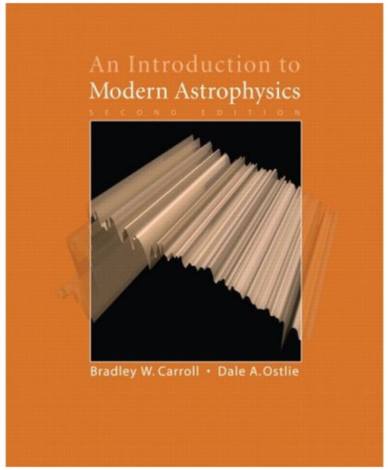
# Lecture 14:
# Stellar evolution –
## Low-intermediate mass stars and red giants

Professor David Alexander
Ogden Centre West 119

Chapter 13 of Carroll and Ostlie



# Aims of lecture

Key concept: the factors that drive the evolution of stars

<u>Aims:</u>

- Understand the factors that drive the evolution of stars both on and off the main sequence and why the evolution of stars is a function of mass

- Understand the evolution of low-intermediate mass stars from the main sequence to the horizontal branch, giant branch(es), and white dwarfs

- Know and be able to define and use:

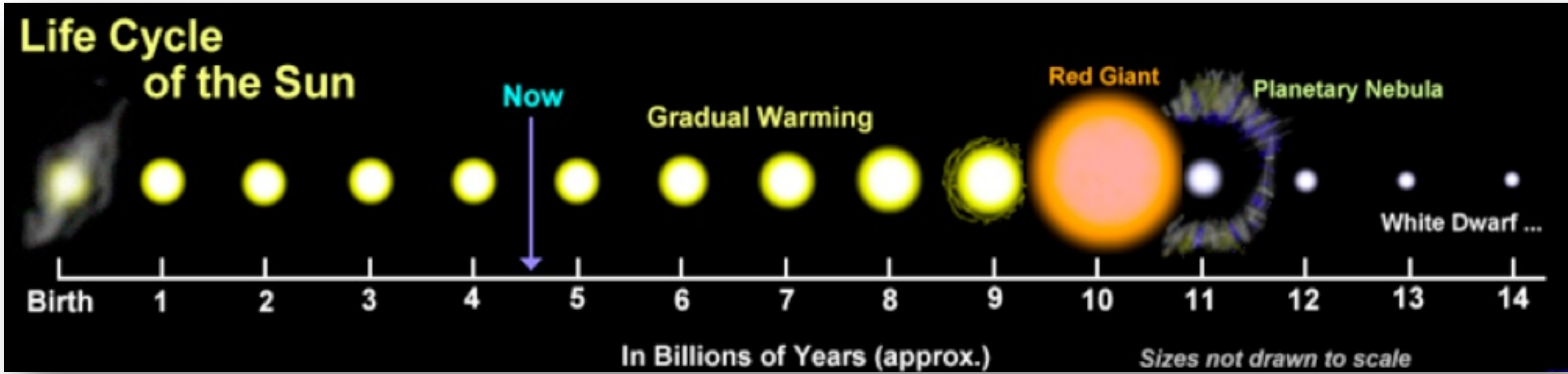
$$t = \frac{X\xi Mc^2}{L}$$

Nuclear fusion lifetime

$$t = 10^{10}\left(\frac{M_{Sun}}{M}\right)^{\alpha-1} yrs$$

Mass-dependent main sequence lifetime

# What drives the evolution of stars?




**Major factors that drive the evolution of stars:**

(1) Abundance changes: an increase in the mean molecular mass ($\mu$) with time driving T and $\rho$ increases in the core

(2) Fusion size increase (and fusion in a shell around the core) driven by an increase in T and $\rho$ in the core, thereby increasing the luminosity produced from fusion

**DRIVEN BY FUSION**

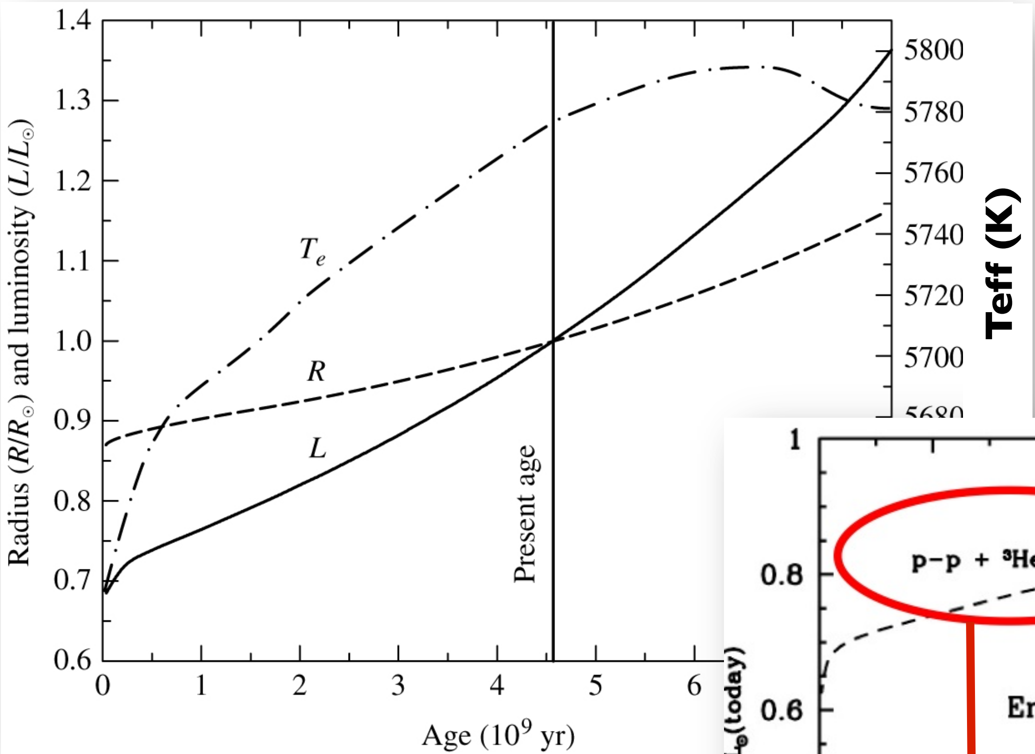
(3) Slow gravitational contraction: an increase in $\rho$, T, and P which will occur due to
- an increase in $\mu$ with time (driven by fusion)
- a decrease in internal pressure (e.g., a decrease in fusion)

(4) Fast gravitational collapse when fusion ceases, which will cause a large increase in $\rho$, T, and P

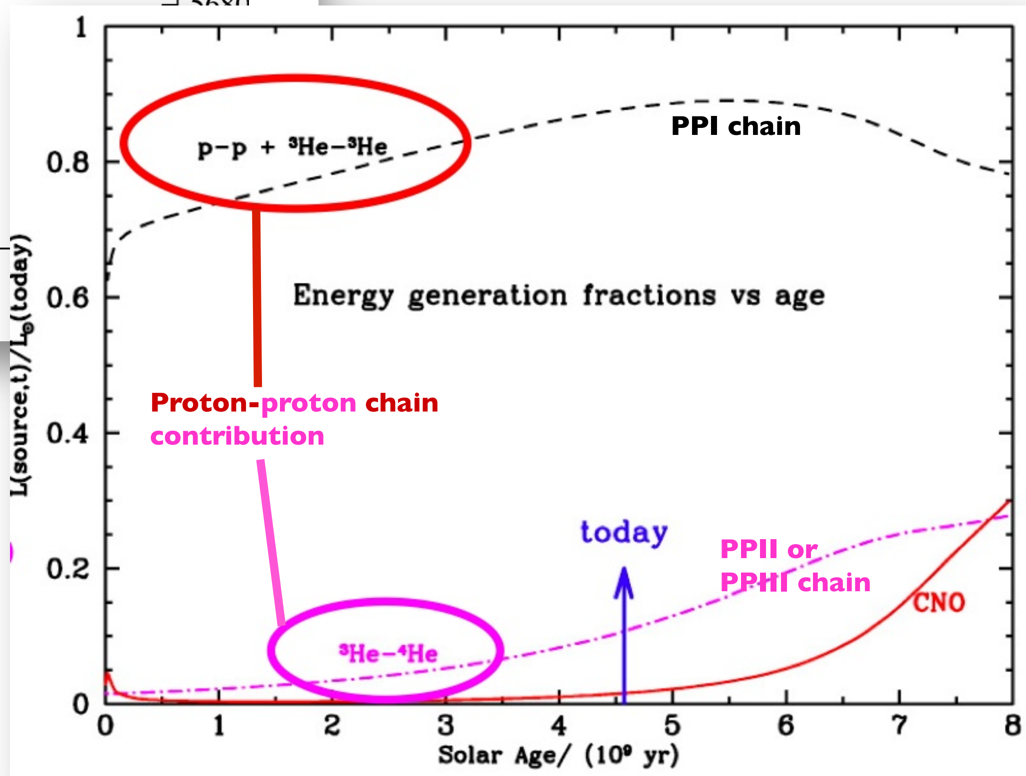
**DRIVEN BY CONTRACTION/ COLLAPSE**

# Example: evolution of Sun on the main sequence

**Predicted evolution of the Sun on the main sequence**

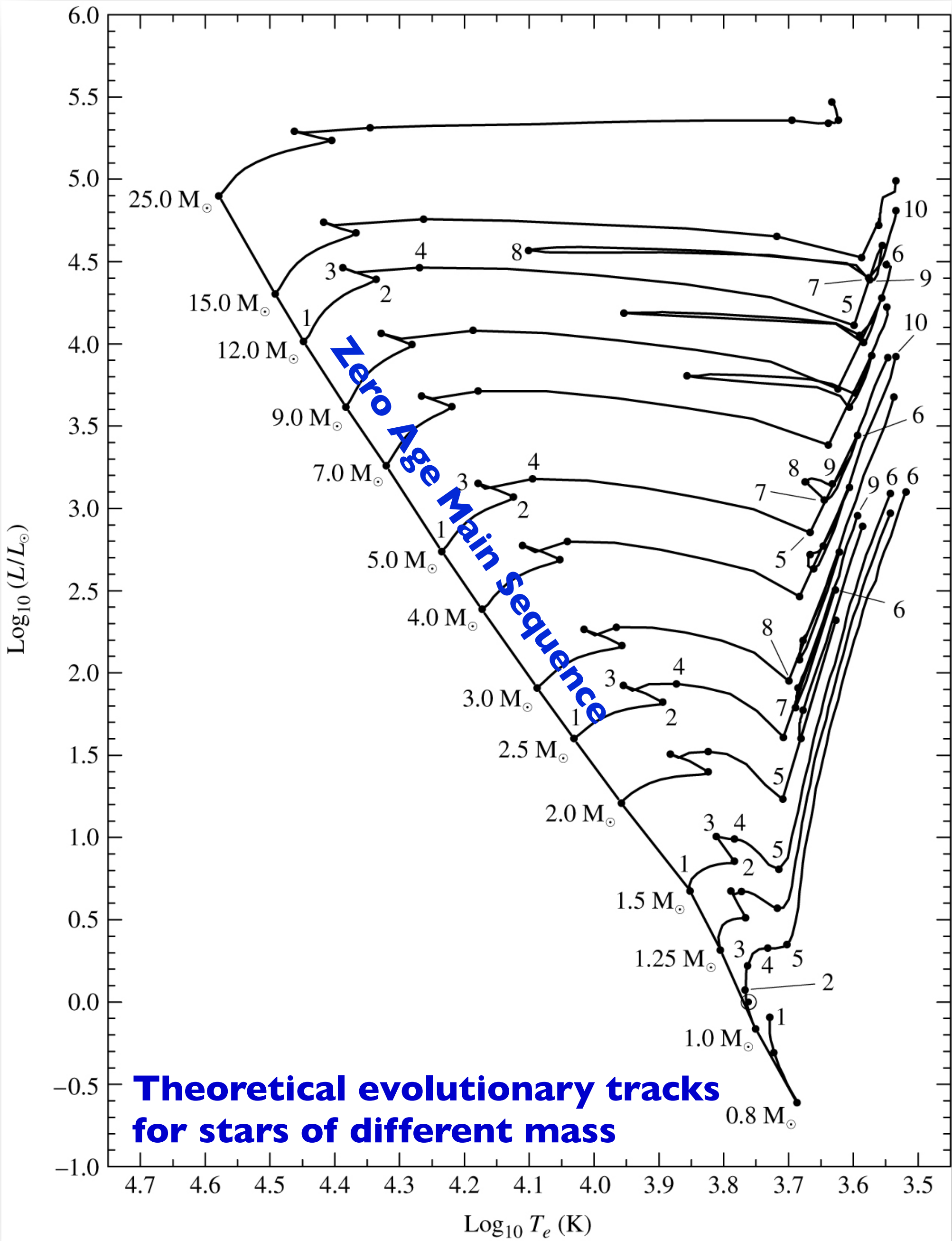



The temperature and luminosity increase will cause the Sun to move on the HR diagram as it ages. So often the term zero-age main sequence is used for the starting points of stars on the main sequence (see next slide)




Luminosity (and radius) increase due to increase in core temperature, driving increase in pp chain, larger fusion volume, greater internal pressure (gas and radiation), and increase in the contribution from CNO cycle

# Evolution of stars: HR diagram




We can track the evolution of stars using the HR diagram

Stars evolve both on the main sequence and also off the main sequence

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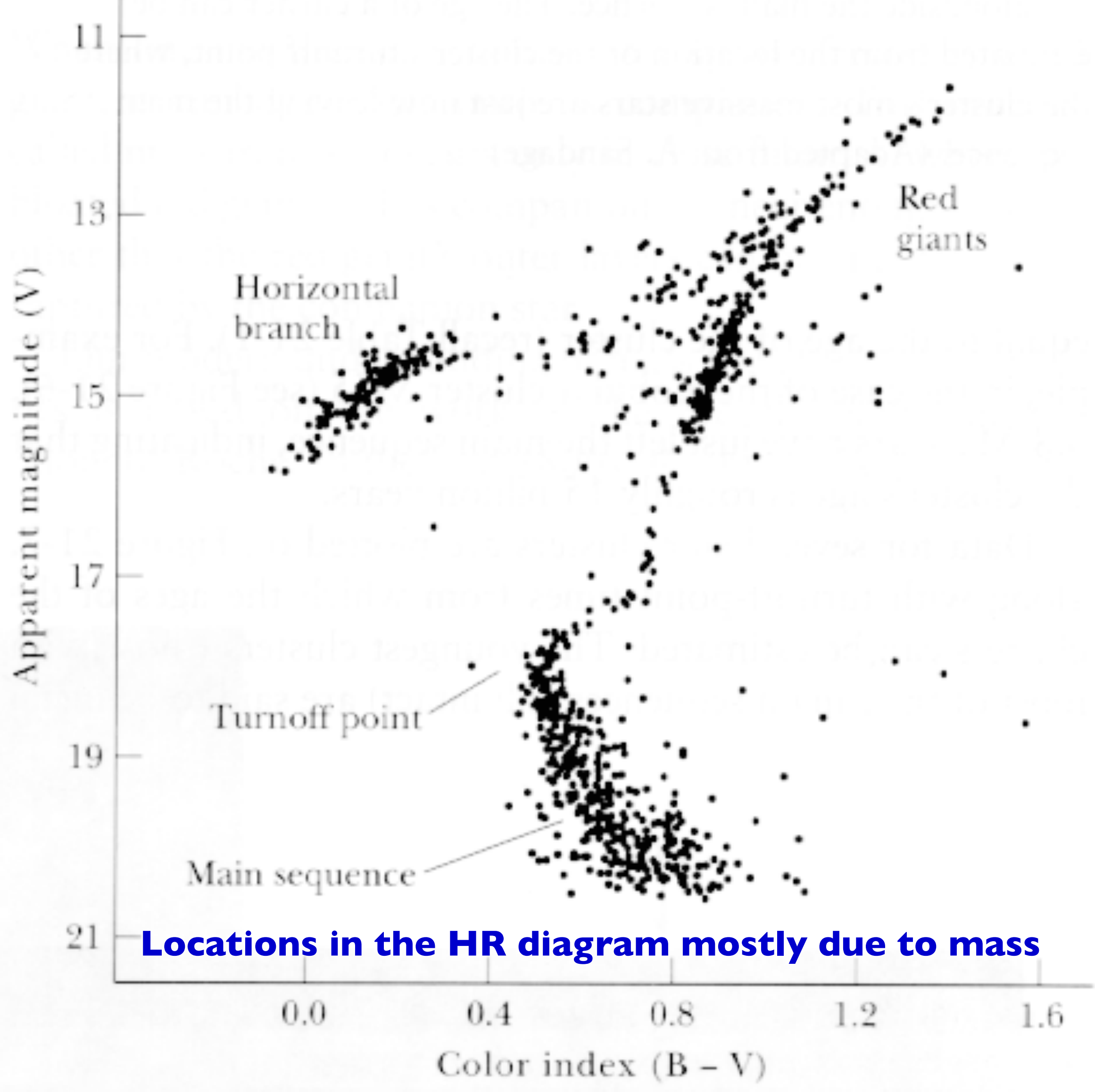
Some post main-sequence evolution phases:

- Red giant phase
- Horizontal branch
- Asymptotic giant branch
- Planetary nebula
- White dwarf

See a later slide for their location on the HR diagram

# Evolution of stars: how can we be confident?

**Stars in a ~8 billion year old stellar cluster**




**Locations in the HR diagram mostly due to mass**

Stars in stellar clusters (i.e., cloud collapse/fragmentation: lecture 13) formed at the same time: ~8 billion years ago in this example

The different locations of points is due to the different masses: the HR tracks therefore show where stars of a given mass will lie after ~8 billion years of evolution

These HR tracks become particularly powerful when you study many stellar clusters with different ages

These constraints provide <u>critical</u> empirical input into our understanding of the evolution of stars and theoretical models

# Evolution of stars: nuclear fusion lifetimes

The lifetime that a star undergoes nuclear fusion for a given fusion process will be:

$$t = \frac{X\xi Mc^2}{L}$$

**Equation 26**

where $X$ is the fraction of the mass in the star that will be used in the fusion process (e.g., PP chain; CNO cycle), $\xi$ is the mass-to-light efficiency conversion (of the nuclear fusion process), $M$ is the mass of the star, and $L$ is the luminosity of the star

**Mass-dependent main-sequence lifetimes:**

For stars on the main sequence, since $L \propto M^{\alpha}$ (lecture 3) where α~3-4, then

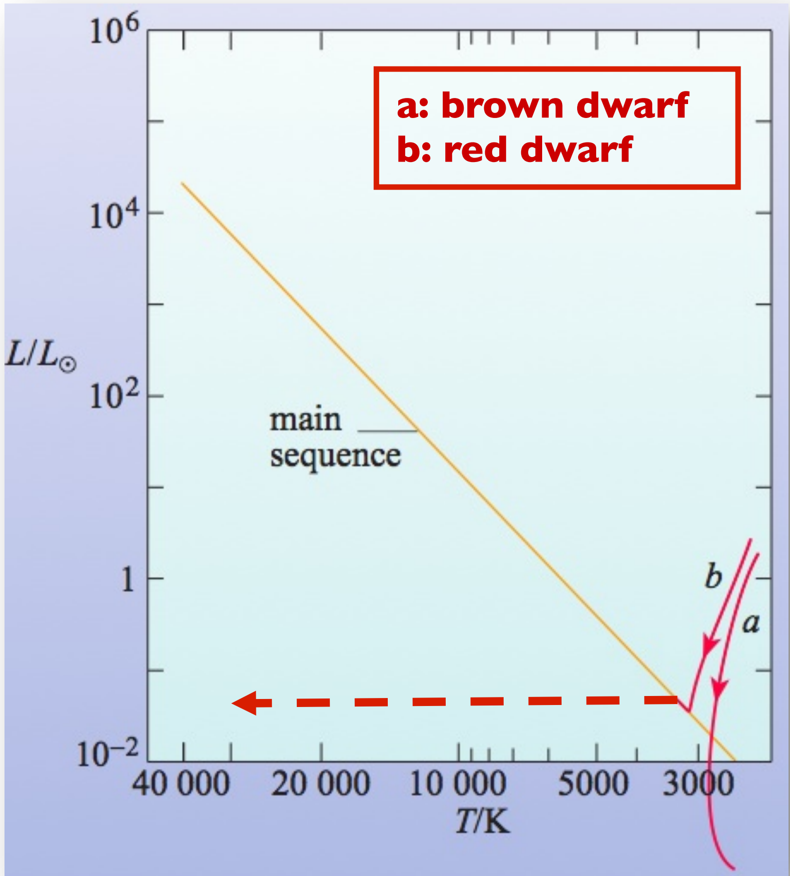
$$t = 10^{10}\left(\frac{M_{sun}}{M}\right)^{\alpha-1} \text{ years}$$

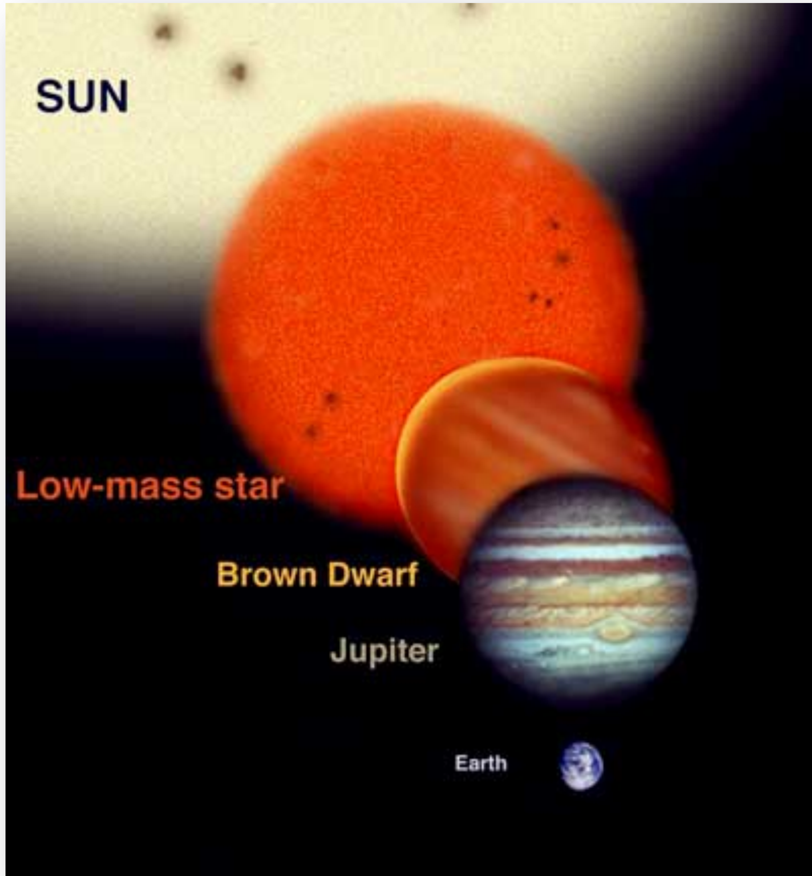
**Equation 27**

When calibrated to the Sun, which will have a main-sequence lifetime of ~$10^{10}$ years. Given the age of the Universe (~$1.37 \times 10^{10}$ years), only stars with masses >0.9 times the mass of the Sun could have completed their main-sequence burning phases.

# Evolution of stars: brown dwarfs and red dwarfs

**Brown dwarfs** have masses <0.08 solar masses and radiate through gravitational collapse - they are essentially protostars that never achieve nuclear fusion. They therefore never reach the main sequence and so are not genuine stars. Lifetime calculated from the Kelvin-Helmholtz time.




**Red dwarfs** are stars of ~0.08-0.4 solar masses. They undergo Hydrogen fusion but never achieve the core temperatures for the further stages of evolution. After leaving the main sequence red dwarfs evolve to become white dwarfs (after ~$6 \times 10^{10}$-$10^{12}$ years: main-sequence lifetime for $\alpha$=3).

**We will now explore the main processes behind the evolution of a low-intermediate mass (~0.4-8 solar masses) star off the main sequence – the example plots shown are for a 1 solar mass star (equivalent to the Sun)**

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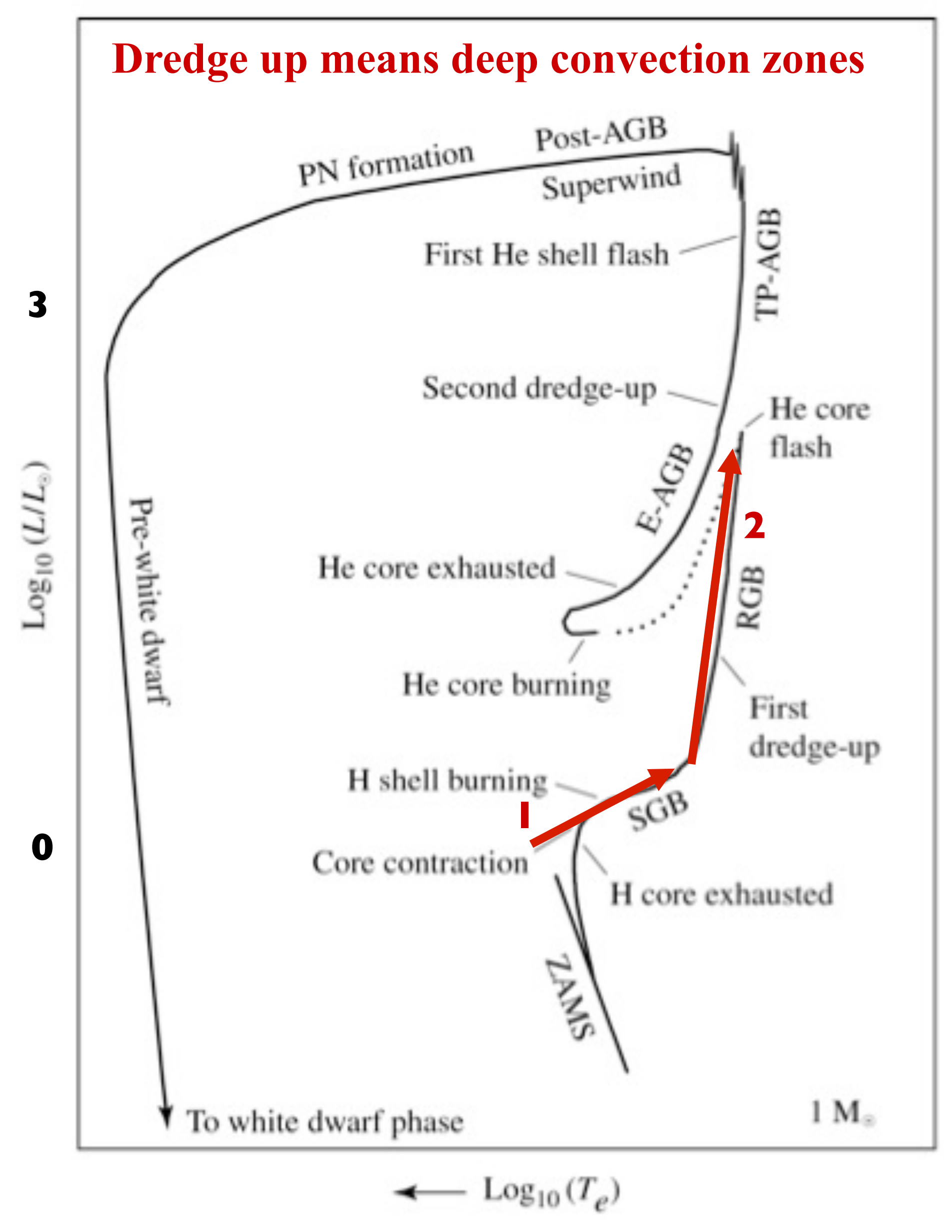
**We will expect a balance between gravitational and thermal pressure (nuclear fusion) with a change in the chemical composition with time**

**Also, remember stars are characterised on the HR diagram by**

$$L = 4\pi R^2 \sigma T_e^4$$

# Shell burning: moving off the main sequence




During the H-H fusion phase the whole star will slowly contract due to chemical changes in the core

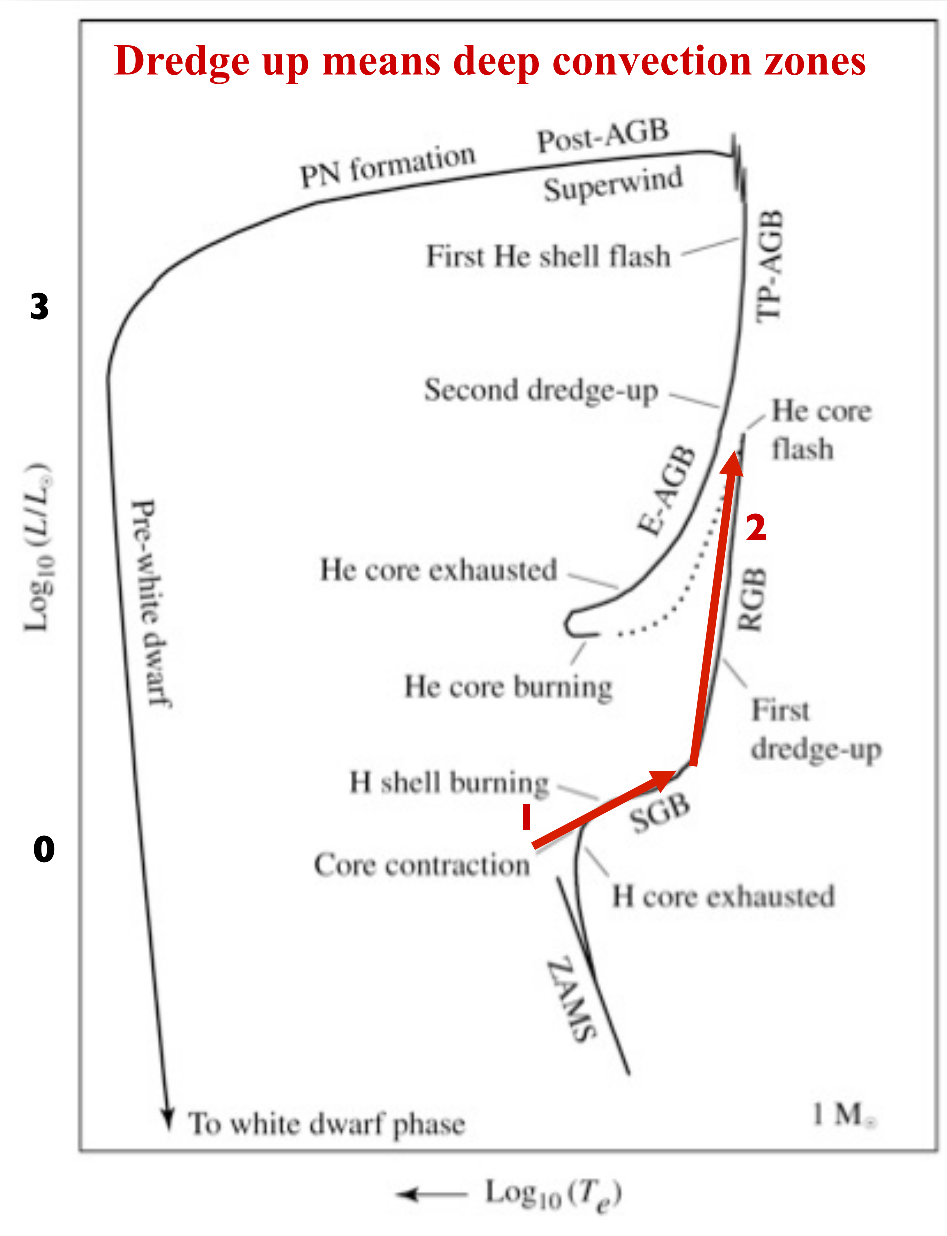
This will heat up the outer regions of the core and if the temperature is high enough then:

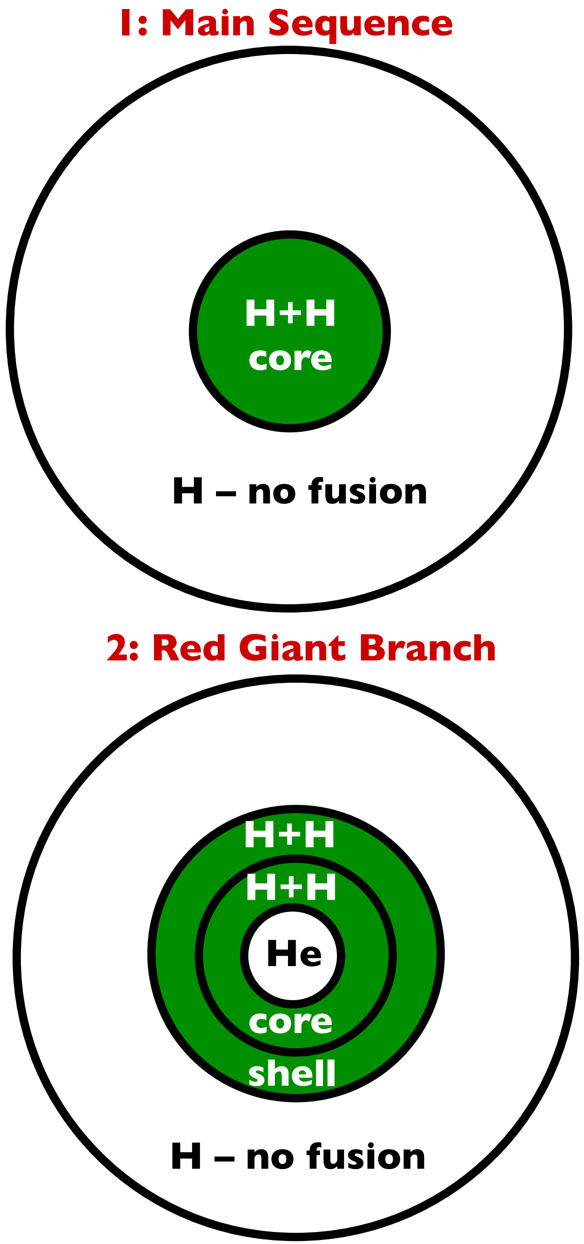
**Hydrogen fusion will commence in a shell around the core**

During shell-fusion phases the star will increase in size since there will be multiple contributions to the luminosity: shell fusion, possible core fusion, and thermal energy from the contraction plus an increase in output due to CNO cycle ($T^{17}$!)

The outer layers of the star will expand and the effective temperature of the star (at the "surface") will drop in response to the expansion, moving the star along the **Sub-Giant Branch (SGB)** and up the **Red Giant Branch (RGB)**

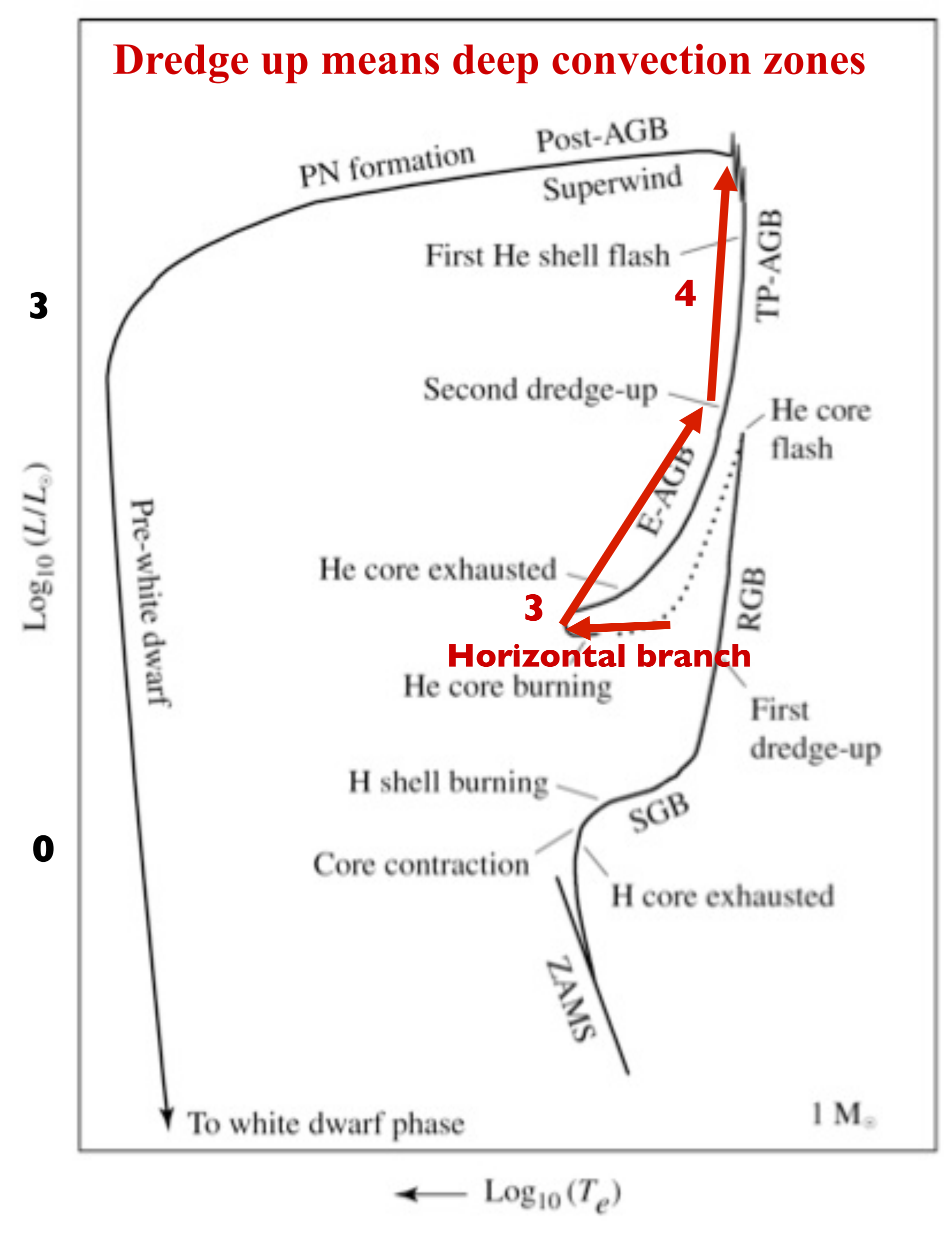
# Shell burning: moving off the main sequence




**Note: not drawn to scale**

# Horizontal branch: Helium-fusion phase




When H-fusion at the core ceases the star contracts/collapses until the core is hot enough for Helium fusion via the triple-alpha process ($T \sim 10^8$ K)

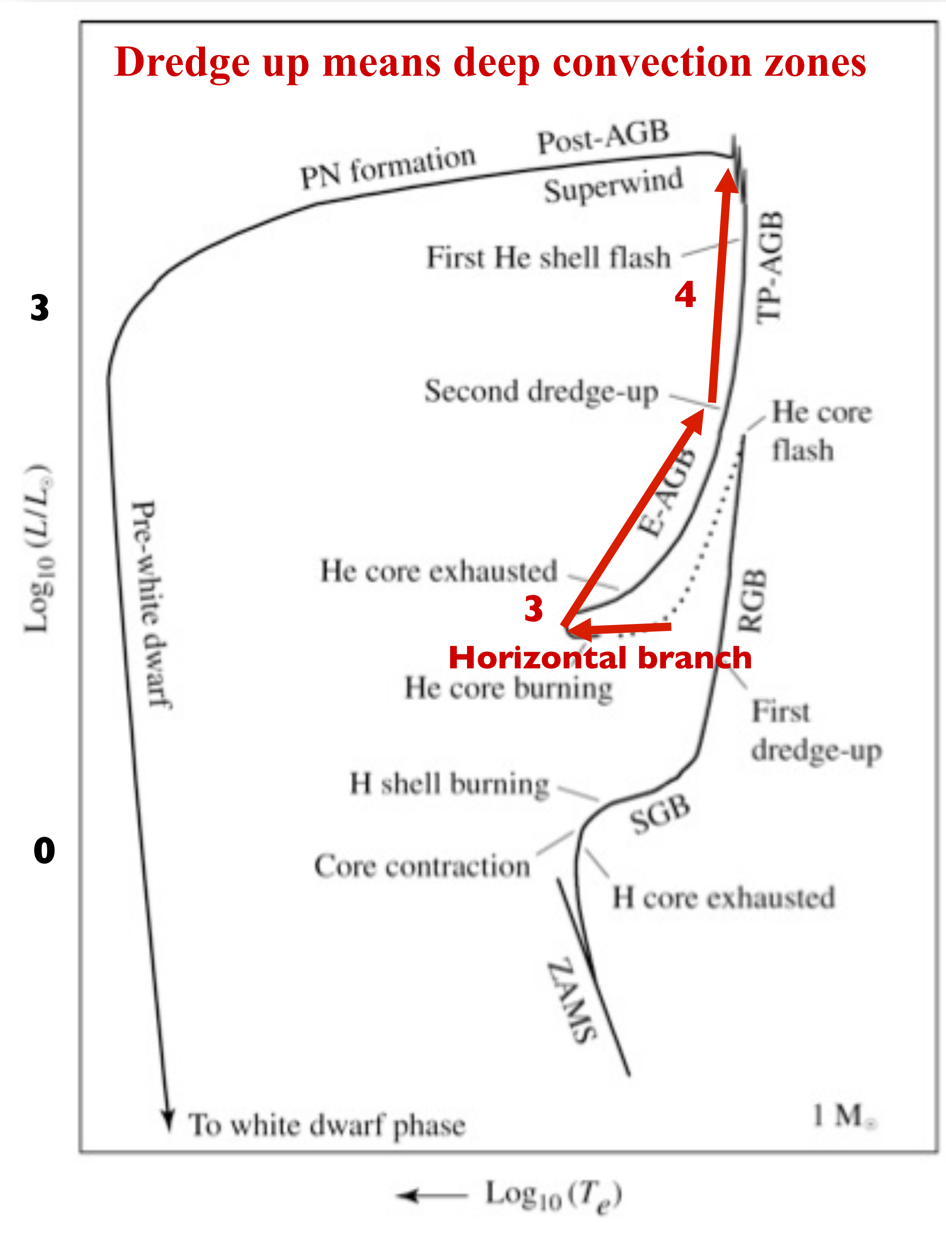
The luminosity of the star now comes from He-core fusion and H-shell fusion. The star is now on the **Horizontal Branch (HB),** which is the He-fusion equivalent of the main sequence. But He-fusion is ~10 times less efficient than H-fusion so this phase is comparatively short

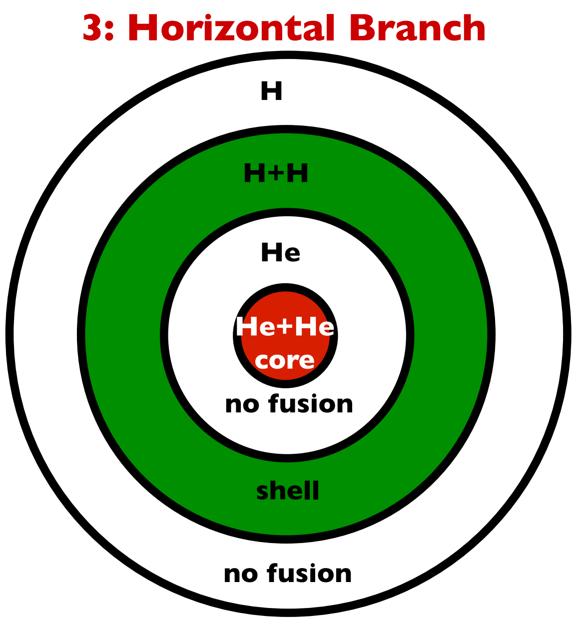
**How much less time will the star lie on the HB than the MS?**

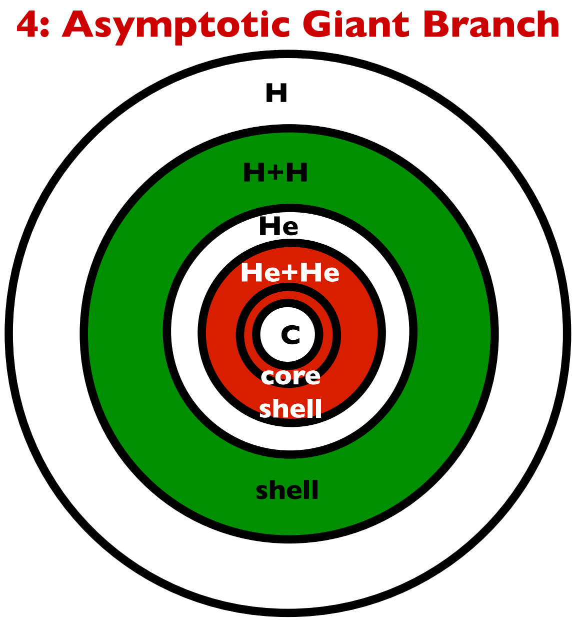
With the increasing mean molecular mass (Helium to Carbon and Oxygen) the stars gets hotter and He-shell fusion is initiated - the star becomes very luminous (recall the very high temperature dependency for triple alpha: $T^{40}$!). We now reach the

**Asymptotic Giant Branch (AGB)**

# Horizontal branch: Helium-fusion phase

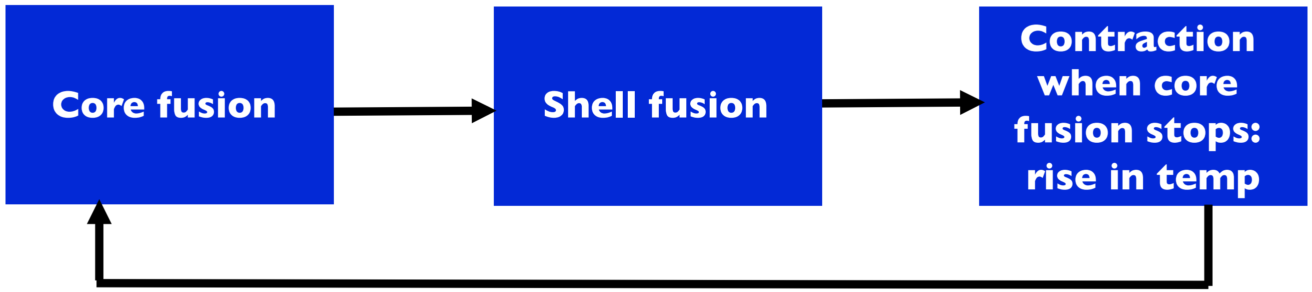



Why no He fusion between H-fusion shell and He-fusion shell?

You may have noticed a pattern to the evolution of stars - similar processes occur during each new cycle of nuclear fusion (presuming sufficient temperatures are reached at each stage)



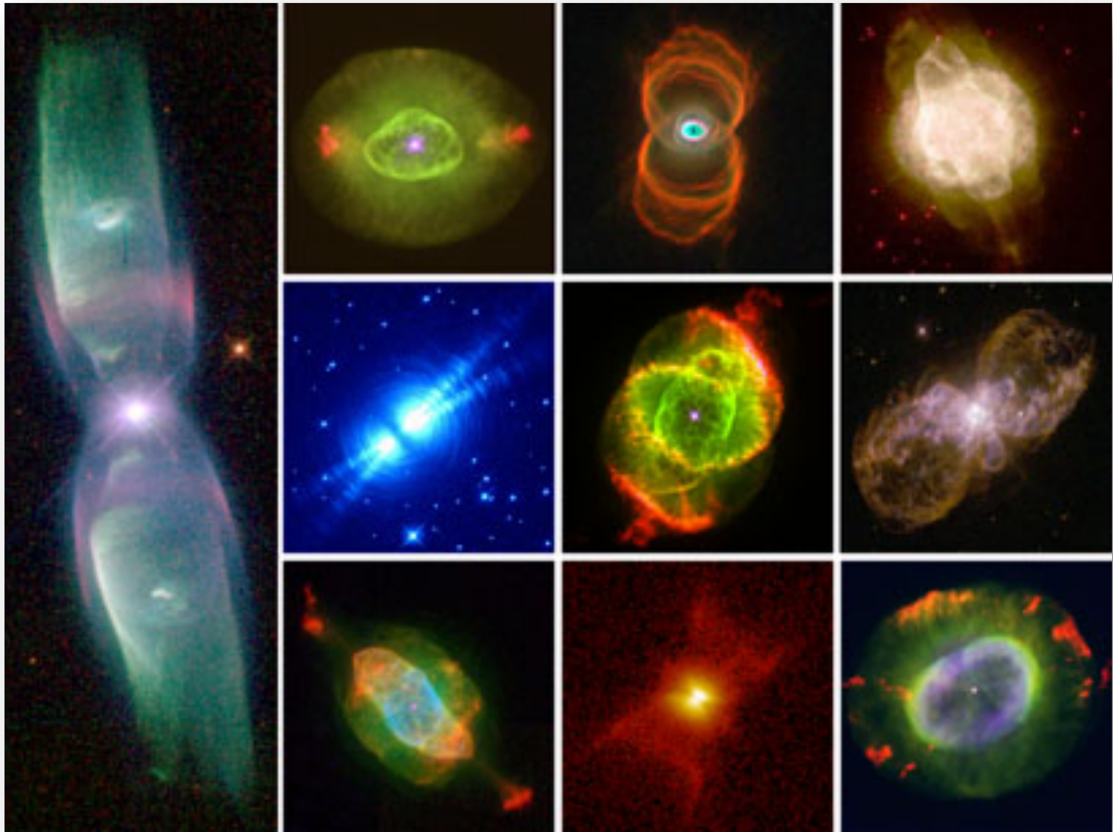

A star of <8 solar masses cannot raise its core temperature high enough for Carbon fusion and its fusion life is now at an end and it is destined to become a white dwarf, after ejecting its outer layers and producing a beautiful planetary nebula (PN)

In the next lecture we will see how more massive stars evolve

# Planetary nebula (PN): last throes of a dying star

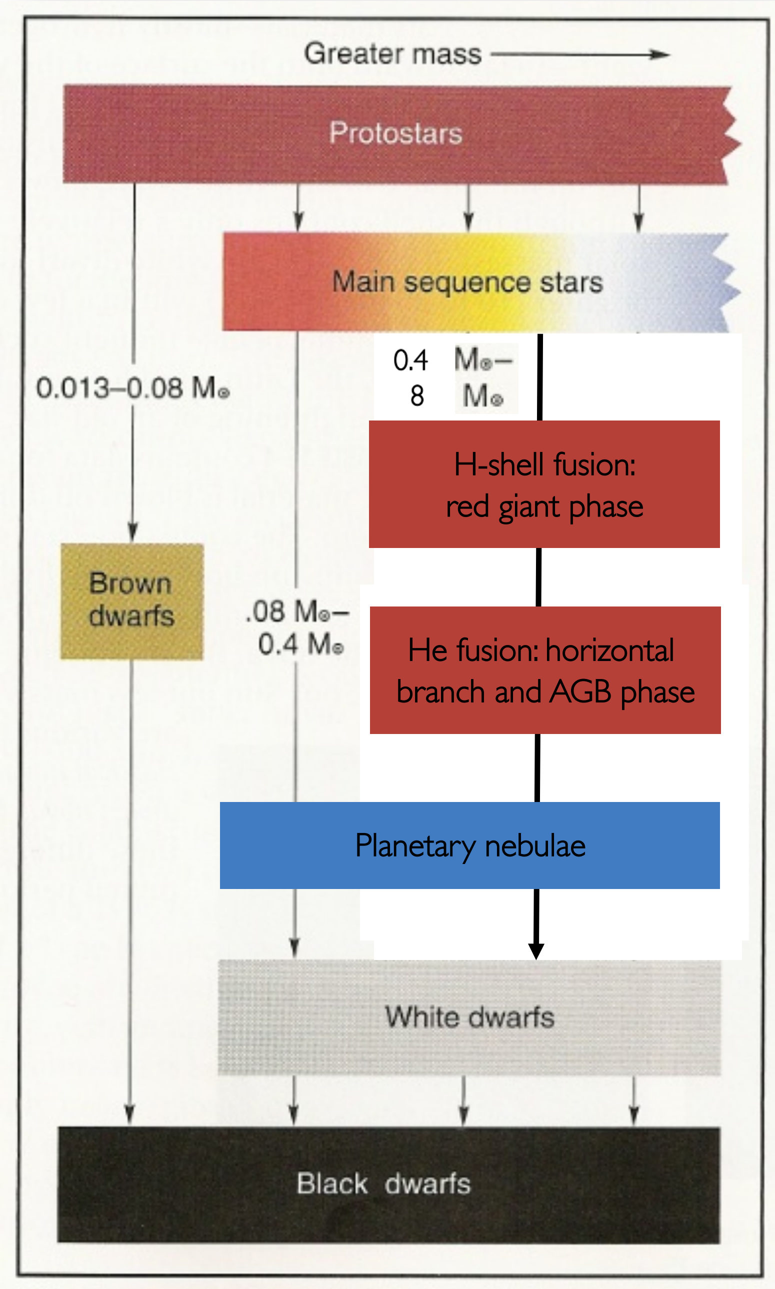
**The outer envelopes of the star are expelled (v~10-30 km/s) – shocks/pulses due to unstable later nuclear fusion stages. The expelled gas is excited and ionised by the photons of the dying star (white dwarf) producing the planetary nebula**

**The expelled gas is excited/ionised by the dying star producing a PN (see below)**



**There are ~15,000 PNs in the Galaxy alone, each of which exist for ~10,000 years before the gas is dissipated. Each PN contains ~0.5 solar mass of material so the interstellar medium is enriched at a rate of ~1 solar mass/year of gas**

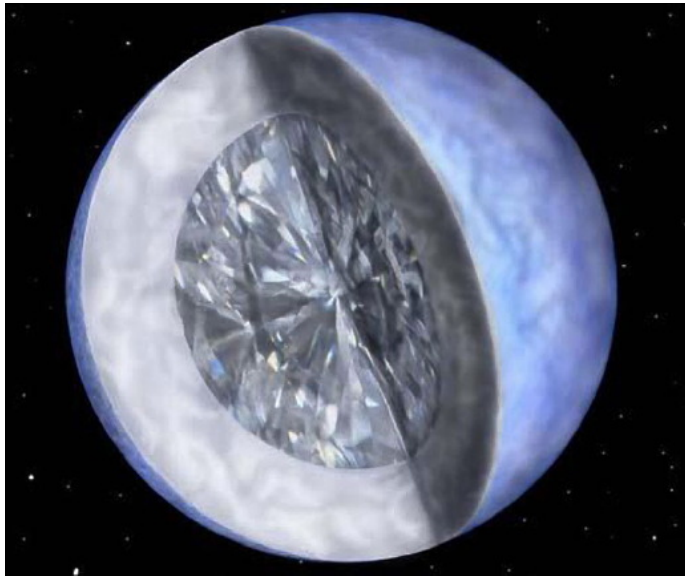
# Summary for the evolution of <8 solar mass stars




**The inert core of a <8 solar mass star is now revealed - a white dwarf held up by electron degeneracy pressure**

**Density of ~$10^9$ kg m$^{-3}$: mass of the Sun, size of the Earth (more in lecture 16)**

**Surface temperature of ~40,000 K, the white dwarf will very slowly radiate its energy away and become a black dwarf**



**White dwarf with a Carbon core - biggest diamonds in the Universe!**