UNIVERSITY OF SURREY

THE 13TH TORINO WORKSHOP ON AGB STARS
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A Binary Grid of AGB Stars

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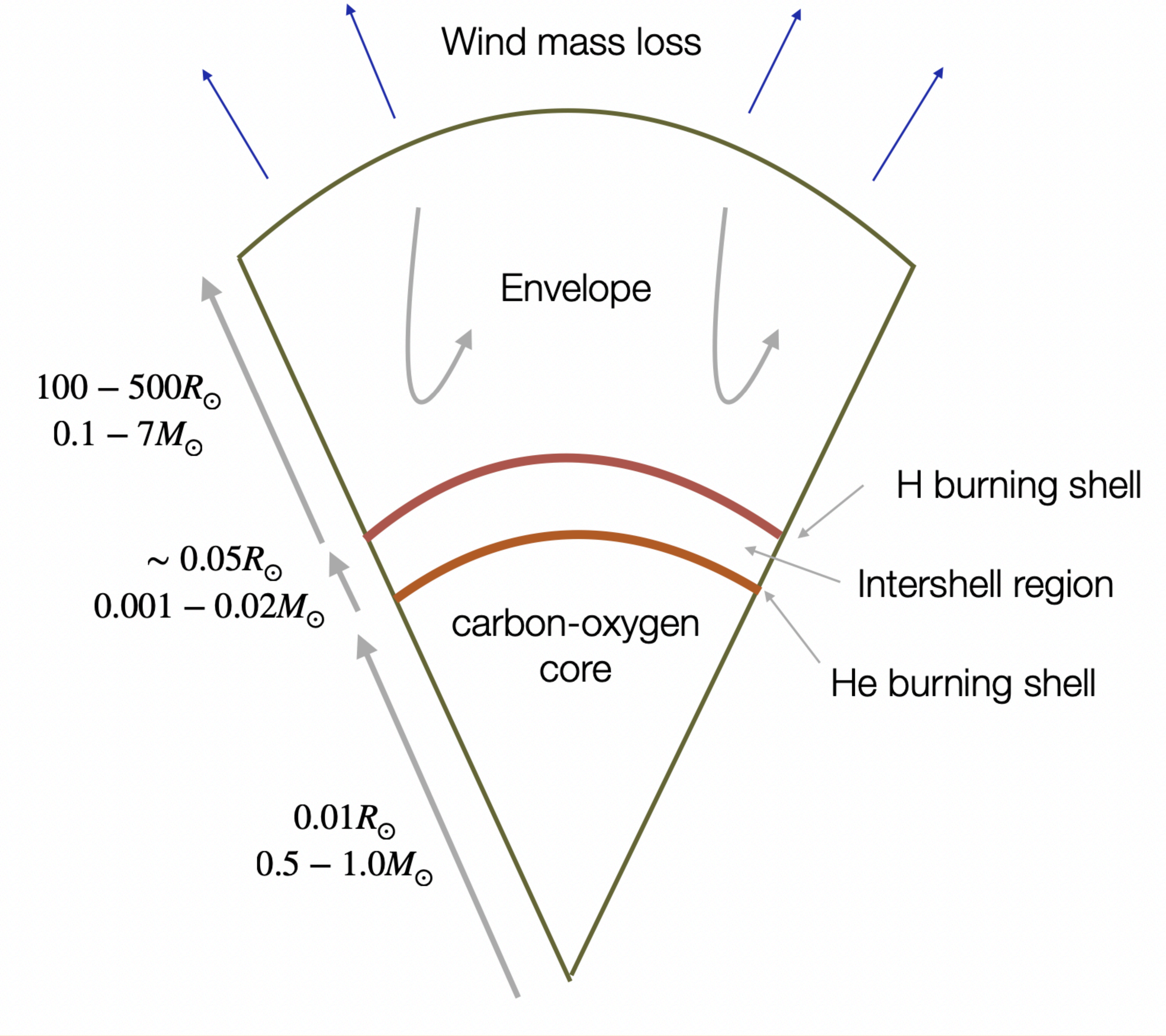
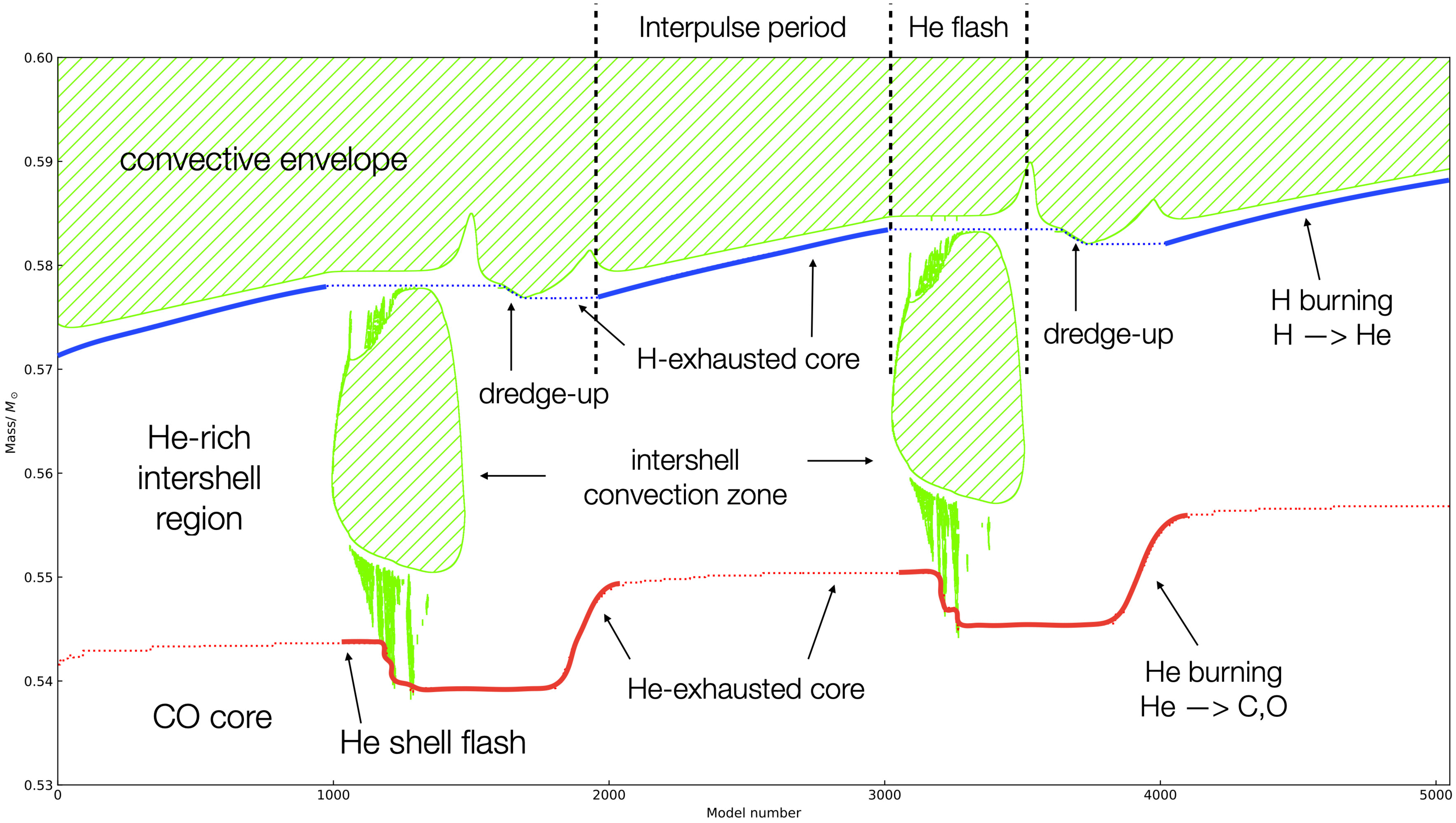
AGB Stars

- The Asymptotic Giant Branch is a late stage in the life of low to intermediate mass stars ($\approx 0.5\text{-}8M_\odot$)
- Periodic thermal pulses every $\approx 10^4\text{-}10^5$ years



$2M_\odot$, Z=0.02 Example



Aims of the grid

1. Fill the parameter space of masses and metallicities with AGB models with the most up-to-date physics
2. Evolve past convergence issues and instabilities with automatic and consistent methods
3. Extract the relevant physics into a tabulated grid for use in the population synthesis code, binary_c (Izzard et al. 2004)
4. Make suitable for populations of binaries by including models with varying core to envelope mass ratios

MESA

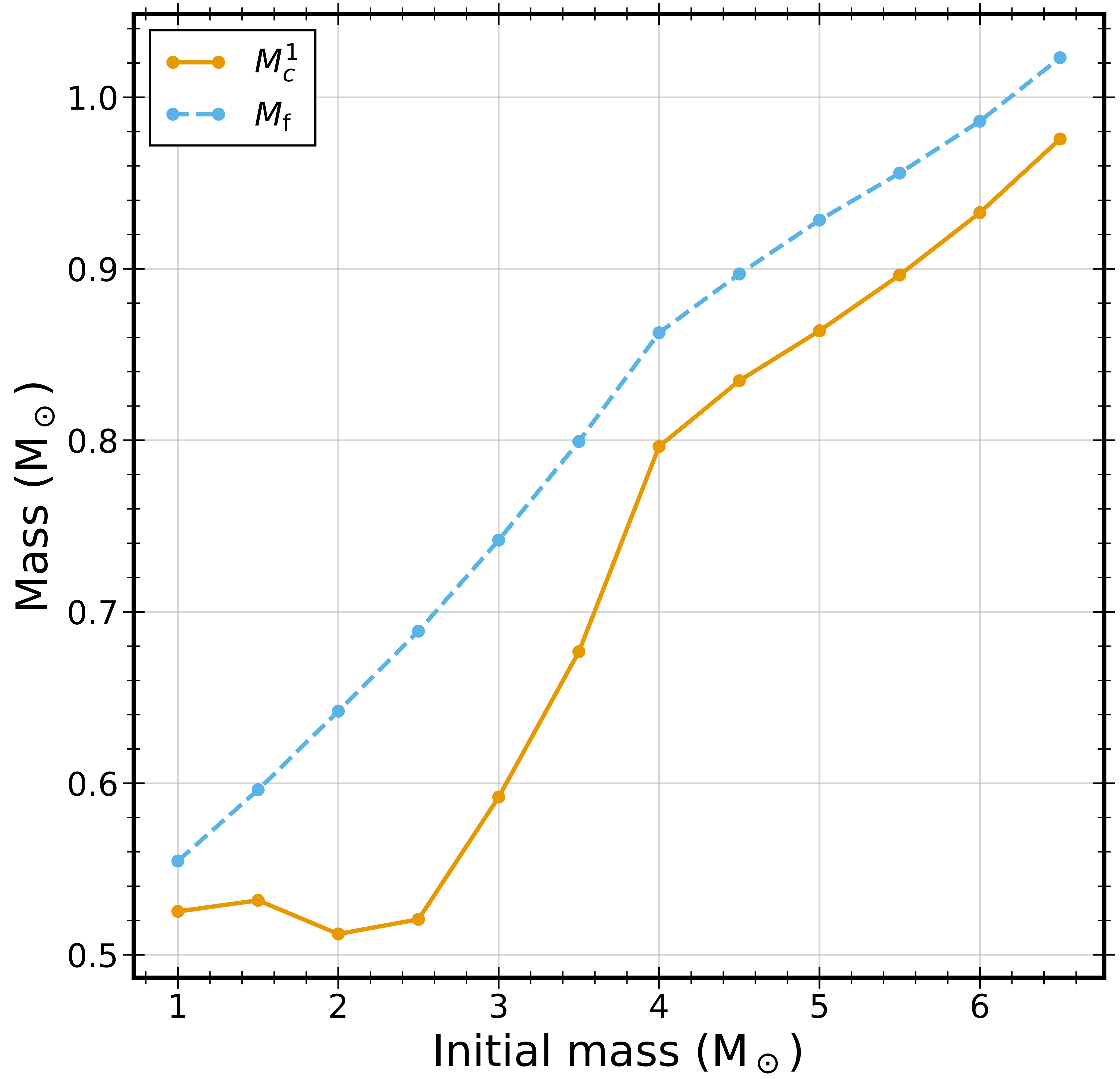
Paxton et al. (2011, 2013, 2015, 2018, 2019)

- Open-source 1D stellar evolution code
- Version mesa-r15140
- AGB Controls:
    - Vassiliadis & Wood (1993) wind mass loss (includes super wind phase)
    - No overshooting
    - AESOPUS opacities with varying CNO abundances (Marigo & Aringer 2009)
    - Henyey et al. (1965) MLT formalism with $\alpha_{\mathrm{mlt}} = 2.0$

AGB Models

$M_i/\mathrm{M}_\odot$	$M_c^1/\mathrm{M}_\odot$	$M_\mathrm{f}/\mathrm{M}_\odot$	No. of TPs
1.0	0.525	0.555	8
1.5	0.532	0.596	13
2.0	0.512	0.642	25
2.5	0.521	0.689	32
3.0	0.592	0.742	33
3.5	0.677	0.799	38
4.0	0.796	0.863	35
4.5	0.835	0.897	42
5.0	0.864	0.928	53
5.5	0.896	0.956	60
6.0	0.933	0.986	67
6.5	0.976	1.023	77
7.0	1.028	>1.063	>83

The core mass at the first thermal pulse (M_c^1), final mass (M_f) and number of thermal pulses for AGB models with initial masses $1 \leq M_i/\mathrm{M}_\odot \leq 7$ and $Z = 0.017$. The $M_i = 7\mathrm{M}_\odot$ model did not reach the end of the TP-AGB due to convergence problems.



Instabilities and Convergence Issues

- Physical conditions sampled by models are quite extreme
- Recurring thermal instability of the helium-burning shell requires codes to be robust on short timescales during the thermal pulse cycle.
- AGB stars are notoriously difficult to model with full stellar evolution codes due to instabilities
- Will provide a summary of instabilities and convergence issues for the full parameter space of masses and metallicities
- Solutions to help the models converge

Controls for Convergence Issues

Energy transport equation in inter-shell

- Can't converge energy transport equation in inter-shell region during He-shell flash
- Use form of dP/dm which is suitable for dynamic situations rather than hydrostatic dP/dm (use_dPrad_dm_form_of_T_gradient_eqn = .true.)
- Ignore residuals of energy transport equation (convergence_ignore_equL_resisduals = .true.)

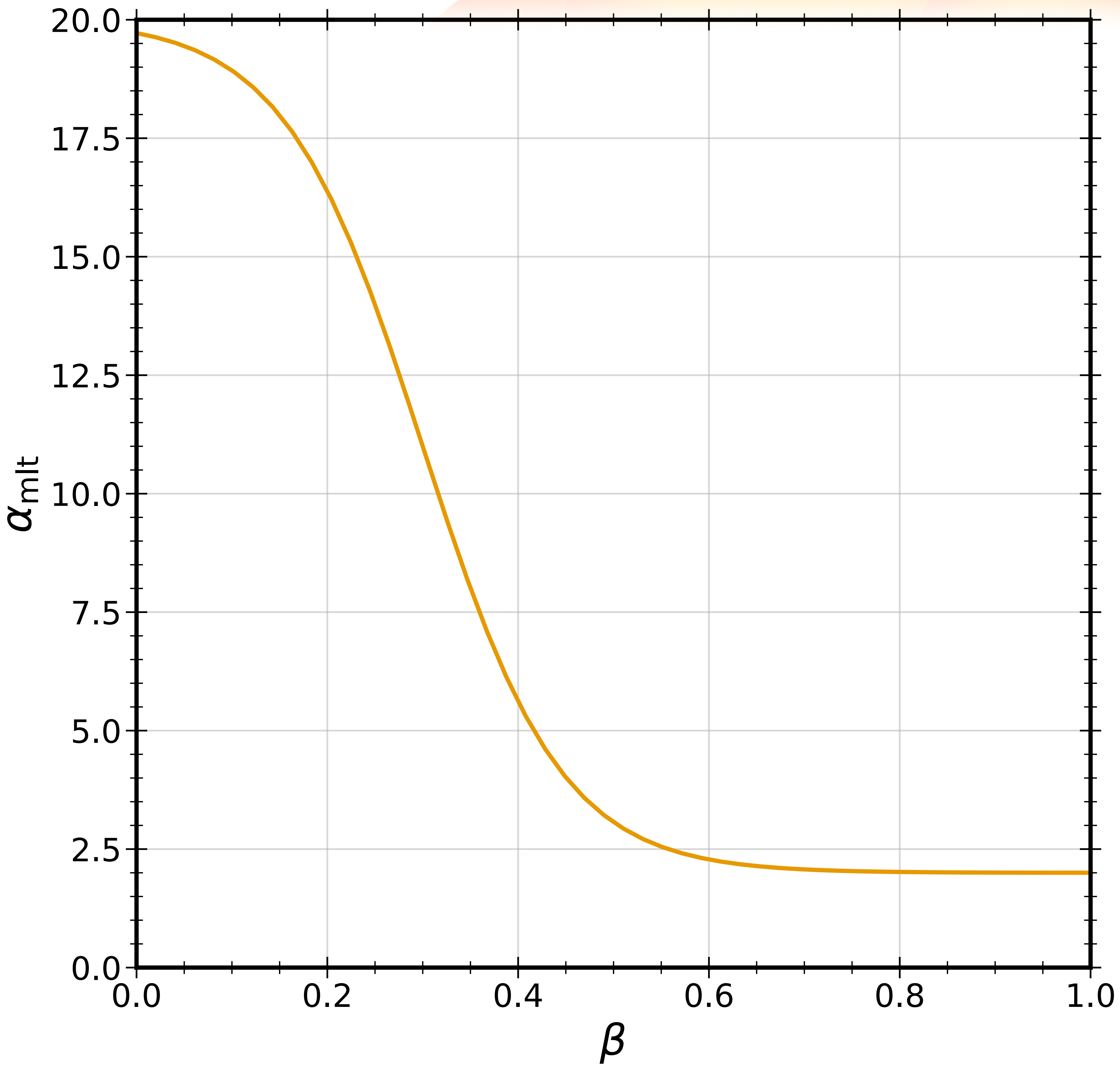
Momentum equation at surface

- Struggles to converge momentum equation in surface cell during He-shell flash
- Development of a runaway surface expansion
- **Solution:** Turn on hydrodynamic terms in stellar structure equations during He-shell flash

Fe-peak Instability

Lau et al. (2012)

- Density at the base of the convective envelope decreases as mass is lost
- Iron opacity peak ($T \approx 2 \times 10^5\ \mathrm{K}$) leads to accumulation of an energy excess
- Radiation pressure supplies an increasing amount of pressure required for hydrostatic equilibrium and $\beta = P_{\mathrm{gas}}/P \to 0$
- Increase mixing length parameter as a function of β,

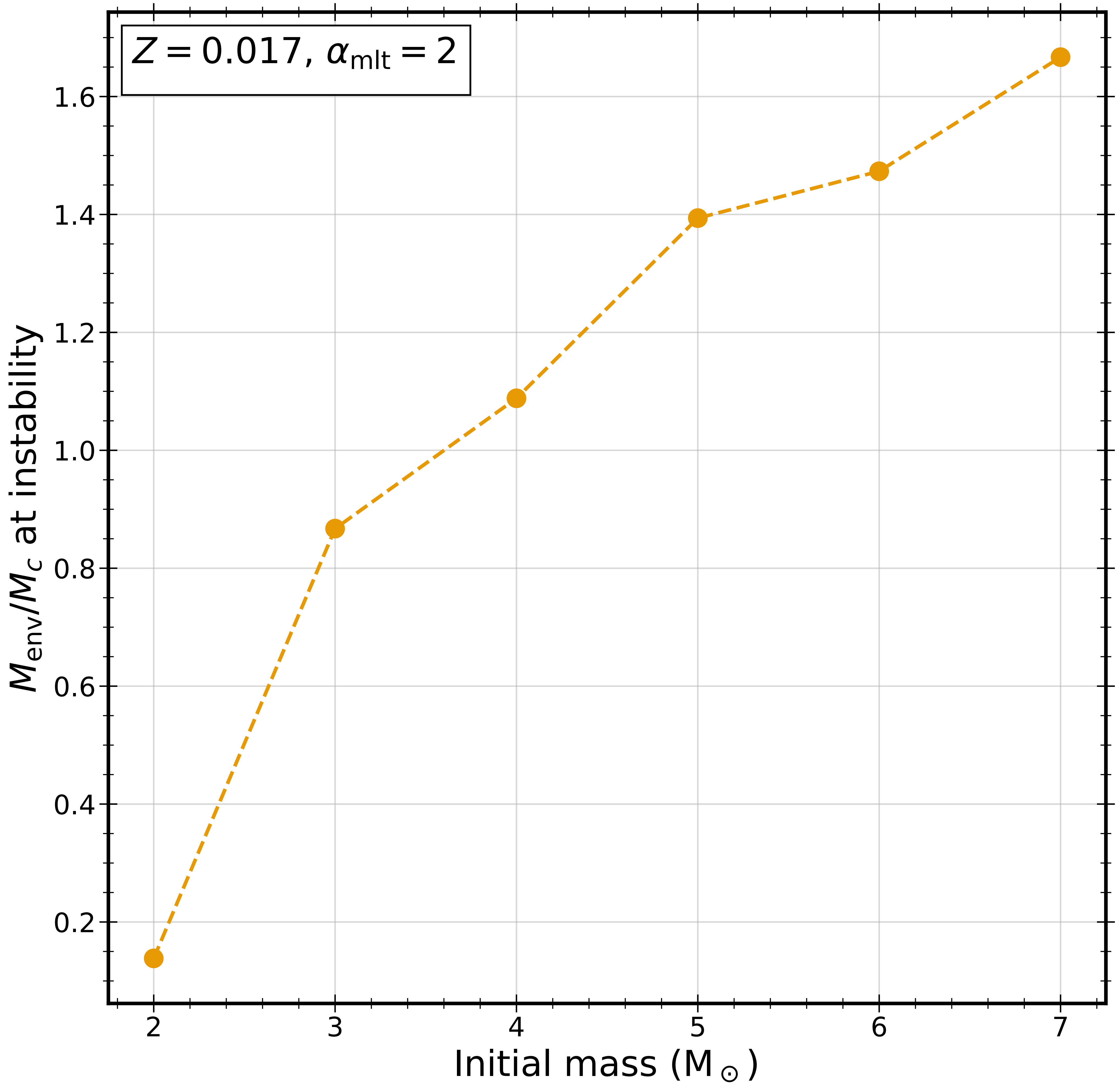


$$\alpha_{\mathrm{mlt}} = 20 - \frac{20 - \alpha_{\mathrm{mlt,base}}}{1 + 10^{-6(\beta - 0.3)}}$$

Fe-peak Instability Results

$M_i/\mathrm{M}_\odot$	$M_c/\mathrm{M}_\odot$	$M_{\mathrm{env}}/\mathrm{M}_\odot$	Thermal Pulse No.	Total No. Pulses
1	No instability	-	-	8
2	0.64	0.12	24	25
3	0.74	0.64	32	33
4	0.86	0.93	31	34
5	0.92	1.28	45	53
6	0.97	1.44	53	67
7	1.06	1.76	71	>83

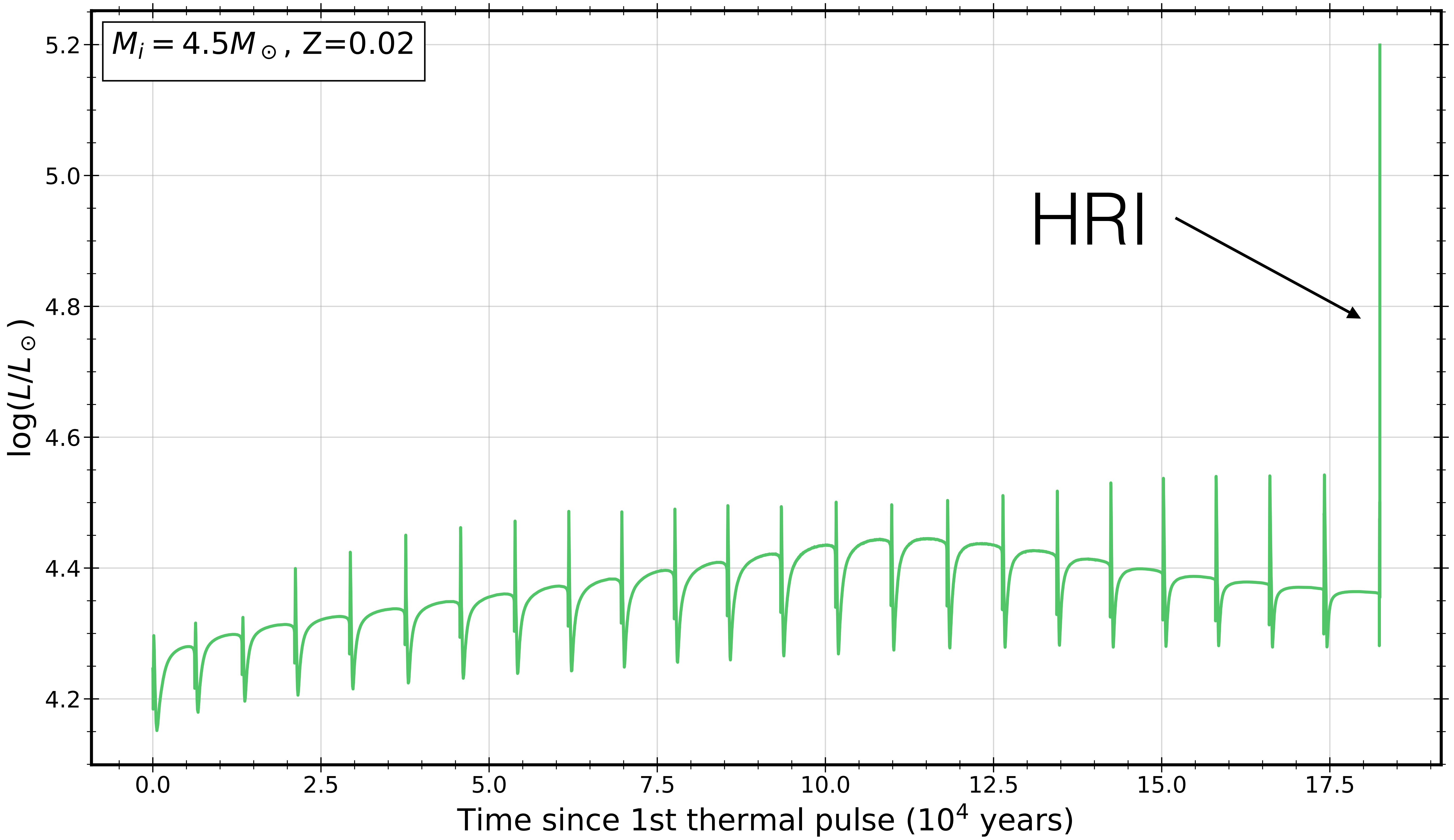
The core mass (M_C), envelope mass (M_{env}) and thermal pulse number at the onset of the Fe peak instability for models with $Z = 0.017$ and $\alpha_{\mathrm{mlt}} = 2$. The last column is the total number of thermal pulses for the same model, but with the increased mixing length parameter routine.



Hydrogen Recombination Instability

Wagenhuber & Weiss (1994)

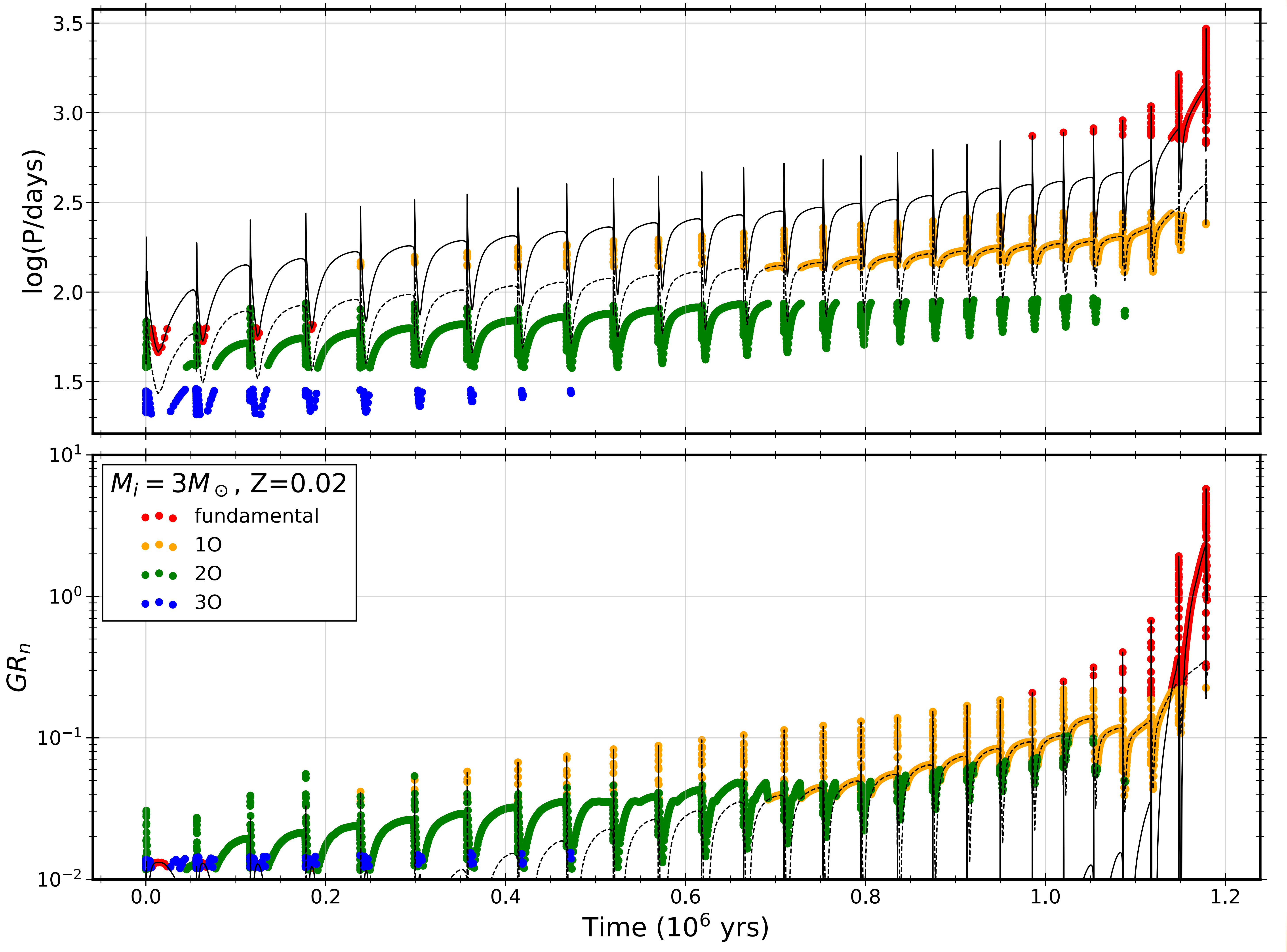
- Runaway expansion during the luminosity peak of a thermal pulse
- Driven by the recombination of hydrogen within a thermally and dynamically unstable envelope
- Doesn't occur in our current grid of models



Pulsation Models

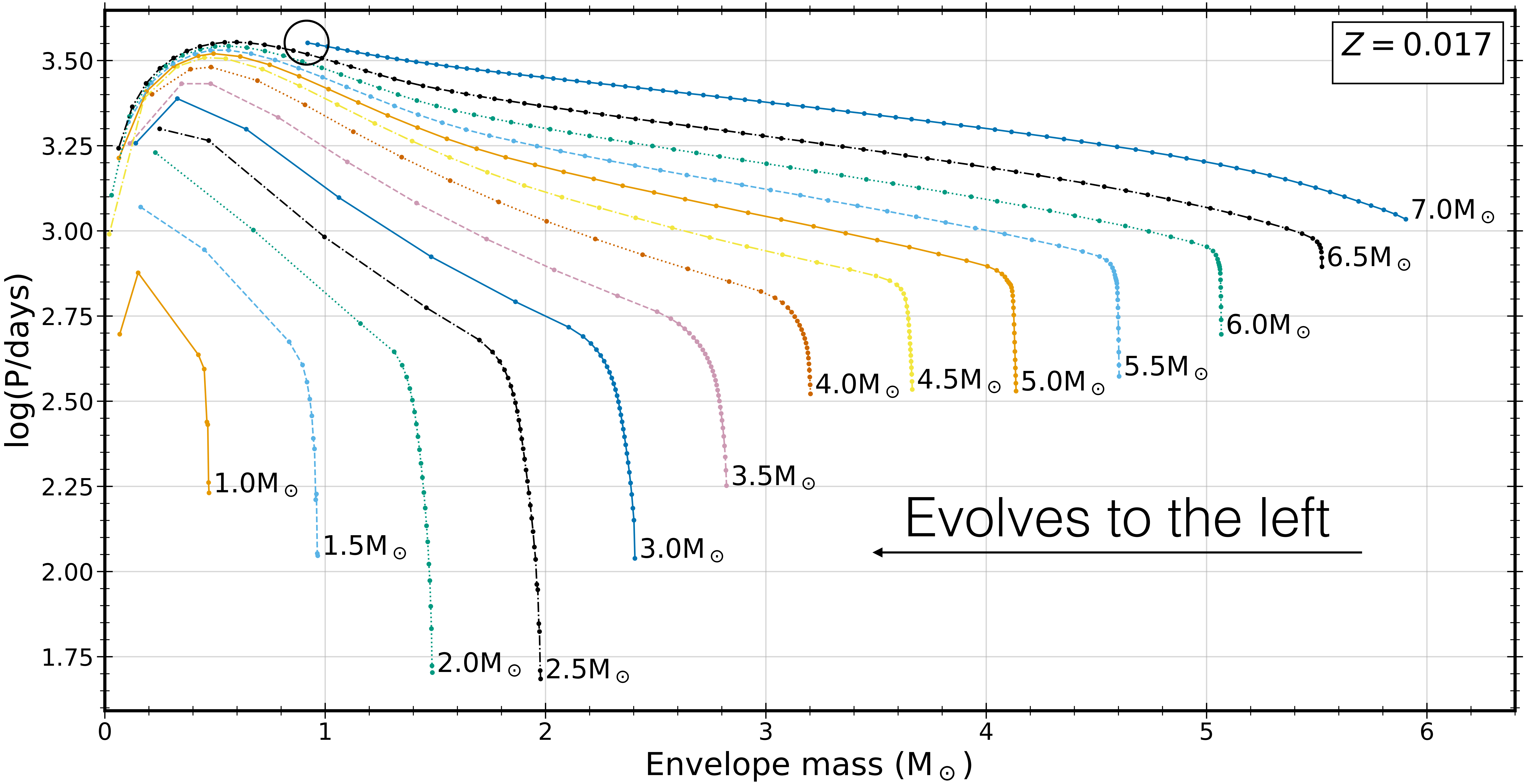
Trabucchi et al. (2019)

- Non-adiabatic linear pulsation models
- Star evolves from higher order pulsation modes to lower order to fundamental
- Period and growth rates increase as envelope becomes more dynamically unstable
- Dynamically unstable pulsations likely to lead to dynamical mass ejections (Clayton 2018)



AGB Pulsations

Period from Trabucchi et al. (2019, eq 12)

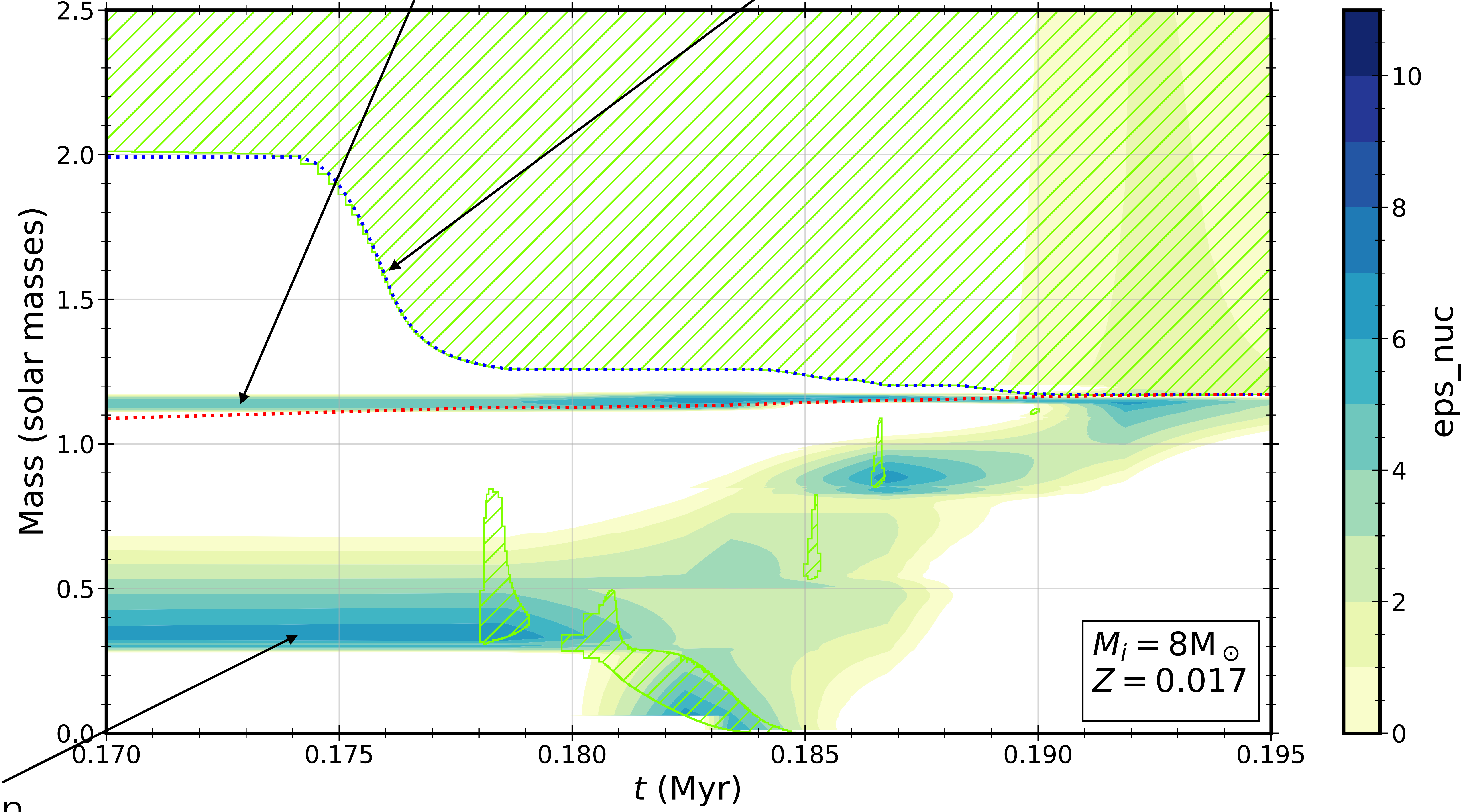


Evolves to the left

SAGB Models

Challenge 1: carbon burning

- Ignites during EAGB
- Requires $M_c \gtrapprox 1.05\mathrm{M}_\odot$
- MESA suitable due to diffusive mixing scheme (Karakas et al. 2021, Jones at al. 2013)



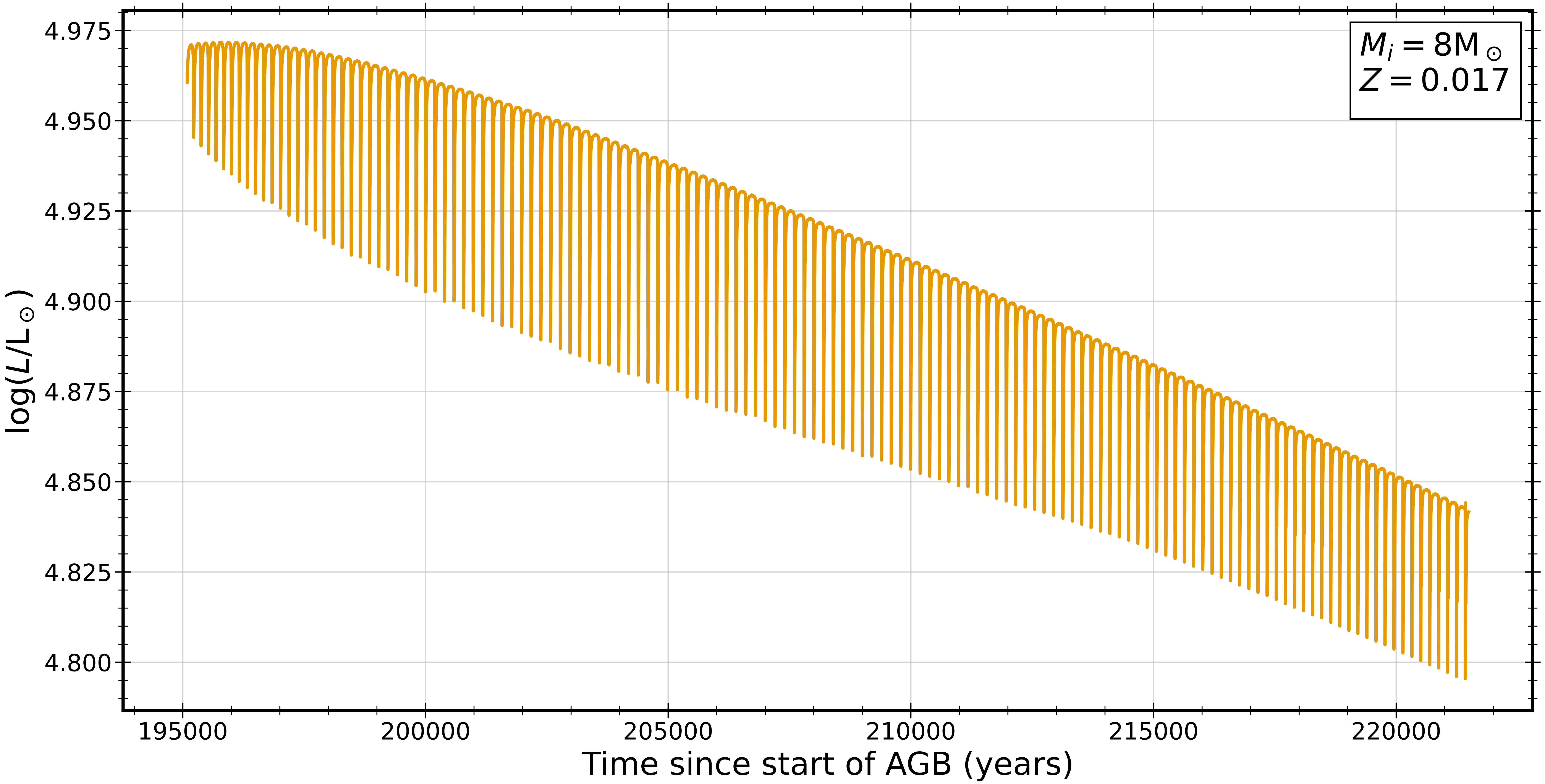
He burning shell

2nd dredge-up

Off centre carbon ignition

SAGB Models

Challenge 2: computation time



- 139 pulses
- 433,000 timesteps
- ≈ week of computation time
- Remaining $M_{\rm env} = 3.5\rm M_\odot$

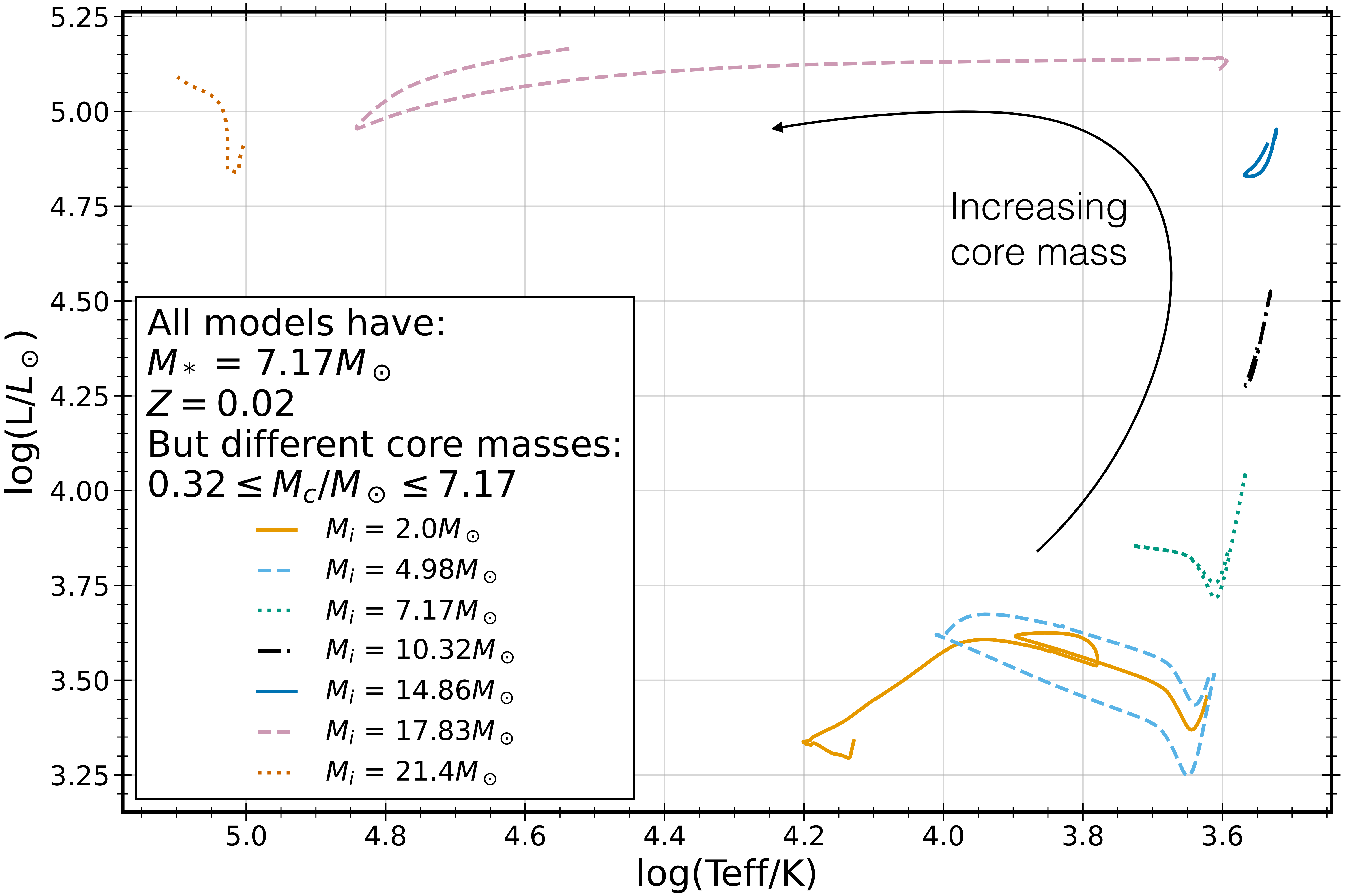
AGB grid for binary_c

Izzard et al. (2004, 2006, 2009, 2018)

- Will produce a tabulated grid of AGB models to replace the analytical formulae used in the synthetic AGB model of Izzard et al. (2004)
- Required physics includes…
    - Interpulse periods, core masses, luminosity and radii
    - Details of third dredge-up
    - Envelope temperature and density profiles for hot bottom burning
    - Central and surface abundances

Core Helium Burning Grid

- Suitable for population synthesis of **binaries that transfer mass**
- At start of core helium burning increase and decrease mass to produce CHeB models with **varying envelope to core mass ratios**
- Upper mass limit set as $M_t \leq 10M_i$
- Lower mass limit set to produce **He stars**



Conclusions

1. Will fill the parameter space of masses and metallicities with AGB models with the most up-to-date physics

2. Want to evolve past convergence issues and instabilities with automatic and consistent methods

    - **Can currently evolve models with $Z = 0.017$, $1 \leq M/\mathrm{M}_\odot \leq 6.5$ to the end of the TP-AGB using methods described**

    - **Will be testing for other metallicities and SAGB stars**

3. Will extract the relevant physics into a tabulated grid for use in the population synthesis code, binary_c (Izzard et al. 2004)

4. Will make suitable for populations of binaries by including models with varying core to envelope mass ratios

    - **Have already produced binary grids for core helium burning stars**