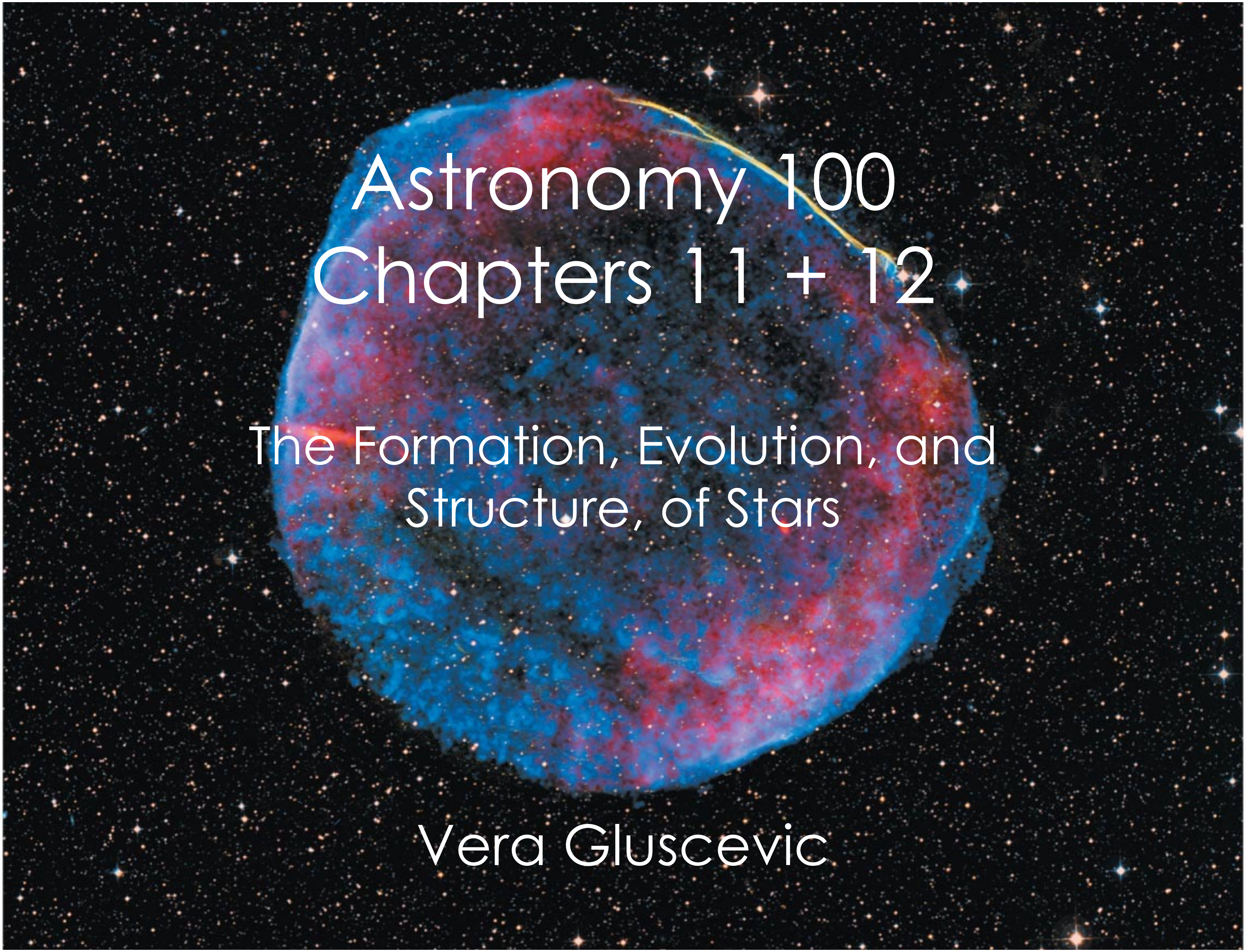
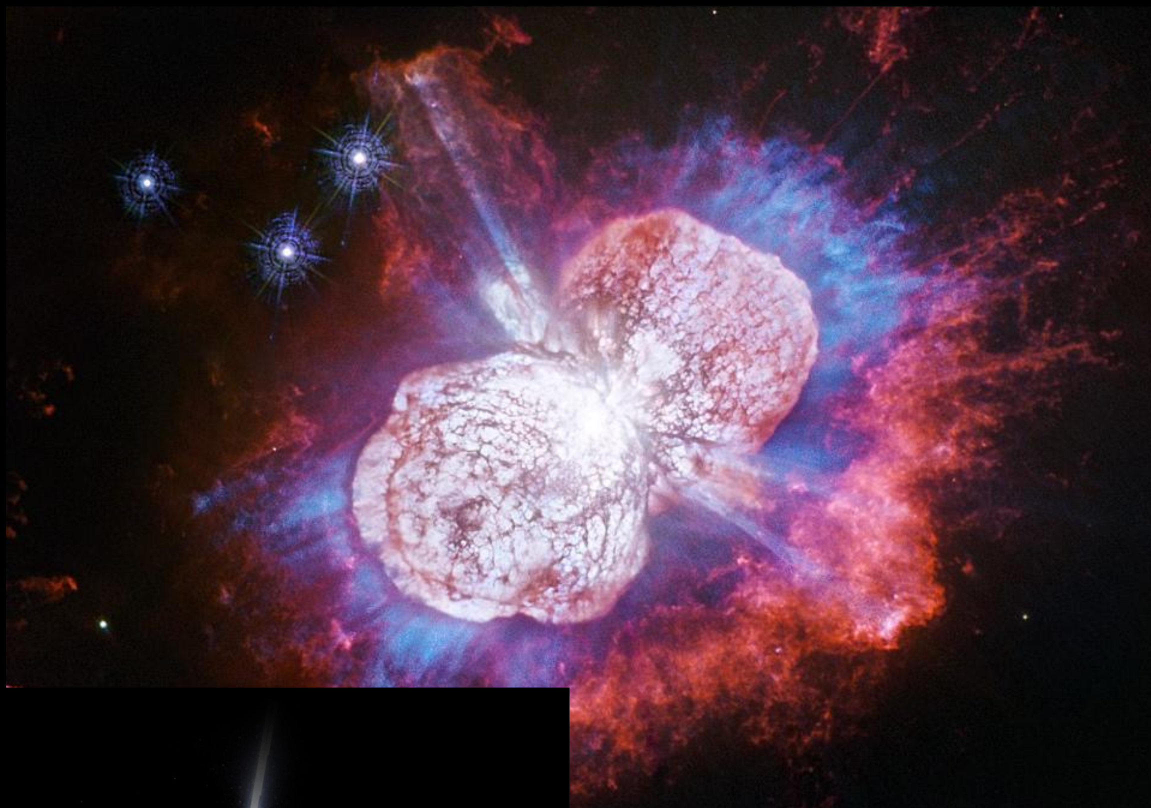


Astronomy 100
Chapters 11 + 12

The Formation, Evolution, and Structure, of Stars

Vera Gluscevic

Plan for this lesson:
Where does it all come from?

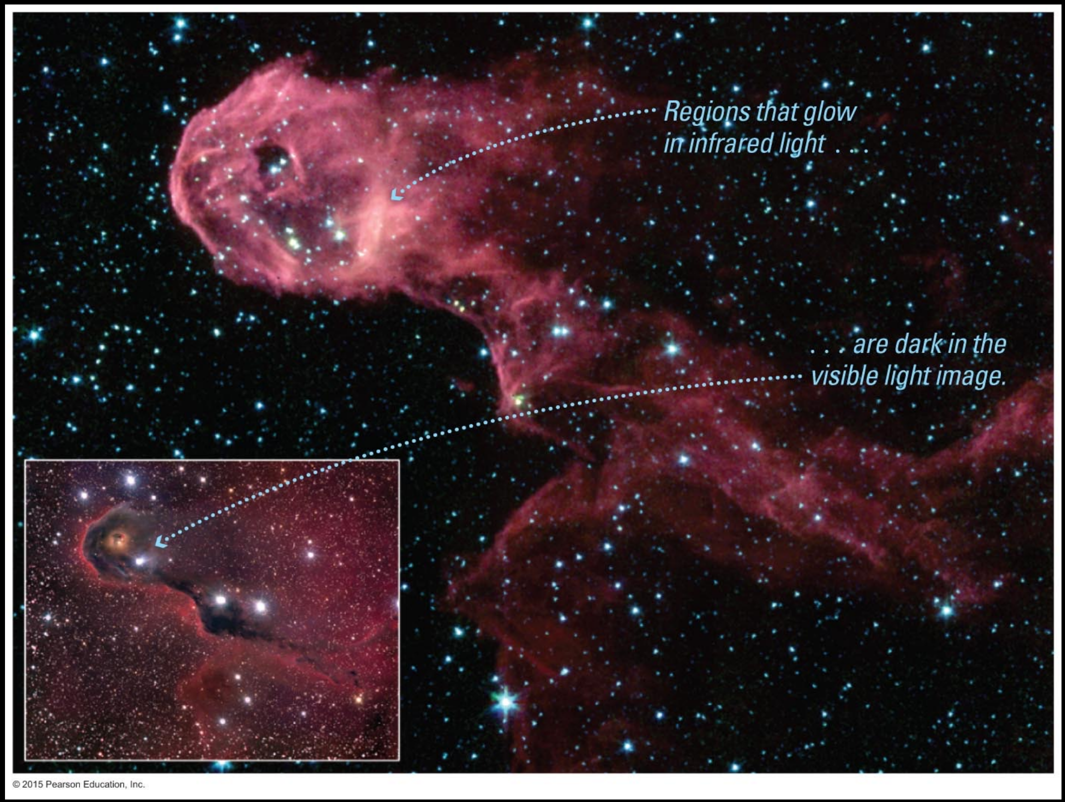


It starts with a nebula...

The life cycle of stars

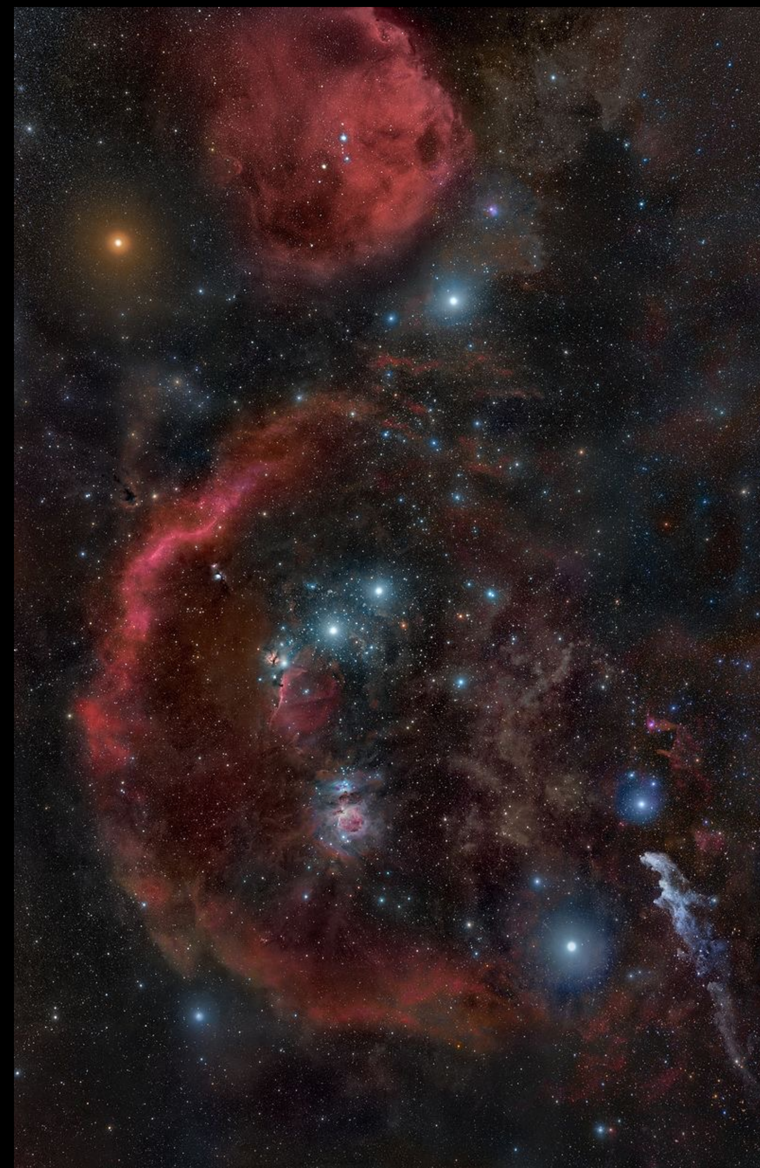
The interstellar medium

- Most of the interstellar volume is filled with atomic H.
- Stars (and planets) are born in cold **molecular clouds** consisting mostly of hydrogen molecules (H_2).
- Molecular clouds emit infrared but are dark in visible light.



Giant molecular clouds

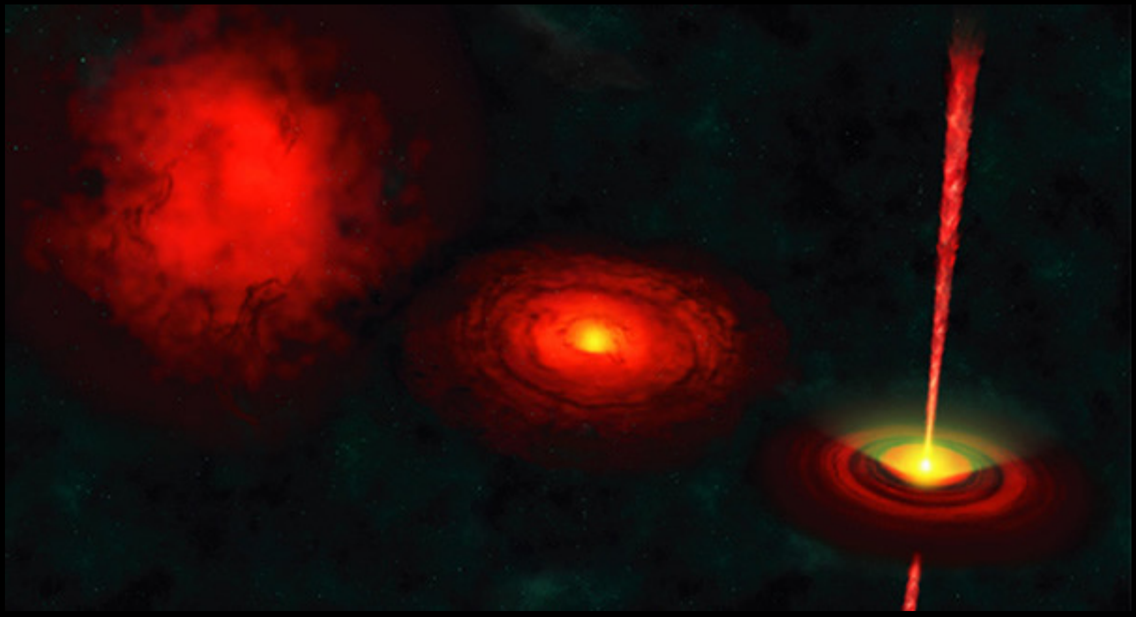
- Massive reservoirs of interstellar matter at temperature 10-20 K.
- Birthplaces of stars.



left: HST: Eagle nebula ("Pillars of creation", few ly in length, 7000 ly away; false color; eroded away by UV light from stars); right: Orion Molecular Cloud Complex.

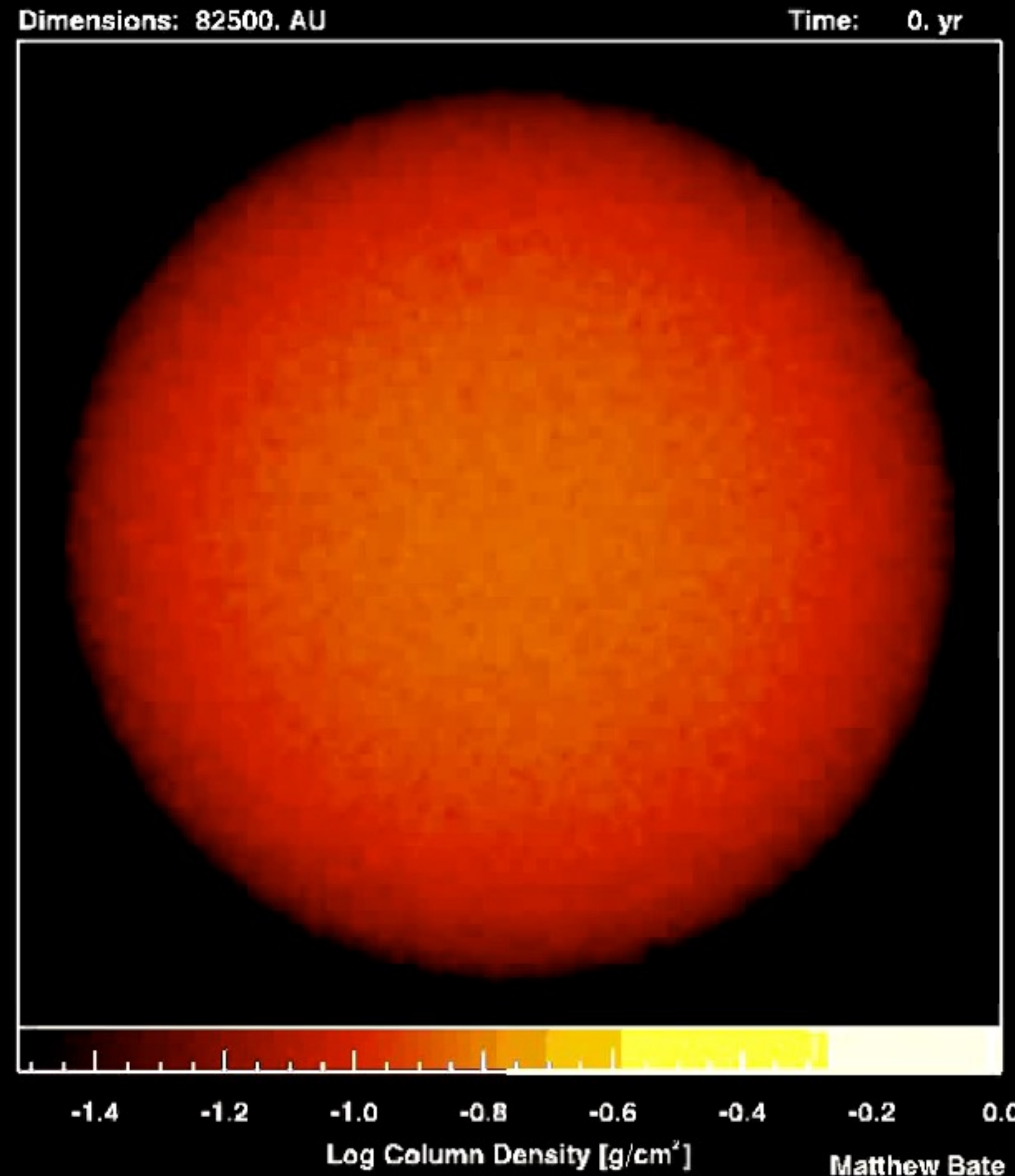
The birth of stars

- Collapse of interstellar cloud leads to rotation and formation of a **protostar** in the center.
- Protostar contracts and heats until core temperature is sufficient for hydrogen fusion.
- Contraction ends when energy released by hydrogen fusion balances energy radiated from surface.
- A protostar becomes a <u>star</u> (and settles on the MS of HR diagram) <u>when the radiation from its nuclear fusion reaches its surface for the first time</u>.



Star Formation

A simulation of star formation in a molecular cloud with initial size 1.2 ly across and initial mass 50 M_{SUN}.



Star Cluster Formation Movie

Protostars and the HR Diagram

- More massive protostars become main sequence stars in much less time (for Sun-like star, 30 Myr).
- Tracks in the HR diagram to the right represent the paths of protostars of different initial mass.
- Stars remain hidden until they cross the Birth Line (red dashed line)--when the radiation from its nuclear fusion reaches its surface for the first time.

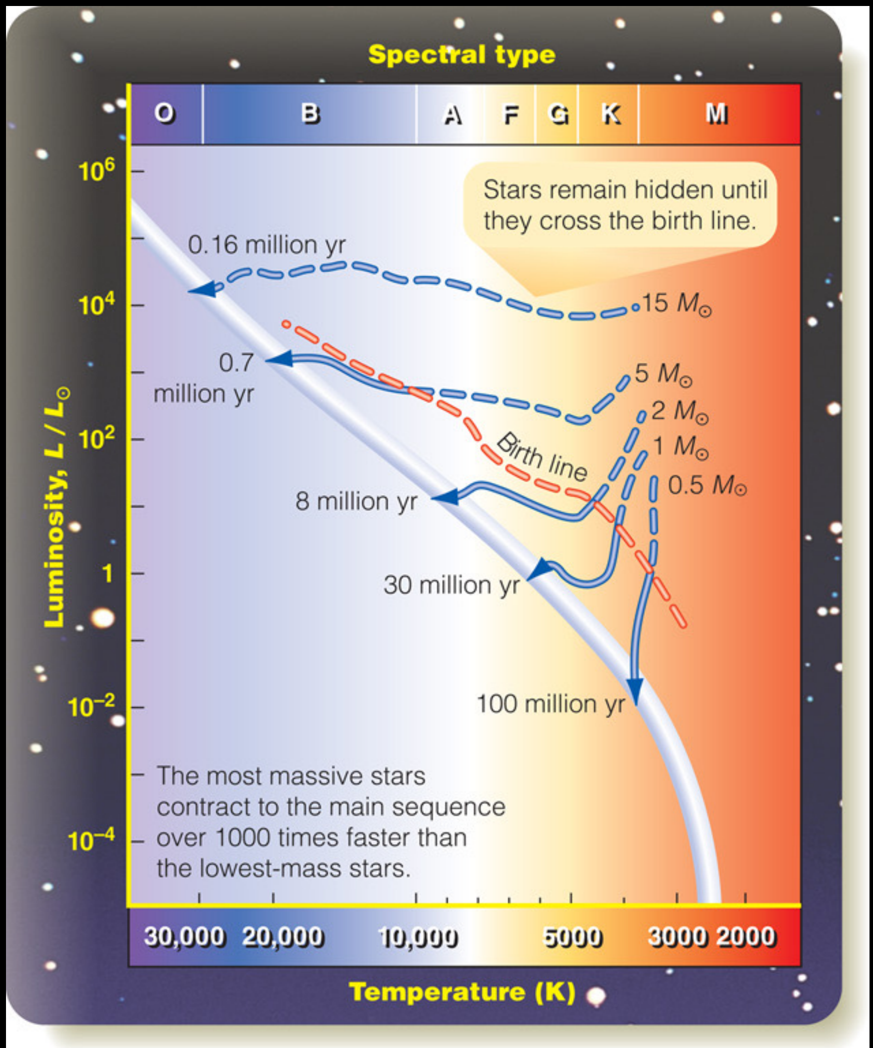


Illustration design by Michael A. Seeds; © 2016 Cengage Learning®

question for you

How will the fusion rate of a two solar mass star compare to the fusion rate of a four solar mass star?

A. They will have the same fusion rate.
B. The more massive star will have twice the fusion rate.
C. The more massive star will have a fusion rate that is two times slower.
D. none of the above

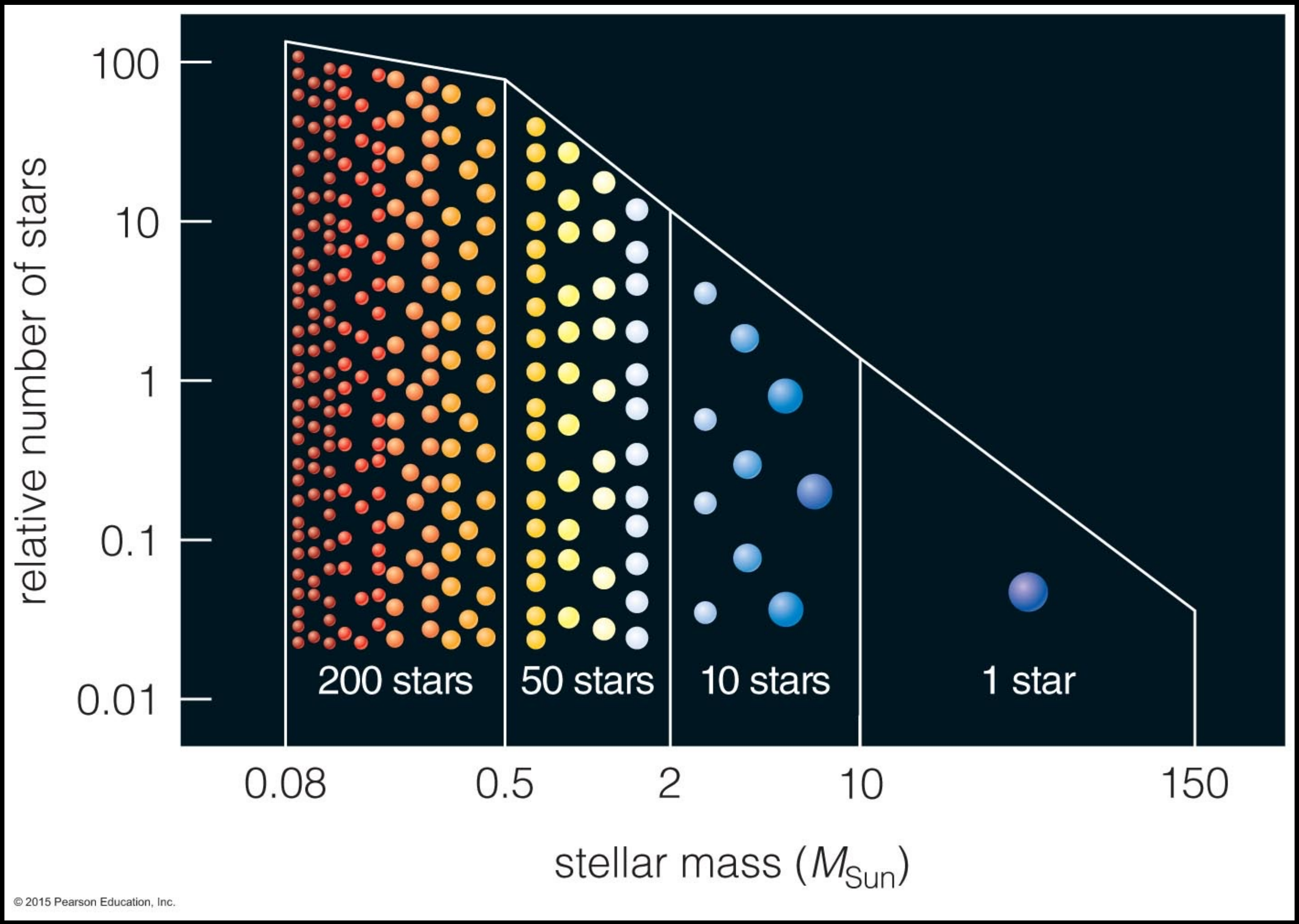
question for you

How will the fusion rate of a two solar mass star compare to the fusion rate of a four solar mass star?

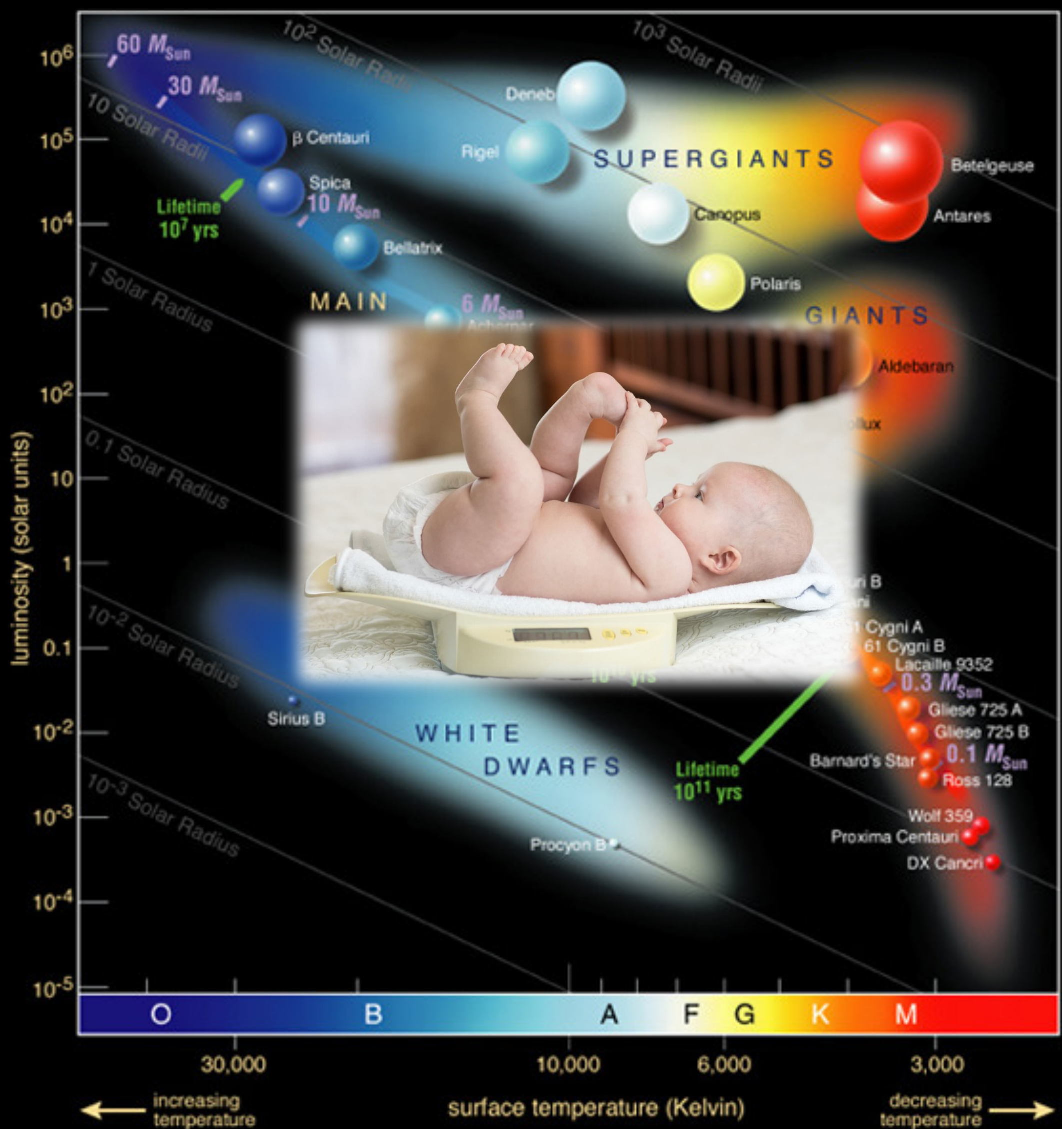
A. They will have the same fusion rate.
B. The more massive star will have twice the fusion rate.
C. The more massive star will have a fusion rate that is two times slower.
D. none of the above

A star is born.
Its mass decides everything.

Star size at birth: in an average molecular cloud...

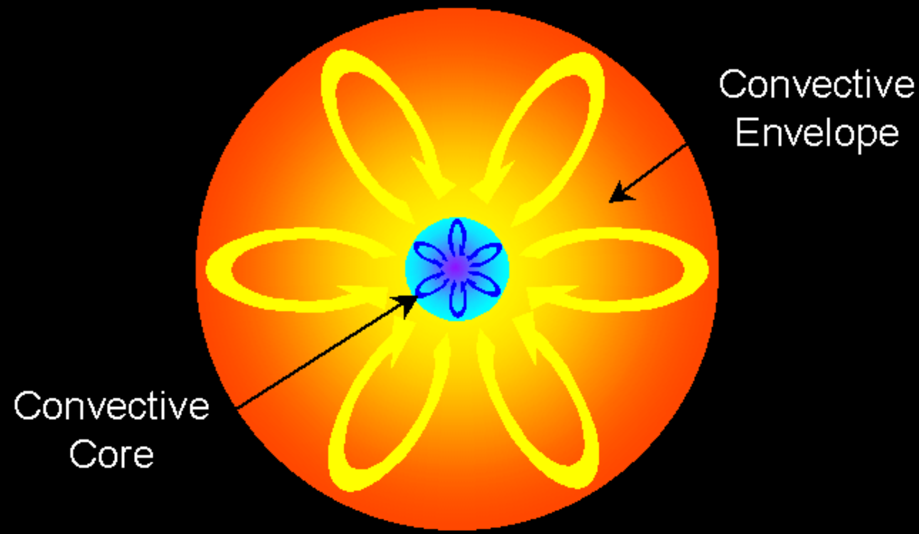


Stars by mass: low, medium, high

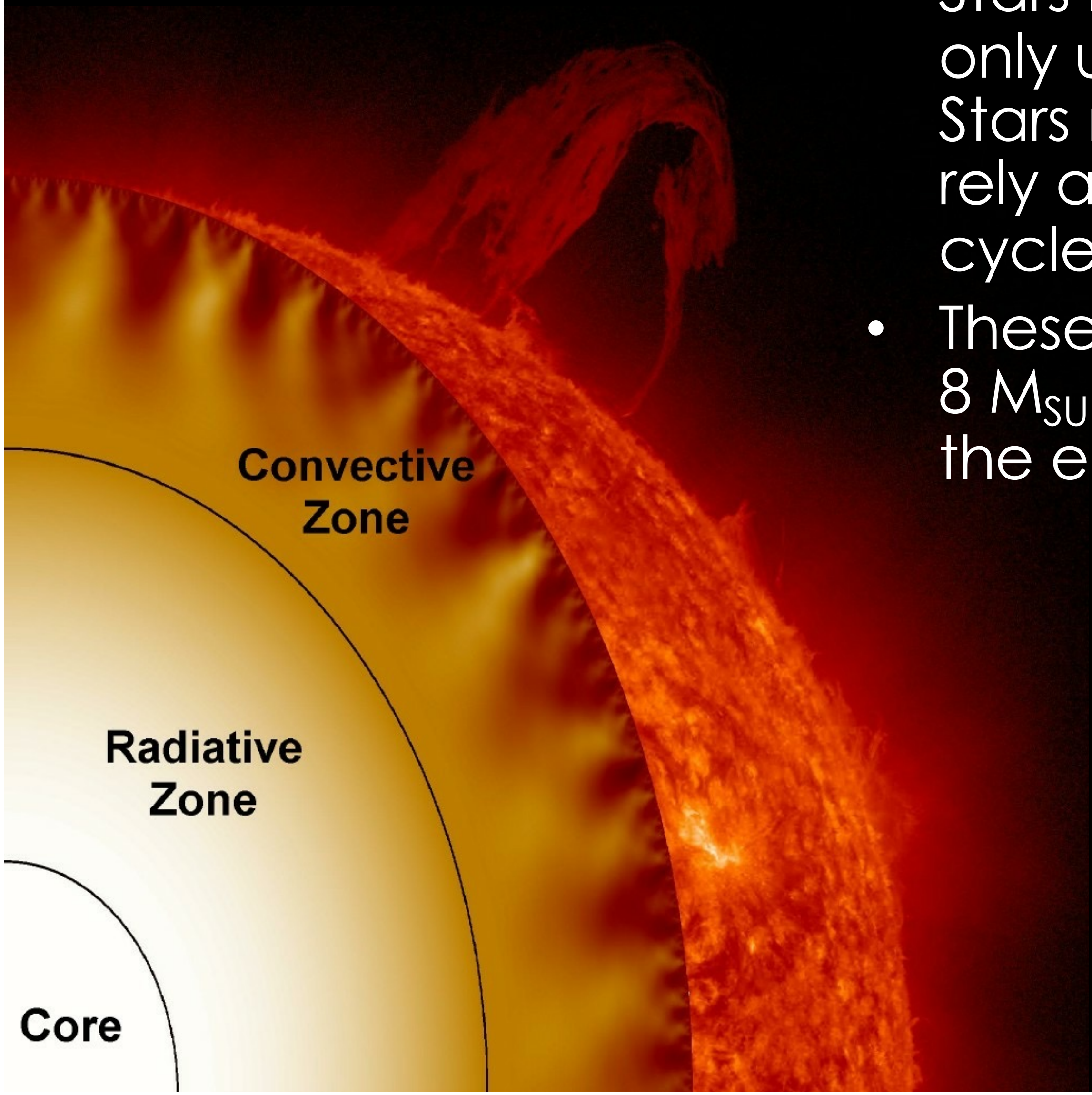


Lowest mass stars: 0.08 – 0.5 M_{SUN}

- **Red dwarf stars** have masses of 0.08 – 0.5 M_{SUN}. Will only carry out hydrogen fusion via the proton-proton chain.
- Red dwarfs have entirely convective interiors and end up **using ALL of their hydrogen**, living for hundreds of billions of years to **trillions of years**.
- The Universe isn't old enough for red dwarfs to have ended their lives.



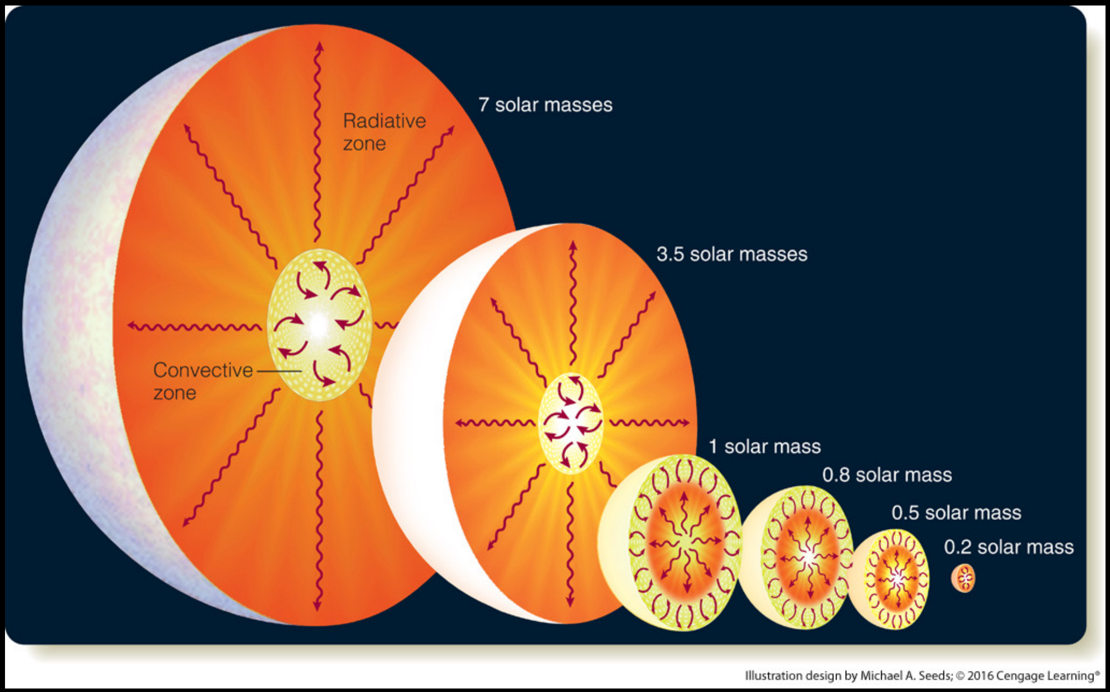
Medium mass stars: 0.5 – 8 M_{SUN}



- Stars less massive than 1.1 M_{SUN} only use proton-proton chain. Stars more massive than 1.5 M_{SUN} rely almost entirely on CNO cycle.
- These stars with masses less than 8 M_{SUN} produce a **white dwarf** at the end of their lives.

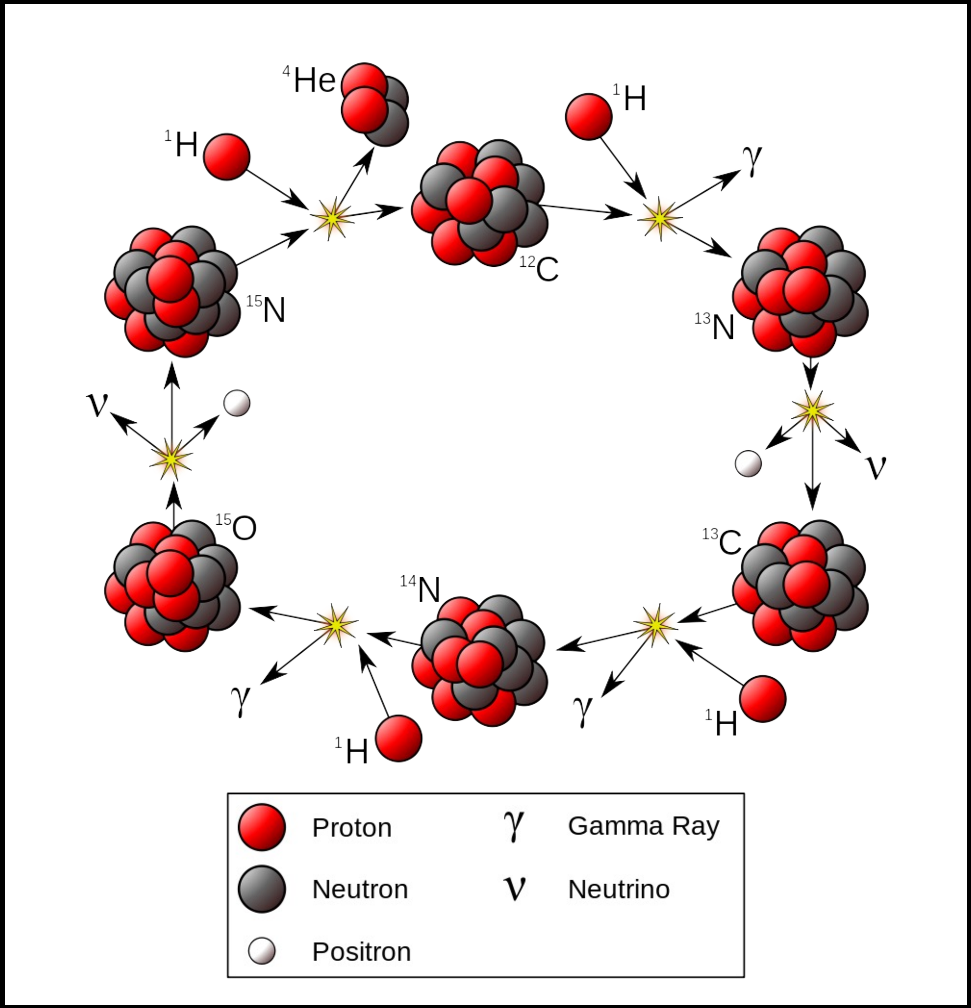
High mass stars: > 8 M_{SUN}

- High-mass stars have masses greater than 8 M_{SUN} and produce energy entirely by the CNO cycle.
- They have convective interiors and radiative shells (opposite of Sun-like stars).
- They explode in **supernova** explosions and leave behind a **neutron star** or a **black hole**.



The CNO Cycle

- Presence of Carbon, Nitrogen and Oxygen in cores of high mass stars acts as **catalyst**.
- CNO cycle becomes dominant for stars more massive than ~1.5 M_{SUN}.
- End result of CNO cycle is exactly the same as the proton-proton chain, but proceeds much faster, and is much more temperature sensitive.



question for you

A typical main sequence star is in a state of:

A. hydrostatic equilibrium.
B. constant contraction.
C. constant expansion.
D. controlled explosion.

question for you

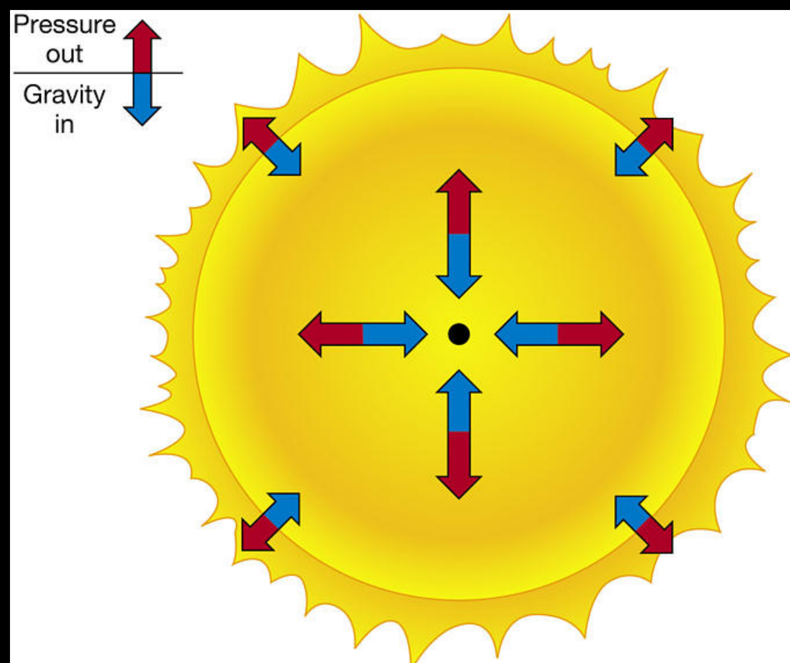
A typical main sequence star is in a state of:

A. hydrostatic equilibrium.
B. constant contraction.
C. constant expansion.
D. controlled explosion.

A star on MS is stable.

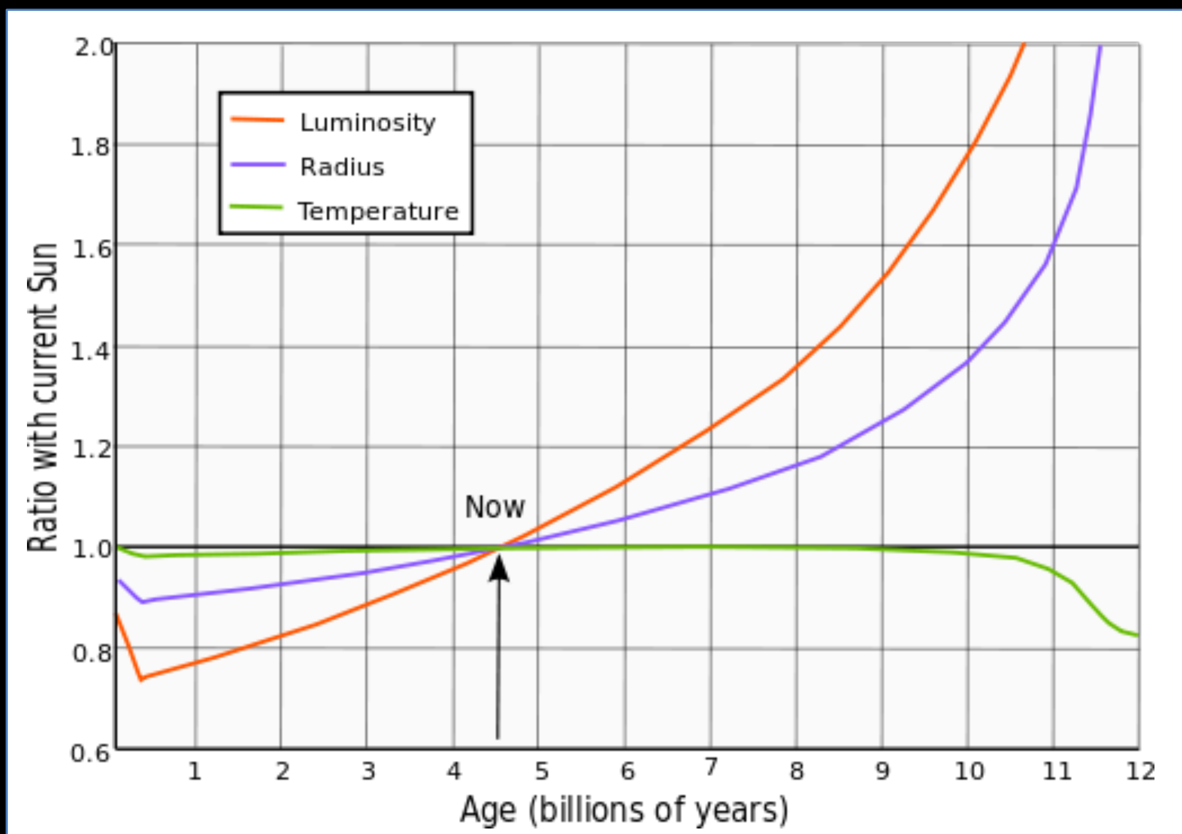
The Main Sequence

- **Hydrostatic equilibrium** keeps the star in balance.
- An increase in the star's central temperature results in a pressure increase, expanding and cooling the star.
- As star ages, its core temperature increases, and the star becomes more luminous.



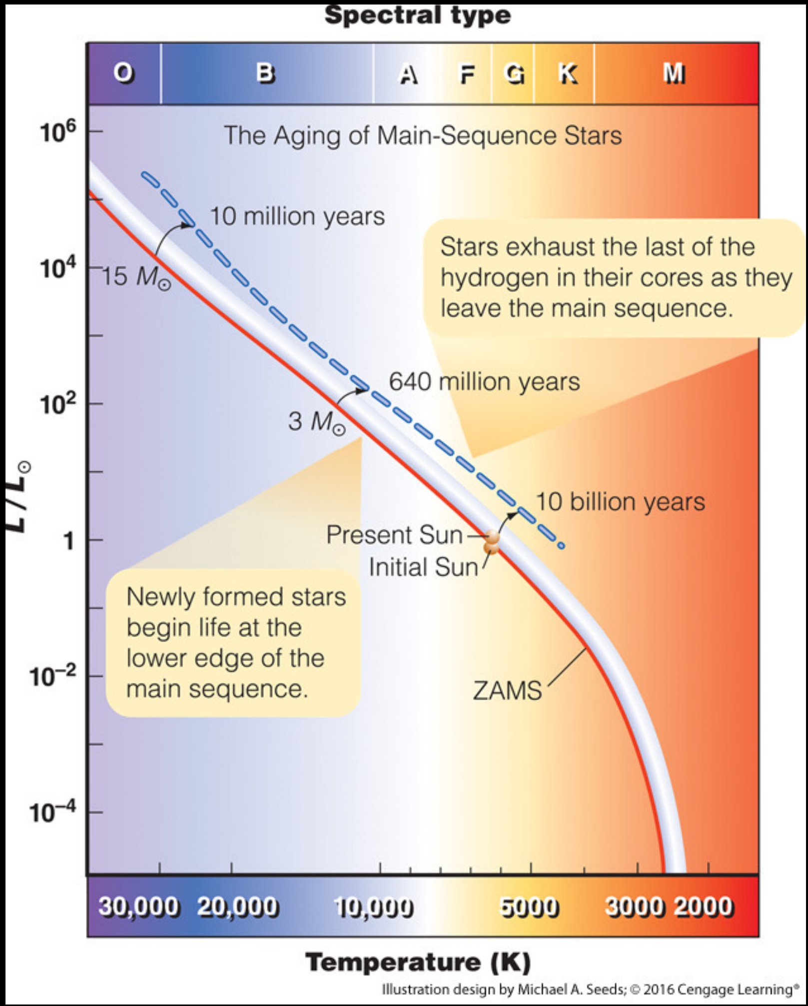
Small changes on the Main Sequence

- The Sun has increased in luminosity by about 25% to 30% in the last 4 billion years.
- In ~1 Gyr, the Sun will be too hot for liquid water to exist on Earth.



Equilibrium is imperfect: the Main Sequence is a band

The red curve on this H-R diagram represents the zero age main sequence (ZAMS). As stars age, they slowly move toward the dashed blue line. So, the Main Sequence is a “band” between the red and dashed blue lines, stylized with the white curve.



question for you

A stars luminosity depends primarily on its

A. Radius
B. Surface temperature
C. Radius and distance from Earth
D. Radius and surface temperature

question for you

A stars luminosity depends primarily on its

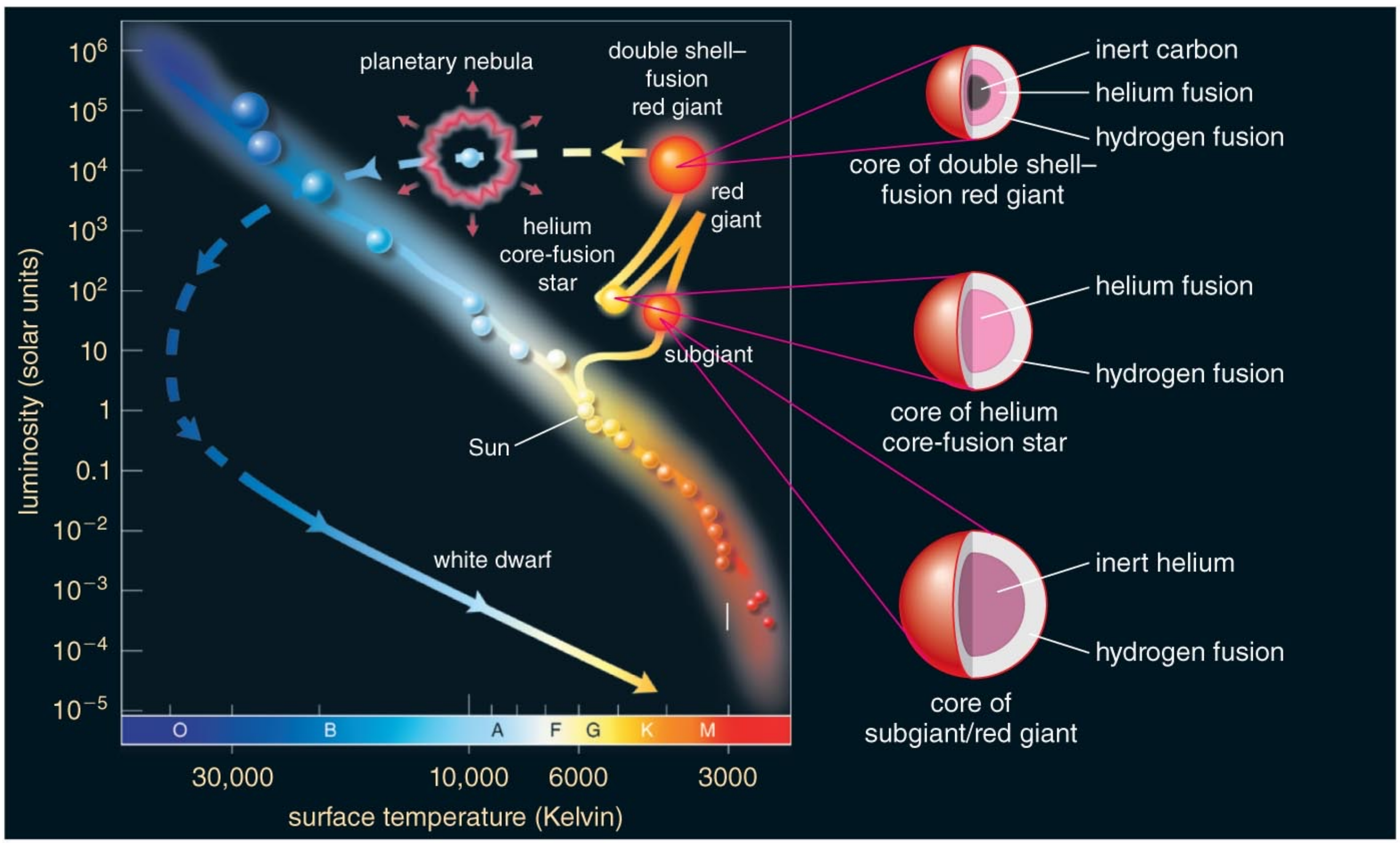
A. Radius
B. Surface temperature
C. Radius and distance from Earth
D. Radius and surface temperature

A star evolves.

The complete life cycle of a Sun-like star

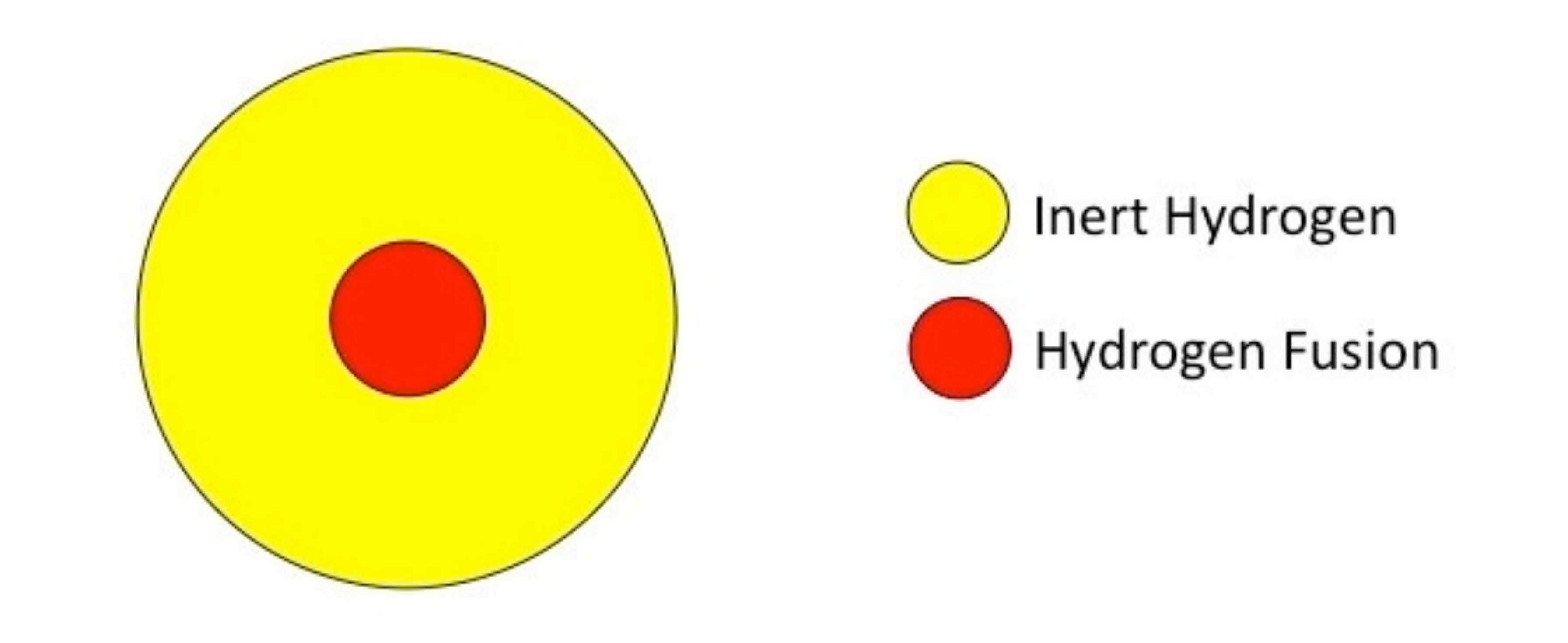
the star getting cooler

the star "puffing up"



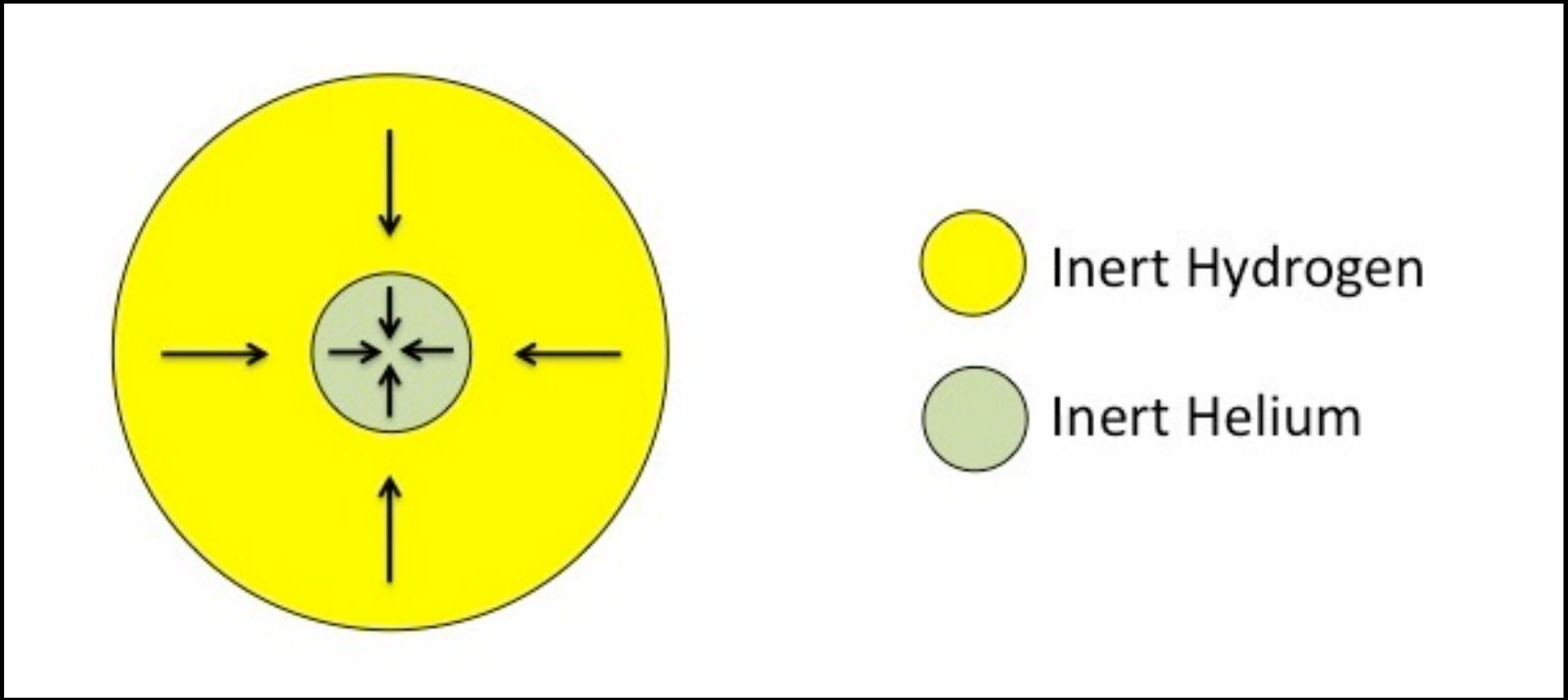
Let's go through this again…

1. A star on the **main sequence** burns H in its core (red).



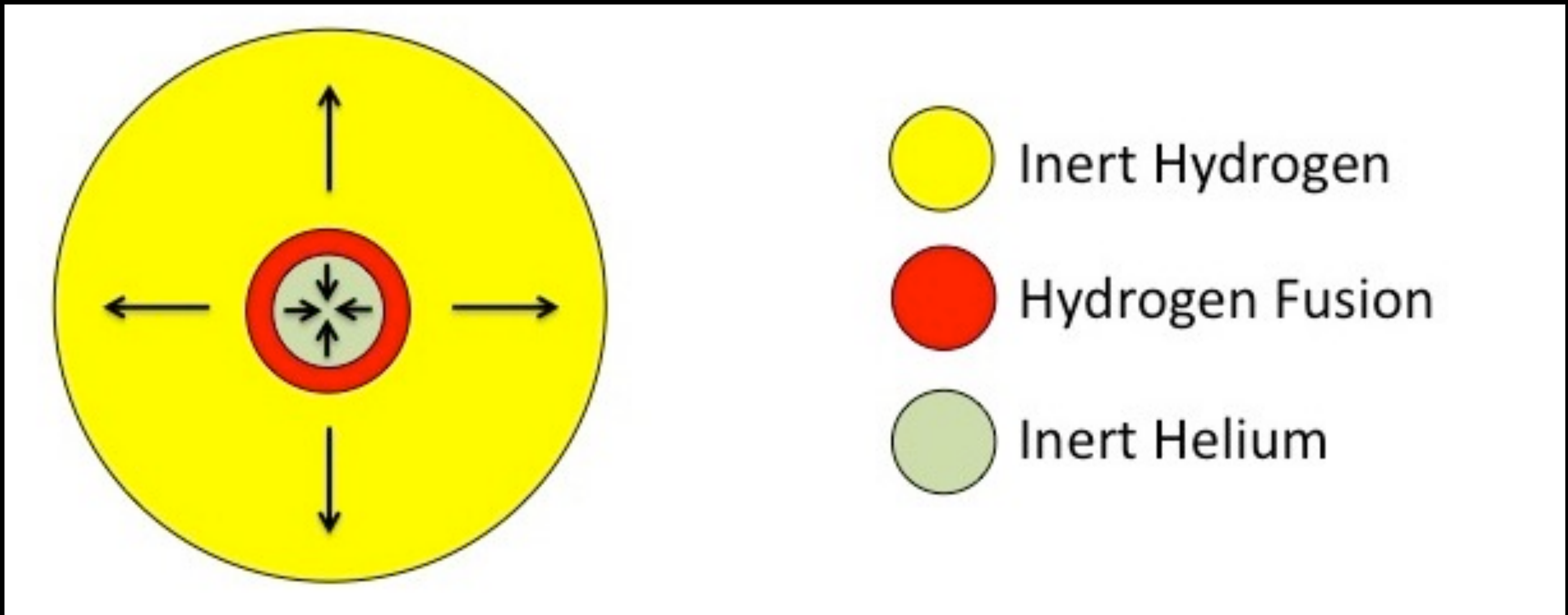
Let's go through this again…

2. The star runs out of H in its core, leaving only inert He behind. Outward pressure balancing gravity decreases, star begins to fall inward.



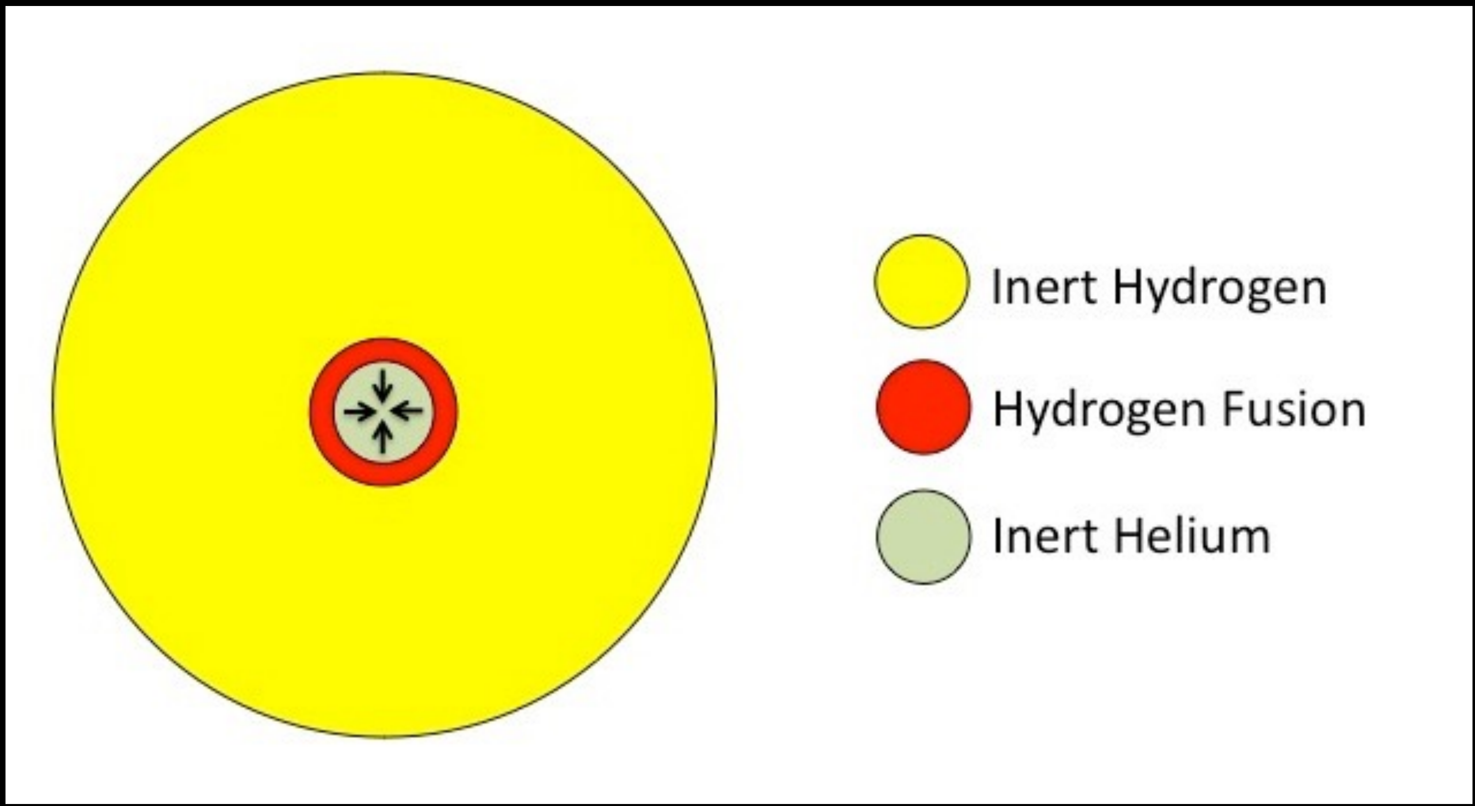
Let’s go through this again…

3. As the star is squeezed inward, temperatures get high enough in a shell around the core for H fusion to begin again. This is **hydrogen shell burning**, and it halts the inward collapse in the outer part of the star but not the inward collapse in its core.



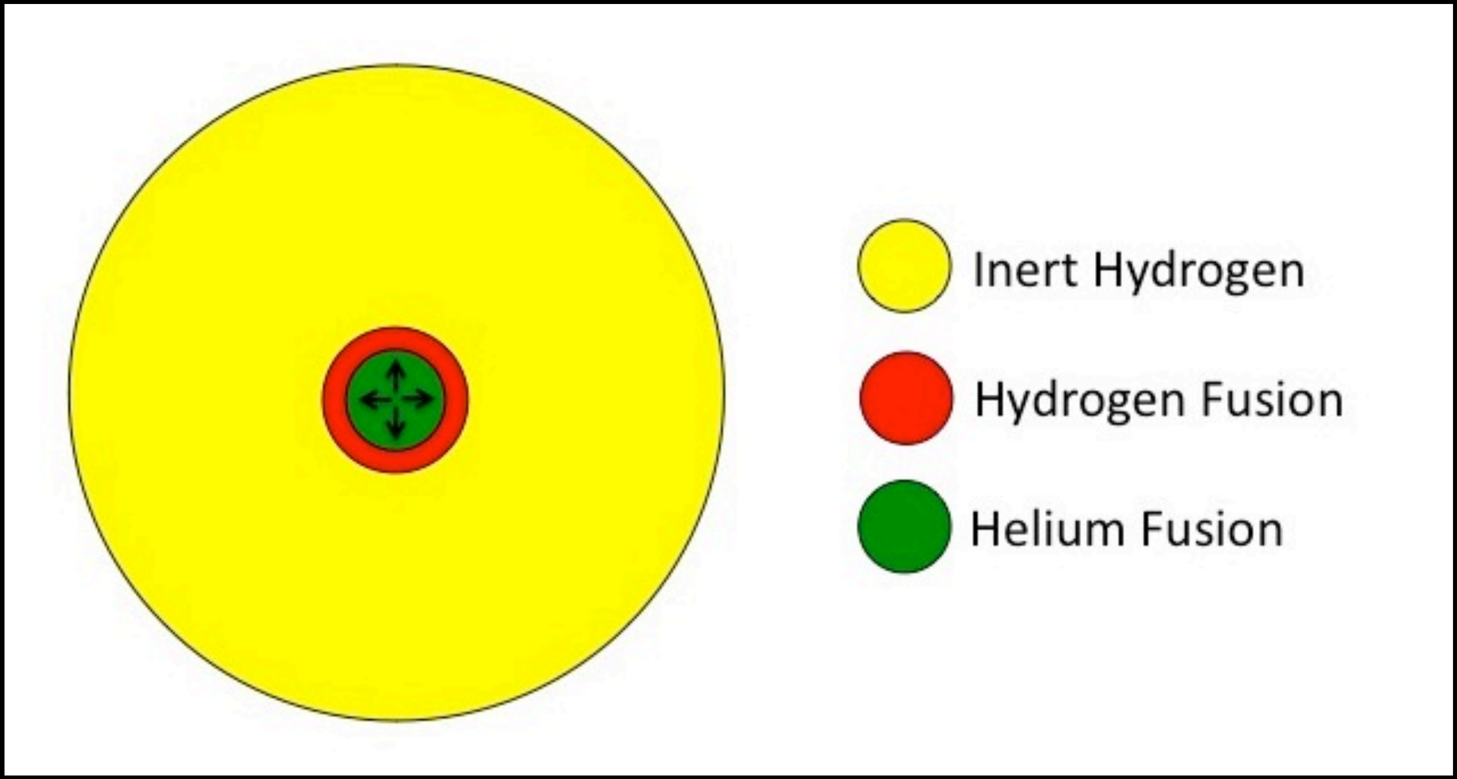
Let's go through this again…

4. Because of H shell burning, the outer layers of the star expand greatly, and the surface temperature of the star decreases. The star is now a **red giant.**



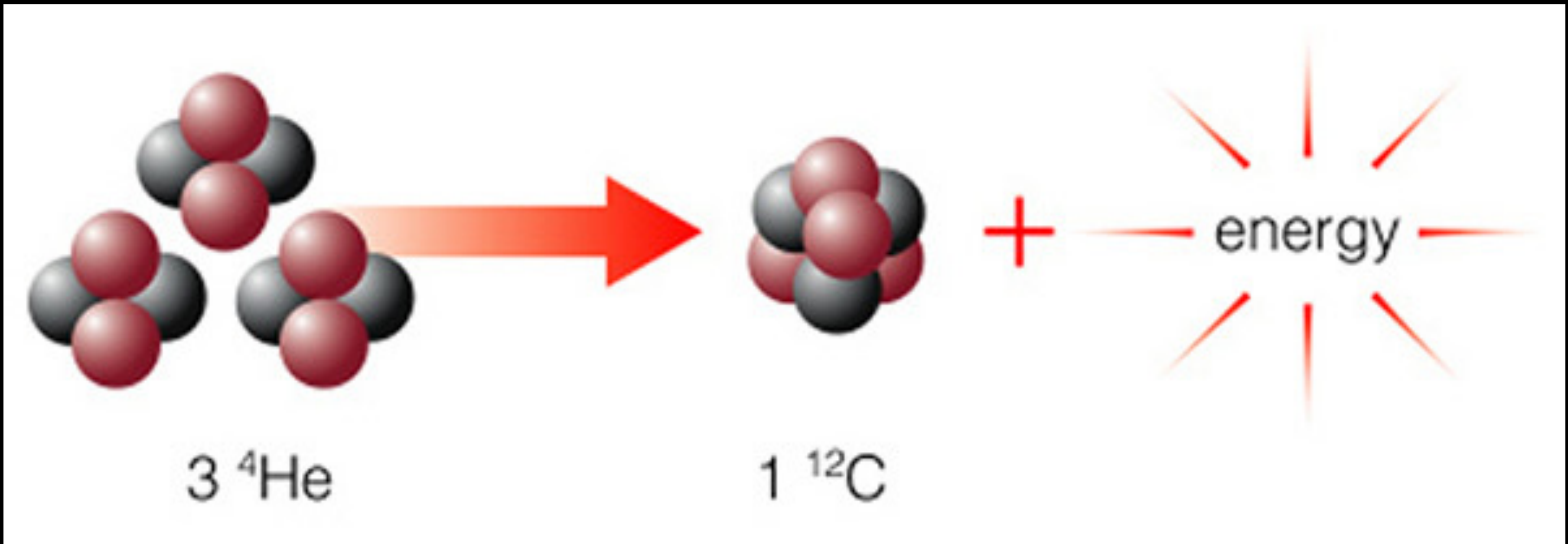
Let’s go through this again…

5. The temperature in the core finally reaches 100 million K, and the He in the core begins to fuse into C. This causes the **helium flash**. The core expands.



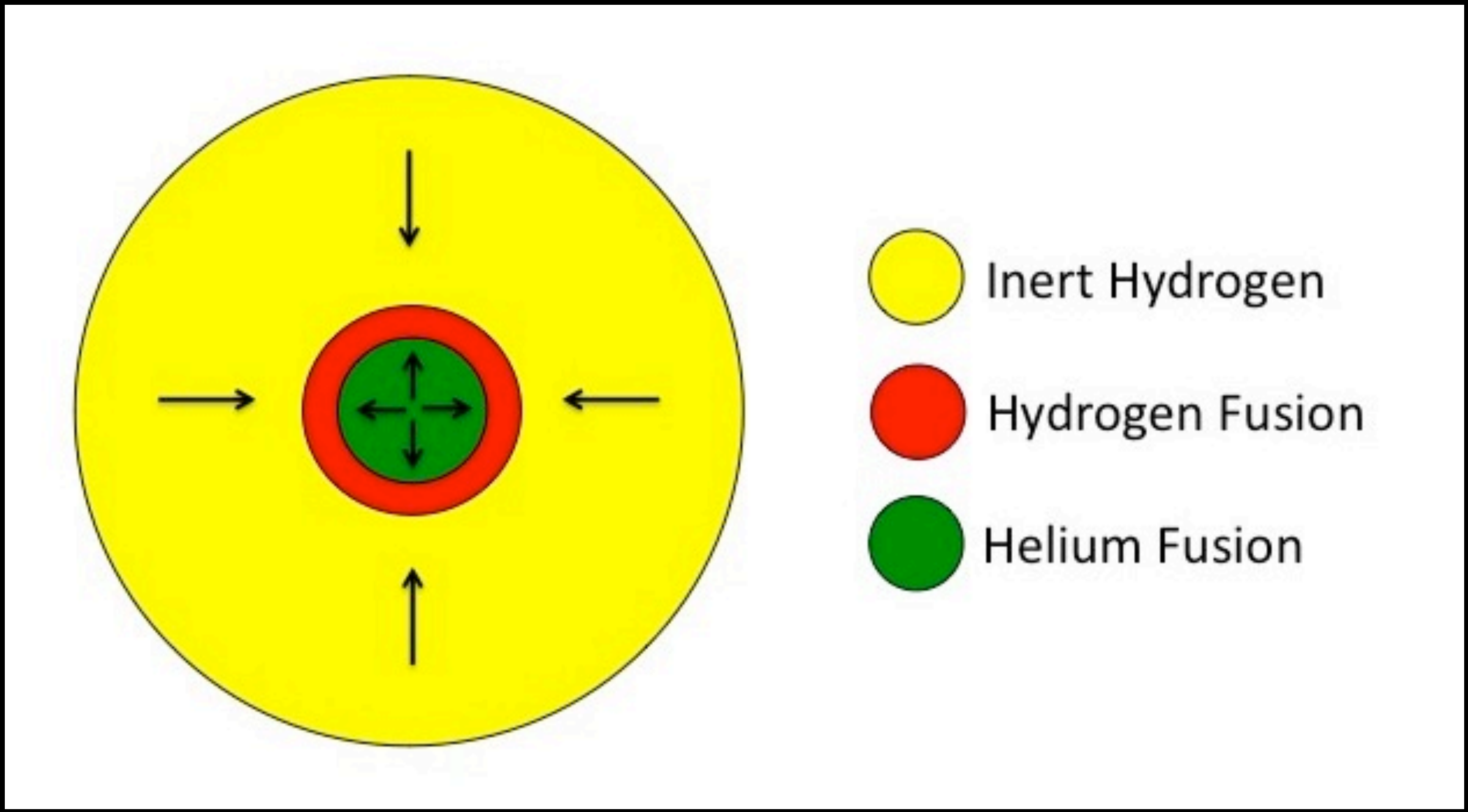
Helium Fusion

- In helium fusion, three helium nuclei (also called alpha particles) fuse to form a nucleus of Carbon-12.
- For a star the size of the Sun, helium burning lasts 100 million years.



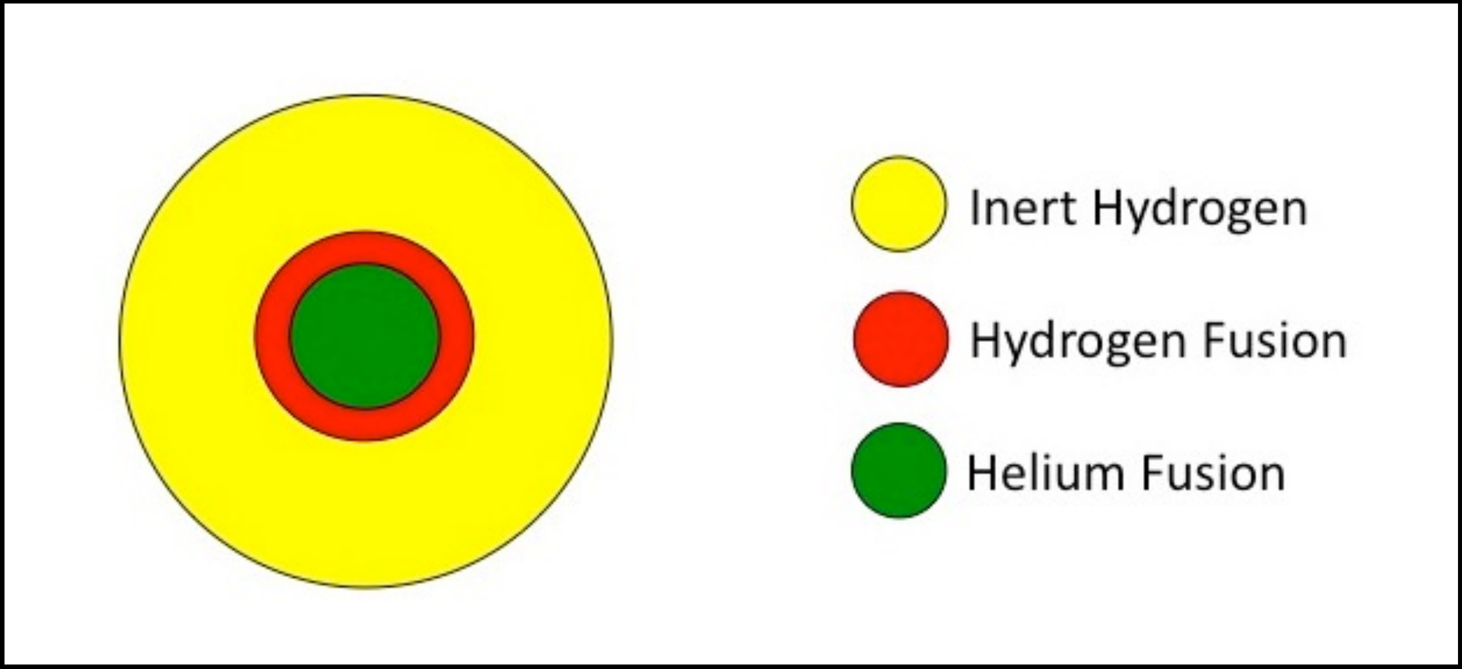
Let's go through this again…

6. The core and hydrogen burning shell expand and cool, reducing fusion rate and outward pressure… Star begins to contract again.



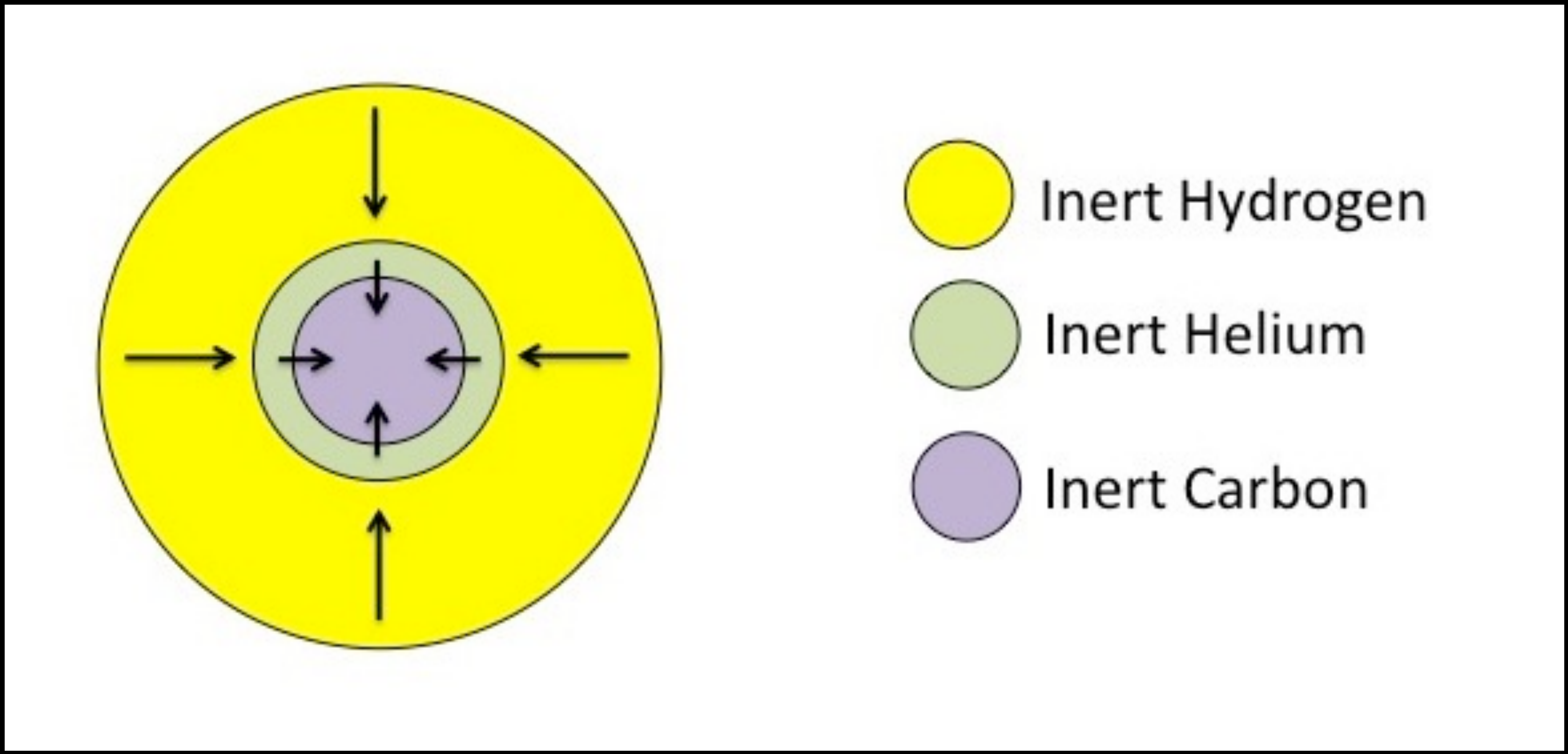
Let's go through this again…

7. A new equilibrium is reached, driven by He fusion in the core and H fusion in a shell around the core. He is fusing in the core to form carbon.



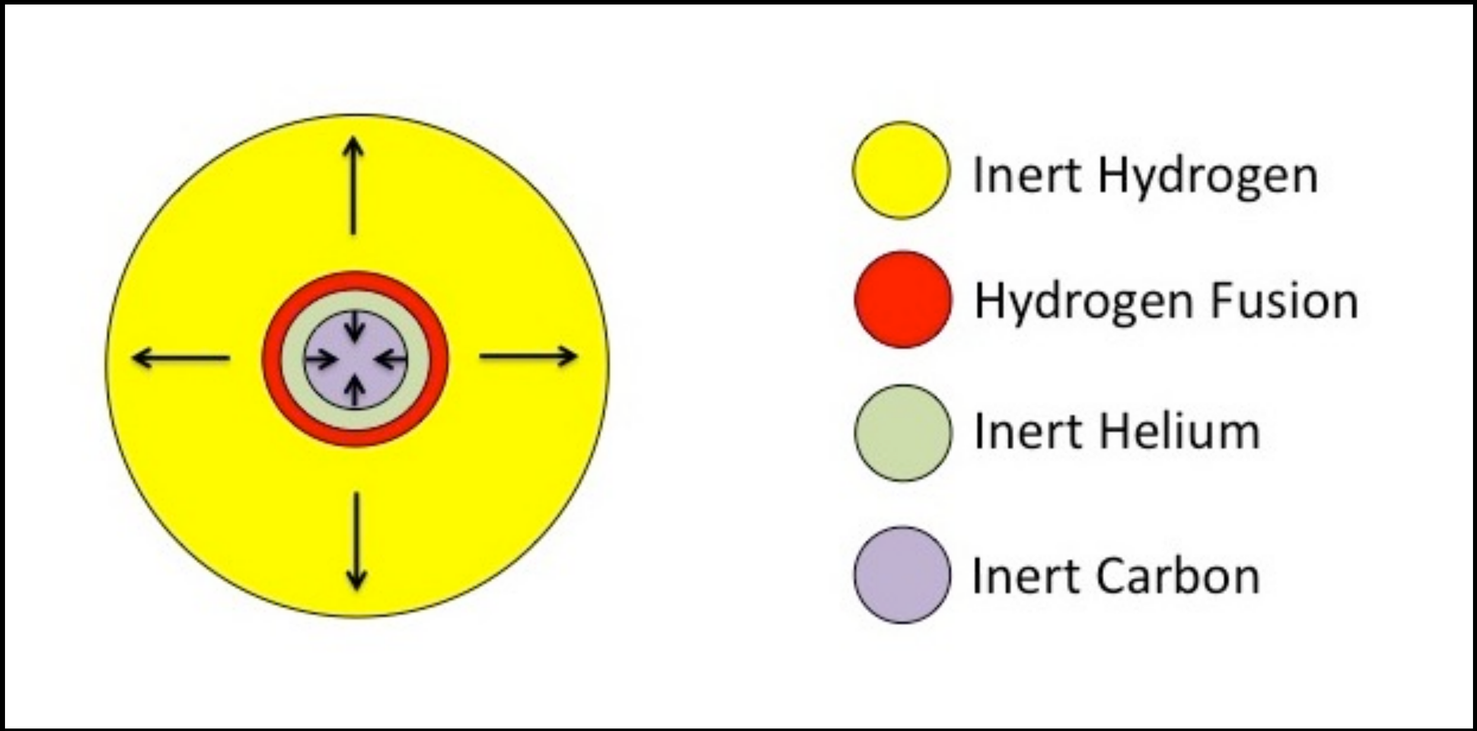
Let’s go through this again…

8. As He in the core is depleted, and H shell burning stops, outward gas pressure decreases again, and star once again collapses.



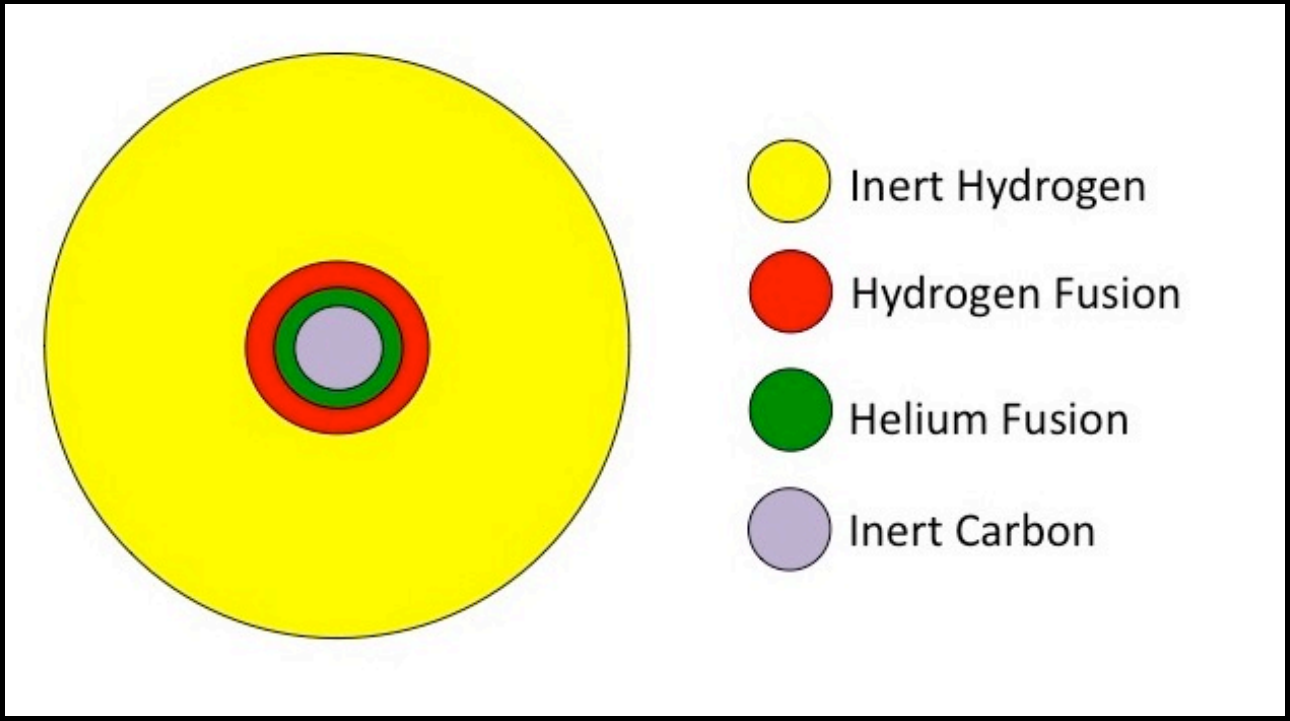
Let's go through this again…

9. Increased pressure leads to H shell burning, but a low mass star will never get hot enough (600 million K) in the core to fuse carbon. Star **expands outward again**.



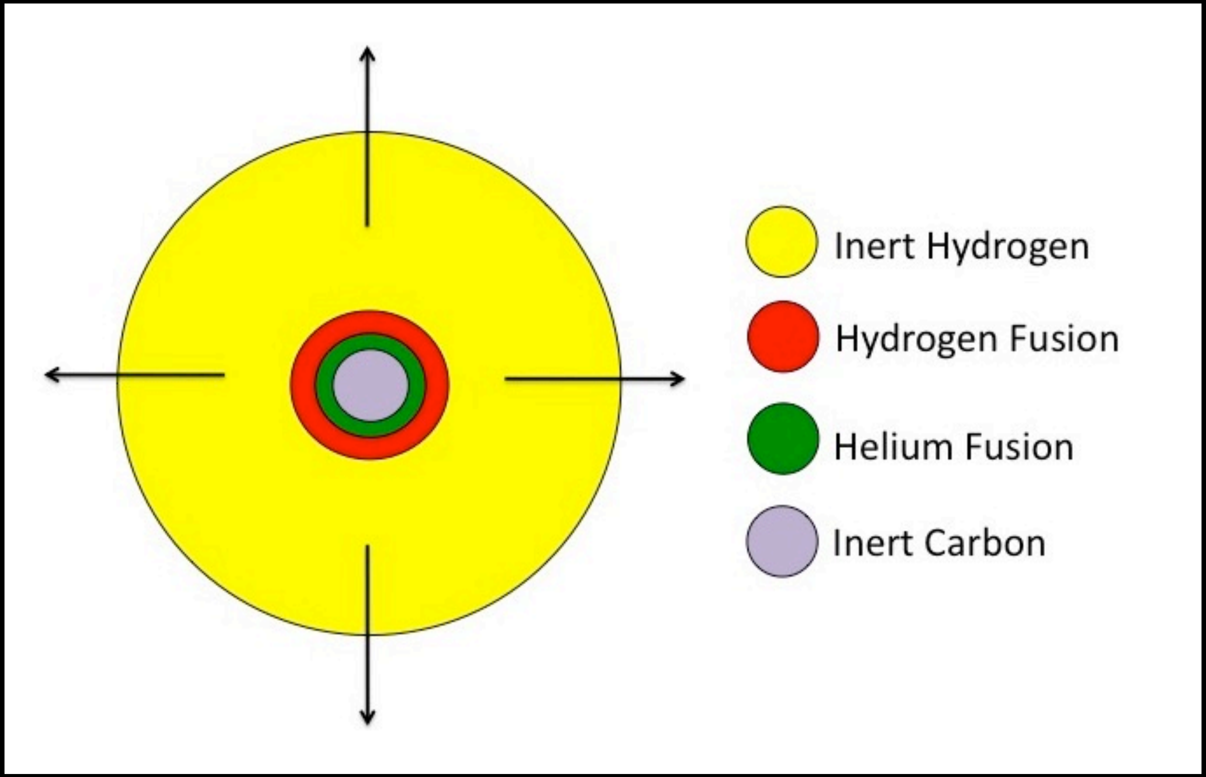
Let's go through this again…

10. Star expands again and once again looks red. Helium begins to fuse in a shell around the core. The star is now a **Double Shell Burning Red Giant**.



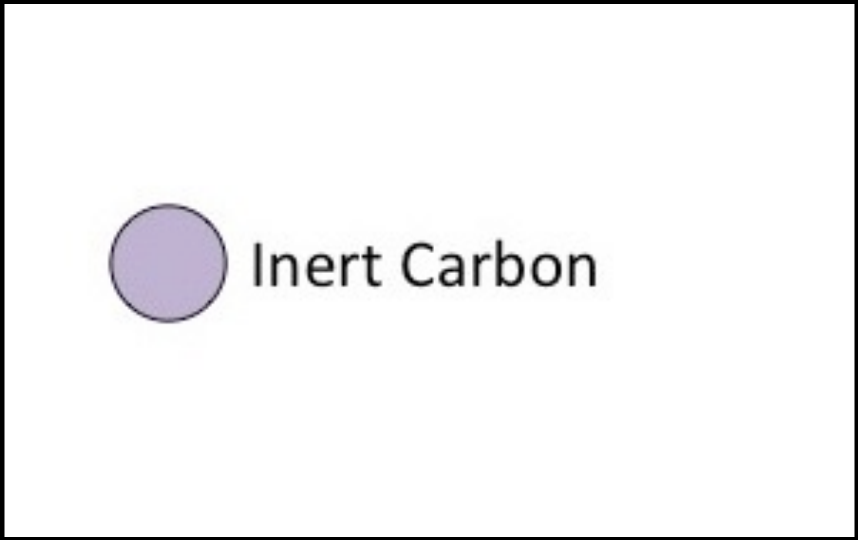
Let's go through this again…

11. Shell burning pushes the outer layers outward, till the star is no longer able to hold on to these layers, and they're ejected in what's called a **planetary nebula**.

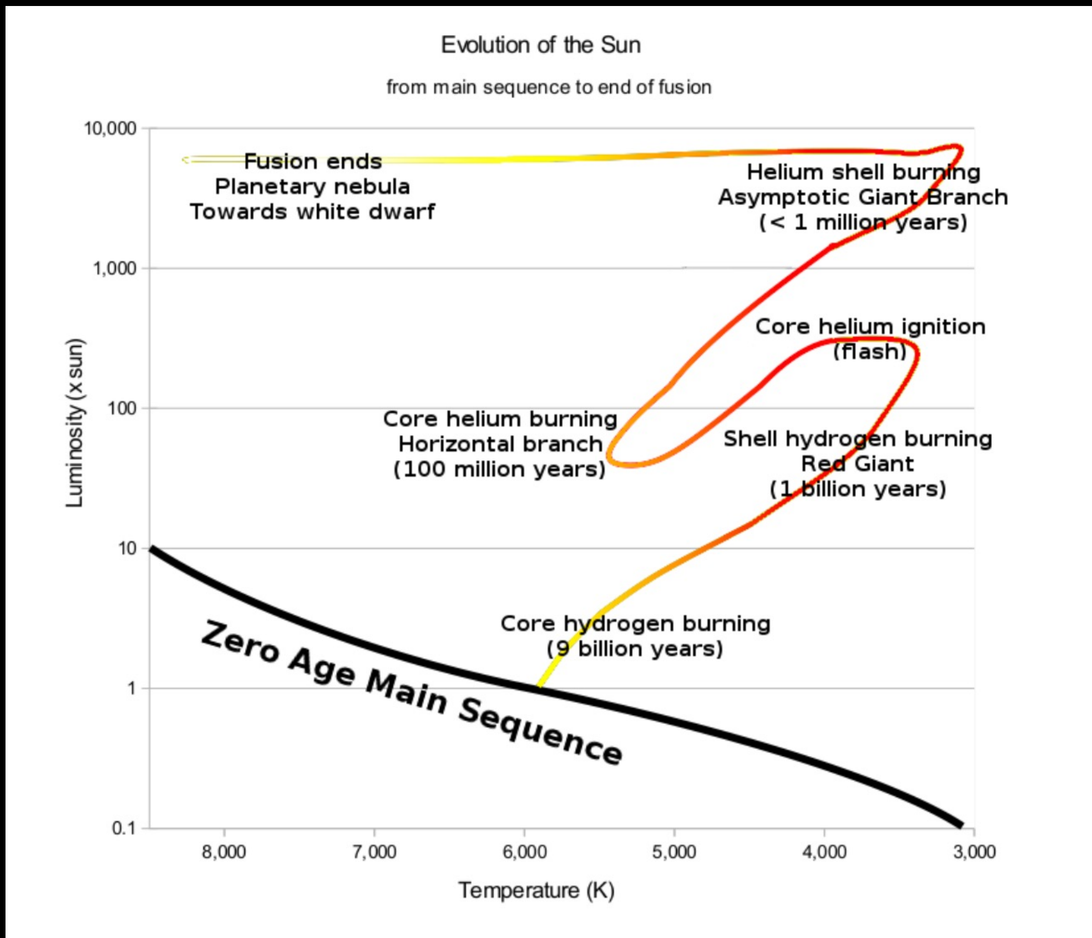


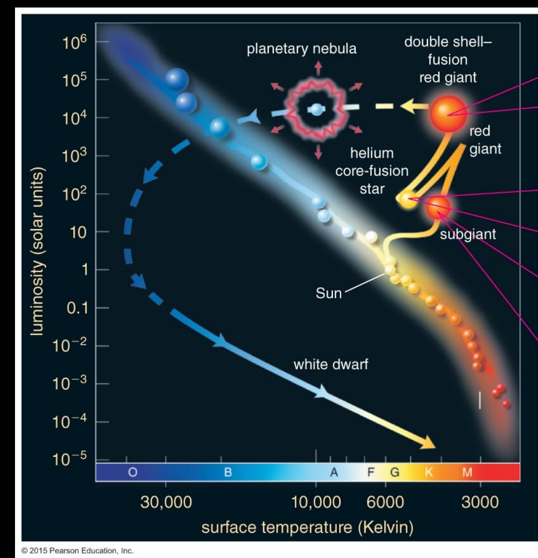
Let's go through this again…

12. What's left behind? A core of inert carbon we call a **white dwarf**. The core gradually cools and fades.



The complete life cycle of a Sun-like star



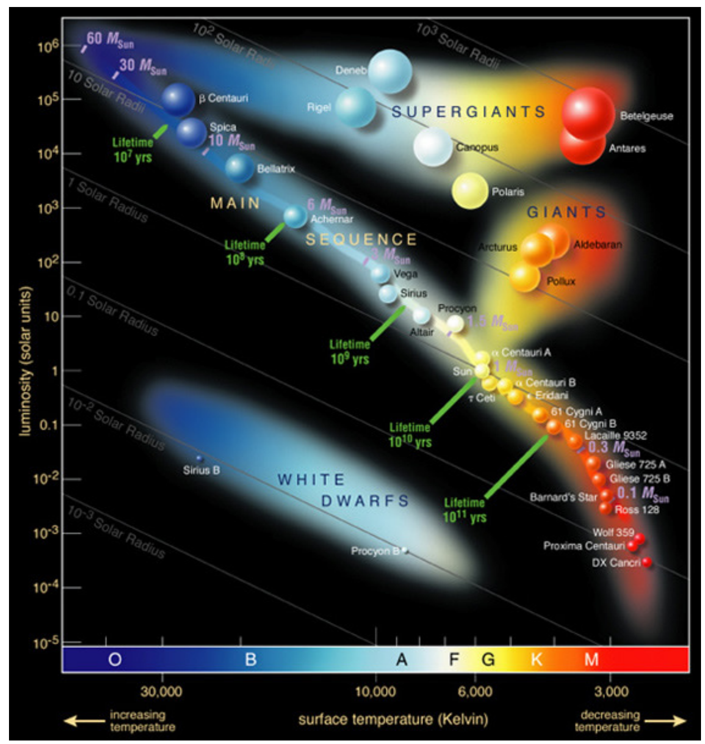


Summary: as the star runs out of hydrogen, it ignites higher layers in its interior, fusing heavier and heavier elements. Its size and luminosity adjust to obey hydrostatic equilibrium in every phase and, as a rasult, the star moves across the HR diagram.

question for you

On a HR diagram, where do you find stars of the largest radii?

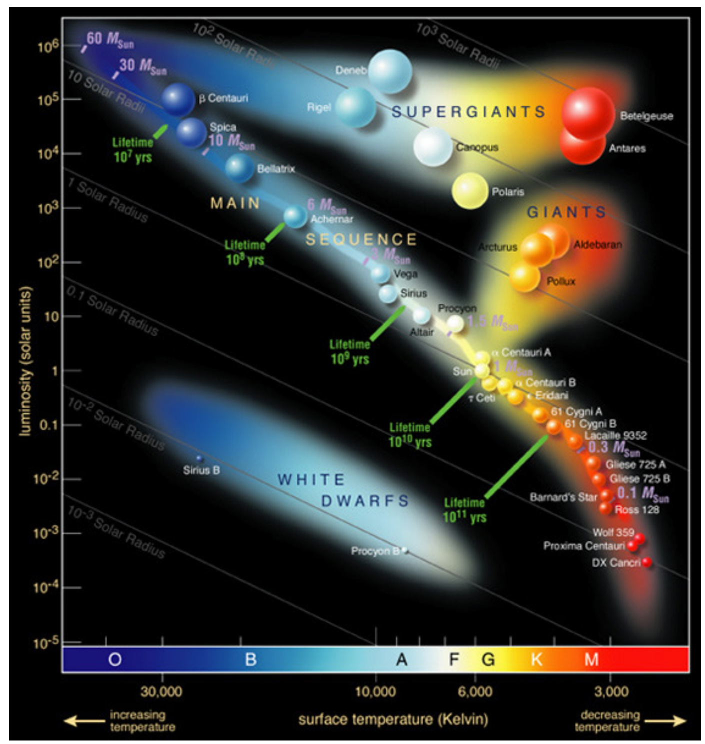
A. Lower right.
B. Upper right.
C. Upper left.
D. Lower left.
E. Everywhere.



question for you

On a HR diagram, where do you find stars of the largest radii?

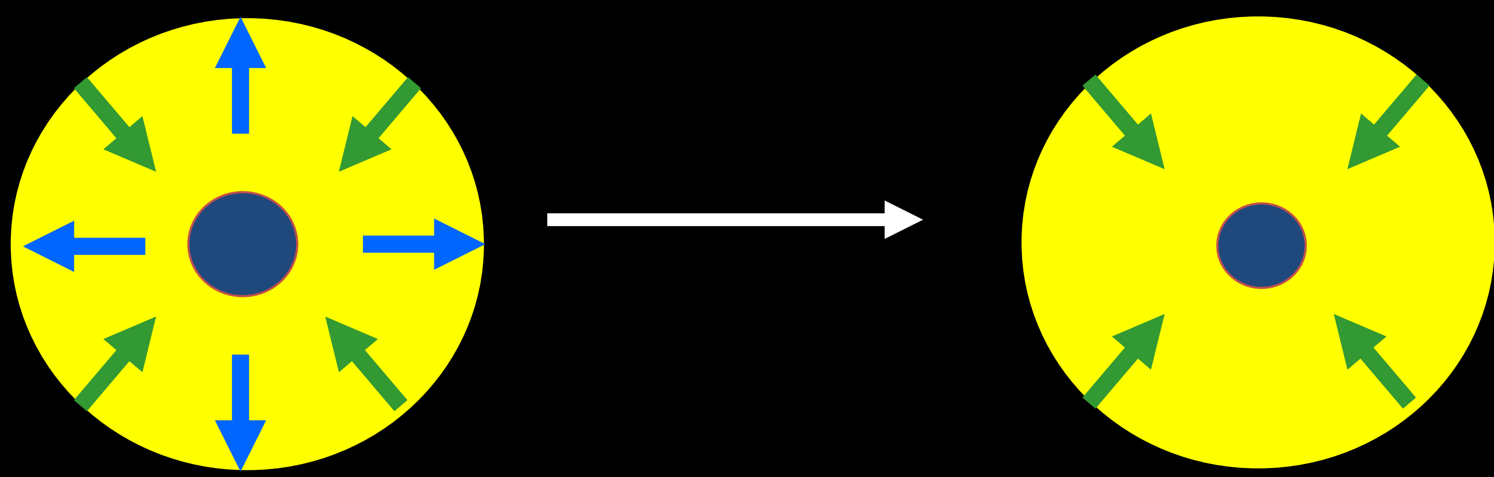
A. Lower right.
B. Upper right.
C. Upper left.
D. Lower left.
E. Everywhere.



Stellar life after the Main Sequence:
Recap.

Stars leave the Main Sequence

- The hydrogen runs out and fusion stops in the core.
- The outward pressure becomes <u>less</u> than the gravitational force and <u>star goes out of balance</u>.



When core hydrogen fusion ceases, a main-sequence star becomes a giant!

- When hydrogen fusion ceases in the core, the star will collapse inward – this causes the layer just outside the core to become so hot and dense that hydrogen fusion will begin in this outer layer.
- The energy produced by hydrogen fusion in this layer just outside the core causes the rest of the star to expand into a giant star.

While the exterior layers expand, the helium core continues to contract and eventually becomes hot enough (100 million Kelvin) for helium to begin to fuse into carbon and oxygen:

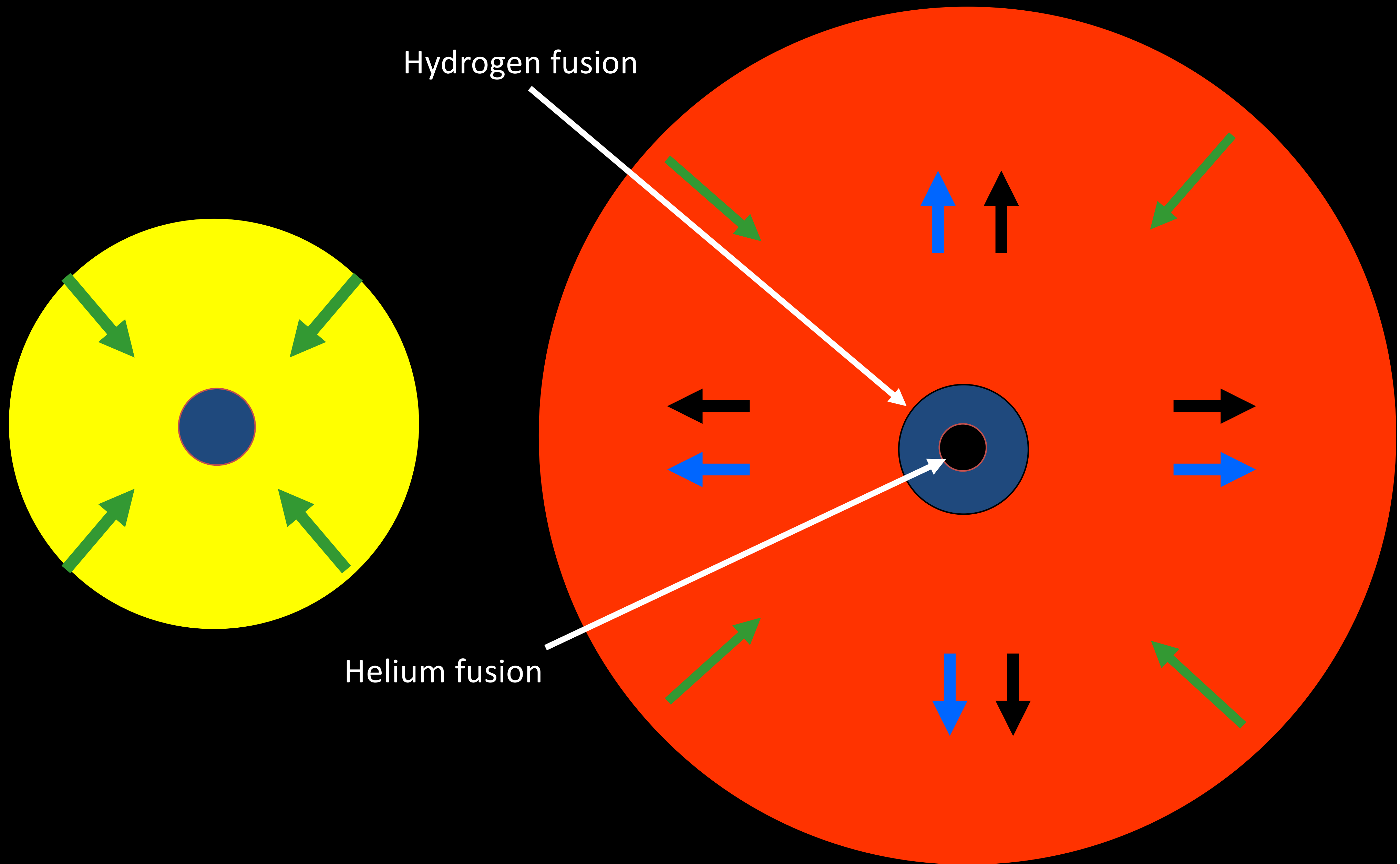
core helium fusion:

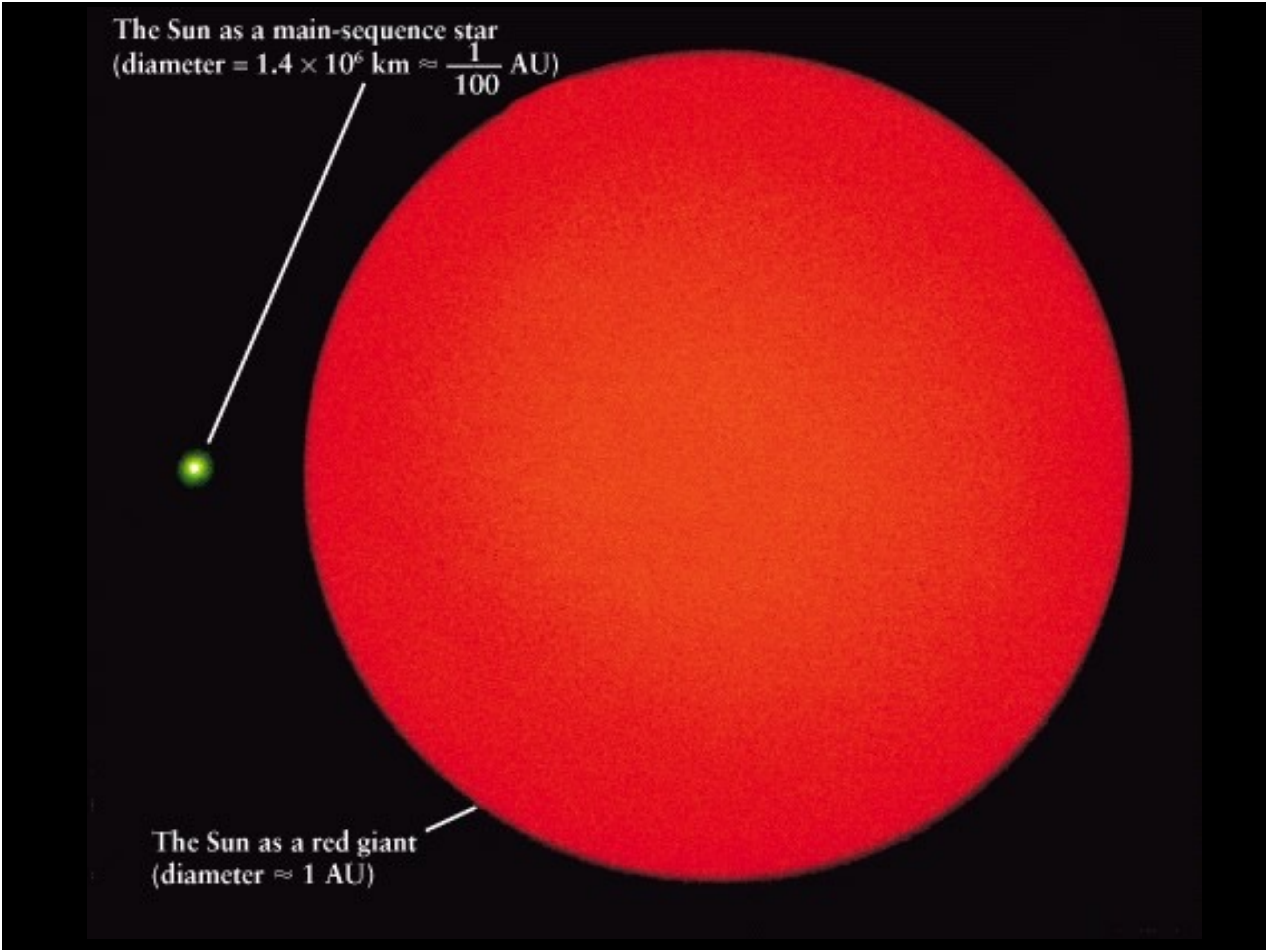
$3\ He \Rightarrow C + energy$

and

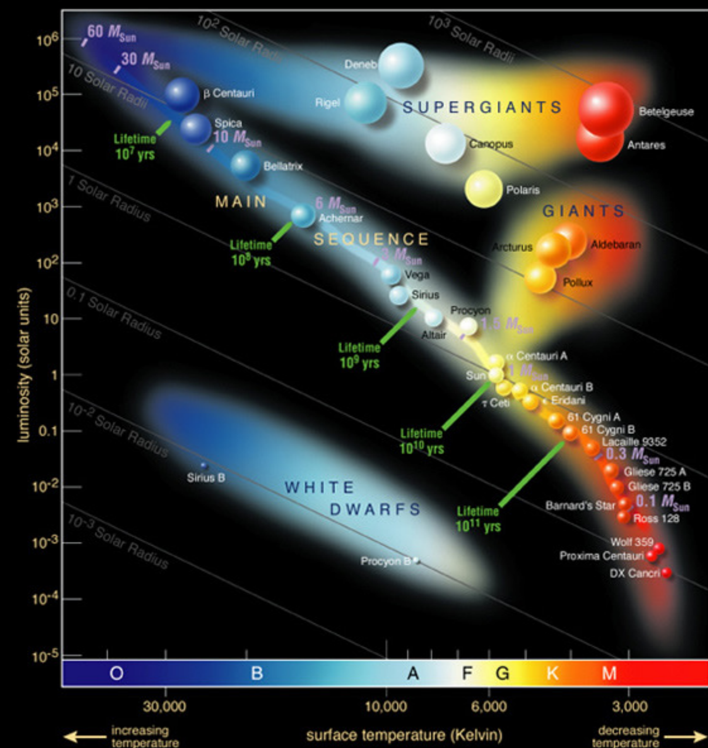
$C + He \Rightarrow O + energy$

Main Sequence stars become **red giants**




The Sun as a main-sequence star
(diameter = 1.4 × 10^6 km ≈ 1/100 AU)
The Sun as a red giant
(diameter ≈ 1 AU)

What happens after core helium fusion stops?

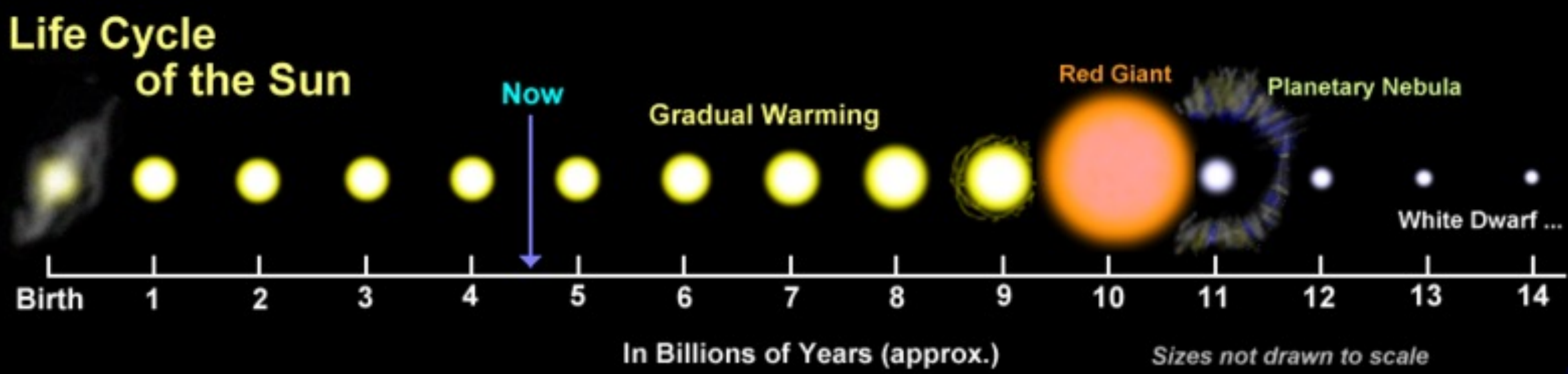


The shell and core equilibrium game continues and the star stays in the "giant" part of the HR diagram.

Depending on the mass of the star, <u>heavier elements can be produced</u>: carbon, oxygen, neon, silicon, the heaviest element being **iron**.

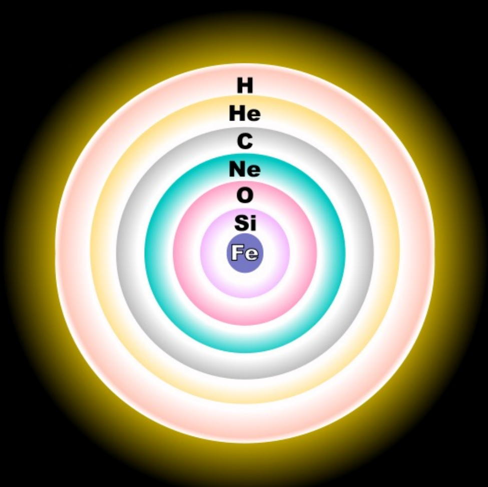
The Medium-Mass Star Timeline

- Main sequence: 10 billion years
- Hydrogen shell burning: 100 million years
- Helium core burning: 50 million years
- Helium shell burning: 10,000 years.

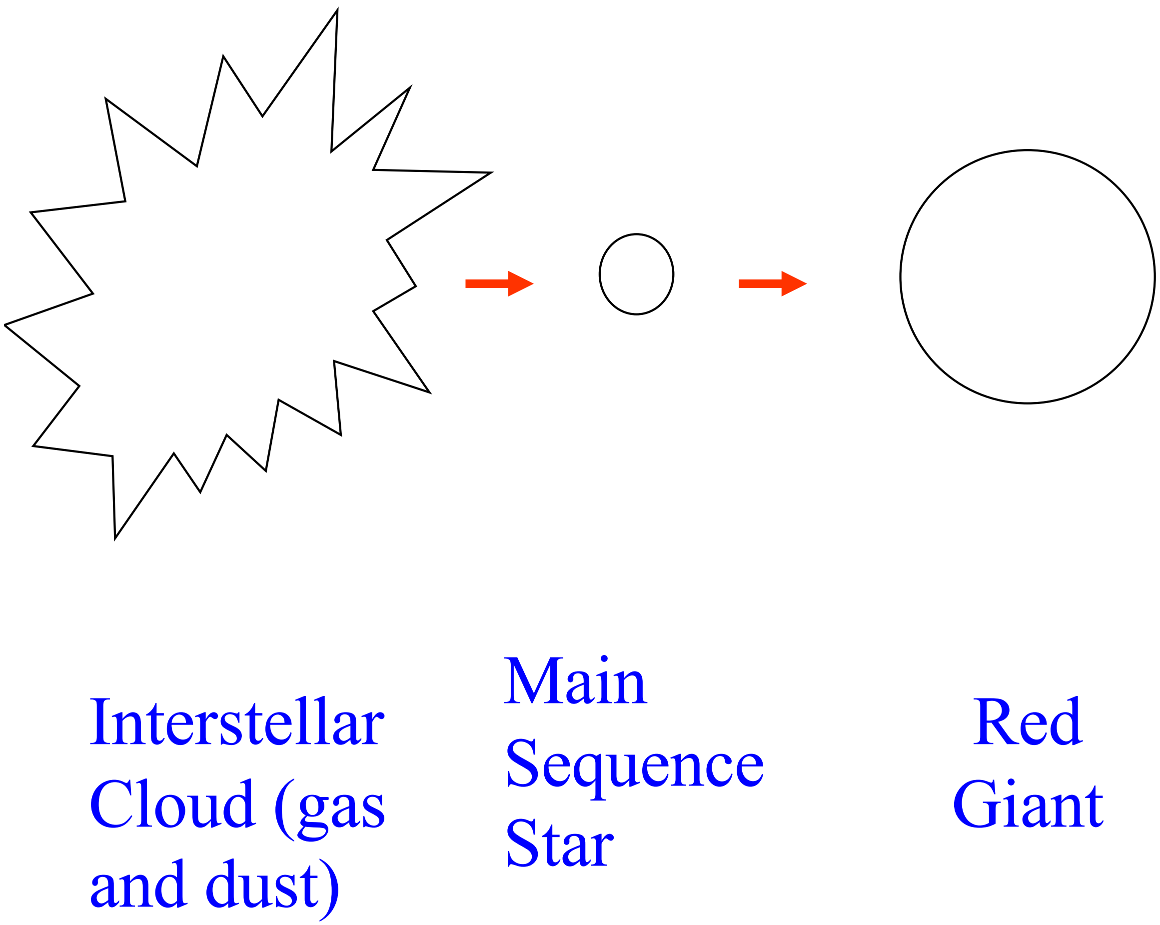


The High-Mass ($20\ M_{SUN}$) Star Timeline

• Main sequence: $H \rightarrow He$	10 million years
• Helium core burning: $He \rightarrow C, O$	1 million years
• Carbon core burning: $C \rightarrow Ne, Na, Mg, Al$	1,000 years
• Neon core burning: $Ne \rightarrow O, Mg$	3 years
• Oxygen core burning: $O \rightarrow Si, S, Ar, Ca$	1 year
• Silicon core burning: $Si \rightarrow Ni$ (decays into Fe)	1 week



Life path of <u>any</u> star



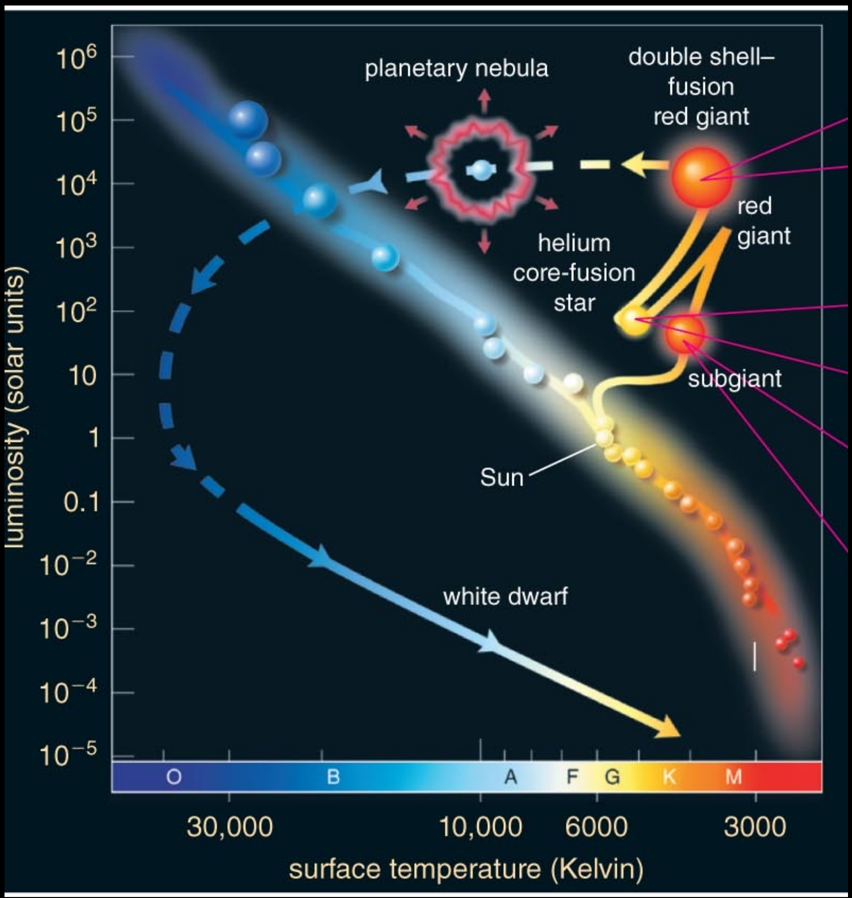
So what happens <u>after</u> the giant phase?

<u>It depends on the mass of the star!</u>

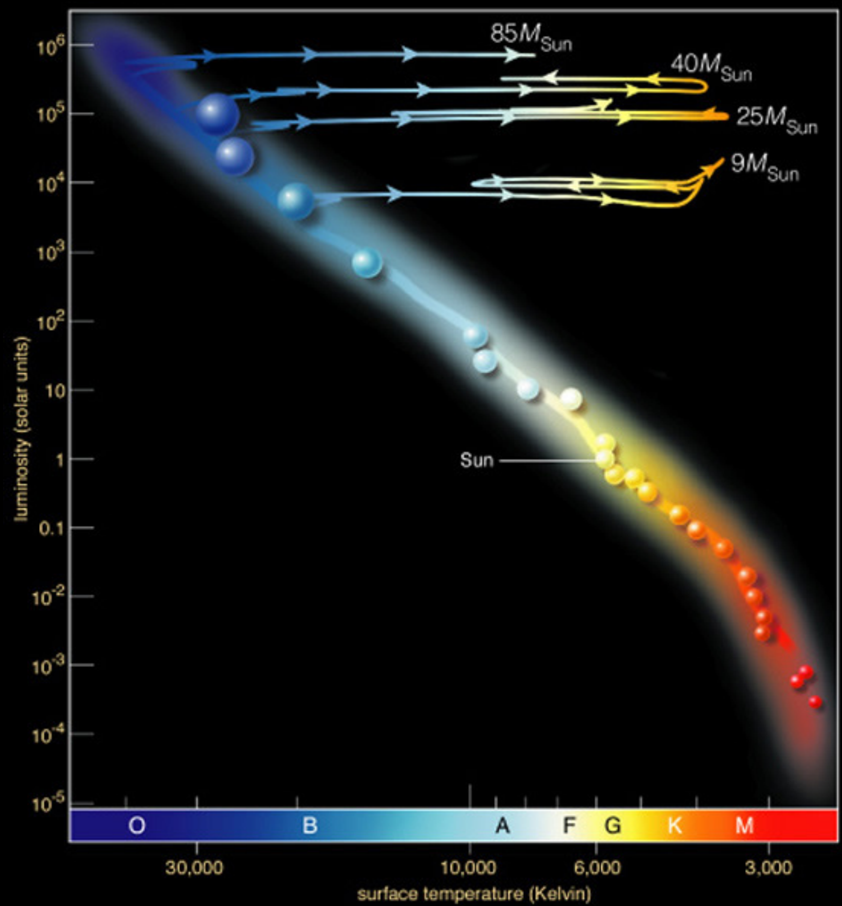
Low mass stars ($< 8\ M_\odot$) have a different fate from high mass stars ($> 8\ M_\odot$)

Dwarfs and Giants

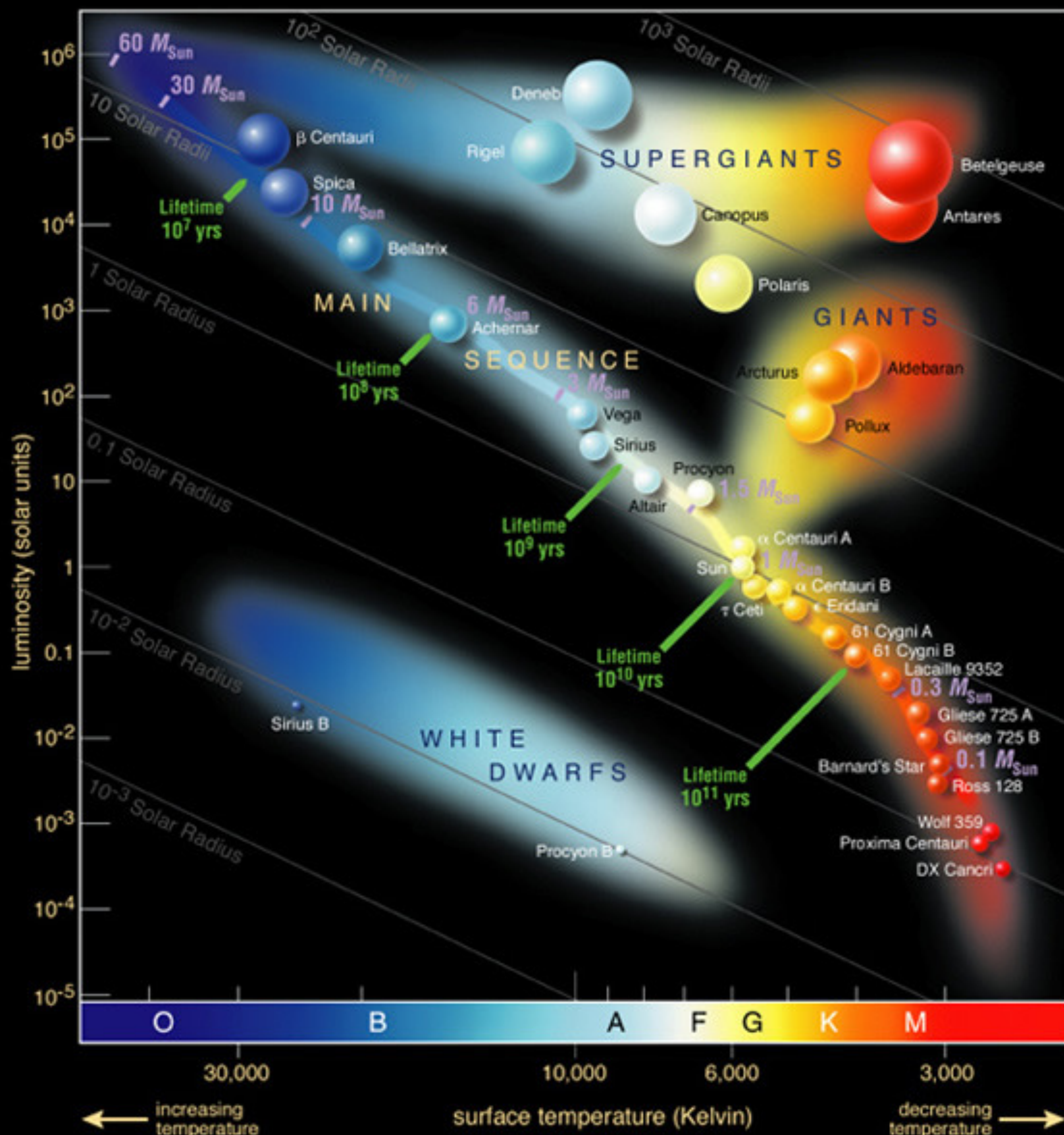
Low and medium-mass stars zig-zag up and down across the HR diagram.



High-mass stars zig-zag horizontally across the HR diagram.



Stars tend to pile up on the HR diagram where temporary equilibrium is found.



questions for you

1. Why does a star expand into a red giant?

   A. Because it's about to explode in a supernova
   B. Because its temperature decreases on the surface
   C. Because its gravity decreases when the star runs out of fuel
   D. Because the pressure temporarily wins over gravity

2. When does a star move in the direction of the lower left corner (down and left) of the HR diagram?

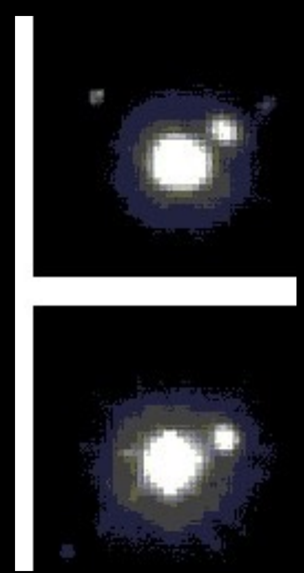
   A. Every time it runs out of fuel in its core
   B. Only when it is turning into a white dwarf
   C. Whenever it contracts
   D. Whenever it is heating up on its surface

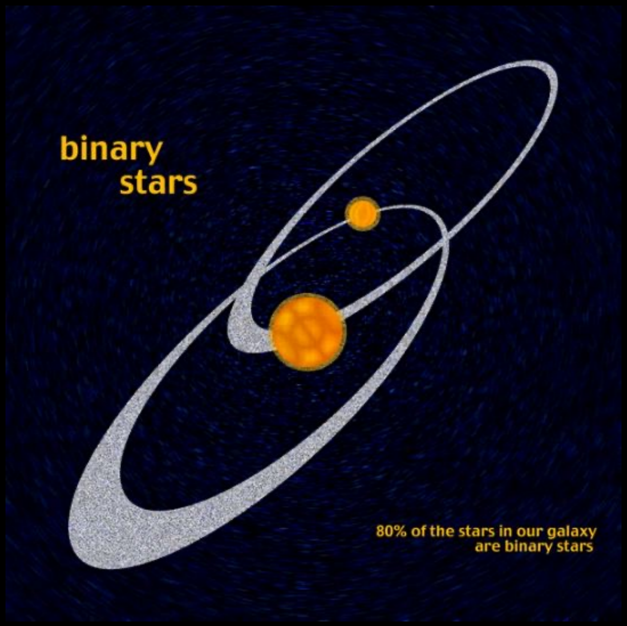
How do we know?

Measuring masses, radii, and ages

How do we measure masses of stars?

- From Newton's laws, we can find an object's mass if it has something orbiting it. For this, we need orbital period and separation/distance.
- **Binary stars** give us an opportunity to measure the masses of different spectral types.



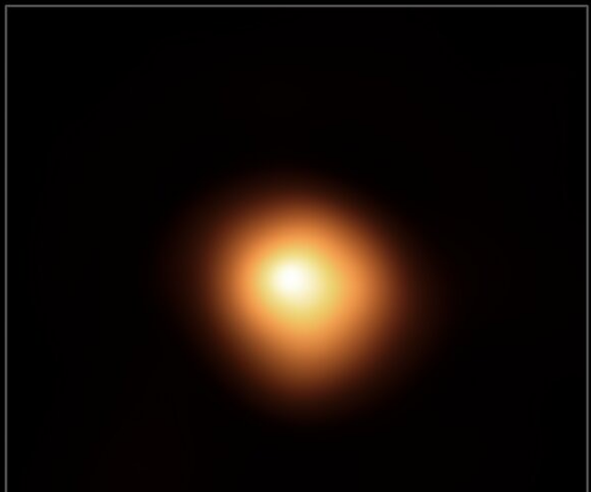


How do we measure radii of stars?

- Calculate from luminosity and surface temperature, from Stefan-Boltzmann law

Luminosity = $5.67 \times 10^{-8} \times$ **A x T**^{4}

- Measure directly using interferometry (hard, can only do for big stars close by)



Jan 2019
Betelgeuse, Orion

Very Large Telescope, Chile

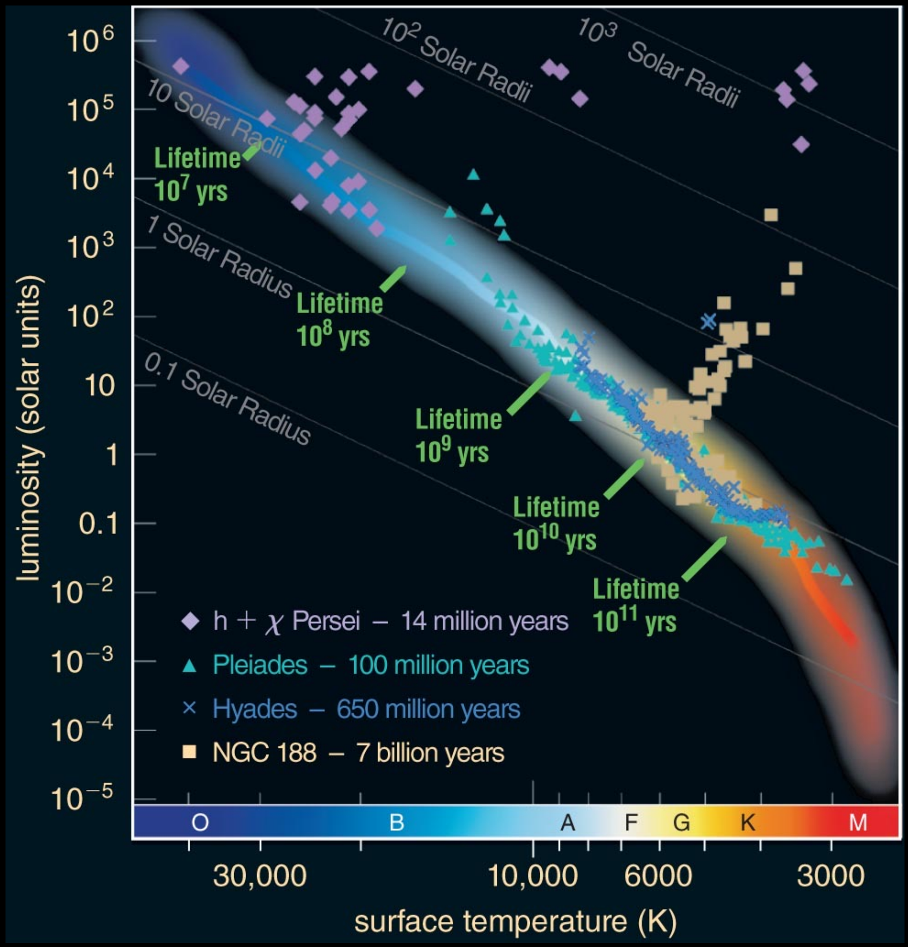
How do we measure ages of stars?

- Hard to do for individual stars precisely.
- All the stars in a star cluster are at roughly the same distance from Earth, and born at the same time.
- **Pleiades** are an example of **open star cluster**, found in the gas-rich disk of the galaxy.
- **Globular clusters** are densely packed star clusters, found in the galactic halo. They are almost as old as the Milky Way.


M45 © Royal Observatory Edinburgh/Anglo-Australian Observatory
Photograph from UK Schmidt plates by David Malin

Star cluster HR diagram

- In a single star cluster, stars that live shorter than the age of the cluster will be gone from the Main Sequence.
- **Main sequence turnoff** for Pleiades is about 100 million years.



Globular cluster HR diagram

www.spacetelescope.org

What did we learn in Chapters 11+12?

- Stars begin their lives as protostars: hydrogen fusion has not yet begun in their cores, and they often eject gas along the axes of rotation.
- Stars form in cold molecular clouds of hydrogen.
- The larger the mass of the star, the shorter the time it spends in the protostellar stage, which ends when hydrogen fusion begins.
- The number of low mass stars that form from a molecular cloud is much much larger than the number of intermediate mass and high mass stars.

What did we learn in Chapters 11+12?

- High mass stars carry out nuclear fusion via the CNO cycle.
- High mass stars easily transition into burning helium (core temperature 100 million K), carbon fusion (600 million K) and oxygen fusion (1 billion K)
- Helium capture is a type of nuclear fusion involving helium and a heavier element (carbon, oxygen, etc.)
- Energy cannot be released from the fusion or fission of iron.
- Stars with masses less than 8 M_{SUN} leave behind a white dwarf.
- Stars more massive than 8 M_{SUN} explode in supernova explosions and leave behind a neutron star or a black hole.