Modelling common-envelope evolution in SPH

Feb 14, 2023

Phantom and MCFOST Users Workshop

Mike Lau

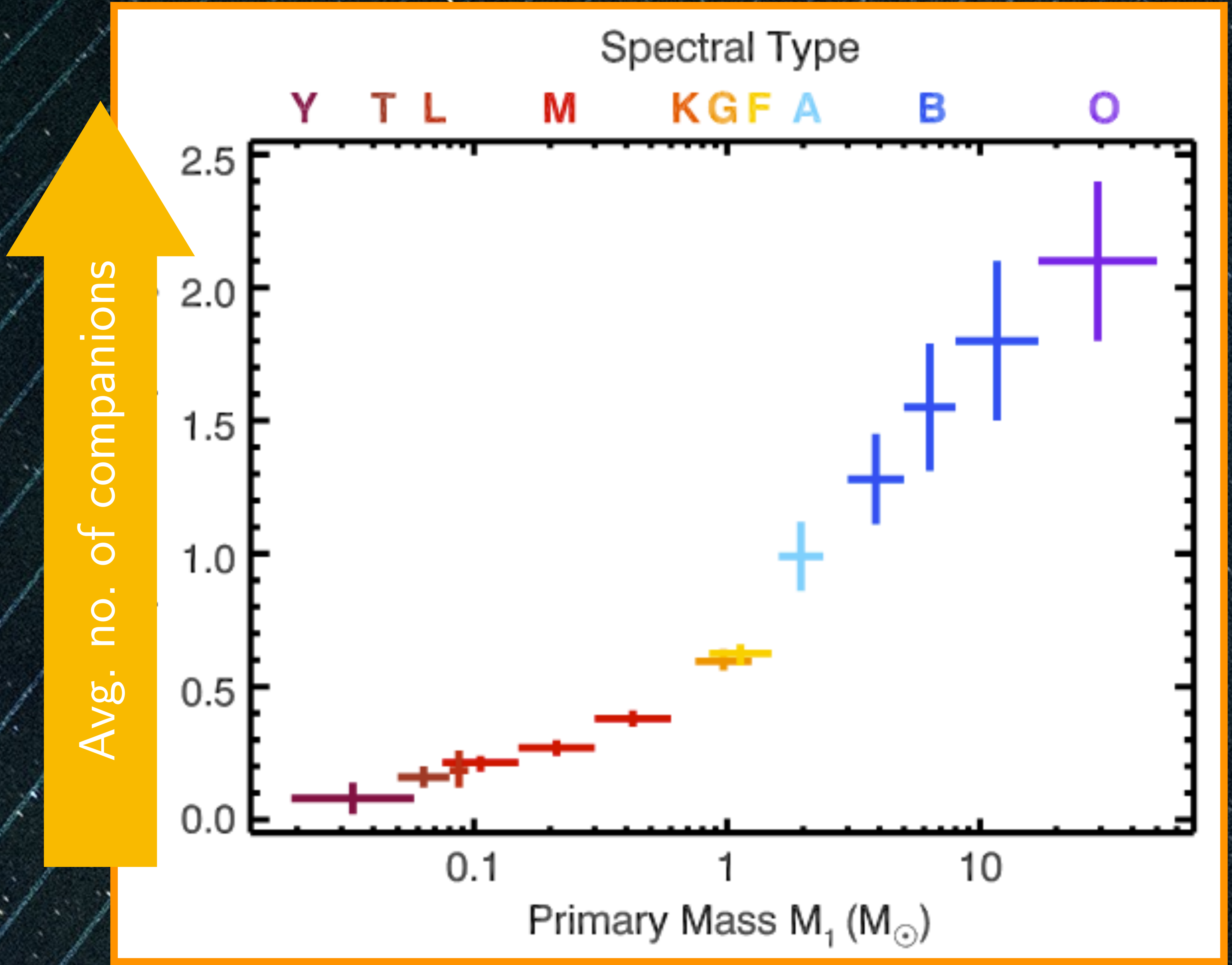
Monash University

Collaborators

Ryosuke Hirai
Daniel J. Price
Ilya Mandel
Orsola De Marco
Miguel González-Bolívar
Matteo Cantiello
Adam Jermyn
Morgan MacLeod

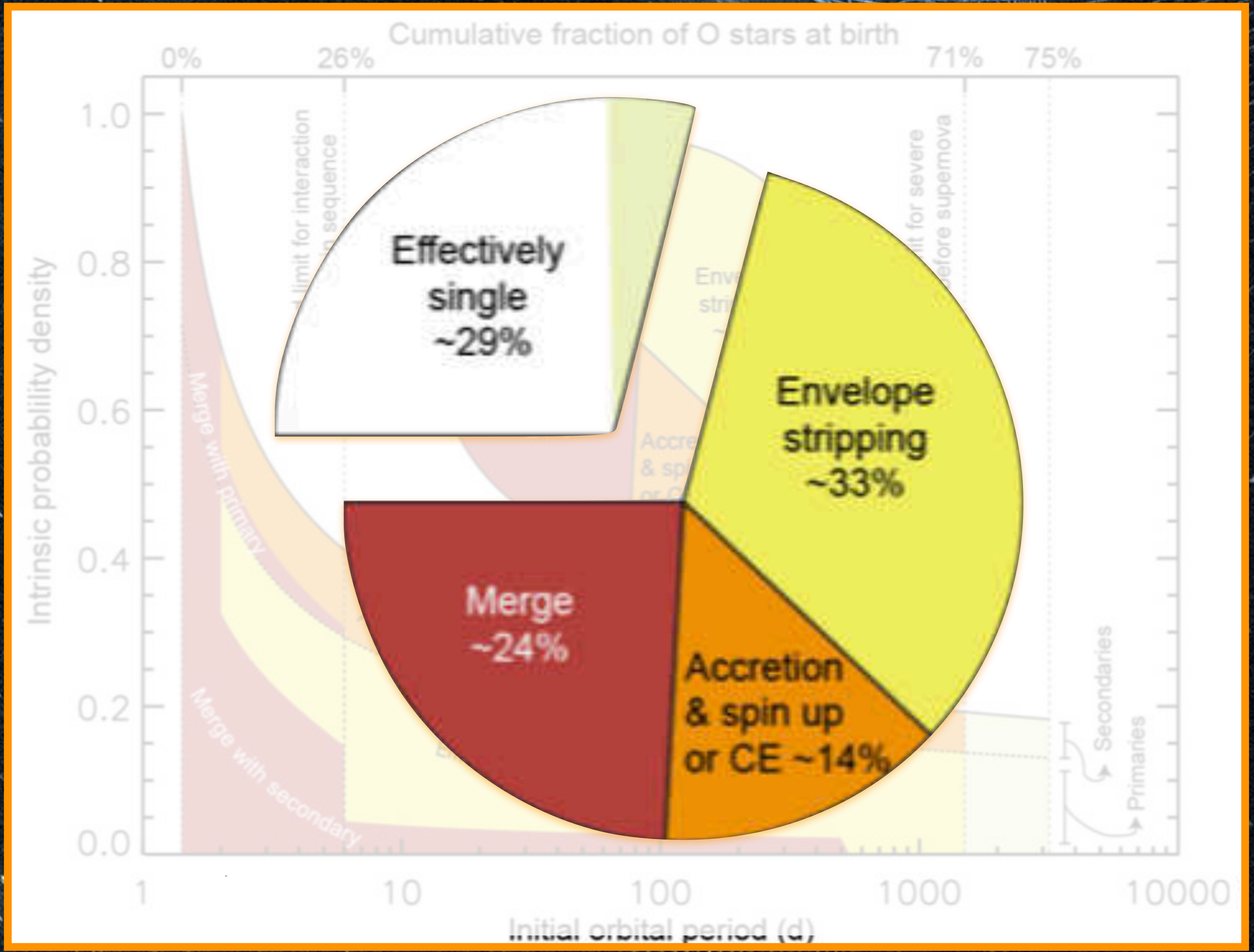
MONASH University
MACQUARIE University SYDNEY·AUSTRALIA
FLATIRON INSTITUTE
CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN
OzGrav ARC Centre of Excellence for Gravitational Wave Discovery

Interactions in stellar multiples



Offner+2022

➡ Stellar multiplicity is common



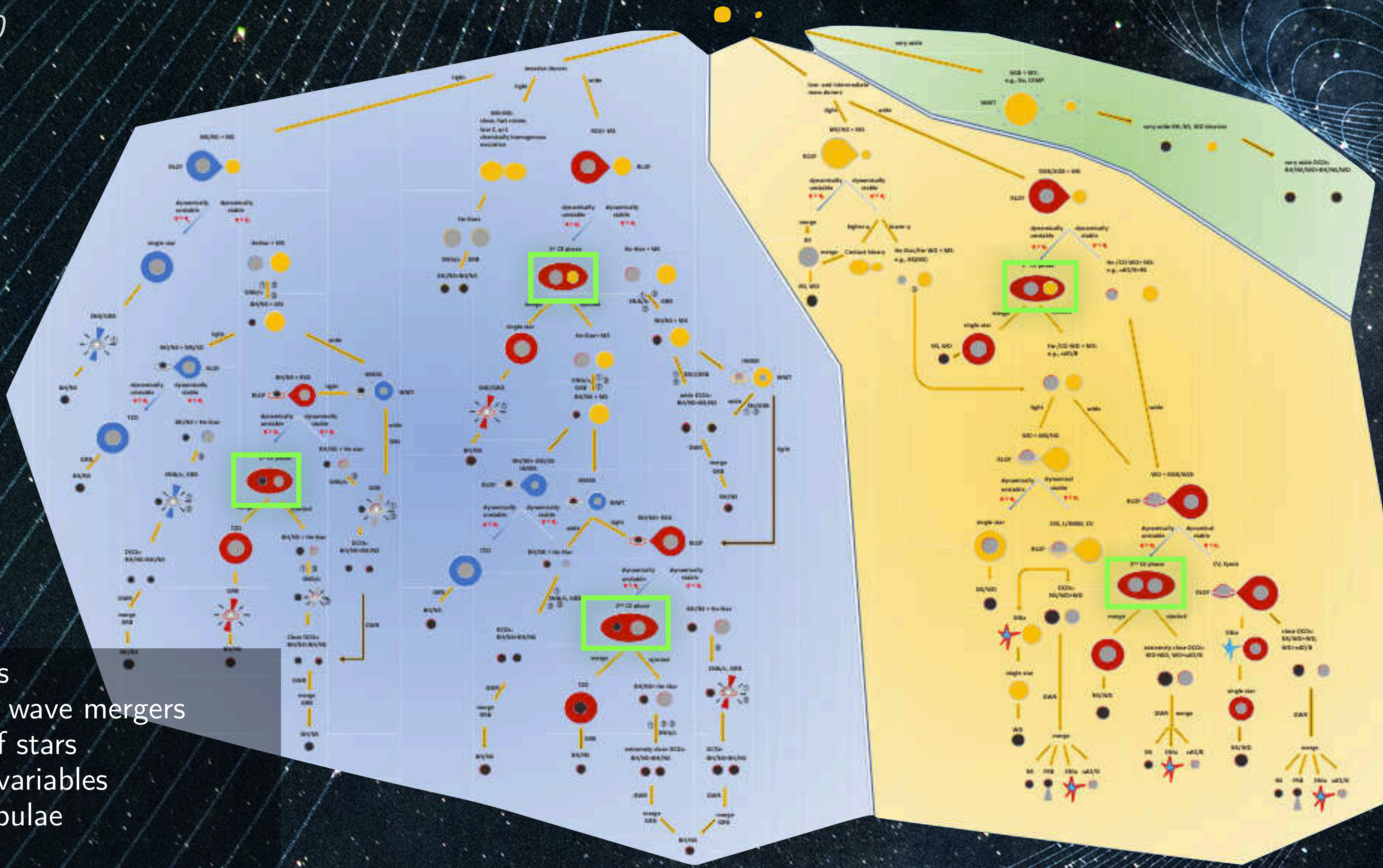
Sana+2012

➡ Binary interactions dominate massive star evolution

Binary evolution tree

Han+2020

Main sequence binary stars

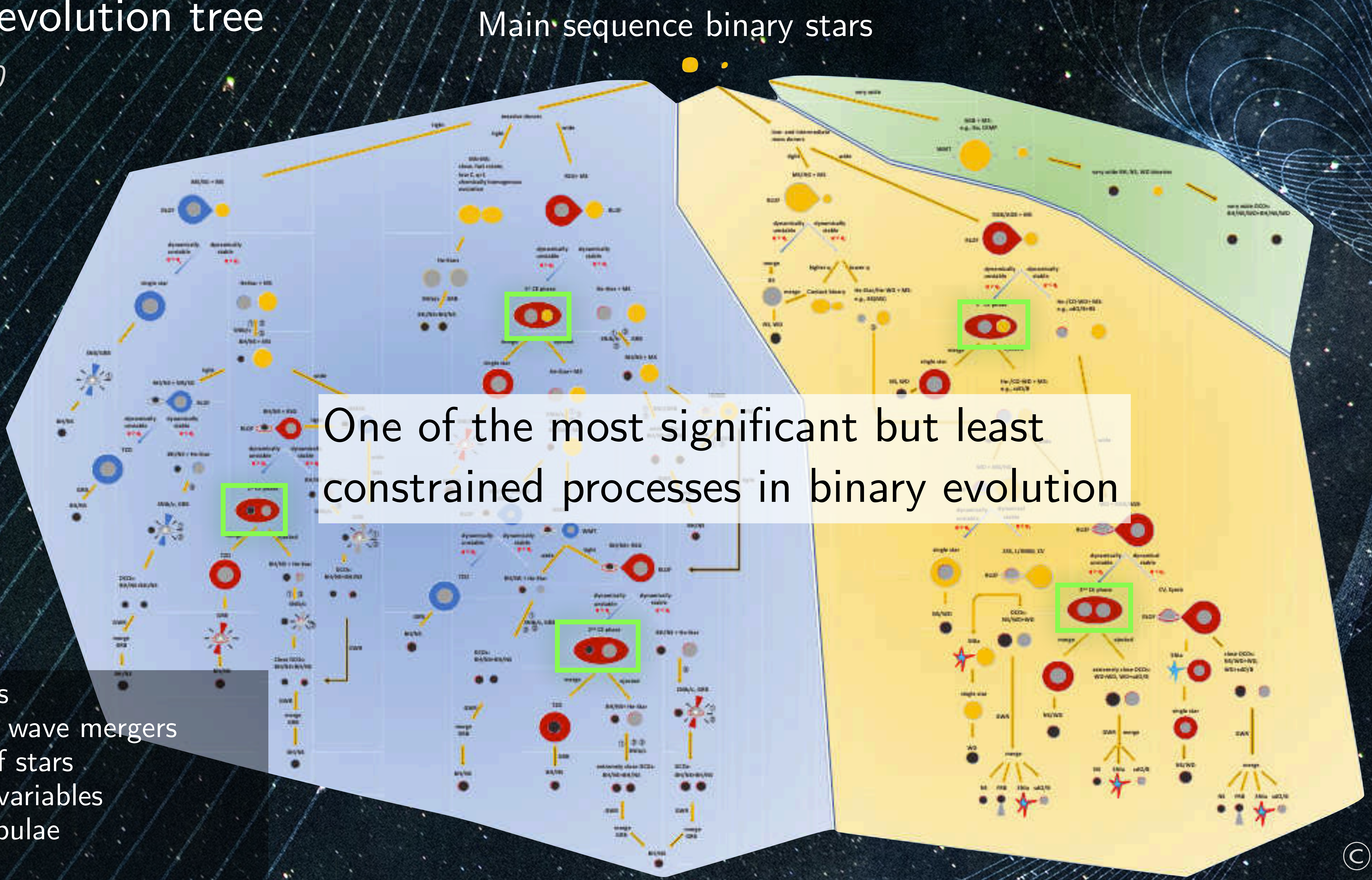


- ➡ X-ray binaries
- ➡ Gravitational wave mergers
- ➡ Hot subdwarf stars
- ➡ Cataclysmic variables
- ➡ Planetary nebulae
- ➡ Type Ia SNe

...

Binary evolution tree

Han+2020

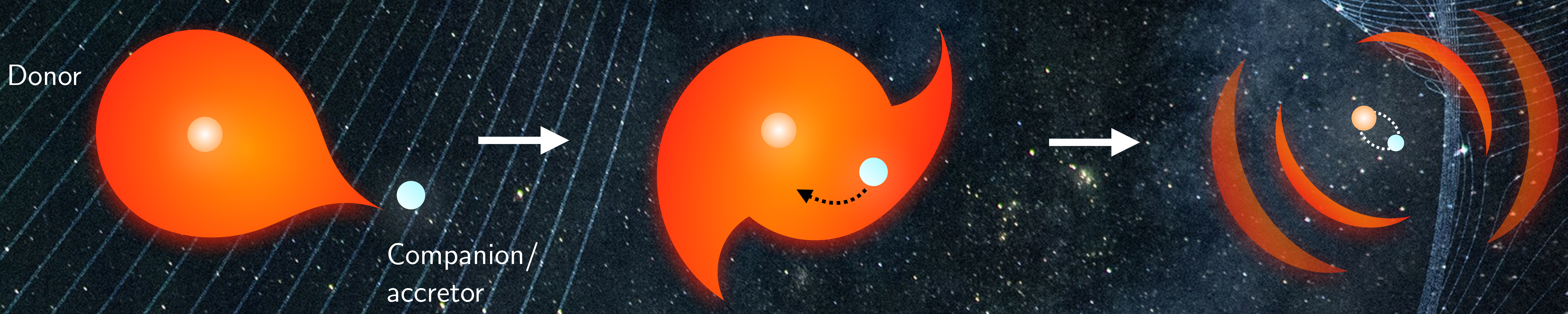


One of the most significant but least constrained processes in binary evolution

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

...

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

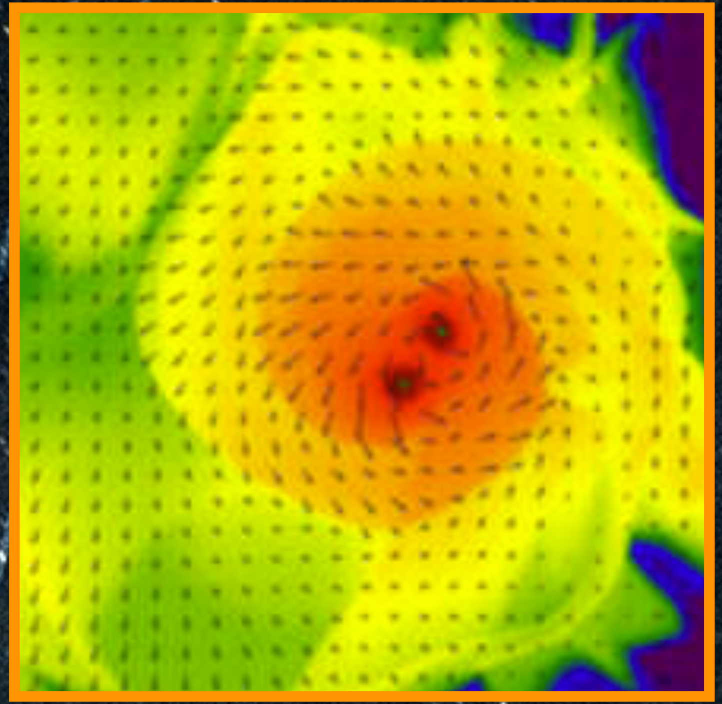
   Expelling the envelope leaves a much tighter binary orbit

Detailed simulations

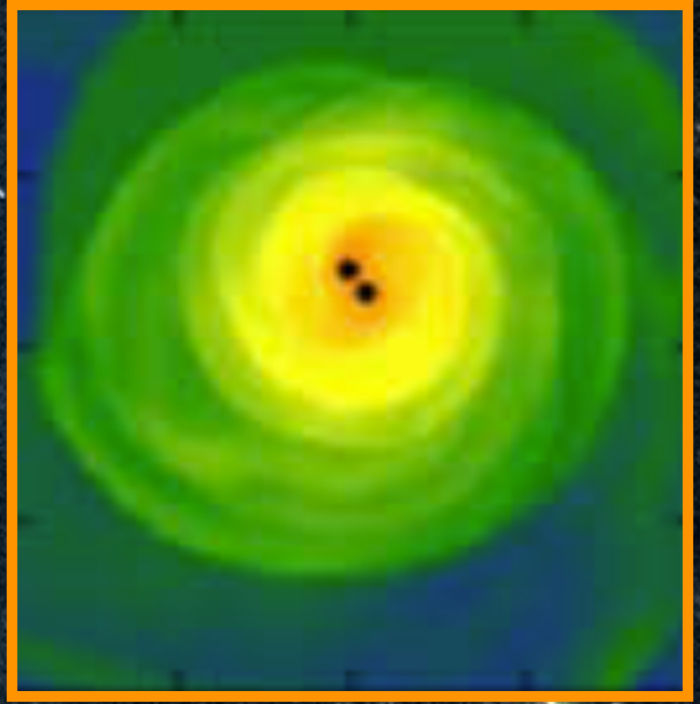
Key questions

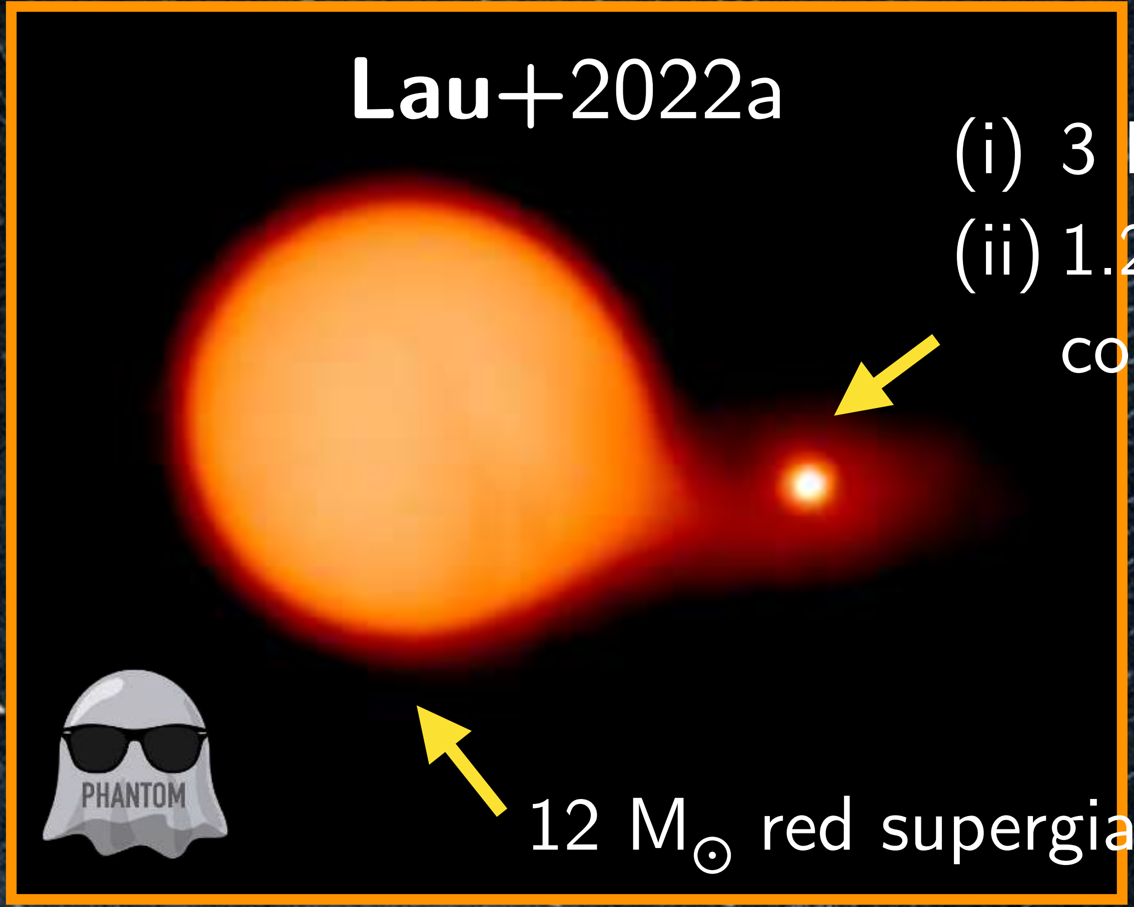
- *Can we fully eject the envelope?*
- *What is the final separation?*

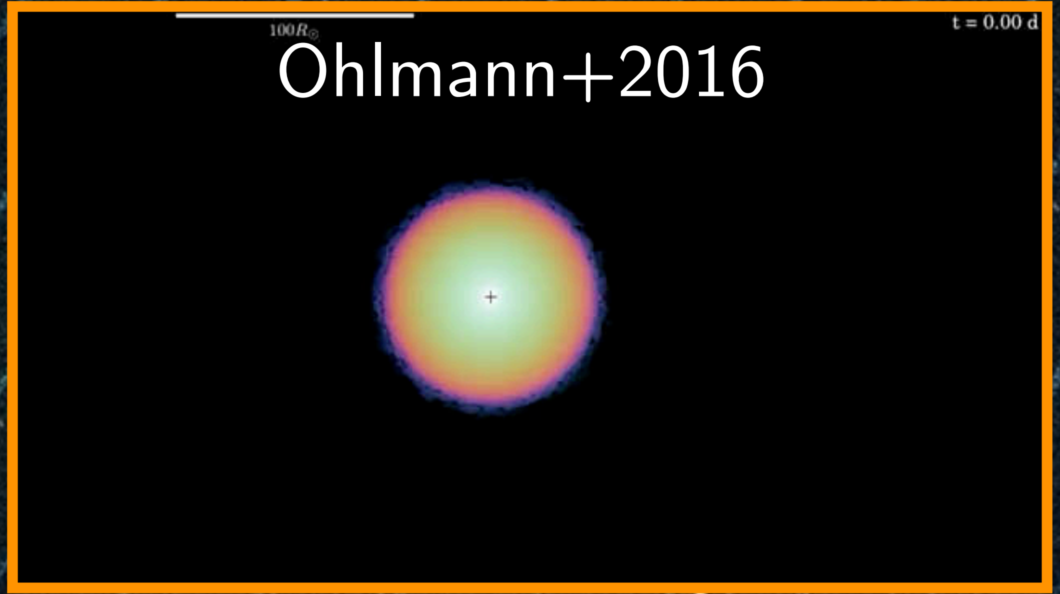
Passy+2012

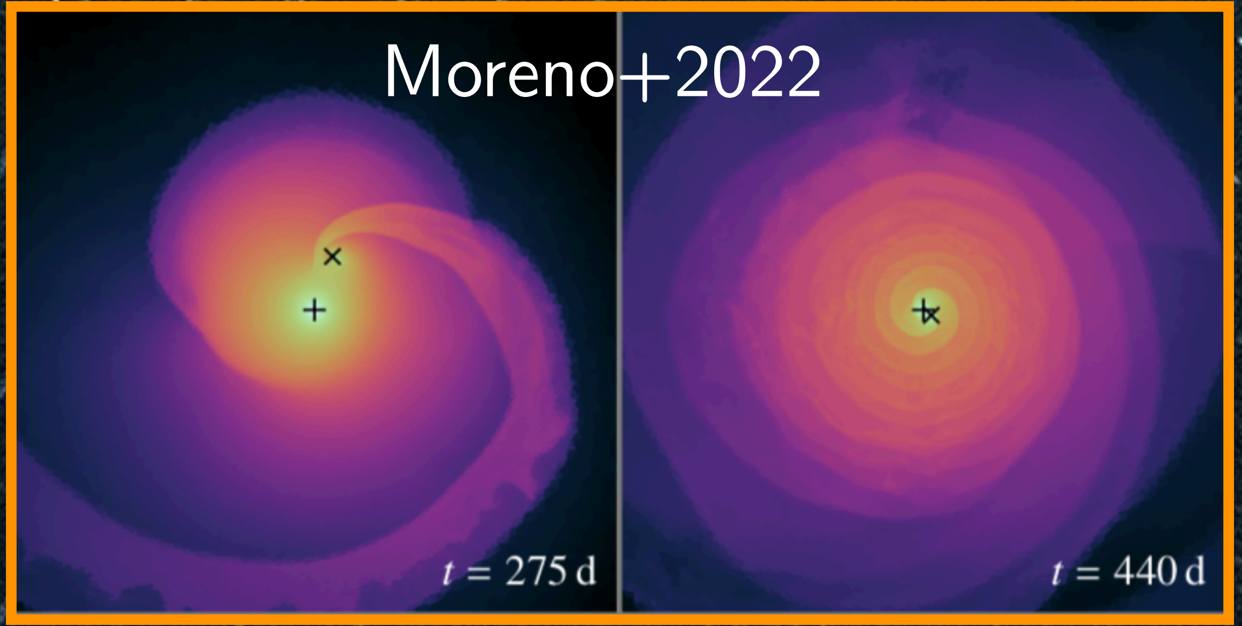


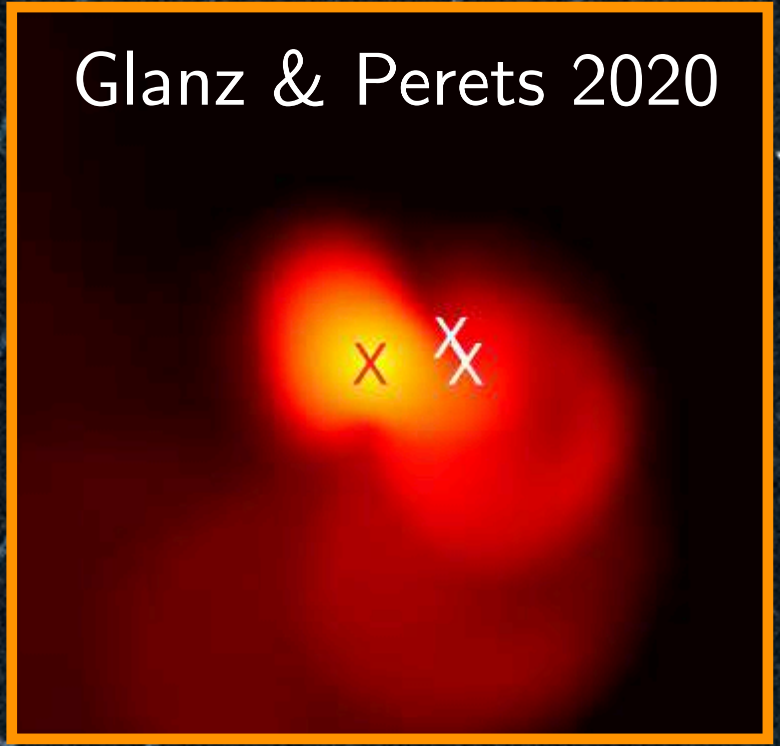
Iaconi+2017

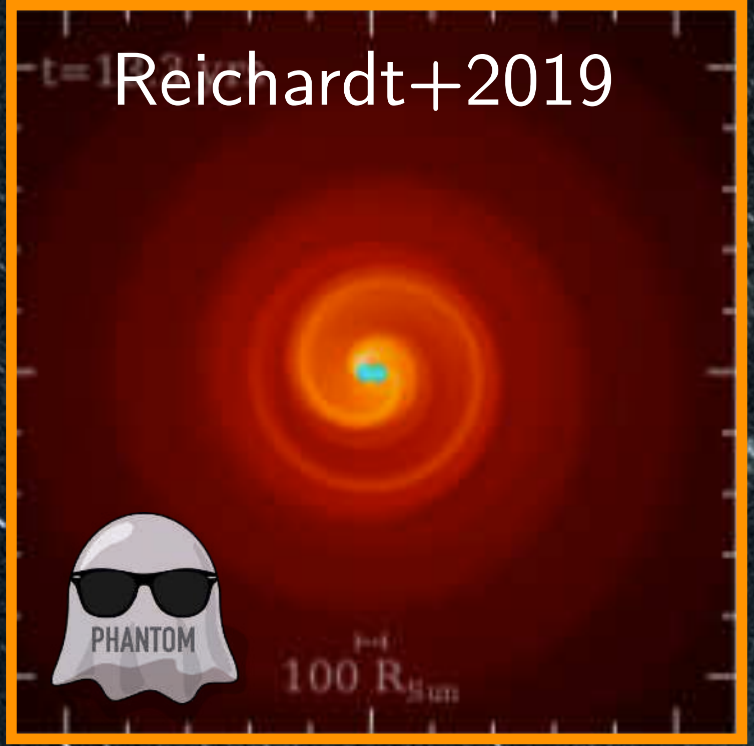












Modelling common envelopes is very difficult

- 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

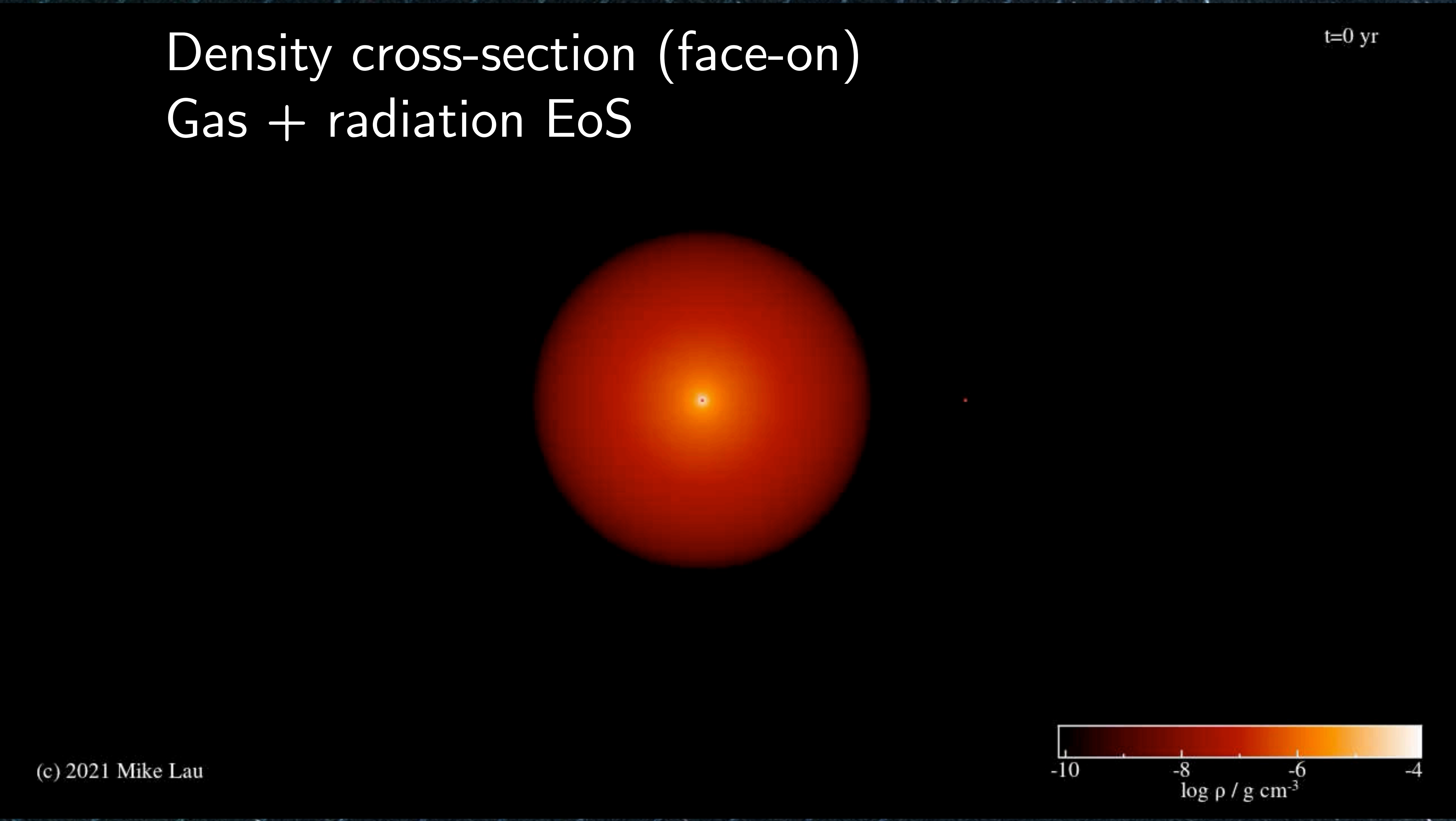
12 $M_\odot$ red supergiant + 3 $M_\odot$ companion

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

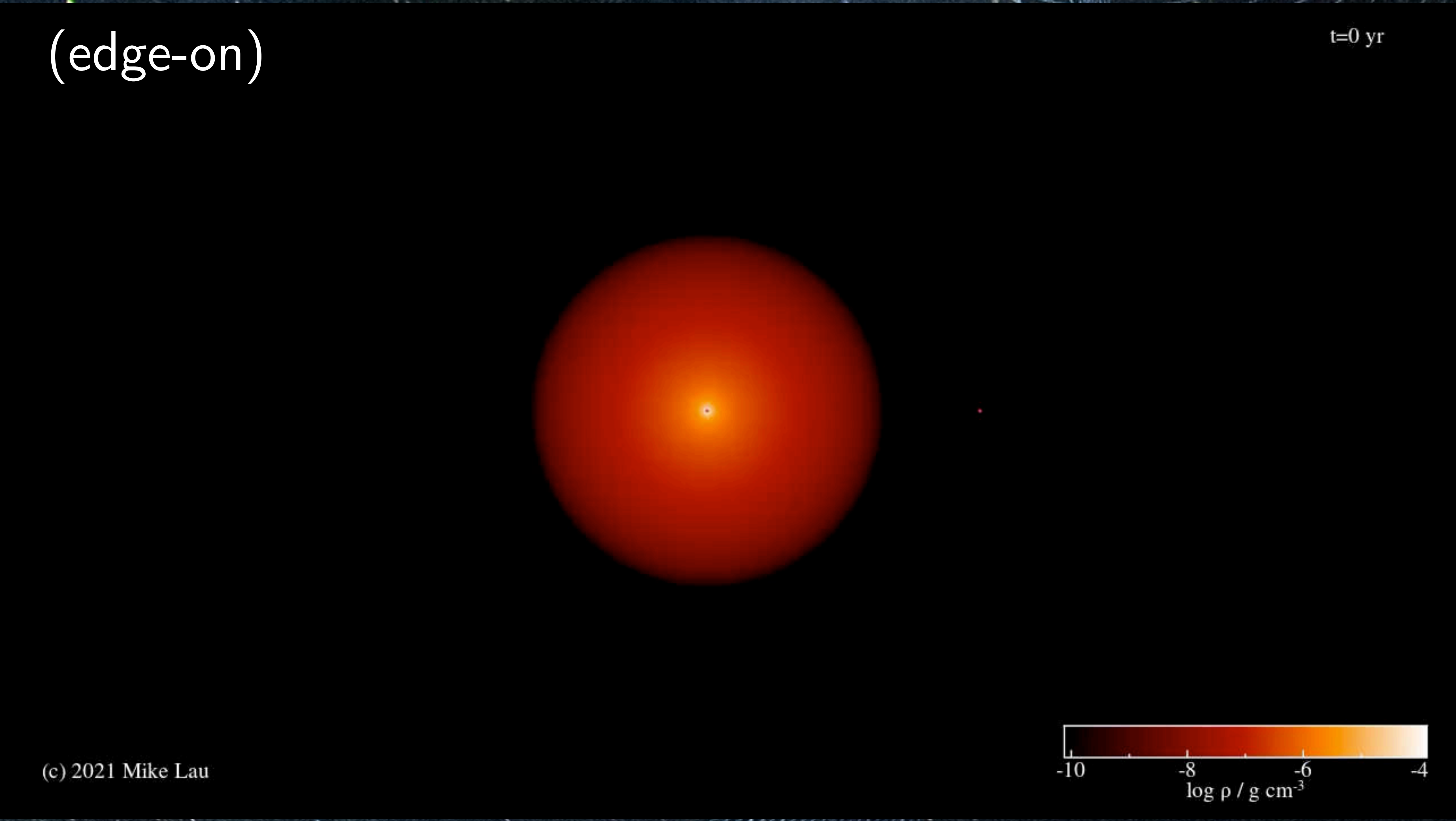
12 $M_\odot$ red supergiant + 3 $M_\odot$ companion

Lau+2022a

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



(edge-on)



Setting up a common envelope simulation

1. Setup a giant star in Phantom

SETUP=star

- Mapping 1D stellar profile
- Star relaxation (*relax-o-matic*)

2. Add companion

moddump=moddump_binary.f90

- Specify orbital parameters
- Companion can be a sink particle or another dump file containing a star

3. Run Phantom

- Self-gravity
- Global time-stepping
- One to few months of wall time
- No conductivity? $\alpha_u = 0$

4. Analysis

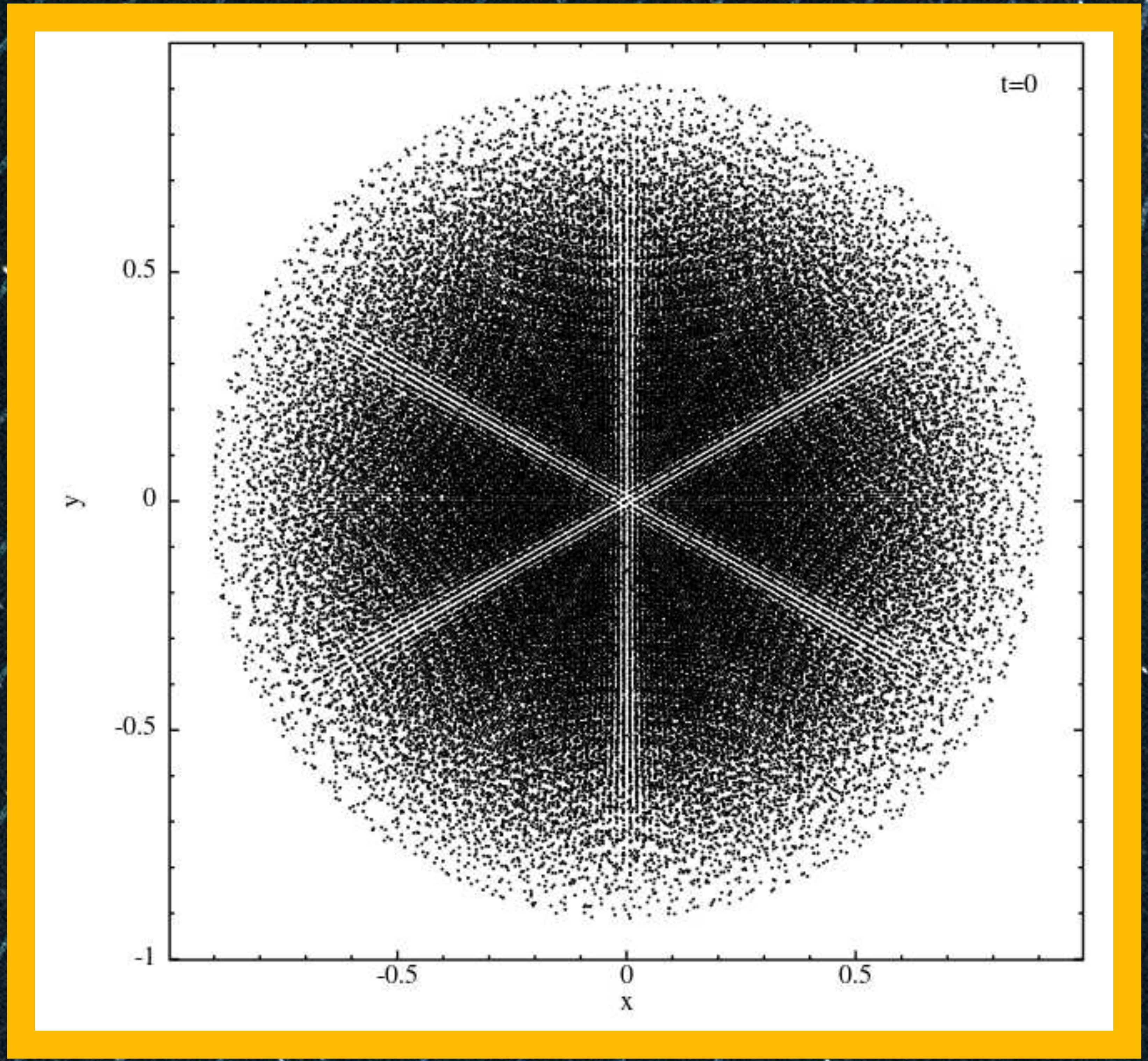
analysis=analysis_common_envelope.f90

- Tom Reichardt, Roberto Iaconi, ML, Miguel González-Bolívar...
- E.g. Unbound mass, energy profile, gravitational drag

Star setup

Pre-2020:

- Stretch mapping from closed-pack lattice
- Relaxation by evolving with velocity damping term



Post-2020:

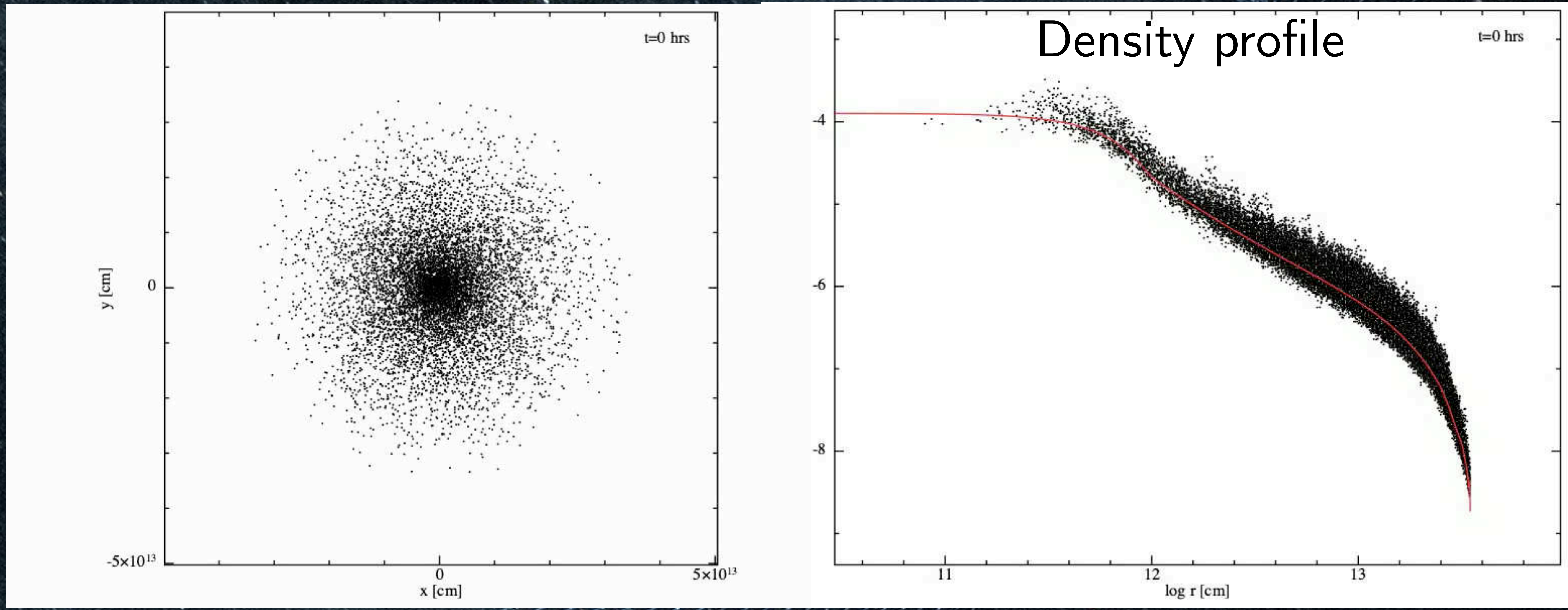
Random uniform sphere with symmetrical particle placement

Daniel Price

"relax-o-matic" asynchronous particle shifting

Daniel Price, **ML**, Ryosuke Hirai, Appendix C, **Lau**+2022a

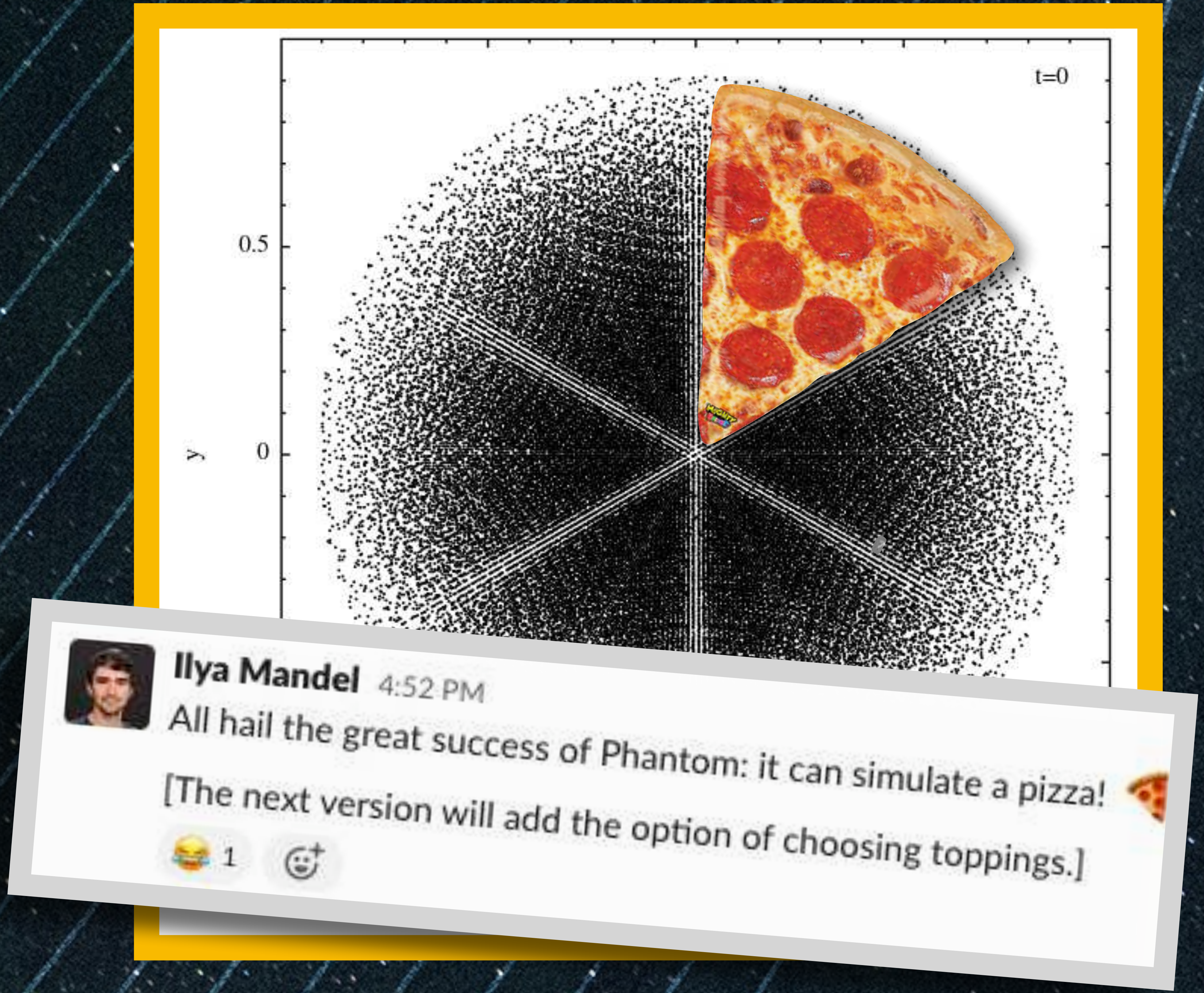
$$\Delta \mathbf{x}_i = \frac{1}{2}(C_{\rm cour} h_i / c_{s,i})^2 \mathbf{a}_i$$



Star setup

Pre-2020:

- Stretch mapping from closed-pack lattice
- Relaxation by evolving with velocity damping term

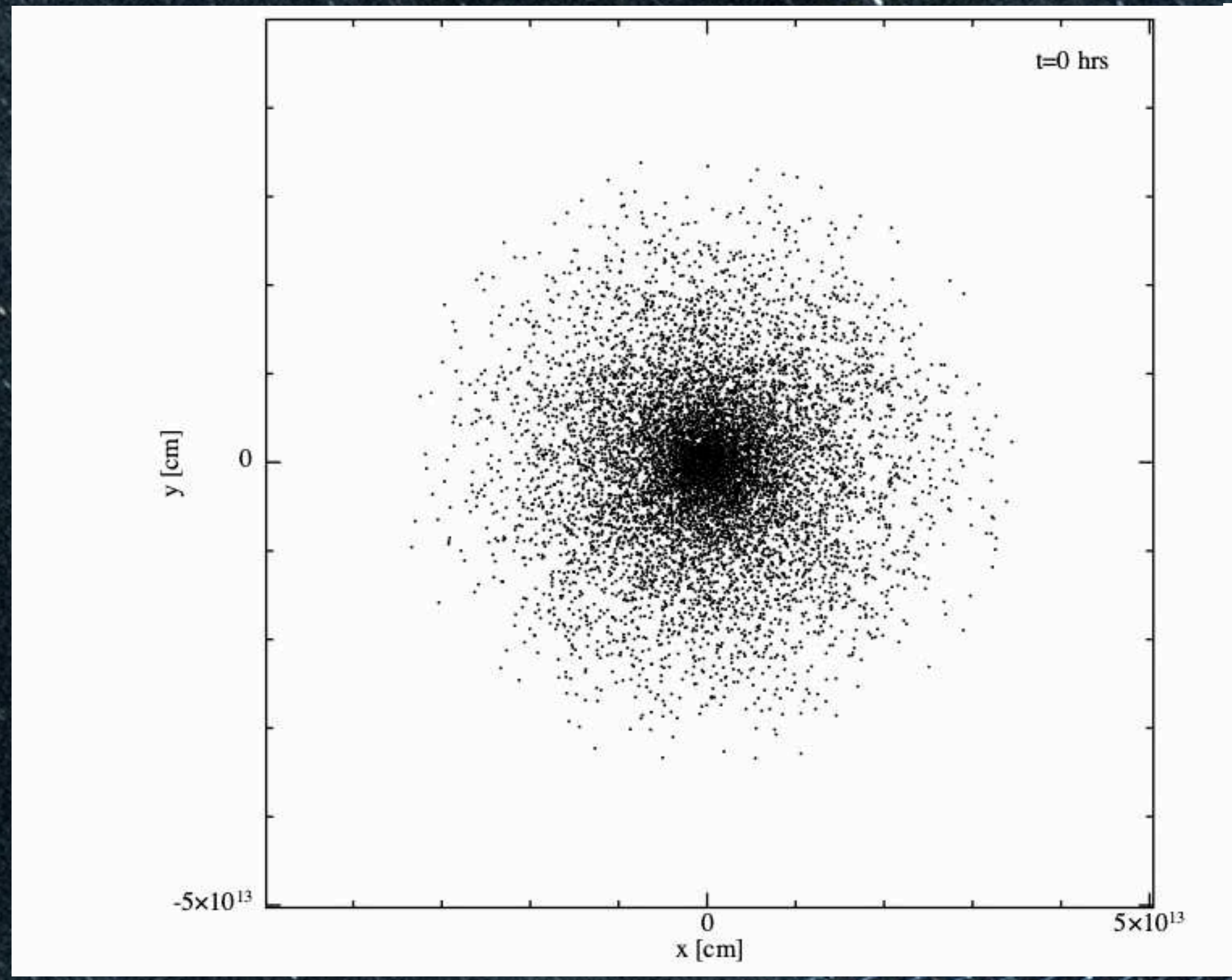


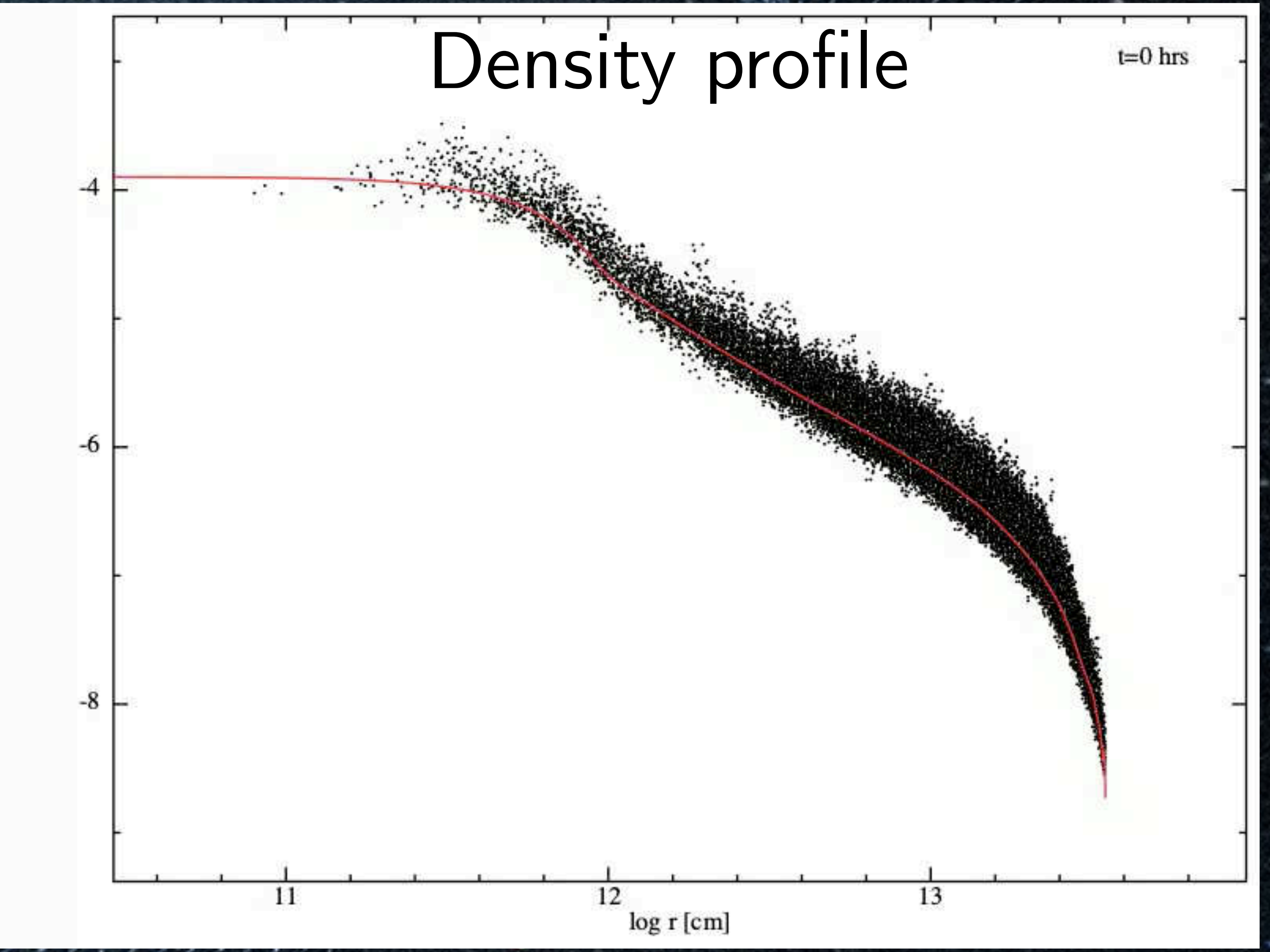
Post-2020:

Random uniform sphere with symmetrical particle placement
Daniel Price

"relax-o-matic" asynchronous particle shifting
Daniel Price, **ML**, Ryosuke Hirai, Appendix C, **Lau**+2022a

$$\Delta \mathbf{x}_i = \frac{1}{2}(C_{\mathrm{cour}} h_i / c_{s,i})^2 \mathbf{a}_i$$



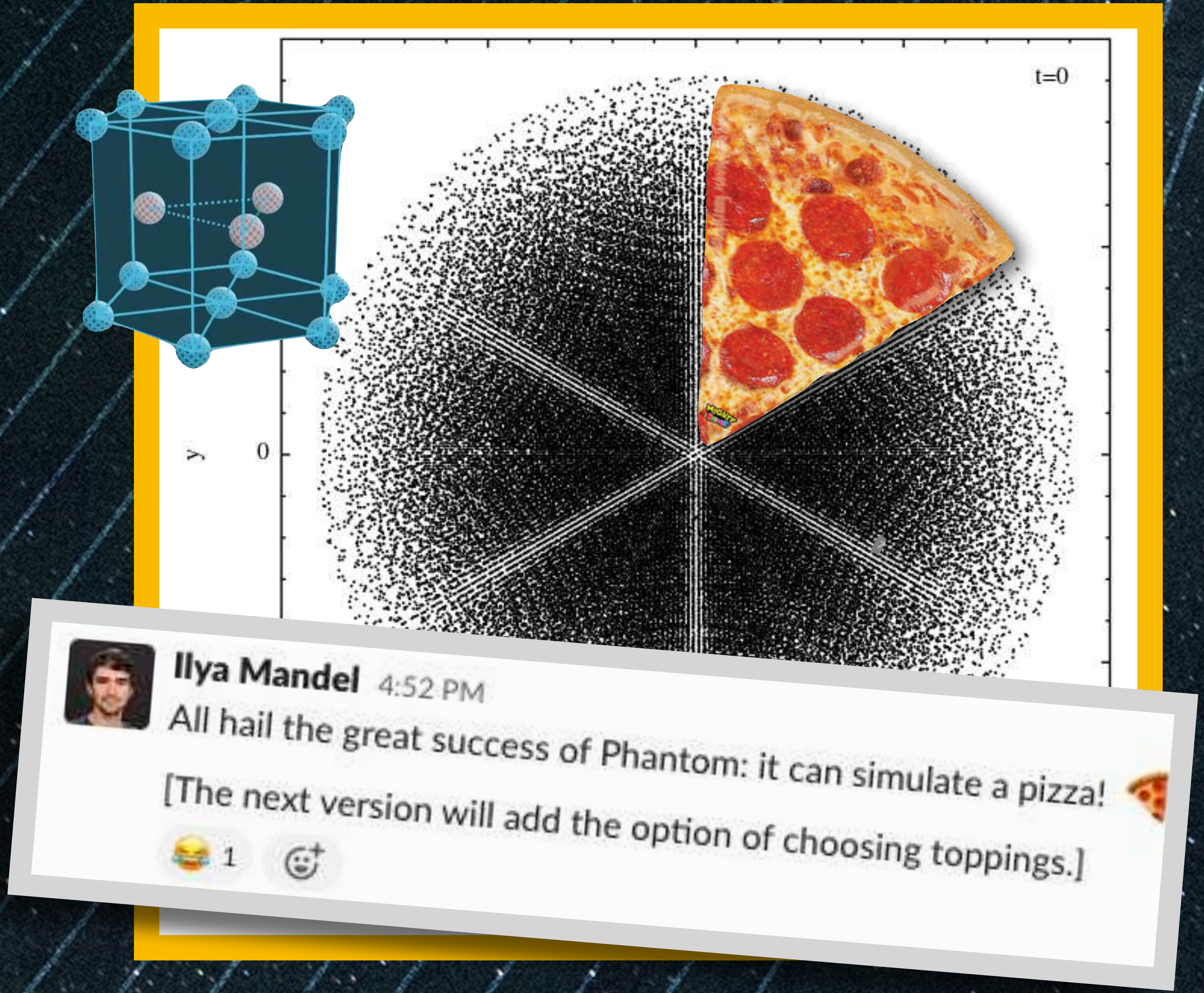


Star setup

Pre-2020:

Stretch mapping from closed-pack lattice

Relaxation by evolving with velocity damping term



Post-2020:

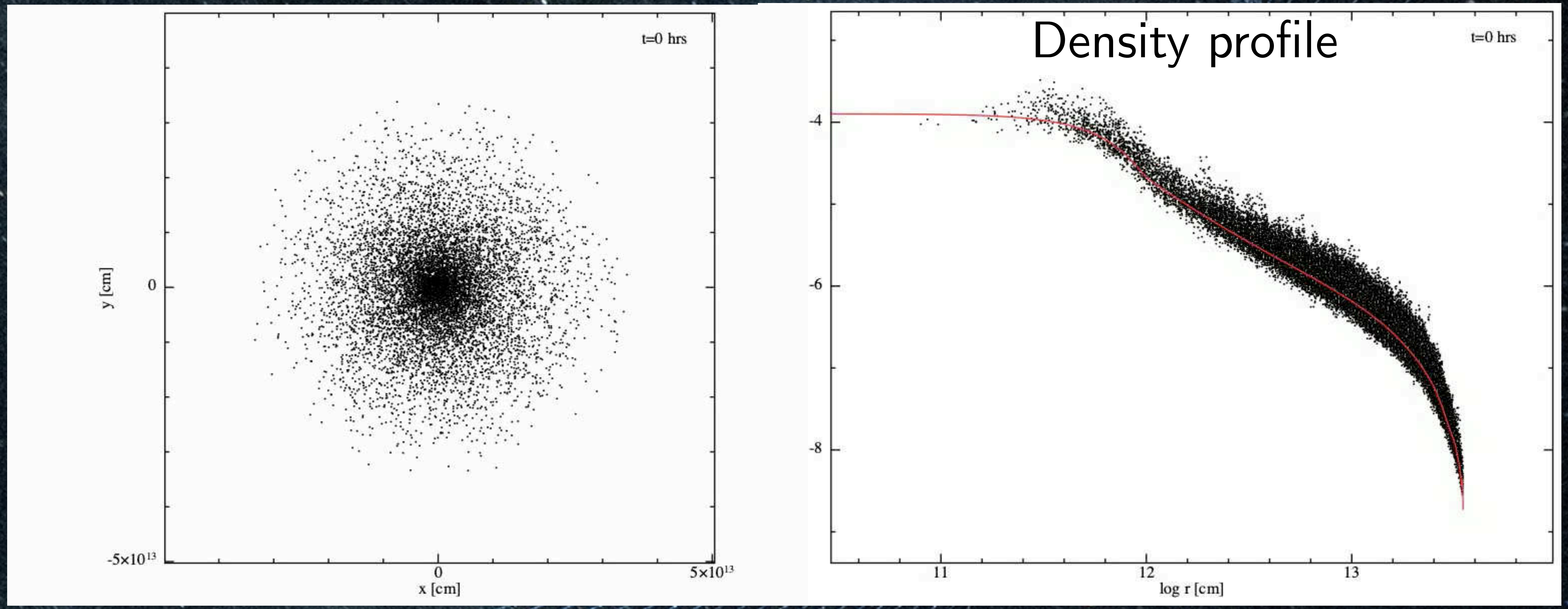
Random uniform sphere with symmetrical particle placement

Daniel Price

"relax-o-matic" asynchronous particle shifting

Daniel Price, **ML**, Ryosuke Hirai, Appendix C, **Lau**+2022a

$$\Delta \mathbf{x}_i = \frac{1}{2}(C_{\rm cour} h_i / c_{s,i})^2 \mathbf{a}_i$$

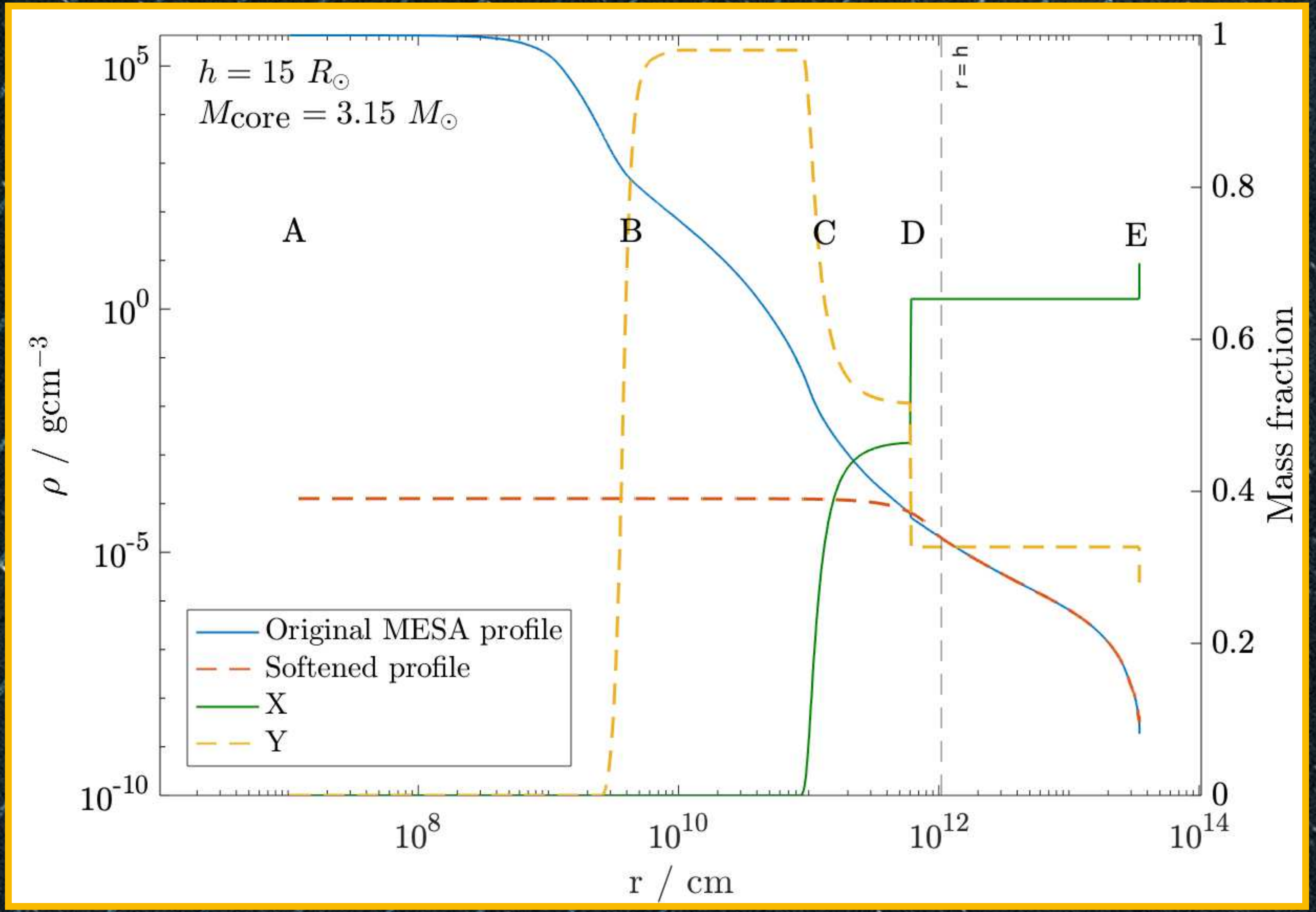


Stellar profile

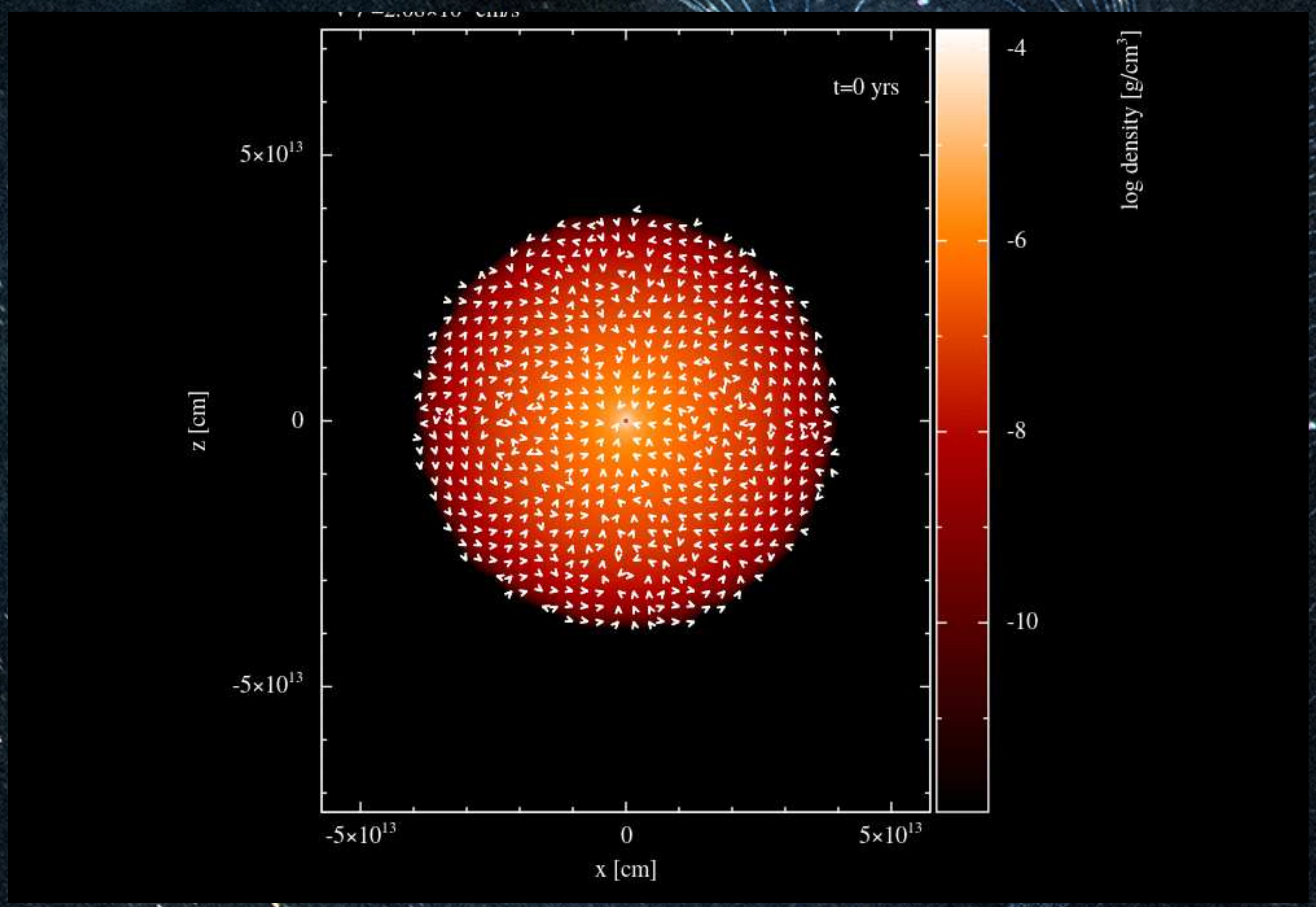
Pre-2020: "Soften" density profile beneath core radius

`set_cubic_core`, `set_fixedentropycore`

ML, Ryosuke Hirai, González-Bolívar (+**ML**) 2022



Transient convection:

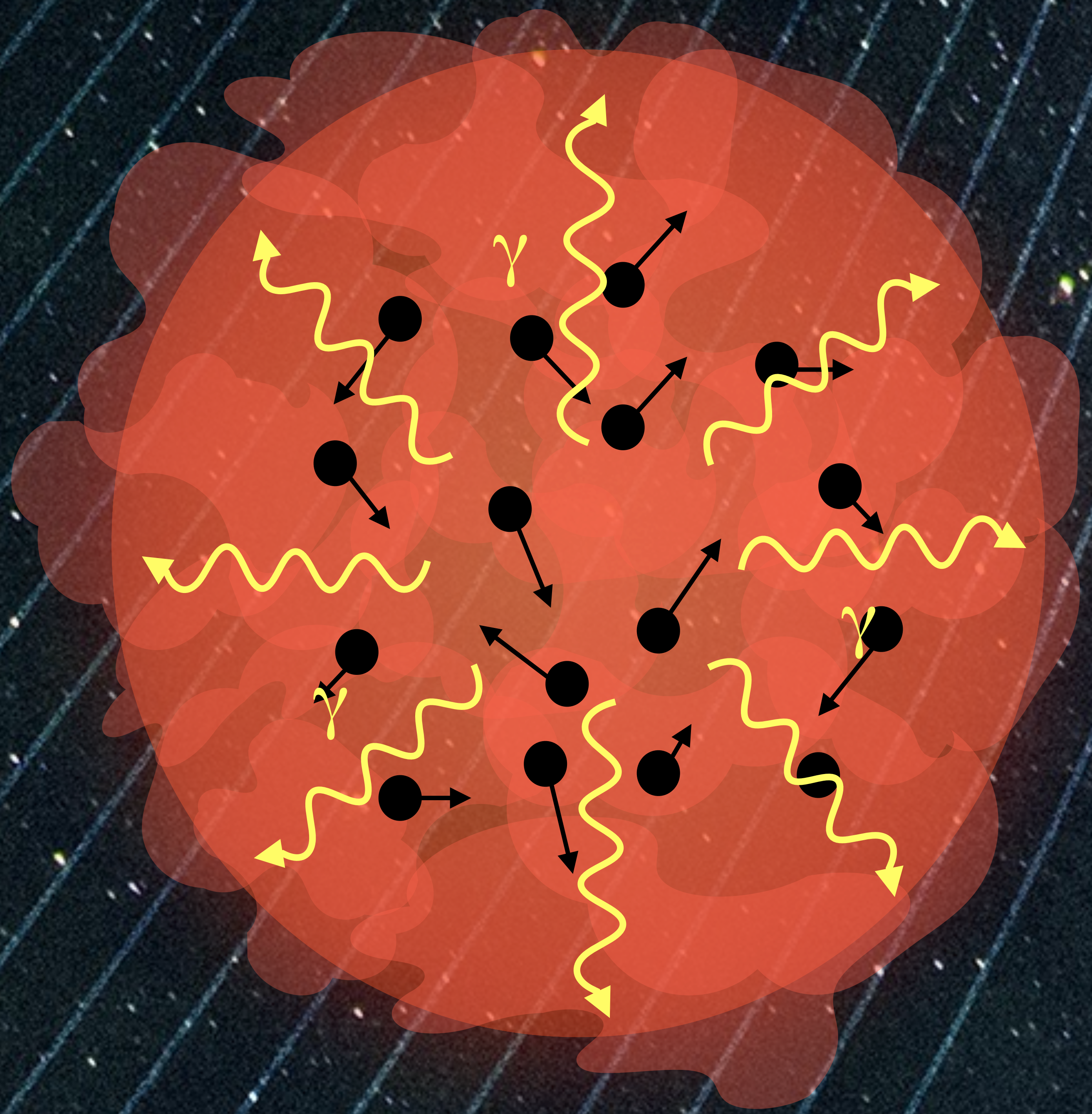


Lau+2022a: Construct flat entropy star to stabilise envelope

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)

New physics, new EoSs



Gas + radiation EoS for red supergiants (`ieos=12`)
__ML__, Ryosuke Hirai, Daniel Price, (Lau+2022a)

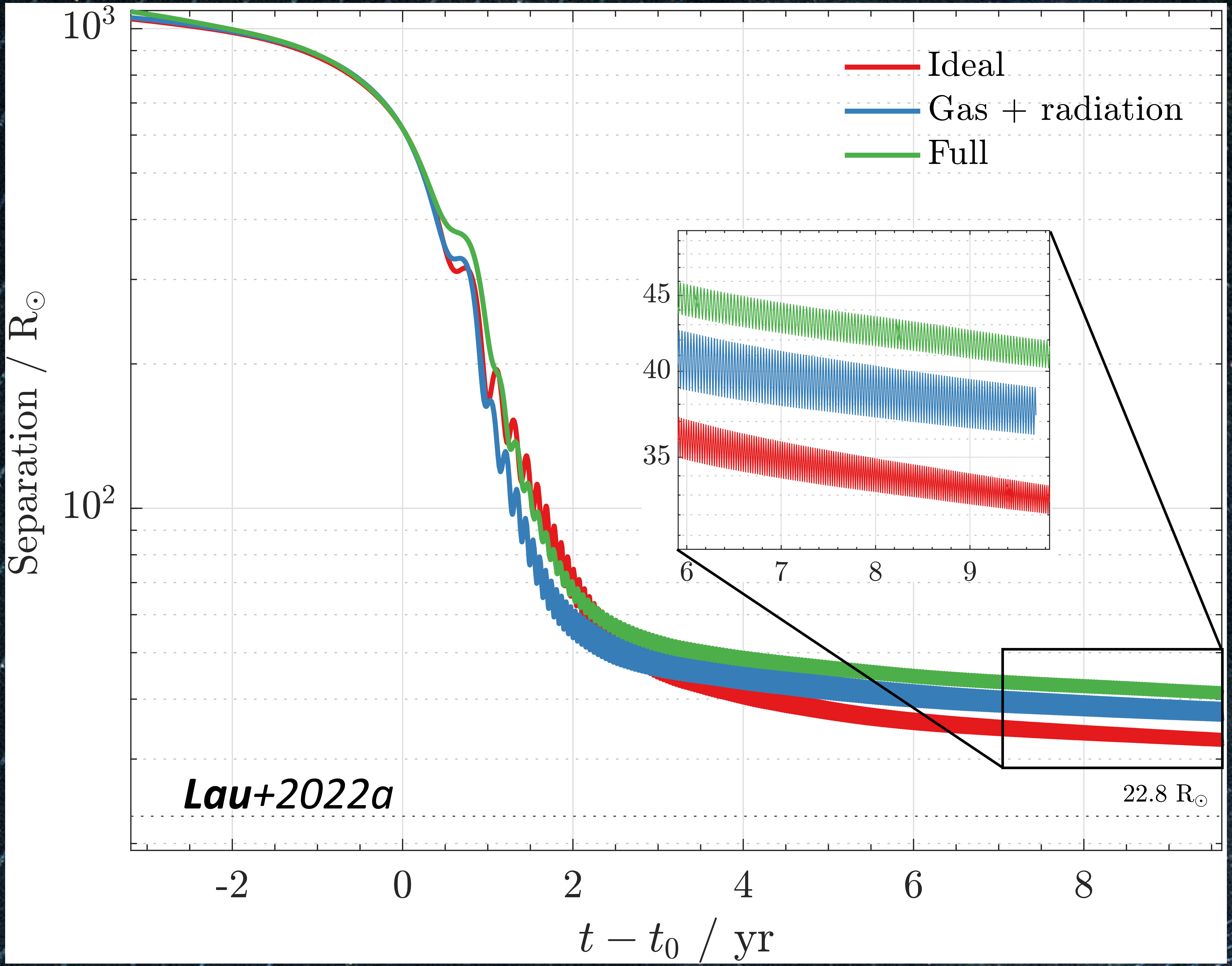
Recombination energy from tabulated OPAL EoS as implemented in MESA (`ieos=10`)
Tom Reichardt (Reichardt+2020)

Gas + radiation + recombination EoS (`ieos=20`)
Ryosuke Hirai, ML, (Hirai+2020, __Lau__+2022b)

$$p = \frac{\rho k_\mathrm{B} T}{\mu m_\mathrm{H}} + \frac{aT^4}{3}$$

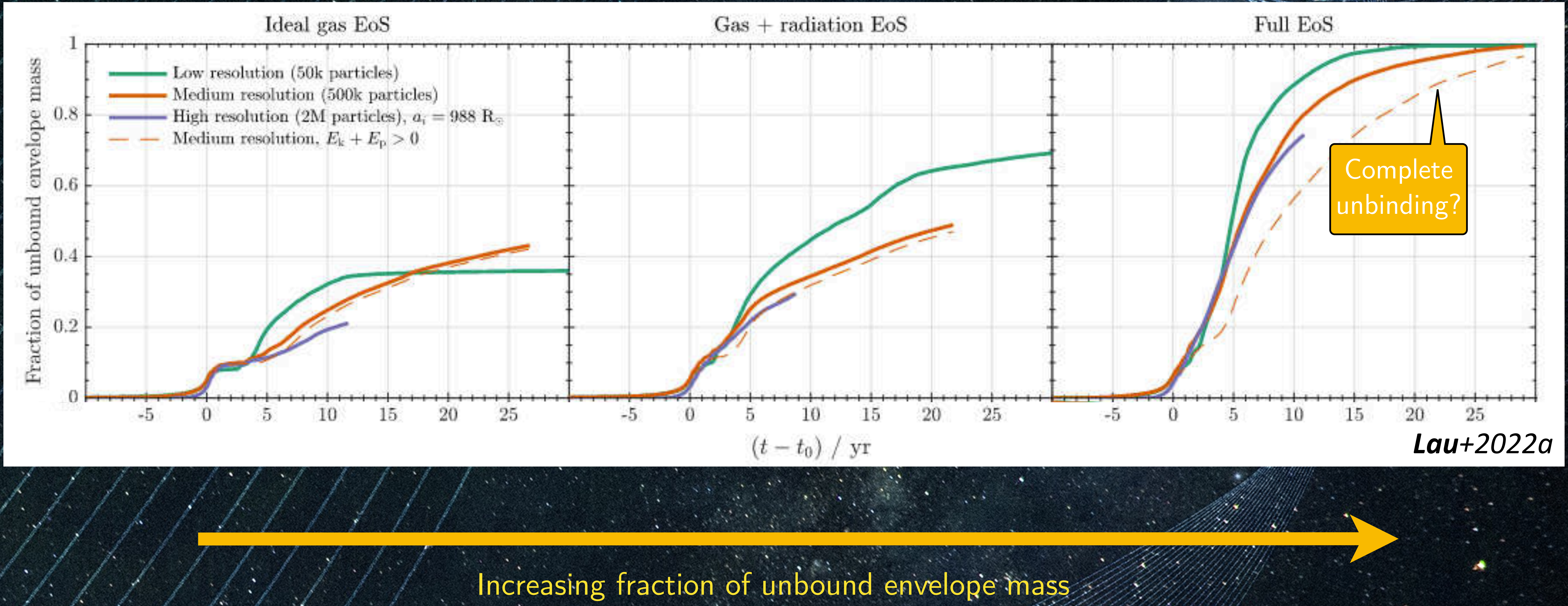
$$u = \frac{3 k_\mathrm{B} T}{2 \mu m_\mathrm{H}} + \frac{aT^4}{\rho} + \varepsilon_\mathrm{ion}(x_i)$$

Final separation



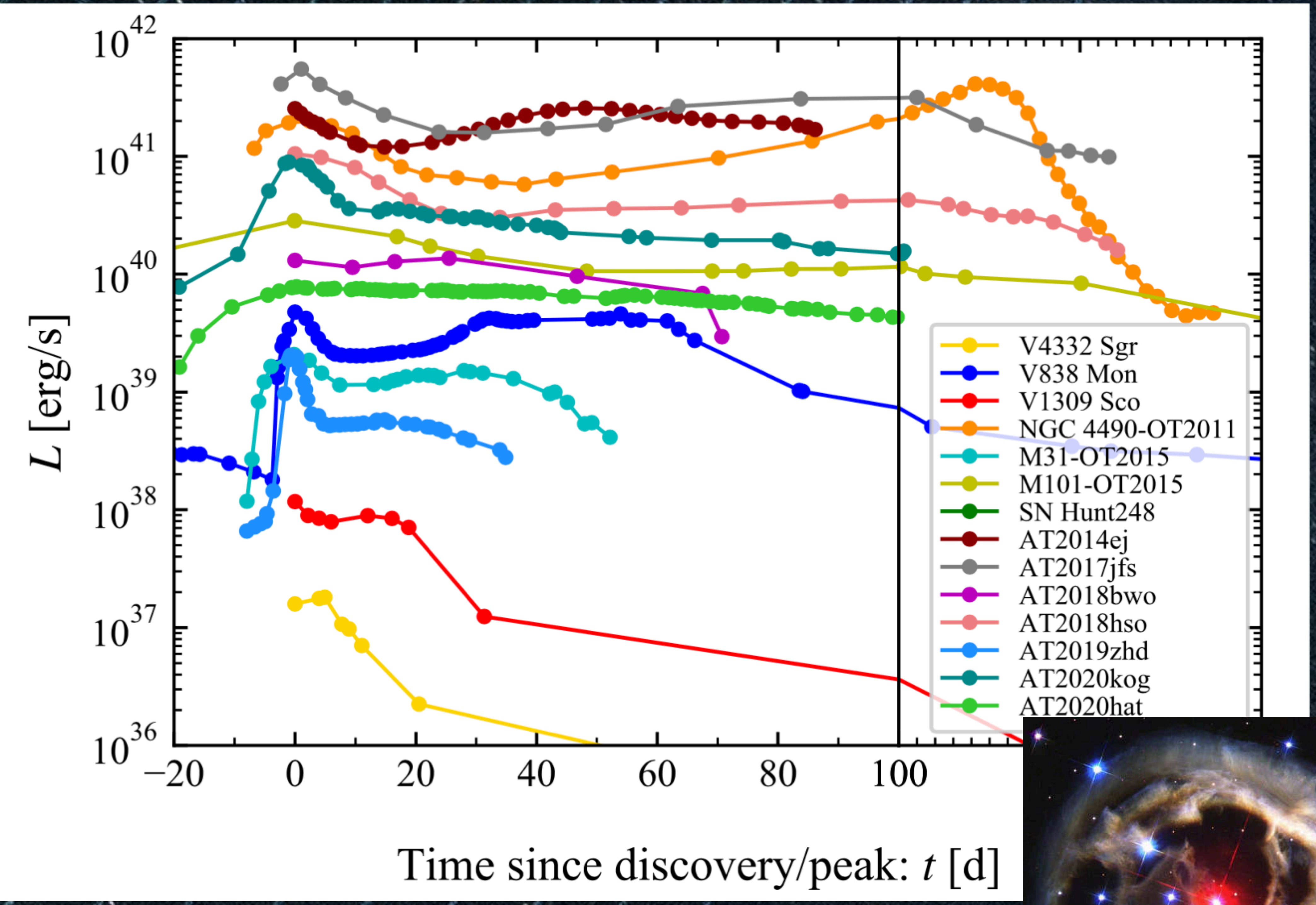
Radiation pressure and recombination energy increase final separation

Unbound mass



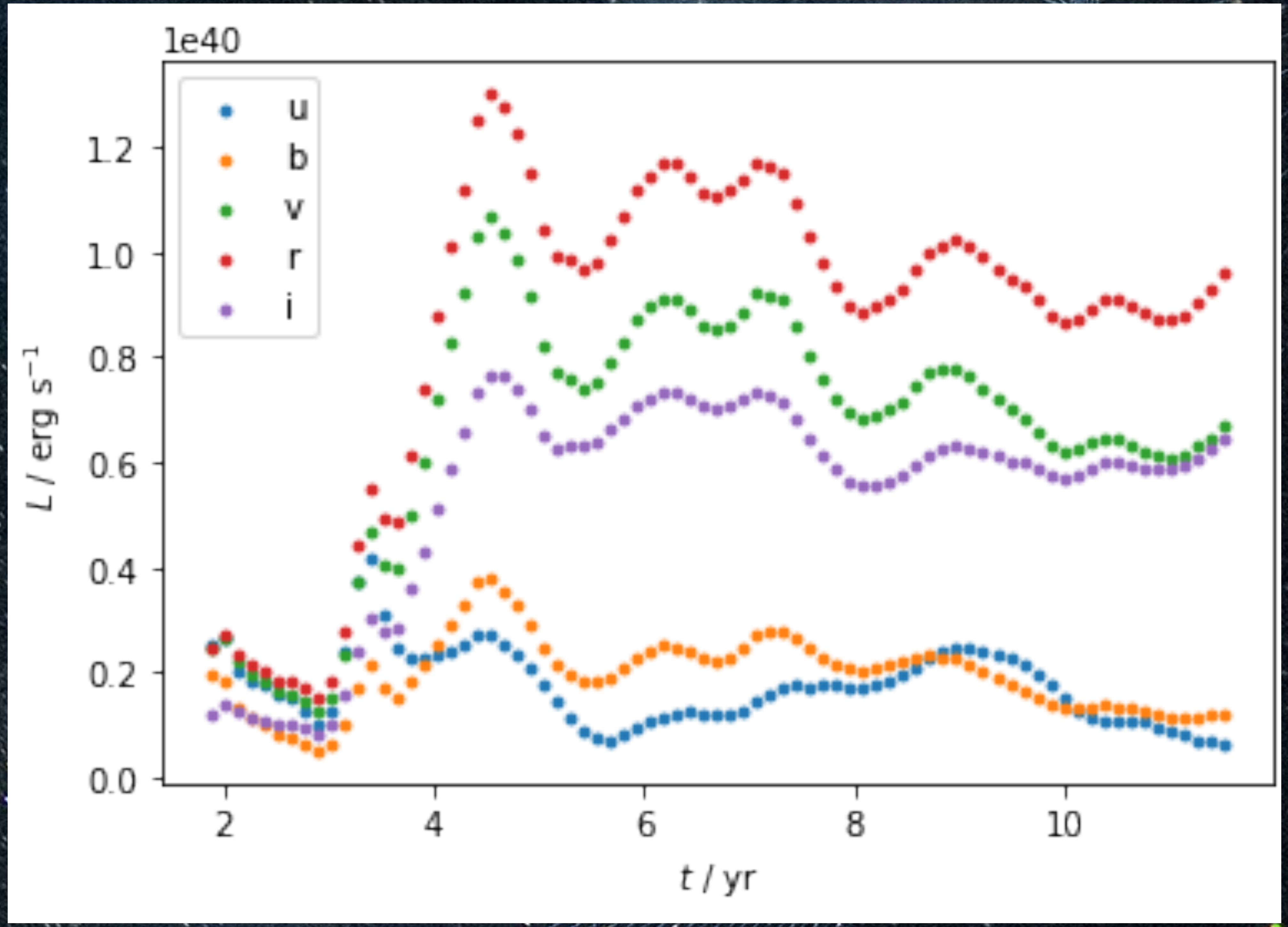
Lightcurves

- Vera Rubin Observatory will detect few hundred luminous red novae (Howitt+2020)



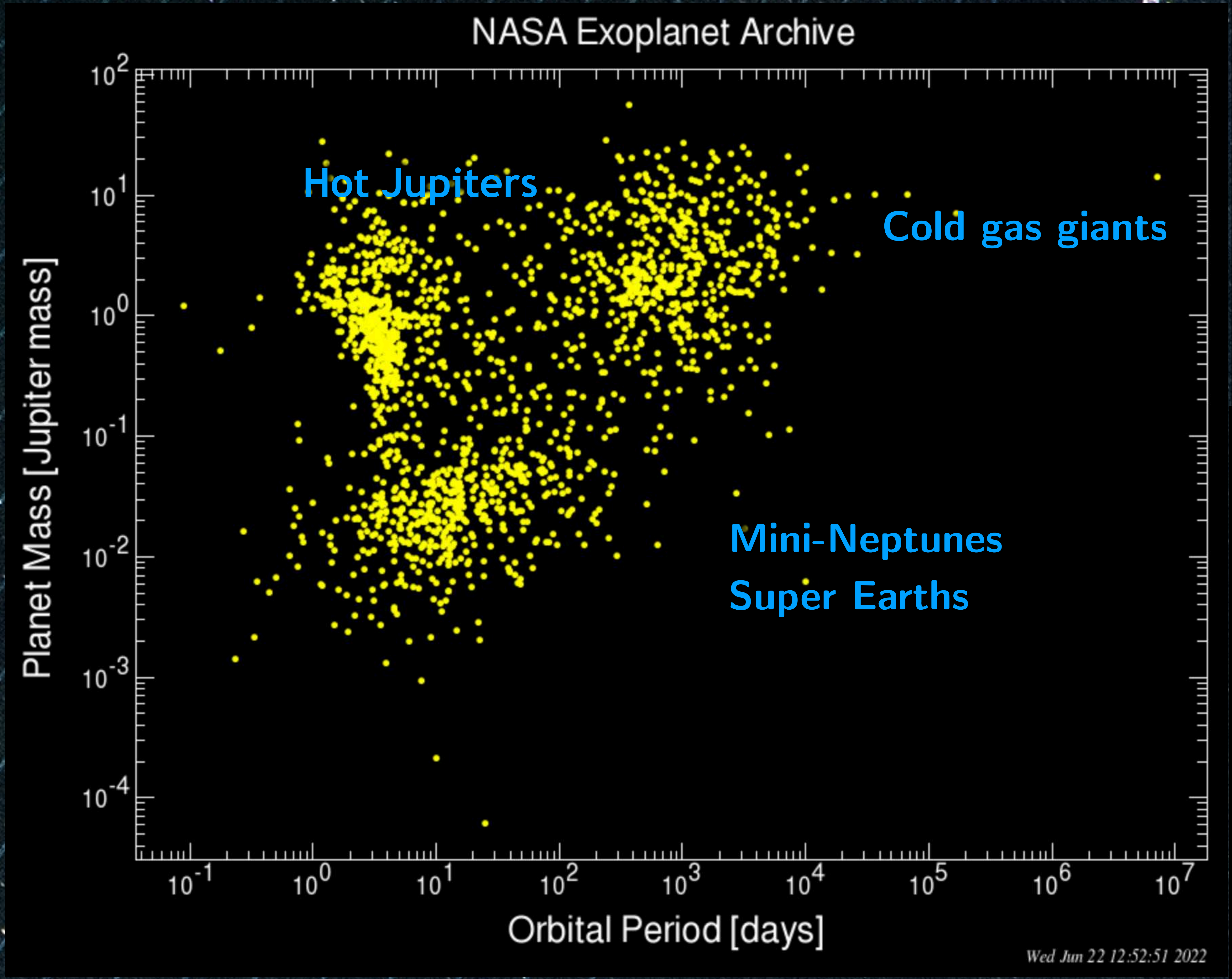
V838 Mon, HST

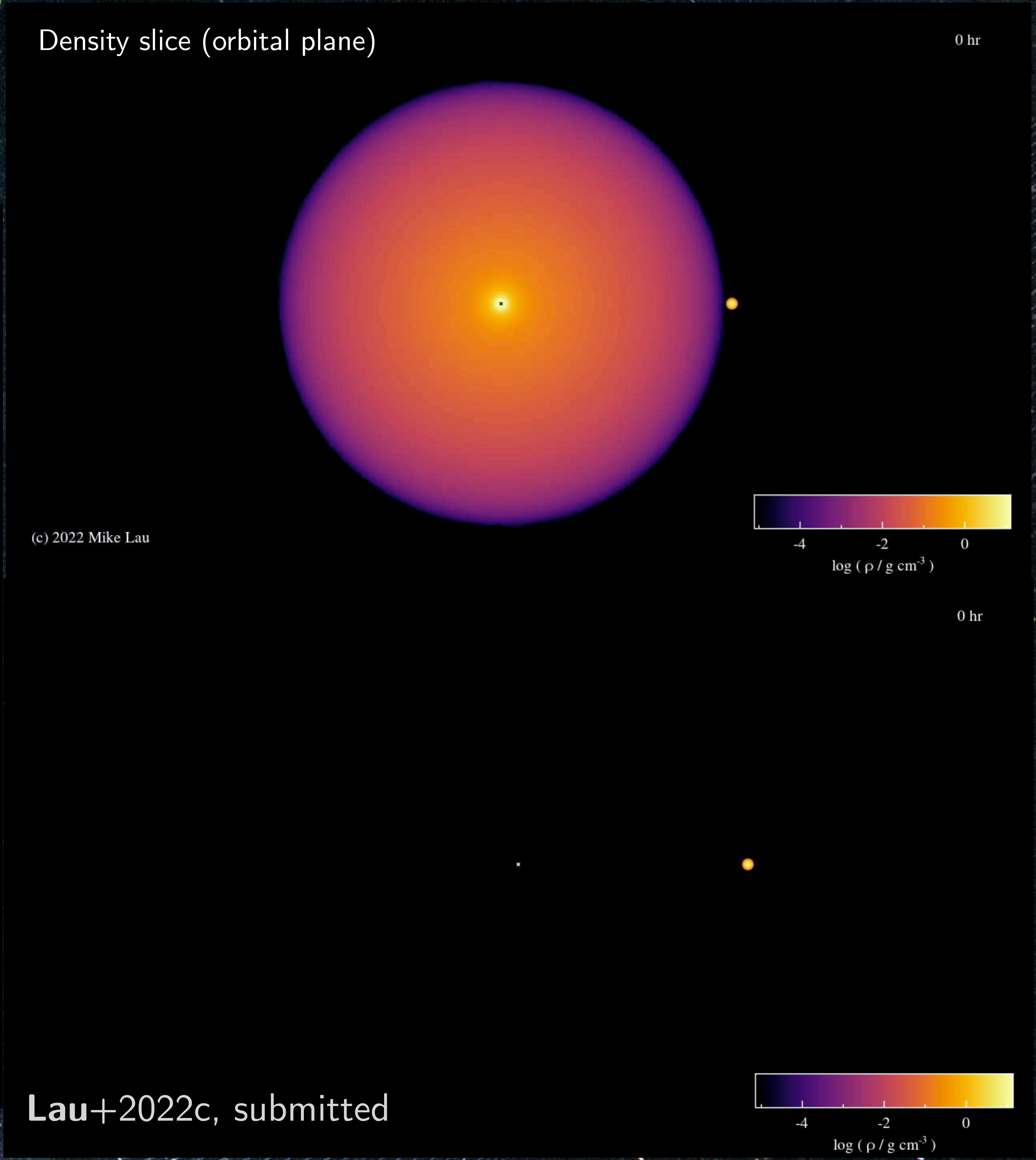
Post-processing **Lau**+2022a simulation with MCFOST atomic line transfer module



BUT, luminosity is too high at late times as the envelope cannot cool

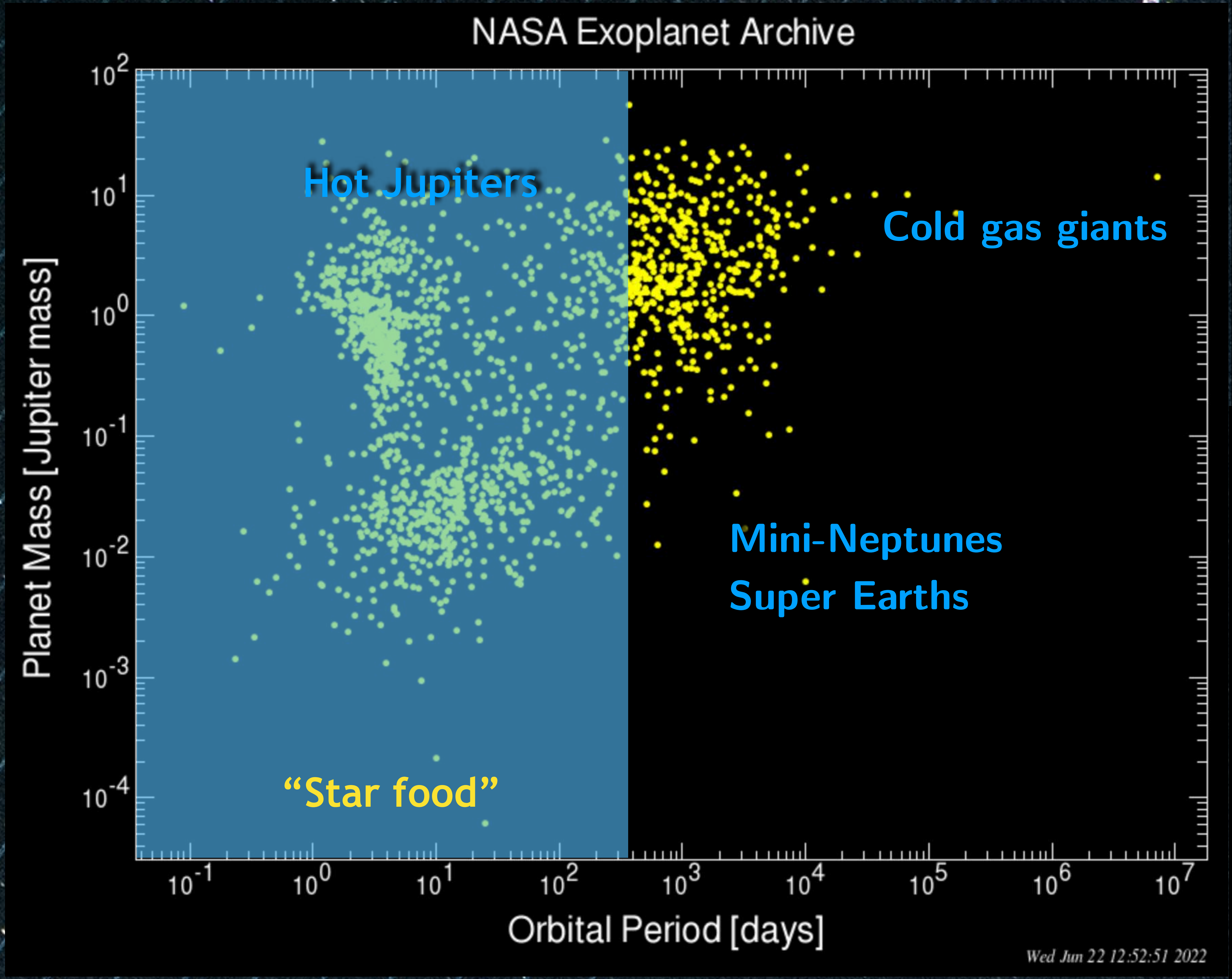
Planetary engulfment

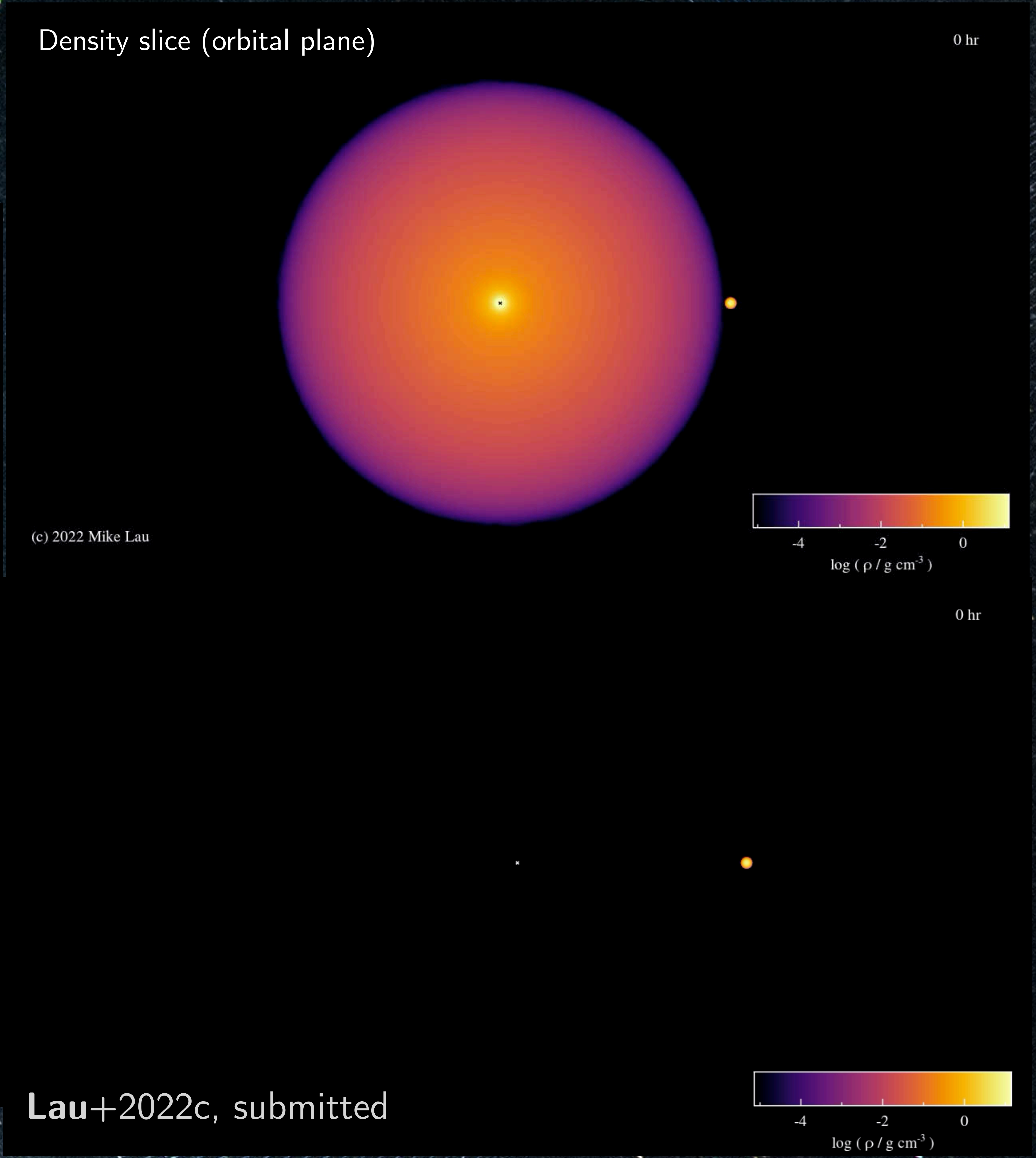




Lau+2022c, submitted

Planetary engulfment





Lau+2022c, submitted

Future outlook

Common-envelope with (implicit) radiation transport

- Self-consistent usage of recombination energy, drive convection, lightcurve calculation (MCFOST), evolve to late stages

Boundary-particle stellar core

- Study core rotation, can "unfreeze" core to continue evolution, more natural way to implement nuclear-burning luminosity

Optimisation and MPI scaling

- More particles
- Can extend start of simulation (onset of RLOF) and/or track deeper spiral-in