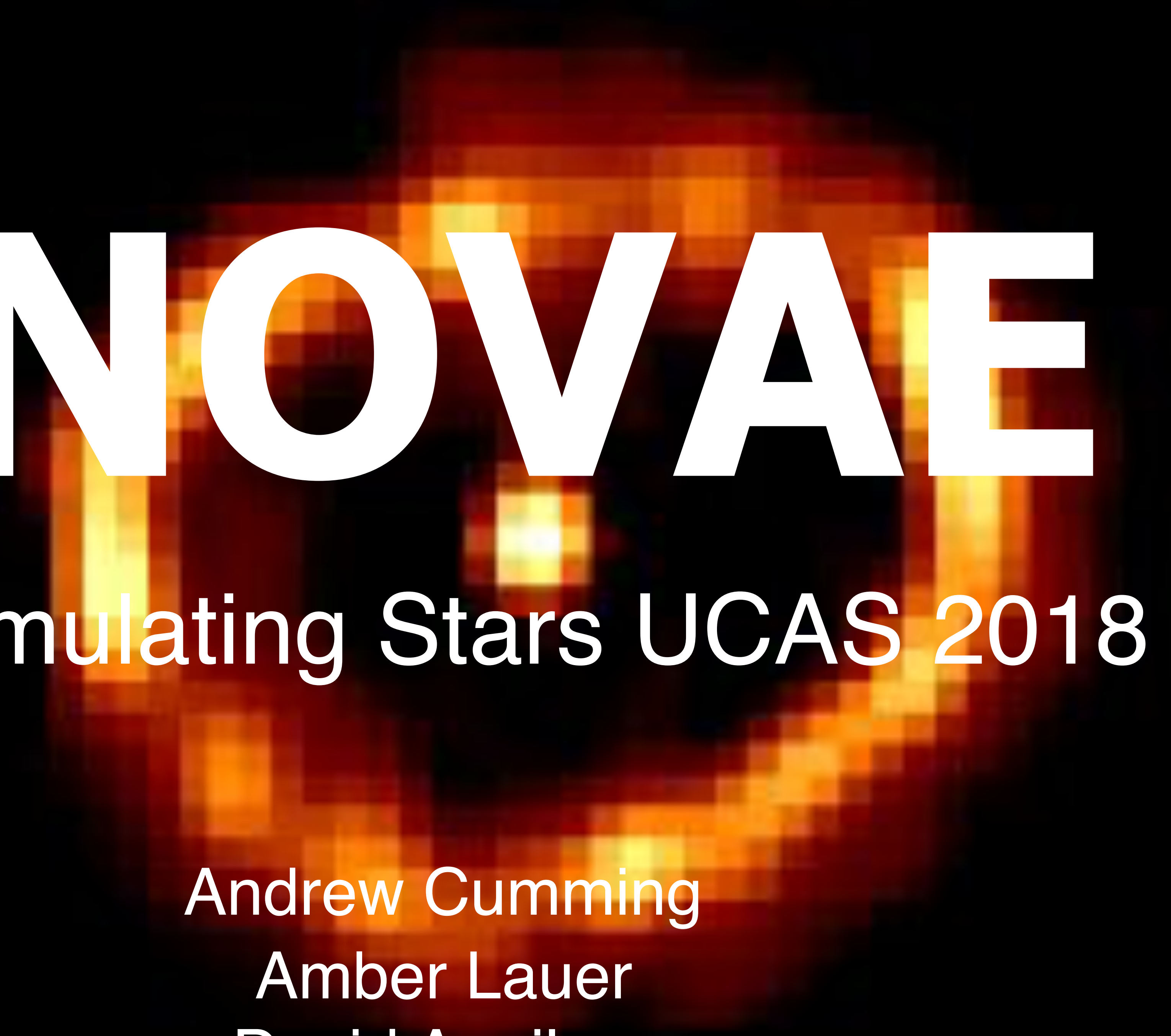

NOVAE

Simulating Stars UCAS 2018

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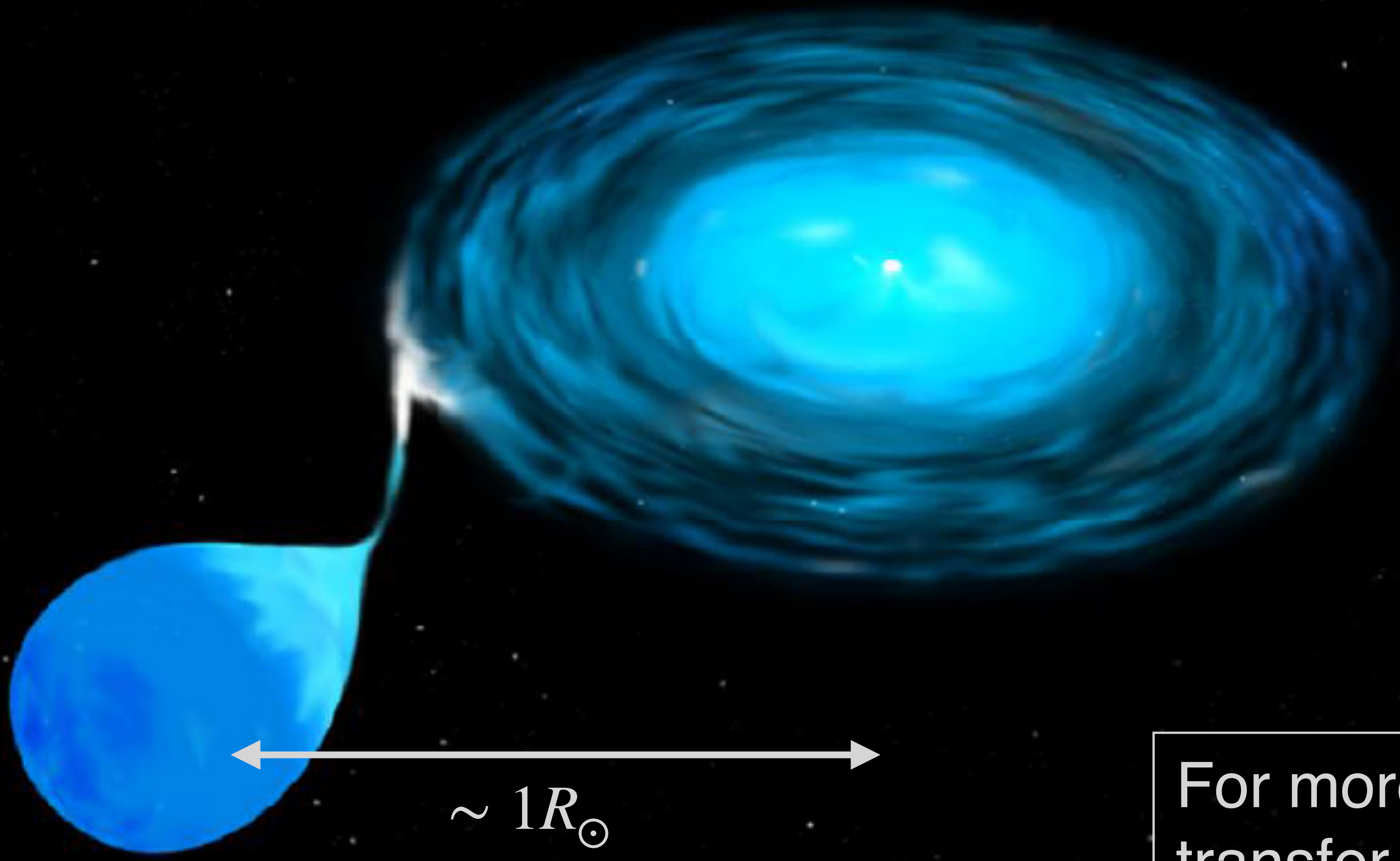
Cataclysmic variables

White dwarfs accreting from a low mass companion star

Orbital periods ~ minutes to days
Accretion rates $\dot{M} \sim 10^{-10} - 10^{-8}\ M_\odot\ \mathrm{yr}^{-1}$

Long-lived systems, lifetimes ~ Gyrs



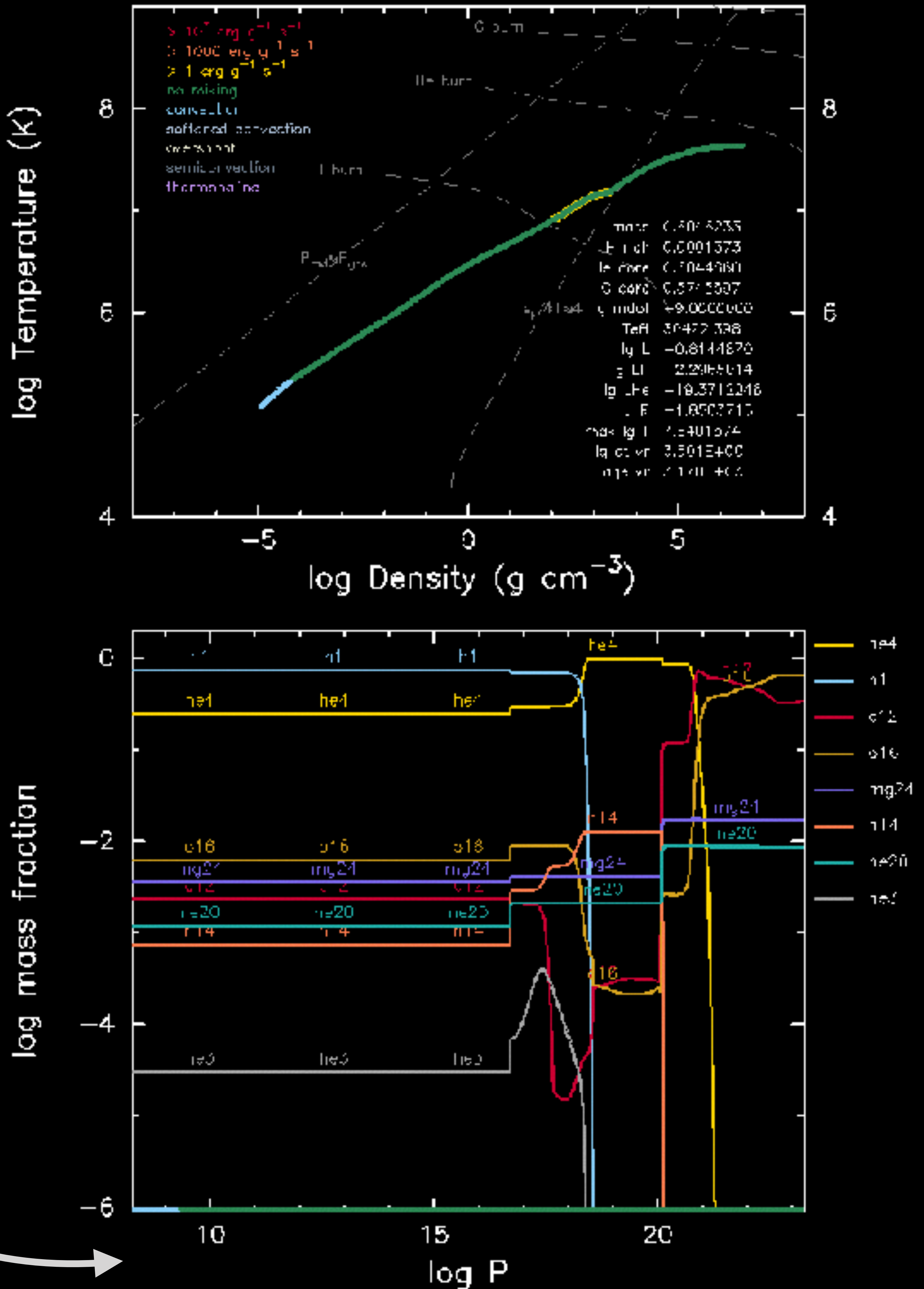
For more on binary evolution, mass transfer and the response of the mass-donating star, see the lectures on Binaries this week

Part 1 : What happens when you accrete hydrogen and helium onto a white dwarf?

Starting model:

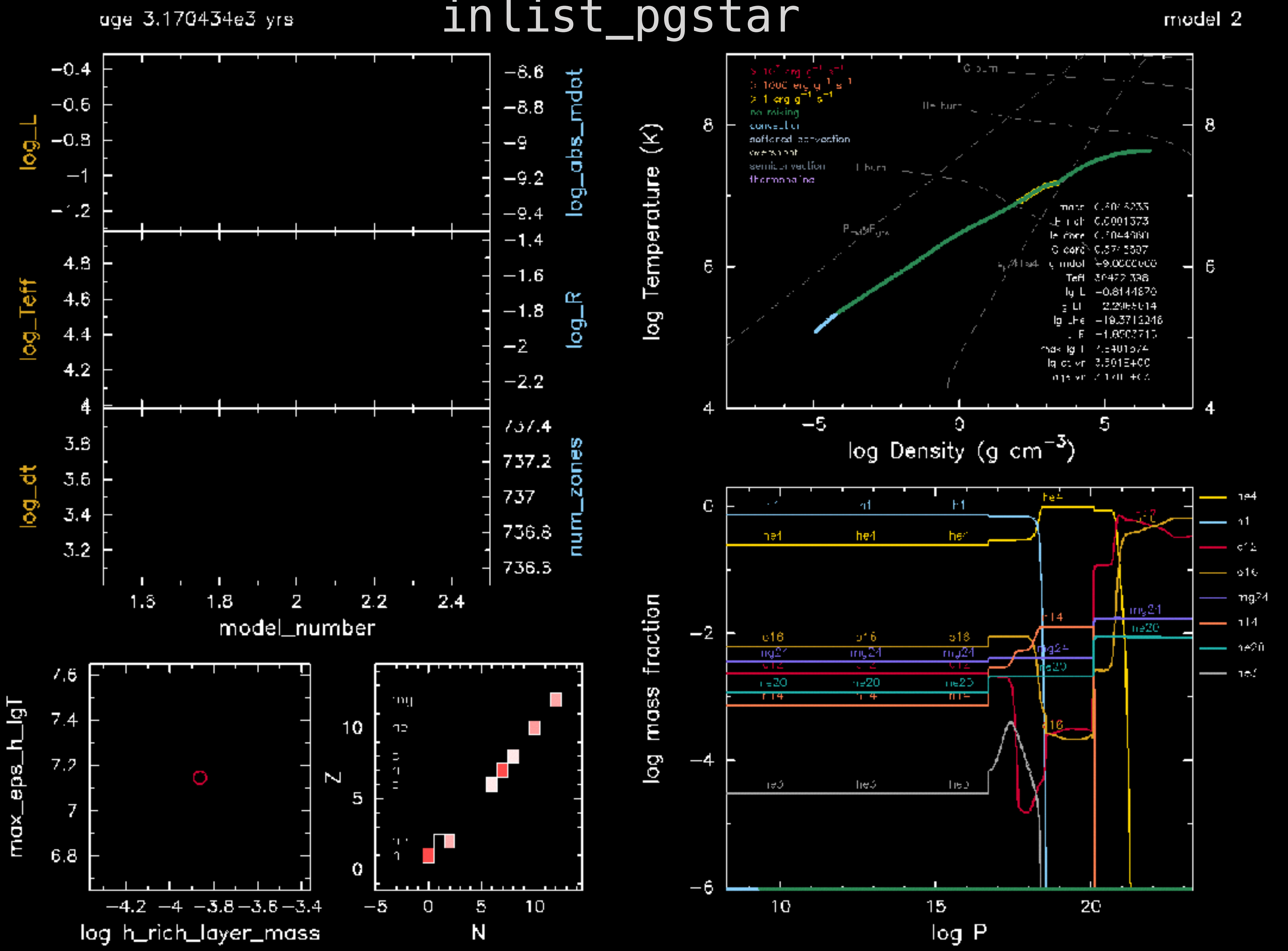
`mesa_wd_M0.6_L-1.mod`

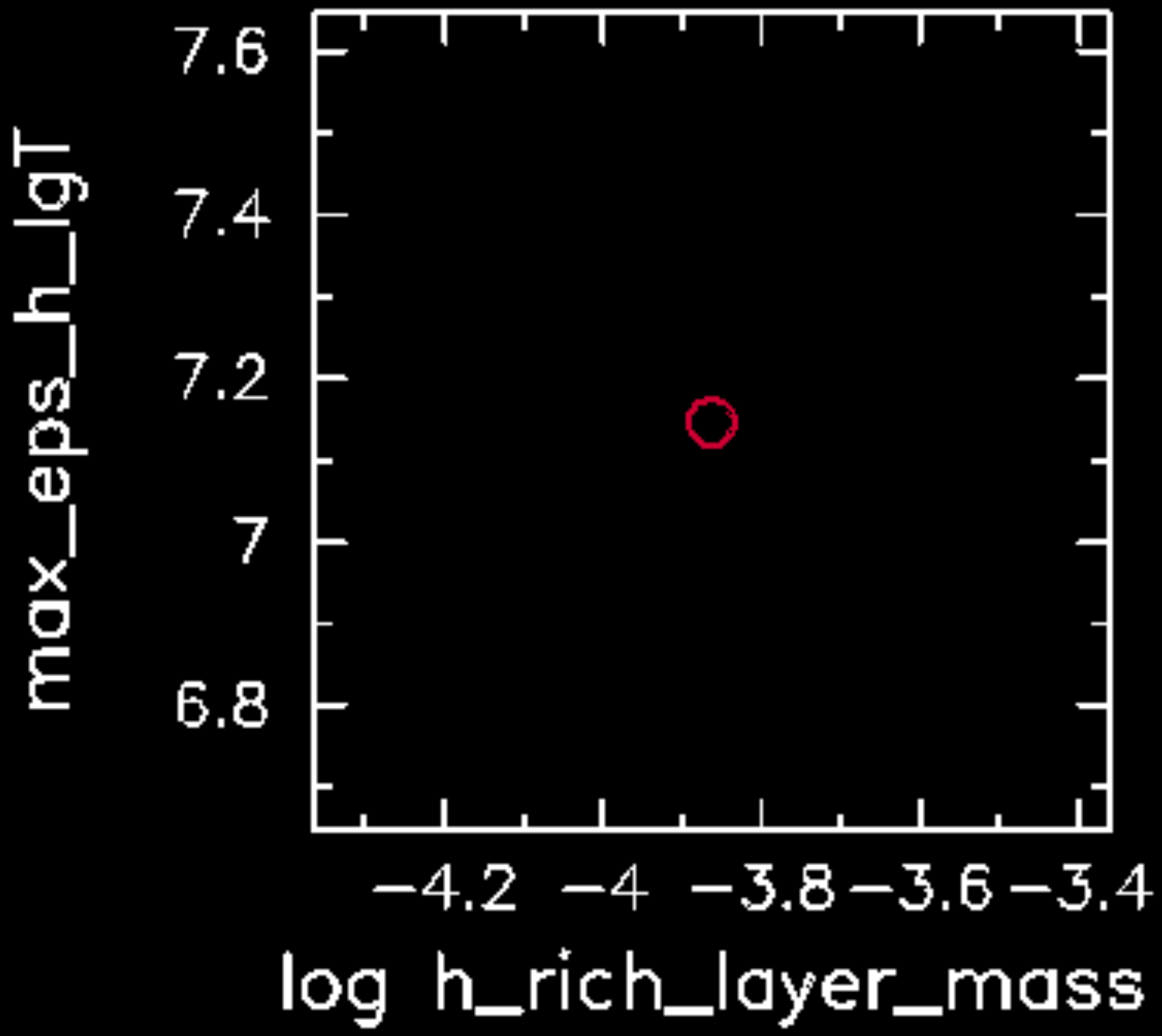
from the `make_co_wd` test suite



Use pressure as independent variable to show the outer parts of the star more clearly

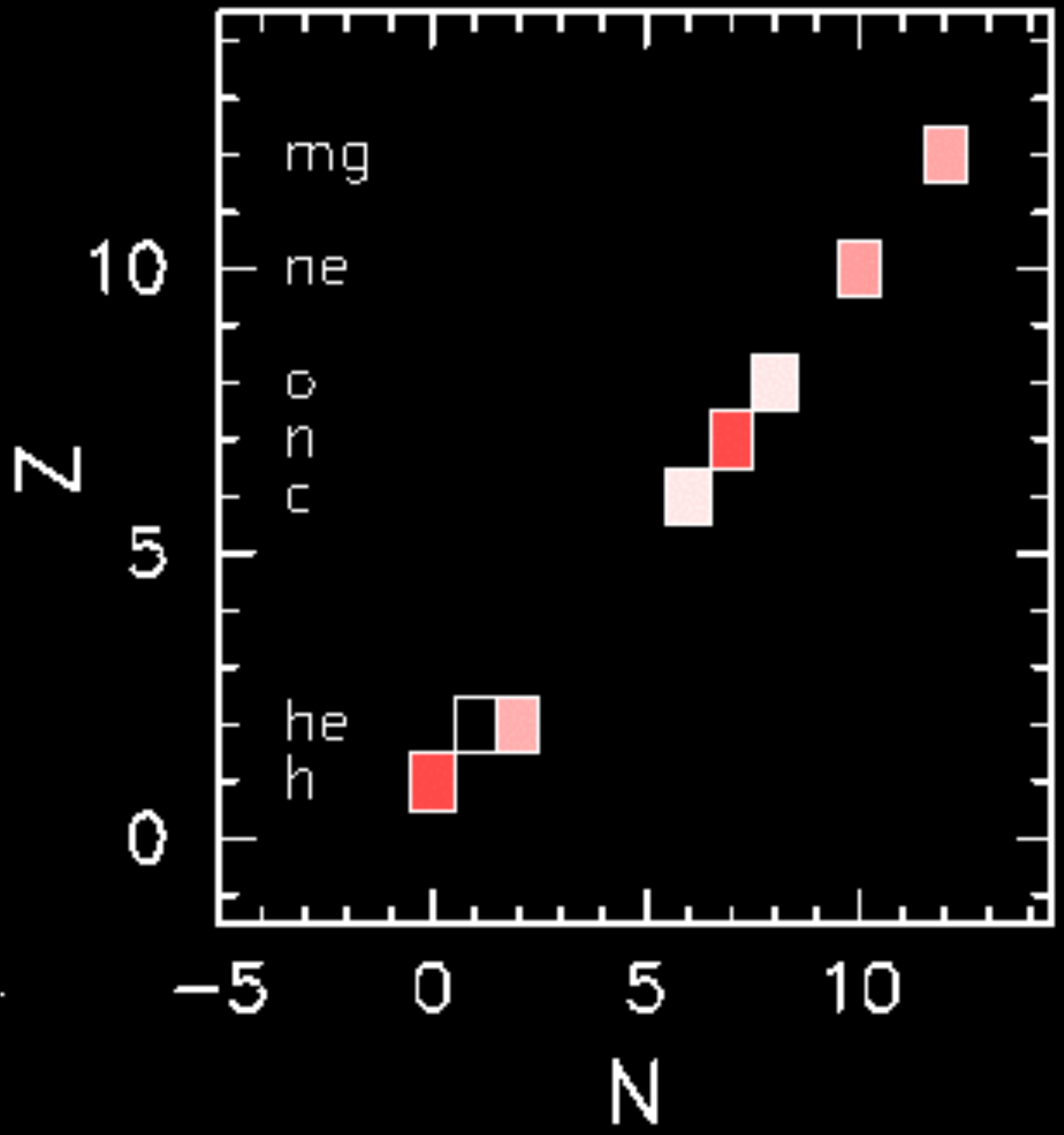
inlist_pgstar





Not sure what these quantities are?
Look in `$MESA_DIR/star/defaults/history_columns.list` :

```
max_eps_h_lgT ! log10 temperature at location of max burn

h_rich_layer_mass ! = star_mass - he_core_mass
```



Network plot

shows the nuclei present in the network and their abundance

we're using basic.net which has a simplified set of nuclei and reactions that covers basic H and He burning up to Mg

color scale:

black —> red —> white

with increasing abundance
(averaged by mass over the whole star)

Luminosity

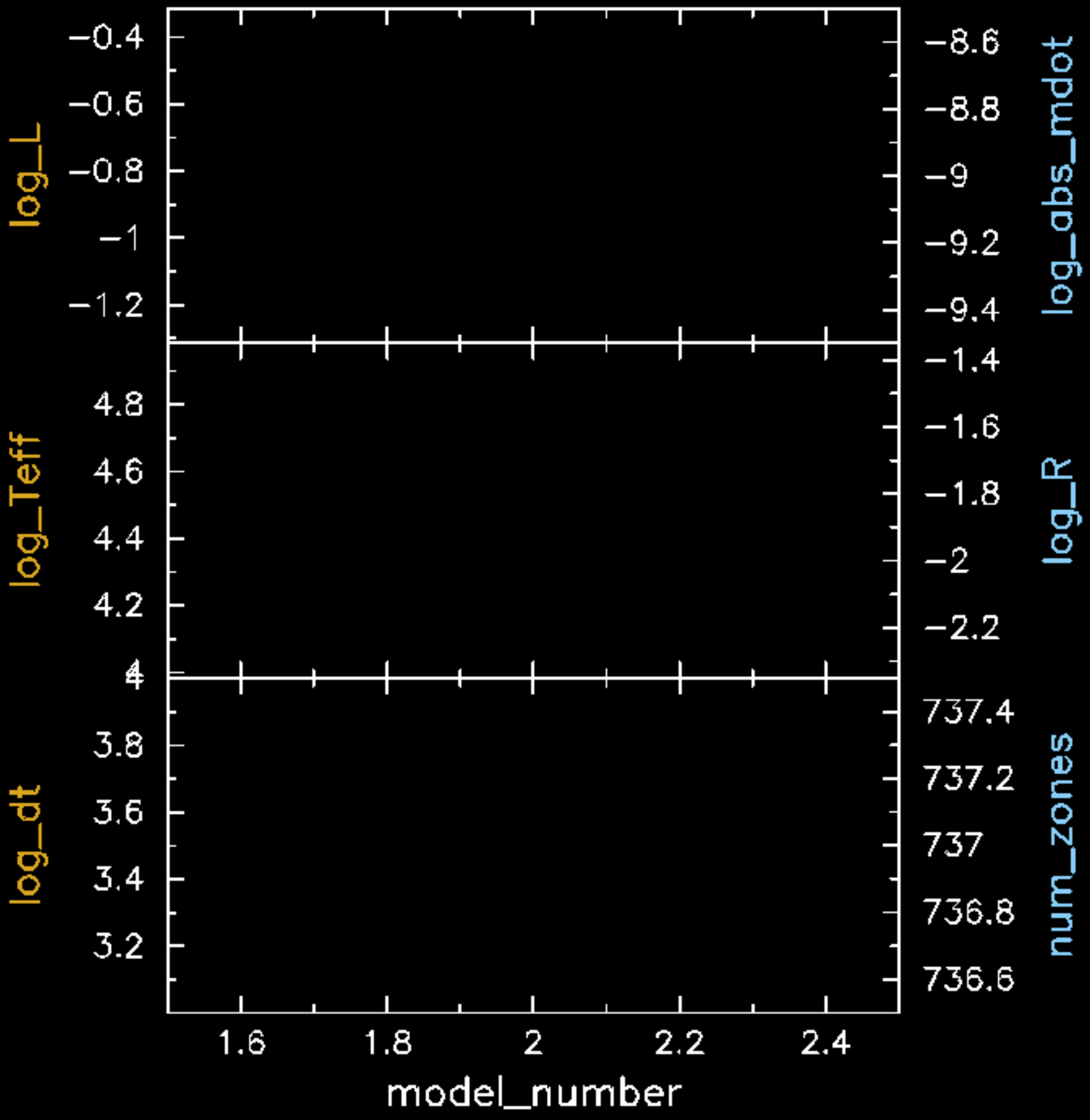
Rate of change of mass

Teff

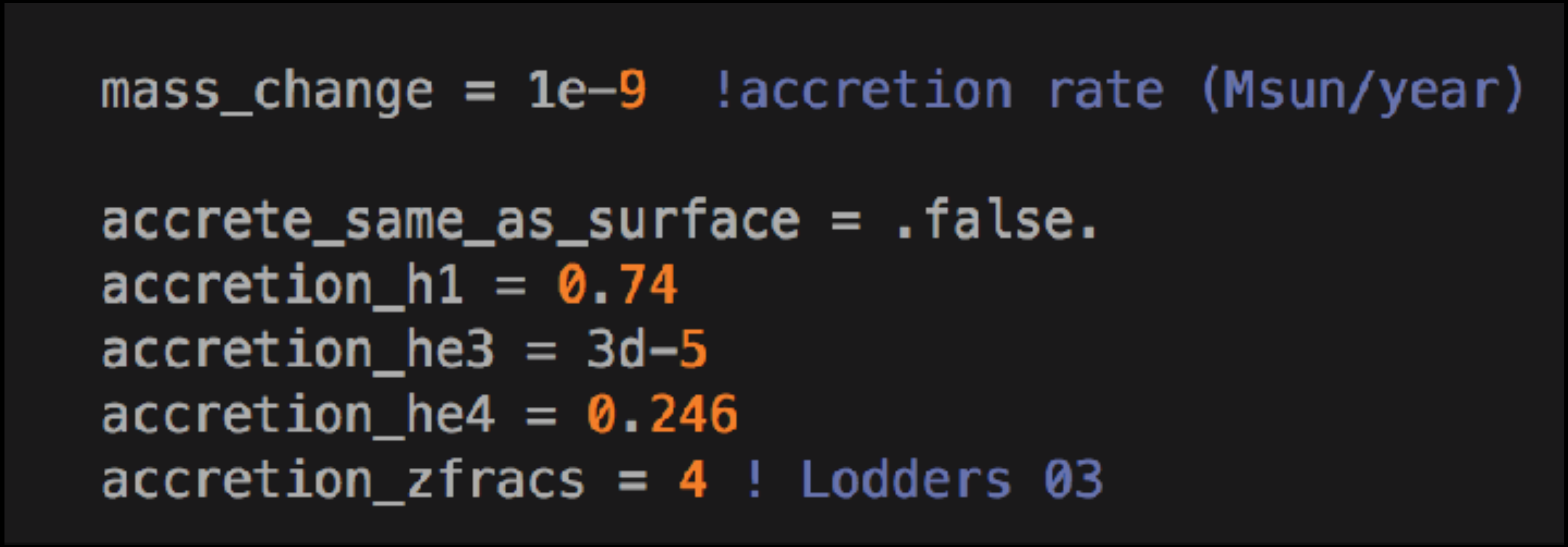
Radius

Time step

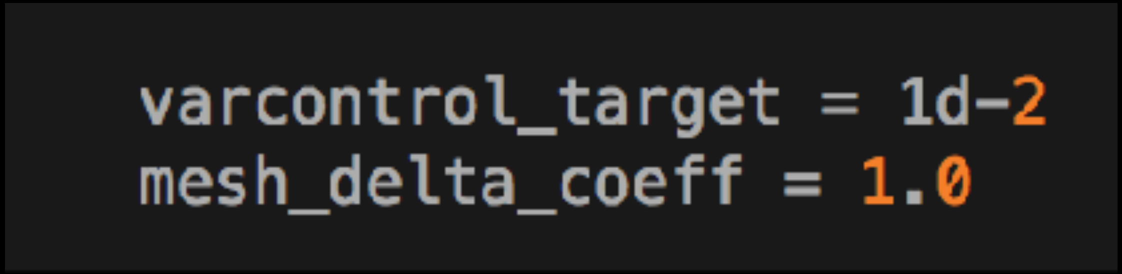
Number of zones



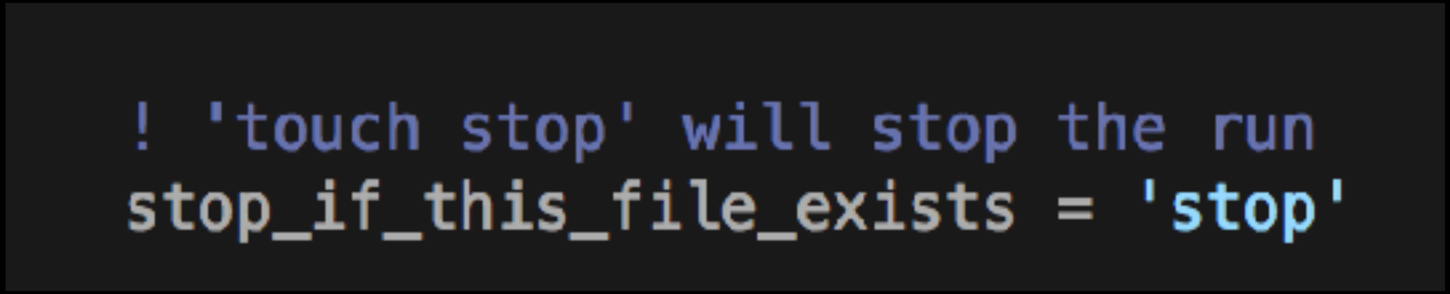
inlist_flash



```
mass_change = 1e-9  !accretion rate (Msun/year)

accrete_same_as_surface = .false.
accretion_h1 = 0.74
accretion_he3 = 3d-5
accretion_he4 = 0.246
accretion_zfracs = 4 ! Lodders 03
```



```
varcontrol_target = 1d-2
mesh_delta_coeff = 1.0
```

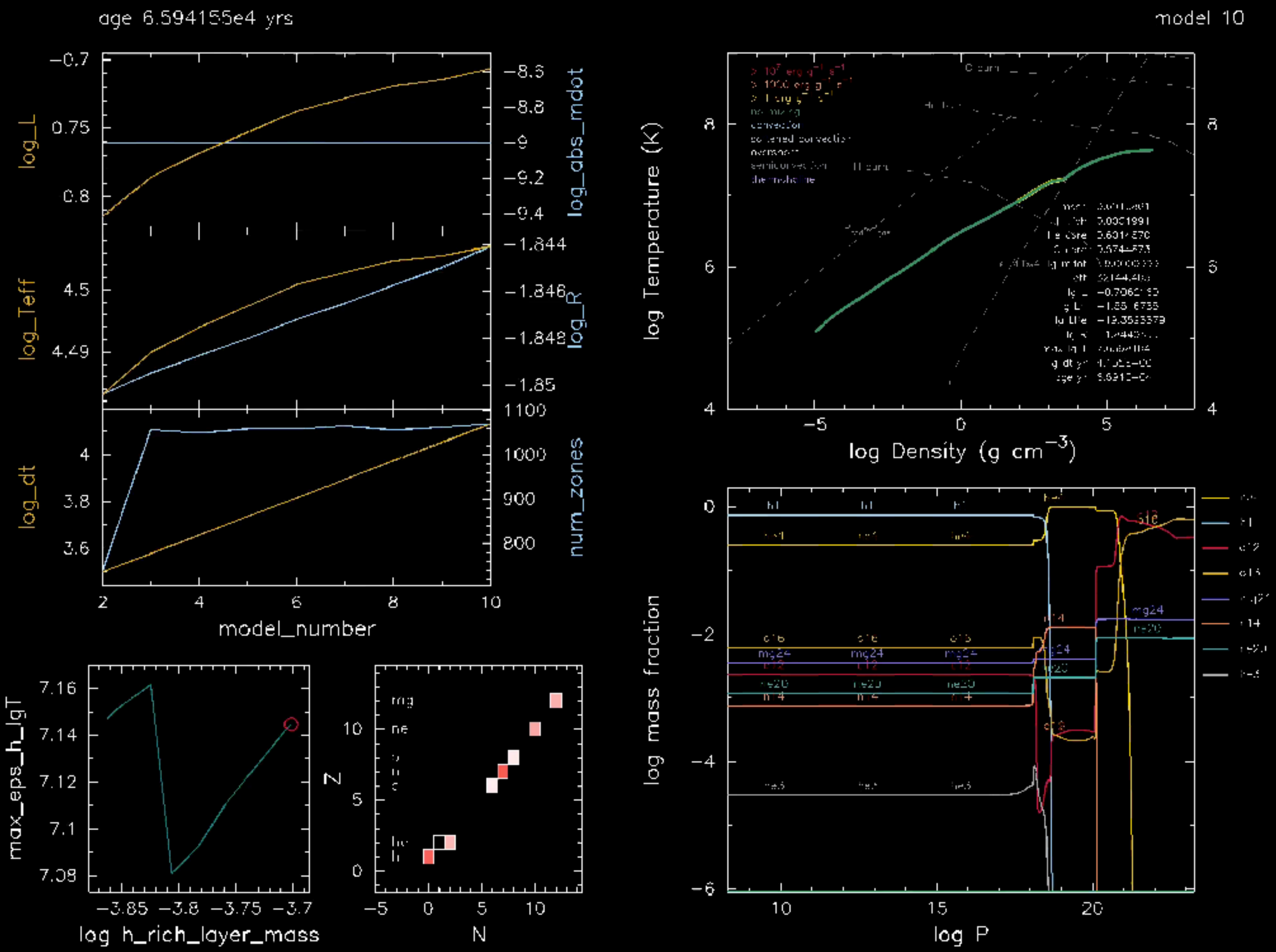


```
! 'touch stop' will stop the run
stop_if_this_file_exists = 'stop'
```

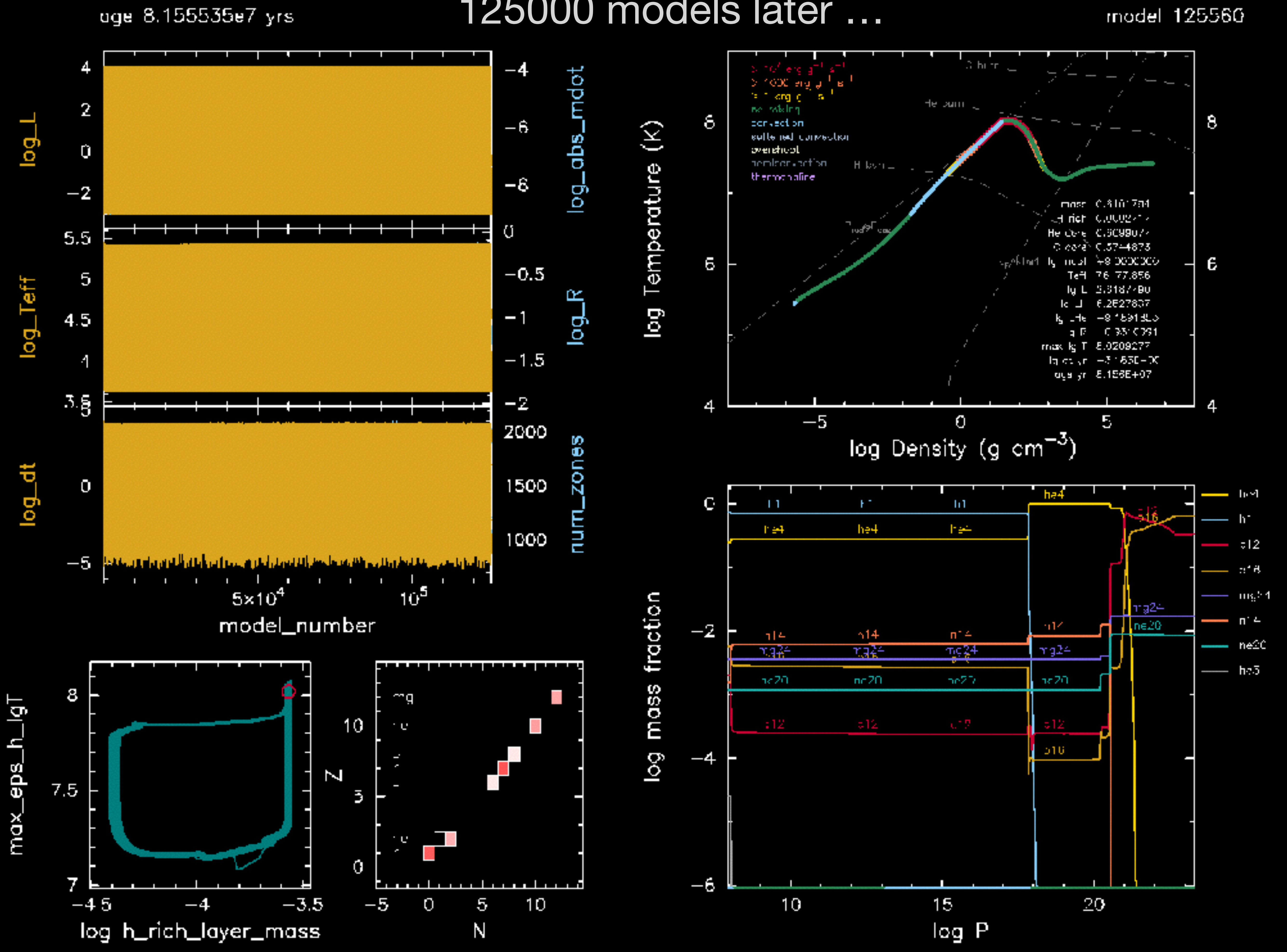
Files are in `lab1.tgz`

Copy these to a new work directory

Run it and see what happens!


age 6.594155e4 yrs
model 10
log_L
log_abs_mdot
log_Teff
log_R
log_dt
num_zones
model_number
log Temperature (K)
log Density (g cm^{-3})
C burn
He burn
H burn
no mixing
convection
softened convection
overshoot
semiconvection
thermohaline
max_eps_h_lgT
log h_rich_layer_mass
Z
N
mg
ne
he
h
log mass fraction
log P
h1
he4
c12
o16
mg24
n14
ne20
he3

125000 models later …



Nuclear reaction rates are very temperature sensitive!

energy generation rate

$$\epsilon_{\rm nuc} \propto T^{\nu}$$

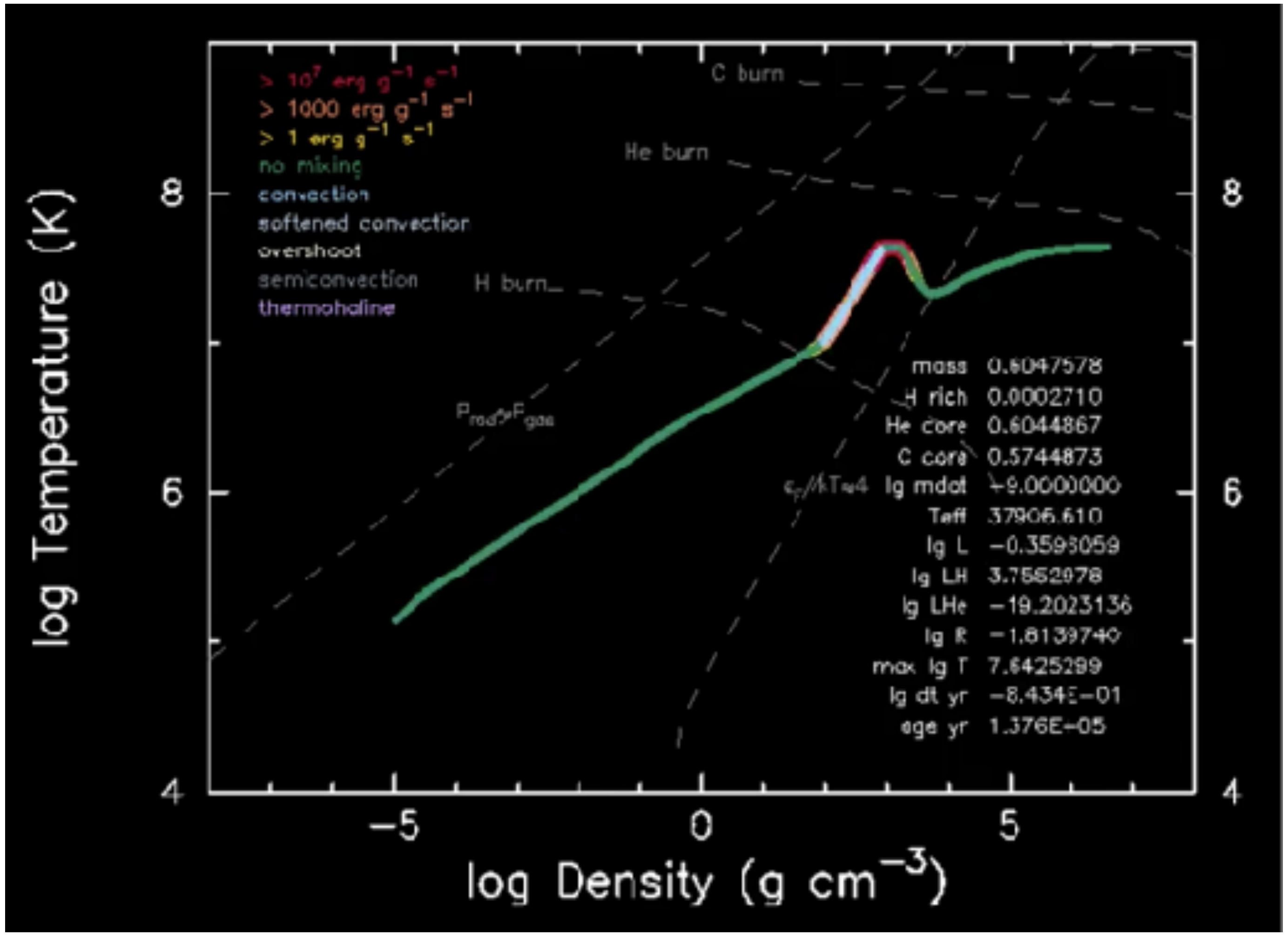
pp	$\nu \sim 4$
p+^{12}C	~ 20
He burning	~ 40

cooling rate

$$\frac{d \ln \epsilon_{\rm cool}}{d \ln T} \sim 4$$

=> thermal runaway

$$\begin{tikzcd} T \uparrow \arrow[r] & \epsilon_{\rm nuc} \uparrow \arrow[l, bend right] \end{tikzcd}$$



Thermonuclear instability in stars

Gravitationally-bound systems usually have *negative* heat capacities

e.g. particle in orbit moves further out if it gains energy, and therefore slows down

e.g. deposit energy into a star —> expansion —> *decrease* in T
(this is why the Sun is thermally stable)

=> thermal instability if pressure is independent of temperature

degeneracy pressure

$$P \propto \rho^{5/3}$$

e.g. He core flash,
C ignition in accreting
white dwarfs

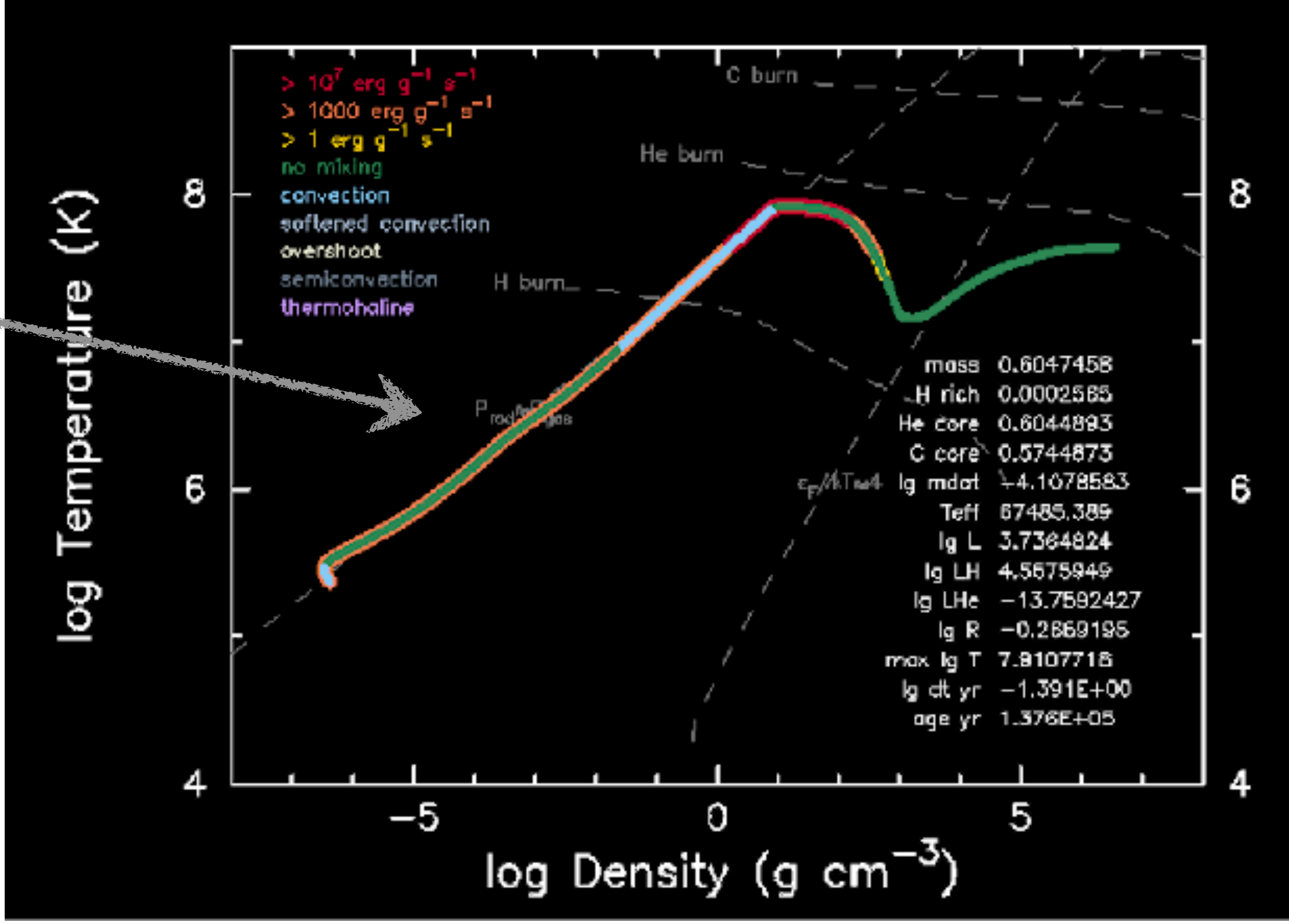
burning in a thin shell

$$P \approx g\frac{\Delta M}{4\pi r^2}$$

e.g. He shell flashes (AGB stars),
novae (accreting white dwarfs),
X-ray bursts (accreting neutron stars)

What stops the runaway?

Envelope reaches a state where radiation pressure begins to dominate $P_{\rm rad} \approx P_{\rm gas}$



This is a sign that the luminosity is reaching the Eddington luminosity

$$L_{\rm Edd} = \frac{4\pi G M c}{\kappa}$$

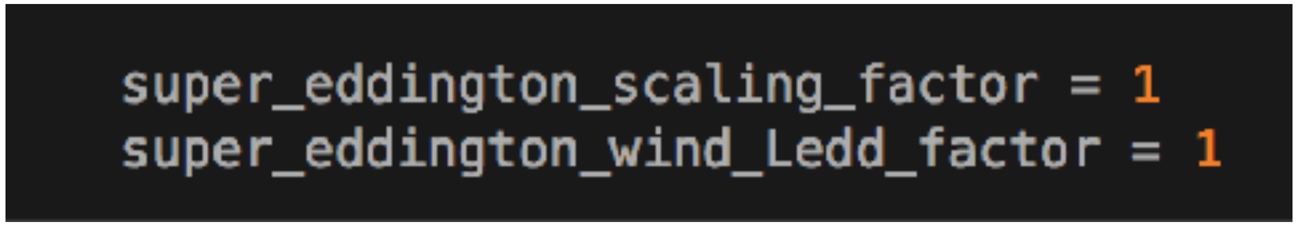
$$\approx 4 \times 10^4 \ L_\odot$$

=> radiation pressure is strong enough to overcome gravity and drive mass away from the star

“Super-Eddington wind”

$$\dot{M} \sim \frac{(L - L_{\rm Edd})}{GM/R}$$

This is implemented in MESA



```
super_eddington_scaling_factor = 1
super_eddington_wind_Ledd_factor = 1
```

Part 2: Looking at the model in more detail

Four questions to answer:

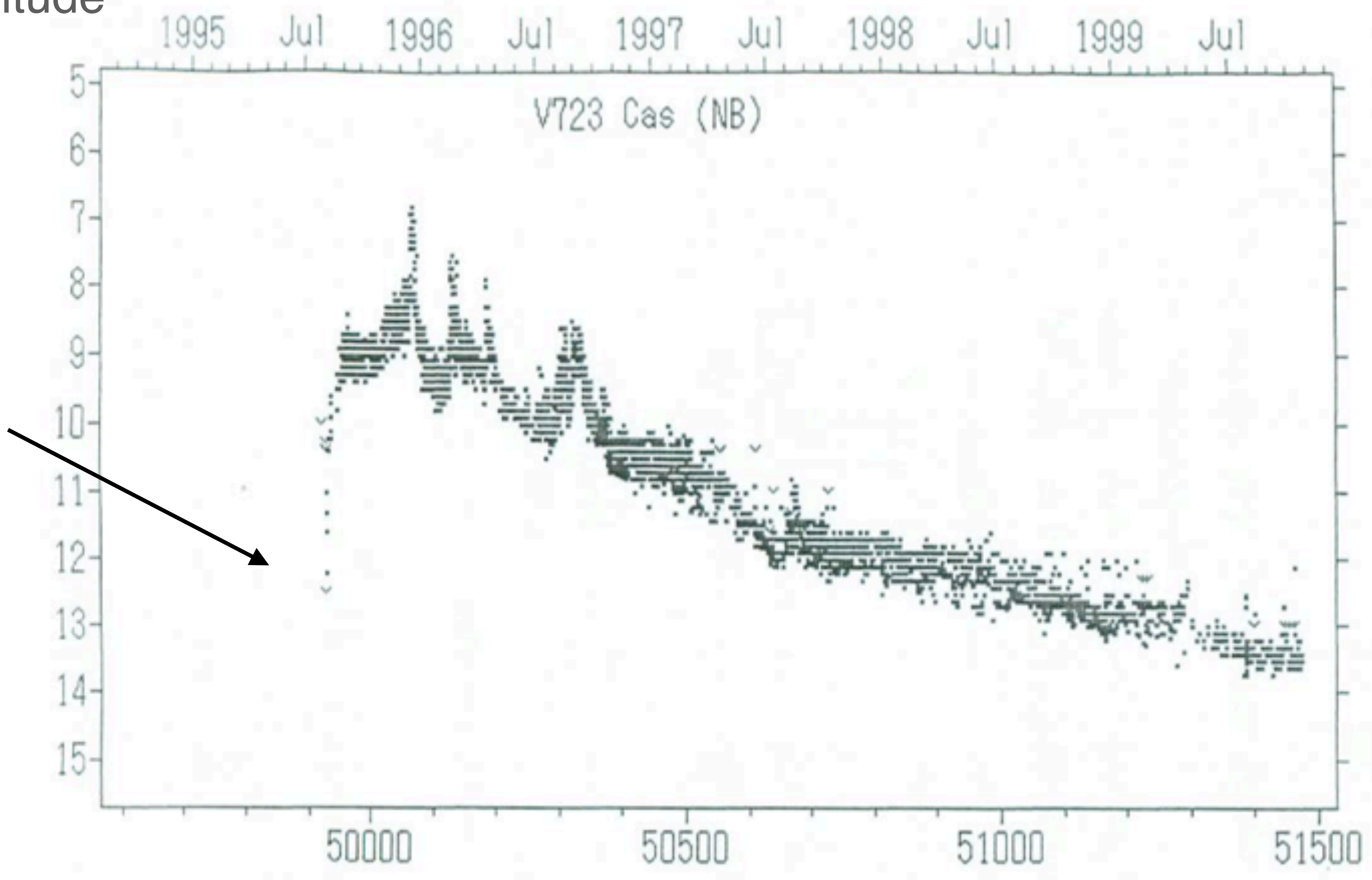
1. What is the recurrence time and ignition mass?
2. Plot L, LEdd, and Lnuc over time during one of the flashes, calculate the timescale for the accreted mass to be ejected or for nuclear burning to consume the hydrogen
3. Plot R and Teff? How would the visual lightcurve compare with the bolometric lightcurve?
4. In the burning layer, how does T, P, H, H/R evolve during the flash?

Work in a group

Jupiter notebook `plot_lightcurve.ipynb`

Example of a nova lightcurve

V magnitude



Typical
rise times
1-3 days

rise of 10
magnitudes
=> factor of
10^4 in
luminosity

days

pre-outburst
level

Recurrence times for novae range from 10's of years (recurrent novae) to 1000's of years (classical novae)

Novae eject mass!

- The nuclear energy release is $\sim 10^{18}\ \mathrm{erg\ g^{-1}}$

compared to gravitational binding energy $GM/R \sim 10^{17}\ \mathrm{erg\ g^{-1}}$

Typically $M_{\mathrm{ejected}} \sim 10^{-4}\ M_{\odot}$ $v_{ej} \sim 10^{3}\ \mathrm{km\ s^{-1}}$

Many implications:

- The expanding envelope/wind can become larger than the binary orbit => extra source of mass loss, chance to study “common envelope” phase

- The ejecta is observed to be enhanced in C, O => mixing with the underlying white dwarf. How this happens is not understood.

- The fact that mass is ejected makes it harder to reach Chandrasekhar mass to make a Type Ia supernova. Recurrent novae are interesting because they involve more massive white dwarfs and may not eject as much mass.

- Novae may contribute to Galactic nucleosynthesis. Overproduction factors (abundance produced relative to solar abundance) of >100 needed. May be important for ^{7}Li, ^{13}C, ^{15}N, ^{17}O, ^{22}Na, ^{26}Al

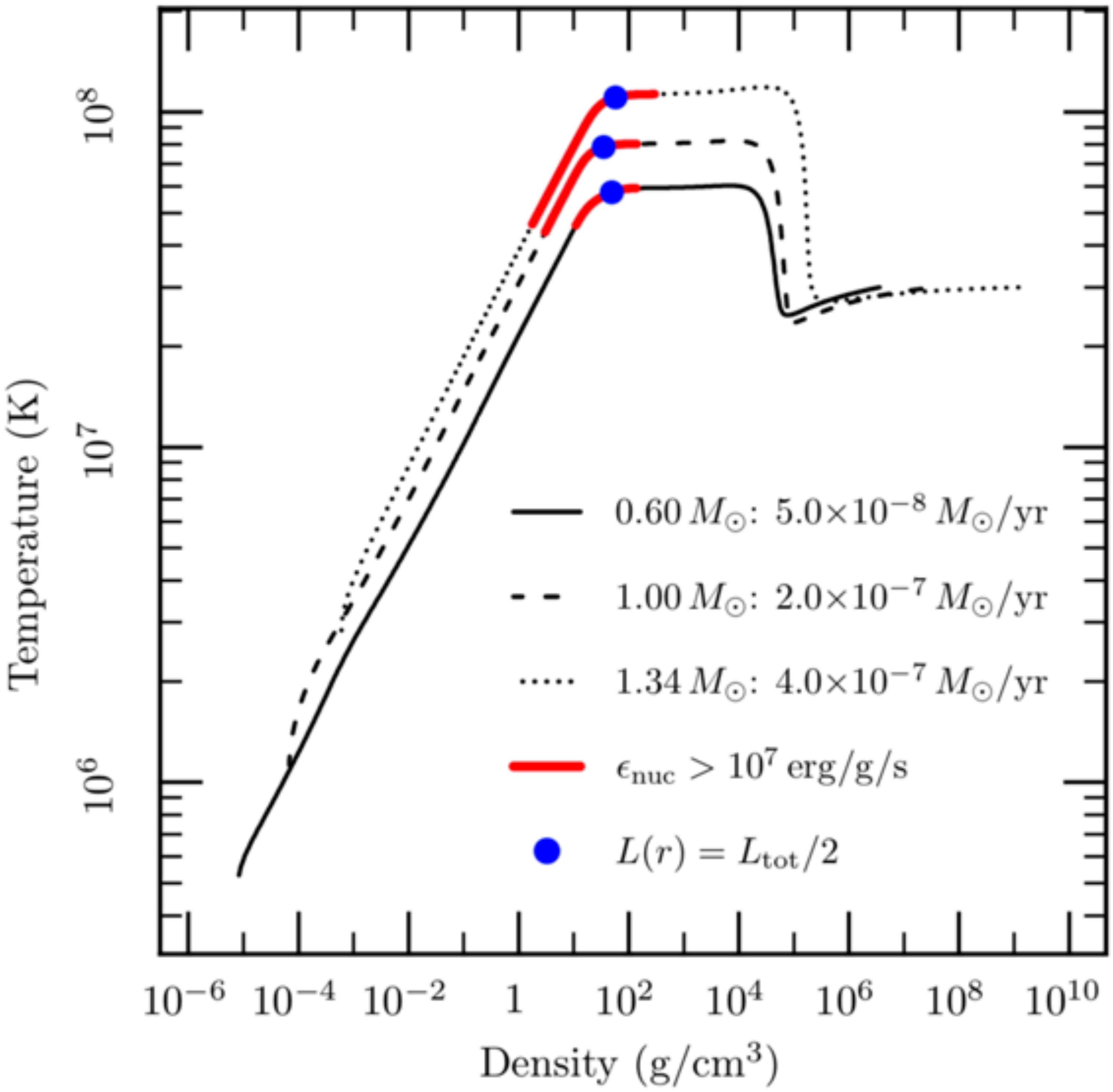
Lab 2: The parameter space of novae

How do nova properties like recurrence time, lightcurve, or the amount of mass ejected depend on

- the white dwarf mass
- accretion rate
- enrichment of the envelope with heavy elements

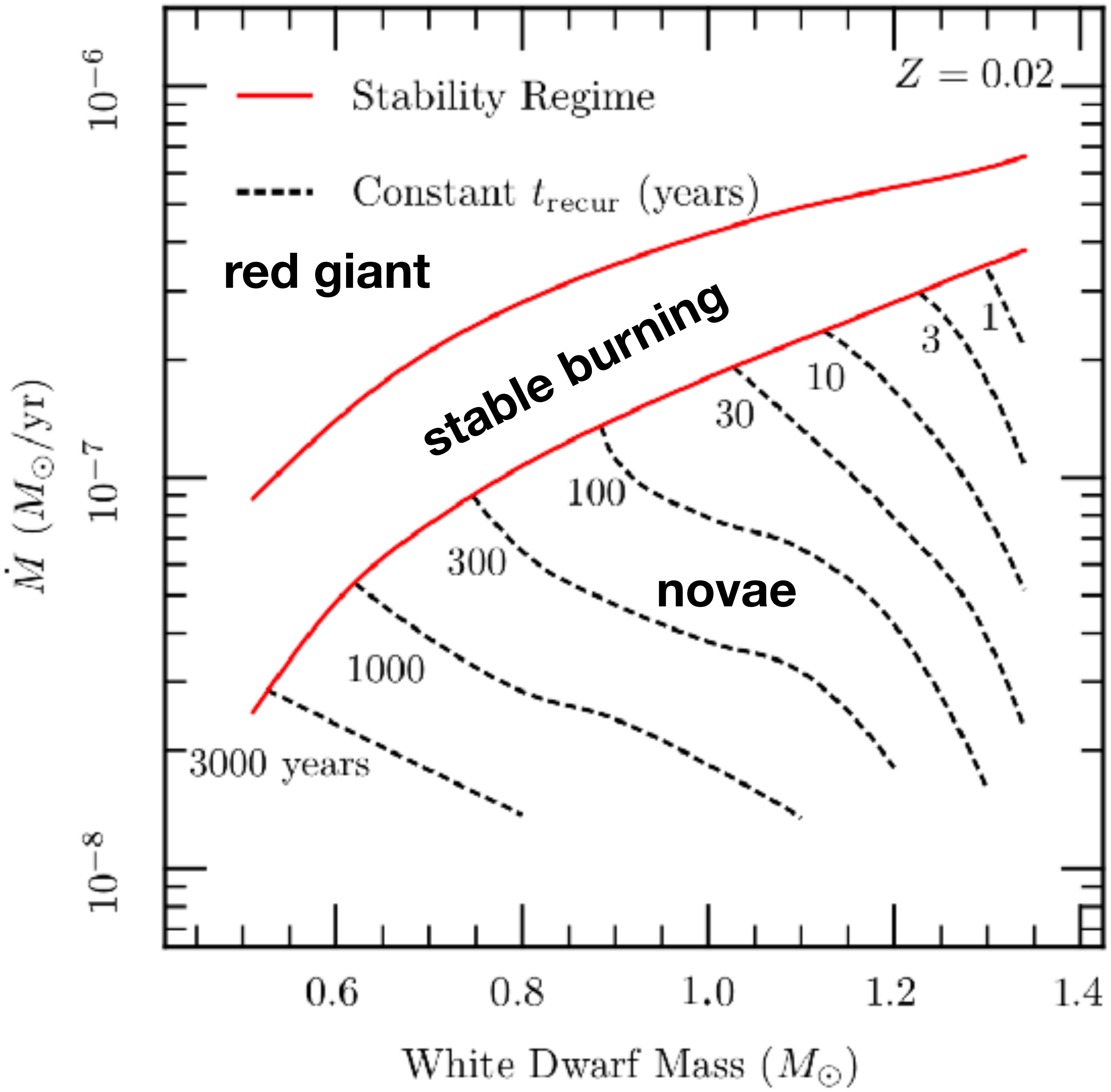
We’ll try to answer this question with MESA simulations

Hydrogen burning stabilizes at high rates



Wolf et al. (2013)

Hydrogen burning stabilizes at high rates



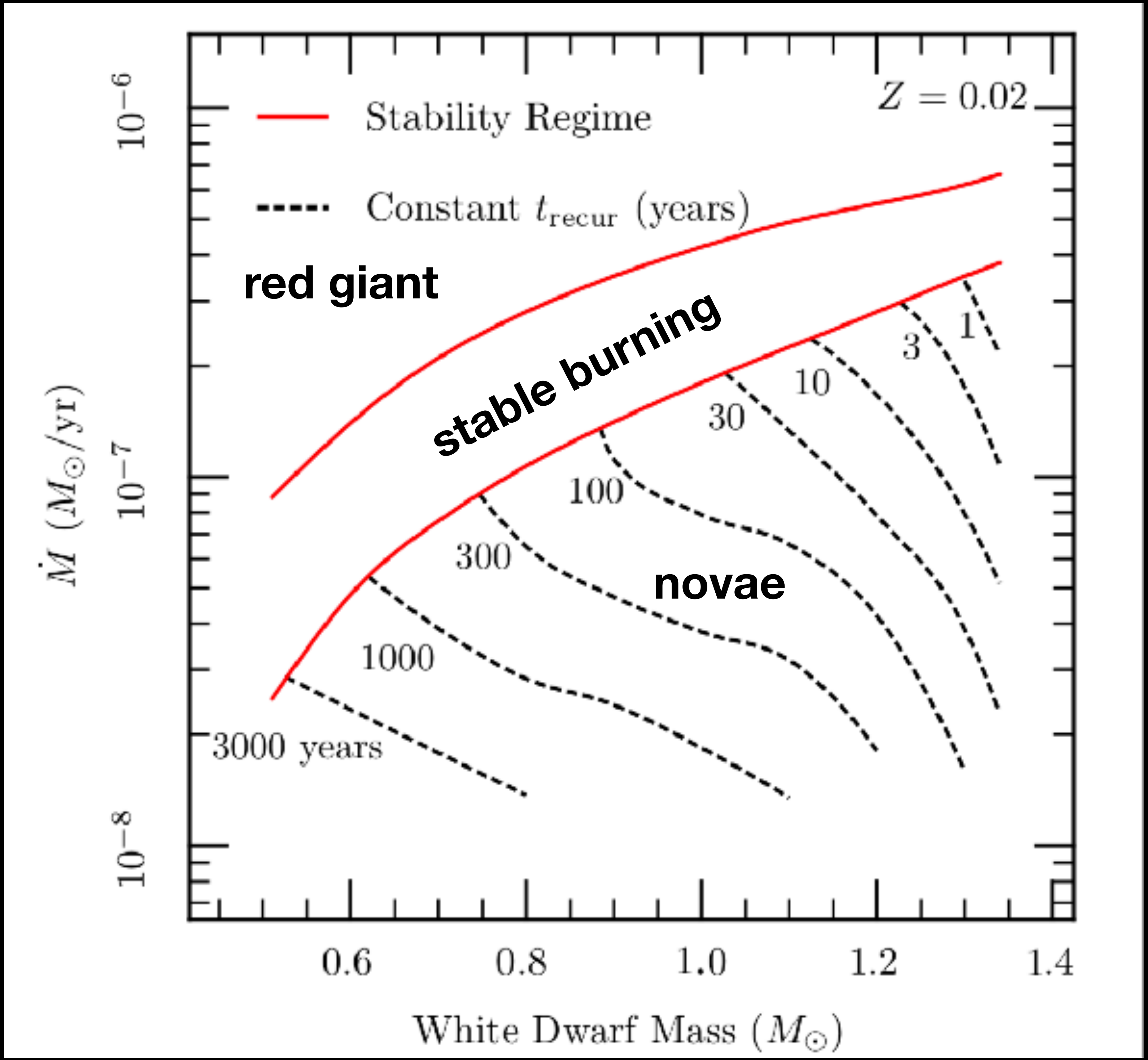
Wolf et al. (2013)

Start with stable burning models from Wolf et al. (2013)

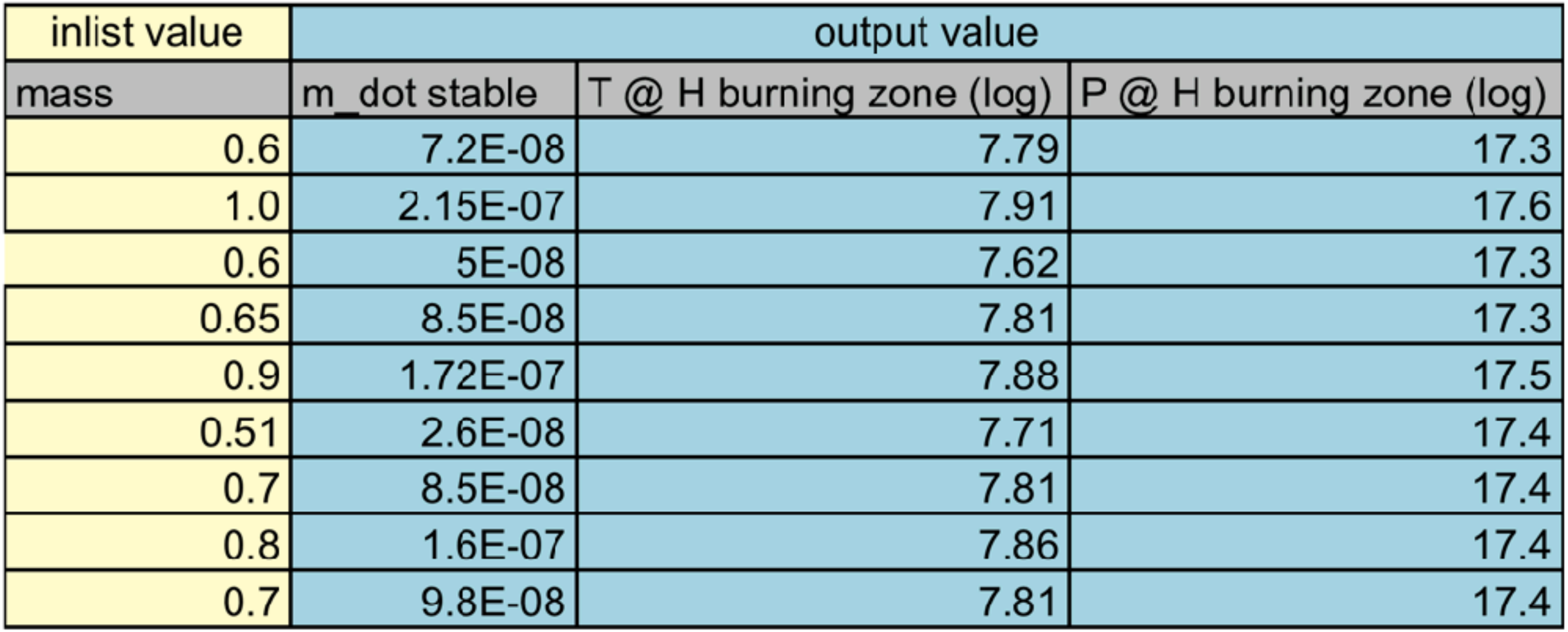
`steady_burning_models.tgz`

Part 1: determine at what accretion rate hydrogen burning becomes stable for different white dwarf masses

Part 2: for different metallicities, work down in accretion rate to explore the region of unstable burning

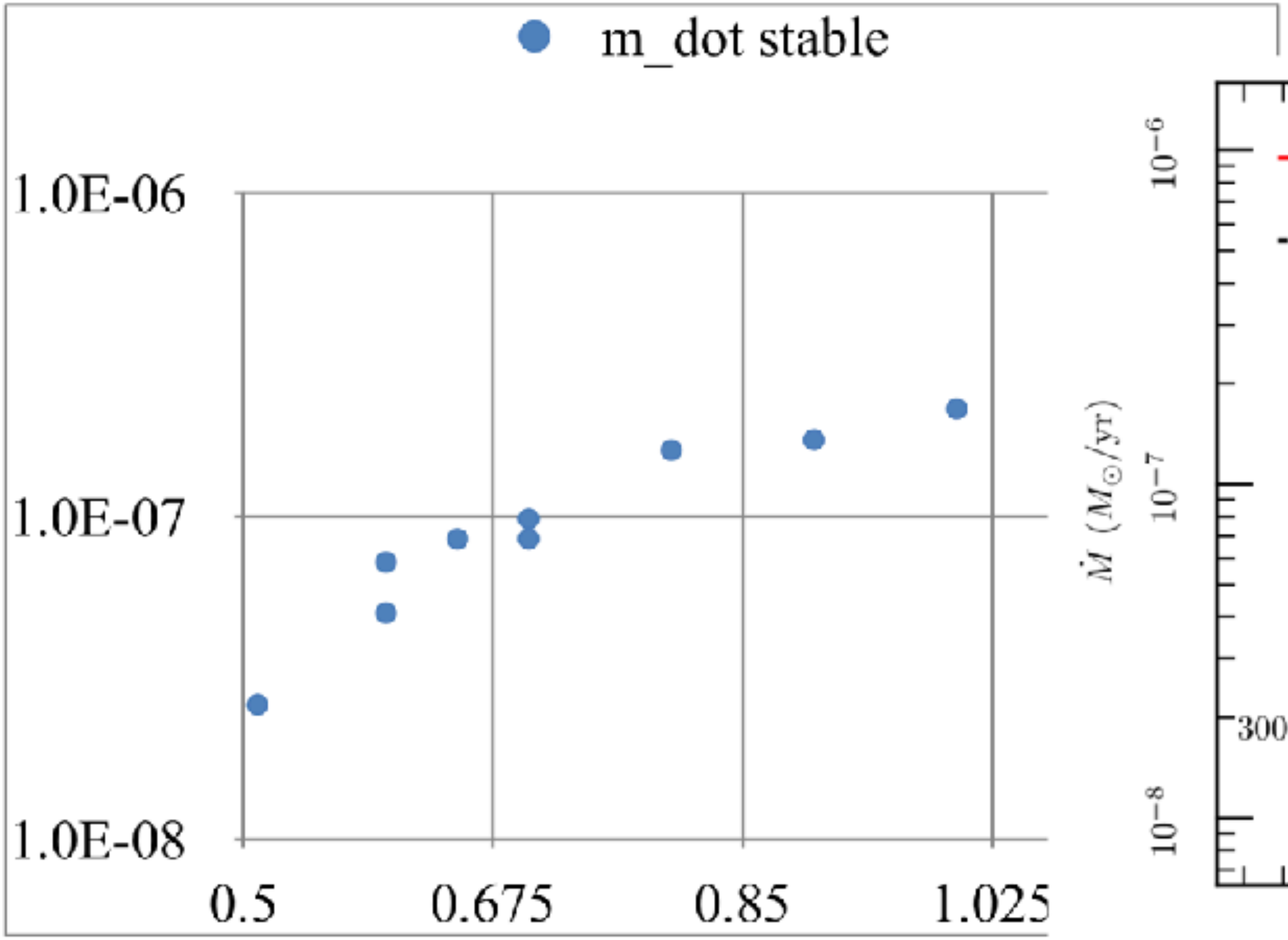


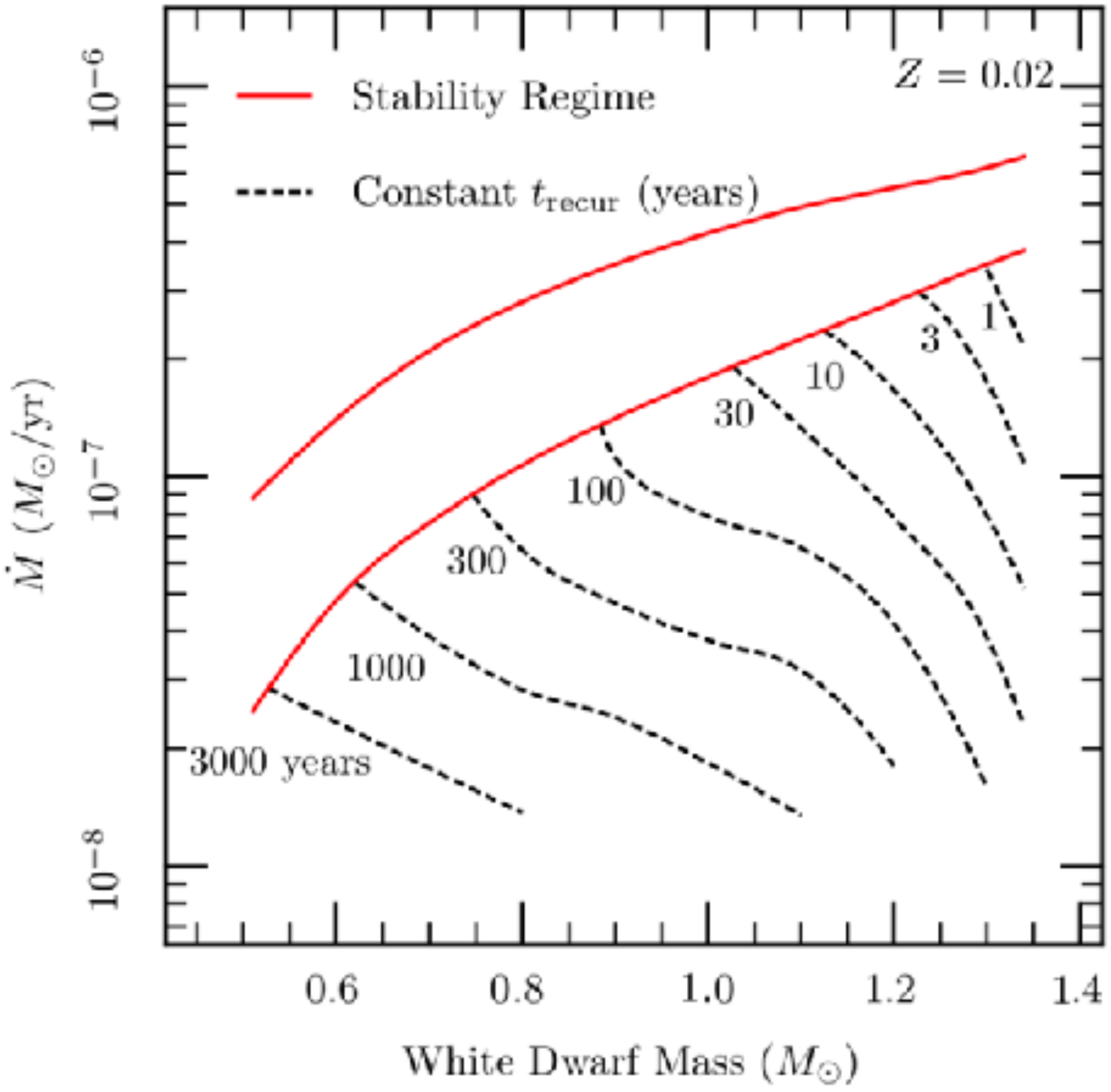
Results for the stable burning boundary from lab 2



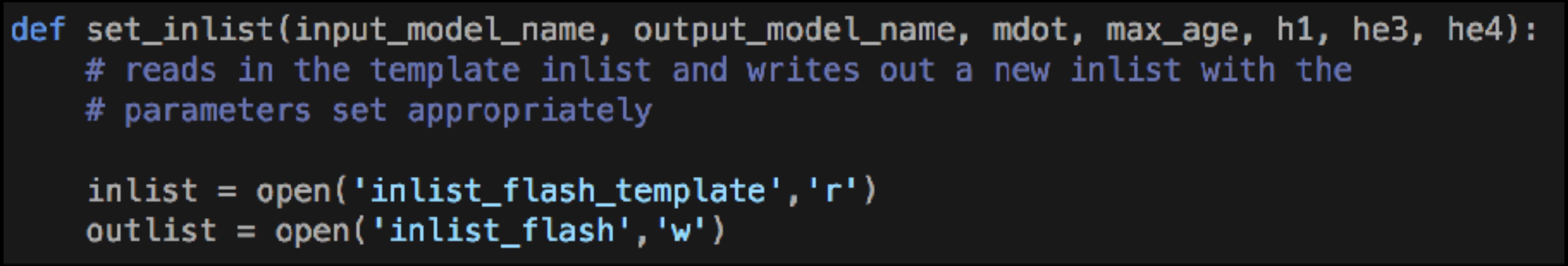
inlist value	output value		
mass	m_dot stable	T @ H burning zone (log)	P @ H burning zone (log)
0.6	7.2E-08	7.79	17.3
1.0	2.15E-07	7.91	17.6
0.6	5E-08	7.62	17.3
0.65	8.5E-08	7.81	17.3
0.9	1.72E-07	7.88	17.5
0.51	2.6E-08	7.71	17.4
0.7	8.5E-08	7.81	17.4
0.8	1.6E-07	7.86	17.4
0.7	9.8E-08	7.81	17.4

Results for the stable burning boundary from lab 2



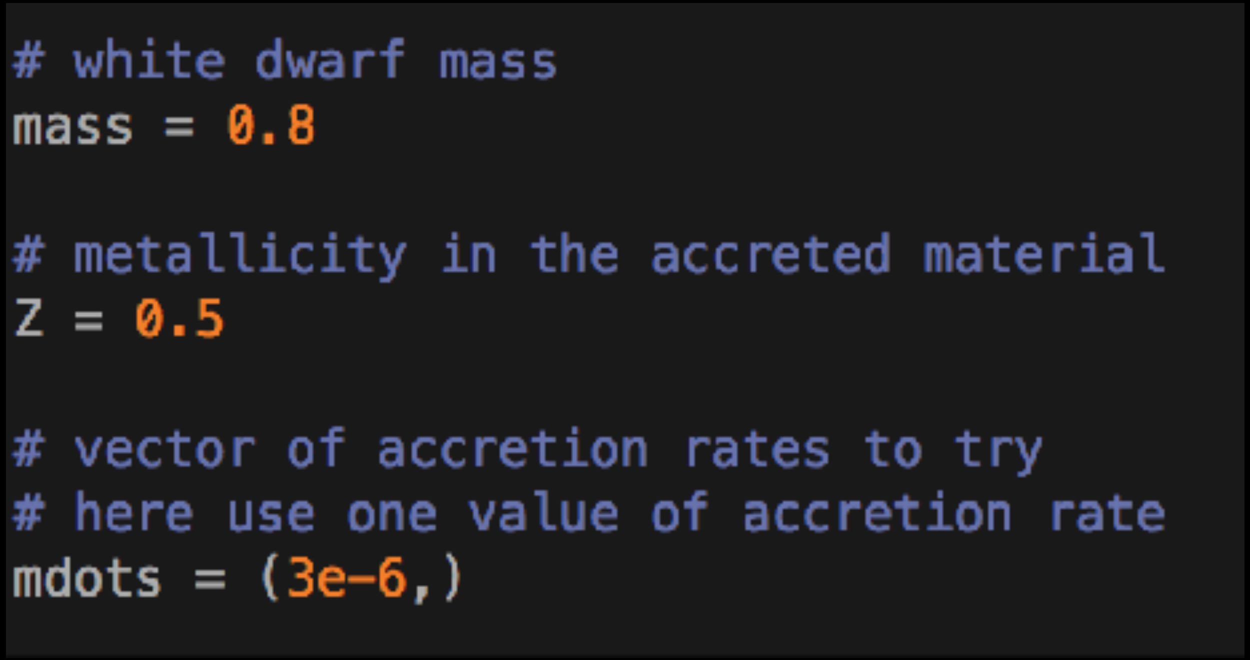


driver.py



```python
def set_inlist(input_model_name, output_model_name, mdot, max_age, h1, he3, he4):
    # reads in the template inlist and writes out a new inlist with the
    # parameters set appropriately

    inlist = open('inlist_flash_template','r')
    outlist = open('inlist_flash','w')
```

Set the parameters:



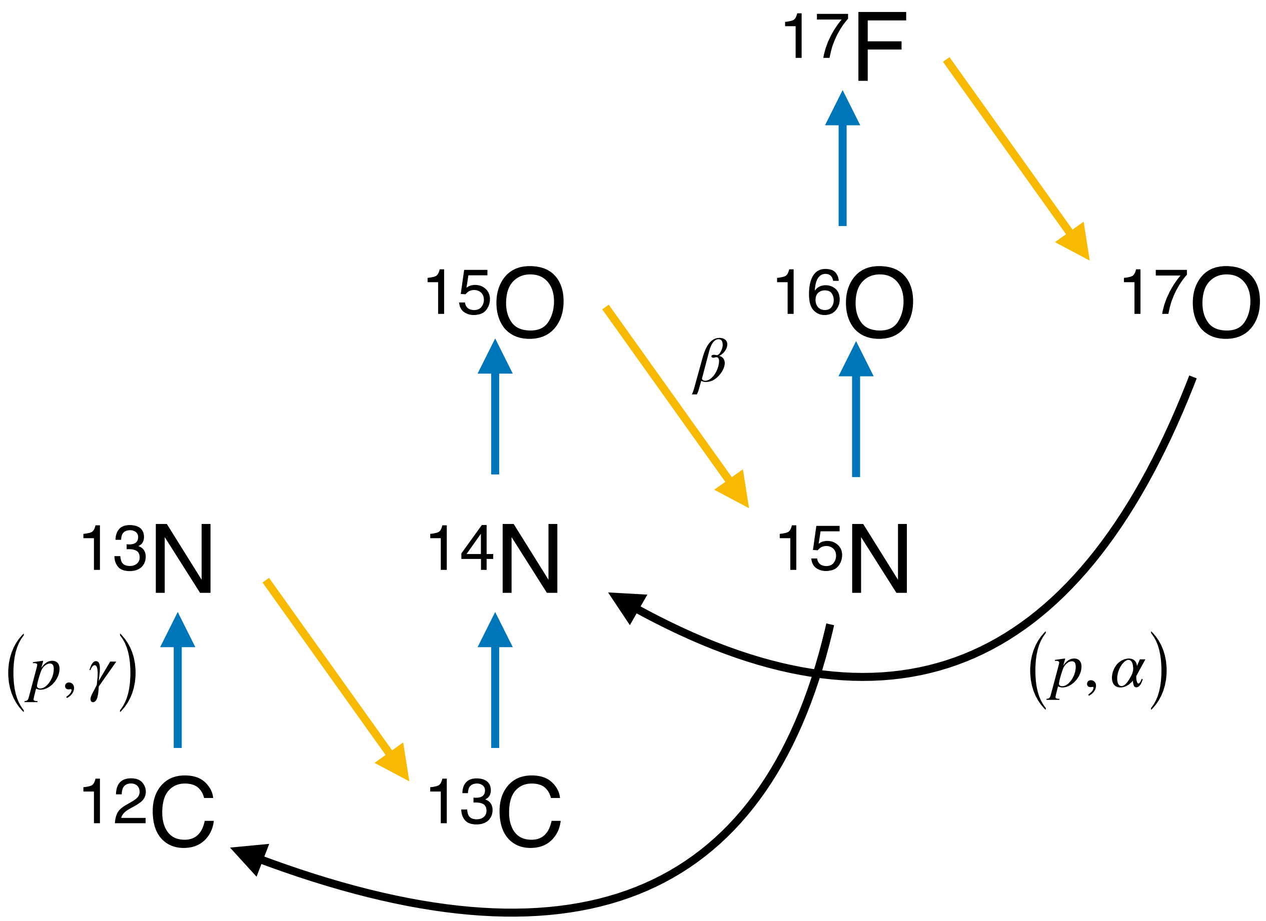
```python
# white dwarf mass
mass = 0.8

# metallicity in the accreted material
Z = 0.5

# vector of accretion rates to try
# here use one value of accretion rate
mdots = (3e-6,)
```

To run MESA then use : `python driver.py`

After the run ends, it saves the model, history file, and makes a movie with an appropriate name, e.g.

```
mesa_nova_0.80Msun_Tc3e7_mdot1e-06_Z0.02.mod
```

CNO cycle



$$\tau\left(^{13}\mathrm{N} \rightarrow ^{13}\mathrm{C}\right) = 863\ \mathrm{s}$$
$$\tau\left(^{15}\mathrm{O} \rightarrow ^{15}\mathrm{N}\right) = 176\ \mathrm{s}$$

p capture on ^{14}N is rate limiting step
=> CNO abundances evolve to ^{14}N

Implication for novae is that the amount of ^{12}C puts a limit on the amount of energy that can be released rapidly during the first stage of the runaway

Early nova simulations found that enhanced C abundance was needed to match the “fast novae” => additional evidence for enrichment

The initial energy release is $\approx 10^{16}\ \mathrm{erg\ g^{-1}} \left(\frac{Z_{\mathrm{CNO}}}{0.01}\right)$

compared with the binding energy $GM/R \sim 10^{17}\ \mathrm{erg\ g^{-1}}$

=> **Z_{CNO} ~ 0.1 needed for rapid mass ejection**

Consistent with observations of abundances, which show elevated levels of C/O or O/Ne/Mg from more massive ONeMg white dwarfs

Mechanism still not understood: shear instabilities, diffusion, convective overshoot

The convective turn-over time is comparable to nuclear timescales

Mixing length (efficient convection) =>

$$v_c \approx \left(\frac{L}{4\pi r^2 \rho}\right)^{1/3} \sim 10^6 \text{ cm s}^{-1} \quad \text{for} \quad L \sim 10^4 \, L_\odot \quad \rho \approx 10 \text{ g cm}^{-3}$$

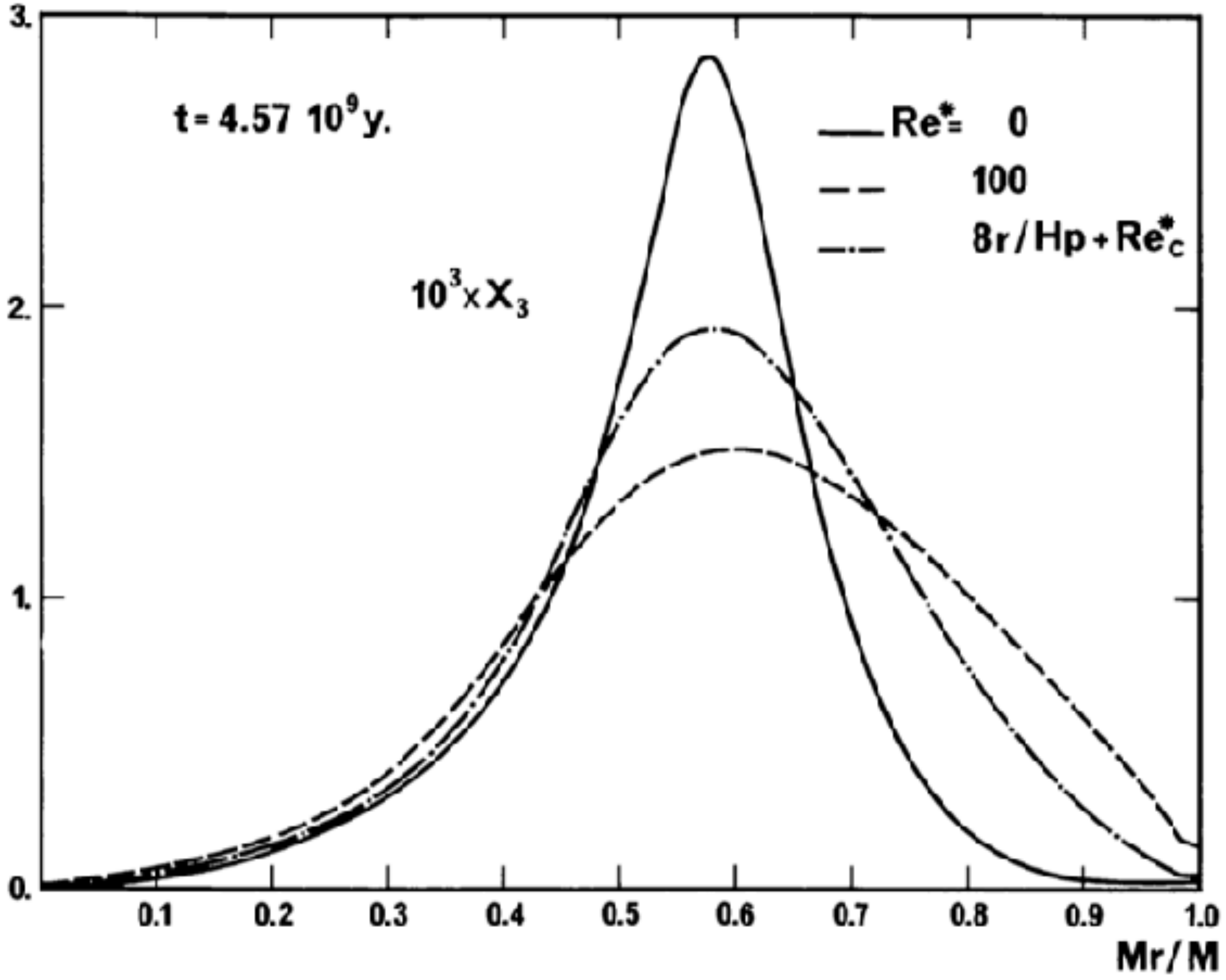
then $H = 10^7$ cm

=> $\frac{H}{v_c} \sim 10$ s

This is shorter than beta-decay times in the CNO cycle => unstable nuclei can be carried to lower density where they deposit energy, enhancing mass loss

Nuclei that would otherwise proton capture can be carried to low density regions where p-captures are slow, e.g. ^{13}C, ^{15}N, ^{17}O, and ^{7}Be (which then later decays to ^{7}Li)

^{3}He profile in the Sun



Lebreton & Maeder (1987)

$^3\mathrm{He}(^3\mathrm{He}, 2p)^4\mathrm{He}$ could influence the ignition mass in novae

(Shara 1980; Shen & Bildsten 2009)