# Today

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

# Another good job on exam!

- Class average was 71%
- Given the difficulty of the exam, this was an exceptional performance
  Between this and your previous exam, you are easily the best ASTR 100 class I've ever had
- Exams will be handed back in your sections

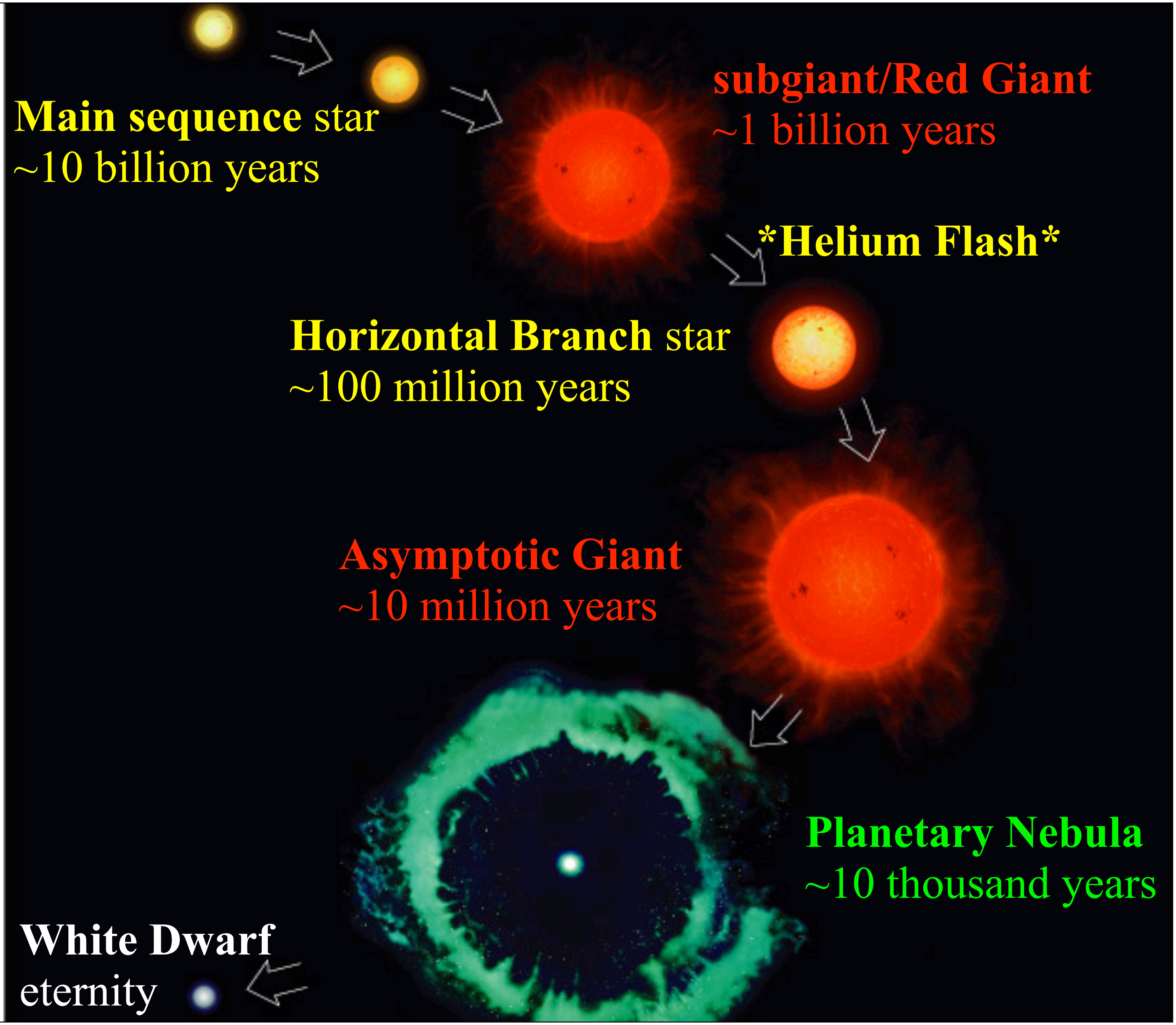
# Extra credit
# (2 points)

- What is the final state of a star like our Sun?

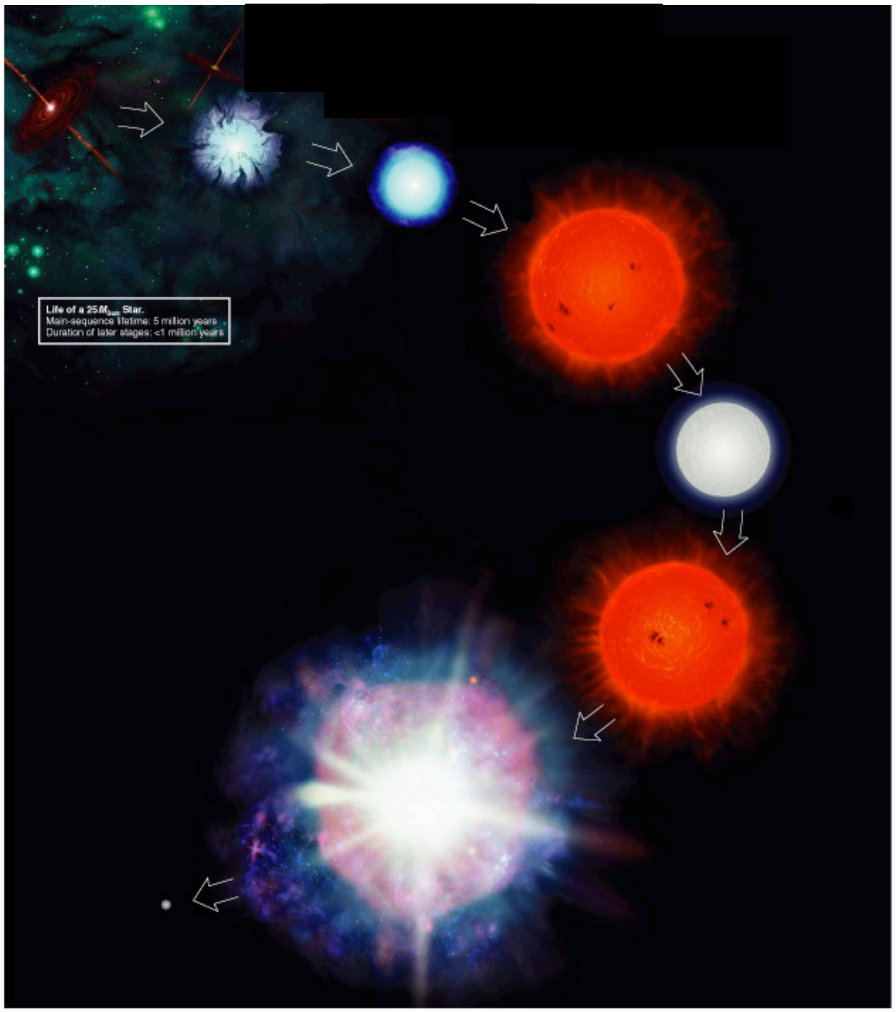
- Be sure to include your name and section number

- You may consult your notes, but do not communicate with anyone else

# Life story of a solar mass star



# The evolution of high-mass stars



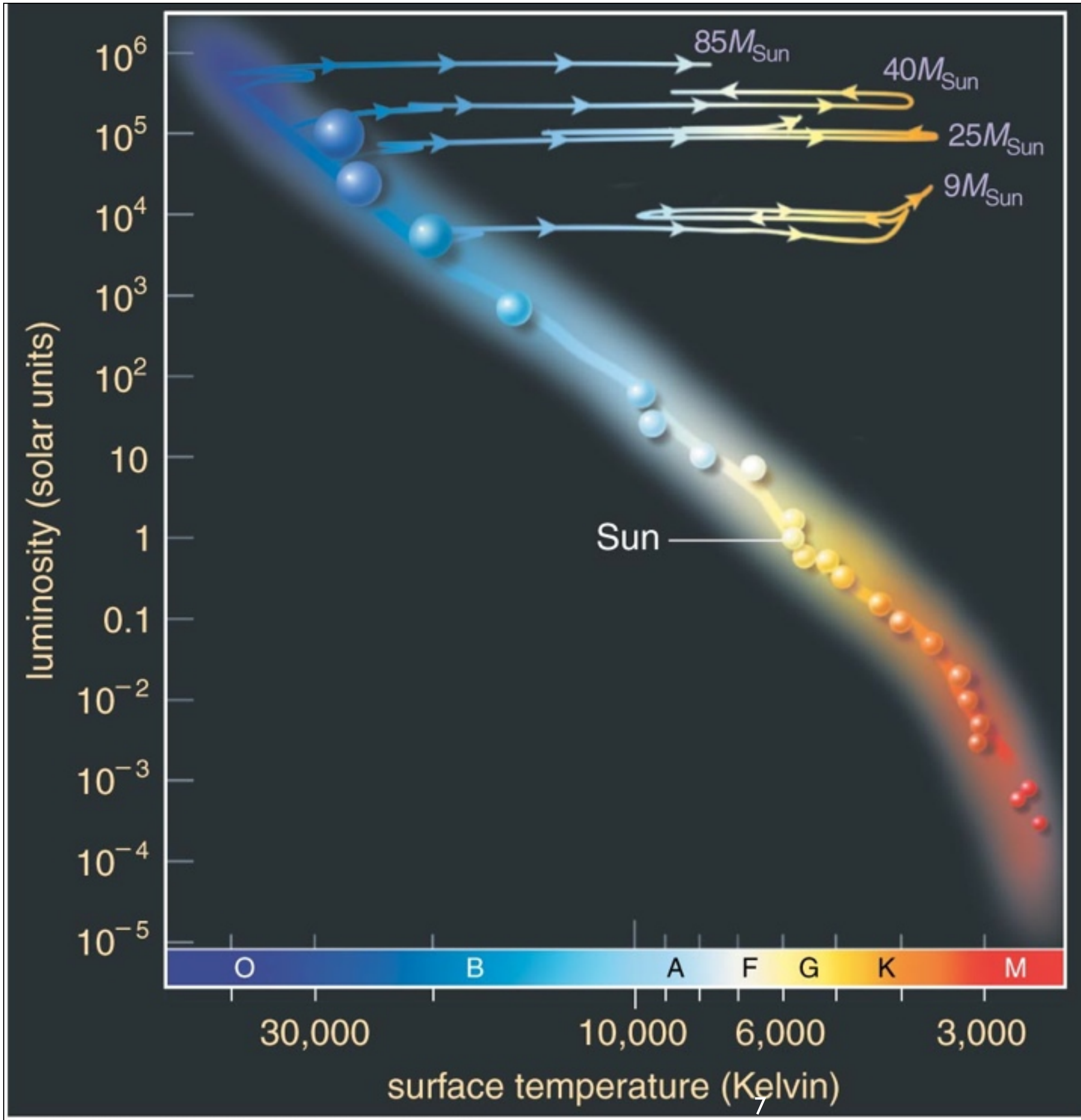

$M > 8M_{\text{Sun}}$

Life video

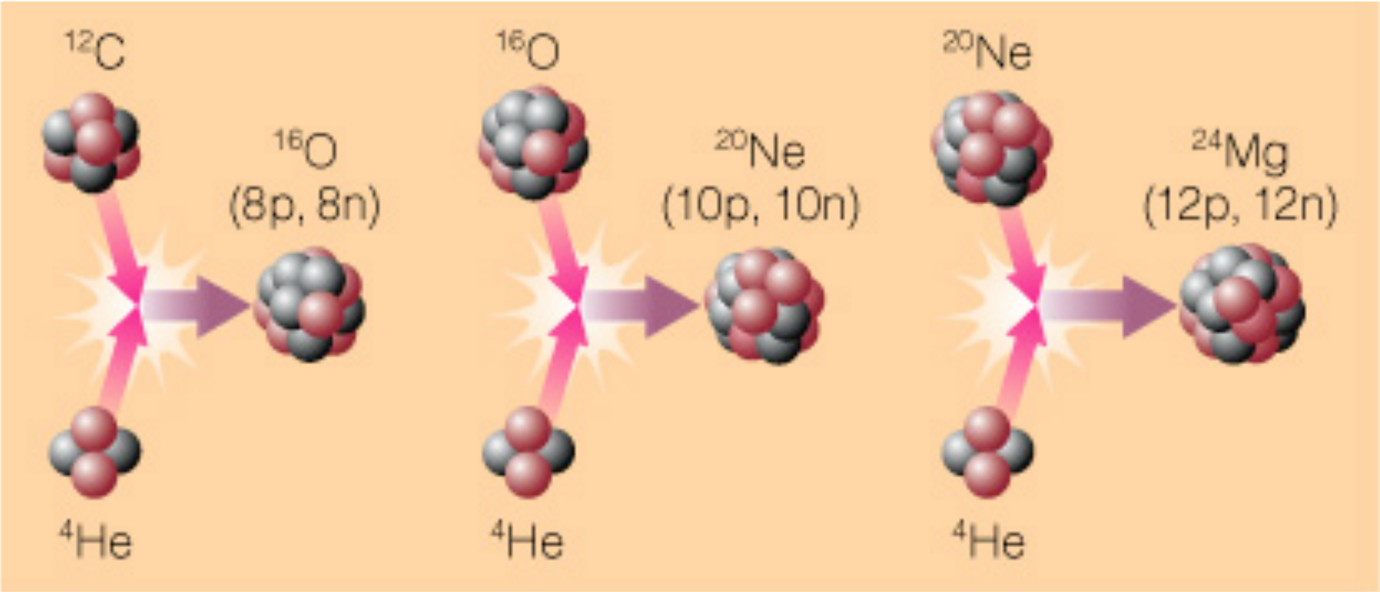
# Life Stages of High-Mass Stars

- 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)

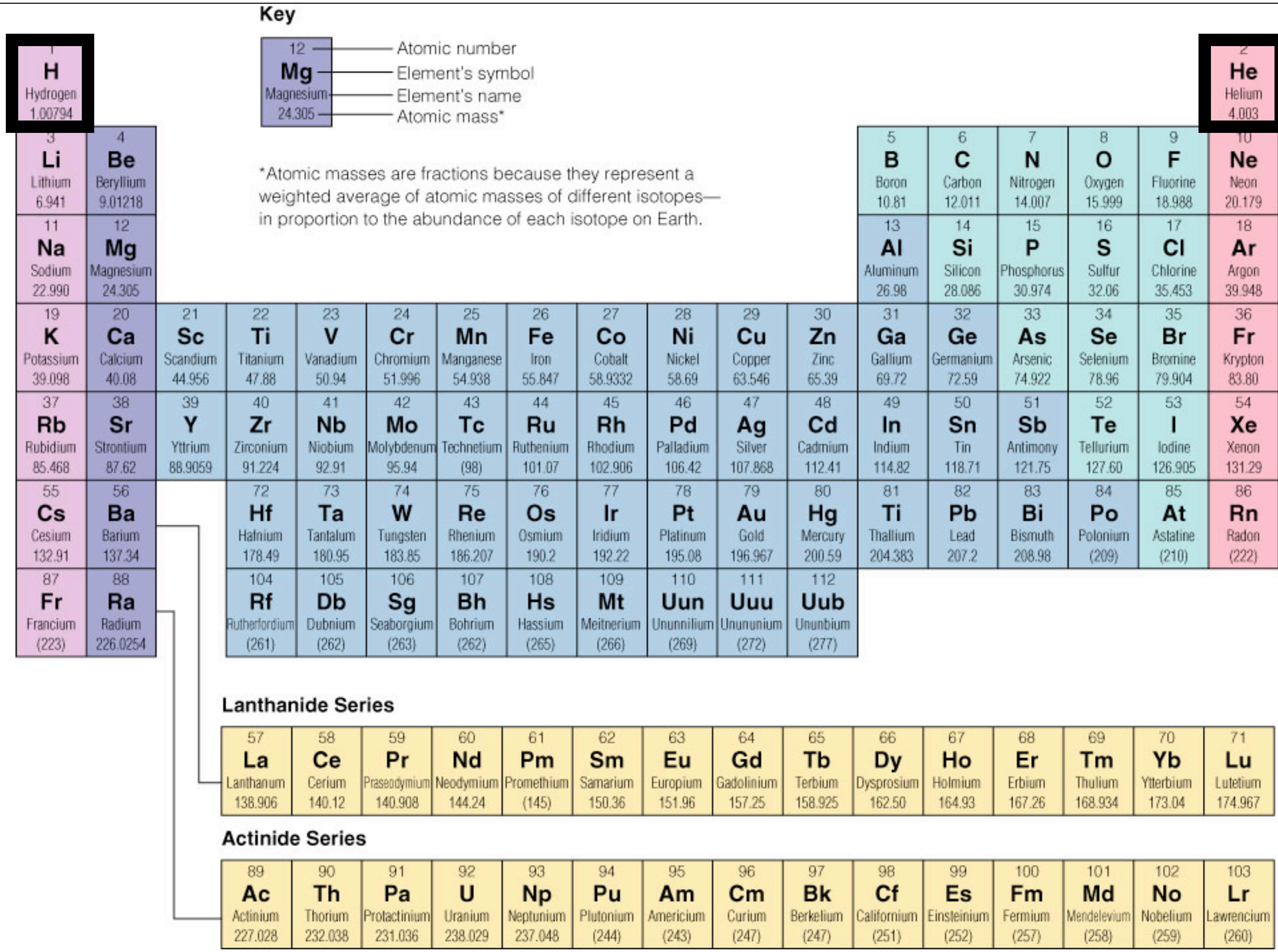
# Supergiants



# High mass stars make the elements necessary for life

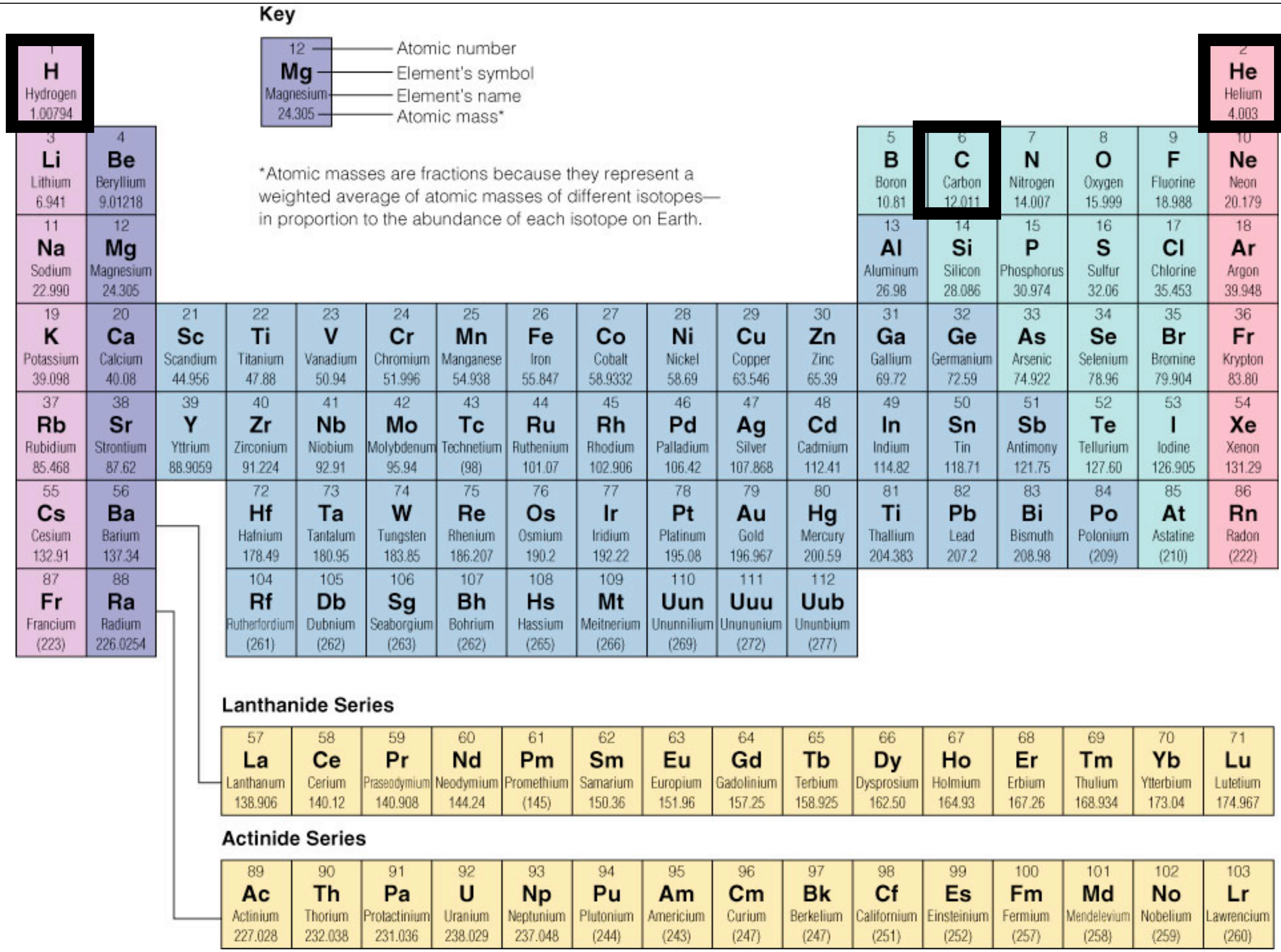



The oxygen and heavier elements in our bodies were made in the nuclear furnace of high mass stars.

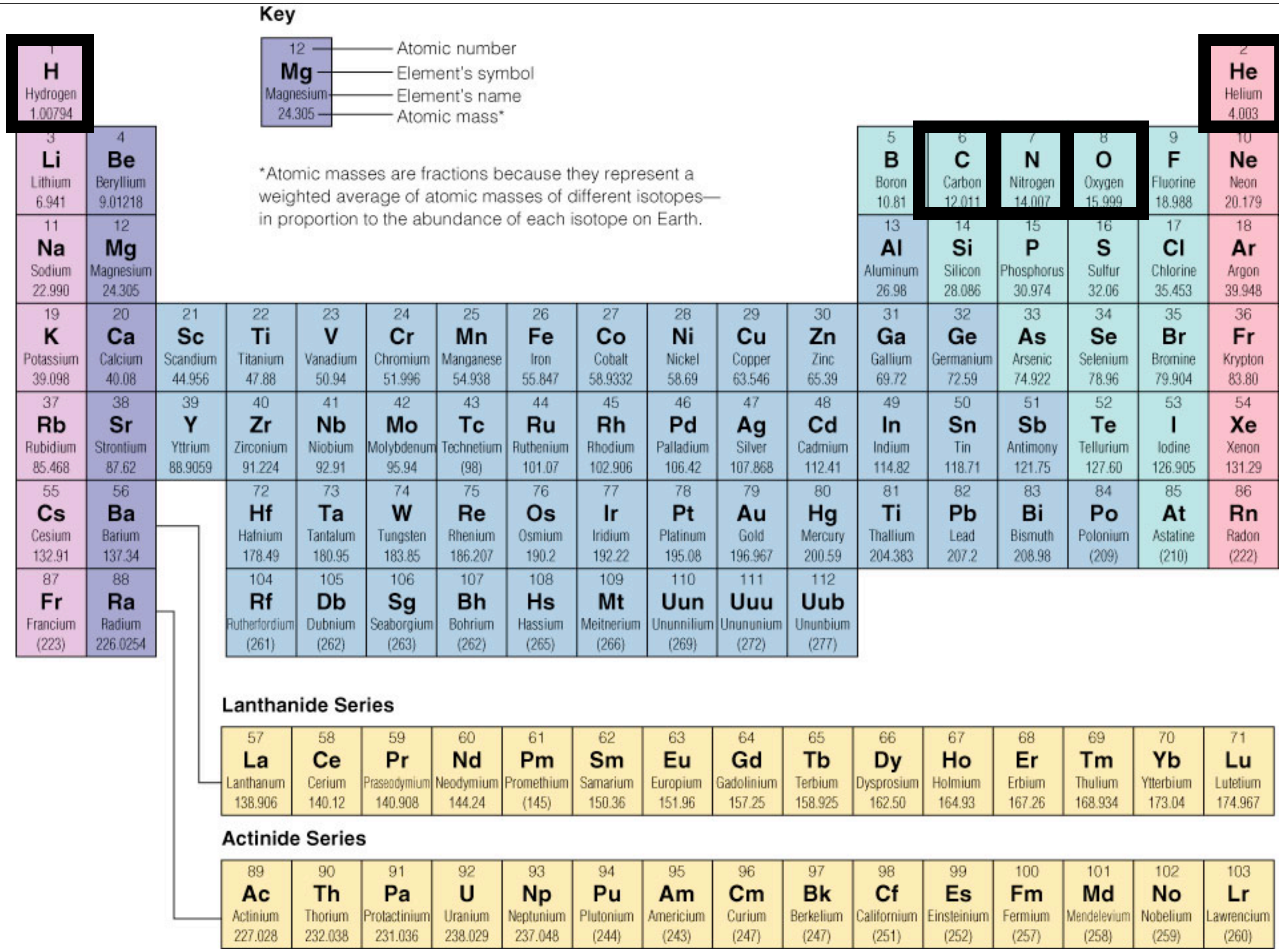



75% H, 25% He is the starting point

— stars make everything else.

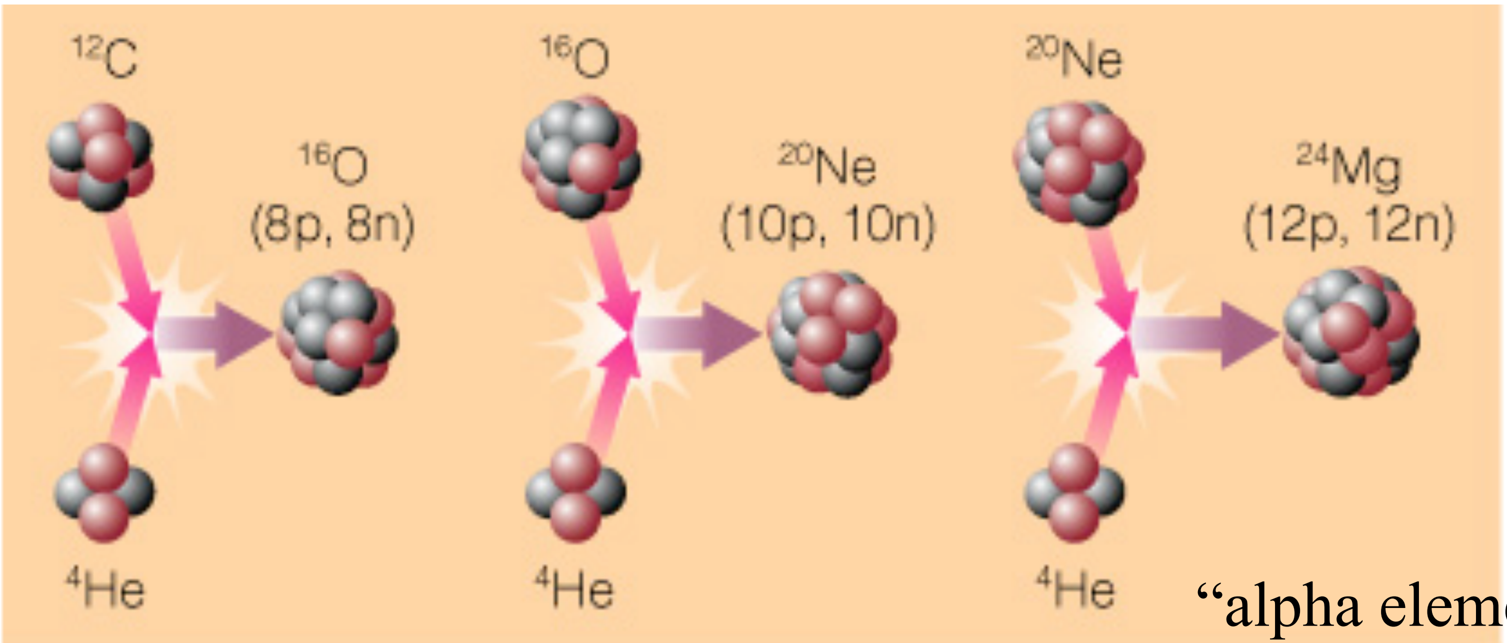



Helium fusion can make carbon in low-mass stars.



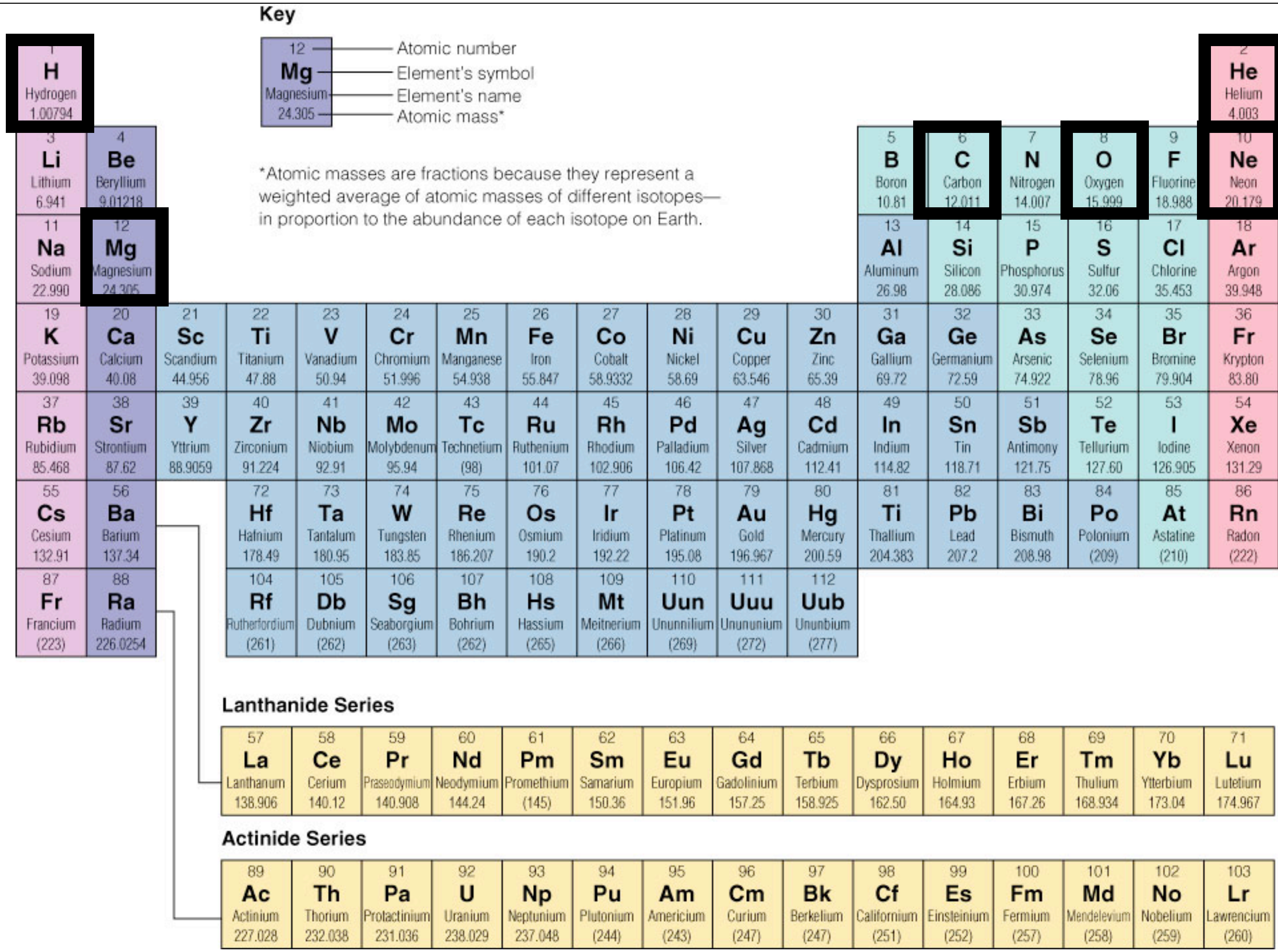

# Fusion can also produce heavier elements

# Helium Capture

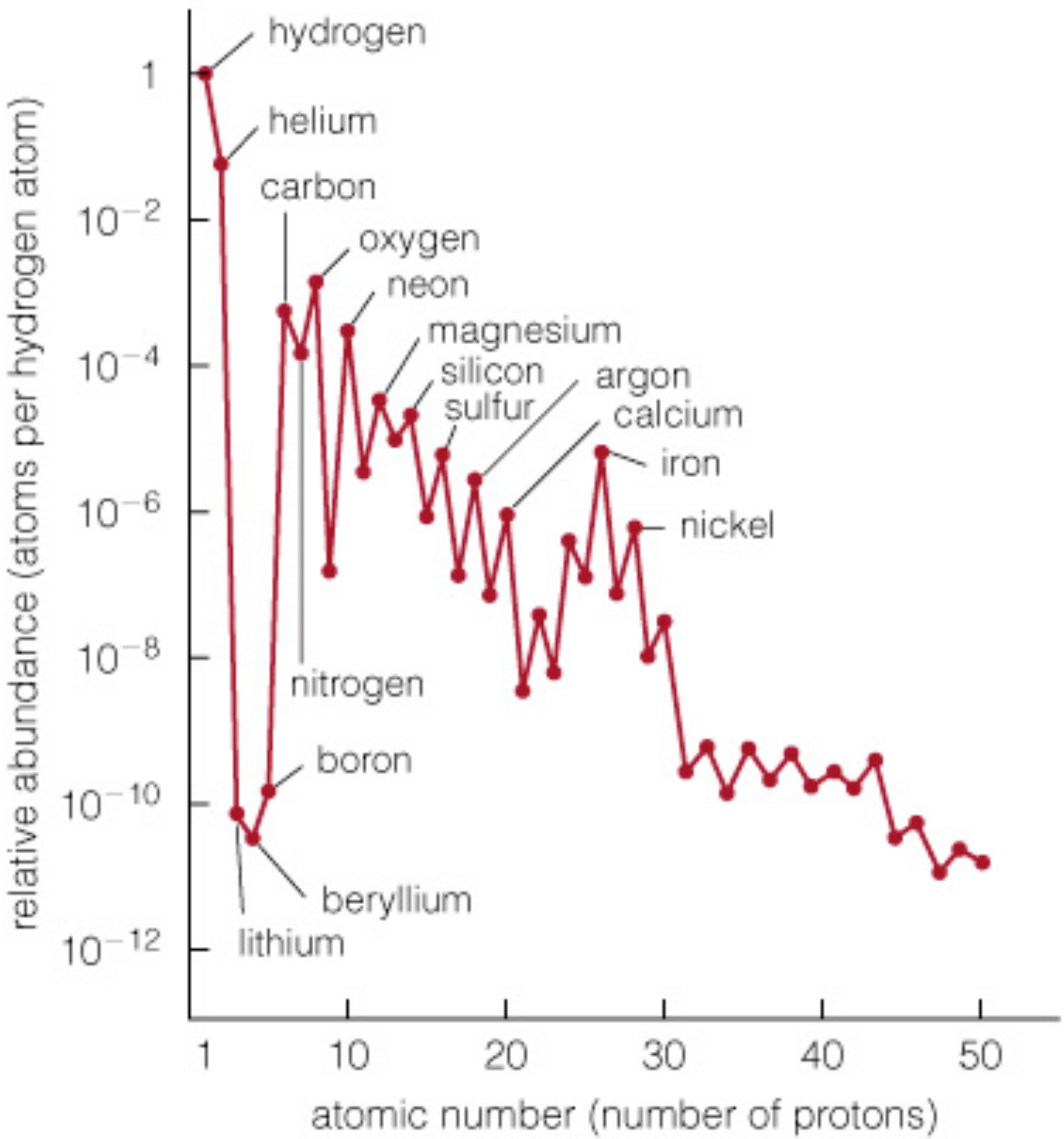



"alpha elements"

- High core temperatures allow helium to fuse with heavier elements.




# Helium capture builds C into O, Ne, Mg …

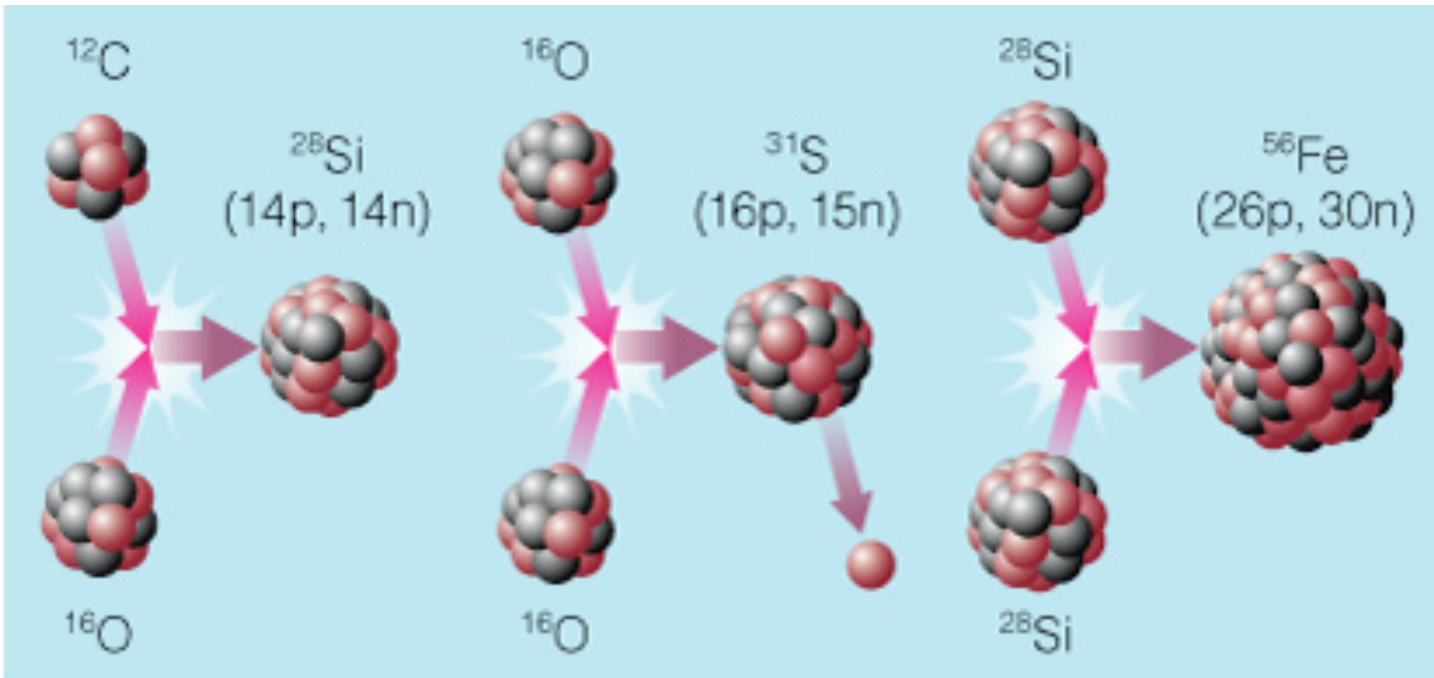



Evidence for helium capture:

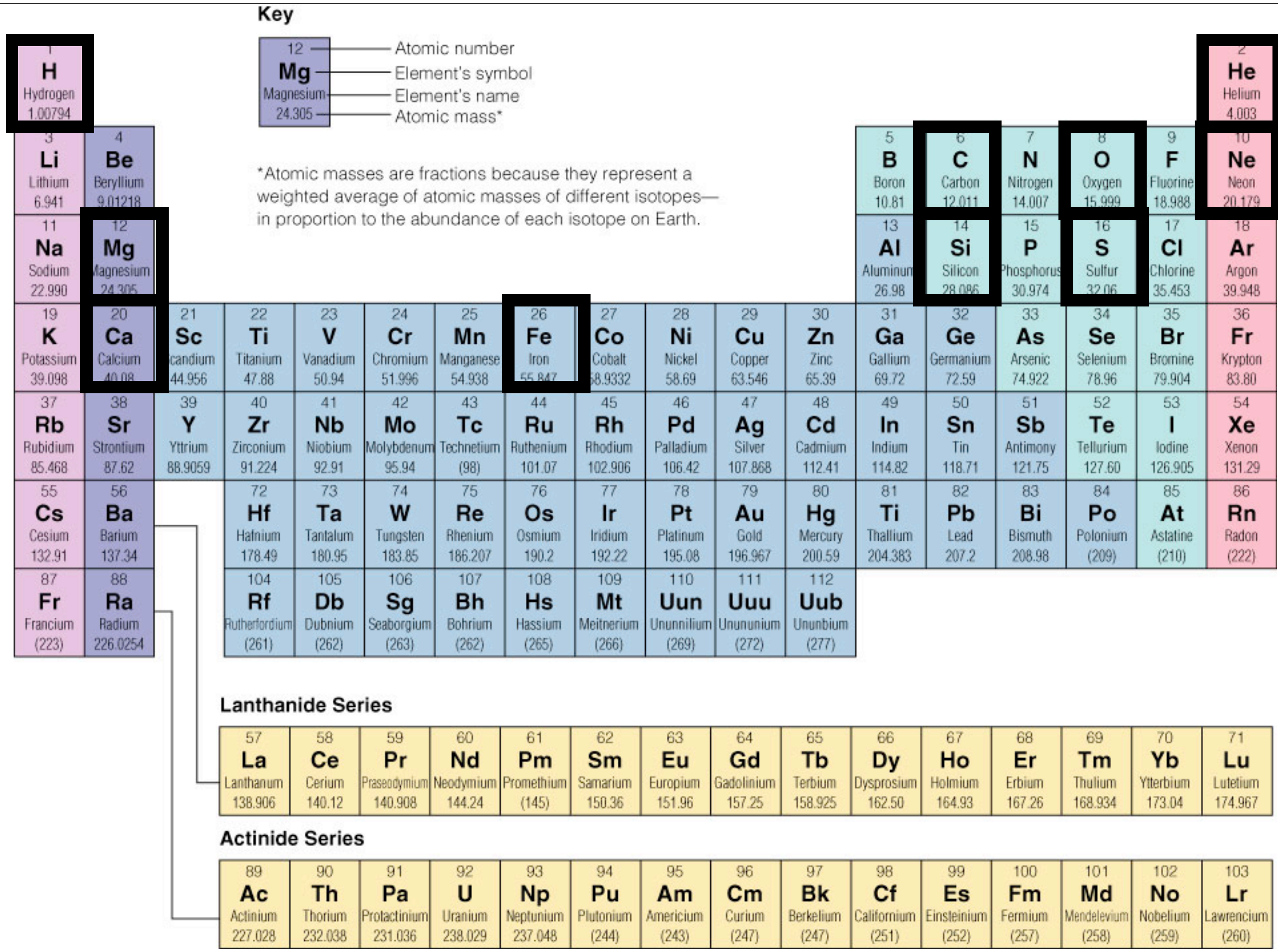
Higher abundances of elements with even numbers of protons

“alpha elements”

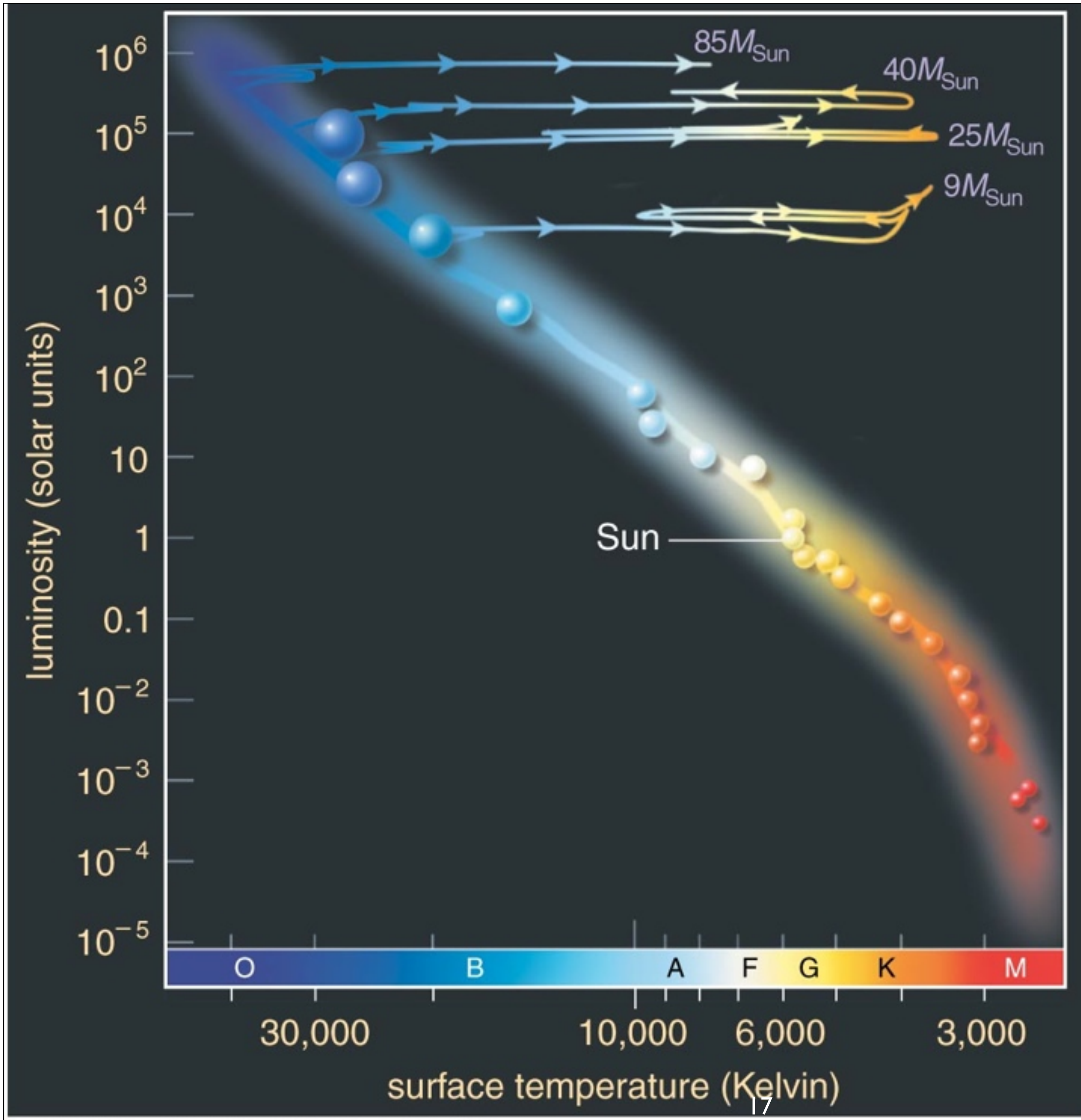
# Advanced Nuclear Burning




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




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



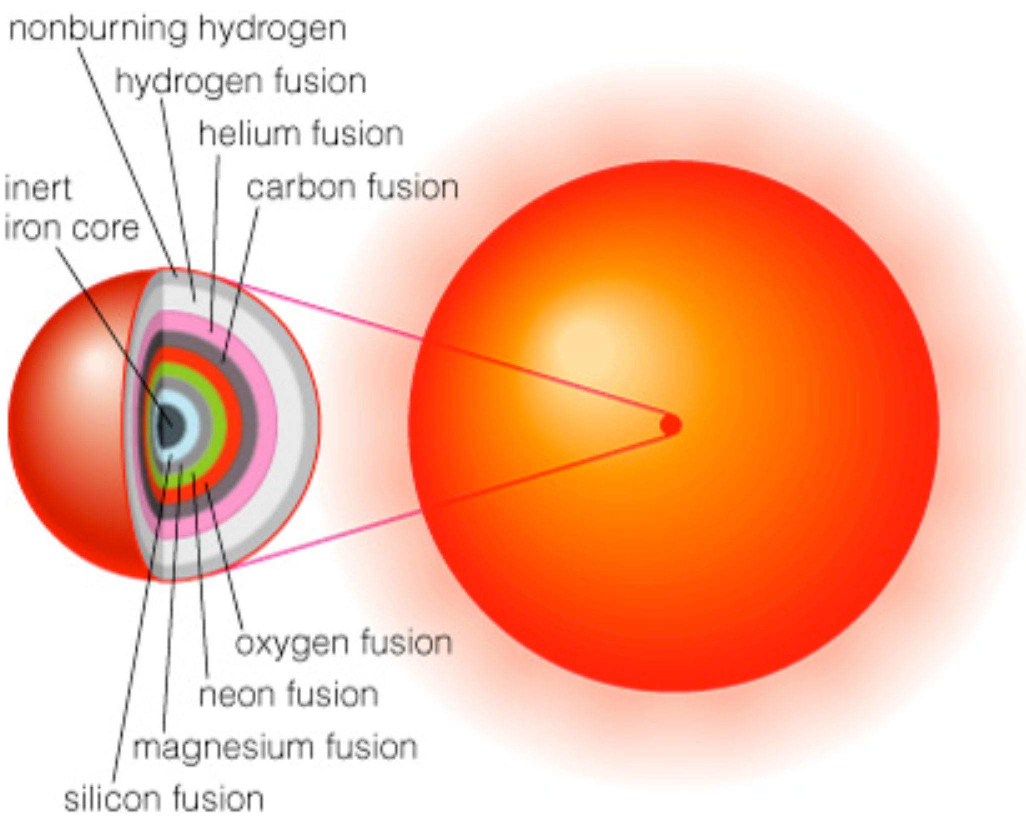



# Supergiants

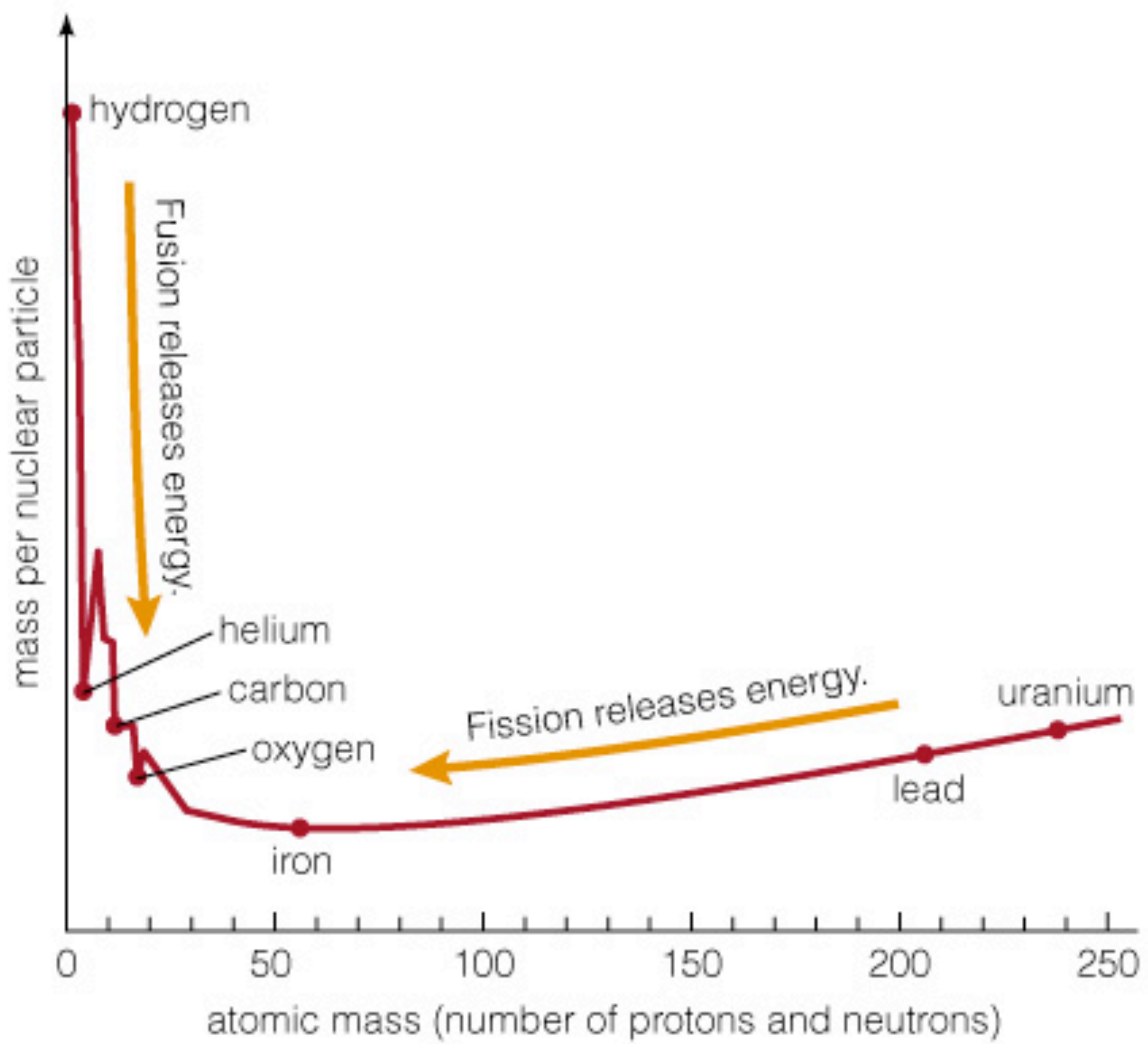
can get a wiggle in evolutionary track as each fuel supply is exhausted.

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

# Multiple-Shell Burning

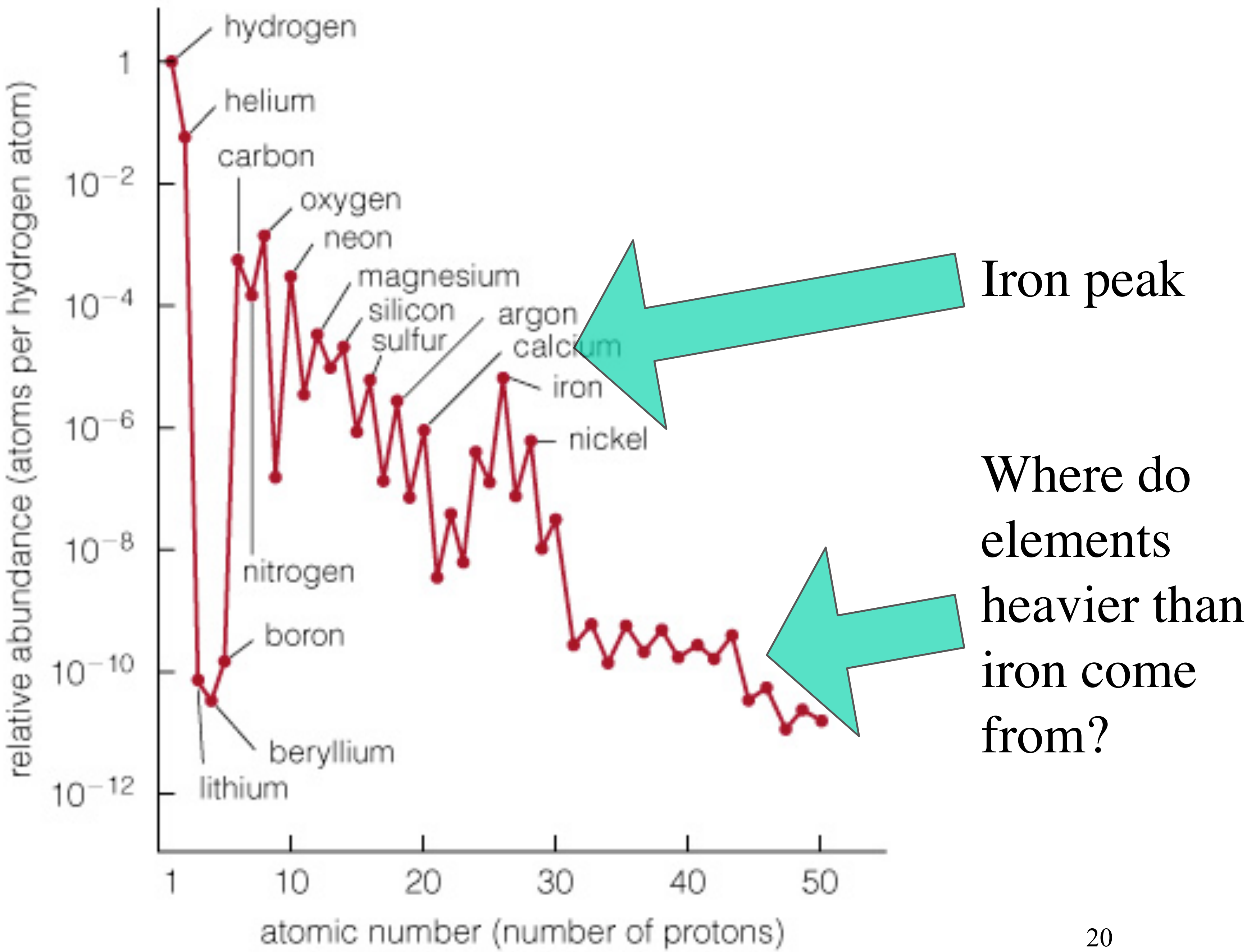



- Advanced nuclear burning proceeds in a series of nested shells.
- Core of high mass (> $8M_{sun}$) near the end of its life




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

(Fe has lowest mass per nuclear particle.)




Where do elements heavier than iron come from?

# Elements heavier than iron

If we can get to iron by fusion in stars, how do we get elements heavier than iron?

A. A source of energy is required to get heavier elements

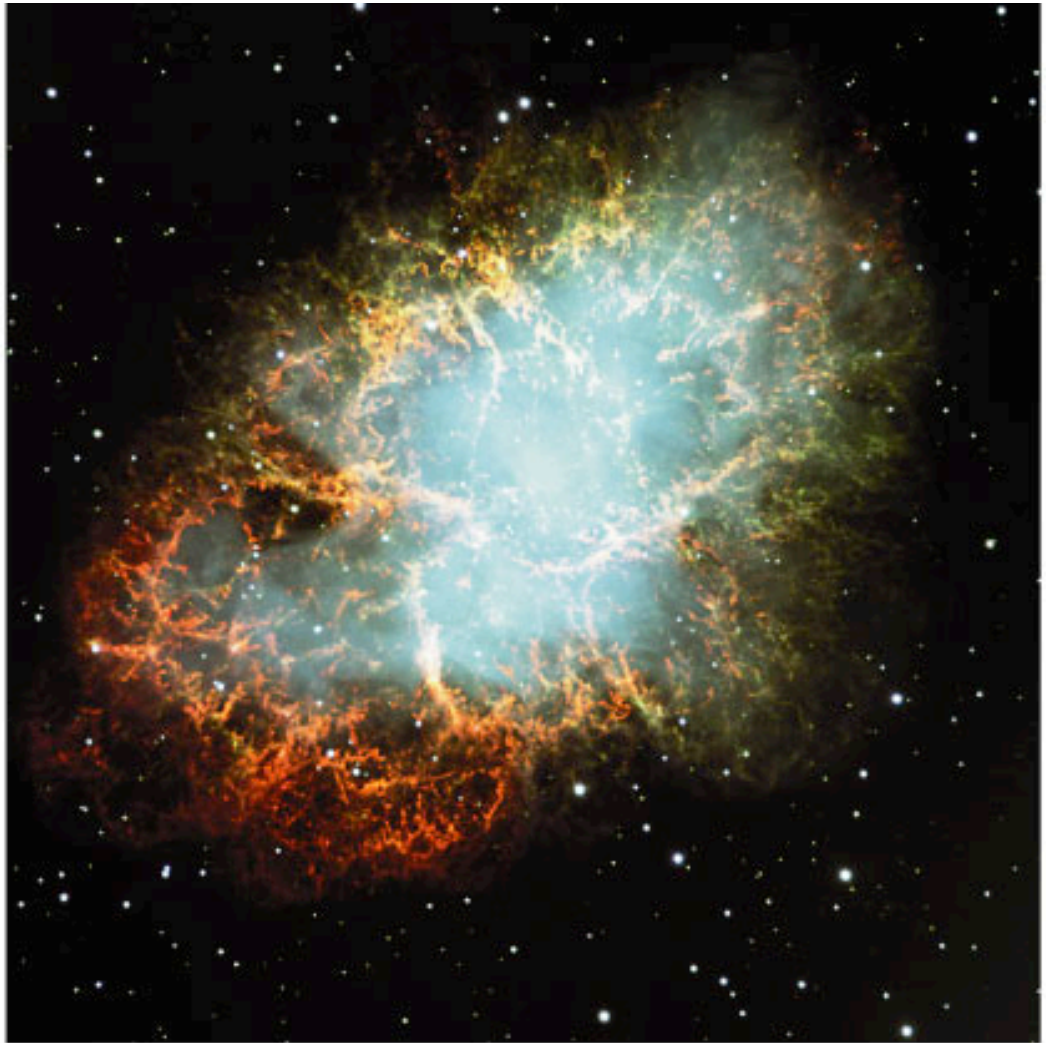
B. Fission of iron gives heavier elements

C. Fusion of iron releases energy and produces heavier elements

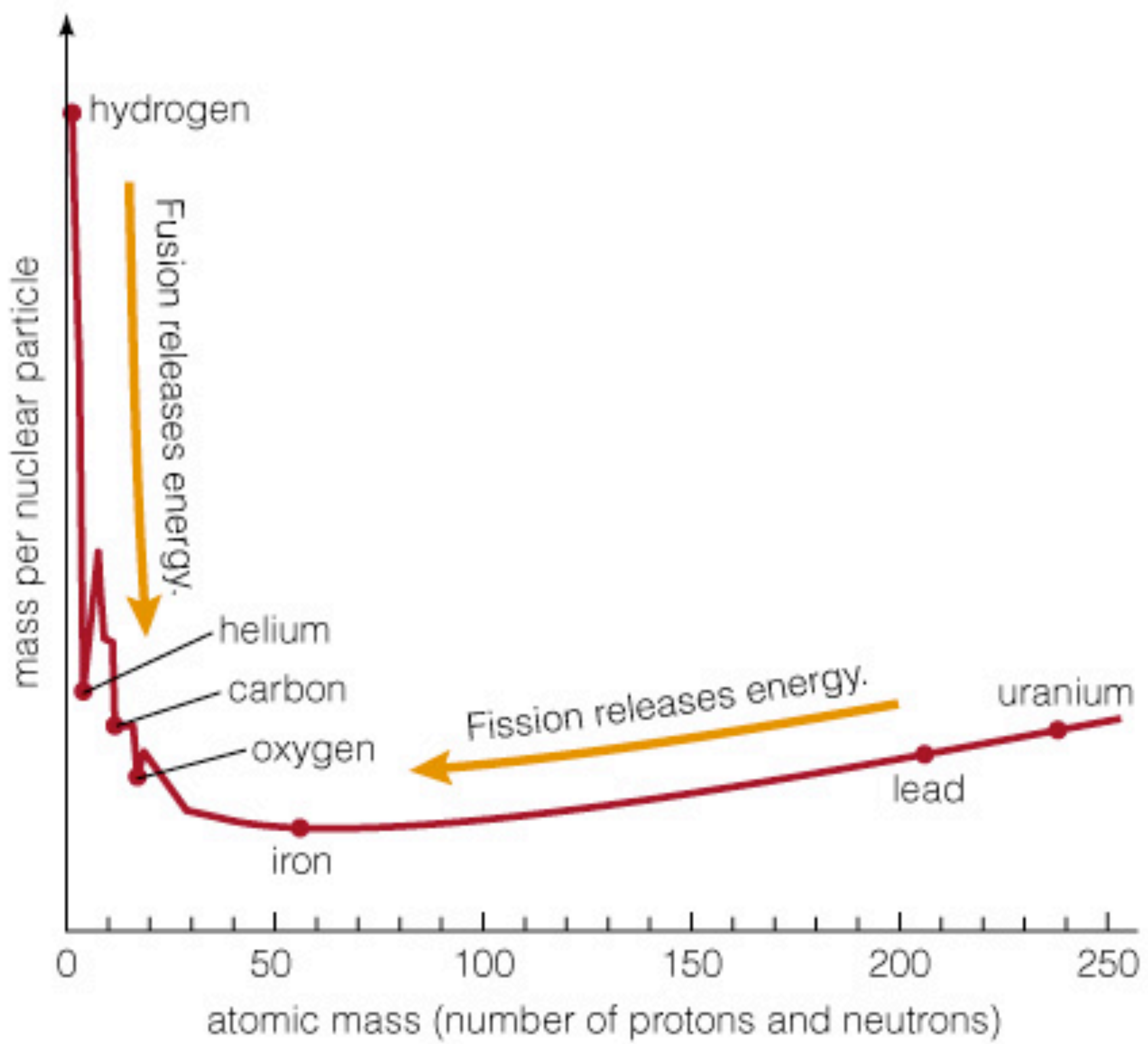
D. Heavier elements are produced by low mass stars

E. I don’t know

# Supernovae!



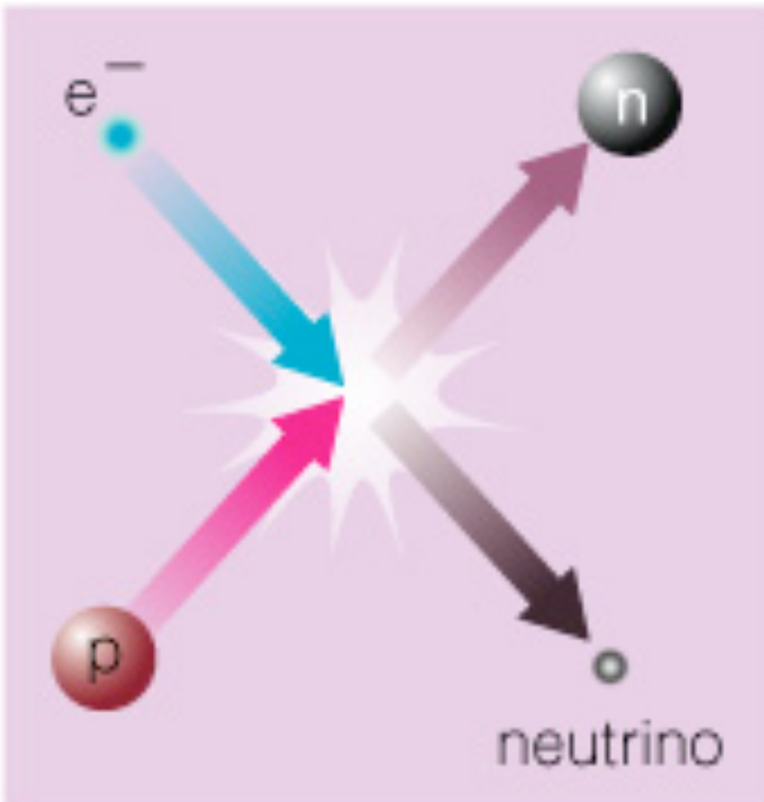
The Elements




Iron is the ultimate ash.

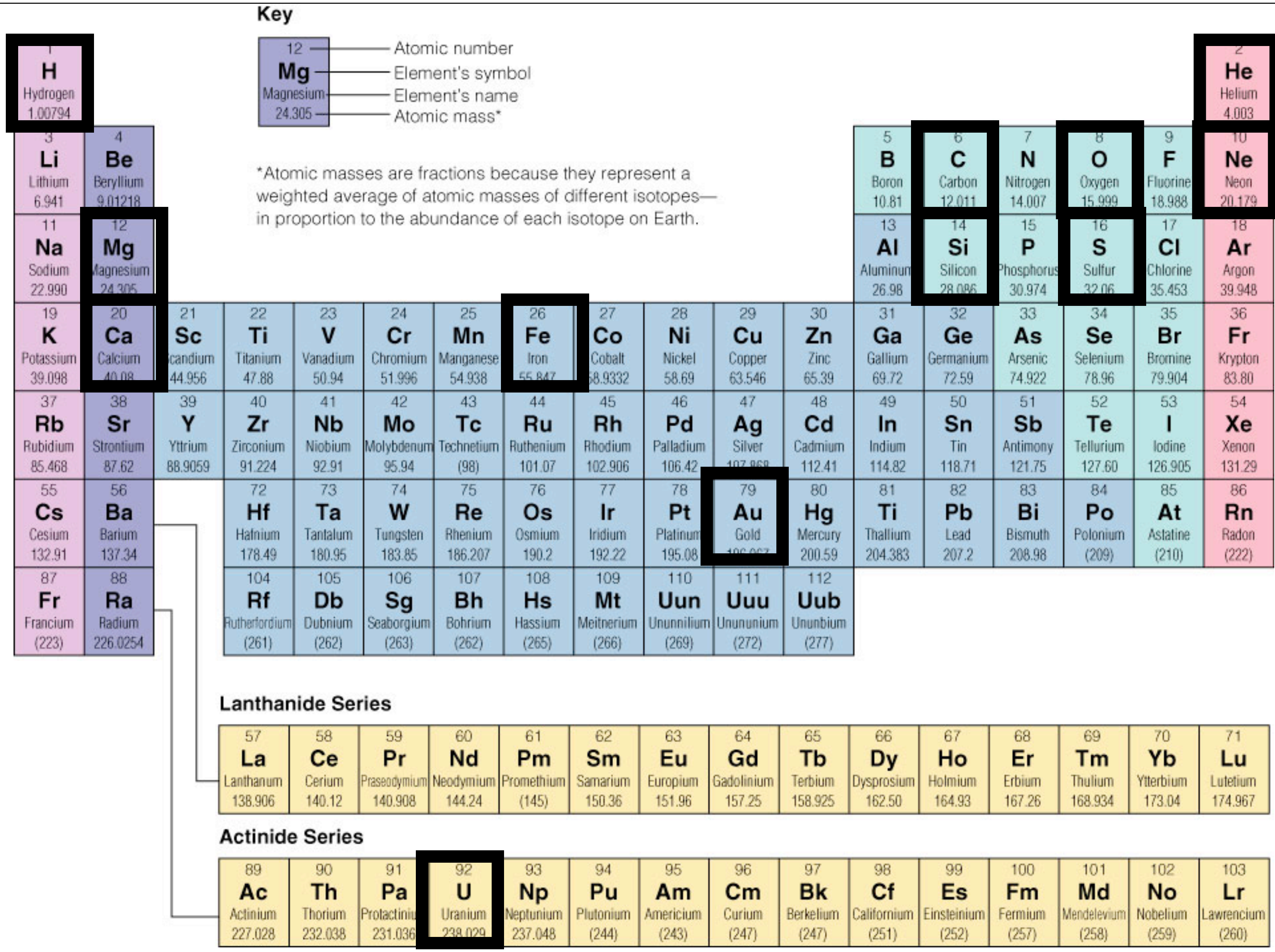
With nothing left to support it, the core collapses and the outer parts explode, carrying elements into space.

# Supernova Explosion

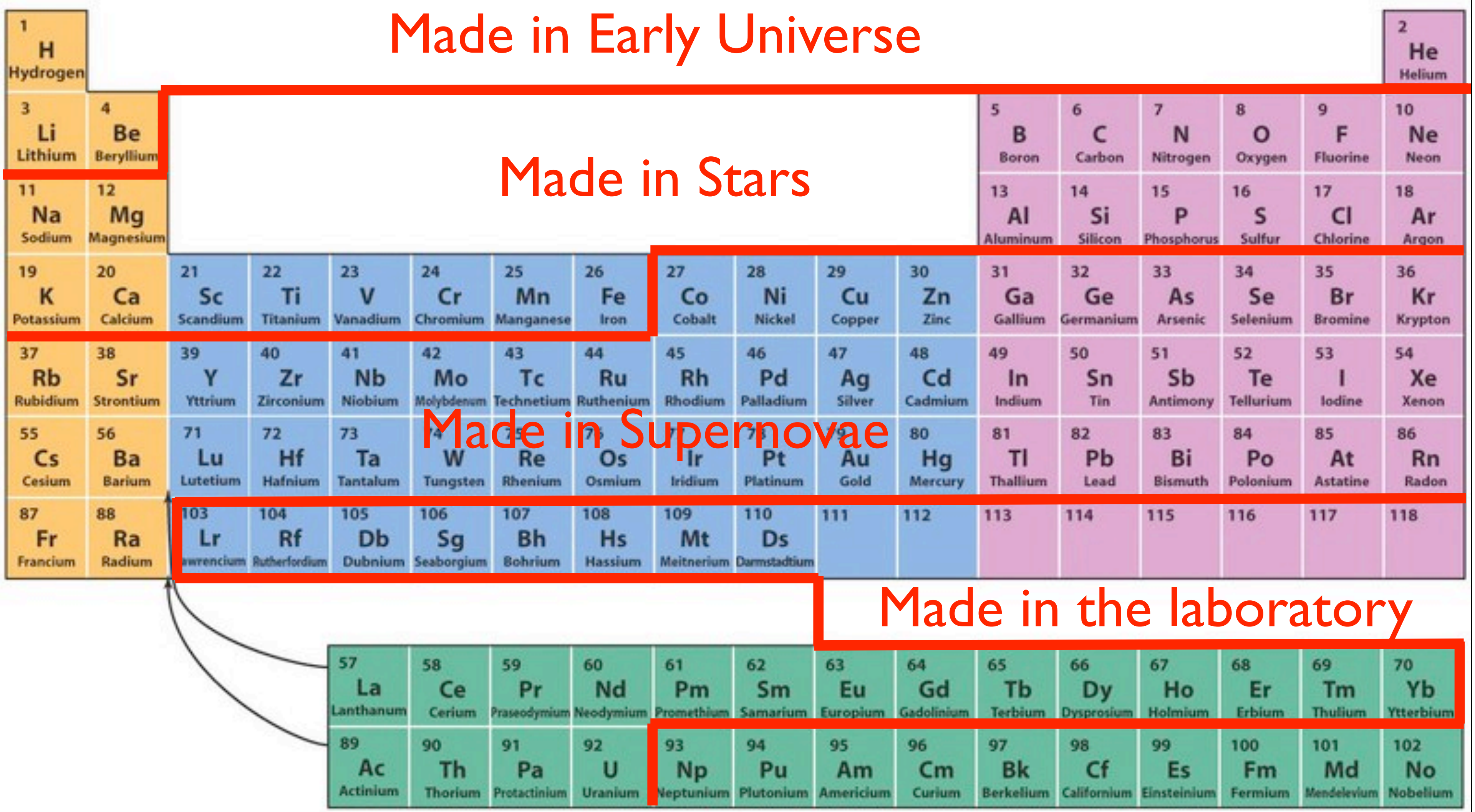



- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.
- Neutrons collapse to the center, forming a **neutron star.**

Simulation, demo




Energy and neutrons released in a supernova explosion enable elements heavier than iron to form, including Au and U.


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 Lawrencium
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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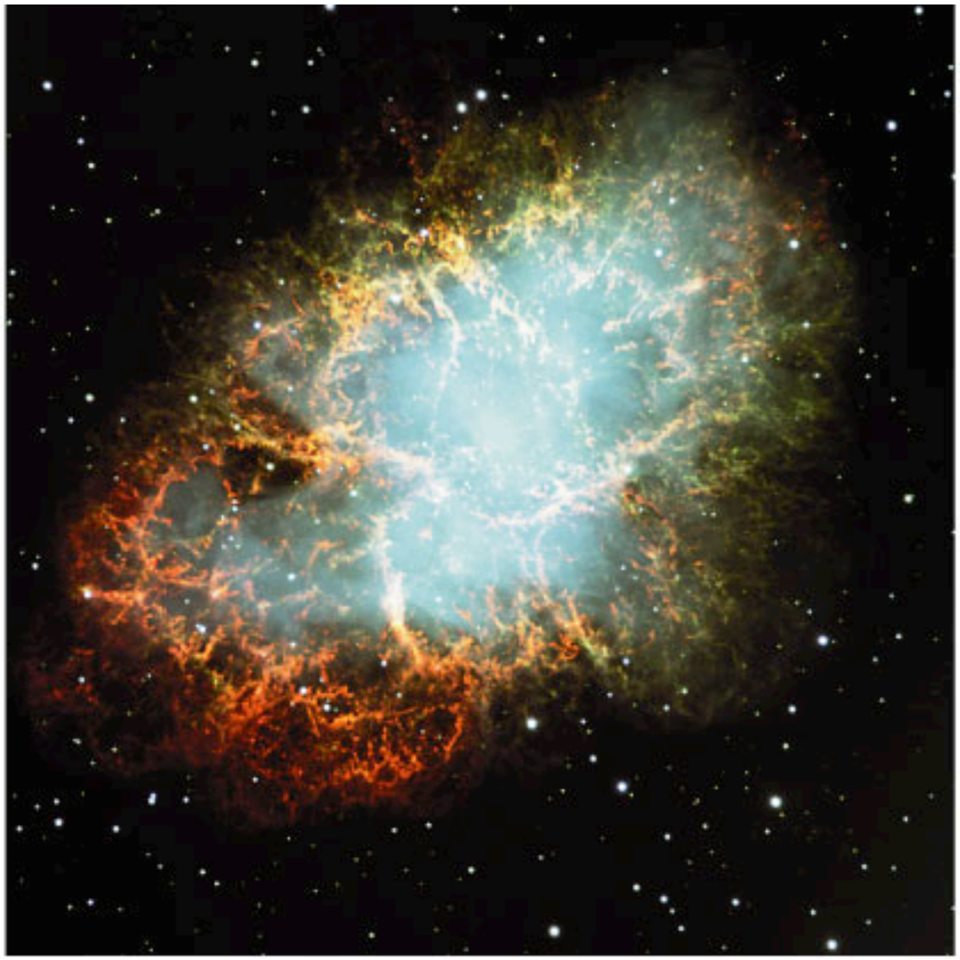
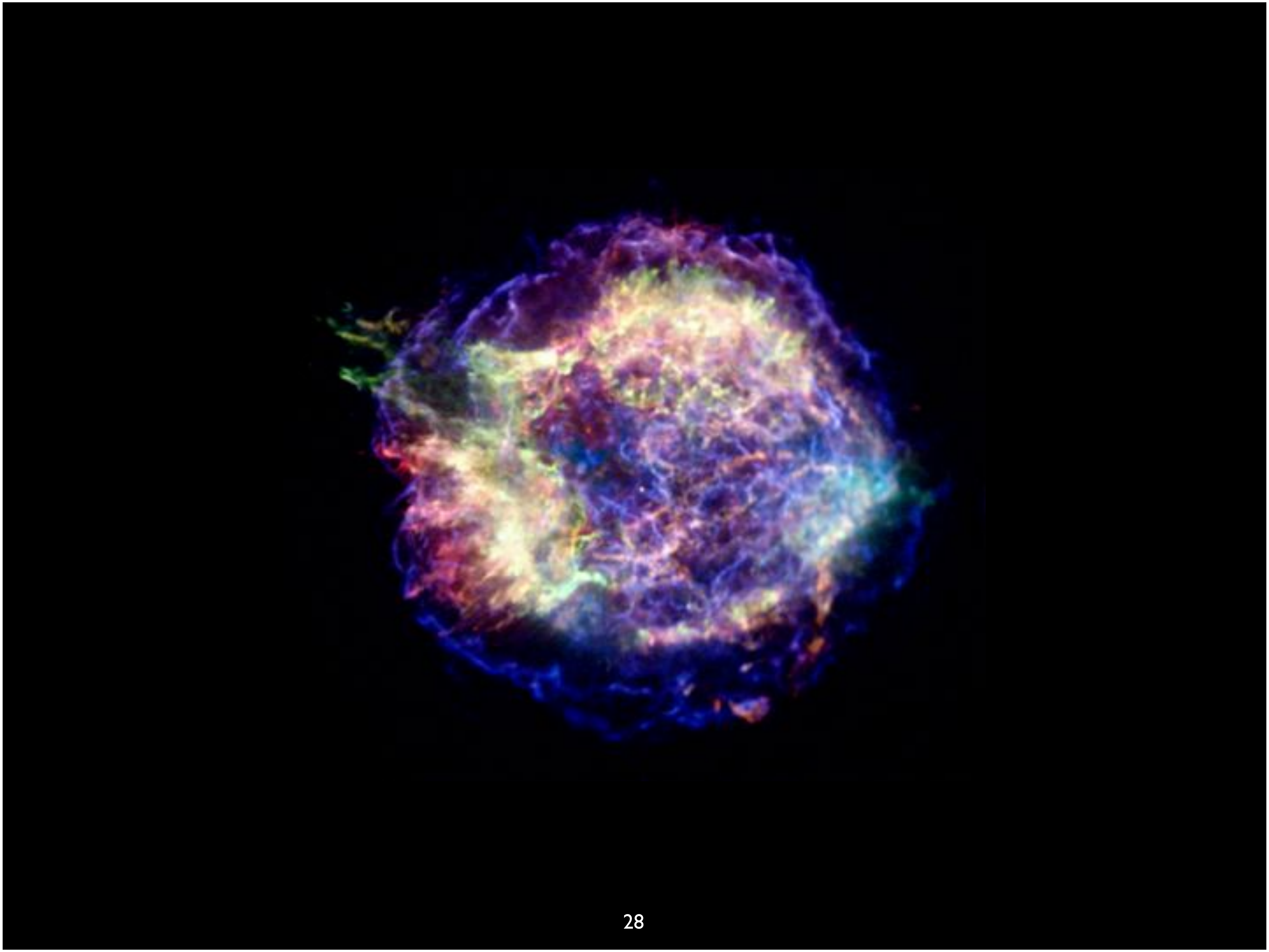
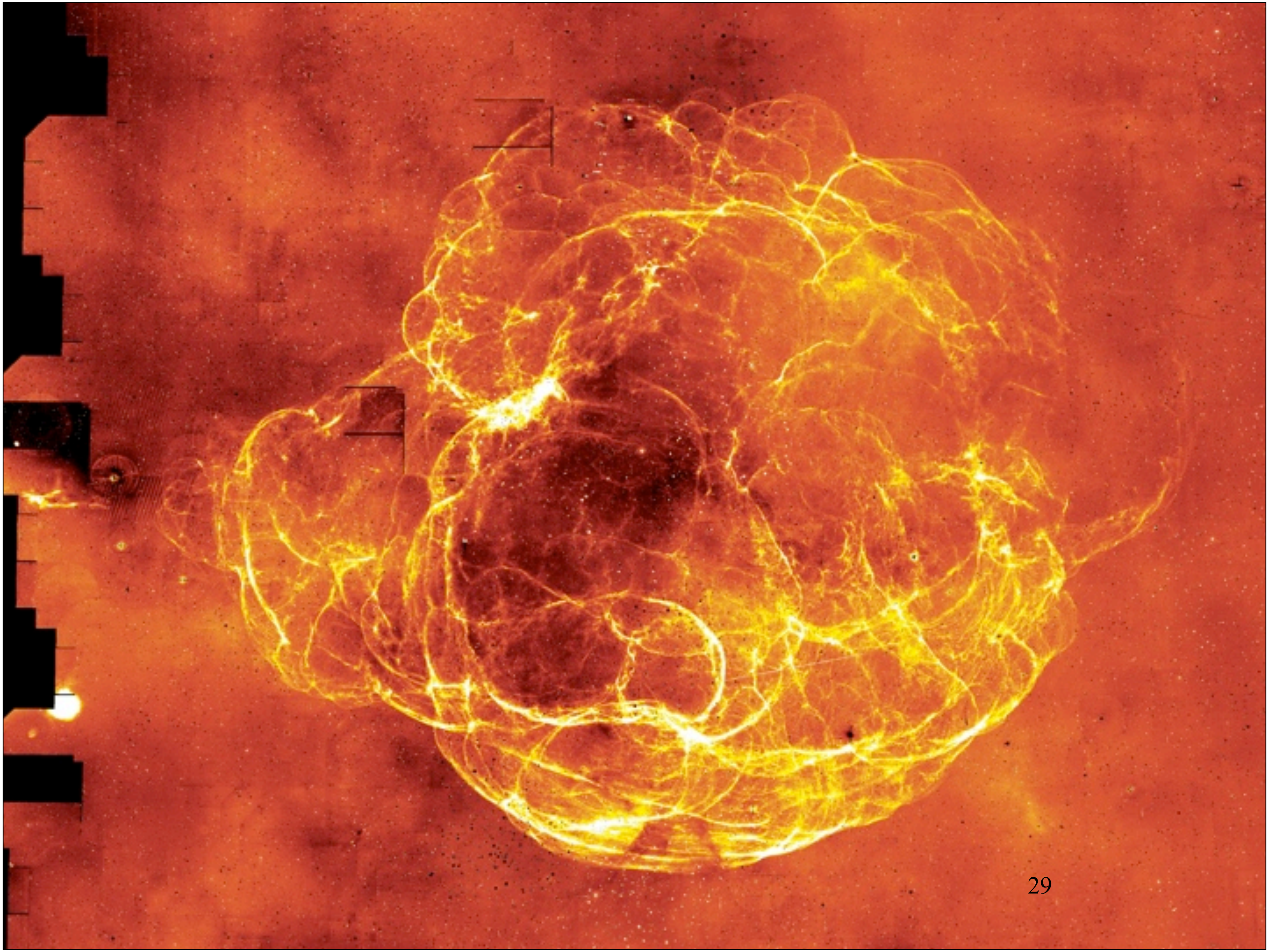
117
118
57 La Lanthanum
58 Ce Cerium
59 Pr Praseodymium
60 Nd Neodymium
61 Pm Promethium
62 Sm Samarium
63 Eu Europium
64 Gd Gadolinium
65 Tb Terbium
66 Dy Dysprosium
67 Ho Holmium
68 Er Erbium
69 Tm Thulium
70 Yb Ytterbium
89 Ac Actinium
90 Th Thorium
91 Pa Protactinium
92 U Uranium
93 Np Neptunium
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

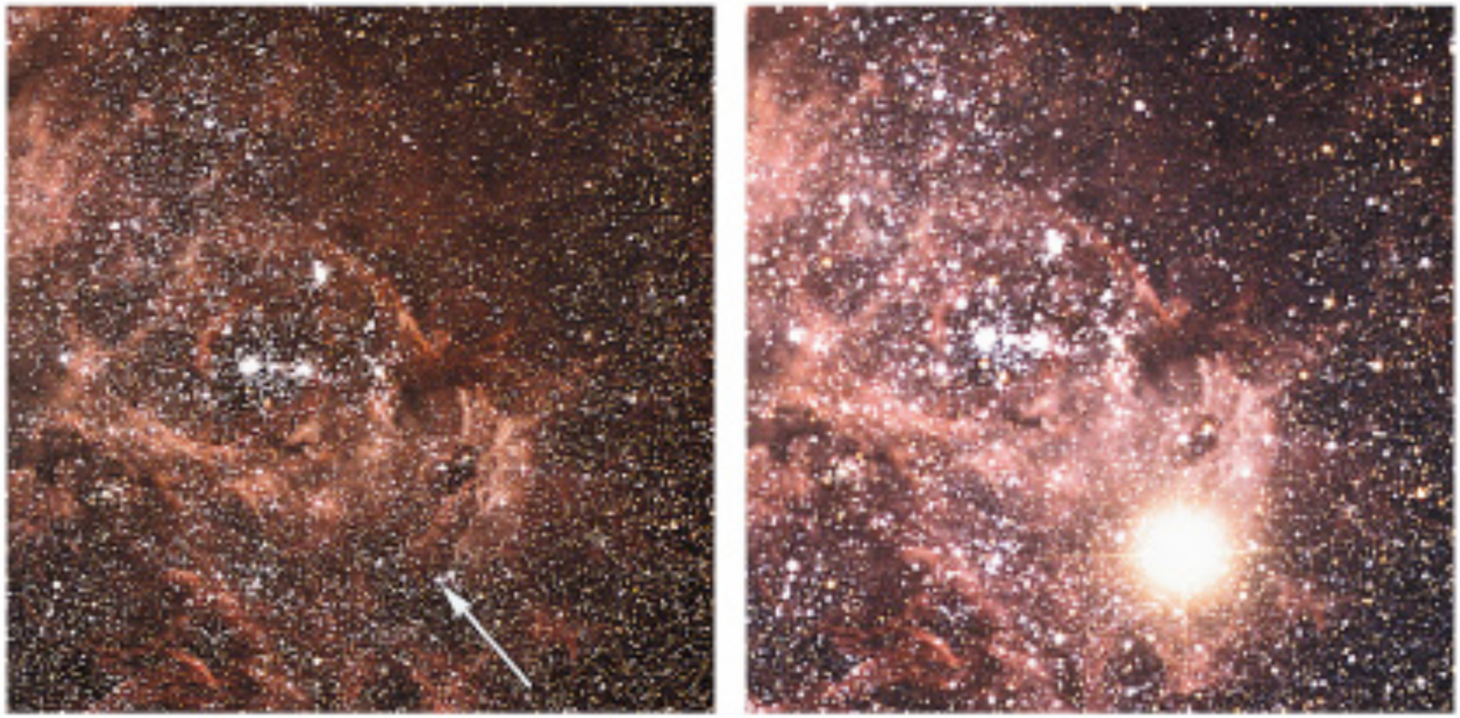


- Energy released by the collapse of the core drives outer layers into space.
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054.

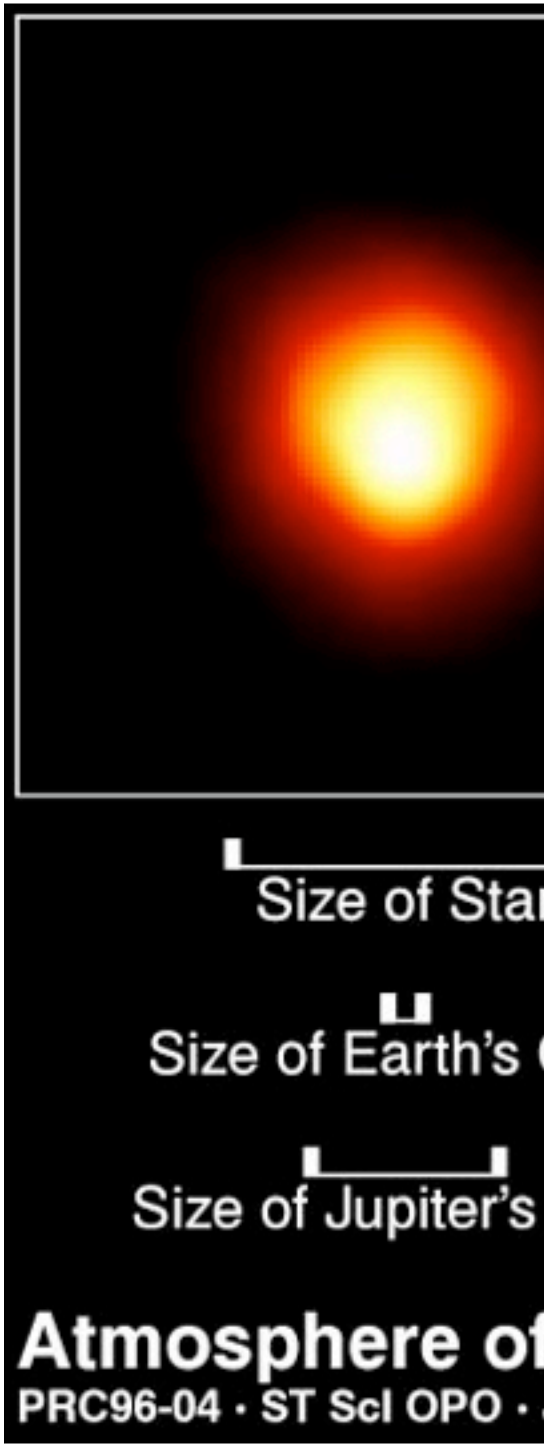




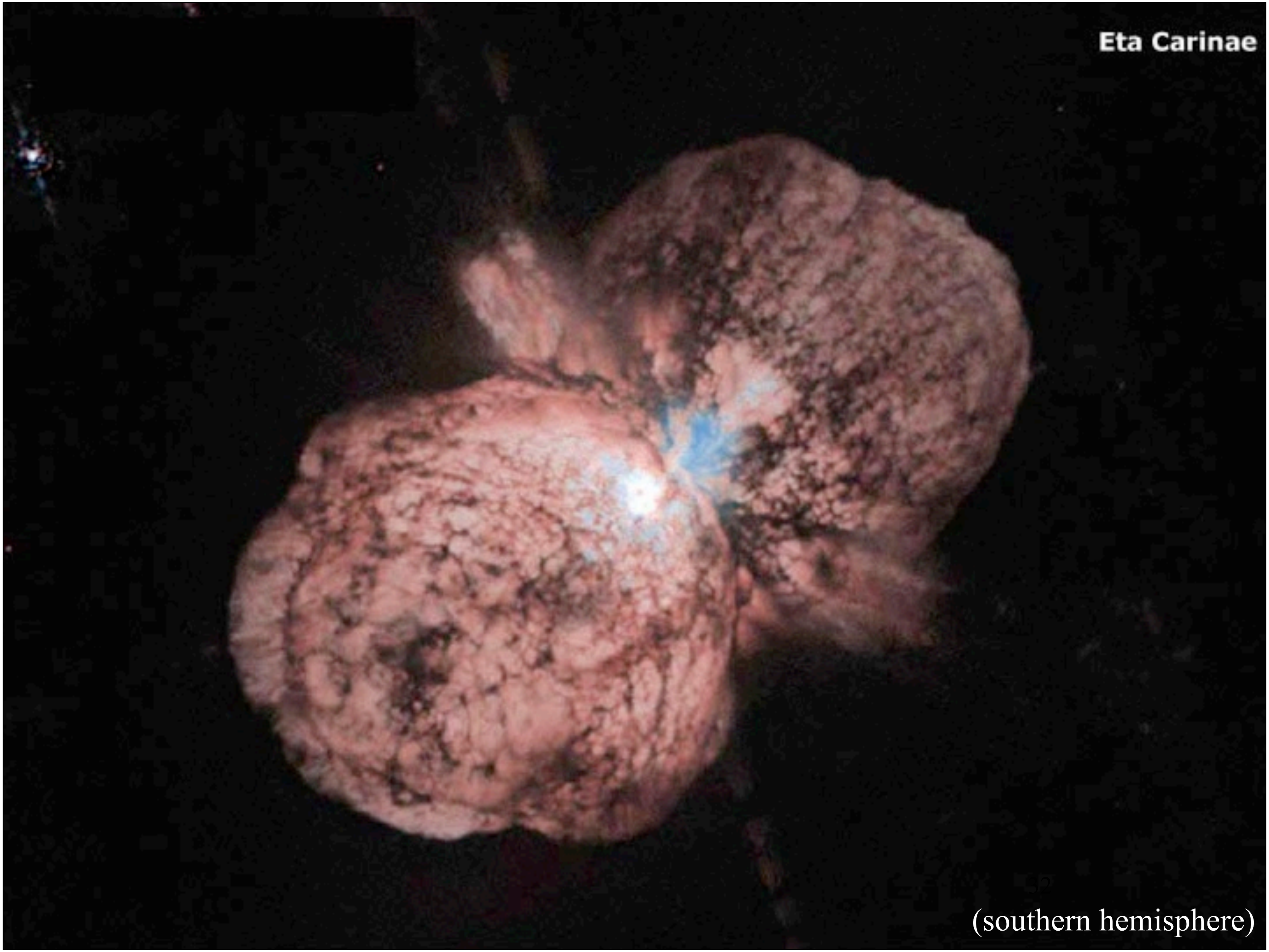
# Supernova 1987A



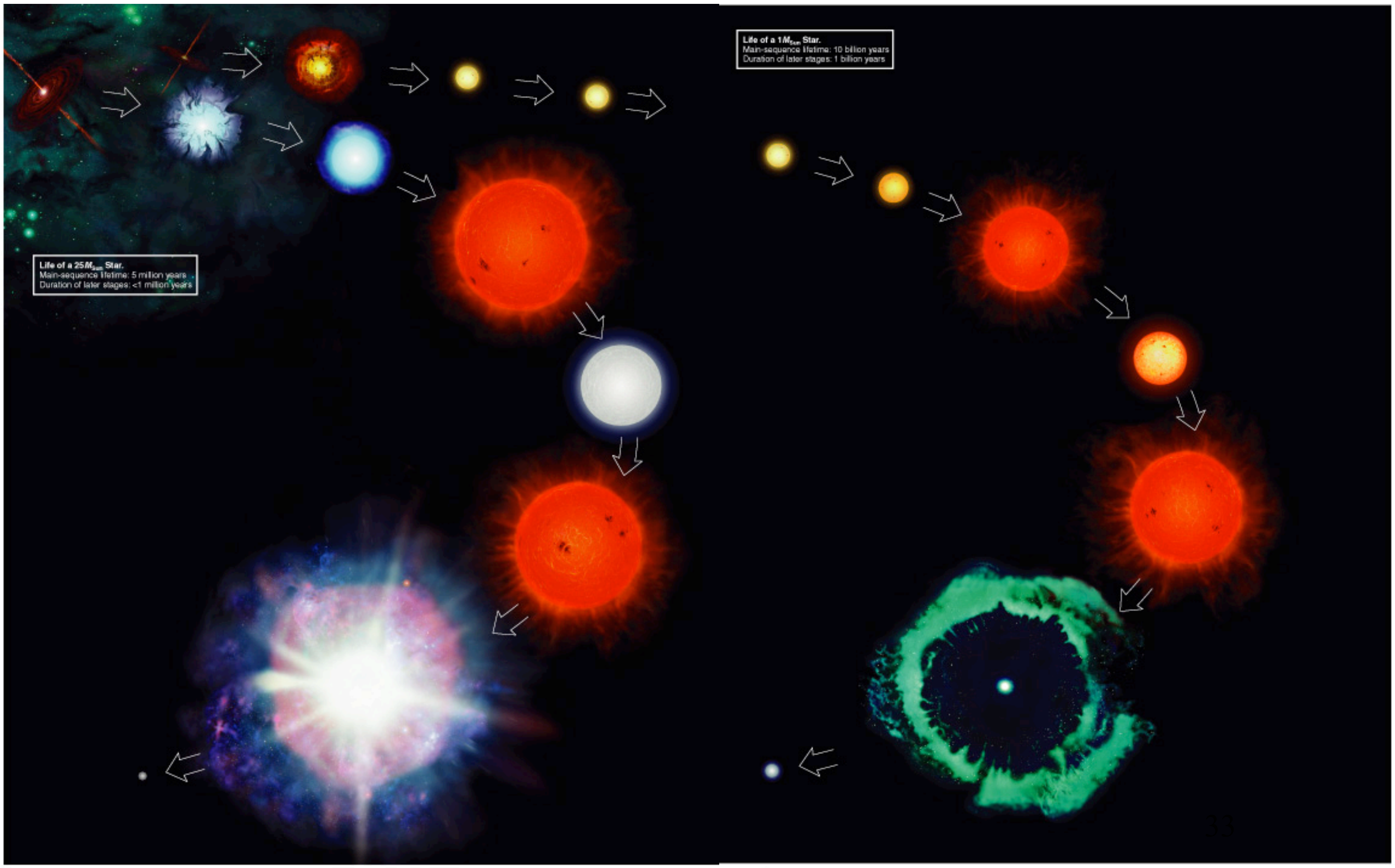
- The closest supernova in the last four centuries was seen in 1987 in the Large Magellanic Cloud.
- Recent discoveries in other galaxies (video)


Size of Sta
Size of Earth's
Size of Jupiter's
Atmosphere of
PRC96-04 · ST ScI OPO ·


Betelgeuse
Bellatrix
Alnitak, Alnilam, Mintaka
Orion Nebula
Rigel
Saiph


Eta Carinae
(southern hemisphere)

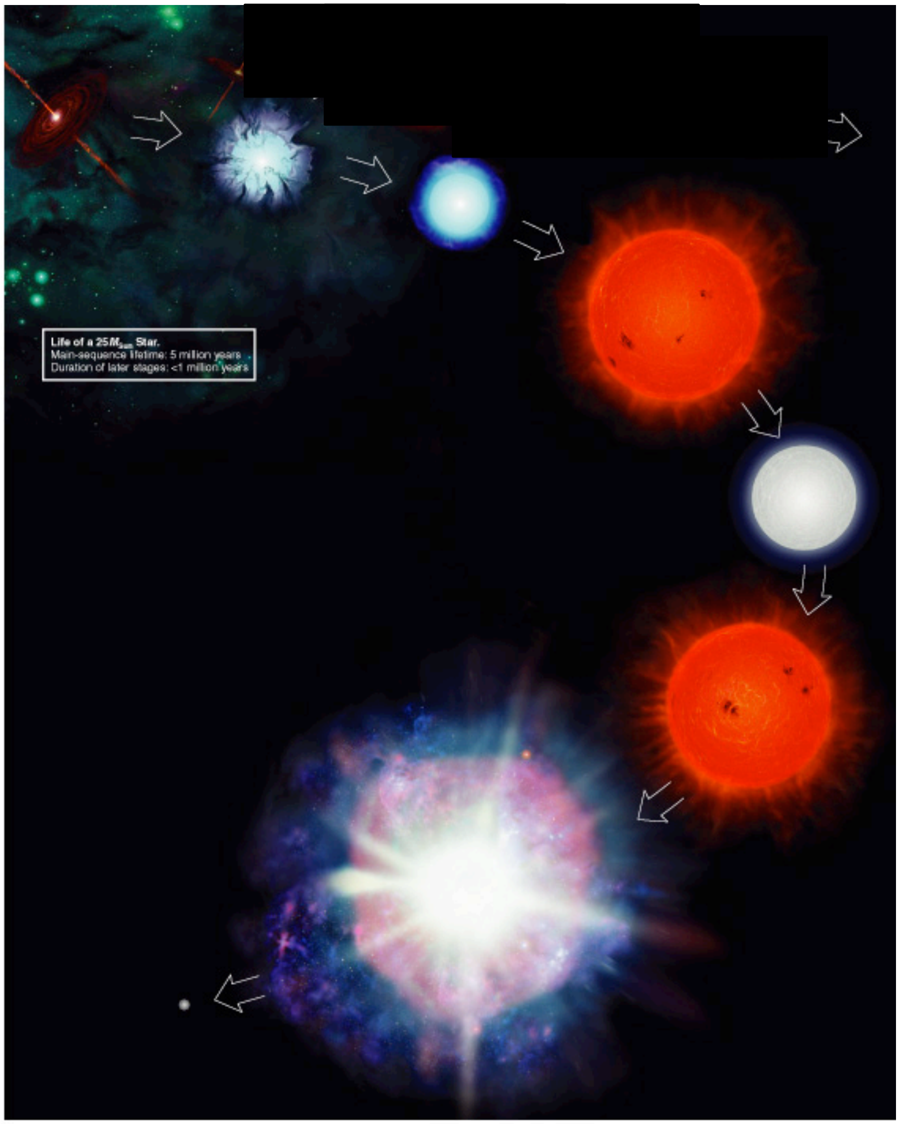
# How does a star's mass determine its life story?



# 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.

# Life Stages of High-Mass Star




*Not to scale!*



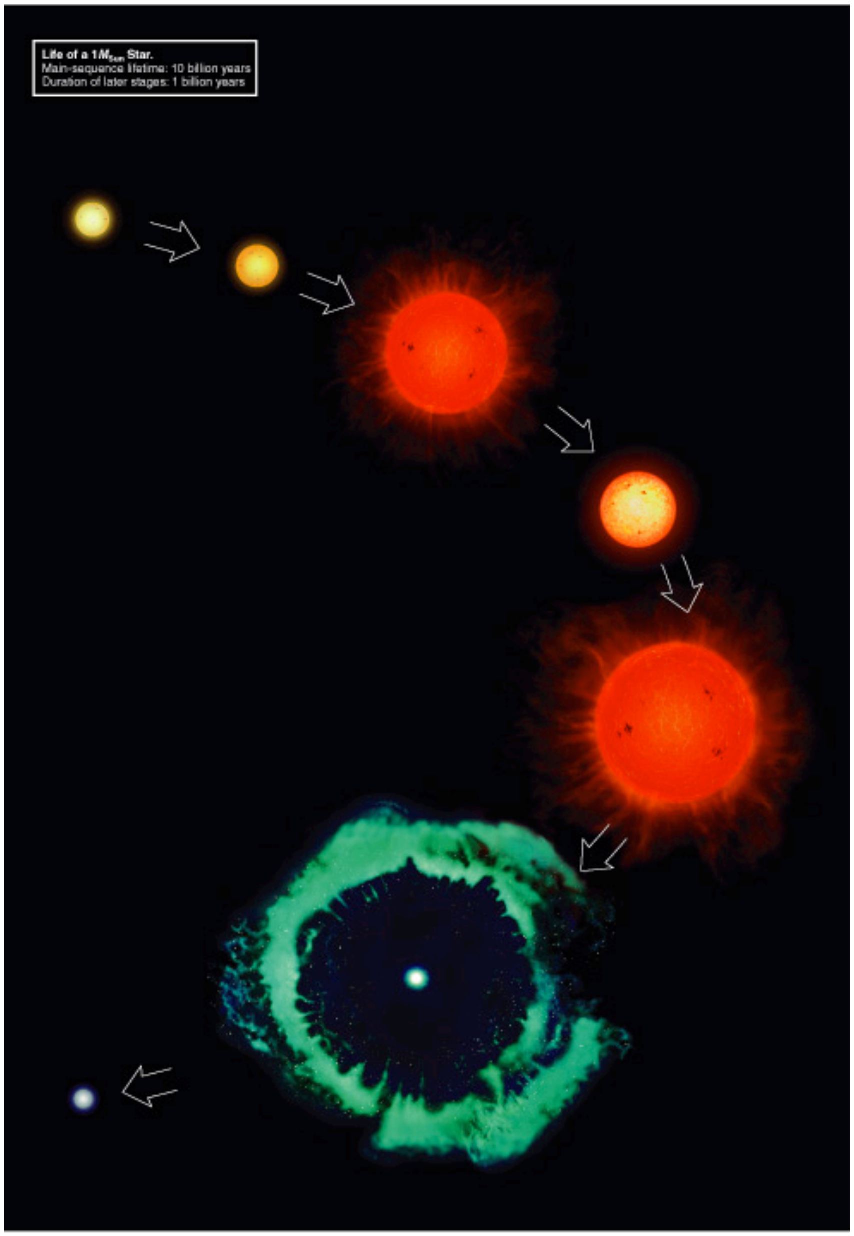
1. Main Sequence: H fuses to He in core

2. Red Supergiant: H fuses to He in shell around He core

3. Helium Core Burning:
   He fuses to C in core while H fuses to He in shell

4. Multiple-Shell Burning:
   many elements fuse in shells

5. Supernova leaves neutron star or black hole behind




*Not to scale!*



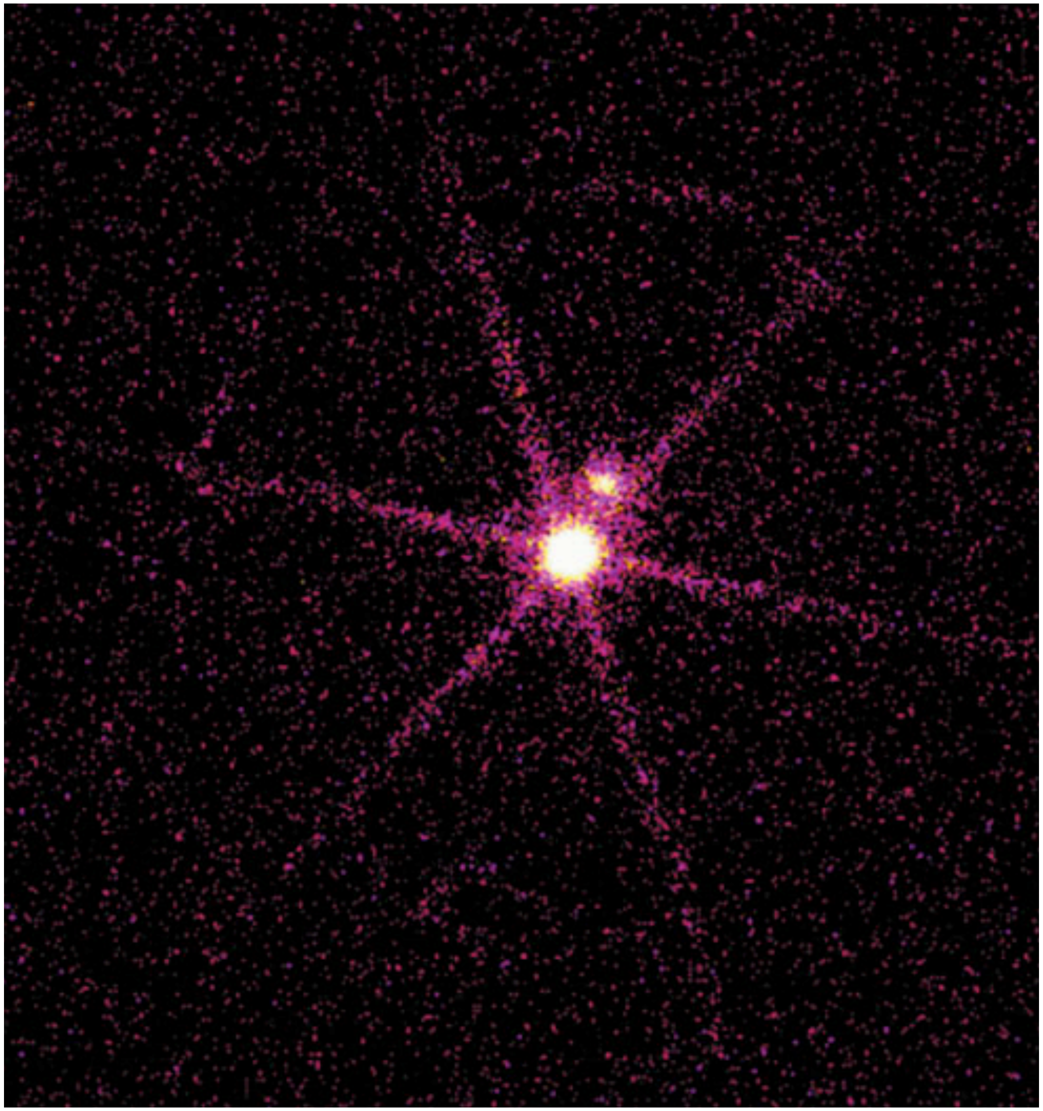
## Low-Mass Star Summary

1. Main Sequence: H fuses to He in core
2. Red Giant: H fuses to He in shell around He core
3. Helium Core Burning: He fuses to C in core while H fuses to He in shell
4. Double-Shell Burning: H and He both fuse in shells
5. Planetary Nebula: leaves white dwarf behind

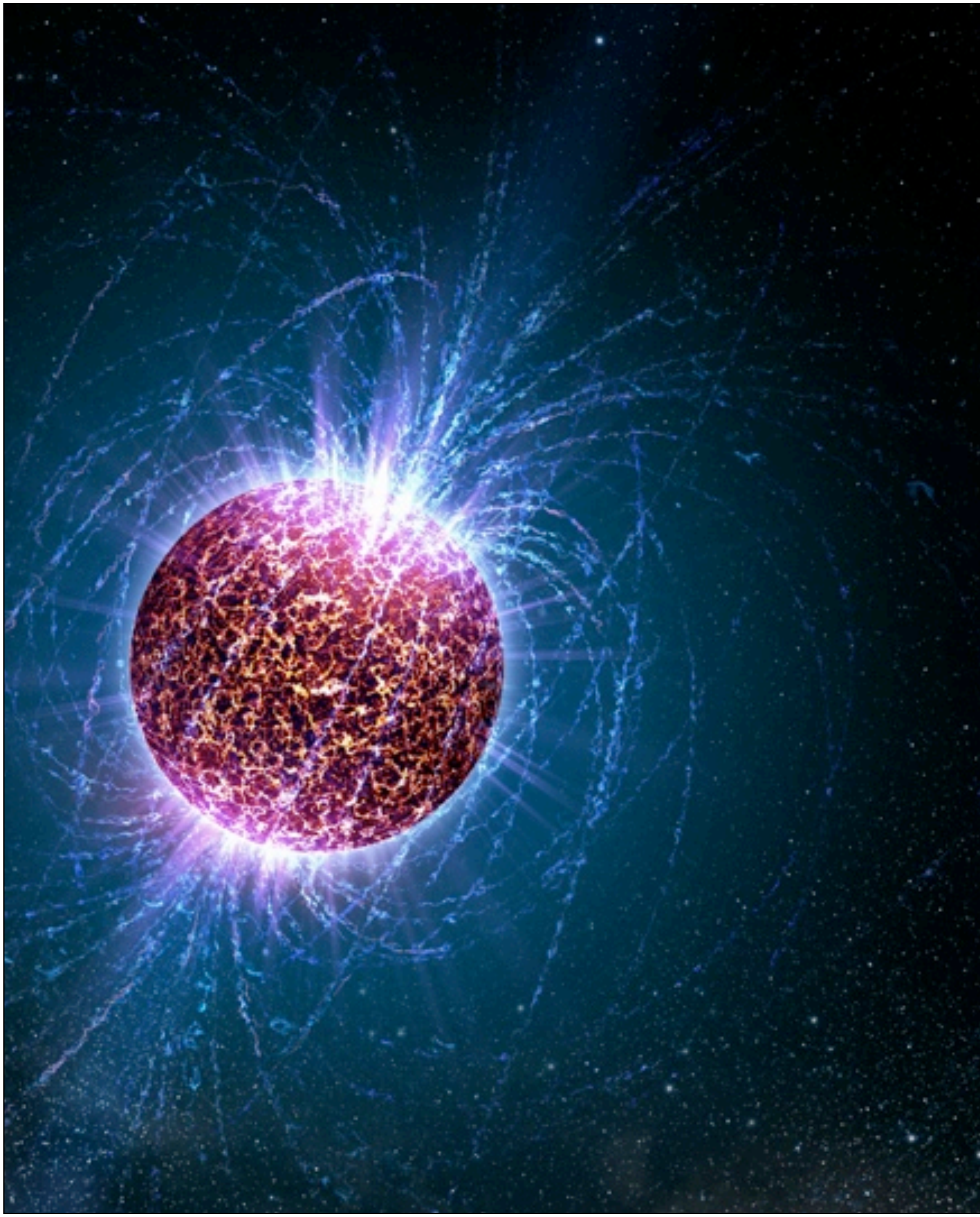
# Dead Stars leave corpses

- White dwarfs
  - remnant core of low mass star
  - supported by electron degeneracy pressure
- Neutron stars
  - remnant core of high mass star
  - supported by neutron degeneracy pressure
- Black Holes
  - remnant of some massive stars
  - gravity's ultimate victory

# White Dwarfs



- White dwarfs are the remaining cores of low mass dead stars.
- The mass of a star compressed into roughly the size of the Earth



# Neutron Stars

Neutron stars are the remnants of massive stars that exploded as supernovae.

The mass of a star compressed to roughly the size of a city (~ 10 km).

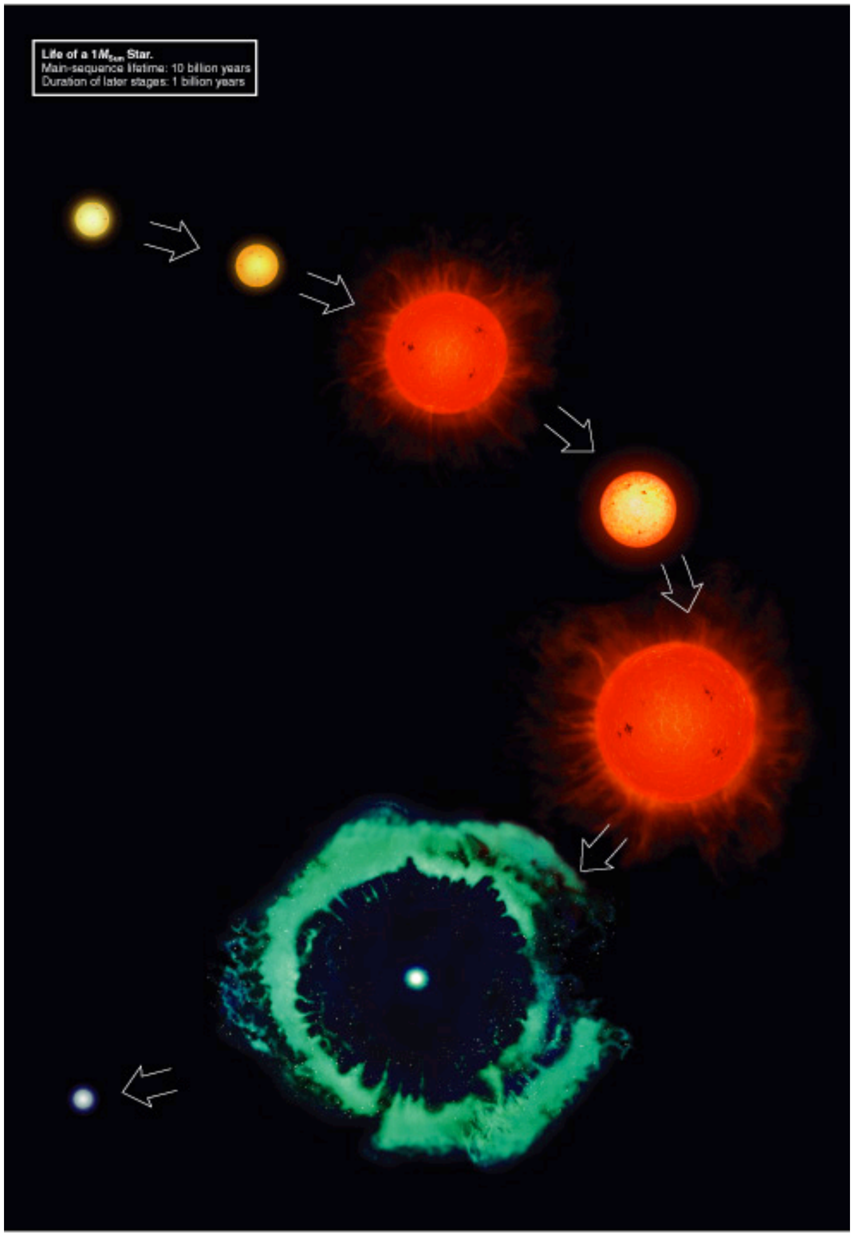
# Black Holes

A ***black hole*** is an object whose gravity is so powerful that not even light can escape it.

Some massive star supernovae can make a black hole if enough mass falls onto the core.

All mass compressed to a mathematical point.

# Reasons for Life Stages




*Not to scale!*

- Core shrinks and heats until it's hot enough for fusion
- Nuclei with larger charge require higher temperature for fusion
- Core thermostat is broken while core is not hot enough for fusion (shell burning)
- Core fusion can't happen if degeneracy pressure keeps core from shrinking