Common envelopes and planetary engulfment in SPH

Feb 15, 2023

Joint Franco-Australian 5th Phantom and MCFOST Users Workshop

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Common-envelope evolution

1. Loss of co-rotation

   A companion star enters the extended envelope of a giant star

   E.g. Tidal instability
   Accretor unable to accept mass quickly enough
   Runaway mass transfer

2. Spiral-in

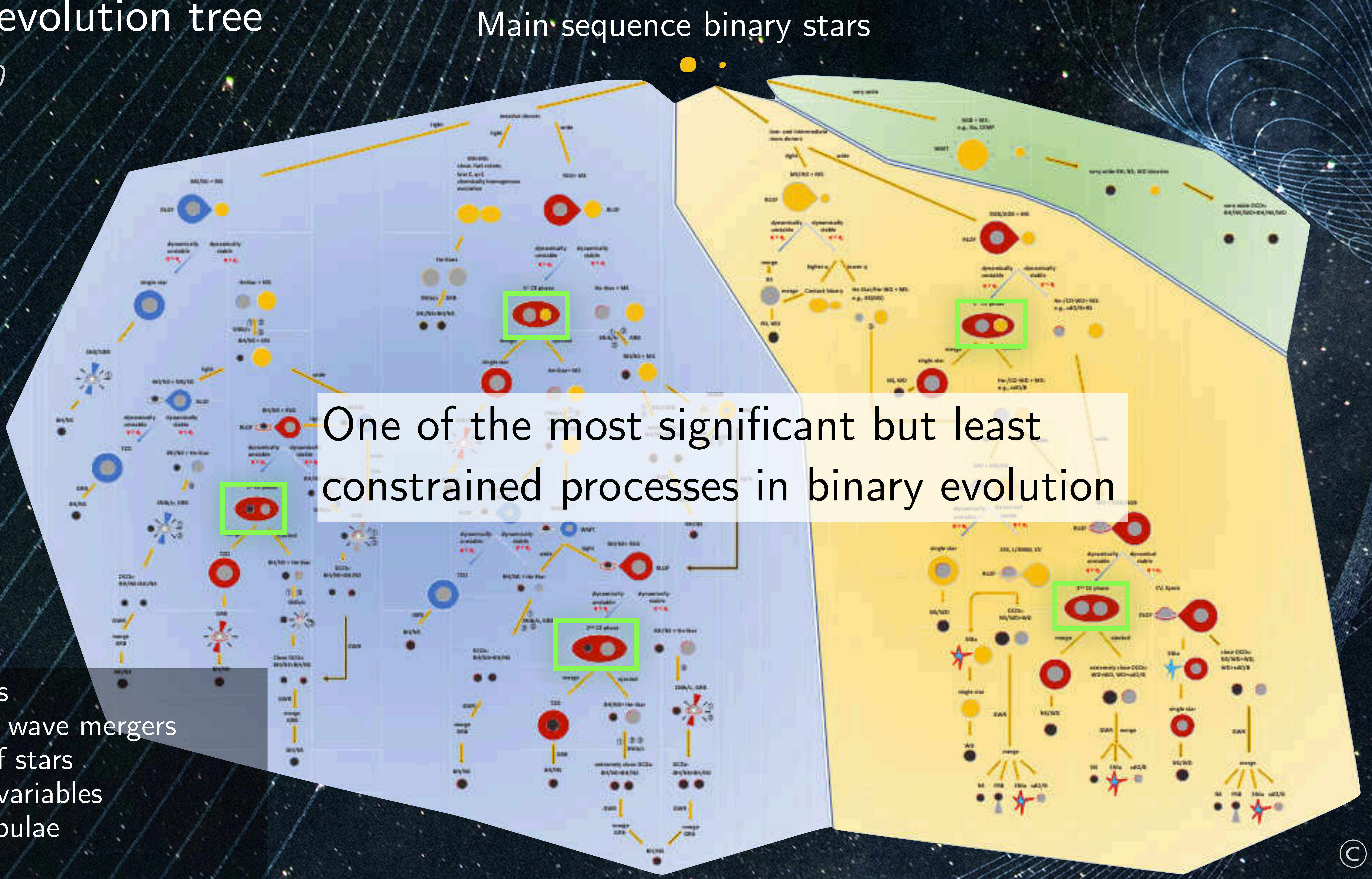
   Dynamical phase: Drag forces deposit orbital energy into the envelope

3. Envelope ejection or merger

   Expelling the envelope leaves a much tighter binary orbit

Binary evolution tree

Han+2020



One of the most significant but least constrained processes in binary evolution

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

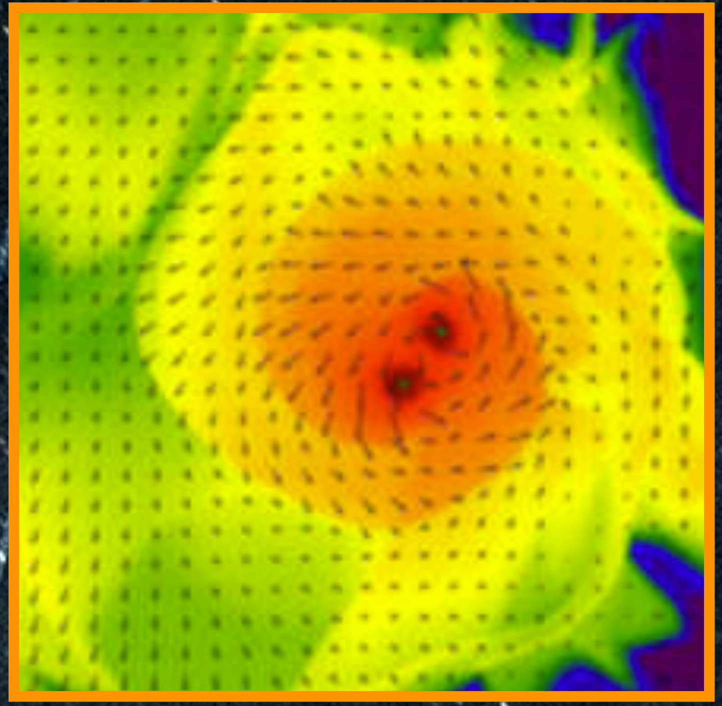
…

Detailed simulations

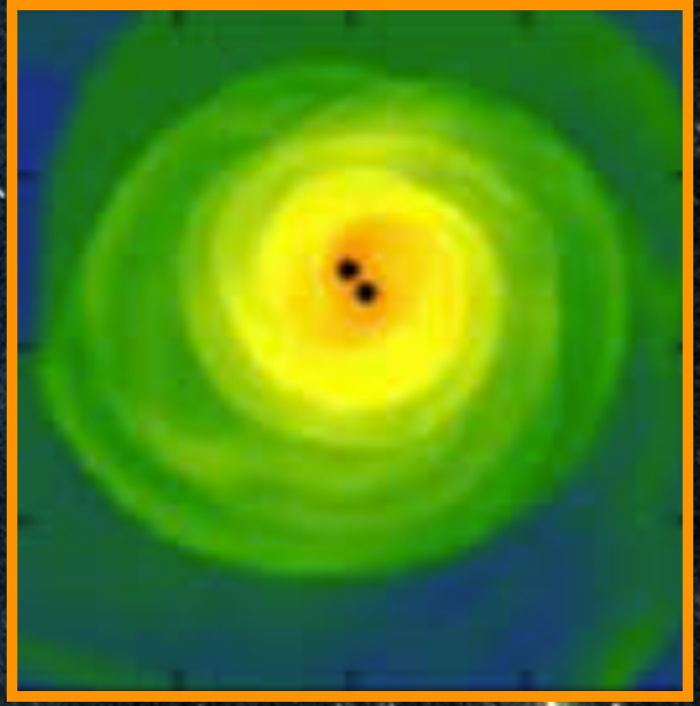
Key questions

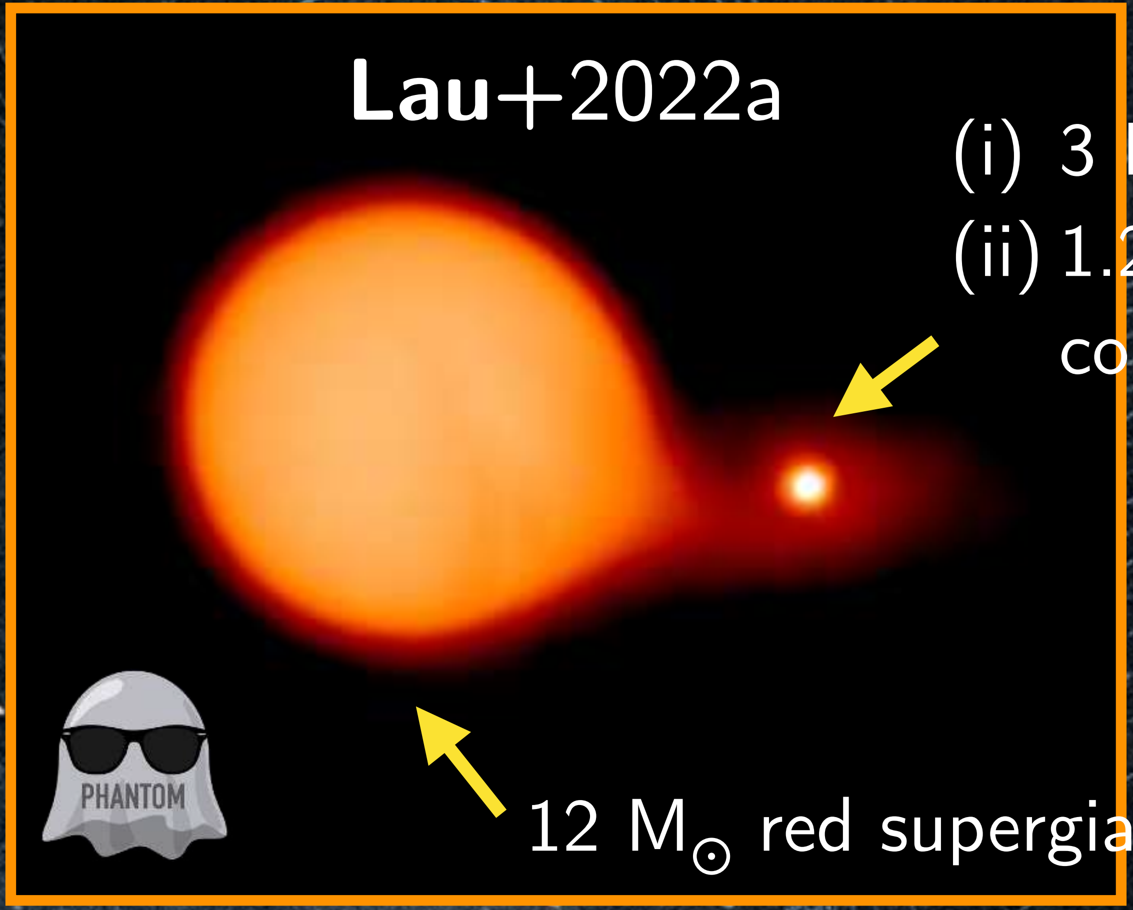
- *Can we fully eject the envelope?*
- *What is the final separation?*

Passy+2012



Iaconi+2017





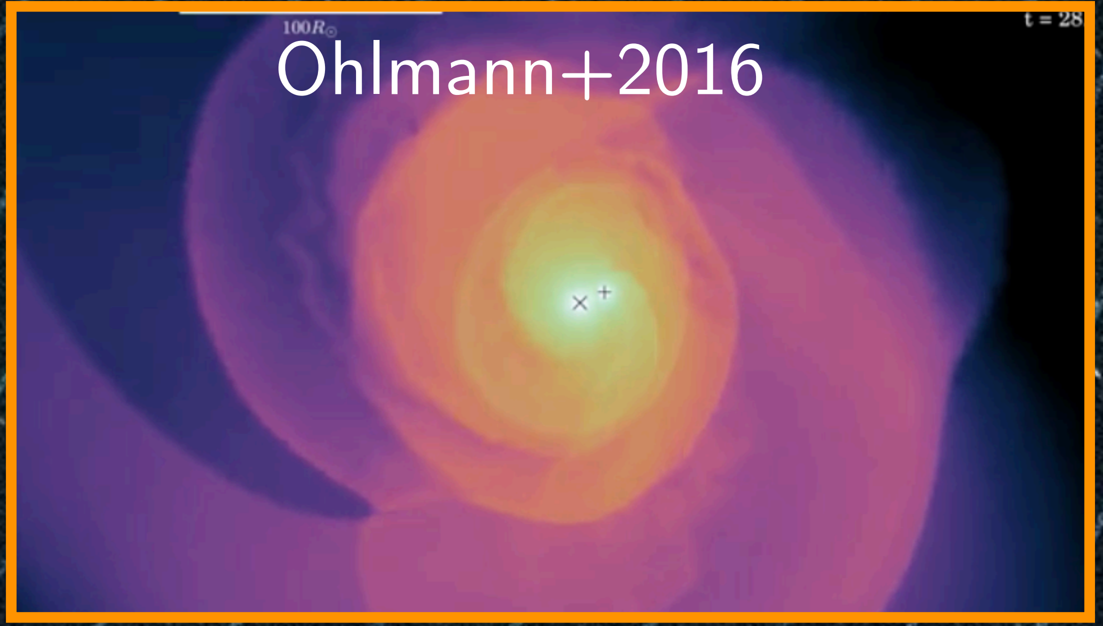
Lau+2022a

(i) 3 $M_\odot$

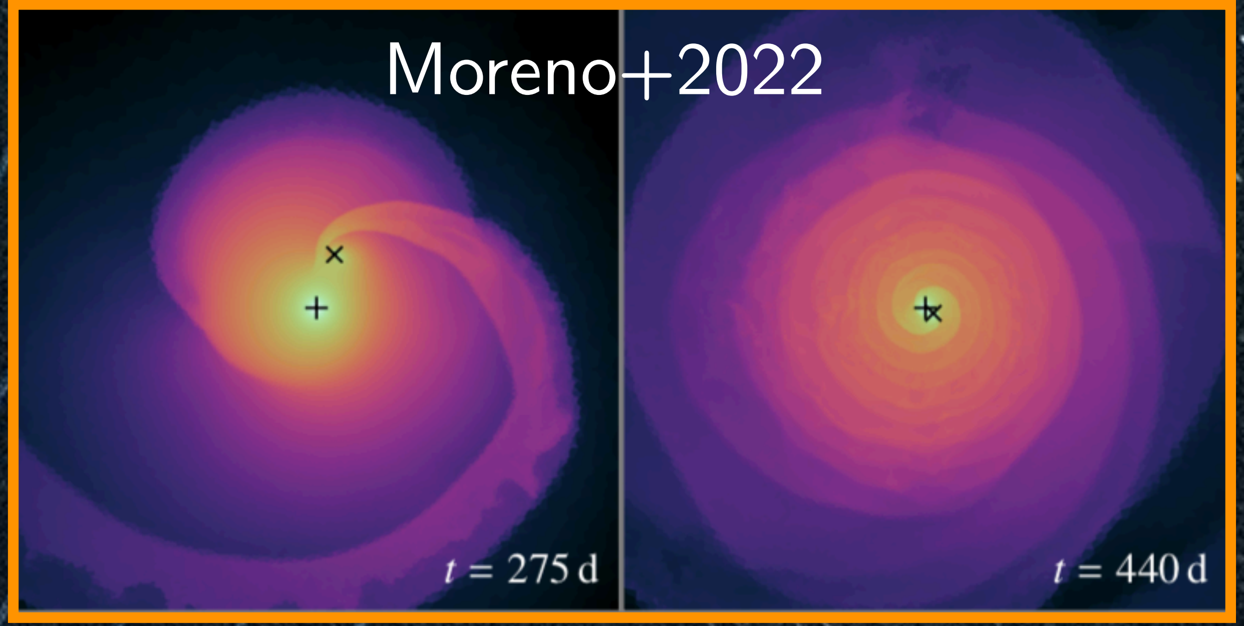
(ii) 1.26 $M_\odot$

companion

12 $M_\odot$ red supergiant donor

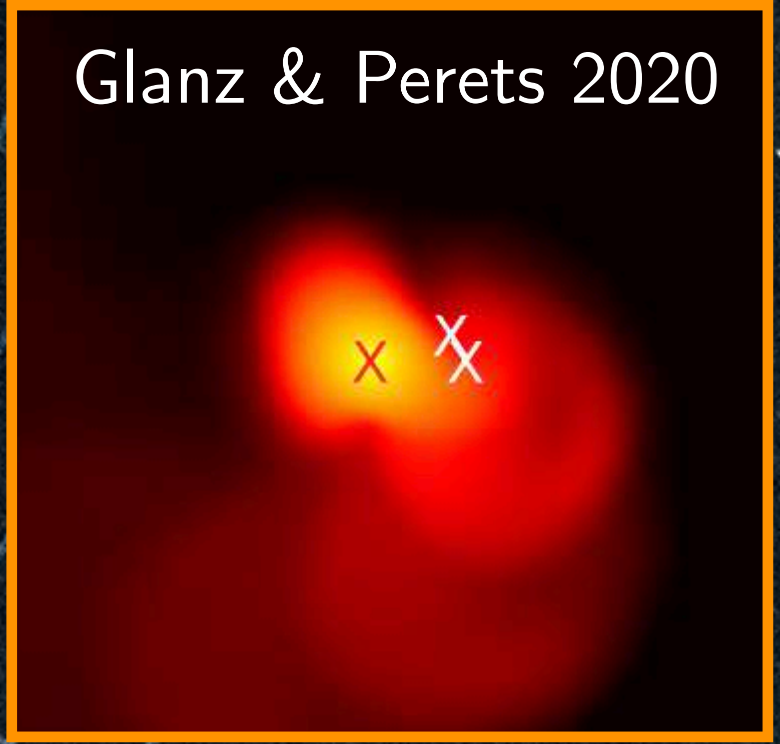


Ohlmann+2016

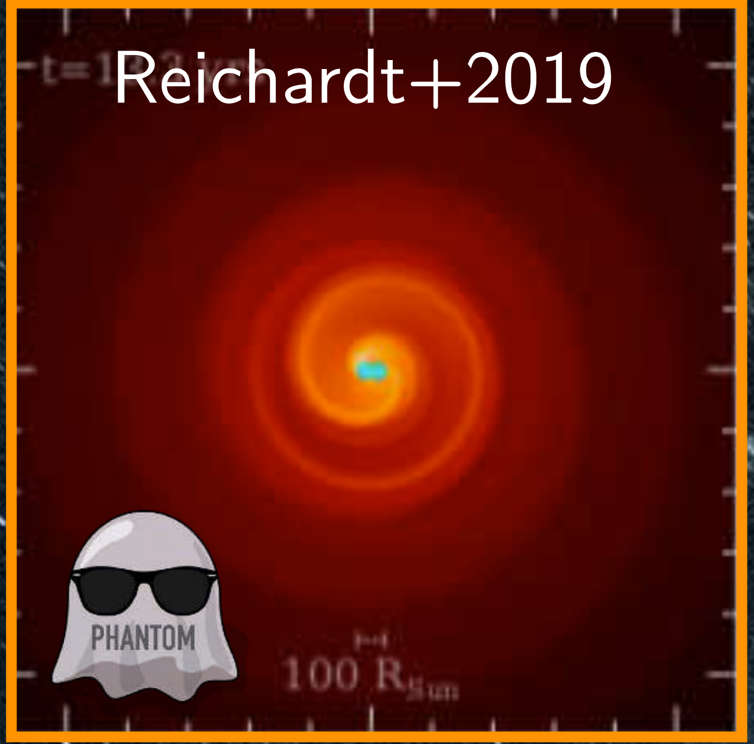


Moreno+2022

González-Bolívar+ (inc **ML**) 2022



Glanz & Perets 2020



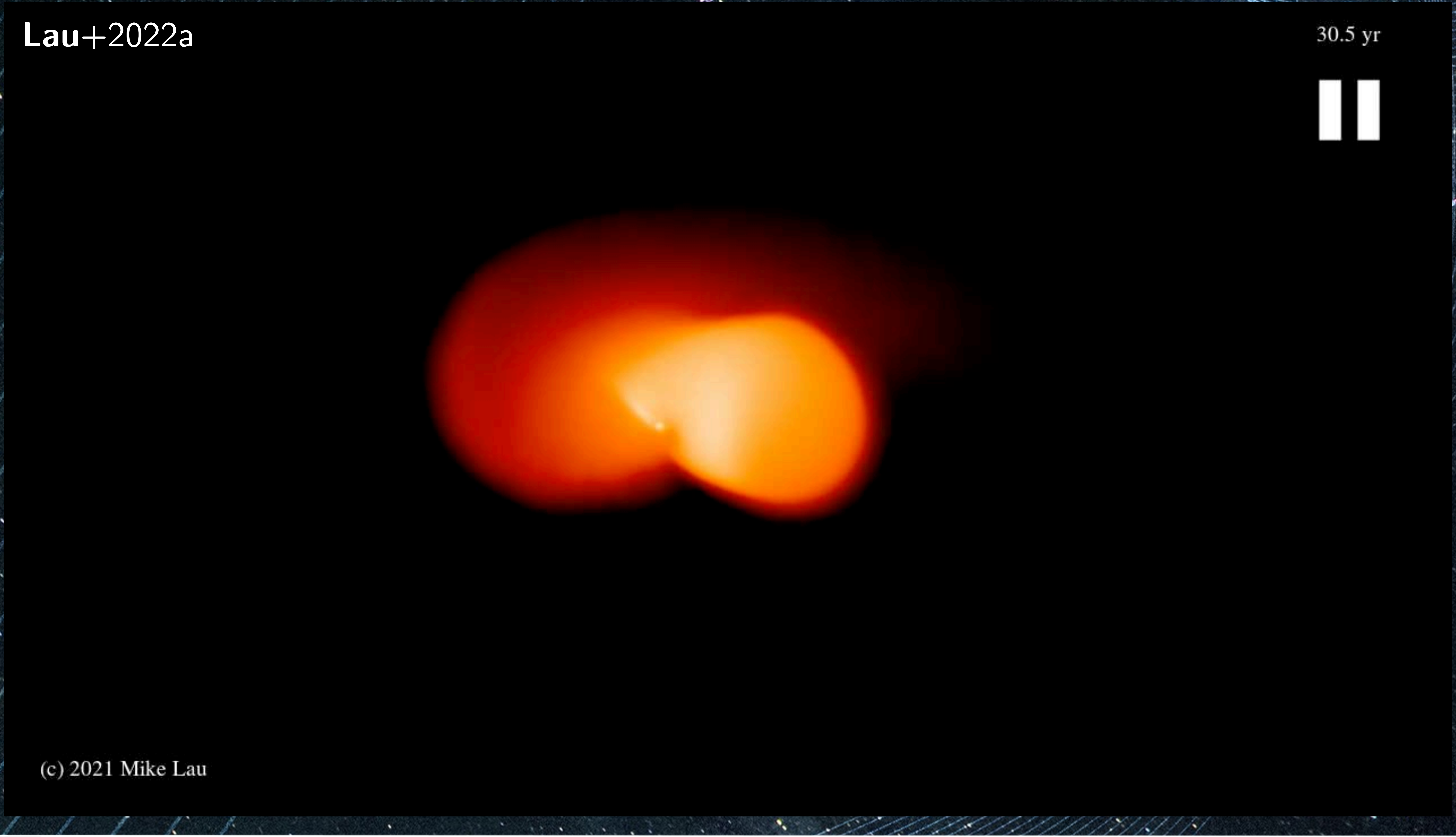
Reichardt+2019

Modelling common envelopes is very difficult

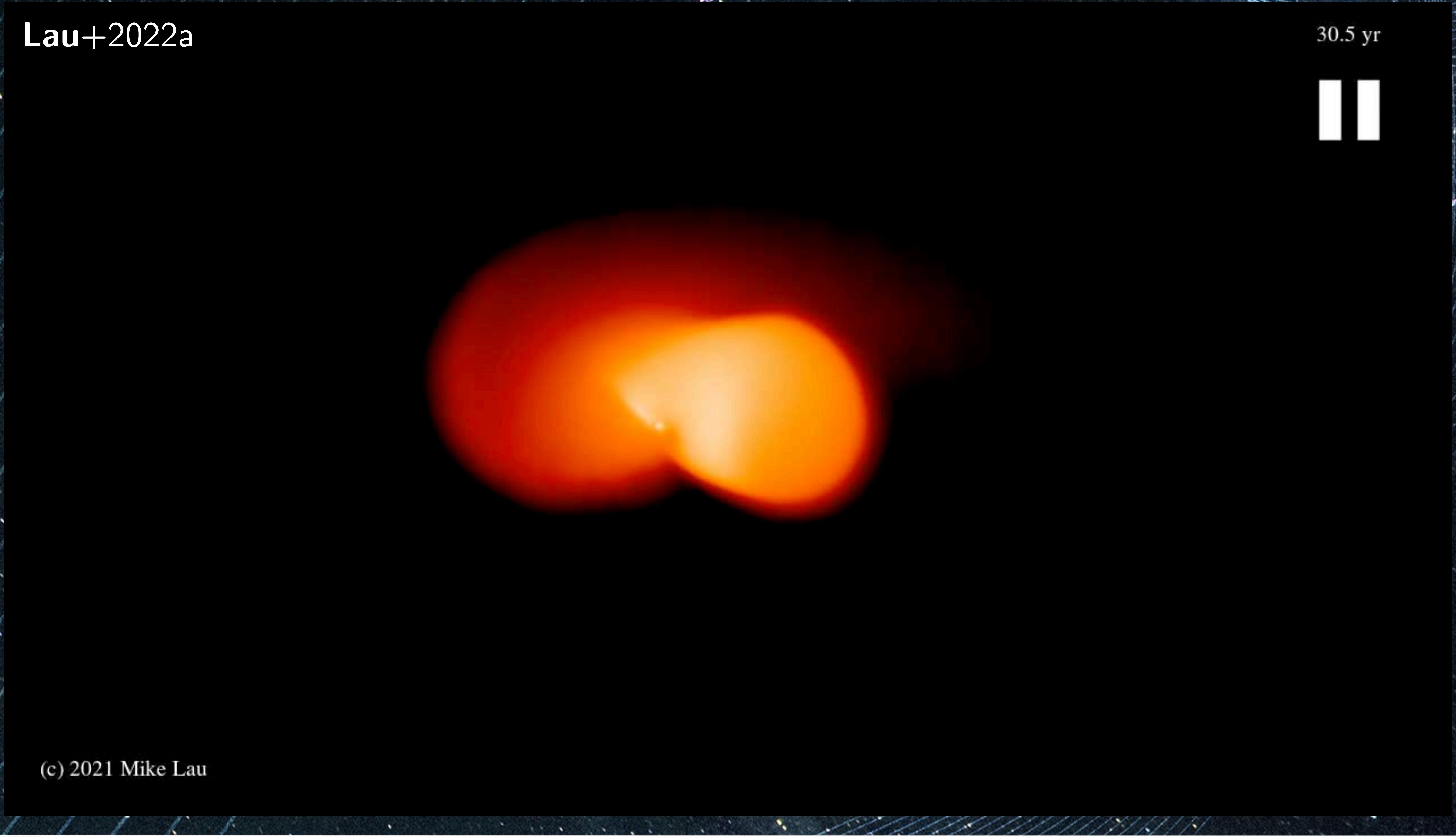
- Multi-dimensional
- Multi-physics: Hydrodynamics, gravity, radiation transport, turbulence(?), nuclear reactions(?), dust(?), jets(?), magnetic fields(?)
- Extreme dynamic range: Up to 8 orders of magnitude
- Unsuccessful in unbinding the entire envelope self-consistently

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

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



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



Lau+2022a

(c) 2021 Mike Lau

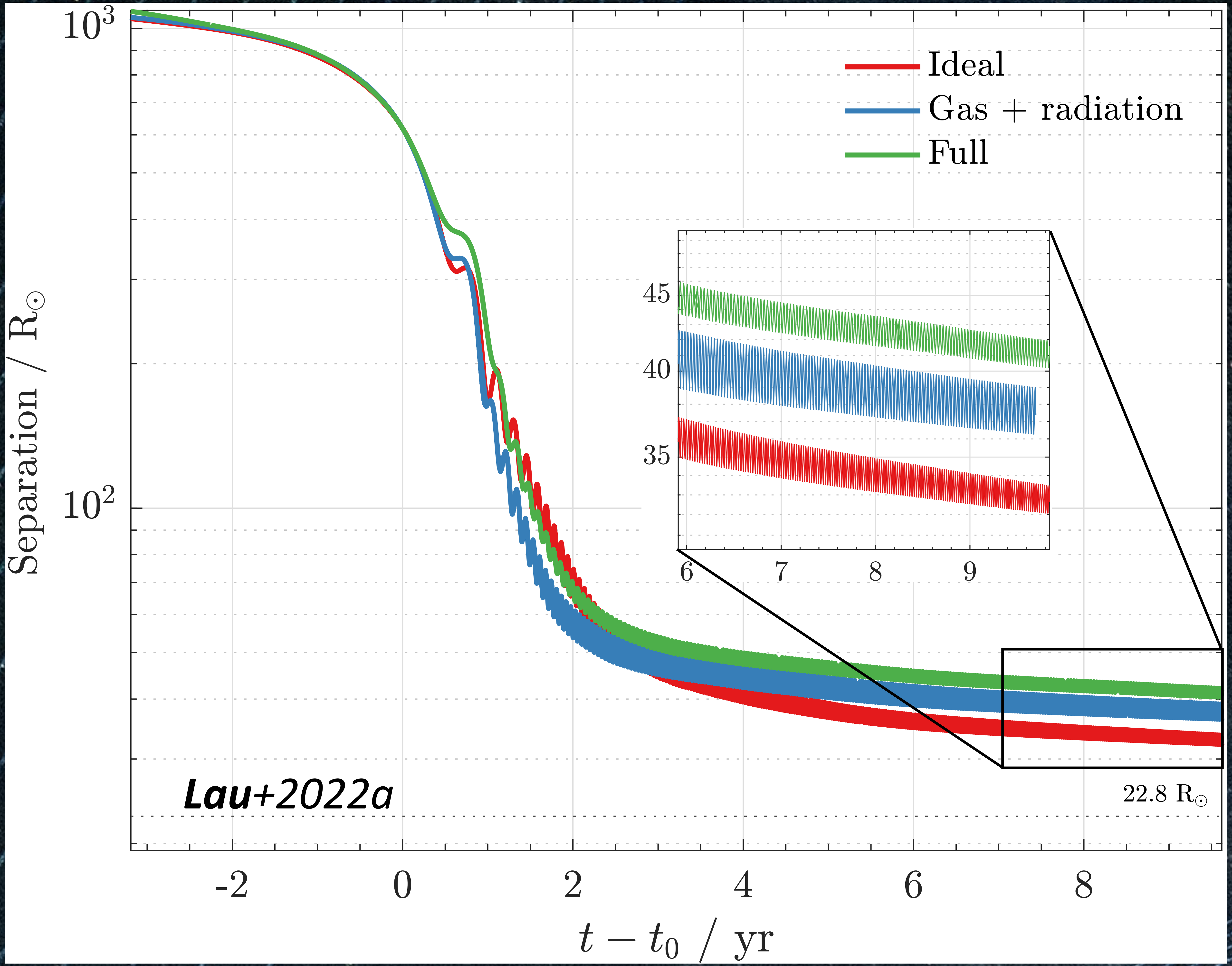
12 $M_\odot$ red supergiant + 3 $M_\odot$ companion

Lau+2022a

Density cross-section (face-on)
Gas + radiation EoS

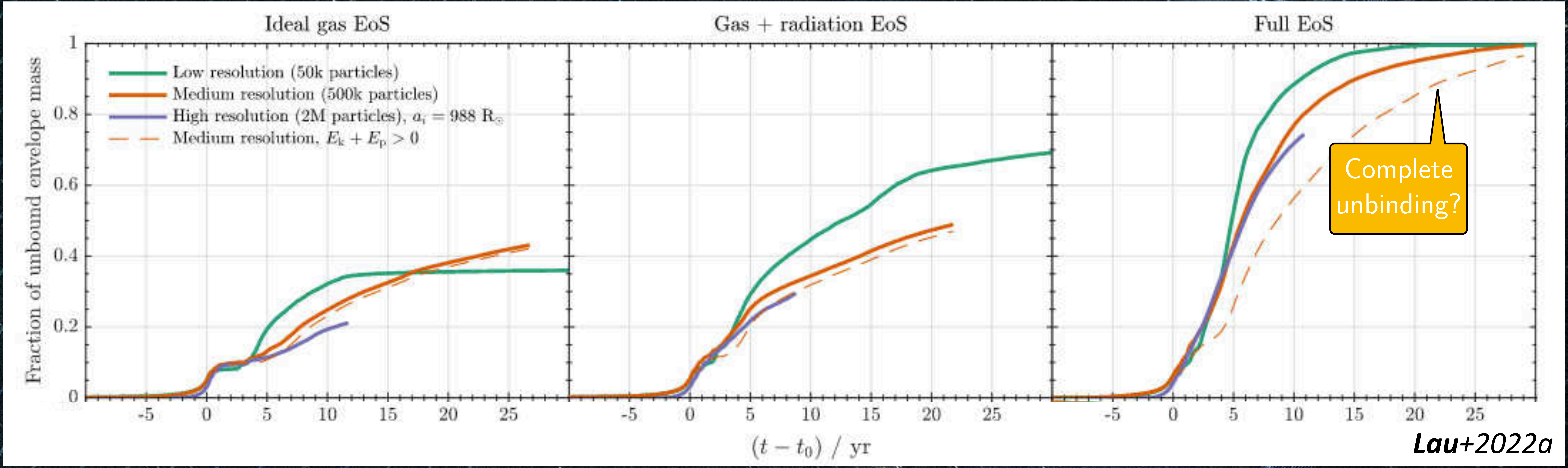
(edge-on)

Final separation



Radiation pressure and recombination energy increase final separation

Unbound mass



Complete unbinding?

Lau+2022a

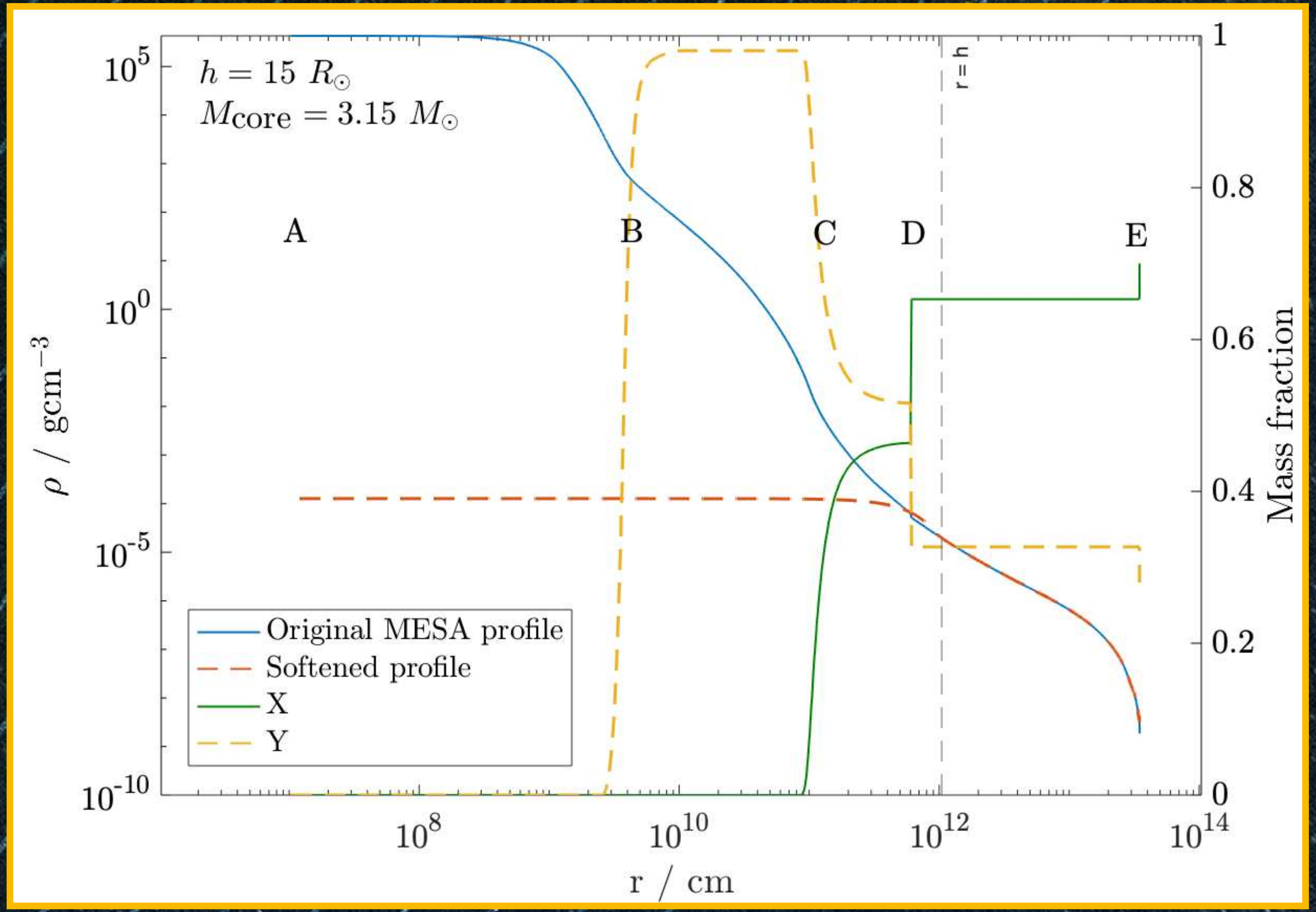
Increasing fraction of unbound envelope mass

Stellar core softening

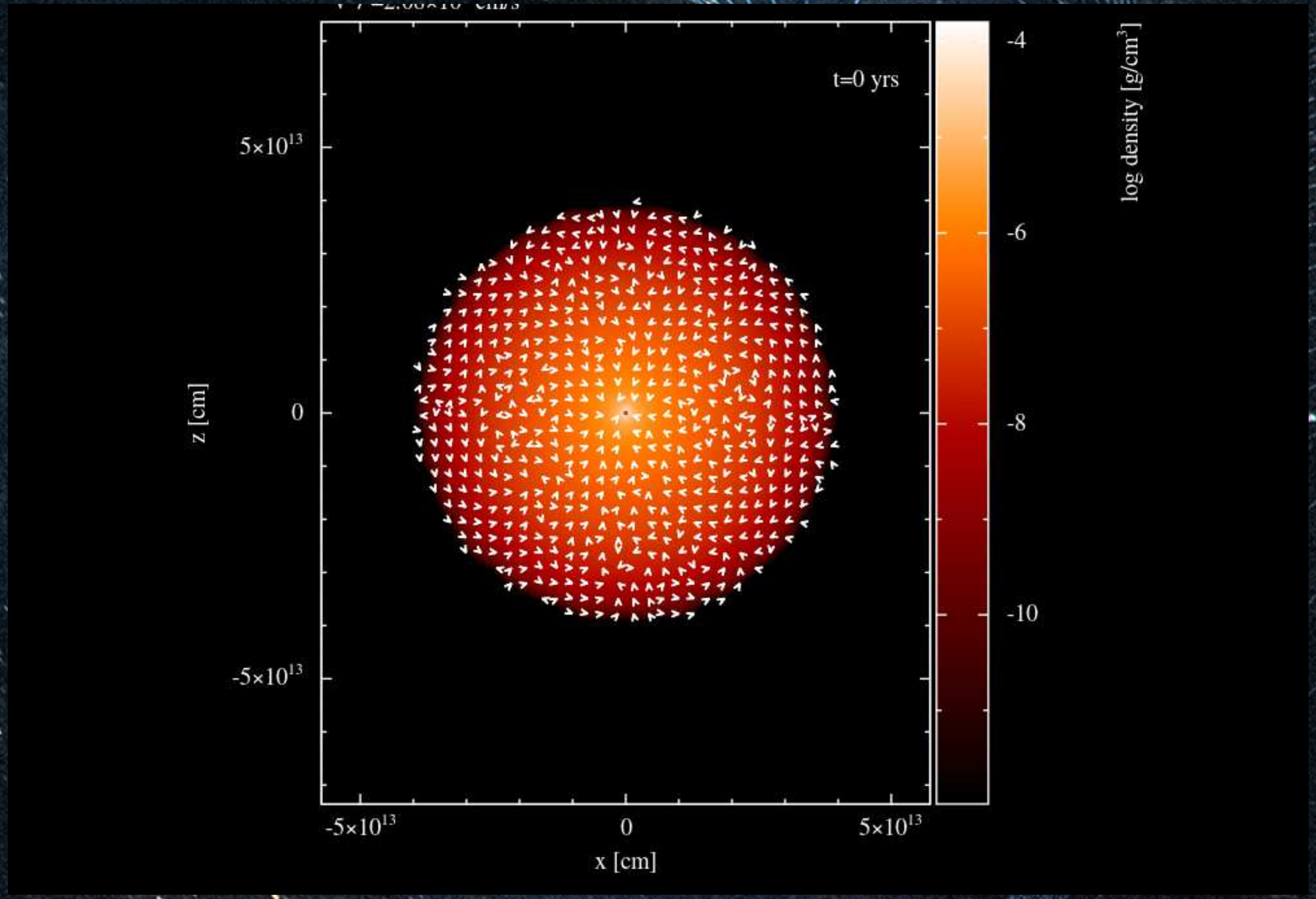
Model stellar "core" with a point mass

`set_cubic_core, set_fixedentropycore`

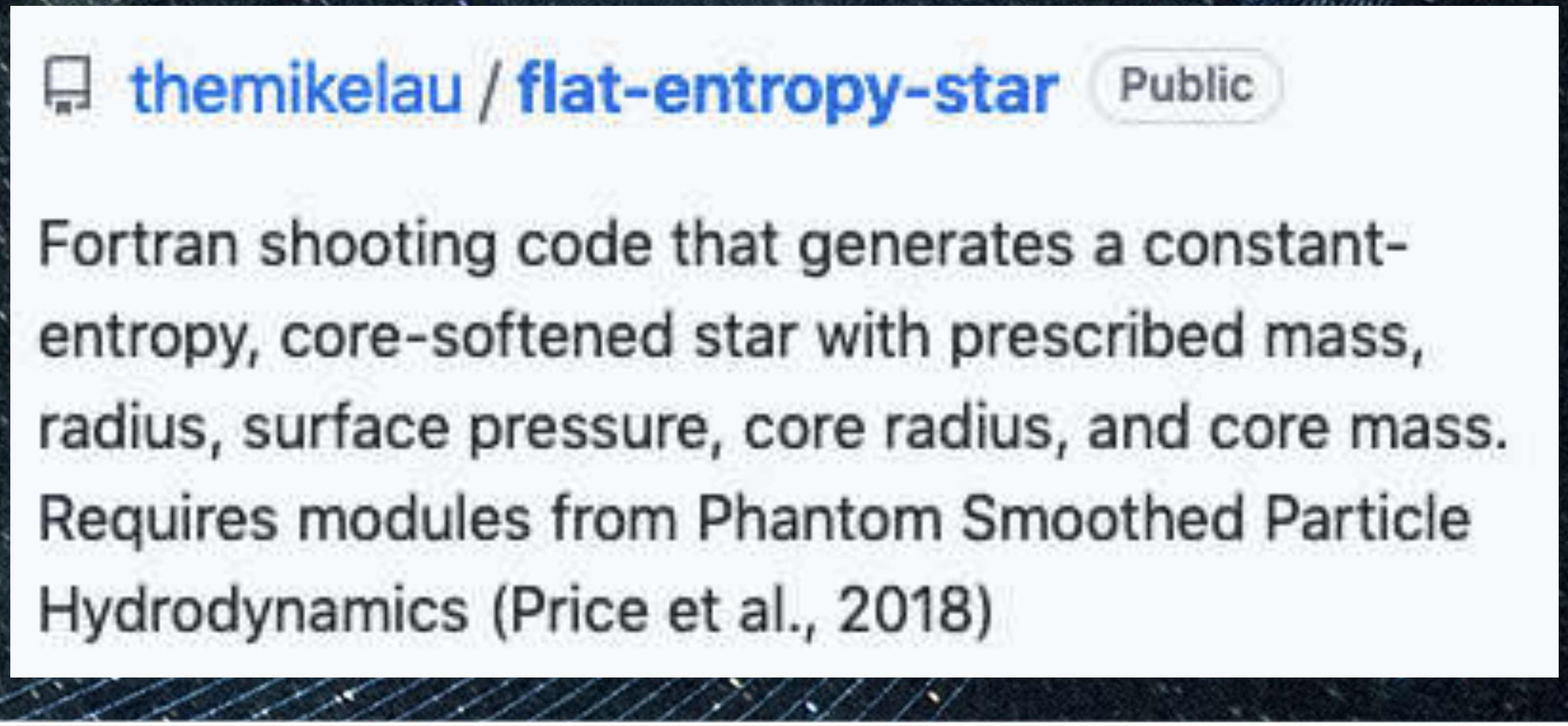
ML, Ryosuke Hirai, Miguel González-Bolívar



Transient convection:



Lau+2022a: Construct flat entropy star to stabilise envelope


themikelau / flat-entropy-star Public

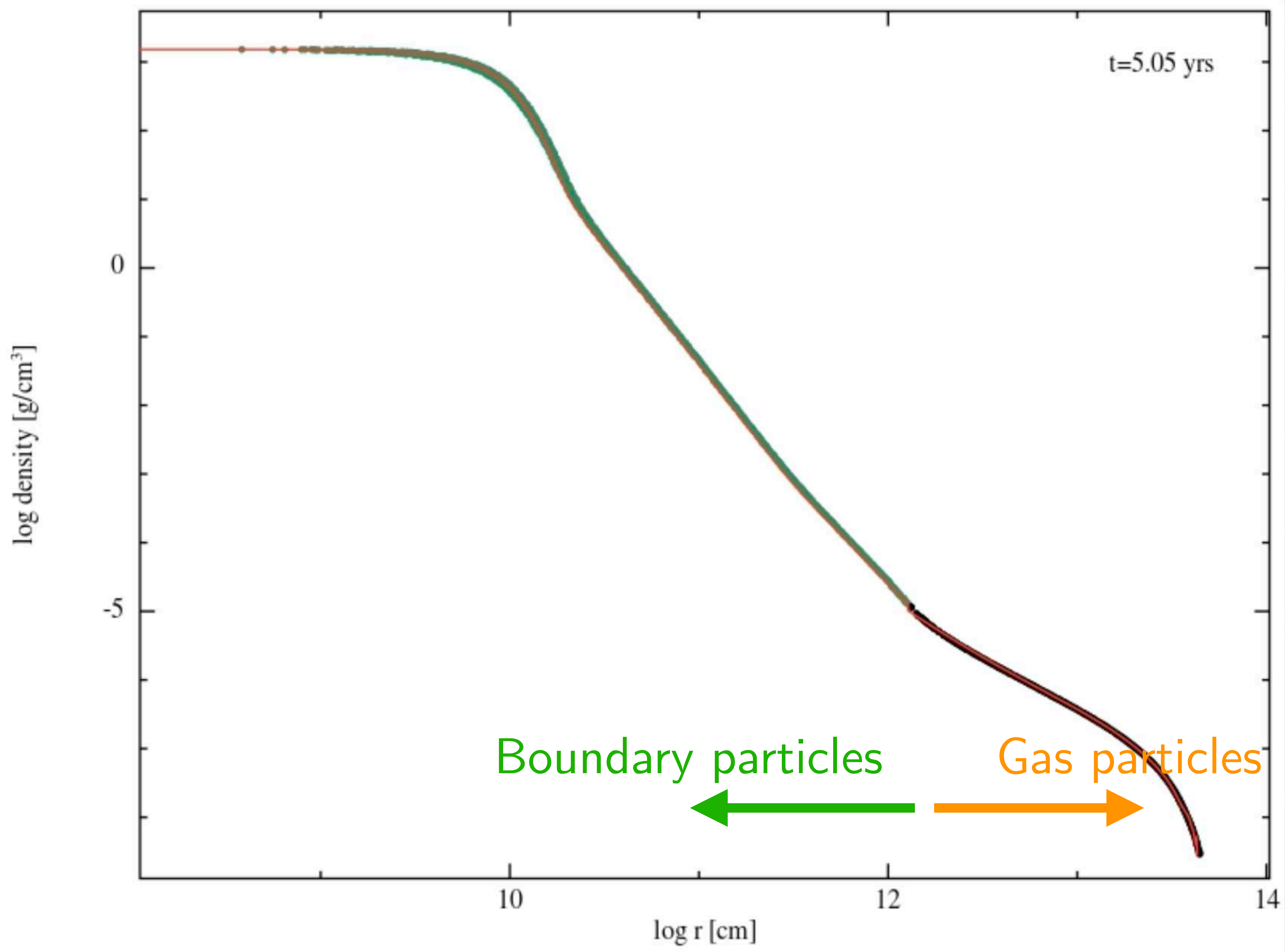
Fortran shooting code that generates a constant-entropy, core-softened star with prescribed mass, radius, surface pressure, core radius, and core mass. Requires modules from Phantom Smoothed Particle Hydrodynamics (Price et al., 2018)

Boundary-particle core

- Map in the entire stellar core as *boundary particles*
- Boundary particles do not limit the Courant timestep
- Boundary-particle core acts as a rigid body

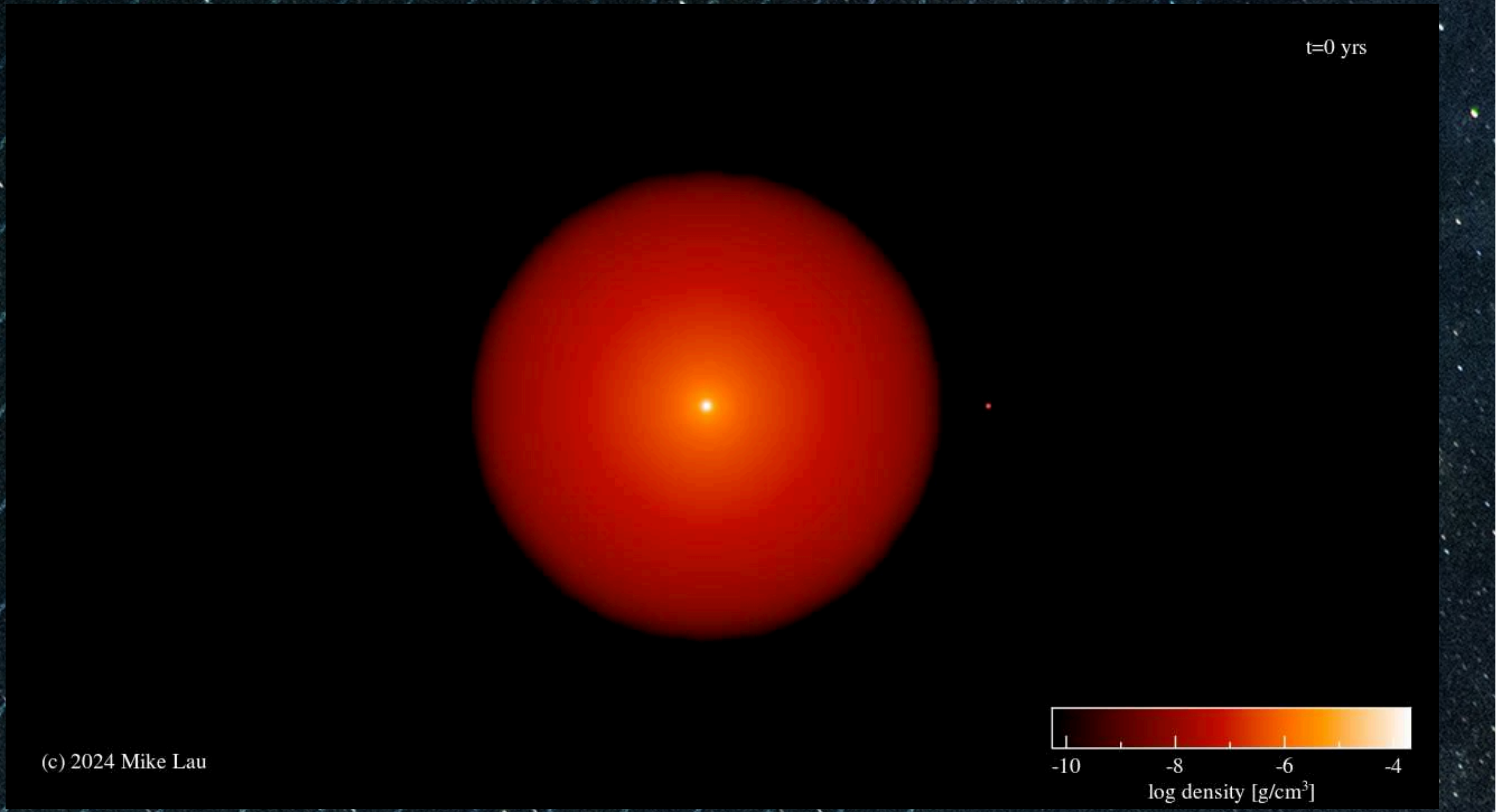
$$\mathbf{f}_i \rightarrow \frac{1}{N_{\rm boundary}} \sum_{j}^{N_{\rm boundary}} \mathbf{f}_j$$

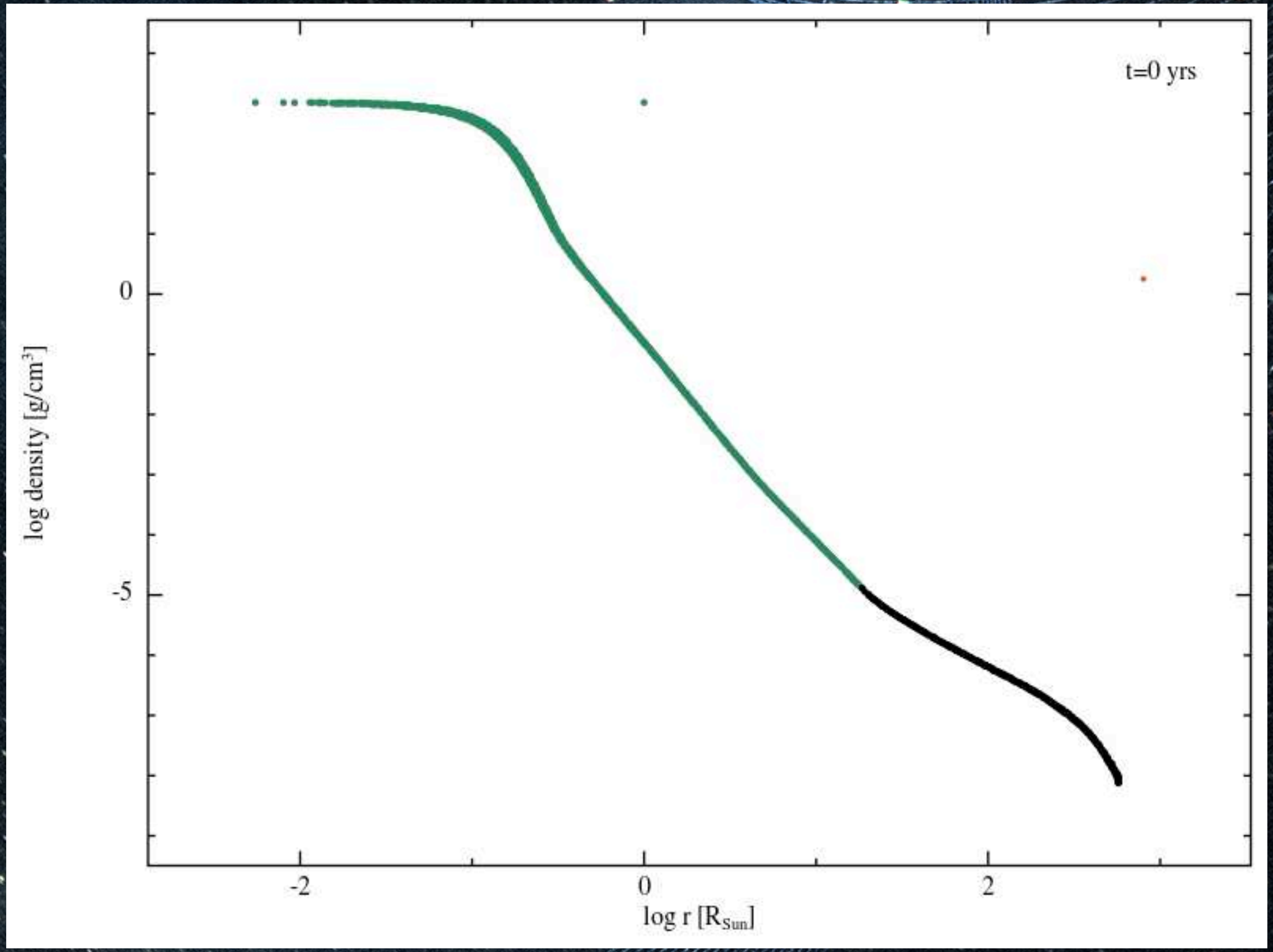
- Boundary particles can be "unfrozen" and converted back into gas particles (`moddump_binary2gas.f90`)



Relaxation for 20 dynamical times

Boundary-particle core

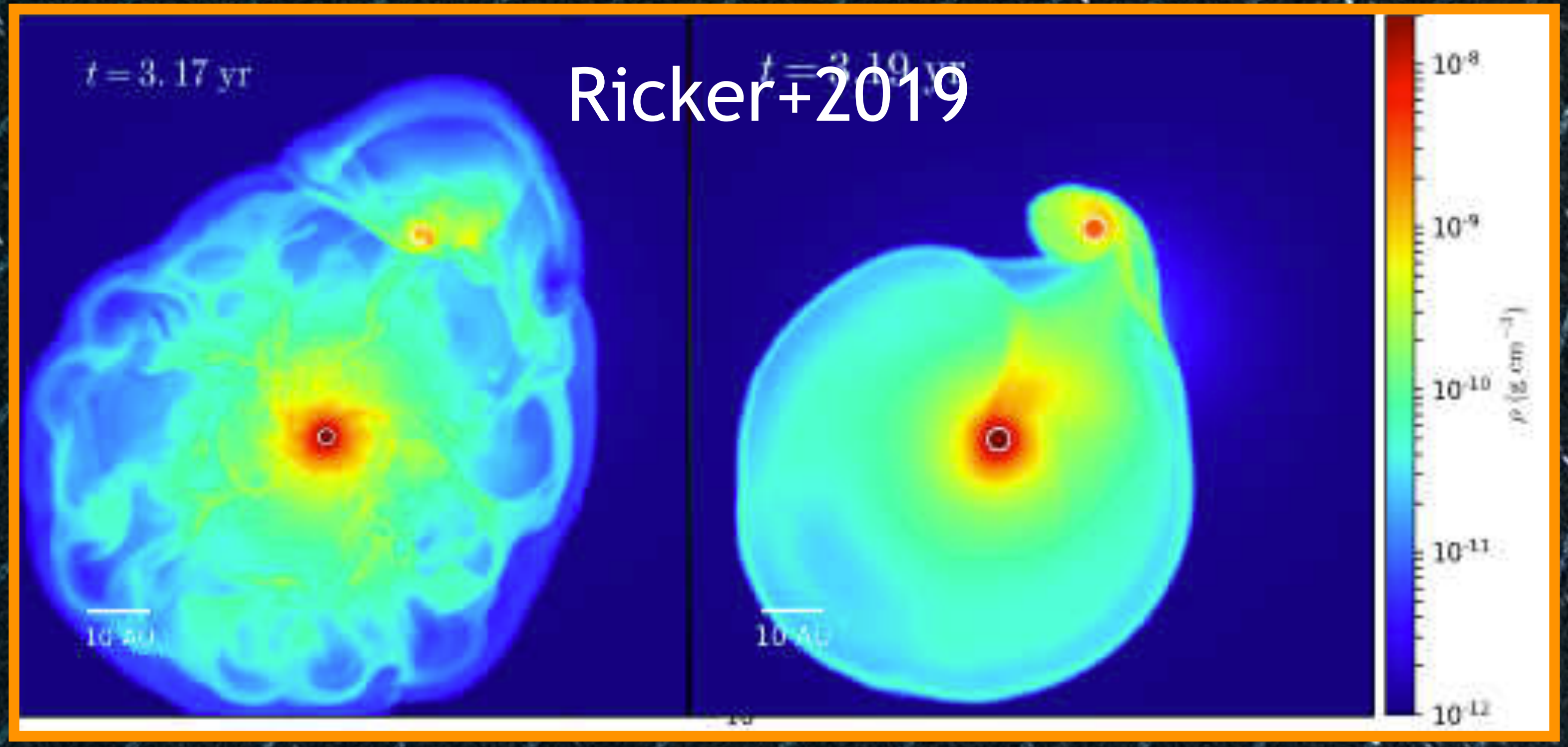


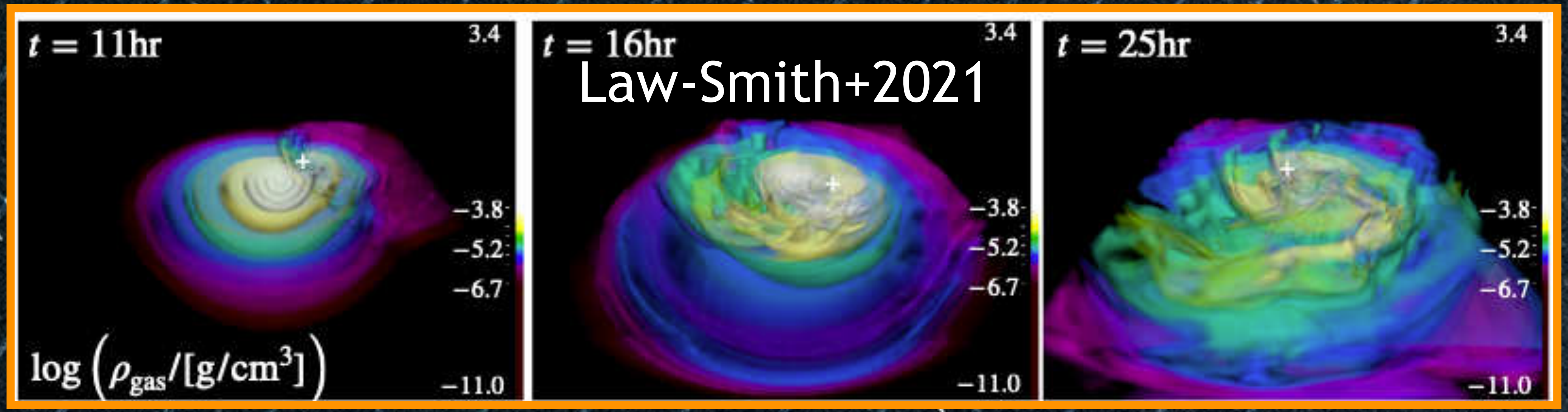


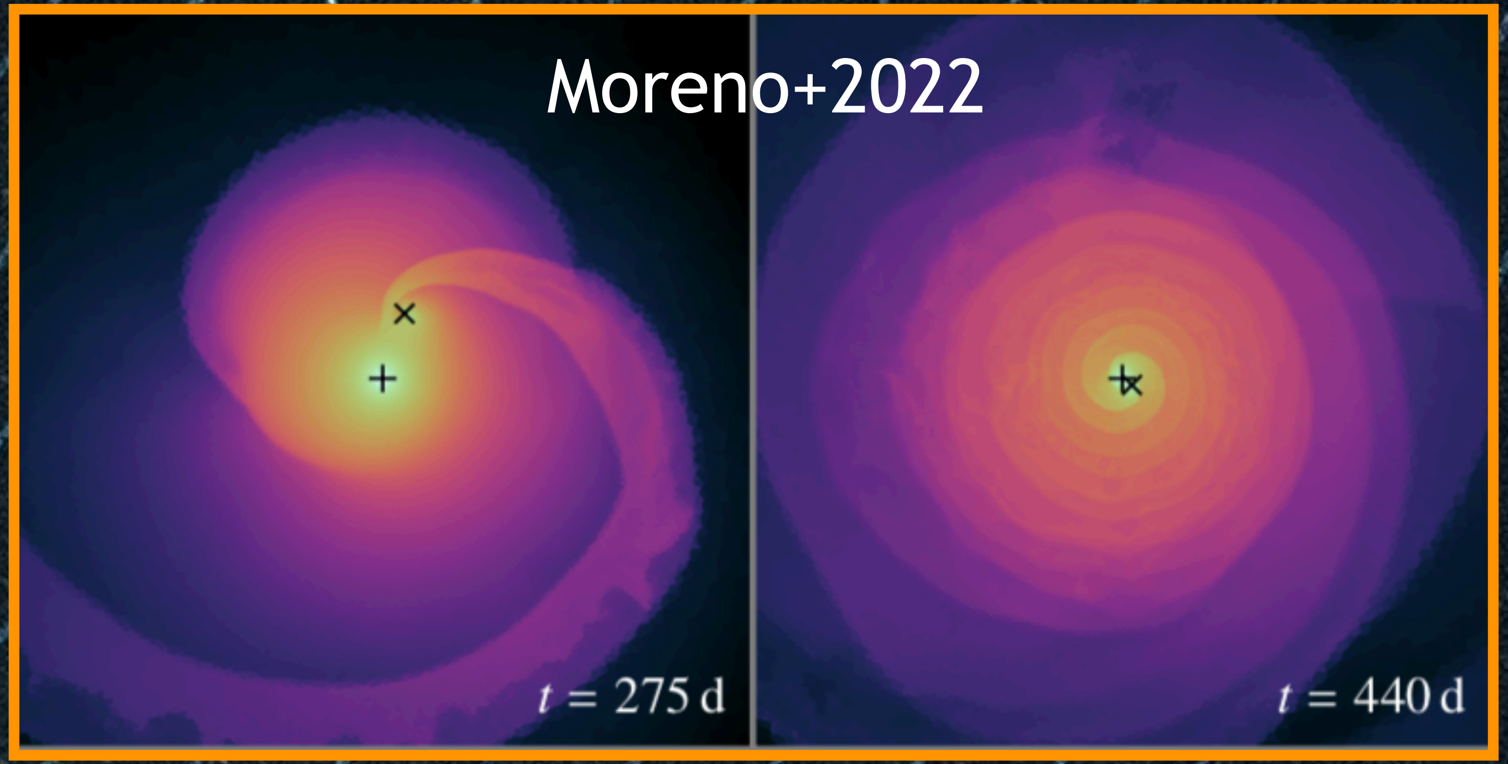
To-do:

- Conserve linear and angular momentum
- Unit testing

Massive star common envelopes


Ricker+2019


Law-Smith+2021


Moreno+2022

Massive star common envelopes are qualitatively different:

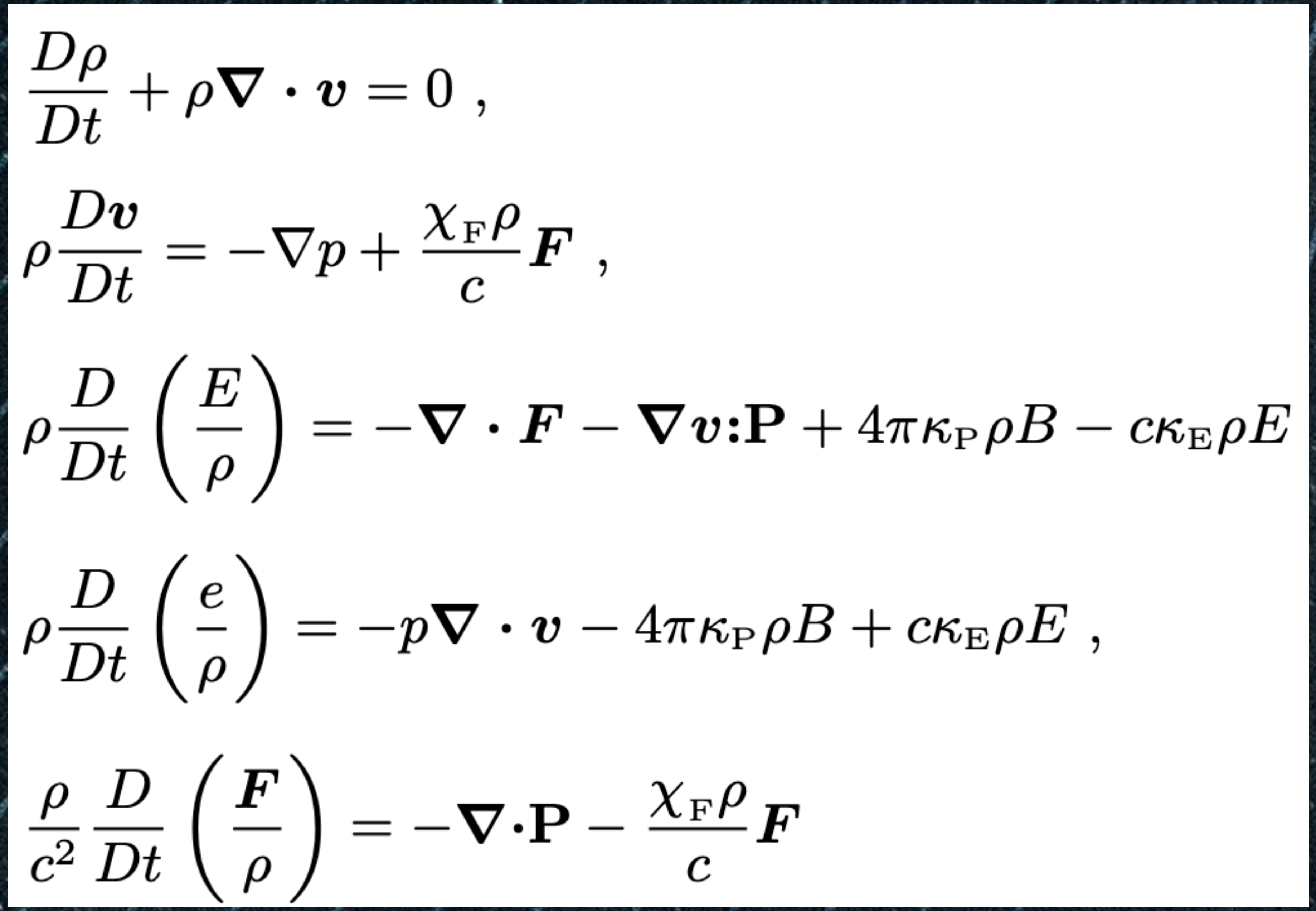
- ~~Significant radiation pressure support~~
- **Short thermal timescales**
- **Qualitatively different envelope structures**

Other implications of radiation transport:

- $L\Delta t_{\rm CE} \sim (10^{38}\ {\rm erg\ s^{-1}})(10\ {\rm yr}) \sim 10^{46}\ {\rm erg}$ → *nuclear burning is also important*
- Lower common-envelope efficiency
- Transport away recombination energy
- Allows sensible lightcurves
- To construct a "realistic" initial profile for the donor envelope, allowing us to simulate different donors

Energy transport in massive star common envelopes

Implemented implicit scheme for flux-limited diffusion in Phantom following Whitehouse & Bate (2004)



$$\frac{D\rho}{Dt} + \rho\boldsymbol{\nabla}\cdot\boldsymbol{v} = 0\ ,$$

$$\rho\frac{D\boldsymbol{v}}{Dt} = -\nabla p + \frac{\chi_{\rm F}\rho}{c}\boldsymbol{F}\ ,$$

$$\rho\frac{D}{Dt}\left(\frac{E}{\rho}\right) = -\boldsymbol{\nabla}\cdot\boldsymbol{F} - \boldsymbol{\nabla v}\mathbf{:P} + 4\pi\kappa_{\rm P}\rho B - c\kappa_{\rm E}\rho E$$

$$\rho\frac{D}{Dt}\left(\frac{e}{\rho}\right) = -p\boldsymbol{\nabla}\cdot\boldsymbol{v} - 4\pi\kappa_{\rm P}\rho B + c\kappa_{\rm E}\rho E\ ,$$

$$\frac{\rho}{c^2}\frac{D}{Dt}\left(\frac{\boldsymbol{F}}{\rho}\right) = -\boldsymbol{\nabla}\cdot\mathbf{P} - \frac{\chi_{\rm F}\rho}{c}\boldsymbol{F}$$

Mihalas & Mihalas (1984), Turner & Stone (2001)

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

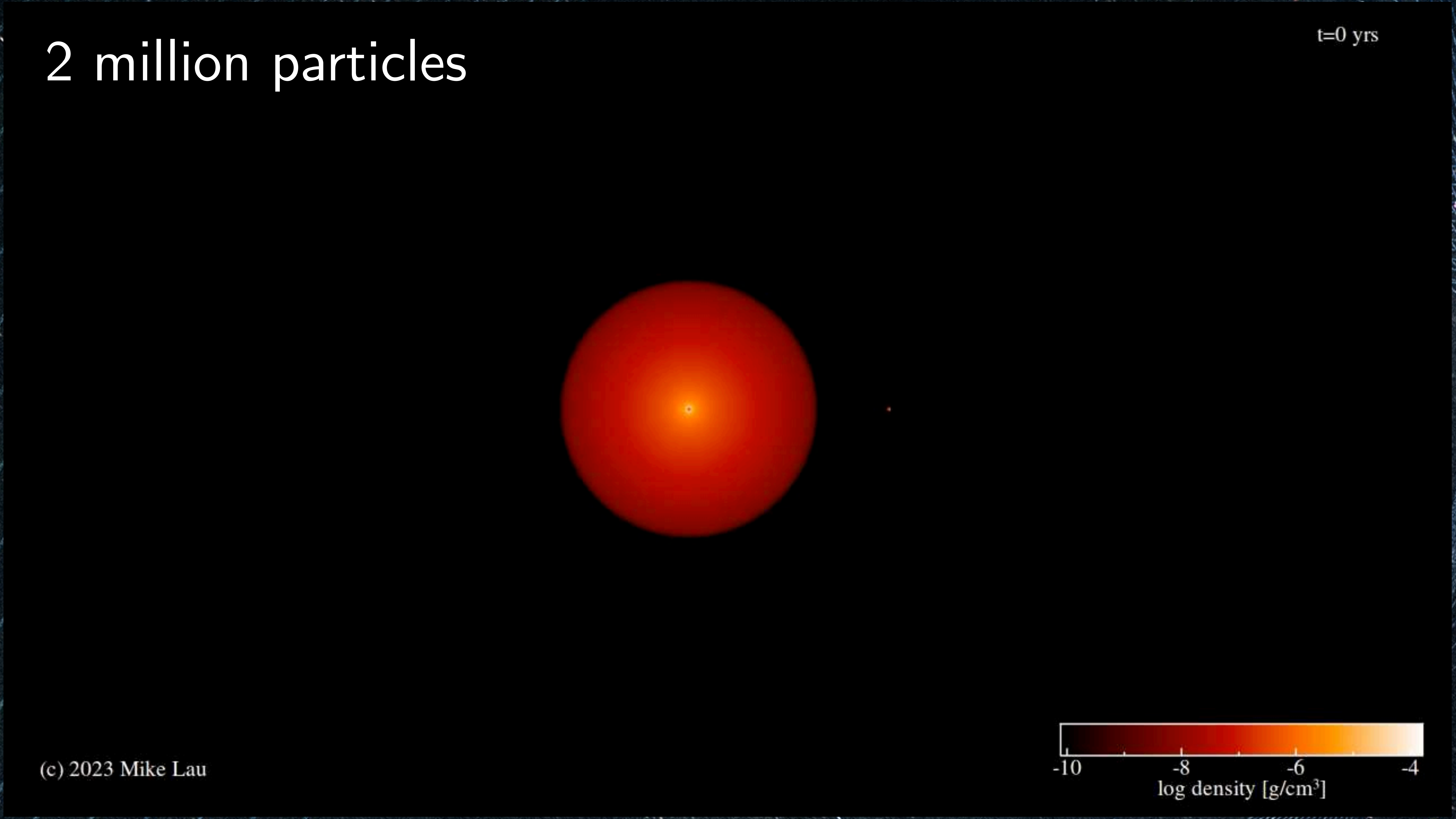
Flux limiter $\lambda \to 1/3$ *Optically thick limit*

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

Assumptions:

- LTE
- Isotropic radiation field (no shadows)
- Diffusion
- Gray opacity

2 million particles



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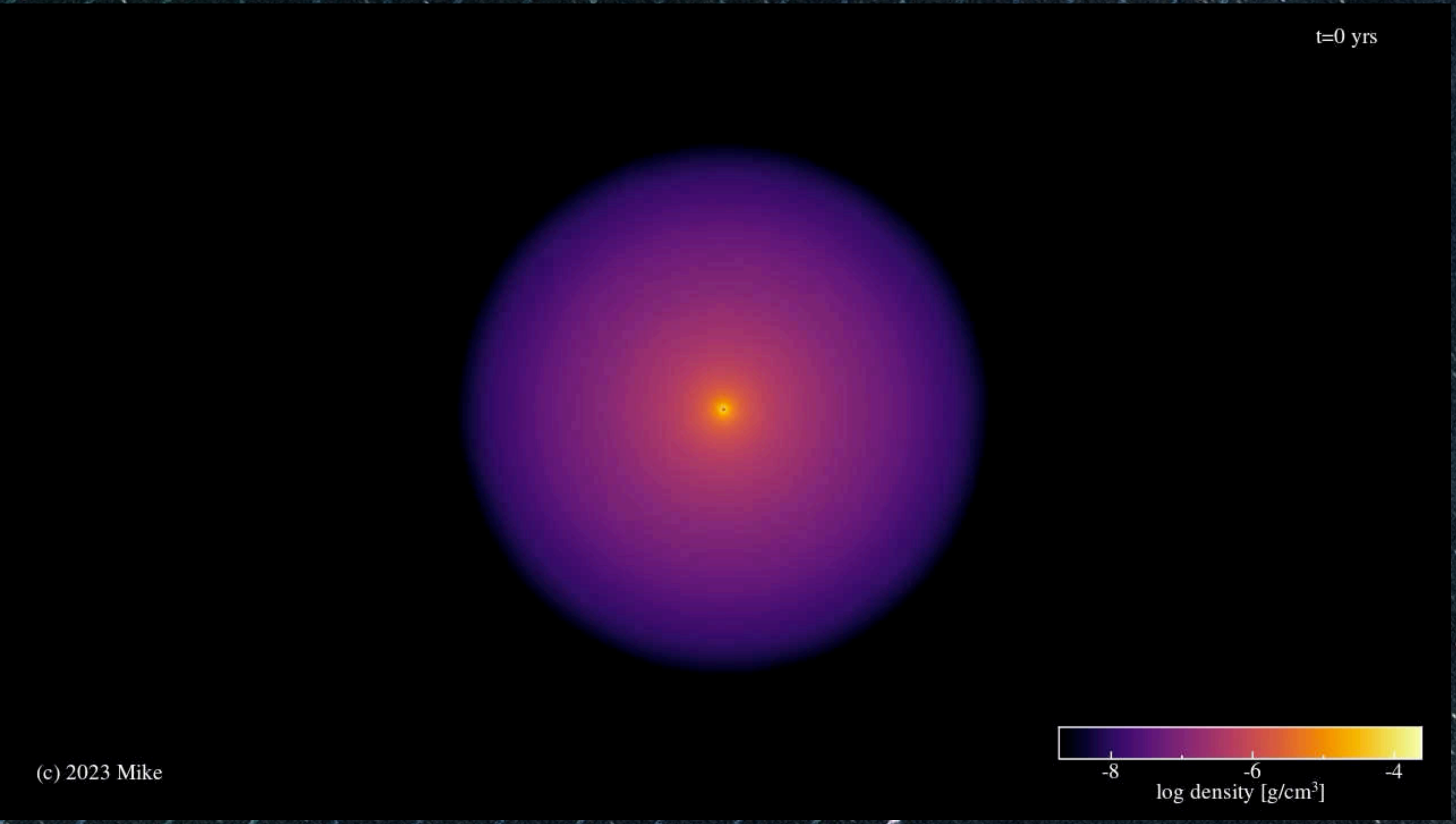
Next steps:

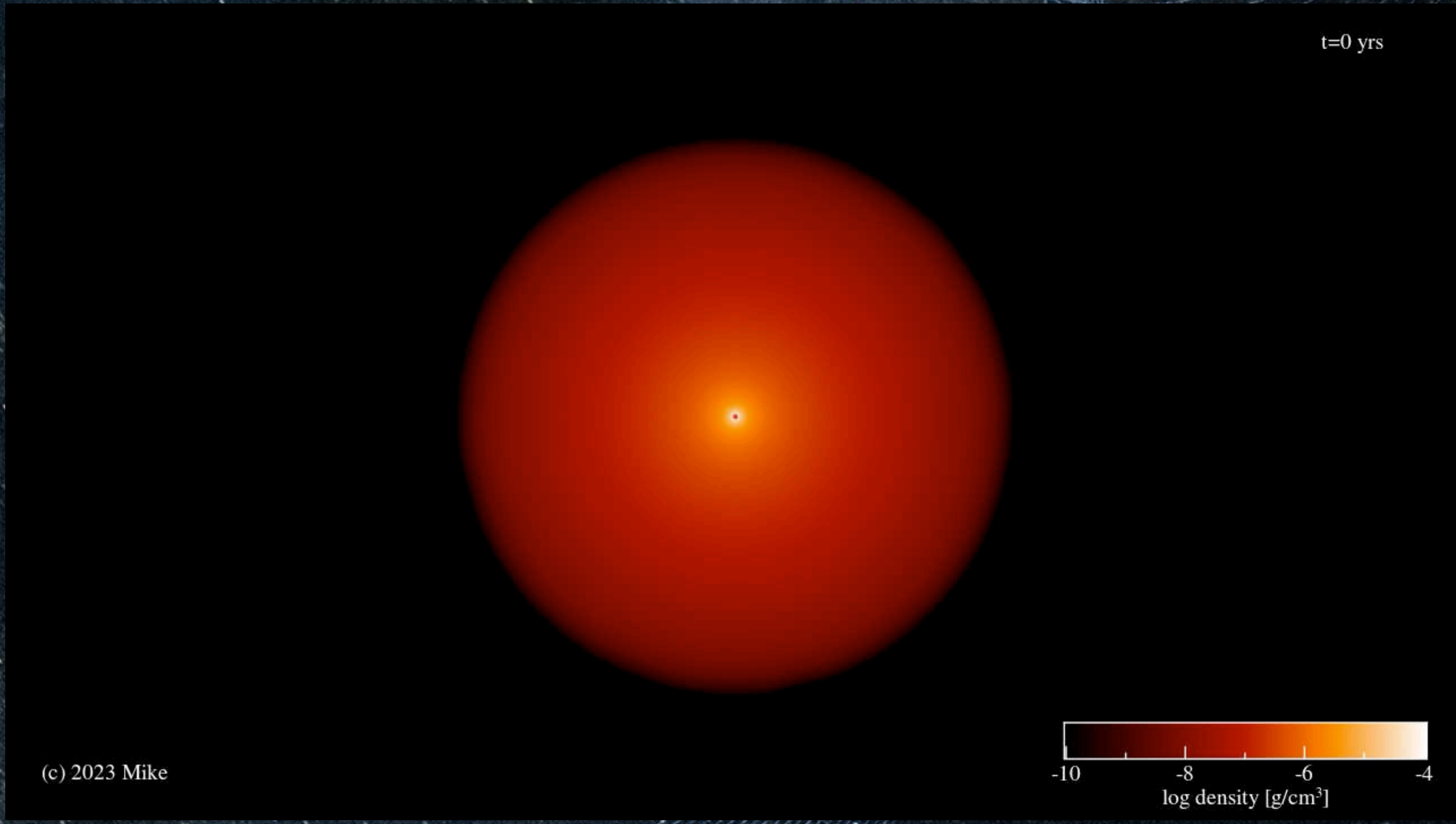
- Further code optimisation
- Develop method for setting up a steady-state convection in the initial stellar envelope

Energy transport in massive star common envelopes

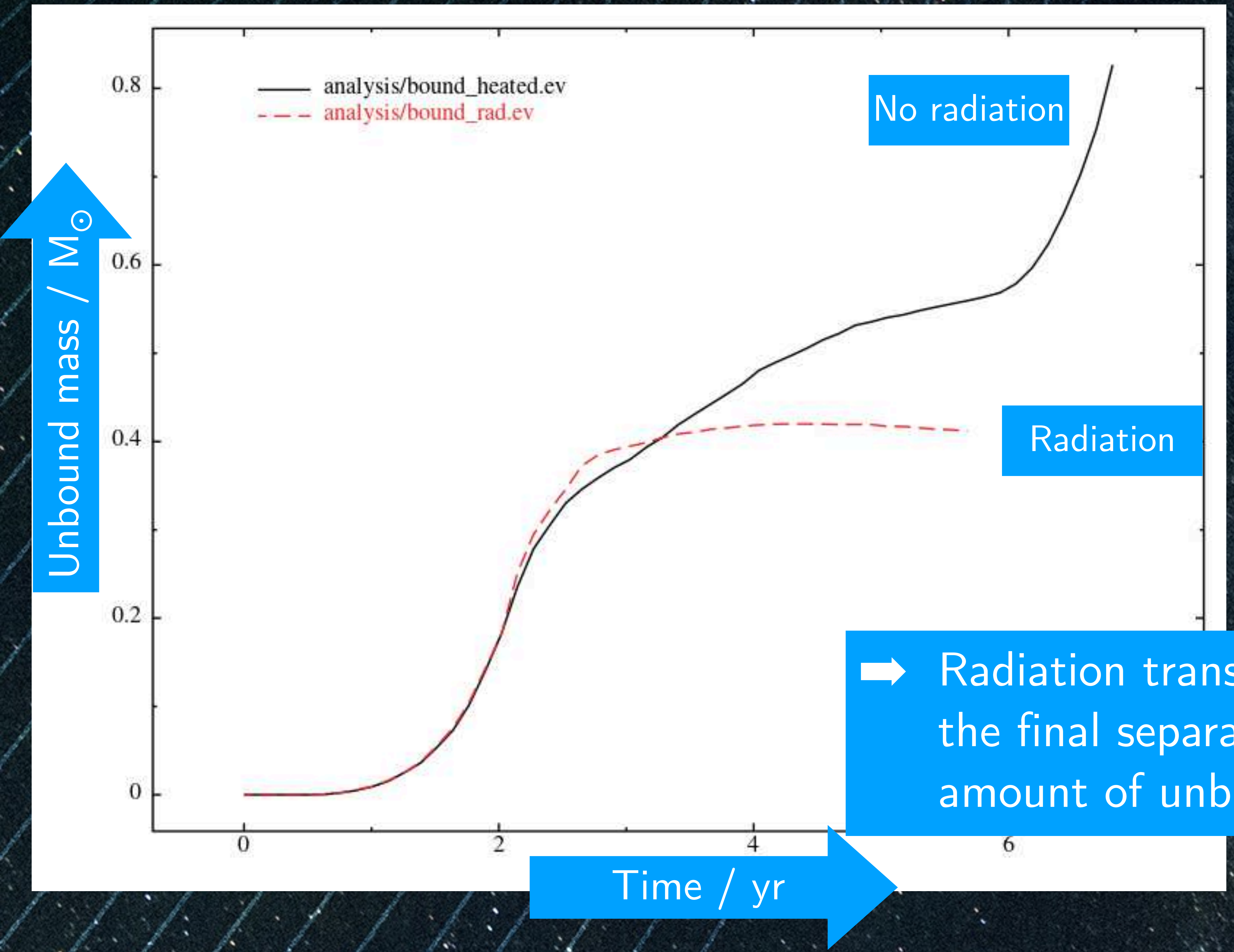
12 $M_\odot$ red supergiant heated with $L_{\rm nuc} = 10^{38}$ erg s^{-1}

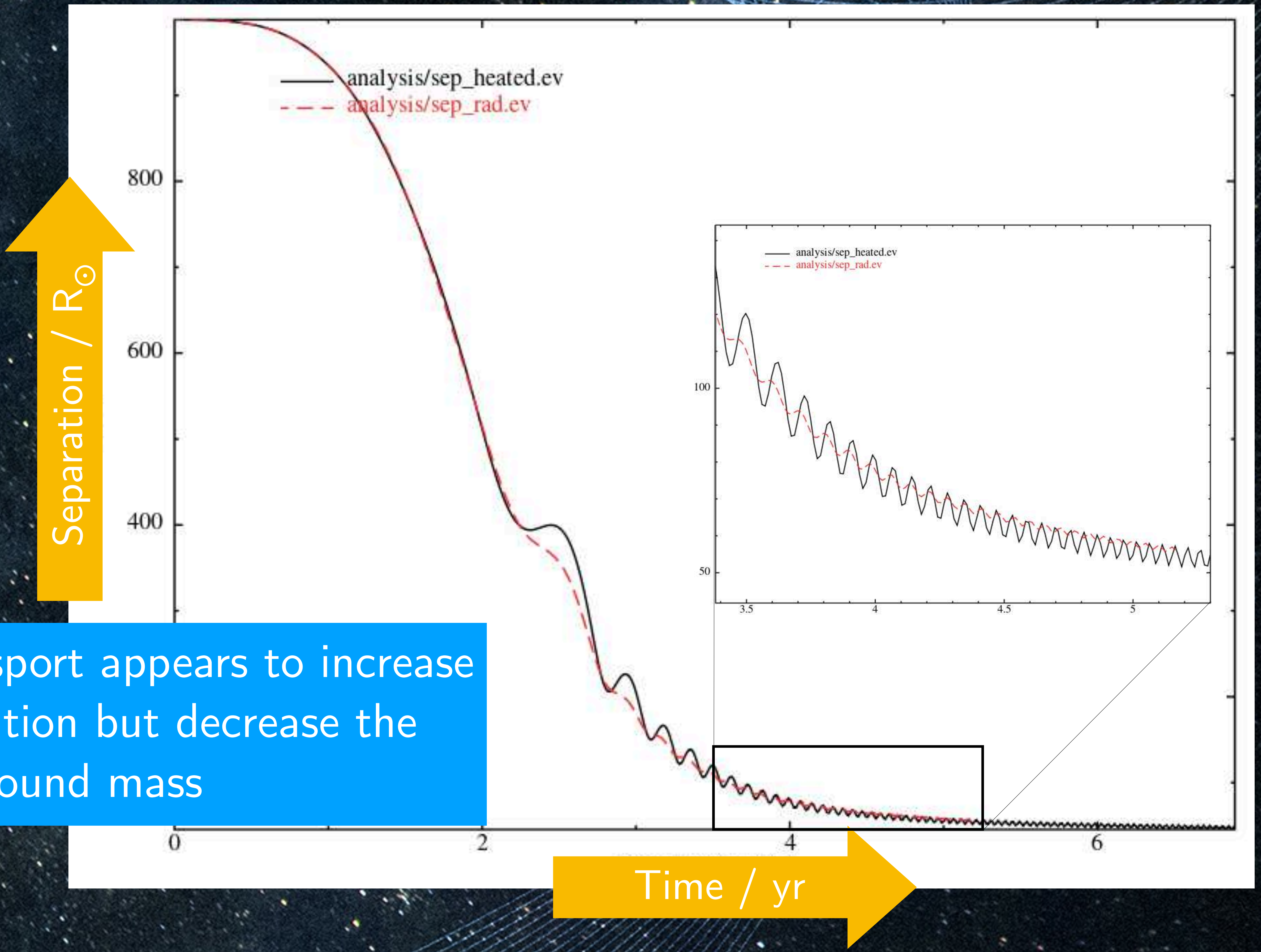


No heating



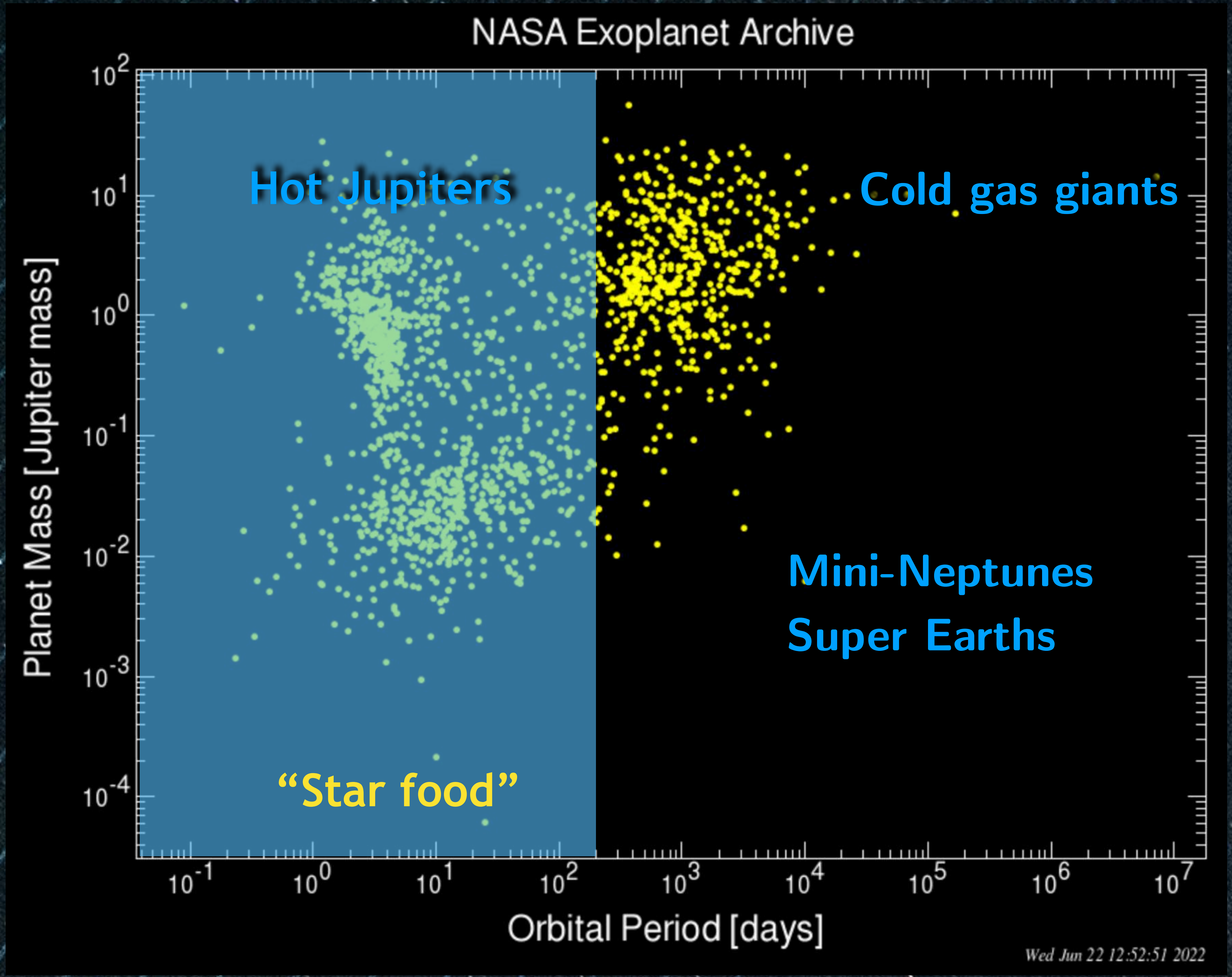
Comparison with 50,000 SPH particles



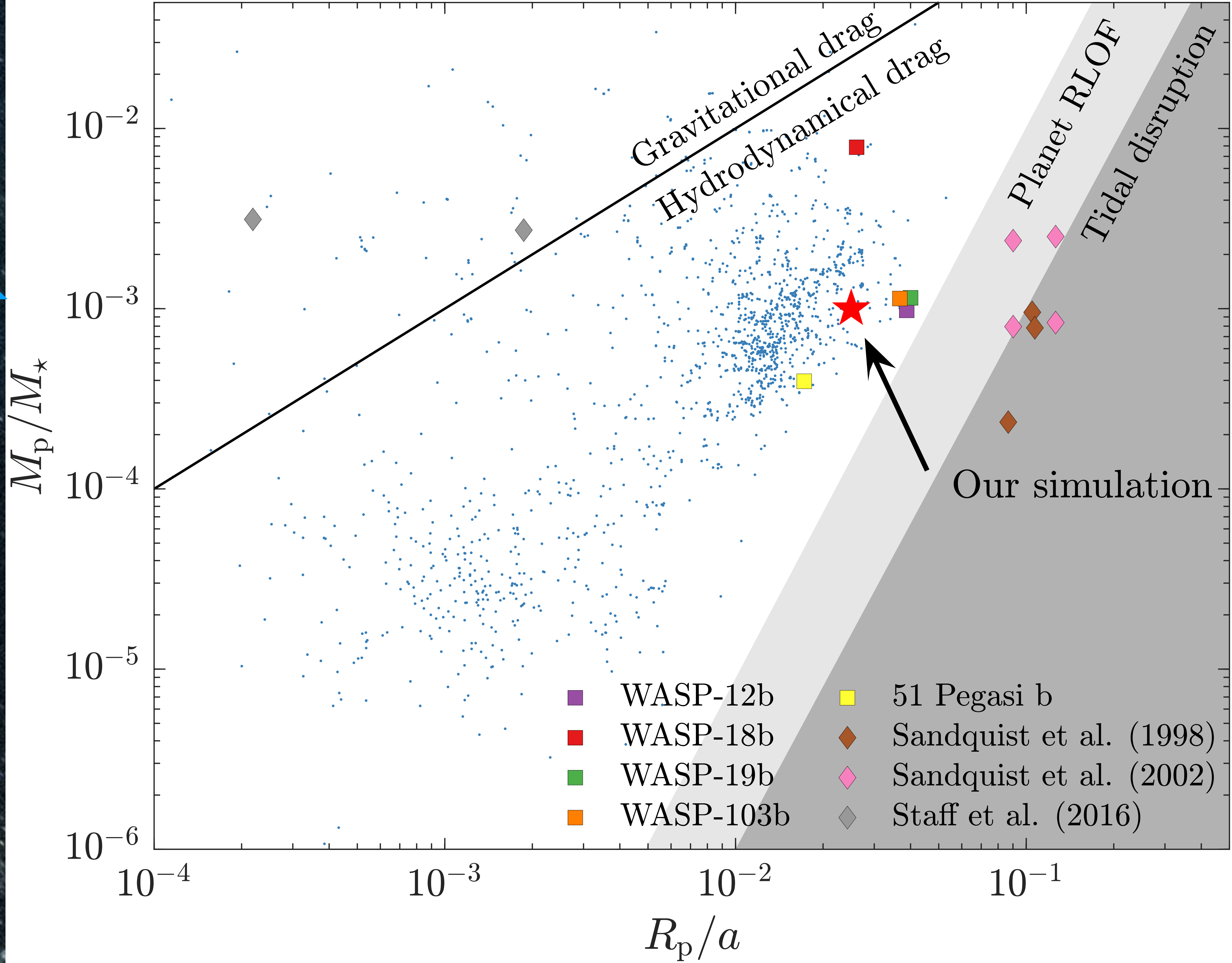


➡ Radiation transport appears to increase the final separation but decrease the amount of unbound mass

Planetary engulfment

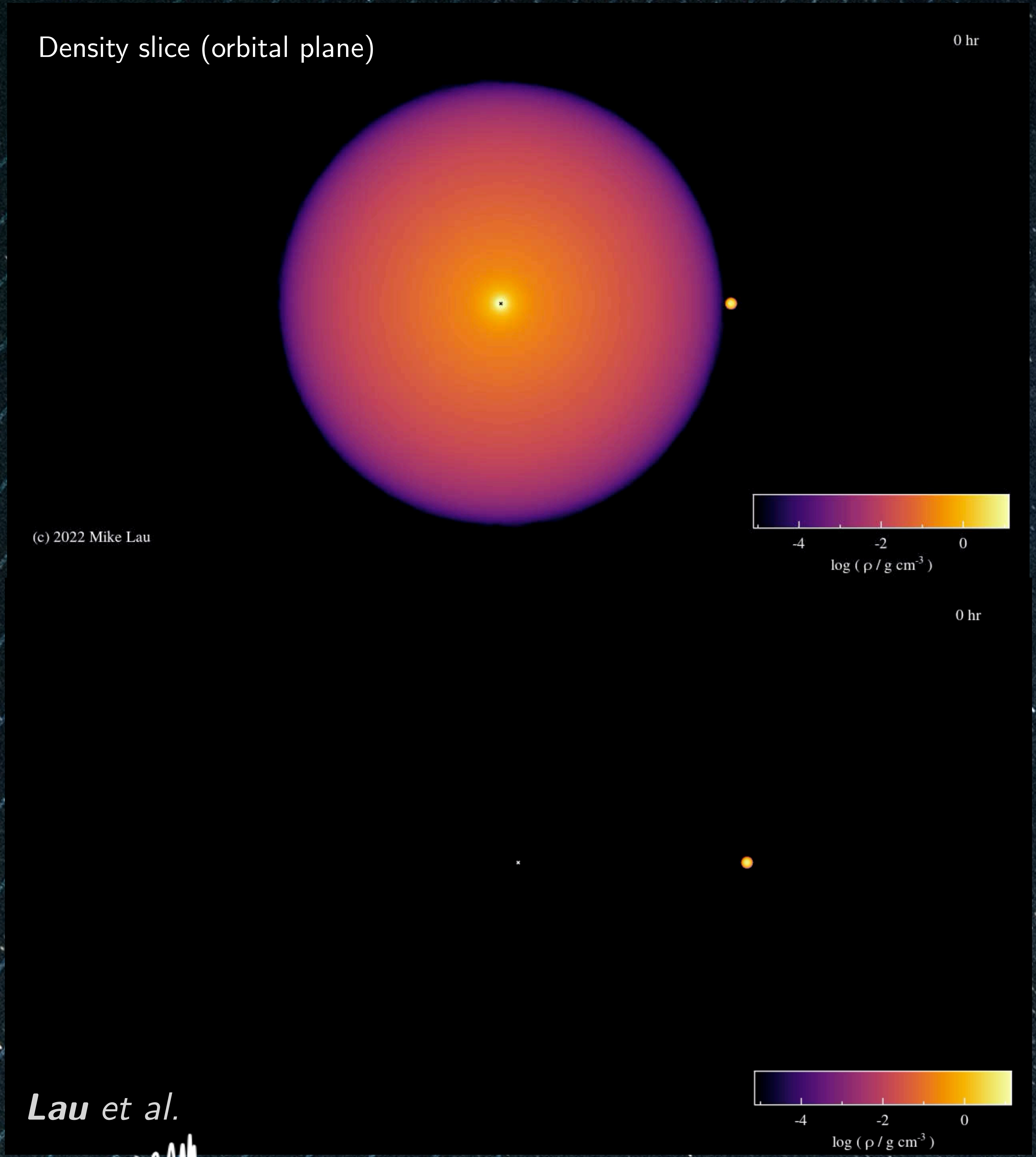


Lau et al.

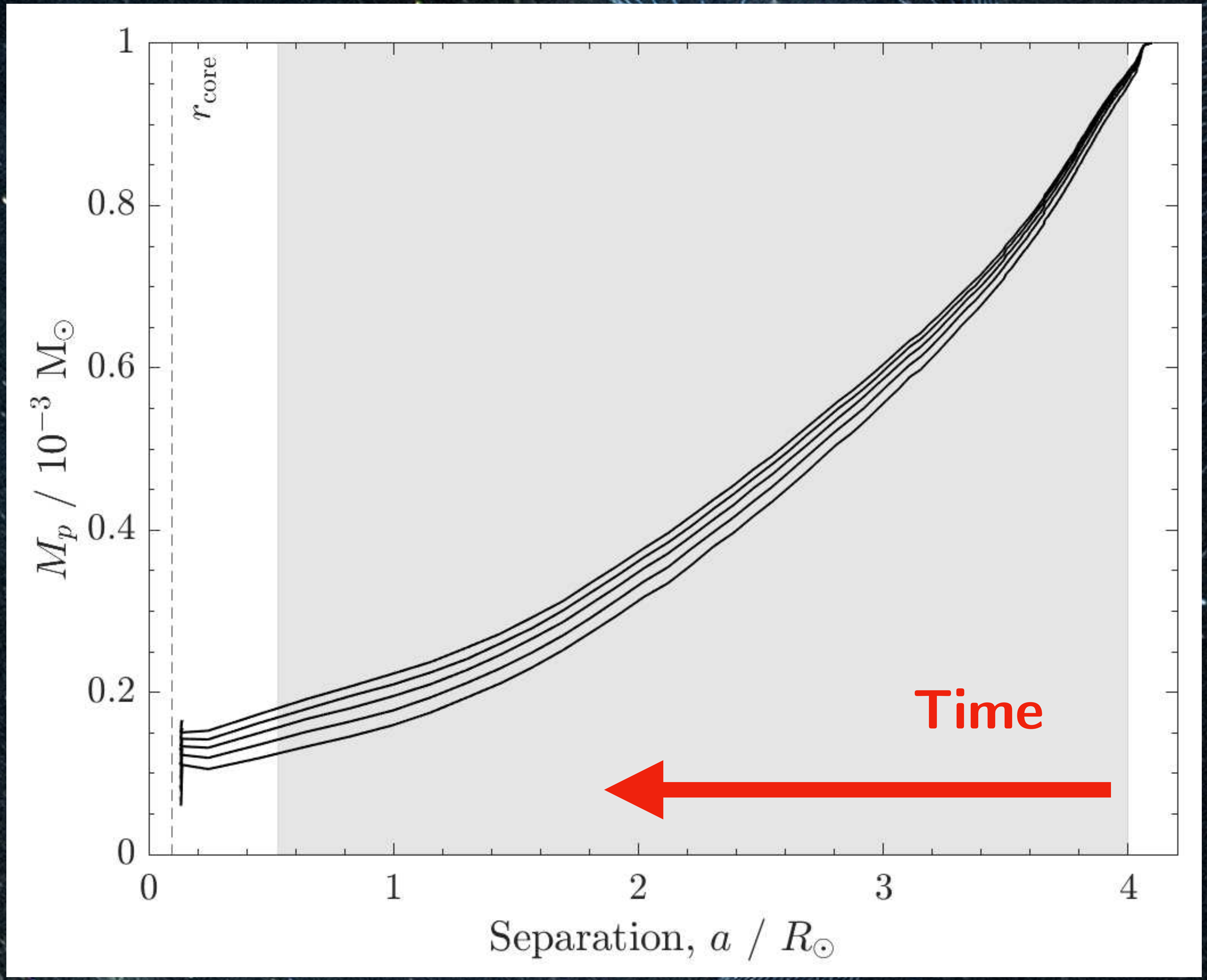


Mass ratio

Radius ratio

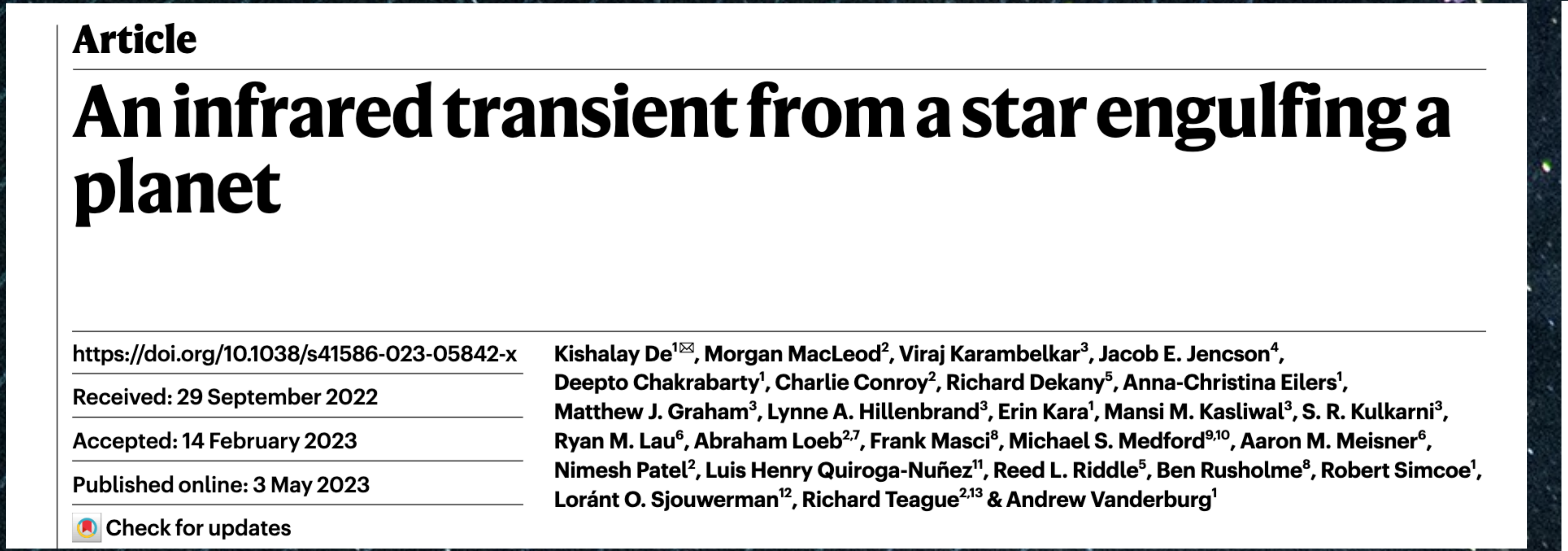


***Lau** et al.*



➡ Significant amount of planet mass is ablated (but this has not converged)

First direct observation: ZTF-SLRN-2020



Article

An infrared transient from a star engulfing a planet

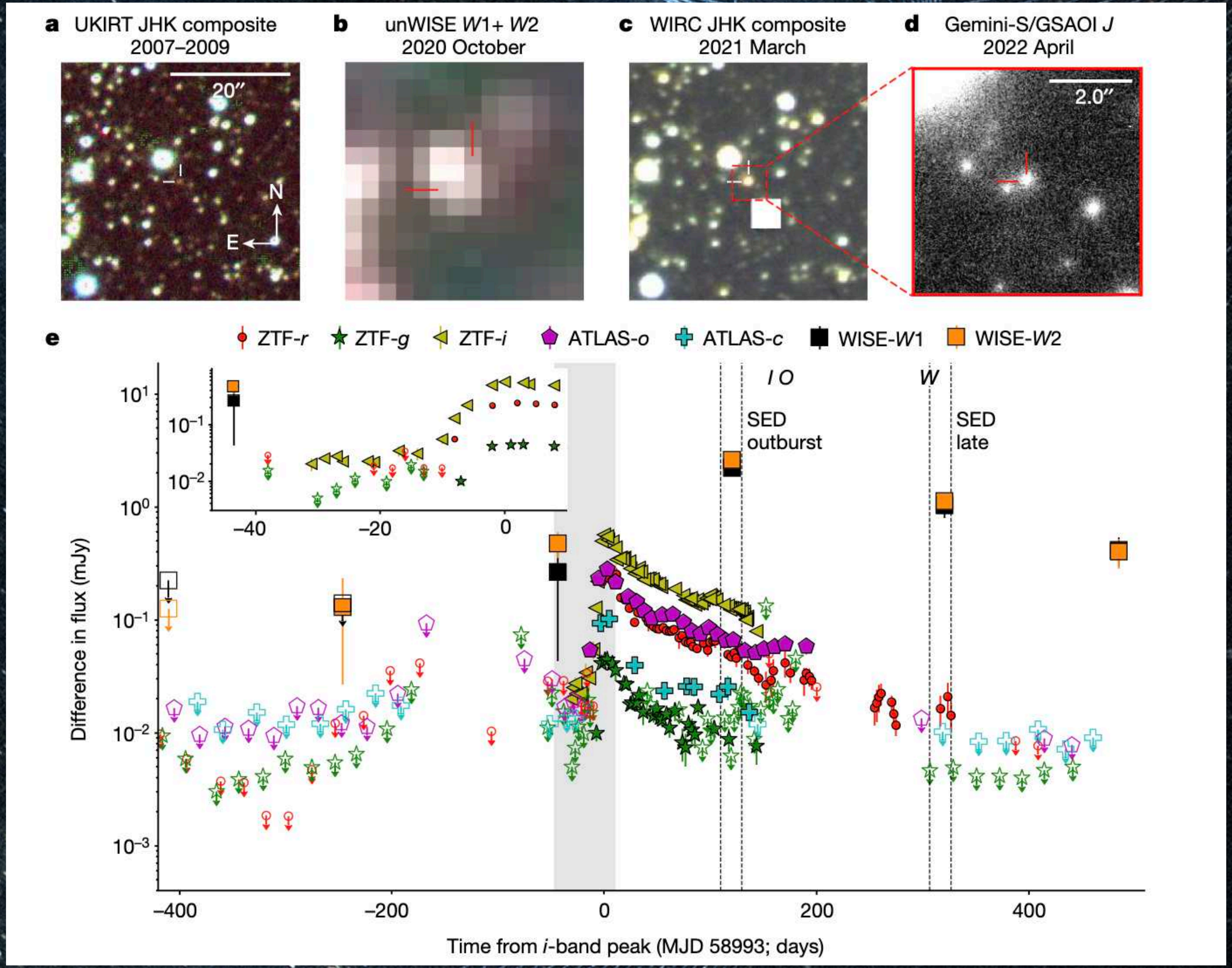
https://doi.org/10.1038/s41586-023-05842-x

Received: 29 September 2022

Accepted: 14 February 2023

Kishalay De[1]✉, Morgan MacLeod[2], Viraj Karambelkar[3], Jacob E. Jencson[4], Deepto Chakrabarty[1], Charlie Conroy[2], Richard Dekany[5], Anna-Christina Eilers[1], Matthew J. Graham[3], Lynne A. Hillenbrand[3], Erin Kara[1], Mansi M. Kasliwal[3], S. R. Kulkarni[3], Ryan M. Lau[6], Abraham Loeb[2,7], Frank Masci[8], Michael S. Medford[9,10], Aaron M. Meisner[6], Nimesh Patel[2], Luis Henry Quiroga-Nuñez[11], Reed L. Riddle[5], Ben Rusholme[8], Robert Simcoe[1], Loránt O. Sjouwerman[12], Richard Teague[2,13] & Andrew Vanderburg[1]

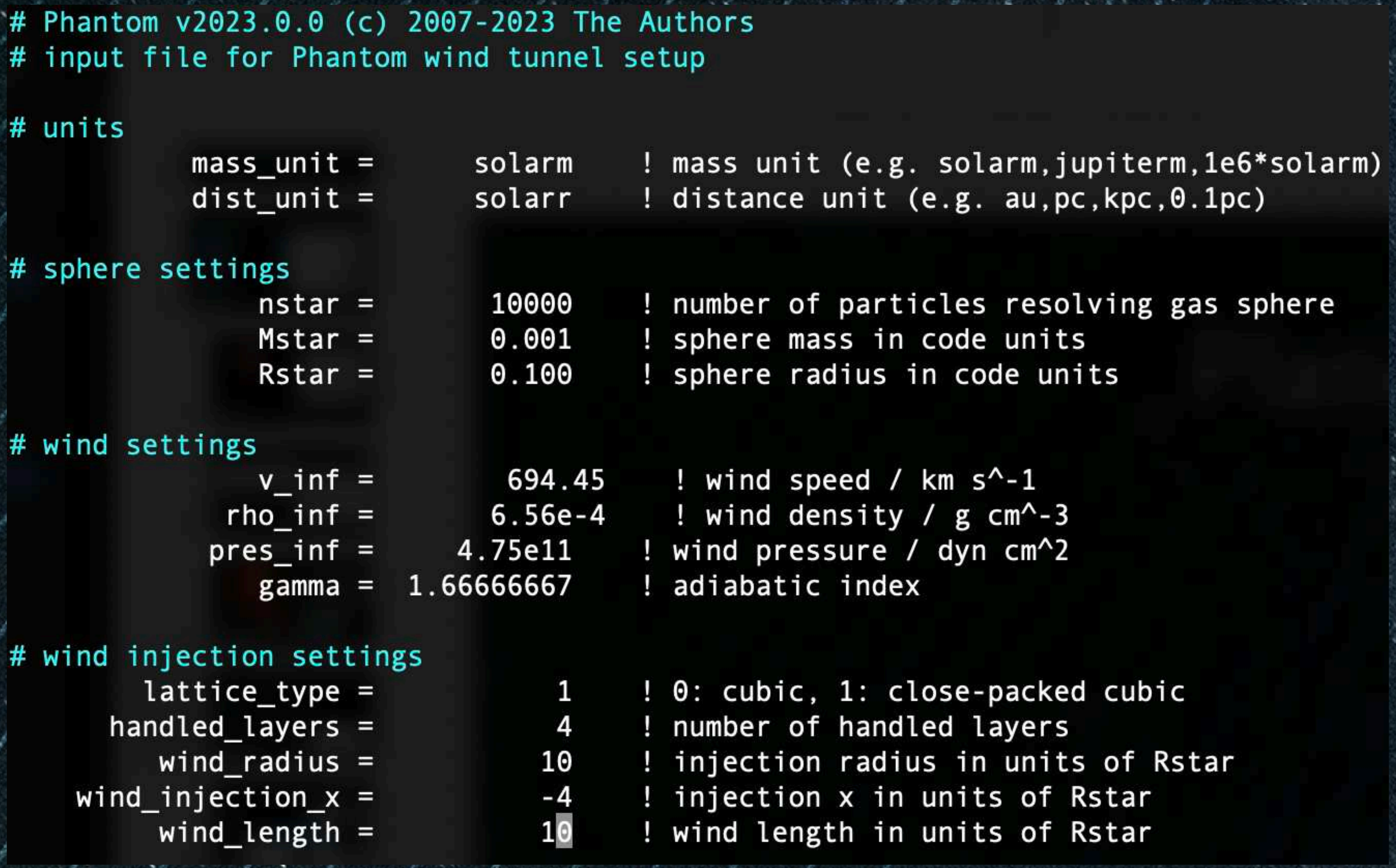
- $0.8 - 1.5\ \mathrm{M}_\odot$ on main-sequence or early subgiant branch $(1\text{–}4\ \mathrm{R}_\odot)$
- Neptune or Jupiter-like planet $\sim 0.1 - 10\ \mathrm{M_J}$
- $L_{\mathrm{bol}} \sim 10^{35}$ erg s^{-1}, 25 d plateau, (consistent with $10^{-5} - 10^{-4}\ \mathrm{M}_\odot$ recombined hydrogen)
- Pre-outburst dust and gas



➡ Consistent with our simulation!

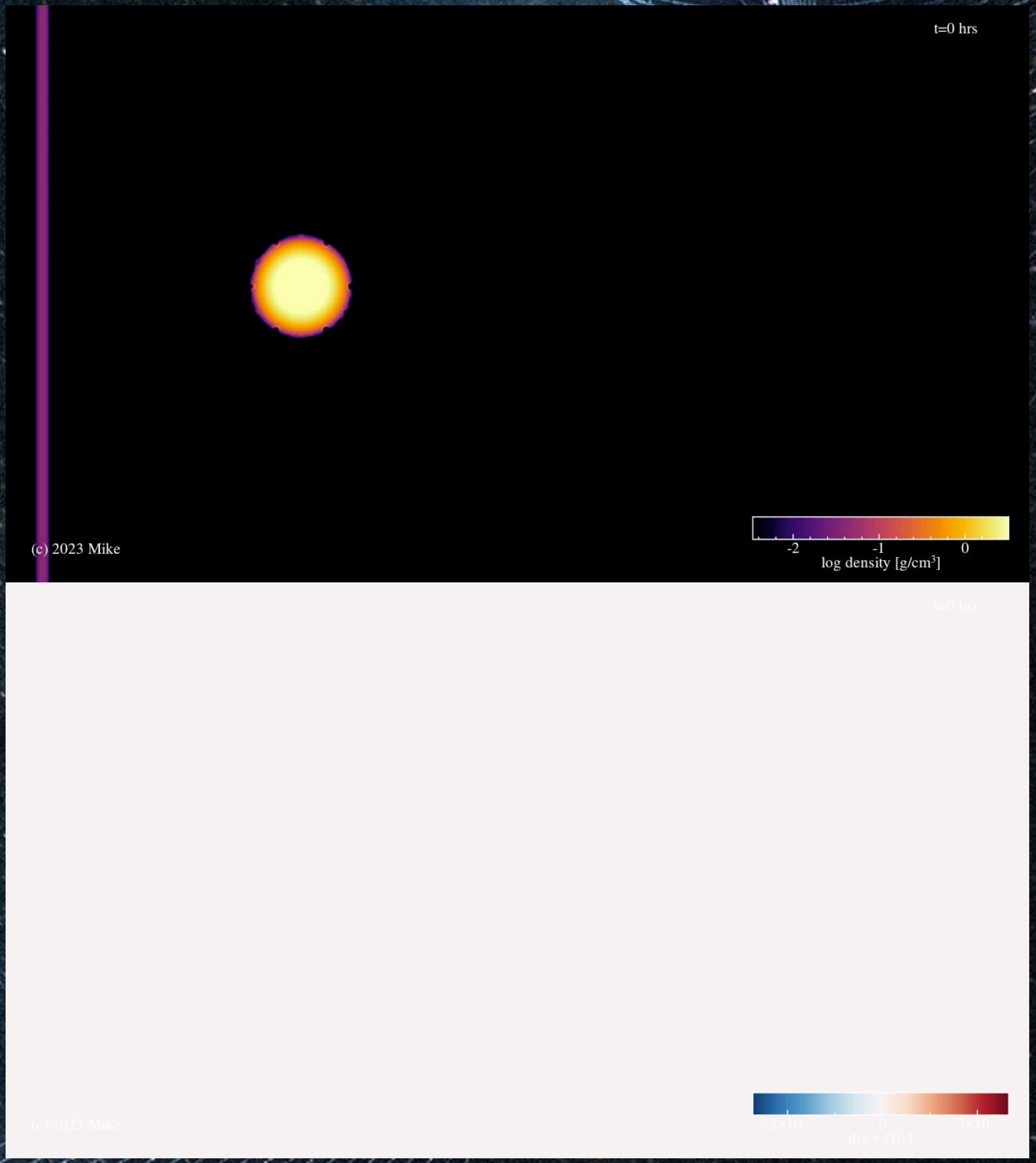
Planet ablation in a wind tunnel

NEW `windtunnel` setup and injection module



```
# Phantom v2023.0.0 (c) 2007-2023 The Authors
# input file for Phantom wind tunnel setup

# units
           mass_unit =      solarm    ! mass unit (e.g. solarm,jupiterm,1e6*solarm)
           dist_unit =      solarr    ! distance unit (e.g. au,pc,kpc,0.1pc)

# sphere settings
               nstar =       10000    ! number of particles resolving gas sphere
               Mstar =       0.001    ! sphere mass in code units
               Rstar =       0.100    ! sphere radius in code units

# wind settings
               v_inf =        694.45    ! wind speed / km s^-1
             rho_inf =       6.56e-4    ! wind density / g cm^-3
            pres_inf =     4.75e11    ! wind pressure / dyn cm^2
               gamma =  1.66666667    ! adiabatic index

# wind injection settings
        lattice_type =           1    ! 0: cubic, 1: close-packed cubic
      handled_layers =           4    ! number of handled layers
         wind_radius =          10    ! injection radius in units of Rstar
    wind_injection_x =          -4    ! injection x in units of Rstar
         wind_length =          10    ! wind length in units of Rstar
```

10^6 planet particles

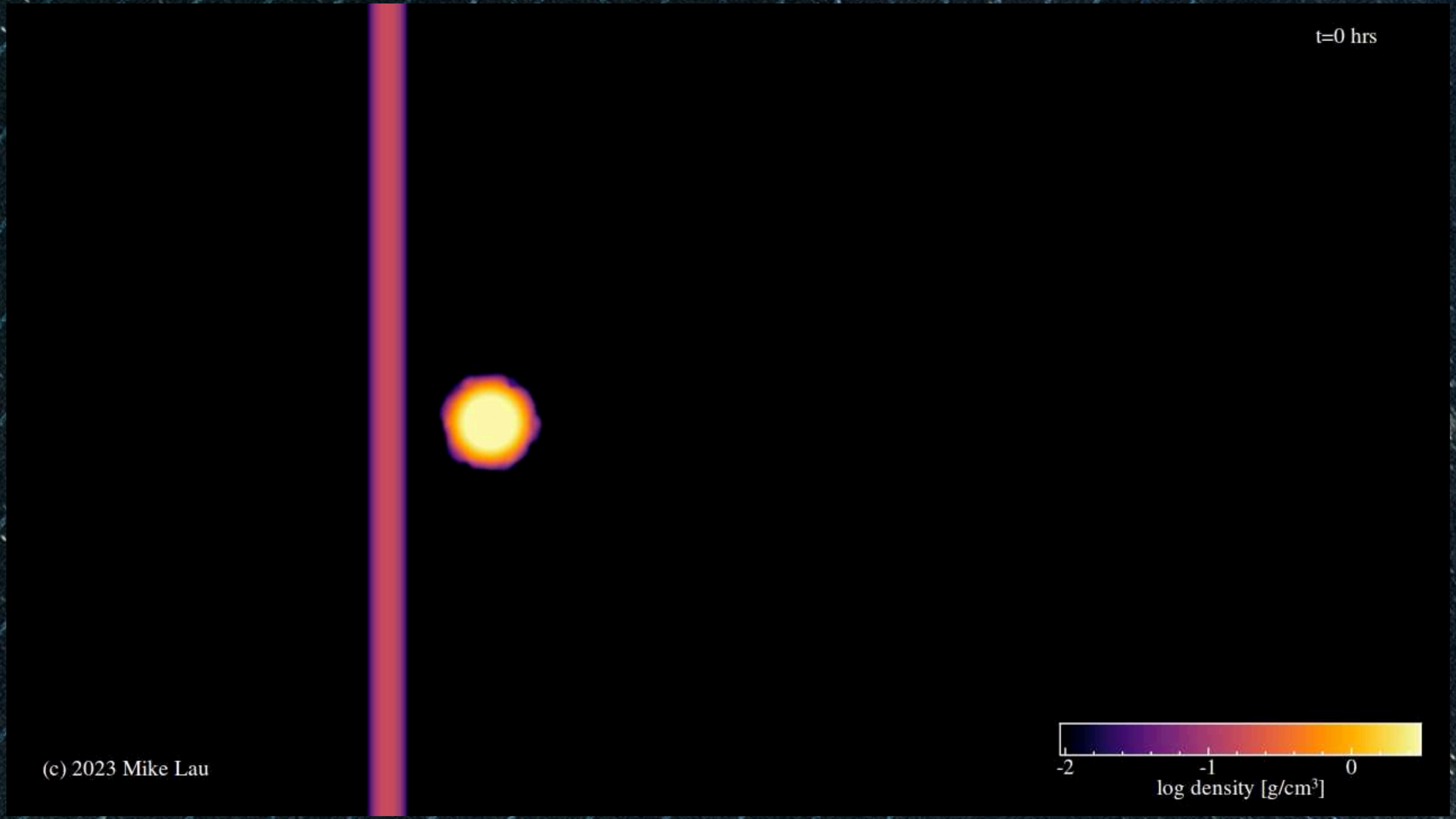


Conditions in convective envelope:

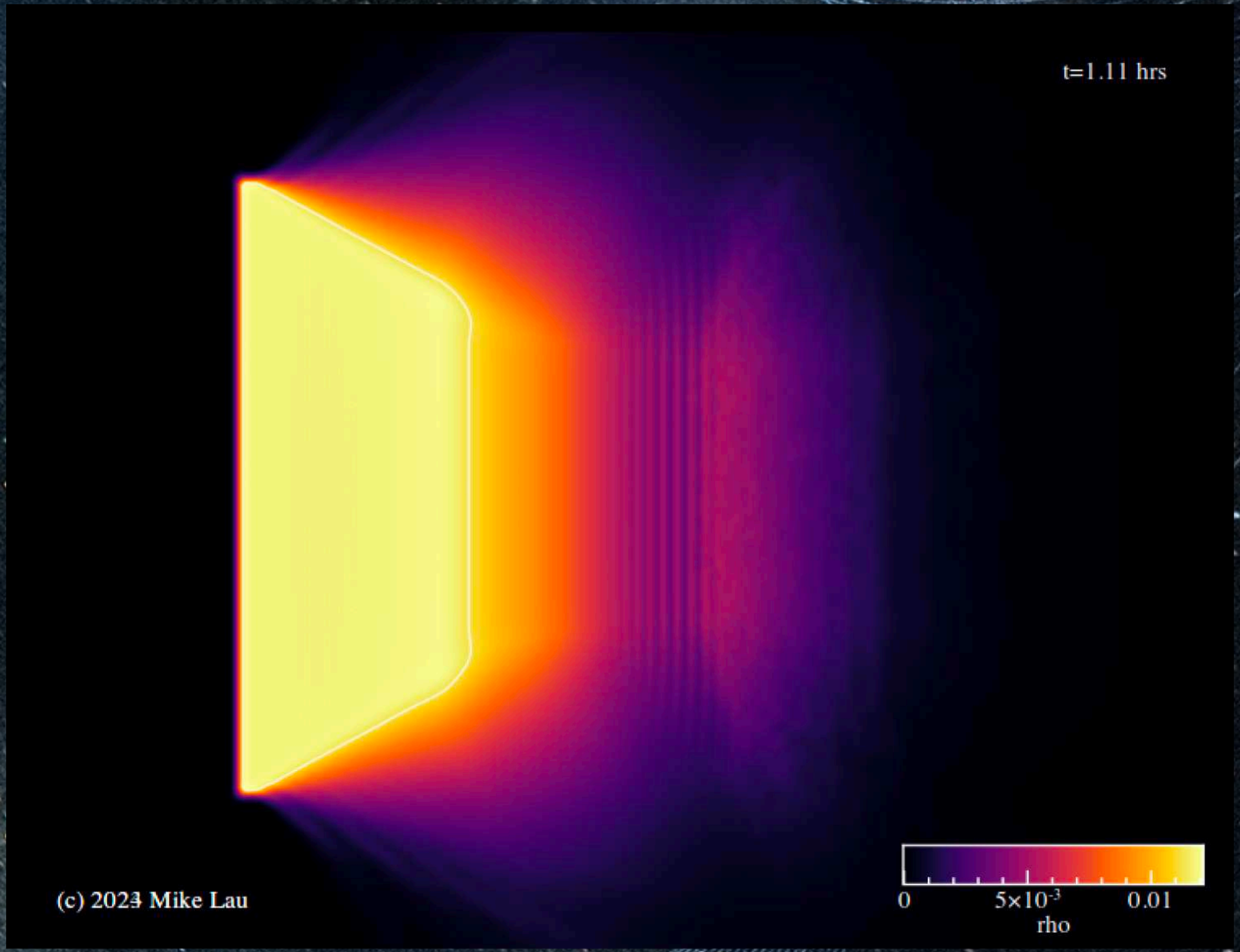
$$\mathscr{M} = 1.3$$
$$v = 230 \text{ km s}^{-1}$$
$$\rho = 0.04 \text{ g cm}^{-3}$$
$$T = 1.2 \times 10^6 \text{ K}$$

Issues

Planet is dragged by a dense wind



Wind spreading/focusing



Possible solution: Continuous readjustment to centre-of-mass velocity of "planet particles"

Summary

Implicit flux-limited diffusion

- Account for radiative losses, calculate lightcurves, evolve to late stages, self-consistent usage of recombination energy

Heating from point masses

- Drive convection in red supergiant envelope

Boundary/rigid-particles

- Can "unfreeze" core to continue evolution, study core rotation,

Wind tunnels ablation

- Study planet ablation process in detail

Common envelopes and planetary engulfment in SPH

Feb 15, 2023

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