STARS - S06

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AMNH After-School Program

AMERICAN MUSEUM OF NATURAL HISTORY

From last class

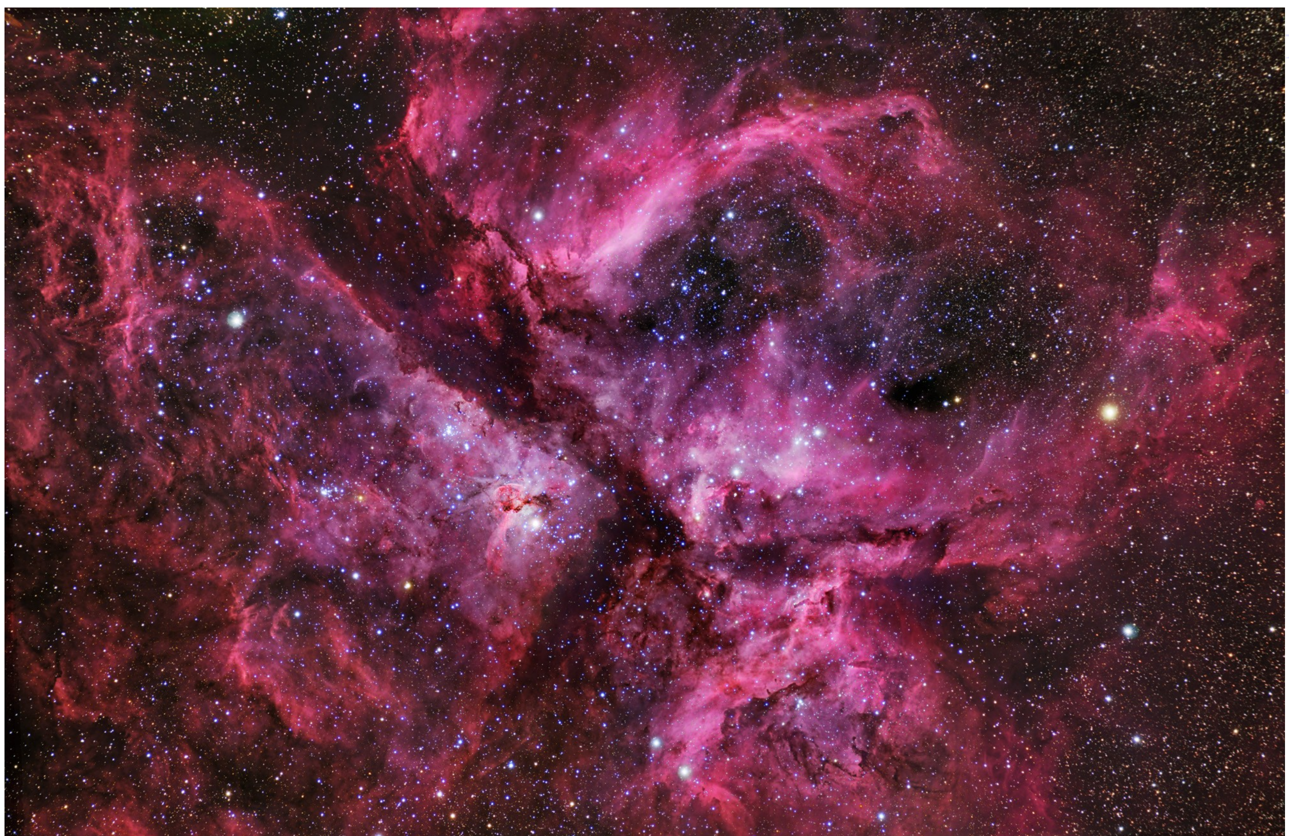
The ISM is not empty. In dense molecular clouds, stars begin to form.

Star formation is governed by gravitational collapse. Thermal pressure opposes it.

Clouds are turbulent. Only the densest clumps form stars.

Angular momentum leads to a circumstellar disk.

Planets [illegible] formation.



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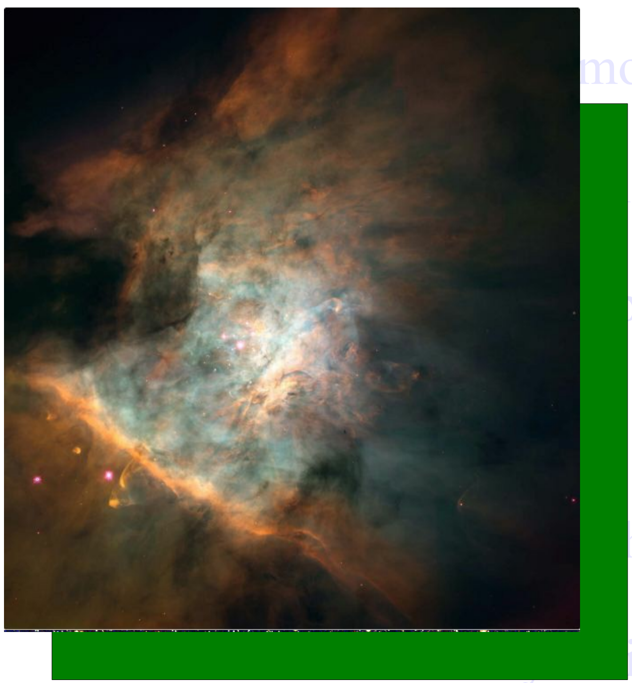

Molecular Cloud Fact Sheet

Temperature	10-50 K
Density	$10^2 - 10^6$ atoms/cm^3
(ISM Density	1 atom/cm^3)
(Air density	**10^{19} atoms/cm^3**)

Irregular and turbulent

Sizes	10-100 parsecs
Mass	$10^2 - 10^6$ solar masses

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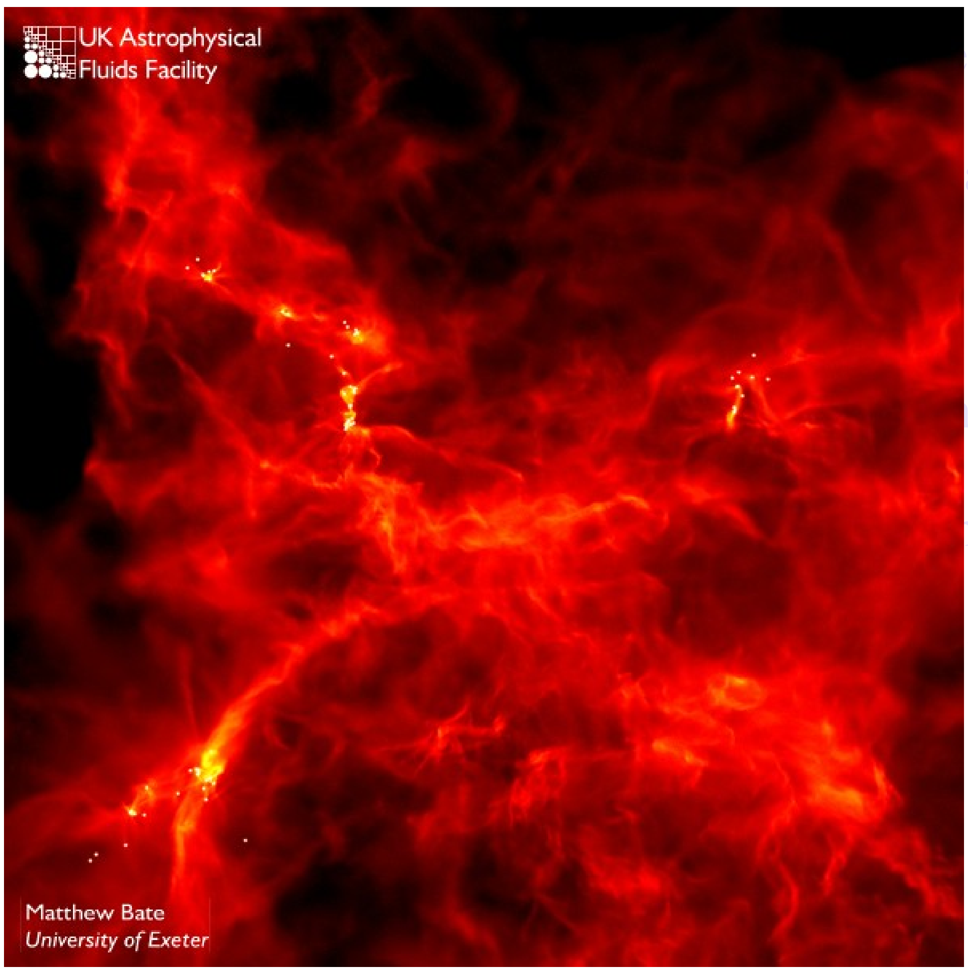
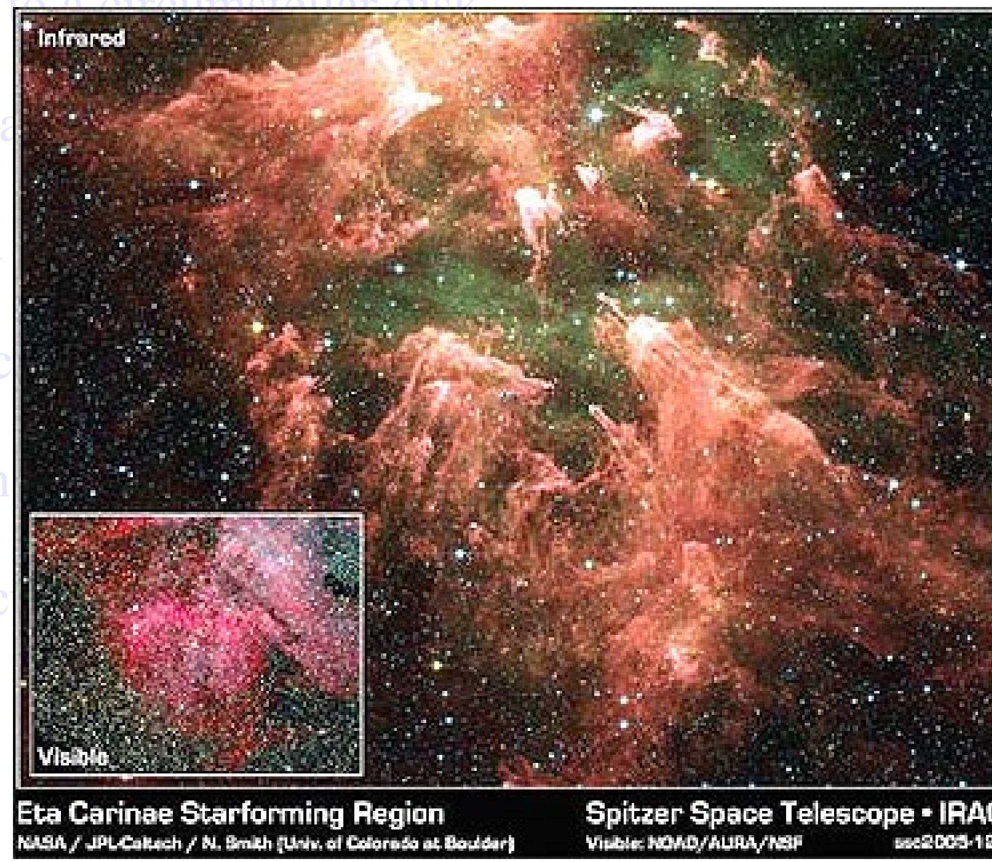


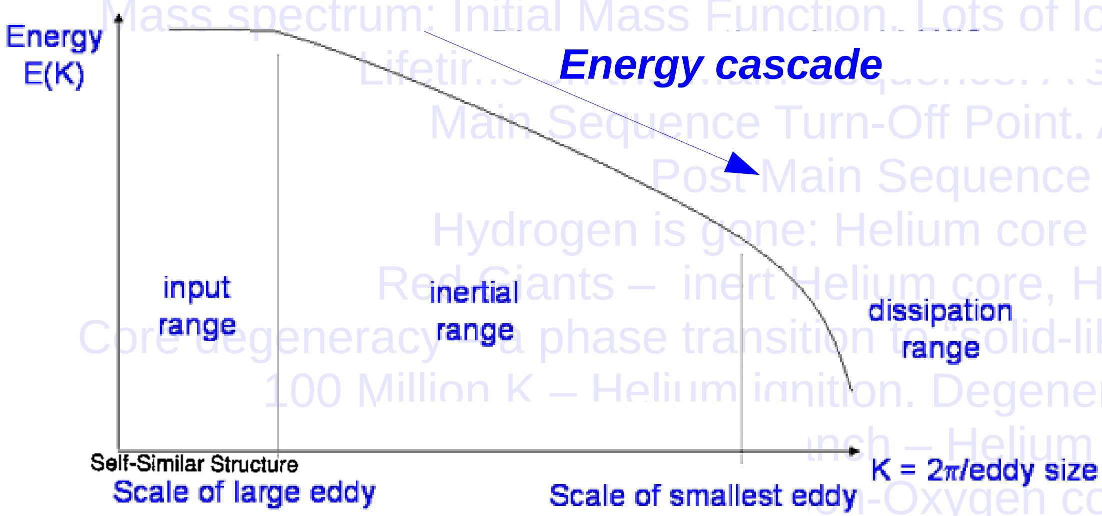
Computer simulation

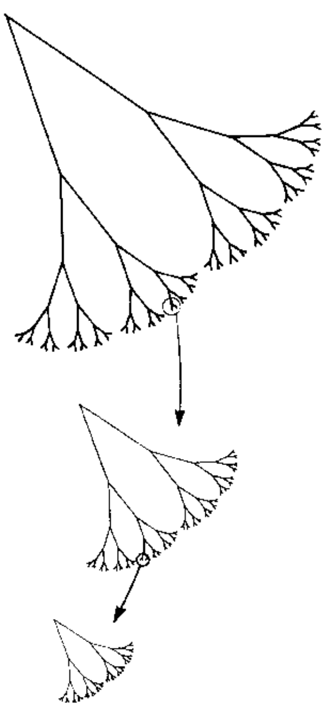


Observation

From last class

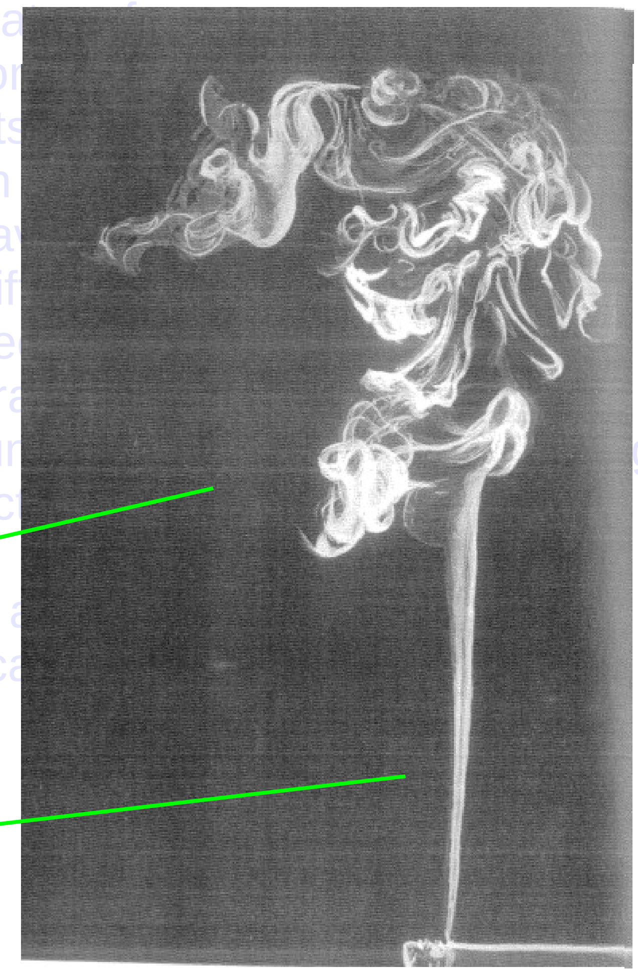
Turbulence is a self-similar flow. Size spectrum is well defined.





Turbulent flow

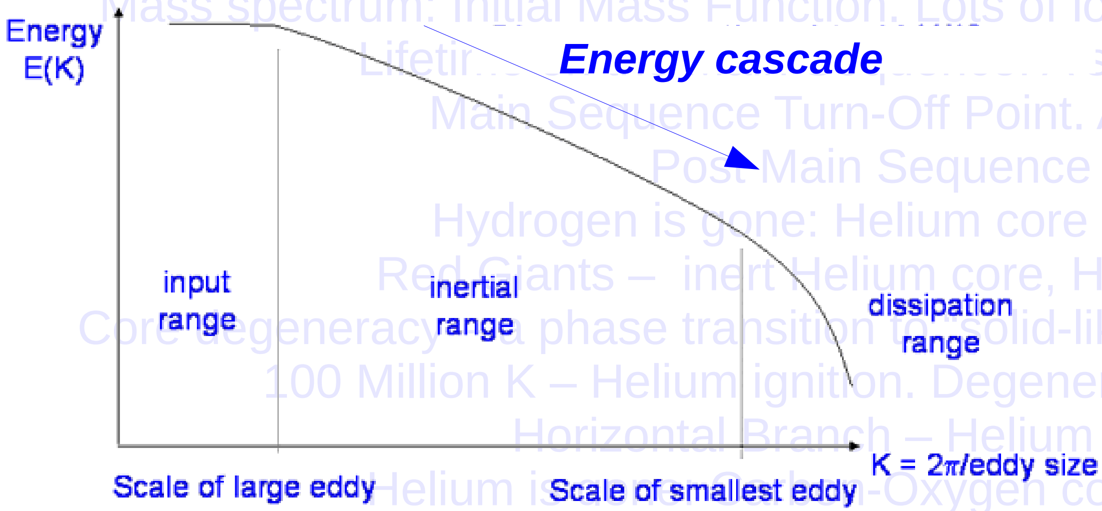
Laminar flow

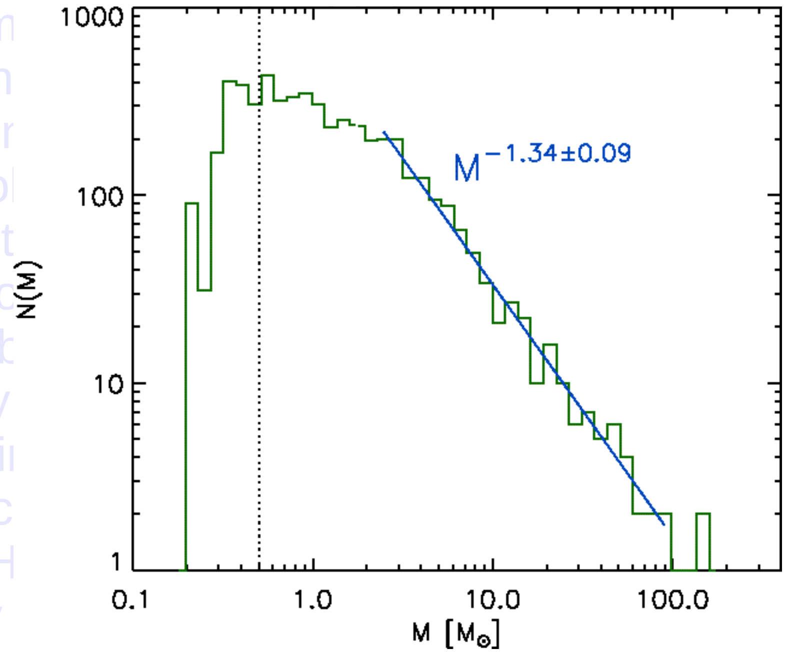


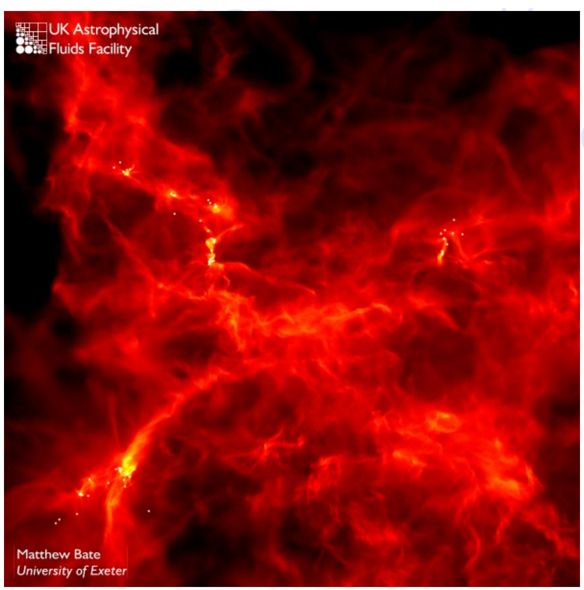
From last class

Turbulence is a self-similar flow. Size spectrum is well defined.

Turbulent fragmentation of a molecular cloud leads to a well defined mass spectrum.







Planetary Nebula

White dwarfs cool in long timescales

From last class

Turbulence is a self-similar flow. Size spectrum is well defined.
Turbulent fragmentation of a molecular cloud leads to a well defined mass spectrum.

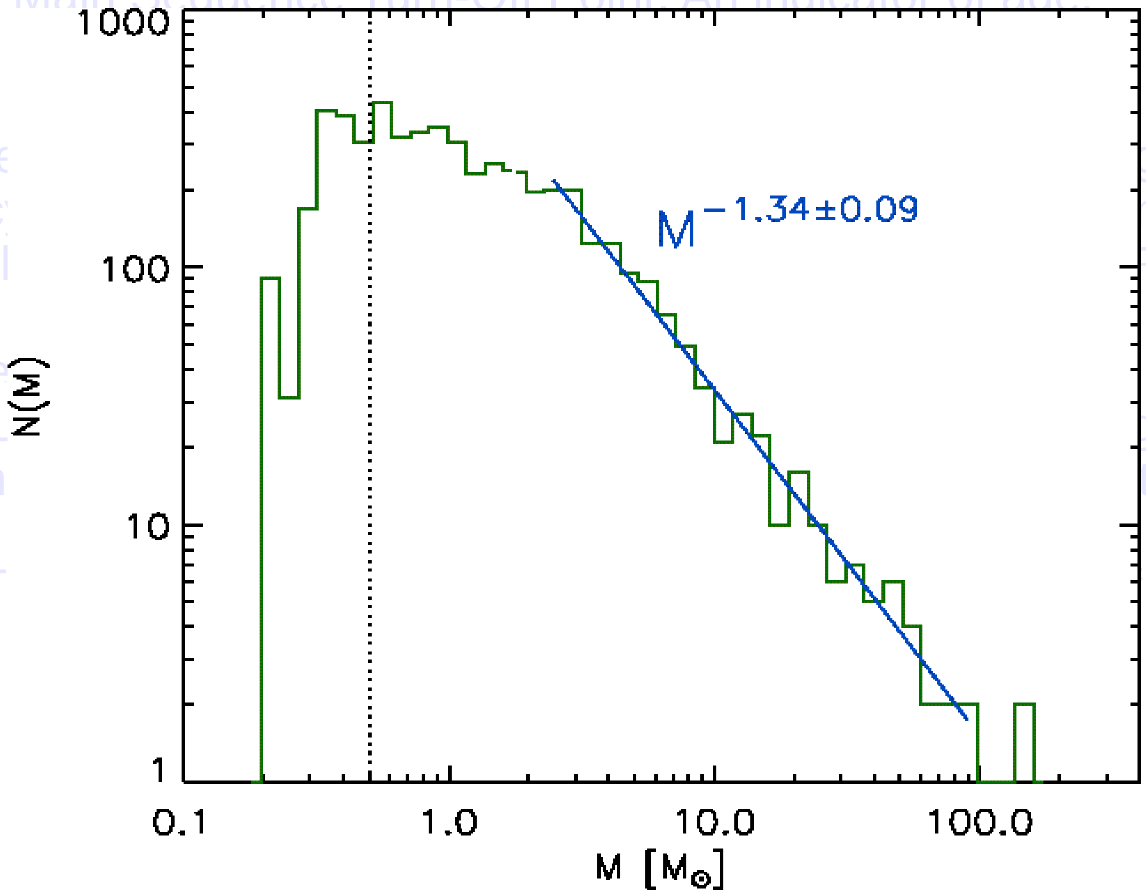
Mass spectrum: ***Initial Mass Function***. Lots of low mass stars, few high mass stars.

Lifetime on the Main Sequence: A strong function of mass.
Main Sequence Turn-Off Point. An indicator of age.

Re g
Core degenerac ntraction stops.
100 Mill

He
Asympt gen Shell Burning
AGB are un tmosphere

T



Lots of low mass stars
Very few high mass stars

Most common mass: 0.5 Msun

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Clouds are turbulent. Only the densest clumps form stars.

Angular momentum leads to a circumstellar disk.

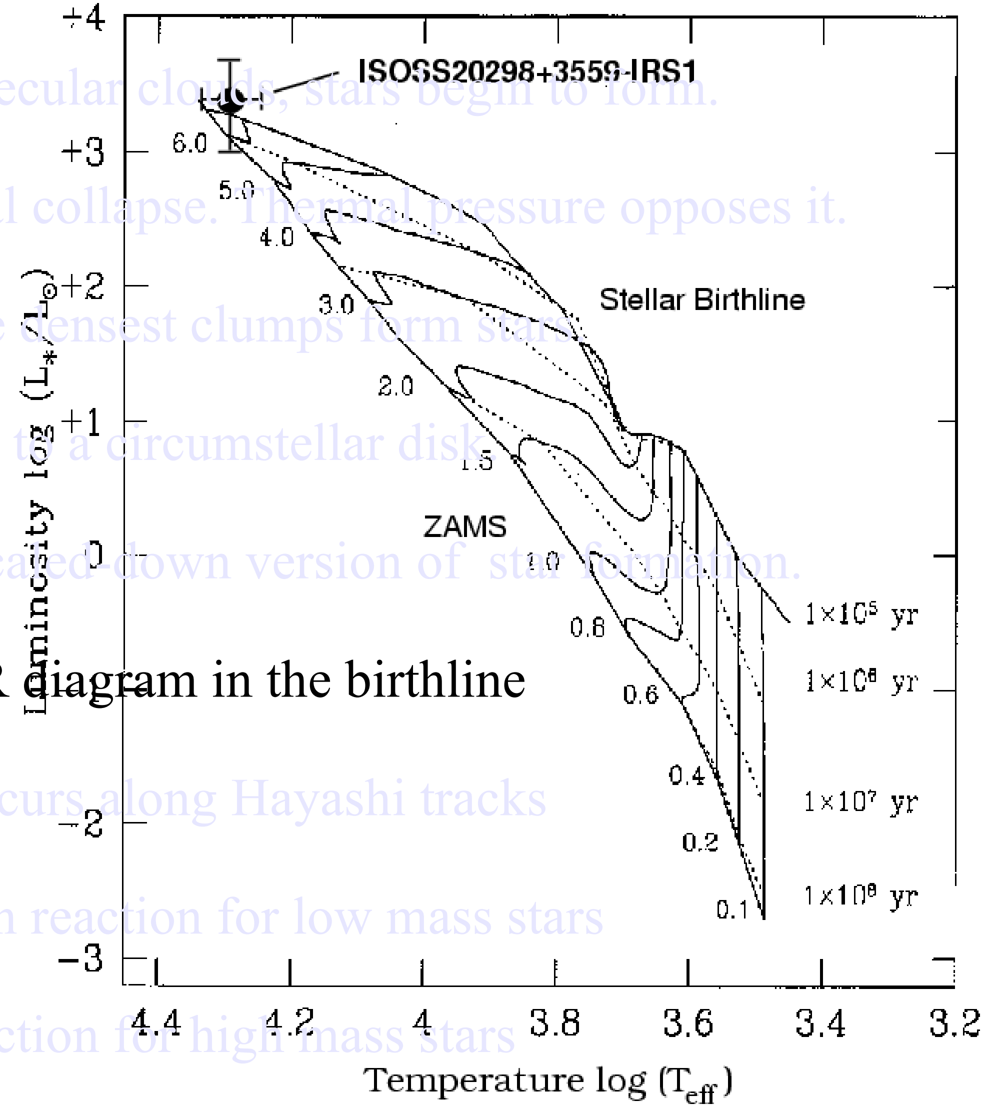
Planets form in the turbulent disk in a scaled-down version of star formation.

Protostars appear in the HR diagram in the birthline

Gravitational contraction occurs along Hayashi tracks

Proton-proton chain is the main reaction for low mass stars

CNO cycle is the main reaction for high mass stars



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Pre Main Sequence Evolution: gravitational contraction along Hayashi tracks

Proton-proton chain is the main reac

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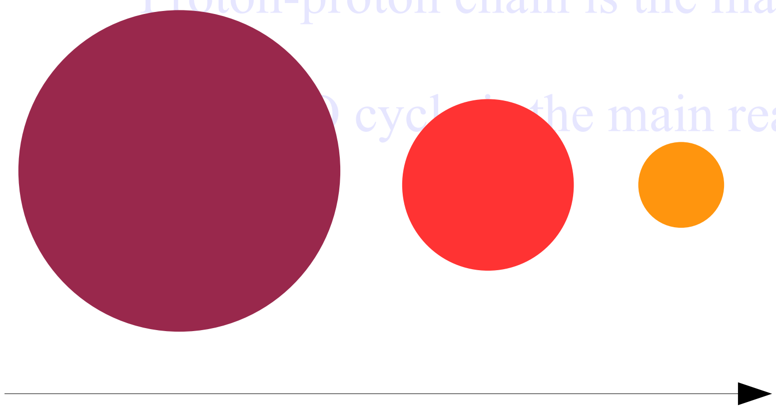

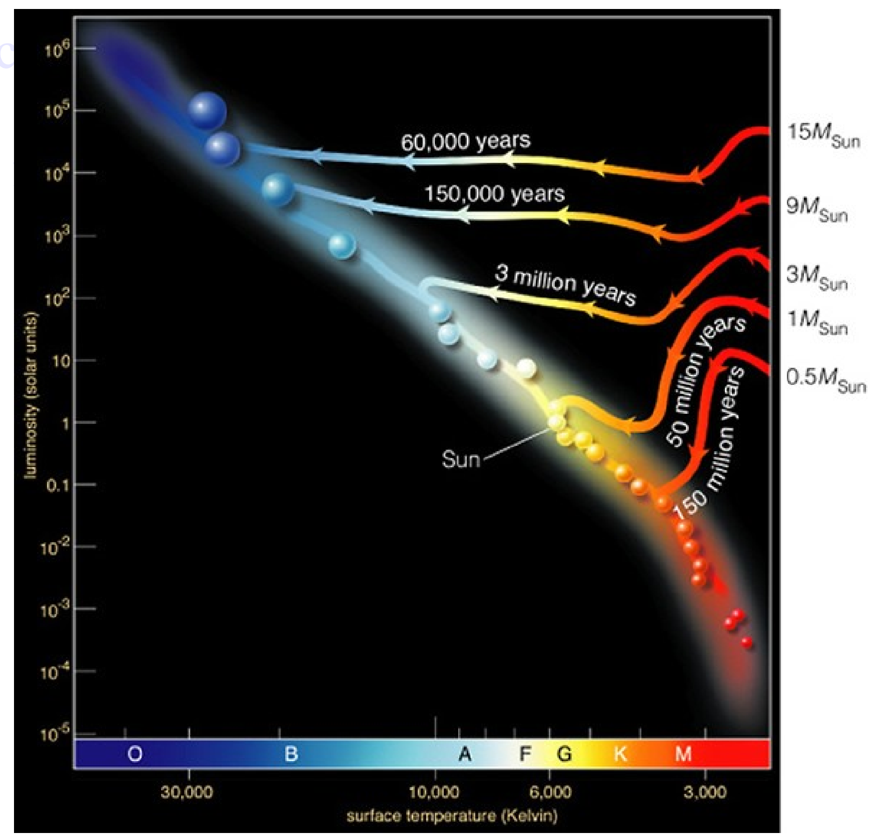

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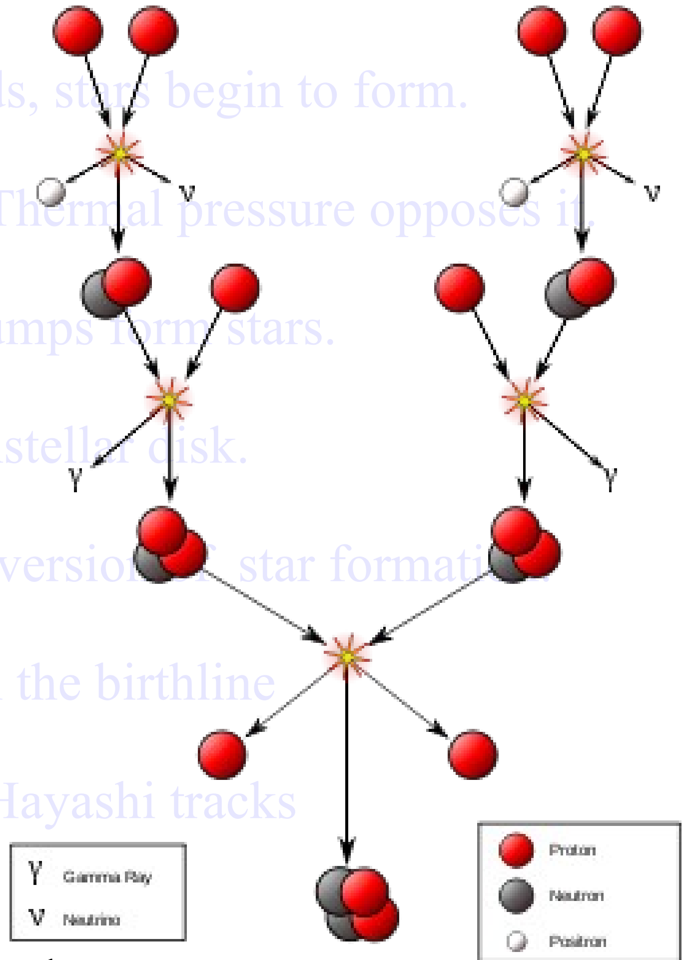

Proton-proton chain is the main reaction for low mass stars

CNO cycle is the main reaction for high mass stars

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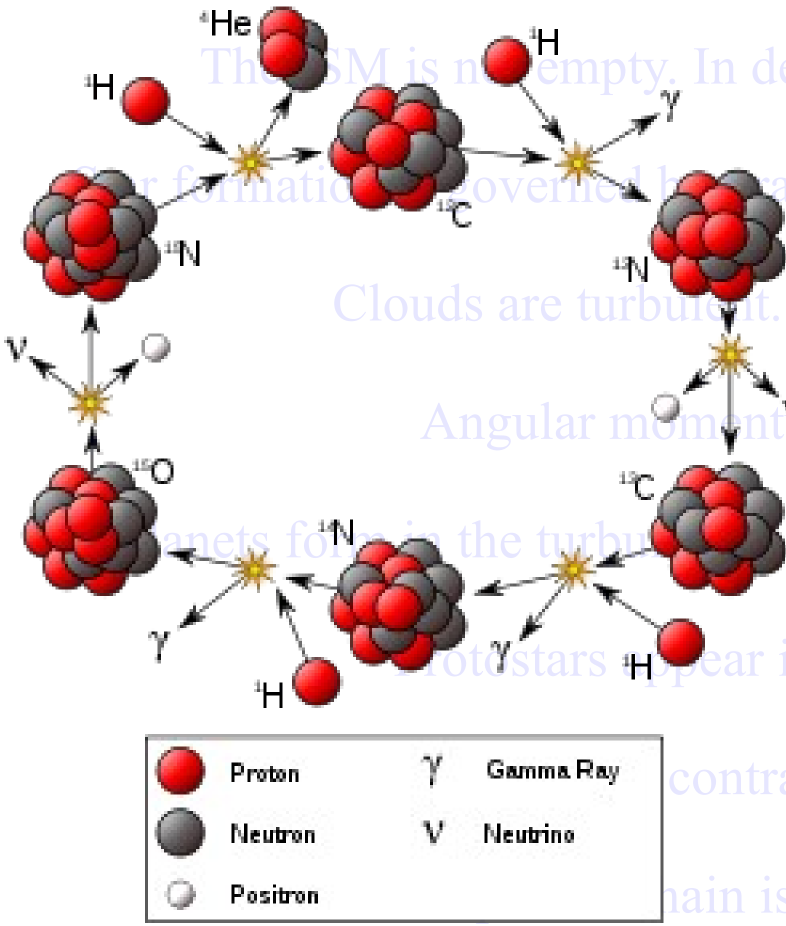


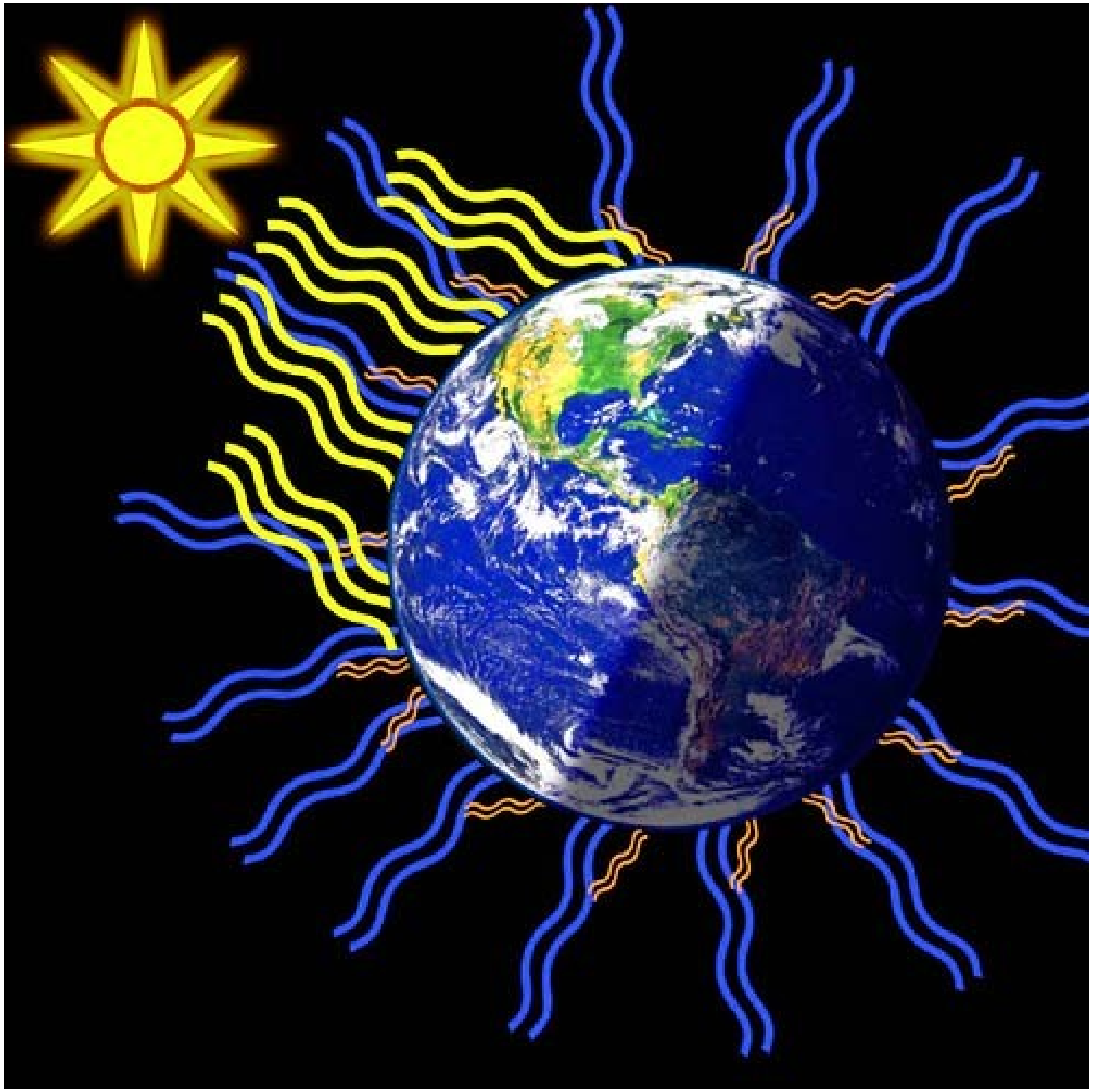
CNO cycle is the main reaction for high mass stars

Outline

- Evolution of low mass stars
  - Lifetime on the Main Sequence
  - Turn-off point
  - Stellar Structure and Evolution
    - Energy source and Stellar Structure in
      - Red Giant Branch
      - Horizontal Branch
      - Asymptotic Giant Branch
    - Planetary Nebulae
    - White Dwarfs

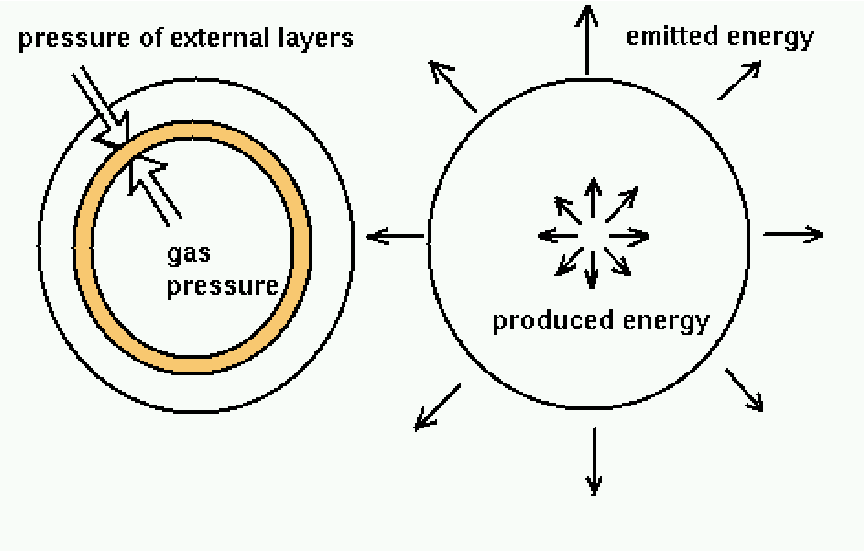
Why is Earth's temperature constant?

Why is Earth's temperature constant?



Radiative equilibrium

Radiative equilibrium



Hydrostatic equilibrium

In every layer, the
upwards push of gas pressure
matches the
inwards pull of gravity

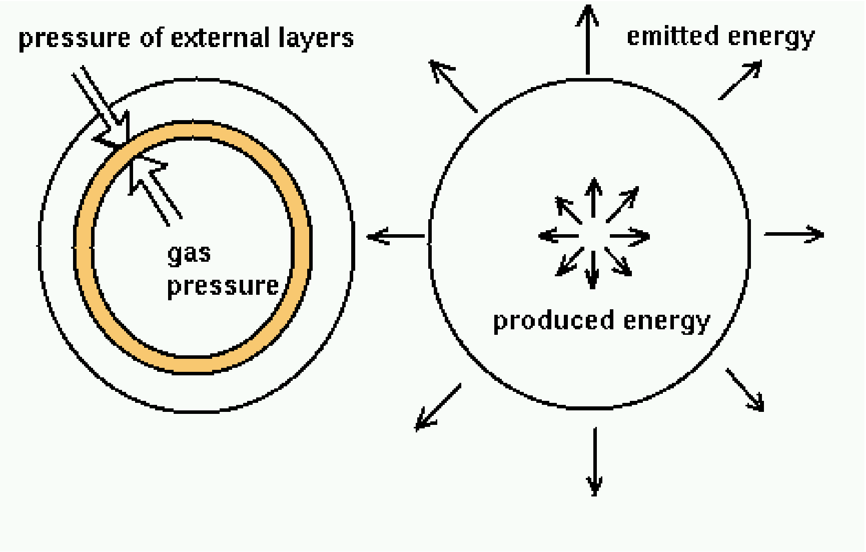
Radiative equilibrium

In every layer
outwards energy flow
matches the
energy injected from below.

(Otherwise, heating or cooling would occur)

Globally, the **Luminosity** (rate at which energy is radiated away) matches the rate of **energy production** at the core.

Radiative cooling

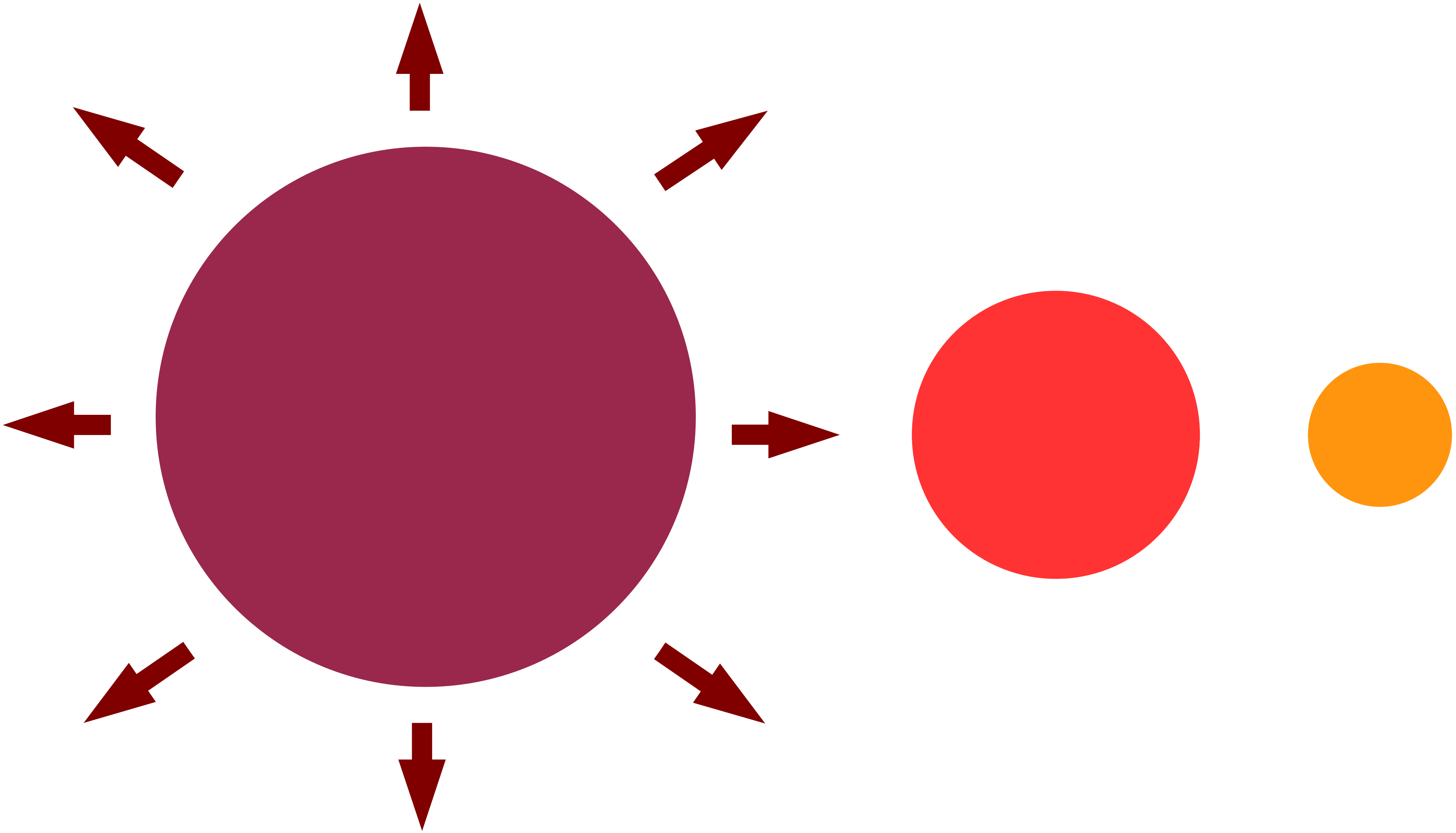


What we call "heat" is actually radiation

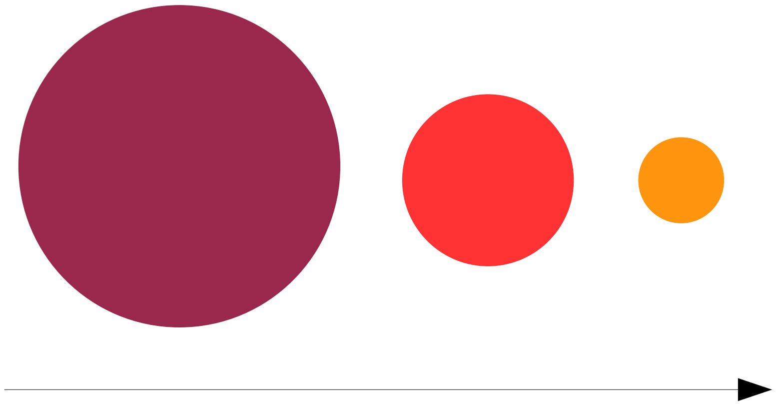
Radiative loss = Cooling

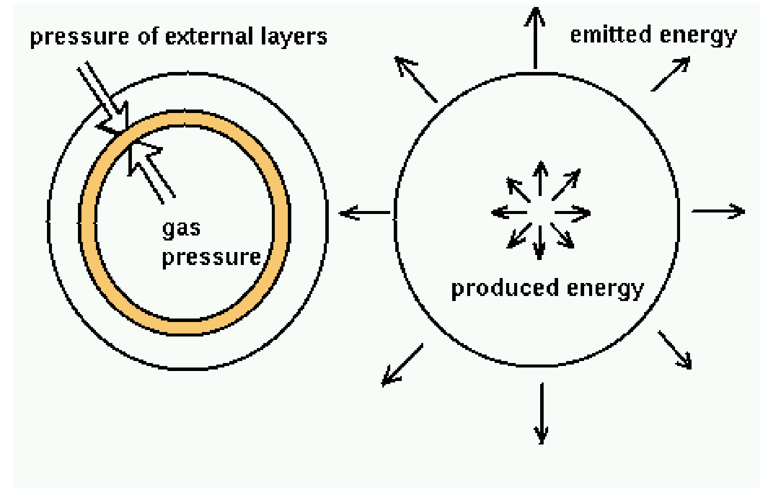
In a star in radiative equilibrium,
radiative losses (cooling)
are matched by
energy production (heating)
from nuclear reactions

So why does a proto-star heat when losing energy?



So why does a proto-star heat when losing energy?





Compression - Heating

Expansion - Cooling

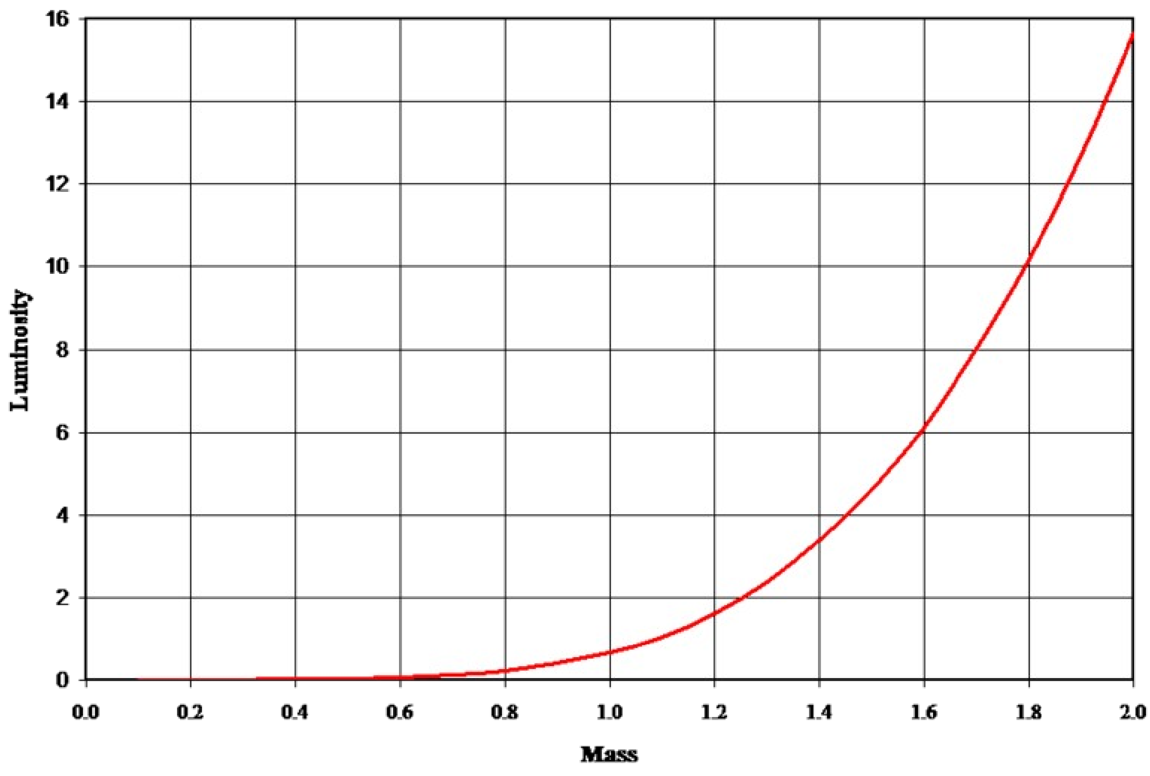
$$pV = nRT$$

1. Cooling leads to a lower pressure
2. Less support against gravity (compression)
3. ***Compression*** leads to ***heating***

Lifetime in the Main Sequence

$$\text{Lifetime} = \frac{\text{Fuel}}{\text{Rate of Fuel Consumption}} = \frac{\text{Energy}}{\text{Luminosity}}$$

Mass – Luminosity relationship



- Luminosity

$$L \propto M^{3.5}$$

- Energy

$$E \propto M$$

- Lifetime

$$t \propto M^{-2.5}$$

Lifetime in the Main Sequence

$$t_{star}/t_{Sun} = \left(M_{star}/M_{Sun}\right)^{-2.5}$$

Lifetime in the Main Sequence

$$t_{star} / t_{Sun} = \left(M_{star} / M_{Sun} \right)^{-2.5}$$

10 Msun – 1 million years

1 Msun - 10 billion years

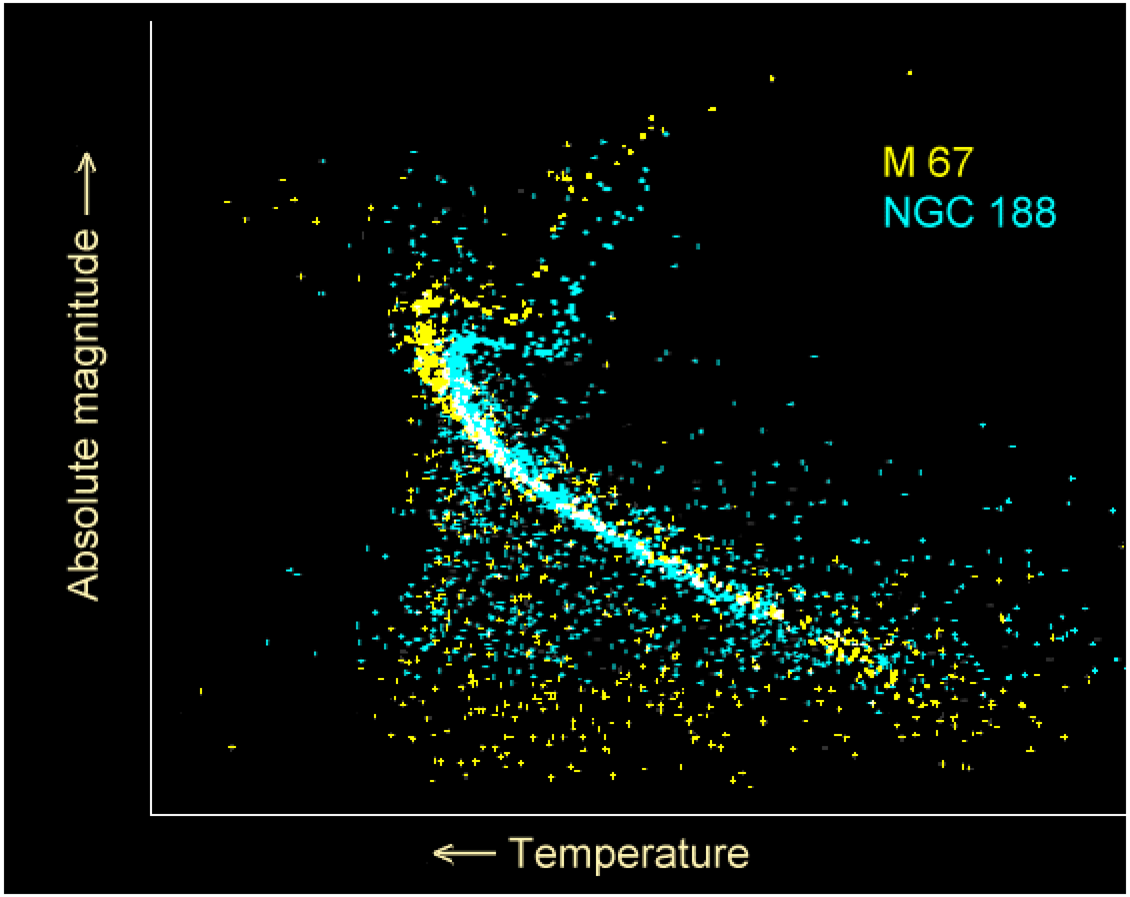
0.1 Msun – 100 trillion years

High mass stars life fast and die young.

Low mass stars will still be around long after we're gone

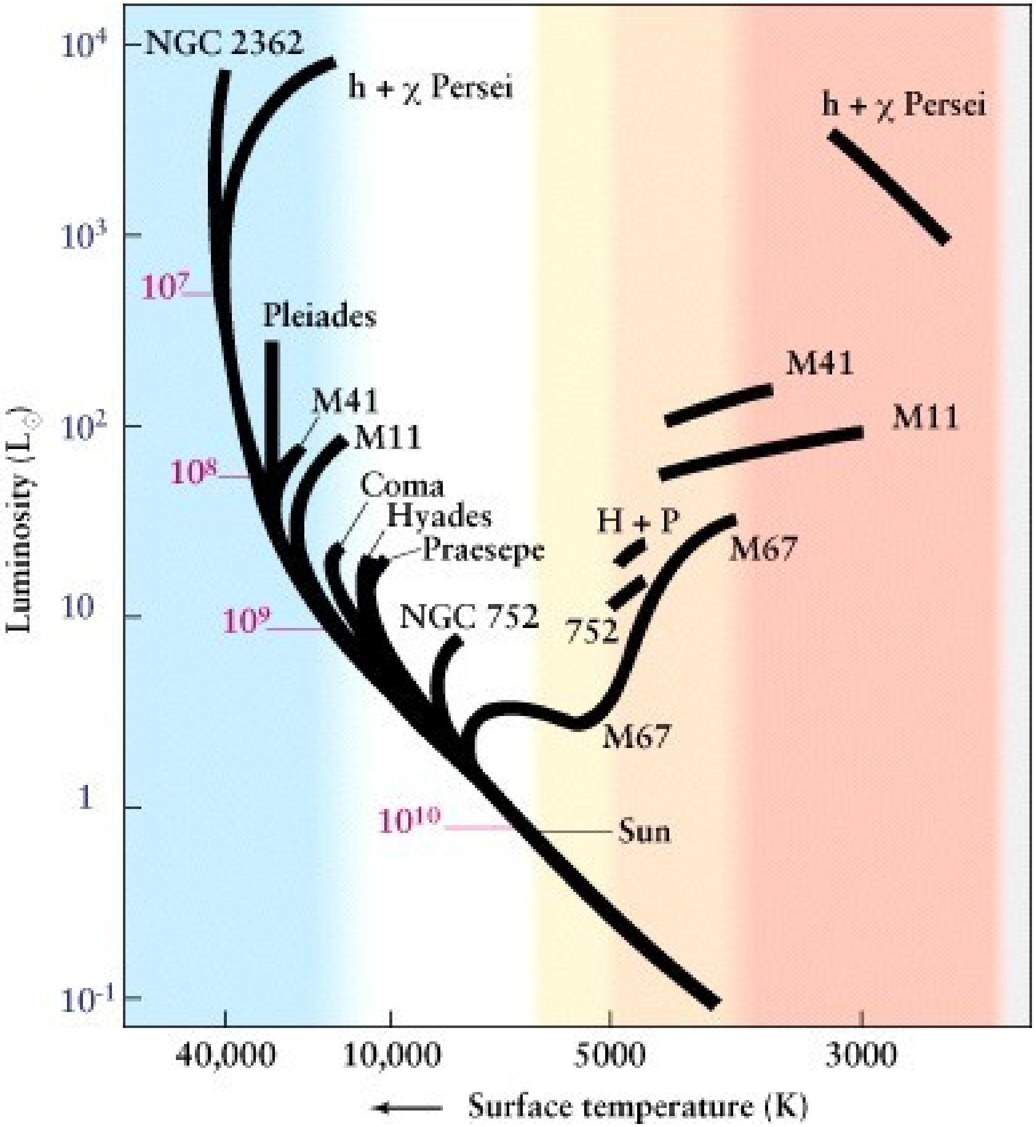
M67

NGC188



Which one is the older?

The Main Sequence Turn-Off Point



As stars age, they leave the main sequence

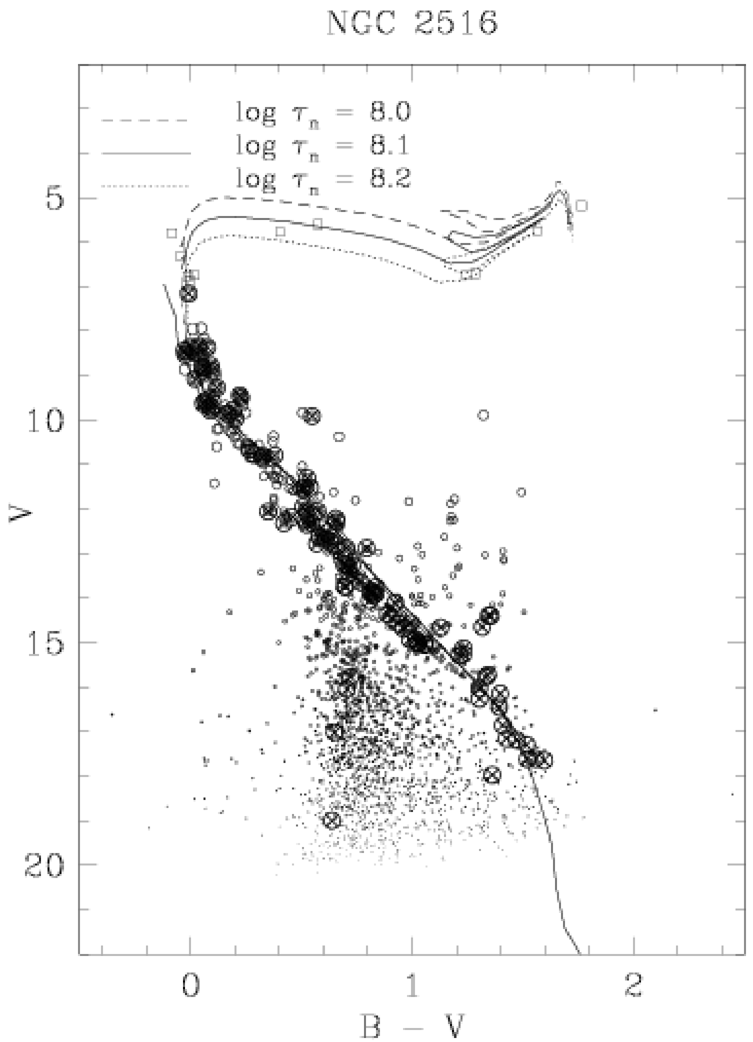
The point where stars are leaving the main sequence is called **turn-off point**

It is a function of age!

Application to clusters:

If you can tell the age of the star at the turn-off point, you can tell the age of the cluster.

The Main Sequence Turn-Off Point



Application to clusters:

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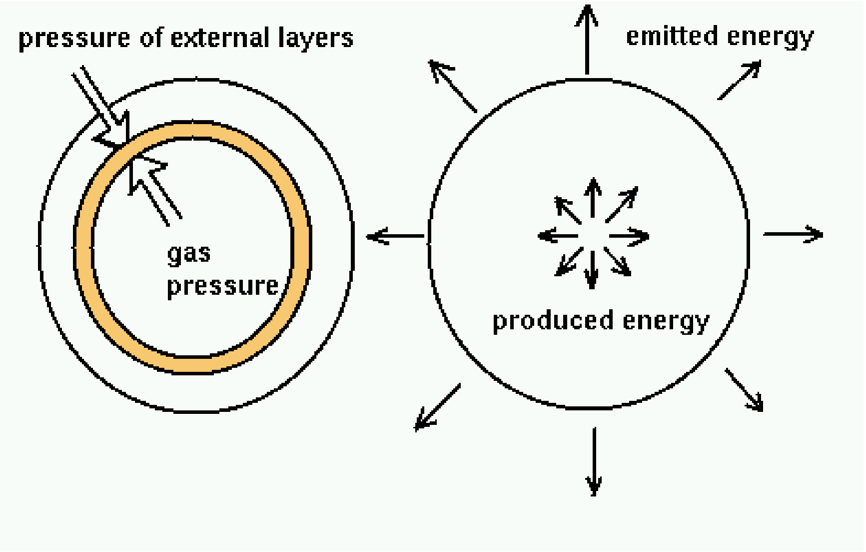
Isochrone Fitting

NGC 2516 – Age ~150 Myr

Hydrogen is gone! Now what?

What will happen to me?

Radiative equilibrium



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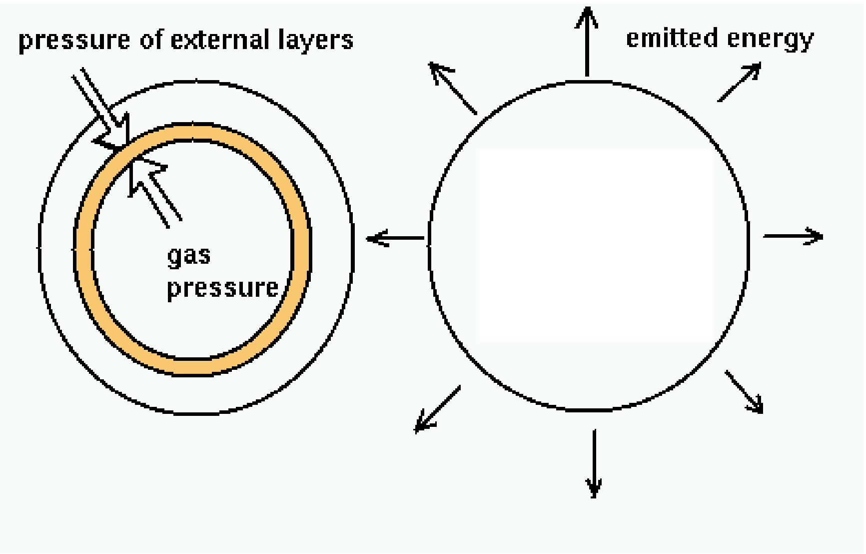

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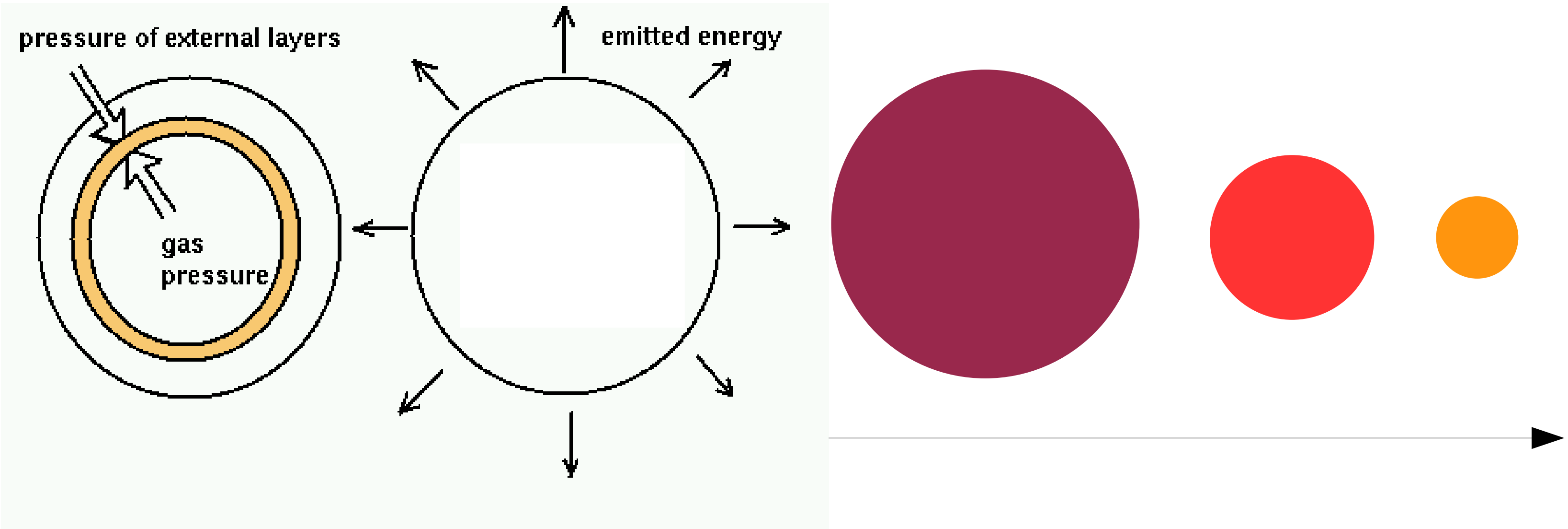

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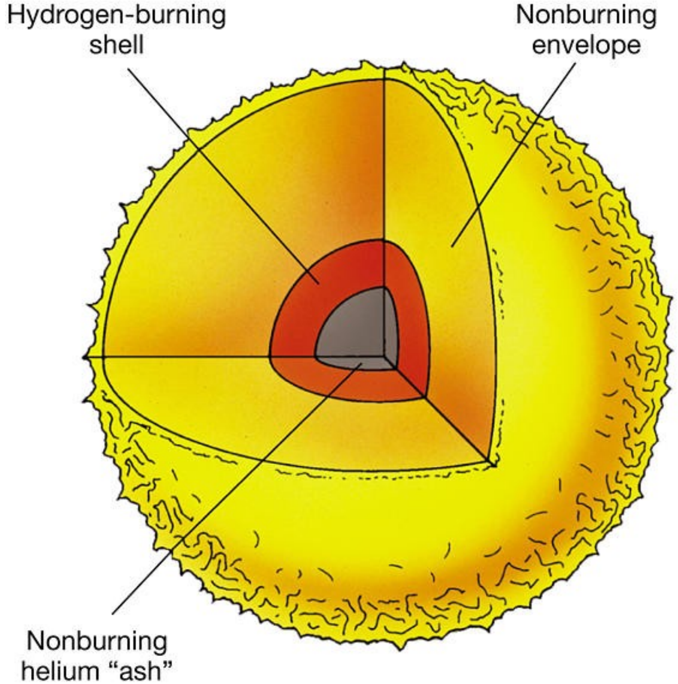
Hydrogen is gone! Now what?

Star stops producing energy.

The star **contracts** and **heats** up.

Eventually, the temperature becomes high enough to **burn hydrogen *around* the Helium core**

Hydrogen shell burning



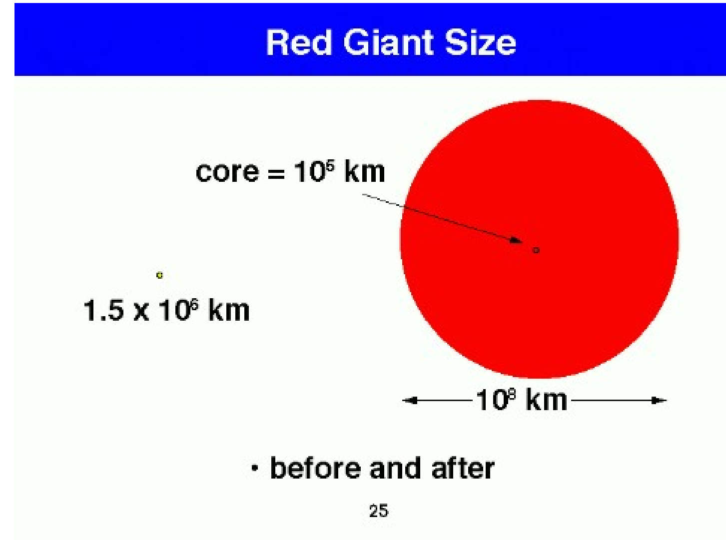
Hydrogen Shell Burning

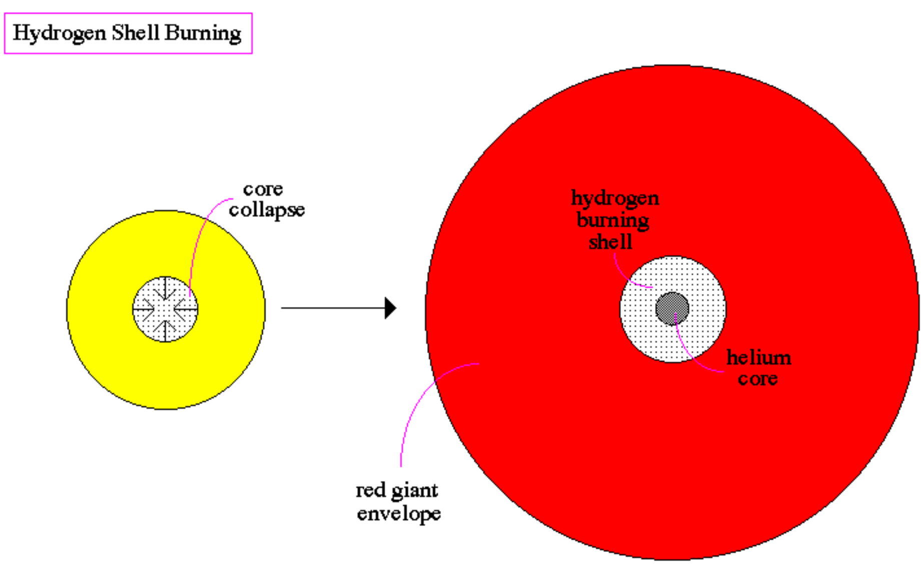
<u>Hydrogen shell burning involves:</u>

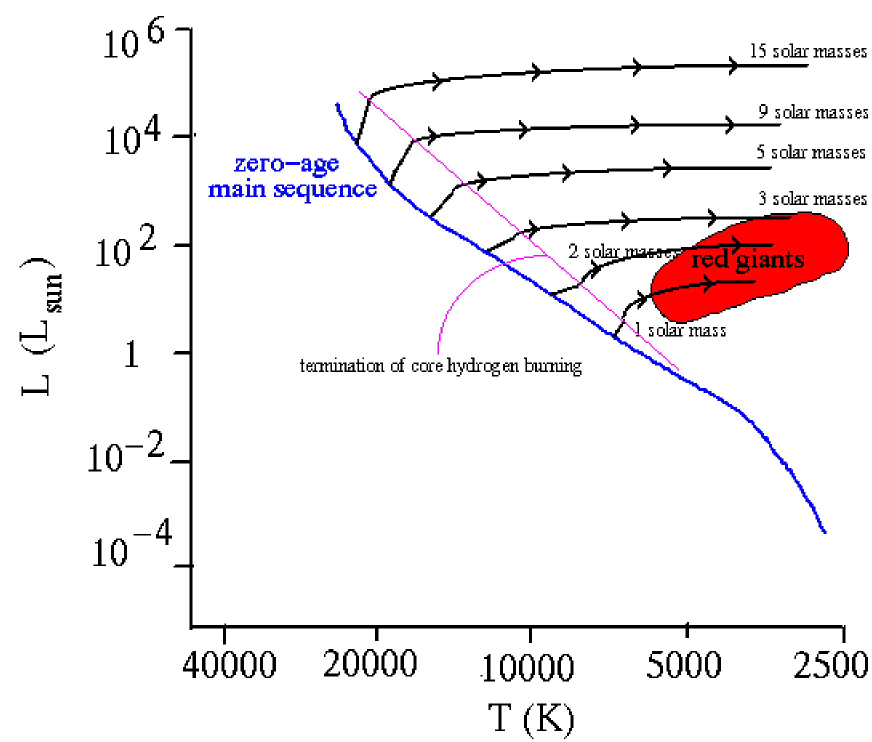
More fuel than in MS-hydrogen burning
Higher temperatures (thus more efficient)

A lot more of energy is being produced.
The star gets very luminous and ***swells***.

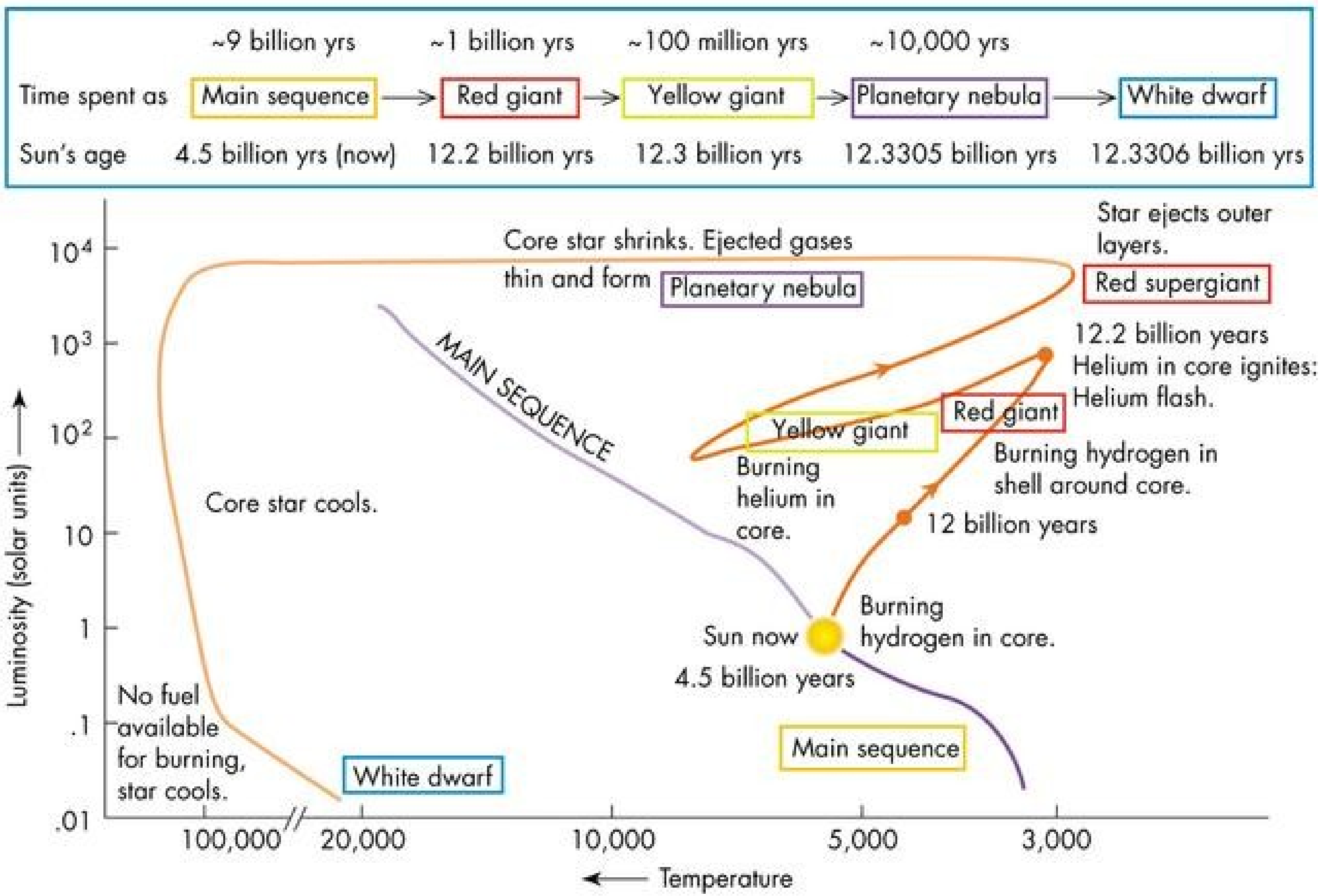
The expansion **cools** the outer layers.
The star becomes a red giant.





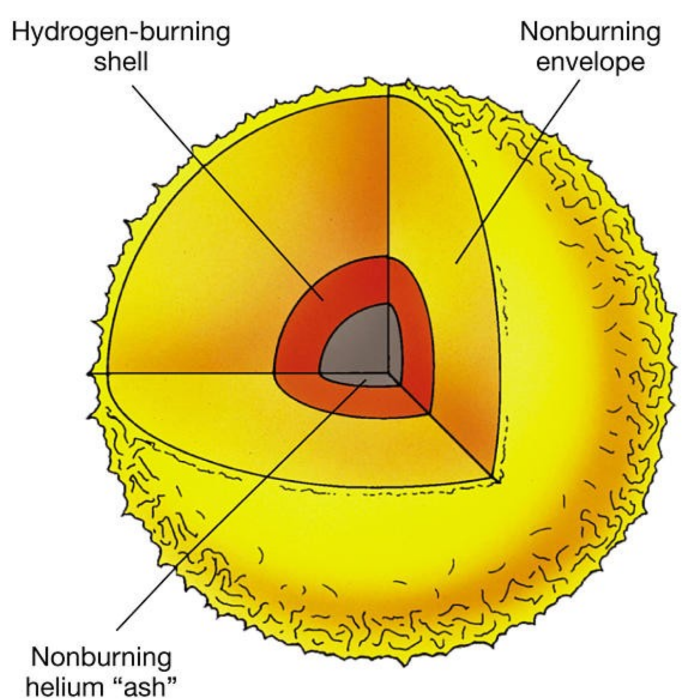


Evolutionary track



What happens to the inert Helium core?

Hydrogen shell burning

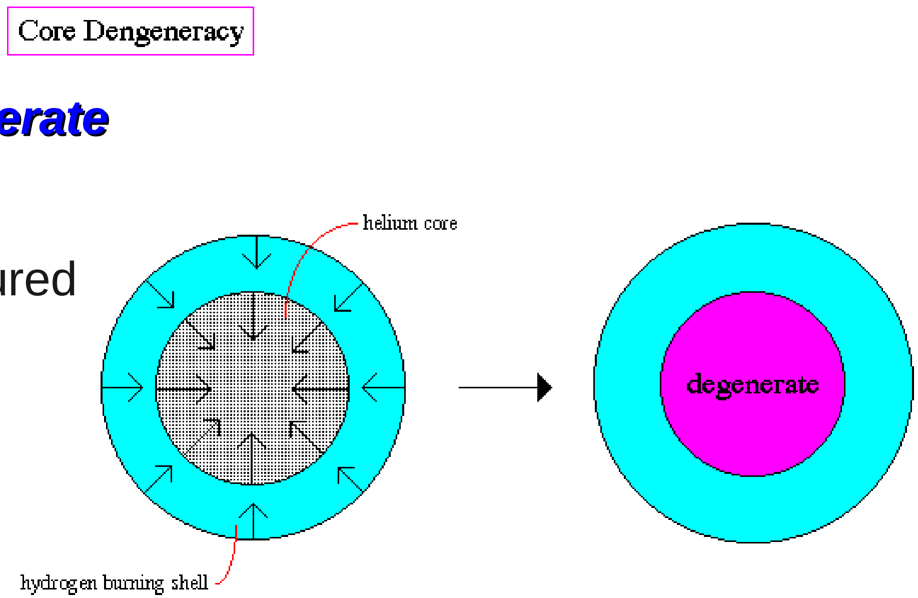


What happens to the inert Helium core?

It keeps contracting and heating
At some point the density is so high it goes ***degenerate***

Degeneracy is just a "fancy" word
What it means is that a ***phase transition*** has occured

It stops behaving like a gas
and starts behaving more ***like a solid***



Ideal Gas

$$p \propto \rho T$$

Temperature rises, pressure rises
Temperature falls, pressure falls

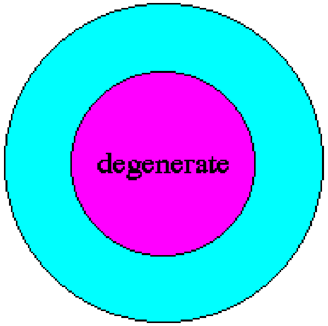
Radiative loss → cooling →
less support against gravity → **contraction**

Degenerate Matter

$$p \propto \rho^{4/3}$$

If temperature rises or falls, pressure couldn't care less

Radiative losses can continue indefinitely
The degenerate core is stable



Helium Fusion

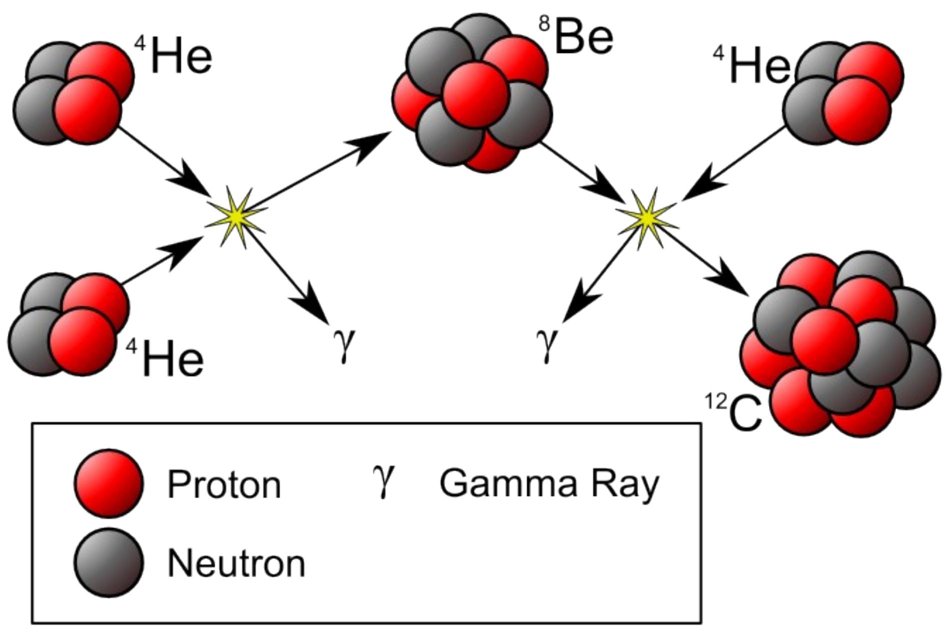
The inner degenerate Helium core is stable
But the outer Helium core keeps contracting and heating

When the temperature reaches 100 million K, ***HELIUM FUSION*** begins
Helium is burned into Carbon (and Oxygen)

Triple Alpha Reaction

(Helium nucleus is called an "alpha" particle)

$3\ He \rightarrow C + energy$
$(C + He \rightarrow O + energy)$



How much energy comes out of Helium fusion?

Triple Alpha Reaction

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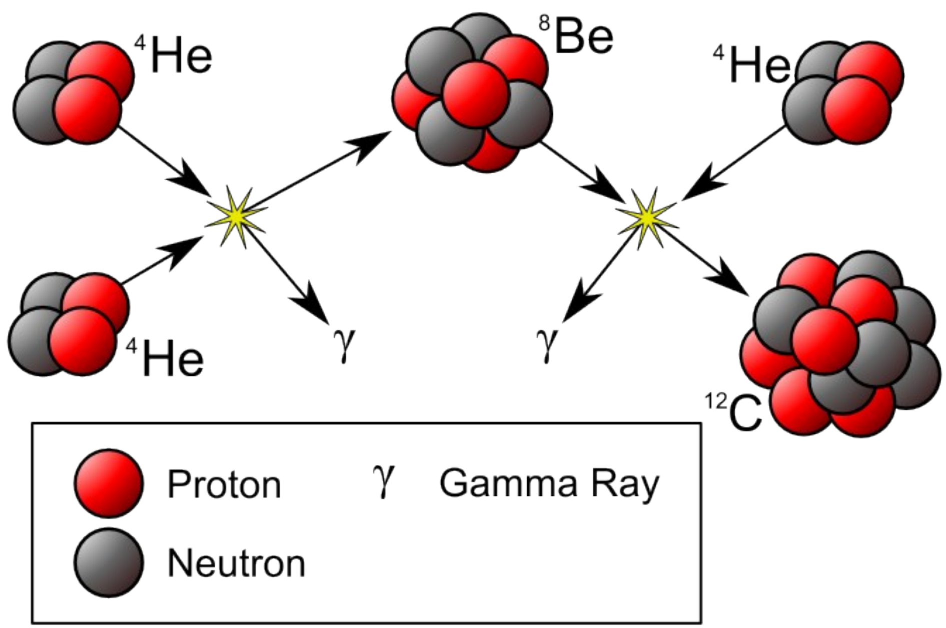
(C + He → O + energy)



The Helium Flash

Fusion ignition in degenerate matter is a bomb ready to explode

Ideal Gas

$$p \propto \rho T$$

Nuclear reactions start

Heating → Expansion → Cooling

Cooling = Less nuclear reactions

Cooling → Contraction → Heating

Thermostat keeps nuclear reactions “tuned”
Controlled fusion

Degenerate Matter

$$p \propto \rho^{4/3}$$

Nuclear reactions start

Heating

Star does not expand

Nuclear burning increases

More Heating

No thermostat

Runaway temperature rise
Runaway fusion

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The Helium Flash

Controlled fusion

Runaway fusion

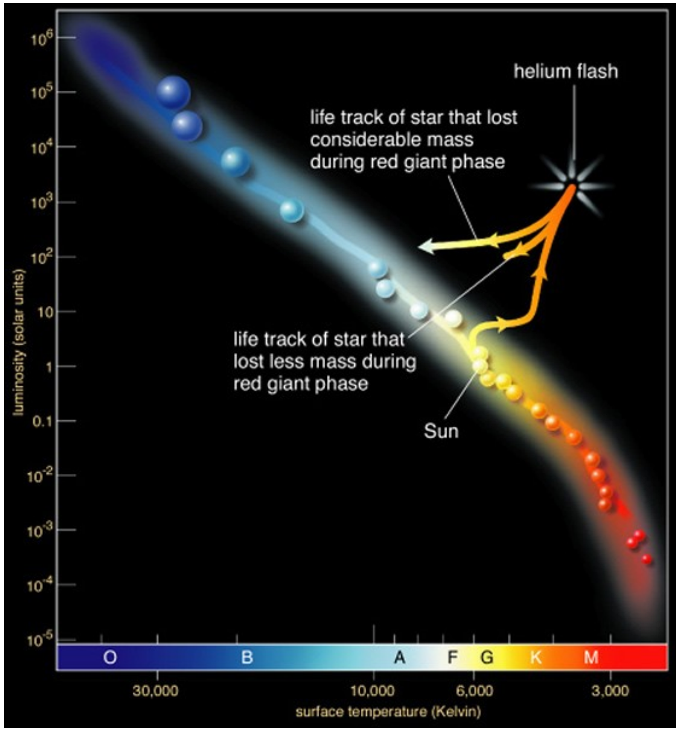
The Helium Flash

Fusion ignition in degenerate matter is a bomb ready to explode

No thermostat! Core just gets hotter and hotter

Runaway Helium burning: **100 billion times the Solar output** in just a few seconds

Helium Flash



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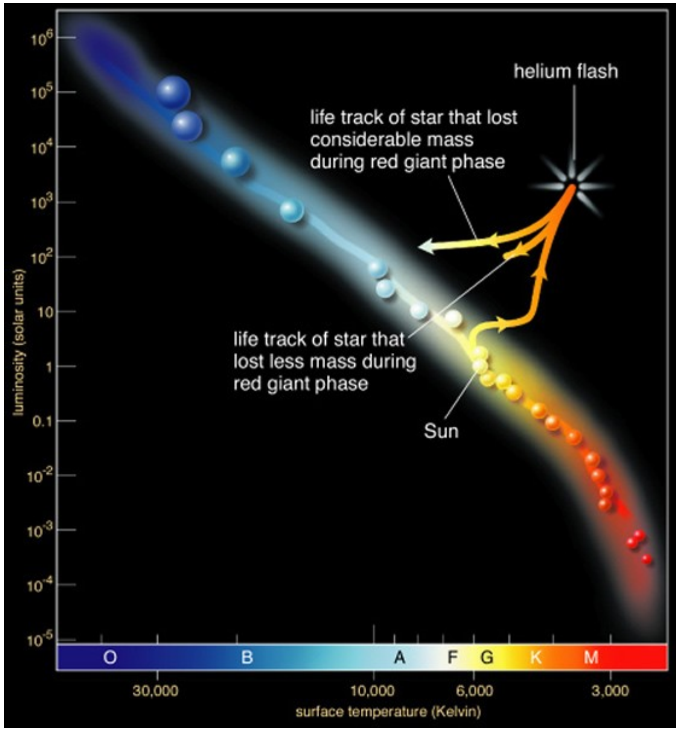
Helium Flash

Yet, nothing is seen

Why?



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Helium Flash

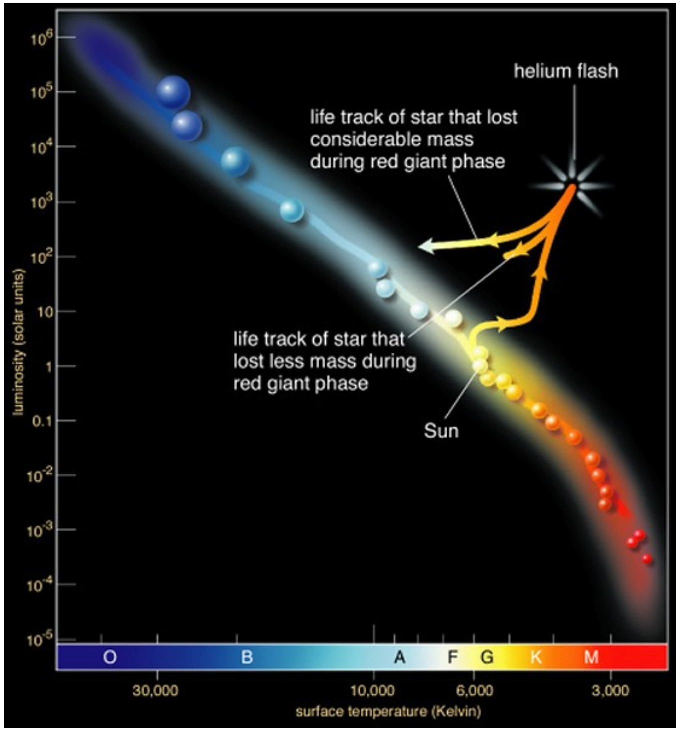
Yet, nothing is seen

Why?

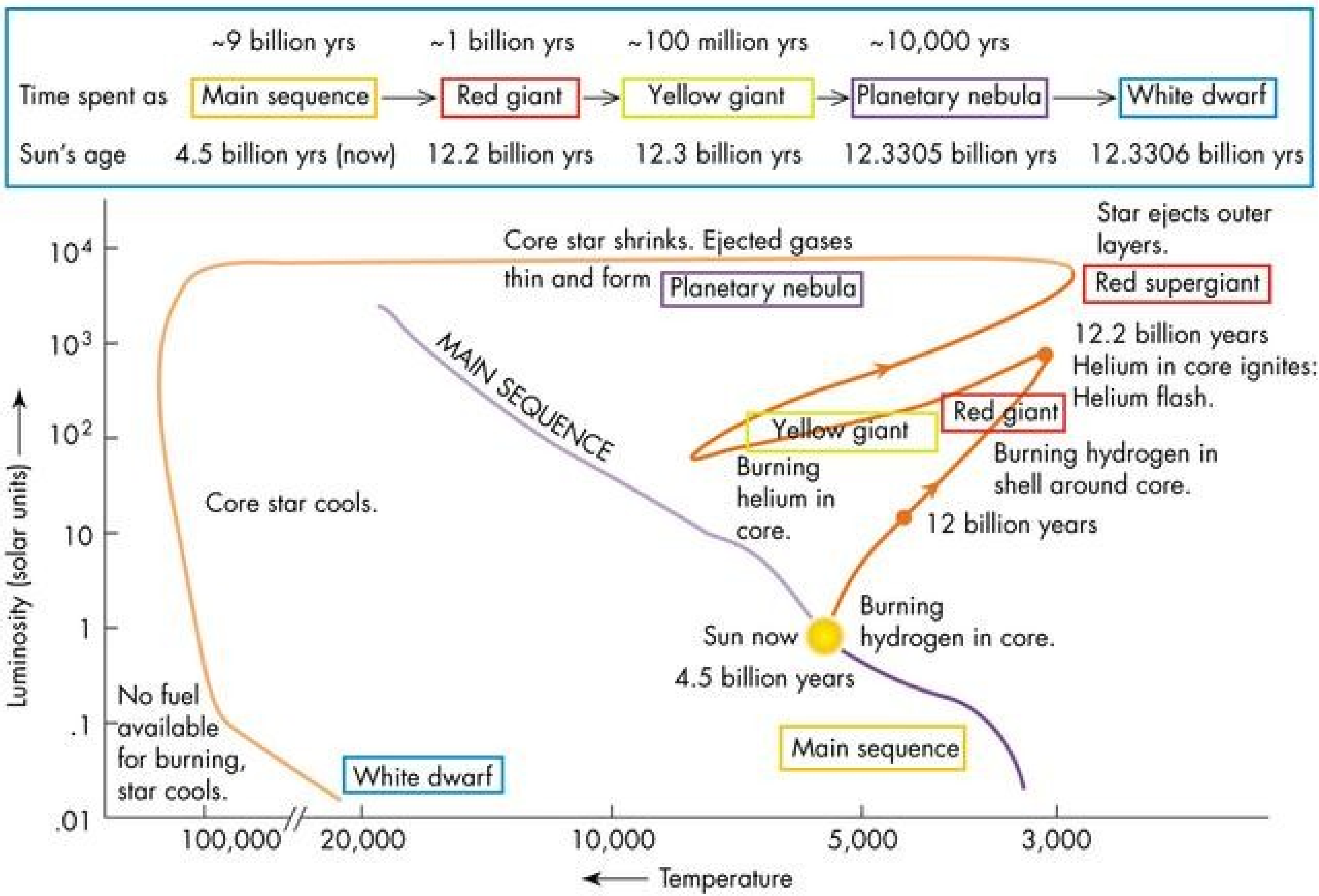
The energy is *ALL* used to lift the degeneracy

(i.e., to "melt" the degenerate core back into a normal gas)

Helium then burns ***steadily*** in a core of normal gas



Evolutionary track



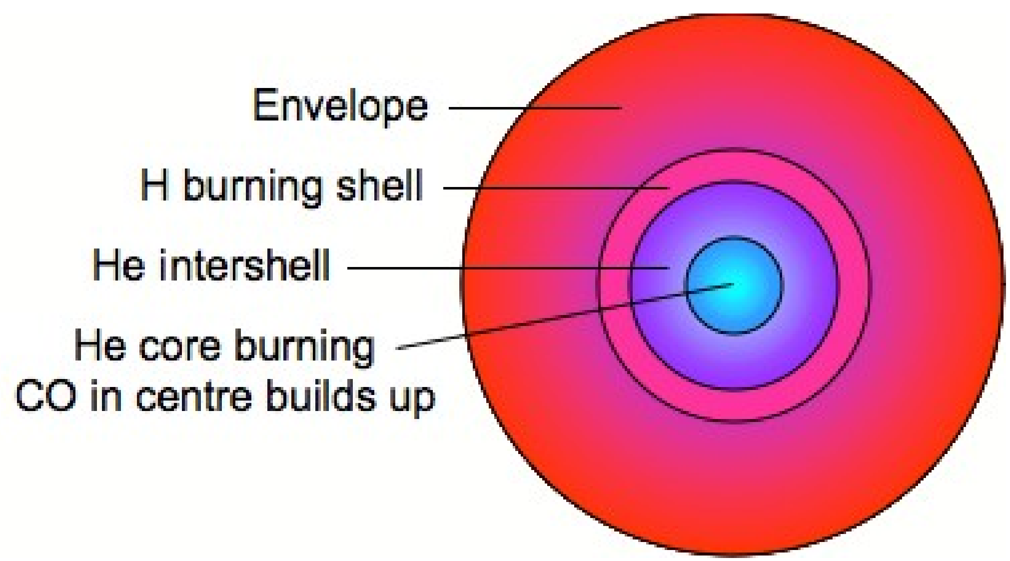
The Horizontal Branch

Helium burning in the core

Hydrogen shell burning

In the HR diagram, the star sets in the **Horizontal Branch**

The Horizontal Branch is the Helium Main Sequence



Helium is gone! Now what?

What will happen to me?

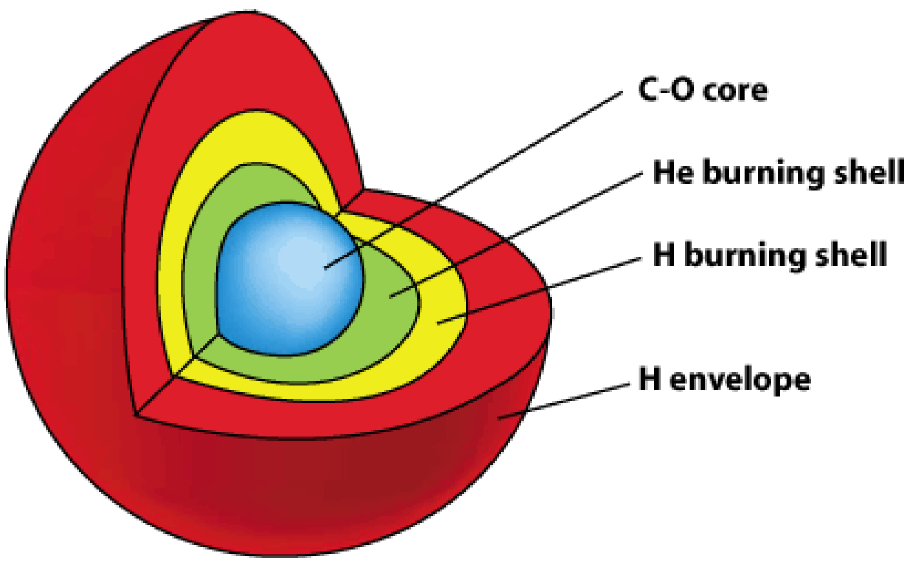
Helium is gone! Now what?

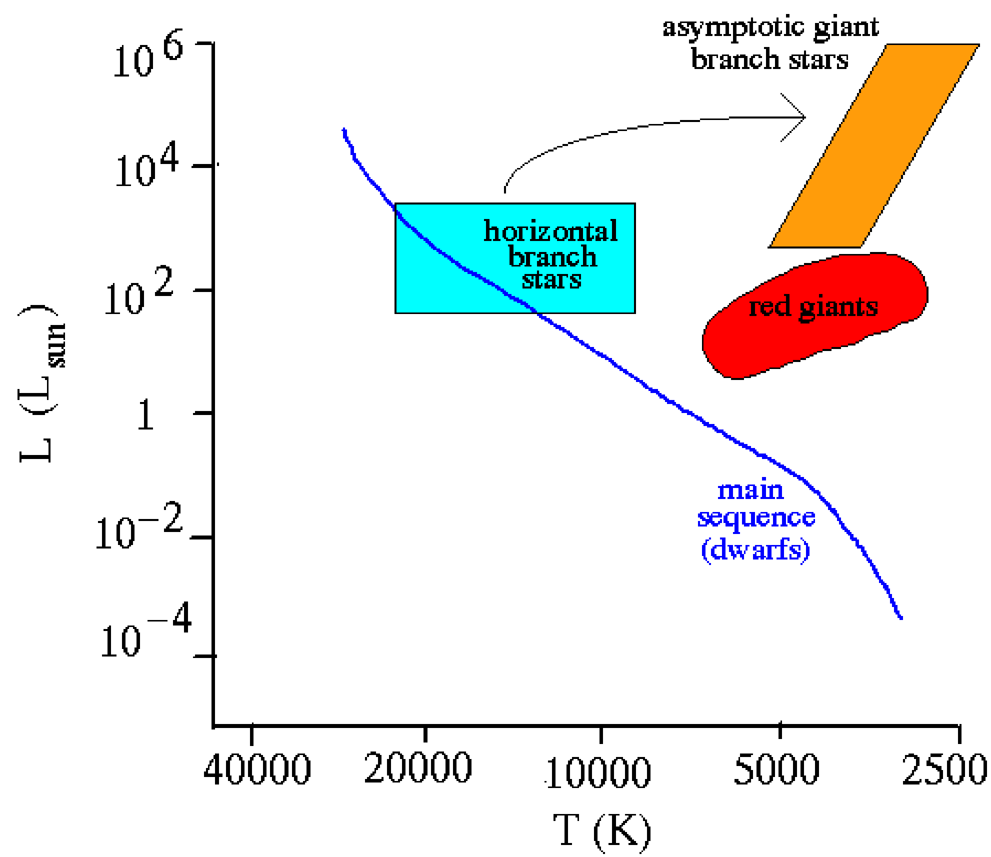
The Carbon-Oxygen core **contracts** and **heats** up.

Helium shell burning

More energy is available, the star swells and becomes a red giant *again*

The star reaches the Asymptotic Giant Branch





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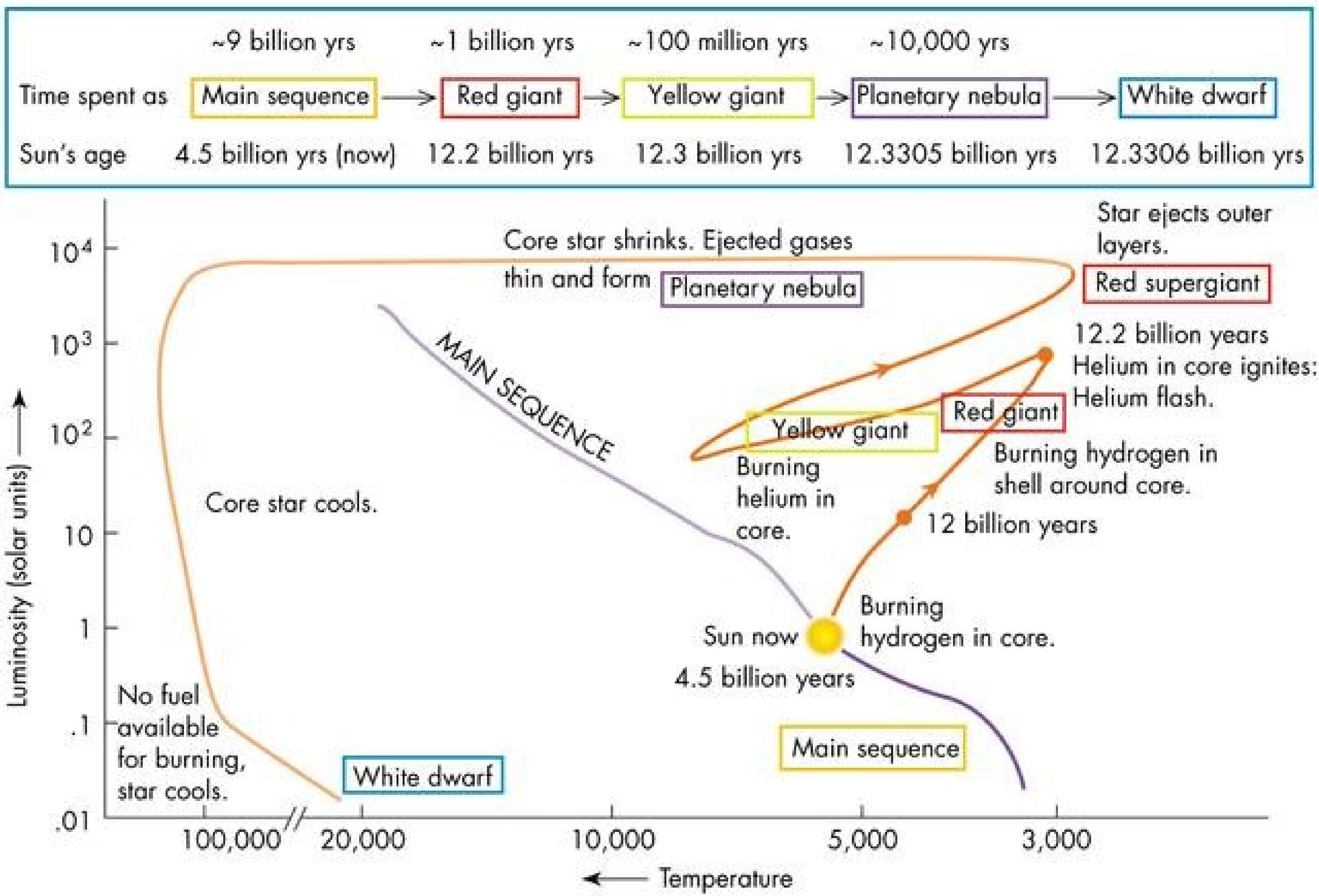
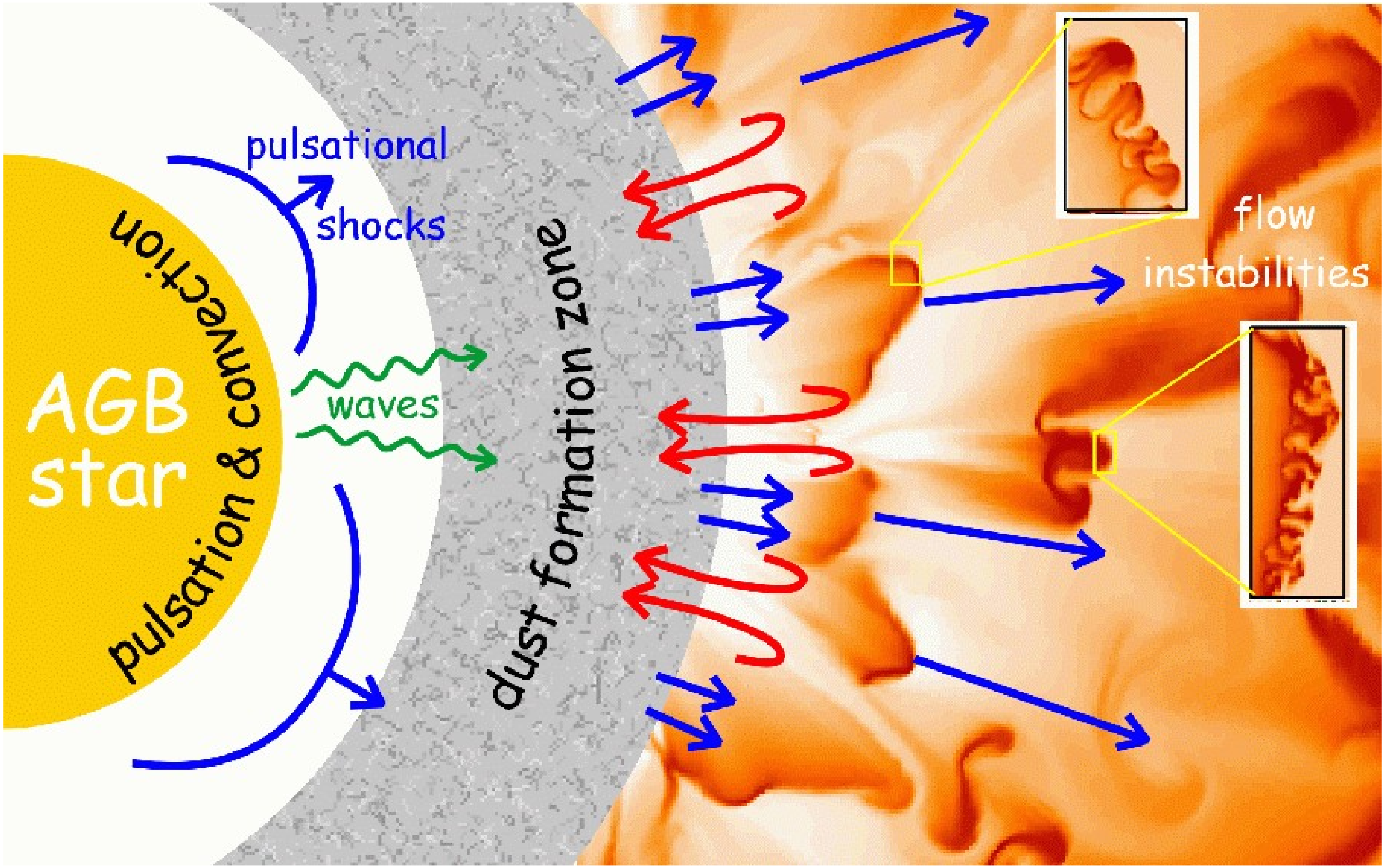


AGB stars are quite unstable

Helium burning is ***very*** sensitive to temperature (~ T^{40})

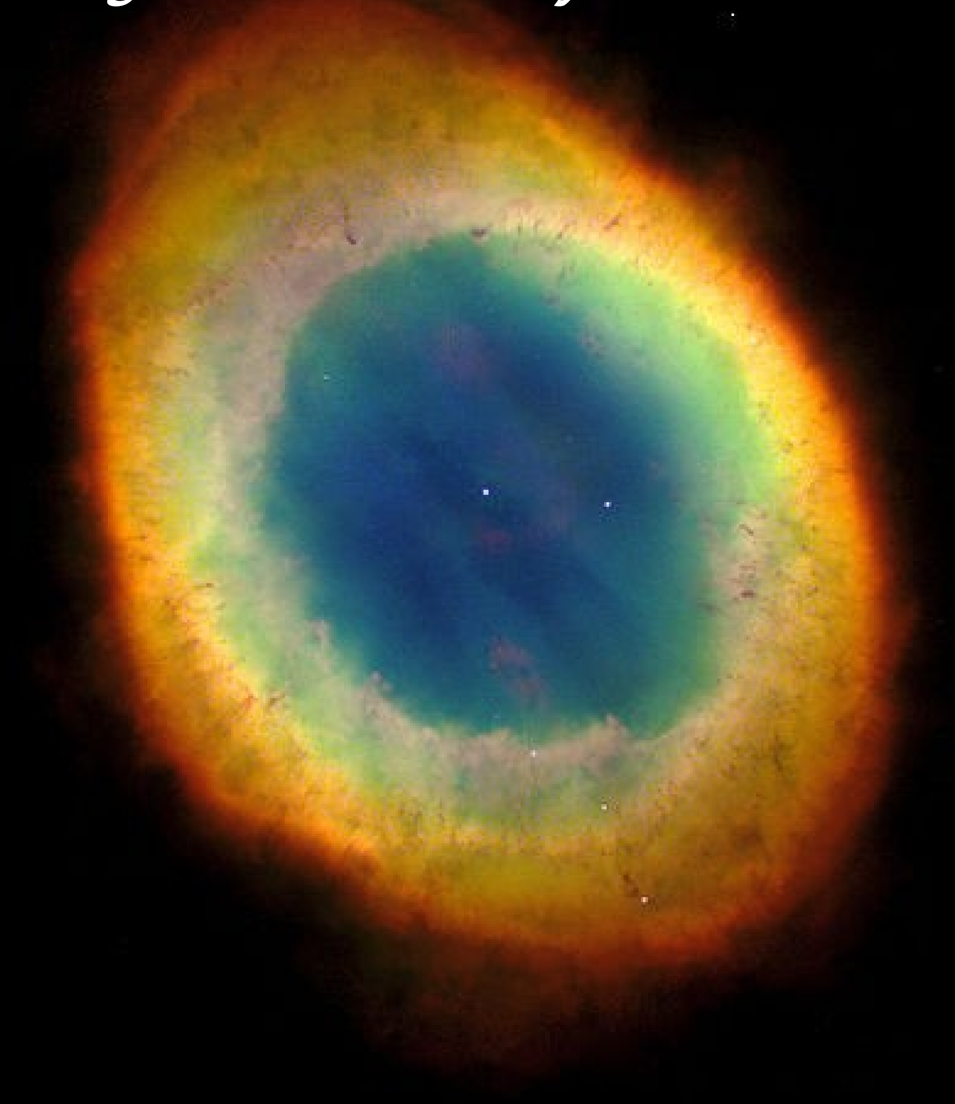
Small temperature fluctuations lead to ***violent*** variations in rate of nuclear reactions

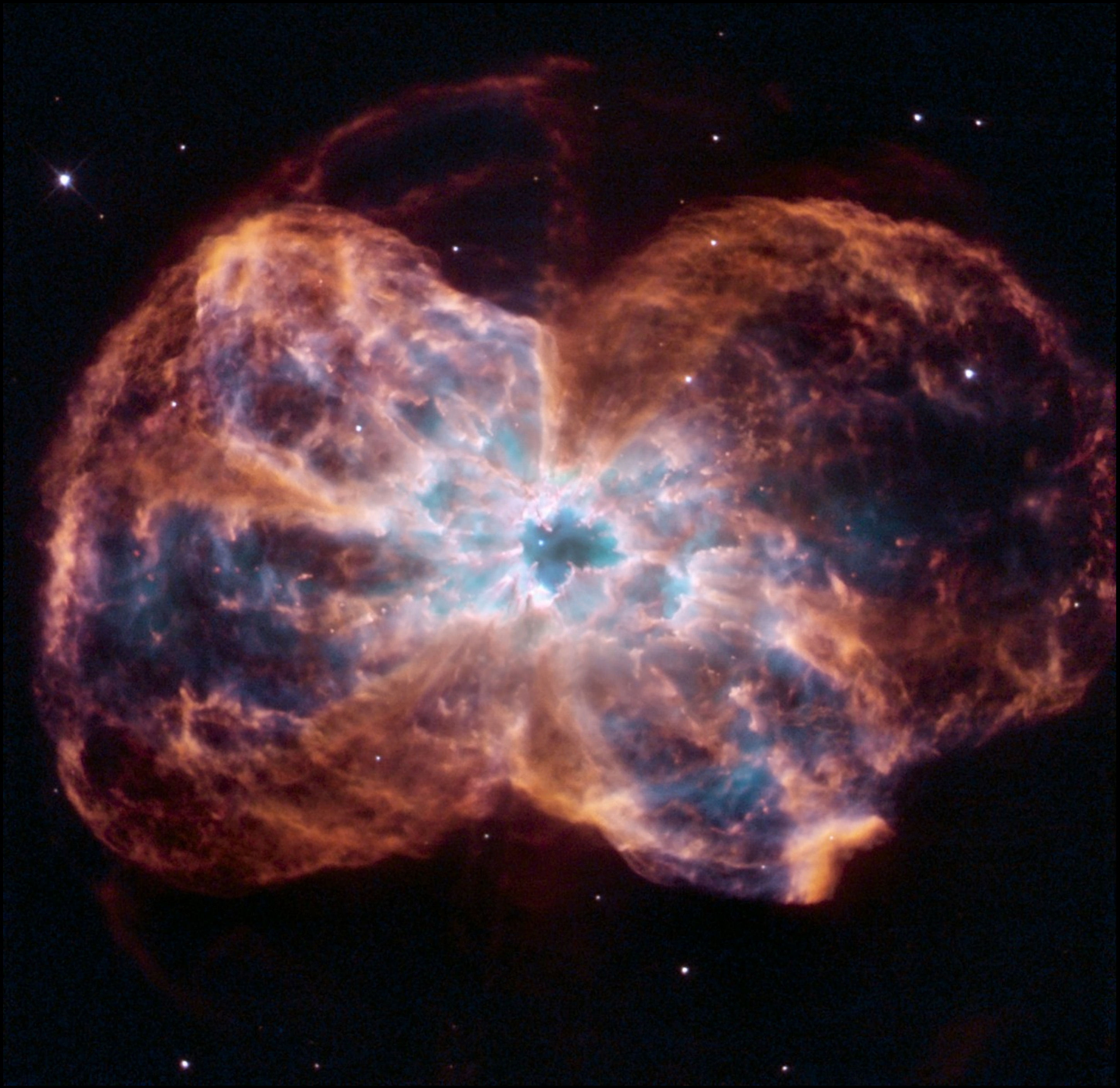
Prone to instabilities



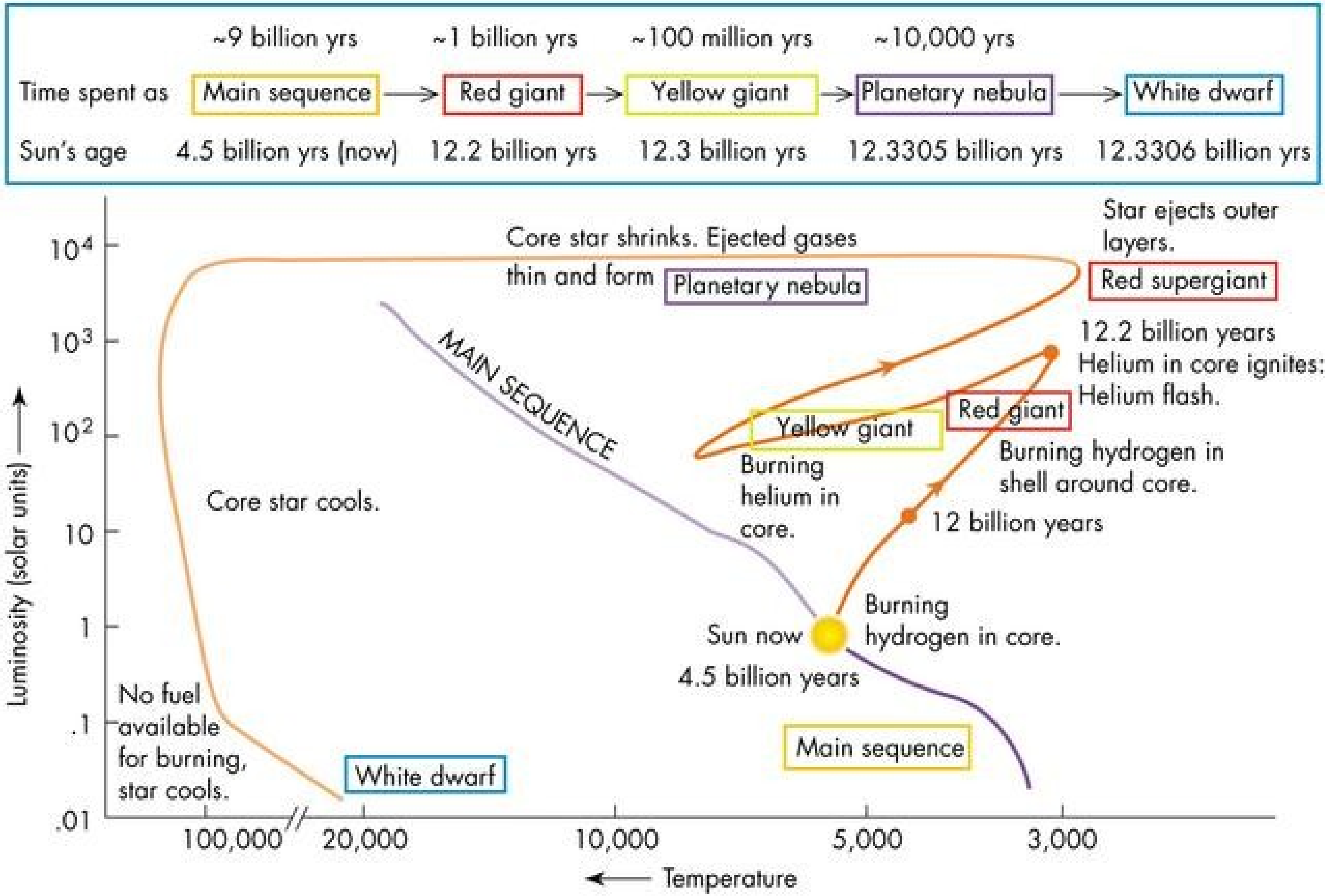
PLANETARY NEBULA

The gracious death of low mass stars



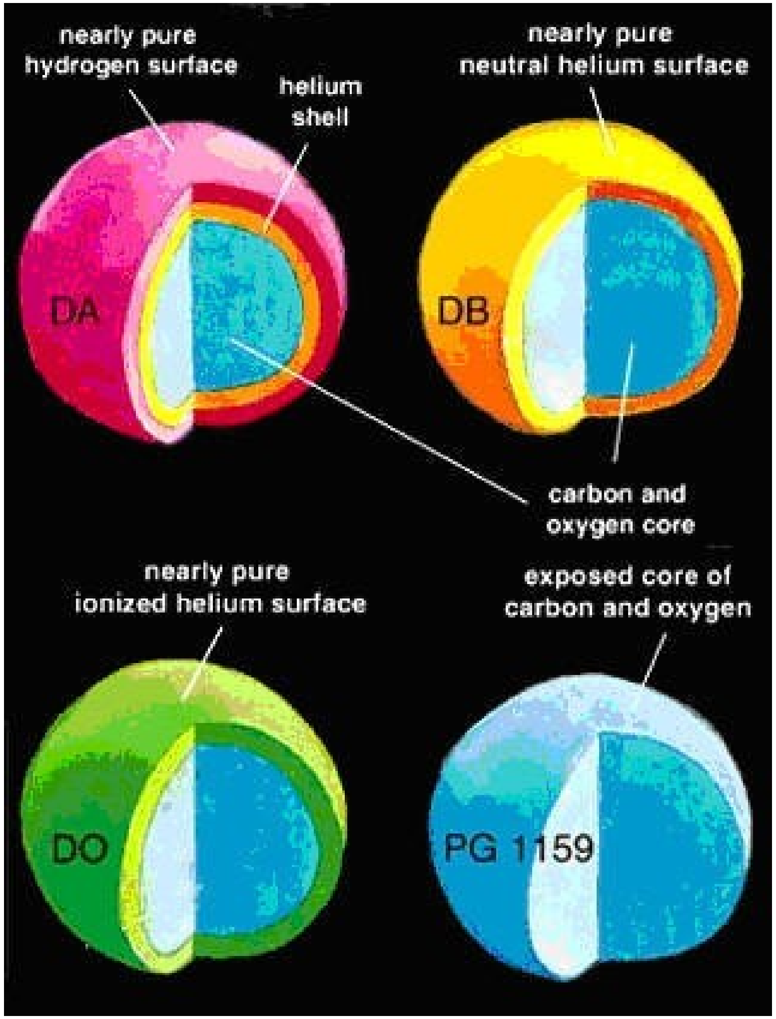


Evolutionary track

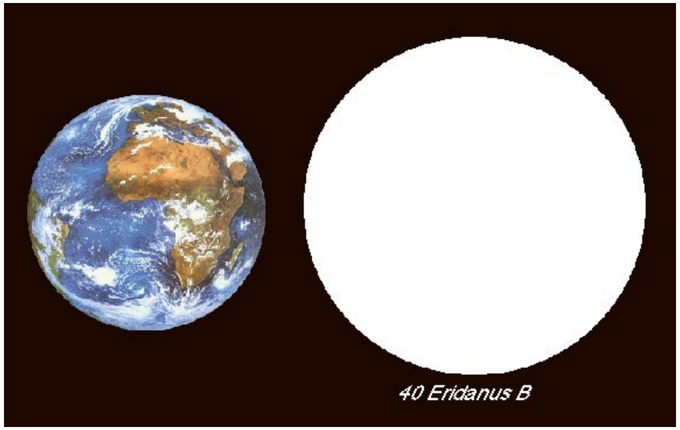


White dwarfs

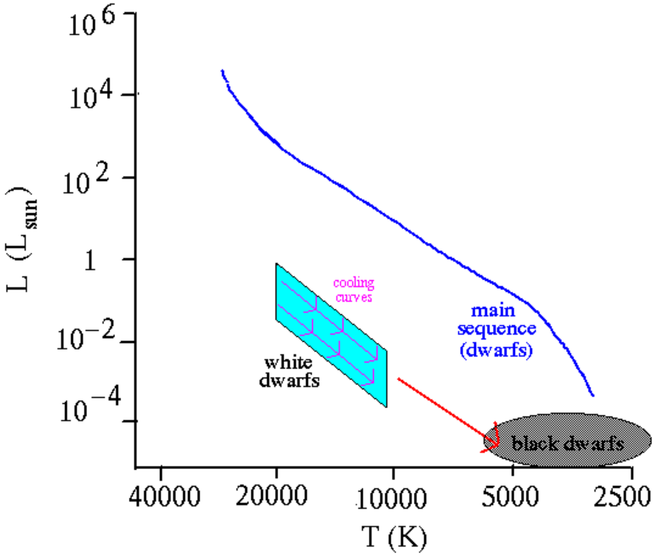
White dwarfs are the exposed degenerate core of the star



Types of white dwarfs



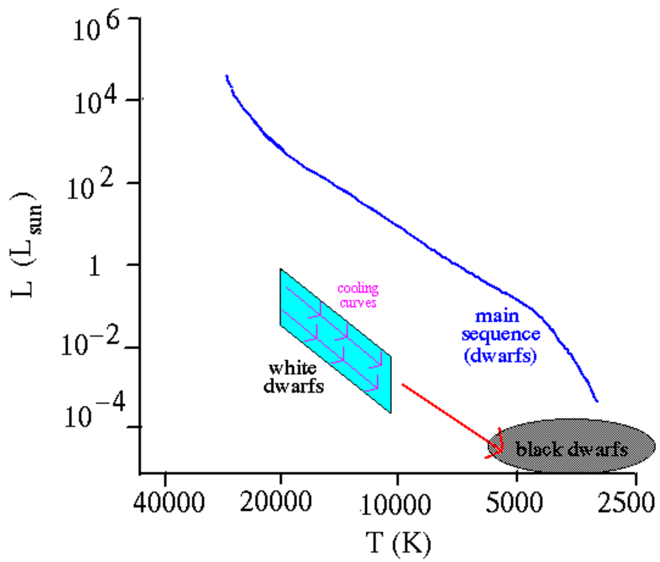
White dwarfs have planetary dimensions...



… and they do little but cooling.

White dwarfs

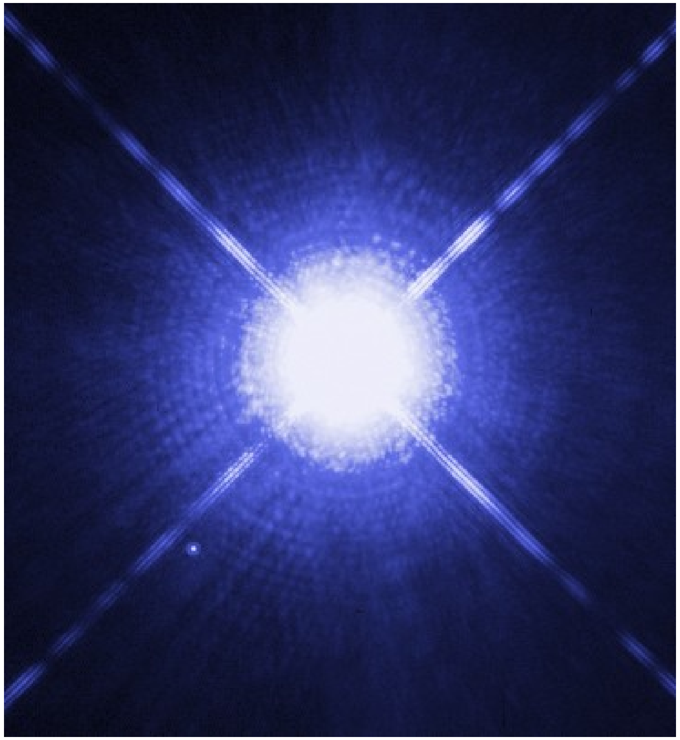
White dwarfs are the exposed degenerate core of the star



No energy production
Supported by degenerate pressure

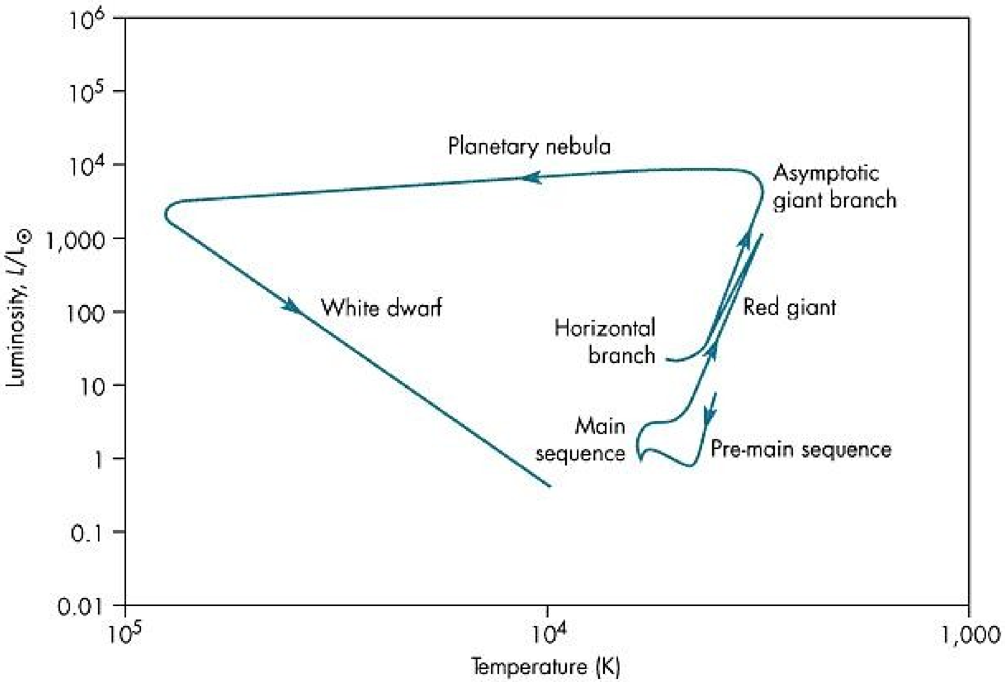
Cooling takes a long time
10^{15} yr to cool down to background temperature

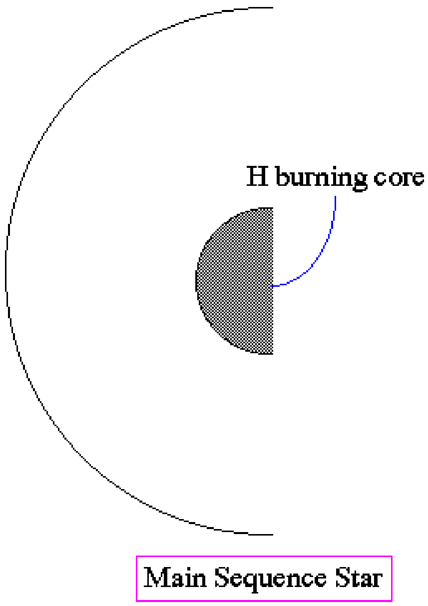
The universe is not old enough to have black dwarfs
Coldest white dwarfs ~5000 K.

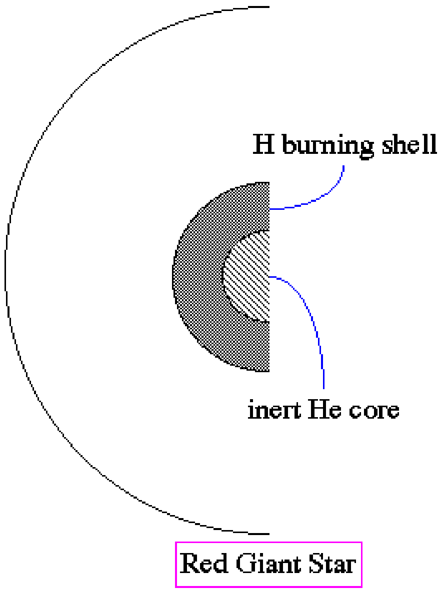


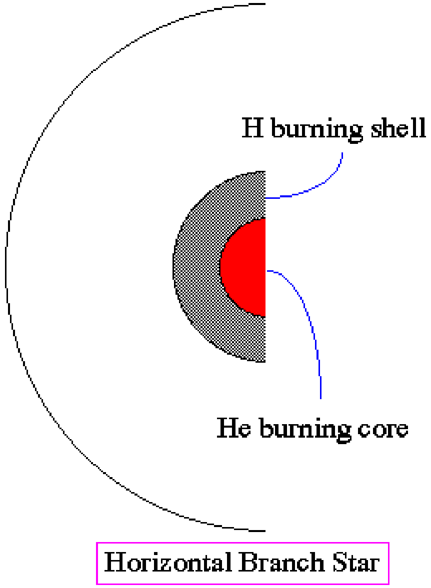
Sirius A (Main Sequence star) and **Sirius B** (White Dwarf)

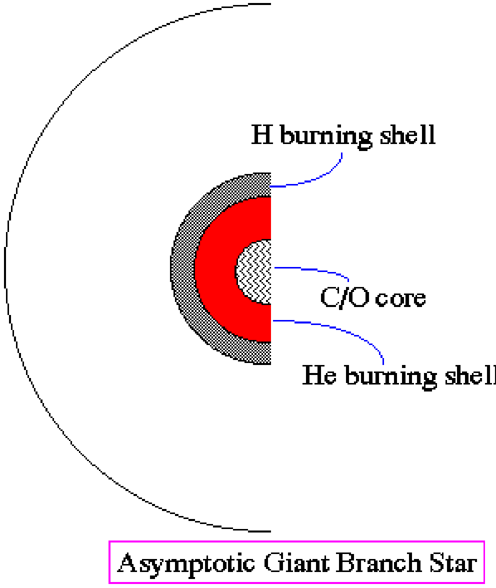
Evolution of a low mass star



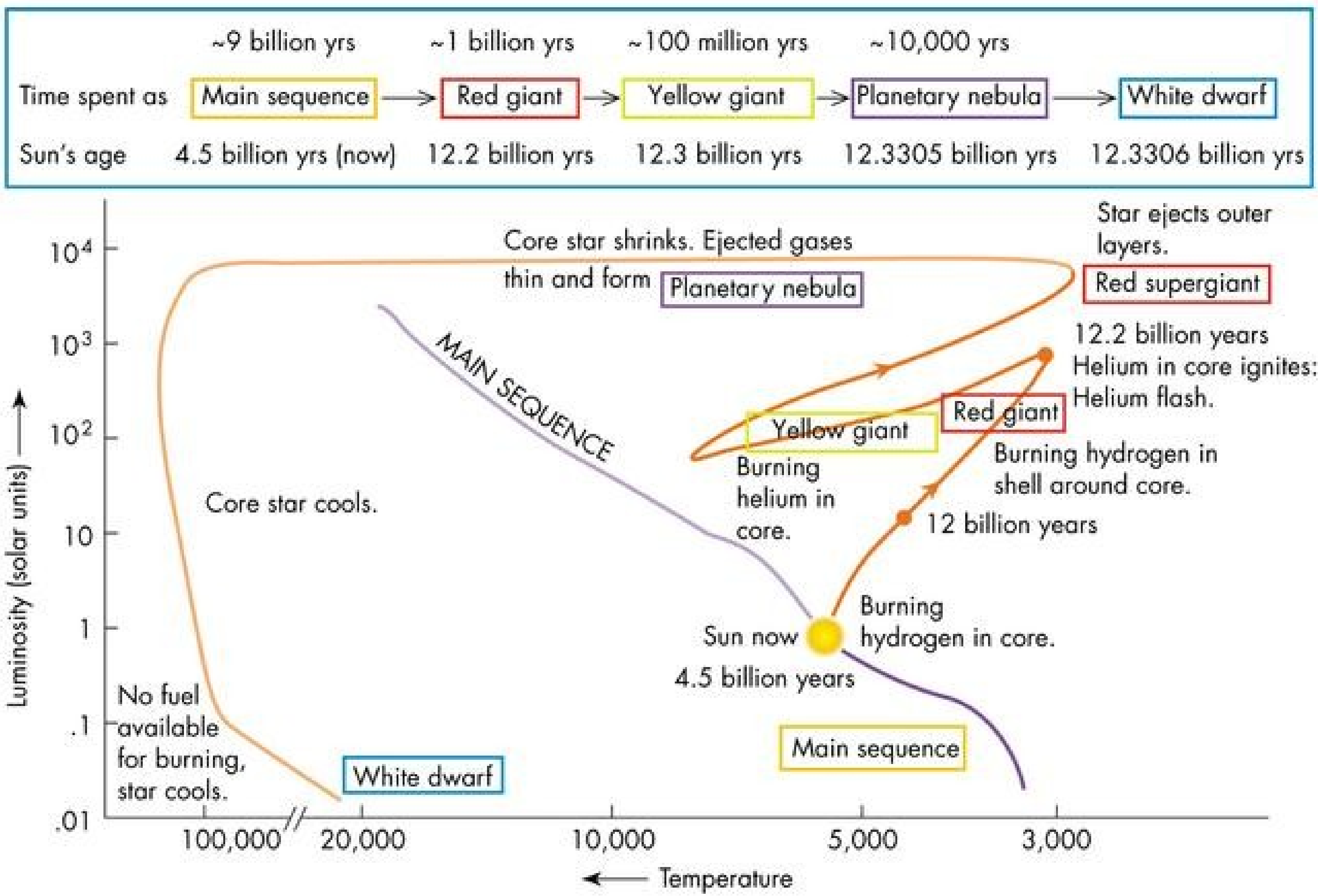






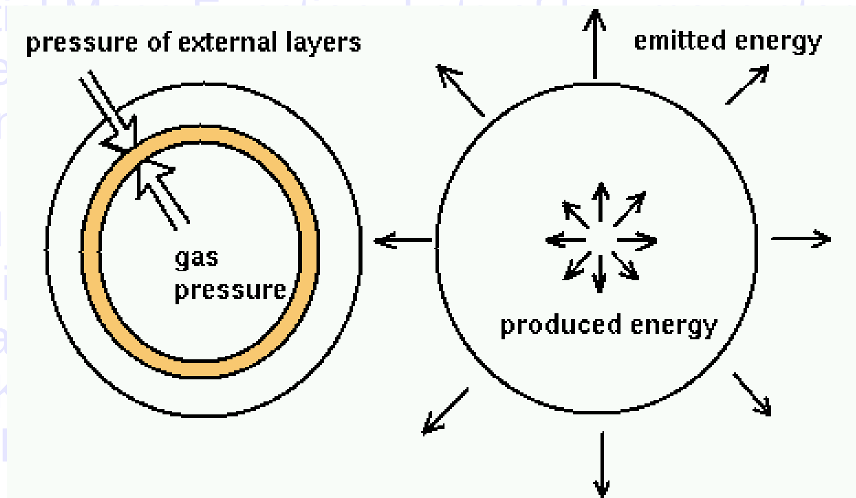


Post-Main Sequence Evolution - Timescales



Let's summarize

Radiative Equilibrium: Heating is matched by cooling



What we call “heat” is actually radiation

Radiative loss = Cooling

In a star in radiative equilibrium,
radiative losses (cooling)
are matched by
energy production (heating)
from nuclear reactions

Let's summarize

Turbulence is a self-similar flow. Size spectrum is well defined.
Turbulent fragmentation of a molecular cloud leads to a well defined mass spectrum.
Mass spectrum: Initial Mass Function. Lots of low mass stars, few high mass stars.
Lifetime on the Main Sequence: A strong function of mass.
Main Sequence Turn-Off Point. An indicator of age.
Post Main Sequence Evolution
Hydrogen is gone: Helium core contracts and heats
Red Giants – inert Helium core, Hydrogen Shell Burning
Core degeneracy – a phase transition to "solid-like" behavior. Core contraction stops.
100 Million K – Helium ignition. Degeneracy is lifted (Helium Flash).
Horizontal Branch – Helium Main Sequence
Helium is gone: Carbon-Oxygen core contracts and heats
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AGB are unstable. Violent pulsations eventually eject the whole atmosphere
Planetary Nebula
The exposed degenerate core is seen as a white dwarf
White dwarfs cool in long timescales

$$t_{star}/t_{Sun} = \left(M_{star}/M_{Sun}\right)^{-2.5}$$

High mass stars life fast and die young.

Low mass stars will still be around long after we're gone

Let's summarize

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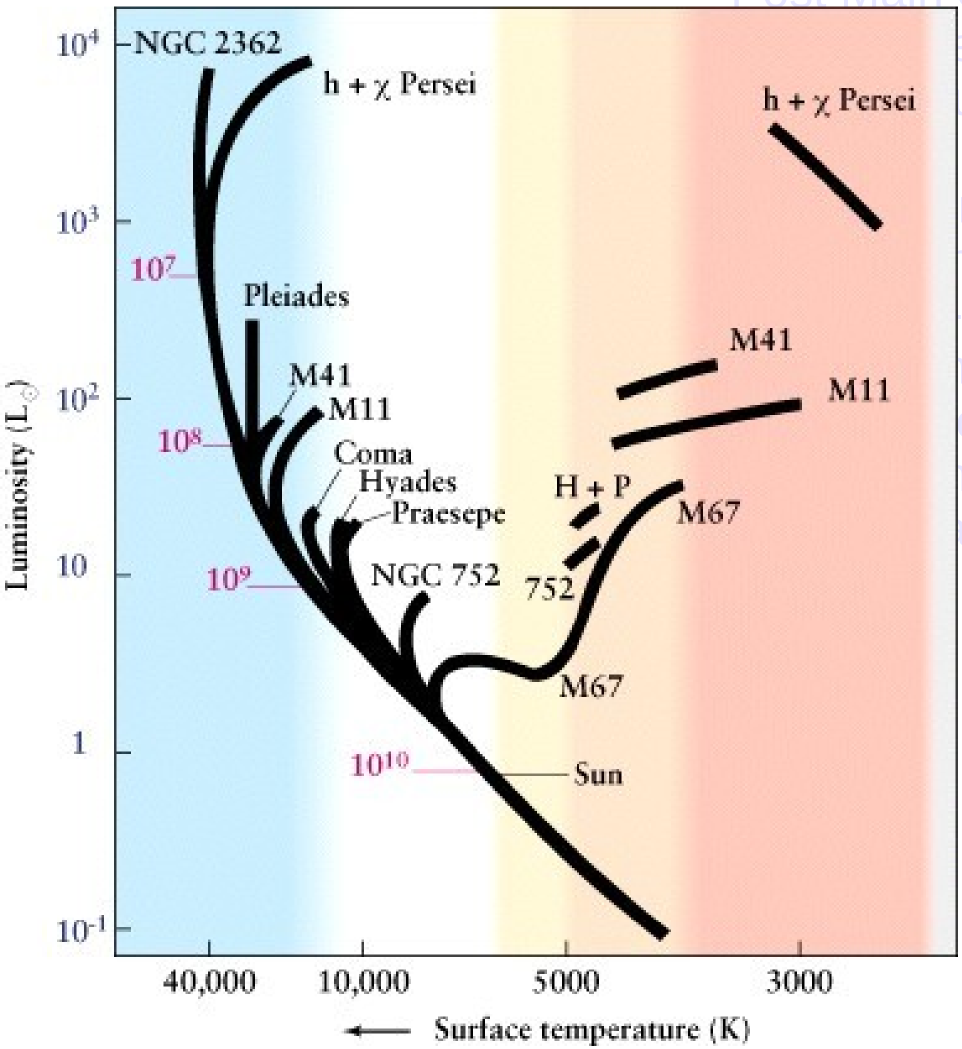

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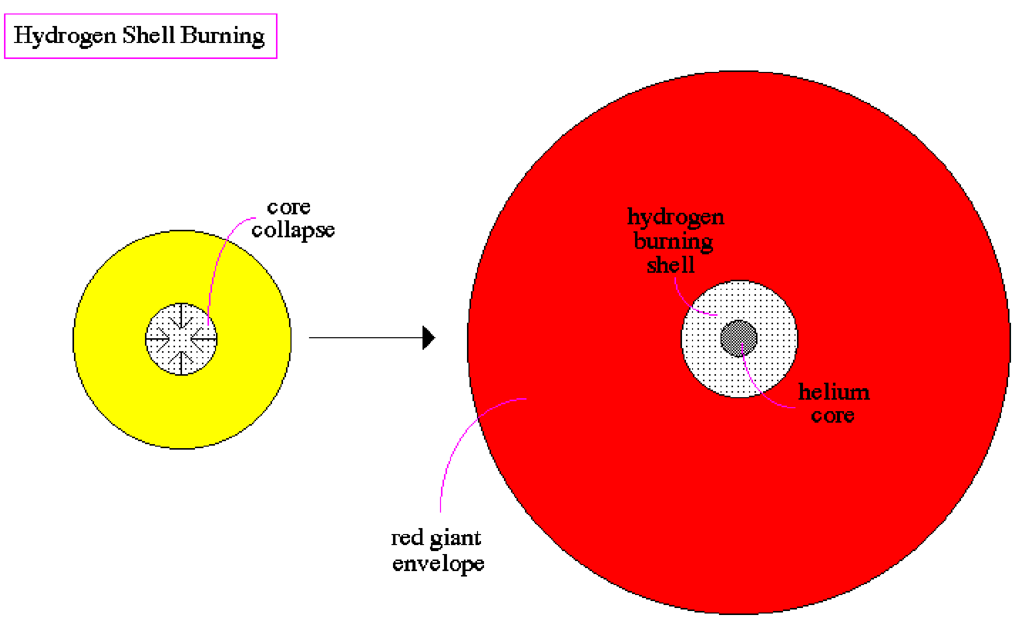

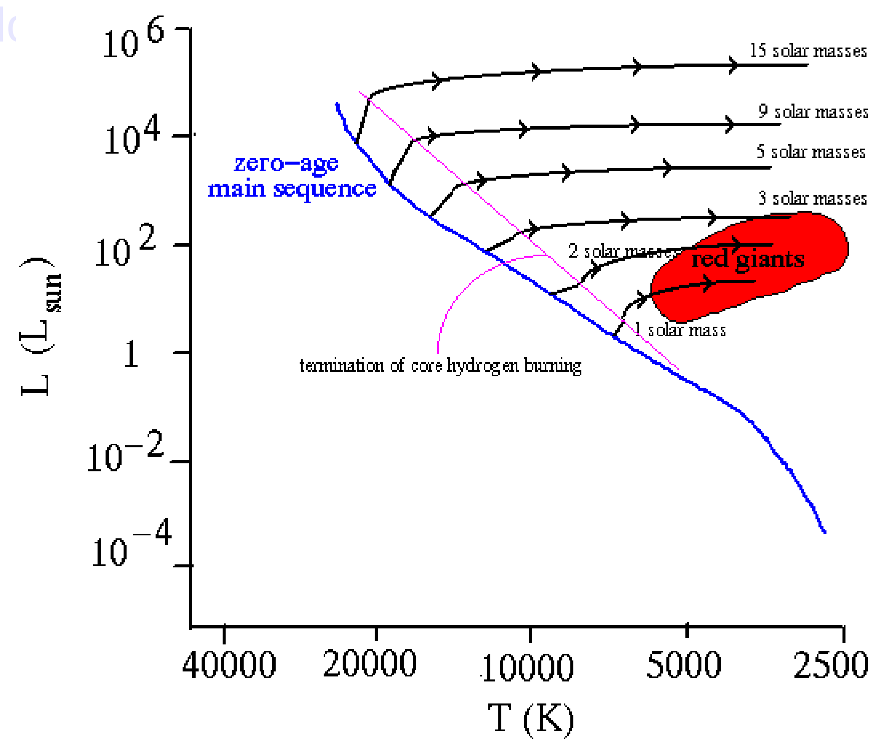

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Ideal Gas

$$p \propto \rho T$$

Temperature rises, pressure rises
Temperature falls, pressure falls

Radiation → less support against gravity
→ **contraction**

Degenerate Matter

$$p \propto \rho^{4/3}$$

If temperature rises or falls, pressure couldn't care less

Radiatve losses can continue indefinitely
The degenerate core is stable

Let's summarize

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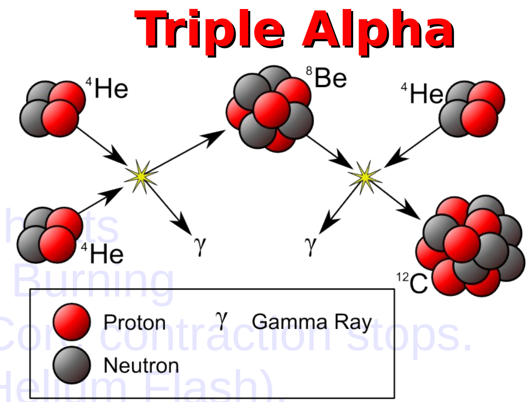
…s cool in l…

Controlled fusion

Runaway fusion

Let's summarize



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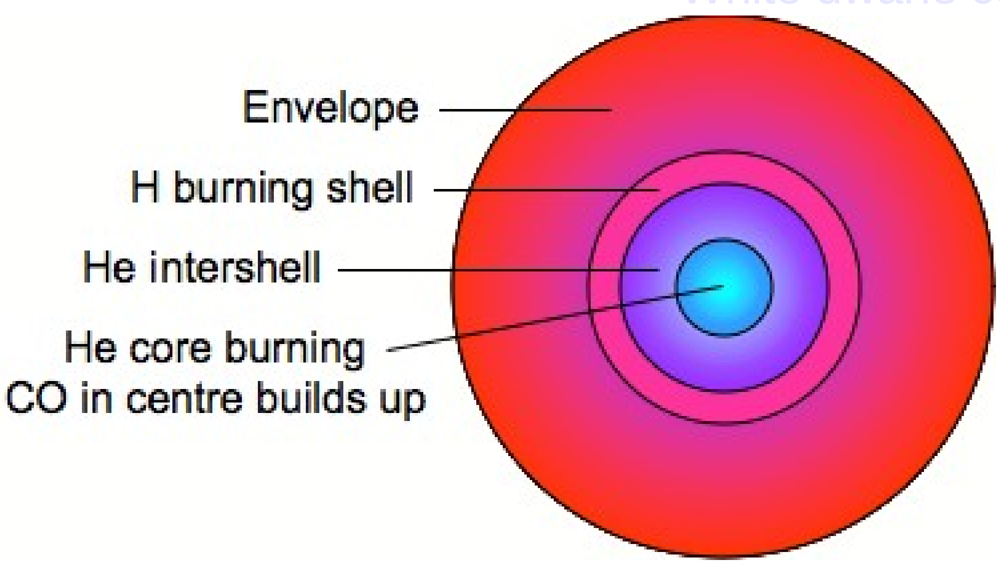

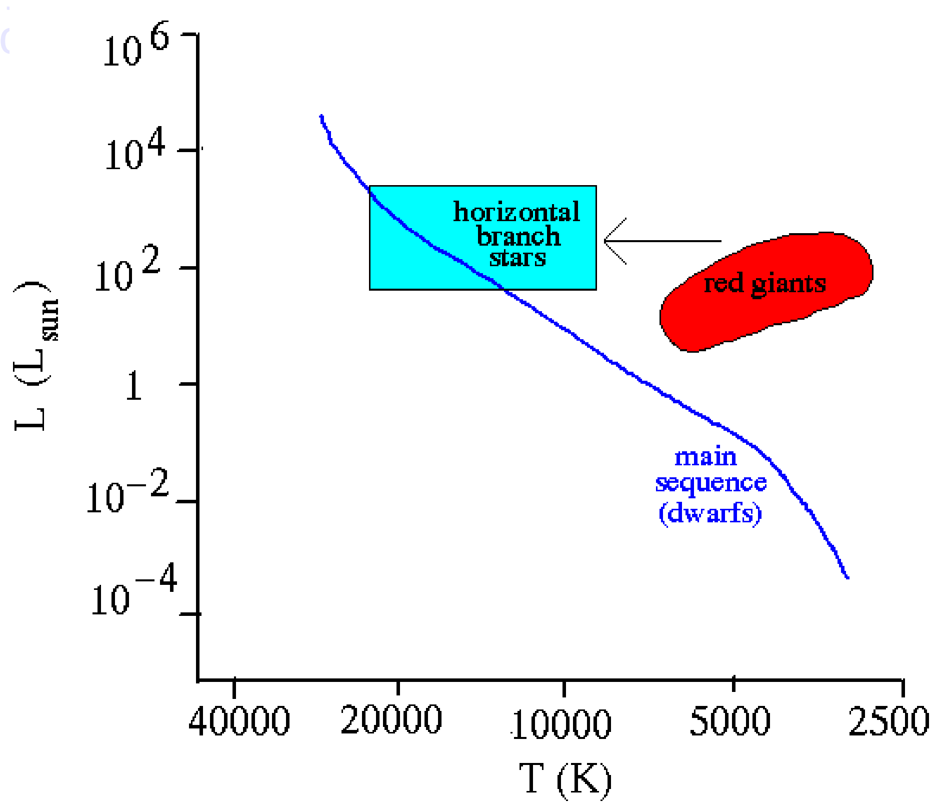

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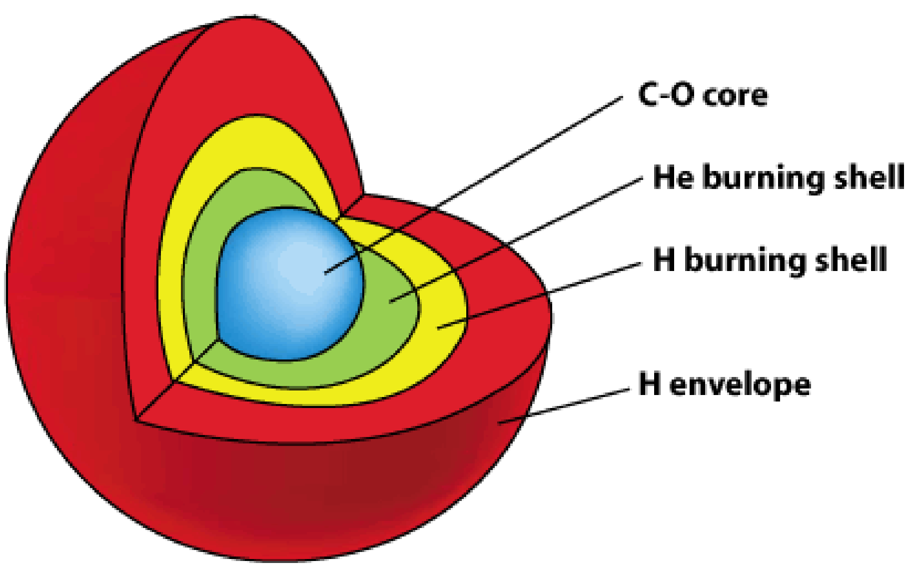

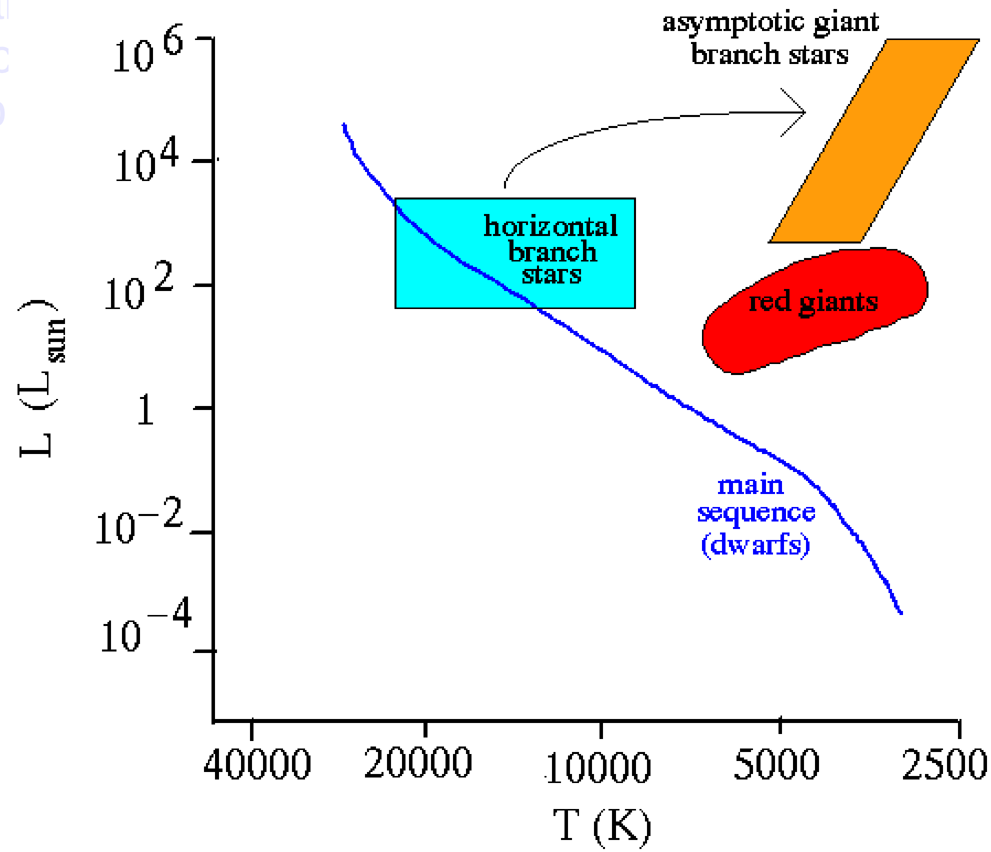

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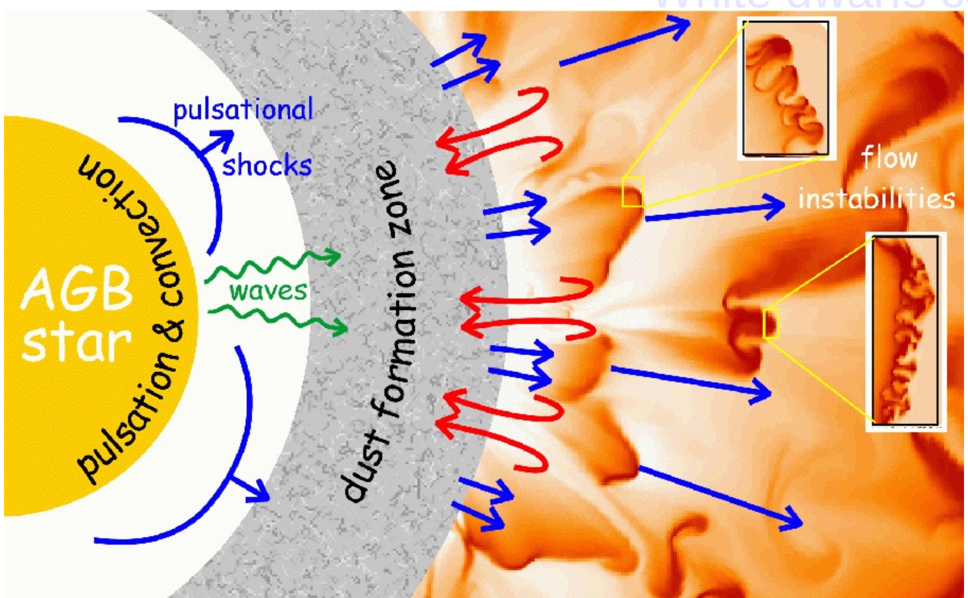
Planetary Nebula

The exposed degenerate core is seen as a white dwarf

White dwarfs cool in long timescales



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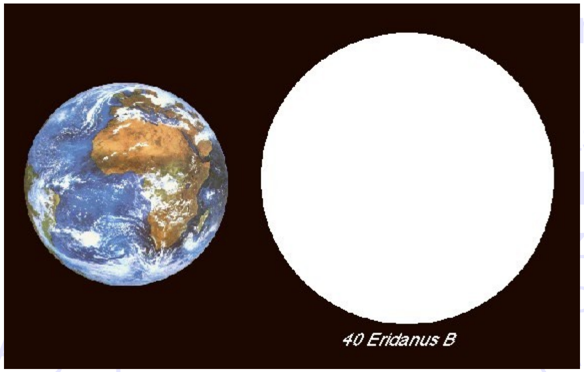

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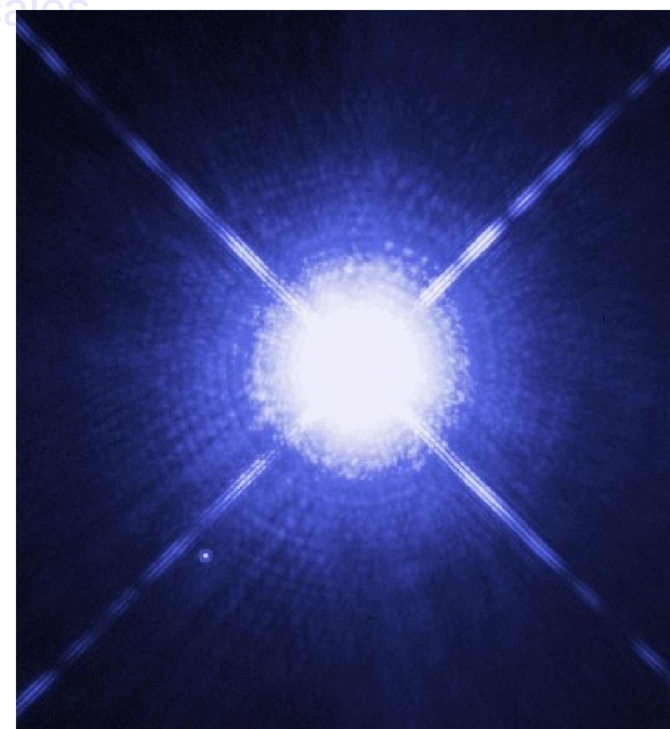
Planetary Nebula

The exposed degenerate CO core is seen as a white dwarf

White dwarfs cool in long timescales



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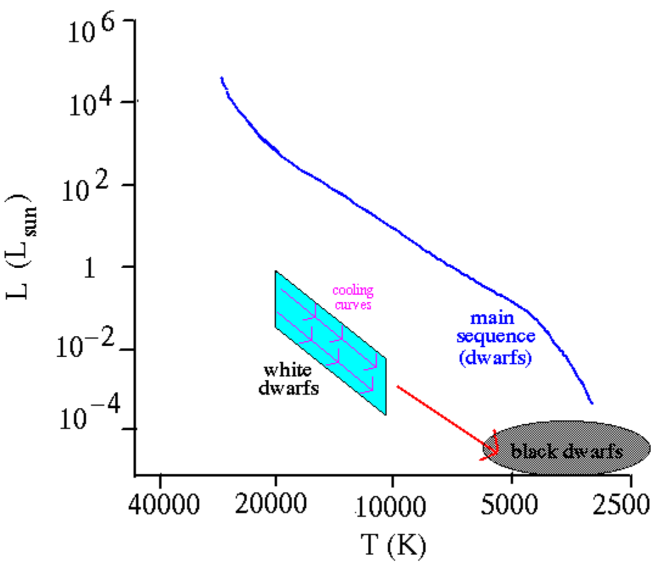


No energy production

Supported by degenerate pressure

Cooling takes a long time

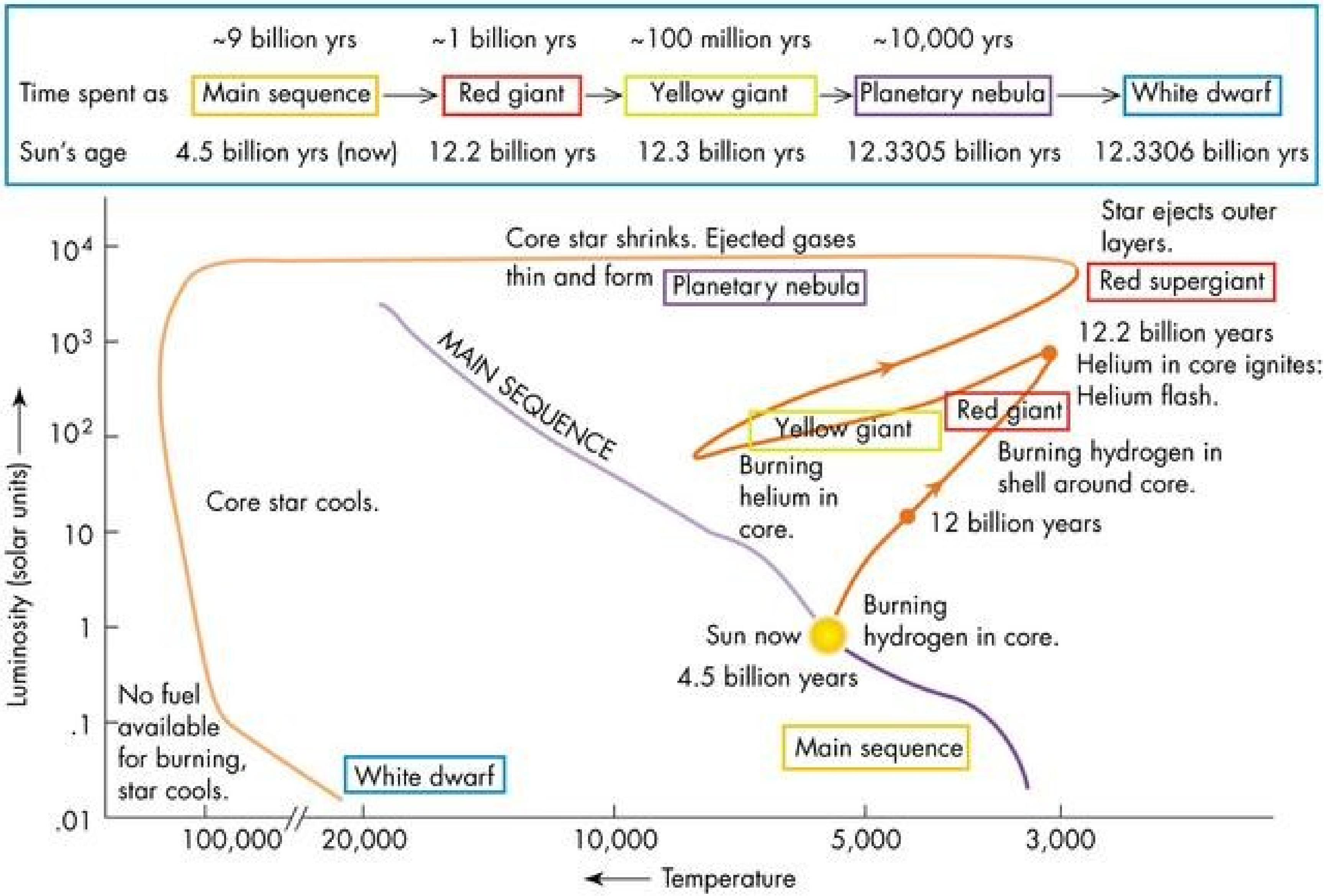
10^{15} yr to cool down to background temperature

The universe is not old enough to have black dwarfs

Coldest white dwarfs ~5000 K.

Let's summarize

Evolutionary track of a low mass star

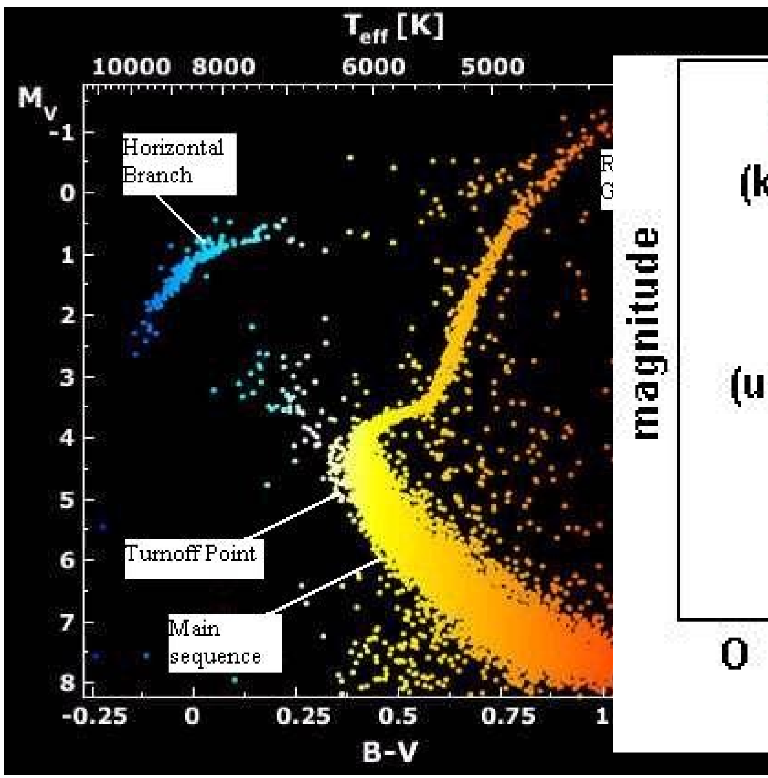


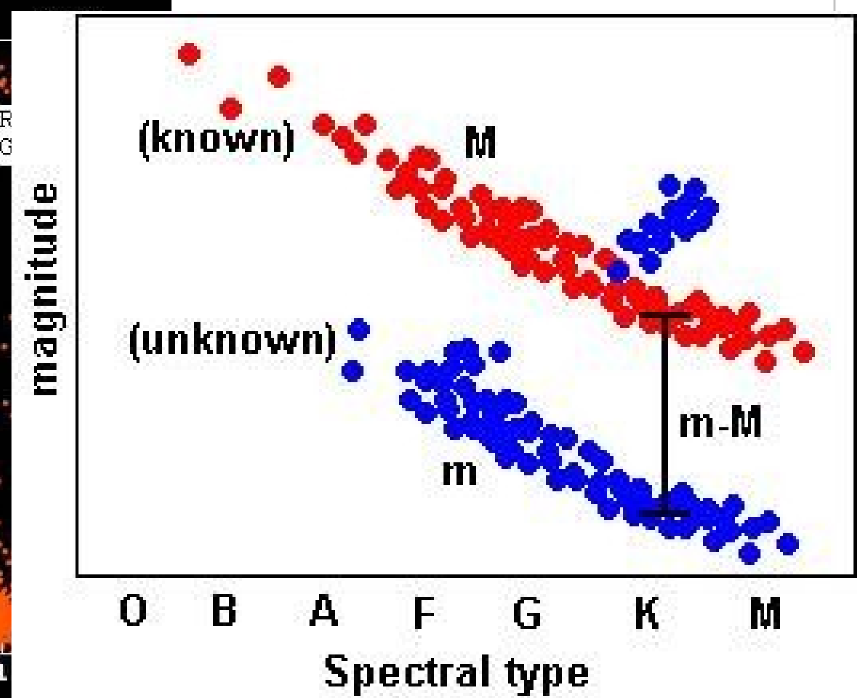
Stellar Distances

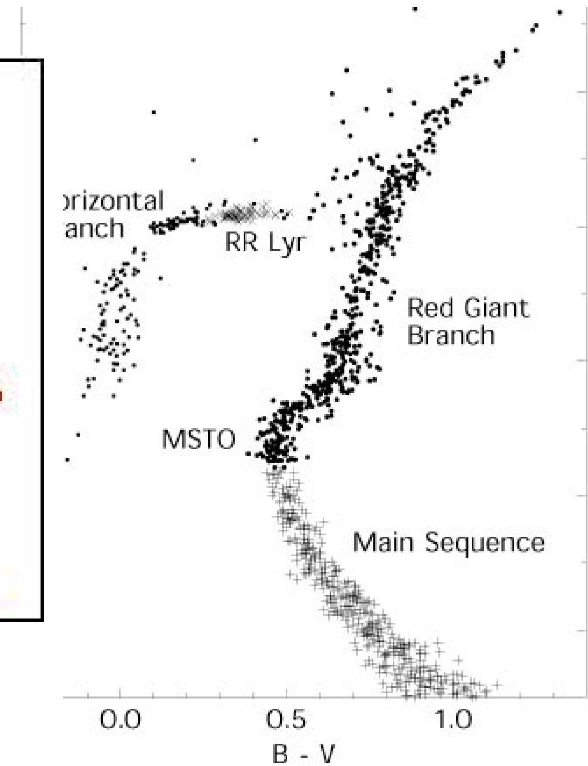
Main Sequence (HR Diagram) fitting

We know the absolute luminosity of the main sequence

Slide the observed sequence and you get the distance modulus!







Calibrated (or from model)

Observed