Session 1: Introduction

MESA School Leuven 2025

Convective Overshooting in Stars

Lecturer: Poojan Agrawal (KU Leuven)

TAs:

Niall Miller (University of Wyoming)

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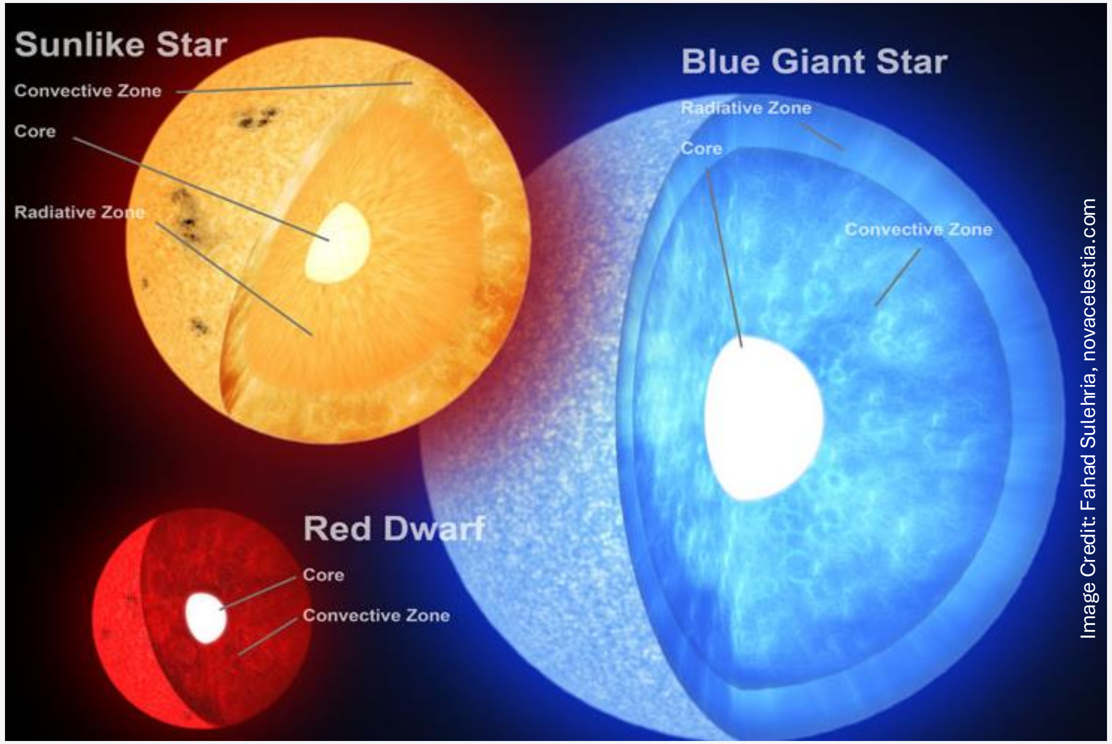
Mathijs Vanrespaille (KU Leuven)

Sunny Wong (University of California Santa Barbara)

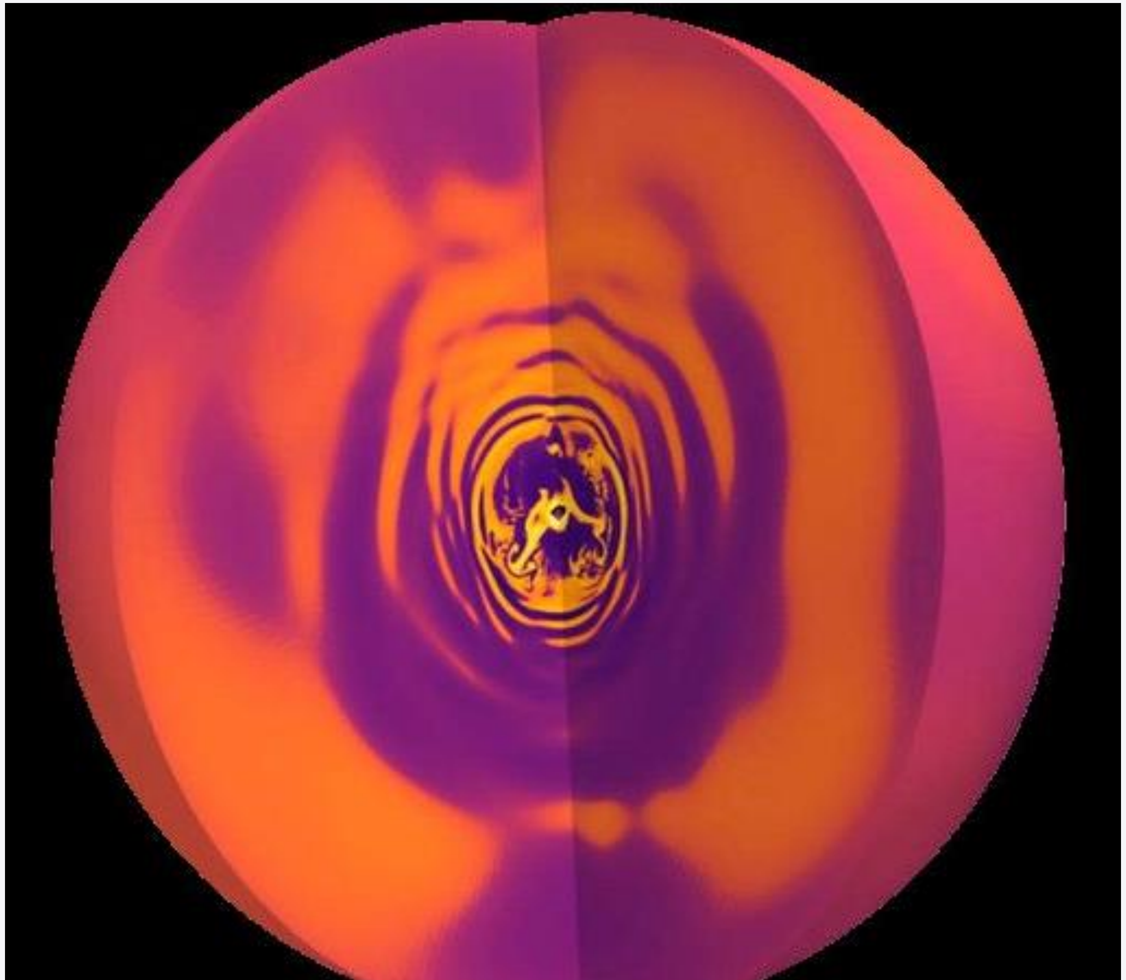


Funded by the European Union

Convection in everyday life

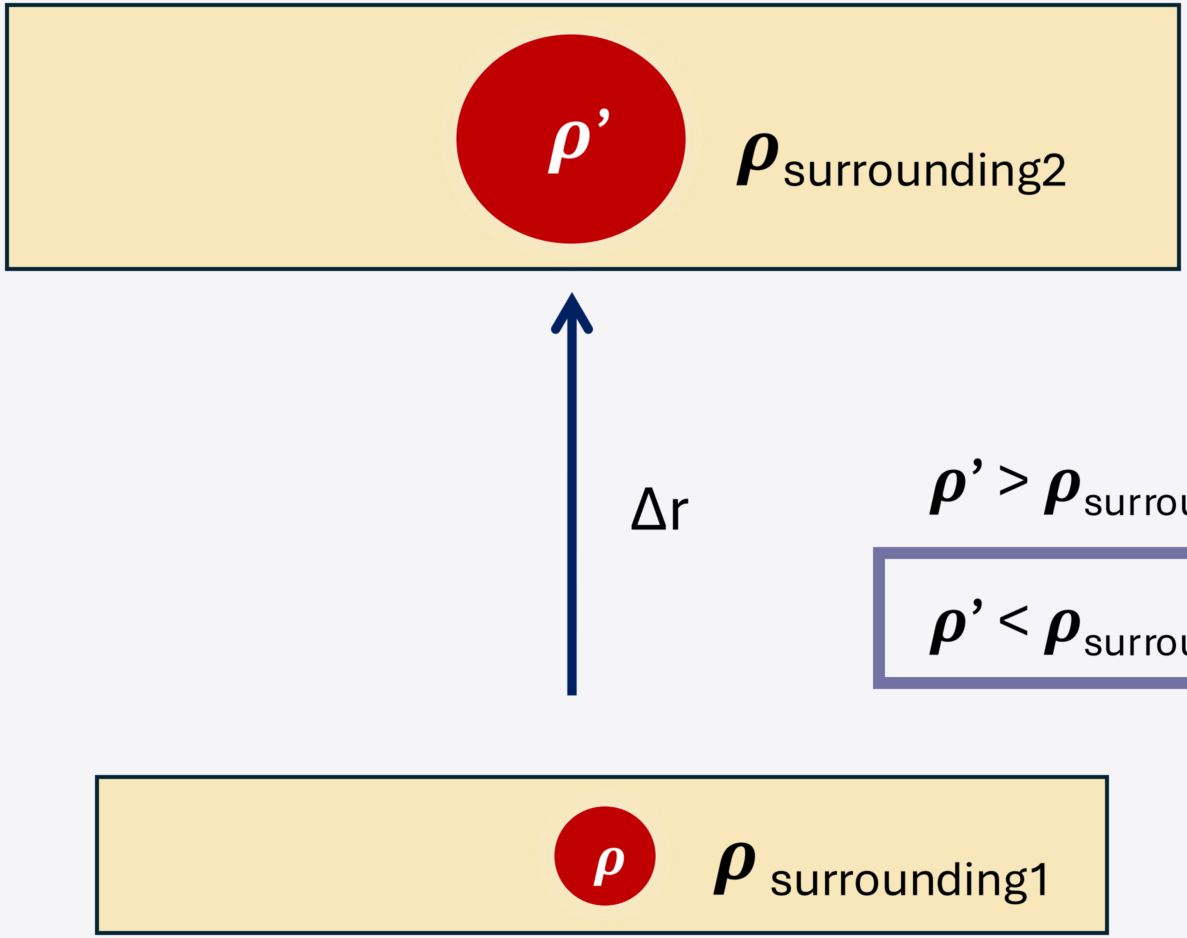
Modelling Convection

- Mode of transport of energy, matter and angular momentum
- Turbulent and dynamic process – best modelled in three-dimensions
- A simple approximation – Mixing length theory – (MLT, Böhm-Vitense, 1958)
- Used in Cox & Giuli 1968, Henyey et al. 1965, amongst many others.



Snapshot from simulations of core convection, Credit: Edelmann et al. 2019

Convection - Density formulation



Heats up and expands

$\rho' > \rho_{surrounding2}$ → stable → oscillations

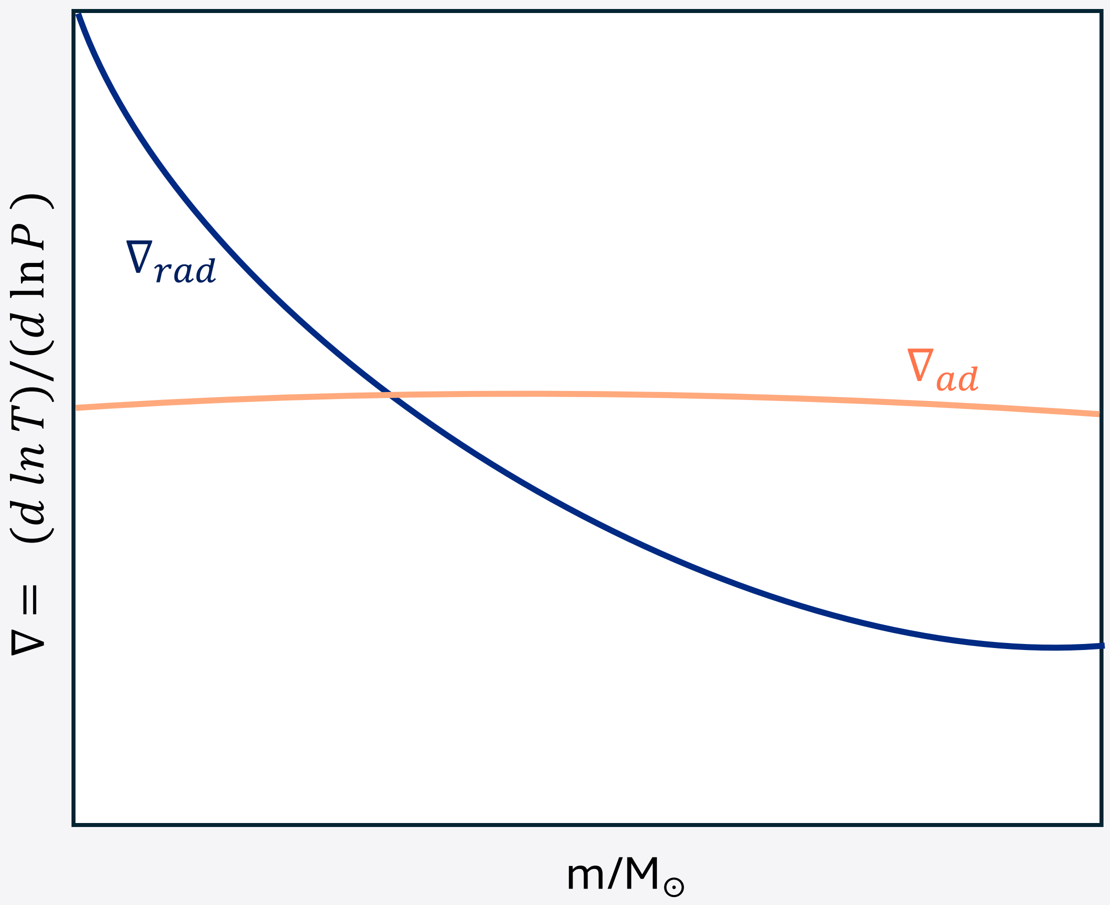
$\boxed{\rho' < \rho_{surrounding2} \rightarrow \text{unstable} \rightarrow \text{convection}}$

Convection - Temperature formulation

- Temperature gradient, $\nabla = \frac{d\ ln\ T}{d\ \ln\ P}$
- Radiative temperature gradient,

  ∇_{rad} – energy carried by radiative transfer
- Adiabatic temperature gradient,

  ∇_{ad} – energy carried by a parcel of gas without exchanging heat with its surroundings.



Convective boundaries

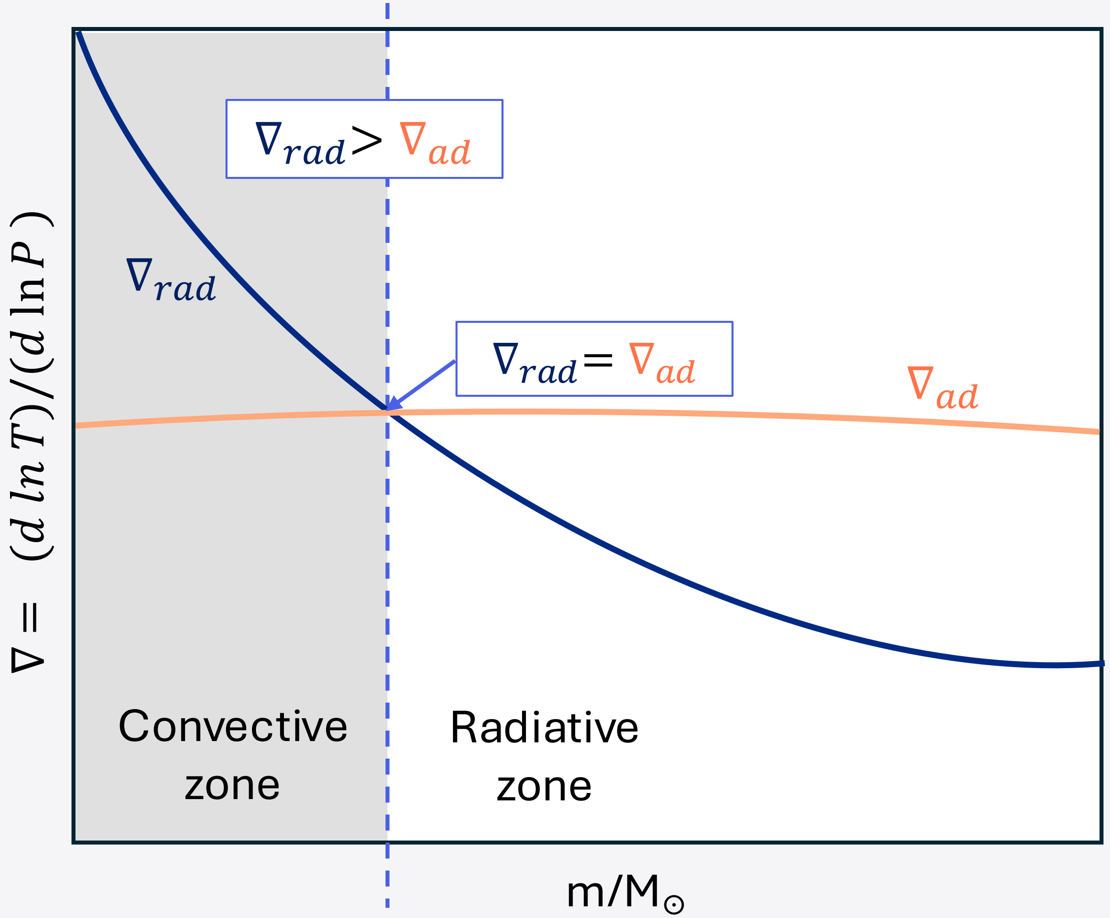
- Convection happens when:

  $\nabla_{rad} > \nabla_{ad}$ (Schwarzschild criteria-named after Karl Schwarzschild)

- Pressure Scale Height,

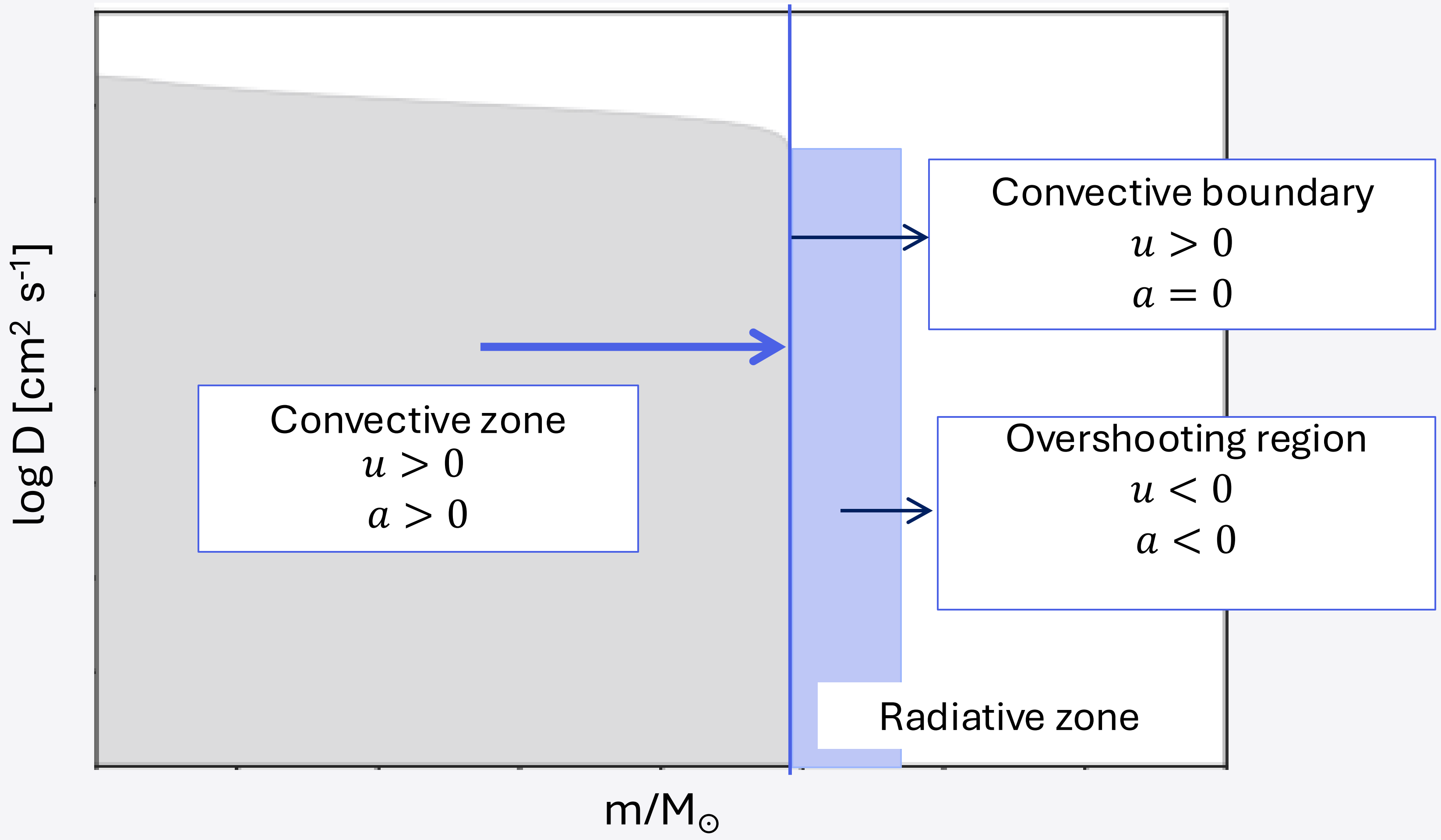
  $$H_P = -\frac{d\,r}{d\,\ln P}$$

- Mixing Length, l = $\alpha_{\text{MLT}} \times H_P$



Convective Overshooting

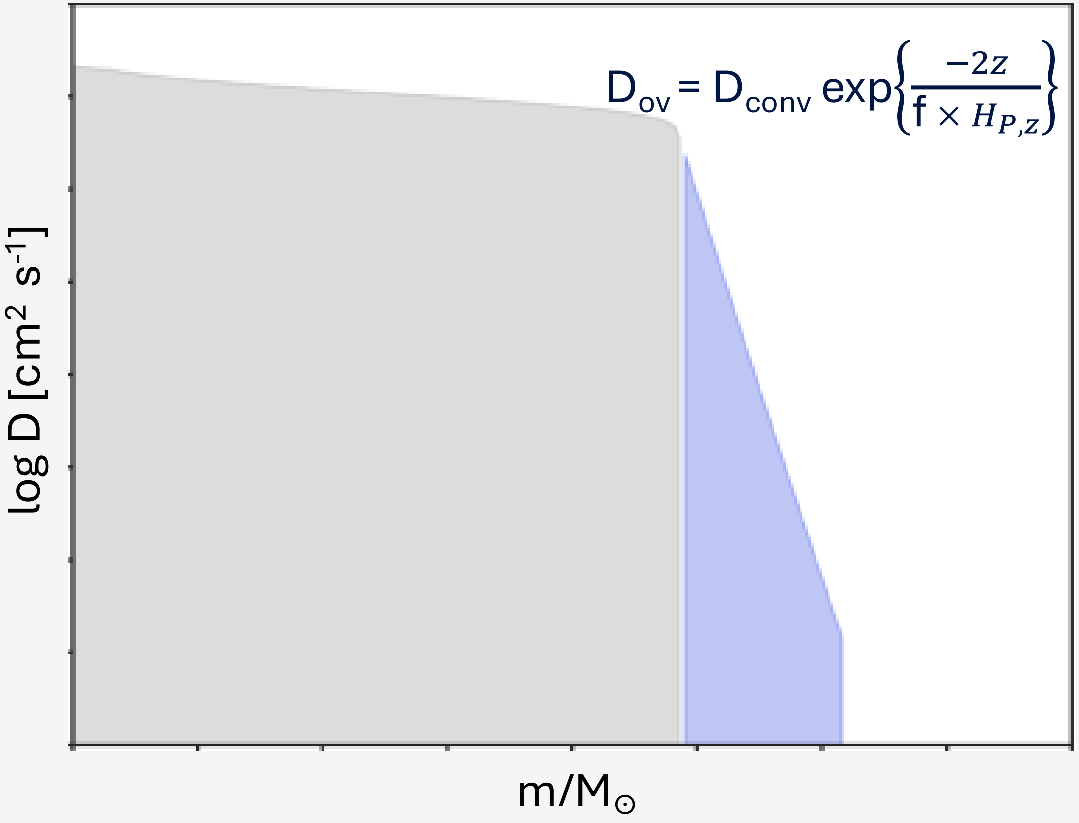
Extending mixing with convective overshoot



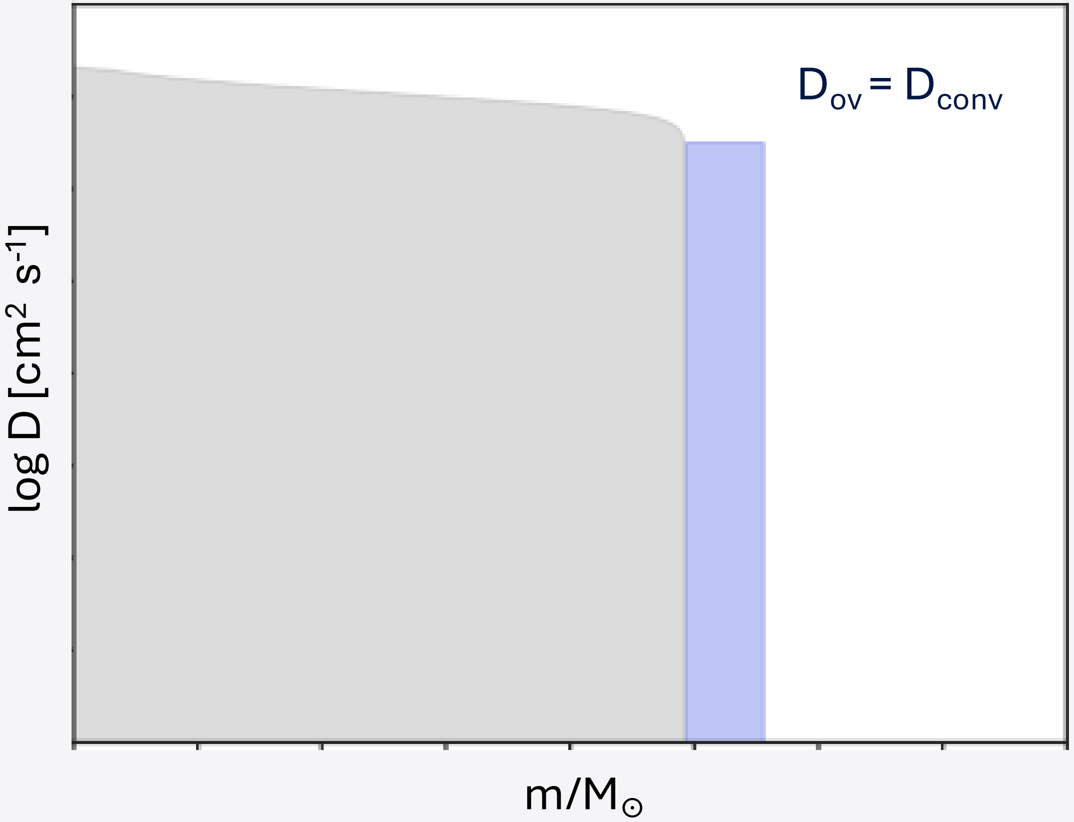
Note: Overshoot only aids chemical mixing but no heat transport.

Overshoot Schemes

Exponential overshoot



Step overshoot



For more overshooting schemes see e.g., Pols et al. (1998), Bressan et al. (1981)

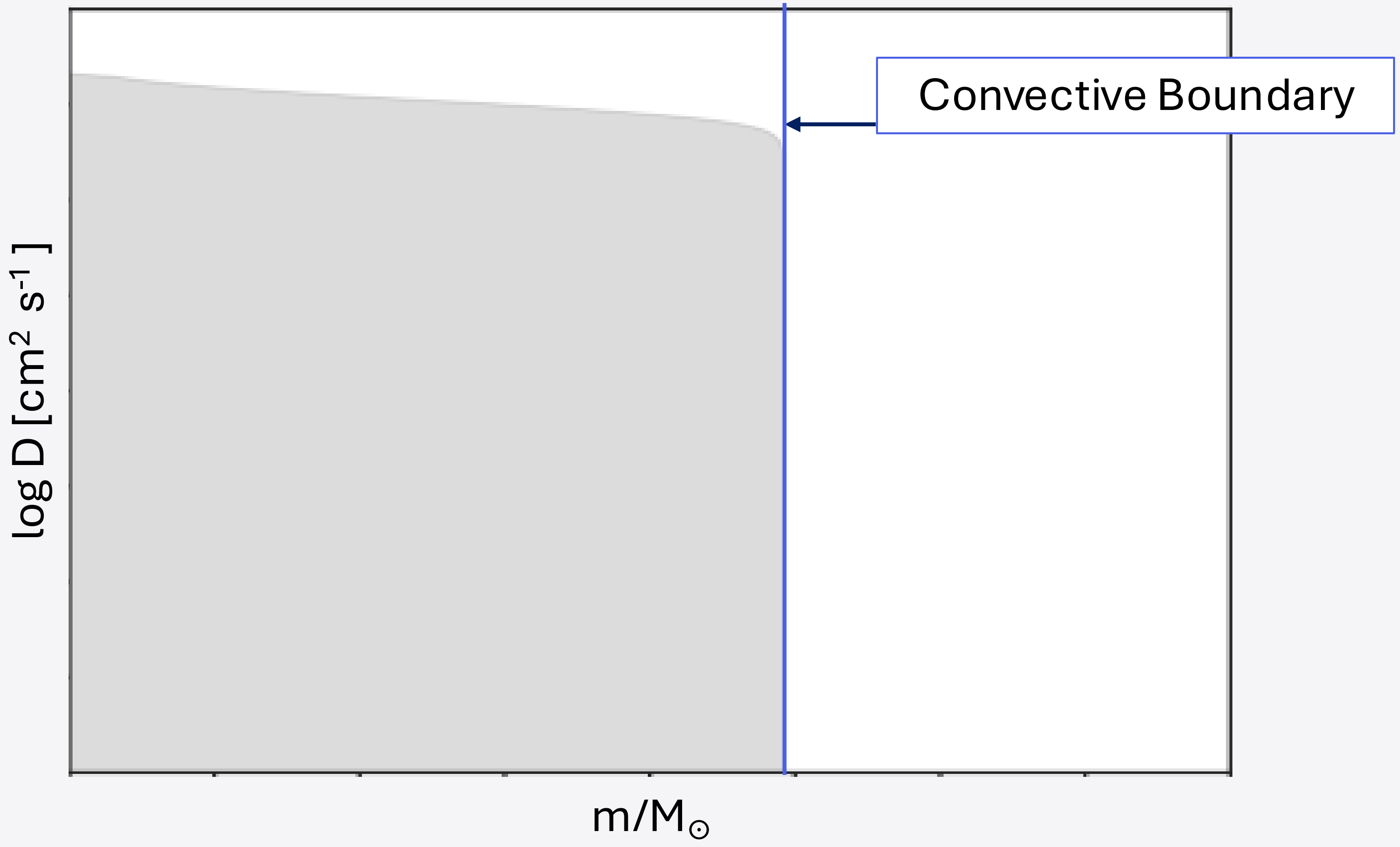
Overshooting: f and f0

Step overshoot:

$D_{ov} = D_{conv}$

Exponential overshoot:

$$D_{ov} = D_{conv} \exp\left\{\frac{-2z}{f \times H_{P,z}}\right\}$$



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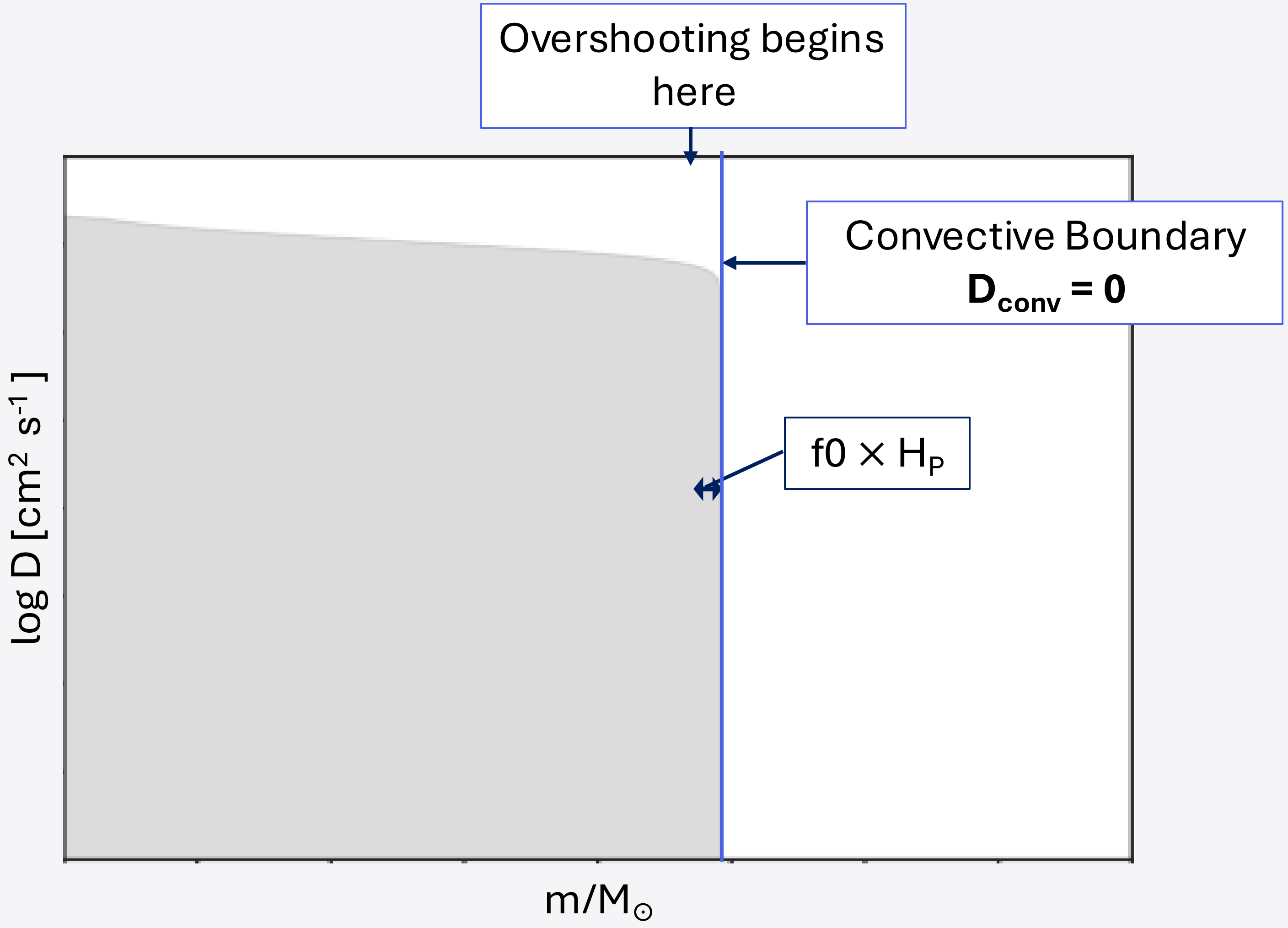
Step overshoot:

$D_{ov} = \mathbf{D_{conv}}$

Exponential overshoot:

$$D_{ov} = \mathbf{D_{conv}} \exp\left\{\frac{-2z}{f \times H_{P,z}}\right\}$$



Overshooting: f and f0

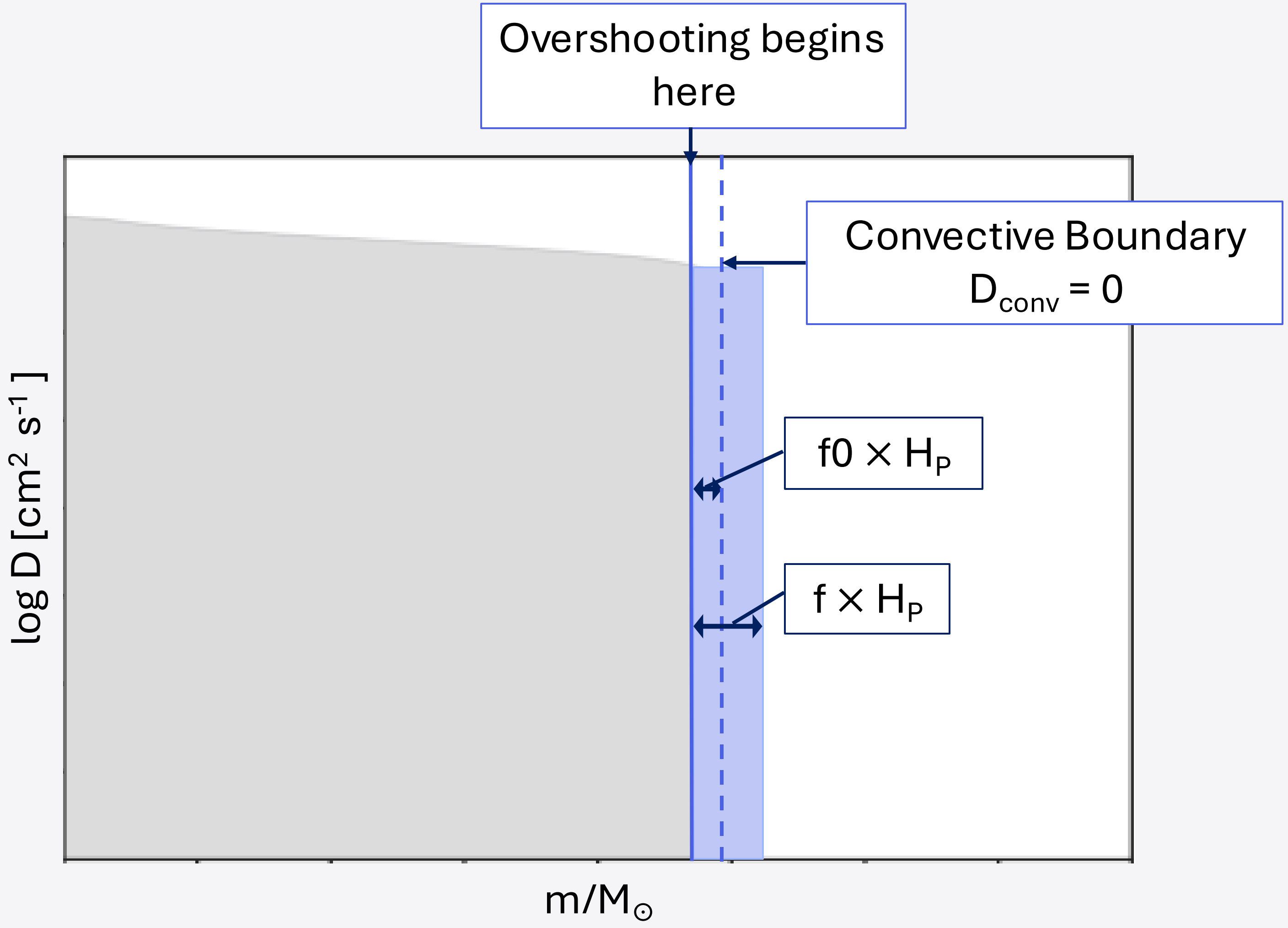
Step overshoot:

$D_{ov} = \mathbf{D_{conv,f0}}$

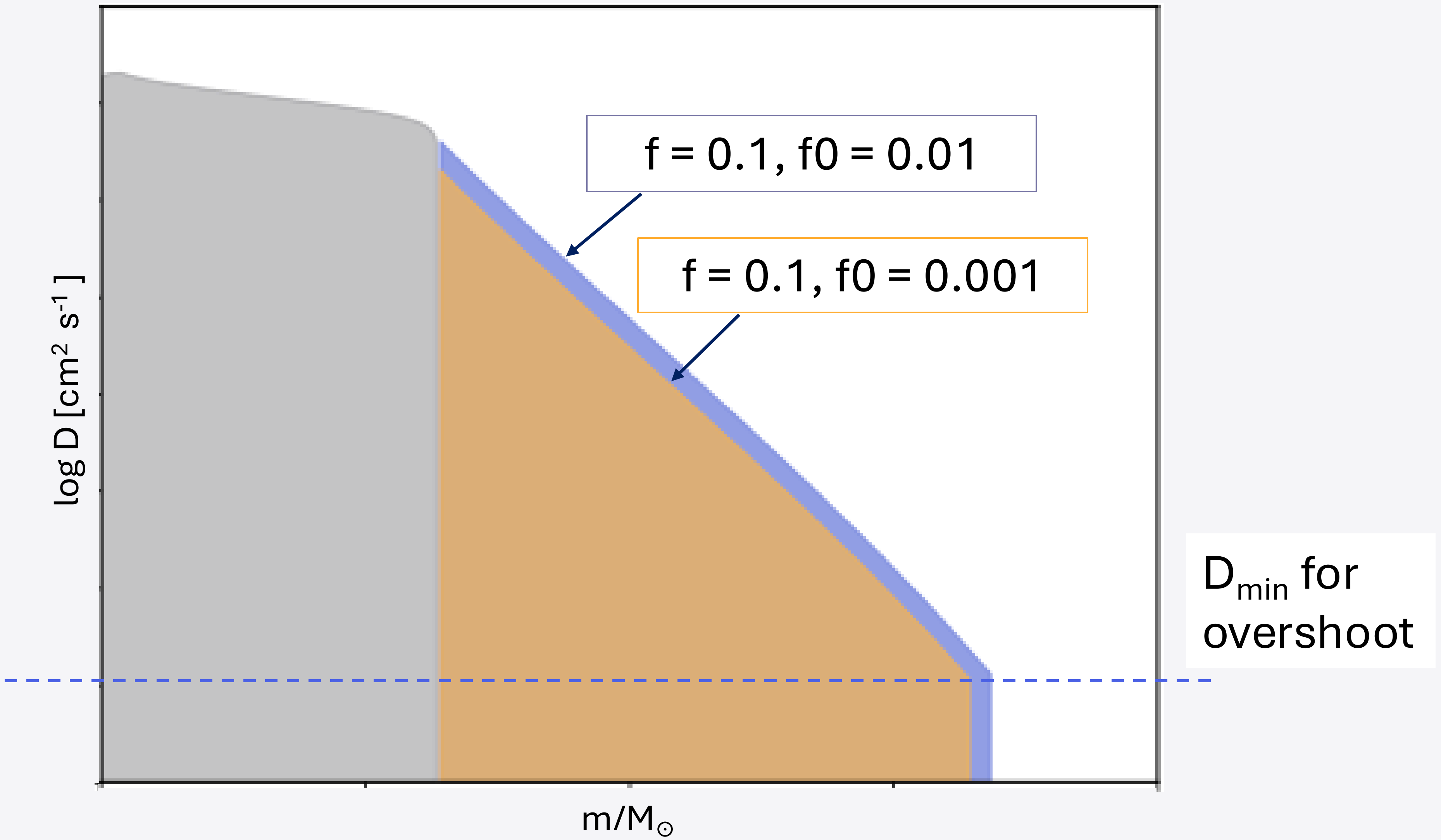
Exponential overshoot:

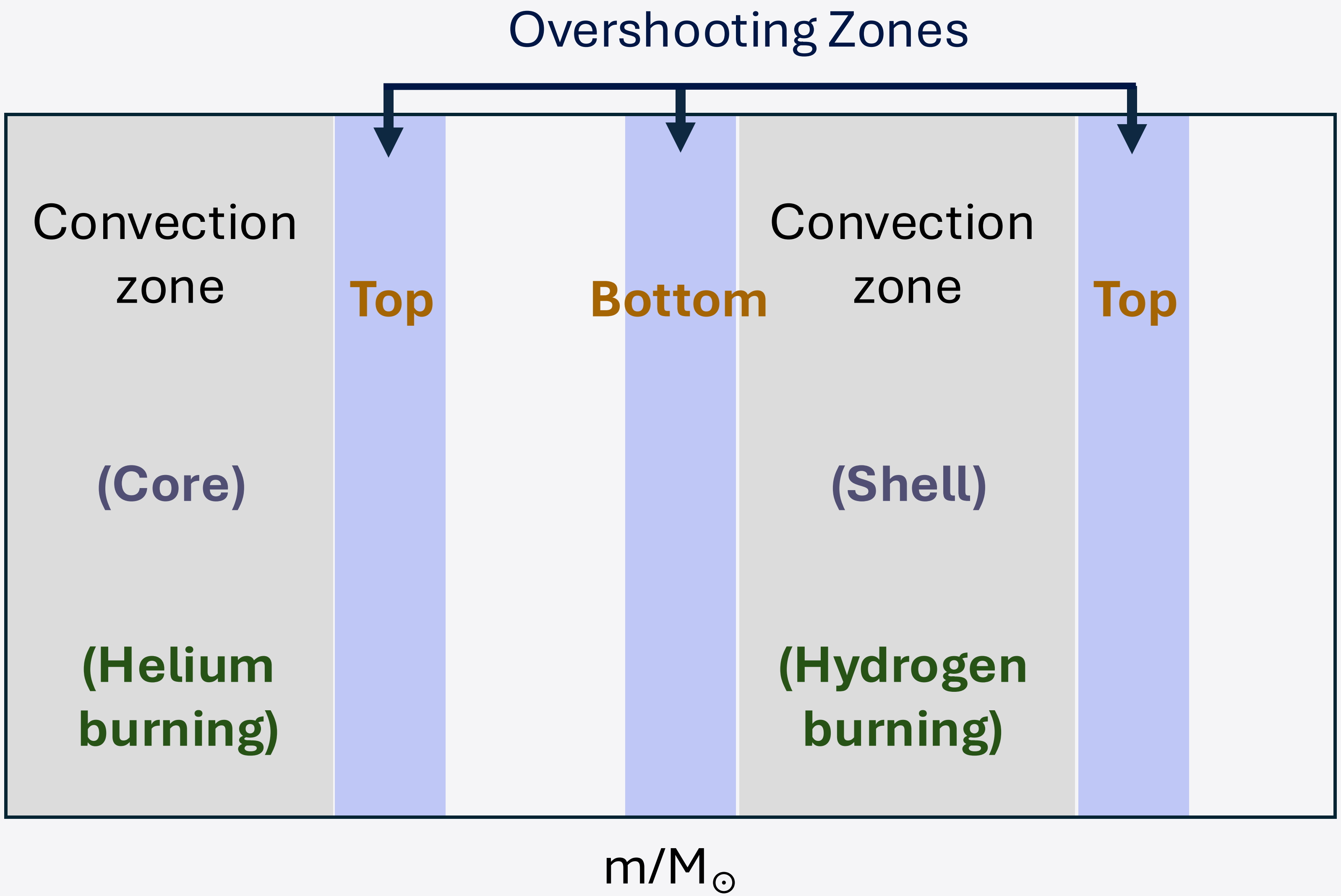
$$D_{ov} = \mathbf{D_{conv,f0}} \exp\left\{\frac{-2z}{f \times H_{P,z}}\right\}$$

f0 determines where overshooting begins
f determines how far overshooting extends



Varying f0





Overshoot Zone Location

Overshoot Boundary Location

Overshoot Zone Type

Overview of today's labs

MaxiLab 1

Modeling core overshooting in main-sequence stars

MiniLab 2

Overshooting during core helium burning (CHeB) phase

Work directory in MESA

Source Code

Input Files

src	**make**
inlist	mk
inlist_pgstar	clean
inlist_project	rn
README.rst	re

Executables for compiling and running MESA

Documentation

Source Folder `src`

run.f90	Main program for MESA
run_star_extras.f90	Fortran Subroutine for adding your custom physics to MESA

Extending MESA with run_star_extras
Bill Wolf

Executables for compiling and running MESA

make	Folder containing makefile with instructions for compiling MESA
mk	Compiles the files in ‘src’ folder, links them against MESA, and produces the ‘star’ executable file.
rn	Runs MESA
re	Resume MESA run starting from a pre-saved photo
clean	Removes the compiled files (e.g., for a fresh compile)

Input Files

inlist	Default input file for MESA

```
&star_job
  read_extra_star_job_inlist(1) = .true.
  extra_star_job_inlist_name(1) = 'inlist_project'
/ ! end of star_job namelist
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```
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```
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→ inlist_project

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```

→ inlist_pgstar

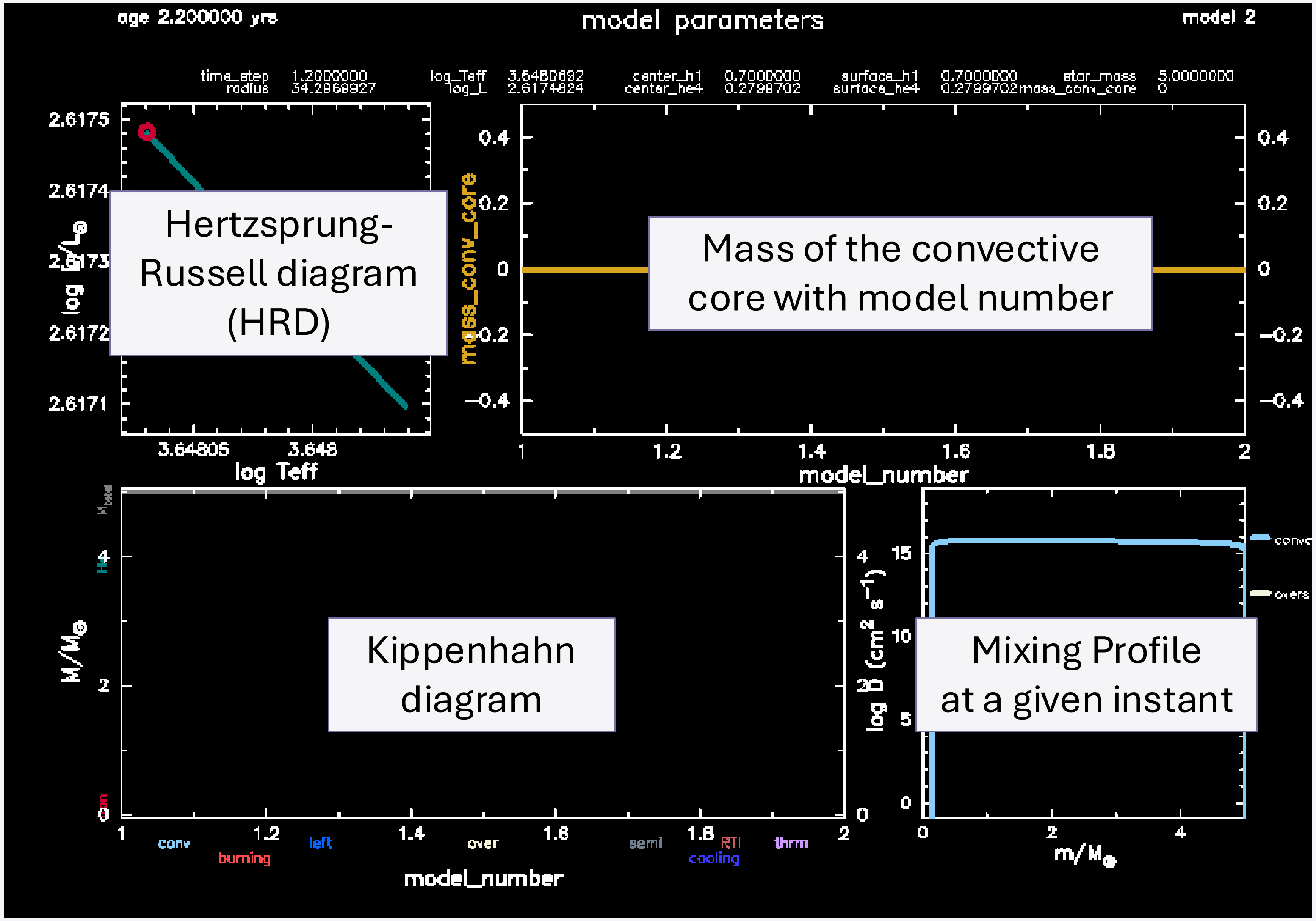
Lab 1
Session 1

Setting up inlists and $5M_{\odot}$ model with overshooting

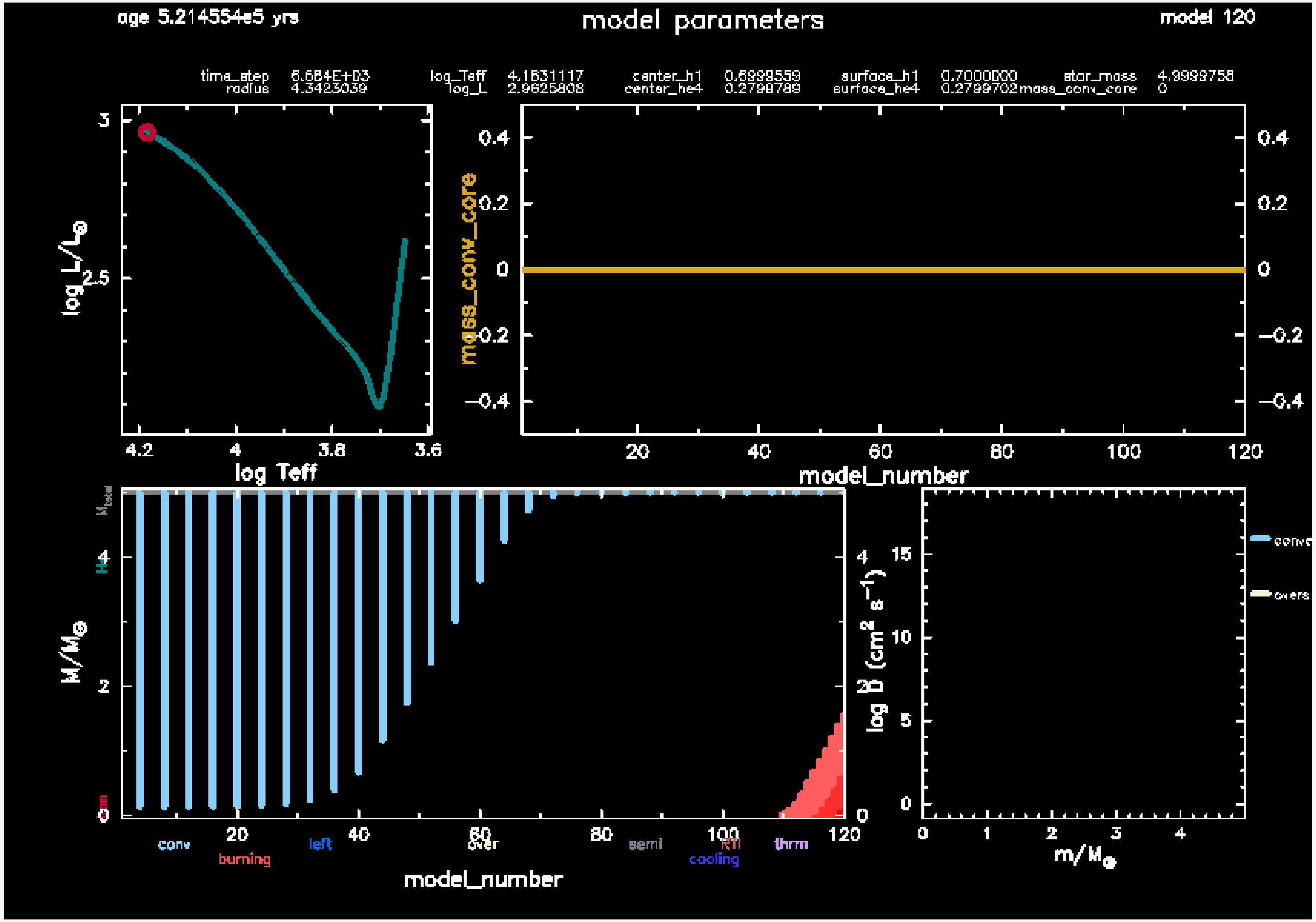
- Setting up your MESA work directory
- Modifying the input physics and saving your final model
- Monitoring the run and customizing output

Session 2: Introduction

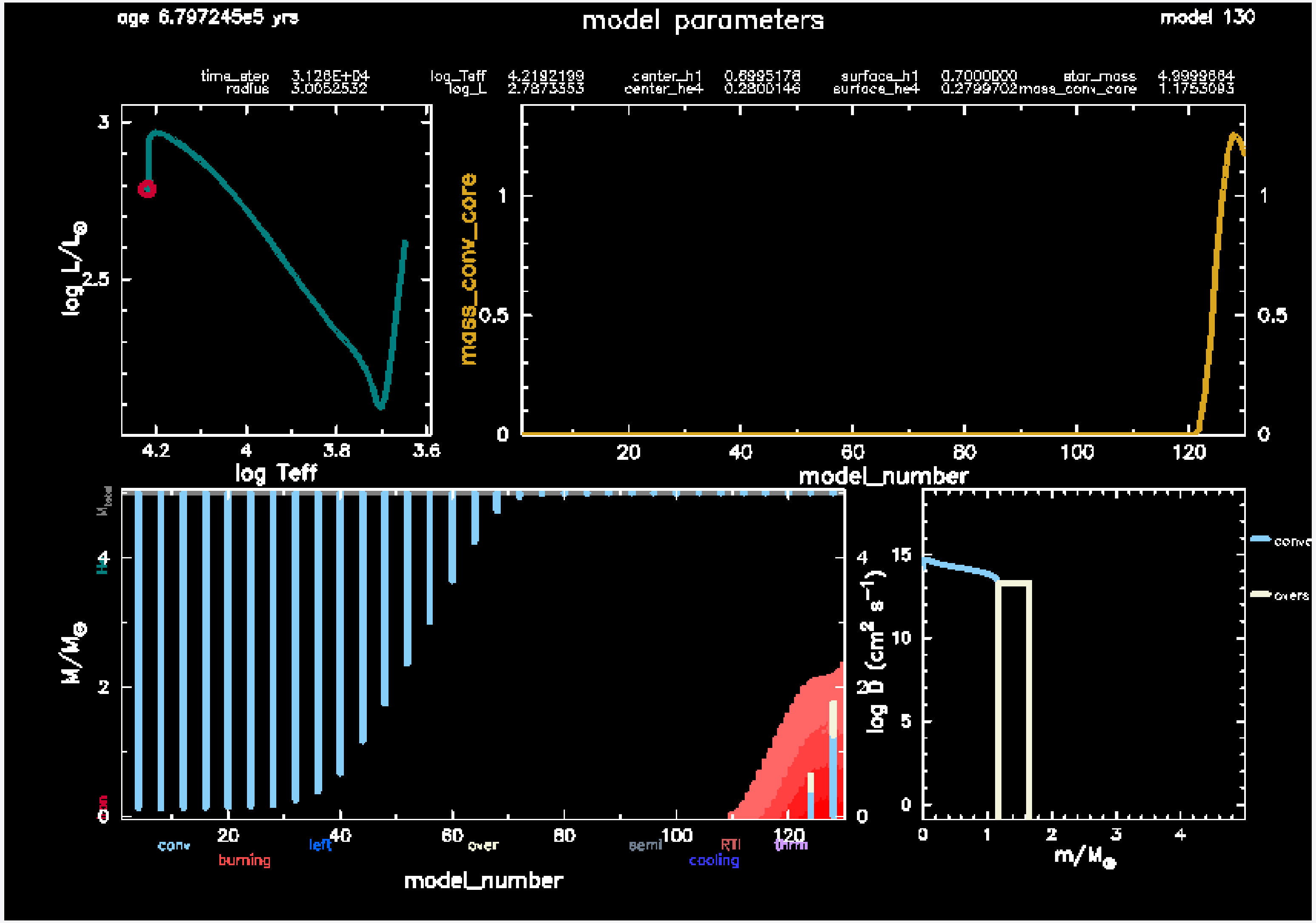
Initial pgplot- 5$M_\odot$ star



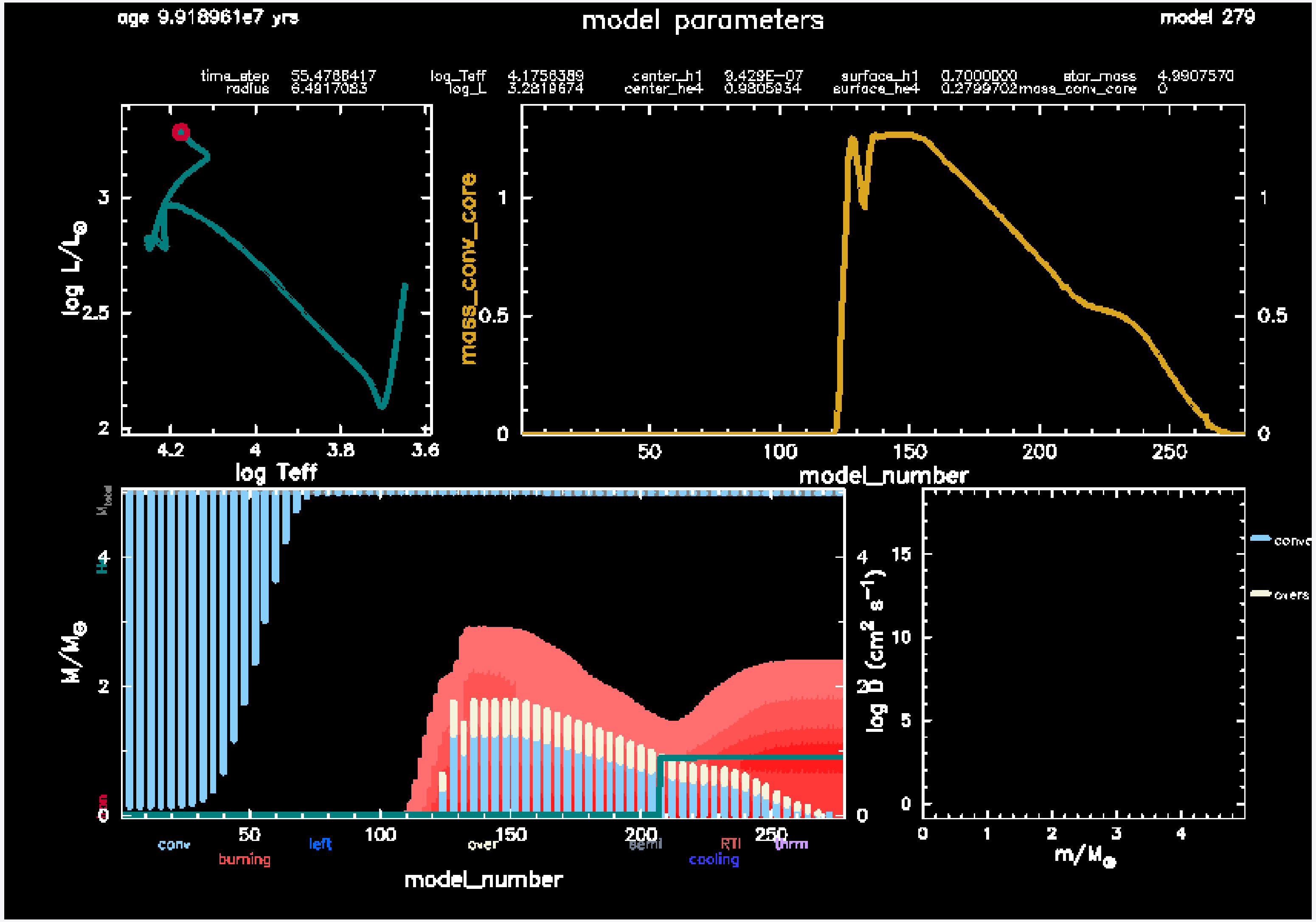
Beginning of hydrogen burning



Formation of convective core



End of main-sequence



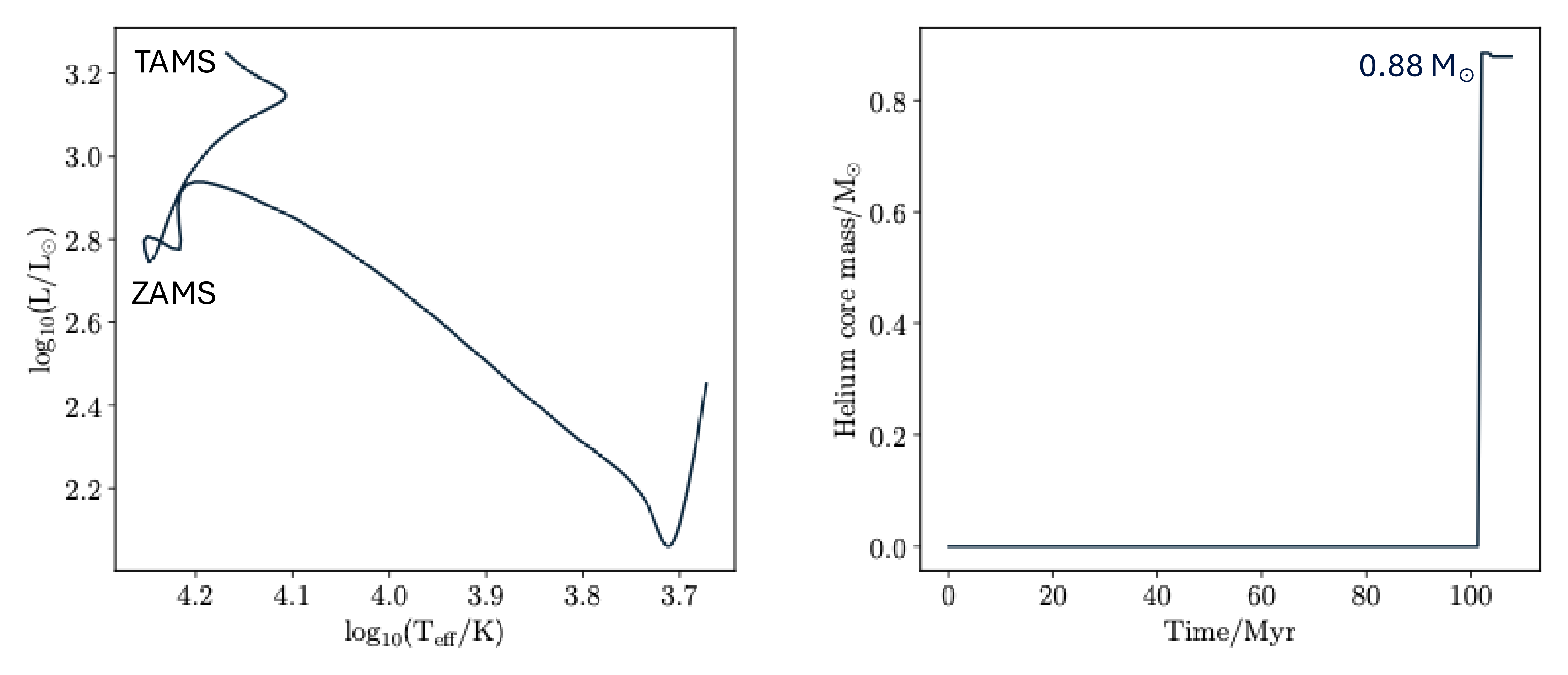
Lab 1 Session 2

Trying different the overshoot settings

- How does changing overshooting changes stellar evolution?
- Pick a value from the spreadsheet, put your name /initials to mark that the values have been taken
- Make your own plots

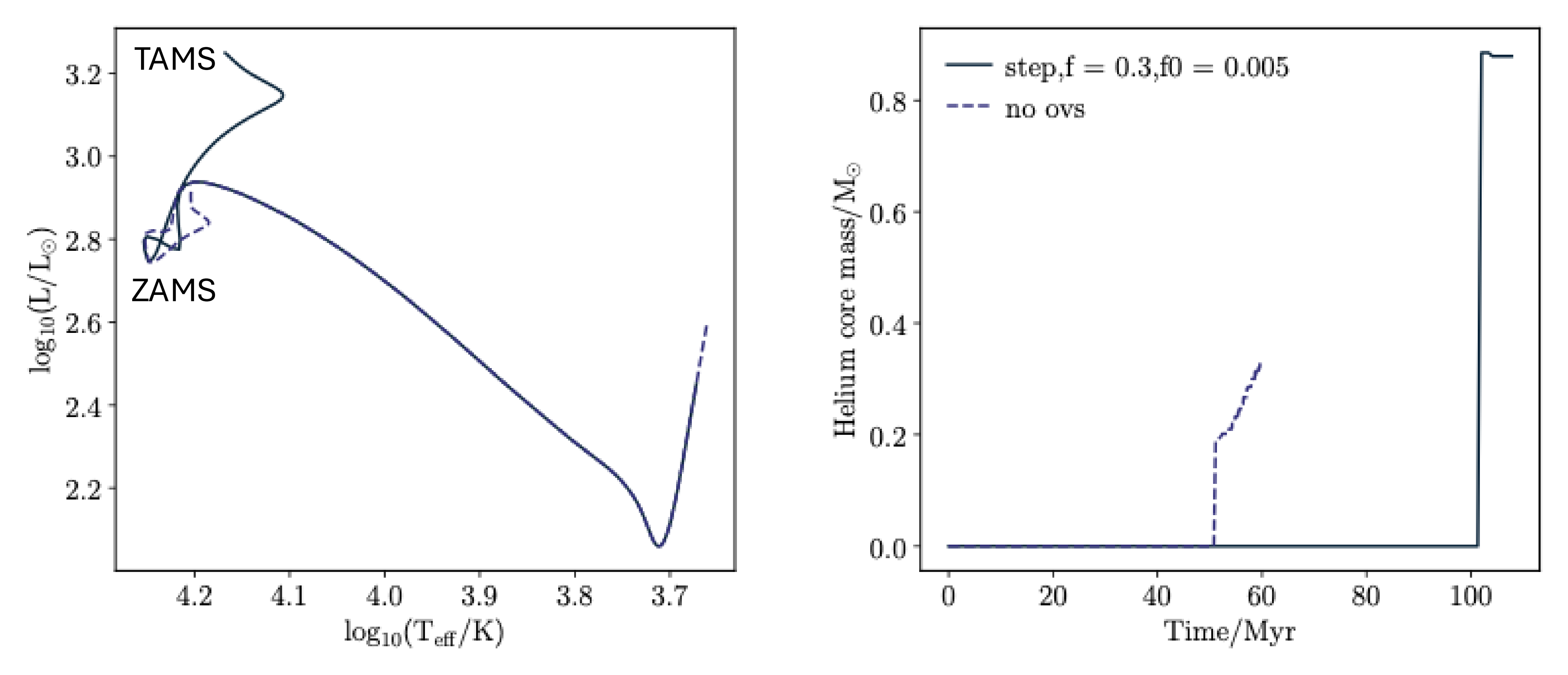
Session 2: Wrap-Up

$5M_\odot$ star

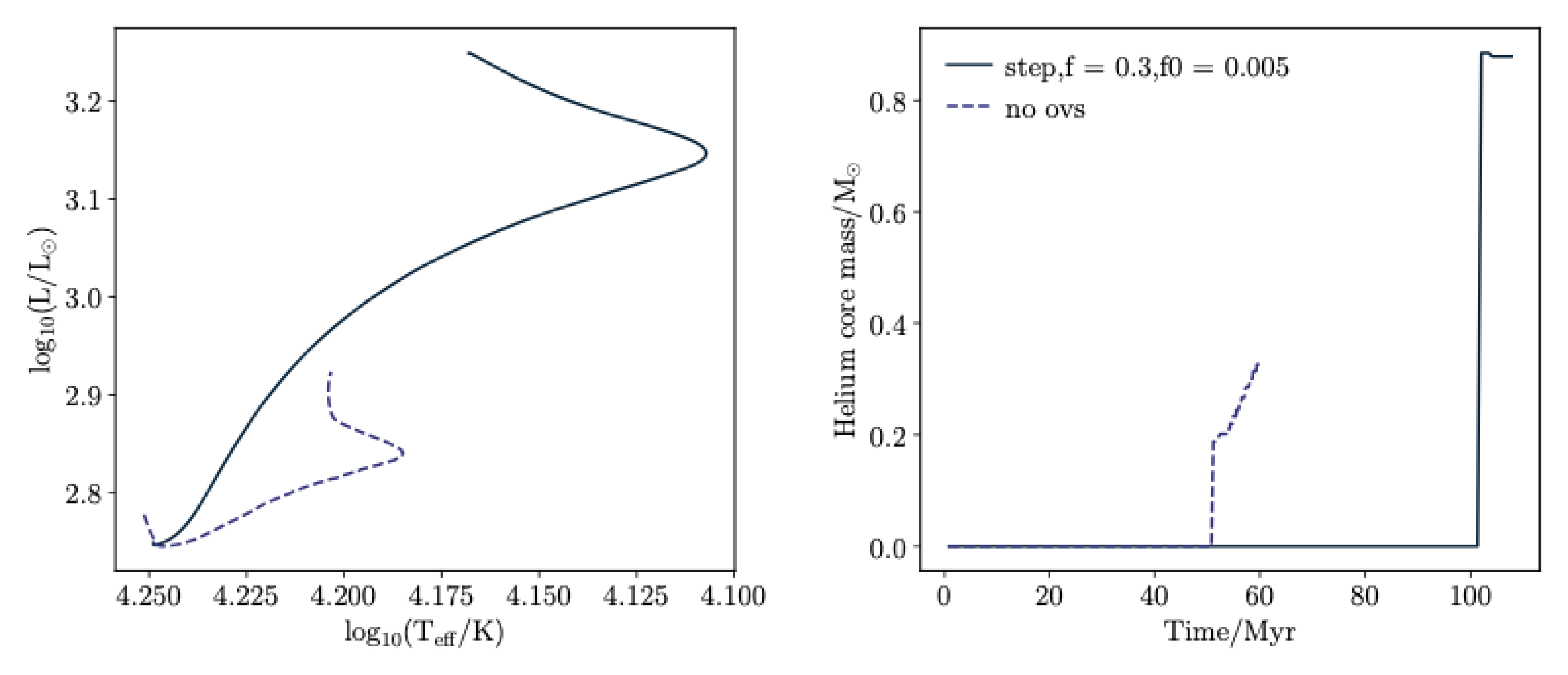


TAMS
ZAMS
3.2
3.0
2.8
2.6
2.4
2.2
$\log_{10}(L/L_\odot)$
4.2
4.1
4.0
3.9
3.8
3.7
$\log_{10}(T_{eff}/K)$
$0.88\ M_\odot$
0.8
0.6
0.4
0.2
0.0
Helium core mass/$M_\odot$
0
20
40
60
80
100
Time/Myr

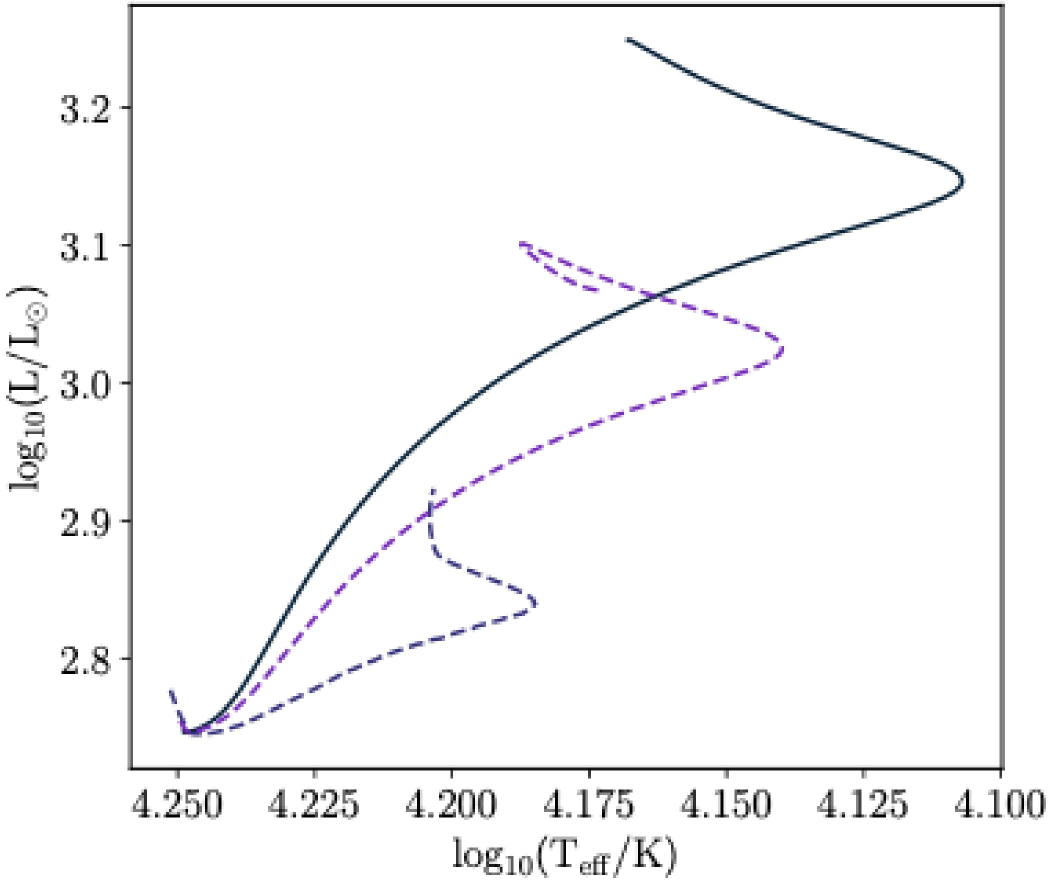
$5M_\odot$ model with and without overshooting

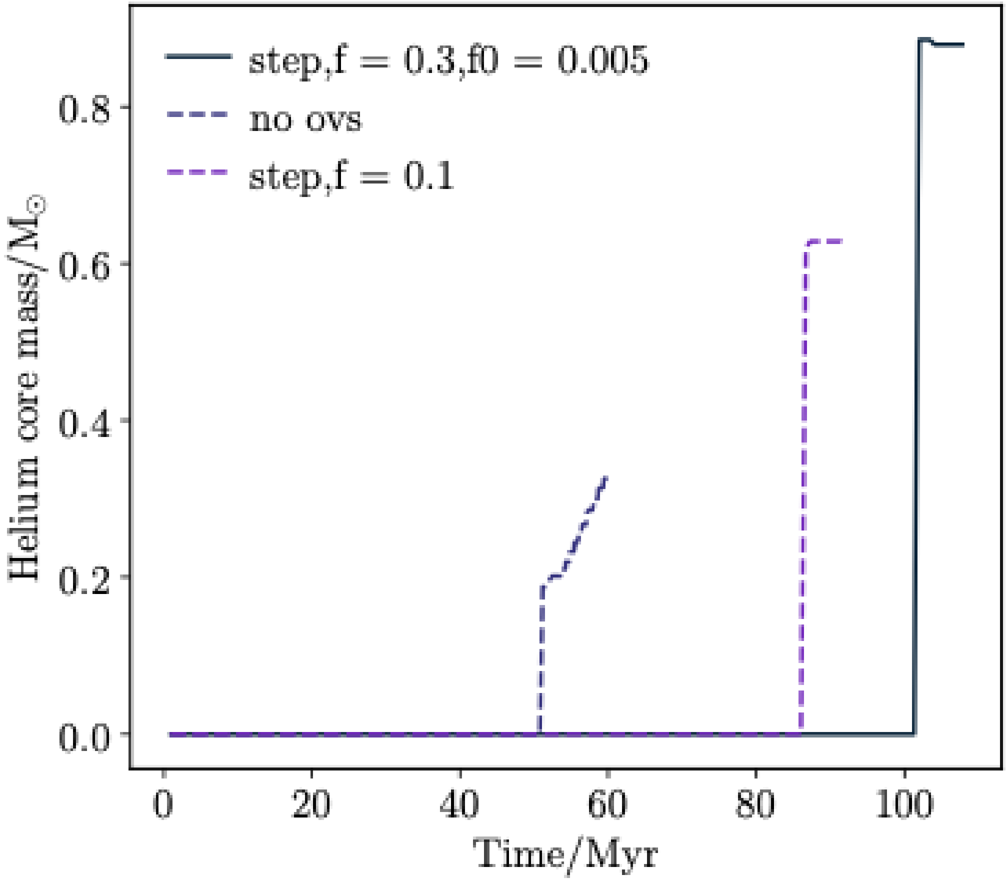


Omitting pre-main-sequence

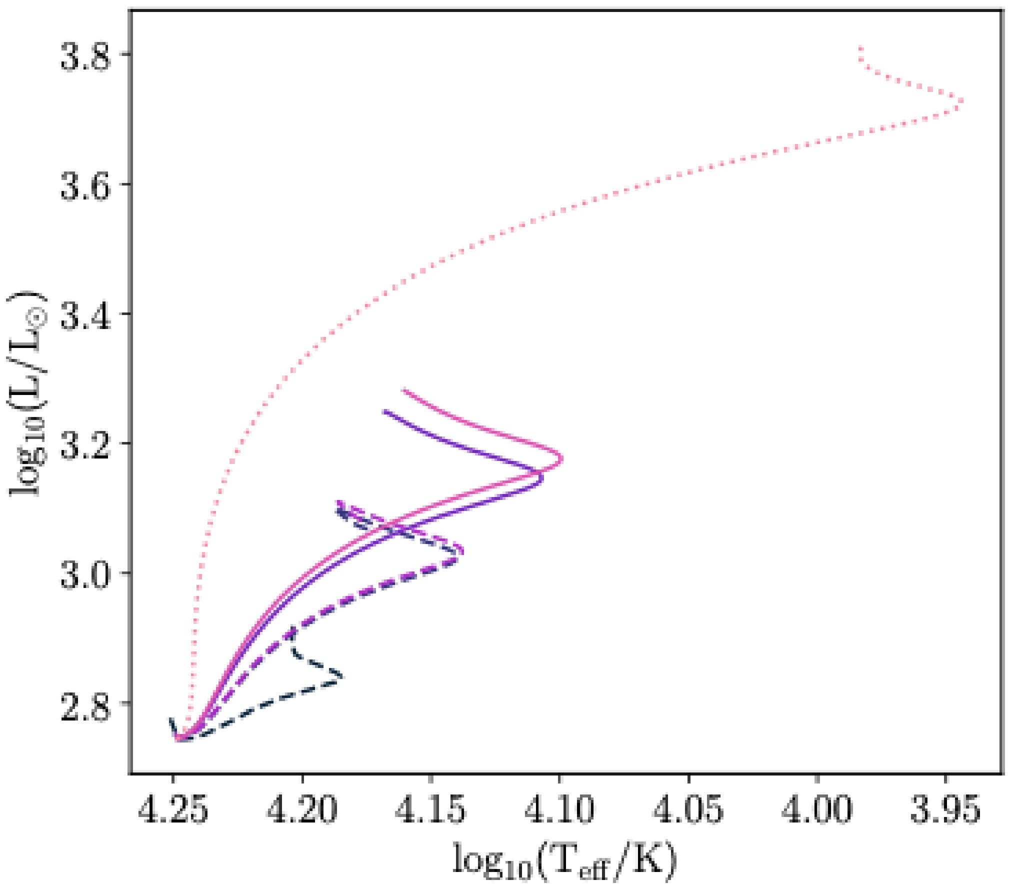


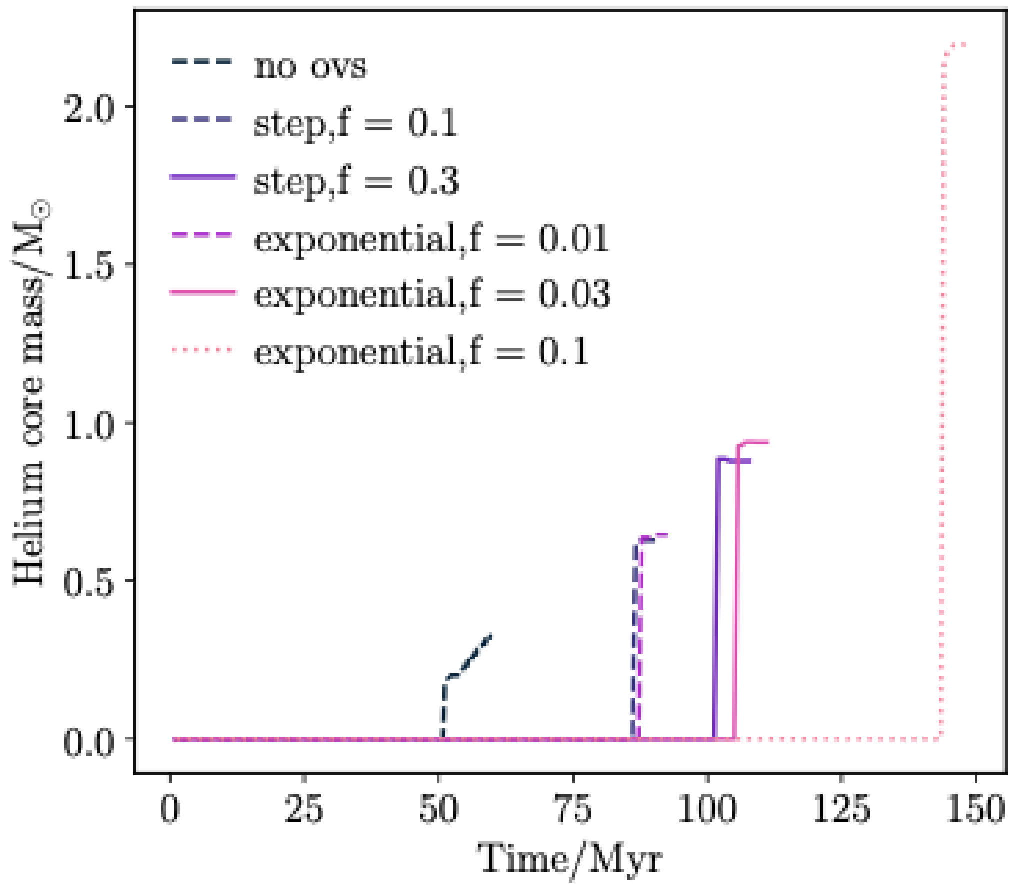
Changing overshoot value



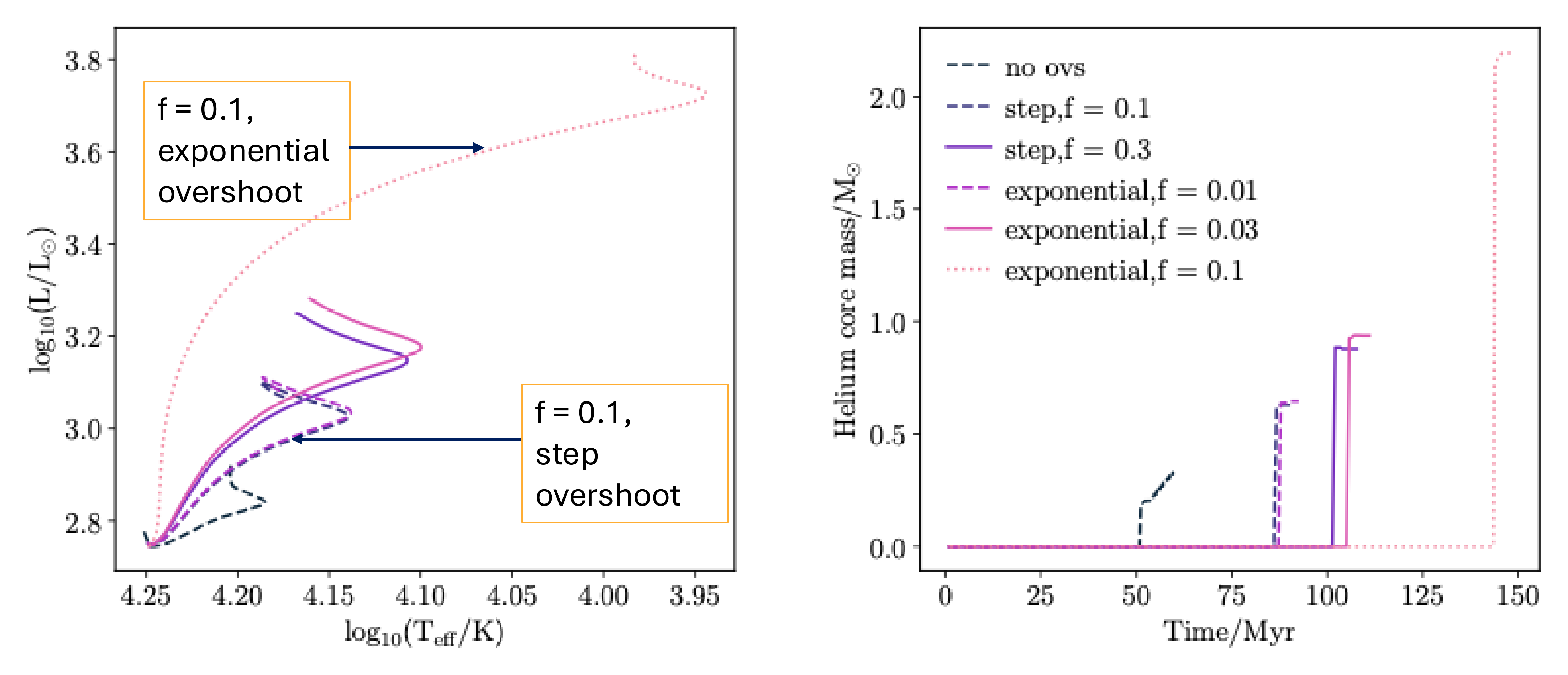


Changing overshoot scheme

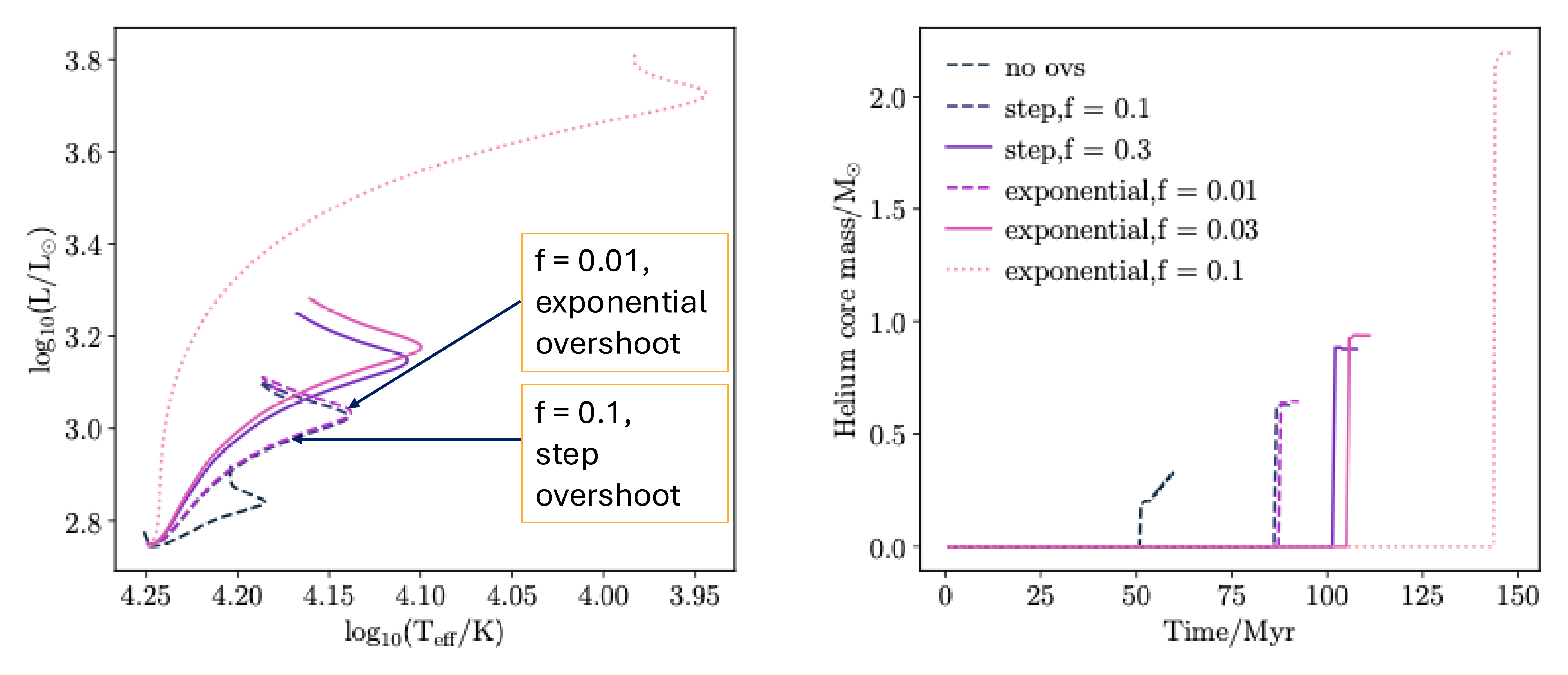




Changing overshoot scheme



Changing overshoot scheme



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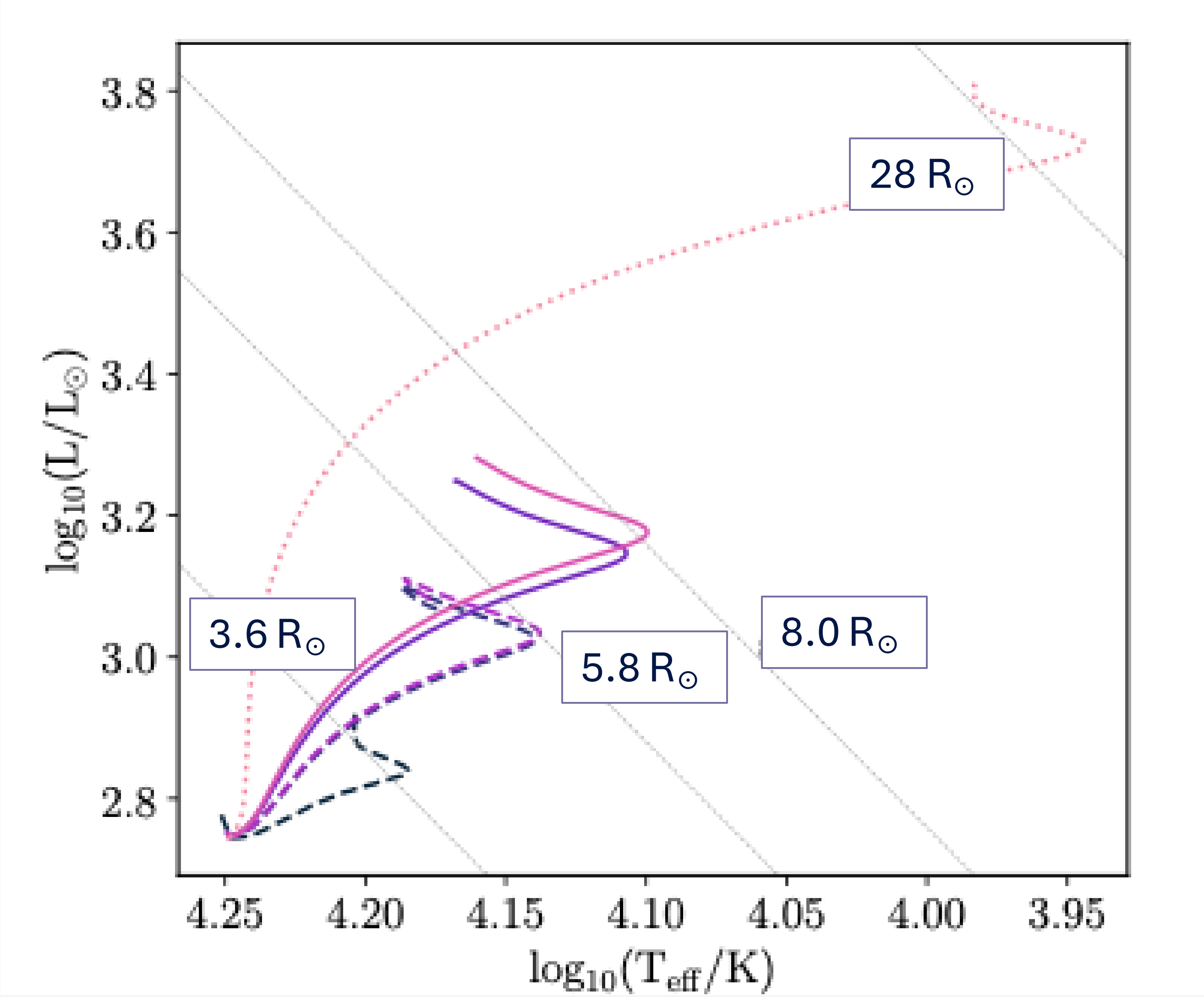
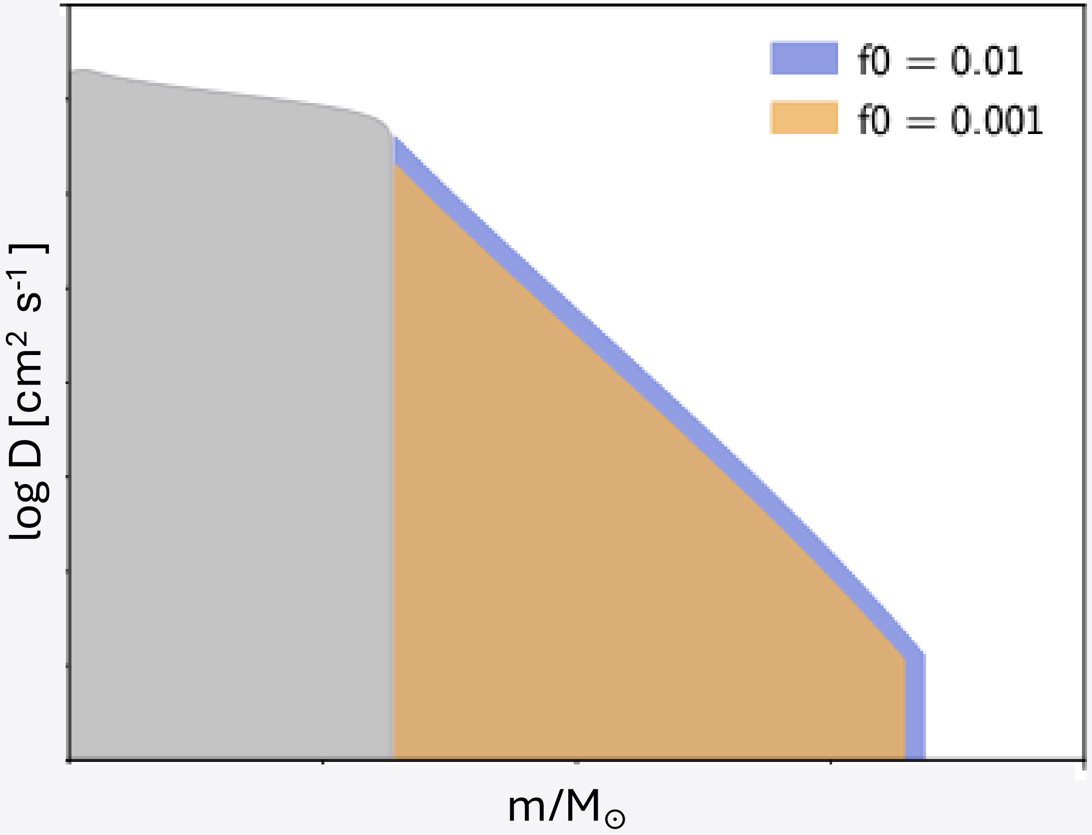
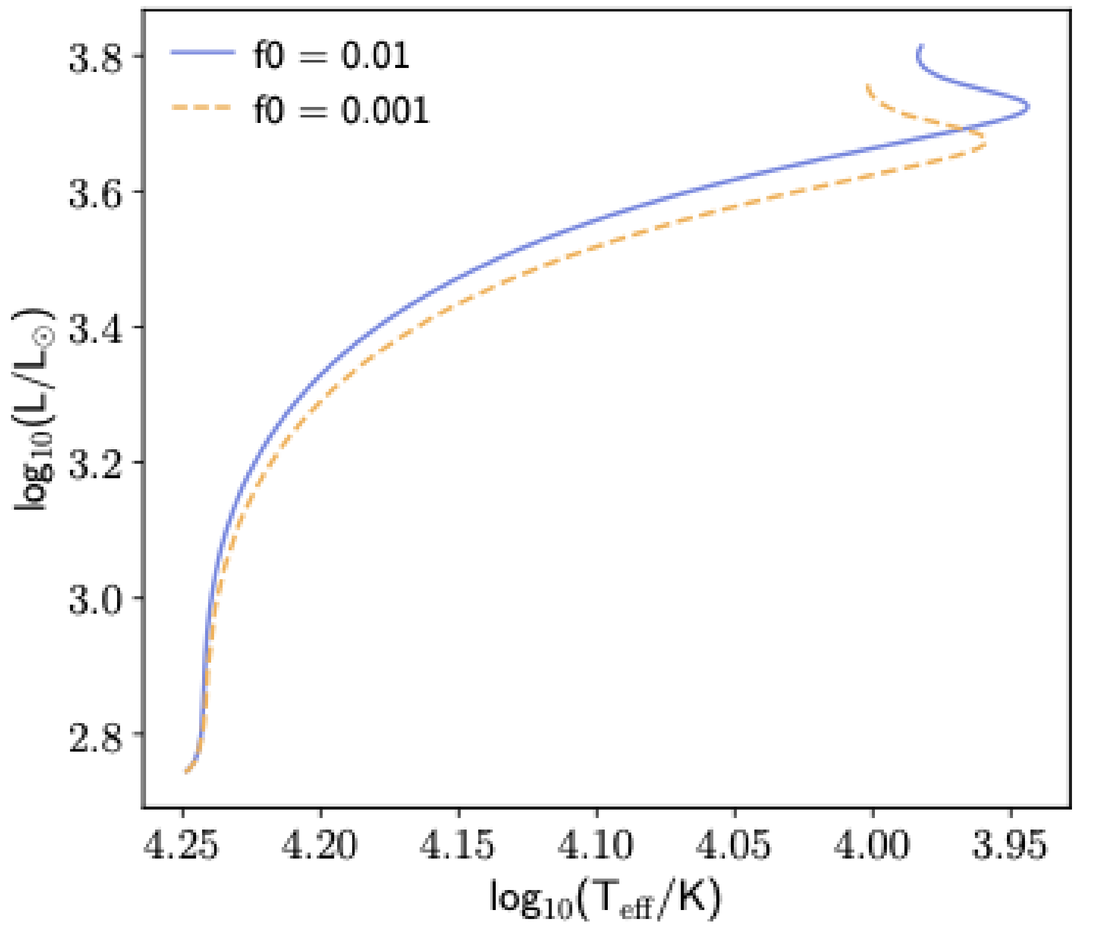
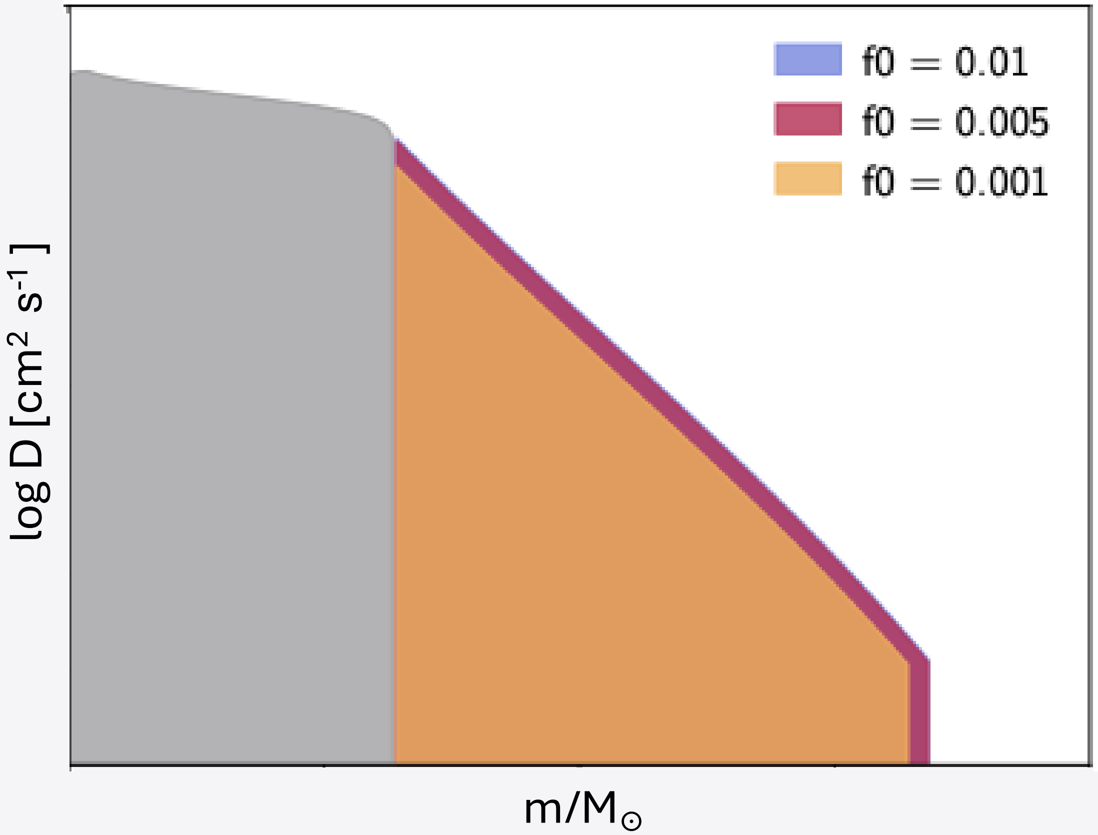


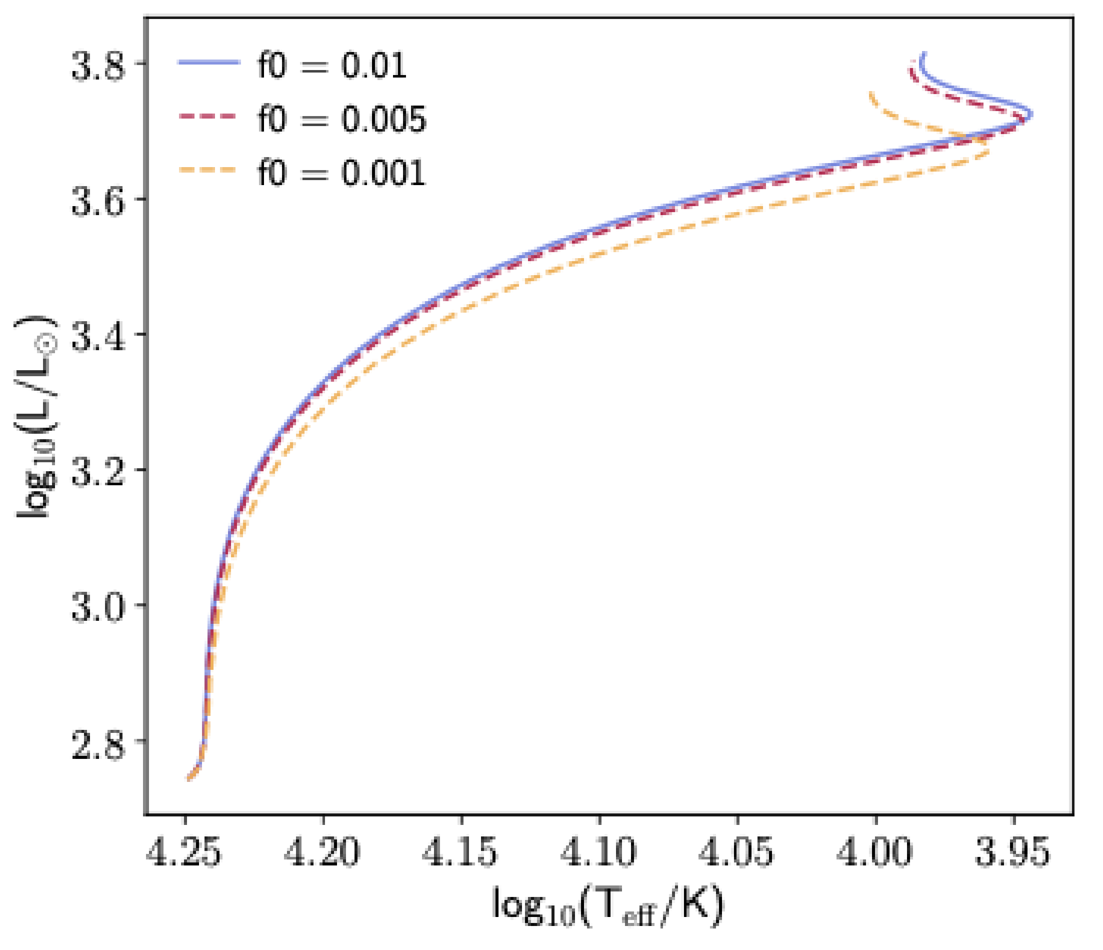
Changing f0 for f = 0.1, exponential overshooting



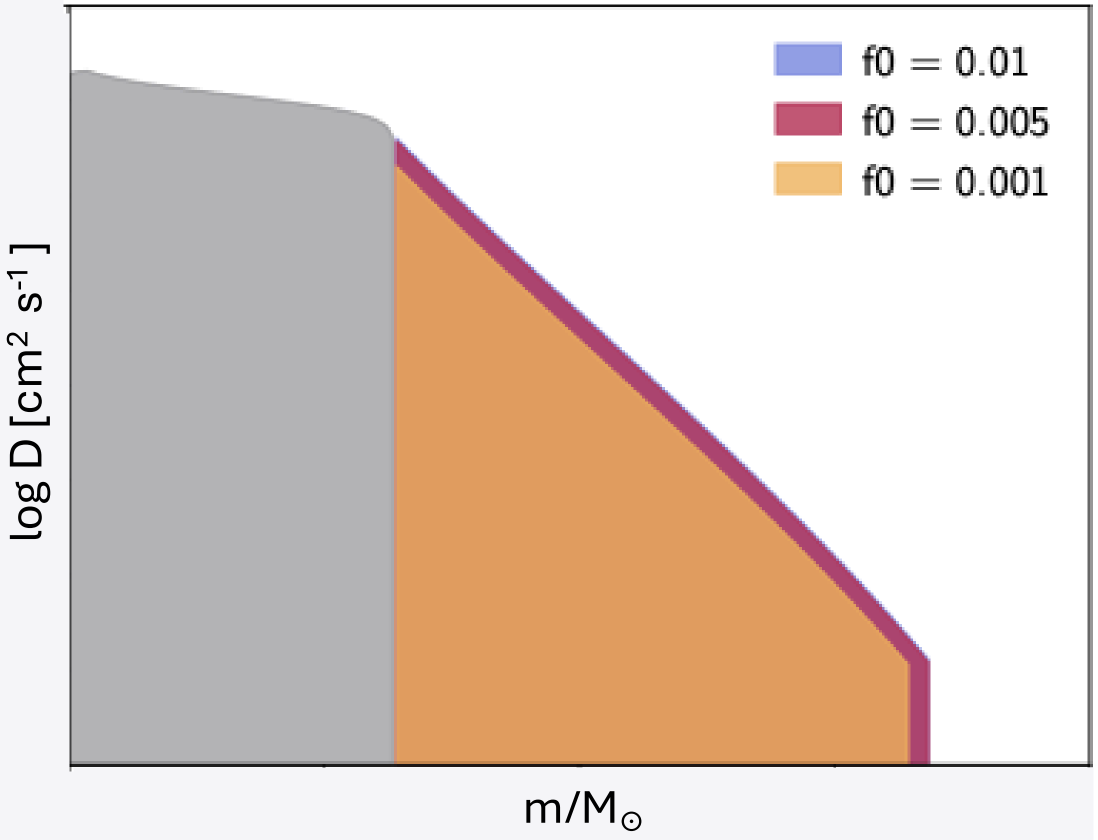


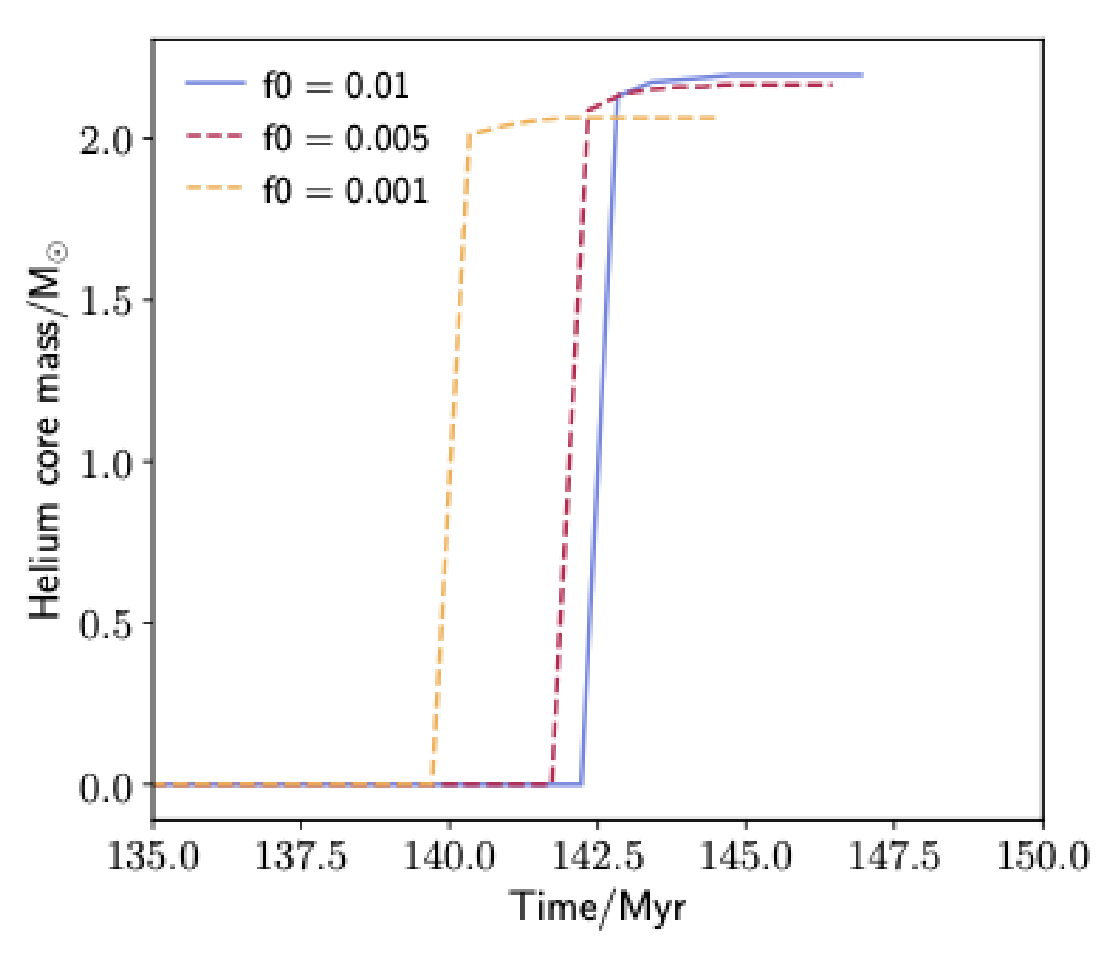
Changing f0 for f = 0.1, exponential overshooting



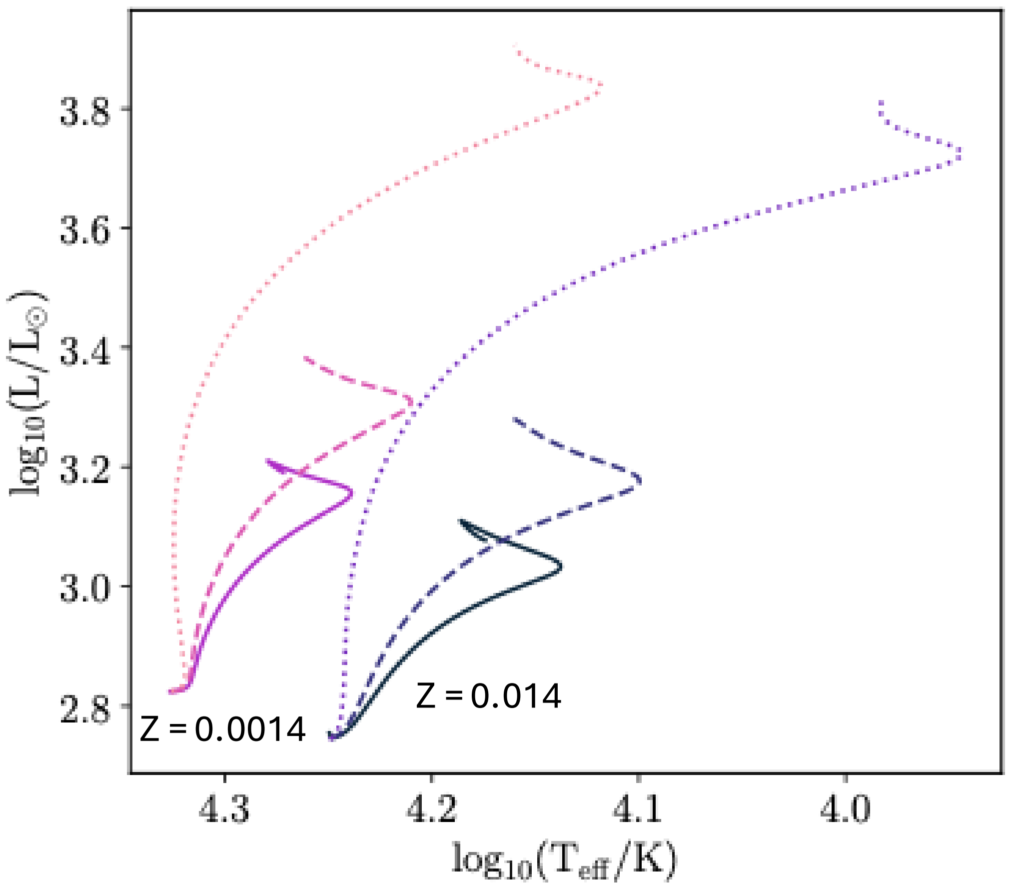


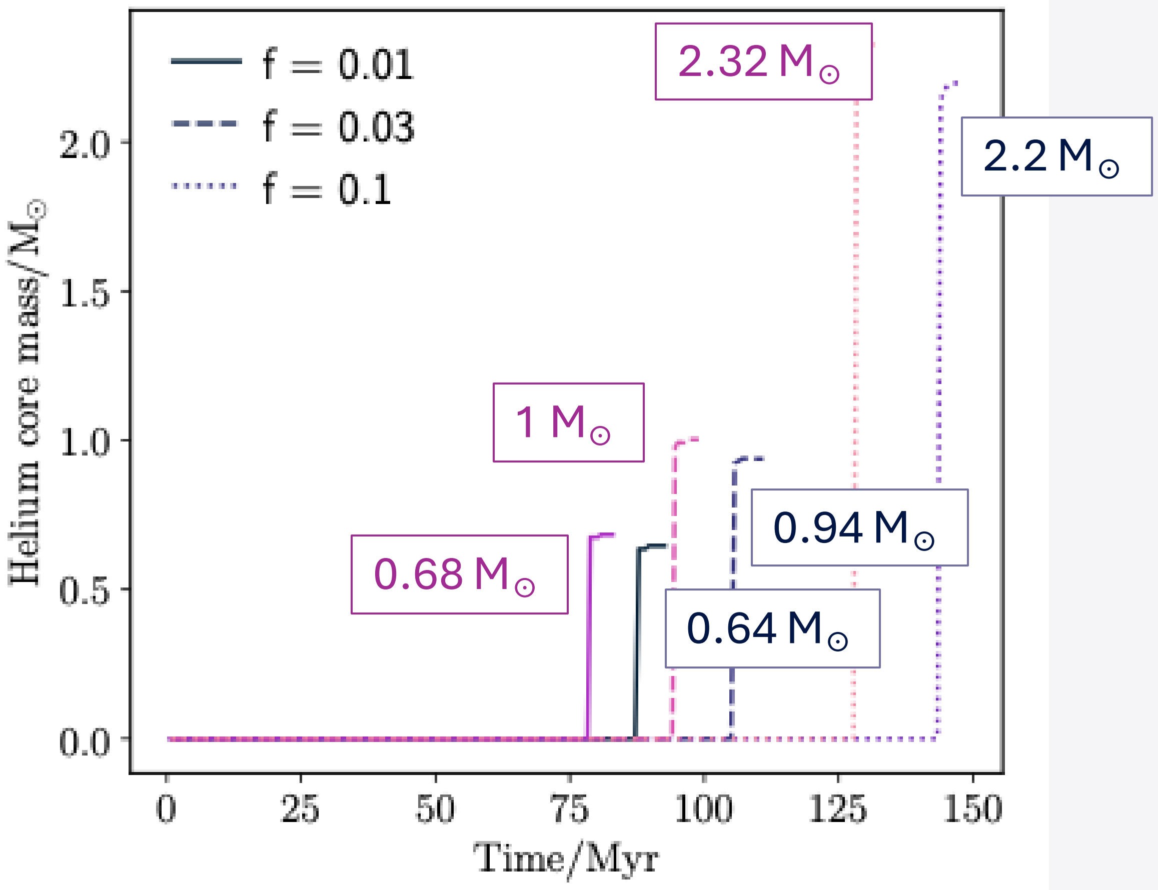
Changing f0 for f = 0.1, exponential overshooting



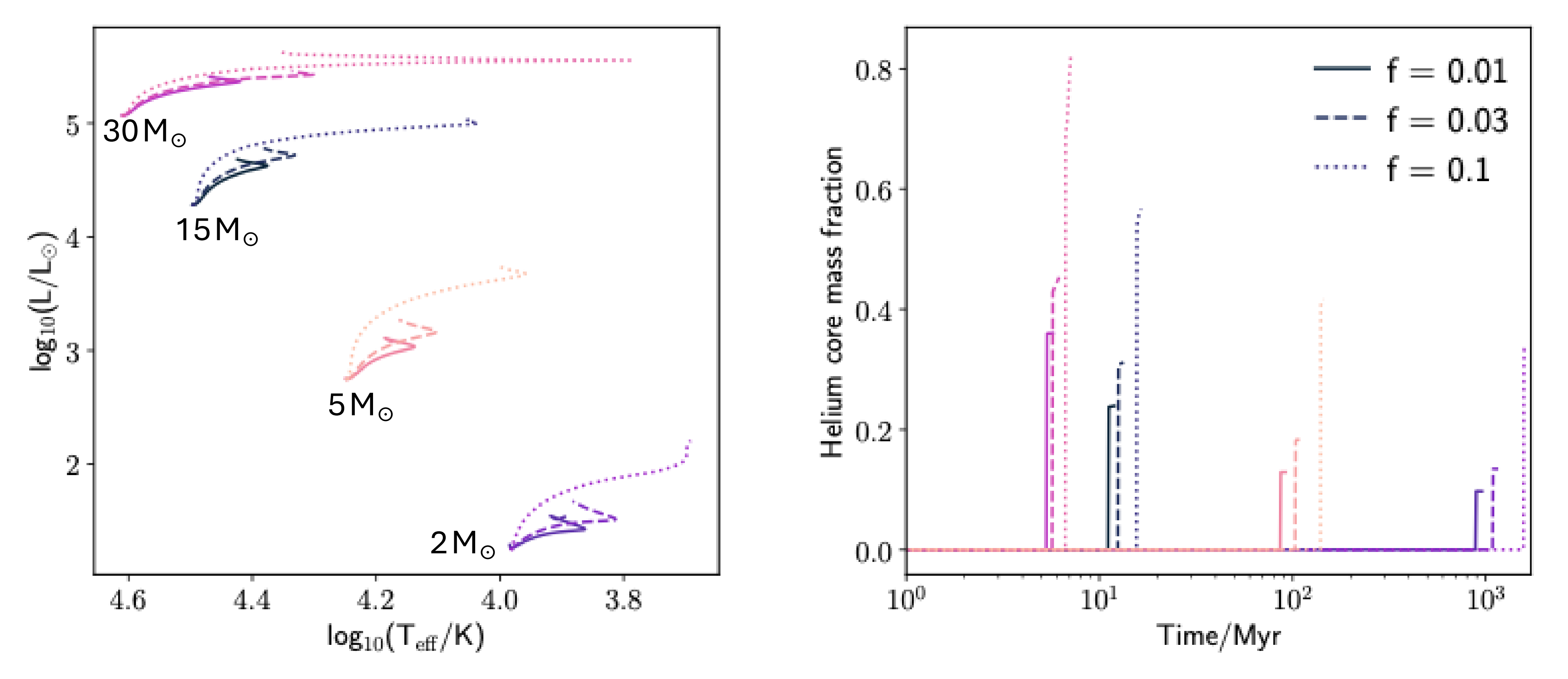


Changing metallicity





Changing mass

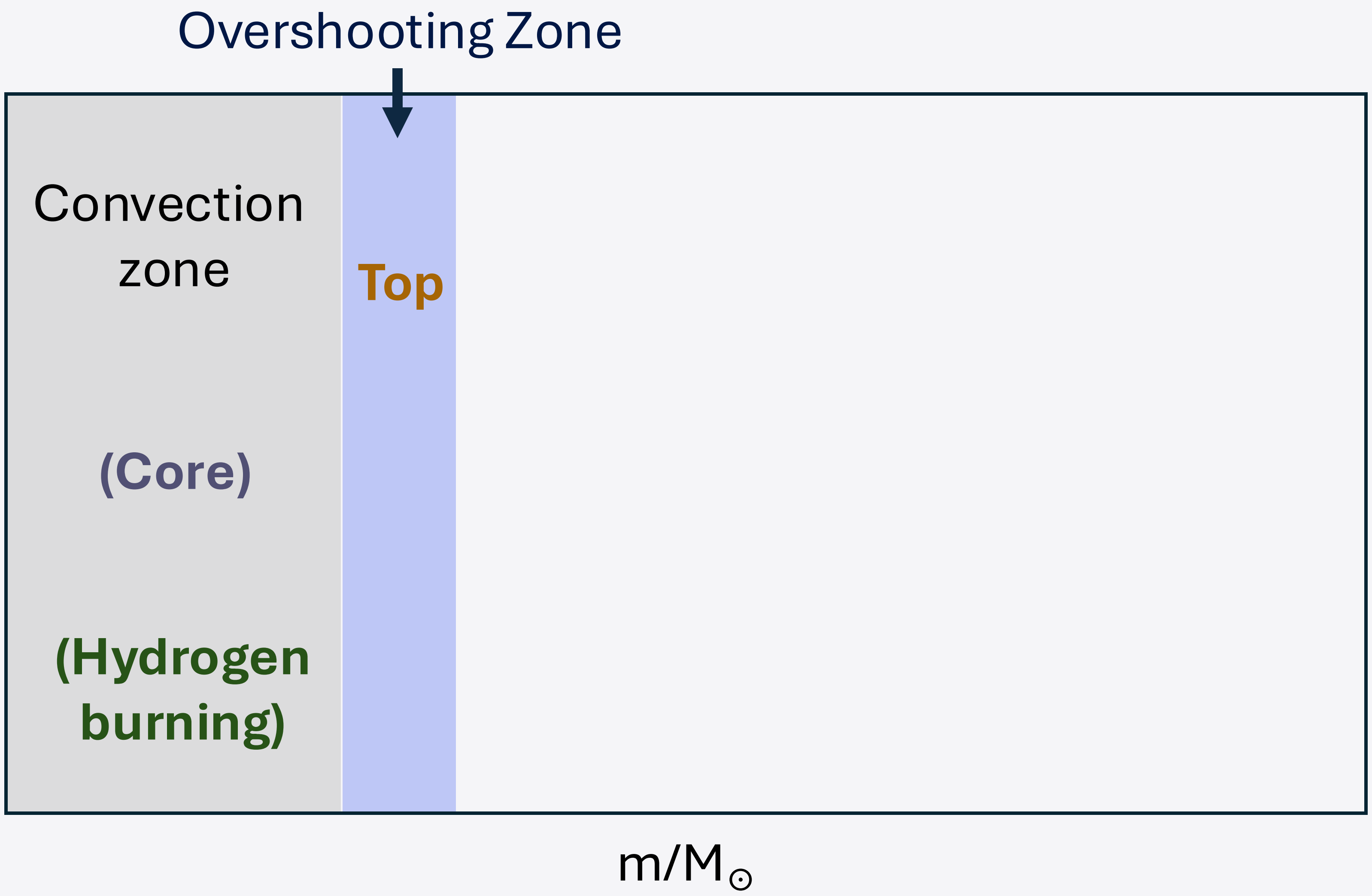


Lab 1: Key Takeaways

Parameter	Effect on Overshoot Mixing	Consequences of Increased Overshooting
Increasing f	Increases the impact of overshoot	• Longer nuclear burning lifetime • Larger radius/ luminosity • Larger core
Increasing f0	Increases overshoot mixing	Same as above
Mass	Increases the impact of overshoot mixing	More pronounced changes in lifetime, radius, luminosity, and core mass at higher mass
Metallicity (Z)	Lower Z are affected more by overshoot mixing	Differences due to Z become more pronounced

Session 3: Introduction

Overshooting during main sequence

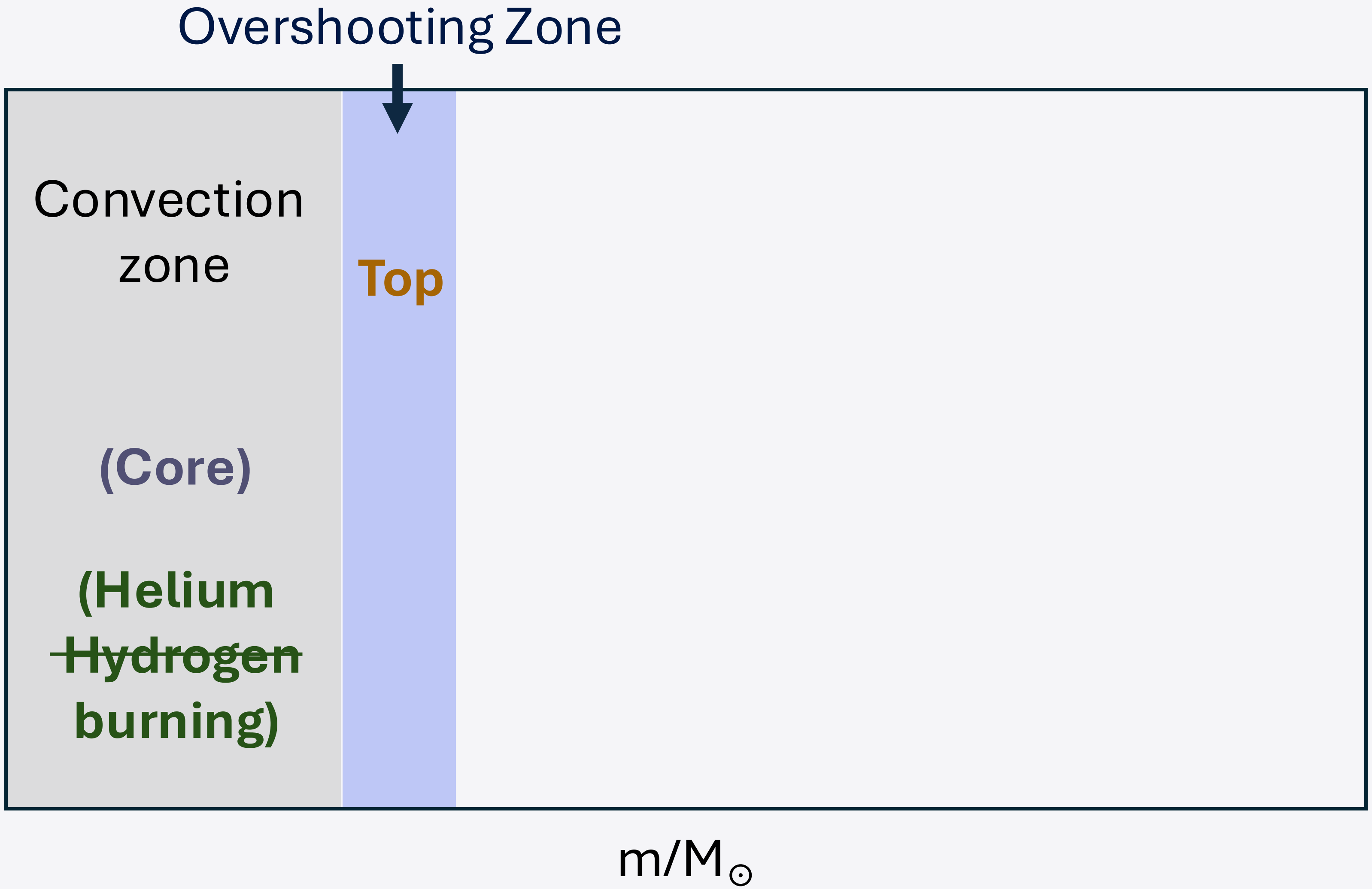


Overshoot Zone Location

Overshoot Boundary Location

Overshoot Zone Type

Overshooting post-main sequence



Overshoot Zone Location

Overshoot Boundary Location

Overshoot Zone Type

Resuming a run in MESA

Photo

- Default - saved in directory \`photos\`
- complete snapshot of the internal state -guaranteed to give the same results
- Version dependent

Model

- Default – None
- Incomplete snapshot of the internal state – not guaranteed to give the same results
- Work across different mesa versions of the same revision

Load pre-saved model : M5_Z0014_fov030_f0ov0005_TAMS.mod

Resuming MESA - Inlists

Don’t need initial conditions anymore but do need conditions for sustaining the run

initial_mass = 5 ! in Msun units
initial_z = 0.014d0

use_Type2_opacities = .true.
Zbase = 0.014d0

Input Files

inlist	Default input file for MESA

```
&star_job
   read_extra_star_job_inlist(1) = .true.
   extra_star_job_inlist_name(1) = 'inlist_project'
/ ! end of star_job namelist
```

```
&controls
   read_extra_controls_inlist(1) = .true.
   extra_controls_inlist_name(1) = 'inlist_project'
/ ! end of controls namelist
```

```
&eos
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```

→ inlist_pgstar

Nested inlists

```
&star_job
   read_extra_star_job_inlist(1) = .true.
   extra
/ ! end
```

```
&star_job
   read_extra_star_job_inlist(2) = .true.
   extra
/ ! end
```

```
&star_job
   read_extra_star_job_inlist(3) = .true.
   extra
/ ! end
```

```
&star_job
   read_extra_star_job_inlist(4) = .true.
   extra_s
/ ! end of
```

```
&star_job
   read_extra_star_job_inlist(5) = .true.
   extra_star_job_inlist_name(5) = 'inlist_extremely_specific'
/ ! end of star_job namelist
```

Lab 2

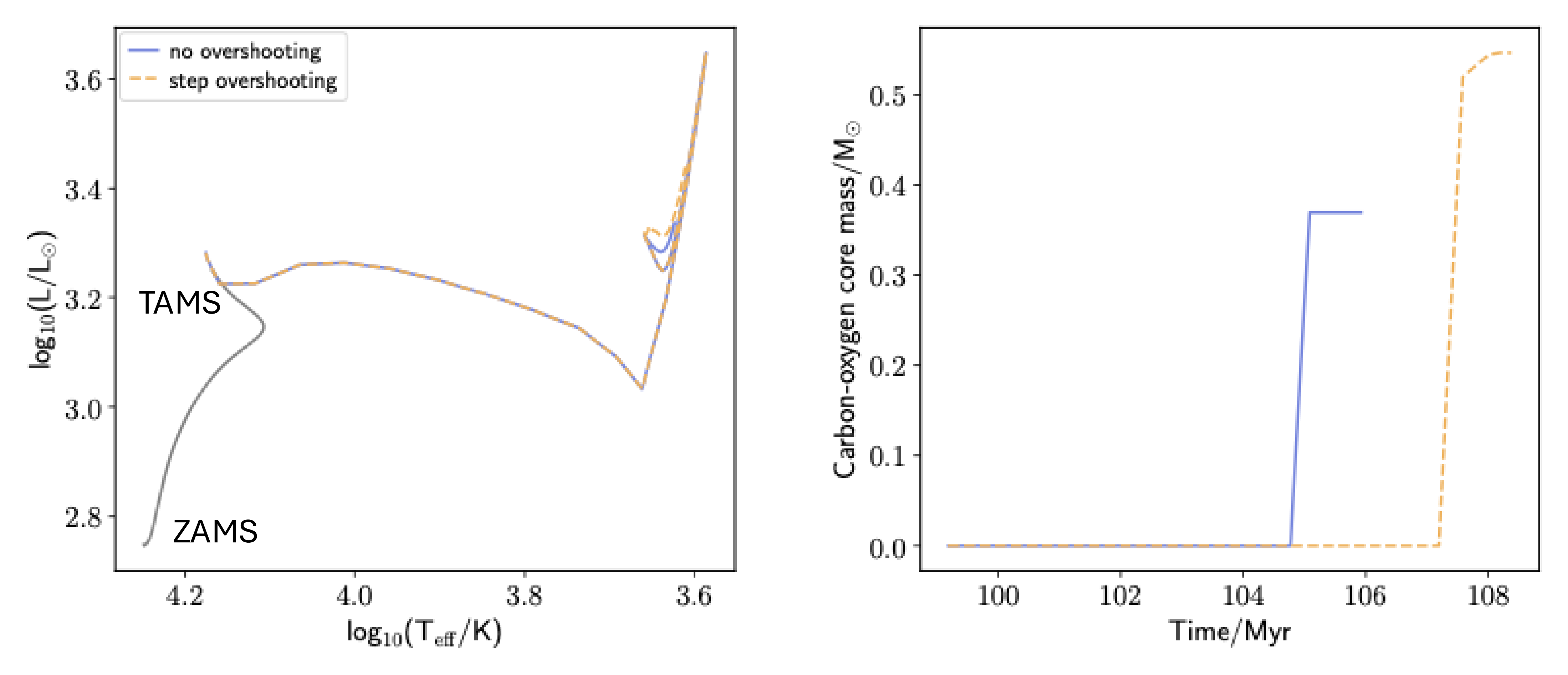
How overshooting affects different stellar phases

Evolve $5M_{\odot}$ model from Session 1 until the end of core helium burning:

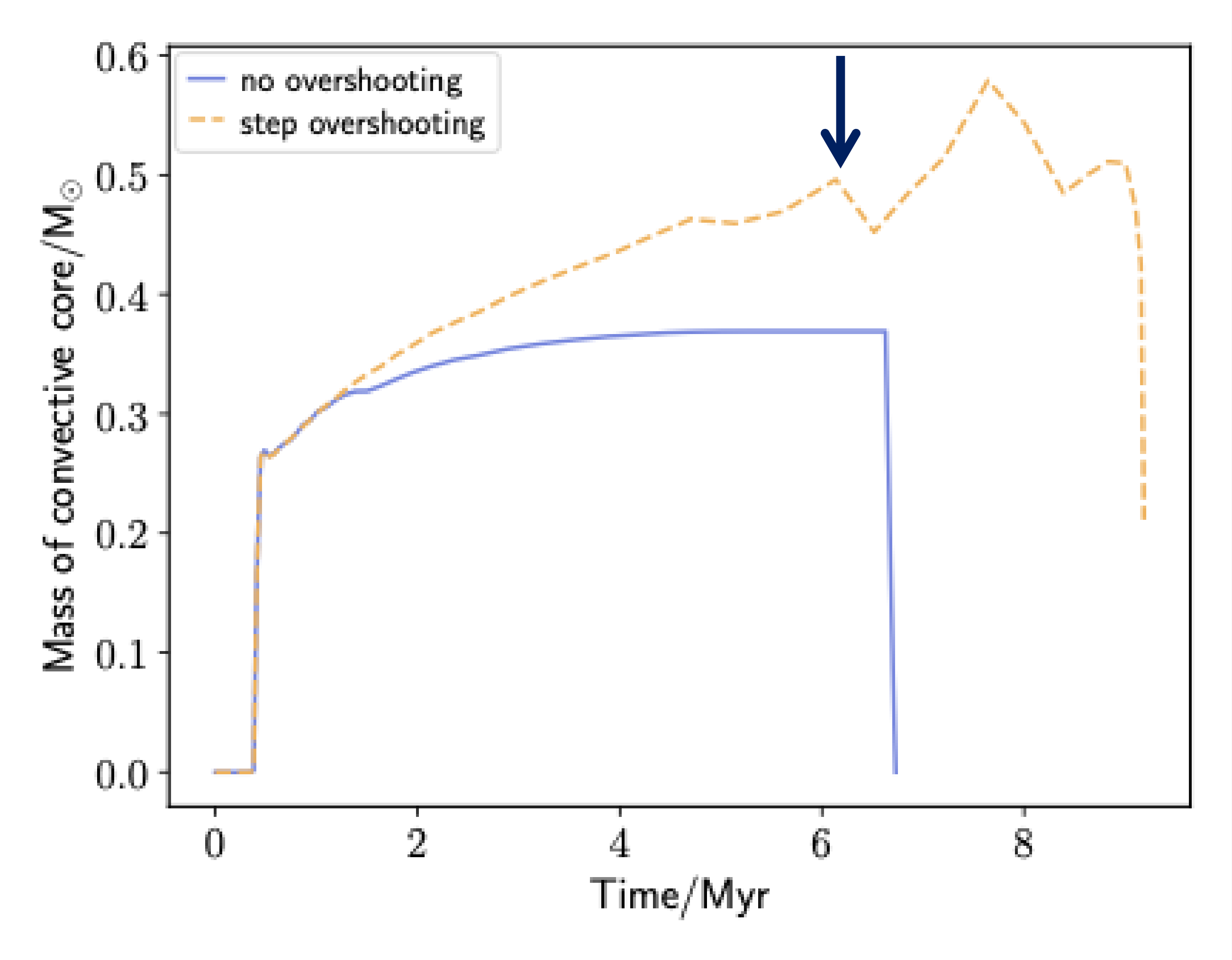
- Without core overshooting
- With step overshooting
- Limit core overshooting in regions with strong chemical gradients

Session 3: Wrap-Up

Overshooting during core helium burning



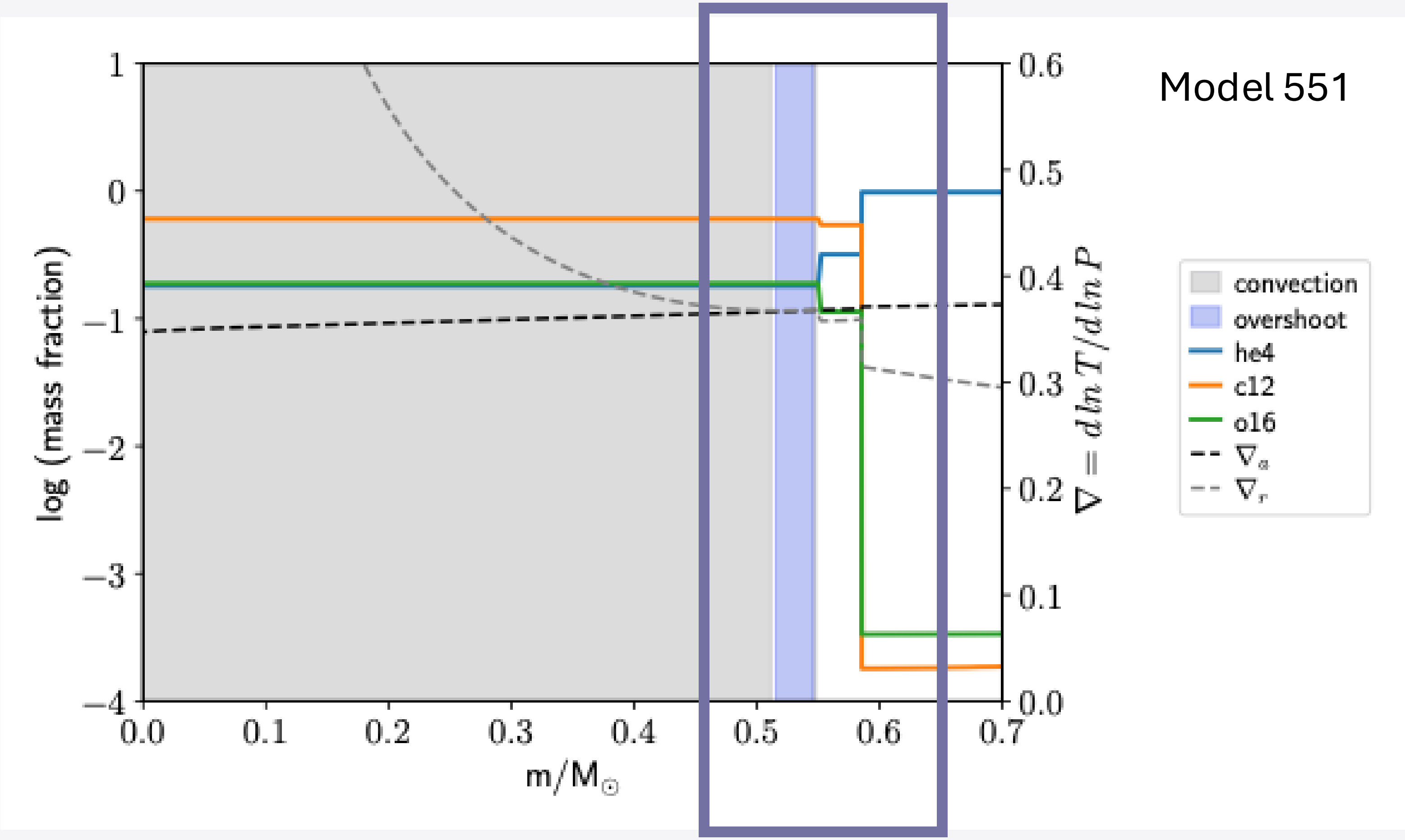
Overshooting during core helium burning



Breathing Pulses

Result of

- Overshoot mixing
- $^{12}C\ (\alpha, \gamma)^{16}O$ reaction
- Free-free opacity (Dominant in low & intermediate mass stars ($<8\,M_{\odot}$).



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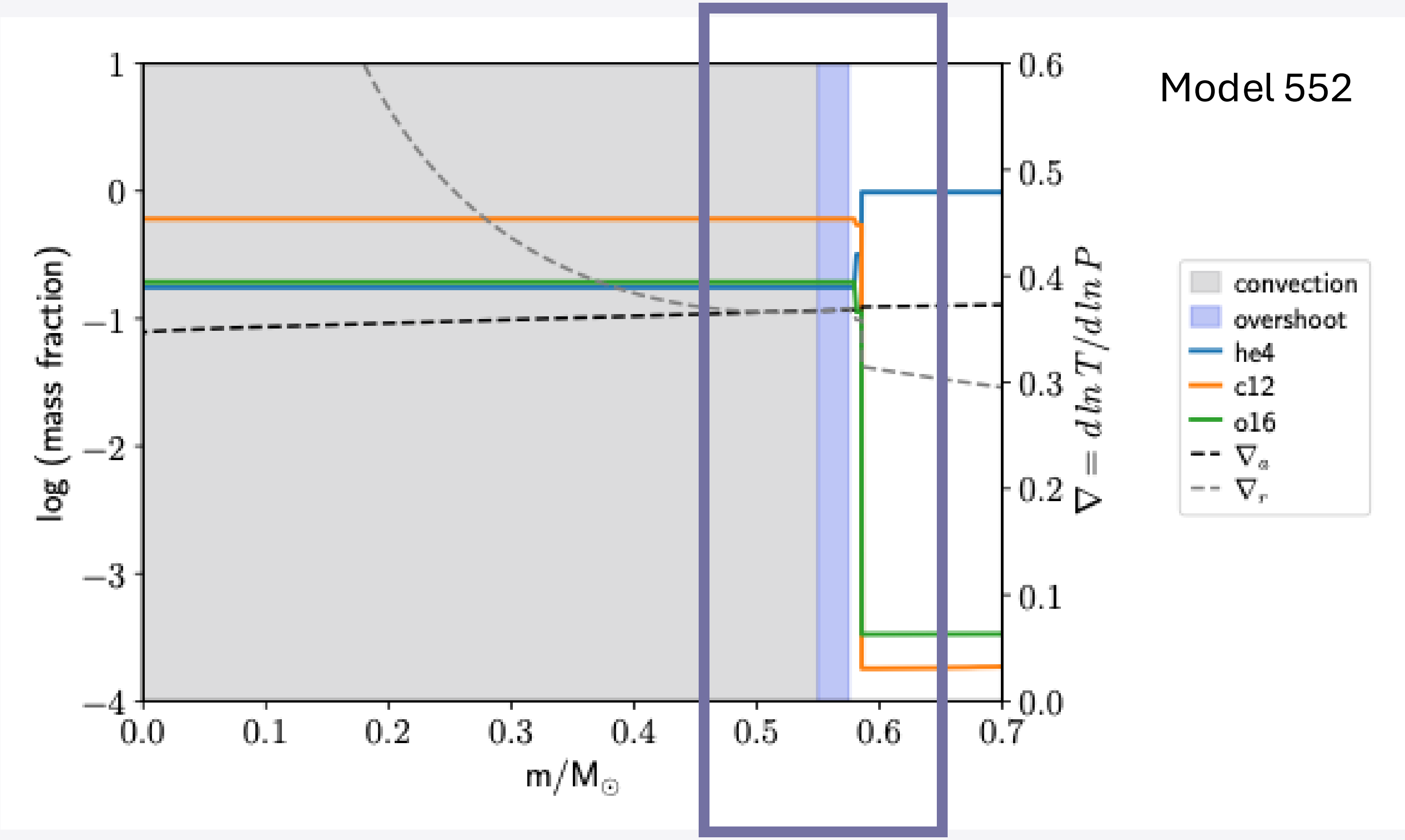

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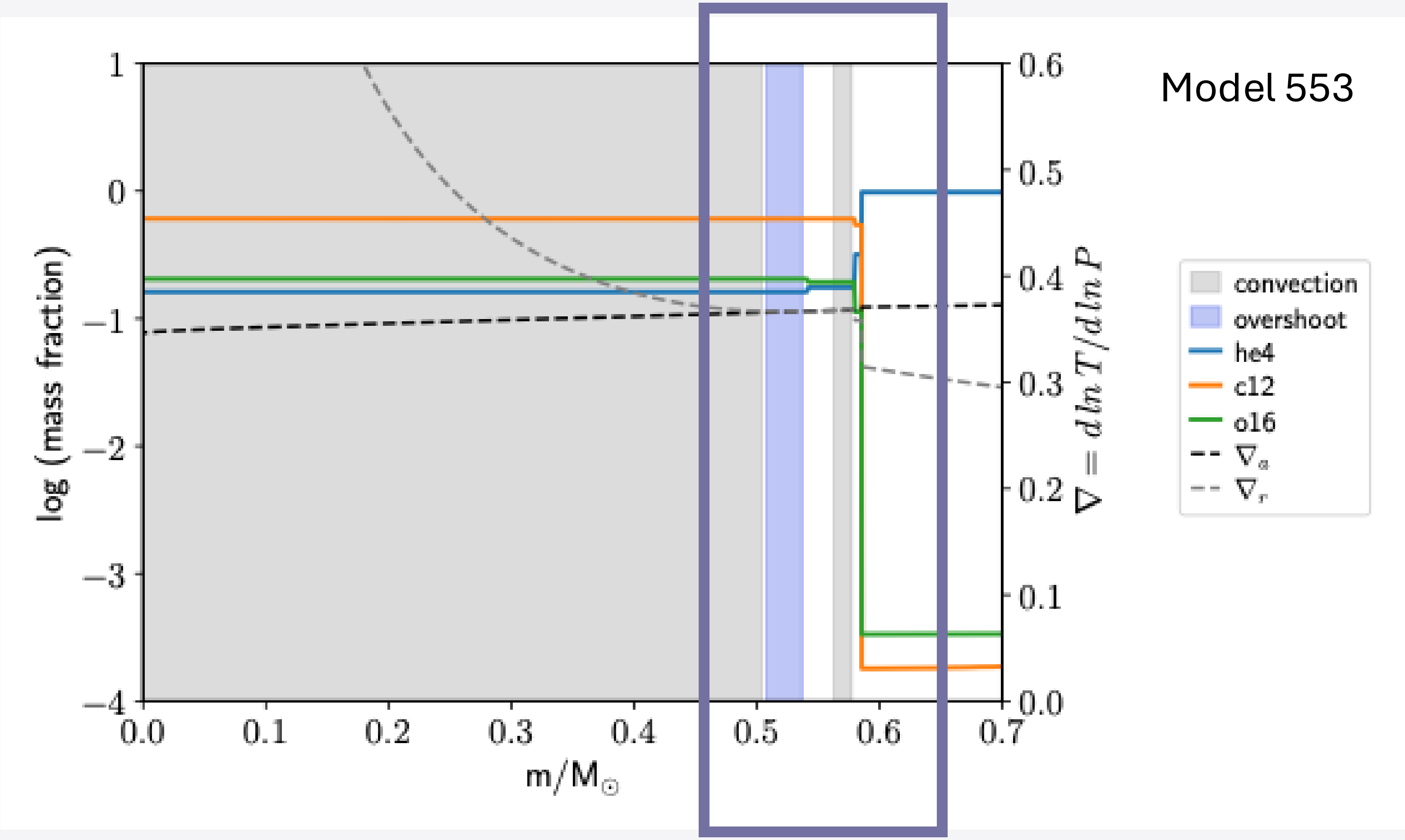
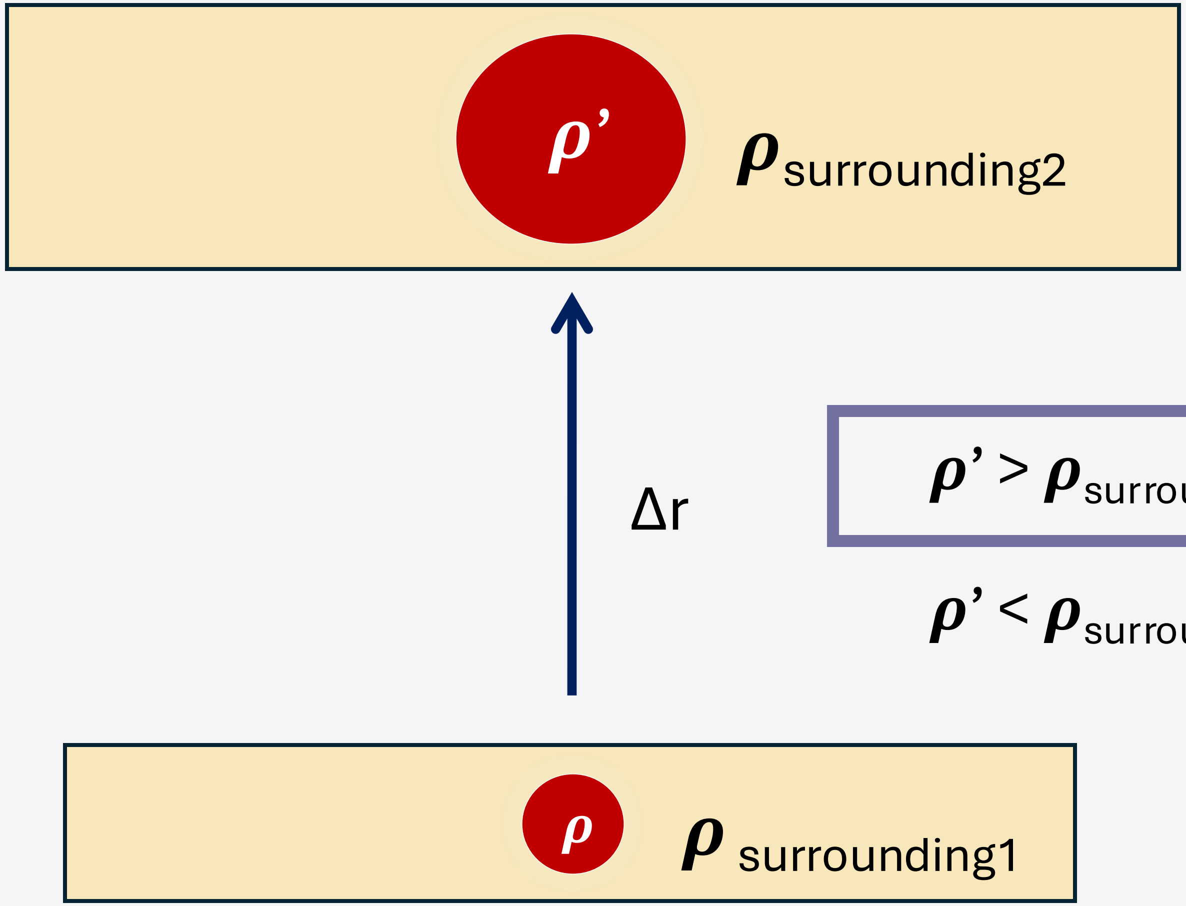


Also see: Castellani et al. 1985, Constantino et al. 2016, Salaris & Cassisi 2017, Paxton et al. 2018, and Córsico & Althaus 2024

Convection - Density formulation



$\boxed{\rho' > \rho_{surrounding2} \rightarrow \text{stable} \rightarrow \text{oscillations}}$

$\rho' < \rho_{surrounding2} \rightarrow$ unstable $\rightarrow$ convection

Heats up and expands

Brunt-Väisälä frequency

Convective stability and Brunt-Väisälä frequency

Brunt-Väisälä frequency squared $\longrightarrow N^2 = \frac{g^2\rho}{P}\frac{\chi_T}{\chi_\rho}(\nabla_{ad} - \nabla + B)$

Convective stability and Brunt-Väisälä frequency

Brunt-Väisälä frequency squared

$$N^2 = \frac{g^2\rho}{P}\frac{\chi_T}{\chi_\rho}\left(\nabla_{ad} - \nabla + \mathrm{B}\right)$$

$$\mathrm{B} = \frac{\mathrm{d}\ln\mu}{\mathrm{d}\ln P}$$

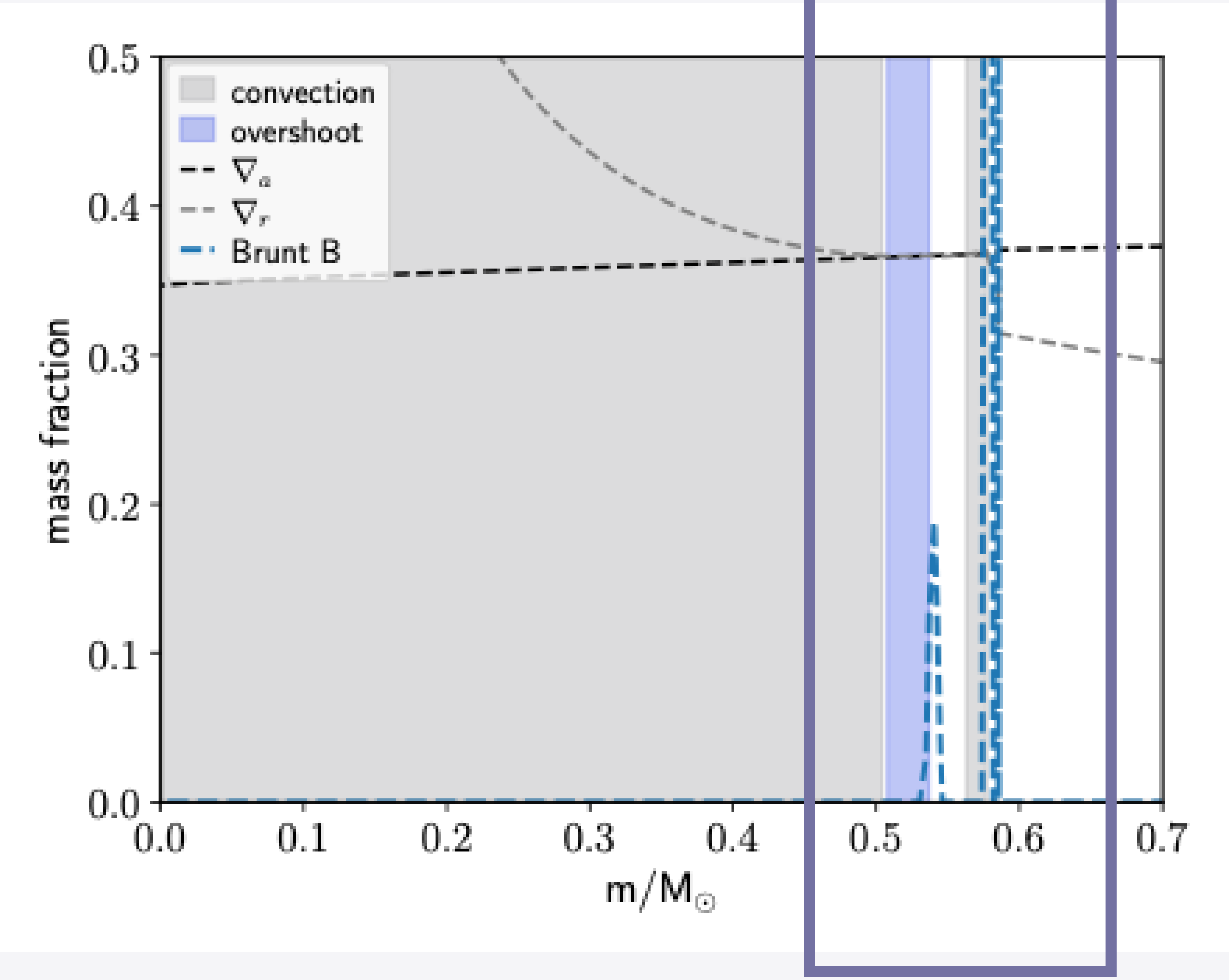
$N^2 > 0 \rightarrow$ Oscillations

$N^2 < 0 \rightarrow$ Convection

$\nabla_{rad} > \nabla_{ad}$ + B (Ledoux Criteria-named after Paul Ledoux)

Brunt composition gradient term / Ledoux term / Brunt_B

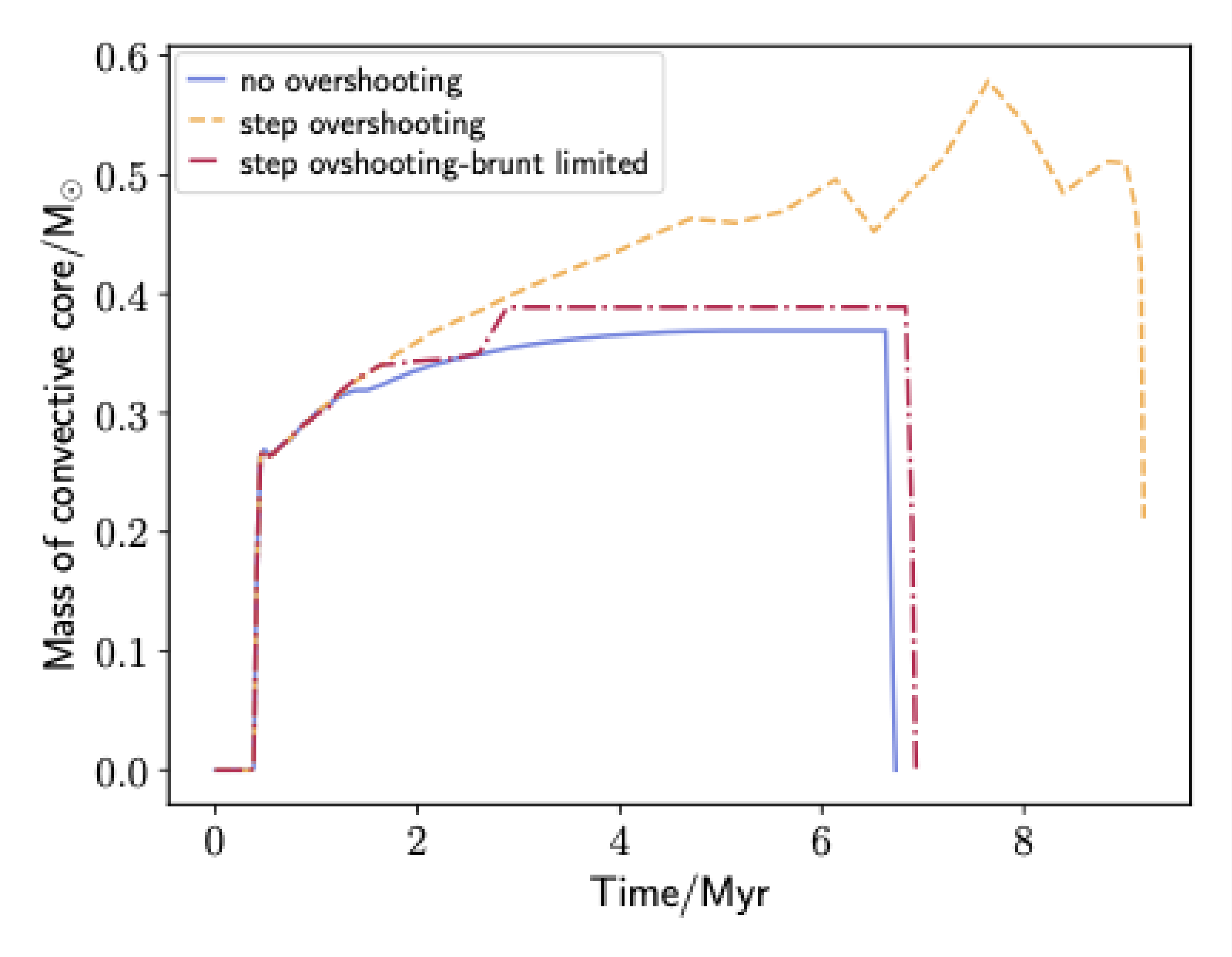
Brunt B



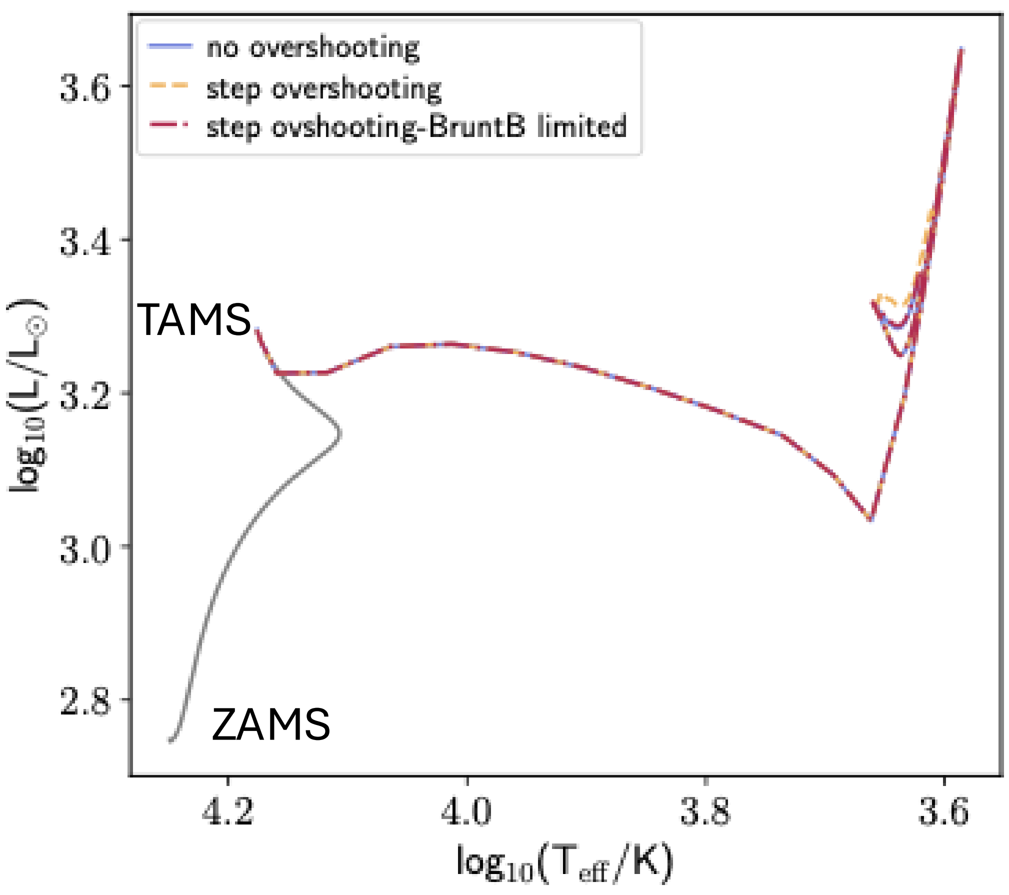
Brunt_B >overshoot_brunt_B_max

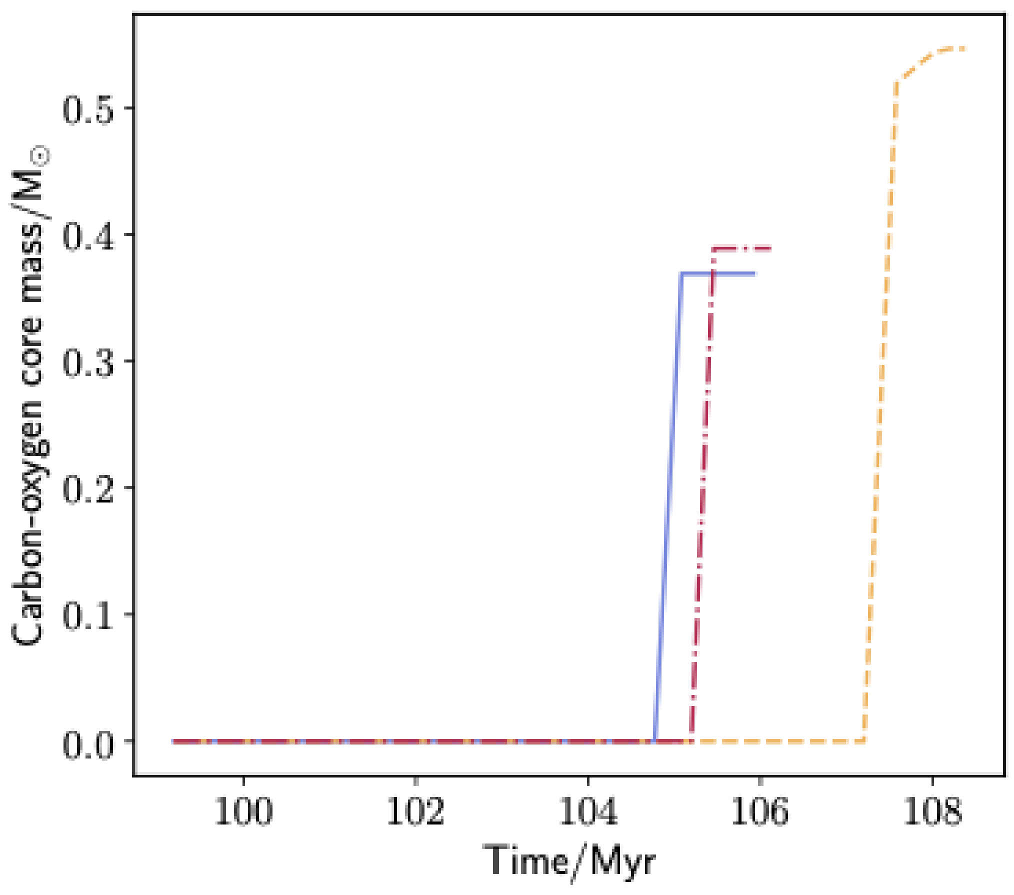
Terminate mixing due to overshoot when composition gradient exceeds a certain threshold

Limiting overshooting using Brunt B factor



Limiting overshooting using Brunt B factor

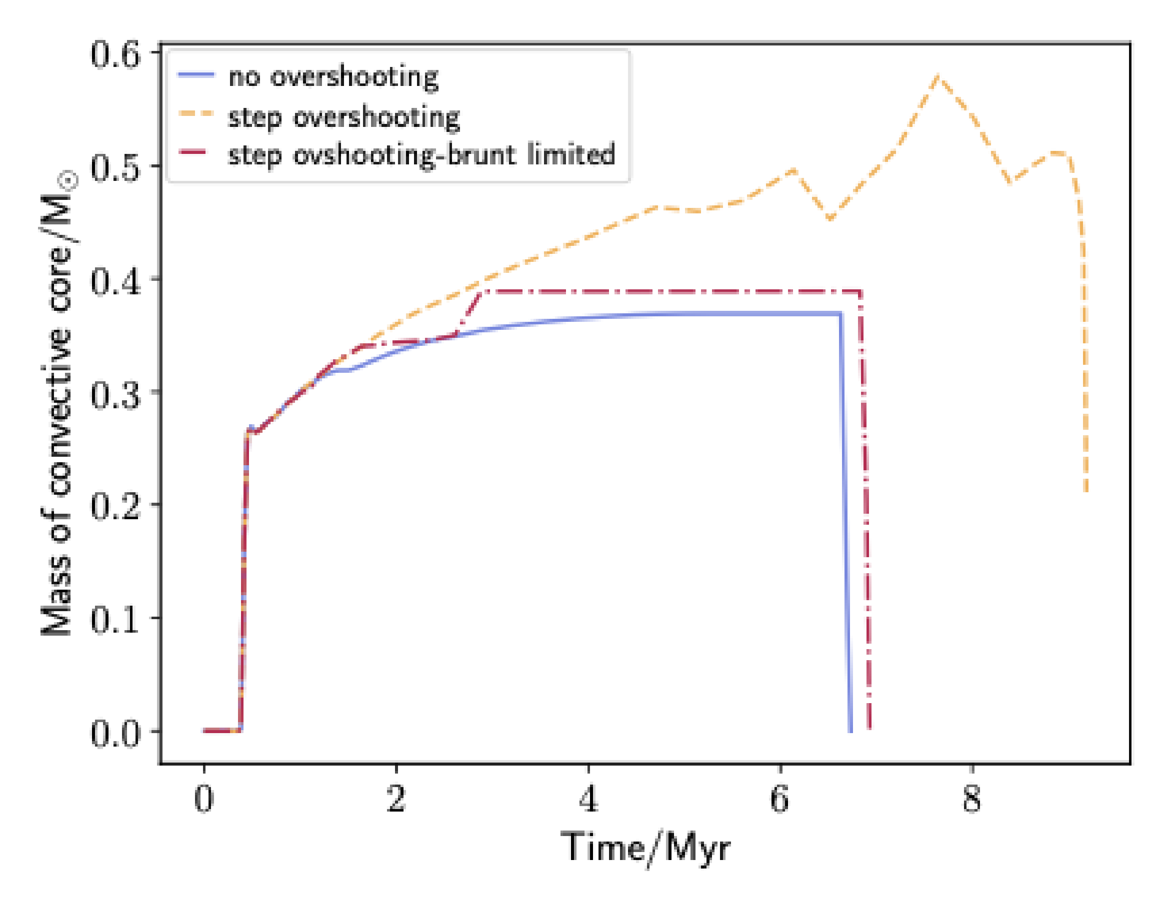




Lab 2: Key Takeaways

Overshooting during core – helium burning:

- Increases core mass, luminosity, radius
- Leads to longer nuclear burning phases
- Can trigger *"breathing pulses"* during core helium burning
- Pulsations or oscillations may dominate in regions with a stabilizing composition gradient



Words of wisdom

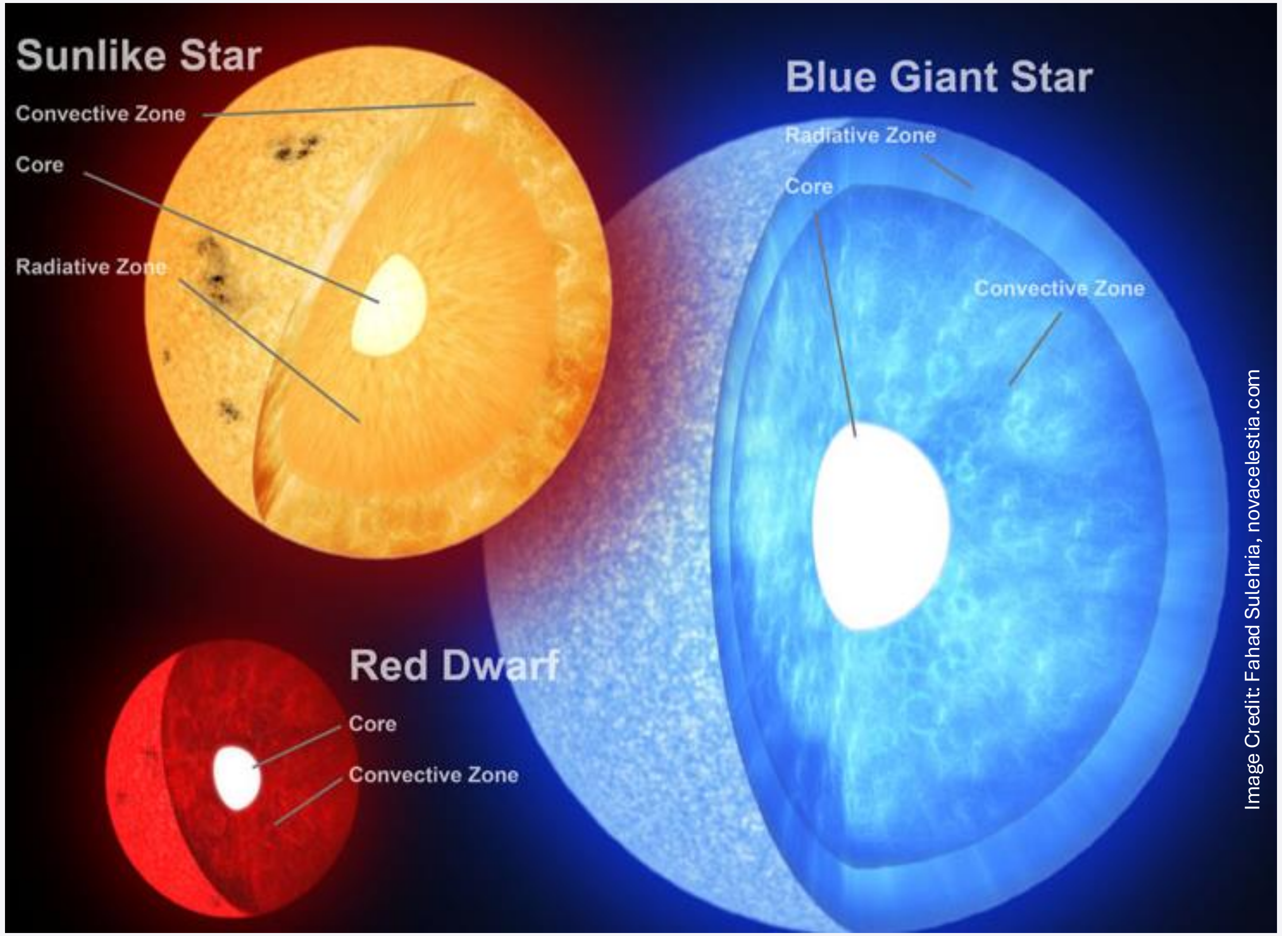
Finally, remember what Peter Eggleton told me when I was first getting started and asked him why something I was trying failed to converge. Peter patiently explained that with stellar evolution the only surprise is when the code *does* converge! And of course he's right. Each step requires a root find for a highly non-linear relation involving anywhere from a few thousand to several hundreds of thousands of variables. It makes me tired just to think about it.

And remember that it takes time to learn how to use the code -- you'll get better at it with experience.

— *Bill Paxton*

Convective Overshooting in Stars

Recap of Day 1

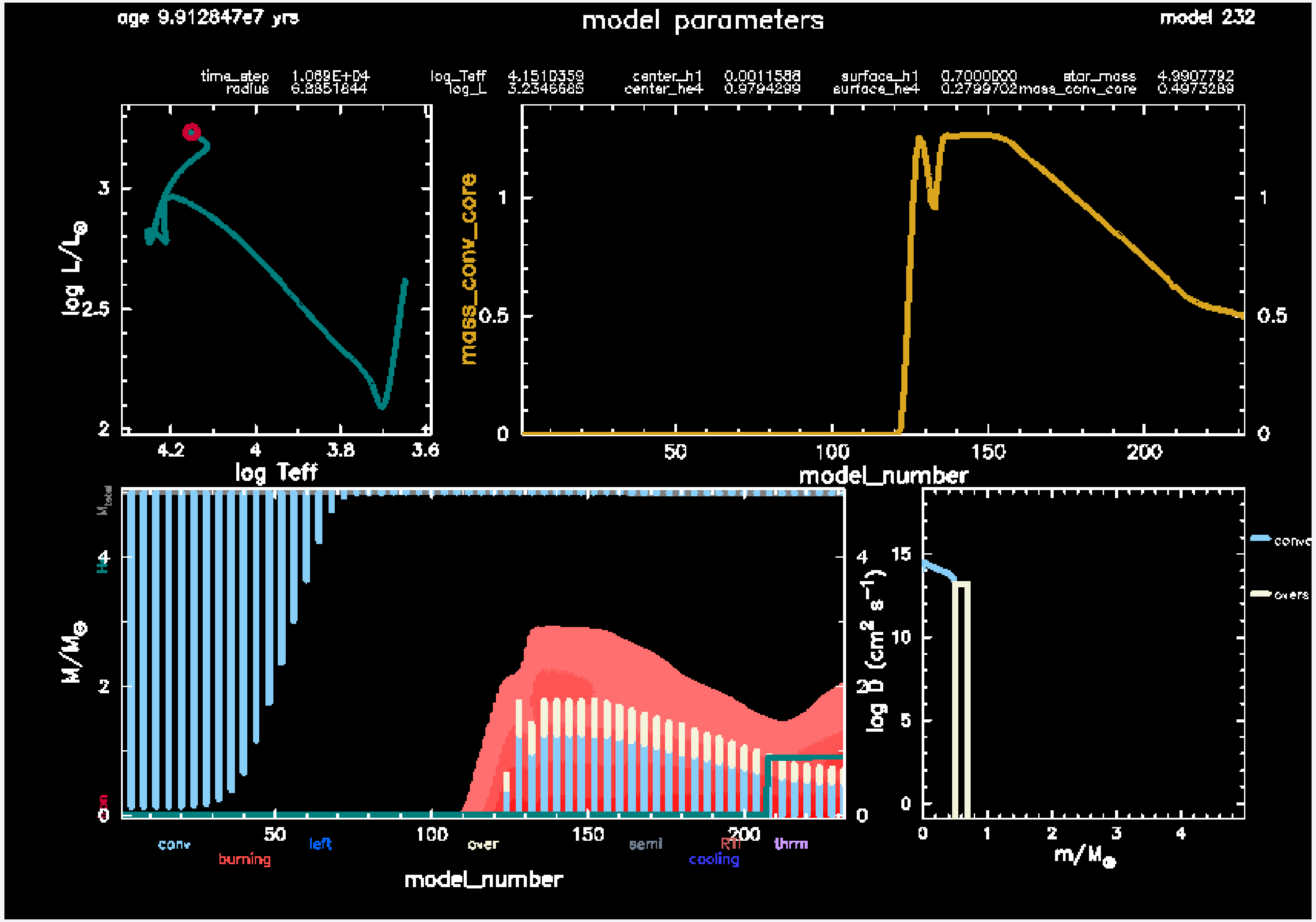


Funded by the European Union

Lab 1: Set up inlists for a 5 $M_\odot$ model

How to evolve a 5 $M_\odot$ star in MESA?

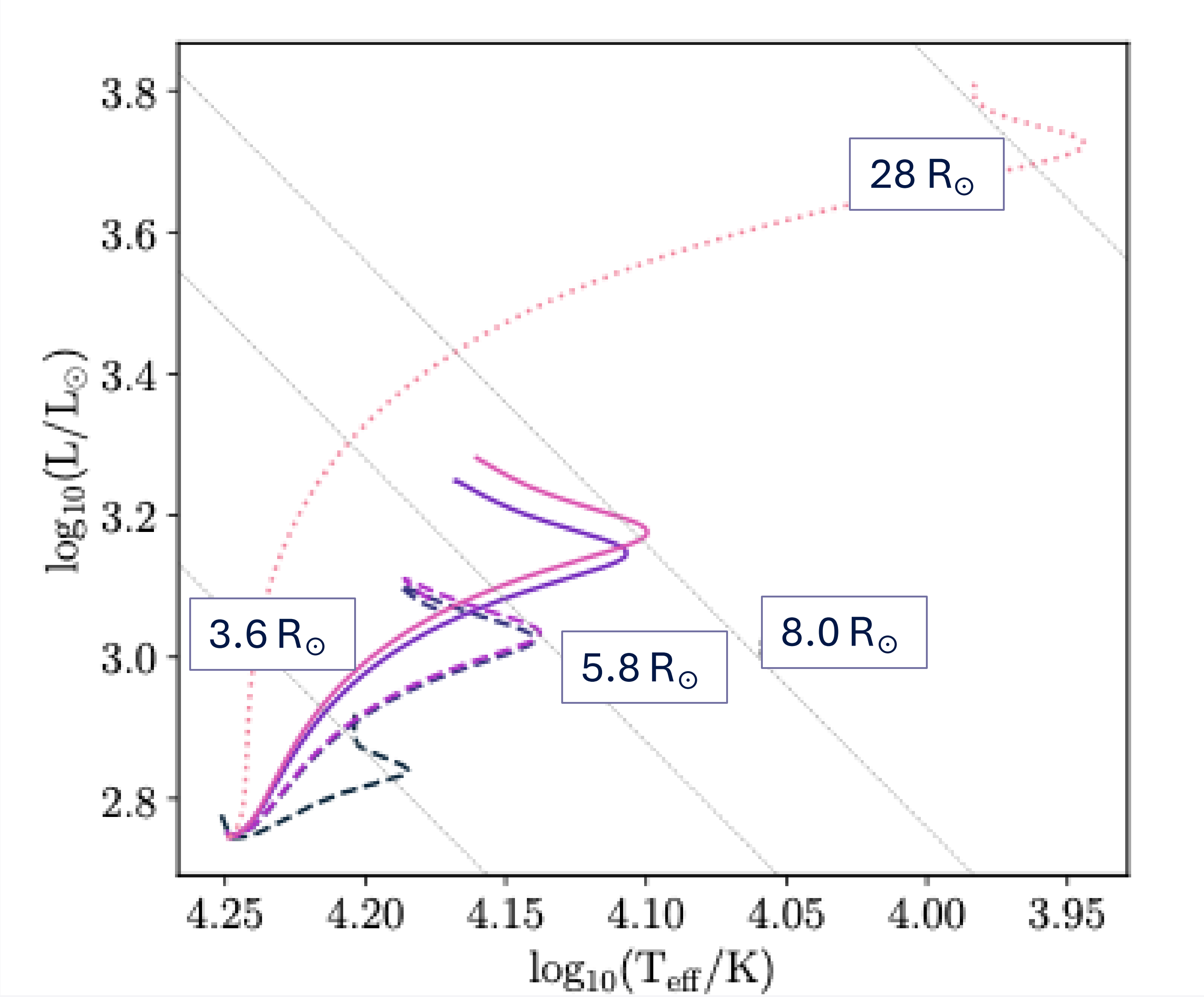
5 $M_\odot$ star with overshooting on the MS



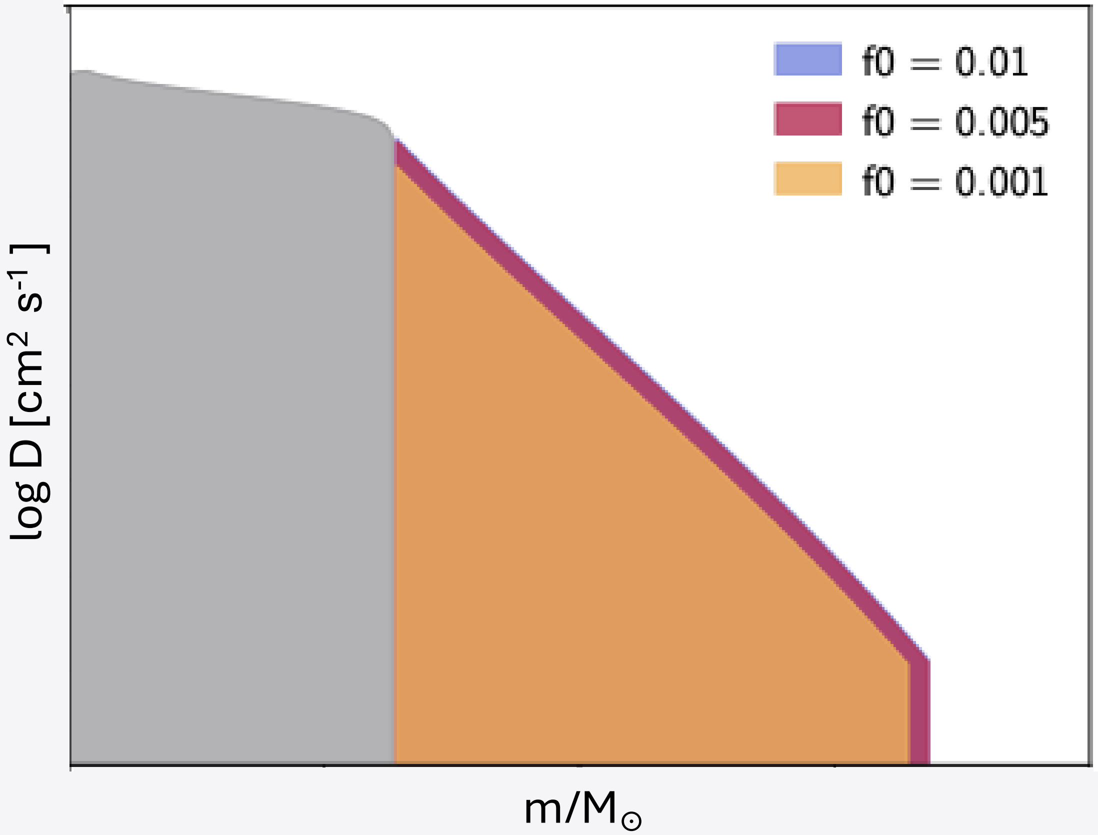
Lab 1: Tried different the overshoot settings

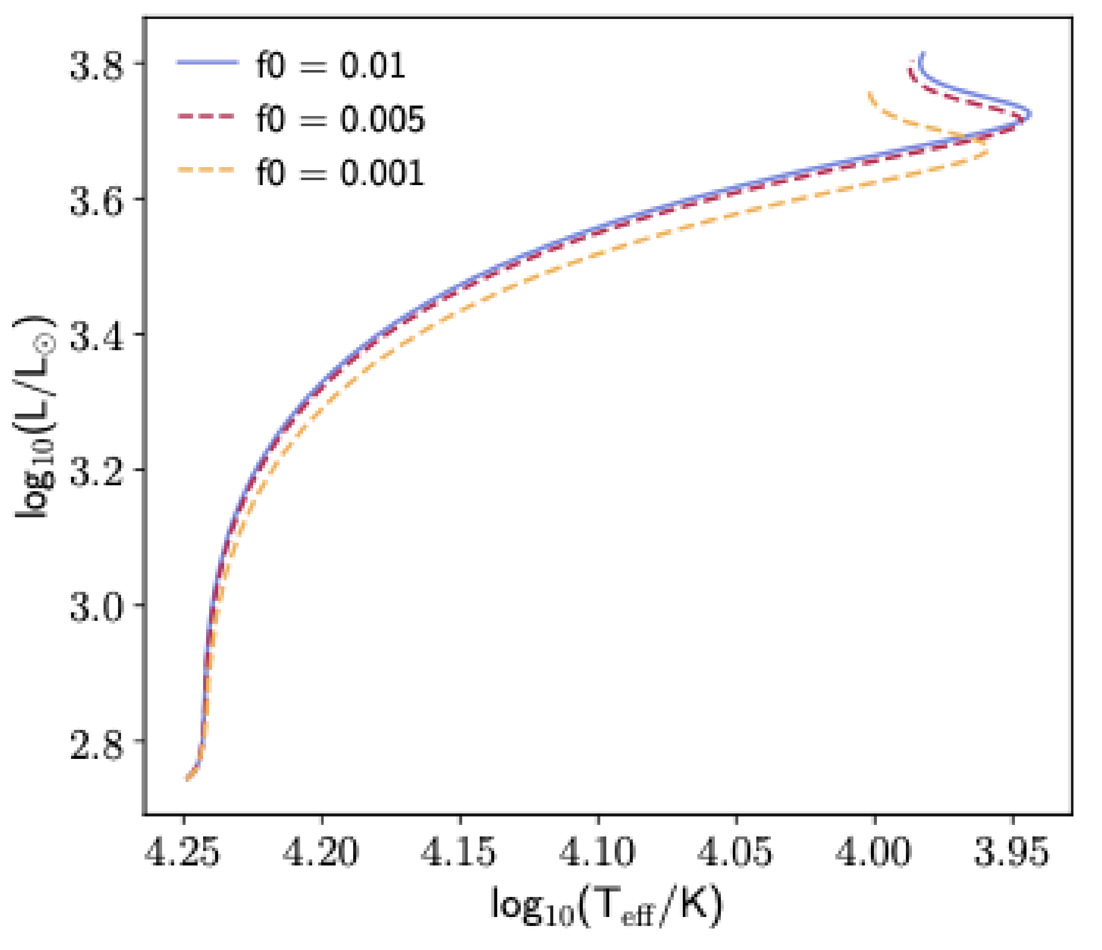
How does changing overshooting changes stellar evolution?

Changing f_overshoot and the overshoot scheme

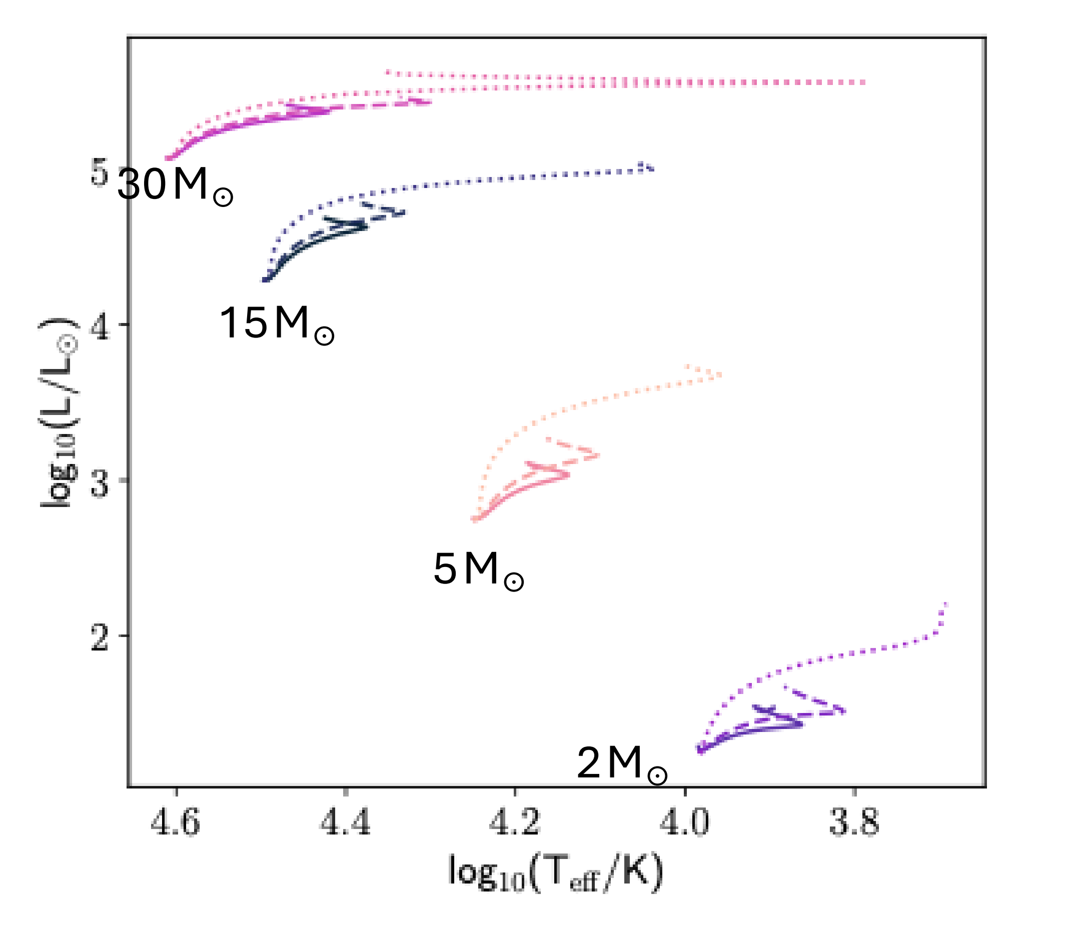


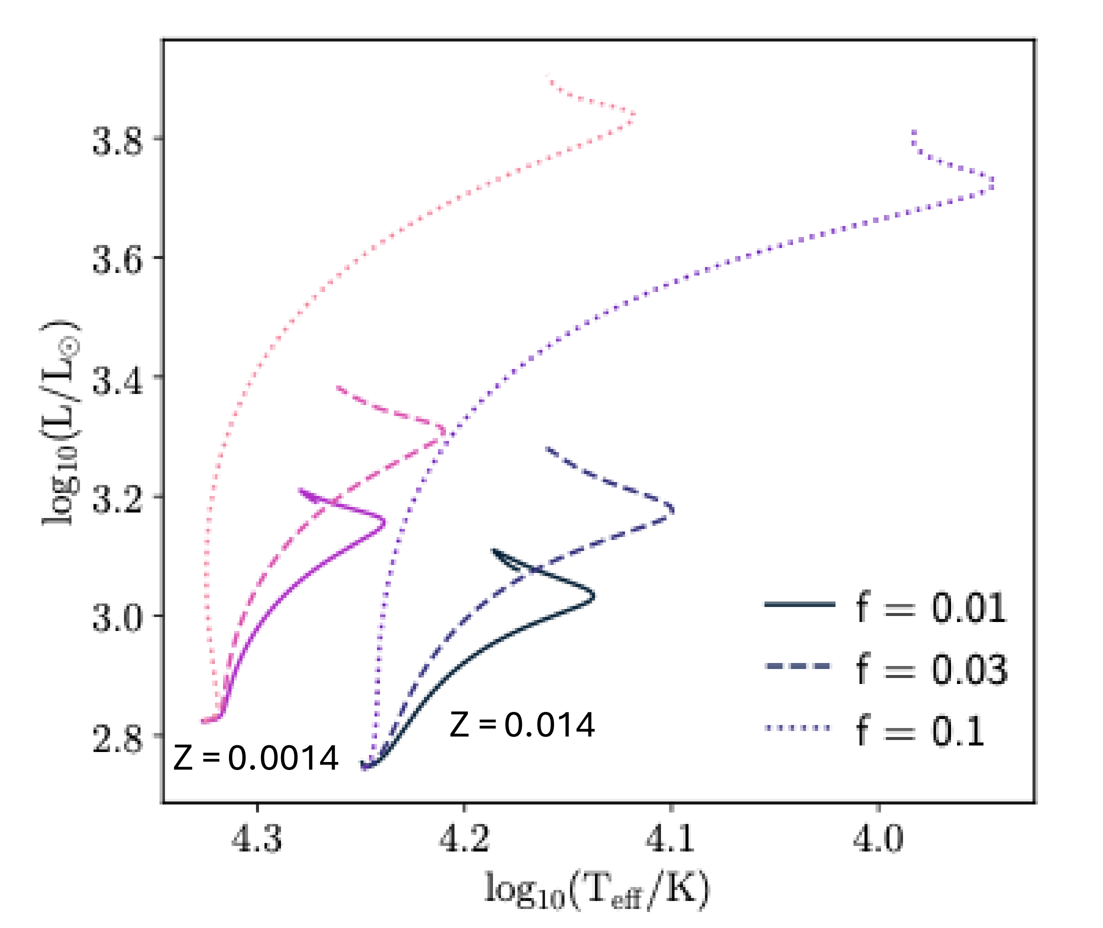
Changing f0 for f = 0.1, exponential overshooting





Changing mass and metallicity

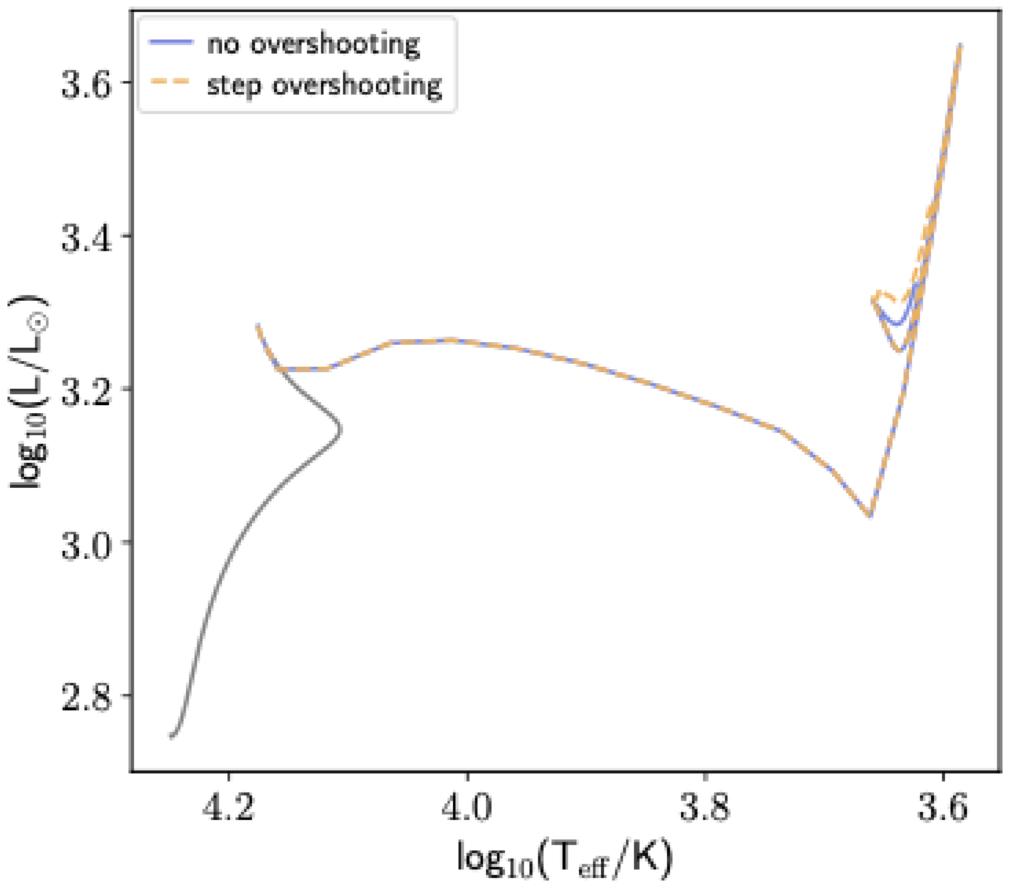


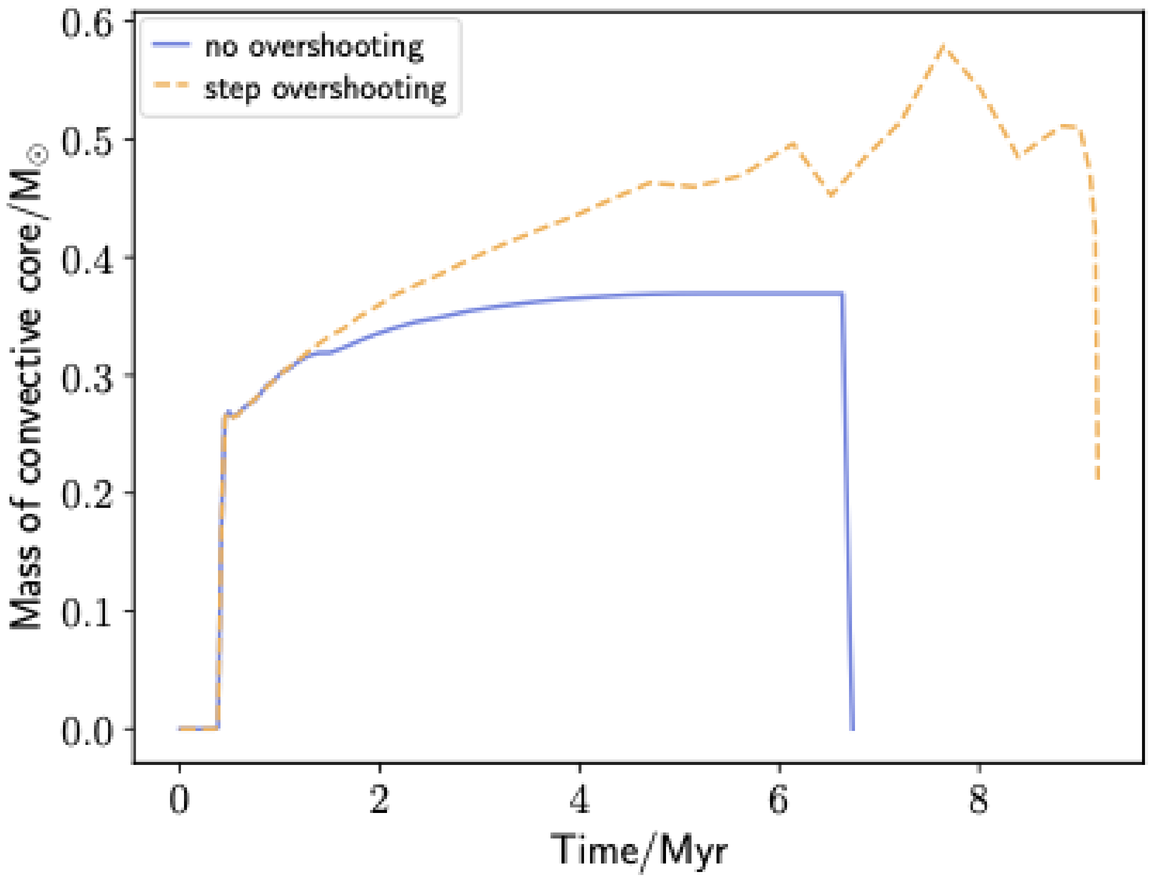


Lab 2: Evolved a 5 $M_\odot$ star model at TAMS till the end of core helium burning

How overshooting affects different nuclear burning phases?

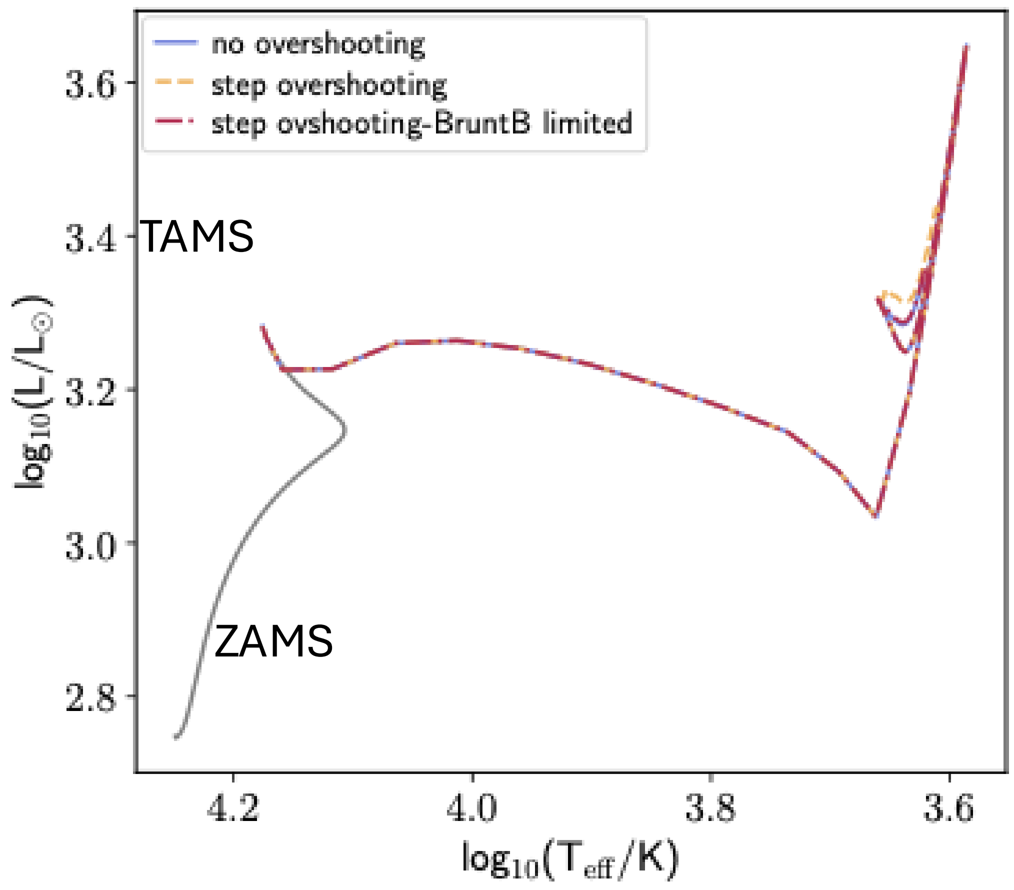
Overshooting during core helium burning

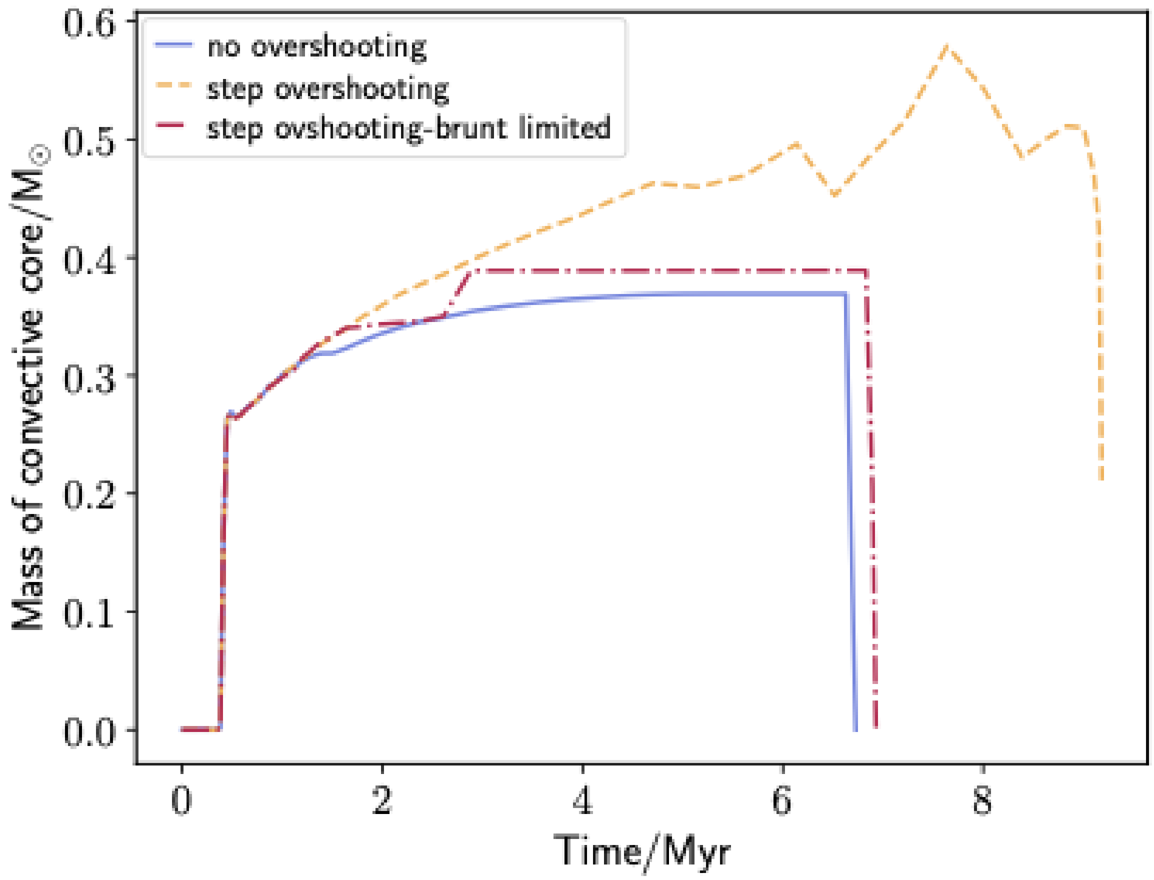




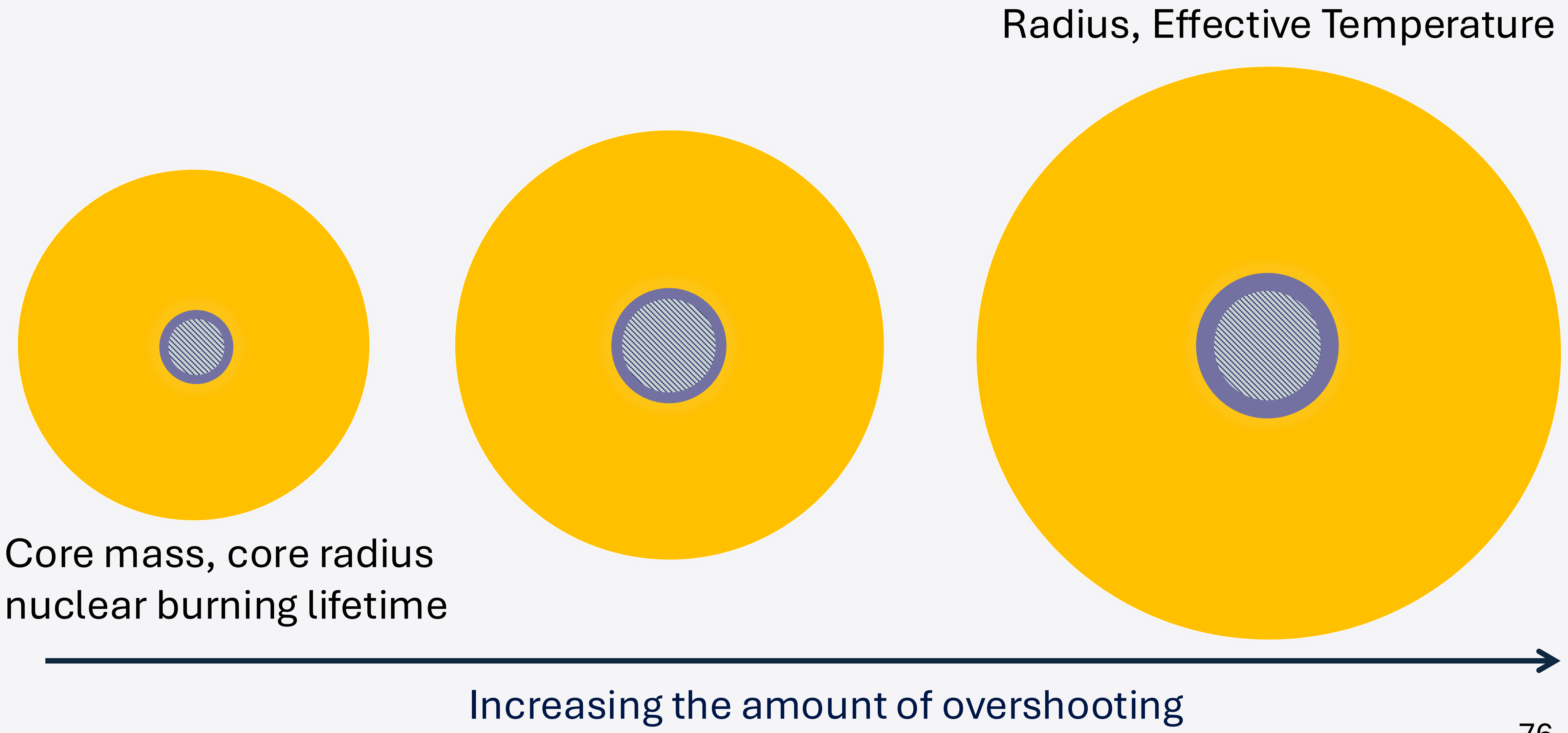
Breathing Pulses

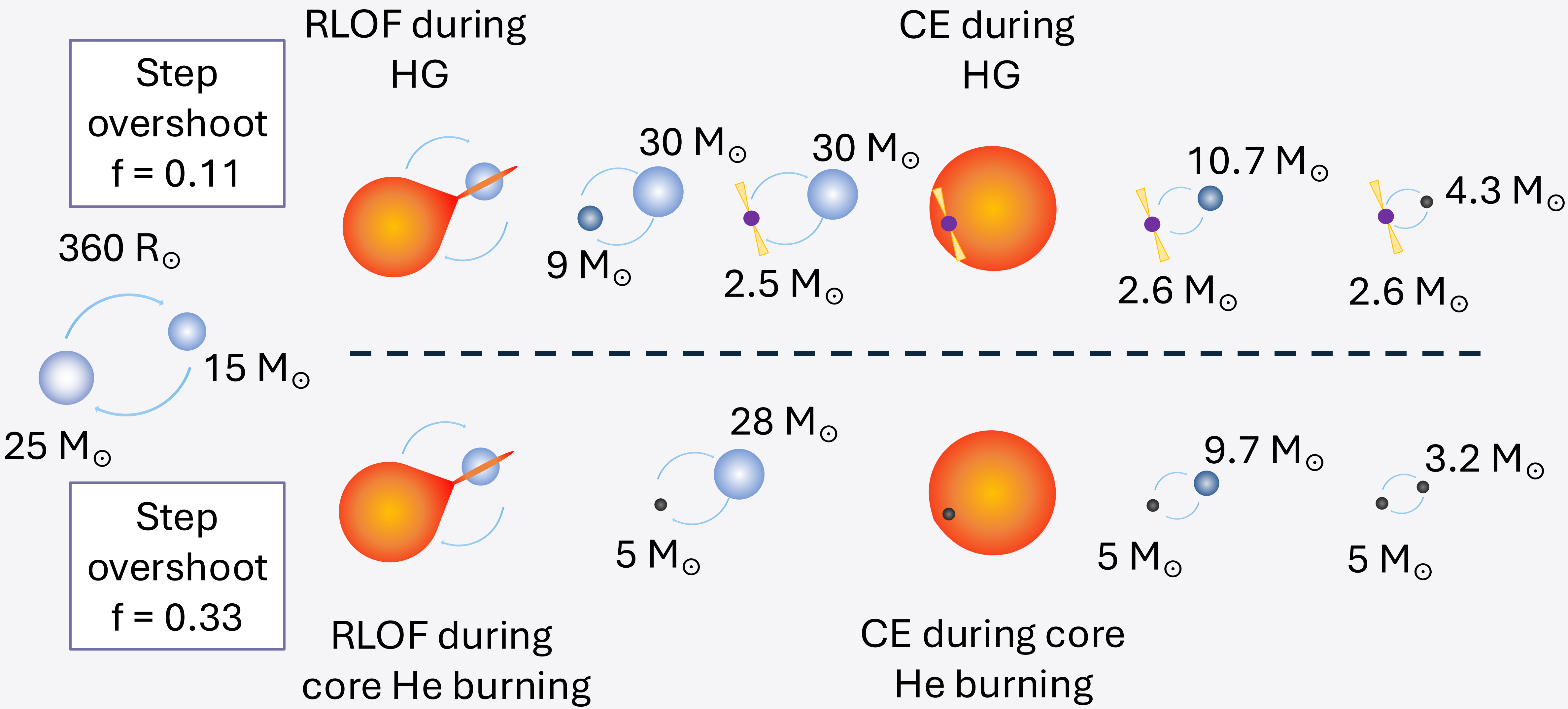
Brunt_B >overshoot_brunt_B_max





Why does this matter?





COSMIC (Breivik et al. 2020) using interpolation from METISSE (Agrawal et al. 2020) and stellar models from MESA (as described in Agrawal et al. 2023)

Day 1: Key Takeaway

Convective overshooting is more than just another parameter in stellar evolution.

It influences every major branch of astrophysics, including:

- planetary evolution
- binary star interactions
- predictions of transient events
- the long-term evolution of stellar populations