Keele University

Darmstadt, March 18

KAVLI IPMU

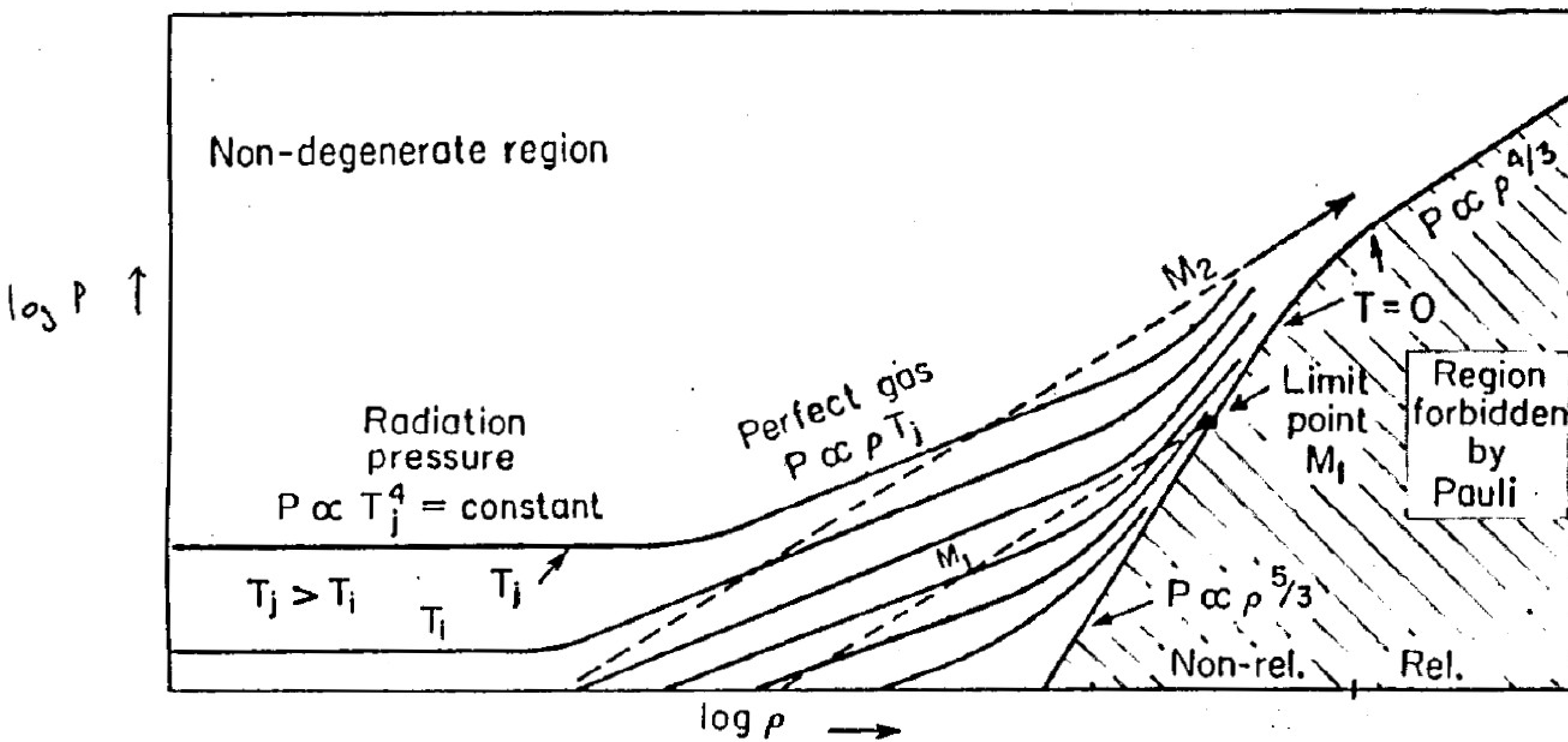
Stellar Evolution Course

L7: Simple Models & Early Evolution

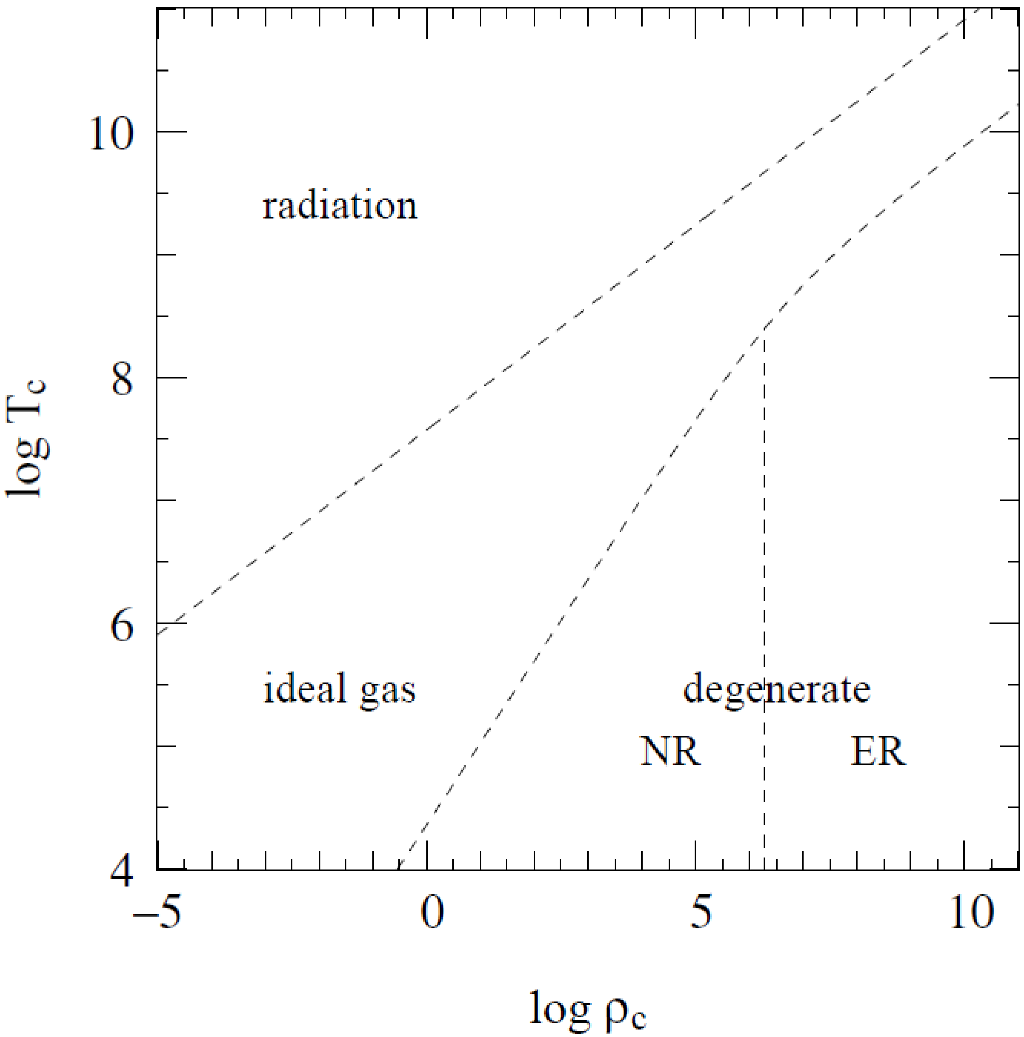
&

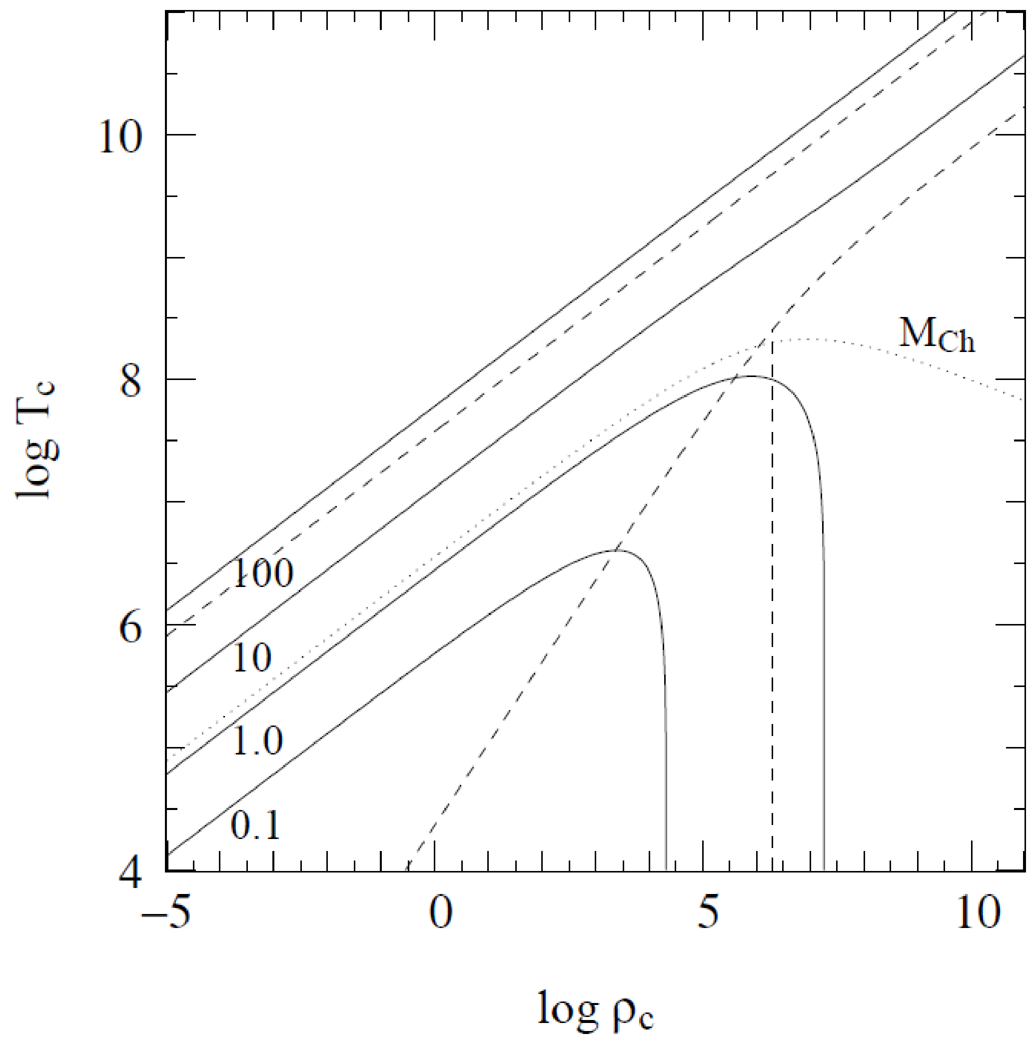
L8: Late Evolution of Intermediate & Low-Mass Stars

Schematic Evolution in P_c – Rho_c

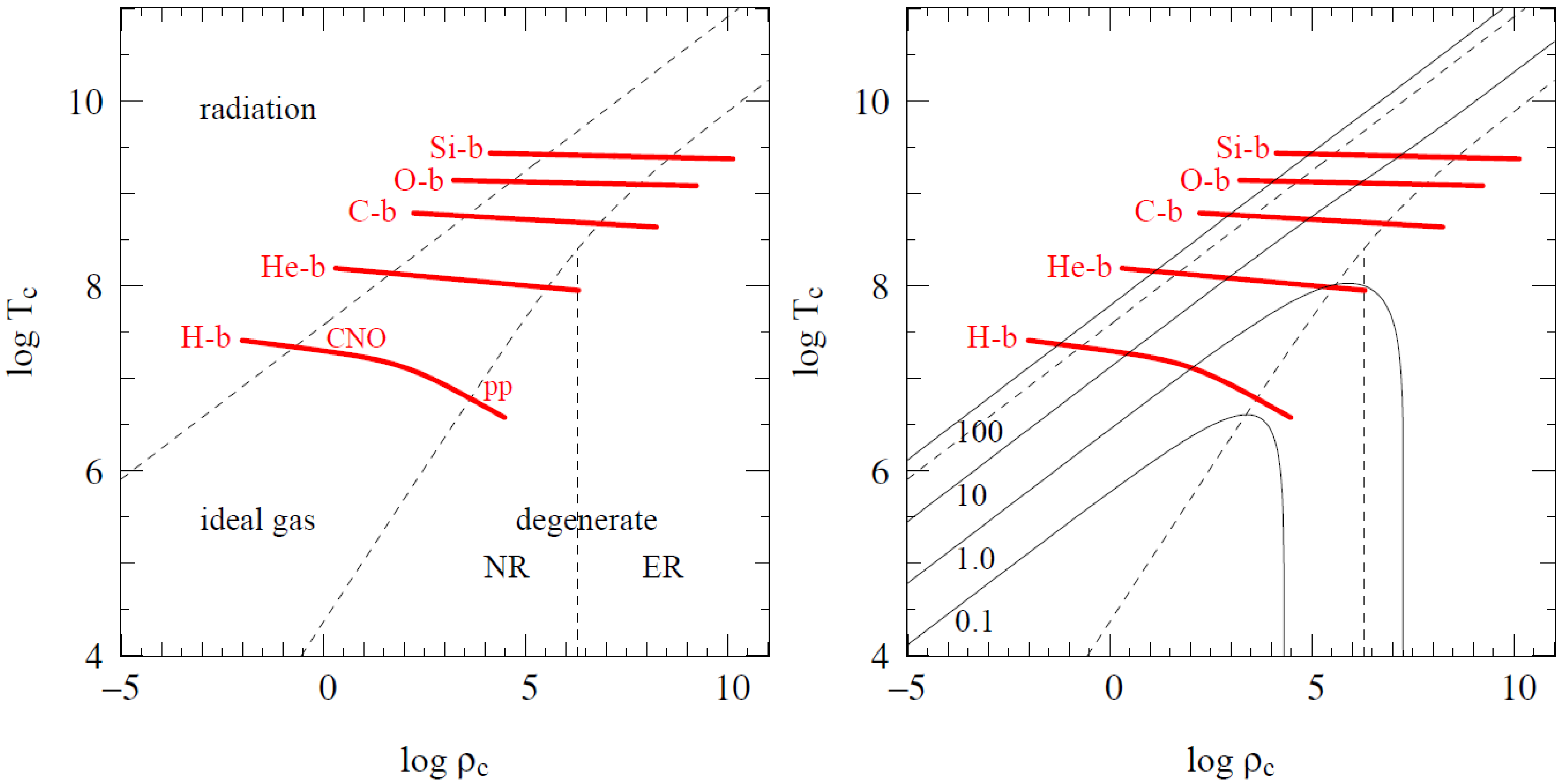


Schematic Evolution in T_c – Rho_c

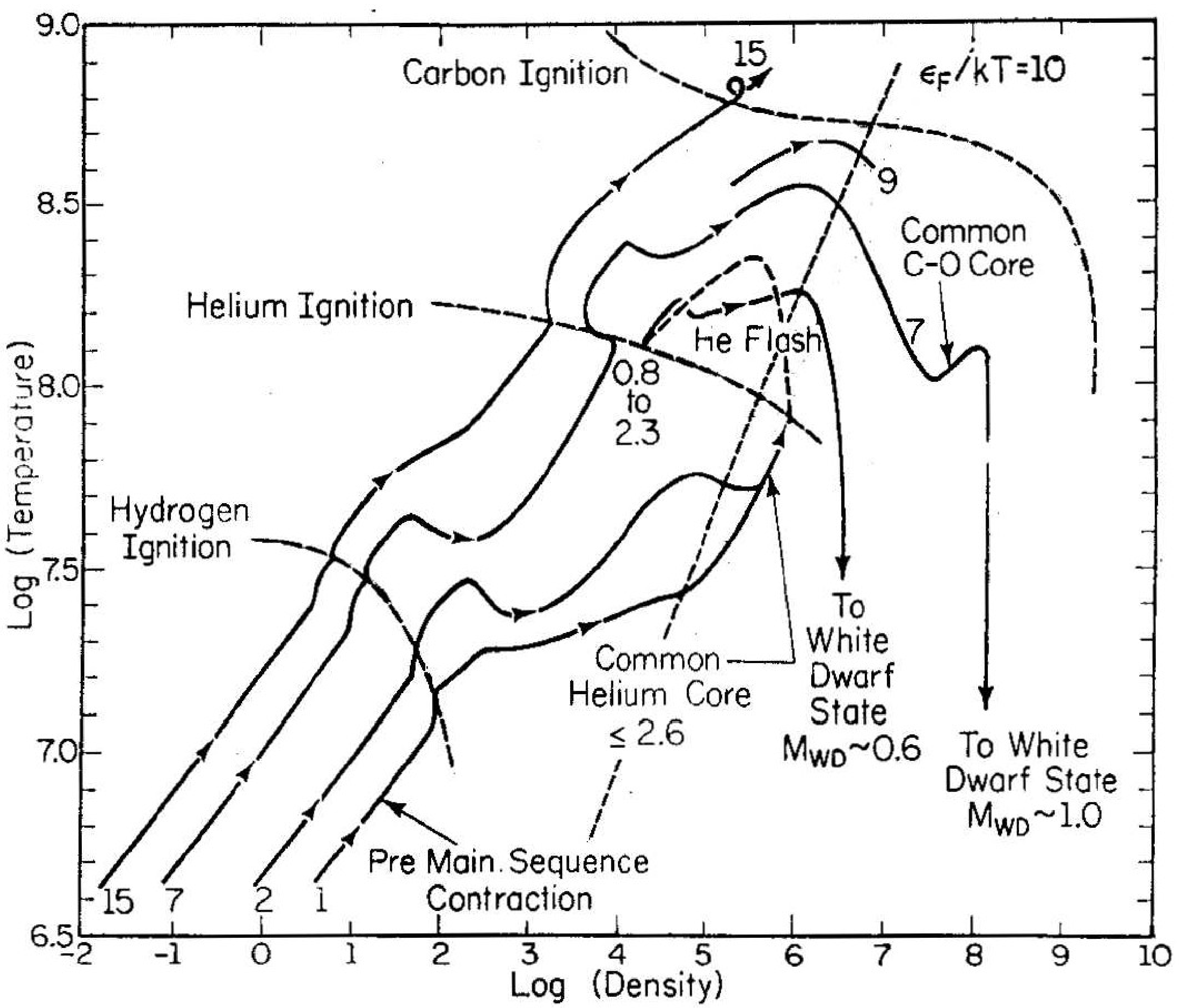




Schematic Evolution in T_c – Rho_c



Schematic Evolution in T_c – Rho_c

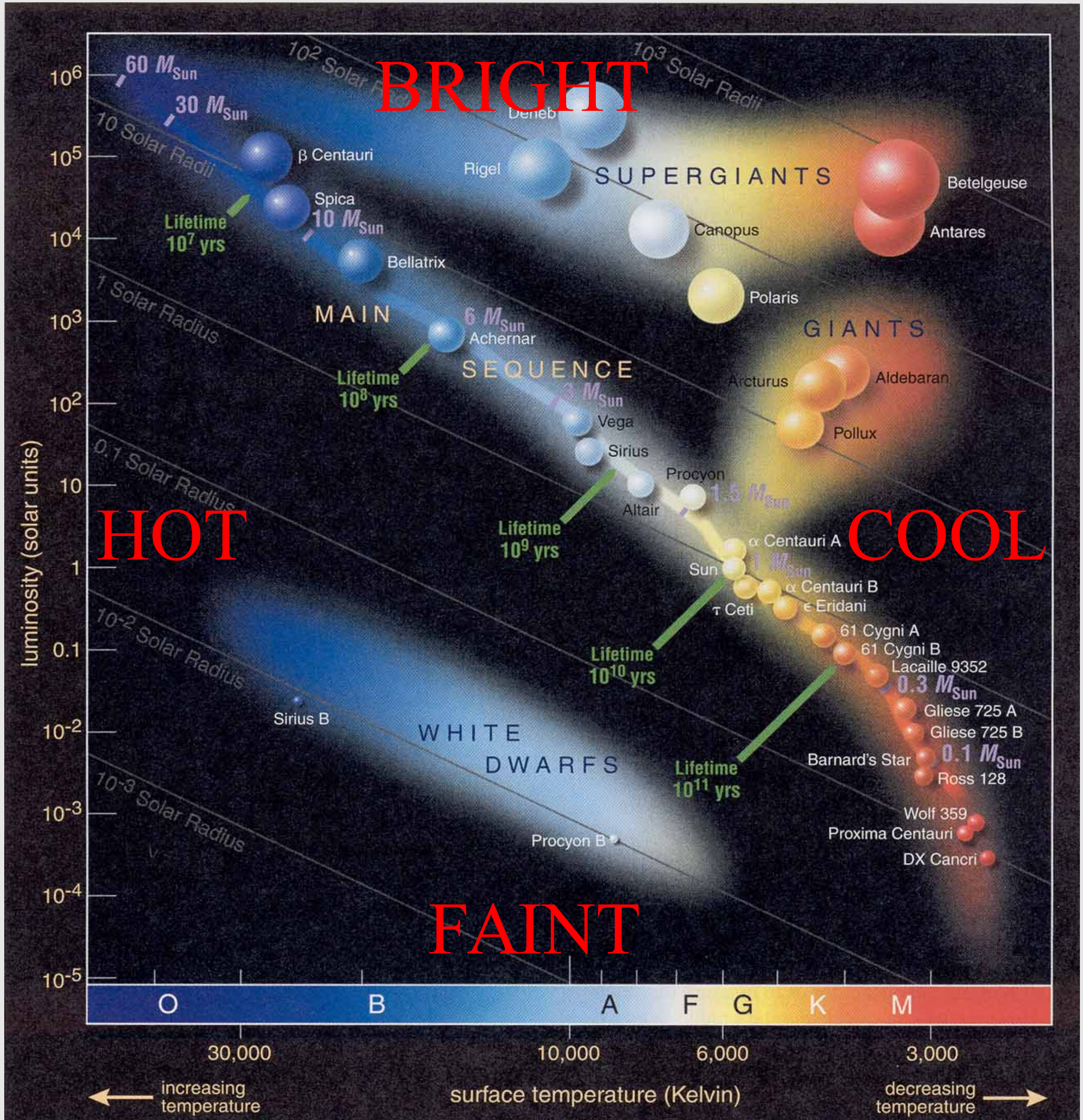


Mass Domains

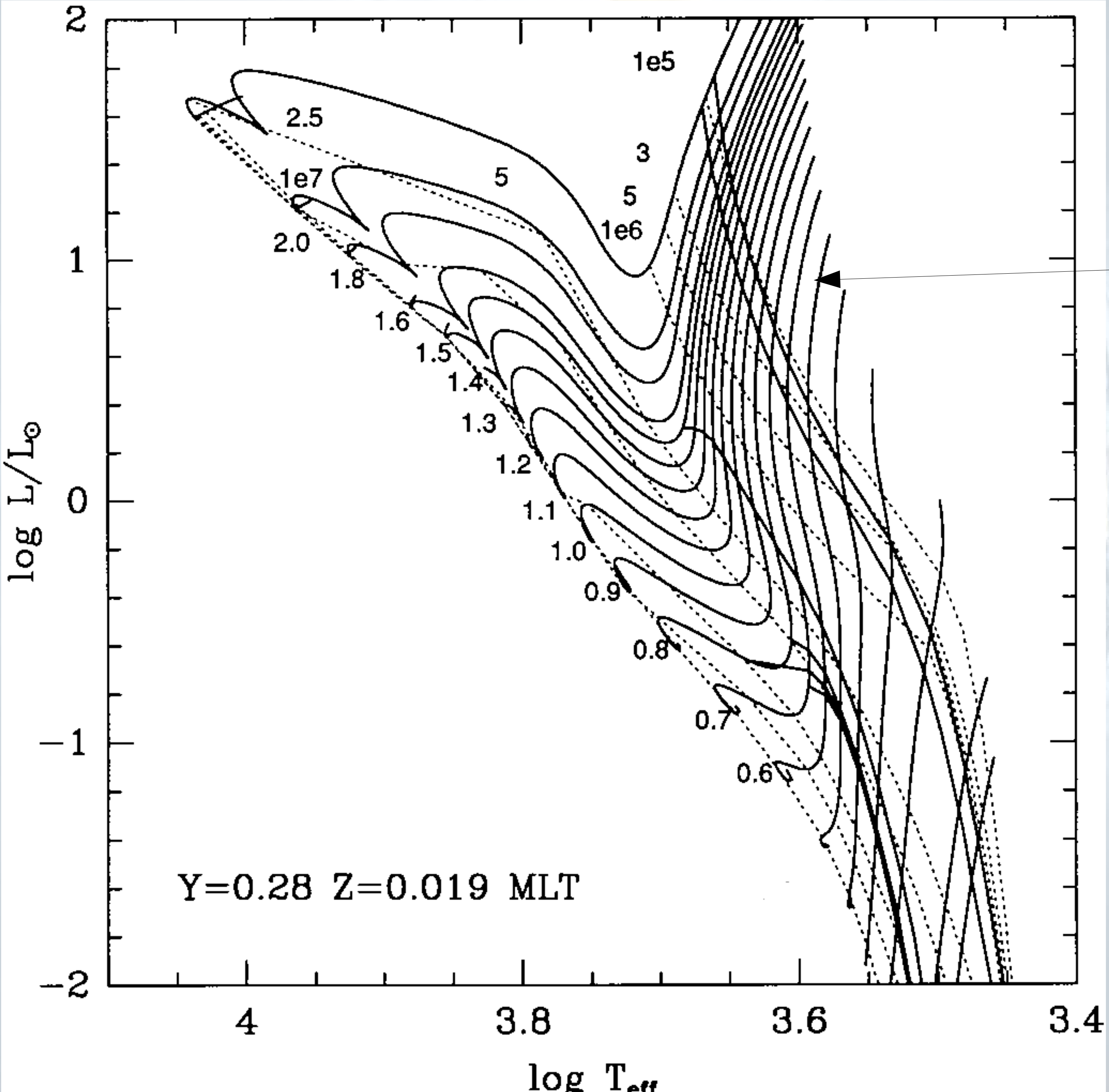
Stars: radiate energy produced internally & are bound by their own gravity

- 0.08 M_{sun} inferior mass limit for core H-burning : Brown Dwarfs
- 0.08 M_{sun} – 0.5M_{sun}: H burning OK, degenerate before core He-burning (lifetime > Hubble time→ no He white dwarf from single stars)
- 0.5-7M_{sun}: core H OK, core He OK (He-flash below 1.8 M_{sun}), degenerate CO white dwarf
- 7-9 M_{sun}: Core C burning OK→ WD(?) or Complete destruction (?) or collapse through electron captures (?)

- ~9 - 150 M_{sun}: core H, He, C, Ne, O, Si-→ Fe cores
- 150-250 M_{sun}: Pair Creation/instability Supernovae


BRIGHT
FAINT
HOT
COOL
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
3 M_{Sun}
1.5 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
SUPERGIANTS
GIANTS
MAIN SEQUENCE
WHITE DWARFS
Deneb
Rigel
Betelgeuse
Antares
Canopus
Polaris
β Centauri
Spica
Bellatrix
Achernar
Arcturus
Aldebaran
Pollux
Vega
Sirius
Procyon
Altair
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

Pre-Main Sequence



Hayashi Line (fully convective)

Zero-Age MS: L-M & R-M Relations (Homology)

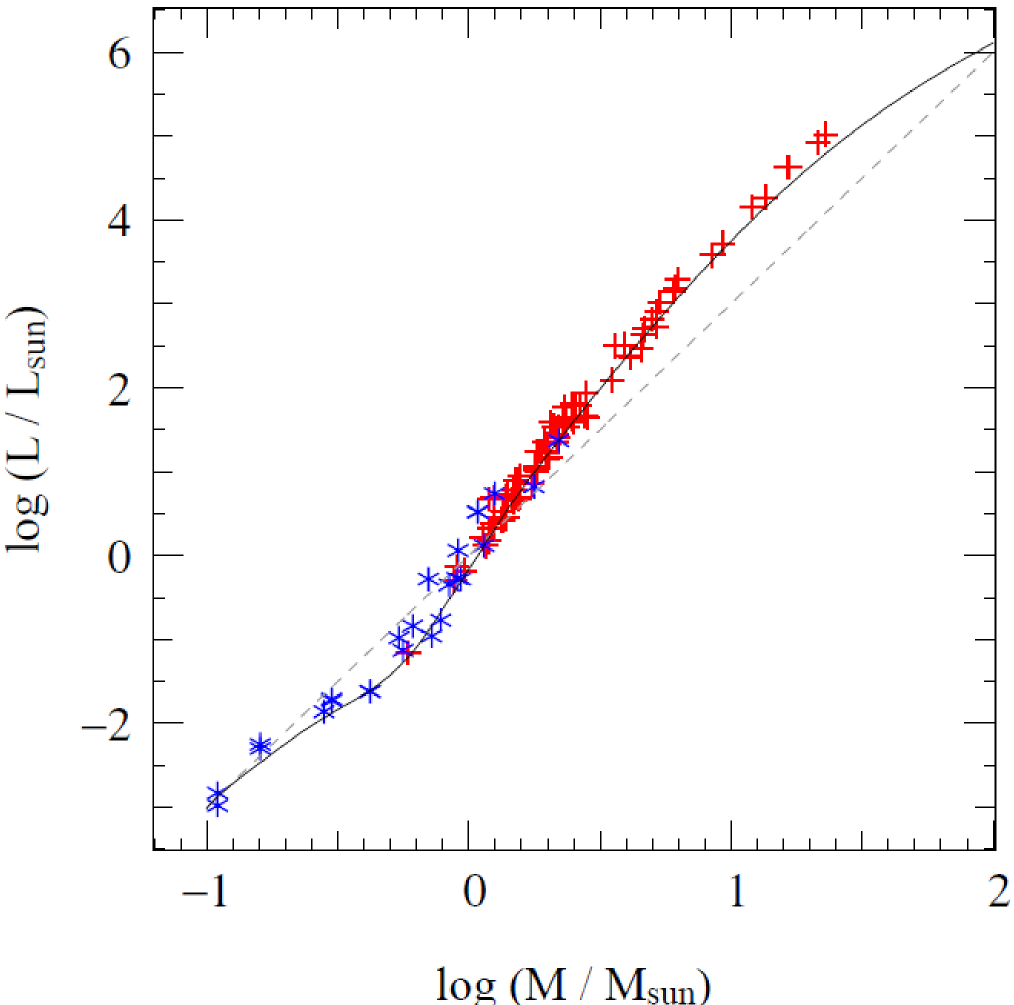
Low-mass stars

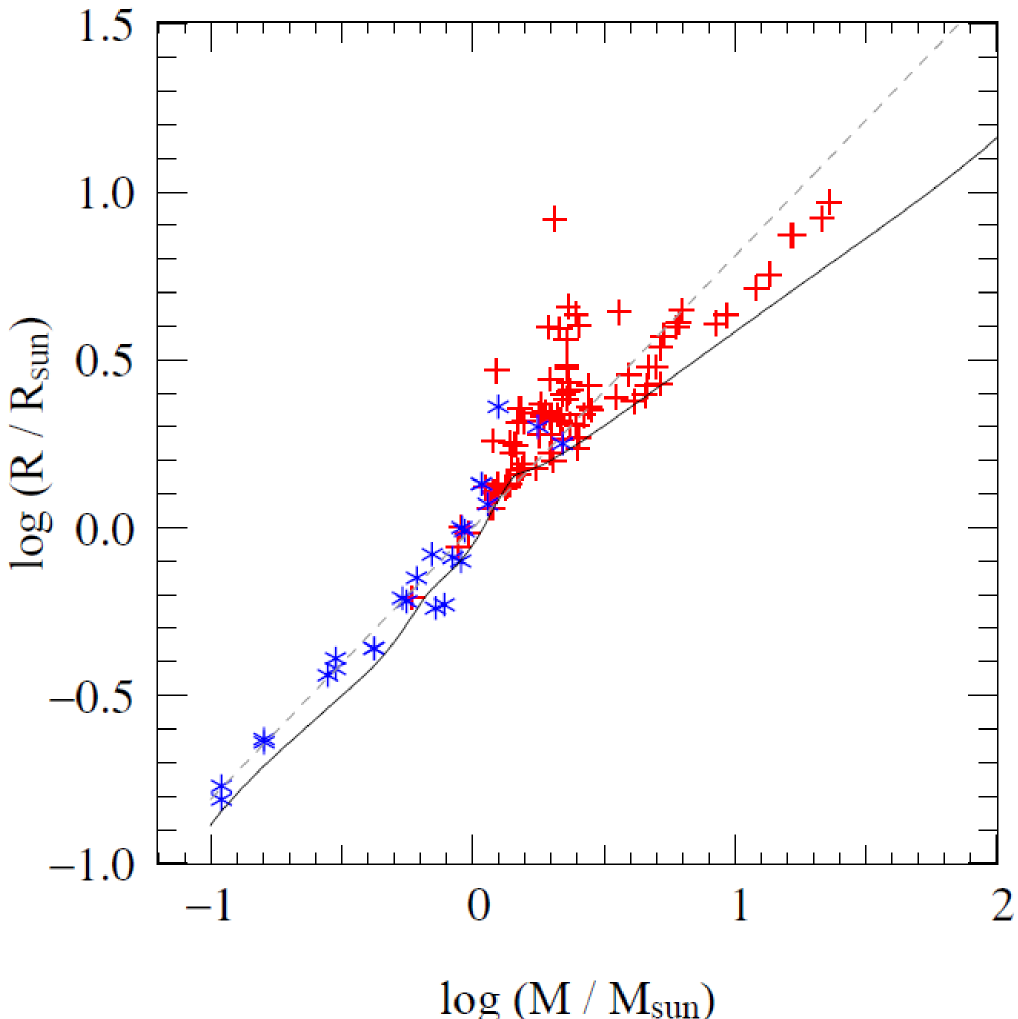
$$L \propto \frac{\beta^4 \mu^4 M^3}{\kappa}$$

High-mass stars

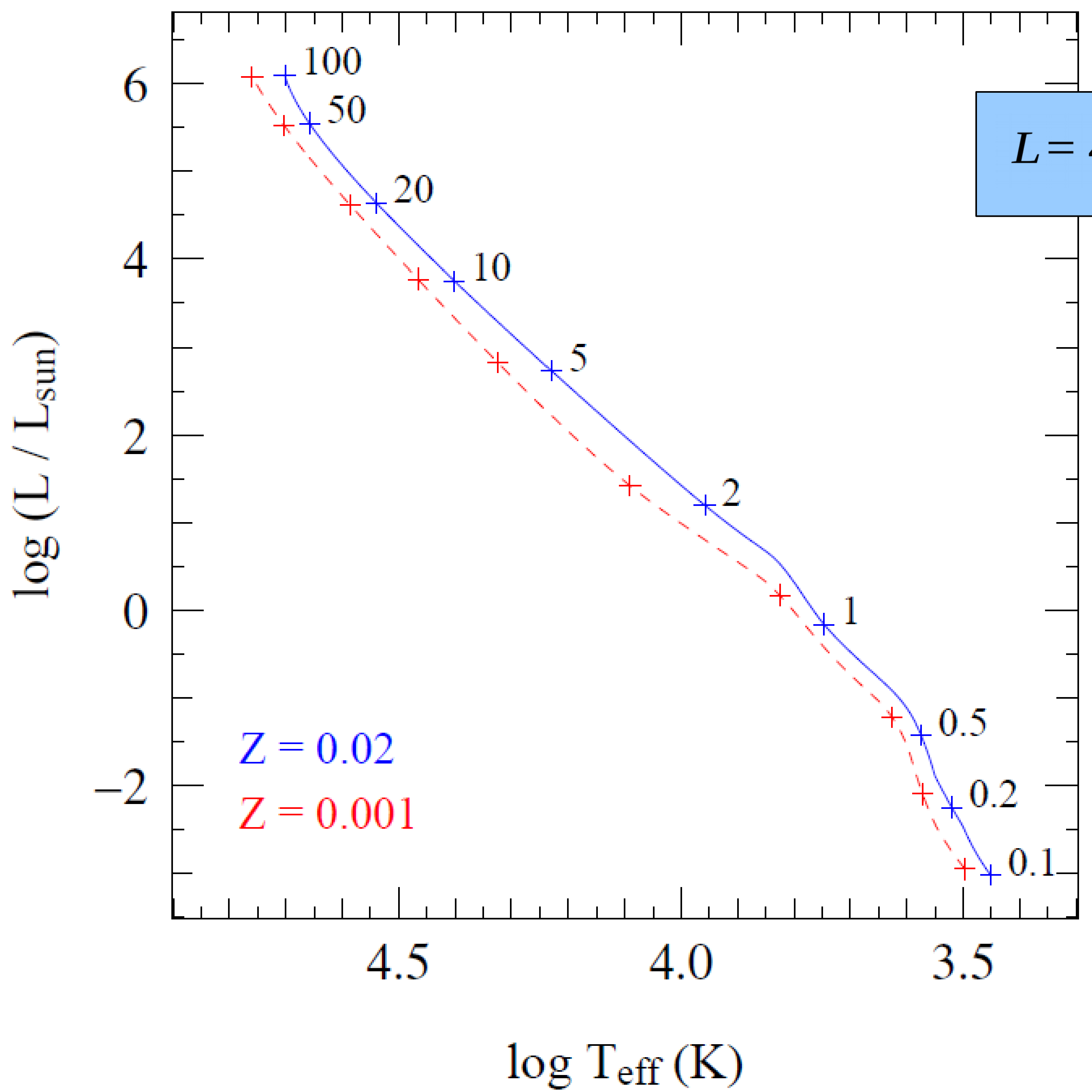
$$L \propto \frac{\mu^4 M}{\kappa}$$

$$R \propto \mu^{\frac{\nu-4}{\nu+3}} M^{\frac{\nu-1}{\nu+3}}.$$



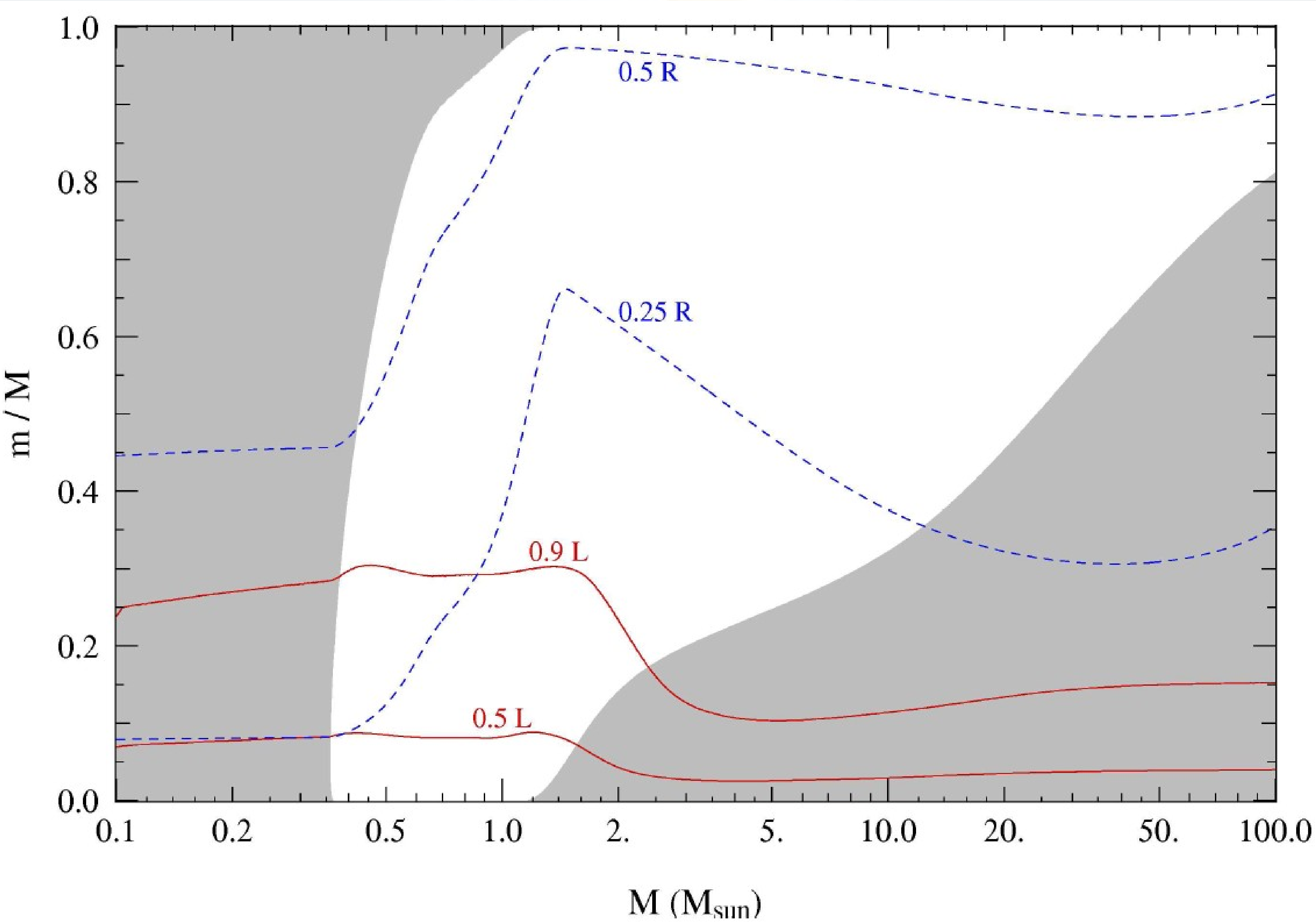


ZAMS: L-Teff (M)

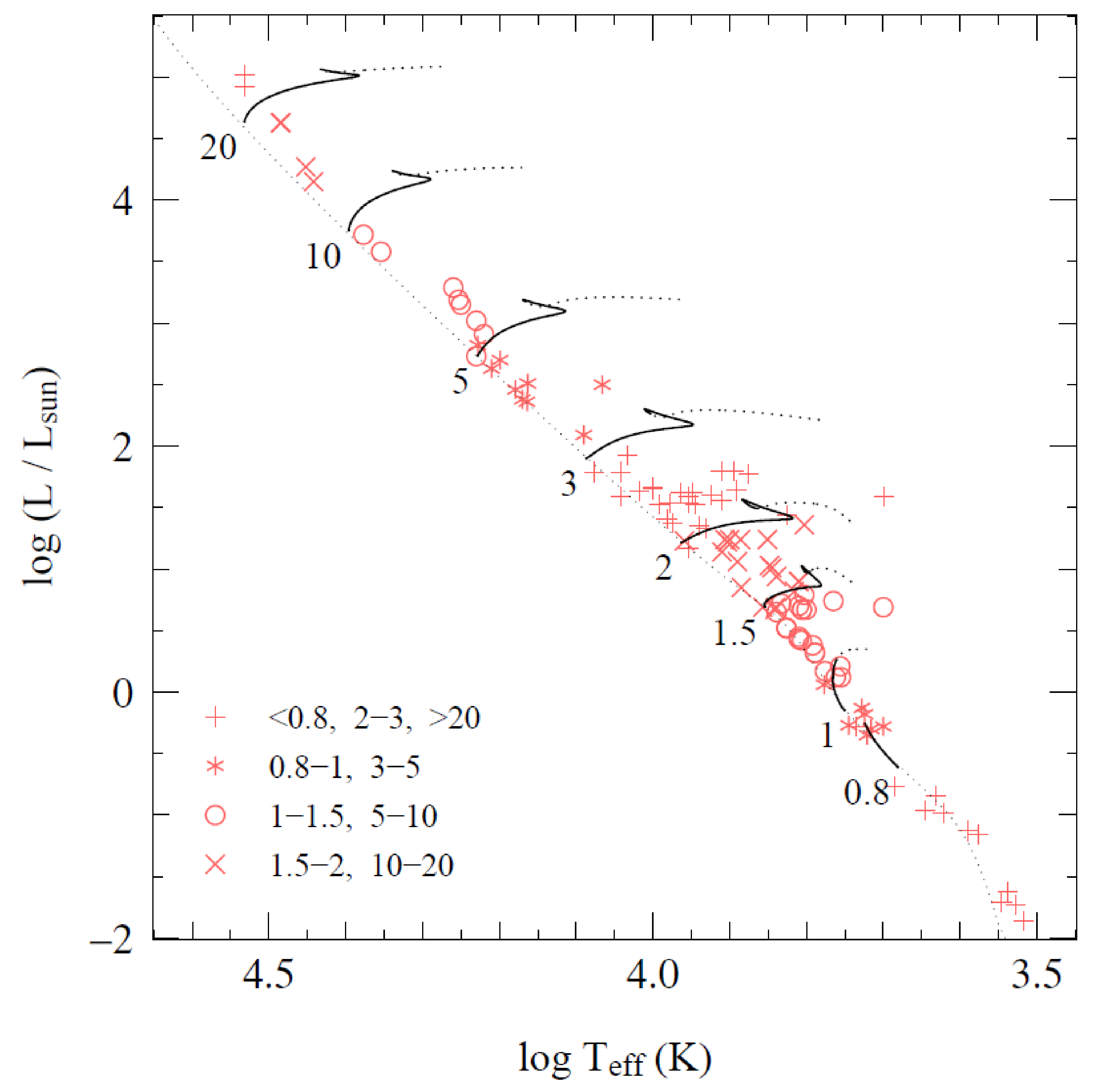


$$L = 4\pi R^2 \sigma T_{eff}^4$$

Convective Regions on ZAMS for Different Masses



ZAMS → TAMS (termination age MS)



Evolution of Composition Inside Stars

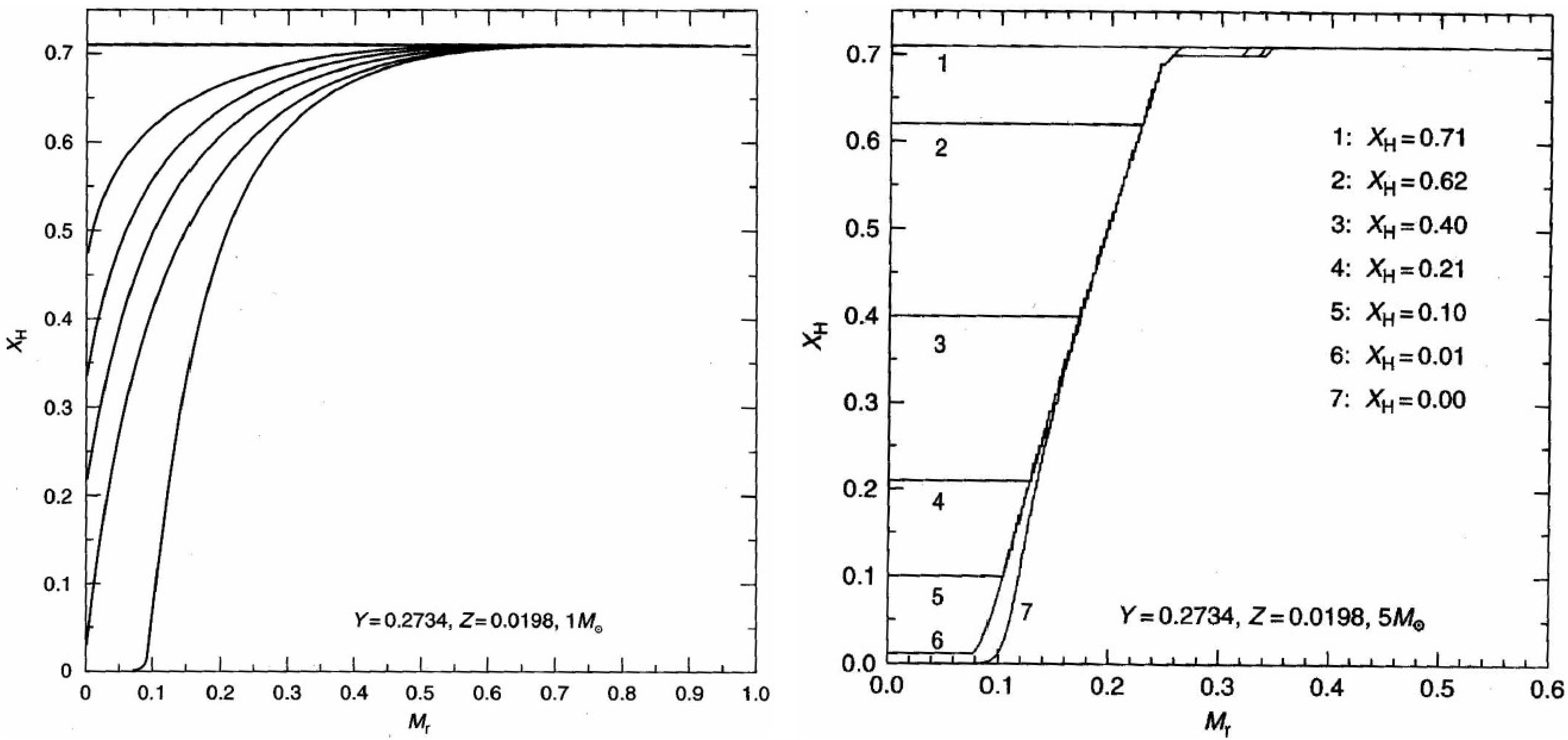
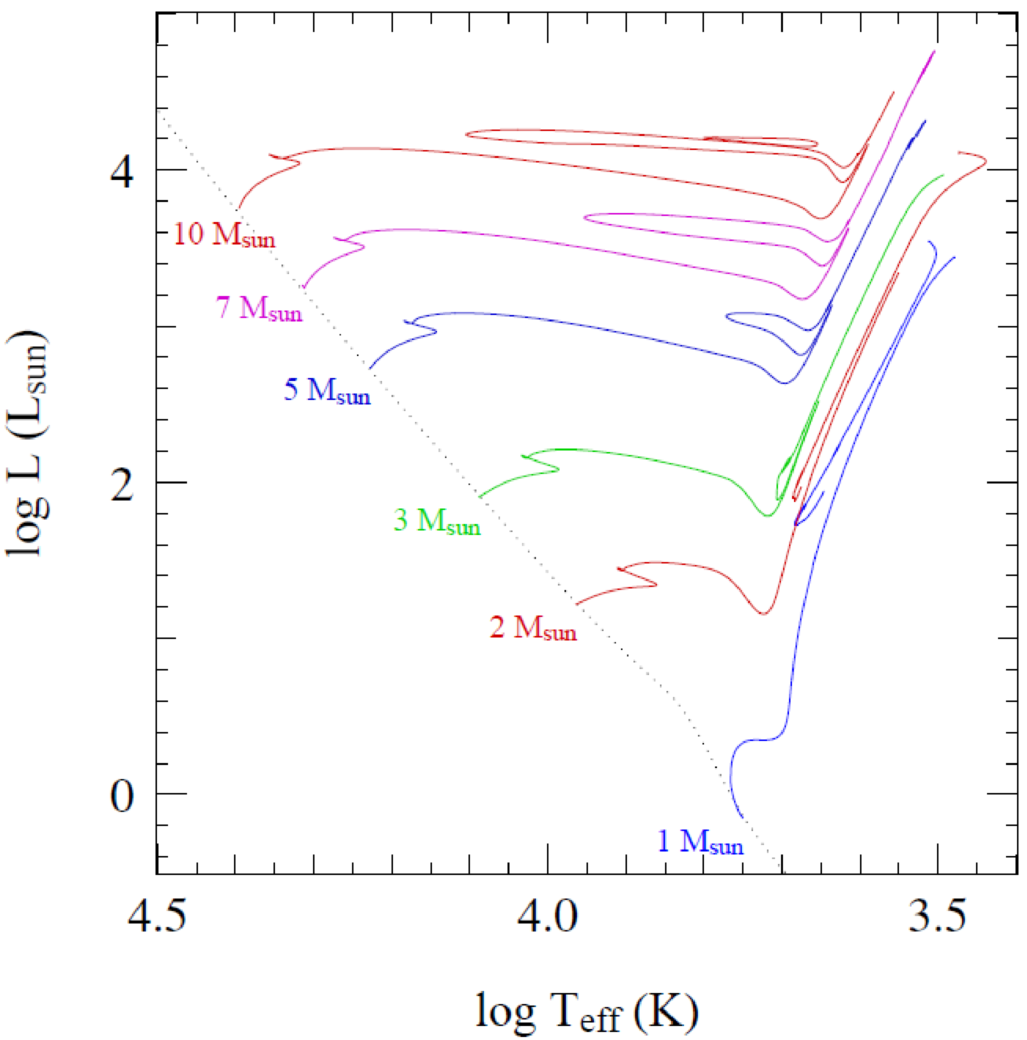
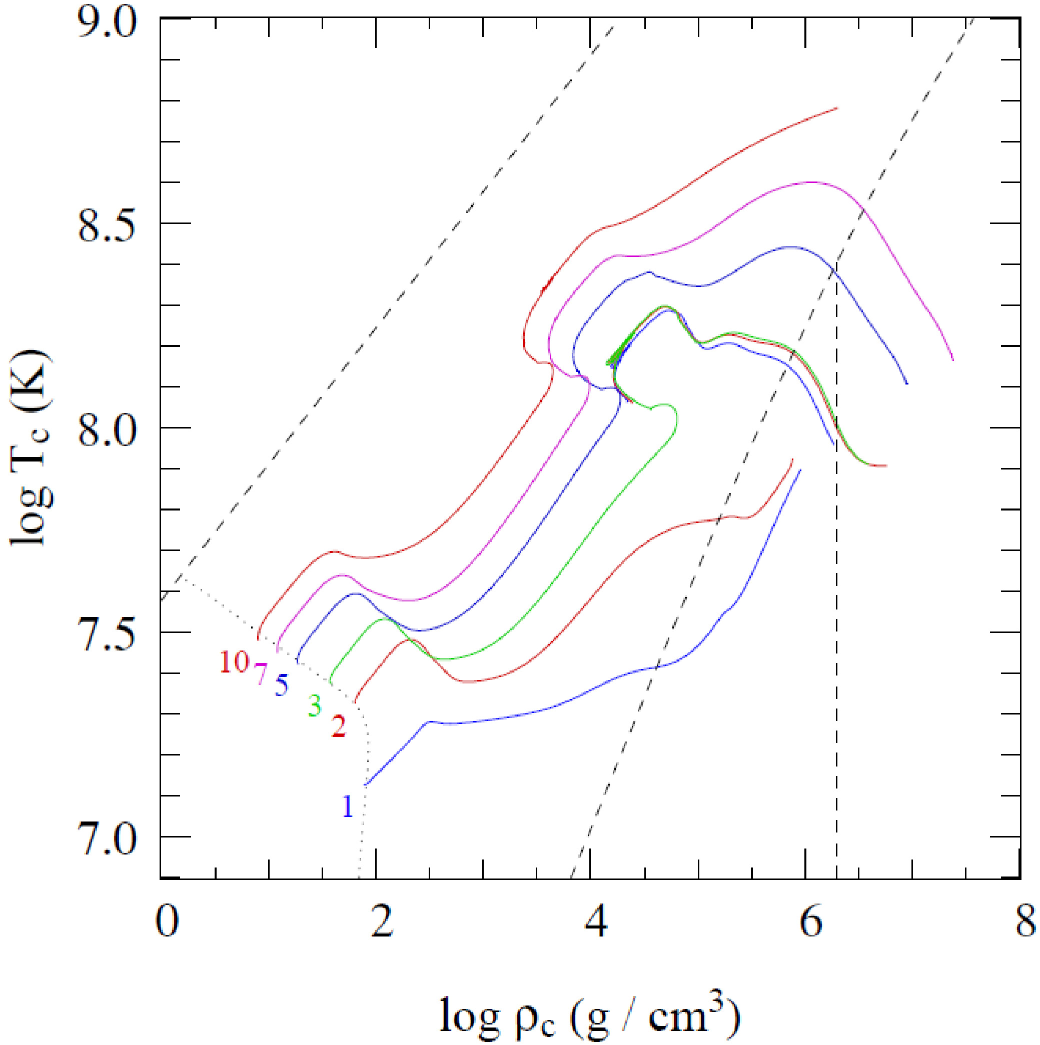


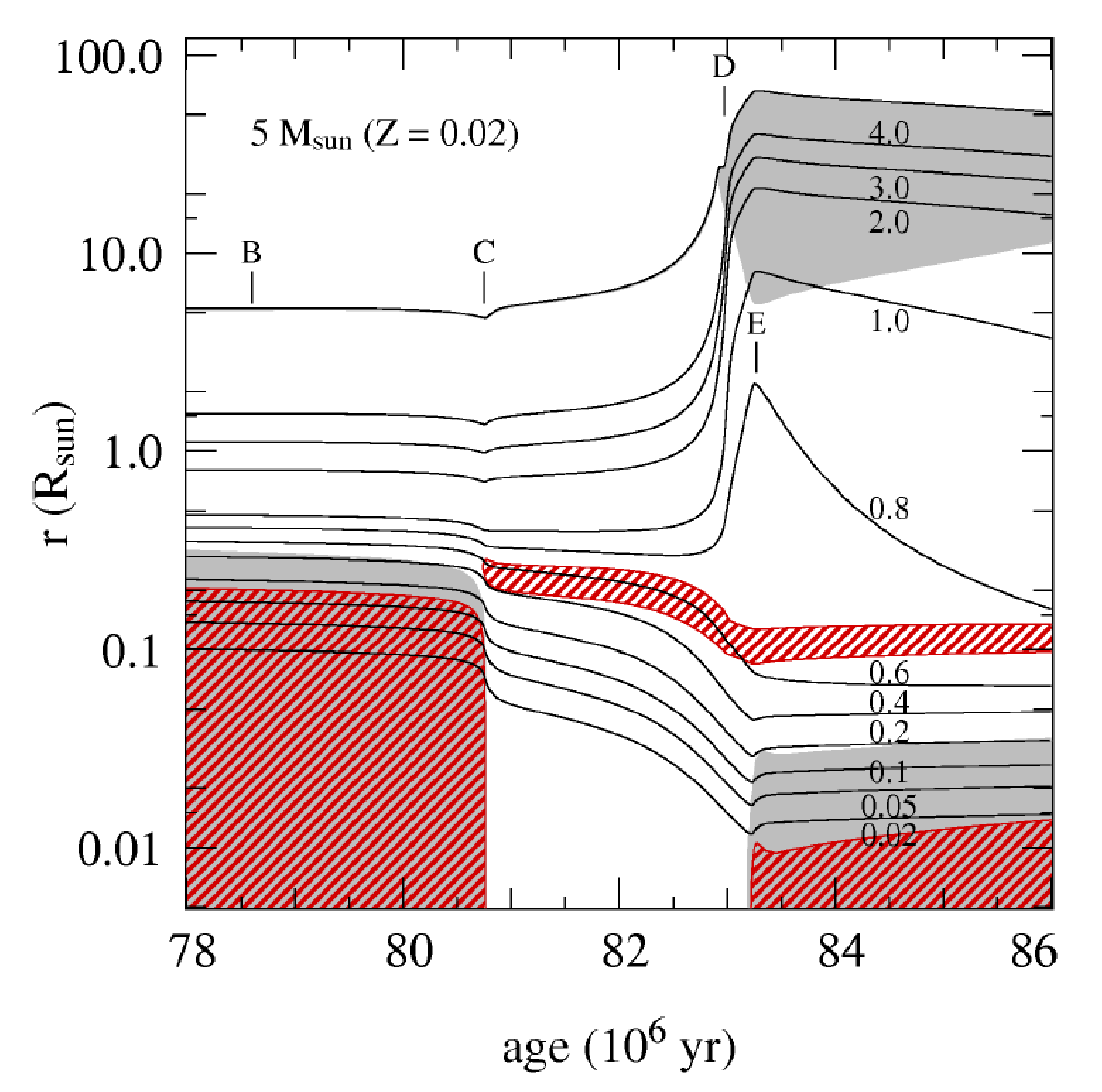
Figure 8.10. Hydrogen abundance profiles at different stages of evolution for a 1 $M_\odot$ star (left panel) and a 5 $M_\odot$ star (right panel) at quasi-solar composition. Figures reproduced from SALARIS & CASSISI.

Post-MS Evolution (He-burning)



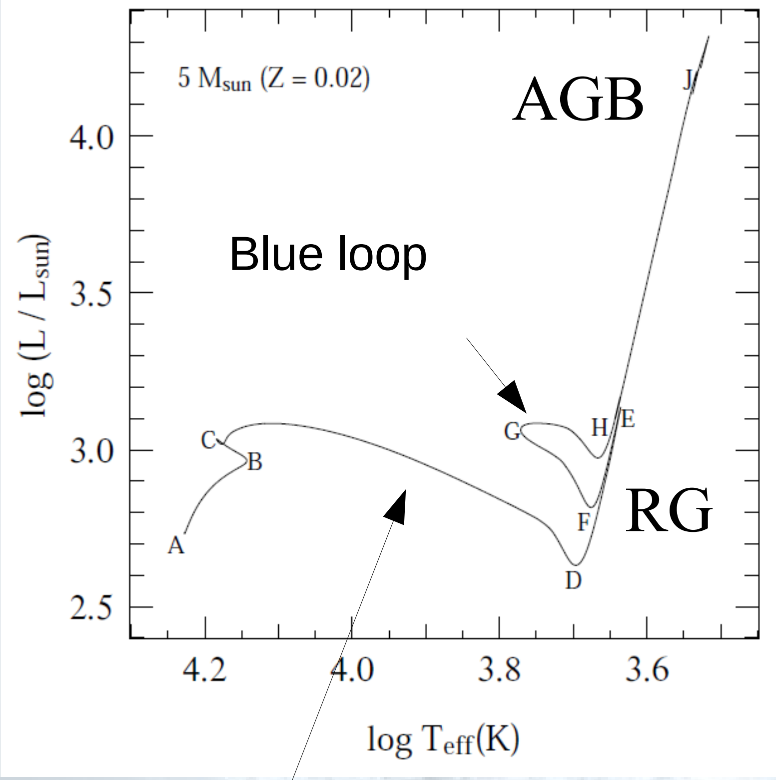


Post-MS Evolution: Mirror Effect

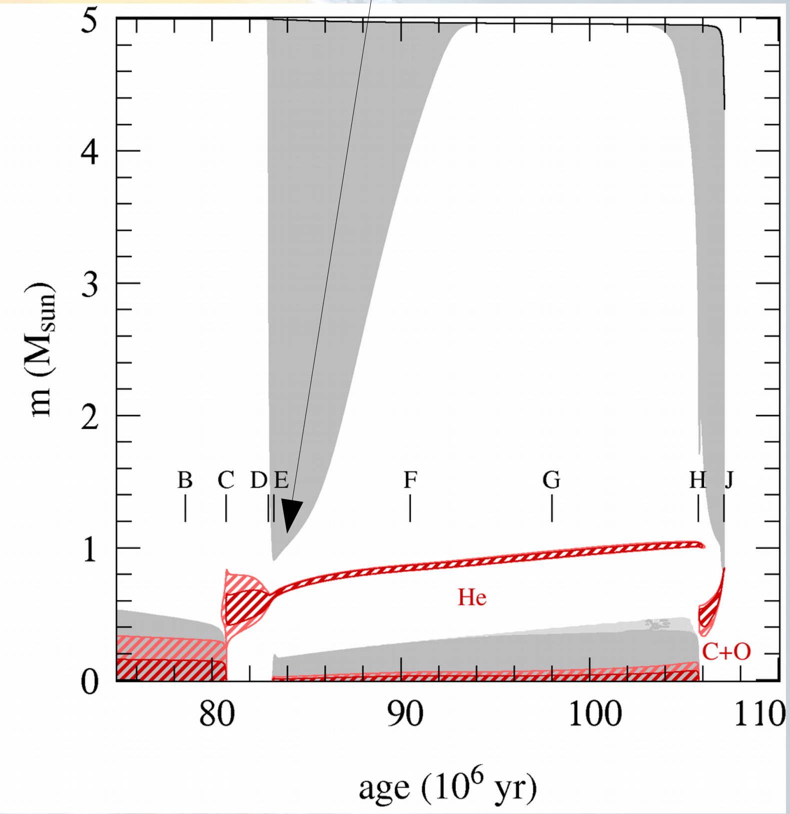


Intermediate Mass Stars

5 M_o star: Evolution through H- and He-burning

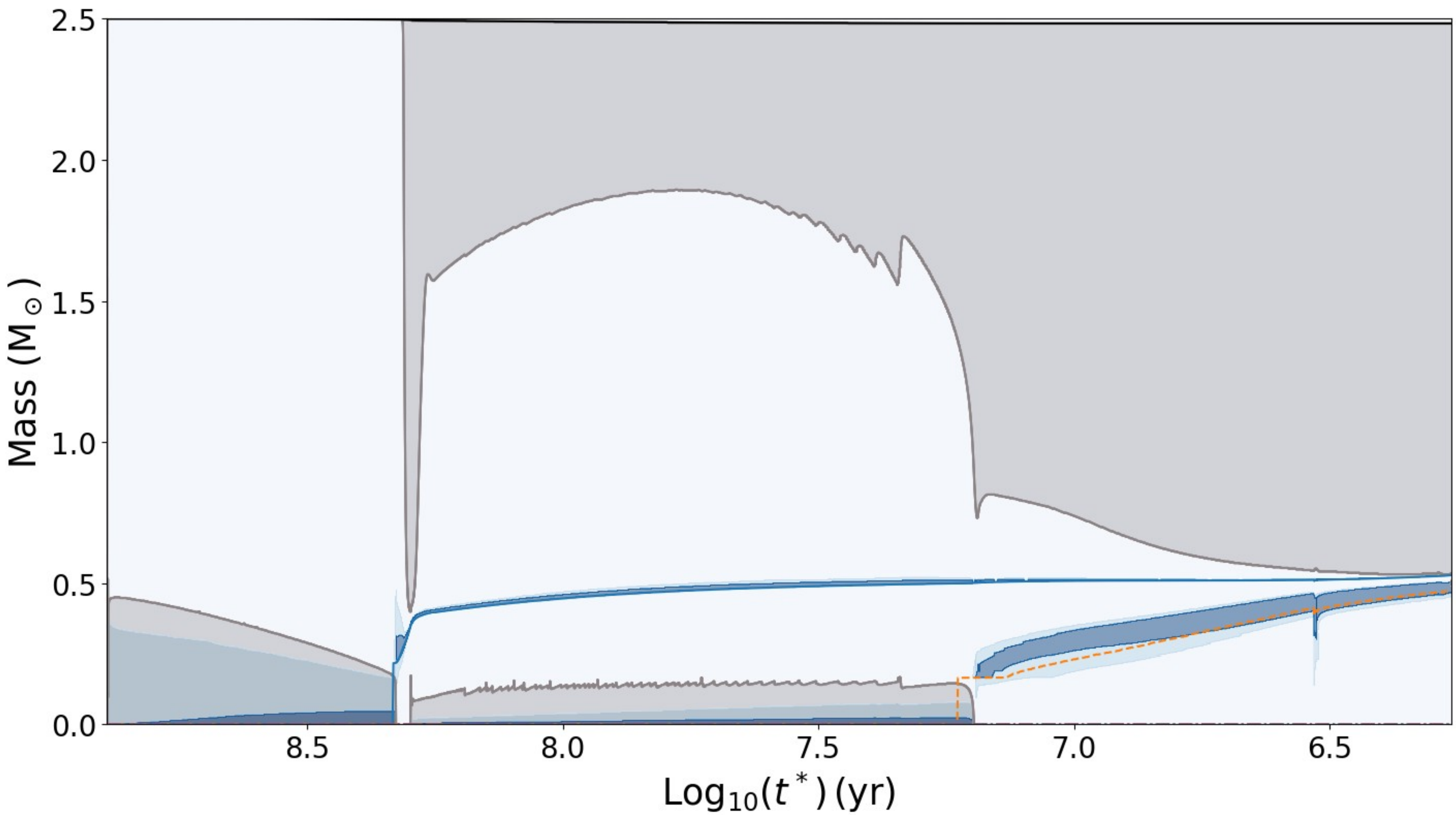


1st dredge-up



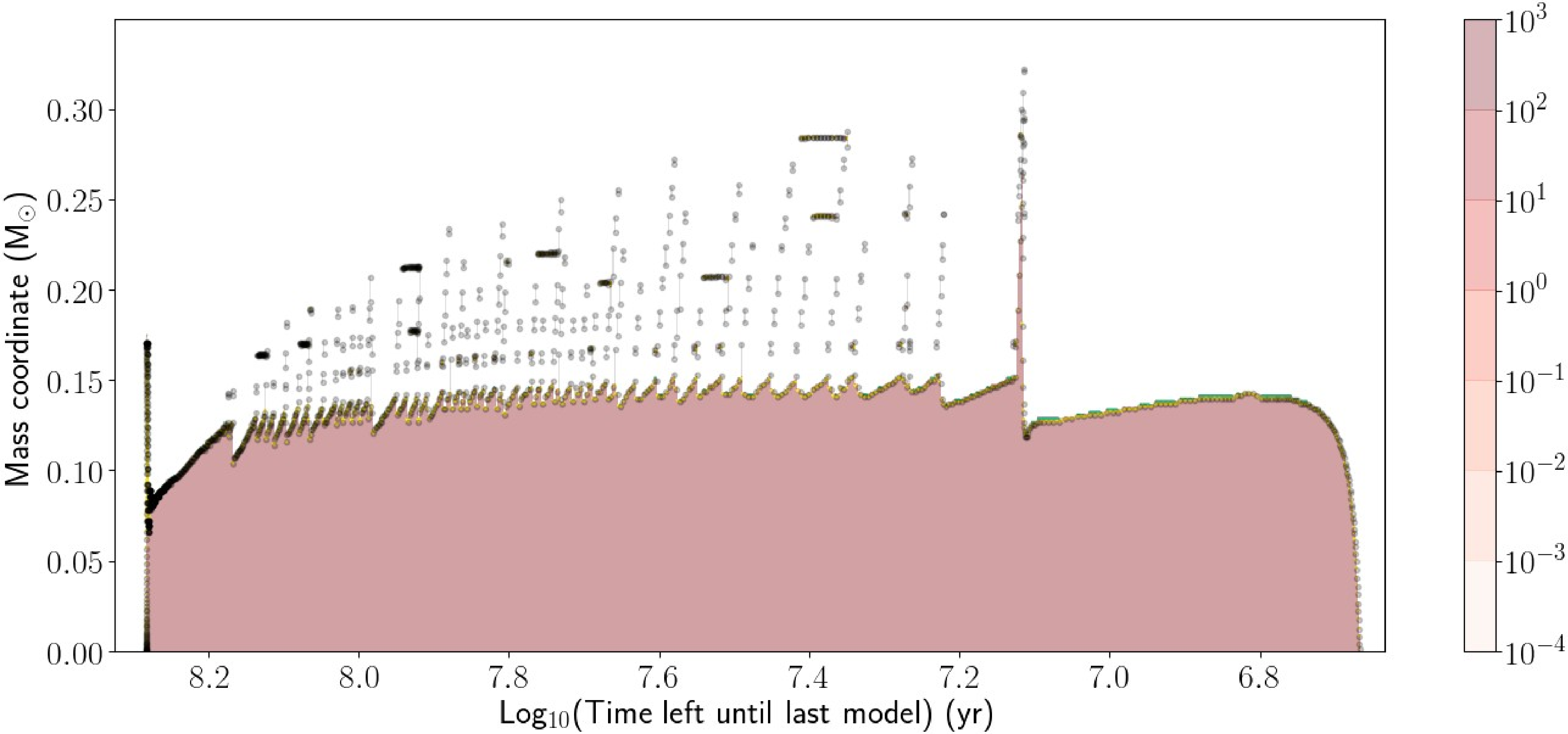
Hertzsprung gap

2.5 Mo MESA model



Den Hartogh et al (in prep)

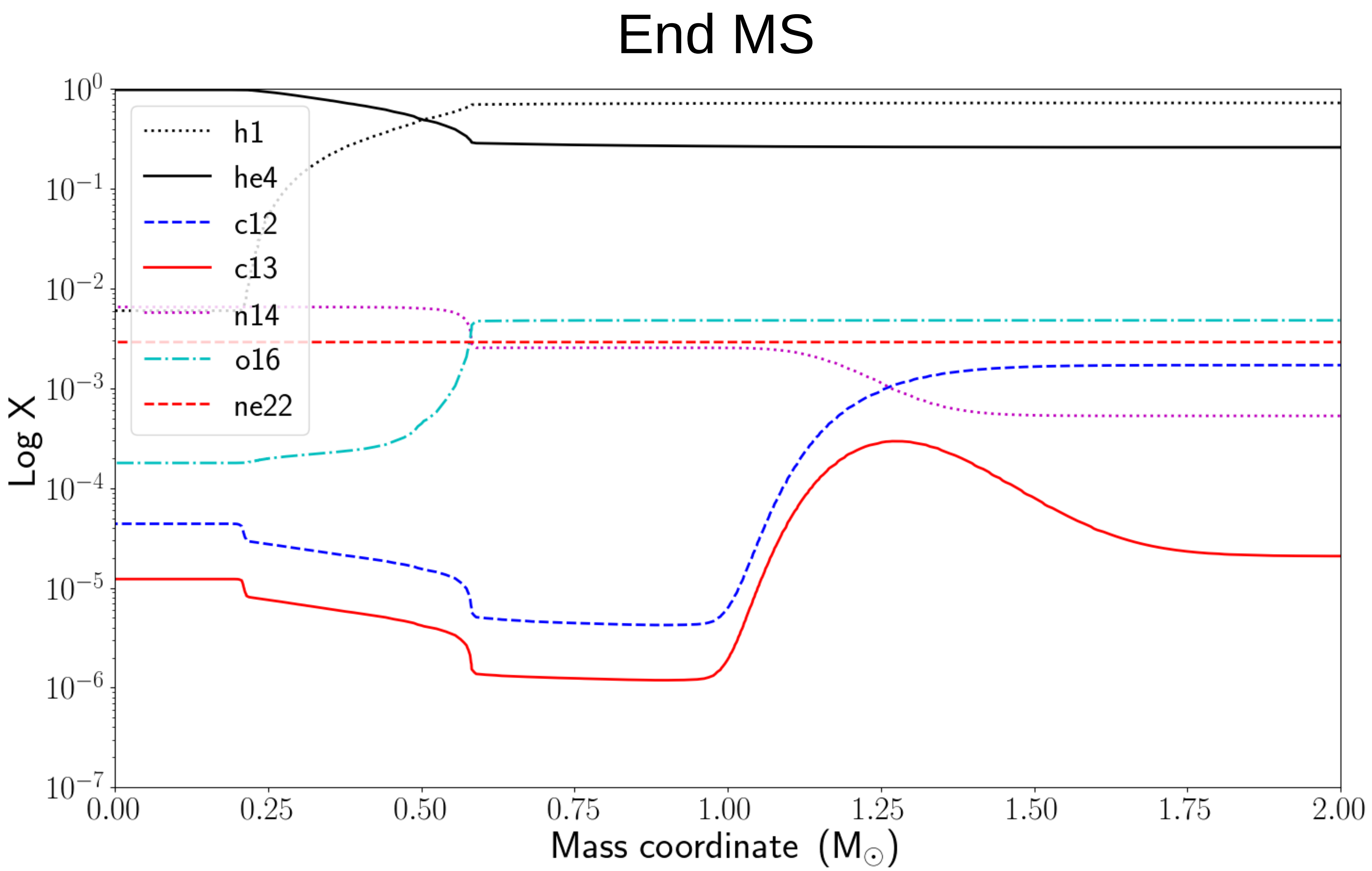
2.5 Mo MESA model



Log$_{10}$(t^*) (yr)

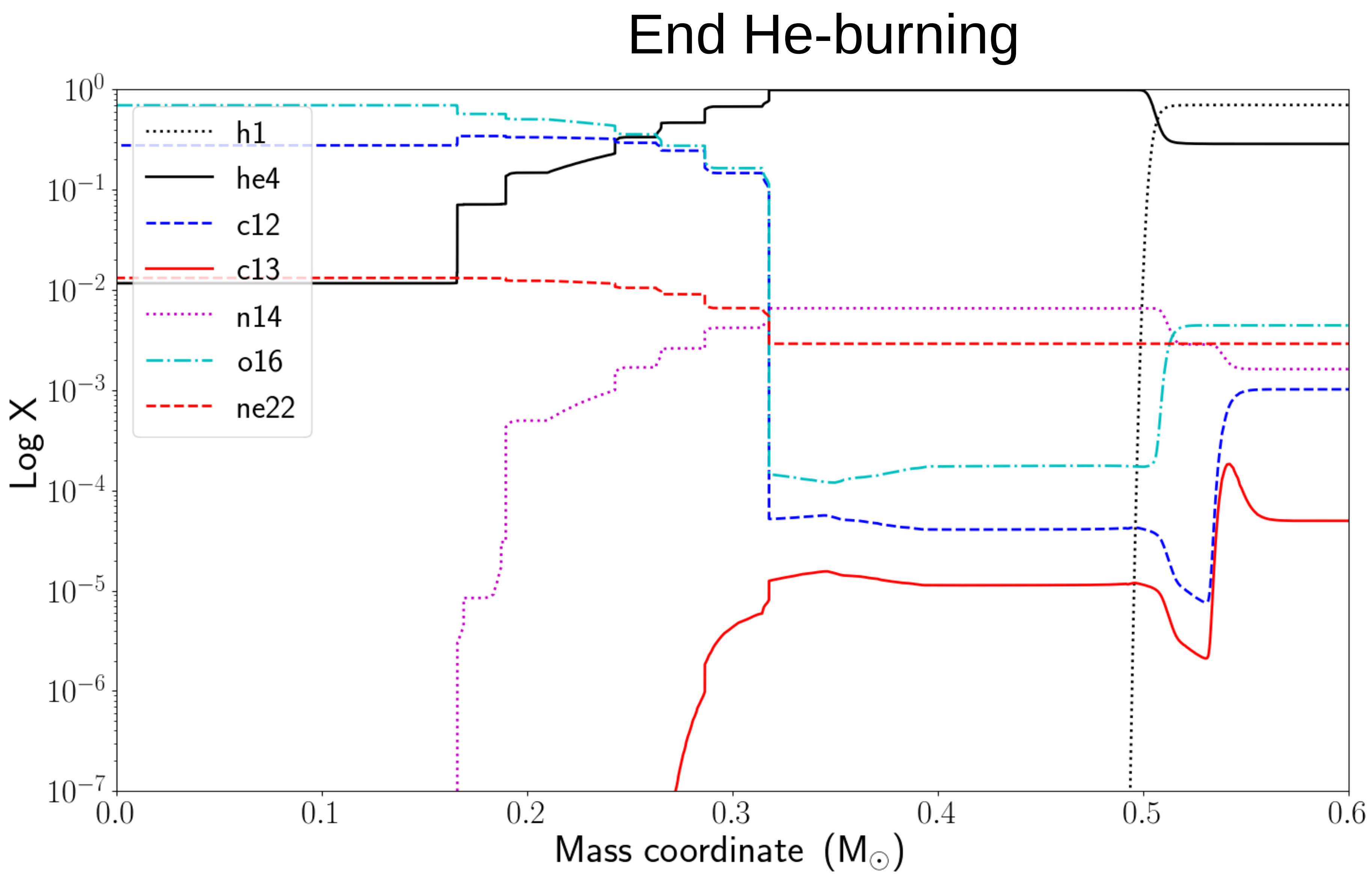
Den Hartogh et al (in prep)

2.5 Mo: Abundance Evolution



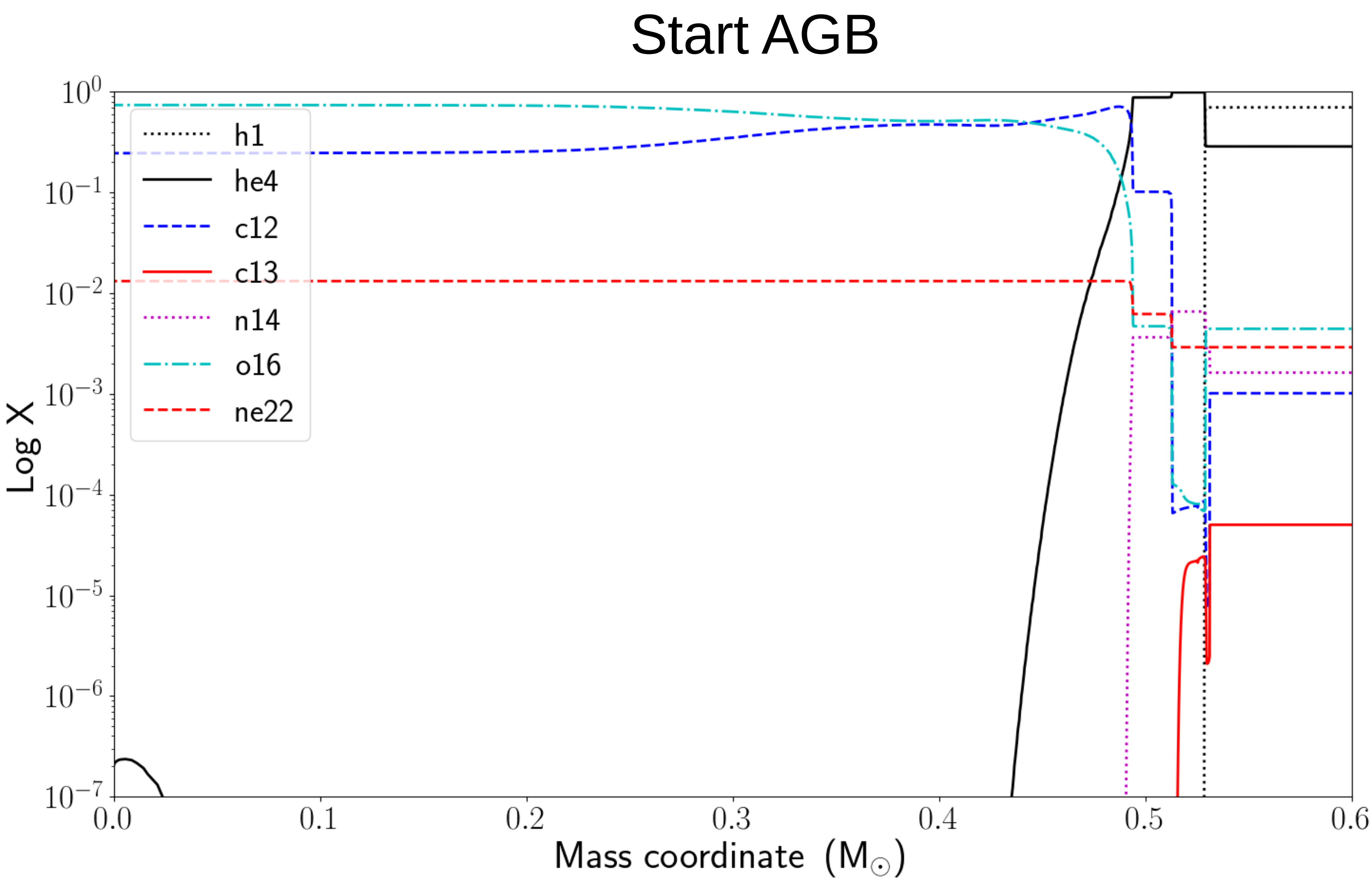
Den Hartogh et al (in prep)

2.5 Mo: Abundance Evolution



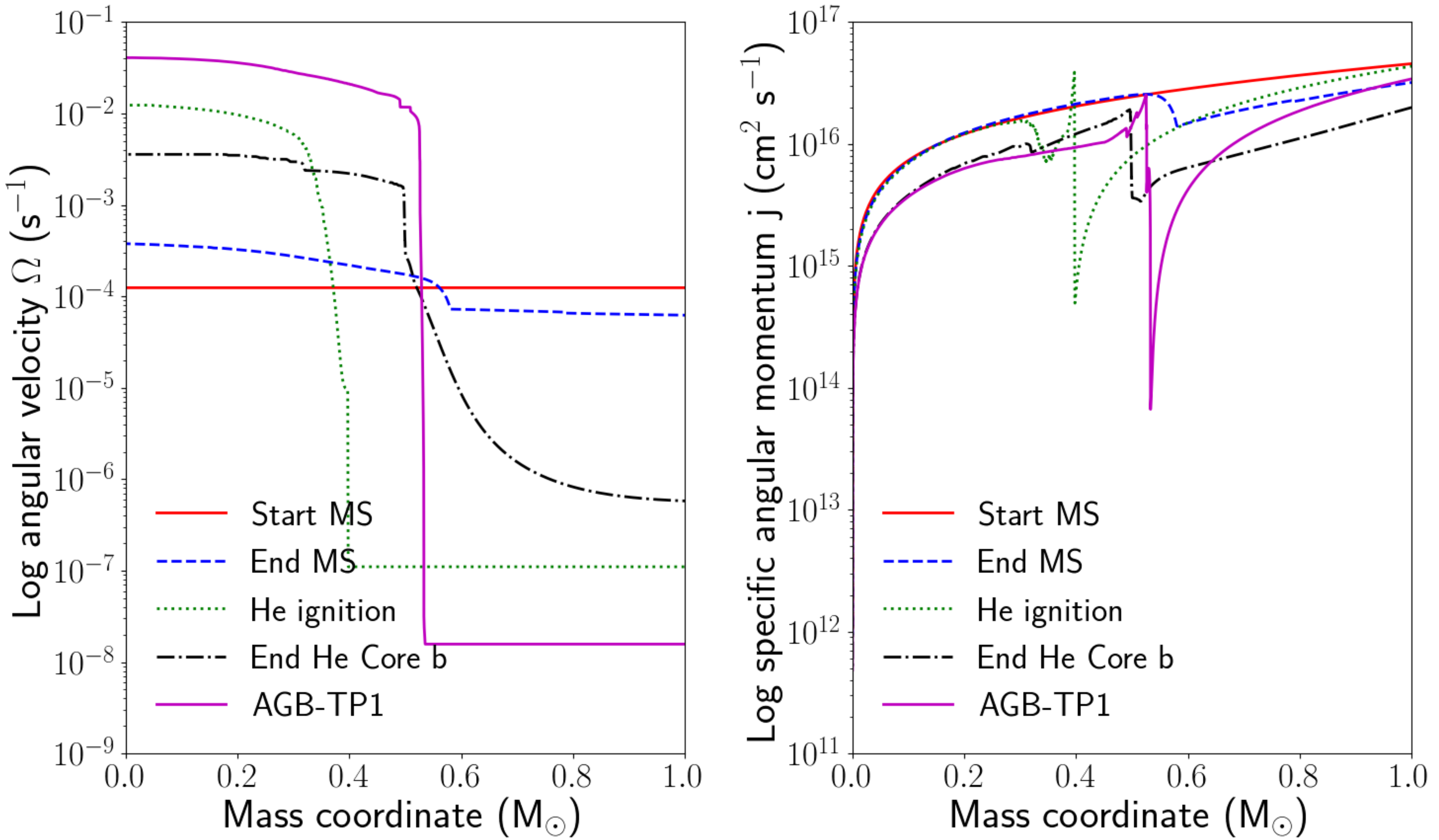
Den Hartogh et al (in prep)

2.5 Mo: Abundance Evolution



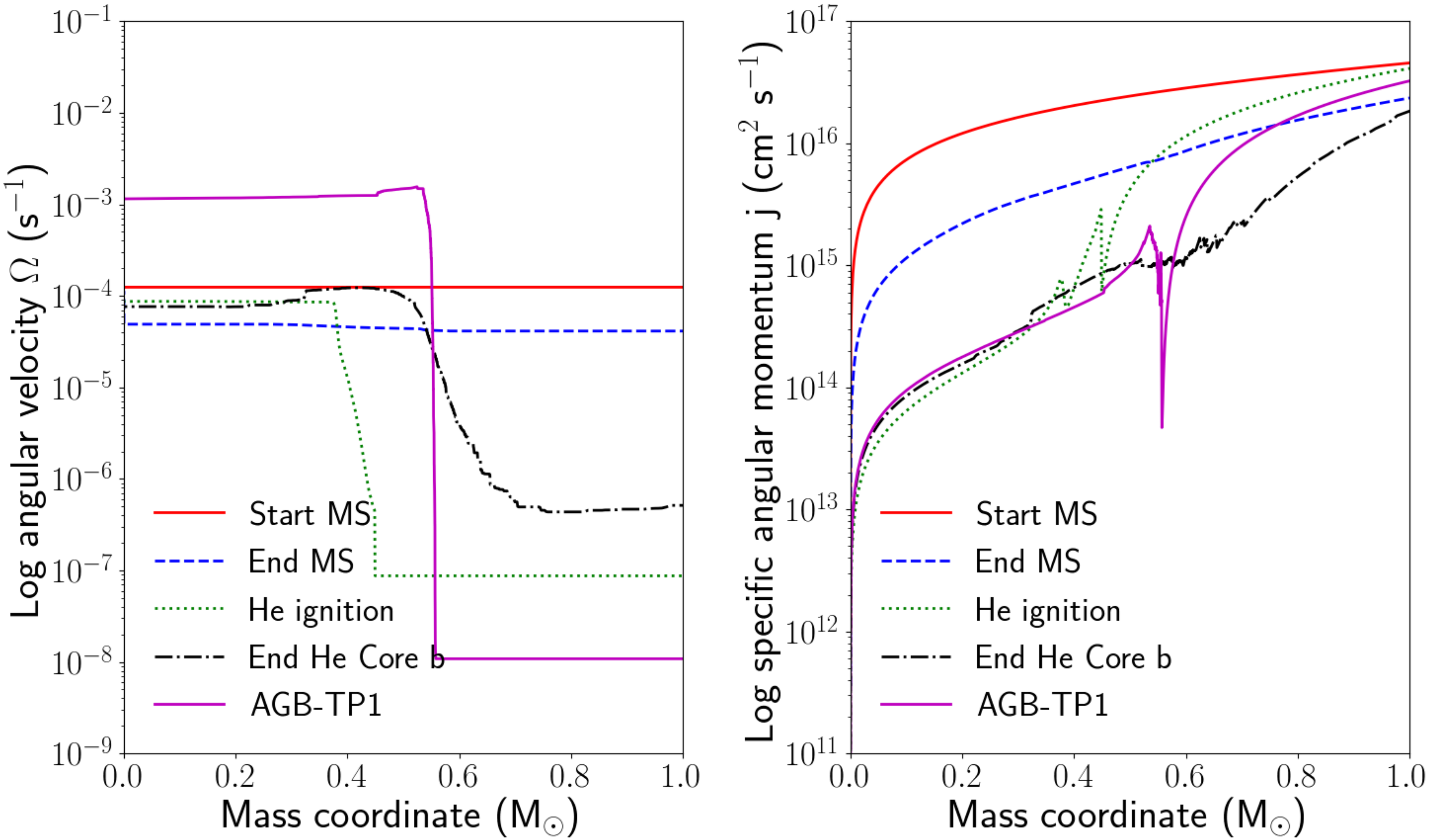
Den Hartogh et al (in prep)

2.5 Mo: Rotation Evolution (no B-fields)



Den Hartogh et al (in prep)

2.5 Mo: Rotation Evolution (with B-fields)



Den Hartogh et al (in prep)

Pulsation Across the HRD

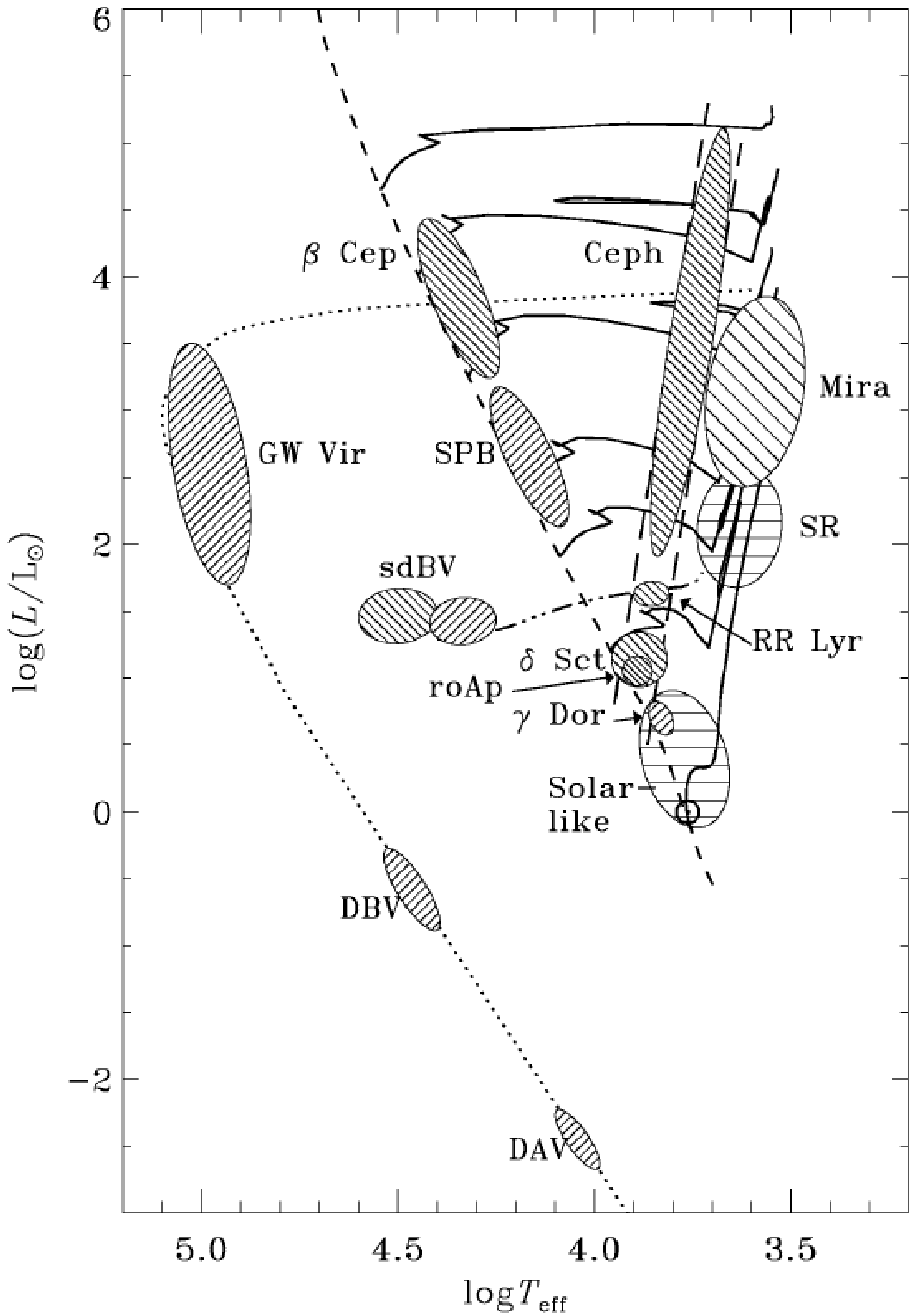
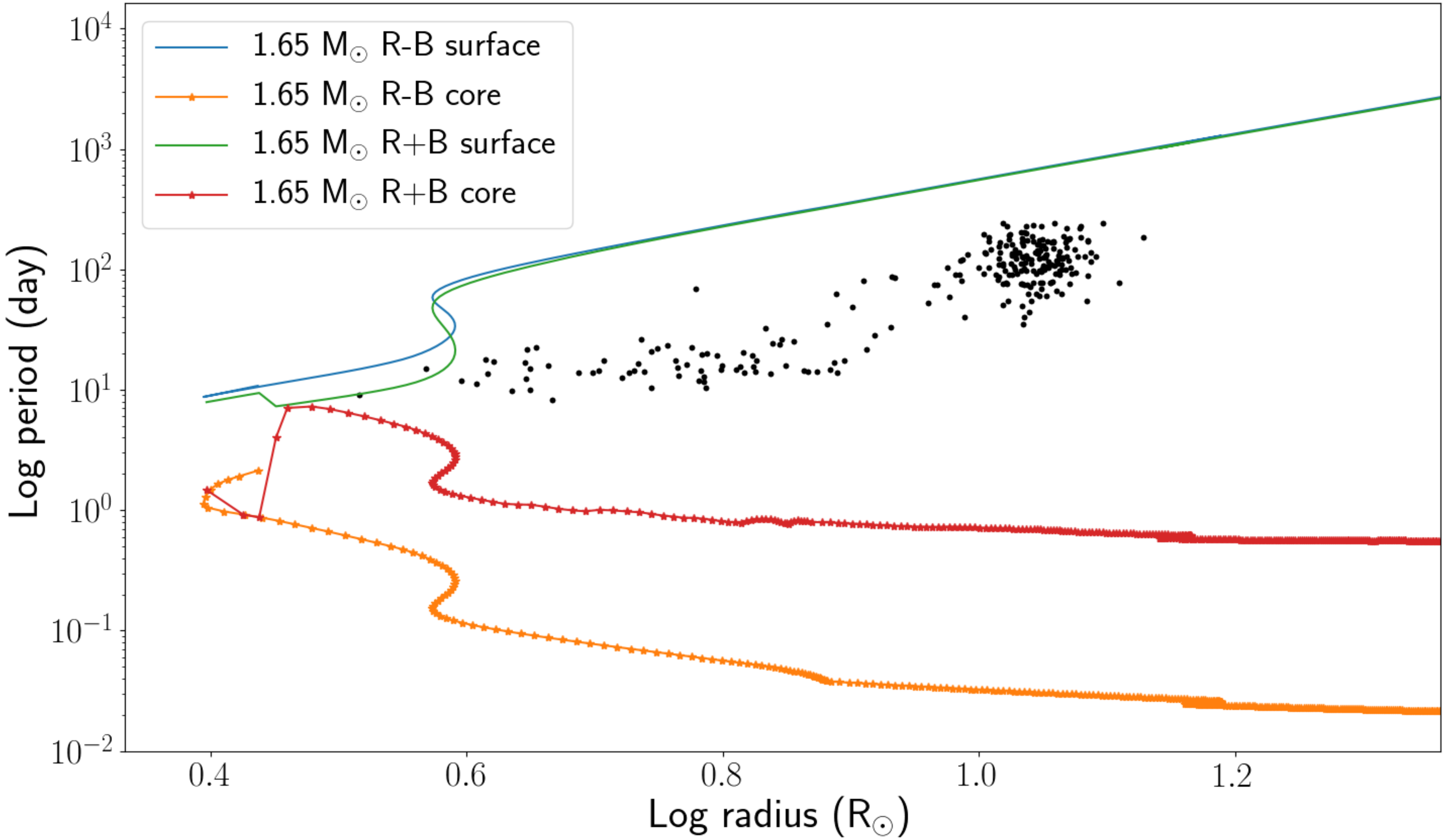


Figure 9.10. Occurrence of various classes of pulsating stars in the H-R diagram, overlaid on stellar evolution tracks (solid lines). Cepheid variables are indicated with 'Ceph', they lie within the pulsational instability strip in the HRD (long-dashed lines). Their equivalents are the RR Lyrae variables among HB stars (the horizontal branch is shown as a dash-dotted line), and the δ Scuti stars (δ Sct) among main-sequence stars. Pulsational instability is also found among luminous red giants (Mira variables), among massive main-sequence stars – β Cep variables and slowly pulsating B (SPB) stars, among extreme HB stars known as subdwarf B stars (sdBV) and among white dwarfs. Figure from Christensen-Dalsgaard (2004).

2.5 Mo: Comparison to Asteroseismology Obs.



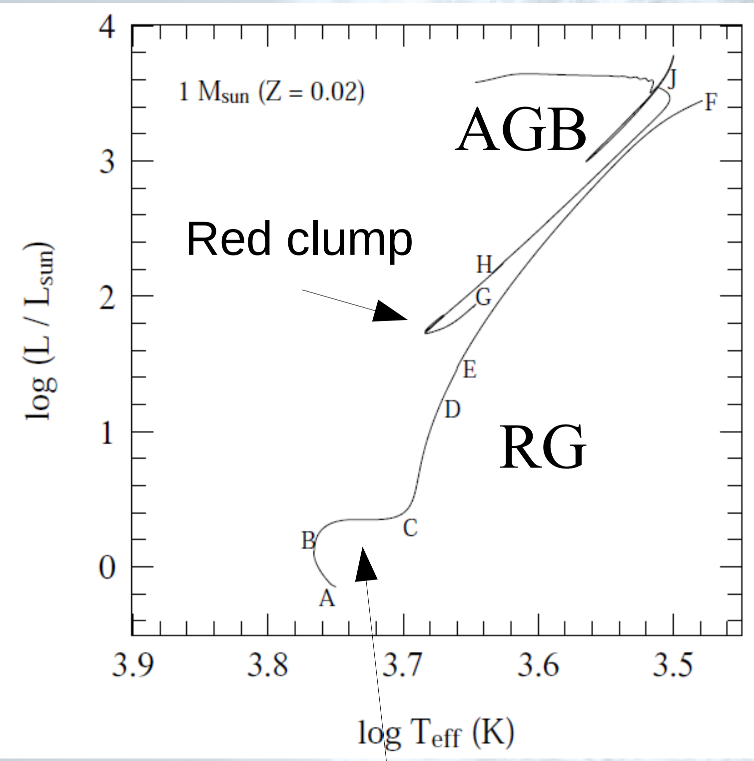
Den Hartogh et al (in prep)

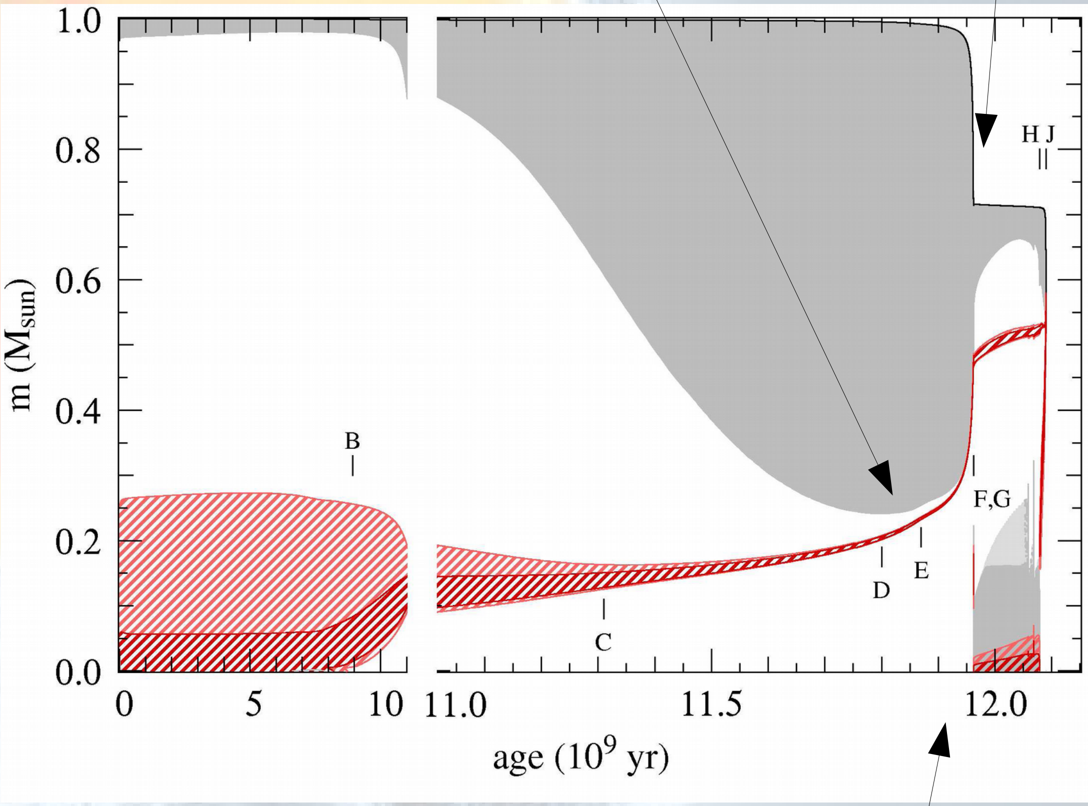
Low-Mass Stars

1 M_o star: Evolution through H- and He-burning

Mass loss

1st dredge-up

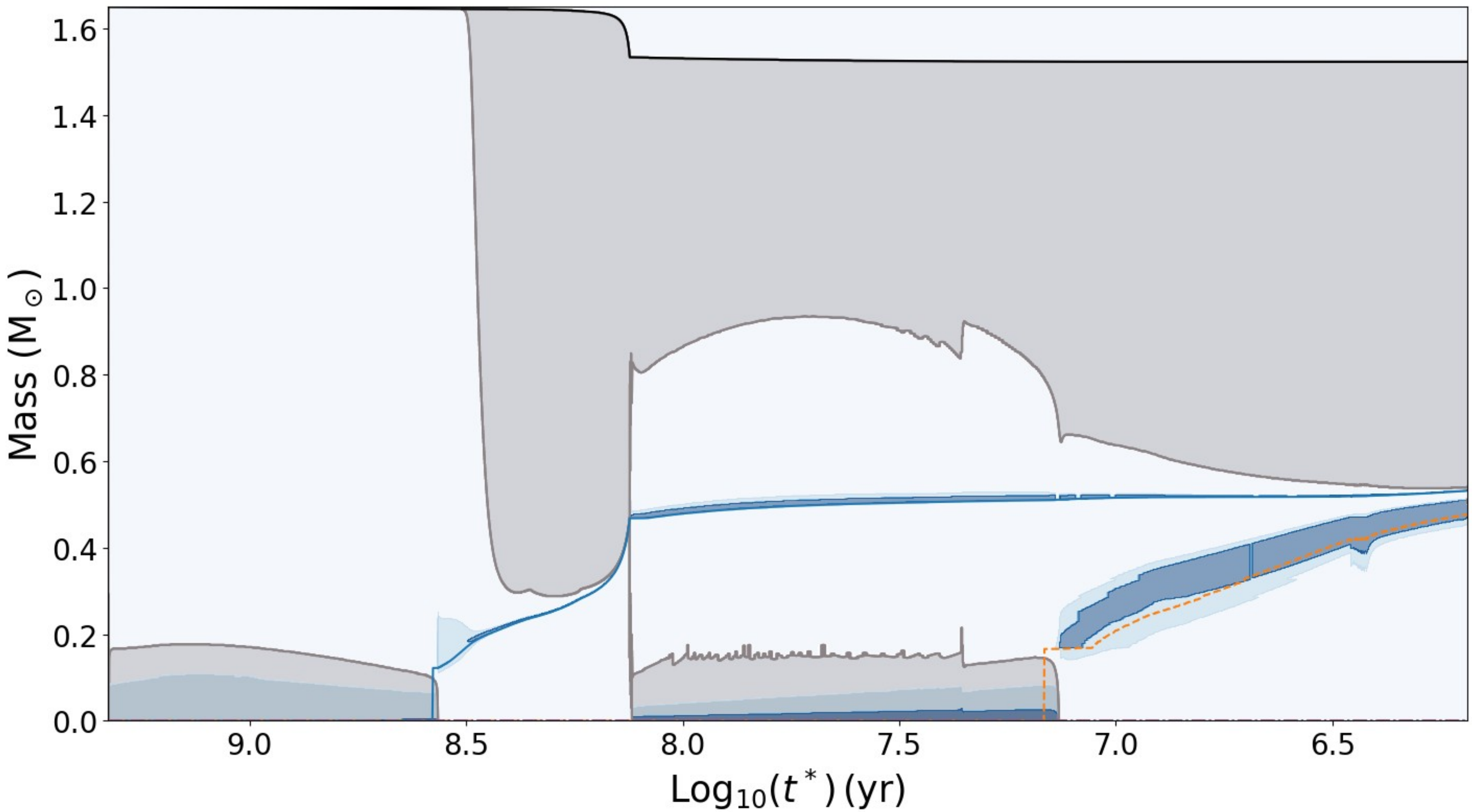




Sub-giant branch
(no Hertzsprung gap)

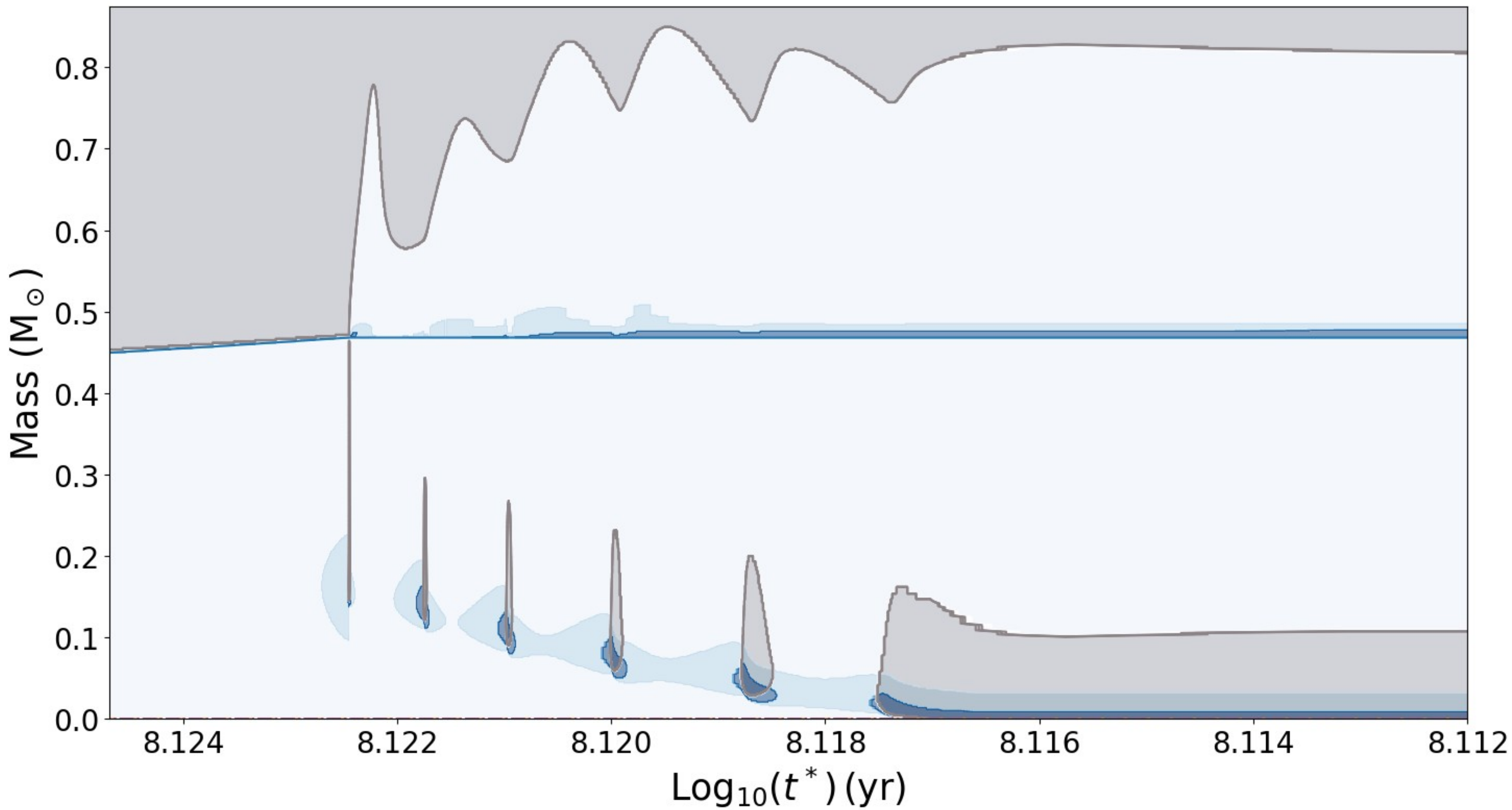
He-flash at point F → G

1.65 Mo MESA model



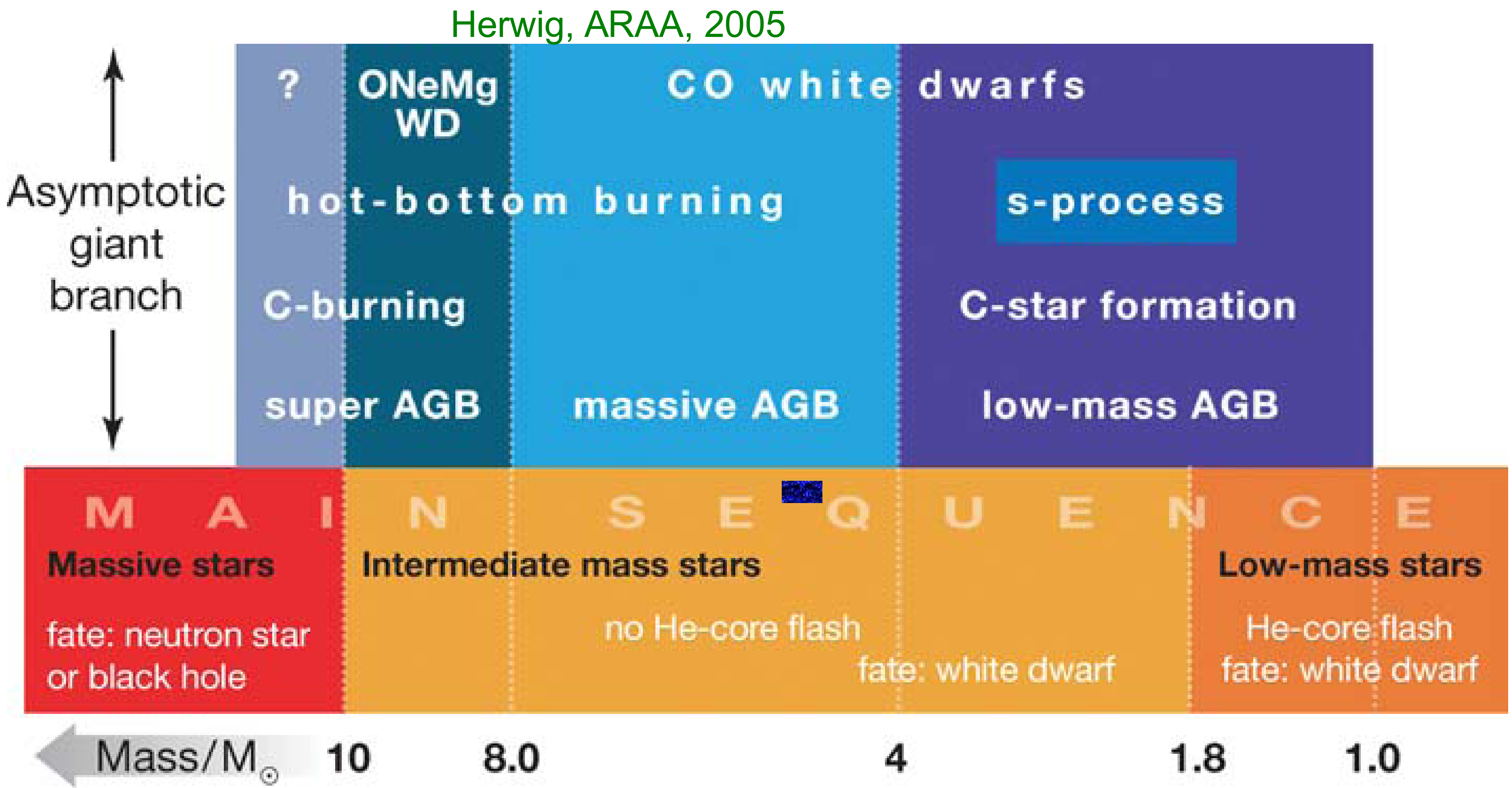
Den Hartogh et al (in prep)

1.65 Mo MESA model



Den Hartogh et al (in prep)

Intermediate & Low-Mass Stars: Late Phases



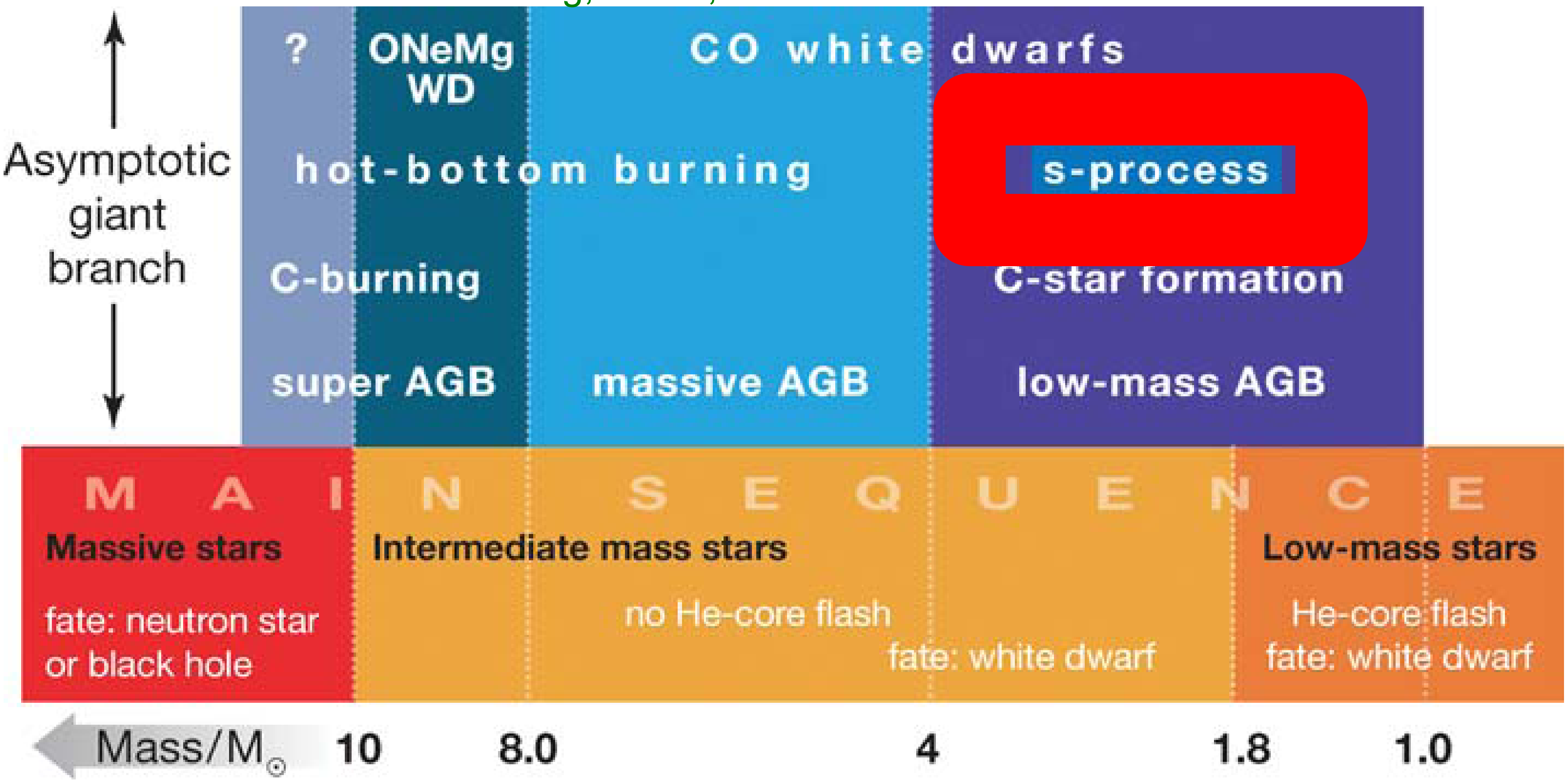
Intermediate-mass stars: 1.8 - 9 M_o do not ignite C-burning in centre

(C-flash for SAGB stars, see later)

Low-mass stars: 0.5-1.8M_o do not ignite He-burning in centre (He-flash)

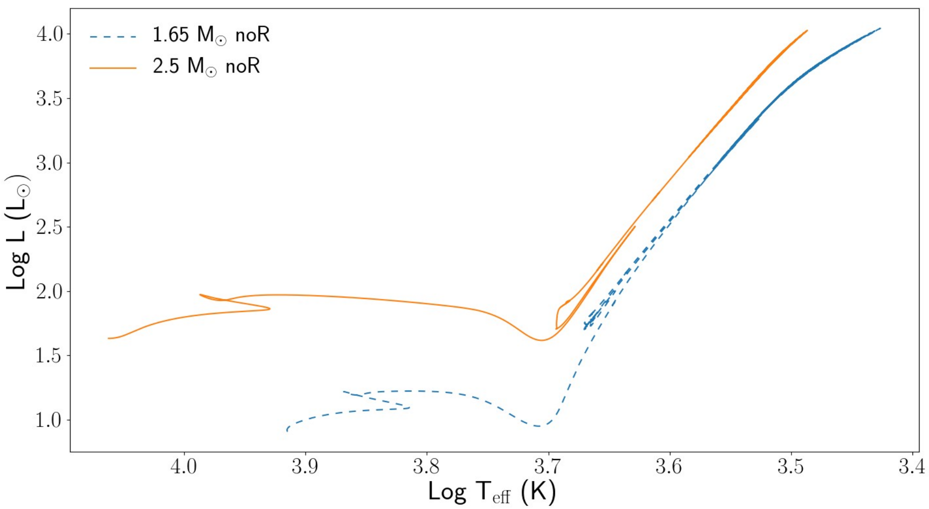
Intermediate & Low-Mass Stars

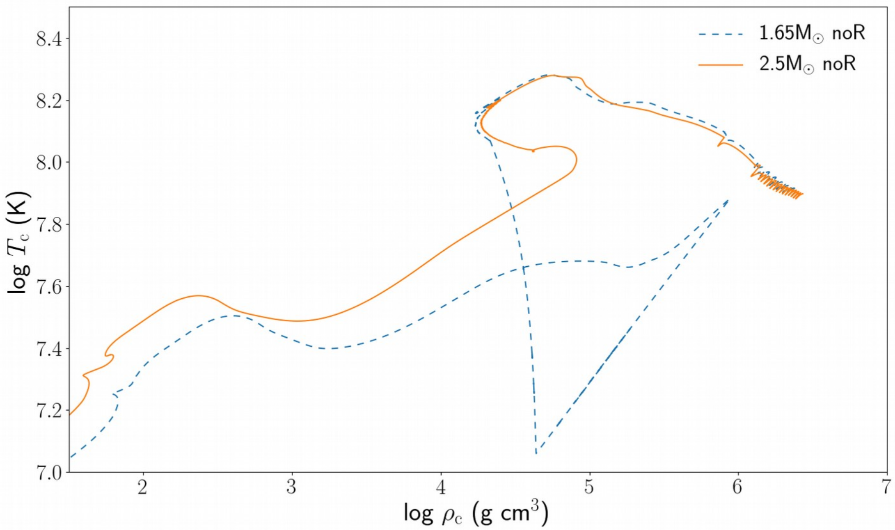
Herwig, ARAA, 2005

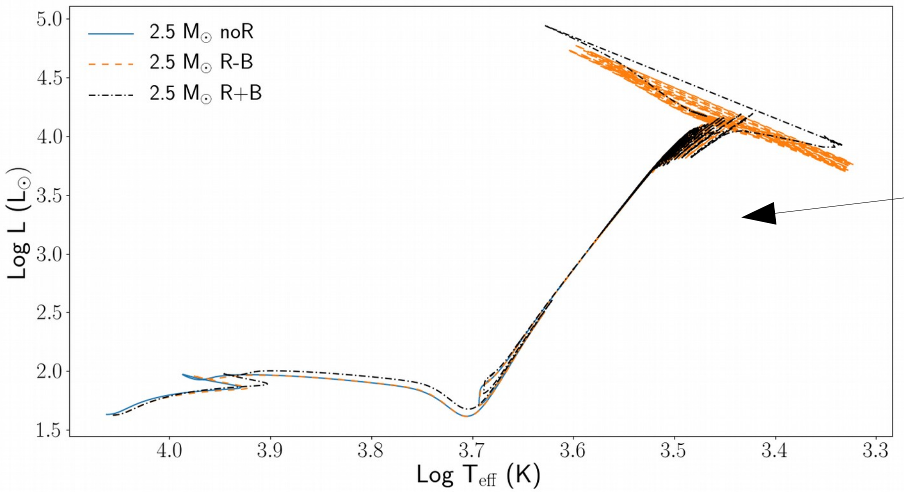


AGB phase & s process in both intermediate-mass stars and low-mass stars!

1.65 & 2.5 Mo MESA models up to AGB phase





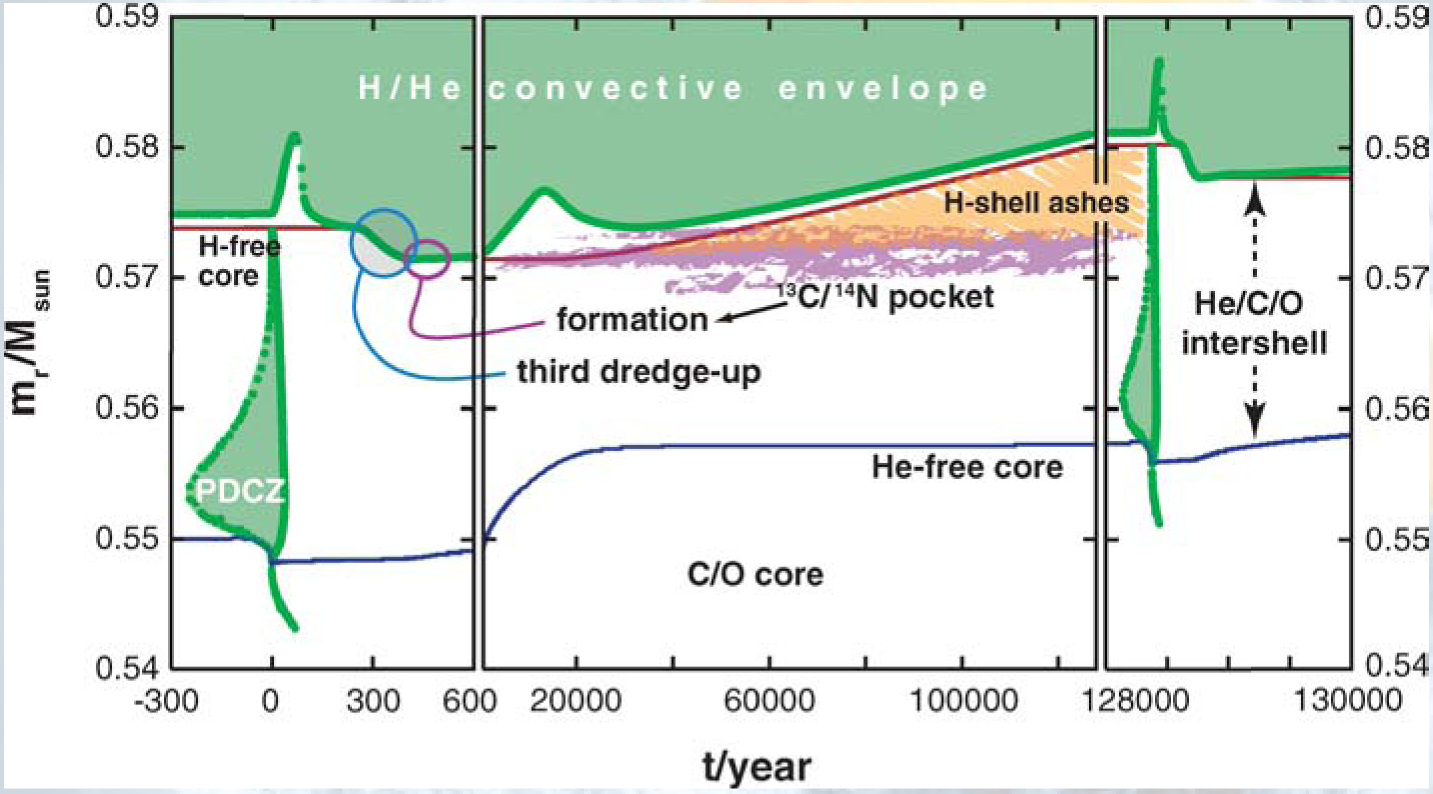


Models with rotation
& rotation + B-fields

Den Hartogh et al (in prep)

Intermediate & Low-Mass Stars

The plot you usually see at conferences for AGB stars:

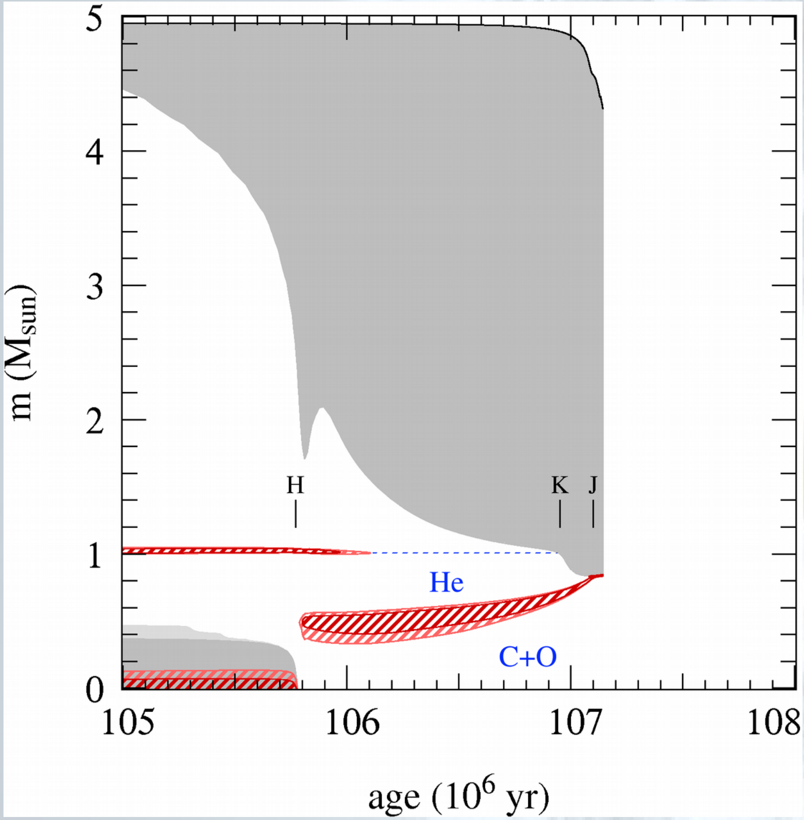


Herwig, ARAA, 2005

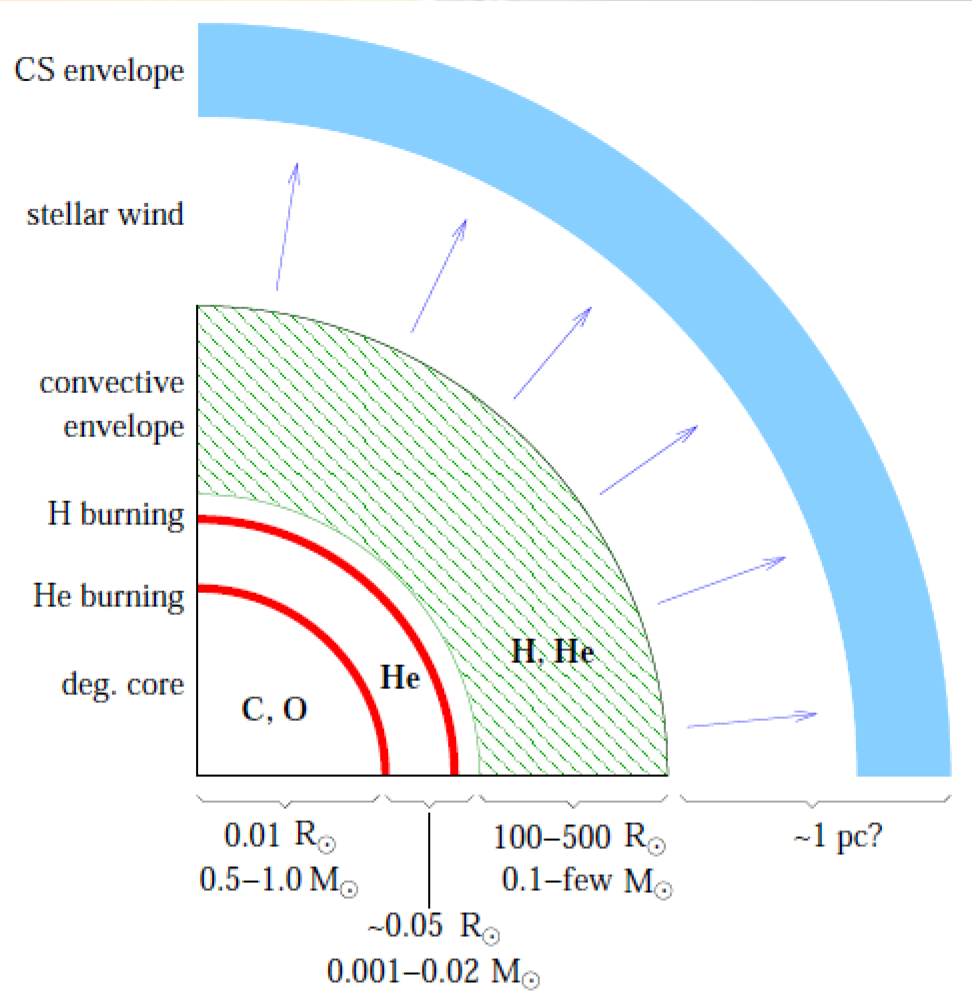
Where does it fit in the star's evolution?

Intermediate & Low-Mass Stars

5 M_o star: early-AGB phase

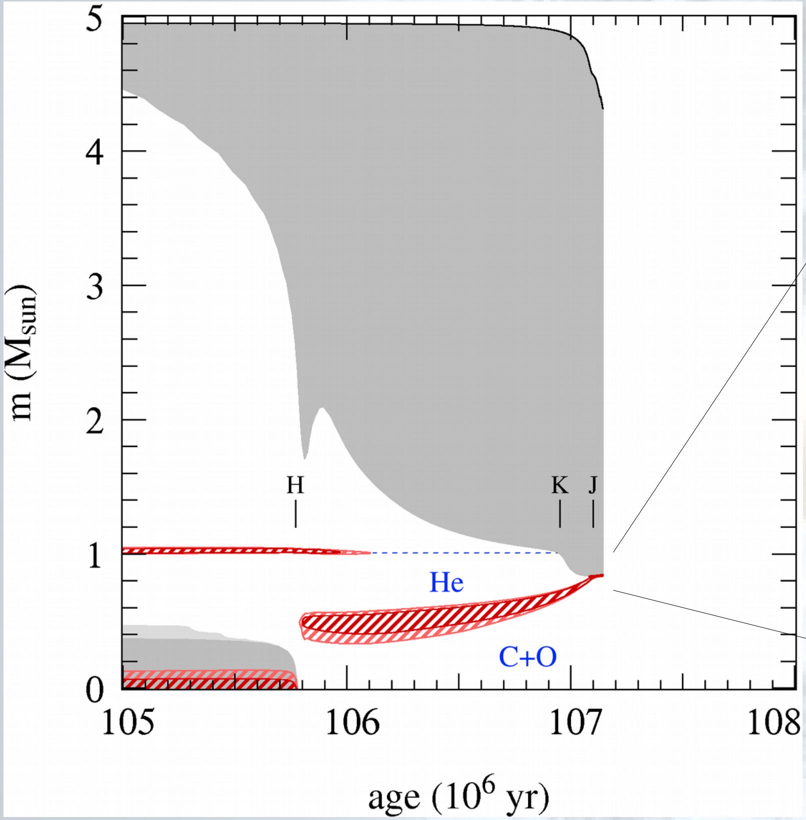


Structure in AGB phase



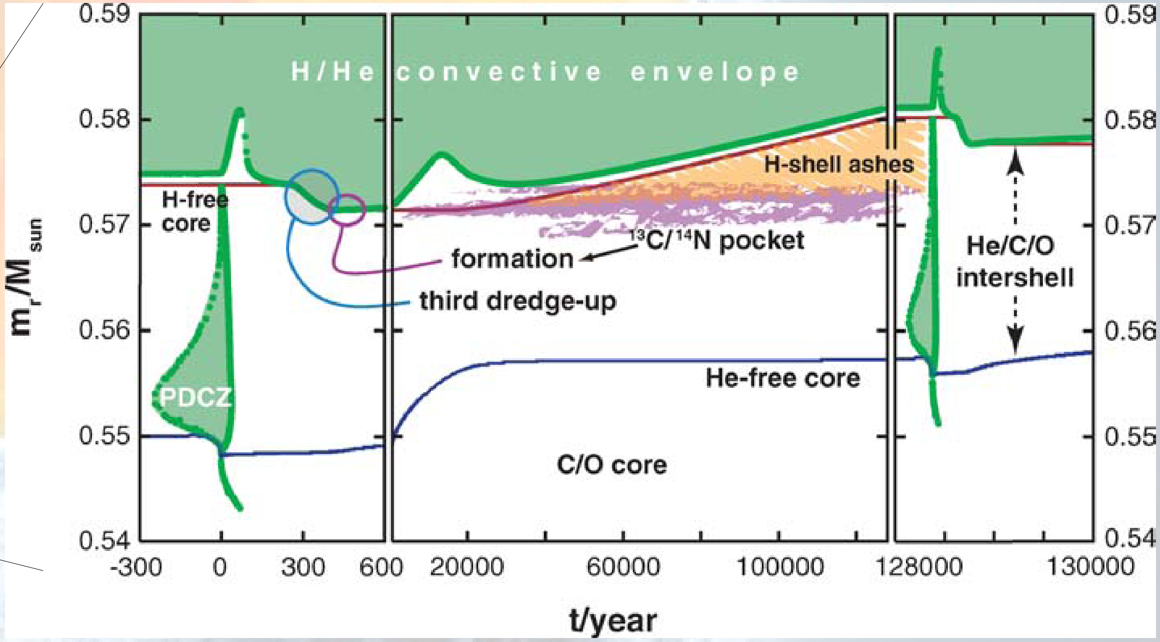
Intermediate & Low-Mass Stars

5 M_o star: AGB phase



From SE notes, O. Pols (2009)

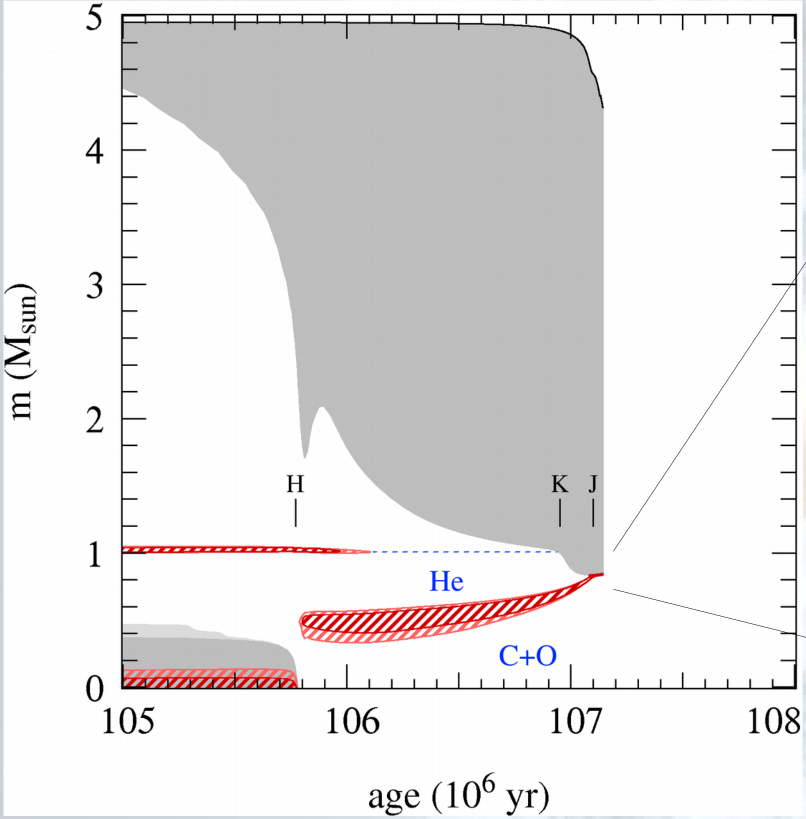
Structure in AGB phase



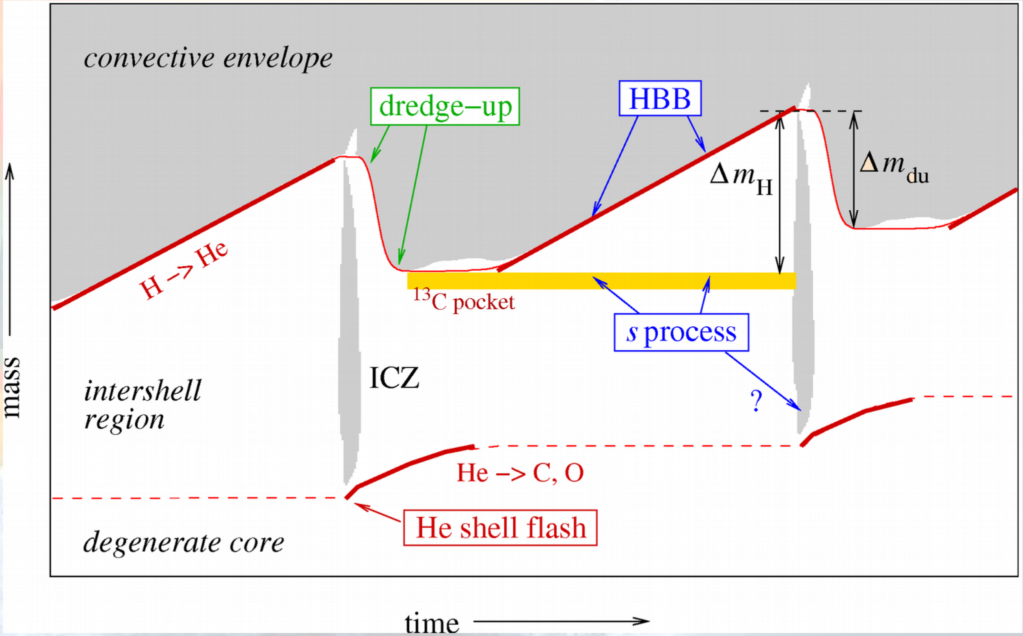
Herwig, ARAA, 2005

Intermediate & Low-Mass Stars

5 M_o star: AGB phase

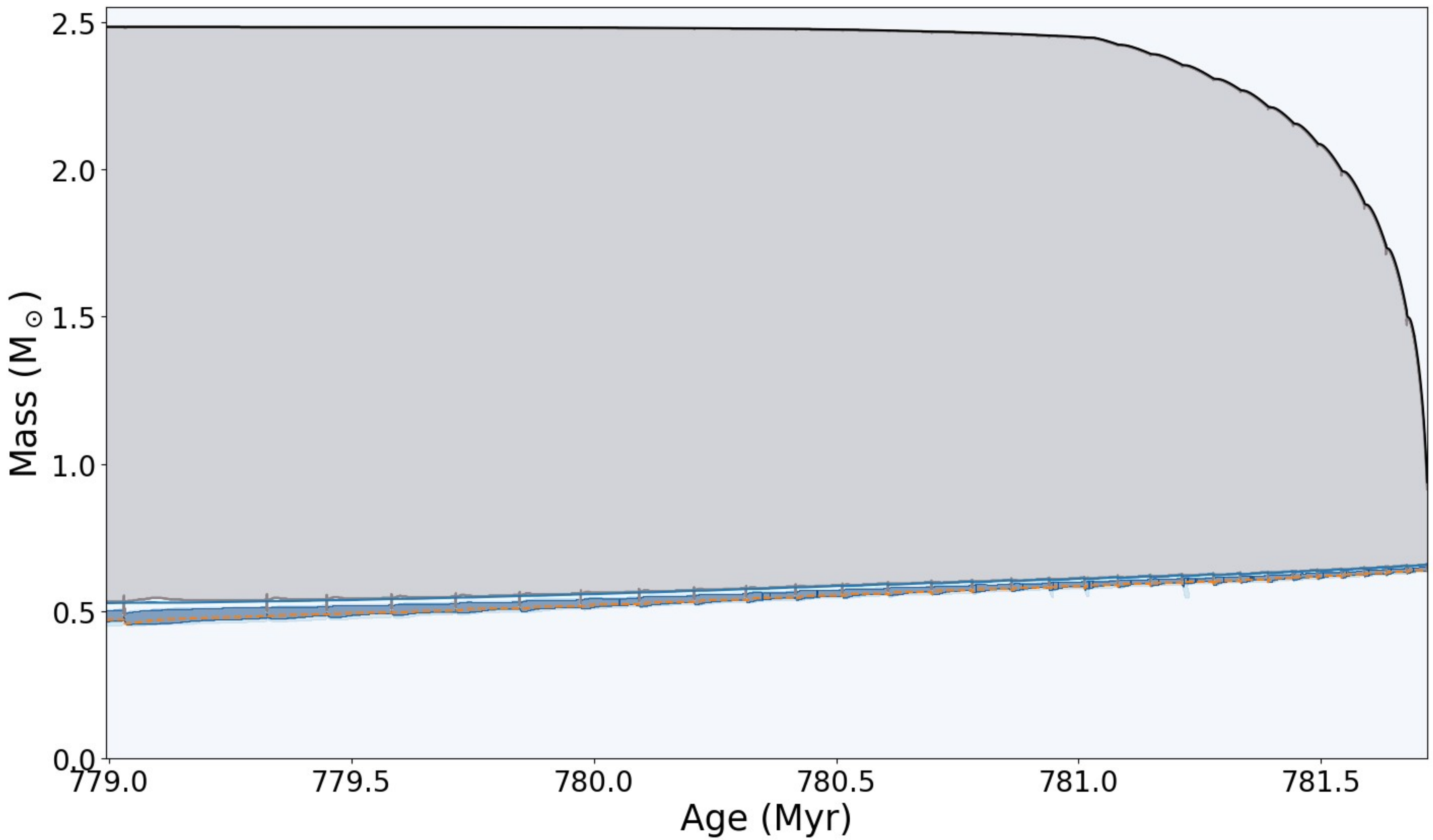


Structure in AGB phase



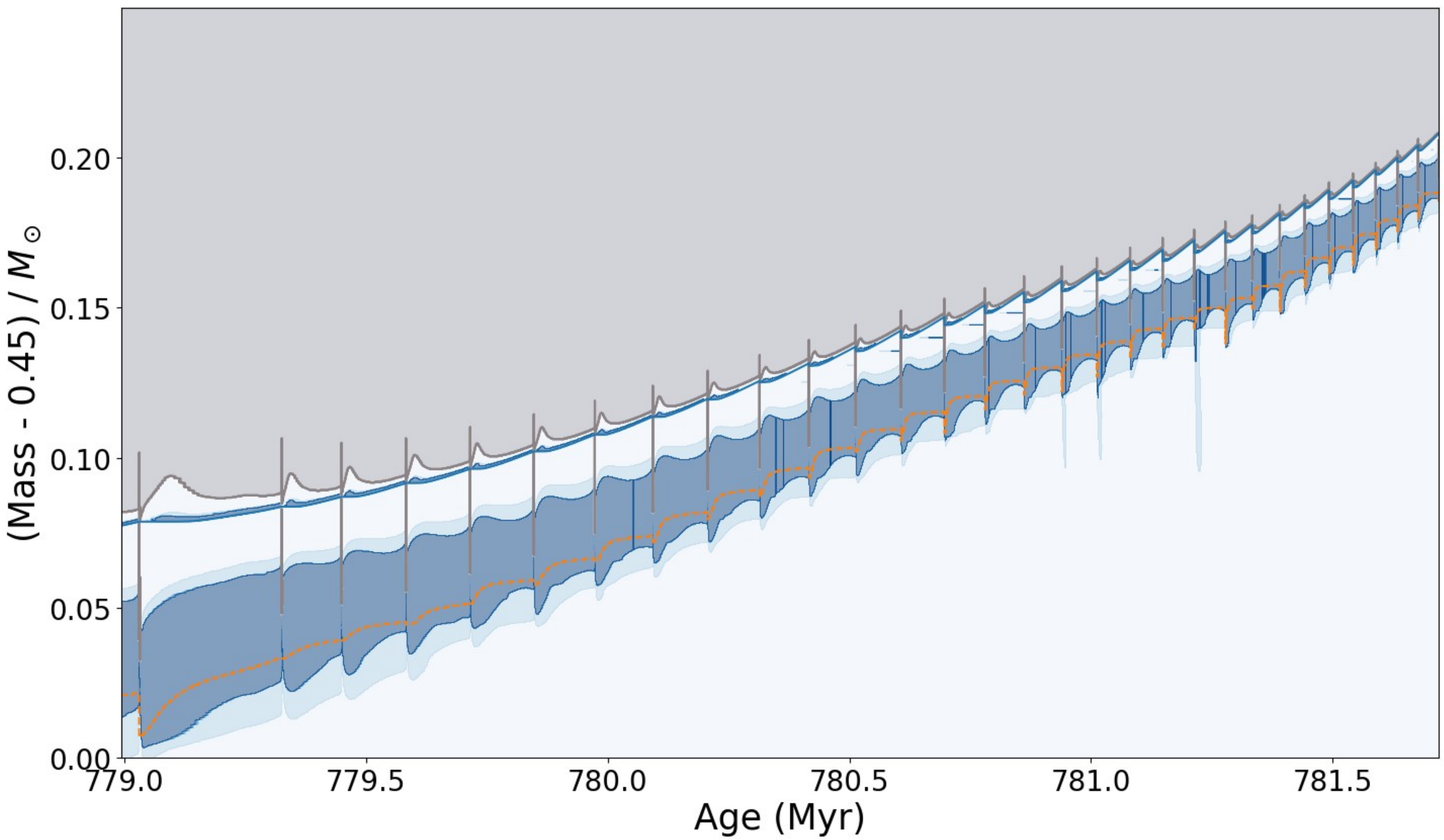
From SE notes, O. Pols (2009)

2.5 Mo MESA model: AGB phase



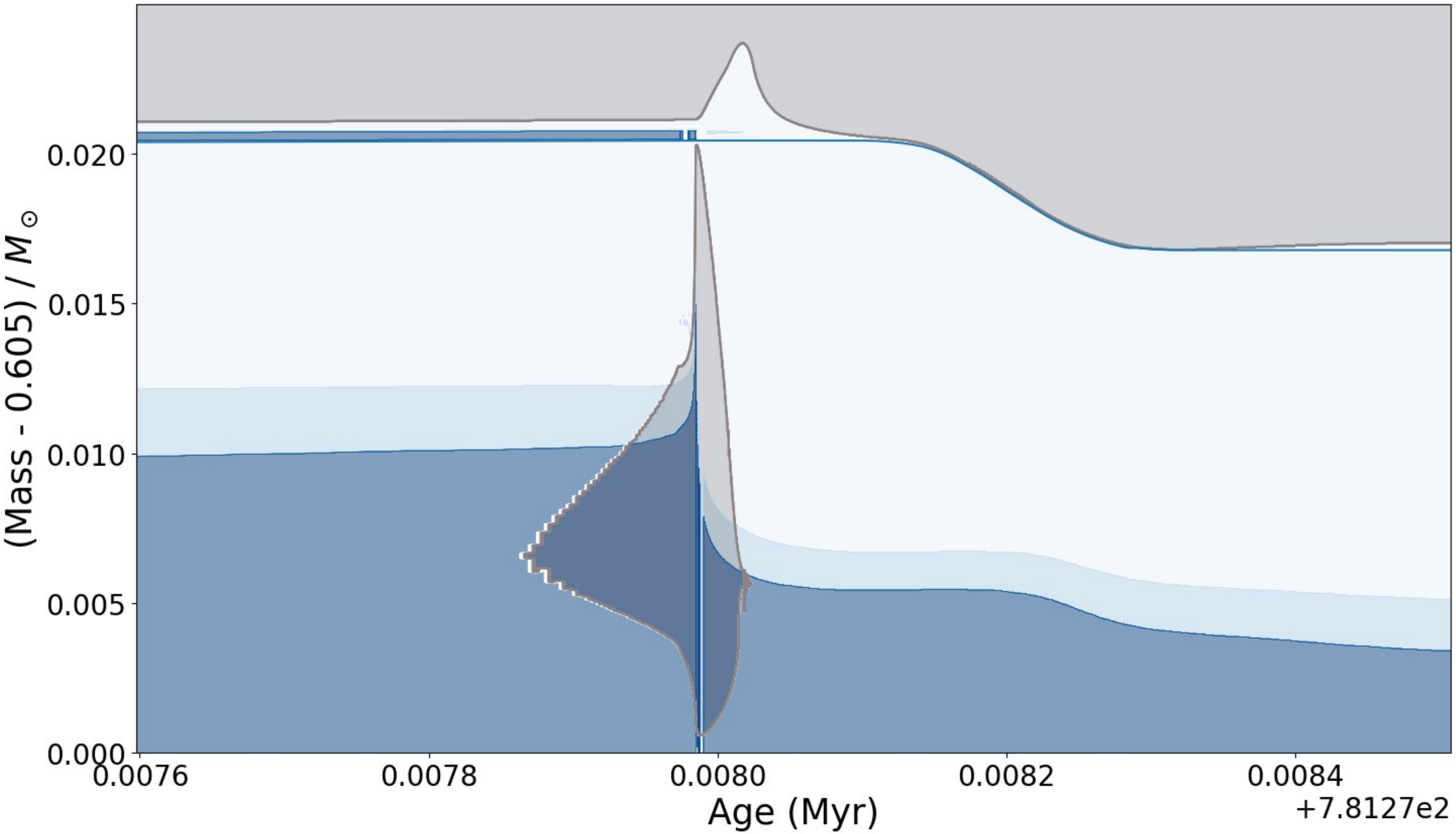
Den Hartogh et al (in prep)

2.5 Mo MESA model: AGB phase



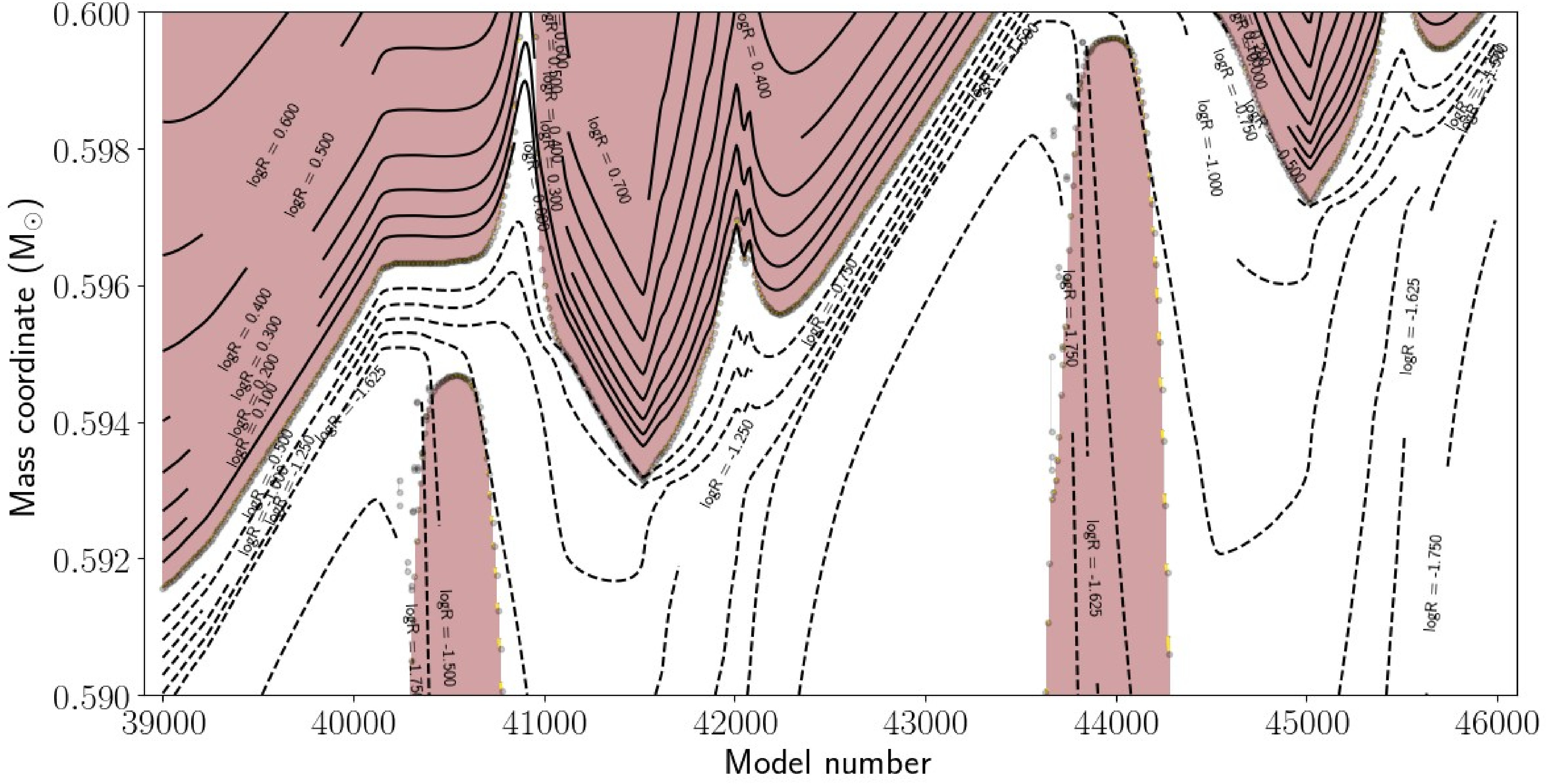
Den Hartogh et al (in prep)

2.5 Mo MESA model: AGB phase



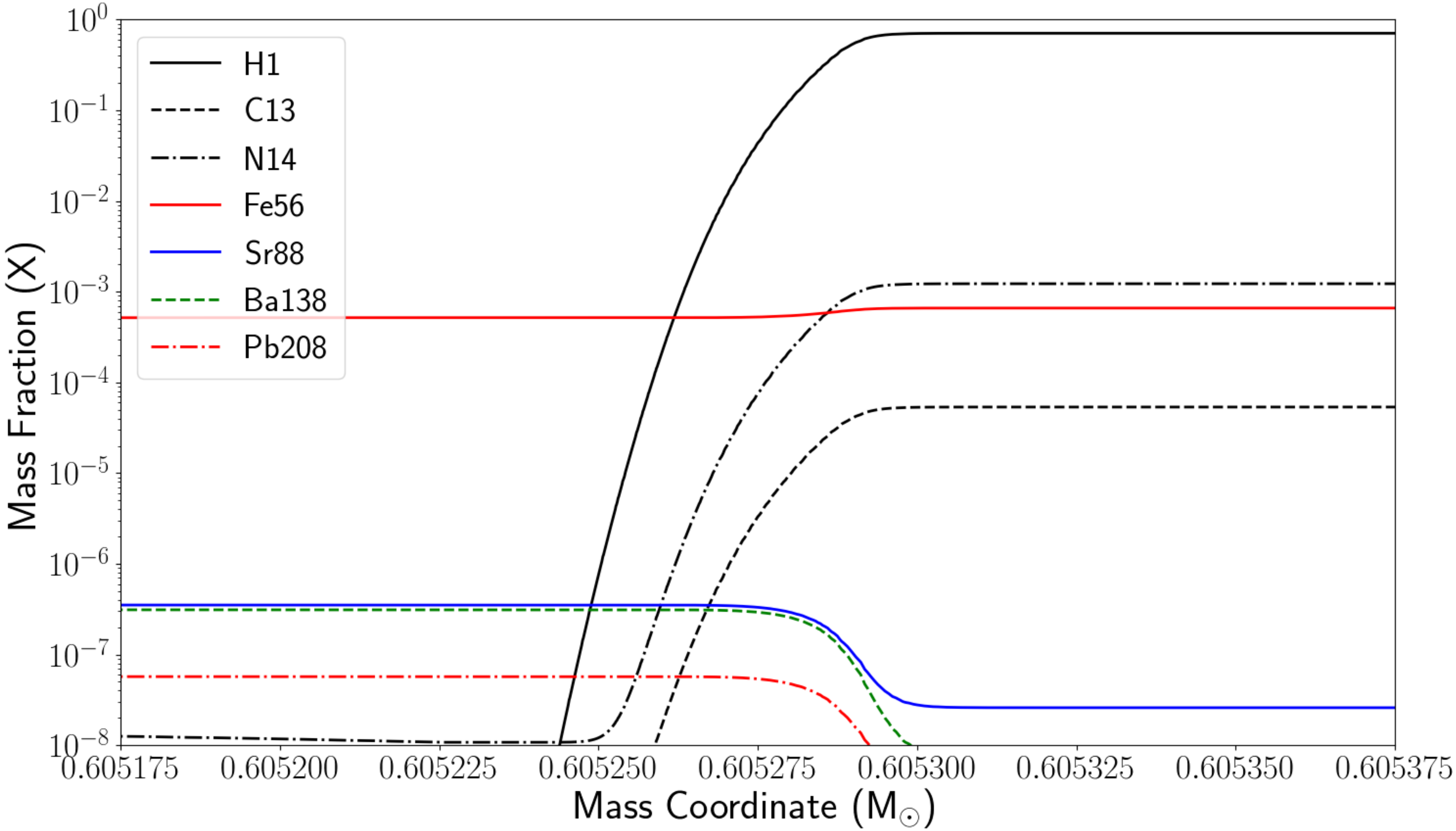
Den Hartogh et al (in prep)

2.5 Mo MESA model: AGB phase



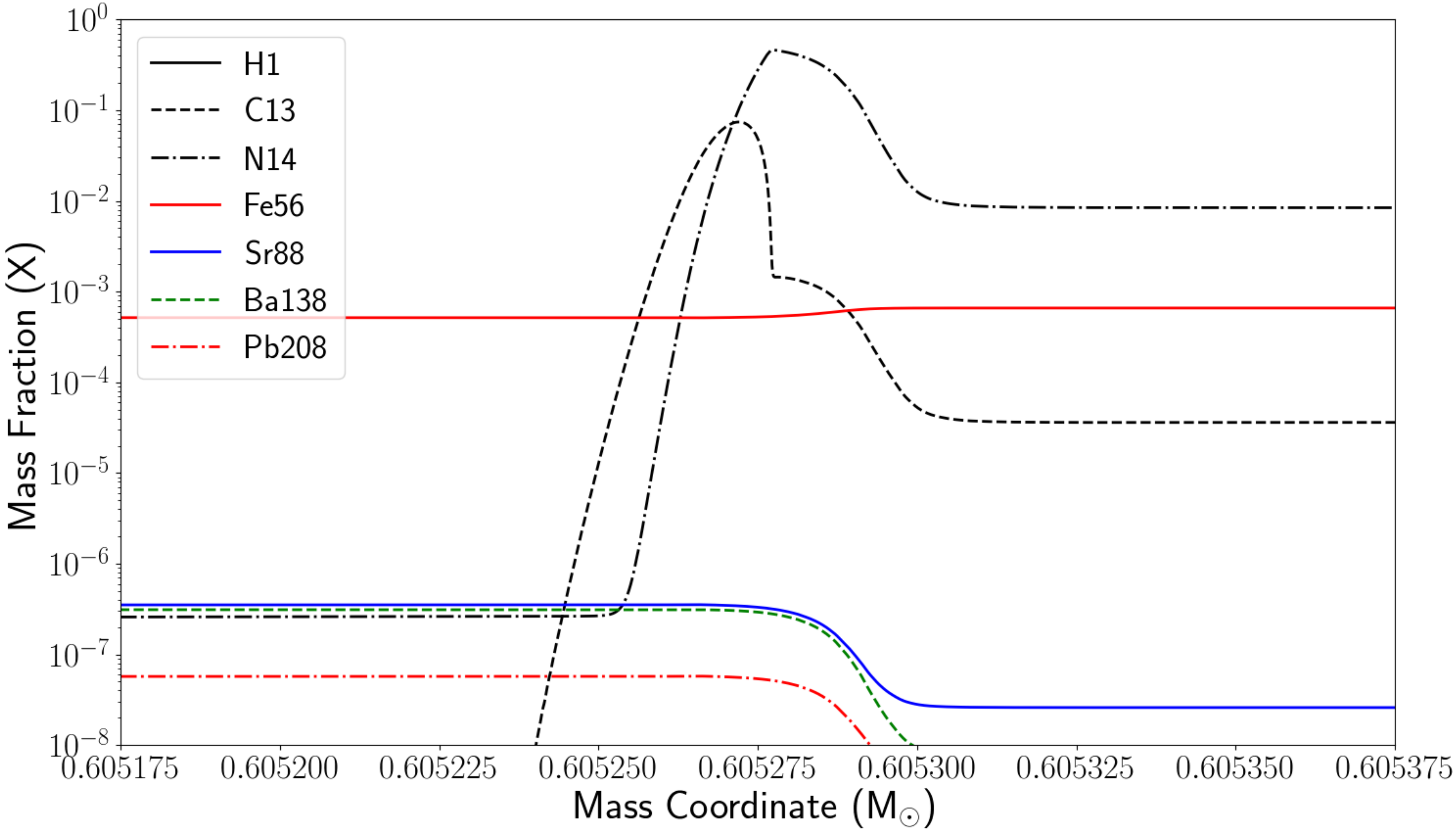
Den Hartogh et al (in prep)

C-13 pocket formation



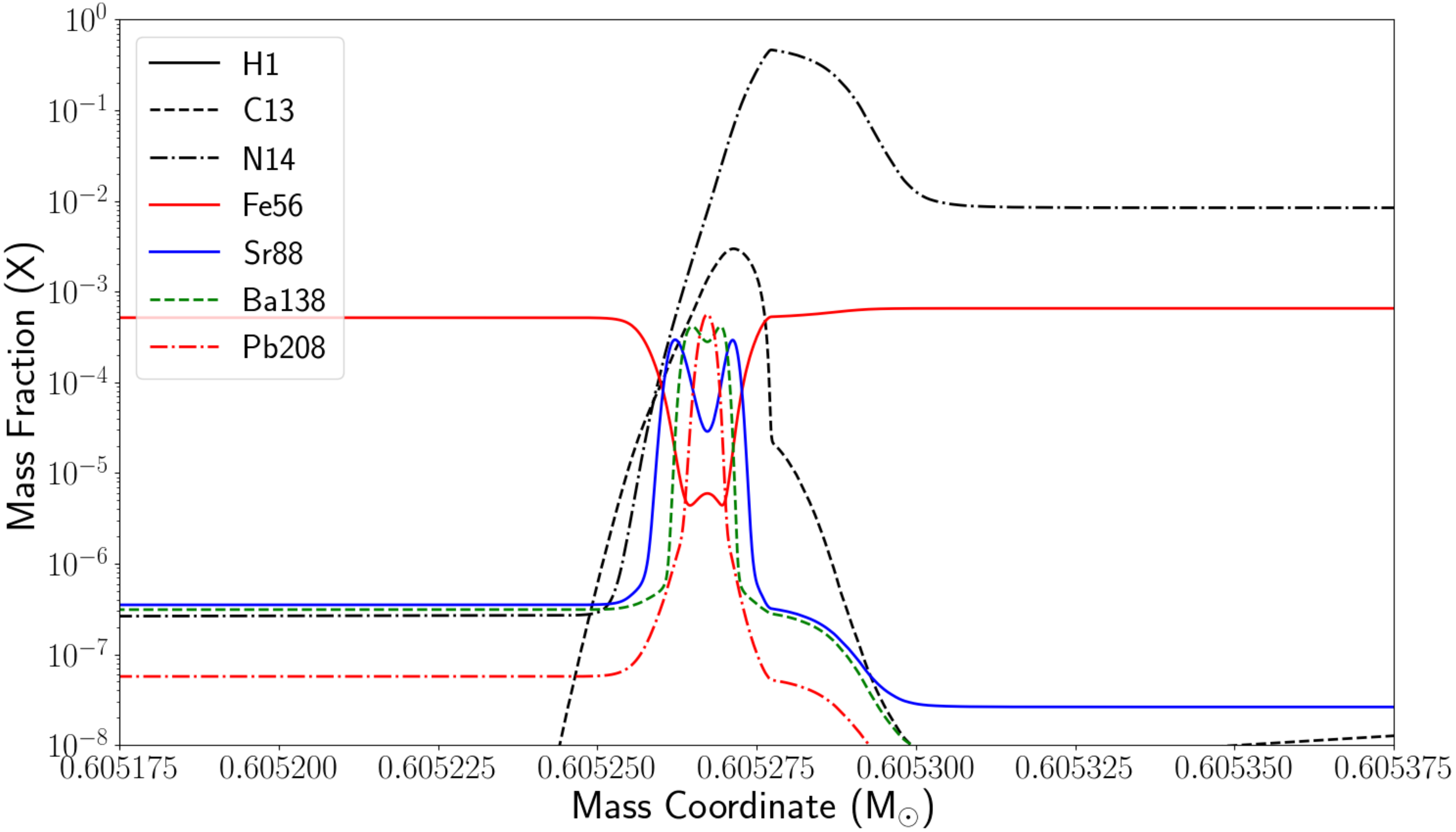
Den Hartogh et al (in prep)

C-13 pocket formation



Den Hartogh et al (in prep)

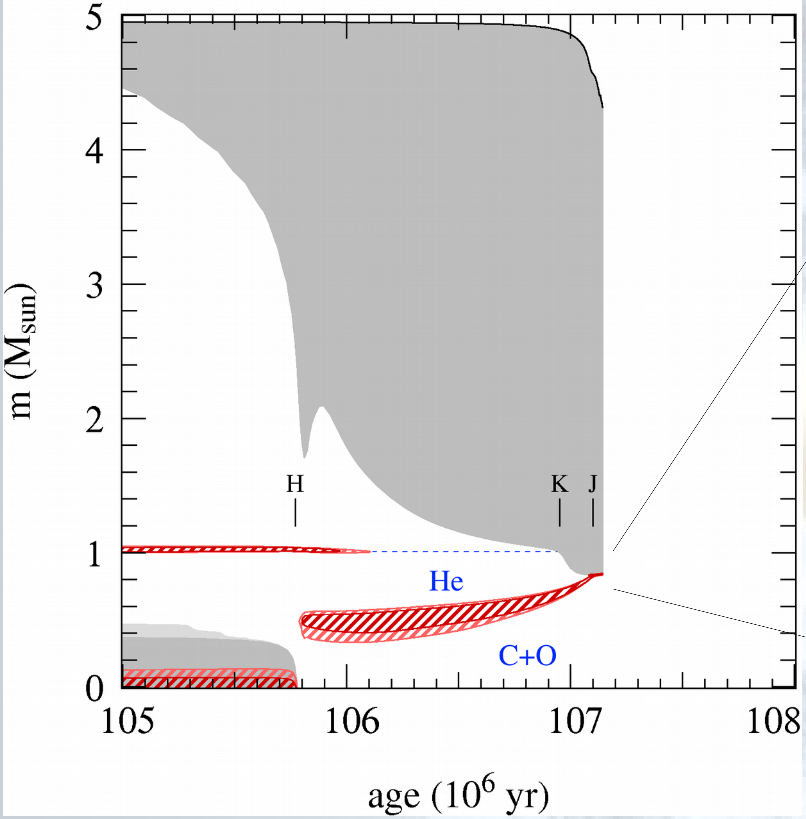
C-13 pocket formation



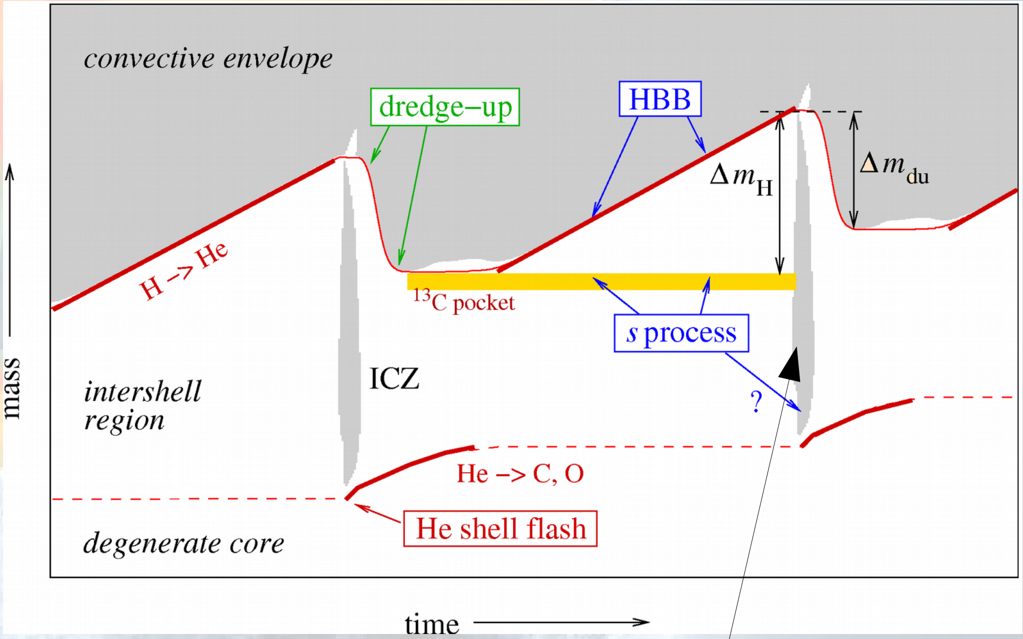
Den Hartogh et al (in prep)

Intermediate & Low-Mass Stars

5 M_o star: AGB phase

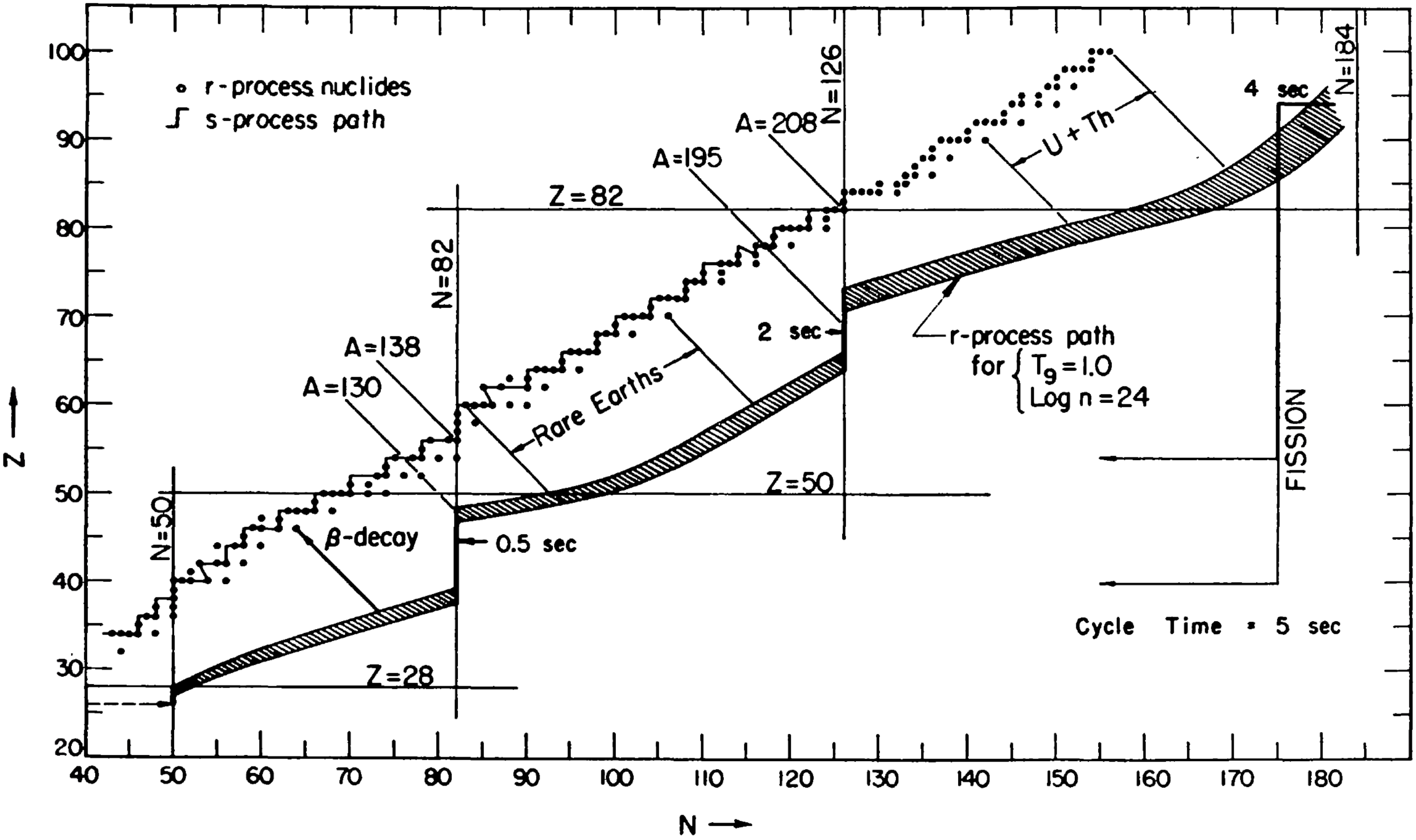


Structure in AGB phase



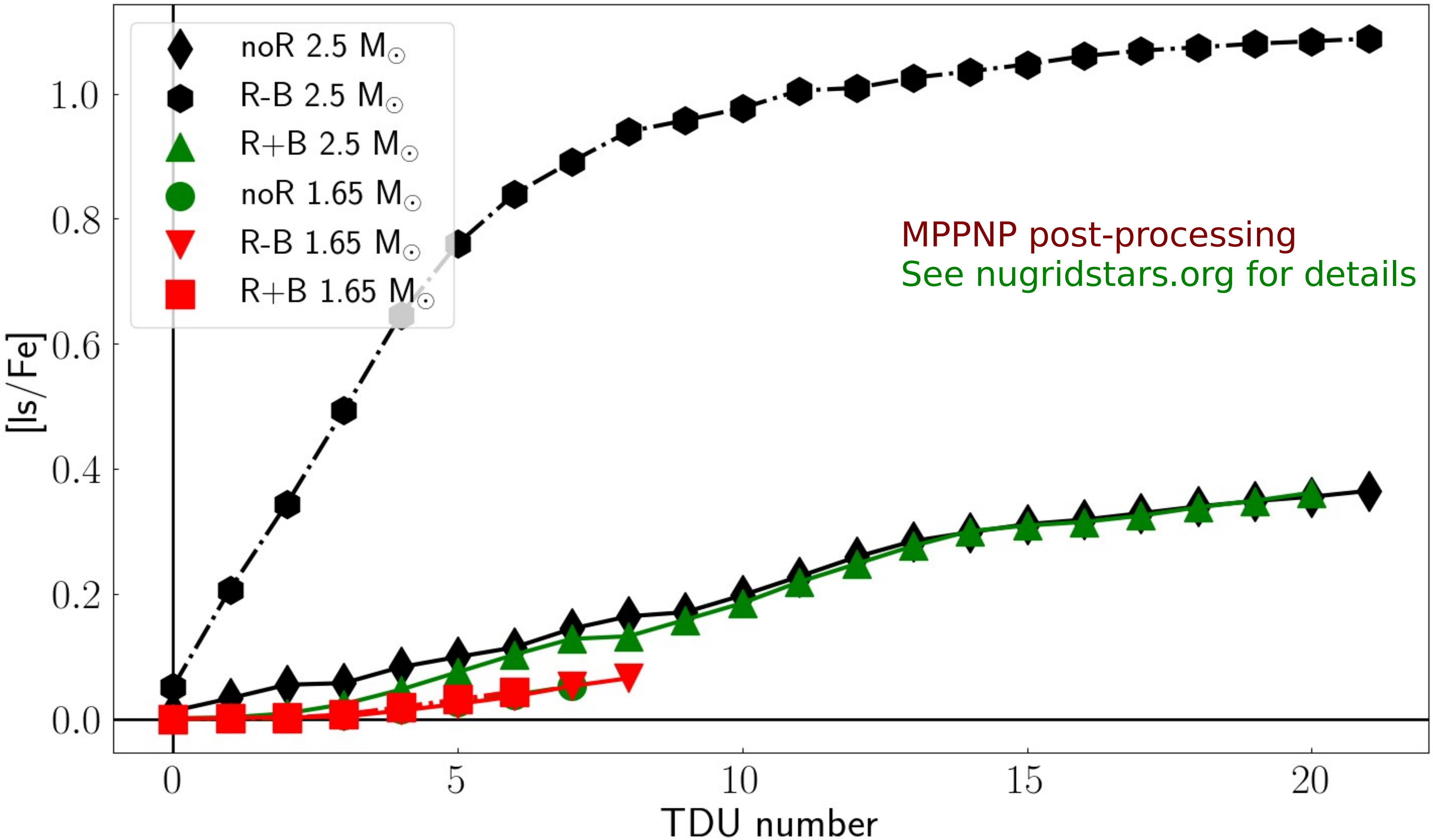
^{22}Ne(a,n) contribution in TP

S-process Production



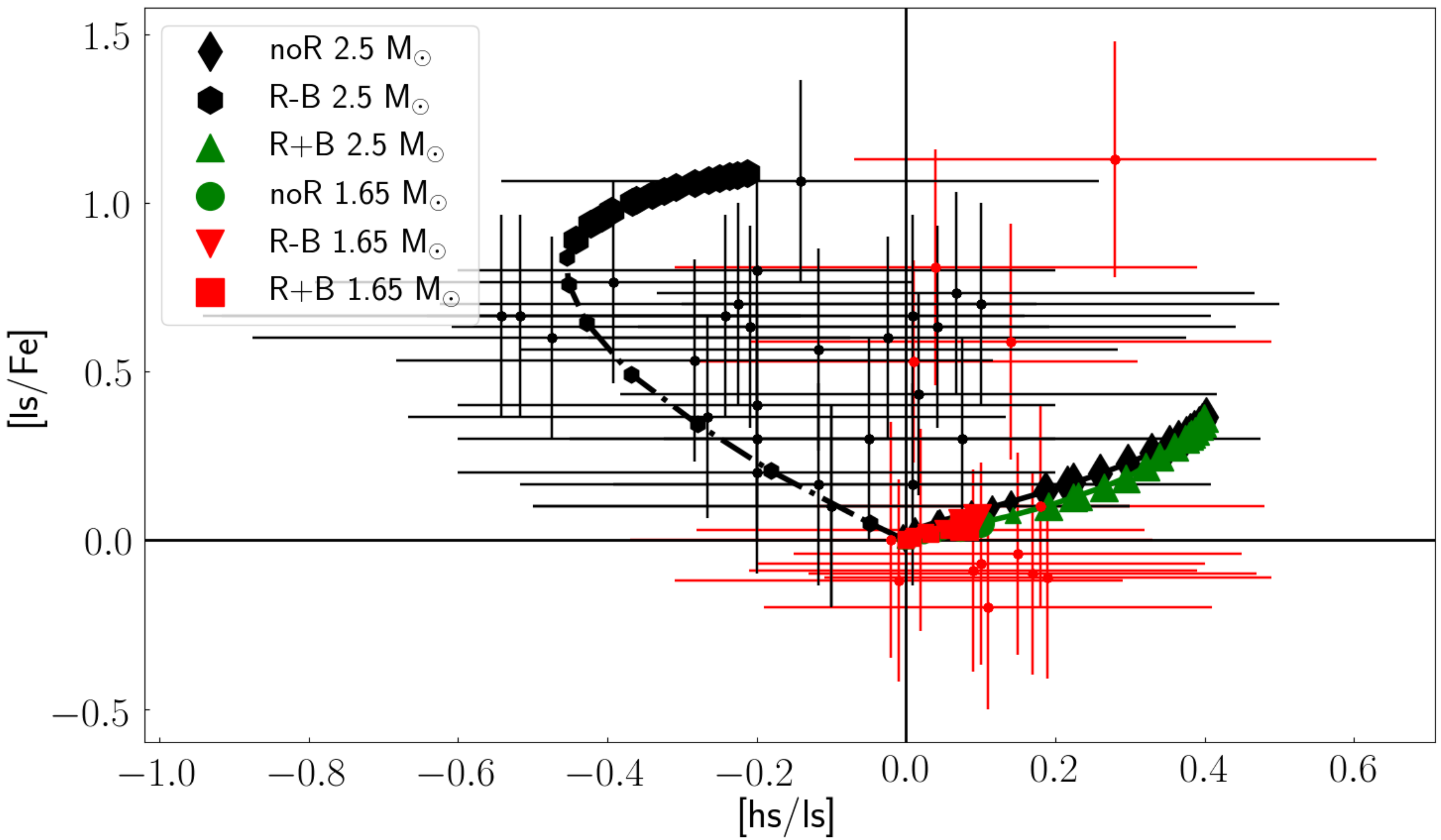
Seeger, Fowler & Clayton (1965)

S-process Production



Den Hartogh et al (in prep)

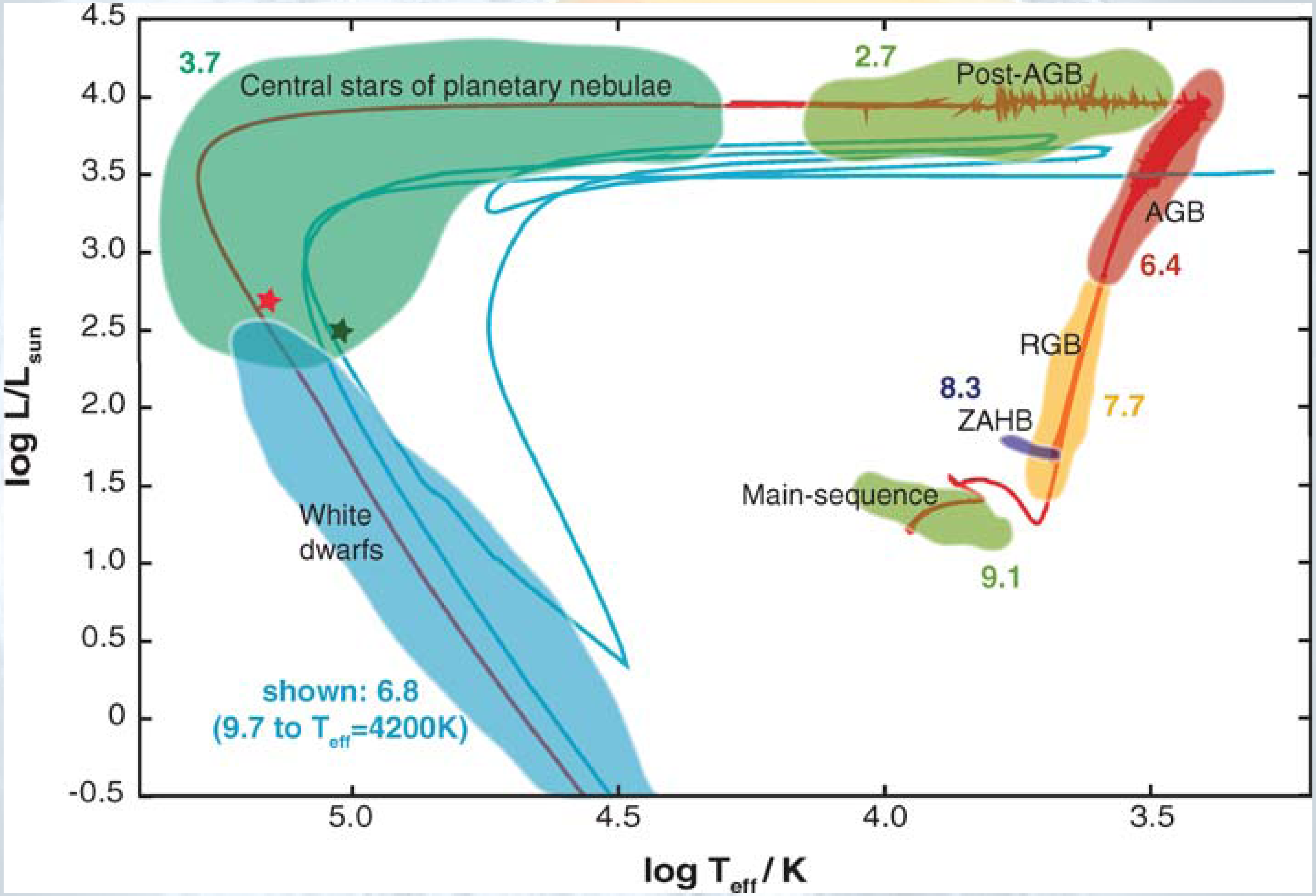
S-process Production



Den Hartogh et al (in prep)

Intermediate & Low-Mass Stars

2 M_o star: post-AGB phase



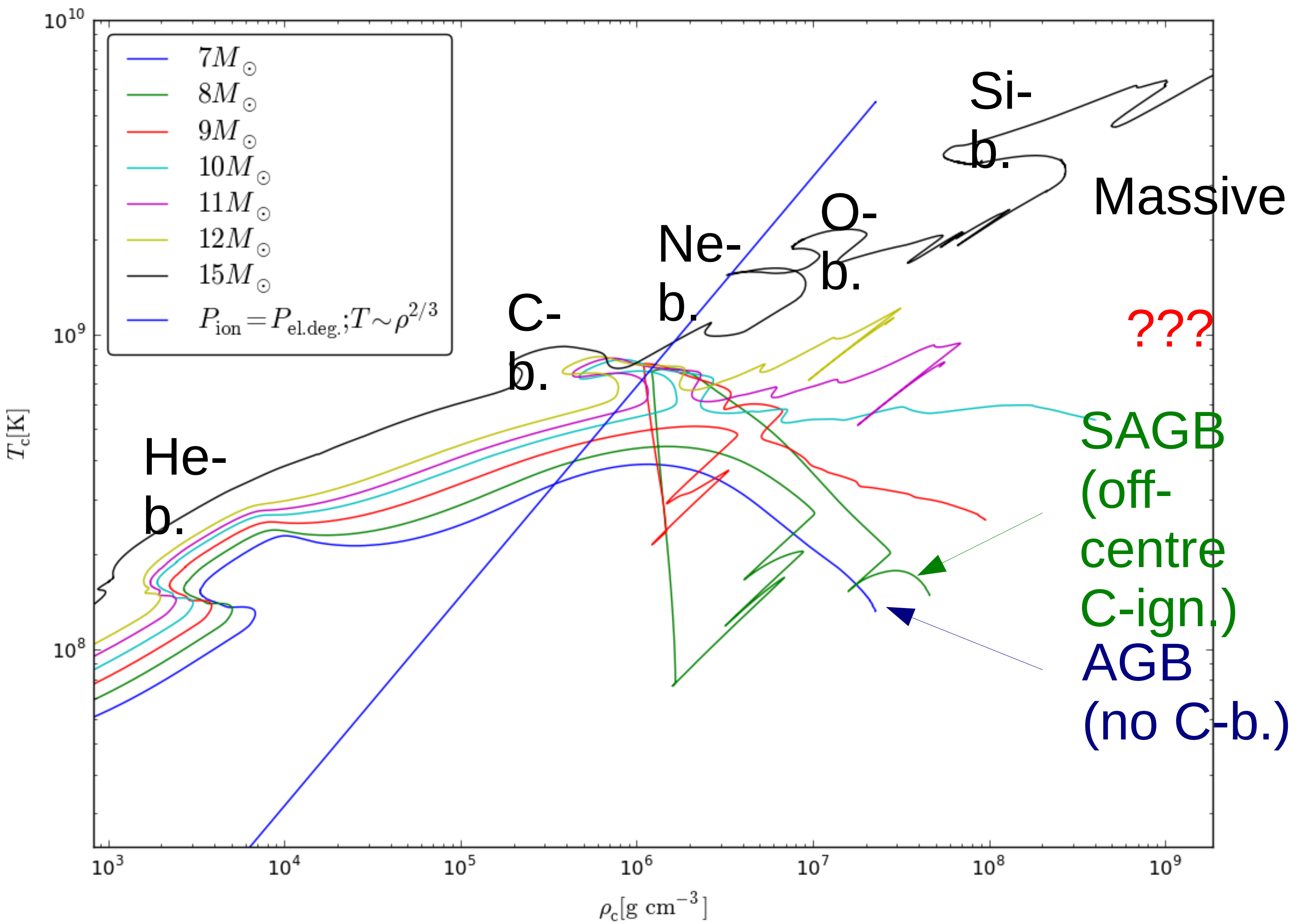
Herwig, ARAA, 2005

Massive/AGB Stars Transition

7-15 M_o models ← MESA stellar evolution code:

http://mesa.sourceforge.net/

Paxton et al 10



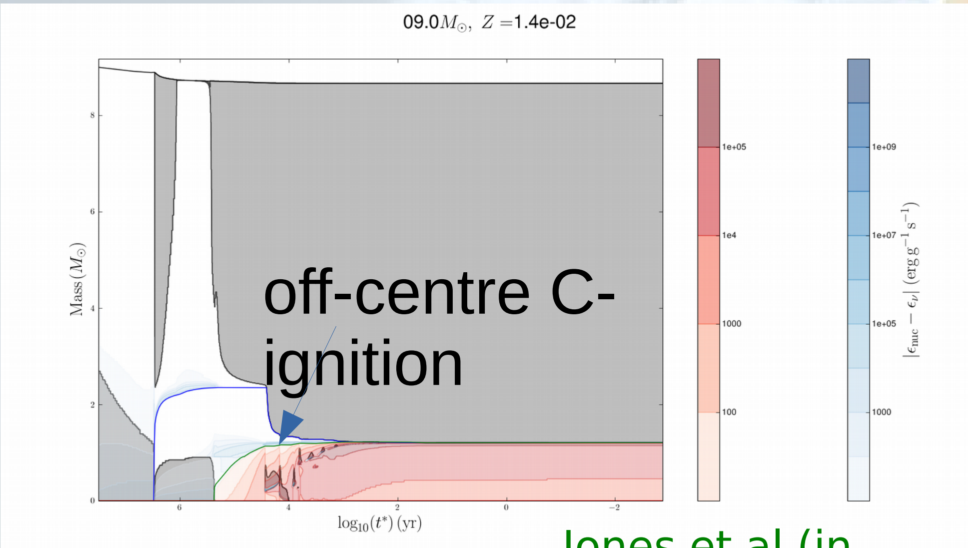
Jones et al 2013; see also Mueller et al 12, Umeda et al 12

SAGB & ECSN progenitors

$M_{up} \leq M \leq M_{mas}$; $M_{up} \approx 8M_{sun}$, $M_{mas} \approx 10M_{sun}$ (TRANSITION MASSES)

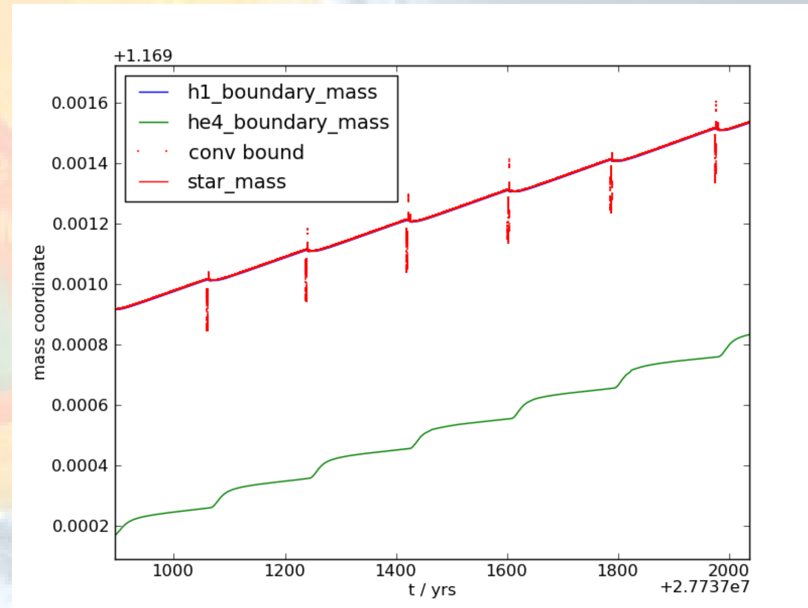
Early evolution like AGBs;

TP-phase → core growth
Dep. on Mdot ↔ mixing



off-centre C-ignition

Jones et al (in prep)



Jones et al (subm.)

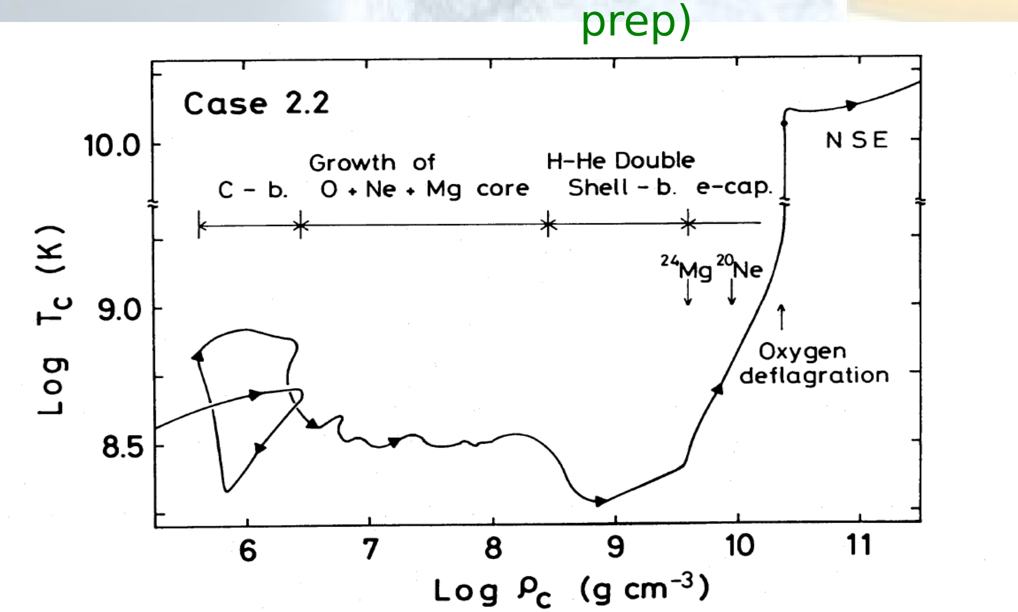
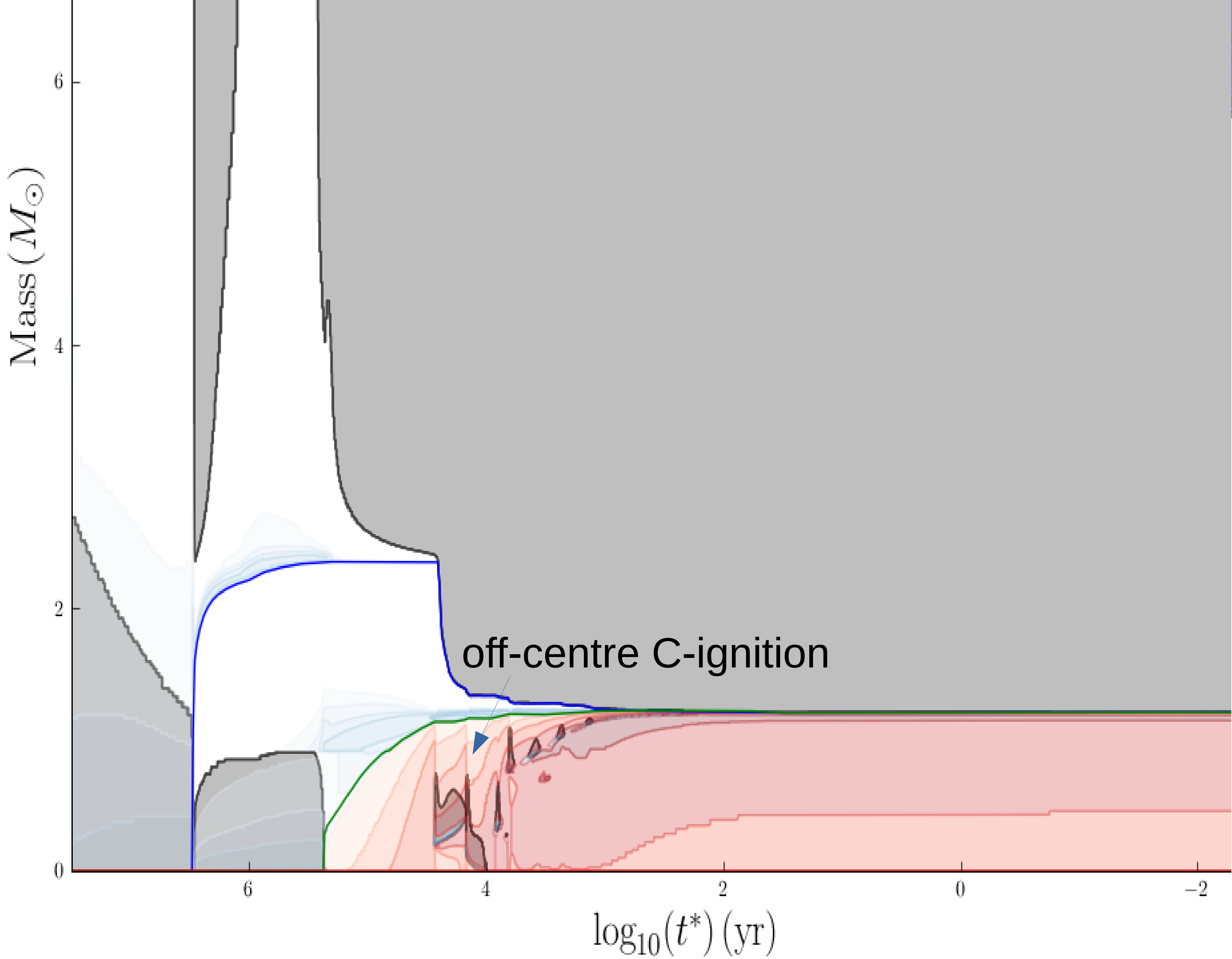


FIG. 4.—Evolutionary track in the central density and temperature diagram

Critical ONeMg core mass = M_{crit} = 1.375
(Miyaji et al. 1980; Nomoto 1984)
See also: Miyaji (1980); Nomoto(1984, 1987); Miyaji & Nomoto (1987); Garcia-Berro, Ritossa and Iben (1990s); Eldridge & Tout (2004); L. Siess (2006, 2007, 2009, 2010), Poelarends (2008); Doherty et al. (2010) ...

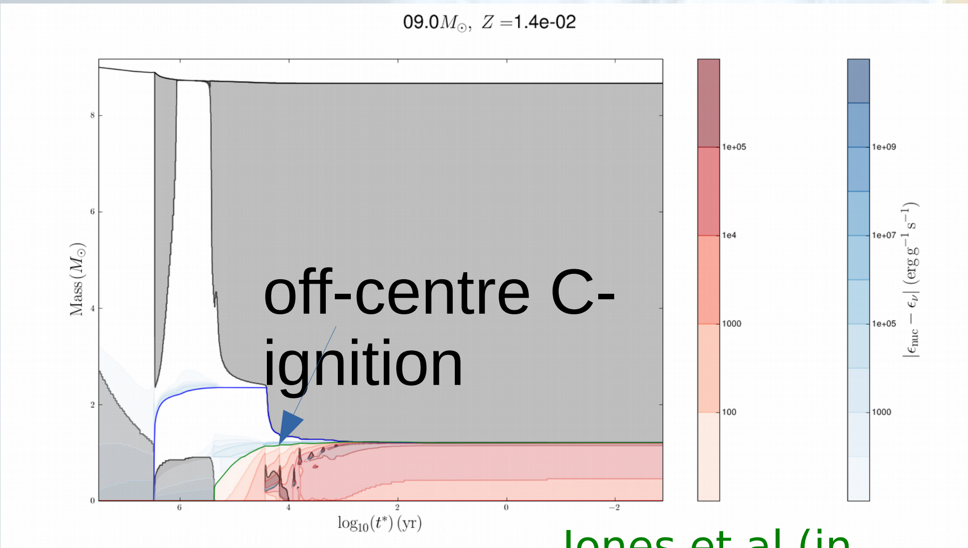


Mass ($M_\odot$)
6
4
2
0
off-centre C-ignition
6
4
2
0
−2
$\log_{10}(t^*)$ (yr)

SAGB & ECSN progenitors

$M_{up} \leq M \leq M_{mas}$; $M_{up} \approx 8M_{sun}$, $M_{mas} \approx 10M_{sun}$ (TRANSITION MASSES)

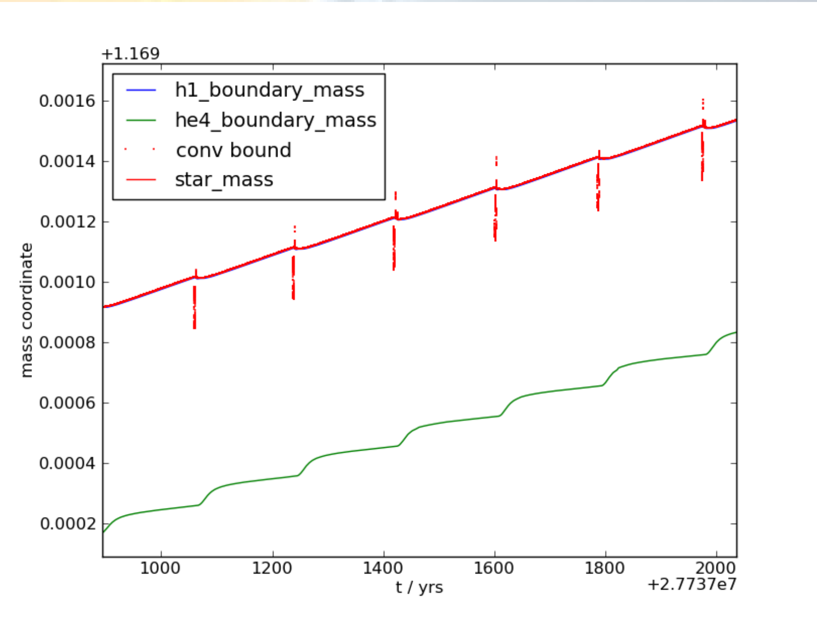
Early evolution like AGBs;



Jones et al (in prep)

TP-phase → core growth

Dep. on Mdot ↔ mixing



Jones et al (subm.)

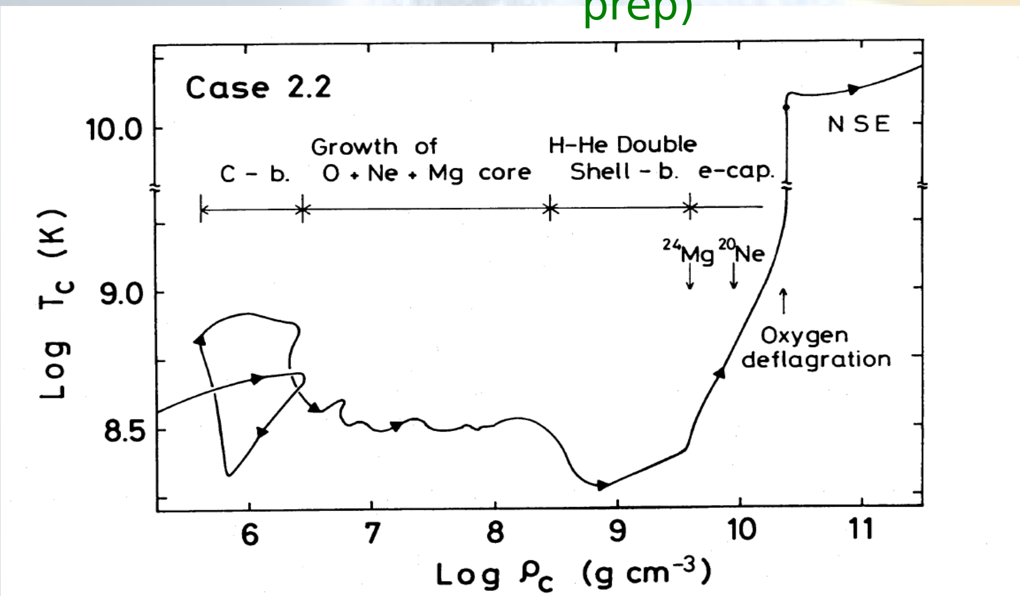


FIG. 4.—Evolutionary track in the central density and temperature diagram

Critical ONeMg core mass = M_{crit} = 1.375

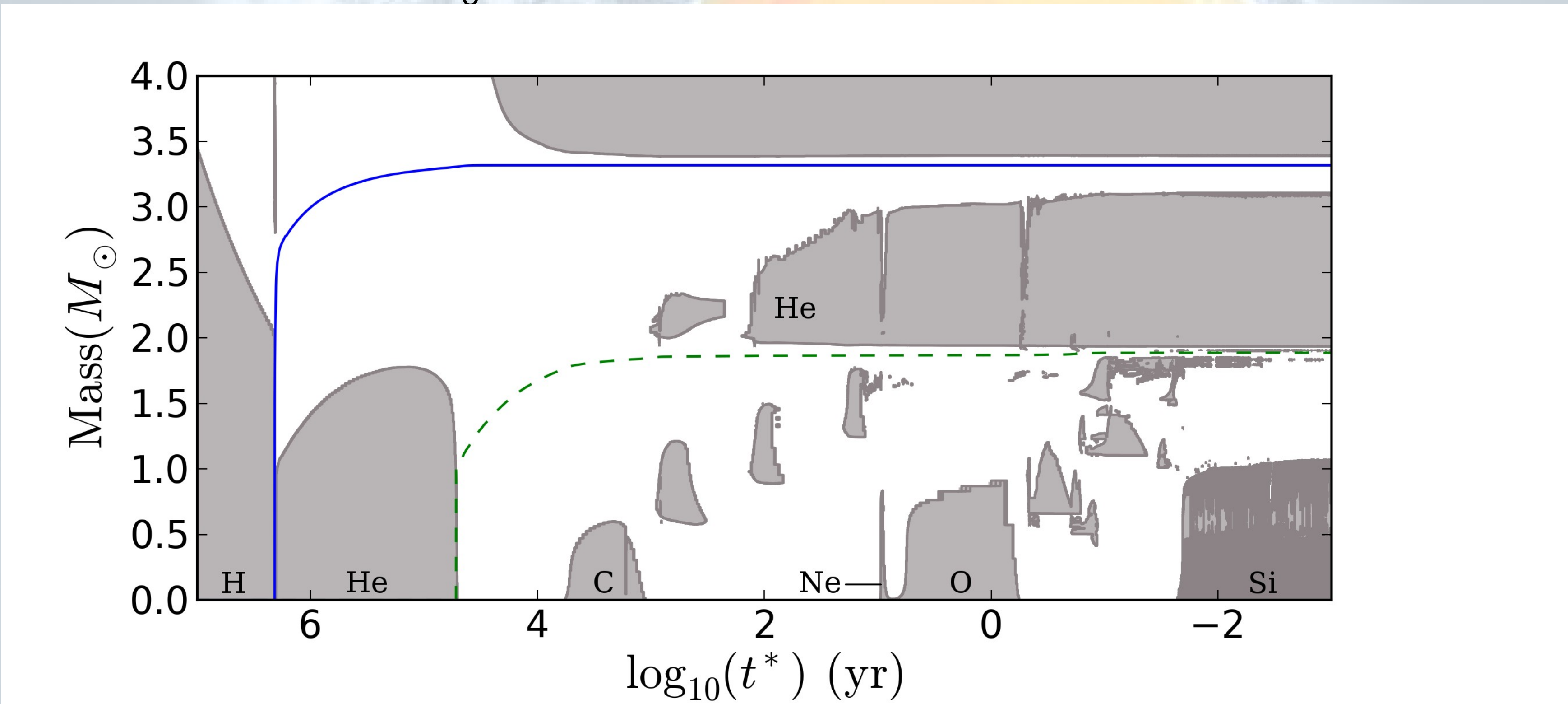
(Miyaji et al. 1980; Nomoto 1984)

See also: Miyaji (1980); Nomoto(1984, 1987); Miyaji & Nomoto (1987); Garcia-Berro, Ritossa and Iben (1990s); Eldridge & Tout (2004); L. Siess (2006, 2007, 2009, 2010), Poelarends (2008); Doherty et al. (2010) ...

Can Massive Stars produce ECSN ?

7-15 M_o models ← MESA stellar evolution code **Paxton et al 10,12**

12 M_o is a typical massive star:



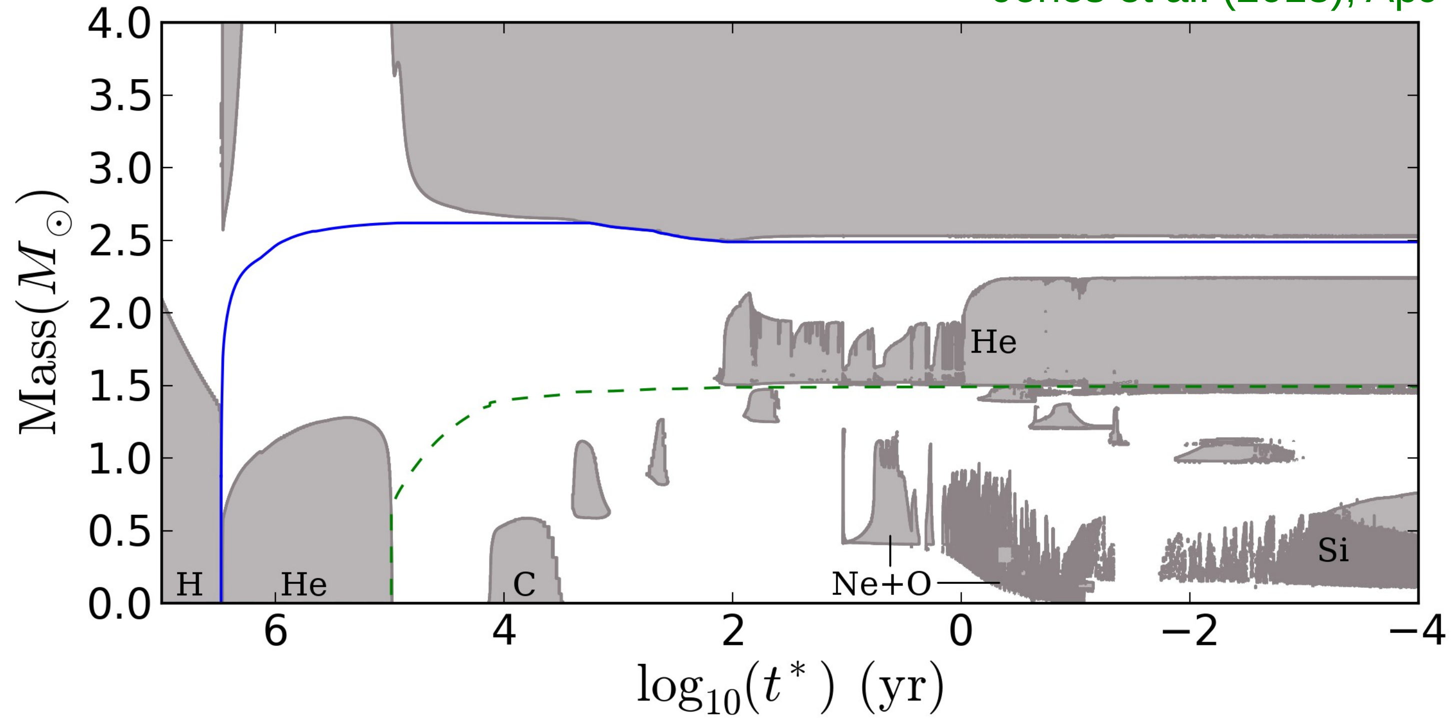
All burning stages ignited centrally. Fate: Fe-CCSN

Jones et al. (2013), ApJ 772, 150;
see also Mueller et al 12, Umeda et al 12, Takahashi et al 13

Can Massive Stars produce ECSN ?

9.5 M_o still a massive star:

Jones et al. (2013), ApJ 772, 150



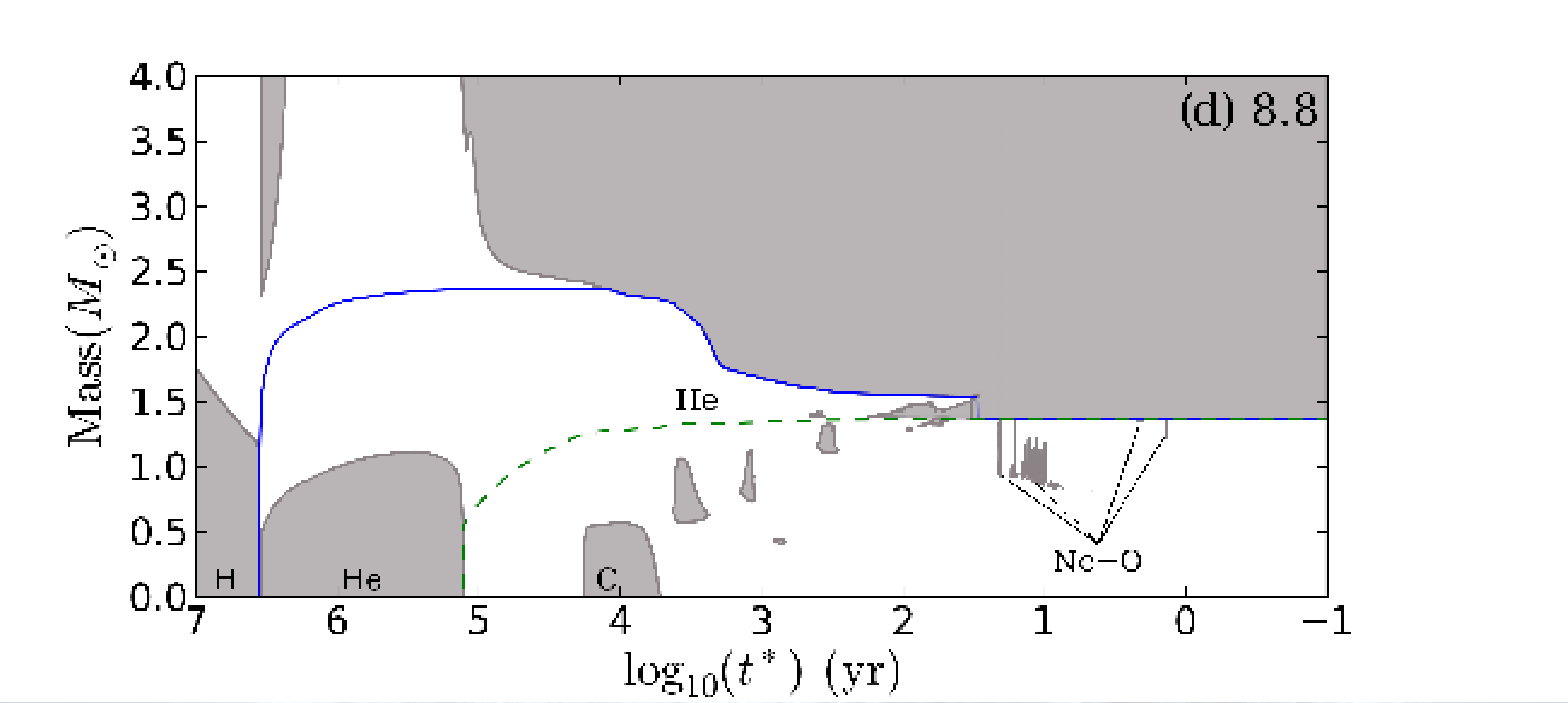
Ne-Si burning stages ignited off-centre. Fate: still Fe-CCSN

Simulations include 114-isotope network!

Can Massive Stars produce ECSN ?

Jones et al. (2013,...),
ApJ 772, 150
See also Nomoto 84: case 2.6
Timmes et al 92,94
Eldridge & Tout 04

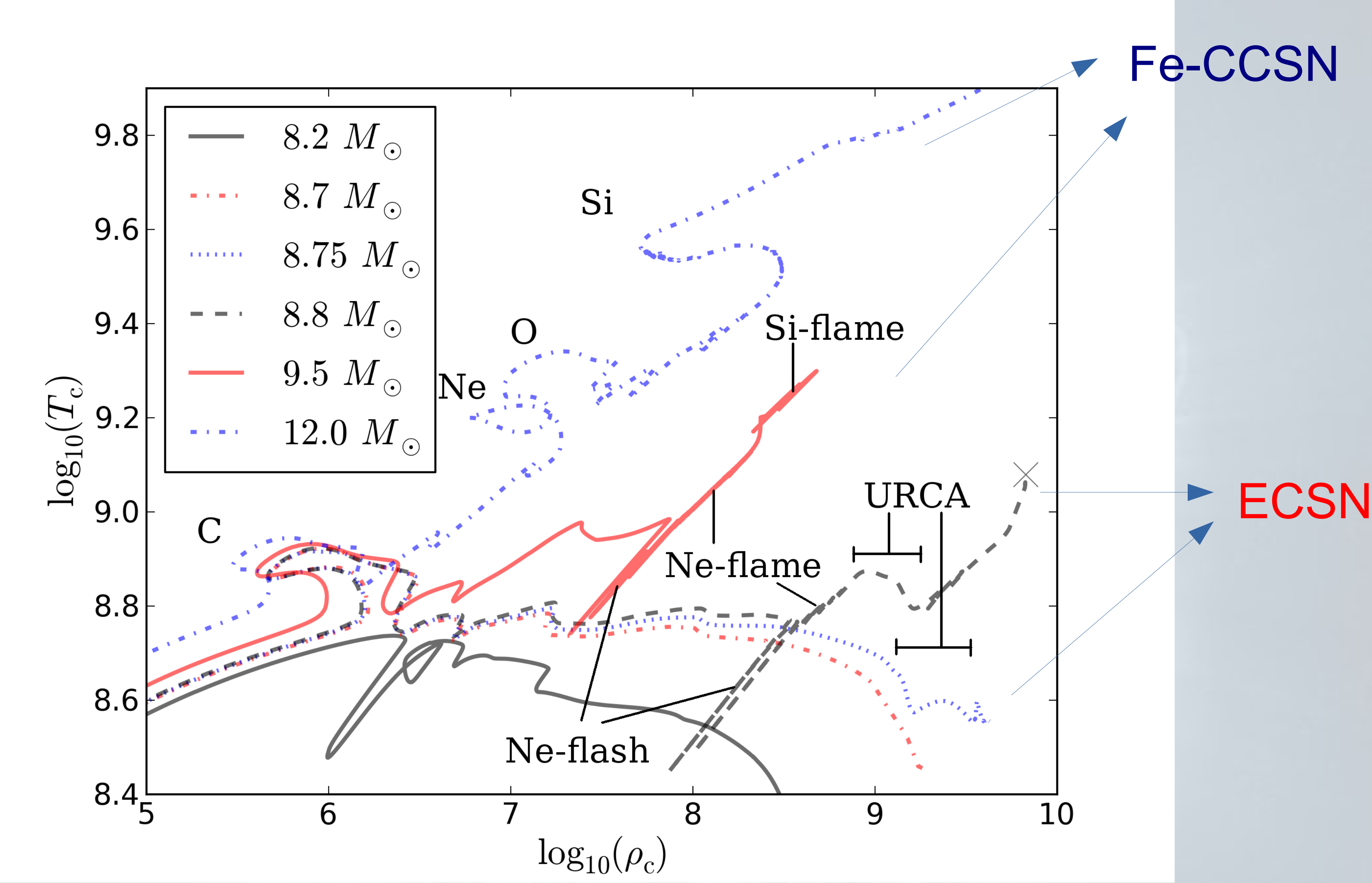
8.8 M_o failed massive star:



Ne-b. starts off-centre but does not reach the centre.
MESA → Oxygen deflagration
Agile-Bolztran for collapse + explosion (Jones et al 2016)
Fate: ECSN

Key uncertainties: convective boundary mixing, mass loss

Fate of Least-Massive MS: ECSN/Fe-CCSN?



Jones et al. (2013), ApJ 772, 150

Both SAGB and failed massive stars may produce ECSN