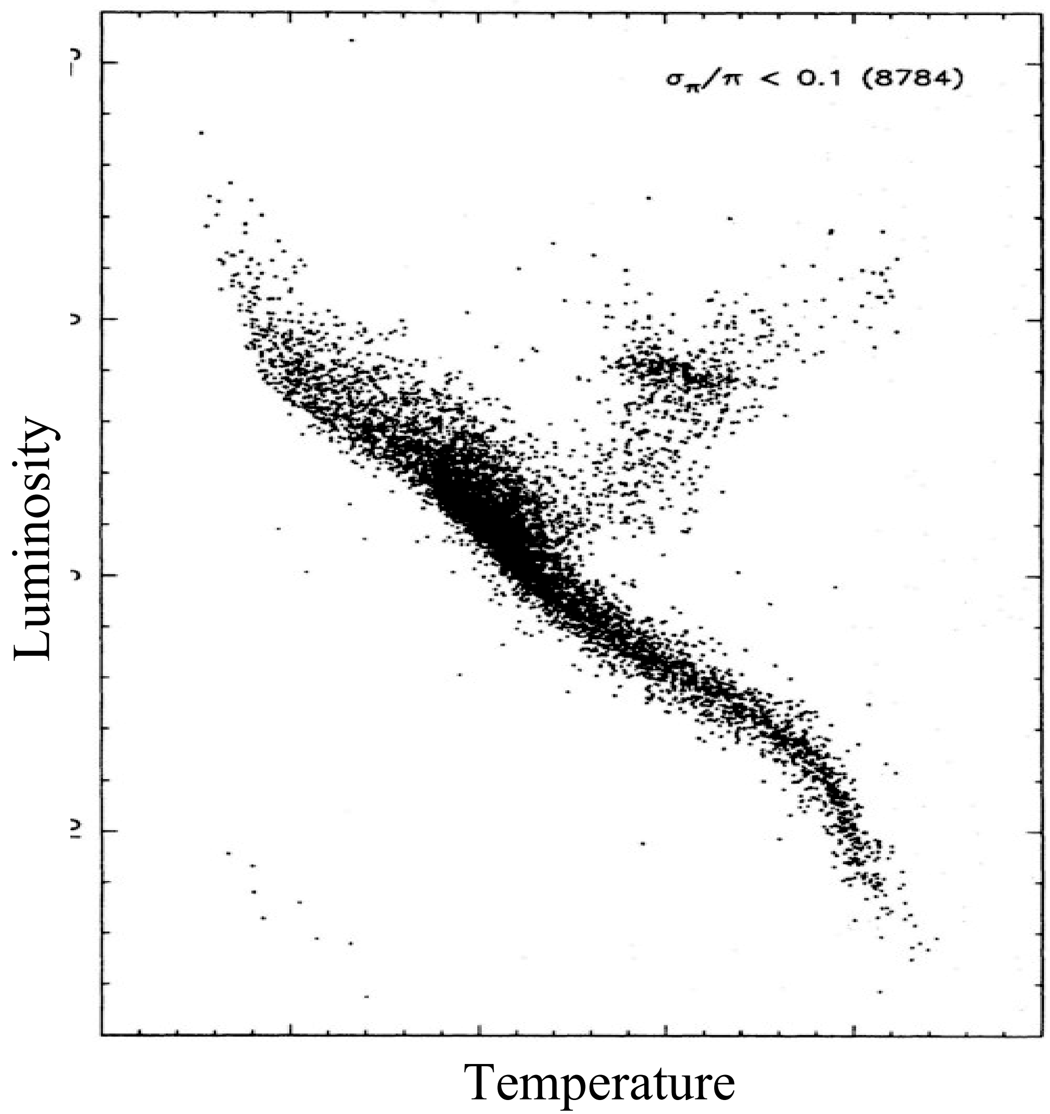
Post-Main-Sequence Evolution: He-burning

- Post-Main sequence Evolution

- The triple-alpha Process

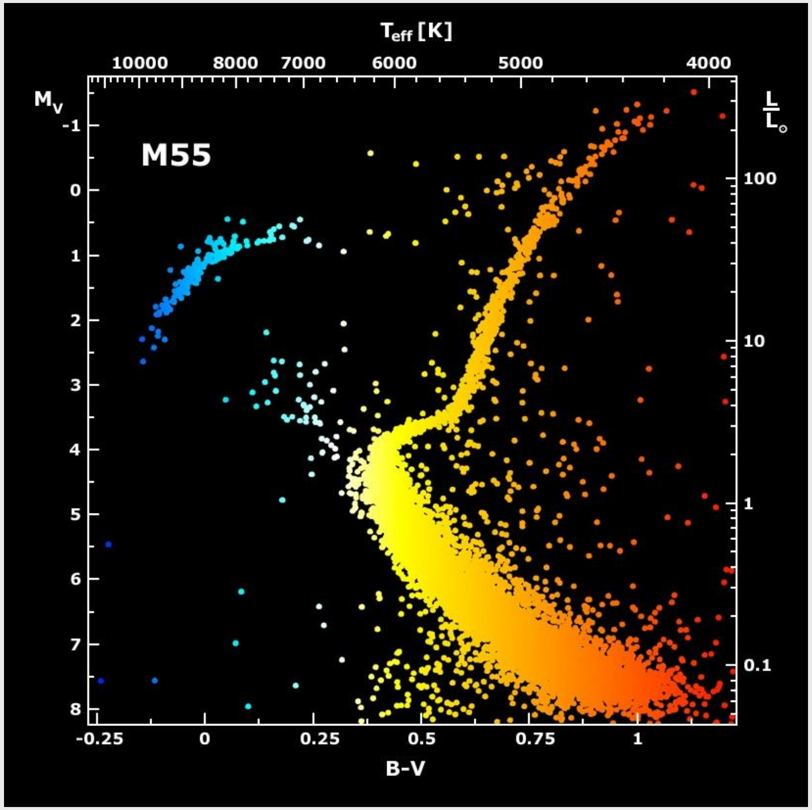
Literature: Iliadis, Chapt. 5.3

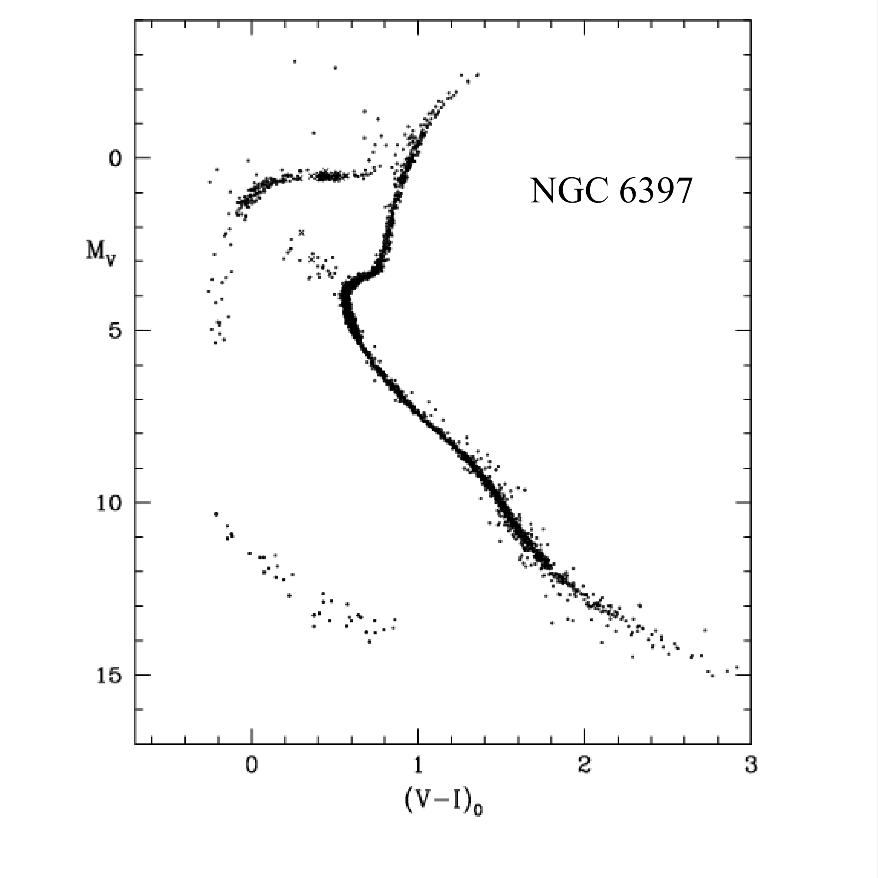
The Real H-R Diagram for Stars near the Sun

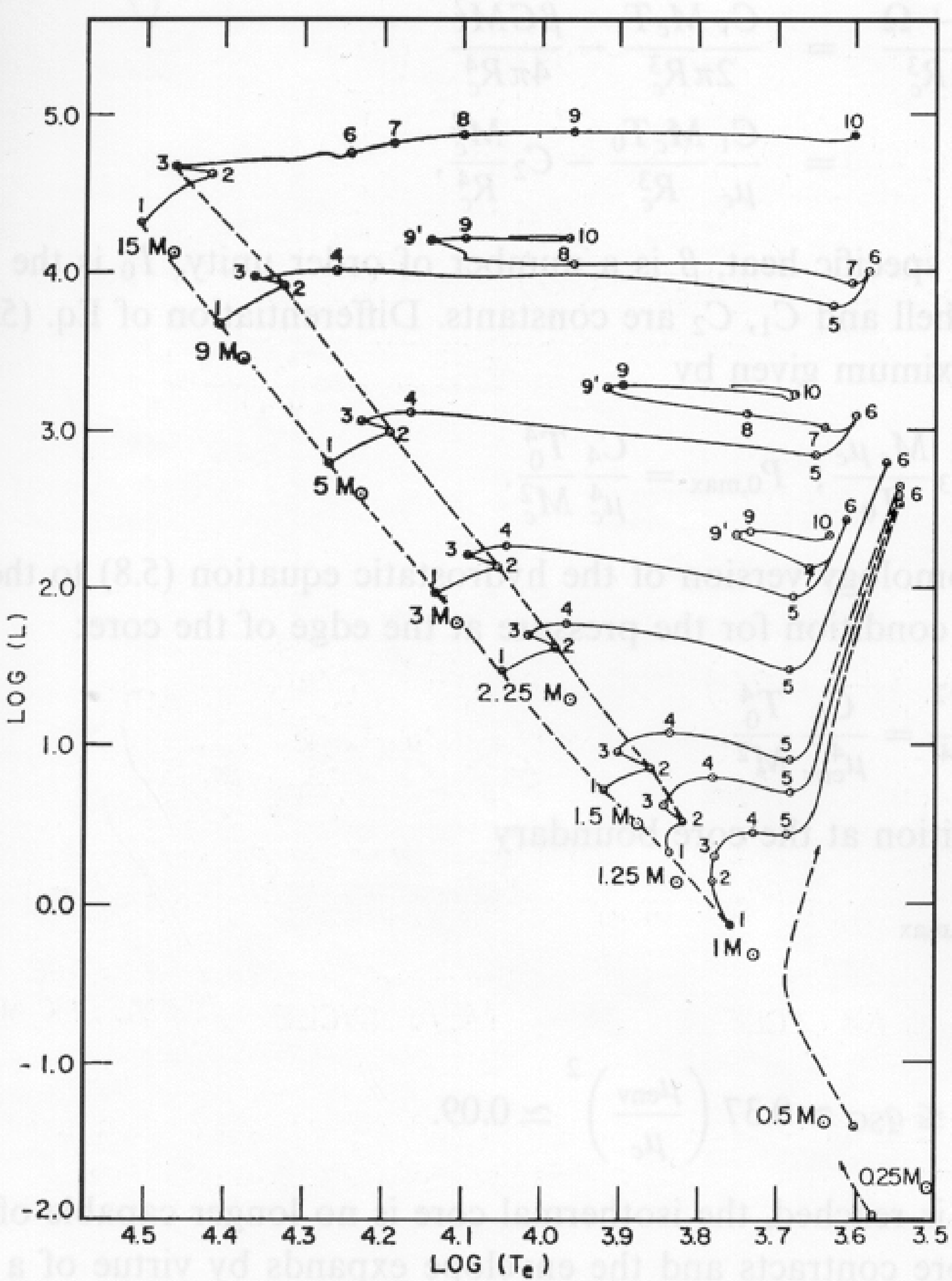


Real H-R Diagrams of Globular Clusters

Real H-R diagrams are messy!

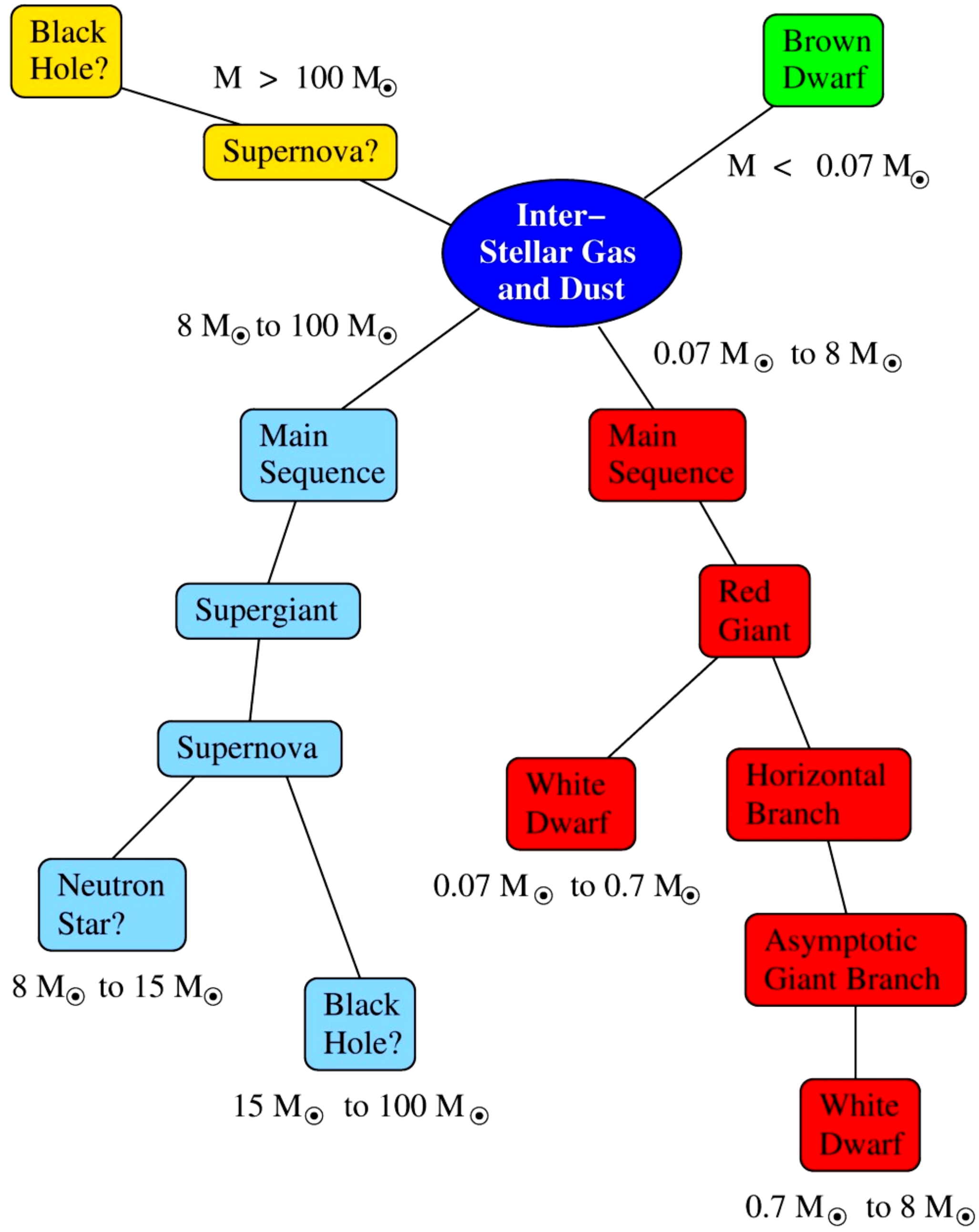


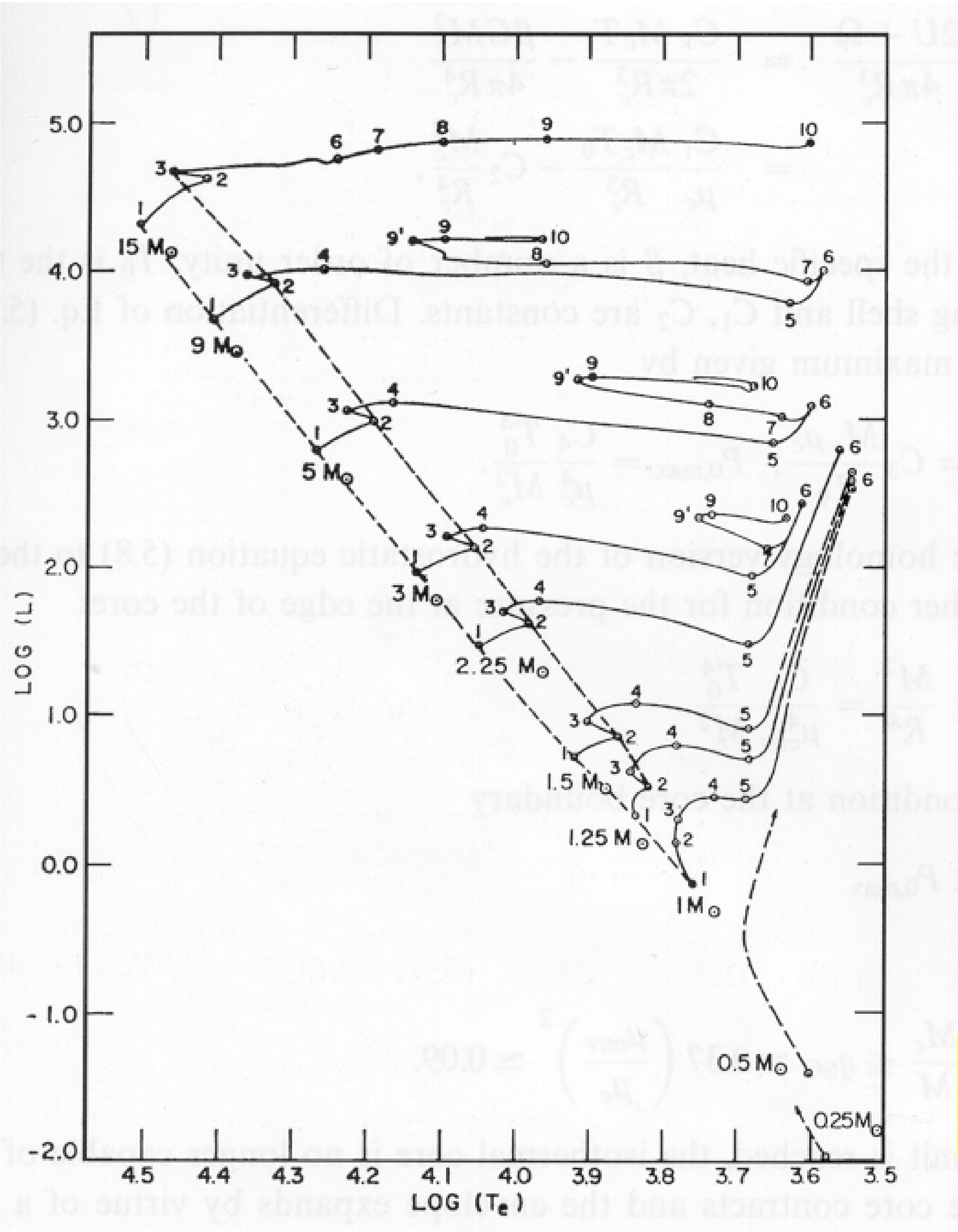




As hydrogen is exhausted in the (convective) core of a star (point 2)
it moves away from the main sequence (point 3)
becomes a fully convective structure
a red giant (5-6)

A Summary of Stellar Evolution



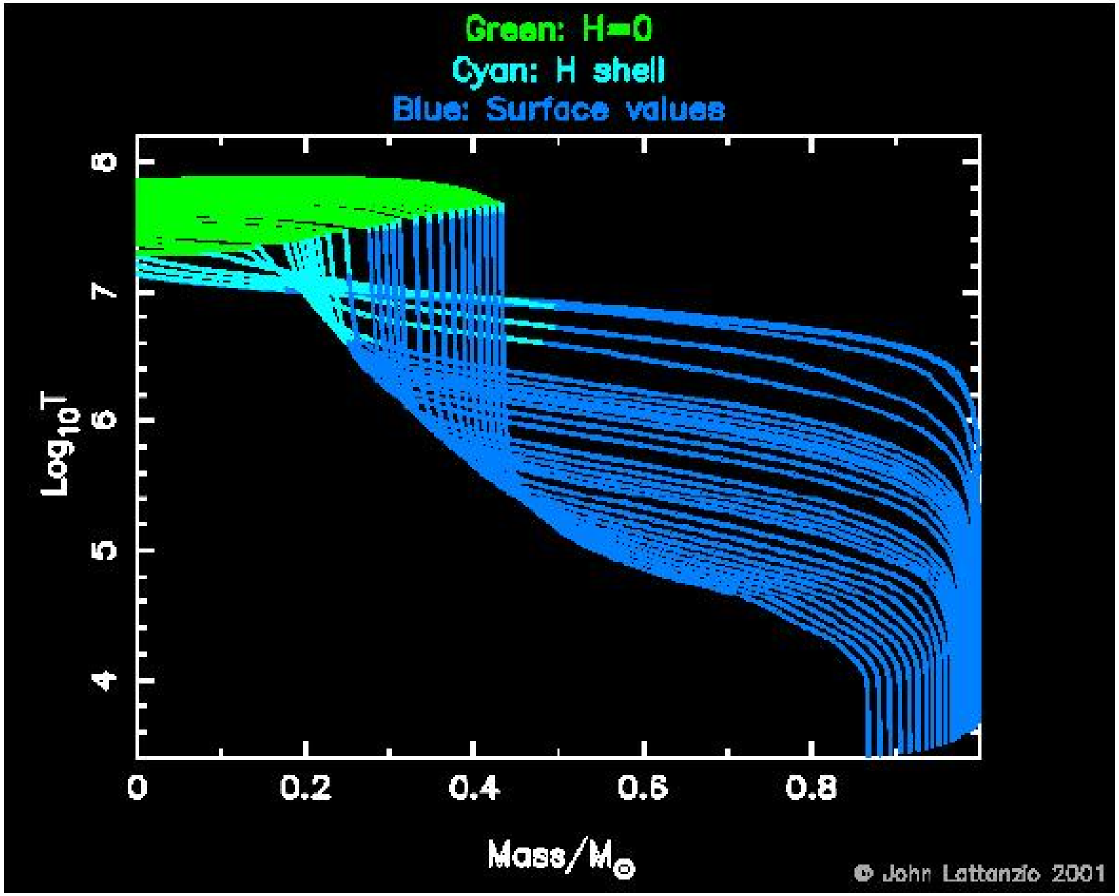


Zero Age Main Sequence (ZAMS): "1"

End of Main Sequence: "2"
(from Kippenhahn & Weigelt, Stellar Structure & Evolution)

Stellar masses are usually given in ZAMS mass !

Temperature Evolution during H-shell Burn.



- H depletes with time → isothermal core

T-rises to support pressure

Steep gradient at outer edge of burning zone

The Isothermal Core

- L(r) = 0 without energy production

(Chandrasekhar Limit for core)

- Maximum central T can be reached

mass $[M_{Ch}]$	T_{max} $[10^9 K]$	$Y_e \rho$ [g cm^{-3}]
0.100	0.0392	1.79×10^4
0.316	0.195	2.88×10^5
0.501	0.399	1.12×10^6
0.631	0.586	2.77×10^6
0.794	0.929	1.07×10^7
0.891	1.250	3.65×10^7
0.931	1.530	9.66×10^7
0.966	2.170	2.84×10^8
0.983	3.060	8.08×10^8
0.986	3.430	1.13×10^9

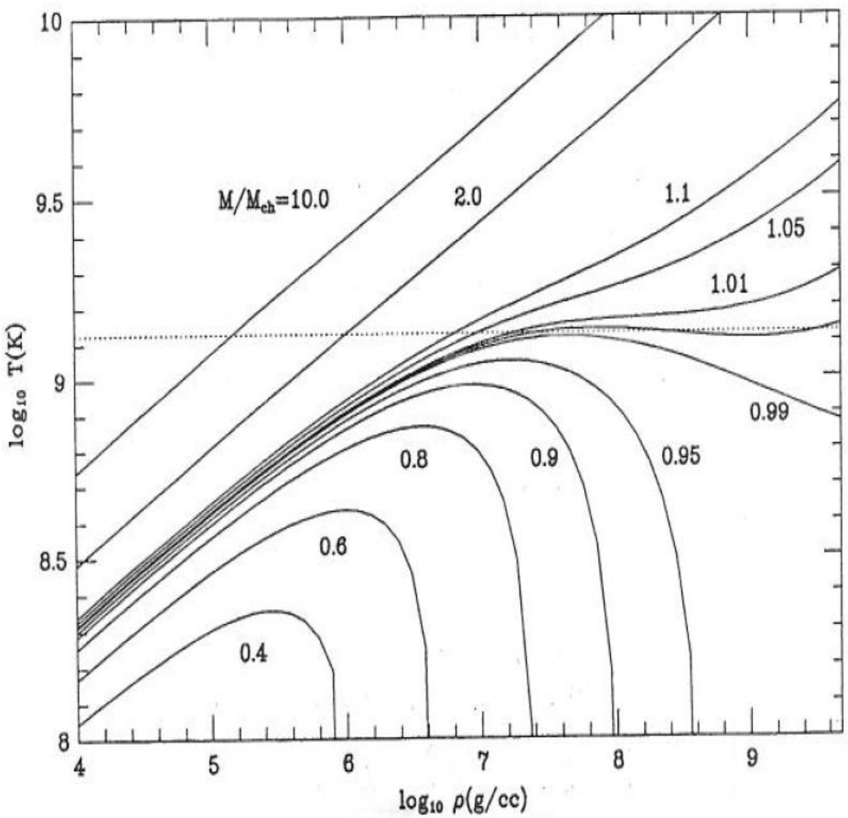
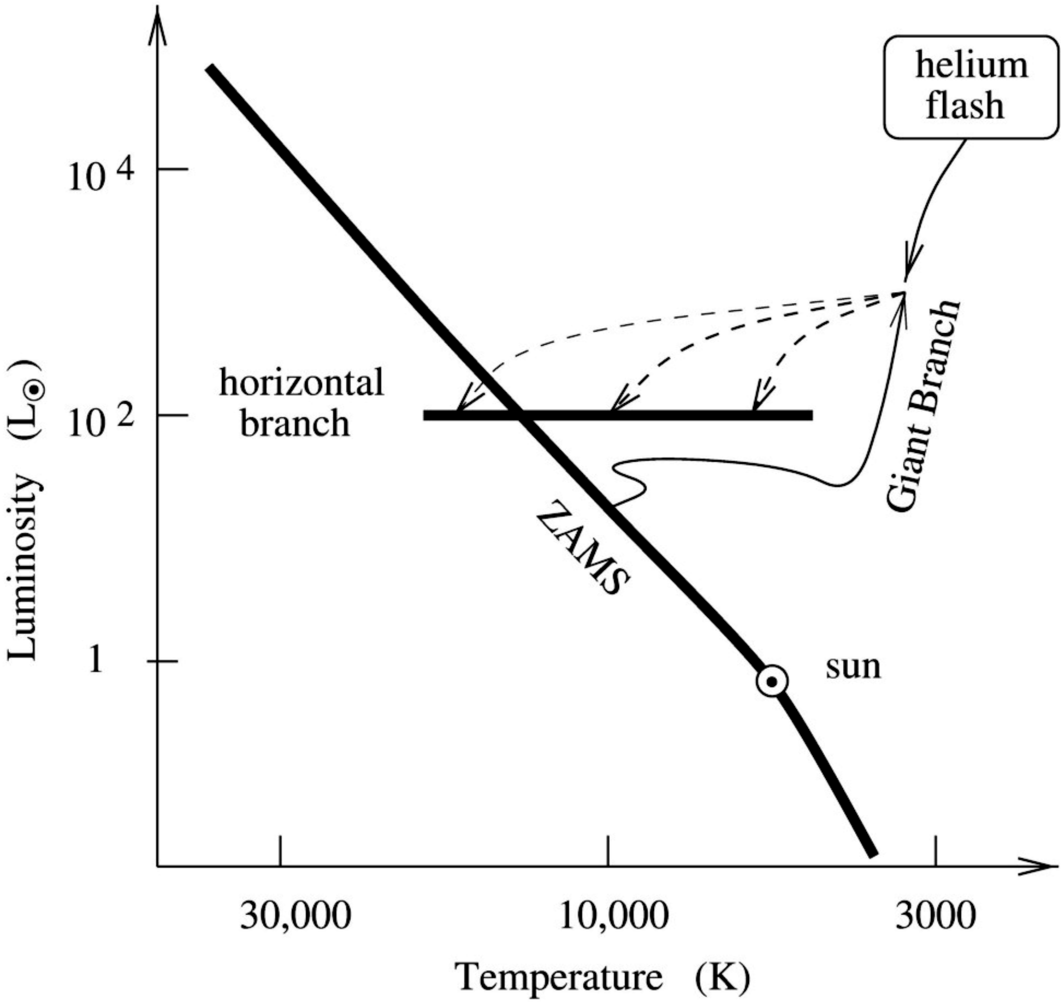


Fig. 6.3. $\rho - T$ for Ignition Masses

Evolution of a 2 M Star to the Horizontal Branch

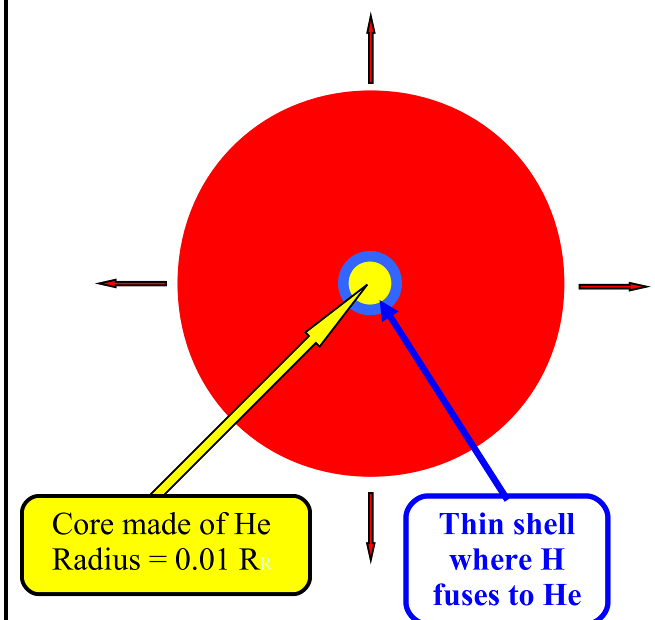


Red Giants

Luminosity up to 1000 L

Temperature = 3000 K

Radius up to 50 R

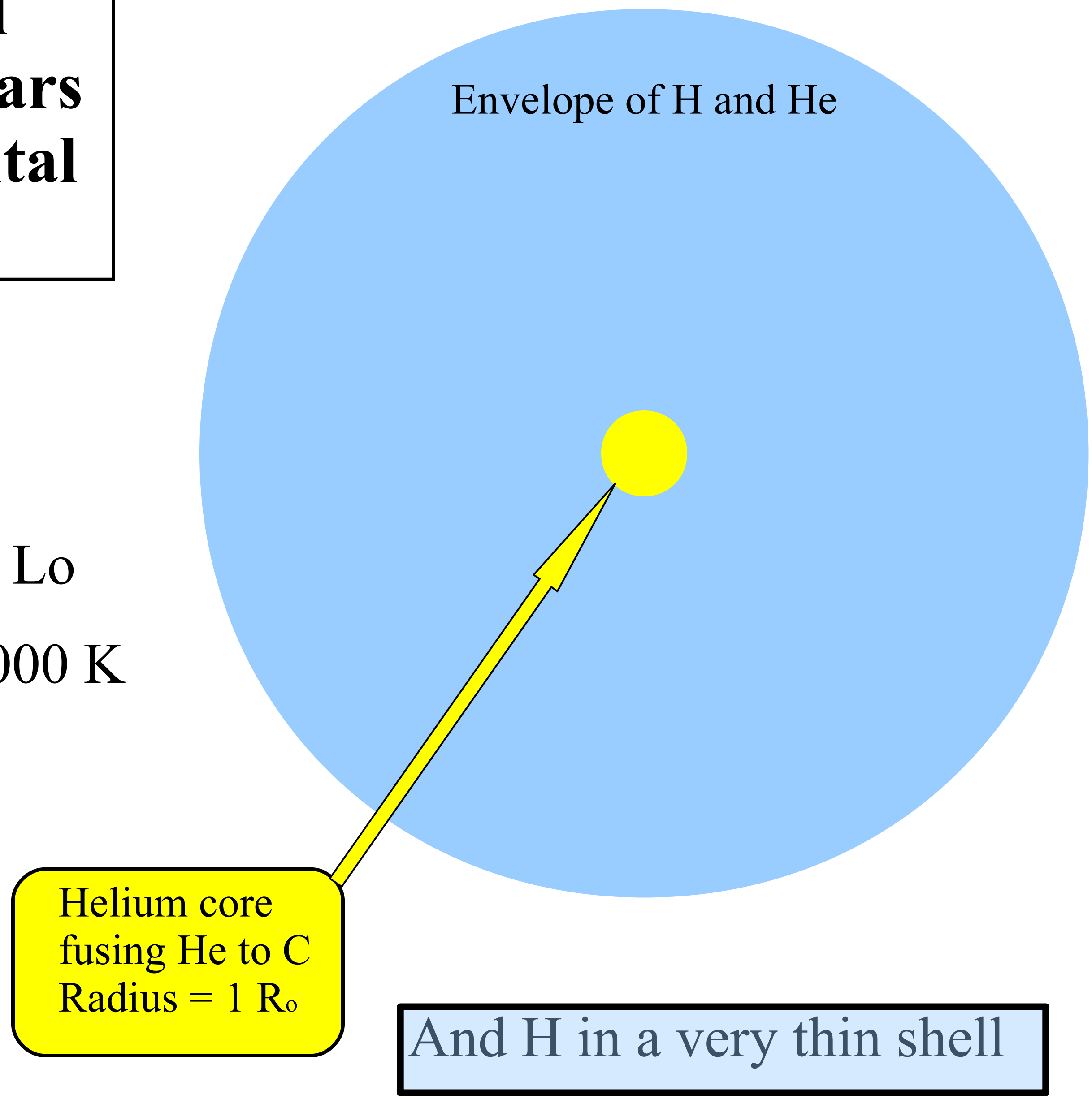


The Internal Structure of Stars on the Horizontal Branch

Radius = 10 Ro

Luminosity = 100 Lo

Temperature = 20,000 K to 5000 K

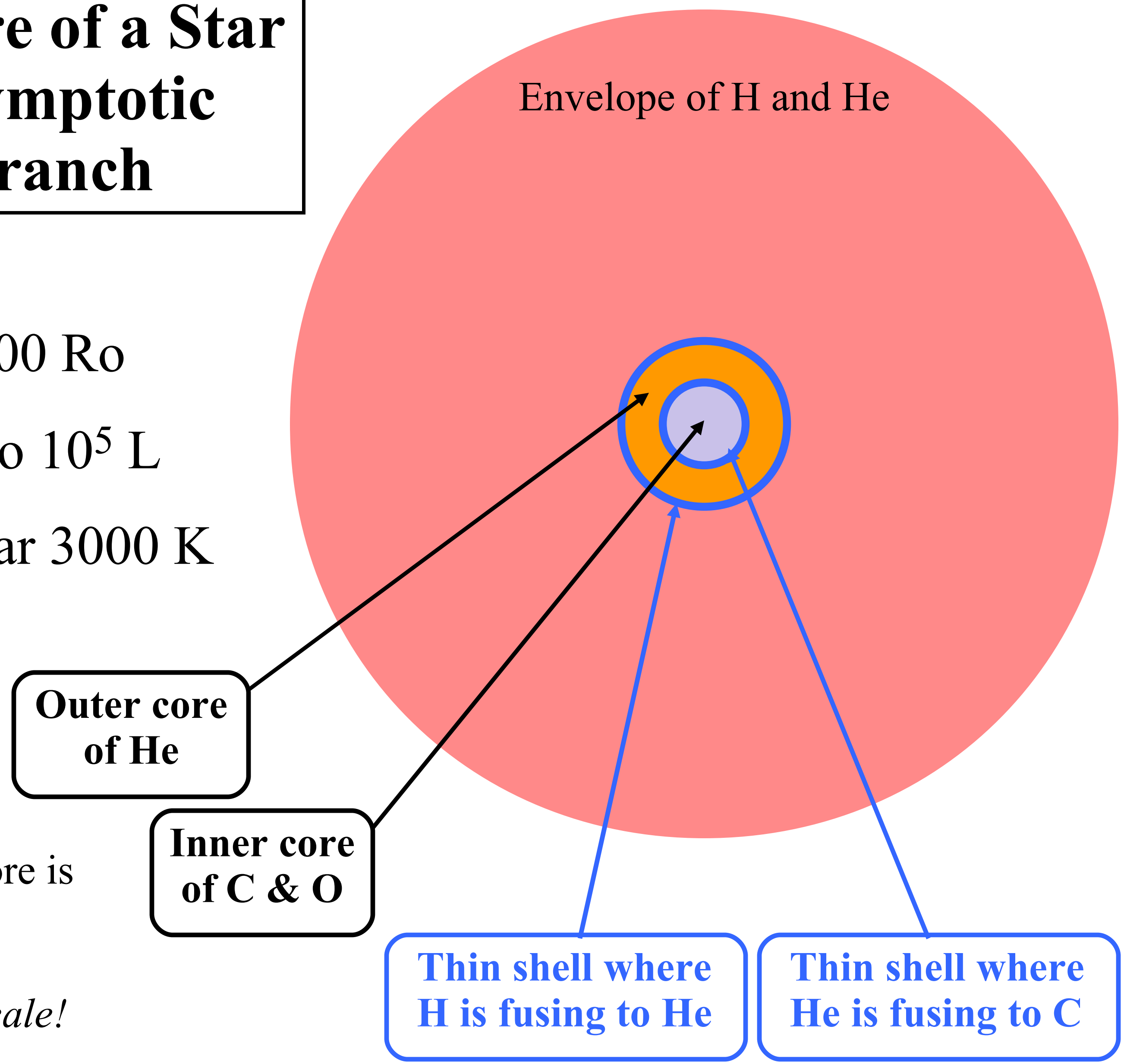


The Structure of a Star on the Asymptotic Giant Branch

Radius up to 1000 Ro

Luminosity up to 10^5 L

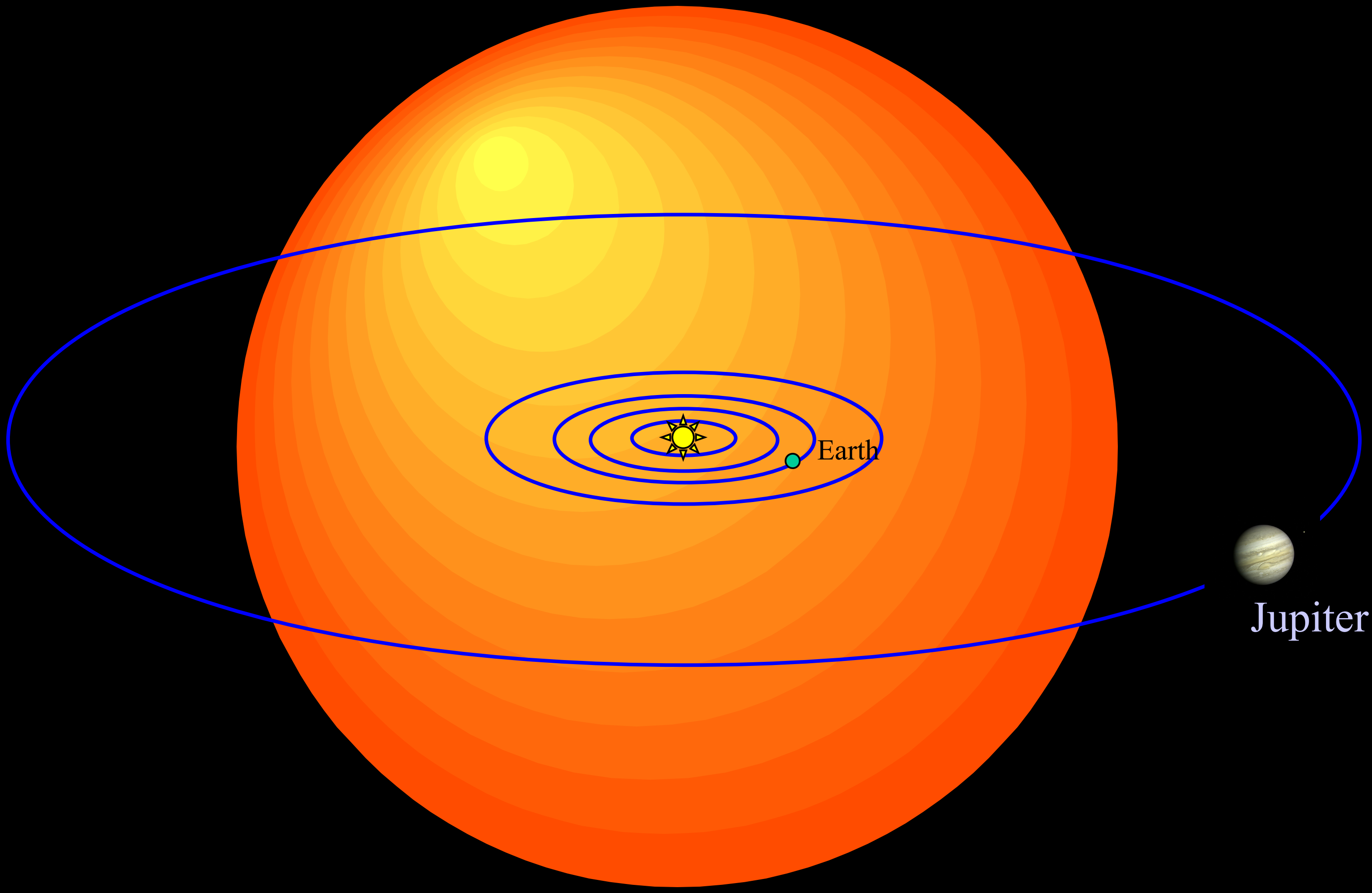
Temperature near 3000 K



The radius of the core is only 0.01 R_o.

It is not shown to scale!

AGB Star Compared to the Solar System



Helium burning 1 – the 3Ô process

Step 1:

$\alpha + \alpha \rightarrow {}^{8}Be$

unbound by ~92 keV – decays to 2 α in 2.6 10^{-16} s

=> small equilibrium abundance of ^{8}Be is established, nevertheless

Step 2:

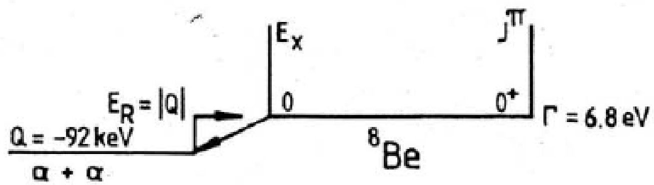
$^{8}Be + \alpha \rightarrow {}^{12}C$ would create ^{12}C at excitation energy of ~7.7 MeV

1954 Fred Hoyle realized that the fact that there is carbon in the universe requires a resonance in ^{12}C at ~7.7 MeV excitation energy

1957 discovered by Cook, Fowler, Lauritsen and Lauritsen at CALTECH with the correct properties (at 7.654 MeV)

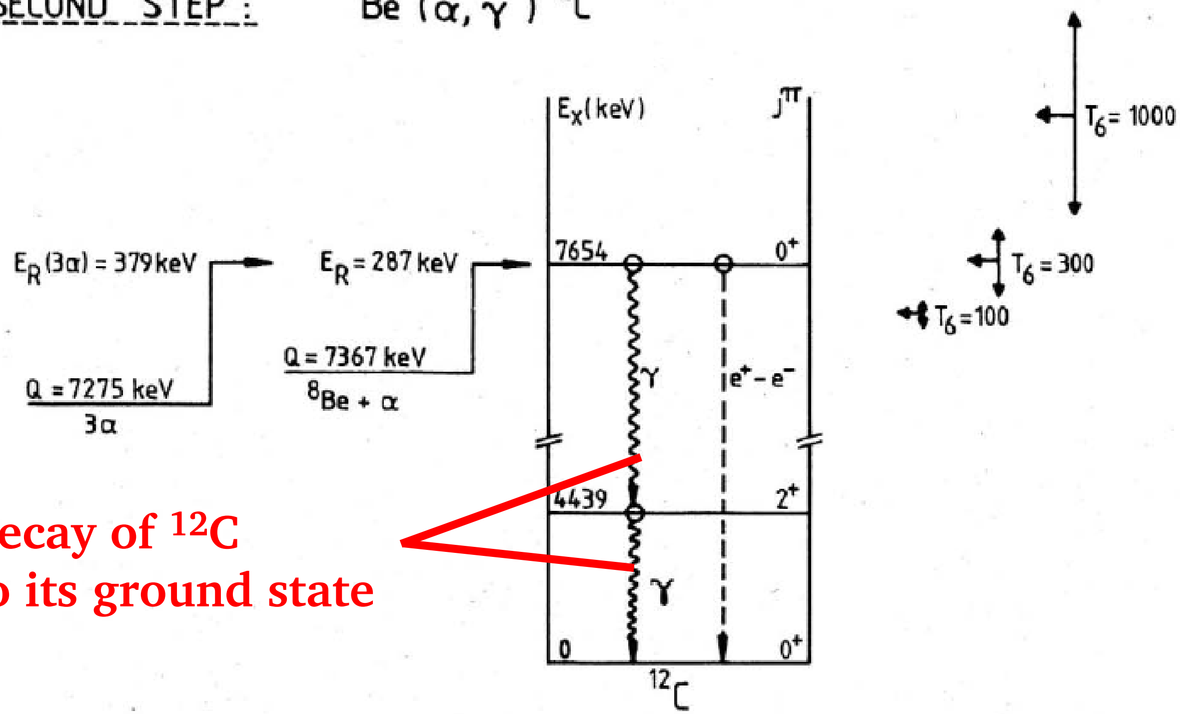
Step 3: Gamma-decay

FIRST STEP: $\alpha + \alpha \rightleftharpoons {}^{8}Be$



^{8}Be ground state is in a
92 keV resonance
for the α+α reaction

SECOND STEP: $^{8}Be(\alpha,\gamma)^{12}C$



γ decay of ^{12}C into its ground state

Total Reaction Rate in Triple α/Part I:

Equilibrium reactions during first steps (fast and small energies)

$$\alpha + \alpha <=> {}^{8}\mathrm{Be}$$

$${}^{8}\mathrm{Be} + \alpha <=> 12\mathrm{C}^{+} \ (7.6\,\mathrm{MeV})$$

C (7.6 MeV) is given by Equilibrium Equation:

$$Y_{12\mathrm{C}(7.6\,\mathrm{MeV})}\left(\frac{2\pi\hbar^2}{m_{12\mathrm{C}}kT}\right)^{3/2} = Y_{4He}^{3}\rho^{2}N_A^{2}\left(\frac{2\pi\hbar^2}{m_{4\mathrm{He}}kT}\right)^{9/2} e^{-Q/kT}$$

with $Q/c^2 = m_{12C(7.7)} - 3\mathrm{m}_\alpha$ and $\mathrm{m}(12\mathrm{C}) \approx 3\ \mathrm{m}(\alpha)$

$$Y_{12\mathrm{C}(7.6\,\mathrm{MeV})} = 3^{3/2}\,Y_{4\mathrm{He}}^{3}\rho^{2}N_A^{2}\left(\frac{2\pi\hbar^2}{m_{4\mathrm{He}}kT}\right)^{3} e^{-Q/kT}$$

Total Reaction Rate in Triple α/Part II:

Gamma-decay-reaction determines speed/ total reaction rate !!!

$$r = Y_{12C(7.6MeV)} \rho N_A \frac{\Gamma_\gamma}{\hbar}$$

Rem:: r is dominated by resonance

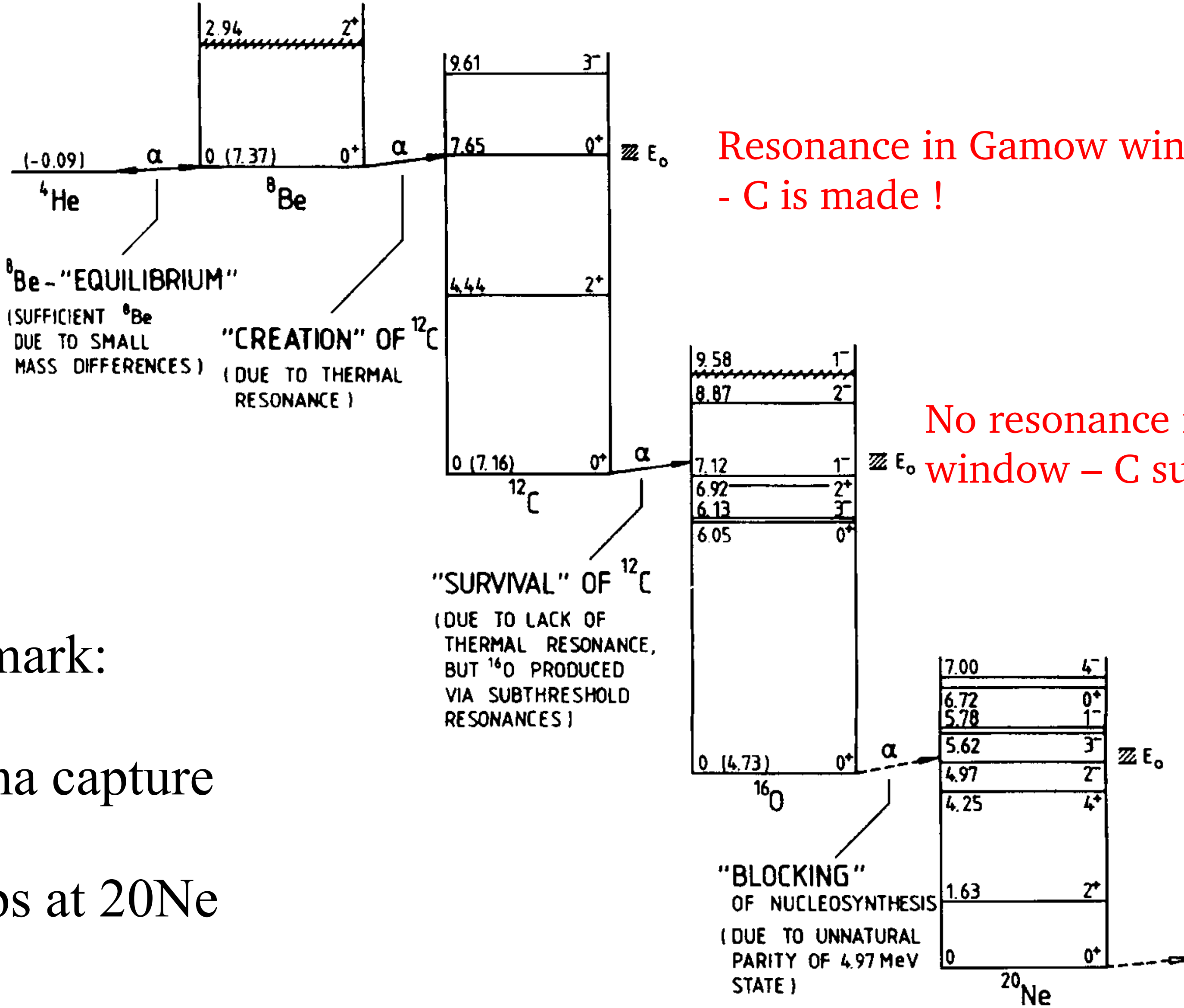
Reaction rate of Helium burning in stellar environment:

$$r(3\alpha) = 1/6 \;\; Y_\alpha^2 \, \rho^2 \, N_A^2 \, \langle \alpha\alpha\alpha \rangle$$

$$N_A^2 \langle \alpha\alpha\alpha \rangle = 6 \cdot 3^{3/2} \rho^2 N_A^2 \left(\frac{2\pi\hbar^2}{m_{4He} kT} \right)^3 \frac{\Gamma_\gamma}{\hbar} e^{-Q/kT}$$

Energy generation is dominated by this transition

Helium burning/Part 2: $^{12}C(\alpha,\gamma)$



Resonance in Gamow window - C is made !

No resonance in Gamow window – C survives !

Remark:

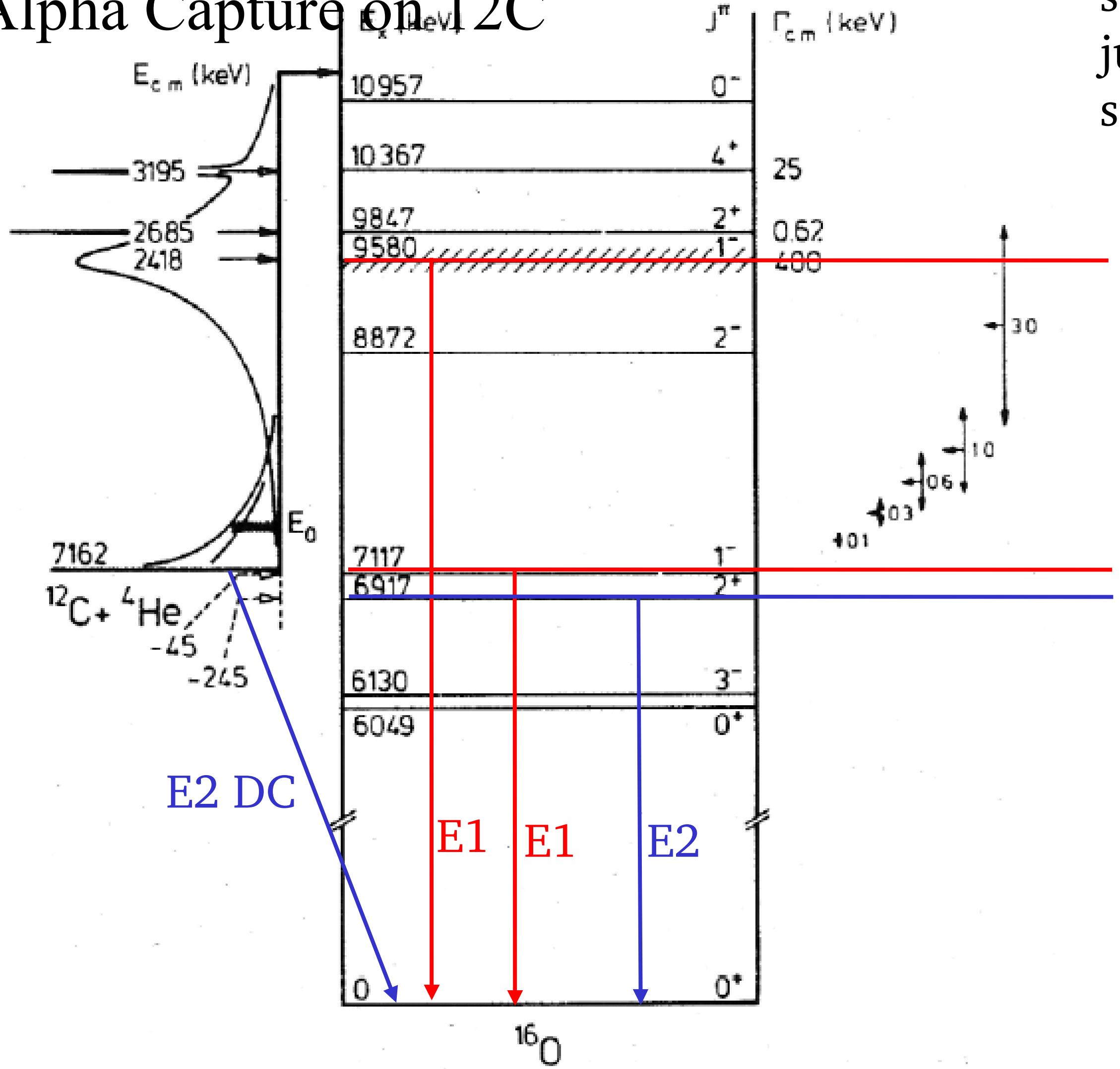
alpha capture

stops at 20Ne

But some C is converted into O …

Alpha Capture on 12C

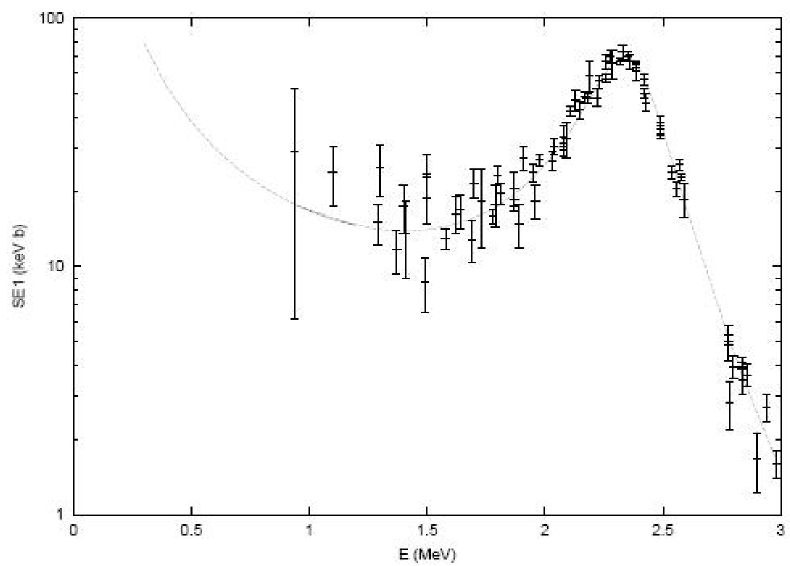
some tails of resonances just make the reaction strong enough …



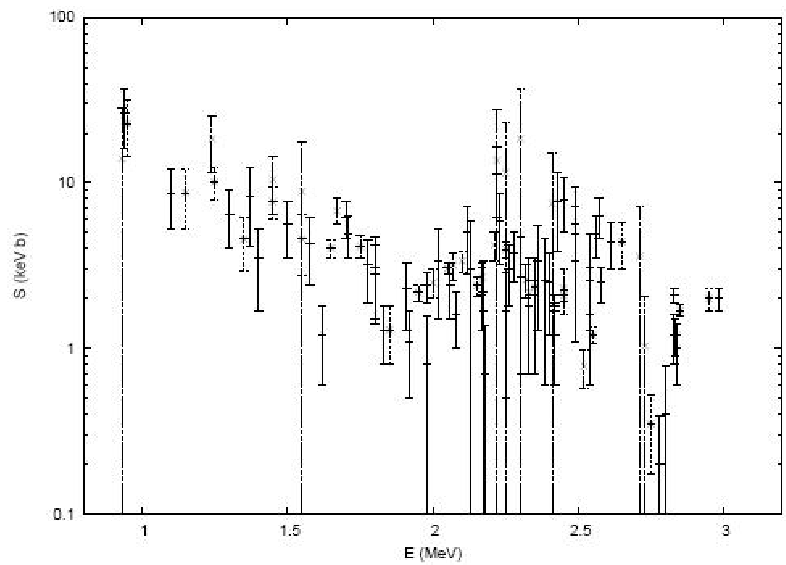
complications:

- very low cross section makes direct measurement impossible
- subthreshold resonances cannot be measured at resonance energy
- Interference between the E1 and the E2 components

E1 and E2 12C(alpha,gamma) 16 Data



E1 data and S-factor fit



E2 data

Total S(300 keV) is about 170 $\pm$ 40 keV b.

Therefore:

Uncertainty in the $^{12}C(\alpha,\gamma)$ rate is the single most important nuclear physics uncertainty in astrophysics

Affects:

- C/O ration → further stellar evolution (C-burning or O-burning ?)
- iron (and other) core sizes (outcome of SN explosion)
- Nucleosynthesis (see next slide)

Some current results for S(300 keV):

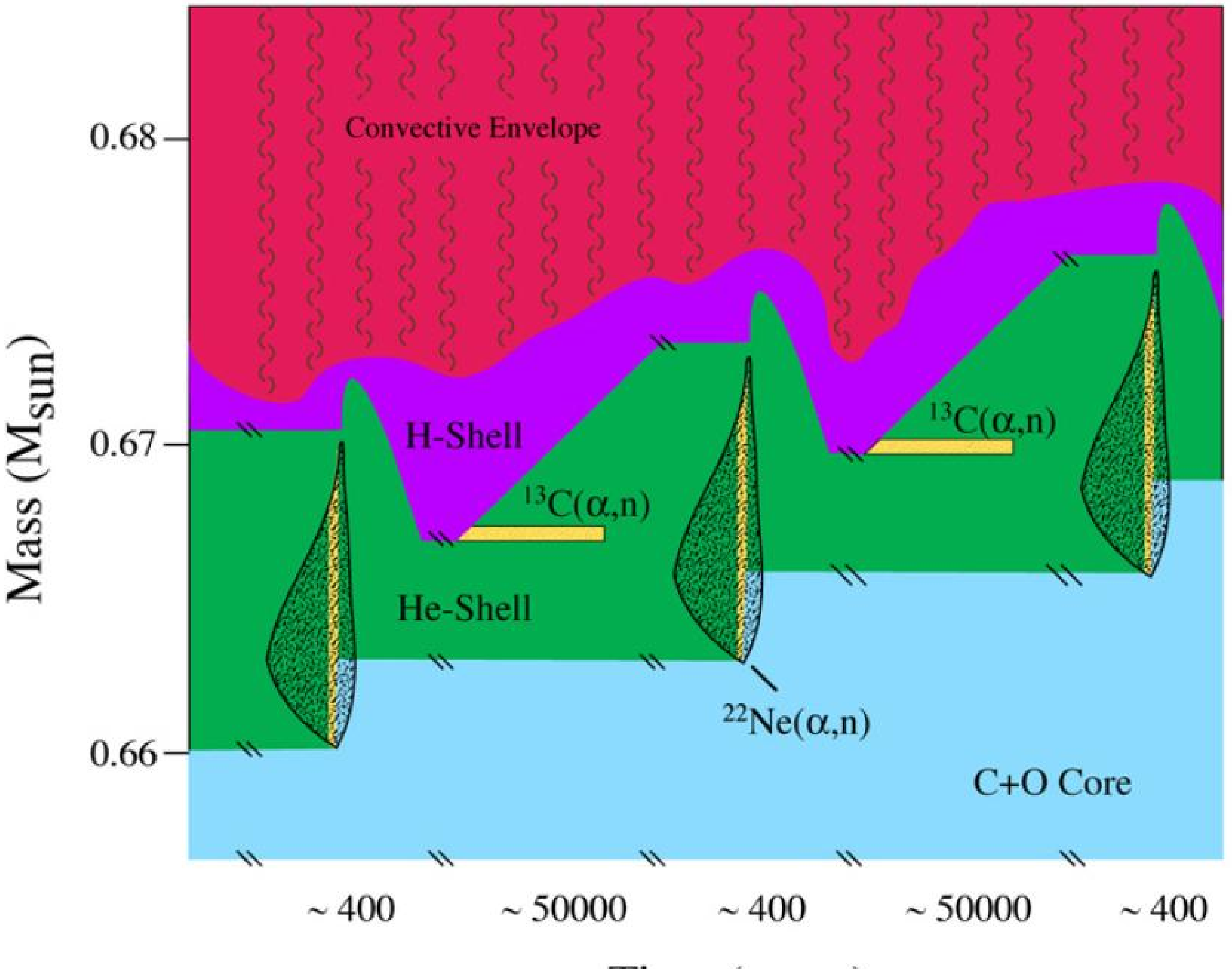
S_{E2}=53+13-18 keV b (Tischhauser et al. PRL88(2002)2501

S_{E1}=79+21-21 keV b (Azuma et al. PRC50 (1994) 1194)

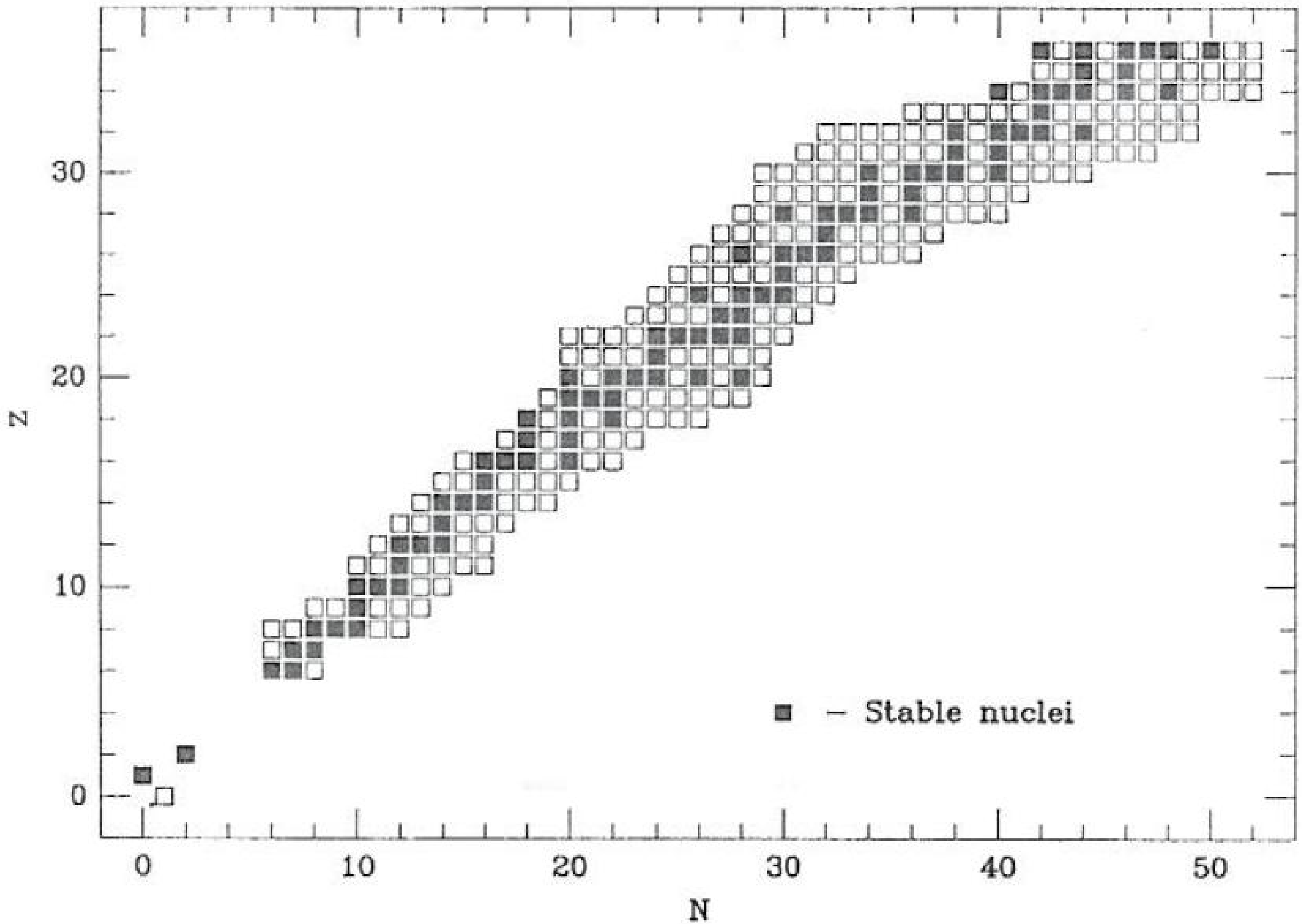
But others range among groups larger !

The 3rd Dredge Up in Massive Stars

25 Mo



Extended alpha network for massive stars



Major Reactions during He Burning

(a) basic energy generation

$^{4}\mathrm{He}(2\alpha,\gamma)^{12}\mathrm{C}$ $\quad$ $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}[(\alpha,\gamma)^{20}\mathrm{Ne}]$

(b) neutron sources

$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(e^{+}\nu)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$ $\ ^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$

$^{12}\mathrm{C}(\mathrm{p},\gamma)^{13}\mathrm{N}(e^{+}\nu)^{13}\mathrm{C}(\alpha,\mathrm{n})^{16}\mathrm{O}$

(c) high temperature burning with neutron sources

$^{22}\mathrm{Ne}(\mathrm{n},\gamma)^{23}\mathrm{Ne}(e^{-}\bar{\nu})^{23}\mathrm{Na}(\mathrm{n},\gamma)^{24}\mathrm{Na}\ (e^{-}\bar{\nu})^{24}\mathrm{Mg}$

$^{20}\mathrm{Ne}(\mathrm{n},\gamma)^{21}\mathrm{Ne}(\alpha,\mathrm{n})^{24}\mathrm{Mg}$

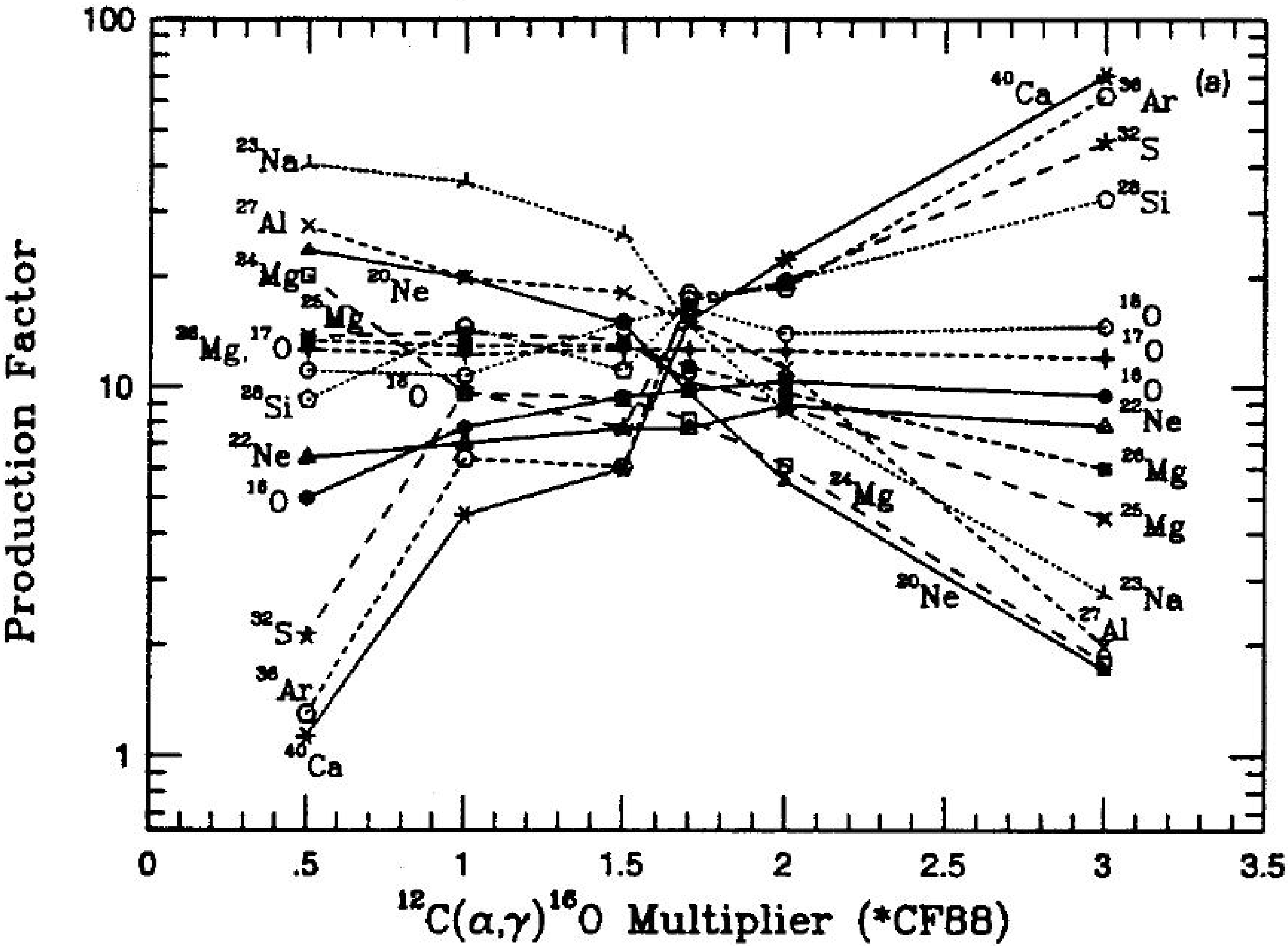
further s-processing via neutron captures and β-decays $\quad$ $^{24}\mathrm{Mg}(\mathrm{n},\gamma)^{25}\mathrm{Mg}$ etc.

production of heavy elements $\quad$ $^{56}\mathrm{Fe}(\mathrm{n},\gamma)^{57}\mathrm{Fe}(\mathrm{n},\gamma)^{58}\mathrm{Fe}$ etc.

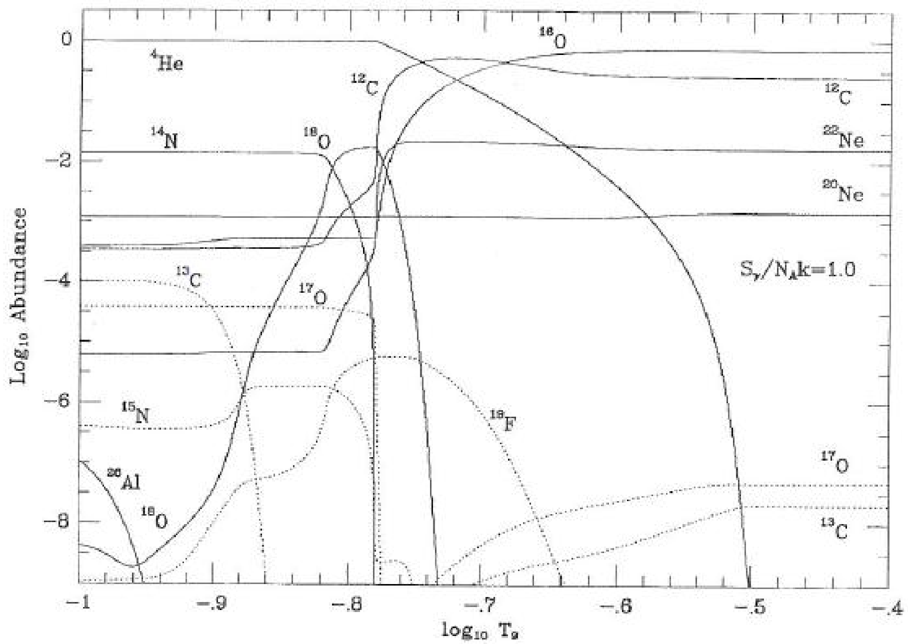
s-process: Slow neutron Capture

- as soon as you produce neutrons, they react because the lack

Influence of 12C(alpha,gamma) on Nucleosynthesis



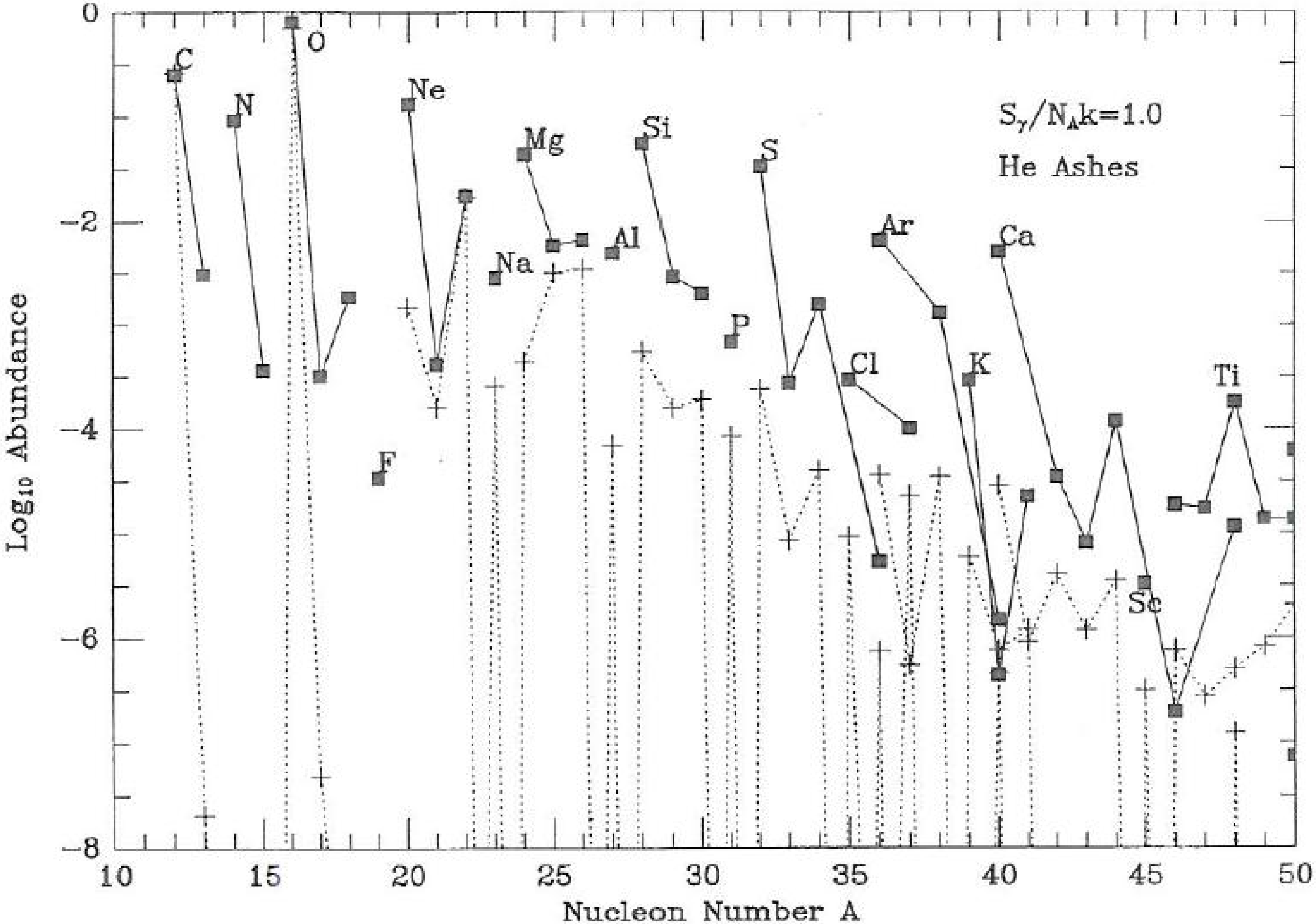
Abundance Structure at the end of the He-core Burning (25Mo)



$T_8 = 1.25 - 1.5$: ^{14}N is depleted, replaced by ^{18}O via $^{14}N(\alpha,\gamma)^{18}F(\beta\nu)^{18}O$; first nucleus with neutron excess

$T_8 \approx 1.6$: ^{4}He depletion and main phase of helium burning begins; first ^{12}C, then ^{16}O are produced; ^{22}Ne is produced by competition of $^{18}O(\alpha,\gamma)^{22}Ne$ and $^{22}Ne(\alpha,\gamma)^{26}Mg$ and $^{22}Ne(\alpha,n)^{25}Mg$; free neutrons appear

Abundances compared to solar values



Squares: solar

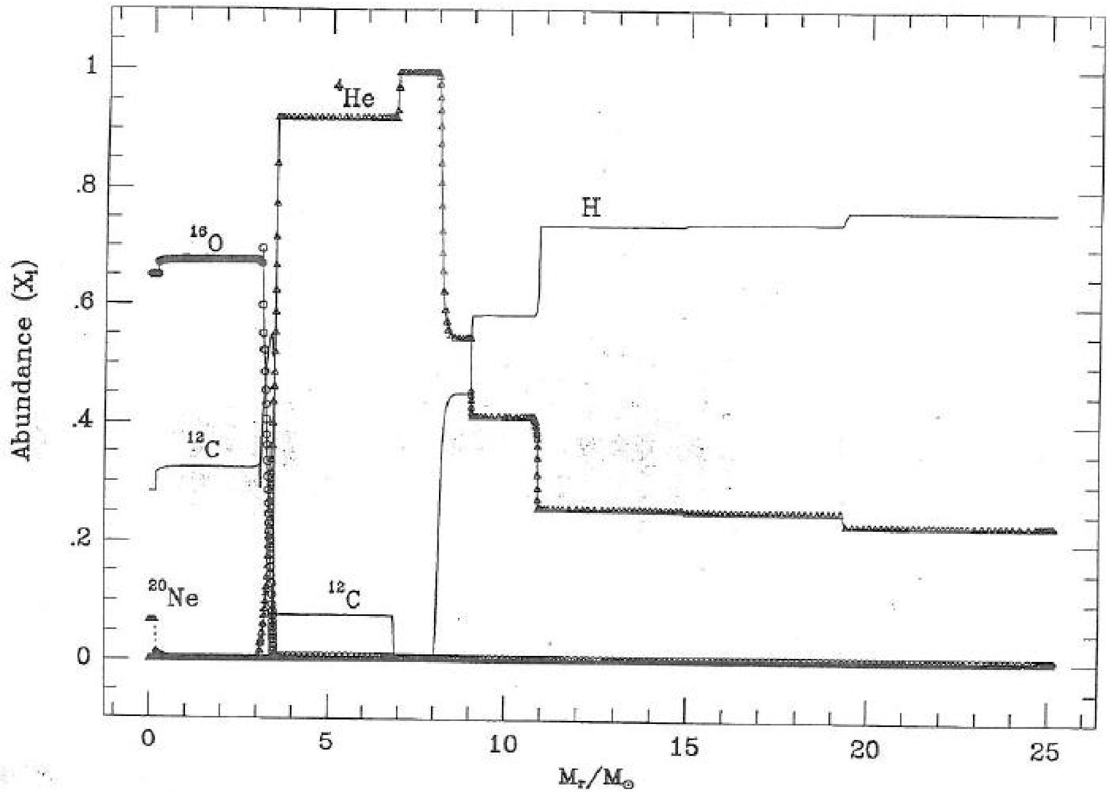
Post-Main-Sequence Evolution beyond He

- Post He-burning Evolution of Massive Stars

- Alpha capture, NSE and advanced stages of stellar evolution

Literature: Iliadis, Chapt. 5.3

Stellar Structure after central He Burning

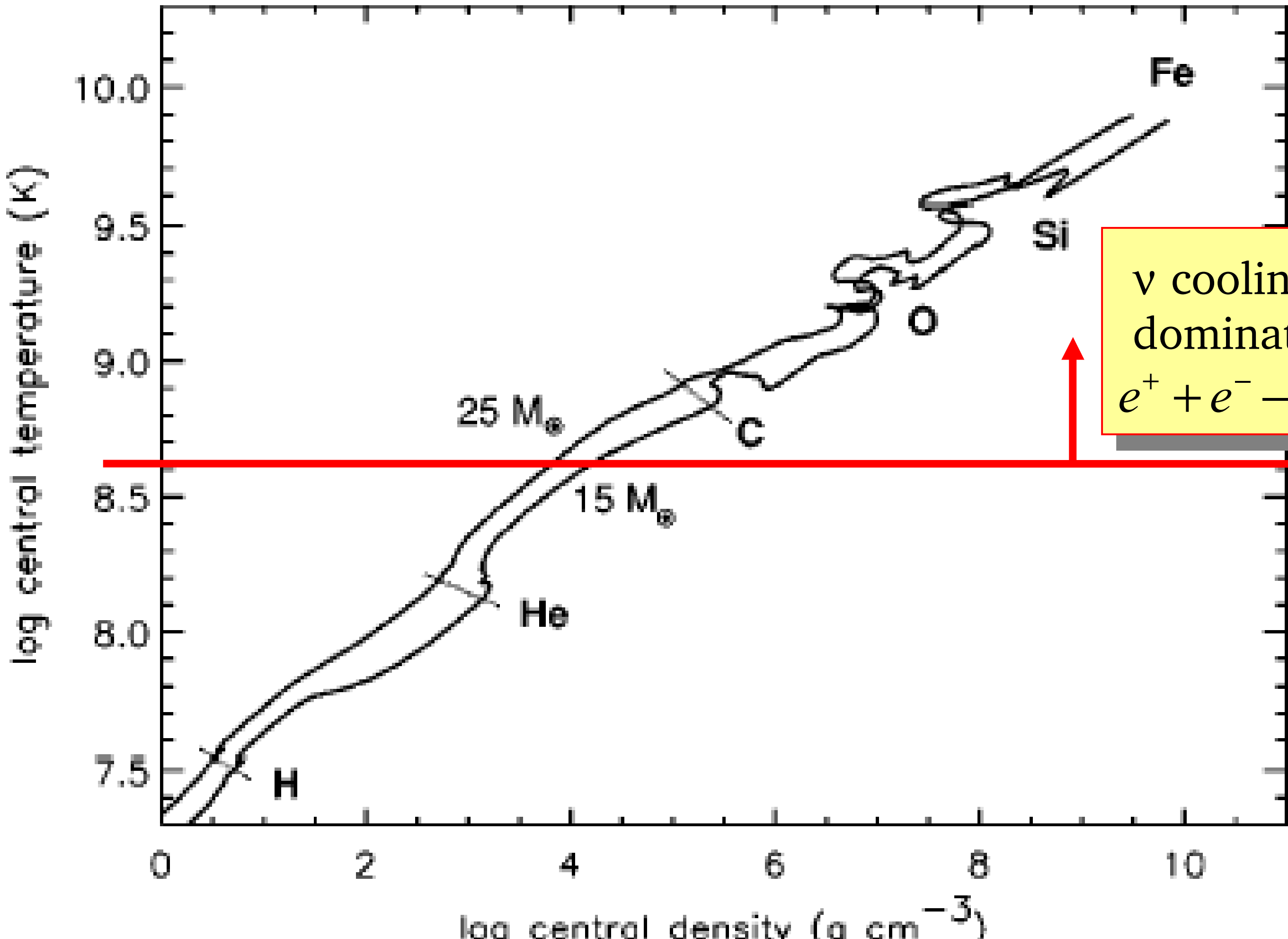


mass fractions of 25 $M_\odot$ star

- $M(r) > 11 M_\odot$: matter not processed
- $8 M_\odot < M(r) < 11 M_\odot$: partial hydrogen burning
- $6 M_\odot < M(r) < 8 M_\odot$: complete H, but no He burning
- $3.3 M_\odot < M(r) < 6 M_\odot$: incomplete He burning, ^{12}C enhanced, no ^{16}O
- $M(r) < 3.3$: complete He burning, proceeds to advanced burning

(Weaver & Woosley, 1998)

Further evolution of burning conditions



ν cooling dominates

$e^{+} + e^{-} \longrightarrow \nu + \overline{\nu}$

Woosley, Heger, Weaver, Rev. Mod. Phys 74 (2002) 1015

Carbon burning

Burning conditions:

for stars > 8 $M_\odot$ (solar masses) (ZAMS)

T~ 600-700 Mio
$\rho \sim 10^5$-10^6 g/cm^3

Major reaction sequences:

$$
\begin{aligned}
{}^{12}C + {}^{12}C \rightarrow {}^{24}Mg^* &\rightarrow {}^{23}Mg + n - 2.62\ \text{MeV} \\
&\rightarrow {}^{20}Ne + \alpha + 4.62\ \text{MeV} \\
&\rightarrow {}^{23}Na + p + 2.24\ \text{MeV}.
\end{aligned}
$$

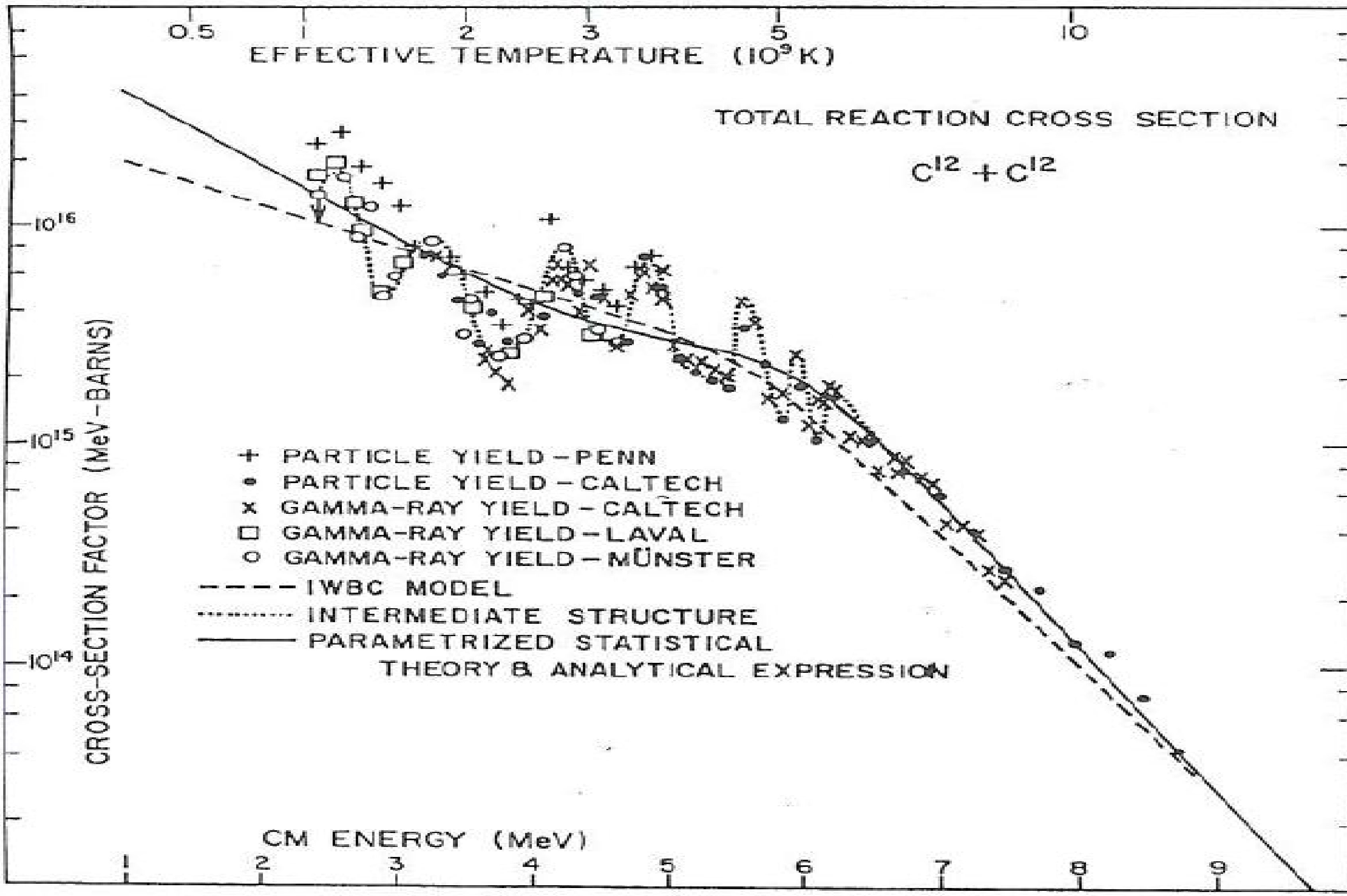
dominates by far

of course p's, n's, and a's are recaptured … ^{23}Mg can b-decay into ^{23}Na

Composition at the end of burning:

mainly ^{20}Ne, ^{24}Mg, with some ^{21,22}Ne, ^{23}Na, ^{24,25,26}Mg, ^{26,27}Al

12C(12C,gamma)24Mg



Major Reactions during Carbon Burning

(a) basic energy generation

$^{12}C(^{12}C,\alpha)^{20}Ne$ $^{12}C(^{12}C,p)^{23}Na$
$^{23}Na(p,\alpha)^{20}Ne$ $^{23}Na(p,\gamma)^{24}Mg$ $^{12}C(\alpha,\gamma)^{16}O$

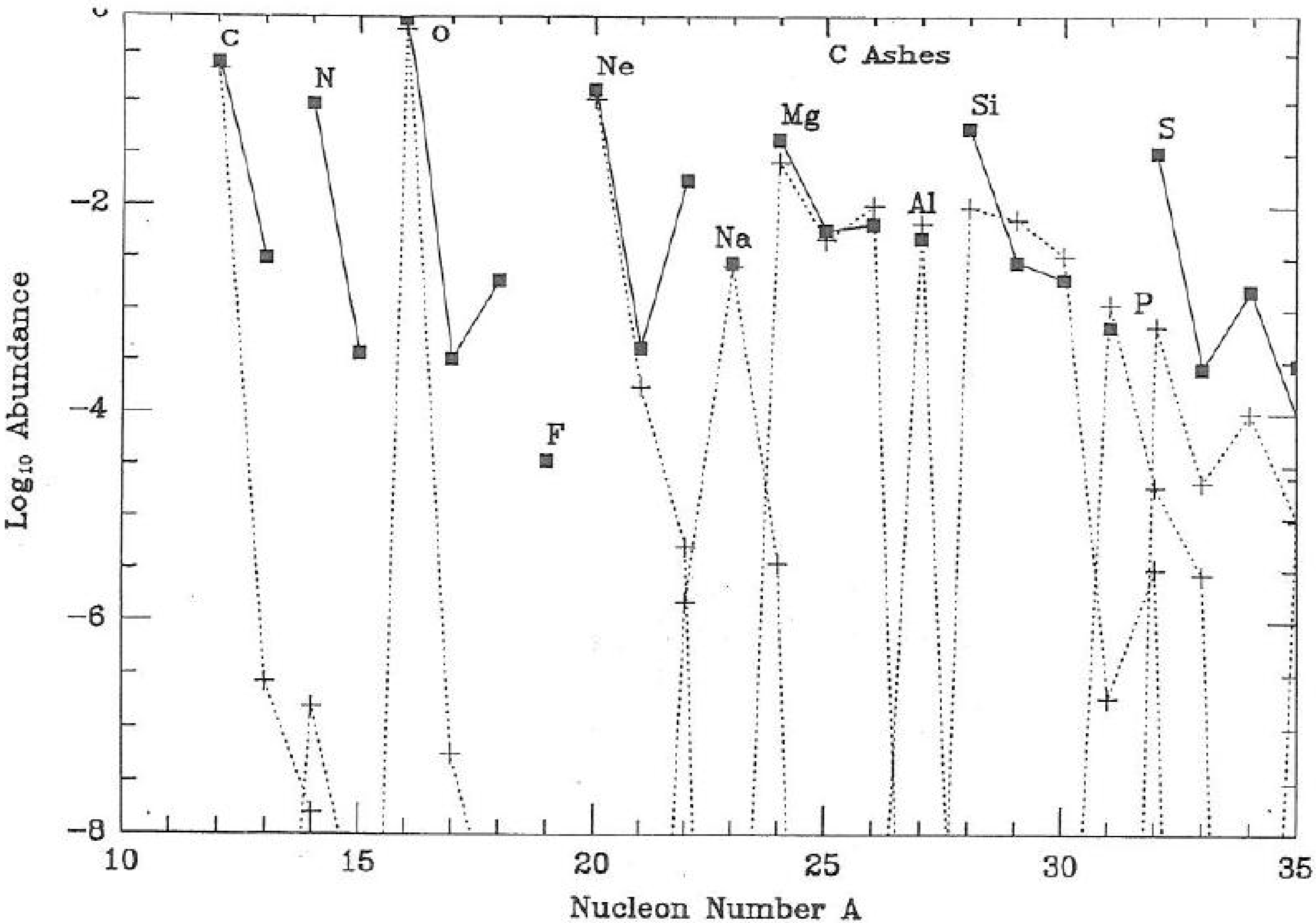
(b) fluxes $> 10^2 \times$(a)

$^{20}Ne(\alpha,\gamma)^{24}Mg$ $^{23}Na(\alpha,p)^{26}Mg(p,\gamma)^{27}Al$
$^{20}Ne(n,\gamma)^{21}Ne(p,\gamma)^{22}Na\ (e^+\nu)^{22}Ne(\alpha,n)^{25}Mg(n,\gamma)^{26}Mg$
$^{21}Ne(\alpha,n)^{24}Mg$ $^{22}Ne(p,\gamma)^{23}Na$ $^{25}Mg(p,\gamma)^{26}Al(e^+\nu)^{26}Mg$

(c) low temperature, high density burning

$^{12}C(p,\gamma)^{13}N(e^+\nu)^{13}C(\alpha,n)^{16}O(\alpha,\gamma)^{20}Ne$
$^{24}Mg(p,\gamma)^{25}Al(e^+\nu)^{25}Mg$
$^{21}Ne(n,\gamma)^{22}Ne(n,\gamma)^{23}Ne(e^-\bar{\nu})^{23}Na(n,\gamma)^{24}Na(e^-\nu)^{24}Mg$ + s-processing

Final composition of Carbon Burning



Neon burning

Burning conditions:

for stars > 12 $M_\odot$ (solar masses) (ZAMS)

T~ 1.3-1.7 Bio K
$\rho \sim 10^6$ g/cm^3

Why would neon burn before oxygen ???

Answer:

Temperatures are sufficiently high to initiate **photodisintegration** of ^{20}Ne

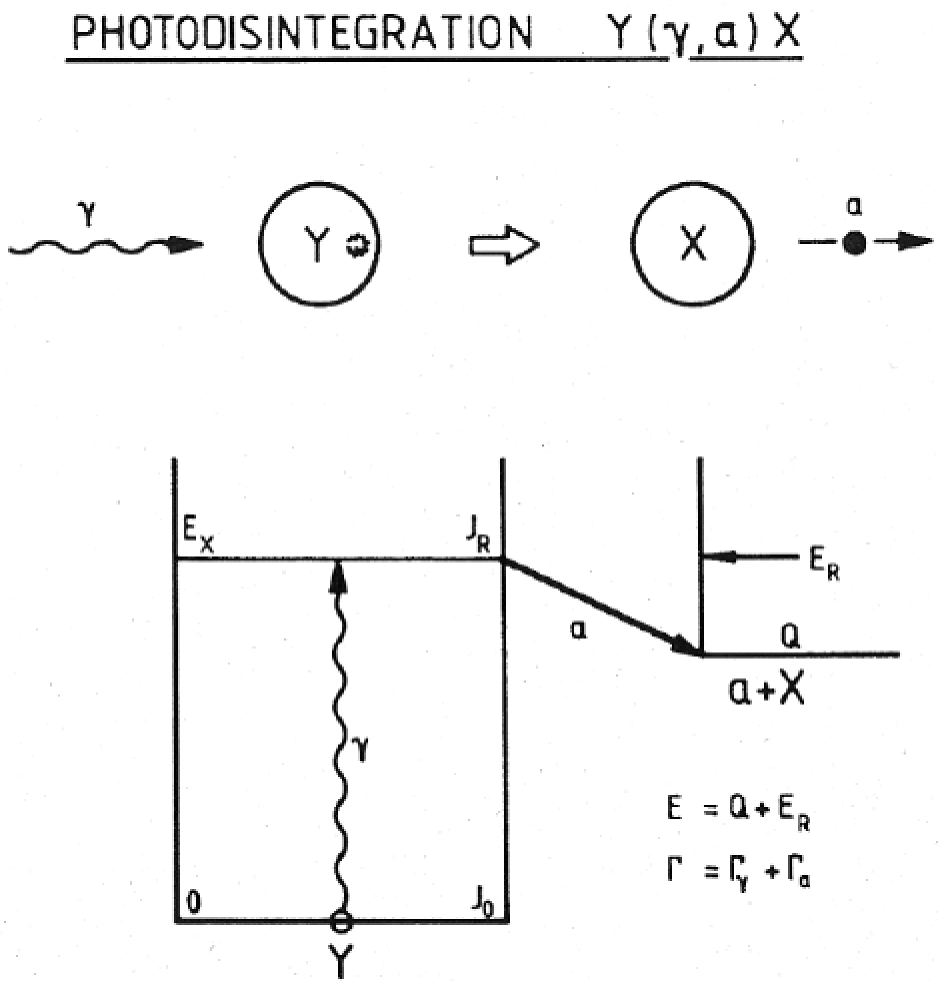
$$\left.\begin{array}{l} ^{20}Ne+\gamma \rightarrow \, ^{16}O + \alpha \\ ^{16}O+\alpha \rightarrow \, ^{20}Ne + \gamma \end{array}\right\}$$ equilibrium is established

this is followed by (using the liberated helium)

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

so net effect: $$2\,^{20}Ne \rightarrow \, ^{16}O + \, ^{24}Mg + 4.59 \text{ MeV.}$$

Photodisintegration



(Rolfs, Fig. 8.5.)

Major Production During Ne-Burning

(a) basic energy generation

$^{20}\mathrm{Ne}(\gamma,\alpha)^{16}\mathrm{O}$ $\quad$ $^{20}\mathrm{Ne}(\alpha,\gamma)^{24}\mathrm{Mg}(\alpha,\gamma)^{28}\mathrm{Si}$

(b) fluxes $> 10^2 \times$(a)

$^{23}\mathrm{Na}(\mathrm{p},\alpha)^{20}\mathrm{Ne}$ $\quad$ $^{23}\mathrm{Na}(\alpha,\mathrm{p})^{26}\mathrm{Mg}(\alpha,\mathrm{n})^{29}\mathrm{Si}$

$^{20}\mathrm{Ne}(\mathrm{n},\gamma)^{21}\mathrm{Ne}(\alpha,\mathrm{n})^{24}\mathrm{Mg}(\mathrm{n},\gamma)^{25}\mathrm{Mg}(\alpha,\mathrm{n})^{28}\mathrm{Si}$

$^{28}\mathrm{Si}(\mathrm{n},\gamma)^{29}\mathrm{Si}(\mathrm{n},\gamma)^{30}\mathrm{Si}$

$^{24}\mathrm{Mg}(\alpha,\mathrm{p})^{27}\mathrm{Al}(\alpha,\mathrm{p})^{30}\mathrm{Si}$

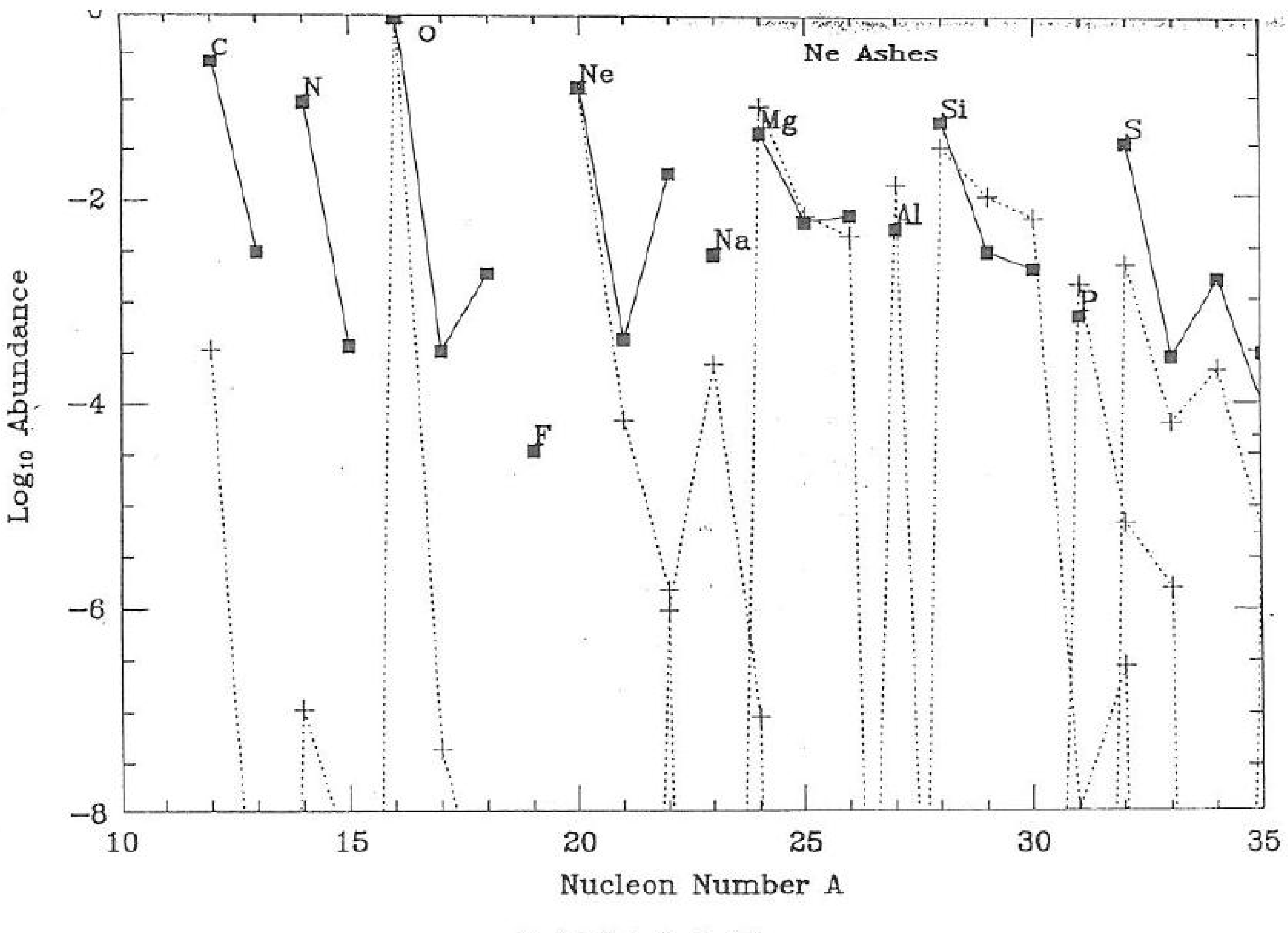
$^{26}\mathrm{Mg}(\mathrm{p},\gamma)^{27}\mathrm{Al}(\mathrm{n},\gamma)^{28}\mathrm{Al}(e^{-}\bar{\nu})^{28}\mathrm{Si}$

(c) low temperature, high density burning

$^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}(\mathrm{n},\gamma)^{26}\mathrm{Mg}(\mathrm{n},\gamma)^{27}\mathrm{Mg}(e^{-}\bar{\nu})^{27}\mathrm{Al}$

$^{22}\mathrm{Ne}$ left from prior neutron-rich carbon burning

Outcome of Ne Burning



Calculations of inverse reaction rates

A reaction rate for a process like ^{20}Ne+γ → ^{16}O + α can be easily calculated from the inverse reaction rate ^{16}O+α → ^{20}Ne + γ using the formalism developed so far.

In general there is a simple relationship between the rates of a reaction rate and its inverse process (if all particles are thermalized)

Derivation of "detailed balance principle":

Consider the reaction A+B → C with Q-value Q in thermal equilibrium.
Then the abundance ratios are given by the Saha equation:

$$\frac{n_A n_B}{n_C} = \frac{g_A g_B}{g_C}\left(\frac{m_A m_B}{m_C}\right)^{3/2}\left(\frac{kT}{2\pi\hbar^2}\right)^{3/2} e^{-Q/kT}$$

In equilibrium the abundances are constant per definition. Therefore in addition

$$\frac{dn_C}{dt} = n_A n_B < \sigma\upsilon > - \lambda_C n_C = 0$$

or $$\frac{\lambda_C}{< \sigma\upsilon >} = \frac{n_A n_B}{n_C}$$

If $<\sigma v>$ is the A+B→ C reaction rate, and λ_C is the C →A+B decay rate

Therefore the rate ratio is defined by the Saha equation as well !

Using both results one finds

$$\frac{\lambda_C}{< \sigma v >} = \frac{g_A g_B}{g_C} \left(\frac{m_A m_B}{m_C} \right)^{3/2} \left(\frac{kT}{2\pi\hbar^2} \right)^{3/2} \mathrm{e}^{-Q/kT}$$

or using $m_C \sim m_A + m_B$ and introducing the reduced mass μ

Reminder: Nuclear Abundances in NSE

The **ratio of the nuclear abundances in NSE to the abundance of free protons and neutrons** is entirely determined by

$$Z \cdot \mu_p + N \cdot \mu_n = \mu_{(\mathrm{Z,N})}$$

which only depends on the chemical potentials

$$\mu = mc^2 + kT \ln\left[\frac{n}{g}\left(\frac{h^2}{2\pi mkT}\right)^{3/2}\right]$$

So all one needs are **density**, **temperature**, and for each nucleus **mass** and **partition function** (**one does not need reaction rates** !! - except for determining whether equilibrium is indeed established)

Solving the two equations on the previous page yields for the abundance ratio:

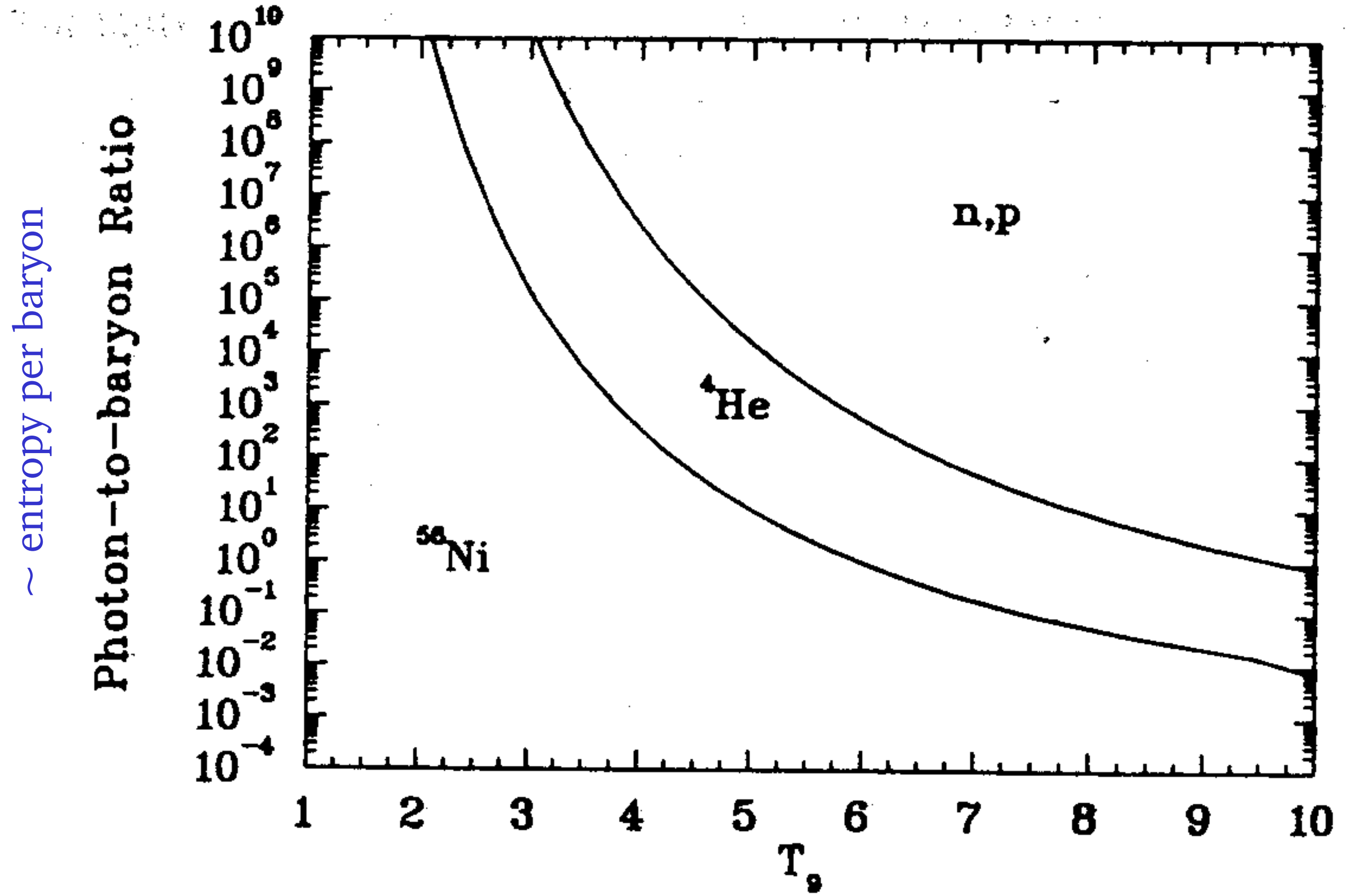
$$Y(Z,N) = Y_p^Z Y_n^N G(Z,N)(\rho N_A)^{A-1} \frac{A^{3/2}}{2^A} \left(\frac{2\pi\hbar^2}{m_u kT} \right)^{\frac{3}{2}(A-1)} \mathrm{e}^{B(Z,N)/kT}$$

$$\sum_i A_i Y_i = 1$$

$$\sum_i Z_i Y_i = Y_e$$

- higher density favors (heavier) nuclei
- higher temperature favors free nucleons (or lighter nuclei)
- nuclei with high binding energy are strongly favored

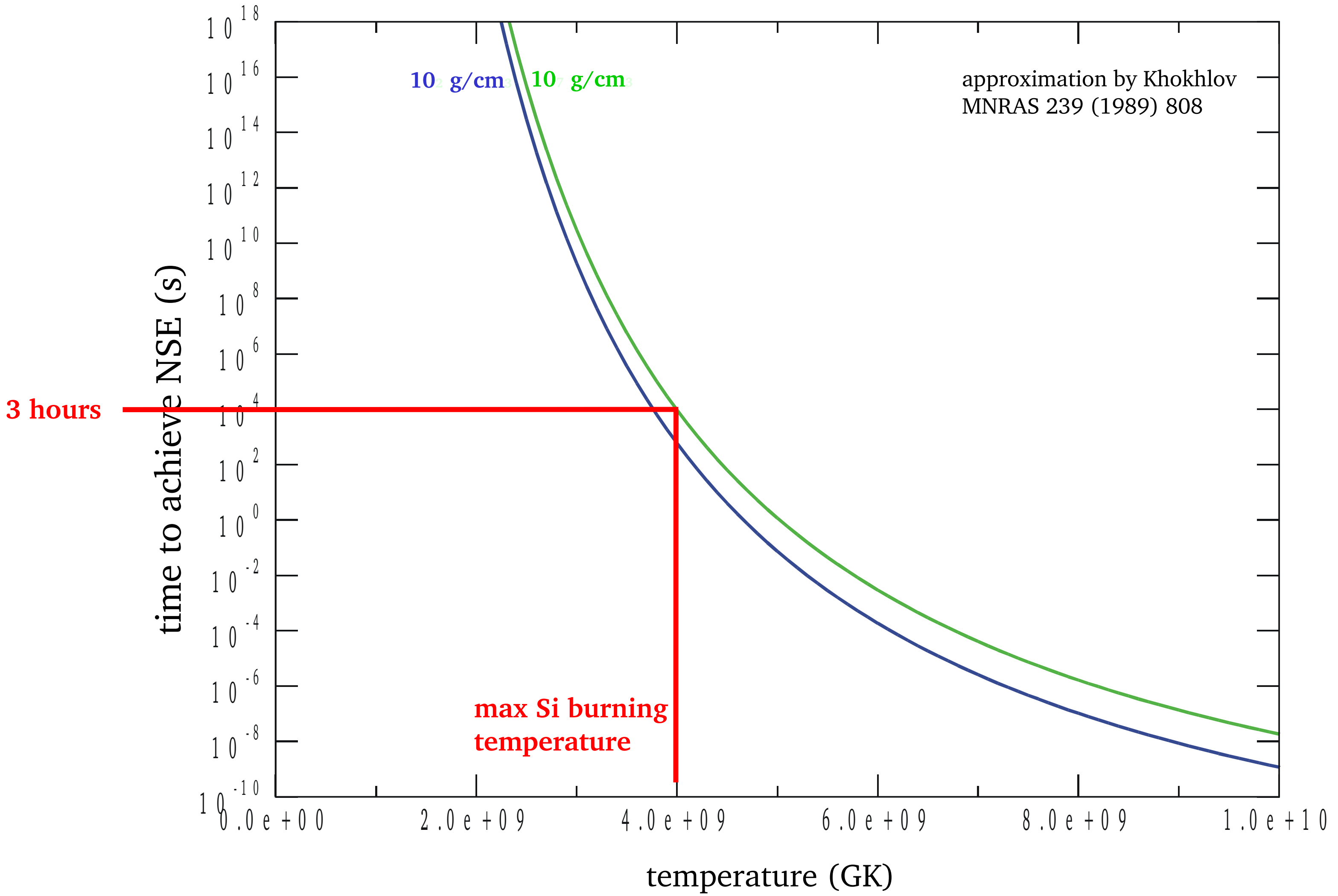
NSE composition (Y_e=0.5)



after Meyer, Phys Rep. 227 (1993) 257 "Entropy and nucleosynthesis"

NSE is established on the timescale of these reaction rates (the slowest reaction)

A system will be in NSE if this timescale is shorter than the timescale for the temperature and density being sufficiently high.



for temperatures above ~5 GK even explosive events achieve full NSE

Oxygen burning

Burning conditions:

T~ 2 Bio
ρ ~ 10^7 g/cm^3

Major reaction sequences:

$$^{16}O + ^{16}O \rightarrow ^{32}S^* \rightarrow ^{31}S + n + 1.45\ \mathrm{MeV} \quad (5\%)$$

$$\rightarrow ^{31}P + p + 7.68\ \mathrm{MeV} \quad (56\%)$$

$$\rightarrow ^{30}P + d - 2.41\ \mathrm{MeV} \quad (5\%)$$

$$\rightarrow ^{28}Si + \alpha + 9.59\ \mathrm{MeV}. \quad (34\%)$$

plus recapture of n,p,d,α

Main products: QSE

Ca

Major Processes during Oxygen Burning

(a) basic energy generation

$^{16}O(^{16}O,\alpha)^{28}Si$ $^{16}O(^{12}O,p)^{31}P$ $^{16}O(^{16}O,n)^{31}S(e^{+}\nu)^{31}P$

$^{31}P(p,\alpha)^{28}Si(\alpha,\gamma)^{32}S$

$^{28}Si(\gamma,\alpha)^{24}Mg(\alpha,p)^{27}Al(\alpha,p)^{30}Si$

$^{32}S(n,\gamma)^{33}S(n,\alpha)^{30}Si(\alpha,\gamma)^{34}S$

$^{28}Si(n,\gamma)^{29}Si(\alpha,n)^{32}S(\alpha,p)^{35}Cl$

$^{29}Si(p,\gamma)^{30}P(e^{+}\nu)^{30}Si$

electron captures

$^{33}S(e^{-},\nu)^{33}P(p,n)^{33}S$

$^{35}Cl(e^{-},\nu)^{35}S(p,n)^{35}Cl$

(b) high temperature burning

$^{32}S(\alpha,\gamma)^{36}Ar(\alpha,p)^{39}K$

$^{36}Ar(n,\gamma)^{37}Ar(e^{+}\nu)^{37}Cl$

$^{35}Cl(\gamma,p)^{34}S(\alpha,\gamma)^{38}Ar(p,\gamma)^{39}K(p,\gamma)^{40}Ca$

$^{35}Cl(e^{-},\nu)^{35}S(\gamma,p)^{34}S$

$^{38}Ar(\alpha,\gamma)^{42}Ca(\alpha,\gamma)^{46}Ti$

$^{42}Ca(\alpha,p)^{45}Sc(p,\gamma)^{46}Ti$

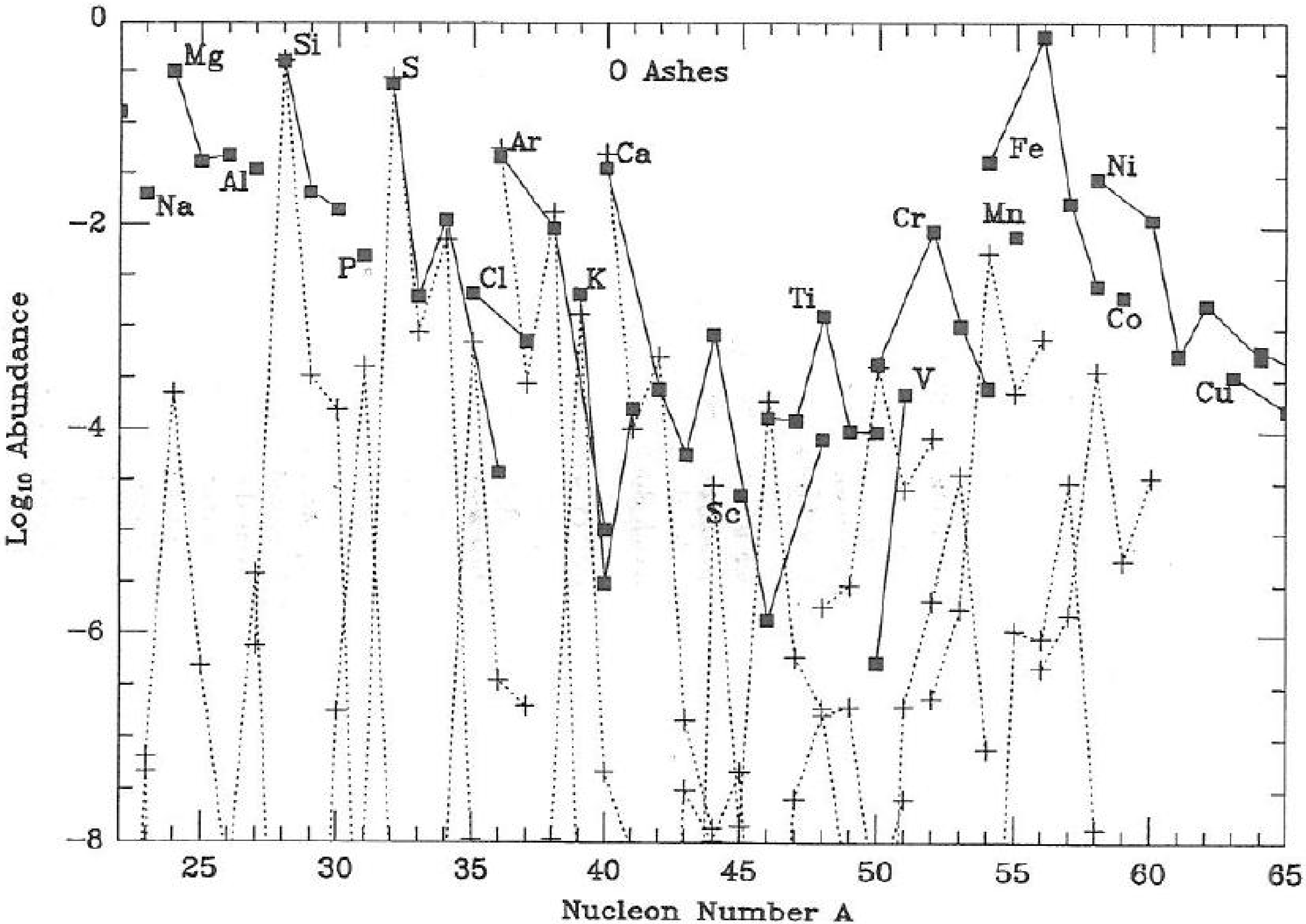
(c) low temperature, high density burning

$^{31}P(e^{-}\nu)^{31}S$ $^{31}P(n,\gamma)^{32}P$

$^{32}S(e^{-},\nu)^{32}P(p,n)^{32}S$

$^{33}P(p,\alpha)^{30}Si$

Products of hydrostatic O burning



Silicon burning

Burning conditions:

T~ 3-4 Bio
ρ ~ 10^{9} g/cm^{3}

Reaction sequences:

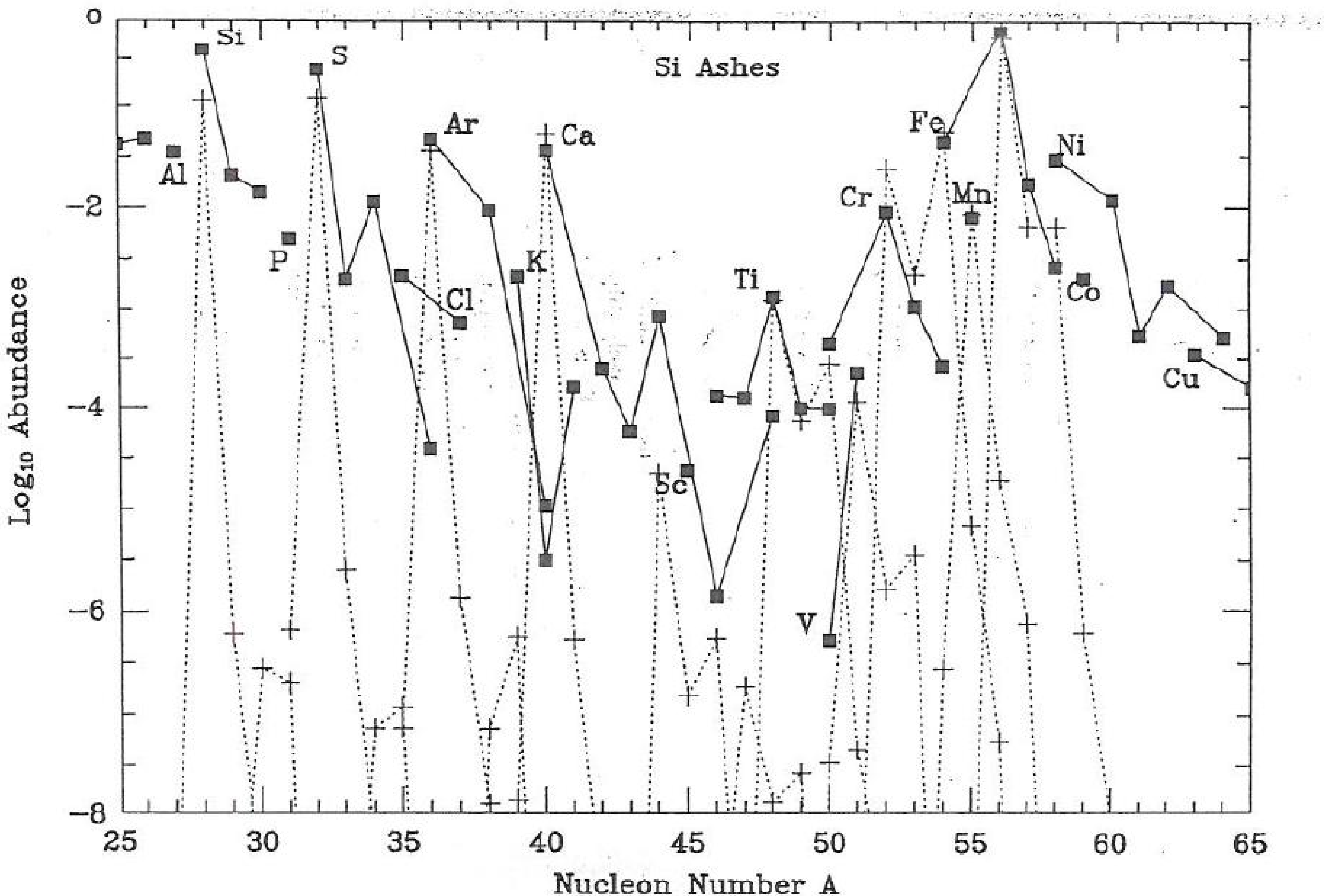
- Silicon burning is fundamentally different to all other burning stages.
- **Complex network of fast (γ ,n), (γ ,p), (γ ,a), (n,γ), (p,γ), and (a,γ) reactions**
- The net effect of Si burning is: 2 ^{8}Si --> ^{6}Ni,

<u>need new concept to describe burning:</u>

Nuclear Statistical Equilibrium (NSE)

Quasi Statistical Equilibrium (QSE)

Products of hydrostatic Si Burning



Summary stellar burning

TABLE 8.1 Evolutionary Stages of a 25 $M_\odot$ Star[a]

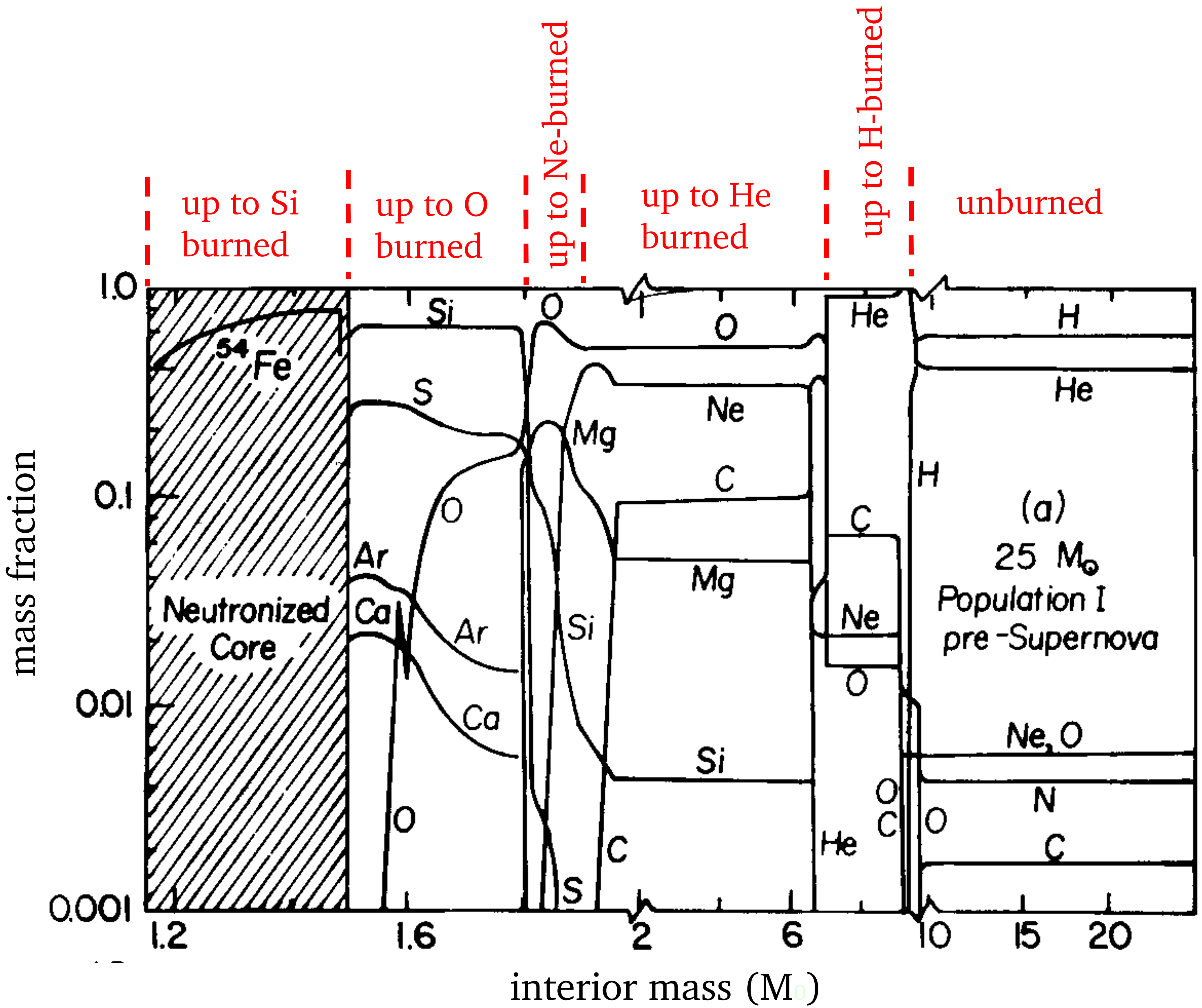
- $>0.8 M_0$
- $>8 M_0$
- $>12 M_0$

Stage	Time Scale	Temperature (T_9)	Density (g cm^{-3})
Hydrogen burning	7×10^6 y	0.06	5
Helium burning	5×10^5 y	0.23	7×10^2
Carbon burning	600 y	0.93	2×10^5
Neon burning	1 y	1.7	4×10^6
Oxygen burning	6 months	2.3	1×10^7
Silicon burning	1 d	4.1	3×10^7
Core collapse	seconds	8.1	3×10^9
Core bounce	milliseconds	34.8	$\simeq 3 \times 10^{14}$
Explosive burning	0.1–10 s	1.2–7.0	Varies

Why do timescales get smaller ?

<u>Note:</u> Kelvin-Helmholtz timescale for red supergiant ~10,000 years, so for massive stars, no surface temperature - luminosity change for C-burning and beyond

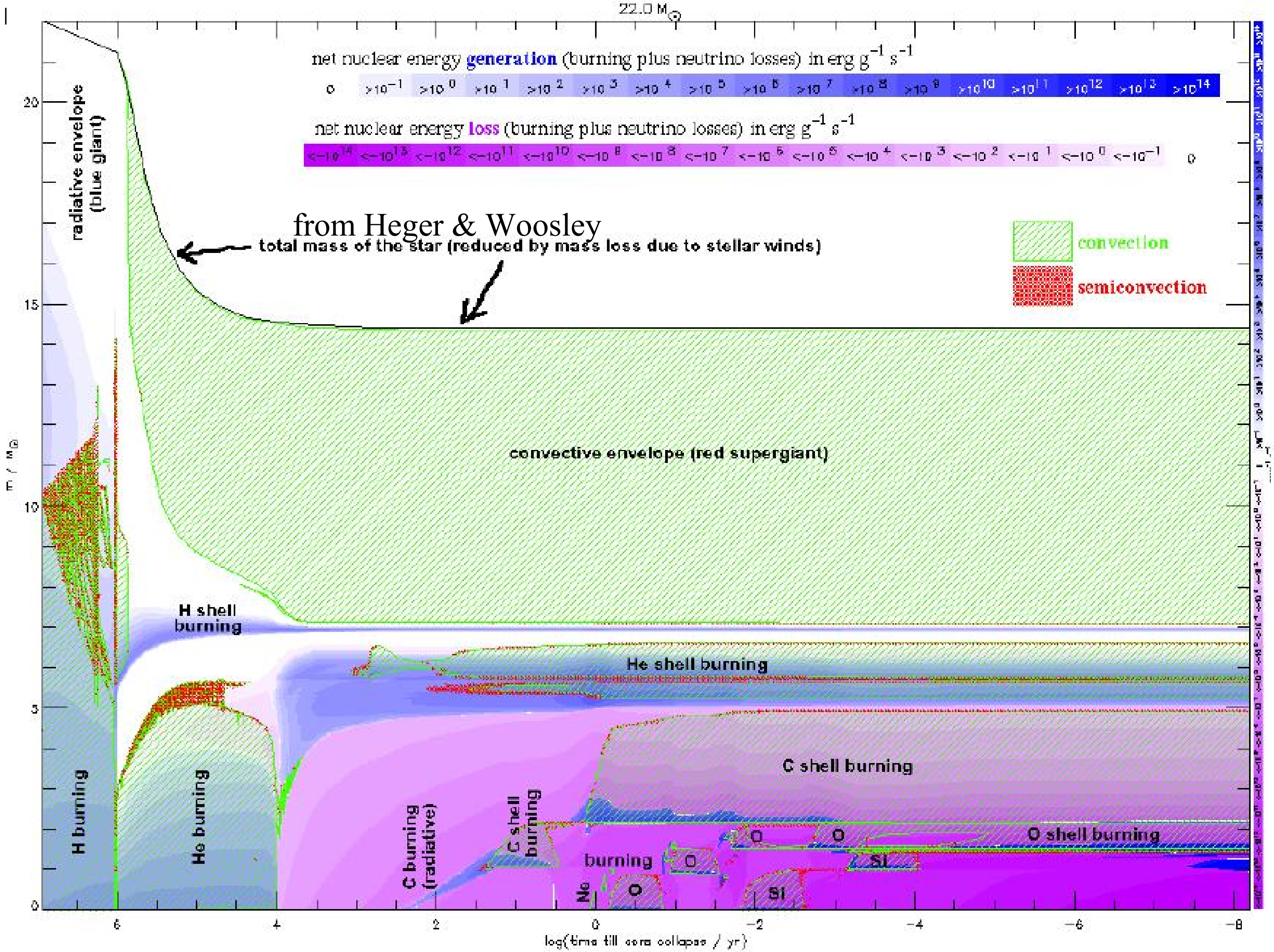
Final composition of a 25 M☉ star:



Summary: Main Products of Hydrostatic Burning

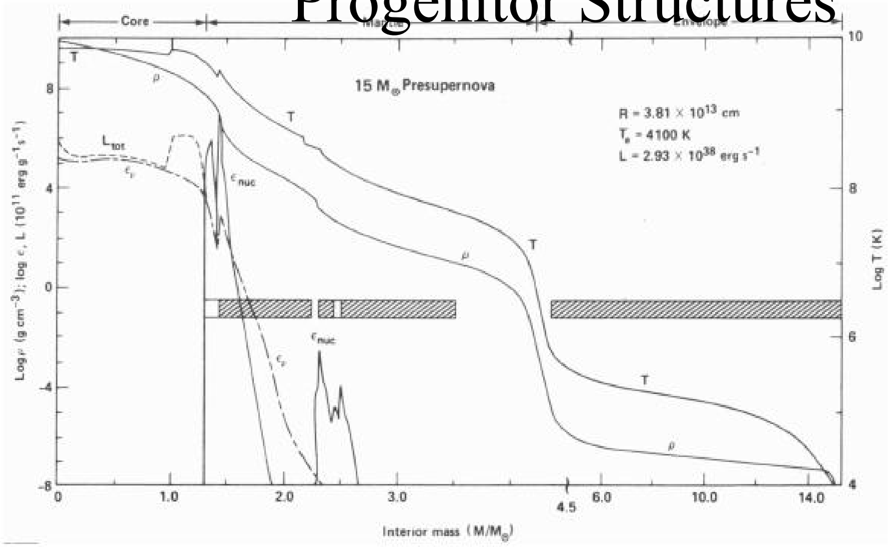
Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4\,H \xrightarrow{CNO} {}^4He$
He	O, C	^{18}O, ^{22}Ne s-process	0.2	10^6	$3\,He^4 \rightarrow {}^{12}C$ $^{12}C(\alpha,\gamma)^{16}O$
C	Ne, Mg	Na	0.8	10^3	$^{12}C + {}^{12}C$
Ne	O, Mg	Al, P	1.5	3	$^{20}Ne(\gamma,\alpha)^{16}O$ $^{20}Ne(\alpha,\gamma)^{24}Mg$
O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}O + {}^{16}O$
Si	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$^{28}Si(\gamma,\alpha)\ldots$

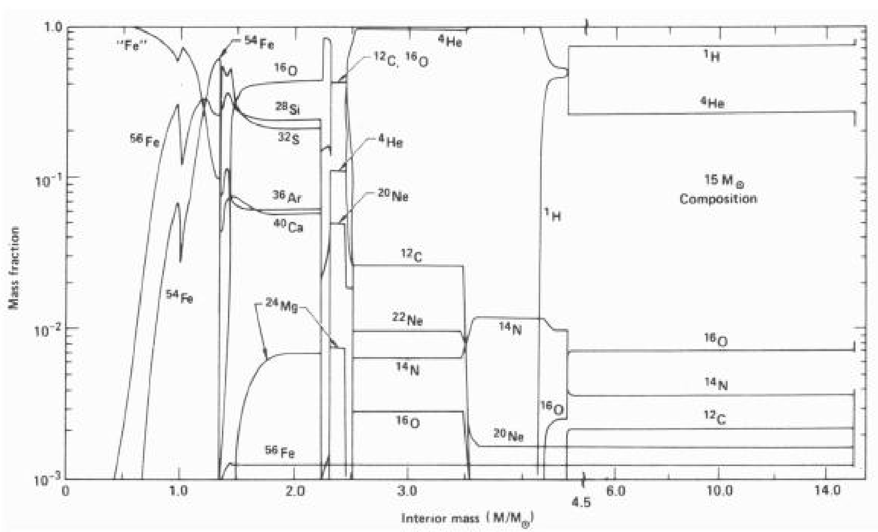
Summary: Stellar Evolution of Massive Stars

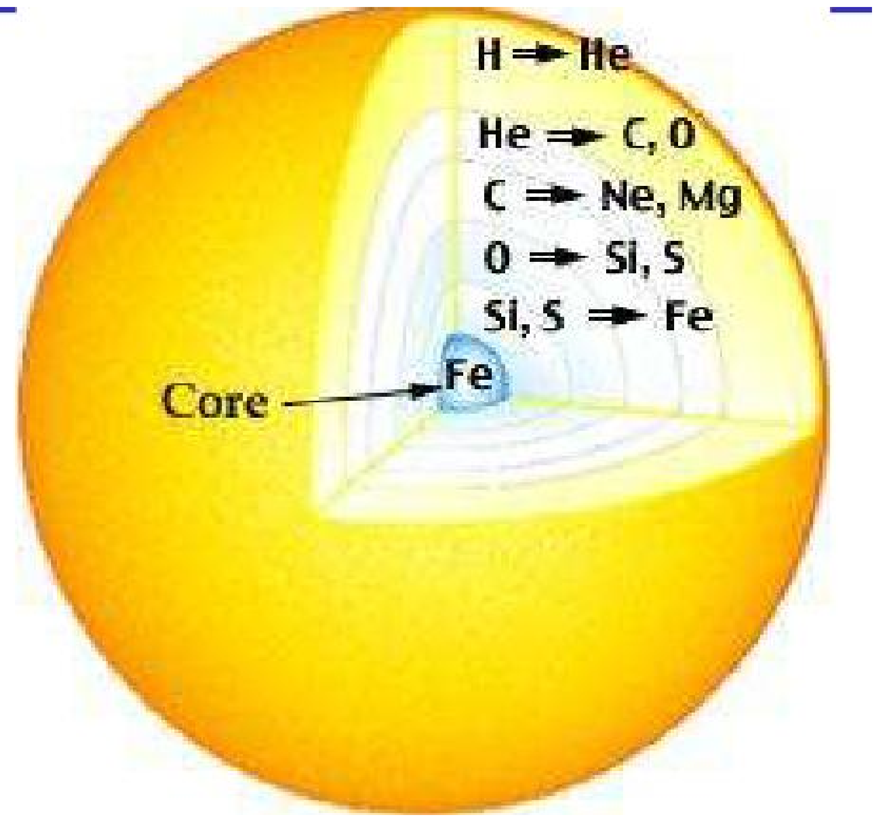


Next: Exploding Stars /Supernovae

Progenitor Structures







Summary: Stellar Evolution Stages

hydrogen burning						
$M_{\rm initial}$	T	ρ	M	L	R	τ
$M_\odot$	10^7 K	g cm^{-3}	$M_\odot$	$10^3 L_\odot$	$R_\odot$	Myr
1	1.57	153	1.00	0.001	1.00	~1,100
15	3.53	5.81	14.9	28.0	6.75	11.1
20	3.69	4.53	19.7	62.6	8.03	8.13
25	3.81	3.81	24.5	110	9.17	6.70
75	4.26	1.99	67.3	916	21.3	3.16

helium burning						
$M_{\rm initial}$	T	ρ	M	L	R	τ
$M_\odot$	10^8 K	10^3 g cm^{-3}	$M_\odot$	$10^3 L_\odot$	$R_\odot$	Myr
1	1.25	20	0.71	0.044	~ 100	110
15	1.78	1.39	14.3	41.3	461	1.97
20	1.88	0.968	18.6	102	649	1.17
25	1.96	0.762	19.6	182	1,030	0.839
75	2.10	0.490	16.1	384	1.17	0.478

carbon burning						
$M_{\rm initial}$	T	ρ	M	L	R	τ
$M_\odot$	10^8 K	10^5 g cm^{-3}	$M_\odot$	$10^3 L_\odot$	$R_\odot$	kyr
15	8.34	2.39	12.6	83.3	803	2.03
20	8.70	1.70	14.7	143	1,070	0.976
25	8.41	1.29	12.5	245	1,390	0.522
75	8.68	1.39	6.37	164	0.644	1.07

0 1.0 2.0 3.0 4.5 6.0 10.0 14.0

Interior mass ($M/M_\odot$)

neon burning						
$M_{\rm initial}$	T	ρ	M	L	R	τ
$M_\odot$	10^9 K	10^6 g cm^{-3}	$M_\odot$	$10^3 L_\odot$	$R_\odot$	yr
15	1.63	7.24	12.6	86.5	821	0.732
20	1.57	3.10	14.7	147	1,090	0.599
25	1.57	3.95	12.5	246	1,400	0.891
75	1.62	5.21	6.36	167	0.715	0.569

oxygen burning						
$M_{\rm initial}$	T	ρ	M	L	R	τ
$M_\odot$	10^9 K	10^6 g cm^{-3}	$M_\odot$	$10^3 L_\odot$	$R_\odot$	yr
15	1.94	6.66	12.6	86.6	821	2.58
20	1.98	5.55	14.7	147	1,090	1.25
25	2.09	3.60	12.5	246	1,400	0.402
75	2.04	4.70	6.36	172	0.756	0.908

silicon burning						
$M_{\rm initial}$	T	ρ	M	L	R	τ
$M_\odot$	10^9 K	10^7 g cm^{-3}	$M_\odot$	$10^3 L_\odot$	$R_\odot$	d
15	3.34	4.26	12.6	86.5	821	18.3
20	3.34	4.26	14.7	147	1,090	11.5
25	3.65	3.01	12.5	246	1,400	0.733
75	3.55	3.73	6.36	173	0.755	2.09