Low Mass Stars: Post Main Sequence Evolution

After the main sequence: Hydrogen supply in the core is used up.

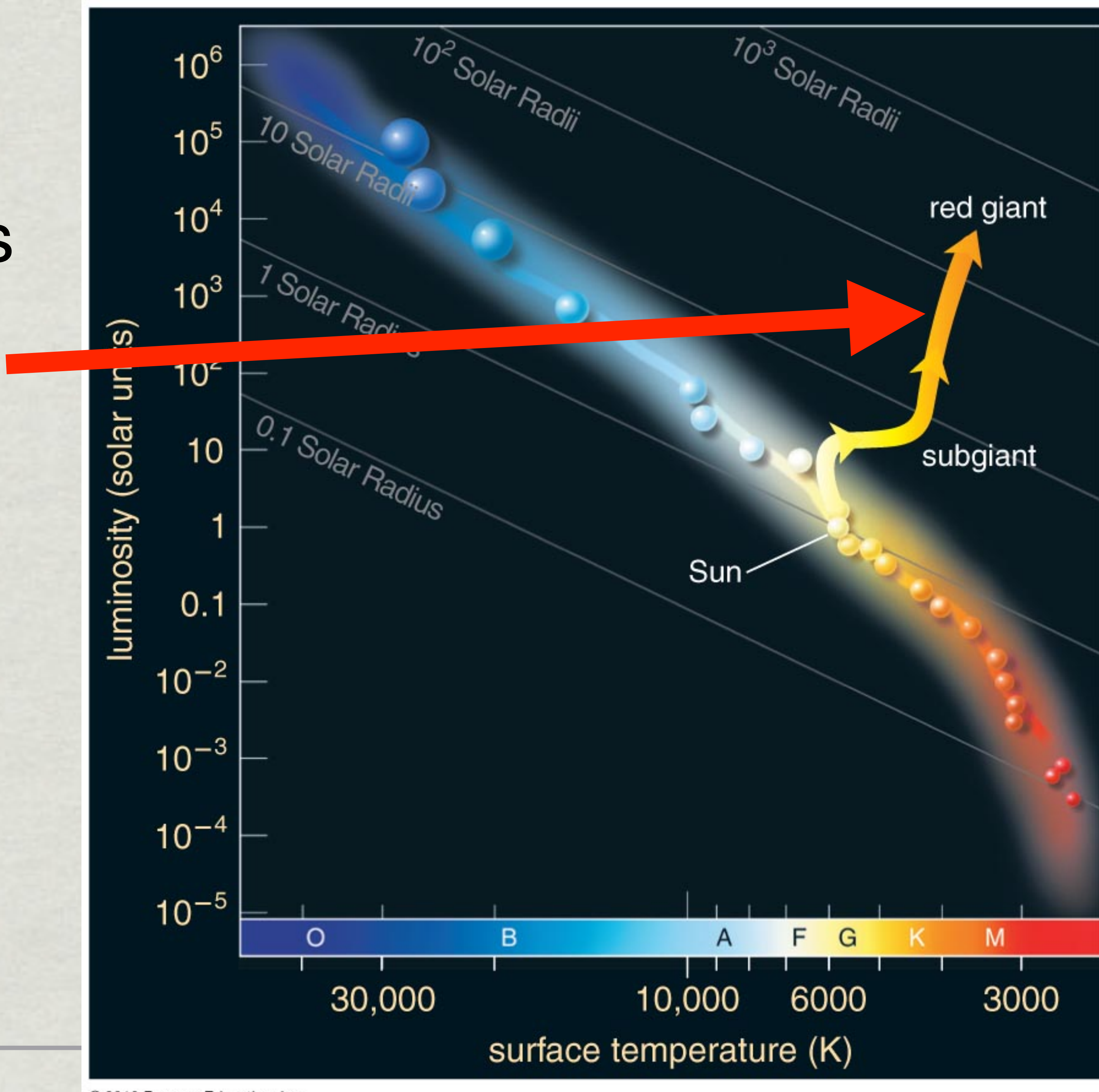
Fusion ends (no fuel!)

Temperature drops → thermal pressure drops

Gravitational equilibrium is broken: No thermal energy generation to balance gravitational force of star's mass.

What happens?   Core collapse!

Gravity wins, causes star to fall in on itself toward the center, get more dense



Low Mass Stars: Post Main Sequence Evolution

After the main sequence: Hydrogen supply in the core is used up.

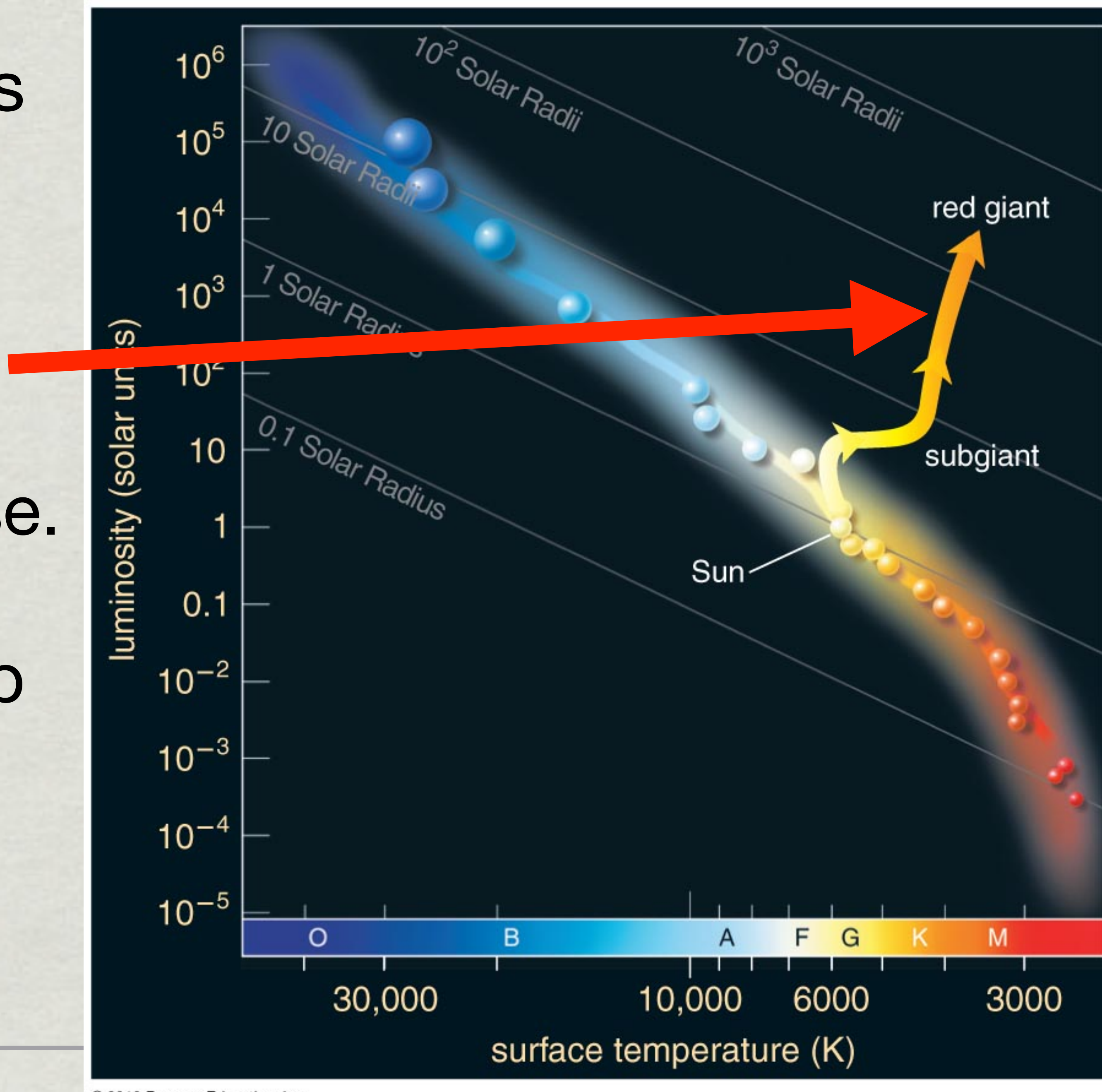
Fusion ends (no fuel!)

Gravitational equilibrium is broken: No thermal energy generation to balance gravitational force of star’s mass

Core collapse!

Gravity wins, star falls in on itself toward the center, gets more dense.

But what we see is a new track, up and to the right on the H-R diagram!
Why?
What stops the collapse?



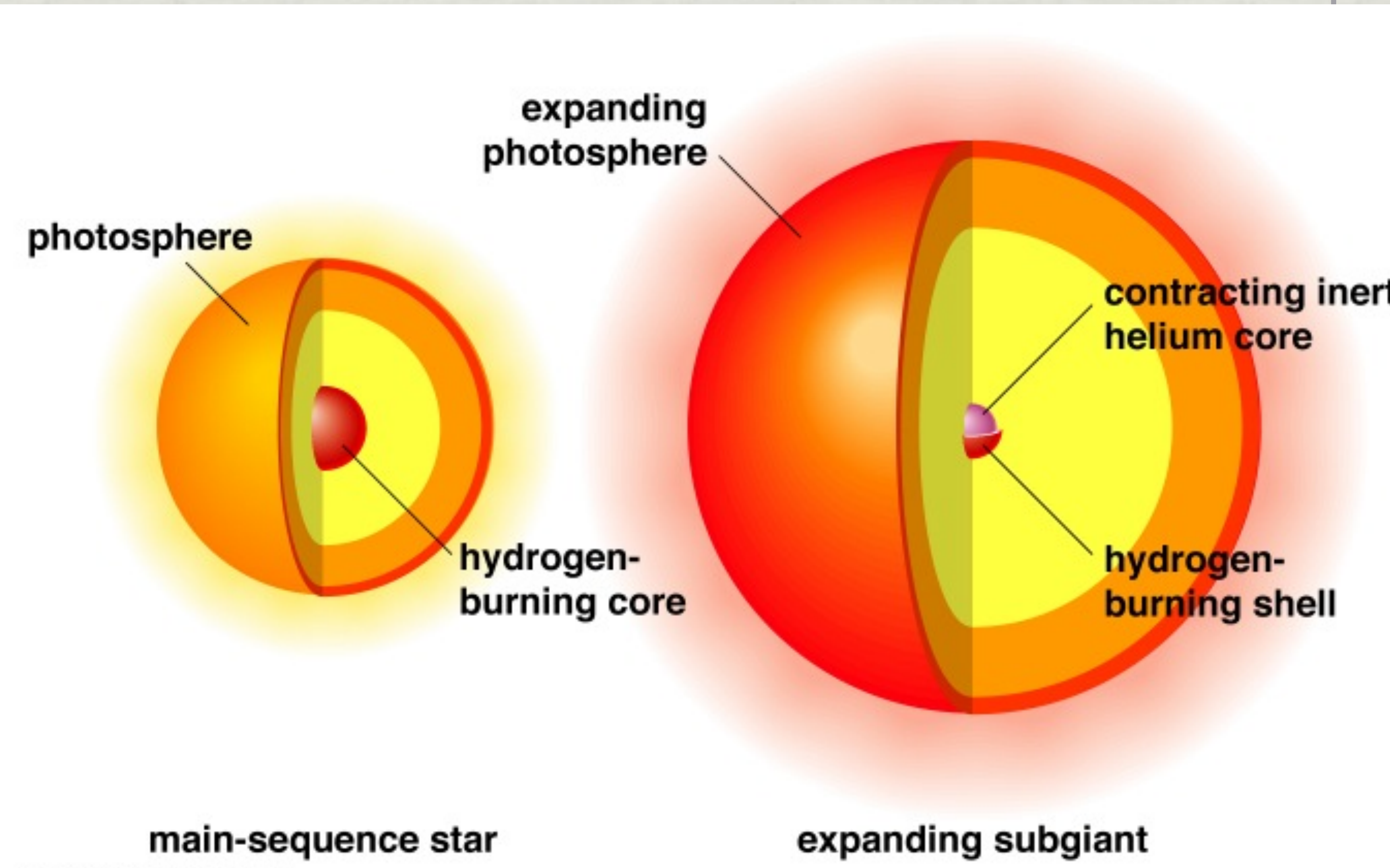
Low Mass Stars: Post Main Sequence Evolution

Core collapse!

As the star collapses, density increases everywhere.

Eventually, material that used to be outside the core becomes as dense as the core used to be: dense enough to start nuclear fusion. Still has plenty of H fuel for nuclear fusion, now it is dense enough for the reactions to start.

Shell “burning”: a narrow sphere outside the core where nuclear fusion converts H→He to generate energy.



Low Mass Stars: Post Main Sequence Evolution

Core collapse!

As the star collapses, density increases everywhere.

Eventually, material that used to be outside the core becomes as
dense as the co
rt nuclear
fusion. Still has
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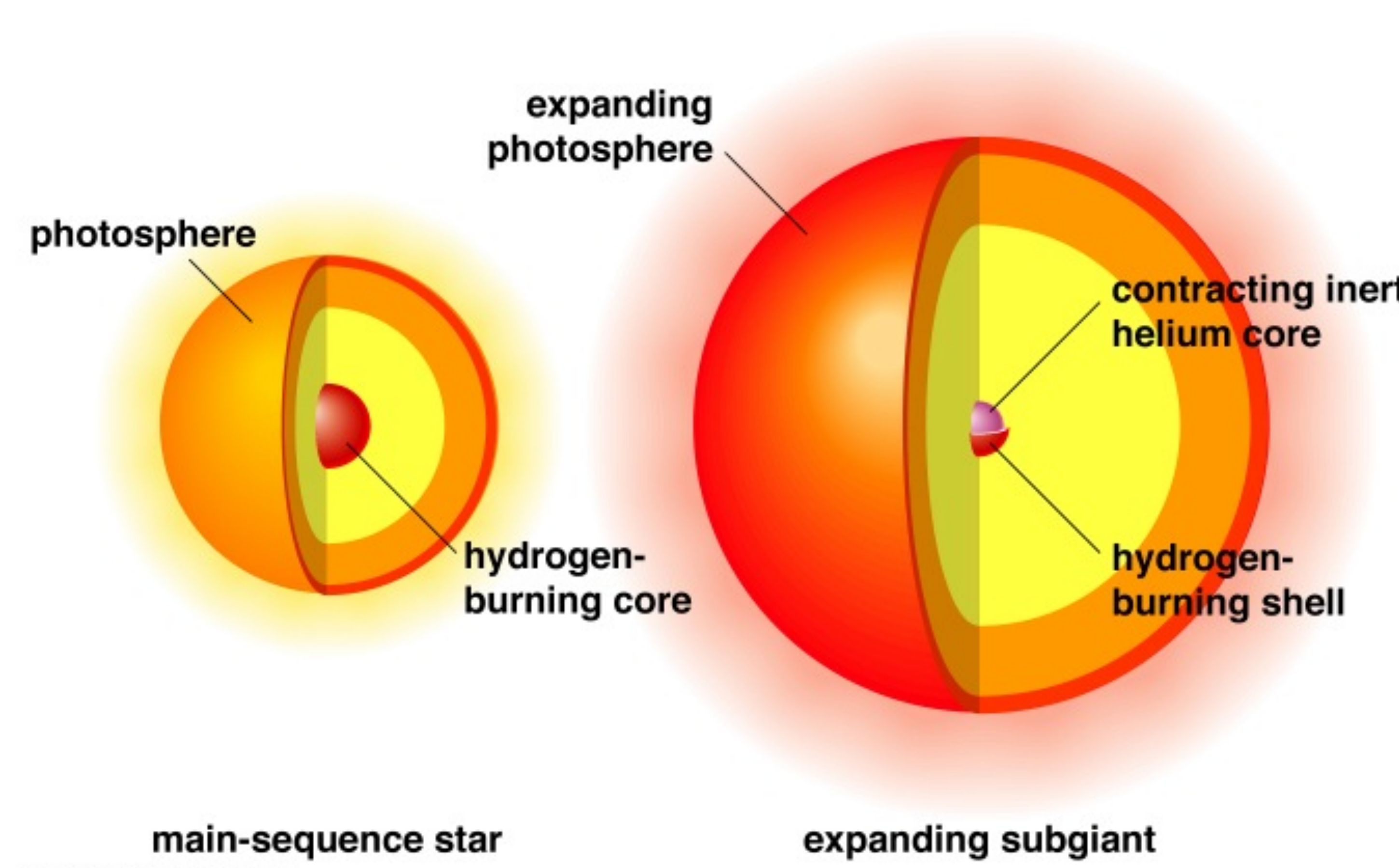
enough for the r

“burning” = using fuel, but using for nuclear fusion, not like you burn firewood or propane or ….

Shell “burning”: a narrow sphere outside the core where nuclear fusion converts H→He to generate energy.



Low Mass Stars: Post Main Sequence Evolution

Shell burning: H→He outside the core where H is used up.

Luminosity increases: Fusion takes place over a larger volume of the star (the shell)

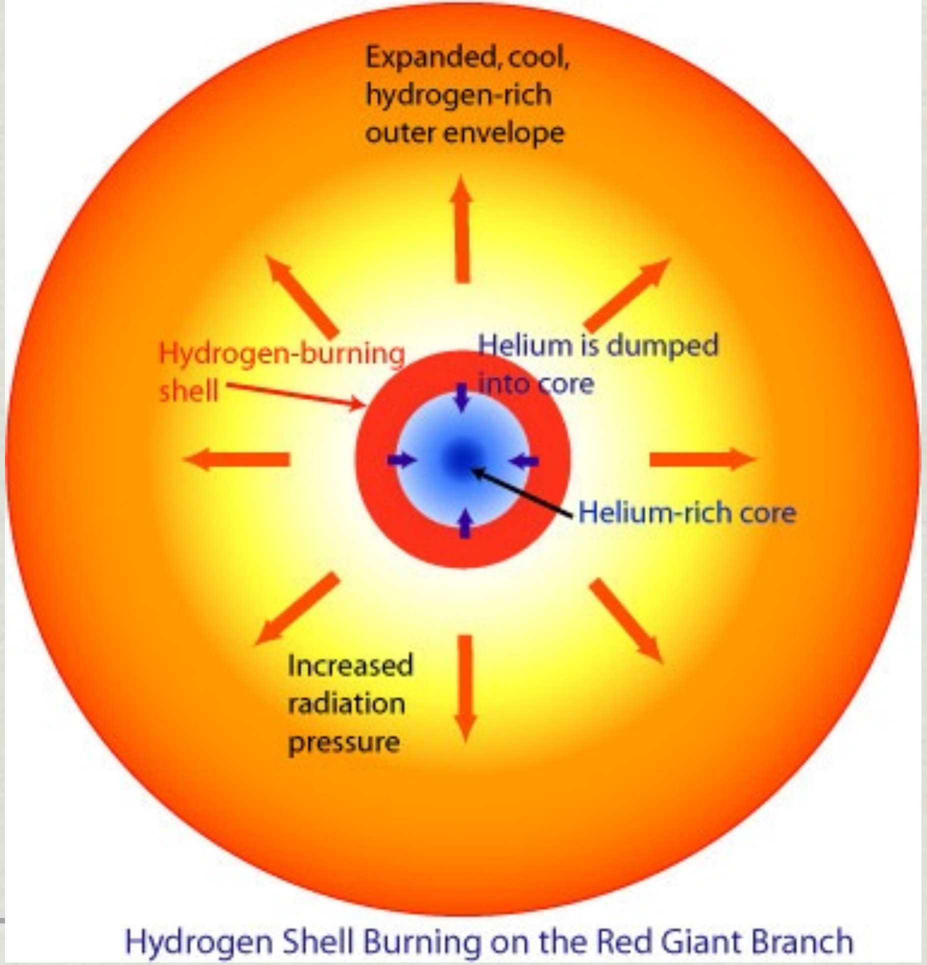
But gravitational equilibrium in the core is still broken: there isn't enough hydrogen fuel for energy generation from nucleosynthesis

Eventually, density gets high enough that degeneracy pressure takes over (see end of Lecture 12)

Now pressure in the core depends on only density.

!!Not like the ideal gas law:
Pressure = k x Temperature x density

So nuclear fusion in the shell generates energy, but is not providing pressure support in the core



Hydrogen Shell Burning on the Red Giant Branch

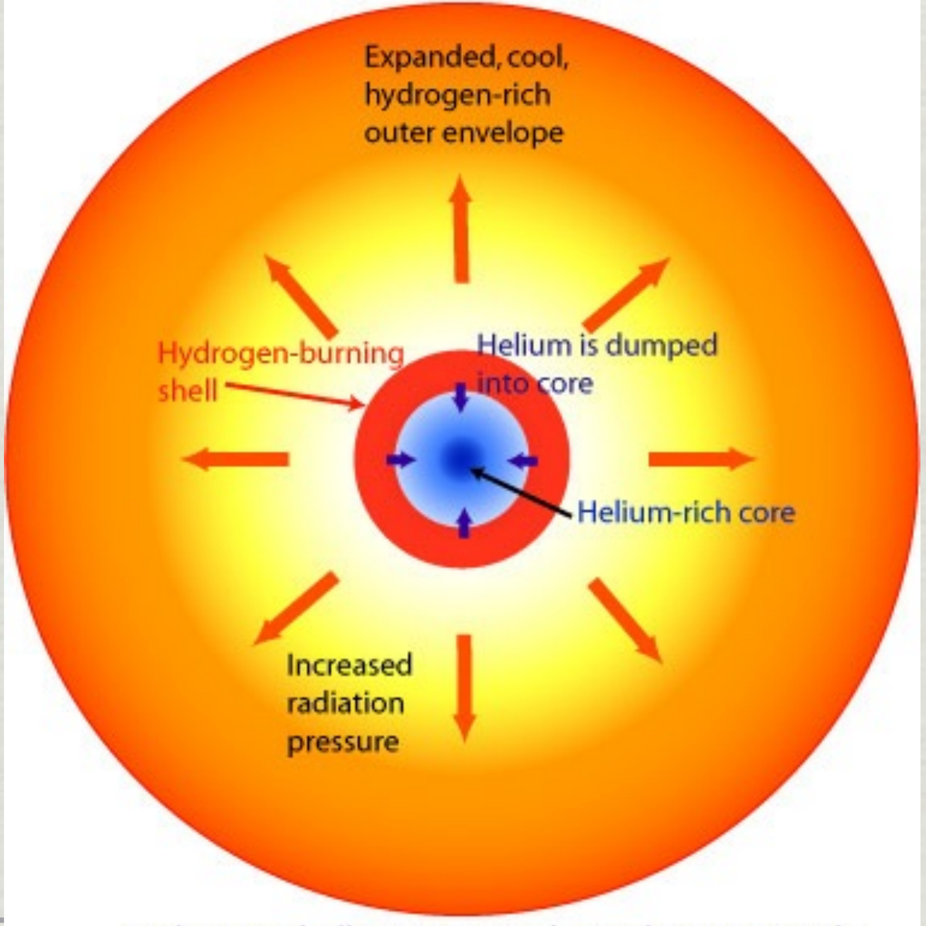
Low Mass Stars: Post Main Sequence Evolution

Shell burning: H→He outside the core where H is used up.

Luminosity increases: Fusion takes place over a larger volume of the star (the shell), but no longer in the core

Degeneracy pressure takes over: pressure now depends only on density, so energy input from the shell burning is not providing pressure support to the core

But energy from the shell burning does heat up the outer layers, cause them to expand - like heating up a balloon.



Hydrogen Shell Burning on the Red Giant Branch

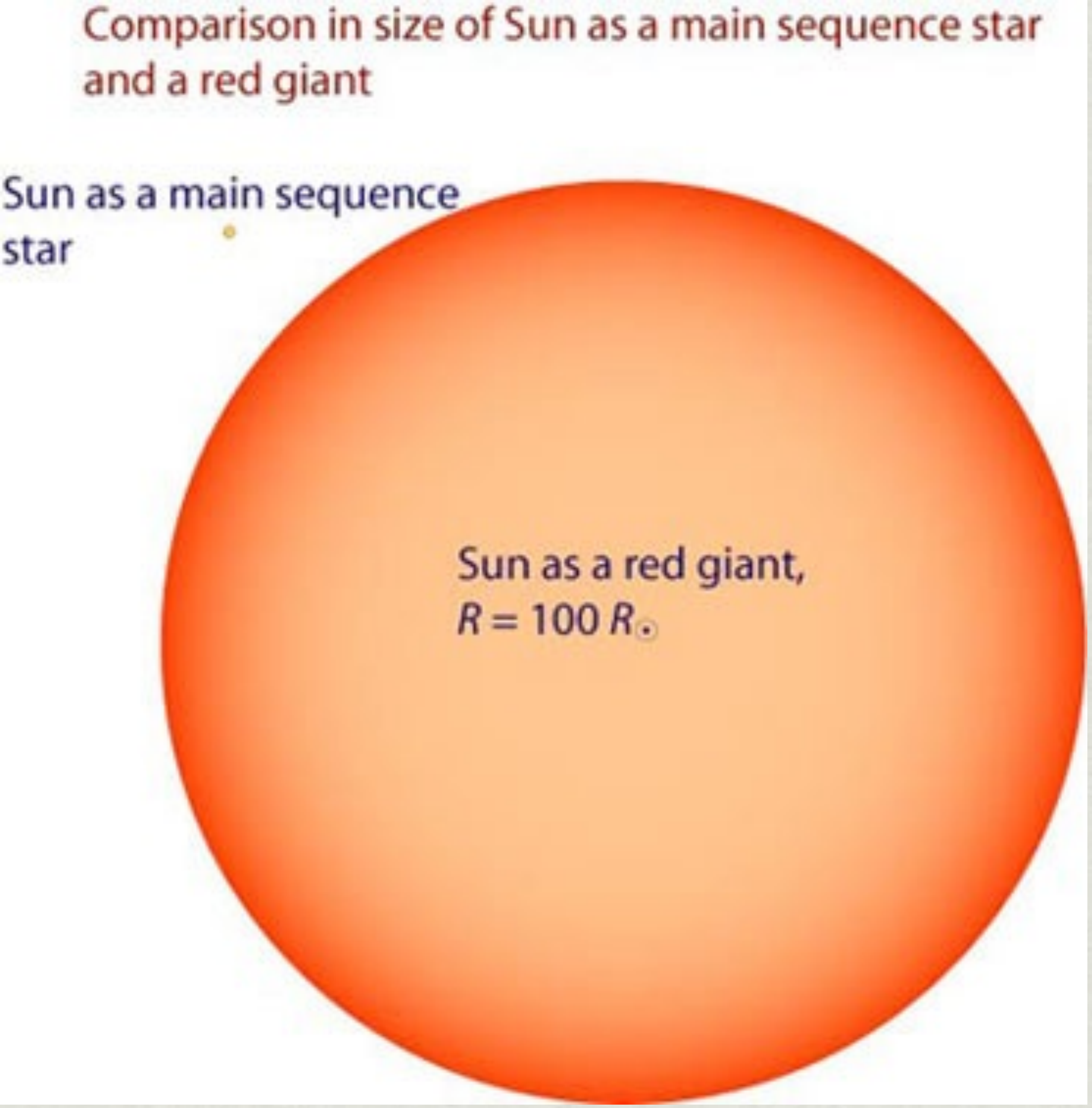
Energy from the shell burning heats up the outer layers, cause them to expand - like heating up a balloon.

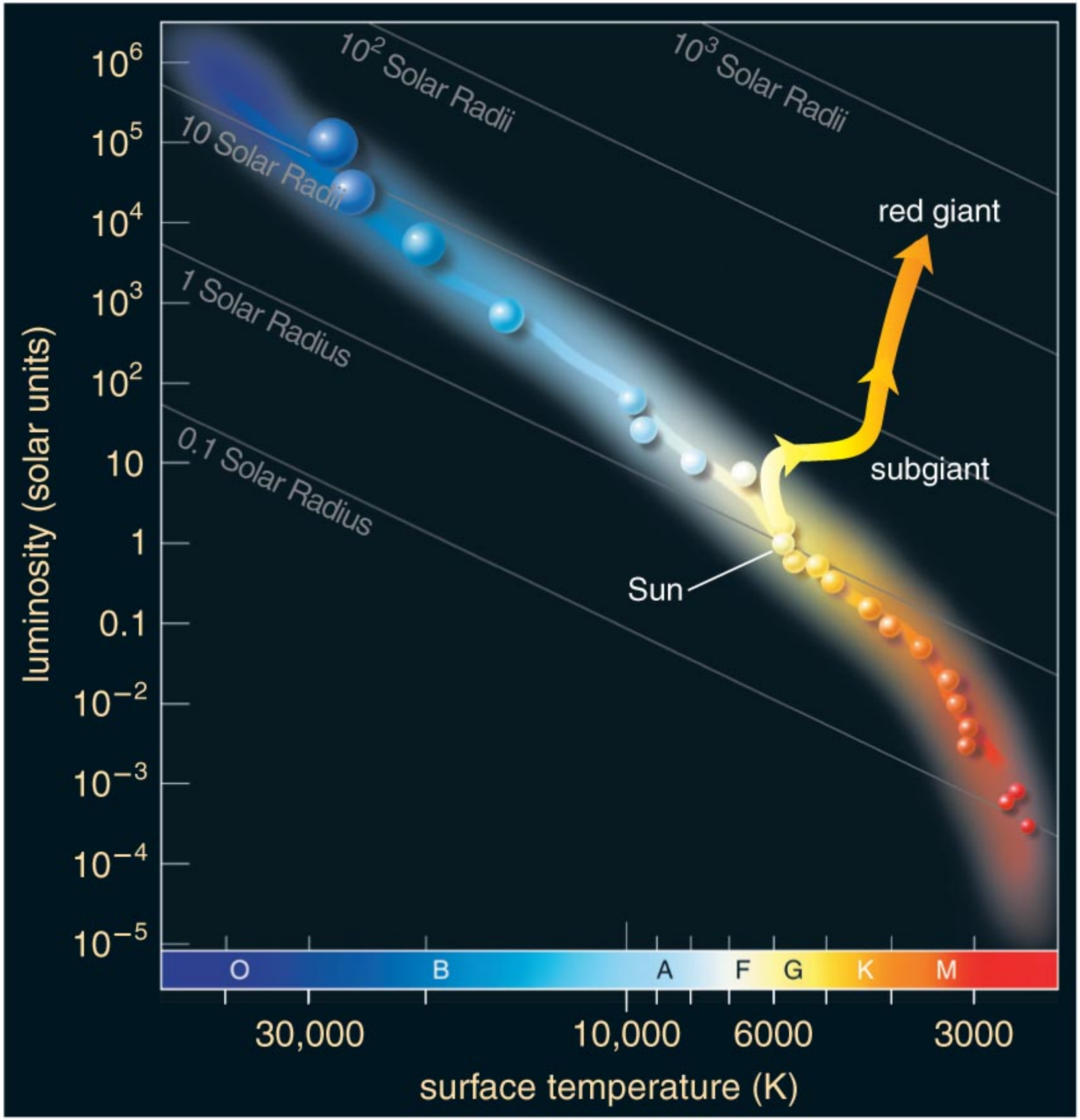
That expansion causes the star to cool

Core keeps collapsing

Shell follows it down, burning faster, making the star brighter, all the time

More luminous but cooler: star becomes a Red Giant


Comparison in size of Sun as a main sequence star and a red giant



10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^−2
10^−3
10^−4
10^−5
luminosity (solar units)
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
red giant
subgiant
Sun
O
B
A
F
G
K
M
30,000
10,000
6000
3000
surface temperature (K)

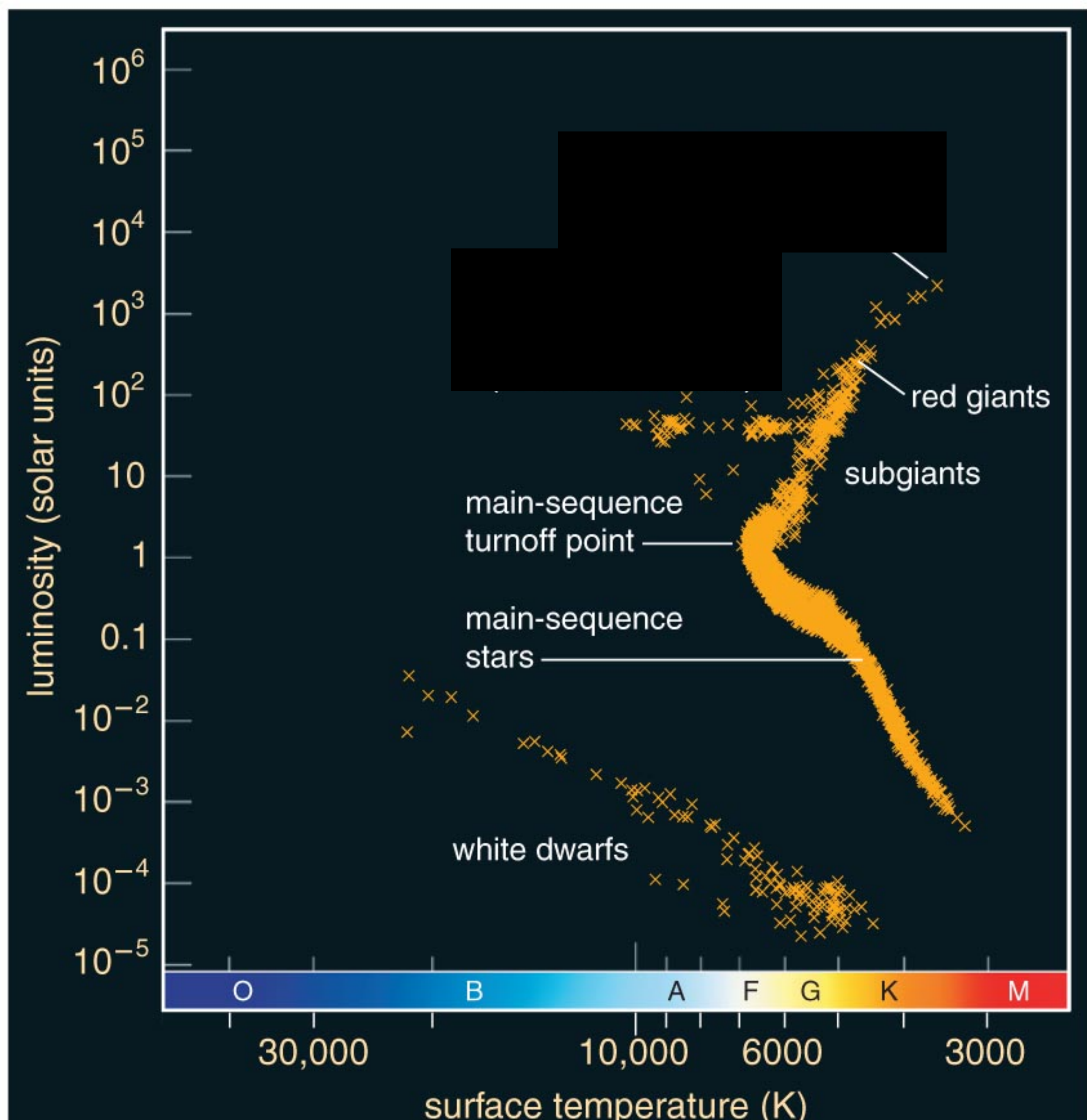
Low Mass Stars: Post Main Sequence Evolution

If the pressure in the core never gets high enough, core never “re-ignites” (re-starts fusion)

Star continues to expand until it escapes from the star. Becomes a planetary nebula.

Star ends with an inert He core supported by degeneracy pressure

Star fades away, becomes a Helium white dwarf



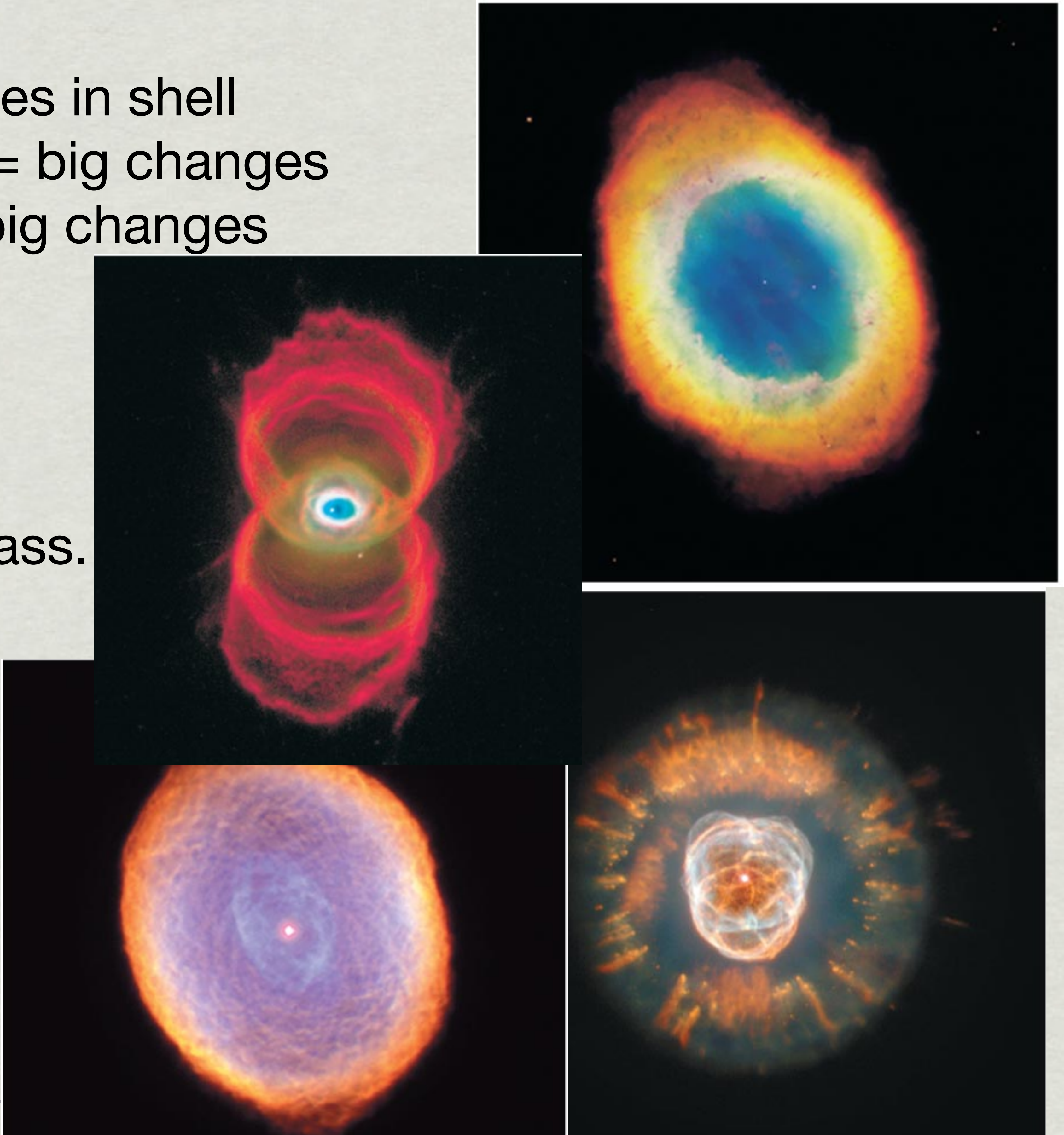
Low Mass Stars: Post Main Sequence Evolution

Brighter, cooler (redder)

Very unstable, big changes in shell nucleosynthesis rates = big changes in thermal pressure = big changes in size.

“Thermal pulses” → outer envelope escapes, star loses mass.

Becomes a planetary nebula which is not really a planet at all!

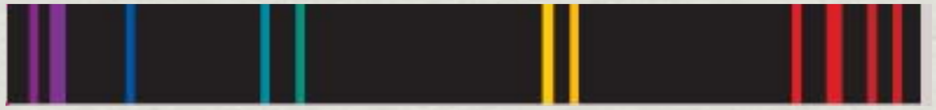


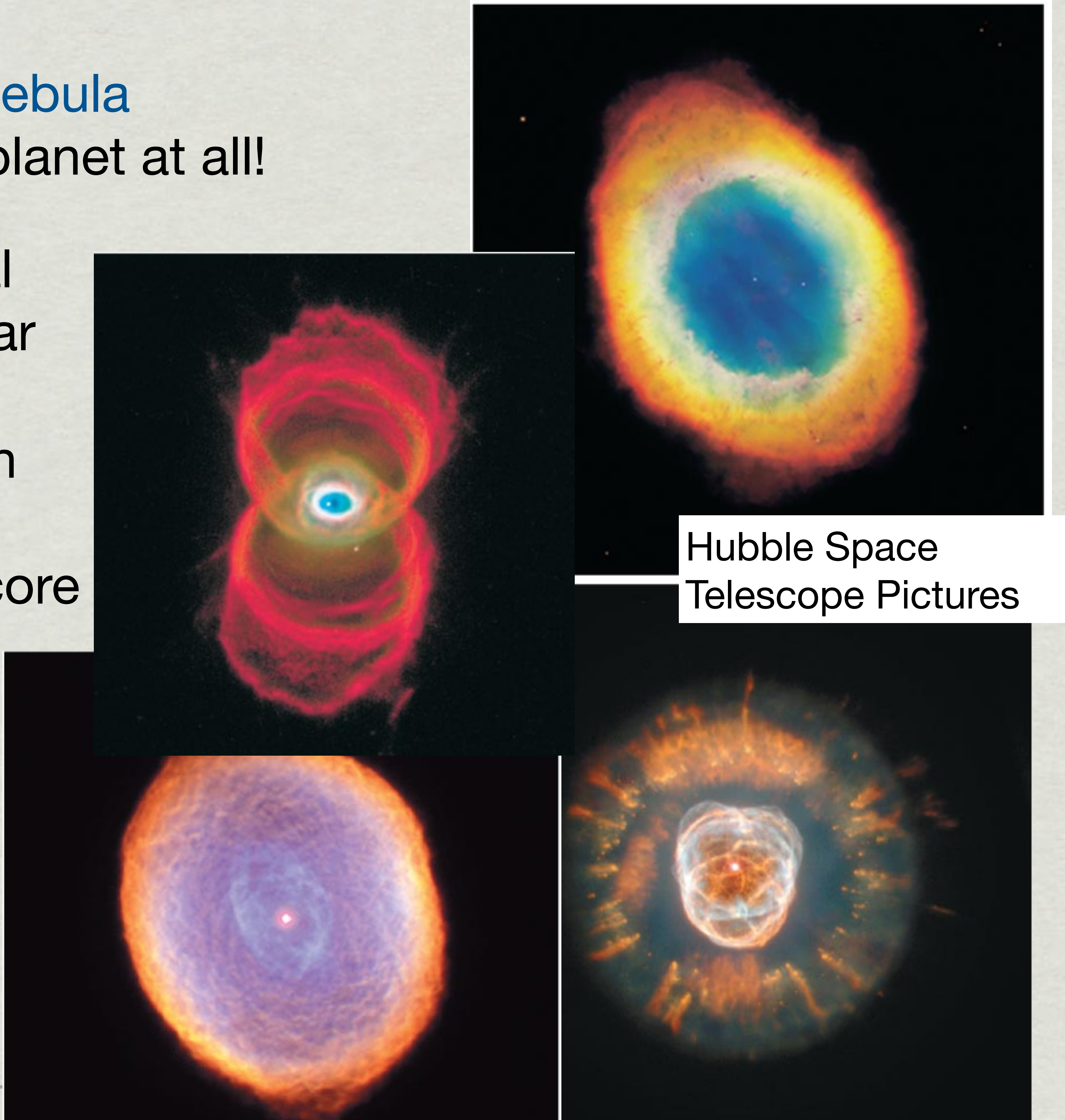
Low Mass Stars: Post Main Sequence Evolution

Becomes a planetary nebula
which is not really a planet at all!

Shells of ejected material
Expanding away from star
→ gas becomes transparent, emission line spectrum.
Heated by the bare core left behind

Emission line spectrum:





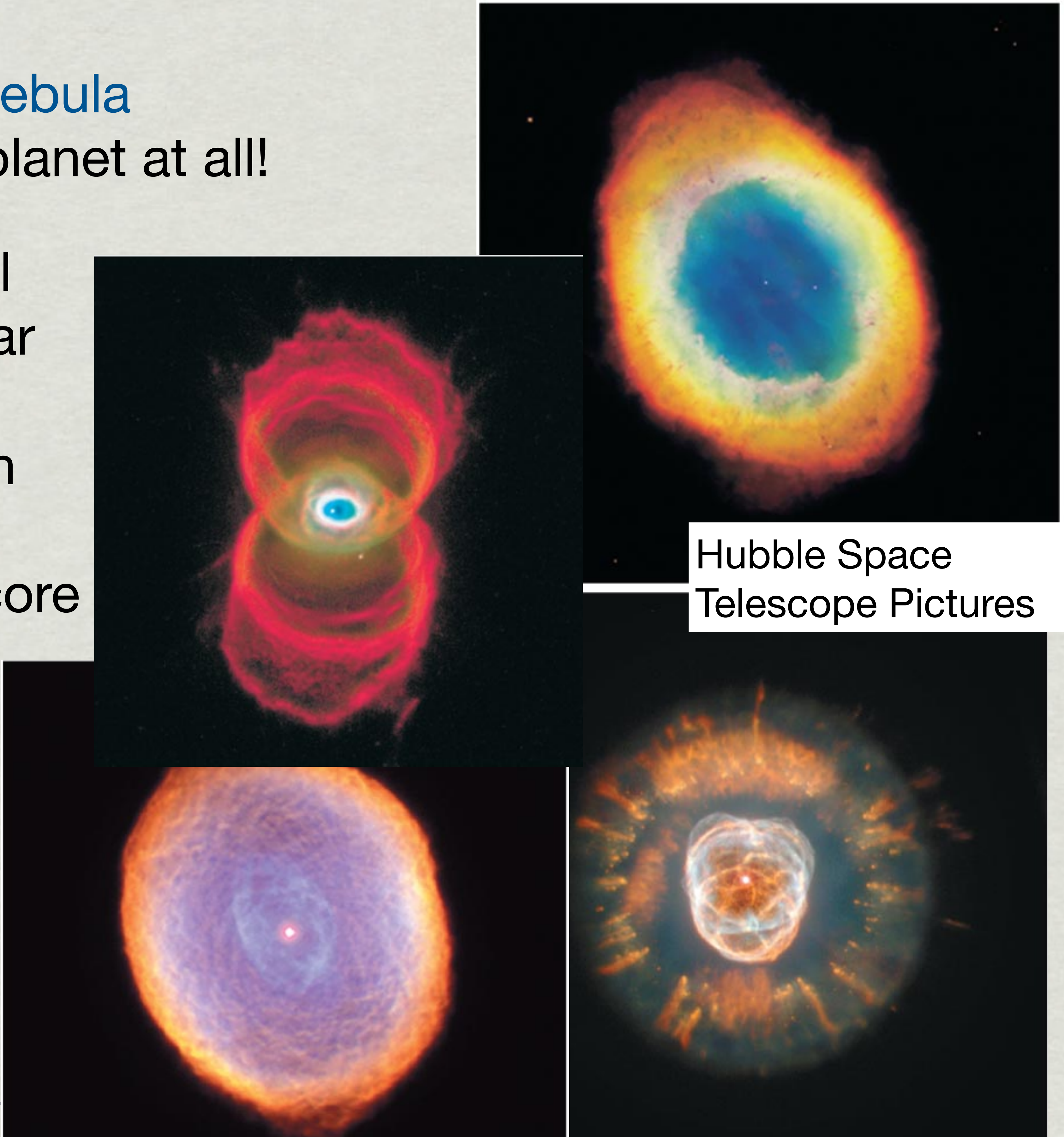
Hubble Space Telescope Pictures

Low Mass Stars: Post Main Sequence Evolution

Becomes a planetary nebula
which is not really a planet at all!

Shells of ejected material
Expanding away from star
→ gas becomes transparent, emission line spectrum.
Heated by the bare core left behind

Called “planetary” because they look like round disks in a small telescope on earth, just as planets do.

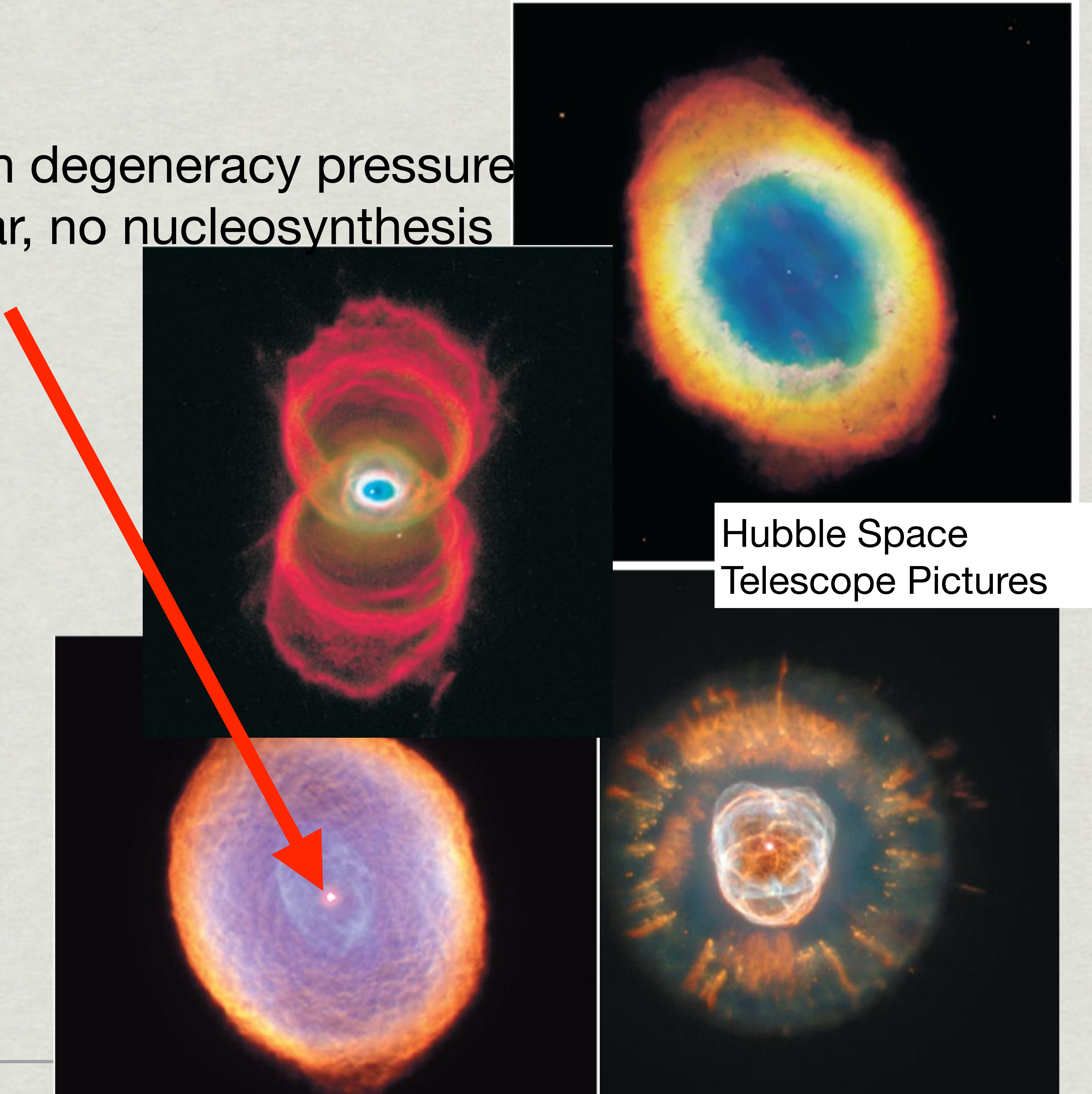


Hubble Space
Telescope Pictures

Low Mass Stars: Post Main Sequence Evolution

White Dwarf

- Supported by electron degeneracy pressure
- Inert He, C core of star, no nucleosynthesis
- Cooling slowly, losing energy, getting less luminous



Hubble Space Telescope Pictures

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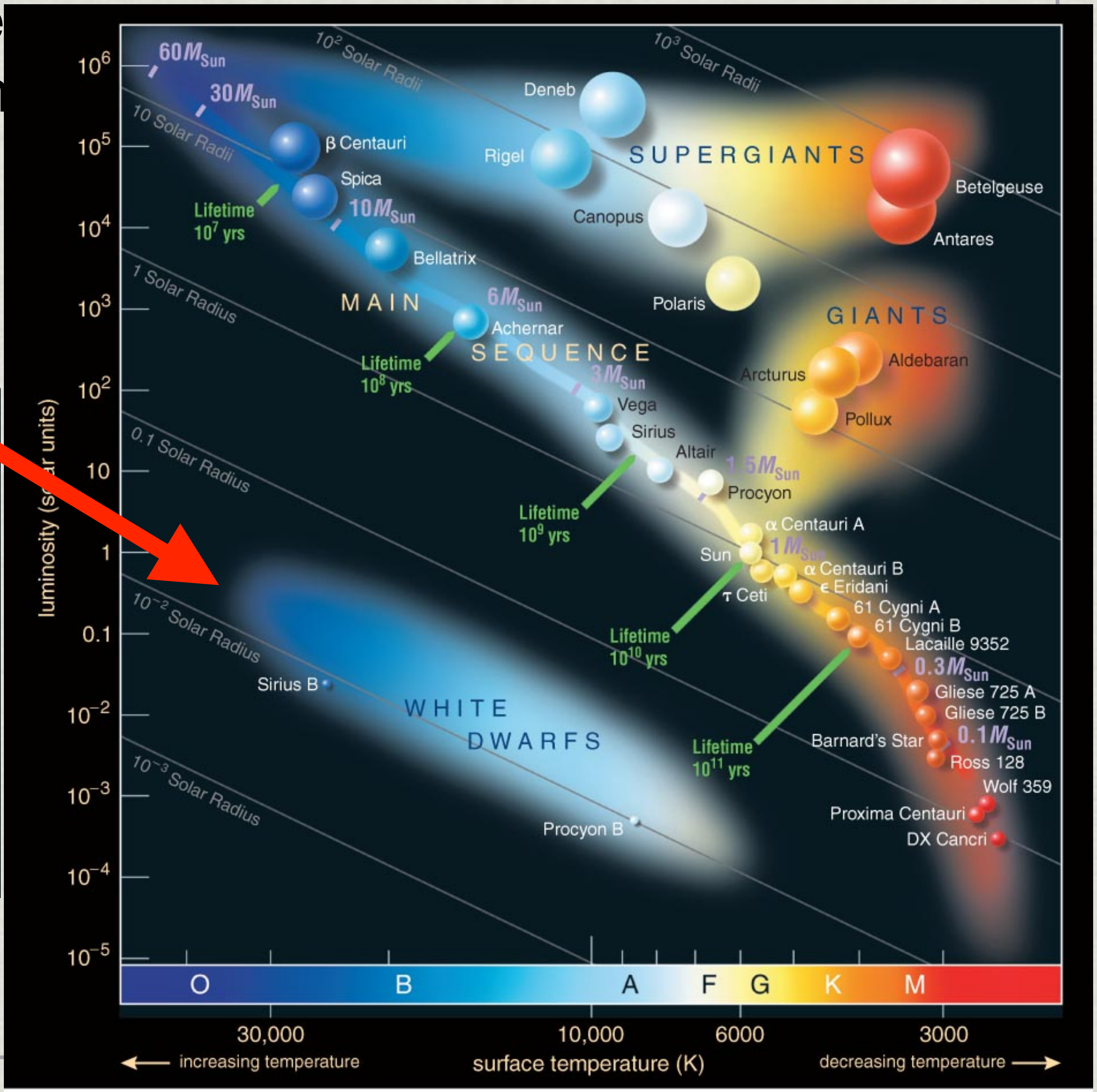
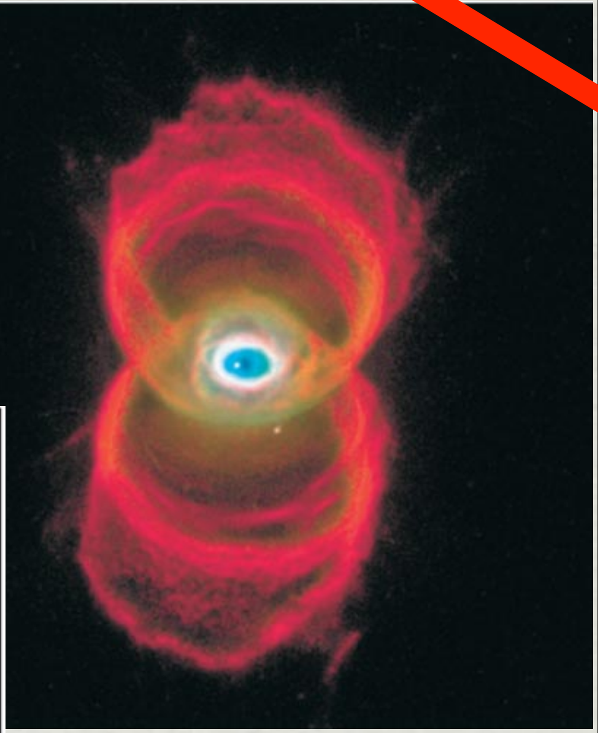


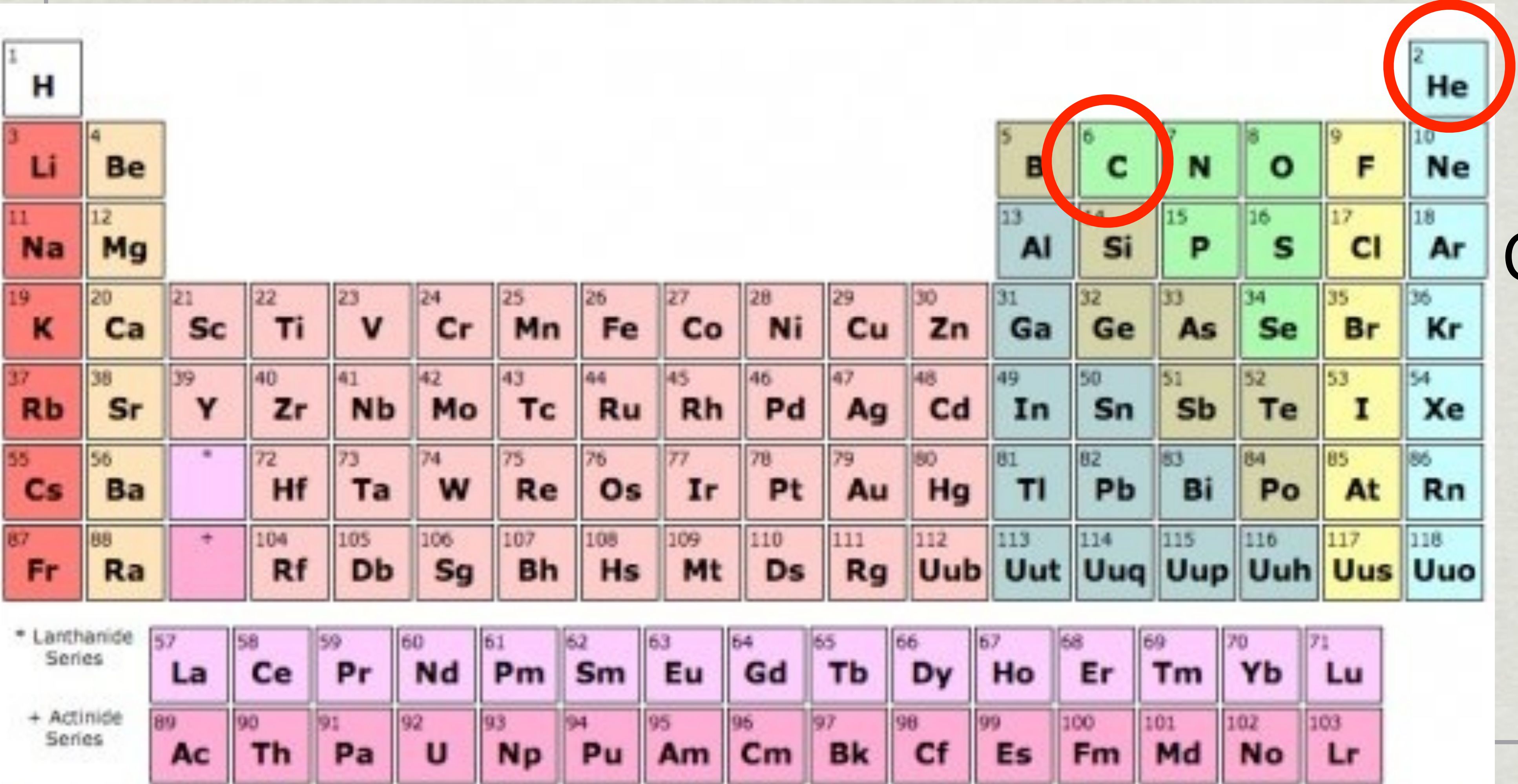


Low Mass Stars: Post Main Sequence Evolution

If the pressure in the core does get high enough, core can re-start nuclear fusion.

But it already used up its hydrogen supply.

Has to go further along the periodic table.



1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	+	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Uub	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo
* Lanthanide Series	57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
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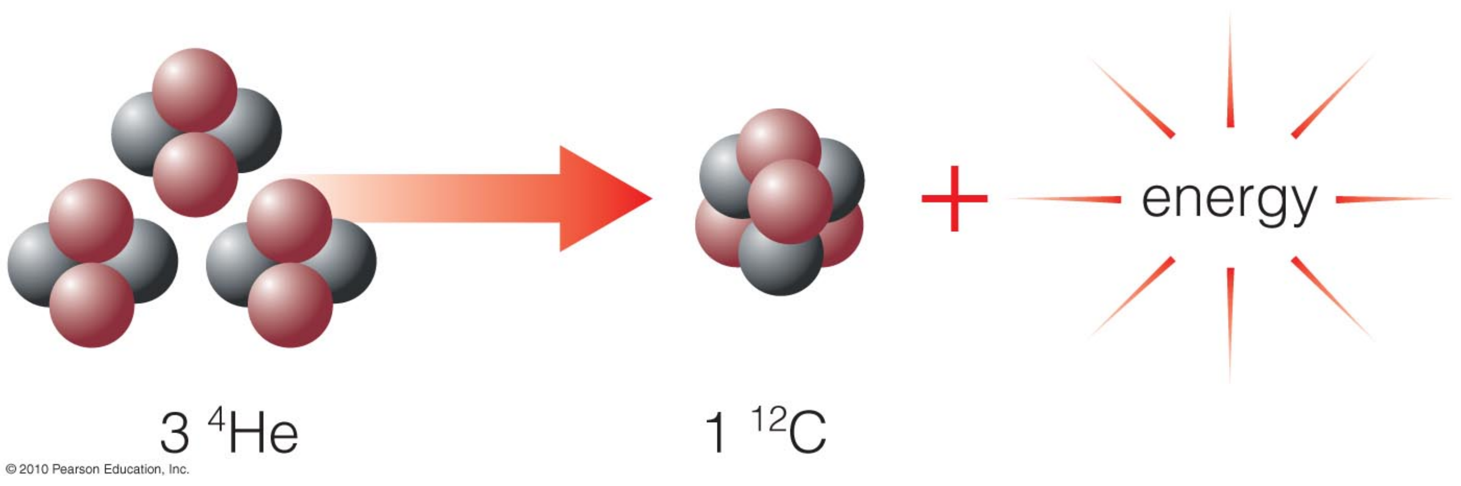
Helium: 2 protons
2 neutrons

Carbon: 6 protons
6 neutrons

Low Mass Stars: Post Main Sequence Evolution

If the pressure in the core does get high enough, core can re-start nuclear fusion. But further along the periodic table.



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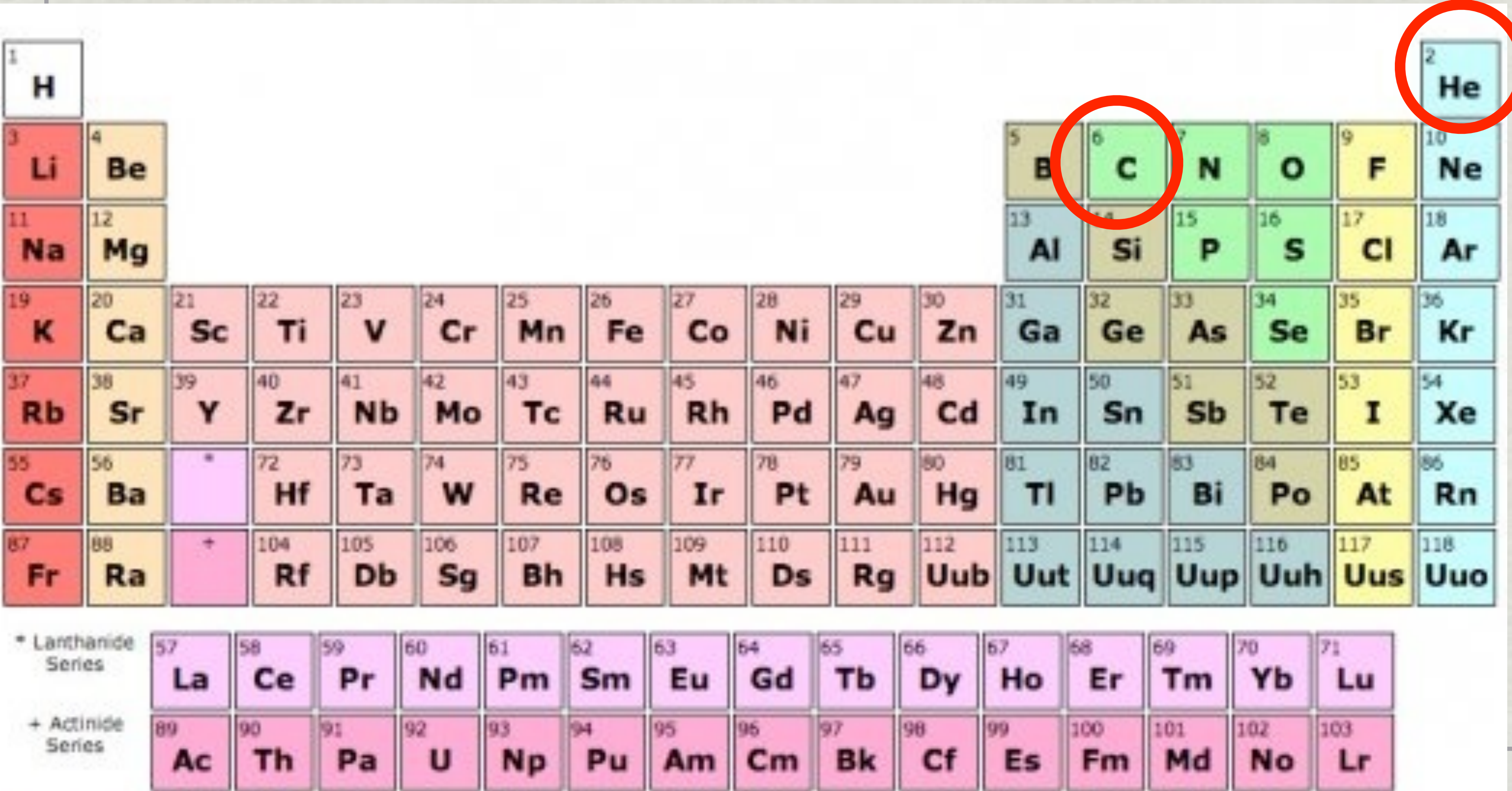

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37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	*	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
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2 neutrons

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6 neutrons

Recap: Nucleosynthesis

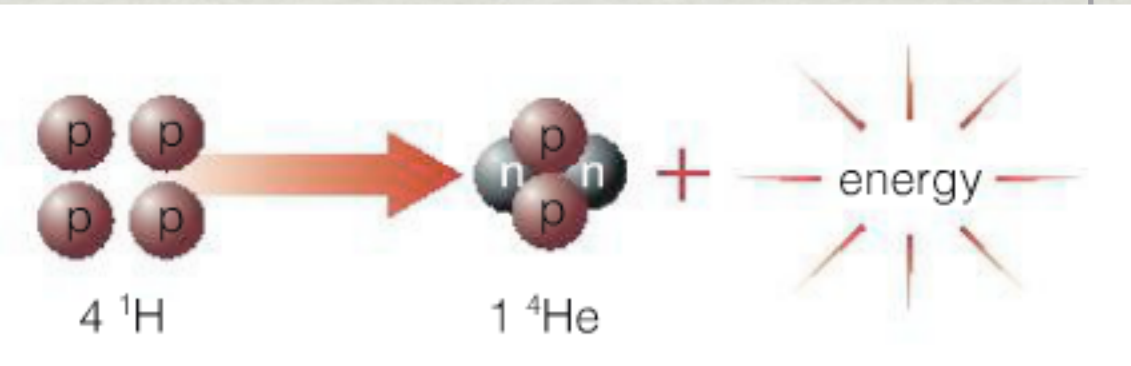
How do you make energy out of 2 x 10^{30} kg of Hydrogen?

One Helium atom is ***less*** massive than 4 Hydrogen atoms?

4 H atoms = 4 protons: 6.693 x 10^{-27} kg
1 He atom = 2 protons + 2 neutrons: 6.645 x 10^{-27} kg (less massive! by 0.7%)

If you stick together Hydrogen atoms to make Helium, the extra mass has to go somewhere.

It becomes energy: **$E = mc^2$**



Mass and energy are the same thing, and transform back and forth using this equation.

Fusing Hydrogen into Helium must release energy

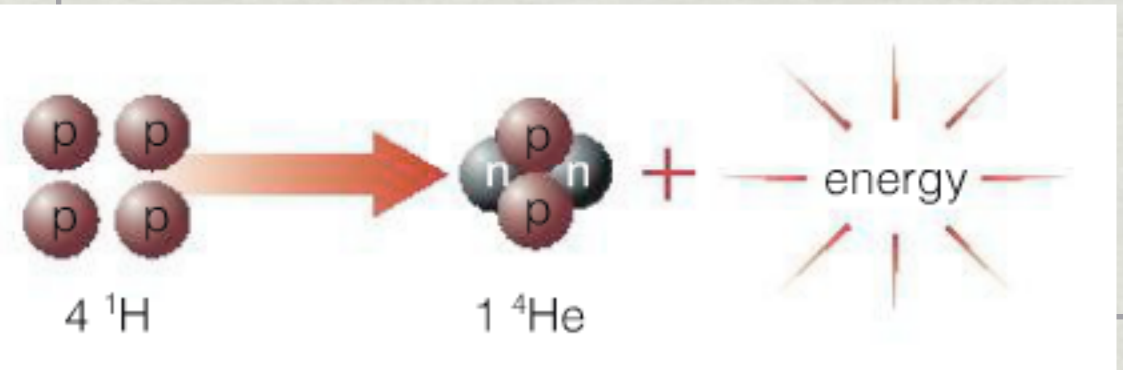
Recap: Nucleosynthesis

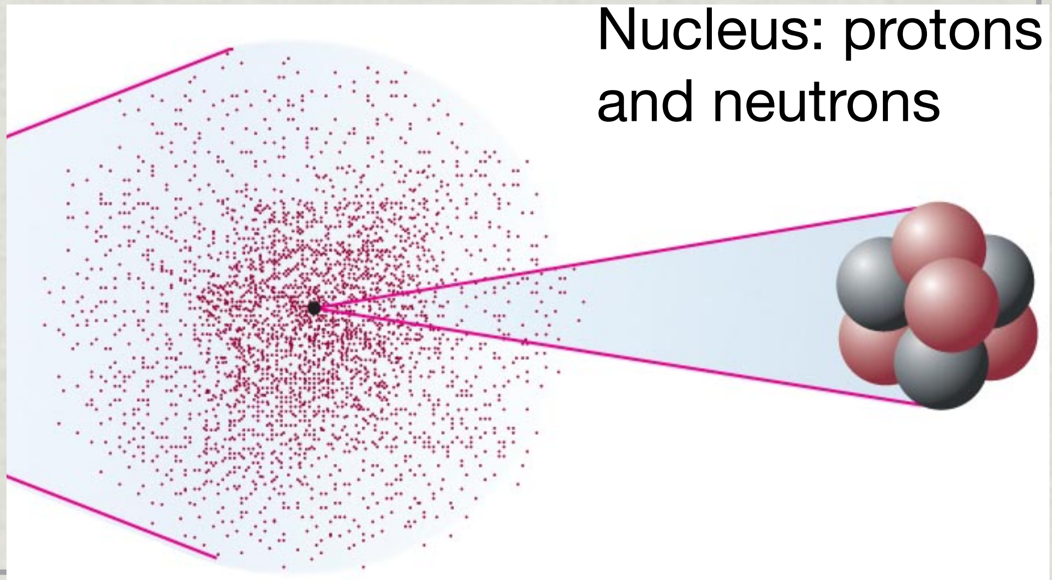
One Helium atom is ***less*** massive than 4 Hydrogen atoms
One Helium atom has more particles in its nucleus, but the mass per particle is less.

1 hydrogen nucleus = 1 proton = 1 particle (neutron or proton)
mass = 1.6726×10^{27} kg
mass per particle = 1.6726×10^{27} kg

1 helium nucleus = 2 protons + 2 neutrons = 4 particles
mass = 6.645×10^{-27} kg
mass per particle = 1.66125×10^{27} kg

So fusing 4 H nuclei to make 1 He causes the mass per particle go go down, but get energy out

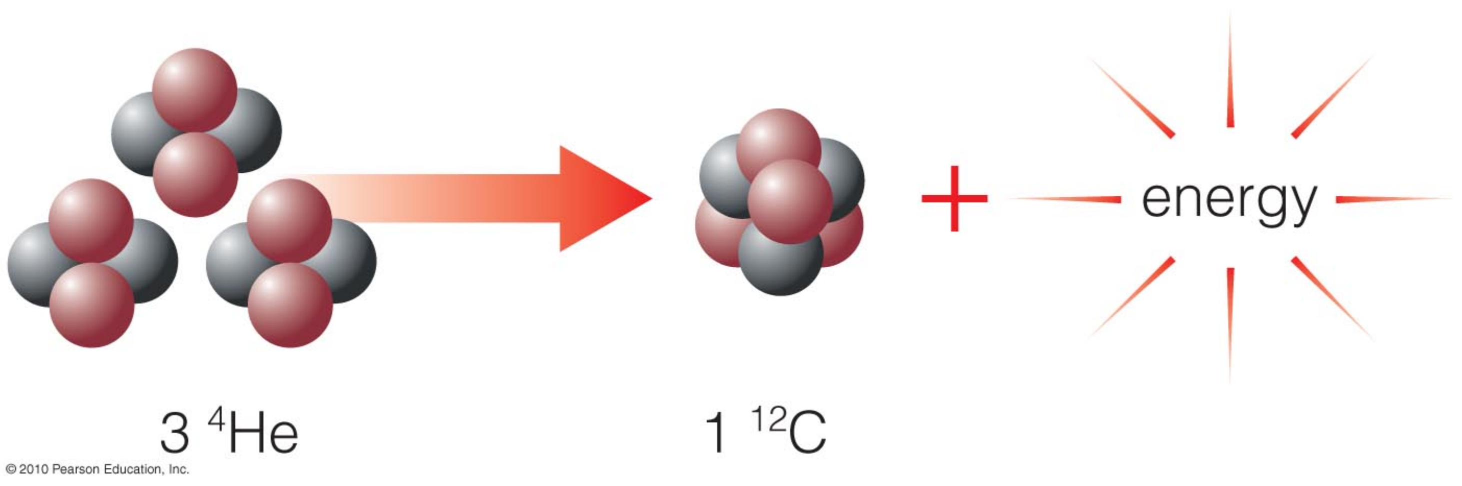



Nucleus: protons and neutrons

Electron cloud

Low Mass Stars: Post Main Sequence Evolution

If the pressure in the core does get high enough, core can re-start nuclear fusion. But further along the periodic table.



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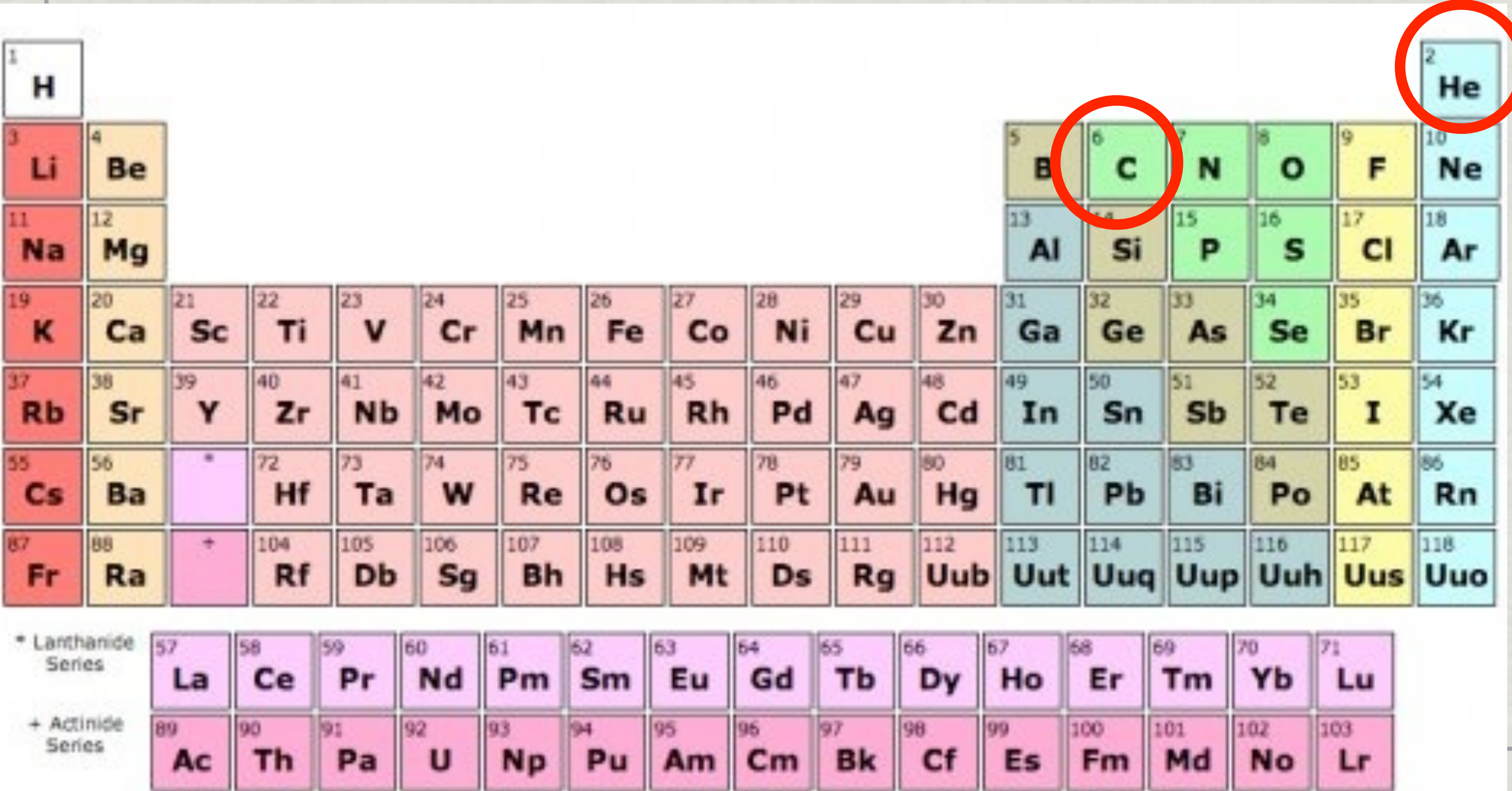

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Helium: 2 protons
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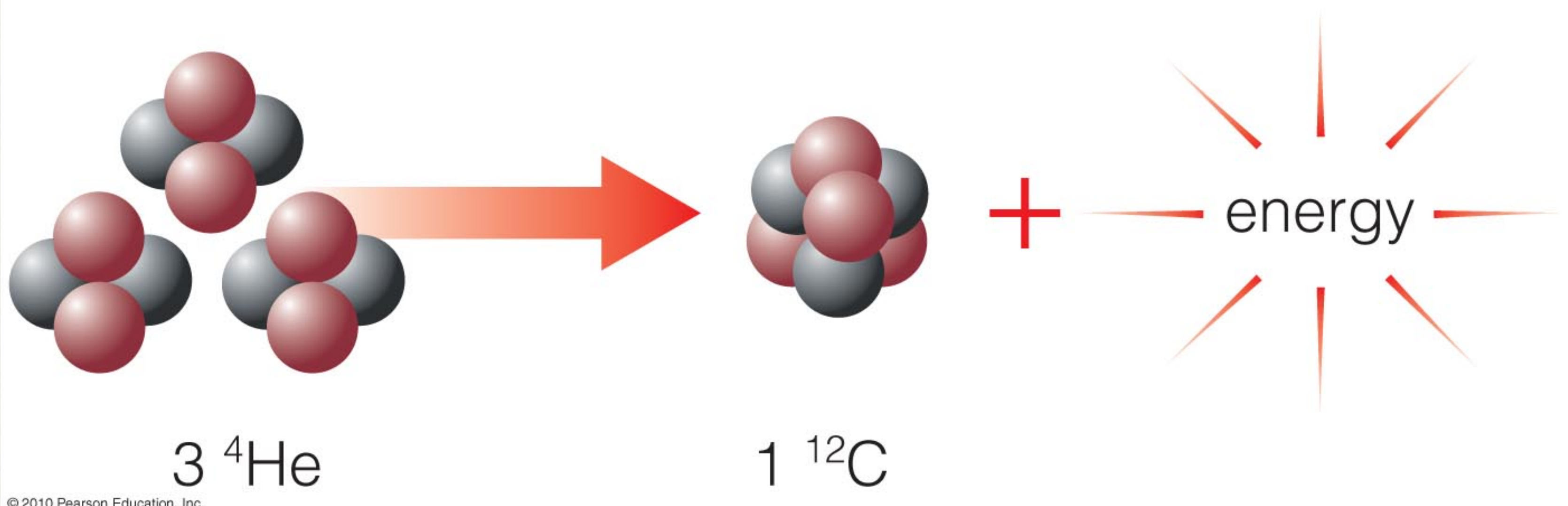
Low Mass Stars: Post Main Sequence Evolution

Helium Flash!

- In a degenerate core, energy generation from He fusion can increase temperature without increasing pressure
- He fusion rate rises quickly as temperature rises
- Nuclear fusion re-starts like a bomb (not a forest fire)
- Pumps in enough energy to re-expand core all at once.
- Removes condition for degeneracy pressure.

Restores thermal pressure support, stable nucleosynthesis regulated by gravitational equilibrium



Fusion in core = thermal pressure support against gravity

Low Mass Stars: Post Main Sequence Evolution

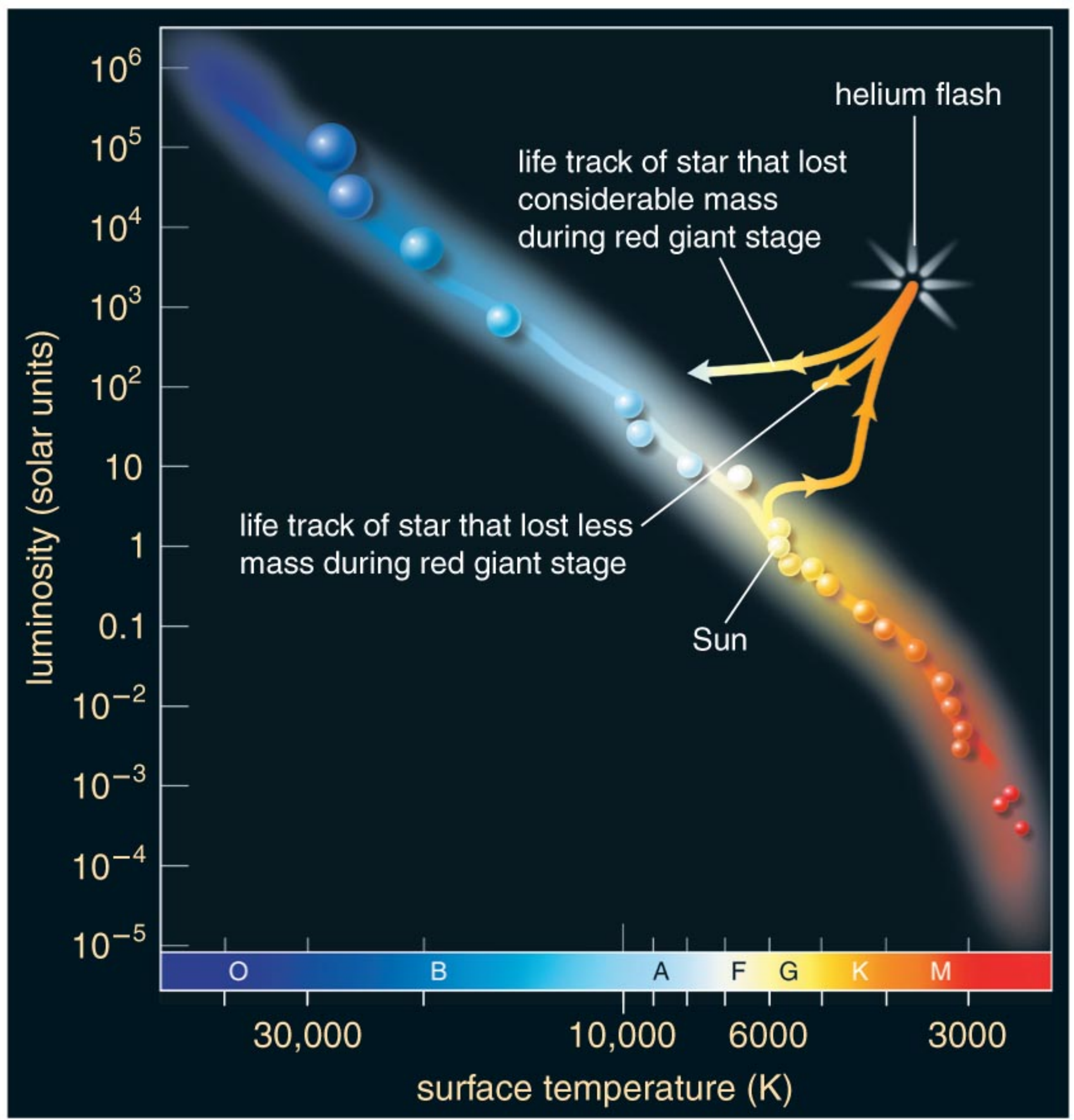
If the pressure in the core does get high enough, core re-ignites

Helium Flash

Followed by stable core fusion, He → C

Star is less luminous than at the peak of the shell-burning, collapsing core state

He burning stars are on the *horizontal branch* in the H-R diagram



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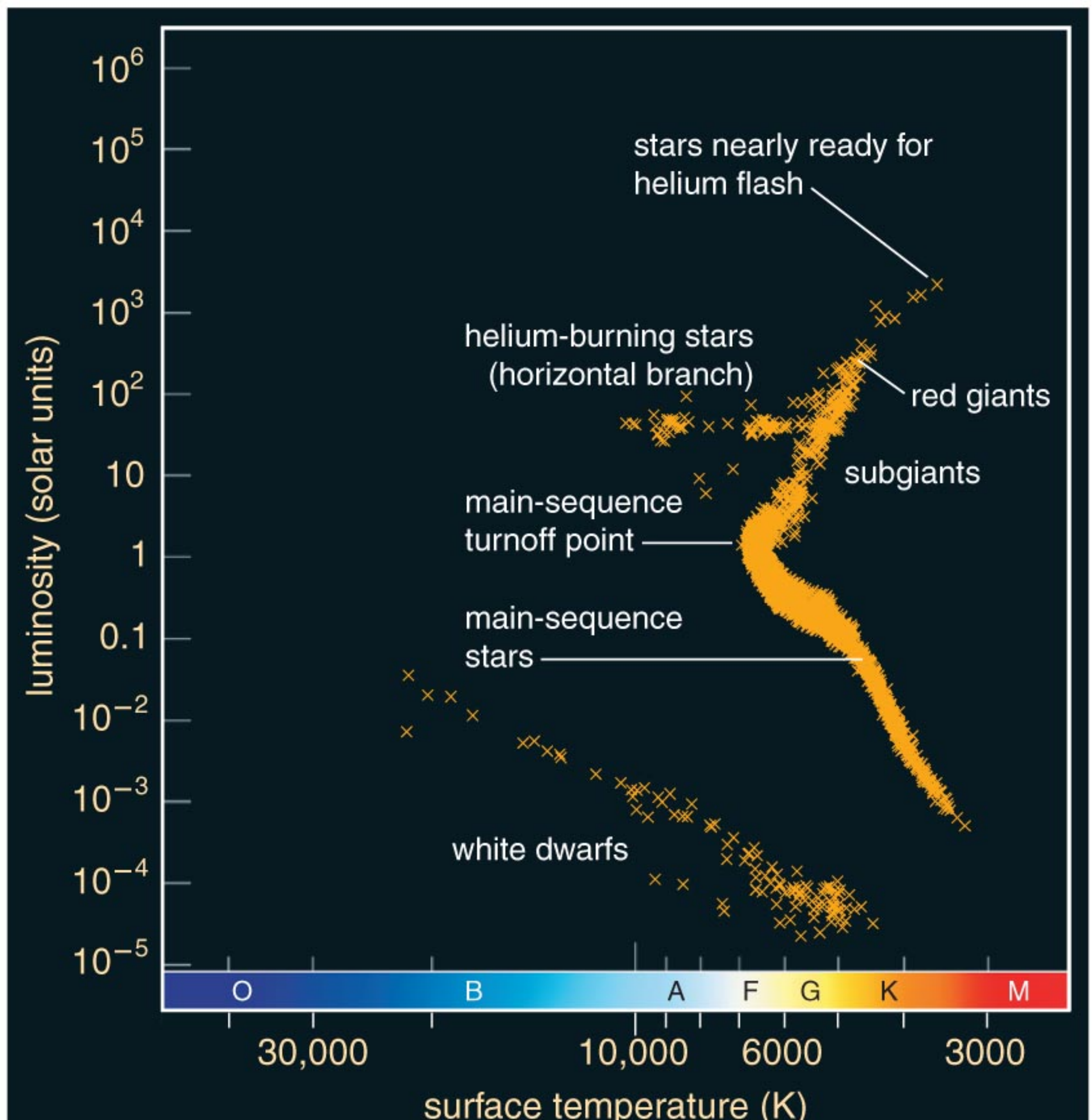

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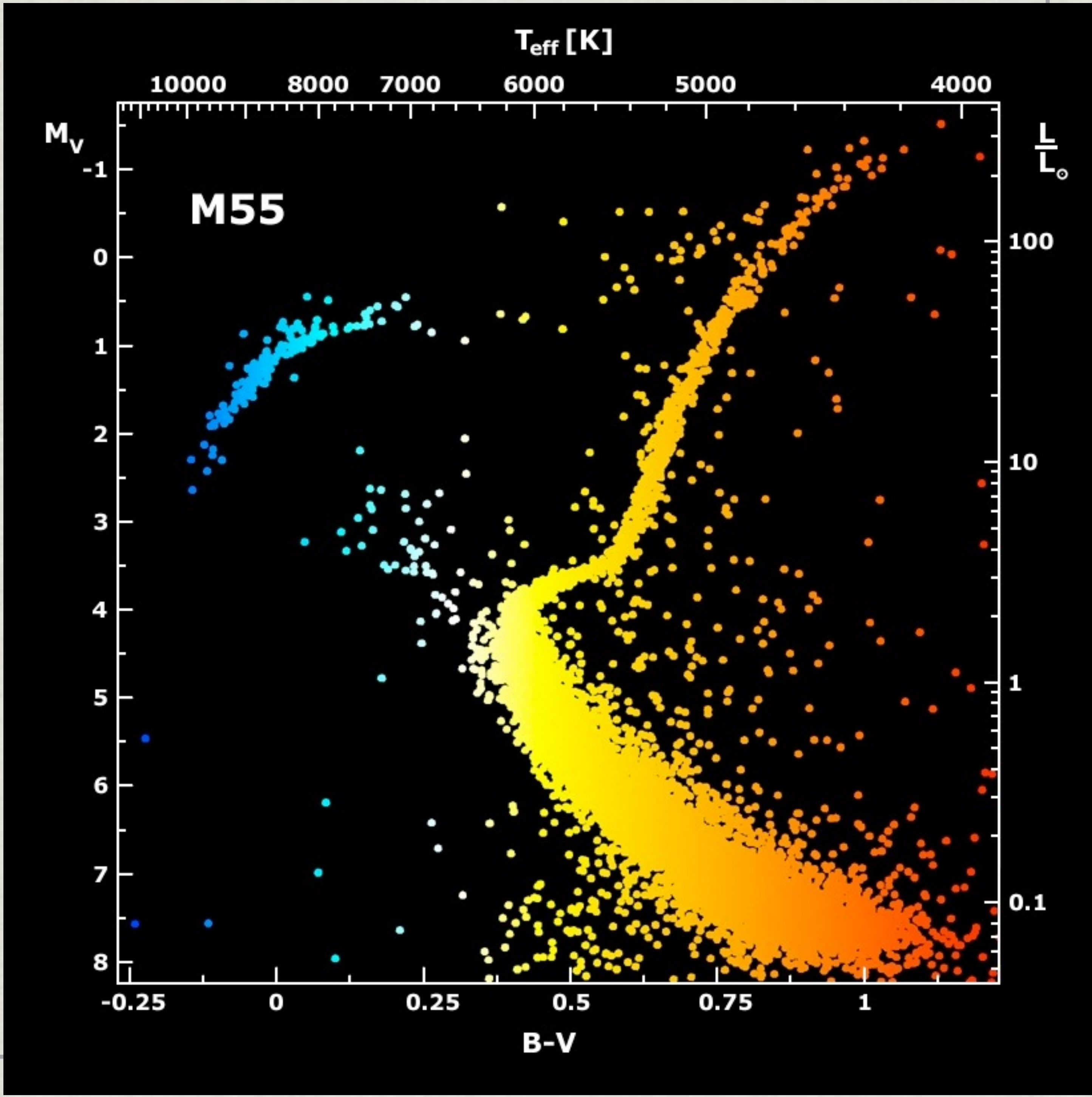

Low Mass Stars: Post Main Sequence Evolution

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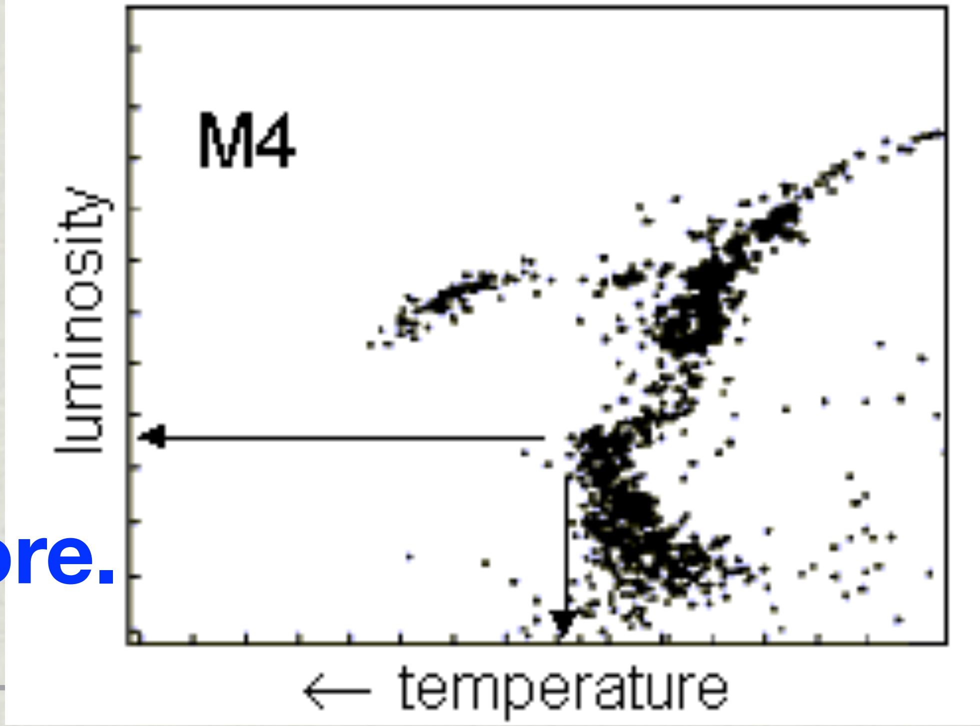


Eventually, star runs out of He in the core. Then what?

Low Mass Stars: Post Main Sequence Evolution

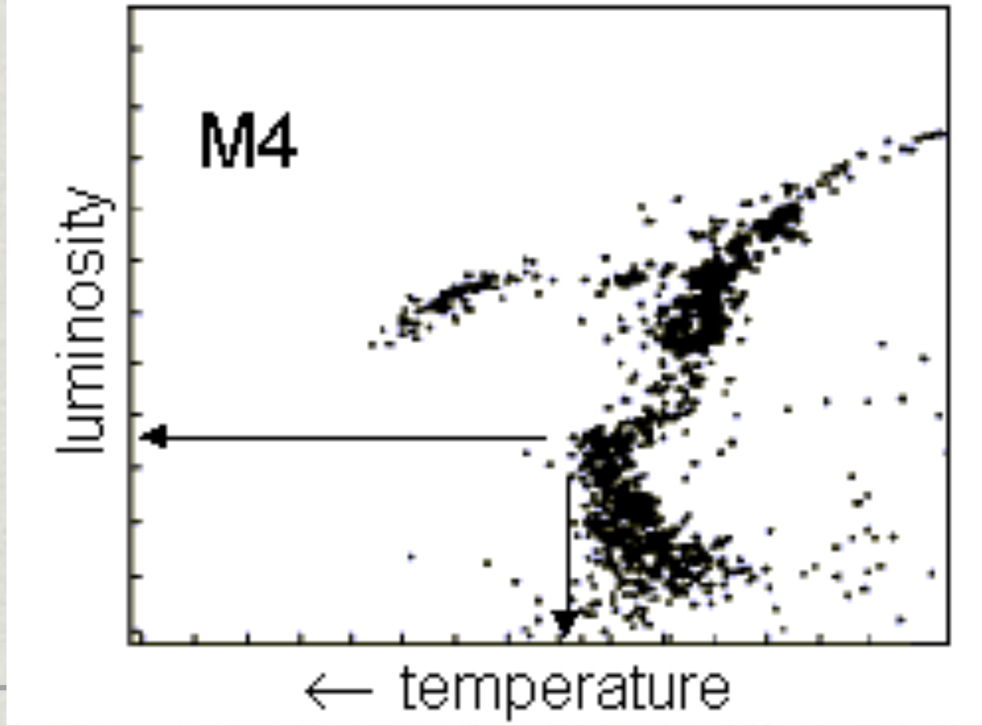
Horizontal Branch: Stable core fusion, He → C

He burning stars are on the *horizontal branch* in the H-R diagram

Eventually, star runs out of He in the core. Then what?

The direct result of running out of He is:

A Nuclear energy generation heats up the core, the star expands
B The core no longer has a source of thermal energy for pressure support, gravitational collapse
C The star cools and expands



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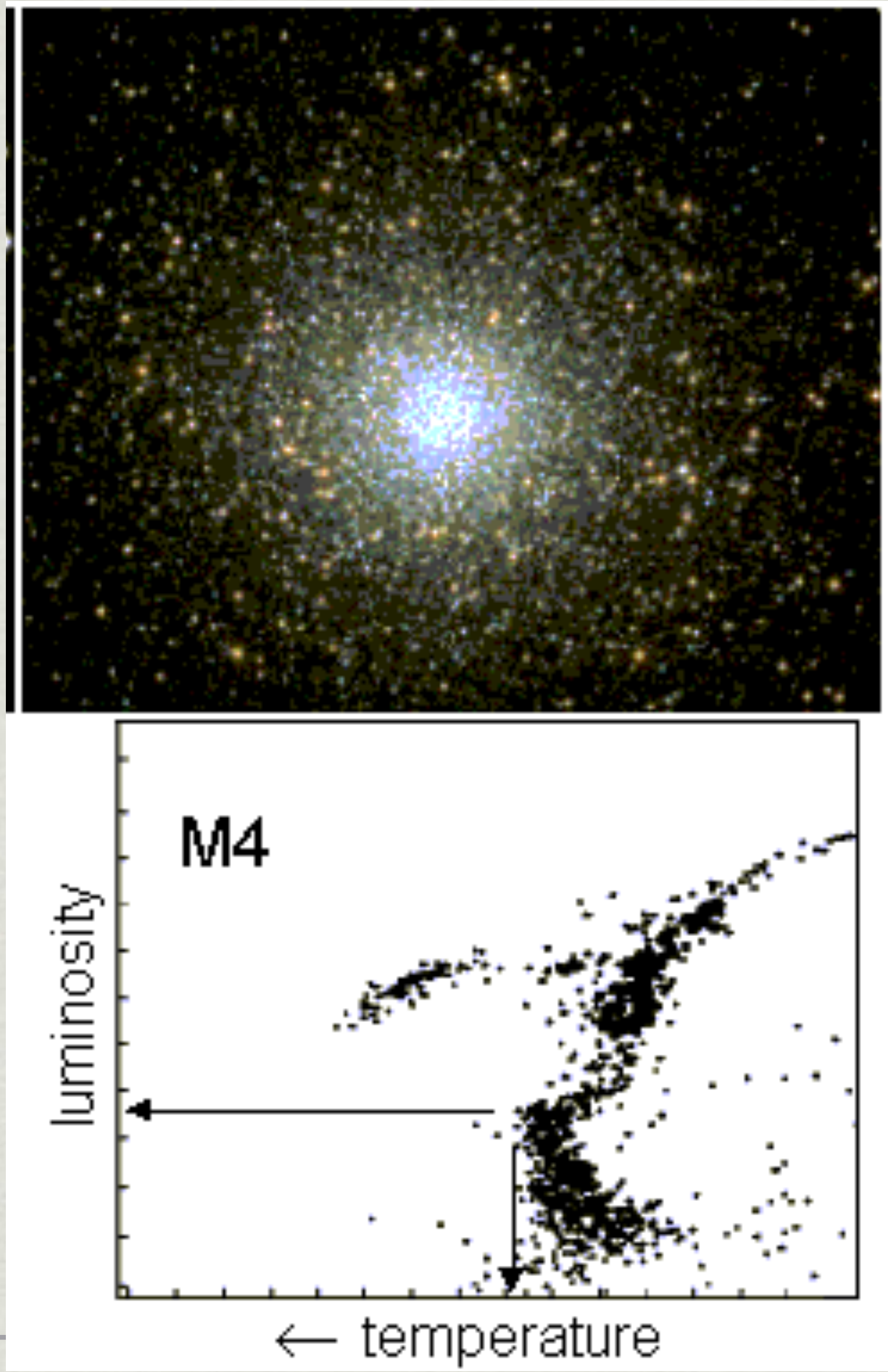


Low Mass Stars: Post Main Sequence Evolution

Eventually, star runs out of He in the core.

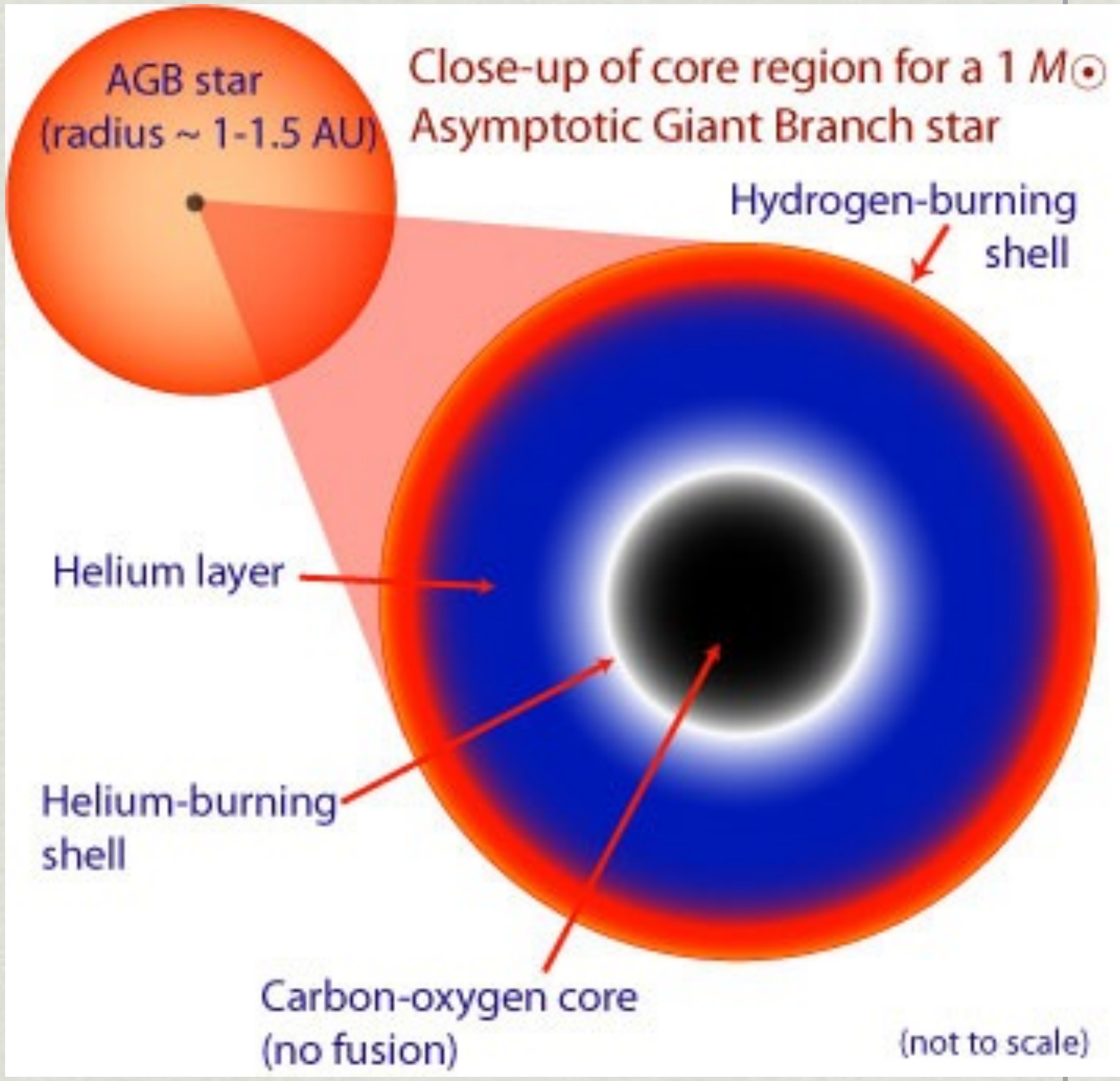
No more nuclear energy generation to hold the star up against gravity.

Star collapses again, same sequence as when it ran out of hydrogen on the main sequence

But now ***double*** shell burning: He → C outside core, H → He outside that.

Star gets brighter, expands and cools

Brighter, cooler (redder).
“asymptotic giant branch”



Low Mass Stars: Post Main Sequence Evolution

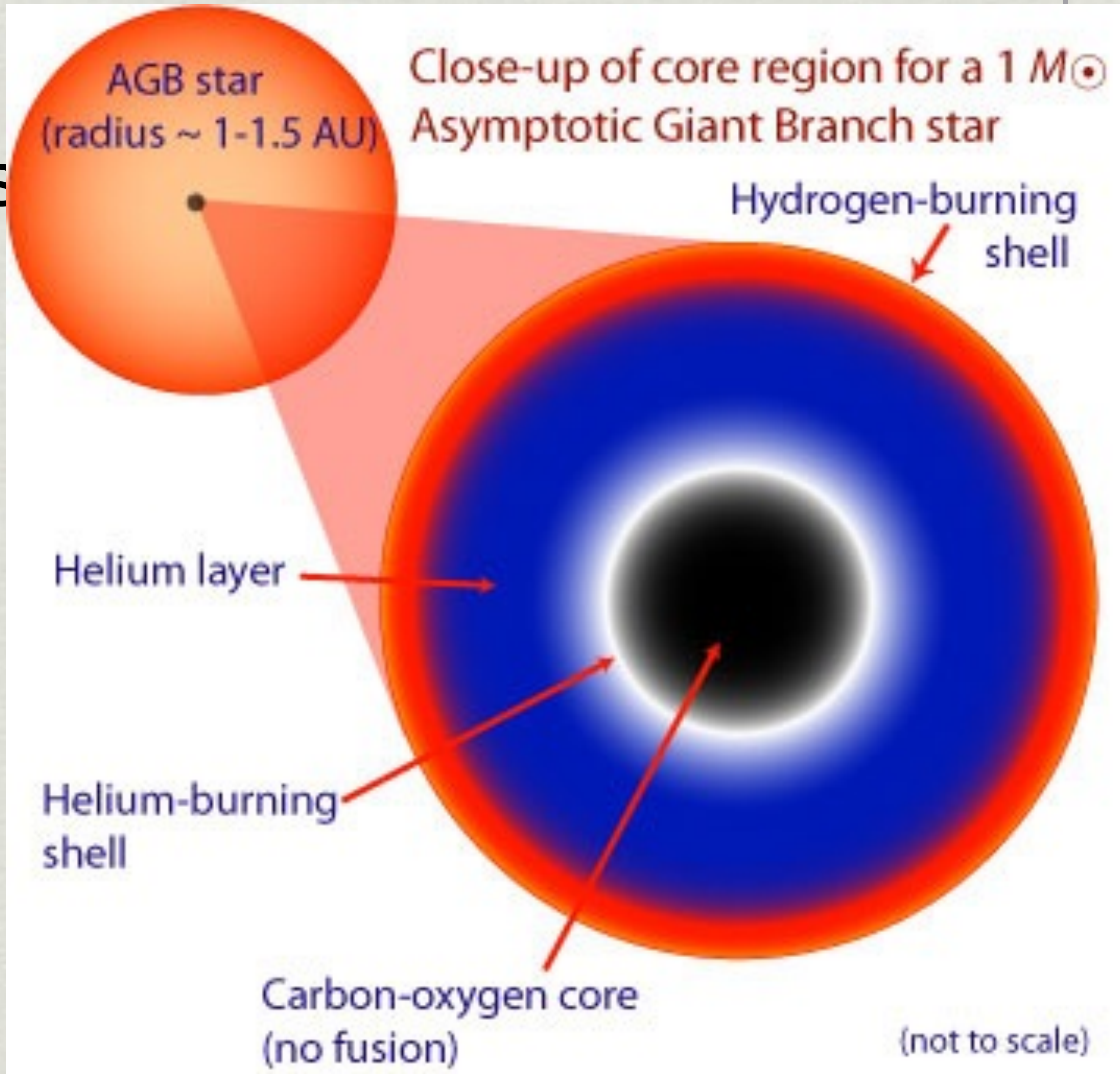
double shell burning: He → C outside core, H → He outside that.

Star gets brighter, expands and cools.

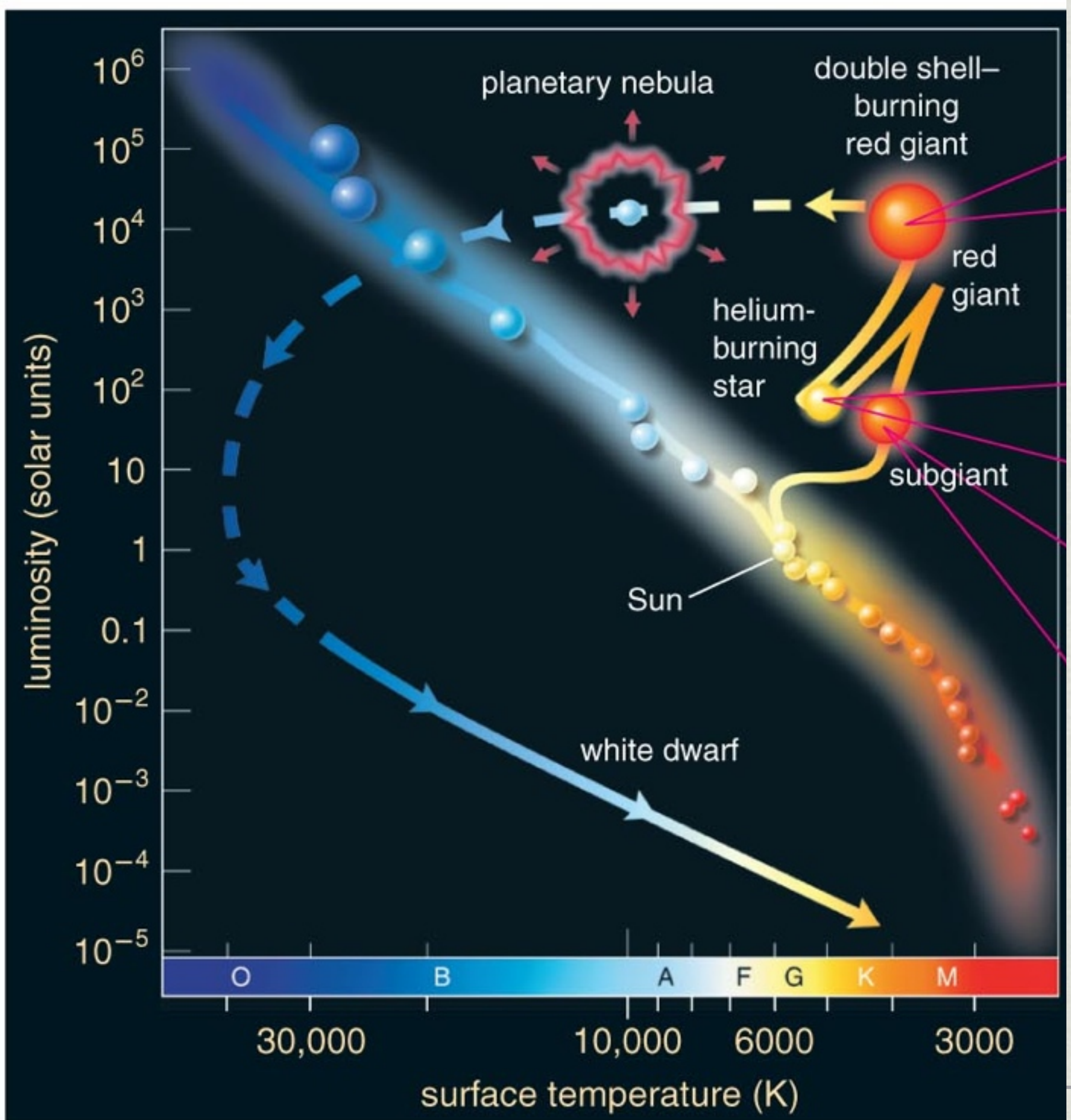
Very unstable, big changes in shell nucleosynthesis rates = big changes in thermal pressure = big changes in size = big changes in luminosity (S-B Law)

"Thermal pulses" → outer envelope pushed out,escapes, star loses mass

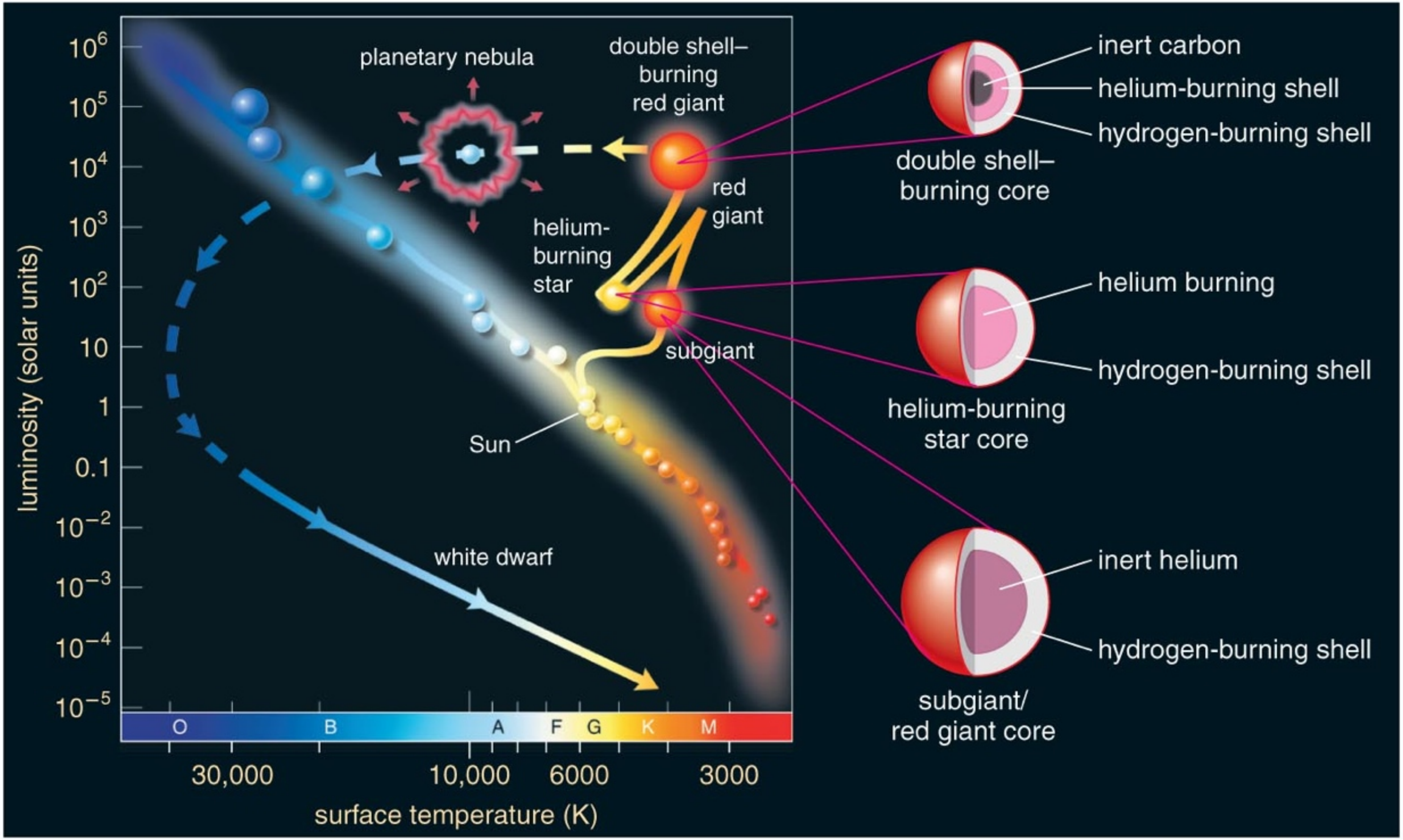
Becomes a planetary nebula
which is not really a planet at all!



Low Mass Stars: Post Main Sequence Evolution

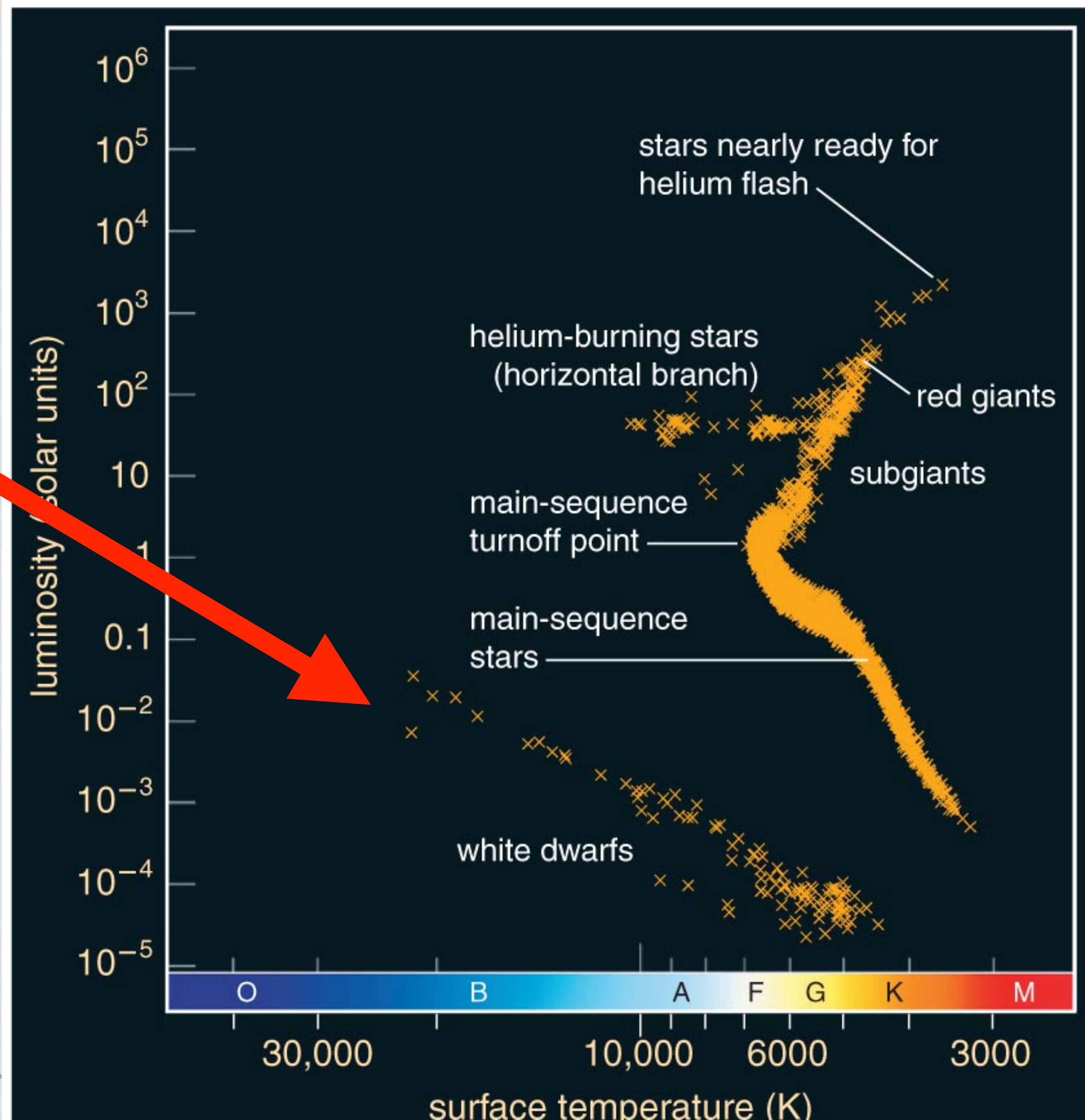


Low Mass Stars: Post Main Sequence Evolution

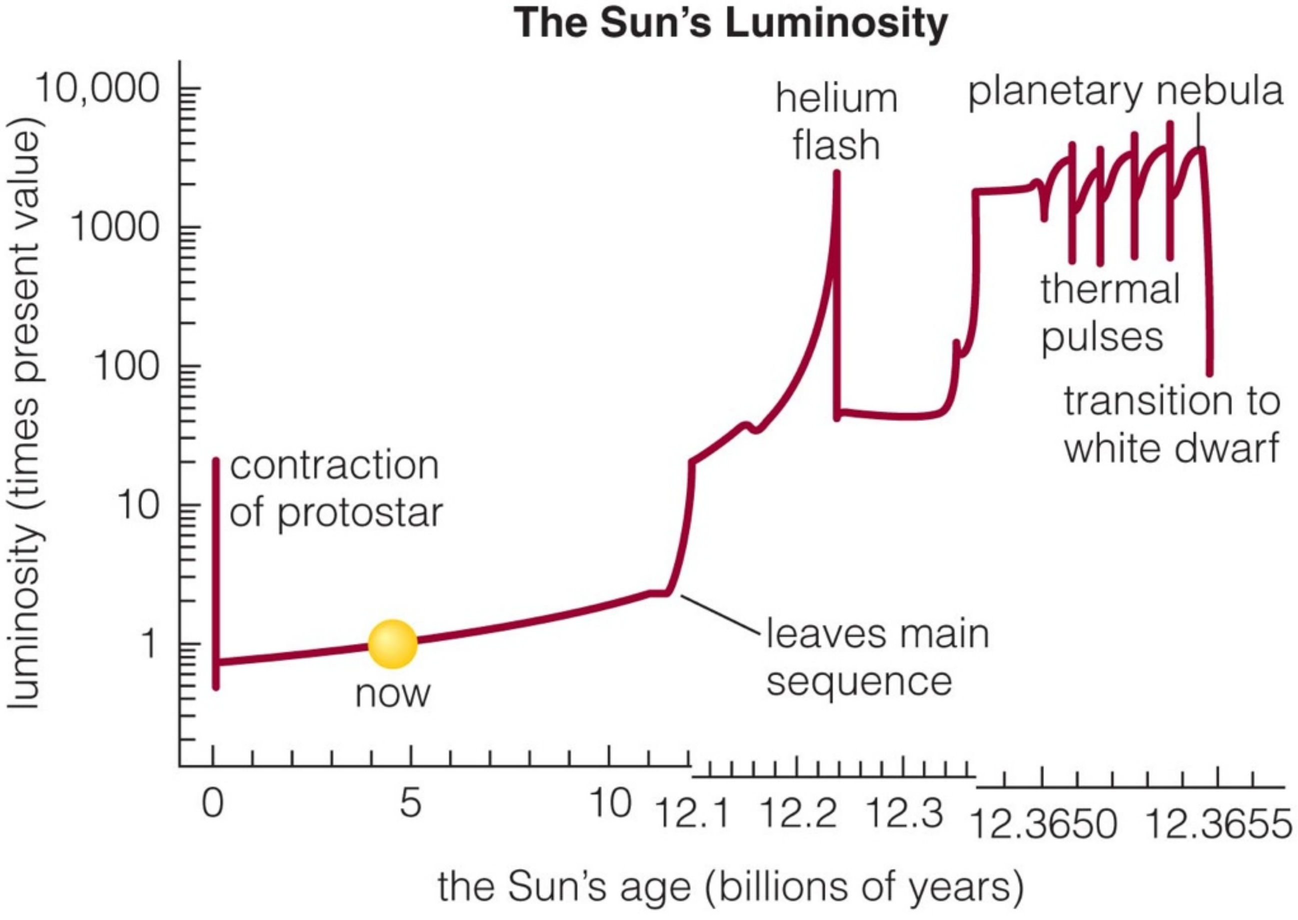


Low Mass Stars: Post Main Sequence Evolution

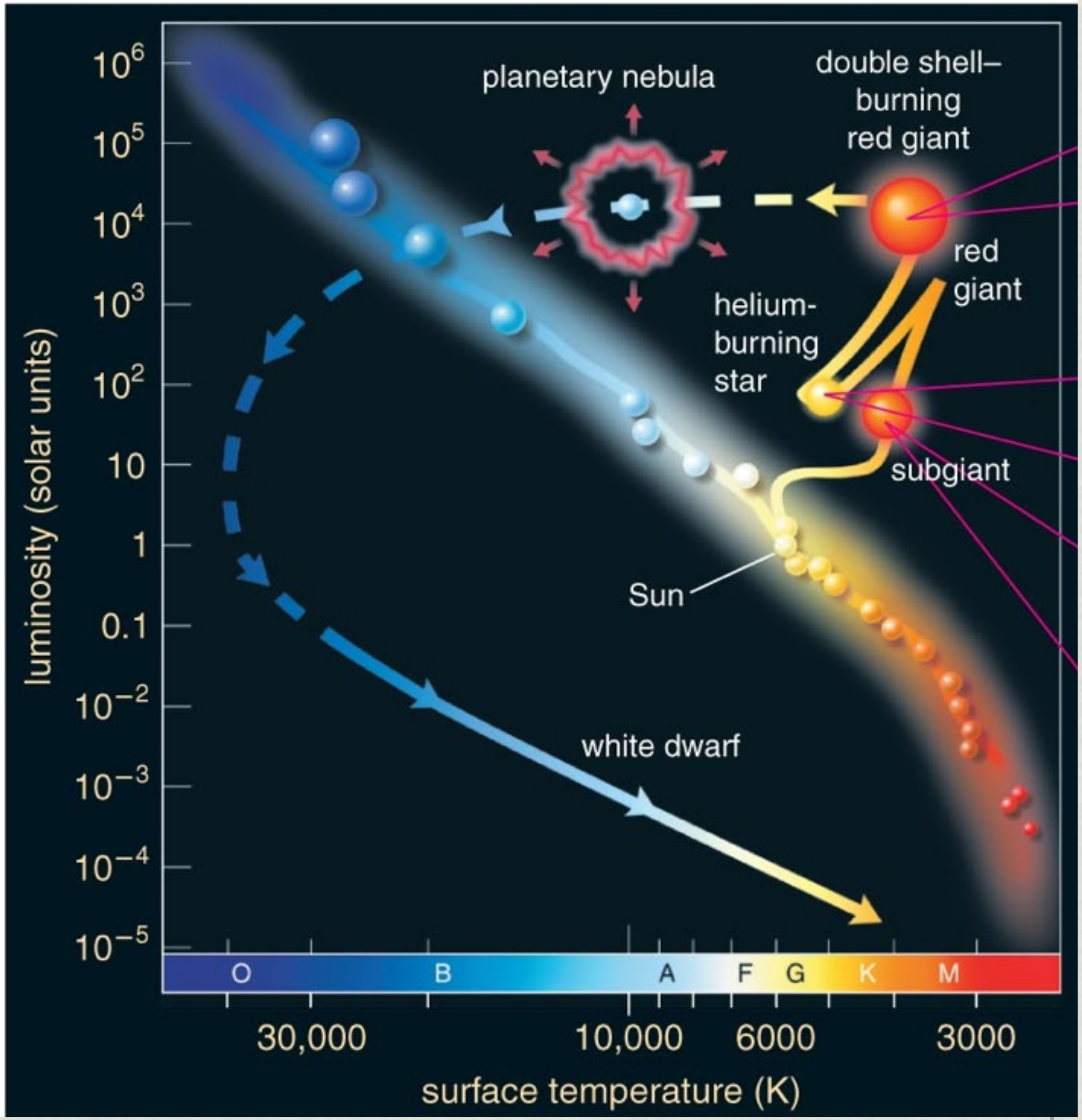
White Dwarf
- Supported by electron degeneracy pressure
- Inert He, C core of star, no nucleosynthesis
- Cooling slowly, losing energy, getting less luminous



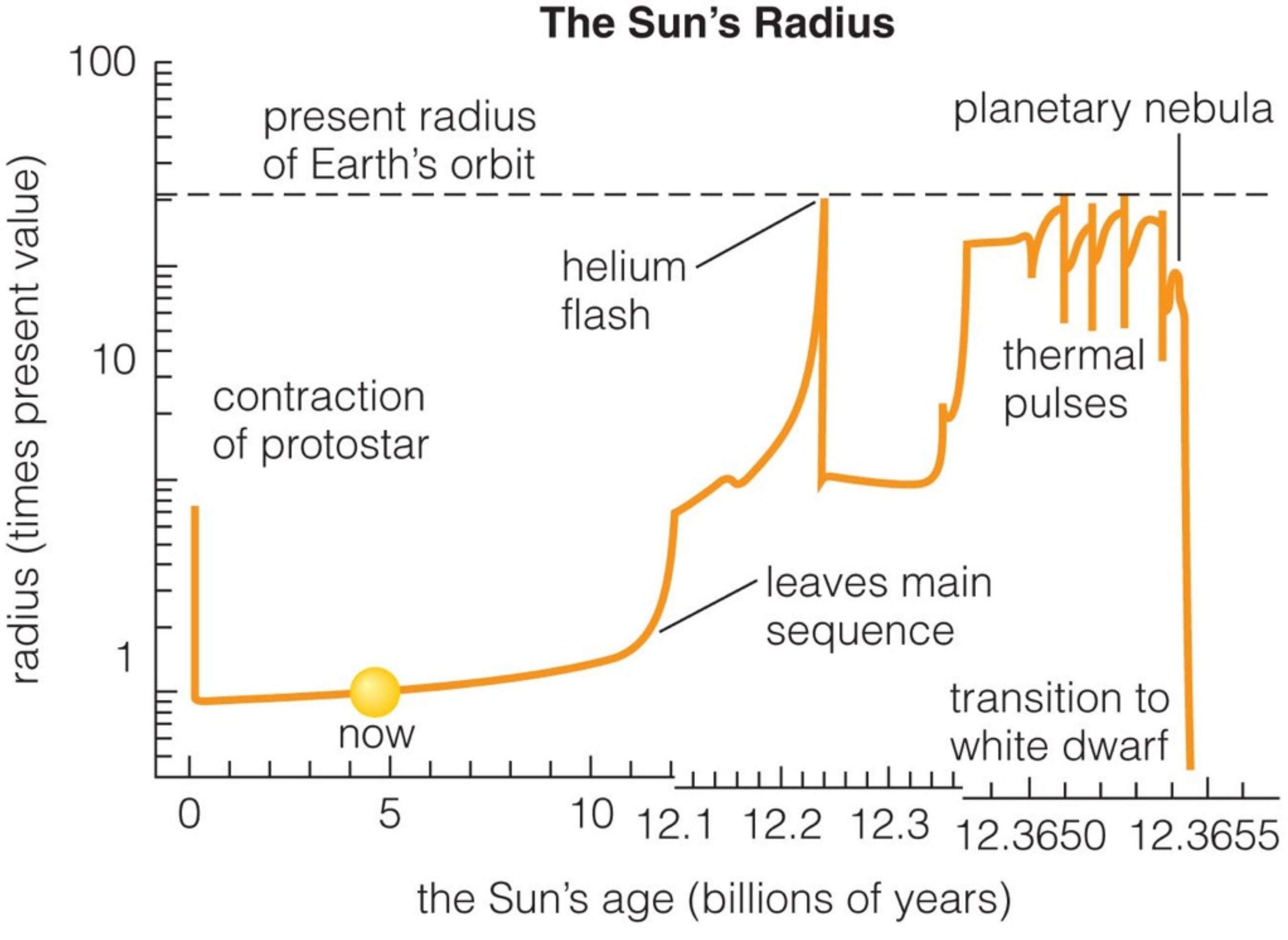
The Sun’s Fate



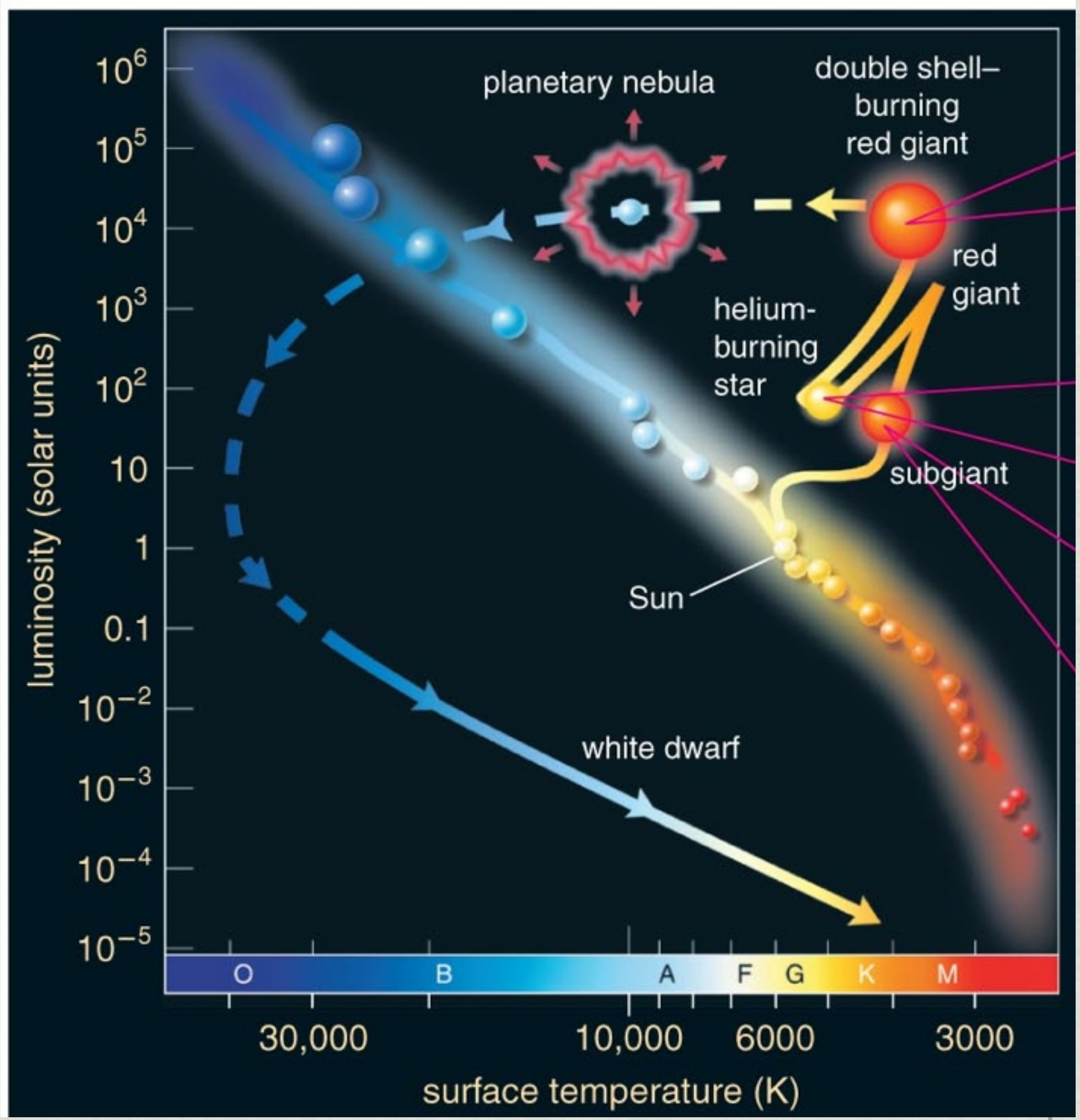
a Changes in the Sun’s luminosity over time.



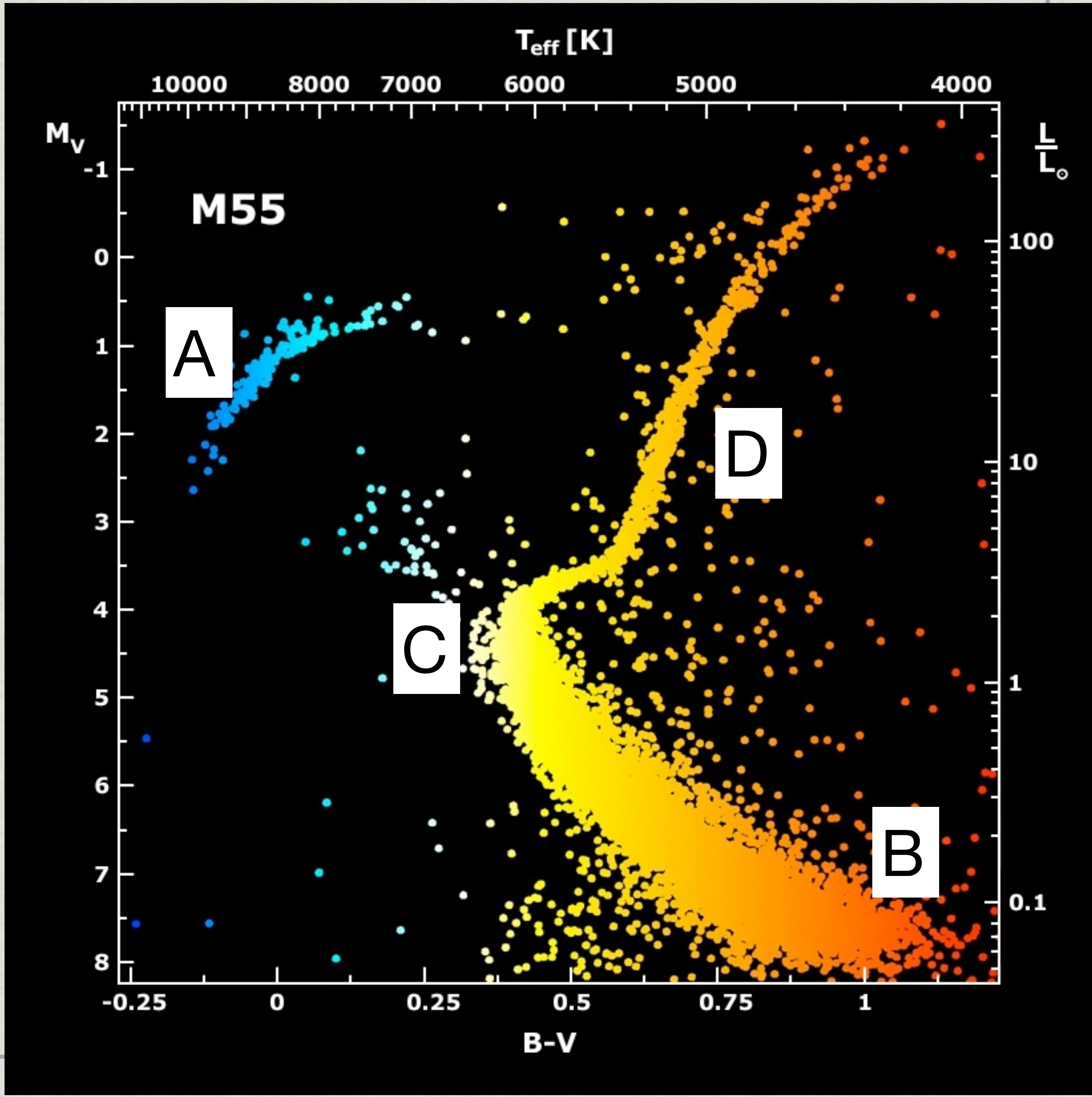
The Sun’s Fate



b Changes in the Sun’s radius over time.



Which stars have run out of H fuel in theirs cores and their cores are collapsing?



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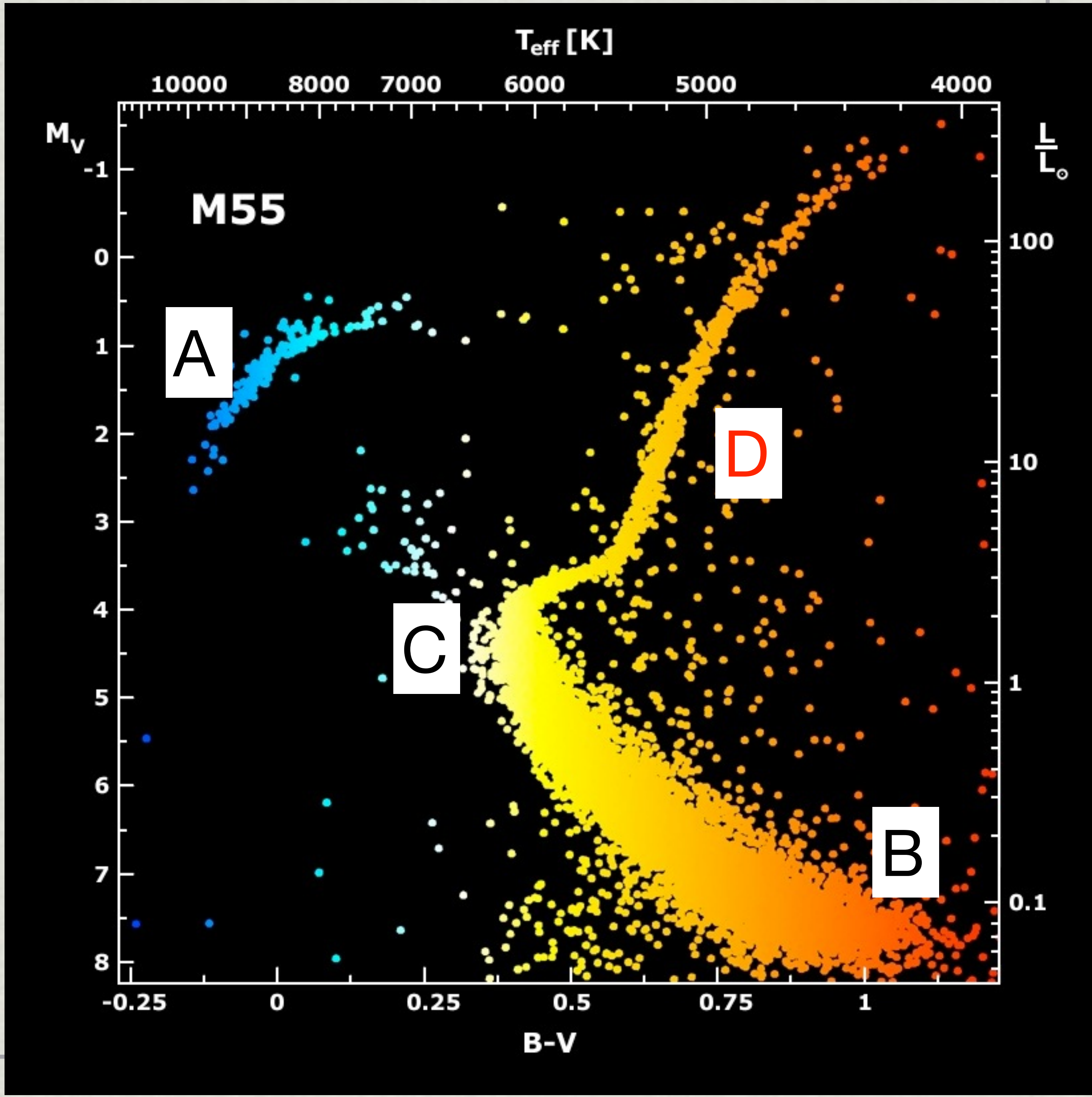
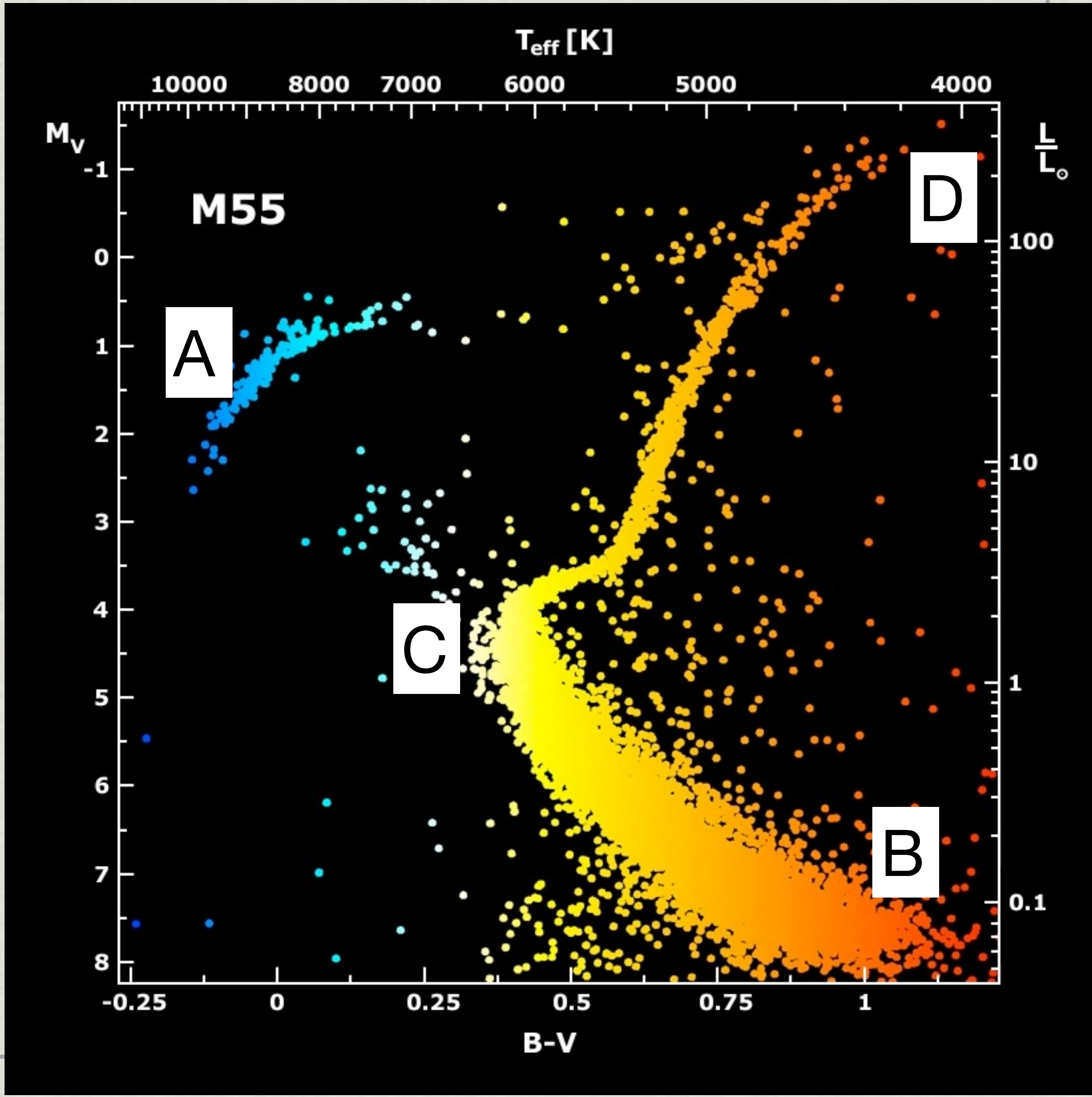


Where is the Main Sequence turnoff?



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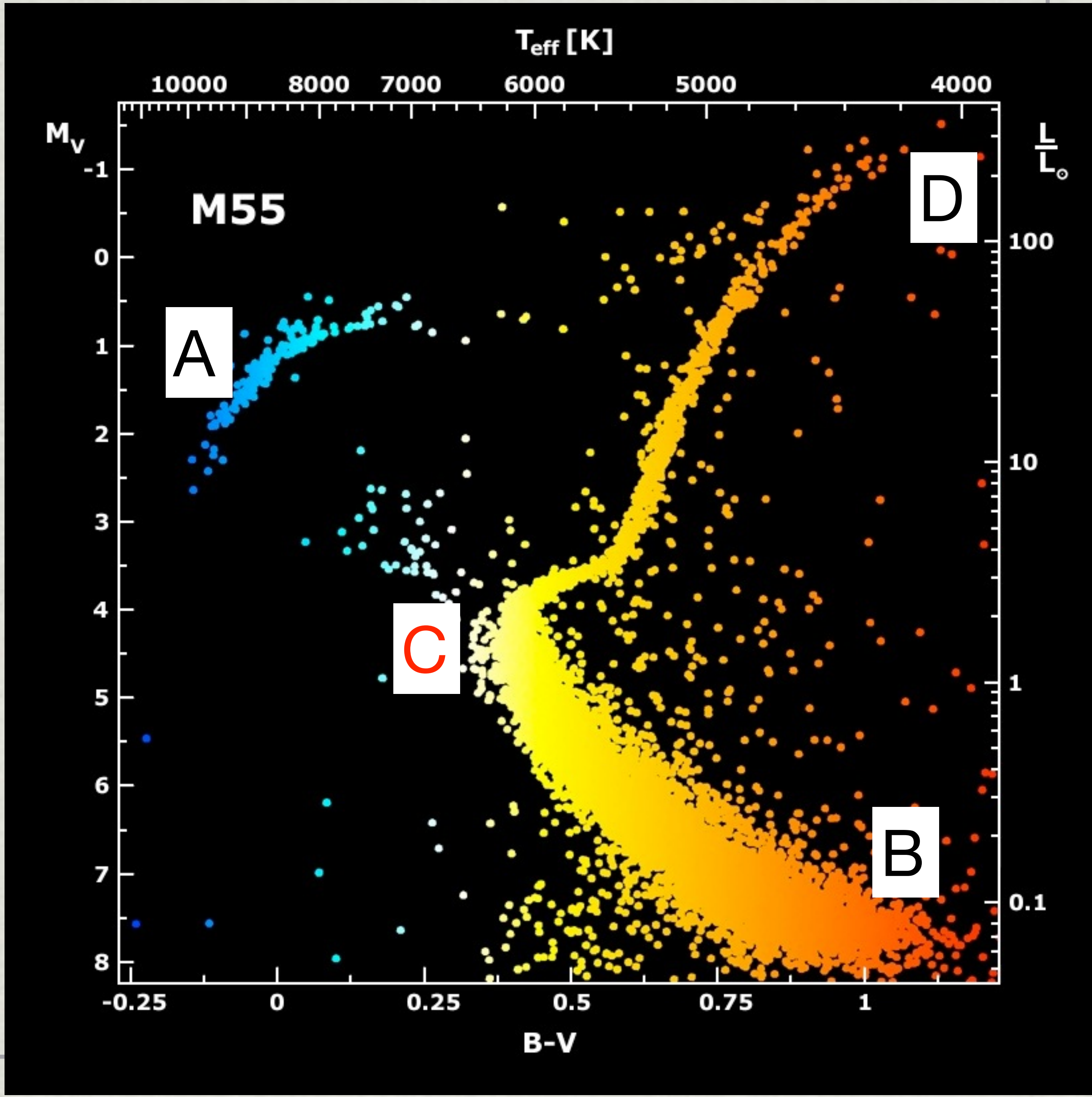
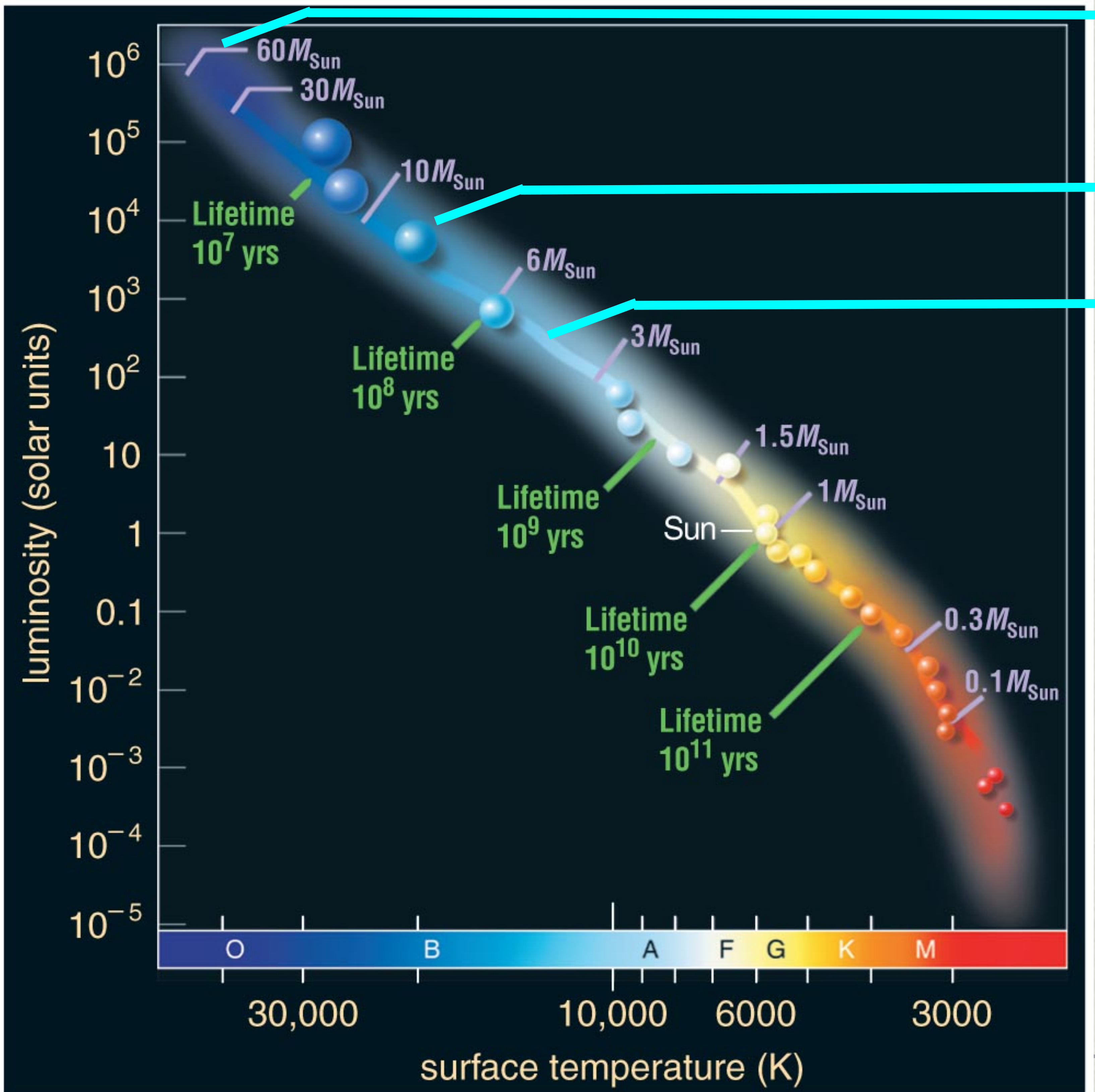


Stellar Evolution After the Main Sequence

Everything depends on mass.



Some definitions:

High mass stars:
$M > 8\ M_{sun}$

Intermediate mass:
$2 < M < 8\ M_{sun}$

These have similar evolution

Low mass stars:
$M < 2\ M_{sun}$

Post Main Sequence Evolution

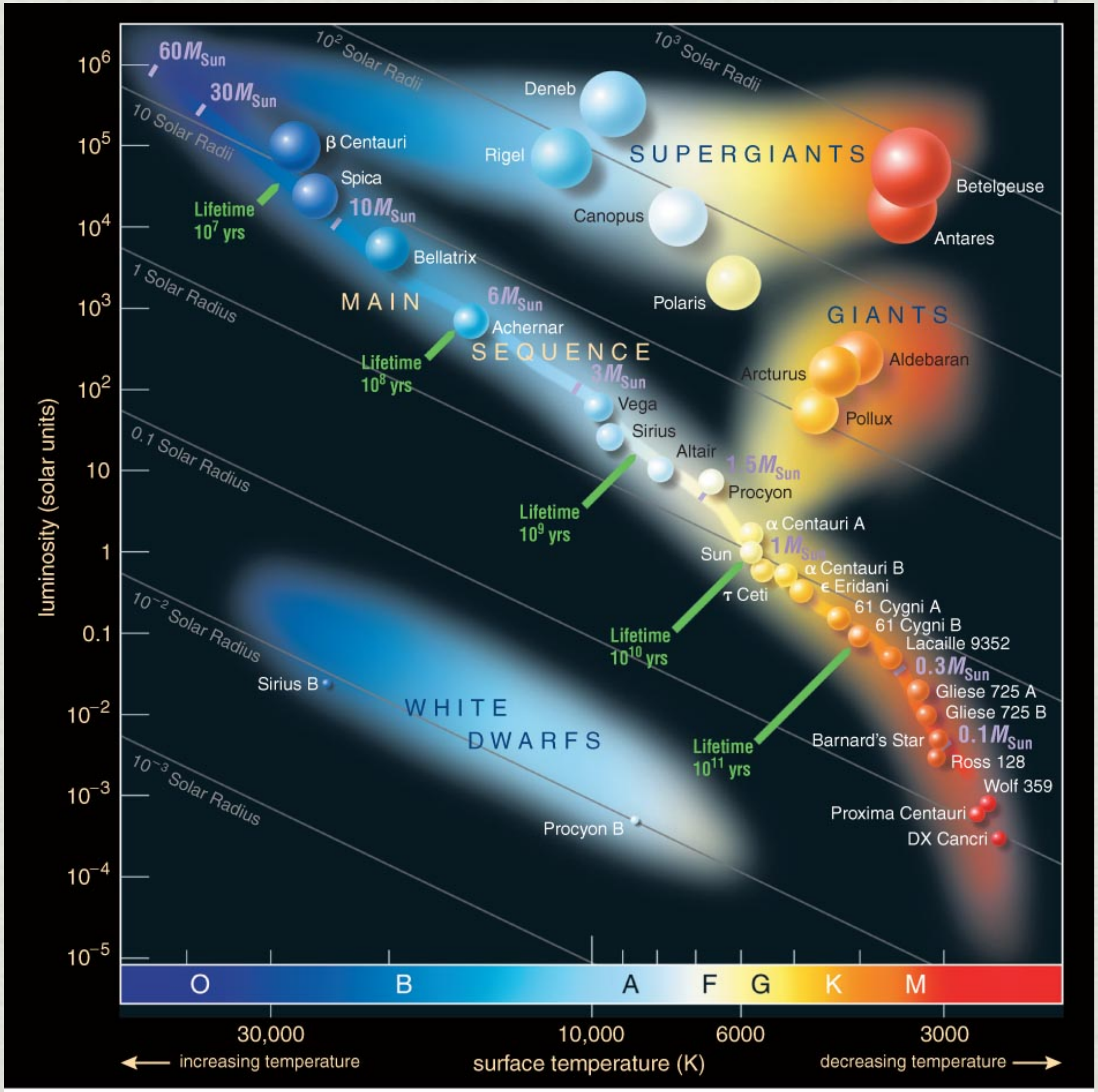
What happens for higher mass stars?

After He supply is exhausted in the core: Collapse, just like lower mass stars

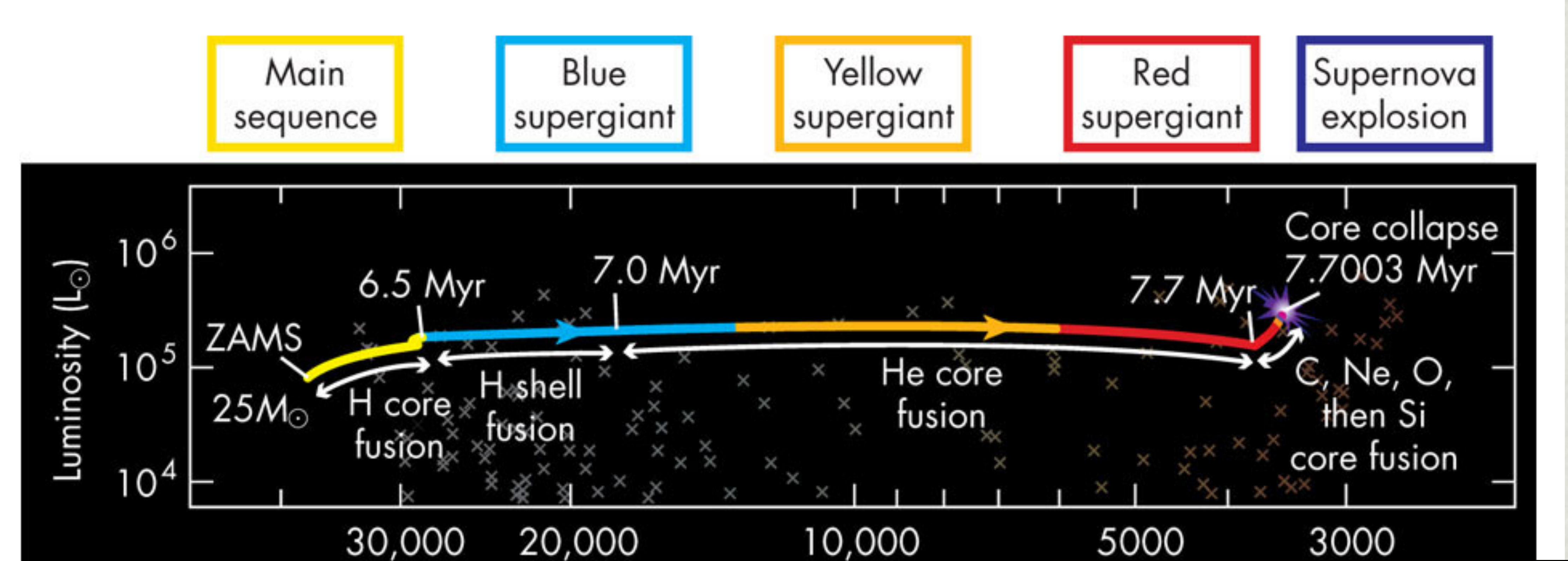
H- and He-burning shells push out the outer layers, star puffs up in radius.

Becomes a cooler giant, just like lower mass stars. Like always for higher mass stars, more luminous: “supergiant”

Gravitational pressure squeezes more, core temperatures are higher in massive stars.



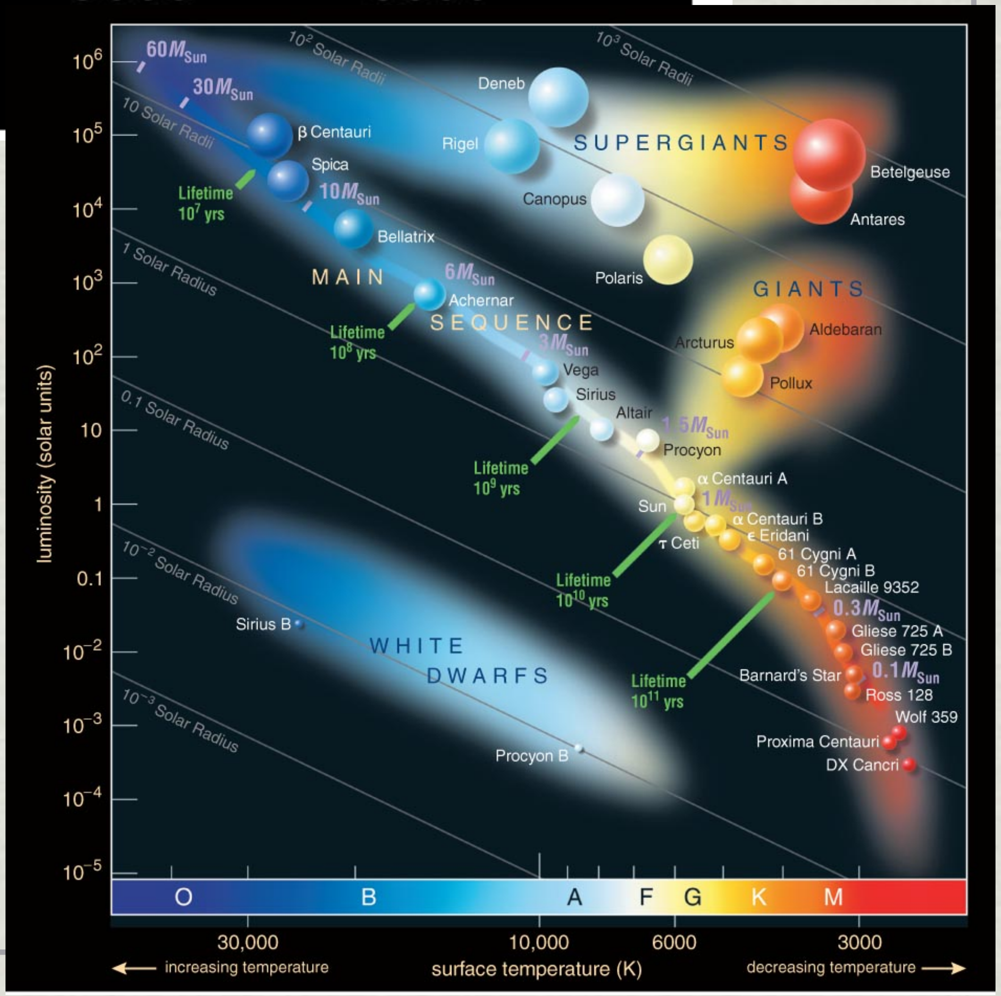
High Mass Stars: Post Main Sequence Evolution



Gravitational pressure squeezes more, core temperatures are higher in massive stars.

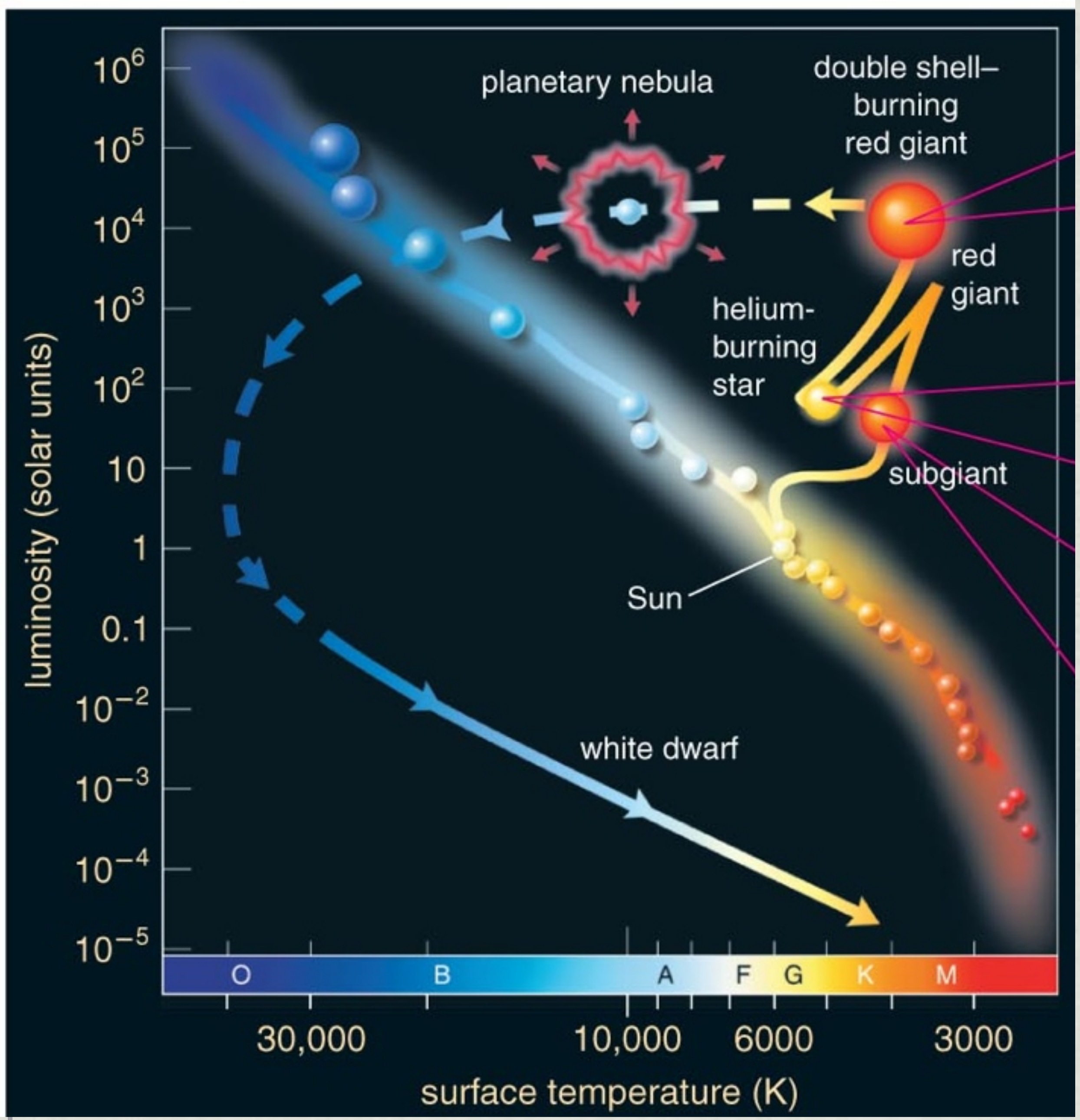
Can start nucleosynthesis beyond He → C

Burns C, then Ne, O and Si so fast it never reaches stable core burning

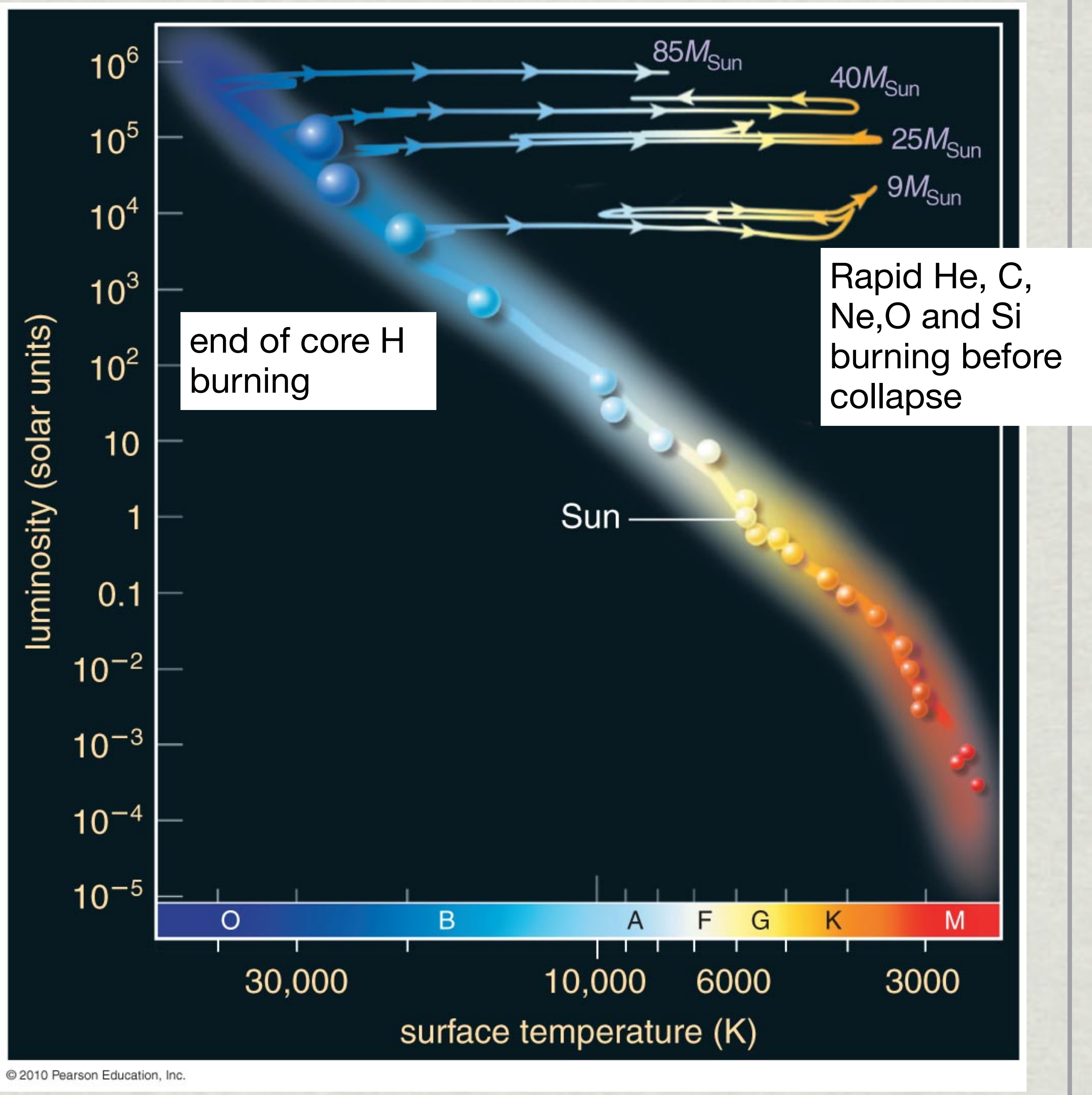


High Mass Stars: Post Main Sequence Evolution

Evolutionary paths



Low mass star, M < 2 Msun



end of core H burning

Rapid He, C, Ne,O and Si burning before collapse

High mass stars, M > 8 Msun

Nucleosynthesis Across and Down the Periodic Table

Where are different elements made?

- We think the universe started in something called the “Big Bang”

- A very hot, very dense ball of mass and energy starting to expand out after a huge explosion

- Very hot and dense = like the core of a star.

- Just like in the core of a star, hot and dense enough for nucleosynthesis to happen

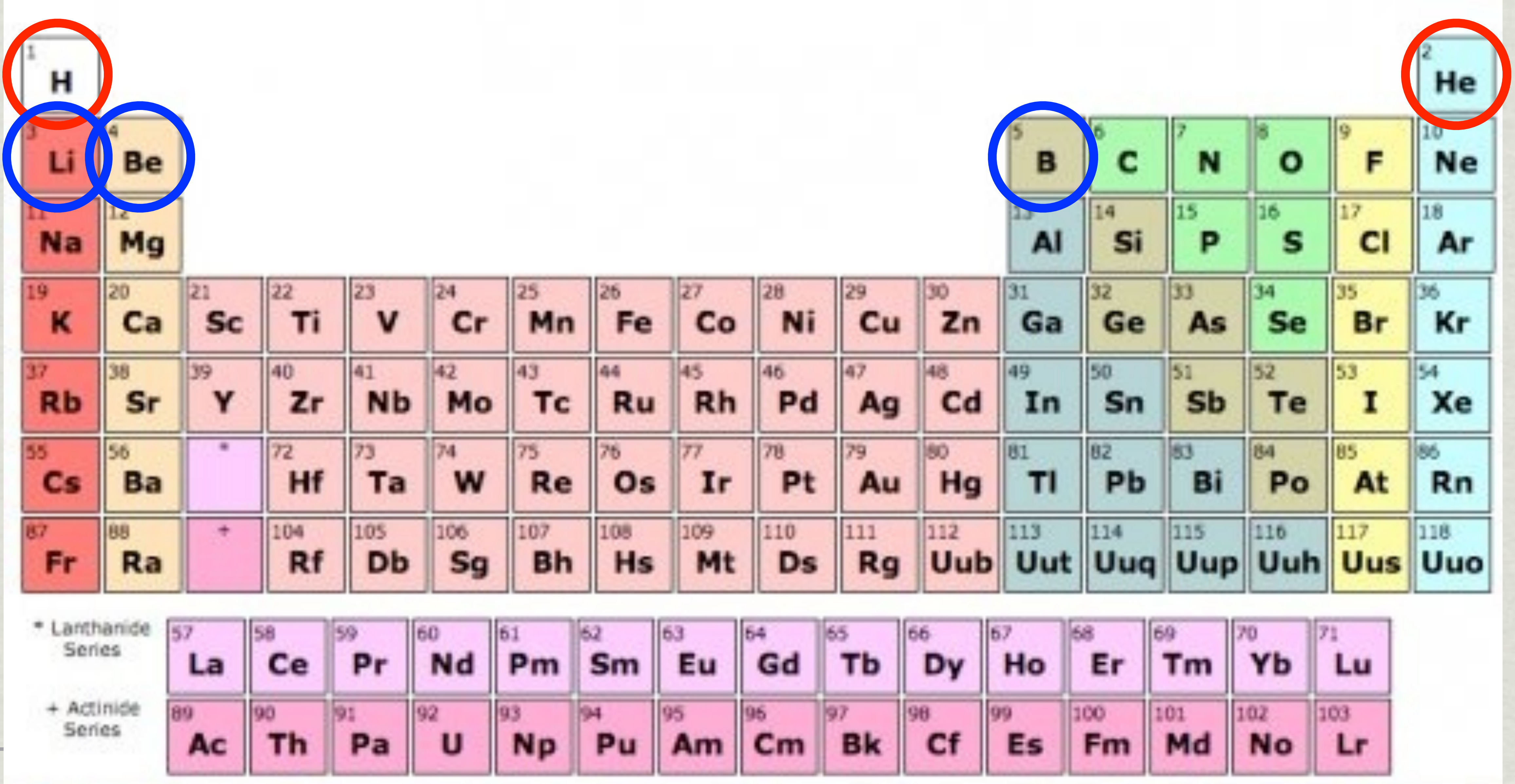
- Universe cools, becomes less dense as it expands outward after the Big Bang

- Eventually, too cool and low density. Nucleosynthesis stops

Nucleosynthesis down the Periodic Table

- Right after universe cooled enough to stop nucleosynthesis, inventory of elements in the Universe was:
75% H, 25% He, tiny amounts of Li, Be, B

- All made by nucleosynthesis in the first 3 minutes of the universe



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High Mass Stars: Post Main Sequence Nuclear Fusion

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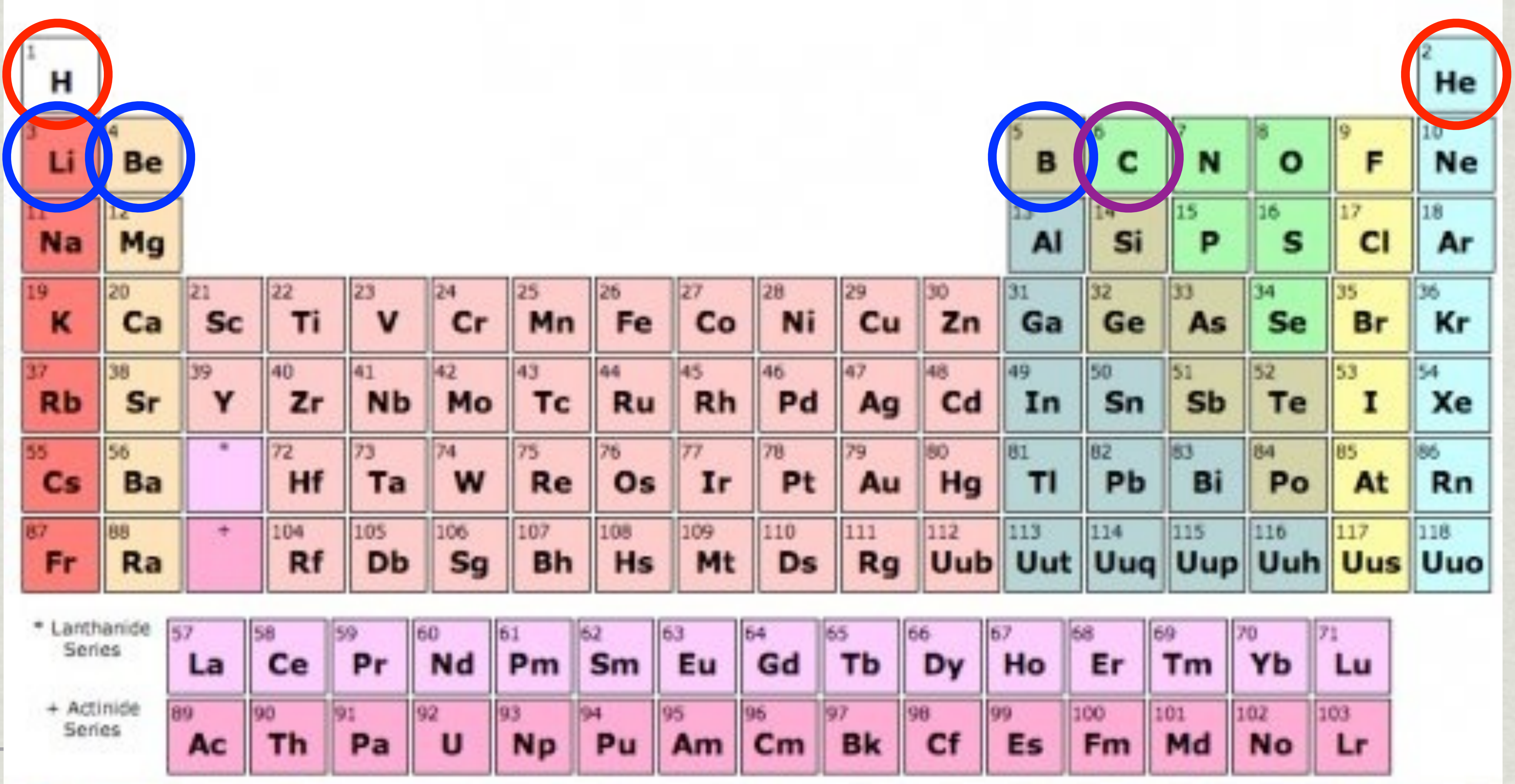

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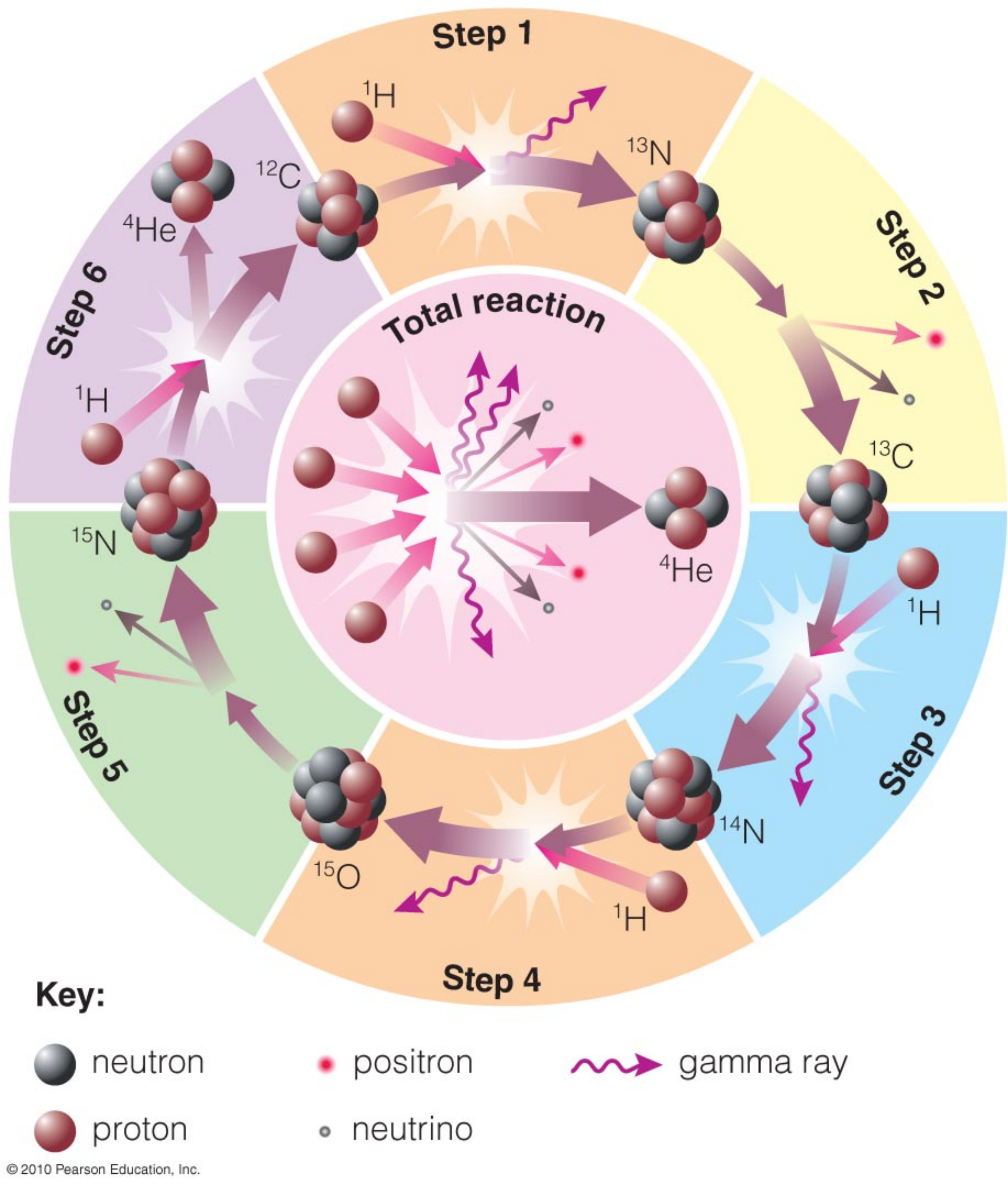
High Mass Stars: Post Main Sequence Nuclear Fusion

Where are the elements made?

H→He burning in intermediate and high mass stars uses the C-N-O cycle.

Burns faster (more energy/sec output to hold up massive stars) but requires higher core density, pressure

Makes N,O along the way



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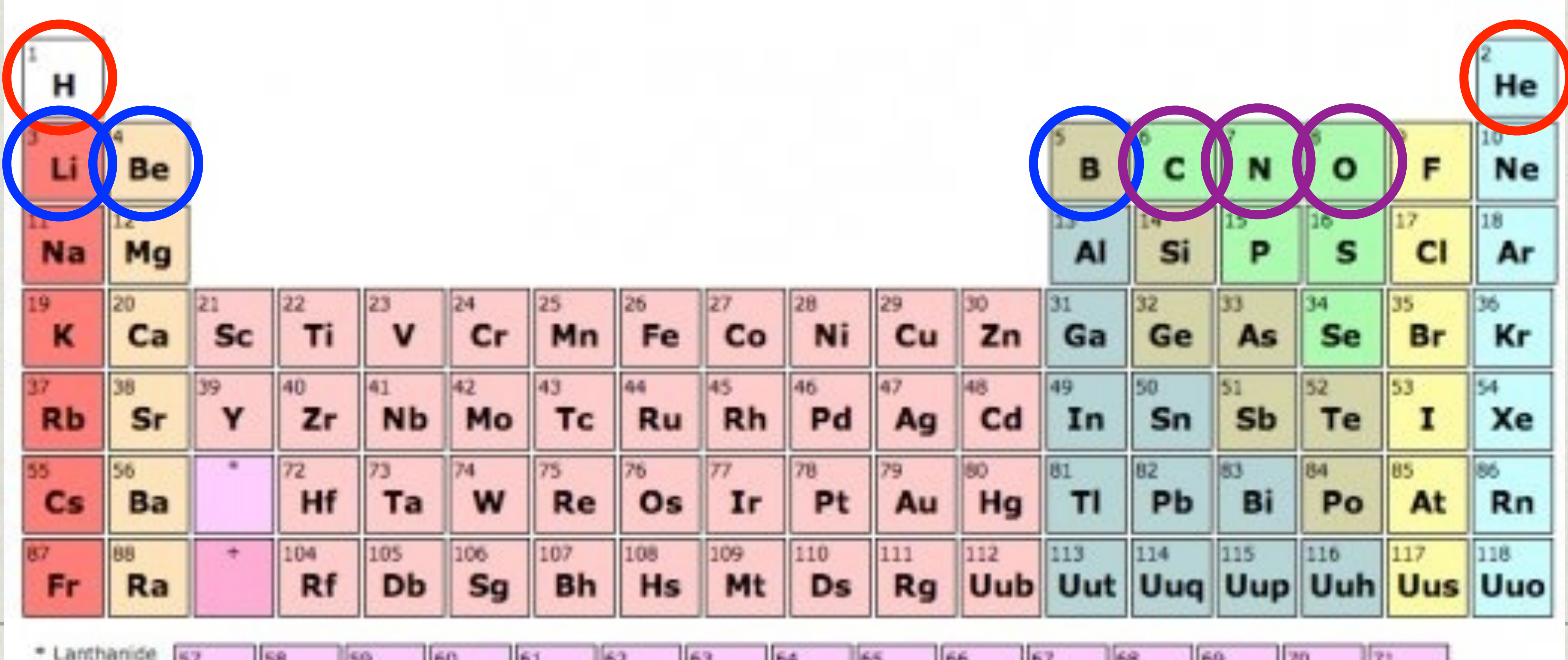

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* Lanthanide

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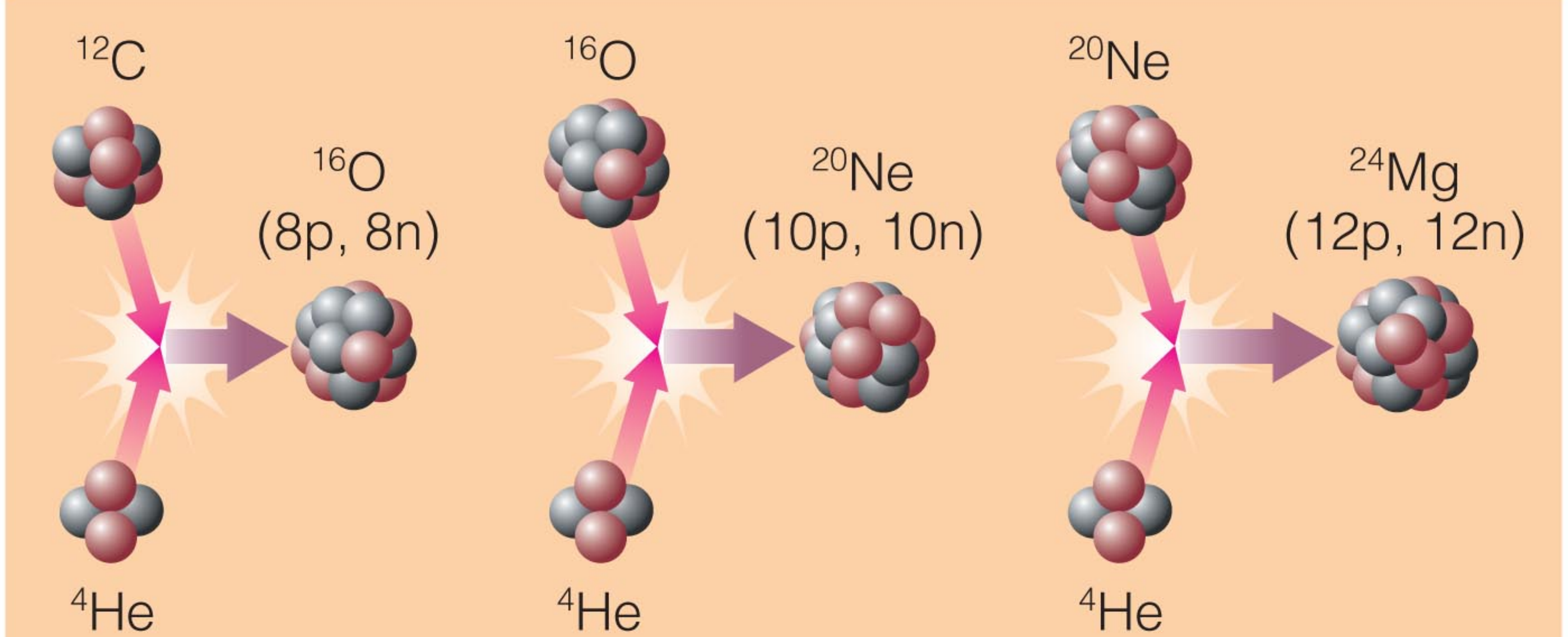
- “alpha” particle (He nucleus) capture: stable fusion reactions add +4 atomic weight, 2 protons



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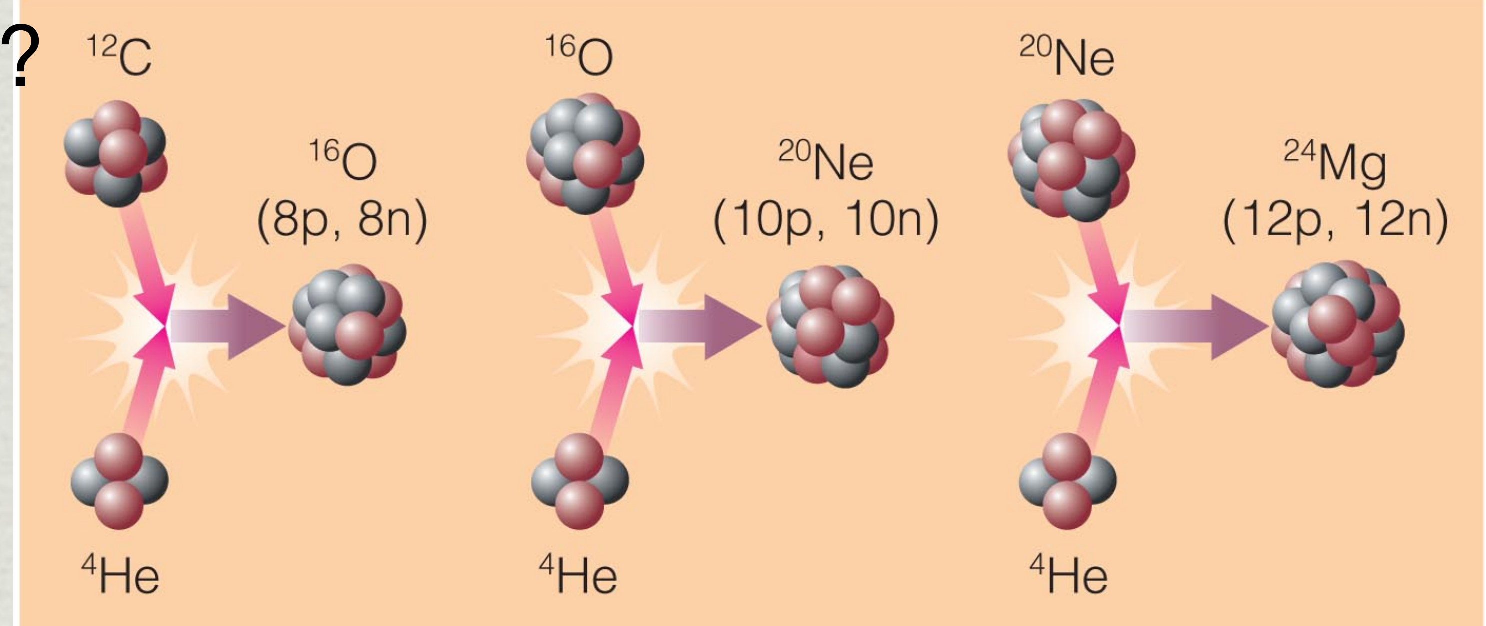

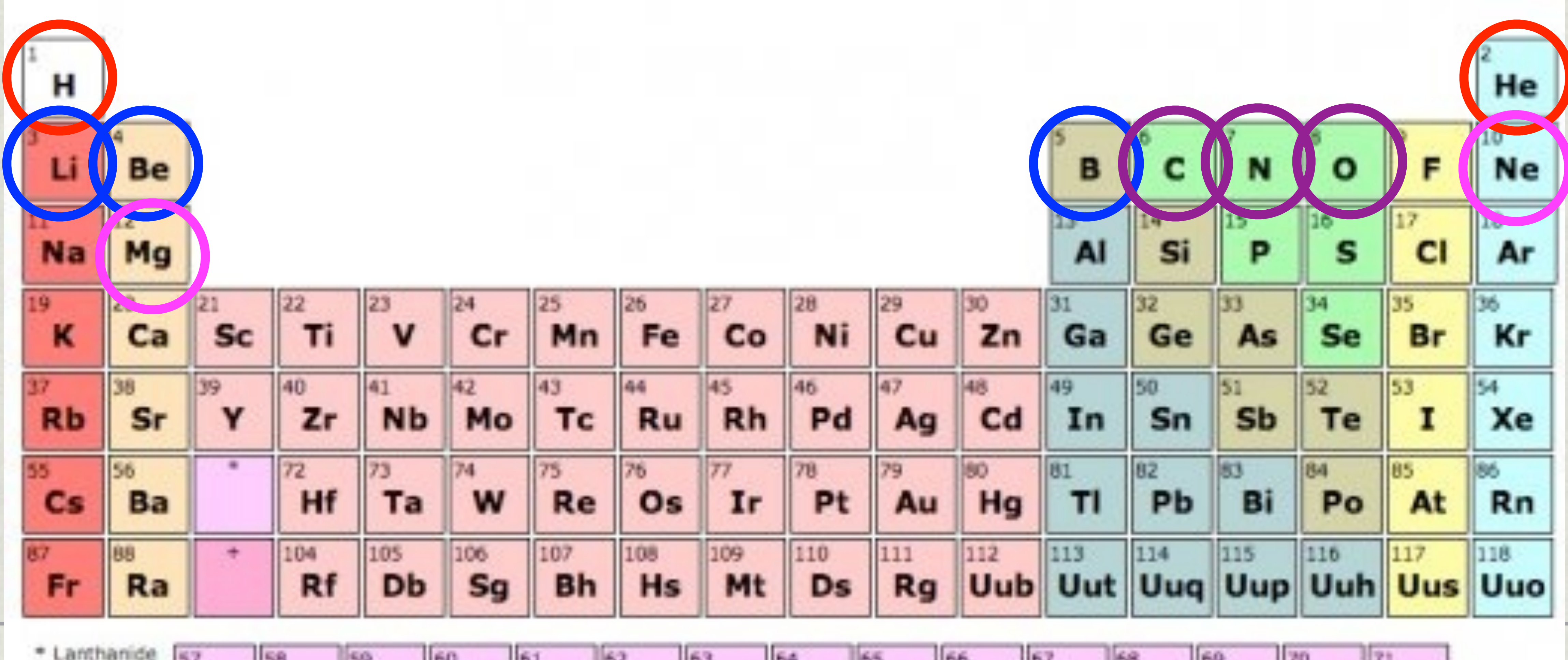

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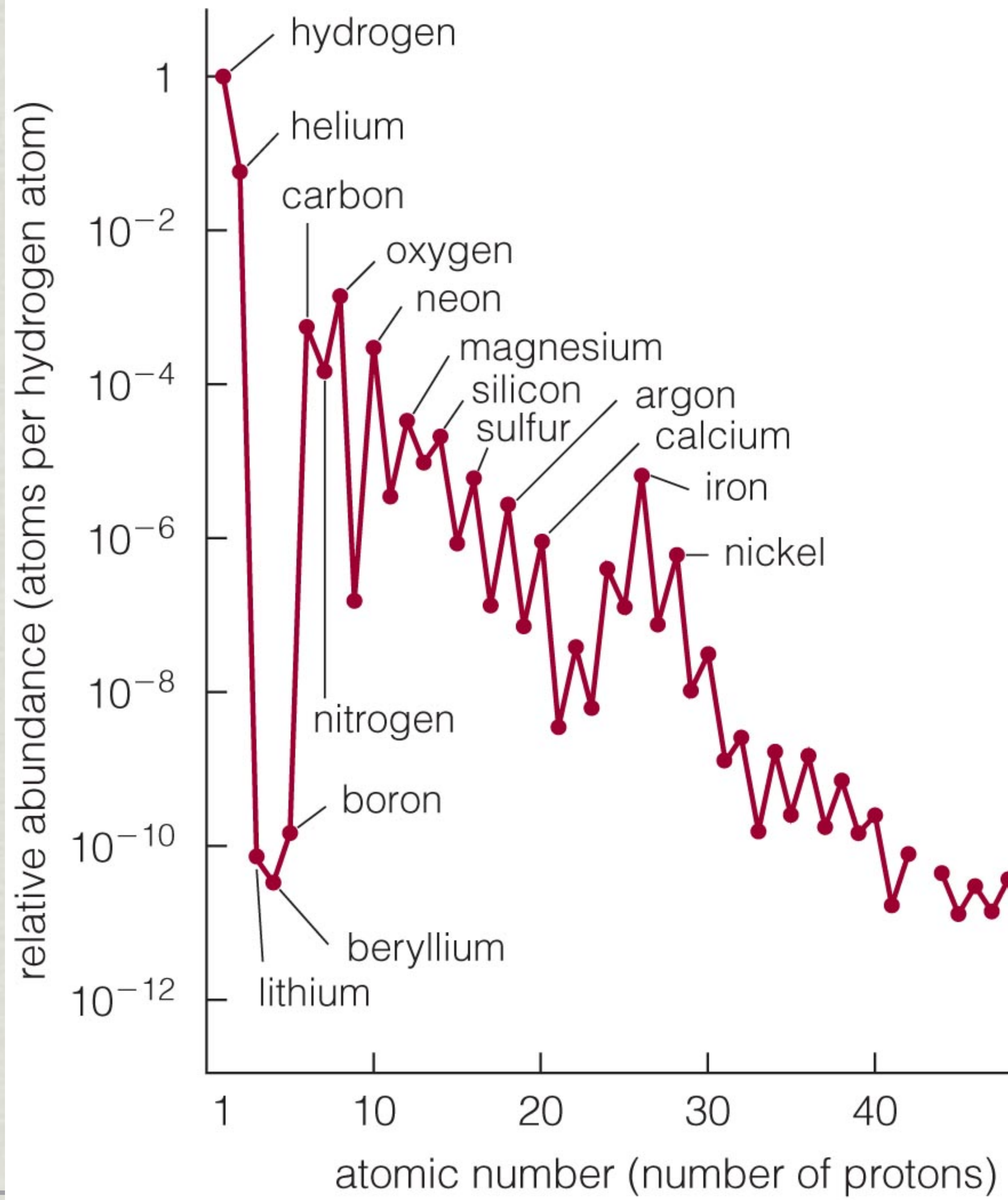
High Mass Stars: Post Main Sequence Nuclear Fusion

Where are the elements made?
- “alpha” particle (He nucleus) capture: stable fusion reactions add +4 atomic weight, 2 protons

Evidence for Helium capture:
high abundance of elements with even numbers of protons

Carbon: 6 protons + 6 neutrons = 3 x He
Oxygen: 8 protons + 8 neutrons = 4 x He
Neon: 10 protons + 10 neutrons 5 x He
Magnesium: 12 protons + 12 neutrons = 6 x He
Silicon: 14 protons + 14 neutrons = 7 x He
Sulfur: 16 protons + 16 neutrons = 8 x He
Calcium: 20 protons + 20 neutrons = 10 x He



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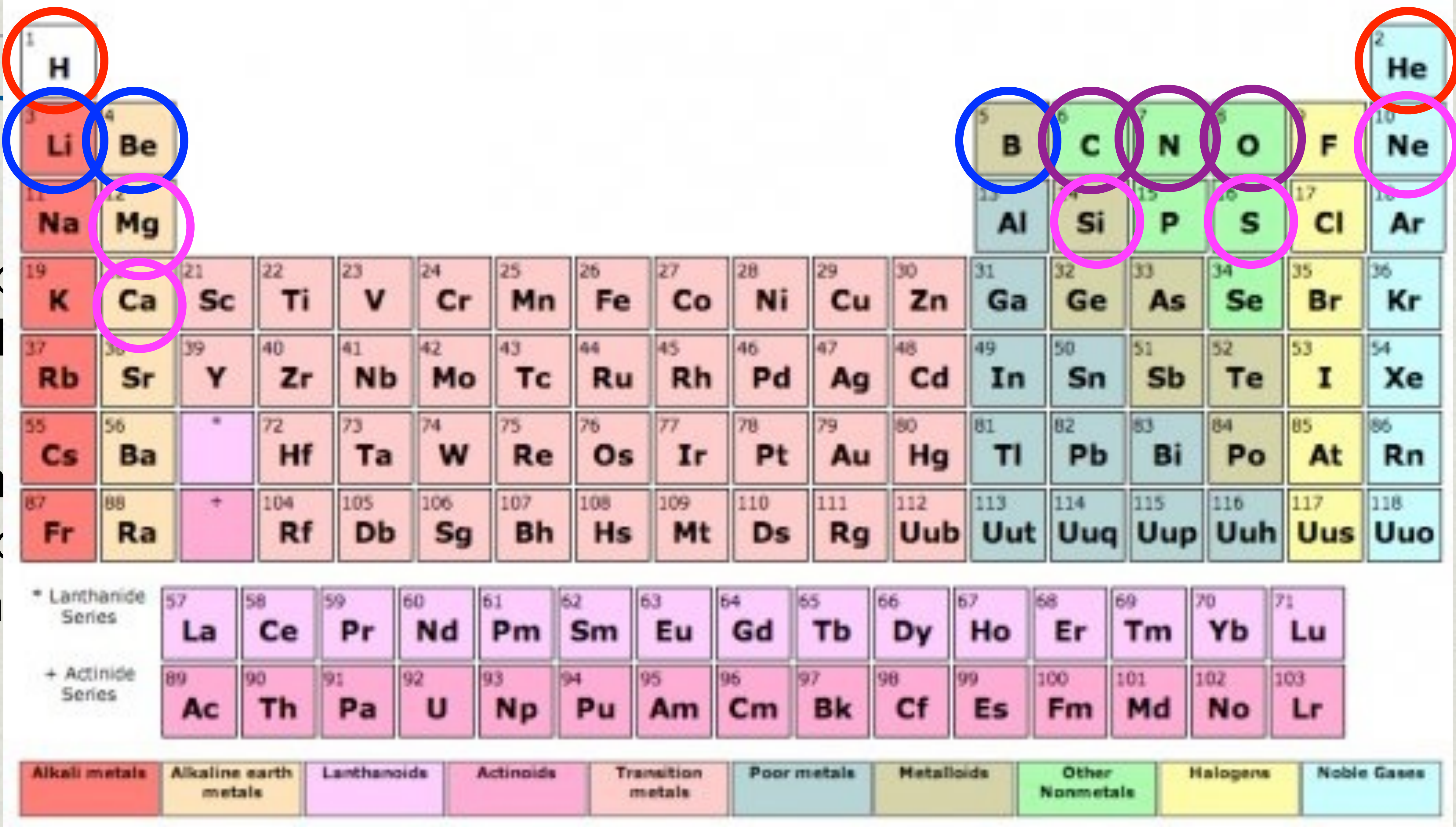

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Alkali metals	Alkaline earth metals	Lanthanoids	Actinoids	Transition metals	Poor metals	Metalloids	Other Nonmetals	Halogens	Noble Gases

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High Mass Stars: Post Main Sequence Nuclear Fusion

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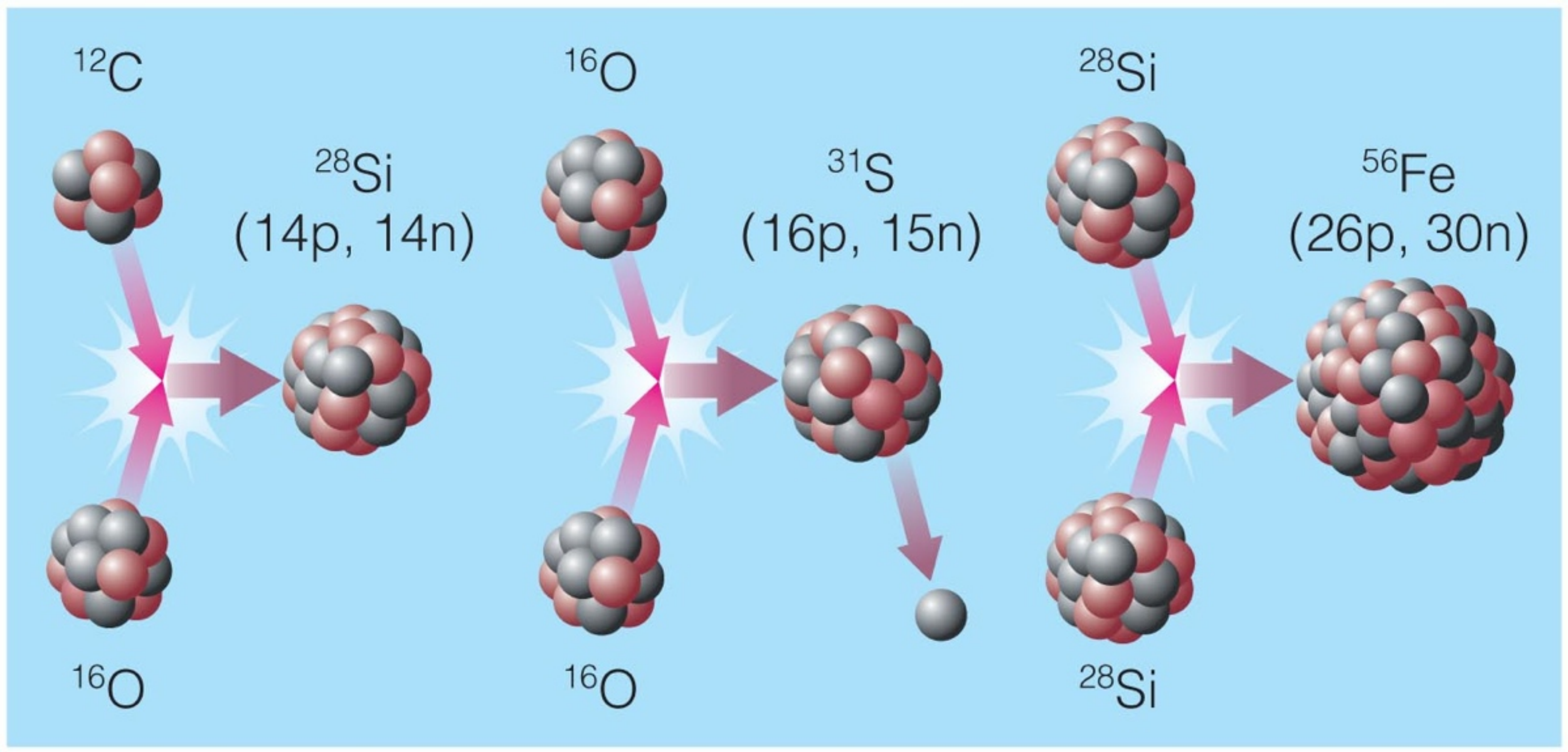
    - In low mass stars, it stays behind as a white dwarf
- Carbon made in low-mass stars that make it to the Helium Flash
- C-N-O cycle in massive stars makes N,O
- “alpha” particle (He nucleus) capture
- if core pressure, temperature high enough, can fuse **really** big nuclei

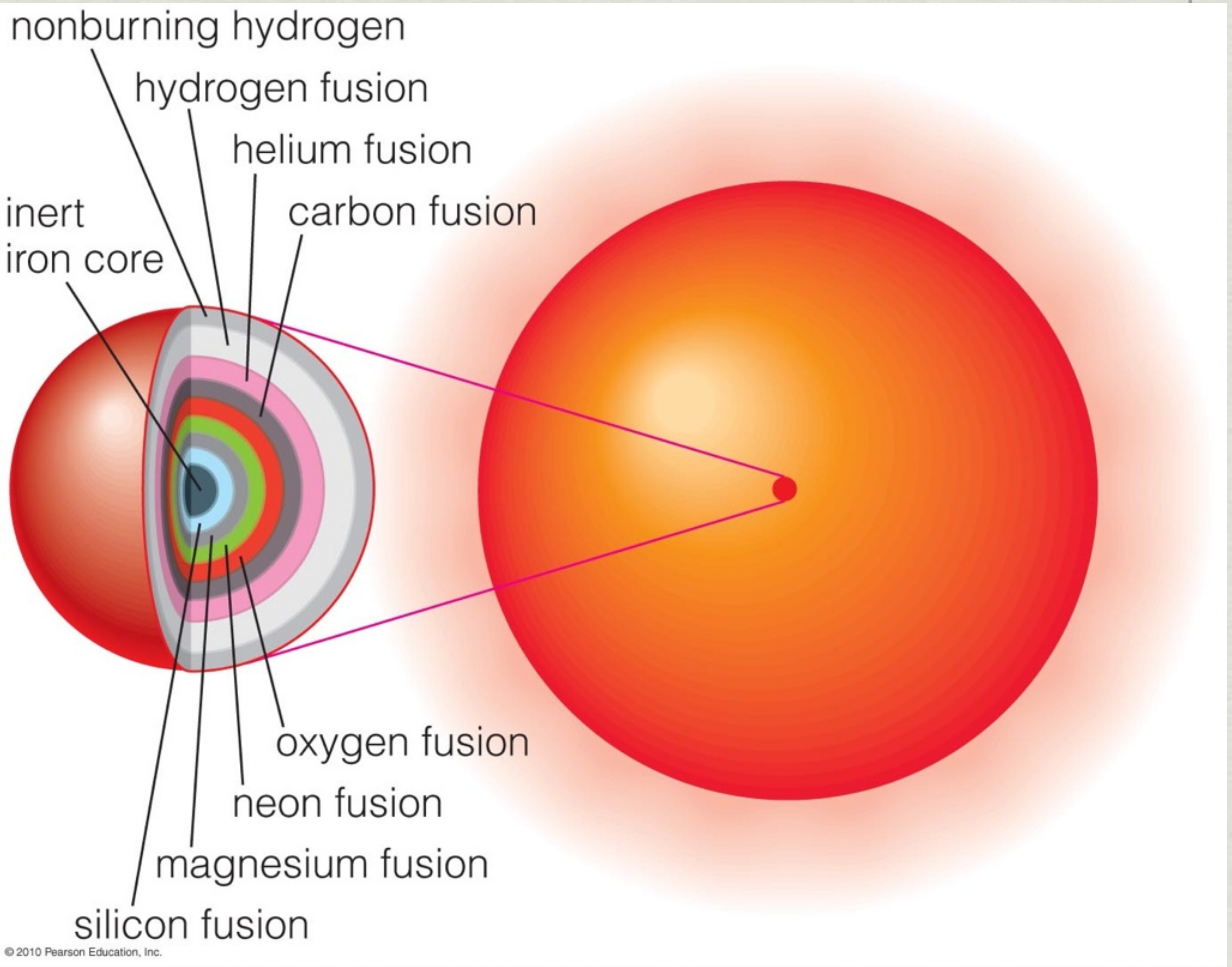


High Mass Stars: Post Main Sequence Fusion

Sequence: all at once

Not enough time for the core to collapse far enough to become degenerate:

New fusion reactions initiated before that can happen



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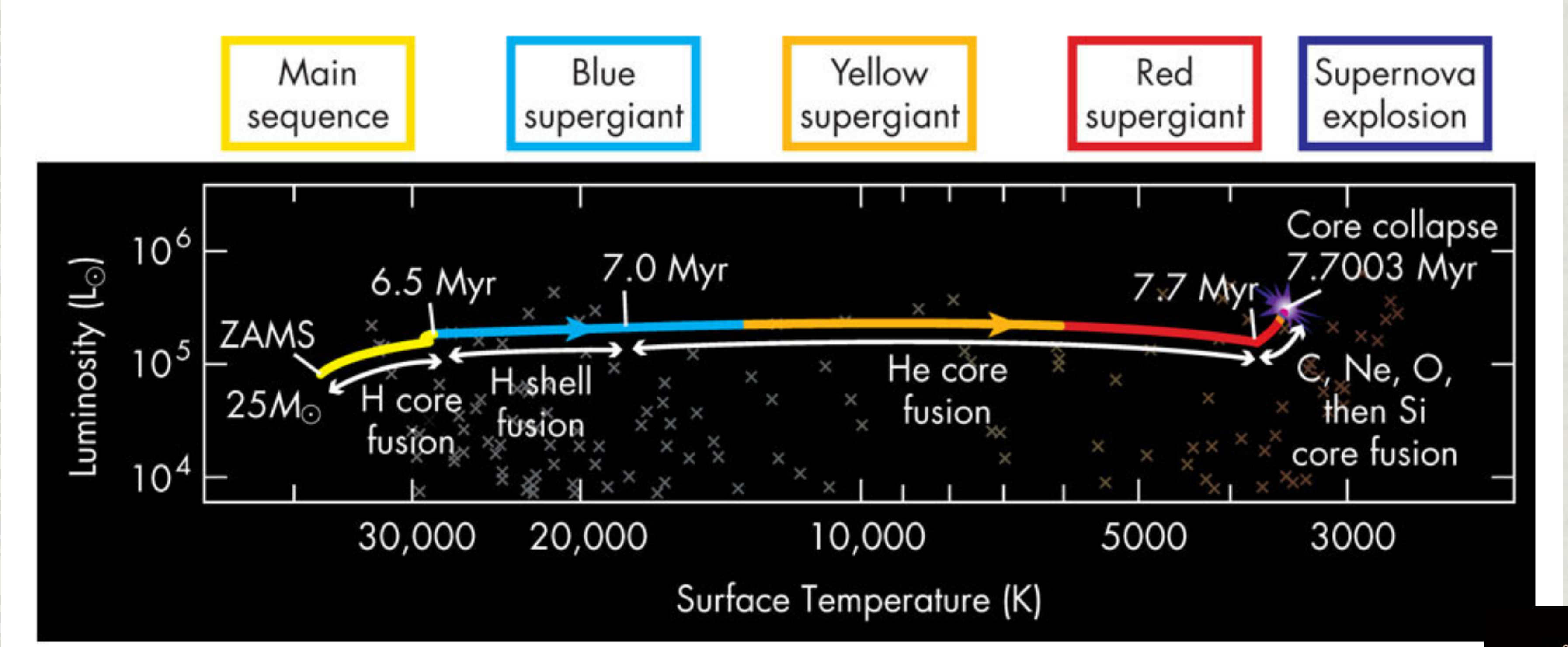
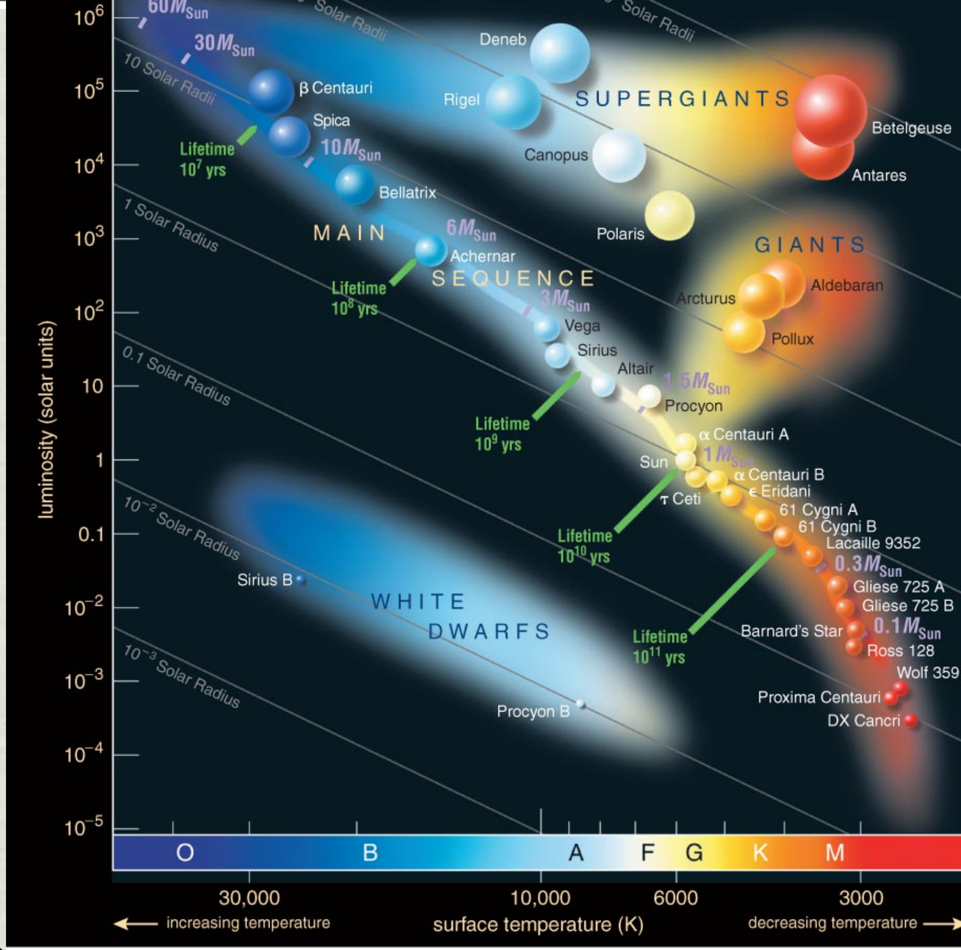
High Mass Stars: Post Main Sequence Evolution

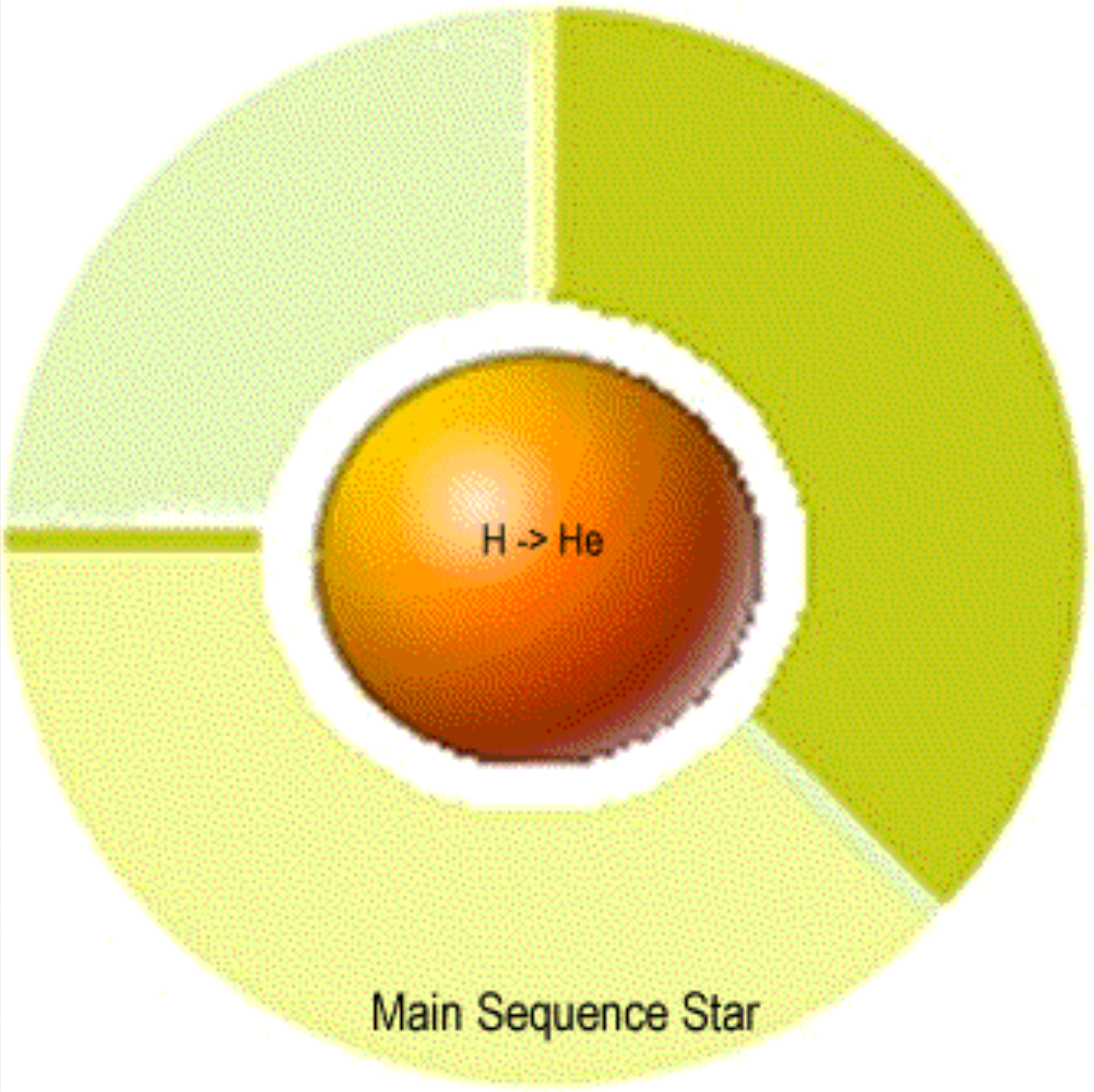




Sequence: all at once

Not enough time for the core to collapse far enough to become degenerate: New fusion reactions initiated before that can happen.

MS time (H core fusion): 6.5 million years
H-shell fusion: 0.5 million years
He core fusion: 0.7 million years
All the rest: 0.0003 million years = 300 years


H -> He
Main Sequence Star

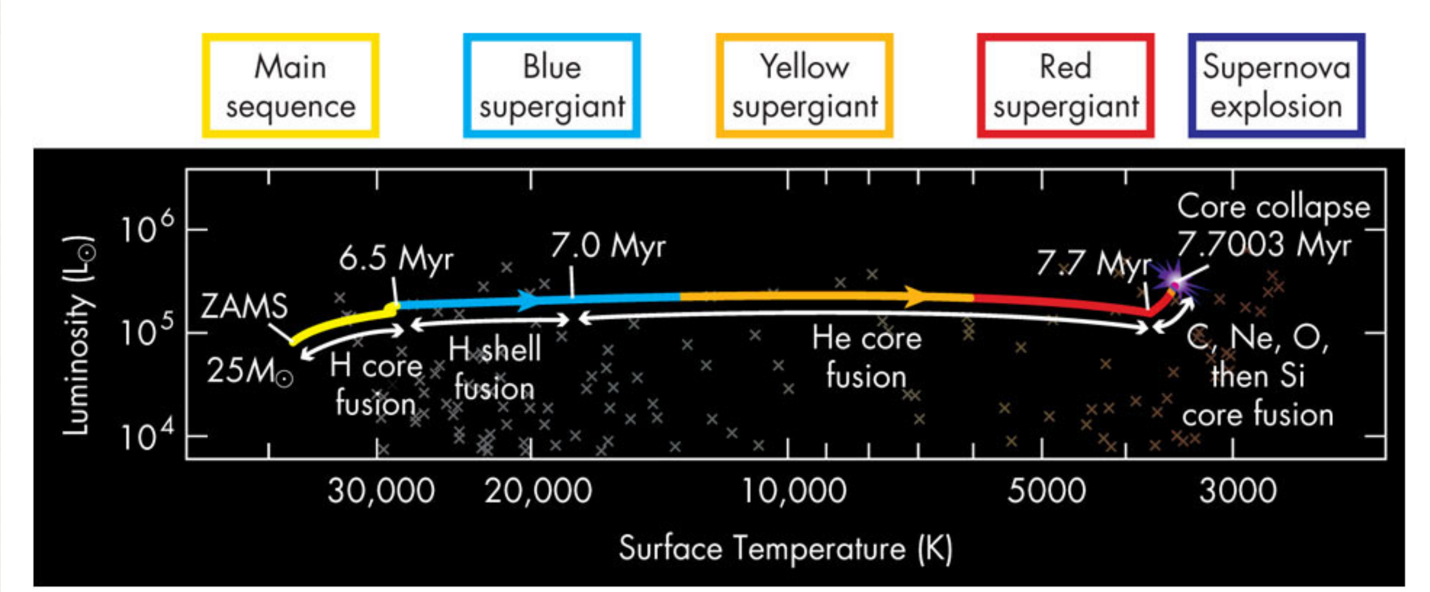
High Mass Stars: Post Main Sequence Evolution

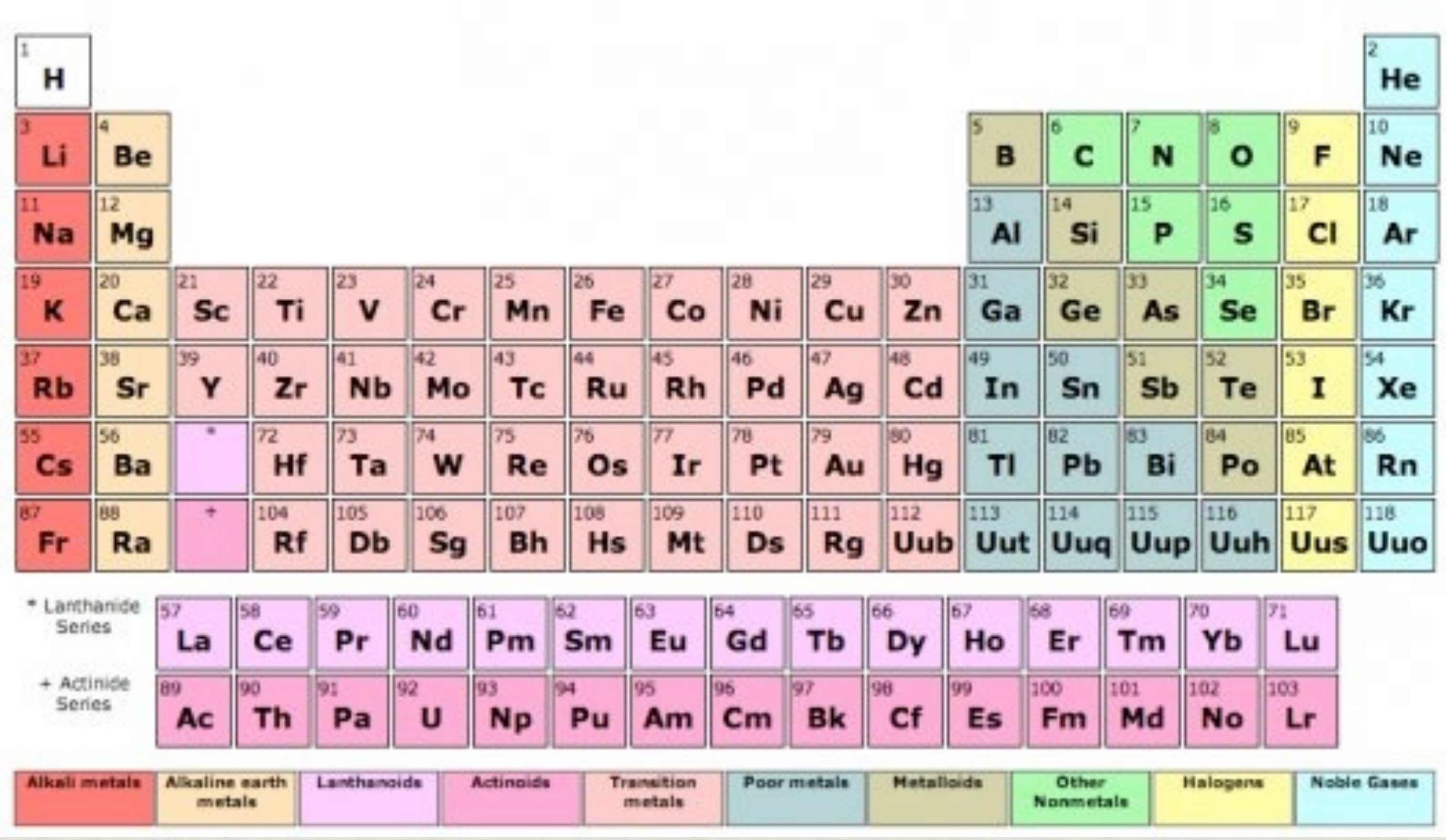
Sequence: all at once

Not enough time for the core to collapse and become degenerate:

New fusion cycles initiated before that can happen

Q: When does it stop?





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Alkali metals	Alkaline earth metals	Lanthanoids	Actinoids	Transition metals	Poor metals	Metalloids	Other Nonmetals	Halogens	Noble Gases

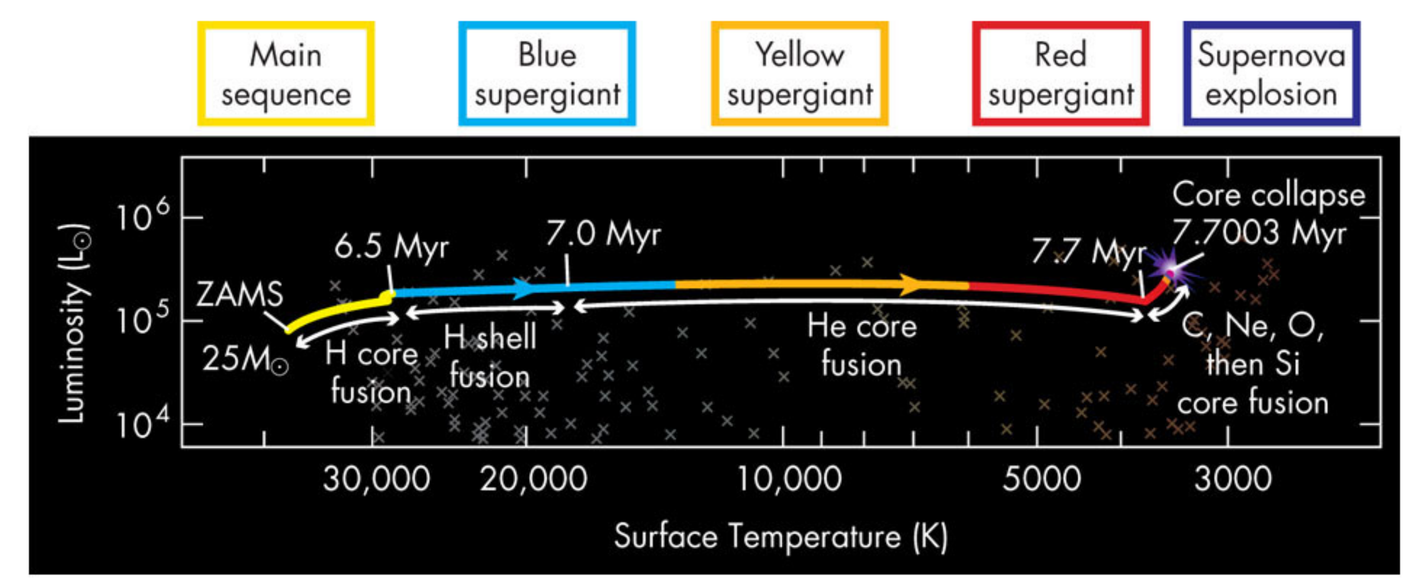
High Mass Stars: Post Main Sequence Evolution

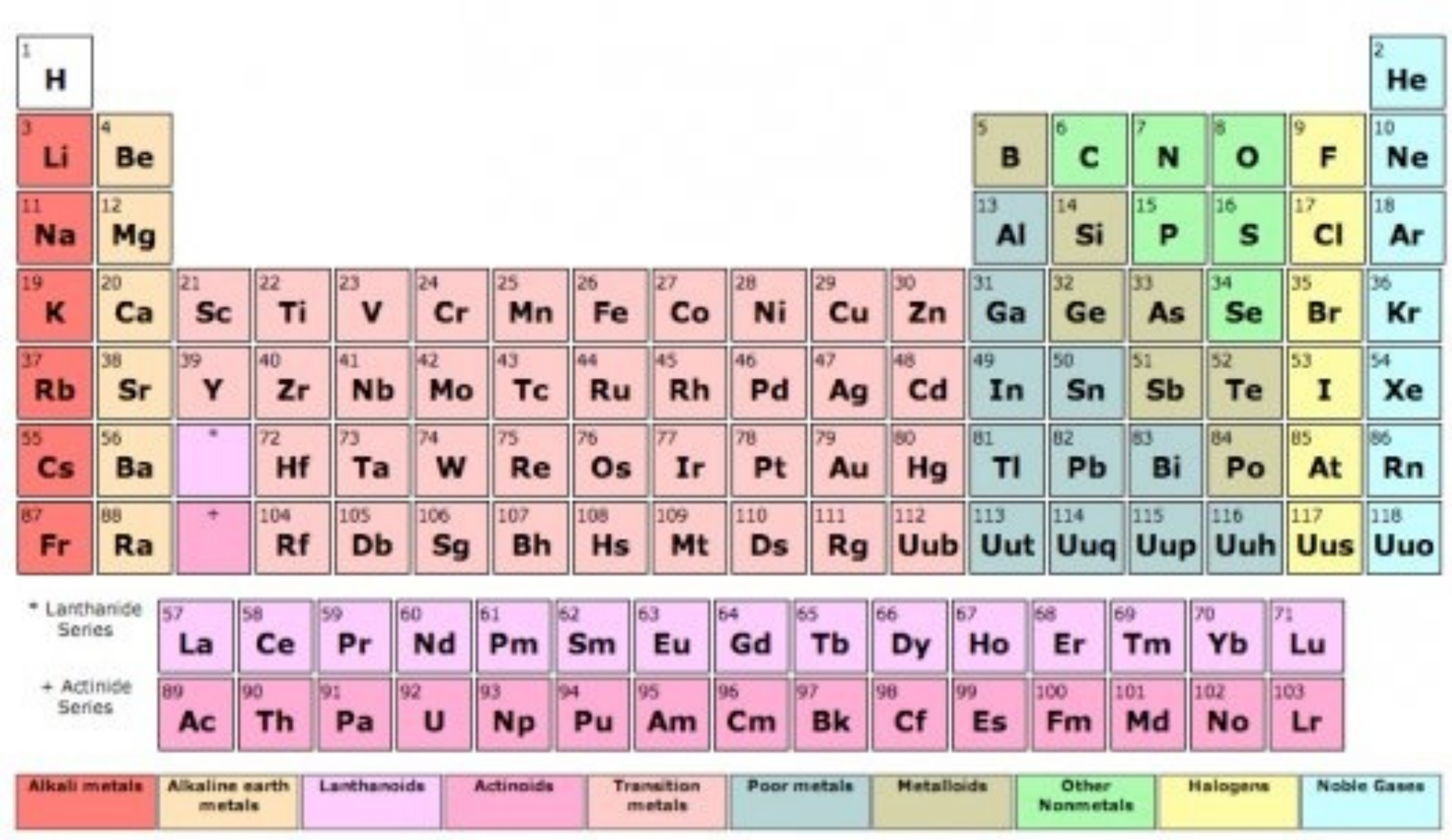
Sequence: all at once

Not enough time for the core to collapse and become degenerate:

New fusion cycles initiated before that can happen

Q: When does it stop?
A: When fusion of new elements doesn't release energy!





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Alkali metals	Alkaline earth metals	Lanthanoids	Actinoids	Transition metals	Poor metals	Metalloids	Other Nonmetals	Halogens	Noble Gases

High Mass Stars: Post Main Sequence Evolution

Mass per particle in the nucleus decreases down the periodic table from H to Fe.

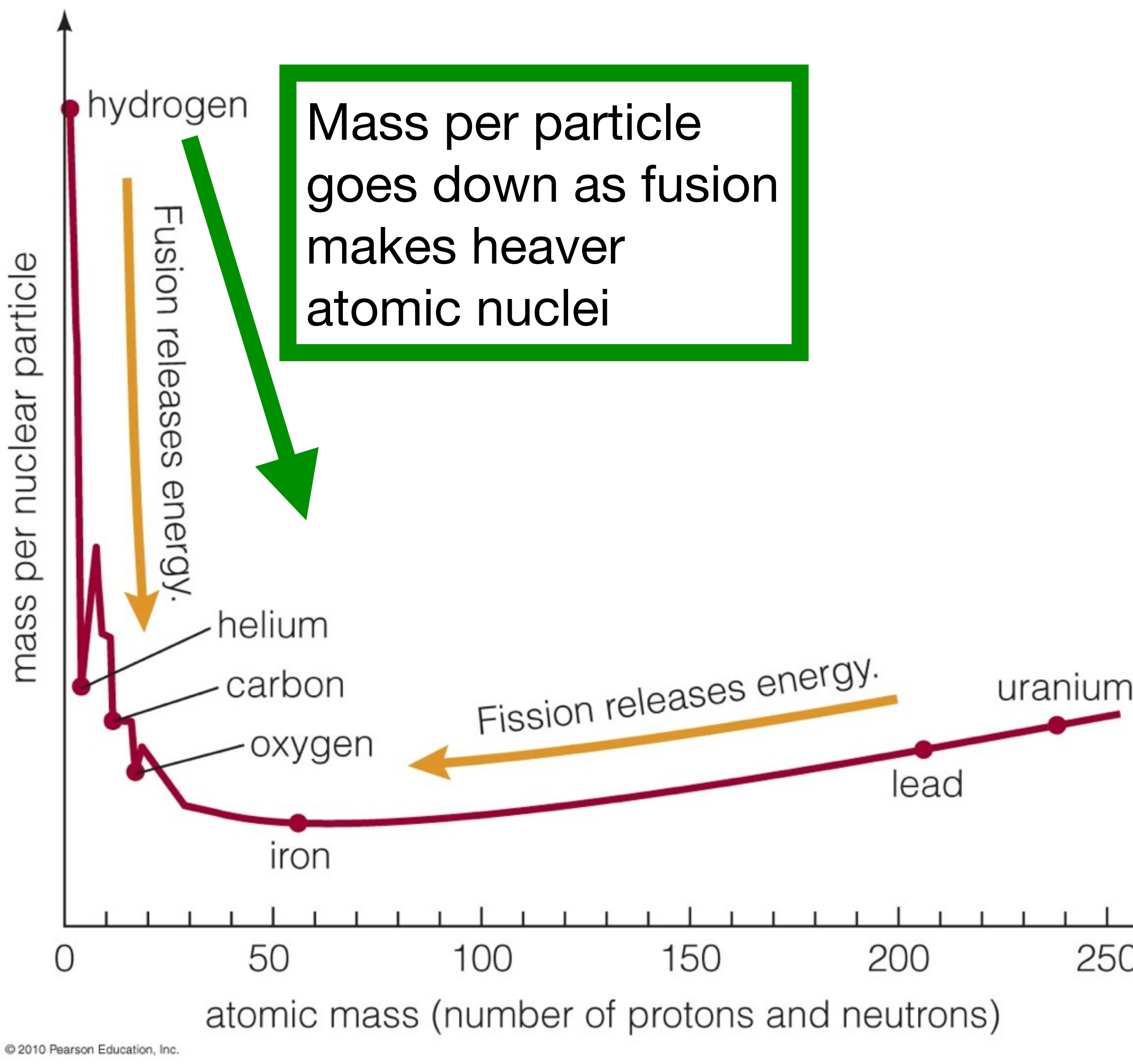
Where does it go?

It is converted to energy as those elements are made!

Remember: of 4 H nuclei > 1 He nucleus.

$\Delta m = \text{Mass}_{4H} - \text{Mass}_{He}$

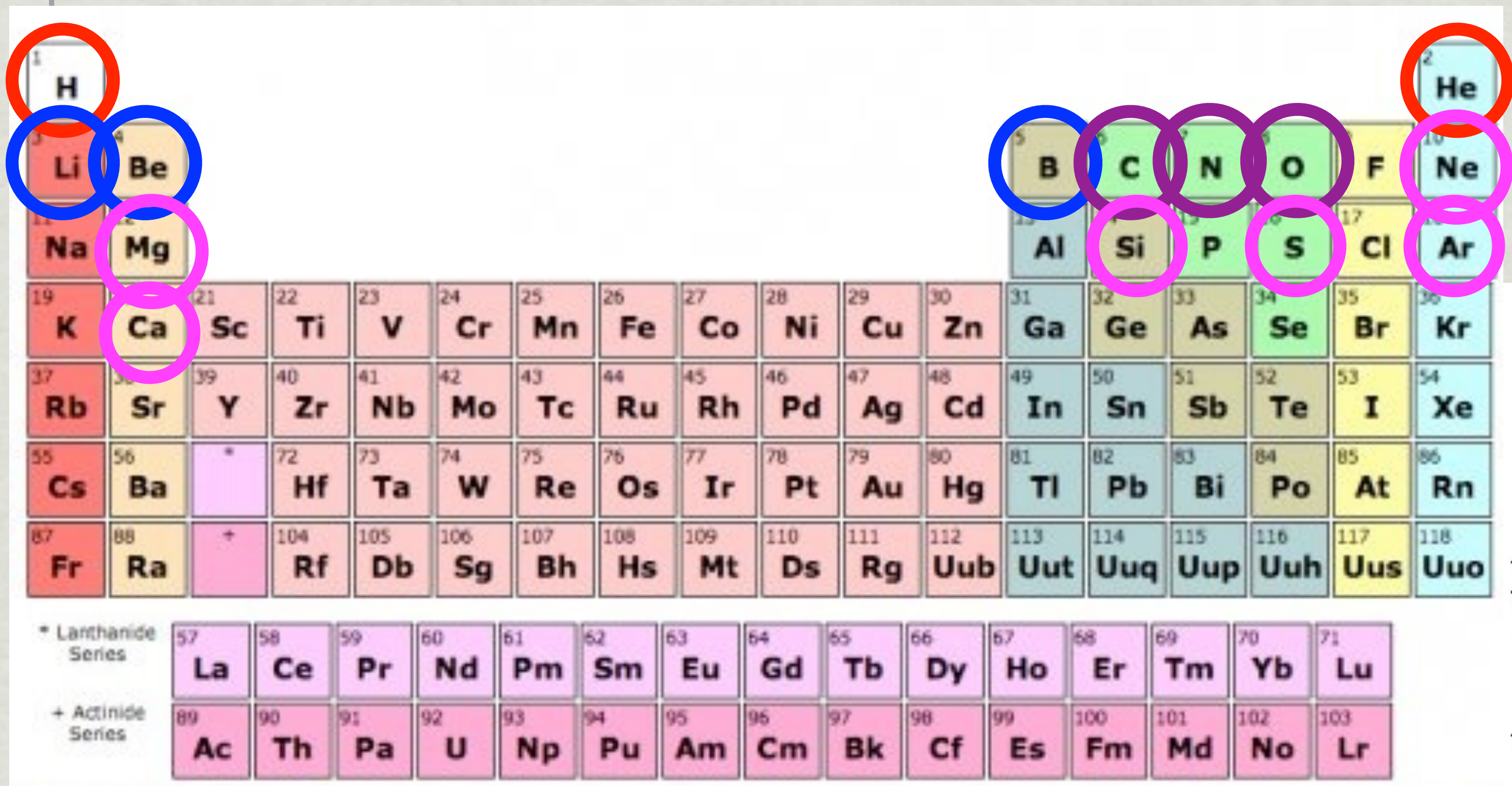
$E_{out} = \Delta mc^2$



Mass per particle goes down as fusion makes heaver atomic nuclei

H, He, ... C...Fe...Ag...Pb...U → increasing number of particles in nucleus for elements in the periodic table

High Mass Stars: Post Main Sequence Evolution



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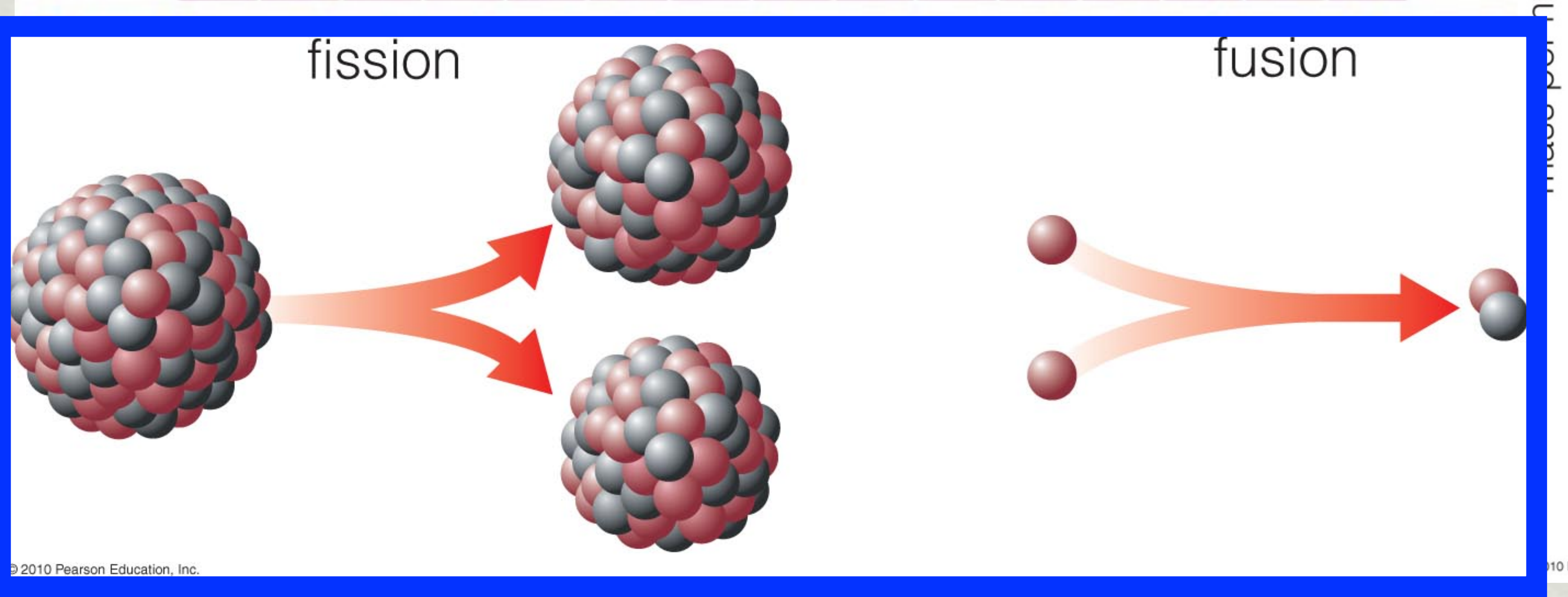
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	*	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	+	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Uub	Uut	Uuq	Uup	Uuh	Uus	Uuo

* Lanthanide Series	La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
+ Actinide Series	Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



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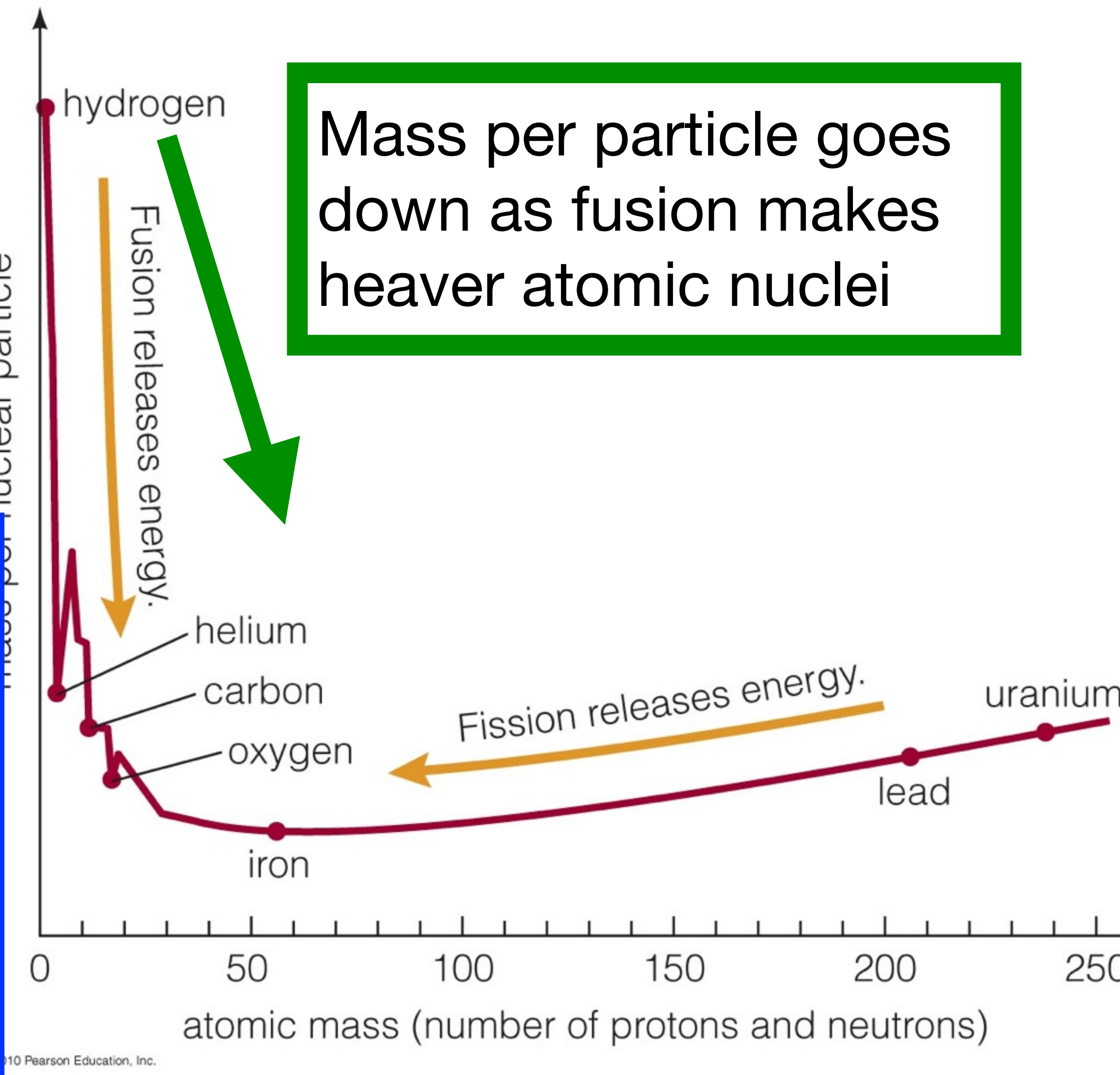

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Mass per particle goes down as fusion makes heaver atomic nuclei

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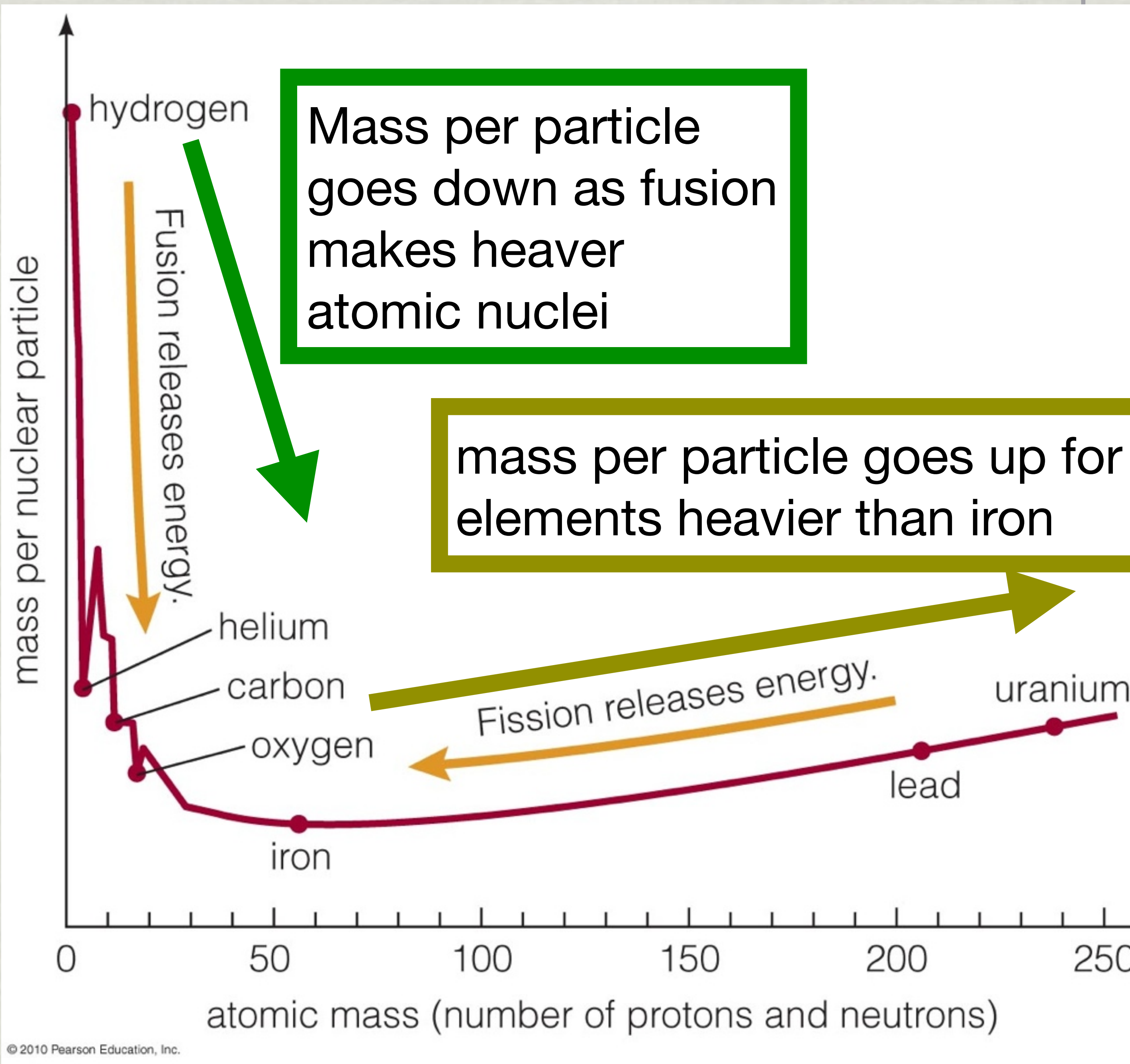
High Mass Stars: Post Main Sequence Evolution

Mass per particle (neutron, proton) in the nucleus increases for elements heavier than Fe.

Mass per particle of a lead nucleus > Mass per particle of an iron nucleus.

$\Delta m = \mathrm{Mass}_{\mathrm{Fe}} - \mathrm{Mass}_{\mathrm{Pb}} < 0$
No energy out by fusing nuclei to make lead!

How are these elements made?
Put energy ***in*** during the explosions that end the lives of massive stars



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Mass per particle goes down as fusion makes heaver atomic nuclei

mass per particle goes up for elements heavier than iron

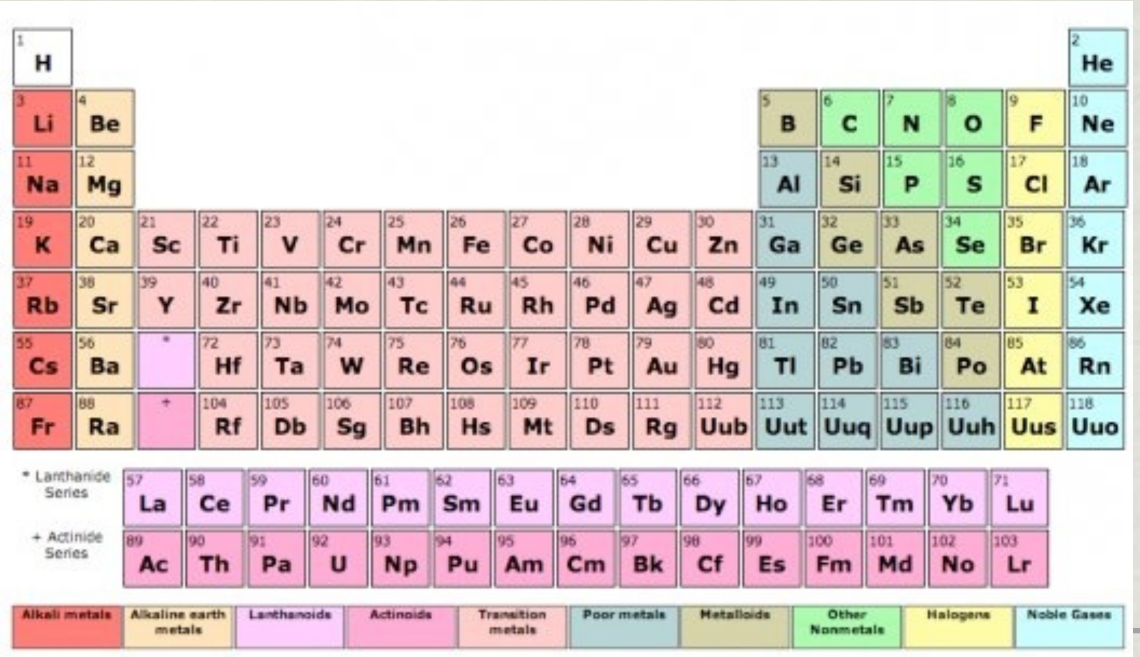
H, He, ... C...Fe...Ag...Pb...U → increasing number of particles in nucleus for elements in the periodic table

High Mass Stars: Post Main Sequence Evolution

Iron (Fe) is the end of the line for fusion.

Fe nucleus has lowest mass per particle: no conversion of mass to energy when you add more particles

Now gravity can win as the core collapses. Star can't generate energy to hold itself up with thermal pressure.



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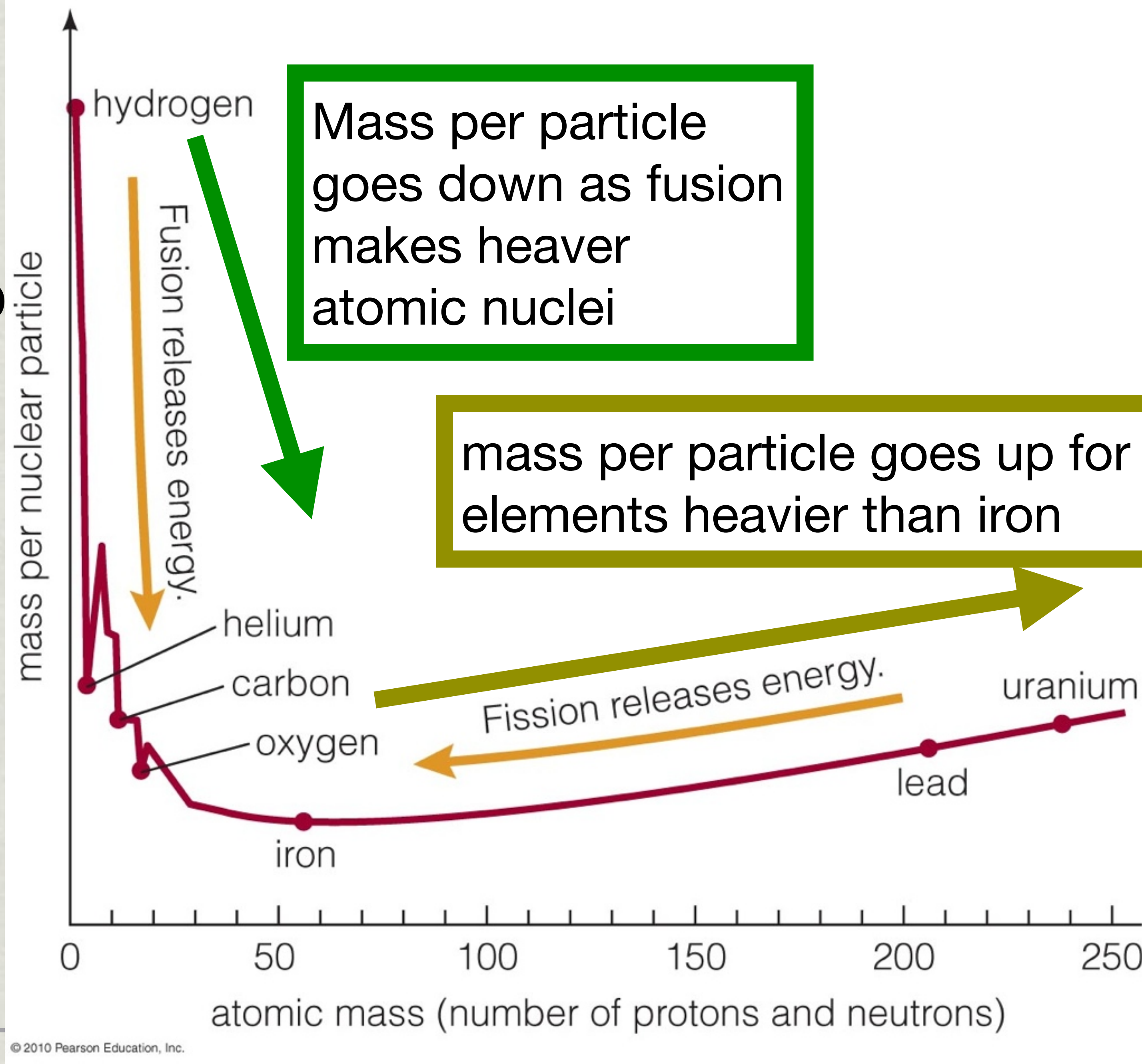
Alkali metals	Alkaline earth metals	Lanthanoids	Actinoids	Transition metals	Poor metals	Metalloids	Other Nonmetals	Halogens	Noble Gases



Mass per particle goes down as fusion makes heaver atomic nuclei

mass per particle goes up for elements heavier than iron

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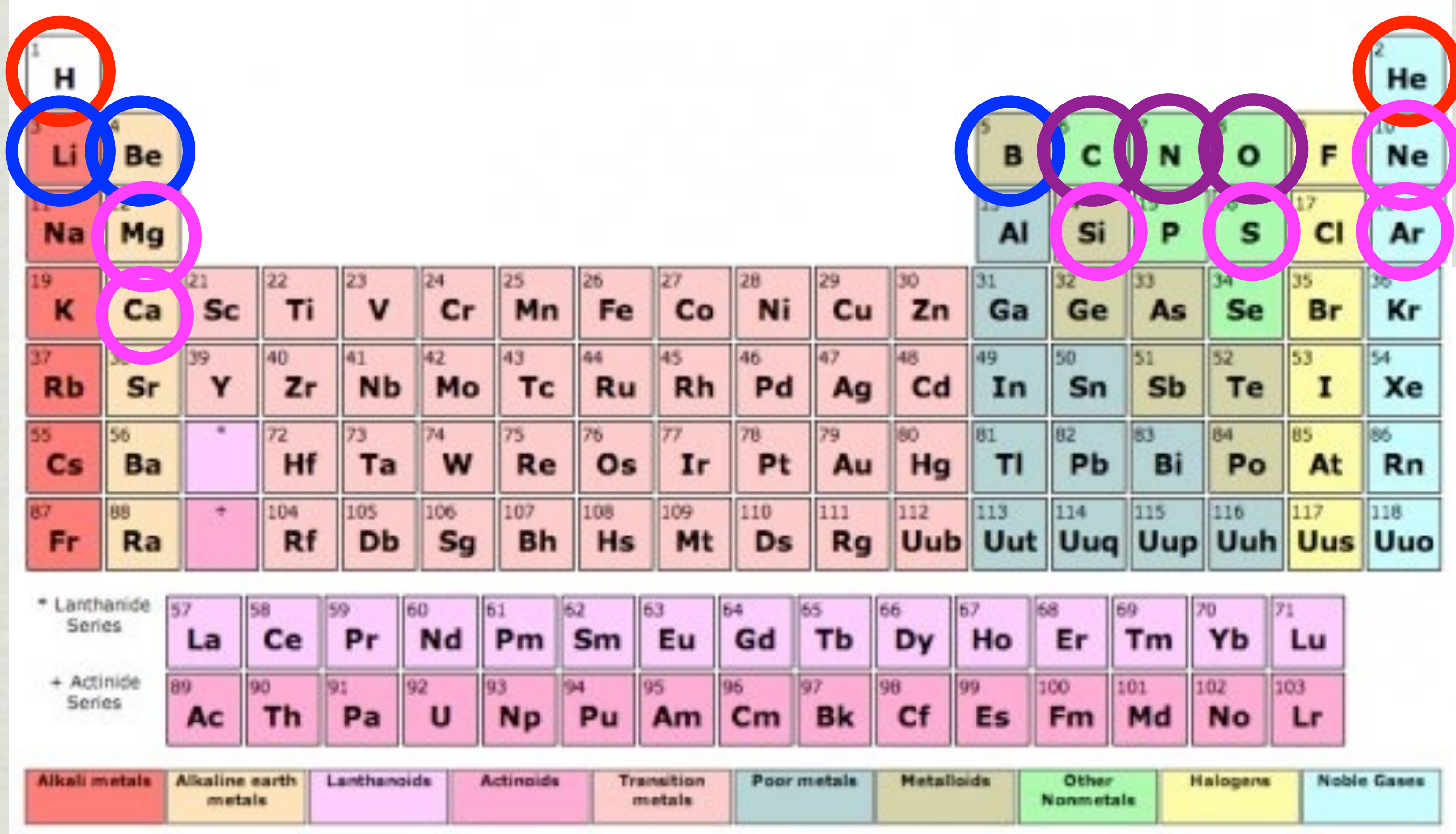
High Mass Stars: Post Main Sequence Evolution



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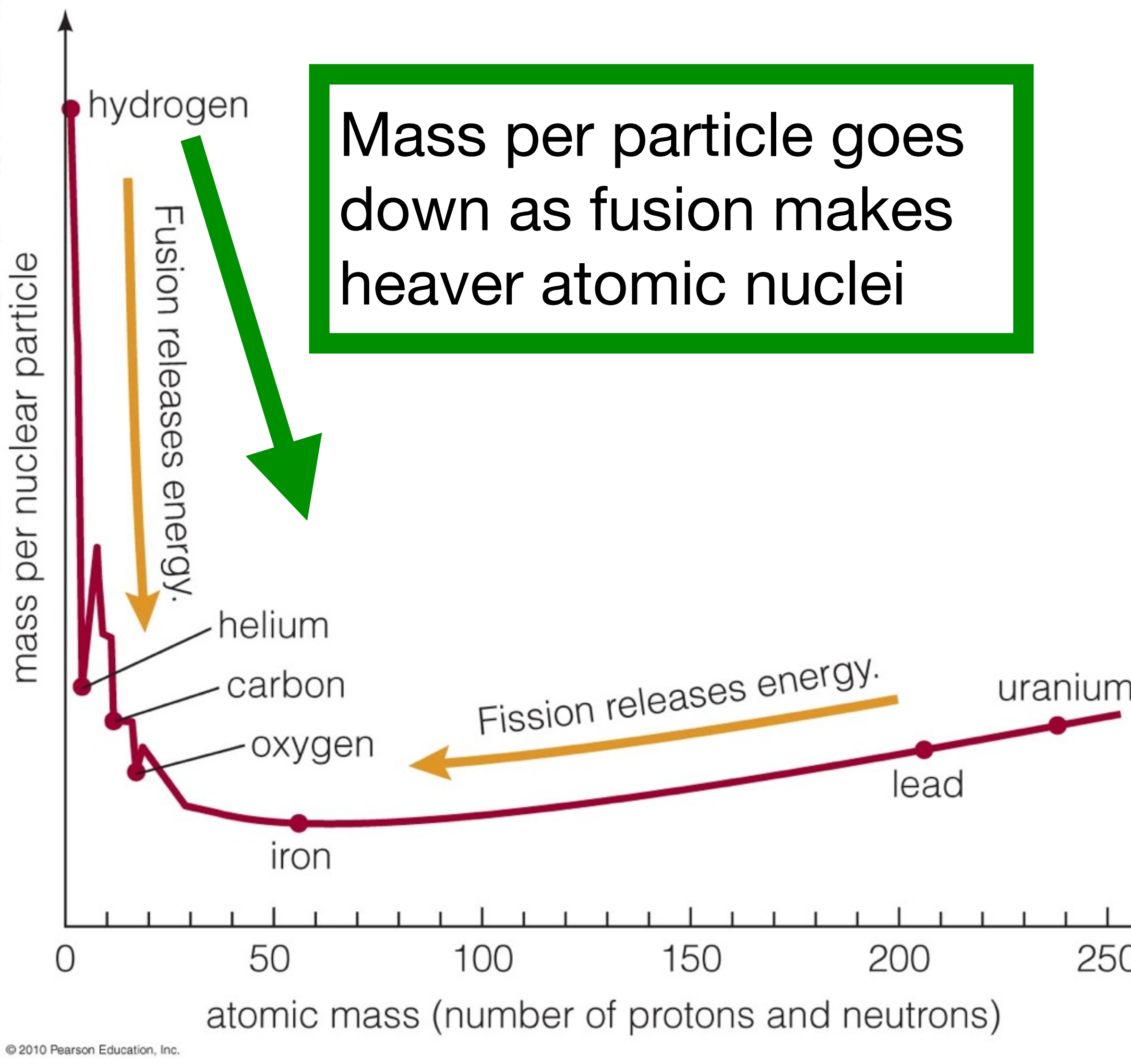
Which reaction gives more energy?

A 4 H -> He

B 6 He -> Mg

C 2 Zr -> Hg



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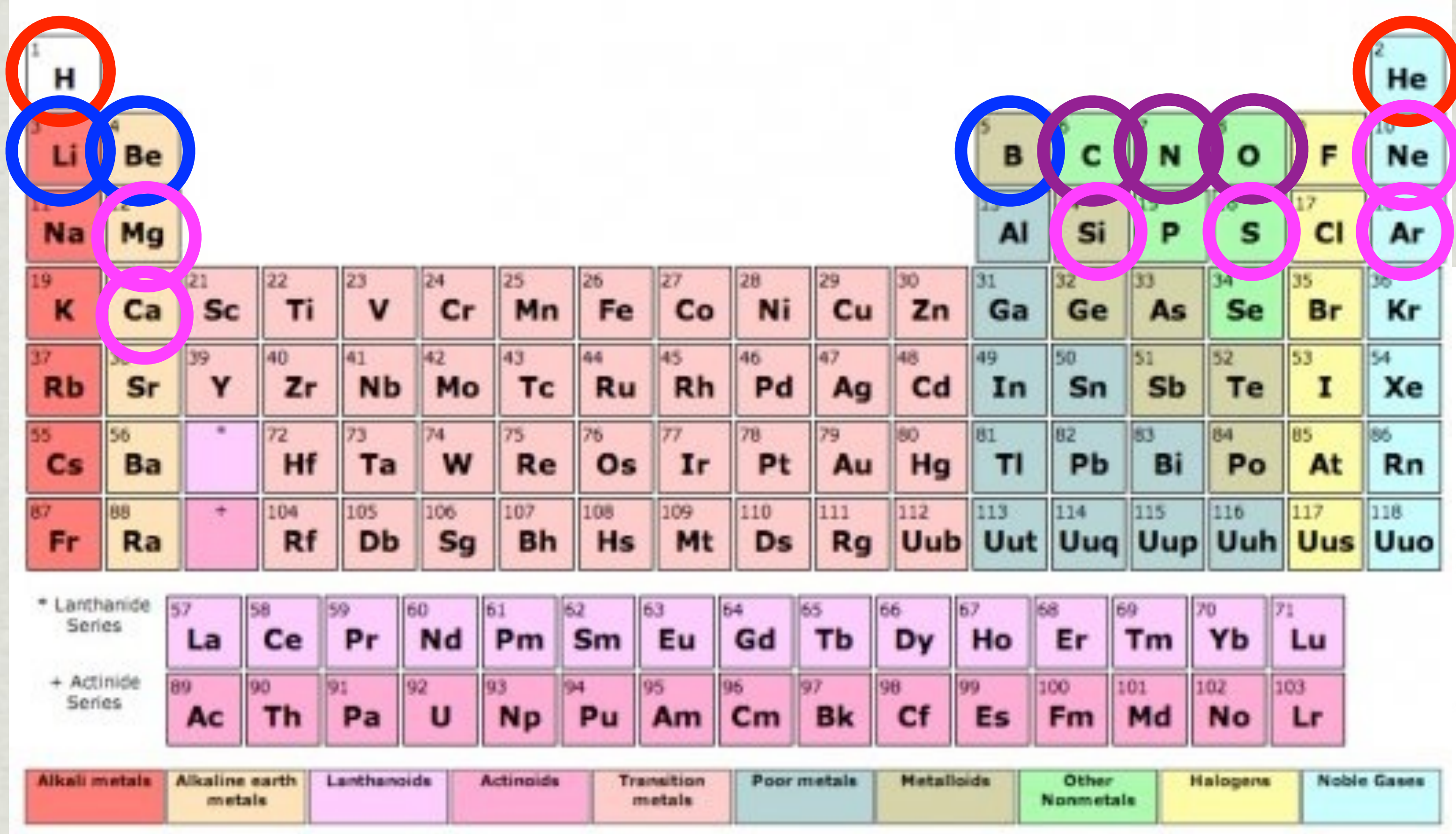

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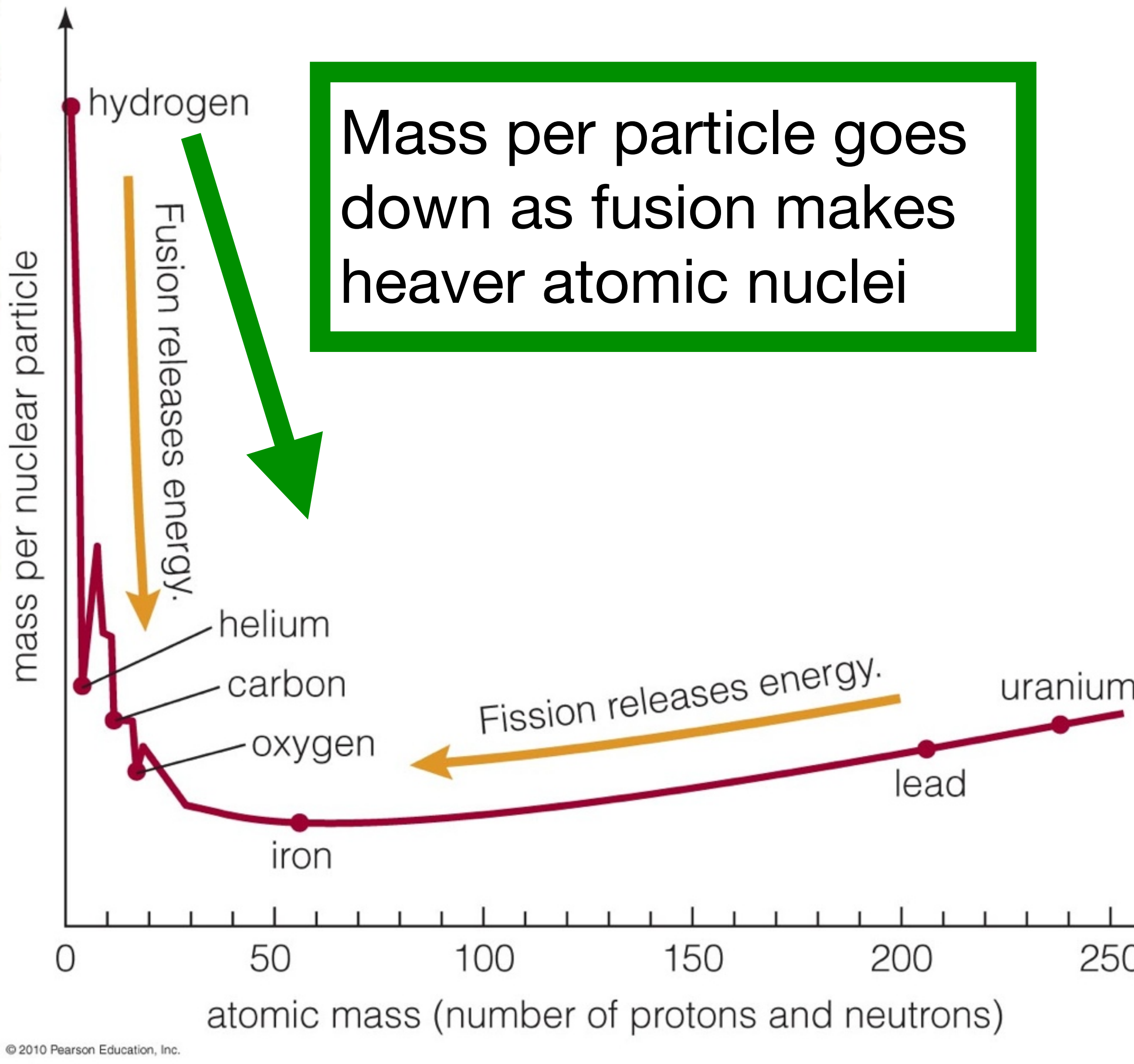

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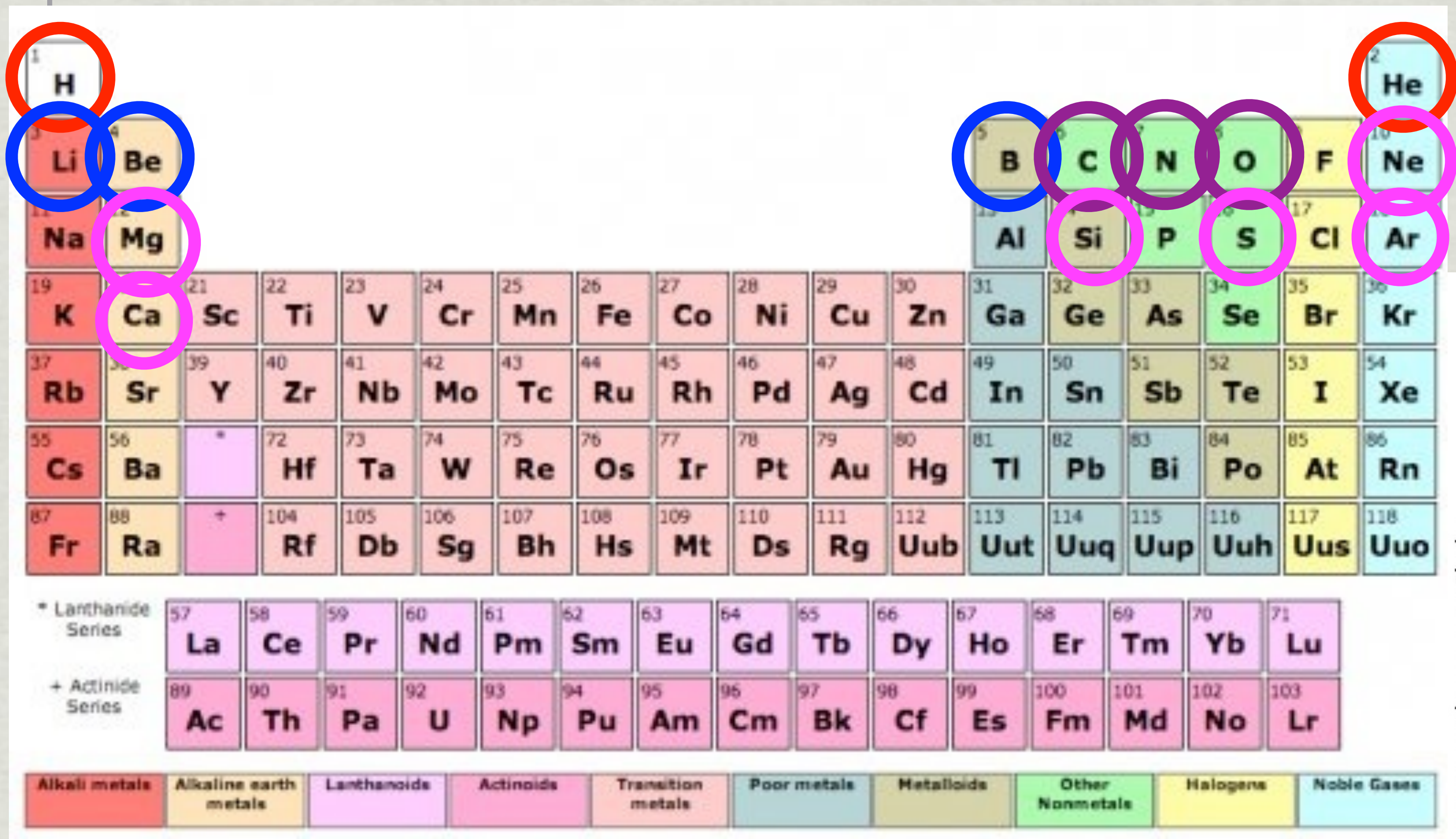
High Mass Stars: Post Main Sequence Evolution

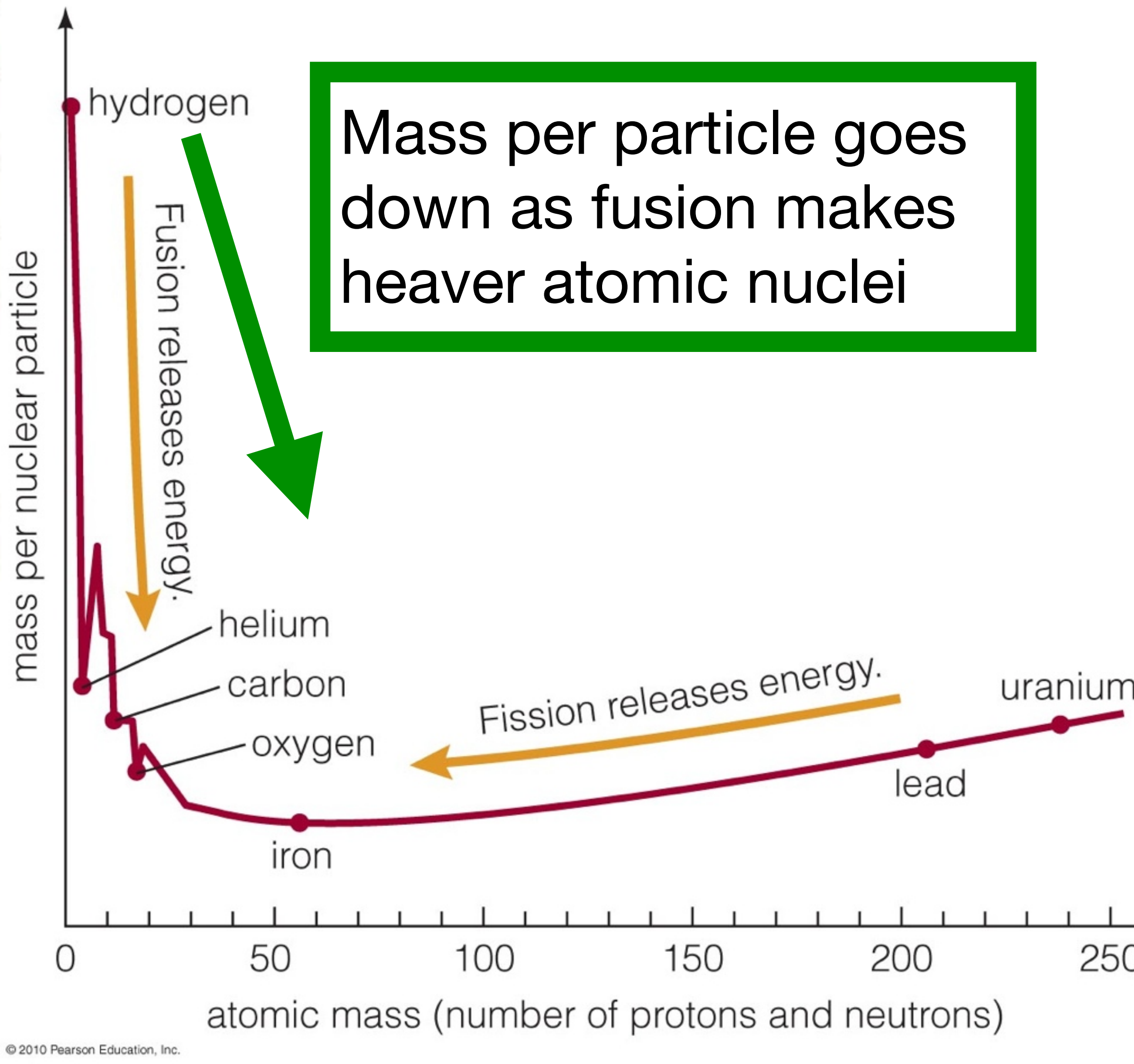


Which reaction requires energy input?

A 4 H -> He

B 6 He -> Mg

C 2 Zr -> Hg



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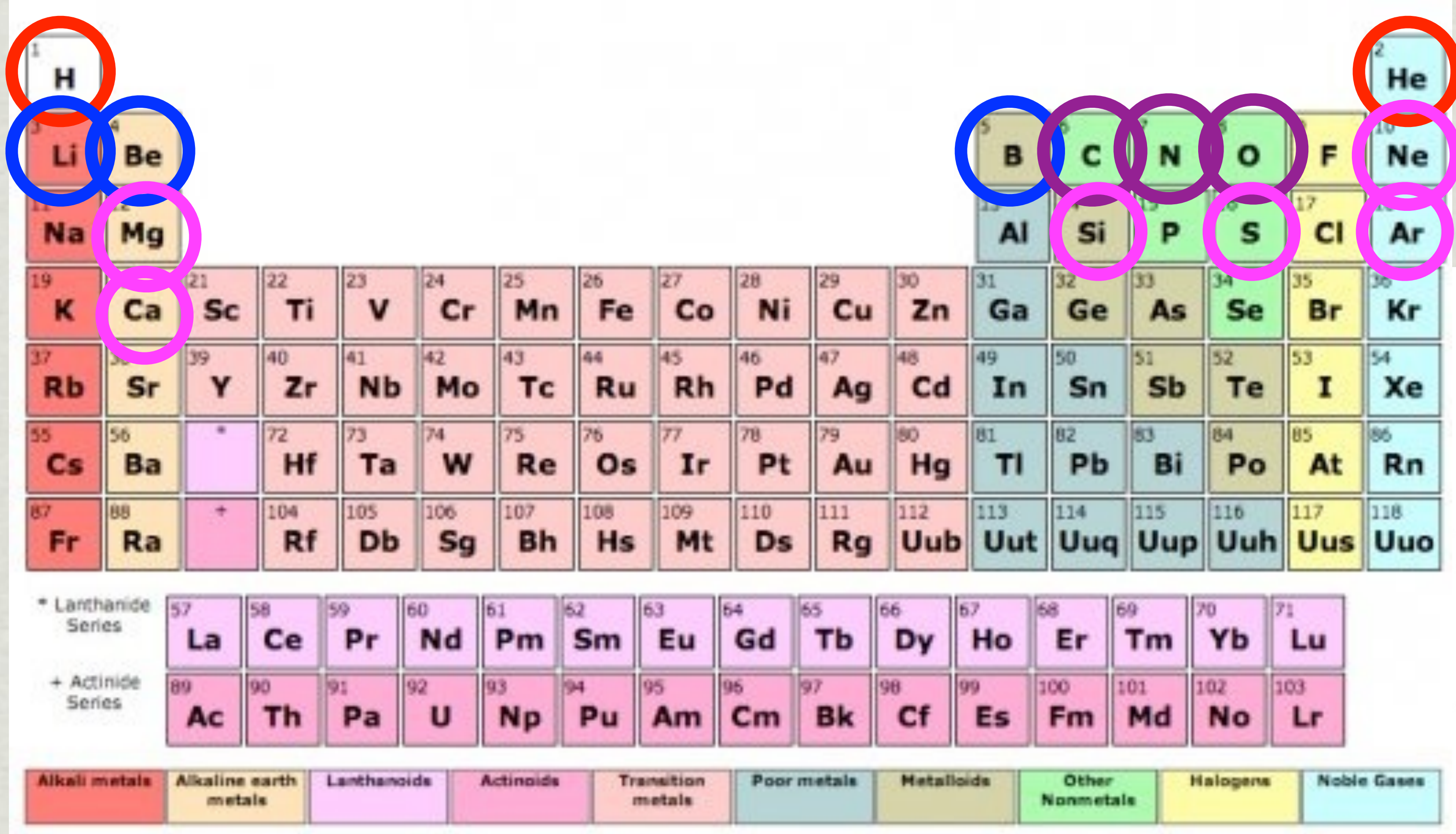

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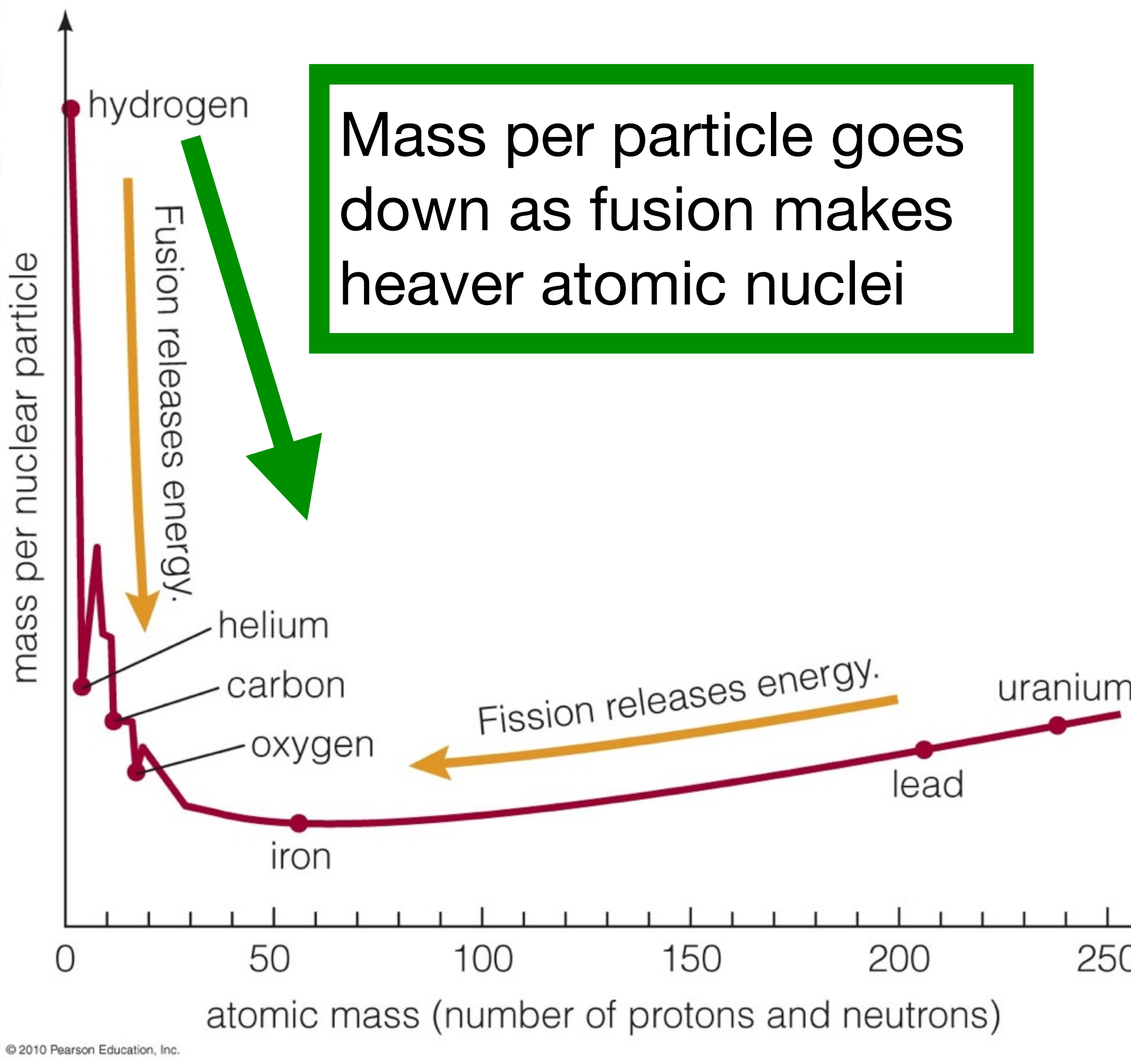

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Ends of High Mass Stars: Core Collapse Supernovae

Fusion ends
Core continues to collapse

For $M > 8\ M_{sun}$, gravity is so strong that electron degeneracy pressure fails, can't hold up the star

Think about that: conditions in the star want to violate the Exclusion Principle and the Heisenberg Uncertainty Principle. That's serious pressure!

Collapse continues: pressure is so intense that it causes electrons and protons to combine into neutrons. Core becomes like a giant atomic nucleus

- releases a burst of high energy atomic particles called neutrinos when this happens
- Huge burst of energy: 10^{46} Joules

Ends of High Mass Stars: Core Collapse Supernovae

Core of degenerate neutrons

- $M_{core} < 3\ M_{sun}$

Neutron degeneracy pressure holds up the core, stops collapse

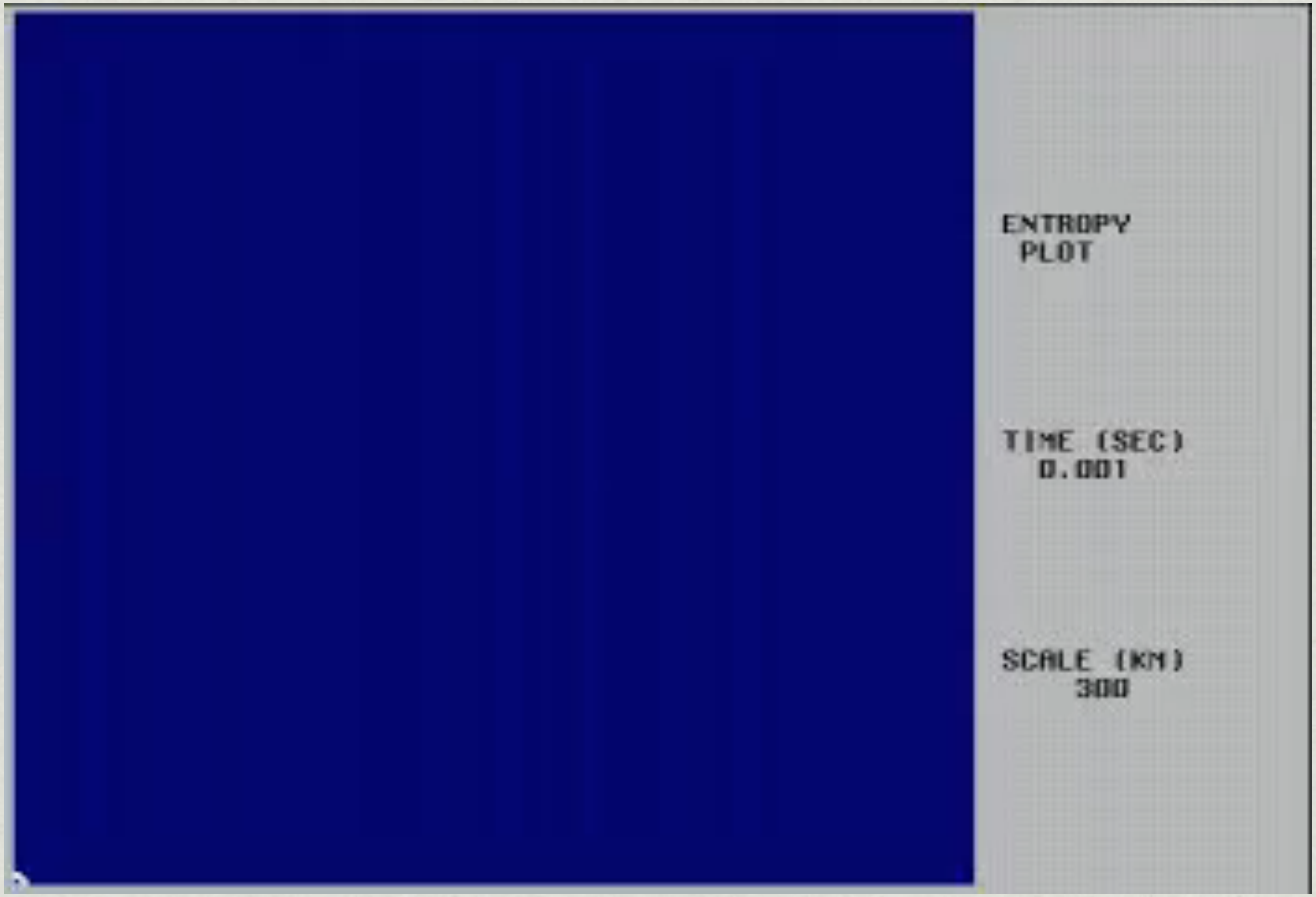
We started with M > 8 Msun. What about the rest?

Outer layers were collapsing, too.

They hit the core and get blasted with the 10^{46} Joules released when the core fused to neutrons.

- bounces back from the core, gets extra energy boost by absorbing about 1% (10^{44} Joules) of
  the energy released in the fusion to neutrinos

http://www.youtube.com/watch?feature=player_detailpage&v=e-91PbbaKI8


ENTROPY
PLOT
TIME (SEC)
0.001
SCALE (KM)
300

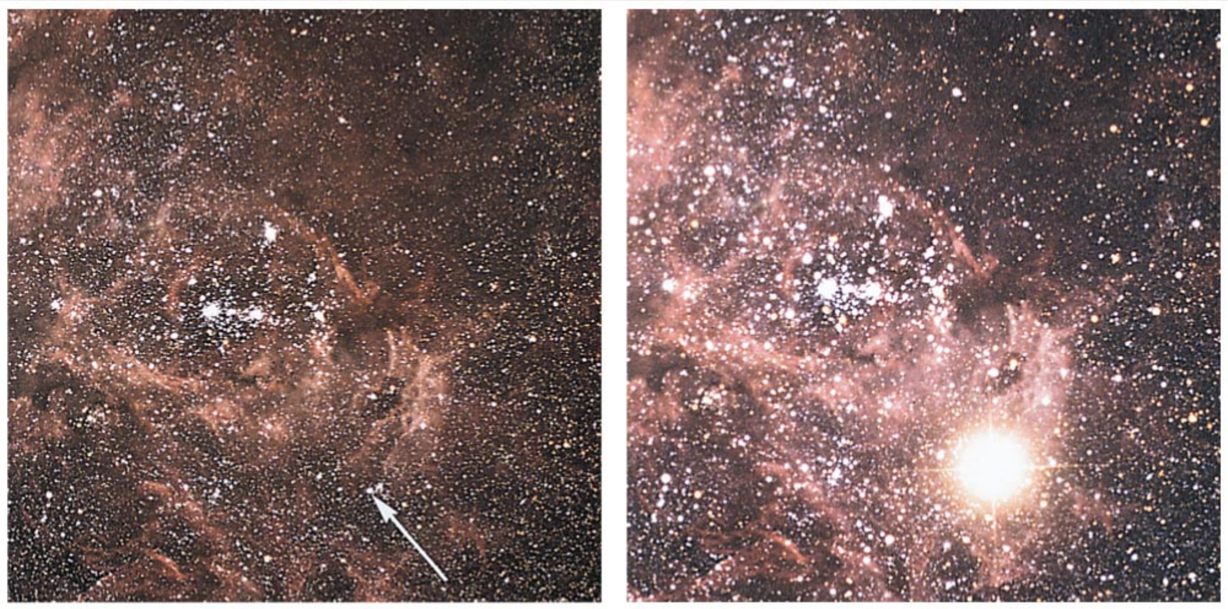
Ends of High Mass Stars: Core Collapse Supernovae

Energy from bounce and the neutron fusion pushes the outer layers of the star out in a supernova explosion

10^{44} ergs all at once, 10 billion times the luminosity of the sun

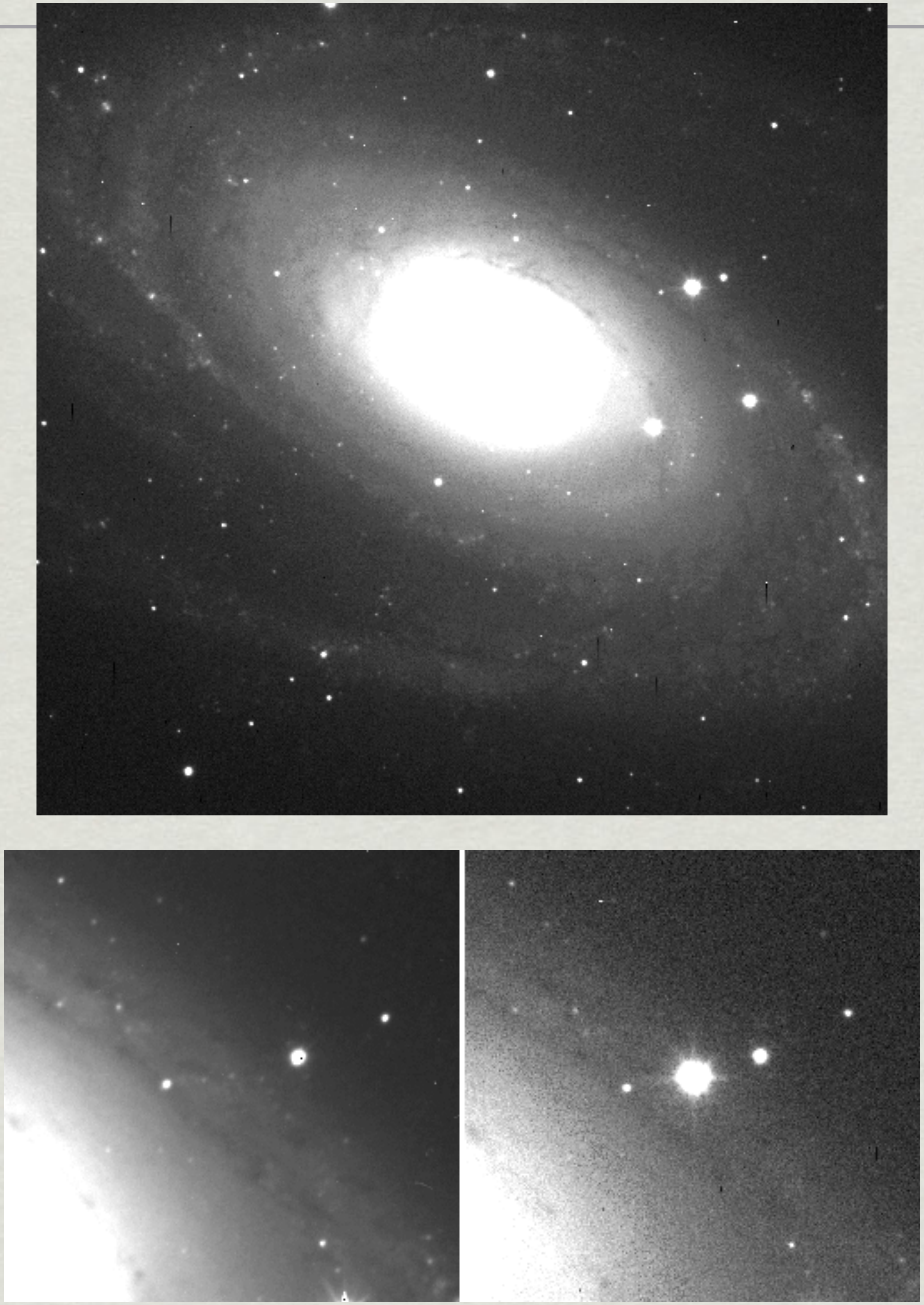
About the same total luminosity as our entire Galaxy

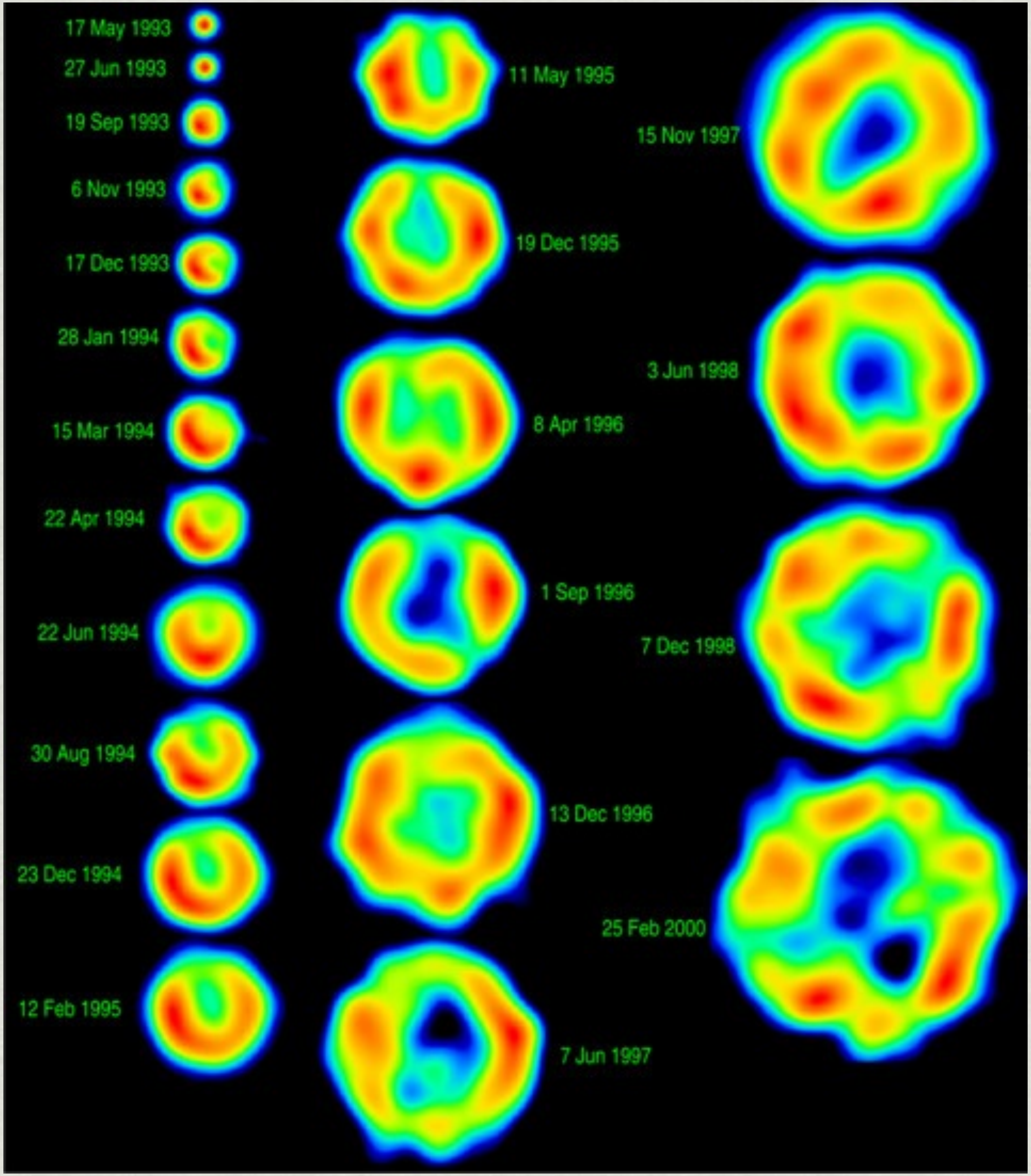
Expands out as a shell of hot, glowing gas
- becomes transparent as it expands -> lower density
- shell of gas with an emission line spectrum: a supernova remnant



Neutron core stays behind, becomes a neutron star

http://www.youtube.com/watch?feature=player_detailpage&v=j7Y0uRsMrh4



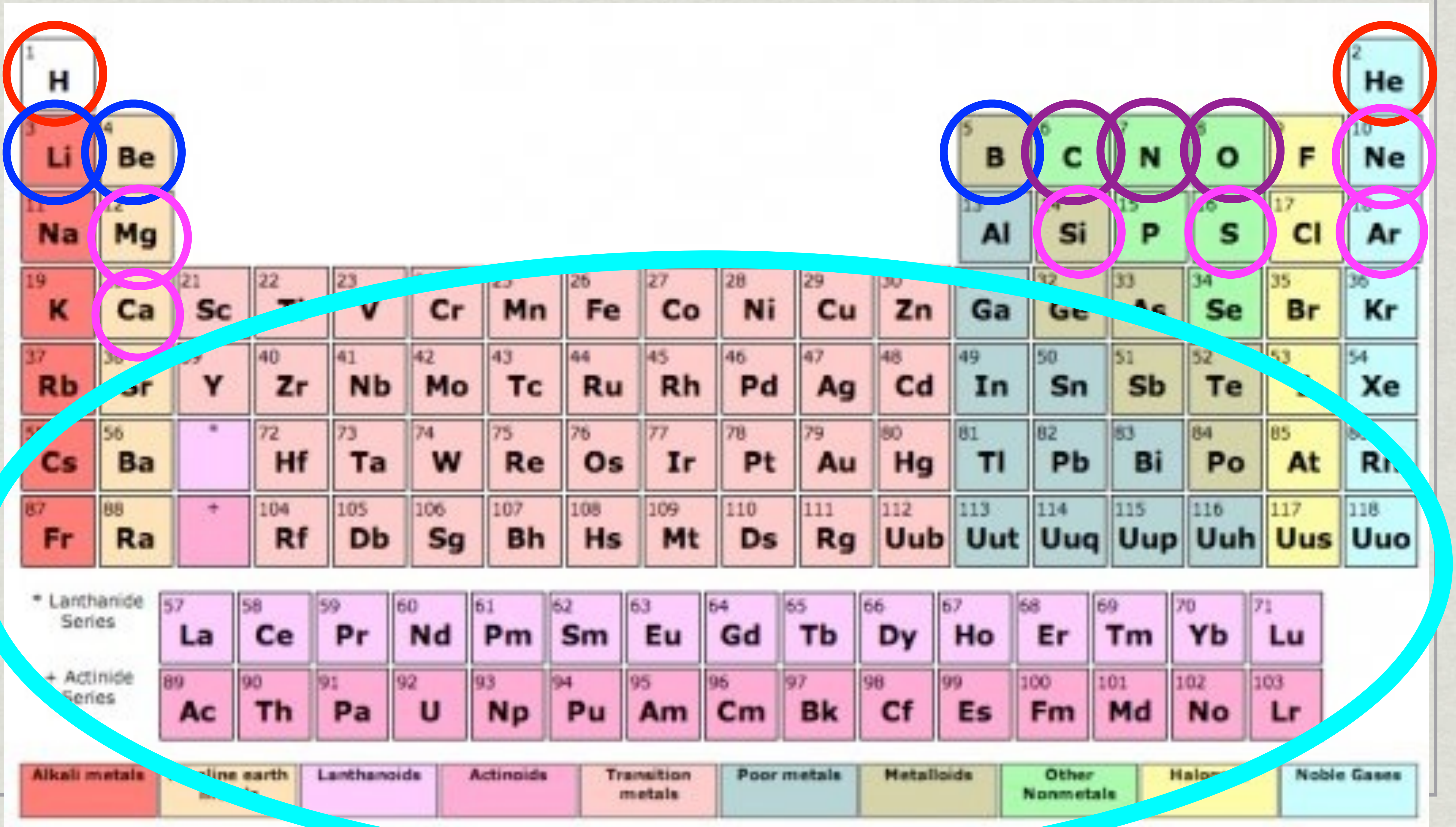


SN 1993J
Expansion

Ends of High Mass Stars: Core Collapse Supernovae

High energy, density in the explosion makes a heavy element factory.

Energy available to make elements heavier than iron



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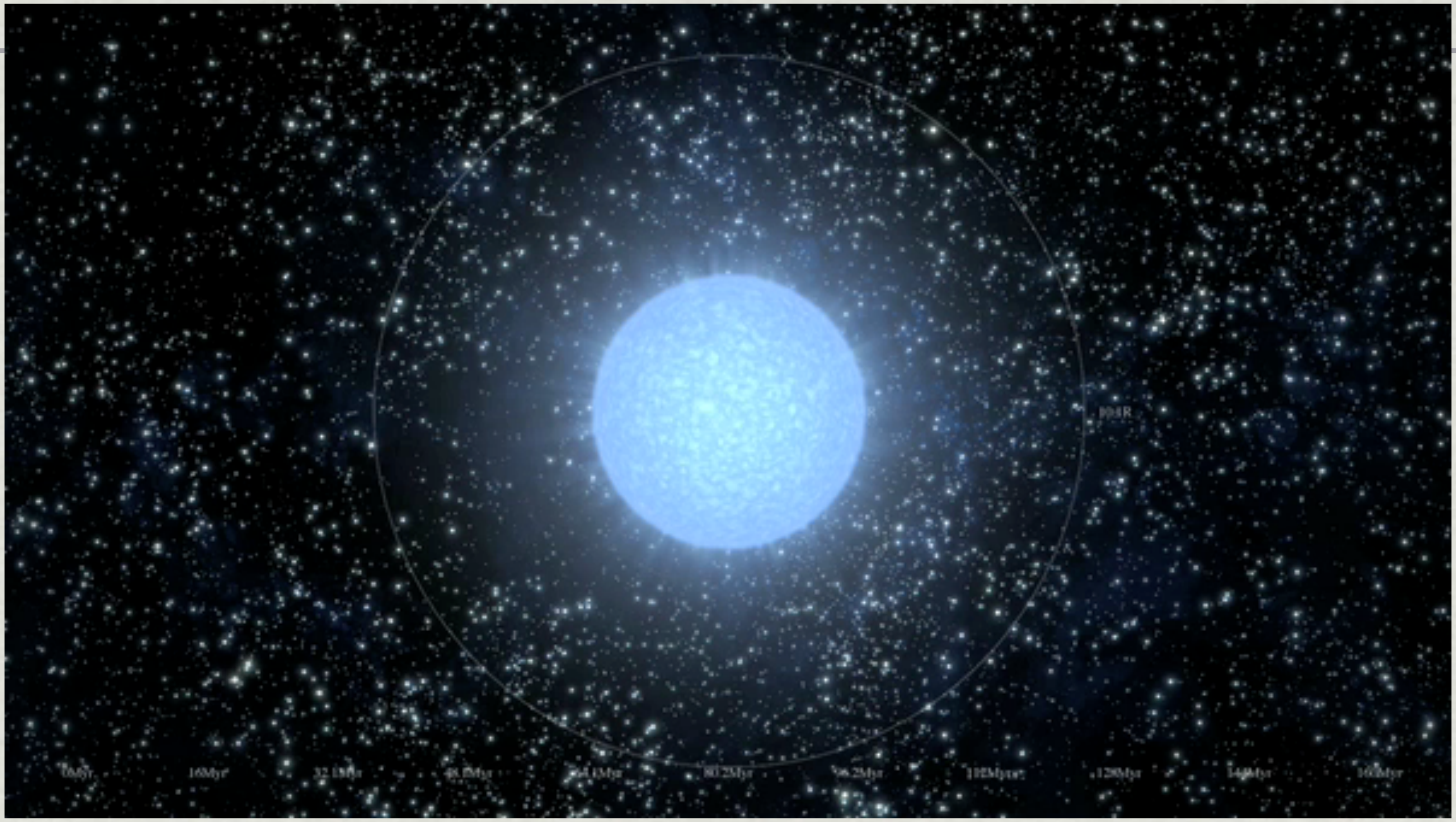
10 Msun



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