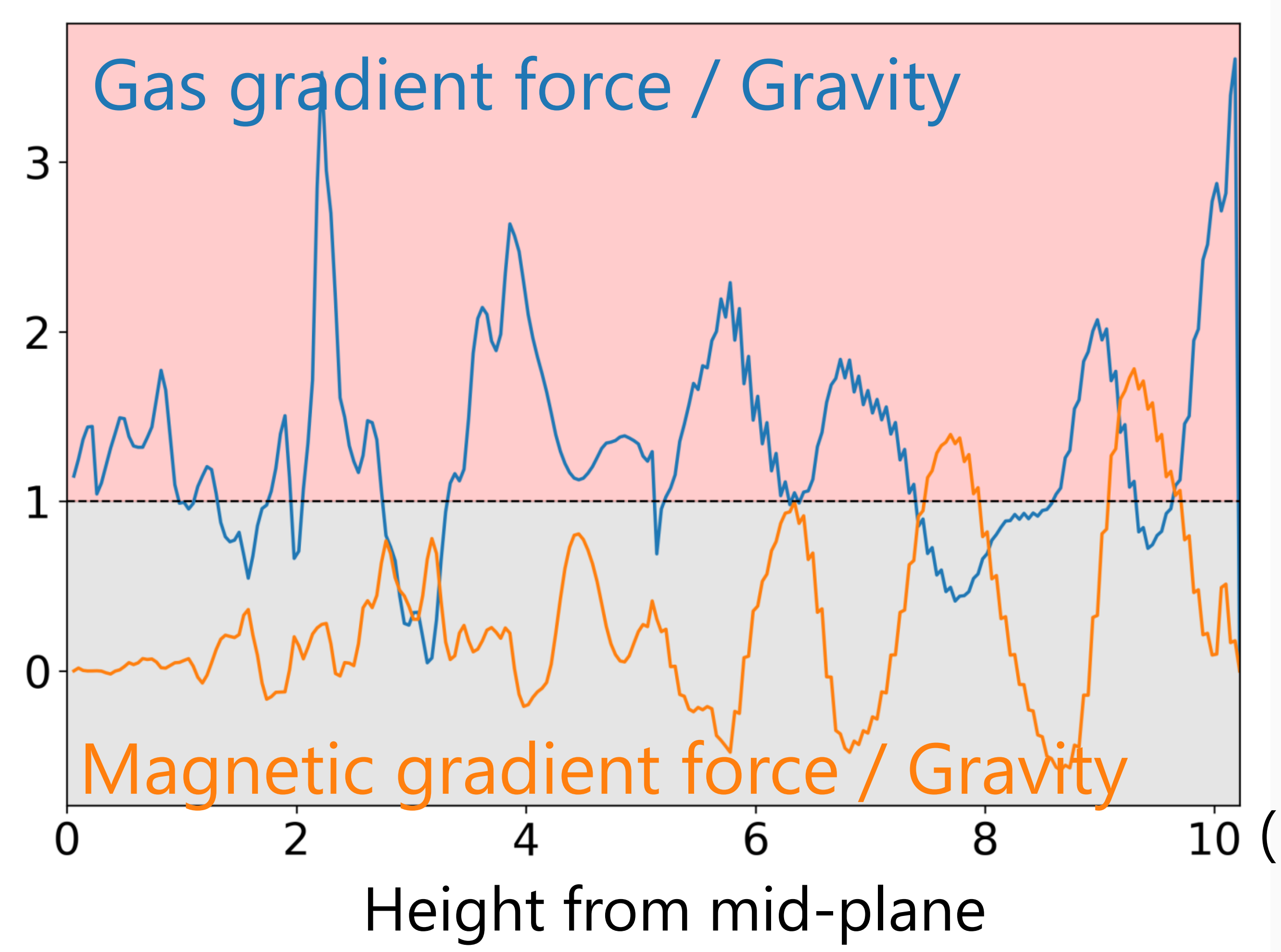
- Magnetic pressure gradient force
- Magnetic centrifugal force
- Gas pressure gradient force

In most polar regions,
magnetic pressure < gas pressure



Define region $v_z \gtrsim v_{\mathrm{esc}}$
as the outflow region

Discussion: The Drive Mechanism of Outflow



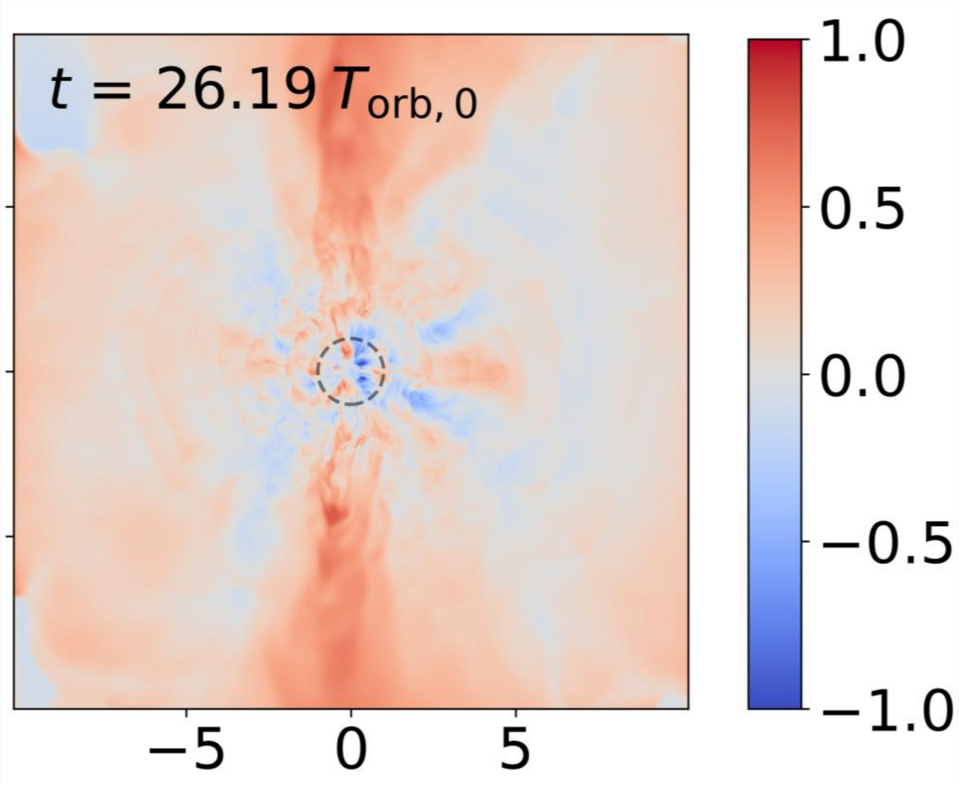
$(\times R_1 = 12.4\ \mathrm{au})$

Gas gradient forces are dominant throughout the entire region.

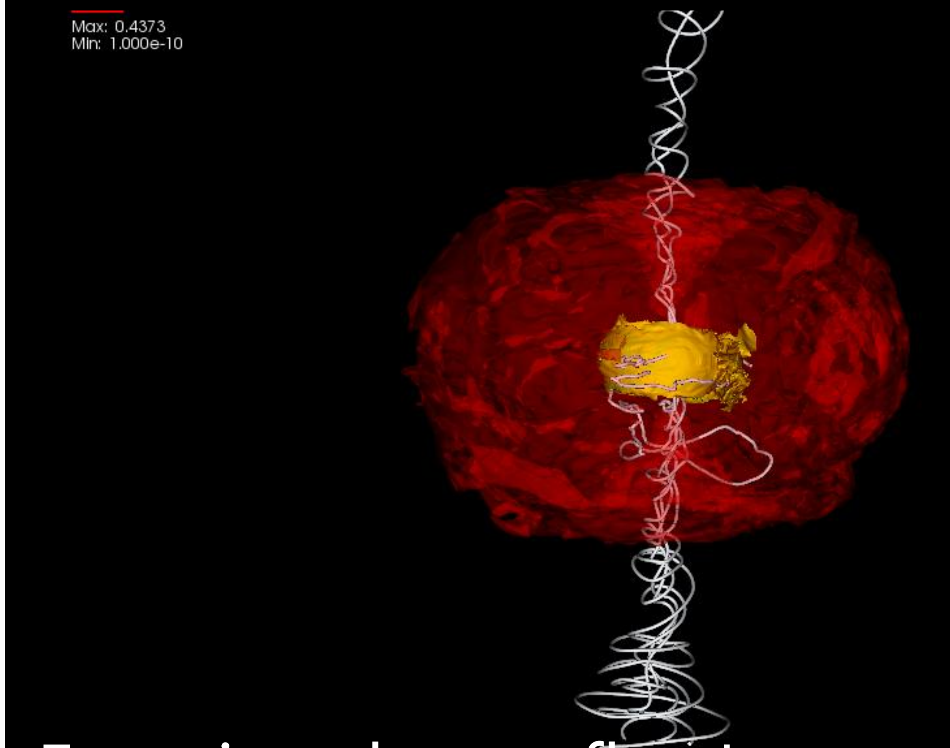
→ The outflow is driven by gas grad.

→ What is the role of the B-field?

Discussion: The role of magnetic field



Plot of magnetic field lines at the same time



Ensuring the outflow's passage via a magnetic field?

Summary and future work

- We performed 3D MHD sim. targeting the CE of massive binaries
- Confirmation of outflow driven by gas pressure gradient forces
- Other analysis about ejecta which interact with circumbinary disk