Part C

Late burning stages

Prospects for stars to ignite heavier fuels

$$\frac{dP}{dr} = -G\frac{m(r)\rho(r)}{r^2}$$

χ : Factor of order unity that accounts for e.g. $\bar{\rho}_{core}/\,\rho_c$, and general absorber for doing a rough approximation.

$$P_c \approx \frac{GM_{core}\bar{\rho}_{core}}{R_{core}} = \left[R_{core} \approx \left(\frac{M_{core}}{3/(4\pi)\;\bar{\rho}_{core}}\right)^{\frac{1}{3}}\right] = \chi G M_{core}^{2/3}\rho_c^{4/3}$$

c for central

Upon H exhaustion stars develop a **core** + **envelope** structure : Don't use total M but M_{core}

$$P \approx \frac{\Re}{\mu}\rho T + K_\gamma\left(\frac{\rho}{\mu_e}\right)^\gamma$$

Gas pressure plus degeneracy pressure

Then, combining these two equations gives

$$\frac{\Re}{\mu}T_c = \chi G M_{core}^{2/3}\rho_c^{1/3} - K_\gamma \rho_c^{\gamma-1}\mu_e^{-\gamma}$$

Thus, a link between T_c and ρ_c for a given M_{core}.

For $\gamma = 5/3$ (non-relativistic electrons):

$$\frac{\Re}{\mu}T_c = \rho_c^{1/3} * \left[\underbrace{\chi G M_{core}^{2/3}}_{C_1} - \underbrace{K_{5/3}\mu_e^{-5/3}\rho_c^{1/3}}_{C_2 * \rho_c^{1/3}}\right]$$

Small $\boldsymbol{\rho_c}$: **Degeneracy unimportant and $\boldsymbol{T_c}$ grows as ~ $\boldsymbol{\rho_c^{1/3}}$.**

Large $\boldsymbol{\rho_c}$: → **$\boldsymbol{T_c}$ will peak and turn down**. "Degeneracy prevents further T_c increase". Note for too large ρ_c the formalism breaks down as T_c would become negative.

In Exercise Set 1: calculate T_c^{max} versus M_{core}.

Prospects for stars to ignite heavier fuels

If ρ_c is too large we instead have to use relativistic degeneracy, $\gamma = 4/3$:

$$\frac{\Re}{\mu} T_c = \rho_c^{1/3} * \left[\underbrace{\chi G M_{core}^{2/3}}_{C_1} - \underbrace{K_{4/3} \mu_e^{-4/3}}_{C_3} \right]$$

As long as $C_1 > C_3$, or equivalently

$$M_{core} > \left(\frac{K_{4/3}}{G}\right)^{3/2} \chi^{-3/2} \mu_e^{-2} = \underbrace{0.3 \chi^{-3/2} \left(\frac{\mu_e}{2}\right)^{-2}}_{"M_{crit}"} M_\odot$$

The temperature can keep rising indefinately.

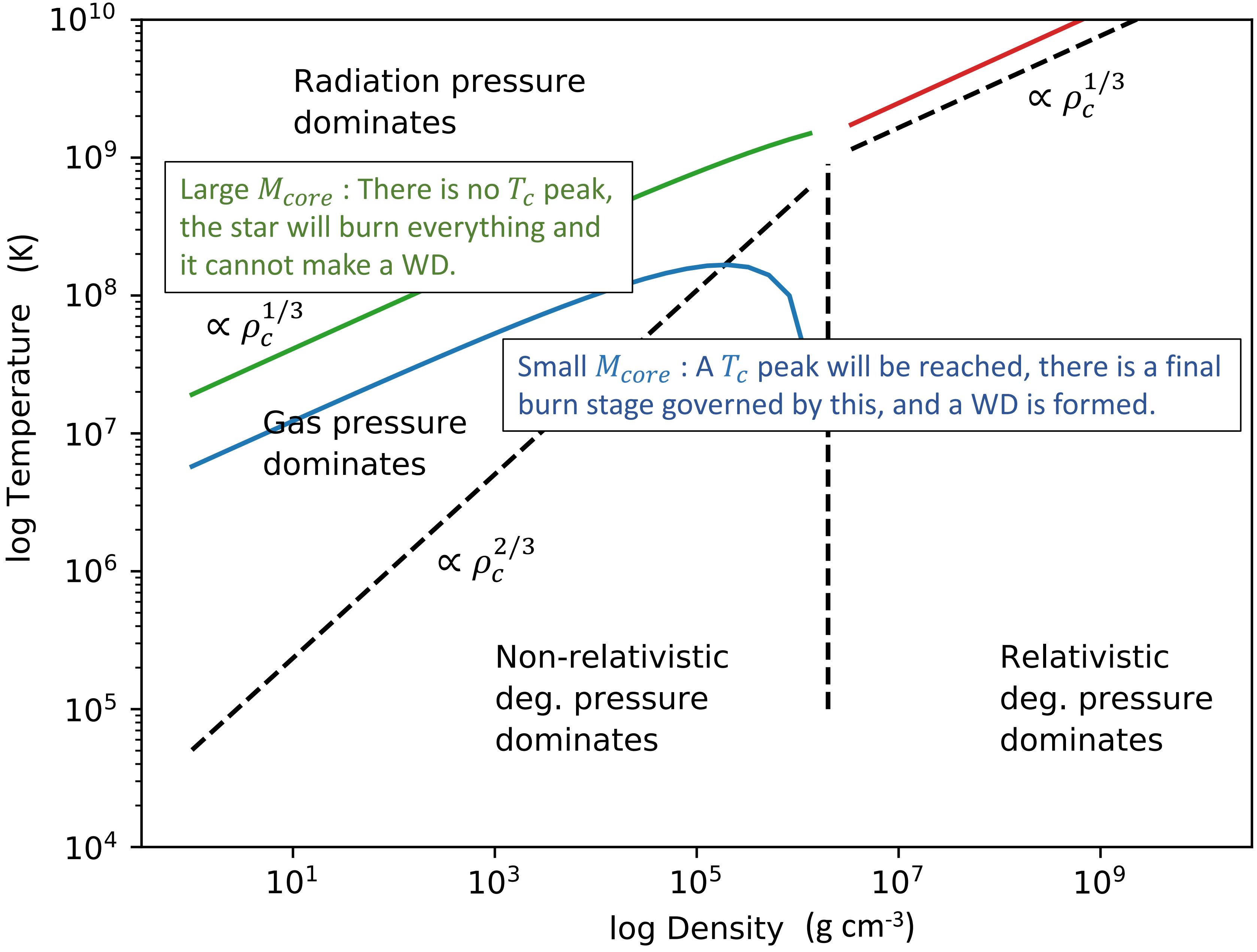
Care: Cores can have relativistic electrons, but pressure still be dominated by gas pressure.

If we have relativistic degeneracy, expect to be at or over M_{Ch} → $M_{crit} \sim M_{Ch}$.

Stellar cores with $M_{core} \gtrsim M_{Ch}$ will heat up indefinately and must ignite C (and later fuels).

Stellar cores with $M_{core} \lesssim M_{Ch}$ may ignite C depending on what their peak T_c becomes ($\gtrsim$ 7E8 K needed for C burning).

Prospects for stars to ignite heavier fuels



Large M_{core} : There is no T_c peak, the star will burn everything and it cannot make a WD.

Small M_{core} : A T_c peak will be reached, there is a final burn stage governed by this, and a WD is formed.

Can similarly show that when radiation pressure dominates, again $T_c \sim \rho_c^{1/3}$.

$T_c \sim \rho_c^{1/3}$ “rules” in the (T_c, ρ_c) plane.

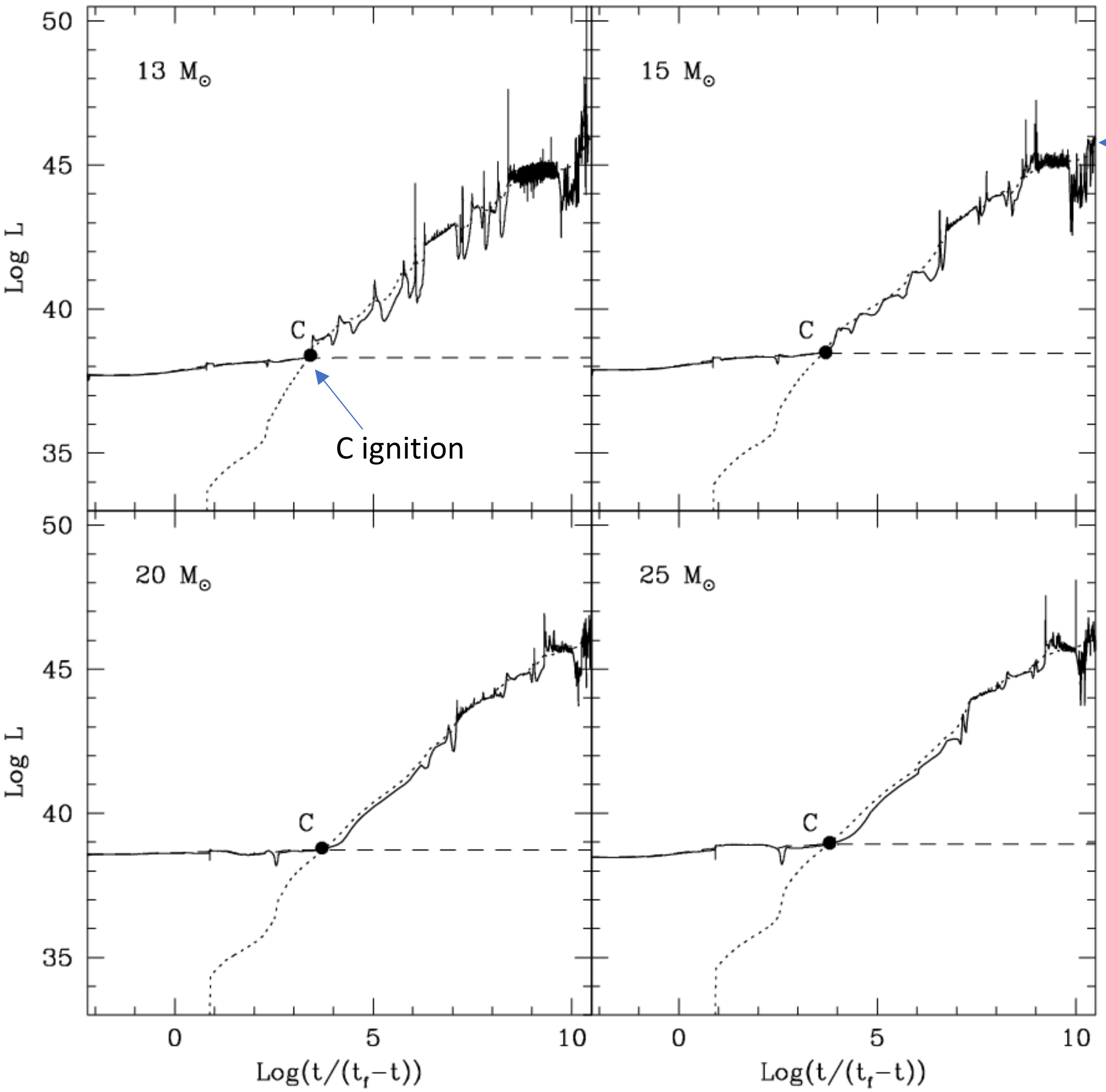
Degeneracy flattens tracks compared to $T_c \sim \rho_c^{1/3}$.

Neutrino cooling

In the late burning stages **neutrino cooling** becomes dominant → qualitatively different evolution because neutrinos do not contribute to the pressure.

The star struggles to maintain thermal pressure support (the neutrino leakage “robs” it of thermal energy) → starts to burns furiously and **fuels burn out much faster than before**.

Four of the six major burning stages in stars (C, Ne, O, and Si burning) occur under conditions of strong neutrino cooling.

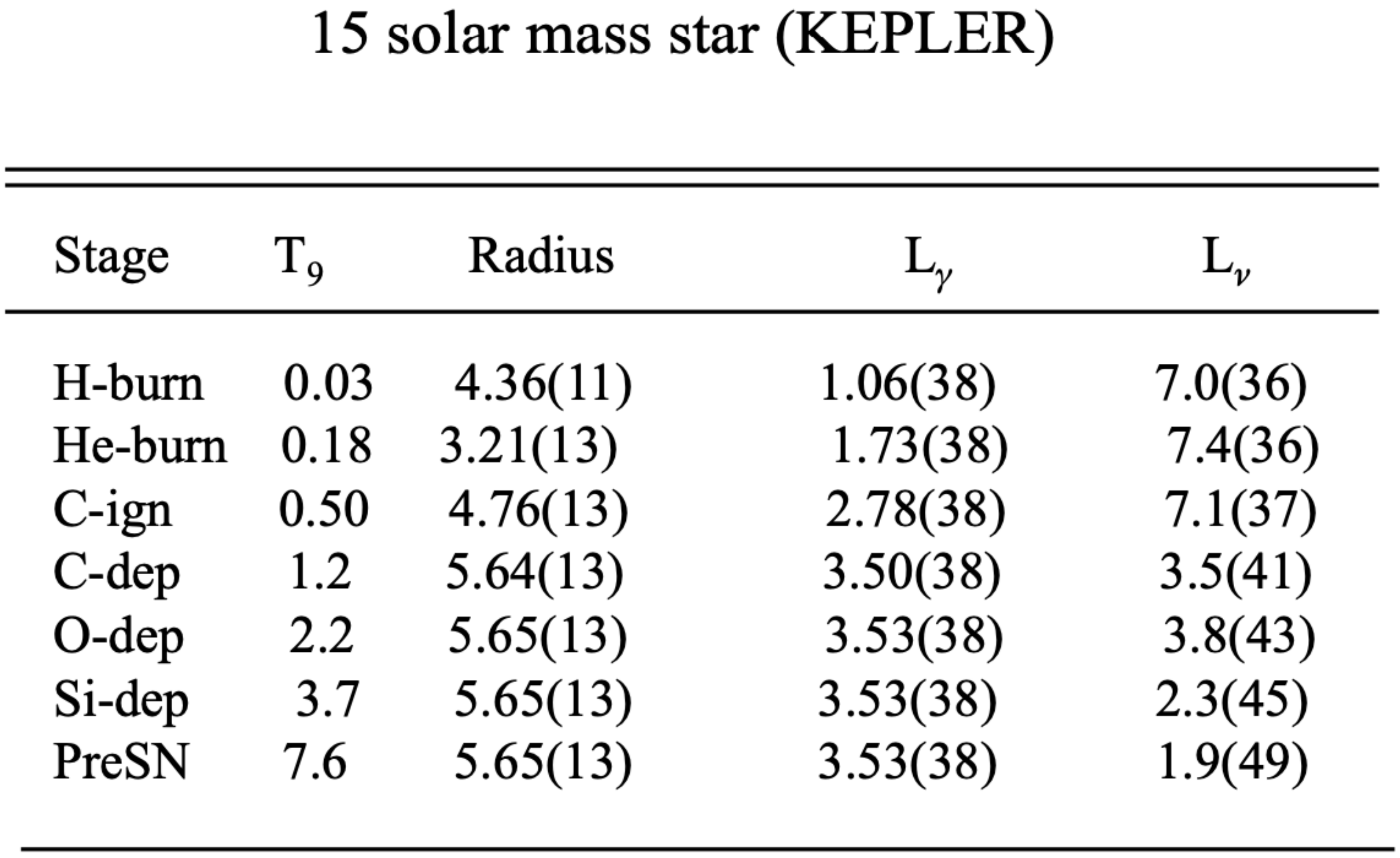


C ignition

Neutrino luminosity

Photon luminosity

Neutrino vs photon luminosity



15 solar mass star (KEPLER)

Stage	T_9	Radius	L_γ	L_ν
H-burn	0.03	4.36(11)	1.06(38)	7.0(36)
He-burn	0.18	3.21(13)	1.73(38)	7.4(36)
C-ign	0.50	4.76(13)	2.78(38)	7.1(37)
C-dep	1.2	5.64(13)	3.50(38)	3.5(41)
O-dep	2.2	5.65(13)	3.53(38)	3.8(43)
Si-dep	3.7	5.65(13)	3.53(38)	2.3(45)
PreSN	7.6	5.65(13)	3.53(38)	1.9(49)

S. Woosley

L_γ changes quite little, dominated by shell He burning in late stages.

Neutrino cooling processes

Good reference: Clayton book section 3.6

Two most important ones:

1] Pair annihilations

Nominally photons have enough energy to pair produce at $T \gtrsim \frac{2m_ec^2}{k} \sim 10^{10}$ K. However, production in the Maxwell-Boltzmann tail starts to have a thermodynamic impact already at $T \sim 3 * 10^8$ K.

Radiation ↔ $e^- + e^+$

$\boldsymbol{\nu} + \bar{\boldsymbol{\nu}}$ leakage
(1 in ~10^{19} times)

$\boxed{=2m_ec^2/kT}$

$$\varepsilon_\nu = 4.9 * 10^{18} T_9^3 \exp(-\frac{11.89}{T_9})\rho^{-1} \qquad \text{erg g}^{-1}\text{ s}^{-1} \quad T_9 < 1$$

$$= 4.6 * 10^{15} T_9^9\, \rho^{-1} \qquad T_9 > 1$$

Note no density dependence of cooling per unit volume (= $\varepsilon_\nu * \rho$) : Because positrons are destroyed by electrons their abundance tend to be inversily proportional to n_{e-} and then $n_{e-} * n_{e+}$ = constant.

Origin of T^9: If relativistic, $n_{e+} \sim n_{e-} \sim T^3$. $\sigma \sim T^2$. Energy per reaction $\sim T$ → $T^3 * T^3 * T^2 * T = T^9$

2] Plasma neutrino cooling

Plasma frequency

degeneracy suppression factor

$$\omega_p = 5.6 * 10^4 \sqrt{n_e} * \left(1 + 6.6 * 10^{-21} * n_e^{2/3}\right)^{-1}$$

γ → $e^+ + e^-$ decay becomes allowed as photon "obtains an effective rest mass" in the presence of plasma waves.

$$\varepsilon_\nu = 7.4 * 10^{21} \left(\frac{\hbar\omega_p}{m_ec^2}\right)^6 \left(\frac{kT}{m_ec^2}\right)^3 \rho^{-1} \text{ erg g}^{-1}\text{ s}^{-1}, \hbar\omega_p \leq kT$$

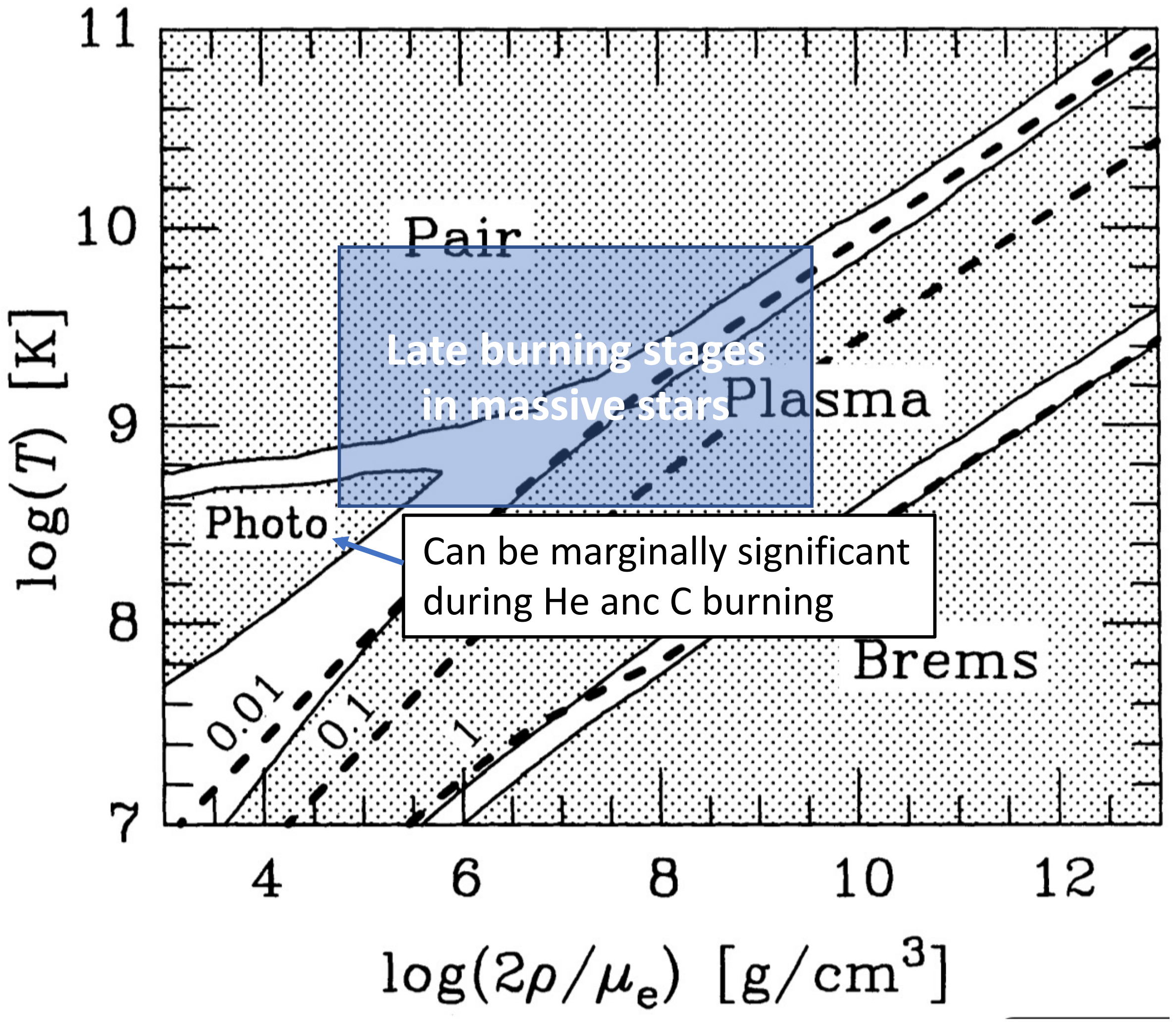
$$= 3.3 * 10^{21} \left(\frac{\hbar\omega_p}{m_ec^2}\right)^{7.5} \left(\frac{kT}{m_ec^2}\right)^3 * \exp(\frac{\hbar\omega_p}{kT})\, \rho^{-1}, \hbar\omega_p \geq kT$$

Neutrino cooling processes

Other neutrino cooling processes:

- **Photo-neutrino** (a Compton scattering where the outgoing e- is replaced by a neutrino and anti-neutrino)
- **Neutrino Bremsstrahlung :** Normal Bremsstrahlung but neutrino and anti-neutrino emitted instead of a photon (happens in small fraction of cases)
- **Synchrotron neutrinos** Same as above.

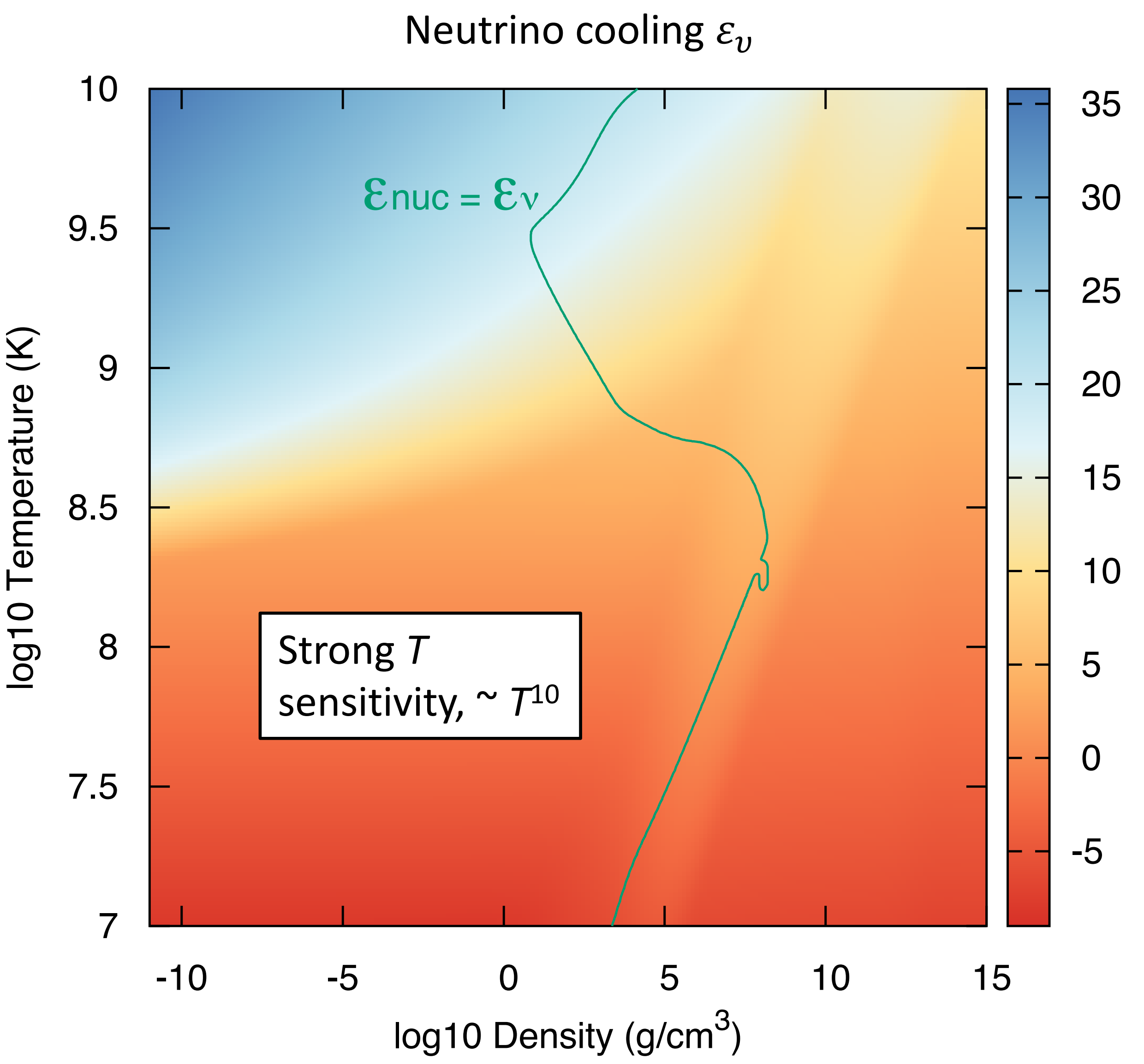
Neutrino cooling regimes



Late burning stages in massive stars

Can be marginally significant during He anc C burning

Haft 1994

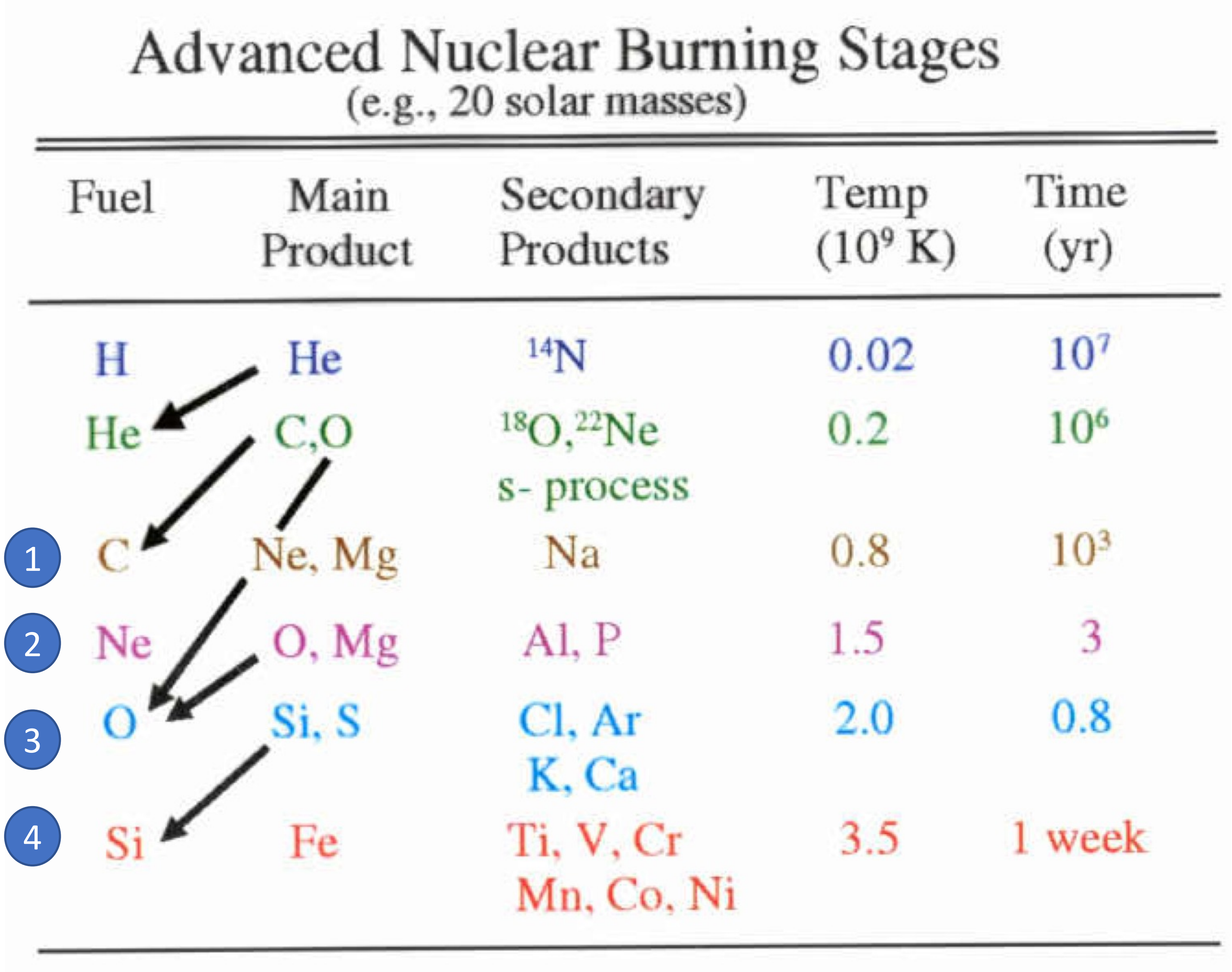


Neutrino cooling ε_υ

Strong *T* sensitivity, ~ T^{10}

Late burning stages in massive stars: pair annihilation process (low ρ) and plasma process (high ρ) most important.

Late burning stages: overview



Advanced Nuclear Burning Stages

(e.g., 20 solar masses)

	Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)
	H	He	^{14}N	0.02	10^7
	He	C,O	^{18}O, ^{22}Ne s- process	0.2	10^6
1	C	Ne, Mg	Na	0.8	10^3
2	Ne	O, Mg	Al, P	1.5	3
3	O	Si, S	Cl, Ar K, Ca	2.0	0.8
4	Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week

Credit: S. Woosley

Fowle and Hoyle 1964:

Because nuclear energy generation always has a much steeper T dependency (>~ T^{30}) than neutrino cooling (~T^{10}); stellar contraction will always be halted by burning of remaining fuel.

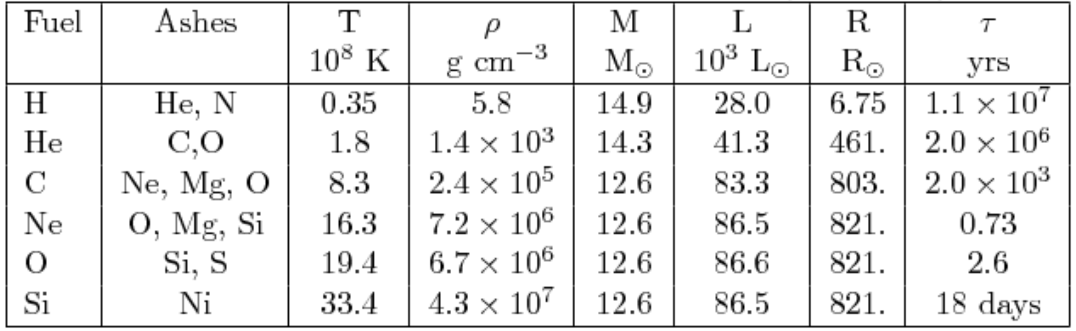
This means the core can be stopped from continued contraction as long as there is some fuel with burning potential left.

However, one exception:
Electron capture supernovae (more in Part D).

Late burning stages: overview

$15\ M_O$

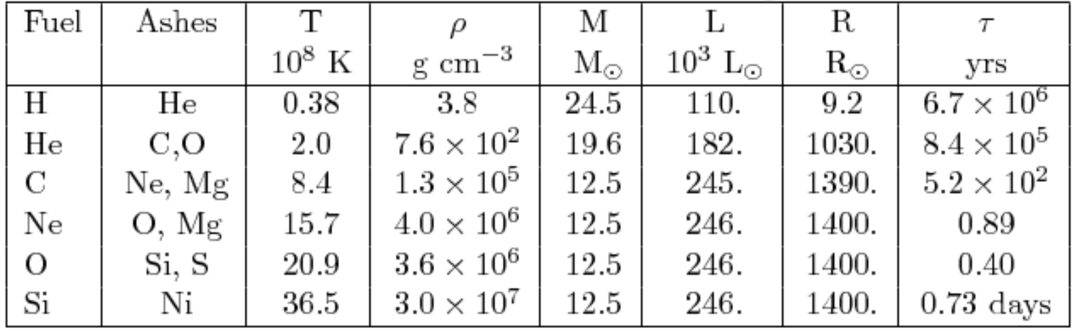
Table 1: **Burning stages for a 15 $M_\odot$ star (WHW02)**



Fuel	Ashes	T 10^8 K	ρ g cm^{-3}	M $M_\odot$	L $10^3\ L_\odot$	R $R_\odot$	τ yrs
H	He, N	0.35	5.8	14.9	28.0	6.75	1.1×10^7
He	C,O	1.8	1.4×10^3	14.3	41.3	461.	2.0×10^6
C	Ne, Mg, O	8.3	2.4×10^5	12.6	83.3	803.	2.0×10^3
Ne	O, Mg, Si	16.3	7.2×10^6	12.6	86.5	821.	0.73
O	Si, S	19.4	6.7×10^6	12.6	86.6	821.	2.6
Si	Ni	33.4	4.3×10^7	12.6	86.5	821.	18 days

$25\ M_O$

Table 2: **Same as above for a 25 $M_\odot$ star**



Fuel	Ashes	T 10^8 K	ρ g cm^{-3}	M $M_\odot$	L $10^3\ L_\odot$	R $R_\odot$	τ yrs
H	He	0.38	3.8	24.5	110.	9.2	6.7×10^6
He	C,O	2.0	7.6×10^2	19.6	182.	1030.	8.4×10^5
C	Ne, Mg	8.4	1.3×10^5	12.5	245.	1390.	5.2×10^2
Ne	O, Mg	15.7	4.0×10^6	12.5	246.	1400.	0.89
O	Si, S	20.9	3.6×10^6	12.5	246.	1400.	0.40
Si	Ni	36.5	3.0×10^7	12.5	246.	1400.	0.73 days

Credit: S. Woosley

CARBON BURNING

Carbon burning reactions

$T_9 = 0.5\text{-}1$, $\rho \sim 10^5\ \mathrm{g\ cm^{-3}}$.

$^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg}^* \rightarrow {}^{20}\mathrm{Ne} + \alpha + 4.62\ \mathrm{MeV}$ ~50%
$^{23}\mathrm{Na} + \mathrm{p} + 2.24\ \mathrm{MeV}$ ~50%
$^{23}\mathrm{Mg} + \mathrm{n} - 2.60\ \mathrm{MeV}$ ~0.1%

Note branching ratios depend on T as different excited states in $^{24}\mathrm{Mg}^*$ entered depending on T.

Direct $^{24}\mathrm{Mg}$ production by $^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg} + \gamma + 13.93\ \mathrm{MeV}$ unprobable/inefficient, Mg is not made by direct $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ fusion but by the secondary reactions

$$^{20}\mathrm{Ne} + \alpha \rightarrow {}^{24}\mathrm{Mg} + \gamma$$

$$^{23}\mathrm{Na} + \mathrm{p} \rightarrow {}^{24}\mathrm{Mg} + \gamma$$

Oxygen is left relatively untouched so ashes are still 60-70% O by mass (similar to what went in as fuel from He burning).

Principal production: $^{20,21}\mathrm{Ne}$, $^{23}\mathrm{Na}$, $^{24,25,26}\mathrm{Mg}$, $^{26,27}\mathrm{Al}$

<u>Typical yields</u>

$^{16}\mathrm{O}$	70%
$^{20}\mathrm{Ne}$	20%
$^{24}\mathrm{Mg}$	5%
$^{23}\mathrm{Na}$	0.5%
$^{26}\mathrm{Al}$	0.5%

Neutron excess changing reactions in C-burning

Significant proton production in main pathways of C burning (previous slide). These protons react further e.g. as

^{20}Ne(p, γ)^{21}Na(e+&υ)^{21}Ne ← η =0.048

Neutron excess $\eta = \frac{N_n - N_p}{N_n + N_p}$

continuing as

^{21}Ne(p, γ)^{22}Na(e+&υ)^{22}Ne (α,n) ^{25}Mg (p, γ) ^{26}Al (e+&υ) ^{26}Mg ← η =0.077

N_n number of neutrons (free and bound)
N_n number of protons (free and bound)

Another important reation is

^{12}C(p, γ)^{13}N(e+&υ)^{13}C(α,n)^{16}O This neutron can capture on e.g. ^{20}Ne to make ^{21}Ne

Overall :

- **At zero or low *Z*, C burning creates a neutron excess where none (or small) existed in the starting fuel (the seeds here, ^{20}Ne and ^{12}C, do not require any initial ^{14}N or similar).**

- **At *Z* ~ solar, η is increased somewhat (factor ~2) compared to the starting fuel value (see He burning section).**

The temperature of C burning

For ρ = 2*10^5 g cm^{-3}, X(^{12}C) = 0.2:

T_9	$\varepsilon_{\mathbf{nuc}}$	ε_{ν}
0.6	3.4E3	1.7E5
0.7	4.0E5	1.0E6
0.8	2.2E7	9.6E6
0.9	6.0E8	7.4E7
1.0	1.0E10	4.2E8

← Balance reached between 0.7 and 0.8 GK

If $\varepsilon_{\text{nuc}} >> \varepsilon_{\nu}$,the core must heat up and *T* increases.

If $\varepsilon_{\text{nuc}} << \varepsilon_{\nu}$,the core must cool and *T* decreases.

→ burning occurs for **thermal balance condition (**$\varepsilon_{\text{nuc}} = \varepsilon_{\nu}$ **)** as long as star has time to adjust its structure before the burning is over. <u>This condition is valid as a global one, i.e. see ε_{nuc} and ε_{ν} as total ones integrated over the core.</u>

Because of the very strong *T*-dependencies for both ε_{nuc} and ε_{ν}, the burning temperature becomes quite specific and only one fuel burns at a given time (at a given point in the star).

Carbon burning time-scale

$\lambda \approx 4 * 10^{-11} T_9^{29}$ cm^3 s^{-1}

$$n_{12} = \frac{N_{12C}}{V} \ (?)$$

$$\downarrow$$

$$\tau_{nuc} = \frac{N_{12C}}{\lambda n_{12C}^2 * V} = \frac{1}{\lambda n_{12C}} \sim \frac{1}{\lambda \varrho X_{12C}/12}$$

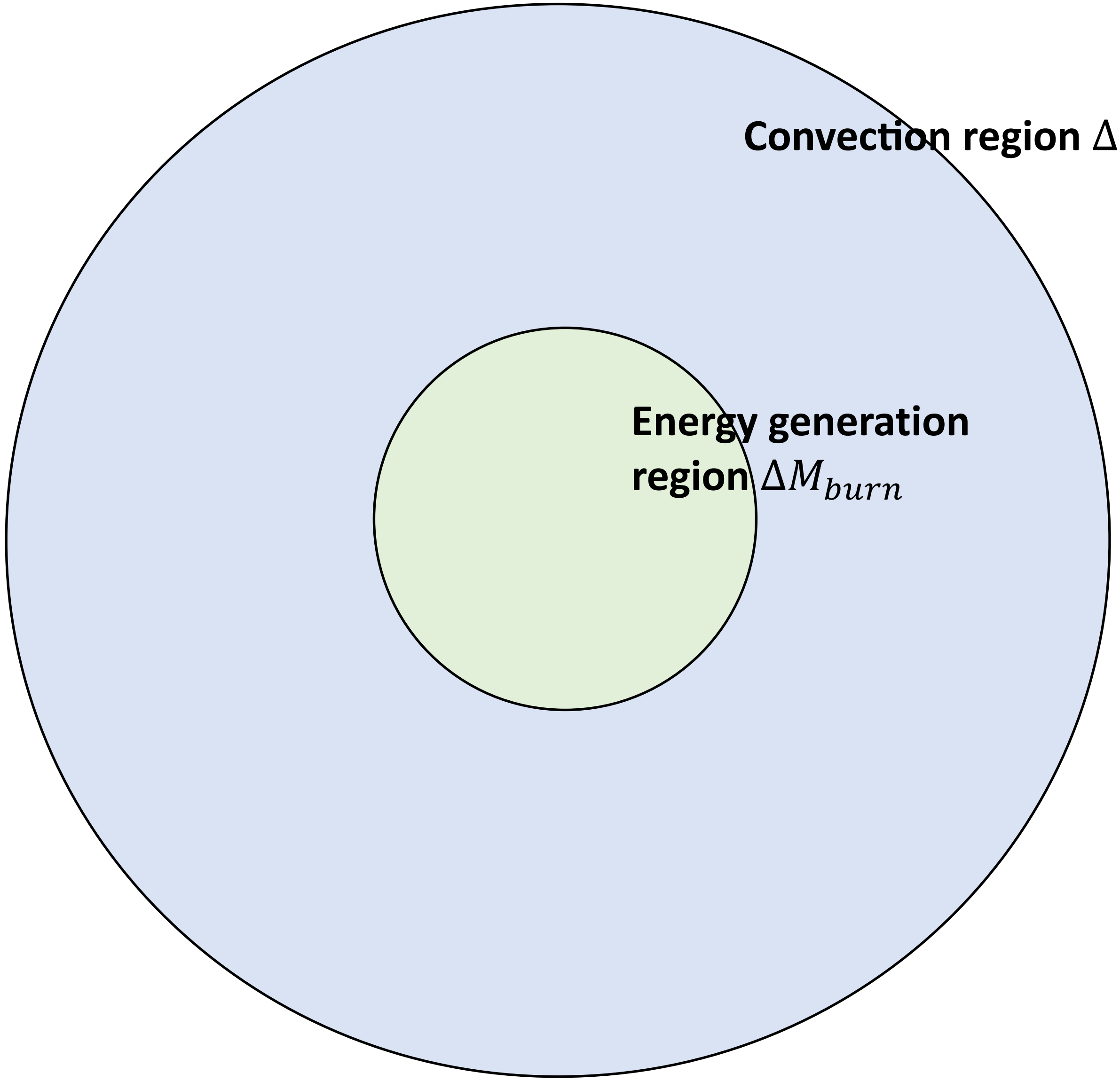
For $\lambda = 6 * 10^{-14}$ cm^3 s^{-1} (the value for $T_9 = 0.8$), $\varrho = 2 * 10^5$ g cm^{-3} , and X(^{12}C)= 0.1, get $\tau_{nuc} \sim \mathbf{300y.}$

Actual values in S.E. models are indeed a few hundred years for quite massive stars.

However, stars with M$_{ZAMS}$ =10 - 20 M$_{sun}$ have durations up to ~2000y, almost a factor 10 longer.

What is the origin of this discrepancy?

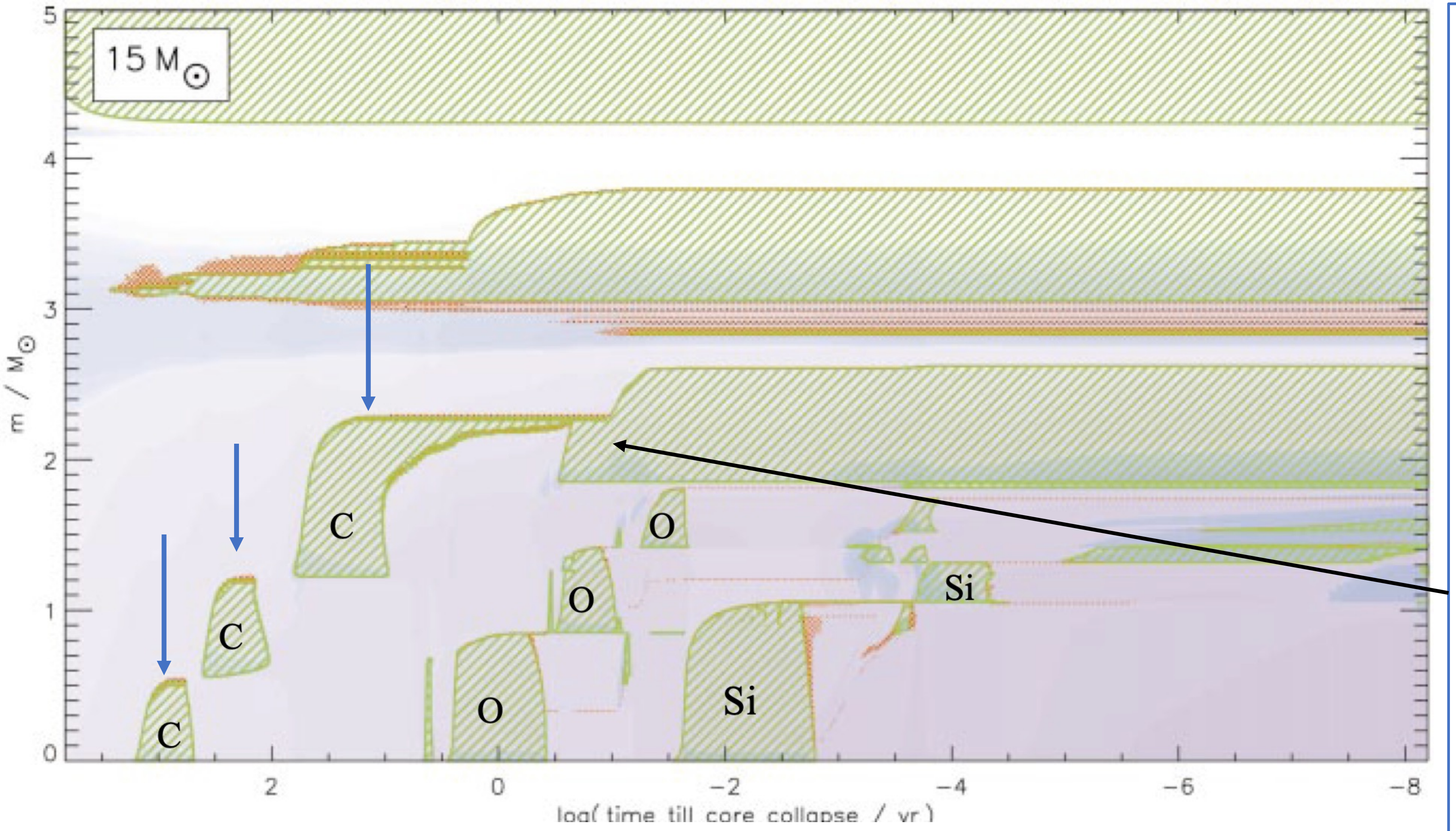
When convection is active, it lengthens the burn time by ~ $\Delta M_{conv}/\Delta M_{burn}$



Convection region ΔM_{conv}

Energy generation region ΔM_{burn}

C burning in a 15 M_{sun} star



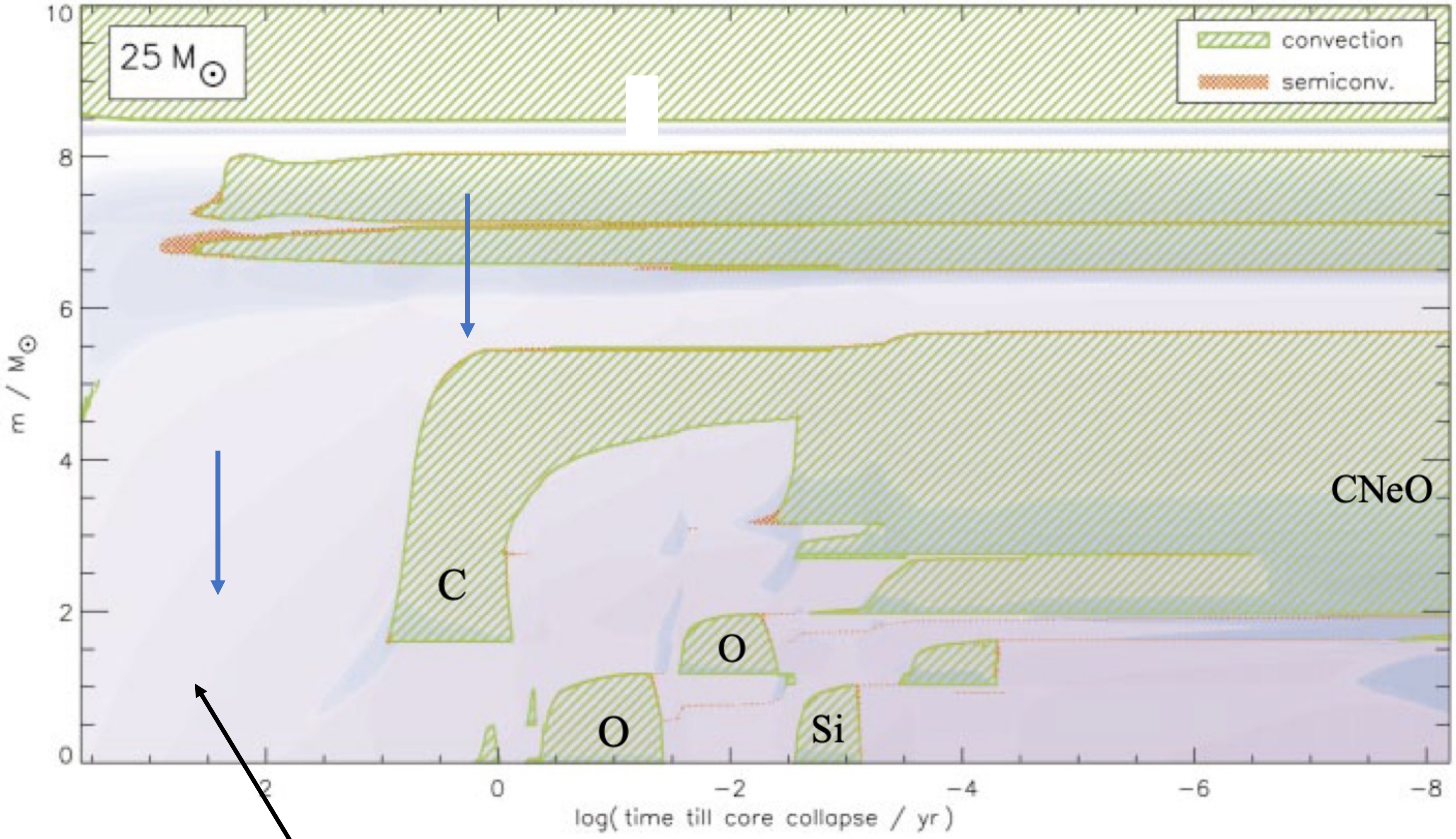
Woosley and Heger 2002

Convective core burning (innermost ~0.5 $M_\odot$,~2000y) followed by **two episodes of convectice shell burning** (~0.5 - 1.2 and ~1.2 - 2.2 $M_\odot$, resp.,~100y).

The shell burnings occur at higher T and last shorter. This is the stuff to be ejected in the supernova.

Note the dramatic changes in last few years of star's life: the convective C shell changes along with changes deeper in the star.

C burning in a 25 M_{sun} star



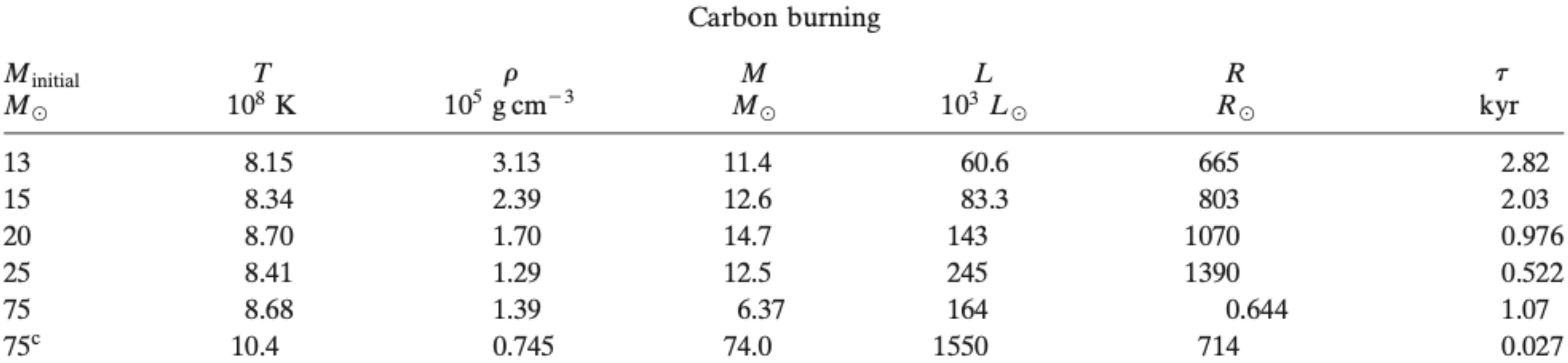
Non-convective core burning (innermost ~1.5 $M_\odot$,~300y) followed by **one episode of convective shell burning** (~1.5-5 $M_\odot$,~10y)

In more massive stars X(^{12}C) is lower → energy generation is too small to trigger convection.

Carbon core burning not centrally convective in more massive stars.

Woosley and Heger 2002

C burning in M_{ZAMS} = 13 - 75 $M_{\odot}$ stars



Carbon burning

M_{initial} $M_{\odot}$	T 10^8 K	ρ 10^5 g cm^{-3}	M $M_{\odot}$	L 10^3 $L_{\odot}$	R $R_{\odot}$	τ kyr
13	8.15	3.13	11.4	60.6	665	2.82
15	8.34	2.39	12.6	83.3	803	2.03
20	8.70	1.70	14.7	143	1070	0.976
25	8.41	1.29	12.5	245	1390	0.522
75	8.68	1.39	6.37	164	0.644	1.07
75^{c}	10.4	0.745	74.0	1550	714	0.027

Woosley and Heger 2002

Which stars can ignite C burning?

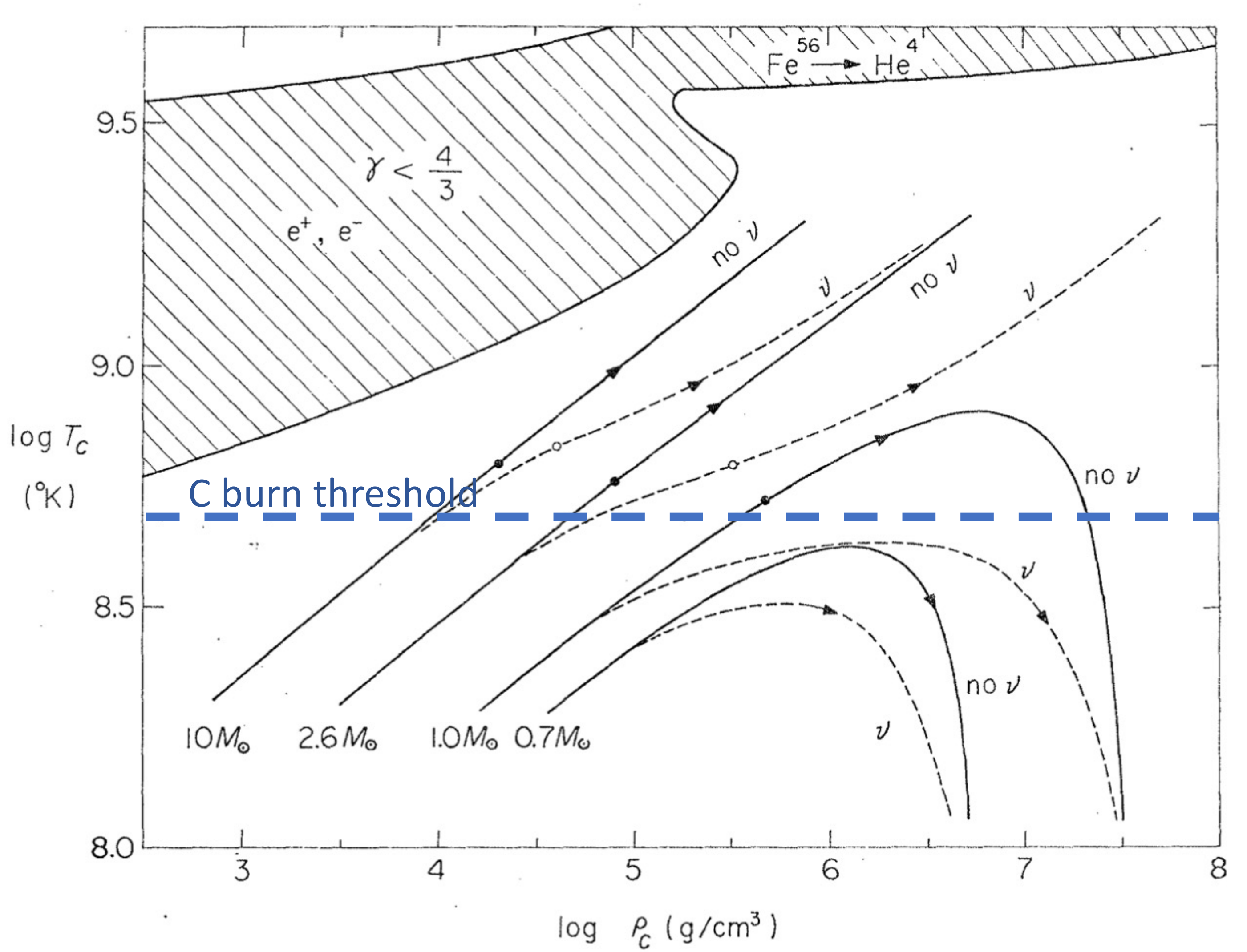


Fig. 1. The variations of the central temperature with the central density. The solid and dashed curves represent the cases without and with neutrinos, respectively. The closed and open circles denote the onset stage of carbon burning, which will be described in §4.

Murai 1968:

$M_{\mathrm{CO}} > 1.06\ M_\odot$ **critical CO core mass for C ignition.**

Holds up well in modern calculations.

C burning at low core masses

The lowest CO core mass (at core He burning exhaustion) that ignites carbon is around **1.06** $M_\odot$; requires (isolated, $M - M_\alpha$ approximation) He cores $M_{\mathrm{He}} \gtrsim 1.8\ M_\odot$.

Note that $M_{\mathrm{He}} < 1.8\ \ M_\odot$ cores also later do not ignite C even though the CO core can be grown up and above 1.06 $M_\odot$ (towards ~1.26 $M_\odot$) by shell He burning: this growth is too slow to raise the core temperature enough).

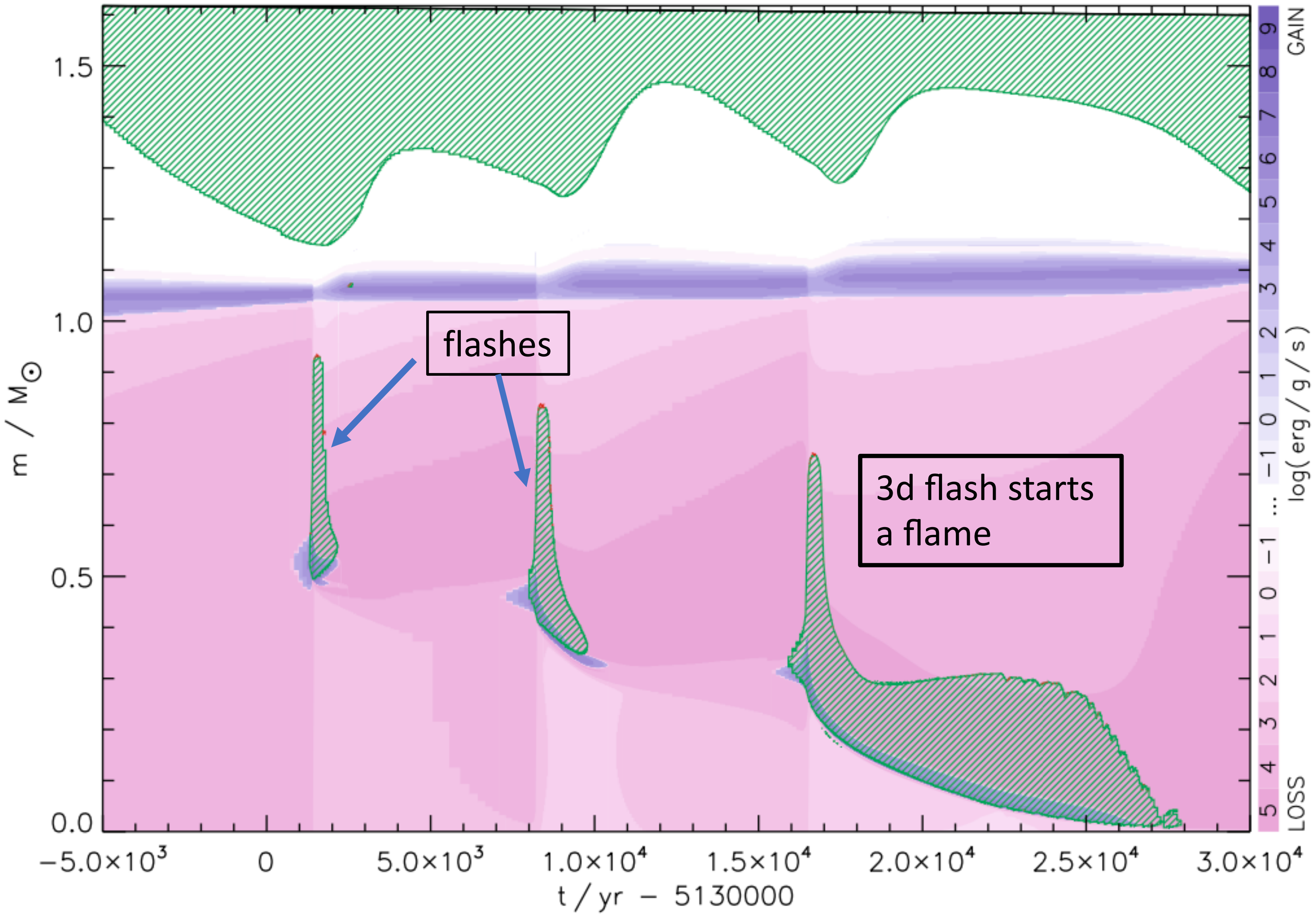
For $M_{CO} = 1.06 - 1.30\ M_\odot$ (M_{He}~$1.8 - 2.5\ M_\odot$) C ignition is **off-centre** (less and less so for higher mass). This is because neutrino cooling and degeneracy allows non-central *T* peaks.

Multiple **C flashes** (intervals $\sim$few 10^3y) precede the final birth of a **flame** that propagates to the centre. That final burning takes $\sim 10^3$y. Compare to He flashes in low-mass stars ($M_{\mathrm{He}} \lesssim 0.5\ \ M_\odot$).

For $M_{\mathrm{CO}} > 1.30\ M_\odot$ ($M_{\mathrm{He}} \gtrsim 2.5\ M_\odot$) ignition is central.

If the overlying layers are lost by winds/thermal pulses before the CO core grows towards M_{Ch} by He shell burning, the star ends as a **ONeMg white dwarf**. Theoretically possible for $M_{\mathrm{He}}(\mathrm{isolated}) \sim 1.8 - 2.7\ M_\odot$.

C burning at low core masses

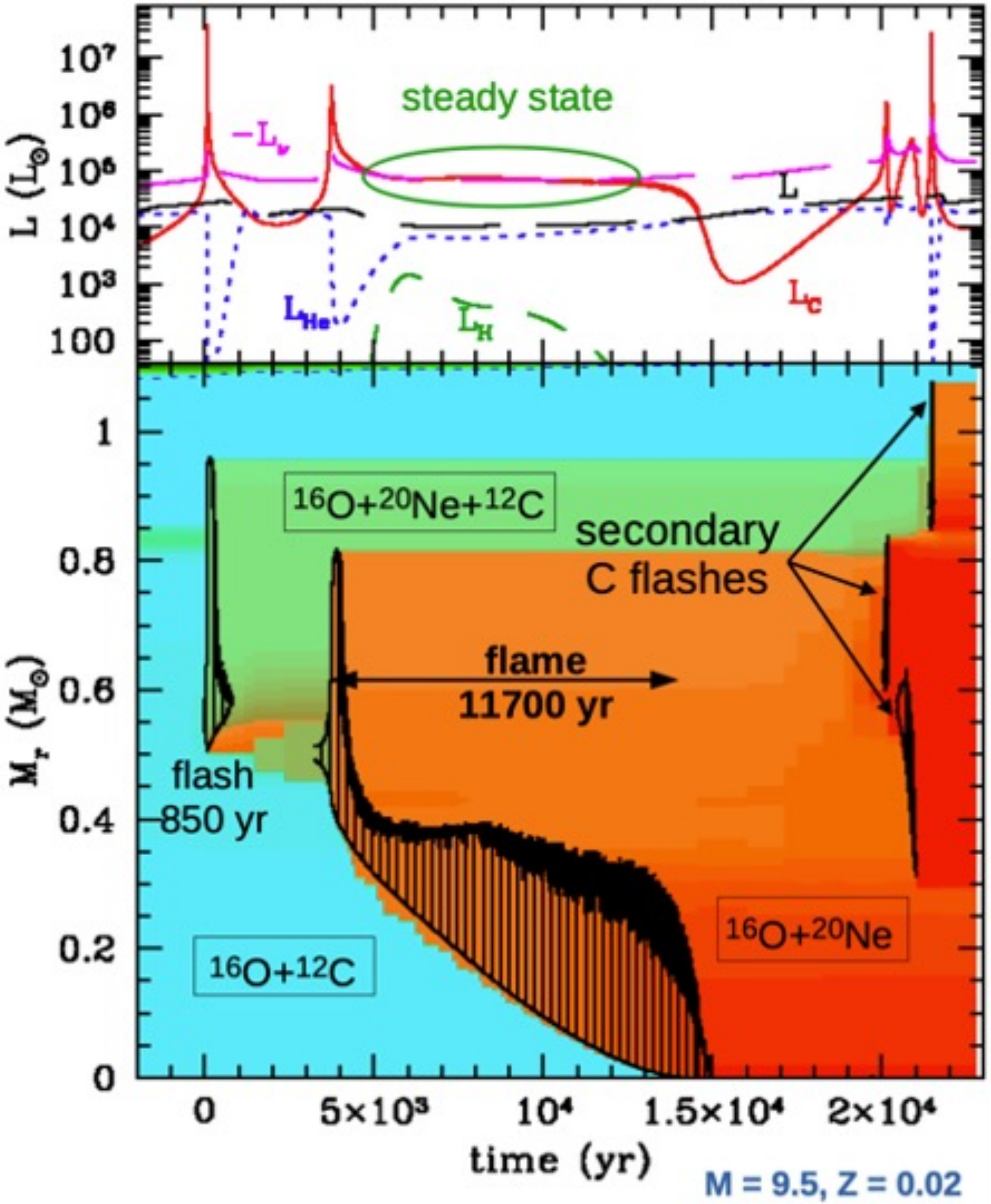


flashes

3d flash starts a flame

Woosley 2019

C burning at low core masses



L. Siess

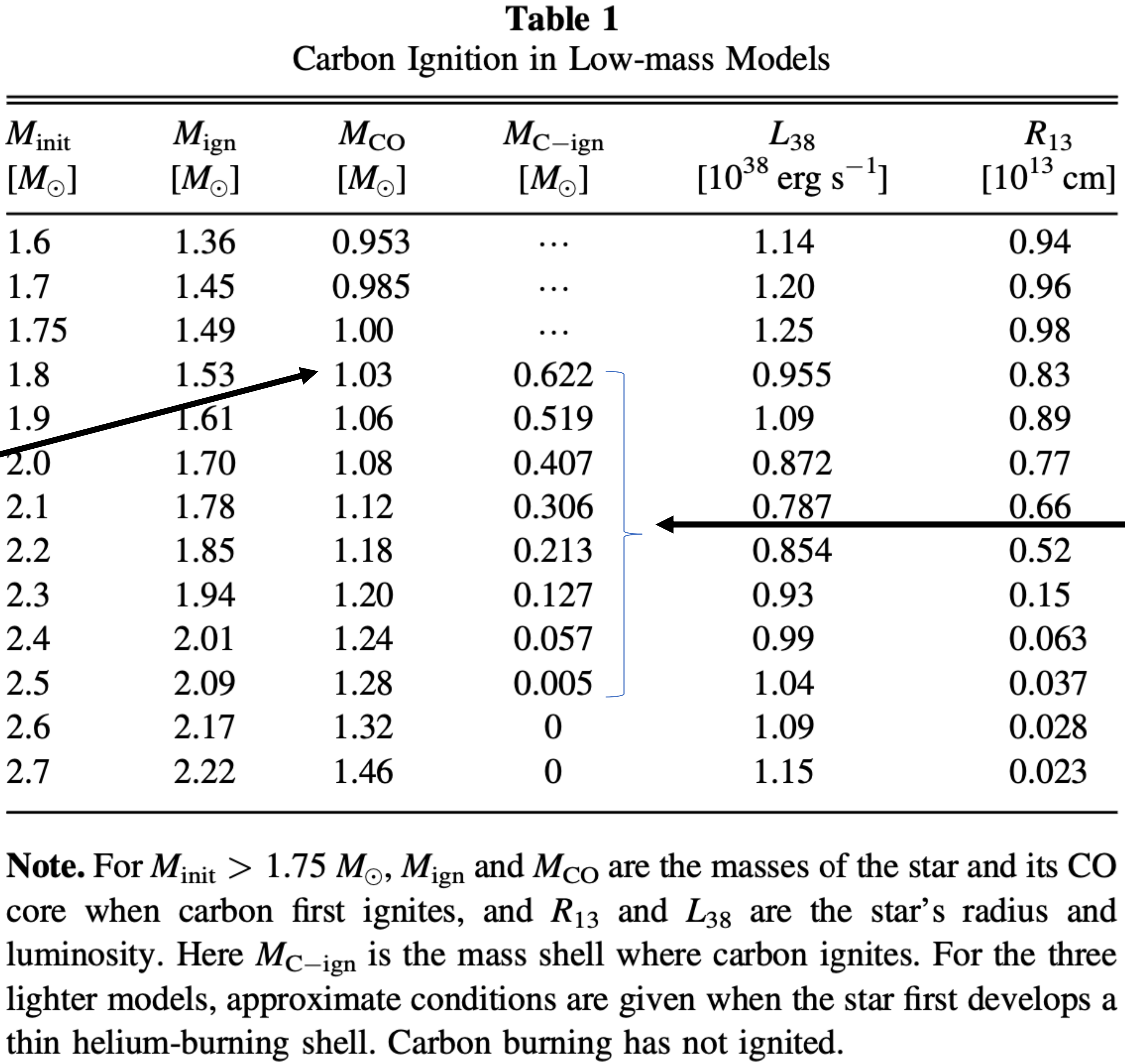


Table 1
Carbon Ignition in Low-mass Models

$M_{\rm init}$ $[M_\odot]$	$M_{\rm ign}$ $[M_\odot]$	$M_{\rm CO}$ $[M_\odot]$	$M_{\rm C-ign}$ $[M_\odot]$	L_{38} $[10^{38}$ erg s$^{-1}]$	R_{13} $[10^{13}$ cm$]$
1.6	1.36	0.953	···	1.14	0.94
1.7	1.45	0.985	···	1.20	0.96
1.75	1.49	1.00	···	1.25	0.98
1.8	1.53	1.03	0.622	0.955	0.83
1.9	1.61	1.06	0.519	1.09	0.89
2.0	1.70	1.08	0.407	0.872	0.77
2.1	1.78	1.12	0.306	0.787	0.66
2.2	1.85	1.18	0.213	0.854	0.52
2.3	1.94	1.20	0.127	0.93	0.15
2.4	2.01	1.24	0.057	0.99	0.063
2.5	2.09	1.28	0.005	1.04	0.037
2.6	2.17	1.32	0	1.09	0.028
2.7	2.22	1.46	0	1.15	0.023

Note. For $M_{\rm init} > 1.75\ M_\odot$, $M_{\rm ign}$ and $M_{\rm CO}$ are the masses of the star and its CO core when carbon first ignites, and R_{13} and L_{38} are the star's radius and luminosity. Here $M_{\rm C-ign}$ is the mass shell where carbon ignites. For the three lighter models, approximate conditions are given when the star first develops a thin helium-burning shell. Carbon burning has not ignited.

He core mass

C ignition
for $M_{\rm CO} \geq 1.03\ M_\odot$
(compare
Murai's 1.06 $M_\odot$).

Off-centre ignition in
$1.03 - 1.30\ M_\odot$ range

Woosley 2019

Super-AGB stars

Super-AGB stars are AGB stars where the core has ignited also C and thus have an ONeMg core being formed. Predicted above a M_{ZAMS} mass threshold $M_{\mathrm{up}} \sim 8\ M_{\odot}$ (CO core mass must exceed $1.06\ M_{\odot}$).

Term definition

No clear observational identification yet of sAGB stars. Almost indistinguishable from RSGs. Some indirect evidence e.g. Ne novae, massive WDs.

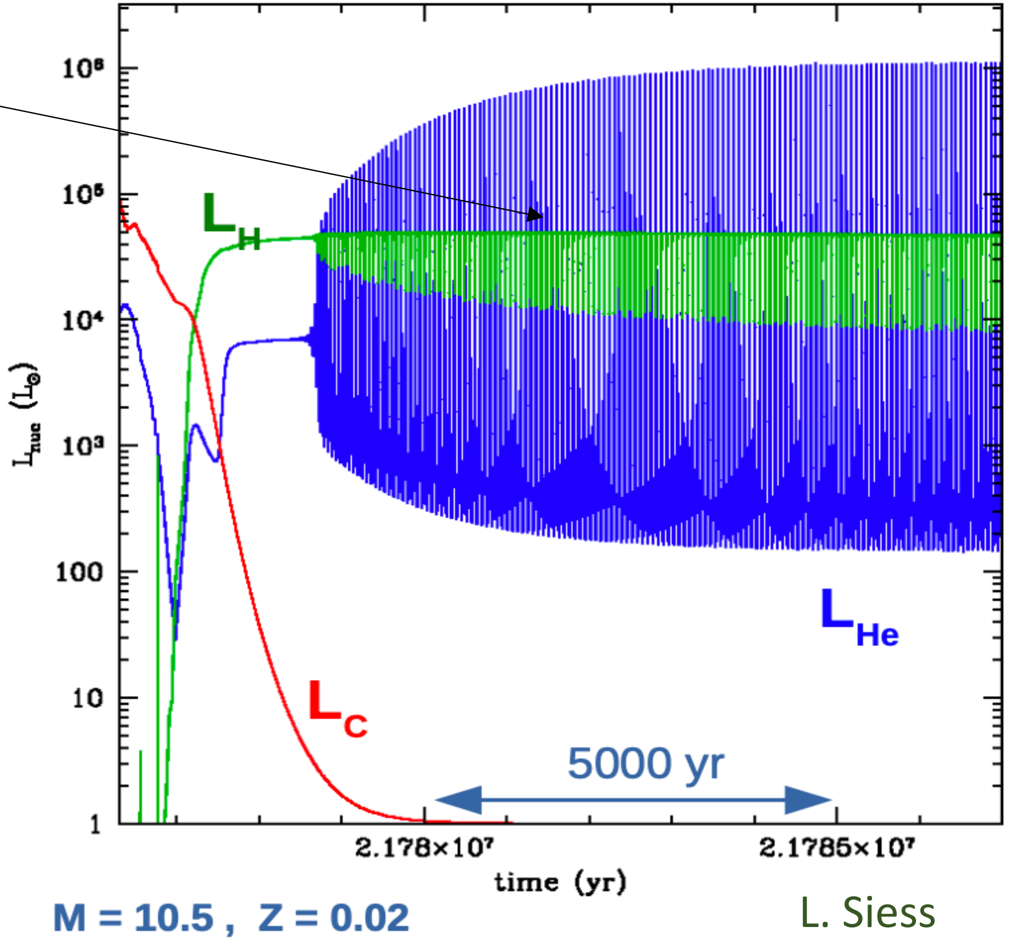
Typically **thousands of thermal pulses** in the C-burning phase.

- Duration ~ few years
- ~100y between the pulses
- Mass involved $\sim 10^{-4}\ M_{\odot}$

Theoretically, two possible fates

1. ONeMg white dwarf
2. Electron capture supernova (ECSN, see PartD). Happens if ONeMg core manages to grow to ~$1.38\ M_{\odot}$ before all envelope is lost.

Massive white dwarfs are known whereas ECSNe have not been convincingly established → **First path likely dominant or maybe even exclusive.**



L. Siess

NEON BURNING

Neon burning

$T_9 = 1.5$, $\rho \sim (3\text{-}10)*10^6$ g cm^{-3}

At ~1.5 GK, **neon starts 'melting' by photodisintegration** (inverse process to radiative capture) : photons break up nuclei in analogous way to how they break up atoms by photoionization.

$^{20}Ne + \gamma \rightarrow {}^{16}O + \alpha - 4.7$ MeV

For ^{16}O and ^{24}Mg the α dissociation energy is 7.2 MeV and 9.3 MeV, respectively,
→ ^{20}Ne is most fragile of thee three (at 4.7 Mev diss. energy) and melts first.

Most alphas merge back, but some capture on ^{20}Ne:

$^{20}Ne + \alpha \rightarrow {}^{24}Mg + 9.3$ MeV

All in all:

$2\ {}^{20}Ne \rightarrow {}^{16}O + {}^{24}Mg + 4.6$ MeV

($^{25,26}Mg$, ^{27}Al existed from C burning)

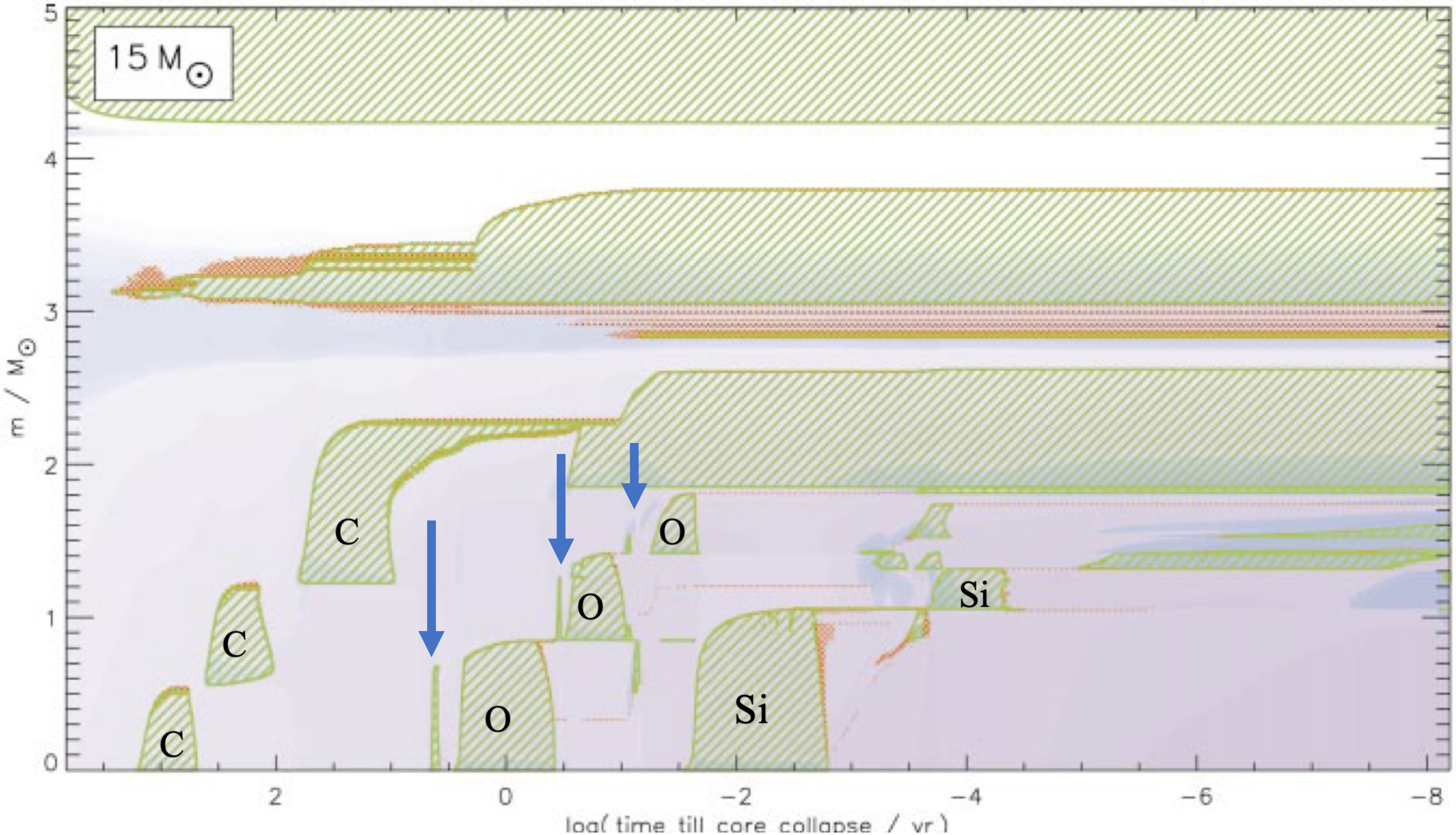
Secondary reactions $^{24}Mg(\alpha,\gamma)^{28}Si$ $^{25}Mg(\alpha,\gamma)^{29}Si$ $^{26}Mg(\alpha,\gamma)^{30}Si$ $^{27}Al(\alpha,\gamma)^{30}Si$ $^{30}Si(\alpha,\gamma)^{31}P$

Principal production: ^{16}O, ^{24}Mg, ^{28}Si, $^{29,30}Si$, ^{31}P, ^{26}Al

<u>Typical yields</u>

^{16}O	80%
^{24}Mg	10%
^{28}Si	5%

Ne burning in a 15 M_{sun} star



Convective core and two convective shell burnings, as in C burning.

Brief, followed very quickly by O burning.

In this example all layers will be further burnt -> That ash will not get ejected as it is. But can be different in other models.

Neon ignition mass

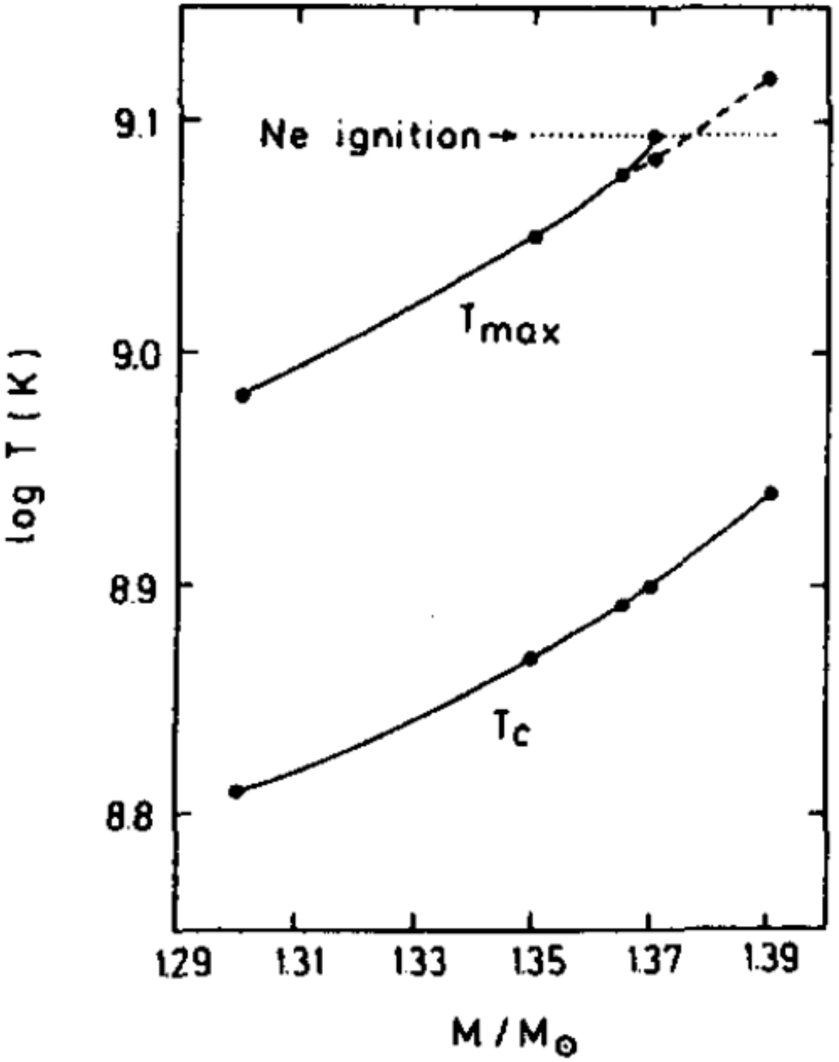


Fig. 3 Nomoto 1984a (a good paper to understand core evolution and ignition conditions).

Analogous the the C ignition mass ($1.06\ M_\odot$), for Ne burning the core mass threshold is $\mathbf{1.37}\ \boldsymbol{M_\odot}$ (Boozer 1973, Nomoto 1984), which corresponds to $M_{\rm He}\sim 2.65\ M_\odot$.

OXYGEN BURNING

Oxygen burning

$T_9 = 1.8$, $\rho \sim 10^7$ g cm^{-3}

$^{16}O + ^{16}O \rightarrow ^{32}S^* \rightarrow ^{28}Si + \alpha + 9.6$ MeV	~34%
$^{31}P + p + 7.7$ MeV	~56%
$^{30}P + d - 2.4$ MeV	~5%
$^{31}S + n + 1.5$ MeV	

Secondary reactions e.g. $^{28}Si(\alpha, \gamma)^{32}S$ + many others

Many nuclei made are now radioactive. Also electron capture reactions start to be important → <u>neutron excess increases significantly.</u>

s-process elements here get destroyed by photodisintegration, “melt into iron group”.

Principal production: ^{28}Si, ^{32,33,34}S, ^{35,37}Cl, ^{36,38}Ar, ^{39,41}K, ^{40,42}Ca

<u>Typical yields</u>	
^{28}Si	45%
^{32}S	40%
^{36}Ar	5%
^{40}Ca	3%

Neutron excess changing reactions in O-burning

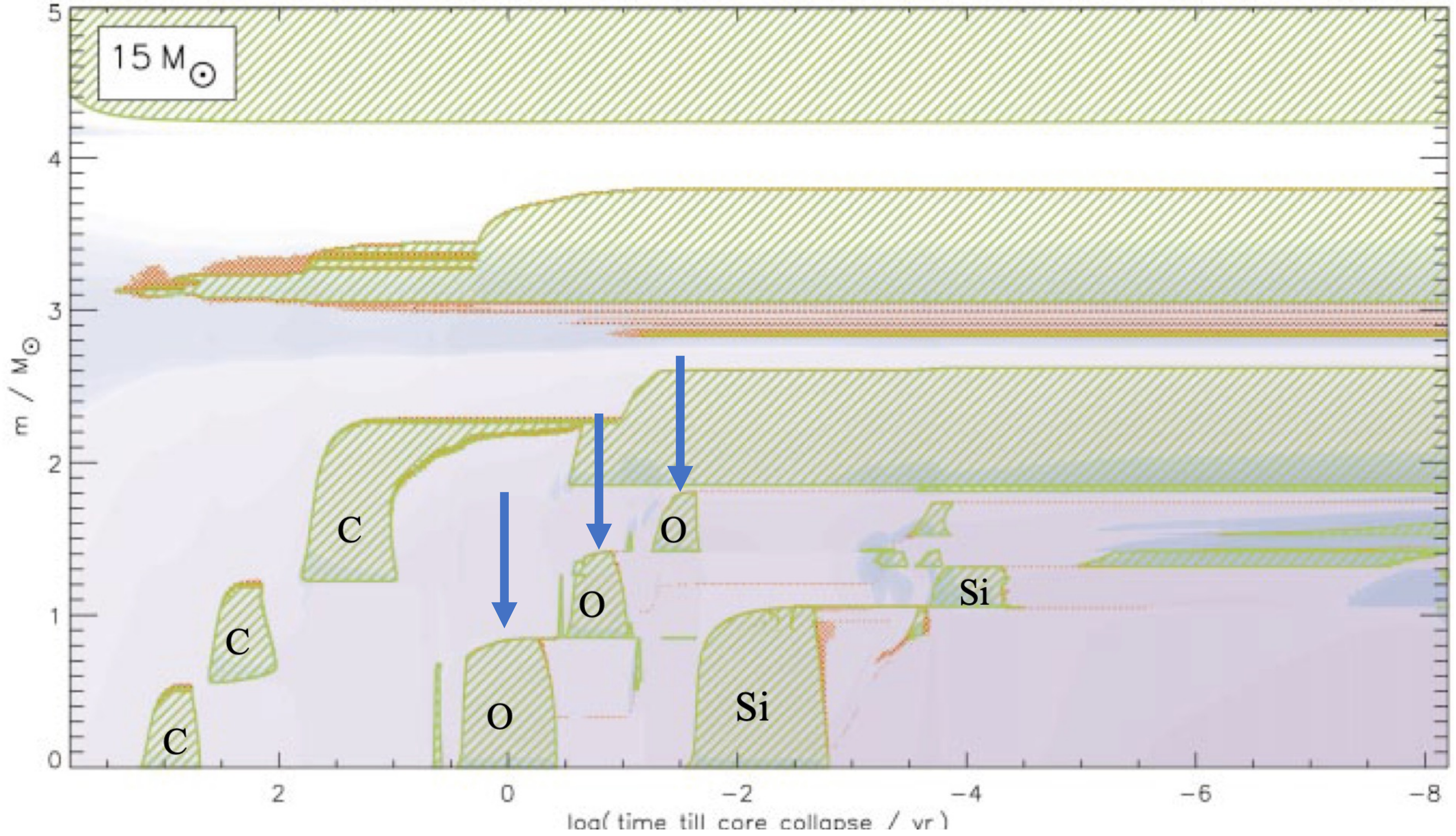
At the end of <u>core</u> O burning, η > 0.01 and very non-solar abundances (which have $\eta \sim 10^{-3}$) arise
→ this material cannot (regularly) be ejected back into the ISM.

It is not only specific element abundances and ratios that matter for this argument: it is η itself.

One can draw a conclusion that these cores in massive stars must form some kind of remnant rather than be ejected. If $M > M_{Ch}$ it can't be a white dwarf. What is it then?

<u>Shell</u> O burning gives less strong η production ($\eta \sim 3 * 10^{-3}$) as lower density means fewer electron capture reactions, and also burning does not have time to complete before star reaches collapse point. Still, the abundances are quite far from solar also from shell burning and it would be problematic if this material is frequently ejected also.

O burning in a 15 M_{sun} star



Core and two shell burnings, as in C and Ne burning. Reach out to $1.6\,M_\odot > M_{\mathrm{Ch}}$.

Not all ash reprocessed by next (and final) burning stage.

SILICON BURNING

Silicon burning

T_9 ~ 3.5 , ρ ~ 10^8 g cm^{-3}

Neutrino emission by weak interactions now important.

τ_{nuc} ~ 1d → MLT problematic

Photodisintegration and alpha ”bake-ups”

$^{28}Si(\gamma, \alpha)^{24}Mg(\gamma, \alpha)^{20}Ne$…

E.g. ^{28}Si as start fuel:

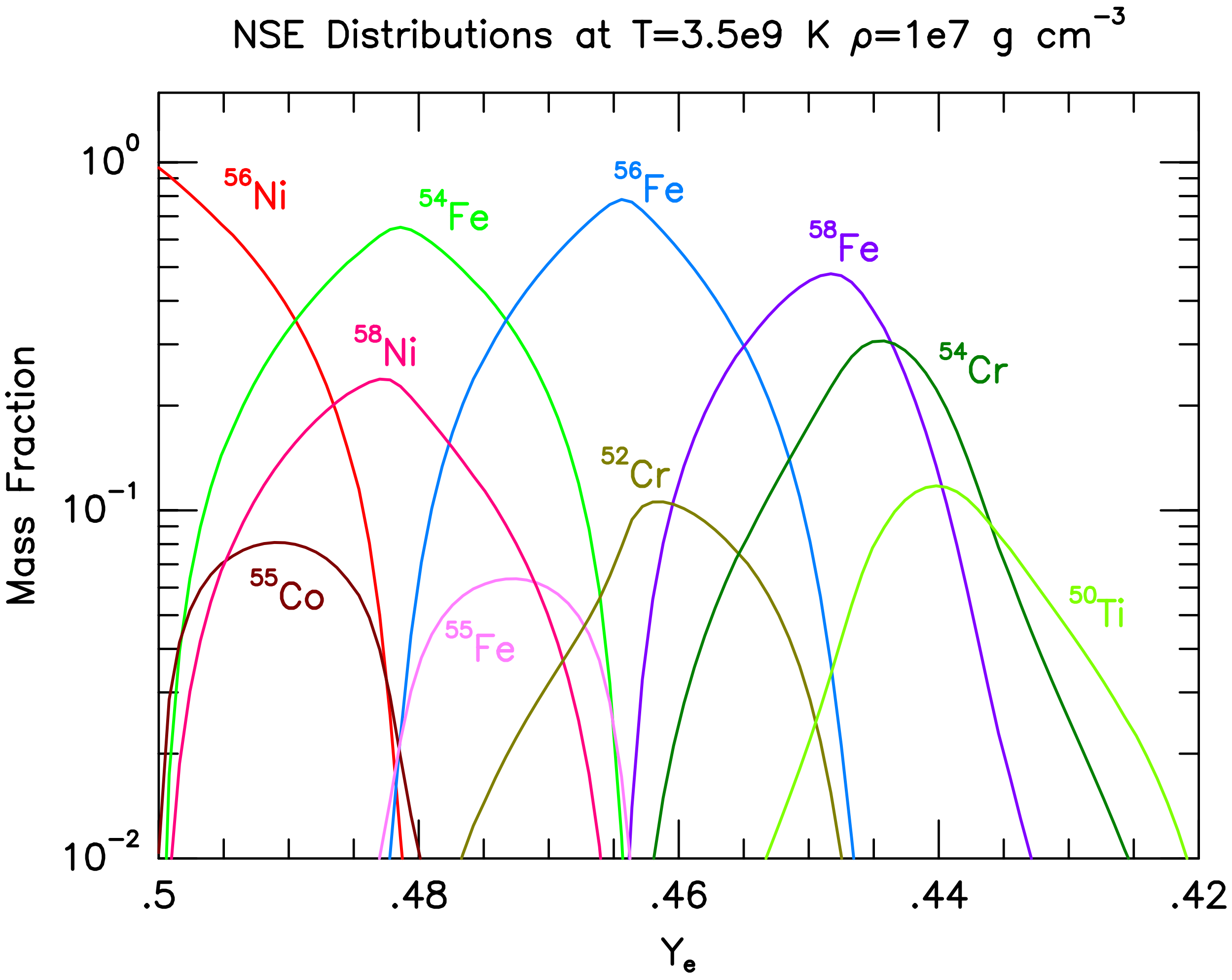
$^{28}Si(\alpha, \gamma)^{32}S\ (\alpha, \gamma)^{36}Ar\ (\alpha, \gamma)^{40}Ca\ (\alpha, \gamma)^{44}Ti\ (\alpha, \gamma)^{48}Cr\ (\alpha, \gamma)^{52}Fe\ (\alpha, \gamma)\mathbf{^{56}Ni}$

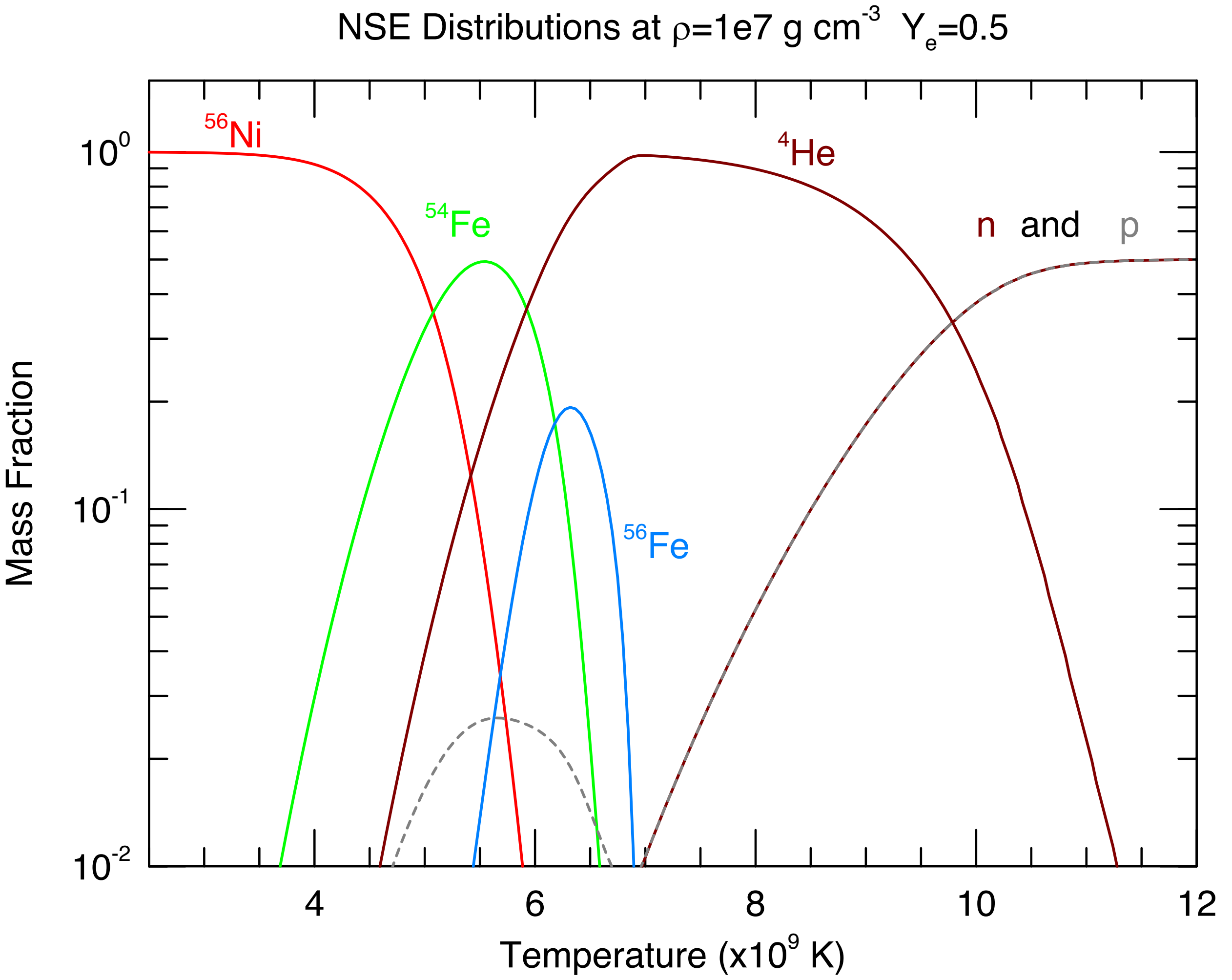
However in the core, the fuel composition from O burning is mainly ^{30}Si, ^{34}S, ^{38}Ar and one gets instead:

$^{30}Si(\alpha, \gamma)^{34}S\ (\alpha, \gamma)^{38}Ar\ (\alpha, \gamma)^{42}Ca\ (\alpha, \gamma)^{46}Ti\ (\alpha, \gamma)^{52}Cr\ (\alpha, \gamma)\mathbf{^{54}Fe}\ (\alpha, \gamma)\mathbf{^{58}Ni}$

T and ρ are now so high that **nuclear statistical equilibrium (NSE) is** approached: all strong interactions (but not the weak ones) in detailed balance. Can show that in NSE, production favors most tighly bound nucleus for given η.

NSE distributions



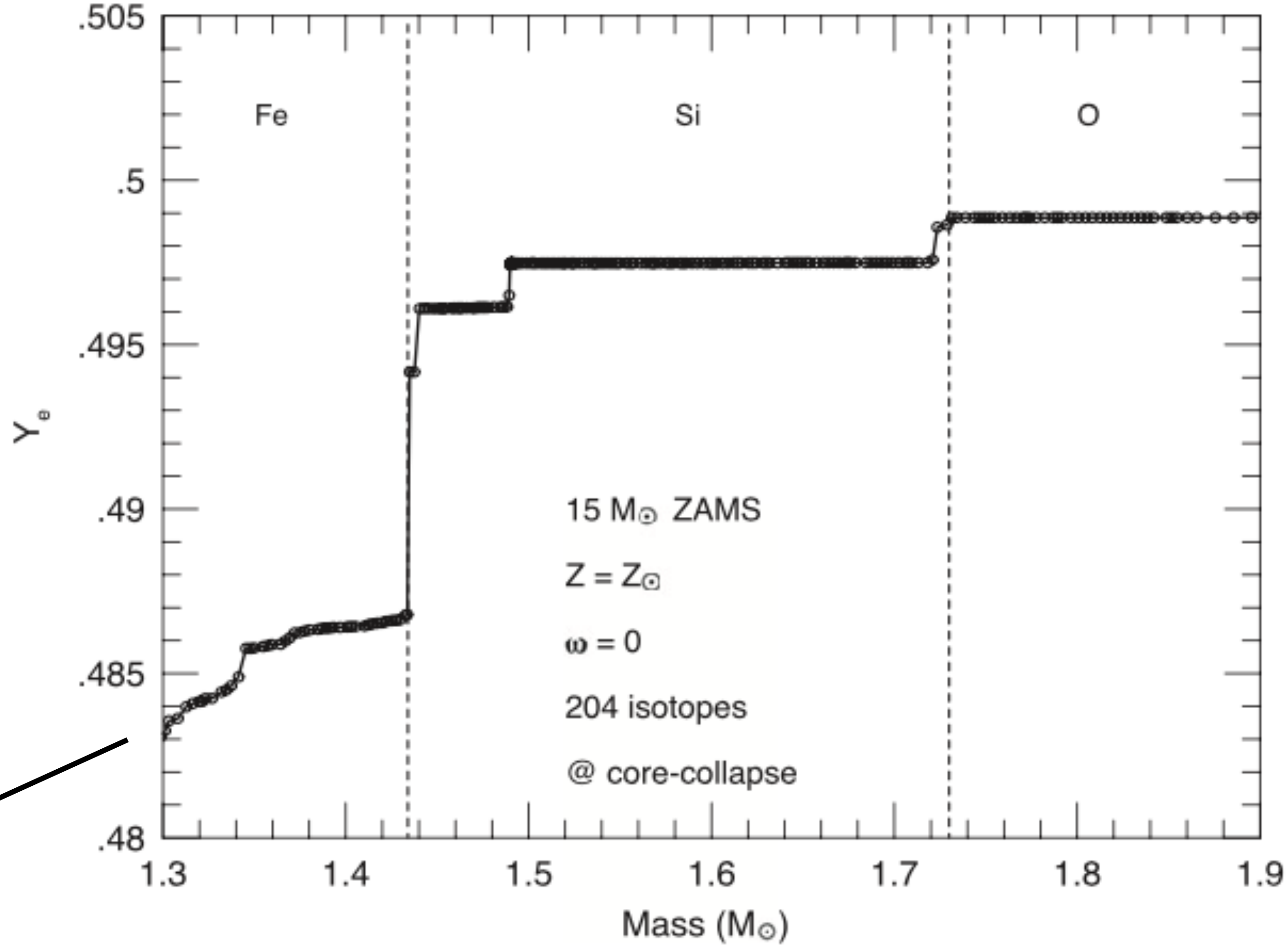


Neutron excess changing reactions during Si-burning

15 M_{sun} star: At Si depletion $\eta \gtrsim 0.15$ in centre of iron core ($Y_e \lesssim 0.43$), ~ 0.03 at outer edge ($Y_e \lesssim 0.485$), on average $\eta \sim 0.1$ ($Y_e \sim 0.45$) .

Core is now "heavily deleptonized". Large number of electron capture reactions responsible.

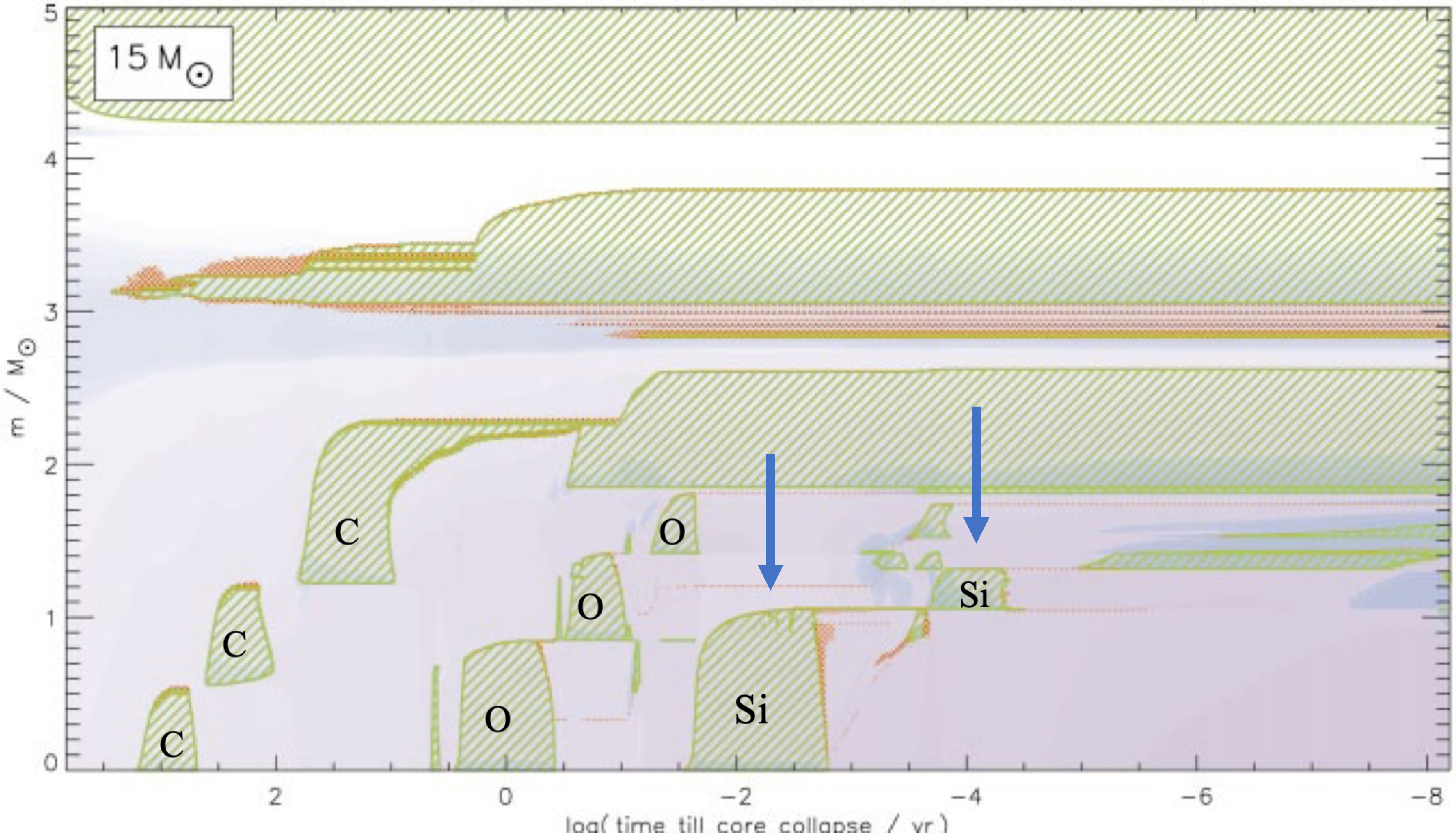
$$\boxed{Y_e \equiv \frac{1-\eta}{2}}$$



Continues to $Y_e \sim 0.43$ at m=0

Jerkstrand+2015

Si burning in a 15 M_{sun} star



Core (~1 $M_{\odot}$) and **one shell burning** (1-1.2 $M_{\odot}$). Shell ignites 1h before collapse.

Not all O-burning material is reprocessed: an ”Si shell” will reside outside the Fe core formed by the Si burning.

Si shell

Iron core

Silicon burning at low core masses

Off-centre ignition in the lowest-mass CO cores $(1.37 - 1.65\ M_\odot)$.

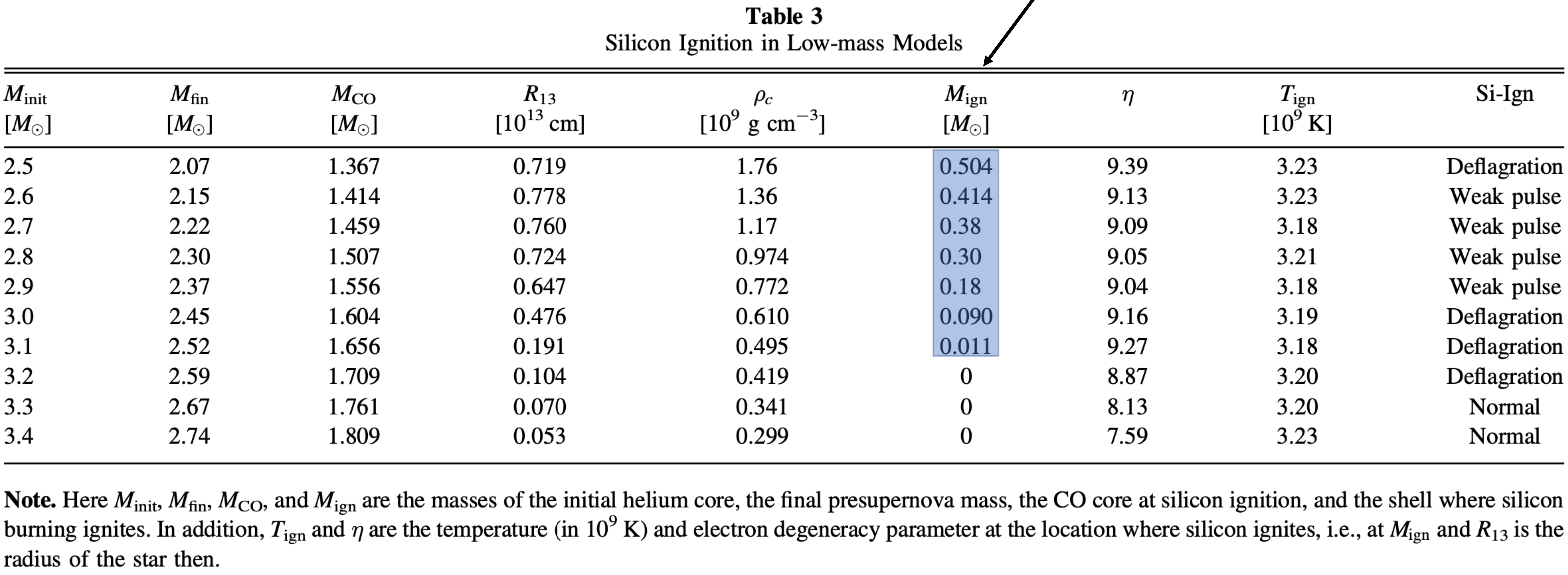


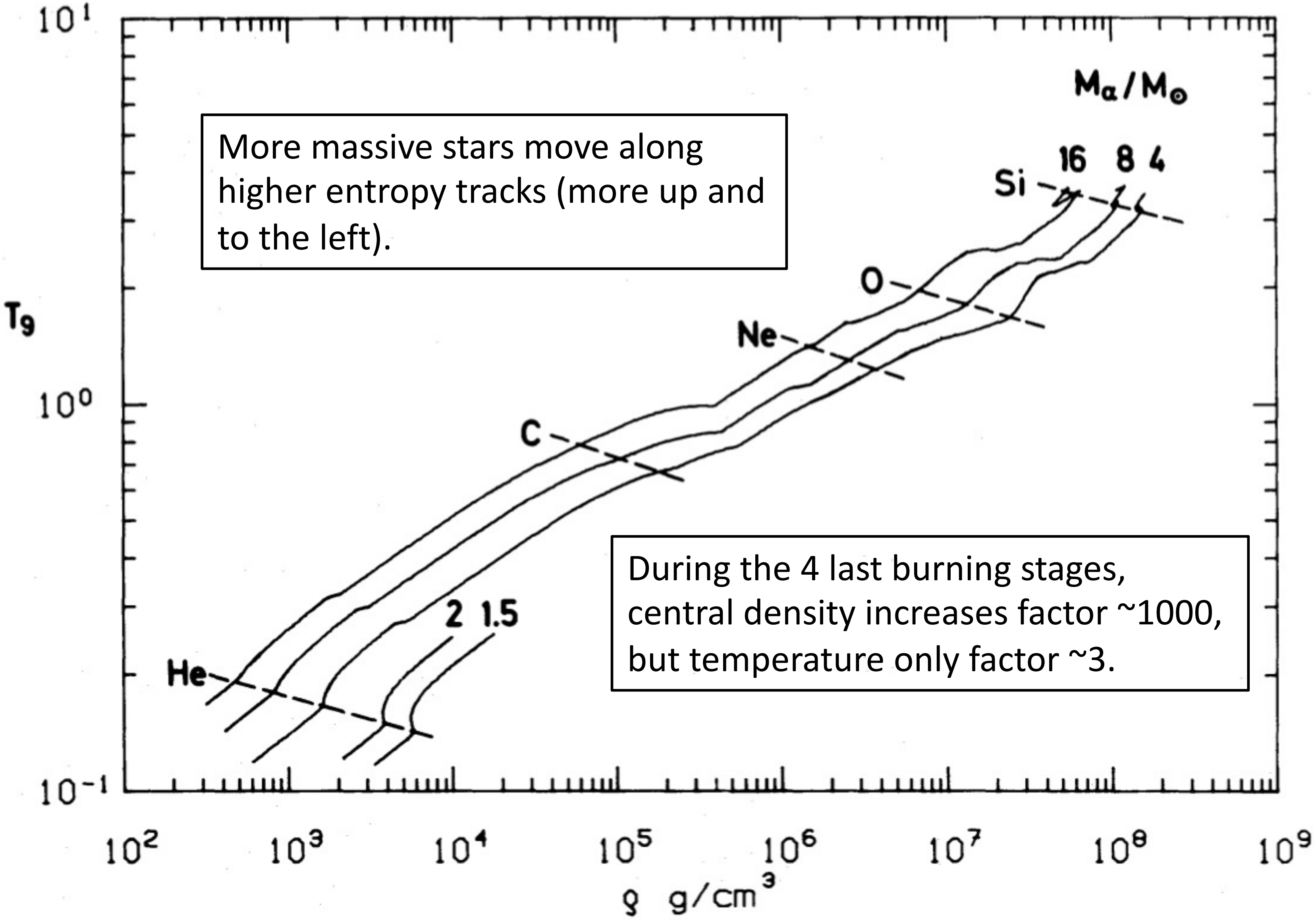
Table 3
Silicon Ignition in Low-mass Models

$M_{\rm init}$ $[M_\odot]$	$M_{\rm fin}$ $[M_\odot]$	$M_{\rm CO}$ $[M_\odot]$	R_{13} $[10^{13}$ cm$]$	ρ_c $[10^9$ g cm$^{-3}]$	$M_{\rm ign}$ $[M_\odot]$	η	$T_{\rm ign}$ $[10^9$ K$]$	Si-Ign
2.5	2.07	1.367	0.719	1.76	0.504	9.39	3.23	Deflagration
2.6	2.15	1.414	0.778	1.36	0.414	9.13	3.23	Weak pulse
2.7	2.22	1.459	0.760	1.17	0.38	9.09	3.18	Weak pulse
2.8	2.30	1.507	0.724	0.974	0.30	9.05	3.21	Weak pulse
2.9	2.37	1.556	0.647	0.772	0.18	9.04	3.18	Weak pulse
3.0	2.45	1.604	0.476	0.610	0.090	9.16	3.19	Deflagration
3.1	2.52	1.656	0.191	0.495	0.011	9.27	3.18	Deflagration
3.2	2.59	1.709	0.104	0.419	0	8.87	3.20	Deflagration
3.3	2.67	1.761	0.070	0.341	0	8.13	3.20	Normal
3.4	2.74	1.809	0.053	0.299	0	7.59	3.23	Normal

Note. Here $M_{\rm init}$, $M_{\rm fin}$, $M_{\rm CO}$, and $M_{\rm ign}$ are the masses of the initial helium core, the final presupernova mass, the CO core at silicon ignition, and the shell where silicon burning ignites. In addition, $T_{\rm ign}$ and η are the temperature (in 10^9 K) and electron degeneracy parameter at the location where silicon ignites, i.e., at $M_{\rm ign}$ and R_{13} is the radius of the star then.

Woosley 2019

Summary of late burning stages



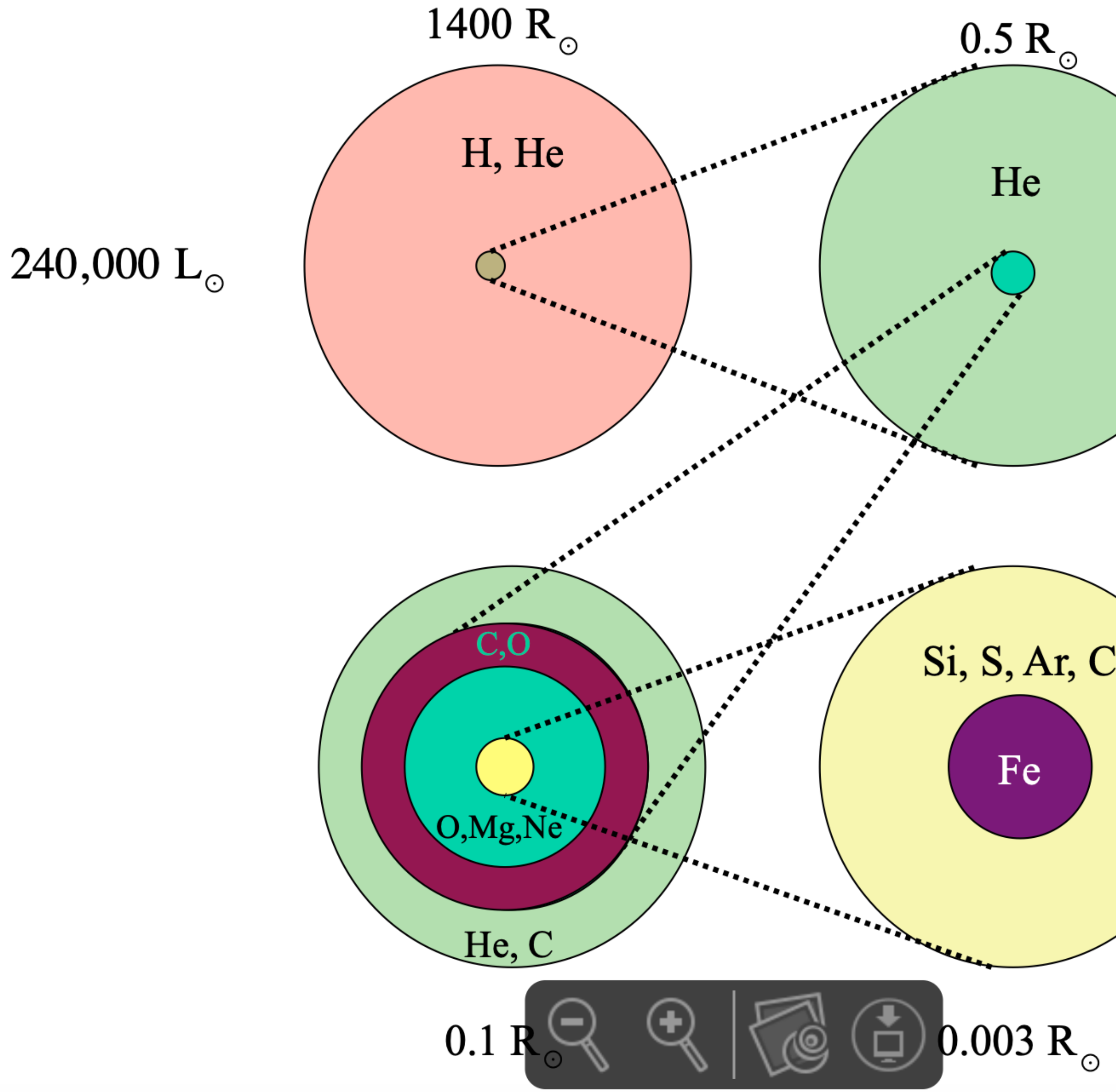
More massive stars move along higher entropy tracks (more up and to the left).

During the 4 last burning stages, central density increases factor ~1000, but temperature only factor ~3.

Arnett 1985

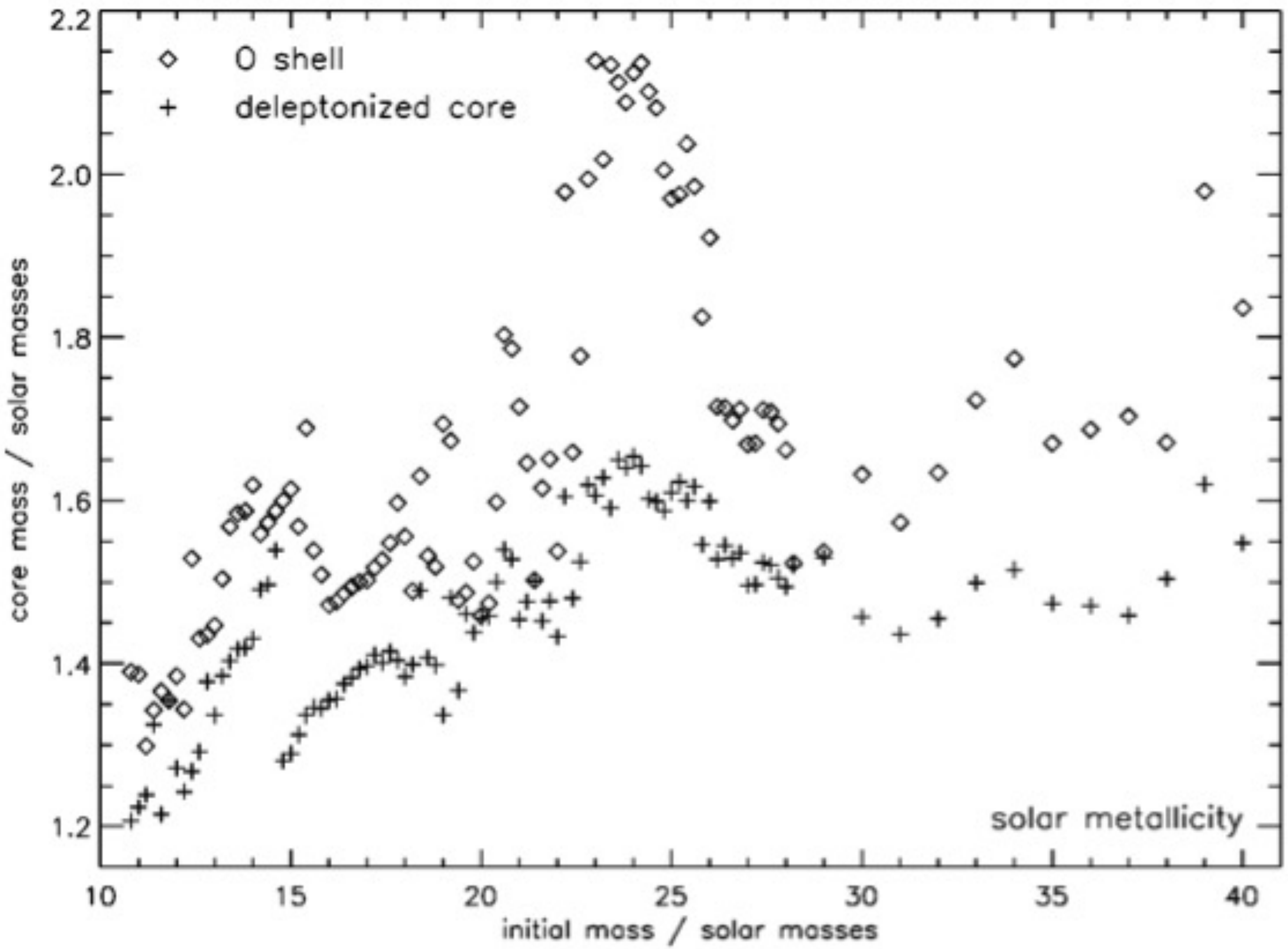
FINAL STRUCTURE AND APPEARANCE OF THE STAR

25 $M_\odot$ Presupernova Star (typical for 9 - 130 $M_\odot$)



Credit: S Woosley

Final iron core masses



Woosley and Heger 2002

Non-monotonic behavoir of $M_{\mathrm{Fe-core}}$ vs M_{ZAMS}, but overall more massive stars tend to make more massive Fe cores.

Iron cores with

$$\boldsymbol{M > M_{\mathrm{Ch}} = 1.46 \left(\frac{\mu_e}{2}\right)^{-2} M_\odot}$$

are doomed to collapse : no more thermo-nuclear energy is extractable and there is no electron degeneracy solution.

The deleptonization to $\eta{\sim}0.1$ $(Y_e{\sim}0.45)$ gives

$$\mu_e = 2/(1-\eta) = 1/Y_e \sim 2.2$$

→ $M_{\mathrm{Ch}}{\sim}$ 1.20 $M_\odot$

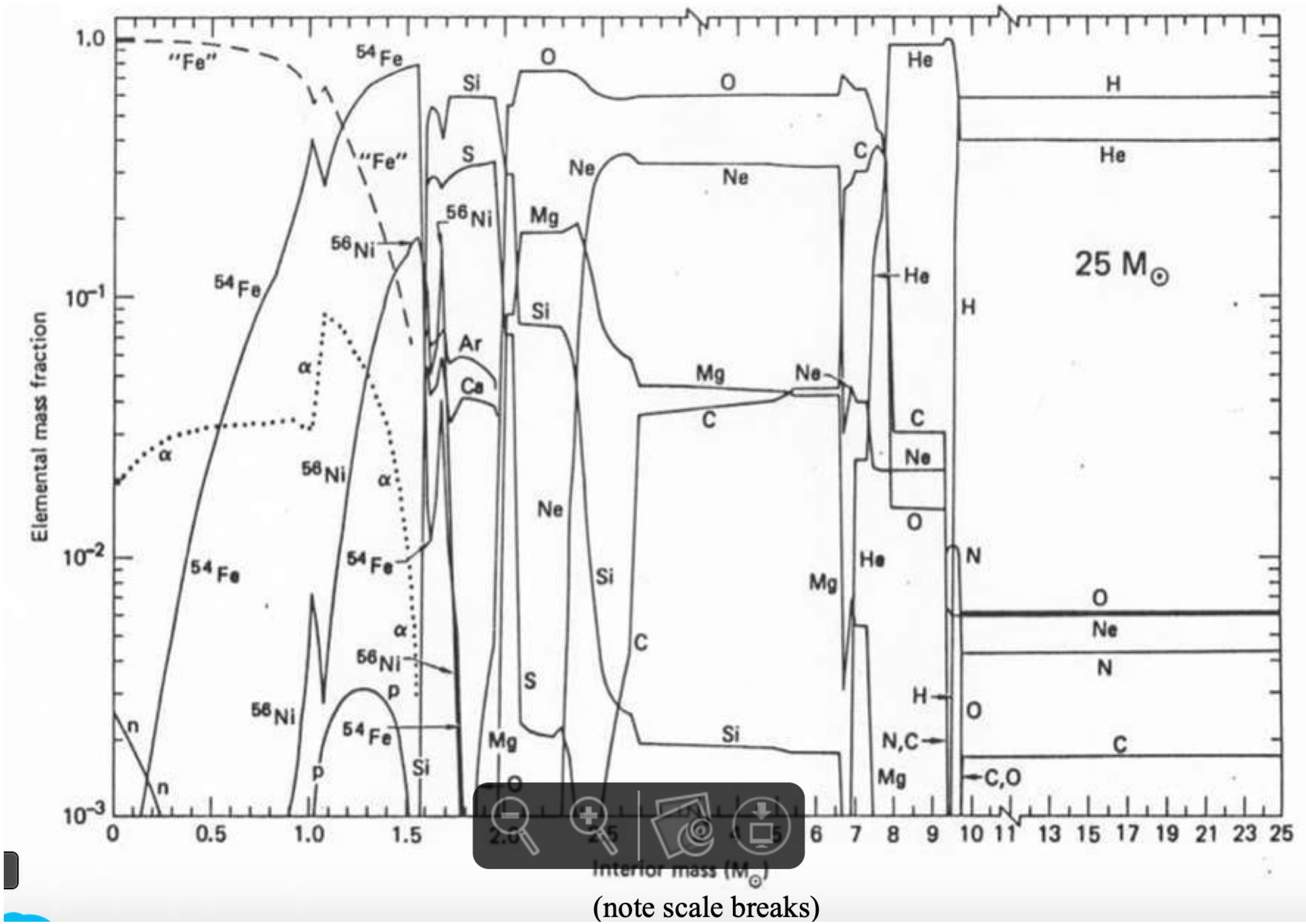
Other effects compared to ideal *T*=0 polytrope (GR corrections, Coulomb screening, presence of overlying shell) make few % correction to this value.

Example of final composition profile : “onion layers”

Burn stage:

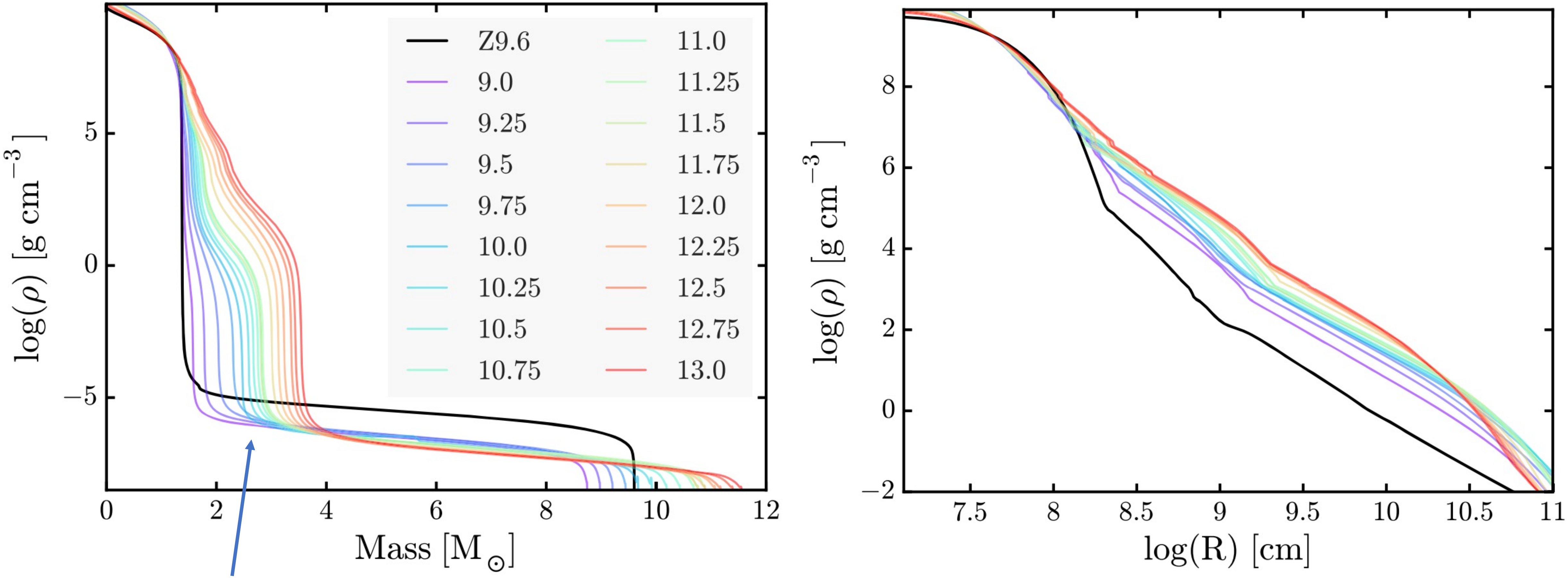
Si | O | Ne | C | He | He * | H

* Incomplete



S. Woosley

Density profile at collapse stage



Core - envelope structure

Sukhbold+2016

Response of the envelope and surface to the core changes

The thermal adjustment time for the envelope is roughly its Kevin-Helmholz time-scale,

$$\tau_{KH} \approx \frac{GM^2}{2RL} = 30\mathrm{y}\left(\frac{M}{10\ M_\odot}\right)^2\left(\frac{R}{500\ R_\odot}\right)^{-1}\left(\frac{L}{10^5\ L_\odot}\right)^{-1}$$

Shorter than the C burning life-time in massive stars (~10^3 y) , but longer than the later burning phases (<~ 1y)→

- **The star may change its (*L*,T_{eff}) when it enters the C burning phase, and thus show that it enters its last ~1000y of evolution.**

- **The star is not capable to show such a sign when entering Ne, O, or Si burning and has <1y left of evolution. Certainly not for BSGs (eg SN 1987A) and neither for (most) RSGs.**

For C-burning, the photon luminosity does in fact not change because the total energy generation is dominated by shell He burning (compare how shell H burning dominates during core He burning). For example, $L_\gamma = 2.8*10^{38}$ erg/s at C ignition and $3.5*10^{38}$ erg/s at C depletion in a 15 M_{sun} model.

Response of the envelope and surface to the core changes

However, in recent years much evidence has been accumulating that supernova progenitor stars often do seem signal their imminent collapse in another way: by strong mass ejections from their surfaces in the last years/decades.

Lies the answer to this behaviour in the much shorter hydrodynamic time-scale?

$$\tau_{hydro} = \sqrt{\frac{R}{g}} = \left[g \sim \frac{GM}{R^2}\right] = \sqrt{\frac{R^3}{GM}} \sim 50d \left(\frac{R}{500\ R_{\odot}}\right)^{3/2} \left(\frac{M}{15\ M_{\odot}}\right)^{-1/2}$$

Can one not just see what stellar evolution models predict? Well, one should remember that stellar evolution codes do not simulate the convection with formation of blobs, shocks, internal gravity waves in detail. For example, mixing length theory has a fundamental assumption that convection is subsonic. Complex and potentially dramatic phenomena like overshooting are also, simplifying, treated as smooth diffusion processes.

As with the surprising progenitor of SN 1987A (a BSG rather than a RSG), the recent surprising discovery of pre-SN activity has again reminded us that modern stellar evolution models are still highly simplistic and do not predict all key properties of massive star.