“I always wanted to be somebody. I should have been more specific.”

Lily Tomlin

HW3 and Quizzes 10 & 11 due Tuesday.

Test 2 will be on blackboard Monday & Tuesday, April 18-19.

Sample test will be posted next week.

Evolution so far:

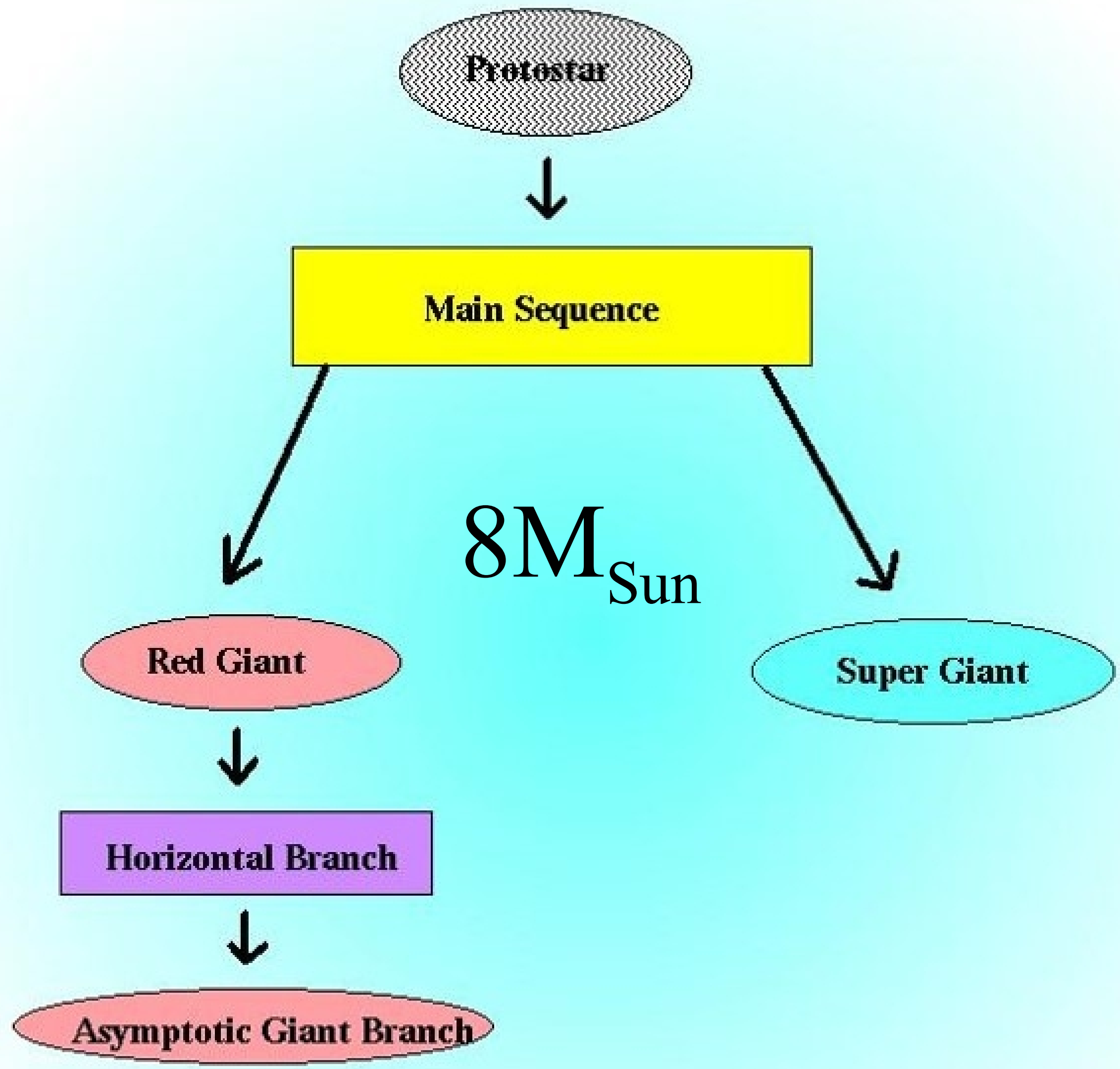
Protostars: Energy from **gravity** (shrinking)

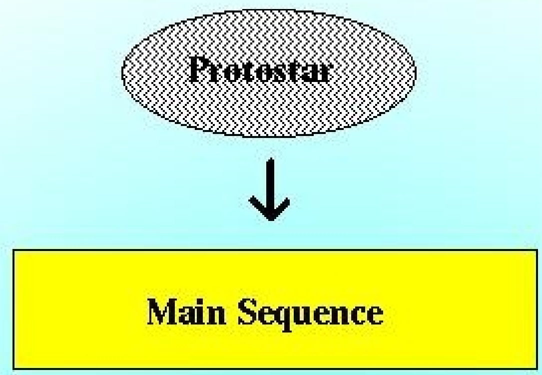
Main Sequence: Energy from **fusion** converting **H to He** in their cores

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

Horizontal branch: Fusion of He -> C

AGB: Energy from gravity

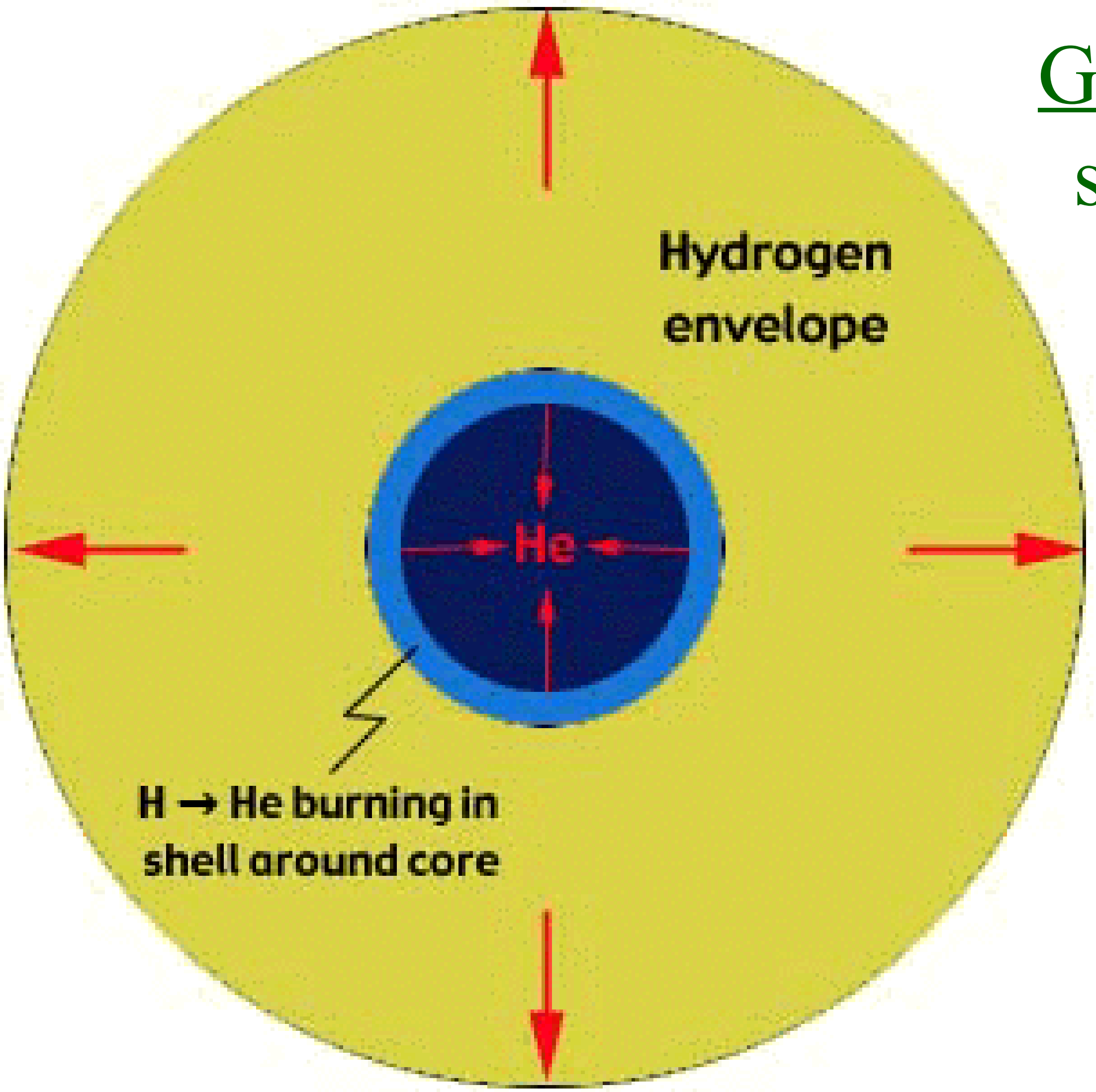




Stage 2: During the main sequence, stars convert H into He in their cores. We have relations for how bright they are and how long they spend on the main sequence

$$L_{\rm MS} = M^{3.5} = \sqrt{M} \times M \times M \times M \times M$$

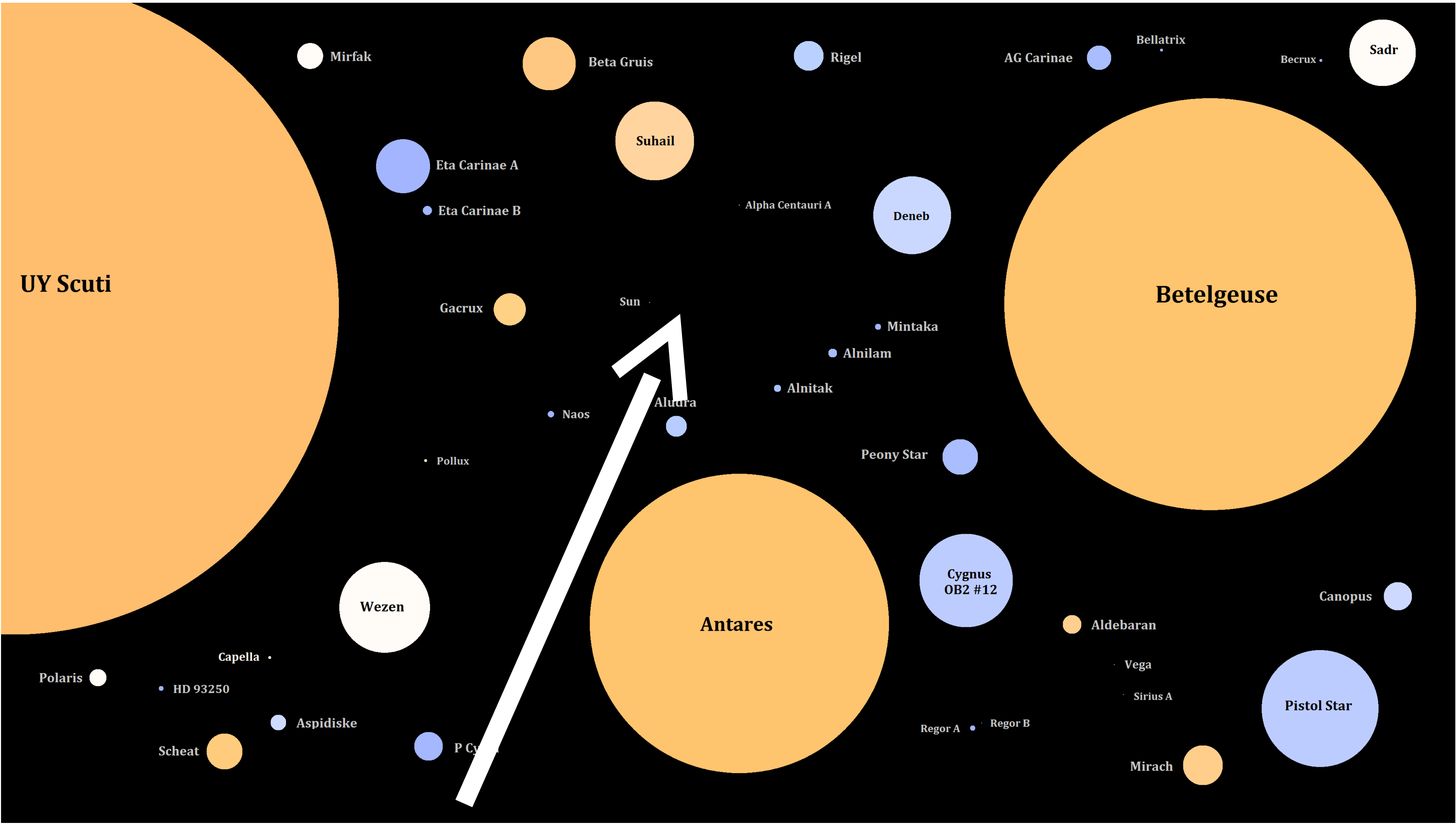
$$t_{\rm MS} = \frac{1 \times 10^{10}}{M^{2.5}} = \frac{1 \times 10^{10}}{\sqrt{M} \times M \times M \times M} \text{yrs}$$

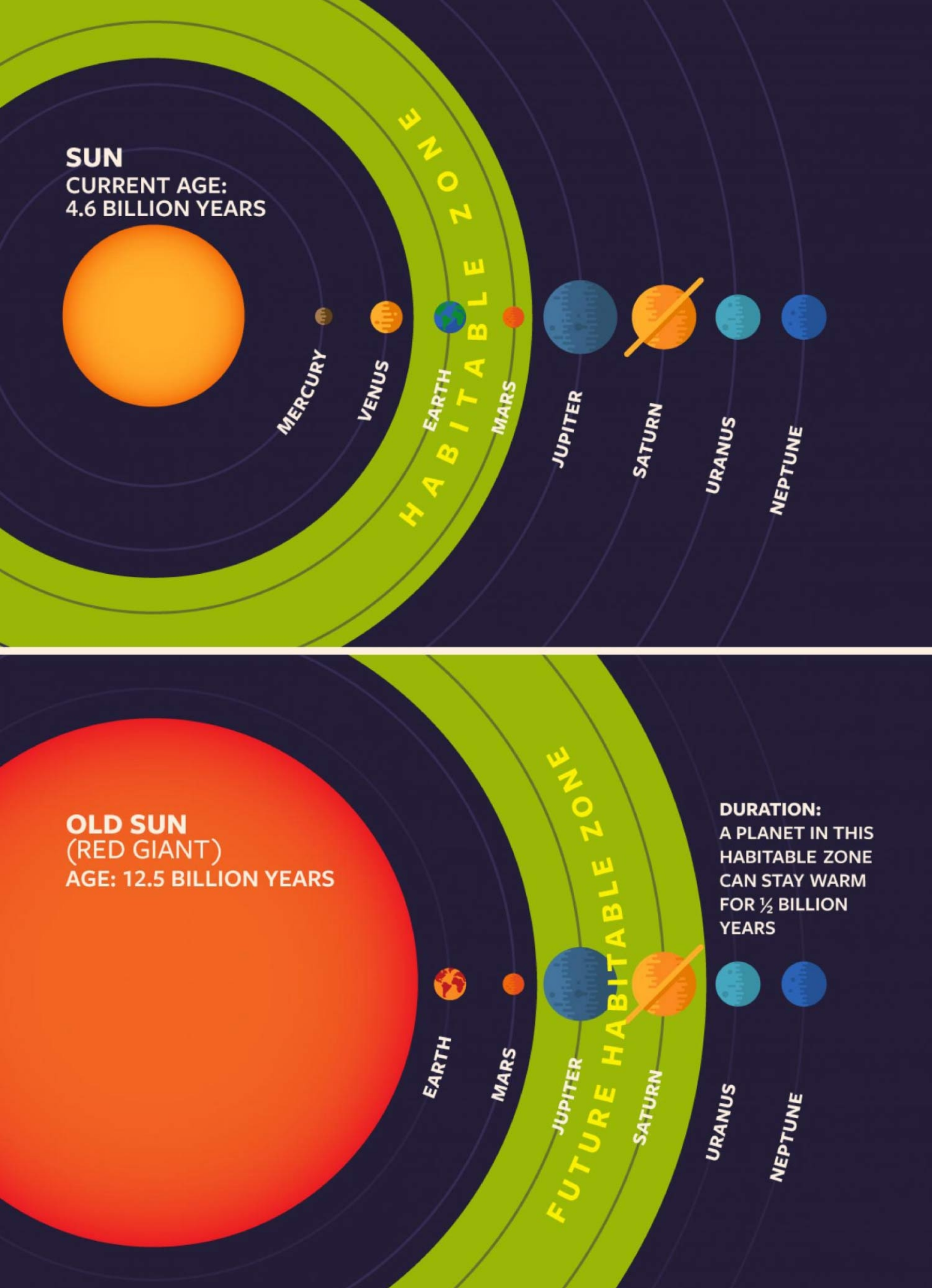


<u>Gravity</u> is again the source of heat for pressure against collapse.

During the Red Giant phase, the core is shrinking (and getting hotter) and the shell surrounding the core is expanding in reaction to the hotter core.

Giant stars are really giant!



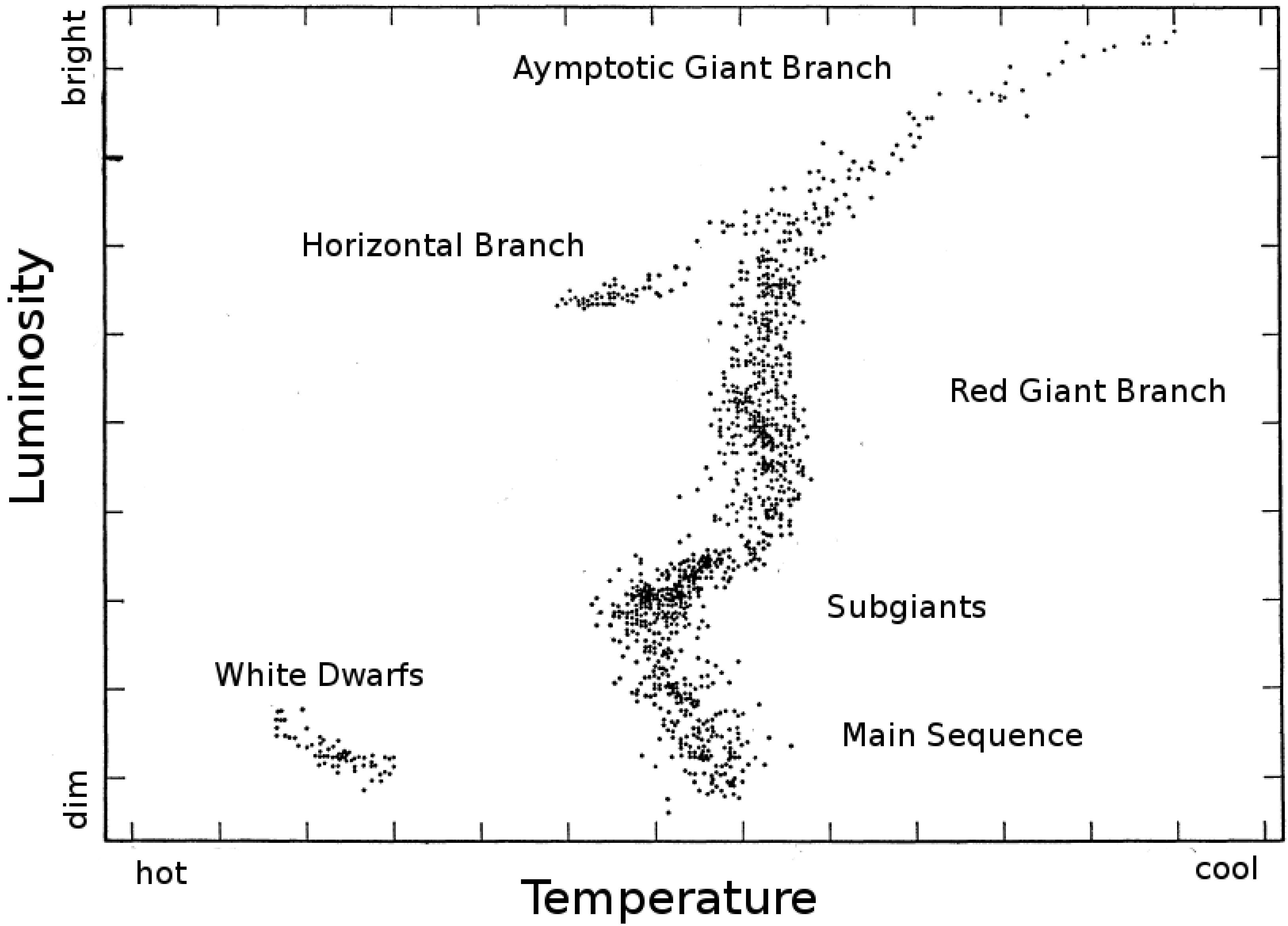


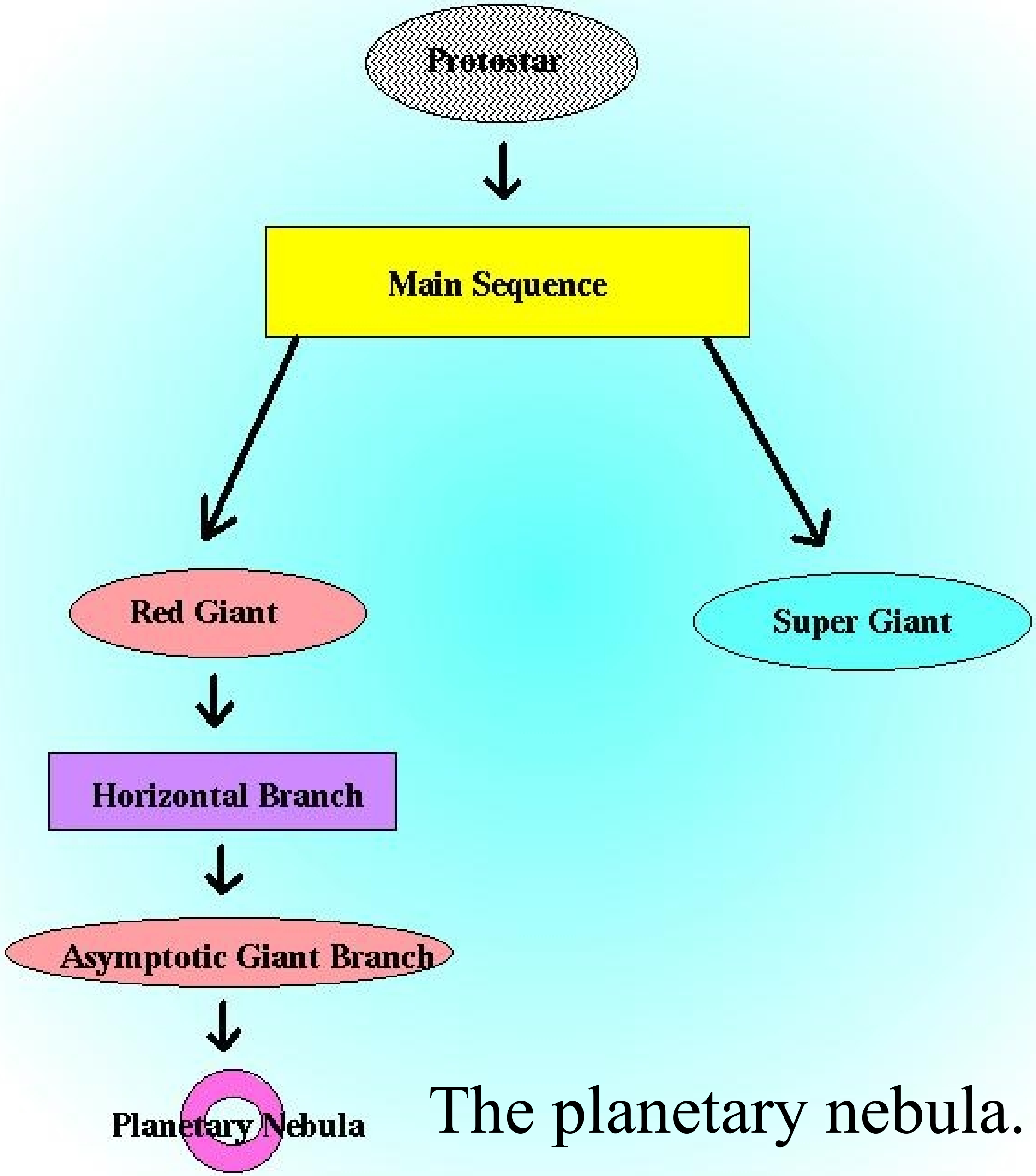
When our Sun becomes a red giant star, it will expand out to around Venus' orbit.

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

Image credit: sci-news.com

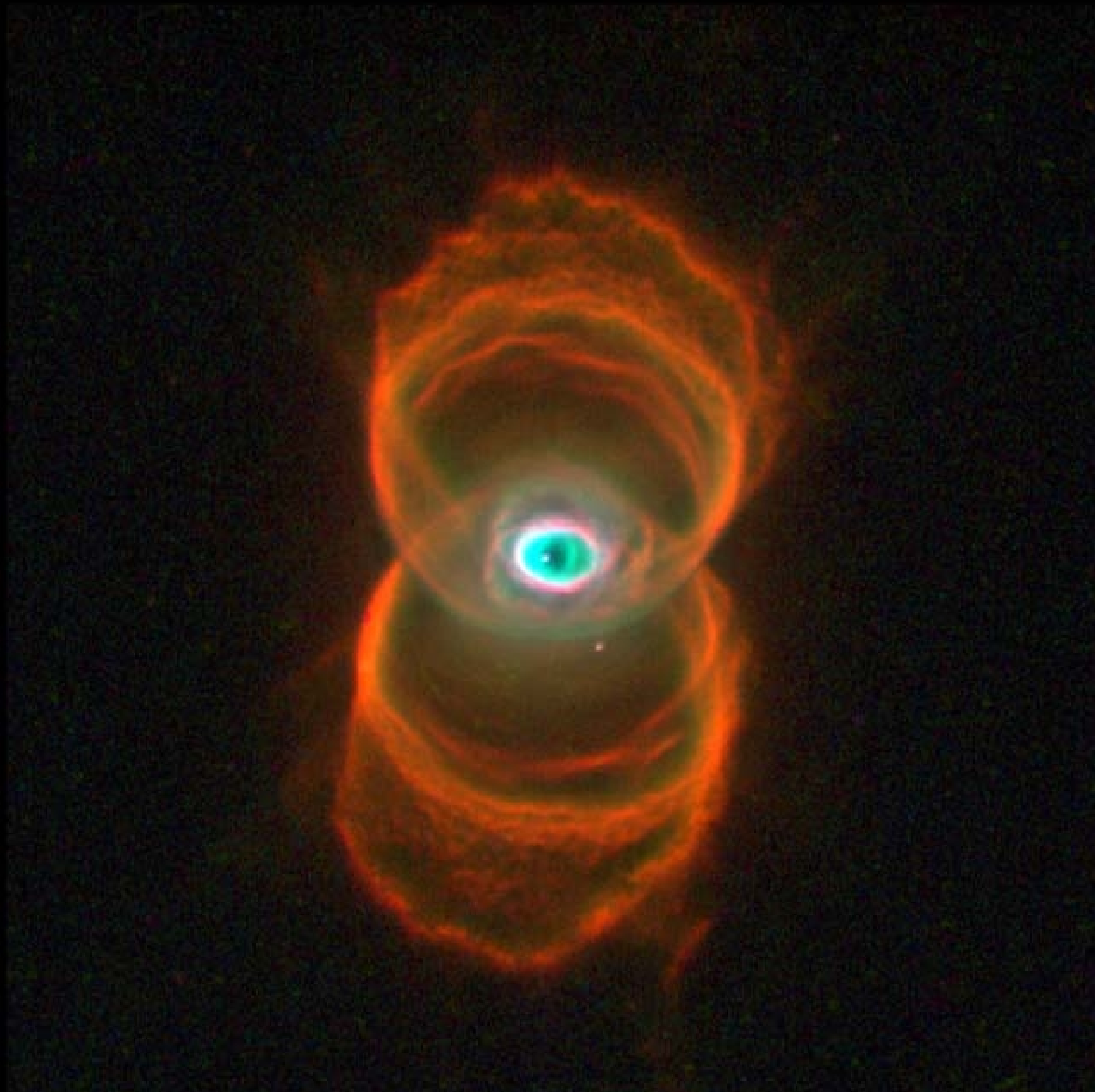
AGB stars are very similar to Red Giants, just bigger (and with a He burning shell).





The planetary nebula.

The shock waves sent out by the spasmodic He burning shell increases 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

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.

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How will our Sun end?

- it will explode
- it will end as a white dwarf
- it will not end, but will shine forever
- it will expand until it takes up all of space
- None of the above

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Poll locked. Responses not accepted.

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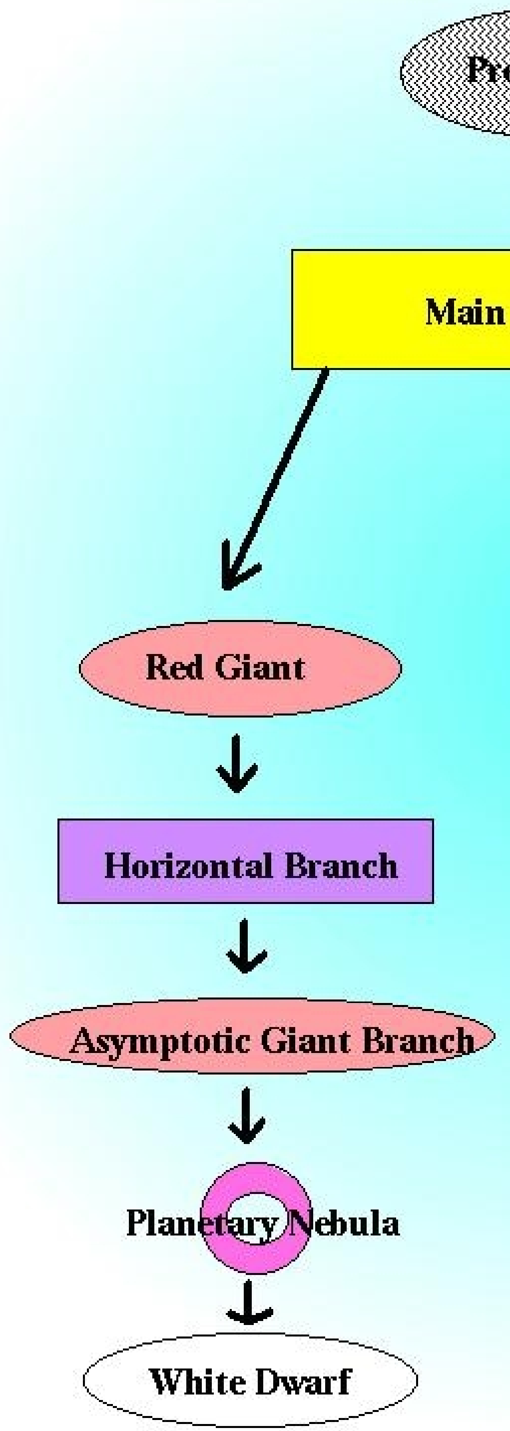
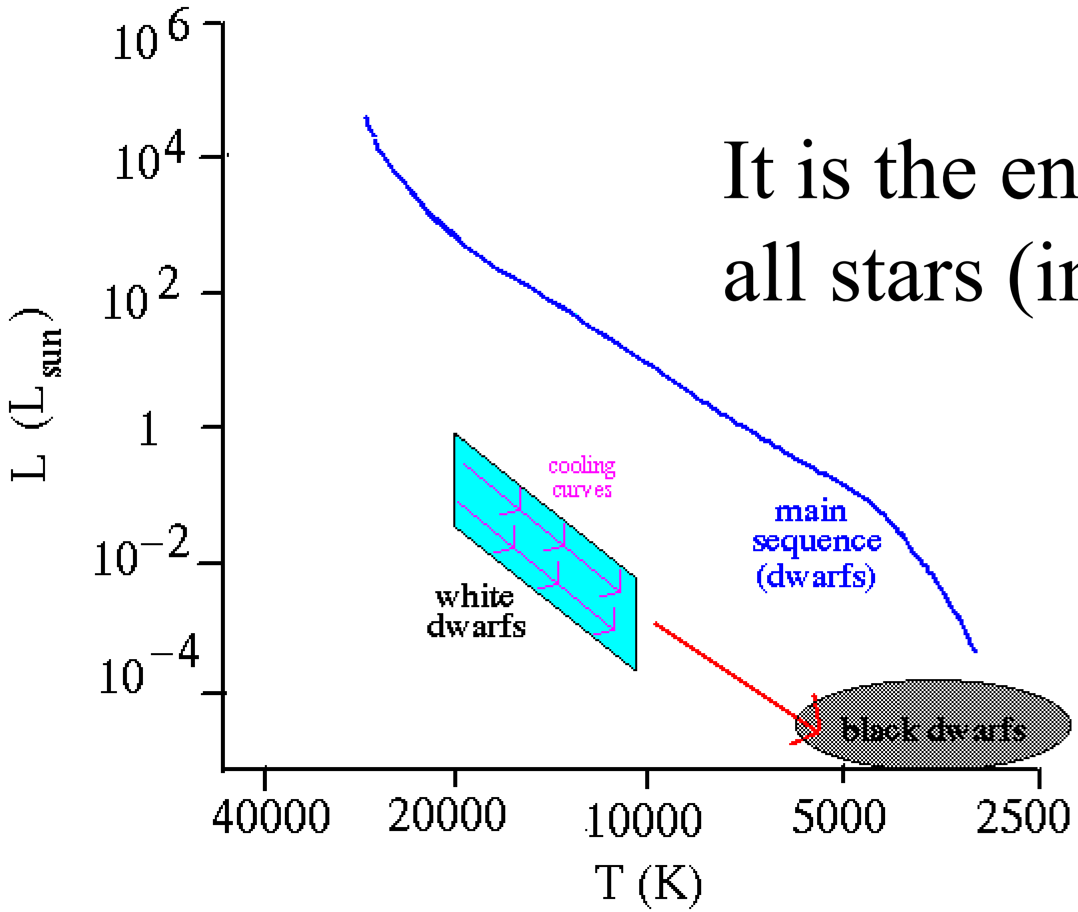


Stars < $8M_{Sun}$ end up as white dwarfs.

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)

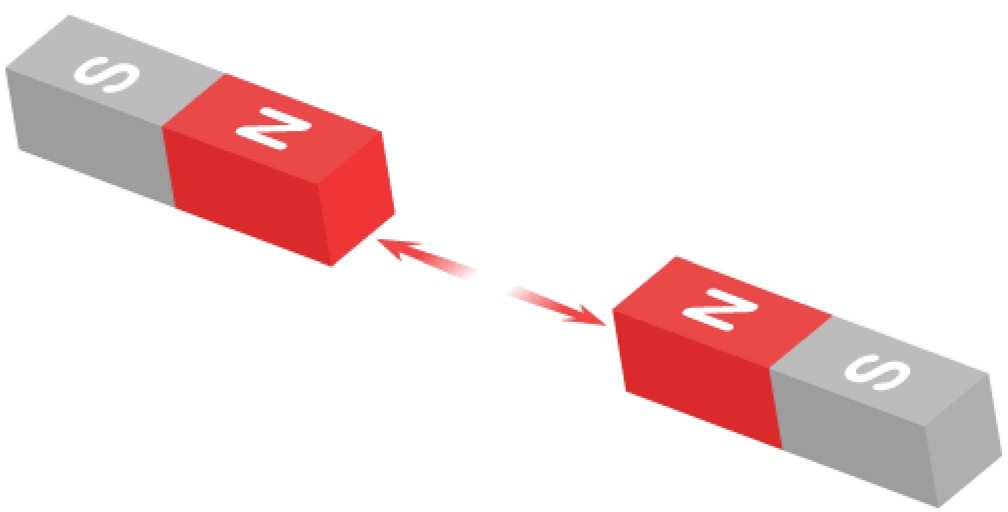
White dwarfs

- 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.

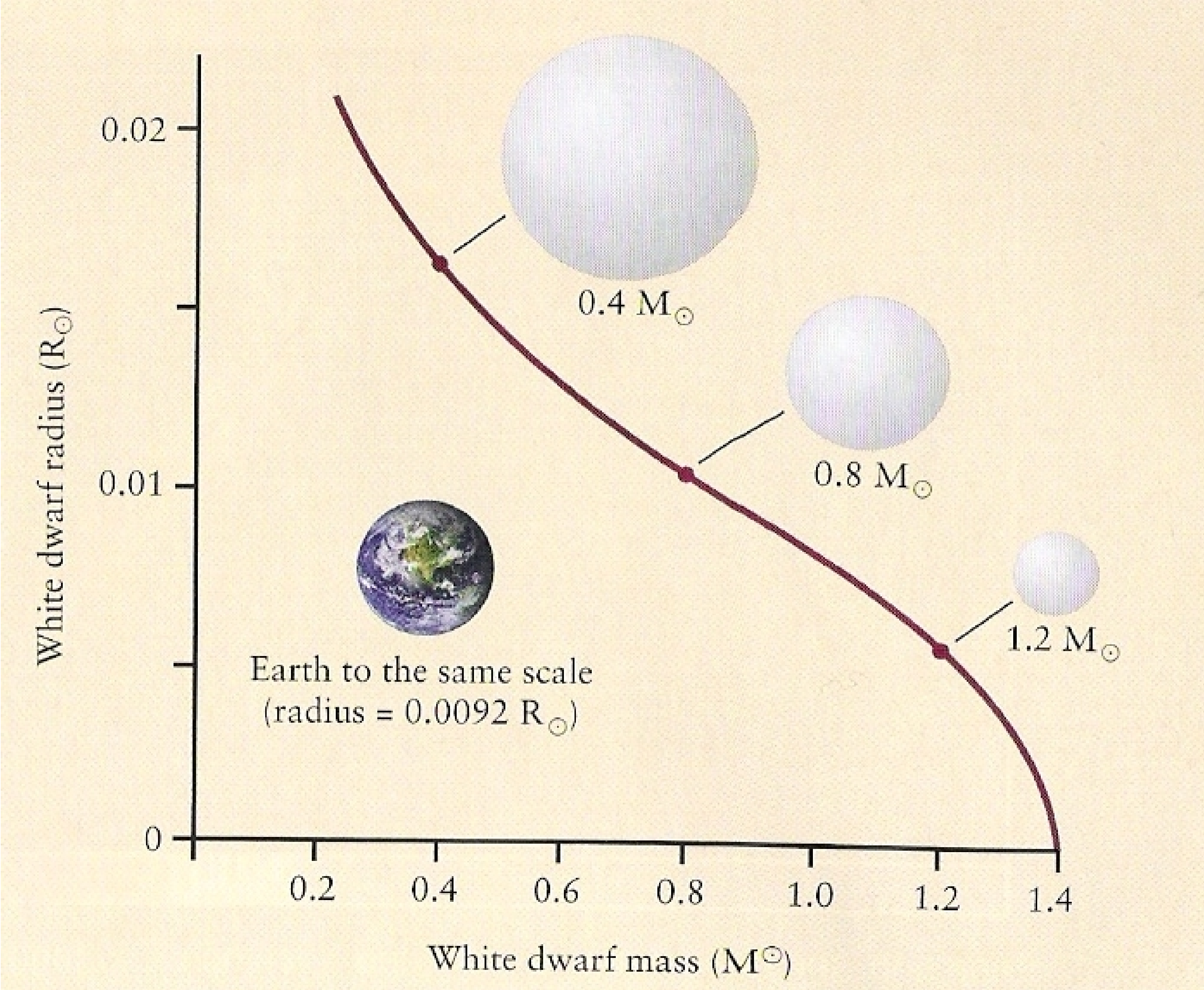
The weight on top pushes the atoms closer together, making the star smaller.

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 ($R_\odot$)
0.4 $M_\odot$
0.8 $M_\odot$
1.2 $M_\odot$
Earth to the same scale
(radius = 0.0092 $R_\odot$)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
White dwarf mass ($M_\odot$)

White dwarfs

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

Evolution so far:

Protostars: energy from gravity

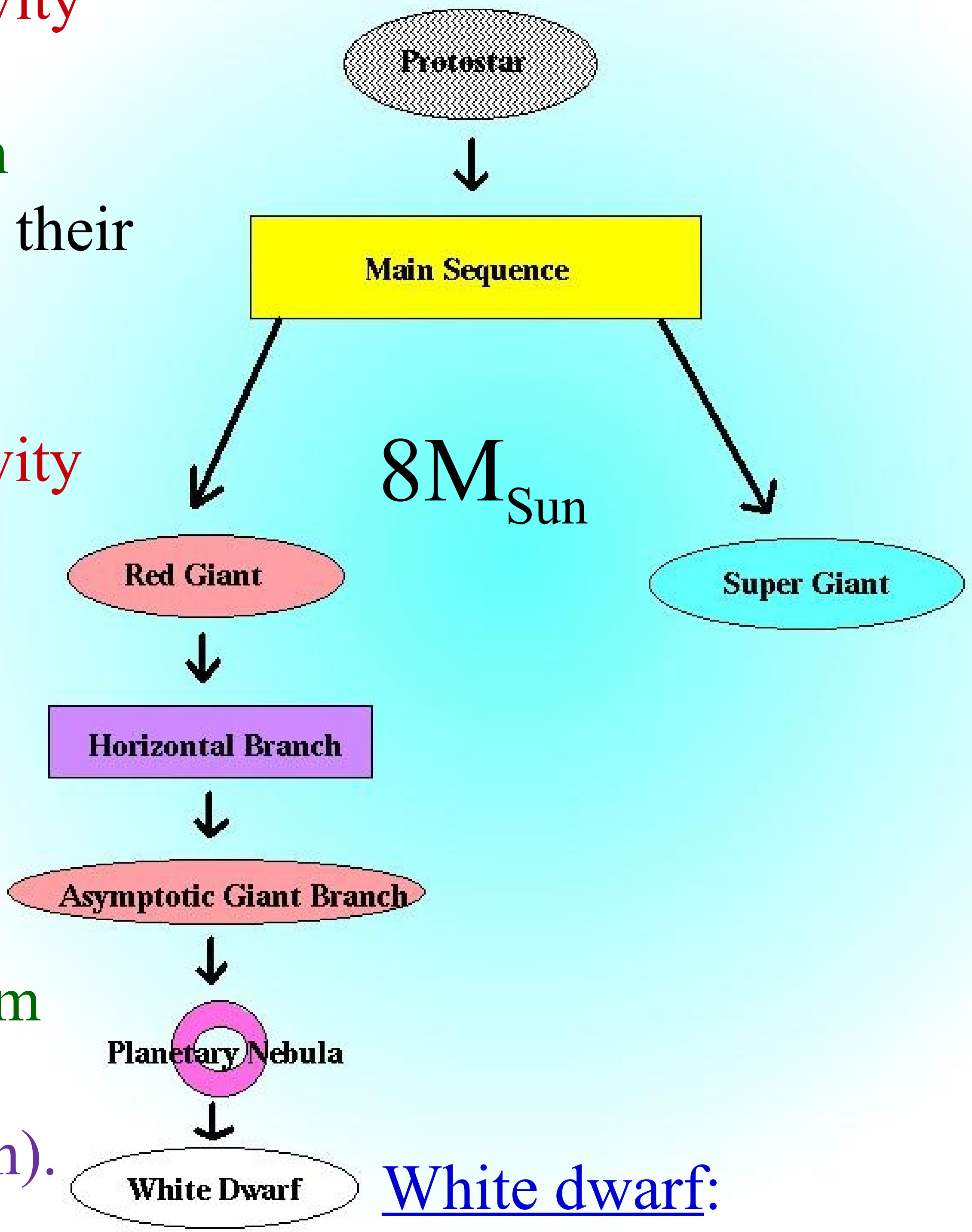
Main Sequence: energy from fusion converting H to He in their cores

Red giants: energy from gravity

Horizontal branch: fusion of He to C

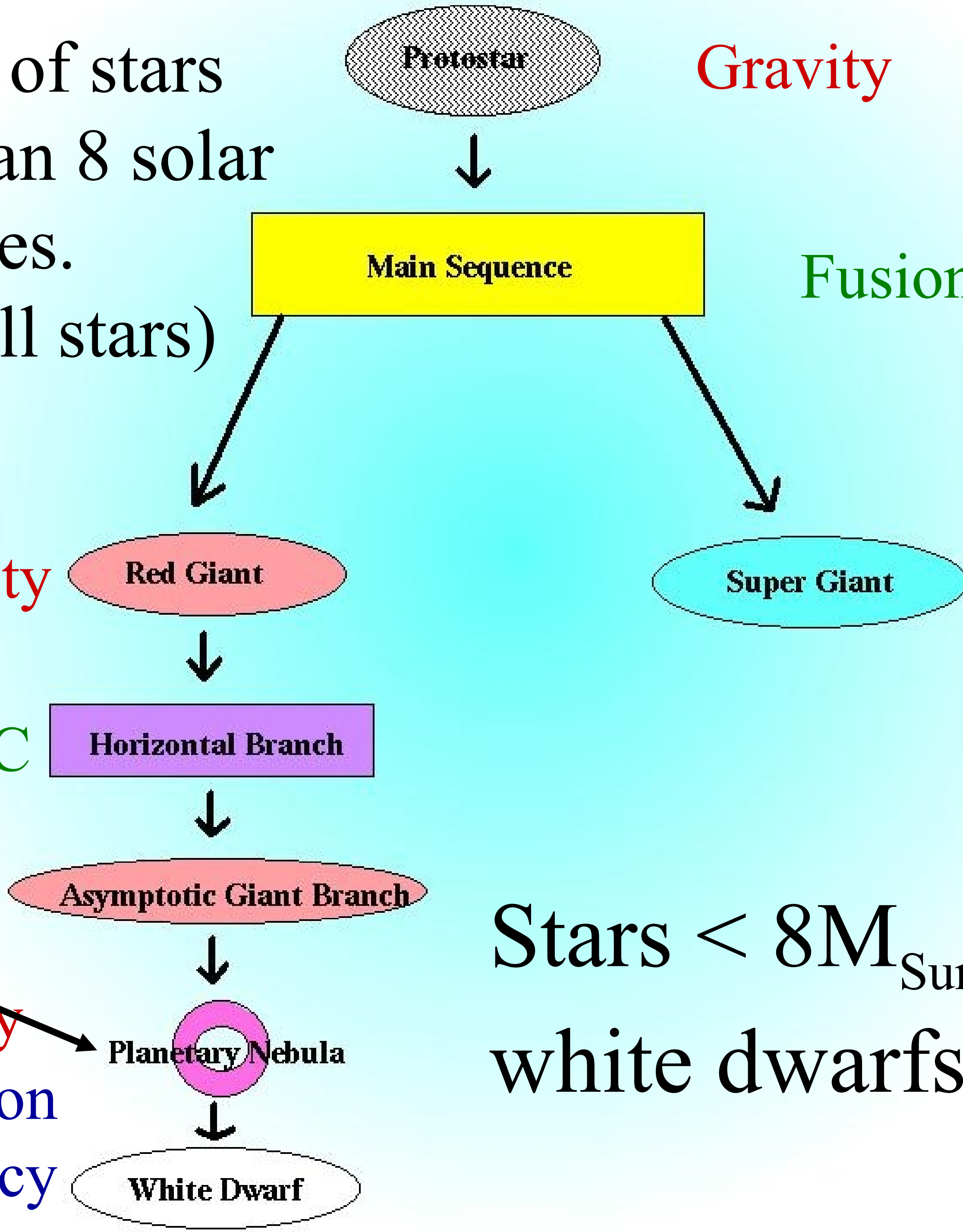
AGB: energy from gravity

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



White dwarf:

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



Gravity

Fusion H to He

Gravity

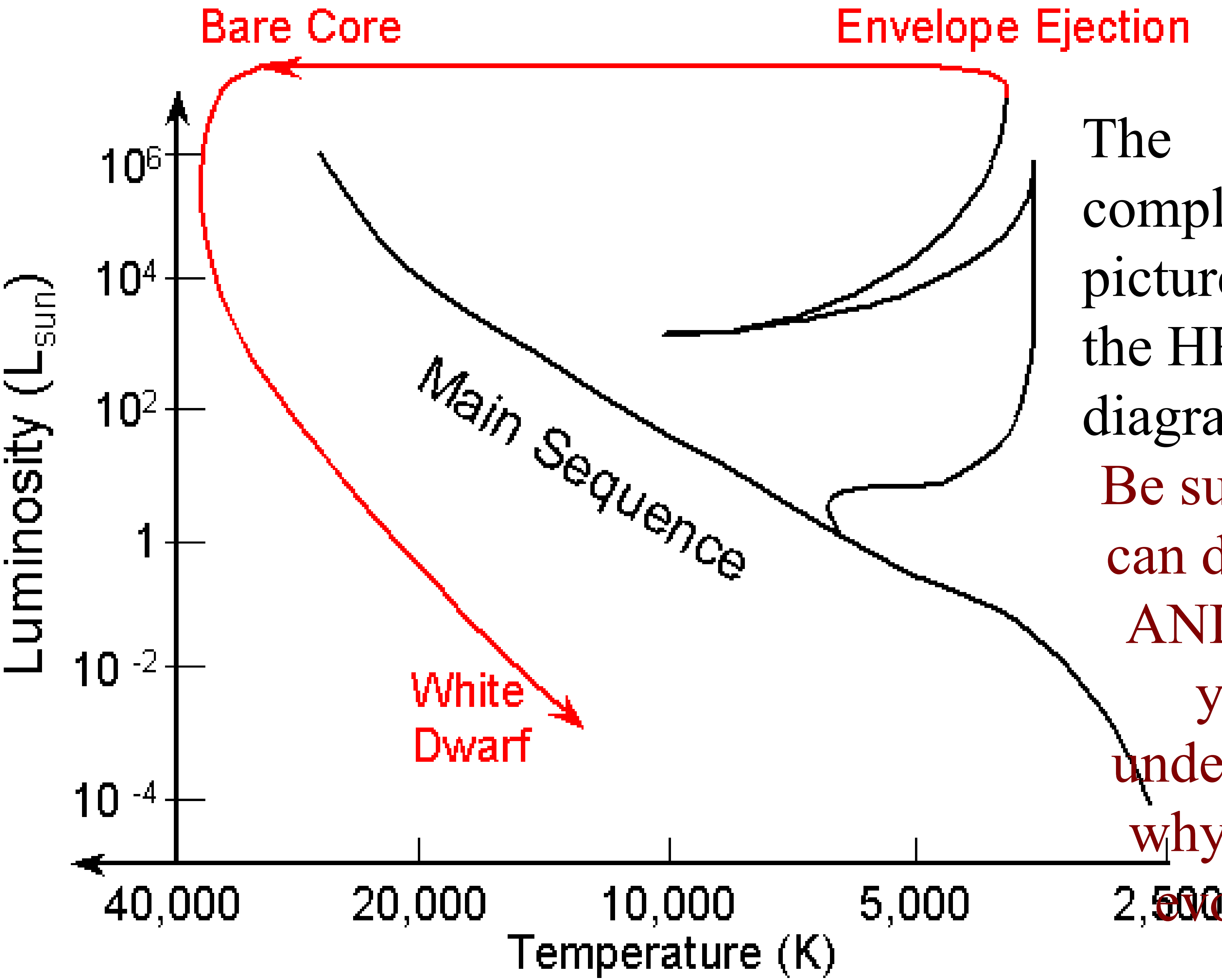
Fusion He to C

Gravity

Gravity

Electron degeneracy pressure.

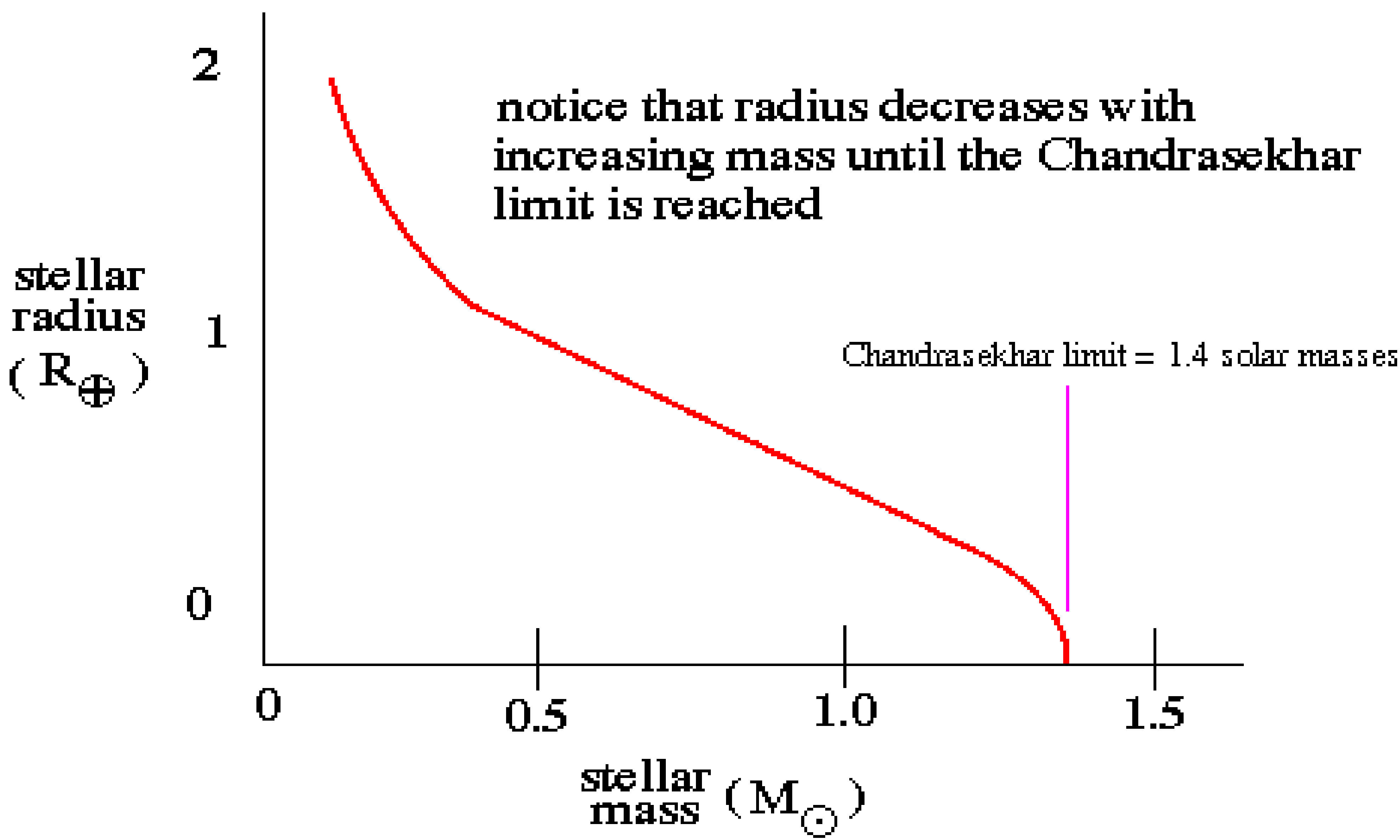
Stars < $8M_{Sun}$ end up as white dwarfs.



The complete picture on the HR diagram.

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

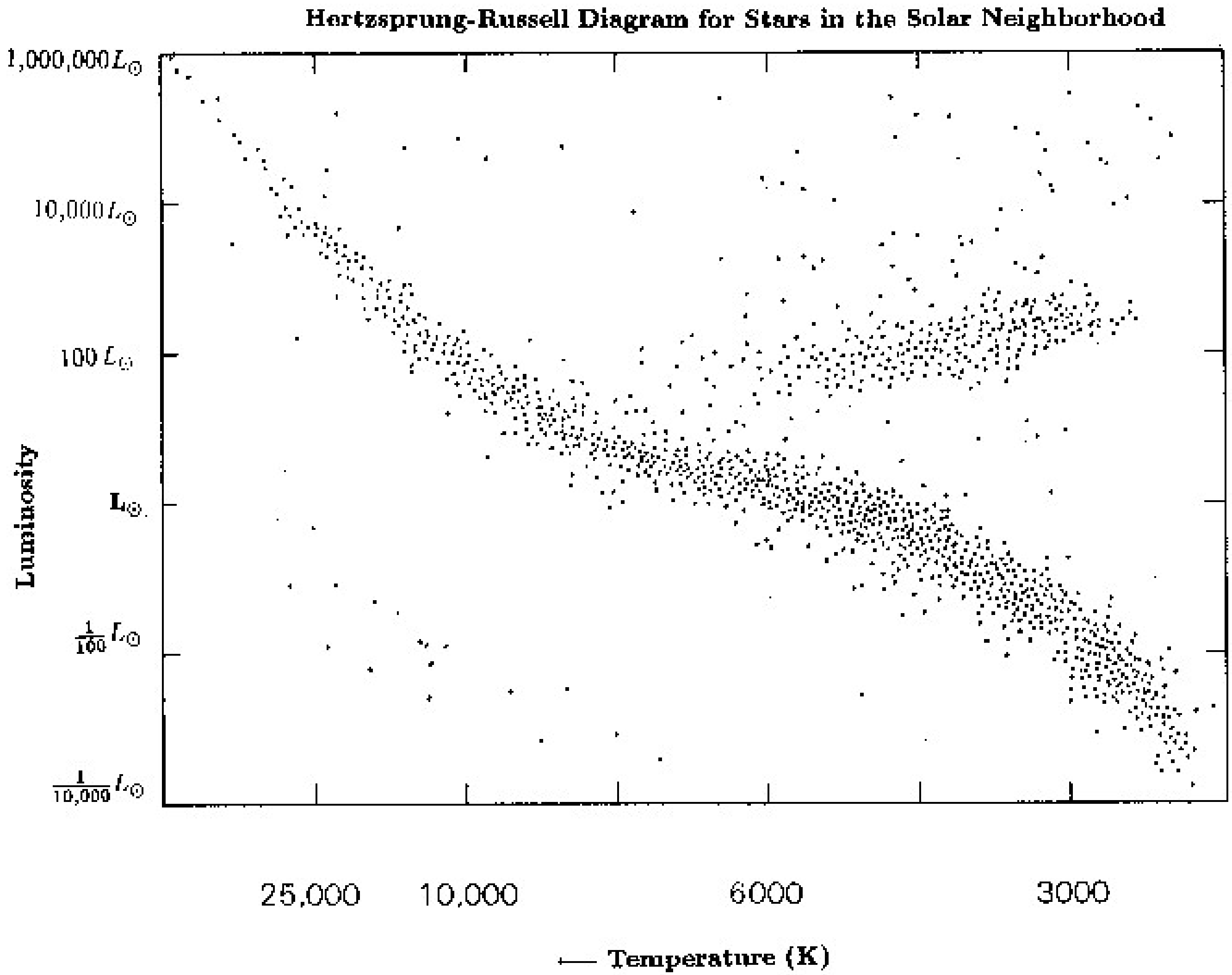
Mass–Radius Relation for White Dwarfs



So what?

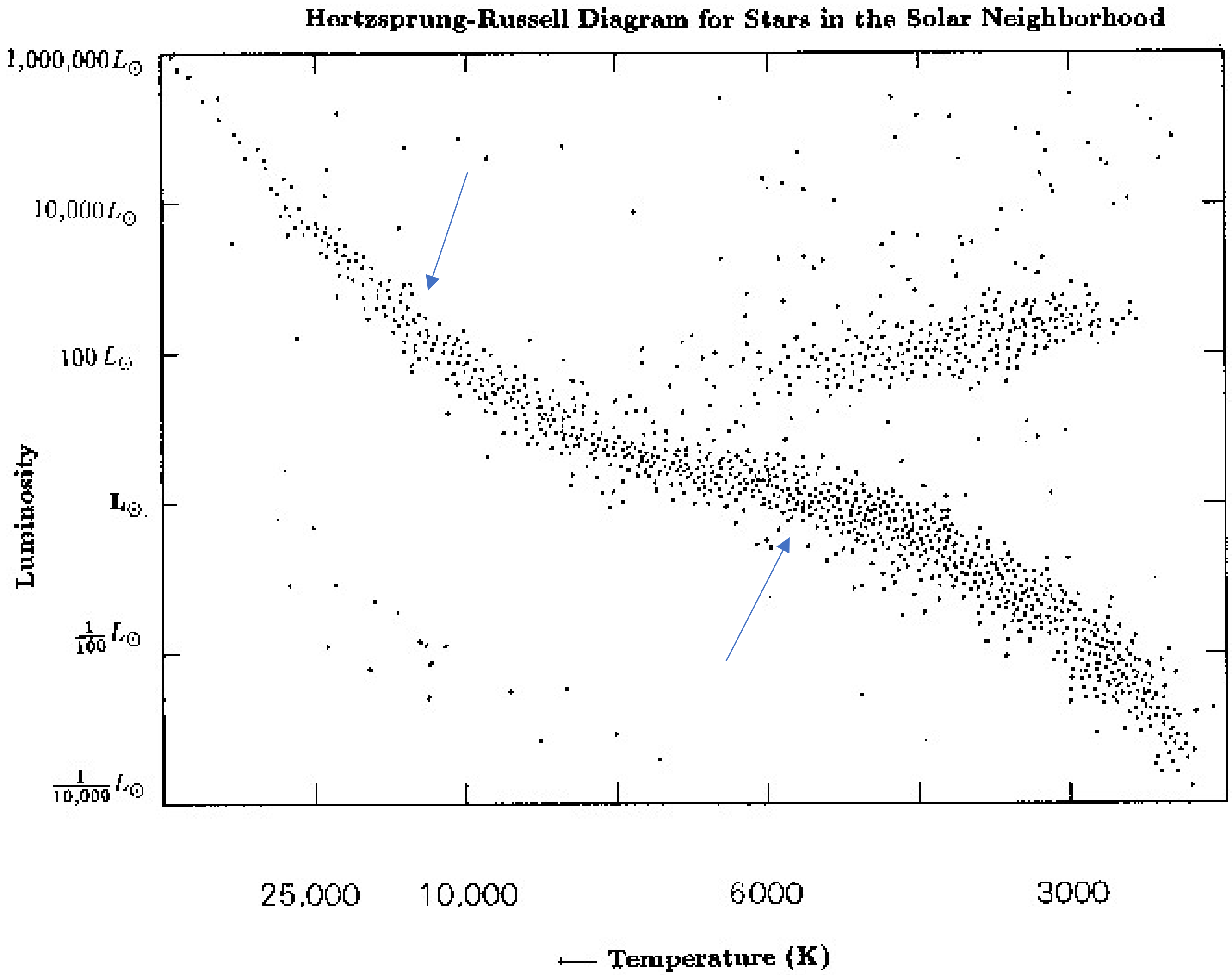
Any star <8 solar masses will become a white dwarf. They might be near 1.4 solar masses, but always below it.

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



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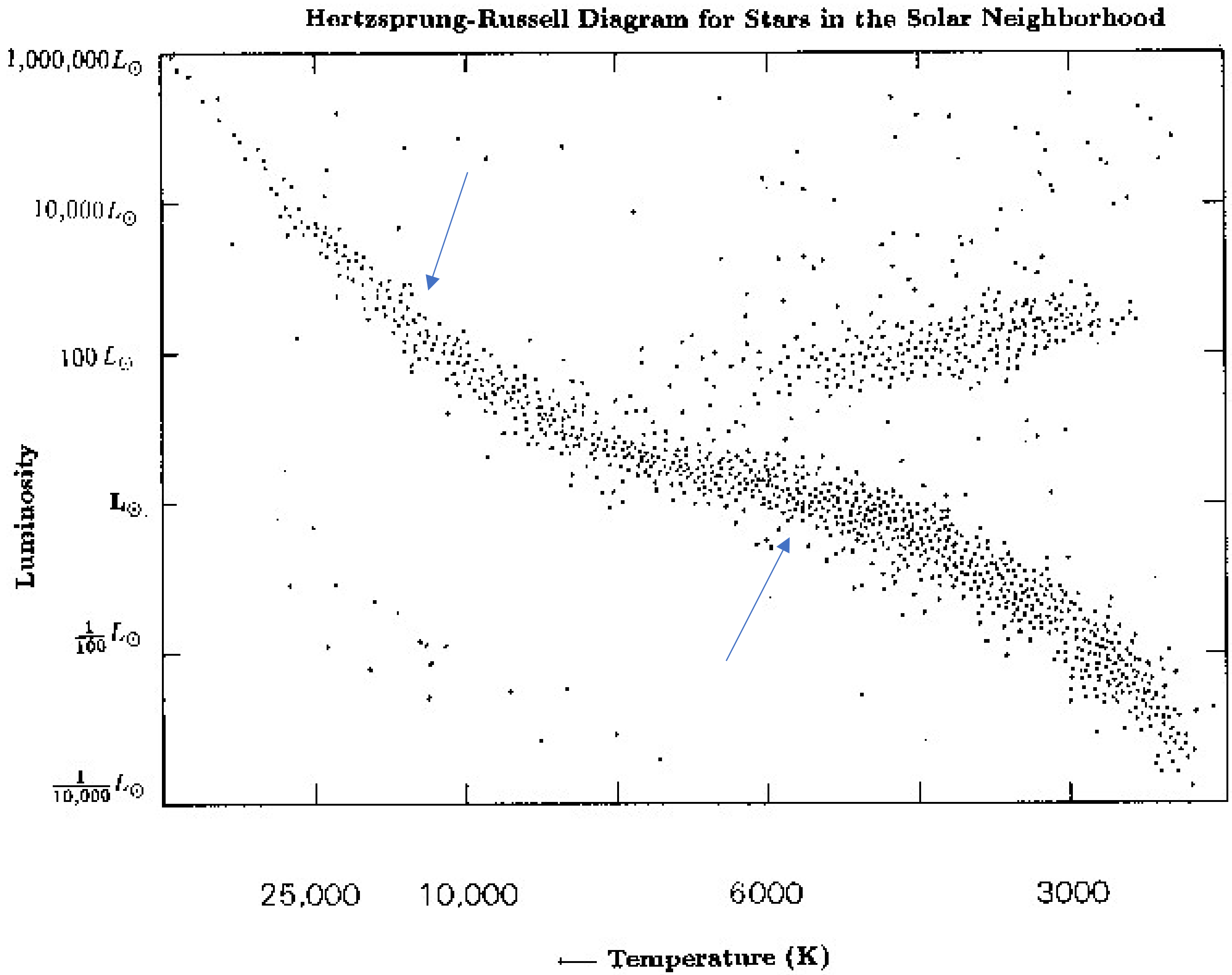
That means the blue star is more massive than the yellow star.



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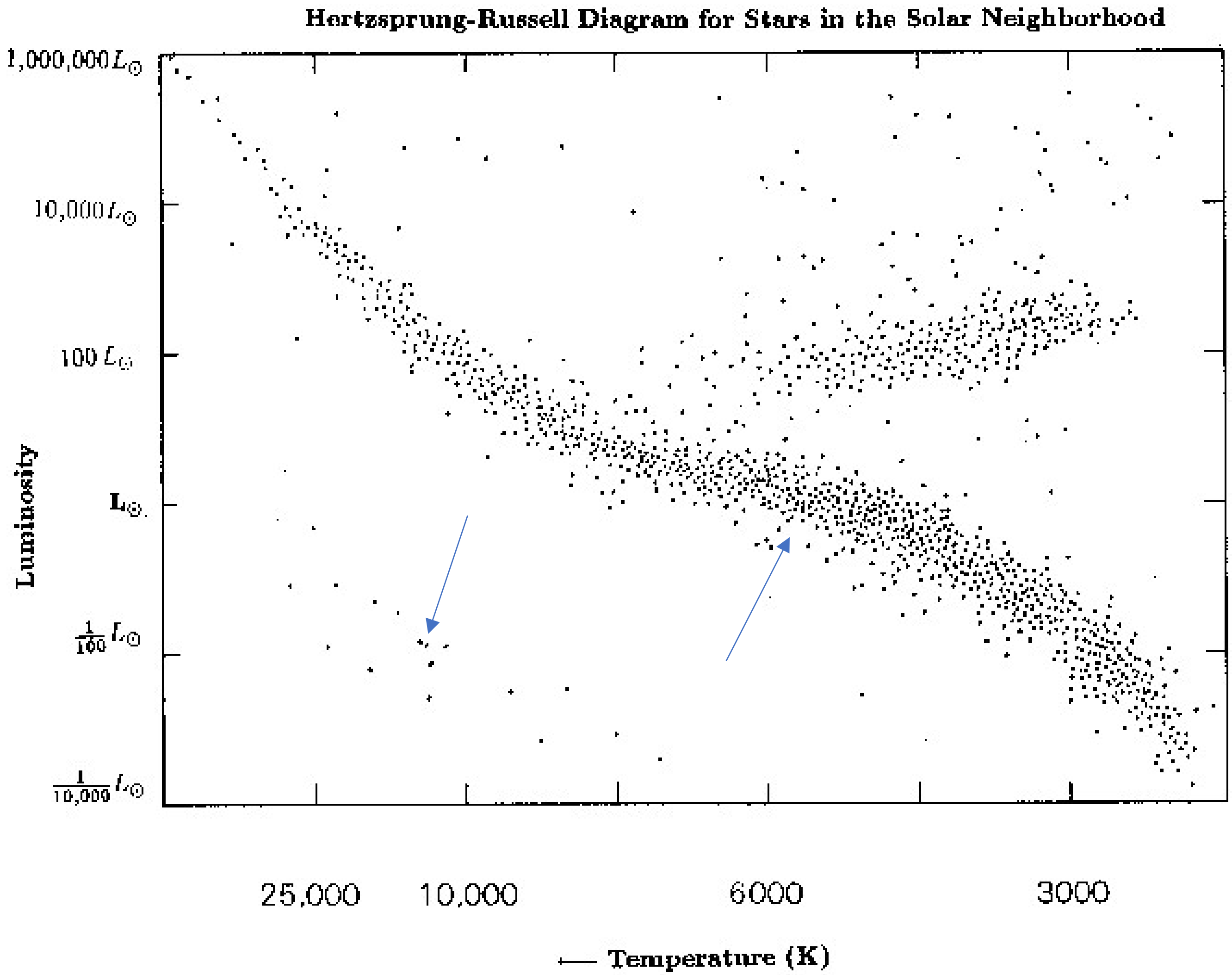
More massive stars evolve faster.



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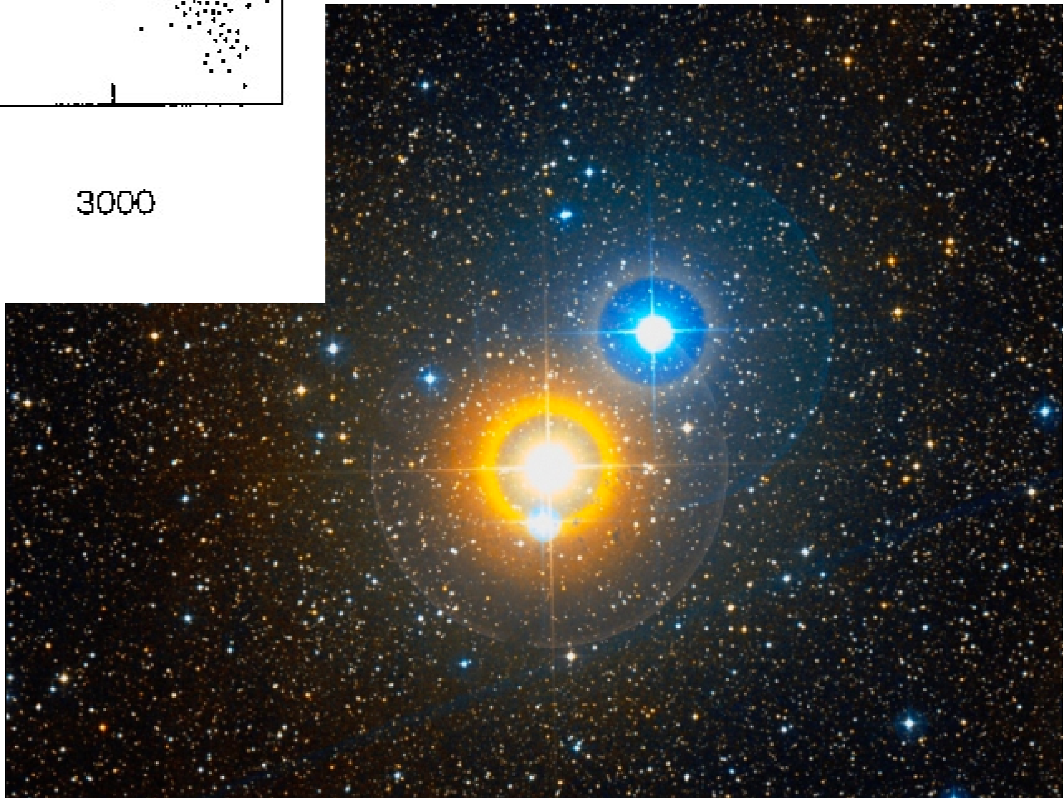
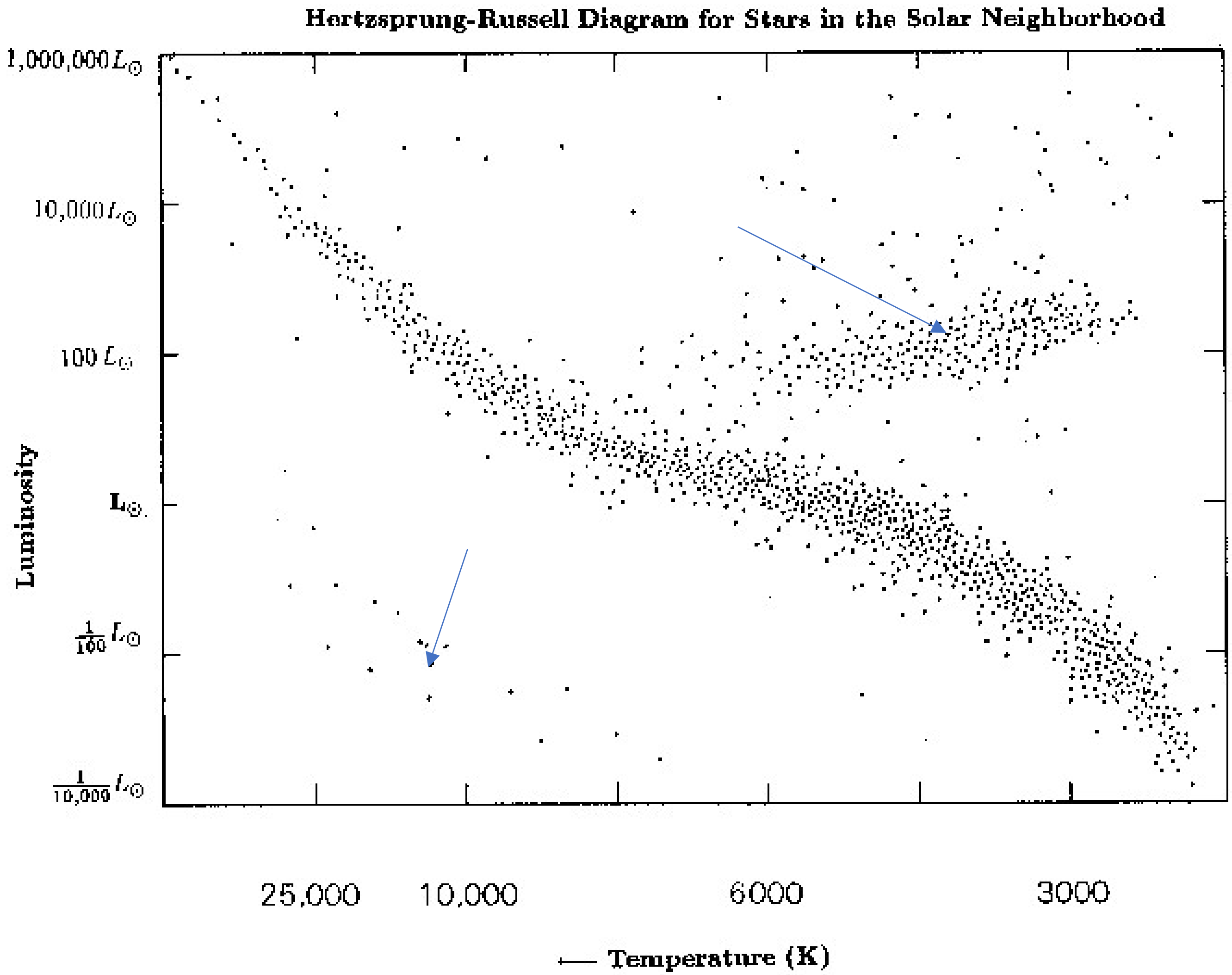


So the blue star evolves and becomes a white dwarf while the yellow star is still on the main sequence



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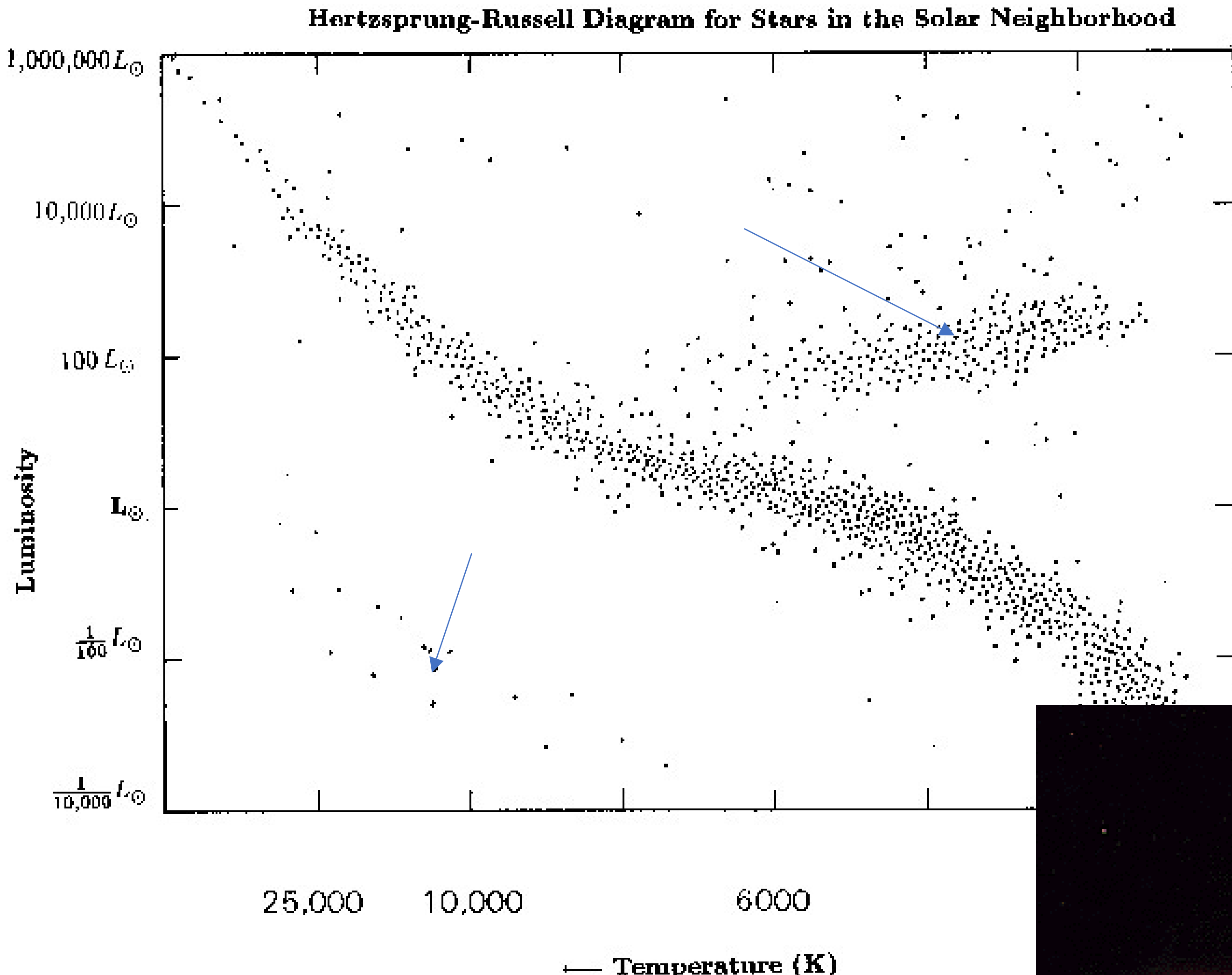
Then the yellow star expands into a red giant.



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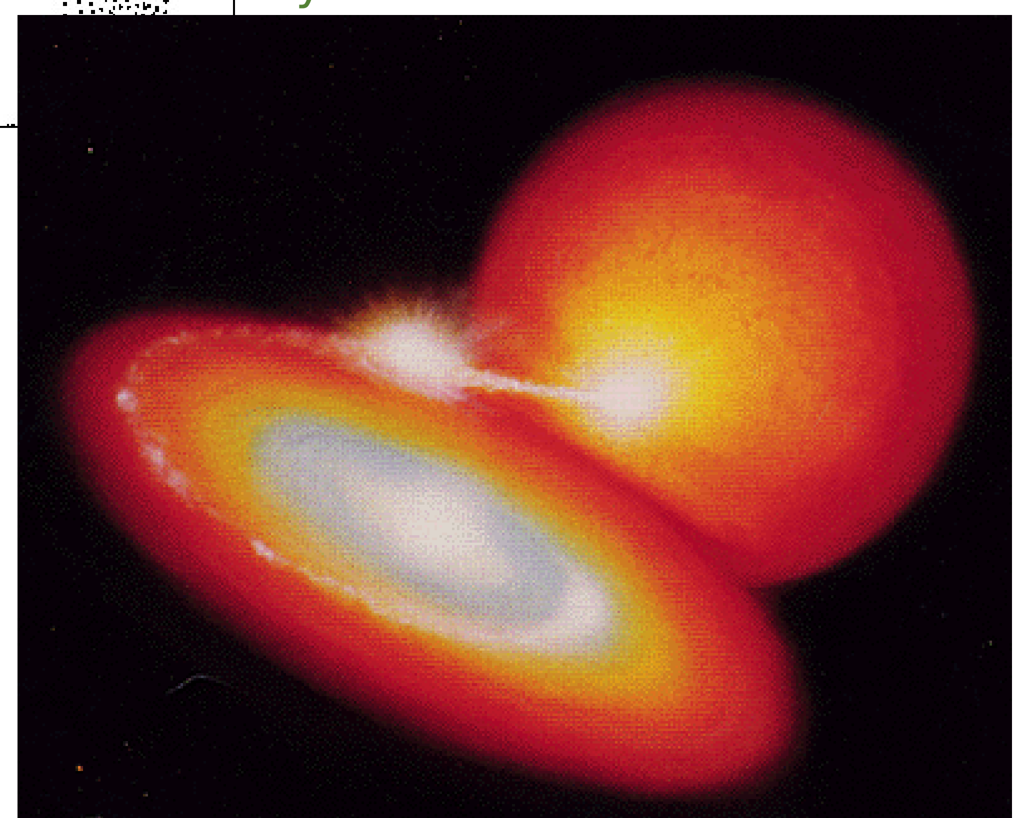
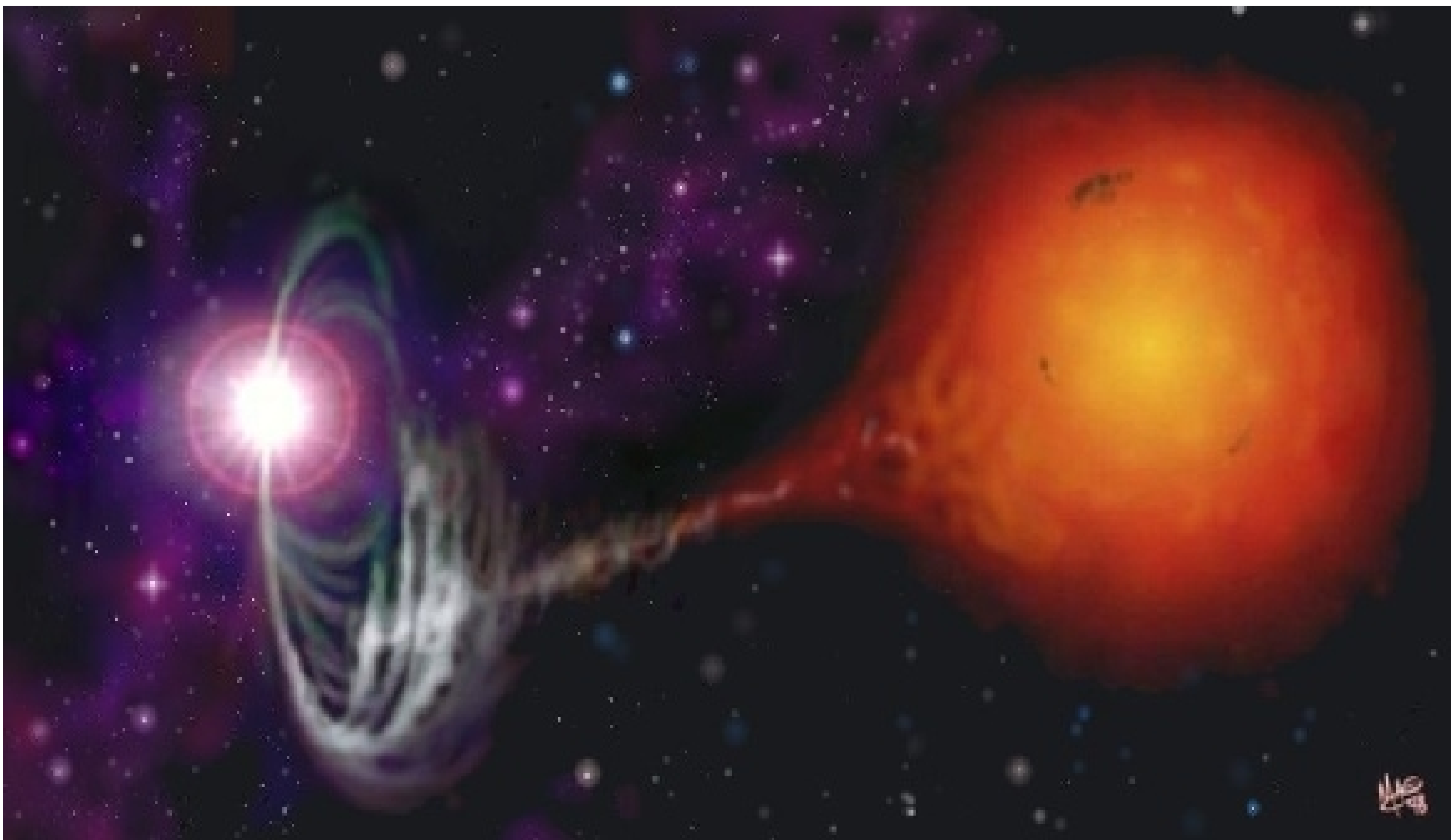


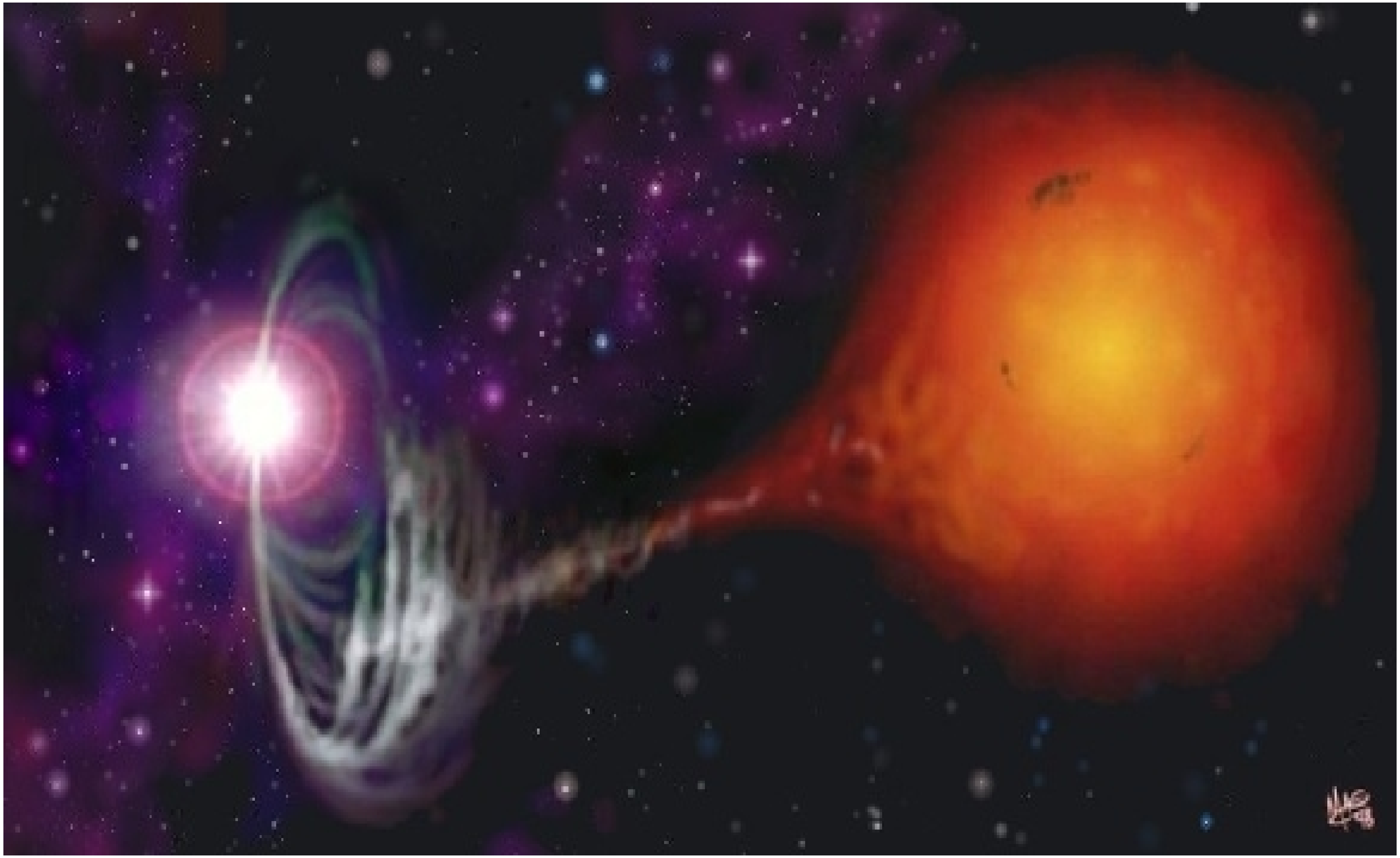
Then the yellow star expands into a red giant. Now the white dwarf’s gravity can take material from the companion.

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

The white dwarf 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

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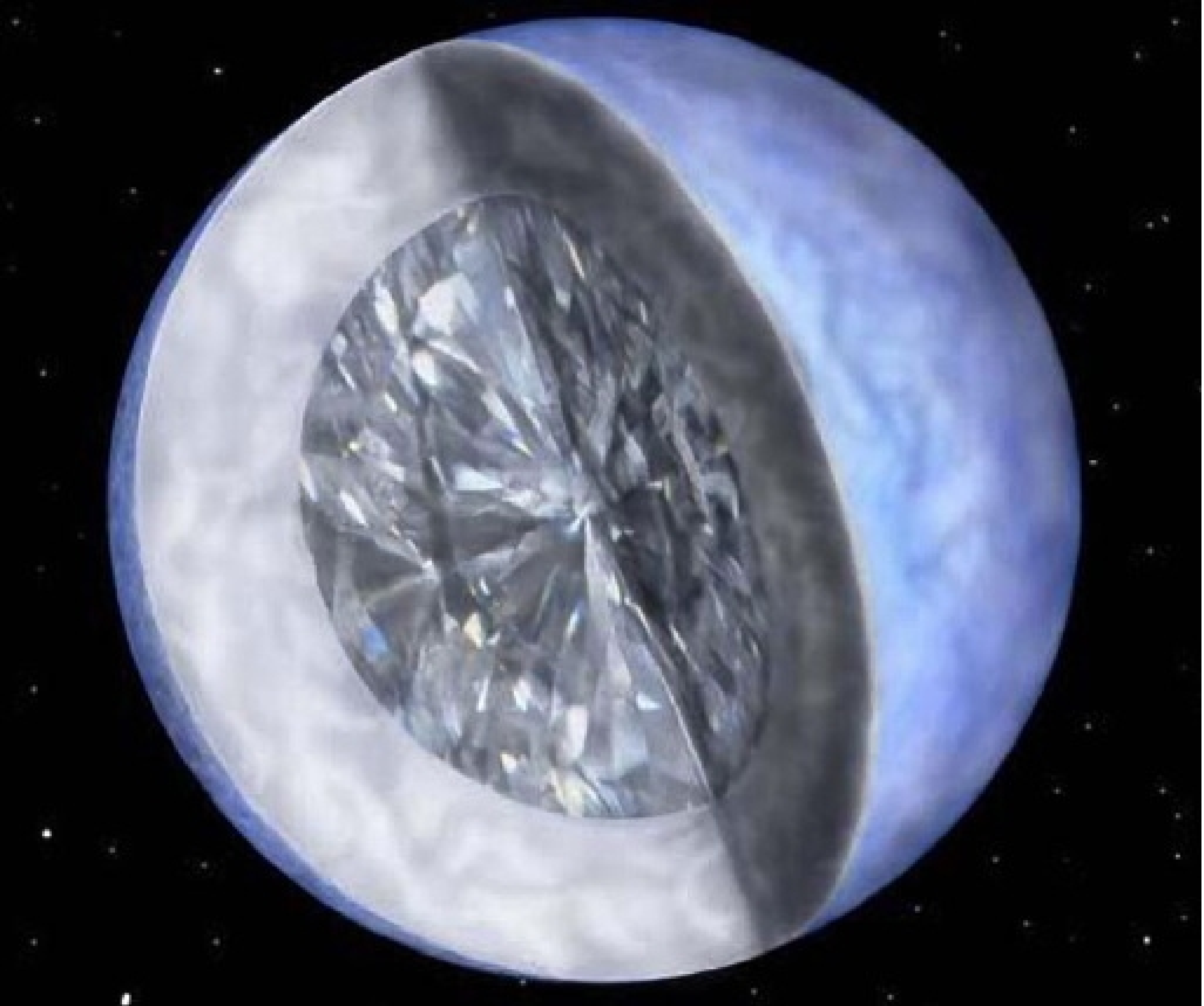
As the core cools, it will crystallize.

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?



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Which star evolves faster?

- A 2 solar mass star
- A 4 solar mass star
- They evolve at the same rate
- They don't evolve at all.

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For the rest of space....

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

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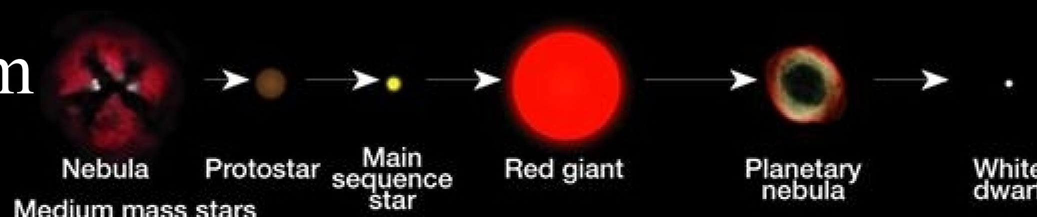
Chemical Enrichment

Our solar system
2% metals



Planetary nebula
returns 3% metals

H and He are only slightly reduced

For the rest of space....

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

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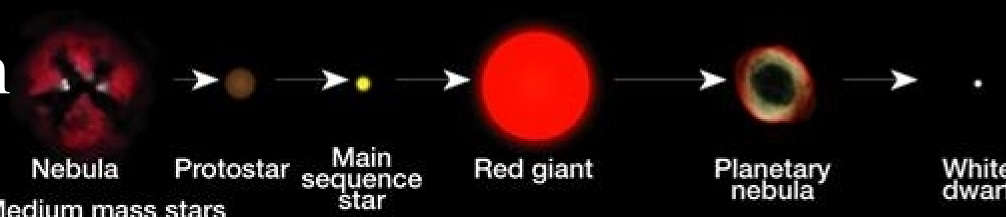

Planetary nebula
returns 3% metals

What about before our Sun?

For the rest of space....

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

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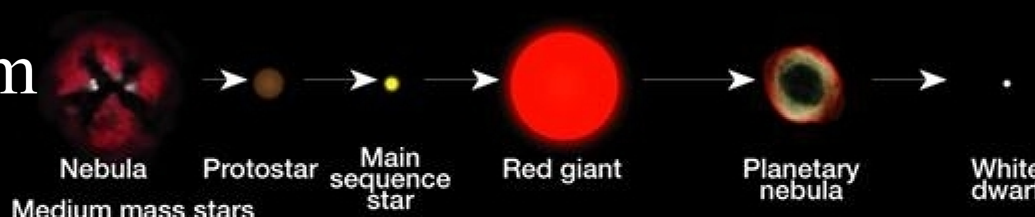
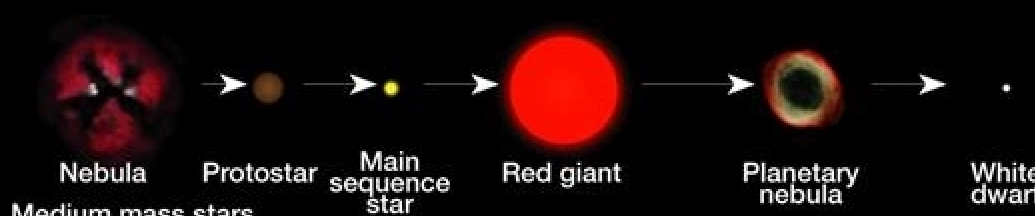


Planetary nebula returns 3% metals

Before our Sun?

Previous star:
1% metals



Planetary nebula returns 2% metals

And before that?

For the rest of space....

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

Chemical Enrichment

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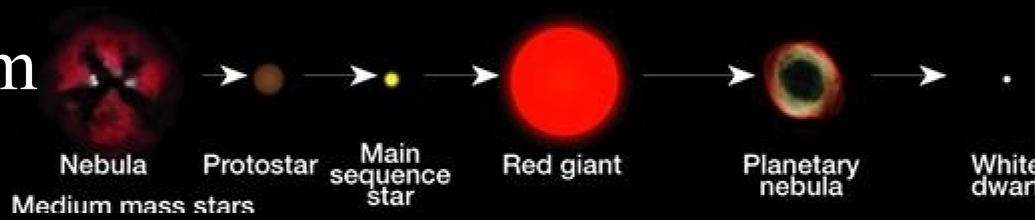

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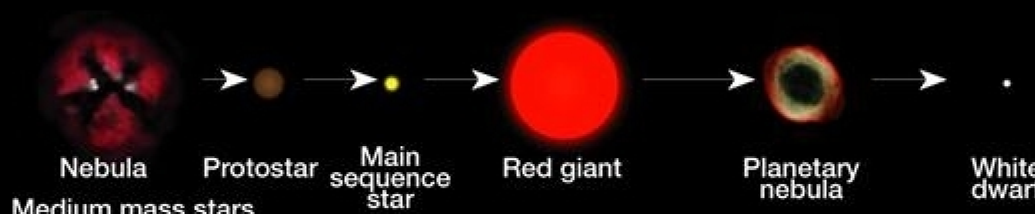
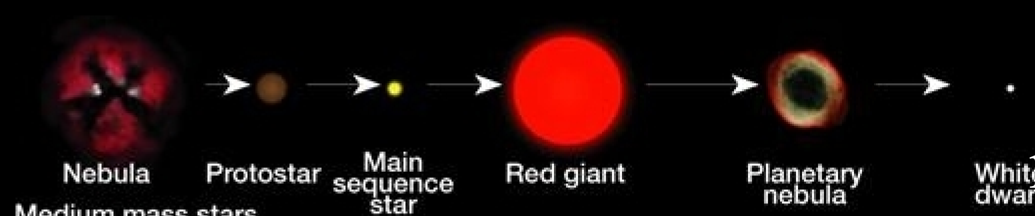


Planetary nebula returns 2% metals

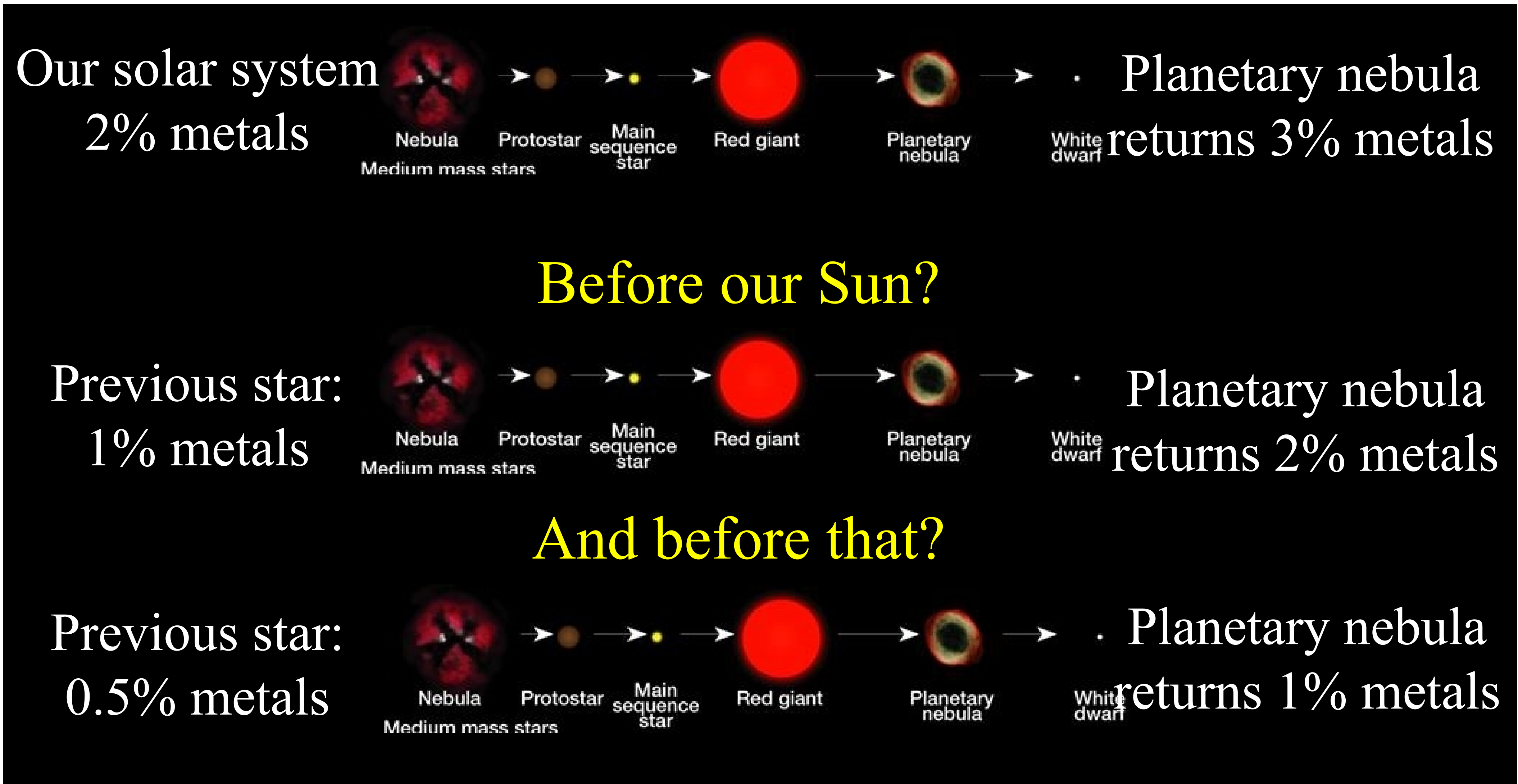
And before that?

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'?



Enrichment

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

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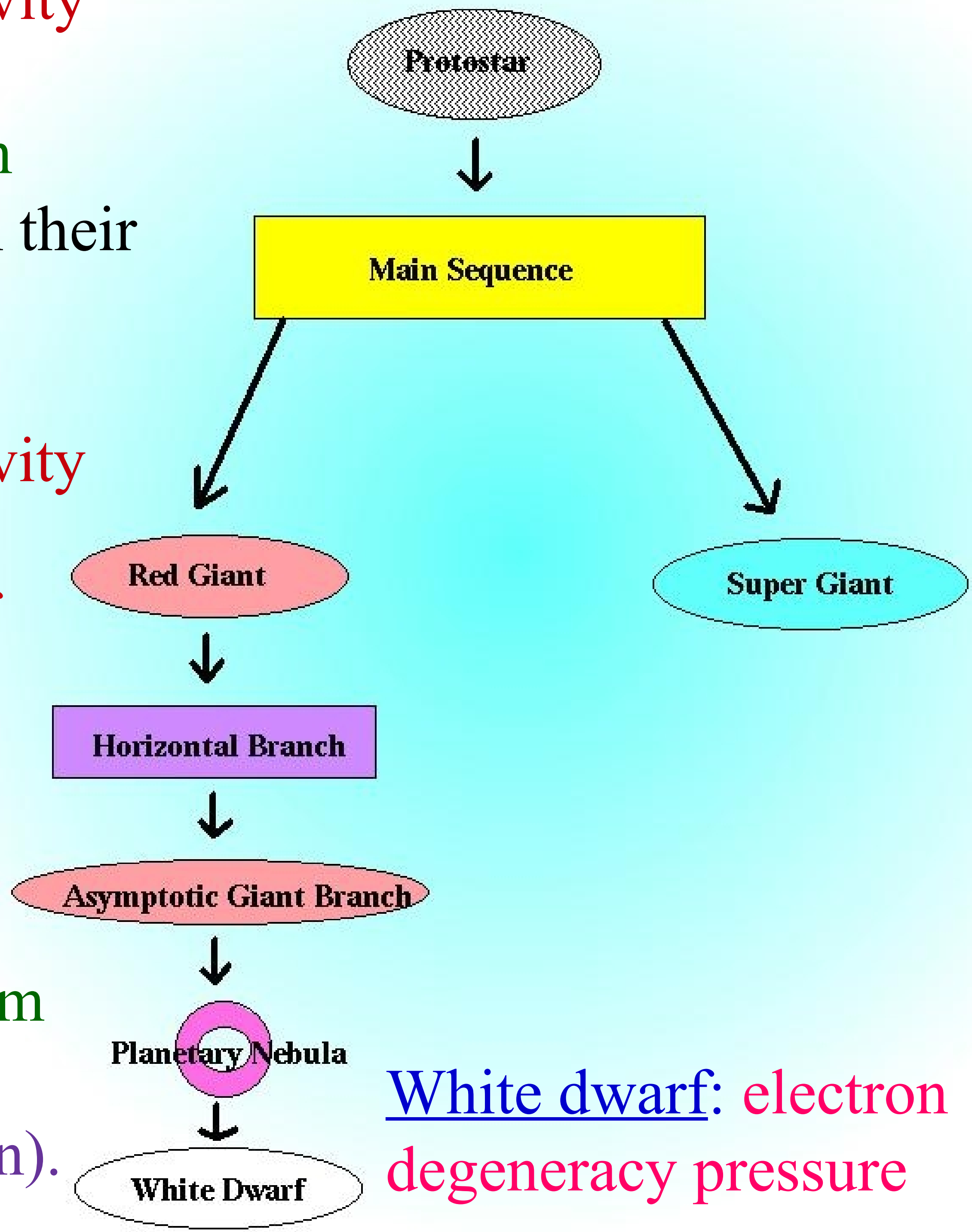
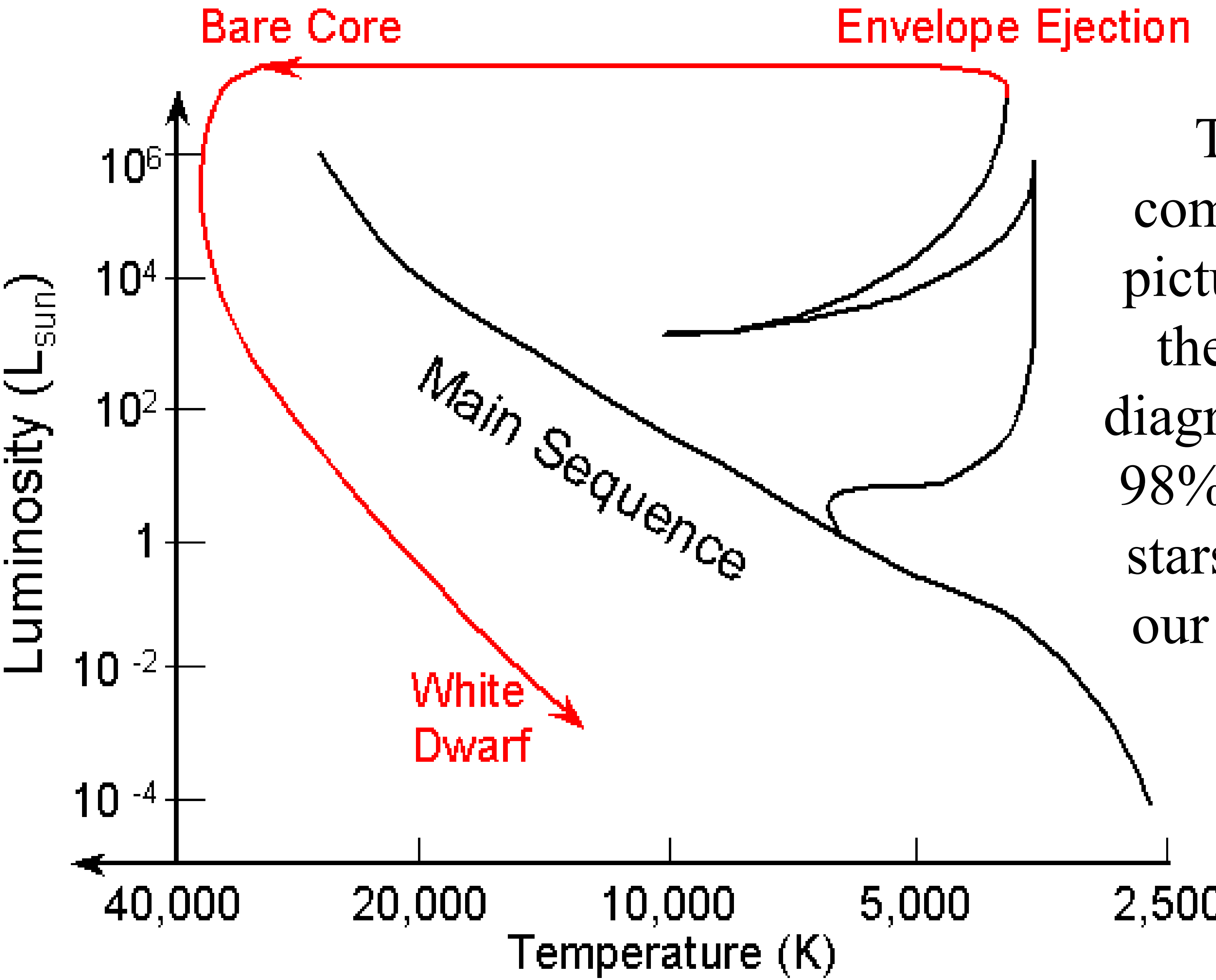
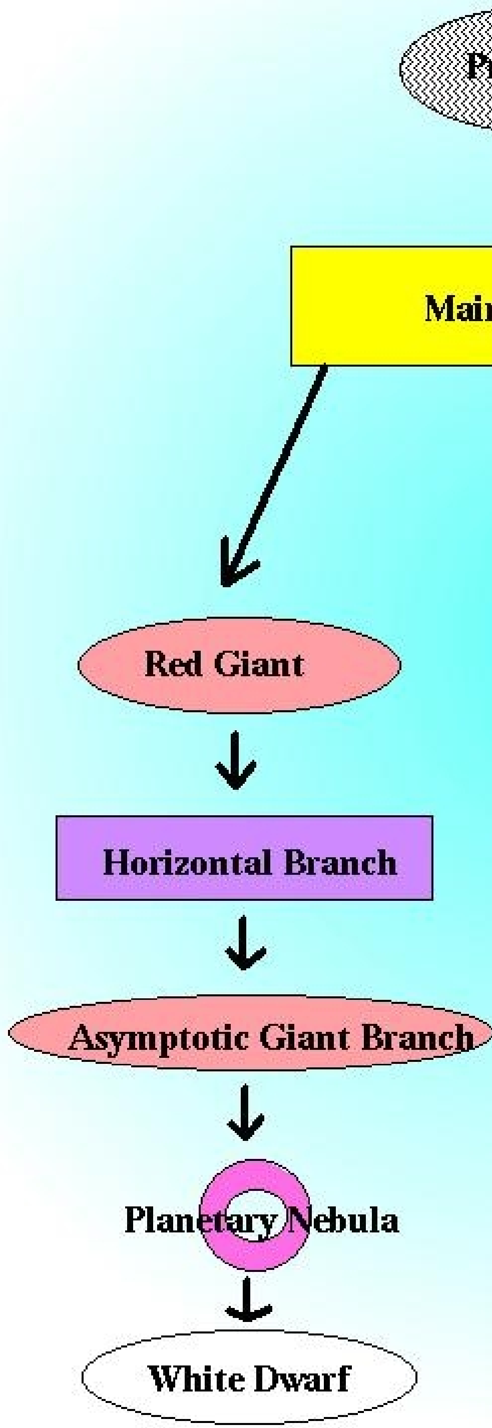


White dwarf: electron degeneracy pressure



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.

Supergiants

The cores of more massive stars are already hotter.

As they have more mass, they get more energy from gravity without having to change their size much.

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Supergiants are able to begin converting He to C/O very soon after exhausting H in their core.

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As they have more mass, they get more energy from gravity without having to change their size much.

Supergiants are able to begin converting He to C/O very soon after exhausting H in their core.

But their cores are hotter than on the main sequence, so the envelope expands.

Supergiants

Supergiants are able to begin converting He to C/O very soon after exhausting H in their core.

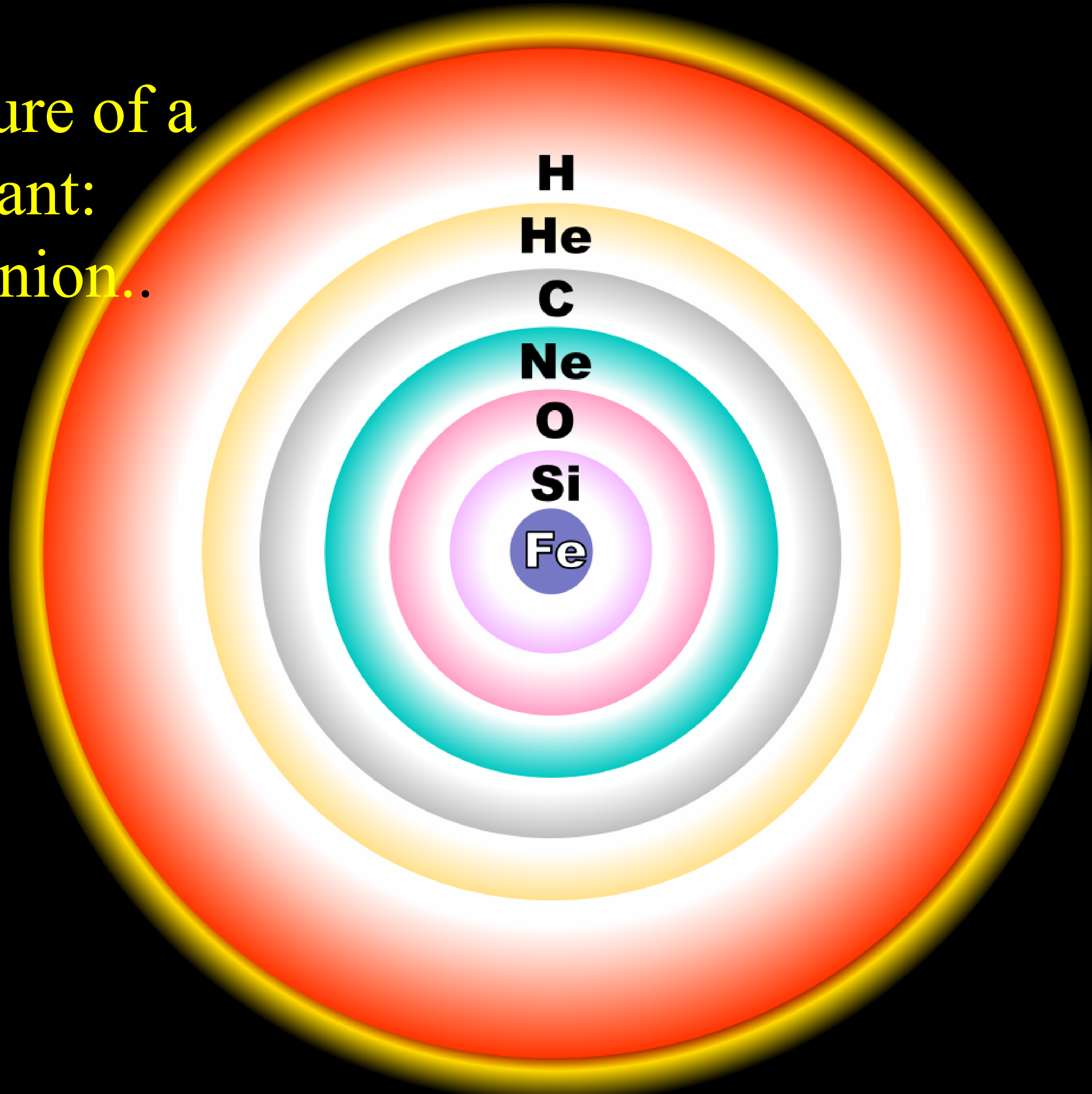
When that's depleted, they convert C to O, Ne, Na and Mg

When that's depleted, they convert O to Mg, S, P, and Si

Then Si to Co, Fe, and Ni

Between each nuclear burning stage, the shell expands and the core contracts, heating up before it can burn the next fuel.

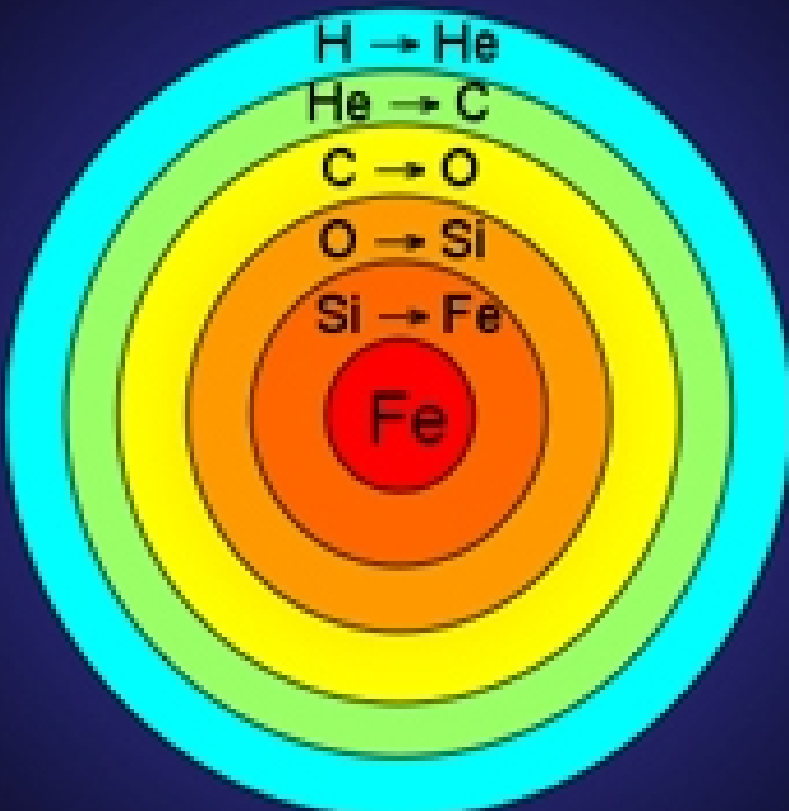
Late structure of a
supergiant:
Like an onion..



Fuel Sources

Source	Temp	Density	Energy out
H	4 million K	10-100 g/cc	6.55 MeV
He	100 million K	1,000 to 1 million g/c	0.61 MeV
C	600 million K	0.1 to 100 million g/c	0.54 MeV
O	1 billion K	1 billion g/cc	0.3 MeV
Si	3 billion K	3 billion g/cc	0.18 MeV

Fusion Timescales

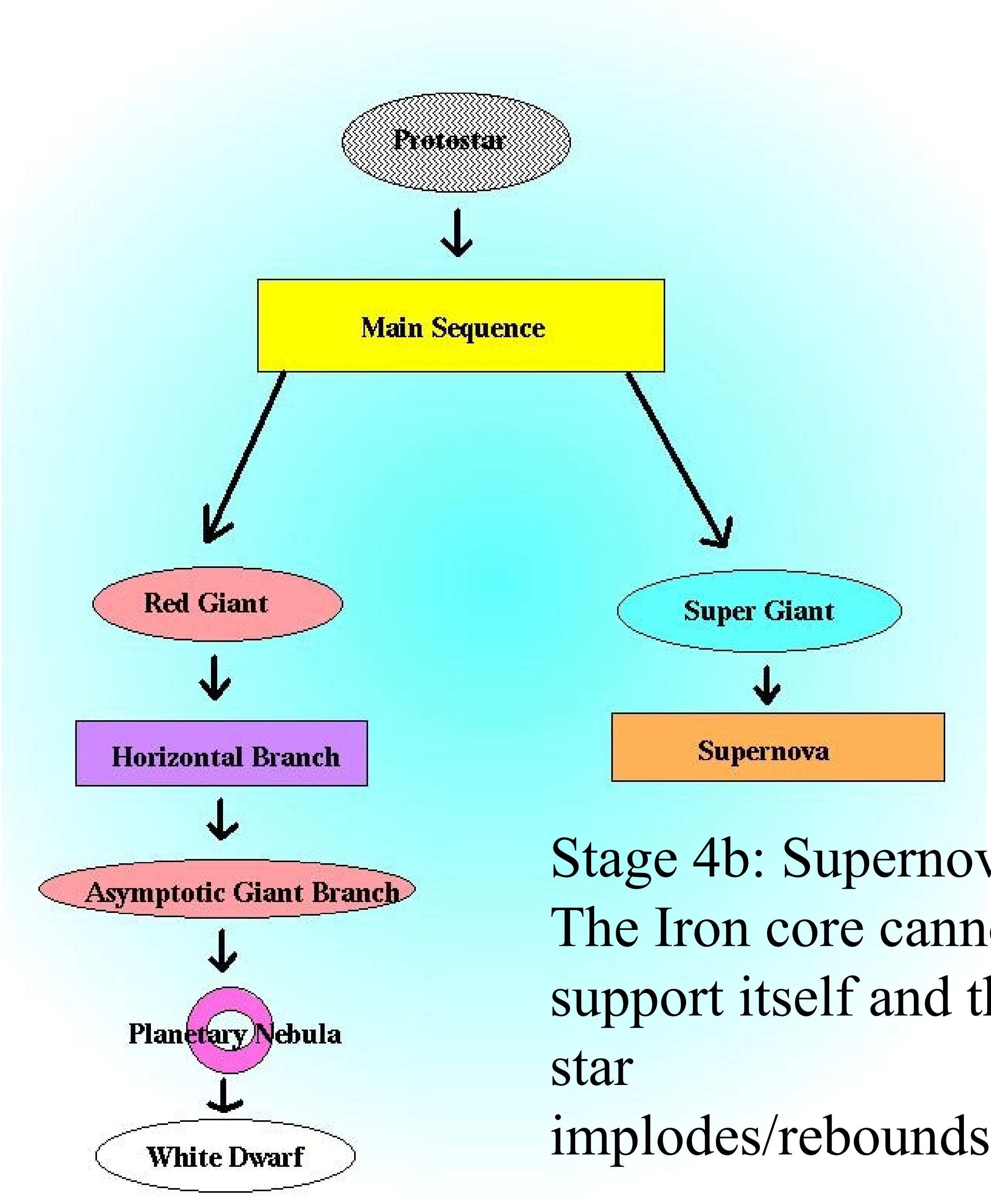


For a 25 solar mass star:

Stage	Duration
H → He	7×10^6 years
He → C	7×10^5 years
C → O	600 years
O → Si	6 months
Si → Fe	1 day
Core Collapse	1/4 second

So what happens when you've built up an Iron core?
What can Iron do to support itself?

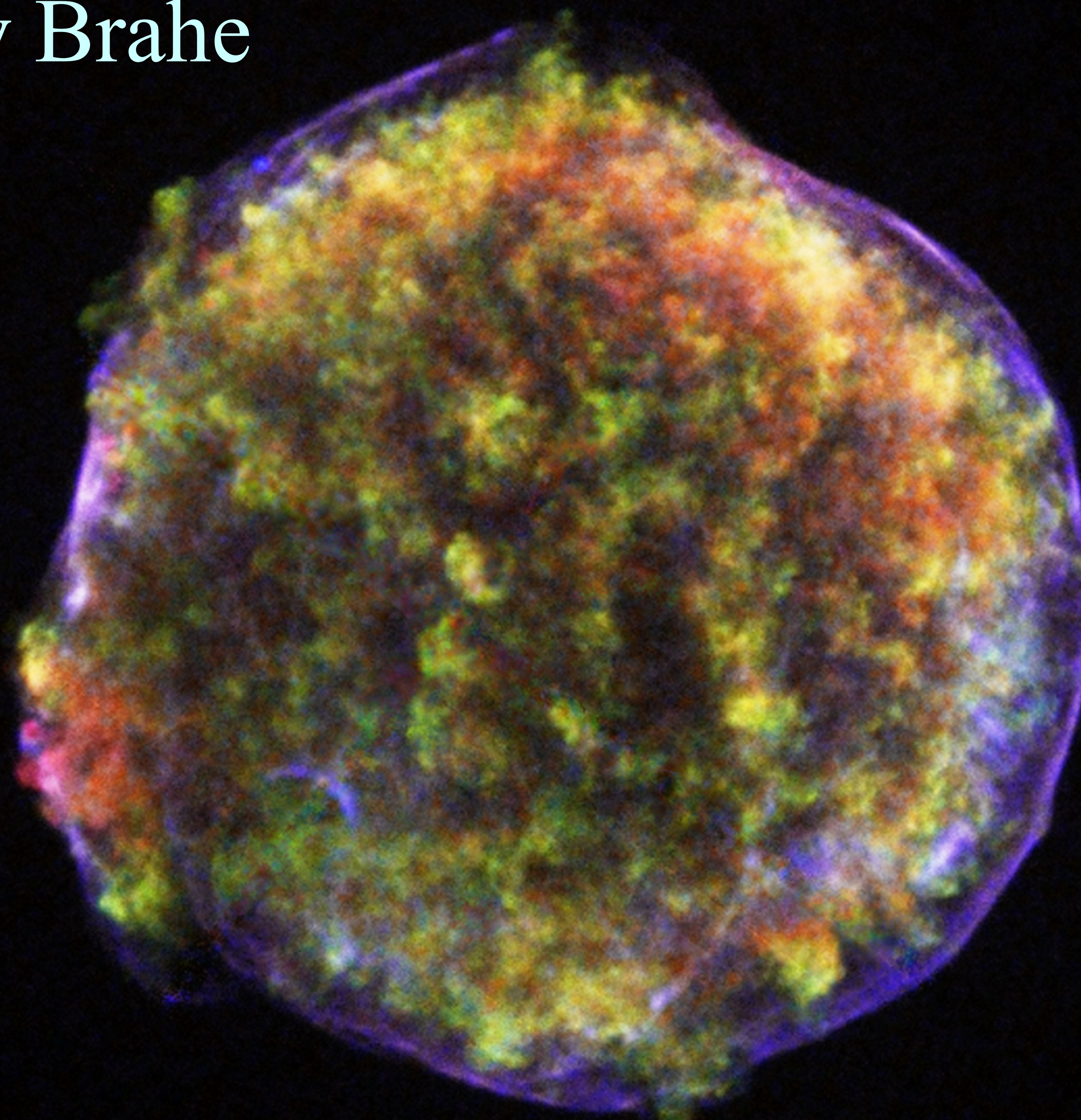
NOTHING!



Stage 4b: Supernova
The Iron core cannot support itself and the star implodes/rebounds.

The Crab Nebula: A remnant from a supernova in 1054.

Observed by Brahe
in 1572




Kepler's supernova
remnant from 1604.

Iron Fusion

It takes energy to fuse Iron. So when Iron gets too hot and compressed, rather than providing energy to support the star, it begins fusion and *takes* energy away from the star.

The core collapses in less than 1 second!

Iron Fusion

The core collapses in less than 1 second!

When it becomes too compressed, protons and electrons combine to become neutrons.

However, neutrons do not want to combine, so they can support the core (at least for a short time) and the core rebounds- sending the shell exploding out into space.

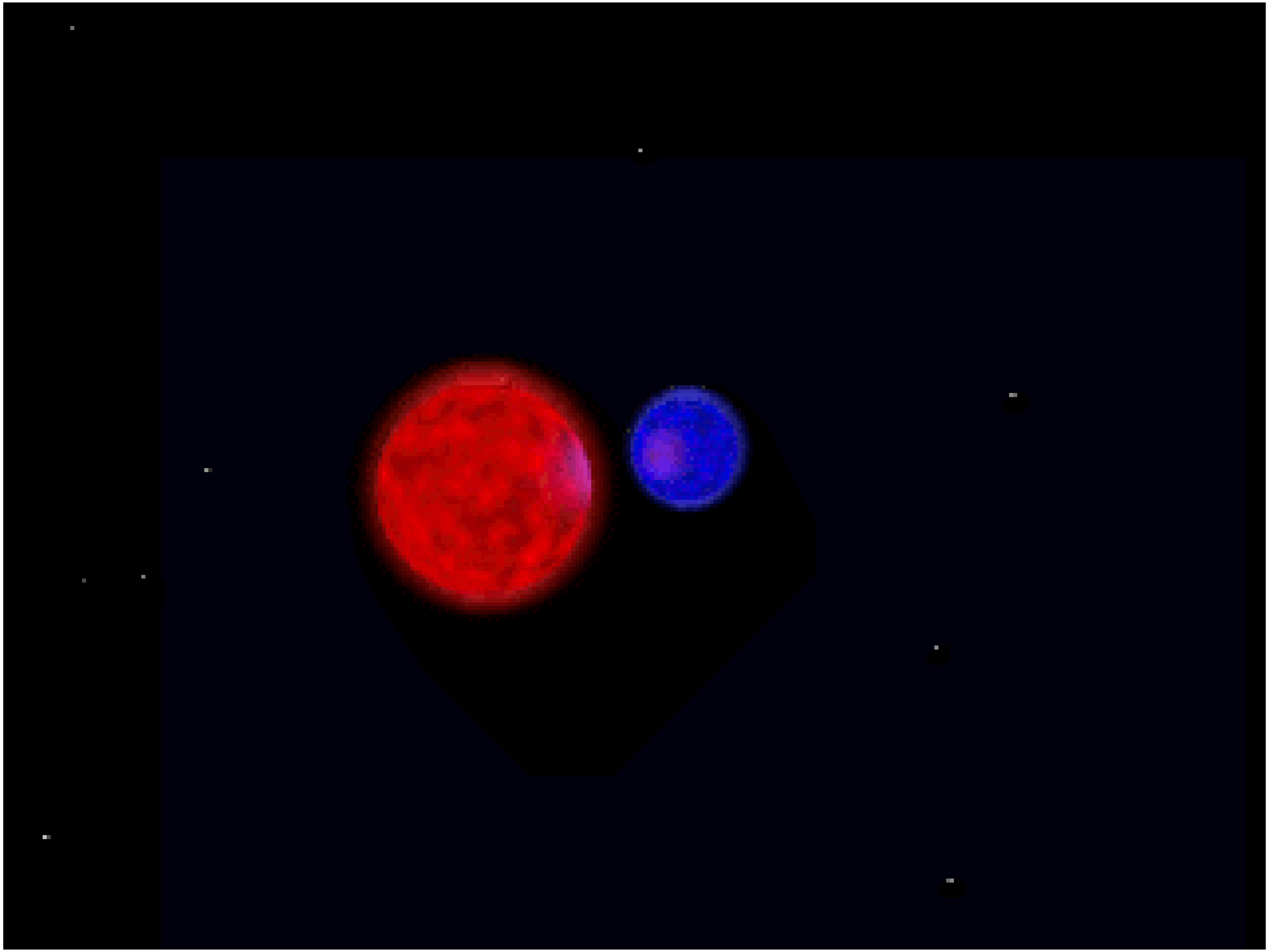
In 1987, a supernova went off in one of our neighboring galaxies. This is the closest supernova since the invention of the telescope.

Stellar recycling

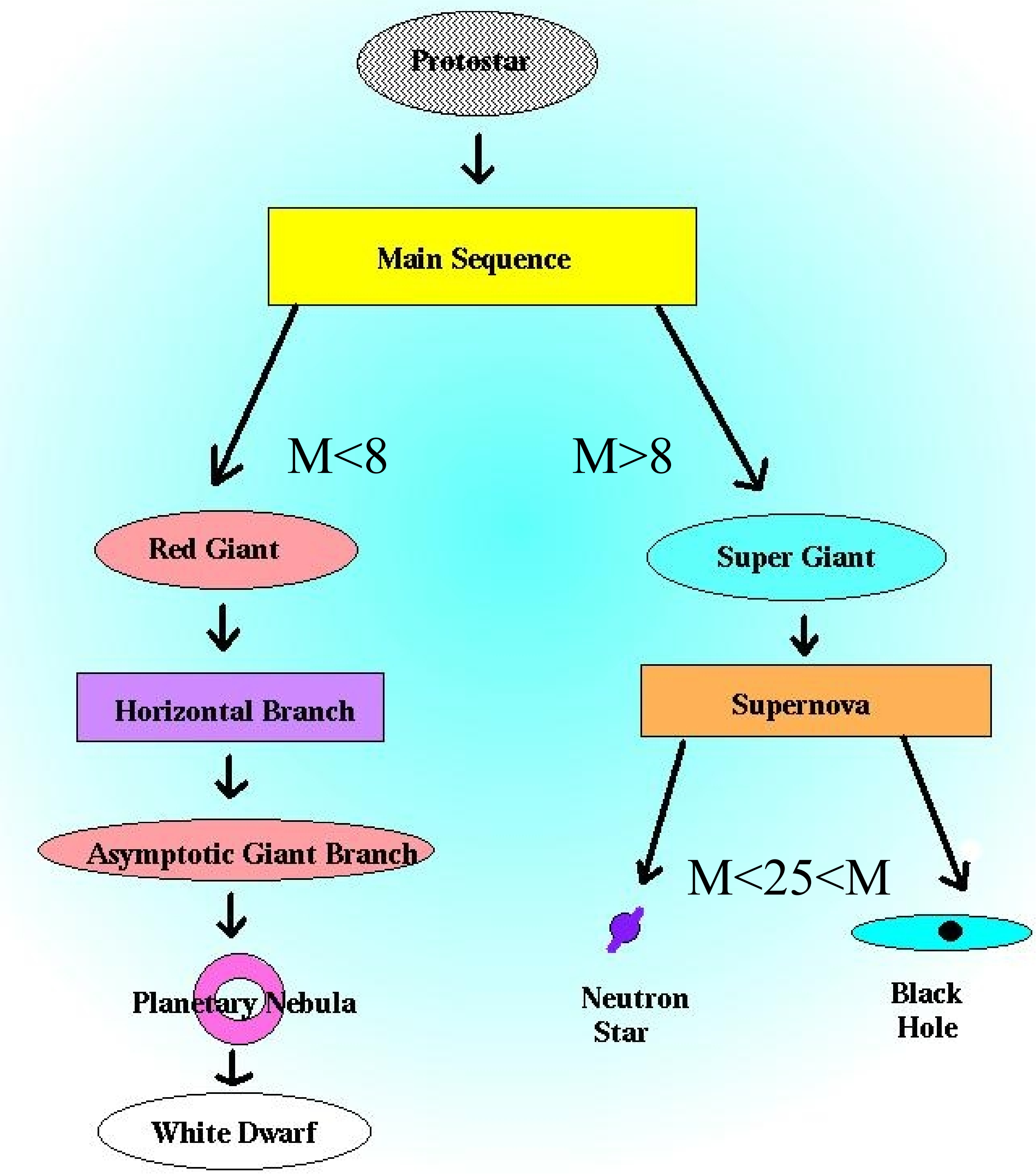
Supernova send many solar masses of material back out into space, for future generations of stars and planets to use.

Supernova can create *any* element as atoms are smashing together at billions of degrees K.

A really interesting (model) binary



But what's left after the supernova of a massive star?



Protostar
Main Sequence
M<8
M>8
Red Giant
Super Giant
Horizontal Branch
Supernova
Asymptotic Giant Branch
M<25<M
Planetary Nebula
Neutron Star
Black Hole
White Dwarf

But what's left after the supernova of a massive star?

- A Neutron Star: Main sequence mass up to 25 solar masses.
- A Black Hole: Main sequence mass greater than 25 solar masses, there is no stopping the collapse. It will become a black hole.

End States of Stars

For main sequence stars with more than 8, but less than 25 solar masses:

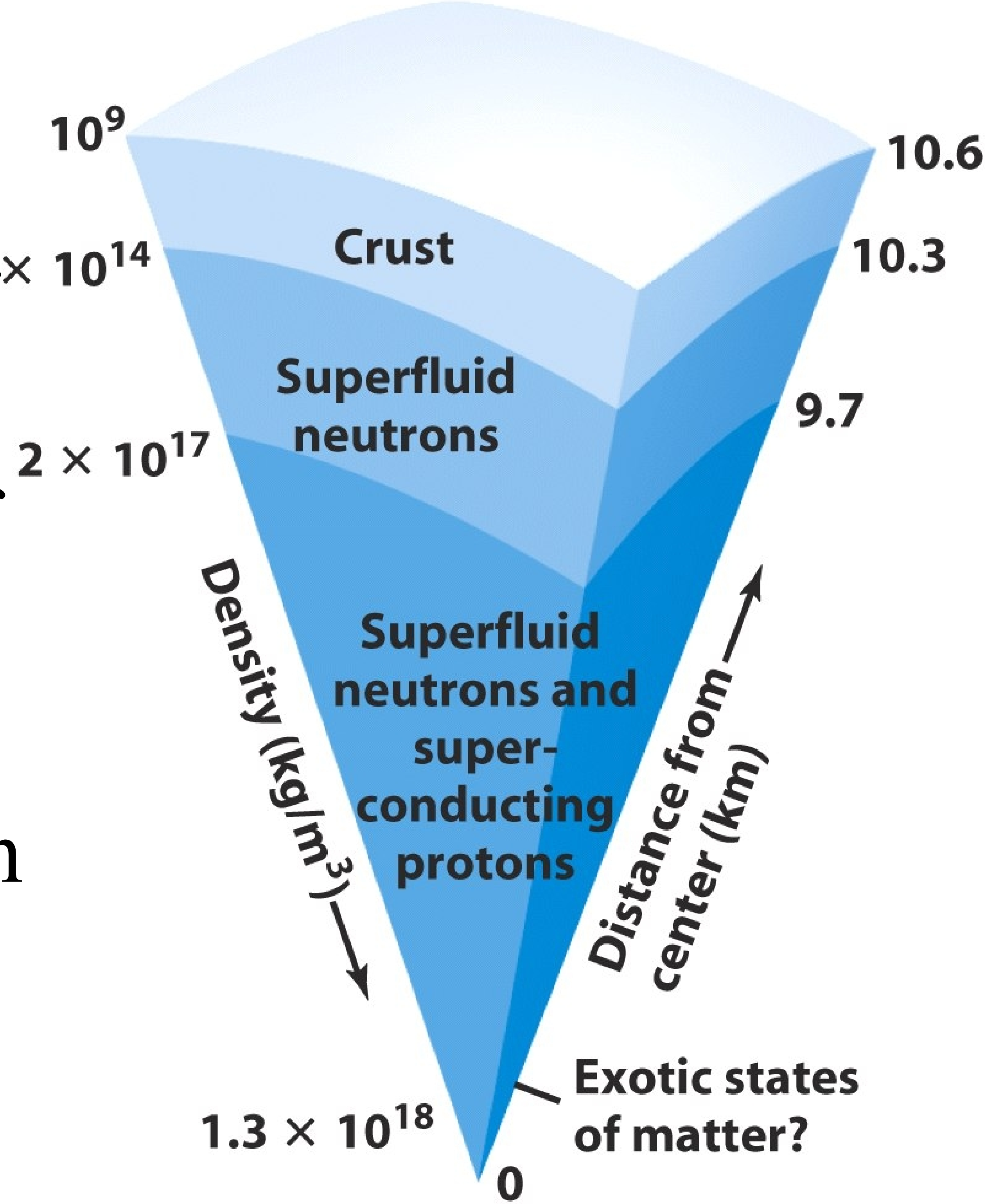
-They end up as Neutron Stars.

-10 to 30km across.

-Neutron stars have an average mass of 1.4 solar masses.

-Neutron stars cannot get larger than about 2.5 solar masses.

The structure of neutron stars. A sugar lump of this matter on Earth would weigh 400 billion tons.

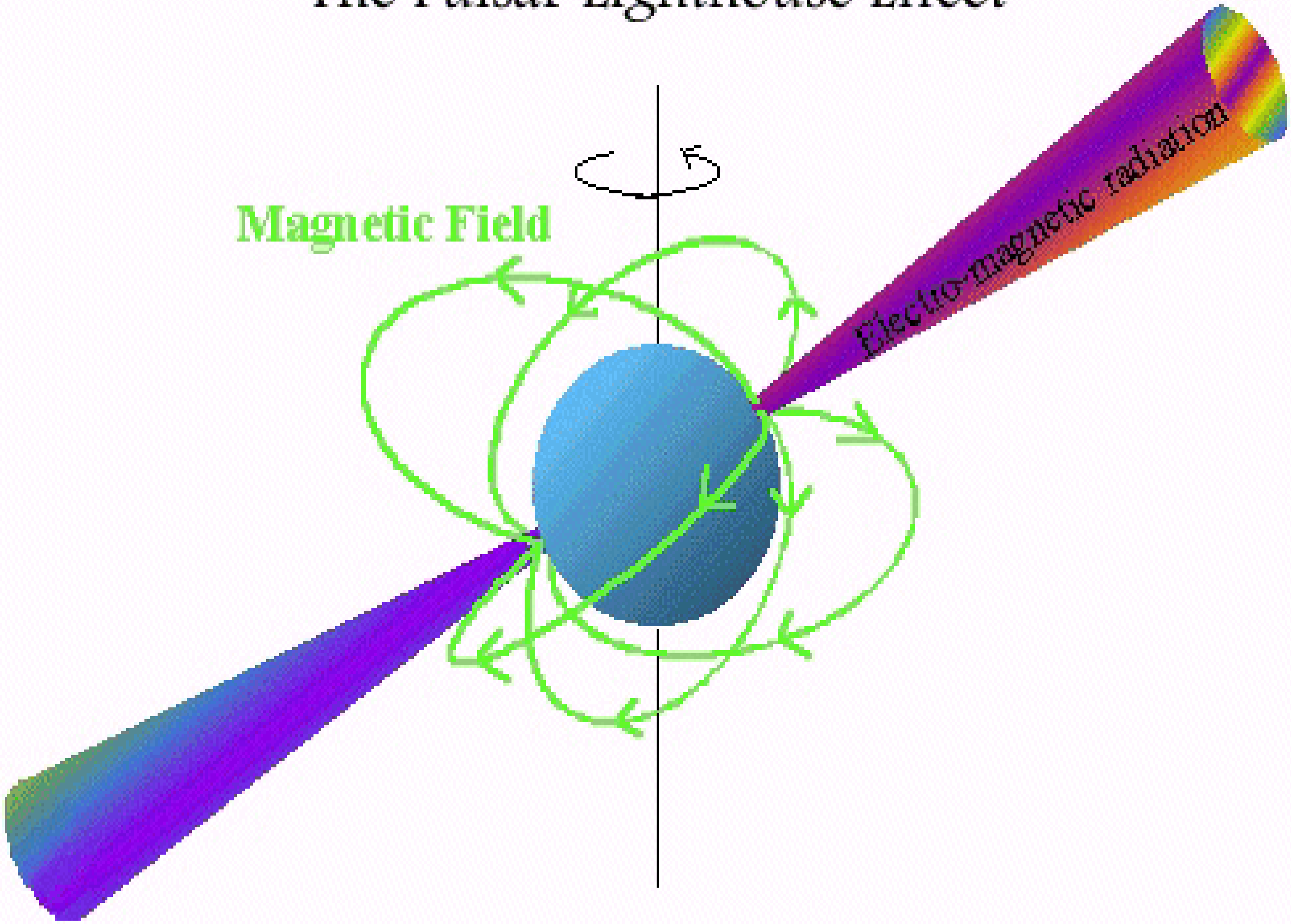


How do you detect something 20km across?
LGM

How do you detect something 20km across?
Pulsars

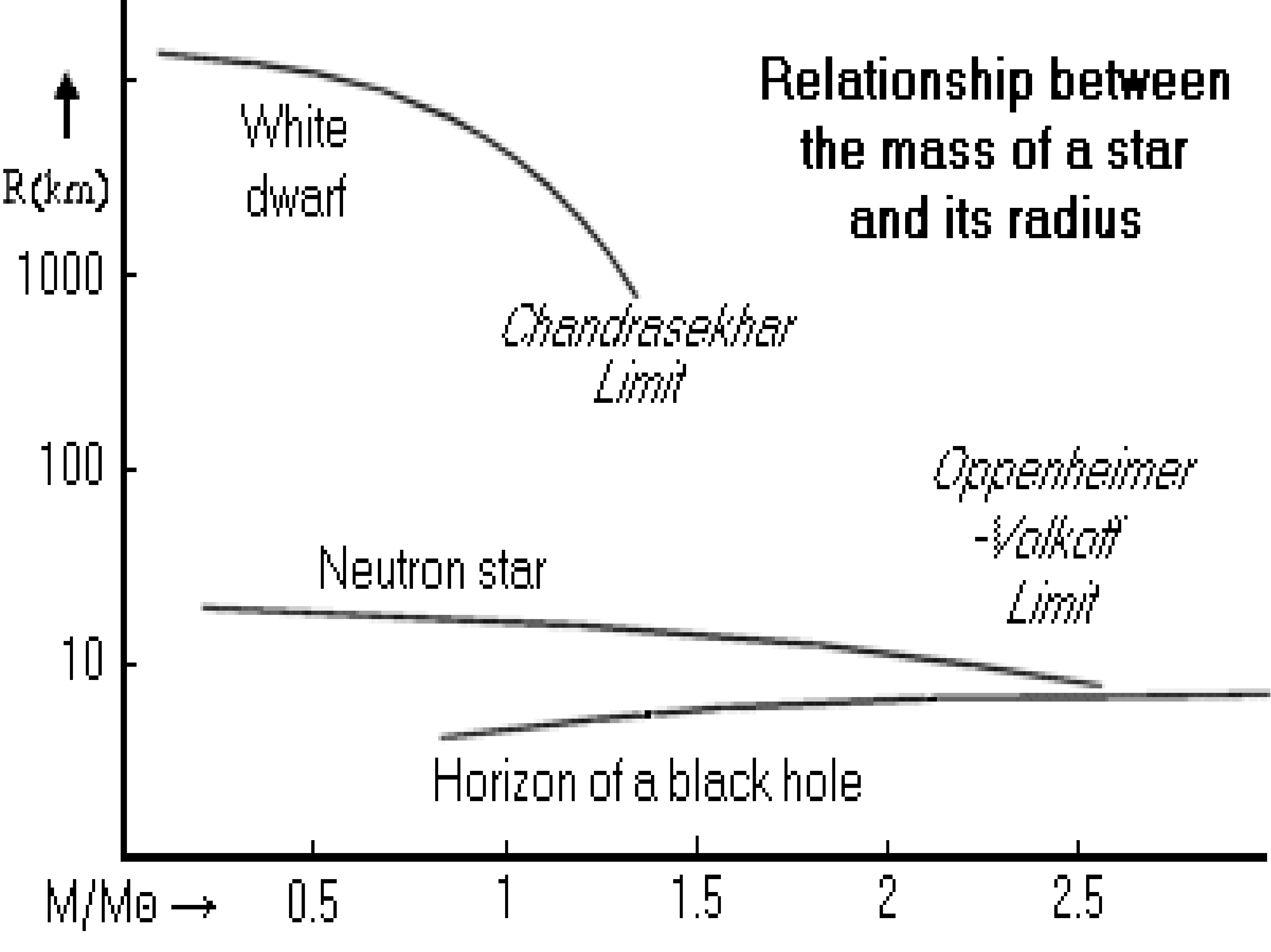
- A special kind of neutron star that "beams" radio waves in our direction.
- Spin (on average) once per second.
- No pulsars spin slower than every 5 seconds
- Strong magnetic fields cause the "beam"

The Pulsar Lighthouse Effect



Why do pulsars spin so fast?

Why don't pulsates 'pulse' longer than every 5 seconds?



Relationship between the mass of a star and its radius
R(km)
1000
100
10
White dwarf
Chandrasekhar Limit
Oppenheimer -Volkoff Limit
Neutron star
Horizon of a black hole
M/Mʘ →
0.5
1
1.5
2
2.5

Neutron stars can exist in pairs.

They have been used to (successfully) test the theory of general relativity.