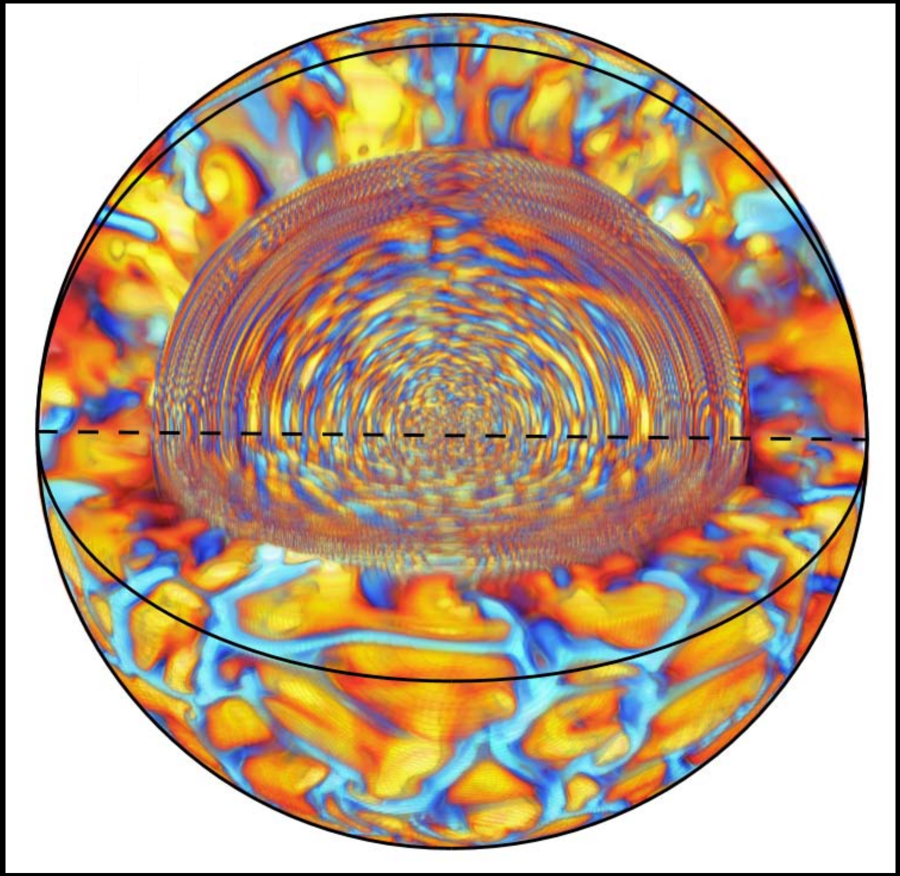
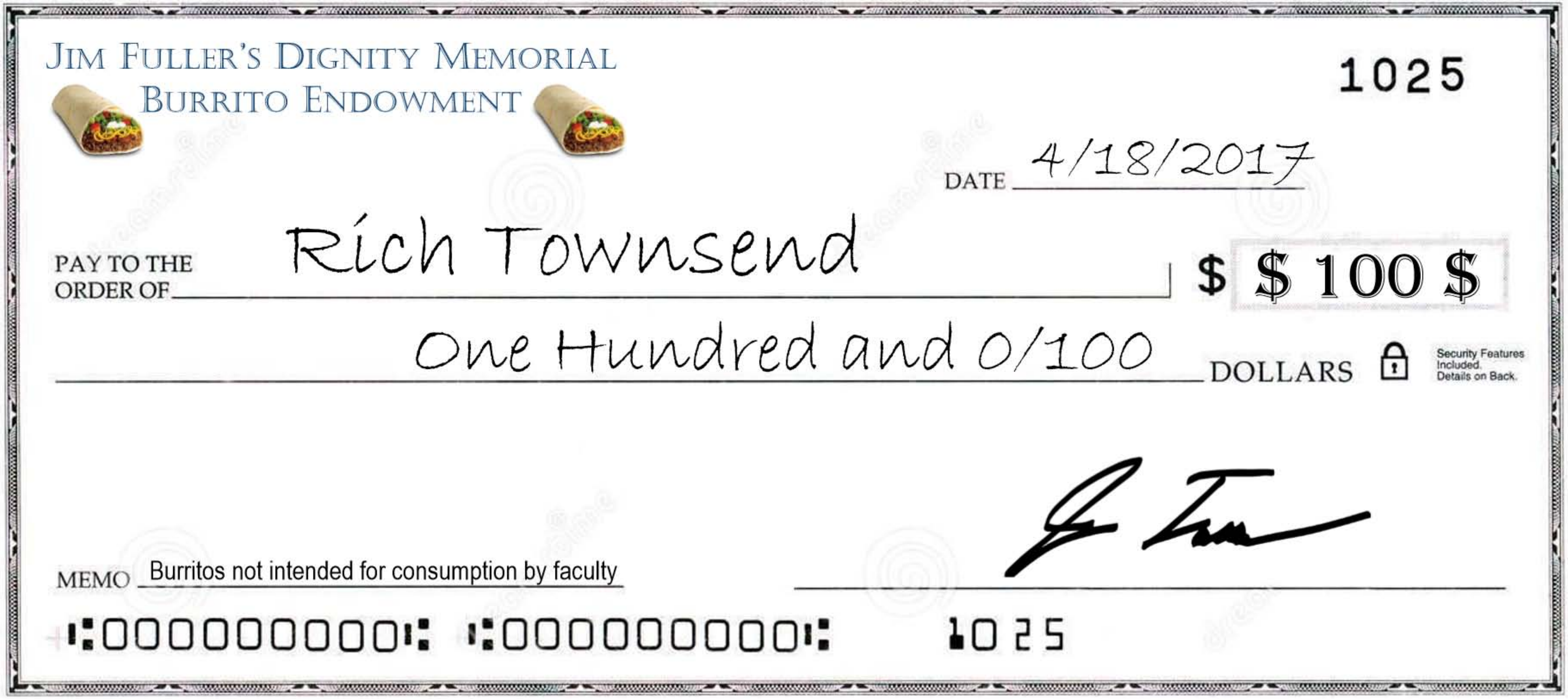
Wave-Driven Pre-Supernova Outbursts

Jim Fuller

KITP/Caltech



Alvan et al. 2014



JIM FULLER'S DIGNITY MEMORIAL
BURRITO ENDOWMENT

1025

DATE 4/18/2017

PAY TO THE ORDER OF Rich Townsend $ $ 100 $

One Hundred and 0/100 DOLLARS

Security Features Included. Details on Back.

MEMO Burritos not intended for consumption by faculty

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Motivation

- Pre-SN outbursts common in interacting SNe
  - Occur in last ~years of star's life
  - Mass loss rates enhanced by factors of ~10^3, can be >> 10^{-3} M_{sun}/yr

- Mild outbursts may be common even in normal SNe

- Unexplained by standard stellar evolution

- Wave-driven outbursts possible solution

Quataert & Shiode (2012)
Shiode & Quataert (2014)

Convection excites gravity waves

Movie made by
Andrea Cristini

Wave Power

- Convection puts energy into waves at a rate

$$L_{\rm wave} \sim \mathcal{M}_{\rm con} L_{\rm con}$$

Lecoanet et al. 2013
Rogers et al. 2013

- Where the convective Mach number is

$$\mathcal{M}_{\rm con} = \frac{v_{\rm con}}{c_{\rm sound}} \ll 1$$

- The convective velocity can be estimated from mixing length theory

Late Stage Massive Stellar Evolution

- During late burning stages, neutrinos carry away burning energy causing burning timescales to be short

$$t_{\rm dyn} \ll t_{\rm nuc} \ll t_{\rm therm}$$
$$L_{\rm nuc} \gg L_*$$

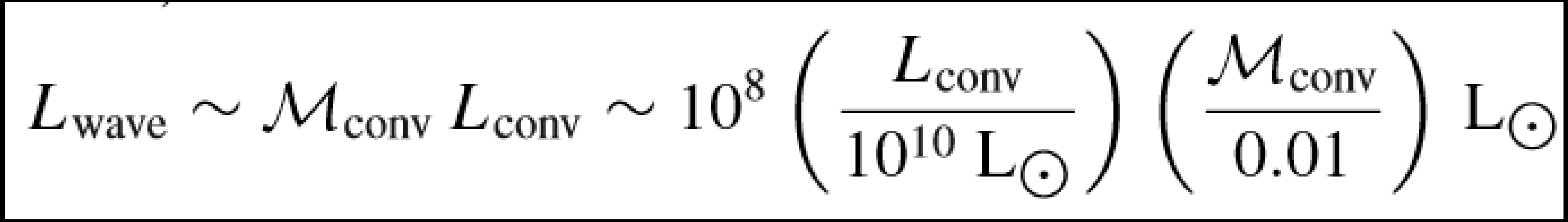
- Consequently, there are situations where

$$L_{\rm wave} \gg L_*$$

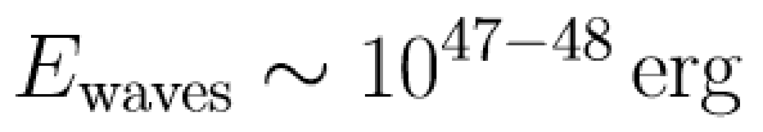
- Waves can transport energy to surface on timescale of ~ $t_{\rm dyn}$

Wave Power in Massive Stars

- Huge energy fluxes during late burning phases



$$L_{\rm wave} \sim \mathcal{M}_{\rm conv} L_{\rm conv} \sim 10^8 \left(\frac{L_{\rm conv}}{10^{10}\,{\rm L}_\odot}\right)\left(\frac{\mathcal{M}_{\rm conv}}{0.01}\right) {\rm L}_\odot$$



$$E_{\rm waves} \sim 10^{47-48}\,{\rm erg}$$

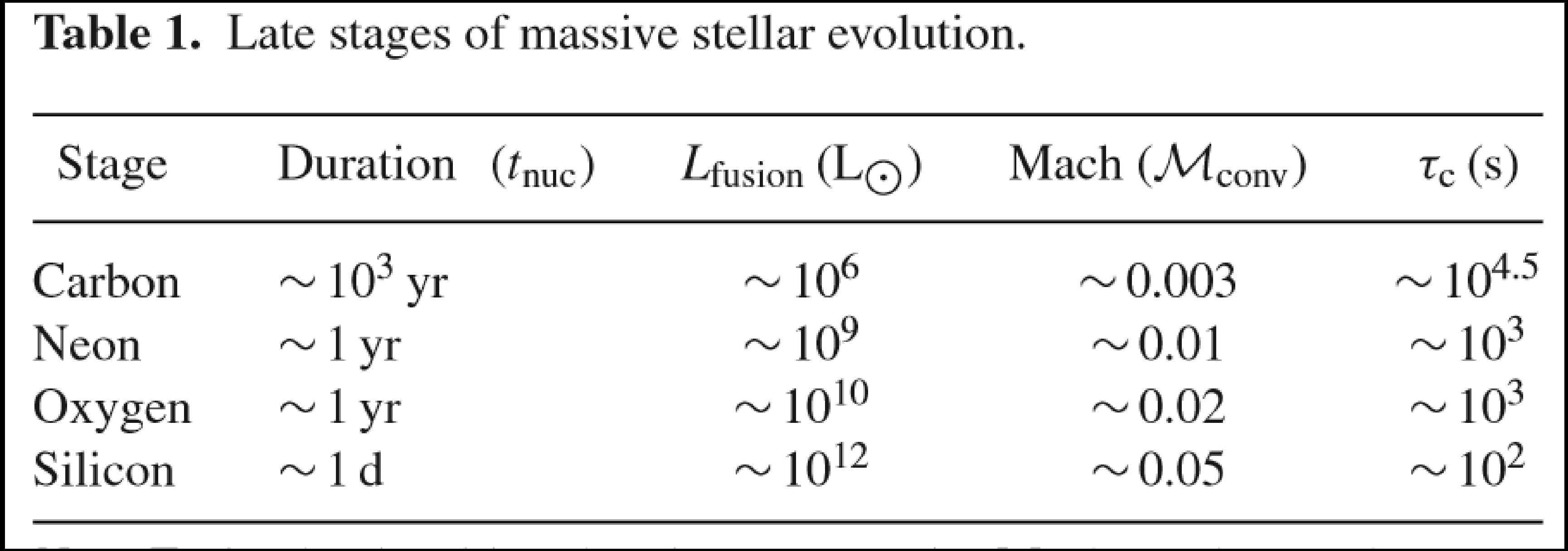
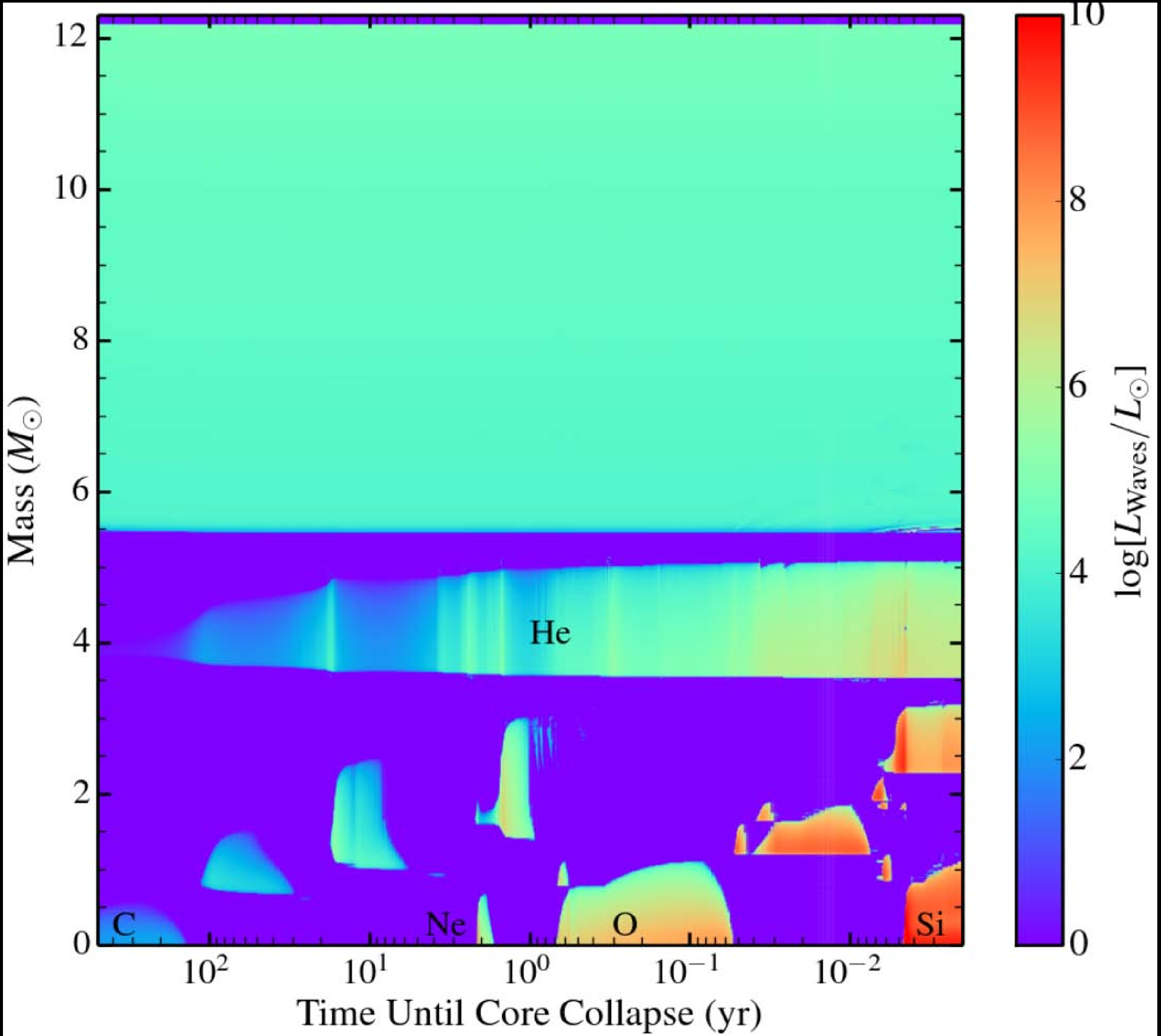


Table 1. Late stages of massive stellar evolution.

Stage	Duration ($t_{\rm nuc}$)	$L_{\rm fusion}$ (${\rm L}_\odot$)	Mach ($\mathcal{M}_{\rm conv}$)	$\tau_{\rm c}$ (s)
Carbon	$\sim 10^3$ yr	$\sim 10^6$	~ 0.003	$\sim 10^{4.5}$
Neon	~ 1 yr	$\sim 10^9$	~ 0.01	$\sim 10^3$
Oxygen	~ 1 yr	$\sim 10^{10}$	~ 0.02	$\sim 10^3$
Silicon	~ 1 d	$\sim 10^{12}$	~ 0.05	$\sim 10^2$

Quataert
& Shiode (2012)


Mass ($M_\odot$)
12
10
8
6
4
2
0
10^2
10^1
10^0
10^{-1}
10^{-2}
Time Until Core Collapse (yr)
He
C
Ne
O
Si
$\log[L_{\rm Waves}/L_\odot]$
10
8
6
4
2
0

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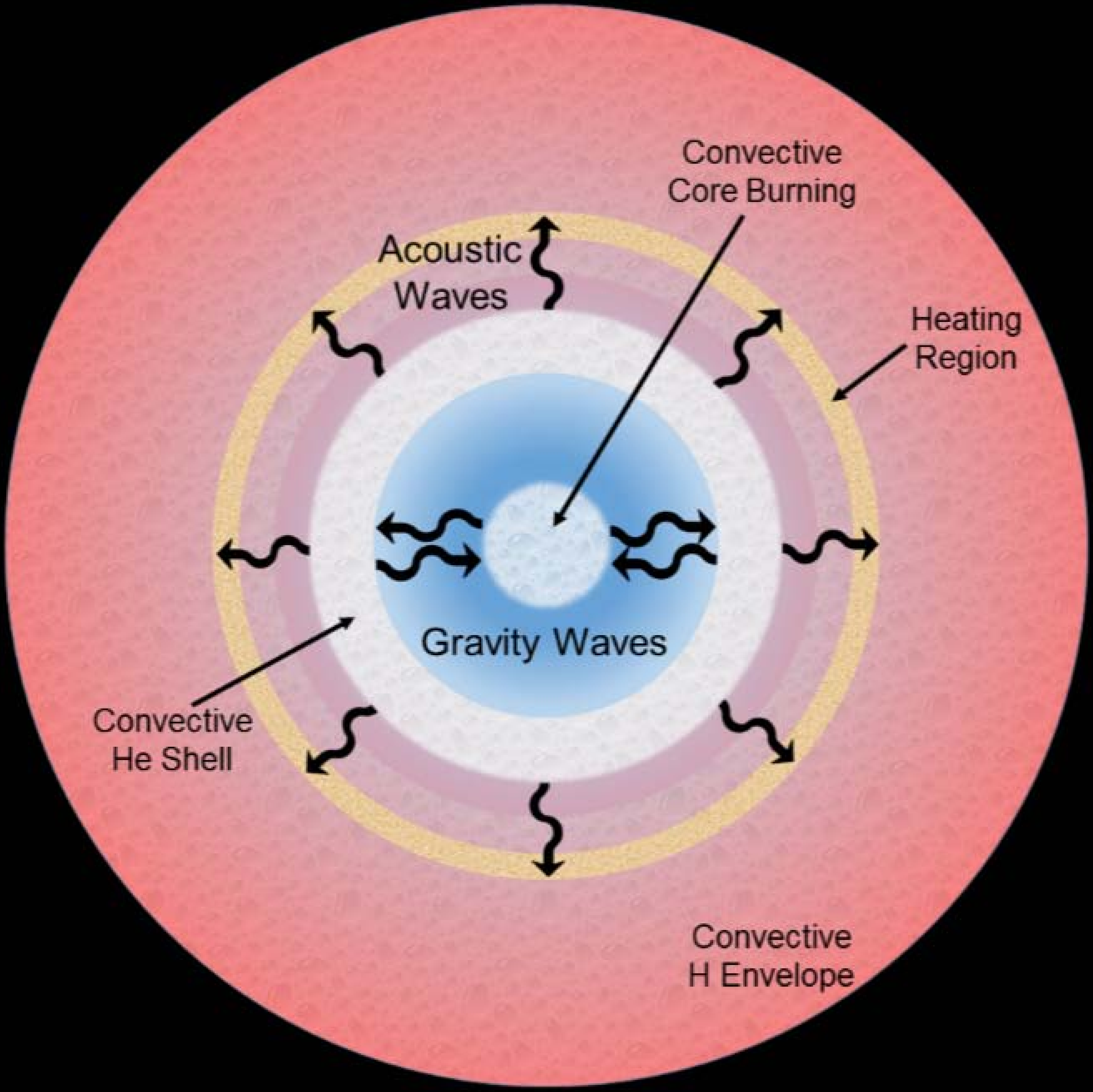

Convective
Core Burning
Acoustic
Waves
Heating
Region
Gravity Waves
Convective
He Shell
Convective
H Envelope

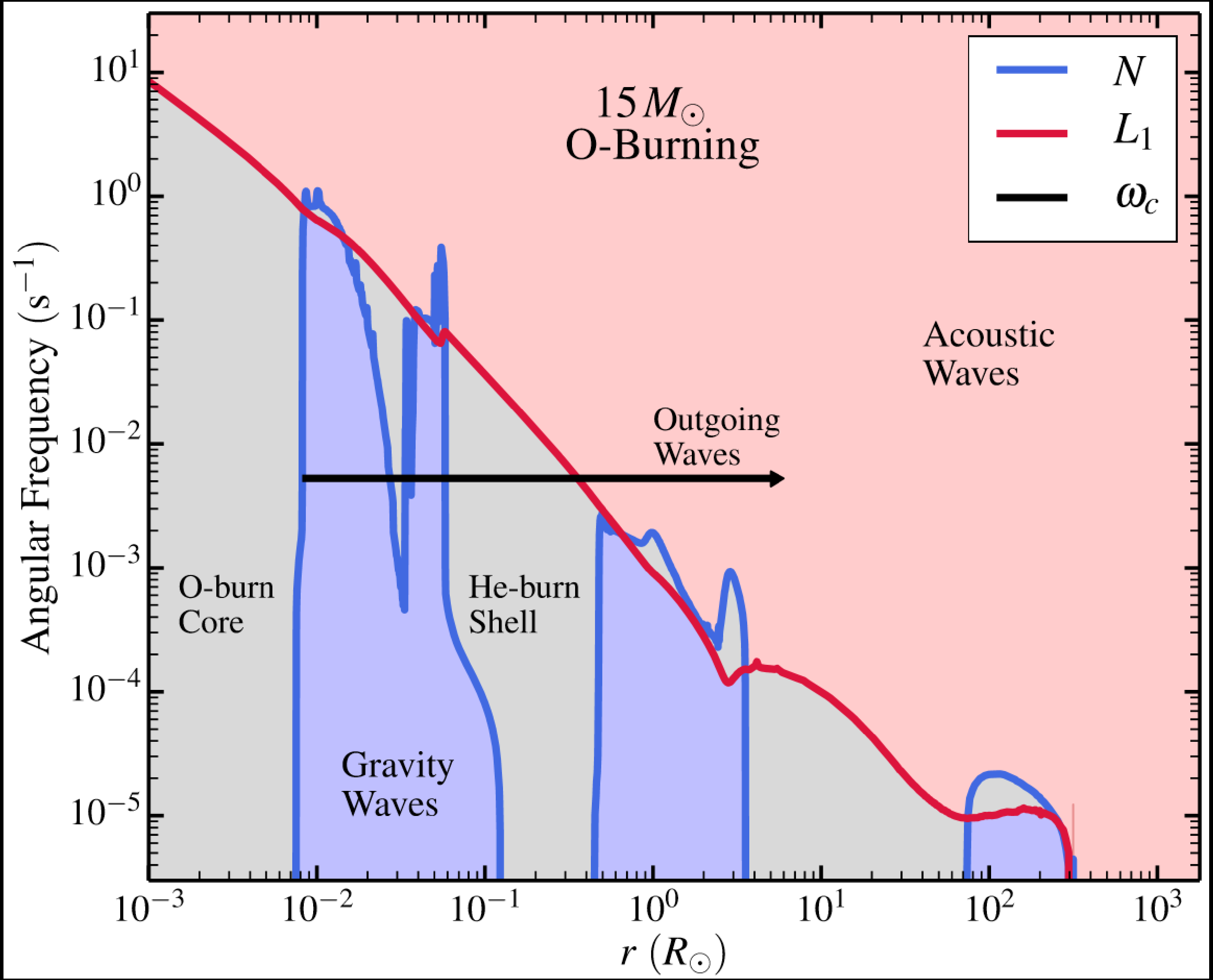
Wave Propagation

- Gravity excited in core must tunnel into stellar envelope as acoustic waves

- Acoustic waves damp in envelope, converting wave energy to thermal energy

$$v_{\rm con} = \left[L_{\rm con}/(4\pi\rho r^2)\right]^{1/3}$$

$$\omega_{\rm con} = 2\pi \frac{v_{\rm con}}{2\alpha_{\rm MLT} H}$$



Methods

- Run MESA models including the effects of wave energy transport

$$\gamma_\nu = \frac{\delta\epsilon_\nu}{\varepsilon} \simeq \frac{\Gamma_1^2 \nabla_{\rm ad}^2 g^2}{N^2 c_s^4} \left(\frac{\partial \ln \epsilon_\nu}{\partial \ln T} \right)_\rho \epsilon_\nu$$

- At each time step, compute
  - Wave generation by nuclear burning convective zones in core
  - Wave propagation and fraction of energy tunneling into the envelope
  - Wave damping energy deposition rate per unit mass at each shell within star

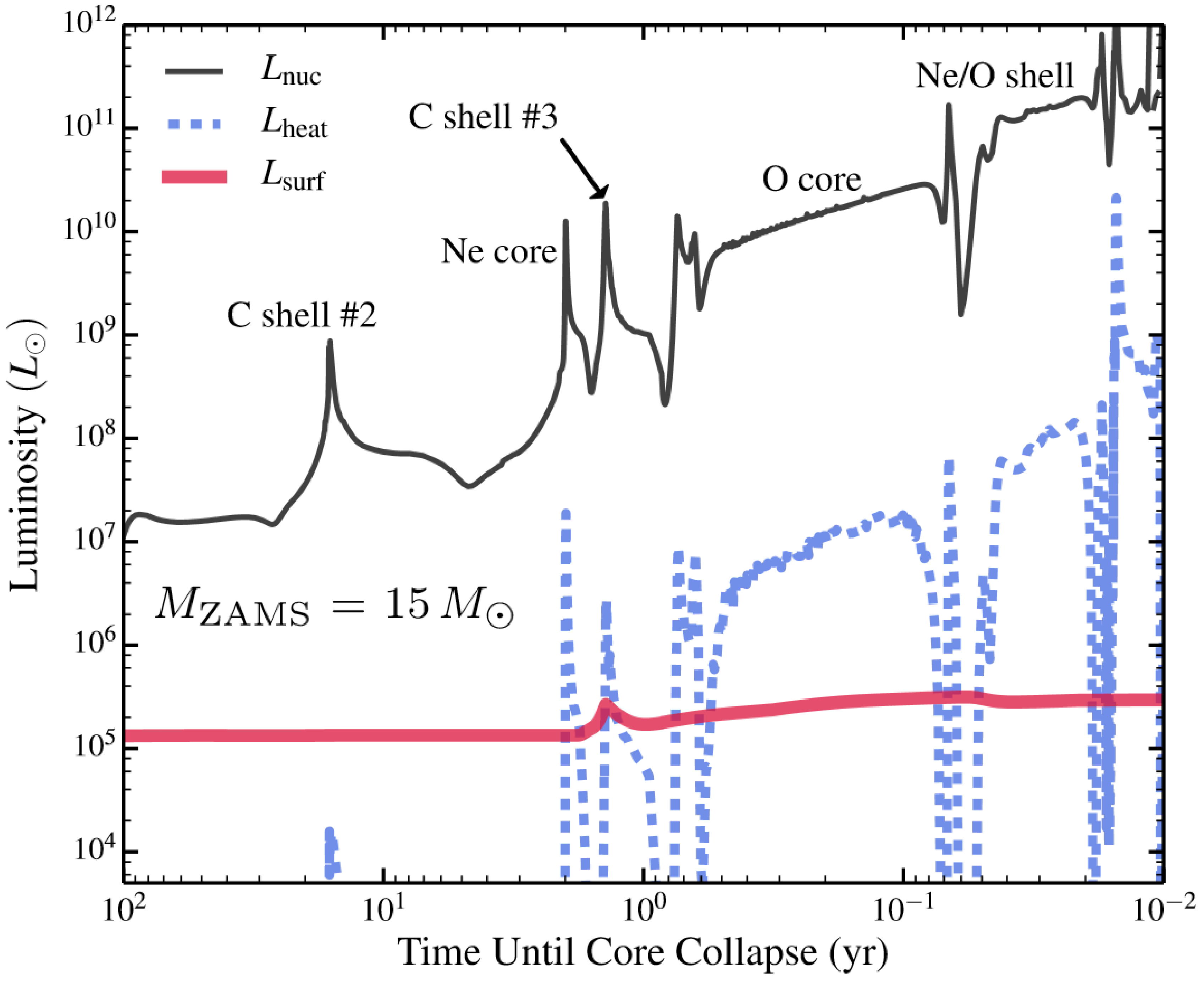
$$L_{\rm heat} = f_{\rm esc} L_{\rm wave} = \left[1 + \frac{T_{\rm shell}^2 + x_\nu}{T_{\rm min}^2} \right]^{-1} L_{\rm wave}$$

$$T_{1,2}^2 = \exp\left(-2 \int_{r_1}^{r_2} |k_r| dr \right)$$

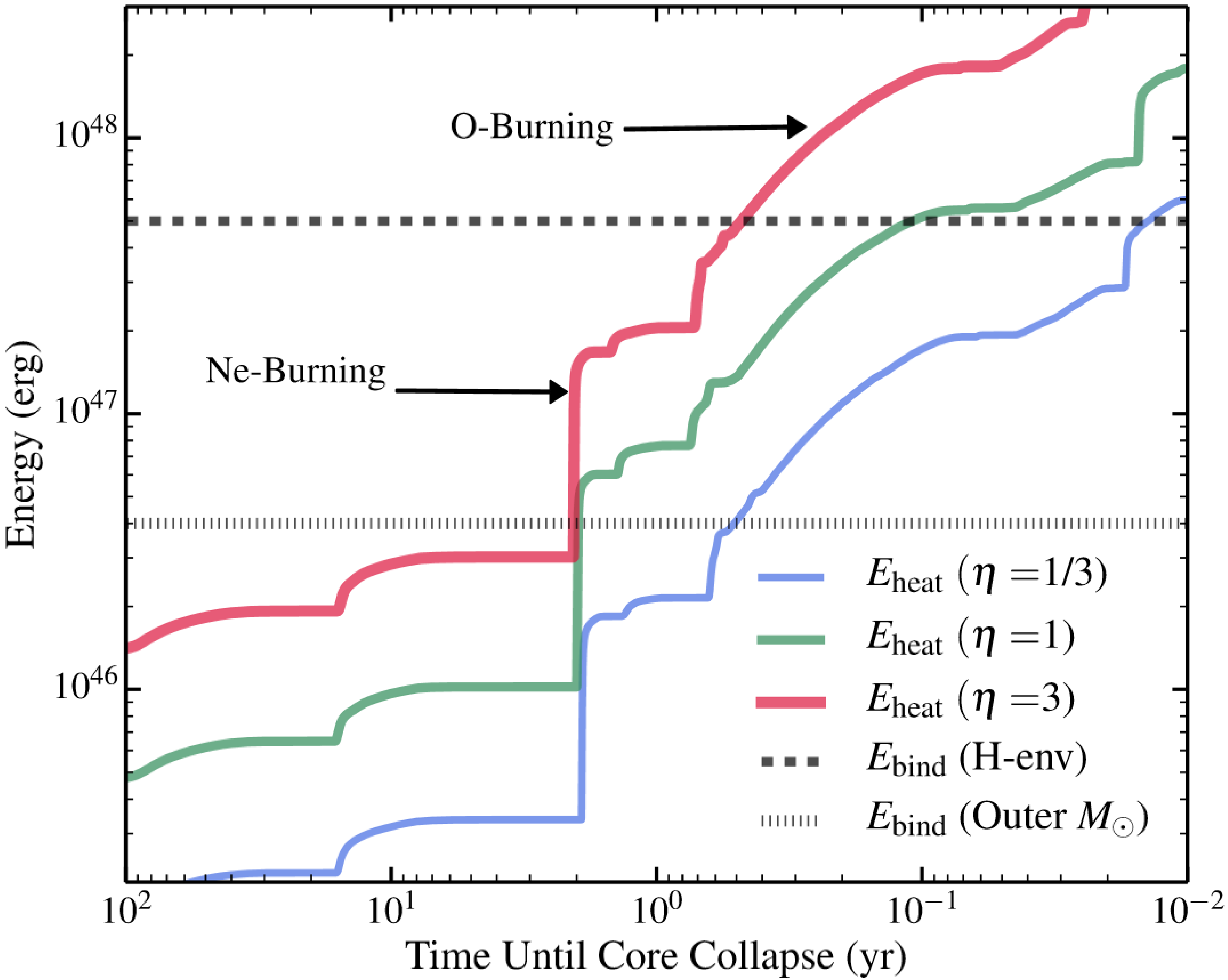
$$k_r^2 = \frac{\left(N^2 - \omega_2\right)\left(L_l^2 - \omega^2\right)}{\omega^2 c_s^2}$$

- Use hydrodynamic version of MESA to allow for high velocity flows

Wave Power



$L_{\rm nuc}$
$L_{\rm heat}$
$L_{\rm surf}$
C shell #2
Ne core
C shell #3
O core
Ne/O shell
$M_{\rm ZAMS} = 15\,M_\odot$
Luminosity $(L_\odot)$
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
Time Until Core Collapse (yr)



O-Burning
Ne-Burning
Energy (erg)
10^{48}
10^{47}
10^{46}
Time Until Core Collapse (yr)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
$E_{\rm heat}$ (η =1/3)
$E_{\rm heat}$ (η =1)
$E_{\rm heat}$ (η =3)
$E_{\rm bind}$ (H-env)
$E_{\rm bind}$ (Outer $M_{\odot}$)

4/25/2017

More Methods

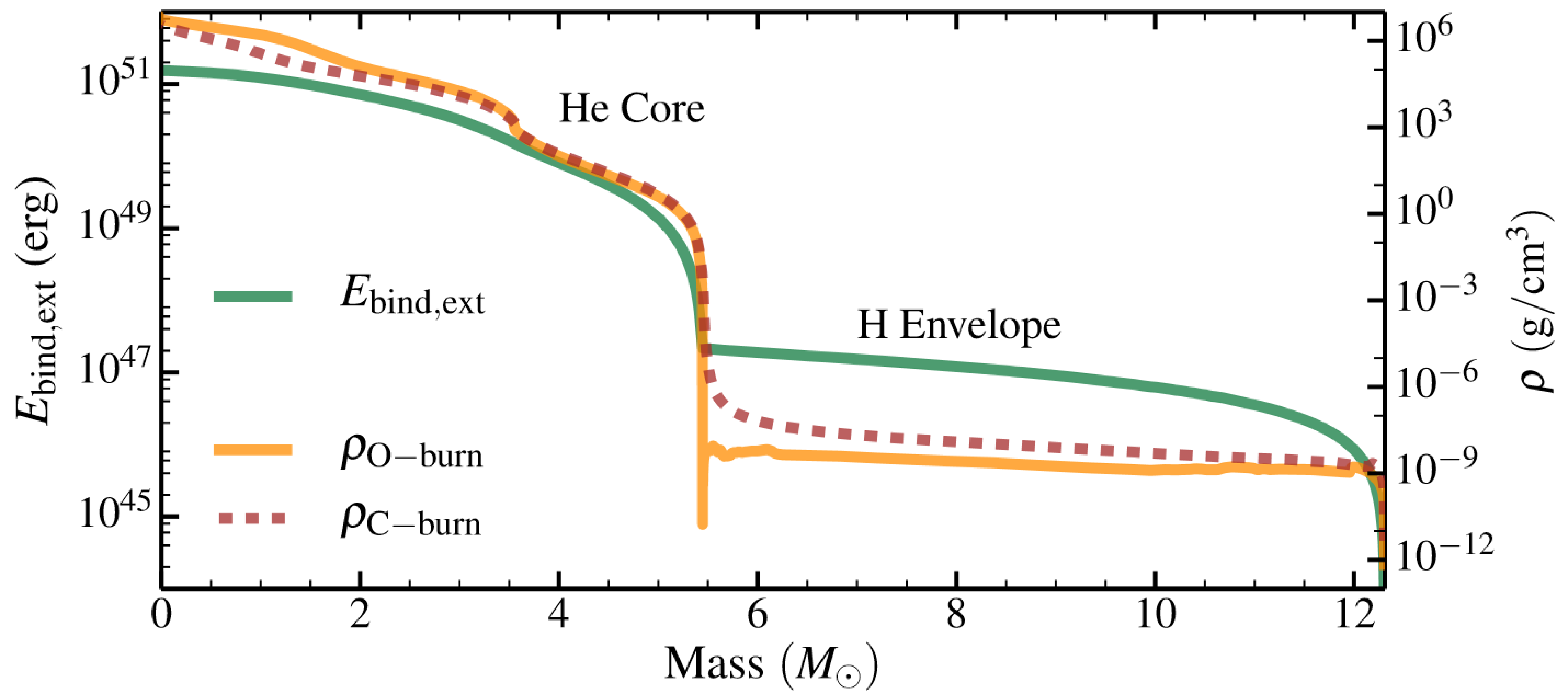
- Run MESA models including the effects of wave energy transport

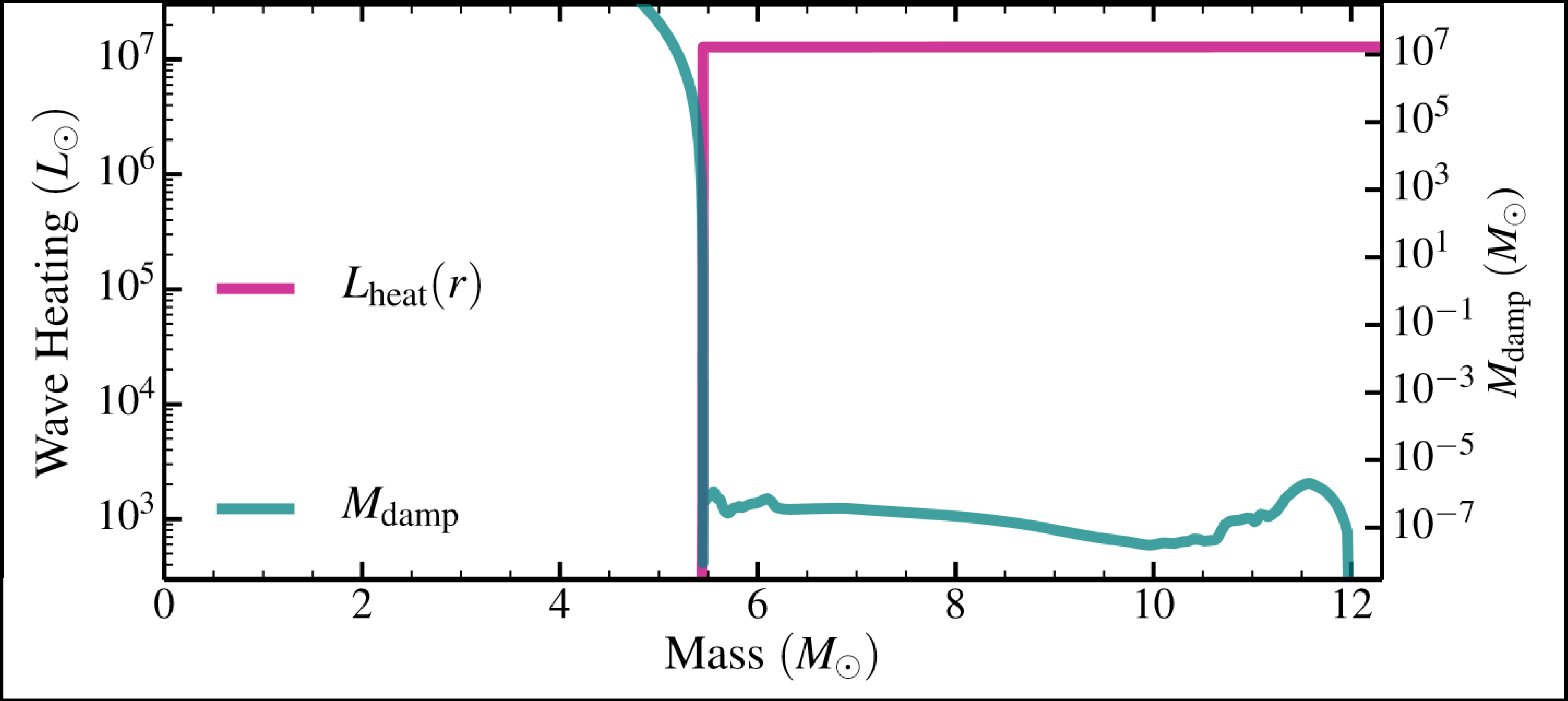
- At each time step, compute
  - Wave generation by nuclear burning convective zones in core
  - Wave propagation and fraction of energy tunneling into the envelope
  - Wave damping energy deposition rate per unit mass at each shell within star

- Use hydrodynamic version of MESA to allow for high velocity flows

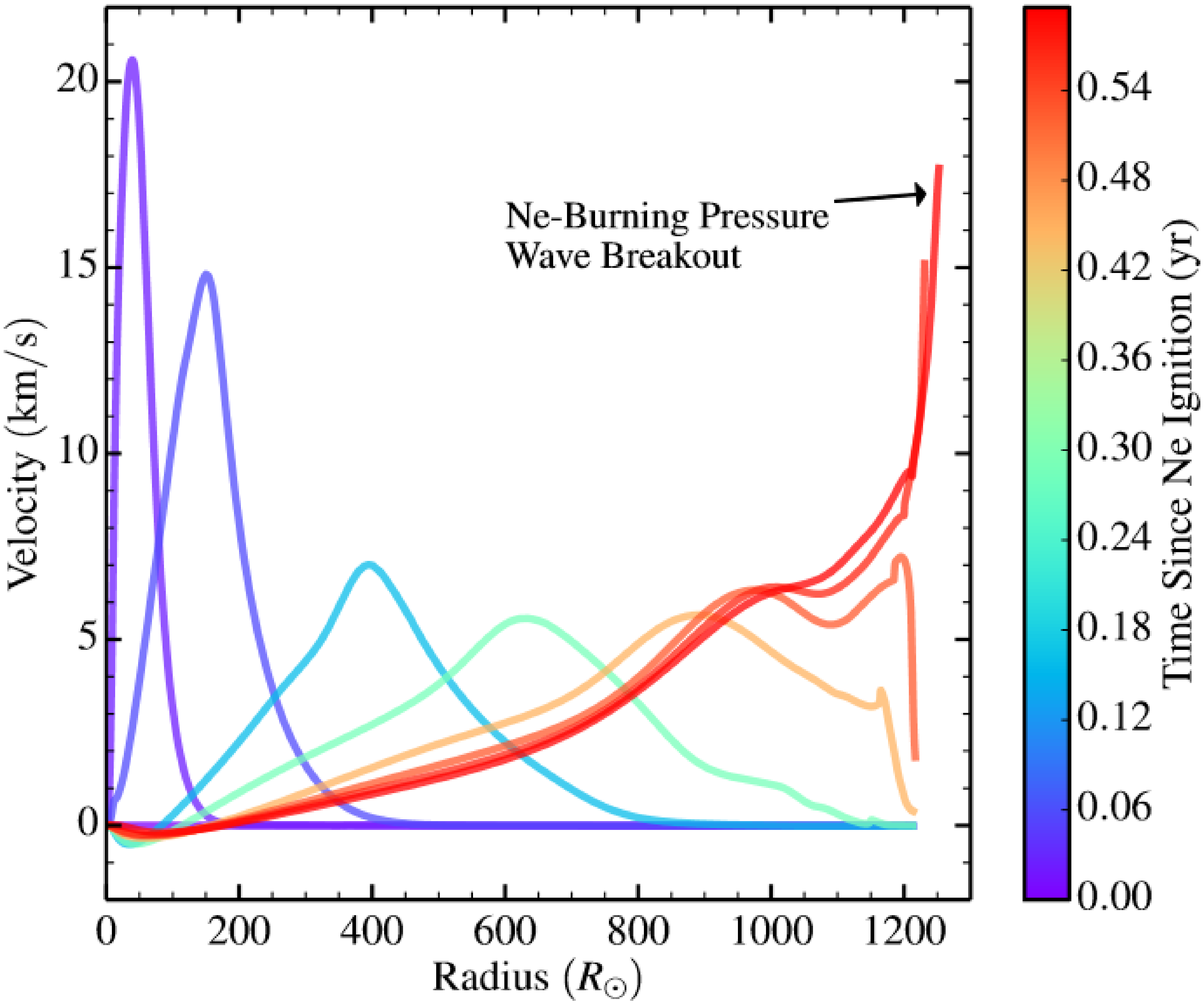
$$\frac{dL_{\rm wave}}{dM} = -\frac{L_{\rm wave}}{M_{\rm damp}}$$

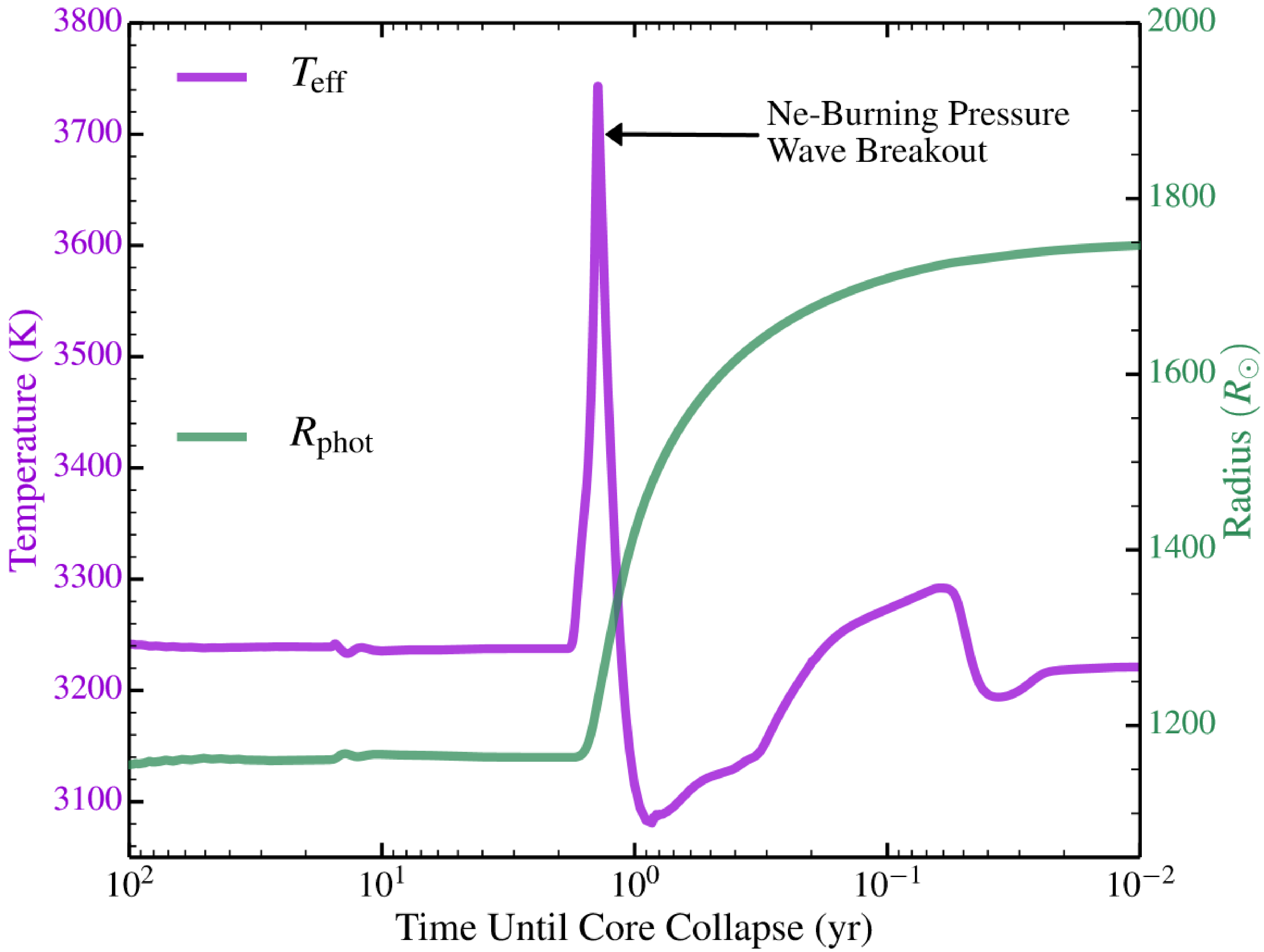
$$M_{\rm damp} = \frac{4\pi\rho r^2 c_s^3}{\omega^2 K} = \frac{3\pi\rho^3 r^2 c_s^3 c_p \kappa}{4\sigma_{\rm SB}\omega^2 T^3}$$


He Core
H Envelope
$E_{\rm bind,ext}$
$\rho_{\rm O-burn}$
$\rho_{\rm C-burn}$
$E_{\rm bind,ext}$ (erg)
10^{51}
10^{49}
10^{47}
10^{45}
ρ (g/cm^3)
10^{6}
10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-12}
0
2
4
6
8
10
12
Mass ($M_\odot$)

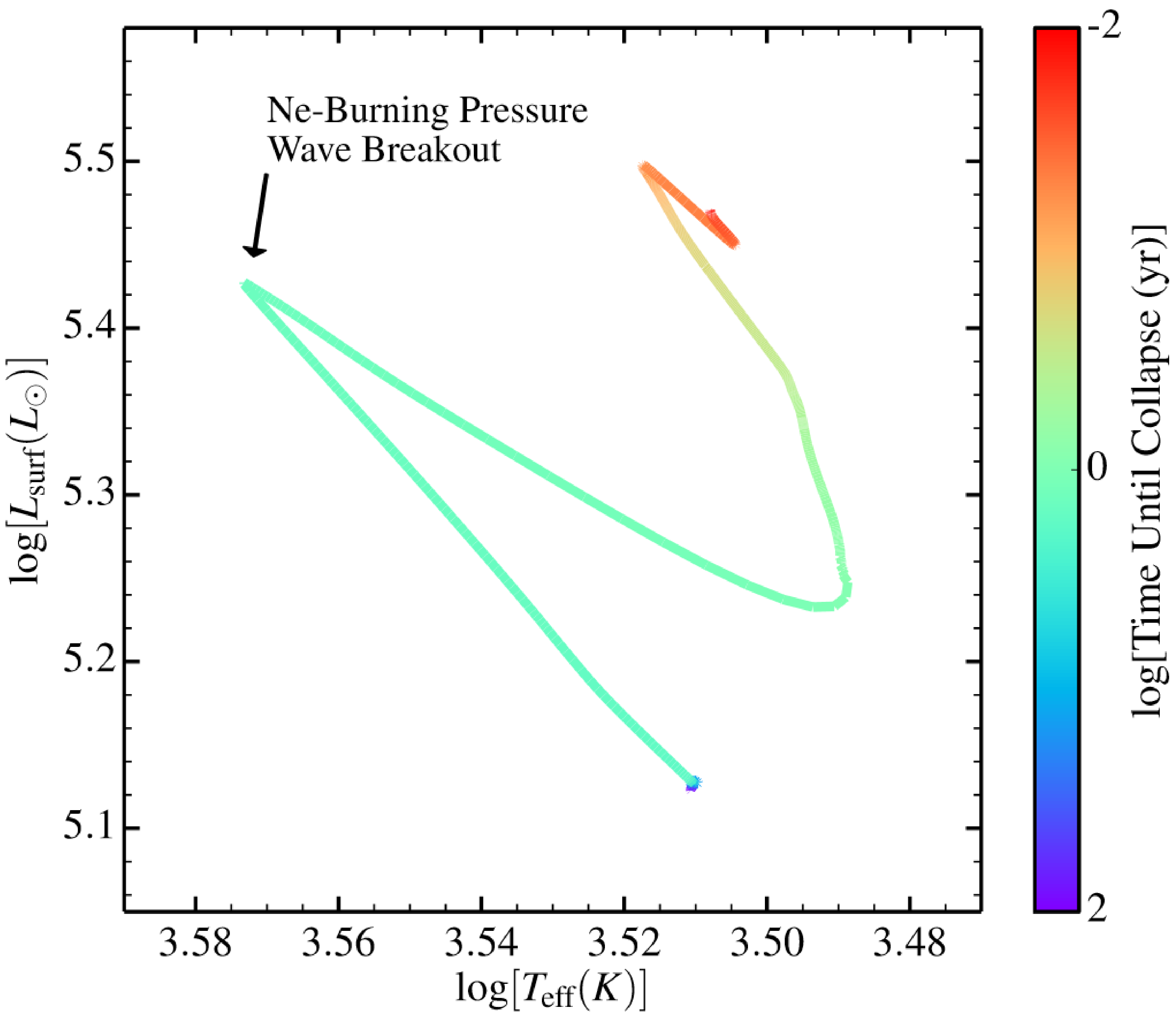

Wave Heating ($L_\odot$)
10^3
10^4
10^5
10^6
10^7
$L_{\mathrm{heat}}(r)$
M_{damp}
M_{damp} ($M_\odot$)
10^7
10^5
10^3
10^1
10^{-1}
10^{-3}
10^{-5}
10^{-7}
0
2
4
6
8
10
12
Mass ($M_\odot$)

$15\ M_{sun}$ Red Supergiant

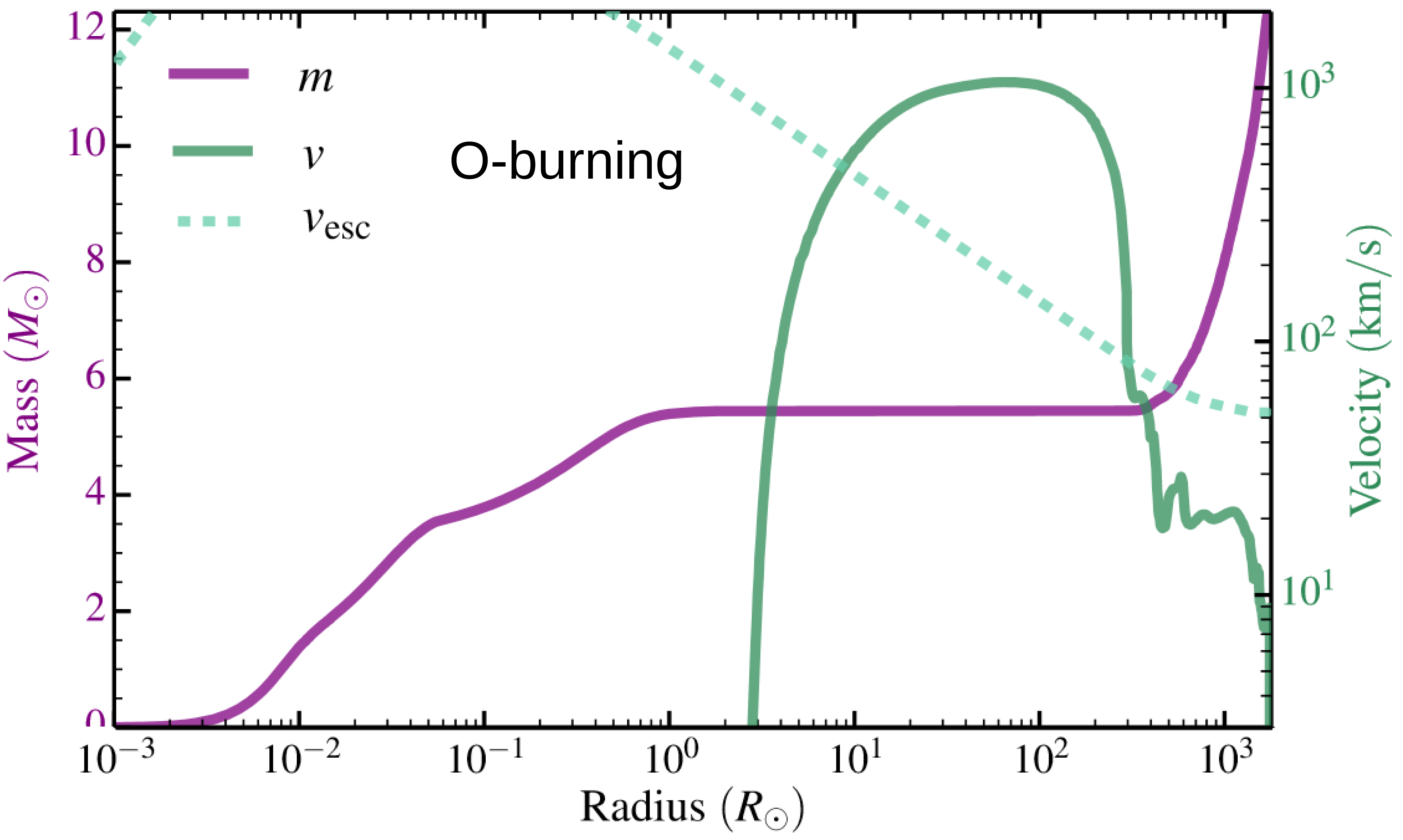

Ne-Burning Pressure Wave Breakout
Velocity (km/s)
0
5
10
15
20
Radius ($R_\odot$)
0
200
400
600
800
1000
1200
Time Since Ne Ignition (yr)
0.00
0.06
0.12
0.18
0.24
0.30
0.36
0.42
0.48
0.54

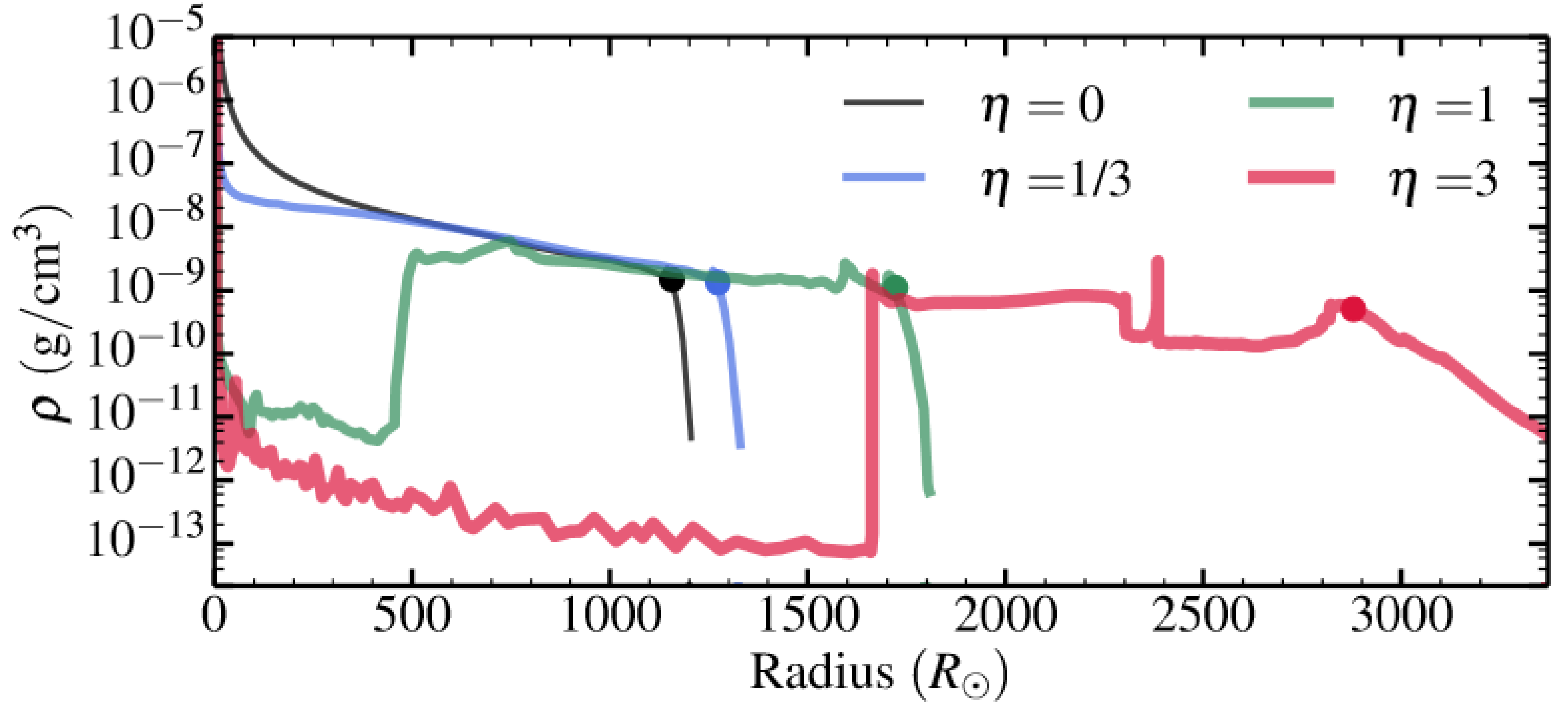


$T_{\rm eff}$
$R_{\rm phot}$
Ne-Burning Pressure Wave Breakout
Temperature (K)
3800
3700
3600
3500
3400
3300
3200
3100
Radius ($R_\odot$)
2000
1800
1600
1400
1200
10^2
10^1
10^0
10^{-1}
10^{-2}
Time Until Core Collapse (yr)



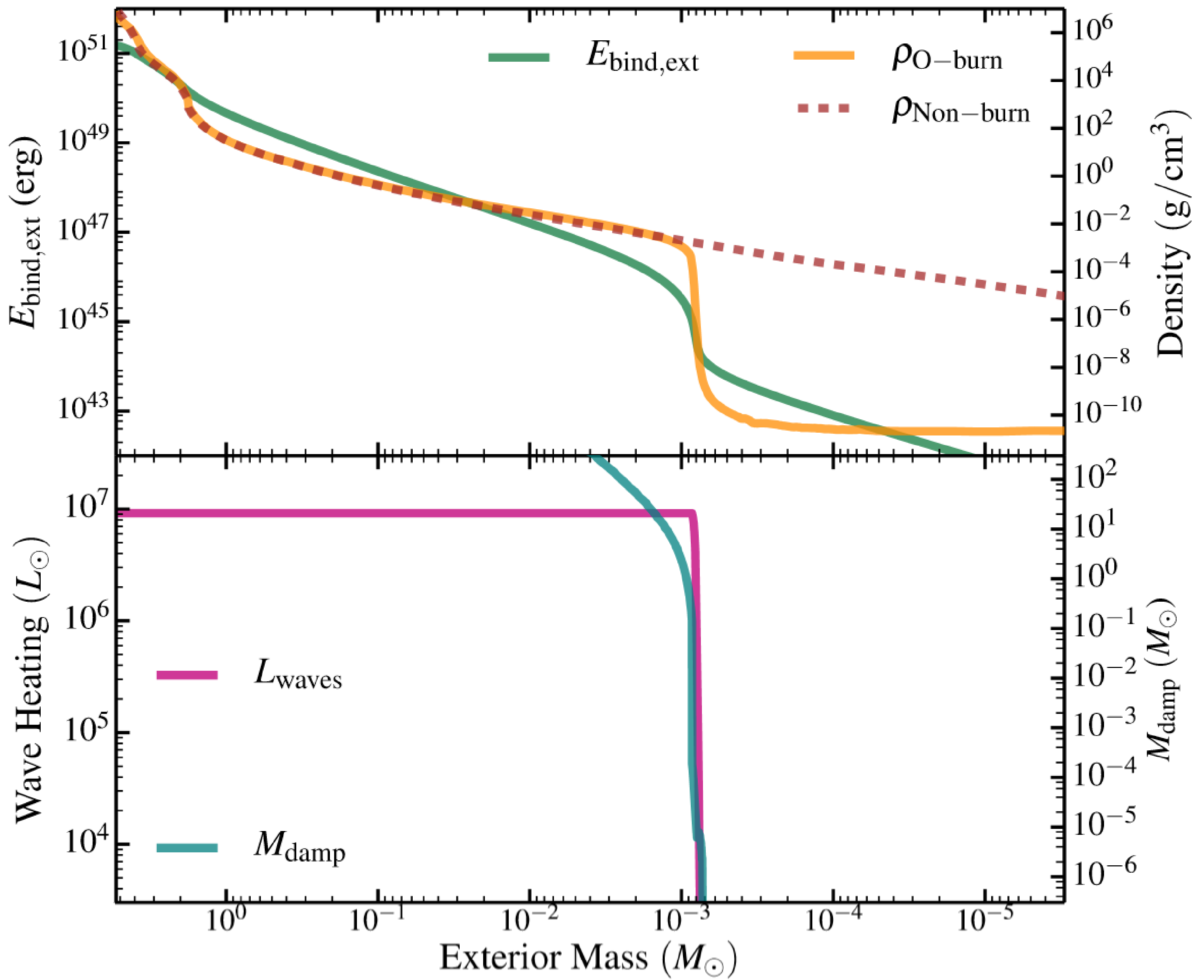
Brightening/dimming by factor of a few in last couple years

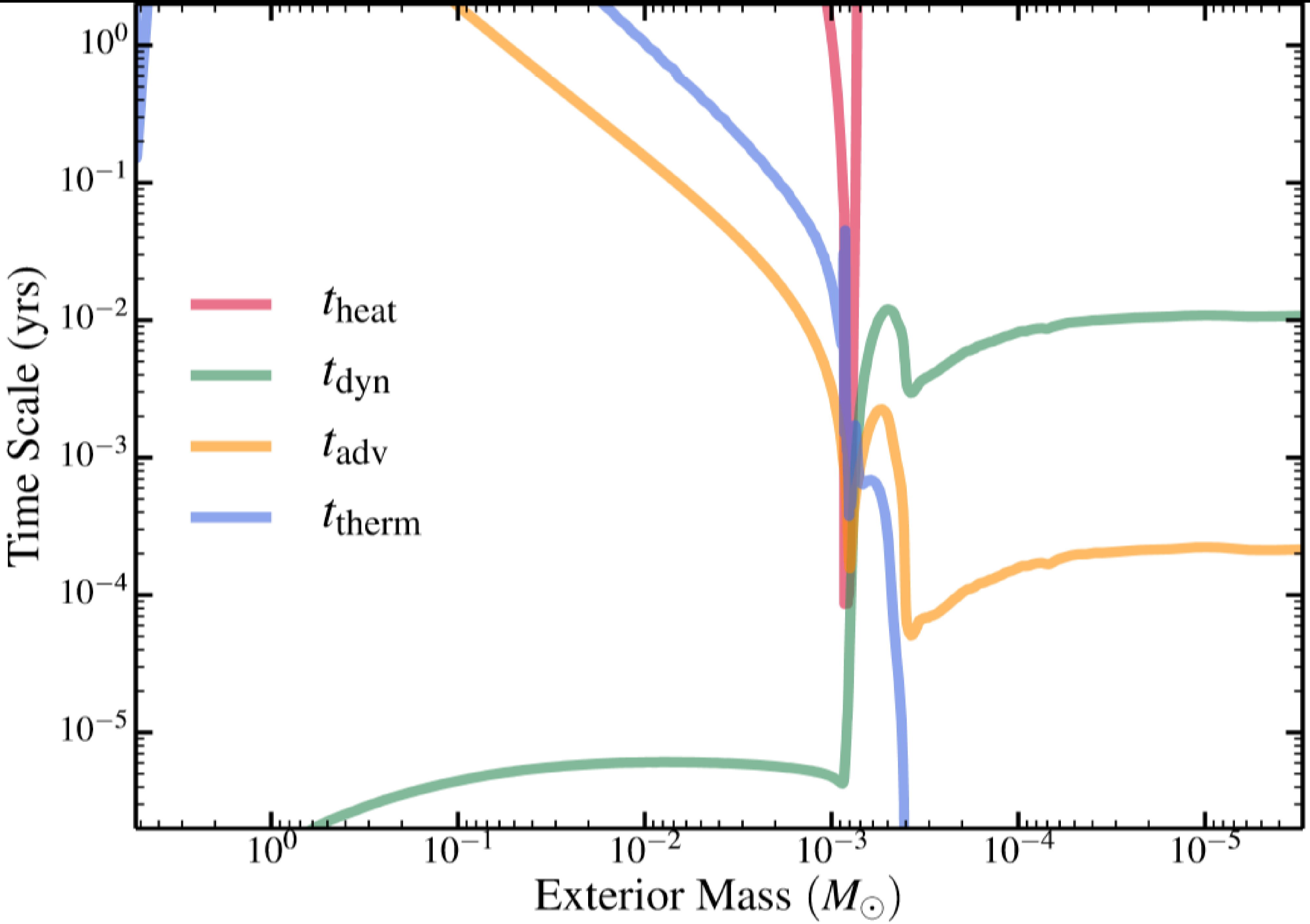

m
v
$v_{\rm esc}$
O-burning
Mass ($M_\odot$)
0
2
4
6
8
10
12
Velocity (km/s)
10^1
10^2
10^3
Radius ($R_\odot$)
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3

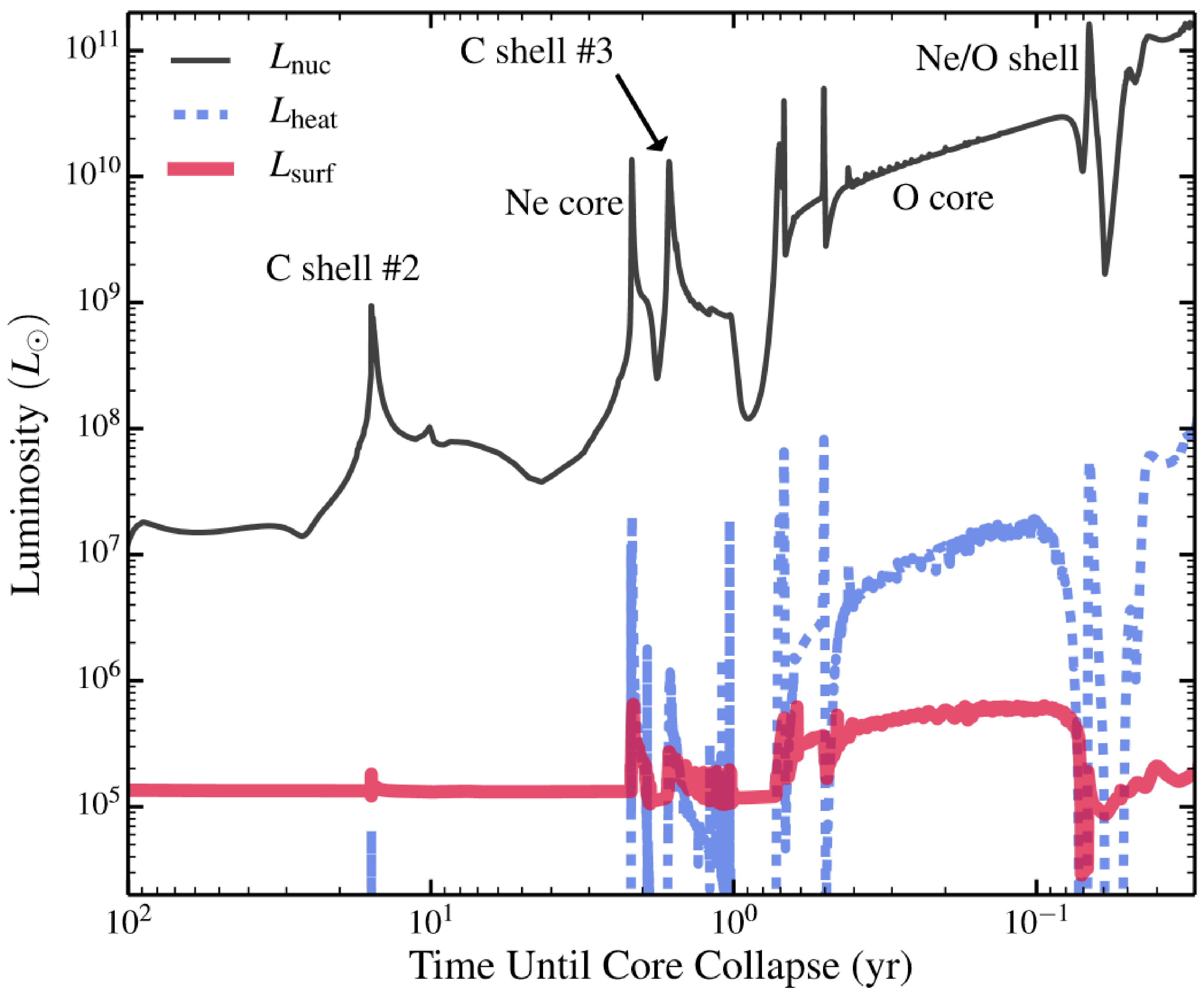

$\eta = 0$
$\eta = 1/3$
$\eta = 1$
$\eta = 3$
ρ (g/cm^3)
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
0
500
1000
1500
2000
2500
3000
Radius ($R_\odot$)

Stripped Stars

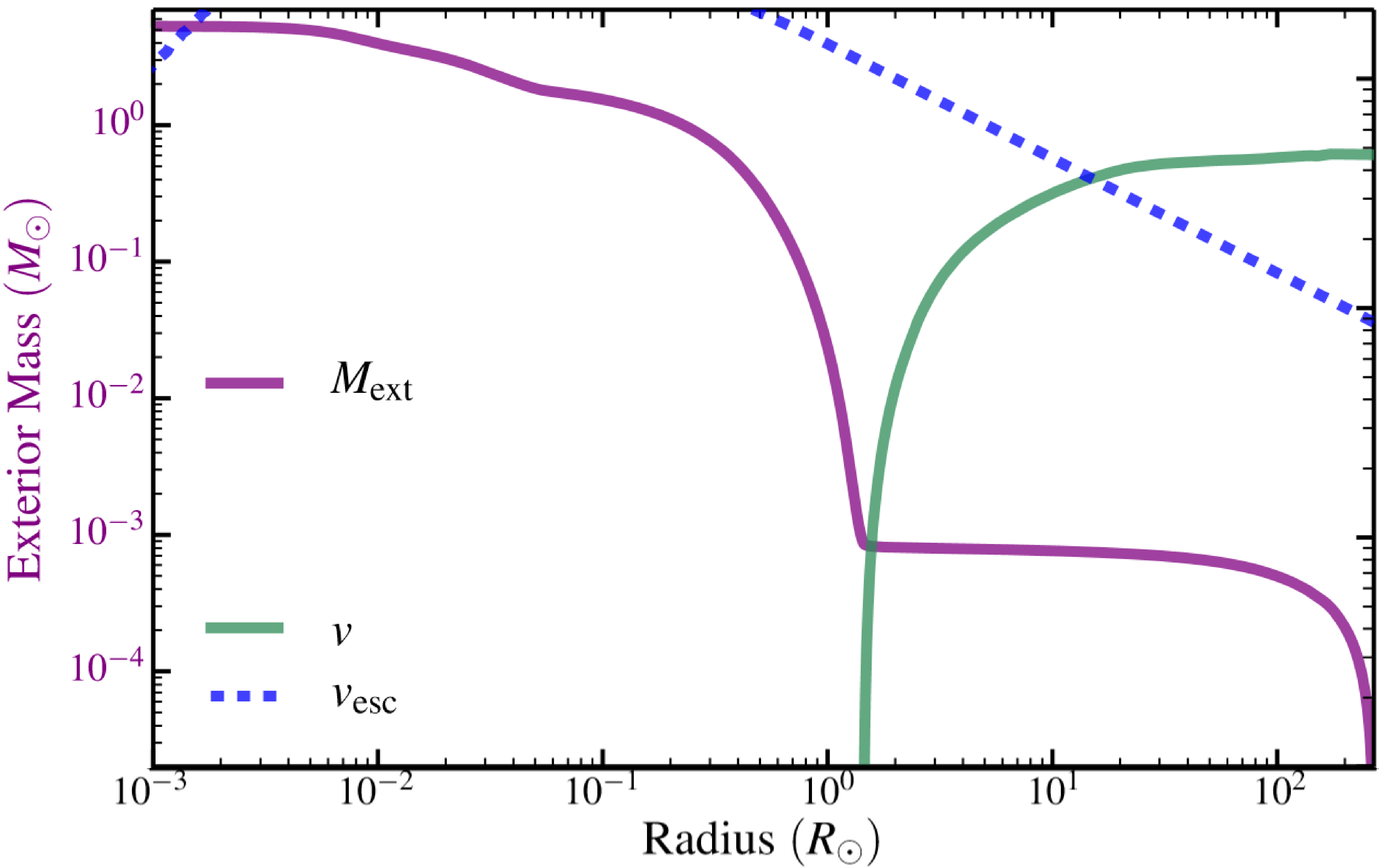
- No thick hydrogen envelope
- Waves still damp at edge of helium core, but now there is very little mass above wave heating region
- Wave heat unbinds atmosphere and launches continuum-driven super-Eddington wind

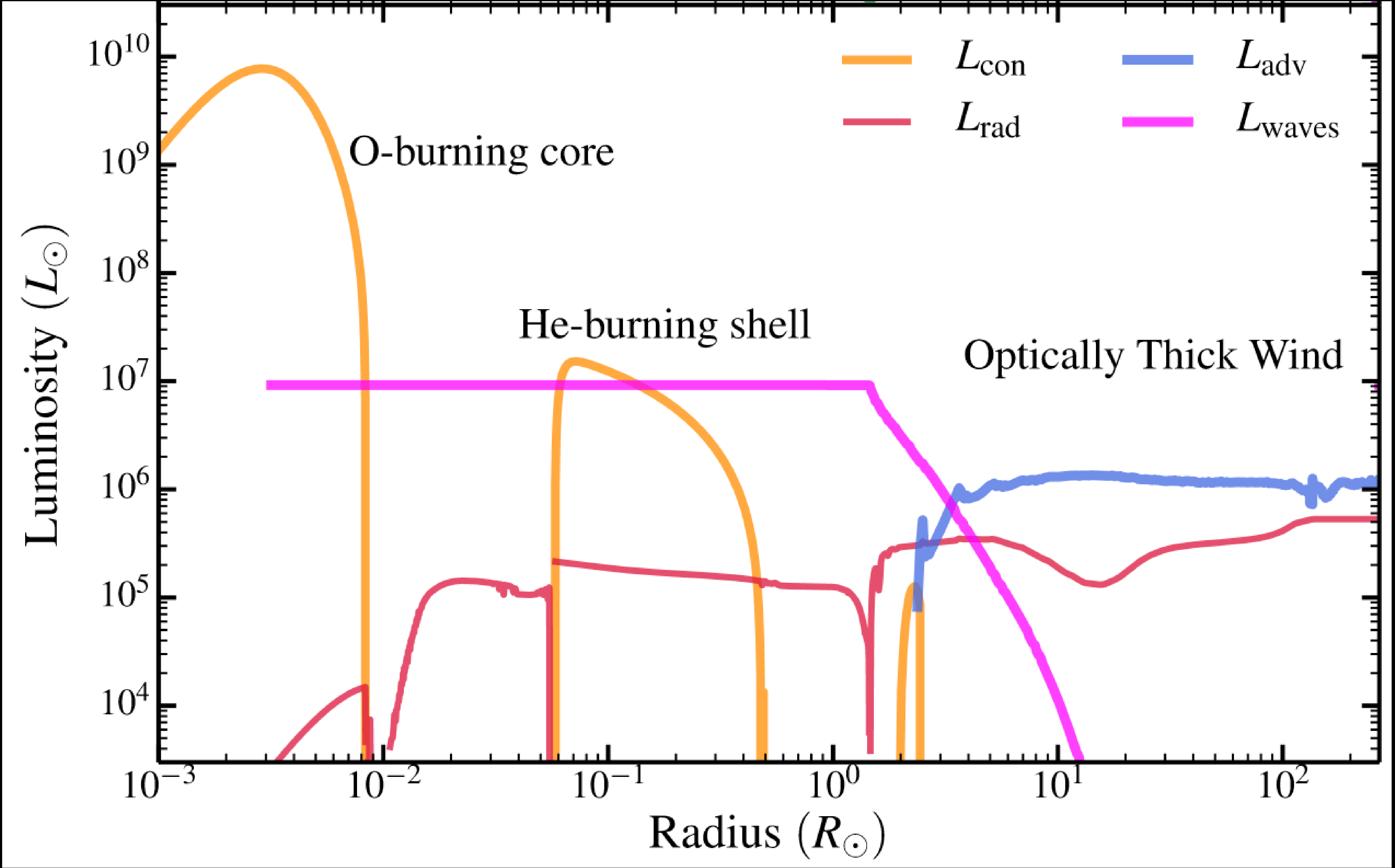


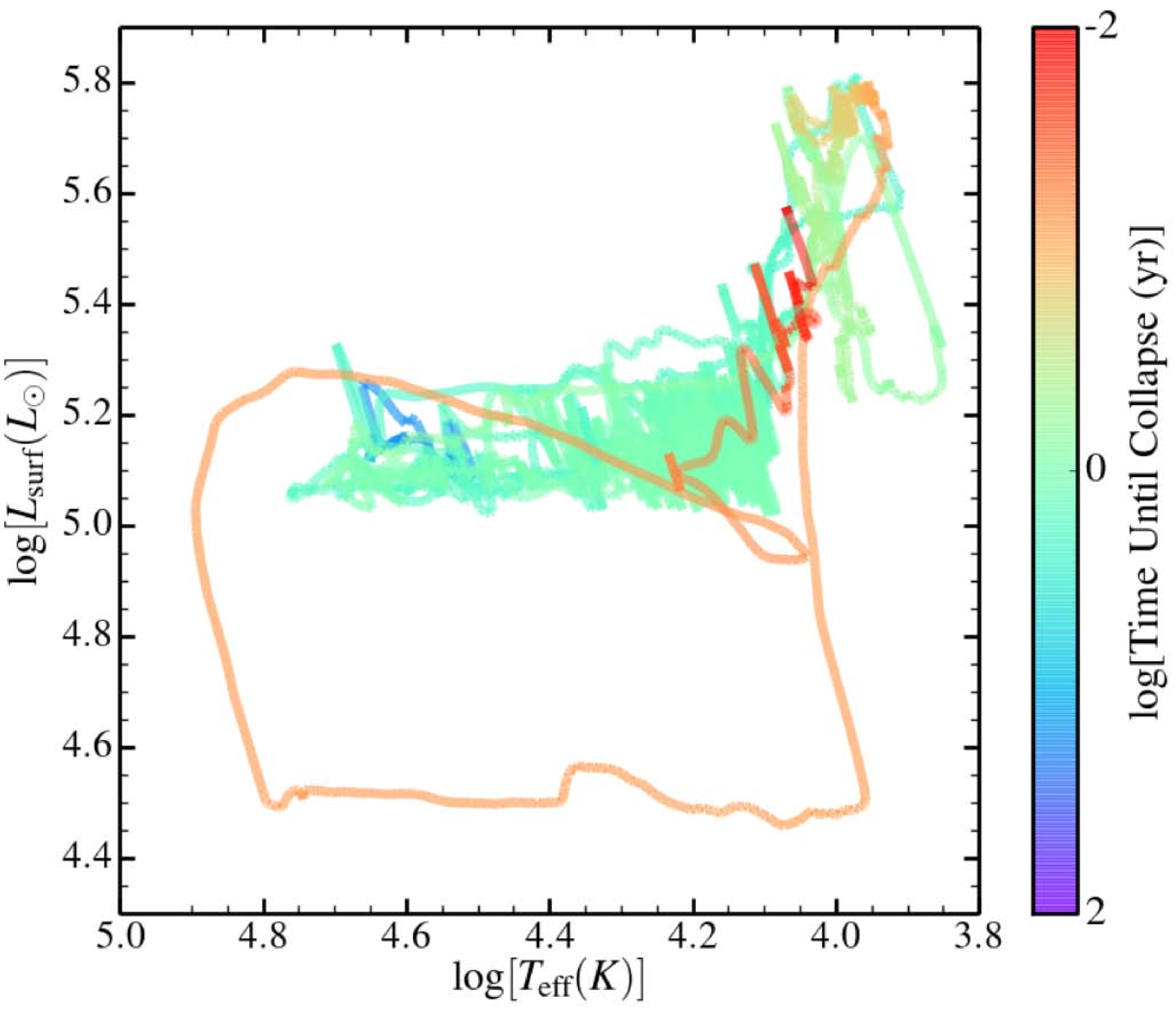

t_{heat}
t_{dyn}
t_{adv}
t_{therm}
Time Scale (yrs)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
Exterior Mass ($M_{\odot}$)
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}

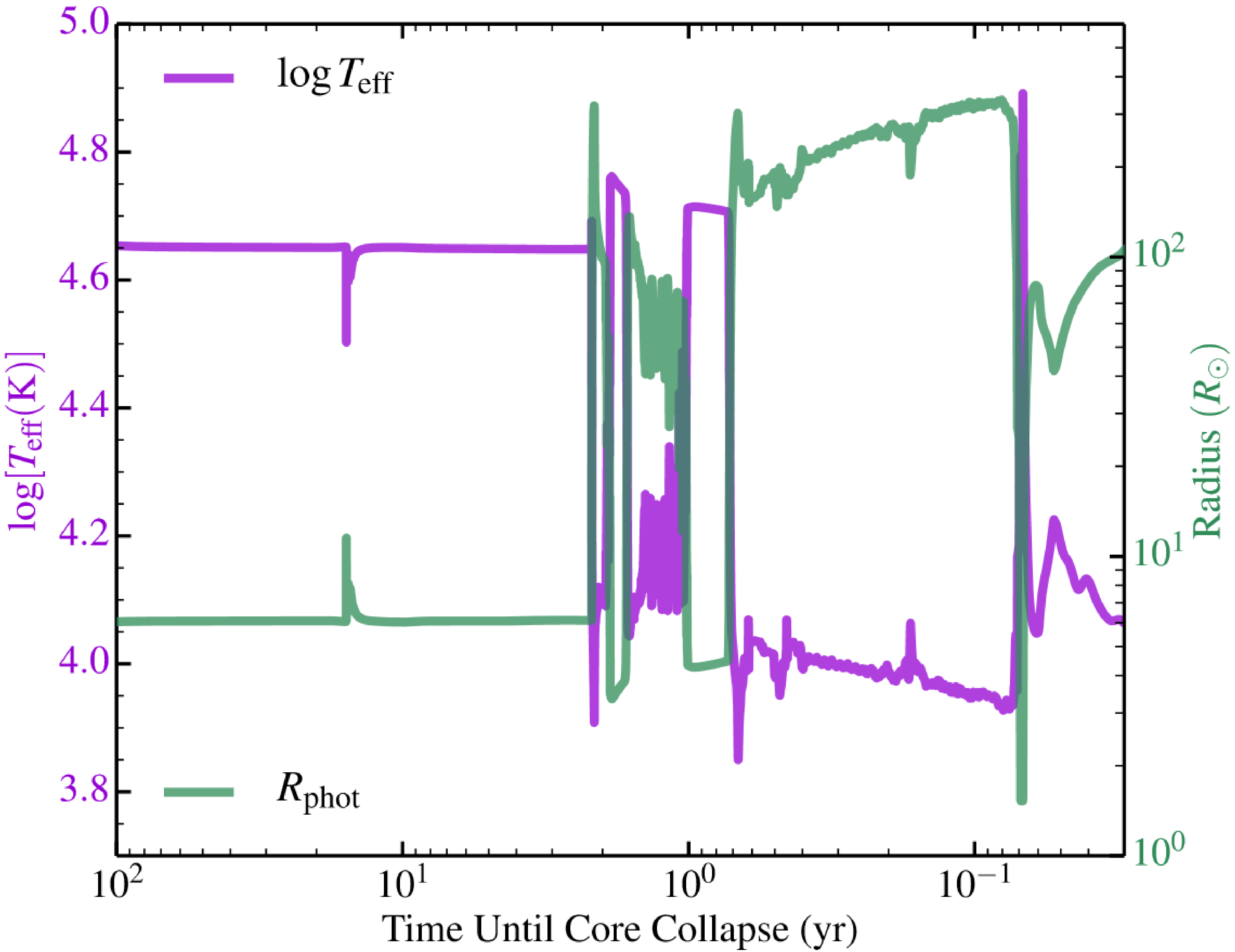


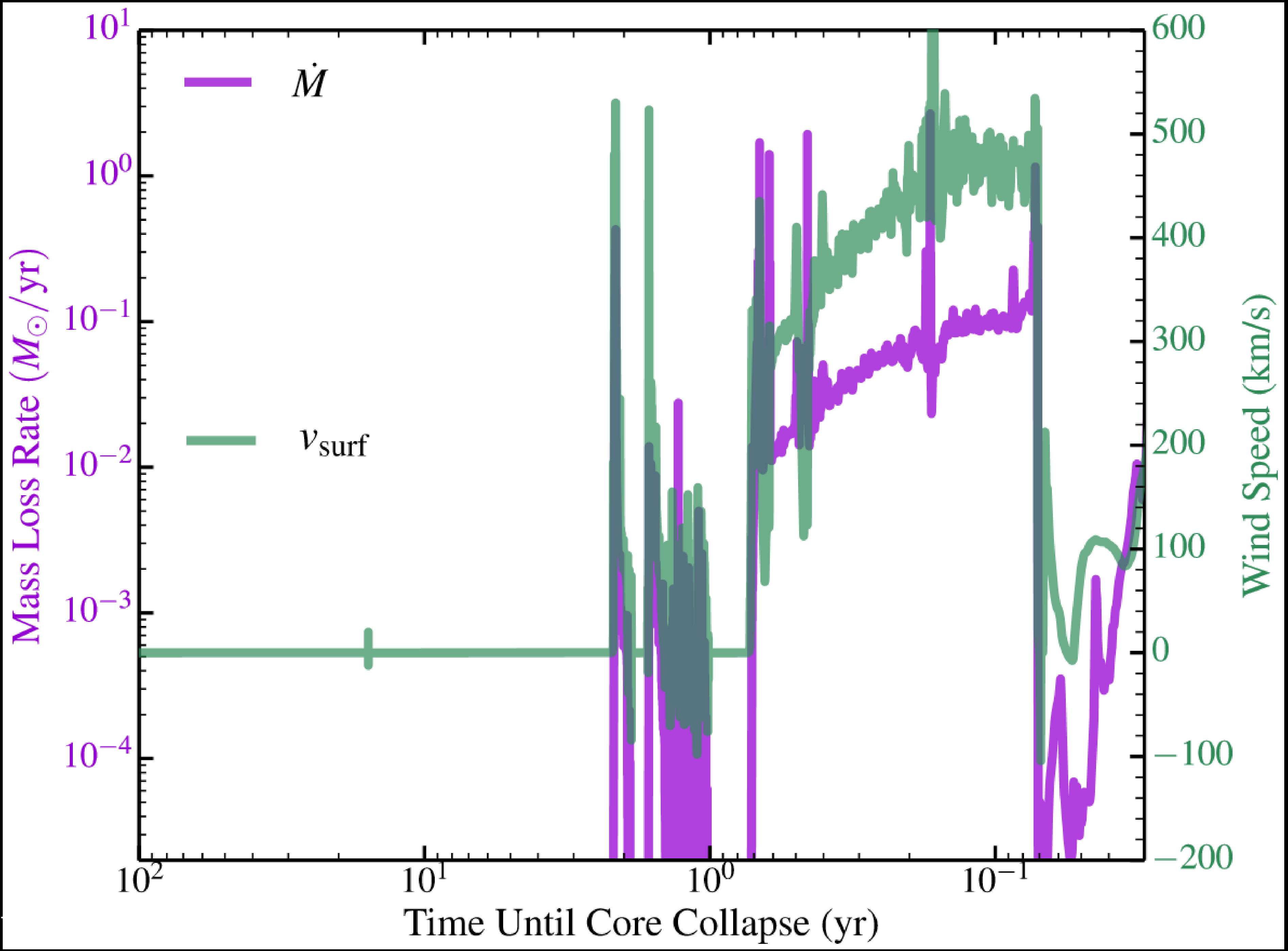
$L_{\rm nuc}$
$L_{\rm heat}$
$L_{\rm surf}$
C shell #3
Ne/O shell
Ne core
O core
C shell #2
Luminosity ($L_\odot$)
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{2}
10^{1}
10^{0}
10^{-1}
Time Until Core Collapse (yr)


Exterior Mass ($M_\odot$)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Velocity (km/s)
10^3
10^2
10^1
10^0
Radius ($R_\odot$)
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
$M_{\rm ext}$
v
$v_{\rm esc}$


$L_{\rm con}$
$L_{\rm adv}$
$L_{\rm rad}$
$L_{\rm waves}$
O-burning core
He-burning shell
Optically Thick Wind
Luminosity ($L_\odot$)
Radius ($R_\odot$)
10^{10}
10^9
10^8
10^7
10^6
10^5
10^4
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2


log[$L_{\rm surf}(L_\odot)$]
5.8
5.6
5.4
5.2
5.0
4.8
4.6
4.4
log[$T_{\rm eff}(K)$]
5.0
4.8
4.6
4.4
4.2
4.0
3.8
log[Time Until Collapse (yr)]
-2
0
2


5.0
4.8
4.6
4.4
4.2
4.0
3.8
$\log[T_{\rm eff}(\rm K)]$
10^2
10^1
10^0
Radius ($R_\odot$)
10^2
10^1
10^0
10^{-1}
Time Until Core Collapse (yr)
$\log T_{\rm eff}$
$R_{\rm phot}$


$\dot{M}$
$v_{\rm surf}$
Mass Loss Rate ($M_\odot$/yr)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Wind Speed (km/s)
600
500
400
300
200
100
0
−100
−200
10^{2}
10^{1}
10^{0}
10^{-1}
Time Until Core Collapse (yr)

Conclusions and Discussion

- Wave heating in RSGs creating Type II SNe can cause mild outbursts, enhanced mass loss (up to ~1 M_{sun}) in final years before SNe
    - Wave heating unlikely to lead to very luminous Type IIn Sne

- Wave heating is very good candidate to create flash-ionized SNe

- Heating affects envelope density structure, likely contributes to type II SNe diversity

- Unlikely to substantially alter core structure (binding energy ~10^{51} erg)

Bonus Material!

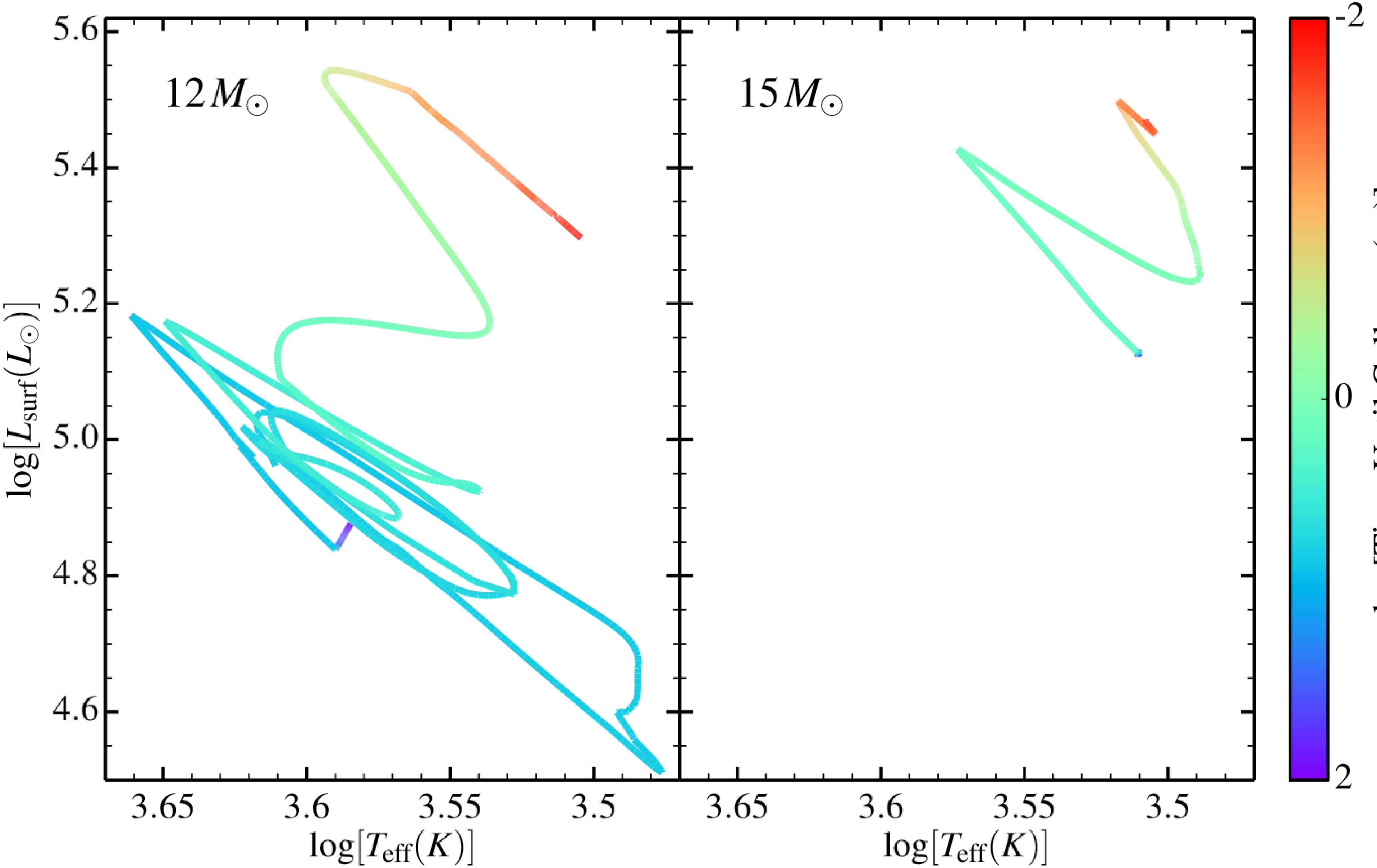
Caveats

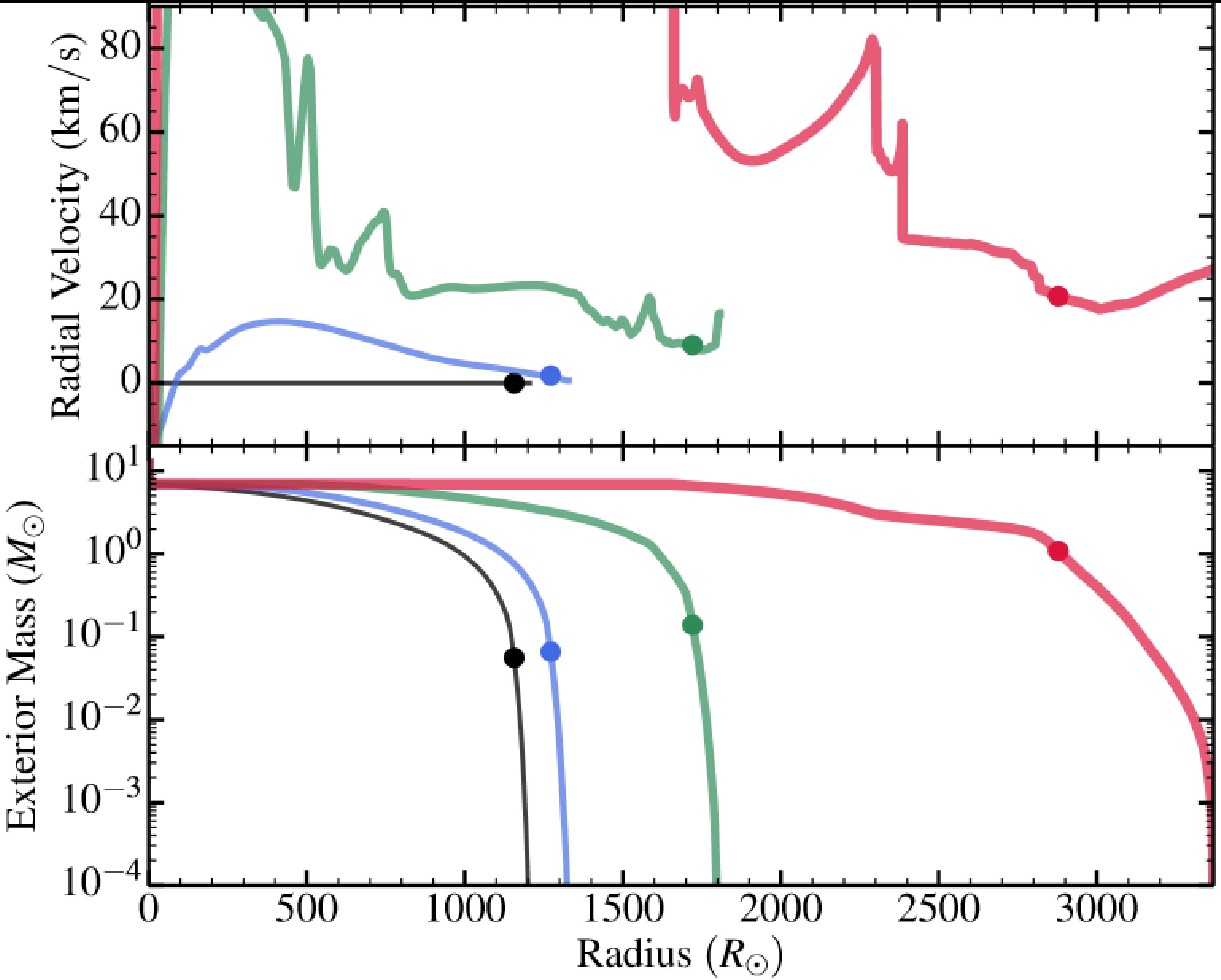
- Binaries, rotation, and magnetic fields
  - Radial expansion may trigger binary interaction → IIn supernova (Mcley & Soker 2014)
  - Core magnetic fields can inhibit gravity wave propagation (talk by Cantiello)

- Hard to explain IIbs, small variability of 2011dh (Szczygieł et al. 2012, Hosseinzadeh et al. 2015), small radius/mass loss of iPTF2013bvn (Cao et al. 2013)

- Progenitor landscape is complex

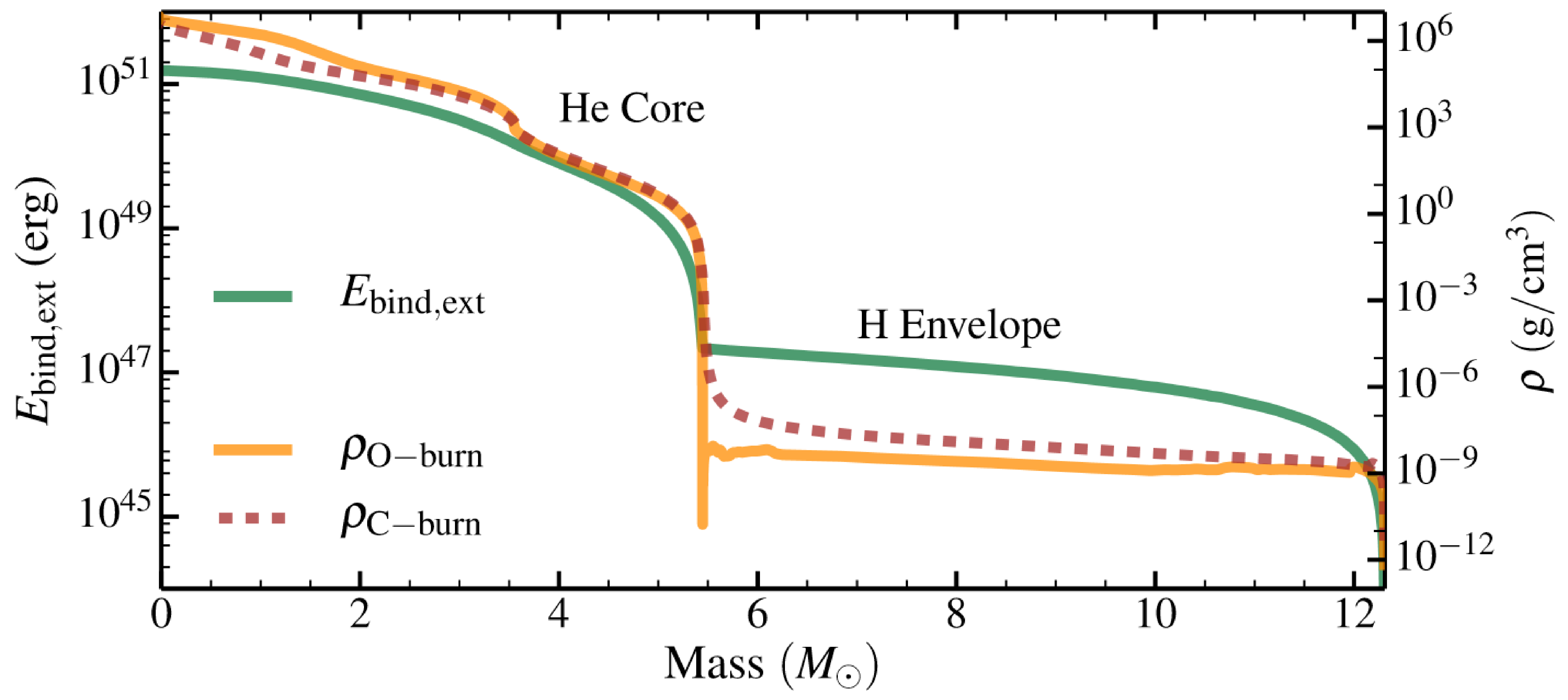
- Burning instabilities also possible (e.g., Meakin & Arnett 2006,2007,2016, Smith & Arnett 2014, Woosley & Heger 2015, Soker & Gilkis 2016,)

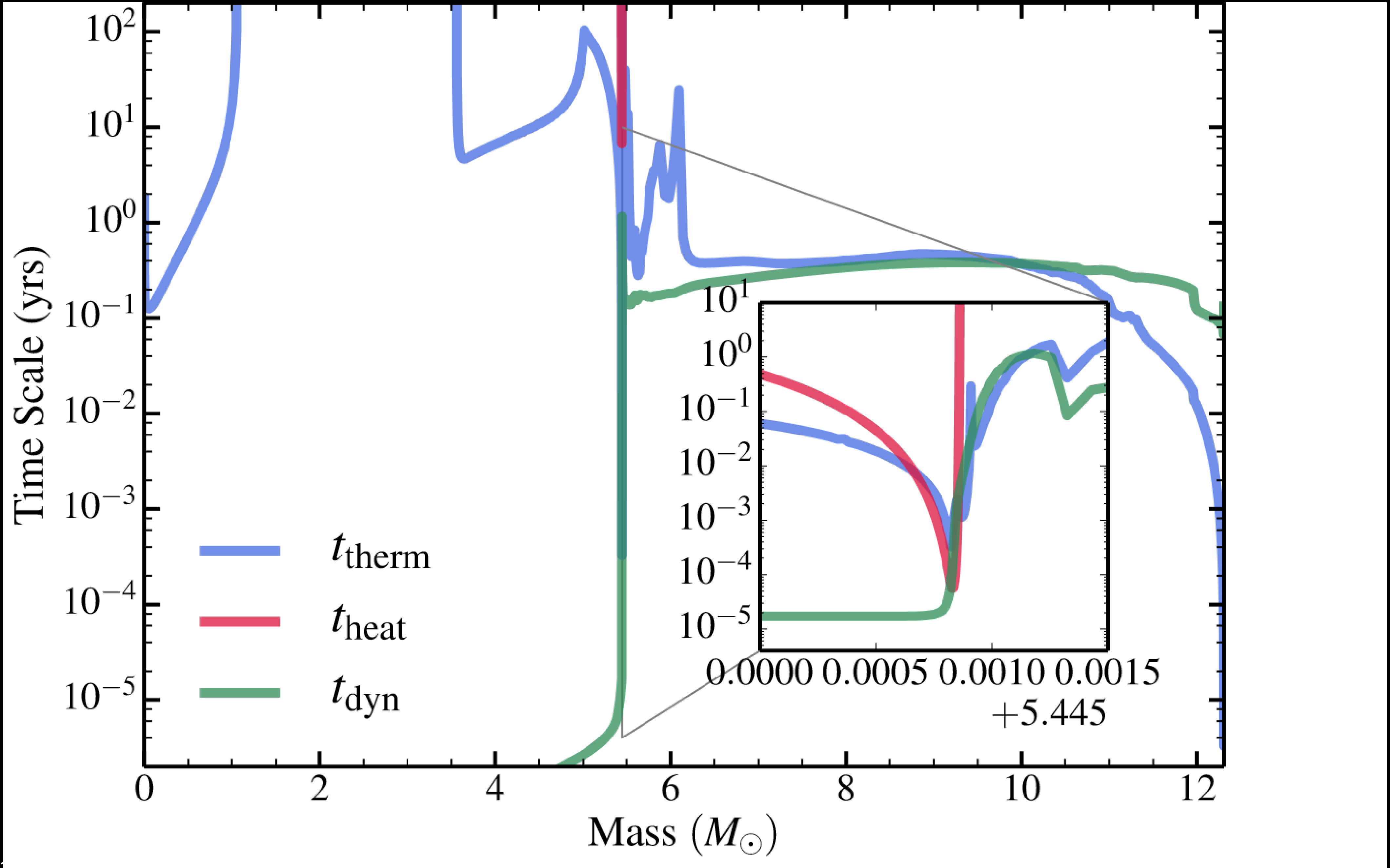

12 $M_\odot$
15 $M_\odot$
$\log[L_{\rm surf}(L_\odot)]$
5.6
5.4
5.2
5.0
4.8
4.6
$\log[T_{\rm eff}(K)]$
3.65
3.6
3.55
3.5
log[Time Until Collapse (yr)]
-2
0
2

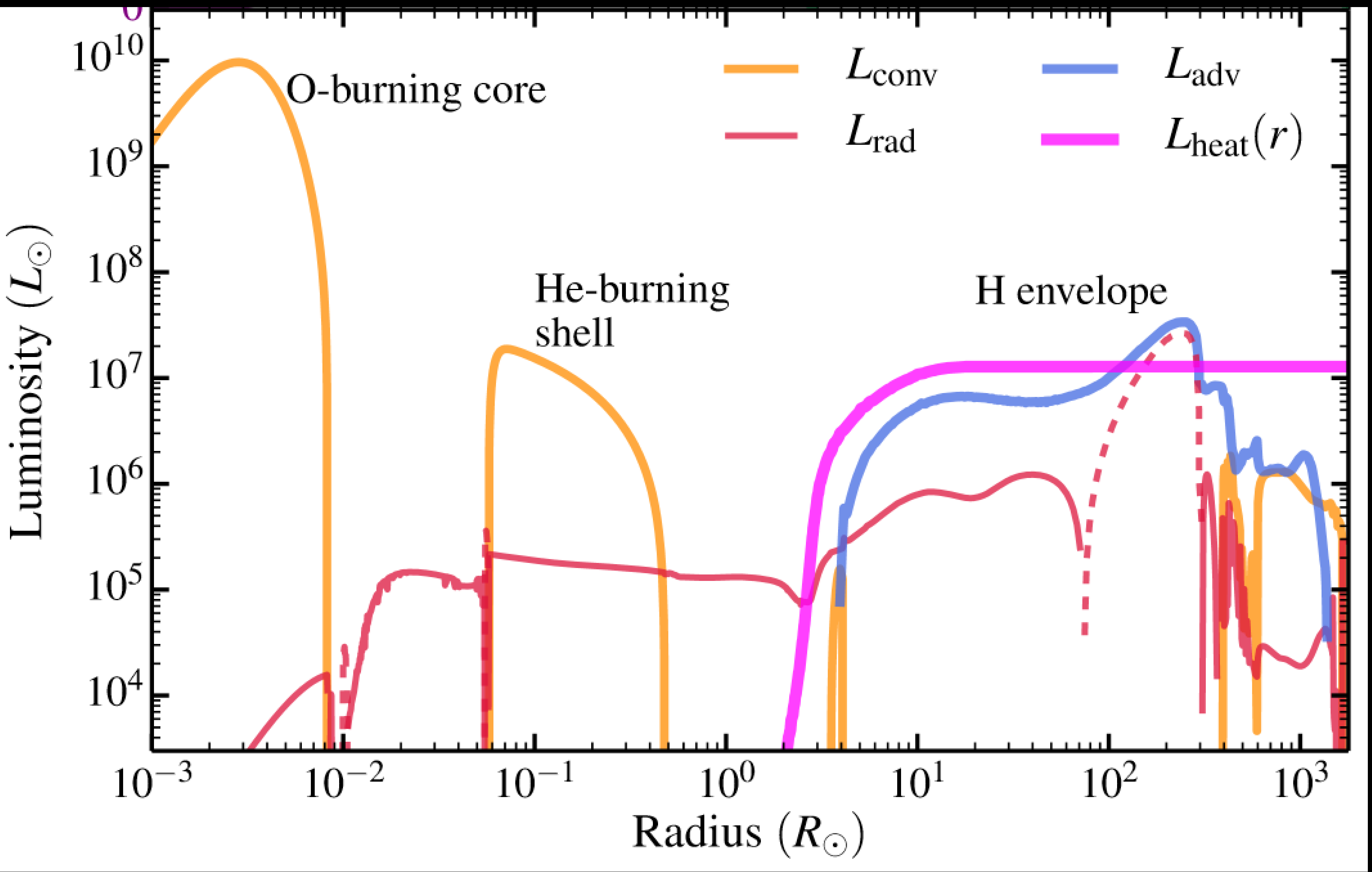


Radial Velocity (km/s)
80
60
40
20
0
Exterior Mass ($M_\odot$)
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
500
1000
1500
2000
2500
3000
Radius ($R_\odot$)

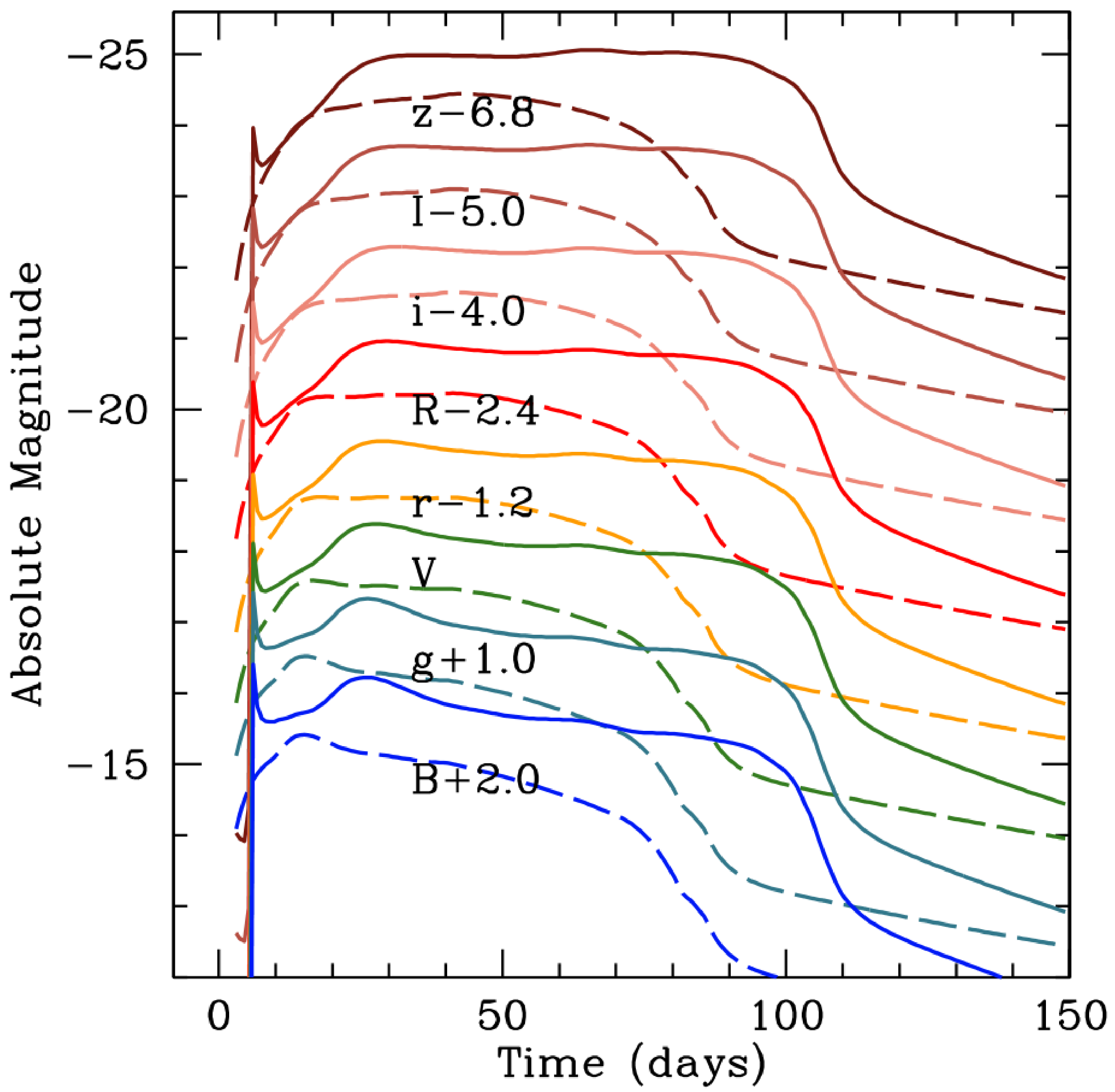
4/25/2017


10^{51}
10^{49}
10^{47}
10^{45}
$E_{\mathrm{bind,ext}}$ (erg)
10^{6}
10^{3}
10^{0}
10^{-3}
10^{-6}
10^{-9}
10^{-12}
ρ (g/cm^3)
He Core
H Envelope
$E_{\mathrm{bind,ext}}$
$\rho_{\mathrm{O-burn}}$
$\rho_{\mathrm{C-burn}}$
0
2
4
6
8
10
12
Mass ($M_\odot$)

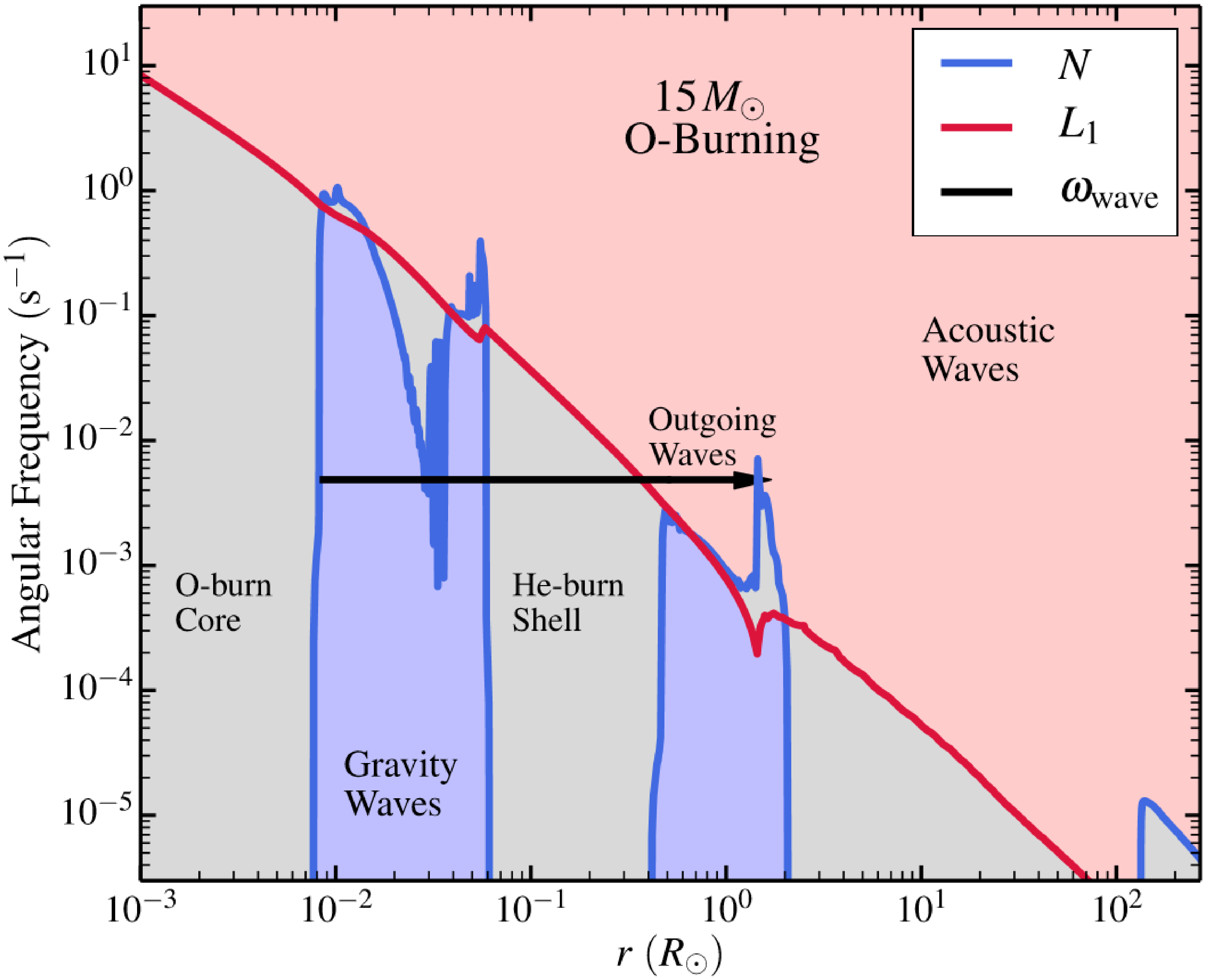

Time Scale (yrs)
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
Mass (M☉)
0
2
4
6
8
10
12
t_therm
t_heat
t_dyn
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
0.0000
0.0005
0.0010
0.0015
+5.445



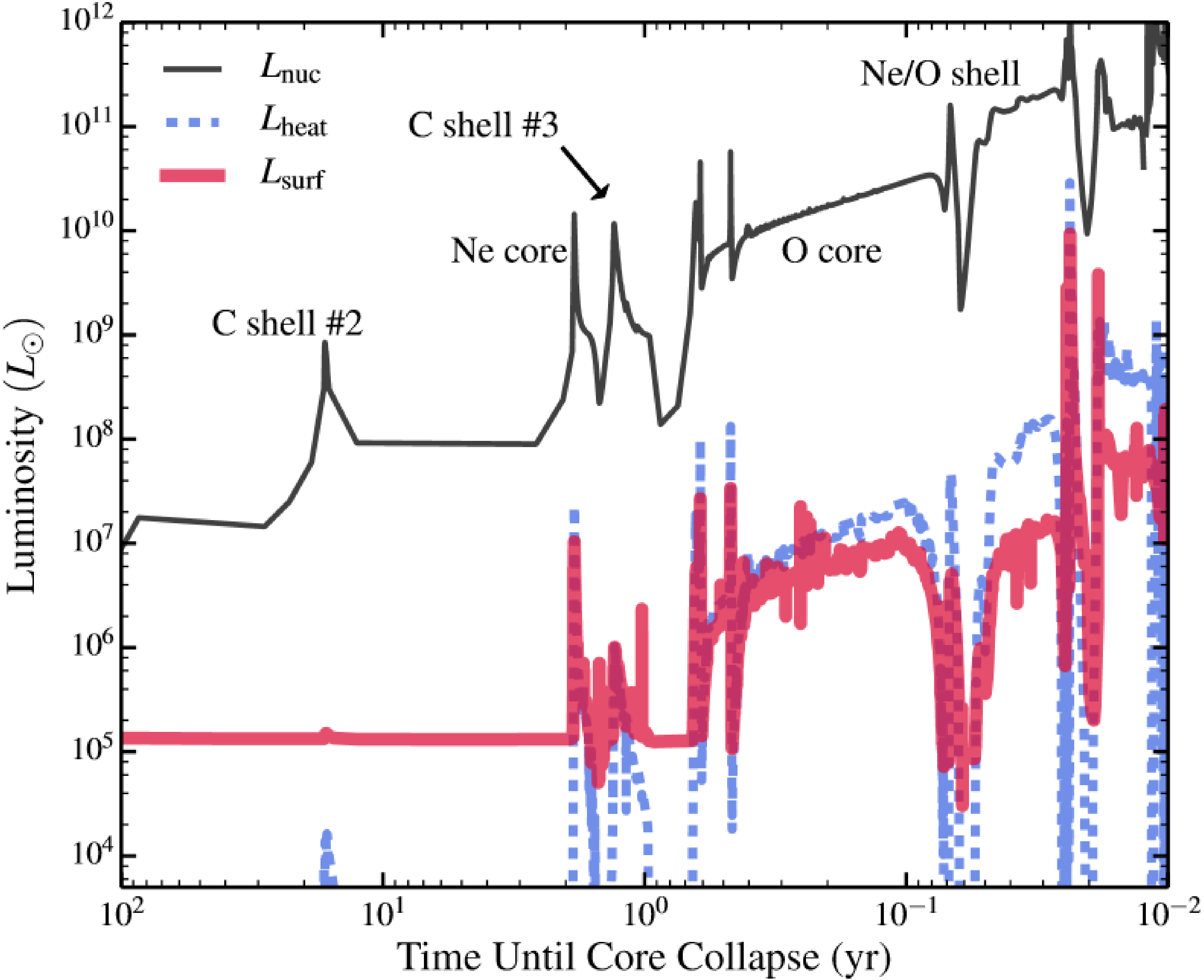
Luminosity $(L_\odot)$
Radius $(R_\odot)$
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
$L_{\rm conv}$
$L_{\rm adv}$
$L_{\rm rad}$
$L_{\rm heat}(r)$
O-burning core
He-burning shell
H envelope



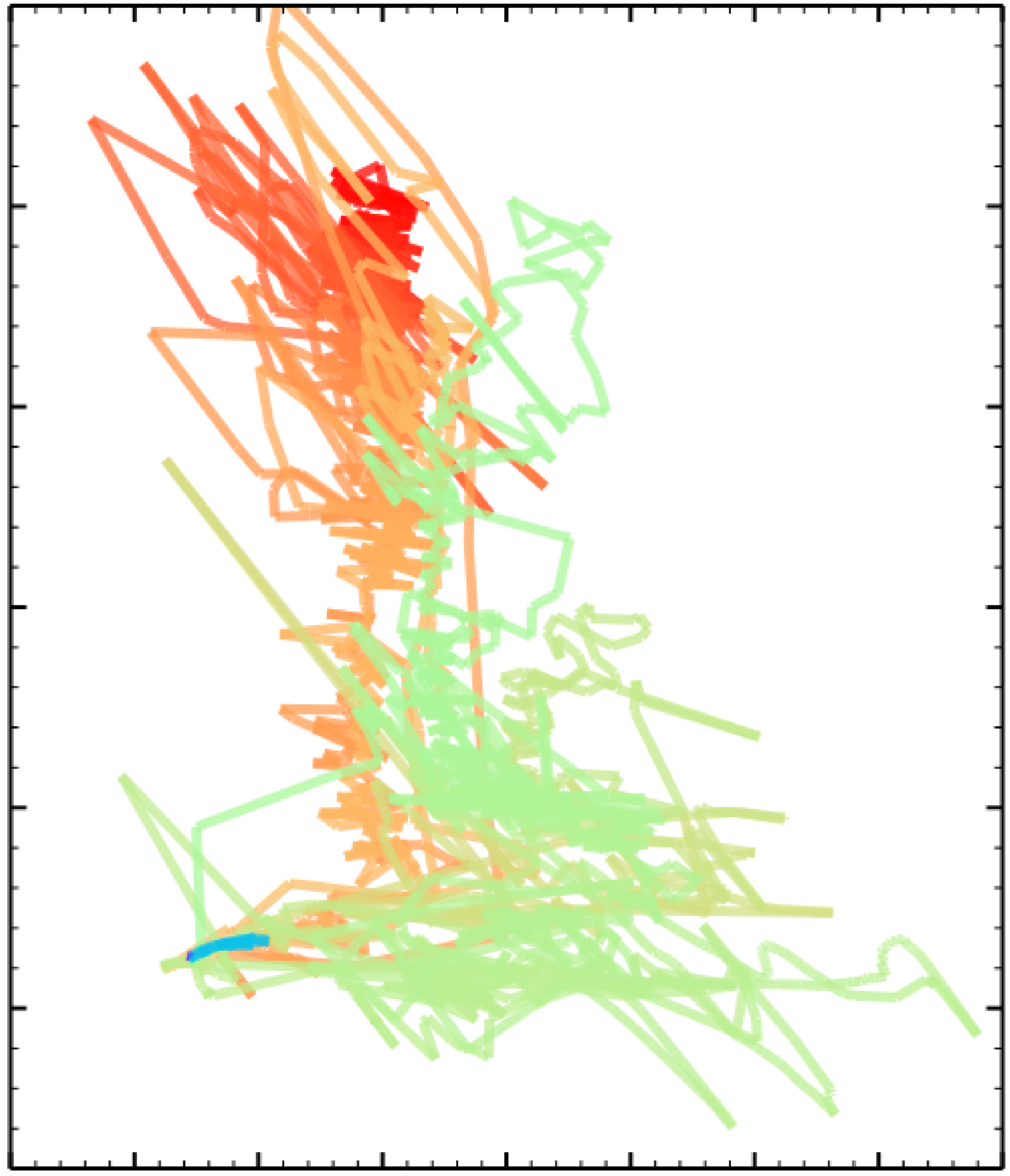
z−6.8
I−5.0
i−4.0
R−2.4
r−1.2
V
g+1.0
B+2.0
−25
−20
−15
Absolute Magnitude
0
50
100
150
Time (days)

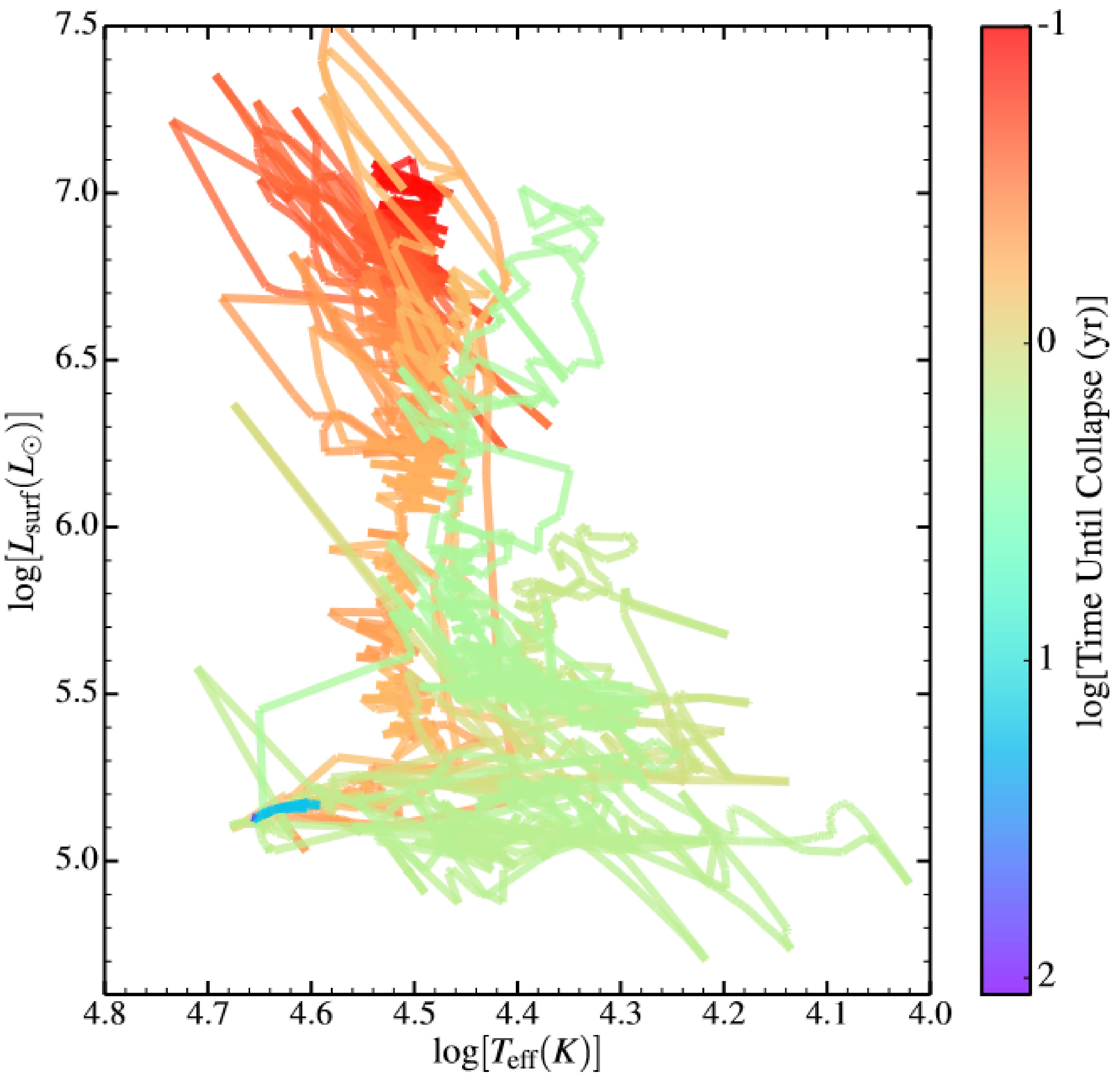


$15\,M_\odot$
O-Burning
N
L_1
$\omega_{\rm wave}$
Acoustic Waves
Outgoing Waves
O-burn Core
He-burn Shell
Gravity Waves
Angular Frequency ($\rm s^{-1}$)
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
r ($R_\odot$)

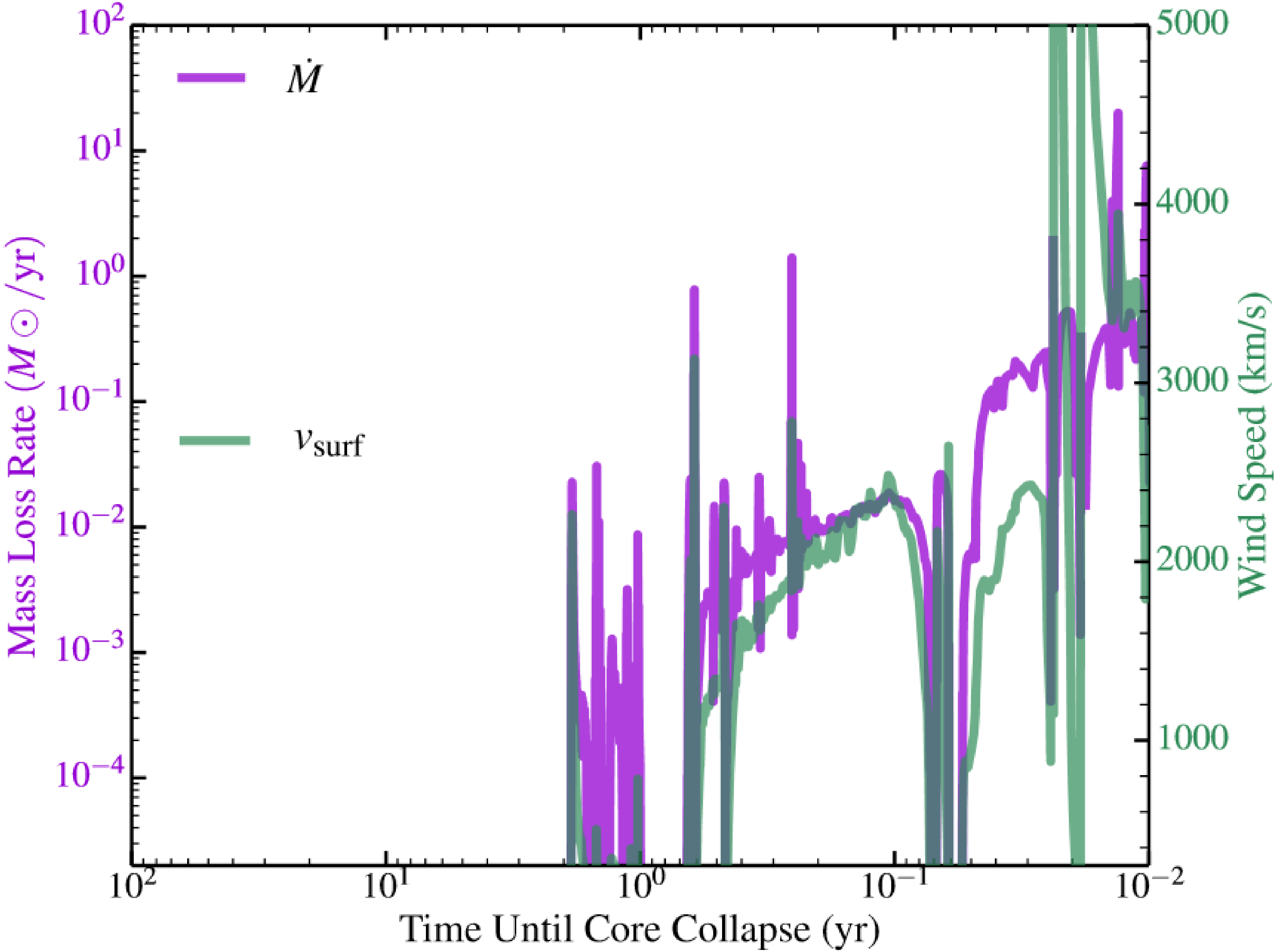


Short thermal time at wave heating region allows for bright outbursts at surface



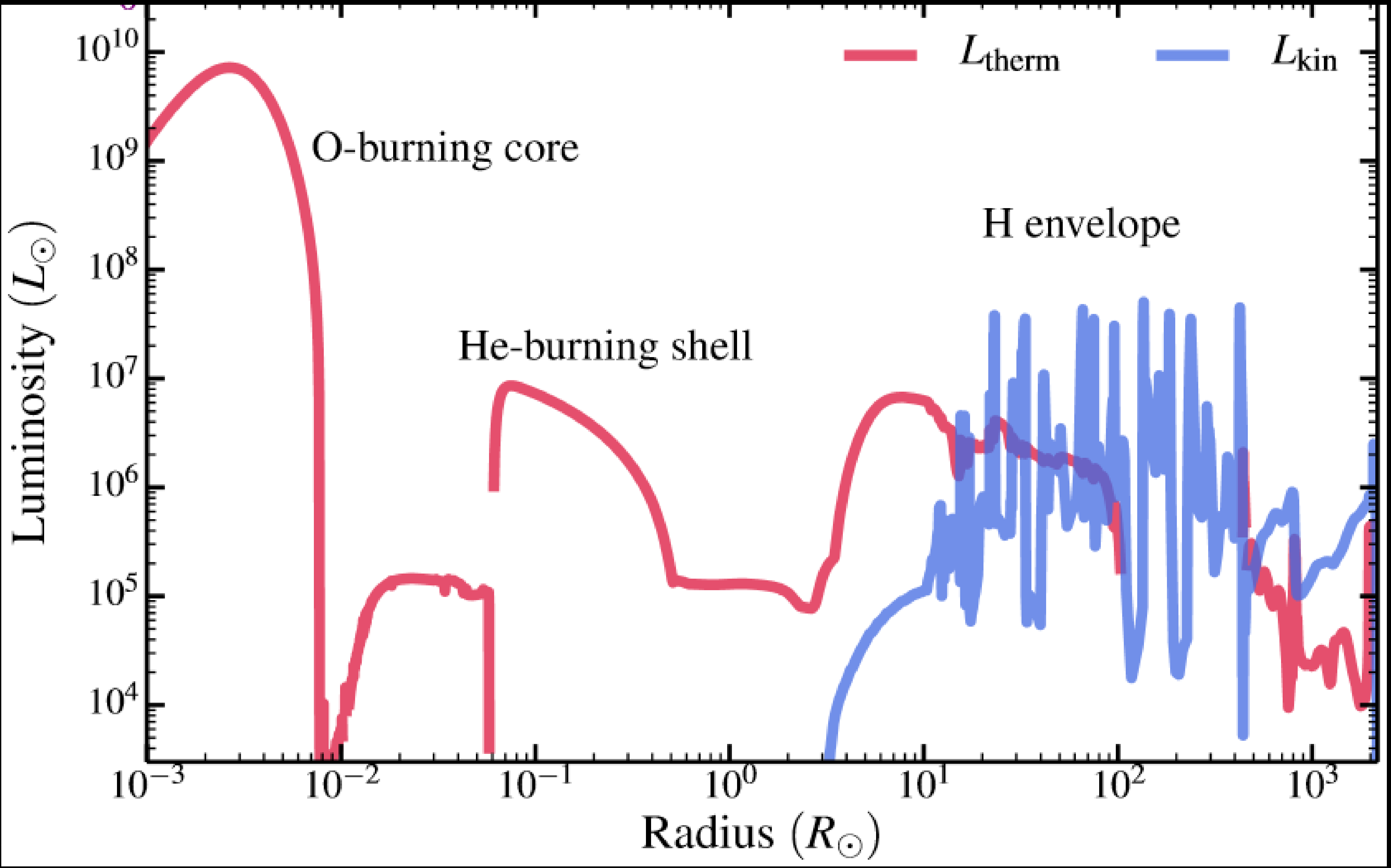


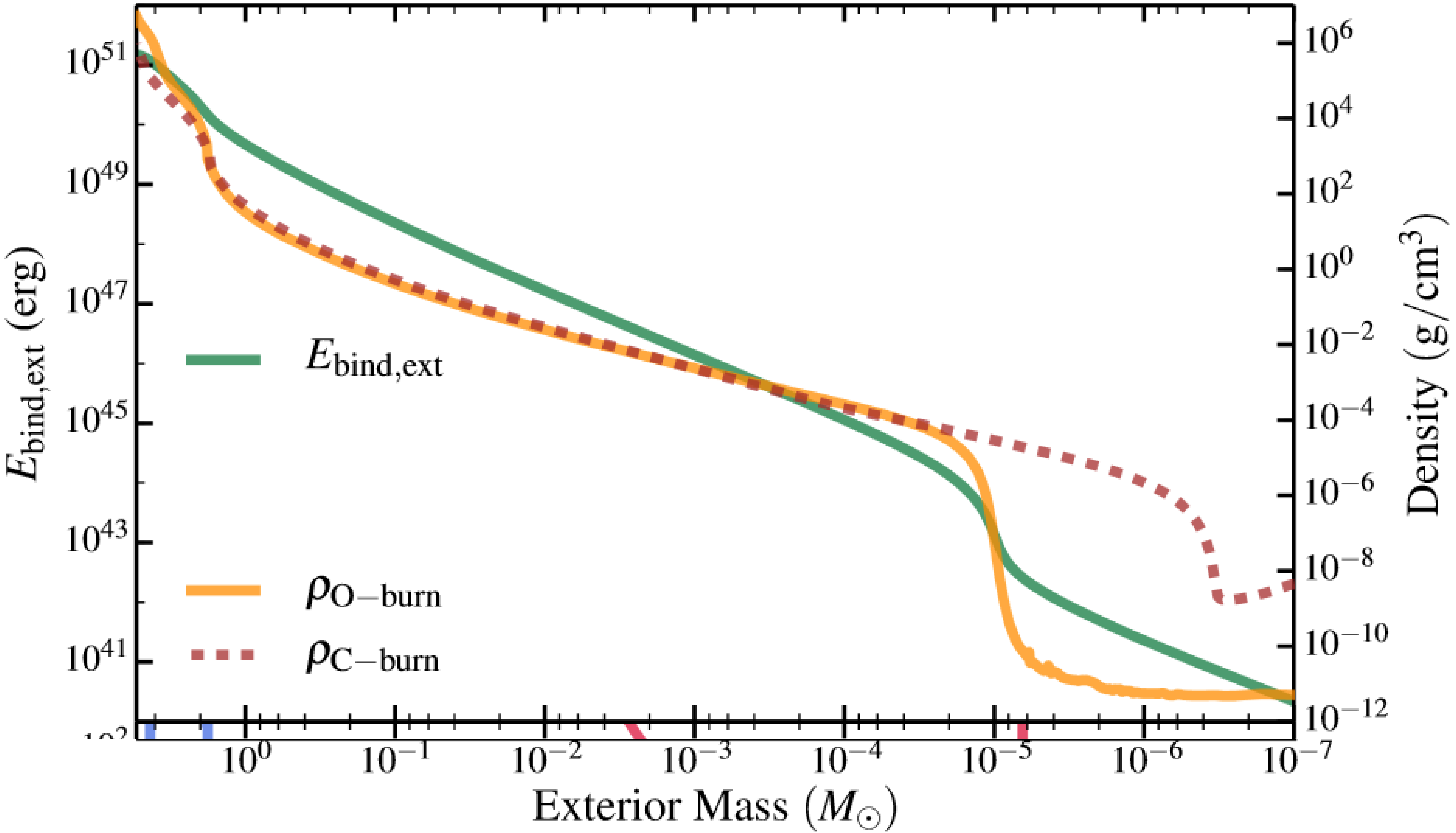
Extreme photometric variability limited to final ~3 years



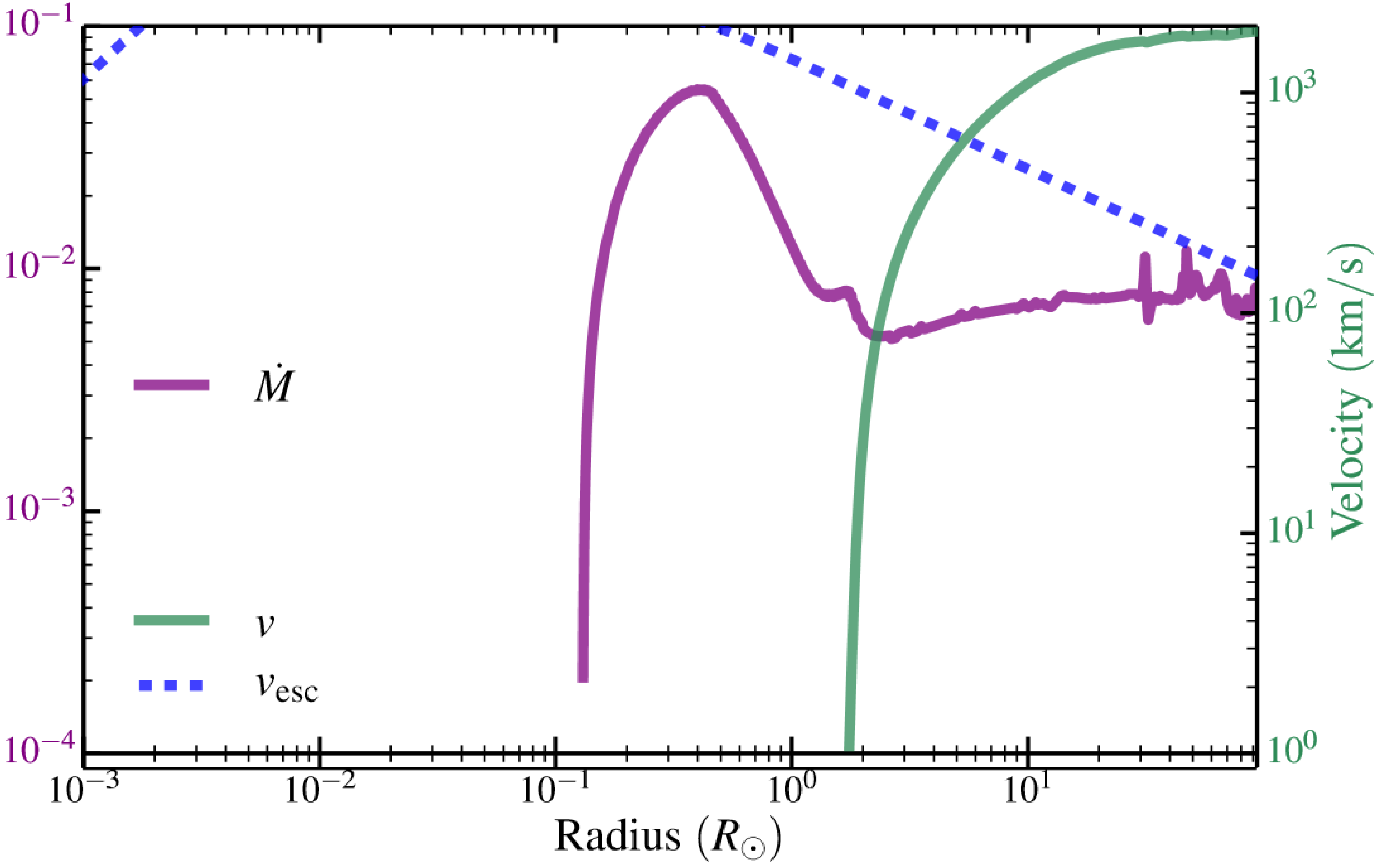
Typical wind speeds of ~2000 km/s, mass loss rates of 10^{-2} M_{sun}/year

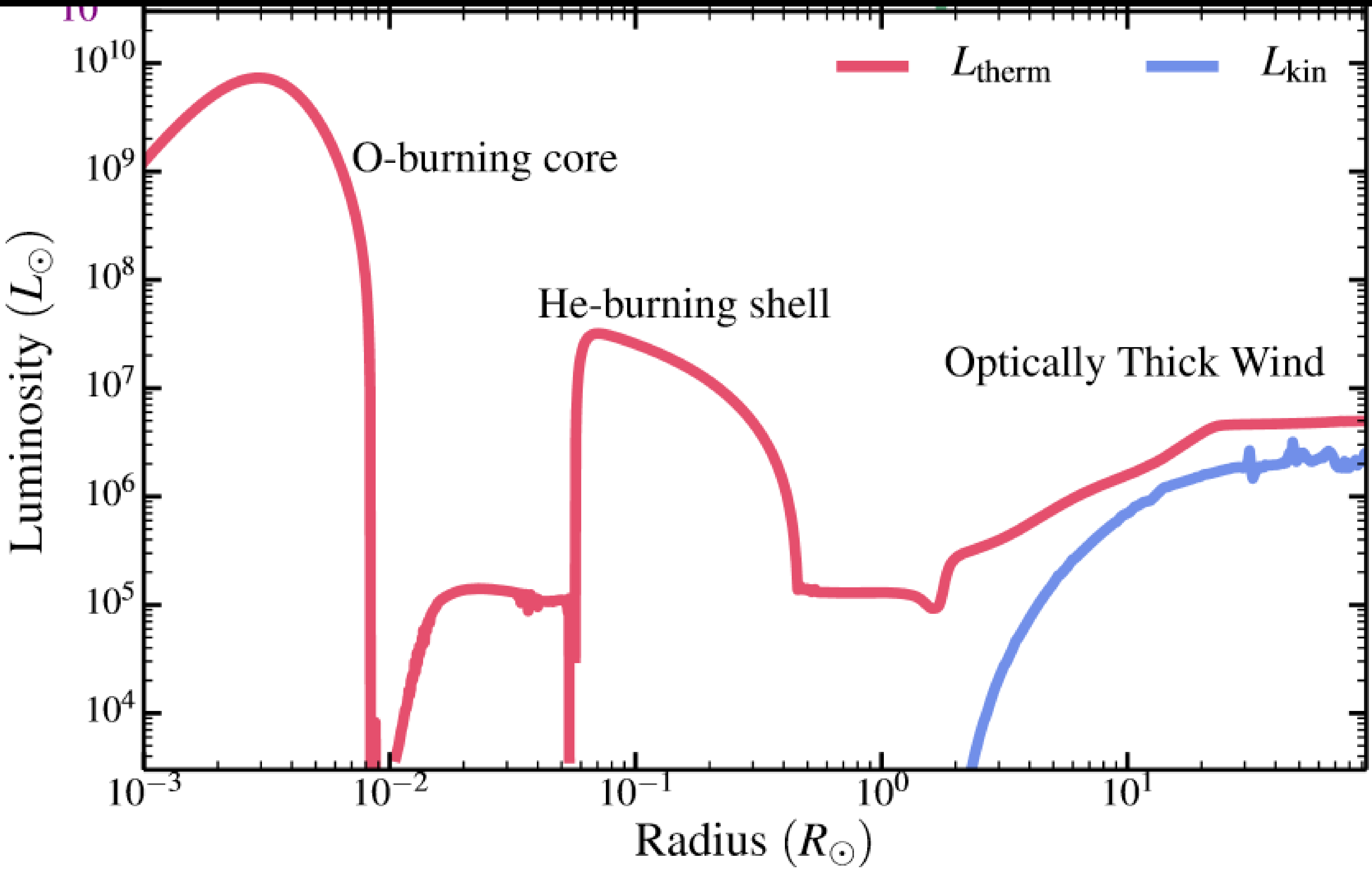
Quataert et al. 2016

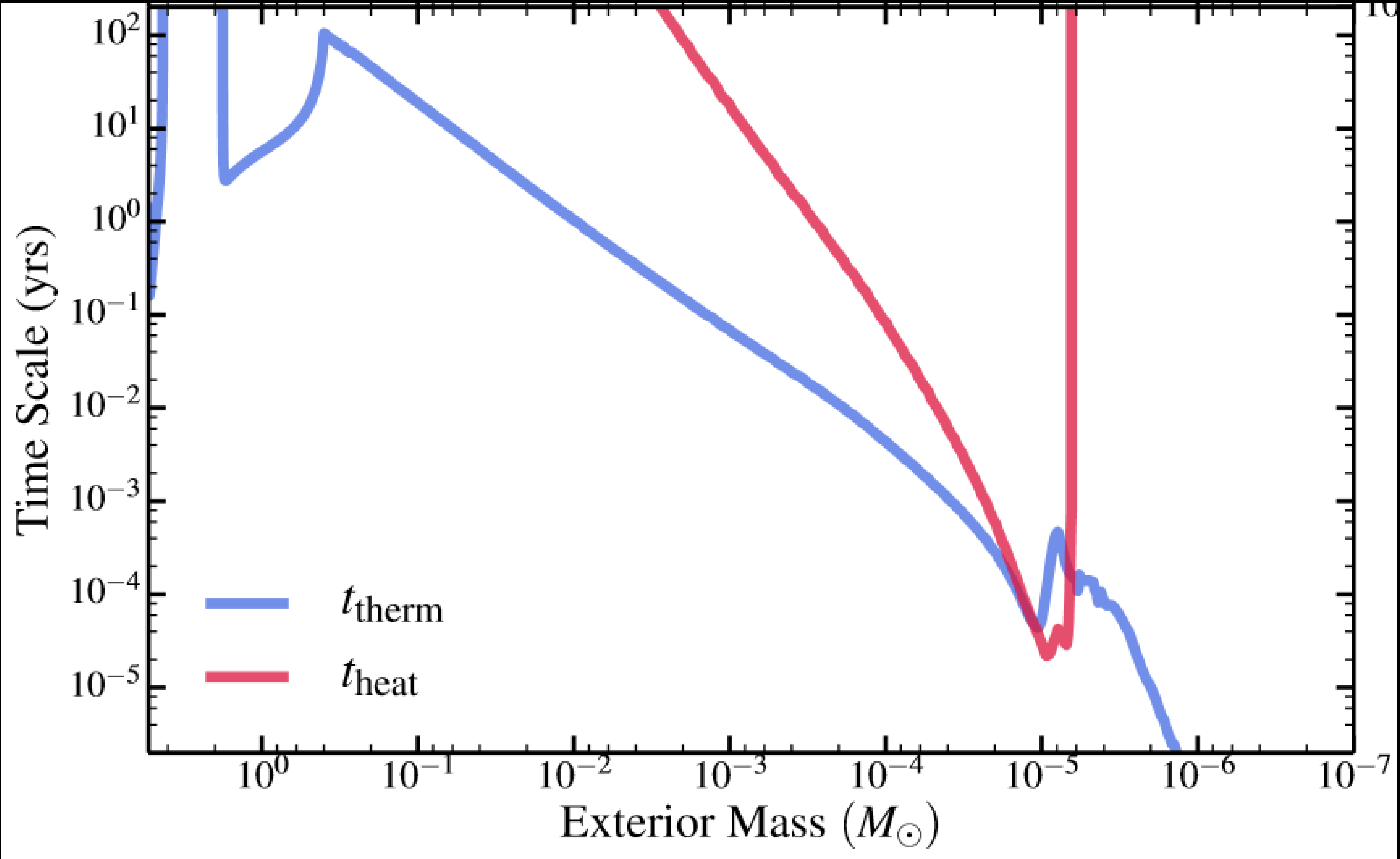

L_{therm}
L_{kin}
O-burning core
He-burning shell
H envelope
Luminosity ($L_{\odot}$)
Radius ($R_{\odot}$)
10^{4}
10^{5}
10^{6}
10^{7}
10^{8}
10^{9}
10^{10}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}



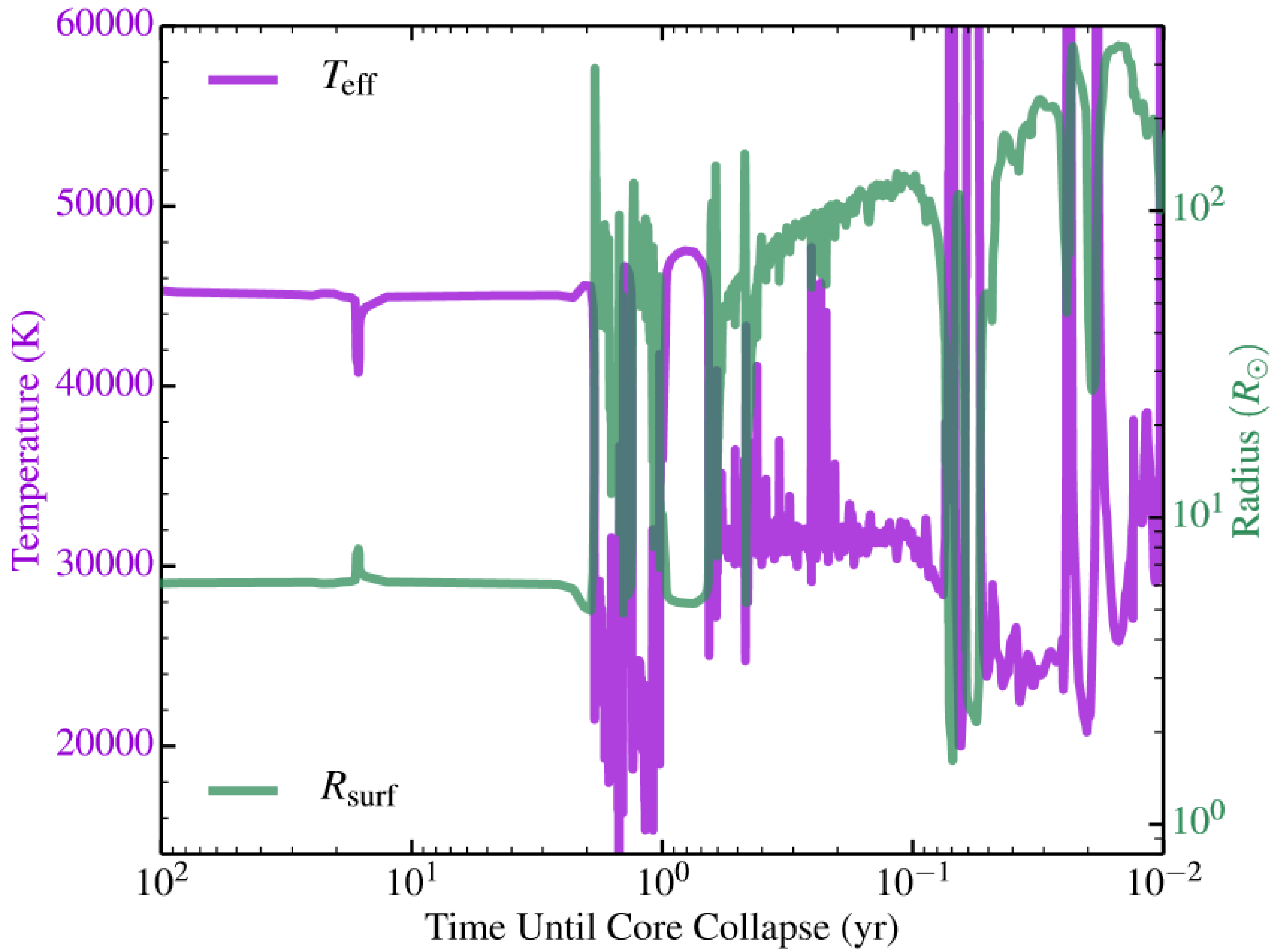
$E_{\mathrm{bind,ext}}$ (erg)
10^{51}
10^{49}
10^{47}
10^{45}
10^{43}
10^{41}
Density (g/cm^3)
10^{6}
10^{4}
10^{2}
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
$E_{\mathrm{bind,ext}}$
$\rho_{\mathrm{O-burn}}$
$\rho_{\mathrm{C-burn}}$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Exterior Mass ($M_{\odot}$)


$\dot{M}\,(M_\odot/\mathrm{yr})$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Velocity (km/s)
10^{3}
10^{2}
10^{1}
10^{0}
$\dot{M}$
v
v_{esc}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Radius ($R_\odot$)

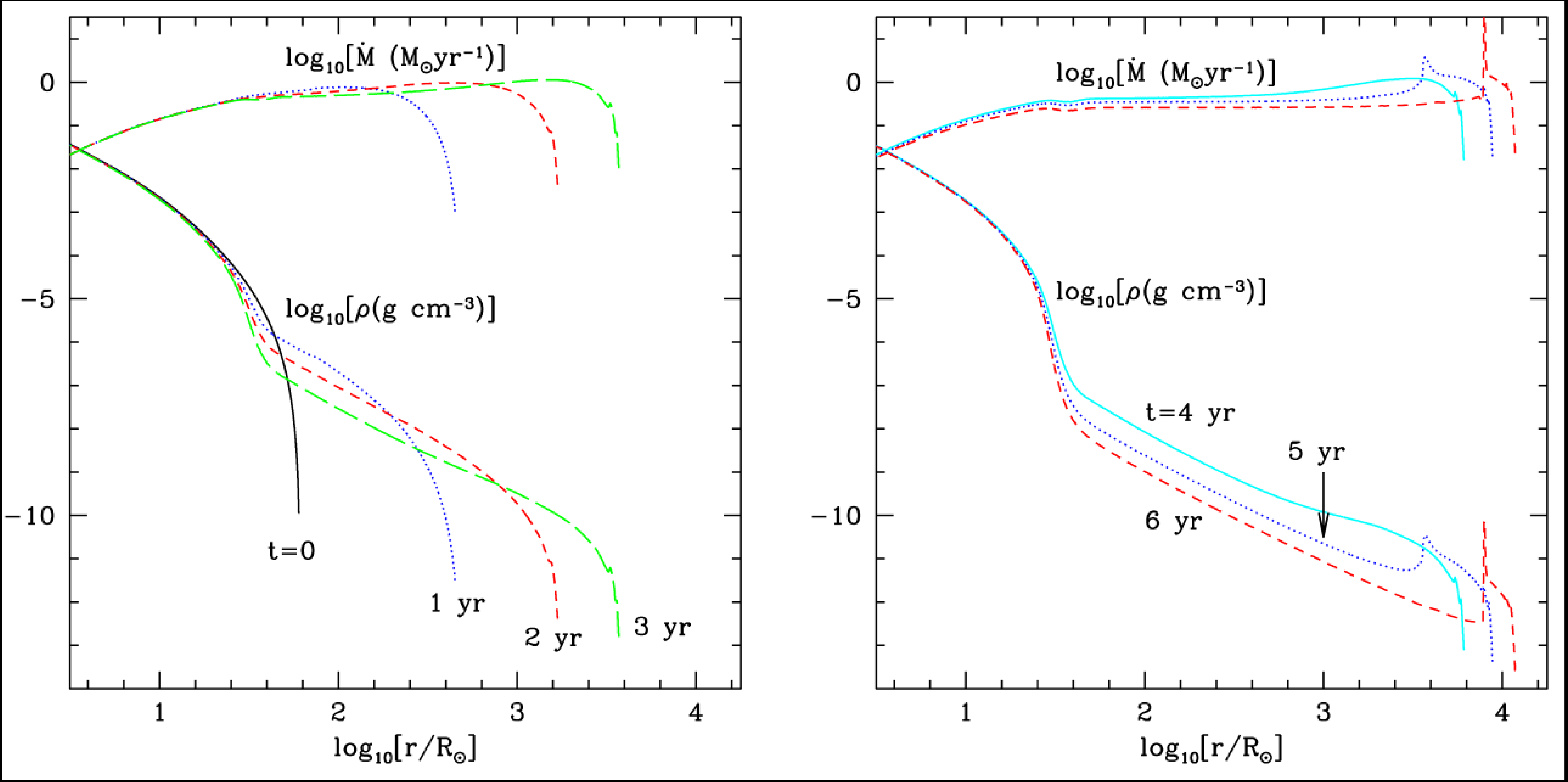

L_{therm}
L_{kin}
O-burning core
He-burning shell
Optically Thick Wind
Luminosity ($L_\odot$)
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
Radius ($R_\odot$)



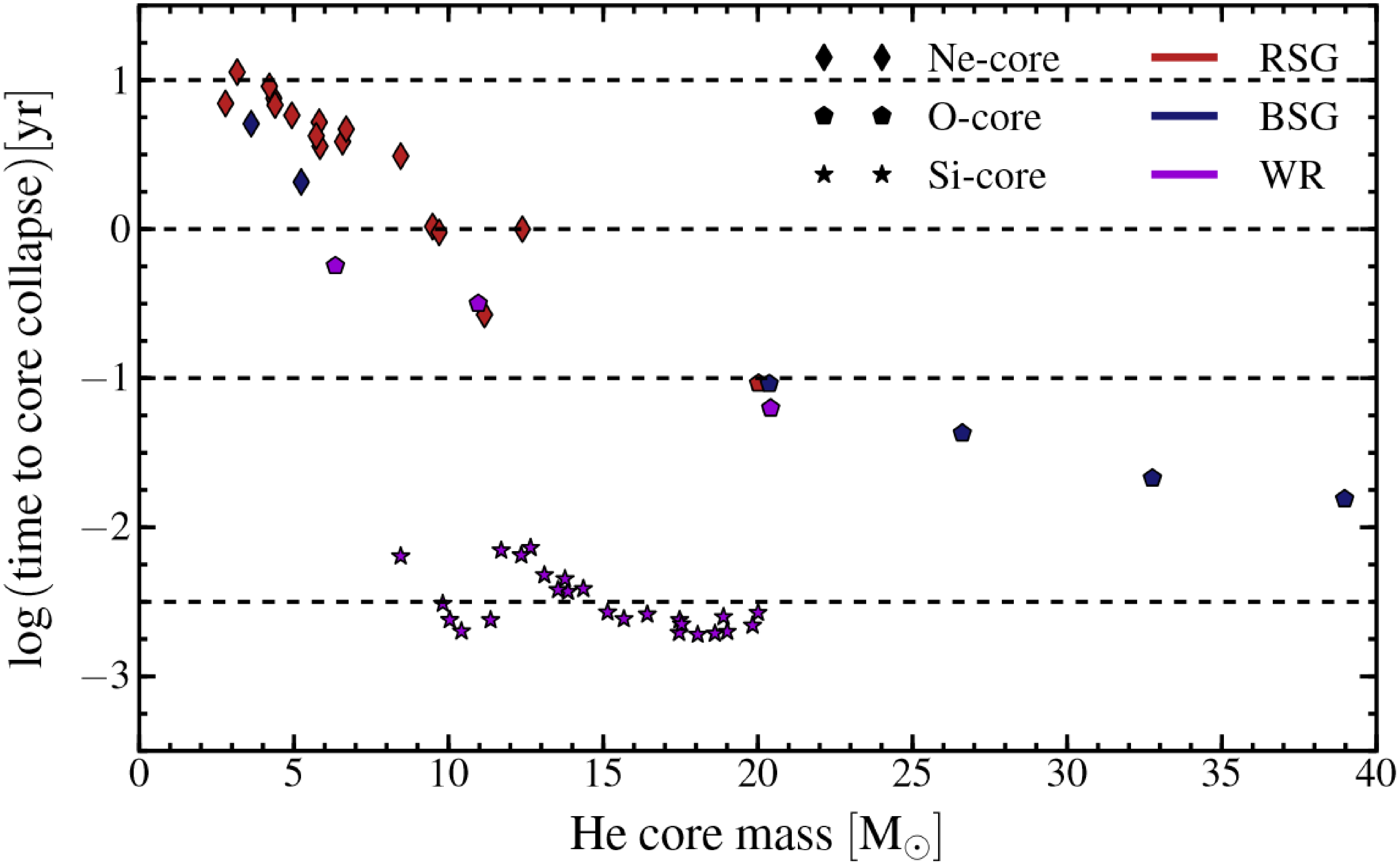
Time Scale (yrs)
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
Exterior Mass ($M_\odot$)
$t_{\rm therm}$
$t_{\rm heat}$



$T_{\rm eff}$
$R_{\rm surf}$
Temperature (K)
60000
50000
40000
30000
20000
Radius ($R_\odot$)
10^2
10^1
10^0
10^2
10^1
10^0
10^{-1}
10^{-2}
Time Until Core Collapse (yr)



$\log_{10}[\dot{M}\ (M_\odot yr^{-1})]$
$\log_{10}[\rho(g\ cm^{-3})]$
t=0
1 yr
2 yr
3 yr
0
−5
−10
1
2
3
4
$\log_{10}[r/R_\odot]$
$\log_{10}[\dot{M}\ (M_\odot yr^{-1})]$
$\log_{10}[\rho(g\ cm^{-3})]$
t=4 yr
5 yr
6 yr
0
−5
−10
1
2
3
4
$\log_{10}[r/R_\odot]$


log (time to core collapse) [yr]
1
0
−1
−2
−3
He core mass [M$_\odot$]
0
5
10
15
20
25
30
35
40
Ne-core
O-core
Si-core
RSG
BSG
WR

Wave Frequencies

- Wave frequencies determine wave properties
- Convection tends to excite waves with frequency

$$\nu_{\rm wave} \sim \nu_{\rm con} \sim \frac{v_{\rm con}}{2H}$$

- Because convection is slow (sub-sonic), wave frequencies are low, meaning convection most efficiently excites gravity waves

Wave Propagation

- After being excited by convection, waves propagate through the star until they damp out

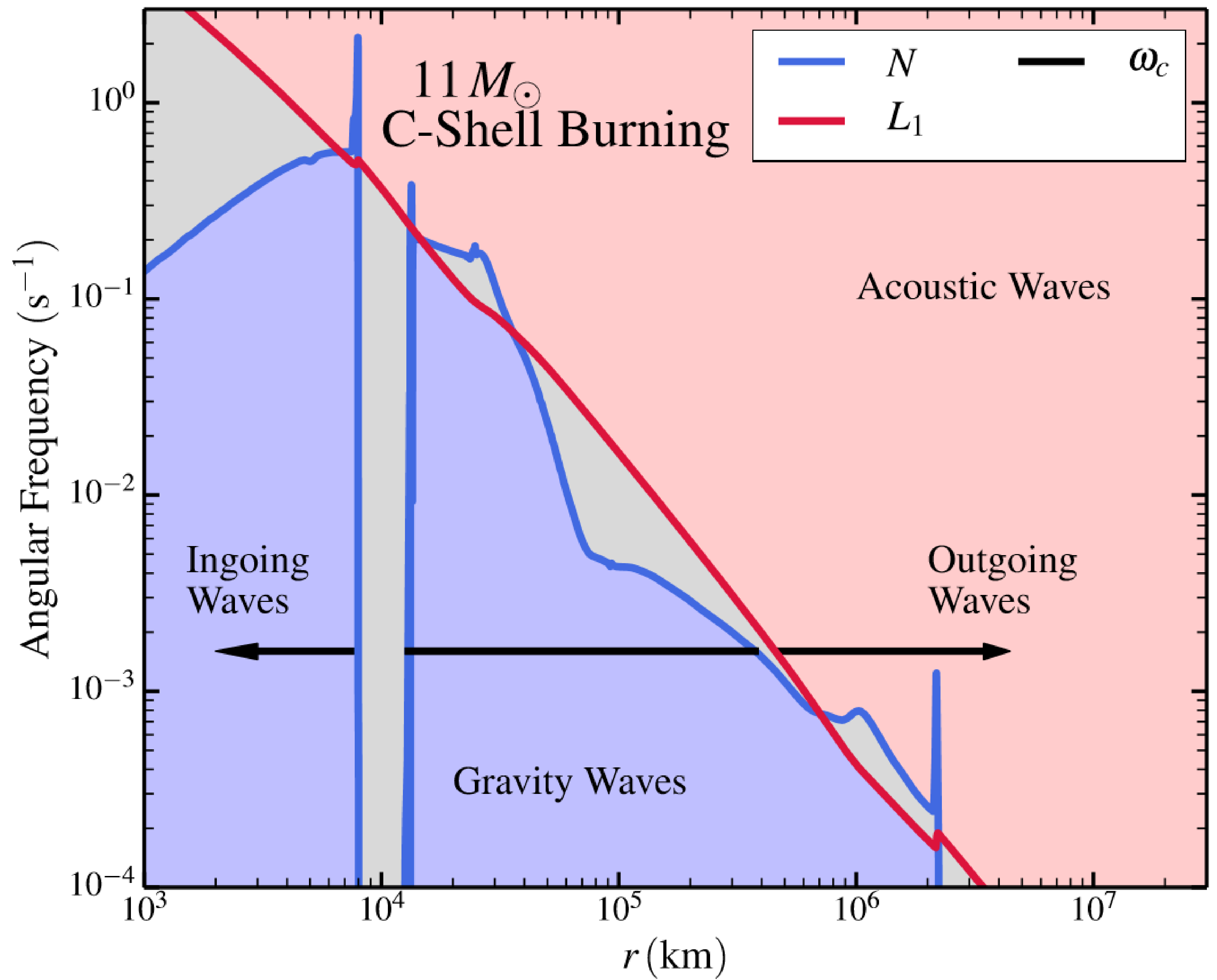
- Wave propagation determined by local values of the Brunt-Vaisala frequency N, and the Lamb frequency L_l
  - Gravity waves where $\omega < N, L_l$
  - Sound waves where $\omega > N, L_l$
  - Partial wave reflection where $\omega = N, L_l$

$$L_l^2 = \frac{l(l+1)c_{\rm sound}^2}{r^2}$$

Wave Tunneling

- To propagate into envelope of a massive star, waves must switch from gravity waves to pressure waves
- Waves "tunnel" through evanescent region separating gravity wave and sound wave cavities, analogous to particle tunneling in quantum mechanics
- Fraction of wave energy that tunnels through evanescent region is

$$T^2 \sim \left(\frac{r_g}{r_p}\right)^{2l}$$


$11\,M_\odot$
C-Shell Burning
N
L_1
ω_c
Acoustic Waves
Ingoing Waves
Outgoing Waves
Gravity Waves
Angular Frequency (s^{-1})
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^3
10^4
10^5
10^6
10^7
$r\,(\mathrm{km})$

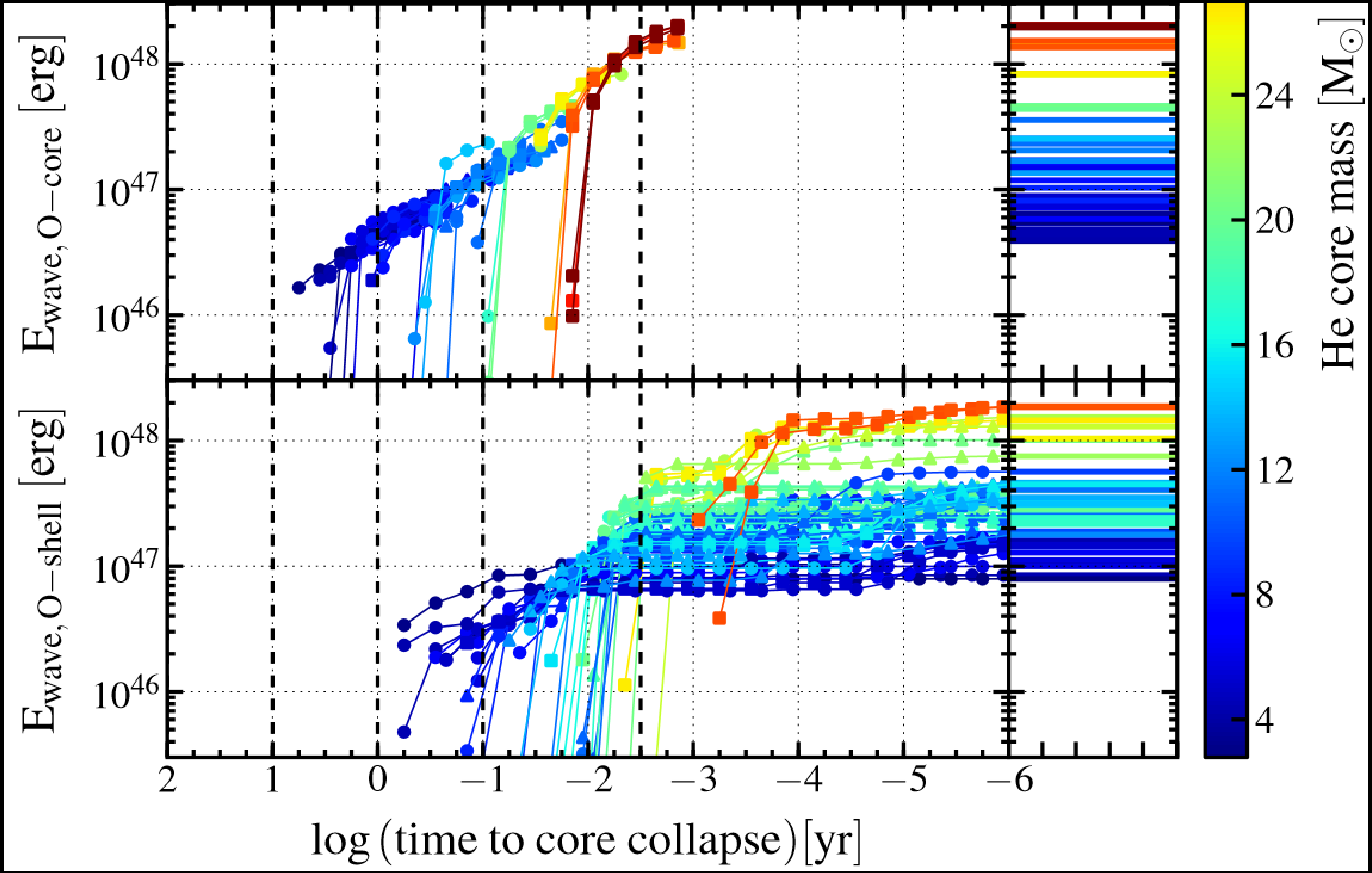
Wave Damping

- Waves can be damped out by various processes such as thermal diffusion, neutrino emission, and non-linear wave breaking

- Wave damping rate due to thermal diffusion is

$$\gamma_{\rm damp} = k_r^2 K_{\rm therm}$$

- In our scenario, waves damp out at base of hydrogen envelope, where they deposit energy as heat



Shiode & Quataert (2014)