Double white dwarf binaries

Sunny Wong, Courtney Crawford, Tryston Raecke

Image credit: University of Warwick

Roadmap

General question: what happens when a helium white dwarf donates mass to a carbon-oxygen white dwarf?

Minilab 1: response of donor and orbit to mass transfer

Minilab 2: response of accretor to accretion

(Part 1: constant accretion rate)

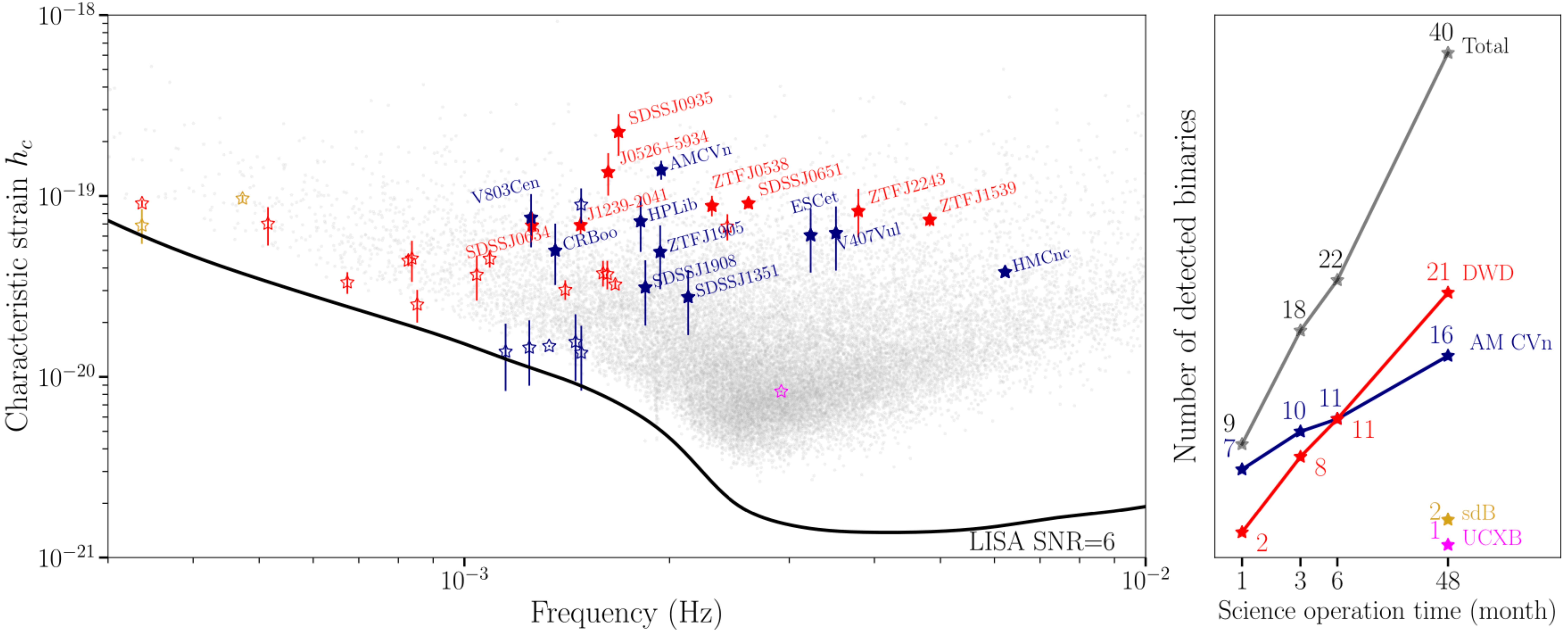
Minilab 3: response of accretor to accretion

(Part 2: realistic binary history)

AM CVn binaries

- Ultracompact binaries with orbital periods between 5 and 69 minutes
- A white dwarf accretes He-rich matter from semi-degenerate donor star
- For review see Solheim 2010, Ramsay+ 2018

AM CVn binaries: gravitational wave sources



Kupfer et al. 2024

White dwarf 101

Supported by electron degeneracy pressure

Hydrostatic equilibrium:

$$\frac{dP}{dr} = -\rho(r)\frac{Gm(r)}{r^2}$$

$$\frac{P}{R} \sim -\frac{M}{R^3}\frac{GM}{R^2}$$

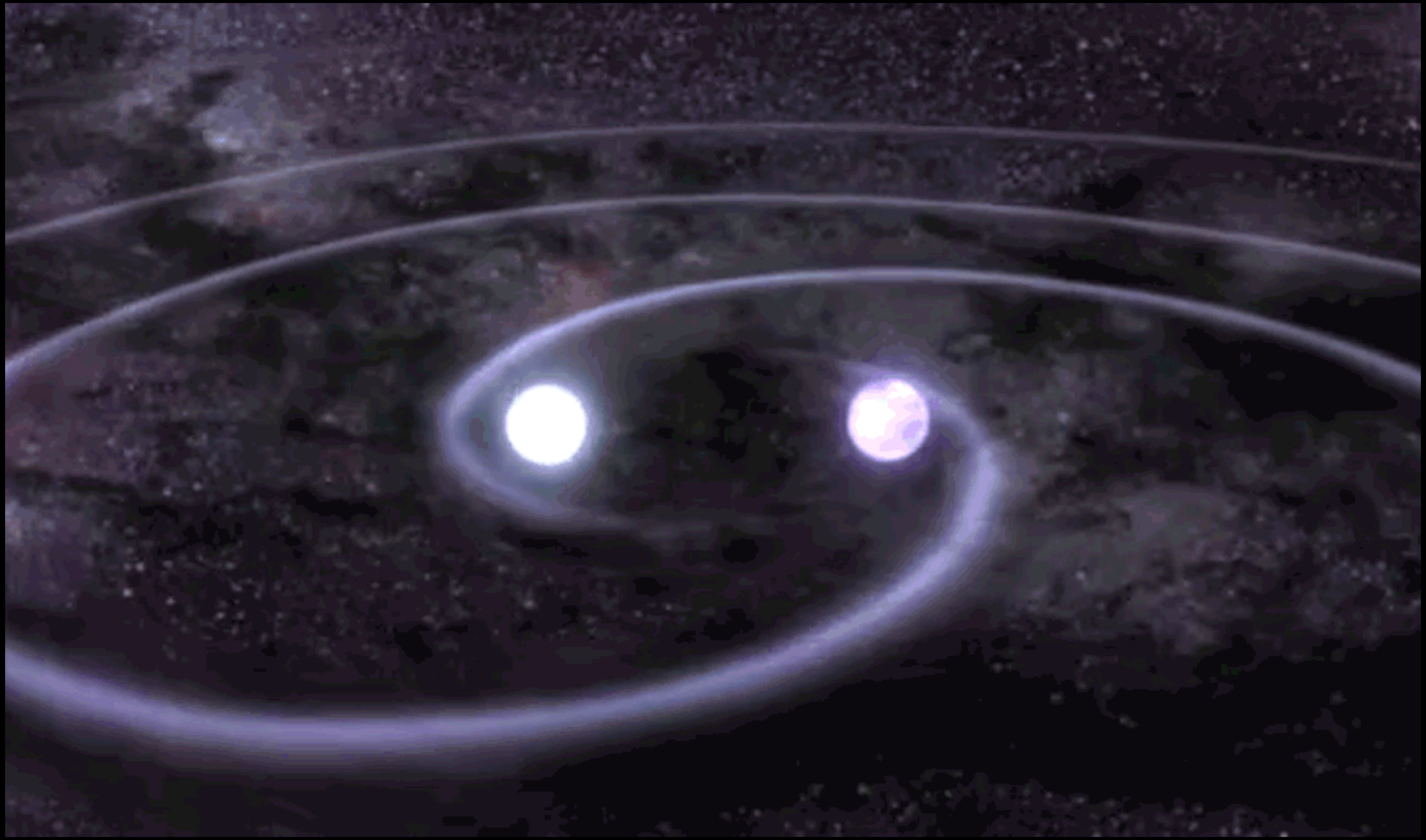
$$P \sim \frac{GM^2}{R^4}$$

Non-relativistic degeneracy: $P \propto \rho^{5/3} \propto \frac{M^{5/3}}{R^5}$

$R \propto M^{-1/3}$:

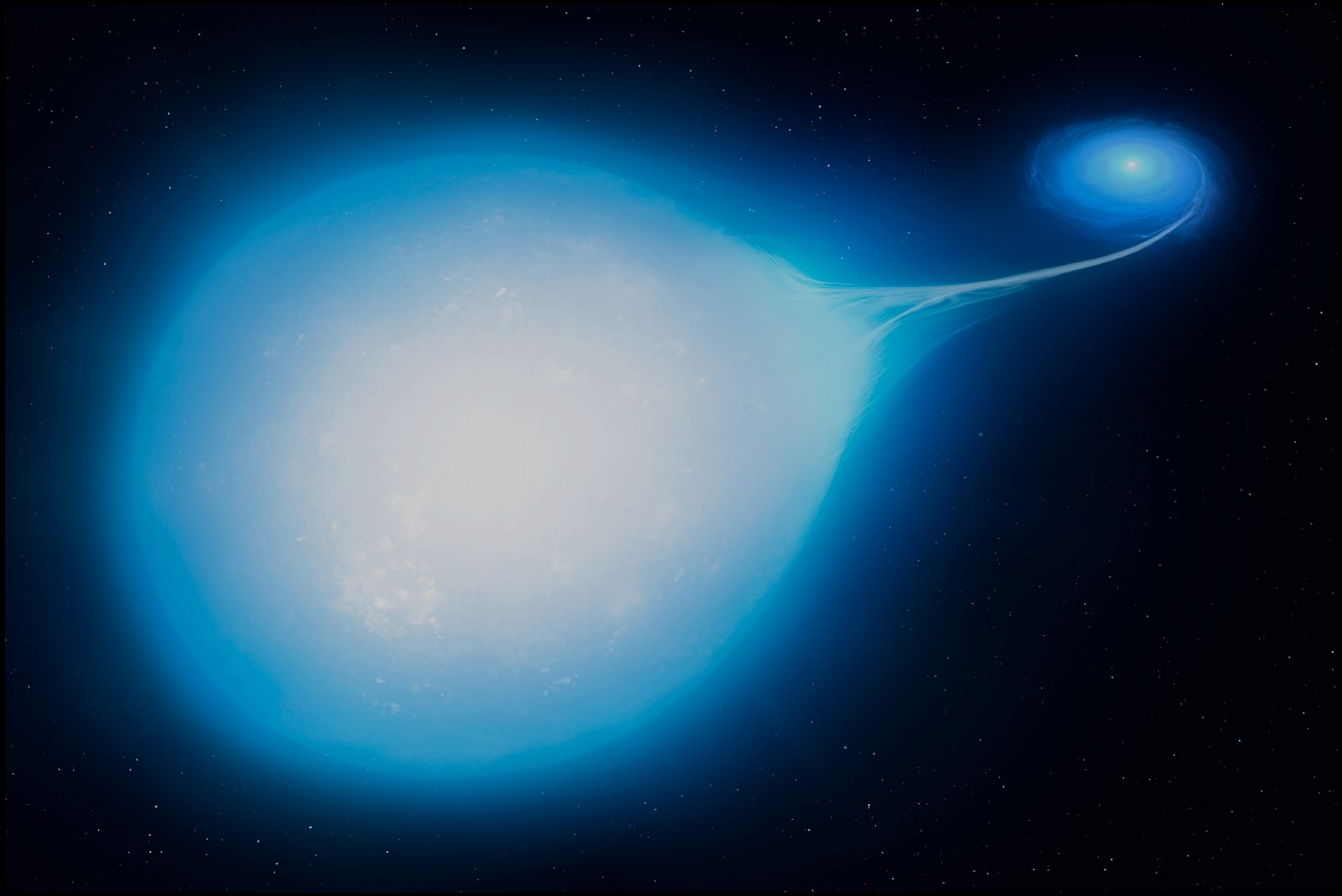
Massive WDs are smaller

Double white dwarf binary: Orbit shrinks due to gravitational waves



Artist illustration

Less massive WD fills its Roche lobe and starts transferring mass



Some mass transfer basics

Here M_1 is donor mass, M_2 is accretor mass, $M_{\rm tot} = M_1 + M_2$

Orbital angular momentum

$$J_{\rm orb} = M_1 M_2 \sqrt{\frac{Ga}{M_{\rm tot}}}$$

Donor (star 1) is Roche-filling:

$$\frac{R_1}{a} = 0.462 \left(\frac{M_1}{M_{\rm tot}} \right)^{1/3}$$

$$J_{\rm orb} \propto M_1^{5/6} M_2 M_{\rm tot}^{-1/3} R_1^{1/2}$$

Some mass transfer basics

$$\frac{\dot{J}_{\mathrm{orb}}}{J_{\mathrm{orb}}} = \frac{5}{6}\frac{\dot{M}_1}{M_1} + \frac{\dot{M}_2}{M_2} - \frac{1}{3}\frac{\dot{M}_{\mathrm{tot}}}{M_{\mathrm{tot}}} + \frac{1}{2}\frac{\dot{R}_1}{R_1}$$

Conservative mass transfer (no mass loss from system):

$$\dot{M}_1 = -\dot{M}_2, \dot{M}_{\mathrm{tot}} = 0$$

Some mass transfer basics

$$\frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = \frac{\dot{M}_1}{M_1}\left(\frac{5}{6} - \frac{M_1}{M_2}\right) + \frac{1}{2}\frac{\dot{R}_1}{R_1}$$

Response of donor radius to mass loss

$$R_1 \propto M_1^n$$

$$\frac{\dot{R}_1}{R_1} = n\frac{\dot{M}_1}{M_1}$$

$$= \frac{\dot{M}_1}{M_1}\left(\frac{5}{6} - \frac{M_1}{M_2} + \frac{n}{2}\right)$$

Need $\frac{M_1}{M_2} < \frac{5}{6} + \frac{n}{2}$ for stable mass transfer

Some mass transfer basics

Need $\dfrac{M_1}{M_2} < \dfrac{5}{6} + \dfrac{n}{2}$ for stable mass transfer

Fully degenerate WDs:

$n = -1/3$ ($R_1 \propto M_1^{-1/3}$)

So need $\dfrac{M_1}{M_2} < \dfrac{2}{3}$

(See Marsh et al. 2004 which accounts for spin of the binary components)

Some mass transfer basics

$$\frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = \frac{\dot{M}_1}{M_1}\left(\frac{5}{6} - \frac{M_1}{M_2} + \frac{n}{2}\right)$$

$$\dot{J}_{\rm orb} = \dot{J}_{\rm gw} + \cancel{\dot{J}_{\rm ml} + \dot{J}_{\rm mb}} + \dot{J}_{\rm ls}$$

Gravitational waves

Magnetic braking

Mass loss from system

Spin-orbit coupling

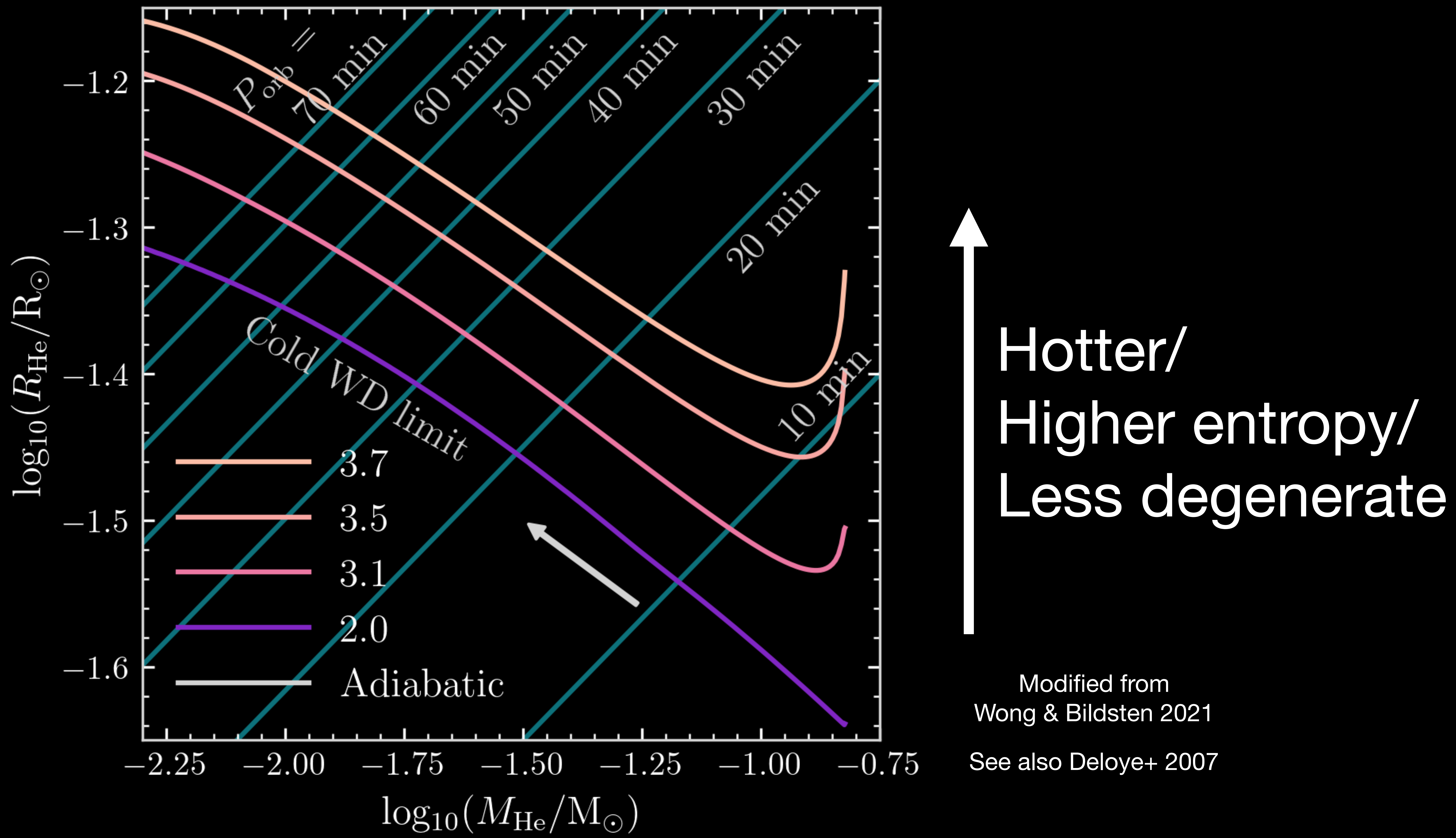
Some mass transfer basics

$$\frac{\dot{J}_{\rm orb}}{J_{\rm orb}} = \frac{\dot{M}_1}{M_1}\left(\frac{5}{6} - \frac{M_1}{M_2} + \frac{n}{2}\right)$$

$$\frac{\dot{J}_{\rm gw}}{J_{\rm orb}} = -\frac{32G^3}{5c^5}\frac{M_1M_2(M_1+M_2)}{a^4} \equiv -\frac{1}{\tau_{\rm gw}}$$

$$\dot{M}_1 = -\frac{M_1}{\tau_{\rm gw}}\left(\frac{1}{5/6 - M_1/M_2 + n/2}\right) \propto -\frac{M_1}{\tau_{\rm gw}}$$

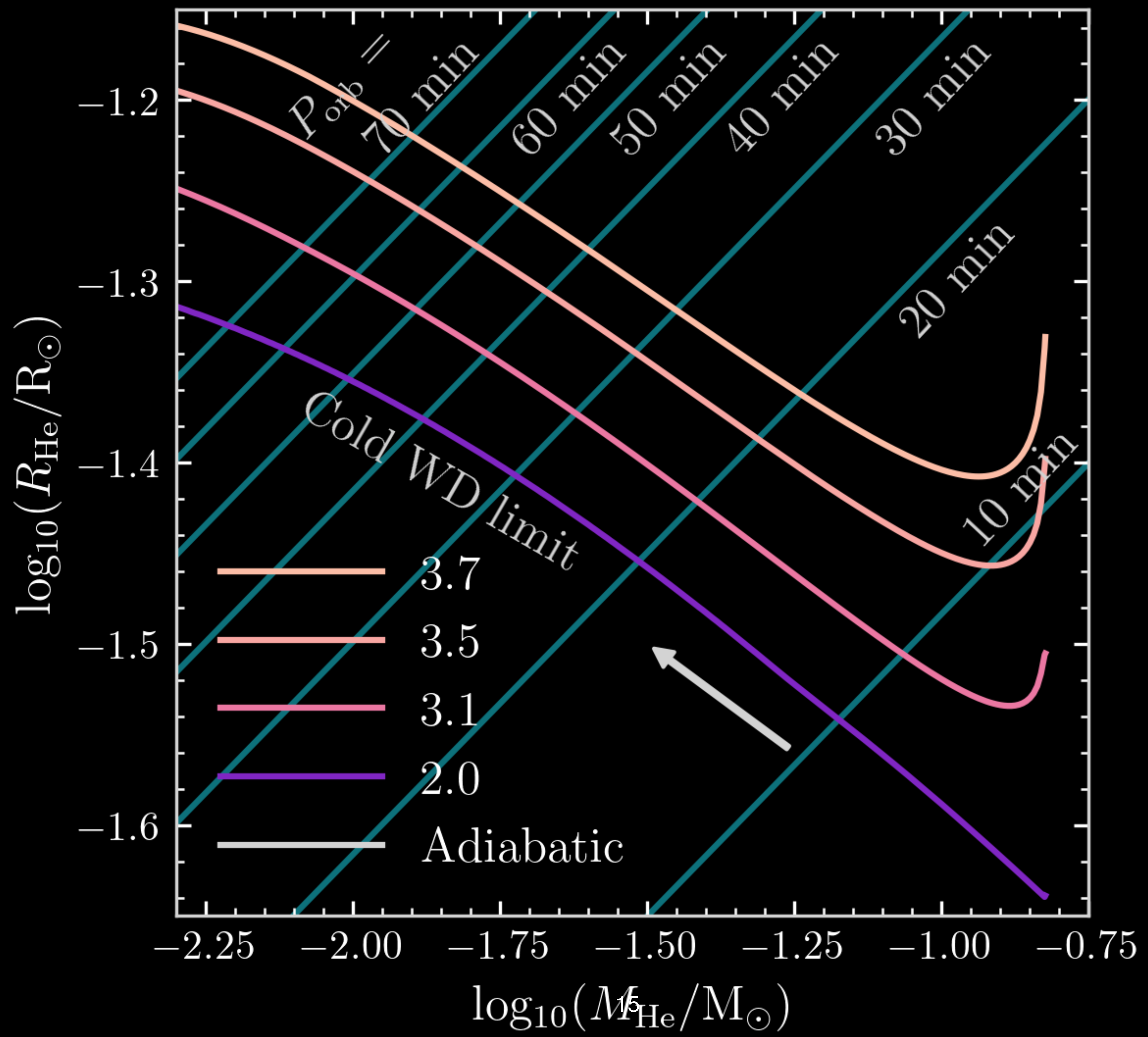
Mass-radius relation set by entropy/degeneracy



Modified from
Wong & Bildsten 2021

See also Deloye+ 2007

As donor loses mass, its radius expands and binary orbit widens

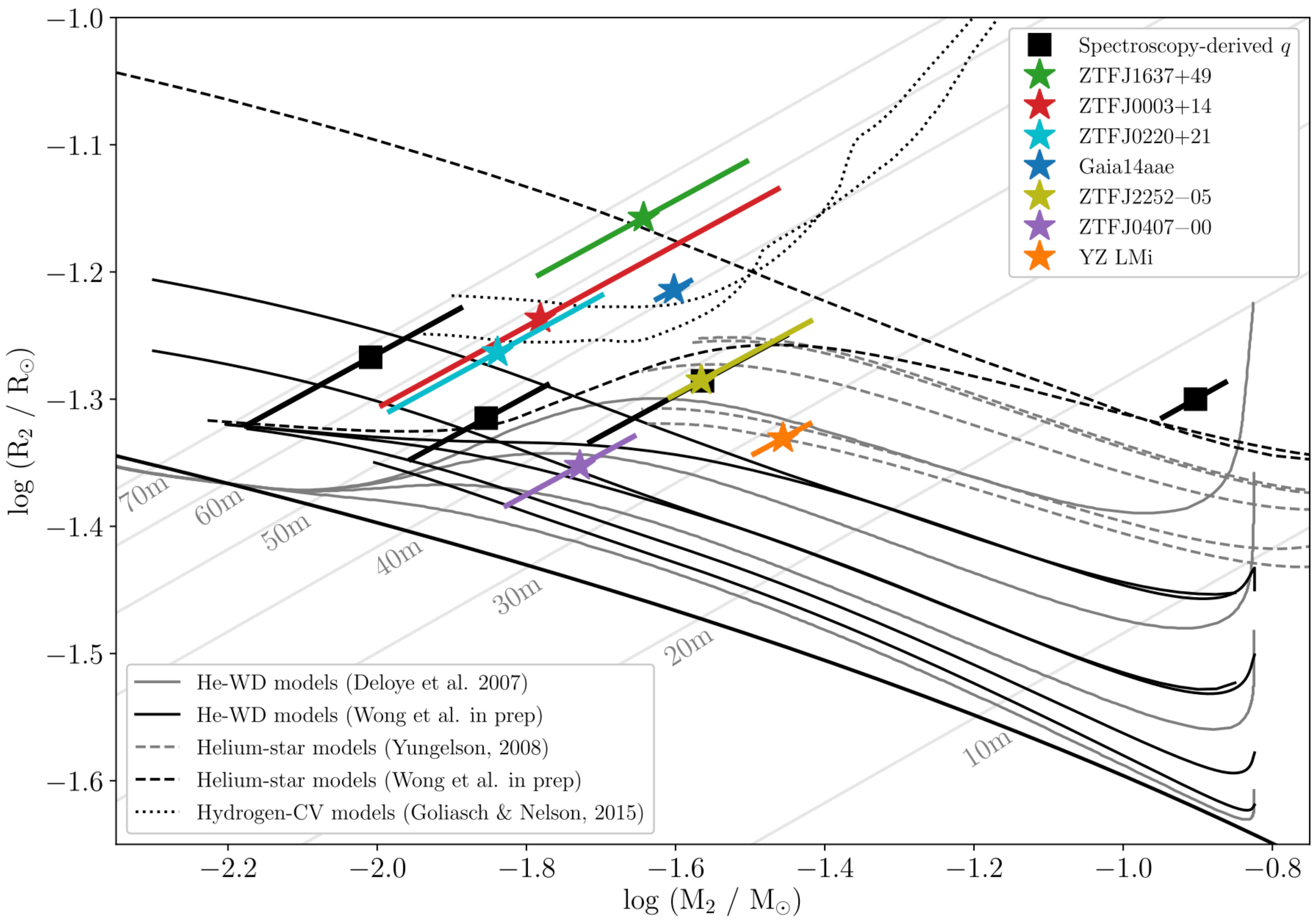


Hotter/
Higher entropy/
Less degenerate

Modified from
Wong & Bildsten 2021

See also Deloye+ 2007

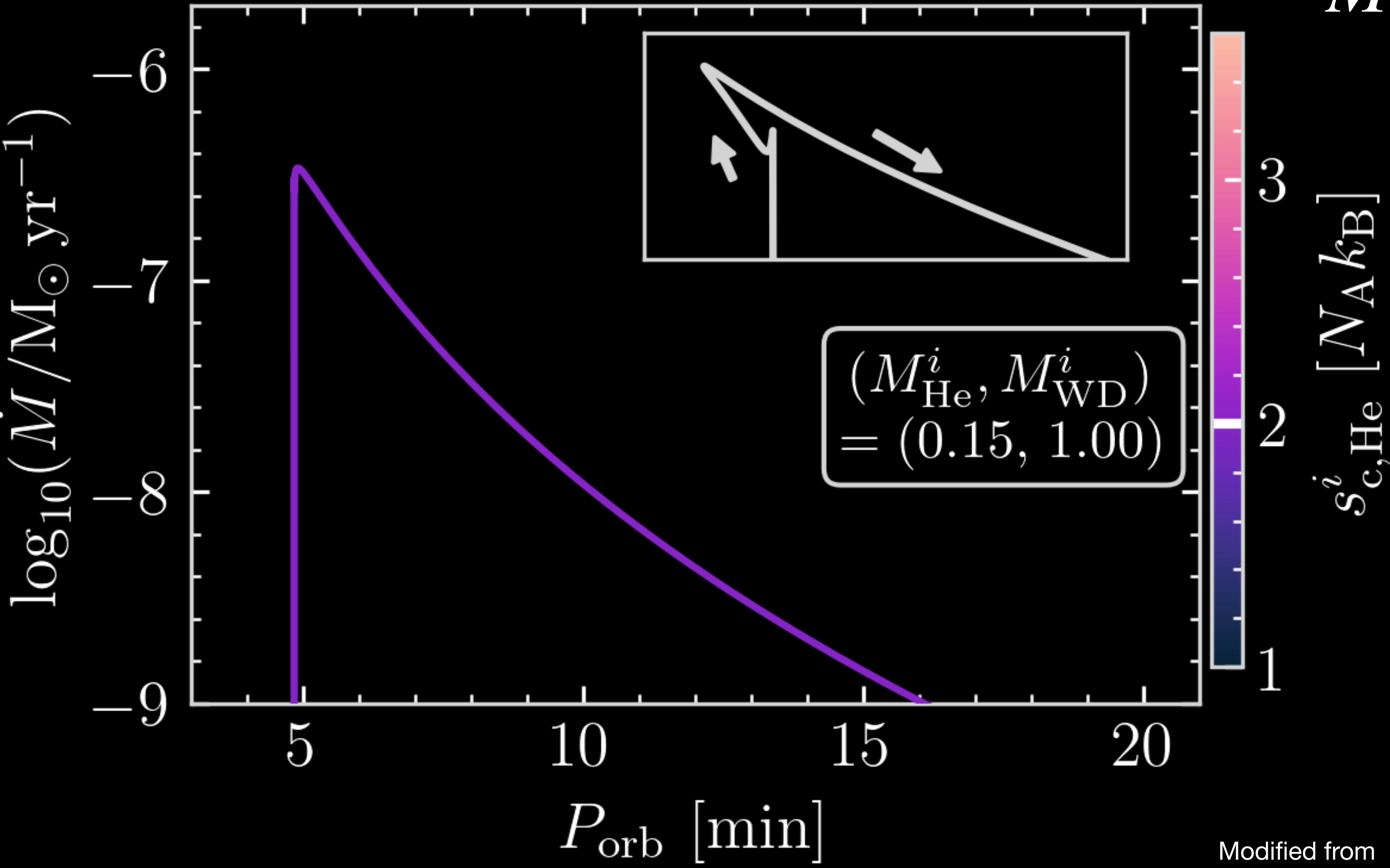
Most AM CVn donors are not fully degenerate



van Roestel+ 2022

Mass transfer with cold He WD

$$\dot{M} \sim \frac{M_{\mathrm{He}}}{\tau_{\mathrm{gr}}}$$

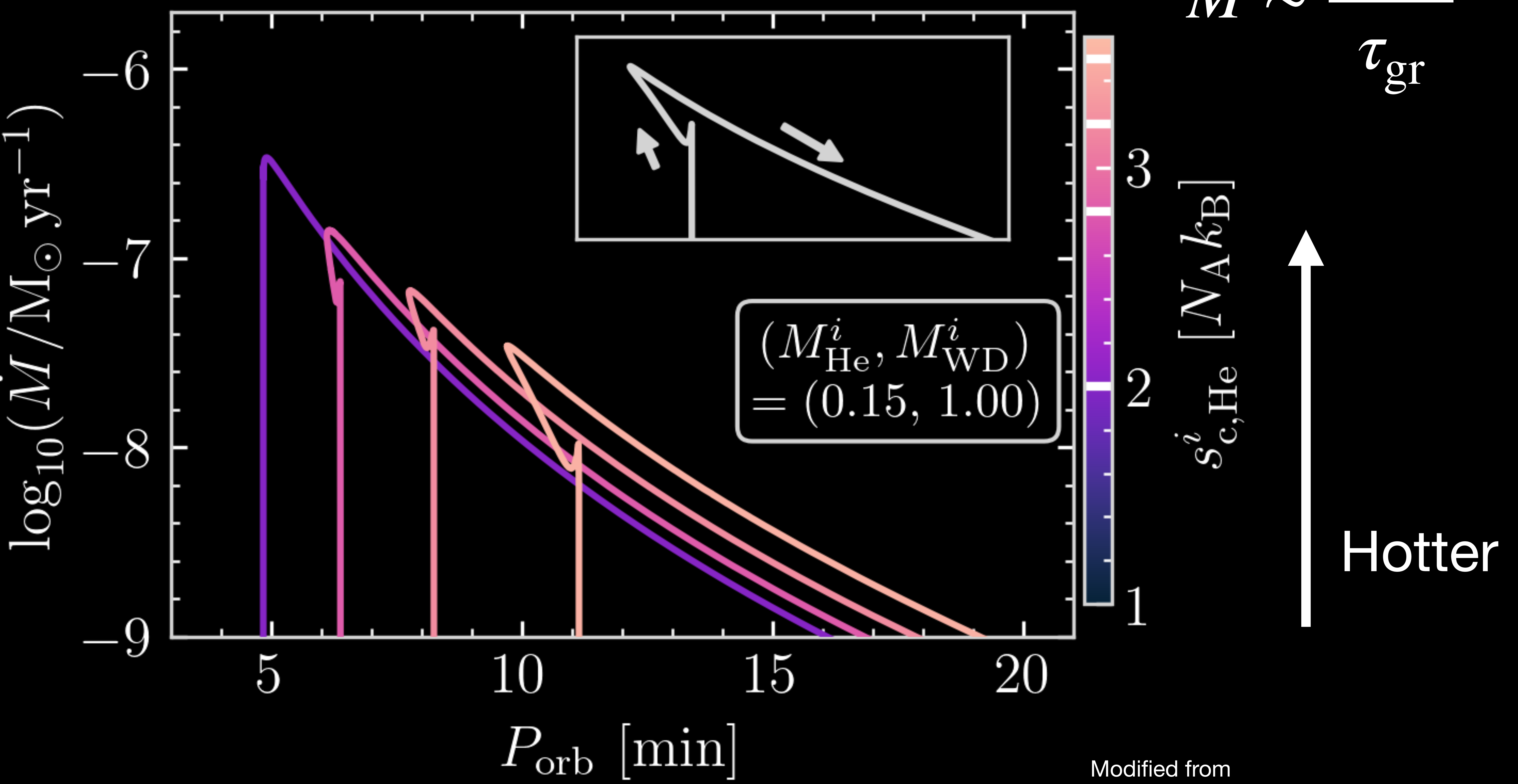


Hotter

Modified from
Wong & Bildsten 2023

Mass transfer with hot He WD

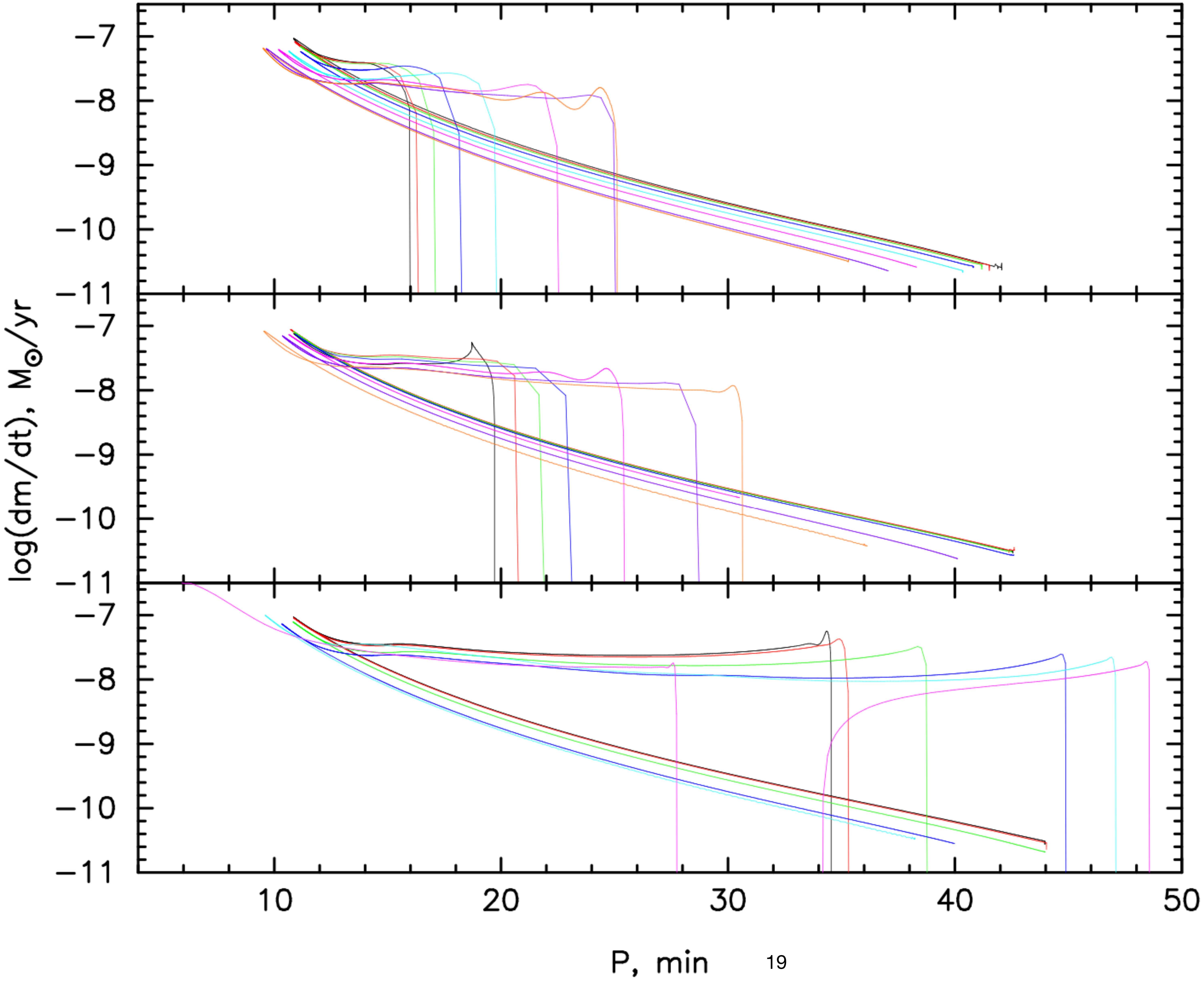
$$\dot{M} \sim \frac{M_{\rm He}}{\tau_{\rm gr}}$$



Modified from
Wong & Bildsten 2023

Mass transfer with He star

$$\dot{M} \sim \frac{M_{\rm He}}{\tau_{\rm gr}}$$

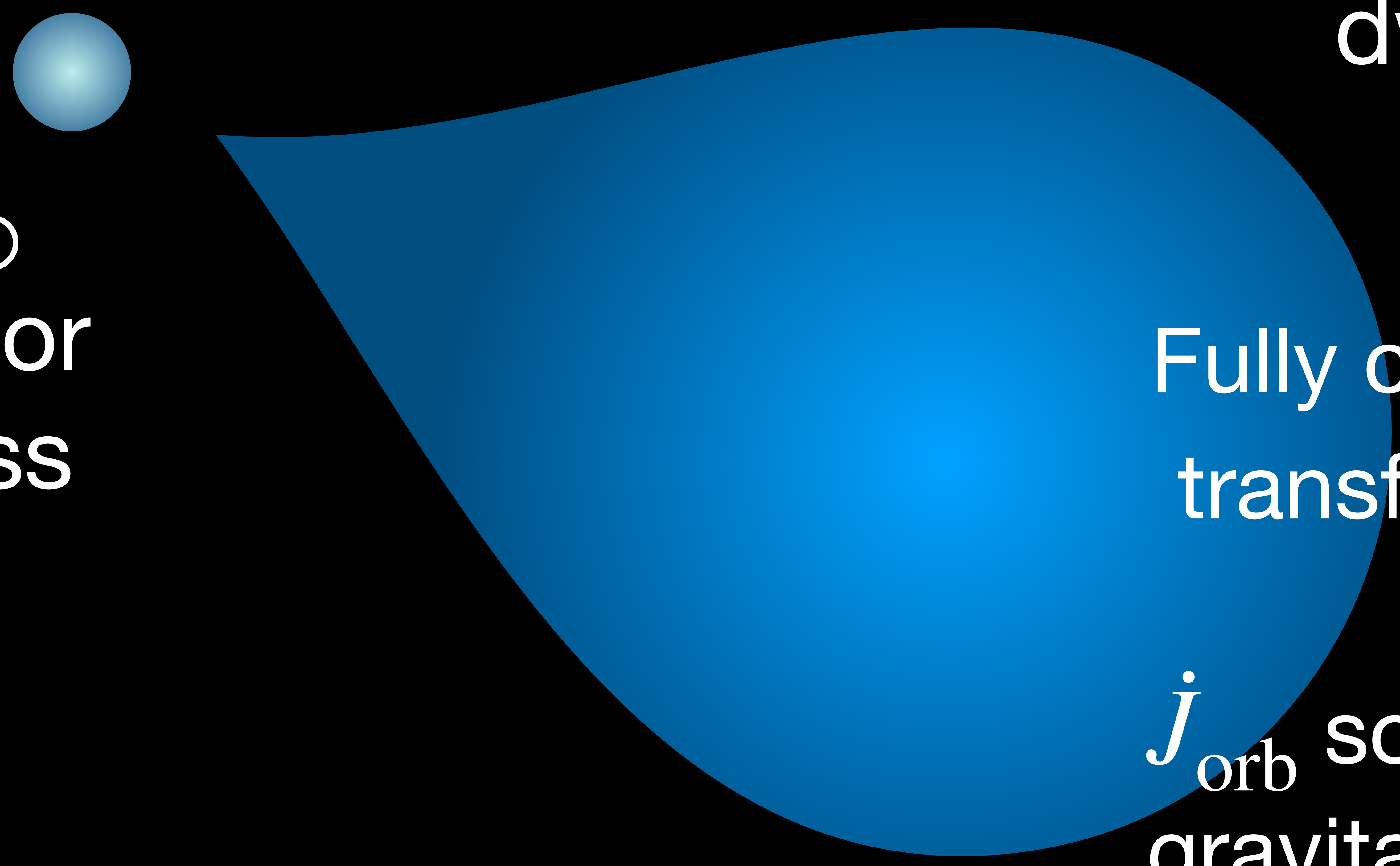


Yungelson 2008 (see also Brooks+ 2015, Sarkar+ 2023)

Binary evolution with MESA

Star 1: helium white dwarf / helium star donor

Star 2: $\gtrsim 0.8\,M_\odot$ white dwarf accretor (treat as point mass here)



Fully conservative mass transfer (i.e., $\dot{M}_{\rm tot} = 0$)

$\dot{J}_{\rm orb}$ solely due to gravitational wave

Keep your history files, needed for Lab 3!

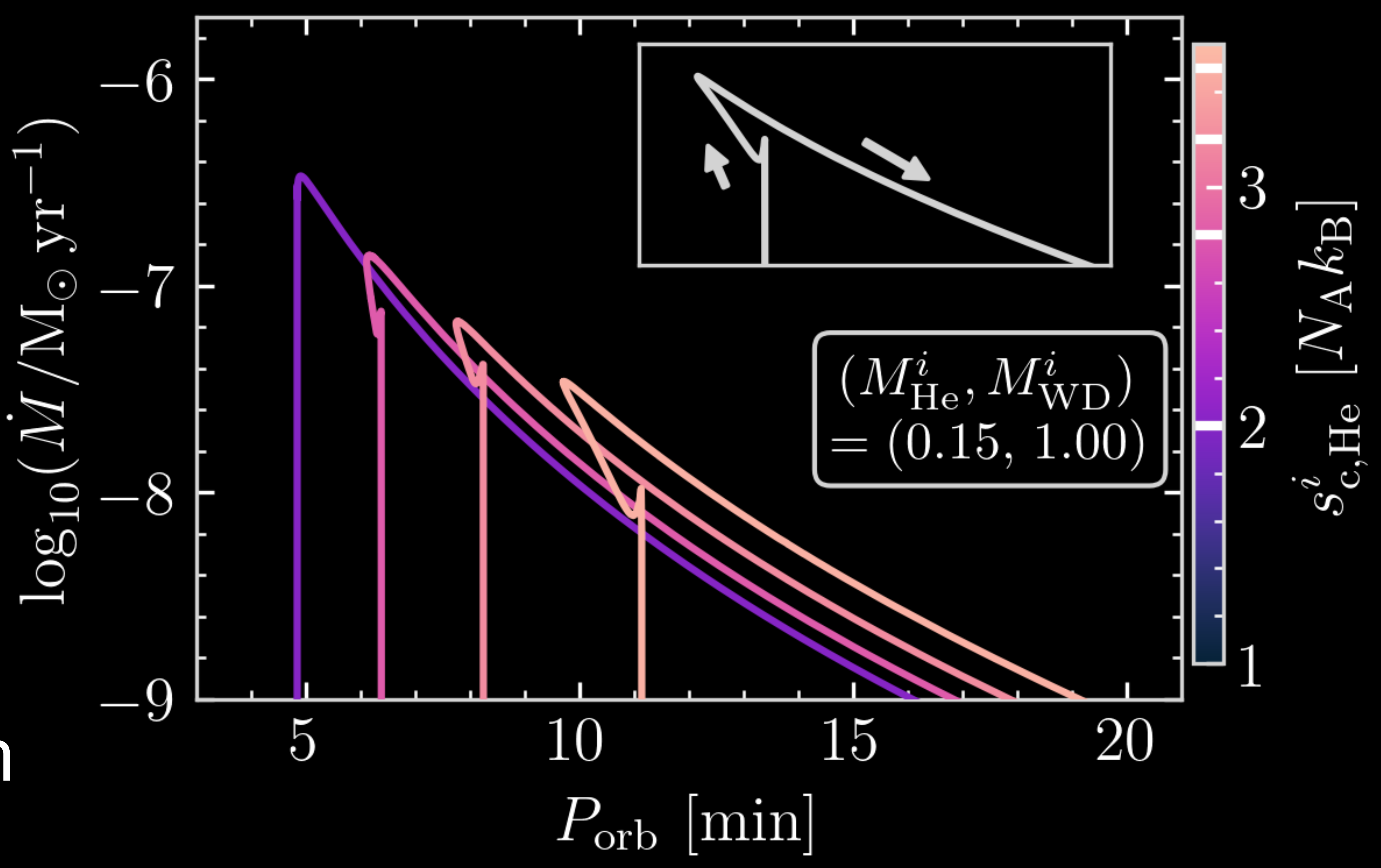
$$\dot{M} \sim \frac{M_{\rm He}}{\tau_{\rm gr}}$$

A semi-degenerate donor star expands as it loses mass

Orbit expands and $\dot{M}$ drops

A higher entropy (less degenerate) donor fills its Roche lobe at longer orbital periods. Peak $\dot{M}$ is lower

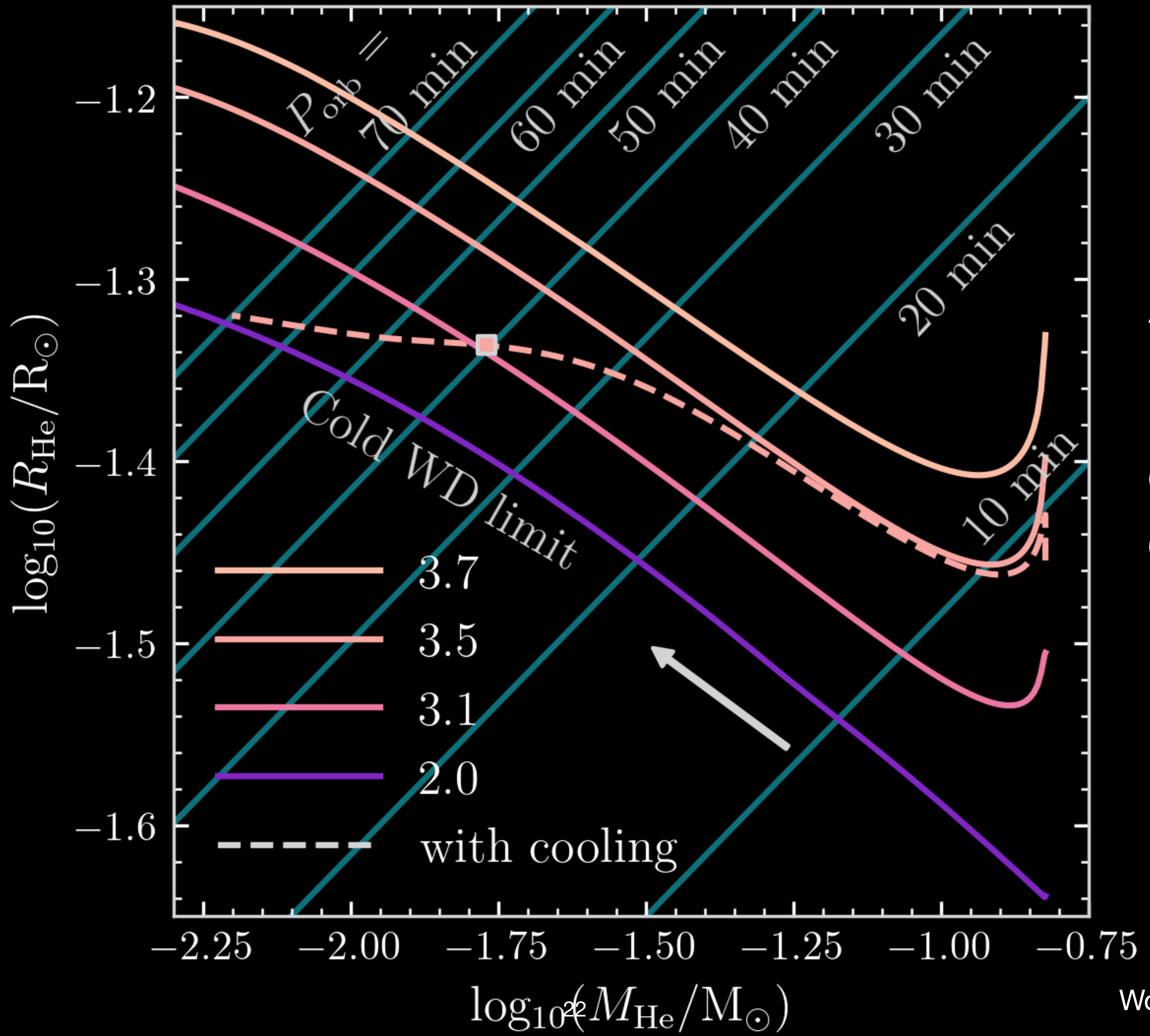
He star donor ceases burning when its mass $\lesssim 0.32\,M_\odot$



Hot / high-entropy WDs initially evolve adiabatically, but can eventually lose entropy and shrink

$$\tau_{\dot{M}} = \frac{M_{\rm He}}{\dot{M}}$$

$$\tau_{\rm th} = \frac{\int c_{\rm p} T dm}{L_{\rm He}}$$



Caveat: no reliable radiative opacity for warm dense He with metals

Modified from Wong & Bildsten 2021

Roadmap

General question: what happens when a helium white dwarf donates mass to a carbon-oxygen white dwarf?

Minilab 1: response of donor and orbit to mass transfer

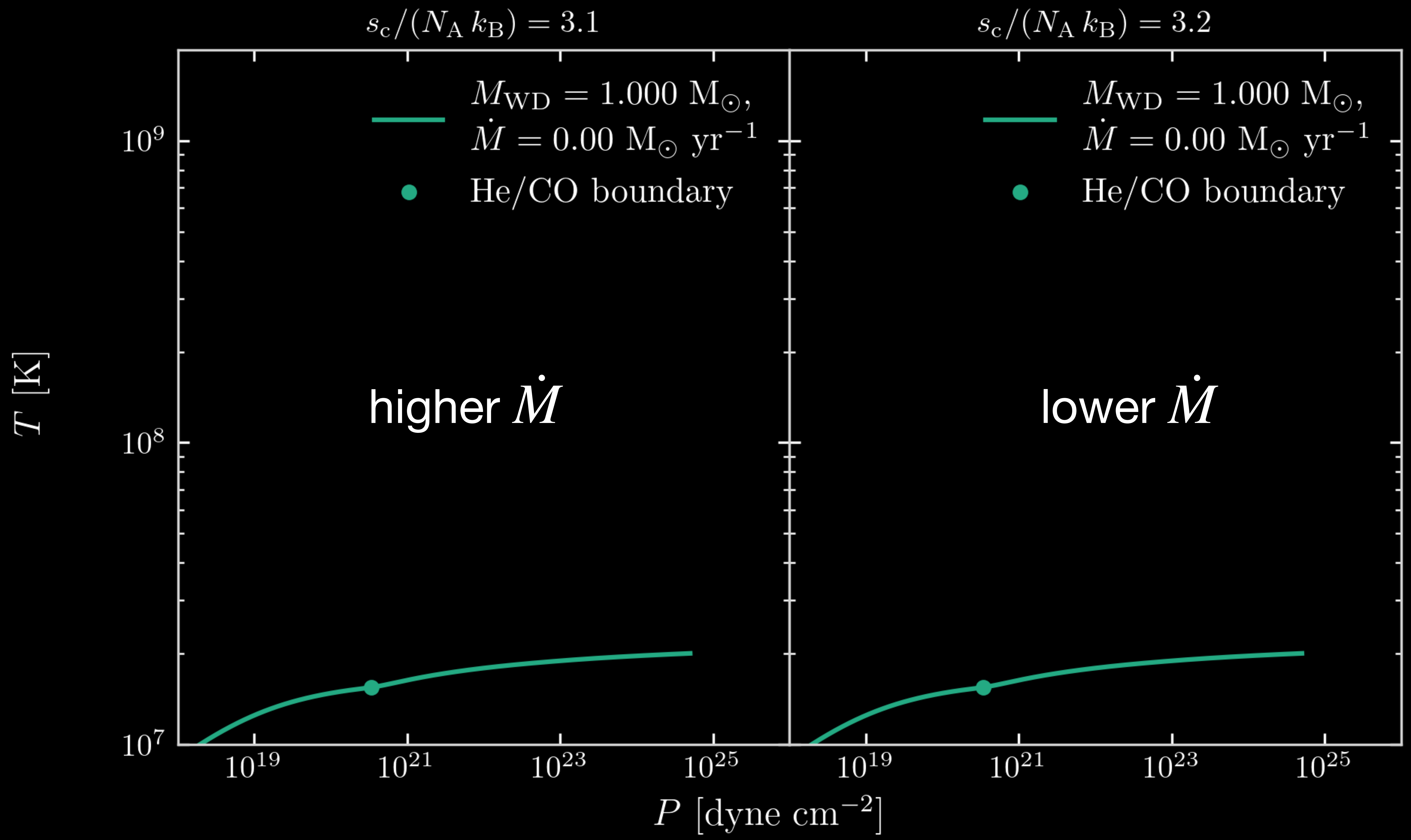
Minilab 2: response of accretor to accretion

(Part 1: constant accretion rate)

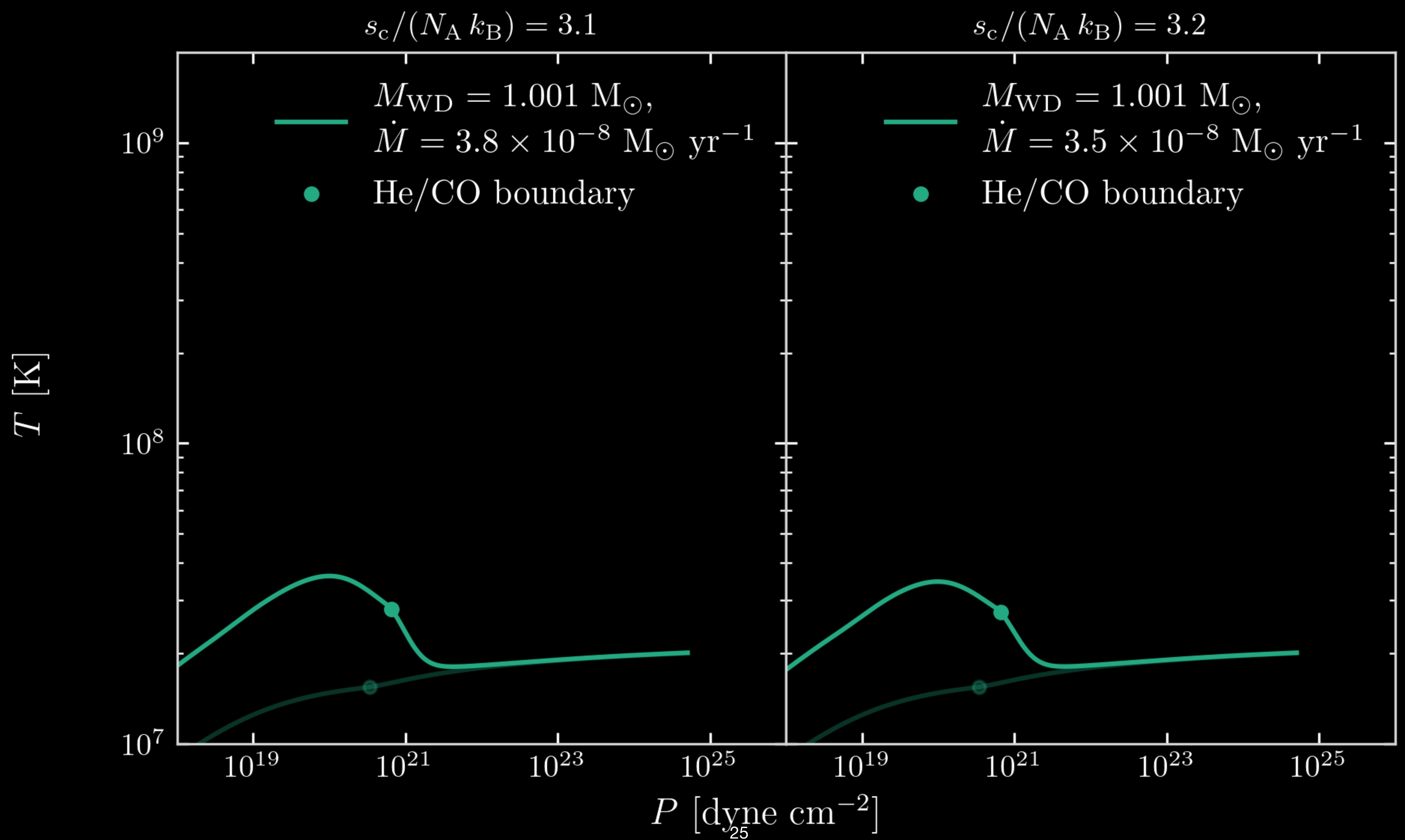
Minilab 3: response of accretor to accretion

(Part 2: realistic binary history)

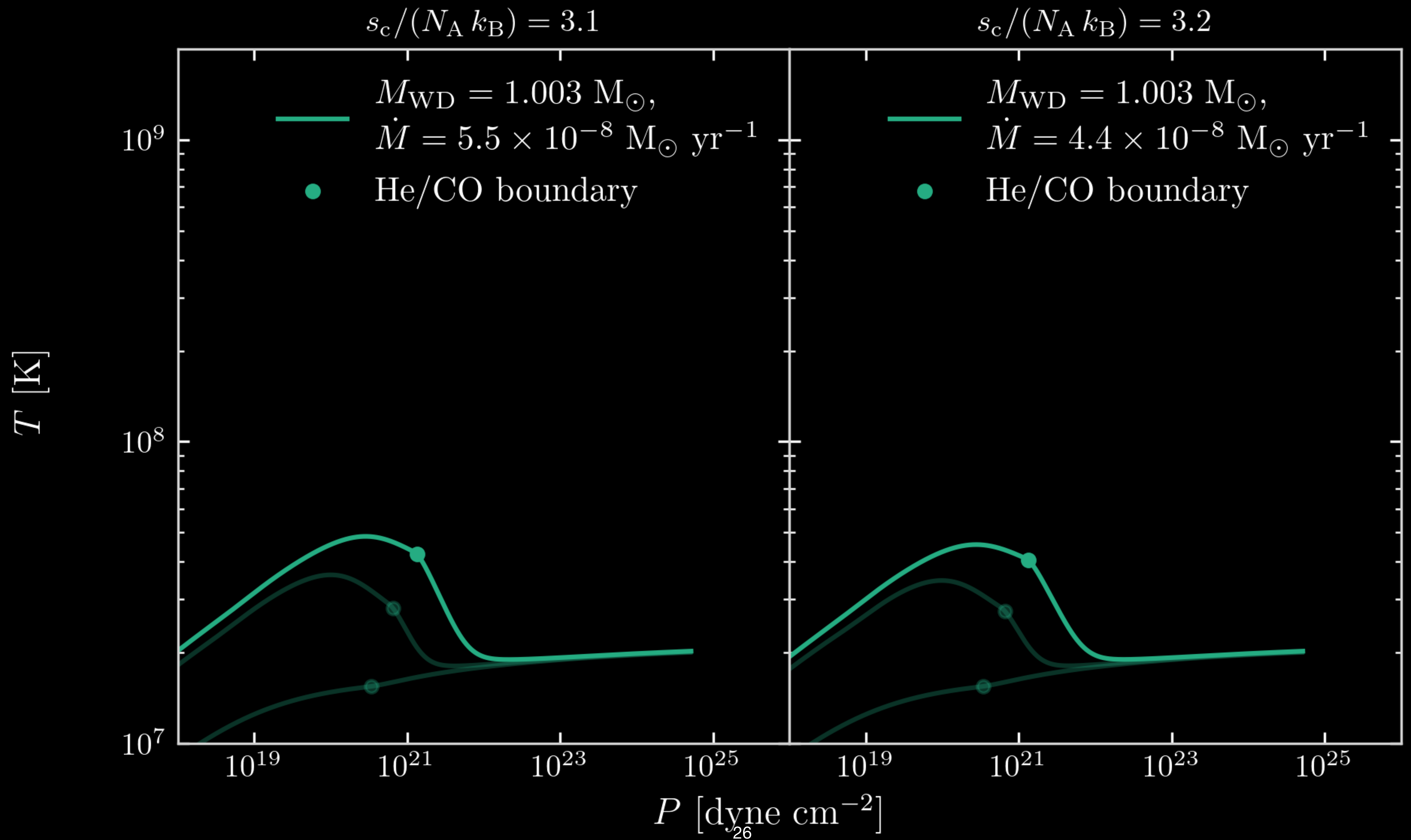
Compression heats up He envelope



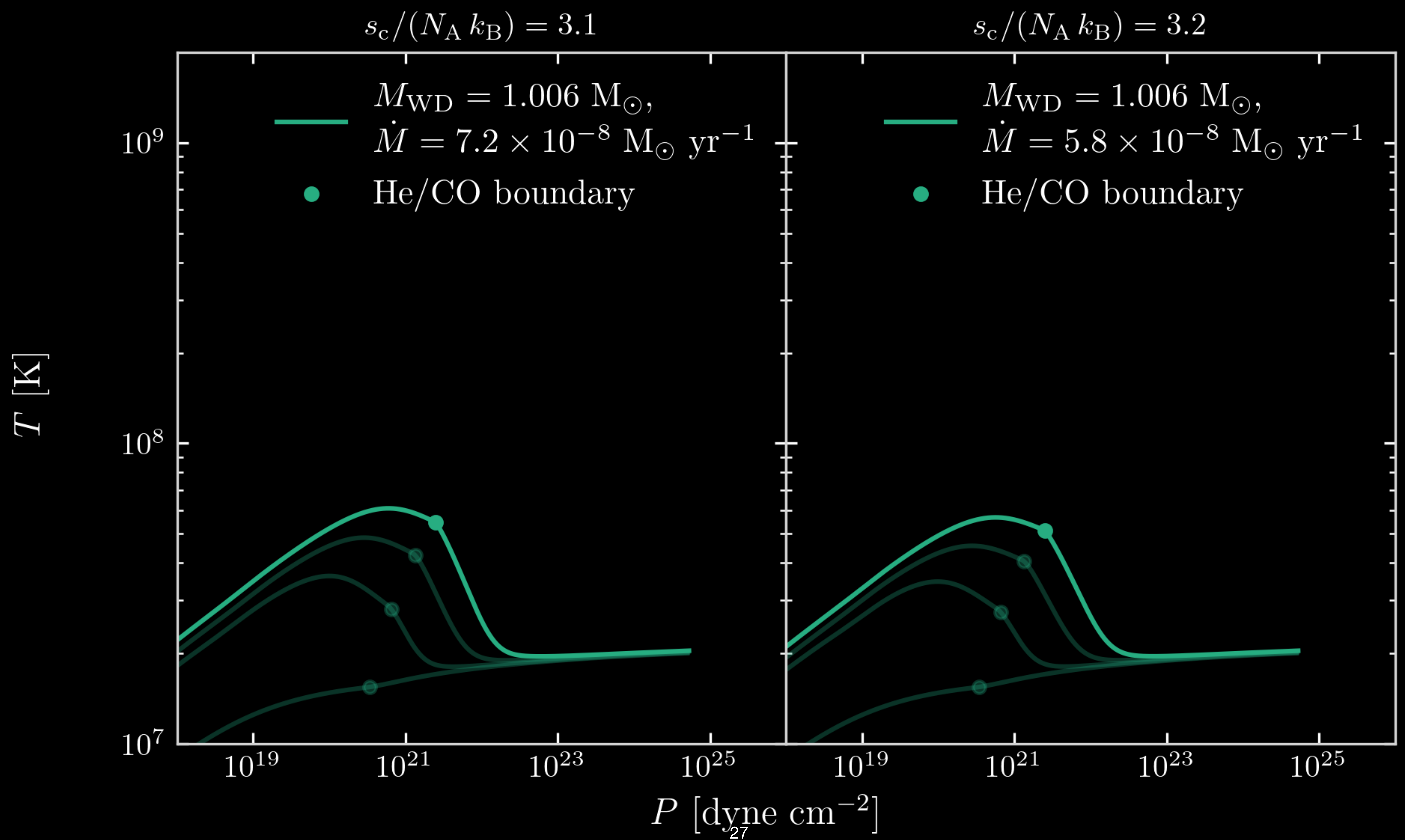
Rapid accretion heats up He envelope



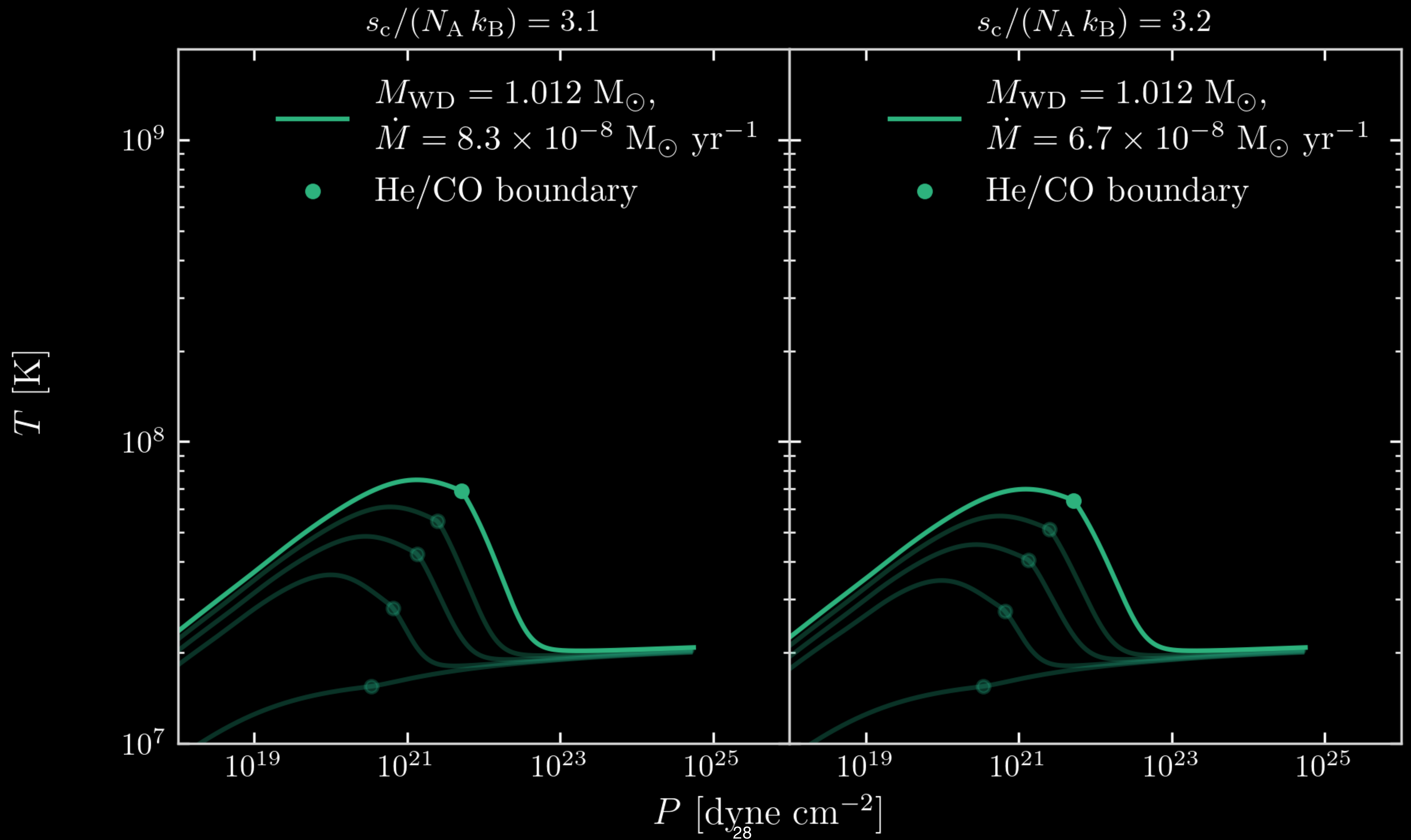
Rapid accretion heats up He envelope



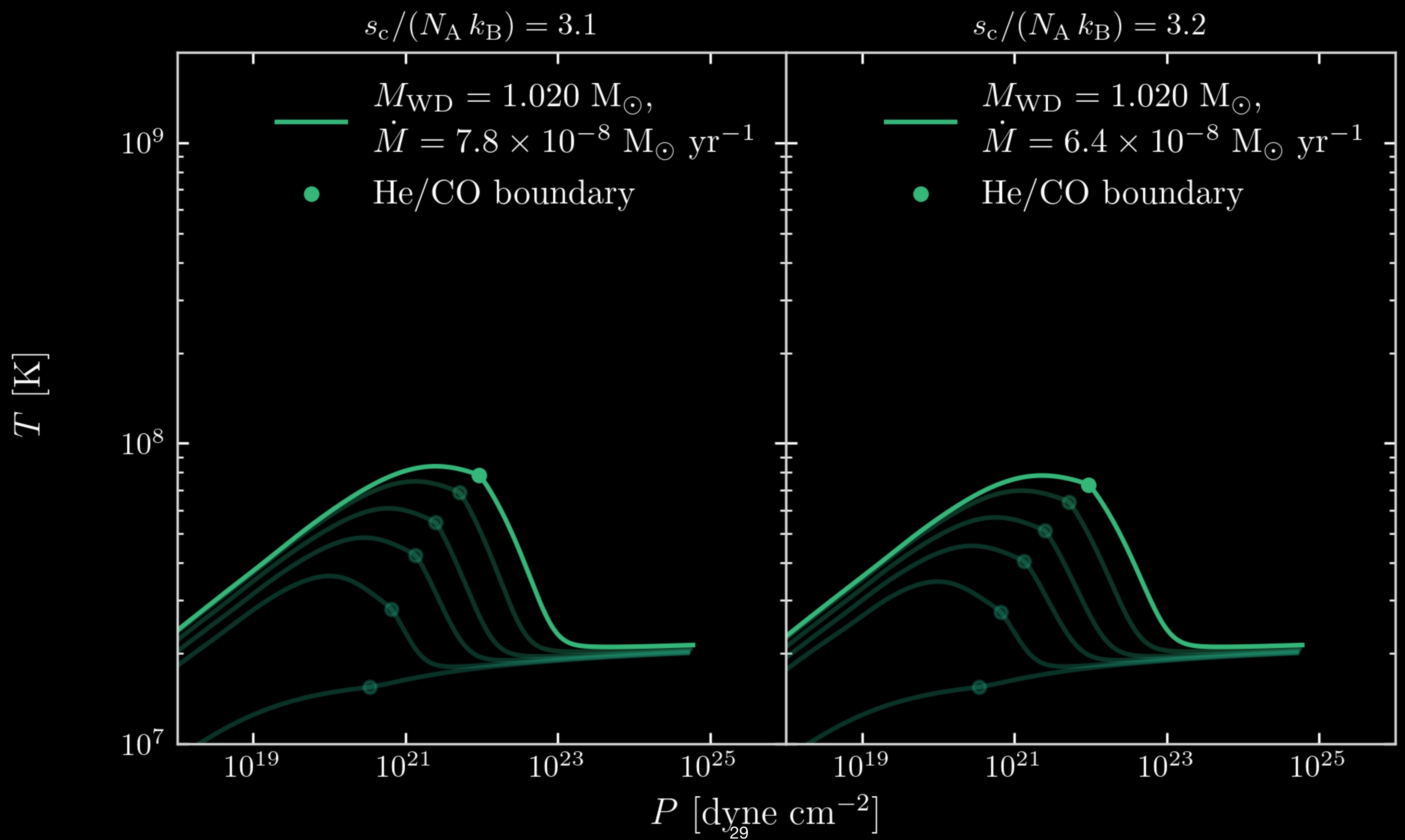
Rapid accretion heats up He envelope



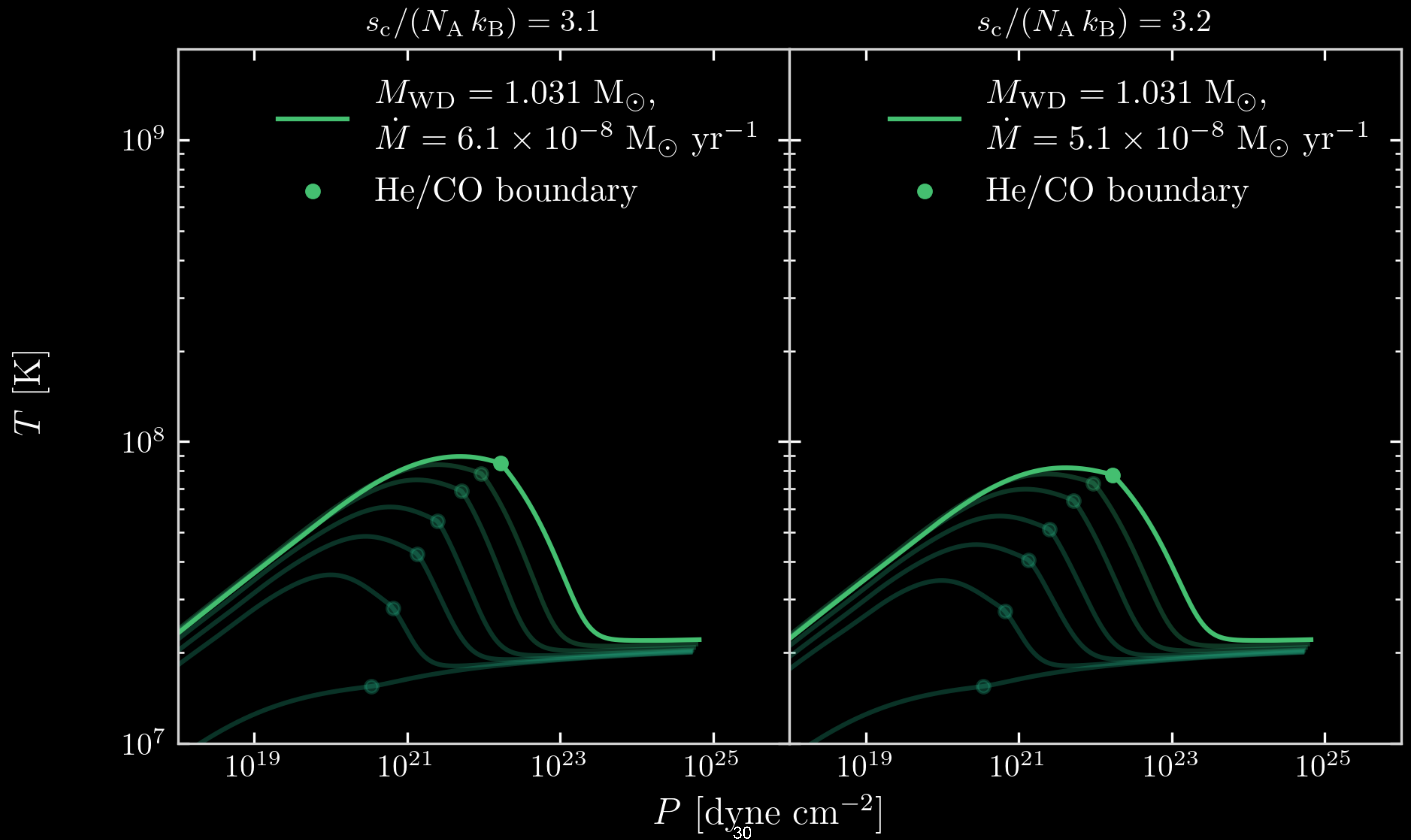
Rapid accretion heats up He envelope



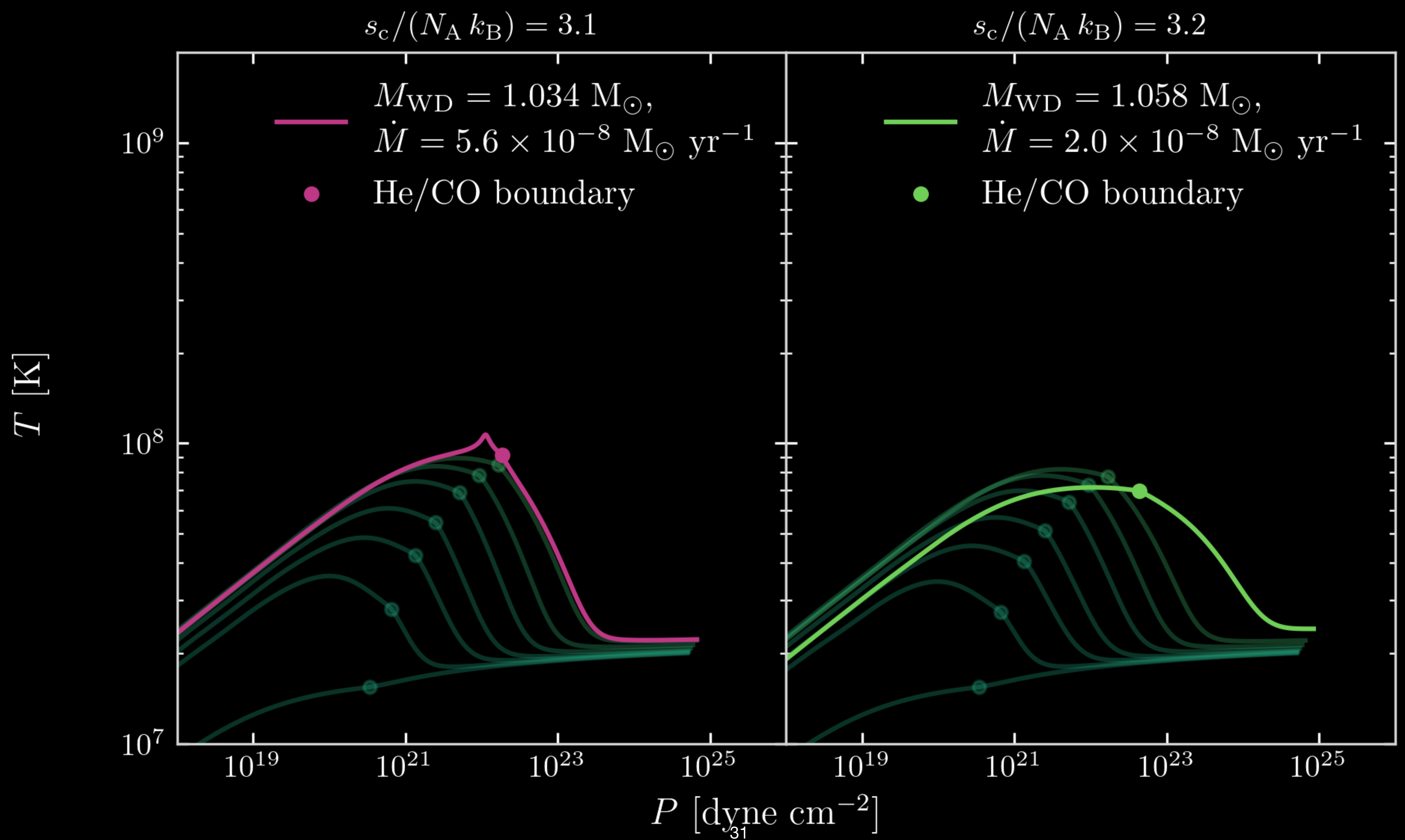
Rapid accretion heats up He envelope



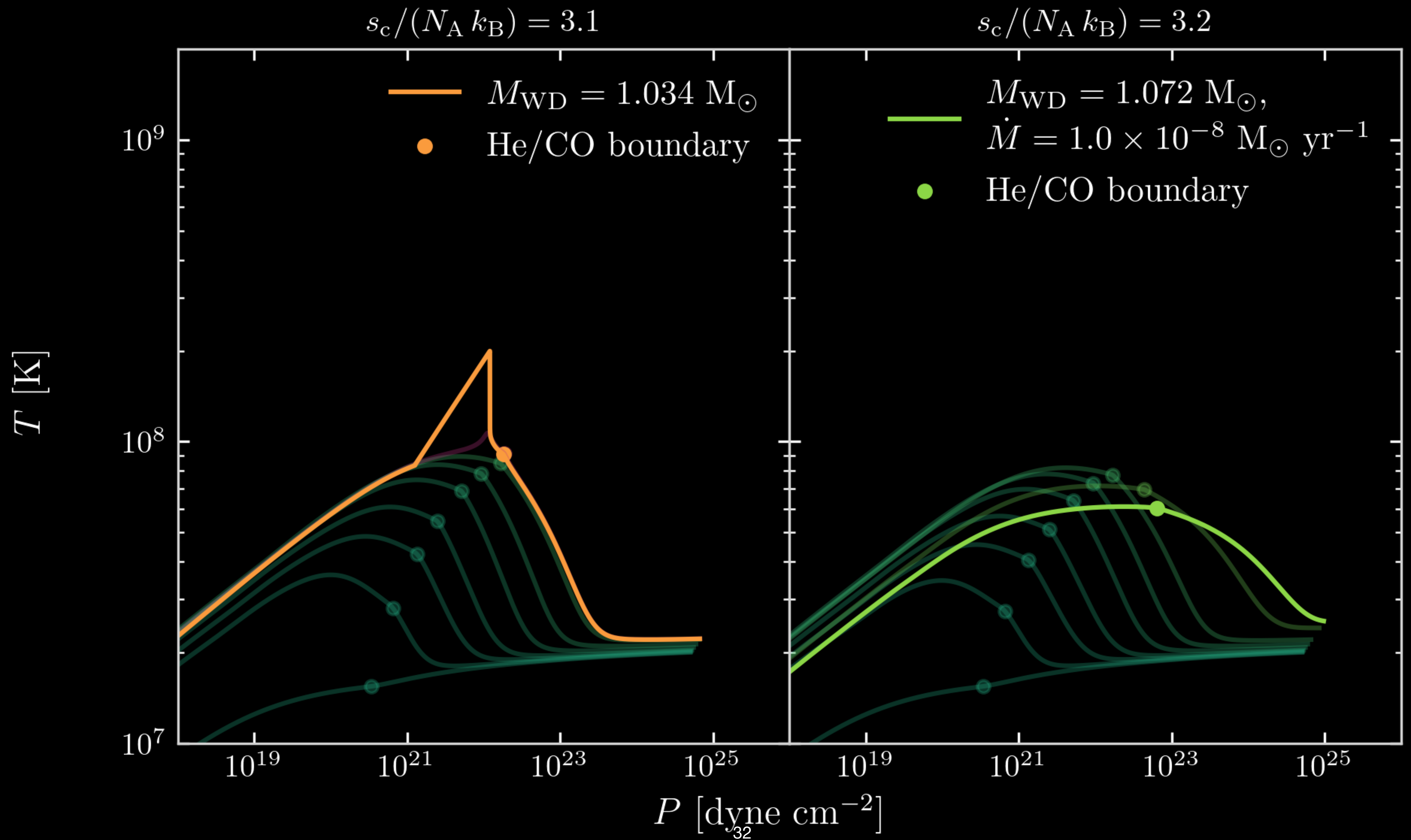
Rapid accretion heats up He envelope



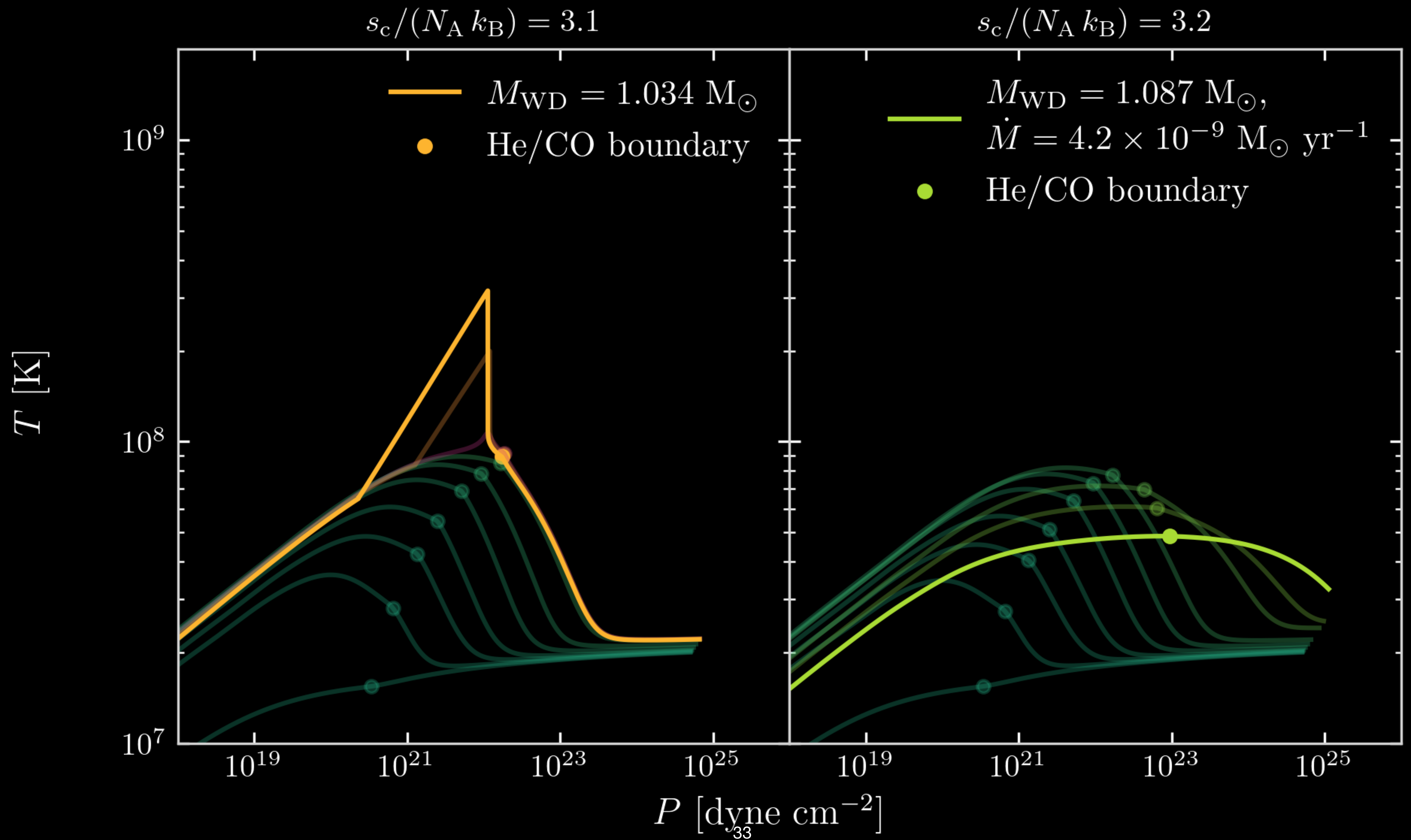
Rapid accretion heats up He envelope



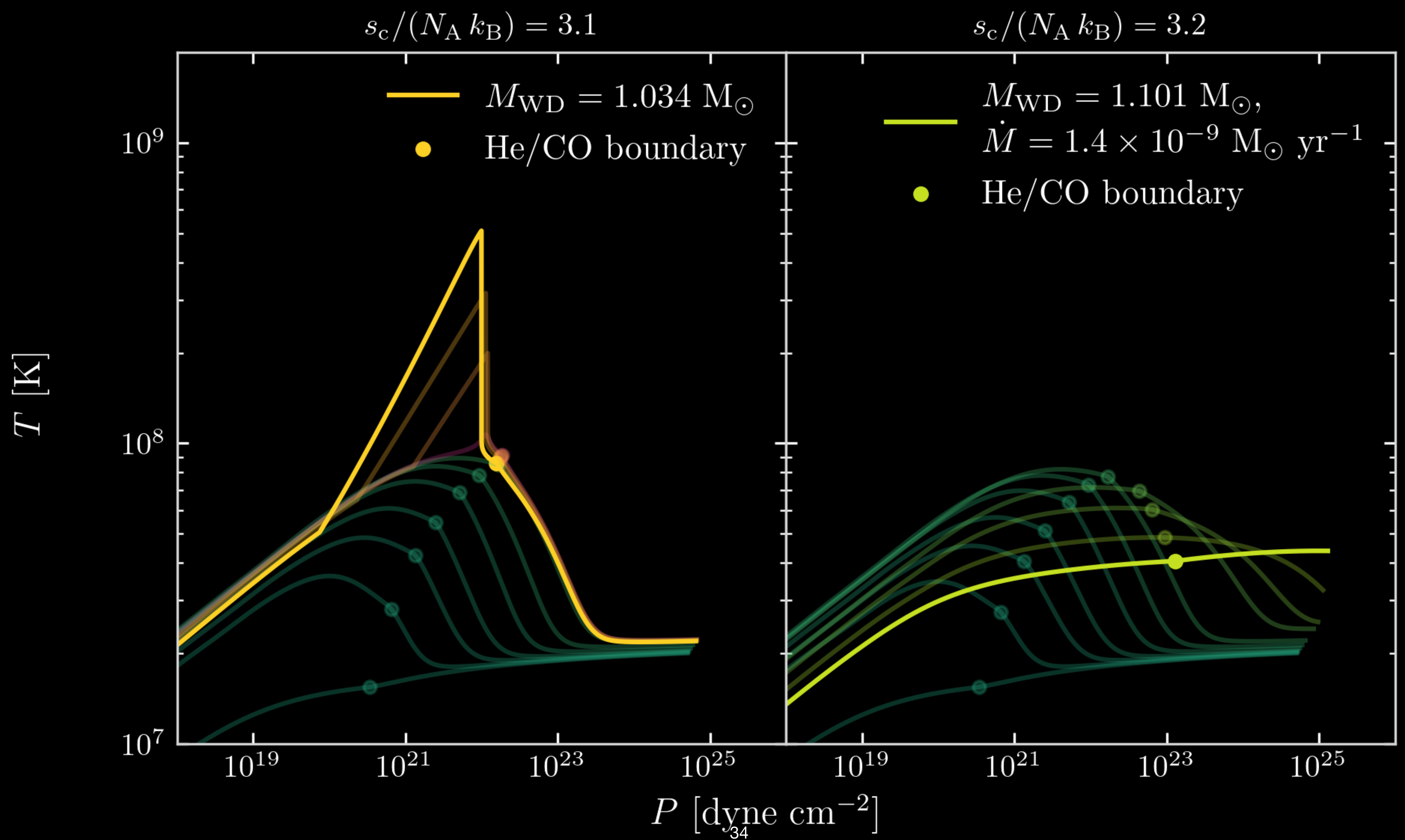
Rapid accretion heats up He envelope



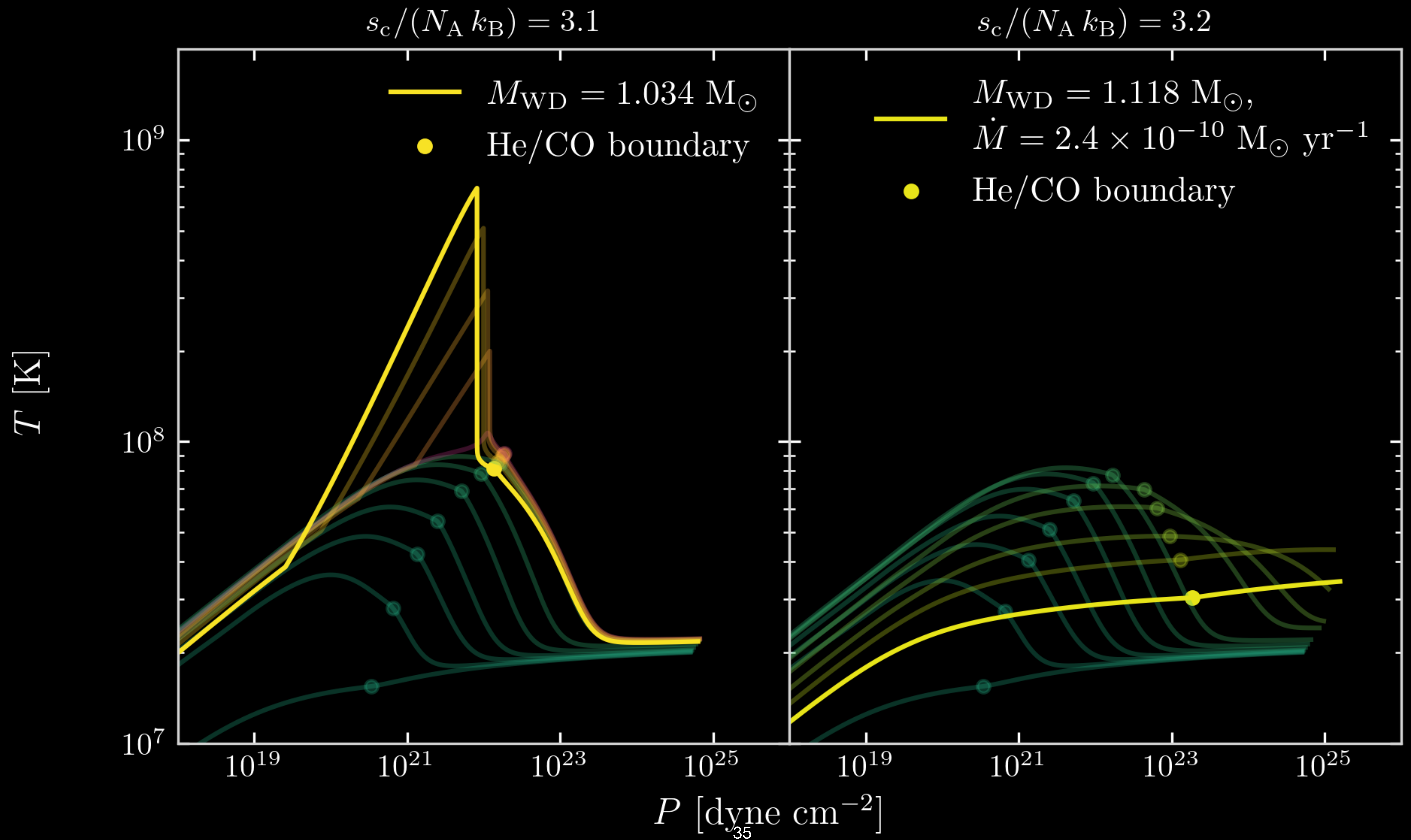
Rapid accretion heats up He envelope



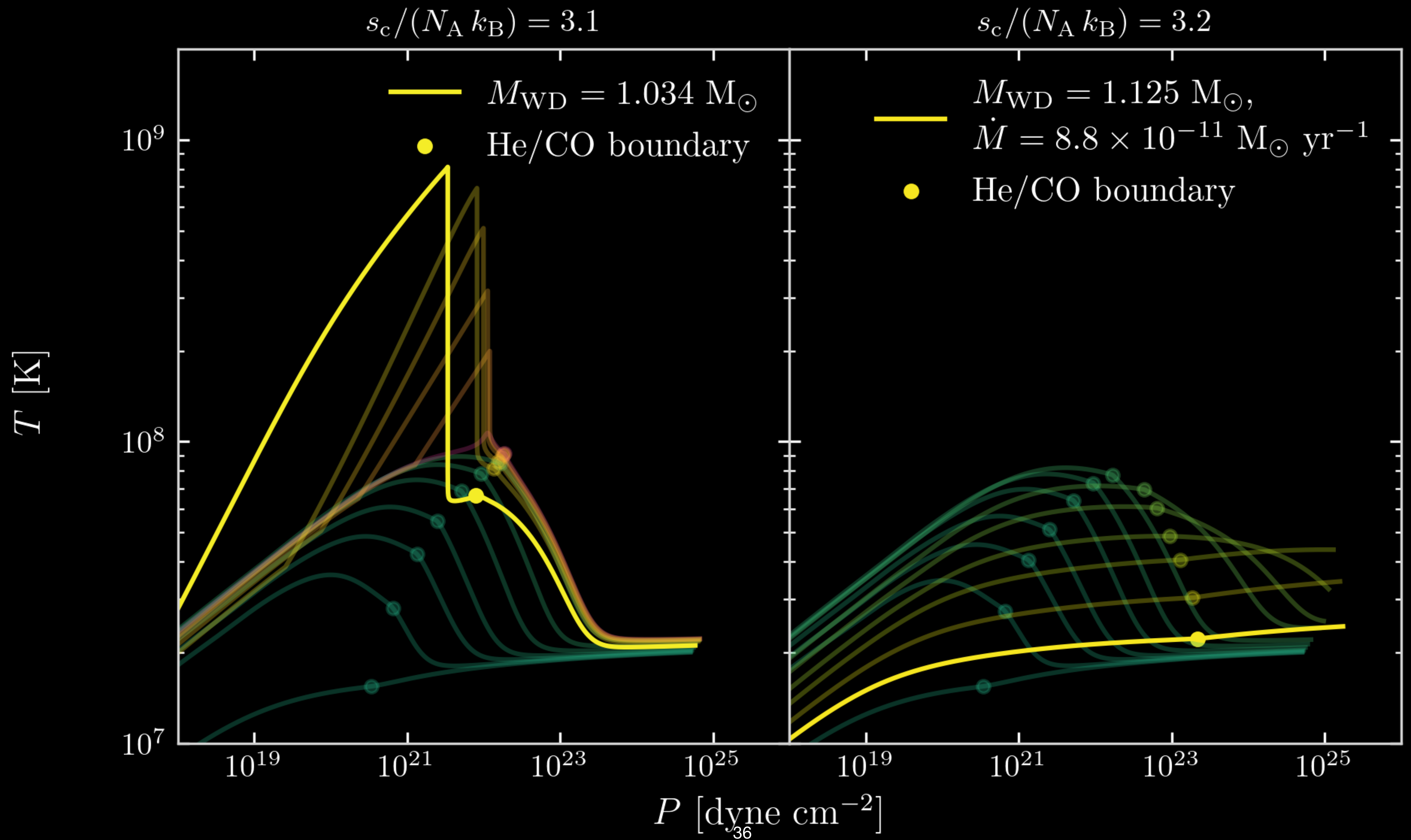
Rapid accretion heats up He envelope



Rapid accretion heats up He envelope



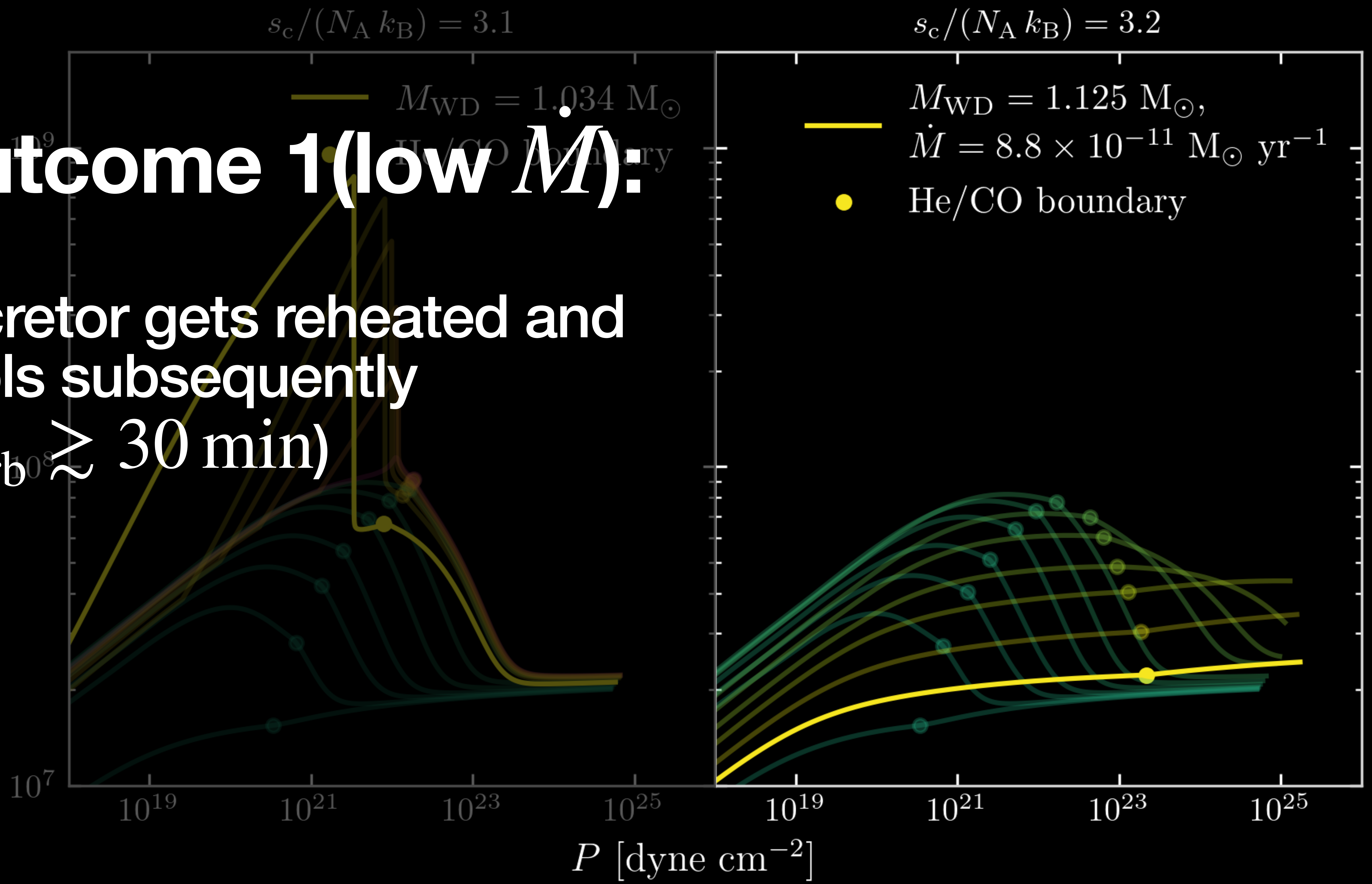
Rapid accretion heats up He envelope



Outcome 1 (low $\dot{M}$):

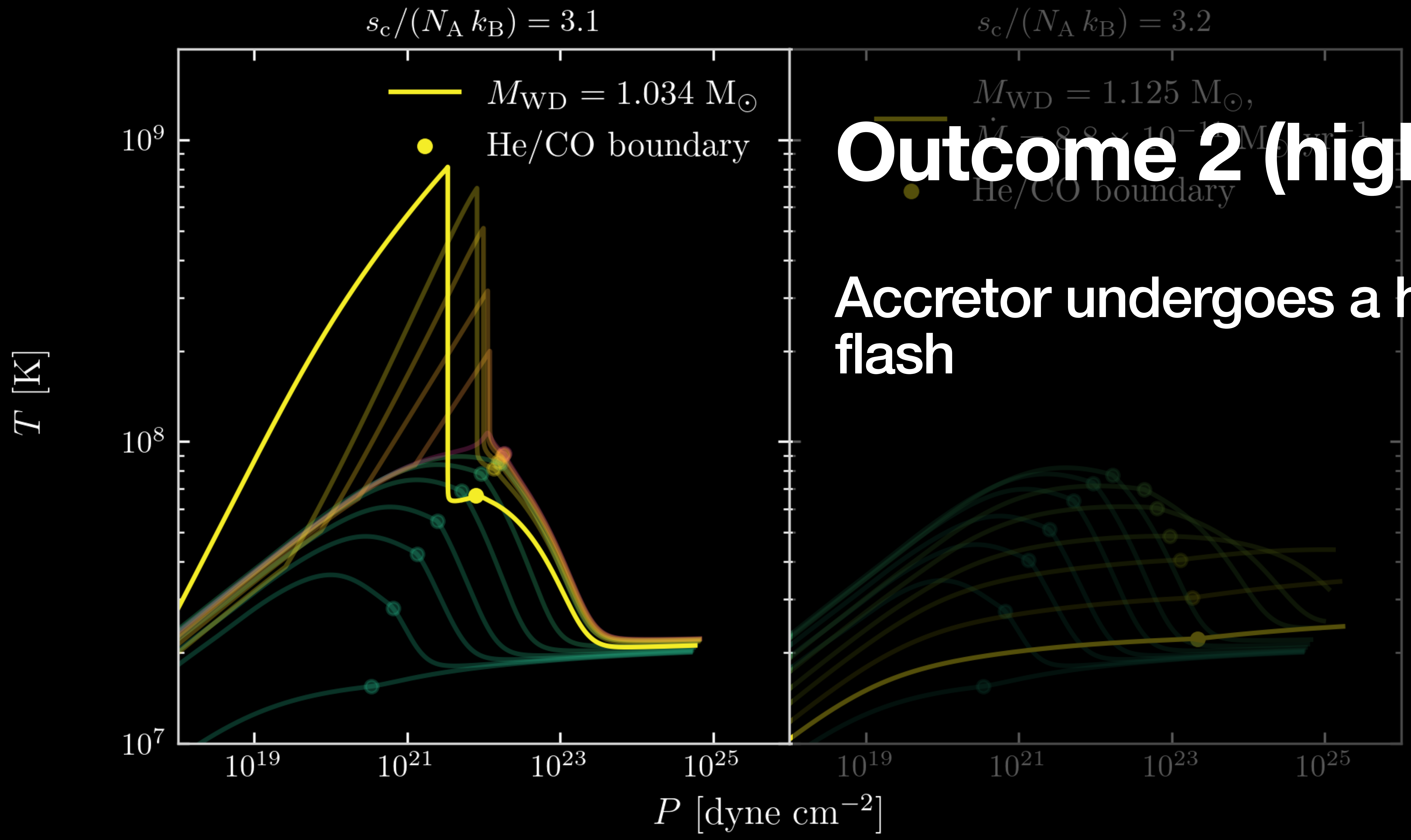
Accretor gets reheated and cools subsequently

($P_{orb} \gtrsim 30$ min)

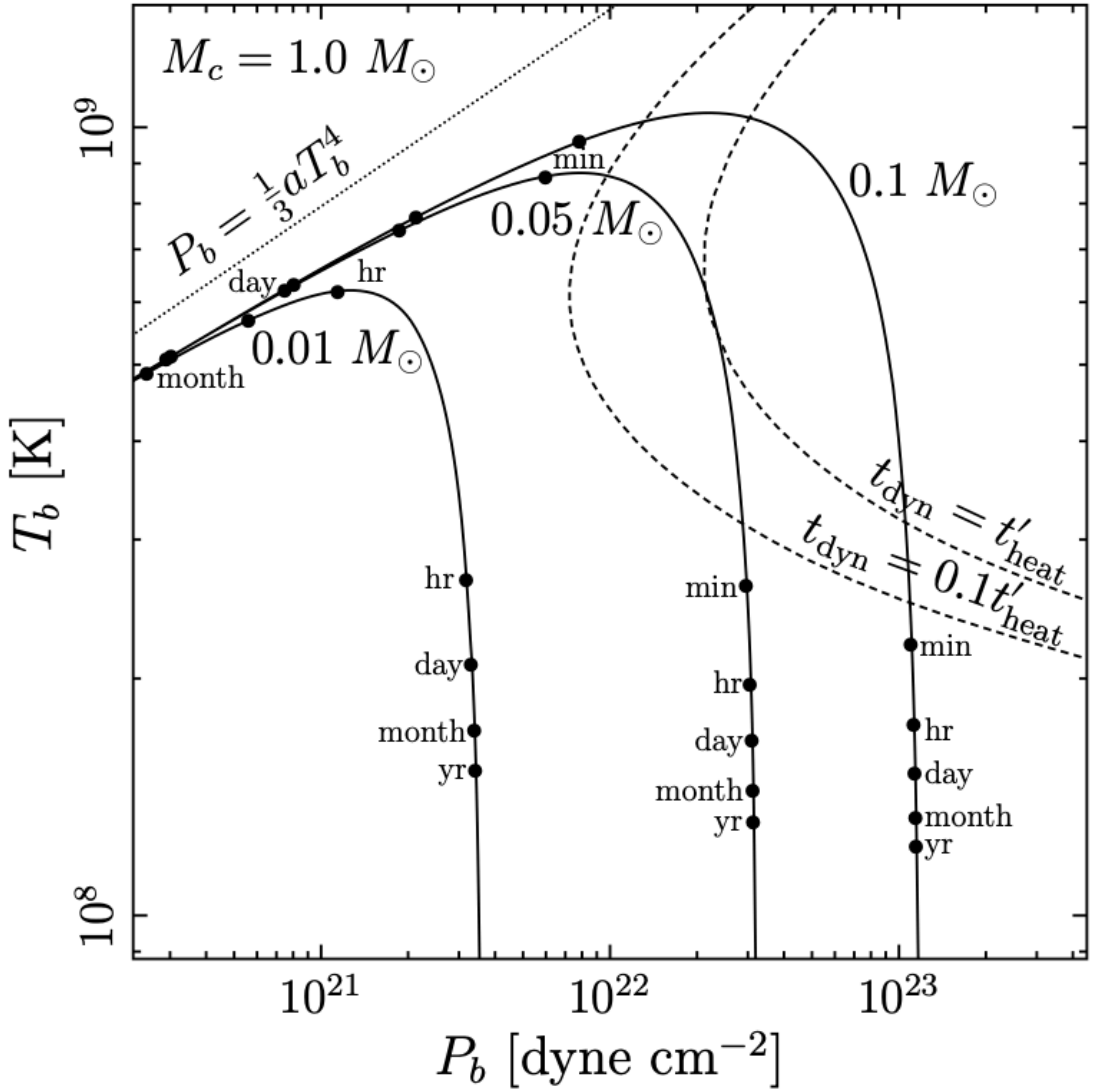


Outcome 2 (high $\dot{M}$):

Accretor undergoes a helium flash



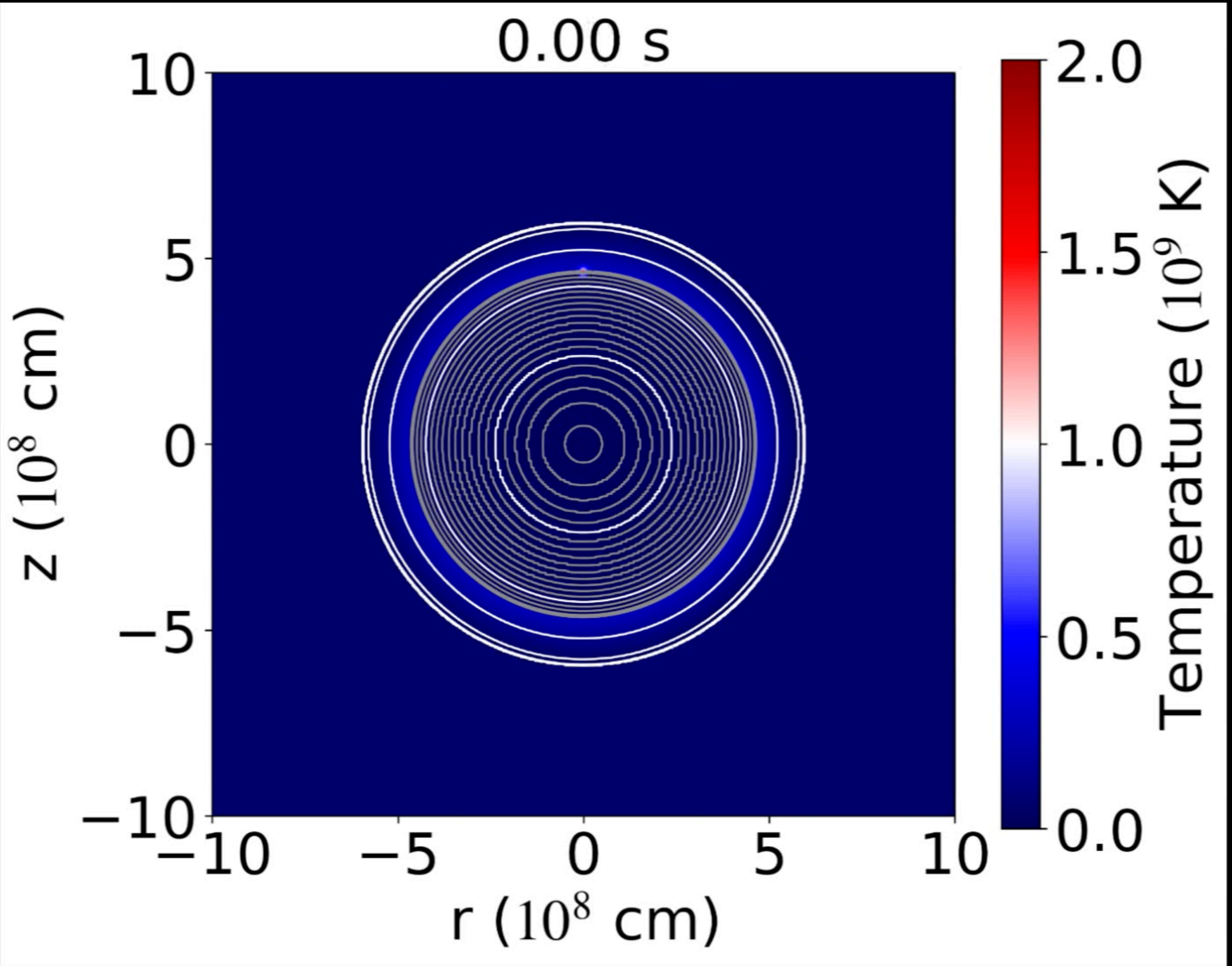
Condition for dynamical He flash



$$t_{\rm dyn} \sim \frac{H}{c_{\rm s}} \gtrsim t_{\rm heat} \sim \frac{c_{\rm p}T}{\epsilon_{\rm nuc}}$$

Shen & Bildsten 2009

Surface Helium detonation sends a shock wave into the Carbon core, causing detonation of Carbon



Simulation by Sam Boos
See Boos+ 2021

Strength of helium flash set by helium shell mass

Helium shell mass set by accretion rate

NCO reaction chain

The following electron capture reaction happens for $\rho \gtrsim 1.25 \times 10^6\,\mathrm{g\,cm^{-3}}$:

$$^{14}\mathrm{N} + e^- \rightarrow {}^{14}\mathrm{C} + \nu_e$$

And recall that during core H burning, the CNO chain mostly yields $^{14}\mathrm{N}$

Bauer+ 2017

NCO reaction chain

The freshly produced $^{14}\mathrm{C}$ undergoes α-capture:

$$^{14}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{18}\mathrm{O} + \gamma$$

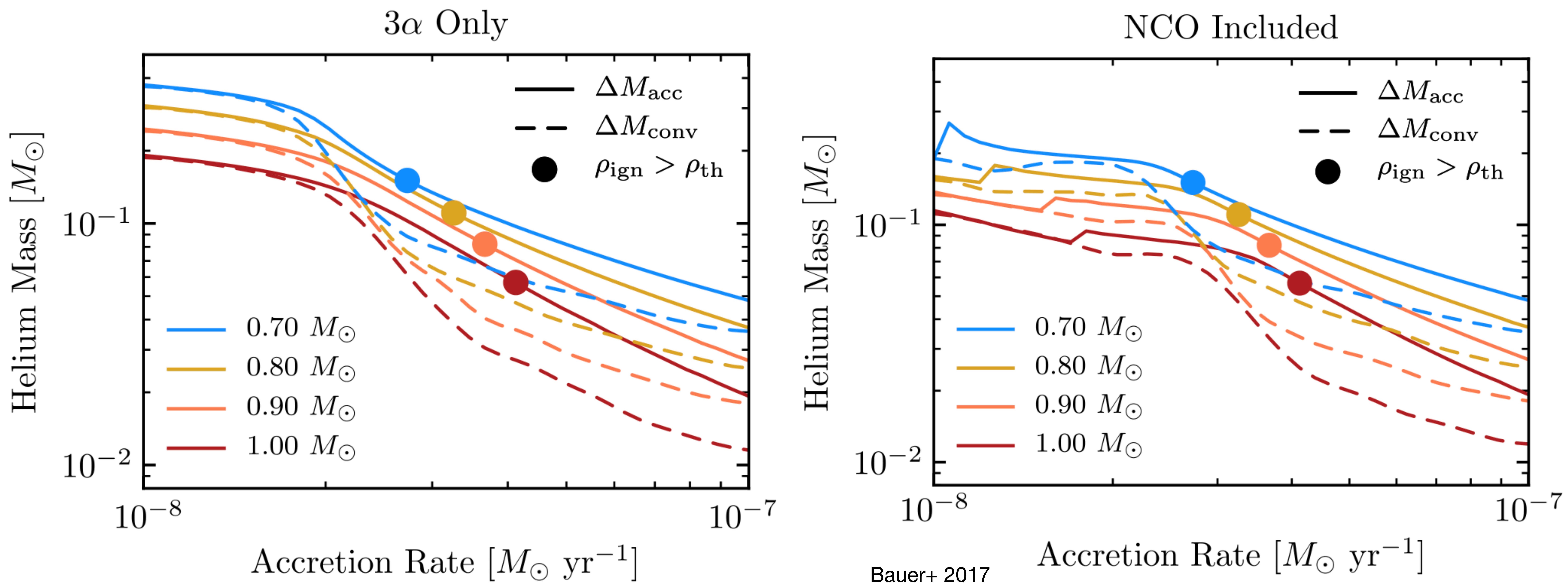
which releases 6.2 MeV per $^{14}\mathrm{C}$ consumed

Accounting for the NCO chain can reduce the He shell mass at ignition

Higher $\dot{M}$, more efficient compressional heating, thinner He shell at ignition

NCO chain matters for low $\dot{M}$

But thicker He shell is better for detonations



Bauer+ 2017

Test suites are a great place to learn how to use MESA

```
(base) mesa@169-231-122-108 custom_rates % cd $MESA_DIR/star/test_suite/custom_rates
(base) mesa@169-231-122-108 custom_rates % ls
README.rst                  history_columns.list        inlist_cool_header          make
TRho-unmodified.data        inlist_NCO_flash            inlist_core                 mk
before_flash.mod            inlist_NCO_flash_header     inlist_core_header          nco.net
ck                          inlist_NCO_hashimoto        inlist_make_he_wd           profile_columns.list
clean                       inlist_NCO_hashimoto_header inlist_make_he_wd_header    re
docs                        inlist_cool                 inlist_pgstar               rn
```

Roadmap

General question: what happens when a helium white dwarf donates mass to a carbon-oxygen white dwarf?

Minilab 1: response of donor and orbit to mass transfer

Minilab 2: response of accretor to accretion

(Part 1: constant accretion rate)

Minilab 3: response of accretor to accretion

(Part 2: realistic binary history)

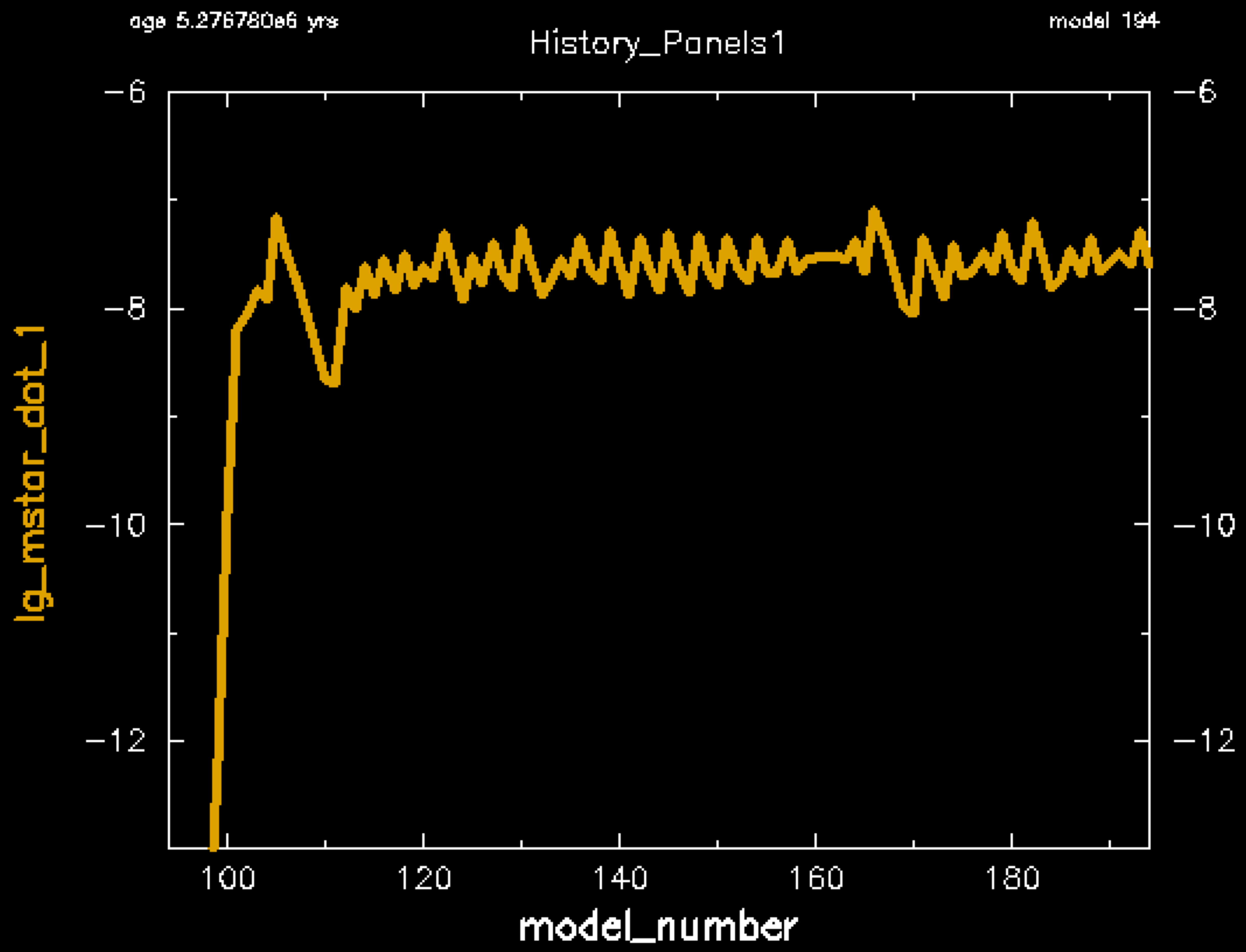
Explicit :

At start of step k, compute $\dot{M}_k$

Take time step Δt and update orbital parameters:

$$M_{1,k+1} = M_{1,k} + \dot{M}_k \Delta t$$

Requires small time steps for numerical stability



Implicit :

At time t, *guess* $\dot{M}$

Take time step Δt and update orbital parameters:

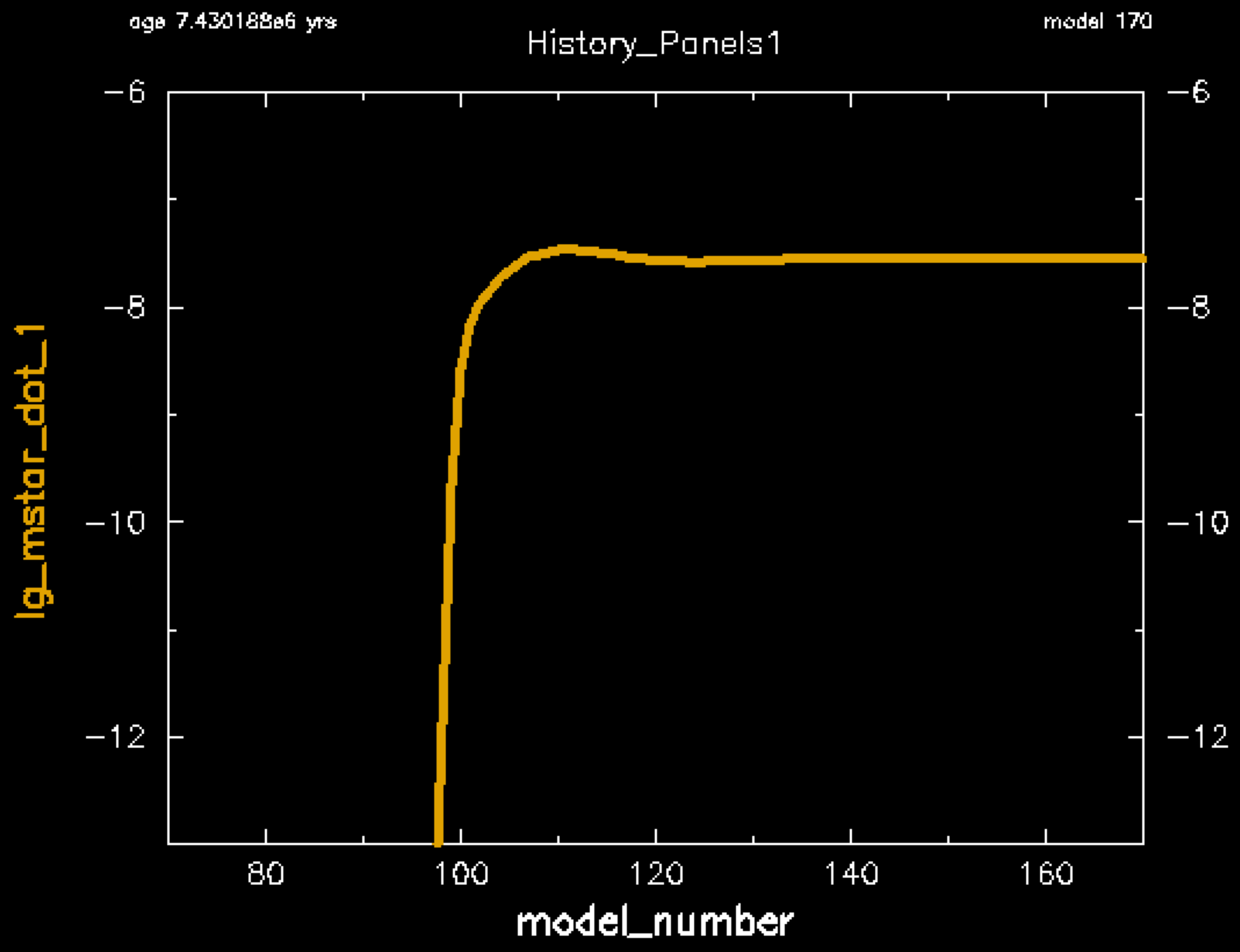
$$M_{1,k+1} = M_{1,k} + \dot{M}\Delta t$$

Compute $\dot{M}_{1,\,k+1}$ at end of step, and check if $|(\dot{M} - \dot{M}_{k+1})/\dot{M}_{k+1}|$ is small

If not, reiterate with different $\dot{M}$

Implicit :

Great for numerical stability, but requires solving both stars for several times *per time step*



Evolve accretor alone, but use the $\dot{M}$ in binary_history.data from Lab 1

(This is fine since what the accretor does doesn't matter to the donor; not fine if we account for spin evolution or if there is mass loss)

*** This is only for the sake of time

don't be afraid of evolve_both_stars = .true. ***

A He star donor leads to a thicker He shell at ignition due to its lower $\dot{M} \sim 10^{-8}\, M_{\odot}$

Similar effects with a higher entropy (hotter) He WD donor

The double detonation mechanism was proposed since the 1980s (e.g., Nomoto+ 1982, Woosley+ 1986)

The binary scenario was CO WD accretor + He star donor

$\dot{M} \sim 10^{-8}\, M_{\odot}\, \mathrm{yr}^{-1}$,

and He shell mass at ignition $\approx 0.15 - 0.20\, M_{\odot}$

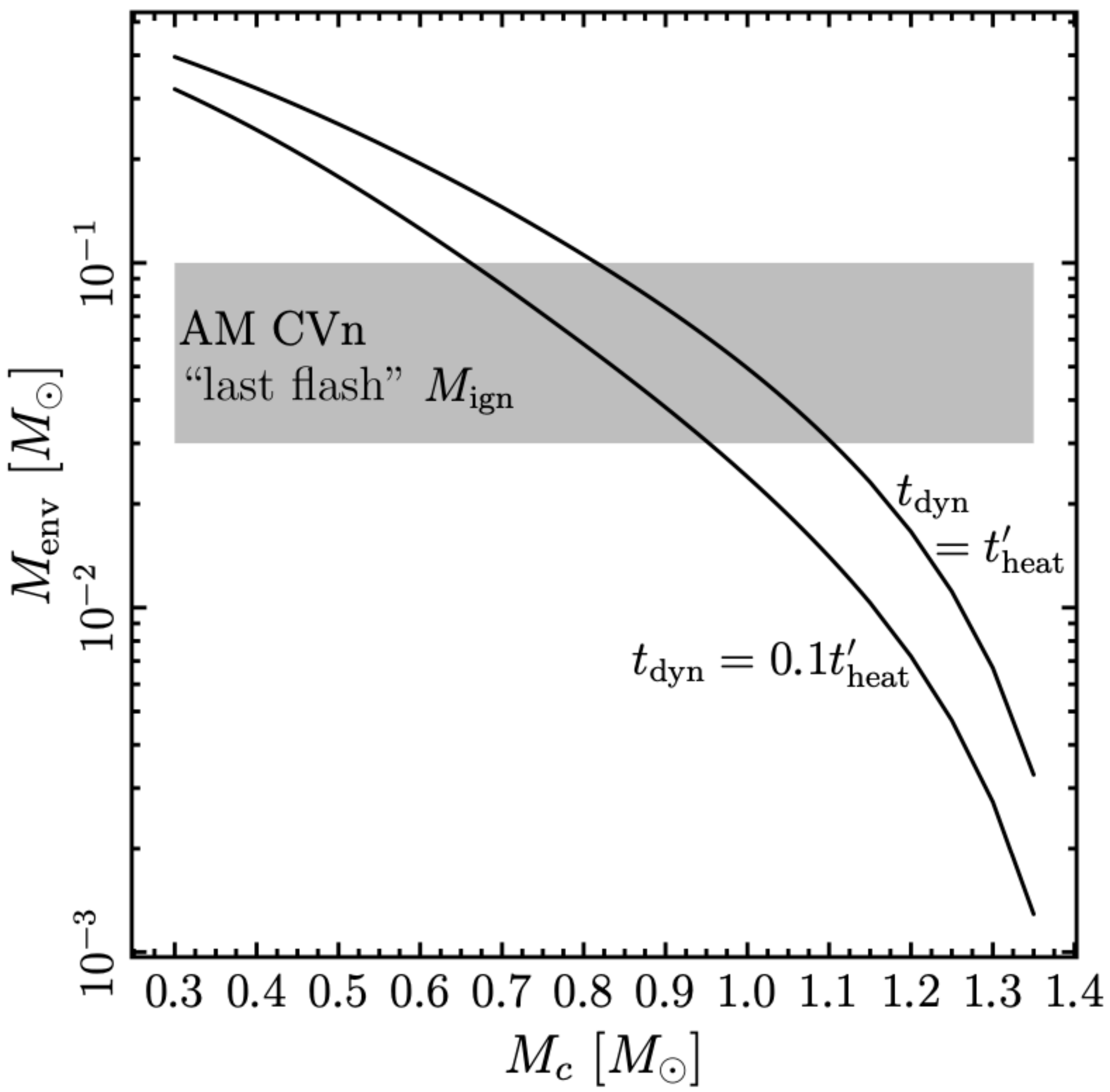
As it turns out, thick He shells $\gtrsim 0.1\, M_\odot$ produce iron-group elements during the He detonation

These heavy elements lead to line-blanketing in the UV, and the resulting explosion does not resemble a normal type Ia supernova

(See De+ 2019 & Polin+ 2019)

So for a long time, the double detonation mechanism was not favored

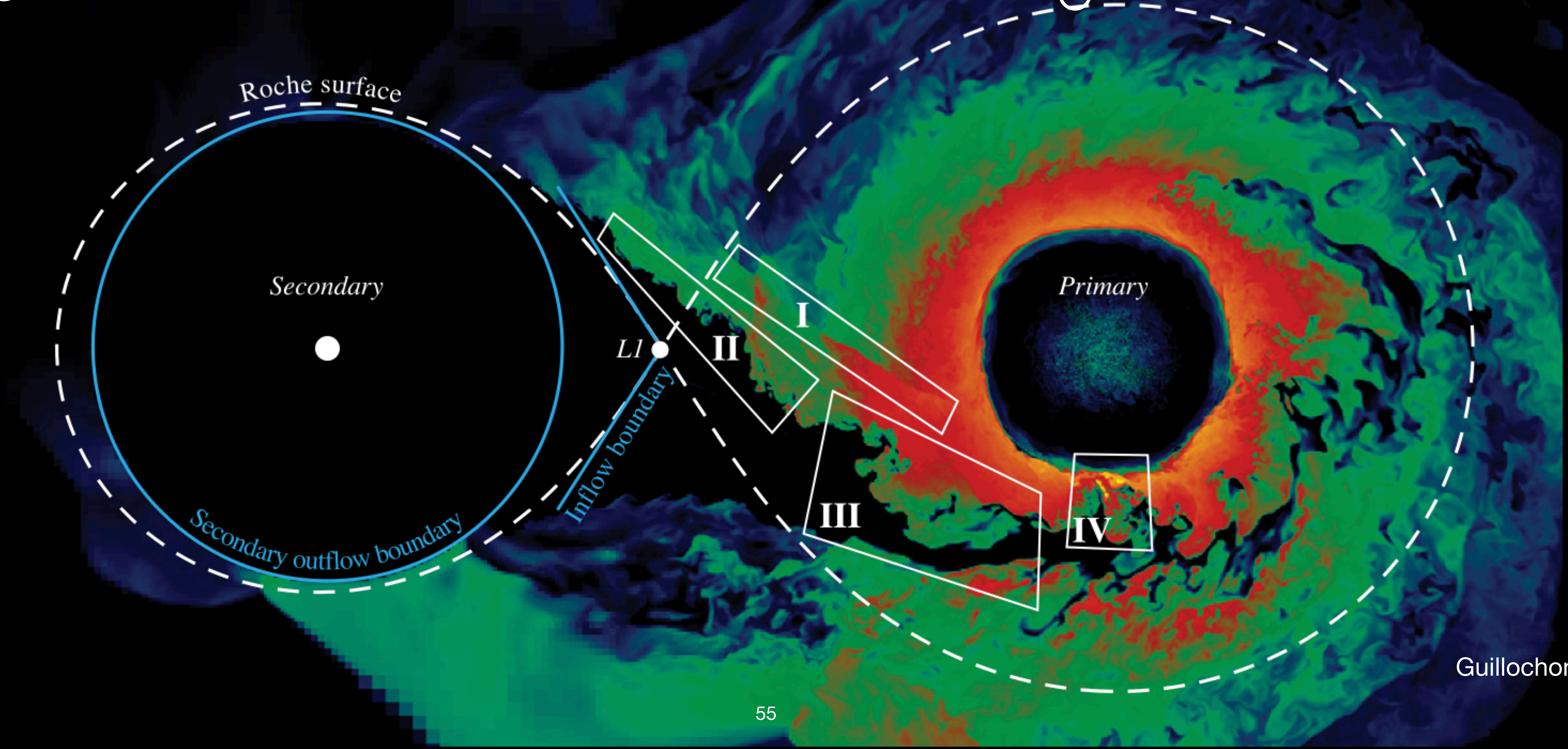
In the late 2000s, it was realized that He WD donors can lead to higher $\dot{M}$ which reduces the He shell mass at ignition to $\lesssim 0.05\,M_\odot$



Shen & Bildsten 2009

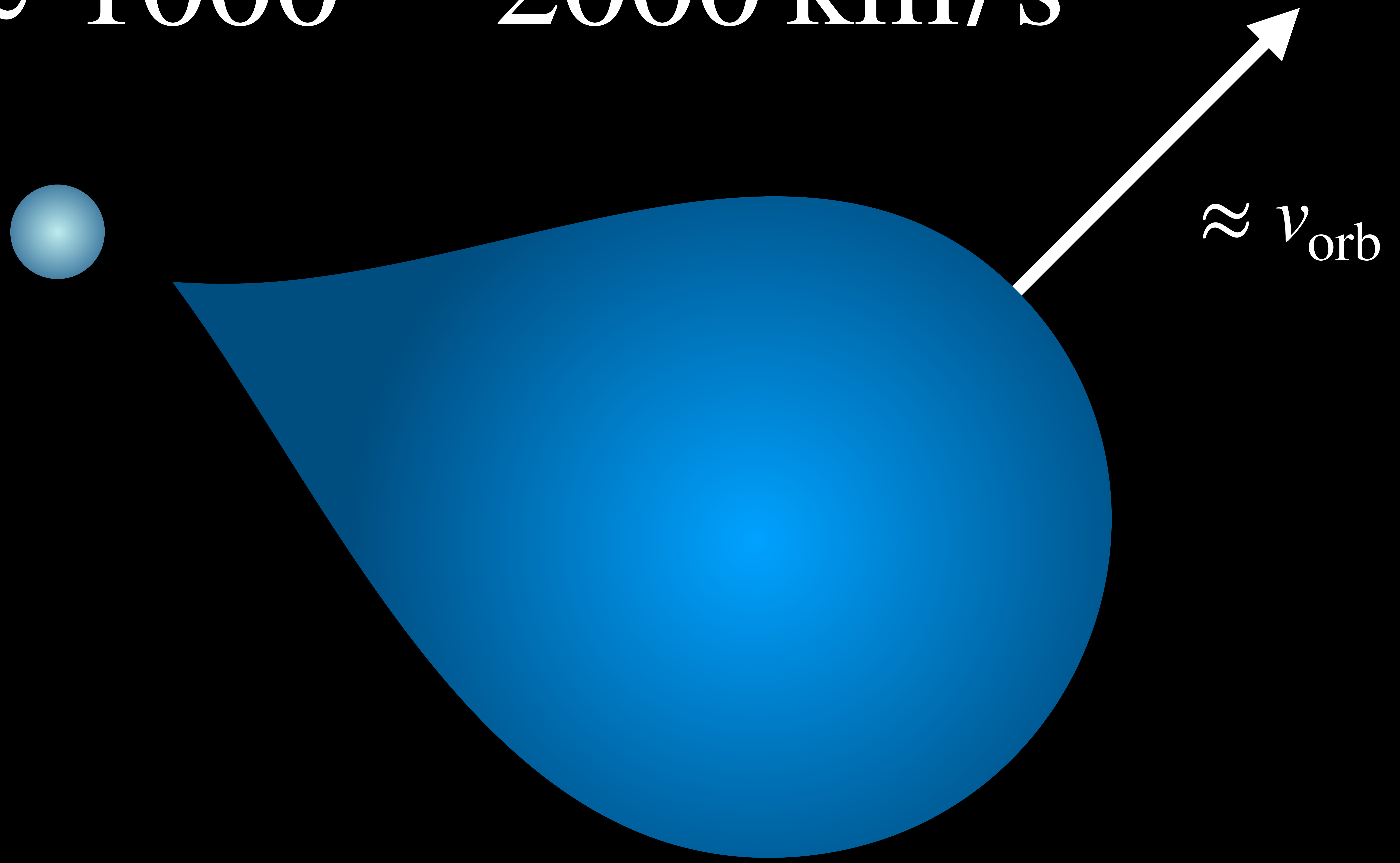
Thinner He shell masses, but still detonable

Around 2010, it was realized that double detonation can also happen during unstable mass transfer after $\approx 0.01\,M_\odot$ of He is accreted

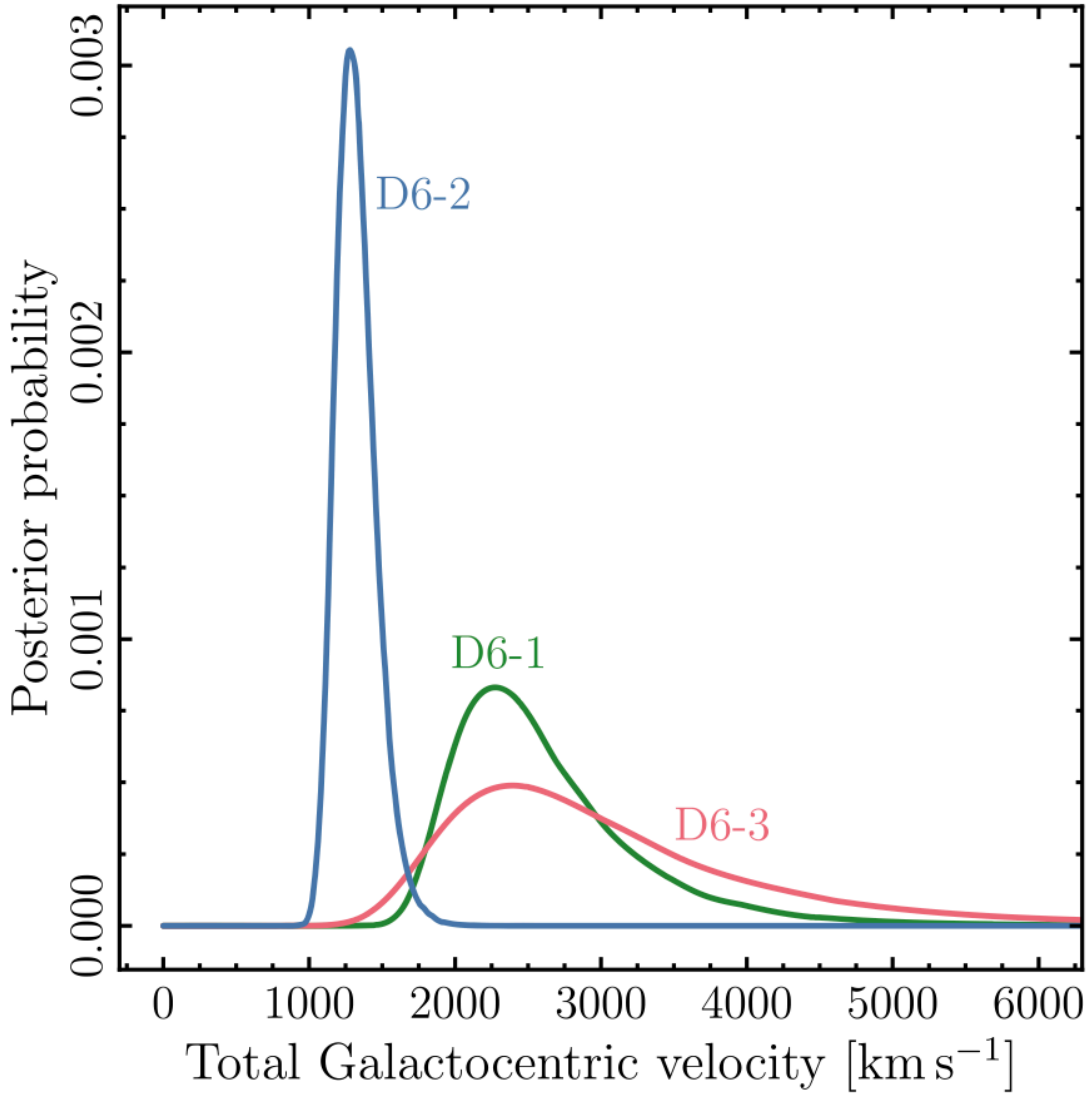


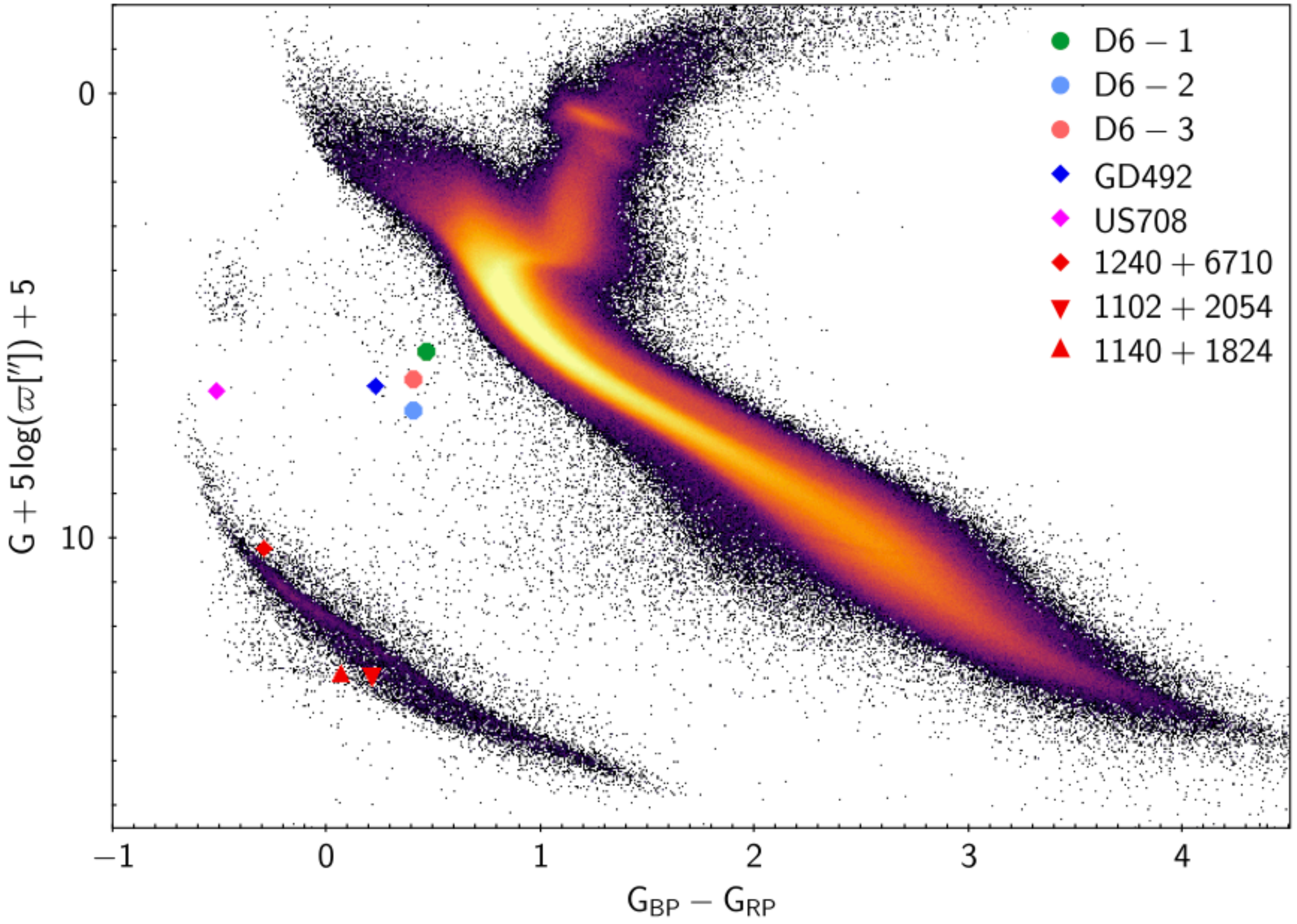
Guillochon et al. 2010

After accretor explodes, the donor is flung off at $v_{\rm orb} \approx 1000 - 2000\,\mathrm{km/s}$



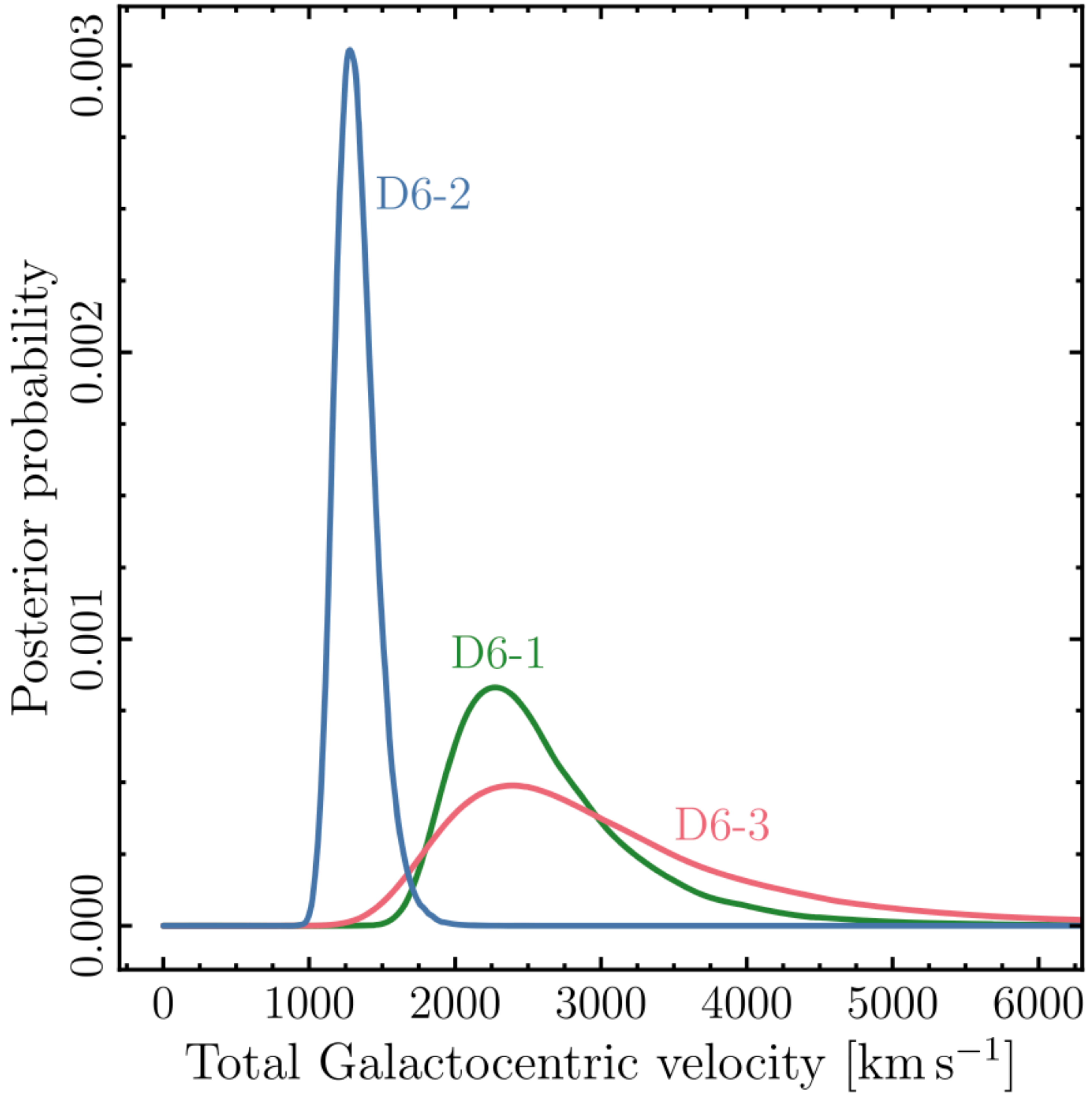
Hypervelocity WDs





Shen et al. 2018 (See also El-Badry+ 2023)

Hypervelocity WDs



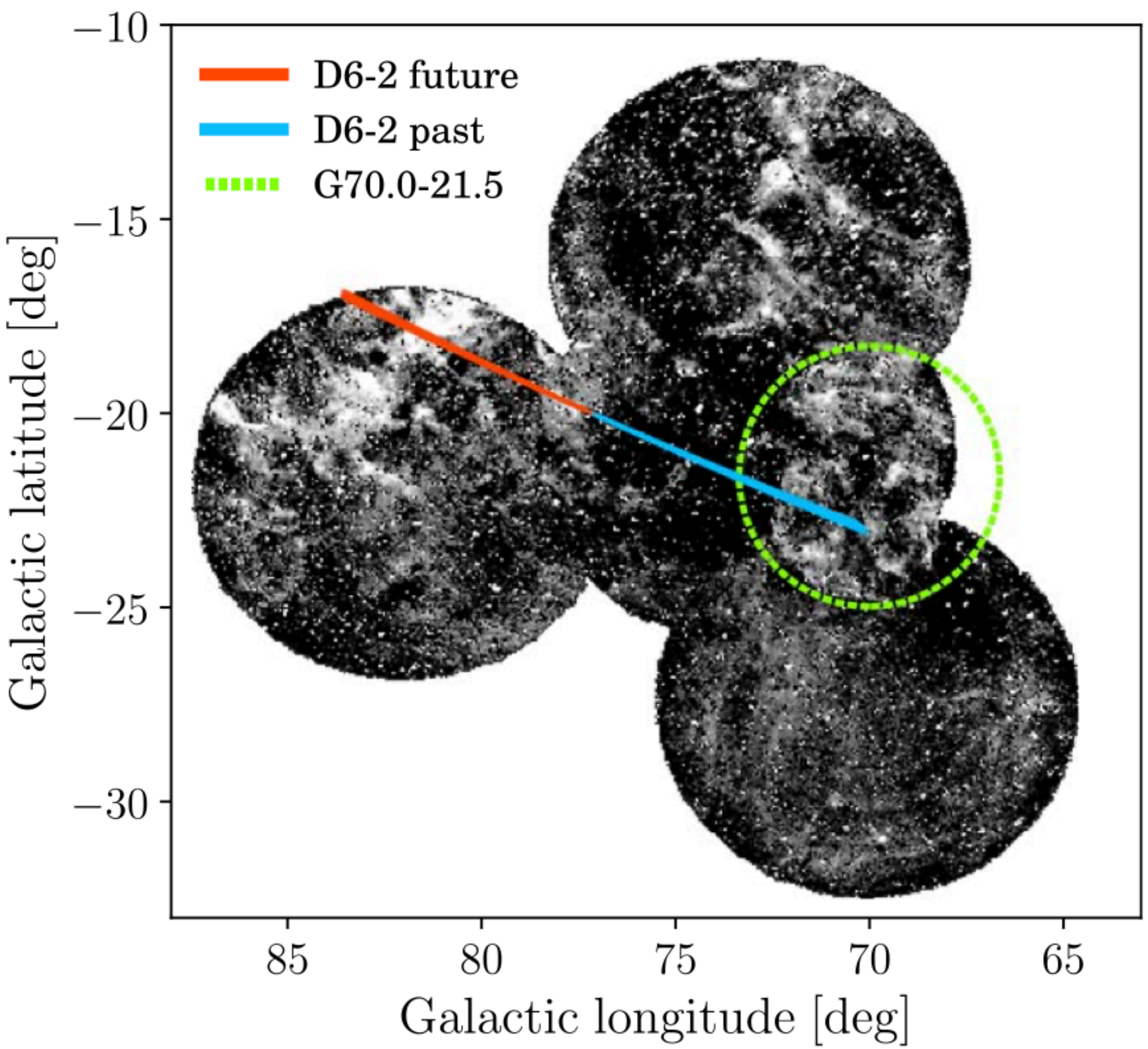
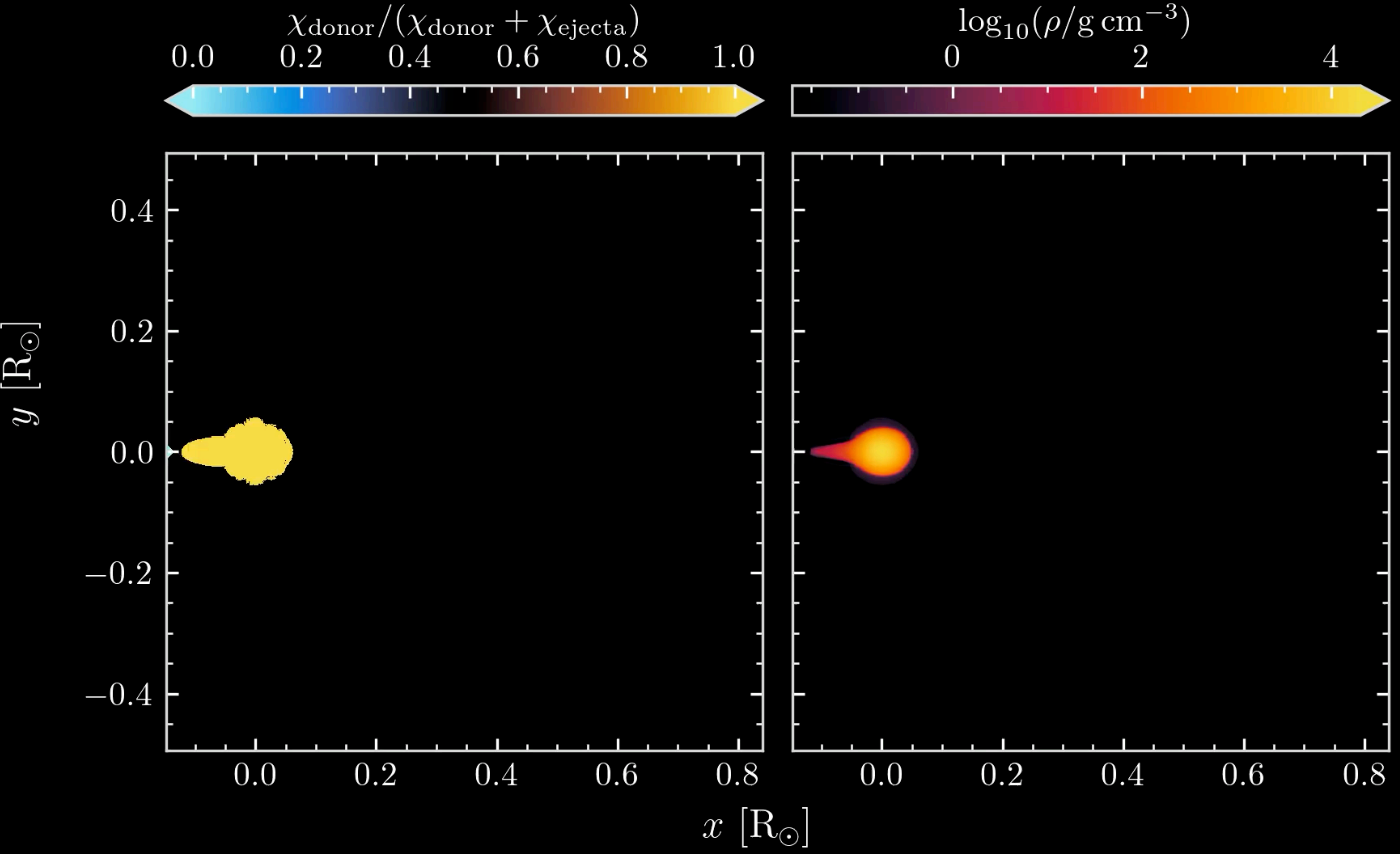


Figure 11. Orbital solution of D6-2 overlaid on Hα images from the Virginia Tech Spectral Line Survey (VTSS; Dennison et al. 1998). The blue and red trajectories extend 9×10^4 yr into D6-2's past and future, respectively. The green circle encompasses the remnant of G70.0–21.5.

Shen et al. 2018 (See also El-Badry+ 2023)

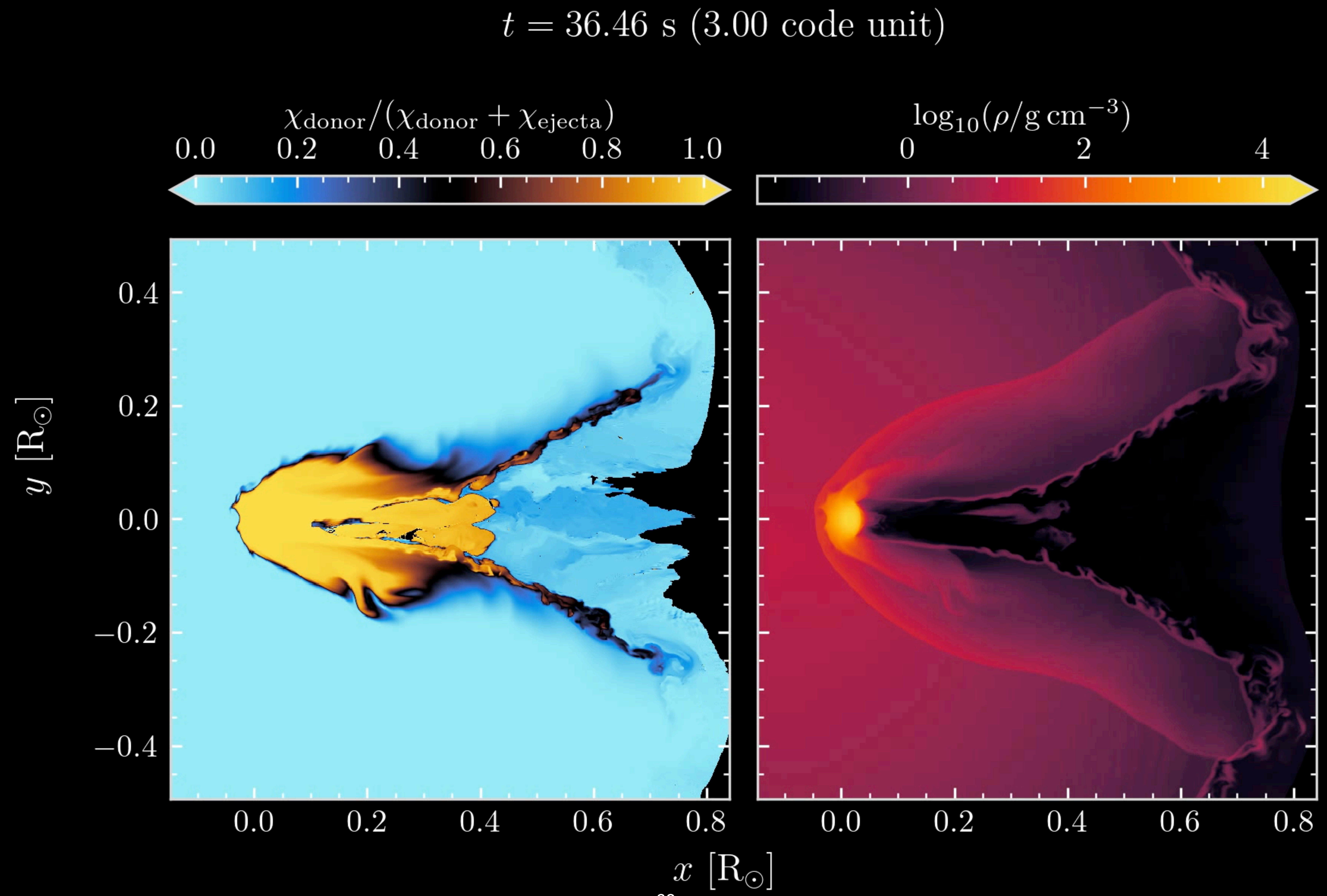
$M_{\rm ej} = 1.00\,M_\odot, E_{\rm KE} = 1.2 \times 10^{51}\,{\rm erg}, M_{\rm He} = 0.126\,M_\odot$

$t = 0.00$ s (0.00 code unit)

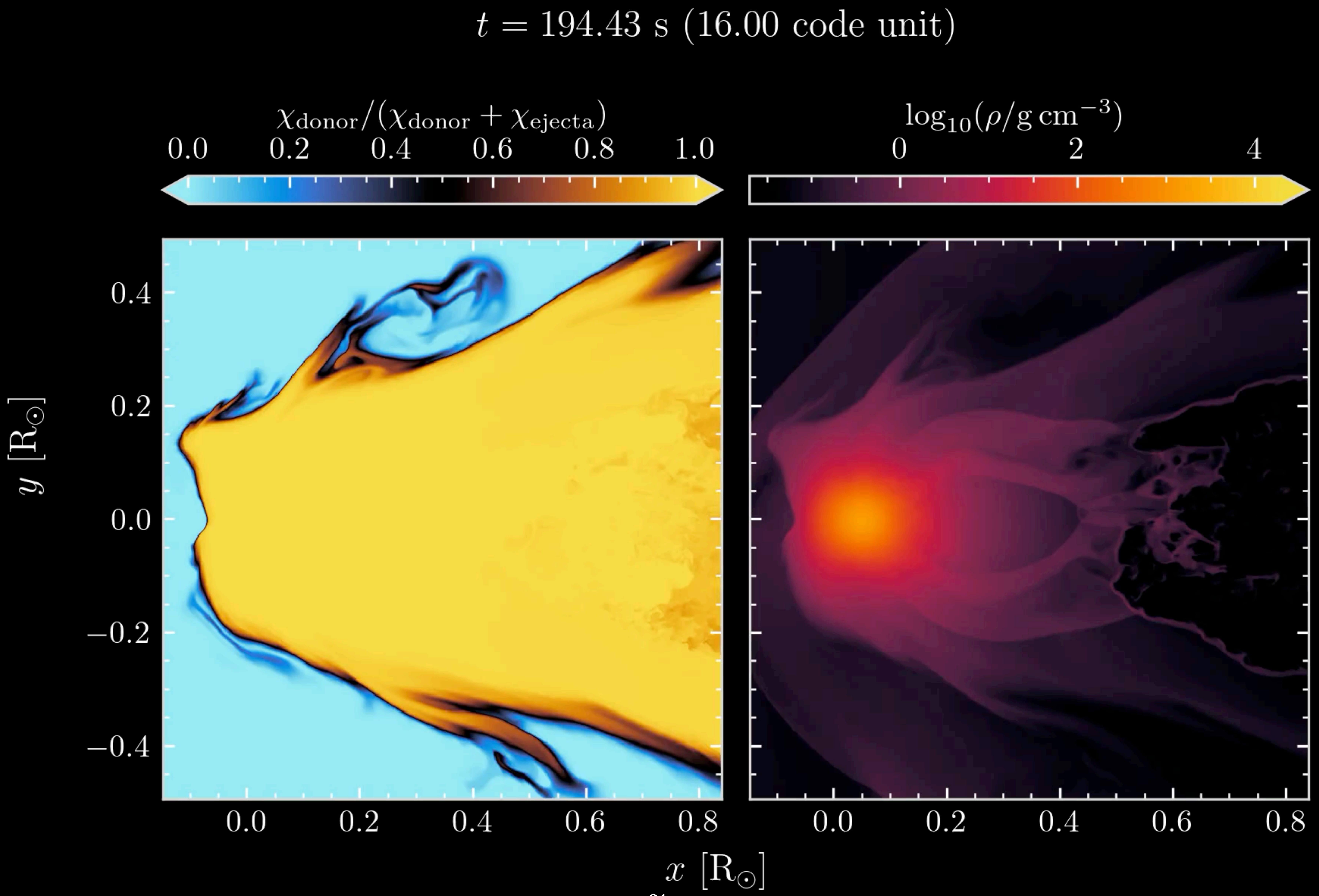


$M_{ej} = 1.00\, M_\odot, E_{KE} = 1.2 \times 10^{51}\, \mathrm{erg}, M_{He} = 0.126\, M_\odot$

-



$M_{\rm ej} = 1.00\,M_\odot, E_{\rm KE} = 1.2 \times 10^{51}\,{\rm erg}, M_{\rm He} = 0.126\,M_\odot$




MESA summer school 2018