"I do not approve of anything that tampers with natural ignorance. Ignorance is like a delicate exotic fruit. Tough it and the bloom is gone."

Lady Bracknell, The Importance of Being Earnest.

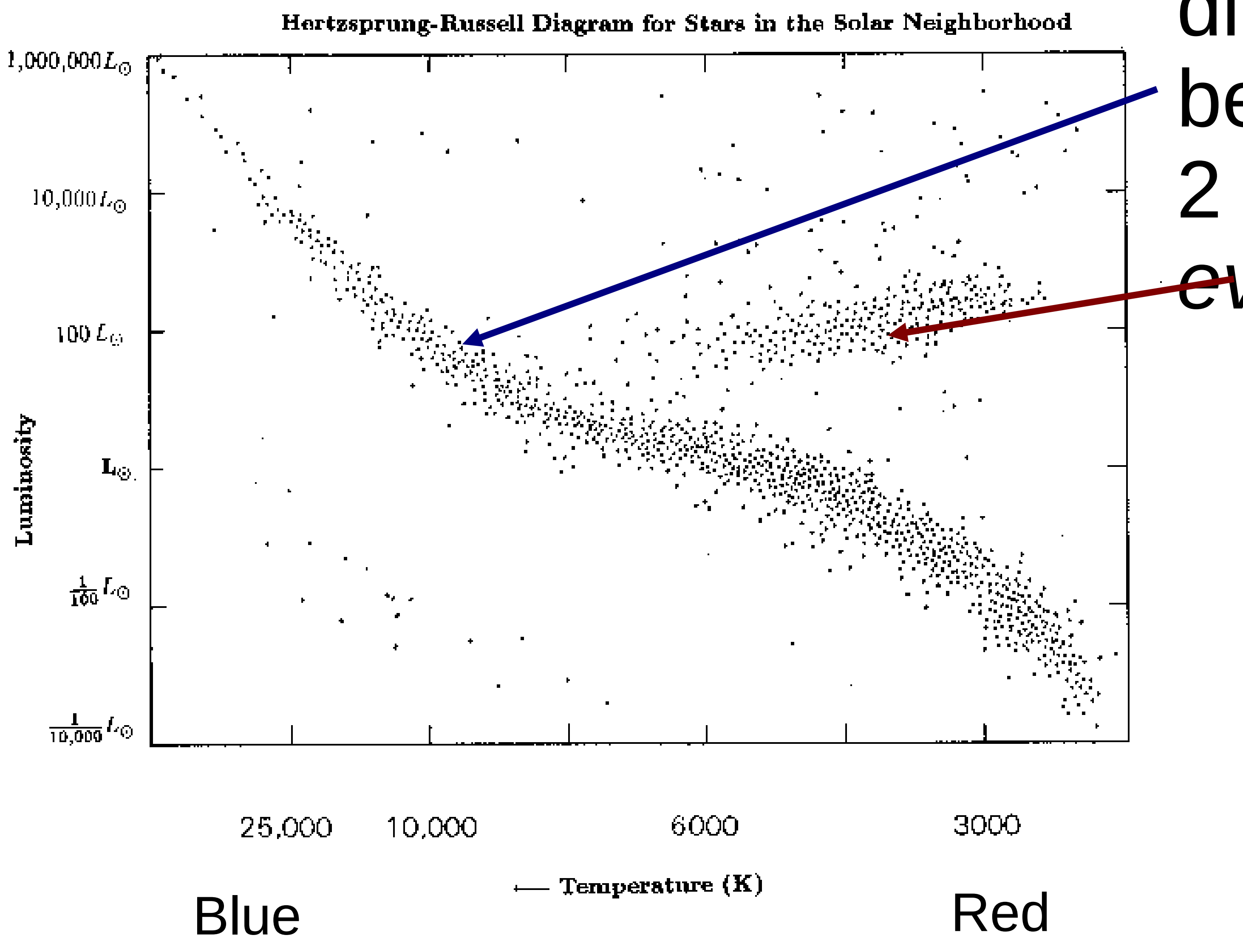
HW3 is due on Monday.

Questions?

Test 2 will be on Wednesday, April 3.

Sample test & review will be posted next week.

HR Diagram



This difference between these 2 stars is *evolution*

"Stellar evolution is driven entirely by the never ending battle between Pressure and Gravity. As imbalances are reached, the star is driven to find a new Energy source."

When a star changes its stage in stellar evolution it changes how it generates energy to support against gravitational collapse.

The Electronic Universe Project at the University of Oregon

The big picture of energy for most stars (<8M_{sun}):

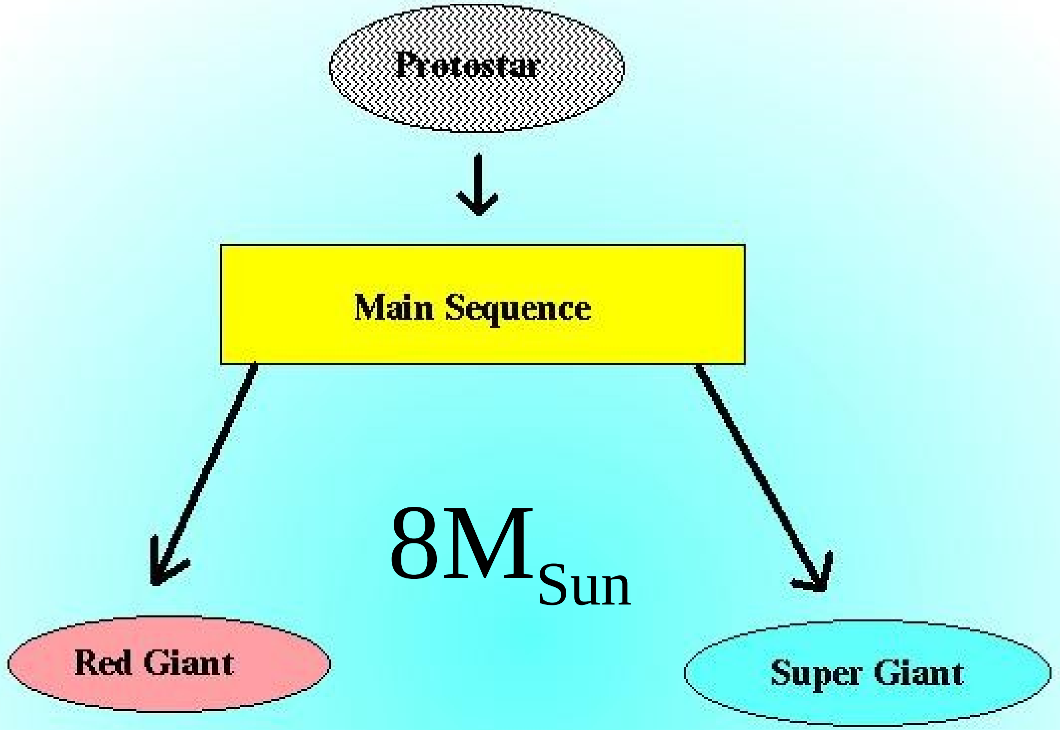
Gravity (protostar)
Fusion (H $\rightarrow$ He) (main sequence)
Gravity (red giant)
Fusion (He $\rightarrow$ C/O) (horizontal branch)
Gravity (AGB/planetary nebular)
End state (white dwarf)

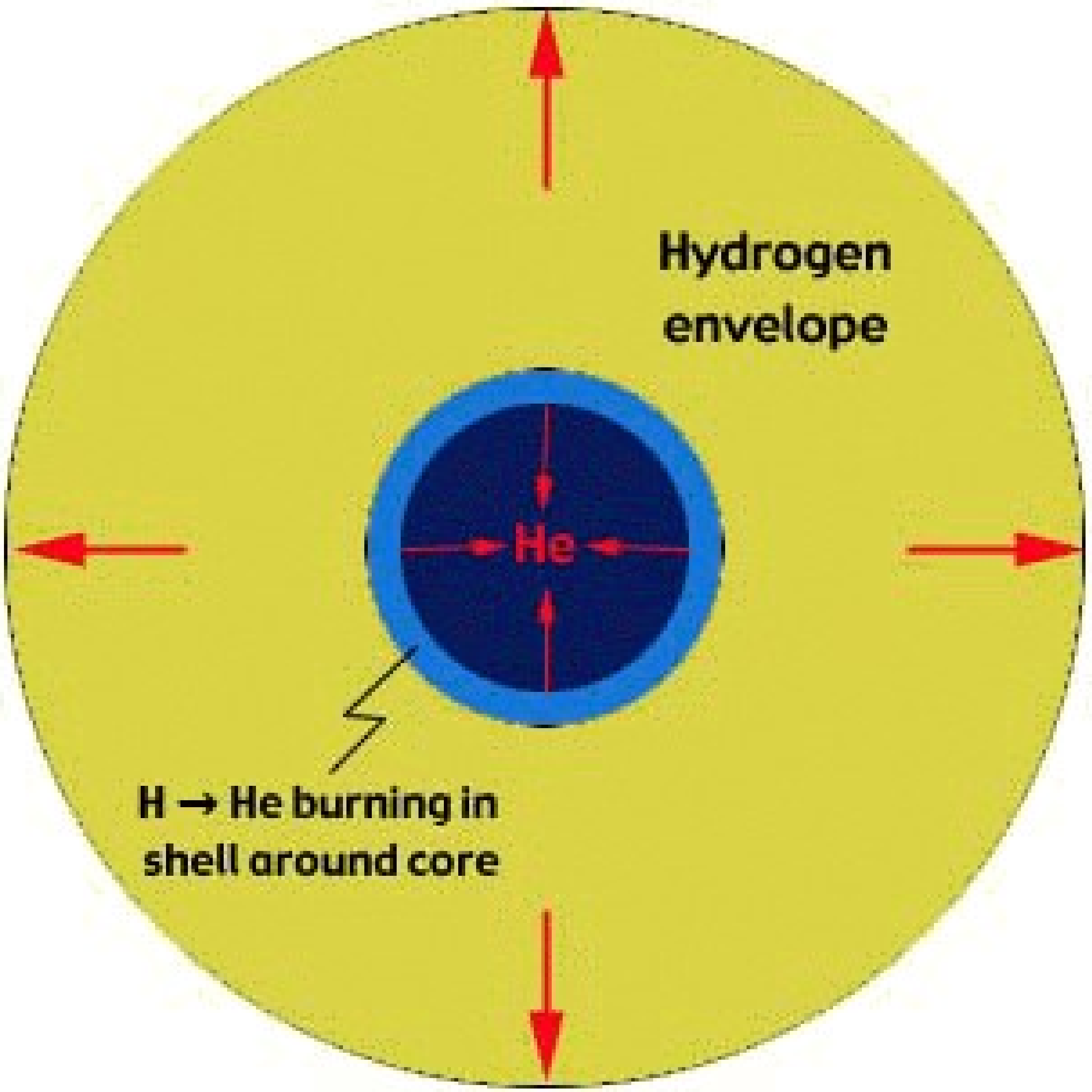
Evolution so far:

Protostars: Energy from **gravity** (shrinking)

Main Sequence: Energy from **fusion** converting **H to He** in their cores

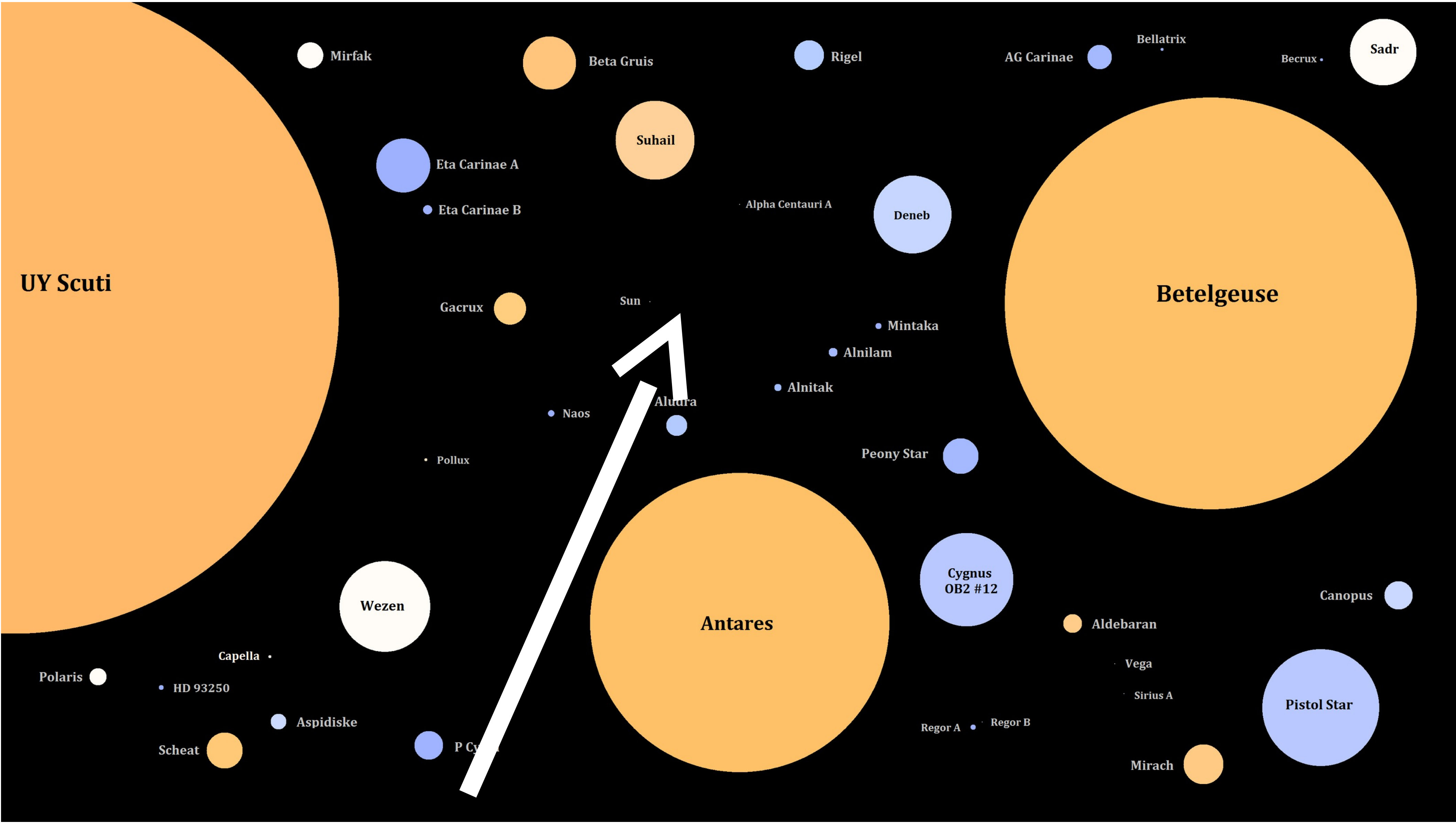
Red giants: Energy from **gravity** (shrinking core). He core shrinks, H shell expands.

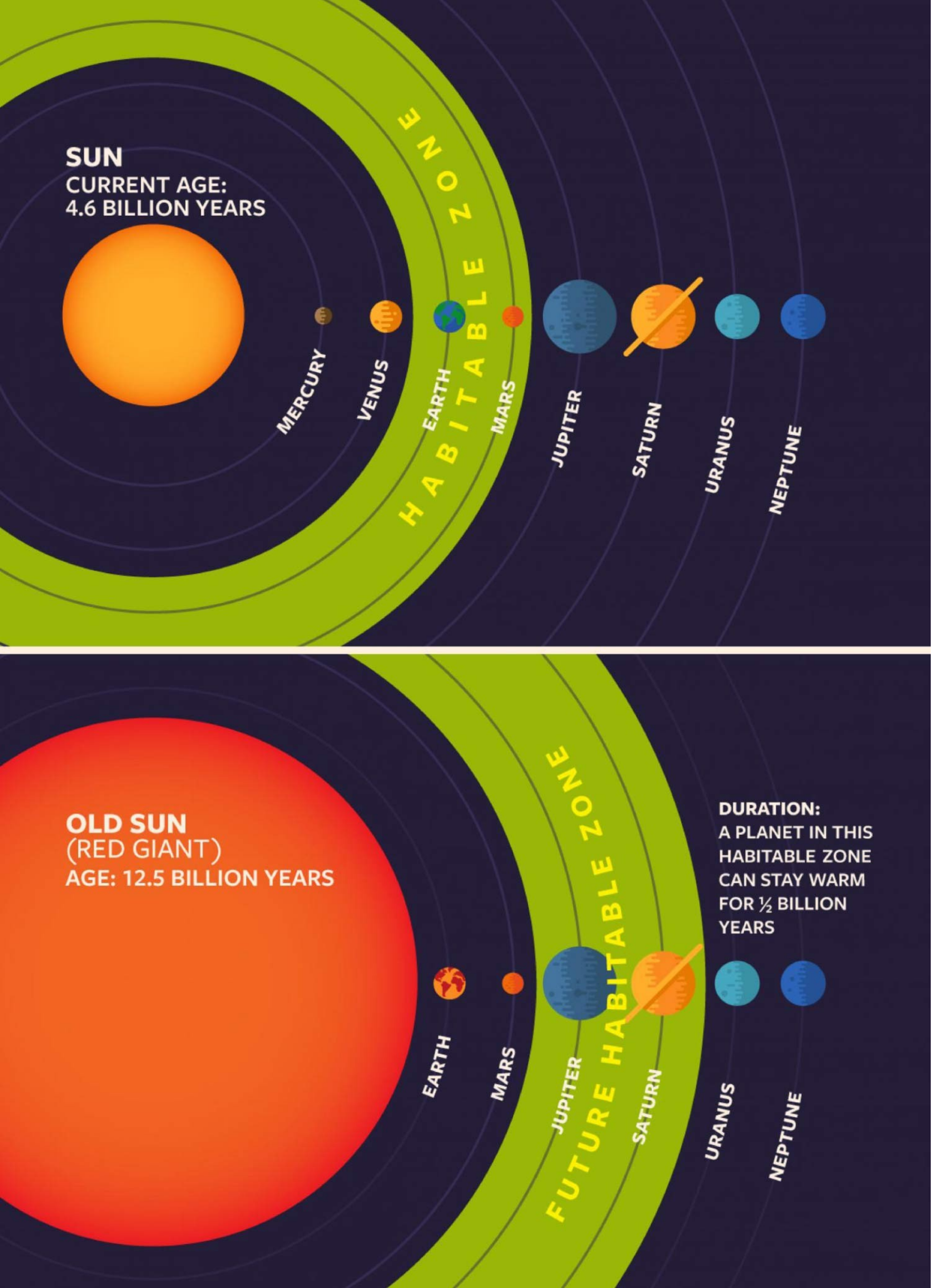




During the Red Giant phase, core =getting smaller, Shell=getting larger

Giant stars can be really giant!

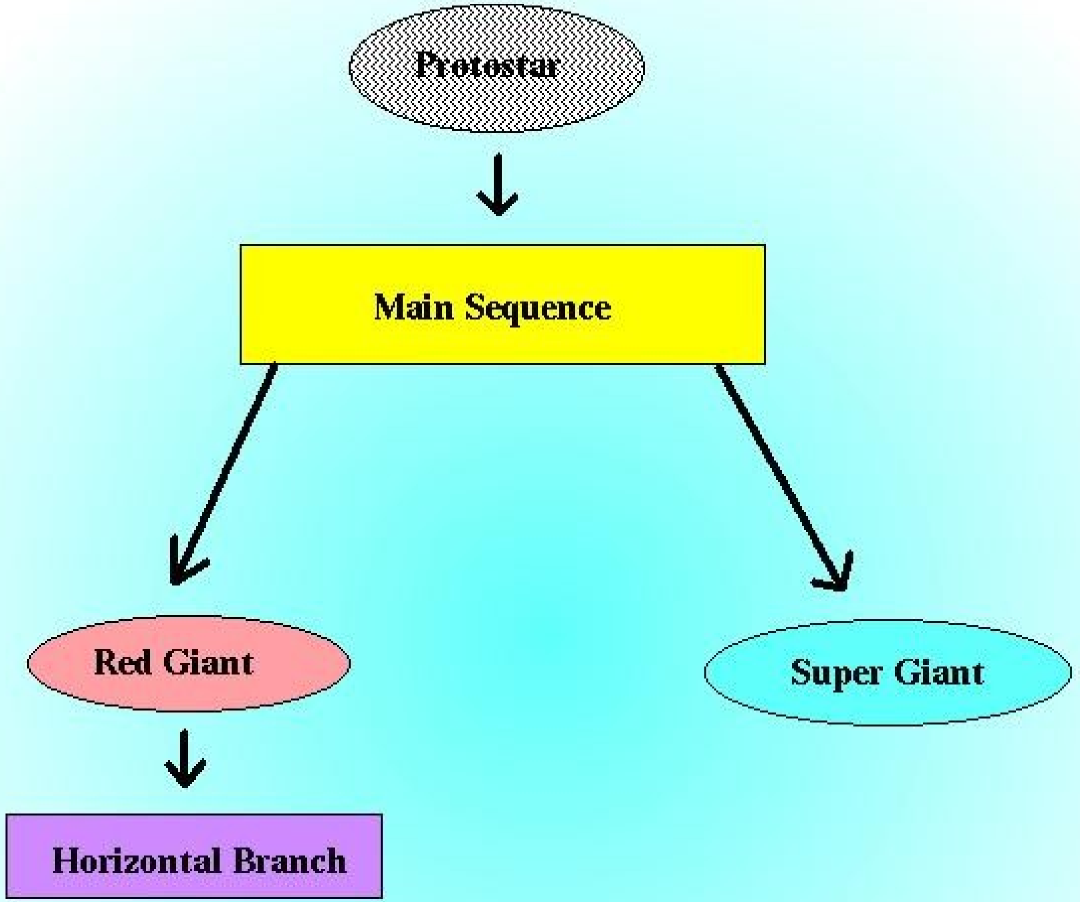




When our Sun becomes a red giant star, it will expand out to around Venus' orbit.

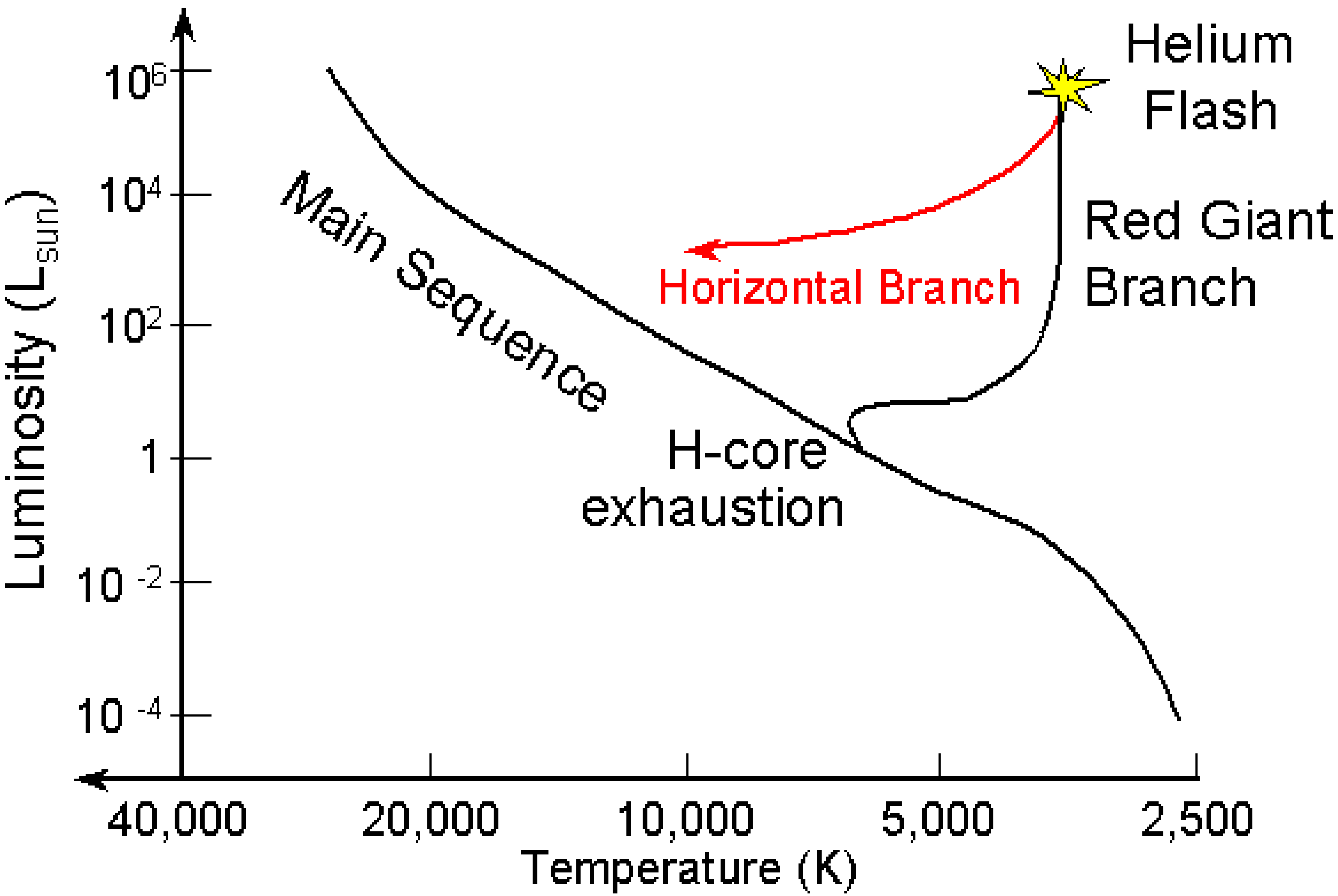
The Earth will still be here, but it will be very hot.

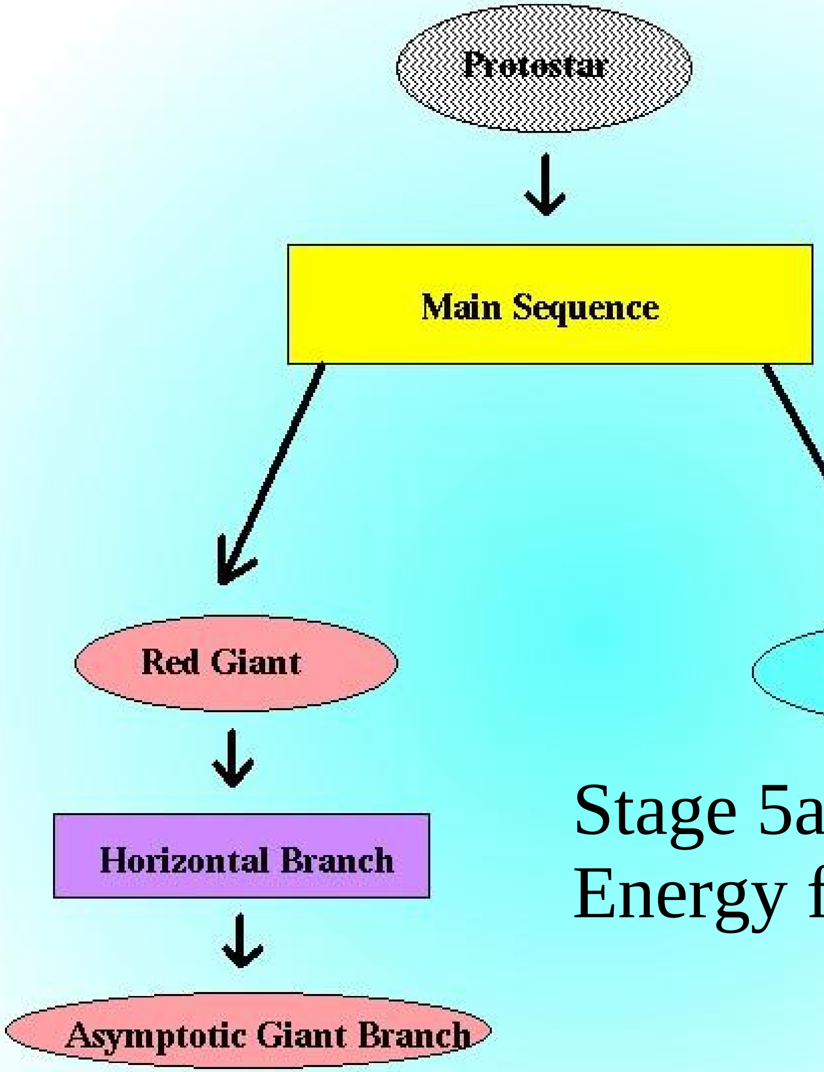
Image credit: sci-news.com



Stage 4a: Once stars begin to convert helium to carbon in the core, they become Horizontal Branch stars.

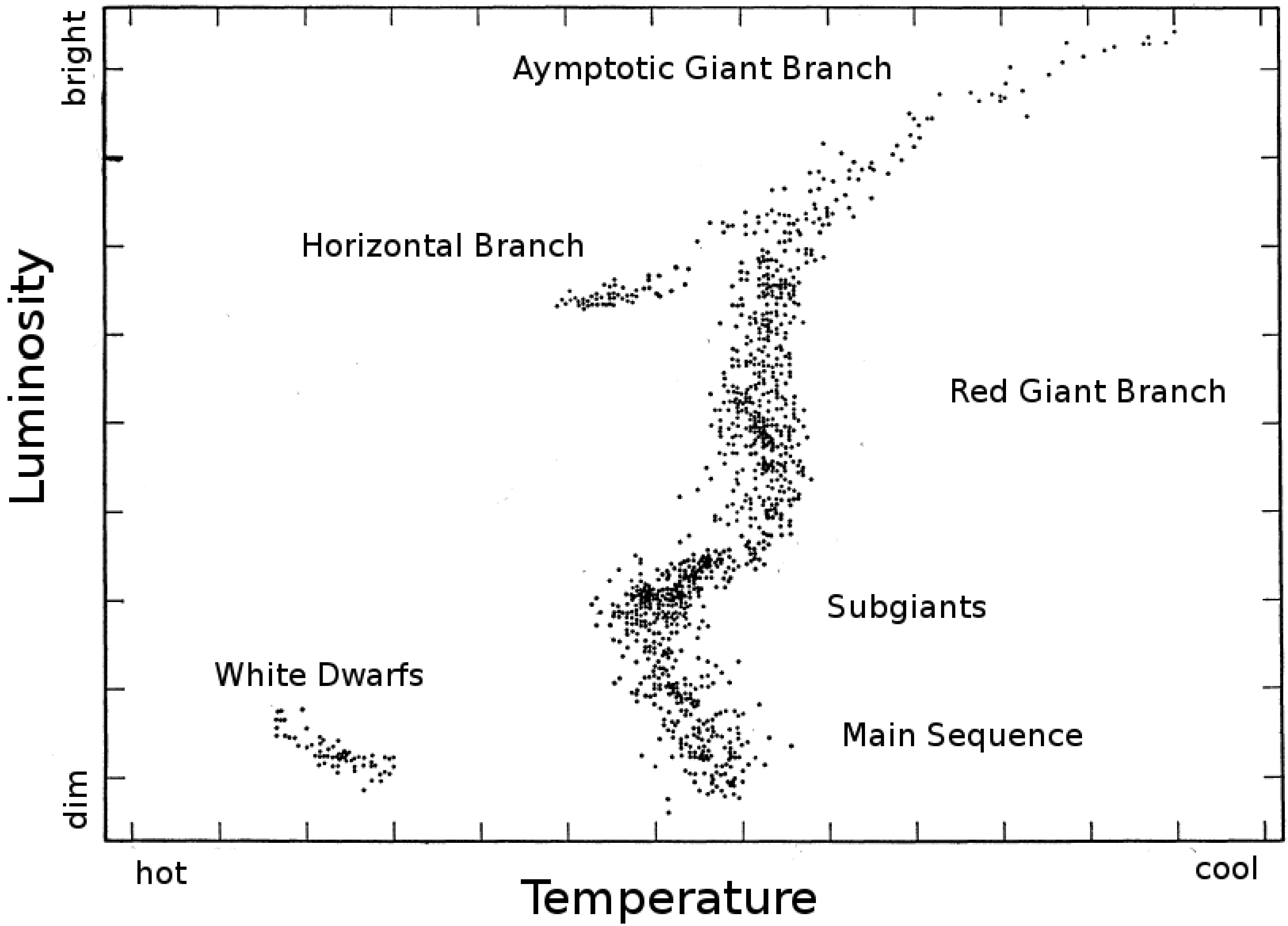
Stars on the horizontal branch are **fusing He to C** in their cores, and H to He in a shell surrounding the core.





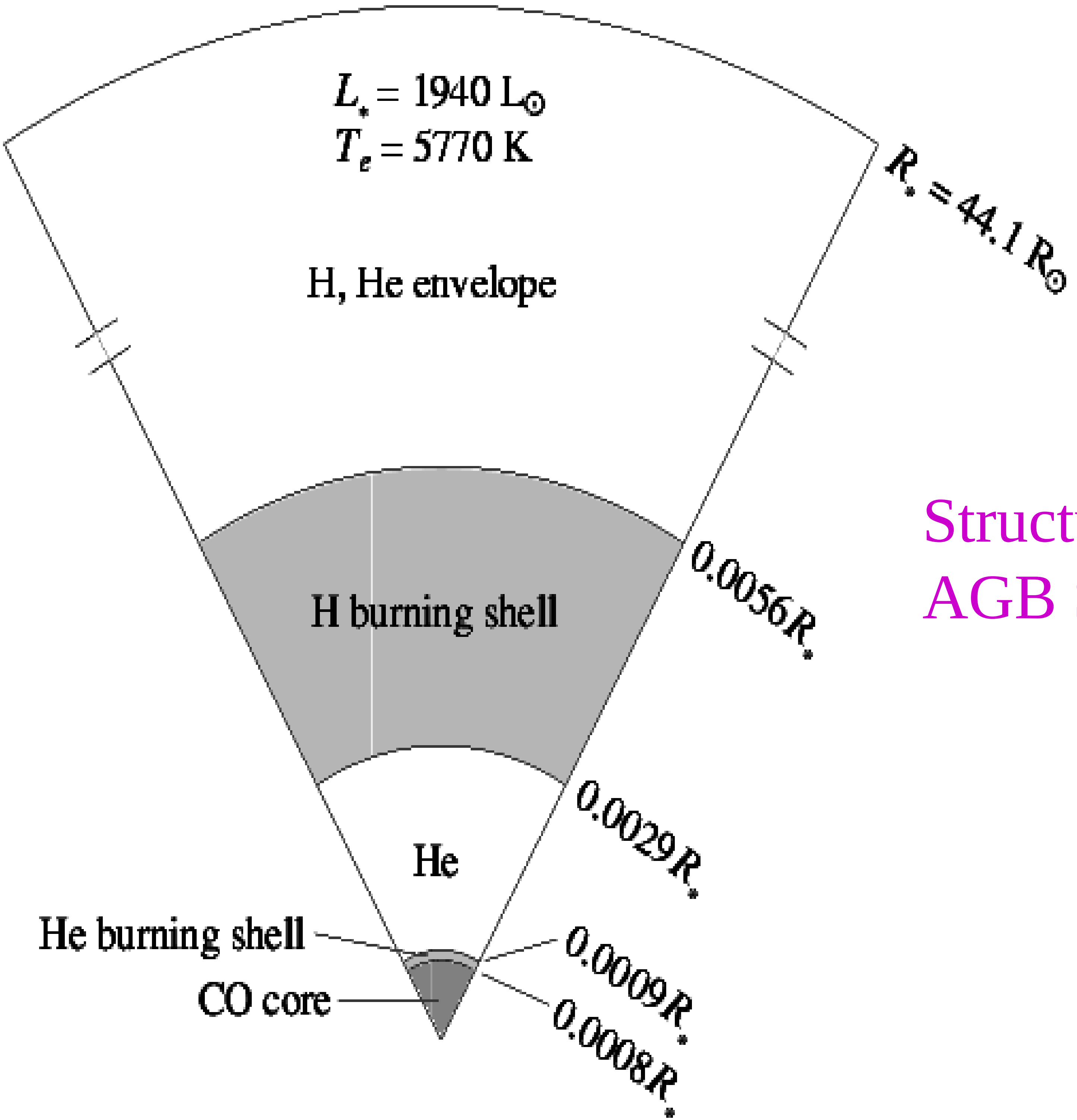
Stage 5a: The AGB.
Energy from gravity

AGB stars are very similar to Red Giants, just bigger (and with a He burning shell).



Quiz 9: If I see a group/cluster of stars, I can assume….

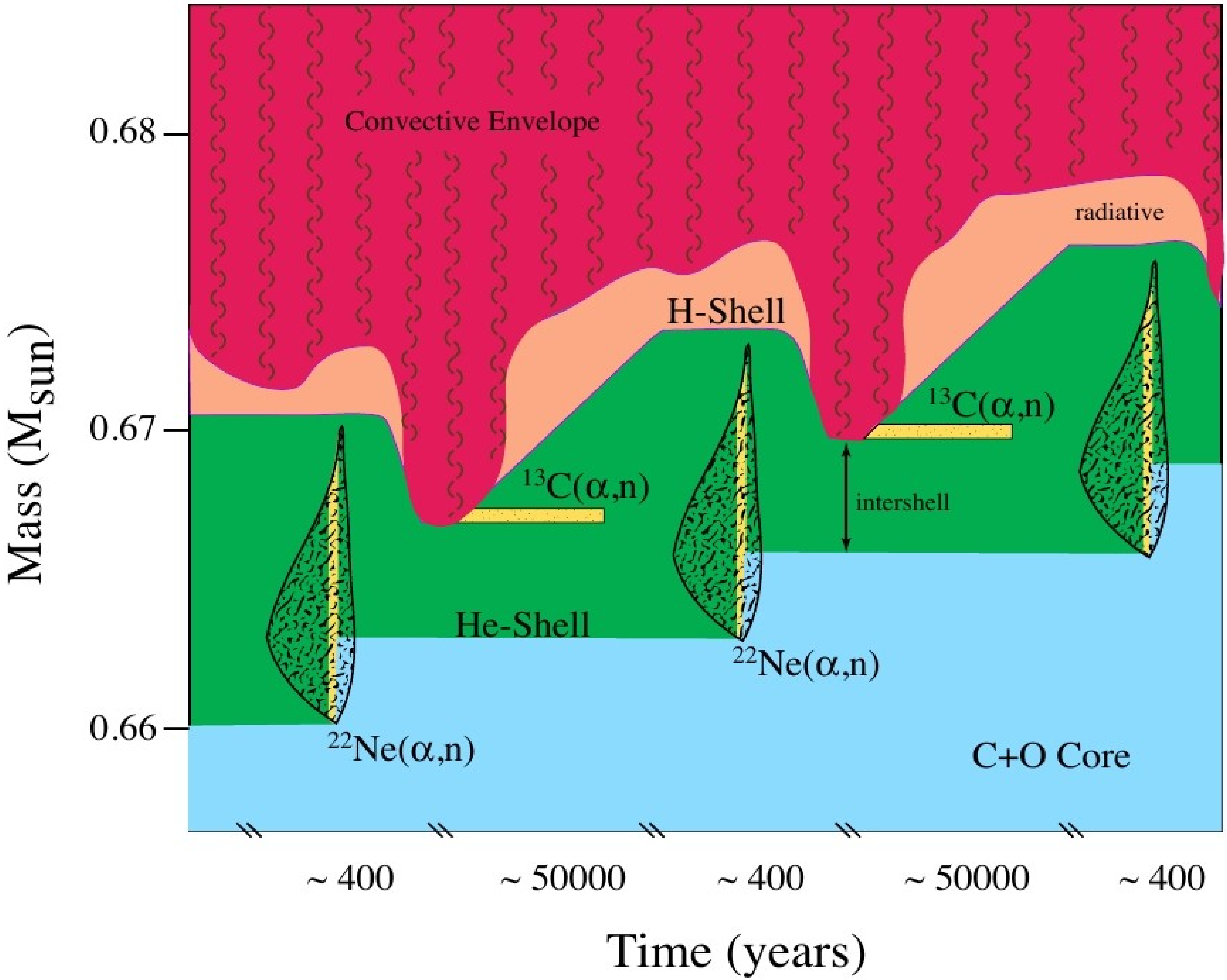
A) they are at the same distance.
B) they formed/started at the same time.
C) they formed from the same cloud of gas.
D) All of the above are most likely true.



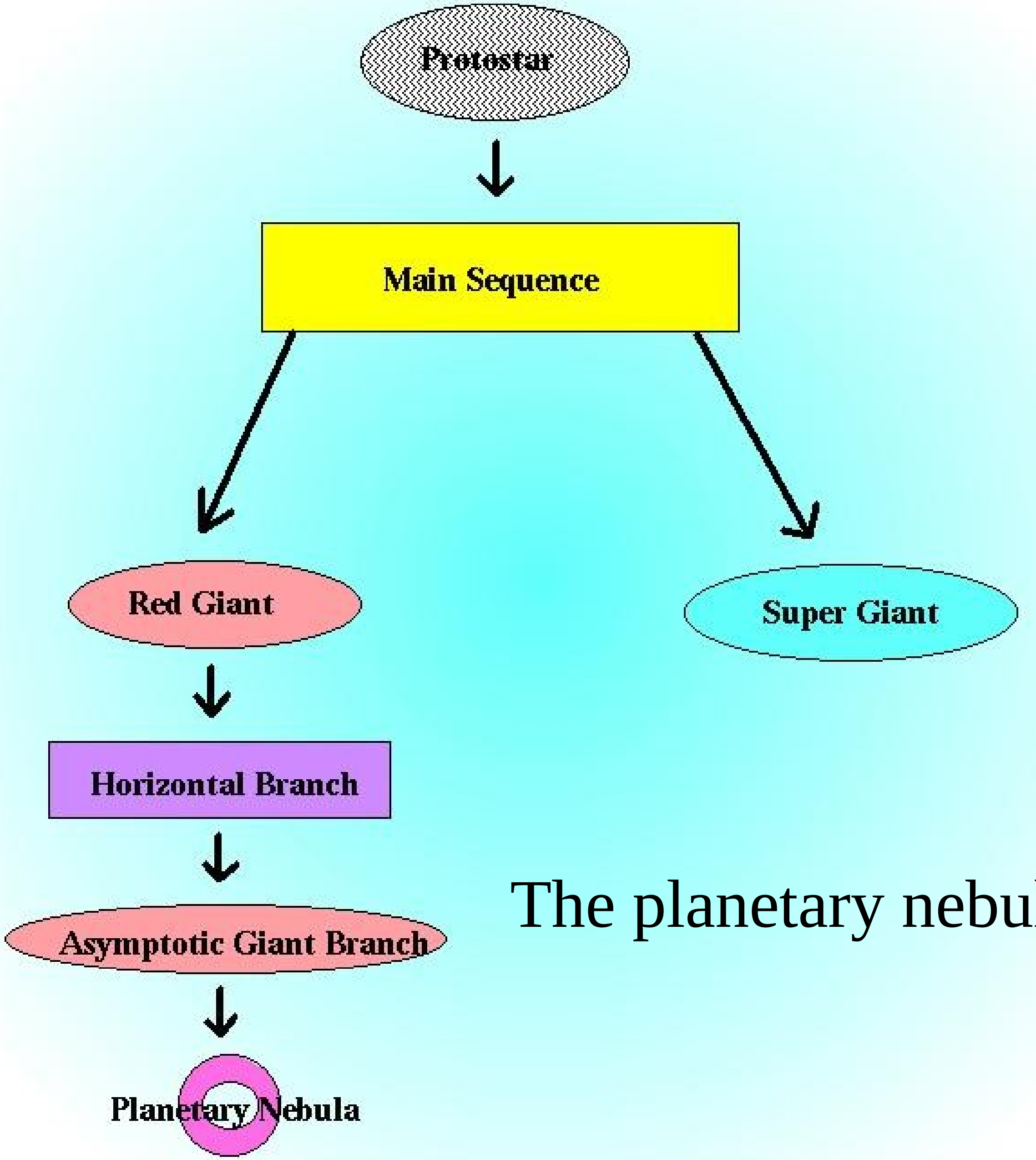
Structure of an AGB Star

Spasmodic fusion

- H fusion makes He ash.
- He fusion is much quicker than H fusion.
- H fusion cannot make He ash quick enough for continuous He fusion.
- He fusion starts and stops.

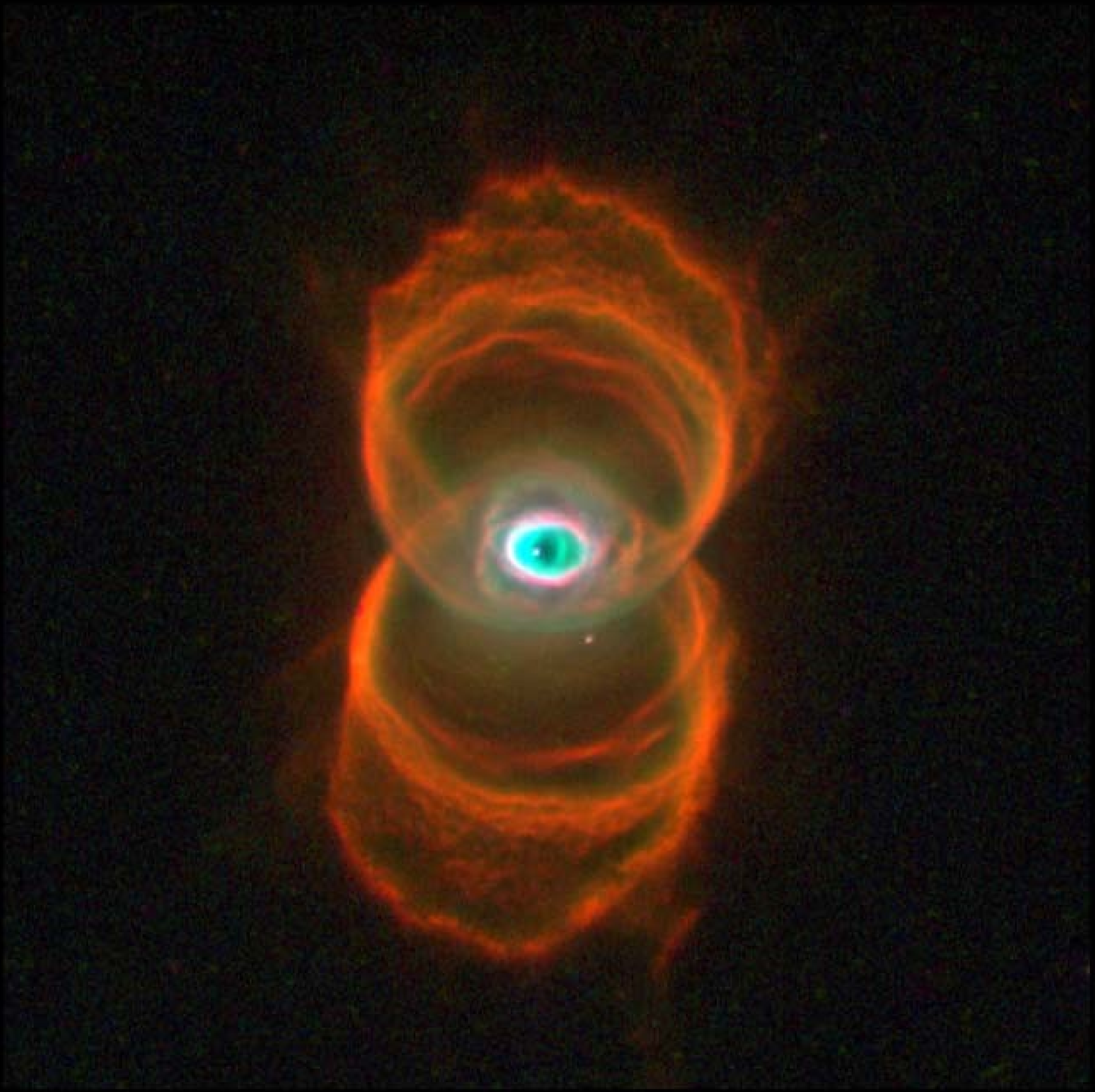

Convective Envelope
radiative
H-Shell
^{13}C(α,n)
^{13}C(α,n)
intershell
He-Shell
^{22}Ne(α,n)
^{22}Ne(α,n)
C+O Core
0.68
0.67
0.66
Mass (M_{sun})
~ 400
~ 50000
~ 400
~ 50000
~ 400
Time (years)

Shell He fusion lasts <400 years (and less each time)
~5,000 years between shell He fusion ‘flashes’
Stars like our Sun will have 10-12 shell He ‘flashes’



The planetary nebula.

The shock waves sent out by the spasmodic He burning shell increase the size of the atmosphere, until it is no longer really connected to the core.

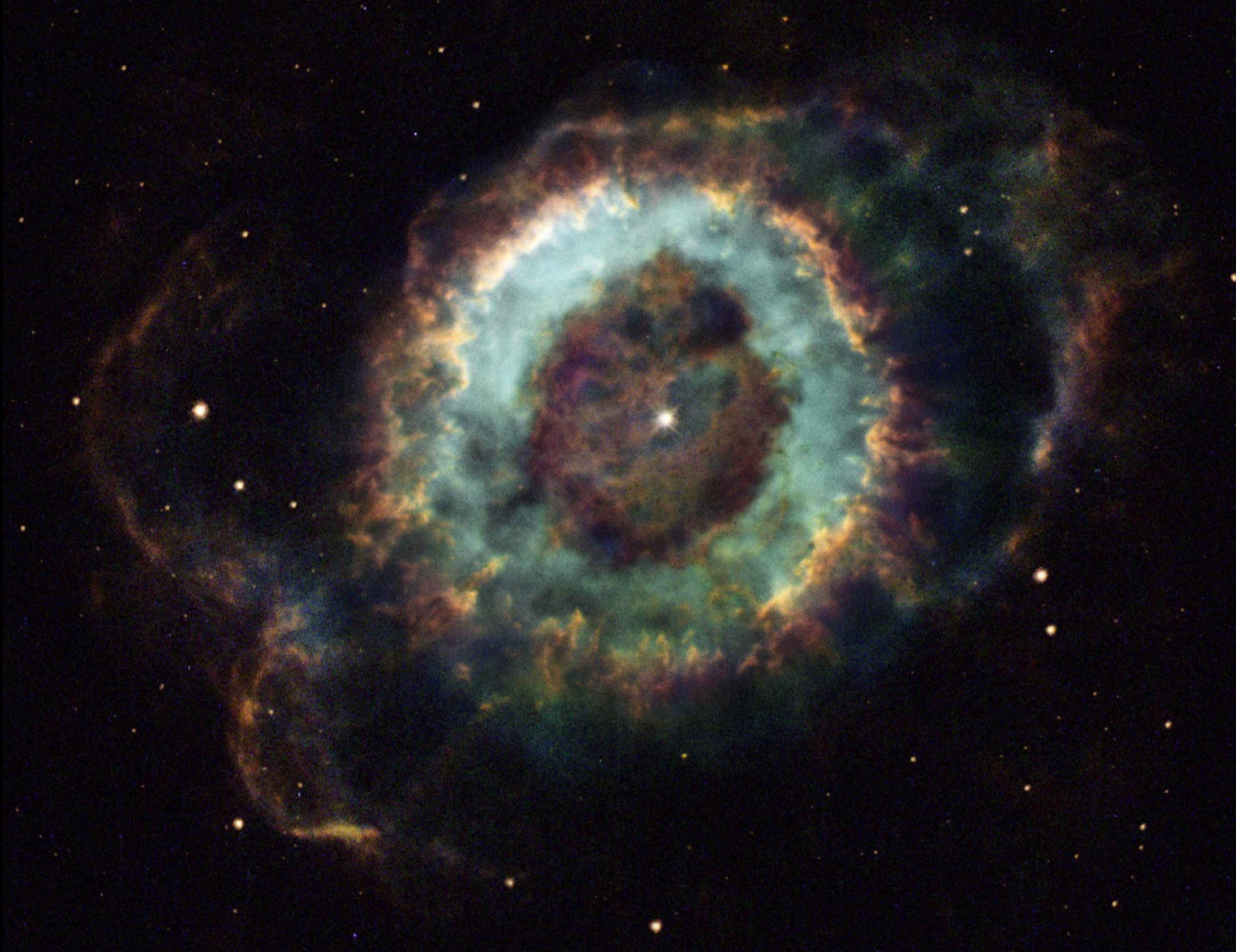


Hourglass Nebula · MyCn18 HST · WFPC2

PRC96-07 · ST ScI OPO · January 16, 1996
R. Sahai and J. Trauger (JPL), the WFPC2 Science Team and NASA

The blinking eye nebula

The Little Ghost nebula



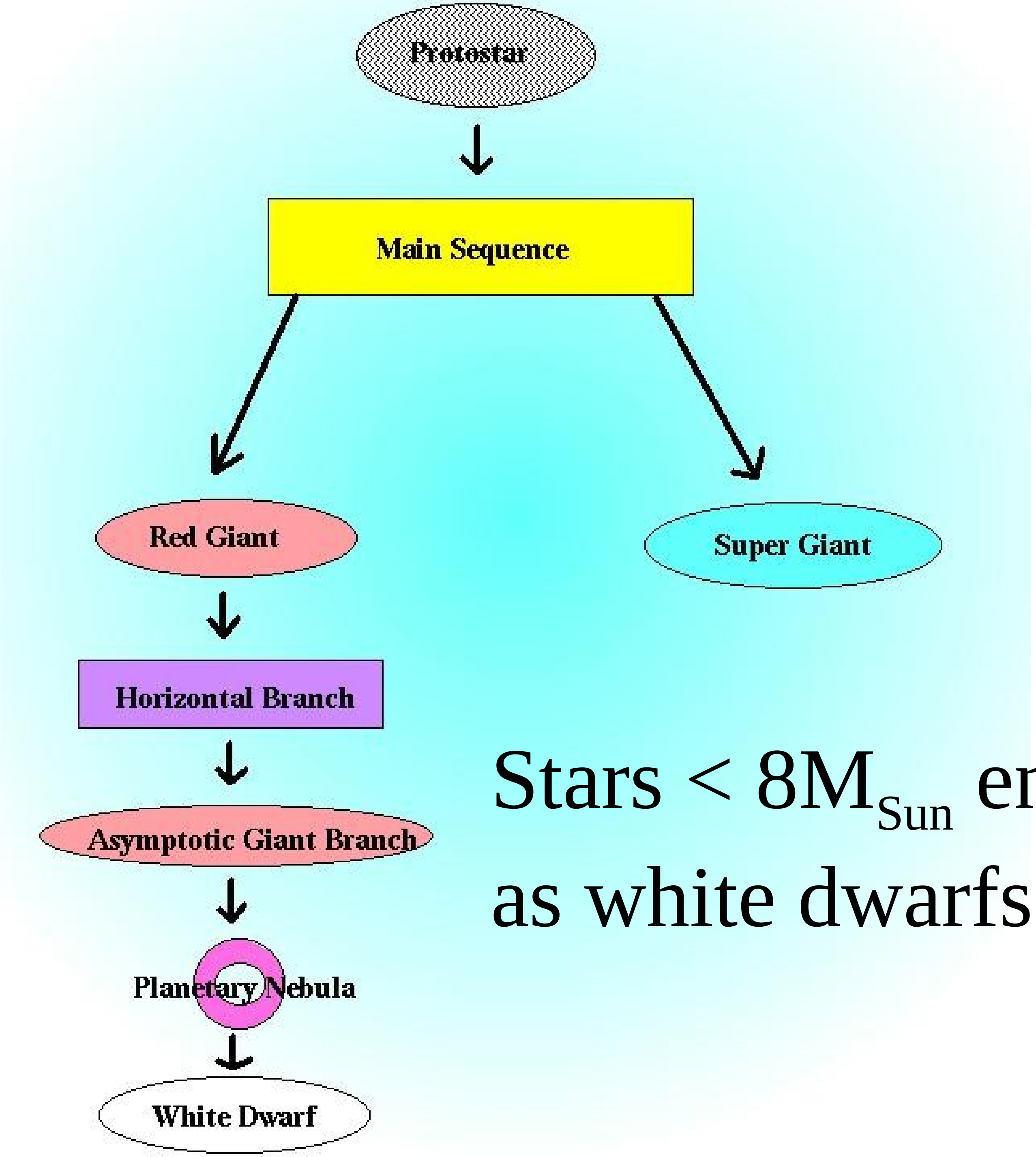
The Owl nebula

The cheeseburger nebula?

Enrichment

During He burning, spare neutrons react with other elements in the star to build up "heavier" elements (like Sr, Ba, and Pb)

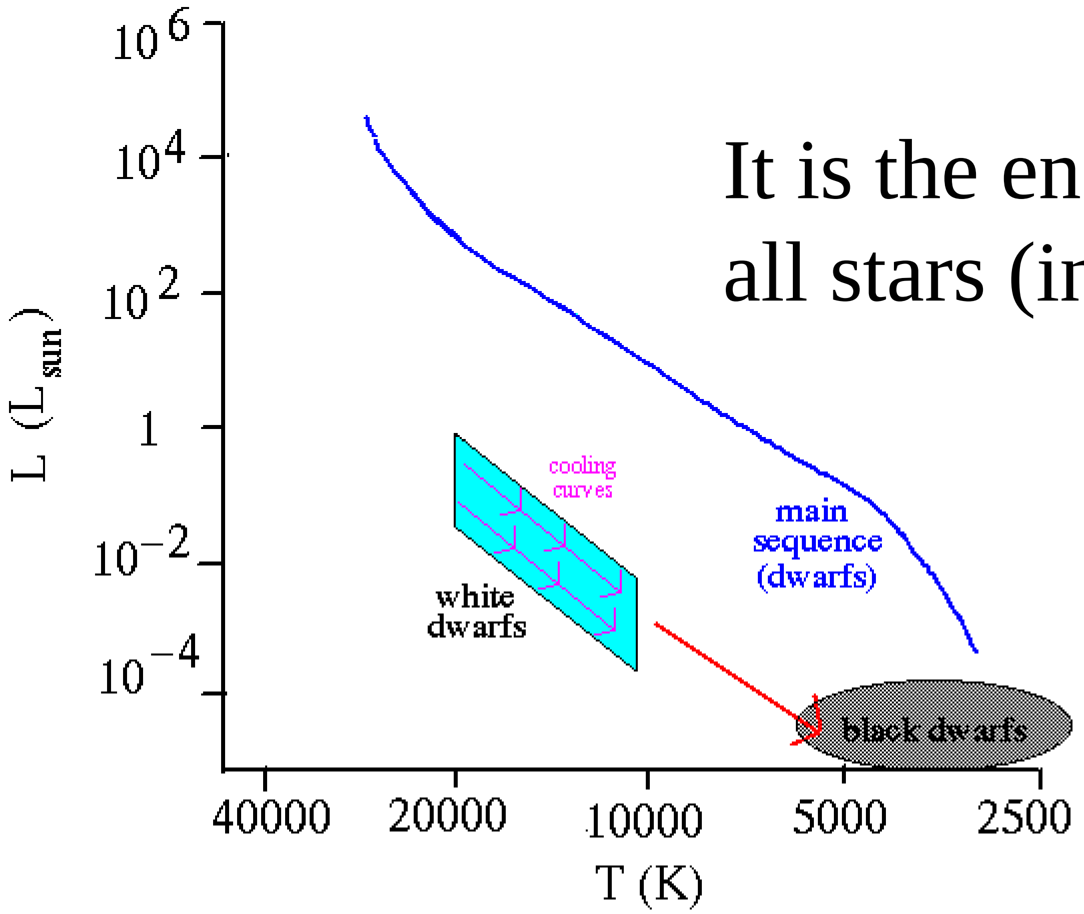
During the planetary nebula phase, these elements (along with the H and He) are put back into space for future generations of stars to use.



Stars < $8M_{Sun}$ end up as white dwarfs.

Once the envelope is expelled back into space, all that is left is the core: now called a White Dwarf

White dwarfs are stars that are doing nothing but cooling (and shrinking a little bit)



It is the end state of 98% of all stars (including our Sun)

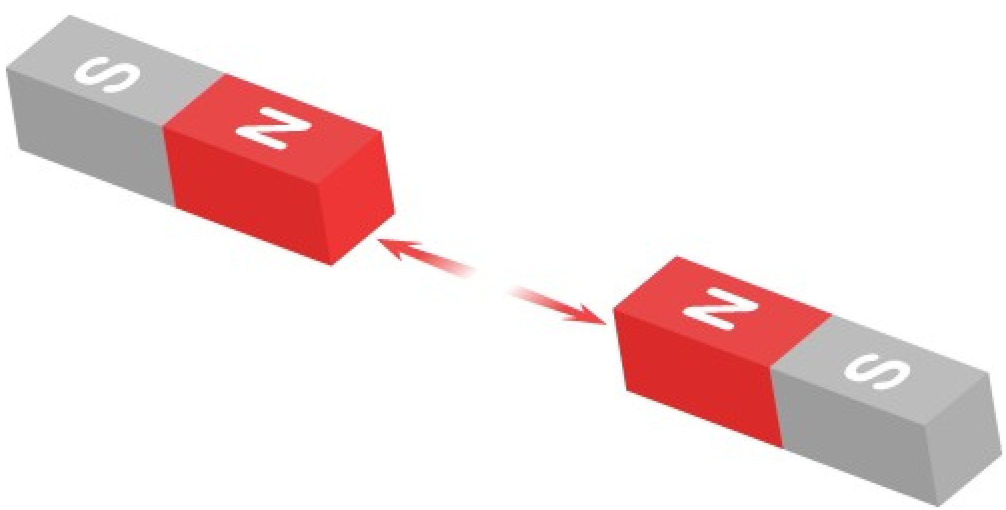
White dwarfs

- White dwarfs are supported by electron degeneracy pressure: their electrons are pushed so tightly together, that they can't get any closer together or they will merge with protons in the nuclei.

- More massive white dwarfs are smaller.

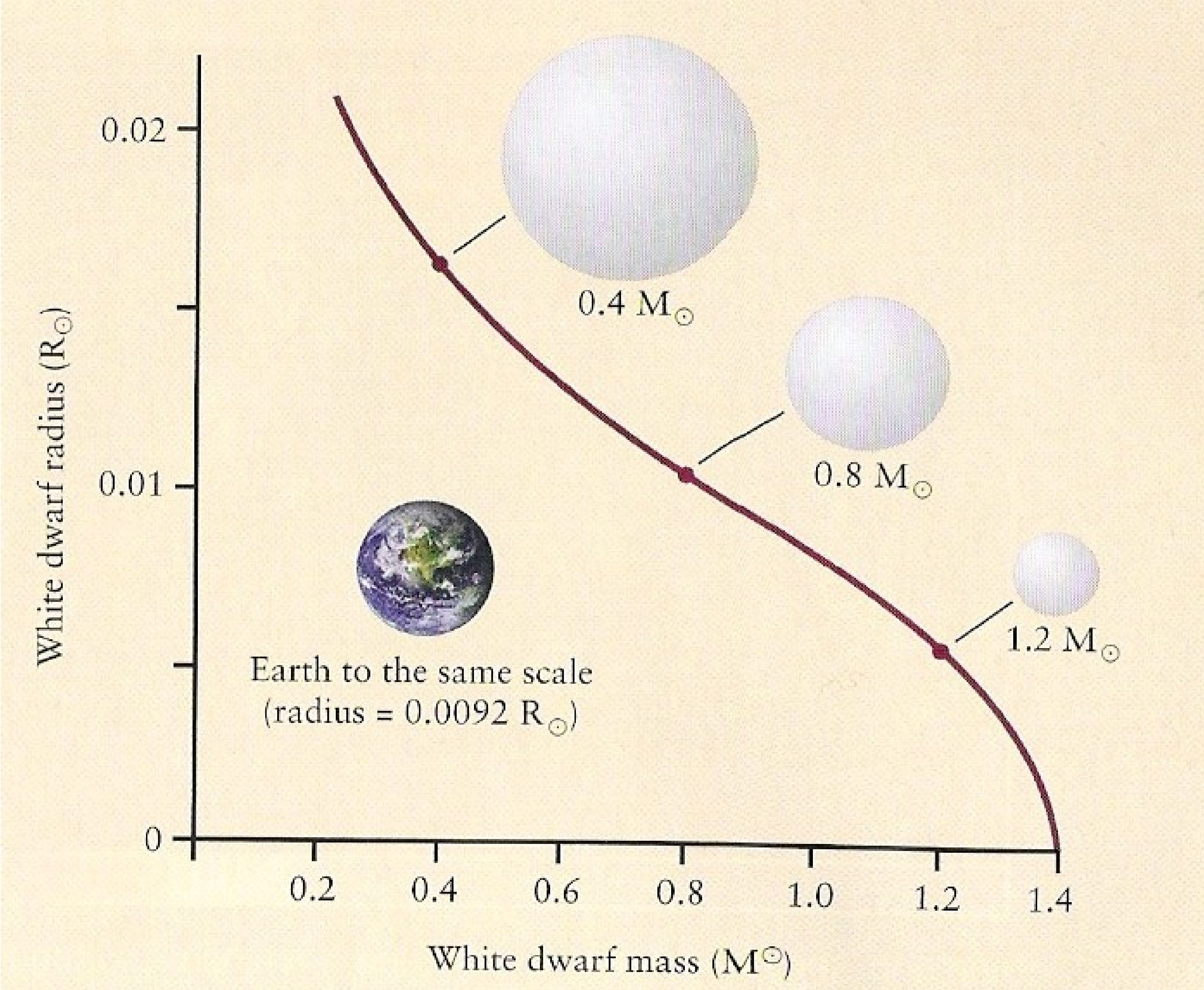
The weight on top pushes the atoms closer together, making the star smaller.

Just like trying to push the same end of 2 magnets together, the closer they get, the harder it is to push.



White dwarfs

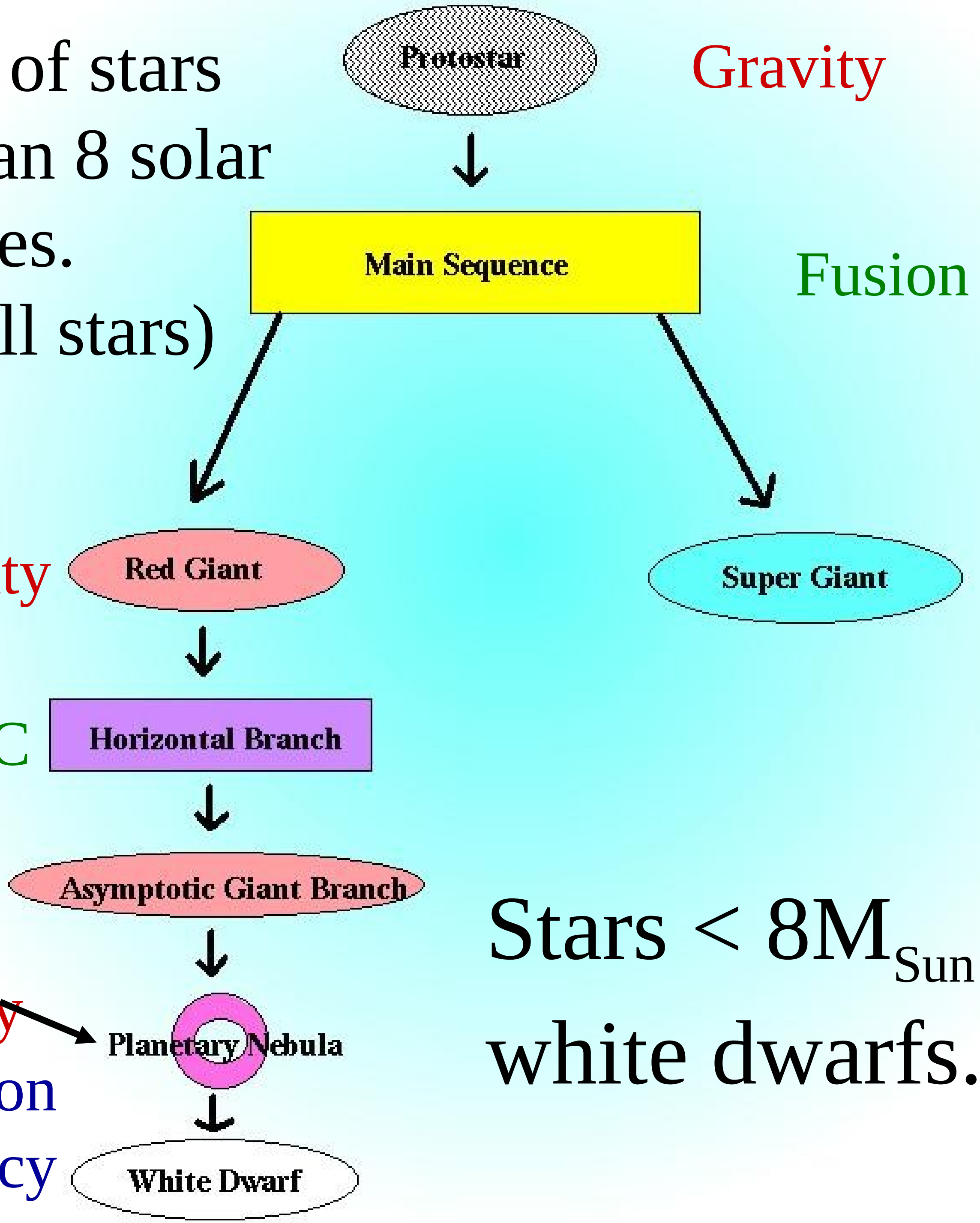
- White Dwarfs are about the size of the Earth. But with 60% the mass of our Sun


0.02
0.01
0
White dwarf radius (R⊙)
0.4 M⊙
0.8 M⊙
1.2 M⊙
Earth to the same scale
(radius = 0.0092 R⊙)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
White dwarf mass (M⊙)

White dwarfs

- Density: about one million g/cc! One teaspoon of white dwarf has as much matter as an entire baseball team!

Evolution of stars with less than 8 solar masses.
(98% of all stars)



Gravity

Fusion H to He

Gravity

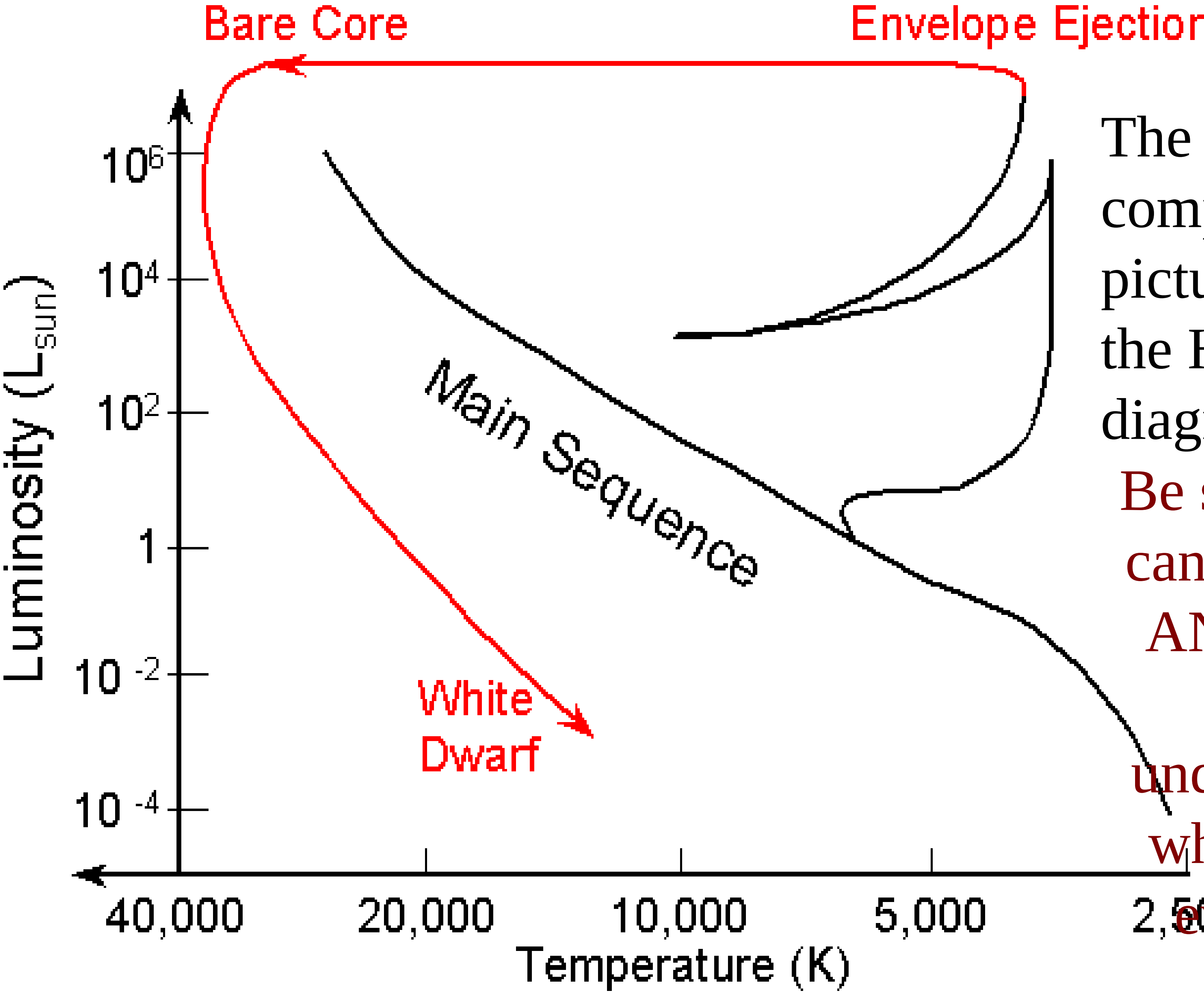
Fusion He to C

Gravity

Gravity

Electron degeneracy pressure.

Stars < $8M_{Sun}$ end up as white dwarfs.



The complete picture on the HR diagram.

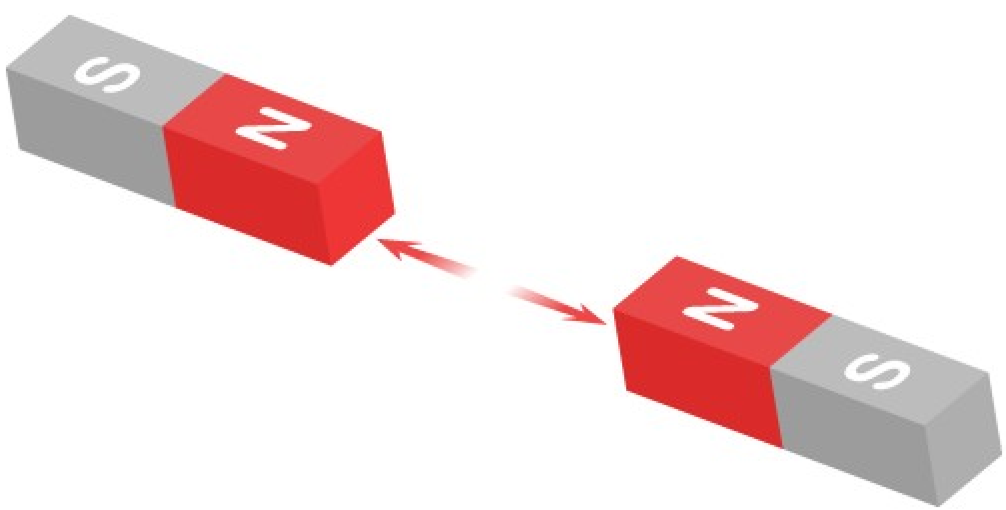
Be sure you can do this. AND that you understand why stars evolve.

White dwarfs

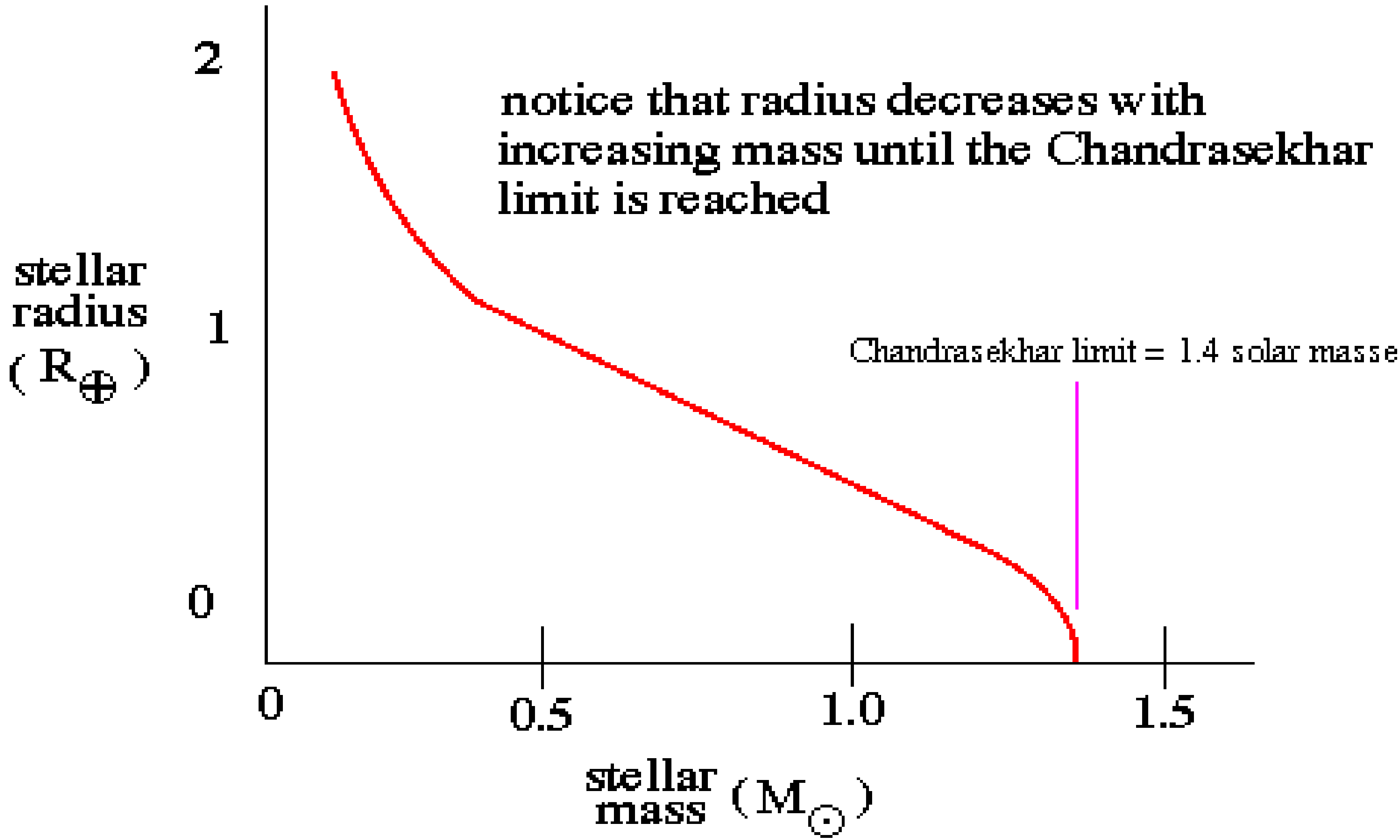
- More massive white dwarfs are smaller.
- But there's a limit: the Chandrasekhar limit of $1.4M_{Sun}$: no white dwarf can have more mass than about one and half of our Suns.

Just like trying to push the same end of 2 magnets together, the closer they get, the harder it is to push.

However, if you push hard enough, you can get them to touch!



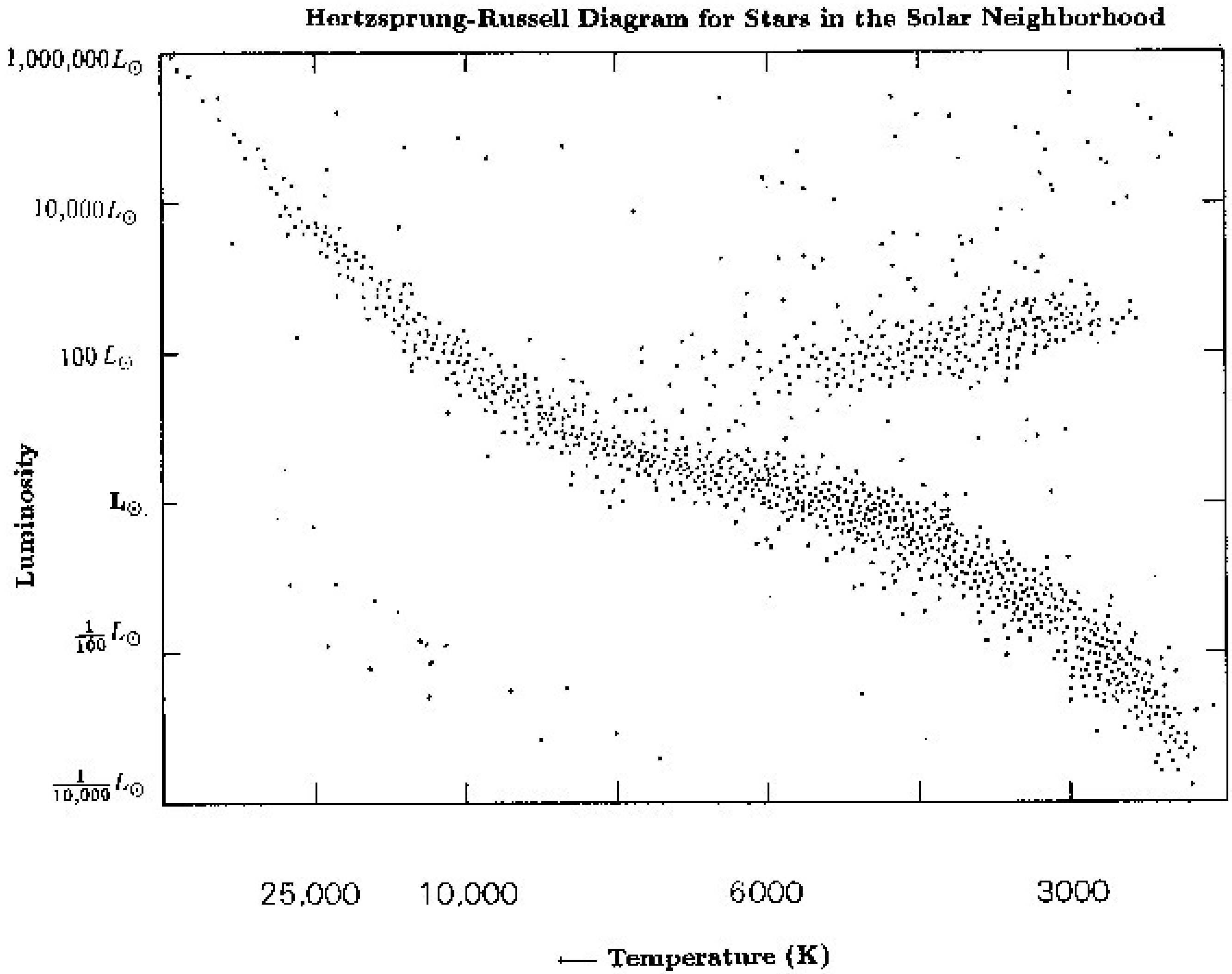
Mass–Radius Relation for White Dwarfs



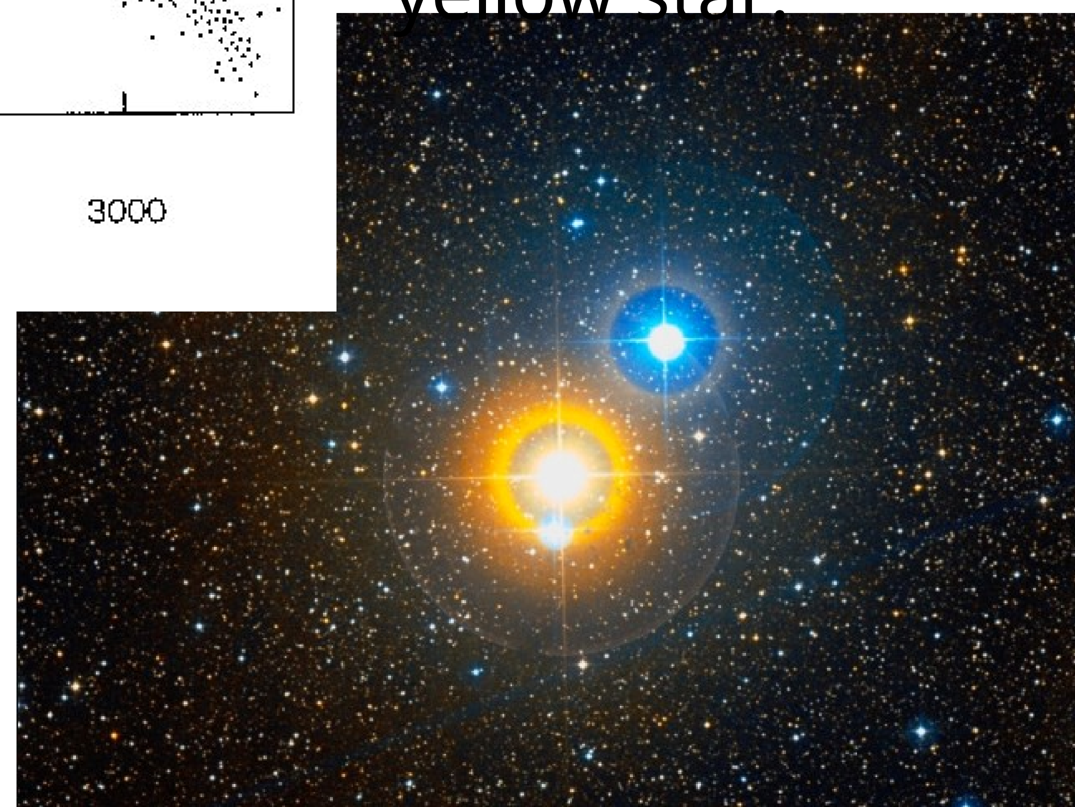
So what?

Any star <8 solar masses will become a white dwarf. They might be near 1.4 solar masses, but always below it.

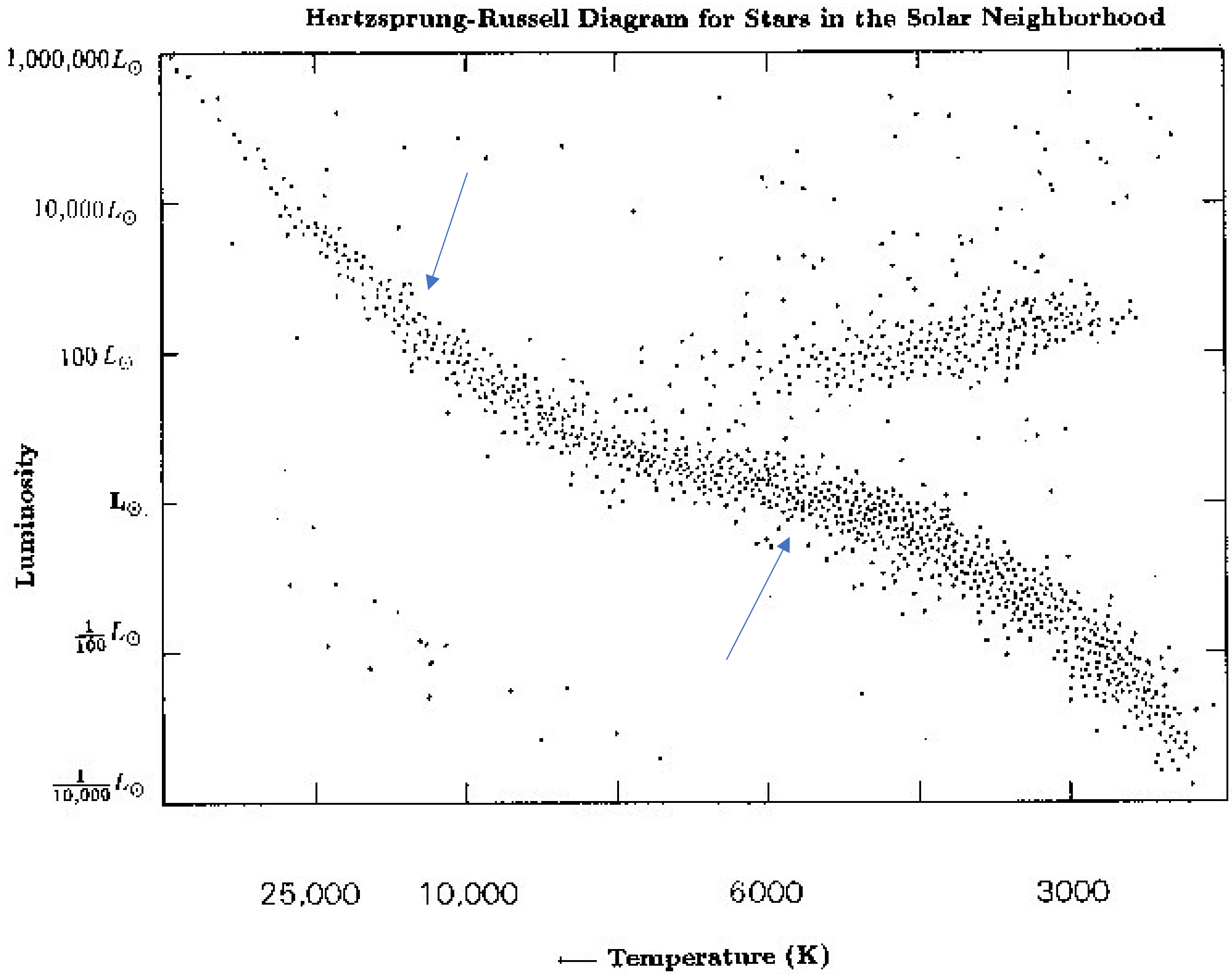
So why does the Chandrasekhar limit have any meaning?



If you have a blue and yellow star on the main sequence, you know that the blue star is hotter than the yellow star.



Many stars are in binary or multiple star systems.



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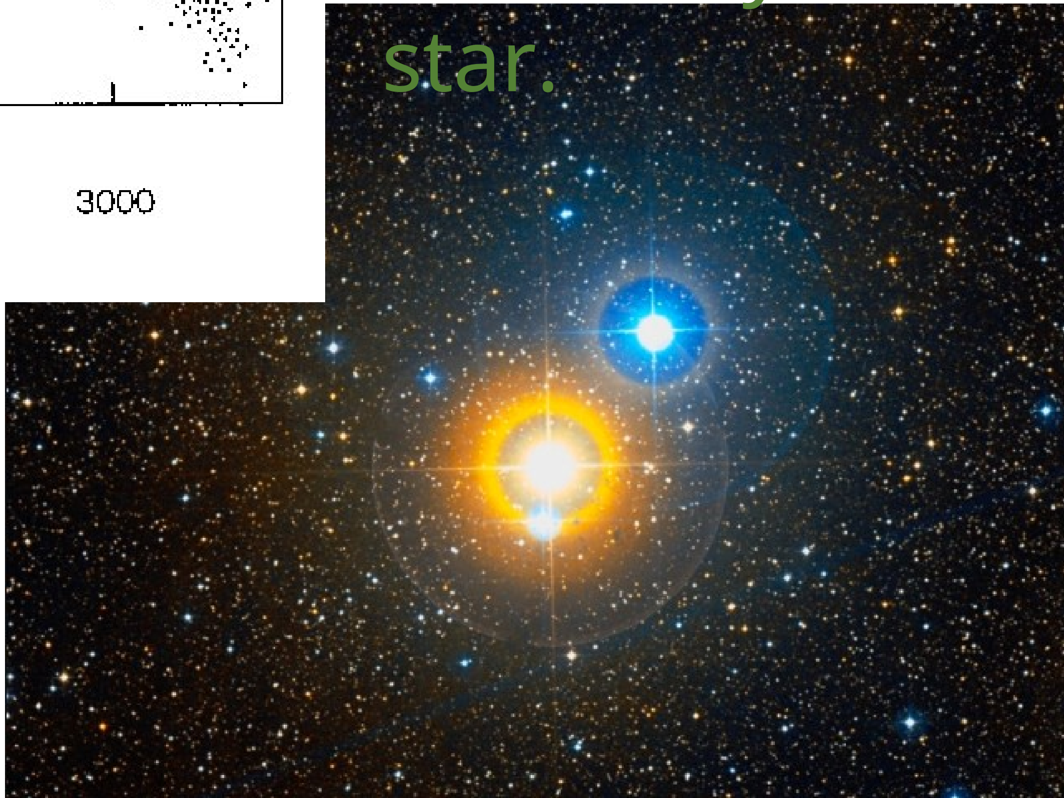
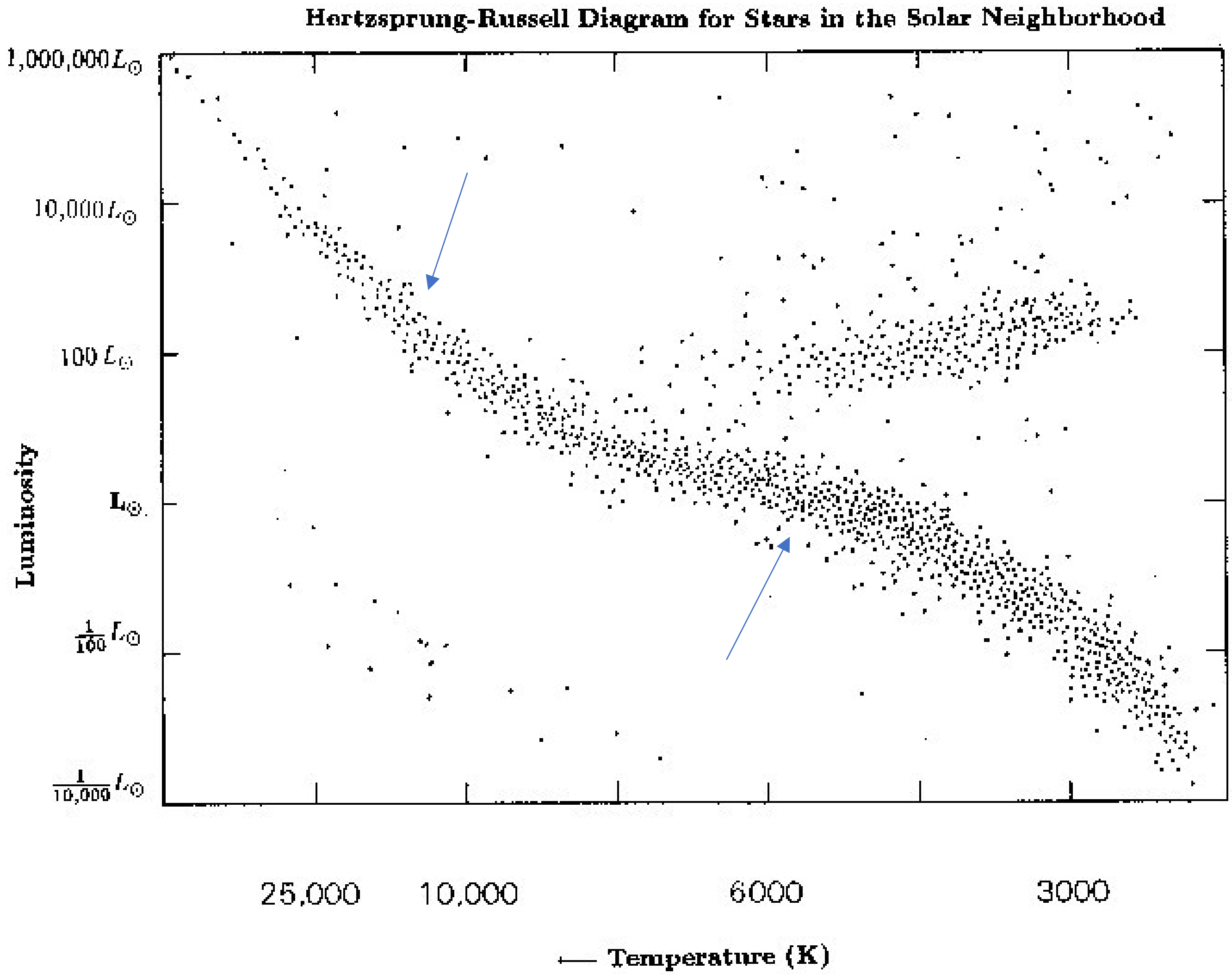
That means the blue star is more massive than the yellow star.





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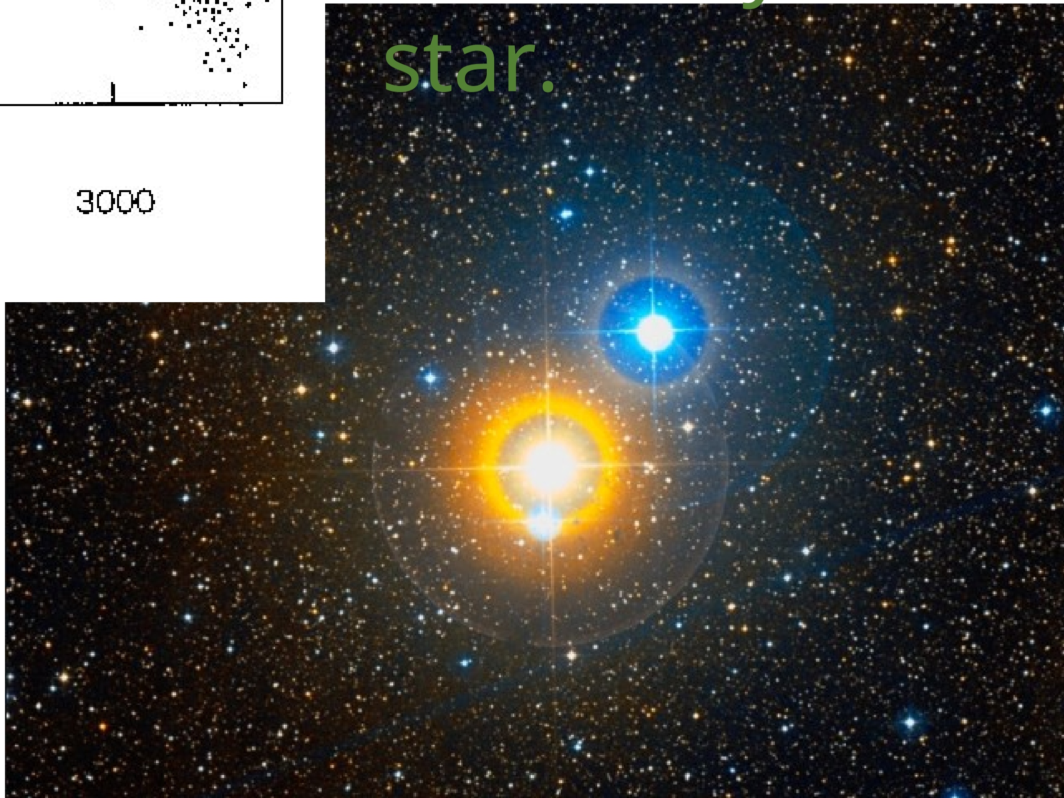
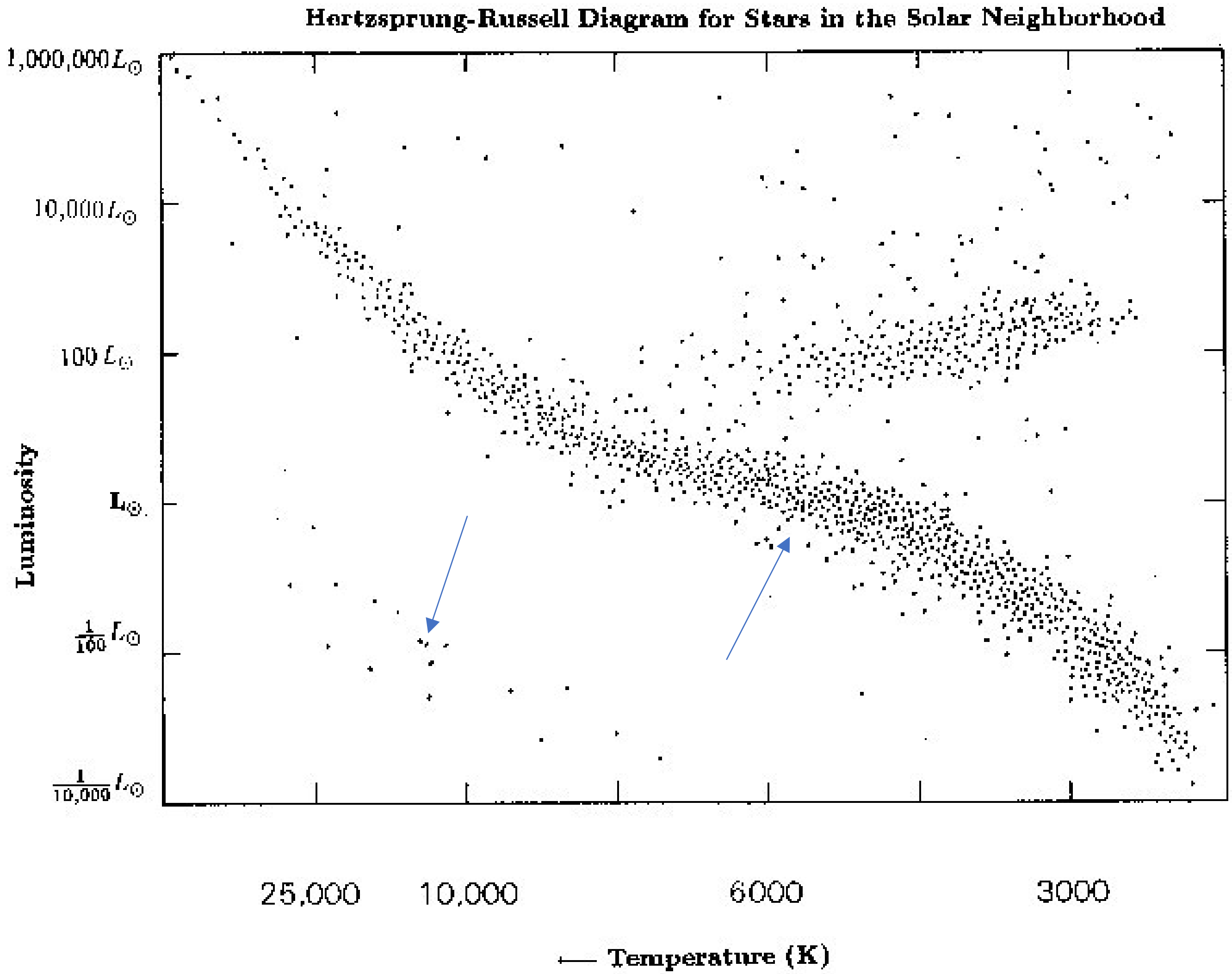


More massive stars evolve faster.



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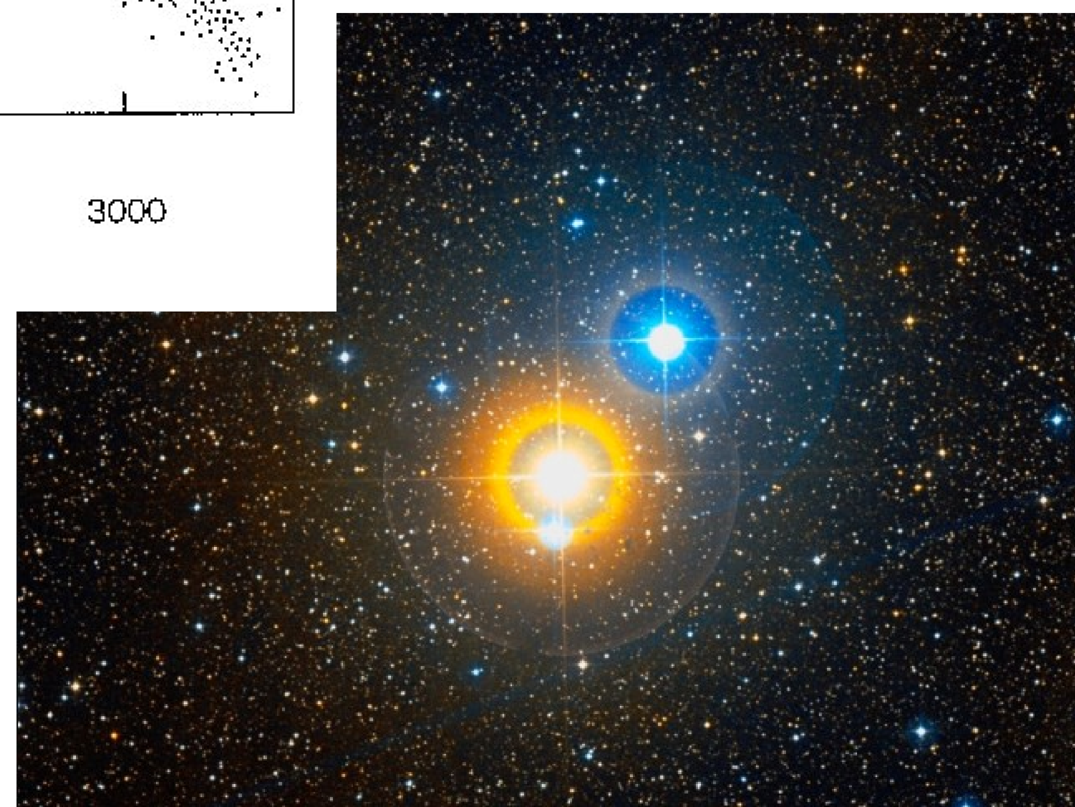
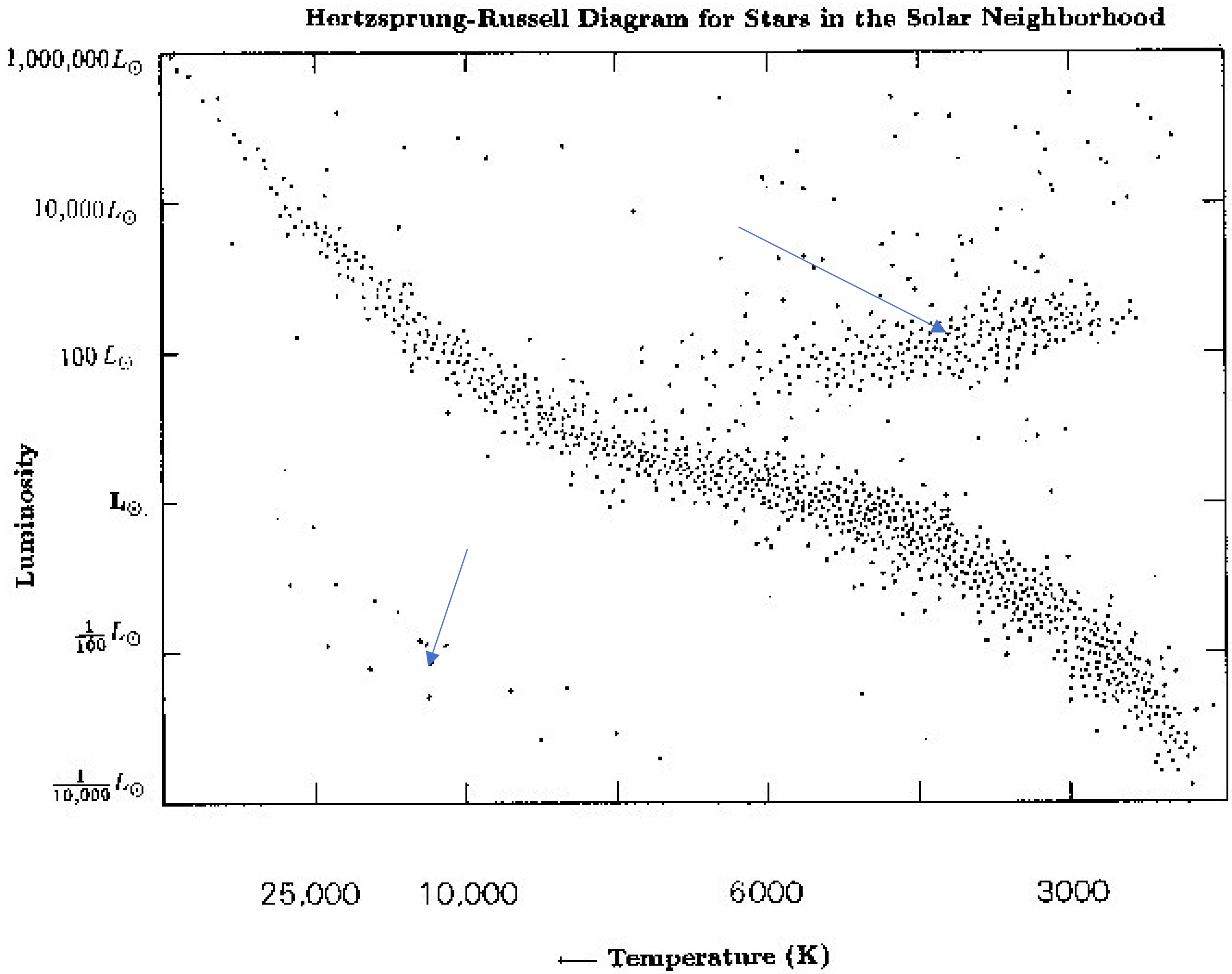
More massive stars evolve faster.

So the blue star evolves and becomes a white dwarf while the yellow star is still on the main sequence





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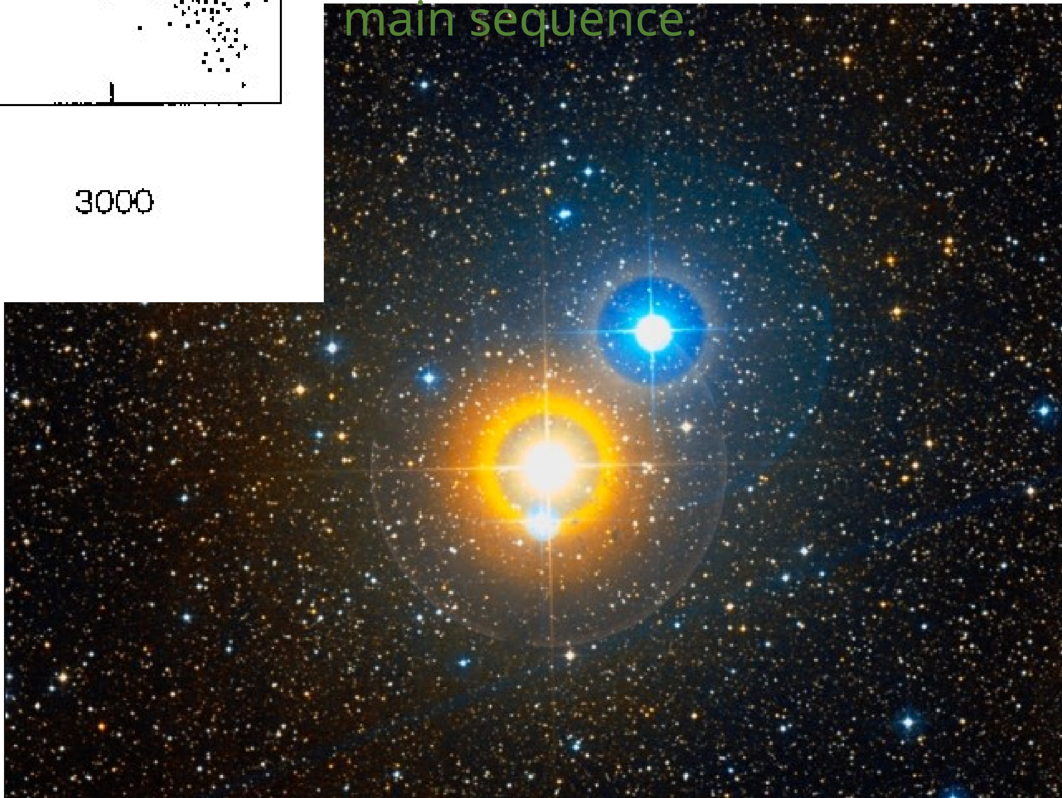
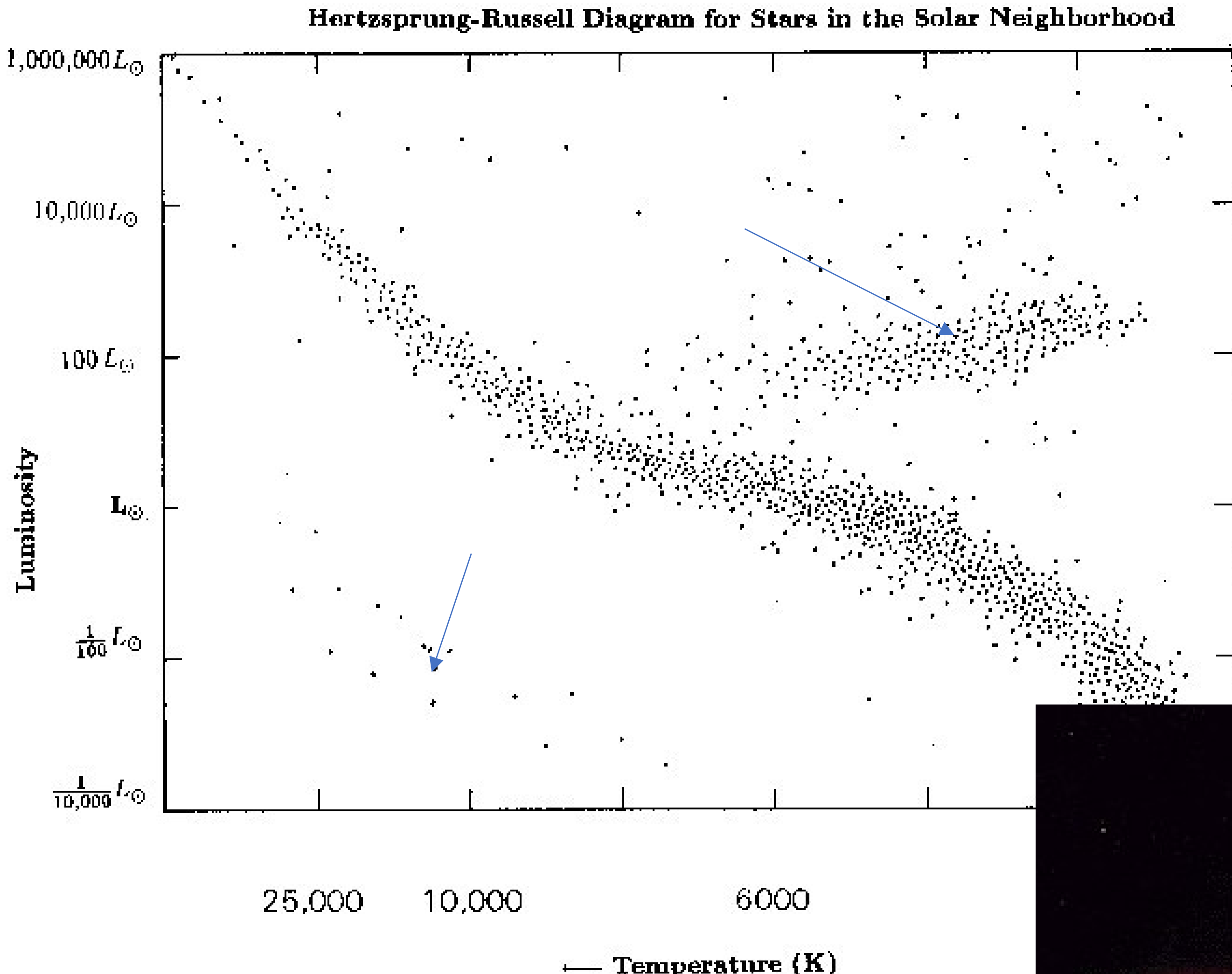


Then the yellow star expands into a red giant.



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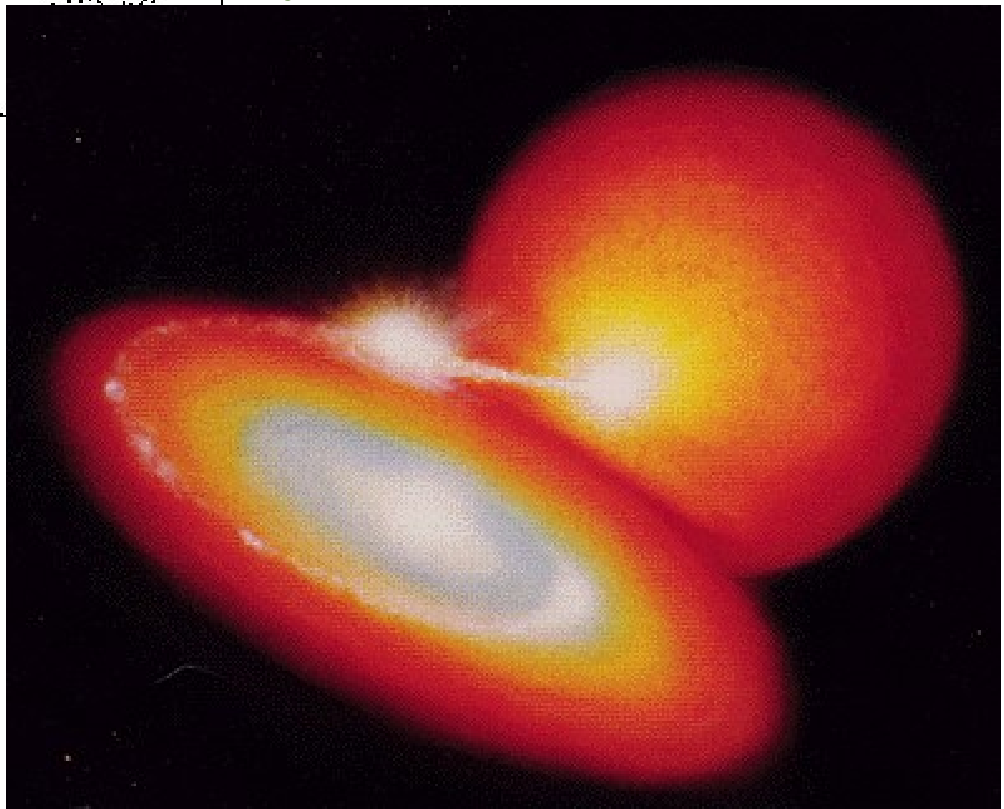


Then the yellow star expands into a red giant.
Now the white dwarf's gravity can take material from the companion.

White dwarfs that are in binaries can actually take mass from their companions.

It can then exceed the Chandrasekhar limit

So what happens if a white dwarf exceeds the Chandrasekhar limit?

It Explodes!

They Explode!

When they exceed the Chandrasehkar limit, they collapse. This causes them to heat up.
Then their degenerate carbon cores begin runaway C fusion.
This happens so drastically that they become supernovas (exploding stars).

Our Sun

Our Sun is not in a binary, so it will **not explode.** It will become a normal white dwarf which will cool, roughly forever.

As the core cools, it will crystallize.

So what?

Our Sun

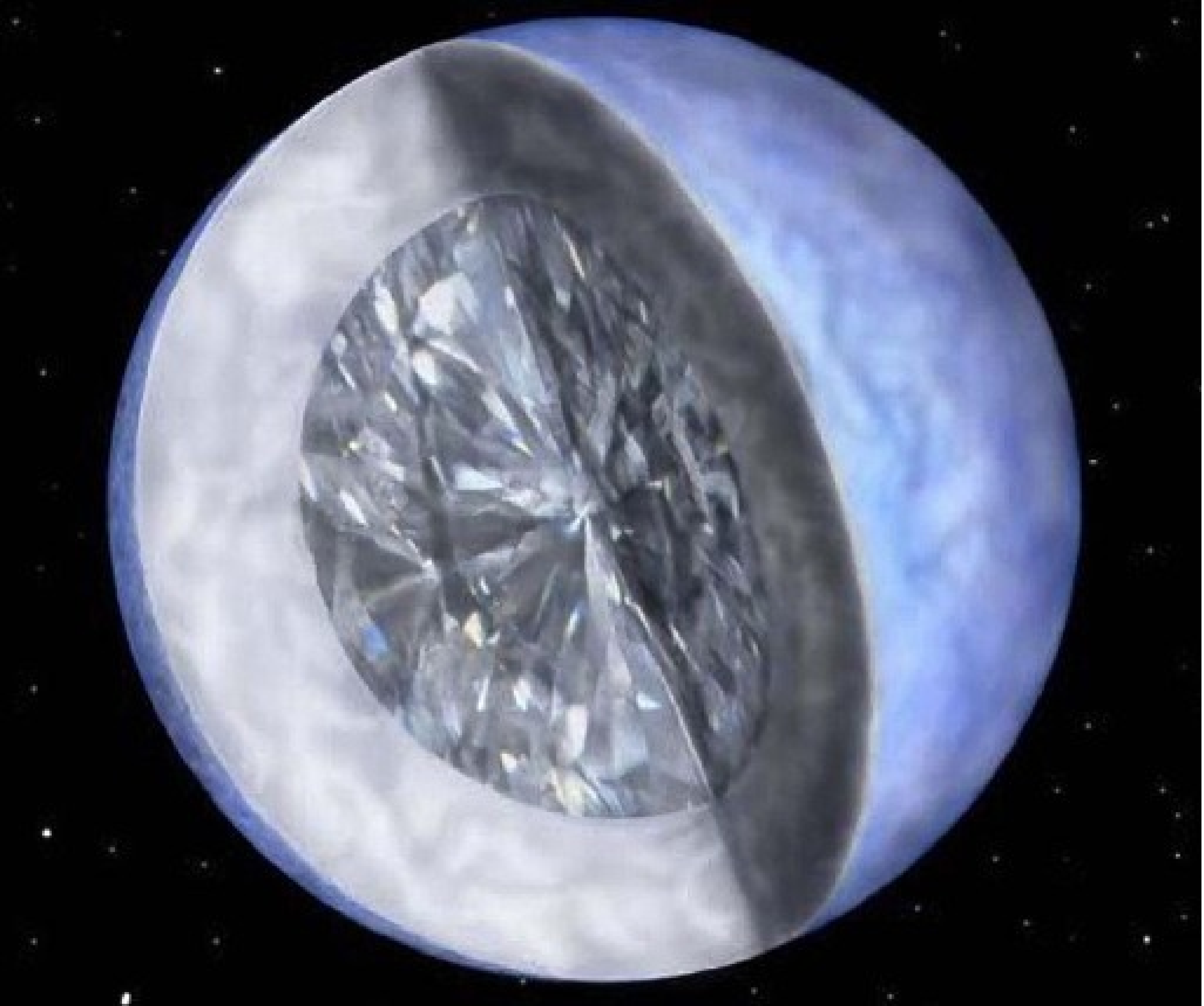
Our Sun is not in a binary, so it will **not explode.** It will become a normal white dwarf which will cool, roughly forever.

As the core cools, it will crystallize.

So what?

What is the core of our Sun made of at that point?

What is the special name for the crystallized form of that element?



Question

Which star evolves faster, a 2 solar mass star or a 4 solar mass star?

A) 2 solar mass star

B) 4 solar mass star.

C) They evolve at the same rate

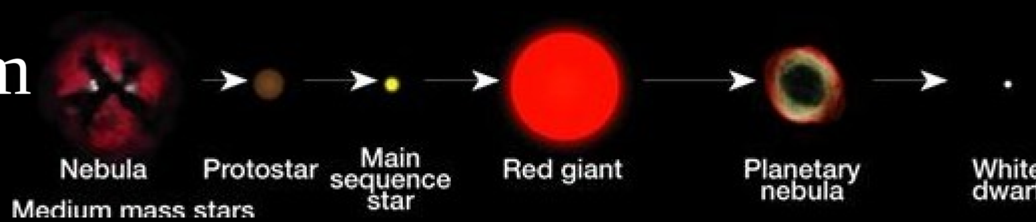
D) They don’t evolve at all.

For the rest of space....

why are the AGB and planetary nebula phases so important for the rest of space?

Chemical Enrichment

Our solar system
2% metals

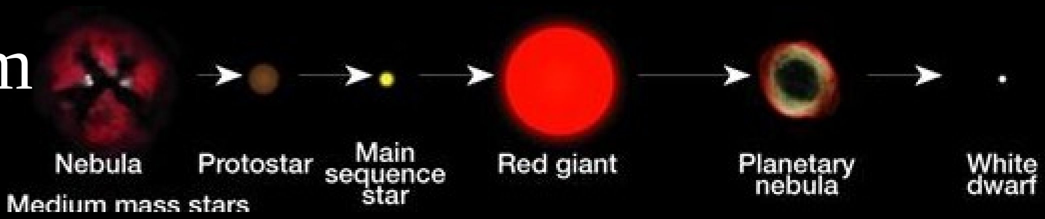


Planetary nebula
returns 3% metals

H and He are only slightly reduced

Chemical Enrichment

Our solar system
2% metals

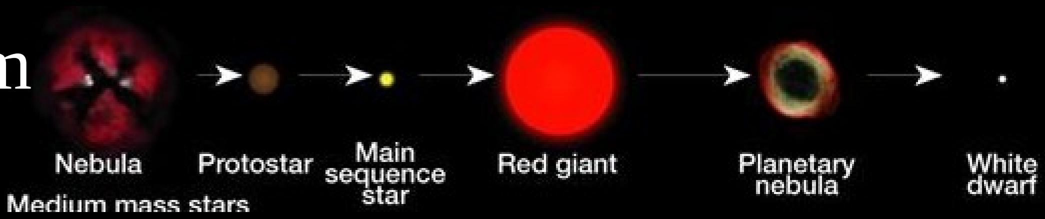


Planetary nebula
returns 3% metals

What about before our Sun?

Chemical Enrichment

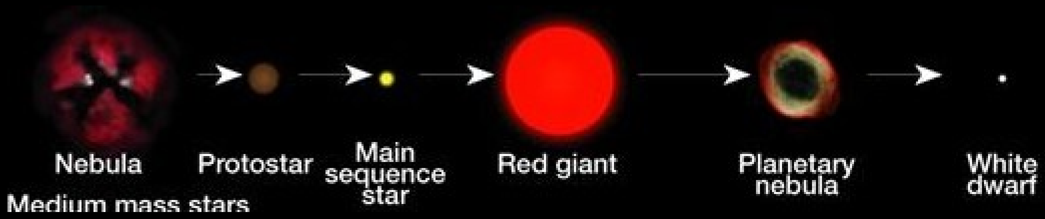
Our solar system
2% metals



Planetary nebula
returns 3% metals

Before our Sun?

Previous star:
1% metals

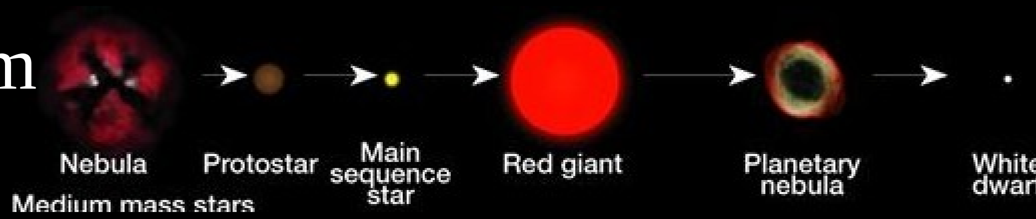


Planetary nebula
returns 2% metals

And before that?

Chemical Enrichment

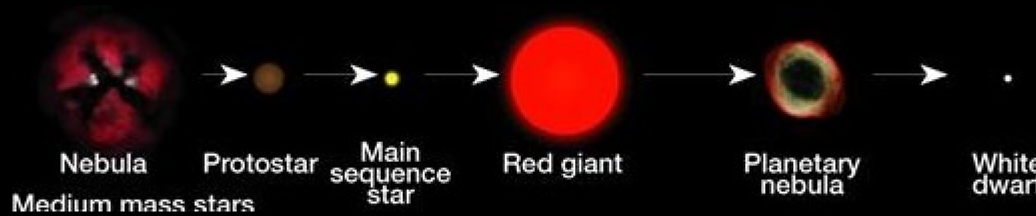
Our solar system
2% metals



Planetary nebula
returns 3% metals

Before our Sun?

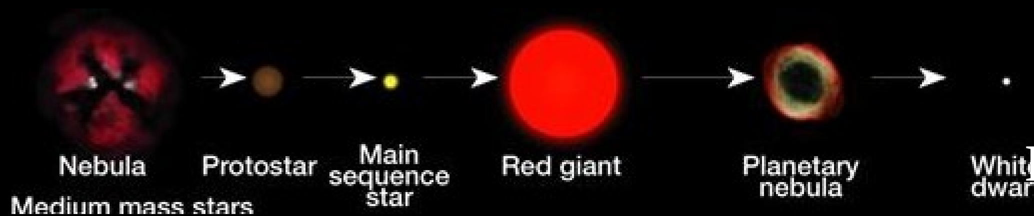
Previous star:
1% metals



Planetary nebula
returns 2% metals

And before that?

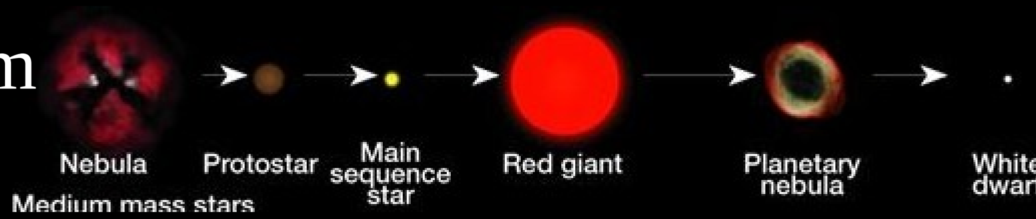
Previous star:
0.5% metals



Planetary nebula
returns 1% metals

If we just keep going back to previous generations of stars, what happens to the ‘metals’?

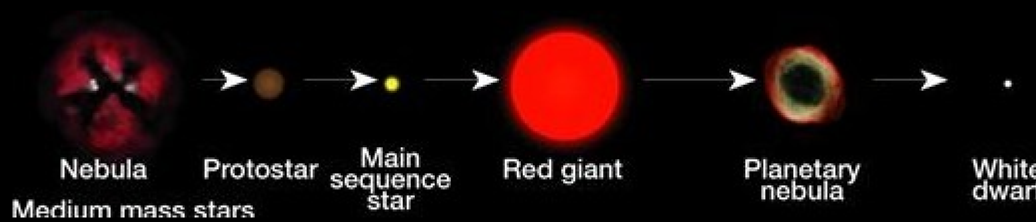
Our solar system
2% metals



Planetary nebula
returns 3% metals

Before our Sun?

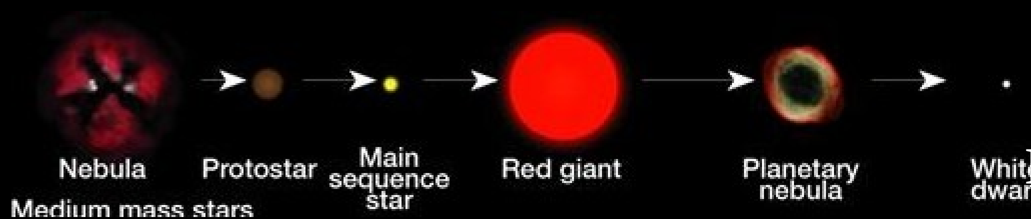
Previous star:
1% metals



Planetary nebula
returns 2% metals

And before that?

Previous star:
0.5% metals



Planetary nebula
returns 1% metals

Enrichment

Takeaway: low-mass stars can make elements up to Pb and this is recycled into the galaxy during the planetary nebula phase.

Evolution so far:

Protostars: energy from gravity

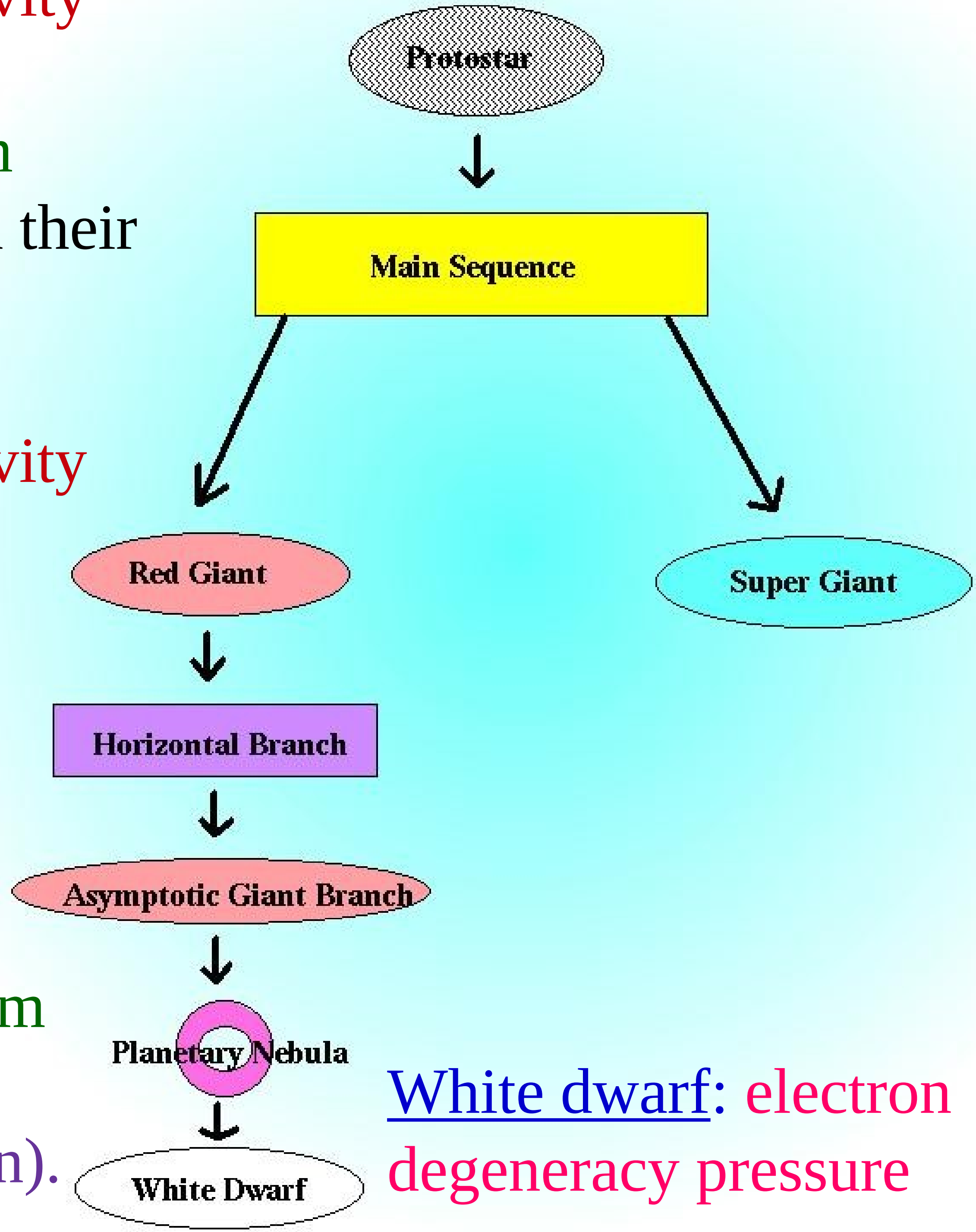
Main Sequence: energy from fusion converting H to He in their cores

Red giants: energy from gravity

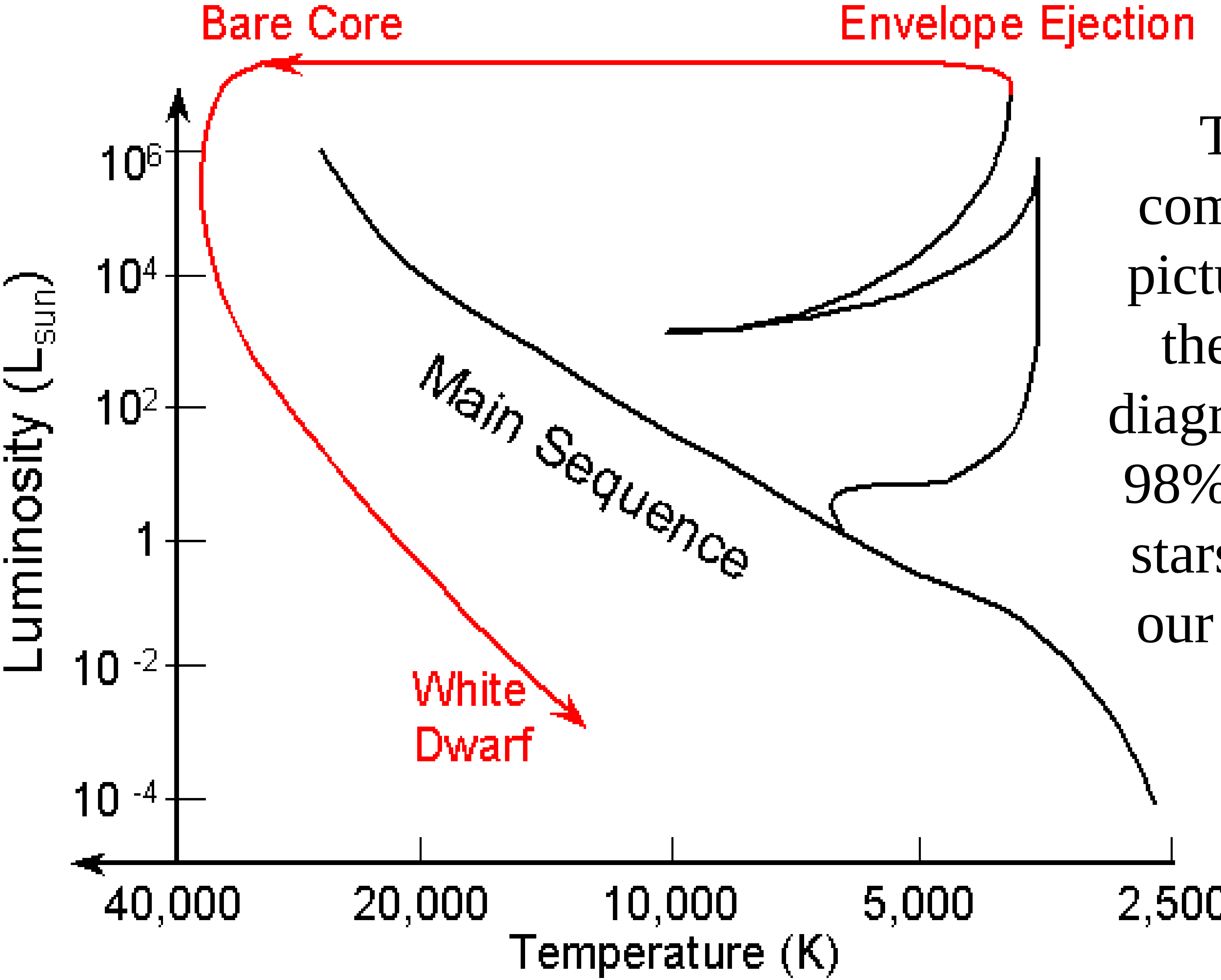
Horizontal branch: fusion of He to C

AGB: energy from gravity

Planetary nebula: energy from gravity and spasmodic shell He fusion (and shell H fusion).

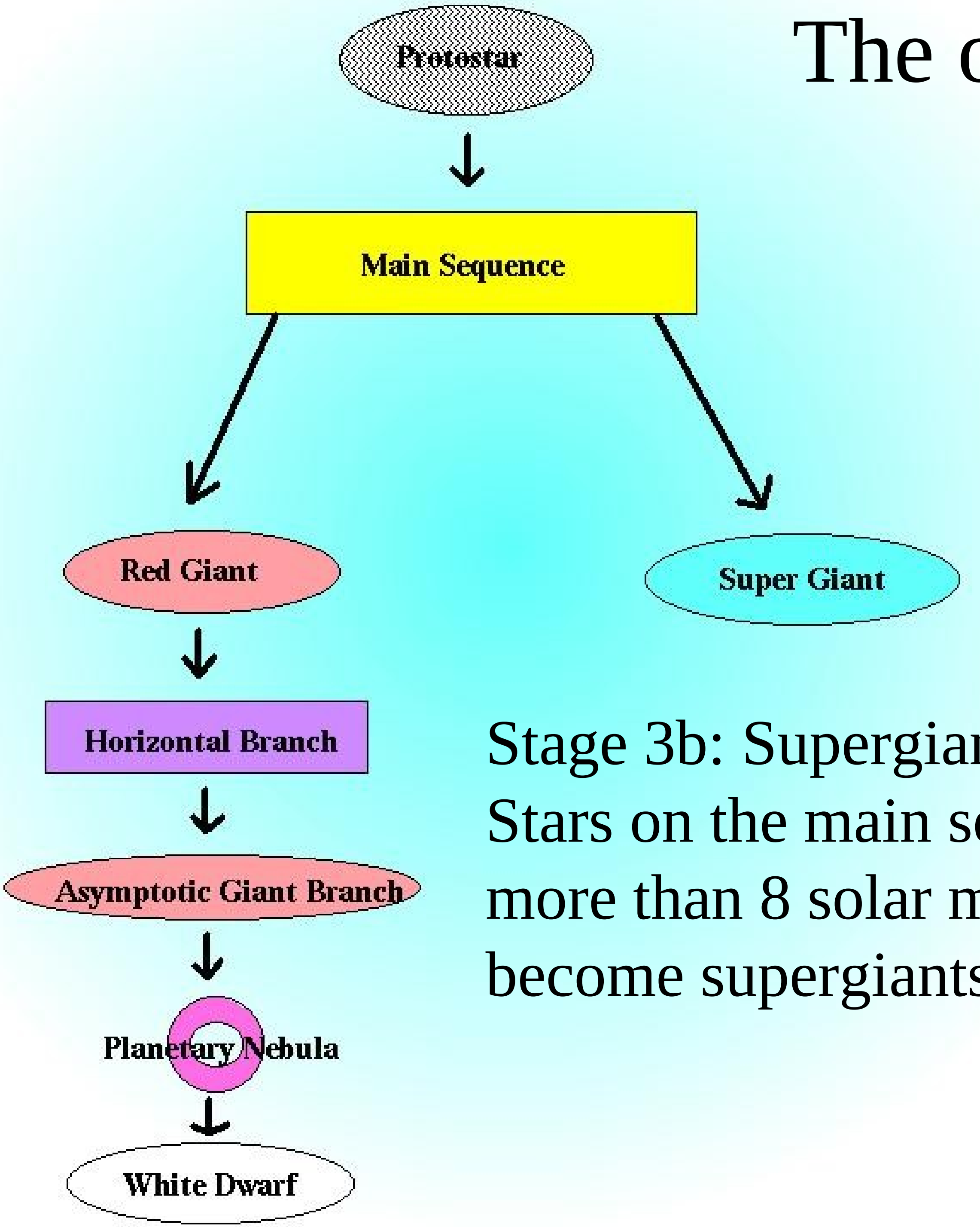


White dwarf: electron degeneracy pressure



The complete picture on the HR diagram for 98% of all stars (like our Sun).

The other side



Stage 3b: Supergiants.
Stars on the main sequence with more than 8 solar masses will become supergiants.