Lecture 3

Post-Main-Sequence Evolution

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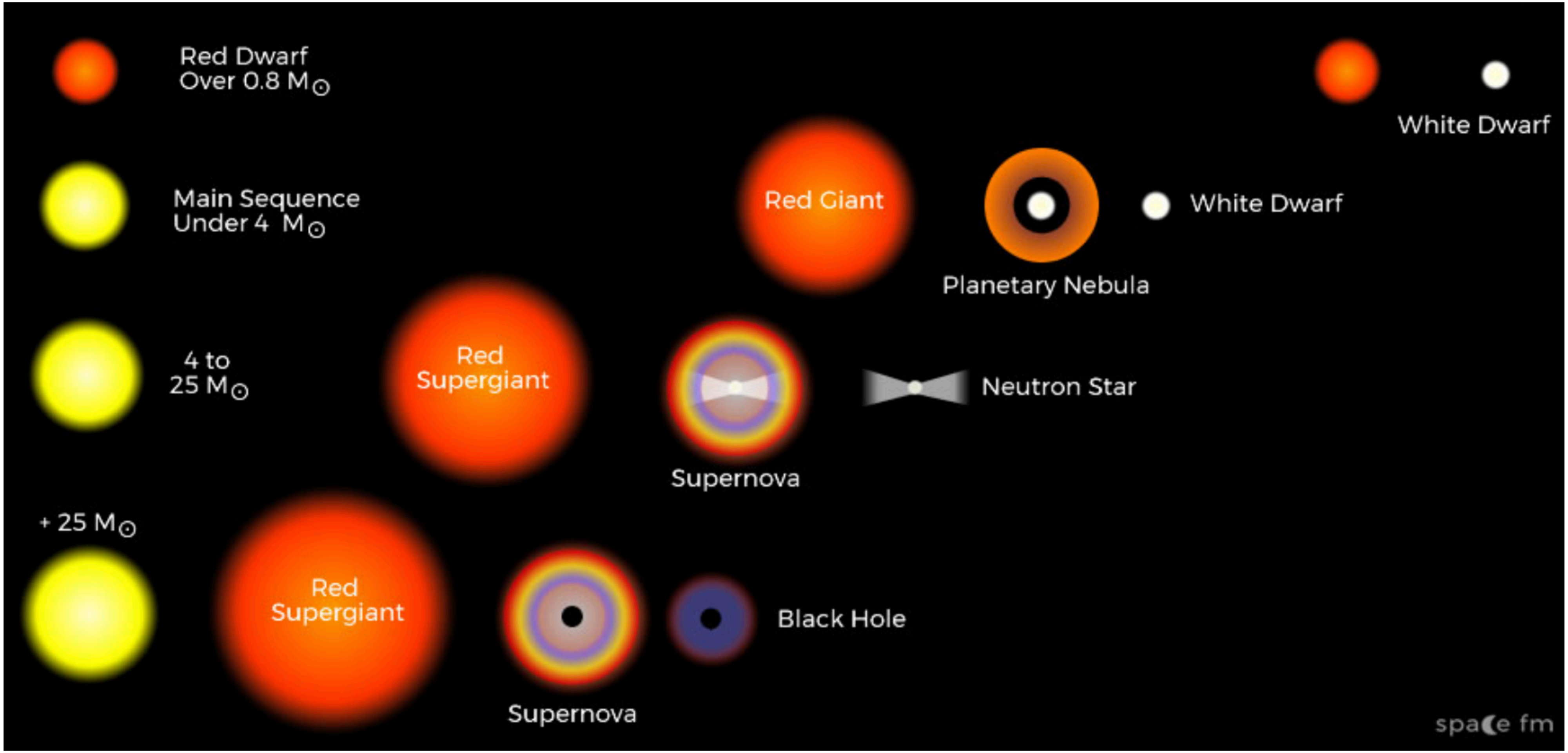
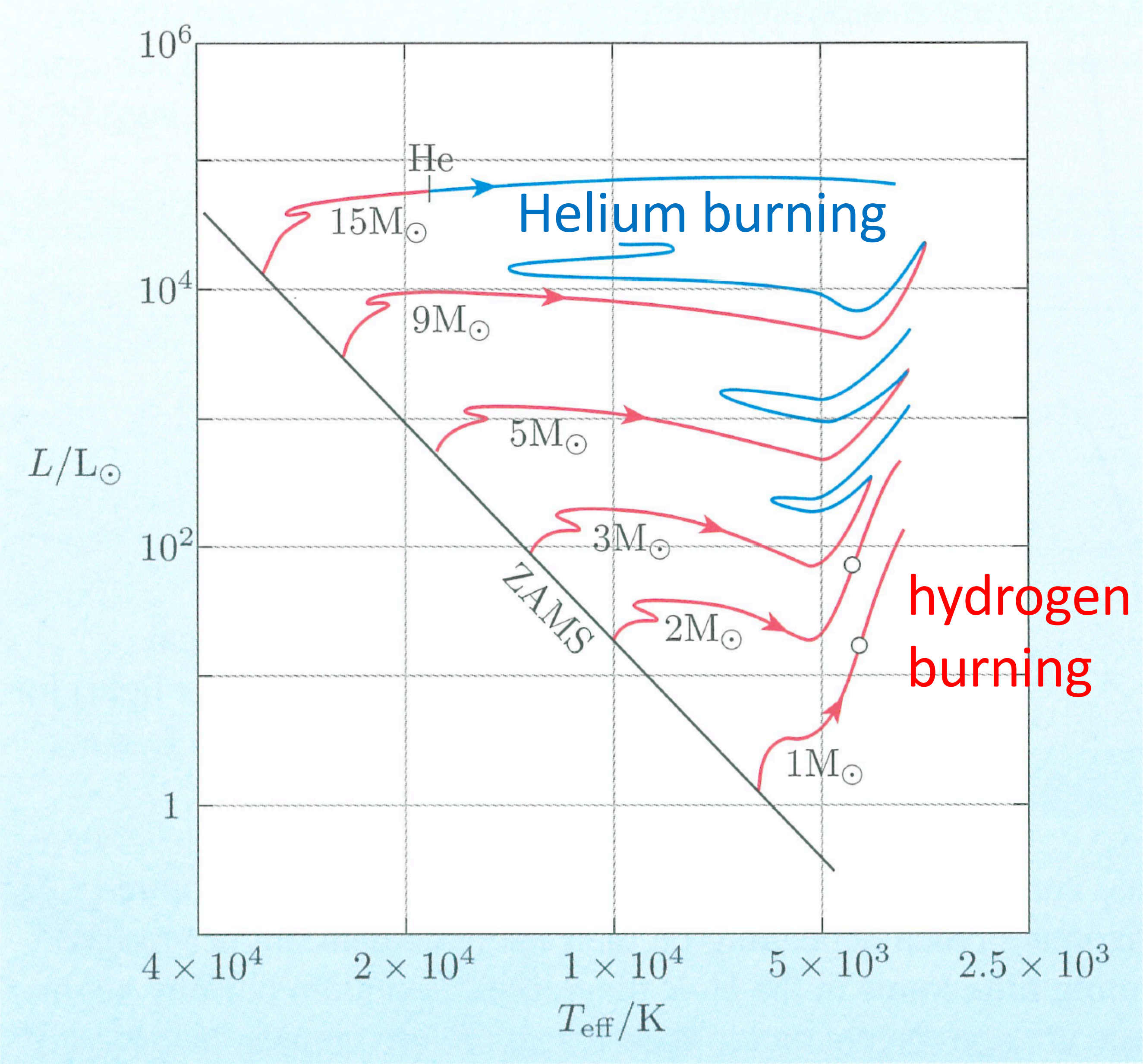
Evolution seen in H-R diagram

www.spacetelescope.org

Stellar life and fate

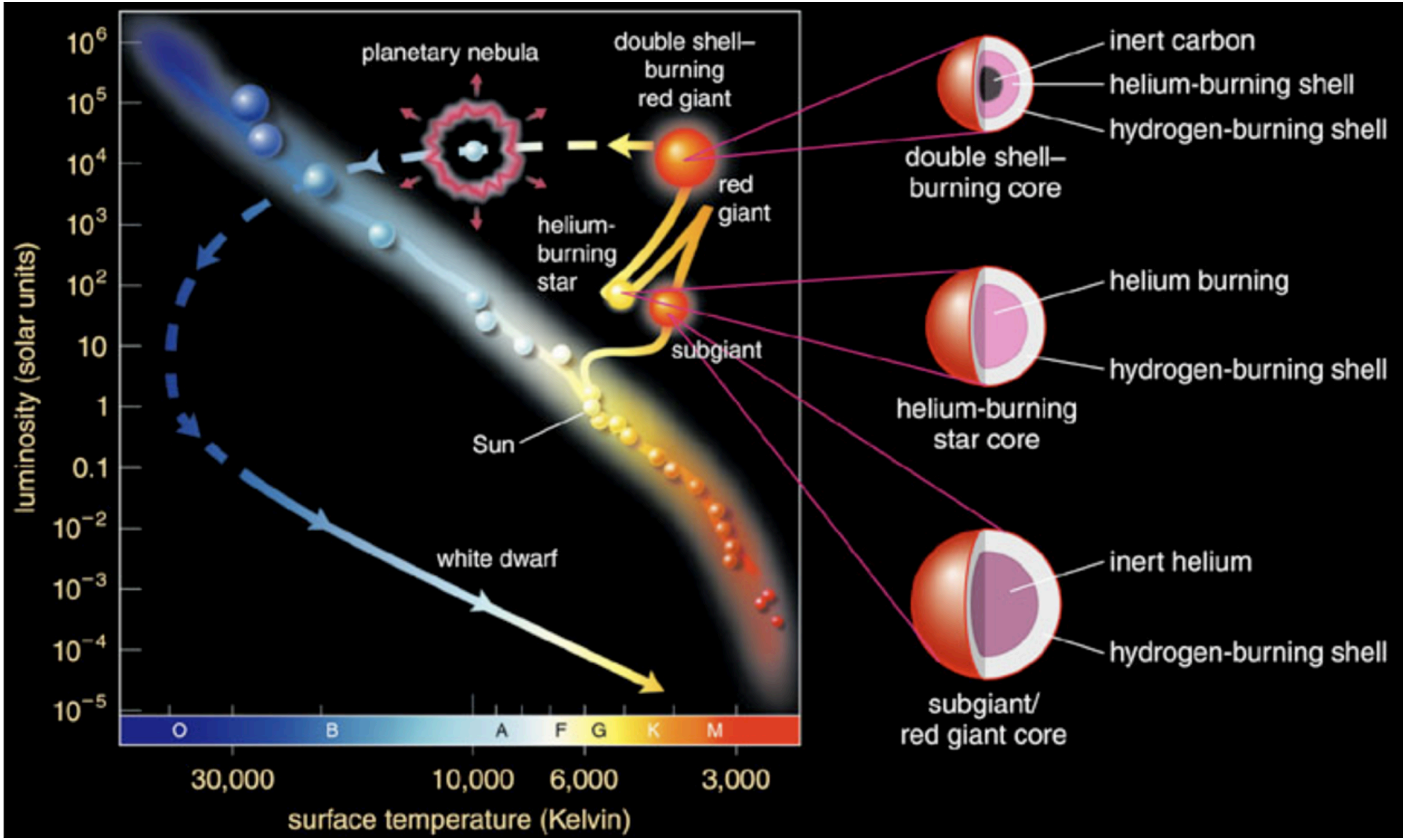


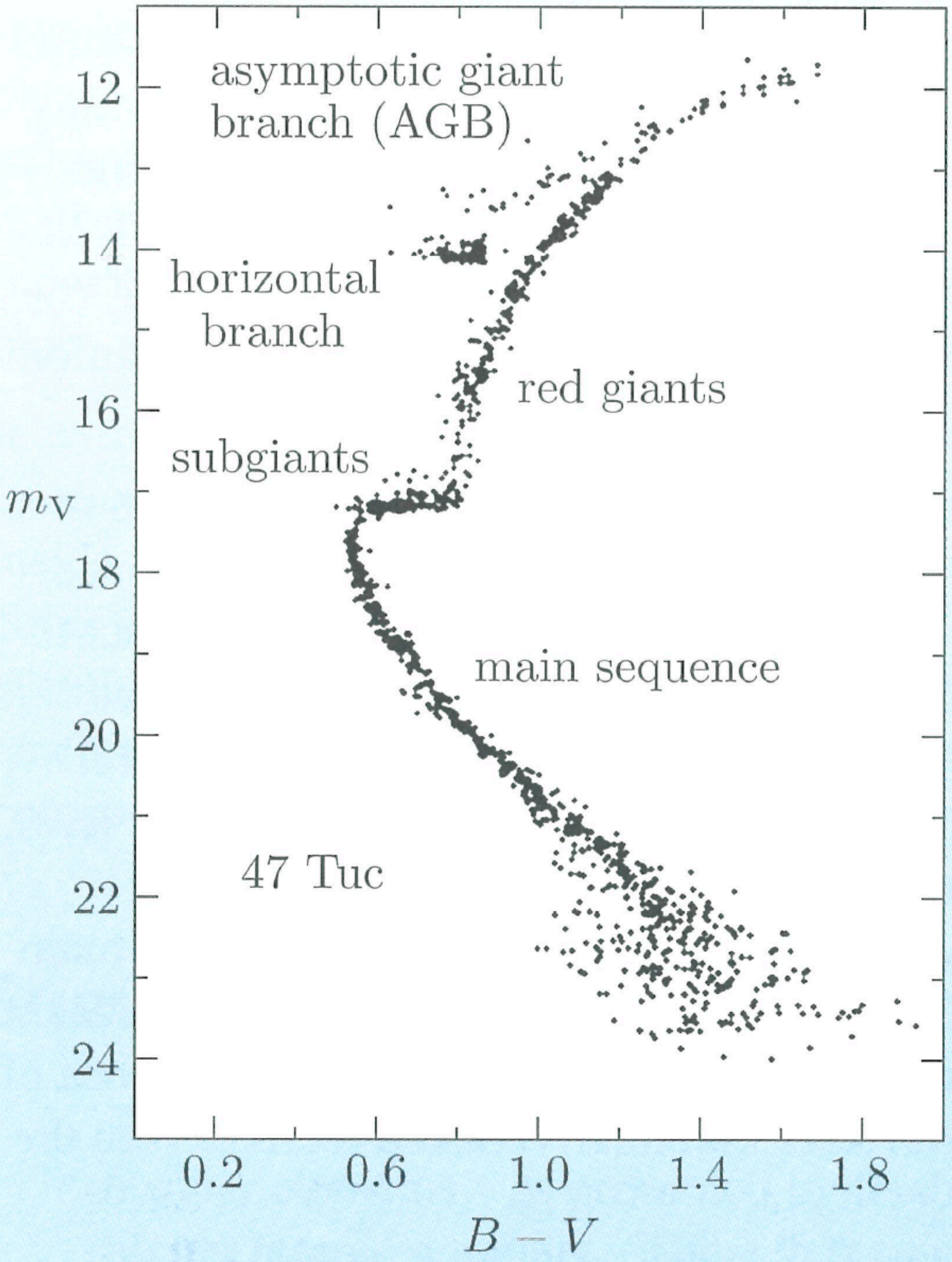
Post-MS evolution



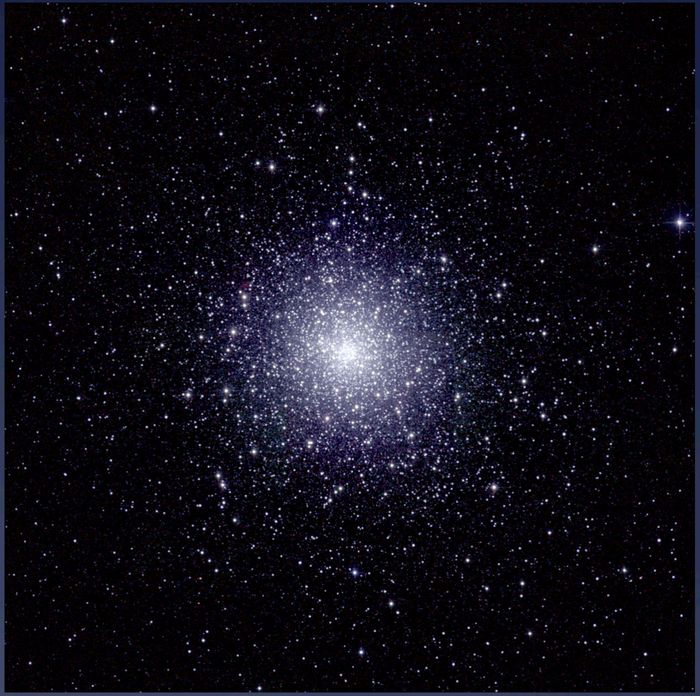
From textbook 1

Evolution of a 1 M_{sun} star

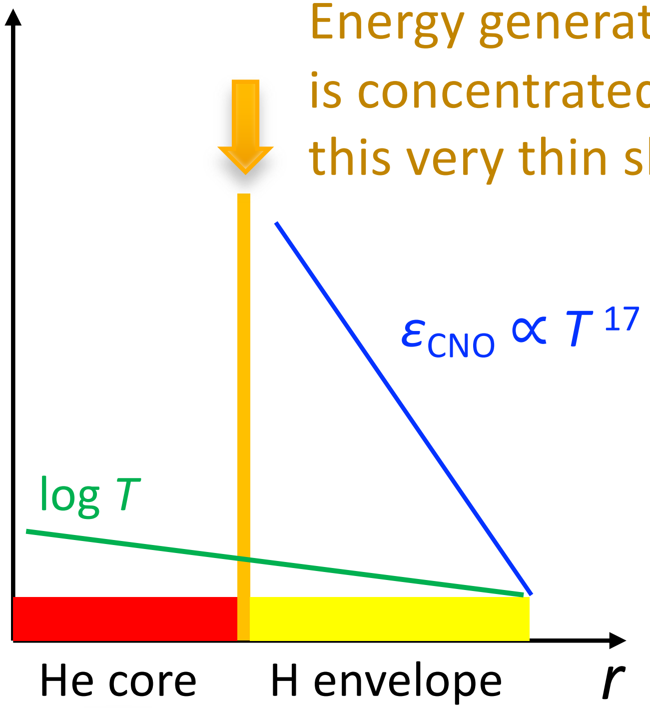


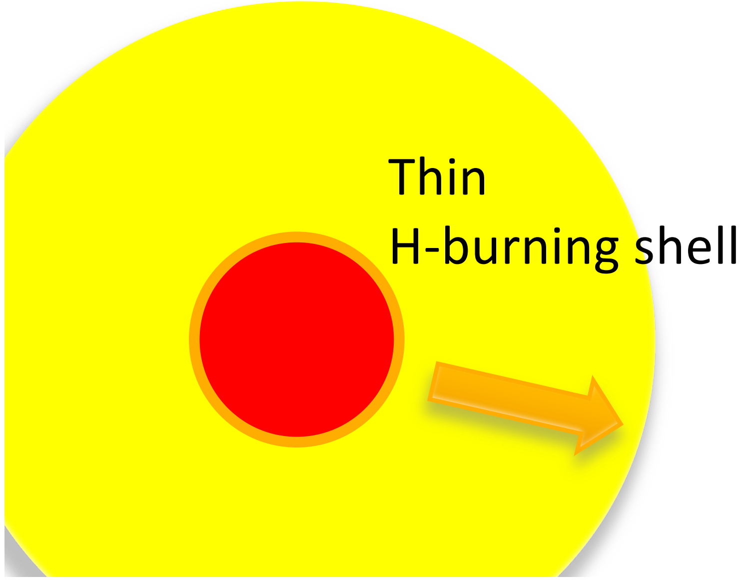


H-R diagram for the member stars in 47 Tuc



Shell-burning and subgiant transition


Energy generation is concentrated in this very thin shell

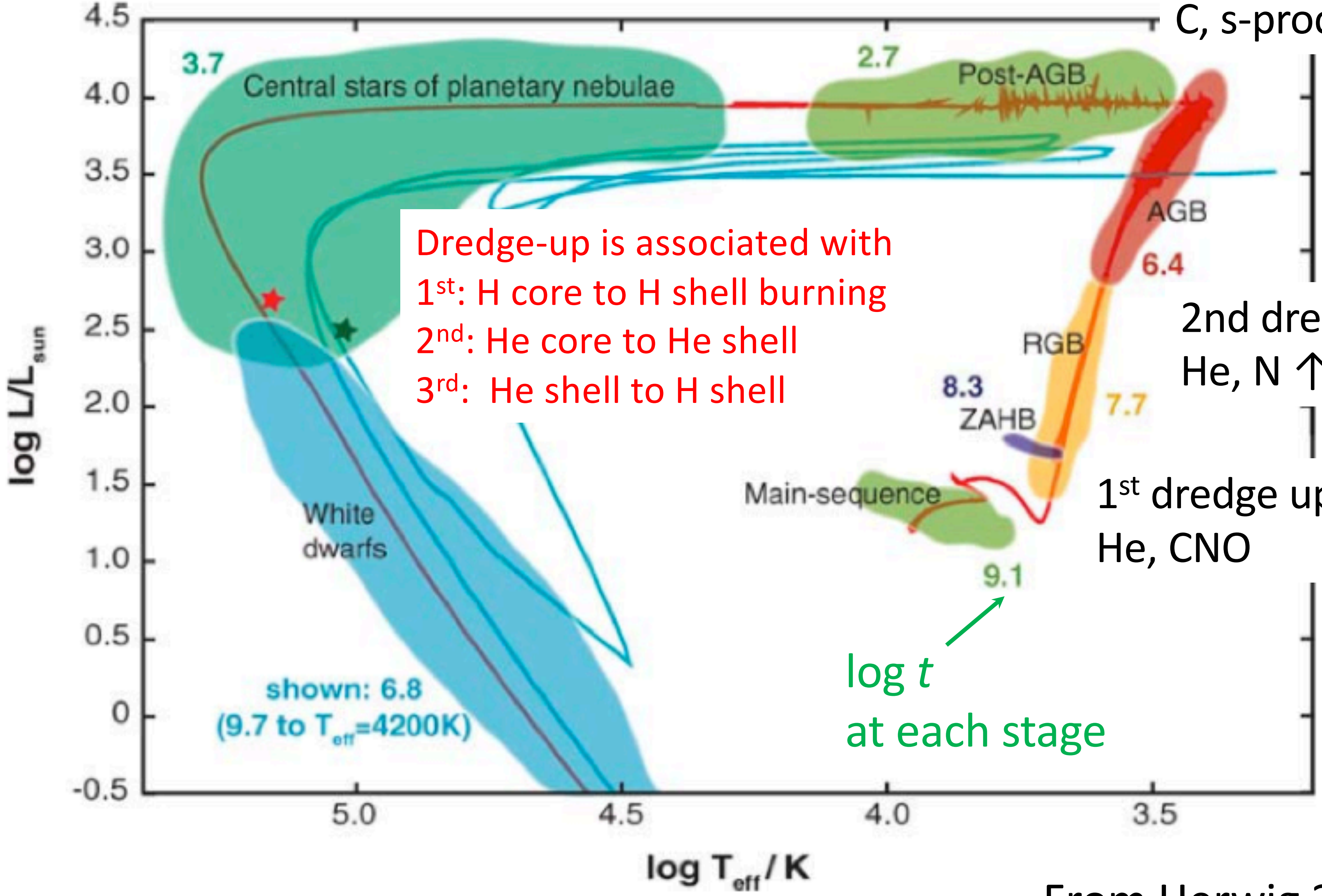


“The core shrinks, and the envelope expands”

This is easy to phrase, but a number of physical processes are involved. Then it is not possible to explain the phenomena in simple terms. But the essence is:

1) After hydrogen exhaustion, the core with inert helium contracts.
2) Hydrogen burning (largely by CNO cycle) occurs within a very thin, hot shell. (Hence called shell-burning)
3) Having a hot core and a burning shell inside, the outer envelop begins expanding.

Evolution of a 2Msun star



Dredge-up is associated with
1st: H core to H shell burning
2nd: He core to He shell
3rd: He shell to H shell

3ed dredge up
C, s-process ↑

2nd dredge up
He, N ↑

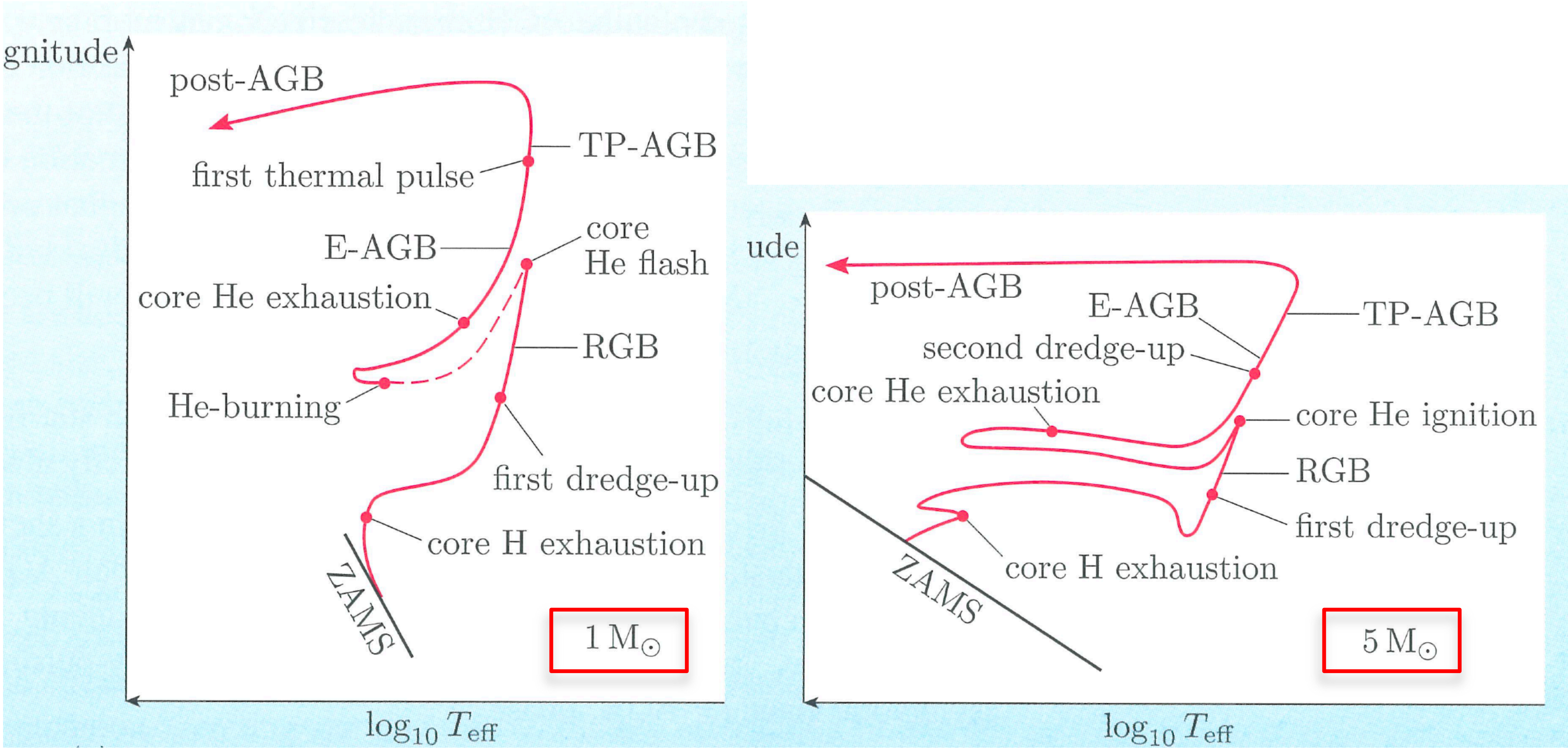
1st dredge up
He, CNO

log *t*
at each stage

From Herwig 2005

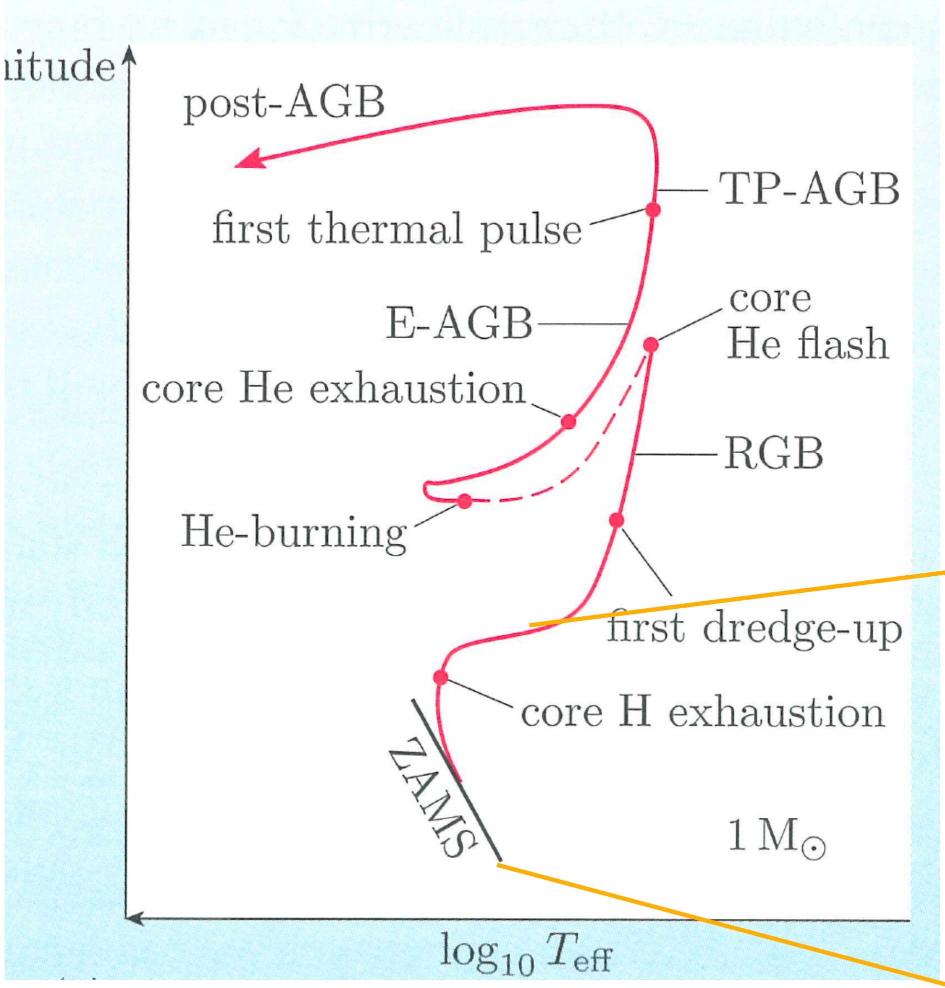
Low-mass/intermediate mass stars

From textbook1

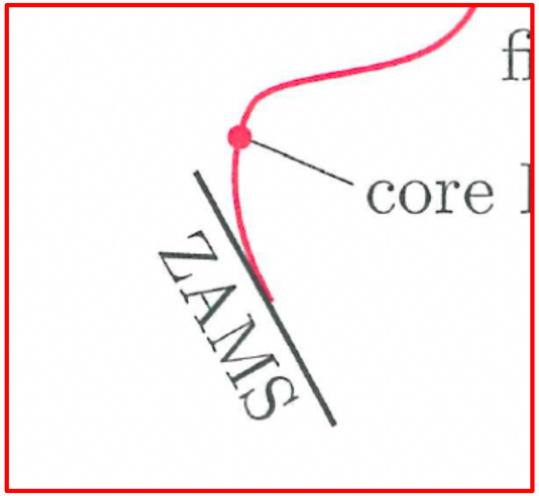


The post-main sequence evolution looks similar overall, but distinction is made at around 1 M_{sun} and around 3 $M_{sun.}$ The latter is the Schoenberg-Chandrasekhar limit, which actually refers to if the helium core mass is larger than 10% of the star.

Low-mass star (like the sun)



Hydrogen burning during MS is by (inefficient) pp-chain. Convection does not occur in the core, and no mixing of burned ash (helium) and fresh hydrogen. This means, when the very central part exhausts hydrogen, there’s still fuel near the center. This causes the transition from core H-burning to shell-burning smoothly. There’s no contraction (blueward) phase here.



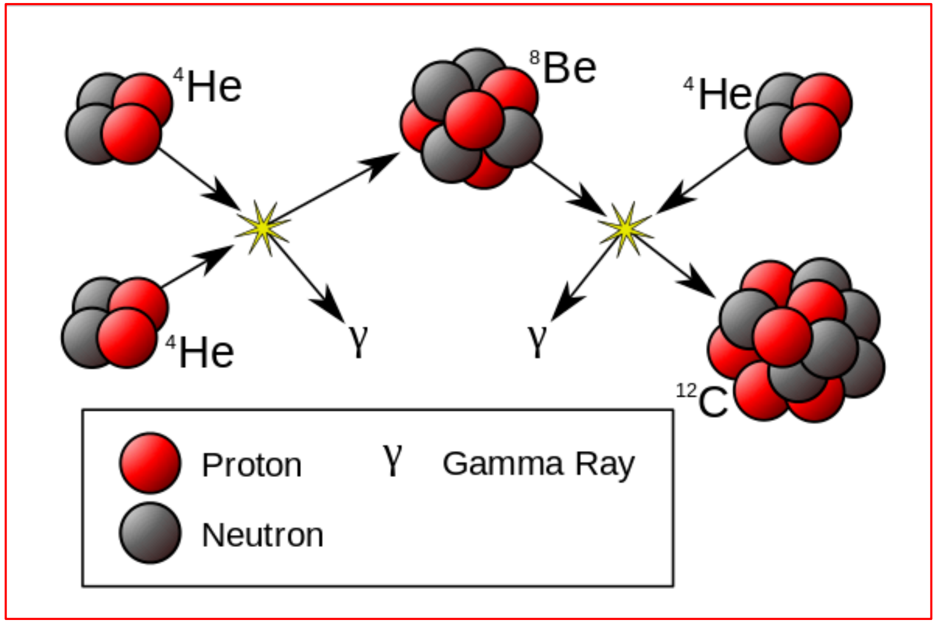
Helium burning

The triple alpha process: He + He + He → C

Step1: $^{4}He + ^{4}He \rightarrow\ ^{8}Be$

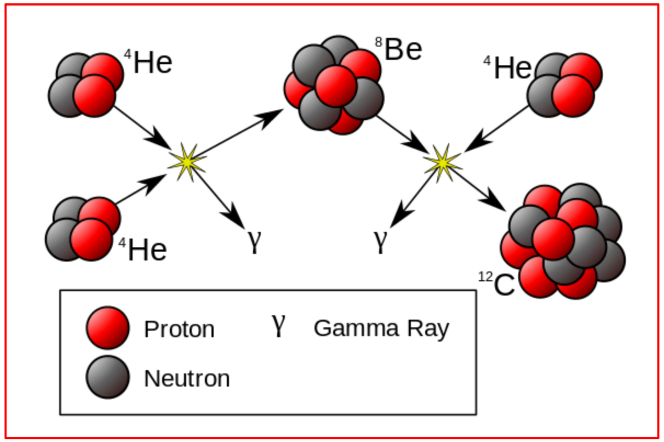
Step2: $^{4}He + ^{8}Be \rightarrow\ ^{12}C^{*}$

Step3: $^{12}C^{*} \rightarrow\ ^{12}C + 2\gamma$



This is a three-body reaction, but is essentially a sequence of two-body reactions. The point (and the difficulty) is that the intermediate product ^{8}Be is unstable. Step 2 must proceed before ^{8}Be radio-actively decays.

Triple-α process



The beryllium-8 nuclei are unstable
(The mass of a ^{8}Be is actually slightly larger than the mass of two 4 He nuclei.)
with lifetime of about 10^{-16} second. So, another ^{4}He nucleus must hit within the extremely brief time, to proceed

Step2: $^4\mathrm{He} + {}^8\mathrm{Be} \rightarrow {}^{12}\mathrm{C}^*$

You can easily imagine this is why the 3-α process occur only in very dense, hot stellar core with $T \sim 10^8$ K and $\rho > 10^5$ kg/m^3.

Furthermore, the step 2 reaction requires a very particular condition: there must be an excited state of $^{12}\mathrm{C}^*$

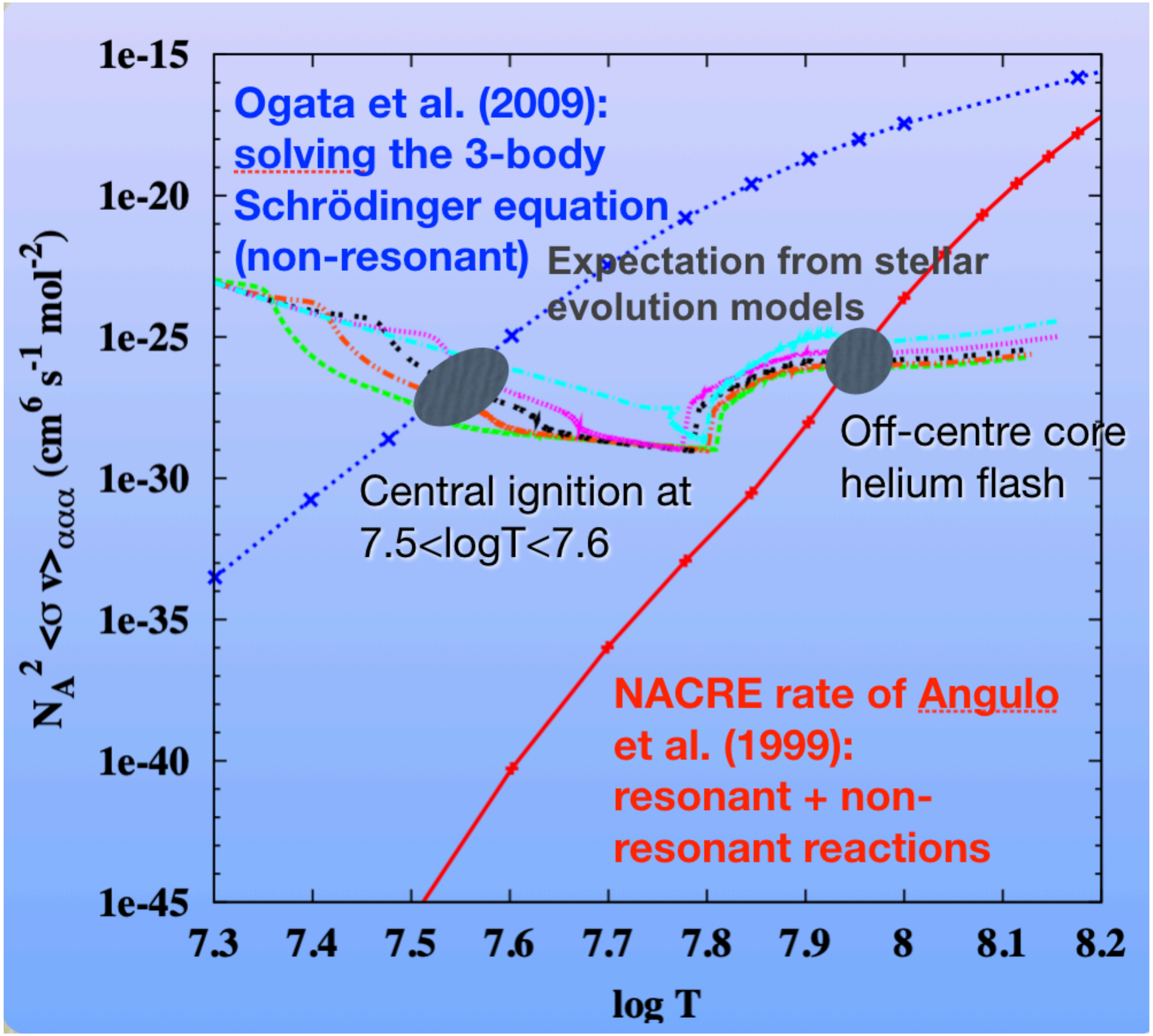
Sir Fred Hoyle

Step2: $^{4}He + {}^{8}Be \rightarrow {}^{12}C^{*}$

The existence of this resonance was predicted by Fred Hoyle before its actual observation, based on the physical necessity for it to exist, in order for carbon to be formed in stars.

“The numbers one calculates from the facts seem to me so overwhelming as to put this conclusion almost beyond question."

Triple-α reaction rate



NACRE: Nuclear Astrophysics Compilation of REaction rates

Let us have a break here

For the triple-α process to occur, the gas must be very hot (> 10^8 K) and dense ($\rho \sim 10^6$ kg/m^3).

Stellar interior is a good place for it, but we also know that the early universe, right after the Big Bang, may be another hot and dense place. HOWEVER, carbon was not produced during Big Bang Nucleosynthesis. Why ?

This is a very interesting question, and the answer really gives you joy of physics in the early universe.

Deuterium bottleneck

A critical step for synthesizing heavy elements is the very first one – deuteron formation.

$p + n \rightarrow d + \gamma$

This reaction occurs rightward if there is no radiation. Under a radiation background (cosmic radiation), the reaction should actually be

$p + n \leftrightarrows d + \gamma$

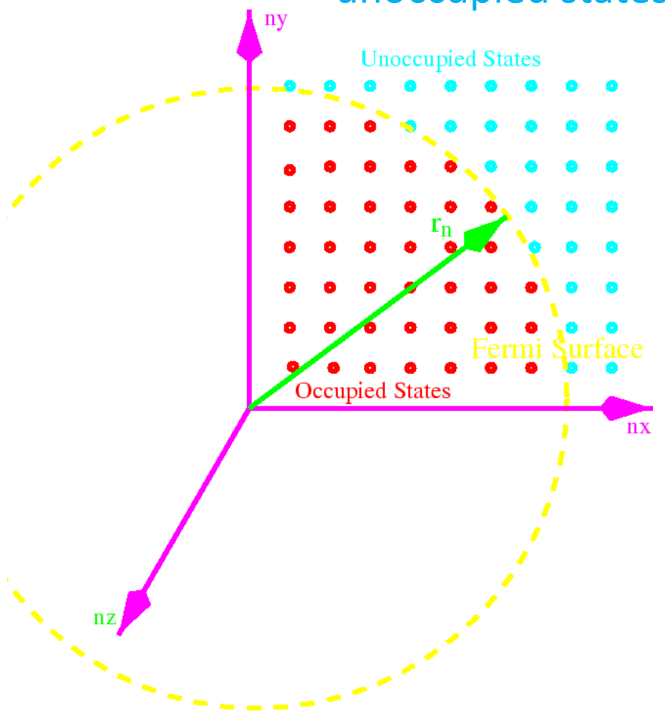
The binding energy of a deuteron is about 2.2 MeV. This means that the leftward reaction (photo-dissociation) is effective until the background radiation temperature falls *very low*.

(Think about why need to wait till $T \sim 0.1$ MeV in the early universe.)

Fermi energy

Cold electrons occupy all the possible low-energy states up to Fermi energy, p_{F}. The energy distribution is rather different from what we expect for ordinary matter/gas.

unoccupied states



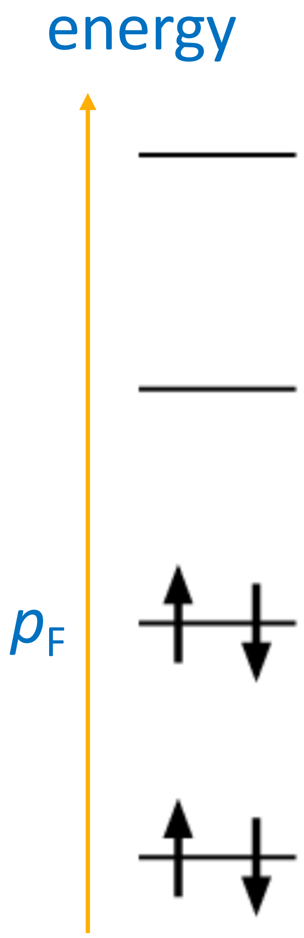
Since the momentum space is in 3D, the number of available states is

$$N = \int_0^{p_{\mathrm{F}}} g \frac{V}{h^3} 4\pi p^2 \mathrm{d}p = \frac{8\pi V}{3h^3} p_{\mathrm{F}}^3$$

where g accounts for two spin states. It can be aslo written

$$p_{\mathrm{F}} = \left(\frac{3n}{8\pi}\right)^{1/3} h$$

Cold degenerated gas



The energy of individual electron is given by $\varepsilon = mc^2 + p^2/2m$, the internal energy of the gas is

$$E = \int_0^{p_F} g\epsilon \frac{V}{h^3} 4\pi p^2 \mathrm{d}p = N\left[mc^2 + \frac{3p_F^2}{10m}\right]$$

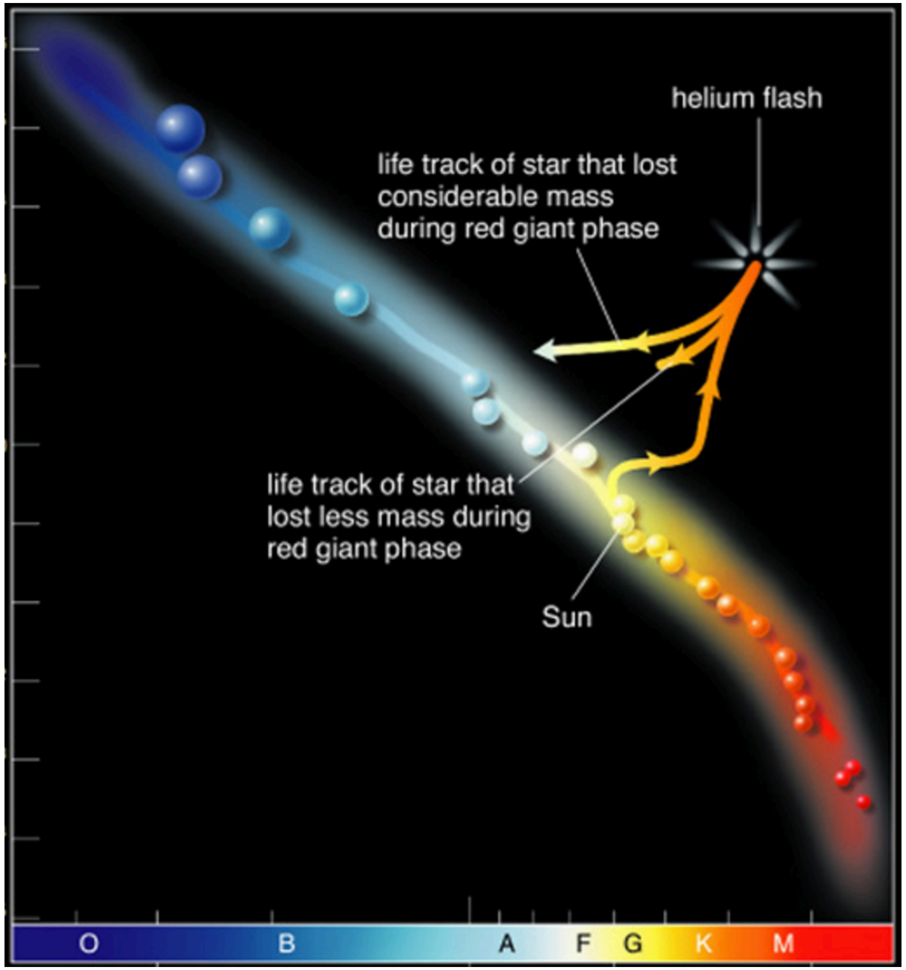
Recall that the pressure of a non-relativistic gas is two-thirds of the kinetic energy density. Hence we have

$$P = n\frac{p_F^2}{5m} = \frac{h^2}{5m}\left(\frac{3}{8\pi}\right)^{2/3} n^{5/3}$$

For "hot" (relativistic) electrons, $\varepsilon \sim pc$, the above quantities are given by

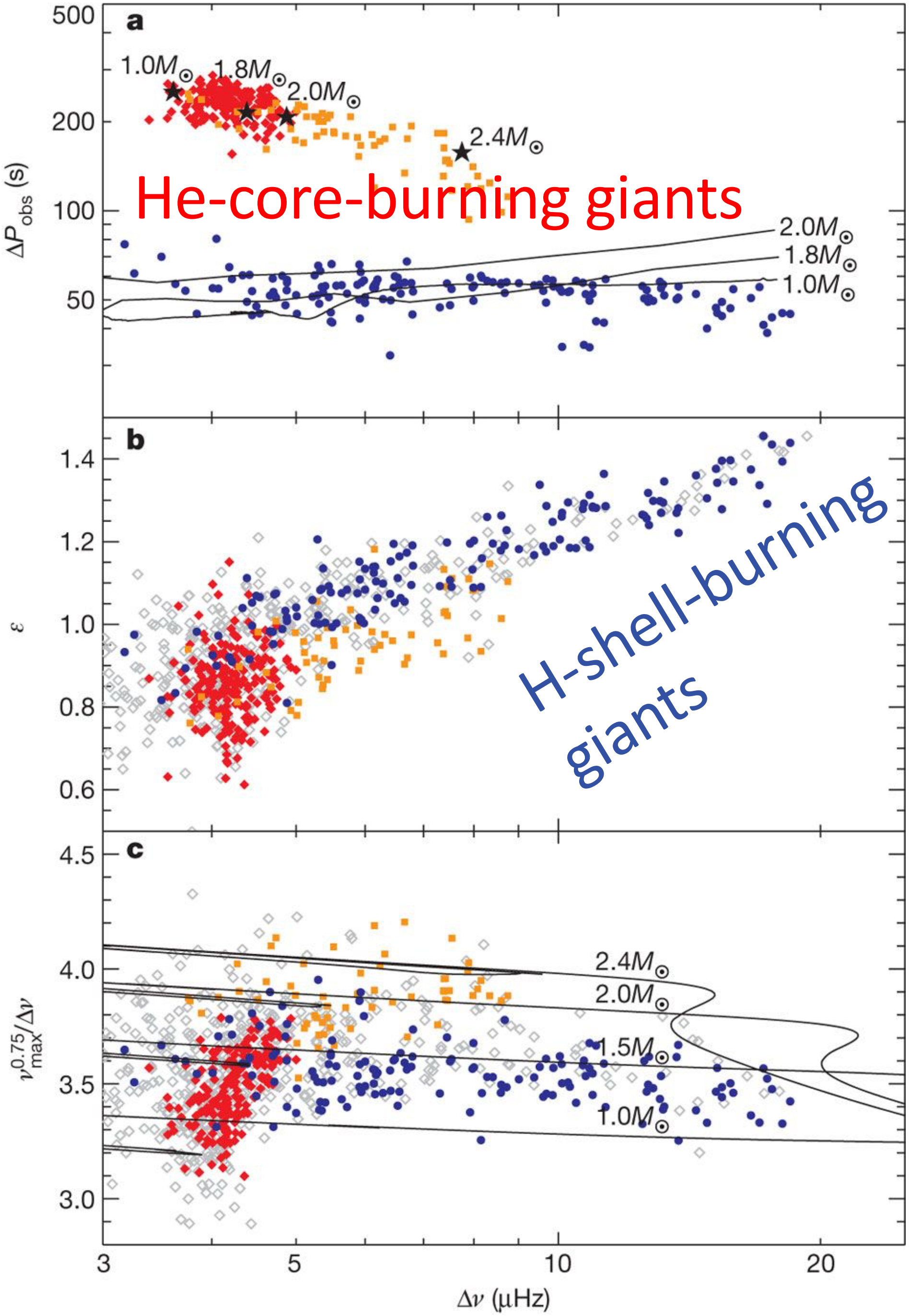
$$E = \frac{4\pi g\, cV}{h^3}\frac{p_F^4}{4} \qquad P = \frac{hc}{4}\left(\frac{3}{8\pi}\right)^{1/3} n^{4/3}$$

Helium flash

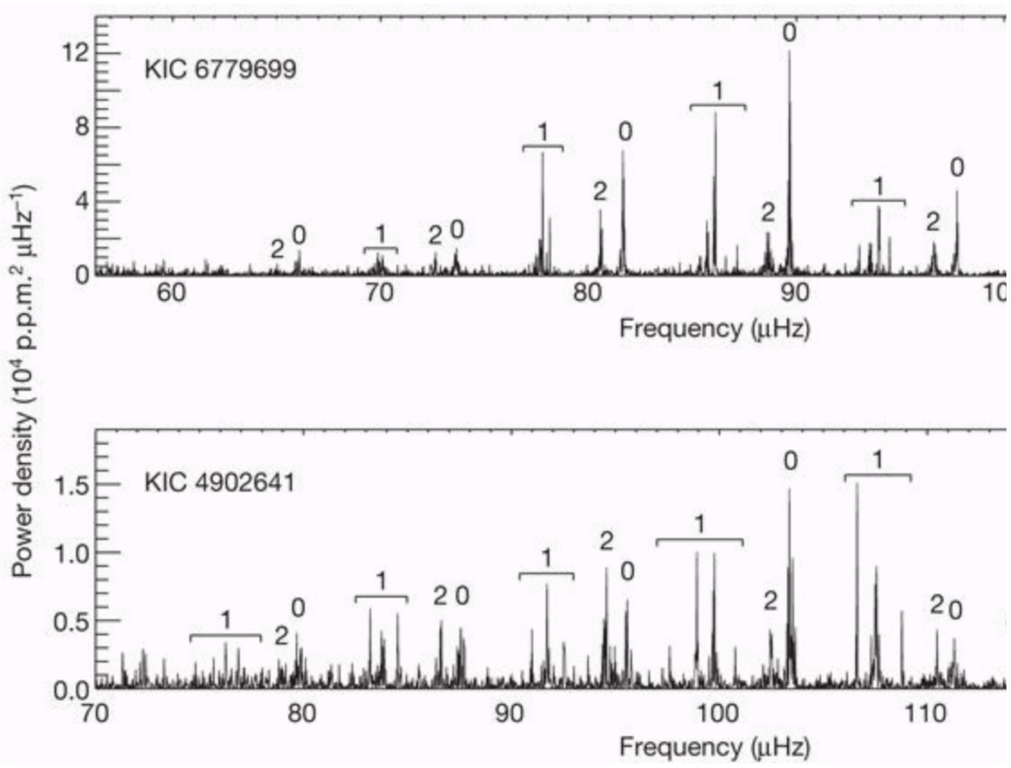


When helium burning begins, it releases huge energy in the stellar core. If the core were a classical gas, the enormous heating just causes the core to expand. However, in a degenerated electron gas, the pressure does not depend on the temperature. Increasing the internal energy by helium burning increases the fusion rate further. This operates in a violent manner. The run-away process is called helium flash, and produces ～ 1 million times luminosity (for a brief moment) than H-burning.

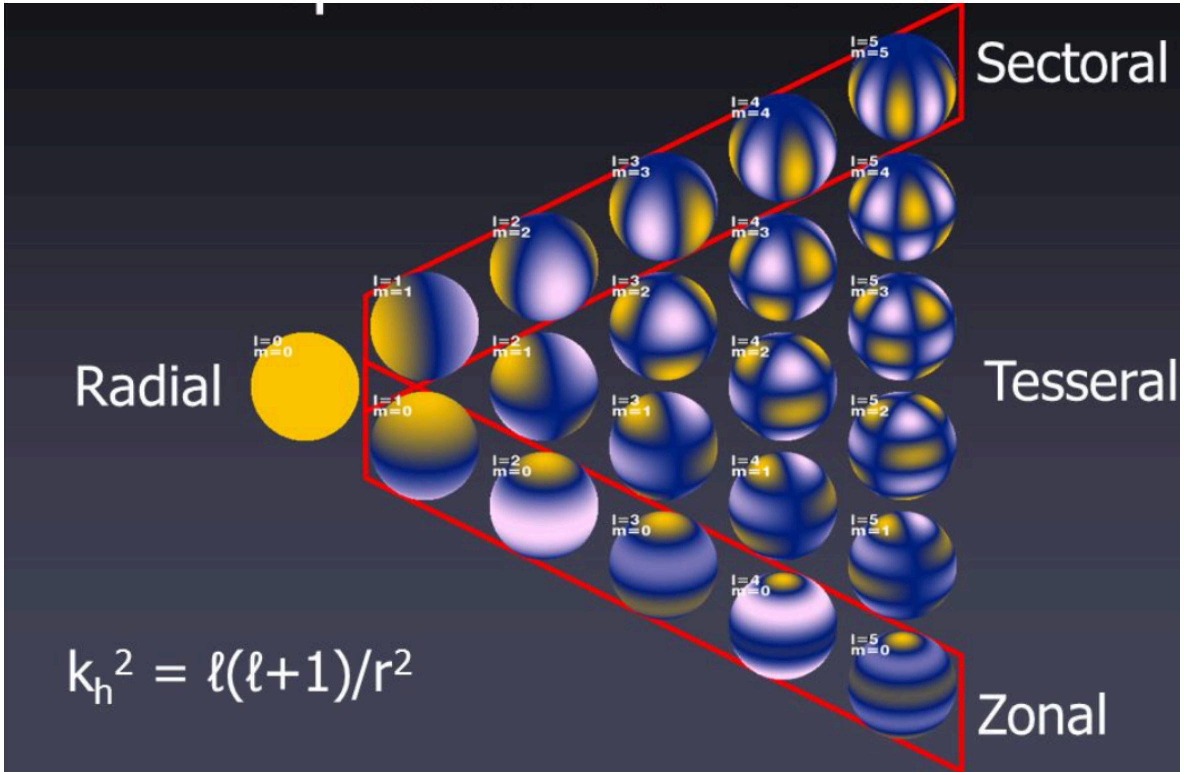
Seismology as a probe of stellar interior

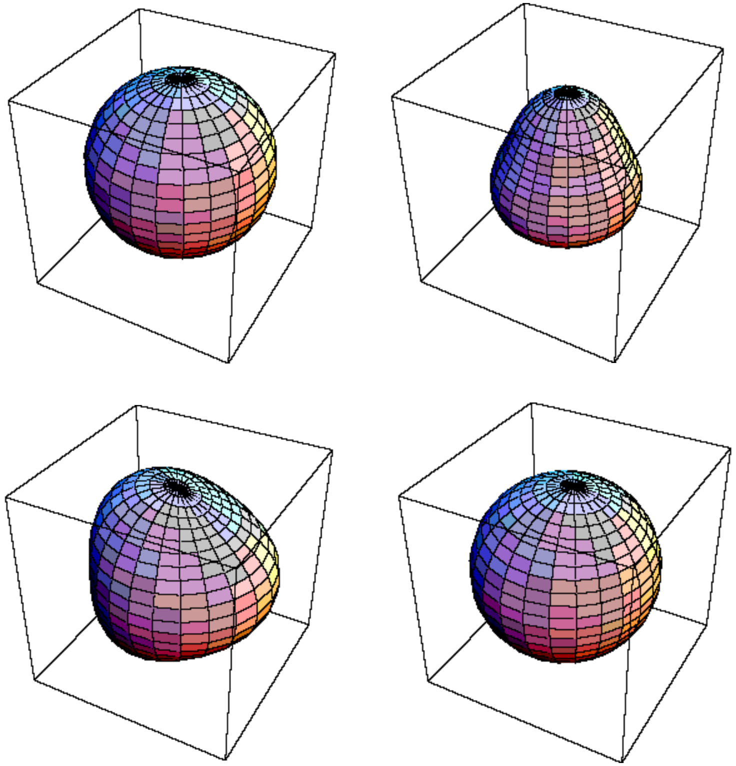

He-core-burning giants

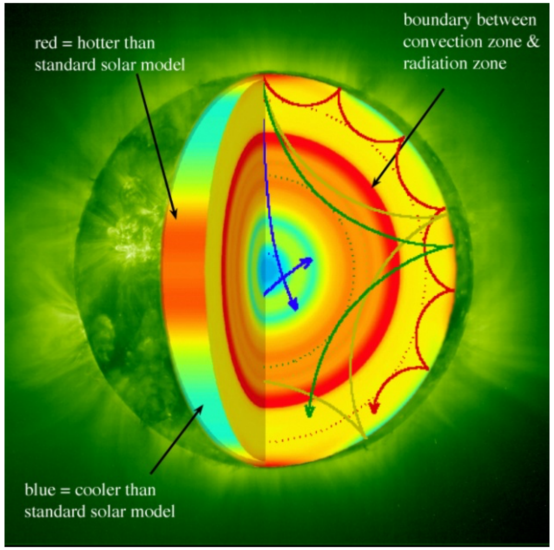
H-shell-burning giants

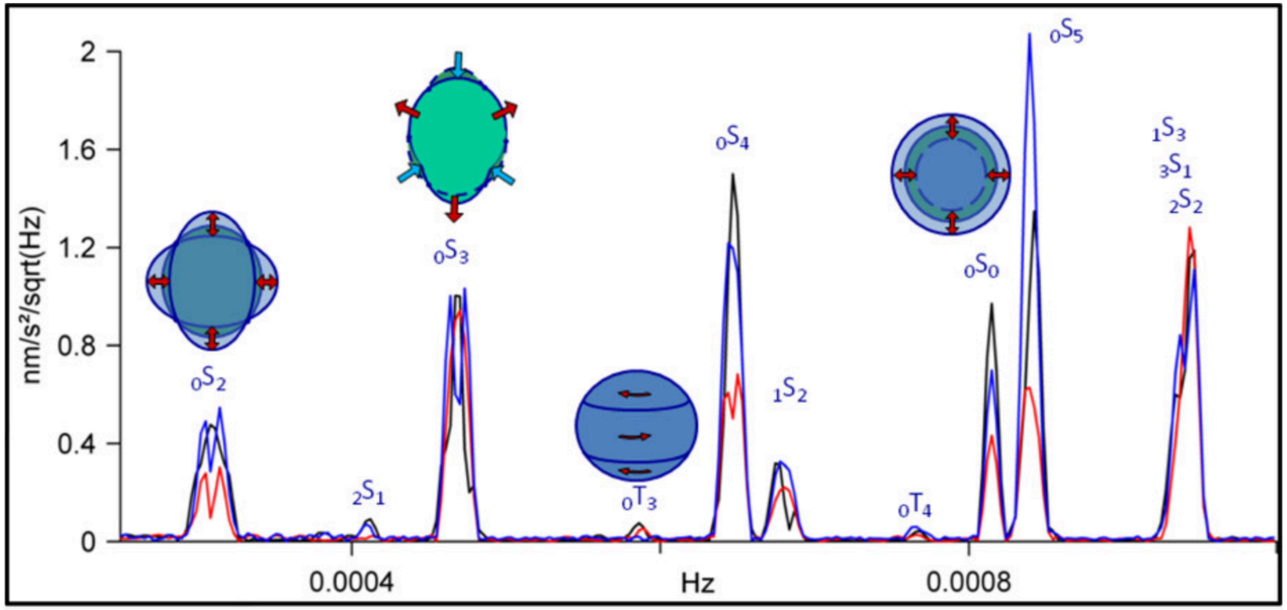


An extremely brief (and sure inefficient) introduction to seismology

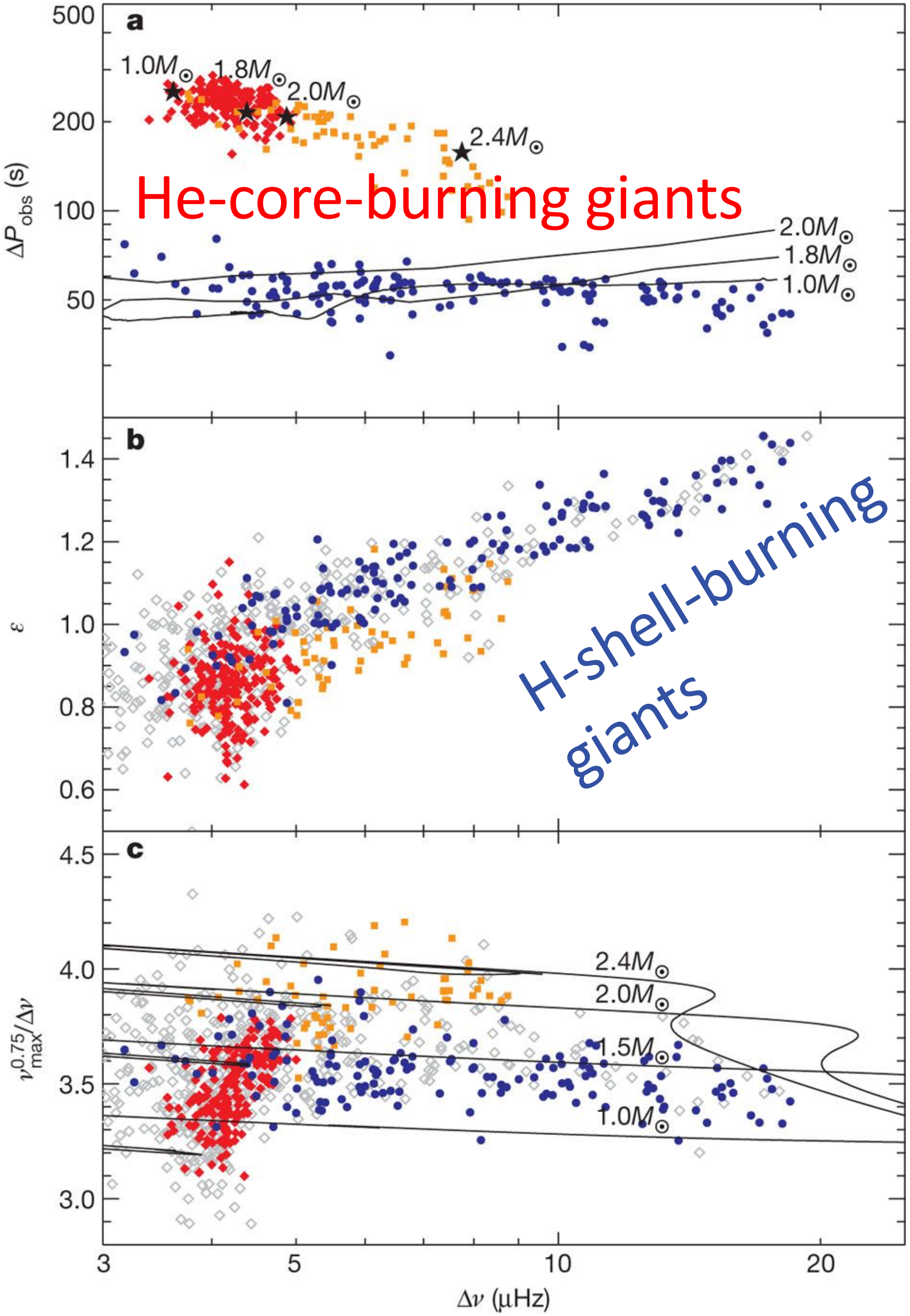








Seismology as a probe of stellar interior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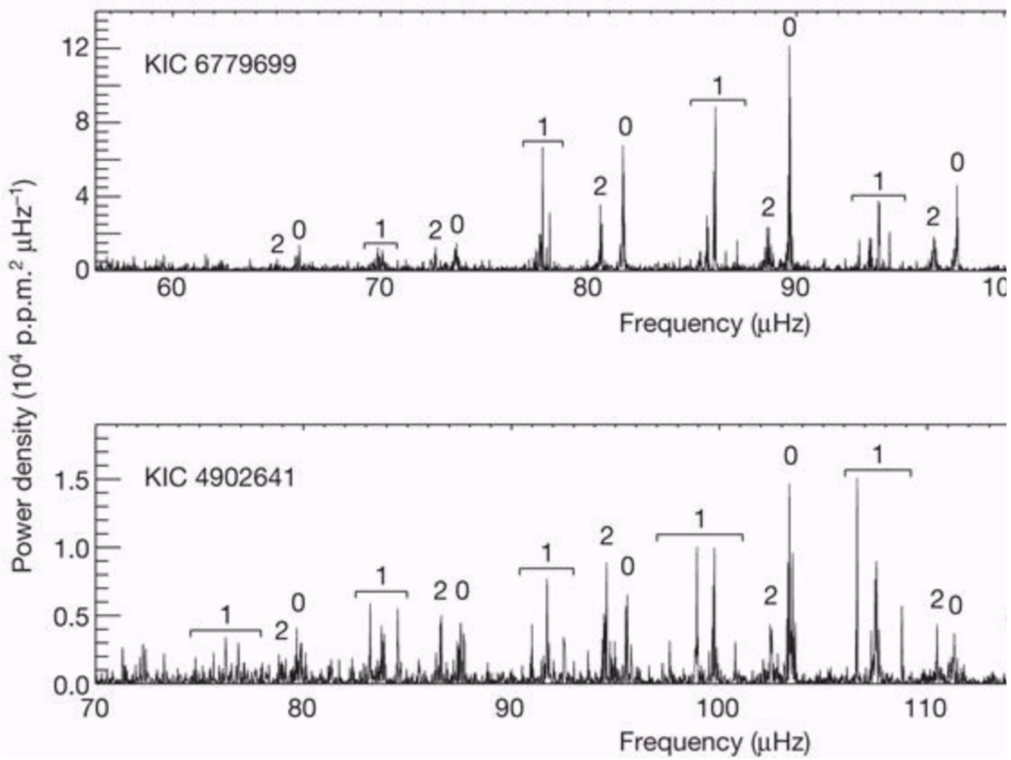
H-shell-burning giants



White dwarf populations

White dwarfs are known with estimated masses as low as 0.17 *M*sun and as high as 1.33 *M*sun, and the mass distribution is strongly peaked at 0.6 *M*sun and 0.8 *M*sun. This is probably a consequence of the star-formation history in Galaxy, the initial stellar mass function, and individual star’s evolution.