Stars

Composition
Stellar Evolution

Typical Stellar composition

- Hydrogen mass fraction $X = 0.74$
- Helium mass fraction $Y = 0.25$
- Heavier elements ("metals"): $Z \approx 0.01$

Abundances of H & He set during Big Bang.
Heavier elements made in previous generations of stars.
Z often called "metallicity" and sometimes referenced to the iron abundance, [Fe/H].

Solar abundances (logarithmic)

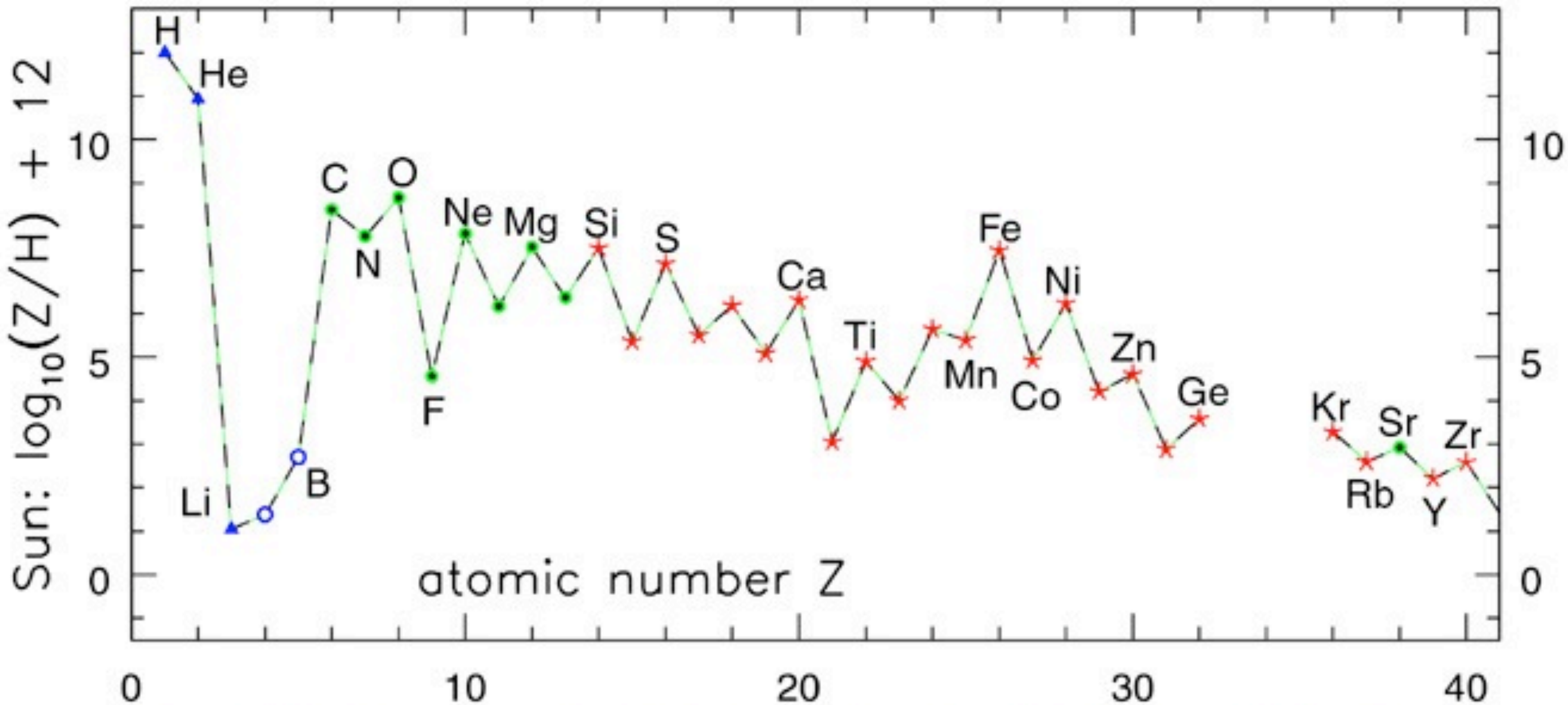
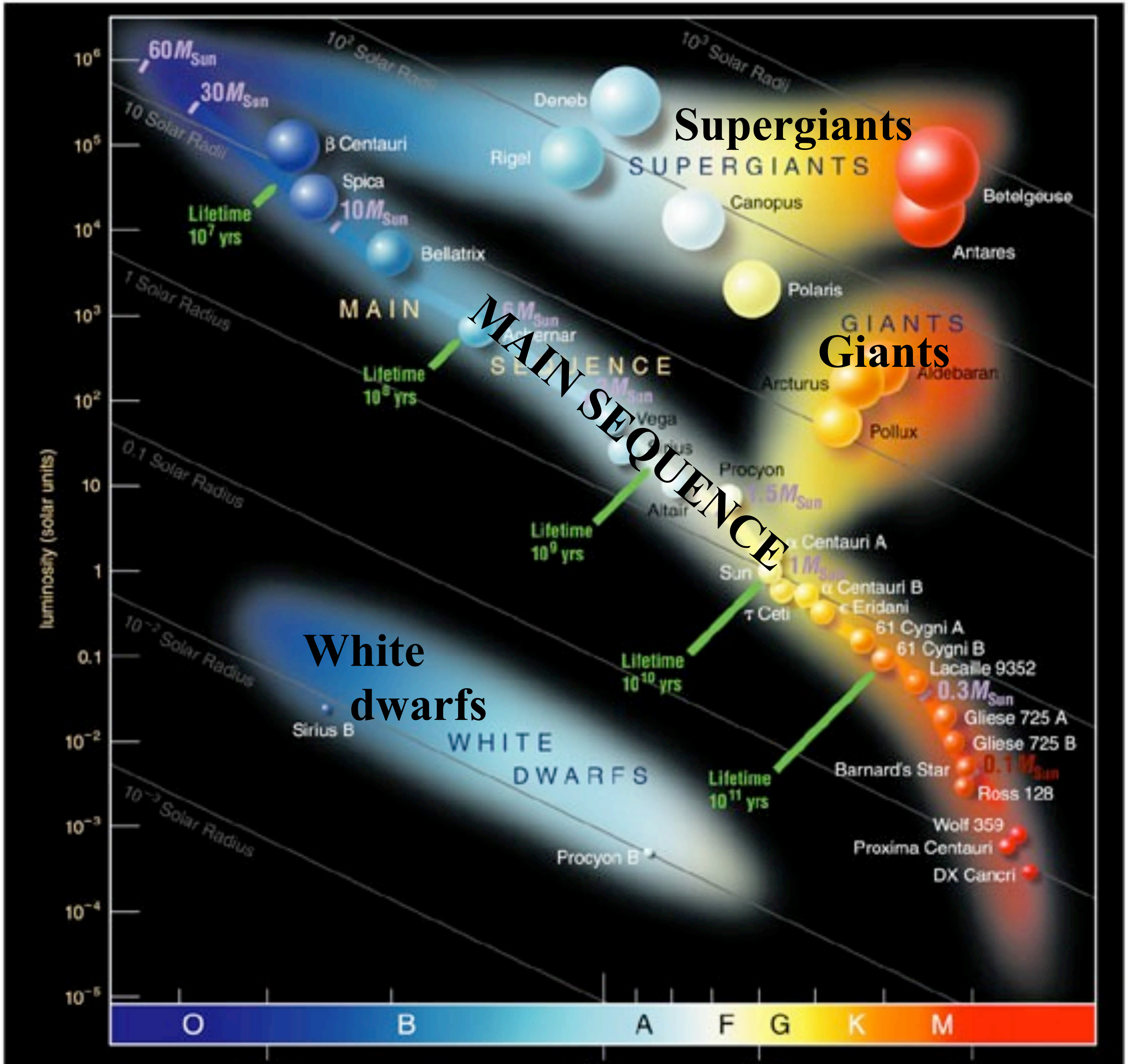


Fig 1.3 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

$$[\mathrm{Fe/H}] = \log \frac{(\mathrm{Fe/H})_\star}{(\mathrm{Fe/H})_\odot}$$

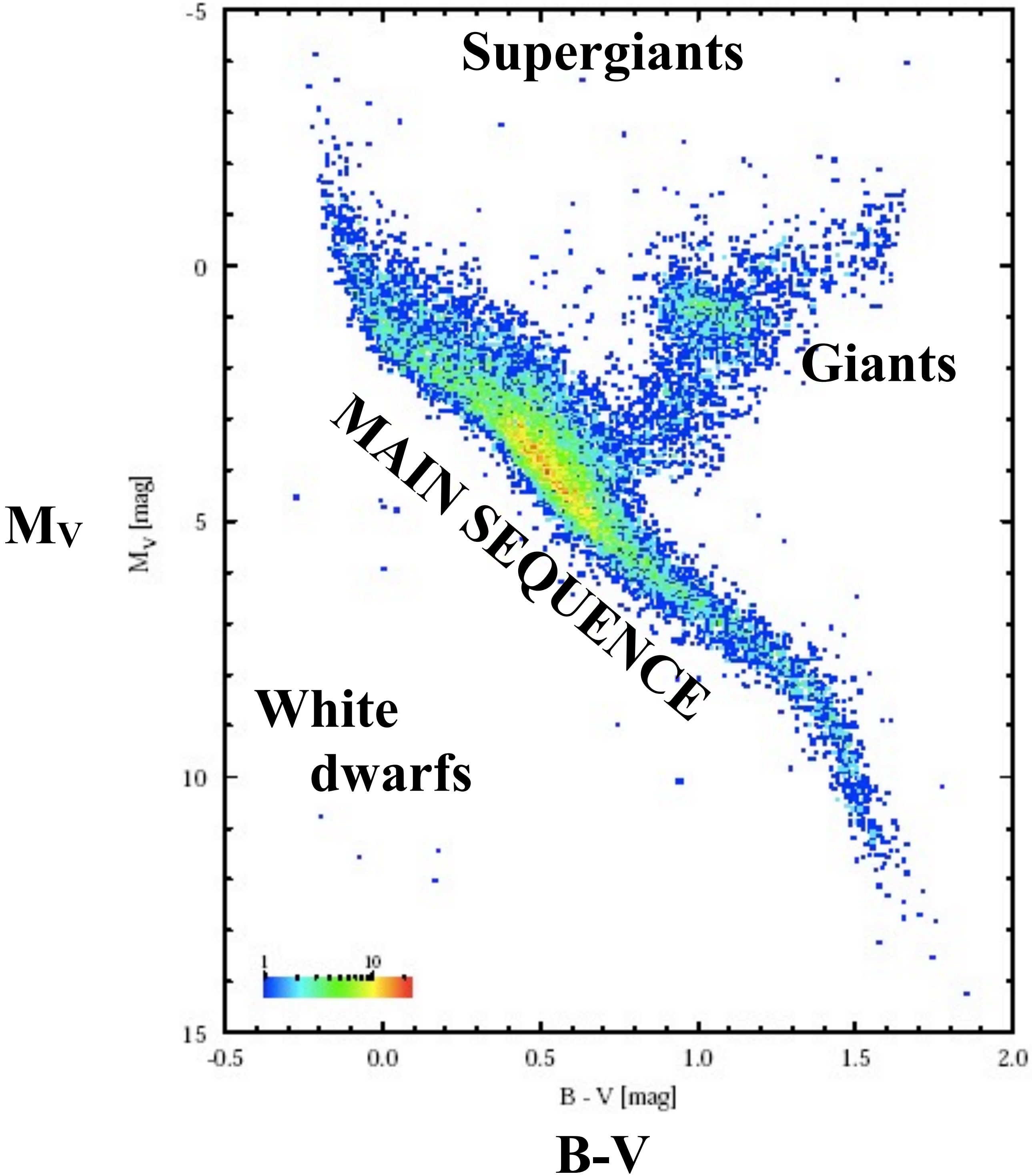
HR diagram

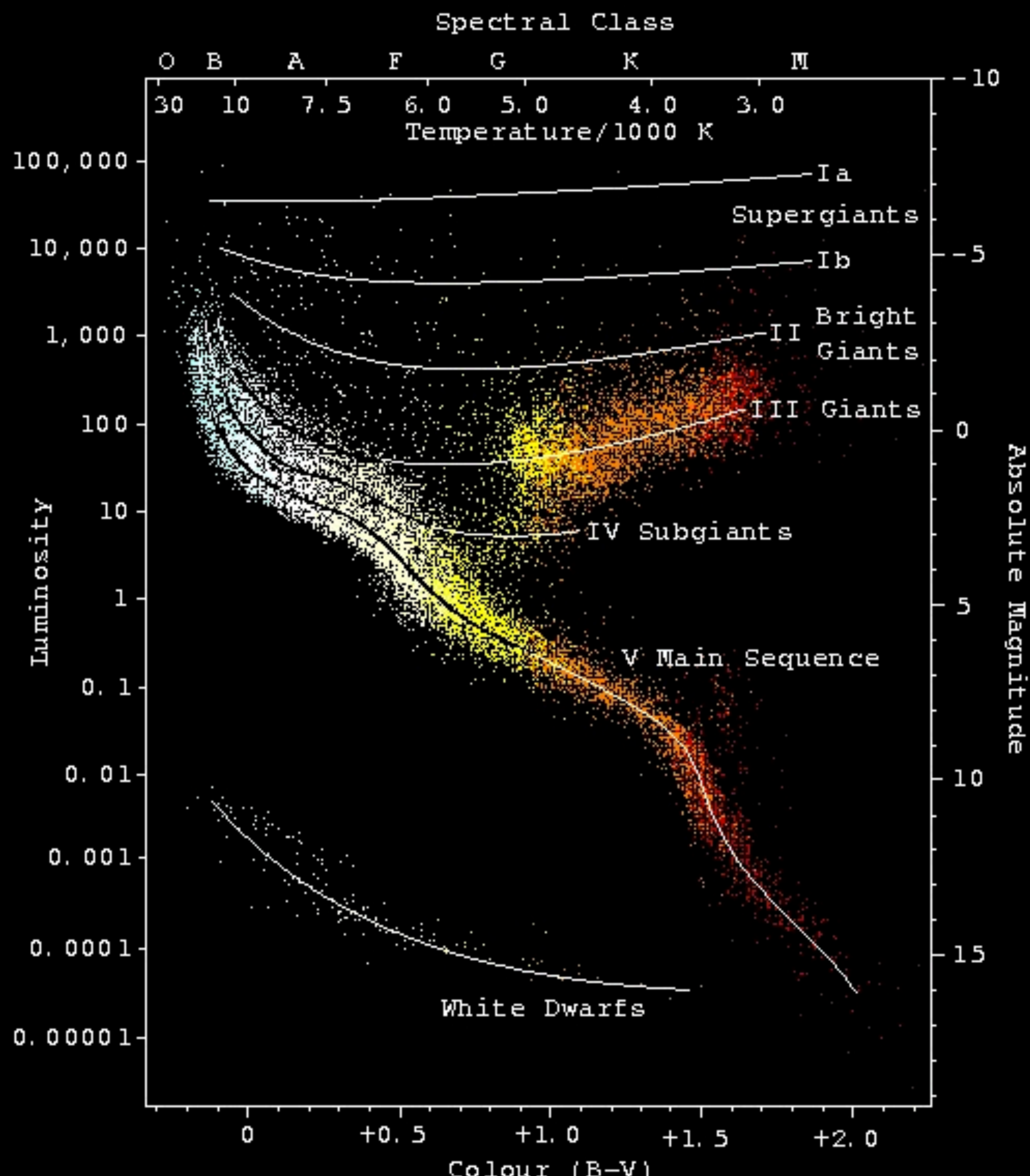
L



T

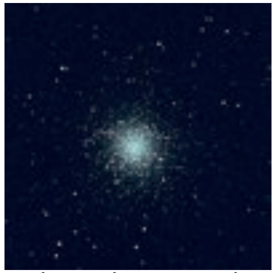
Hipparcos color-magnitude diagram




Spectral Class
O B A F G K M
30 10 7.5 6.0 5.0 4.0 3.0
Temperature/1000 K
Luminosity
100,000
10,000
1,000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
Absolute Magnitude
-10
-5
0
5
10
15
Ia
Supergiants
Ib
II
Bright Giants
III Giants
IV Subgiants
V Main Sequence
White Dwarfs
0
+0.5
+1.0
+1.5
+2.0
Colour (B-V)

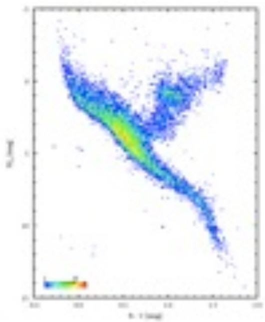
Stellar populations

open cluster



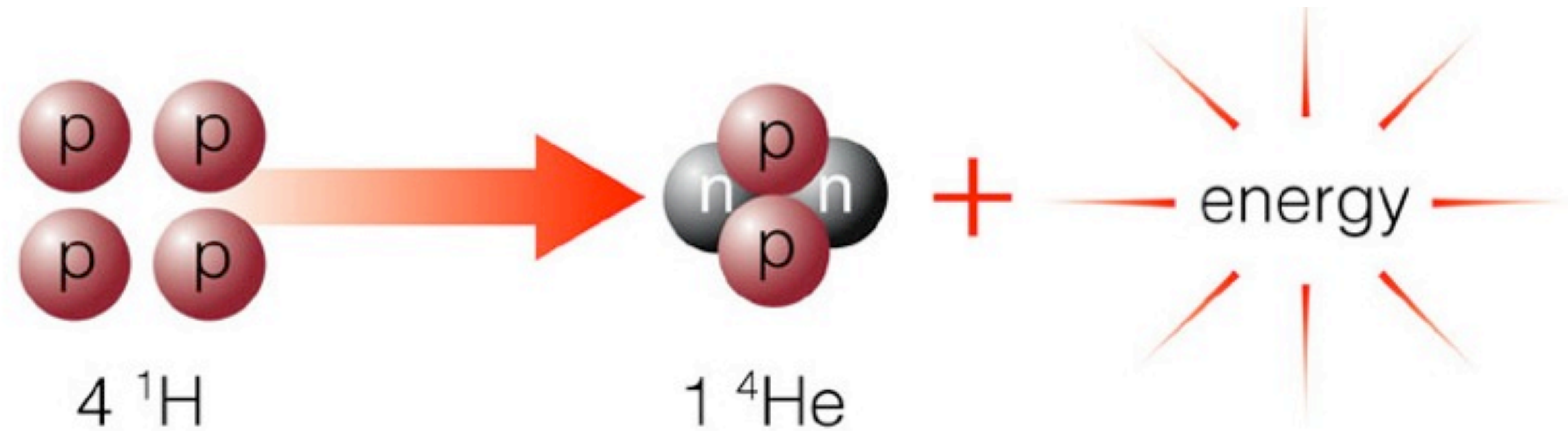
globular cluster

- Simple Single Population (SSP)
  - stars of all masses born at the same time
  - e.g., a star cluster
- Complex stellar population
  - Convolution of many star forming events
  - need to know
    - IMF (initial mass function)
    - Birthrate (star formation rate history)



Cluster distance modulus (overhead)

Nuclear fusion in stars



IN
4 protons

OUT
^{4}He nucleus
2 gamma rays
2 positrons
2 neutrinos

$$E = mc^2 :$$

Total mass is 0.7% lower.

Fusing ^{1}H into ^{4}He

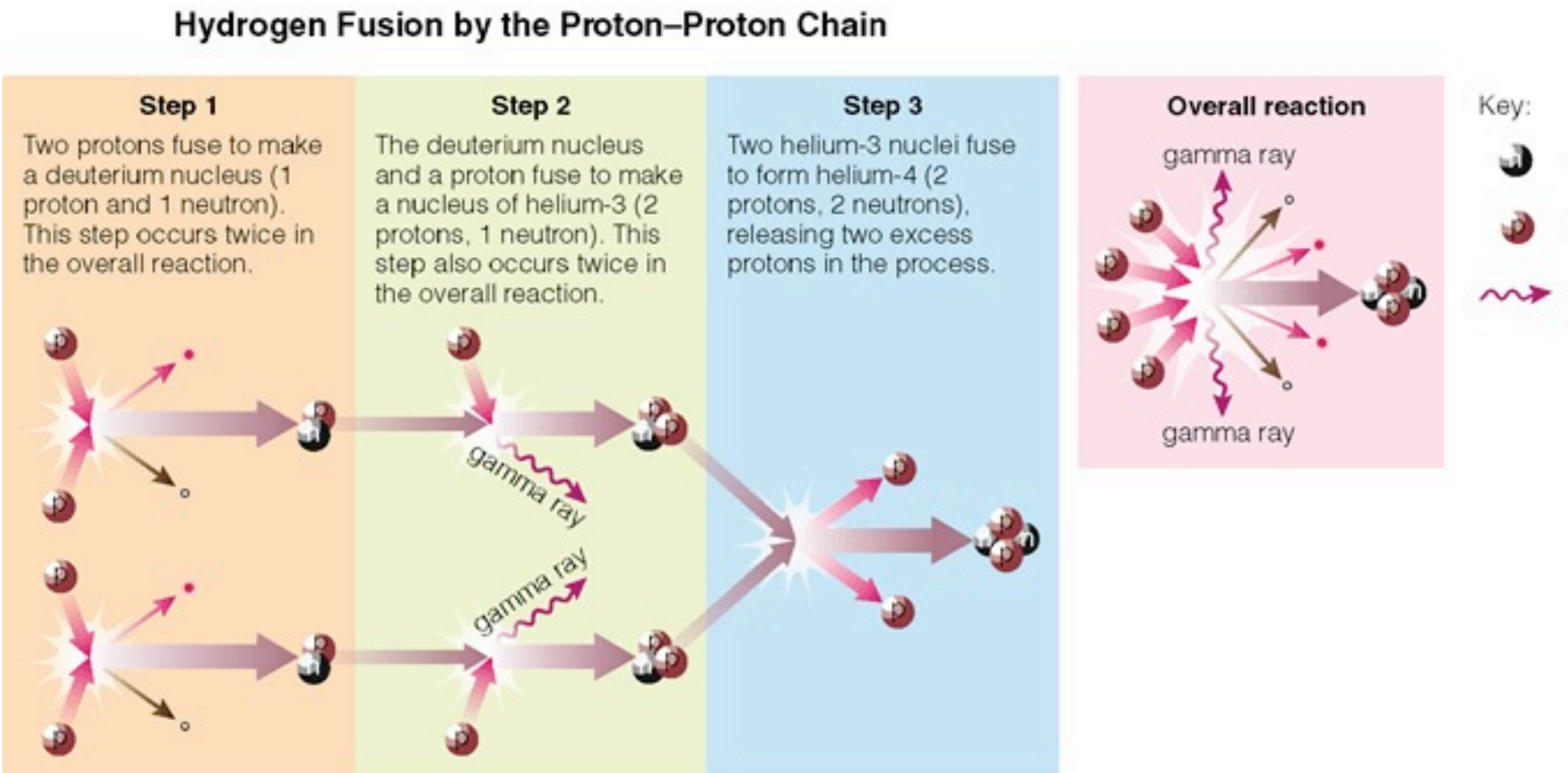
- Proton-proton chain
  - more effective in low mass stars (lower T)

$$M < 1.5 M_{sun}$$

- CNO cycle
  - more effective in high mass stars (higher T)

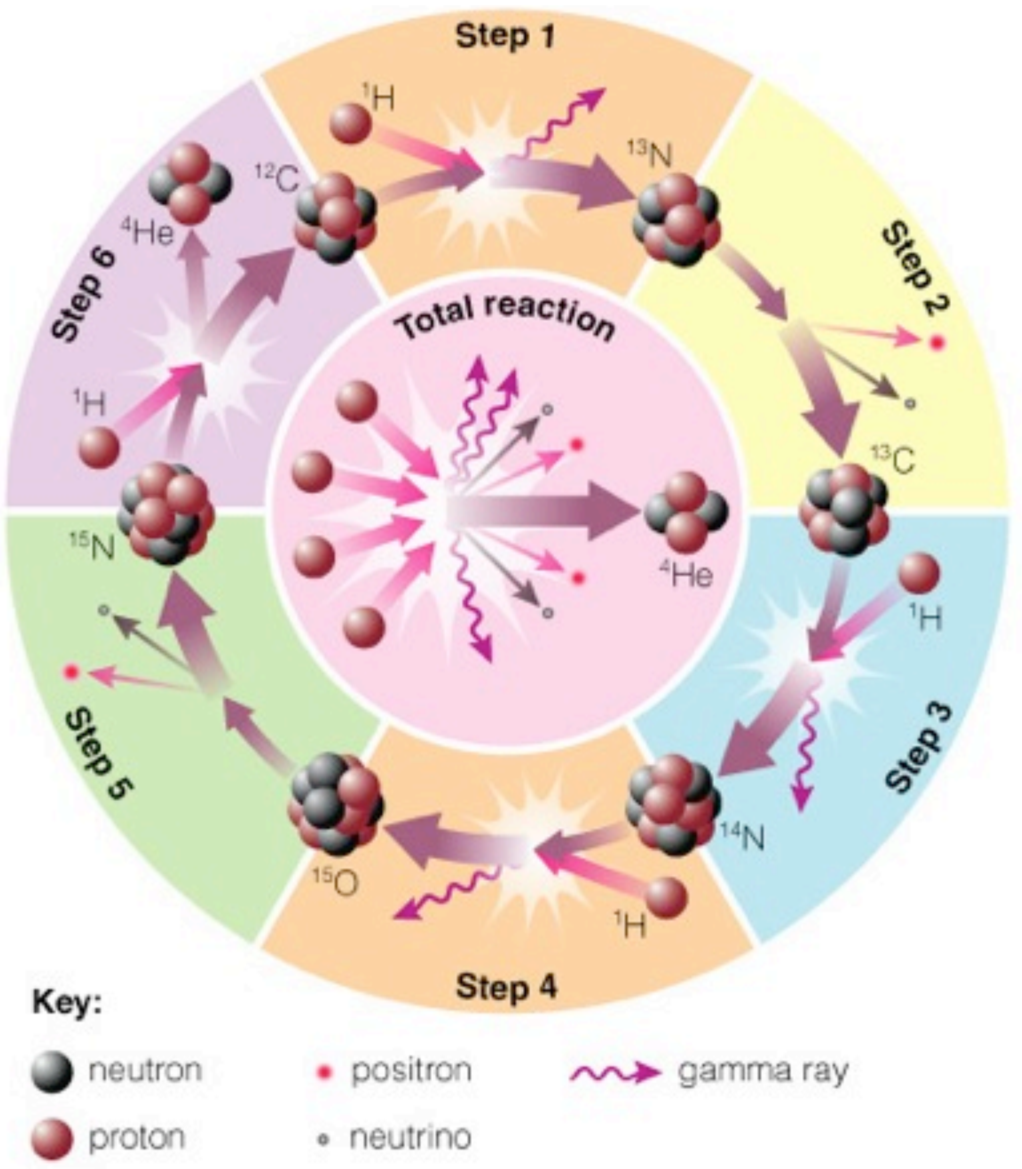
$$M > 1.5 M_{sun}$$

Sun is about 90% proton-proton; 10% CNO cycle.



The first step - getting protons together - is the hardest: on average, takes 10,000,000 years to occur in the sun.

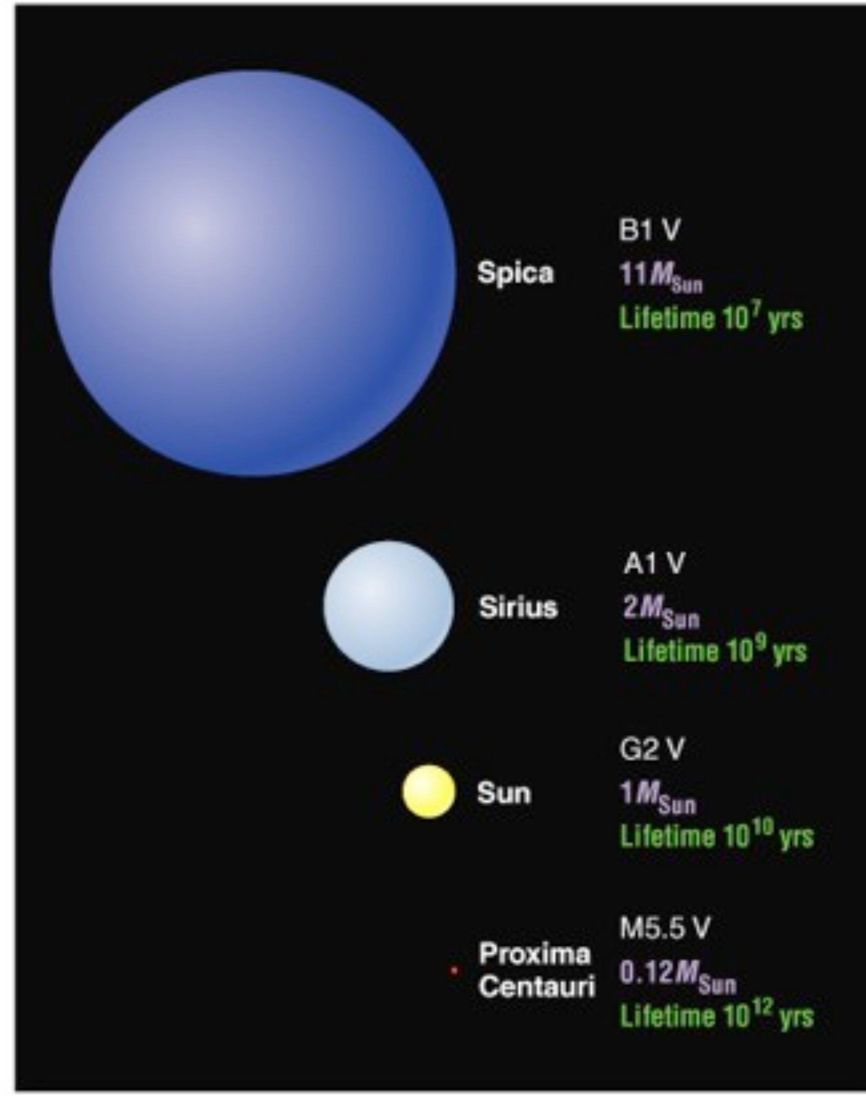
CNO Cycle



- High-mass main-sequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as catalysts.
- Net result the same: 4 protons in; one helium nucleus out.

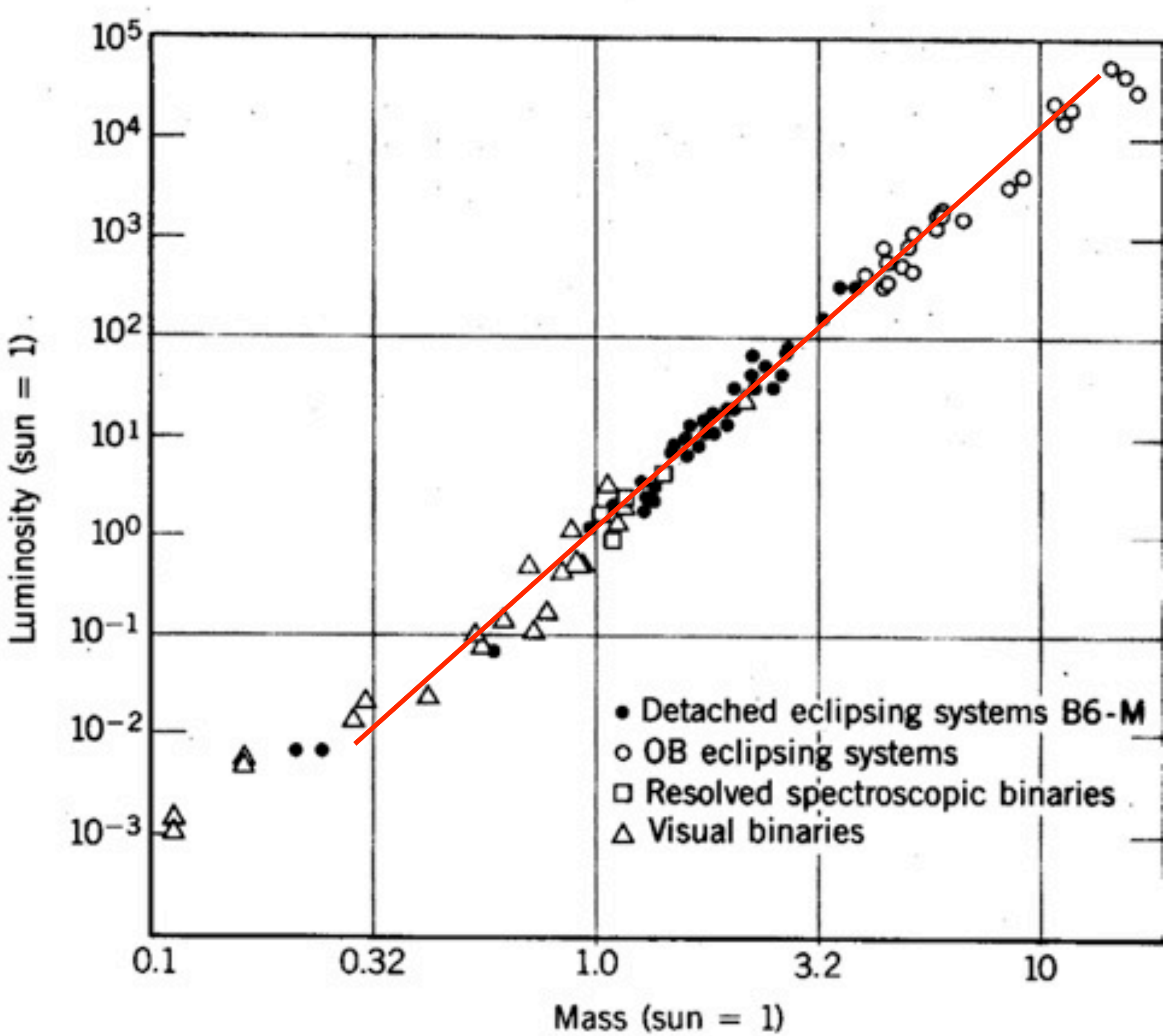
Main Sequence Stars

- Obey scaling relations
- Mass-Radius relation
  - more massive stars are bigger
- Mass-Luminosity relation
  - more massive stars are brighter



Main-sequence stars (to scale)

Mass-Luminosity Relation



The mass–luminosity relation for stars, as determined from binary systems, in which the individual masses can be found.

$0.08\ M_\odot$ = minimum mass for a star

Mass-Luminosity Relation

roughly $L \propto M^4$ (see text for details)

- more massive stars **much** brighter
- use their fuel **much** faster
  - – Mass: fuel supply ($E = mc^2$)
  - – Luminosity: rate of fuel usage

Mass is finite - the stars don't shine forever!

Mass and Lifetime

$$lifetime \propto \frac{energy(mc^2)}{power(L)}$$

$$t \propto \frac{M}{L}$$

M ← fuel

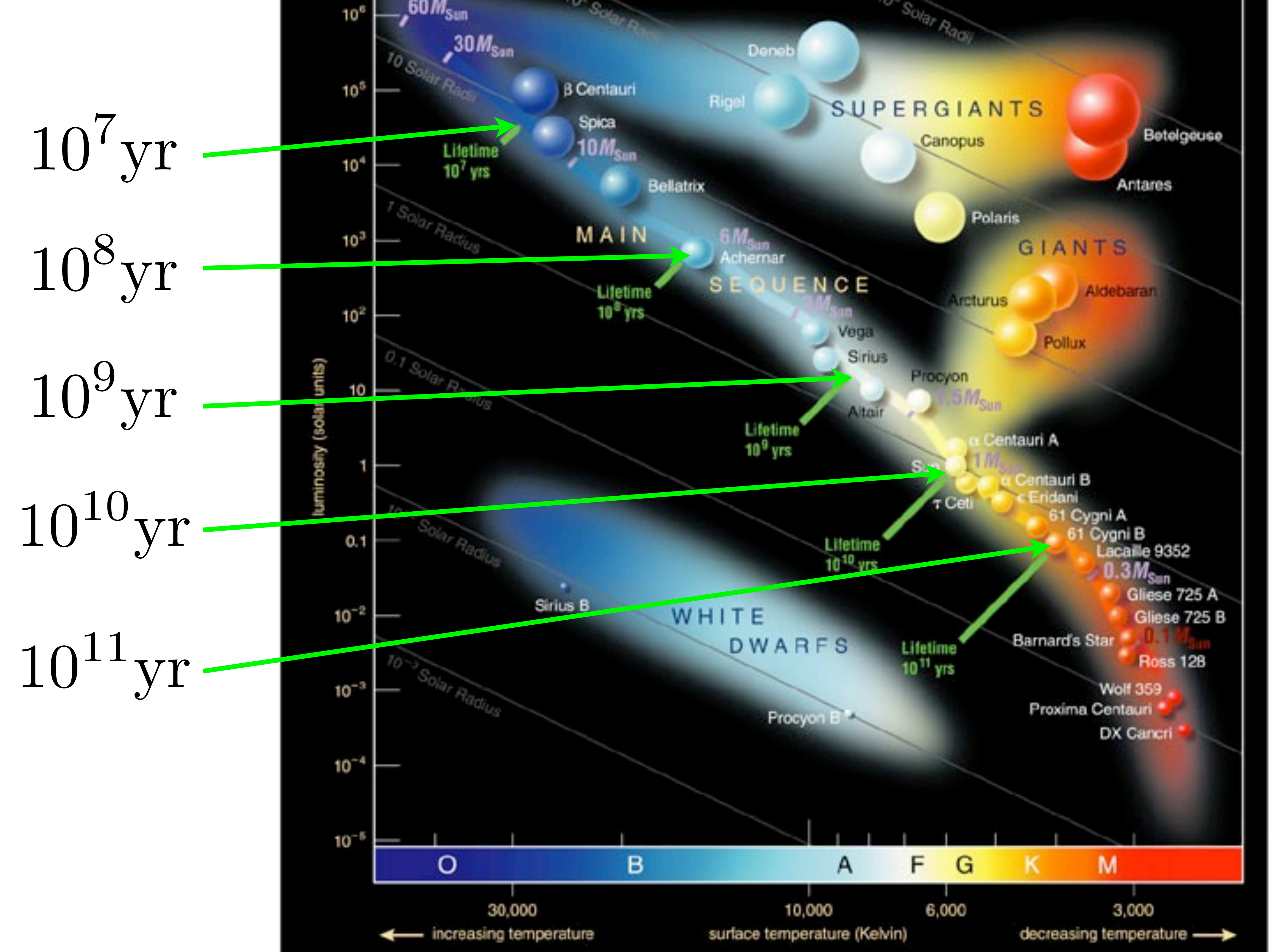
L ← rate of fuel use

Mass and Lifetime: $$t \propto \frac{M}{L}$$

Mass-Luminosity Relation: $$L \propto M^4$$

$$t \propto \frac{M}{L} \propto \frac{M}{M^4} \propto M^{-3}$$

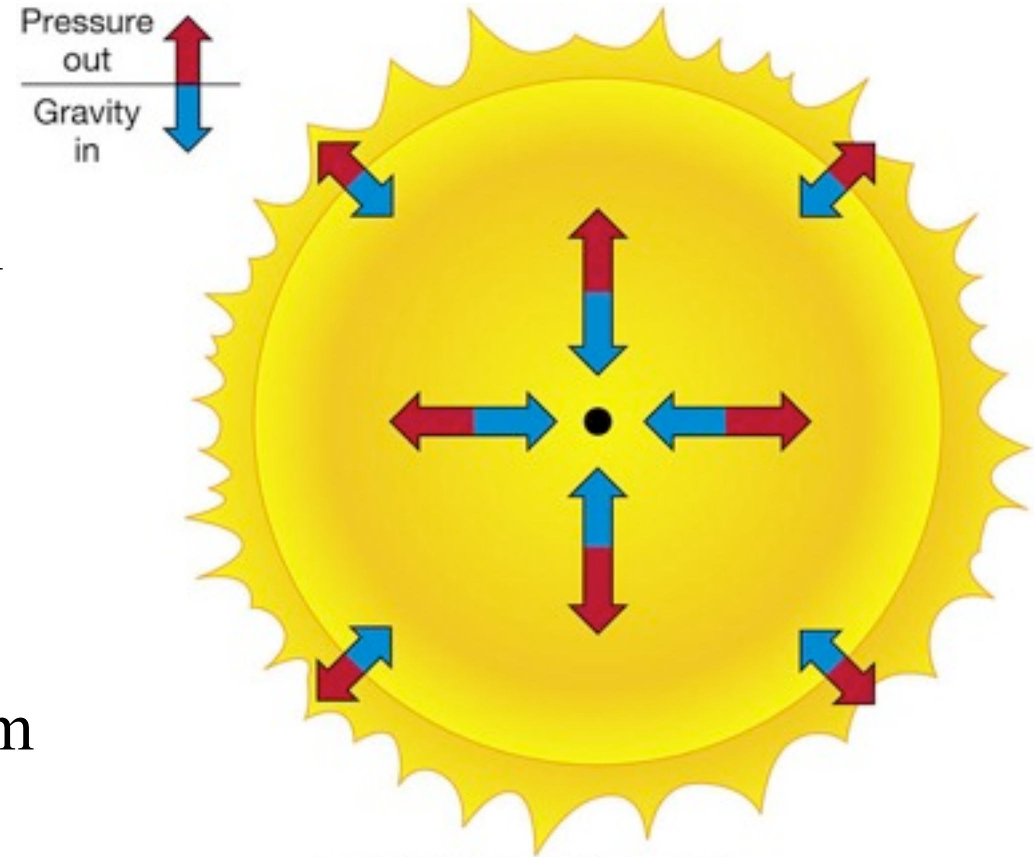
So as mass increases, the main sequence lifetime decreases.



10^7yr
10^8yr
10^9yr
10^{10}yr
10^{11}yr
60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
3 M_{Sun}
1.5 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-3} Solar Radius
Deneb
Rigel
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Altair
Procyon
Canopus
Polaris
Betelgeuse
Antares
Arcturus
Aldebaran
Pollux
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
Sirius B
Procyon B
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

Hydrostatic Equilibrium

Pressure and gravity
in balance



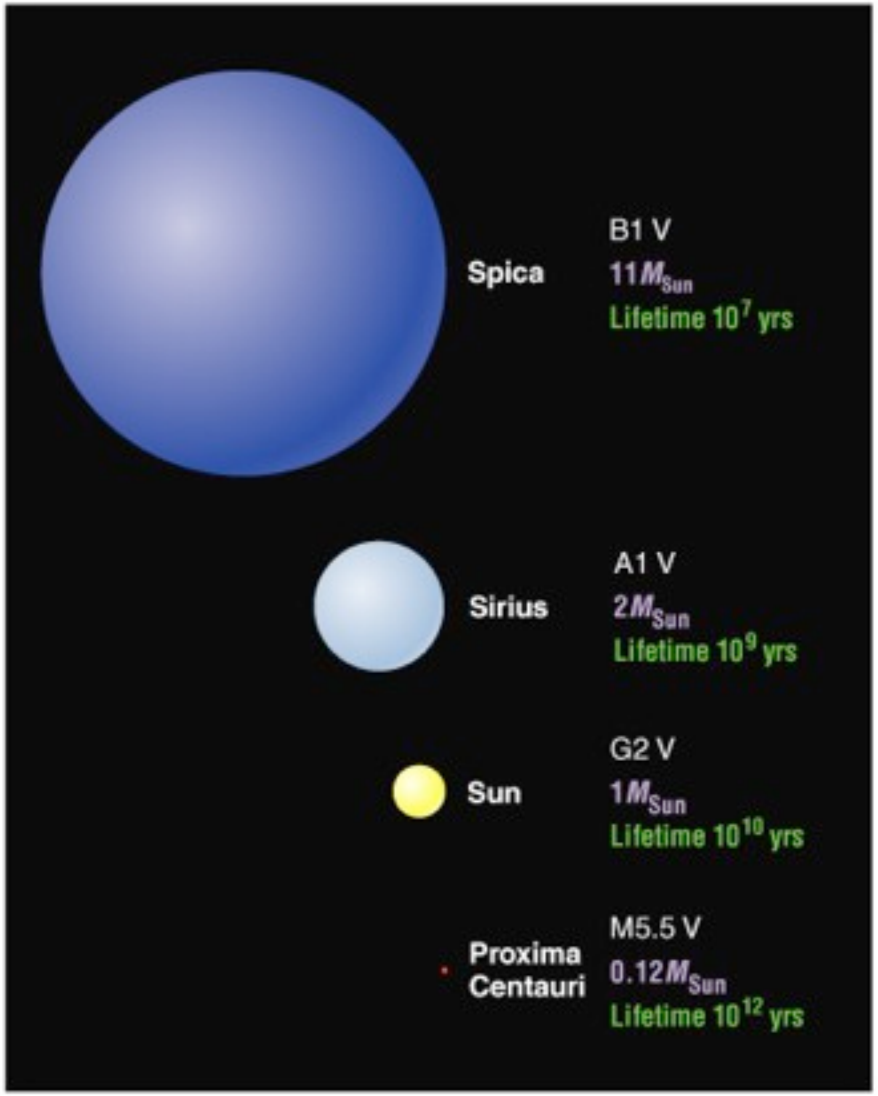
Stars attempt to maintain equilibrium by striking a balance between the gravity of their enormous mass and the pressure produced by the energy of fusion reactions.

A main sequence star is in equilibrium as Hydrogen burning supports it against gravitational collapse.

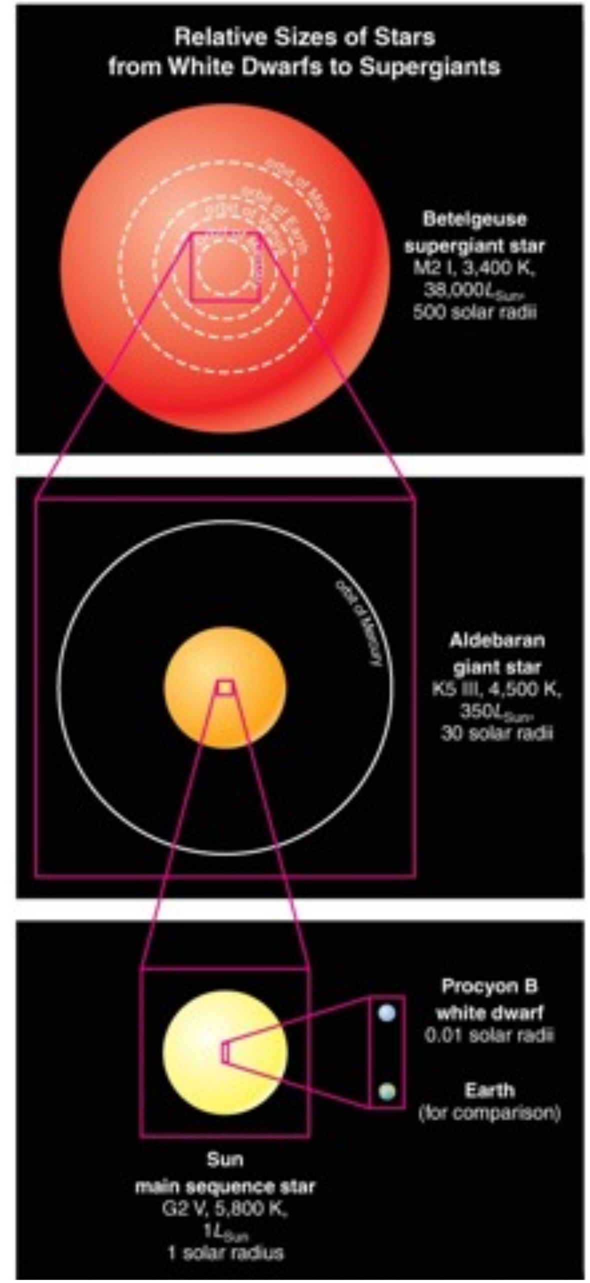
What happens as the hydrogen runs out?

Off the Main Sequence

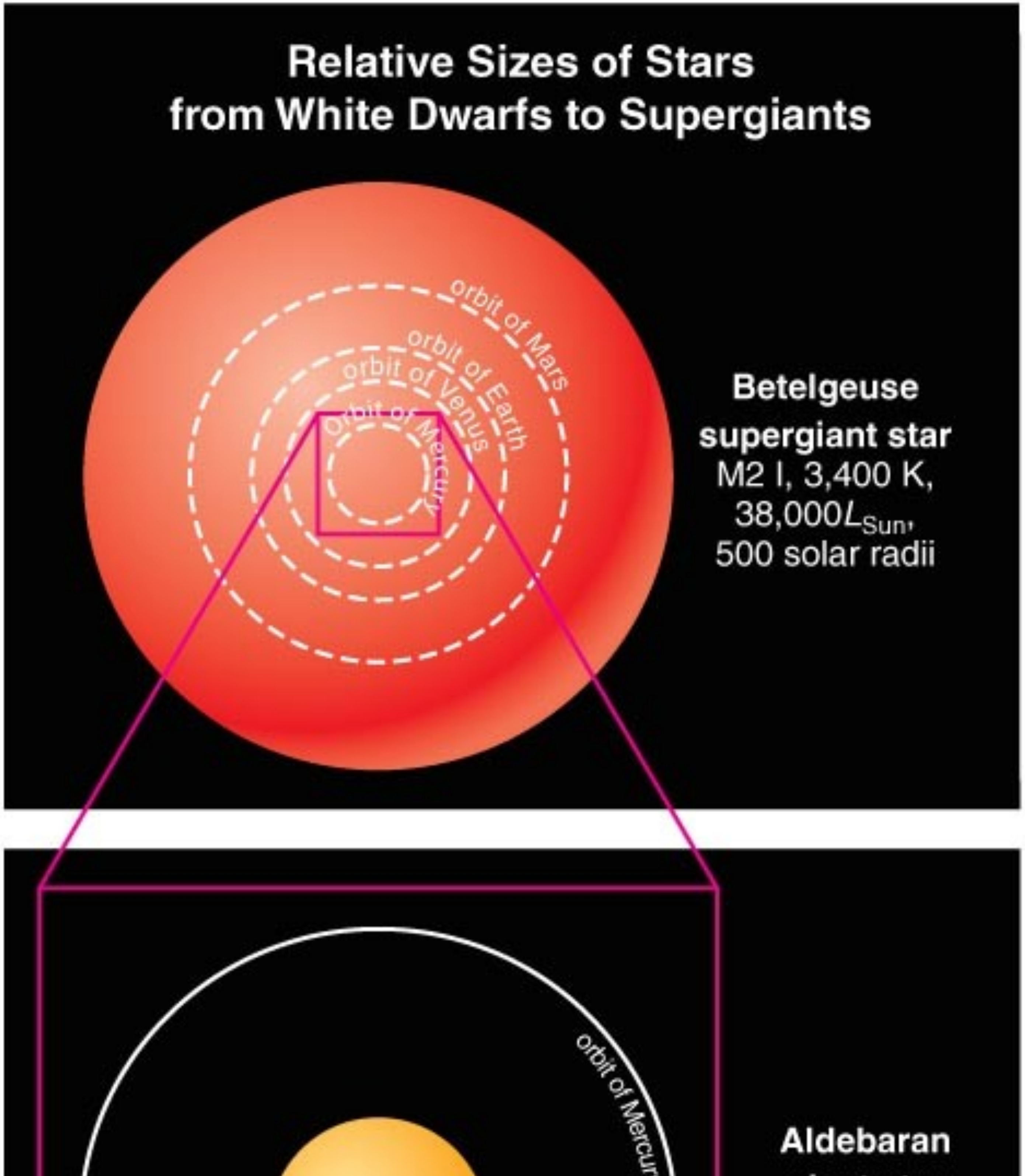
- Stellar properties depend on both mass and age: those that have finished fusing H to He in their cores are no longer on the main sequence.
- All stars become larger and redder after exhausting their core hydrogen: **giants** and **supergiants.**
- Most stars end up small and dim after fusion has ceased: **white dwarfs.**

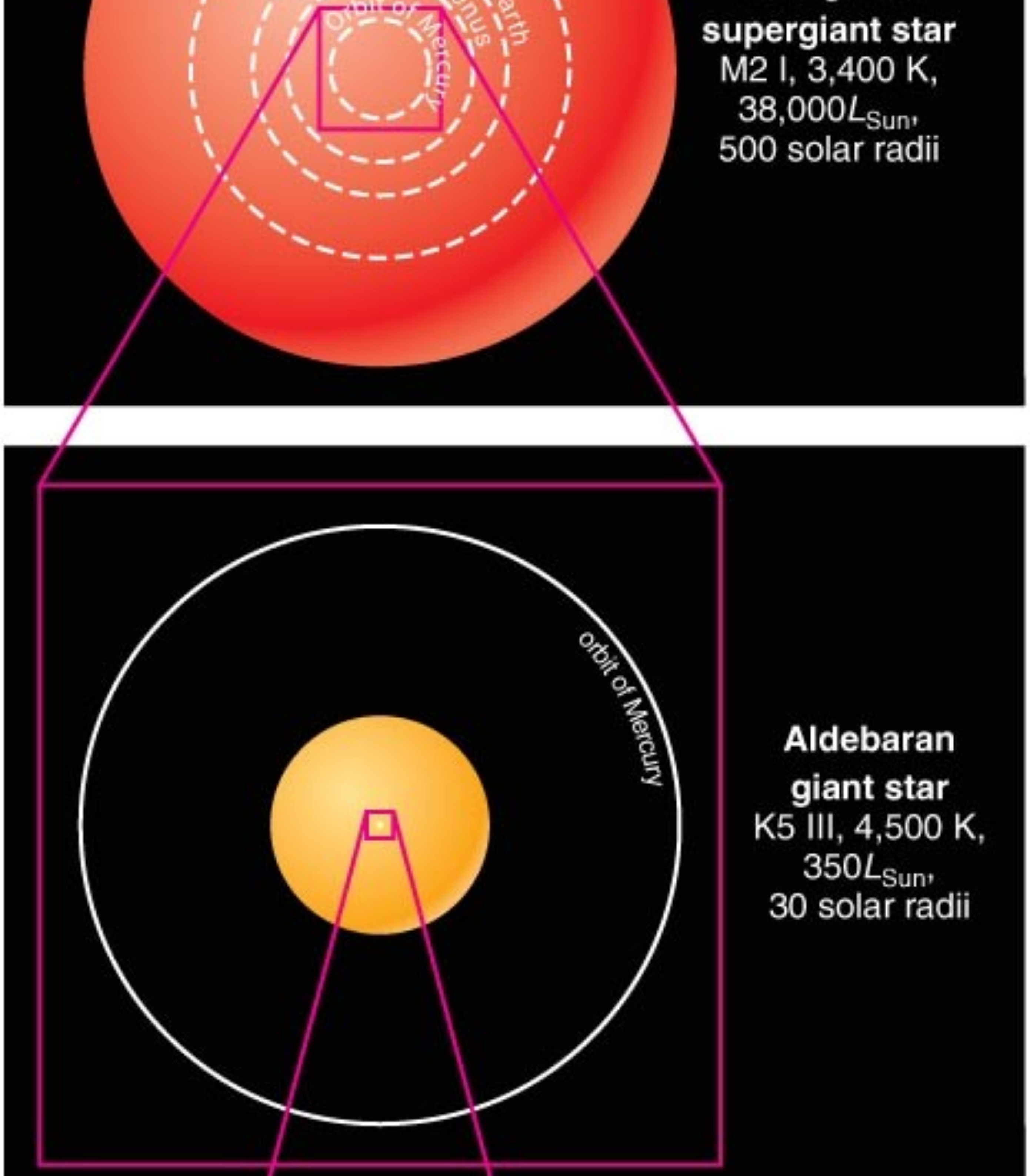


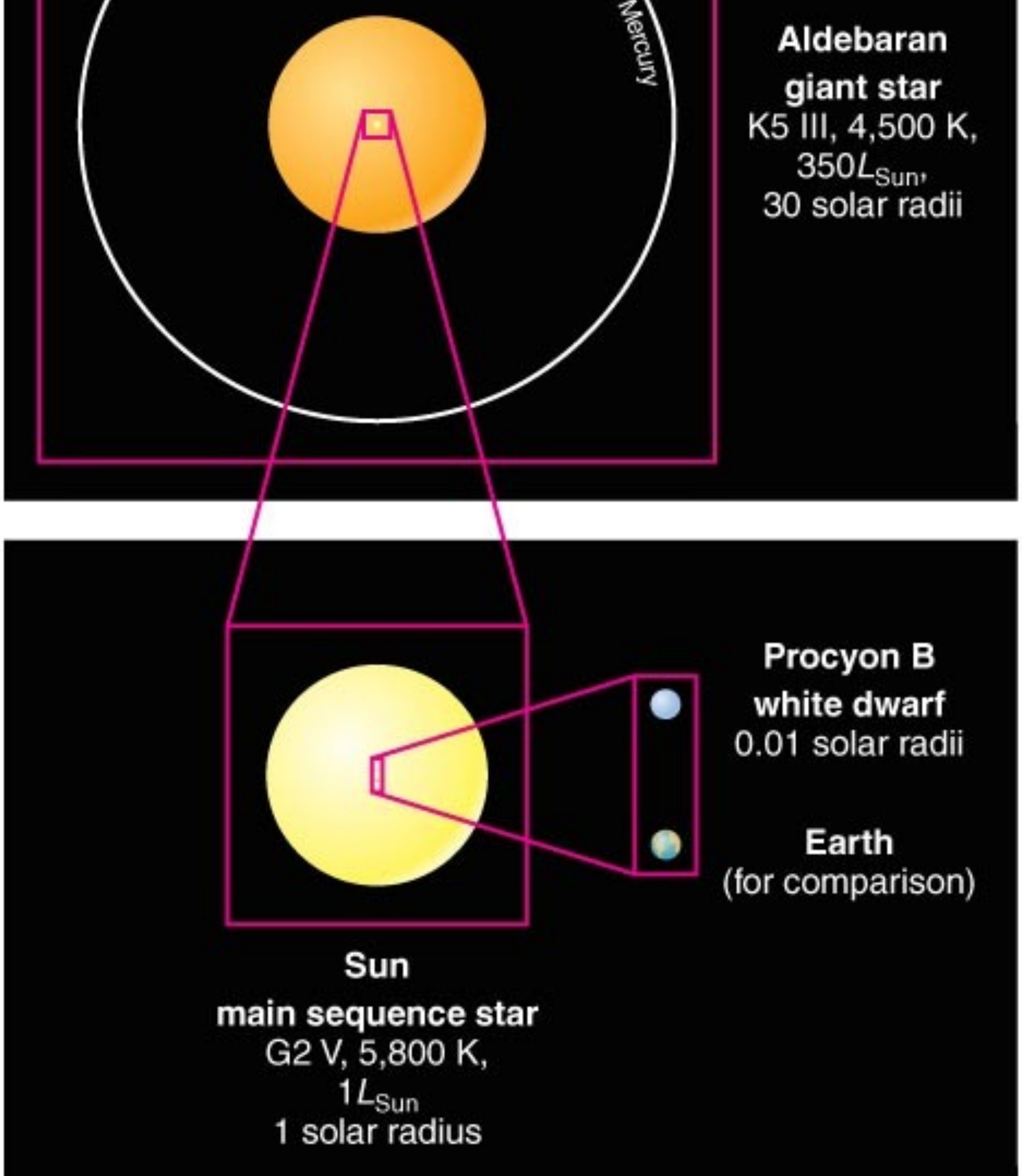
Main-sequence stars (to scale)

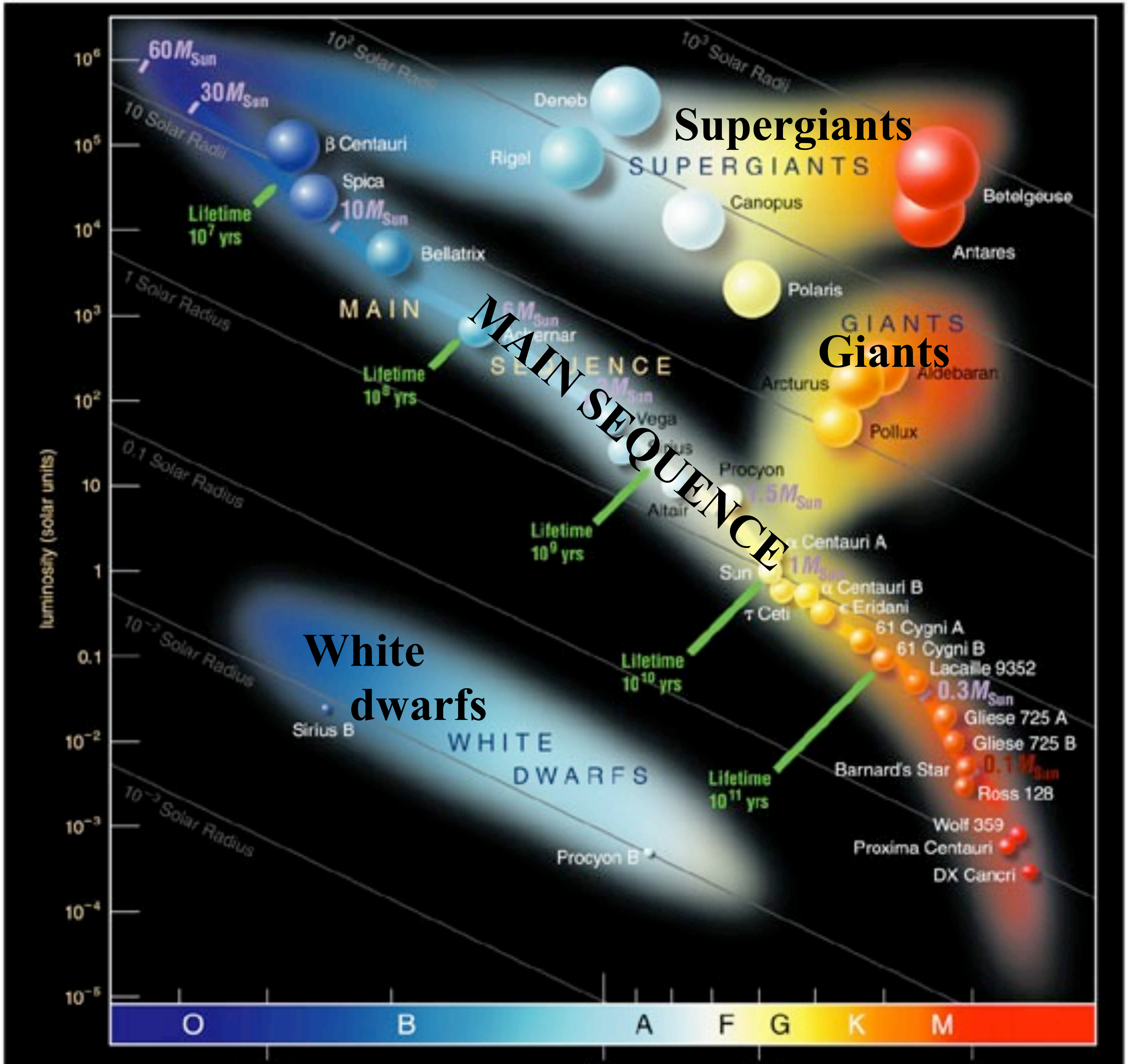


Giants, supergiants, white dwarfs


Relative Sizes of Stars
from White Dwarfs to Supergiants
orbit of Mars
orbit of Earth
orbit of Venus
orbit of Mercury
Betelgeuse
supergiant star
M2 I, 3,400 K,
38,000L_{Sun},
500 solar radii
orbit of Mercury
Aldebaran


supergiant star
M2 I, 3,400 K,
38,000L_{Sun},
500 solar radii
orbit of Mercury
Aldebaran
giant star
K5 III, 4,500 K,
350L_{Sun},
30 solar radii


Mercury
Aldebaran
giant star
K5 III, 4,500 K,
350L_{Sun},
30 solar radii
Procyon B
white dwarf
0.01 solar radii
Earth
(for comparison)
Sun
main sequence star
G2 V, 5,800 K,
1L_{Sun}
1 solar radius


Supergiants
Giants
MAIN SEQUENCE
White dwarfs
SUPERGIANTS
GIANTS
MAIN
WHITE
DWARFS
luminosity (solar units)
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
Deneb
Rigel
Canopus
Betelgeuse
Antares
Polaris
Aldebaran
Arcturus
Pollux
β Centauri
Spica
Bellatrix
Achernar
Vega
Procyon
Altair
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^10 yrs
Lifetime 10^11 yrs
60 M_Sun
30 M_Sun
10 M_Sun
6 M_Sun
1.5 M_Sun
1 M_Sun
0.3 M_Sun
0.1 M_Sun
O
B
A
F
G
K
M

Theoretical evolutionary tracks

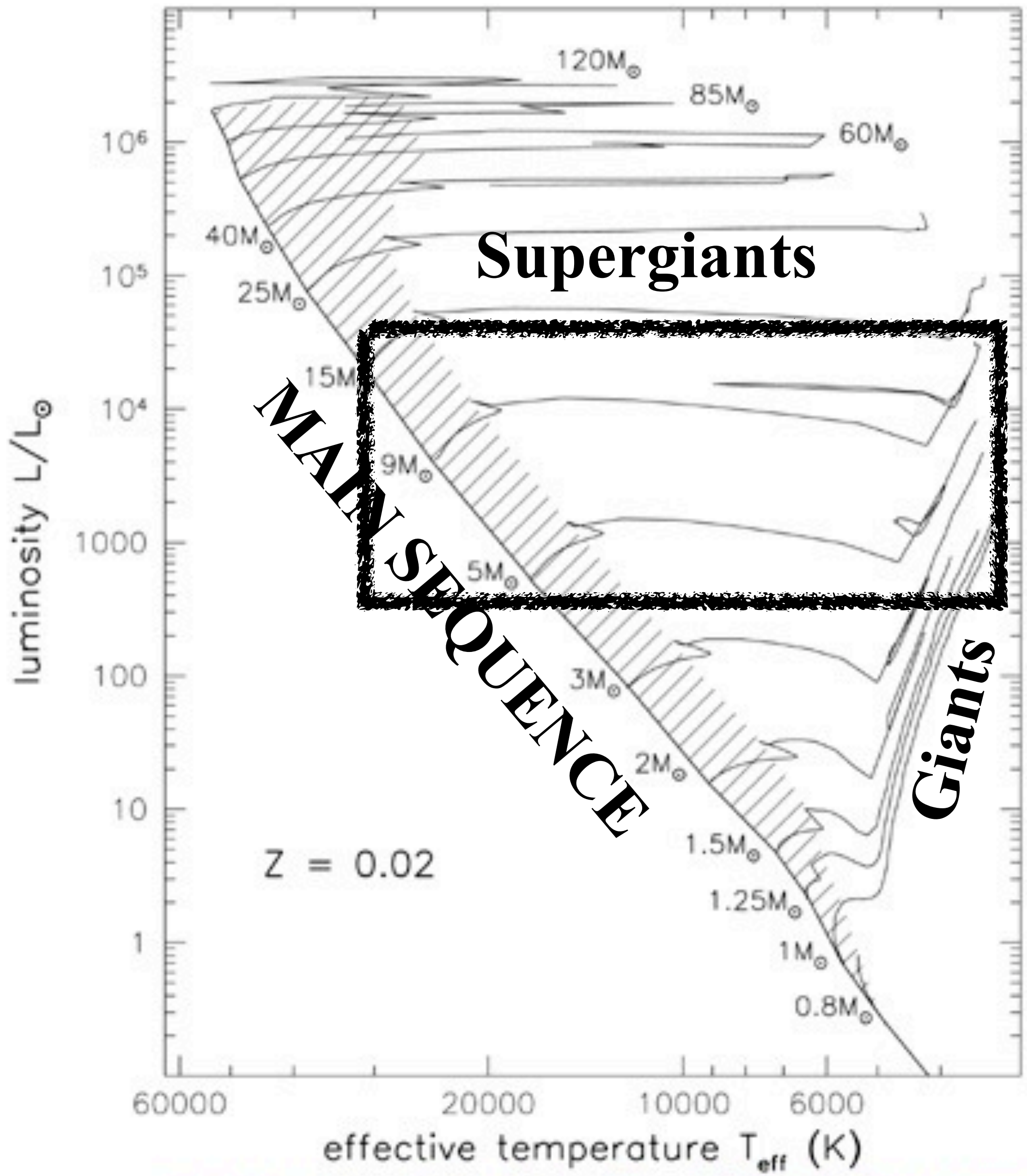


Fig 1.4 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

Evolutionary tracks

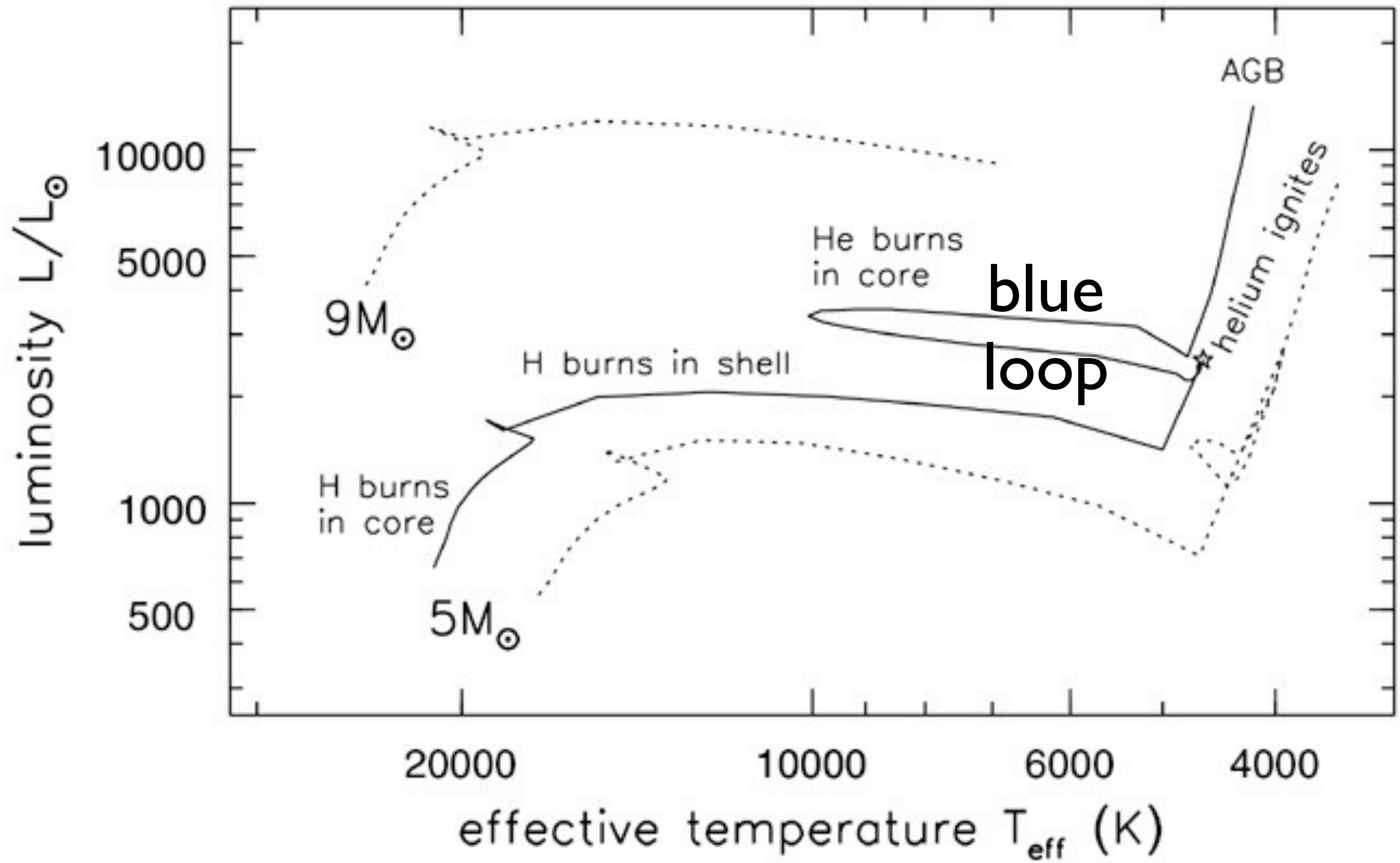
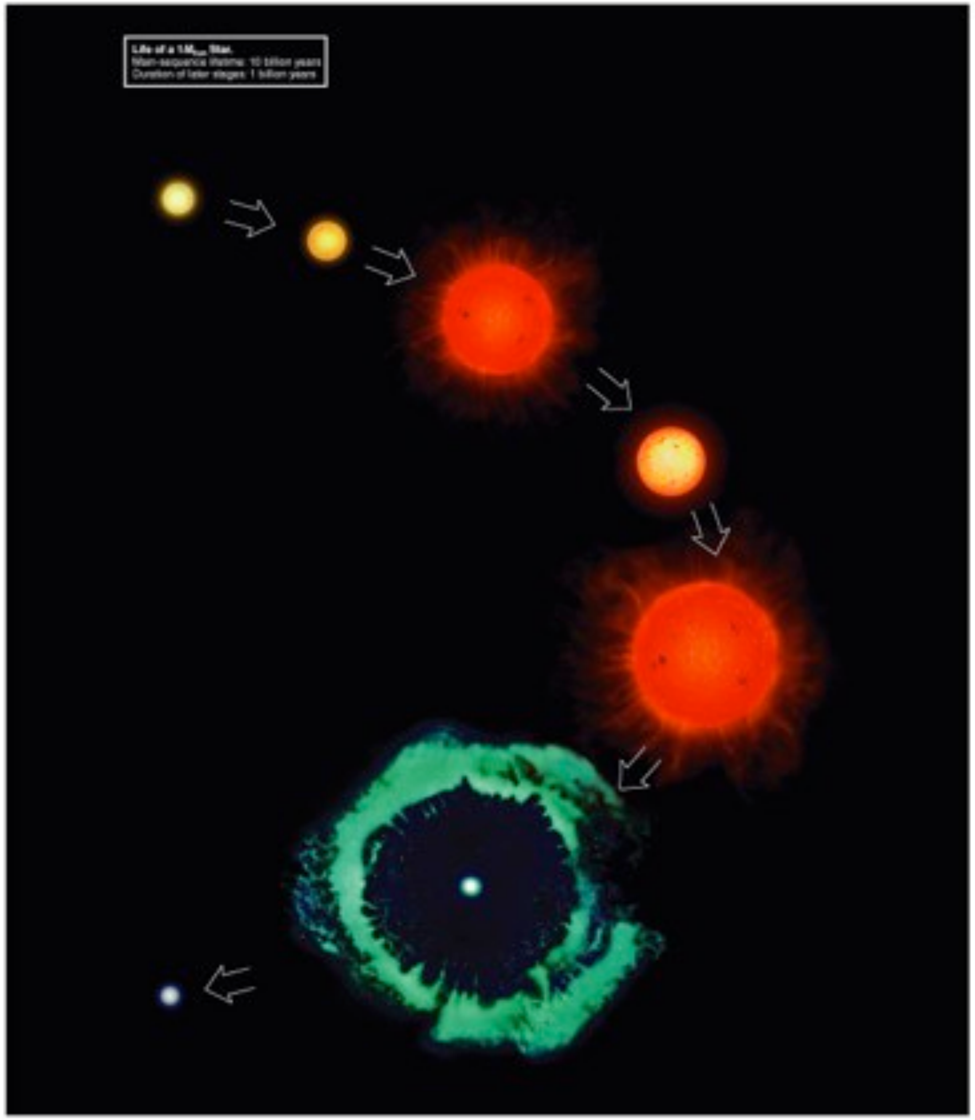


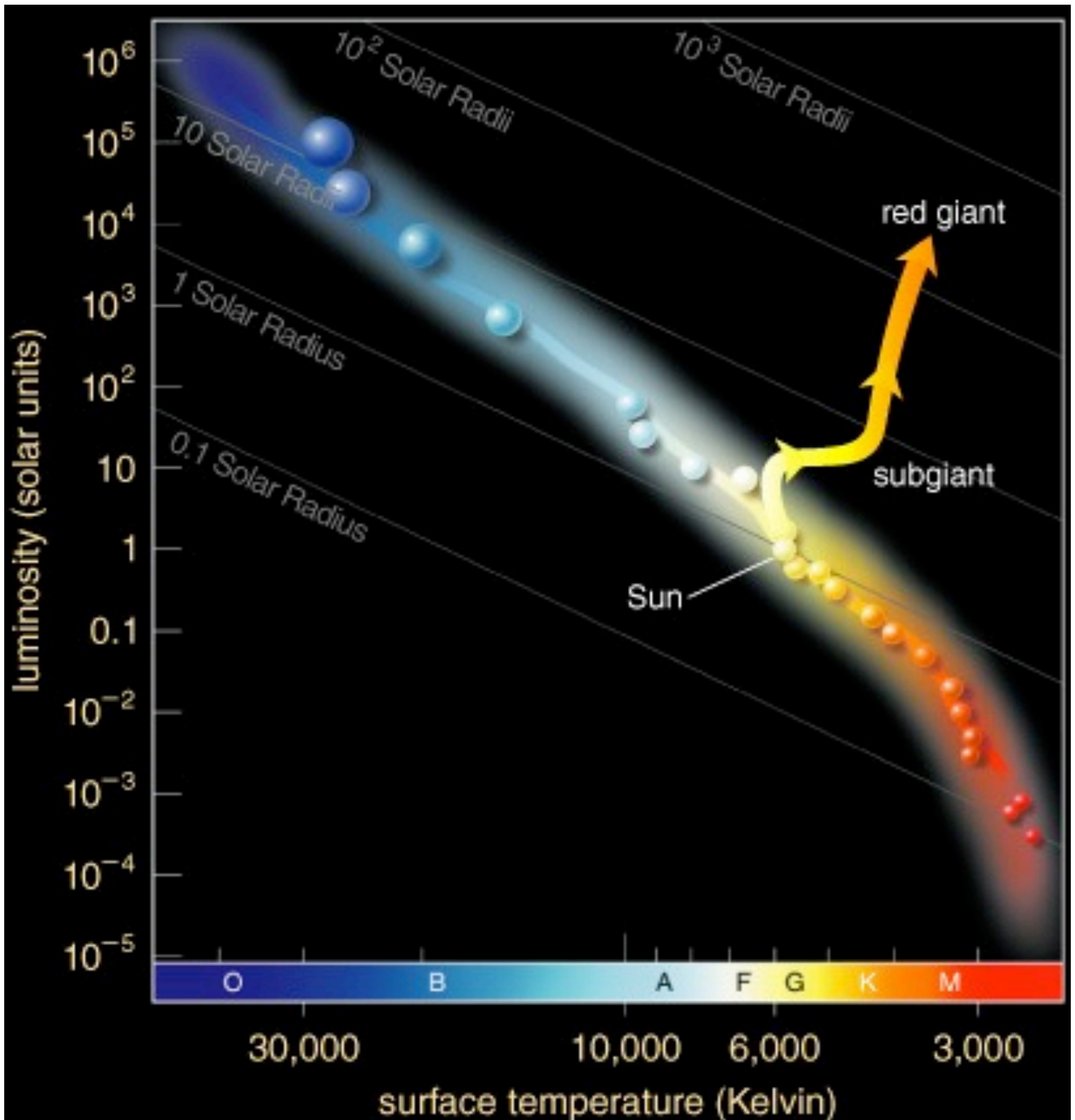
Fig 1.5 'Galaxies in the Universe' Sparke/Gallagher CUP 2007

low metallicity stars have larger blue loops

The life stages of a low-mass star



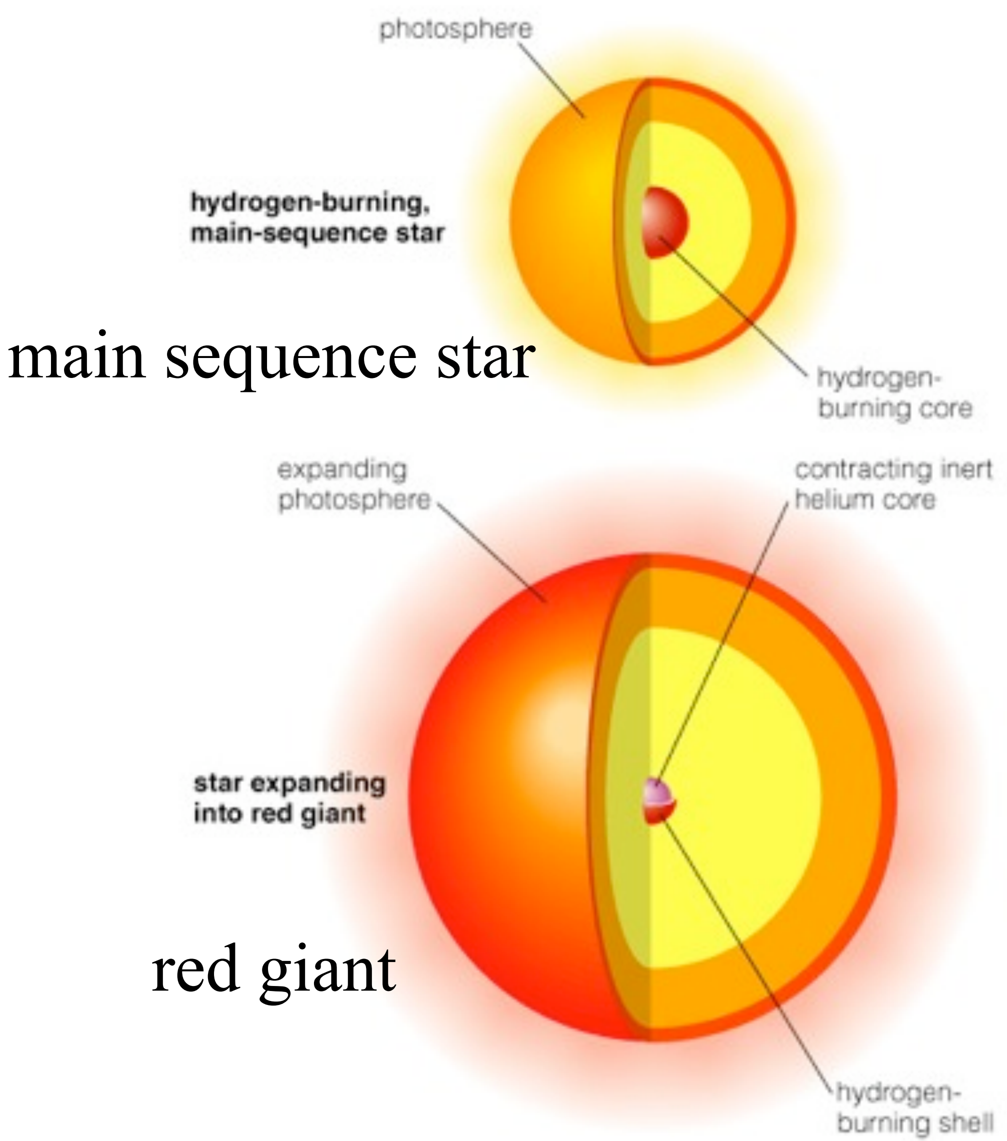
Life Track After Main Sequence



- Observations of star clusters show that a star becomes larger, redder, and more luminous after its time on the main sequence is over.

- At the end of their main sequence life time - when hydrogen in the core is exhausted - stars ascend the **red giant branch**.

After hydrogen fuel is spent



- Without further fusion, the core contracts. H begins fusing to He in a shell around the core.
- As the core contracts, temperature increases, nuclear reaction rates increase (in the shell), and the Luminosity increases.

Helium Flash

- The core continues to shrink and heat as the rest of the star expands and becomes more luminous.
  - Ascends giant branch for a billion years

- At a critical temperature and density, helium fusion suddenly begins.
  - The Helium Flash

- The star evolves rapidly, finding a new equilibrium with He burning in core and H burning in a shell surrounding the core.