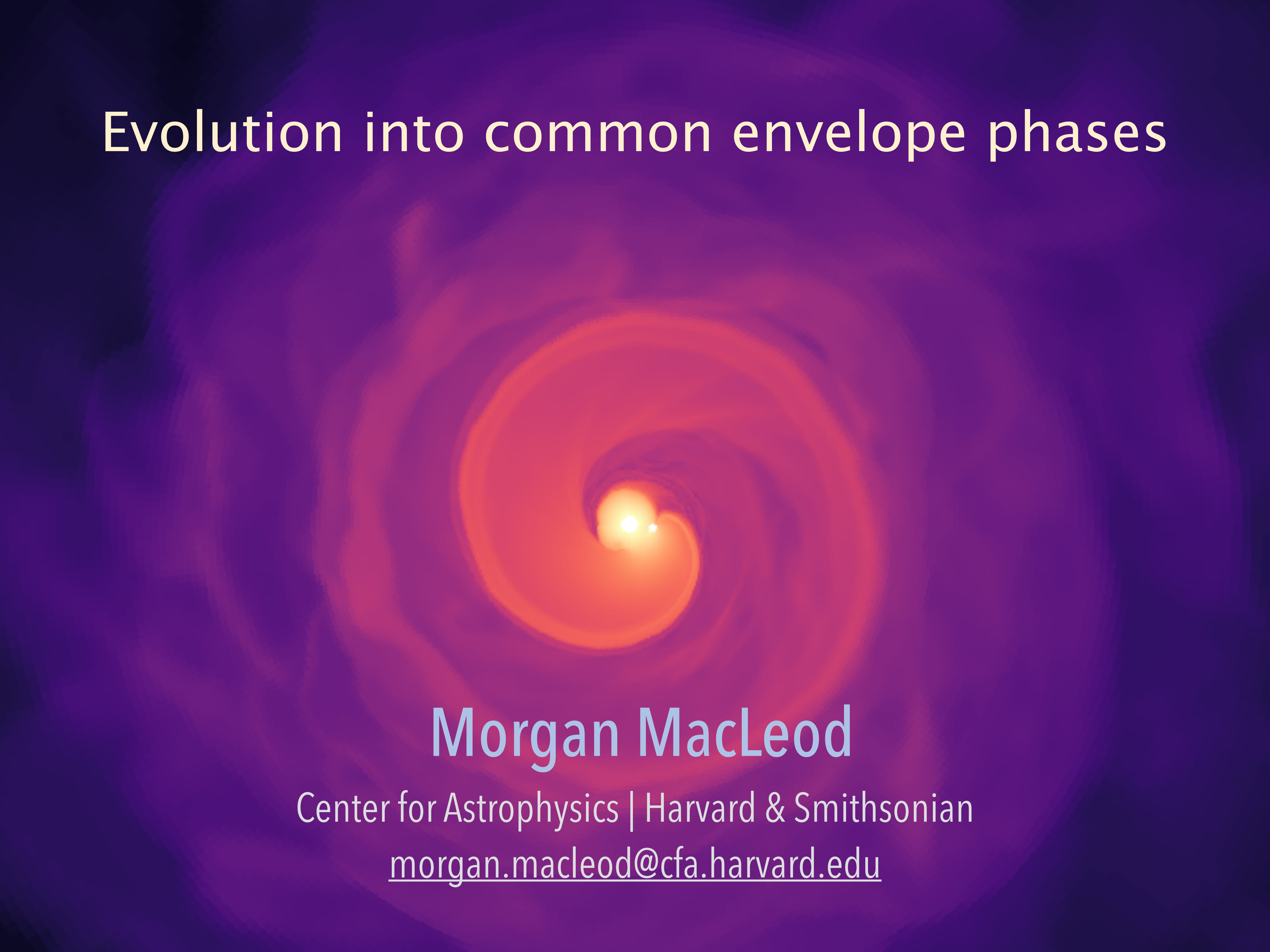
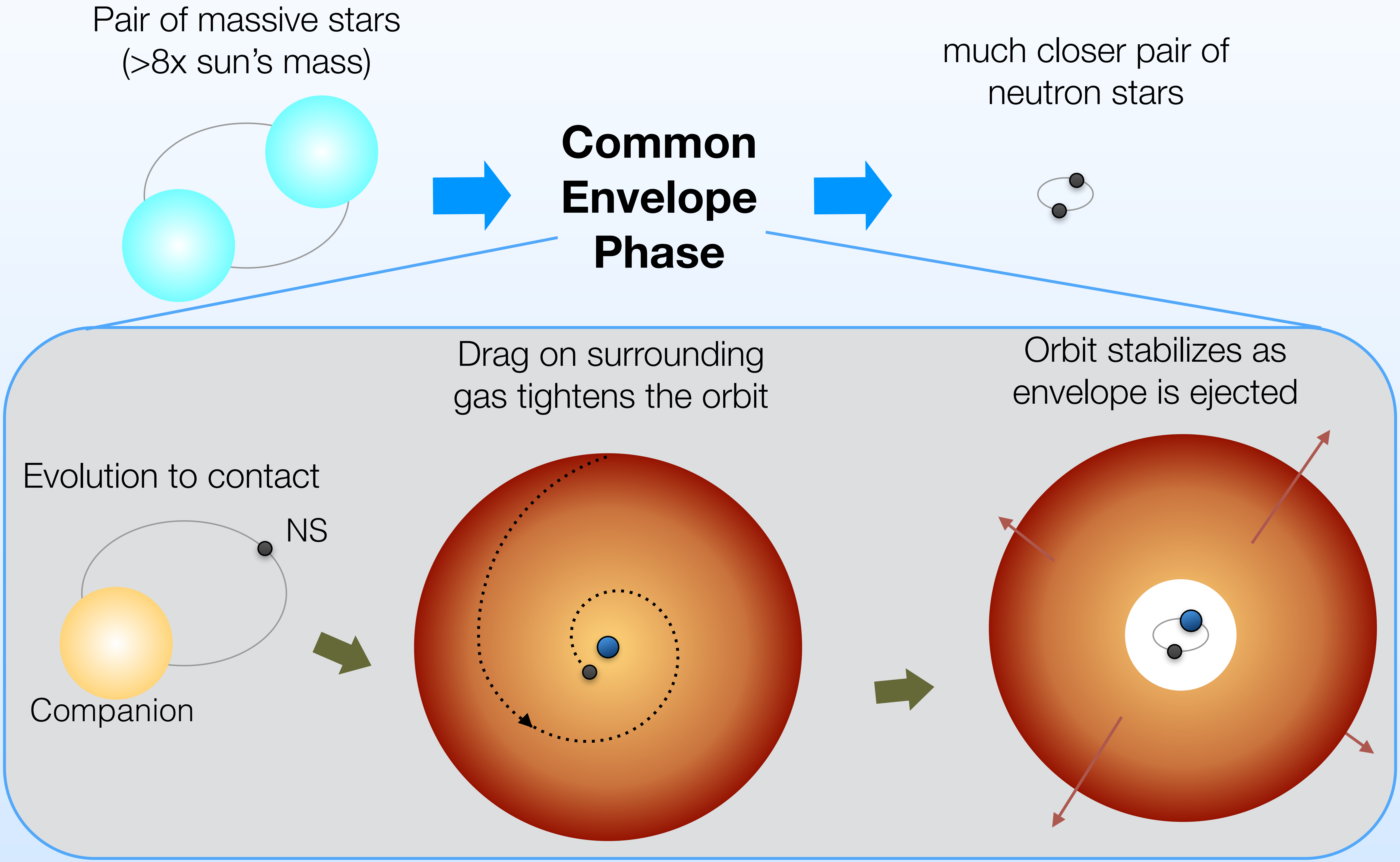


Evolution into common envelope phases

Morgan MacLeod
Center for Astrophysics | Harvard & Smithsonian
morgan.macleod@cfa.harvard.edu

Common envelope interactions transform binary systems

Example: formation of merging pairs of neutron stars



Pair of massive stars
(>8x sun's mass)

**Common
Envelope
Phase**

much closer pair of
neutron stars

Evolution to contact

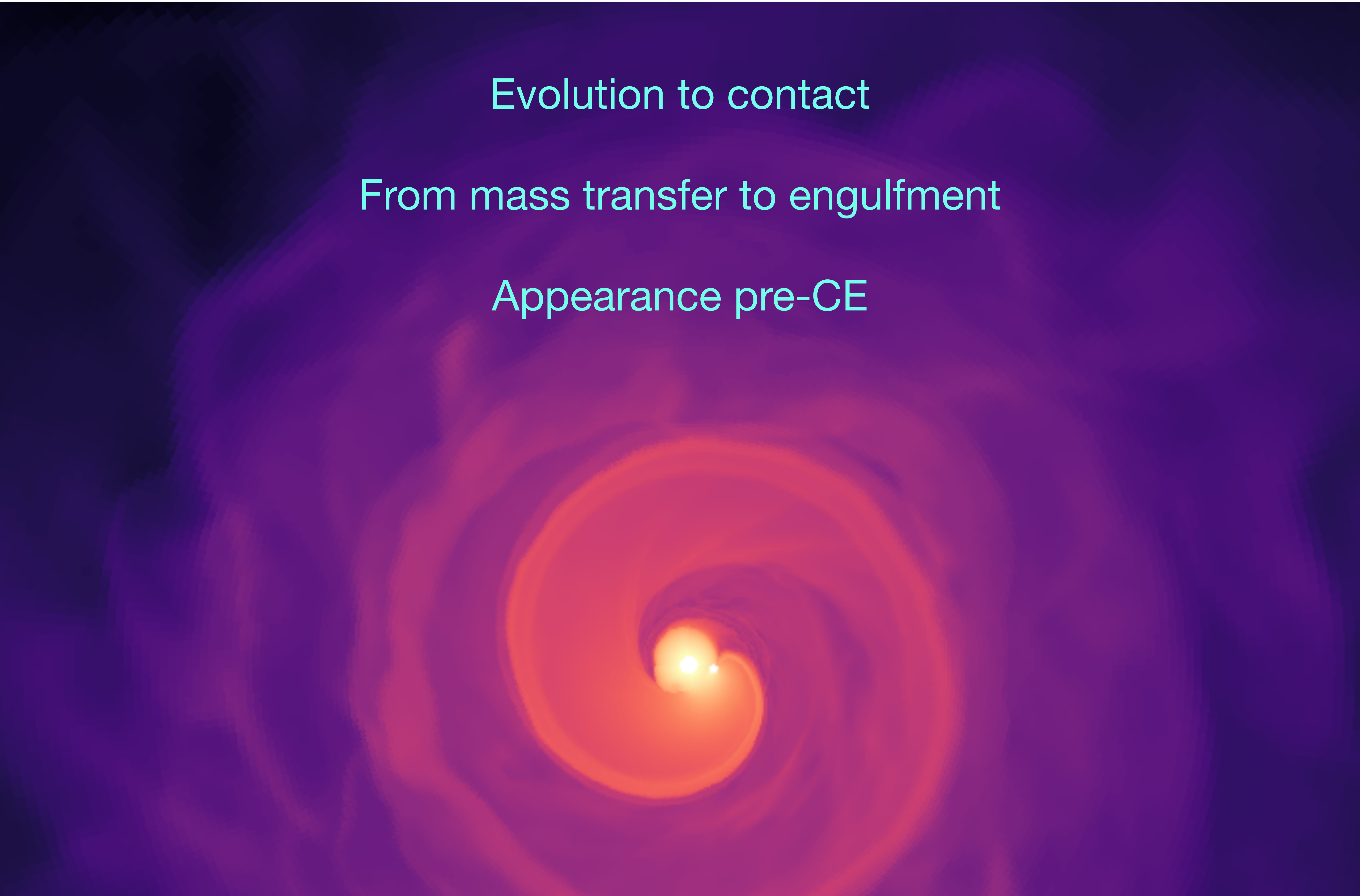
NS

Companion

Drag on surrounding
gas tightens the orbit

Orbit stabilizes as
envelope is ejected

The lead-in to common envelope phases

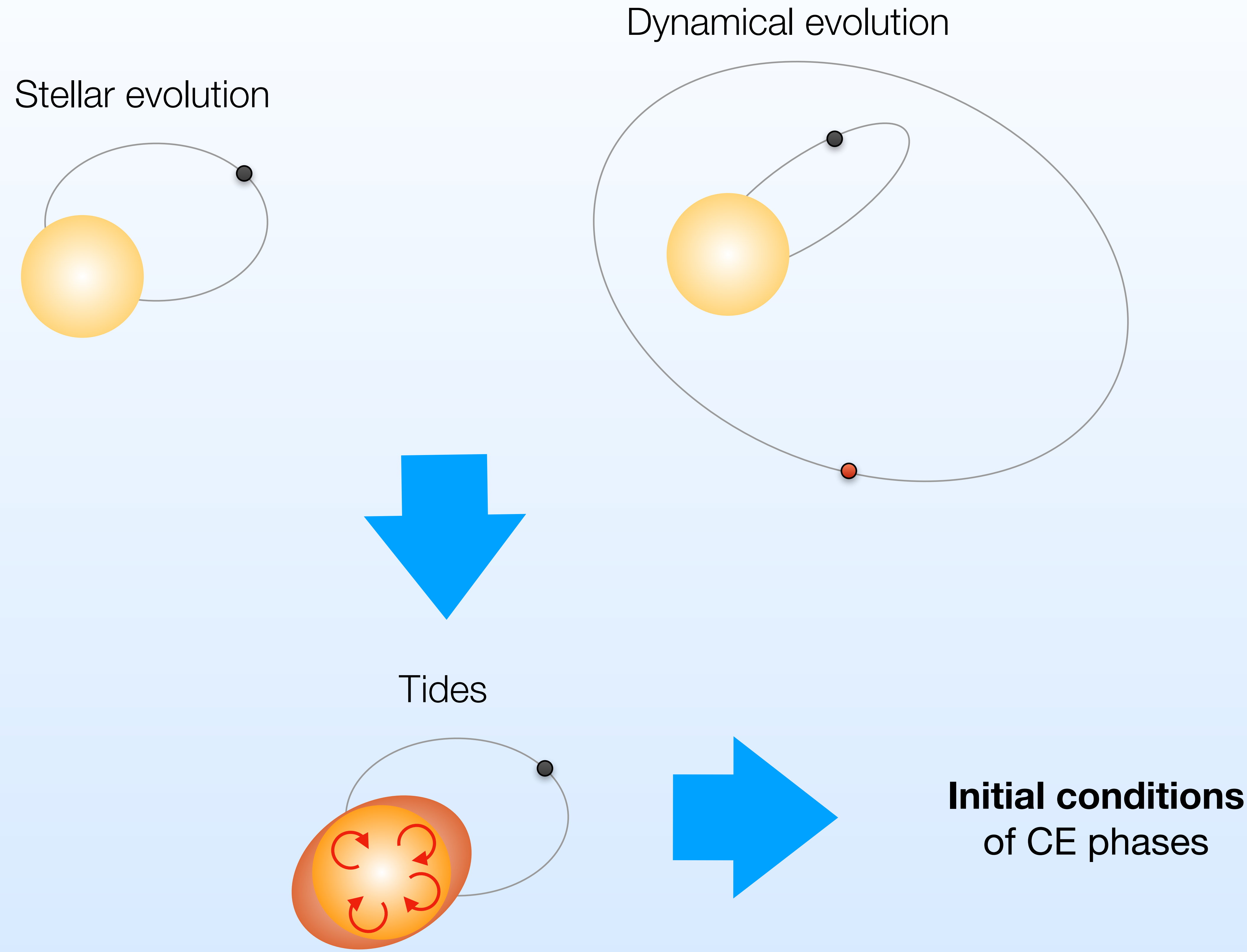


Evolution to contact

From mass transfer to engulfment

Appearance pre-CE

Evolution to contact



Stellar evolution

Dynamical evolution

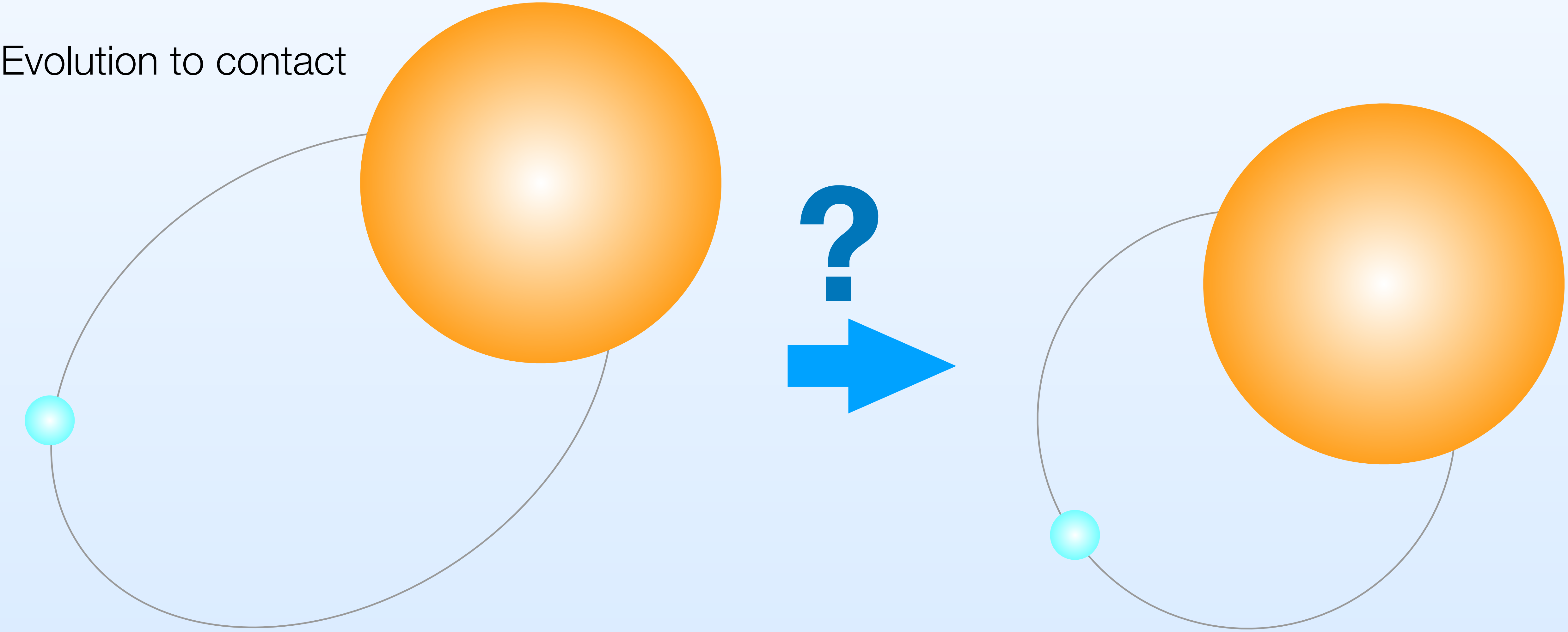
Tides

Initial conditions
of CE phases

Tidal evolution and onset of mass transfer

binaries have a broad eccentricity distribution:

Do tides *synchronize* and *circularize* these systems before mass transfer?



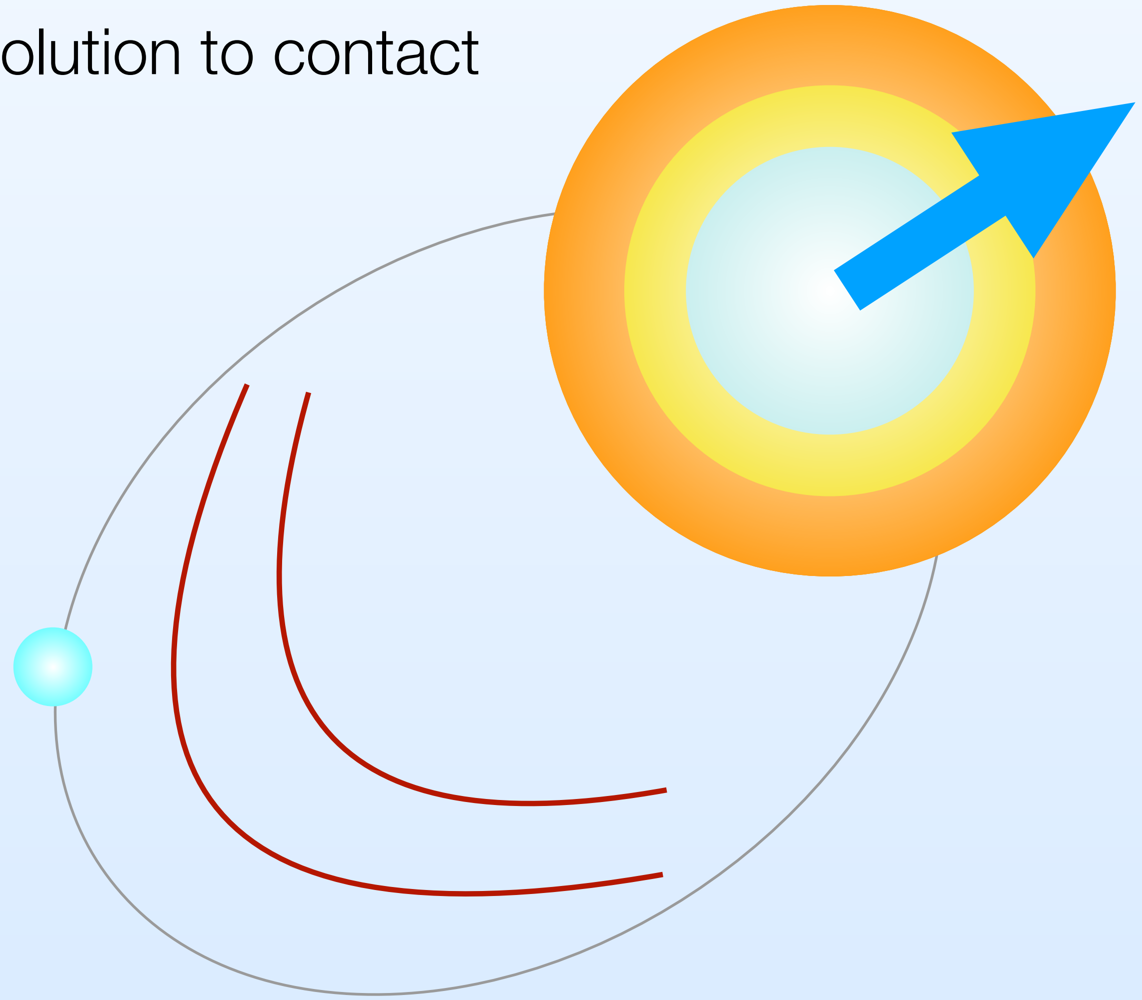
-> competition between donor’s expansion and tidal dissipation

(e.g. Vigna-Gomez+ 2020)

Tidal evolution and onset of mass transfer

binaries have a broad eccentricity distribution:

Do tides *synchronize* and *circularize* these systems before mass transfer?



Evolution to contact

Radius growth timescale

- type of star
- stellar evolutionary state
- consequence of nuclear evolution at core

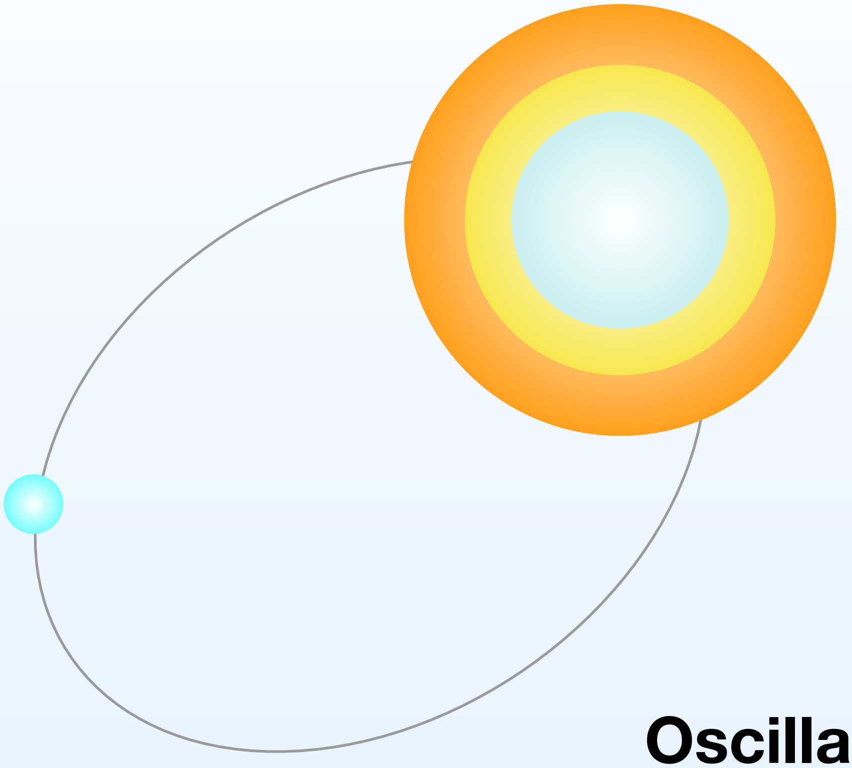
Tidal dissipation timescale

- spectrum of oscillatory modes that are excited by the tide
- dissipation mechanism
- type of stellar envelope (radiative or convective)

-> competition between donor’s expansion and tidal dissipation

(e.g. Vigna-Gomez+ 2020)

Tidal evolution and onset of mass transfer



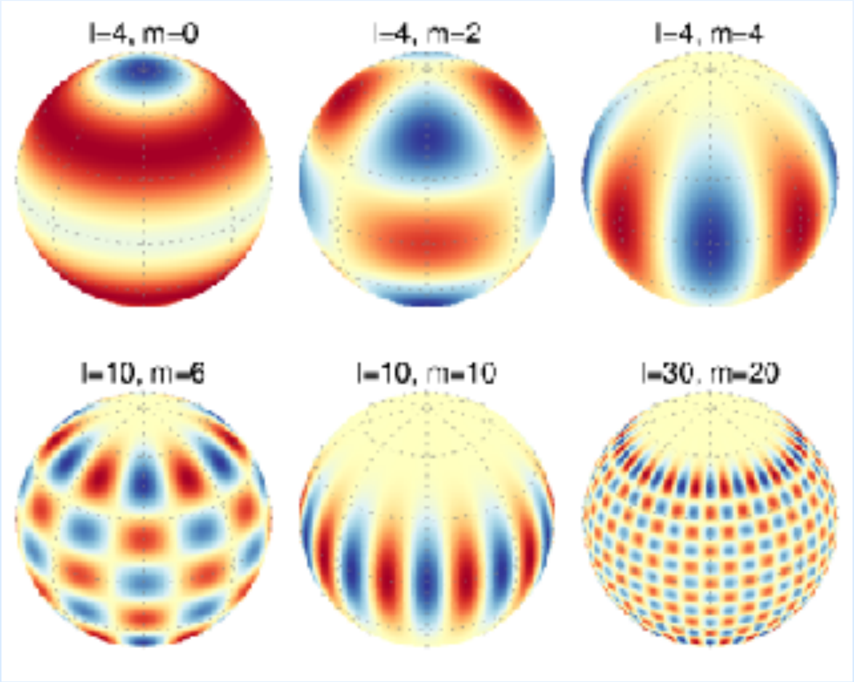
when the **gravitational potential is time-varying** *** in the stellar fluid frame*** the fluid **oscillates around its equilibrium figure.**

—> examples: an eccentric orbit or non-synchronous rotation

—> counter-example: circular orbit and syncrhonous rotation

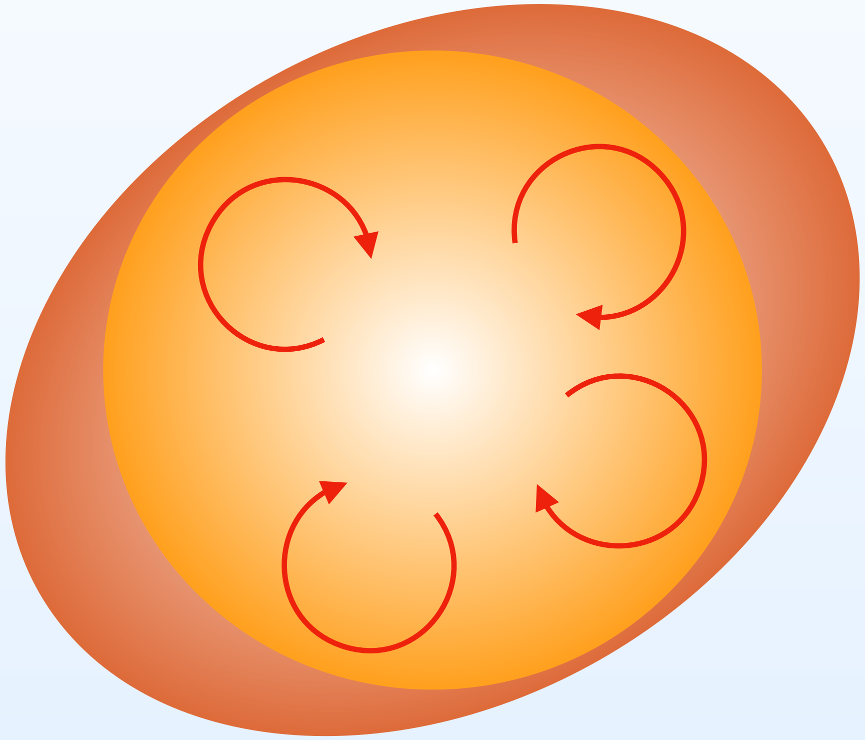
Oscillation implies a "dynamical" tide, vs an "equilibrium" tide

Tidal oscillations are usually expressed in spherical harmonic basis functions. A given oscillatory "mode" has a characteristic frequency and is described by a degree, azimuthal order, and radial wavenumber *(l,m,n)*



Tidal evolution and onset of mass transfer

Convective envelope

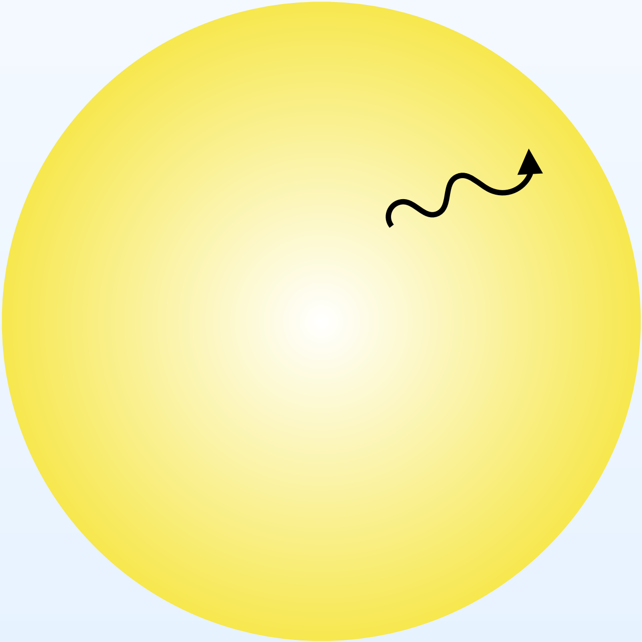


fundamental modes:
n=0, (e.g. l=2, m= +/- 2)

frequency ~ omega_dyn

Dissipation of coherent oscillation through interaction with disordered field of convection

Radiative envelope



gravity (g) modes:
n>>0, (e.g. l=2, m= +/- 2)

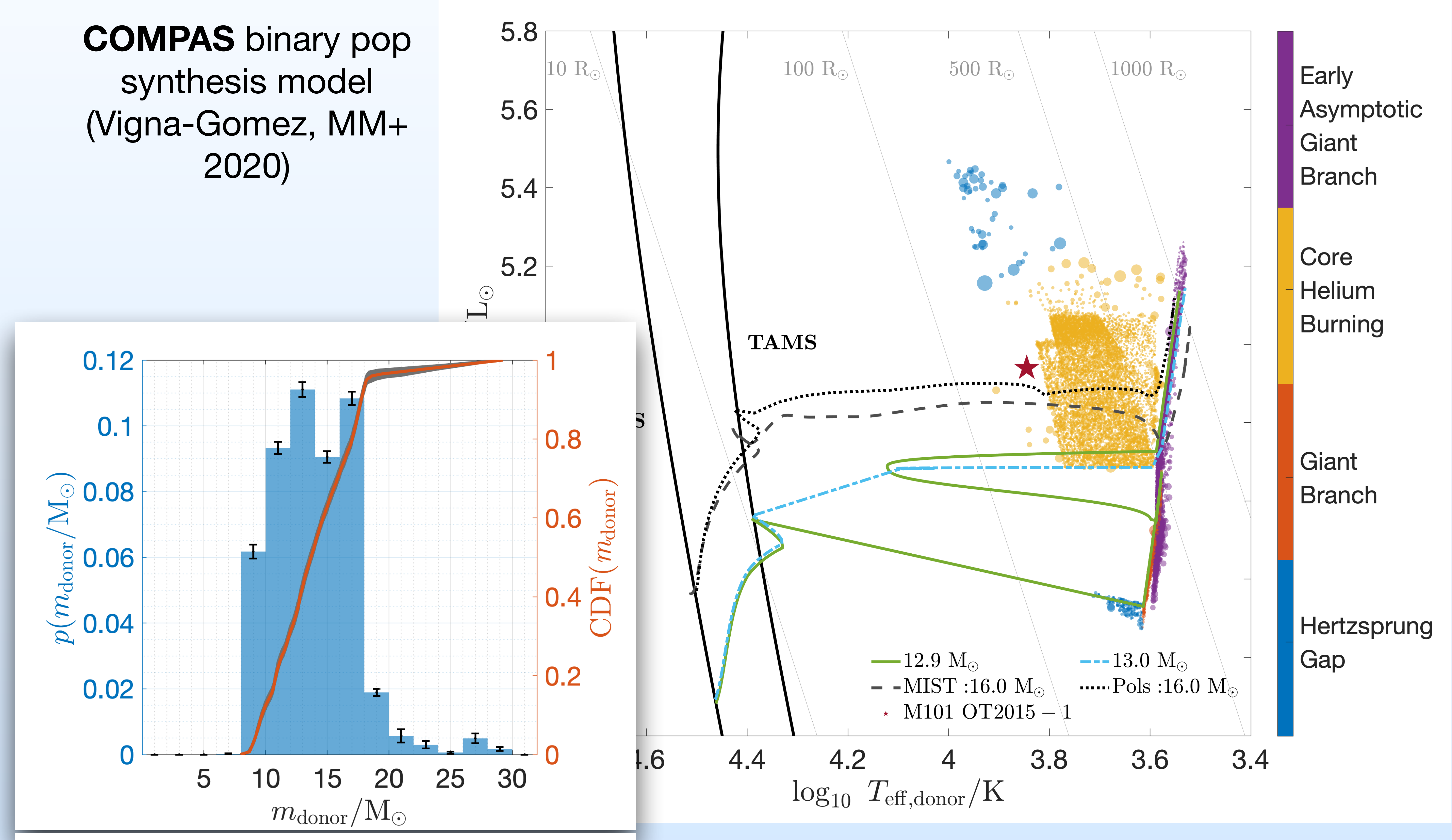
internal bouancy waves with
frequency << omega_dyn

Dissipation through radiative losses (damping) near surface

Typical conditions for NSs in CE phases

Donor stars at the start of dyn. unstable mass transfer
-> That lead to DNS formation

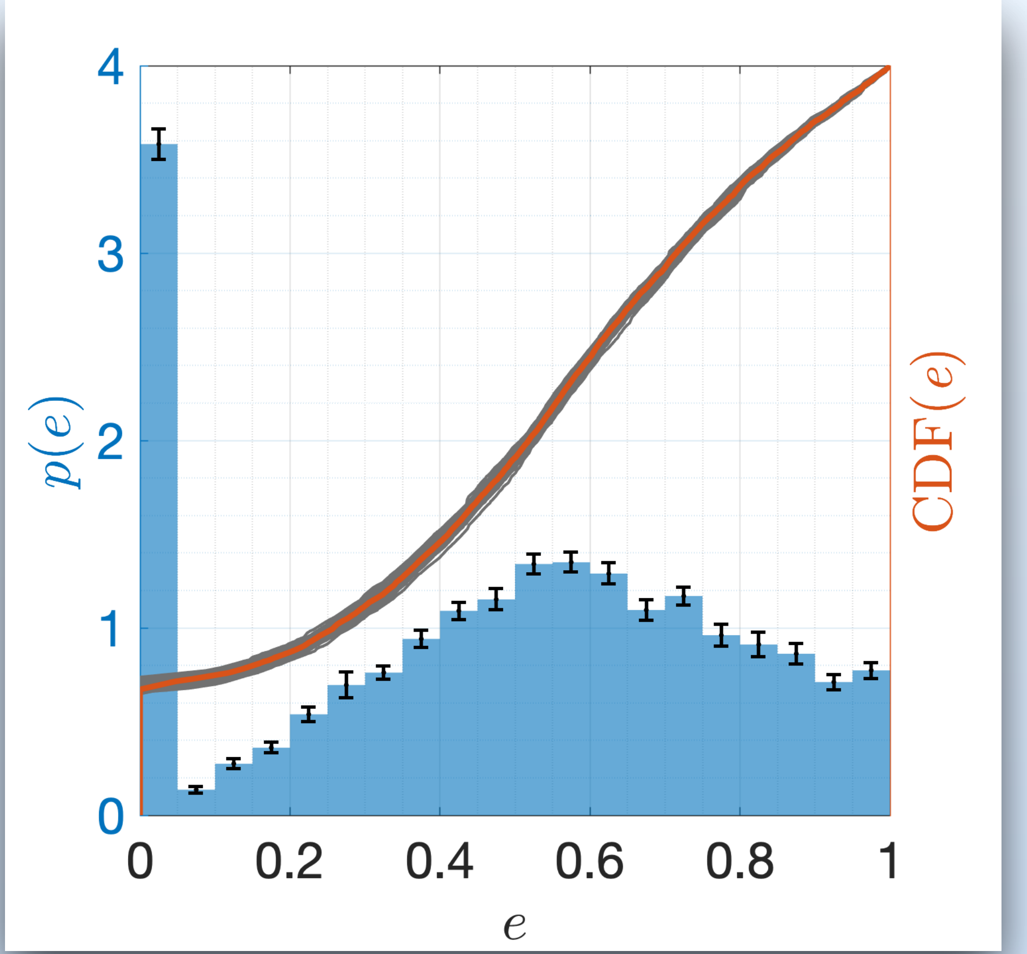
COMPAS binary pop synthesis model (Vigna-Gomez, MM+ 2020)



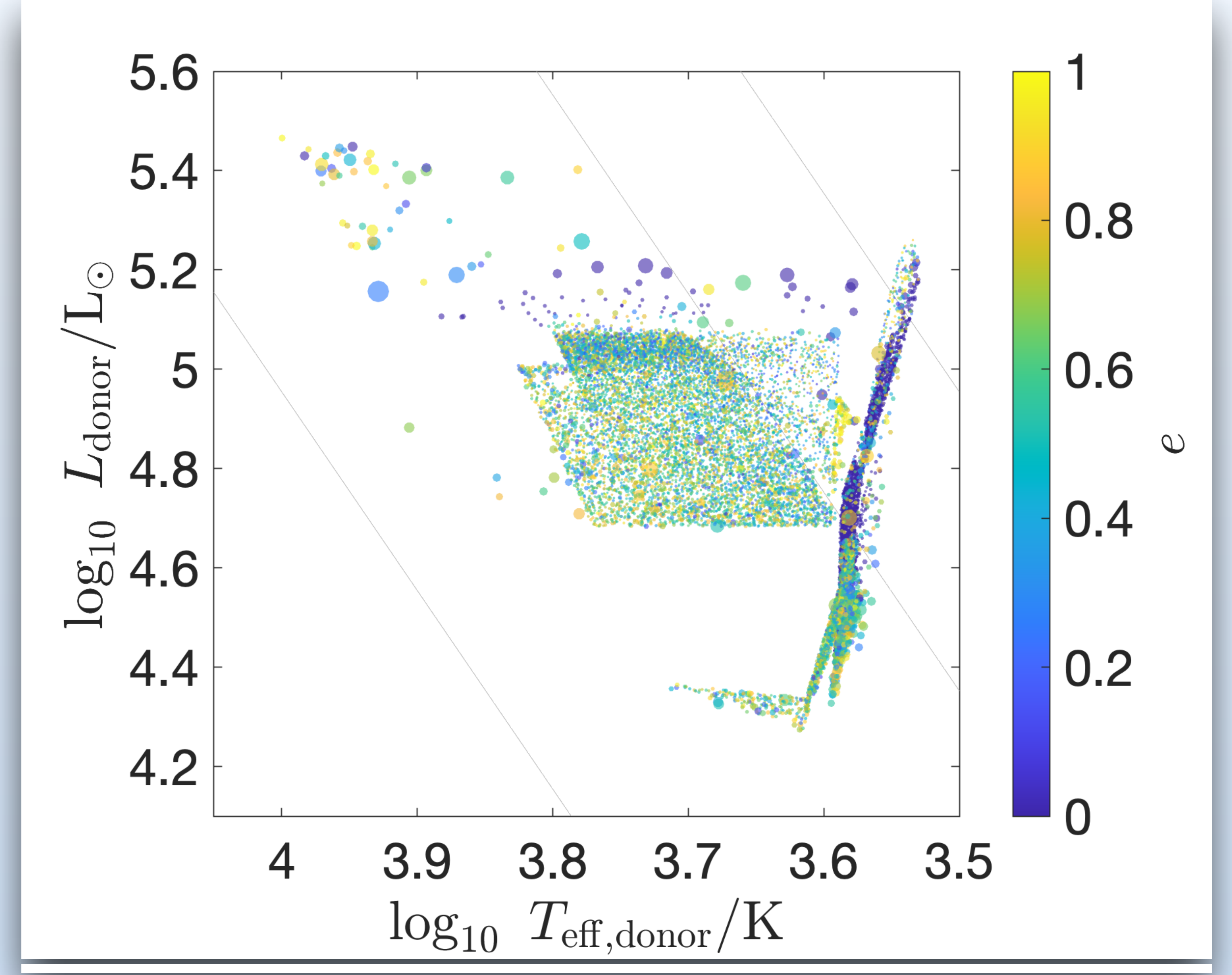
Typical conditions for NSs in CE phases

Donor stars at the start of dyn. unstable mass transfer
-> That lead to DNS formation

COMPAS binary pop synthesis model (Vigna-Gomez, MM+ 2020)



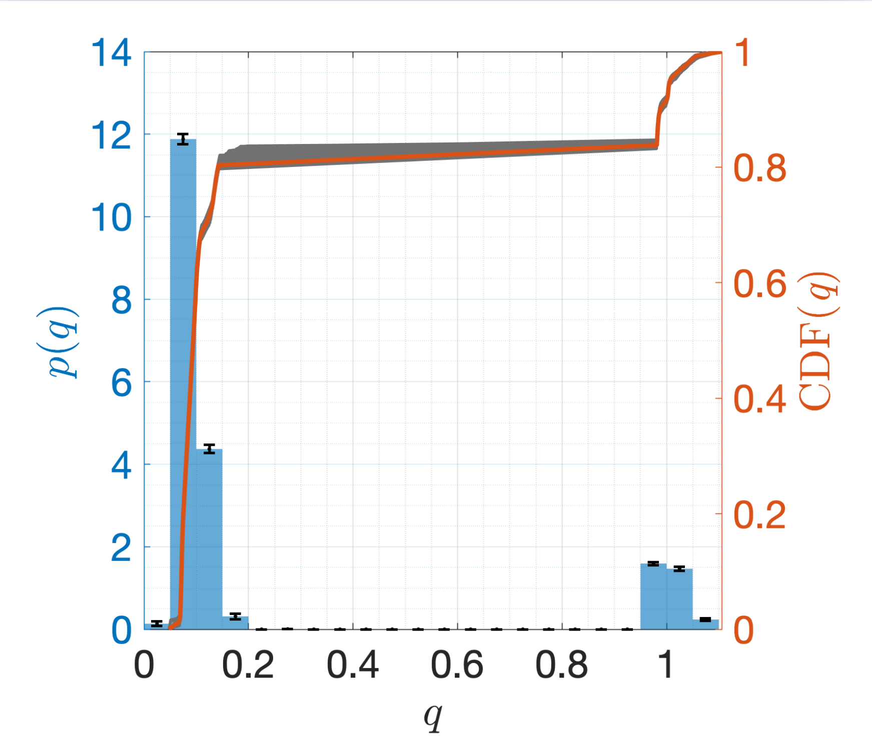
(Note: eccentricities initialized at zero)

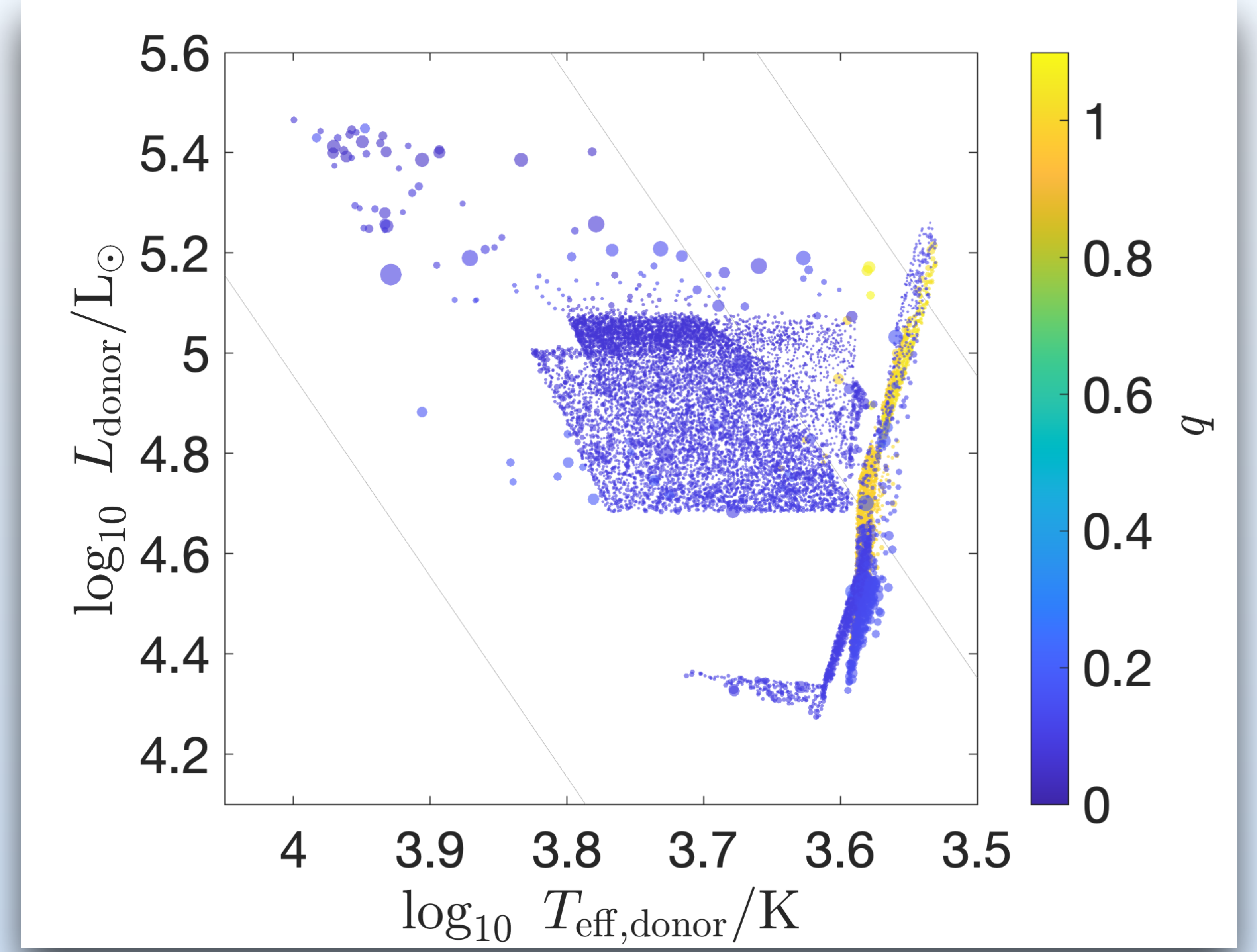


Typical conditions for NSs in CE phases

Donor stars at the start of dyn. unstable mass transfer
-> That lead to DNS formation

COMPAS binary pop synthesis model (Vigna-Gomez, MM+ 2020)

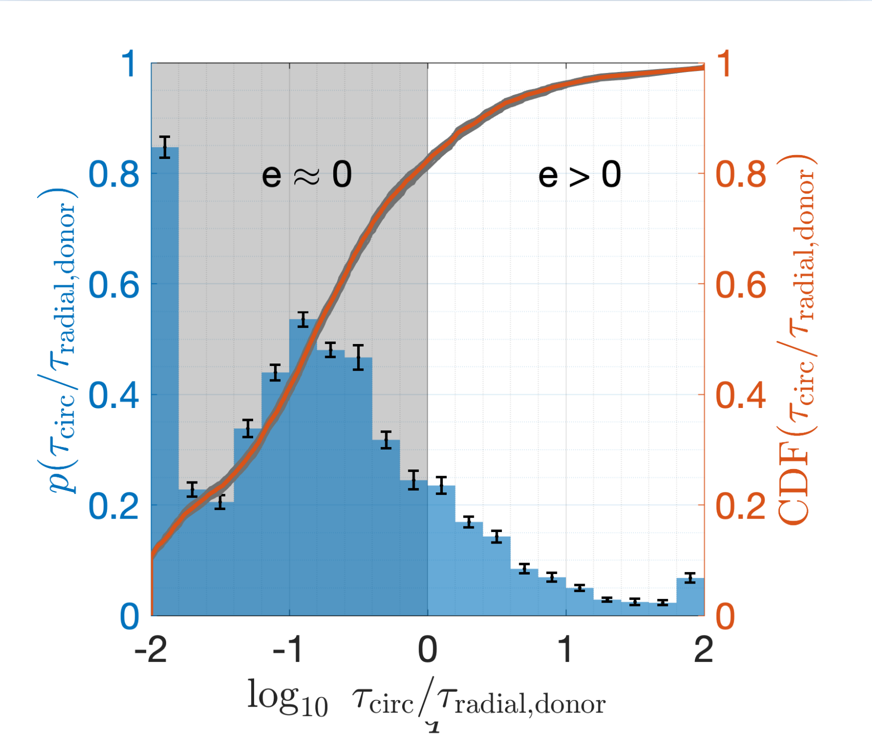


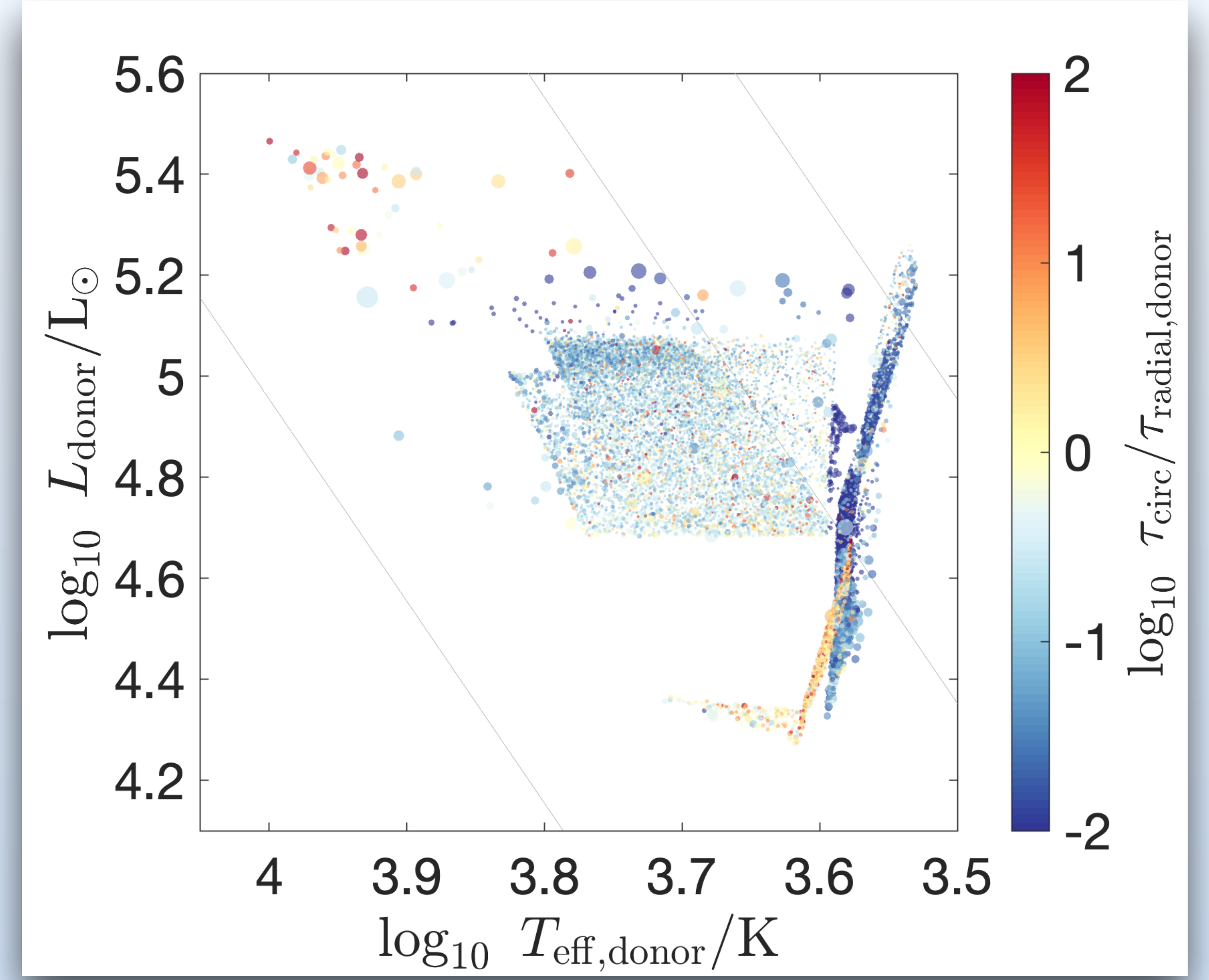


Typical conditions for NSs in CE phases

Donor stars at the start of dyn. unstable mass transfer
-> That lead to DNS formation

COMPAS binary pop synthesis model (Vigna-Gomez, MM+ 2020)





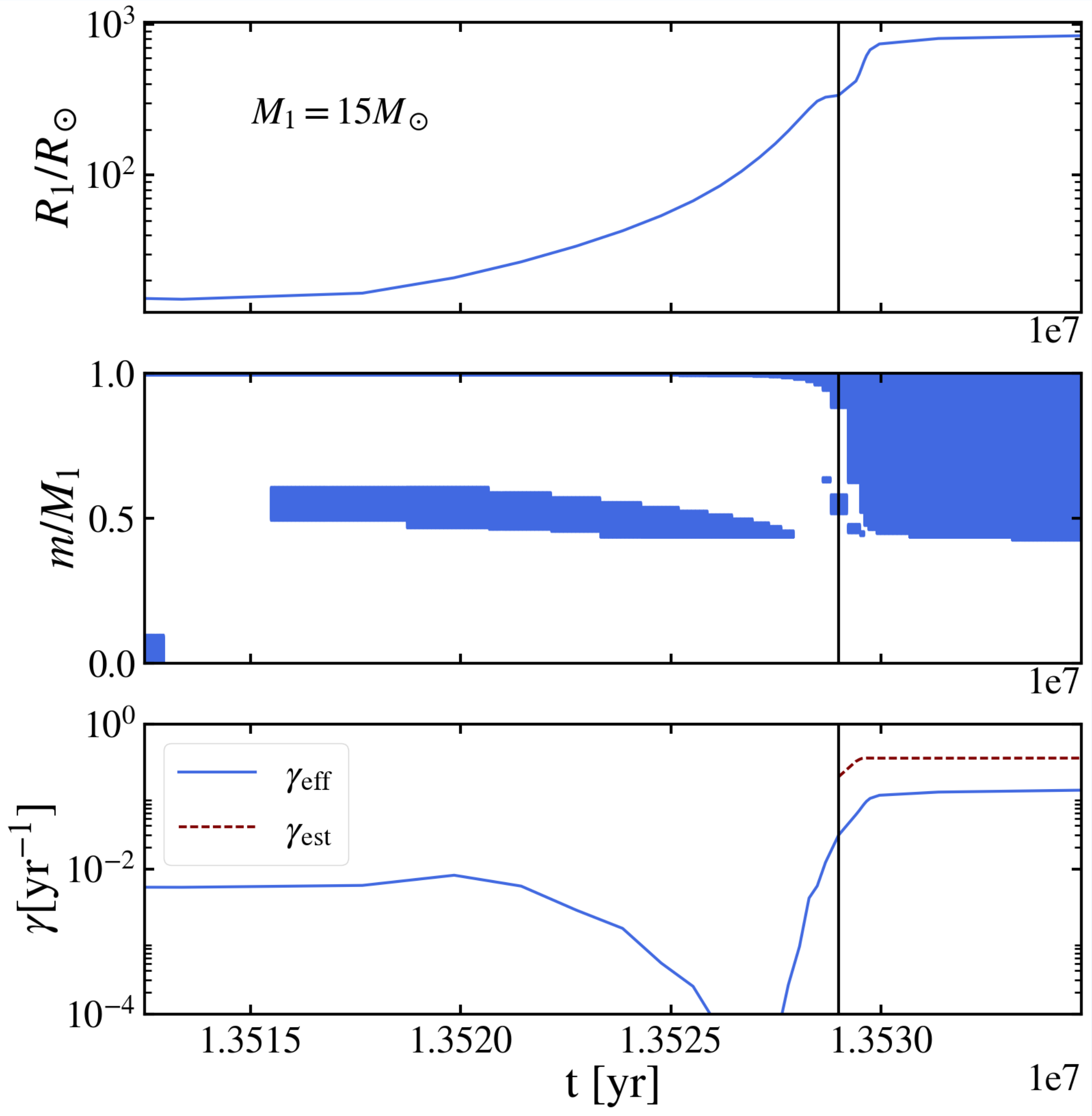
Tidal evolution and onset of mass transfer

More sophisticated modeling of the spectrum of dynamical oscillations excited and their dissipation on the convective field.

dissipation rate estimate:

$$\gamma_{\rm est} \sim \frac{M_{\rm env}}{M_1}\left(\frac{\nu_0}{H^2}\right) \sim \frac{M_{\rm env}}{M_1}\left(\frac{L}{M_{\rm env}R_1^2}\right)^{1/3}$$

$$t_{\rm circ} \equiv \left|\frac{e}{\dot{e}}\right| \sim \frac{1}{\gamma_{\rm est}}\left(\frac{M_1}{M_2}\right)\left(\frac{M_1}{M_t}\right)\left(\frac{a}{R_1}\right)^8$$

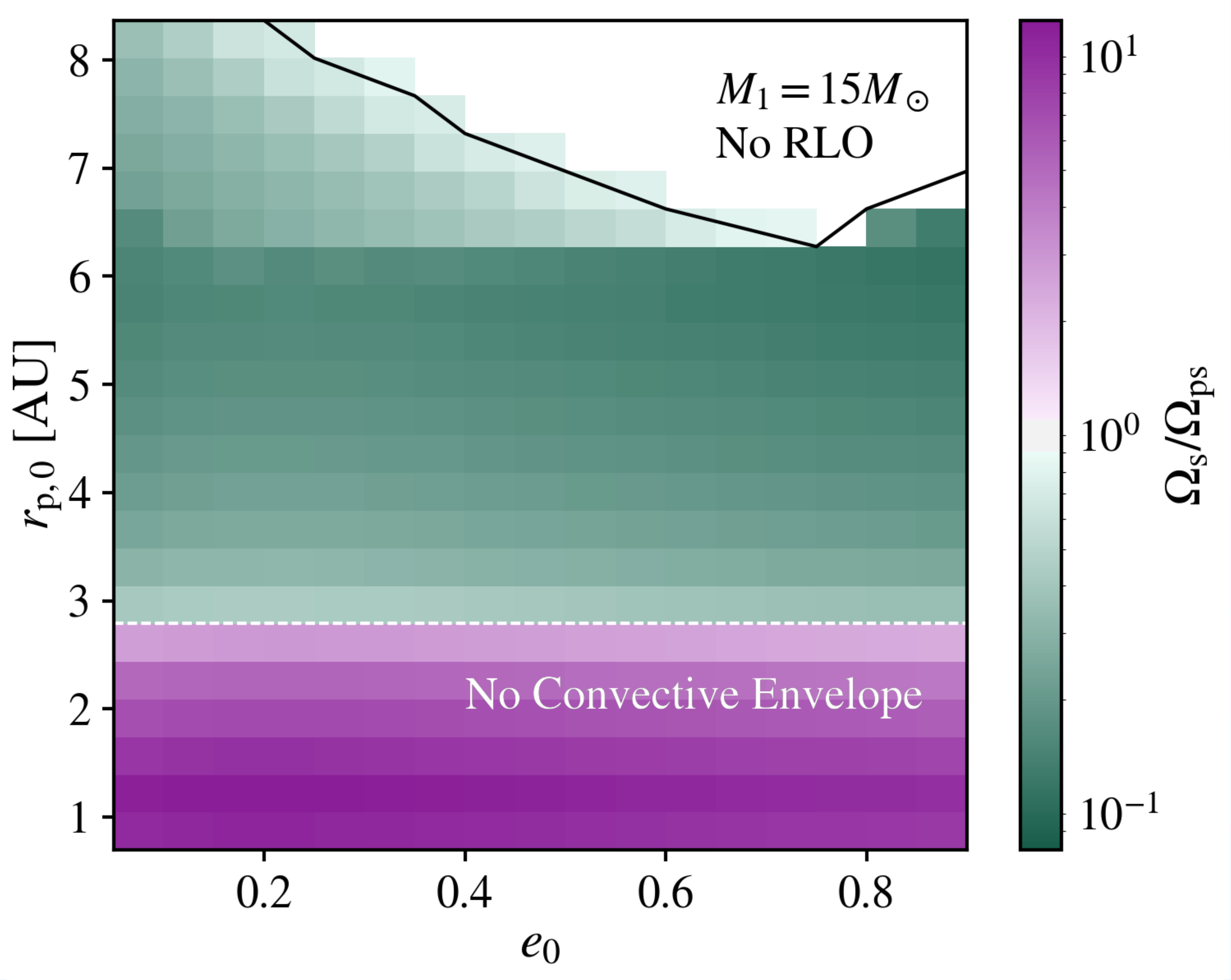


(Vick 2019, Vick, MM+ 2020)

Tidal evolution and onset of mass transfer

More sophisticated modeling of the spectrum of dynamical oscillations excited and their dissipation on the convective field.

$$
\begin{aligned}
\frac{\dot{a}}{a} &= \left.\frac{\dot{a}}{a}\right|_{\mathrm{Tides}} + \left.\frac{\dot{a}}{a}\right|_{\mathrm{Wind}} \\
\frac{\dot{\Omega}_{\mathrm{s}}}{\Omega_{\mathrm{s}}} &= \left.\frac{\dot{\Omega}_{\mathrm{s}}}{\Omega_{\mathrm{s}}}\right|_{\mathrm{Tides}} - \frac{\dot{I}}{I}, \\
\frac{\dot{e}}{e} &= \left.\frac{\dot{e}}{e}\right|_{\mathrm{Tides}},
\end{aligned}
$$

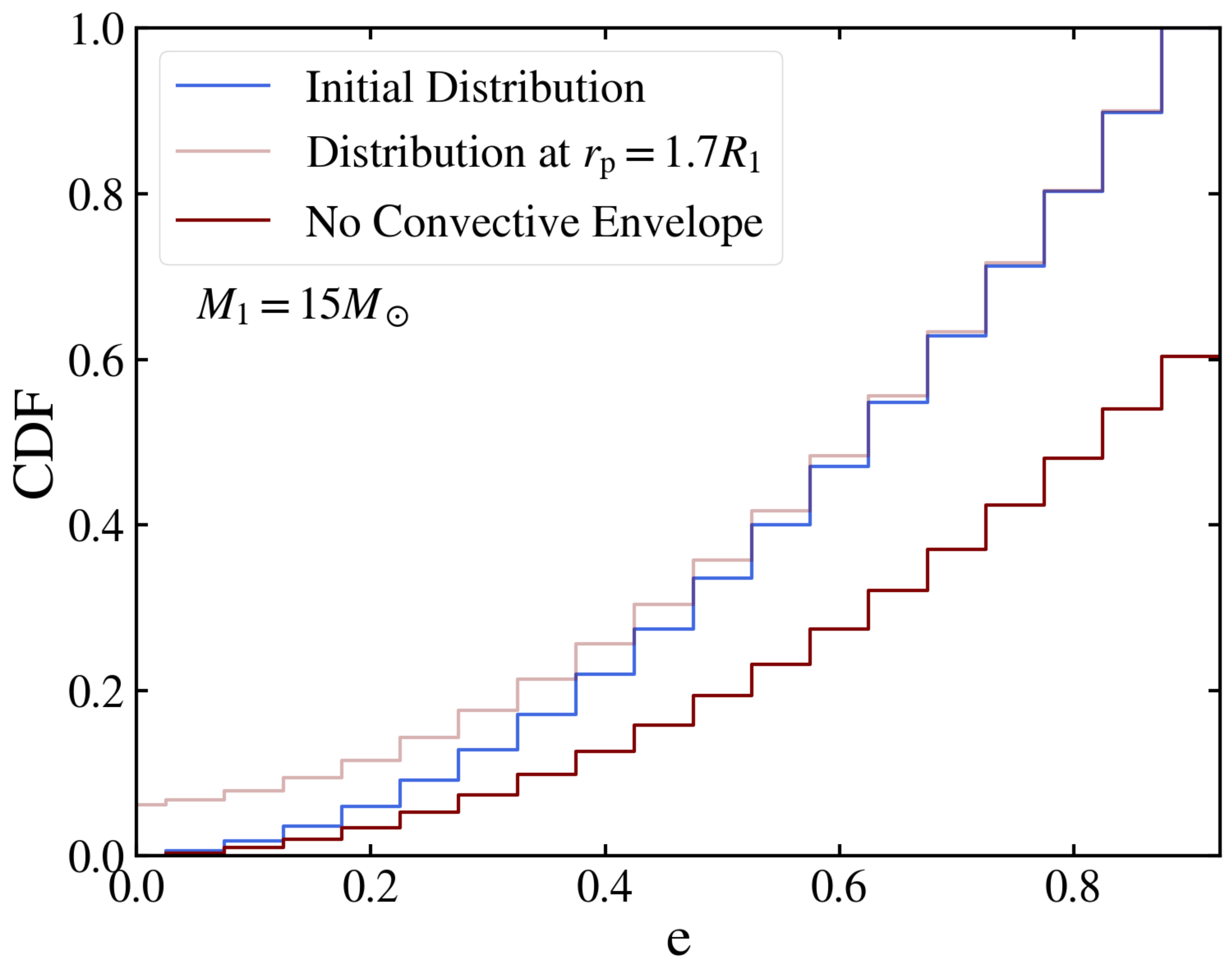


1.4 solar mass companion

(Vick 2019, Vick, MM+ 2020)

Tidal evolution and onset of mass transfer

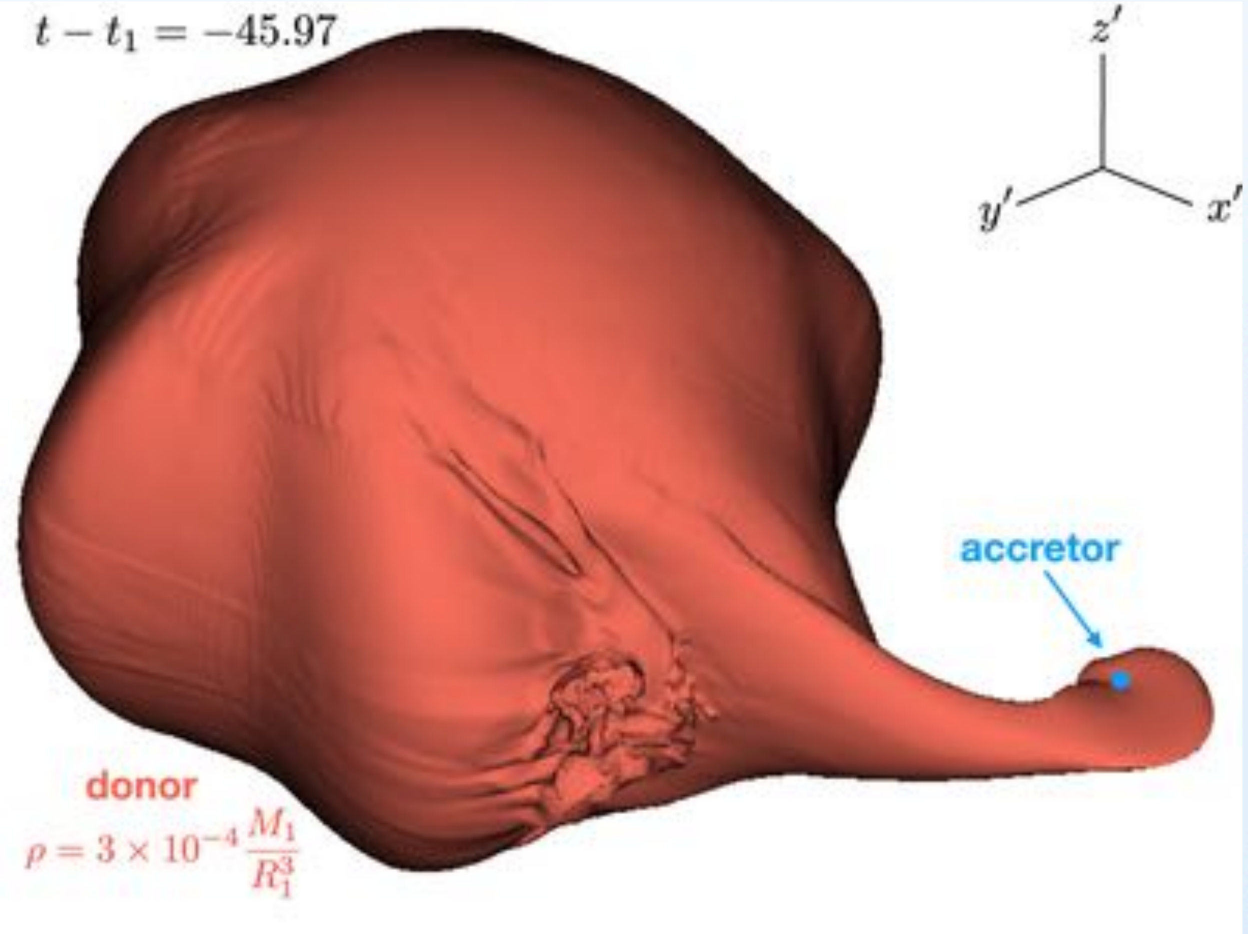
starting with an initially-thermal eccentricity distribution:



(Vick 2019, Vick, MM+ 2020)

Tidal evolution and onset of mass transfer

Often eccentric & asynchronous in massive-star systems!



Dynamical tides w/large amplitudes!
(MacLeod+ 2019)

Eccentric mass transfer
e.g. Glanz+ 2020

The lead-in to common envelope phases

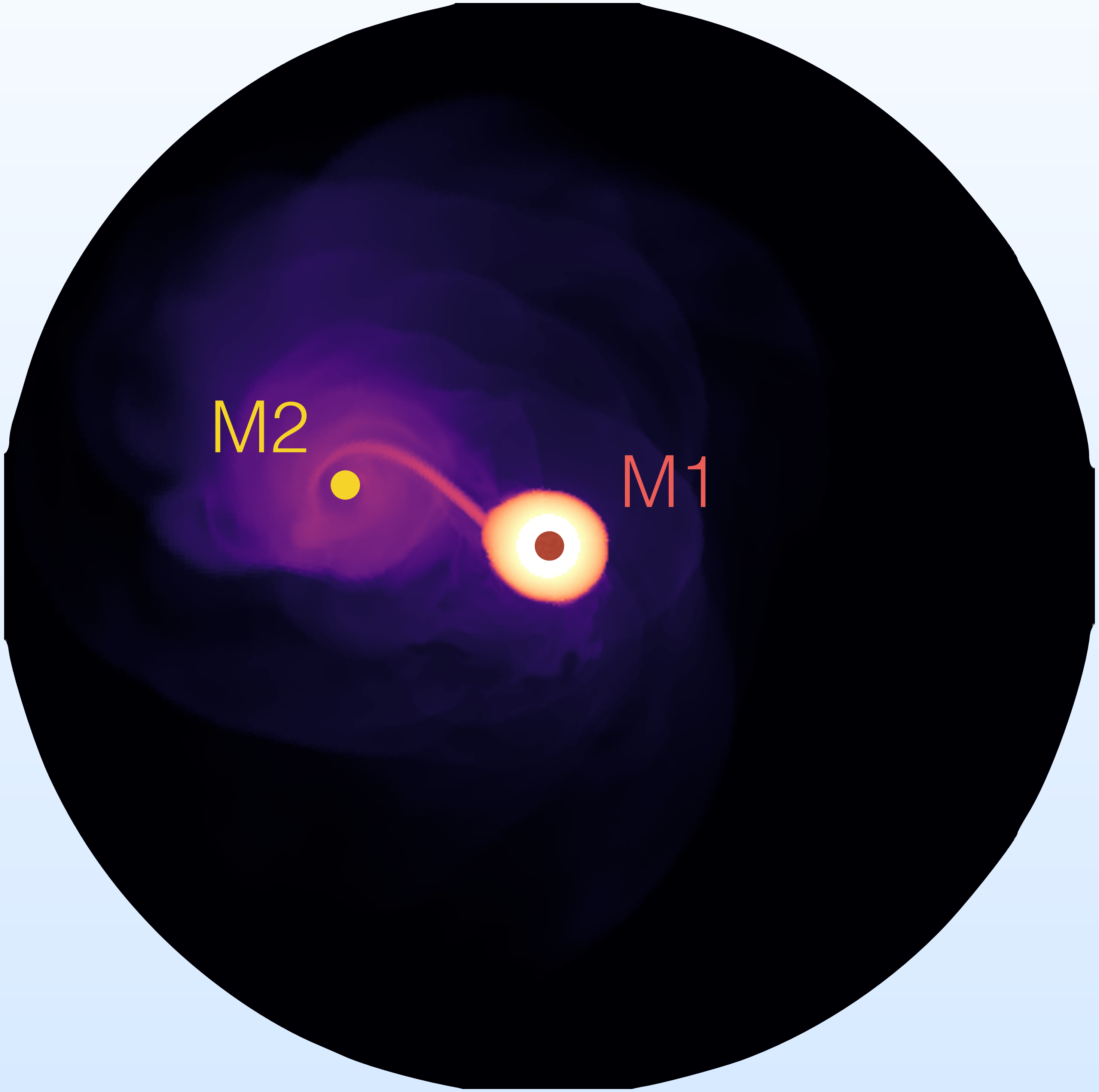
Evolution to contact

From mass transfer to engulfment

Appearance pre-CE

Modeling approach

Studying interacting binaries in Athena++

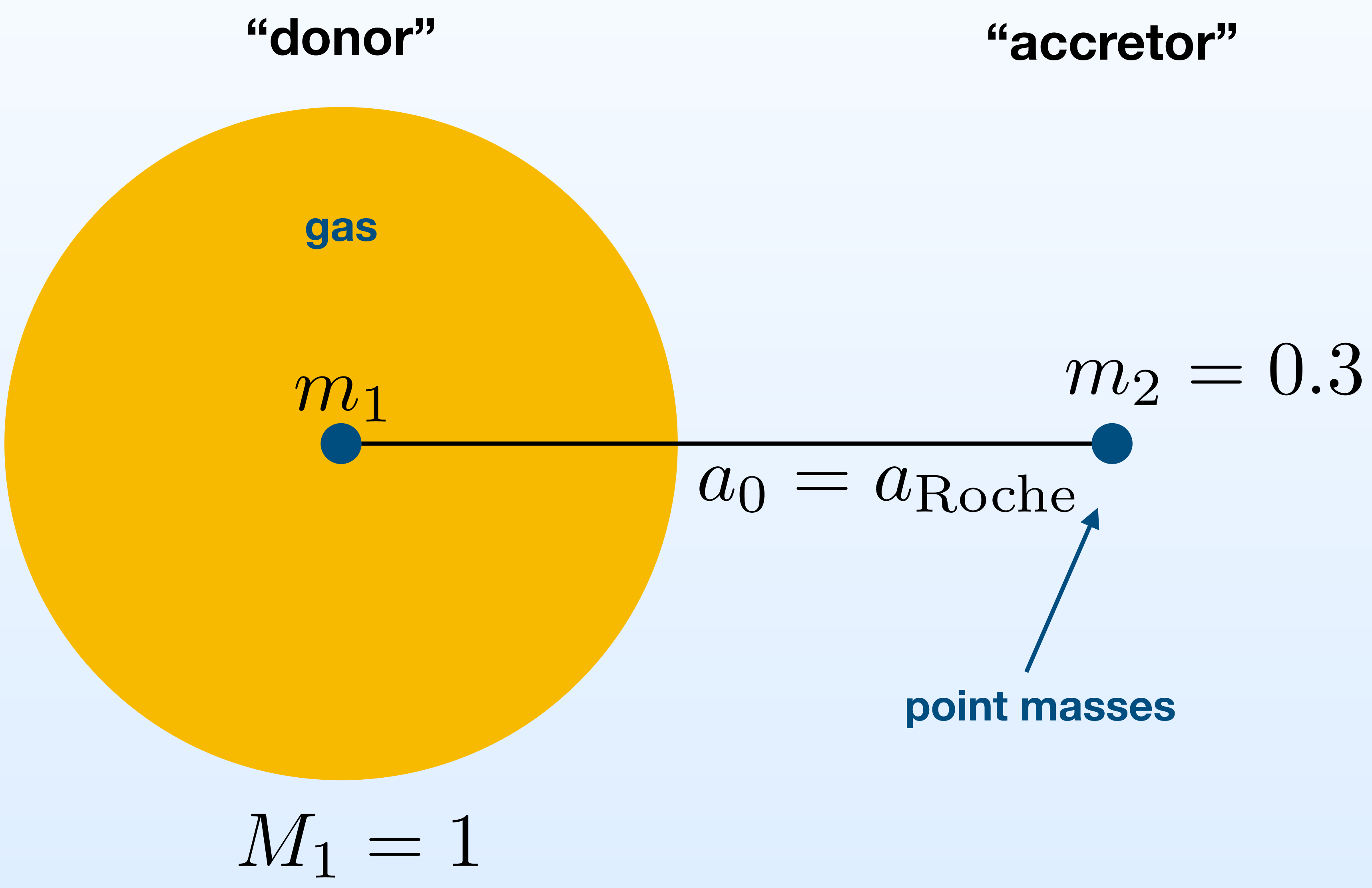


- spherical coordinate system centered on the donor star (excise stellar core!)
- gas in the domain interacts with two point masses, one at the coordinate origin, one orbiting
- simulations are in the reference frame of the donor star, arbitrary frame rotation (add fictitious forces)
- static mesh refinement
- approximate (static) treatment of self-gravity

(MacLeod, Ostriker, & Stone 2018a)

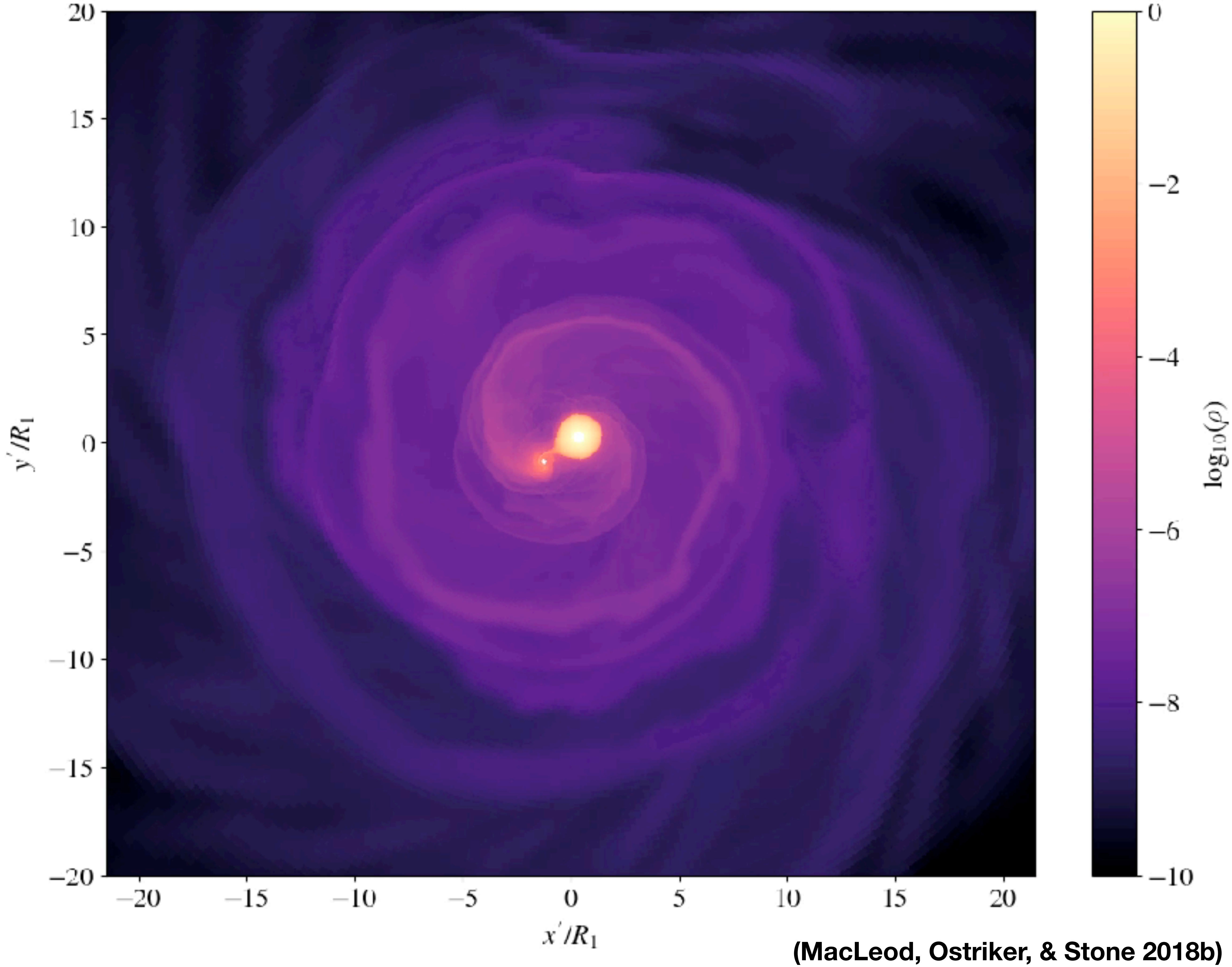
Modeling the onset of a stellar merger

Simulated system:



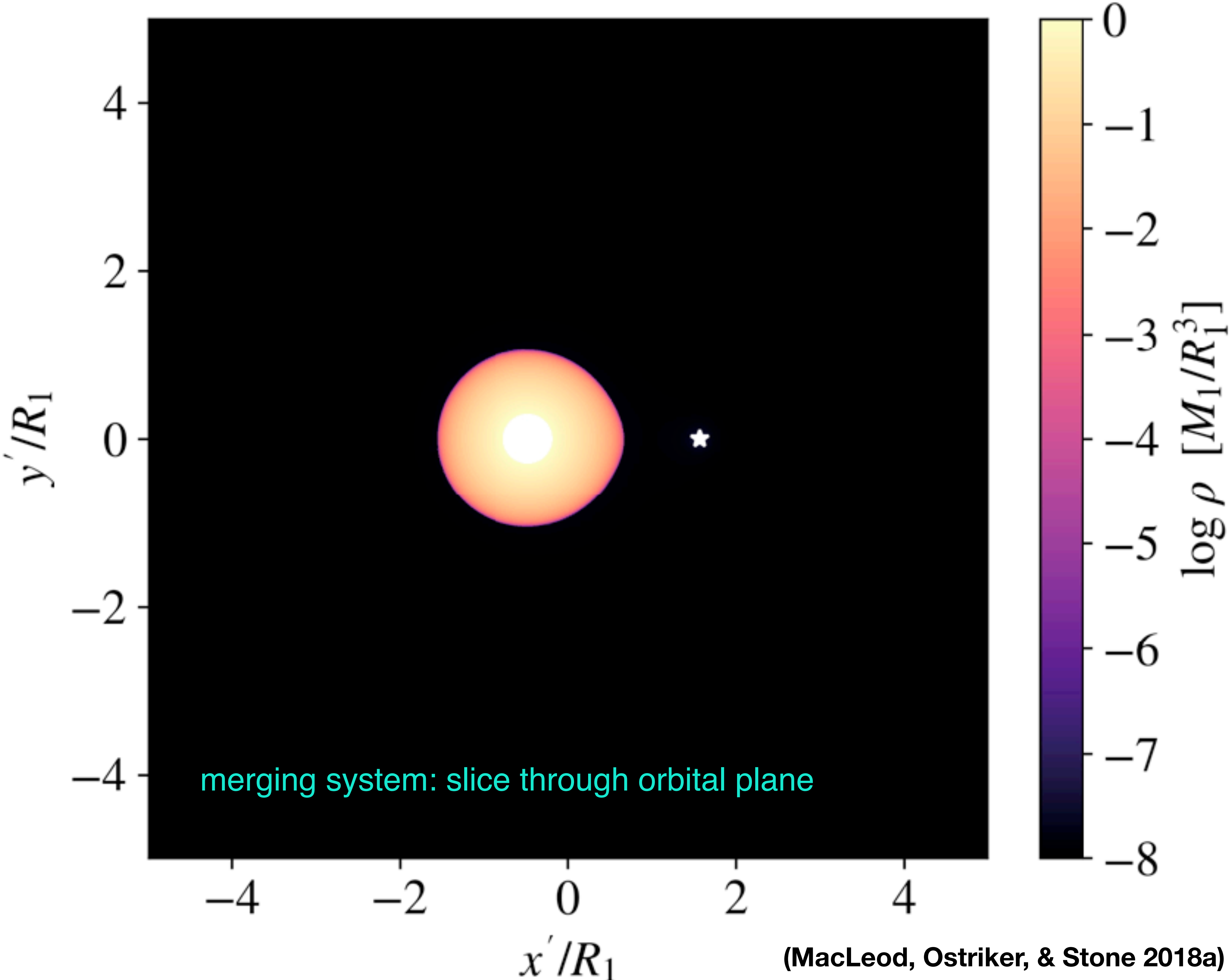
(initially tidally-locked — star co-rotates with the orbit)

Outflows & Ejecta



(MacLeod, Ostriker, & Stone 2018b)

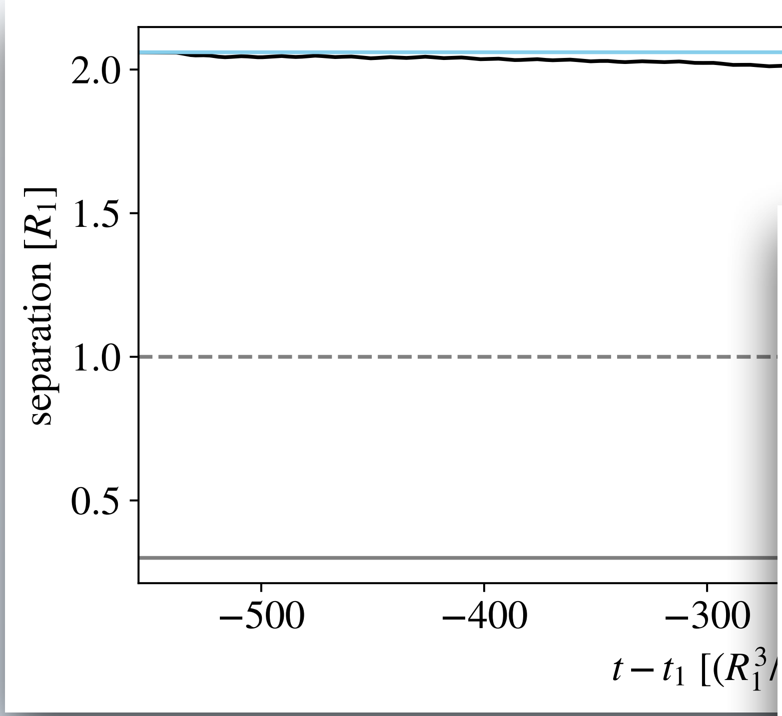
Modeling the onset of a stellar merger

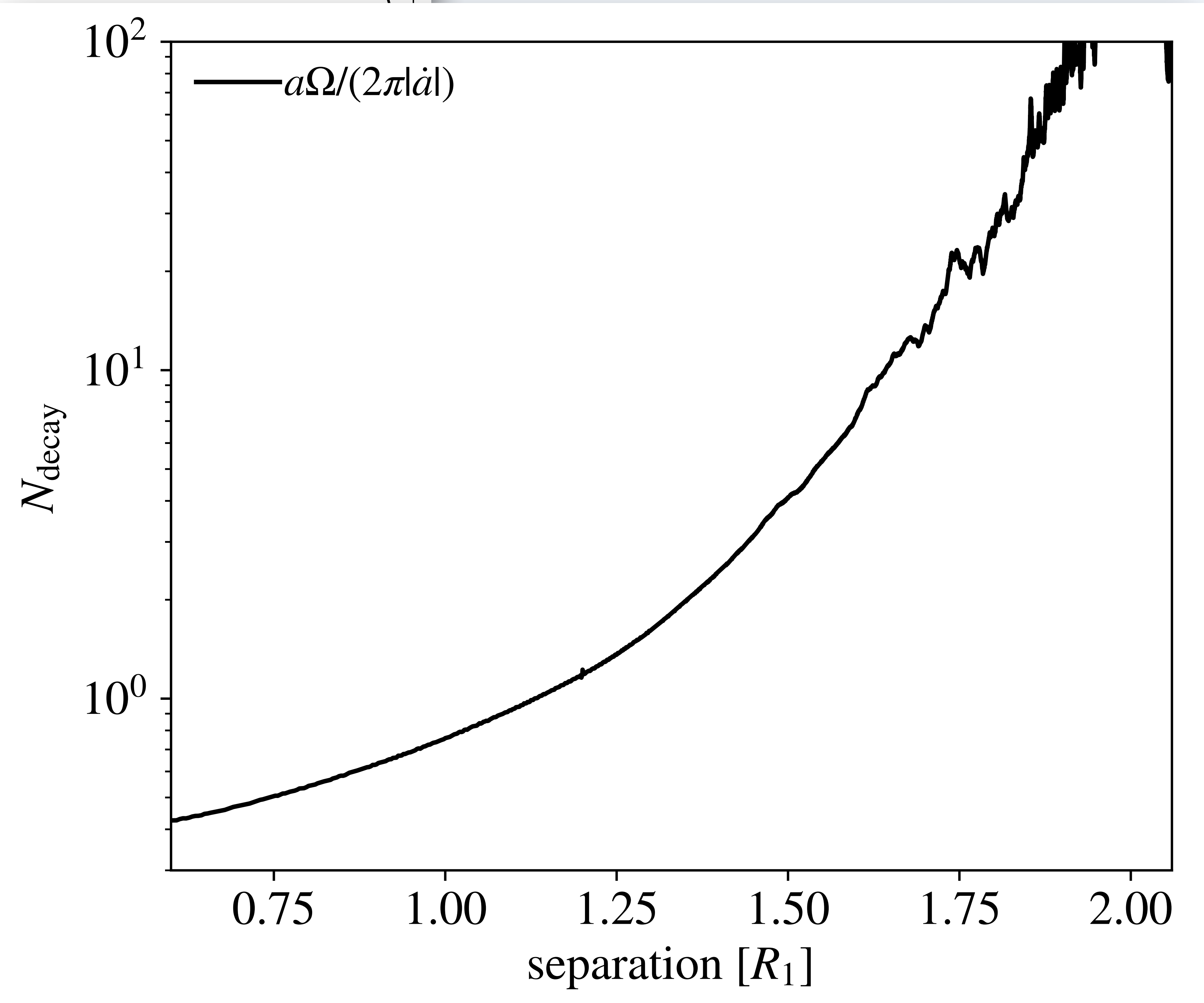


merging system: slice through orbital plane

(MacLeod, Ostriker, & Stone 2018a)

Orbital evolution

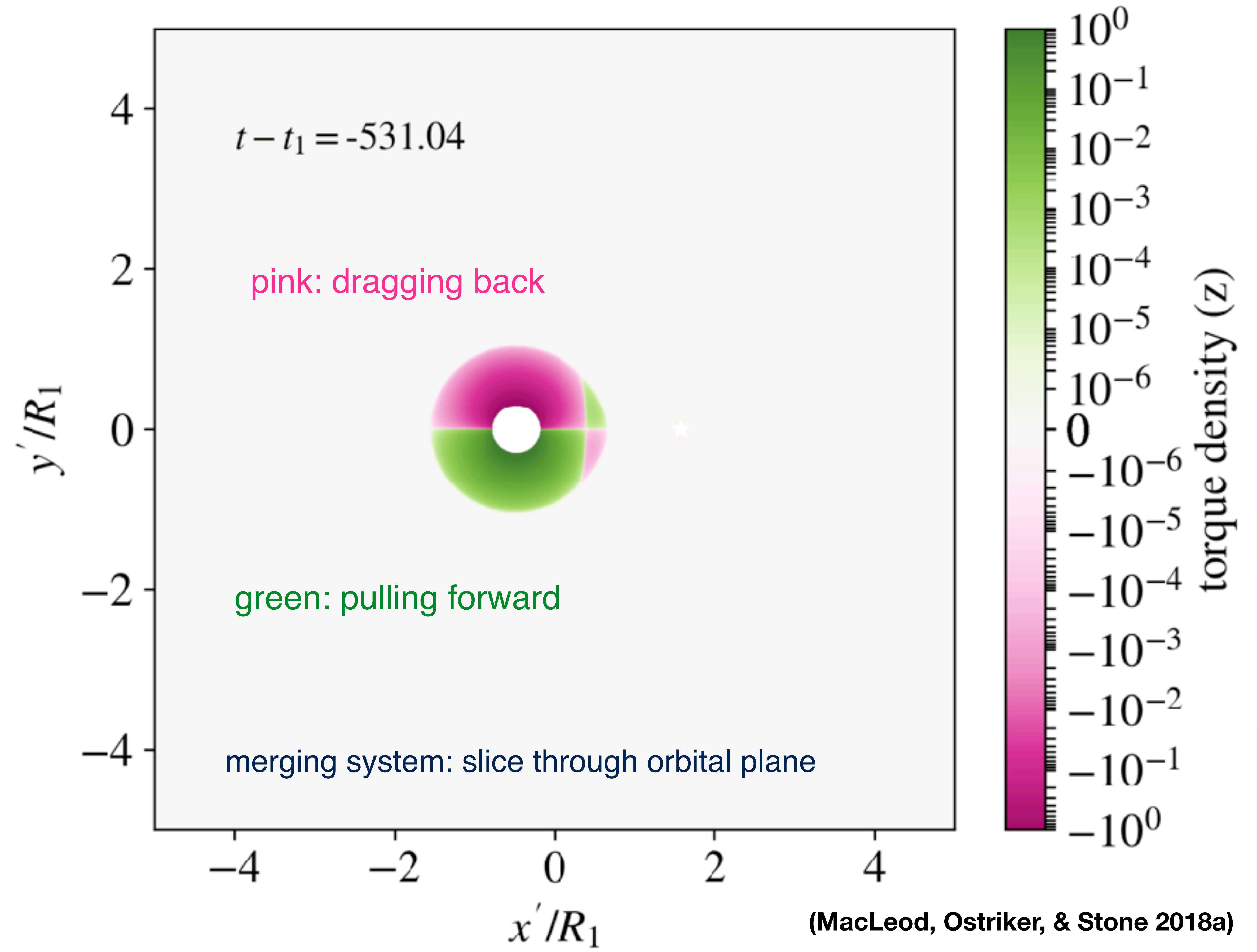




orbital decay starts
gradual, then runs a

(MacLeod, Ostriker, & Stone 2018a)

Angular momentum exchange



pink: dragging back

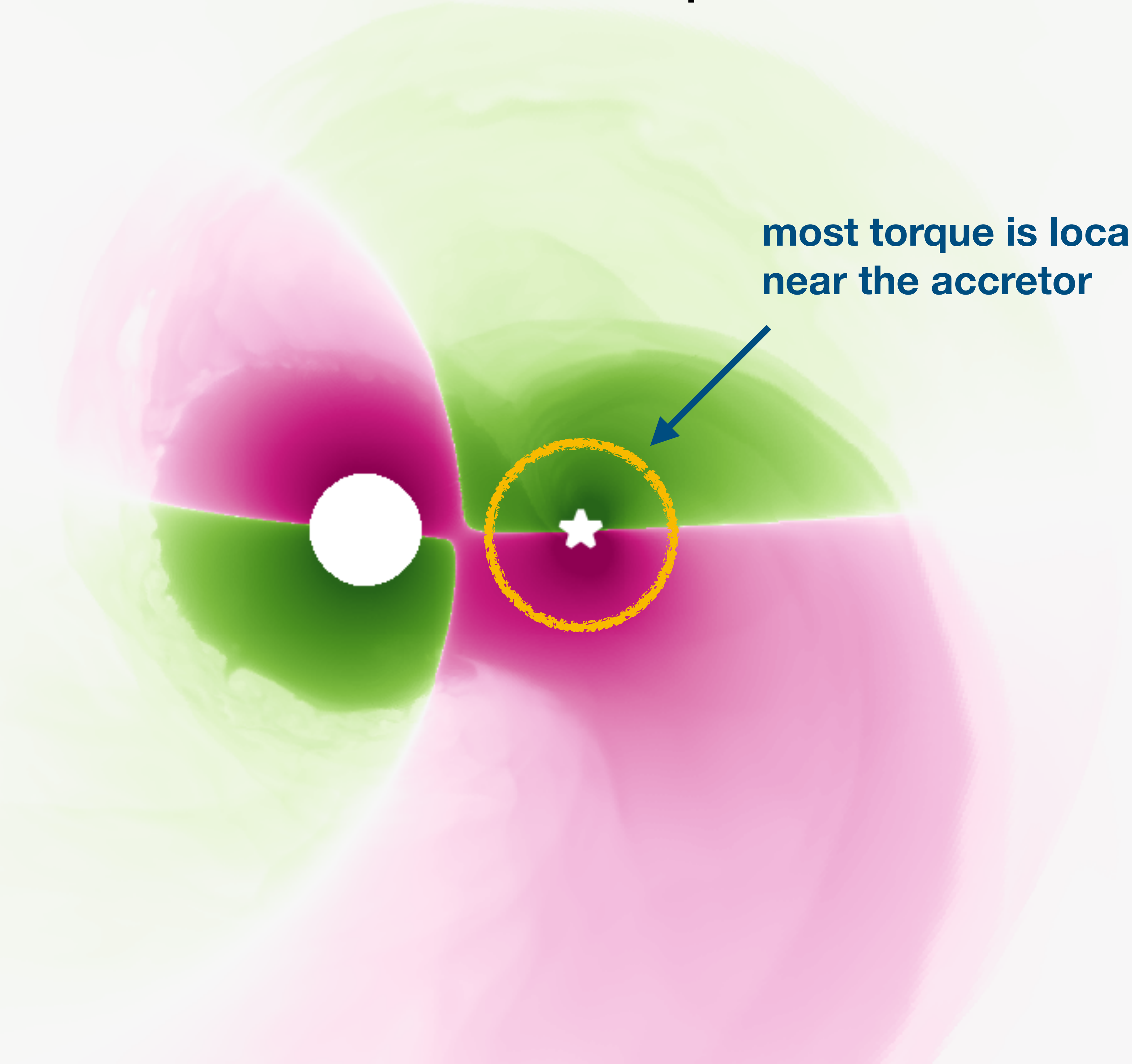
green: pulling forward

merging system: slice through orbital plane

(MacLeod, Ostriker, & Stone 2018a)

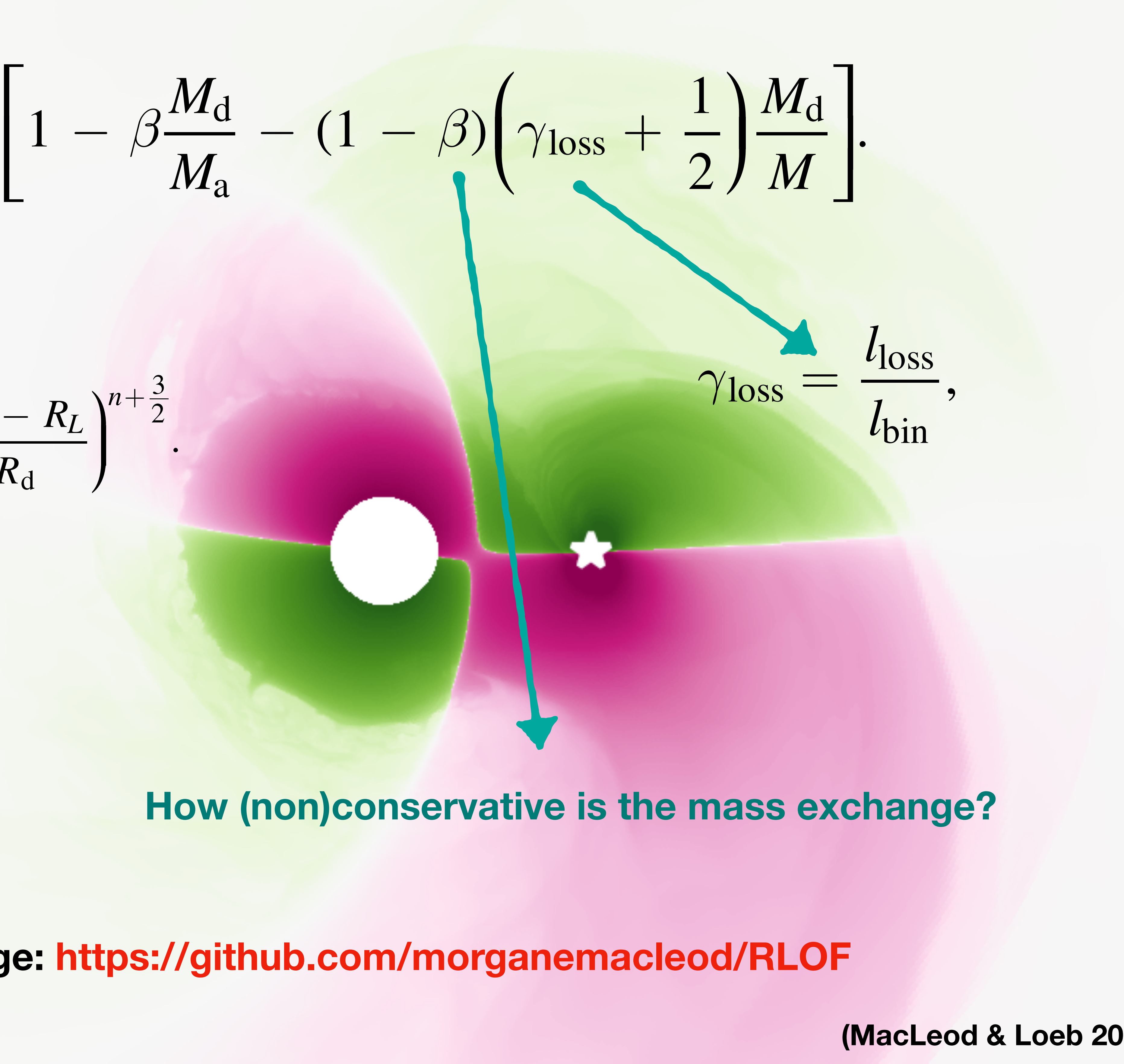
Angular momentum exchange

on which stellar core is most of the net torque exerted?



most torque is localized near the accretor

Representation with point-mass evolution equations



$$\frac{\dot{a}}{a} = -2\frac{\dot{M}_{\mathrm{d}}}{M_{\mathrm{d}}}\left[1 - \beta\frac{M_{\mathrm{d}}}{M_{\mathrm{a}}} - (1-\beta)\left(\gamma_{\mathrm{loss}} + \frac{1}{2}\right)\frac{M_{\mathrm{d}}}{M}\right].$$

$$\dot{M}_{\mathrm{d}} = -\alpha\frac{M_{\mathrm{d}}}{\tau}\left(\frac{R_{\mathrm{d}} - R_L}{R_{\mathrm{d}}}\right)^{n+\frac{3}{2}}.$$

$$\gamma_{\mathrm{loss}} = \frac{l_{\mathrm{loss}}}{l_{\mathrm{bin}}},$$

How (non)conservative is the mass exchange?

RLOF python package: https://github.com/morganemacleod/RLOF

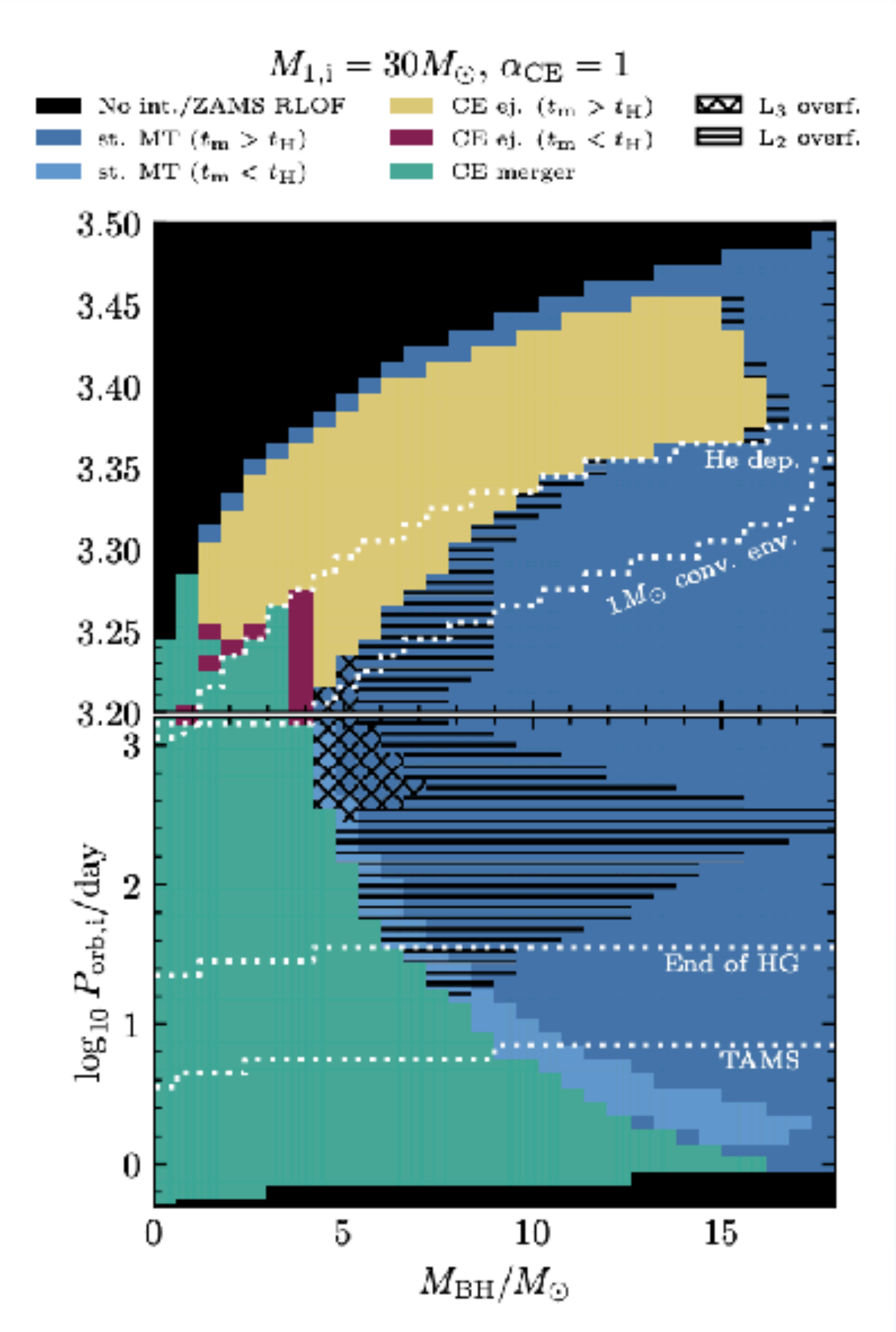
(MacLeod & Loeb 2020a,b)

Thermal evolution and onset of mass transfer

The previous slide assumed a known mass-radius relation for the donor star. This is simple in the case of adiabatic mass loss, but is more complex when the donor star is (partially) thermally adjusting to mass transfer.

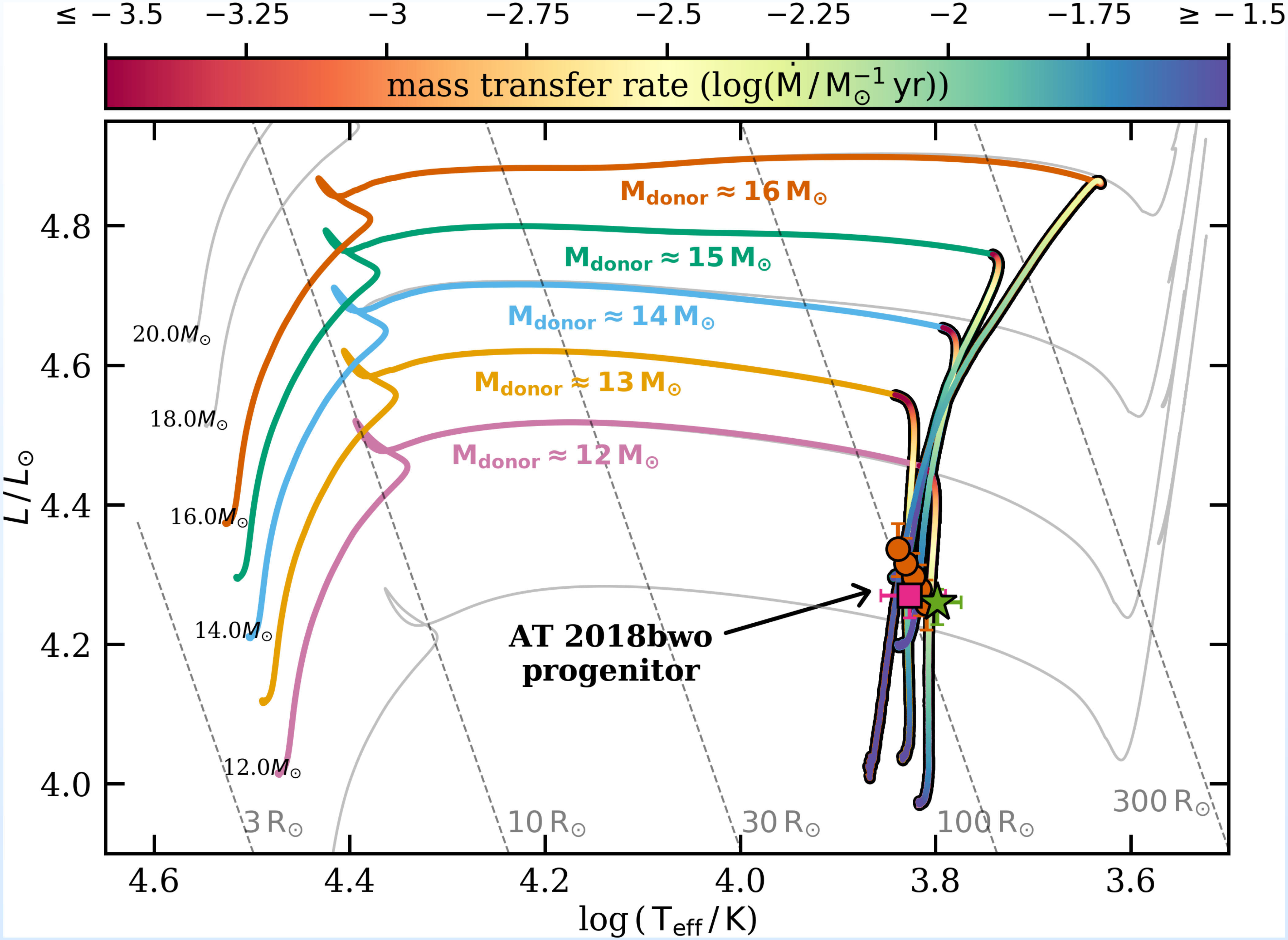
Critical, and subtle, implications for stability of MT

—> See … Pavlovskii+ 2015,2017, Marchant+ 2021



(Marchant+ 2021)

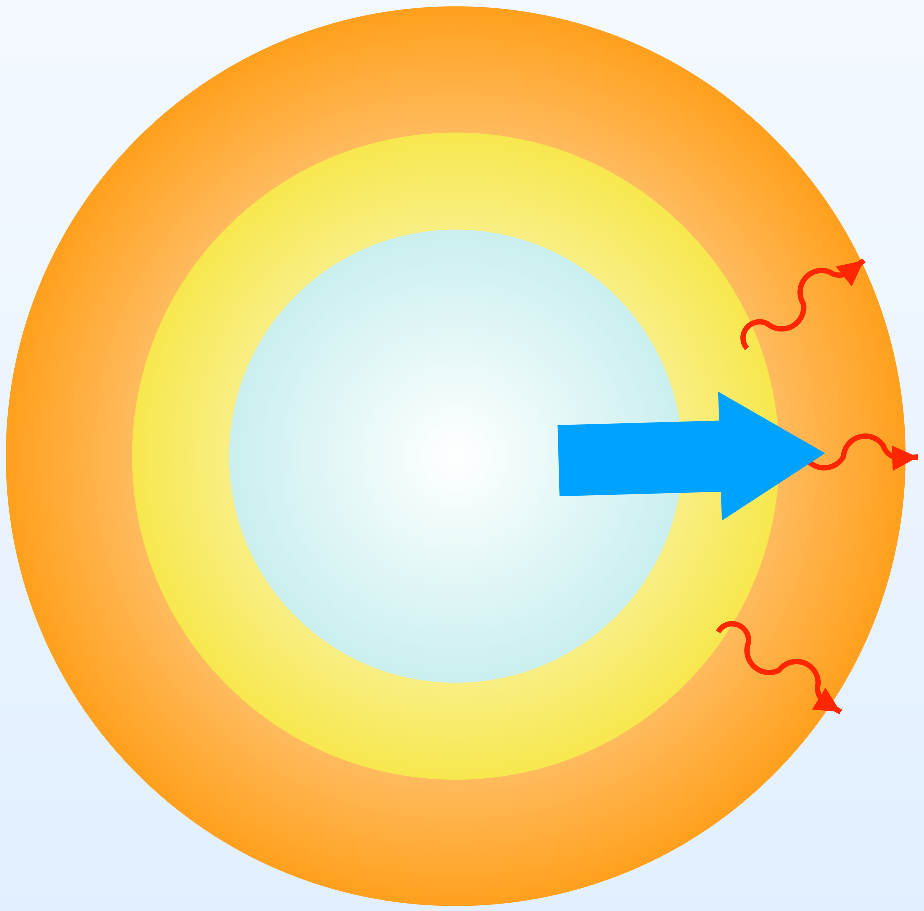
Thermal evolution and onset of mass transfer



(Blagorodnova, Klencki+ 2021)

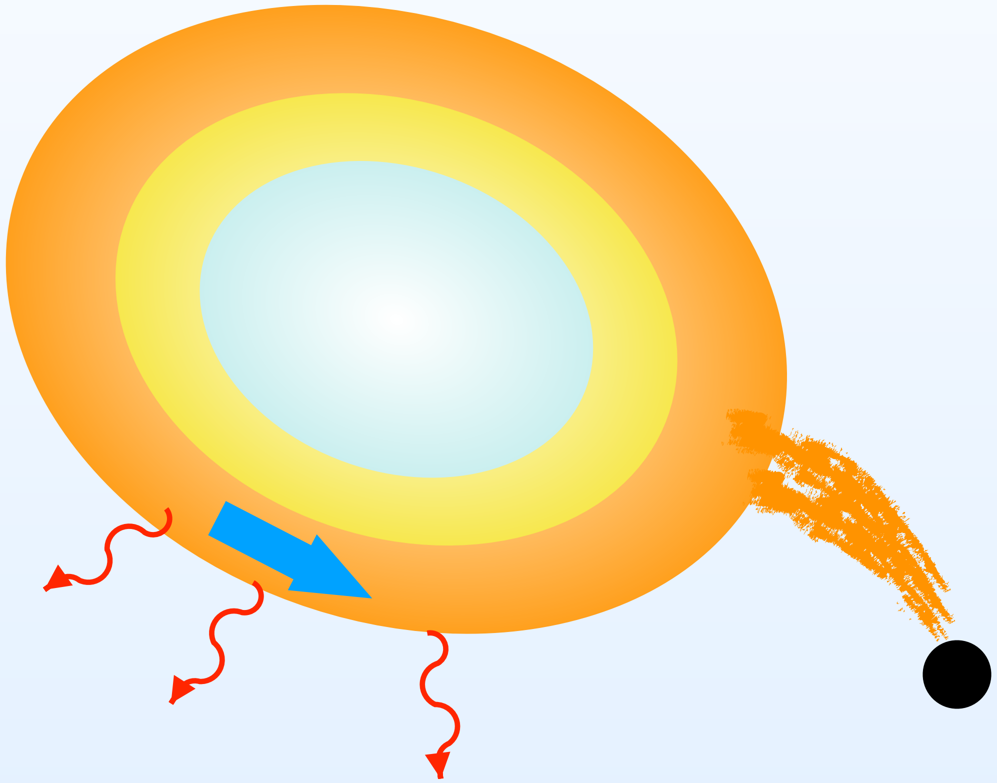
Thermal evolution and onset of mass transfer

Radial mass loss



Bulk flow partially advects the stellar luminosity

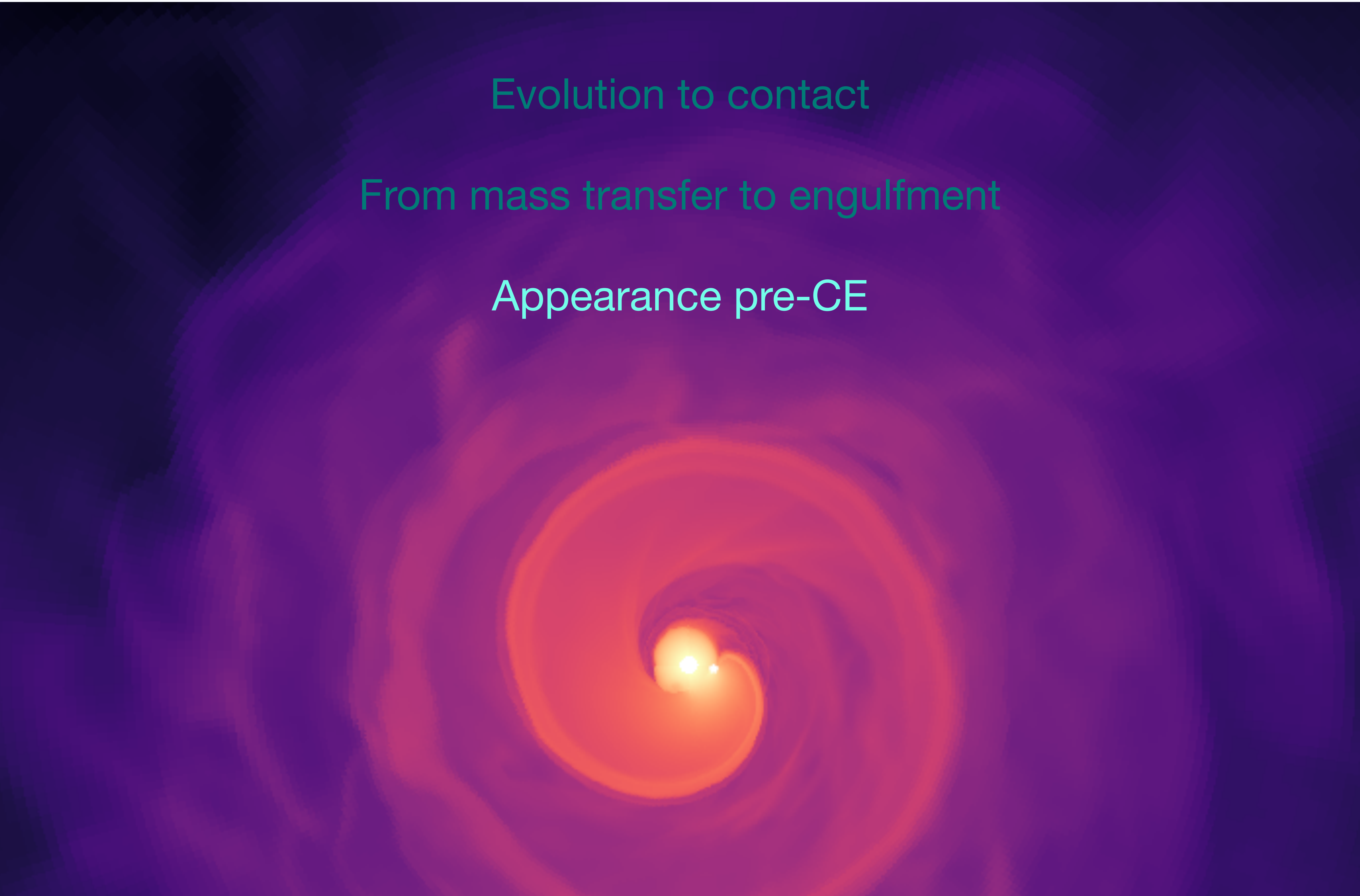
Roche lobe overflow



Advection is ~perpendicular to temperature gradient

—> Expect less advective degradation of stellar luminosity

The lead-in to common envelope phases

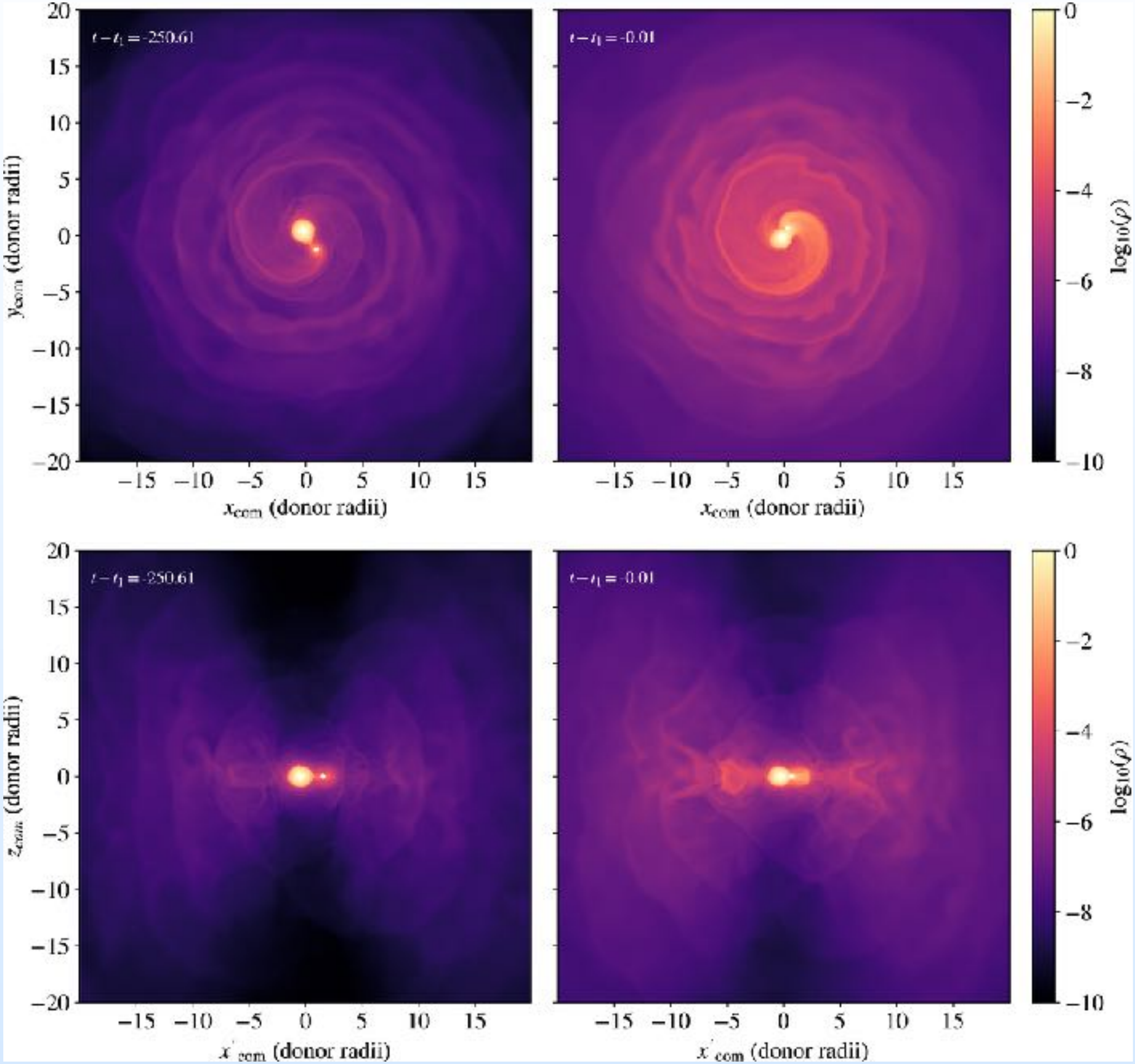


Evolution to contact

From mass transfer to engulfment

Appearance pre-CE

Mass loss in the lead-in to coalescence



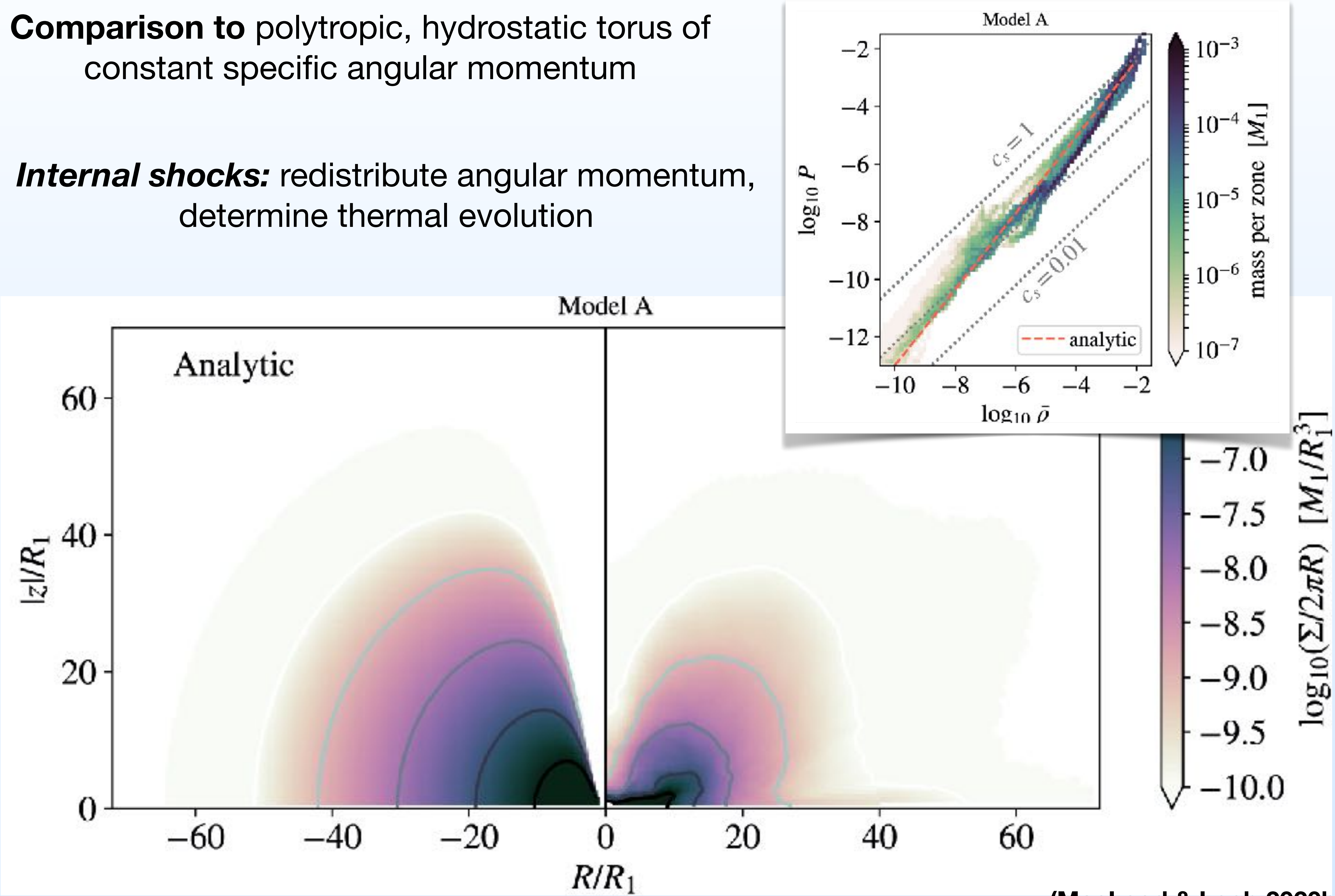
Thick torus of circumbinary material

(MacLeod, Ostriker, & Stone 2018b)

Mass loss in the lead-in to coalescence

Comparison to polytropic, hydrostatic torus of constant specific angular momentum

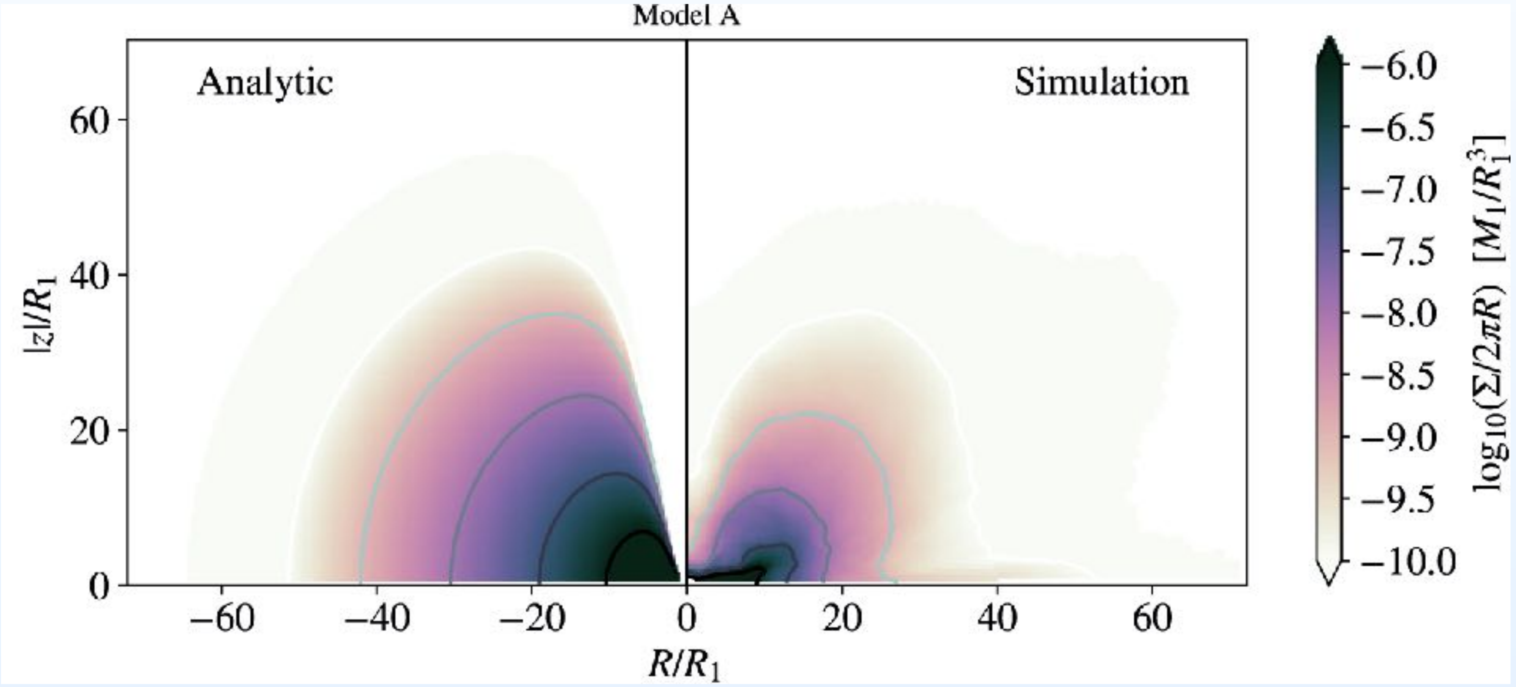
Internal shocks: redistribute angular momentum, determine thermal evolution



(MacLeod & Loeb 2020b)

Mass loss in the lead-in to coalescence

Internal shocks: redistribute angular momentum,
determine thermal evolution



approximate scalings:

$$\rho(R,0) \propto r^{-3}$$

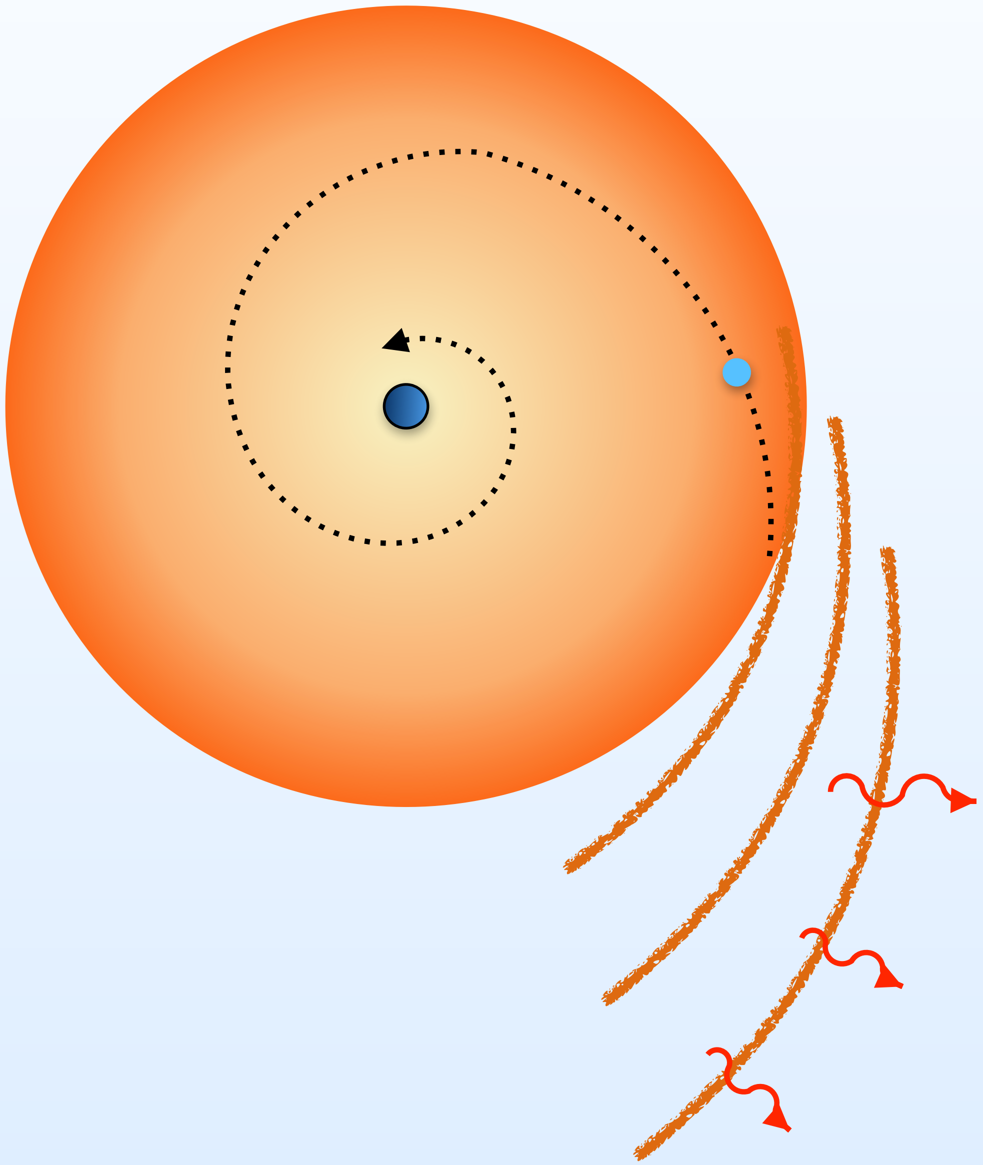
$$T(R,0) \propto r^{-1}$$

steeper than steady wind

proportional to grav. potential

(MacLeod & Loeb 2020b)

Mass loss in the lead-in to coalescence



major increase in **opacity**

$$\kappa_{\rm eff} \sim X_{\rm d}\kappa_d$$

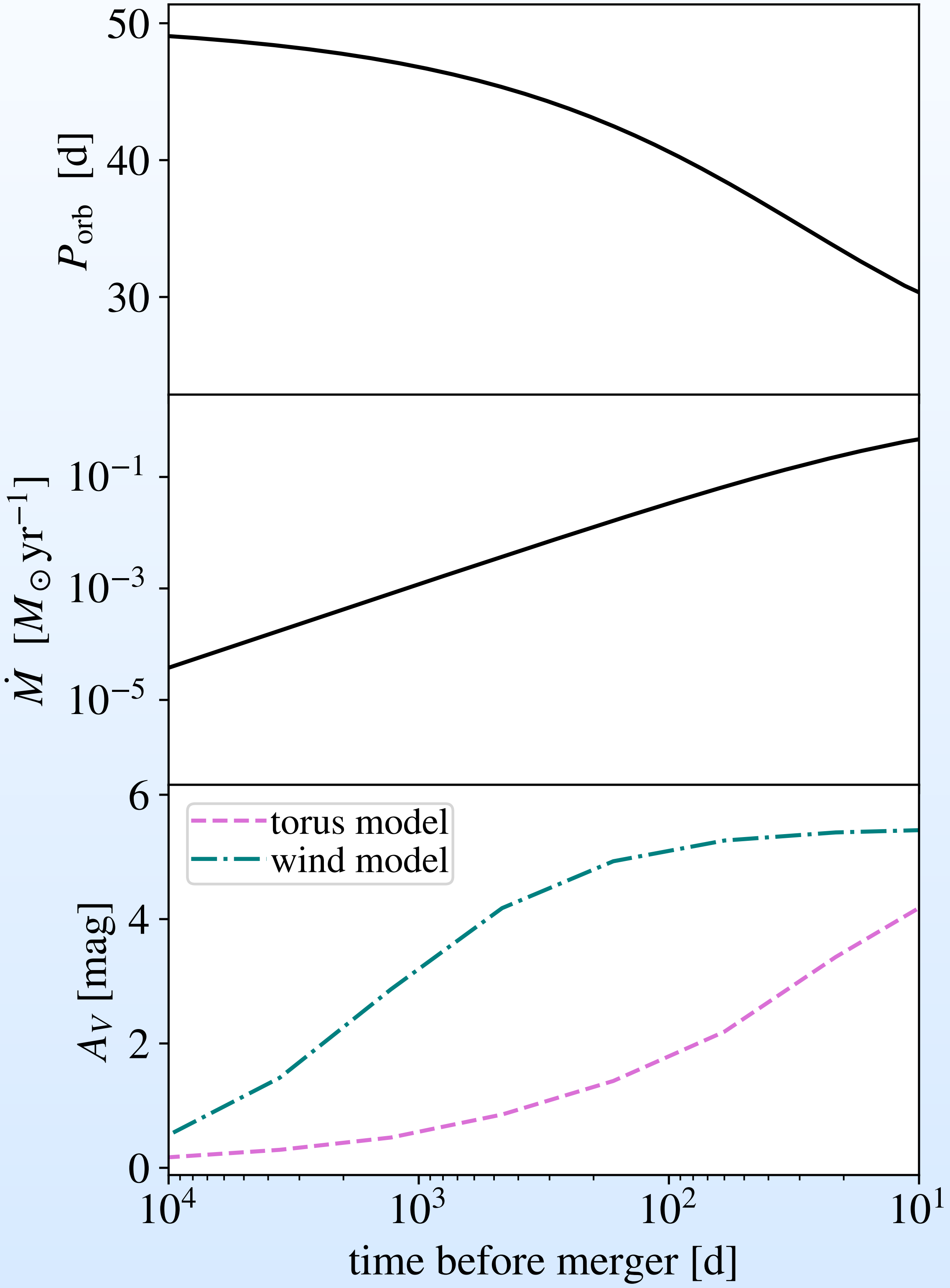
$$\sim 5\ {\rm cm}^2\ {\rm g}^{-1} \left(\frac{X_{\rm d}}{5\times10^{-3}}\right)\left(\frac{\kappa_{\rm d}}{10^3\ {\rm cm}^2\ {\rm g}^{-1}}\right)$$

dust condenses when

$$T \lesssim 10^3\ {\rm K}$$

Mass loss in the lead-in to coalescence

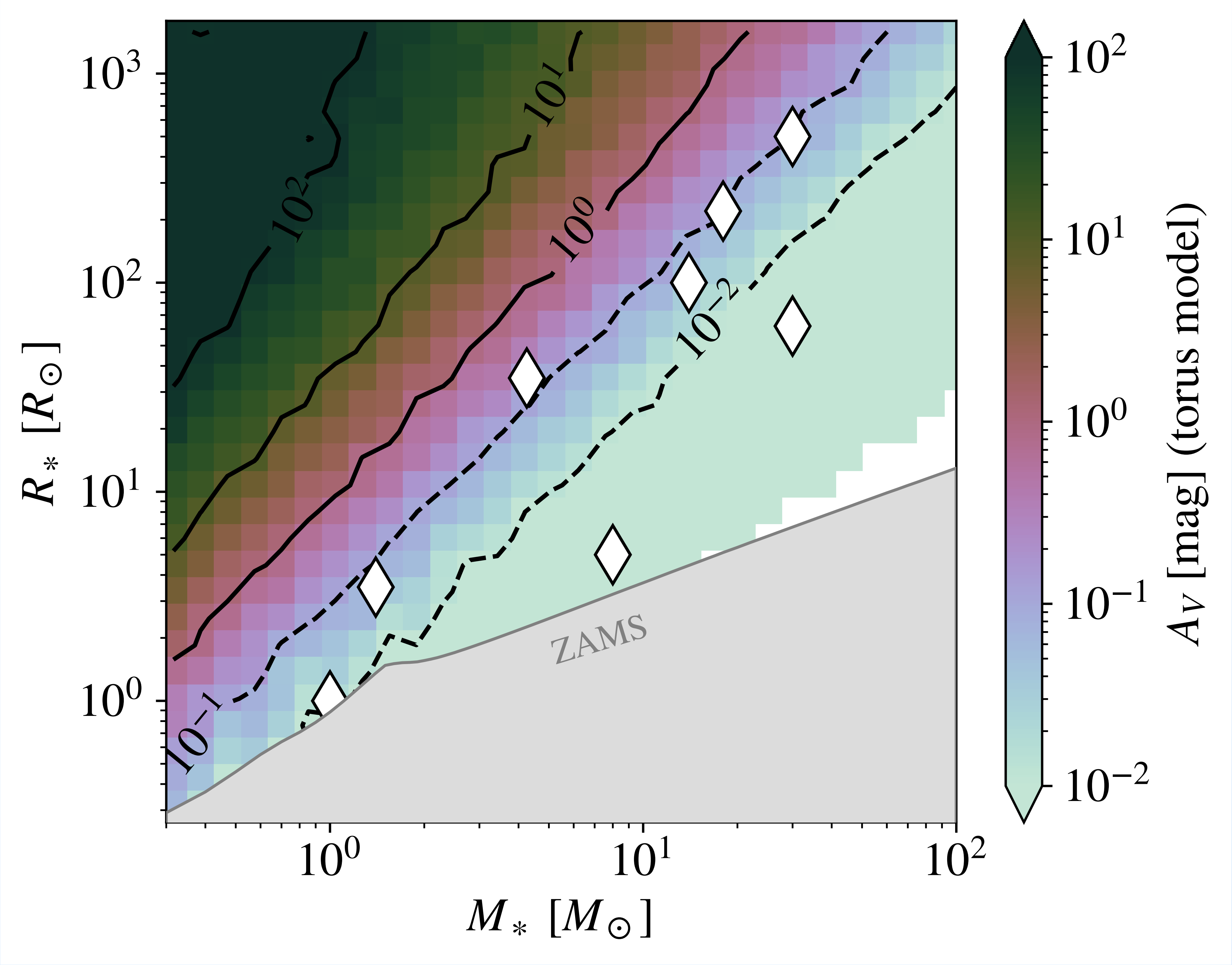
Example merging system: 1 solar mass, 30 solar radii, q=1/3



Dust optical depth increases in the lead-in to merger!

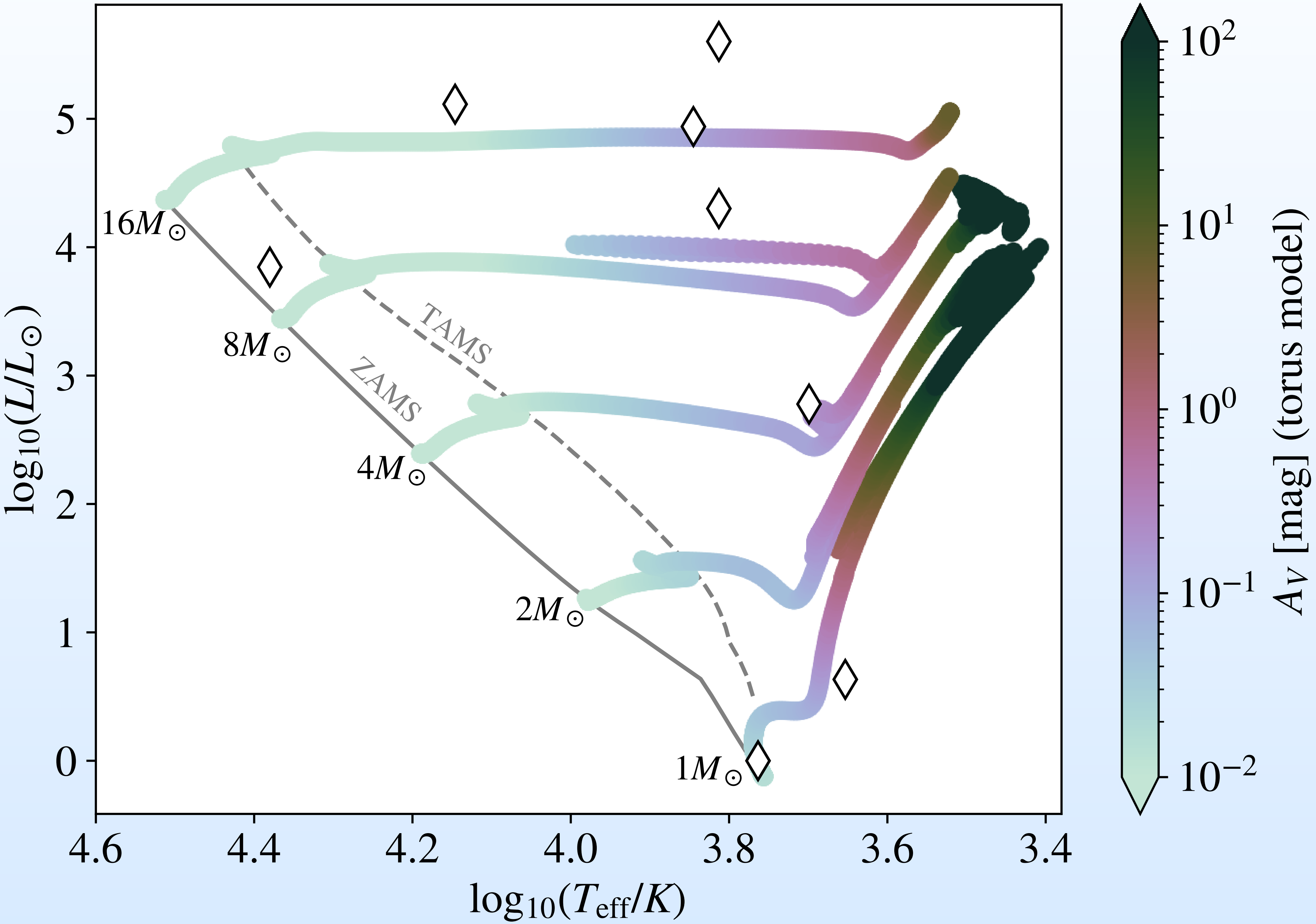
(MacLeod, De, Loeb, 2022)

Dust Obscuration



(MacLeod, De, Loeb, 2022)

Dust Obscuration

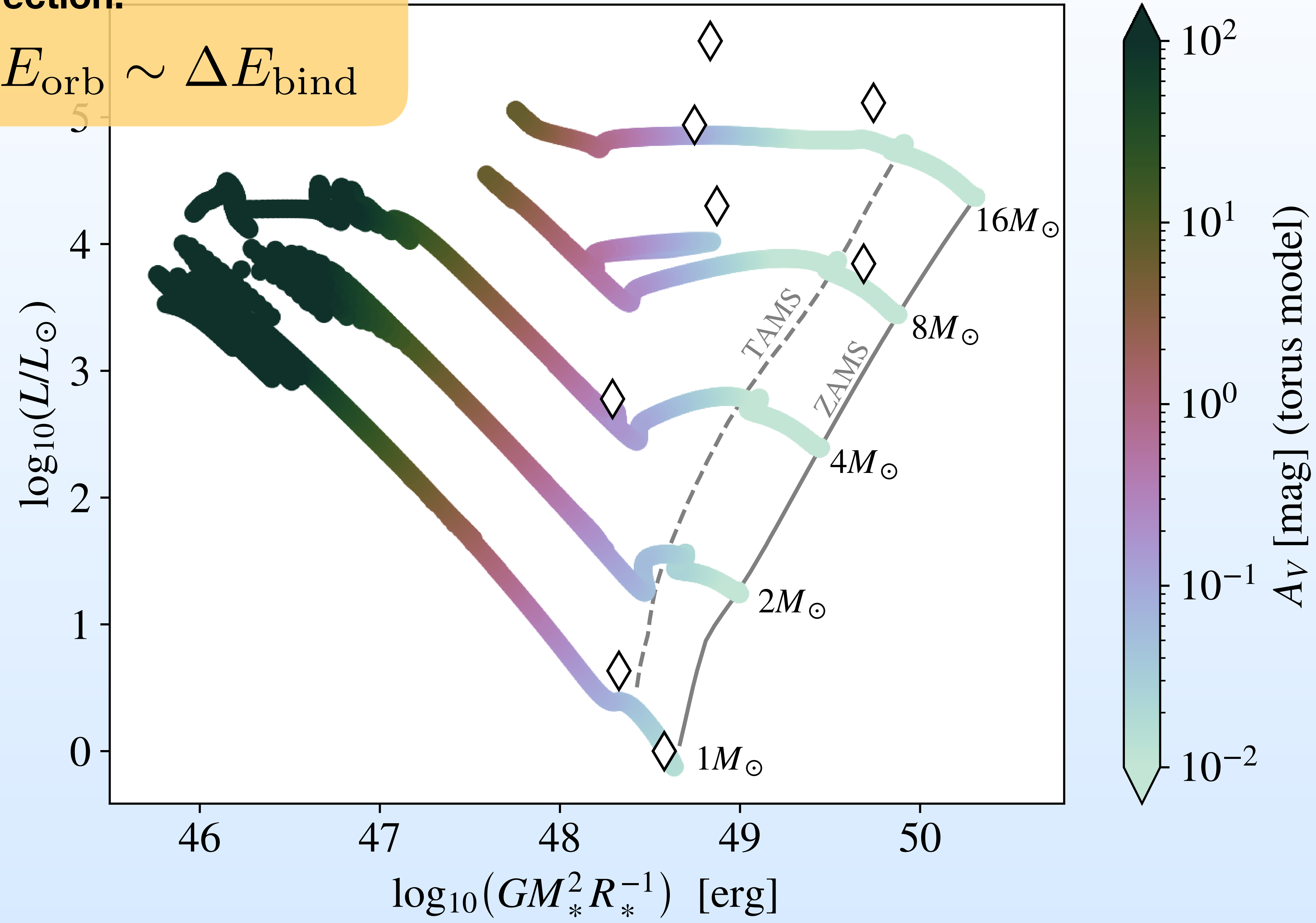


(MacLeod, De, Loeb, 2022)

Dust Obscuration

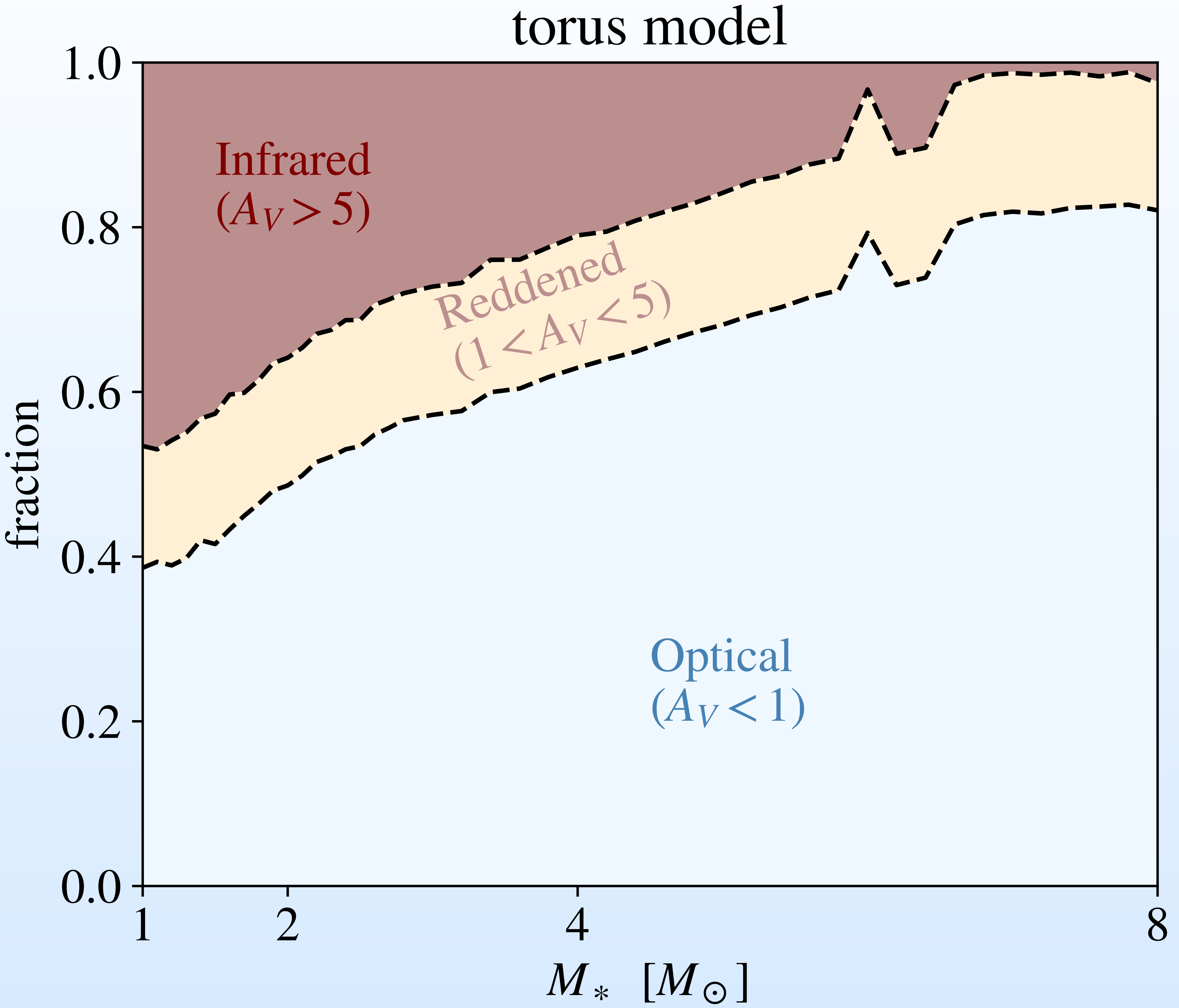
CE ejection:

$$\alpha \Delta E_{\mathrm{orb}} \sim \Delta E_{\mathrm{bind}}$$



(MacLeod, De, Loeb, 2022)

Dust Obscuration

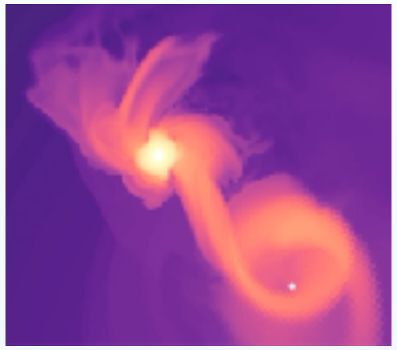


(MacLeod, De, Loeb, 2022)

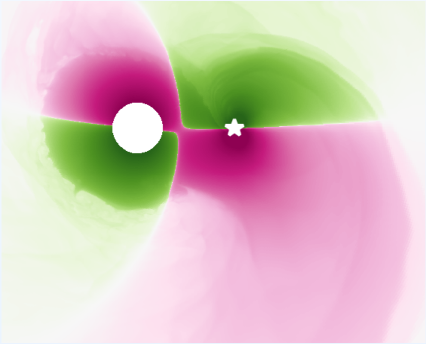
Thank you! Morgan MacLeod: morgan.macleod@cfa.harvard.edu

Summary

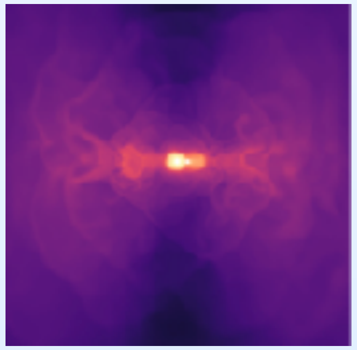
Tides circularize low-mass systems before mass exchange; many massive systems remain eccentric and asynchronous



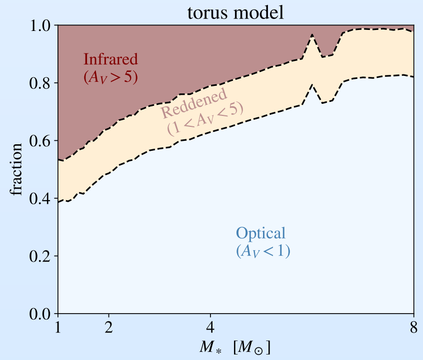
Mass transfer and loss drives systems toward coalescence



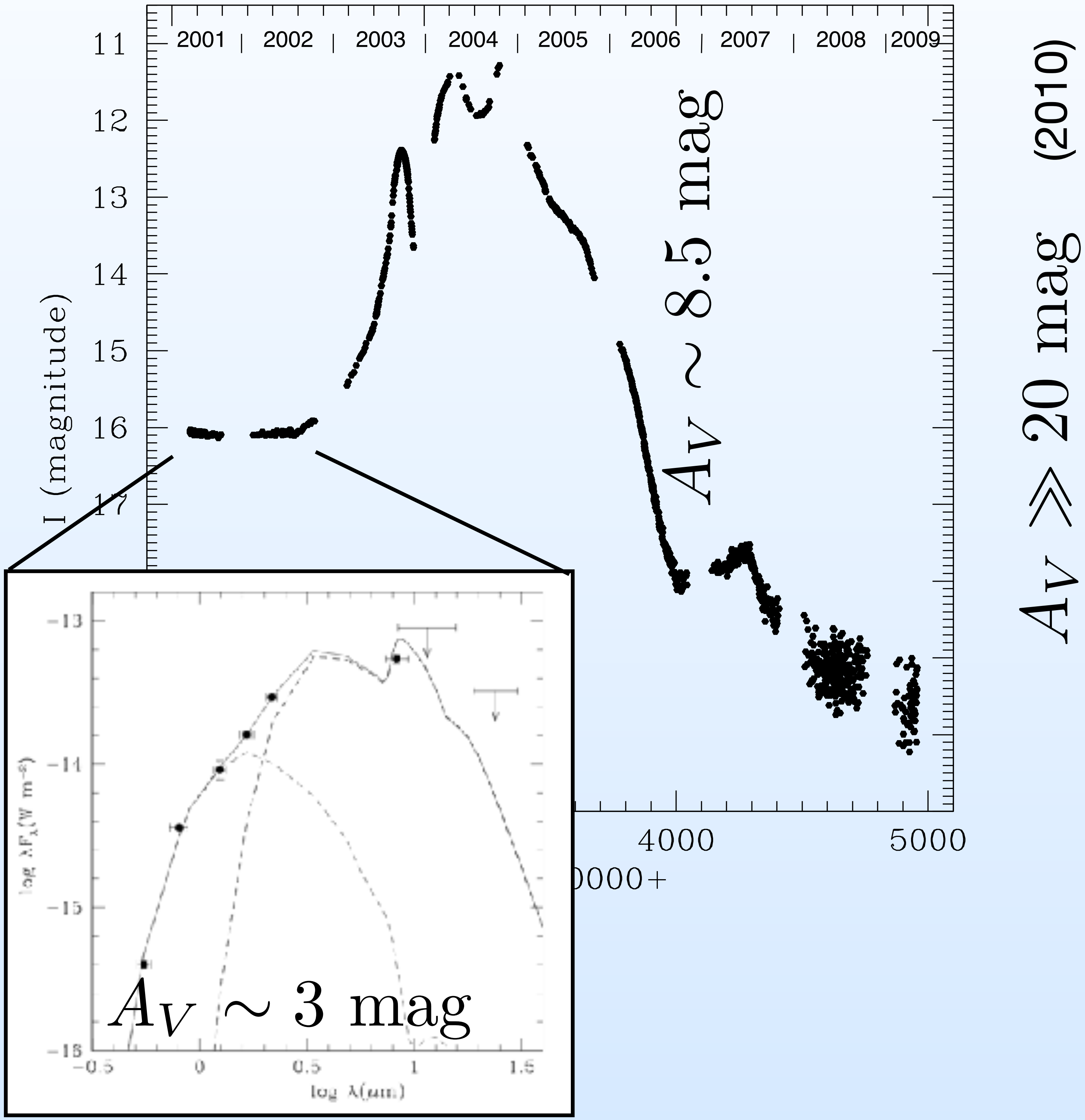
Circumbinary material shapes the observable appearance of transients



CE ejection outcomes should be associated with a population of IR transients



OGLE-2002-BLG360 — dusty, reddened coalescence transient?



Extended progenitor?

Teff ~ 4300 K

Long duration ~ 1000 d