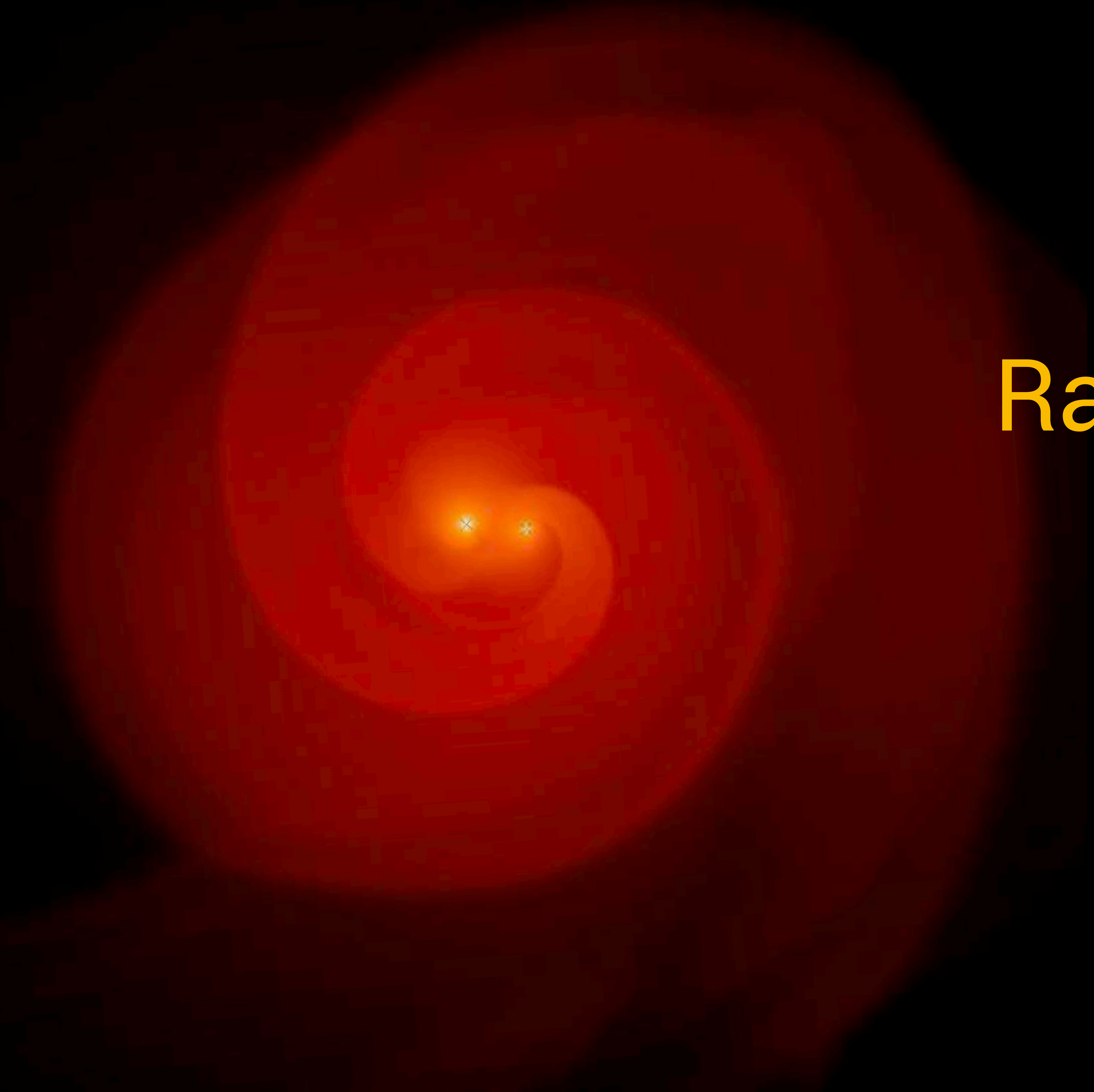

Radiation hydrodynamic simulations of common-envelope evolution

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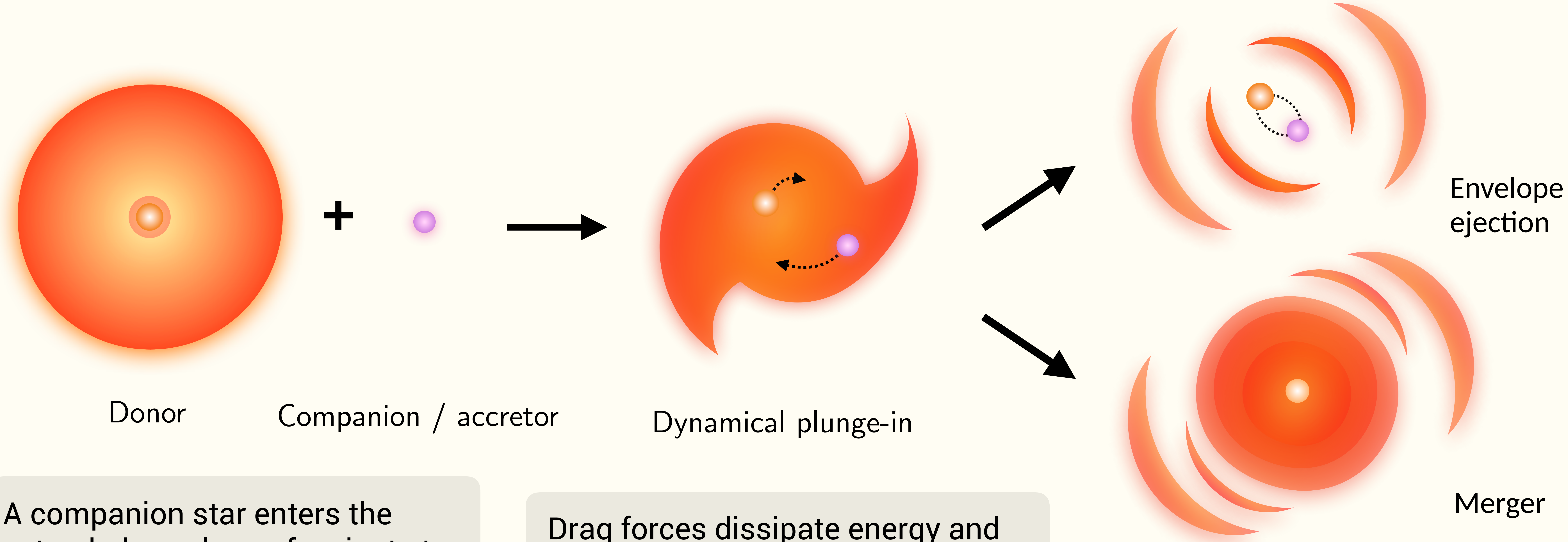
HITS Heidelberg Institute for Theoretical Studies

03/06/25 2nd European Phantom code family users workshop

HITS
Heidelberg Institute for Theoretical Studies

Heidelberg Old Bridge and Castle

Common-envelope evolution

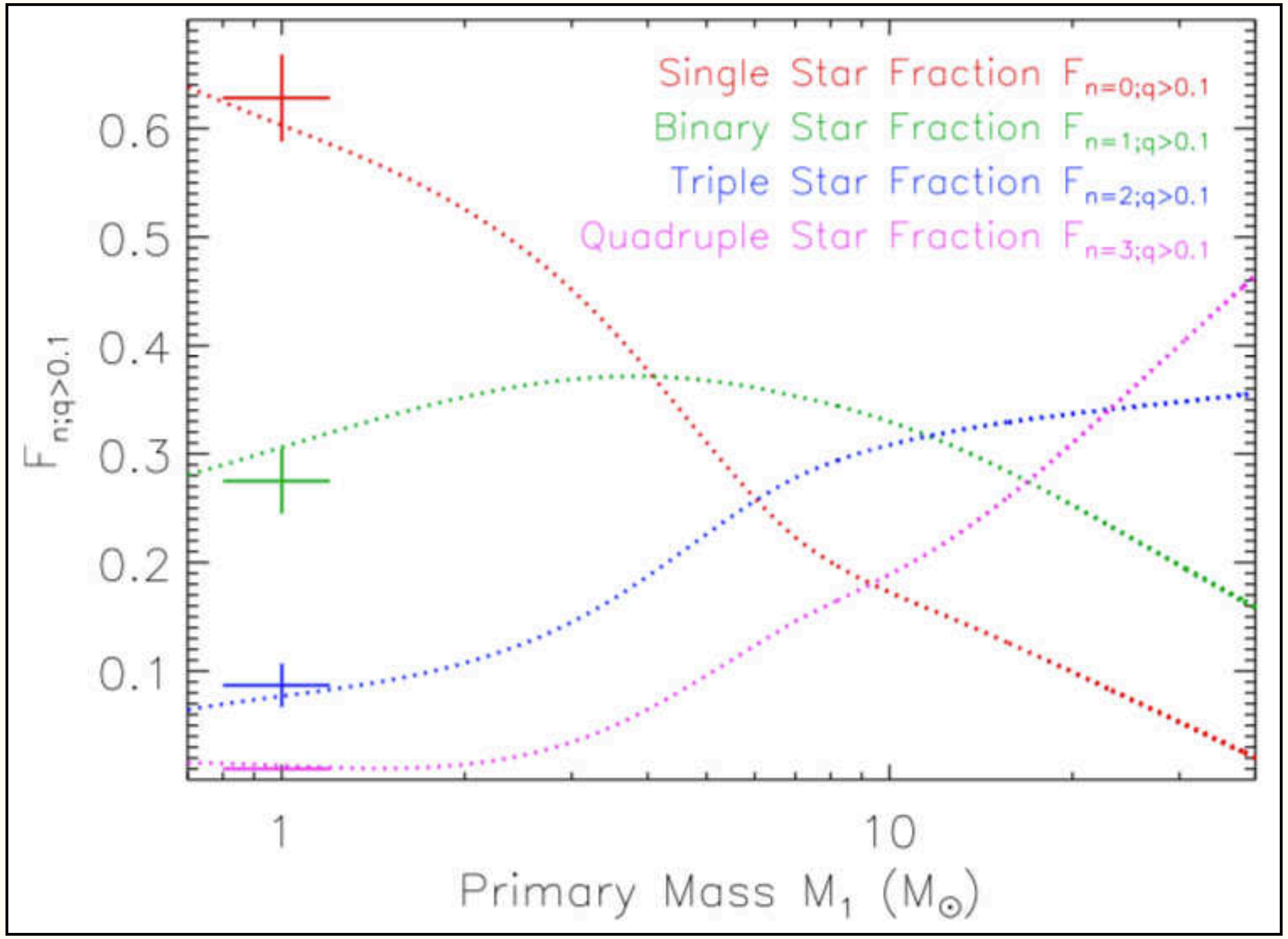


A companion star enters the extended envelope of a giant star without co-rotation

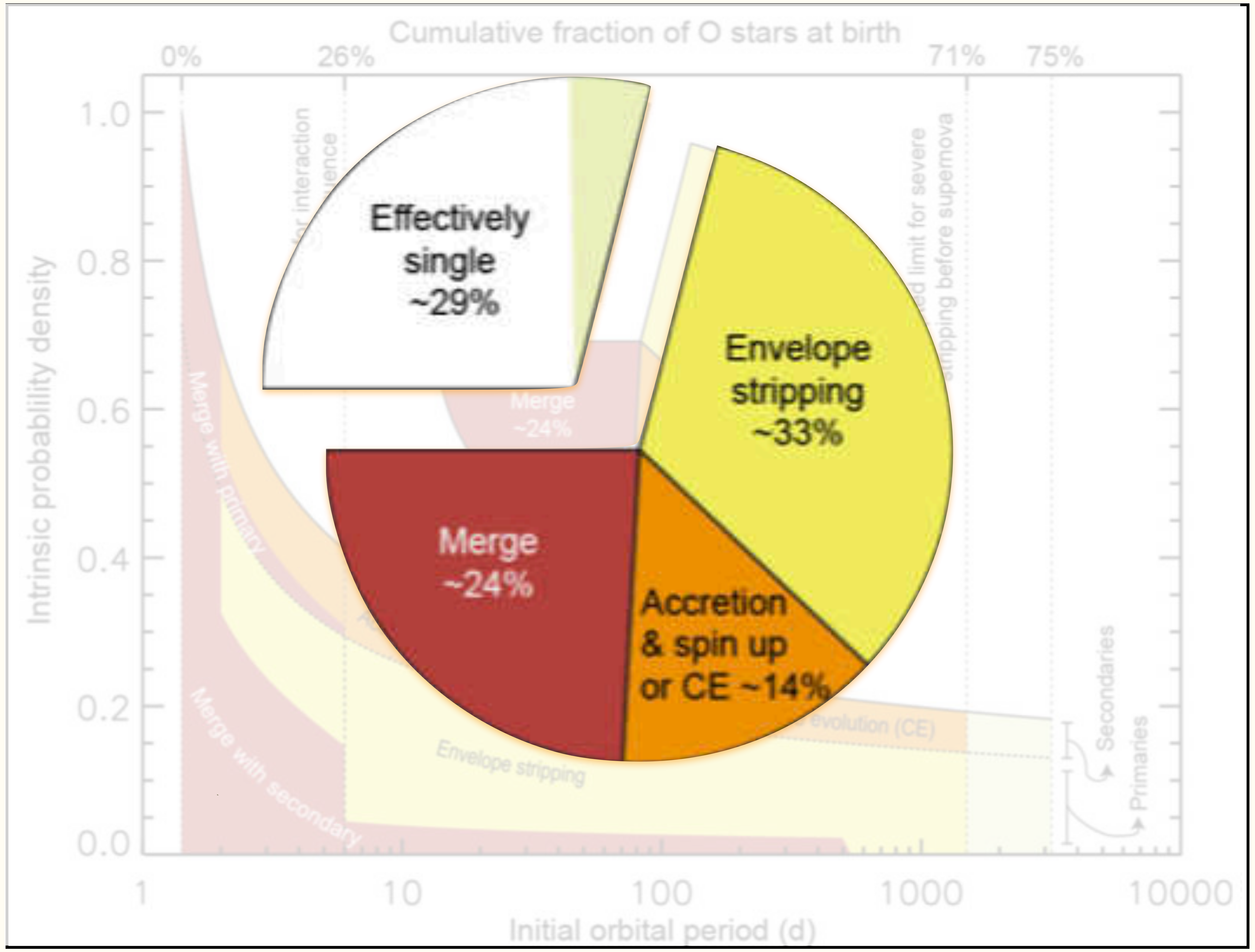
Drag forces dissipate energy and angular momentum in the envelope

Expelling the envelope leaves a much tighter binary orbit

*Adapted from Schneider, **Lau**, Röpke (2025)*



Moe & Di Stefano 2017



Sana+ 2012

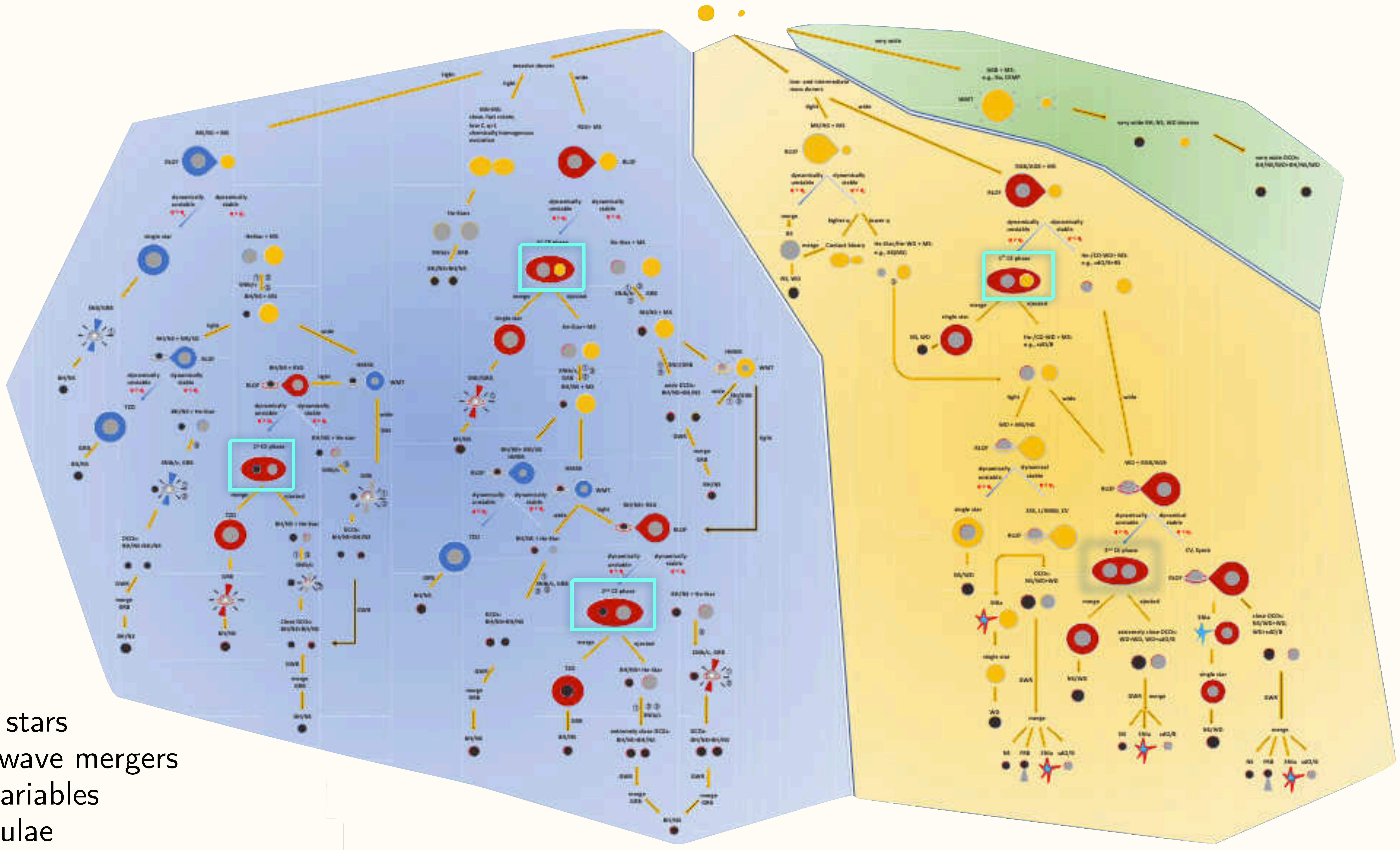
Stellar multiplicity is common

also, Offner+ 2022

Binary interactions dominate massive star evolution

Binary evolution tree

Han+ 2020



Ge 2020

- ➡ X-ray binaries
- ➡ Hot subdwarf stars
- ➡ Gravitational wave mergers
- ➡ Cataclysmic variables
- ➡ Planetary nebulae
- ➡ Symbiotic binaries
- ➡ Type Ia SNe

…

Lau+ 2022a

$12\ M_\odot$ red supergiant + $3\ M_\odot$ companion

Key questions:

- Can we simulate common-envelope ejection?
- What determines the post-common-envelope orbital separation?

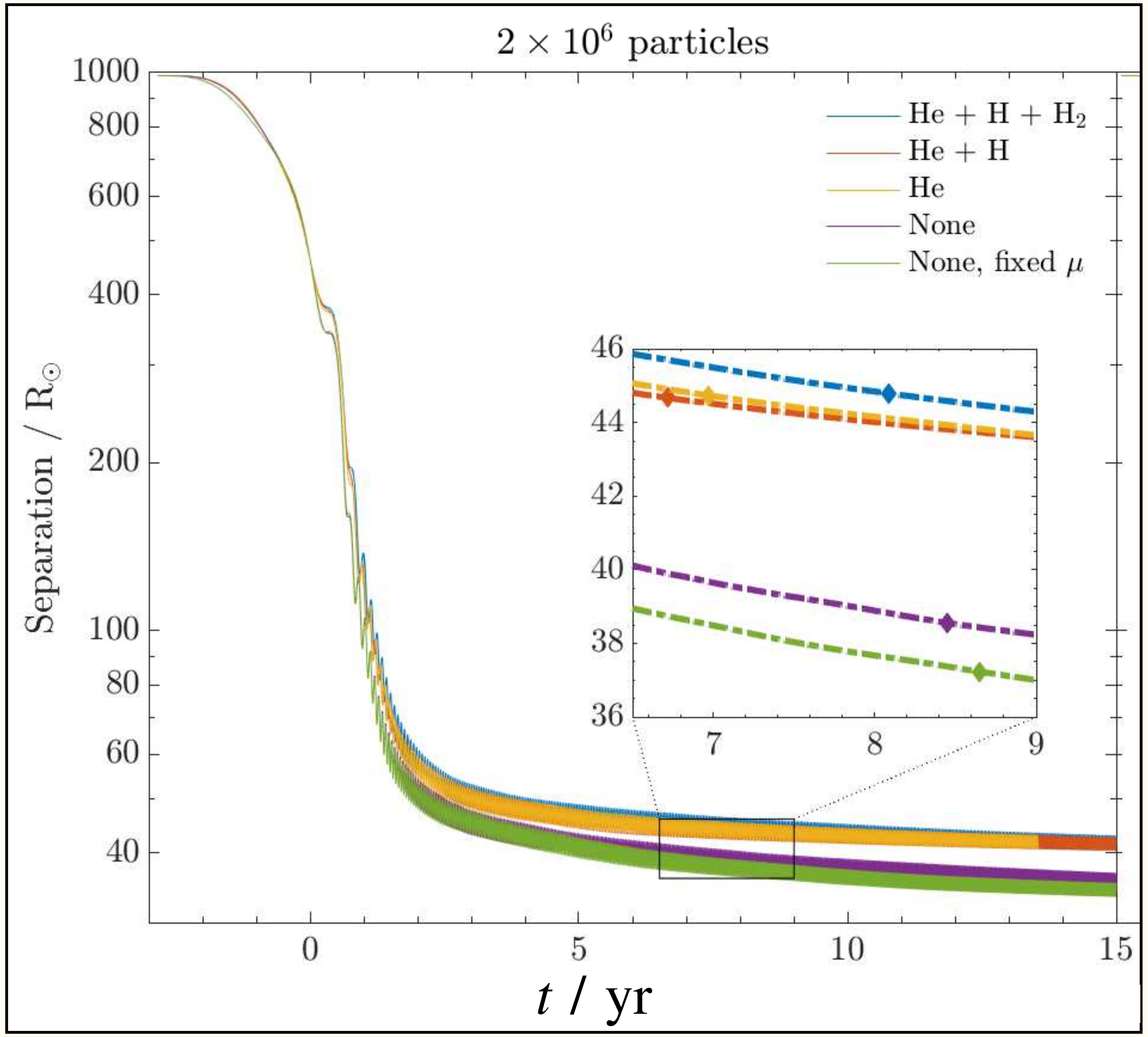
Current state:

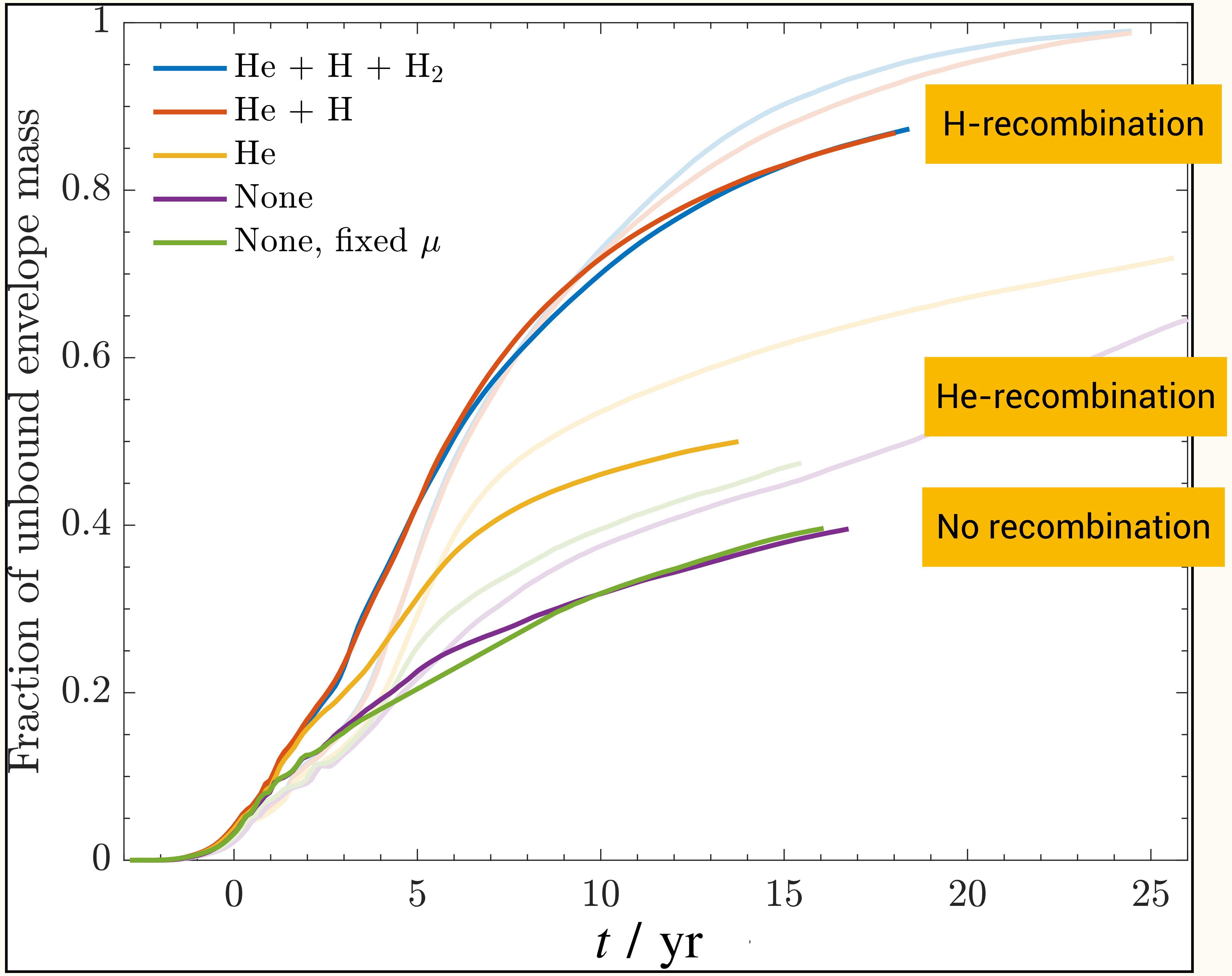
- No 3D simulation has demonstrated complete envelope ejection self-consistently on the dynamical timescale
- Mass ejection occurs on longer timescales
- Inclusion of recombination energy is key

*Nandez+ 2015, Ivanova & Nandez 2016, Reichardt+ 2020, Sand+ 2020, **Lau**+ 2022a,b, Moreno+ 2022, González-Bolívar+ 2022*

Recombination energy is key

Lau+ 2022b





Lau+ 2022a

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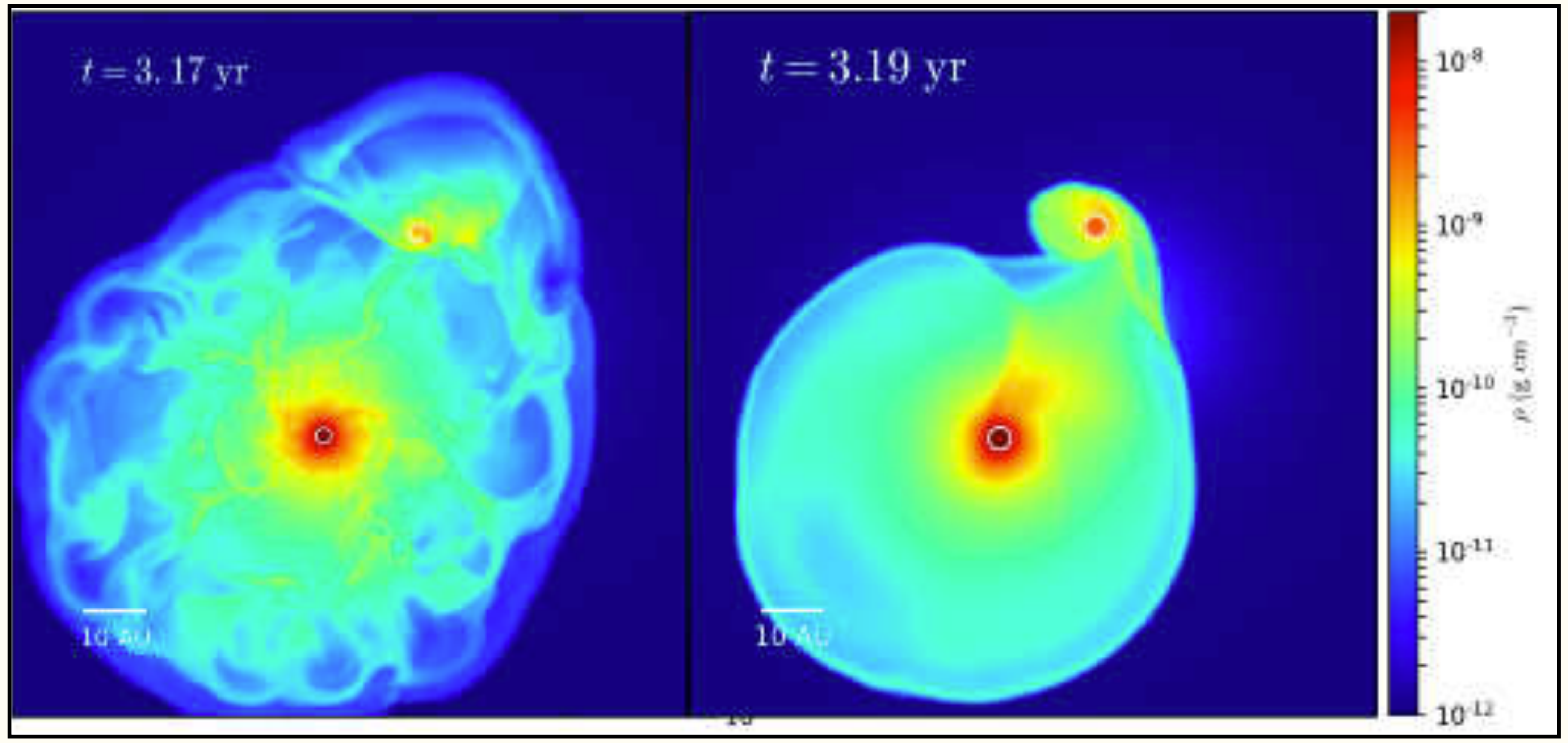
➡ Need radiation transport!

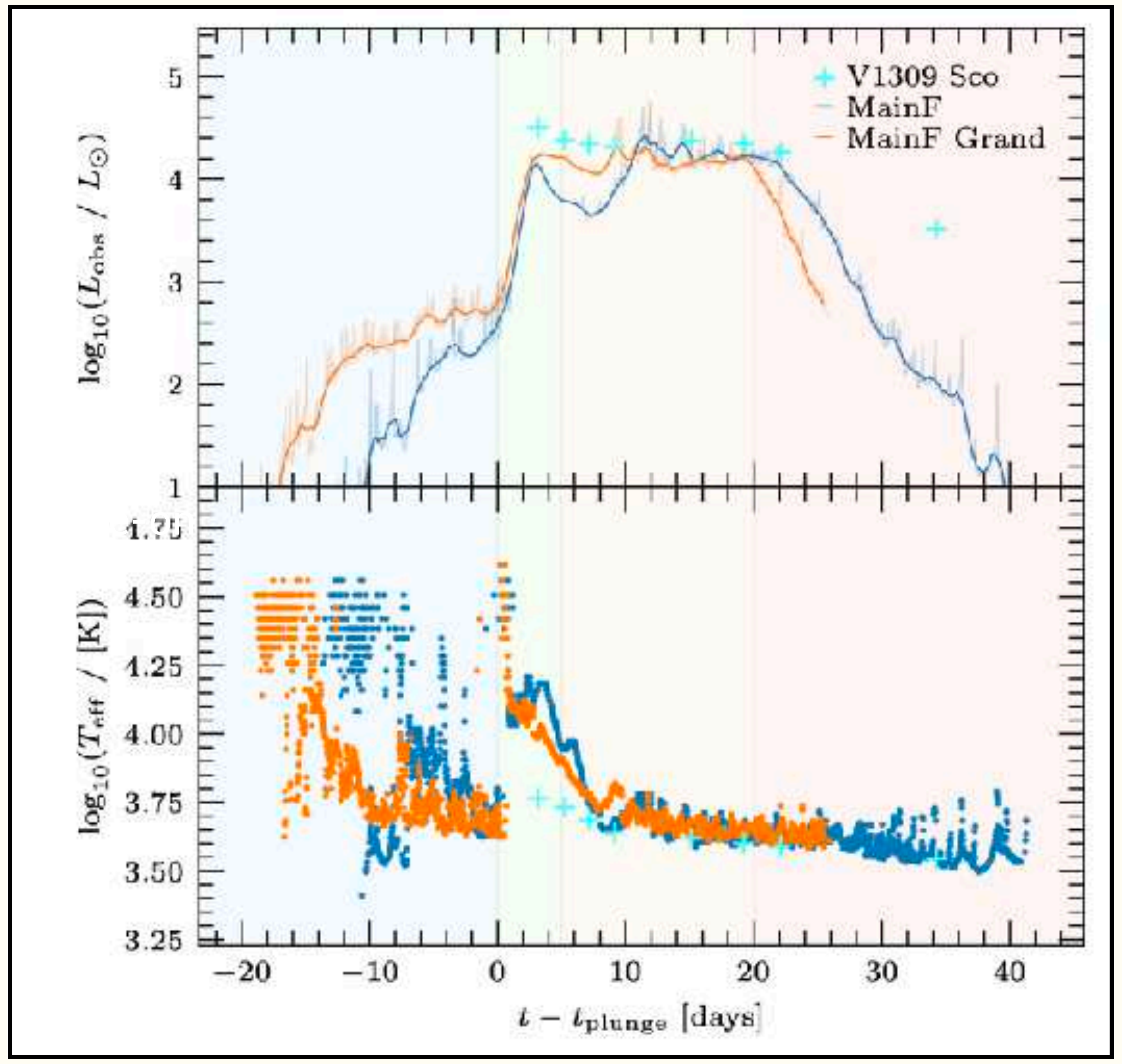
Radiation transport in common envelopes

Ricker+ 2018 (IAU conference proceedings)



Flux-limited diffusion in the AMR code *FLASH*

Hatfull & Ivanova 2025



Flux-limited "emission-diffusion" method in the SPH code *StarSmasher*

Lightcurve model for V1309 Sco

Other implications of radiation transport:

- Transport away recombination energy
- Allows sensible lightcurves
- Required for constructing a "realistic" giant star with envelope convection

Radiation hydrodynamics scheme

<u>Existing implementations of radiation transport in *Phantom*</u>

- Two-temperature flux-limited diffusion following Whitehouse & Bate (2004) with an explicit solver

→ Tiny time steps in optically thin regions

Biriukov 2020 (PhD thesis)

$$\Delta t_{\rm rad} = C\frac{h^2\rho\kappa}{c\lambda} \rightarrow C_{\rm Cour}\frac{h}{c} \ll t_{\rm dyn}$$

- Monte Carlo radiative transfer with *MCFOST*, *CMacIonize*

→ Too expensive in optically thick regions

Pinte+ 2006, 2009

➡ Port implicit radiative diffusion solver from *SPHNG* into Phantom, based on Whitehouse & Bate (2004) and Whitehouse+ (2005)

- Use Gauss-Seidel and backwards Euler method to solve gas and radiation energy equations
- Do not cap time step at $\Delta t_{\rm rad}$
- Set accuracy tolerance for $u,\ \xi$ solutions of 10^{-6}
    - Optically thick regions converge within a few iterations
    - Optically thin regions require considerably more (we set a maximum of 250)

Radiation hydrodynamics scheme

Two-temperature flux-limited diffusion assuming LTE:

$$\frac{D\rho}{Dt} = -\rho\nabla\cdot\mathbf{v}$$

$$\rho\frac{D\mathbf{v}}{Dt} = -\nabla p + \frac{\kappa\rho}{c}\mathbf{F}_{\rm rad} + \rho\mathbf{\Pi}_{\rm shock} - \rho\nabla\Phi$$

$$\rho\frac{D\xi}{Dt} = -\nabla\cdot\mathbf{F}_{\rm rad} - \nabla\mathbf{v}:\mathbf{P}_{\rm rad} + a_{\rm rad}c\kappa\rho(T_{\rm gas}^4 - T_{\rm rad}^4)$$

$$\rho\frac{Du}{Dt} = -p\nabla\cdot\mathbf{v} + \rho\Lambda_{\rm shock} - a_{\rm rad}c\kappa\rho(T_{\rm gas}^4 - T_{\rm rad}^4)$$

Mihalas & Mihalas 1984, Turner & Stone 2001, Whitehouse & Bate 2004

Ideal gas EoS $\quad p = \frac{\rho\mathscr{R}T_{\rm gas}}{\mu} \qquad u = \frac{p}{(\gamma-1)\rho},\ \gamma = 5/3$

Radiation energy $\quad \xi = a_{\rm rad}T_{\rm rad}^4/\rho$

Radiative flux $\quad \mathbf{F} = -\frac{c\lambda}{\kappa\rho}\nabla E$ ← Radiation energy density, $E = \rho\xi$

Flux limiter $\quad \lambda \to 1/3$ Optically thick limit

$|\mathbf{F}| \to cE$ Optically thin limit

Levermore & Pomraning 1981

Opacity tables from the *MESA* stellar evolution code implemented in *Phantom* by Reichardt+ 2020

Tables combine OPAL opacities for the high-temperature regime with SCVH opacities for the low-temperature regime

Rogers+ 1996, Rogers & Nayfonov 2002, Saumon+ 1995

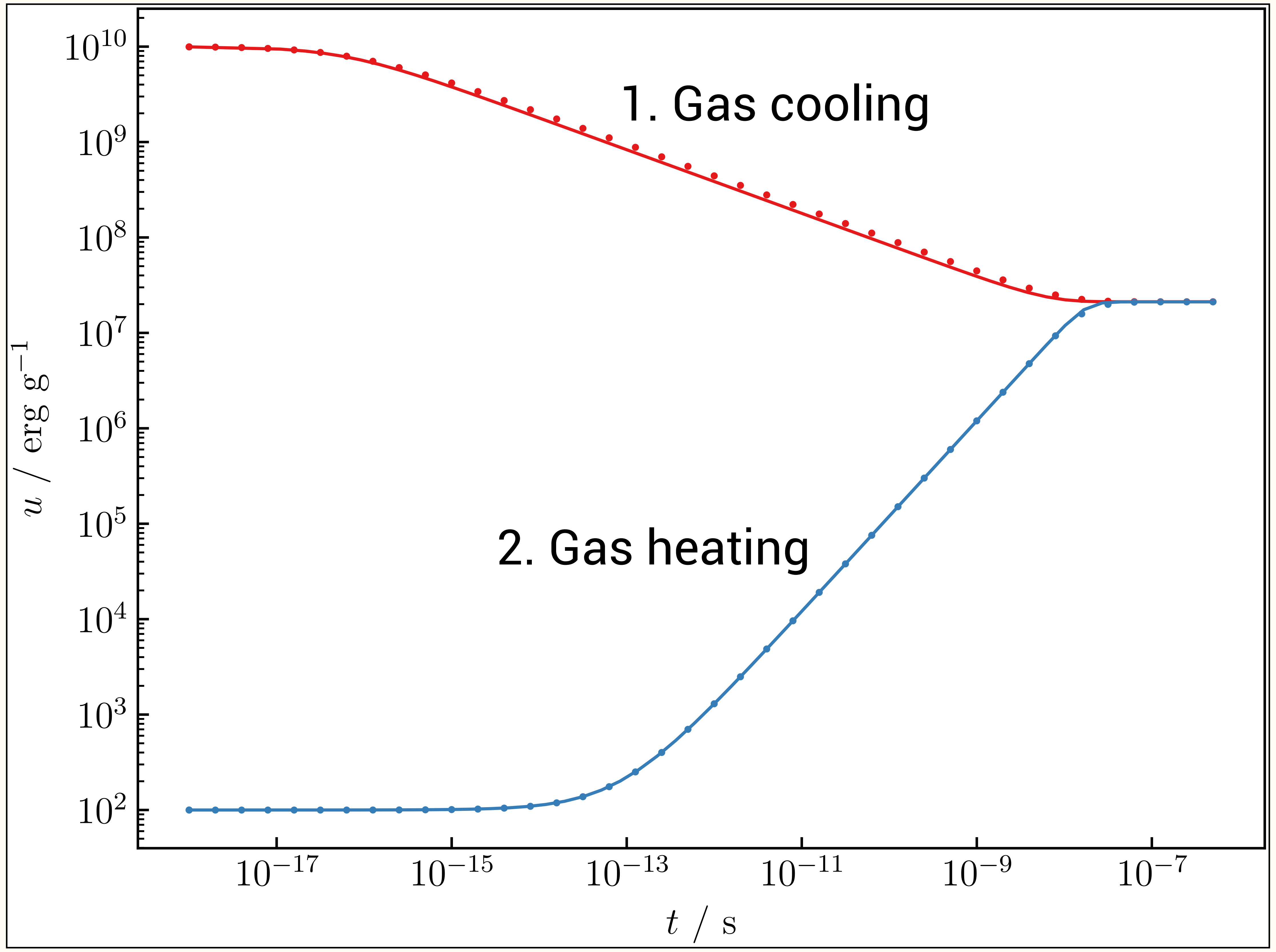
Features/assumptions:

- ξ diffuses along $-\nabla T_{\rm rad}$
- $T_{\rm gas}$ and $T_{\rm rad}$ are decoupled in the optically thin limit
- LTE allows source term to be written as Planck function (but not thermal equilibrium)
- Gray opacity
- No ionisation/recombination energy, but includes opacity changes

Test problems

Gas heating/cooling

Biriukov 2020 (PhD thesis)

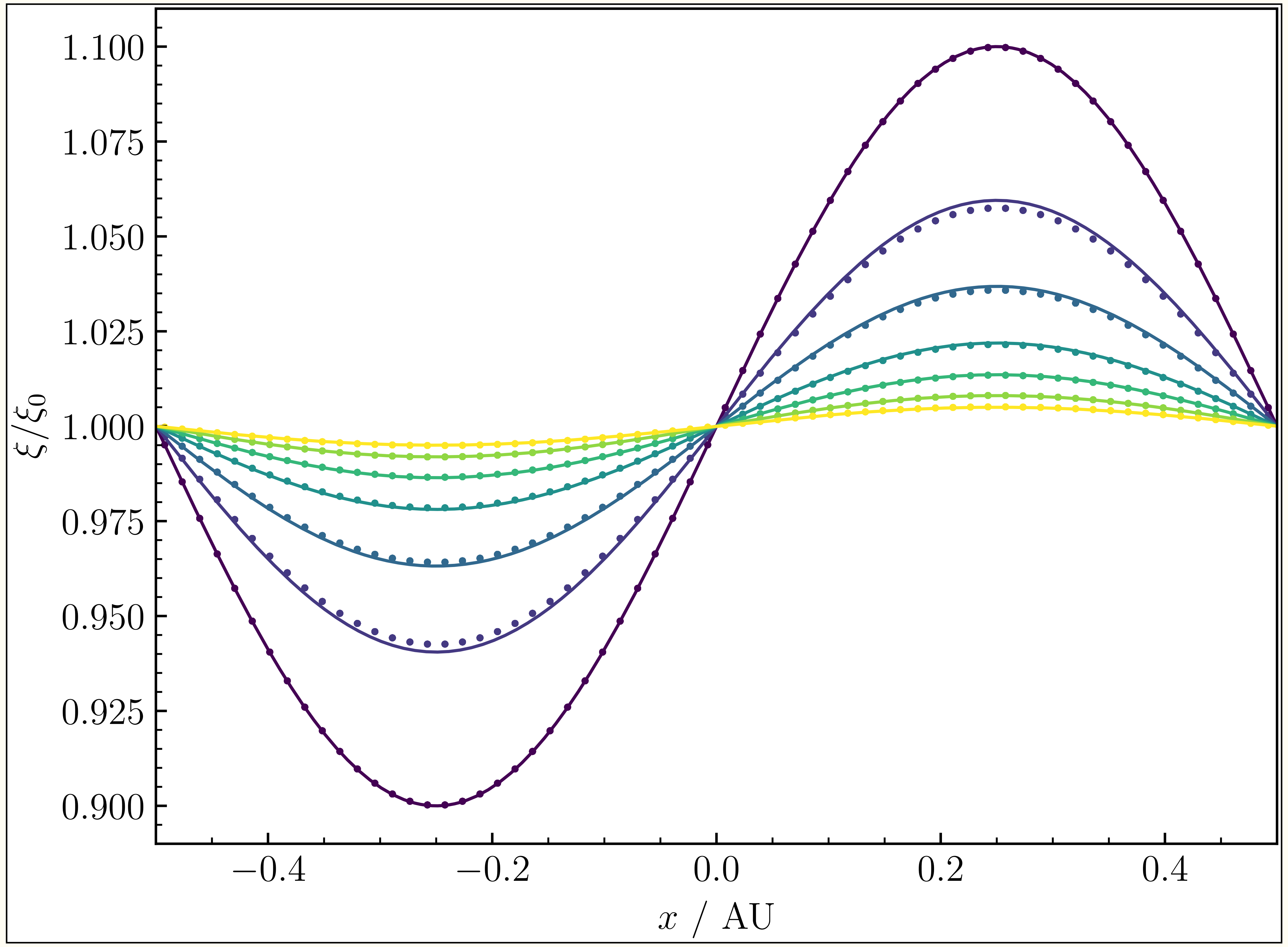


Solid lines: Explicit solver

Markers: Implicit solver (40 time steps)

Diffusion of sinusoid

Biriukov 2020 (PhD thesis)

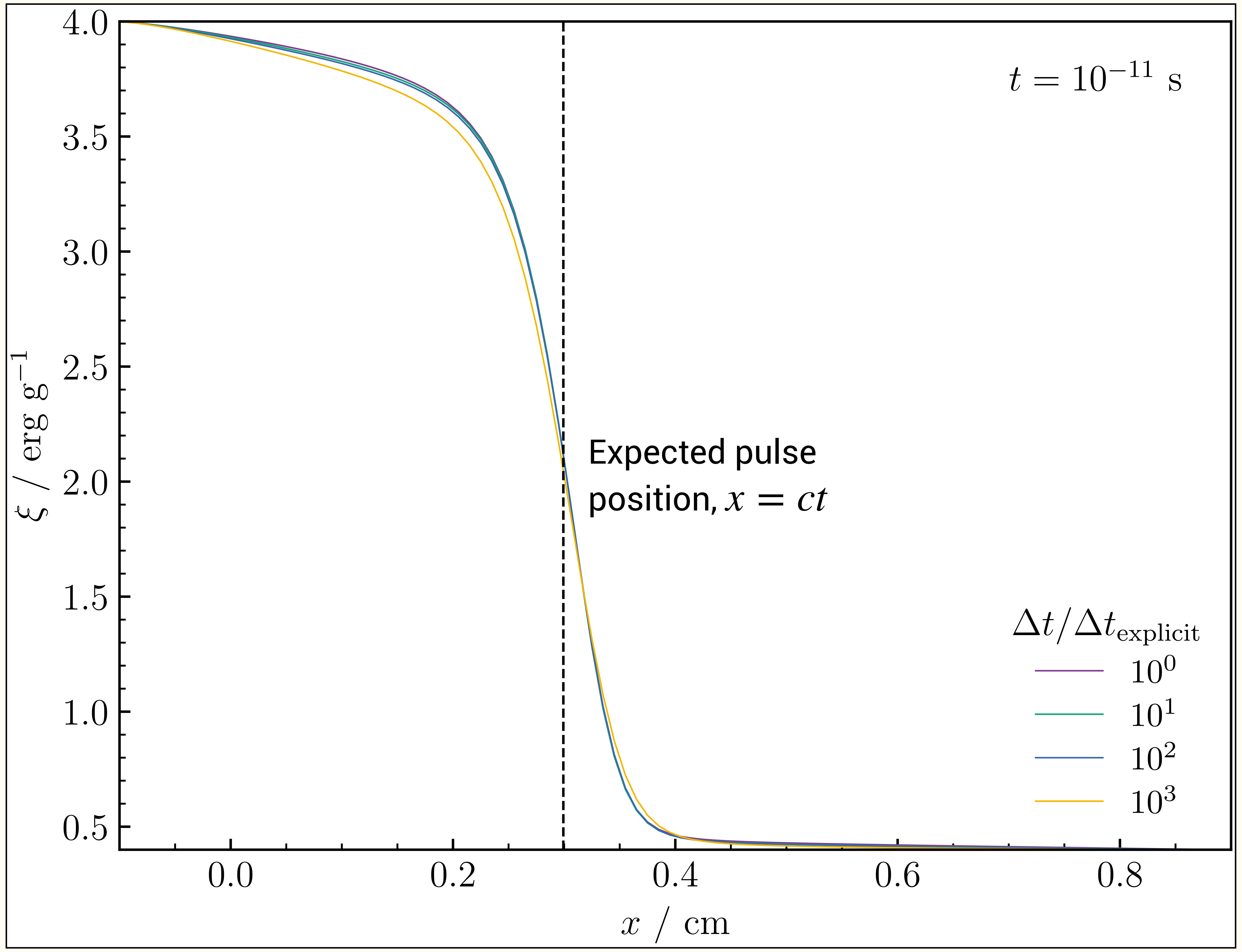


Solid lines: Analytical solution at different times

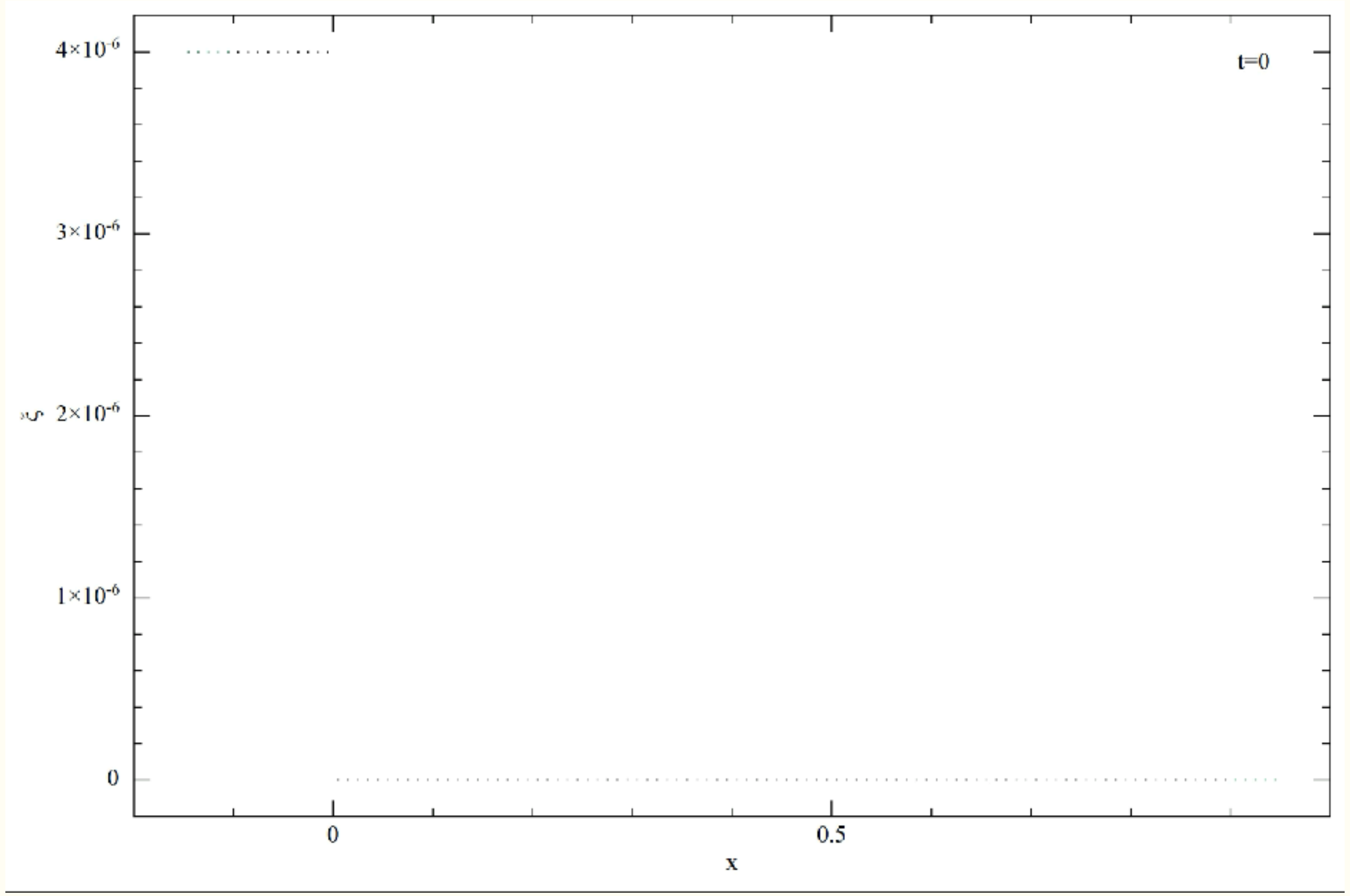
Markers: Implicit solver

Radiation pulse in optically thin medium

Whitehouse & Bate 2004



$\xi_{\rm left} = 10^{10}\xi_{\rm right}$



- Can be reproduced using new option in `SETUP=shock`
- $\xi_{\rm left} = 10\xi_{\rm right}$

Radiative shock tube

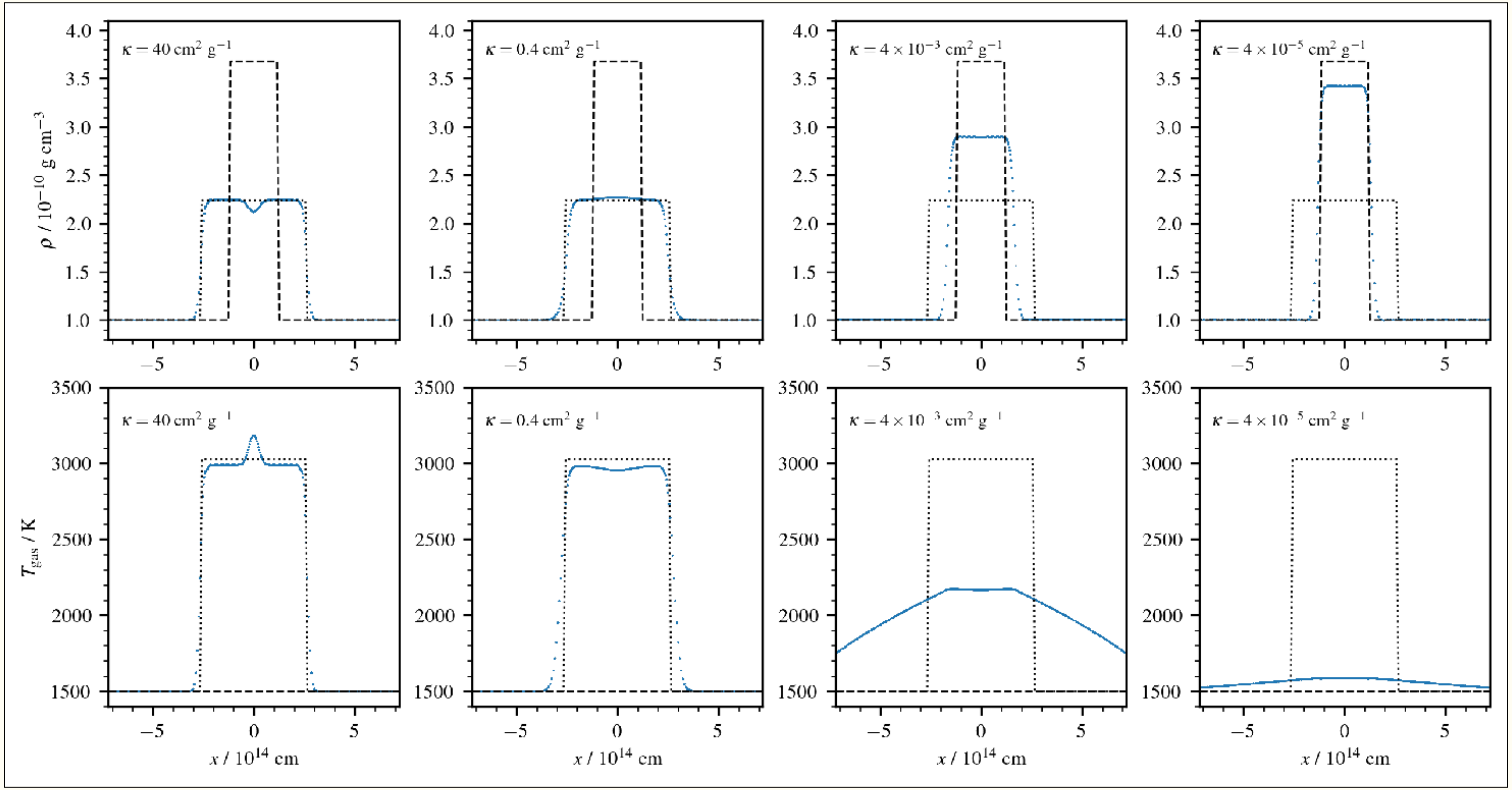
Biriukov 2020 (PhD thesis)

Adiabatic limit
(dotted line)

Isothermal limit
(dashed line)

Density

Temperature



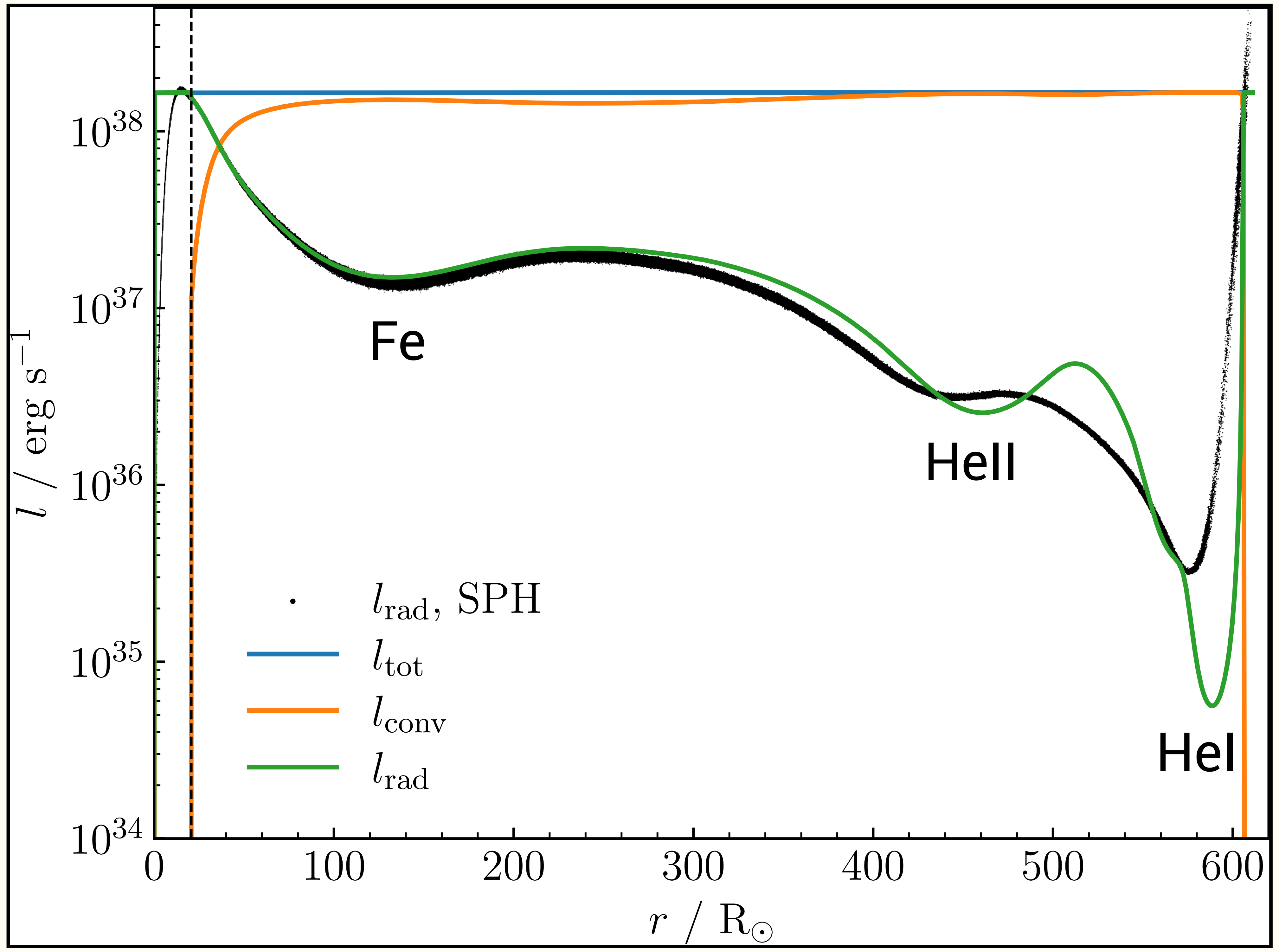
Setup

- Initial conditions are identical to past adiabatic simulations (**Lau+** 2022a,b)
- Donor star is based on a MESA red supergiant model:
  - $\mathrm{M} = 12\ \mathrm{M}_\odot, \mathrm{R} = 618\ \mathrm{R}_\odot, L = 1.68 \times 10^{38}\ \mathrm{erg\ s^{-1}}$
  - Dense helium core is replaced with a point mass that only interacts via cubic-spline-softened gravity
  - Envelope resolved with 2 million SPH particles
- Represent companion using a $3\ \mathrm{M}_\odot$ point mass in a circular, Keplerian orbit

We do not drive envelope convection in the pre-common-envelope donor, and prescribe a flat-entropy initial profile that is convectively stable

***Lau**+ 2022a*

Luminosity profile



Issues:

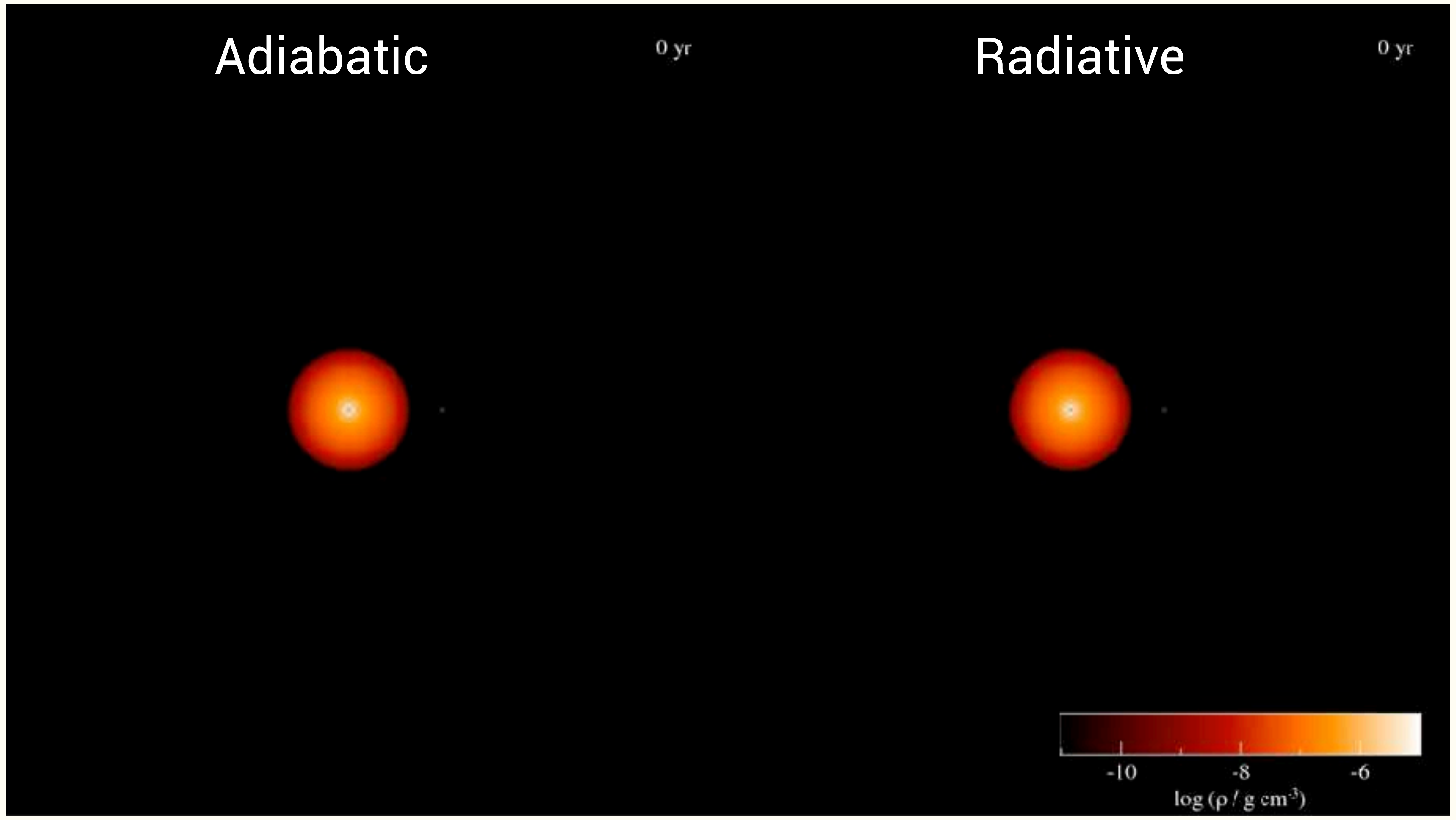
- Envelope is not in thermal equilibrium and will thermally adjust over ~ few years
- Centre of star contracts as energy diffuses outwards

➡ Include a control run where luminosity is compensated through *central point-mass heating*

$$\frac{L\Delta t_{\rm inspiral}}{E_{\rm bind}} = 0.022 \left(\frac{L}{1.7\times10^{38}\ \mathrm{erg\ s^{-1}}}\right)\left(\frac{\Delta t_{\rm inspiral}}{5\ \mathrm{yr}}\right)\left(\frac{E_{\rm bind}}{1.2\times10^{48}\ \mathrm{erg\ s^{-1}}}\right)^{-1}$$

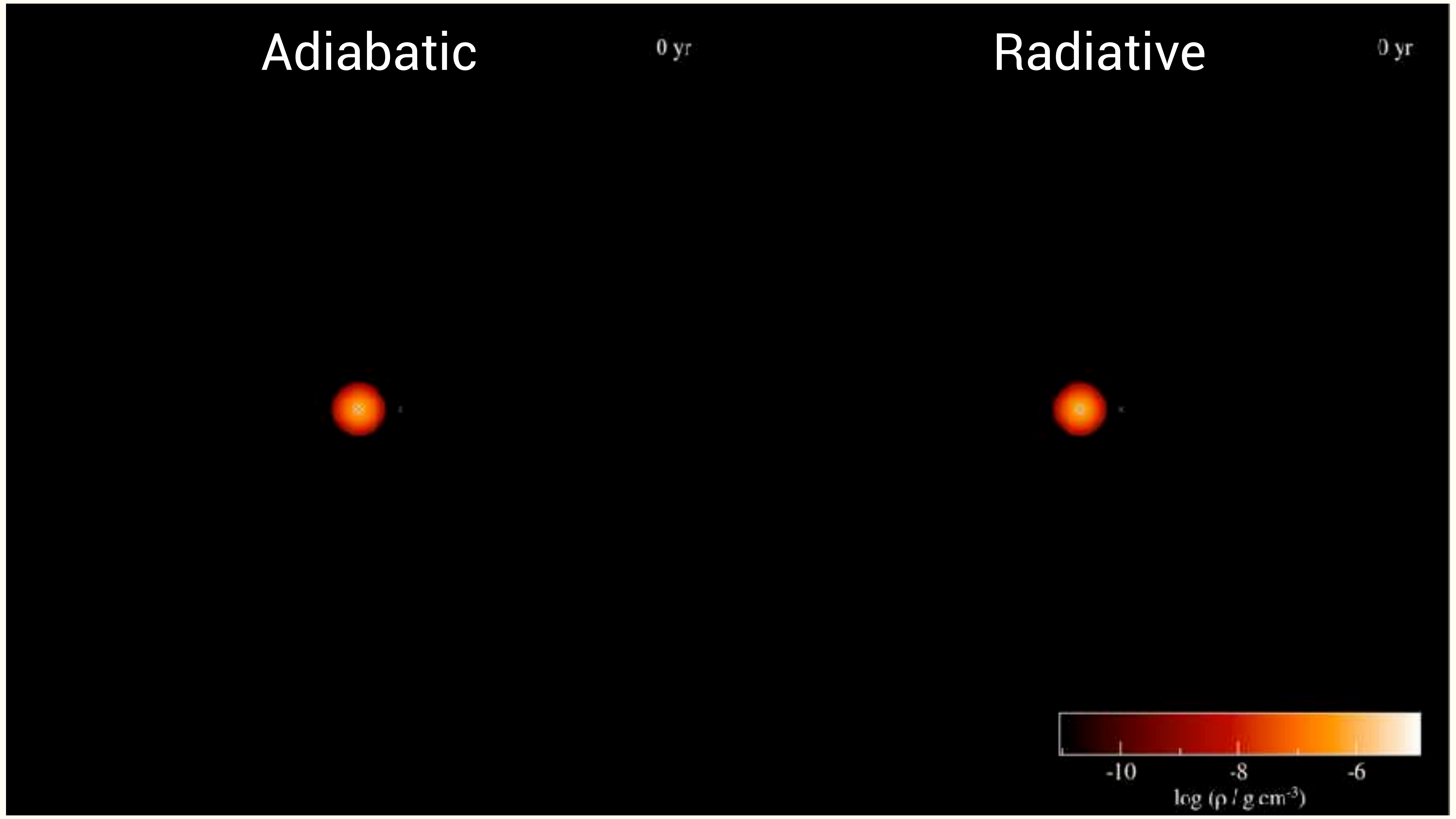
Face-on density slice

Lau+ 2022a **Lau+** 2025

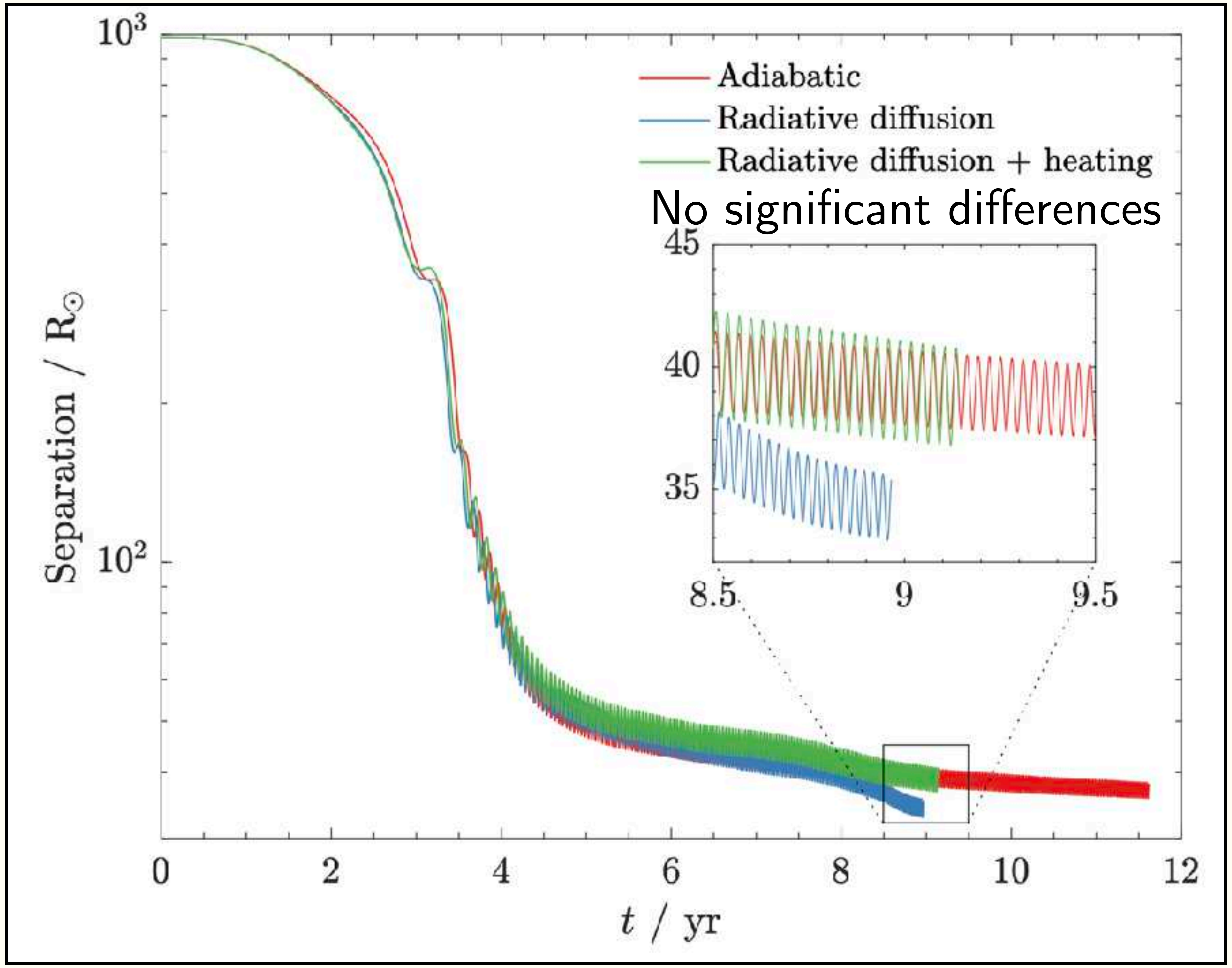


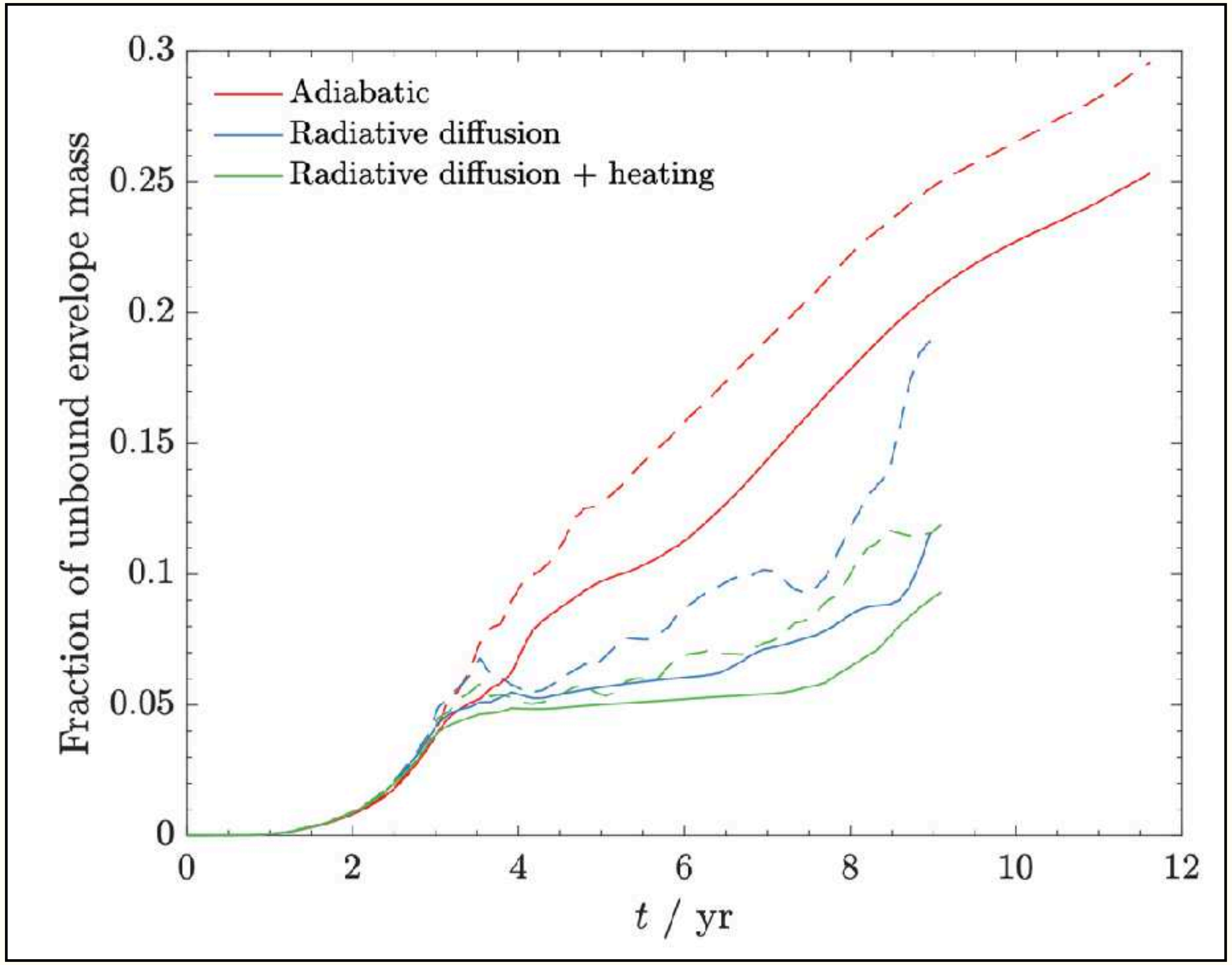
Edge-on density slice

Lau+ 2022a **Lau+** 2025



Lau+ 2025





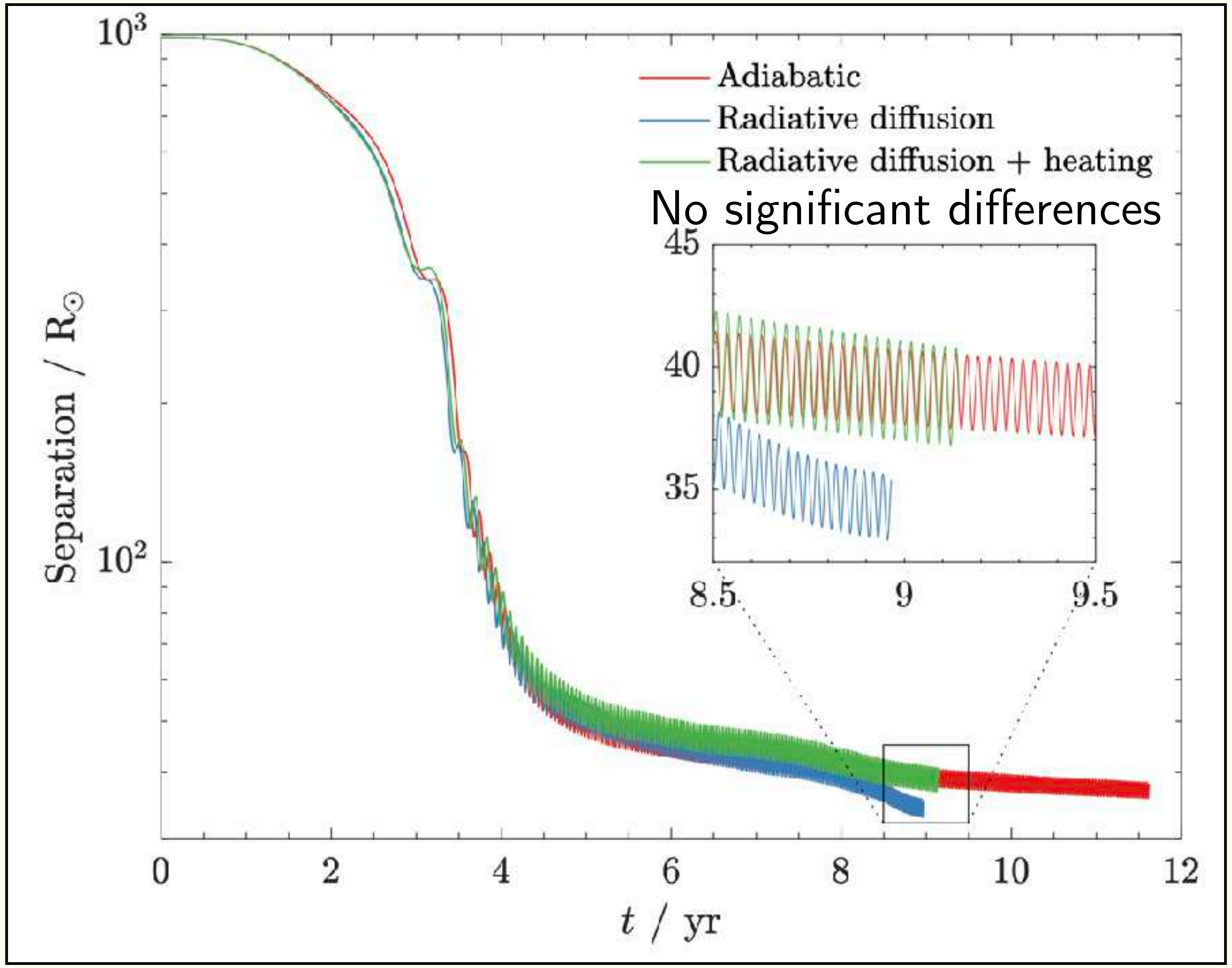
Solid lines: Unbound $\iff e_k + e_p > 0$

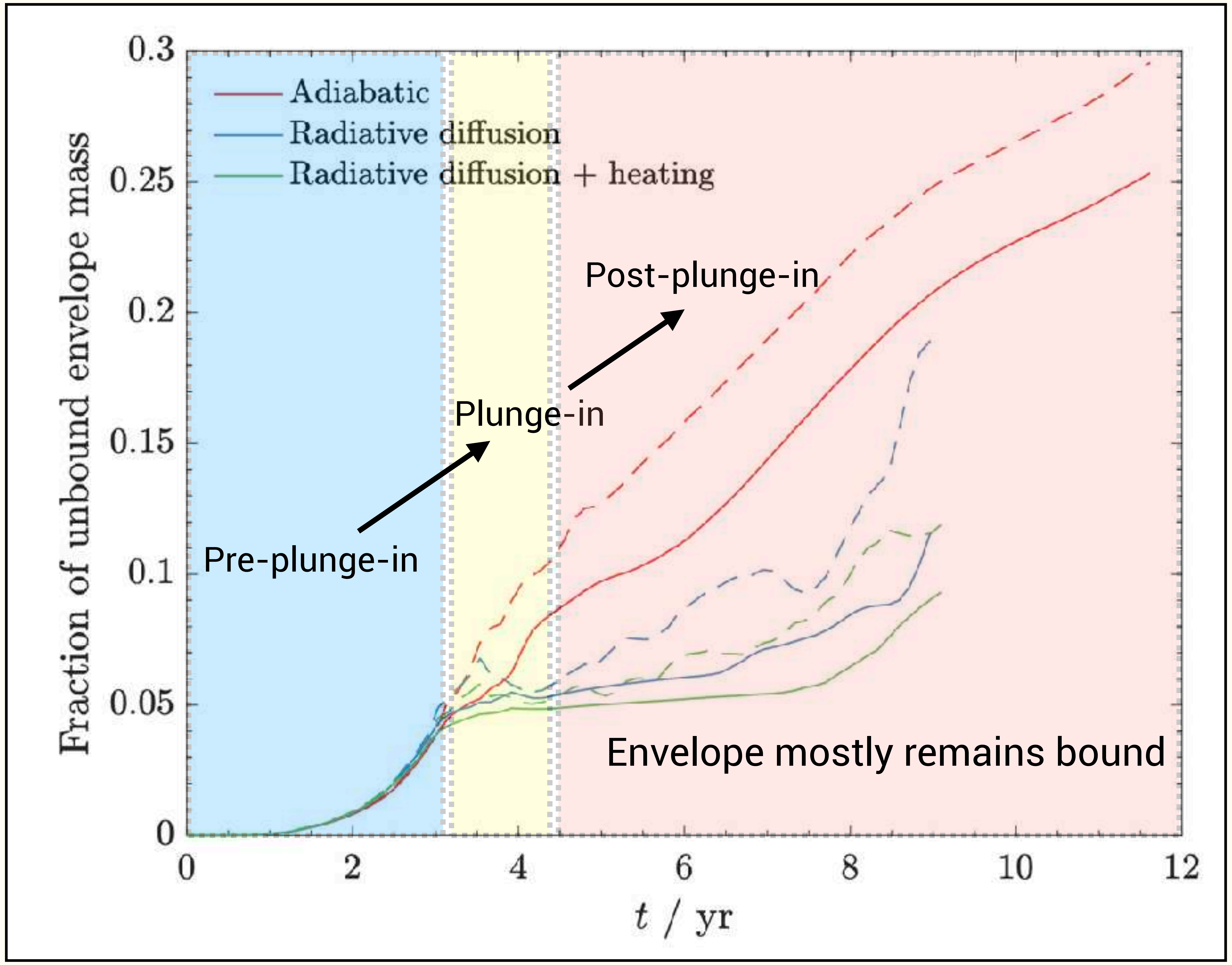
Dashed lines: Unbound $\iff e_k + e_p + e_{\mathrm{th}} > 0$

➡ No significant differences in the post-plunge-in orbital separation

➡ Radiative diffusion significantly suppresses envelope ejection

Lau+ 2025





Solid lines: Unbound $\iff e_k + e_p > 0$

Dashed lines: Unbound $\iff e_k + e_p + e_{th} > 0$

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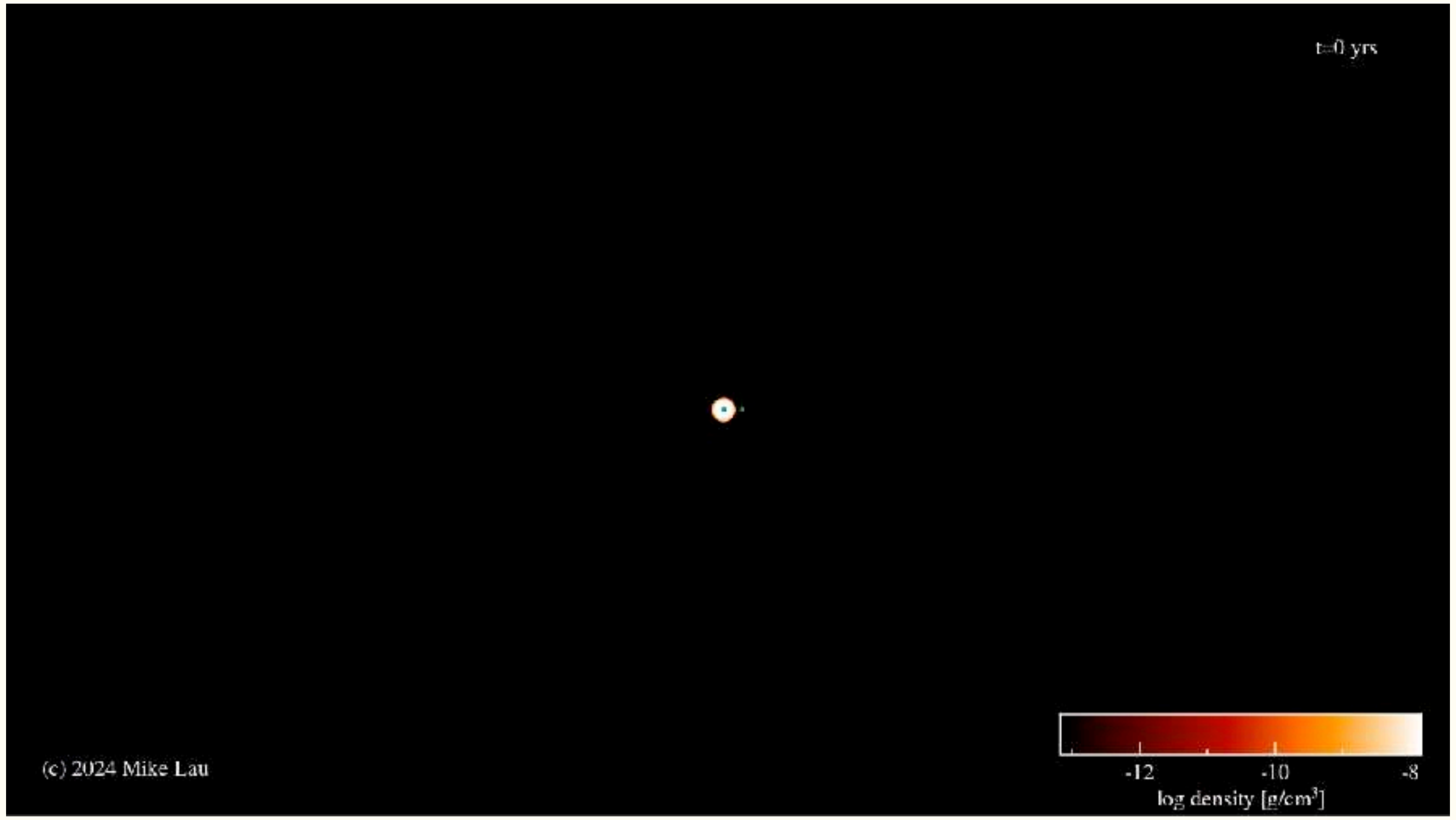
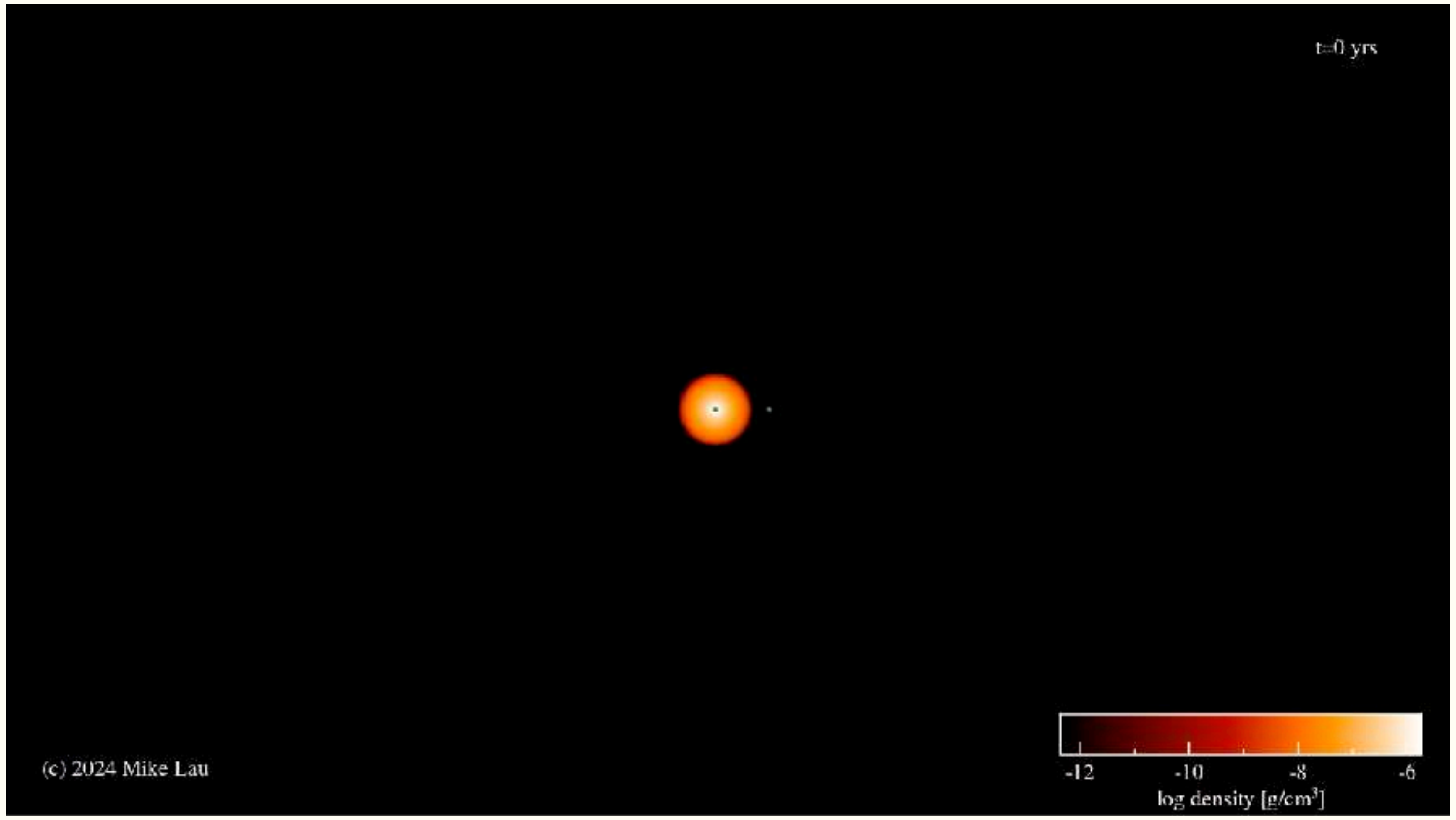
Edge-on density slice

Adiabatic



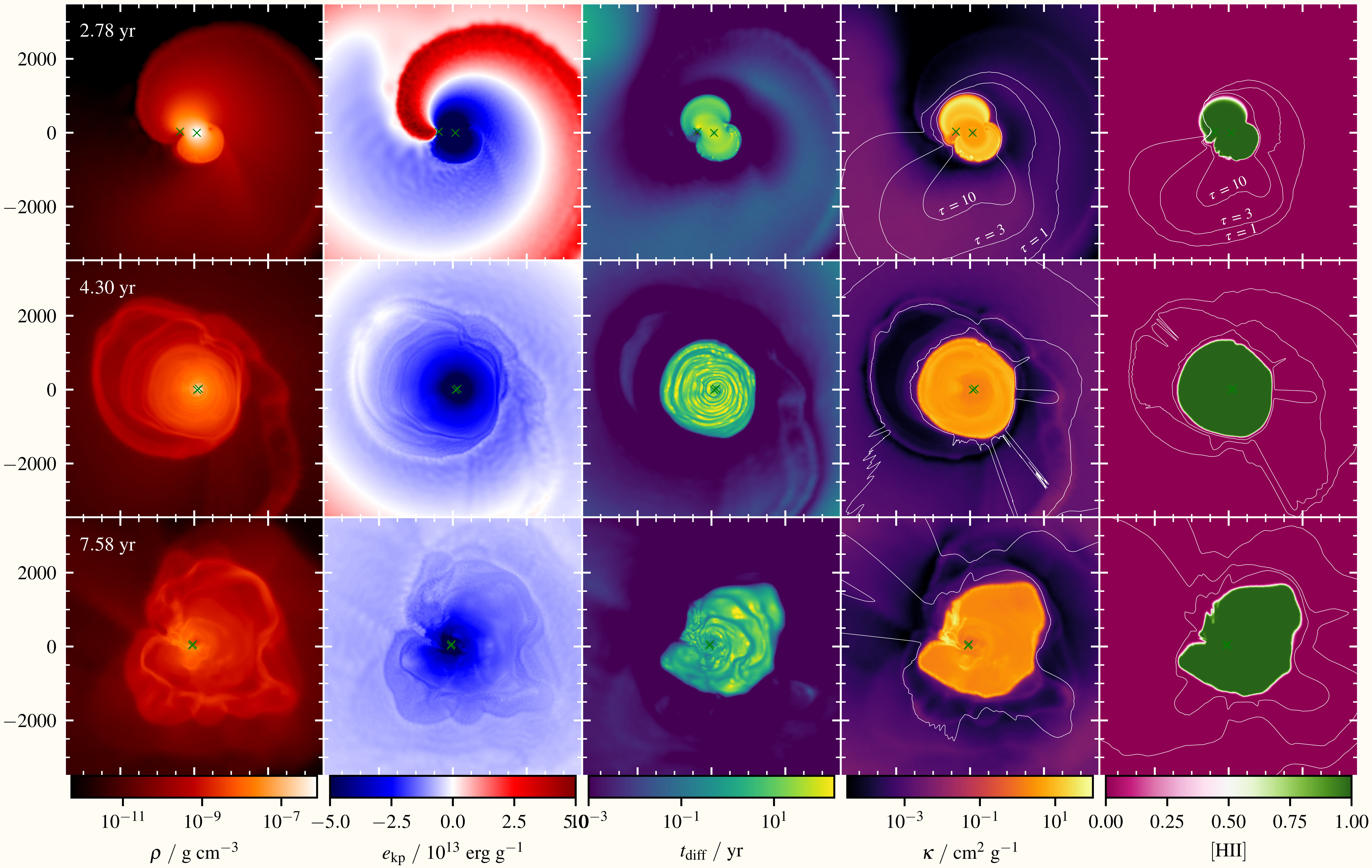
Clear bipolar morphology driven by fast outflows near the central binary

Radiative diffusion



Strong suppression of bipolar morphology due to fall back of ejecta. Obtain weak, intermittent plumes instead

Face-on view



Define local diffusion time,

$$t_{\rm diff} := \frac{\kappa\rho}{c\lambda}\left(\frac{E}{|\nabla E|}\right)^2,$$

as the diffusion time across the temperature scale height

- Steep drop in $t_{\rm diff}$ from ~ 10 to $\lesssim 10^{-4}$ yr over poorly resolved region
- Steep drop in $t_{\rm diff}$ is associated with opacity drop from H recombination
- Bound material has very short $t_{\rm diff}$

Wrapping up: Room for improvement

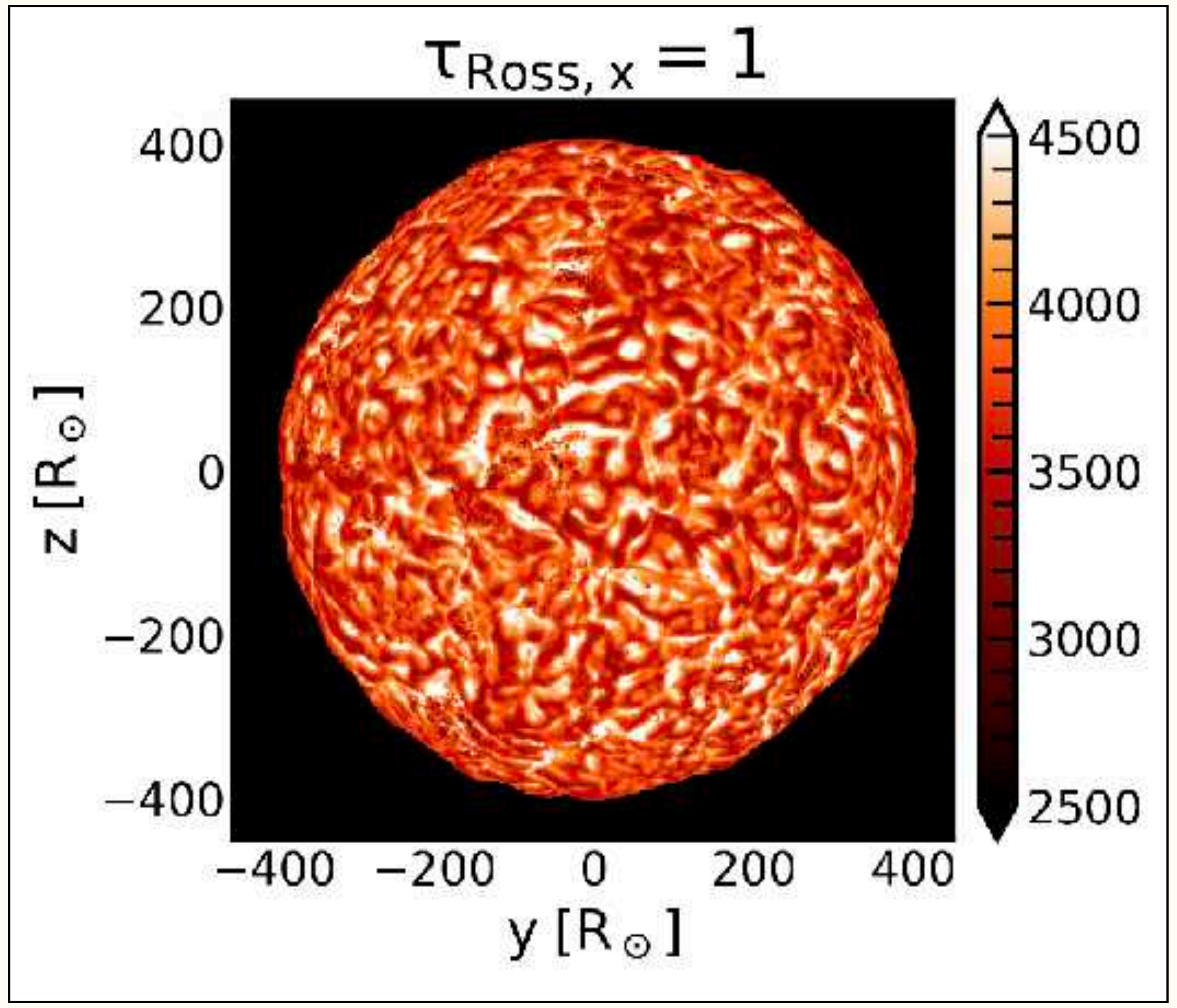
Recombination energy

- Add recombination energy, making substantial progress towards settling the debate on its relevance
  Sabach+ 2017, Grichener+ 2018, Ivanova 2018, Soker+18
- Cannot use MESA EoS tables directly, because radiation energy must be separated out from the total internal energy
- Current progress: Use Ryo Hirai's fits analytical treatment of ionisation physics (gas + radiation + recombination EoS, `ieos=20`), including new fits of c_V accounting for rotational and vibrational degrees of freedom of H_2

Convection and optically thin radiation transport

- A realistic 3D giant star must have convection driven by photospheric cooling
- Photospheric cooling is not correctly captured due to the unresolved photosphere and an initial lack of SPH particles above the photosphere to radiate into

Ma+ 2025: $10\ \mathrm{M}_\odot$ red supergiant



Full 4π envelope convection with resolved photosphere in *AREPO* using Implicit Discrete Ordinates Radiation Transport

Astrophysical implications

Towards non-adiabatic envelope ejection

- A substantial fraction of the envelope is removed on timescales much longer than the dynamical timescale, a so-called *self-regulated phase*

Meyer & Meyer-Hofmeister 1979, Podsiadlowski 2001

- Post-common-envelope binaries with distant tertiary companion support ejection timescales of $10^2 - 10^4$ yr

Michaely & Perets 2019, Igoshev+ 2020

- Traditional "energy formalism" breaks down

Hirai & Mandel 2022

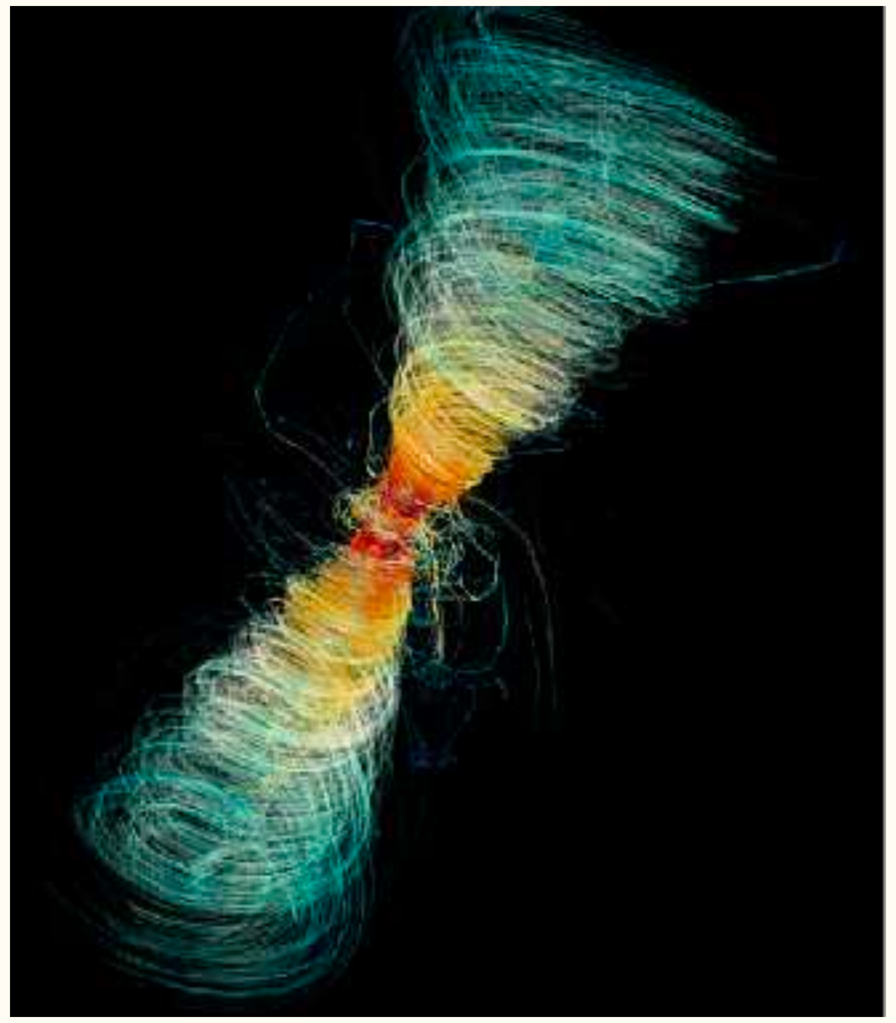
Implications of circumbinary material

- Circumbinary disk torques excite binary eccentricity and tighten orbit
- Circumbinary material could provide circumstellar material for *interacting supernovae* (e.g., SN 2014c)

Brethauer+ 2022, Orlando+ 2024

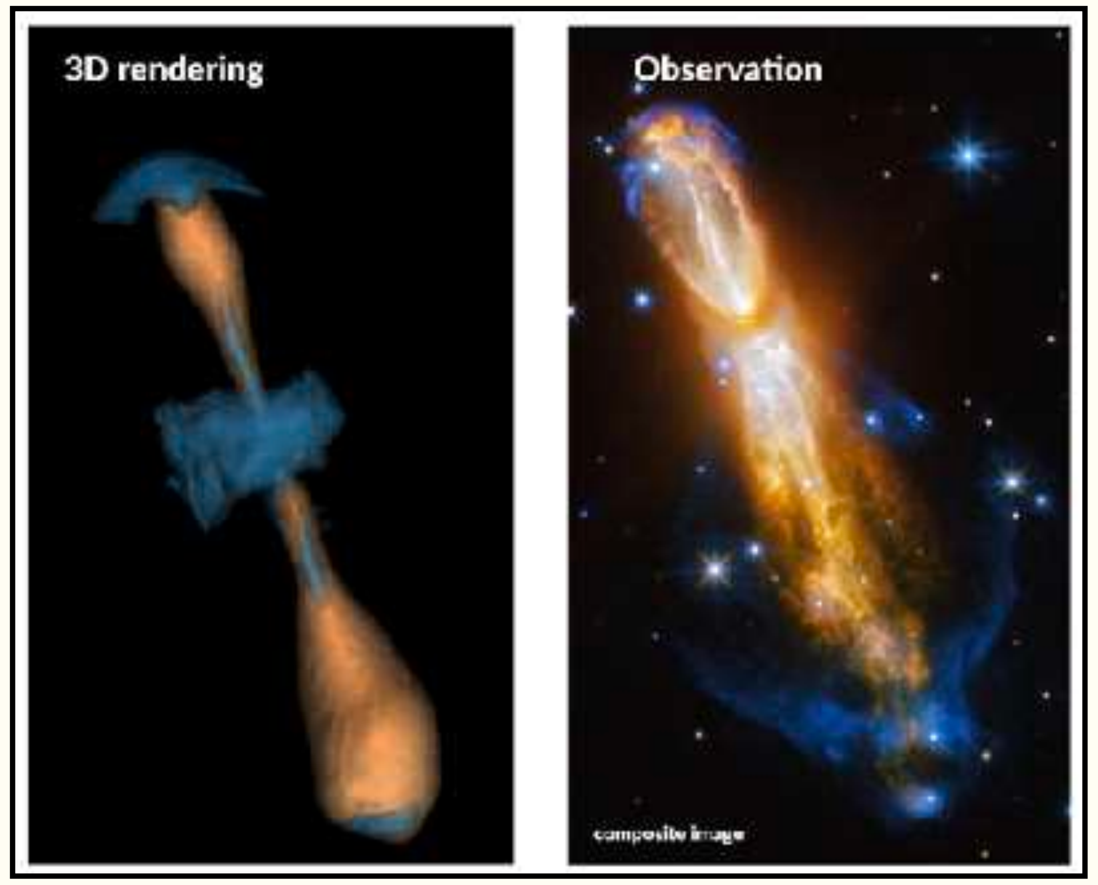
Circumbinary disk + bipolar outflows in MHD simulations

Vetter+ (inc. **Lau**) 2024, 2025



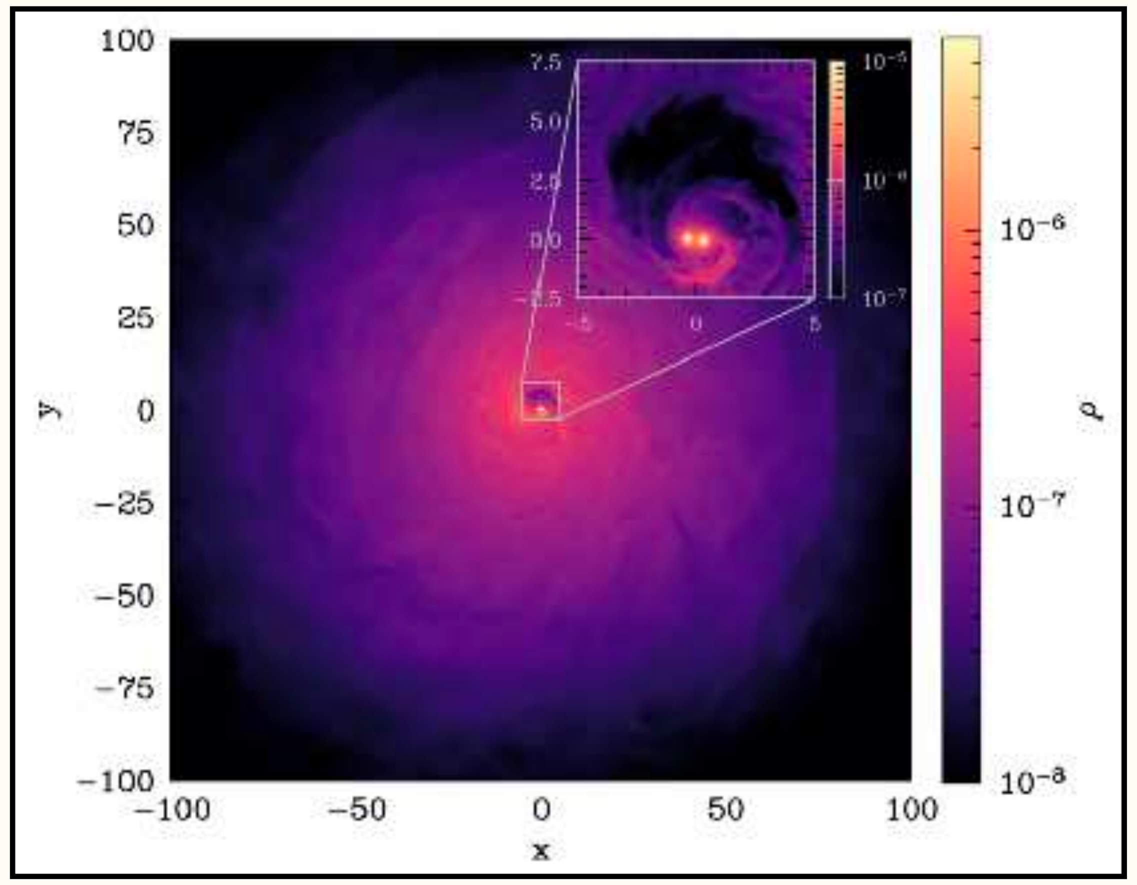
3D rendering of magnetic field lines in bipolar outflow

Ondratschek+ 2022



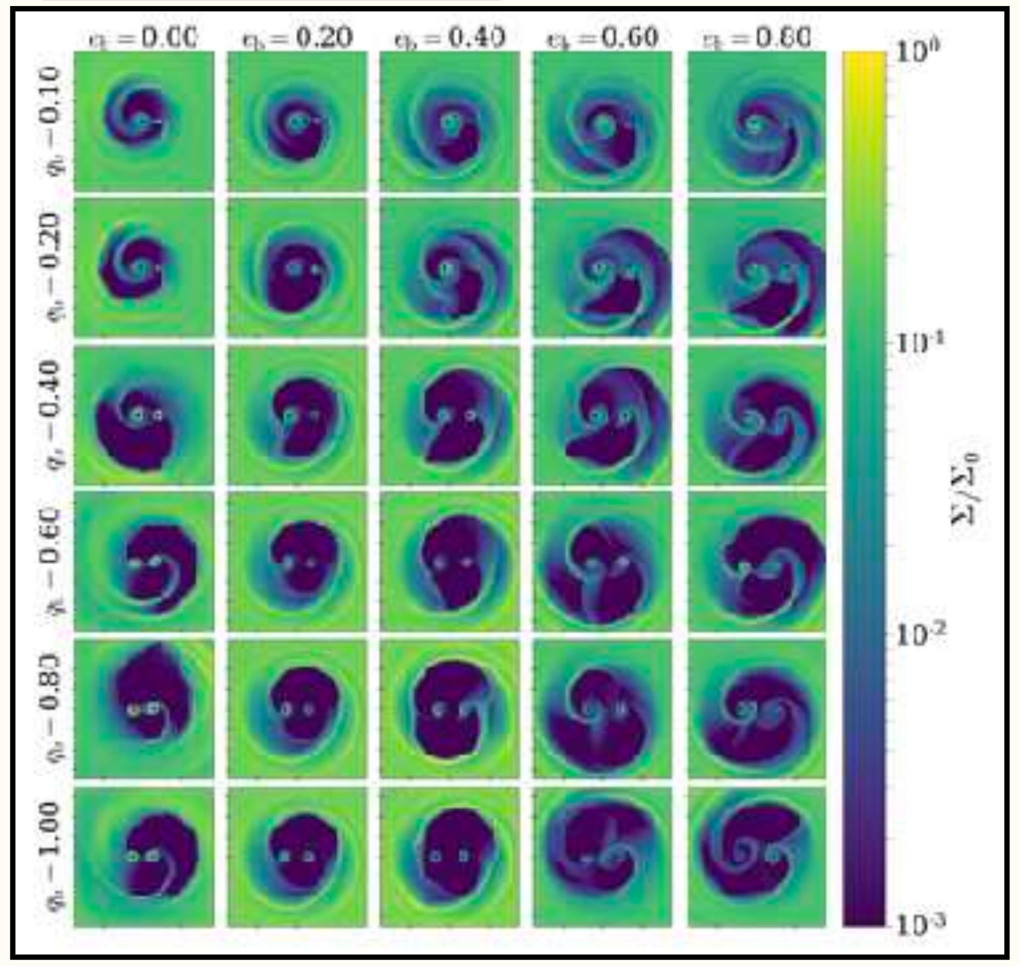
Comparison of ejecta with the Calabash nebula

Gagnier & Pejcha 2025



MHD simulation focusing on post-CE bound ejecta

Siwek+ 2023



Parameter study of circumbinary disk torques

Conclusions

- Common-envelope evolution is a crucial but poorly understood phase in the formation of many astrophysical objects
- We performed one of the first 3D radiation hydrodynamic simulations assuming flux-limited diffusion and grey opacities
- Radiative diffusion significantly suppresses bipolar outflows, reduces the amount of ejected mass, but does not alter the post-plunge-in orbital separation
- Our results support the emerging paradigm of a multi-step common-envelope evolution where a significant amount of the envelope is ejected after the plunge-in