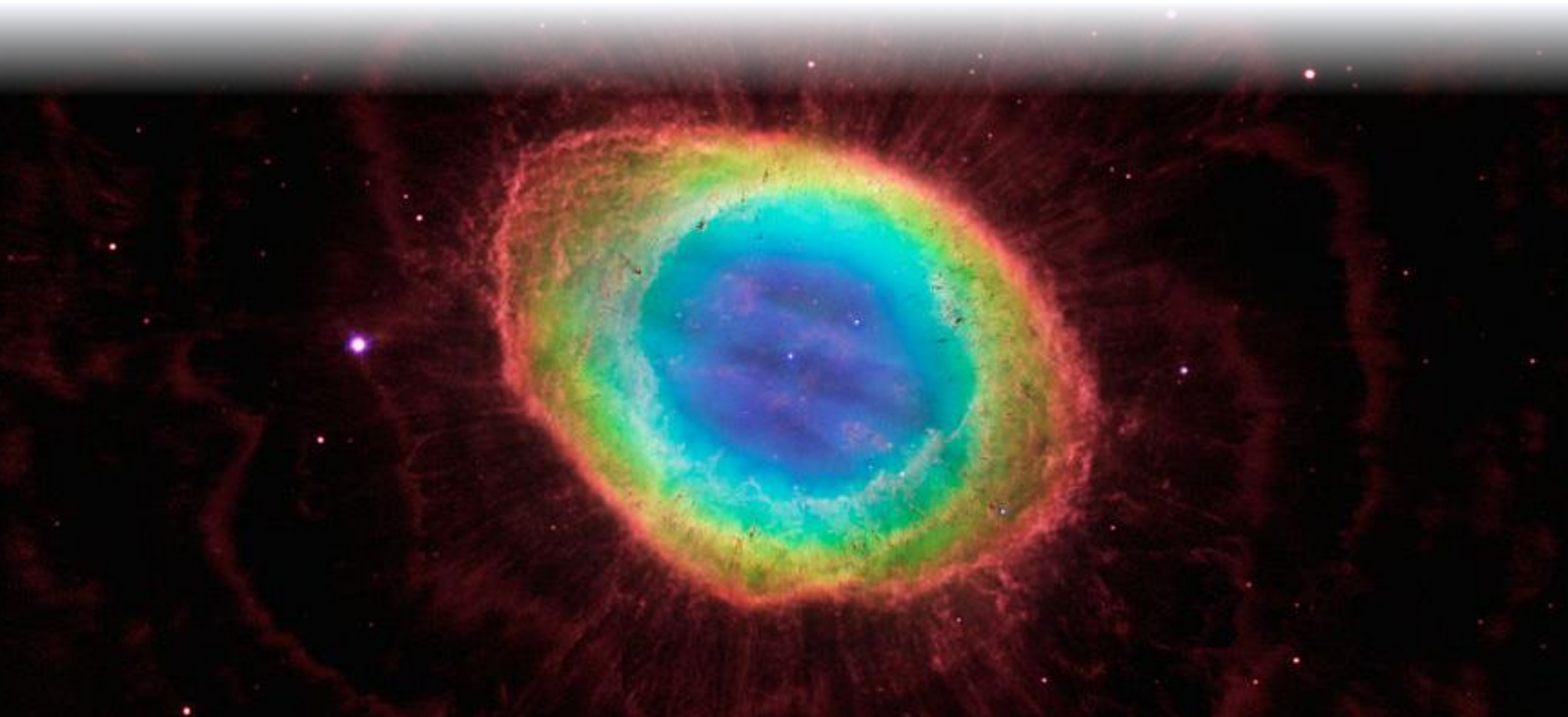
OUR PLACE IN THE UNIVERSE(S)

11: The Evolution of Stars



LECTURE OVERVIEW

Lecture 11:

The Evolution of Stars

By the end of this lecture, you should know…

- How Sun-like main sequence stars evolve
- How more massive star evolve
- How black holes & neutron stars form
- What a supernova is
- Some (more) of the nuclear processes occurring within stars

Stellar Evolution

The fate of all stars are is pre-determined by its mass, which is locked in place when the star forms

Each star is unique

Low & high mass stars evolve differently

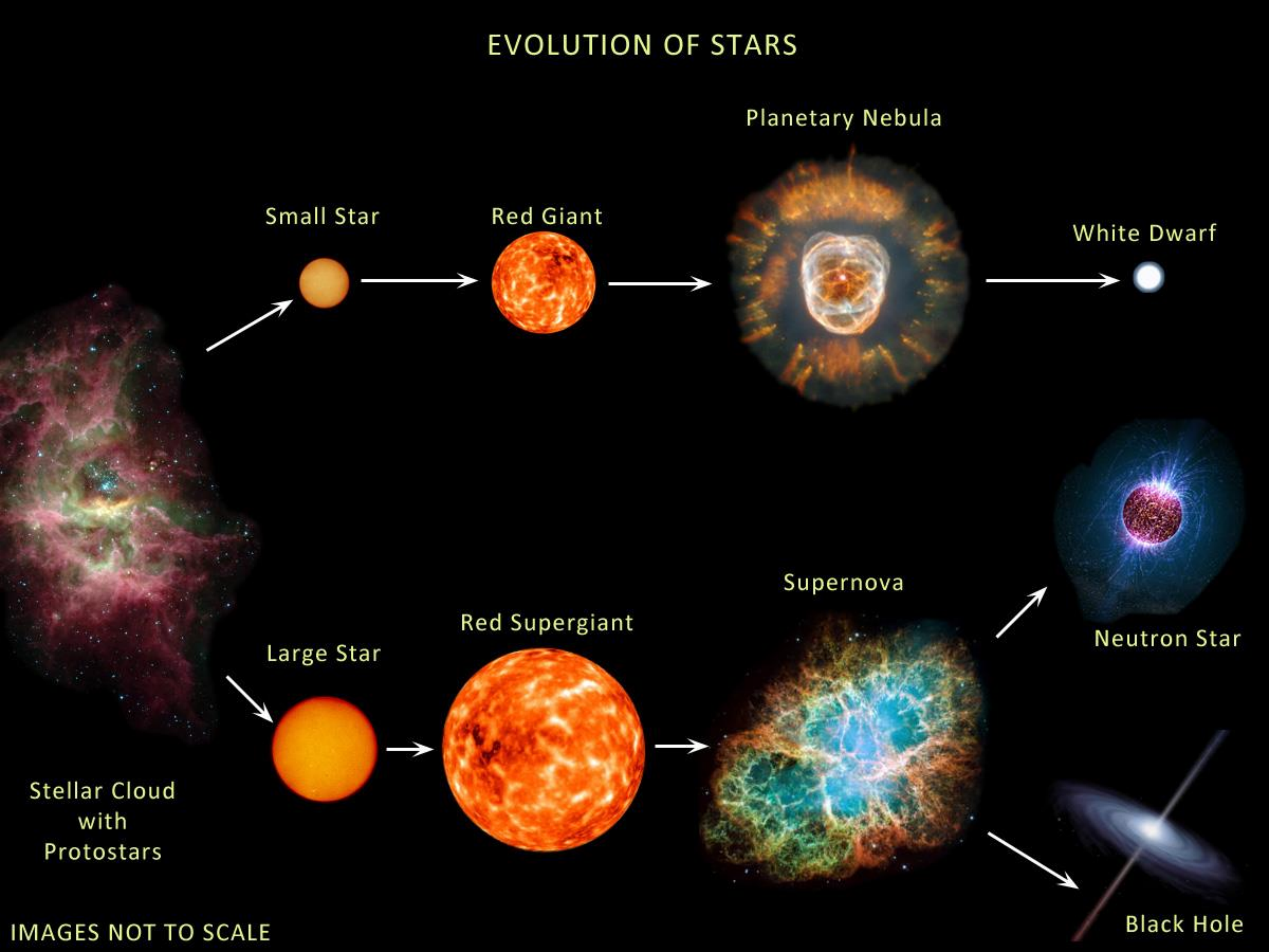
More mass leads to…

» stronger gravity

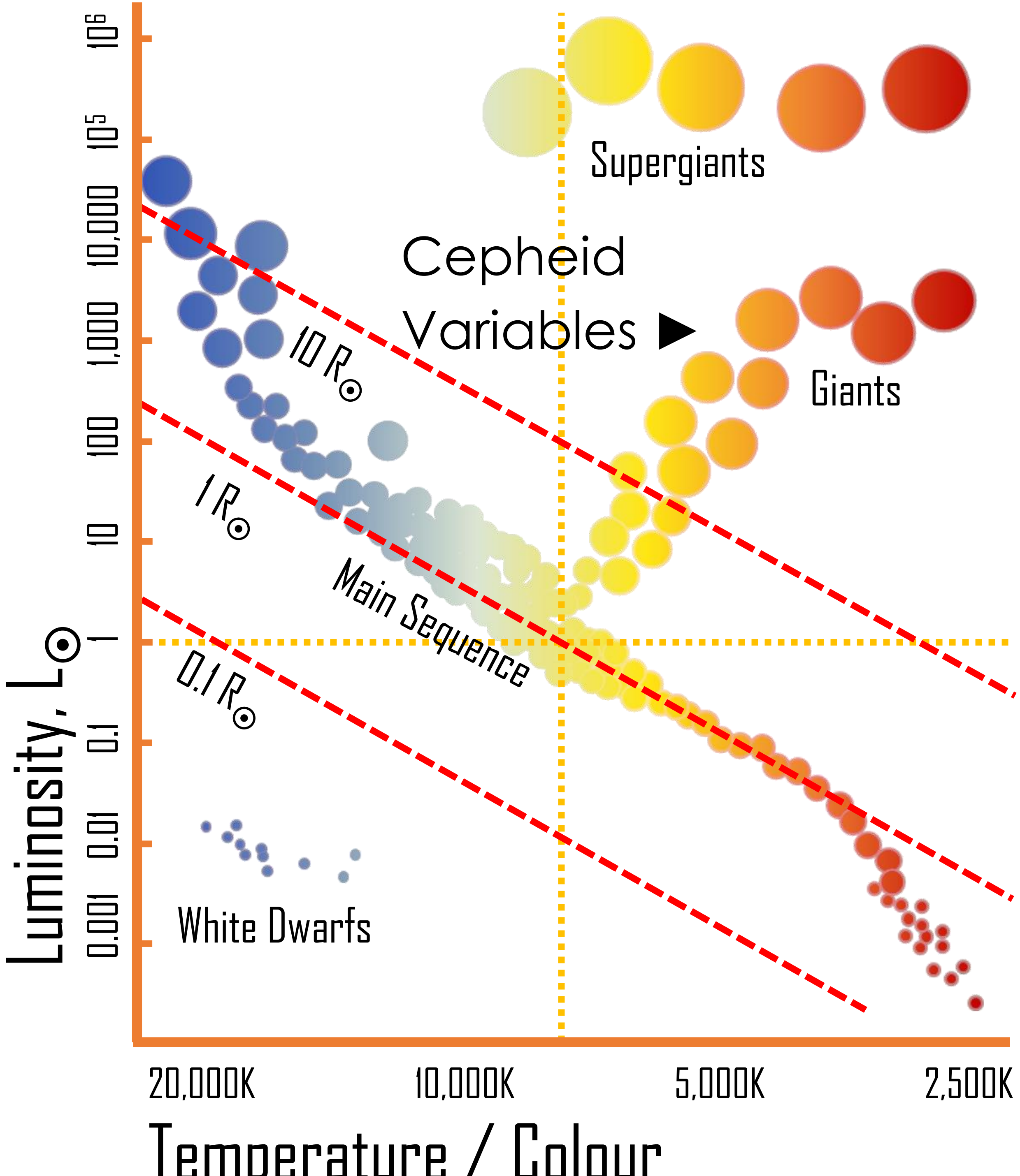
» higher temperature & pressure

» faster nuclear reaction rates

» higher luminosity


EVOLUTION OF STARS
Planetary Nebula
Small Star
Red Giant
White Dwarf
Supernova
Red Supergiant
Neutron Star
Large Star
Stellar Cloud
with
Protostars
Black Hole
IMAGES NOT TO SCALE

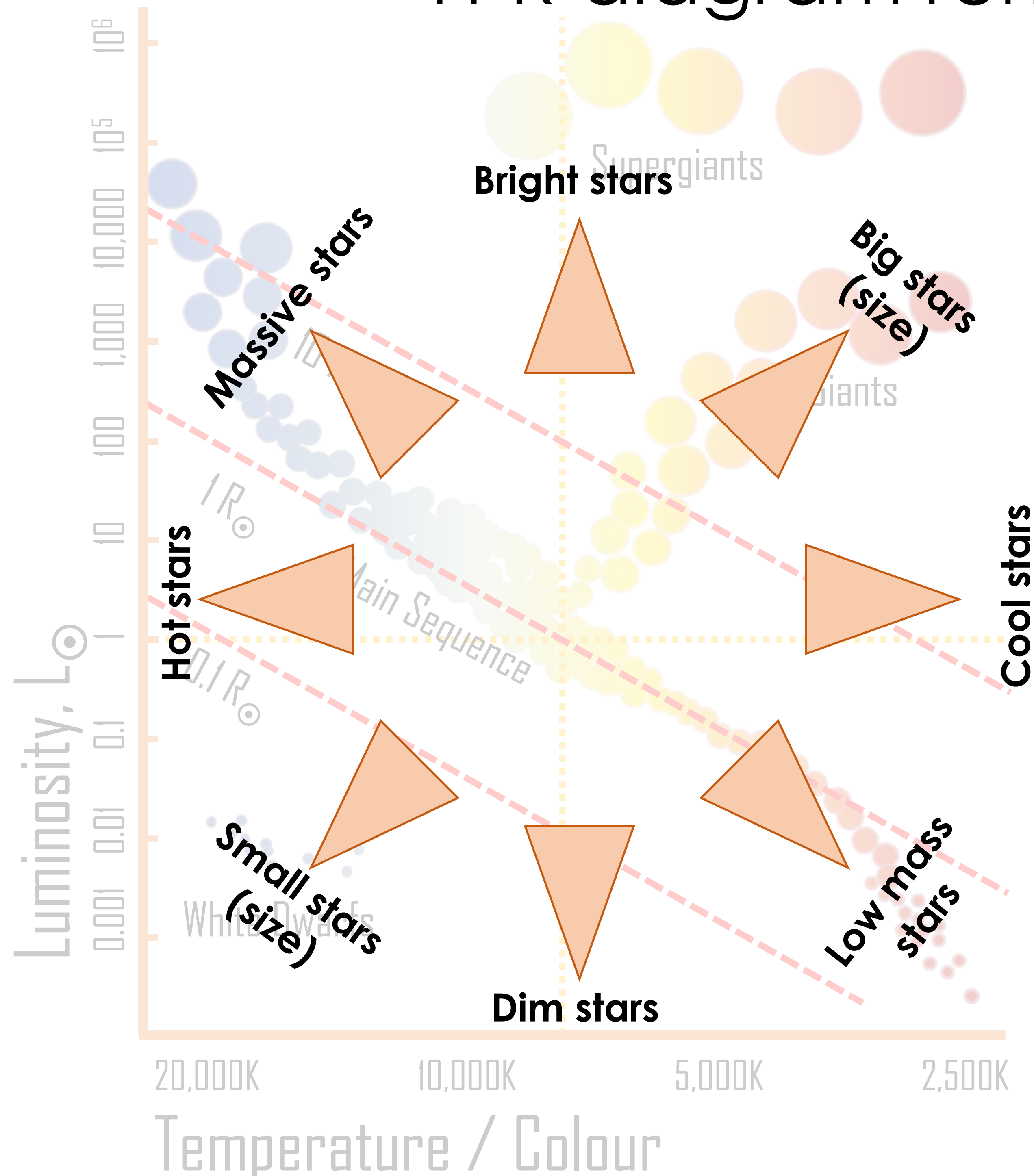
H-R Diagram

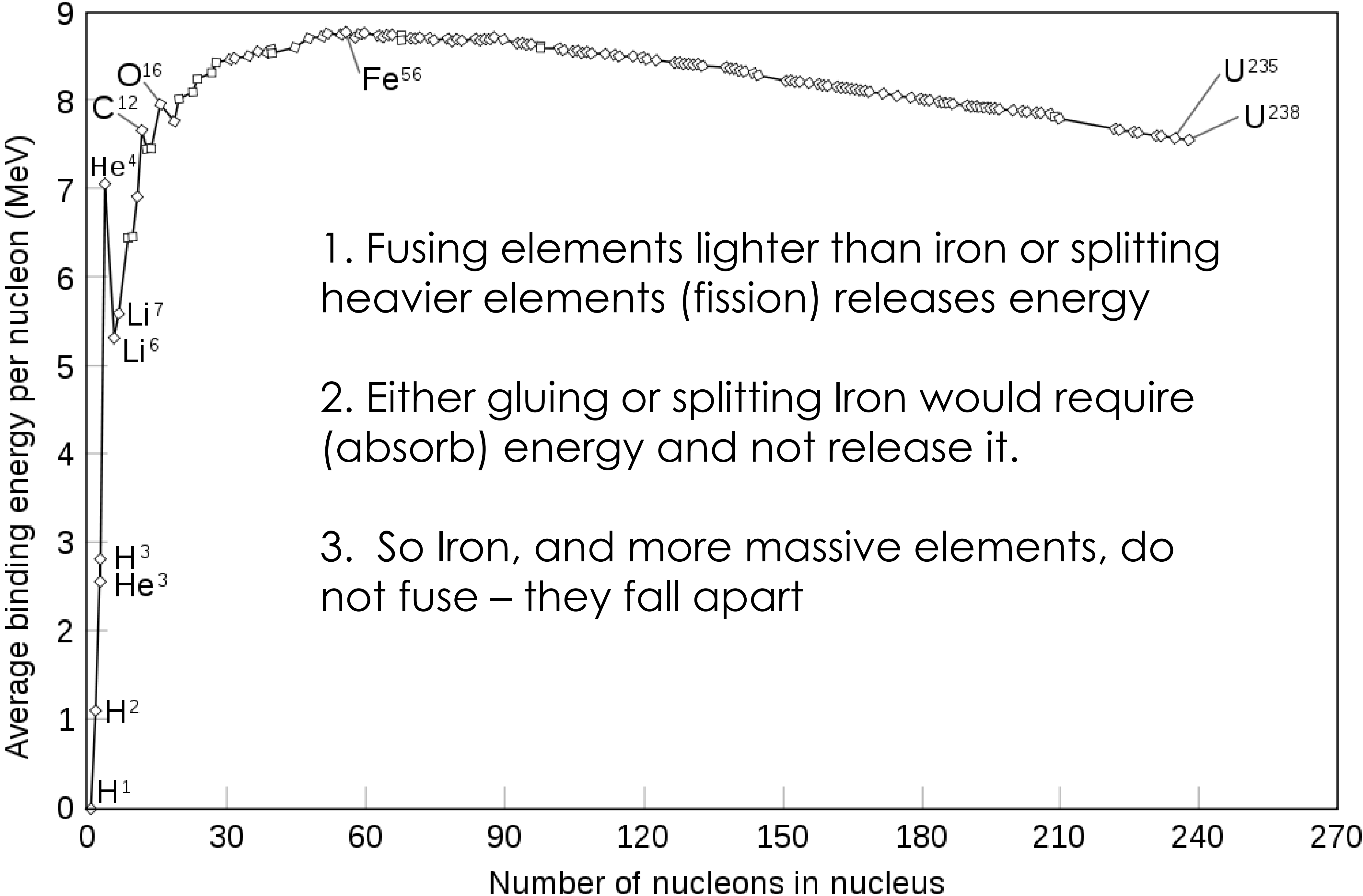


◄Cepheid

H-R diagram reminder…

H-R Diagram



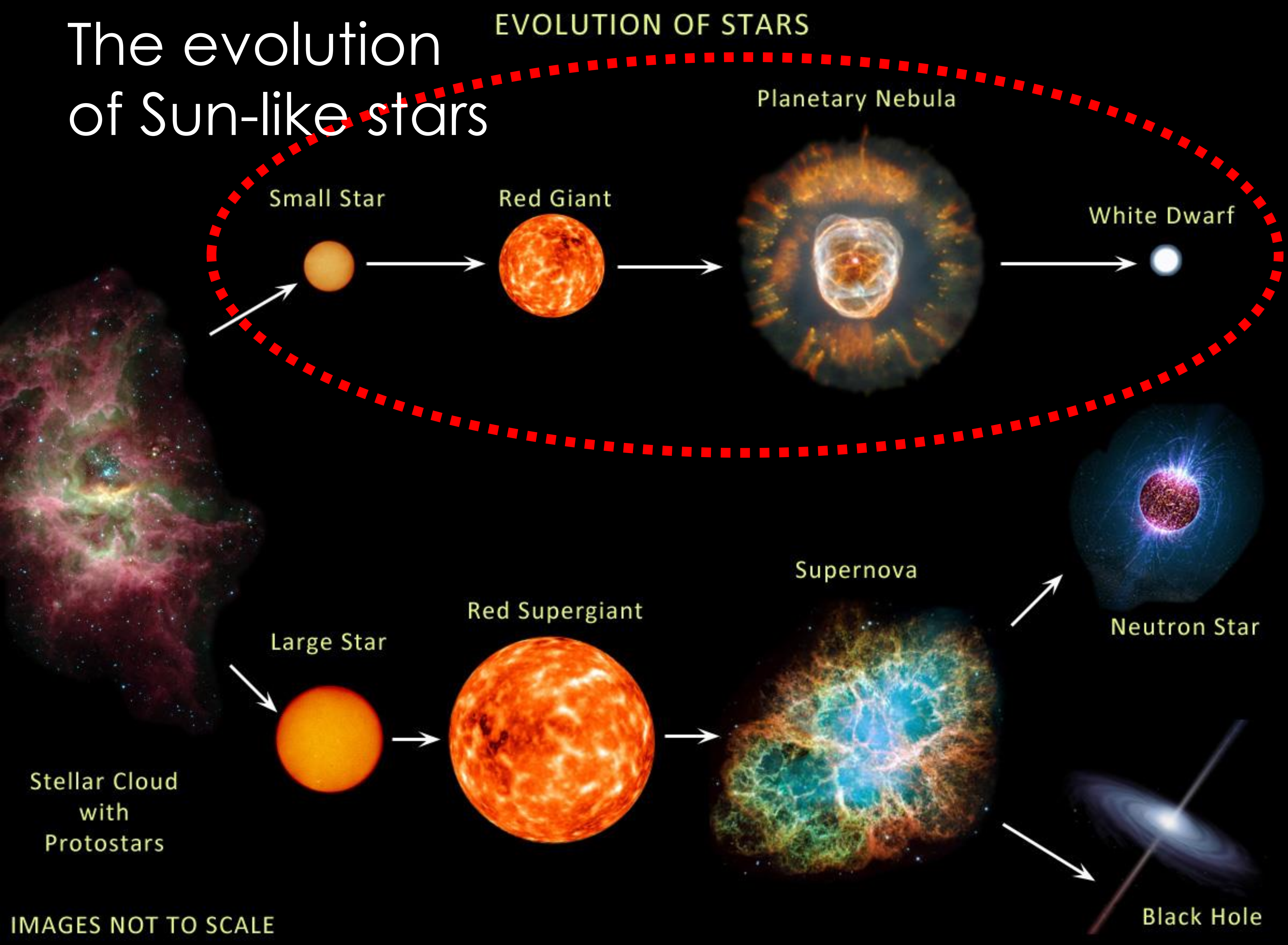


1. Fusing elements lighter than iron or splitting heavier elements (fission) releases energy

2. Either gluing or splitting Iron would require (absorb) energy and not release it.

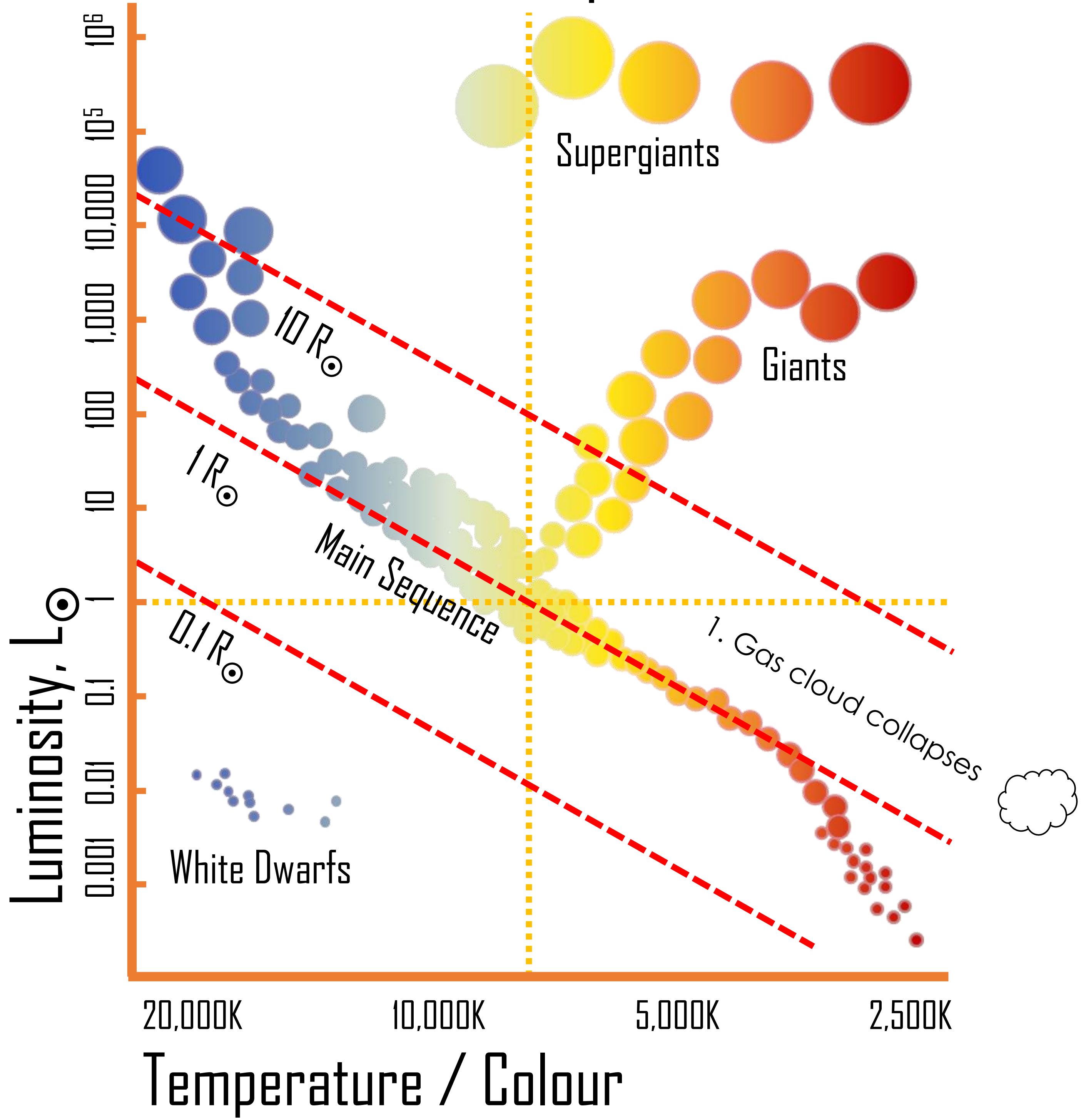
3. So Iron, and more massive elements, do not fuse – they fall apart

The evolution of Sun-like stars



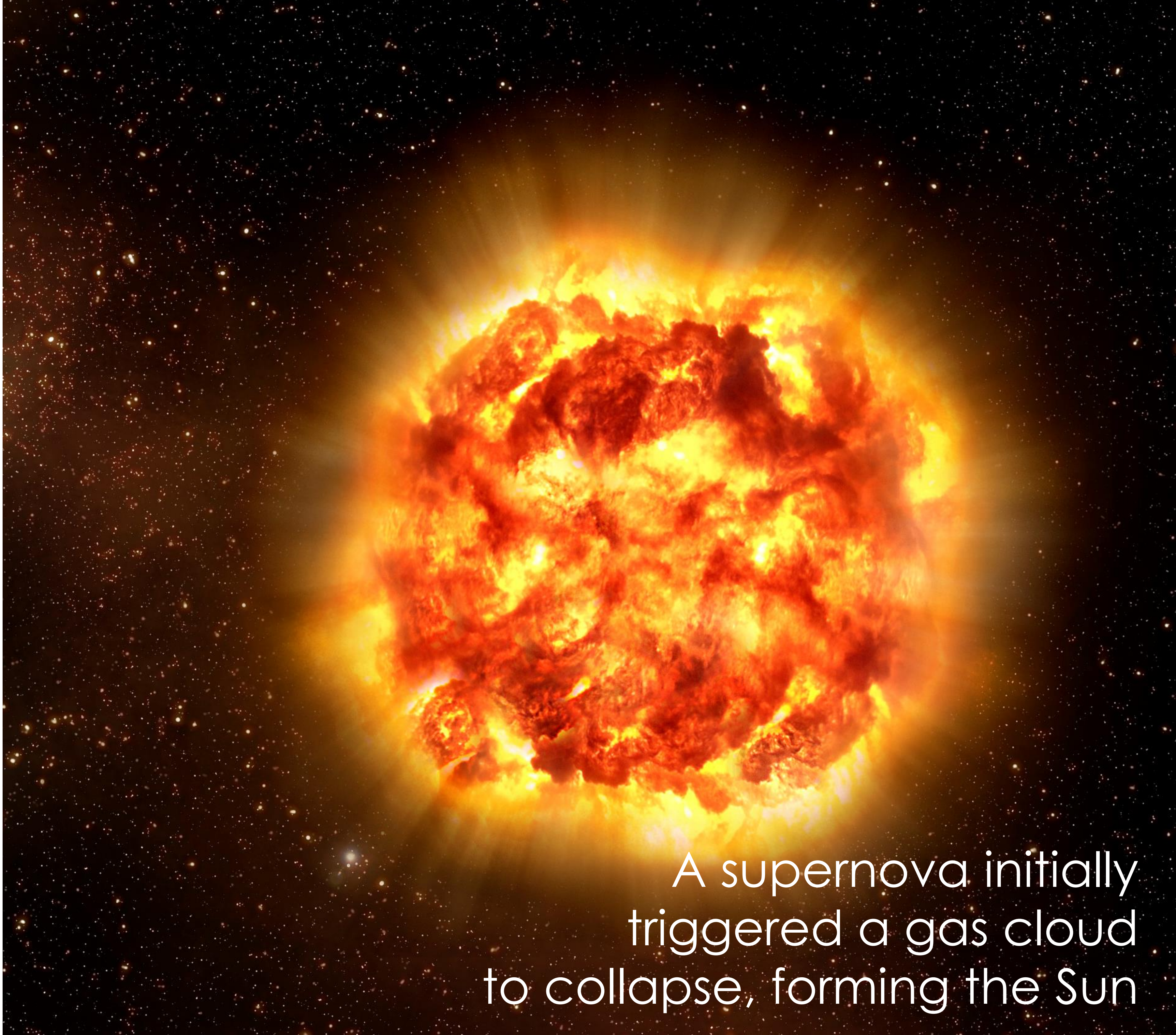
The Sun's Evolution: Step 1

Stellar Evolution



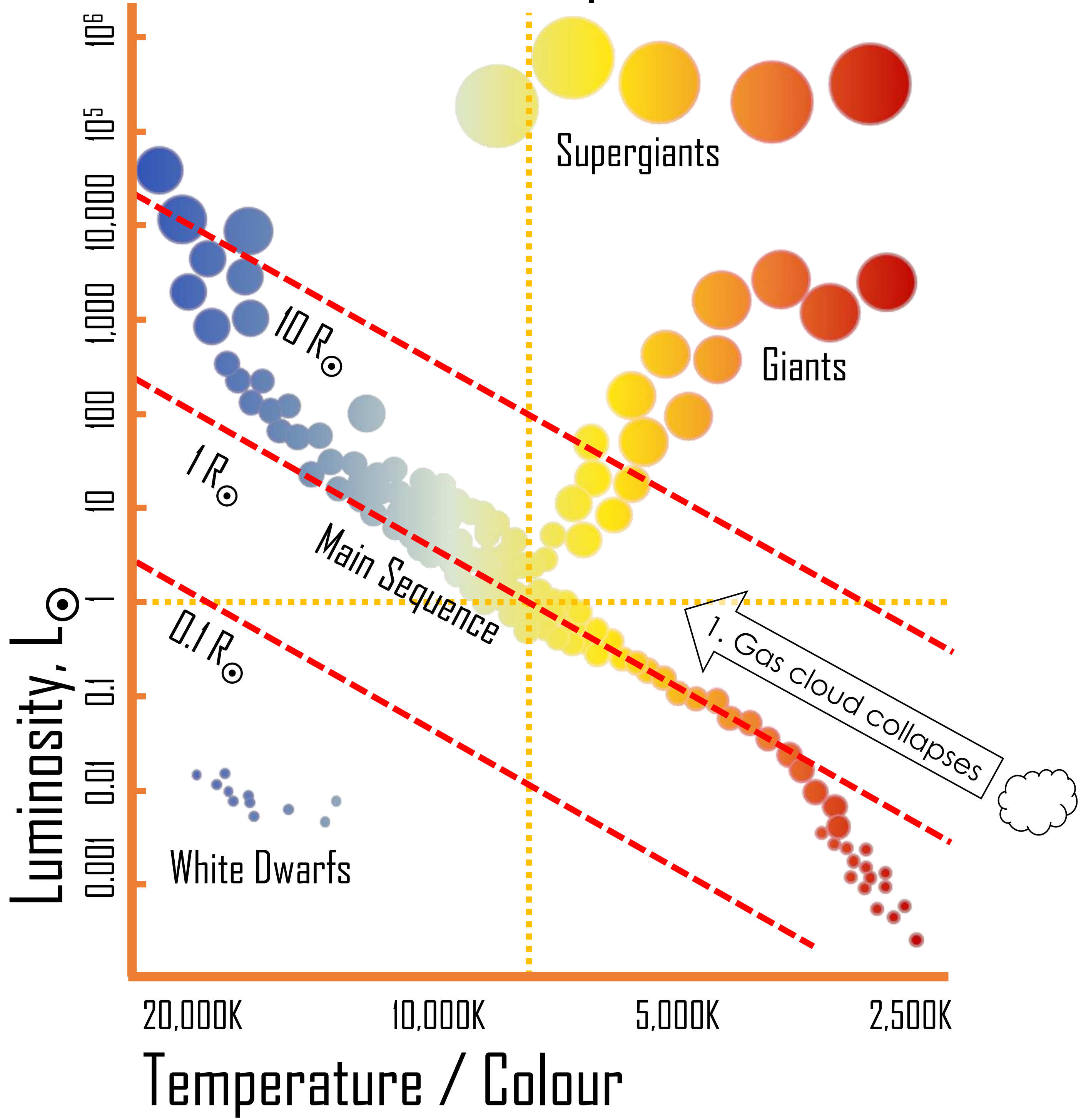

UK Astrophysical Fluids Facility
Stars form from a giant gas cloud…
Matthew Bate
University of Exeter
www.ukaff.ac.uk

Stellar Evolution



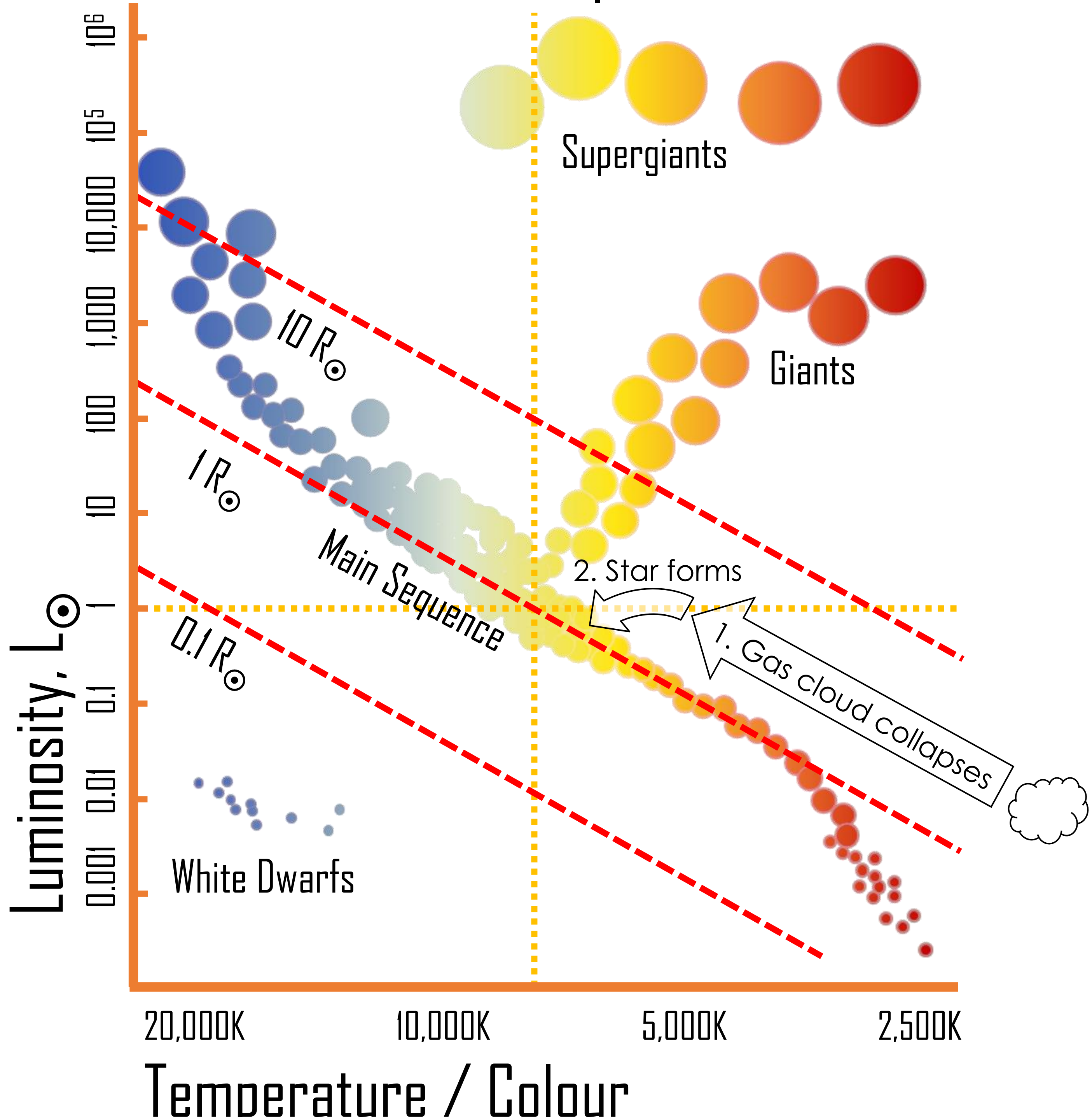
The Sun's Evolution: Step 1

Stellar Evolution



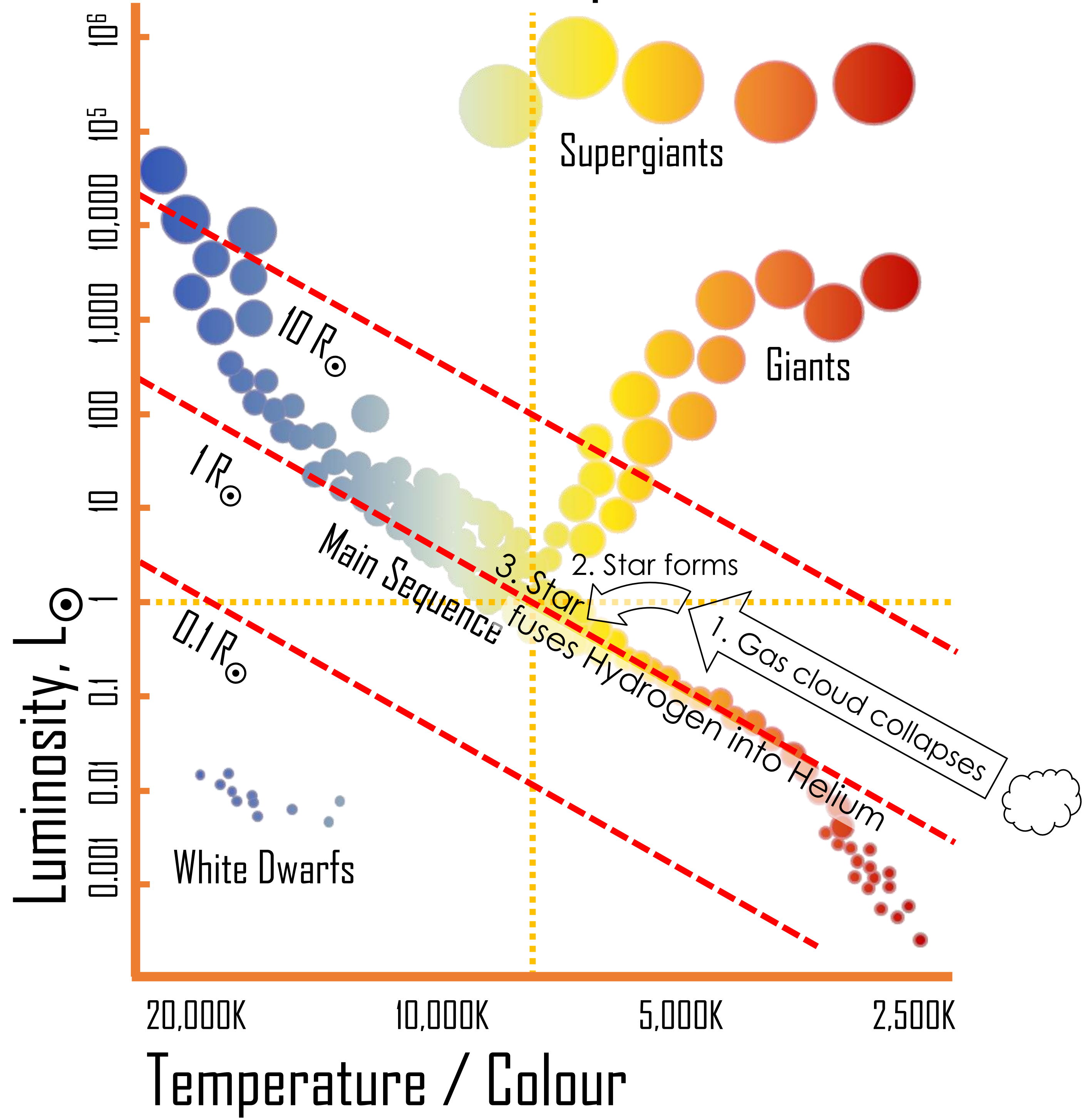
The Sun's Evolution: Step 2

Stellar Evolution



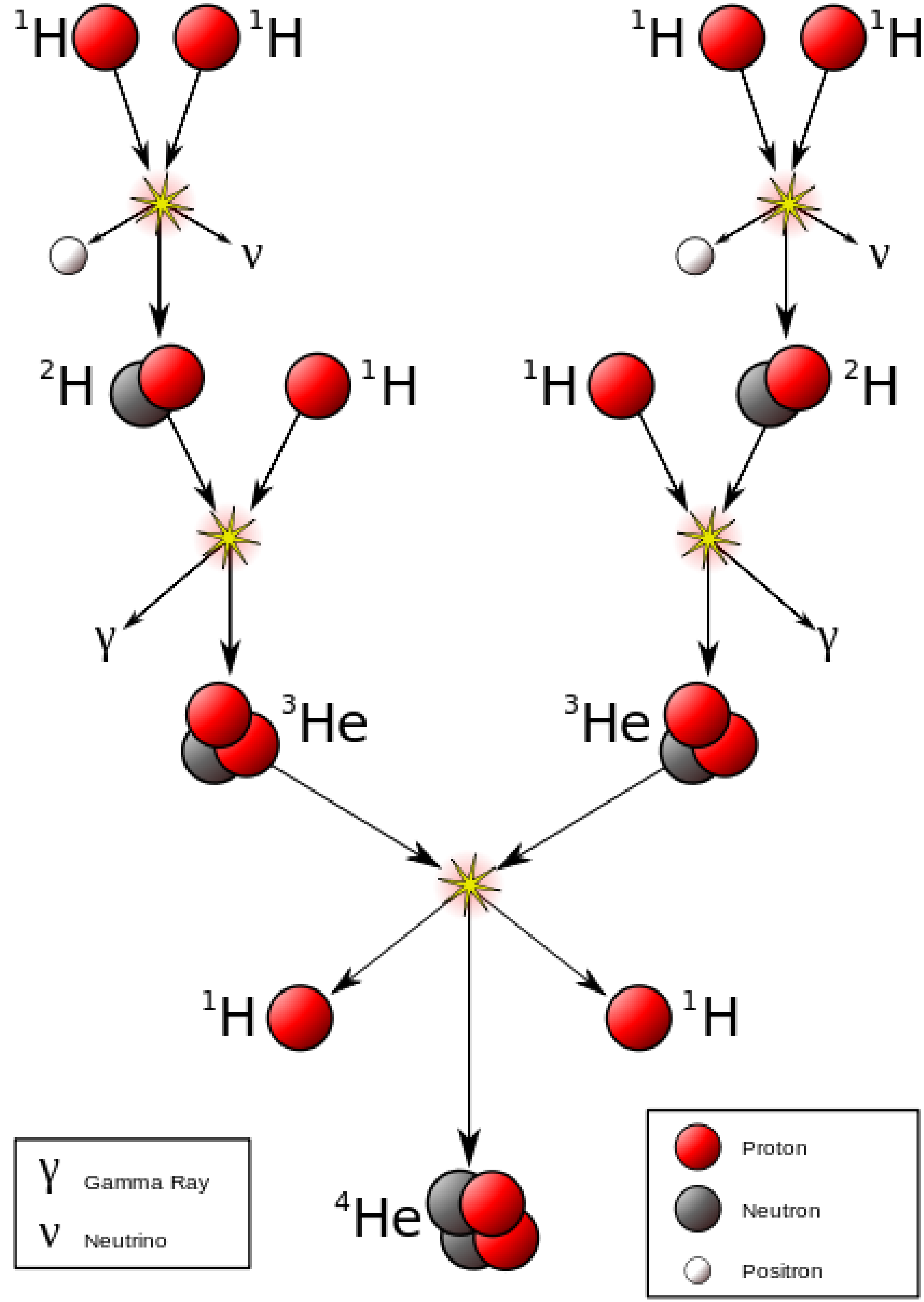
The Sun's Evolution: Step 3

Stellar Evolution



Main Sequence Evolution

In a main sequence star, Hydrogen is fused into helium, releasing energy and increasing a star's luminosity



Helium cannot fuse into heavier nuclei in a main sequence star - they're simply not hot enough to overcome the electrostatic repulsion.

(Positively charged protons inside an atom repel each other, and this is 4x stronger for Helium compared to hydrogen.)

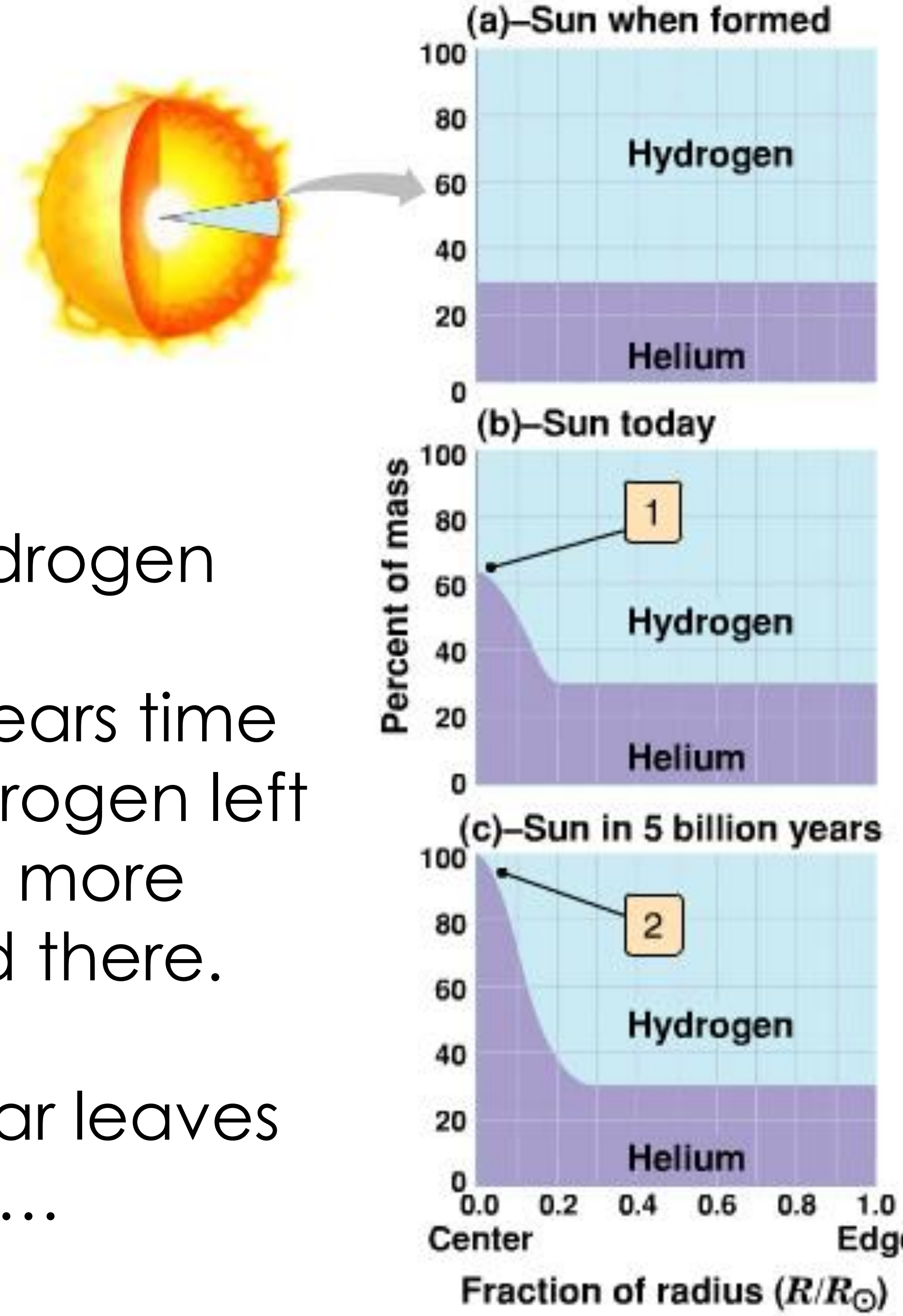
So the Helium made inside the star simply accumulates within the core of a star, like the ash in a fireplace.

Main Sequence Evolution

Today, the Sun's centre consists of 65% helium, 35% hydrogen

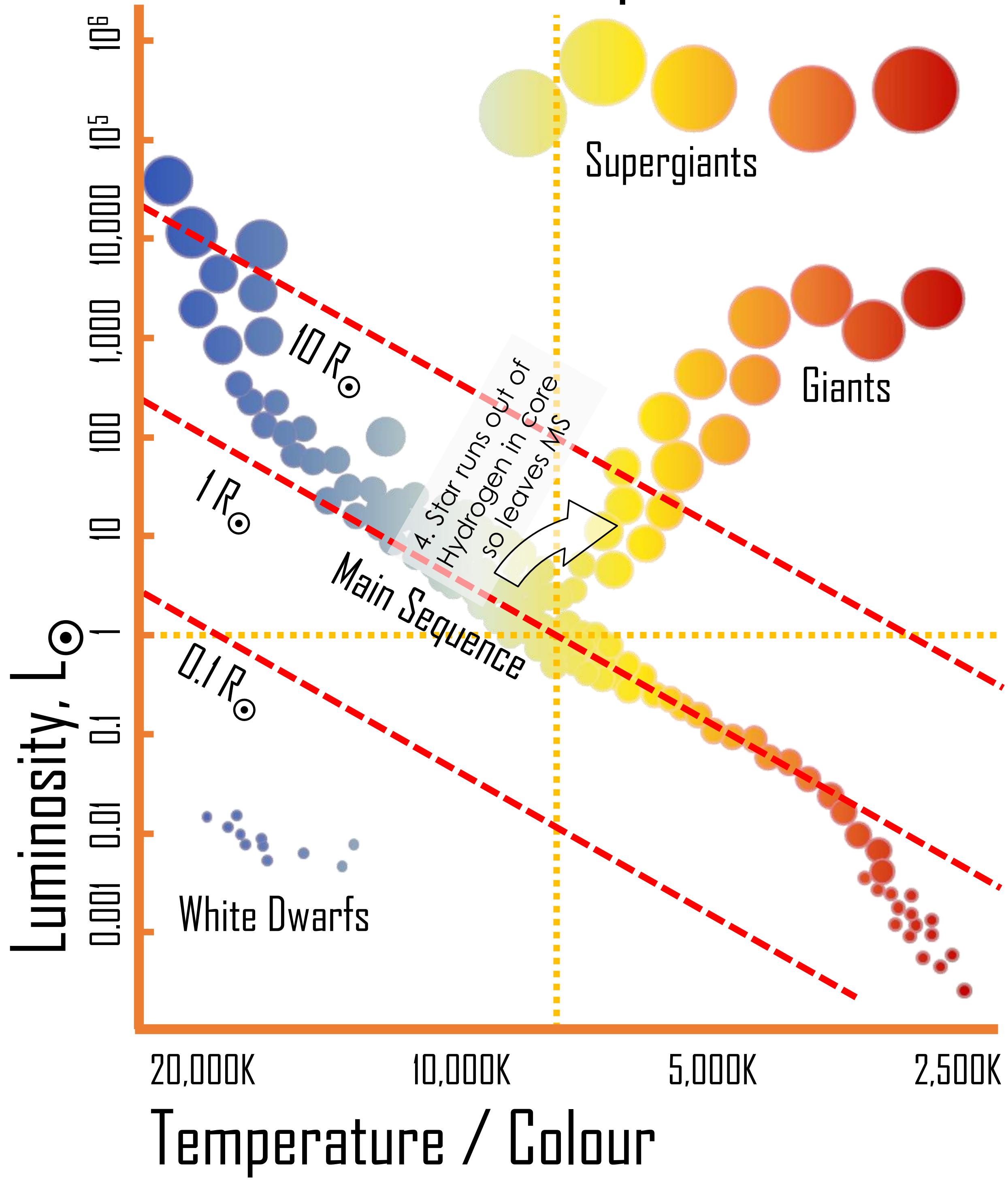
In about 5 billion years time there will be no hydrogen left at the centre, so no more energy is generated there.

At this point, the star leaves the main sequence…



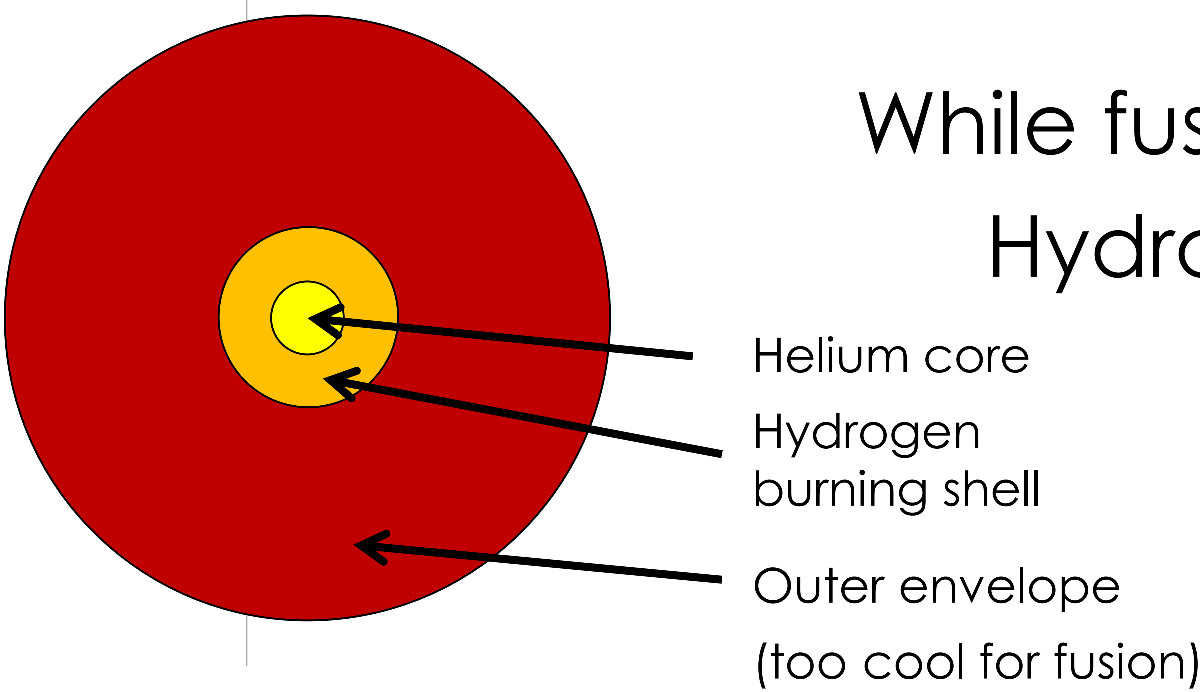
The Sun’s Evolution: Step 4

Stellar Evolution



The core eventually runs out of hydrogen fuel, & so cools & shrinks – gravity wins over the outward pressure of hot gas.

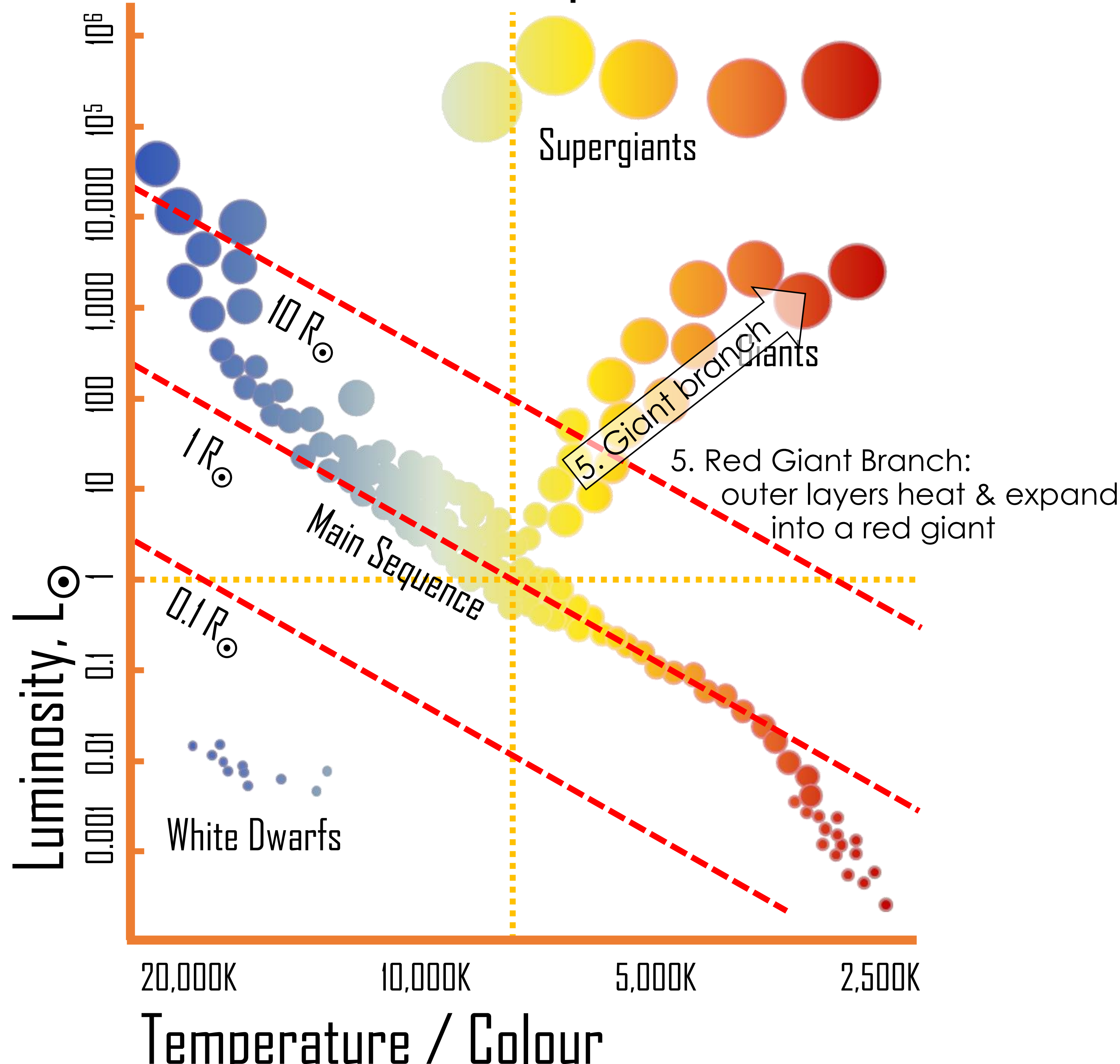
The Helium in the core of a Sun-like star becomes extremely dense (1000kg per cubic cm!) and *degenerate* *(see next lecture)*



While fusion stops in the core, Hydrogen still burns (fuses) into Helium in a shell around the core.

The Sun's Evolution: Step 5

Stellar Evolution



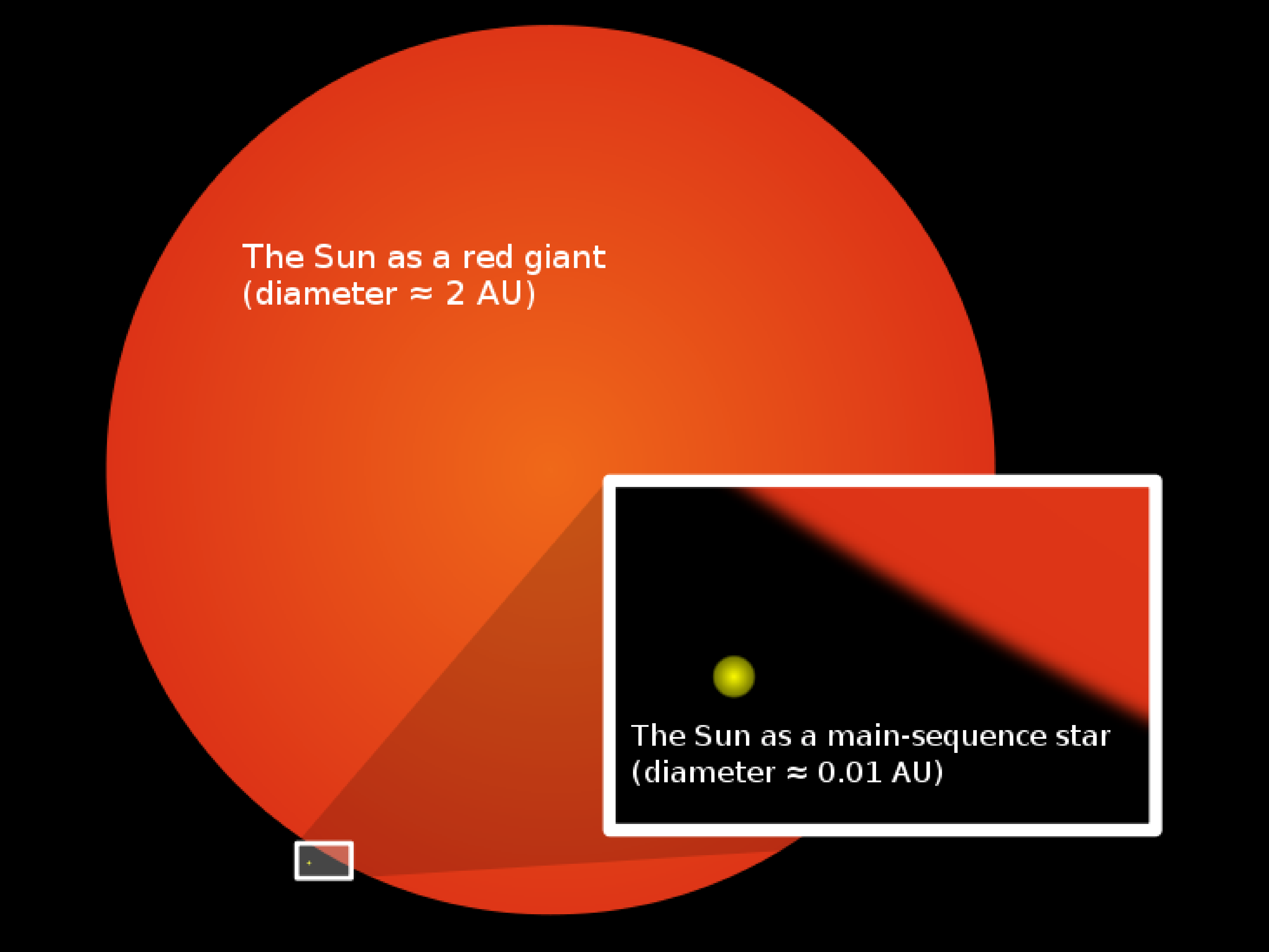
Red Giant Phase

Sun-like stars
Evolve into
Red Giant stars

As the core gets denser, it becomes solid, heats up, causing the surrounding layers to heat and the star (mainly the outer layers) to expand.

As the surface expands it becomes more luminous and cooler (by about 1000K)

200 million years after leaving the main sequence, the star becomes a red giant

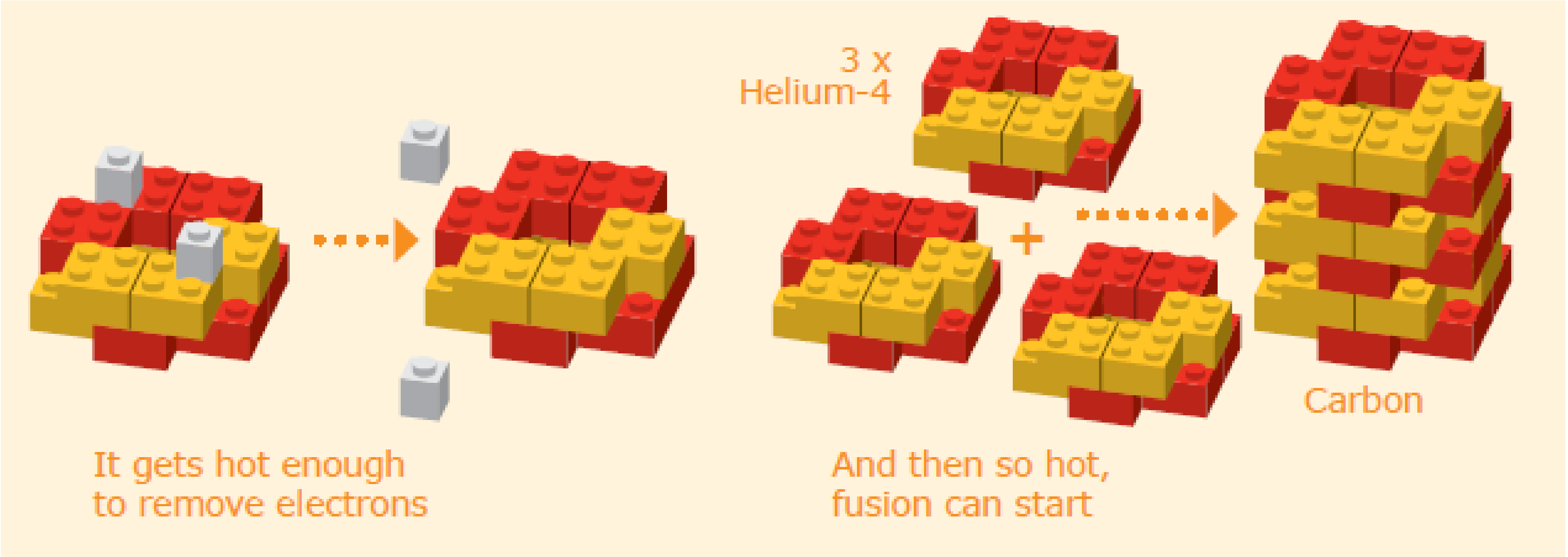

The Sun as a red giant
(diameter ≈ 2 AU)
The Sun as a main-sequence star
(diameter ≈ 0.01 AU)

Core Helium Flash

Eventually, thanks to Hydrogen burning in a shell around the core, the core temperature becomes hot enough for…

Helium to finally fuse into carbon!

This fusion heats the core allowing *even more* helium to fuse – a sudden runaway chain reaction!

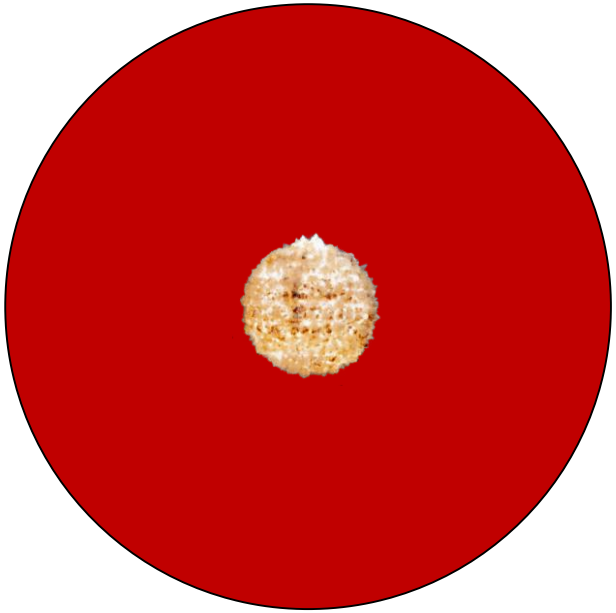


Core Helium Flash

Within *seconds*, temperature is high enough for thermal pressure to overcome gravity.

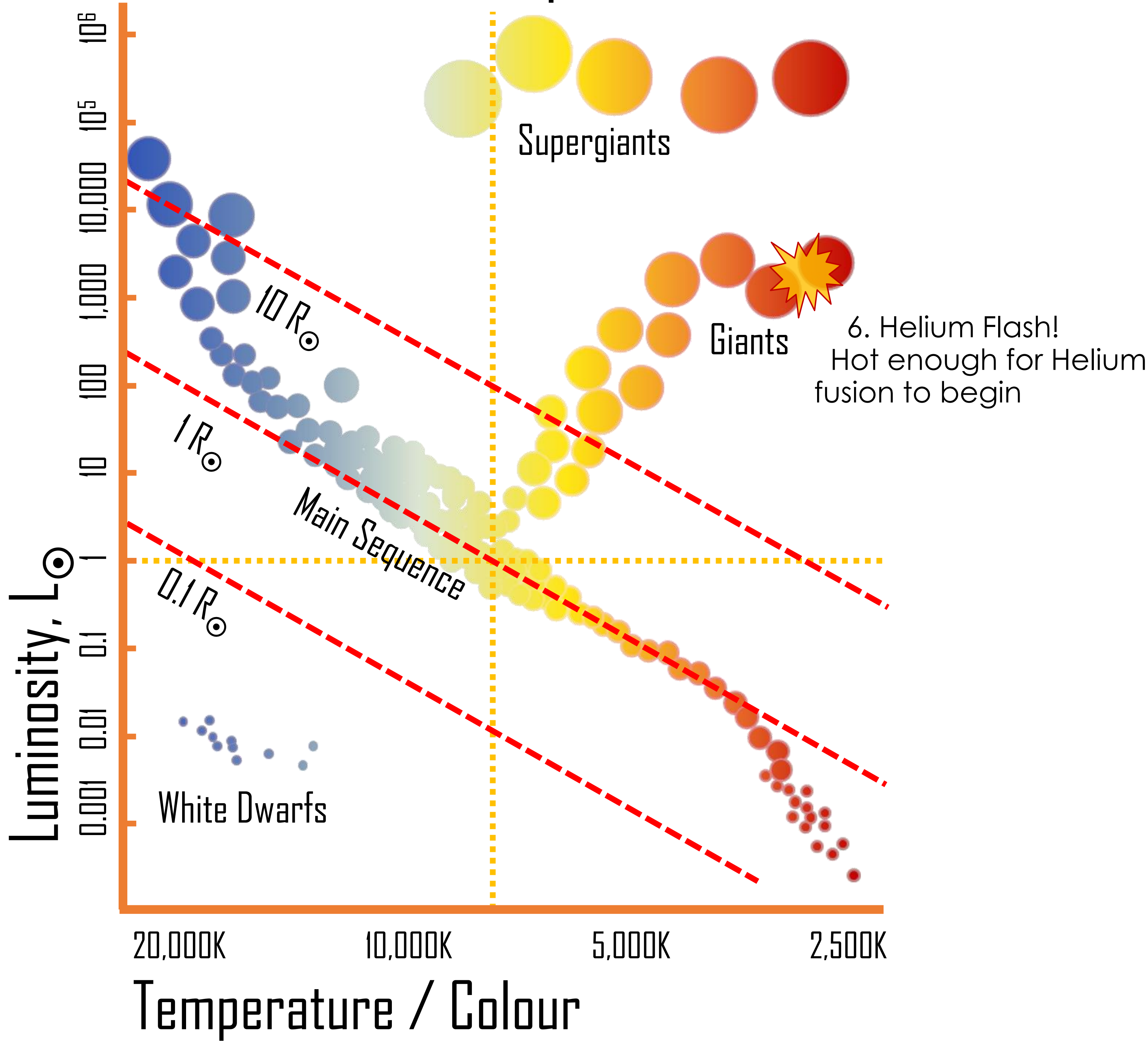
This explosion is called the *Helium flash*.

The inner and outer layers expand, easing the core pressure & causing the nuclear reactions to slow. The star shrinks, its luminosity falls and it stabilises, turning Helium into Carbon.



The Sun's Evolution: Step 6

Stellar Evolution



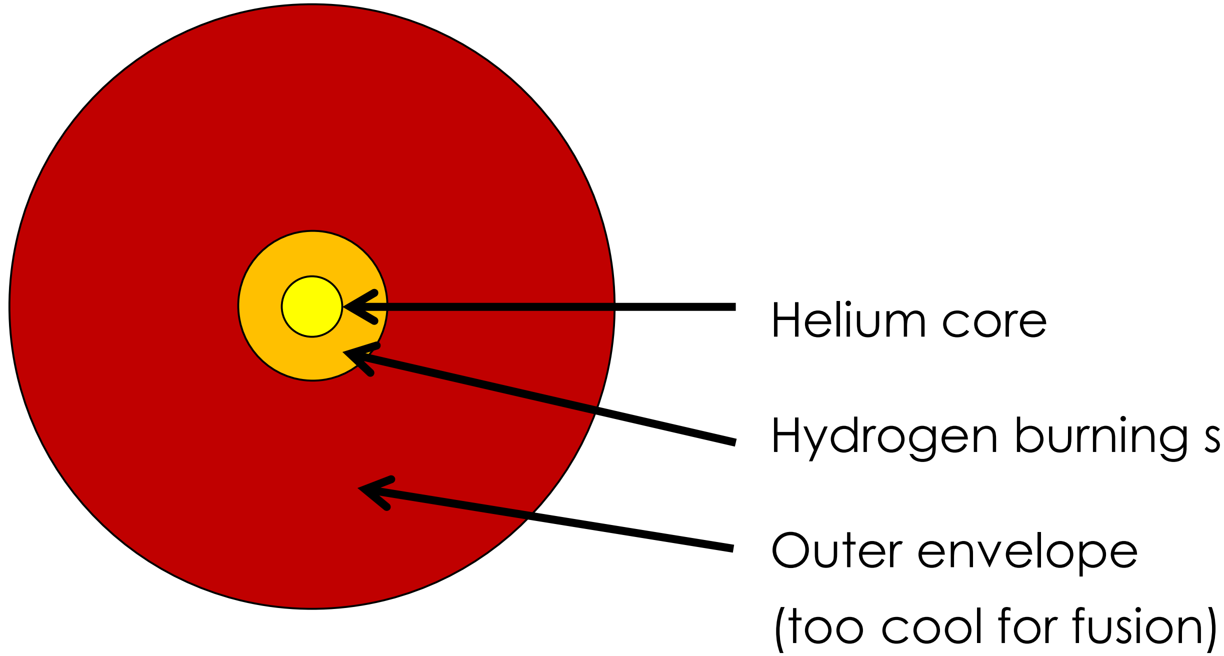
Additional:
Helium flash details

- Core finally gets hot enough (10^8K) for Helium to fuse;
- Helium fusing releases more energy, allowing even more Helium to fuse, and releasing even more energy… an explosive chain-reaction!
- Core suddenly expands!

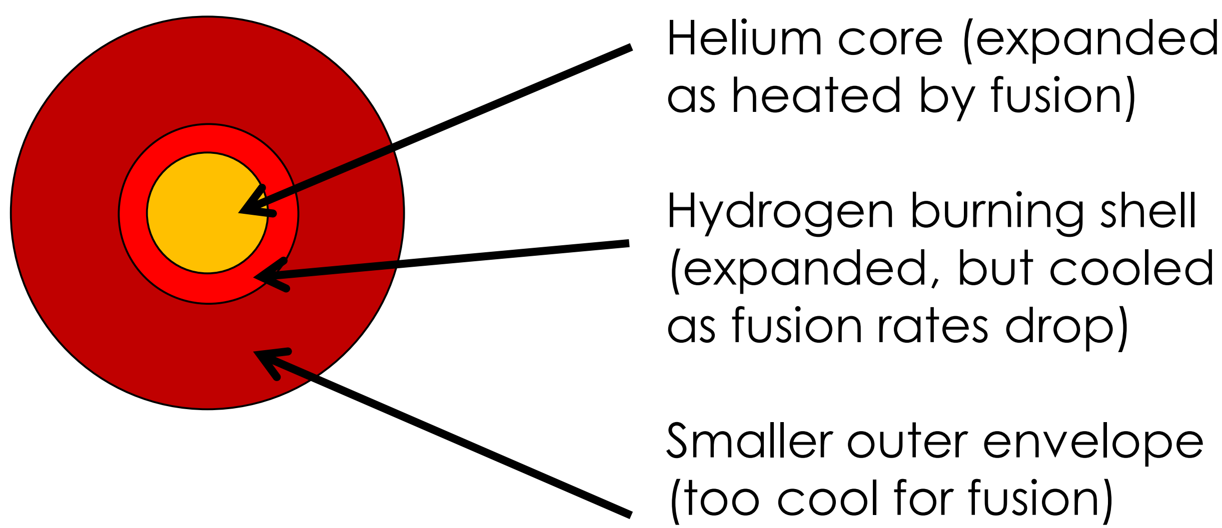
Helium flash!!

- This pushes the Hydrogen burning (fusing) shell out
- The temperature and density of the shell falls (both the energy and the hydrogen within it is spread over a larger volume), which reduces the fusion rate
- This causes it to cool
- Because the shell is cooler, the outer envelop cools too, and so shrinks

Pre Helium Flash

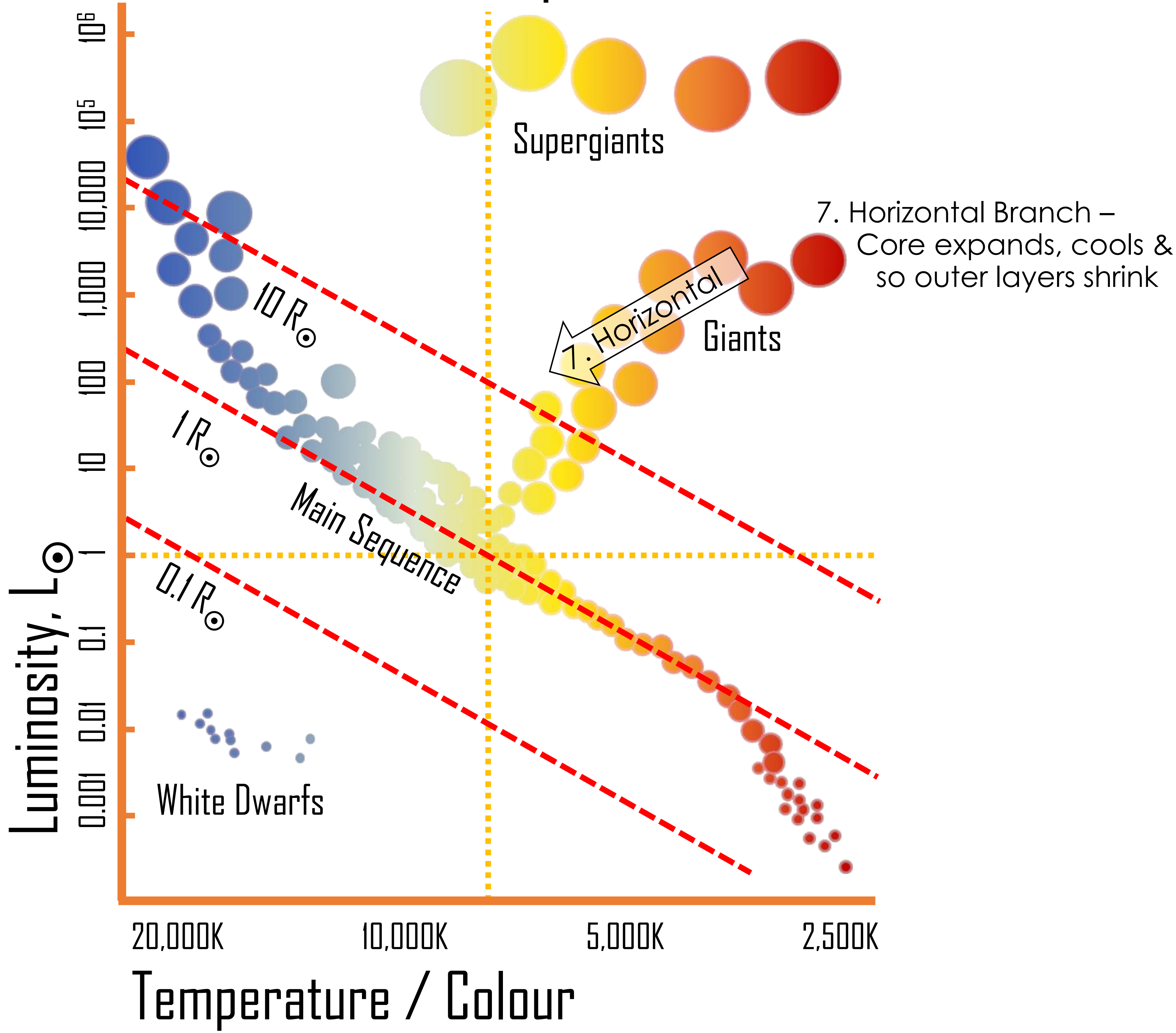


Post Helium Flash



The Sun's Evolution: Step 7

Stellar Evolution



Horizontal Branch Star

The star is now stably fusing

>> helium into carbon in the core

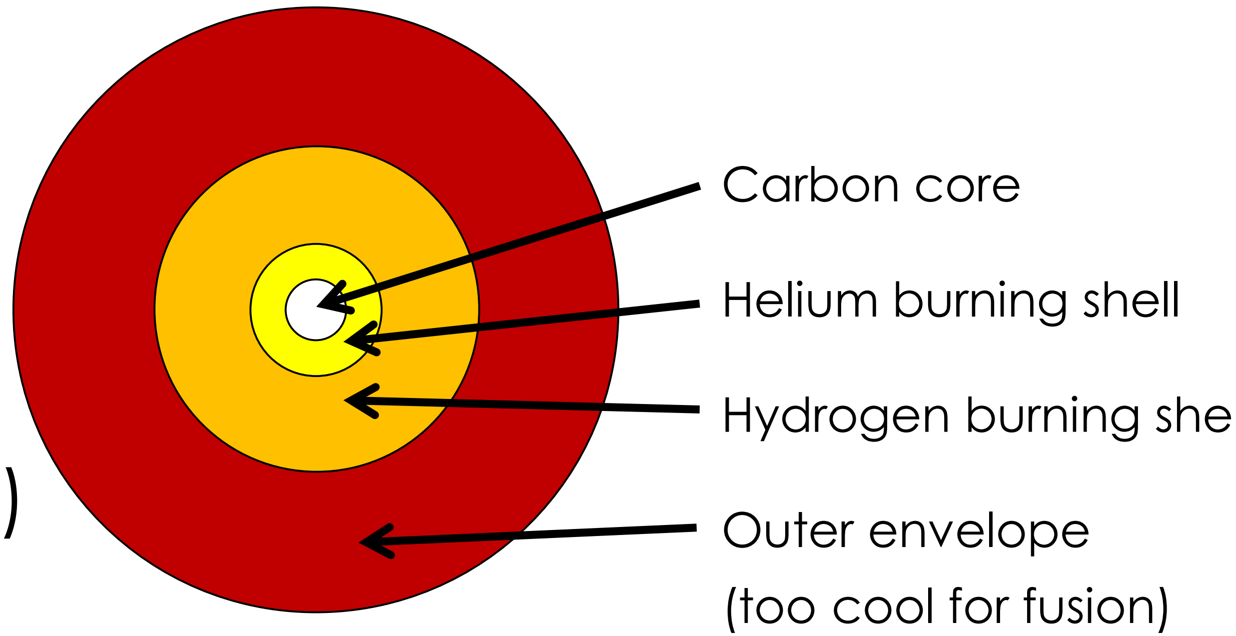
>> and hydrogen into helium in a surrounding shell

This lasts 50 million years until it runs out of Helium fuel in the core…

Asymptotic Giant Branch

The star now has a carbon core, surrounded by helium and hydrogen burning shells.

The star grows larger and redder (again)

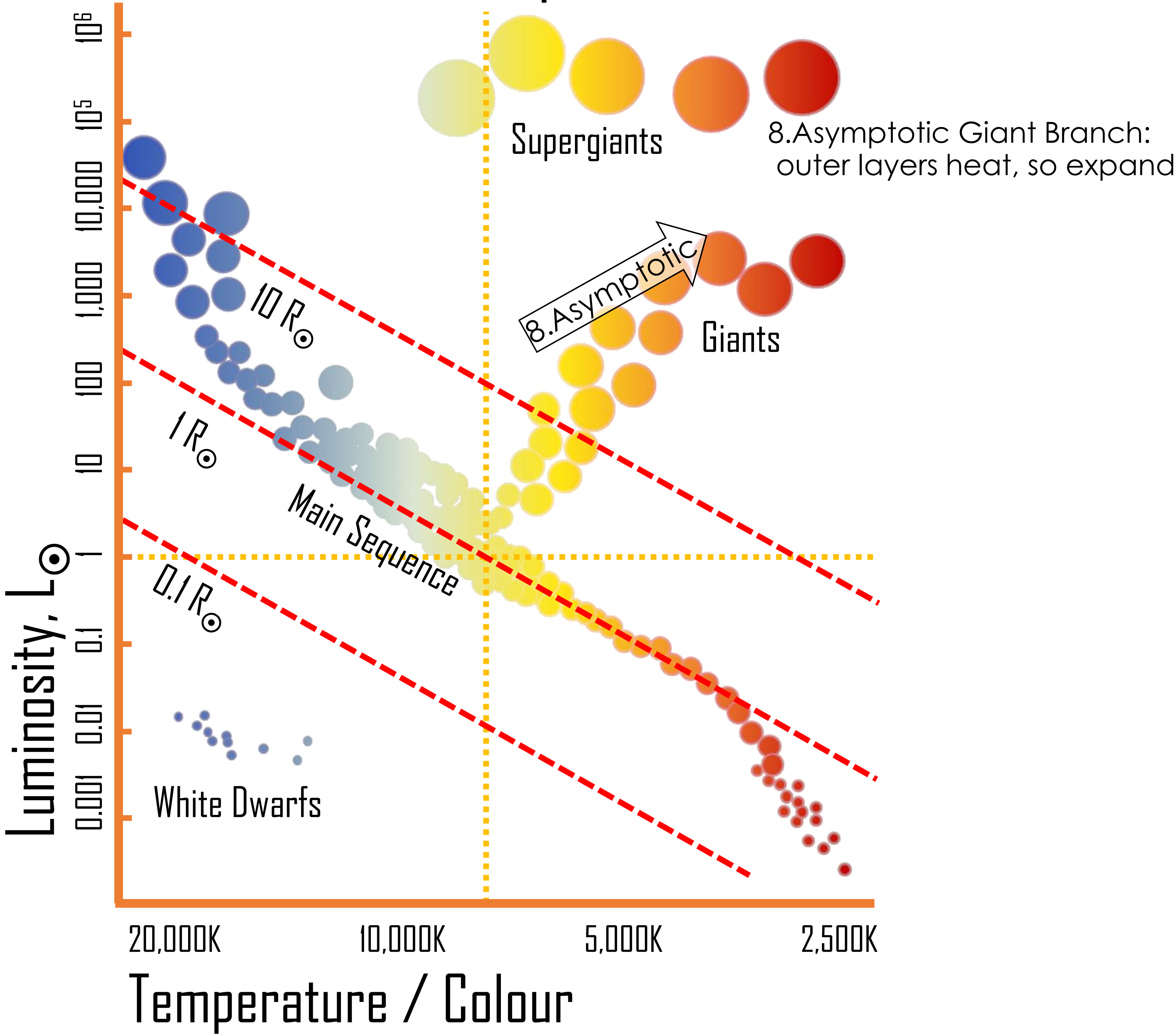


This is similar to when it evolved from a main sequence star into a red giant
- it first became a giant when fusing hydrogen into Helium around the helium core; now it's becoming a giant again fusing Helium into Carbon around a Carbon core.

So it's called an asymptotic giant branch (AGB)

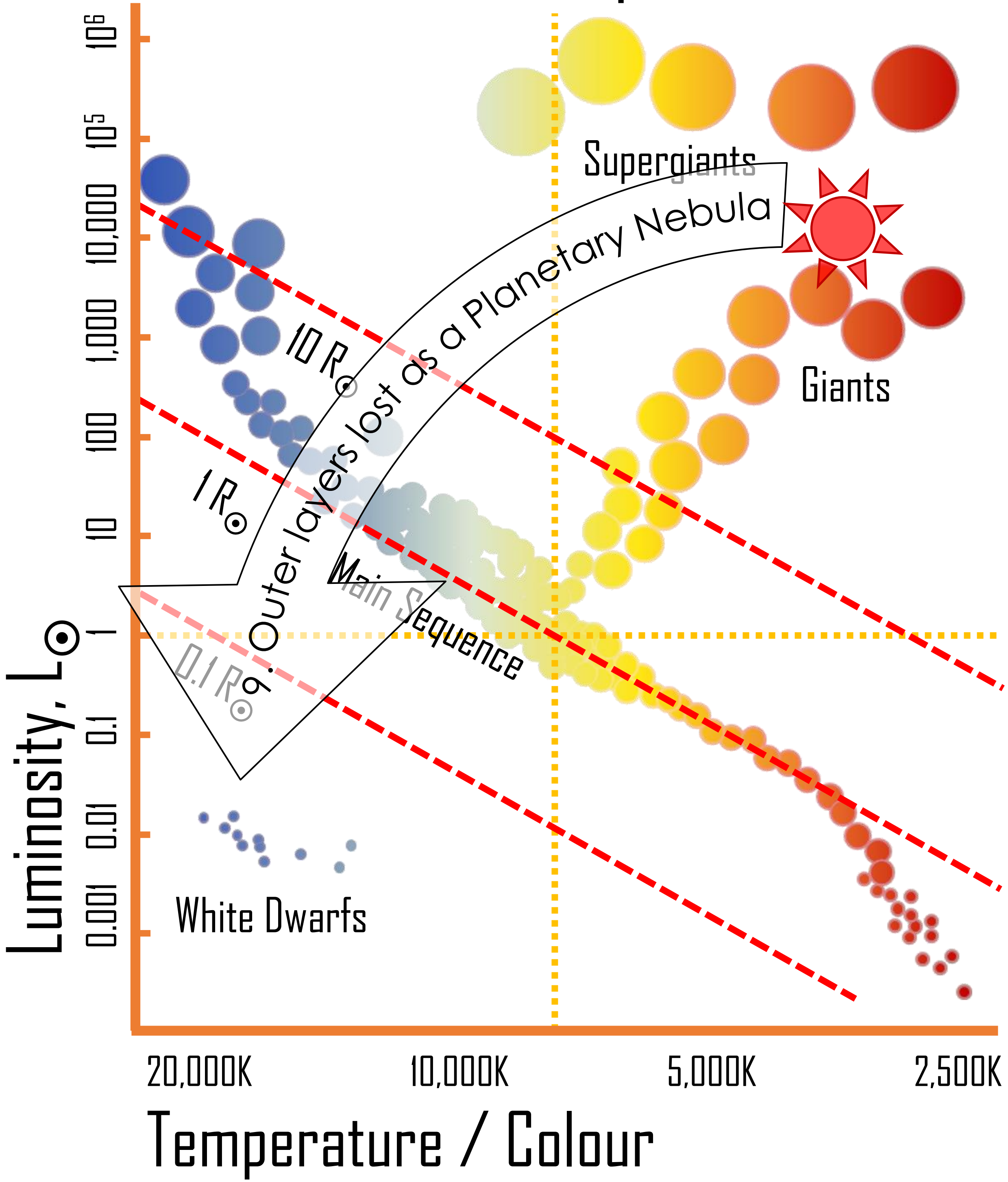
The Sun's Evolution: Step 8

Stellar Evolution



The Sun's Evolution: Step 9

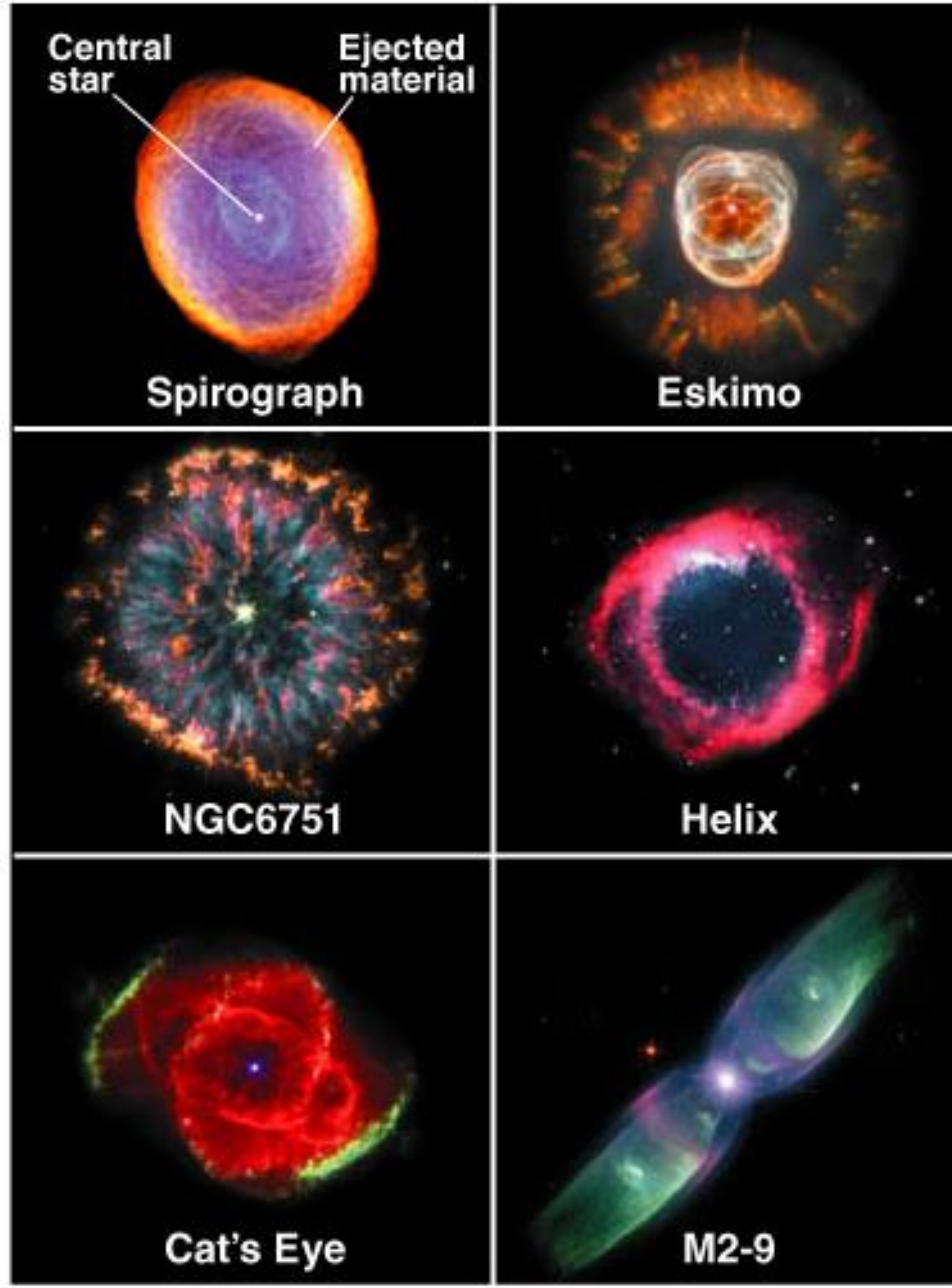
Stellar Evolution



Planetary Nebula

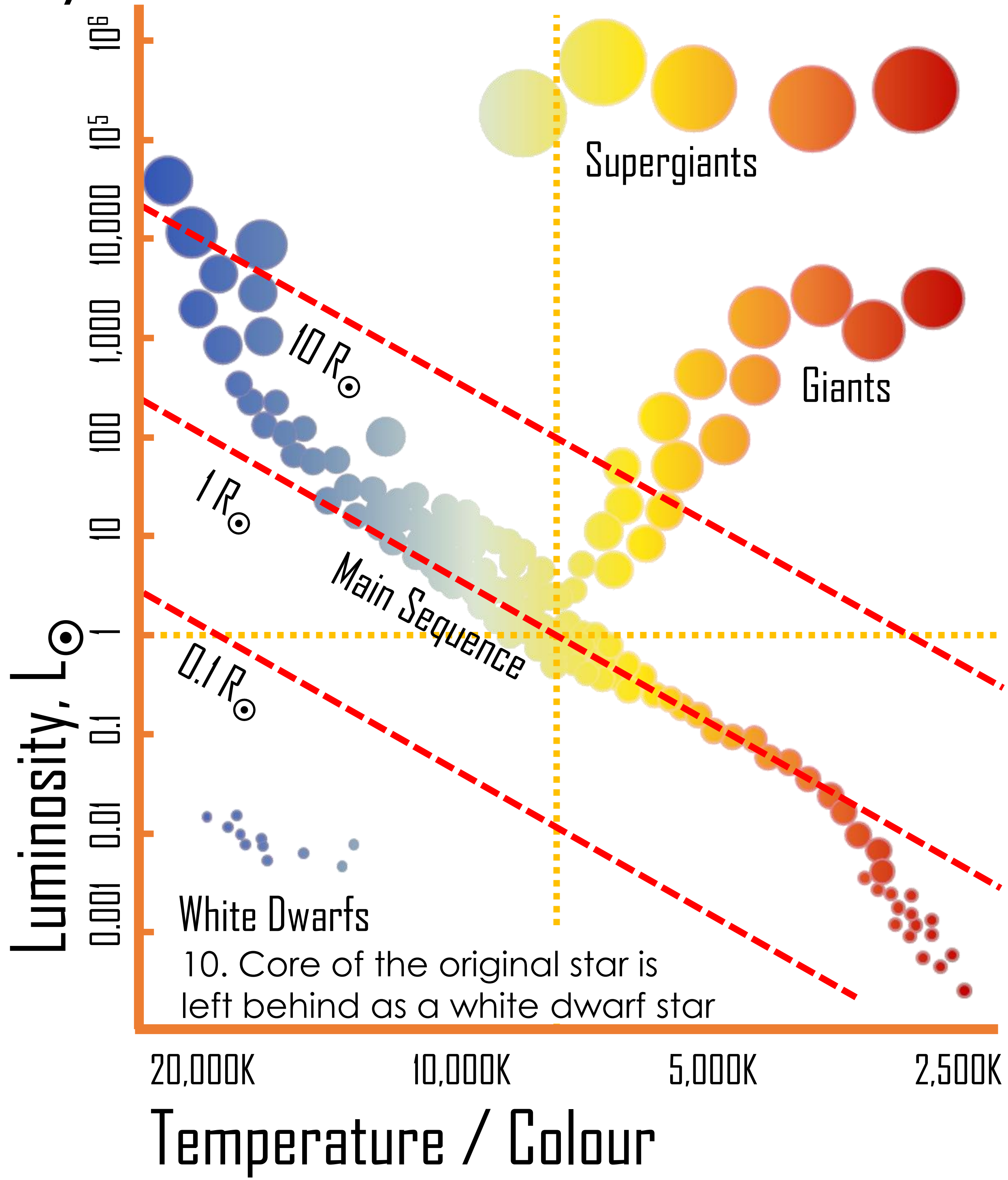
The core temperatures never get hot enough for carbon to fuse, and so AGB stars lose their outer layers as a spectacular planetary nebula.

Planetary nebulae are so-called because they look like planets when seen through small telescopes



Summary of the Sun's Evolution: Step 10

Stellar Evolution



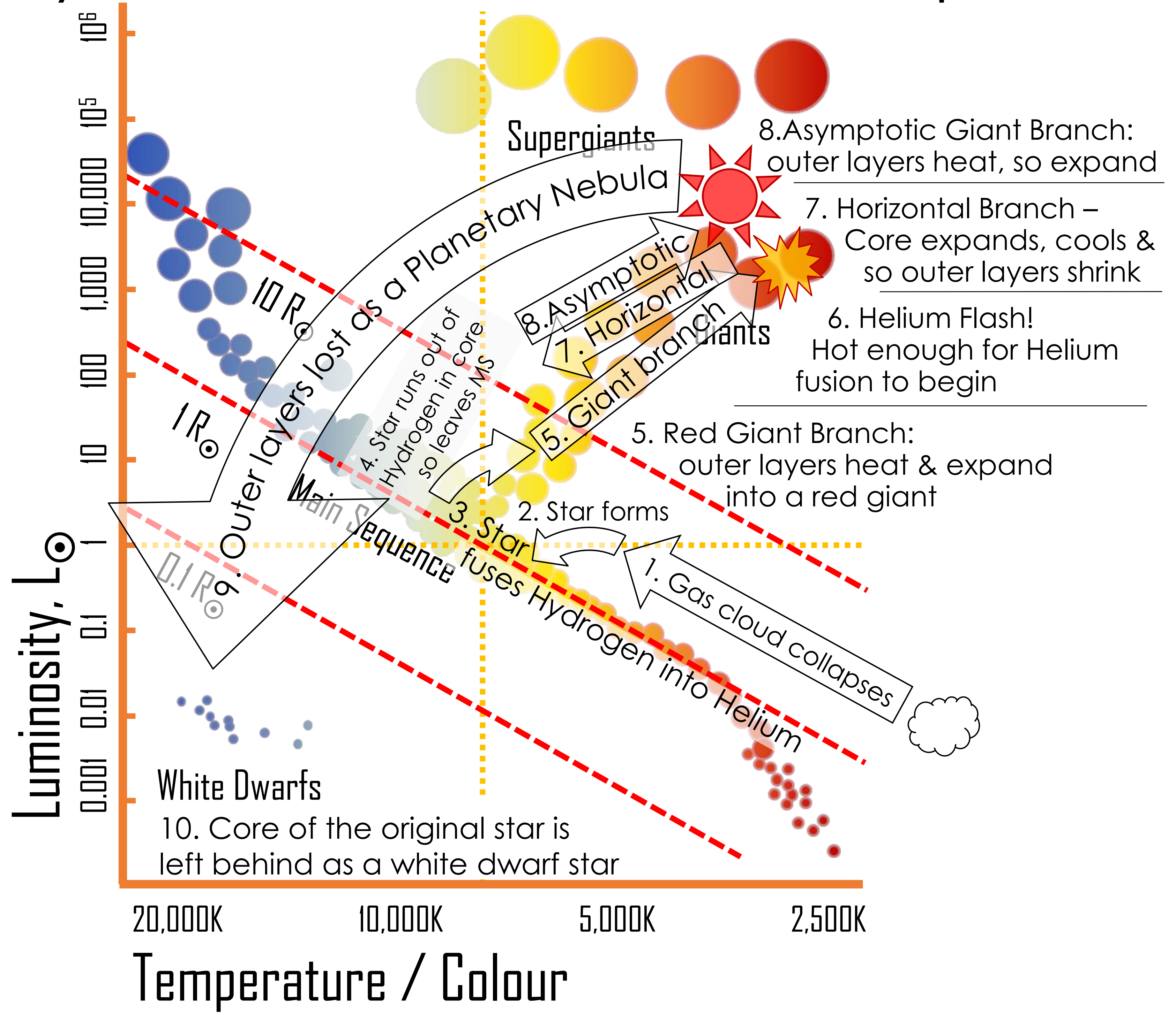
White Dwarf Stars

The remnant left behind is called a white dwarf star

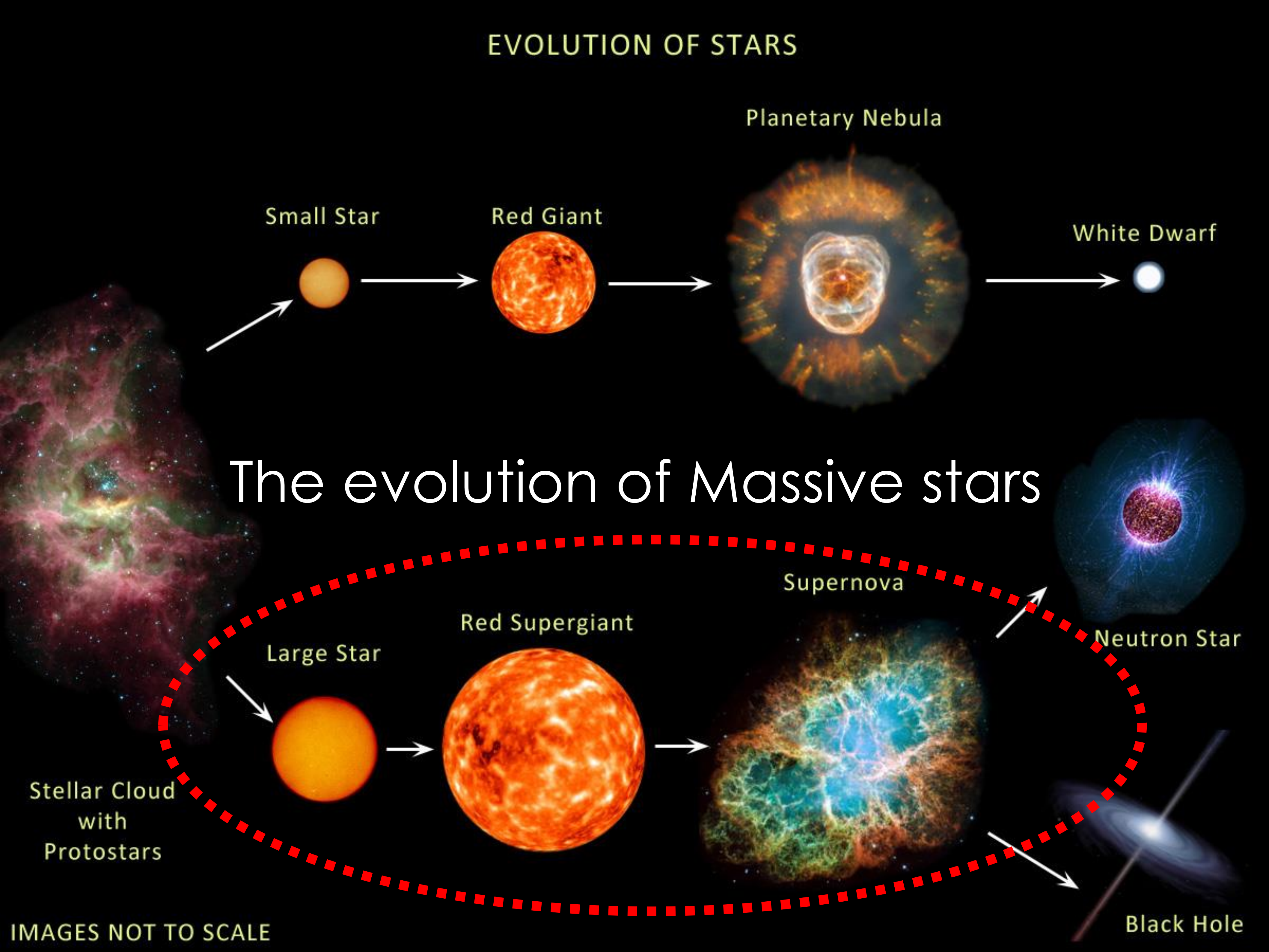
A white dwarf star typically has about the same mass as our Sun, but packed into a volume no bigger than that of the Earth.

Summary of the Sun's Evolution: Step 10

Stellar Evolution

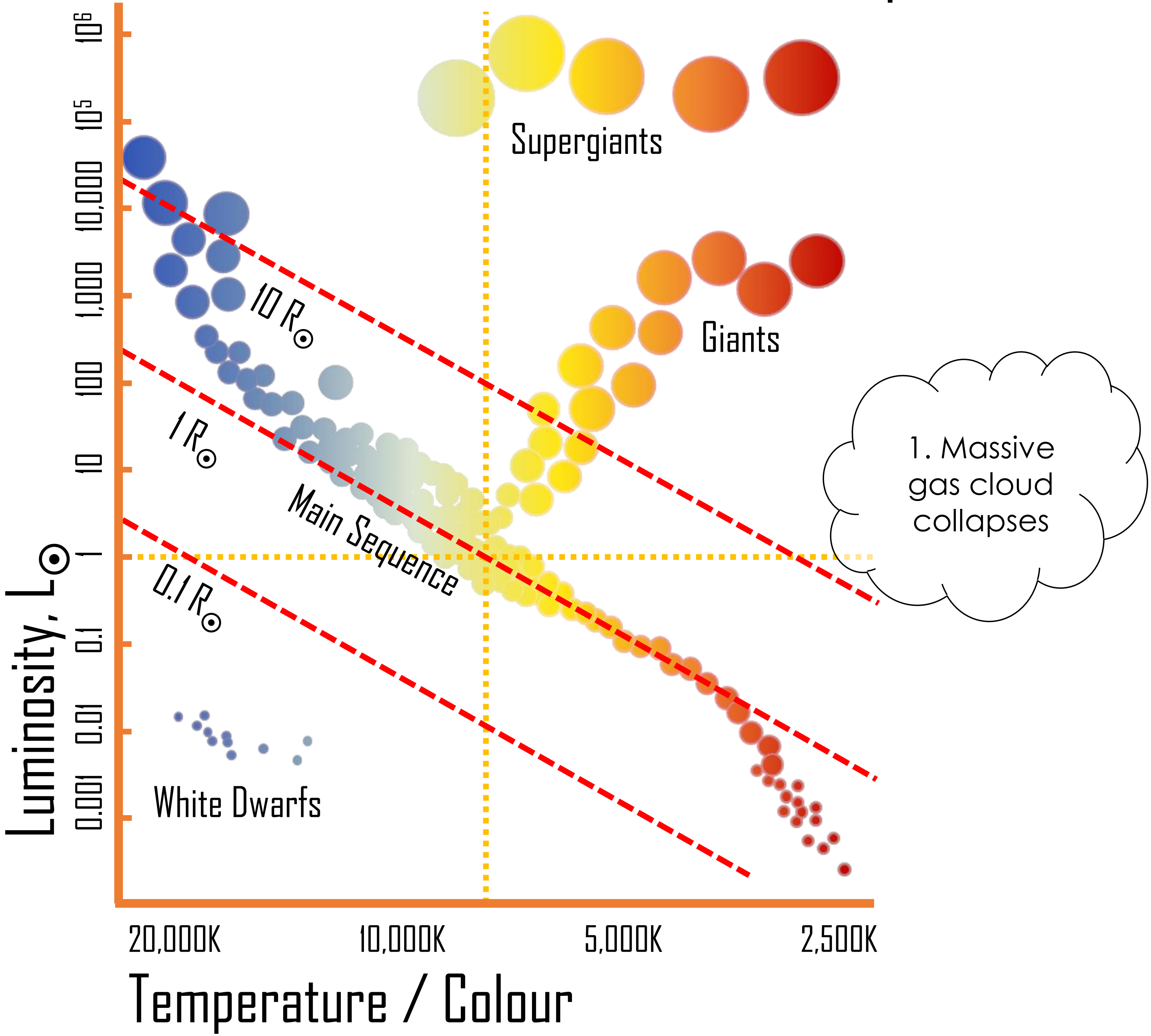


The evolution of Massive stars



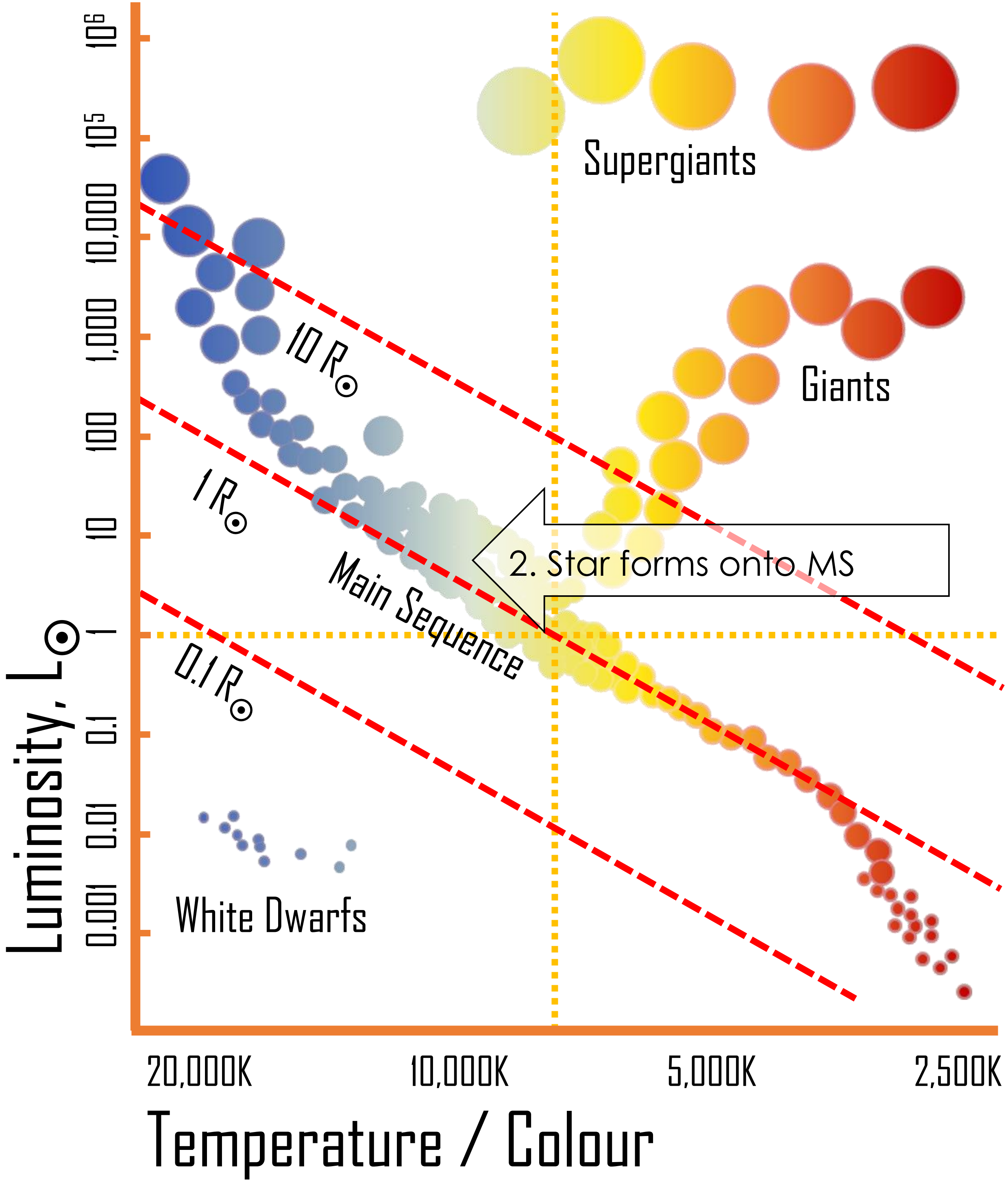
The Evolution of a Massive Star: Step 1

Stellar Evolution



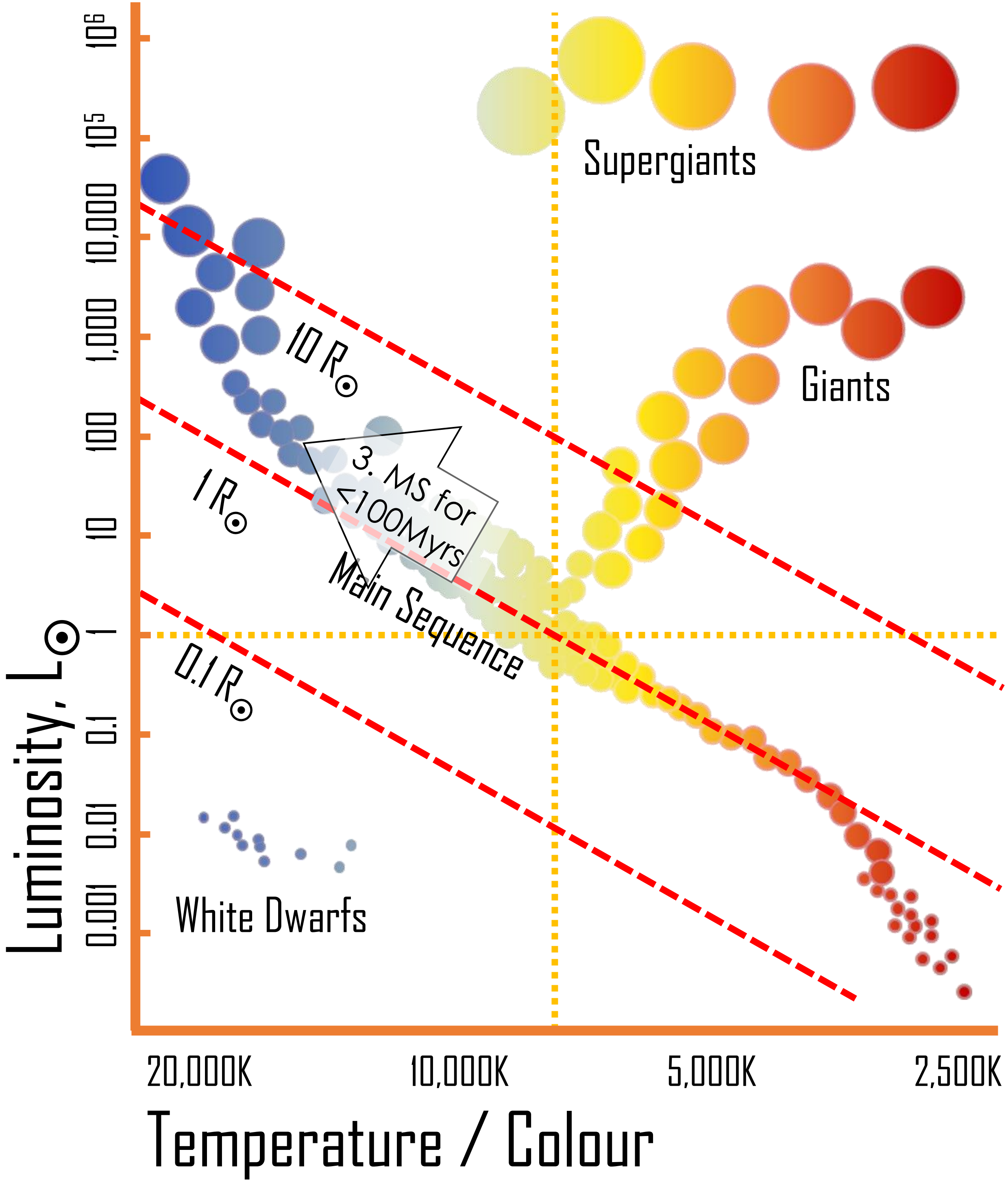
The Evolution of a Massive Star: Step 2

Stellar Evolution

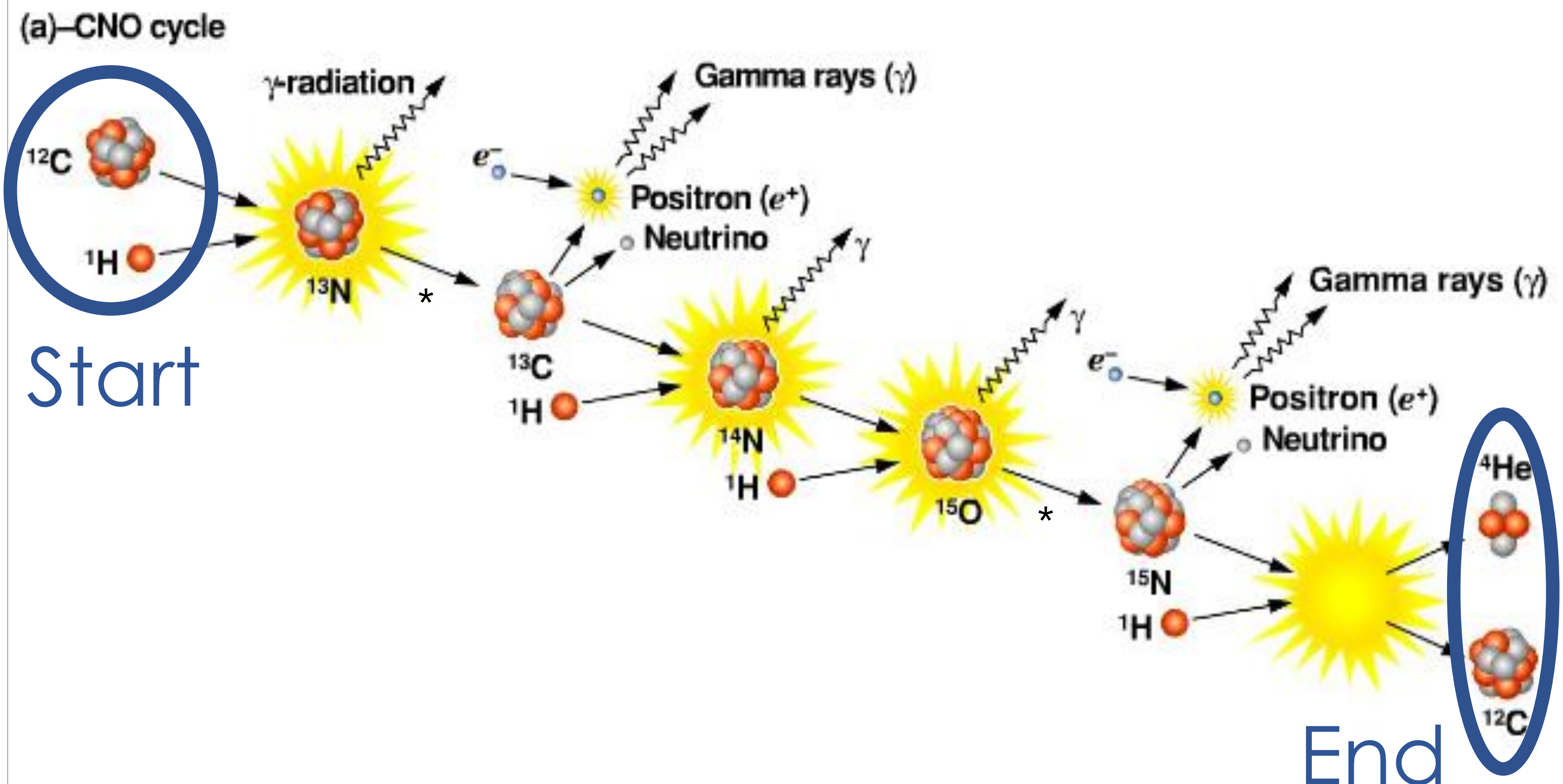


The Evolution of a Massive Star: Step 3

Stellar Evolution



CNO Cycle



In the hotter cores of massive main sequence stars hydrogen fusion can occur by the CNO cycle.

Note that carbon is not consumed – it's a catalyst.

Massive main sequence stars evolve differently

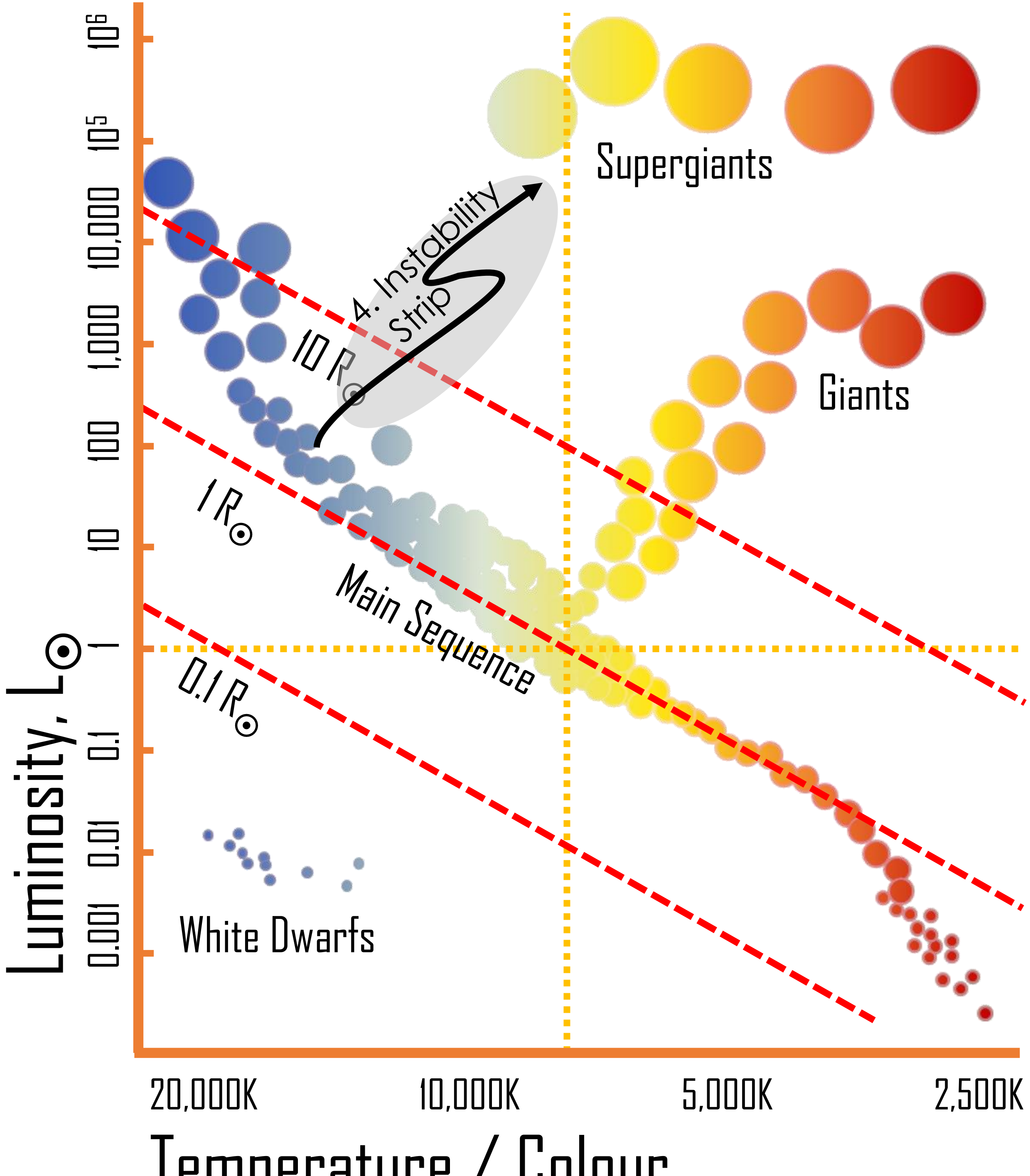
The helium core of a massive star reaches a temperature of 10^8 K *so helium can simply fuse* into Carbon.

So, unlike smaller stars, there is no Helium flash - the star's core makes a smooth transition from burning Hydrogen into Helium, to burning Helium into Carbon.

So a massive star does not become a giant star… it becomes a supergiant instead.

The Evolution of a Massive Star: Step 4

Stellar Evolution



Pulsation Variables

At this stage in their evolution, some massive stars are unstable.

When energy is trapped inside the star it heats the gas causing it to expand.

As it expands, it cools… until gravity is stronger than thermal expansion, and it contracts.

This cycle repeats…

– it's a *Pulsating Variable Star*

Cepheid and RR Lyrae variable stars pulsate over days. Bigger stars take longer to pulse and are brighter.

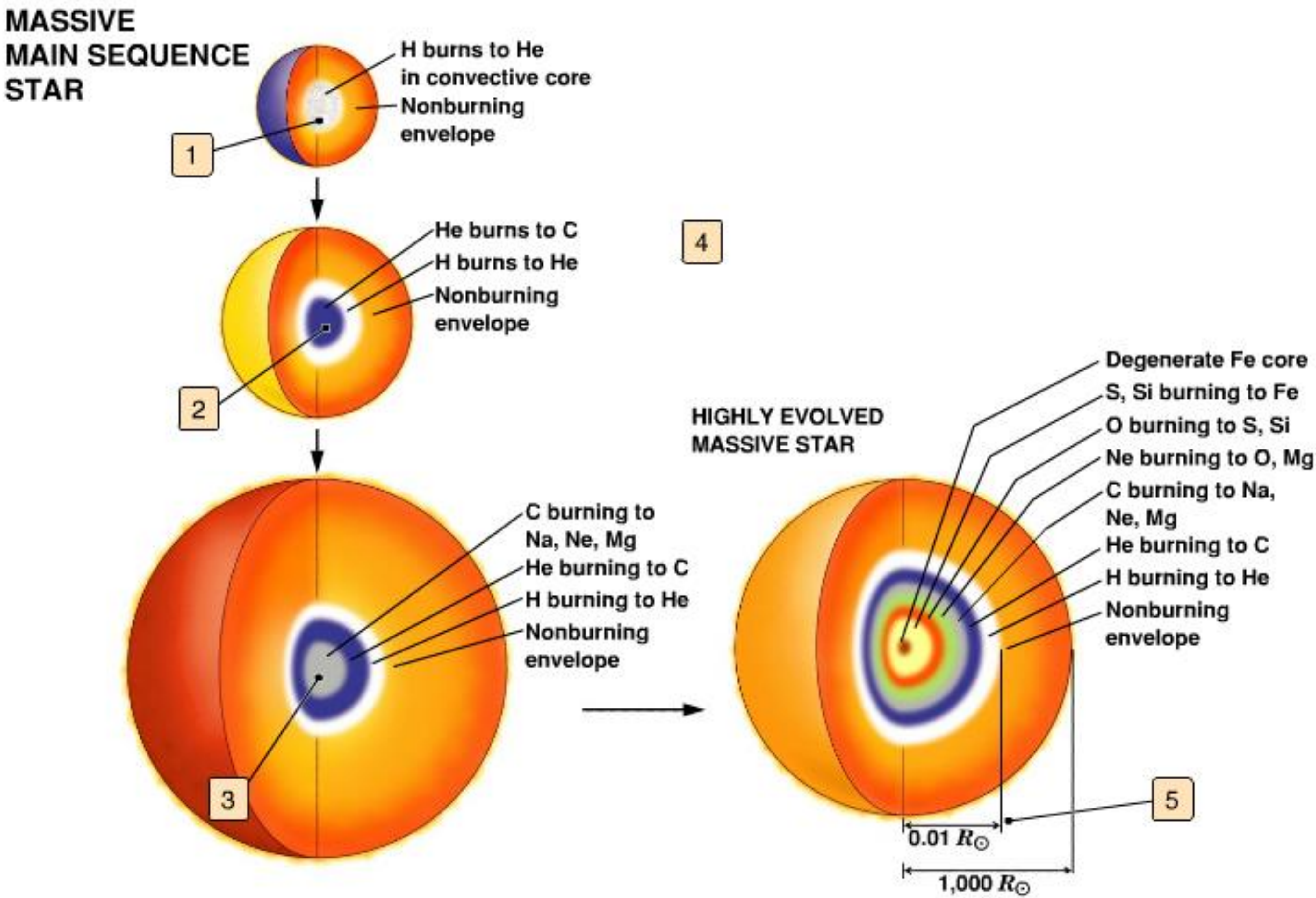
Nucleosynthesis

When a high-mass star runs out of helium in its core, the core shrinks, heats to 8×10^8 K (800M° C!) allowing carbon to fuse into even heavier atomic elements.

[low-mass stars never get hot enough for this]

When the carbon runs out, neon, oxygen and silicon successively fuse in the core.

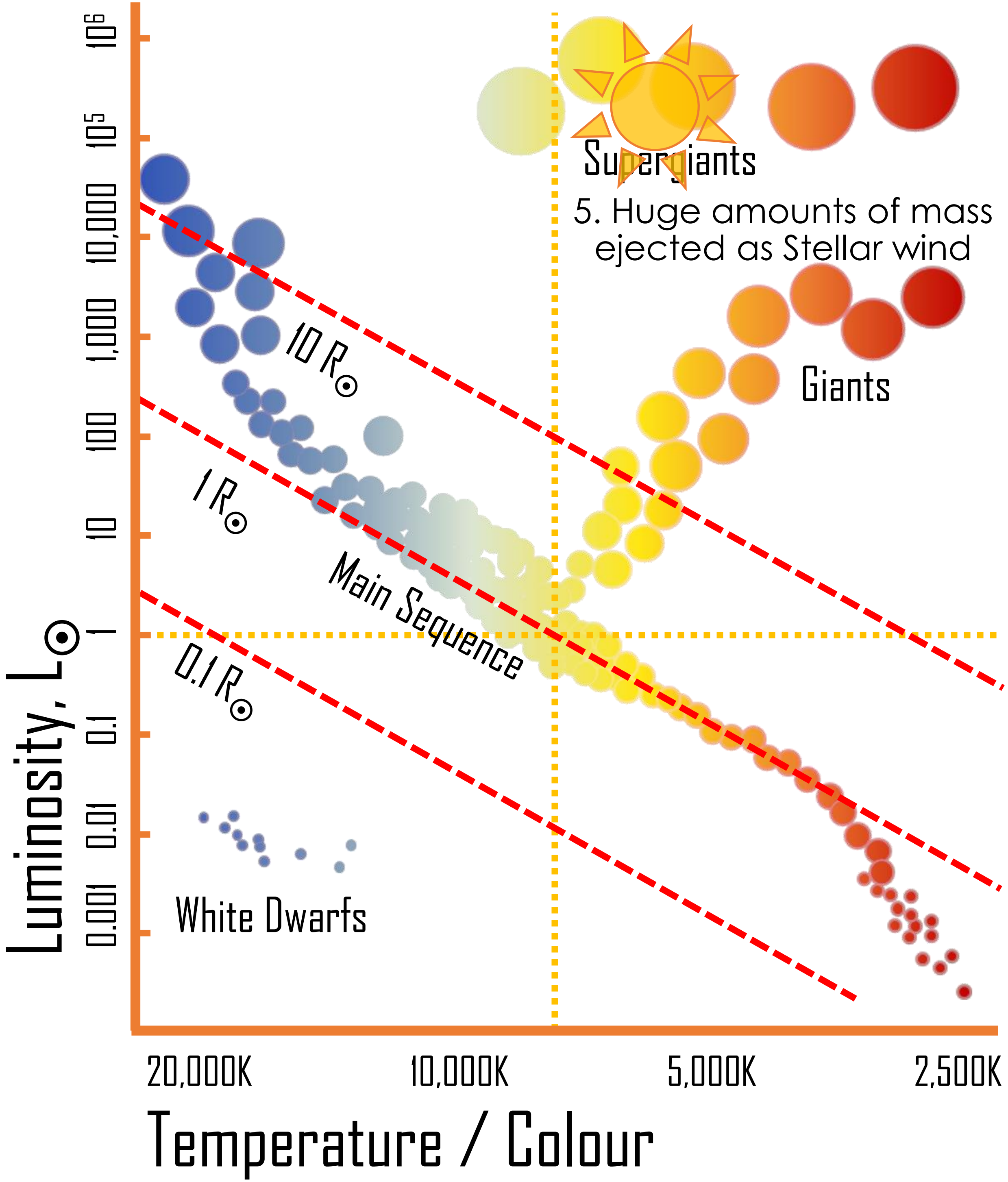
Making heavier nuclei from lighter ones is known as *nucleosynthesis*.



MASSIVE
MAIN SEQUENCE
STAR
H burns to He
in convective core
Nonburning
envelope
1
He burns to C
H burns to He
Nonburning
envelope
2
4
C burning to
Na, Ne, Mg
He burning to C
H burning to He
Nonburning
envelope
3
HIGHLY EVOLVED
MASSIVE STAR
Degenerate Fe core
S, Si burning to Fe
O burning to S, Si
Ne burning to O, Mg
C burning to Na,
Ne, Mg
He burning to C
H burning to He
Nonburning
envelope
5
0.01 $R_\odot$
1,000 $R_\odot$

The Evolution of a Massive Star: Step 5

Stellar Evolution

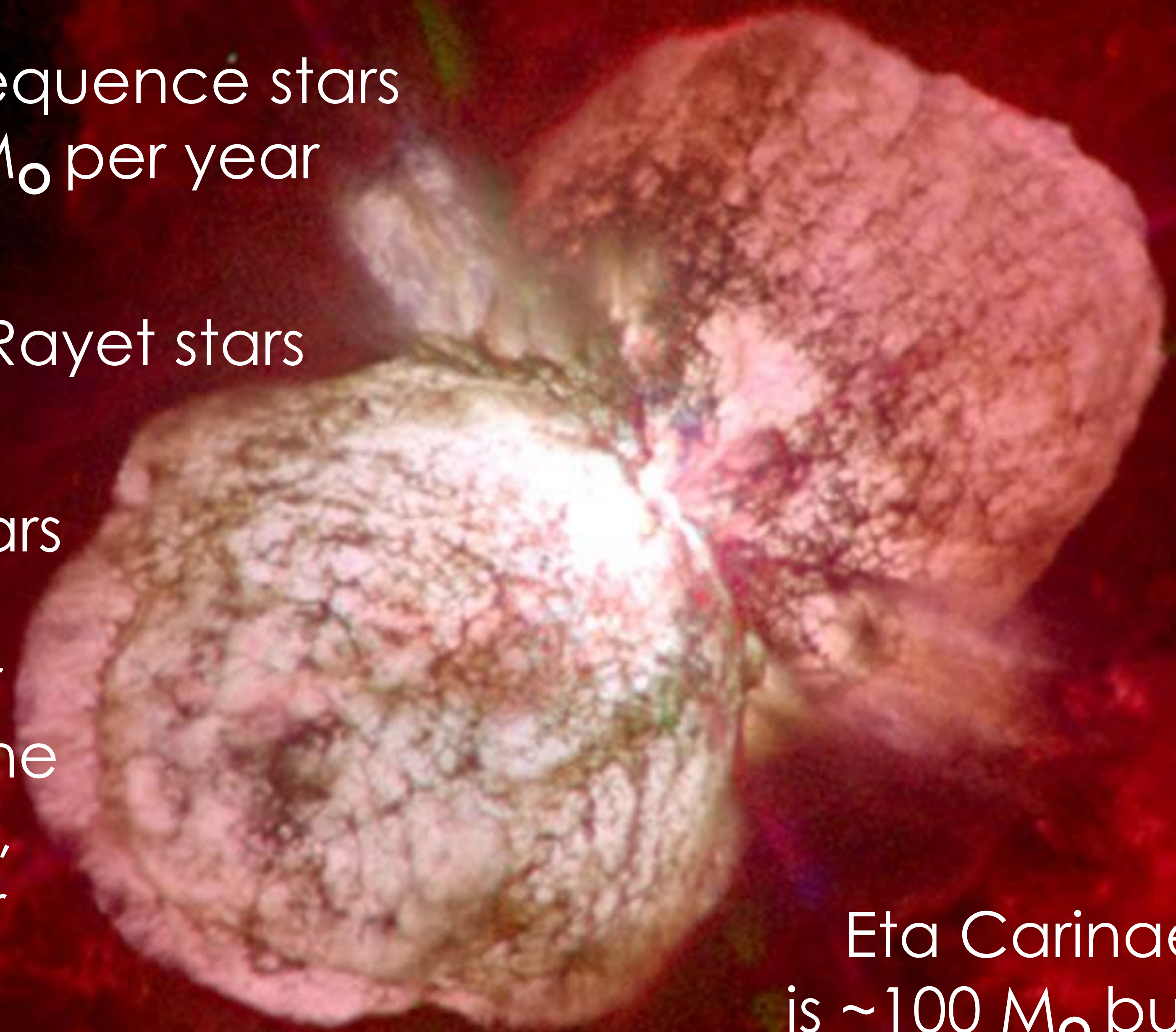


Mass Loss

Massive main sequence stars lose up to 10^{-5} $M_{\odot}$ per year

These are Wolf Rayet stars

Very massive stars (>20 $M_{\odot}$) may lose 20% of their mass while on the main sequence, & 50% over their entire life



Eta Carinae is ~100 $M_{\odot}$ but looses 1 $M_{\odot}$ every 1000 yrs


WR124

End of Fusion

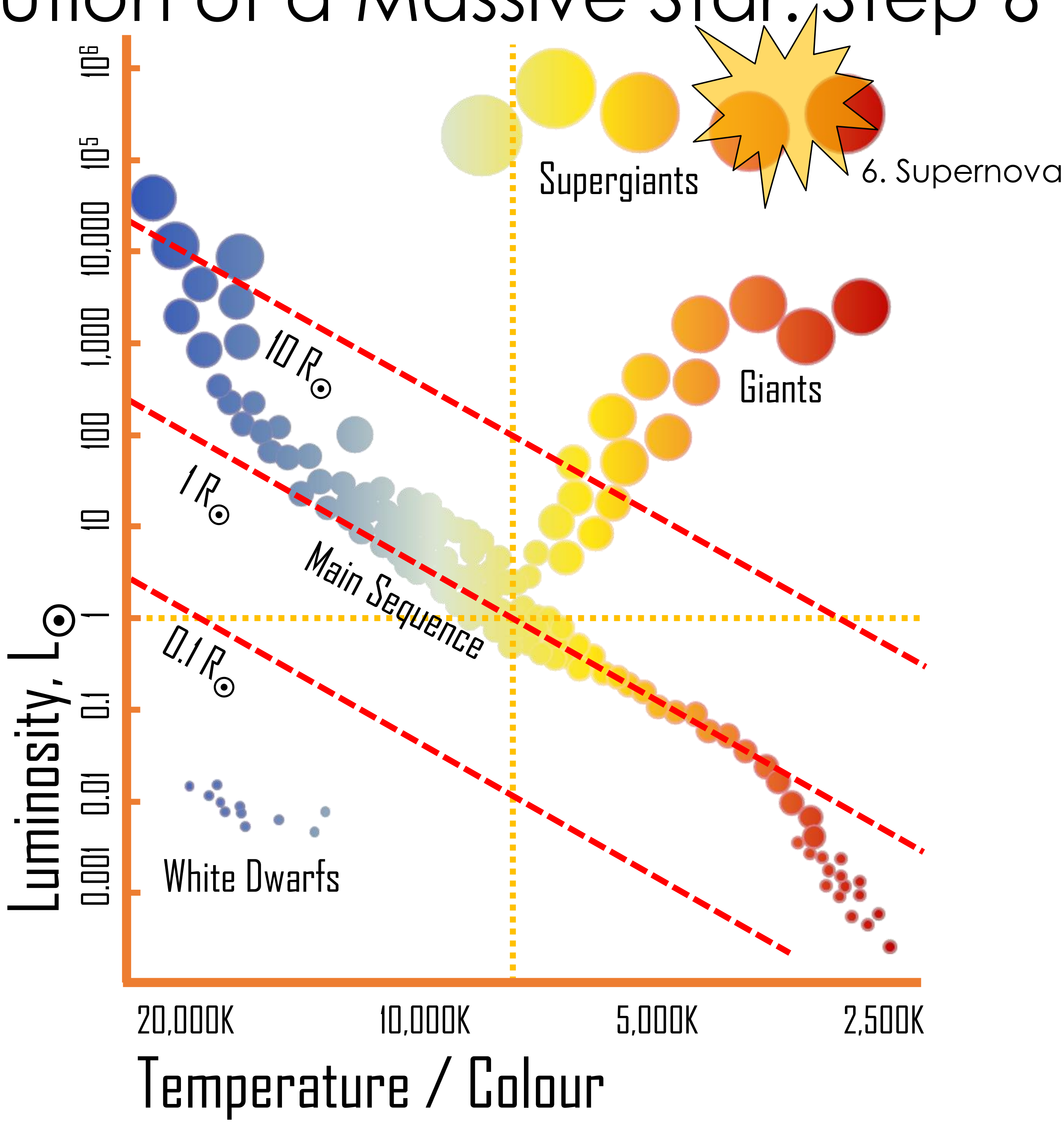
Fusion stops at iron, the most tightly bound atomic nucleus, so no element heavier than iron is fused within stars.

Hydrogen burning lasts for billions of years
Helium burning lasts for ~ 100,000 years
Carbon burning lasts for ~ 1000 years
Neon burning lasts for ~ 1 year
Oxygen burning lasts for ~ 6 months
Silicon burning in Iron lasts for days

Massive stars end their lives in a spectacular *Supernovae* explosions

The Evolution of a Massive Star: Step 6

Stellar Evolution



Supernovae Explosions

Eventually, silicon is all fused into iron in the star's core – the star has totally ran out of fuel.

No more fusion can occur – there is no more heating & gravity finally wins over the outwards pressure of hot gas.

The core collapses within a second, at ¼ speed of light, to 10 tonnes per cubic cm and temperatures of 10 billion K

The collapsing core "bounces", sending a shockwave through the rest of the star, driving out the outer layers

Within hours, this shockwave travels from core to surface, heating it to 500,000 K.

Supernova 1987A in the Large Magellanic Cloud nearby galaxy, was visible to the naked eye in the Southern Hemisphere.

Previous one was in 1604.

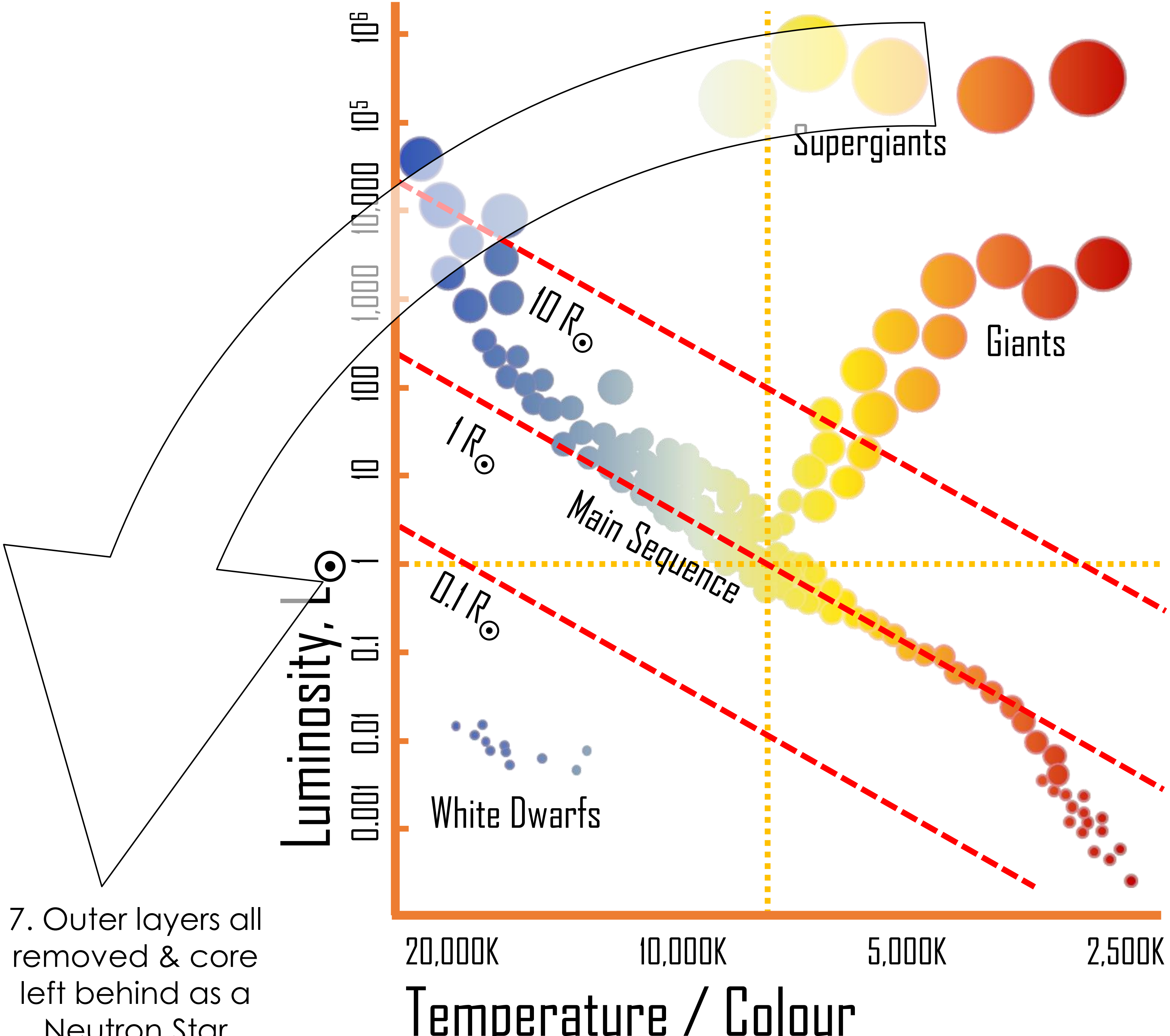
Spreading it around

Supernovae make heavier elements in the violent explosion, and spread these elements into interstellar space.

Supernovae are thus essential for life.

We are literally made up of the material from exploding stars.

The Evolution of a Massive Star: Step 7



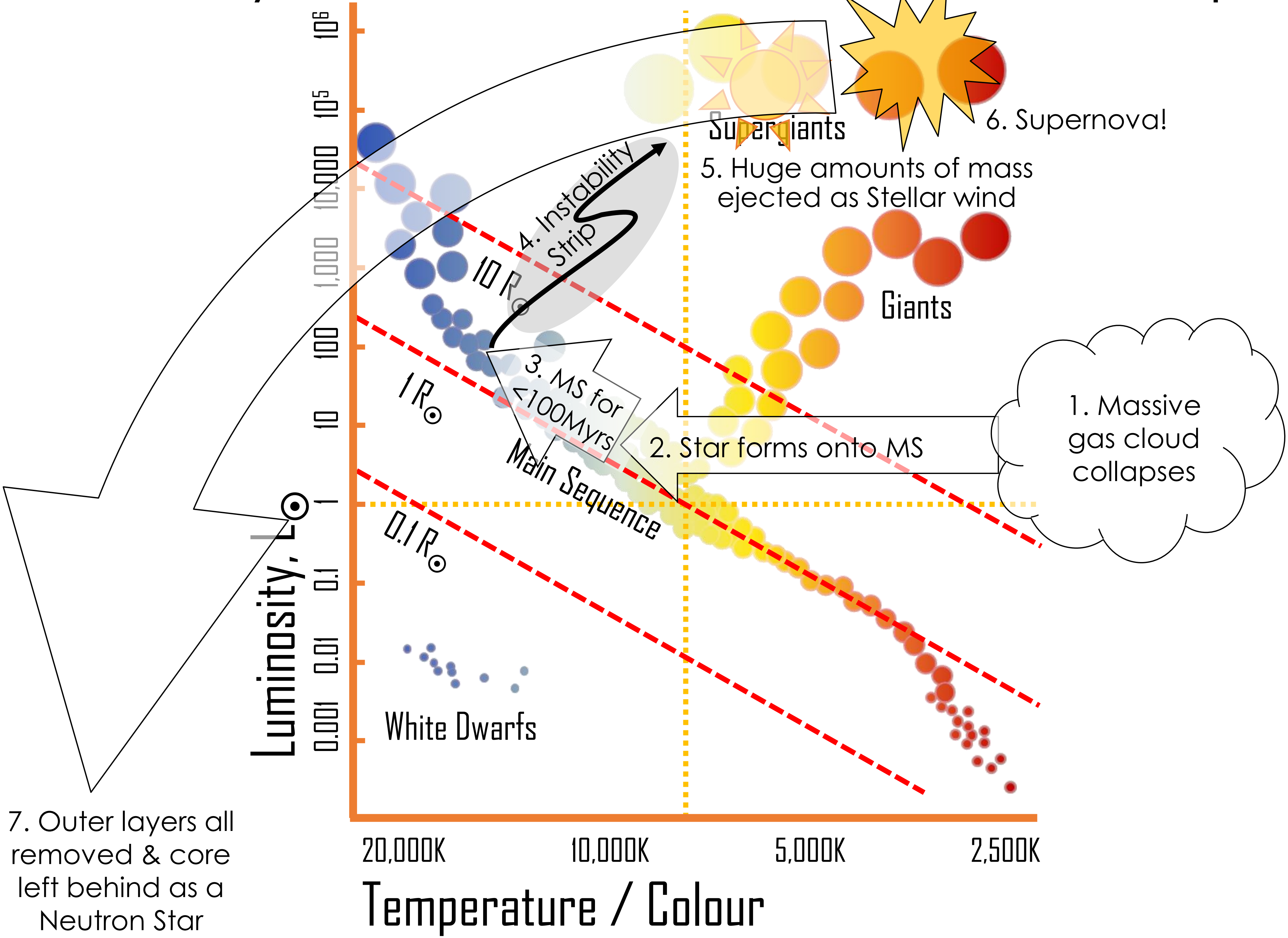
7. Outer layers all removed & core left behind as a Neutron Star

Neutron Stars

If the remaining core is less than 3 $M_\odot$ it becomes a *neutron star*.

More massive stars collapse *into black holes*.

Summary of massive Star's Evolution: Step 7



OUR PLACE
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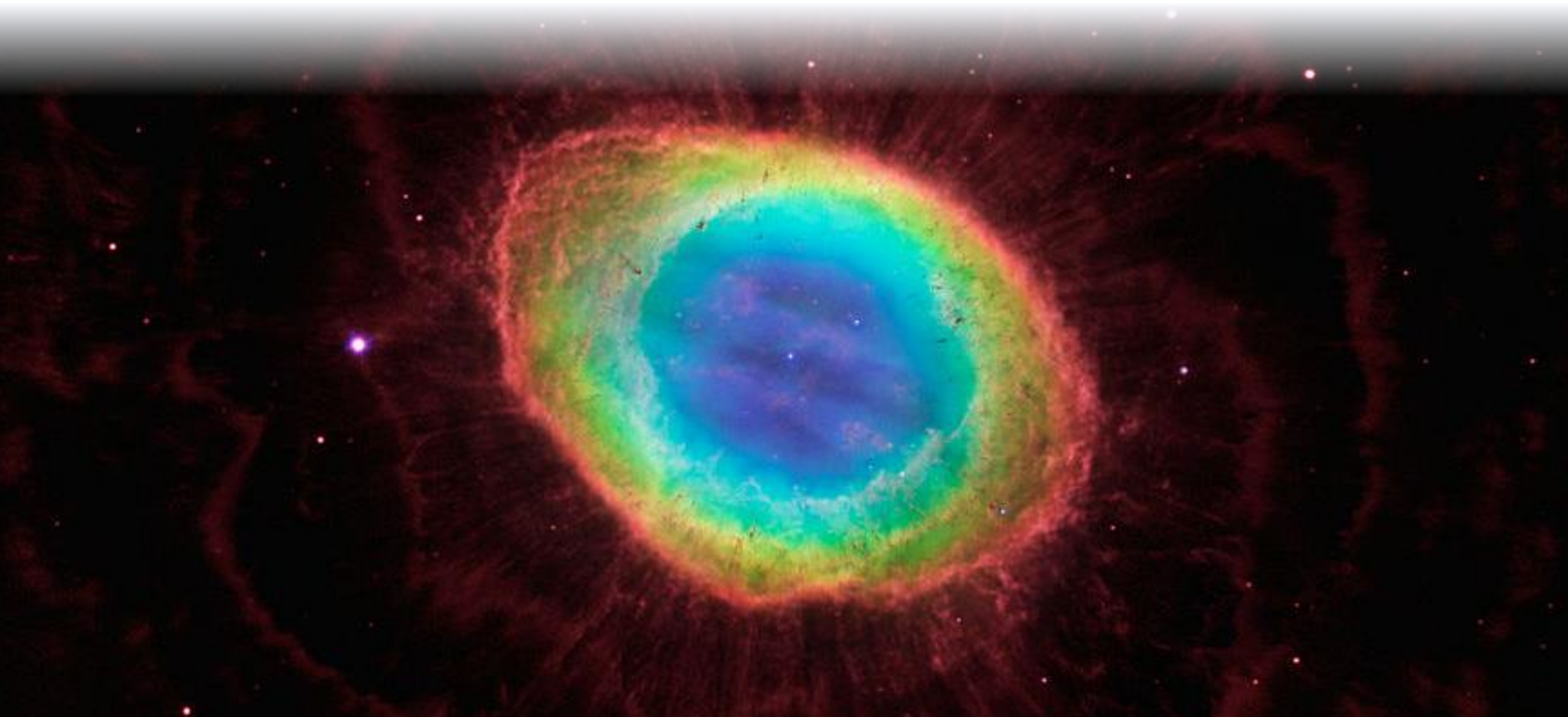
11: The Evolution of Stars



Summaries!

What follows is a…

Summary of the Sun's Evolution

&

Summary of the Evolution of Massive stars

Summary of the Sun's Evolution

1 & 2. Gas cloud collapse and a star forms

3. Star evolves on the Main Sequence

4. H is turned into He, until core is pure He (that's too cool to fuse)

5. H turns to He (and so heats) in the outer layers only
   - So star expands to sub-giant then red-giant (Red Giant Branch)

6. Core temperature increases until Helium fuses into Be & C

   This suddenly allows energy to be released, temperature increases rapidly, causing rapid expansion - the He Flash

7. Core expands, so cools, fusion slows and outer layers shrink

   Now He becomes C in core (Horizontal Branch star)

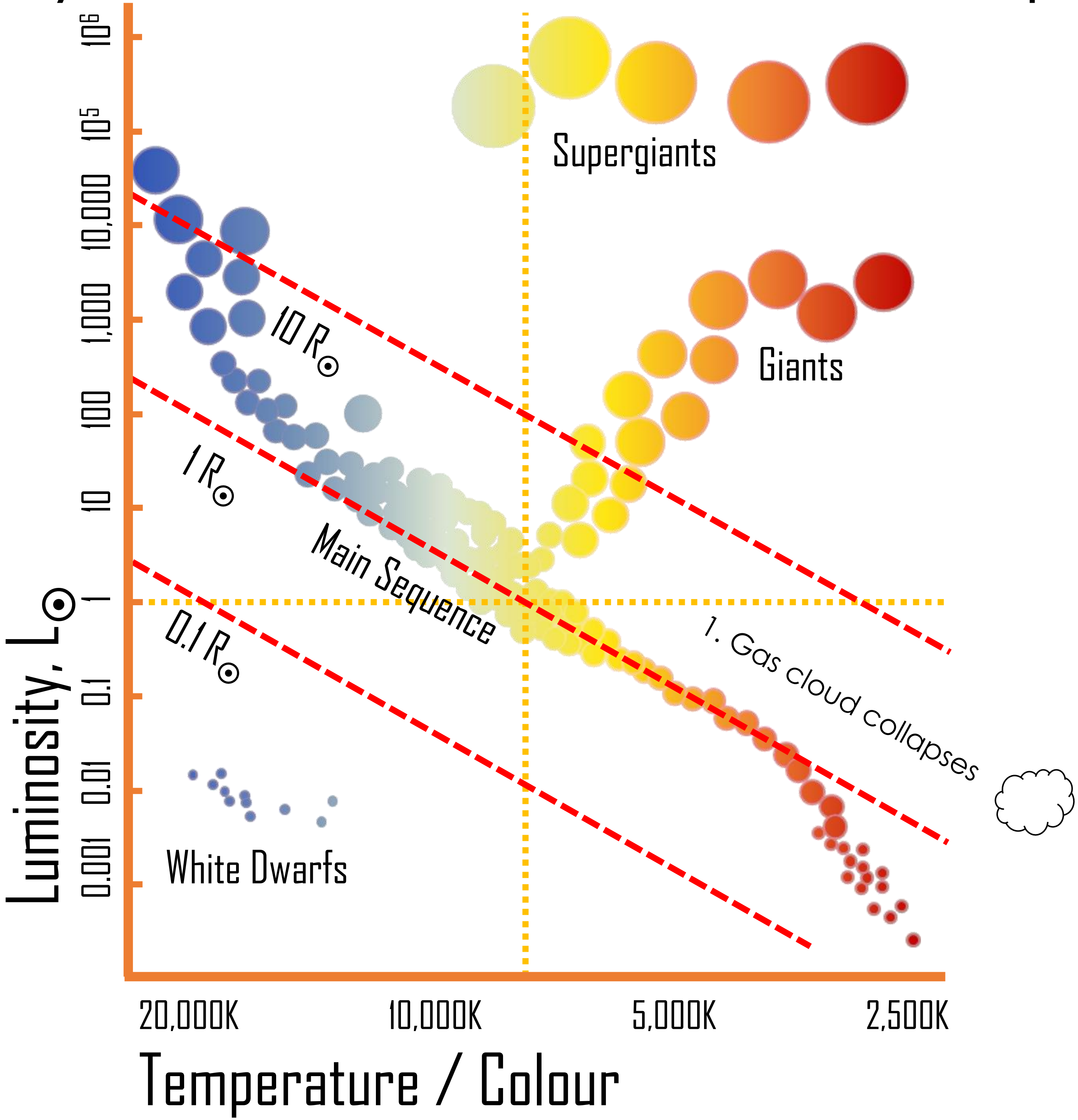
8. Slowly heats and expands again (Asymptotic Giant Branch)

9. This time, outer layers are blown away as Planetary Nebula

10. Core shrinks and fades as a White Dwarf star

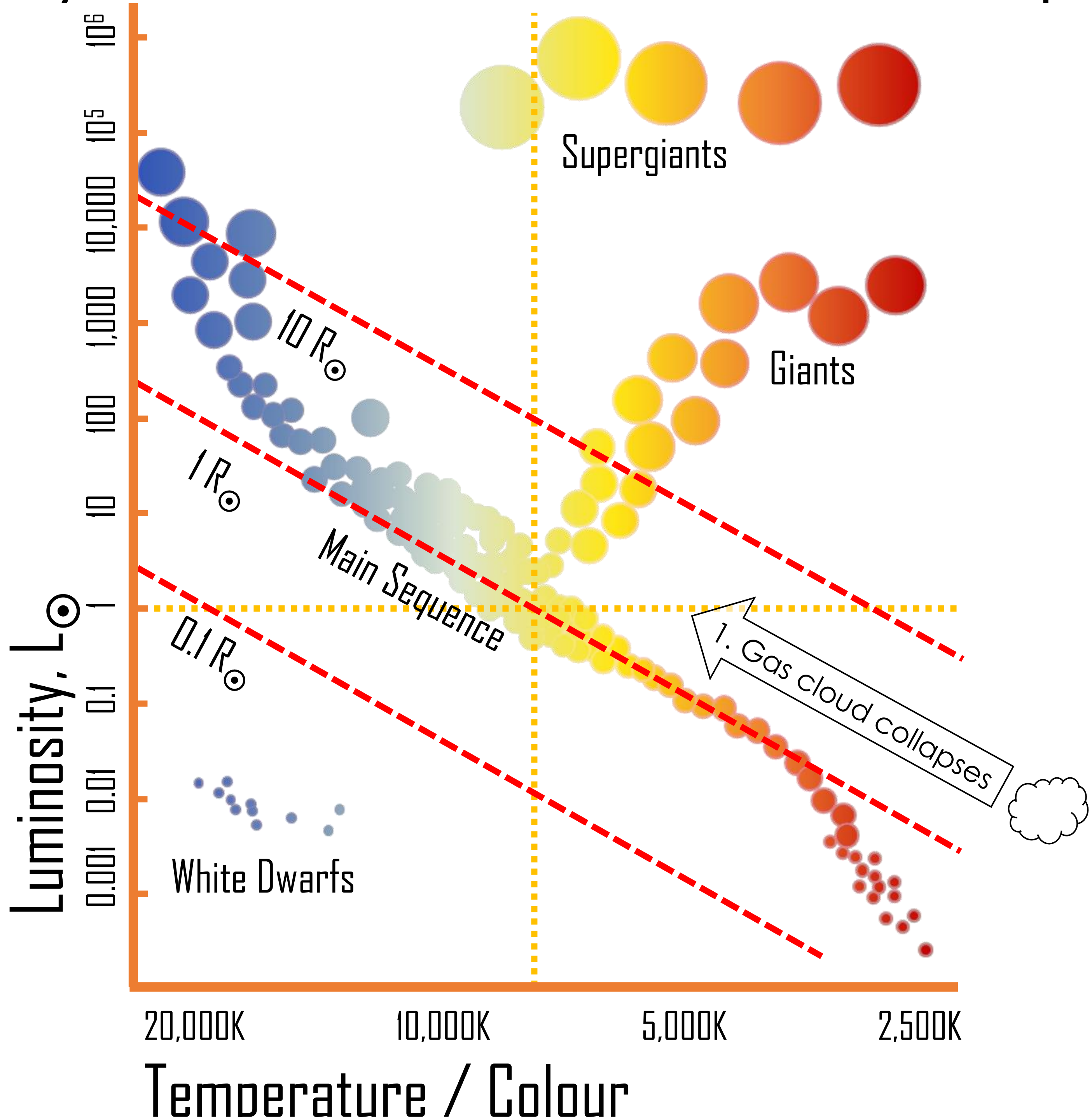
Summary of the Sun's Evolution: Step 1

Stellar Evolution



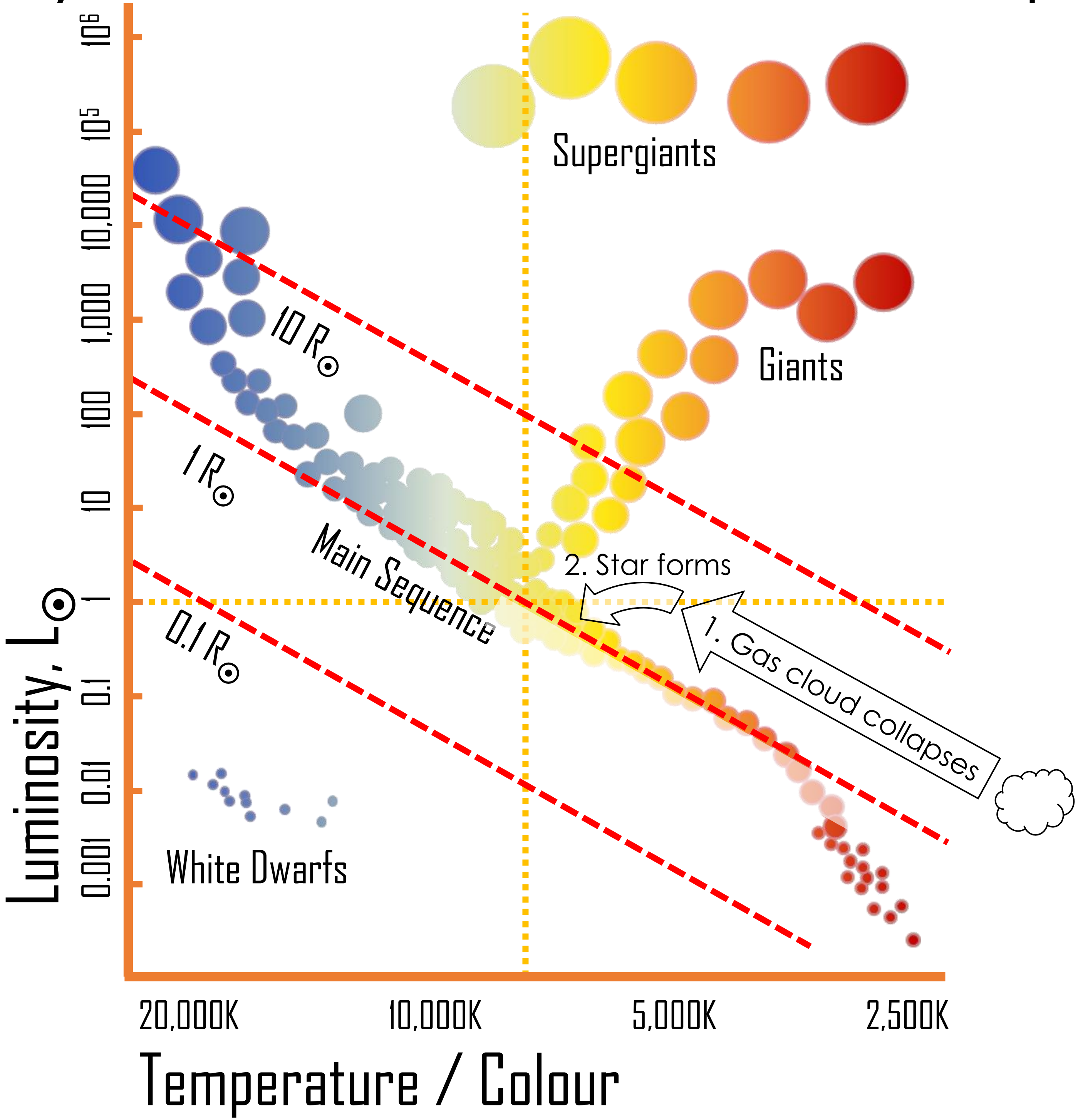
Summary of the Sun's Evolution: Step 1

Stellar Evolution



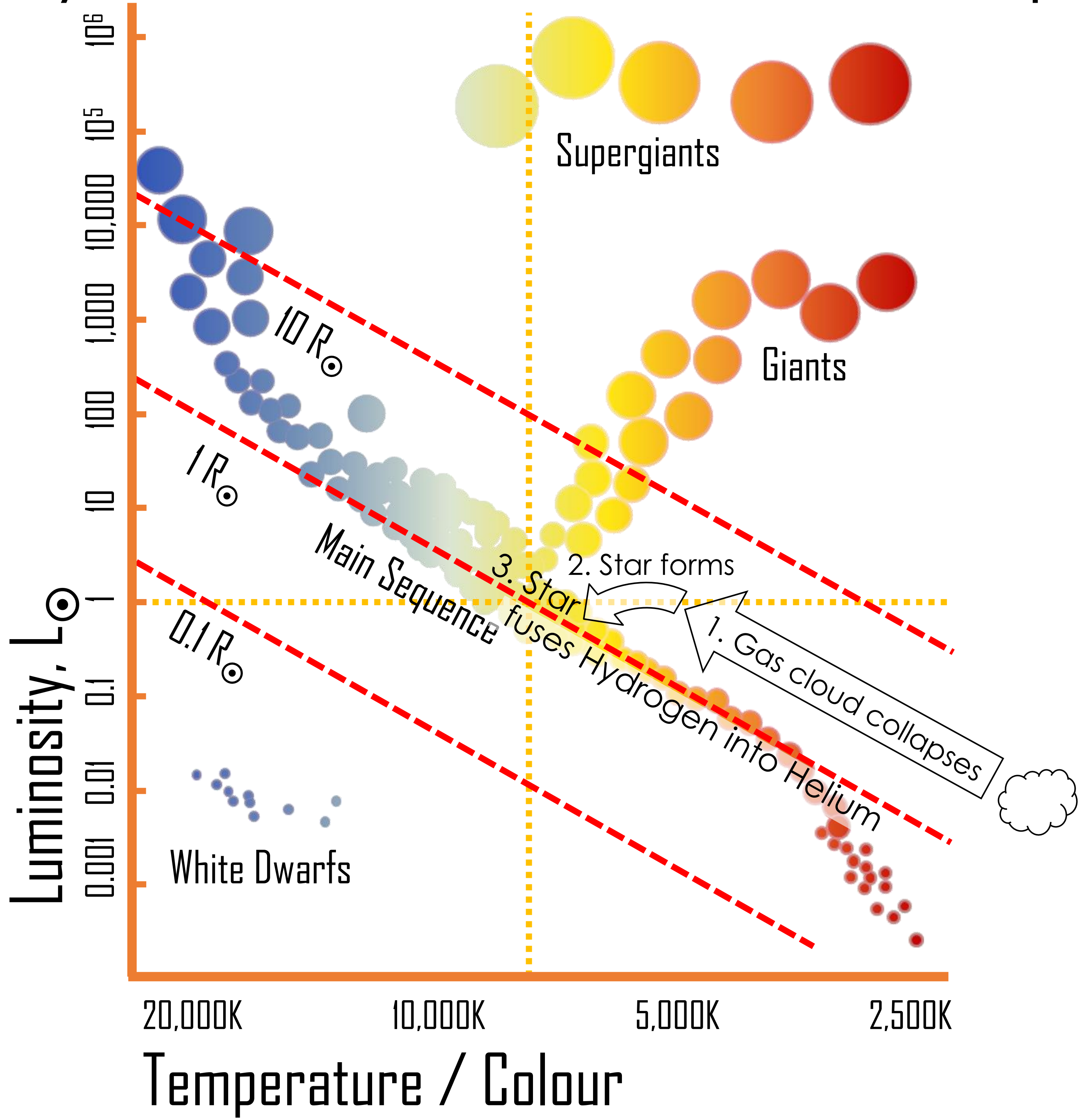
Summary of the Sun's Evolution: Step 2

Stellar Evolution



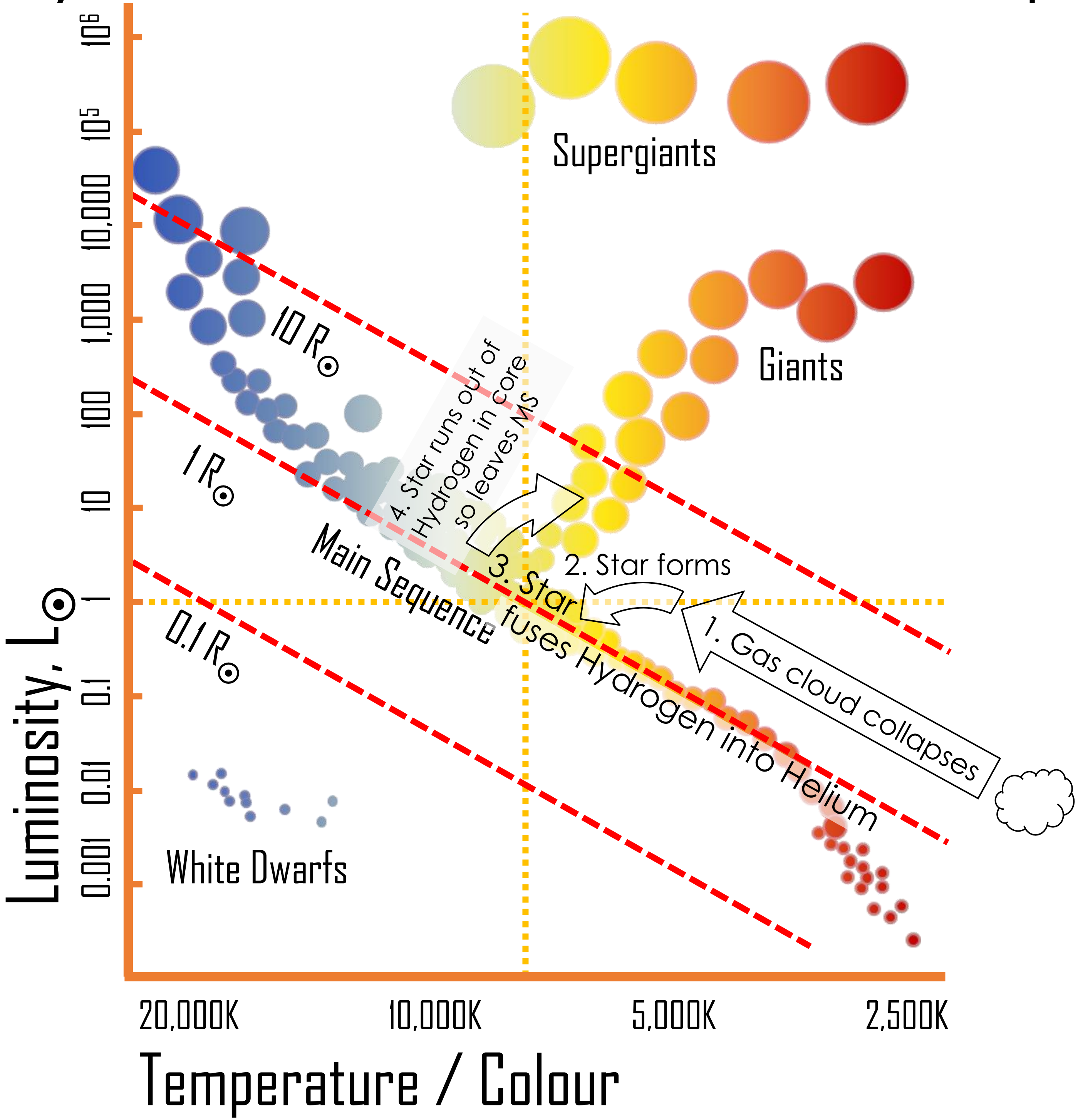
Summary of the Sun's Evolution: Step 3

Stellar Evolution



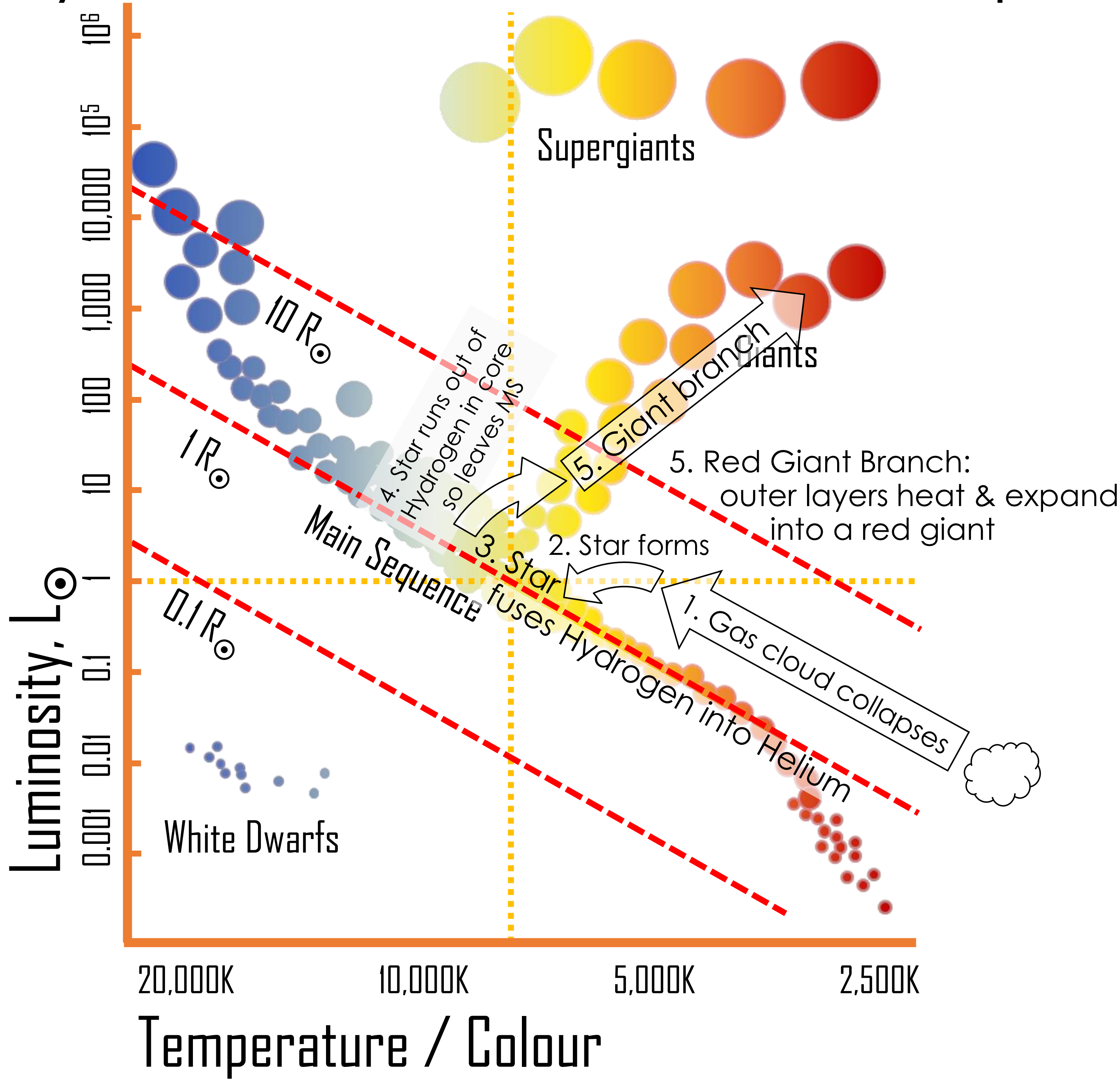
Summary of the Sun's Evolution: Step 4

Stellar Evolution



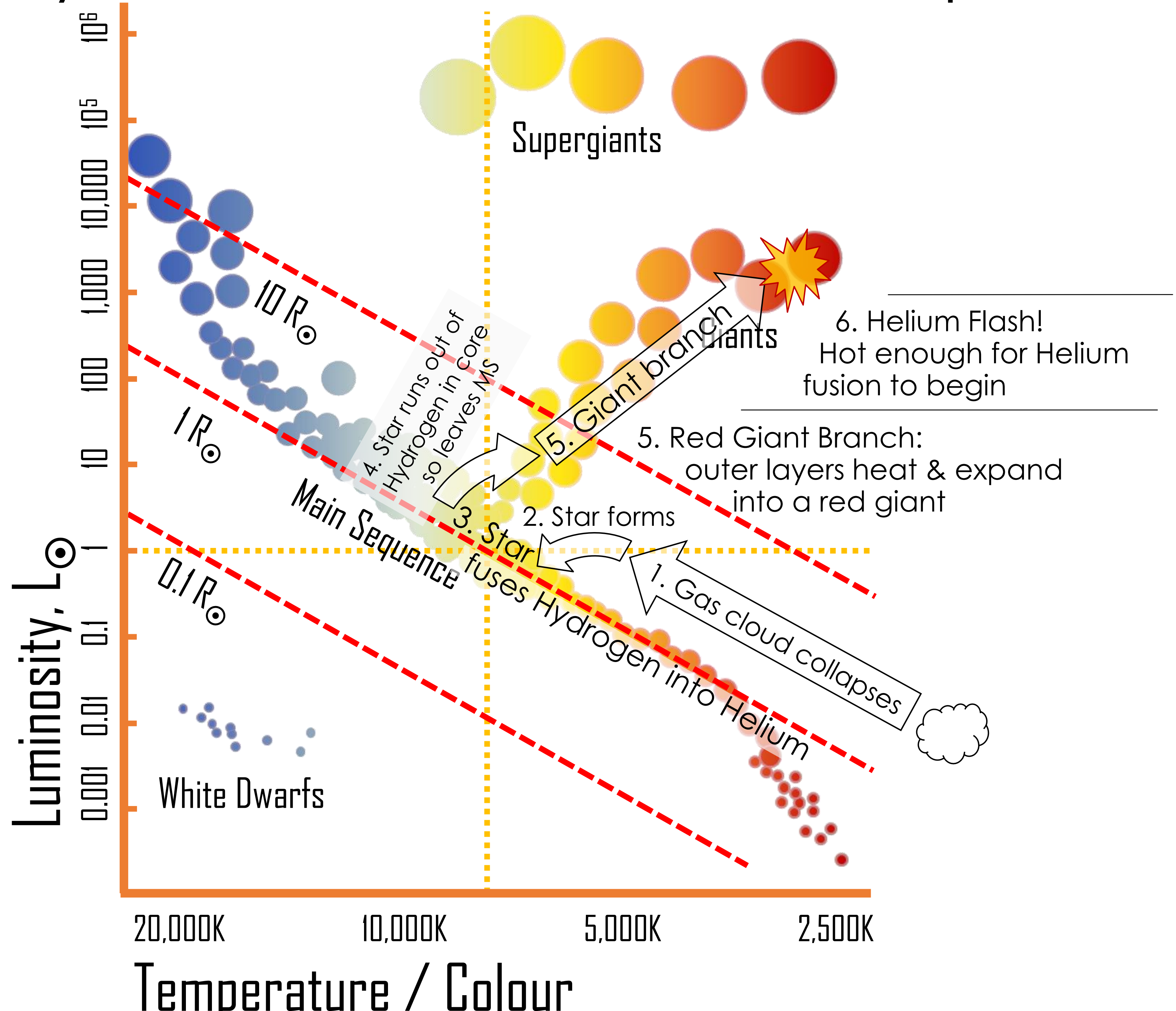
Summary of the Sun's Evolution: Step 5

Stellar Evolution



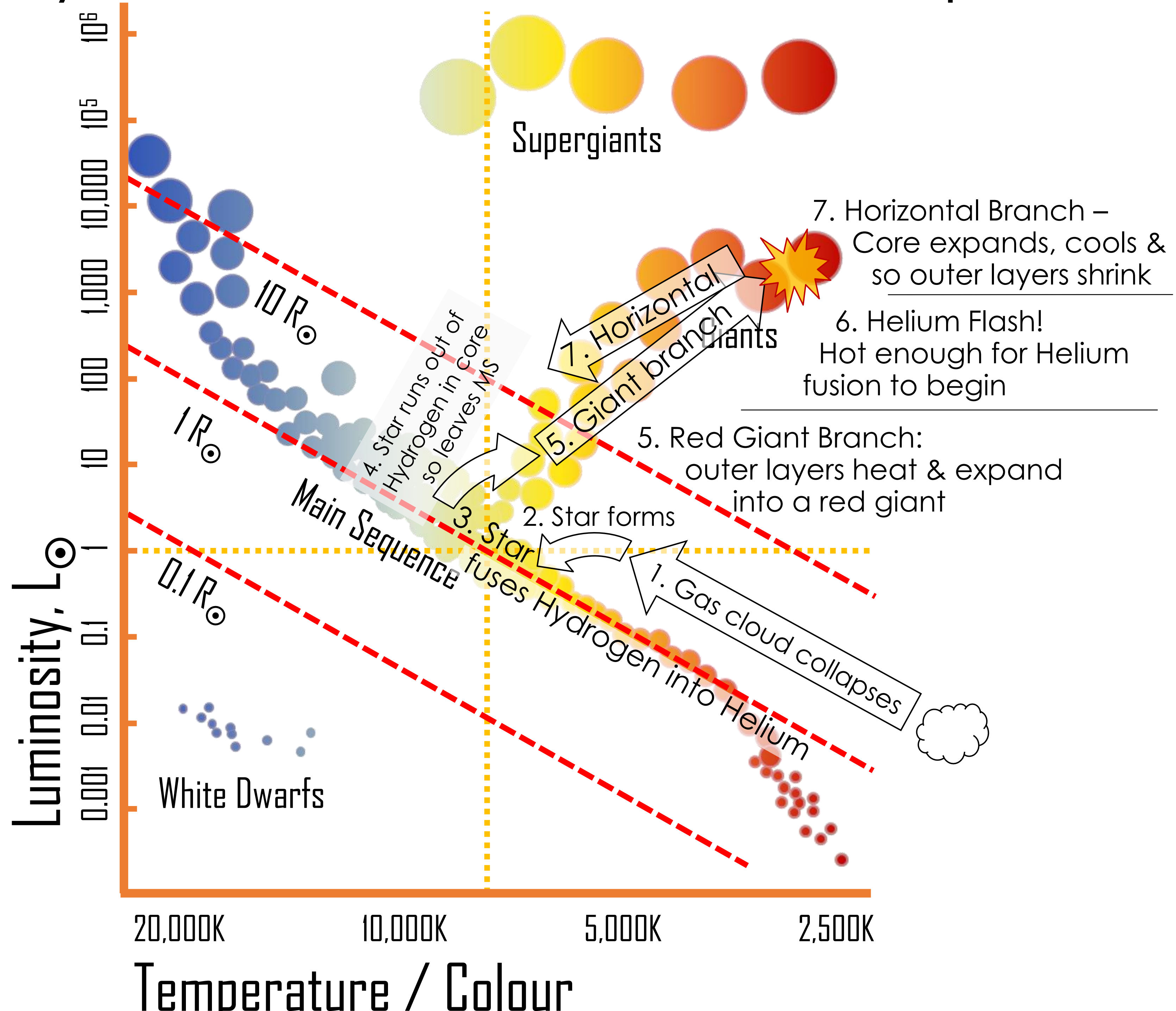
Summary of the Sun's Evolution: Step 6

Stellar Evolution



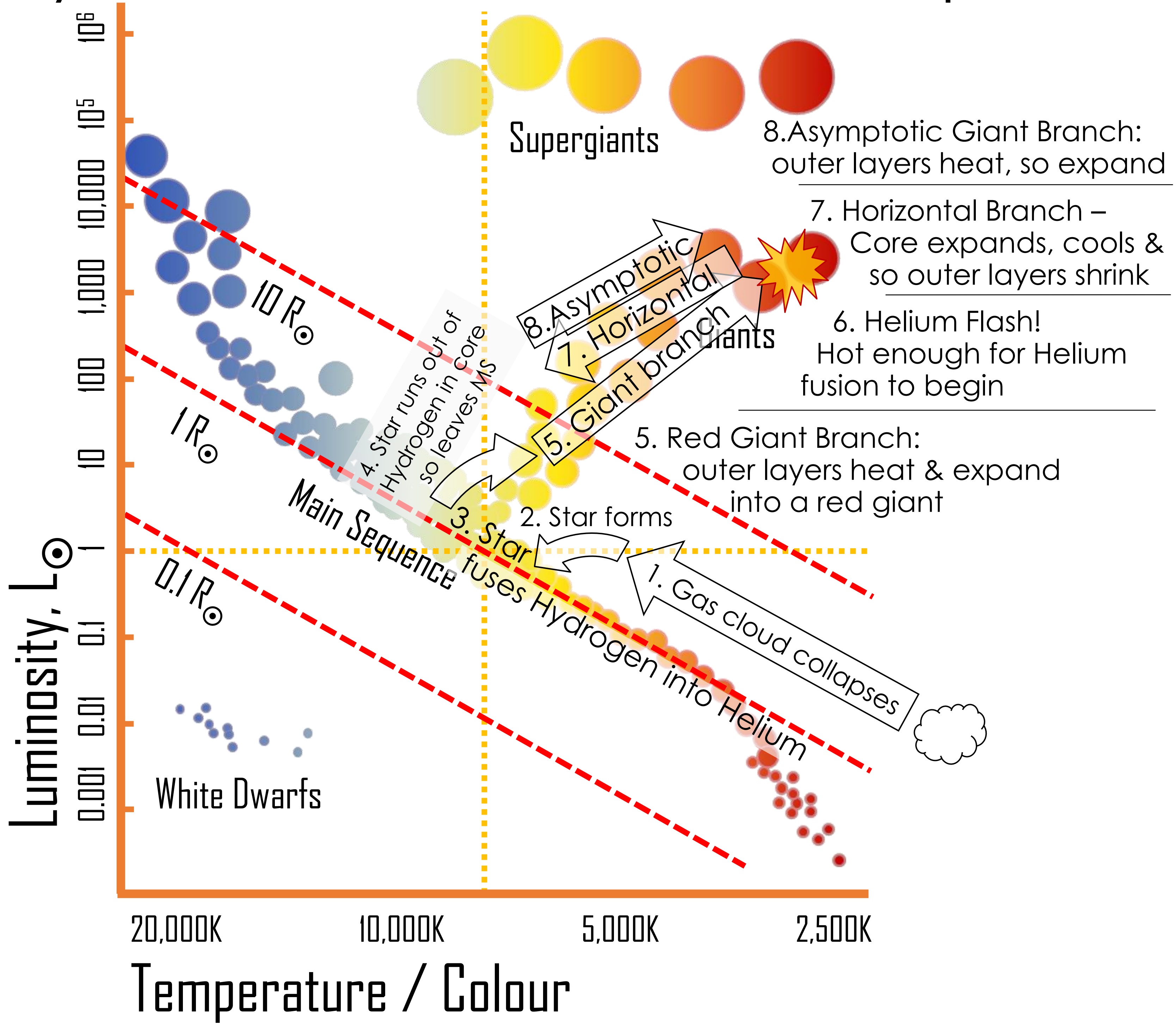
Summary of the Sun's Evolution: Step 7

Stellar Evolution



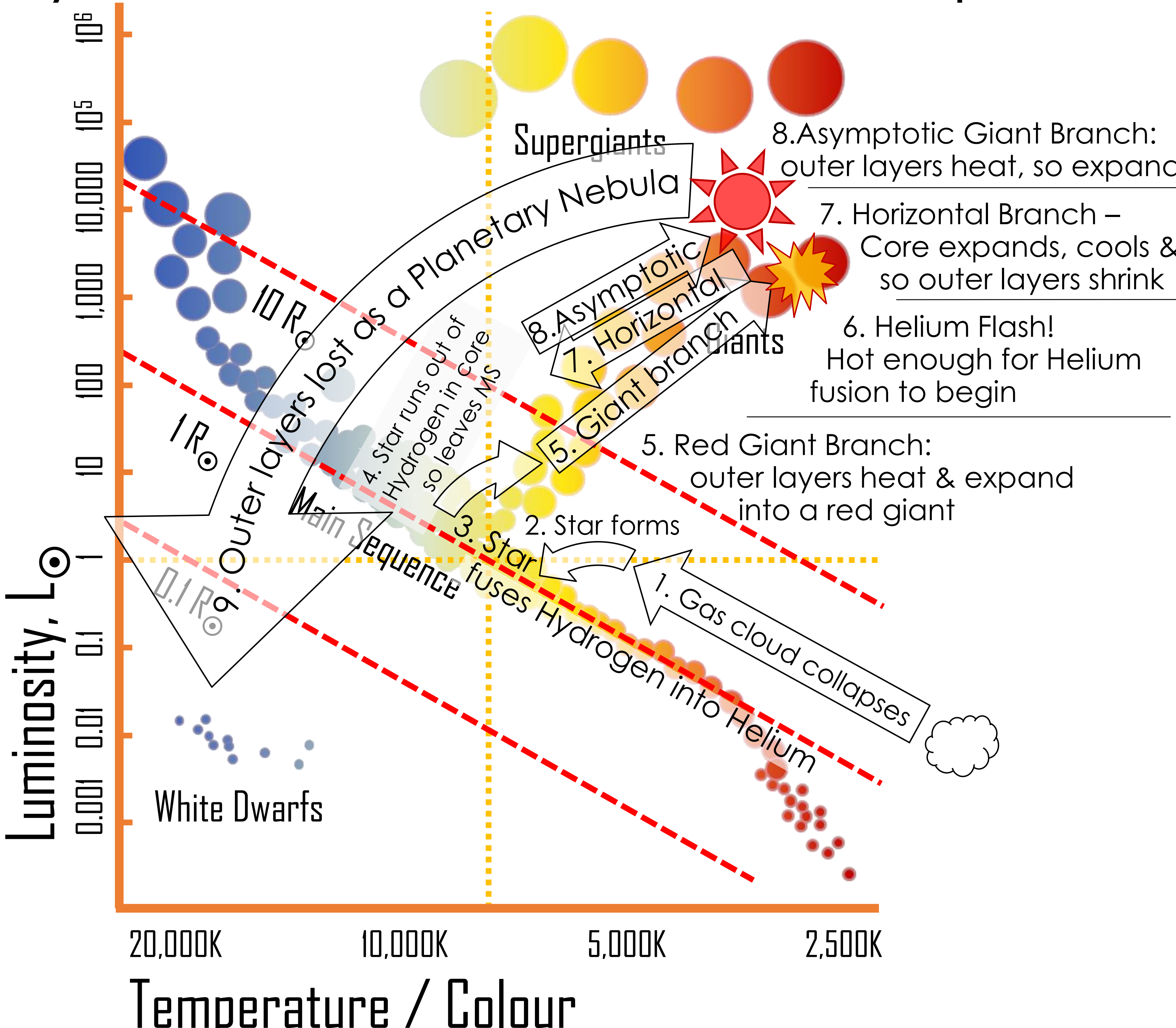
Summary of the Sun's Evolution: Step 8

Stellar Evolution

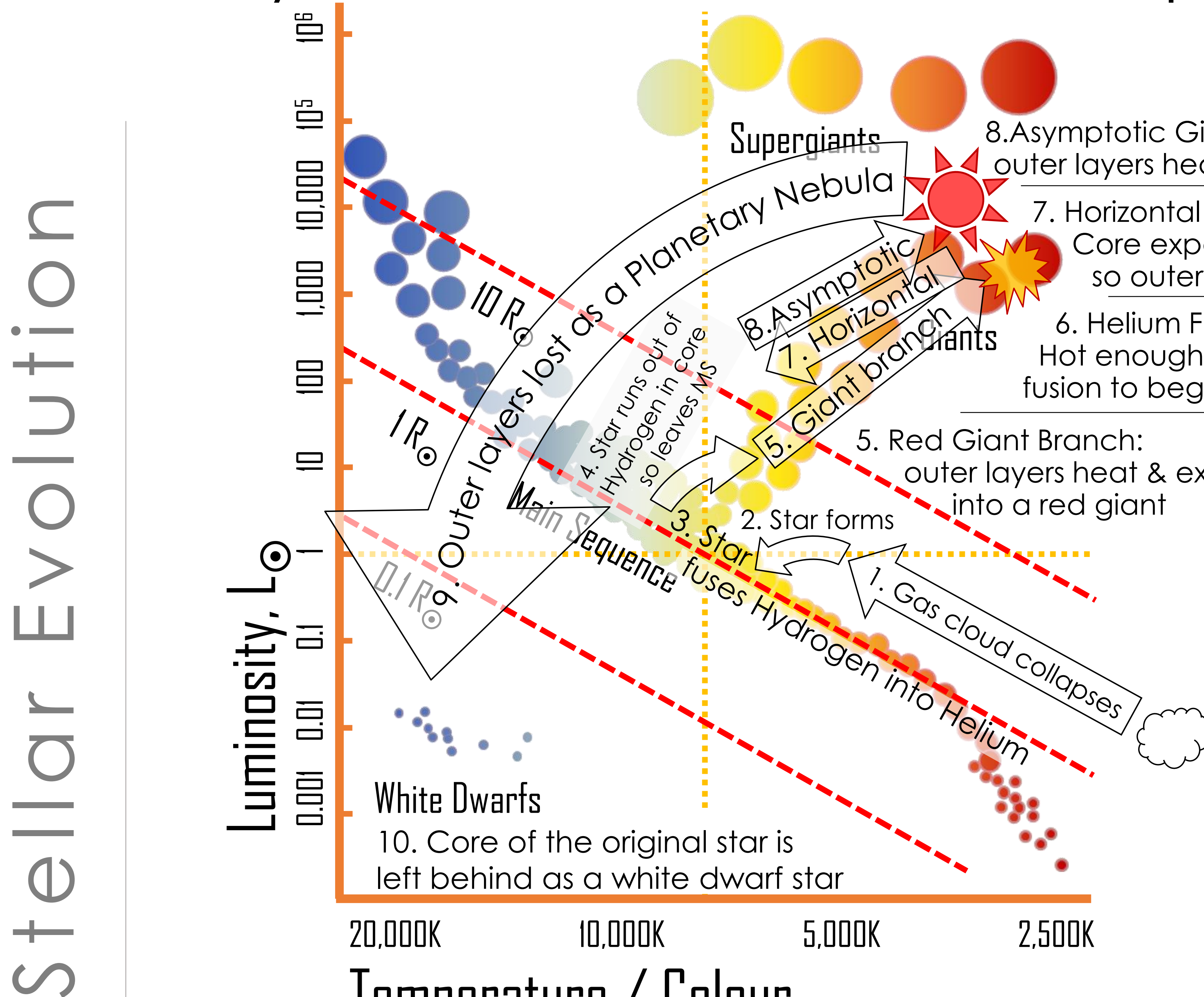


Summary of the Sun's Evolution: Step 9

Stellar Evolution



Summary of the Sun's Evolution: Step 10



Summary of Massive star Evolution

- Massive stars "live fast & die young"
- They are responsible for making all elements heavier than carbon, many of which are essential for life
- *Supernovae* spread these heavy elements throughout space - they will be incorporated into future generations of stars and humans!

- The remnant cores are either *neutron stars* (below about $3M_o$) or *black holes* ($> 3M_o$)

See also http://www.wimp.com/sizestar/

Summary of Massive star Evolution

1 & 2. A gas cloud collapses and a star forms

3. H is turned into He, until core is pure He

4. H turns to He the outer layers, & the core becomes hot enough for He to fuse into C
   - The star expands into a *pulsating variable star*

5. It becomes a *red supergiant star and then a Wolf-Rayet star*

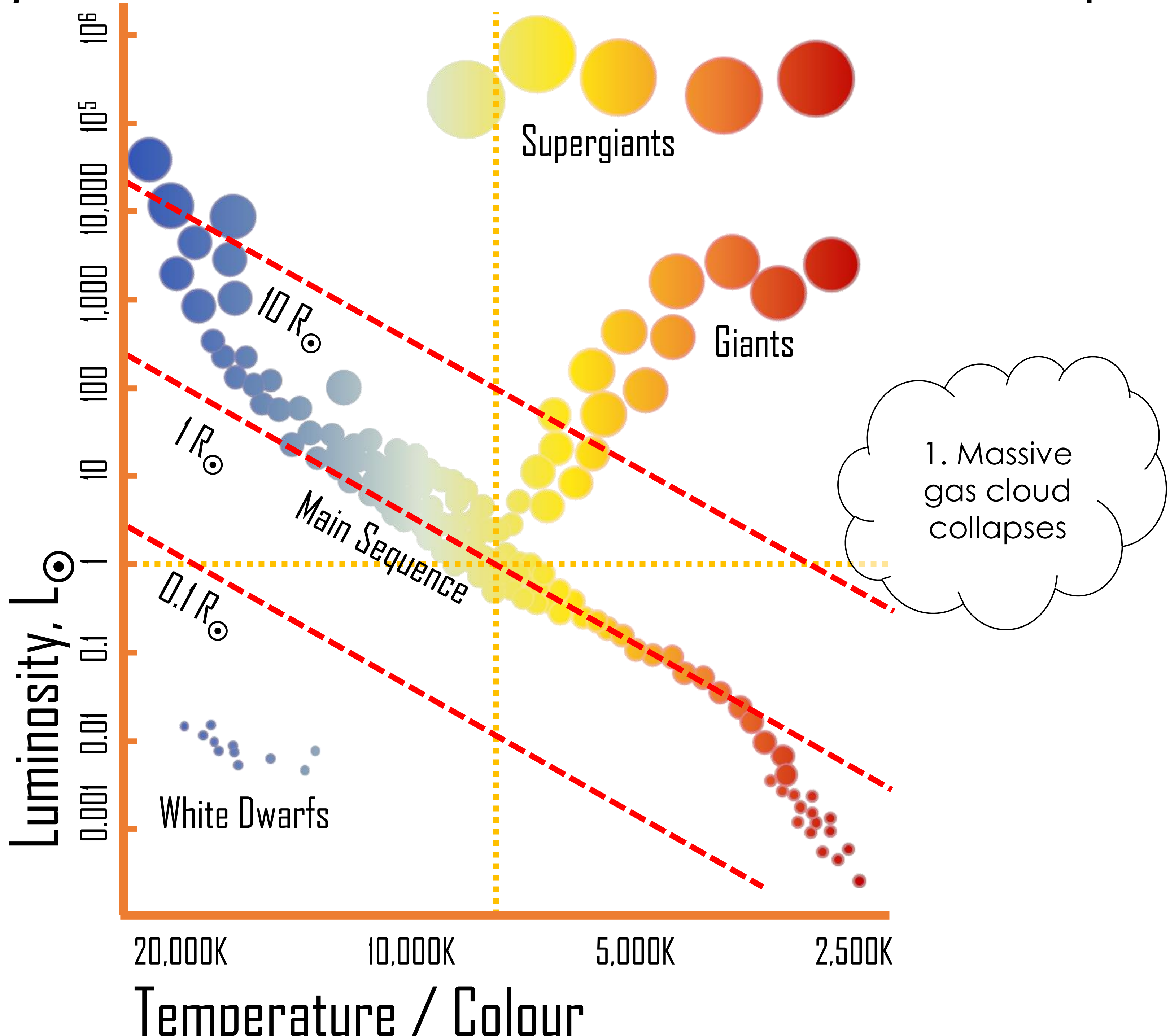
   Heavier elements are made as the core of the star gets hot enough to do so

6. Fusion ends as it runs out of fuel - supernova!

7. Centre collapses to form either a neutron star or black hole

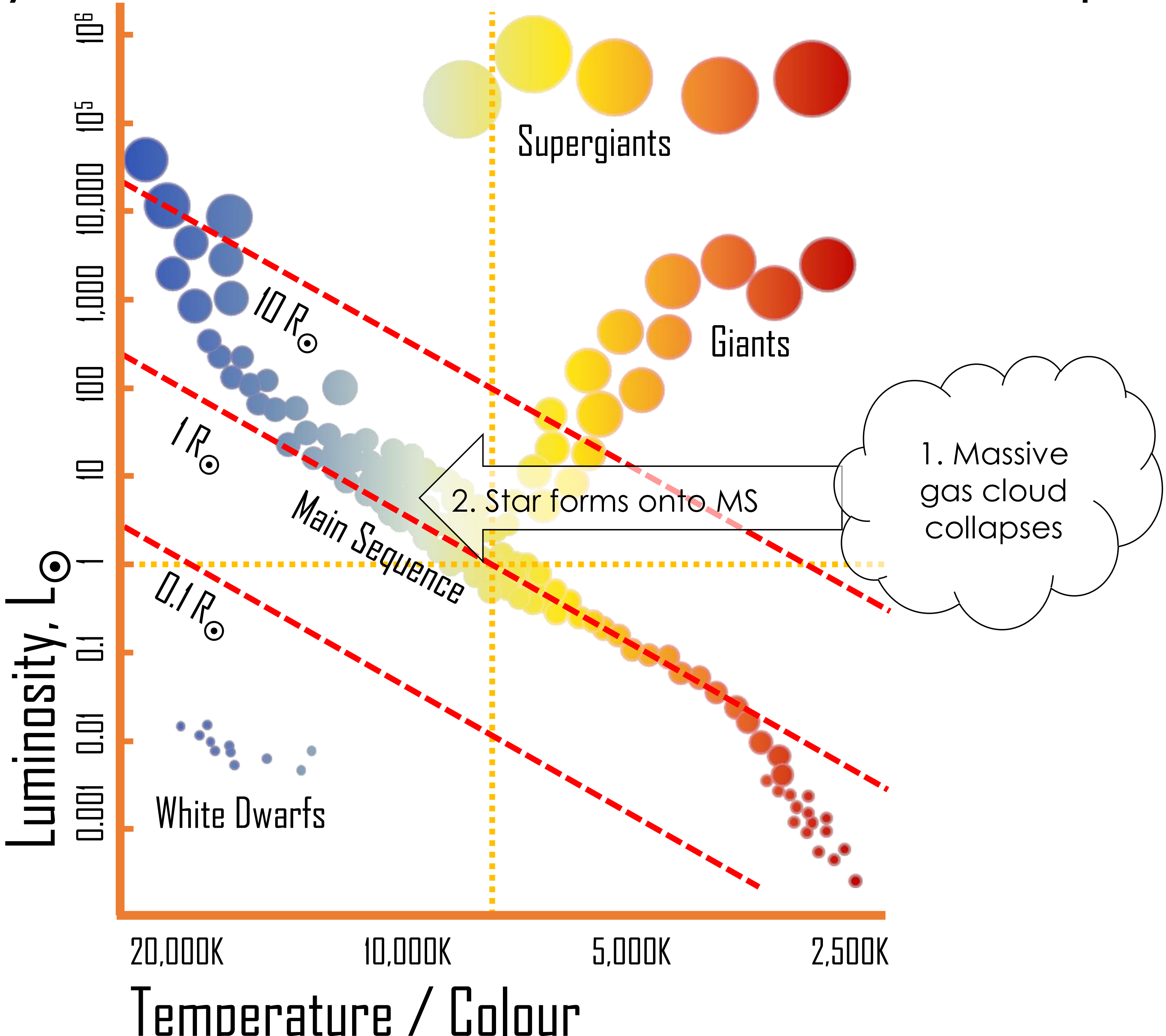
Summary of massive Star's Evolution: Step 1

Stellar Evolution



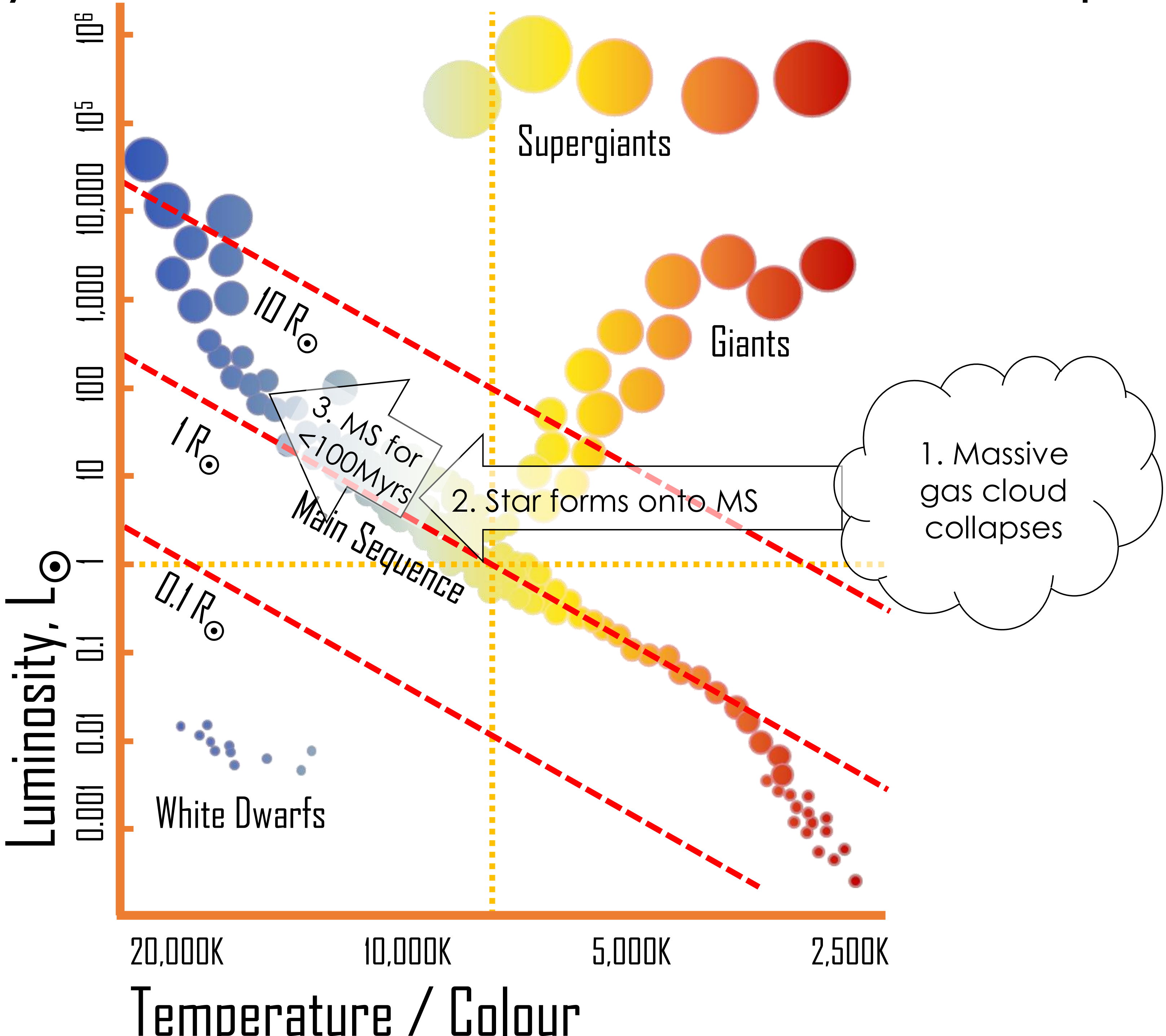
Summary of massive Star's Evolution: Step 2

Stellar Evolution



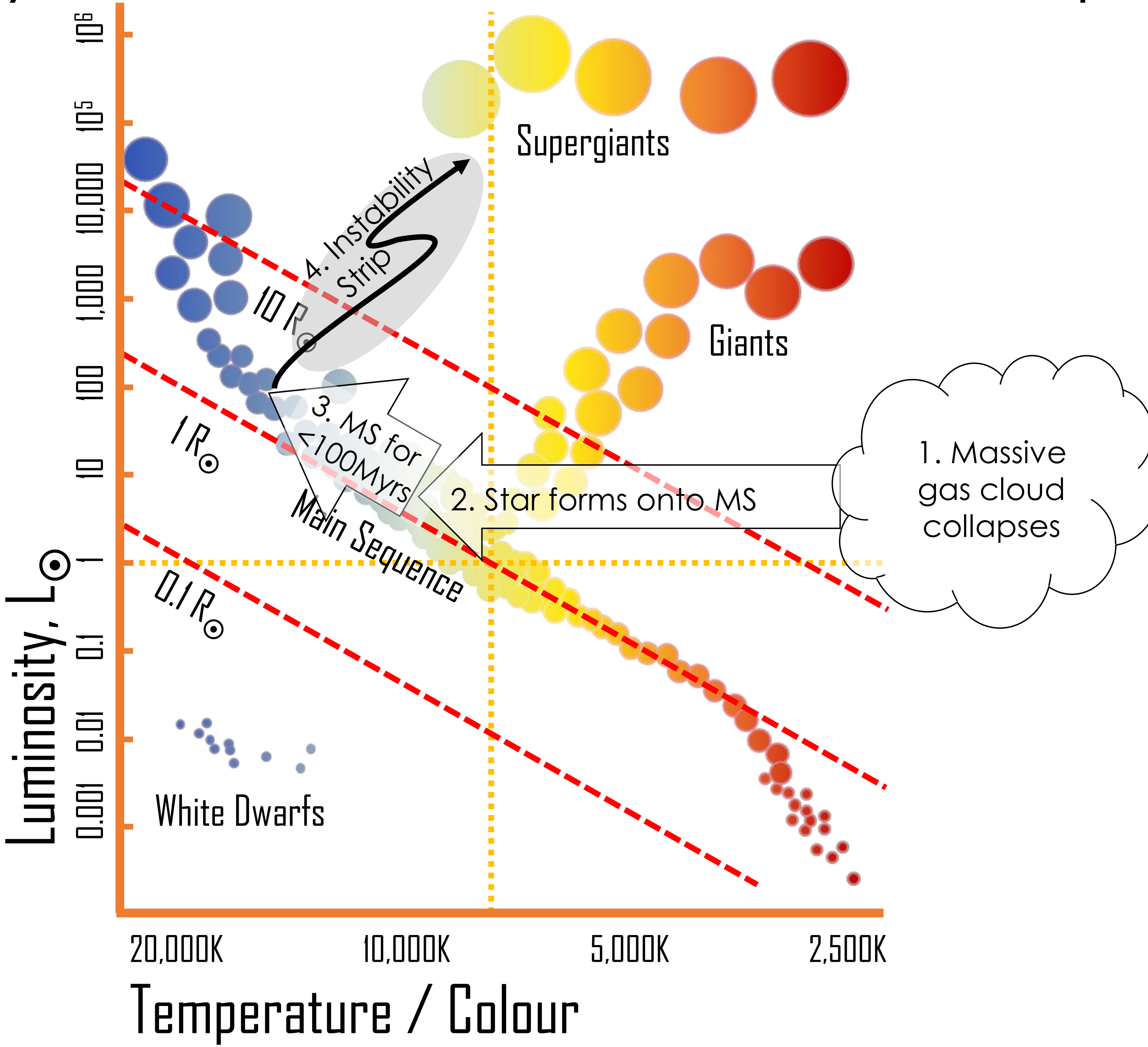
Summary of massive Star's Evolution: Step 3

Stellar Evolution



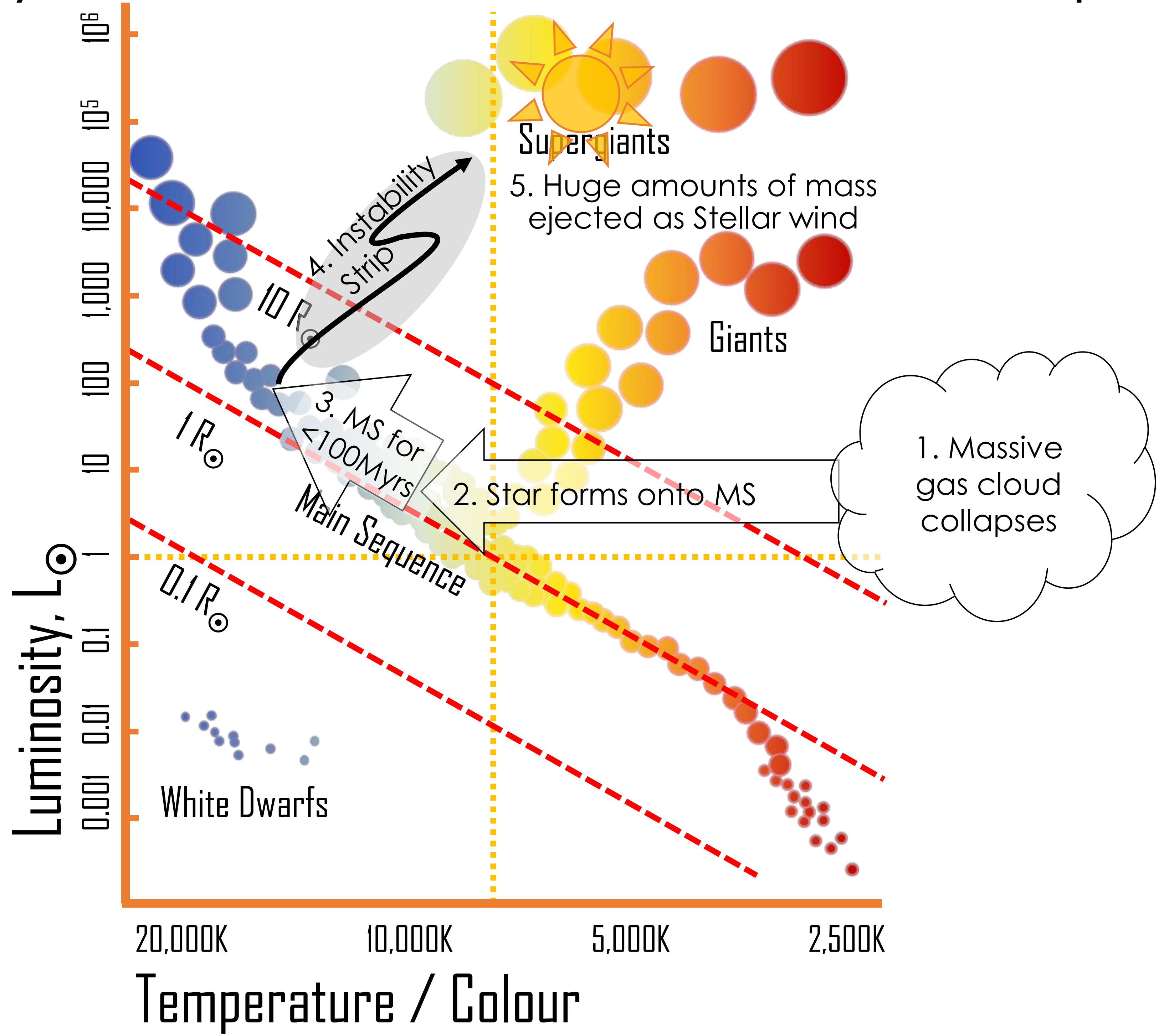
Summary of massive Star's Evolution: Step 4

Stellar Evolution



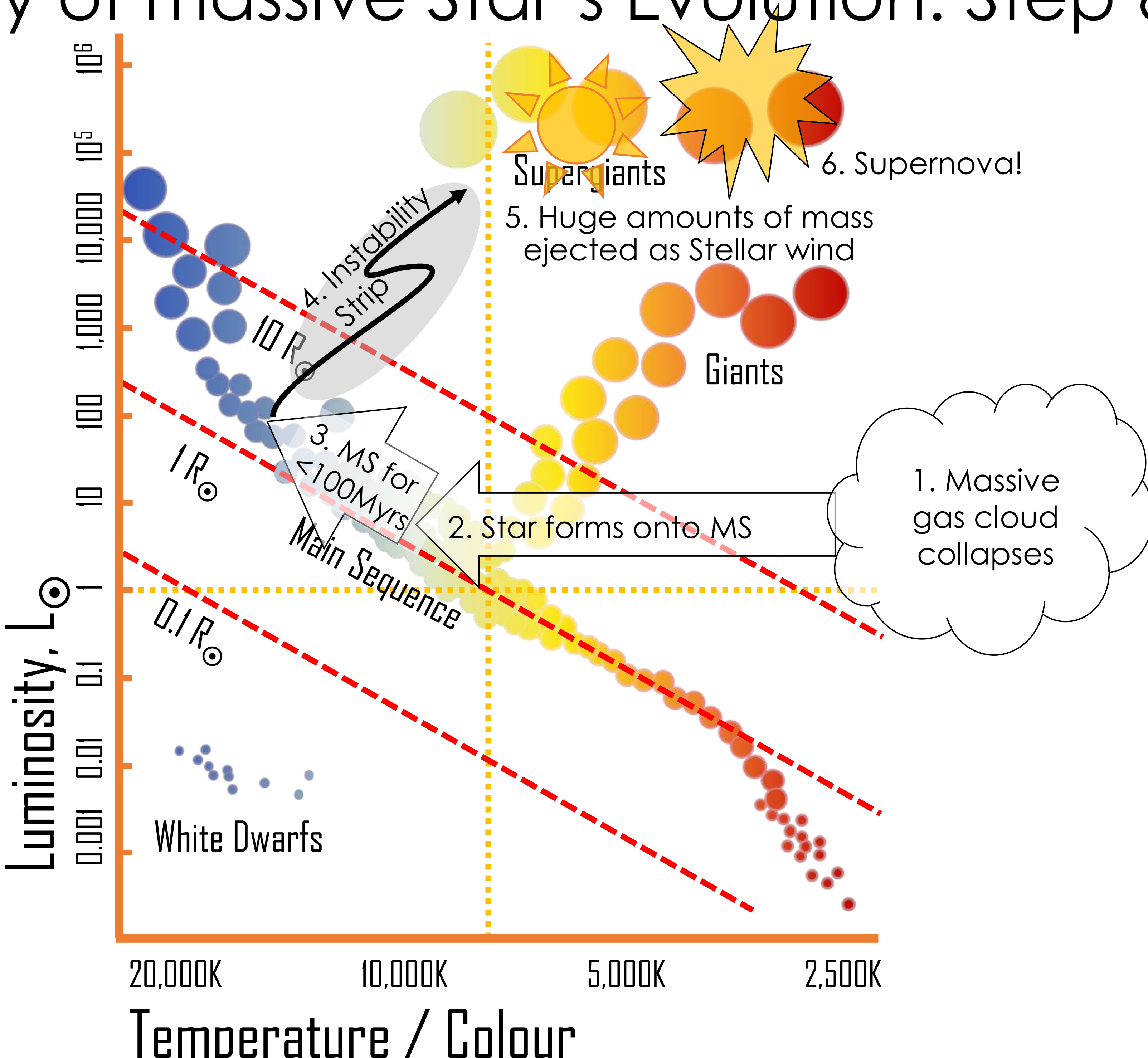
Summary of massive Star's Evolution: Step 5

Stellar Evolution



Summary of massive Star's Evolution: Step 6

Stellar Evolution



Summary of massive Star's Evolution: Step 7