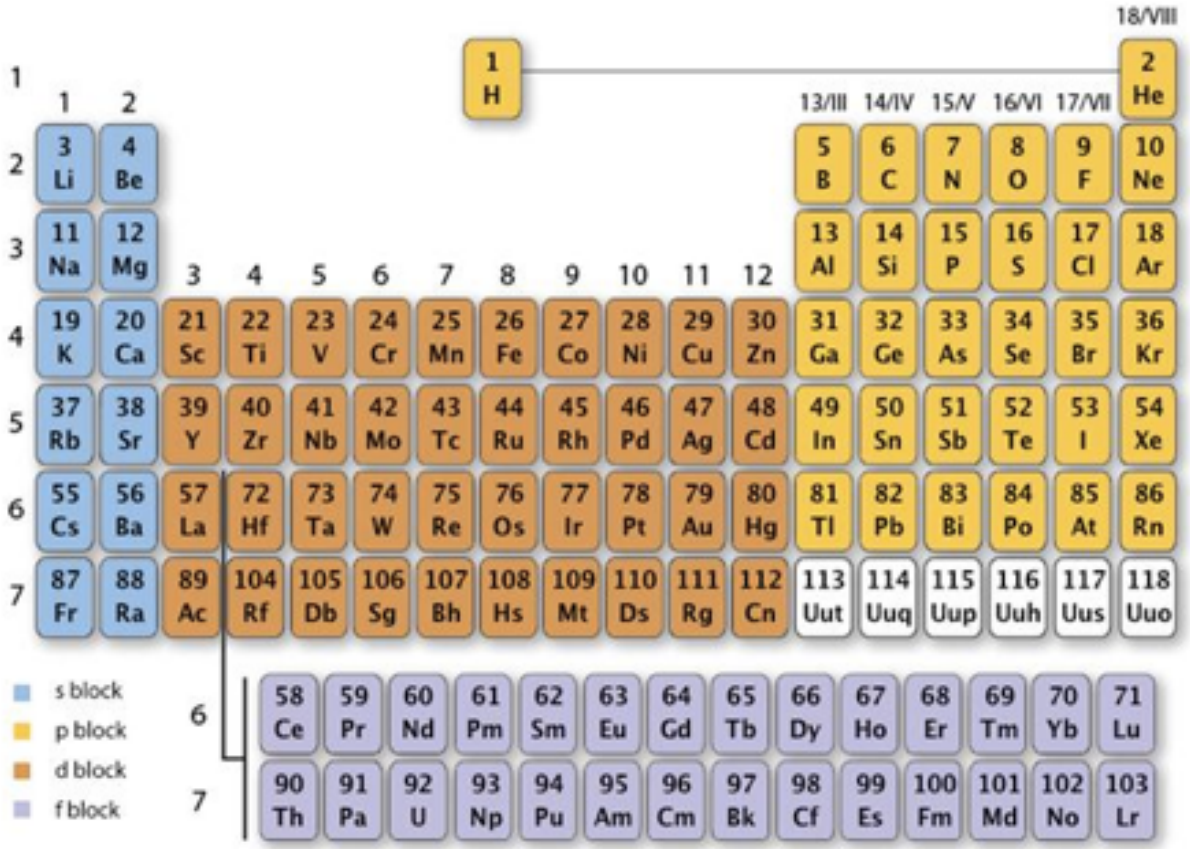
Evolution of massive stars (~8-150 M_sun)

- High luminosity – nuclear reactions go fast, so lifetimes short
- Stellar cores (with nuclear reactions) are now convective, outer regions radiative
- First stages of evolution: CNO burning of H to He
- He burning starts without flash (core is not degenerate)

Introduction in the world of isotopes

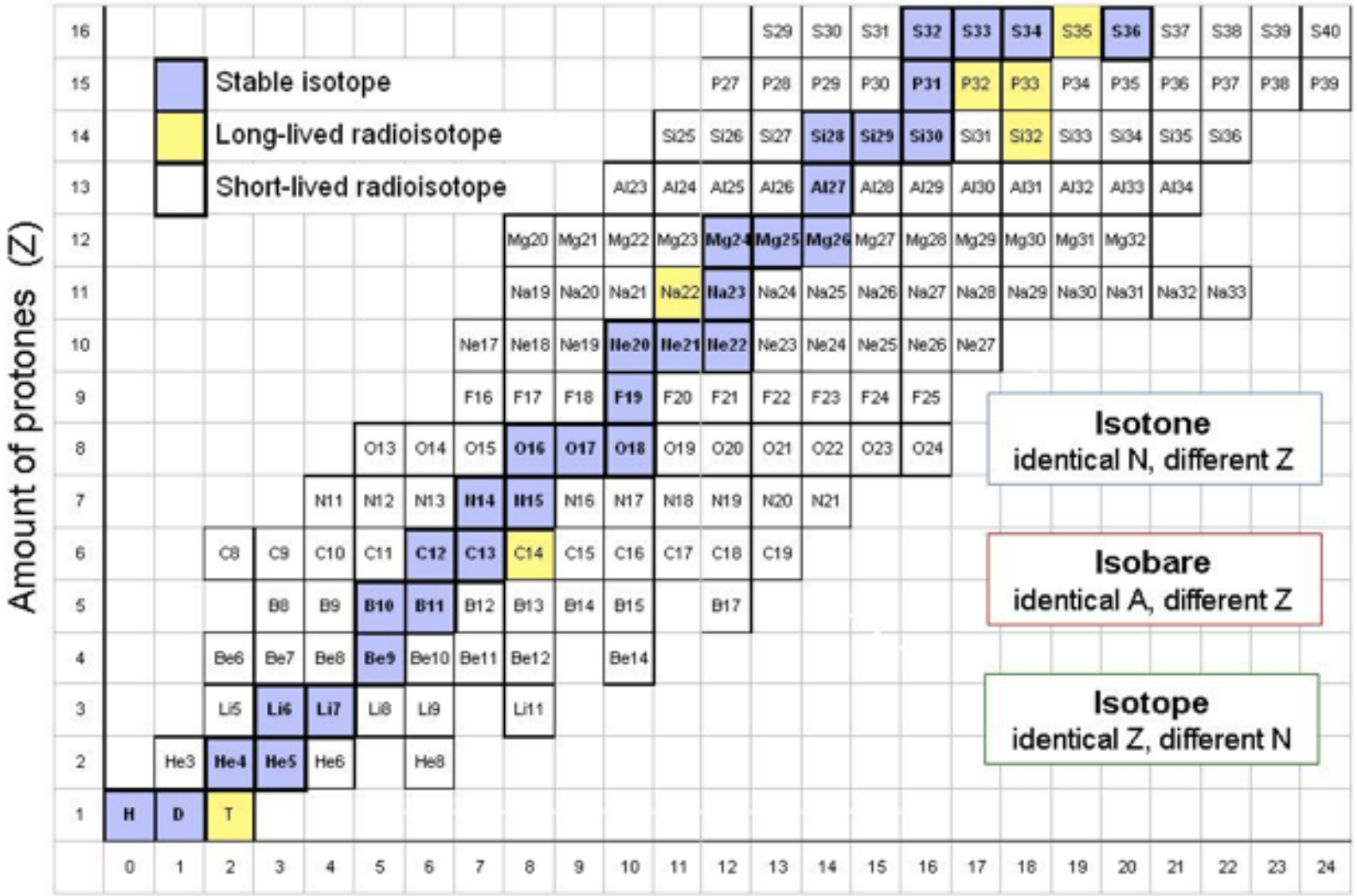
The periodic table of the elements



92 elements → over 1000 isotopes

Isotopes

$$ {}^{A}_{Z}X_{N} \qquad A = Z+N $$



Later stages of nucleosynthesis

- Carbon burning core, He burning shell, H burning shell

$$^{12}_{6}\mathrm{C} + ^{4}_{2}\mathrm{He} \rightarrow ^{16}_{8}\mathrm{O} + \gamma$$

$$^{16}_{8}\mathrm{O} + ^{4}_{2}\mathrm{He} \rightarrow ^{20}_{10}\mathrm{Ne} + \gamma$$

- At this stage the star is in the red-giant region of the HR diagram

Energy loss via neutrinos: speeds up evolution

After helium burning the core contracts and the temperature rises. The most abundant fuel with the lowest charge is carbon (^{12}C). In order to get two carbons to fuse, a temperature of almost a billion K is required (actually 0.8 billion).

At such high temperatures, a new energy loss mechanism comes into play.

$$\text{Gamma rays } (\gamma) \rightleftarrows e^+ + e^-$$

$$\text{Very rarely though } \quad e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e$$

If a star is sufficiently massive, still higher central temperatures can be obtained and many other nuclear products become possible. Examples of available reactions include carbon burning reactions near 6×10^8 K,

$$^{12}_{6}\mathrm{C} + {}^{12}_{6}\mathrm{C} \rightarrow \begin{cases} {}^{16}_{8}\mathrm{O} + 2\,{}^{4}_{2}\mathrm{He} \quad *** \\ {}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} \\ {}^{23}_{11}\mathrm{Na} + p^{+} \\ {}^{23}_{12}\mathrm{Mg} + n \quad *** \\ {}^{24}_{12}\mathrm{Mg} + \gamma \end{cases} \tag{10.66}$$

and oxygen burning reactions near 10^9 K,

$$^{16}_{8}\mathrm{O} + {}^{16}_{8}\mathrm{O} \rightarrow \begin{cases} {}^{24}_{12}\mathrm{Mg} + 2\,{}^{4}_{2}\mathrm{He} \quad *** \\ {}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} \\ {}^{31}_{15}\mathrm{P} + p^{+} \\ {}^{31}_{16}\mathrm{S} + n \\ {}^{32}_{16}\mathrm{S} + \gamma \end{cases} \tag{10.67}$$

Carroll and Ostlie

More nucleosynthesis

Then the star's core goes through successive stages of burning heavier and heavier elements : neon, oxygen, silicon, etc

(also have reactions that produce magnesium, sulfur, etc)

If a star is sufficiently massive, still higher central temperatures can be obtained and many other nuclear products become possible. Examples of available reactions include carbon burning reactions near 6×10^8 K,

$$^{12}_{6}\mathrm{C} + {}^{12}_{6}\mathrm{C} \rightarrow \begin{cases} {}^{16}_{8}\mathrm{O} + 2\,{}^{4}_{2}\mathrm{He} & *** \\ {}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} & \\ {}^{23}_{11}\mathrm{Na} + p^+ & \\ {}^{23}_{12}\mathrm{Mg} + n & *** \\ {}^{24}_{12}\mathrm{Mg} + \gamma & \end{cases} \tag{10.66}$$

and oxygen burning reactions near 10^9 K,

$$^{16}_{8}\mathrm{O} + {}^{16}_{8}\mathrm{O} \rightarrow \begin{cases} {}^{24}_{12}\mathrm{Mg} + 2\,{}^{4}_{2}\mathrm{He} & *** \\ {}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} & \\ {}^{31}_{15}\mathrm{P} + p^+ & \\ {}^{31}_{16}\mathrm{S} + n & \\ {}^{32}_{16}\mathrm{S} + \gamma & \end{cases} \tag{10.67}$$

Carroll and Ostlie

SUMMARY

Advanced Nuclear Burning Stages

(e.g., 20 solar masses)

Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)
H	He	^{14}N	0.04	10^7
He	C,O	^{18}O, ^{22}Ne s- process	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week

Why stop at Fe?

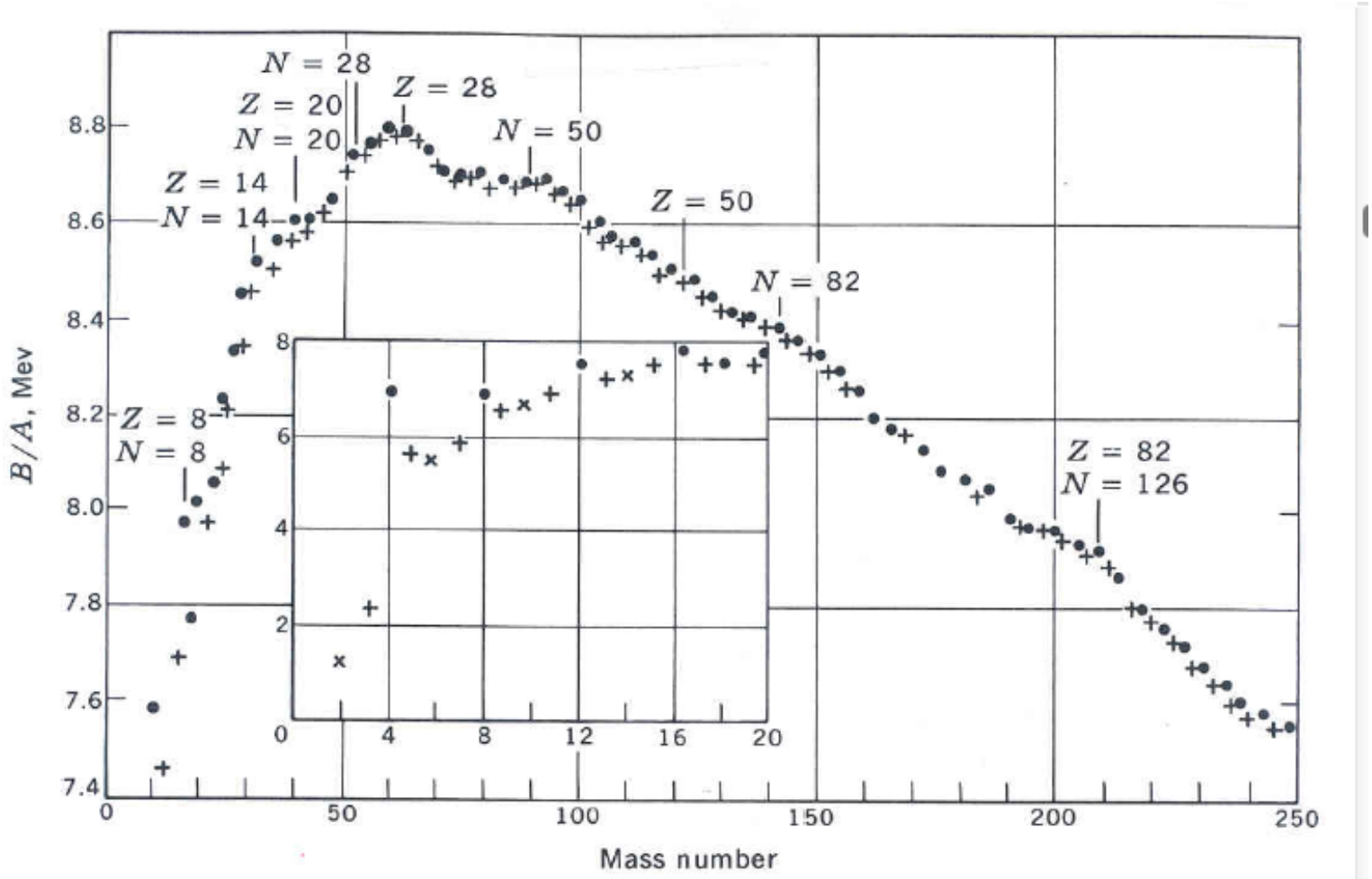
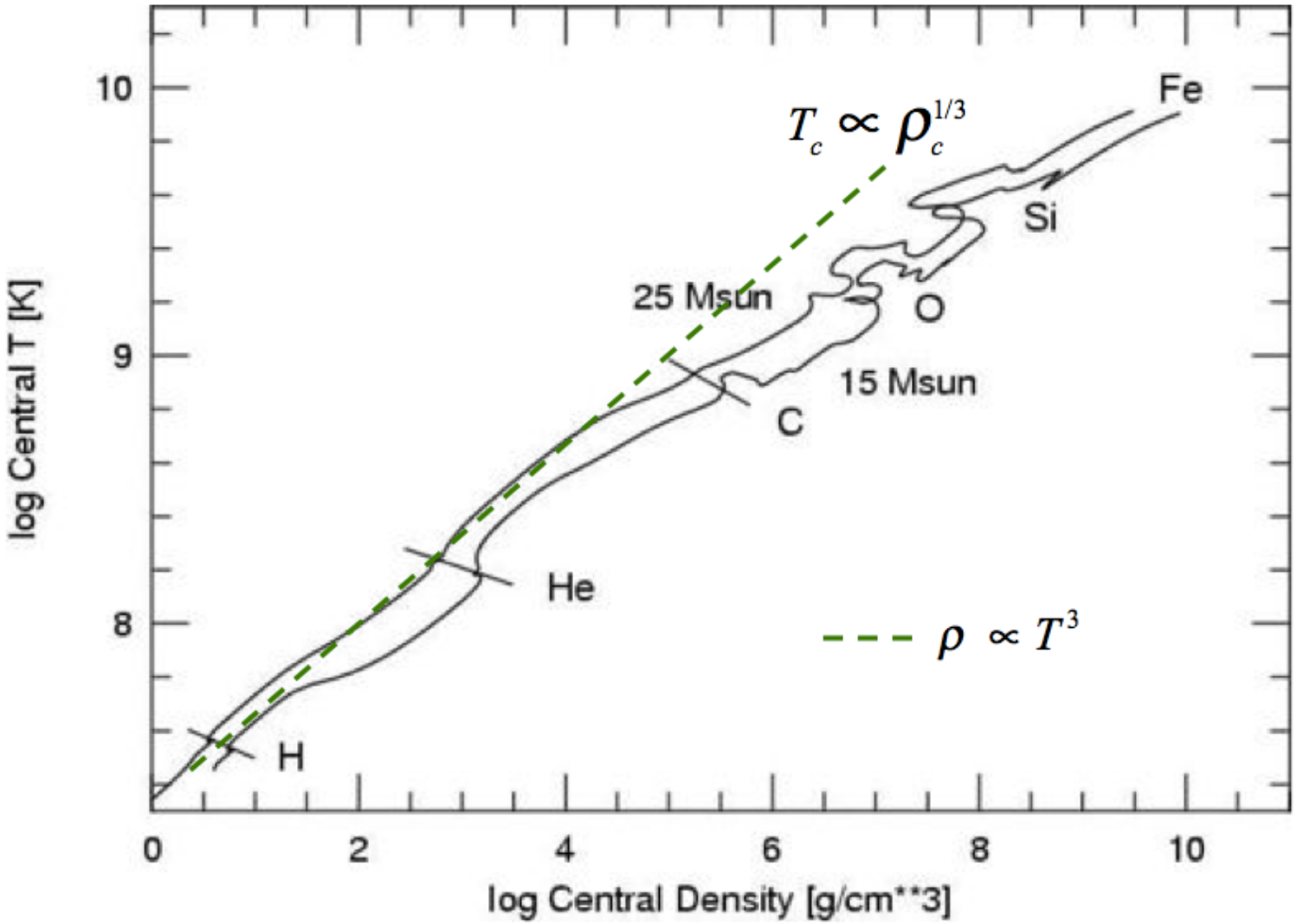
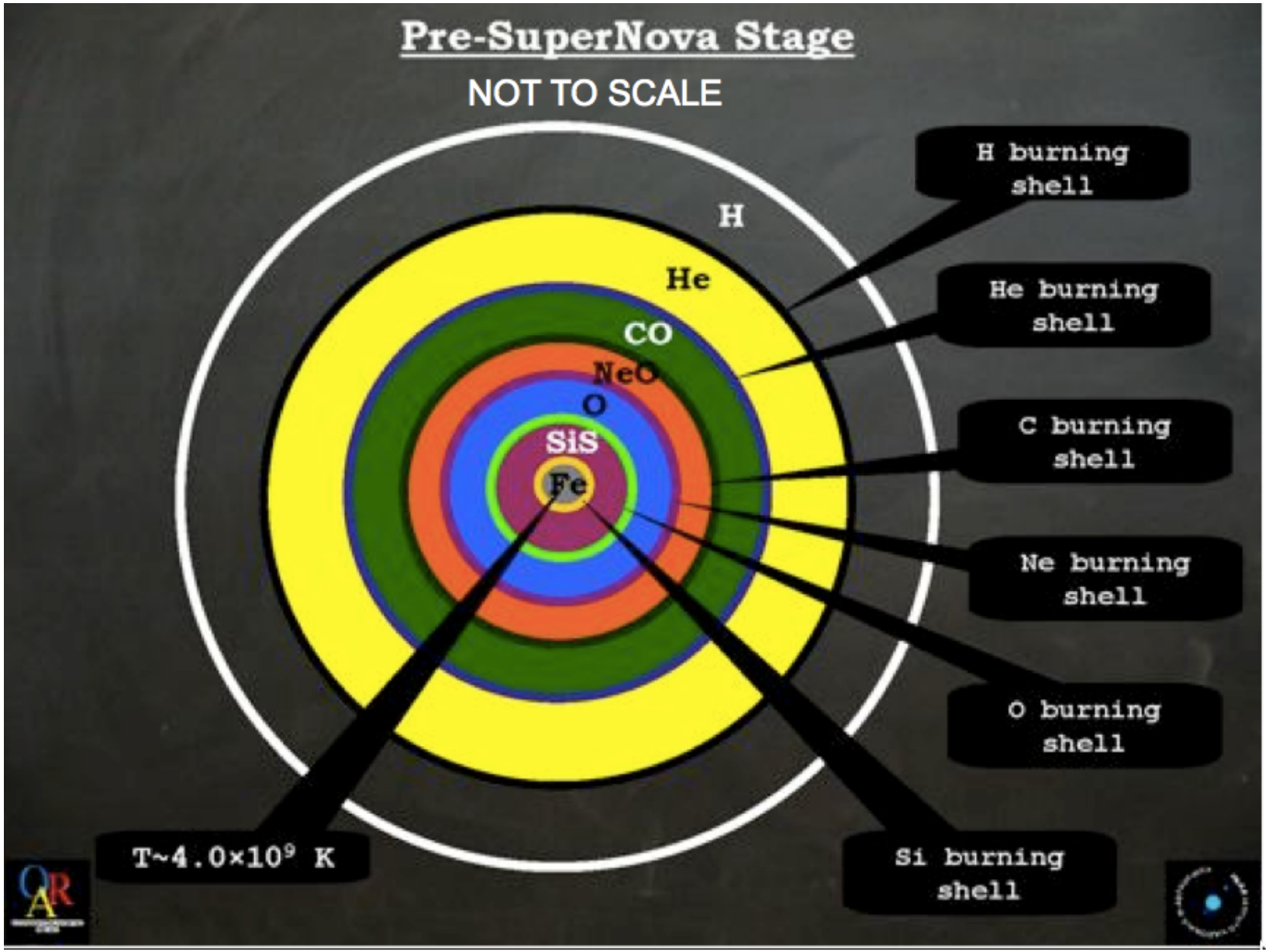


Fig. 7-1 The binding energy per nucleon of the most stable isobar of atomic weight A. The

After each burning stage the core contracts, heats up and ignites another fuel



Stan Woosely UCSC


Pre-SuperNova Stage
NOT TO SCALE
H
He
CO
NeO
O
SiS
Fe
H burning shell
He burning shell
C burning shell
Ne burning shell
O burning shell
Si burning shell
T~4.0×10⁹ K

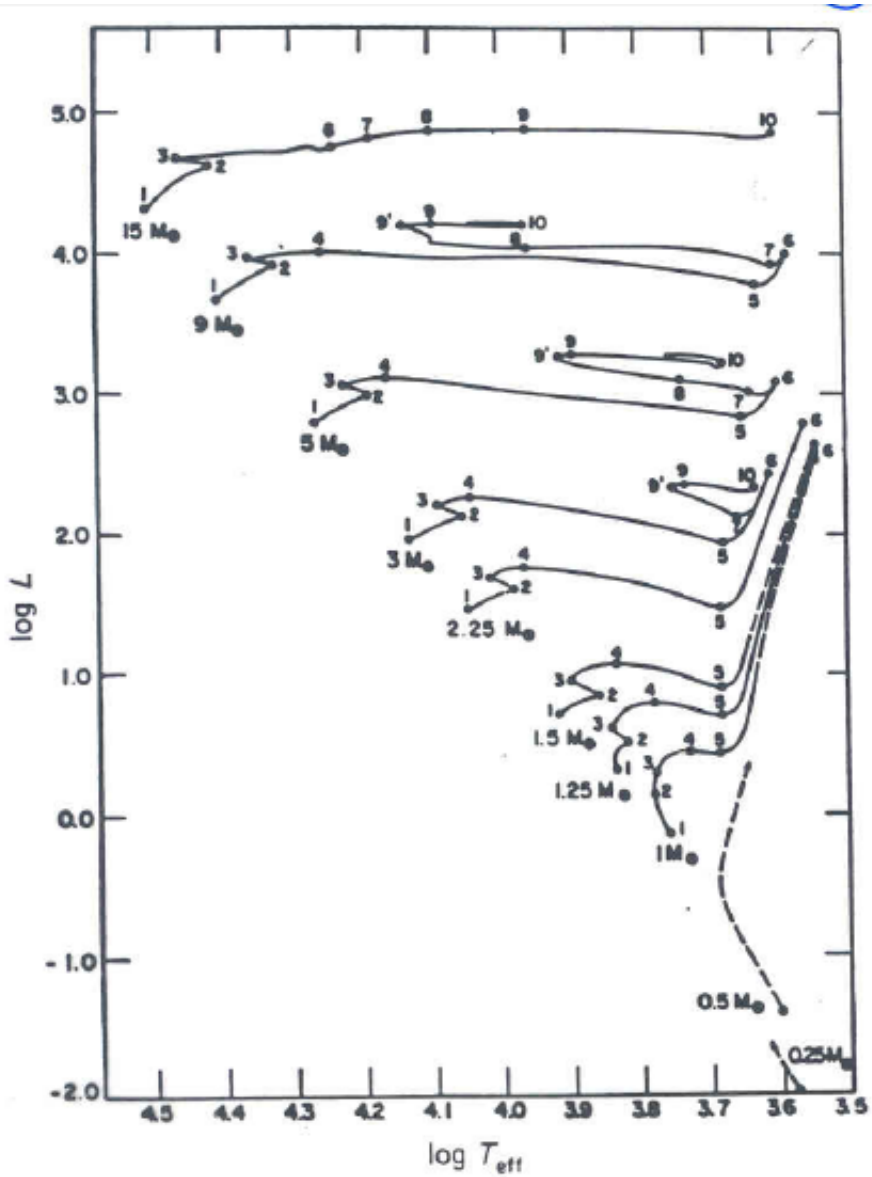


Fig. 15.1. Evolutionary tracks for stars of different masses. For more massive stars the luminosities of the red giants do not increase as much as those for lower mass stars. For the more massive stars the triple-alpha reaction starts soon after they reach the red giant region. The points with the numbers indicate the position for the onset of helium