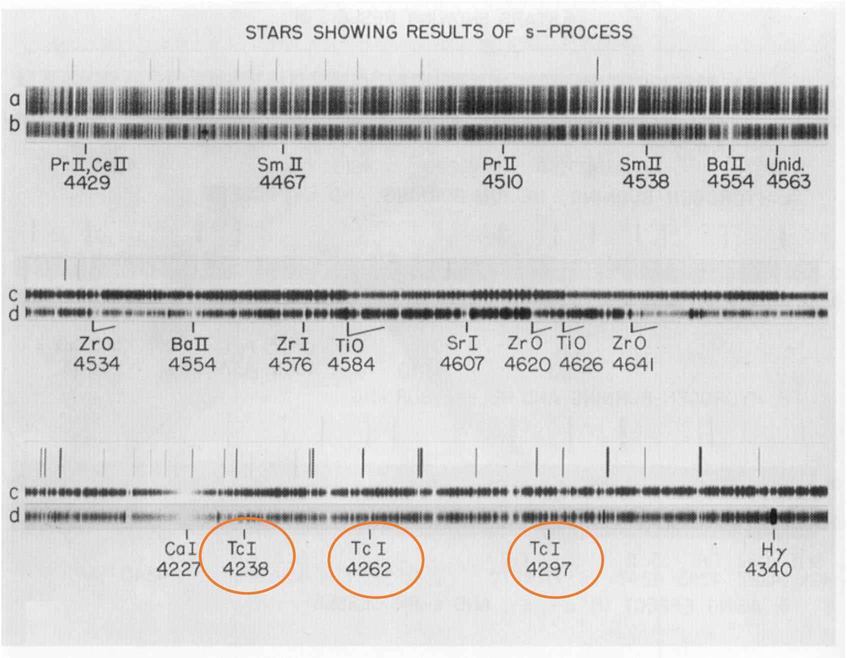
Introduction to stellar evolution

Sara Palmerini

INFN and University of Perugia

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

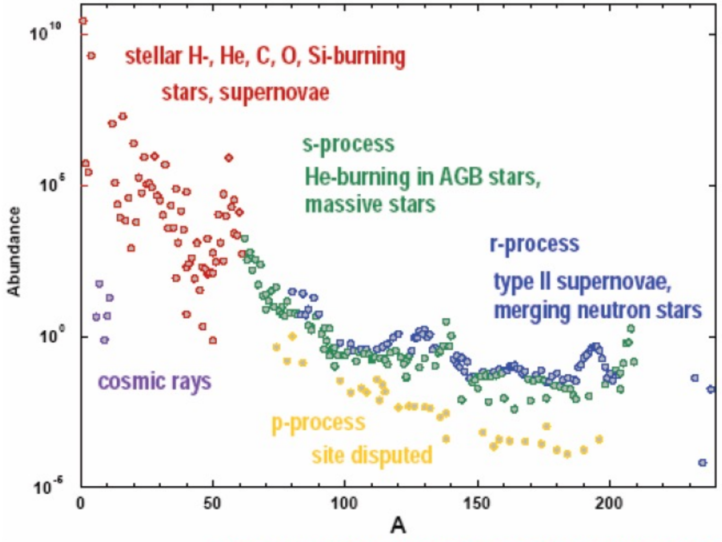
- Known at the time that Tc is an «artificial» element
- Aritificial = someone has to make it
- Meril 1952: «it is surprising to find an unstable element in stars [...] (1) A stable isotope (of technitium) actually exixts although not yet found an Earth; or (2) s-type stars somehow produce technitium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



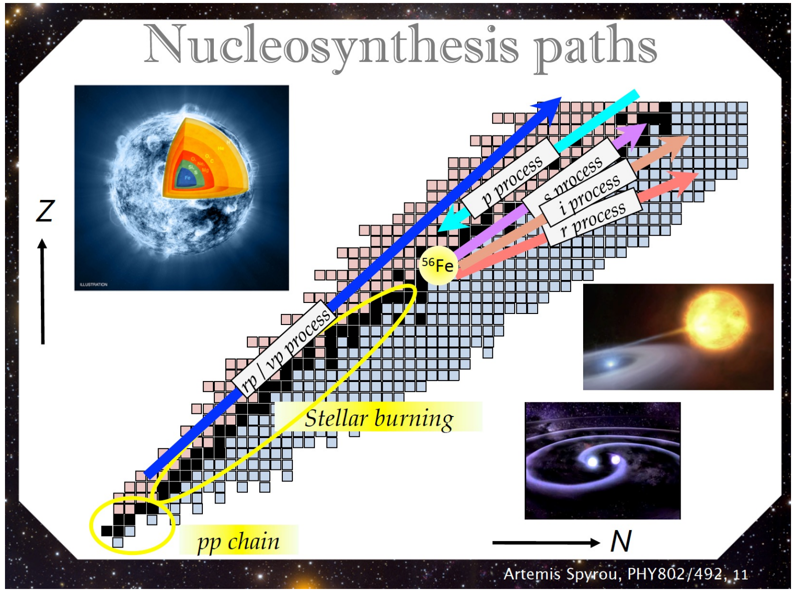
97Ru 2.83 D ε: 100.00%	98Ru STABLE 1.87%	99Ru STABLE 12.76%	100Ru STABLE 12.60%	101Ru STABLE 17.06%	102Ru STABLE 31.55%
96Tc 4.28 D ε: 100.00%	97Tc 4.21E+6 Y ε: 100.00%	98Tc 4.2E+6 Y β-: 100.00%	99Tc 2.111E+5 Y β-: 100.00%	100Tc 15.46 S β-: 100.00% ε: 2.6E-3%	101Tc 14.02 M β-: 100.00%
95Mo STABLE 15.84%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

B^{2}FH: the birth of nuclear astrophysics

Burbidge, Burbidge, Fowler & Hoyle (B^{2}FH): Rev. Mod. Phys. 29 (1957) 547



from: M. Wiescher, JINA lectures on Nuclear Astrophysics



REVIEWS OF

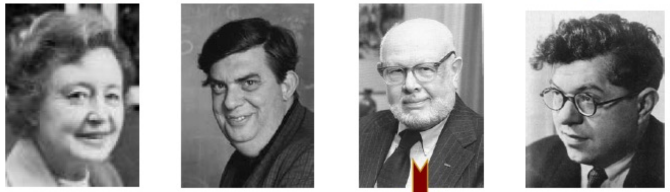
MODERN PHYSICS

VOLUME 29, NUMBER 4 — OCTOBER, 1957

Synthesis of the Elements in Stars*

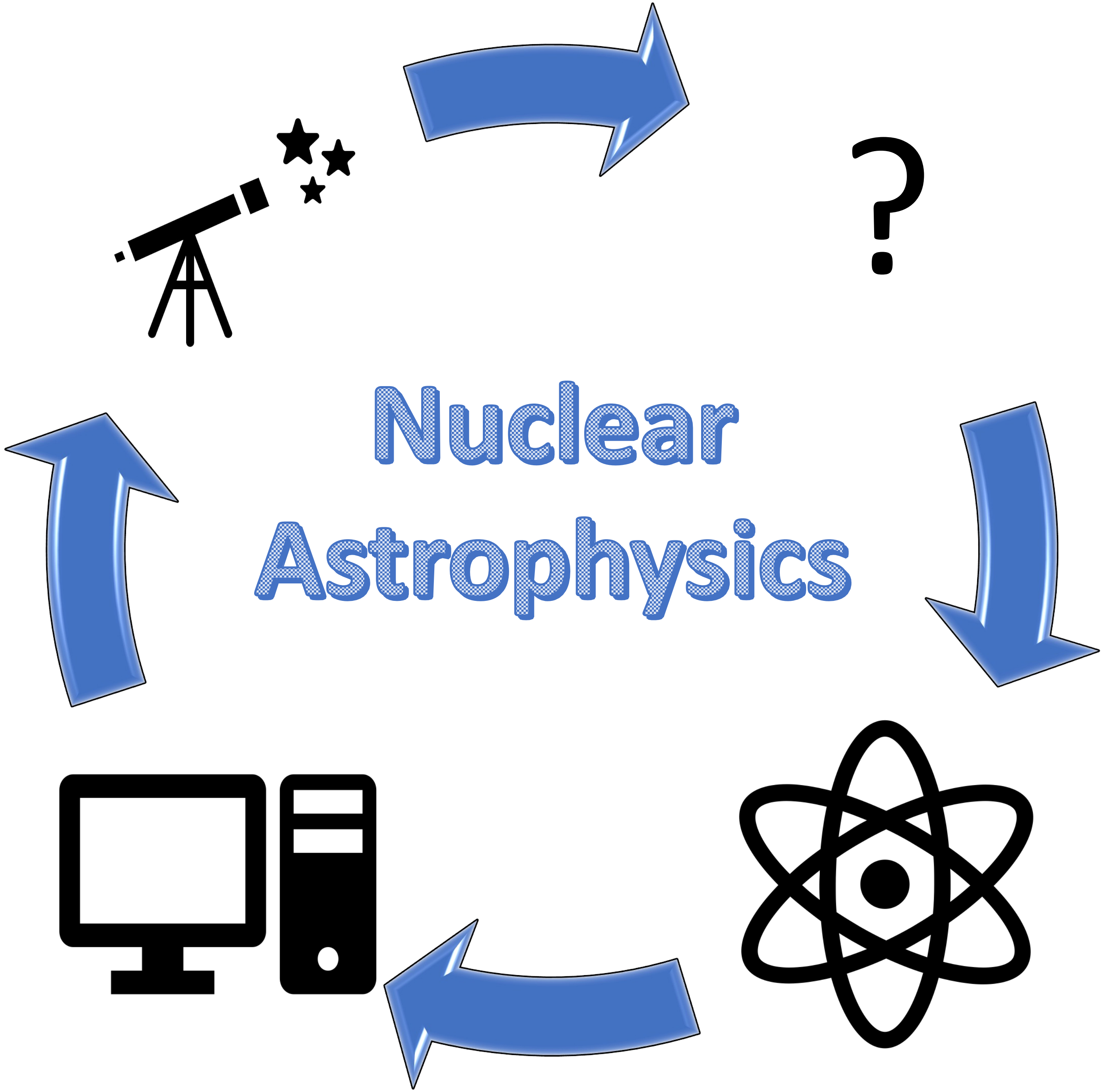
E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

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"


Nuclear
Astrophysics

ELEMENTS IN NATURE

1 H Hydrogen 1.008

2 He Helium 4.003

3 Li Lithium 6.941

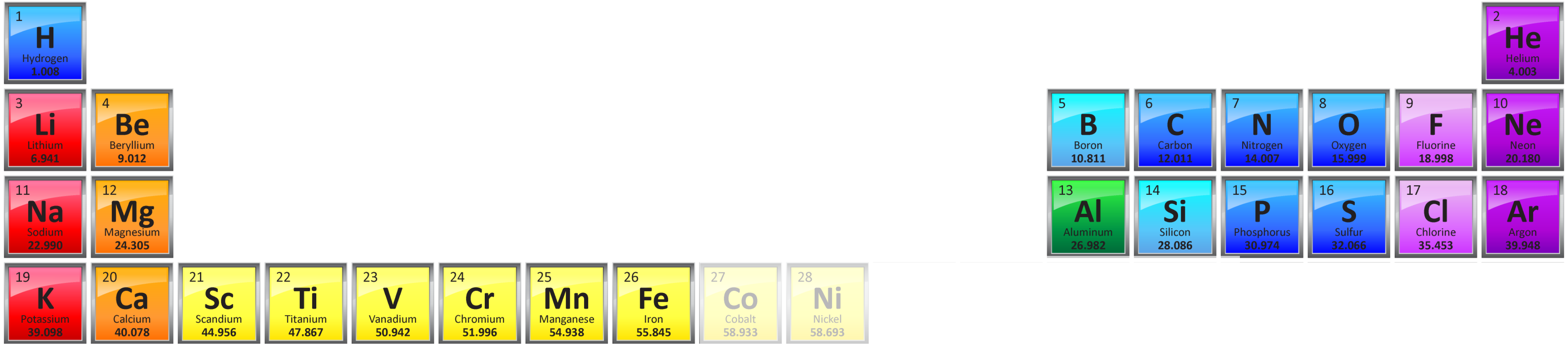
4 Be Beryllium 9.012

Primordial Nucleosynthesis

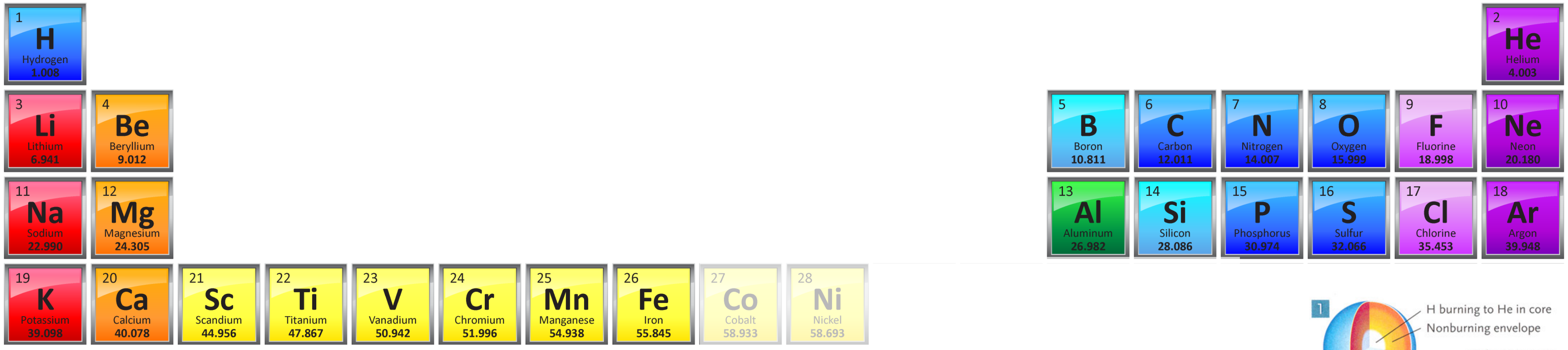
ELEMENTS IN NATURE

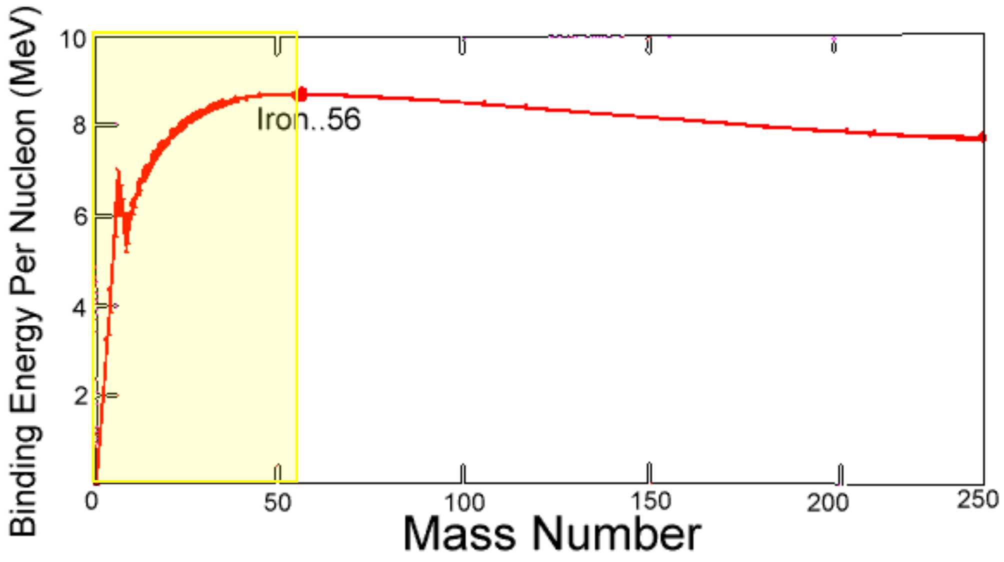
1 H Hydrogen 1.008		2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012	

ELEMENTS IN NATURE

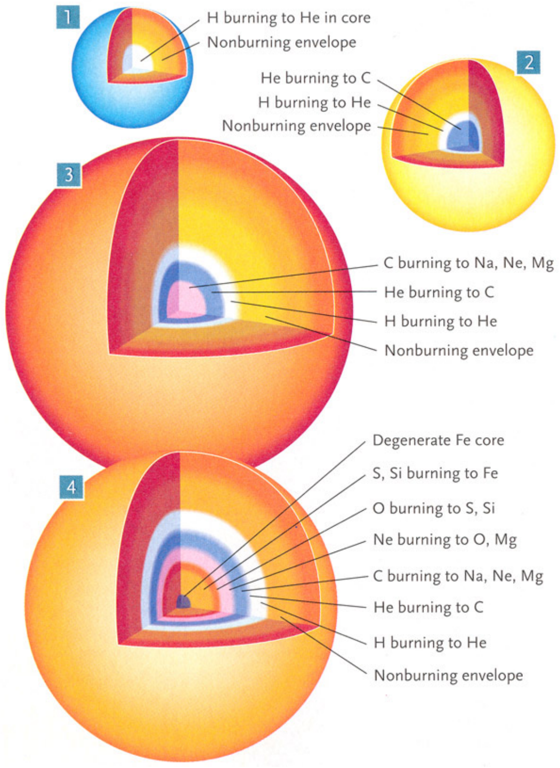


ELEMENTS IN NATURE

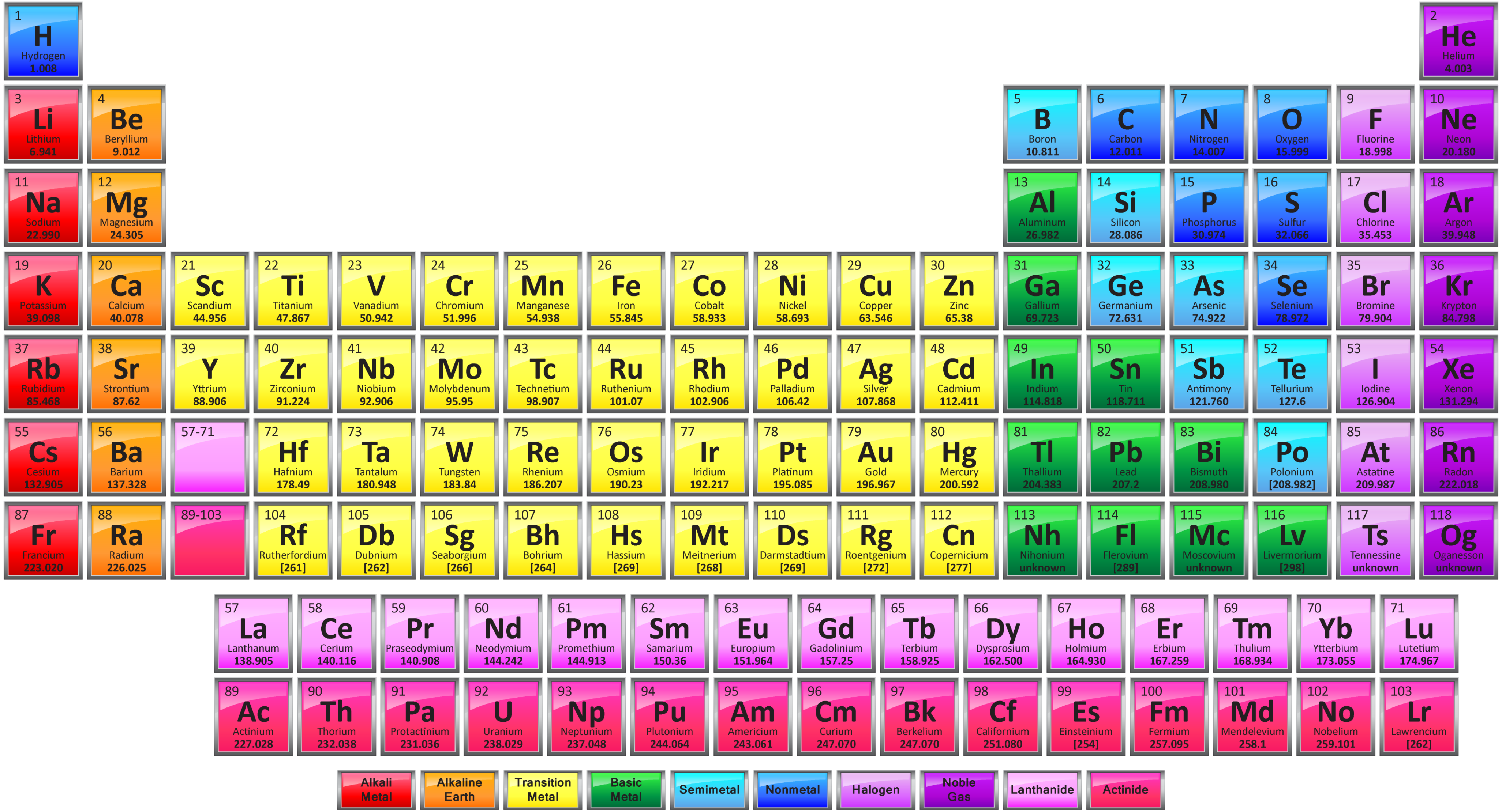




charged-particle induced reaction during quiescent stages of Stellar evolution

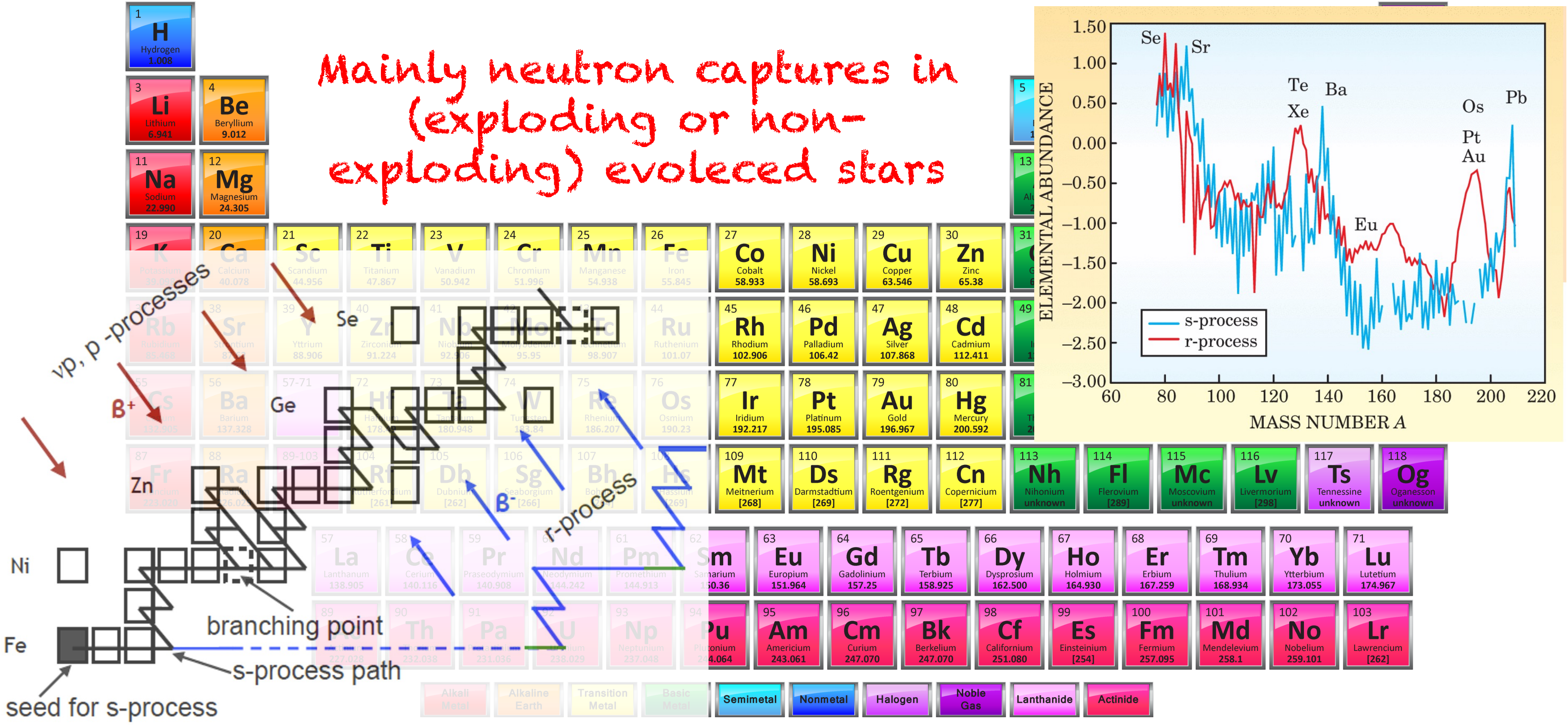


ELEMENTS IN NATURE



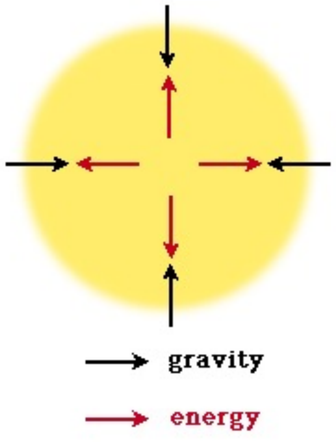
ELEMENTS IN NATURE

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



How does a star work?

Quiescent evolution



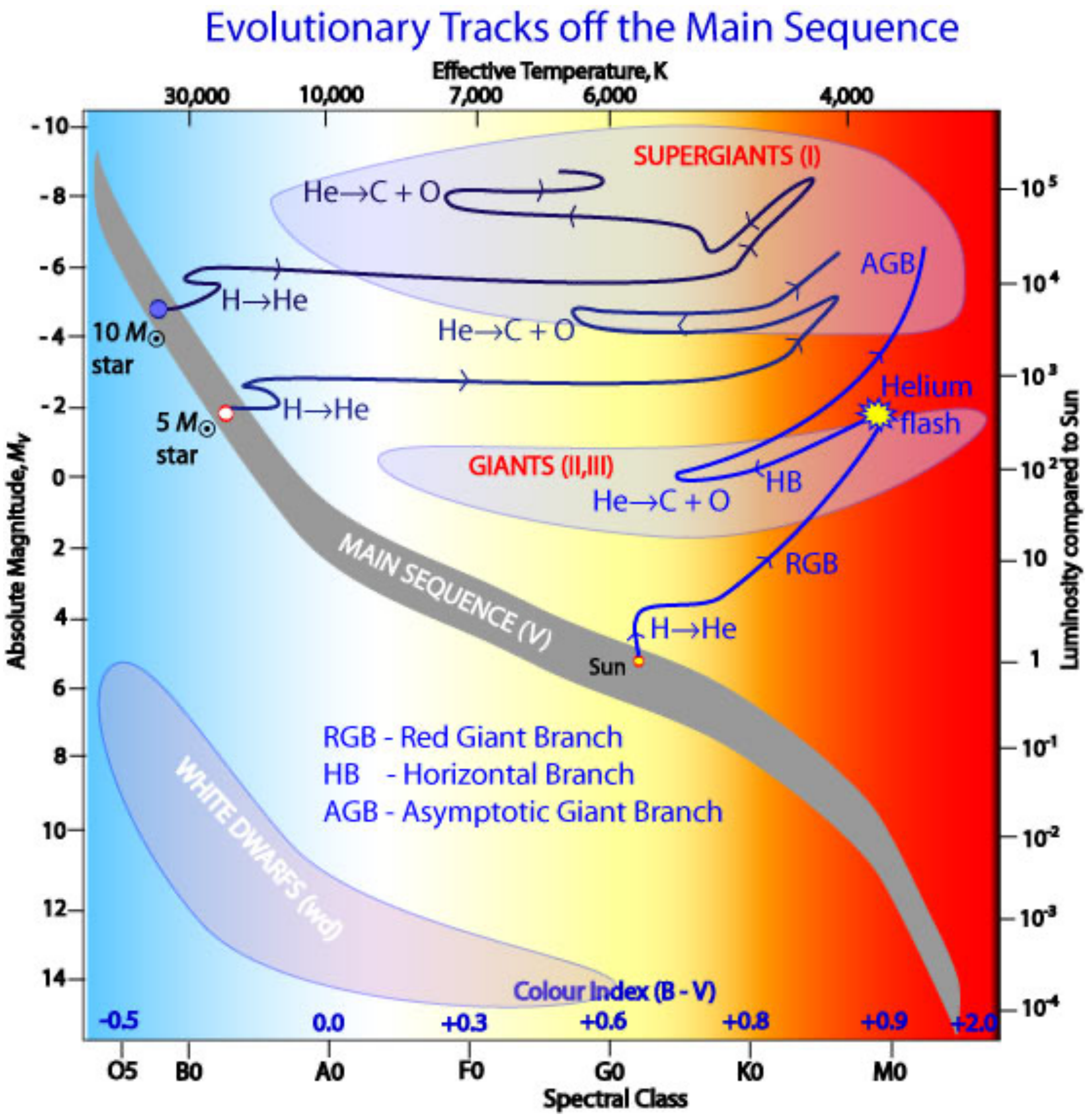
- Stellar structure and evolution controlled by:
  - Gravity → collapse
  - Radiation pressure → expansion
- Star composed of many particles.
  (~10^{57} in the Sun)
- Total energy:
  - gravitational energy of particles (Ω)
  - internal (kinetic) energy of particles (including photons) (U)
- For an ideal gas in hydrostatic equilibrium:

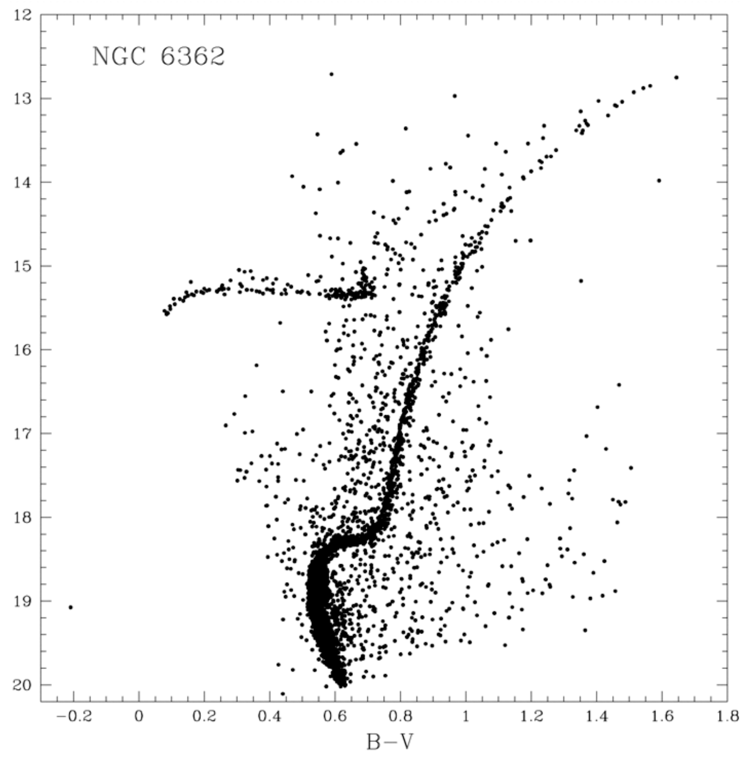
  $2U + \Omega = 0$ virial theorem

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

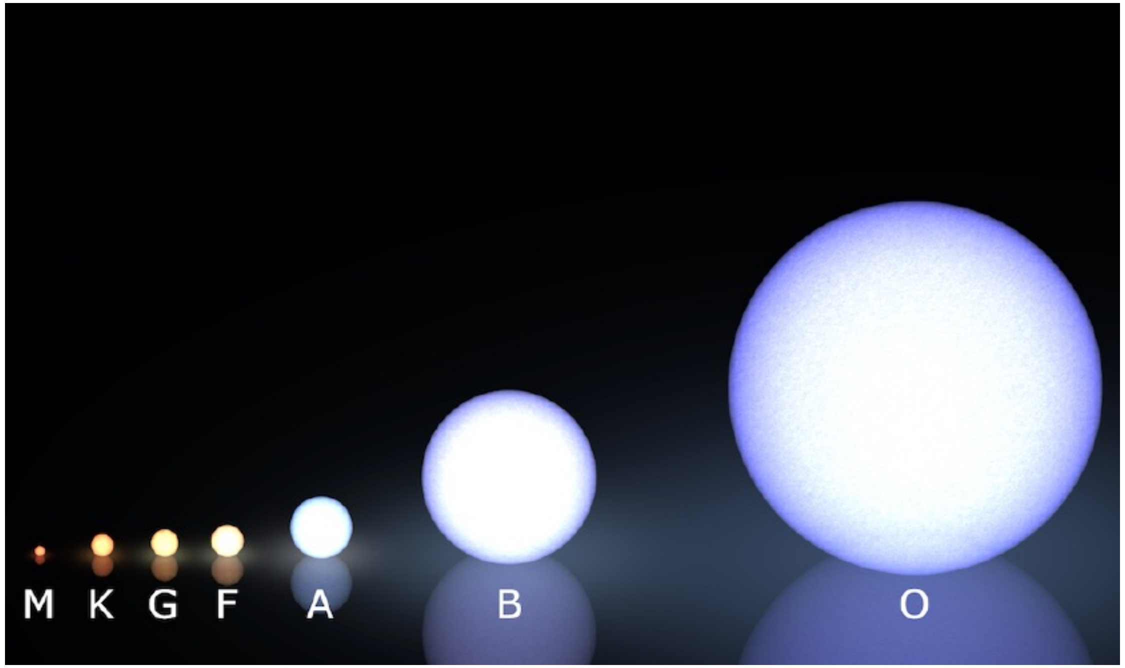
THE HERTZSPRUNG-RUSSELL (COLOR-MAGNITUDE) DIAGRAM AND THE STELLAR EVOLUTION





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

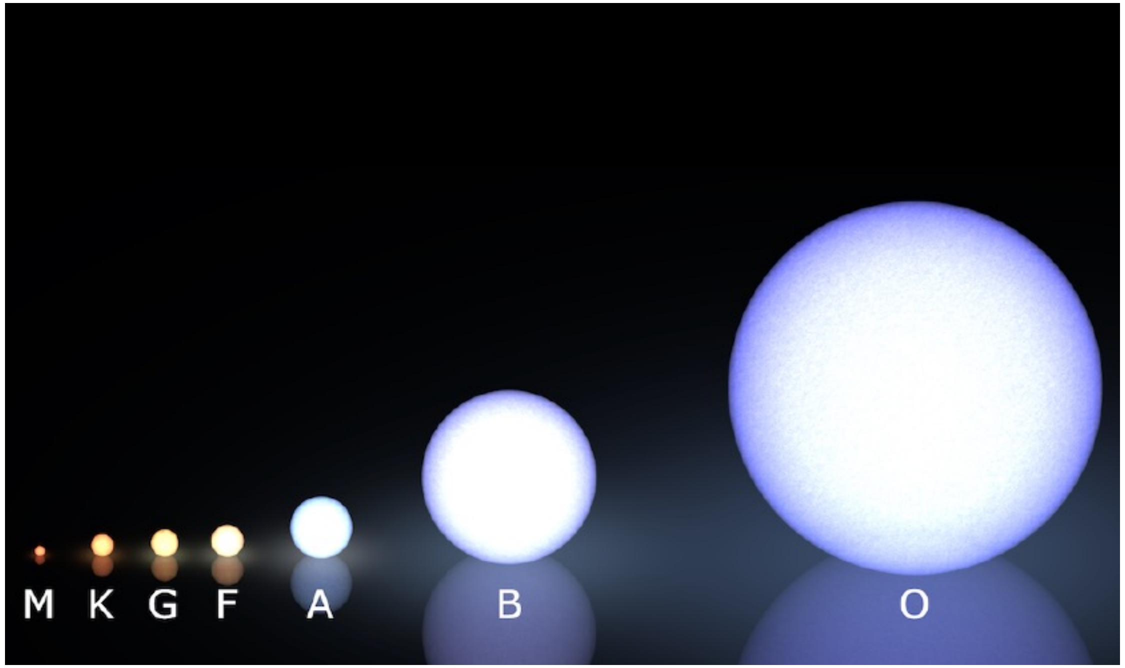
THE MAIN SEQUENCE



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,ρ] to ignite H ($T \sim 10 - 15 \times 10^6$ K and $\rho \sim 10^2\ \mathrm{g\,cm^{-3}}$, 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 → higher rates of nuclear reactions
  - ✓ are more luminous and exhaust H fuel more quickly $L \propto M^{3.5} \rightarrow t_{ms} \propto M^{-2.5}$

THE MAIN SEQUENCE



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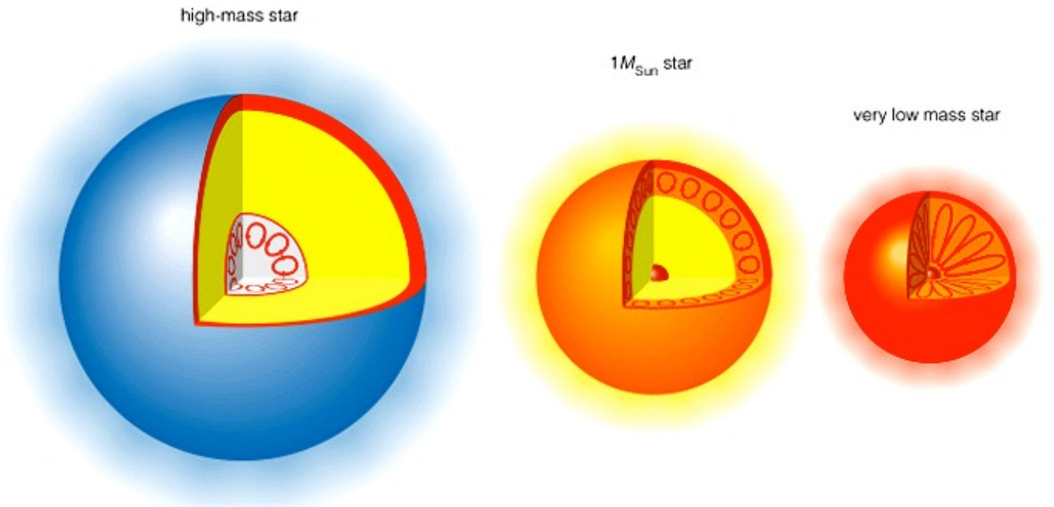
0.50	4000	M	0.03	700,000

Mass essentially determines everything
Chemical composition has a relatively minor effect

…including stellar structures because of the energy transport



Convective core, radiative envelope

Radiative core, convective envelope

Fully convective

HYDROGEN BURNING

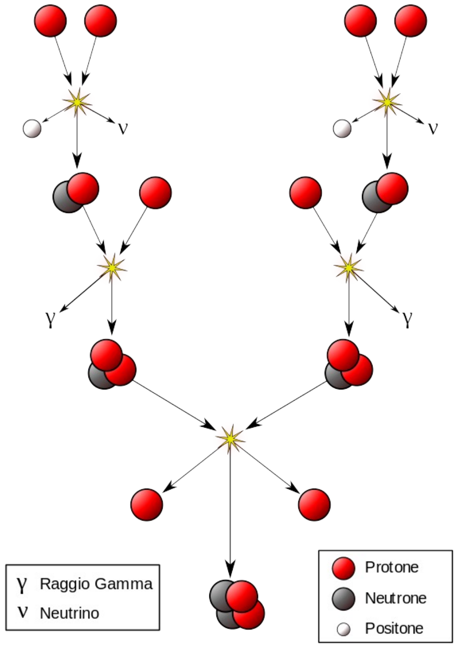
$$4H \rightarrow {}^{4}He + 2\beta^{+} + 2\nu + \; 26\ MeV$$

PROTON-PROTON CHAIN

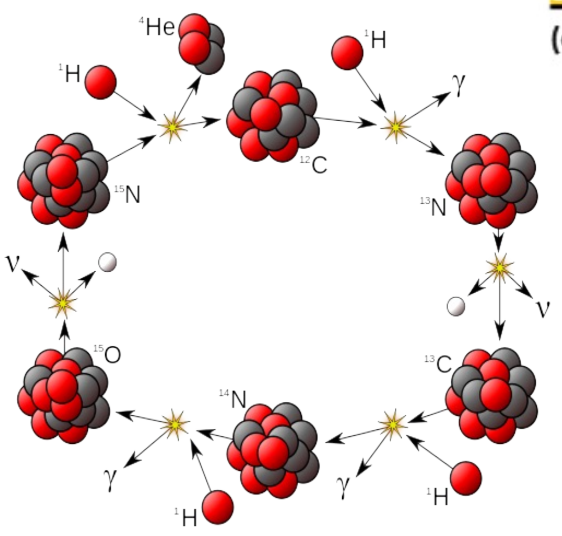
$M < 1.5\ M_{\odot} \Rightarrow T_6 < 30$

CNO CYCLE

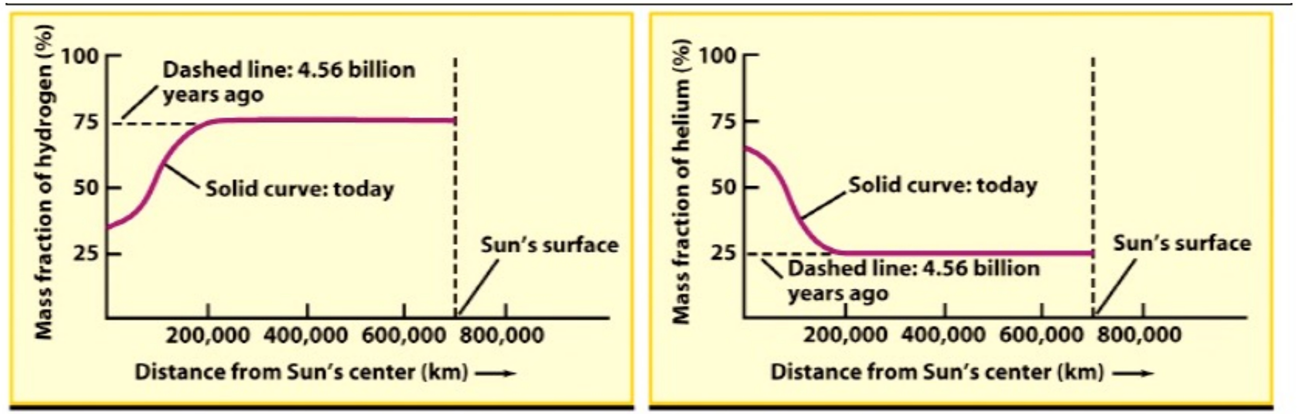
$M \geq 1.5\ M_{\odot} \Rightarrow T_6 > 30$



Q = 25 MeV

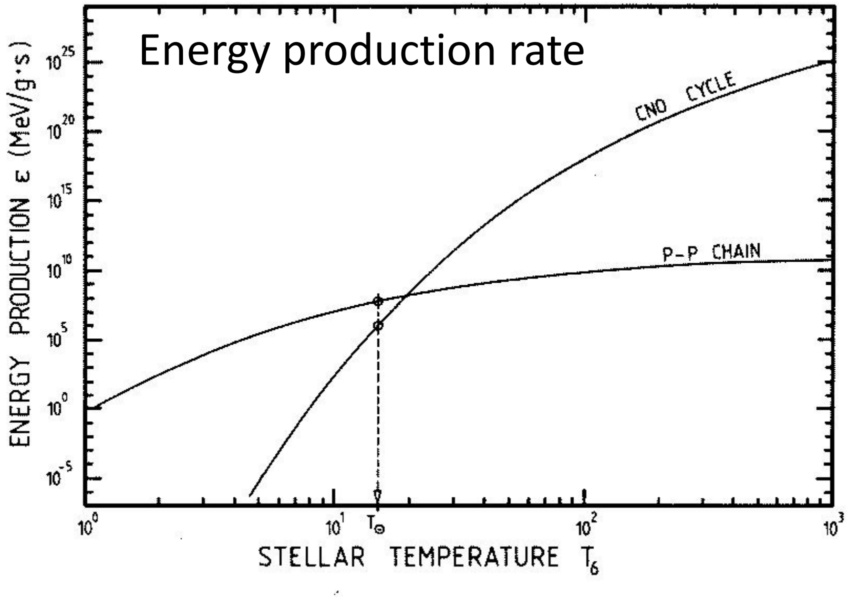


Q = 27 MeV

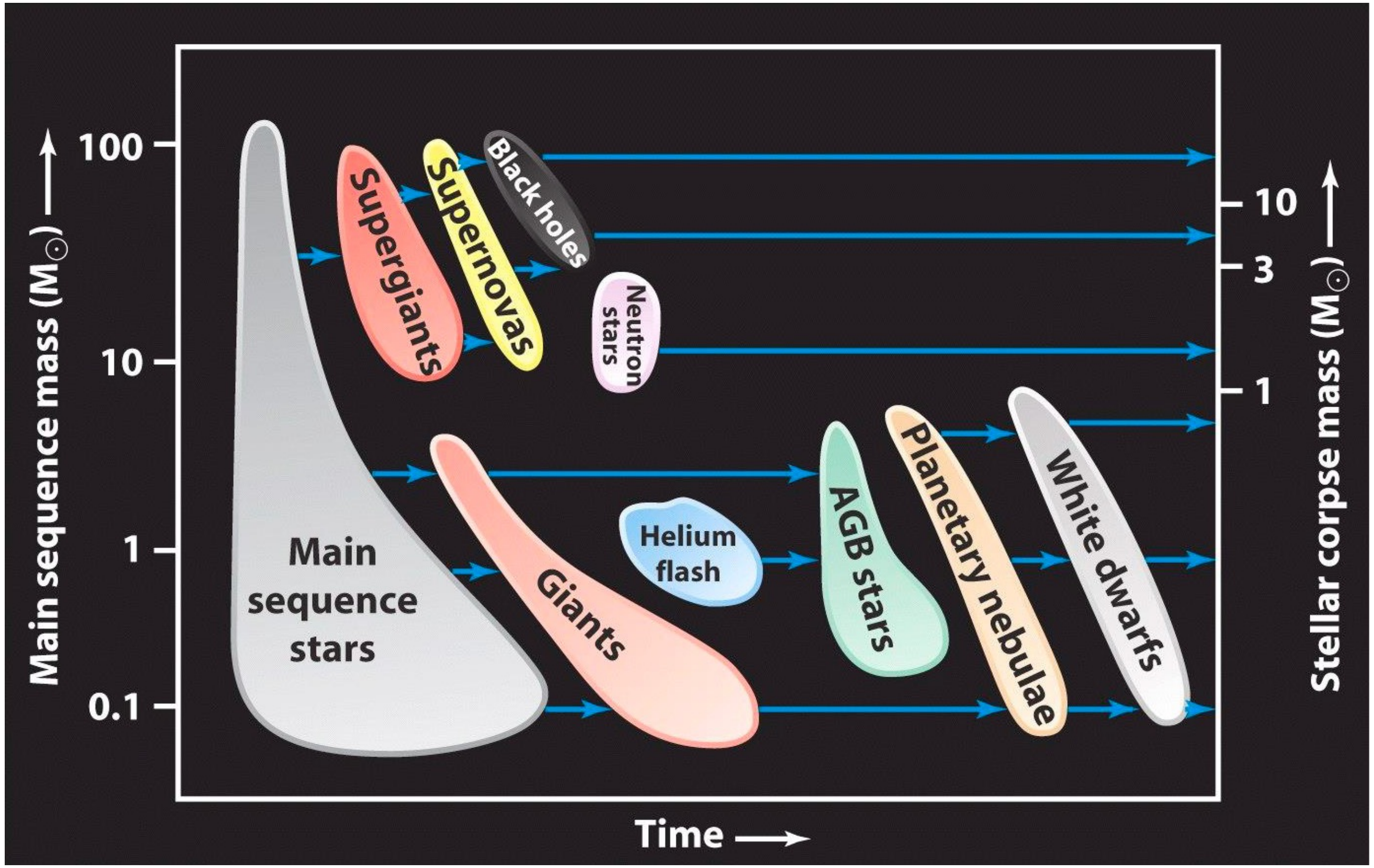


(a) Hydrogen in the Sun's interior

(b) Helium in the Sun's interior



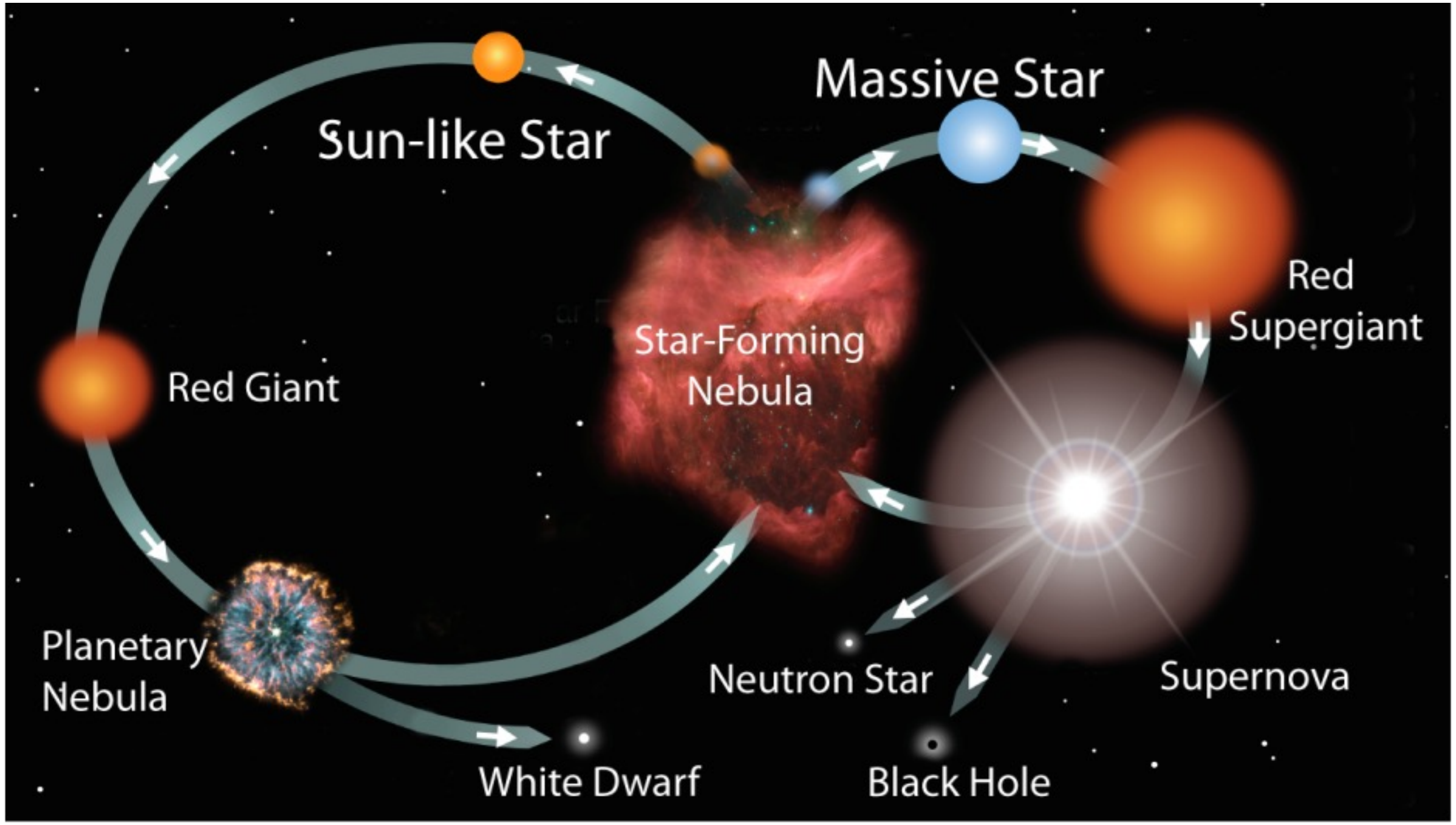
What happens when the core runs out of hydrogen?



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)

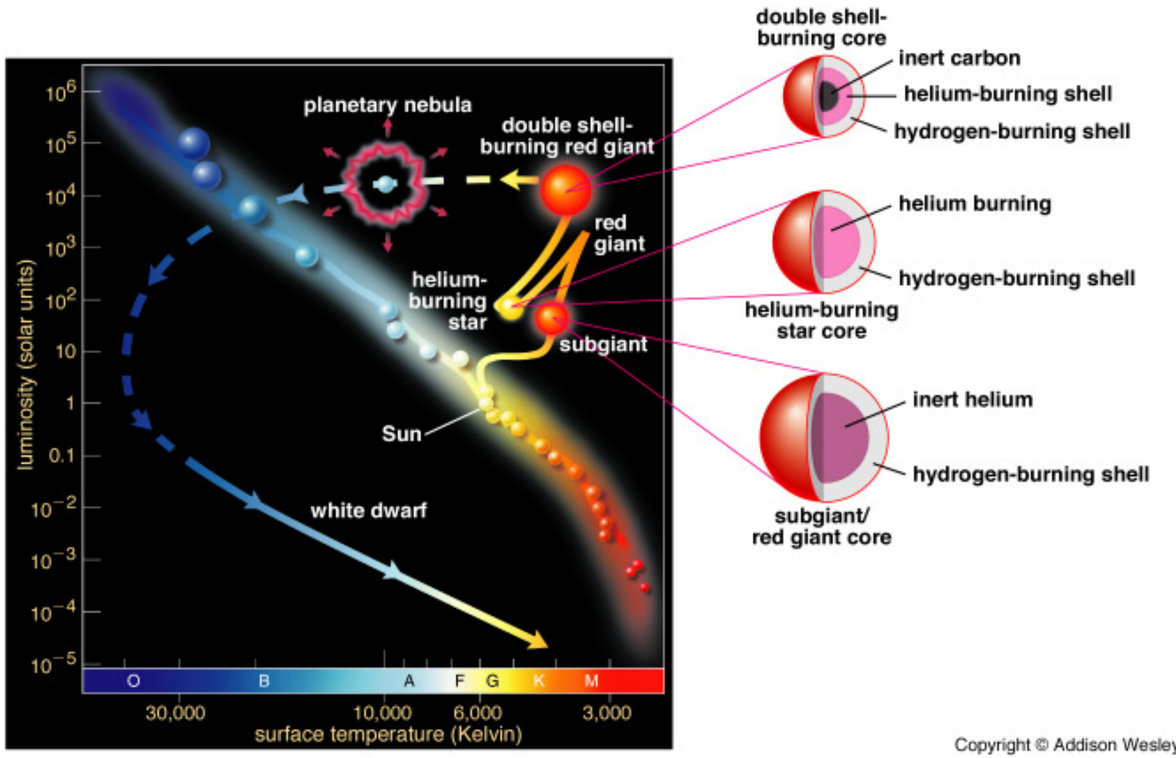
What happens when the core runs out of hydrogen?



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)

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



- There are different types of Red Giant Stars
  1. RGB (Red Giant Branch)
  2. Horizontal branch
  3. AGB (Asymptotic Giant Branch)

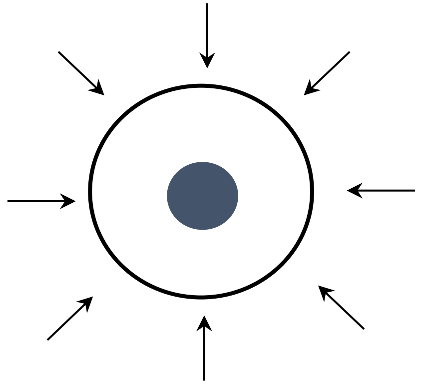
- These differ in position on H-R diagram and ininterior structure

1.RGB (Red Giant Branch) Stars

H exhausted in core

isothermal He core

contraction sets in



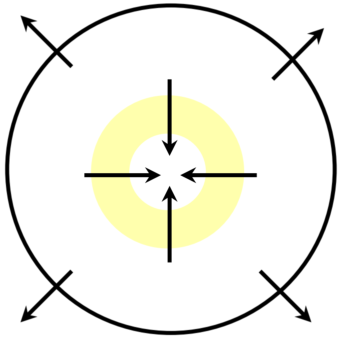
$R \sim 10\text{-}100\, R_i \Rightarrow T_s \sim 3\text{-}4\text{x}10^3$ K

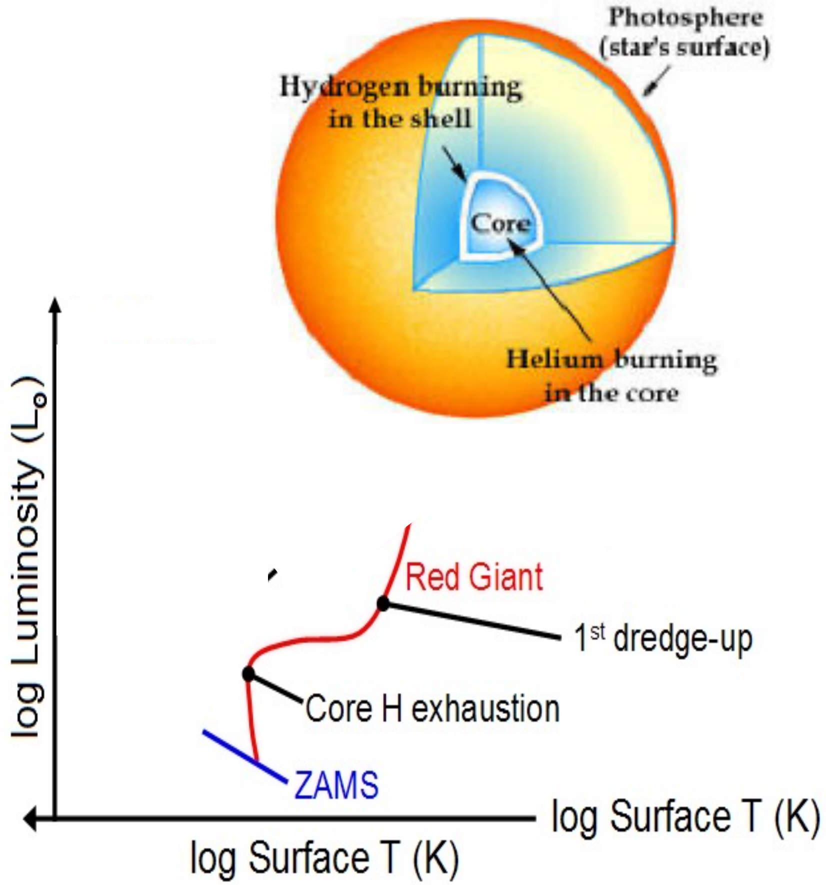
Wien's law: $\lambda_{max}T$ = const.

H-burning shell forms

Core contracts

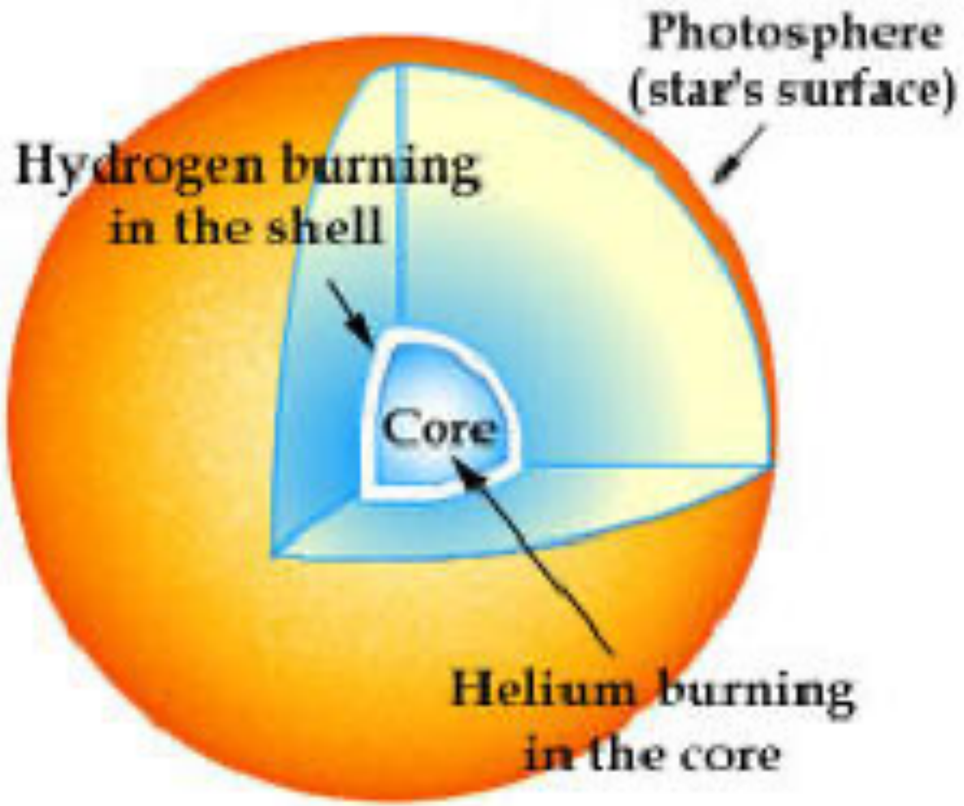
Envelope expanS





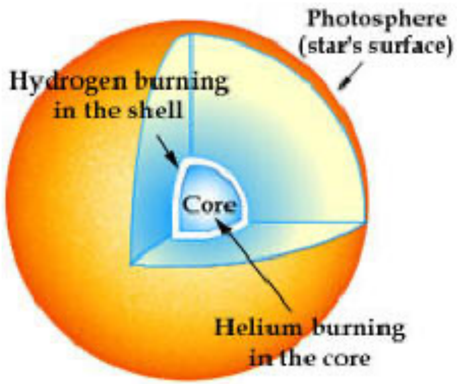
1.RGB (Red Giant Branch) Stars

- 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.



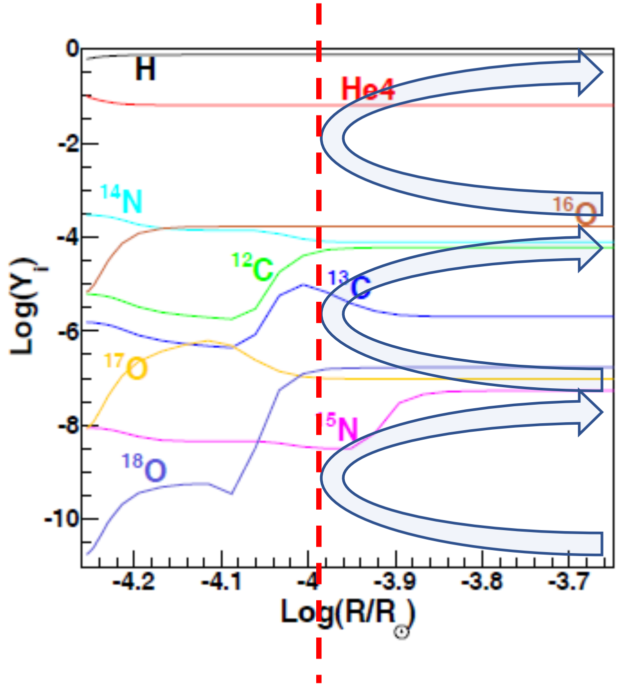


Figure 1.6 Distribution of the abundances of light nuclei in the stellar region mixed by the FDU (of a $1.5M_\odot$ and $Z_\odot$ RGB star). In this region there will be increases in ^{13}C and ^{14}N and sharp decreases in ^{12}C and ^{15}N. After FDU, the envelope composition is then changed to the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

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

Convective envelope reaches $\simeq$ 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:

$^{12}C \sim \frac{2}{3} \times {}^{12}C_{ini}$
$^{13}C \sim (2 - 3) \times {}^{13}C_{ini}$

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

$^{14}N \sim (2 - 3) \times {}^{14}N_{ini}$
$^{15}N \sim \frac{1}{2} \times {}^{15}N_{ini}$

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

$^{16}O = {}^{16}O_{ini}$

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

$^{17}O = (1 - 13) \times {}^{17}O_{ini}$ ($1\,M_\odot \leq M \leq 2.2\,M_\odot$)
$^{17}O = (13 - 5) \times {}^{17}O_{ini}$ ($2.2\,M_\odot \leq M \leq 8\,M_\odot$)

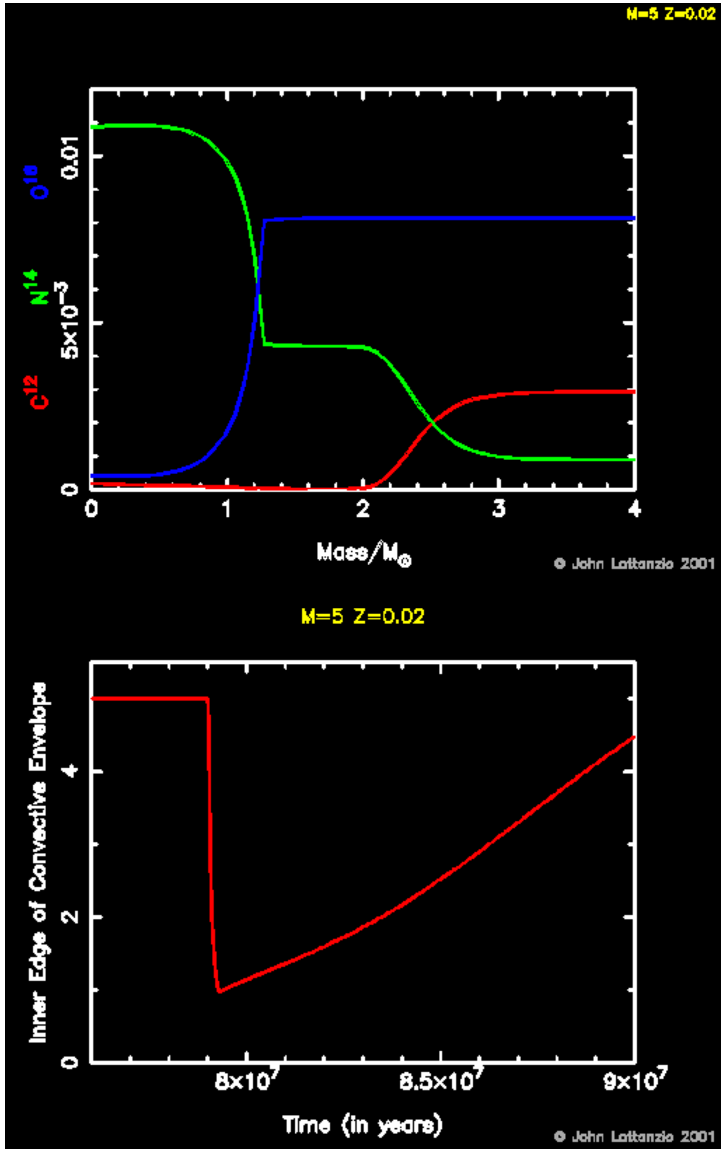
$\frac{^{16}O}{^{17}O} \sim (1 - 1/15) \times (\frac{^{16}O}{^{17}O})_{ini} = 2600 - 200$

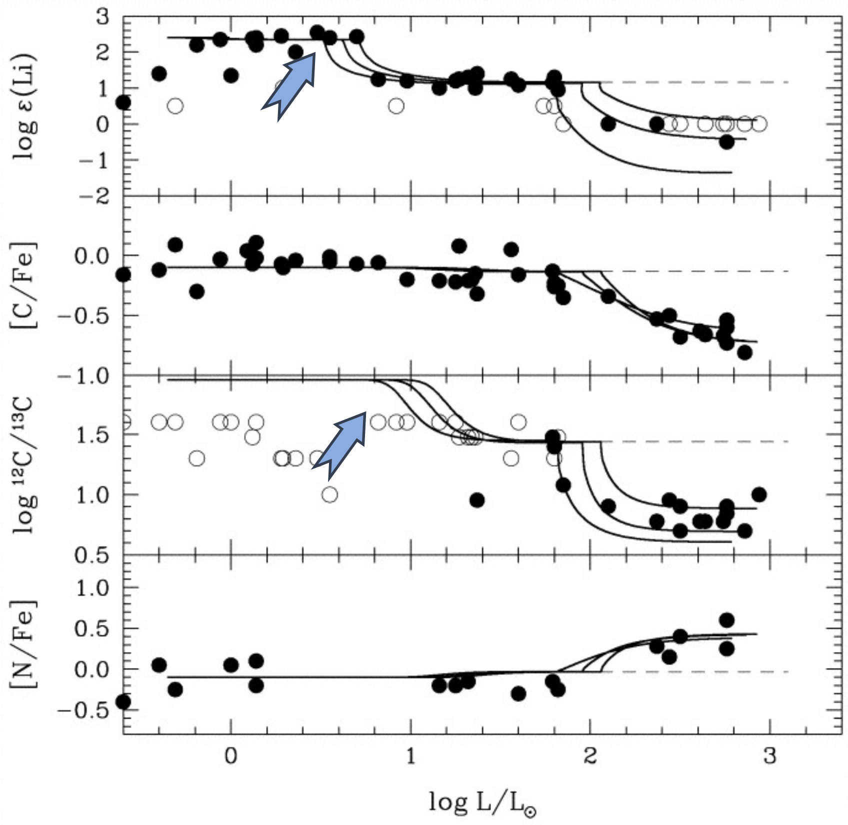
$\frac{^{16}O}{^{18}O} \sim (1.2 - 1.3) \times (\frac{^{16}O}{^{18}O})_{ini} = (600 - 700)$

^{26}Al : no production

The RGB and the First Dredge-up (FDU)

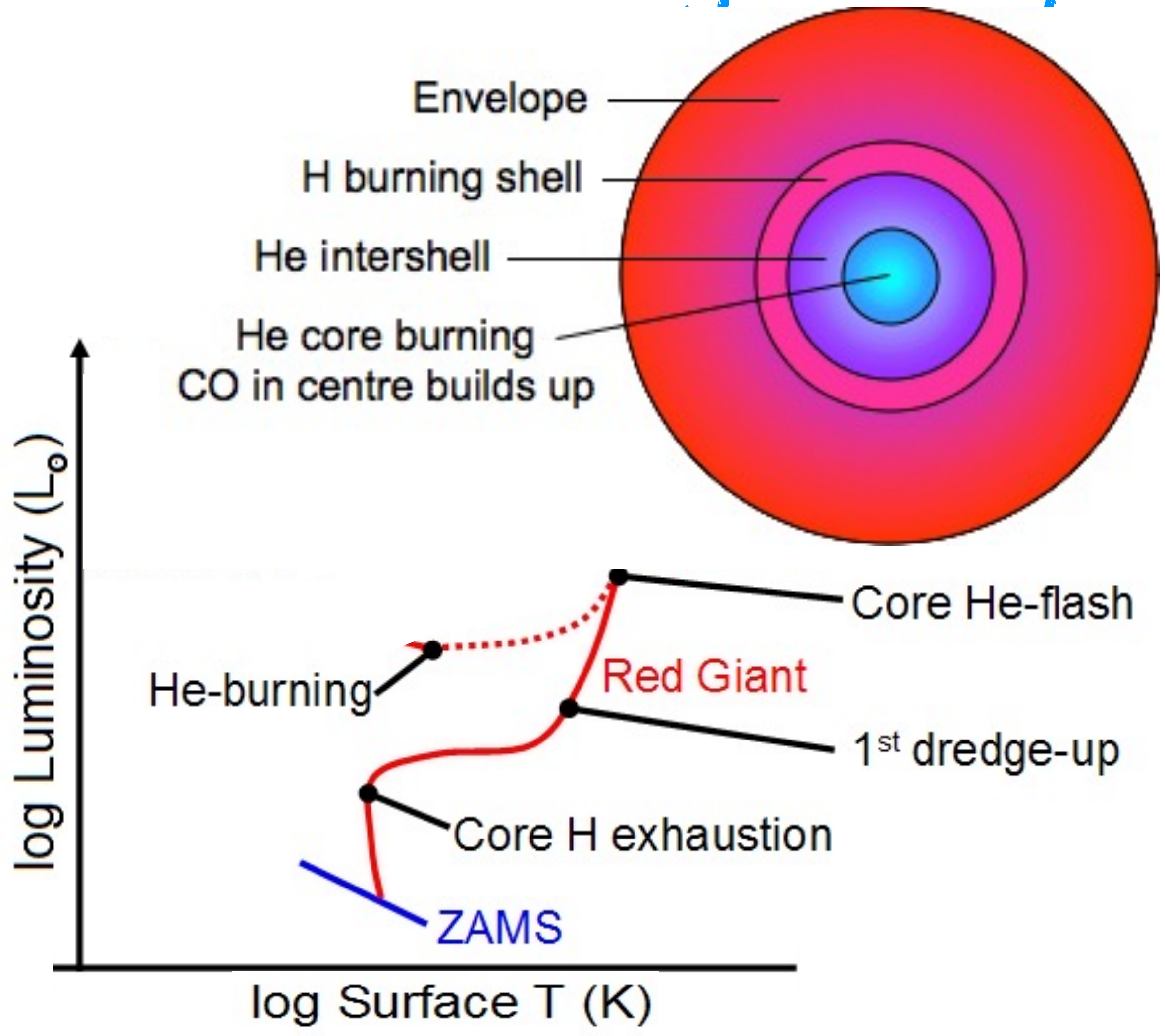
http://users.monash.edu.au/~johnl/StellarEvolnV1/m5z02/FDU_CNO+Mbcevmovie.gif





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= 0.85$M_\odot$ 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

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

$3\alpha \rightarrow {}^{12}C$
${}^{12}C(\alpha,\gamma){}^{16}O$
} Q= 8 MeV

→ $\alpha + \alpha \rightarrow {}^{8}Be$ (Q = –92 keV). ${}^{8}Be$ is unstable against breakup in 2α

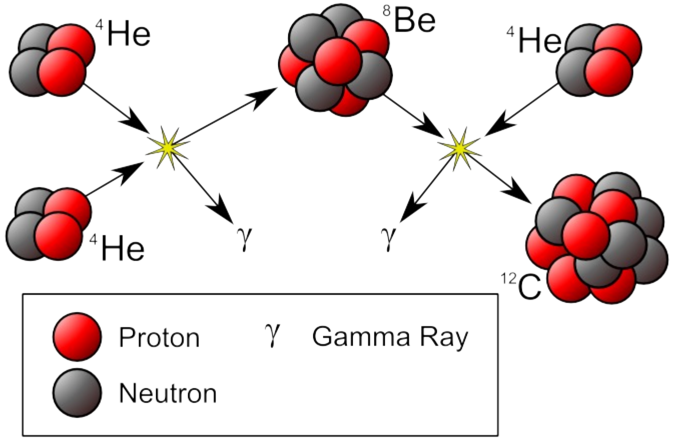
→ $t_{1/2}({}^{8}Be)=3 \quad 10^{-16}$ s > the timescale of an $\alpha + \alpha$ scattering

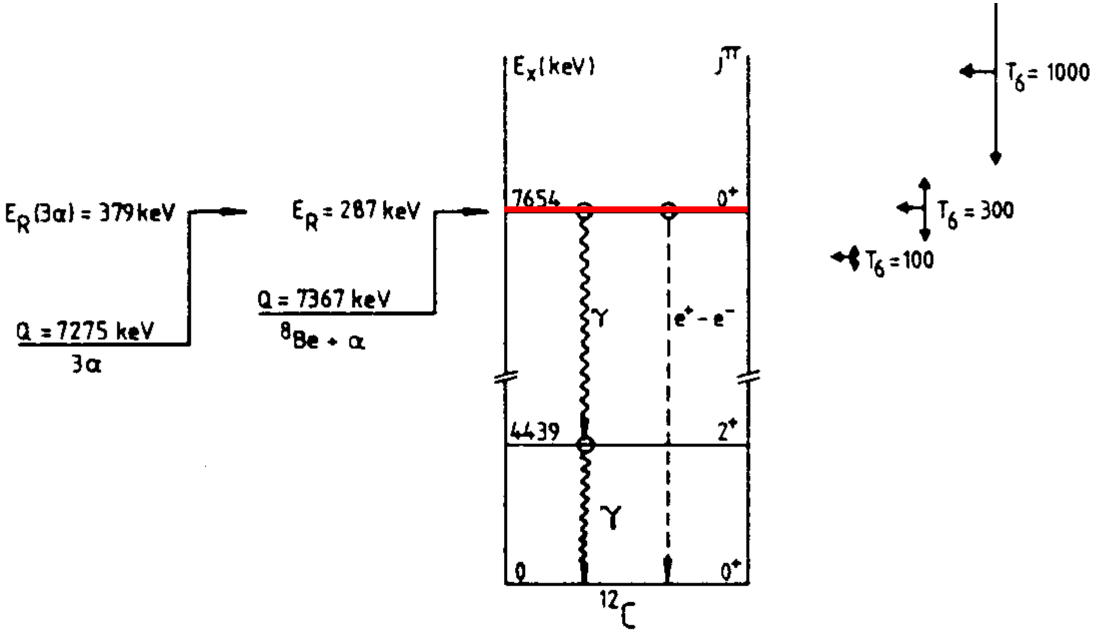
→ a small ammount of ${}^{8}Be$ can build up to reach the $\alpha + \alpha \leftrightarrow {}^{8}Be$ equilibrium

→ ${}^{8}Be + \alpha \rightarrow {}^{12}C + \gamma$ is possible thanks to the Hoyle state (E_x=7.654 MeV, $J^{\pi}=0^+$)

→ ${}^{8}Be(\alpha){}^{12}C^{*}(\gamma)\ {}^{12}C$

→ note: $3\alpha \rightarrow {}^{12}C$ is not a three particle reaction!





2. The HB: the He-burning

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

$3\alpha \rightarrow {}^{12}C$ } Q= 8 MeV
${}^{12}C(\alpha,\gamma){}^{16}O$

→ ${}^{12}C(\alpha,\gamma){}^{16}O$ it is probably the most important reaction in nuclear astrophysics

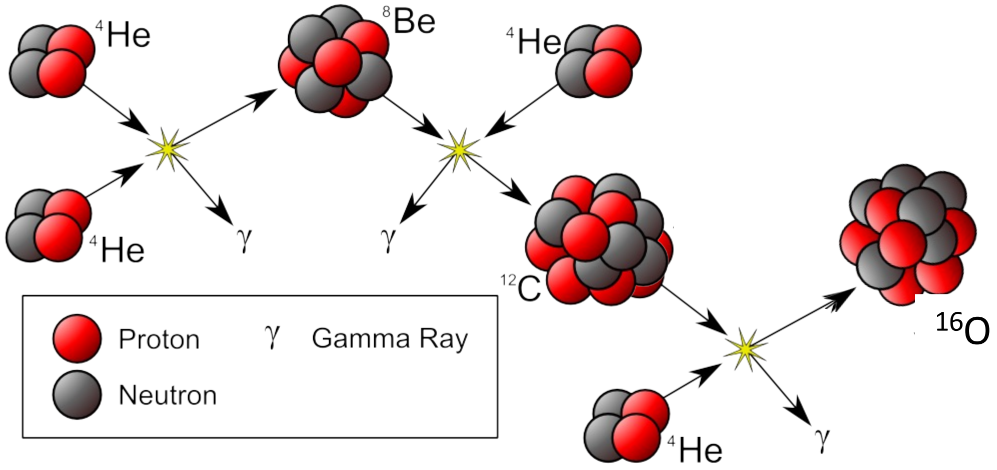
→ Its rate determines how much of the ${}^{12}C$ formed is converted to ${}^{16}O$

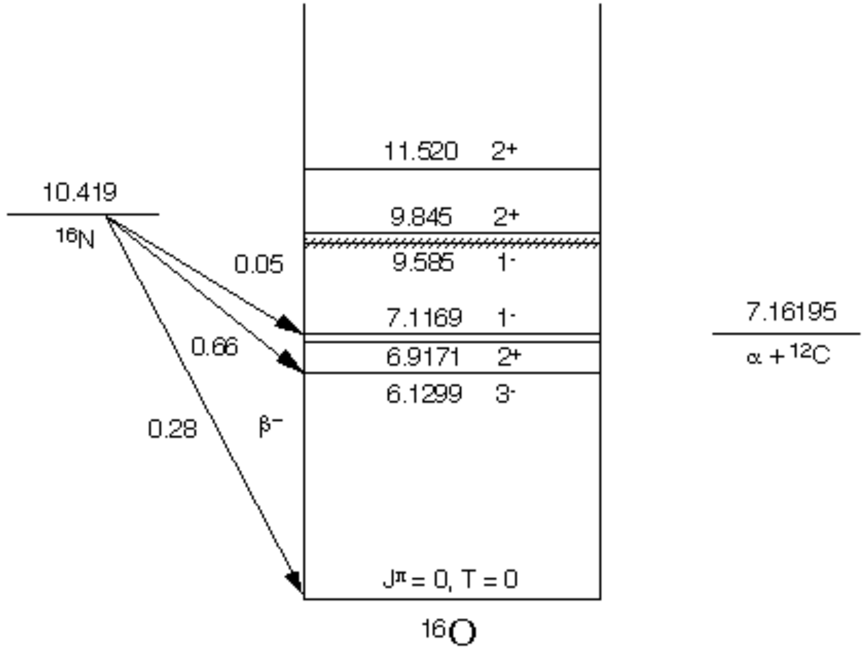
  → thereby the carbon/oxygen abundance ratio in red giant stars

    → set the initial conditions for heavy-ion burning phases

→ The ${}^{12}C(\alpha,\gamma){}^{16}O$ rate is not yet known with very high precision

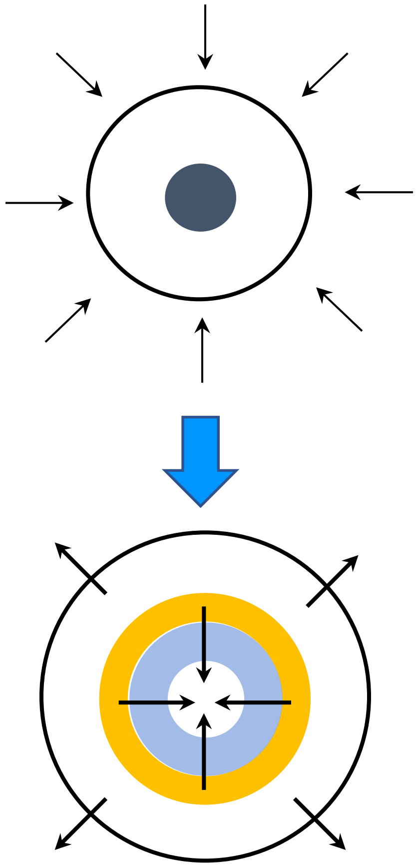
  → unclear wether main product of He-burning is carbon or oxygen!



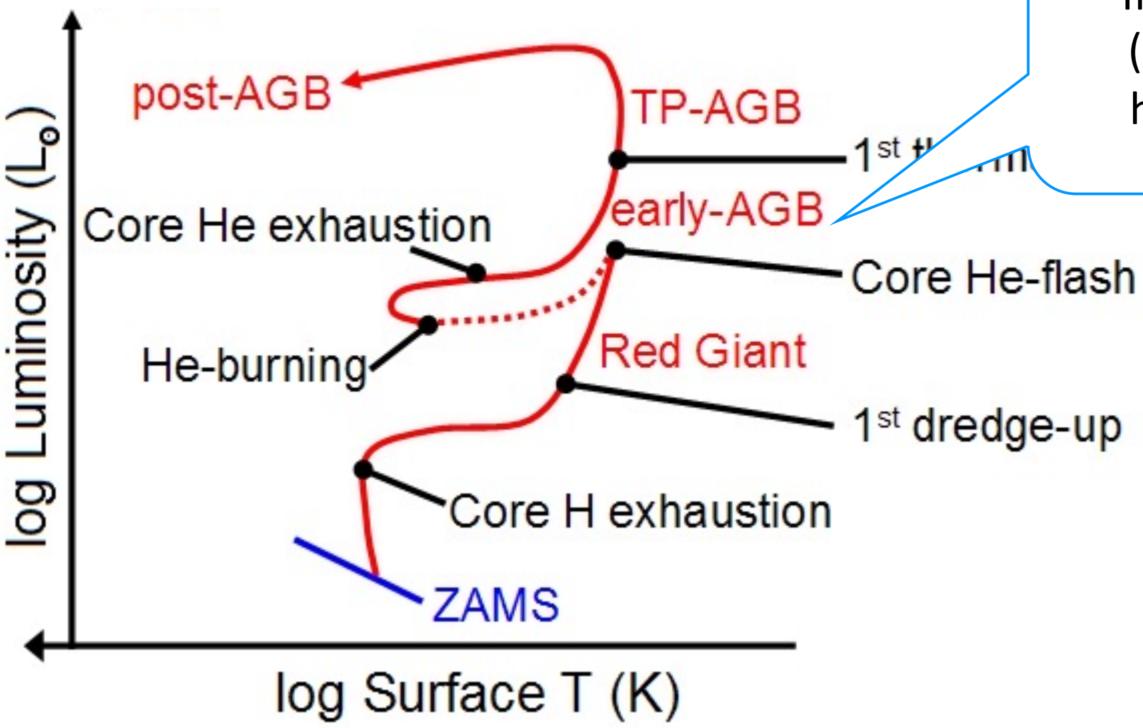


3. AGB (Asymptotic Giant Branch) Stars

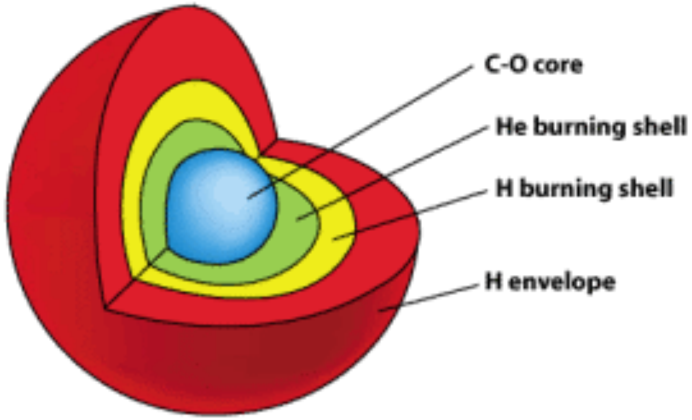
He exhausted in core contraction sets in



H-burning shell
He-burning shell
CO-core

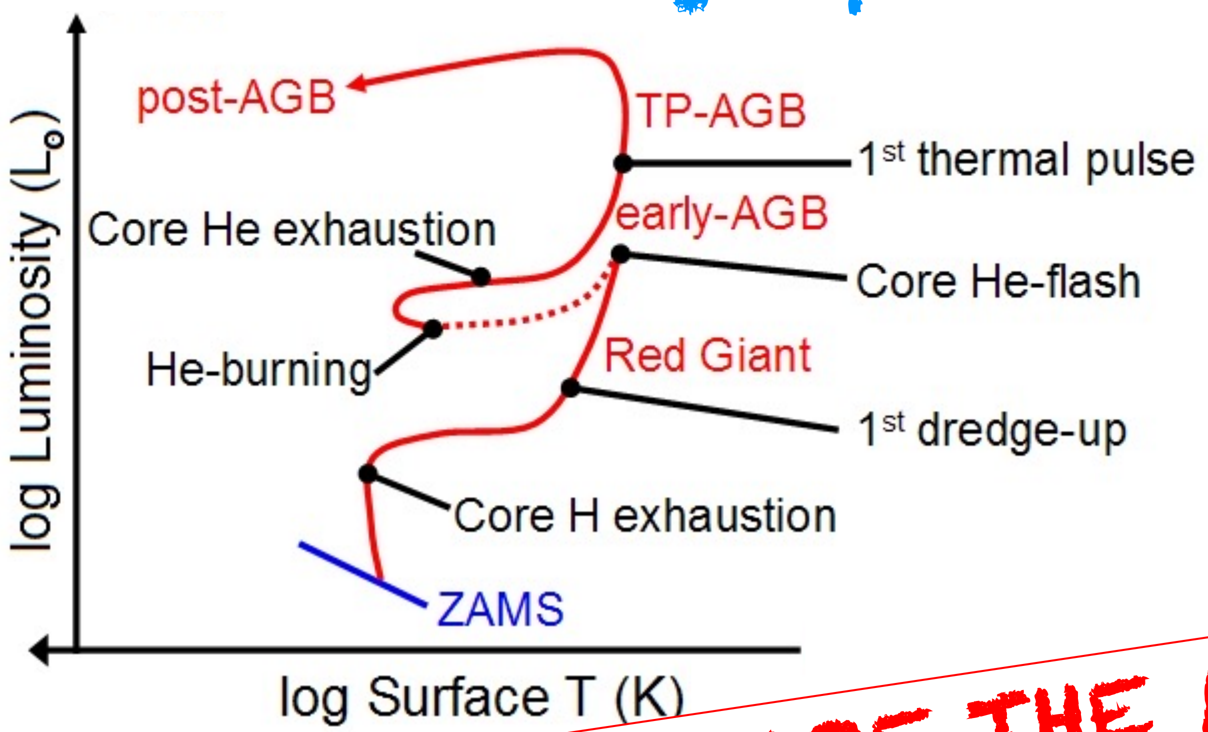


If M> 4$M_\odot$ the second dredge-up (SDU) transports the products of hydrogen-burning to the surface



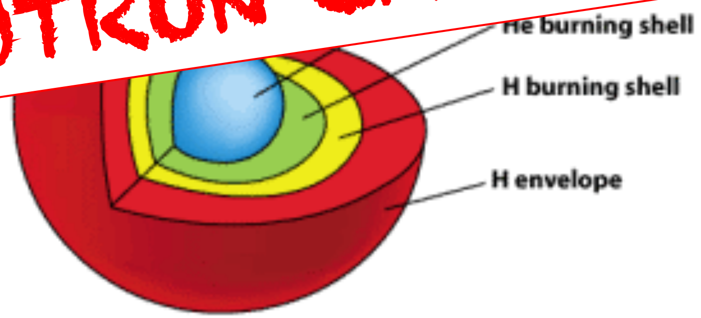
During the early-AGB the main source of energy is He fusion in a shell around the CO core. During this phase the star swells up to giant proportions to become a red giant again.

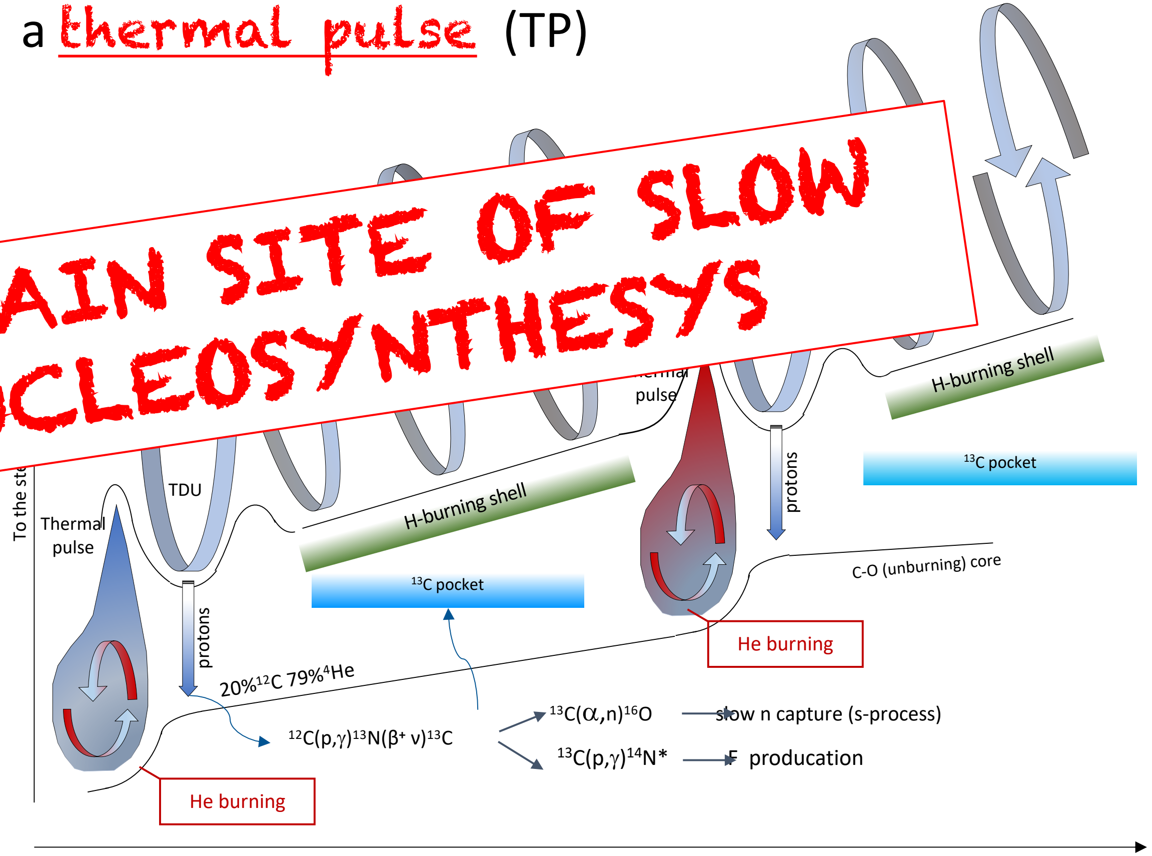
3. AGB (Asymptotic Giant Branch) Stars



During the **Thermal Pulse AGB** phese 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 <u>thermal pulse</u> (TP)

AGB STARS ARE THE MAIN SITE OF SLOW NEUTRON CAPTURE NUCLEOSYNTHESYS





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

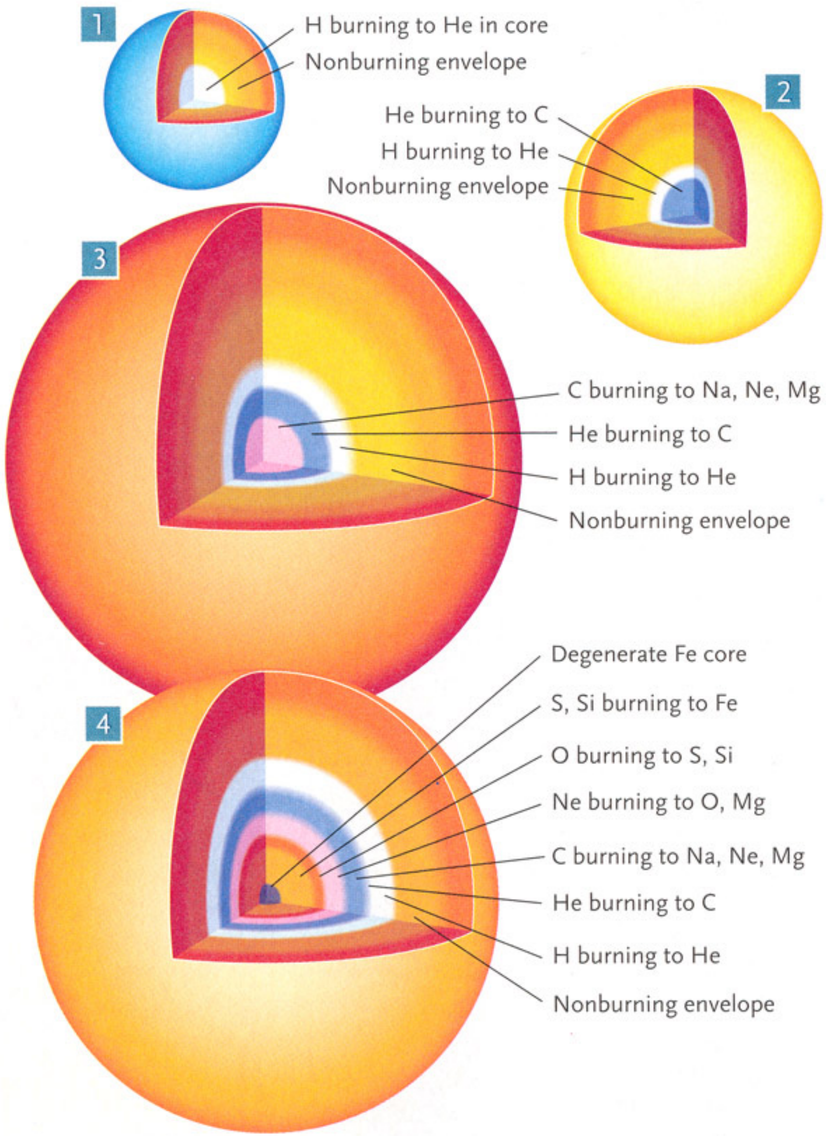
2) chemical composition $\Rightarrow$ nuclear processes

Evolution stages of a 25 $M_\odot$ star

T, ρ

Stage reached	Timescale	T_{core} (10^9 K)	Density (g cm^{-3})
H burning	7×10^6 y	0.06	5
He burning	5×10^5 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

→ SUPERNOVA EXPLOSION (type II) $M \geq 8\ M_\odot$



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t

Aurora Tumino lecture on 12C + 12C and the session devoted to C-fusione on Wednesday morining

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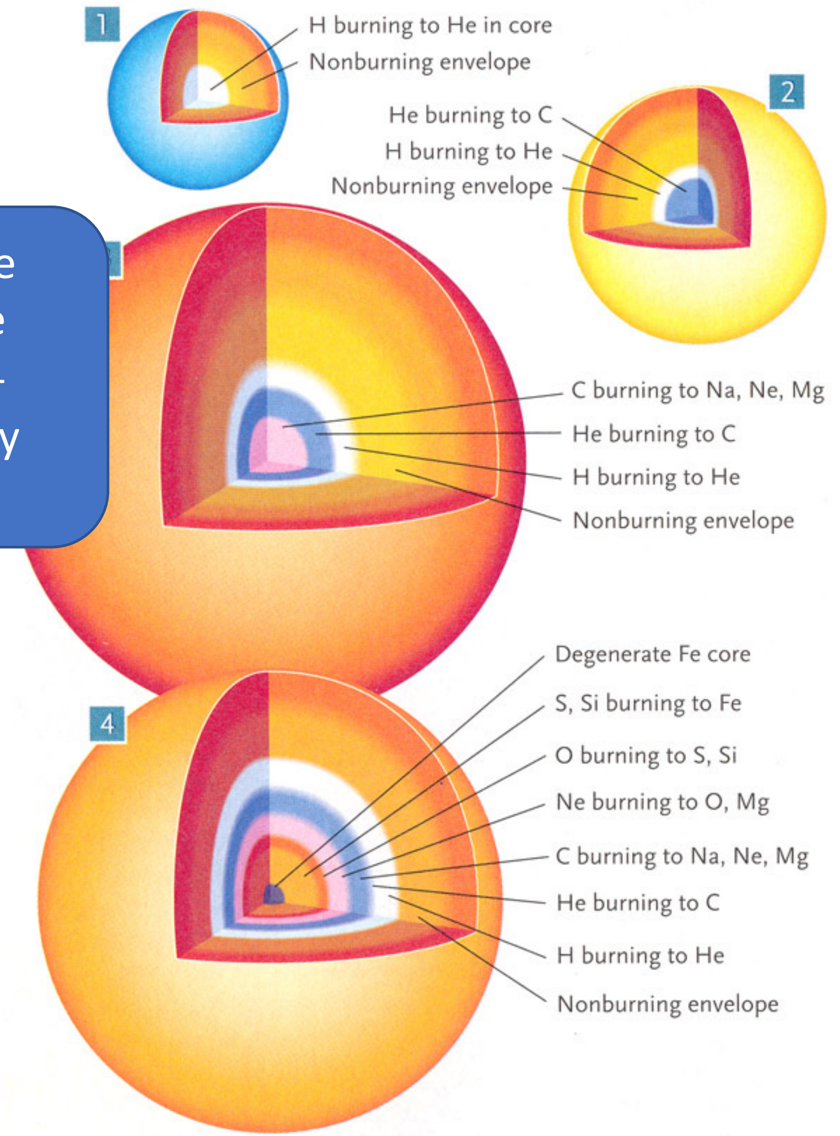
Explosive burning	0.1 – 1 s	1.2 - 7	varies

→ SUPERNOVA EXPLOSION (type II) M ≥ 8 $M_\odot$



SUPER RED-GIANT STARS

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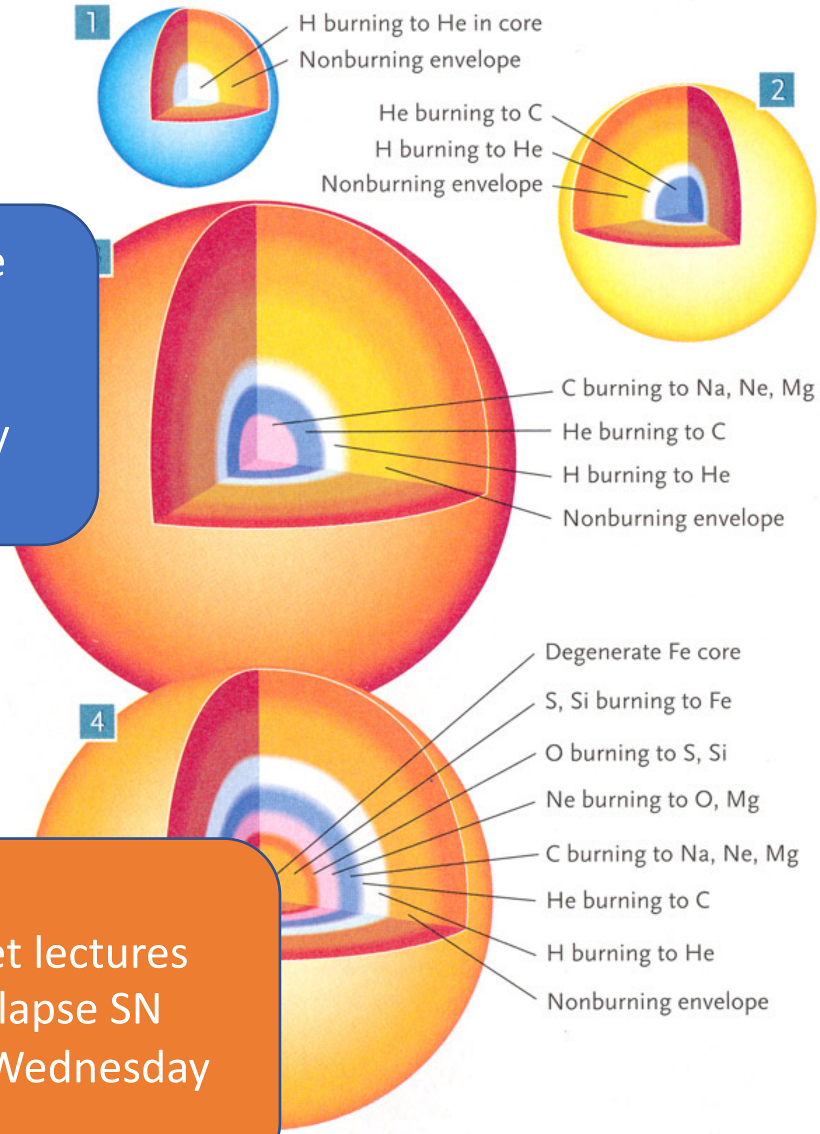
Jerome Guilet lectures on Core collapse SN Tuesday and Wednesday



Why quiescent stages of Stellar evolution are so long?

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