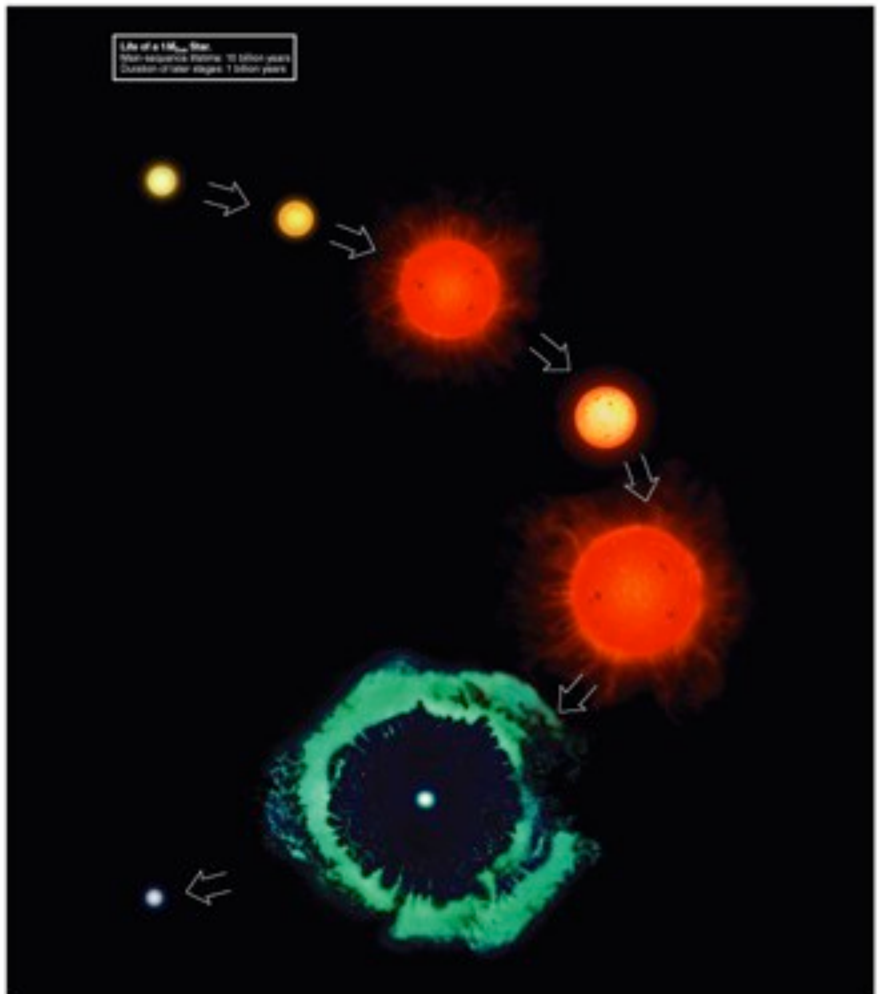
Today

- Stars
  - Evolution of Low and High Mass Stars
  - Nucleosynthesis
  - Supernovae - the explosive deaths of massive stars

The life stages of a low-mass star



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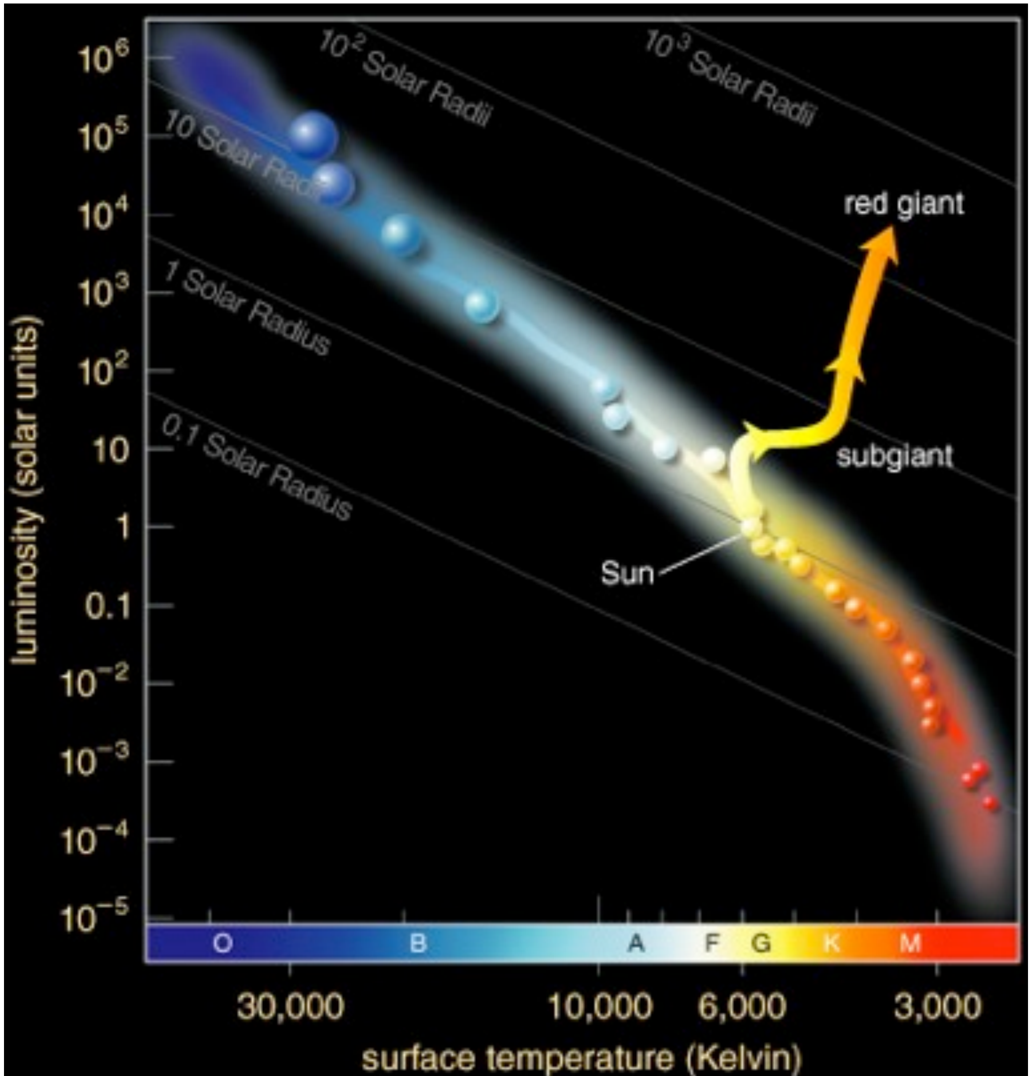
Life Track After Main Sequence



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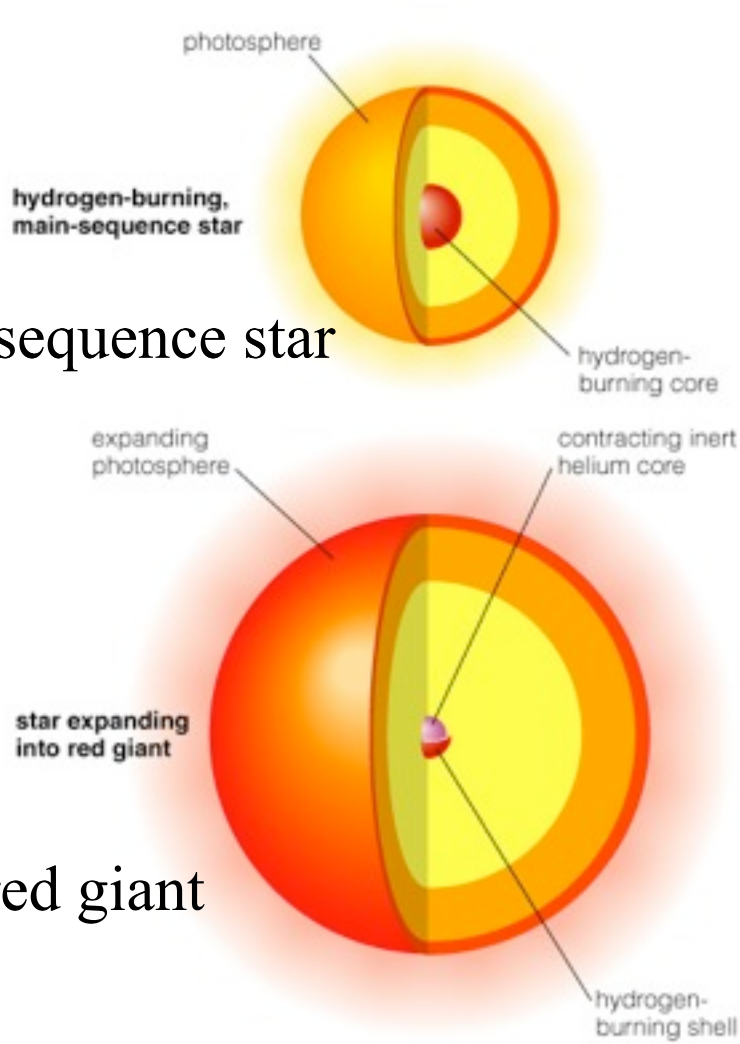
- Observations of star clusters show that a star becomes larger, redder, and more luminous after its time on the main sequence is over.

- At the end of their main sequence life time - when hydrogen in the core is exhausted - stars ascend the **red giant branch**.

After hydrogen fuel is spent



main sequence star

red giant

- Without further fusion, the core contracts. H begins fusing to He in a shell around the core.

- As the core contracts, temperature increases, nuclear reaction rates increase (in the shell), and the Luminosity increases.

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Helium Flash

- The core continues to shrink and heat as the rest of the star expands and becomes more luminous.
  - Ascends giant branch for a billion years

- At a critical temperature and density, helium fusion suddenly begins.
  - The Helium Flash

- The star evolves rapidly, finding a new equilibrium with He burning in core and H burning in a shell surrounding the core.

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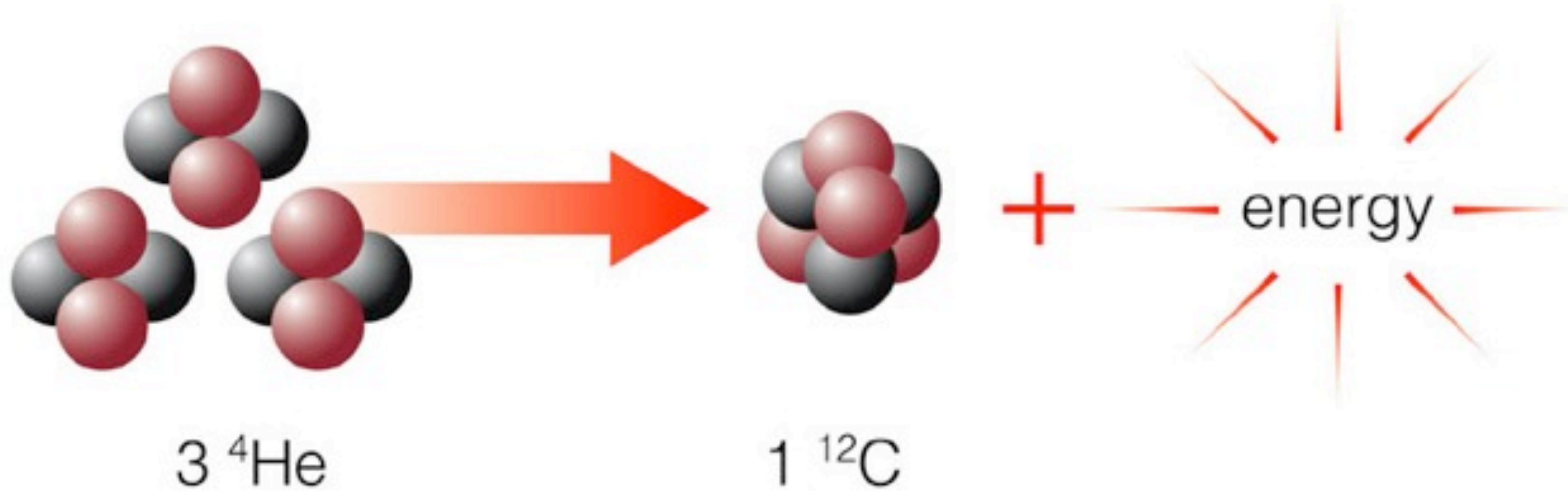

Helium fusion tough—larger charge leads to greater repulsion. Worse, the fusion of two helium nuclei doesn't work; ^{4}He more stable than Beryllium (^{8}Be).

Need three ^{4}He nuclei to make carbon (^{12}C).

Only works because of resonant state of carbon predicted by Fred Hoyle.

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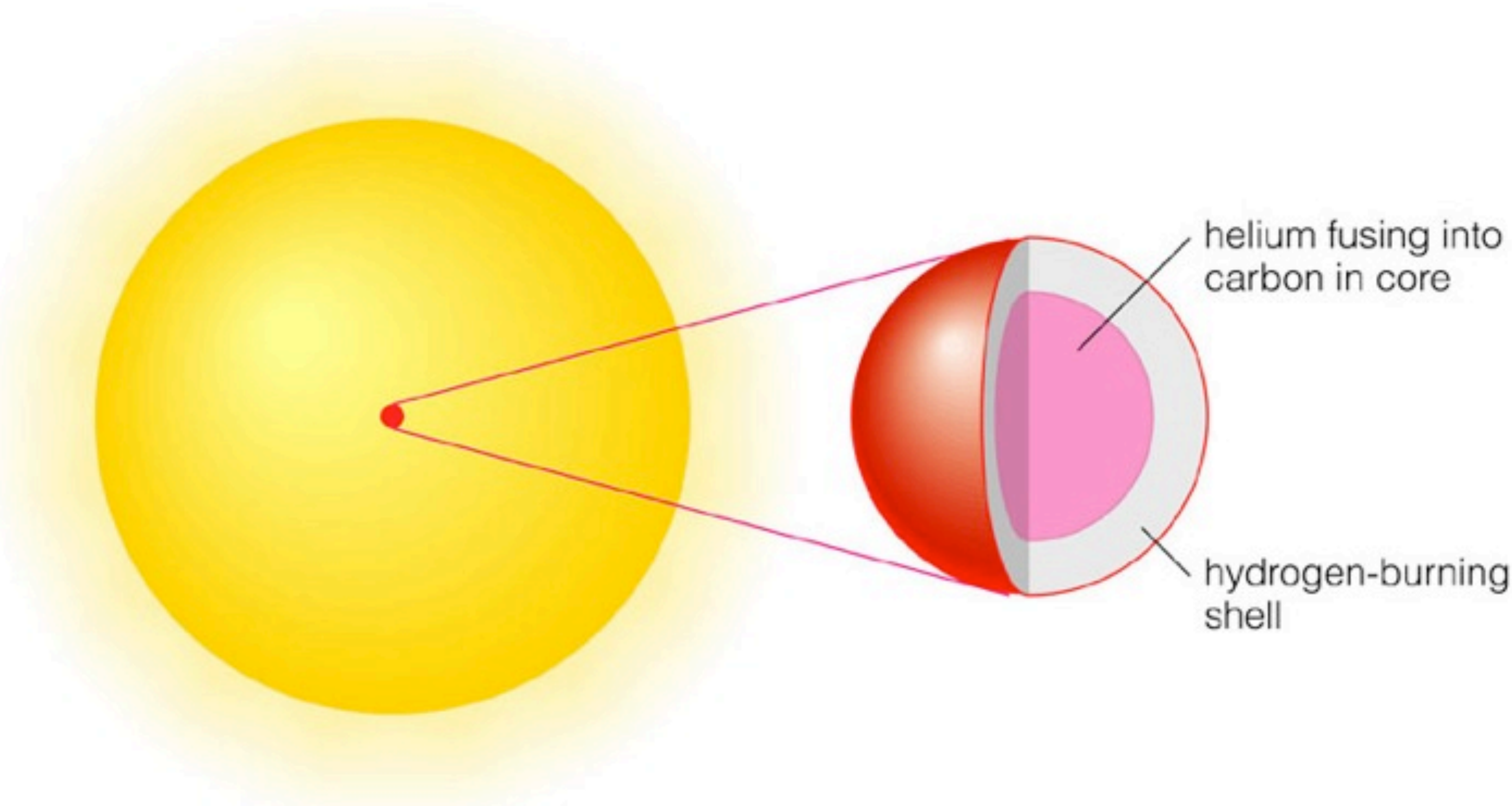

Helium burning stars reside for a brief time on the **Horizontal Branch**.

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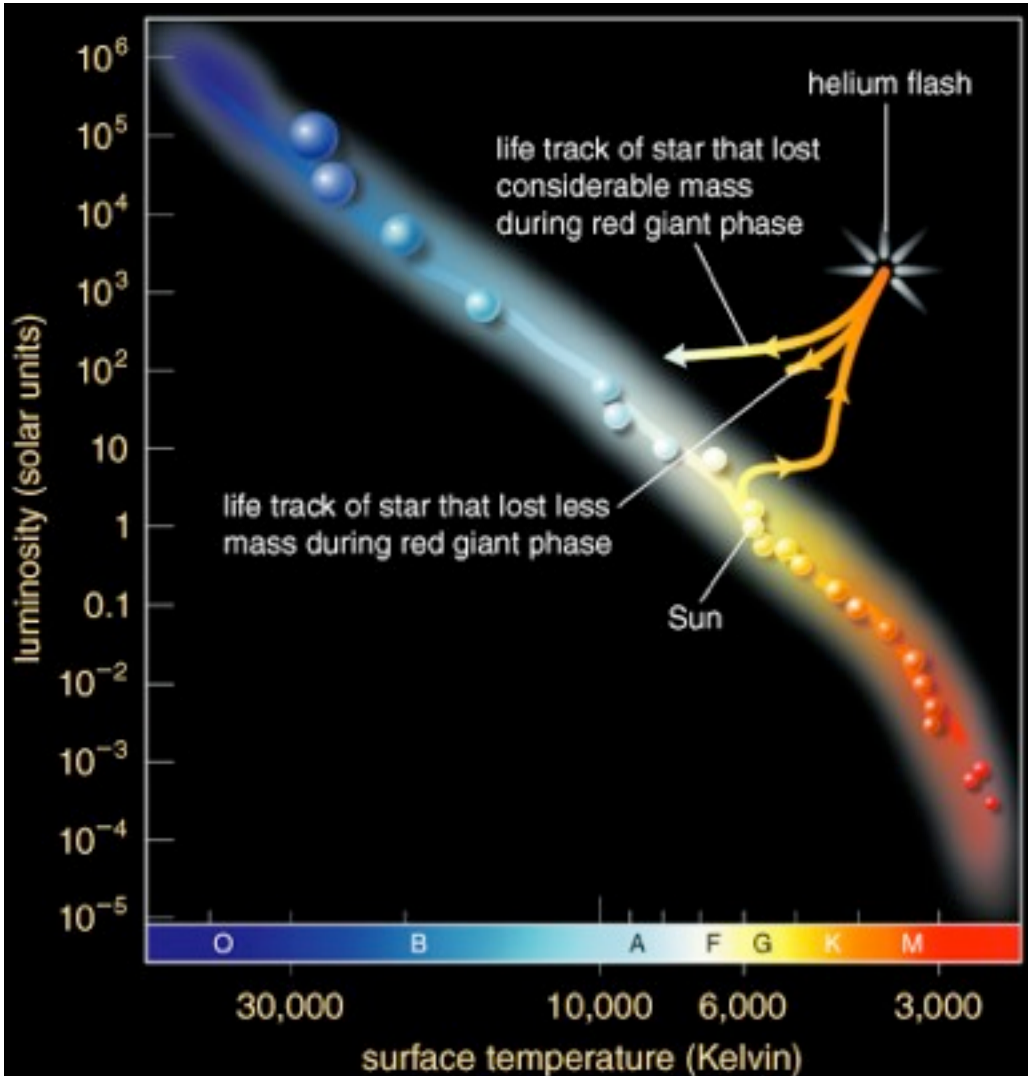
Life Track After Helium Flash



- Red giants shrink and become less luminous after helium fusion begins in the core.

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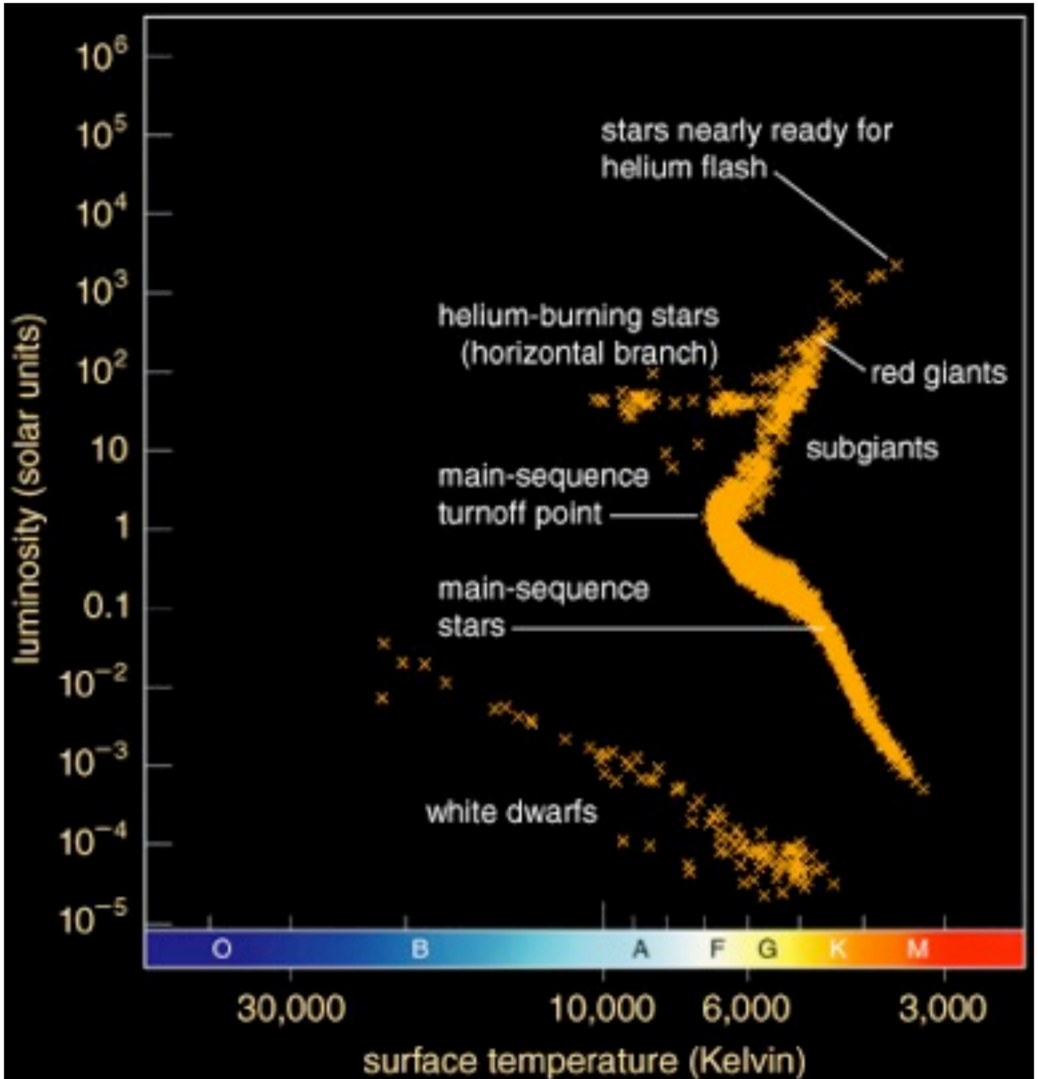
Life Track After Helium Flash



- Helium-burning stars are found in a *horizontal branch* on the H-R diagram.

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Double-Shell Burning

- Helium also gets used up. He continues to fuse into carbon in a shell around the carbon core, and H fuses to He in a shell around the helium layer.

- The star expands again, ascending the **Asymptotic Giant Branch**

- This double-shell-burning stage never reaches equilibrium—the fusion rate periodically spikes upward in a series of *thermal pulses*.

- With each spike, some of the outer layers may be lost to space.

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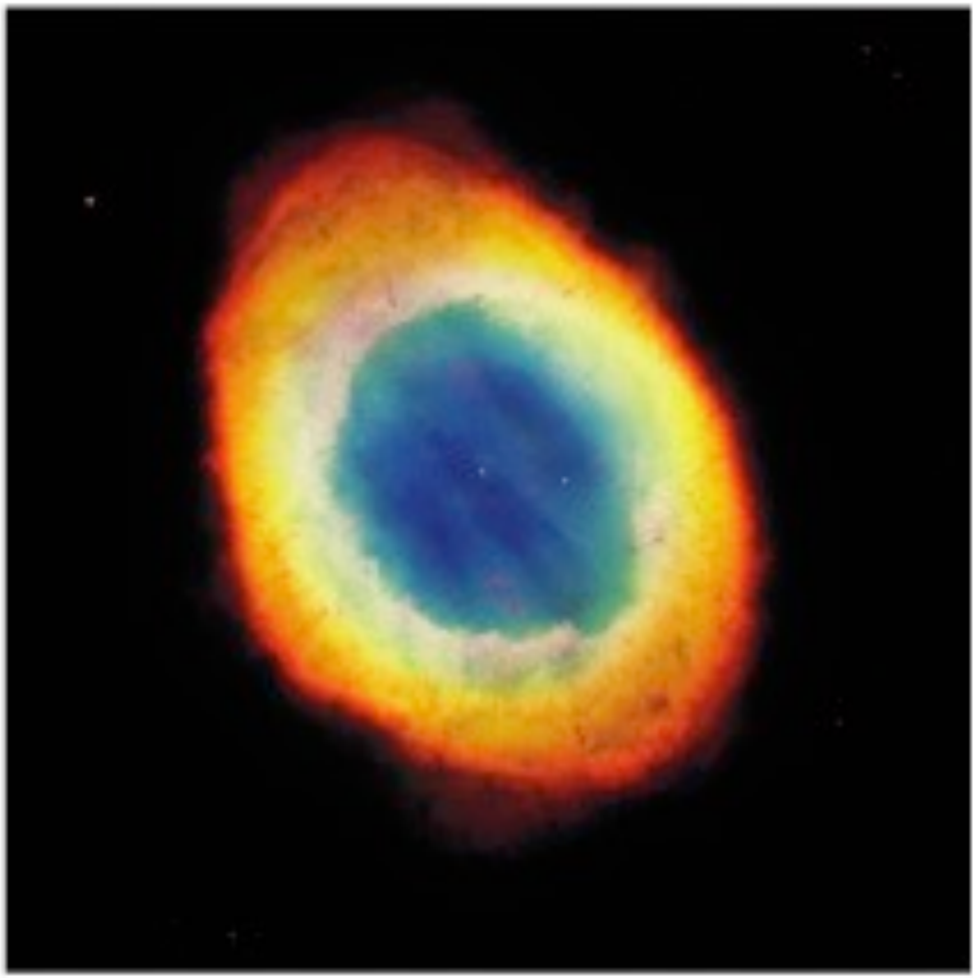
Planetary Nebulae



- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*.
- The core left behind becomes a white dwarf.

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End of Fusion

- Fusion progresses no further in a low-mass star because the core temperature never grows hot enough for fusion of heavier elements (some He fuses to C to make oxygen).

- Degeneracy pressure supports the white dwarf against gravity.

- White dwarf spend eternity cooling off, eventually going dark entirely.

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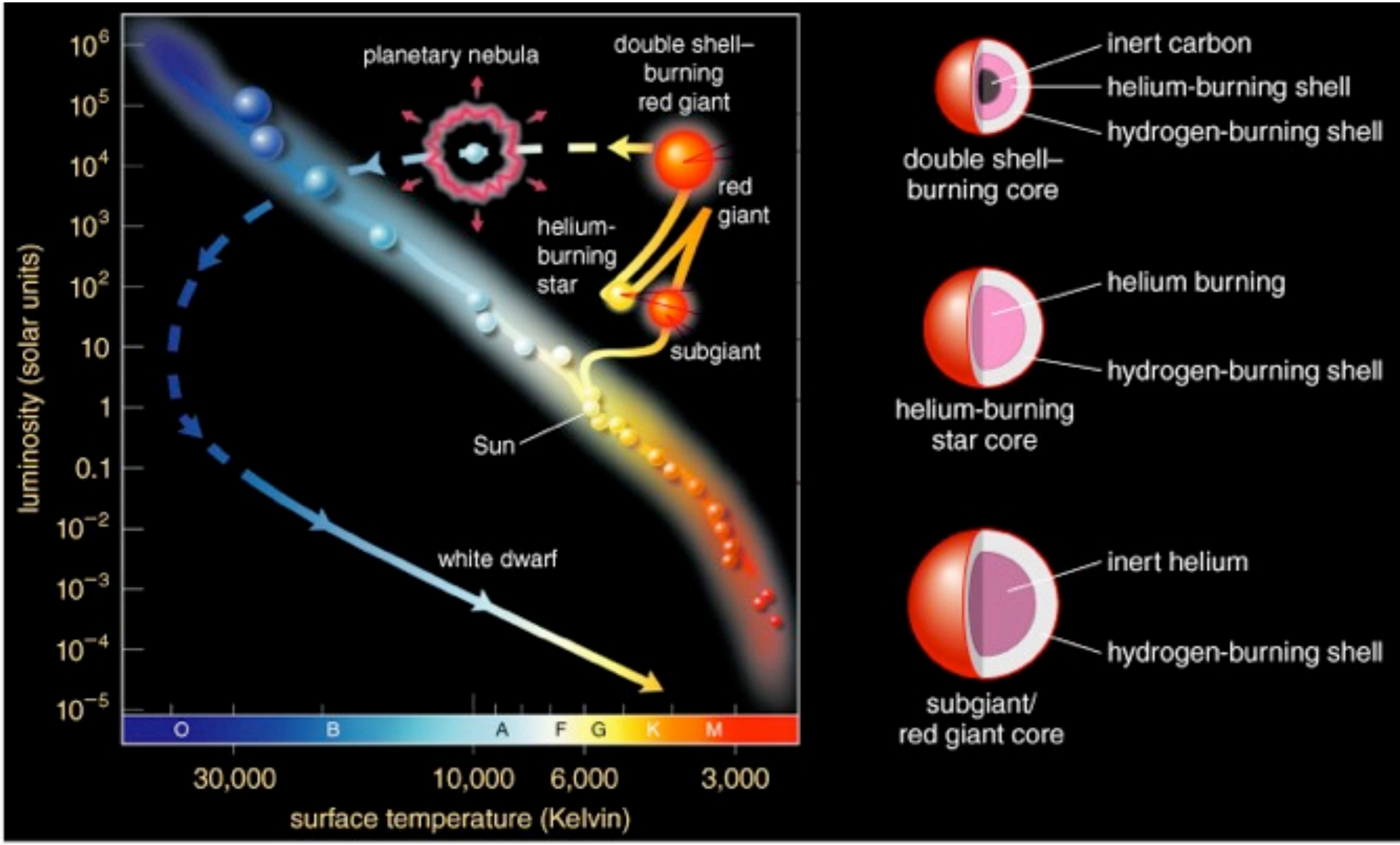
Life Track of a Sun-Like Star



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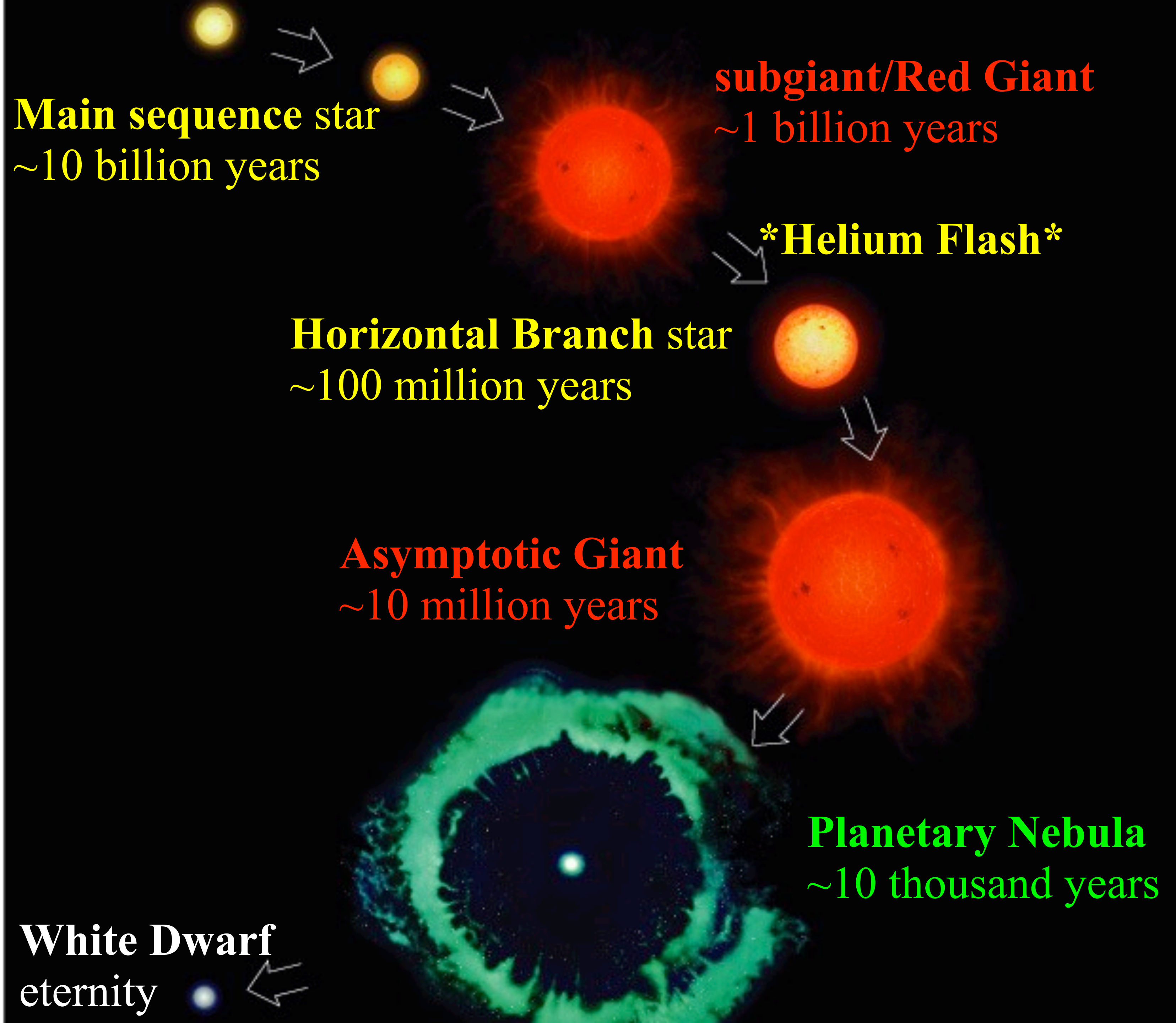
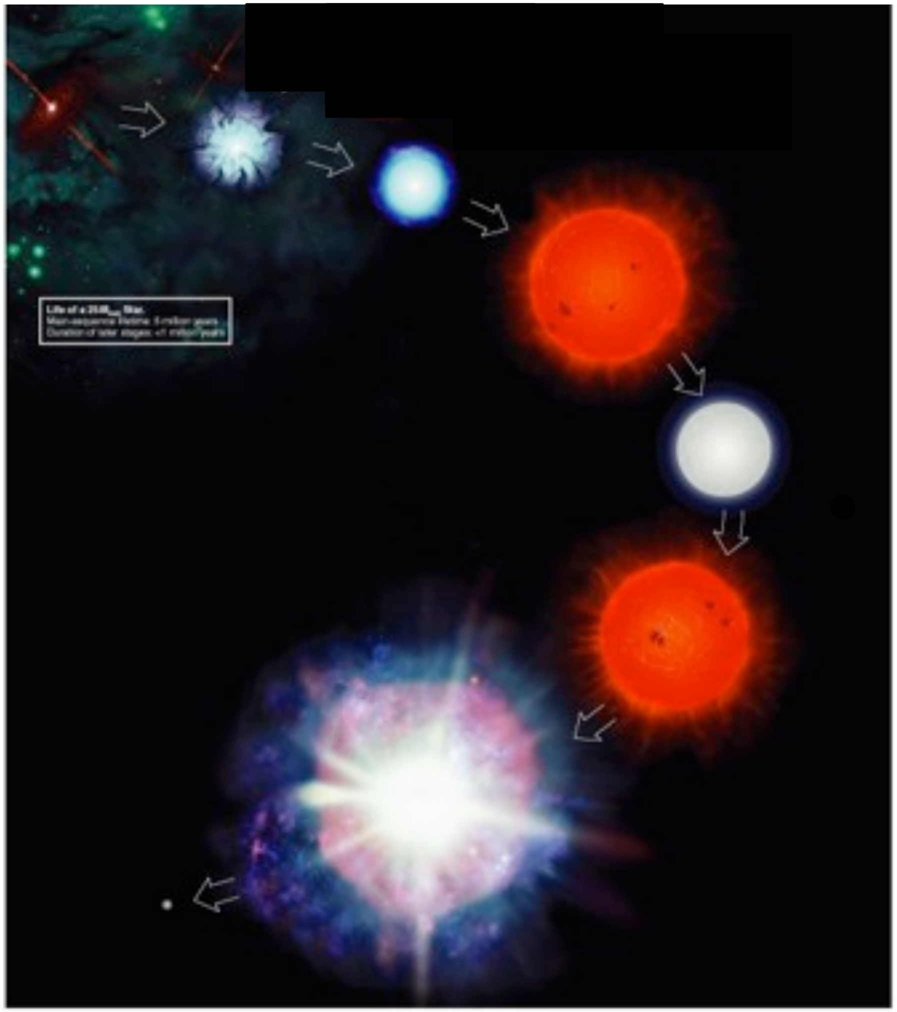
Life story of a solar mass star



The evolution of high-mass stars



$M > 8M_{\text{Sun}}$

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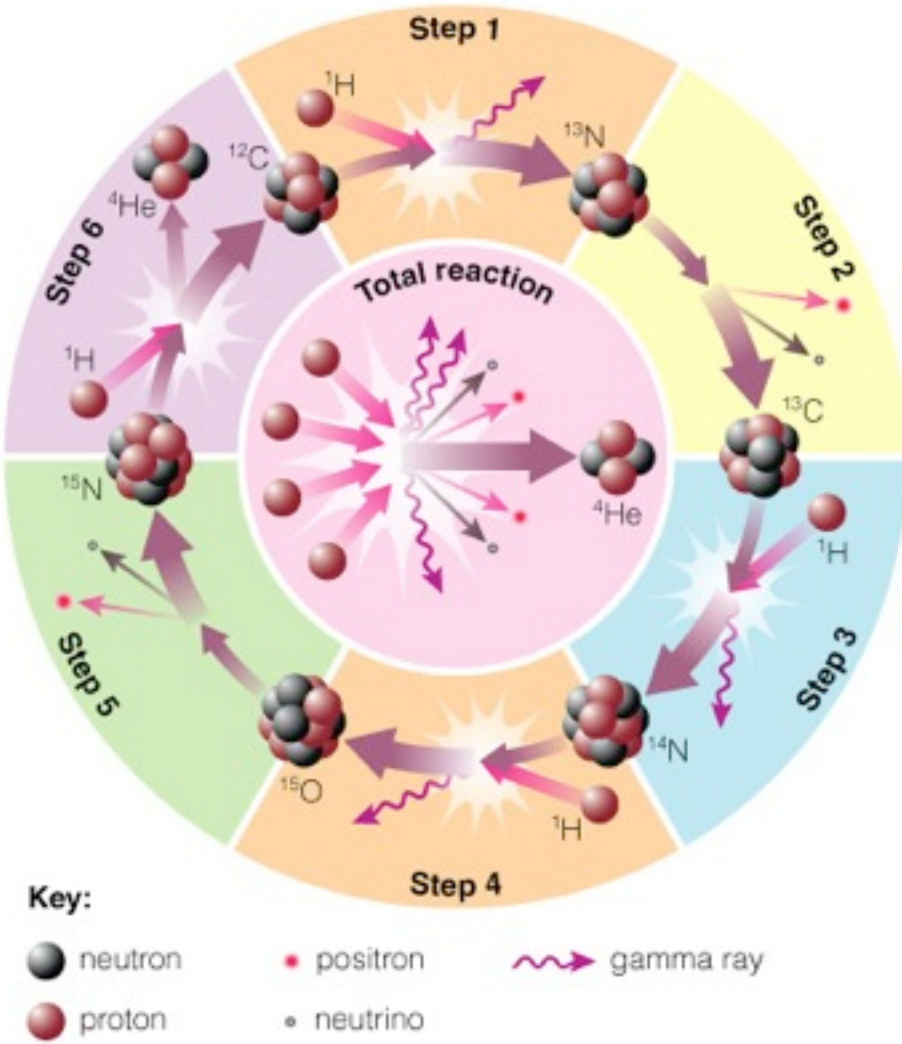
CNO Cycle



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- High-mass main-sequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as catalysts.
- The CNO cycle is more efficient than the proton-proton chain in stars more massive than 1.5 solar masses.

Life Stages of High-Mass Stars

- Late life stages of high-mass stars are similar to those of low-mass stars:
  - —Hydrogen core fusion (main sequence)
  - —Hydrogen shell burning (supergiant)
  - —Helium core fusion (supergiant)

  - —Etc:
    - —more stages of nuclear burning as well
    - —C, O, Ne, Mg, Si, all the way up to Fe (iron)

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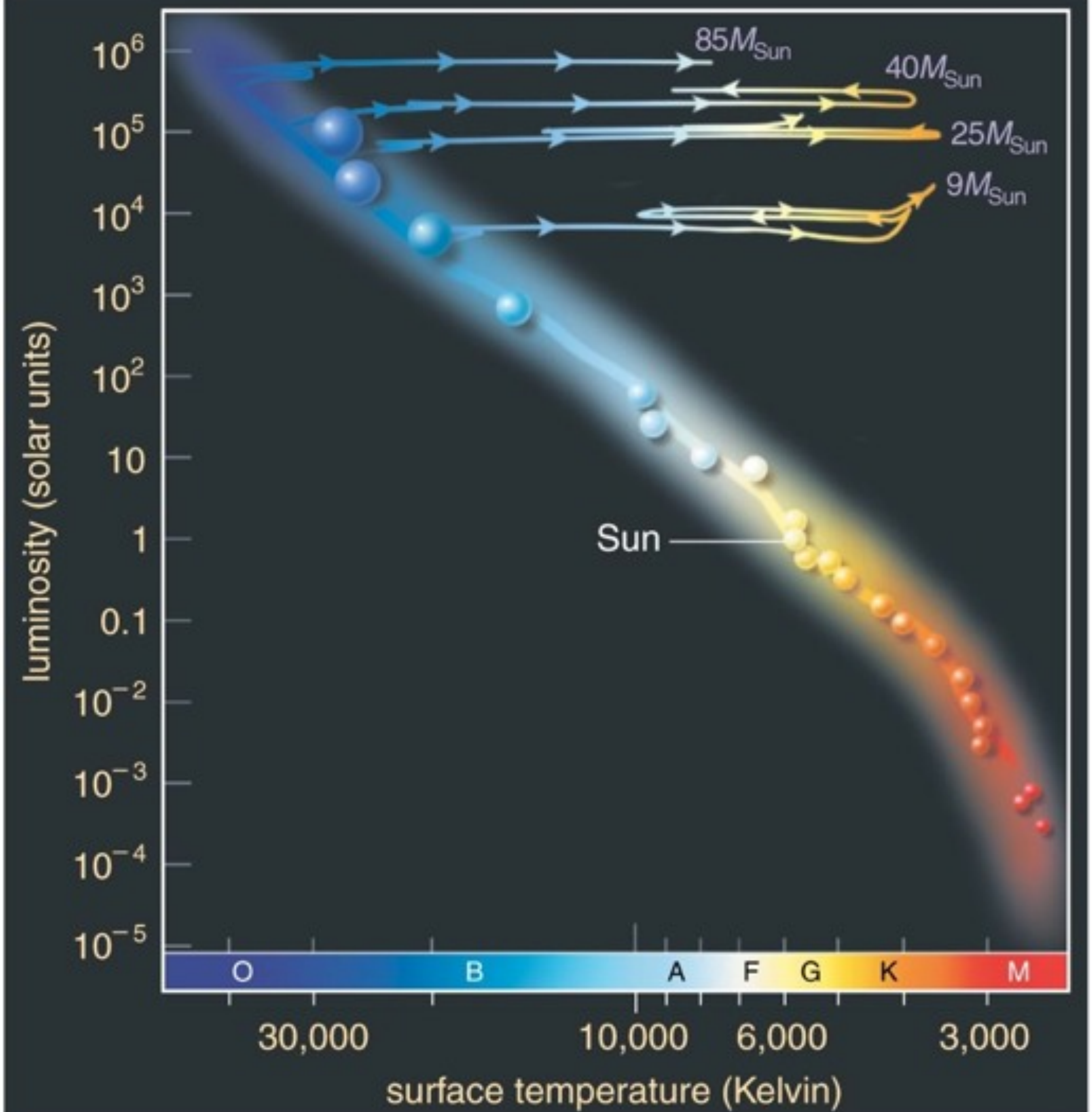

Supergiants

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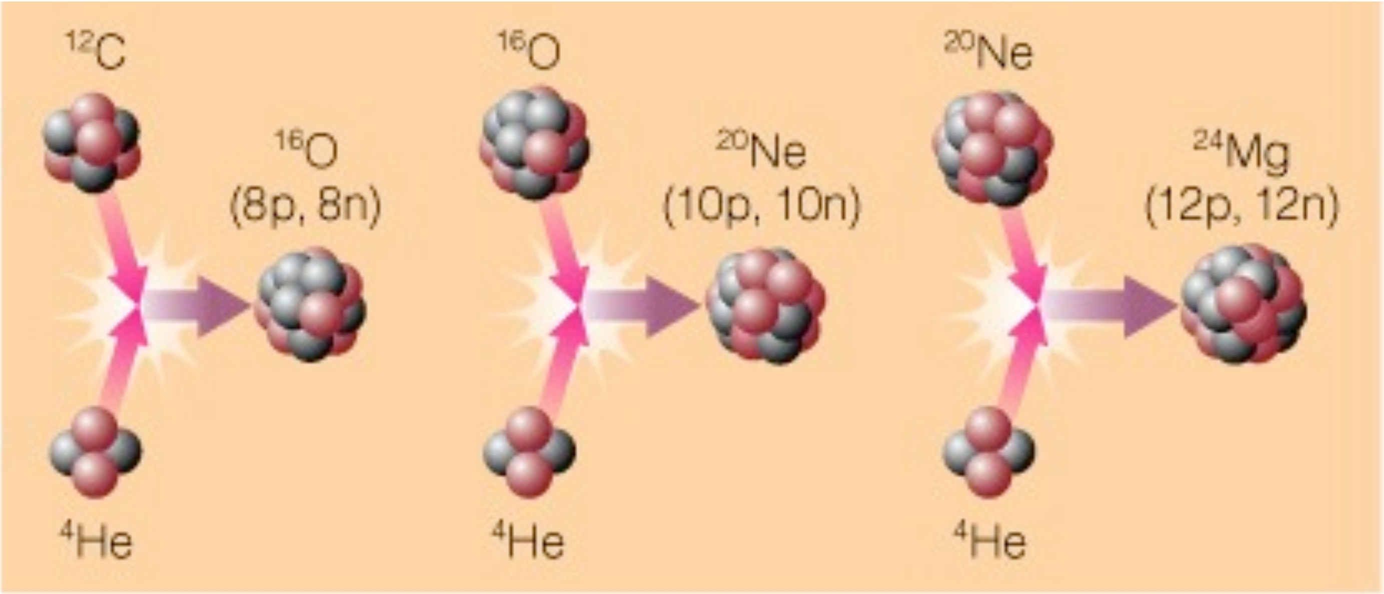
High mass stars make the elements necessary for life



The oxygen and heavier elements in our bodies were made in the nuclear furnace of high mass stars.

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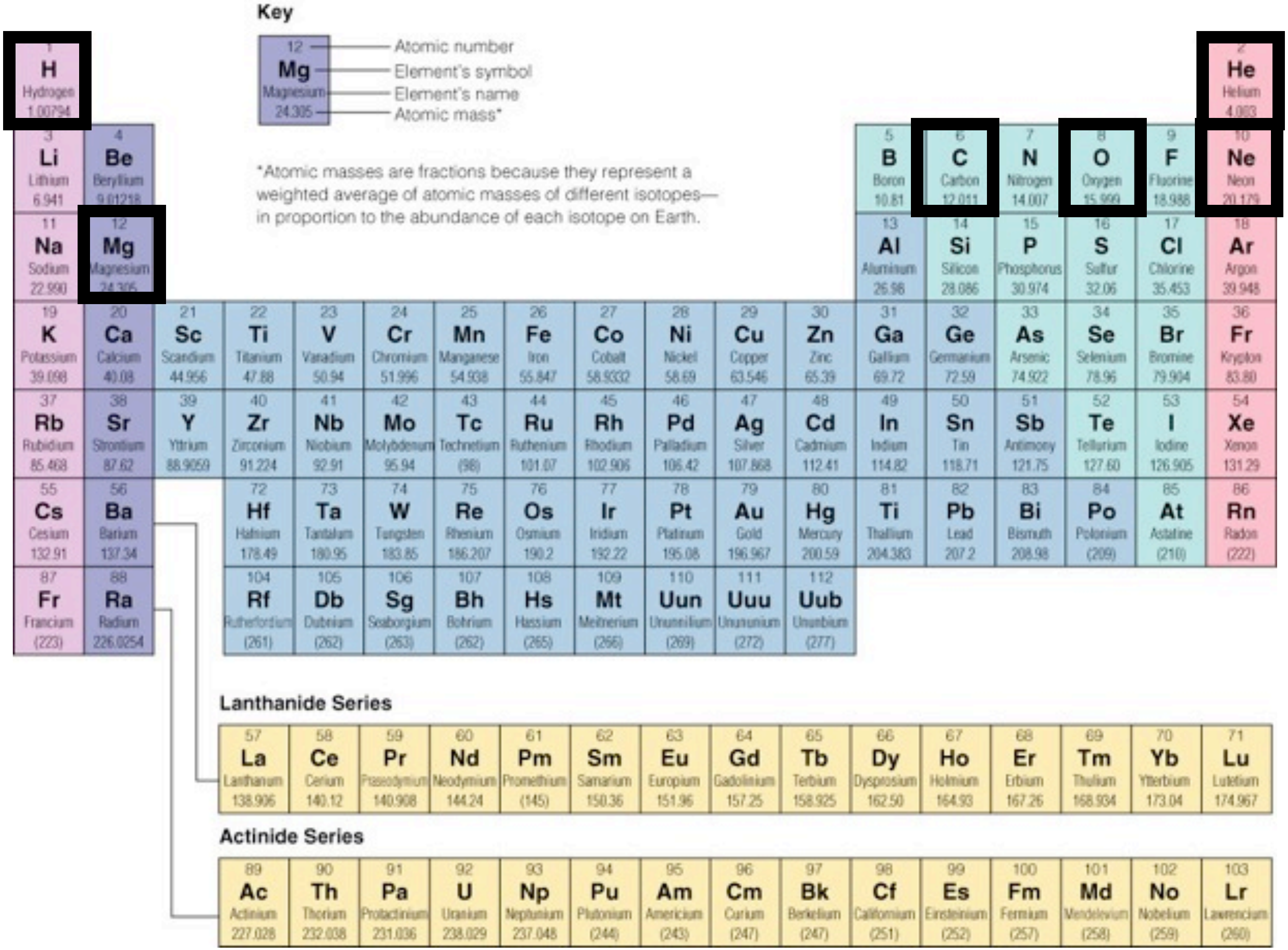

Helium capture builds C into O, Ne, Mg …

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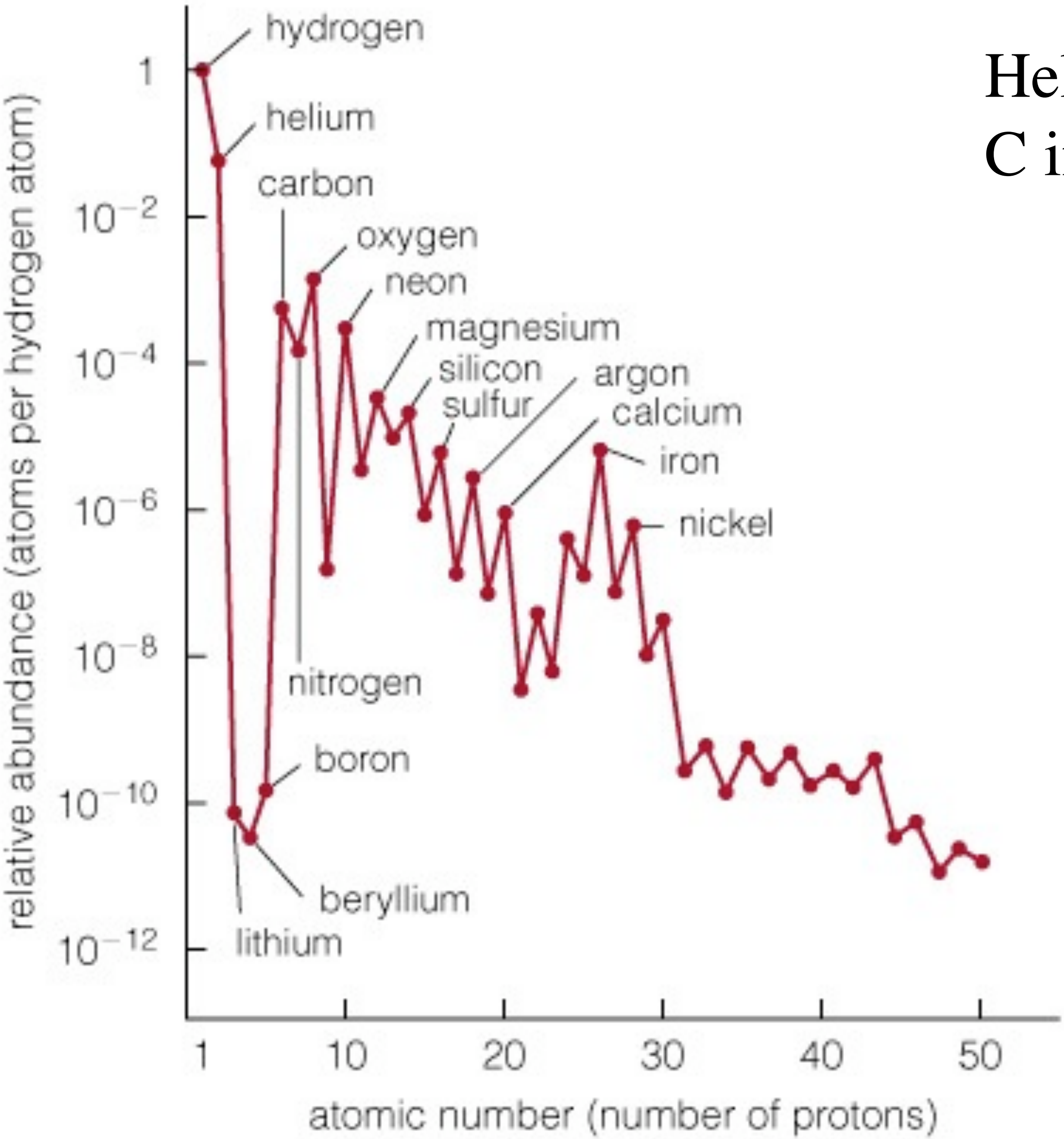

Helium capture builds C into O, Ne, Mg …

Results in a higher abundances of elements with an even numbers of protons -

“alpha elements”

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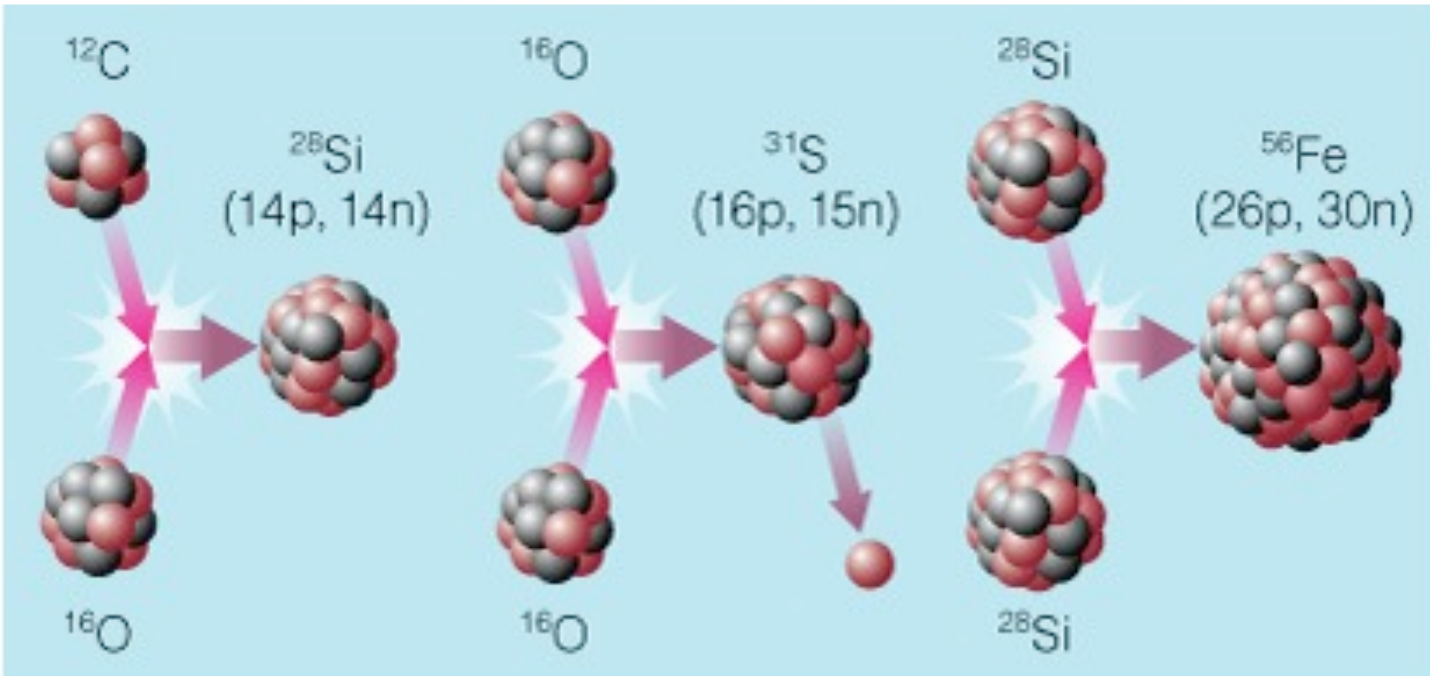
Advanced Nuclear Burning



- Core temperatures in stars with $>8M_{Sun}$ allow fusion of elements as heavy as iron.

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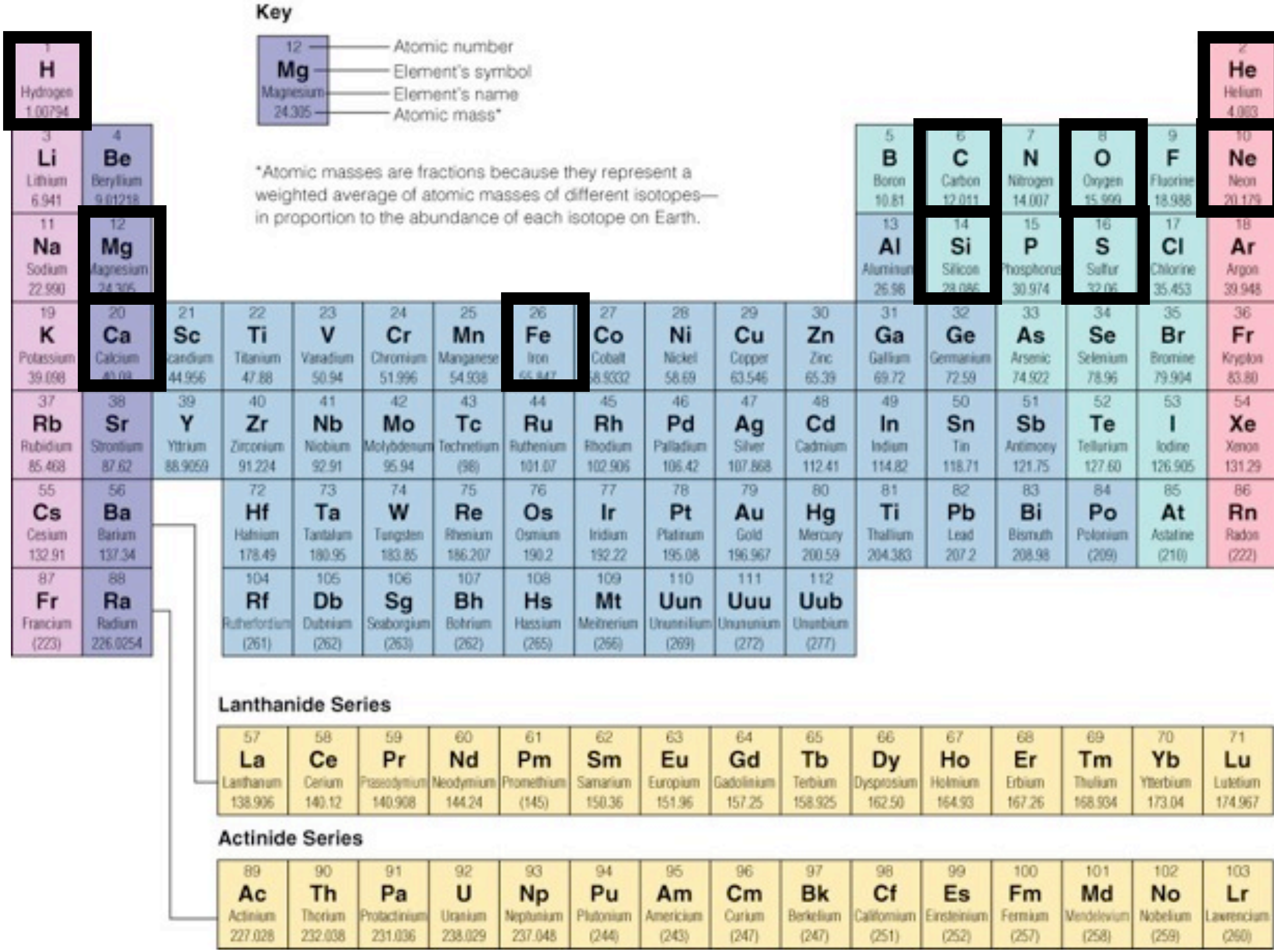

Advanced reactions in stars make elements like Si, S, Ca, and Fe.

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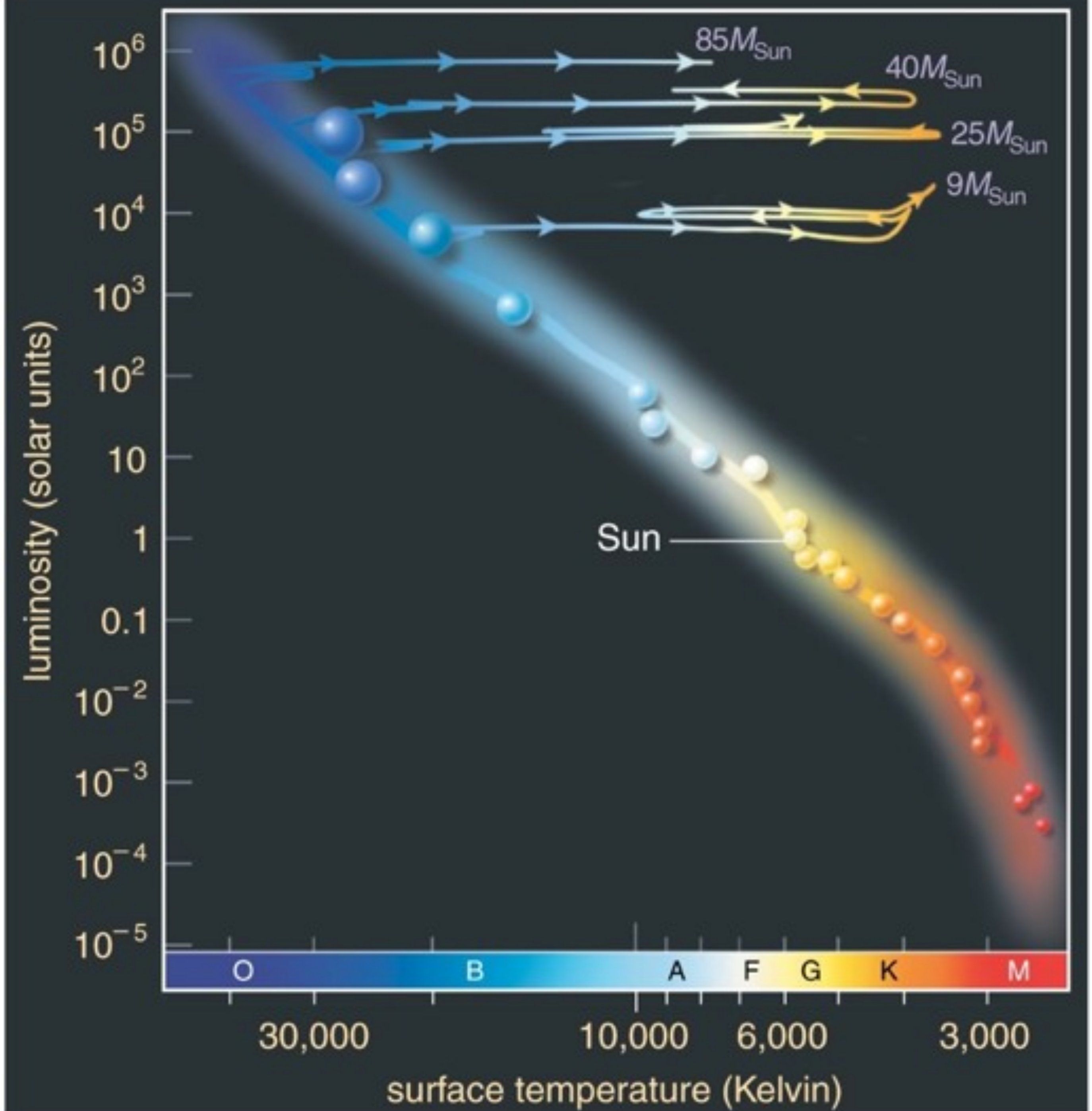

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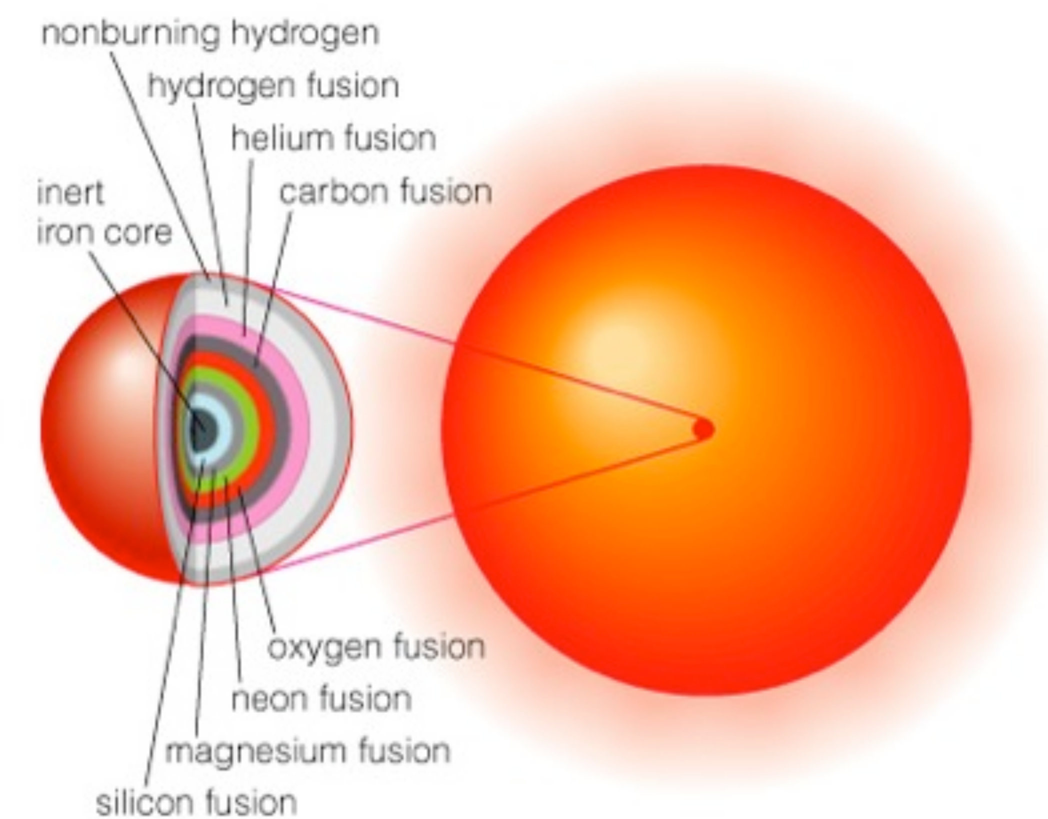
Supergiants

can get a wiggle in evolutionary track as each fuel supply is exhausted.

Evolution very rapid - massive stars live "only" millions of years

Multiple-Shell Burning



- Advanced nuclear burning proceeds in a series of nested shells.
- Core of high mass (> $8M_{sun}$) near the end of its life

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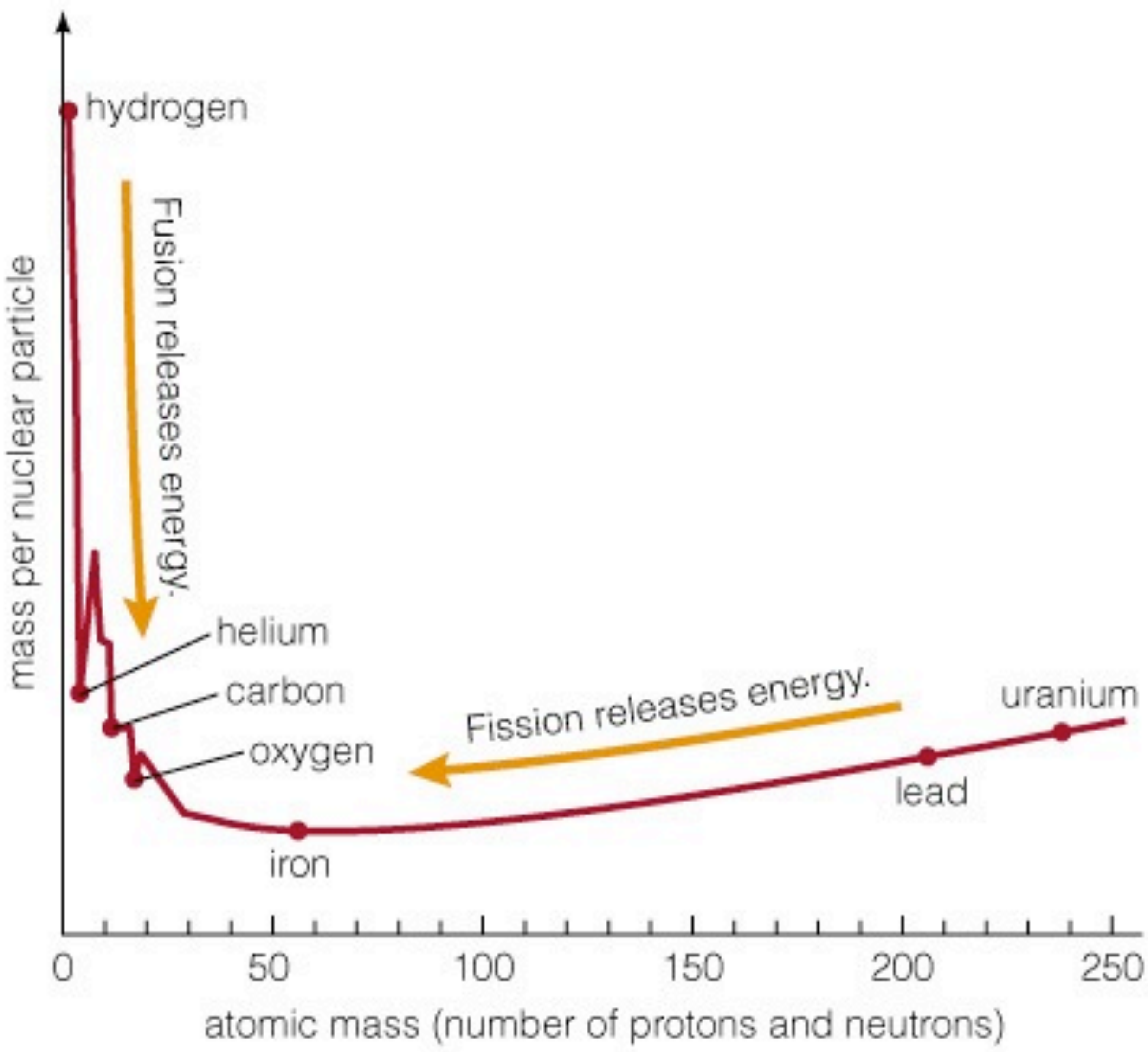

Iron is a dead end for fusion because nuclear reactions involving iron do not release energy.

(Fe has lowest mass per nuclear particle.)

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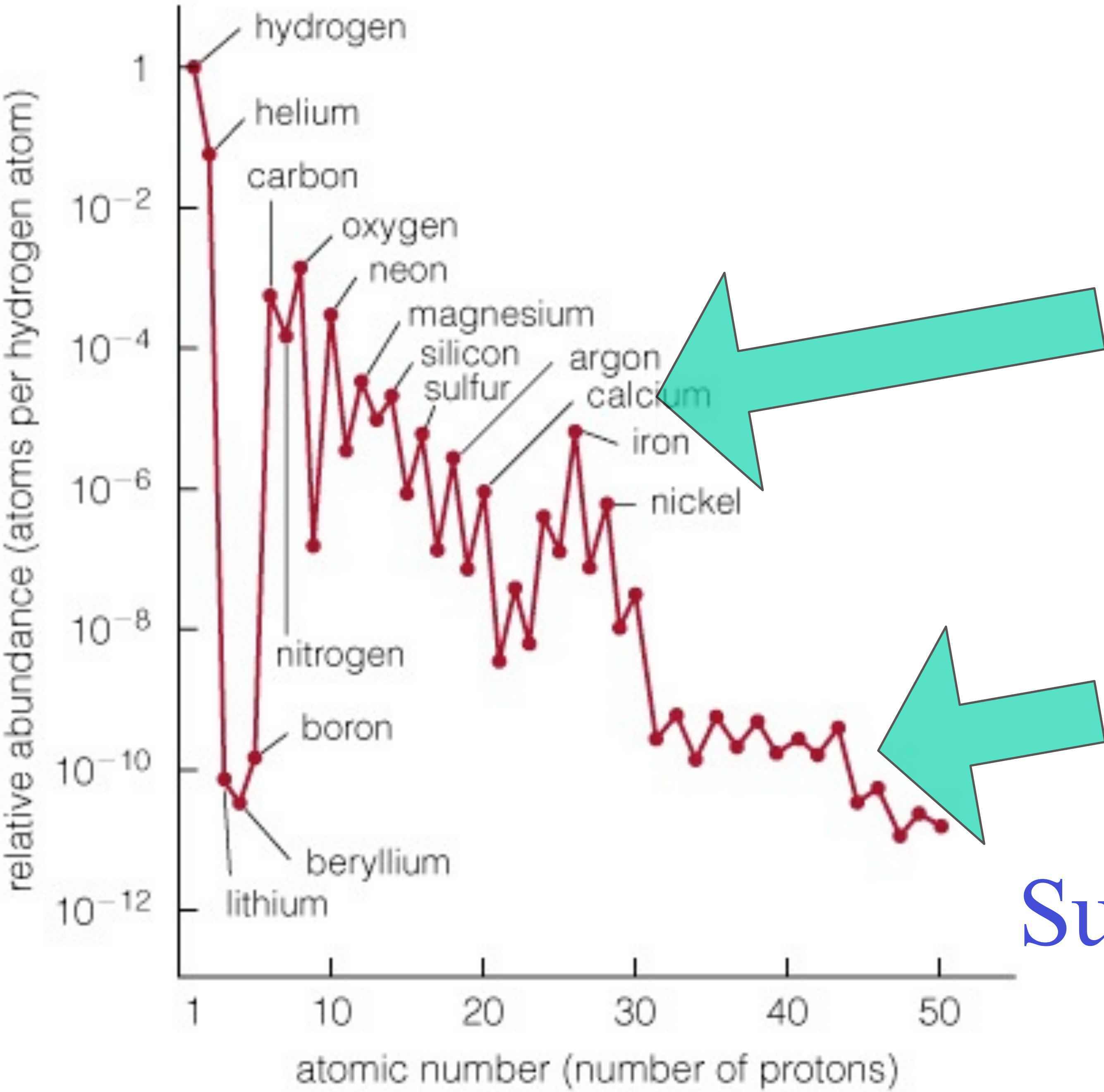

Iron peak

Where do elements heavier than iron come from?

Supernovae!

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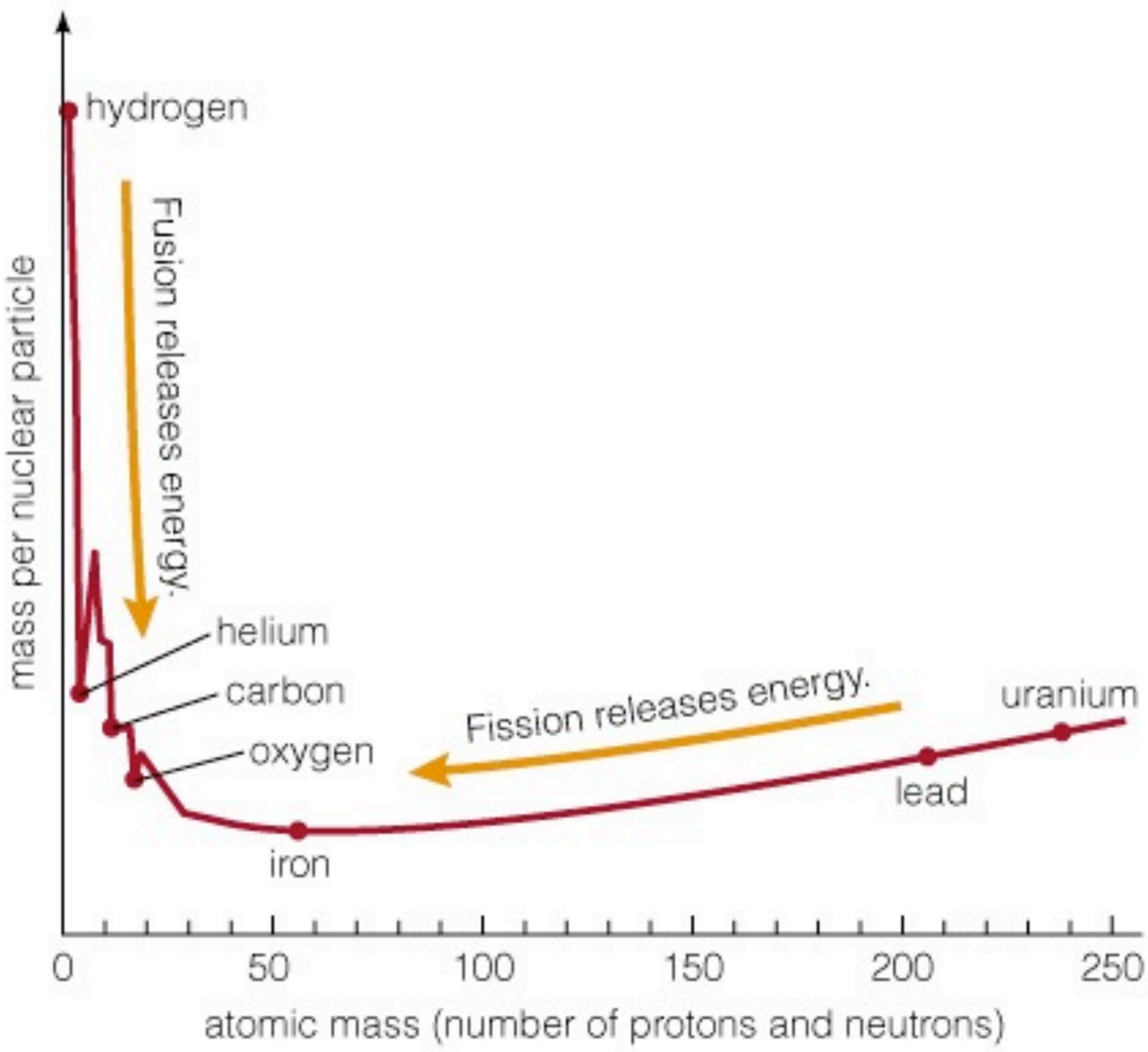

Iron is the ultimate ash.

With nothing left to support it, the core collapses and the outer parts explode, carrying elements into space.

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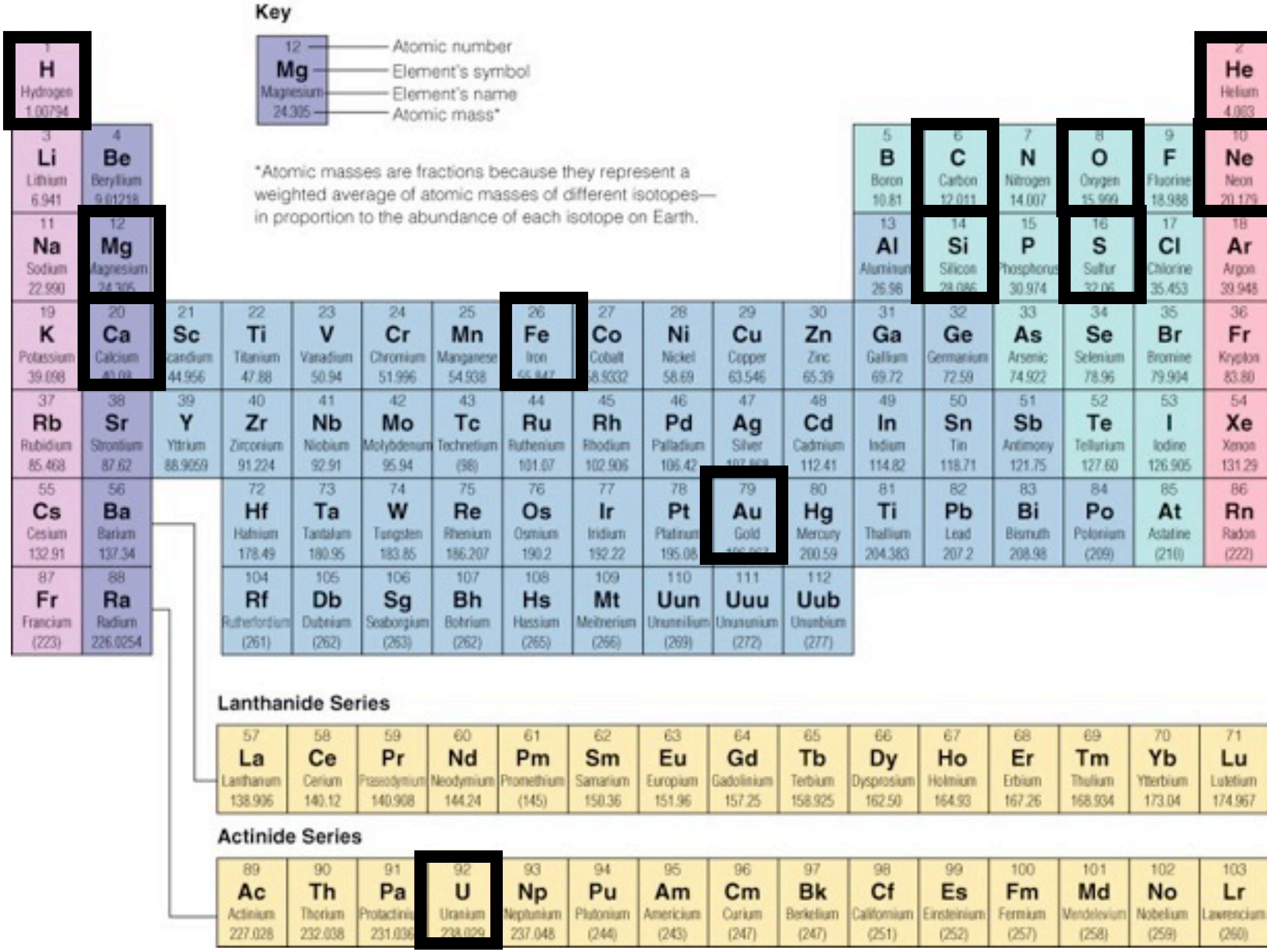

Energy and neutrons released in a supernova explosion enable elements heavier than iron to form, including Au (gold) and Uranium.

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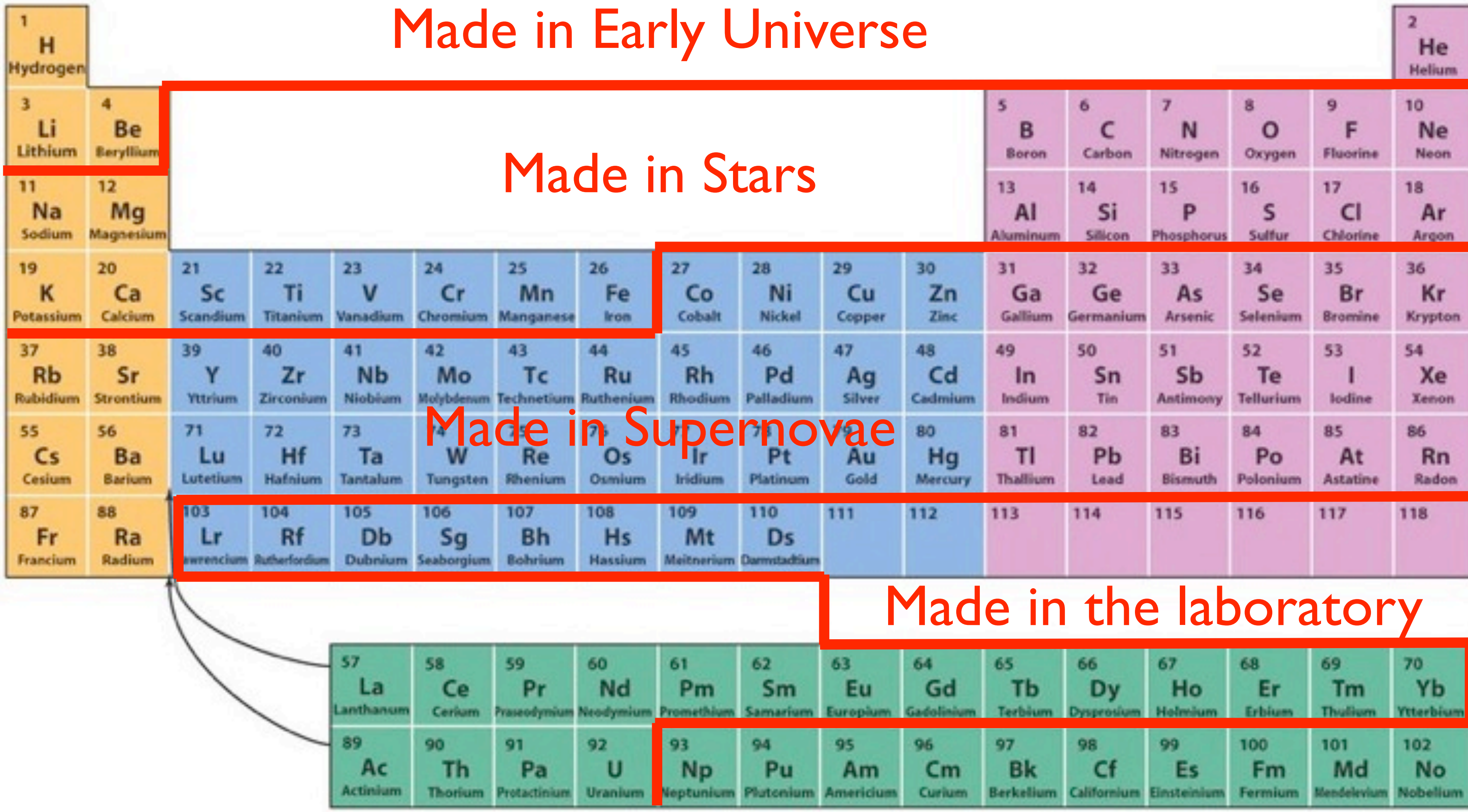
Made in Early Universe
Made in Stars
Made in Supernovae
Made in the laboratory
1 H Hydrogen
2 He Helium
3 Li Lithium
4 Be Beryllium
5 B Boron
6 C Carbon
7 N Nitrogen
8 O Oxygen
9 F Fluorine
10 Ne Neon
11 Na Sodium
12 Mg Magnesium
13 Al Aluminum
14 Si Silicon
15 P Phosphorus
16 S Sulfur
17 Cl Chlorine
18 Ar Argon
19 K Potassium
20 Ca Calcium
21 Sc Scandium
22 Ti Titanium
23 V Vanadium
24 Cr Chromium
25 Mn Manganese
26 Fe Iron
27 Co Cobalt
28 Ni Nickel
29 Cu Copper
30 Zn Zinc
31 Ga Gallium
32 Ge Germanium
33 As Arsenic
34 Se Selenium
35 Br Bromine
36 Kr Krypton
37 Rb Rubidium
38 Sr Strontium
39 Y Yttrium
40 Zr Zirconium
41 Nb Niobium
42 Mo Molybdenum
43 Tc Technetium
44 Ru Ruthenium
45 Rh Rhodium
46 Pd Palladium
47 Ag Silver
48 Cd Cadmium
49 In Indium
50 Sn Tin
51 Sb Antimony
52 Te Tellurium
53 I Iodine
54 Xe Xenon
55 Cs Cesium
56 Ba Barium
71 Lu Lutetium
72 Hf Hafnium
73 Ta Tantalum
W Tungsten
Re Rhenium
Os Osmium
Ir Iridium
Pt Platinum
Au Gold
80 Hg Mercury
81 Tl Thallium
82 Pb Lead
83 Bi Bismuth
84 Po Polonium
85 At Astatine
86 Rn Radon
87 Fr Francium
88 Ra Radium
103 Lr awrencium
104 Rf Rutherfordium
105 Db Dubnium
106 Sg Seaborgium
107 Bh Bohrium
108 Hs Hassium
109 Mt Meitnerium
110 Ds Darmstadtium
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57 La Lanthanum
58 Ce Cerium
59 Pr Praseodymium
60 Nd Neodymium
61 Pm Promethium
62 Sm Samarium
63 Eu Europium
64 Gd Gadolinium
65 Tb Terbium
66 Dy Dysprosium
67 Ho Holmium
68 Er Erbium
69 Tm Thulium
70 Yb Ytterbium
89 Ac Actinium
90 Th Thorium
91 Pa Protactinium
92 U Uranium
93 Np Neptunium
94 Pu Plutonium
95 Am Americium
96 Cm Curium
97 Bk Berkelium
98 Cf Californium
99 Es Einsteinium
100 Fm Fermium
101 Md Mendelevium
102 No Nobelium

Supernova Remnant

- Energy released by the collapse of the core drives outer layers into space.
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054.

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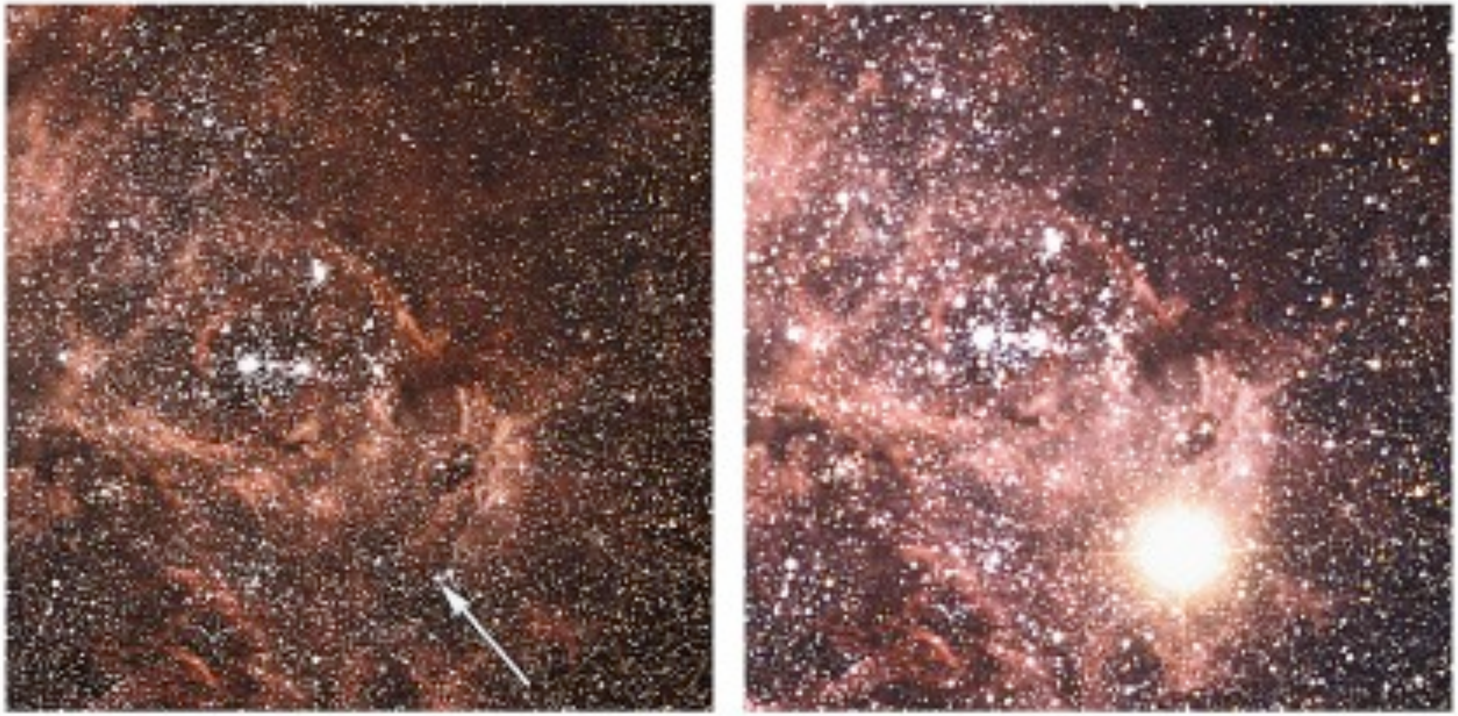
Supernova 1987A



- The closest supernova in the last four centuries was seen in 1987 in the LMC.
- who's next? Betelgeuse? eta Carina?

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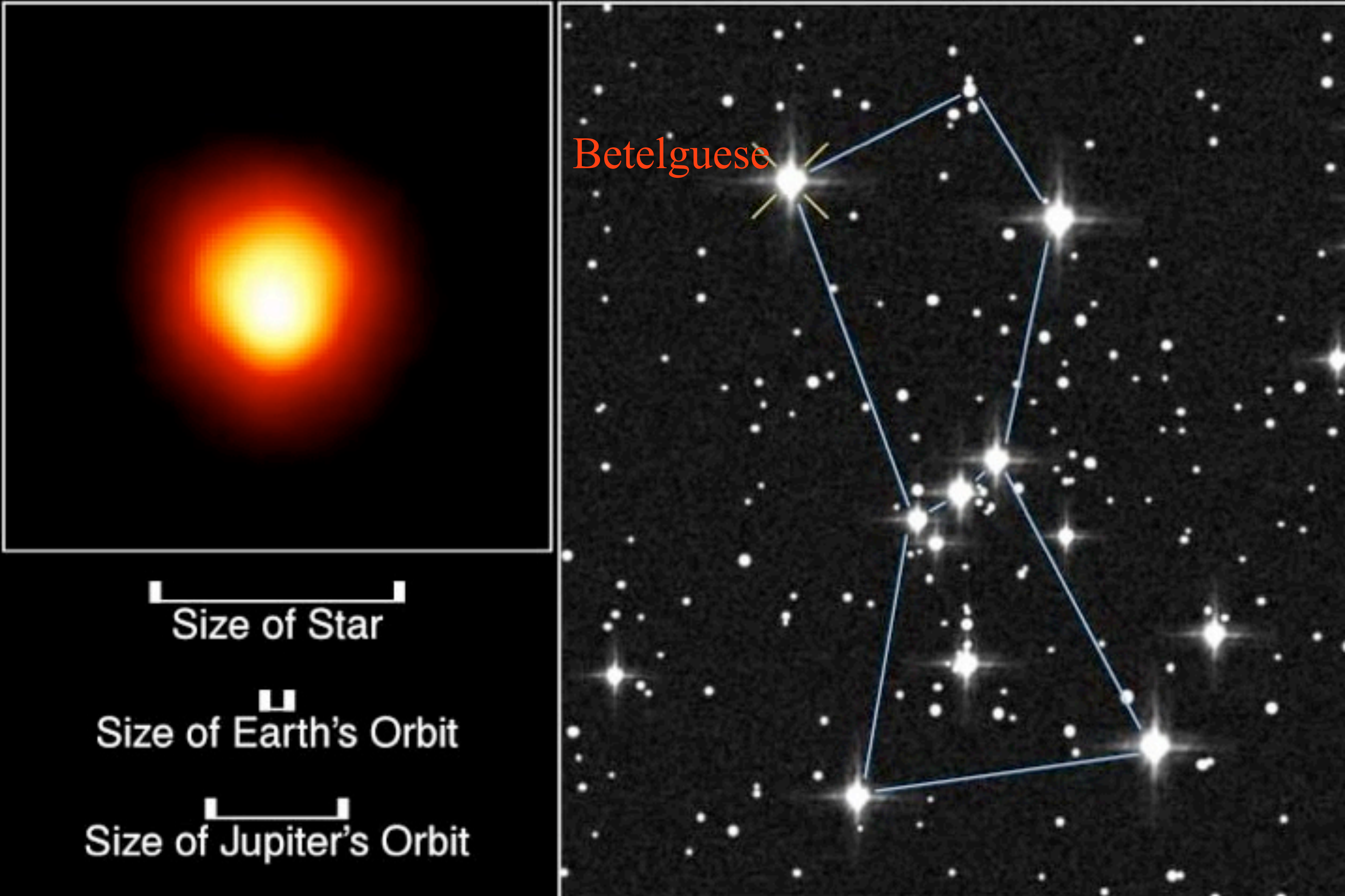
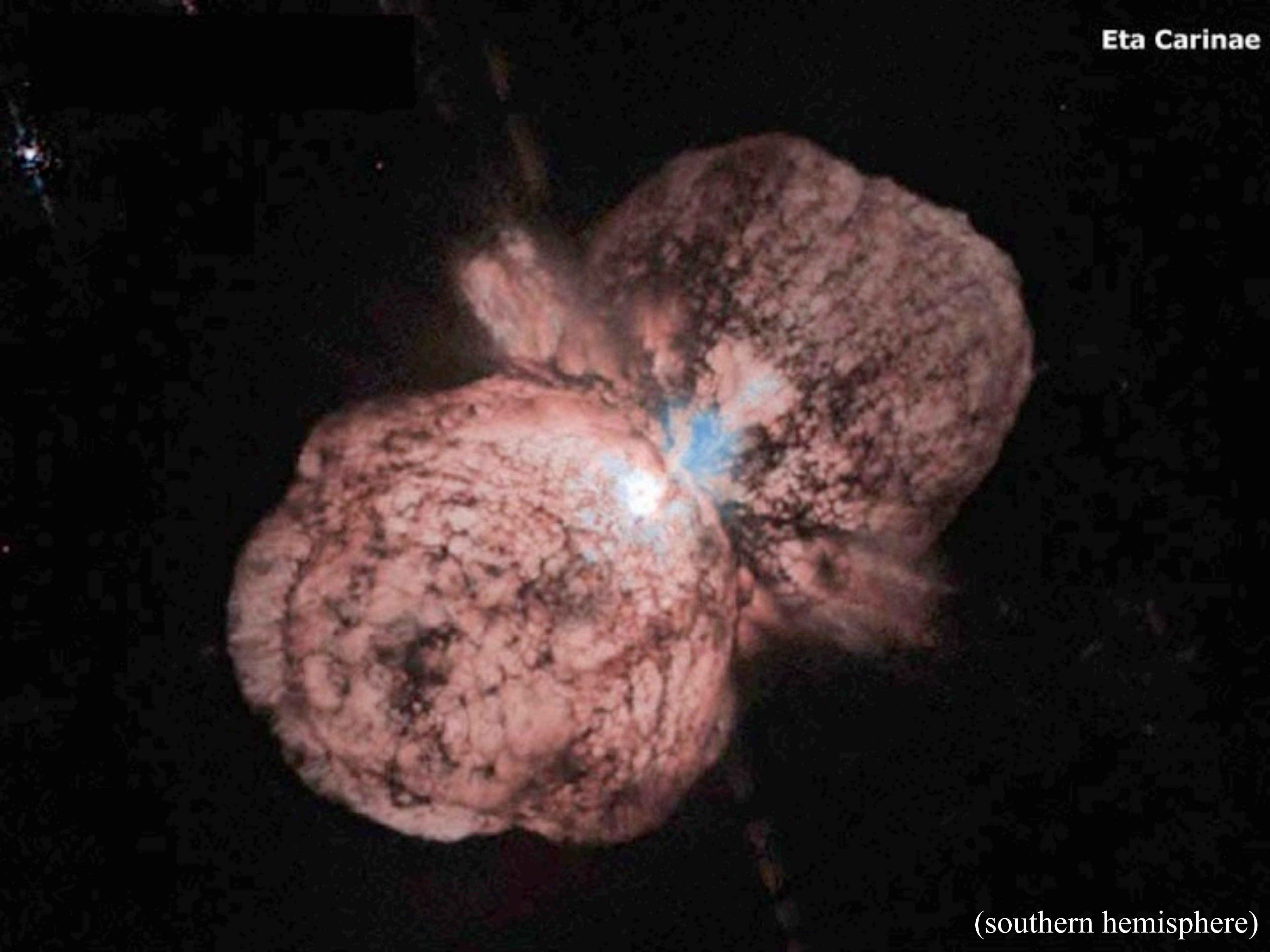


Atmosphere of Betelgeuse HST •

PRC96-04 • ST ScI OPO • January 15, 1995 • A. Dupree (CfA), NASA



(southern hemisphere)

Role of Mass

- A star's mass determines its entire life story because it determines its core temperature.
- High-mass stars have short lives, eventually becoming hot enough to make iron, and end in supernova explosions.
- Low-mass stars have long lives, never become hot enough to fuse beyond carbon nuclei, and end as white dwarfs.

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