



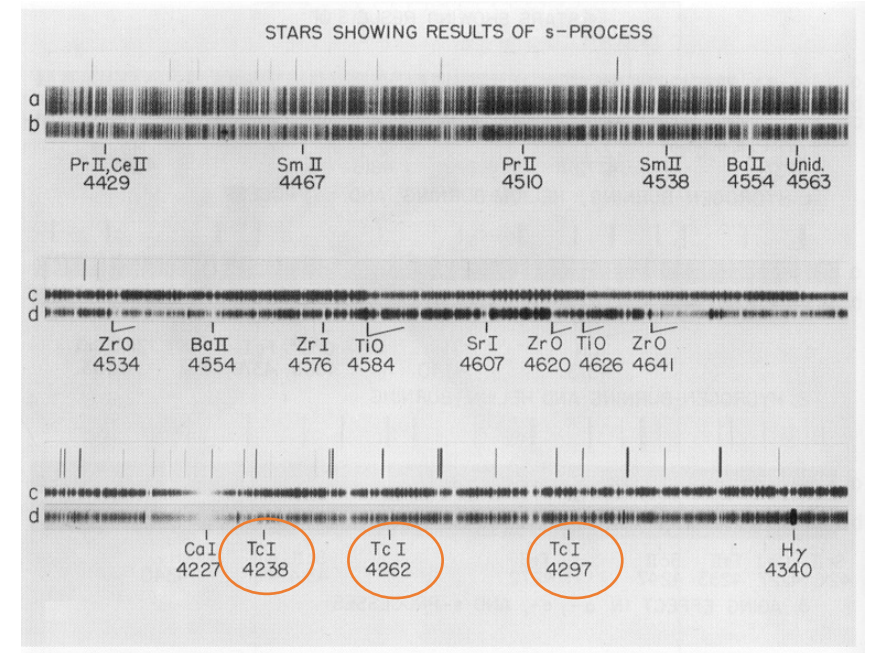
17th Russbach School on Nuclear Astrophysics

Introduction to stellar evolution

Sara Palmerini
INFN and University of Perugia

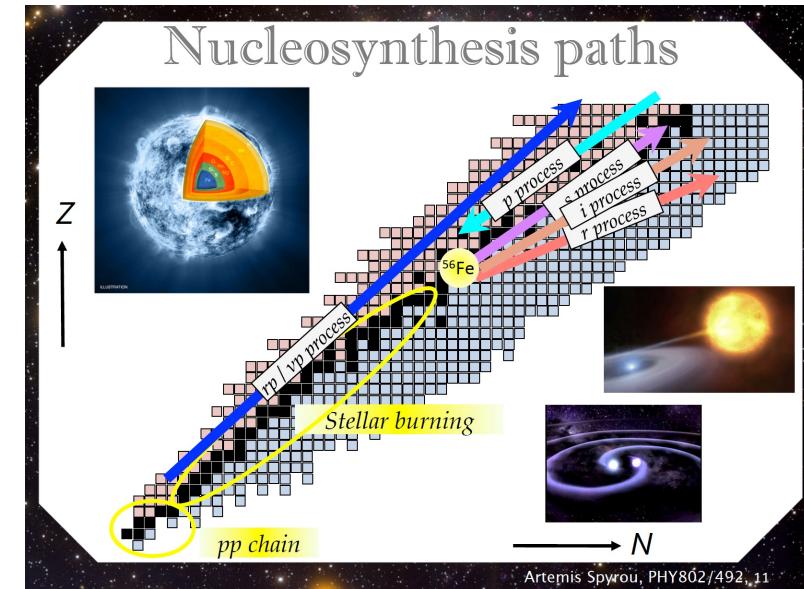
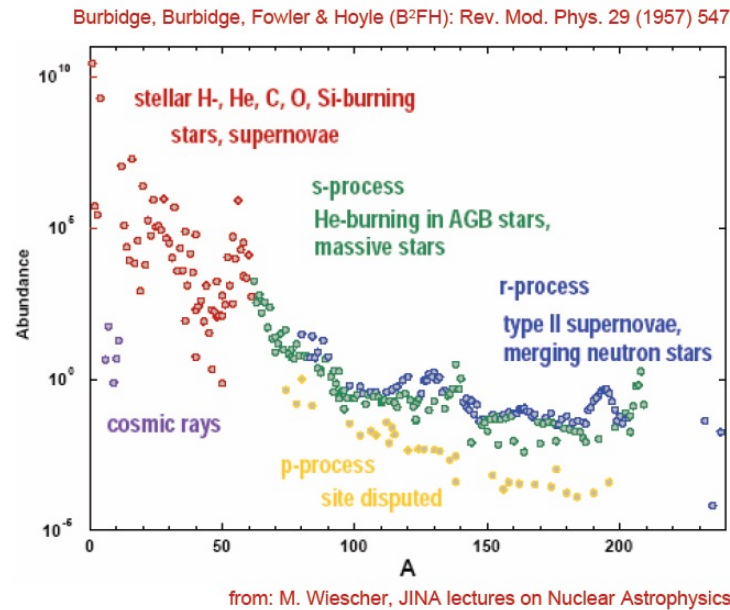
Merrill 1952:
s-star contains Tc ($Z=43$ $T_{1/2}=4$ Gyr)

- Known at the time that Tc is an «artificial» element
- Artificial = someone has to make it
- Merrill 1952: «it is surprising to find an unstable element in stars [...] (1) A stable isotope (of technetium) actually exists although not yet found on Earth; or (2) s-type stars somehow produce technetium as they go along; or (3) s-type stars represent a comparatively transient phase of stellar existence»



⁹⁷ Ru 2.83 D ε: 100.00%	⁹⁸ Ru STABLE 1.87%	⁹⁹ Ru STABLE 12.76%	¹⁰⁰ Ru STABLE 12.60%	¹⁰¹ Ru STABLE 17.06%	¹⁰² Ru STABLE 31.55%
⁹⁶ Tc 4.28 D ε: 100.00%	⁹⁷ Tc 4.21E+6 Y ε: 100.00%	⁹⁸ Tc 4.2E+6 Y β-: 100.00%	⁹⁹ Tc 2.111E+5 Y β-: 100.00%	¹⁰⁰ Tc 15.46 S β-: 100.00% ε: 2.6E-3%	¹⁰¹ Tc 14.02 M β-: 100.00%
⁹⁵ Mo STABLE 15.84%	⁹⁶ Mo STABLE 16.67%	⁹⁷ Mo STABLE 9.60%	⁹⁸ Mo STABLE 24.39%	⁹⁹ Mo 65.976 H β-: 100.00%	¹⁰⁰ Mo 7.3E+18 Y 9.82% 2β-: 100.00%

B²FH: the birth of nuclear astrophysics



REVIEWS OF MODERN PHYSICS

VOLUME 29, NUMBER 4

OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

Burbidge



Burbidge



Fowler



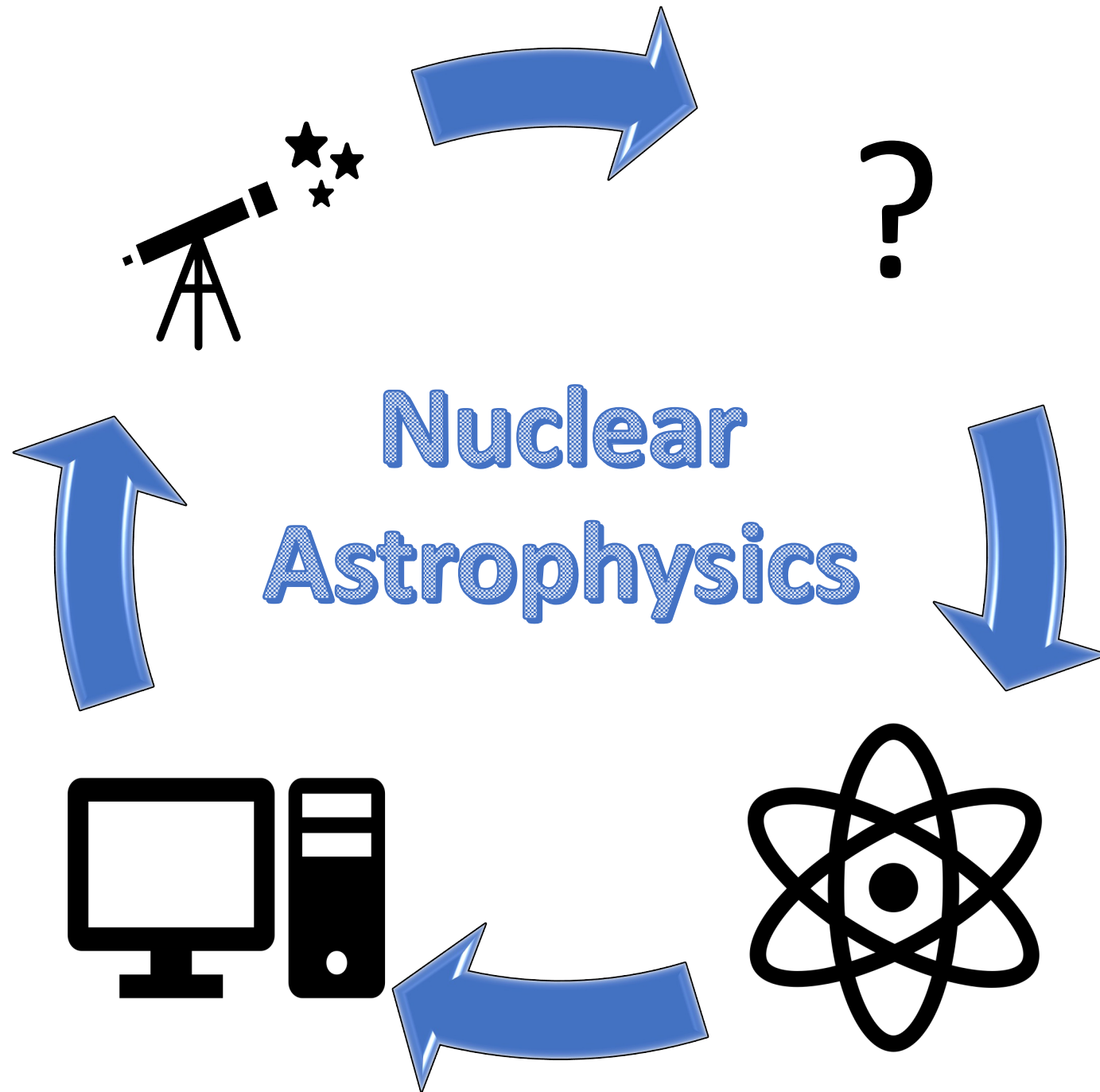
Hoyle



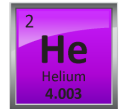
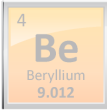
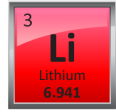
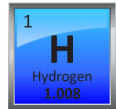
1983
Nobel Prize



"for his theoretical and experimental studies of the nuclear reactions of importance in the formation of the chemical elements in the universe"



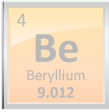
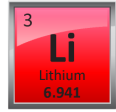
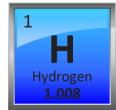
ELEMENTS IN NATURE



Primordial Nucleosynthesis



ELEMENTS IN NATURE

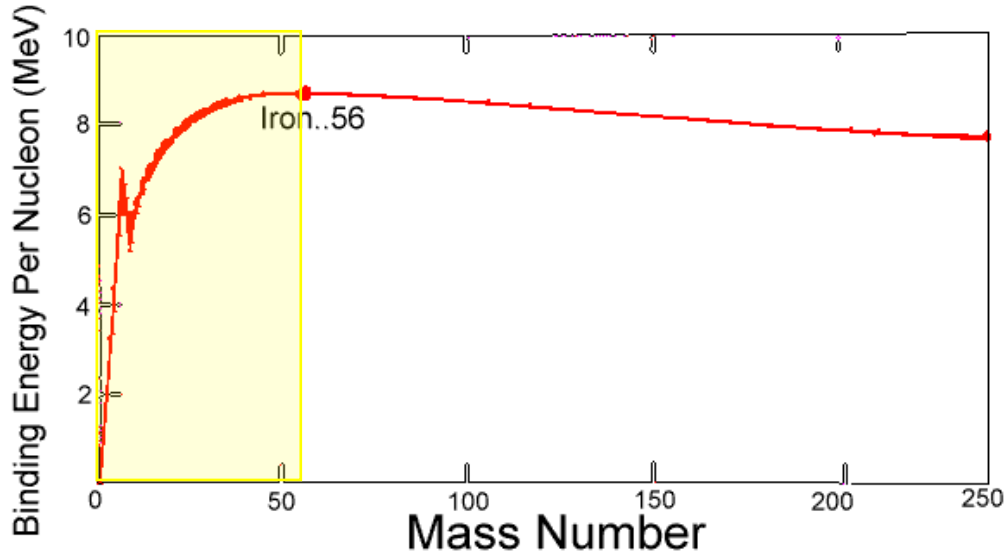


ELEMENTS IN NATURE

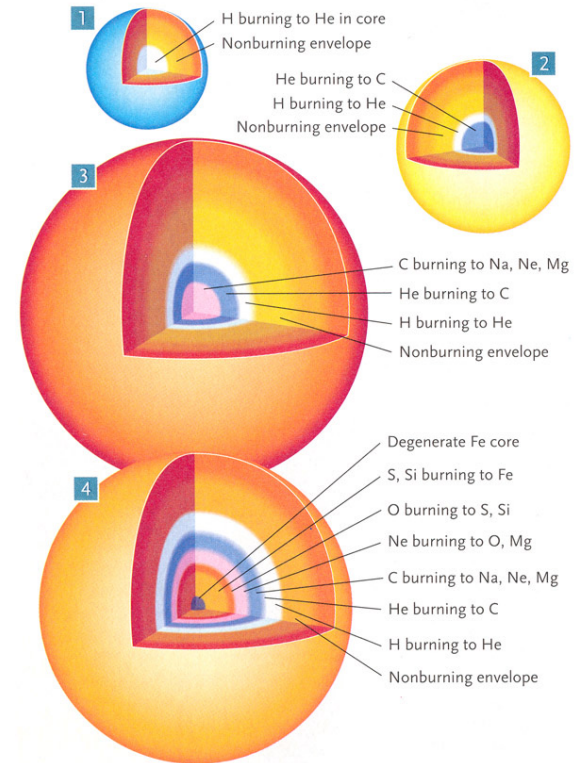
1 H Hydrogen 1.008																	2 He Helium 4.003				
3 Li Lithium 6.941	4 Be Beryllium 9.012															5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305															13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693												

ELEMENTS IN NATURE

The diagram shows the periodic table with elements color-coded to represent their relative abundance in the Sun. Hydrogen (H) and Helium (He) are the most abundant, followed by Oxygen (O), Carbon (C), Nitrogen (N), and Silicon (Si). The diagram illustrates that the Sun is composed of approximately 75% hydrogen and 25% helium, with trace amounts of other elements.



charged-
particle
induced
reaction
during
quiescent
stages
of Stellar
evolution

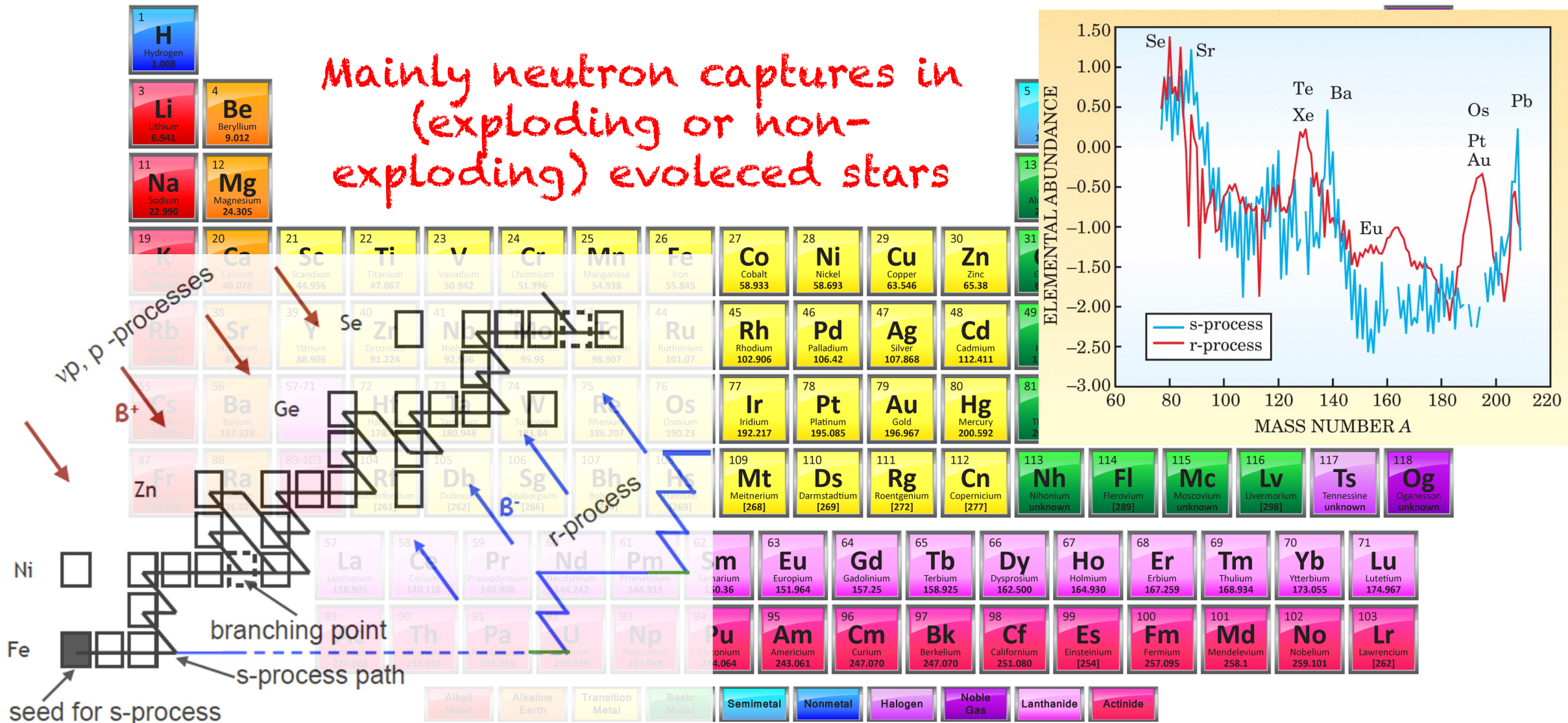


ELEMENTS IN NATURE

1 H Hydrogen 1.008																	2 He Helium 4.003															
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37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294															
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018															
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Nh Nihonium unknown	114 Fl Flerovium [289]	115 Mc Moscovium unknown	116 Lv Livermorium [298]	117 Ts Tennessine unknown	118 Og Oganesson unknown															
																		57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
																		89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]
																		Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide					

ELEMENTS IN NATURE

Mainly neutron captures in
(exploding or non-
exploding) evolved stars



How does a star work?

Quiescent evolution

★ Stellar structure and evolution controlled by:

- ★ Gravity → collapse
- ★ Radiation pressure → expansion

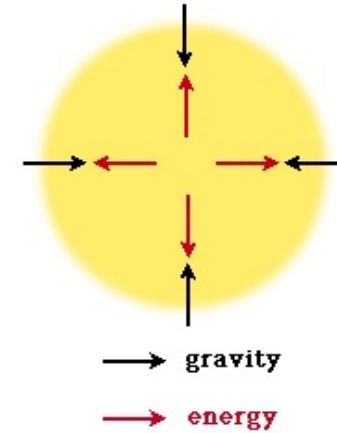
★ Star composed of many particles.
($\sim 10^{57}$ in the Sun)

★ Total energy:

- ★ gravitational energy of particles (Ω)
- ★ internal (kinetic) energy of particles
(including photons) (U)

★ For an ideal gas in hydrostatic equilibrium:

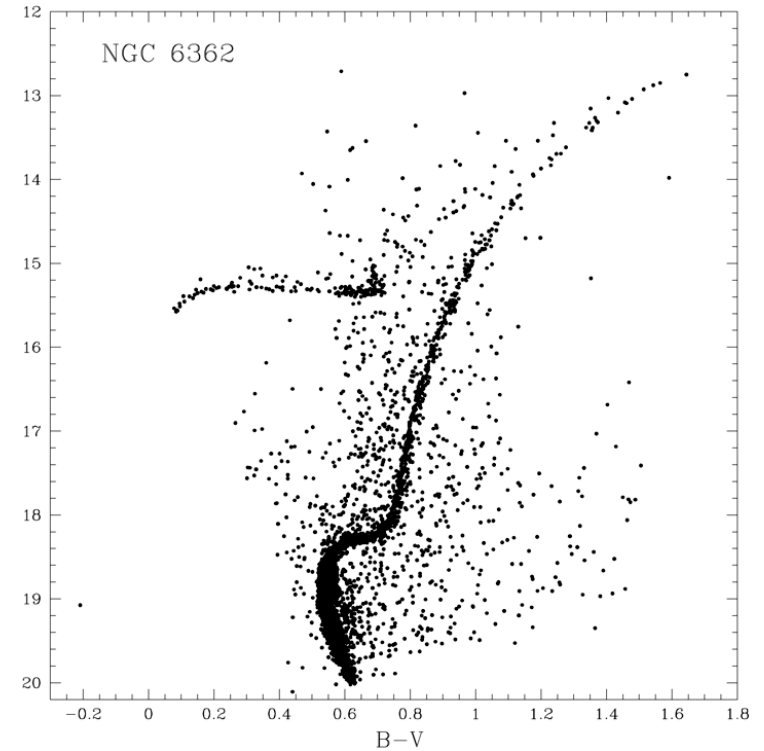
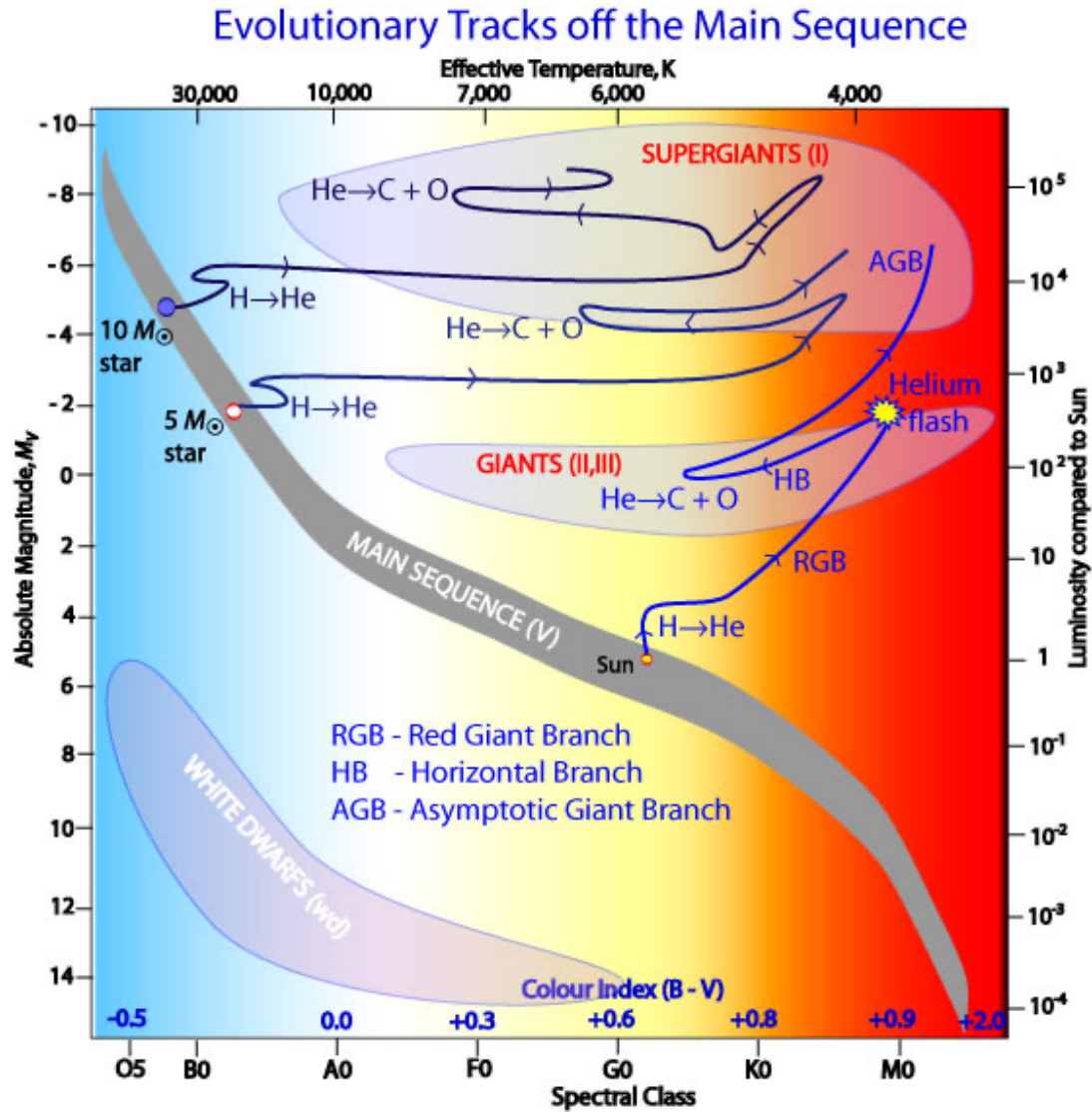
$$2U + \Omega = 0 \text{ virial theorem}$$



In case of pressure imbalance:

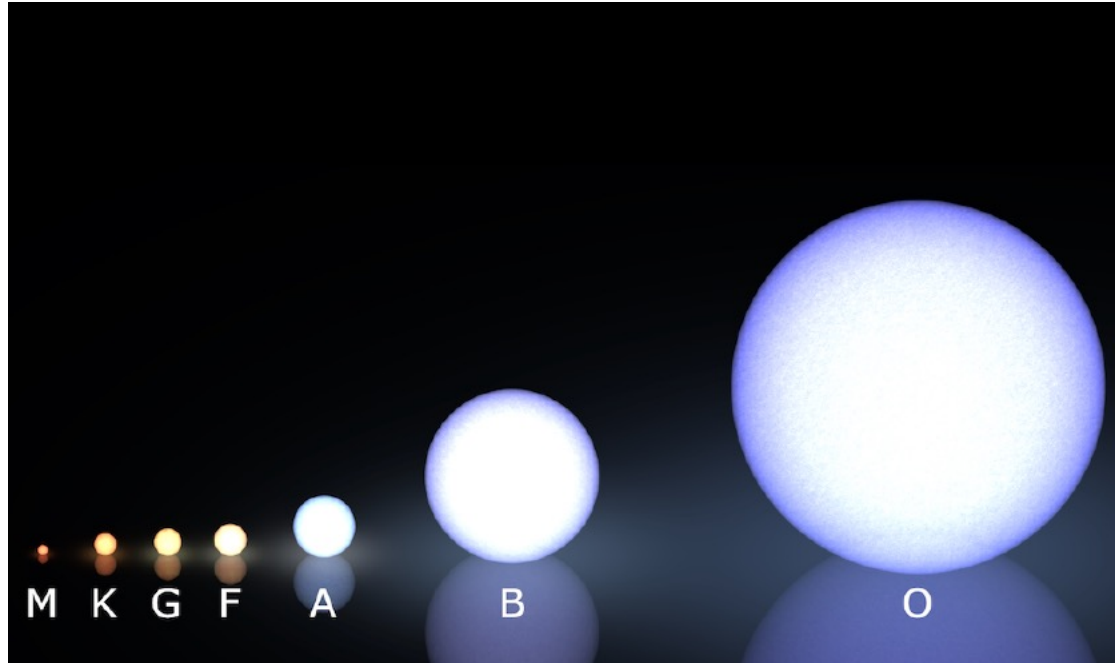
- gravitational contraction sets in
- amount of energy released $-\Delta\Omega$
- internal energy change to restore equilibrium
 $\Delta U = -\frac{1}{2} \Delta\Omega$
- gas temperature increases
- energy excess $-\frac{1}{2} \Delta\Omega$ lost from star in form of radiation

THE HERTZSPRUNG-RUSSELL (COLOR-MAGNITUDE) DIAGRAM AND THE STELLAR EVOLUTION



Each stellar cluster provides a snapshot of what stars of different masses look like at the same age and composition (coeval populations)

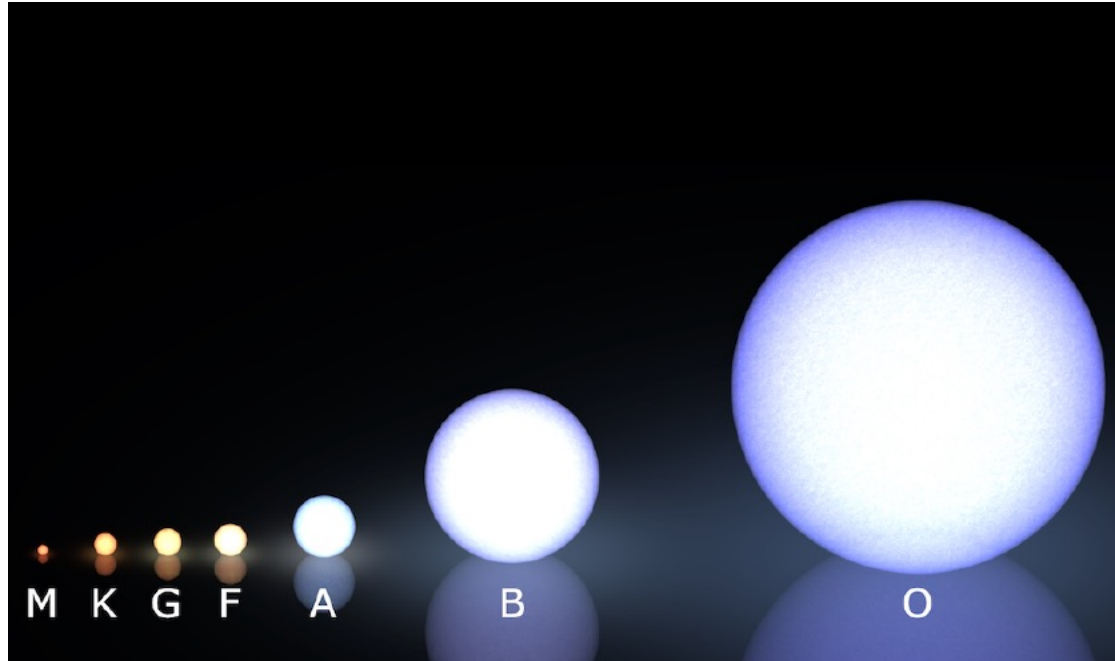
THE MAIN SEQUENCE



Mass (M_{\odot})	Surface temperature (K)	Spectral class	Luminosity (L_{\odot})	Main-sequence lifetime (10^6 years)
25	35,000	O	80,000	4
15	30,000	B	10,000	15
3	11,000	A	60	800
1.5	7000	F	5	4500
1.0	6000	G	1	12,000
0.75	5000	K	0.5	25,000
0.50	4000	M	0.03	700,000

- ✓ On the MS, a star is in a hydrostatic equilibrium, thanks to the H-burning in its core.
- ✓ The mass lower limit is set by the objects which cannot reach the necessary $[T, \rho]$ to ignite H ($T \sim 10 - 15 \times 10^6$ K and $\rho \sim 10^2 \text{ gcm}^{-3}$, i.e. $M < 0.08 M_{\odot}$ brown dwarf)
- ✓ The mass upper limit is set by the Eddington limit $L_{Edd} = 33000 L_{\odot} \frac{M}{M_{\odot}}$
- ✓ Main-sequence lifetime is strongly mass-dependent, since the more massive stars:
 - ✓ Have higher core temperatures \rightarrow higher rates of nuclear reactions
 - ✓ are more luminous and exhaust H fuel more quickly $L \propto M^{3.5} \rightarrow t_{\text{ms}} \propto M^{-2.5}$

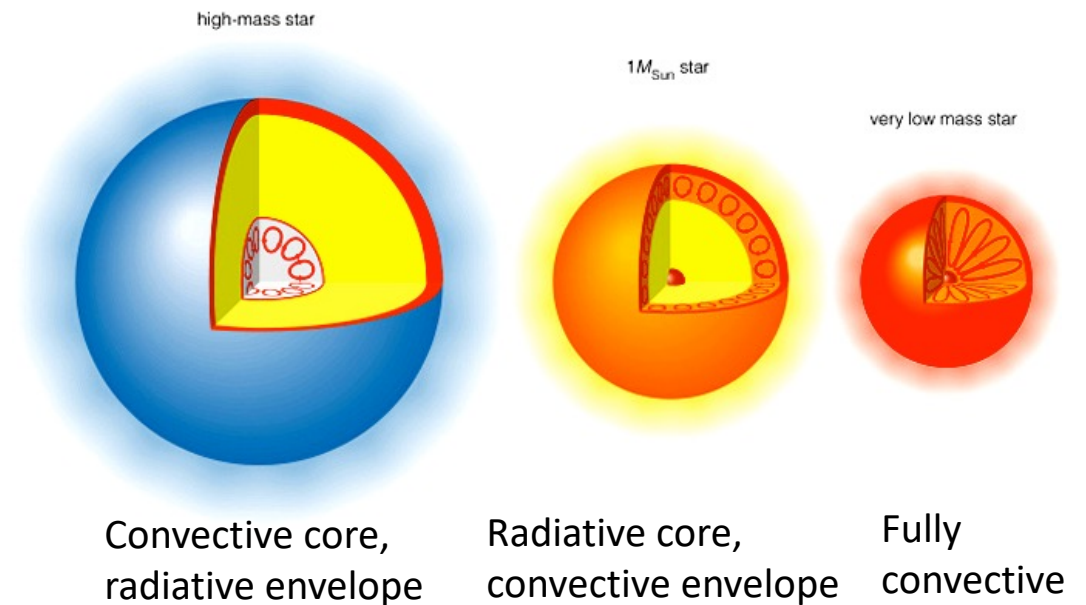
THE MAIN SEQUENCE



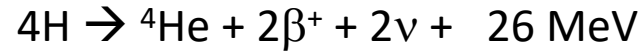
Mass essentially determines everything
Chemical composition has a relatively
minor effect

...including stellar structures because of the energy transport

Mass (M_{\odot})	Surface temperature (K)	Spectral class	Luminosity (L_{\odot})	Main-sequence lifetime (10^6 years)
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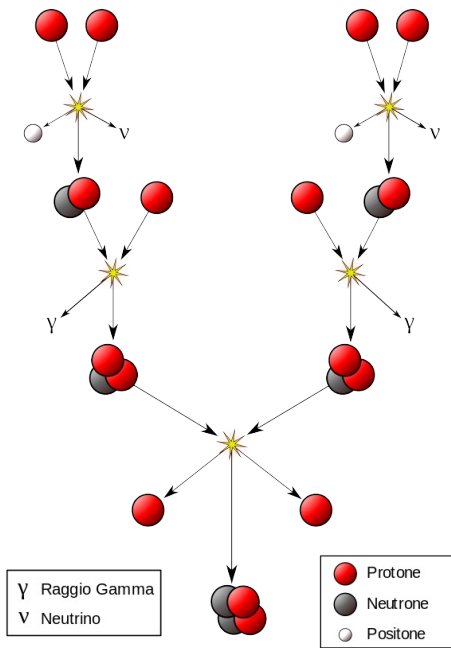


HYDROGEN BURNING



PROTON-PROTON CHAIN

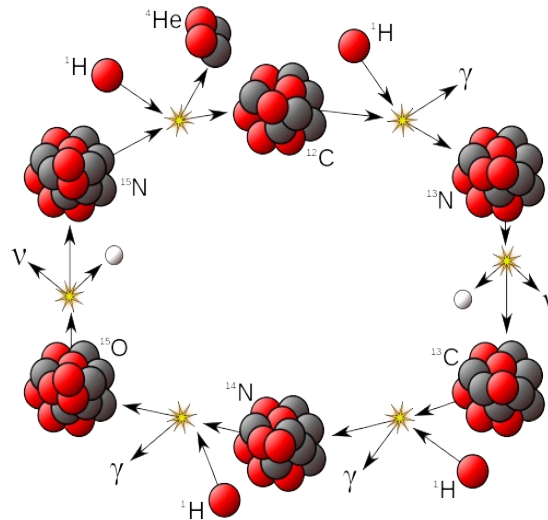
$$M < 1.5 M_{\odot} \Rightarrow T_6 < 30$$



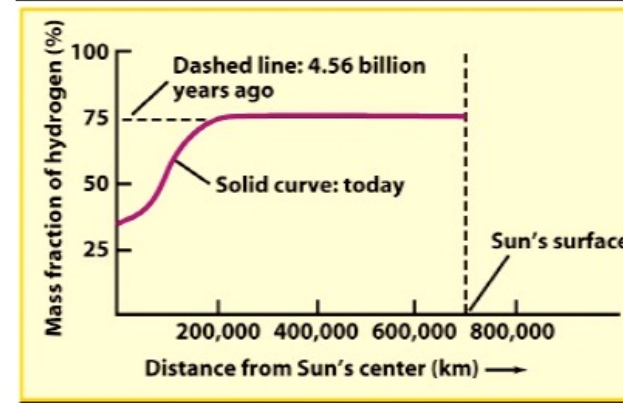
$$Q = 25 \text{ MeV}$$

CNO CYCLE

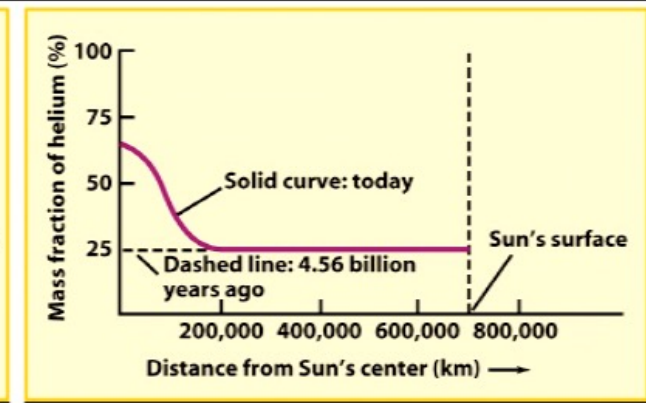
$$M \geq 1.5 M_{\odot} \Rightarrow T_6 > 30$$



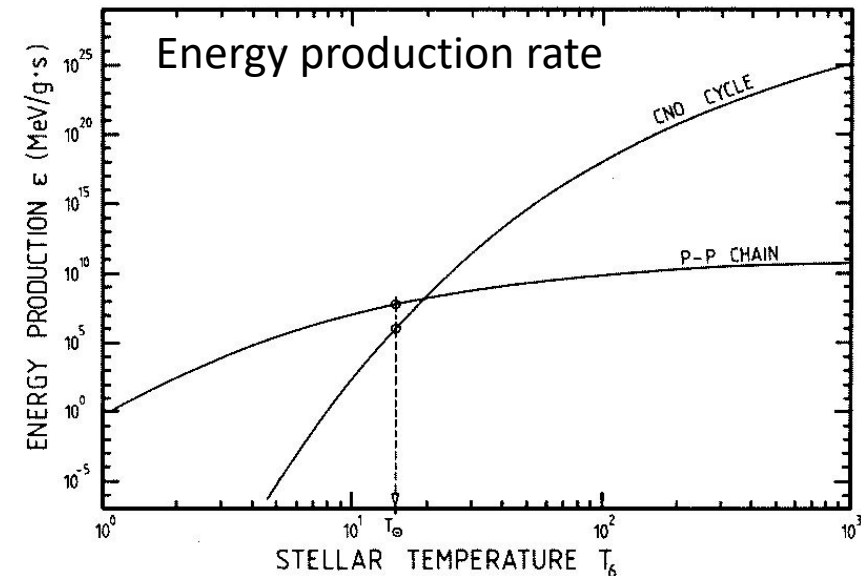
$$Q = 27 \text{ MeV}$$



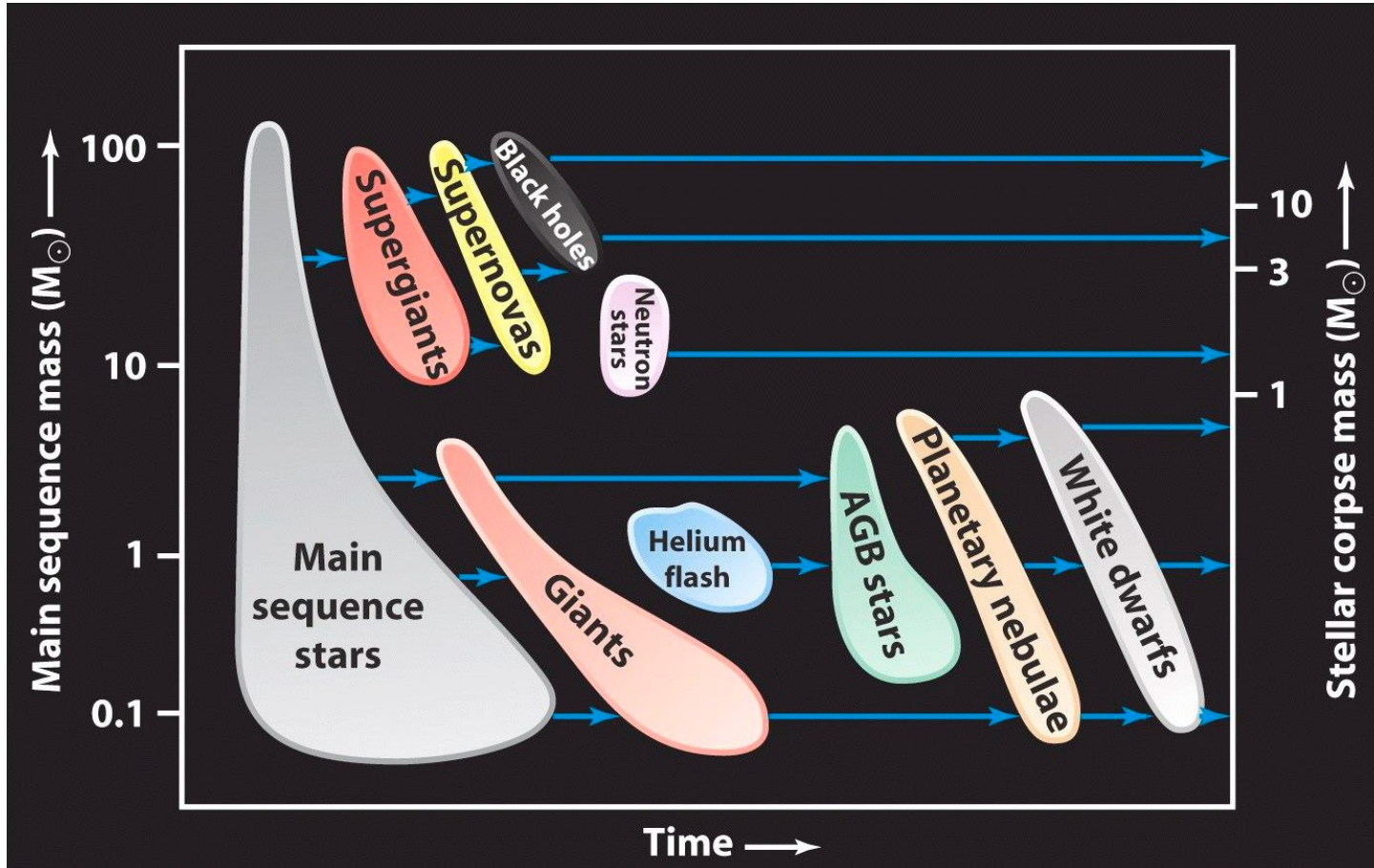
(a) Hydrogen in the Sun's interior



(b) Helium in the Sun's interior



What happens when the core runs out of hydrogen?



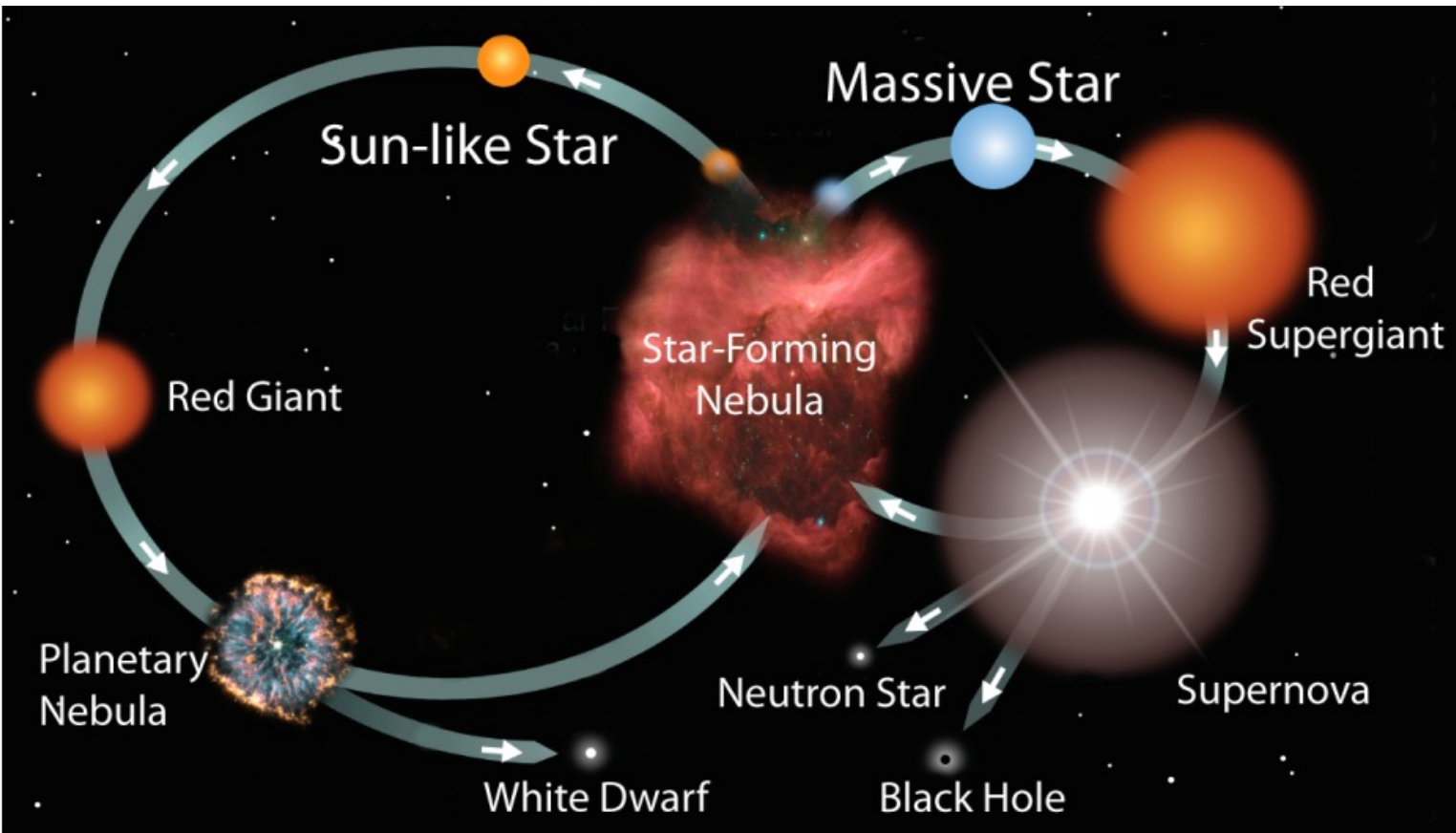
It depends on the stellar mass

- Star begins to collapse, heats up
 - Core contains He, continues to collapse
 - But H burns to He in shell- greatly inflating star
-
- RED GIANT (low mass)
 - SUPERGIANT (high mass)

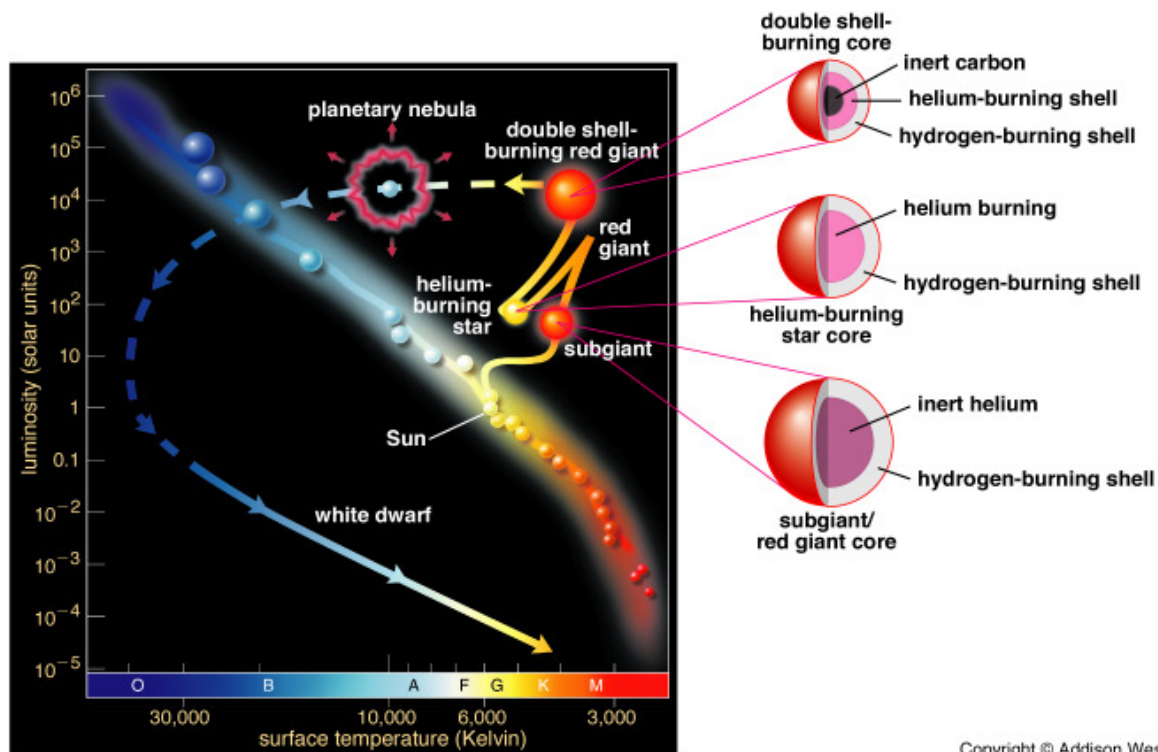
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It depends on the stellar mass

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- Core contains He, continues to collapse
- But H burns to He in shell- greatly inflating star
- RED GIANT (low mass)
- SUPERGIANT (high mass)



When the core runs out of hydrogen...stars become red giants

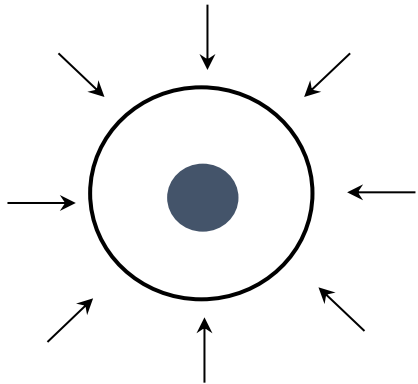


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- There are different types of Red Giant Stars
 1. RGB (Red Giant Branch)
 2. Horizontal branch
 3. AGB (Asymptotic Giant Branch)
- These differ in position on H-R diagram and in interior structure

1. RGB (Red Giant Branch) Stars

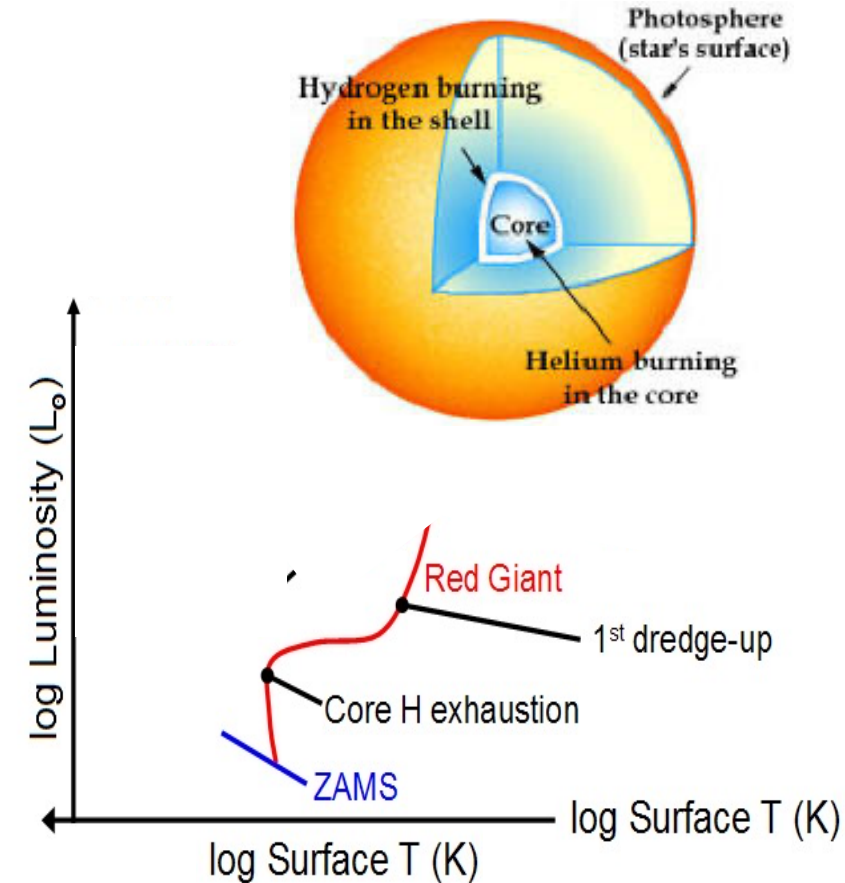
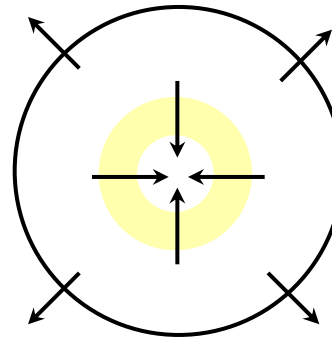
H exhausted in core
isothermal He core
contraction sets in



$R \sim 10-100 R_i \Rightarrow T_s \sim 3-4 \times 10^3 \text{ K}$
Wien's law: $\lambda_{\text{max}} T = \text{const.}$

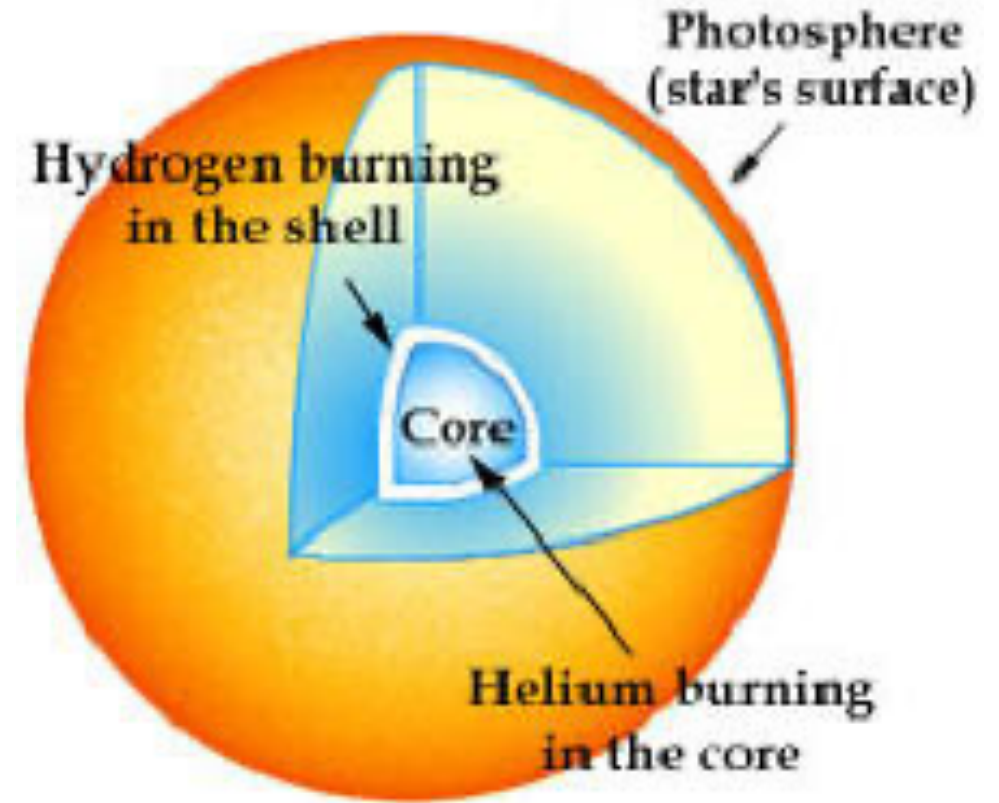


H-burning shell forms
Core contracts
Envelope expands



1. RGB (Red Giant Branch) Stars

- The stellar core collapses, as the internal pressure of the core is insufficient to balance gravity. This gravitational collapse releases energy, heating the region immediately outside the inert core so that H fusion continues in the concentric shell.
- The core of an RGB star of up to a few solar masses stops collapsing when it is dense enough to be supported by electron degeneracy pressure (Hydrostatic equilibrium: the electron degeneracy pressure is sufficient to balance gravitational pressure).
- The core's gravity compresses the H in the layer immediately above it, causing it to fuse faster than during the MS and the star to become more luminous (from 1.000–10.000 times brighter) and expand; the degree of expansion outstrips the increase in luminosity, causing the effective temperature to decrease.



1. RGB (Red Giant Branch) Stars

- THE FIRST DREDGE-UP
- The expanding outer layers of the star are convective, with the material being mixed by turbulence from near the fusing regions up to the surface of the star.
- The penetration of convective envelope in the inner stellar layers makes fusion products visible at the star's surface for the **first time** --> the ashes of H-burning appear at the surface, with altered proportions of CNO isotopes.

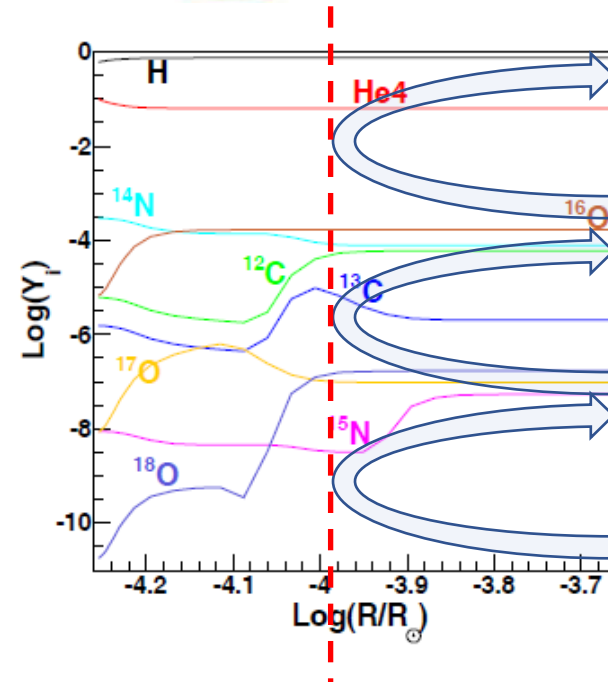
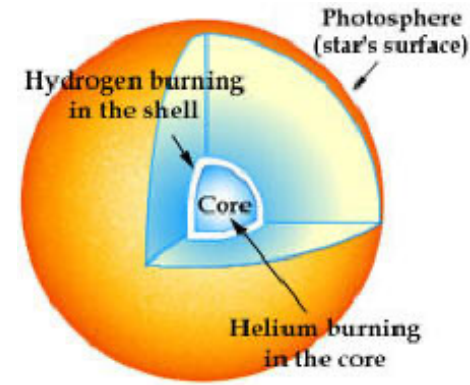


Figure 1.6 Distribution of the abundances of light nuclei in the stellar region mixed by the FDU (of a $1.5M_{\odot}$ and Z_{\odot} RGB star). In this region there will be increases in ^{13}C and ^{14}N and sharp decreases in ^{12}C and ^{15}N . After FDU, the envelope composition is then changed to the average value of represented layers.

FIRST DREDGE-UP (standard evolution, 1-8 M_{\odot})

Convective envelope reaches $\approx 80\%$ of stellar mass

Duration: 3×10^7 yr ($M=1 M_{\odot}$) to 5×10^4 yr ($M=8 M_{\odot}$)

Abundances in the envelope for stars of initial solar composition:

$$^{12}\text{C} \sim \frac{2}{3} \times ^{12}\text{C}_{\text{ini}}$$

$$^{13}\text{C} \sim (2 - 3) \times ^{13}\text{C}_{\text{ini}}$$

$$\frac{^{12}\text{C}}{^{13}\text{C}} \sim \frac{2/3}{(2-3)} \times \left(\frac{^{12}\text{C}}{^{13}\text{C}}\right)_{\text{ini}} \sim (20 - 30)$$

$$^{14}\text{N} \sim (2 - 3) \times ^{14}\text{N}_{\text{ini}}$$

$$^{15}\text{N} \sim \frac{1}{2} \times ^{15}\text{N}_{\text{ini}}$$

$$\frac{^{14}\text{N}}{^{15}\text{N}} \sim (4 - 6) \times \left(\frac{^{14}\text{N}}{^{15}\text{N}}\right)_{\text{ini}} = 1100 - 1600$$

$$^{16}\text{O} = ^{16}\text{O}_{\text{ini}}$$

$$^{18}\text{O} = (0.75 - 1.0) \times ^{18}\text{O}_{\text{ini}}$$

$$^{17}\text{O} = (1 - 13) \times ^{17}\text{O}_{\text{ini}} \quad (1 M_{\odot} \leq M \leq 2.2 M_{\odot})$$

$$^{17}\text{O} = (13 - 5) \times ^{17}\text{O}_{\text{ini}} \quad (2.2 M_{\odot} \leq M \leq 8 M_{\odot})$$

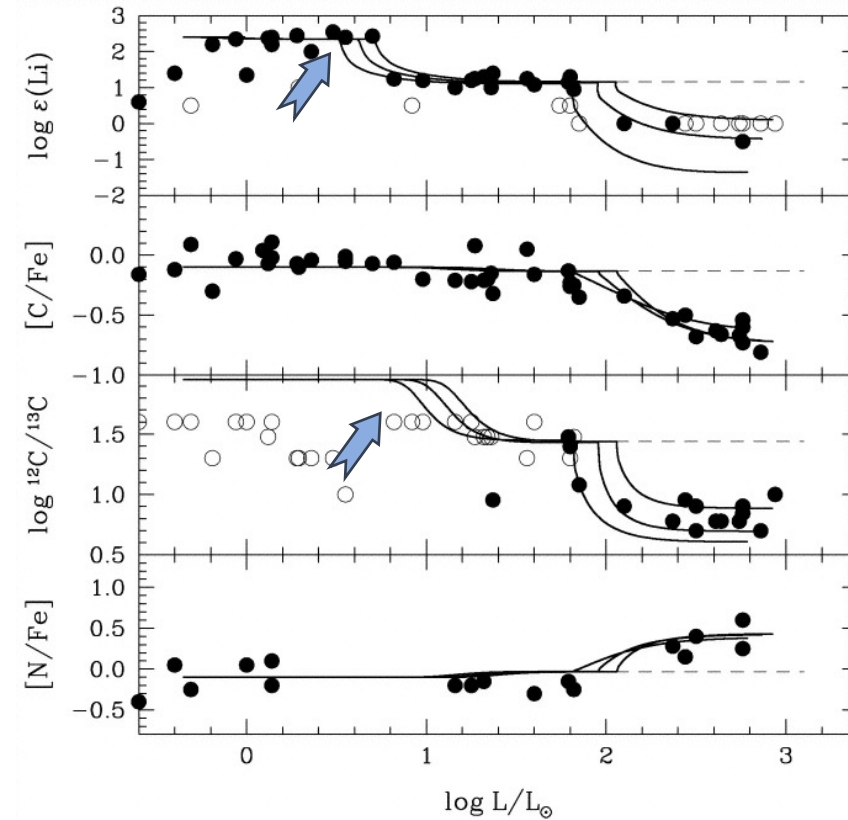
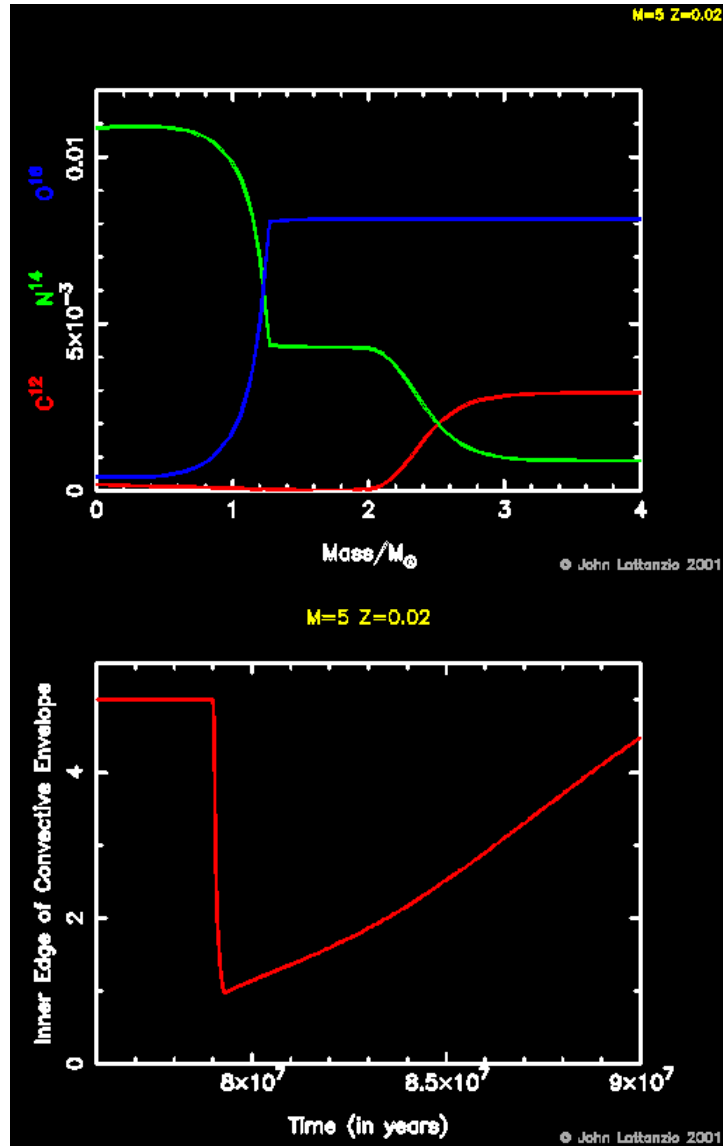
$$\frac{^{16}\text{O}}{^{17}\text{O}} \sim (1 - 1/15) \times \left(\frac{^{16}\text{O}}{^{17}\text{O}}\right)_{\text{ini}} = 2600 - 200$$

$$\frac{^{16}\text{O}}{^{18}\text{O}} \sim (1.2 - 1.3) \times \left(\frac{^{16}\text{O}}{^{18}\text{O}}\right)_{\text{ini}} = (600 - 700)$$

^{26}Al : no production

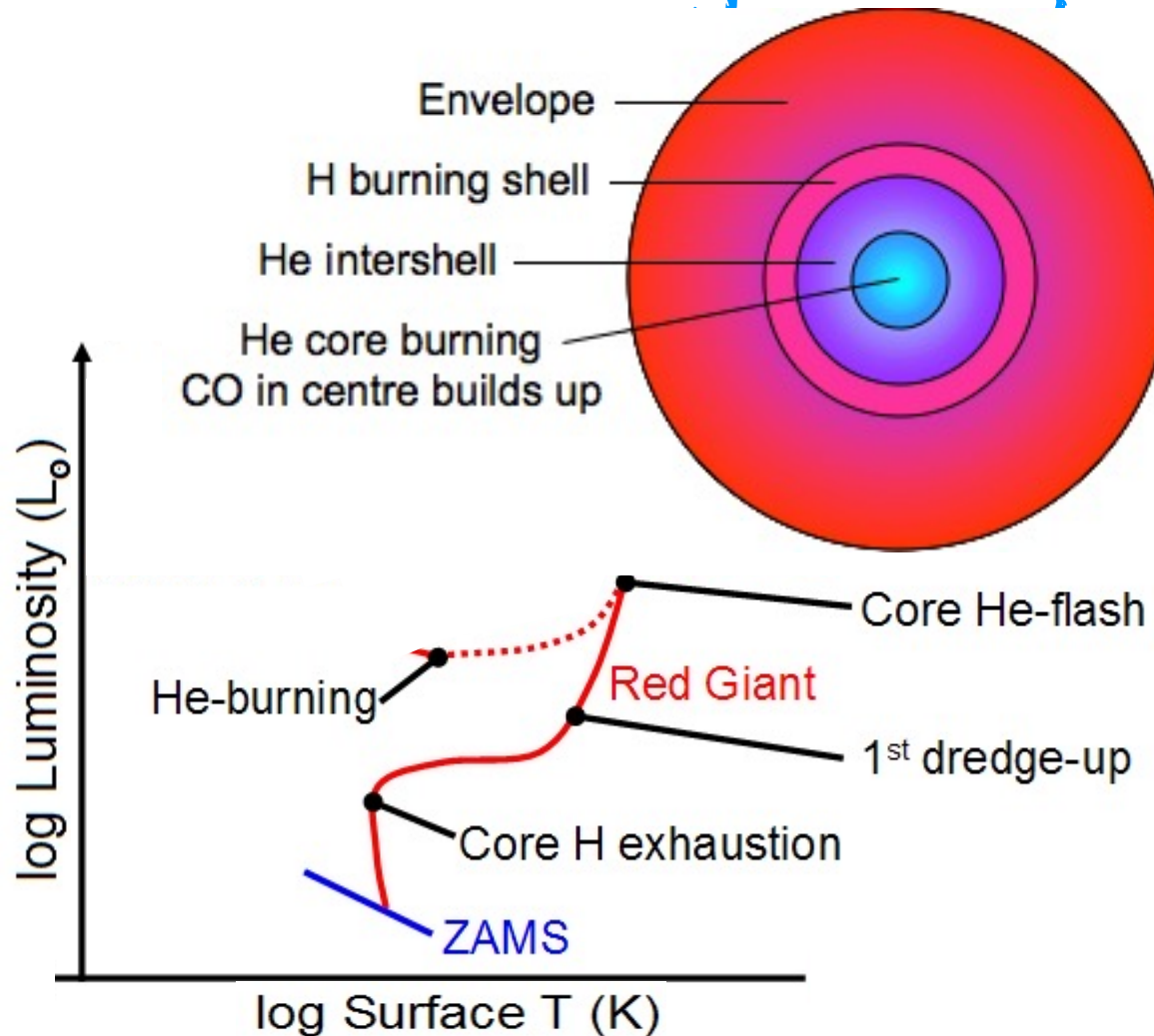
The RGB and the First Dredge-up (FDU)

http://users.monash.edu.au/~john/StellarEvolnV1/m5z02/FDU_CNO+Mbcevmovie.gif



Comparison of the observational data of Gratton et al. (2000) for RGB stars (*filled circles*) with theoretical models (Denissenkov & Vandenberg 2003) for the variations of the surface chemical composition in the model star with $M=0.85M_{\odot}$ due to the FDU and extra mixing on the upper RGB.

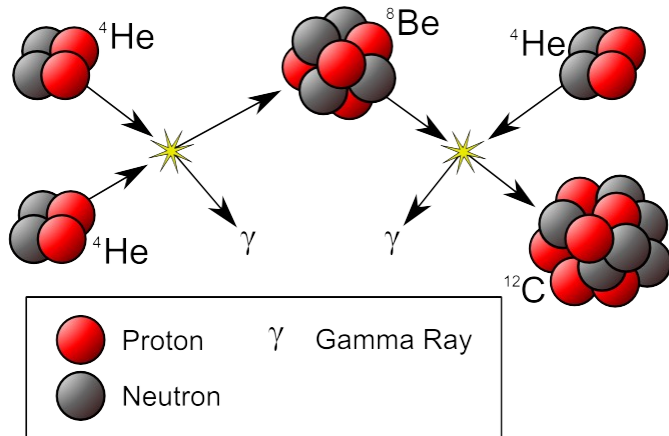
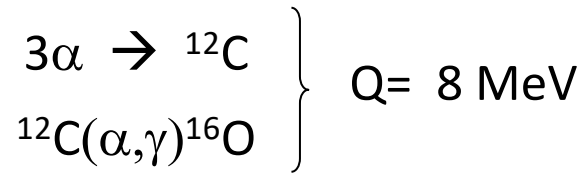
2. The horizontal branch: the core He-burning and the 2nd longest equilibrium phase



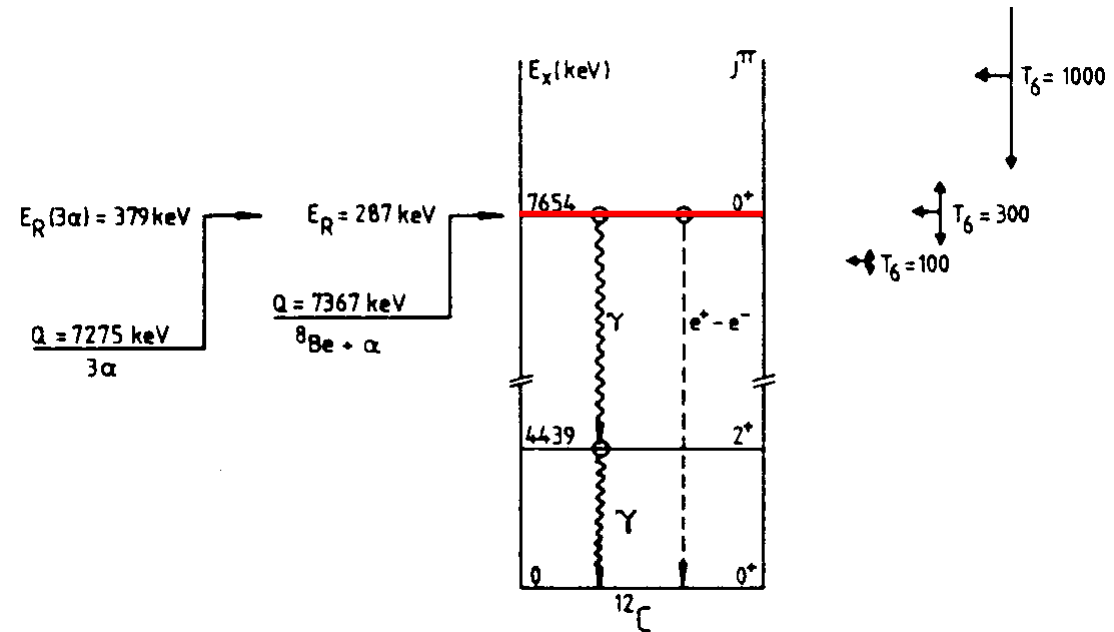
- As the H-shell exhaustion, the core absorbs the resulting helium, causing it to contract further. This eventually leads to ignition of the core He-burning.
- For a star with a $M < 2.25 M_{\odot}$, when the temperature and pressure in the core become sufficient to ignite helium fusion, a [He-flash](#) occurs because of the electron degeneracy in their core. While in more massive stars, the ignition of helium fusion occurs relatively quietly.
- The energy released by He-burning causes the core to expand, so that H fusion in the overlying layers slows and total energy generation decreases. The star contracts and migrates to the [horizontal branch](#) on the HR-diagram, gradually shrinking in radius and increasing its surface temperature.

2. The HB: the He-burning

$T \sim 10^8 \text{ K}$ and $\rho \sim 10^3 \text{ gcm}^{-3}$

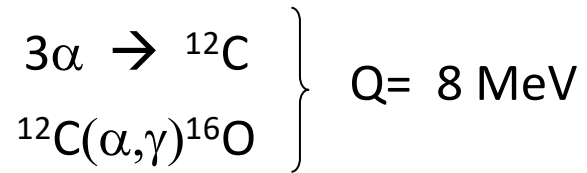


- $\rightarrow \alpha + \alpha \rightarrow {}^8\text{Be}$ ($Q = -92 \text{ keV}$). ${}^8\text{Be}$ is unstable against breakup in 2α
- $\rightarrow t_{1/2}({}^8\text{Be}) = 3 \cdot 10^{-16} \text{ s} >$ the timescale of an $\alpha + \alpha$ scattering
- \rightarrow a small amount of ${}^8\text{Be}$ can build up to reach the $\alpha + \alpha \leftrightarrow {}^8\text{Be}$ equilibrium
- $\rightarrow {}^8\text{Be} + \alpha \rightarrow {}^{12}\text{C} + \gamma$ is possible thanks to the Hoyle state ($E_x = 7.654 \text{ MeV}$, $J^\pi = 0^+$)
- $\rightarrow {}^8\text{Be}(\alpha) {}^{12}\text{C}^*(\gamma) {}^{12}\text{C}$
- \rightarrow note: $3\alpha \rightarrow {}^{12}\text{C}$ is not a three particle reaction!

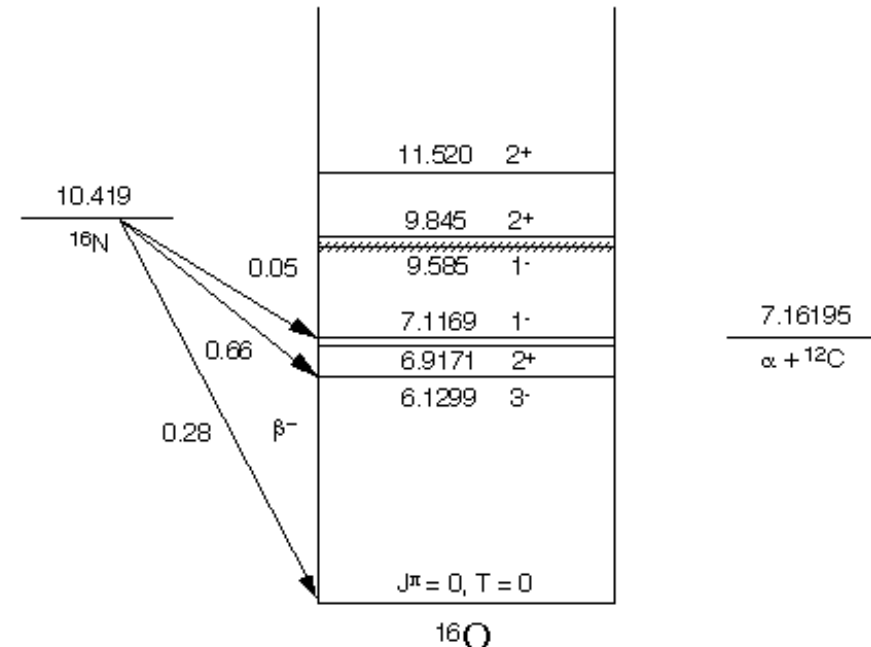
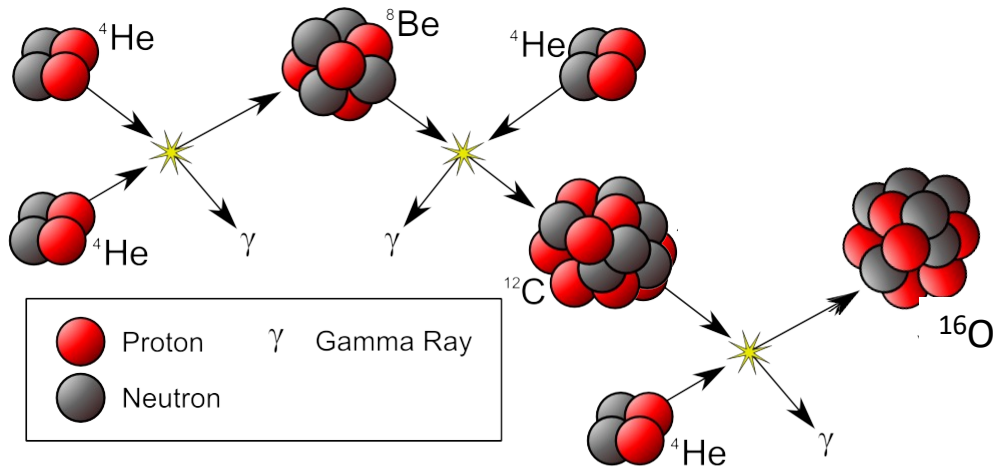


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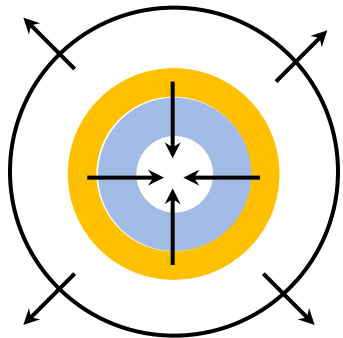
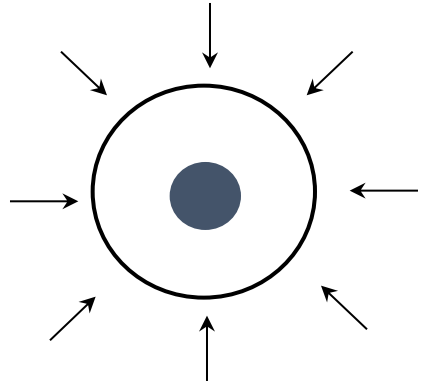


- ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$ it is probably the most important reaction in nuclear astrophysics
- Its rate determines how much of the ${}^{12}\text{C}$ formed is converted to ${}^{16}\text{O}$
 - thereby the carbon/oxygen abundance ratio in red giant stars
 - set the initial conditions for heavy-ion burning phases
- The ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$ rate is not yet known with very high precision
 - unclear whether main product of He-burning is carbon or oxygen!

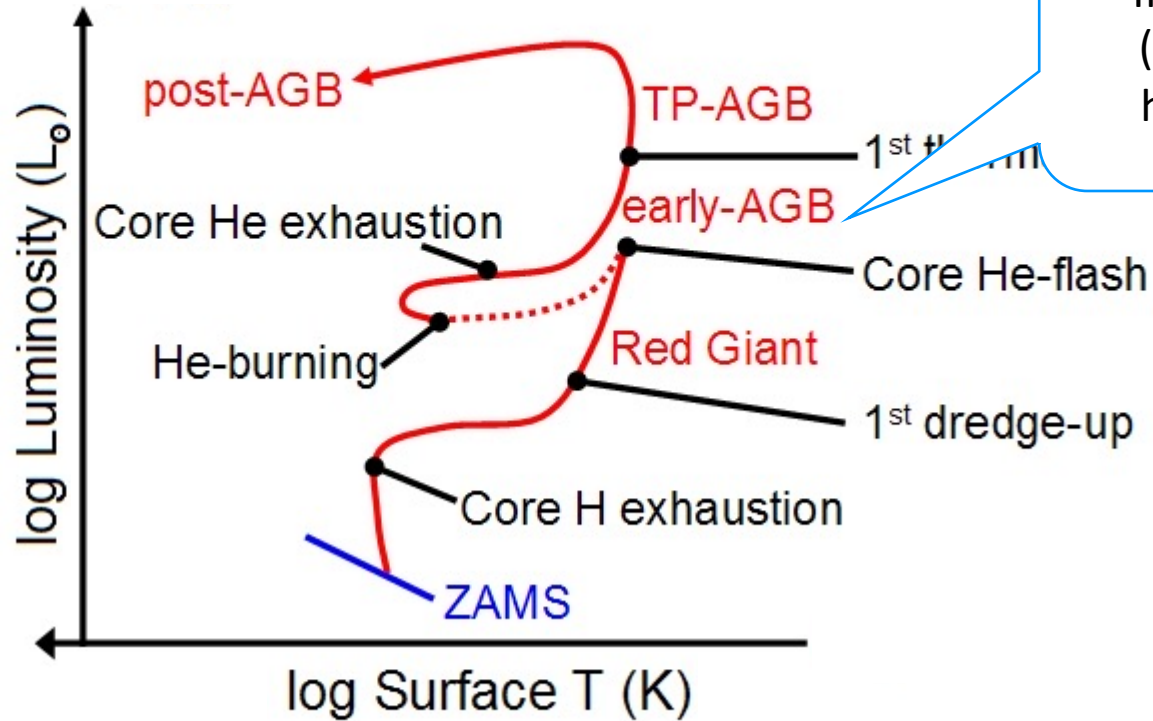


3. AGB (Asymptotic Giant Branch) Stars

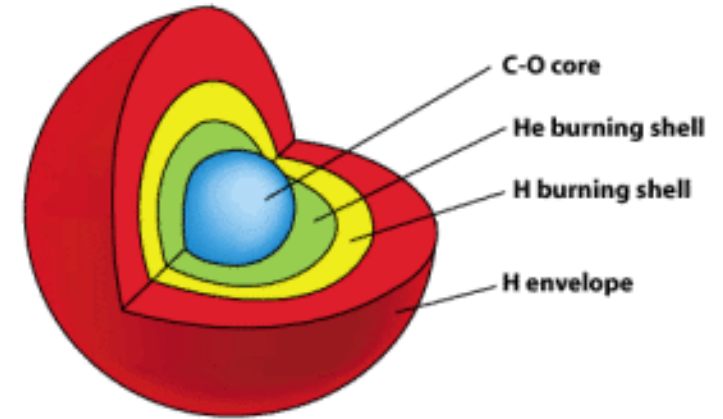
He exhausted in core
contraction sets in



H-burning shell
He-burning shell
CO-core

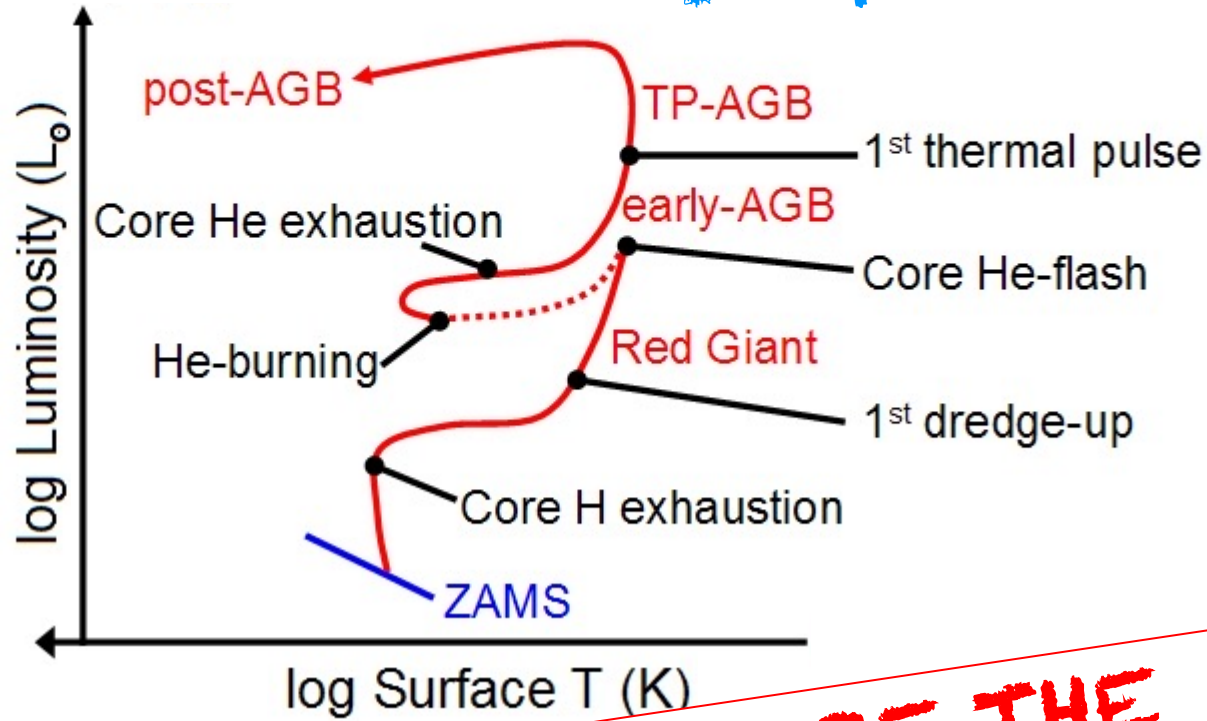


If $M > 4M_{\odot}$ the second dredge-up (SDU) transports the products of hydrogen-burning to the surface



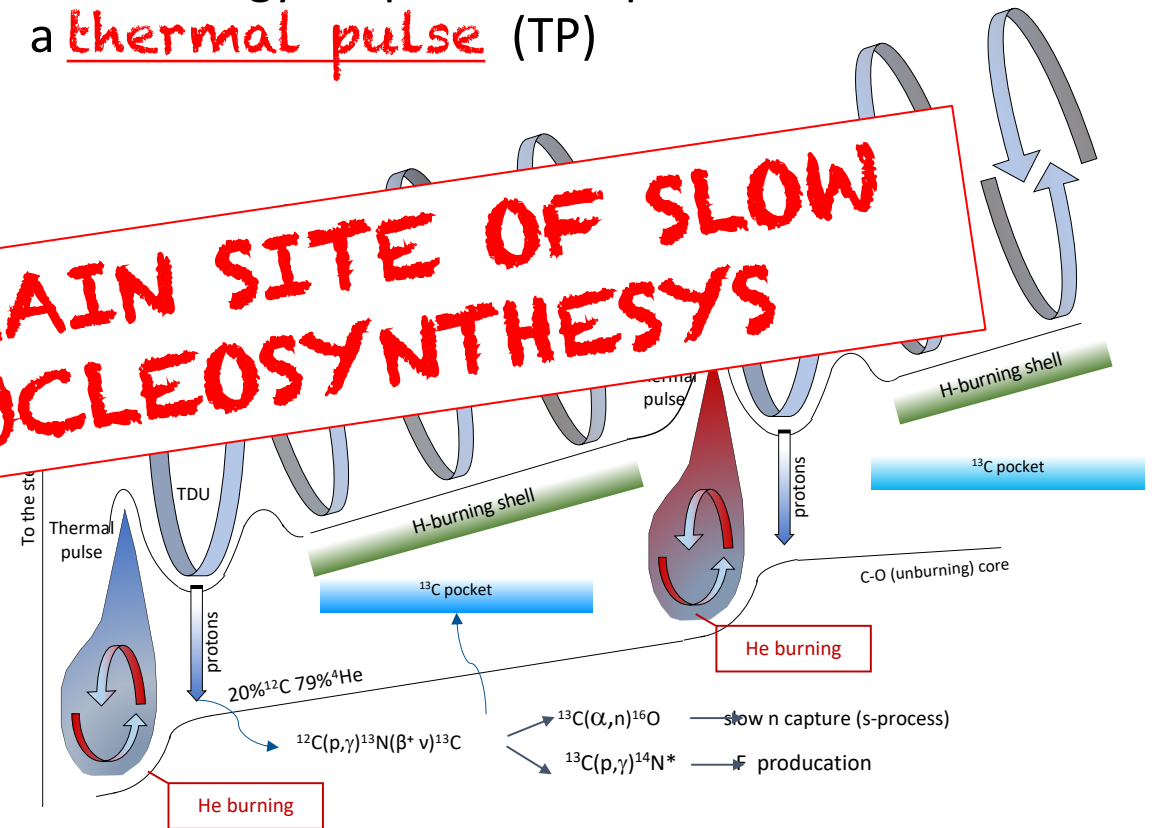
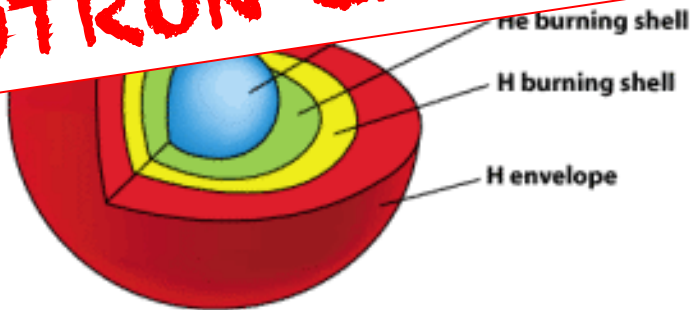
During the **early-AGB** the main source of energy is He fusion in a shell around the CO core. During this phase the star swells up to giant proportions to become a red giant again.

3. AGB (Asymptotic Giant Branch) Stars



During the **Thermal Pulse AGB** phase the majority of the energy is produced by H-burning in a shell closer to the surface of the star. He from the H shell burning builds up and the He shell periodically ignites with dramatic increasing of its energy output. Such episodes are known as a thermal pulse (TP)

AGB STARS ARE THE MAIN SITE OF SLOW NEUTRON CAPTURE NUCLEOSYNTHESIS



SUPER RED-GIANT STARS

Stellar mass (M_{\odot})	Stage reached
< 0.08	no thermonuclear fusion
0.1 - 0.5	H burning
0.5 - 8	He burning
8 - 11	C burning
> 11	all stages

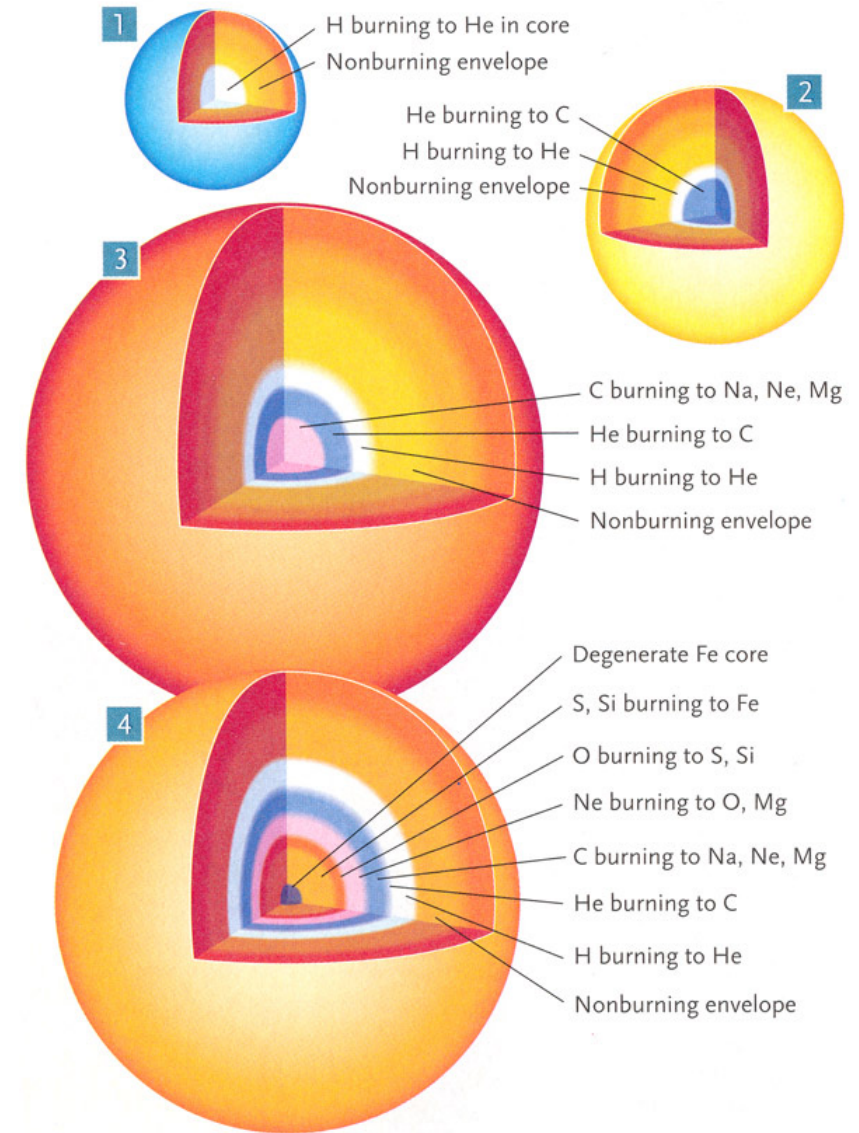
Main parameters:

- 1) mass \Rightarrow central temperature
- 2) chemical composition \Rightarrow nuclear processes

Evolution stages of a $25 M_{\odot}$ star

T, ρ	Stage reached	Timescale	$T_{\text{core}} (10^9 \text{ K})$	Density (g cm^{-3})
	H burning	$7 \times 10^6 \text{ y}$	0.06	5
	He burning	$5 \times 10^5 \text{ y}$	0.23	7×10^2
	C/O burning	600 y / 6 months	0.93 – 2.3	$2 \times 10^5 - 1 \times 10^7$
	Si melting	1 d	4.1	3×10^7
	Explosive burning	0.1 – 1 s	1.2 - 7	varies

\rightarrow SUPERNOVA EXPLOSION (type II) $M \geq 8 M_{\odot}$



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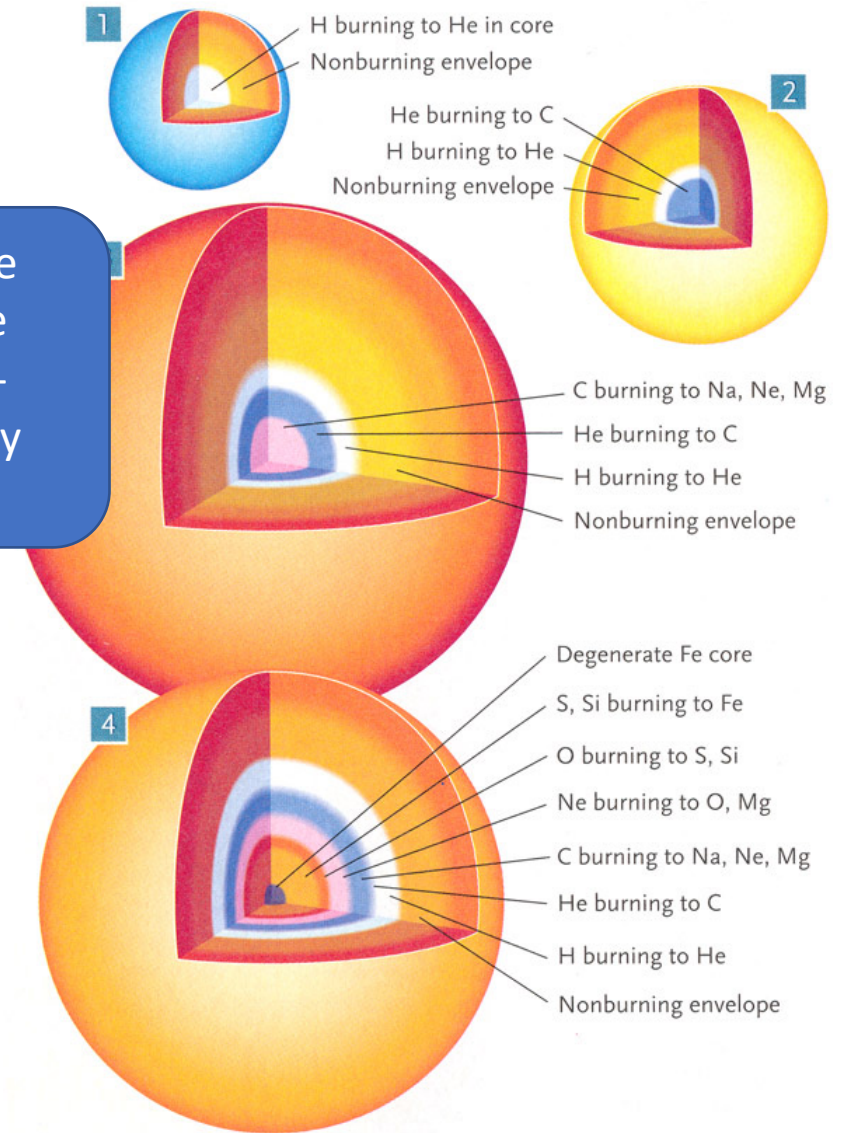
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Aurora Tumino lecture on $12\text{C} + 12\text{C}$ and the session devoted to C-fusione on Wednesday morining

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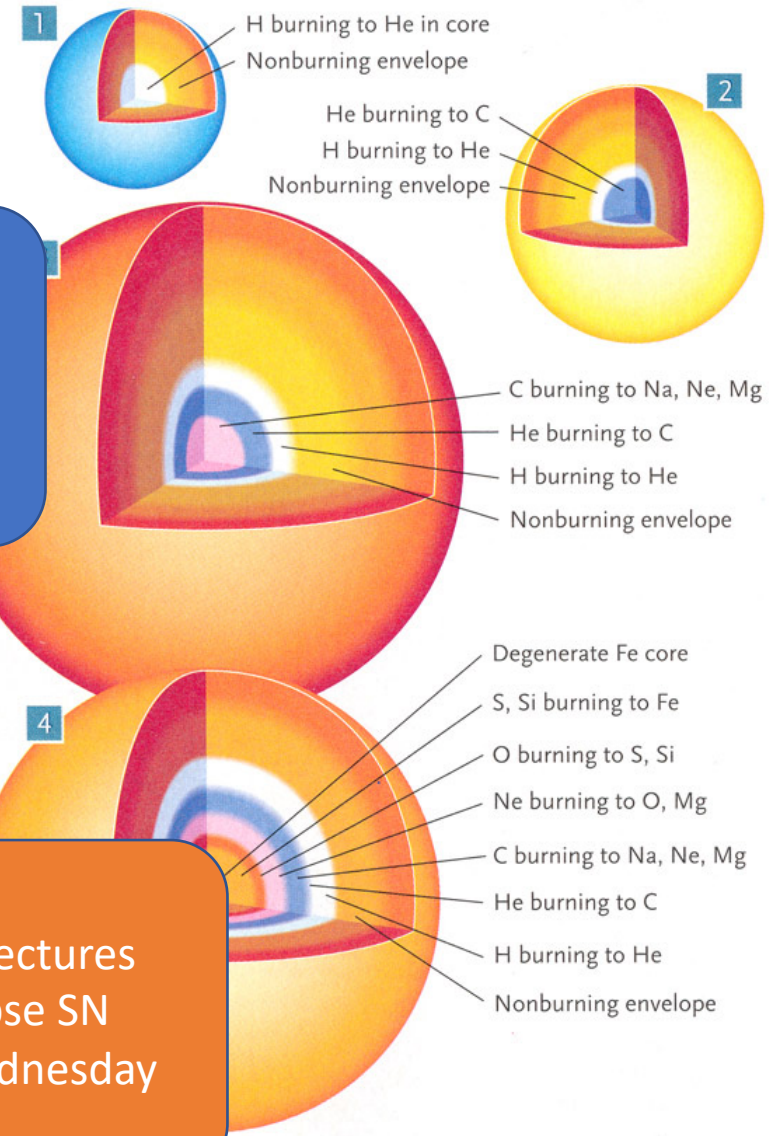
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Jerome Guilet lectures
on Core collapse SN
Tuesday and Wednesday

Why
quiescent
stages
of stellar
evolution
are so
long?

- Fusion reactions among charged particles are burned
- Bottle-neck reactions set the timing