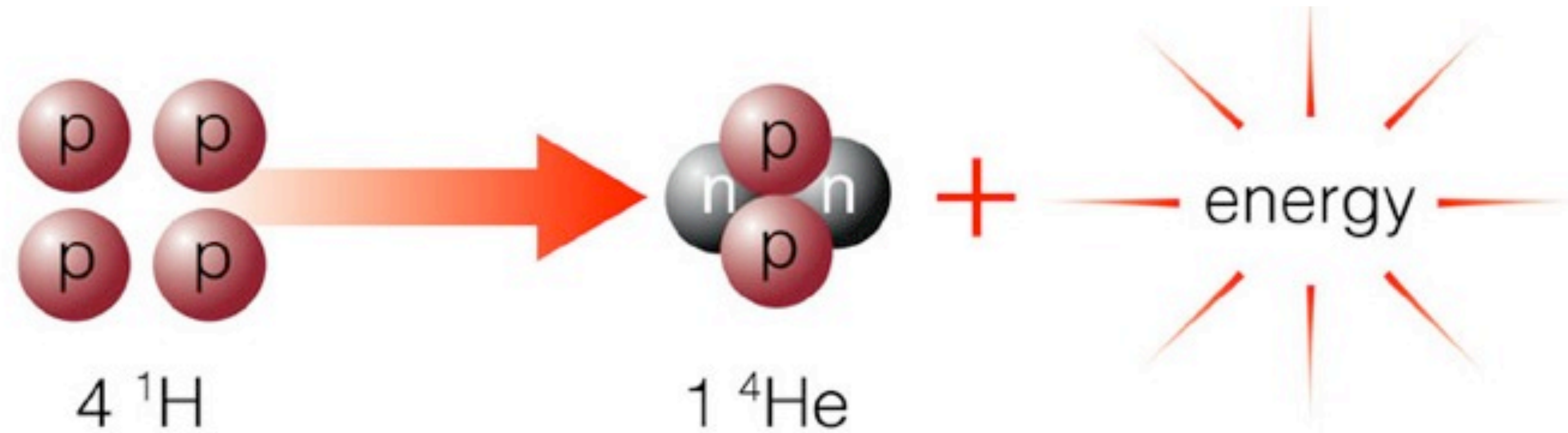
# Today

- Stars
  - Stellar Lifetimes
  - Life cycles of stars
  - Star Clusters

Exam II next time

# Nuclear fusion in stars




***IN***
4 protons

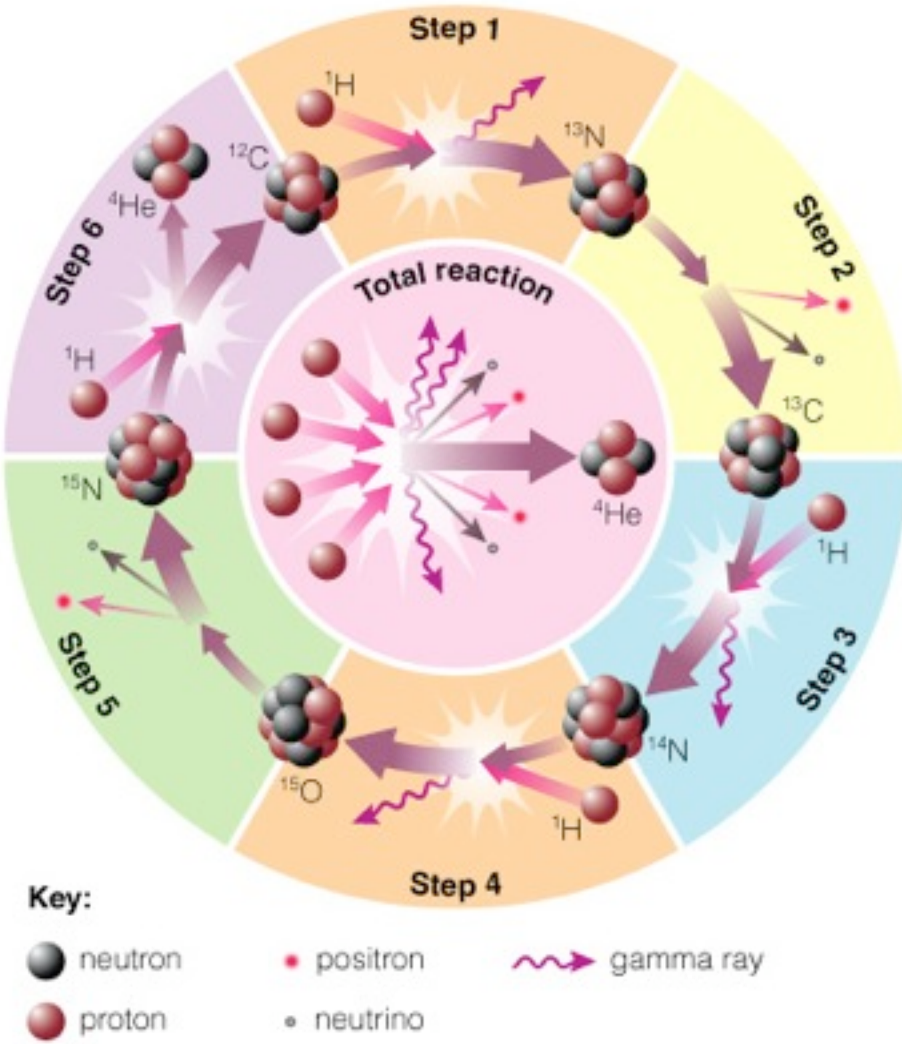
***OUT***
$^4$He nucleus
2 gamma rays
2 positrons
2 neutrinos

$$E = mc^2 :$$

***Total mass is 0.7% lower.***

In addition to the proton-proton chain (see previous lecture):

# 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.

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

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

$$M < 1.5M_{sun}$$

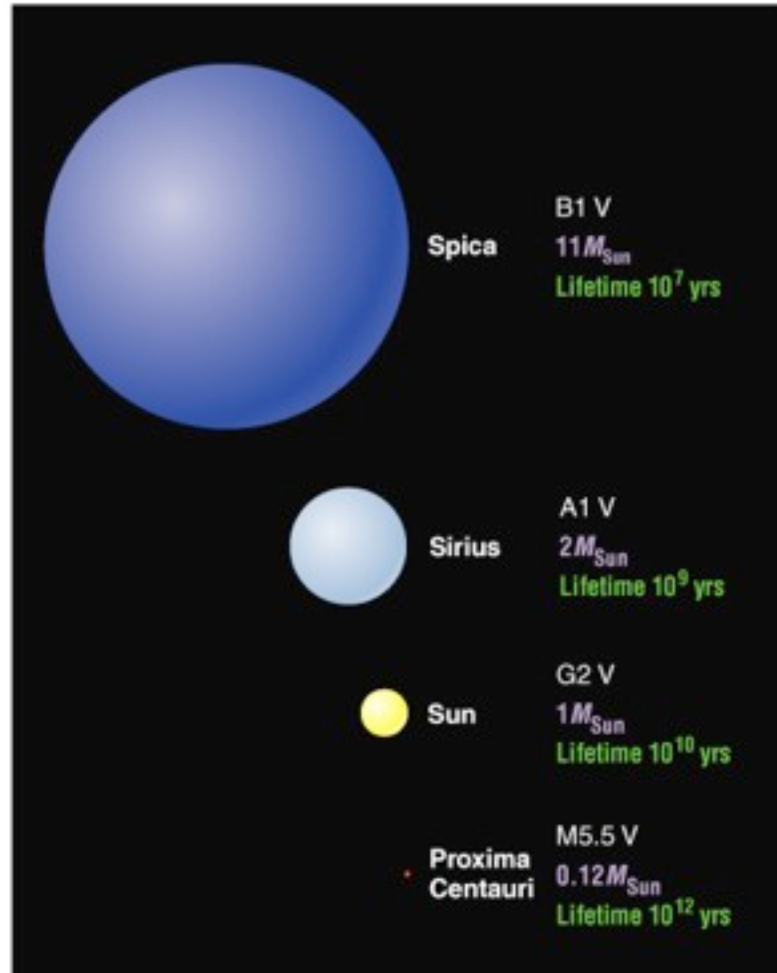
- CNO cycle
  - more effective in high mass stars (higher T)

$$M > 1.5M_{sun}$$

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

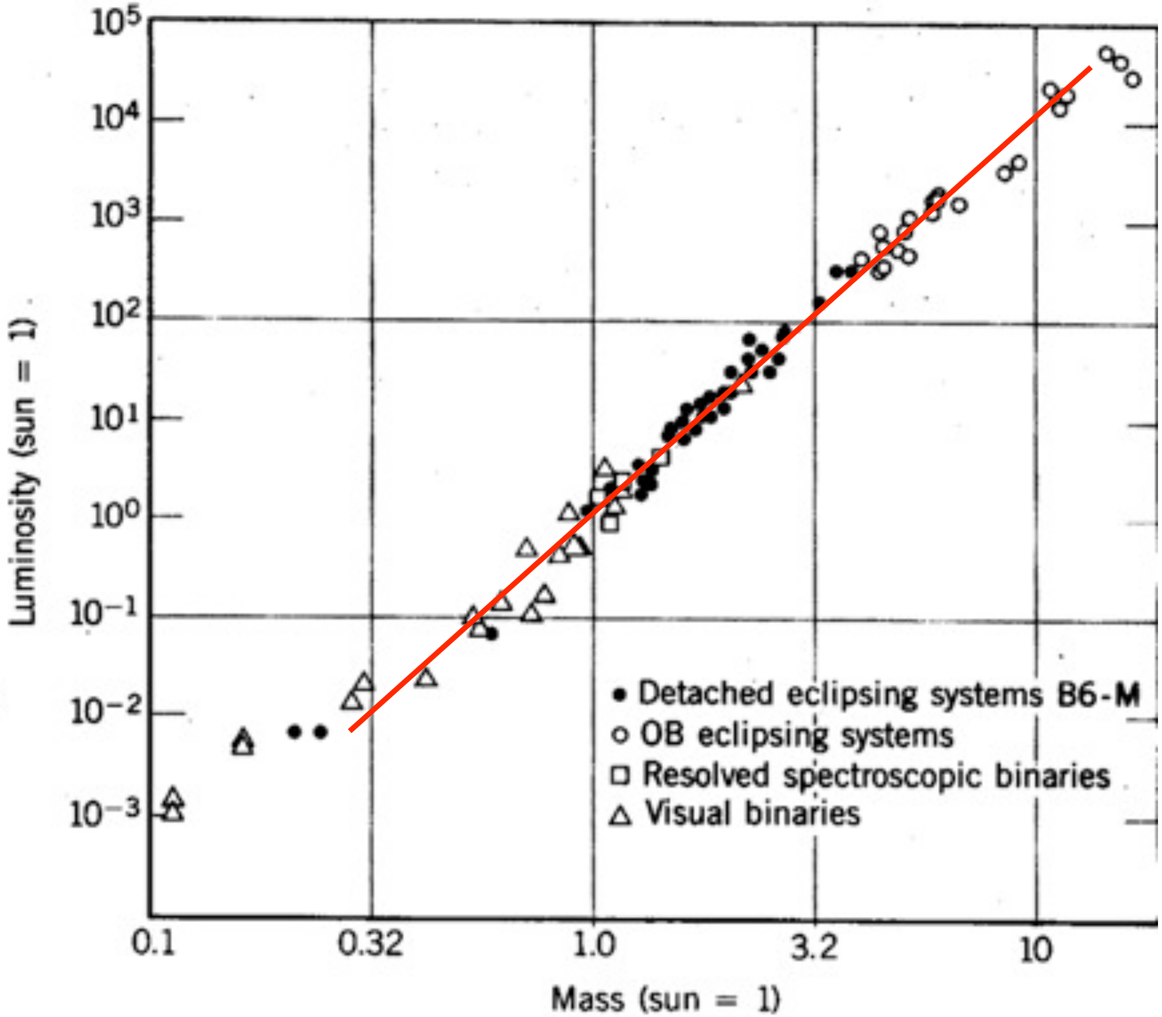
# Main Sequence Stars

- 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.

# Mass-Luminosity Relation

$$L \propto M^4$$

- 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.

# *Mass and Lifetime*

Until core hydrogen (10% of total) is used up

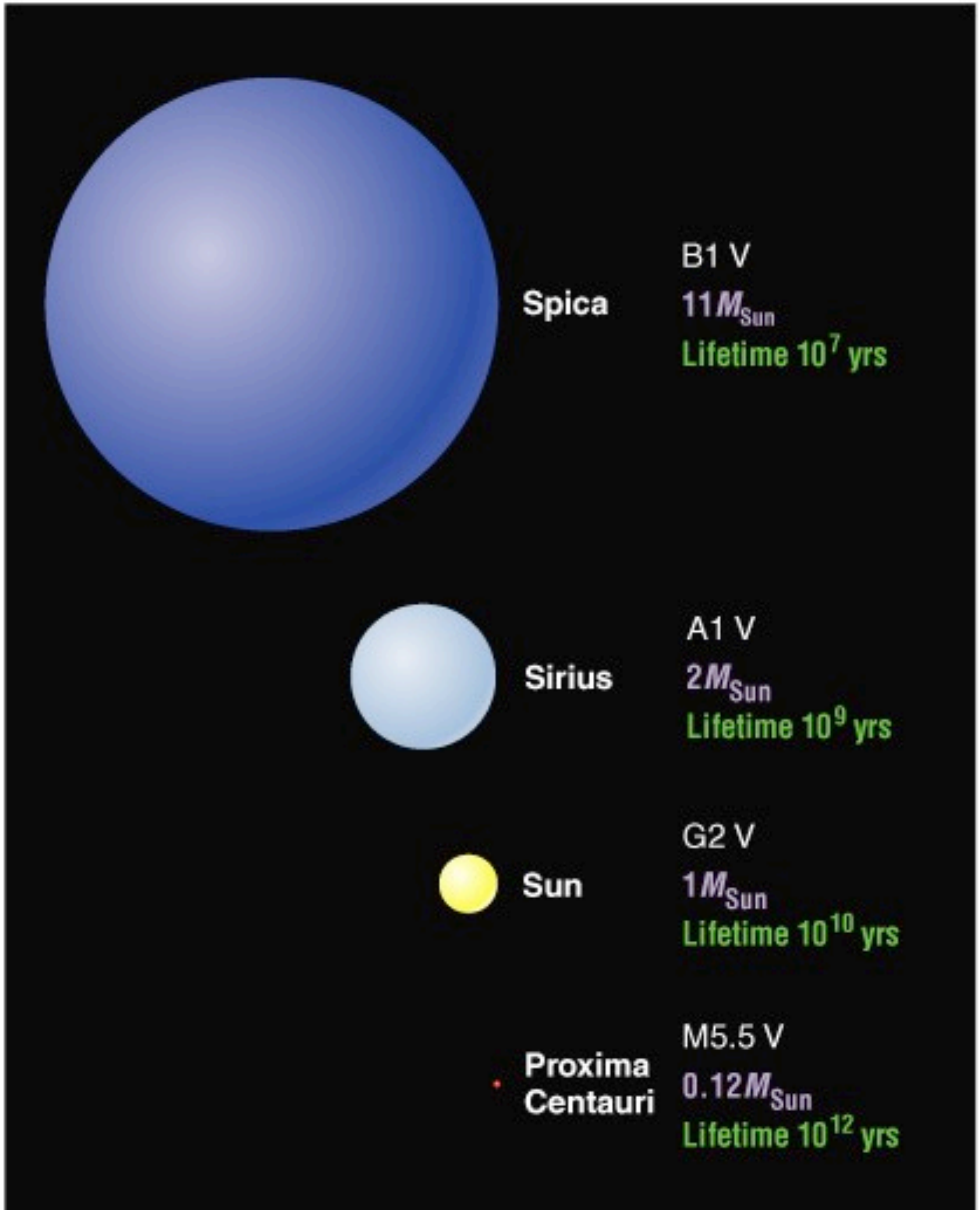
***Sun's life expectancy:*** 10 billion years

***Life expectancy of a 10 $M_{Sun}$ star:***

10 times as much fuel,
but uses it 10,000 times faster

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

$$\text{lifetime}(10\ M_{sun}) \approx \left(\frac{10\ M_{sun}}{10^4\ L_{sun}}\right) 10 \text{ billion years} \approx 10 \text{ million years}$$




For Main-Sequence Stars:

High-mass:

High luminosity

Short-lived

Large radius

Blue

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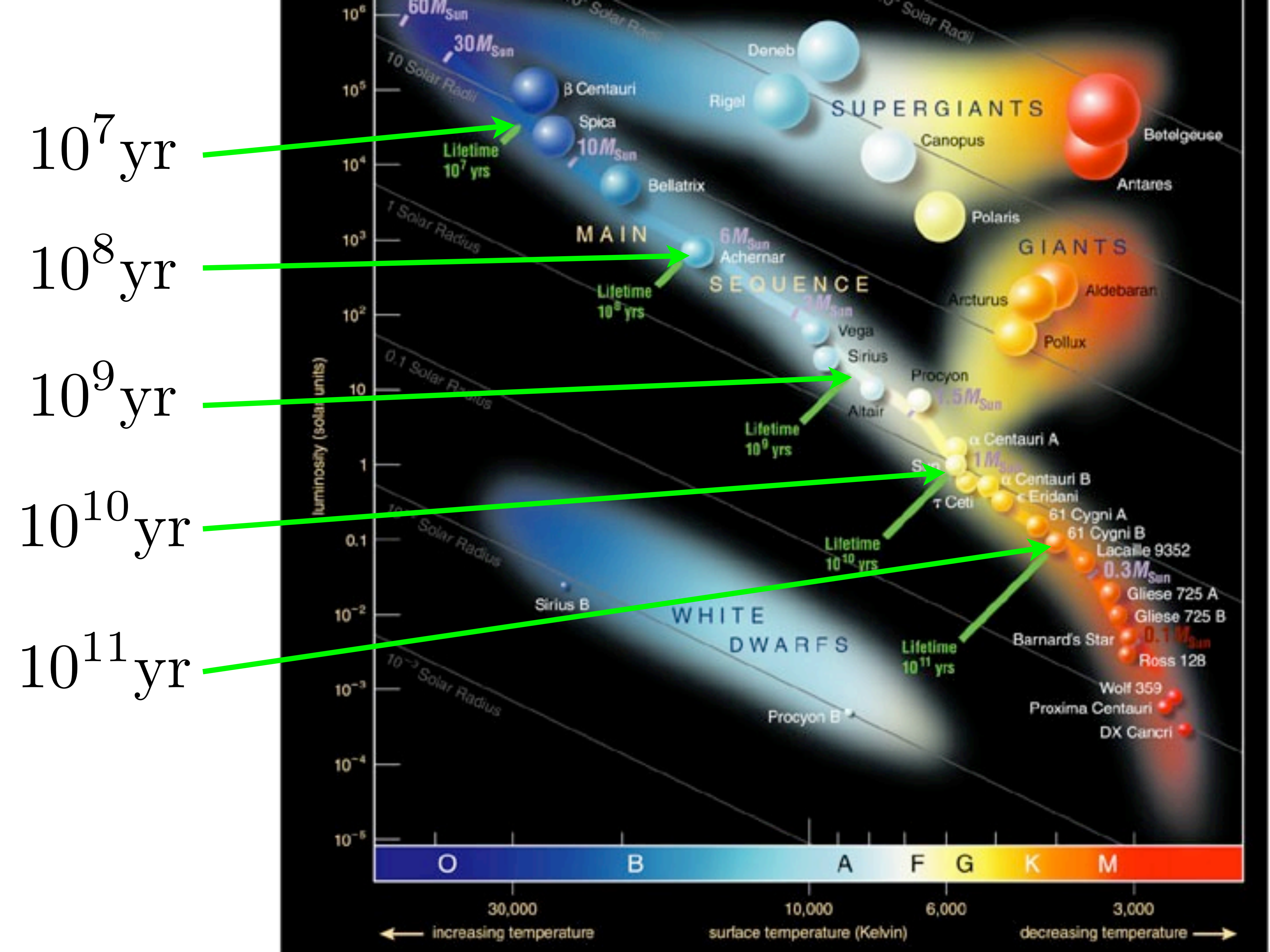
Low-mass:

Low luminosity

Long-lived

Small radius

Red



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

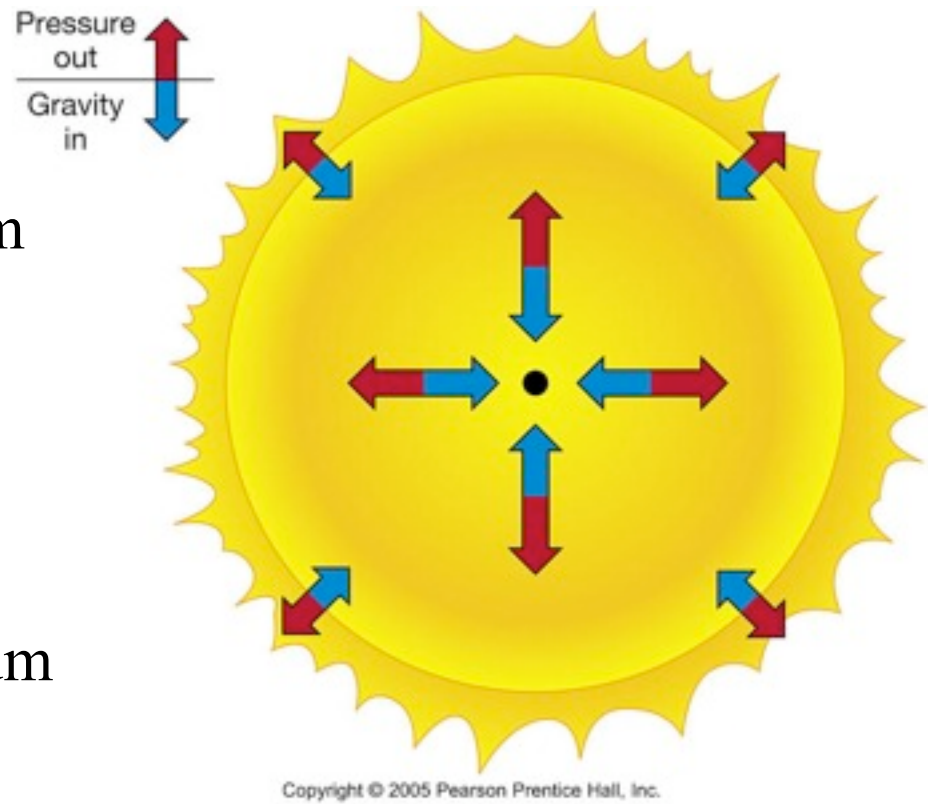
# Hydrostatic Equilibrium

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.

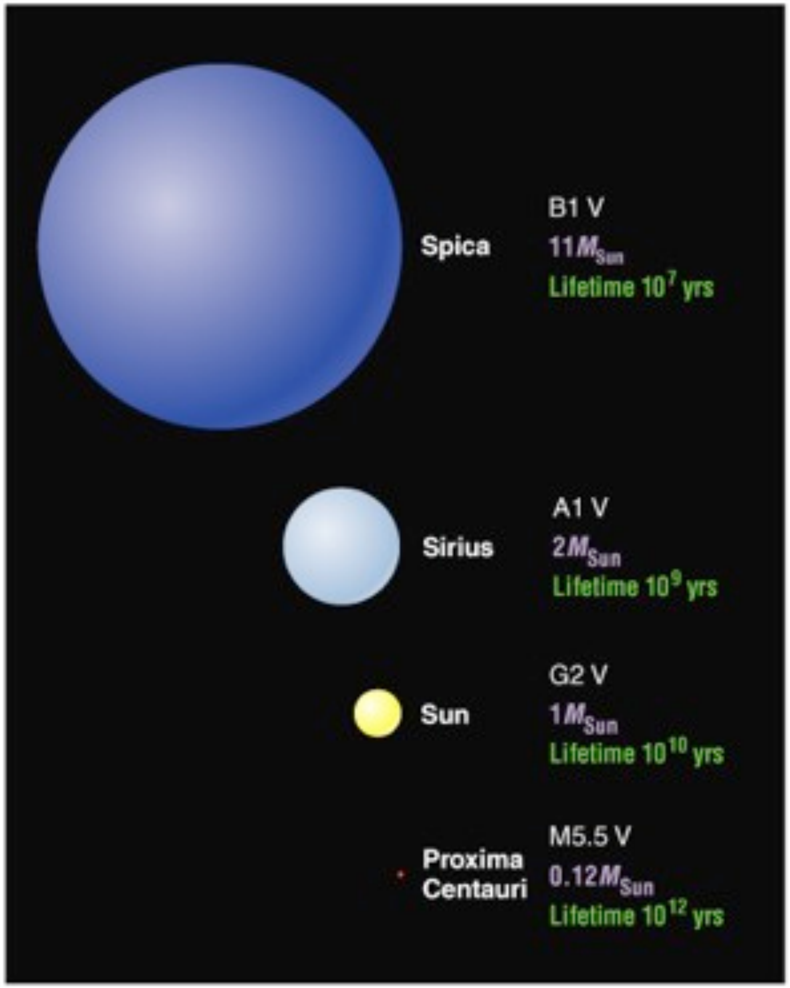
A main sequence star is in equilibrium as Hydrogen burning supports it against gravitational collapse.

What happens as the hydrogen runs out?

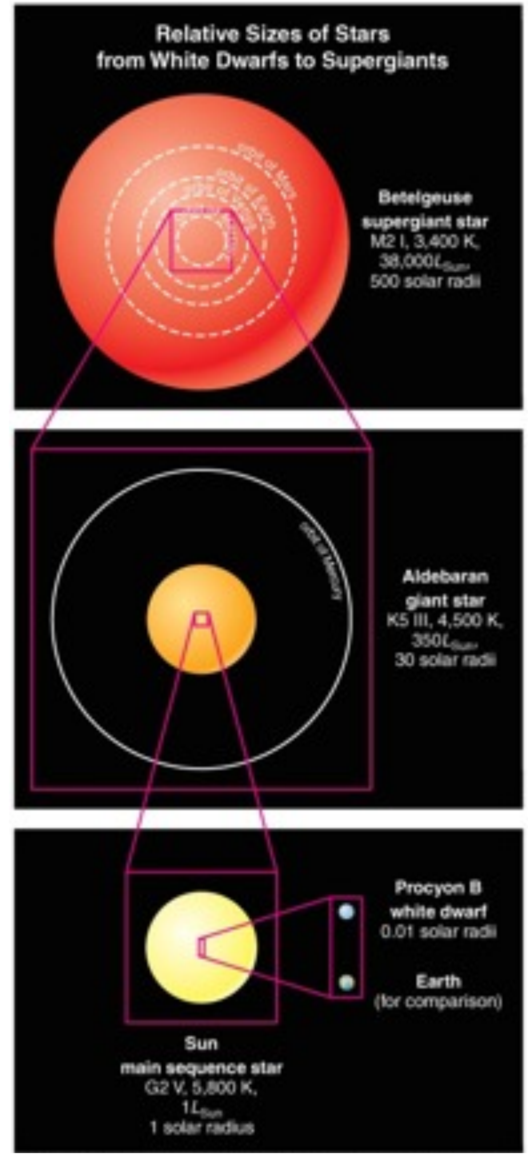


# Off the Main Sequence

- 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.**

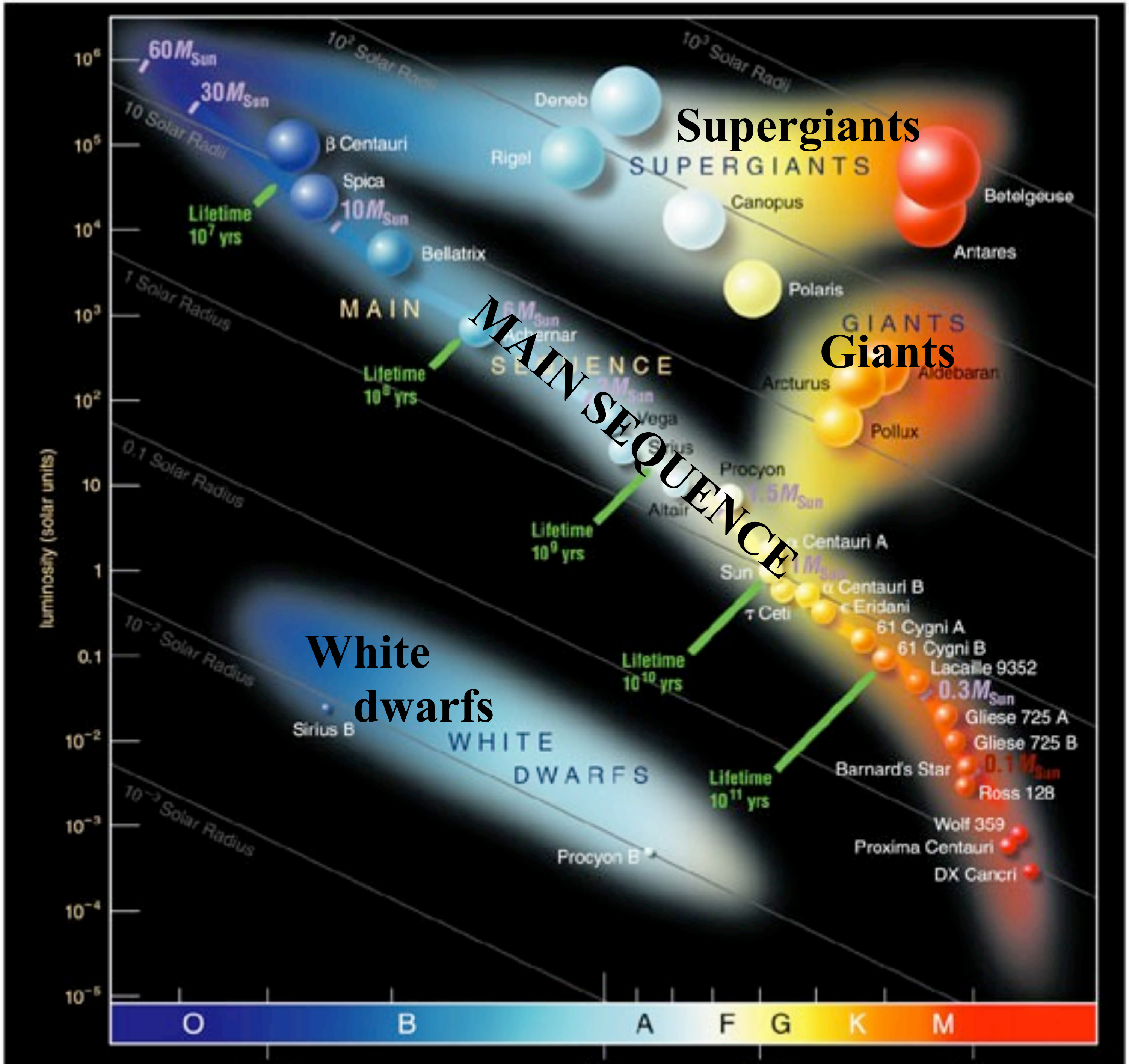



Main-sequence stars (to scale)




Giants, supergiants, white dwarfs

# The various branches of stars in the HR diagram



# Much of this learned from studying Star Clusters

Physically associated groups of stars
All the same age, the same distance away

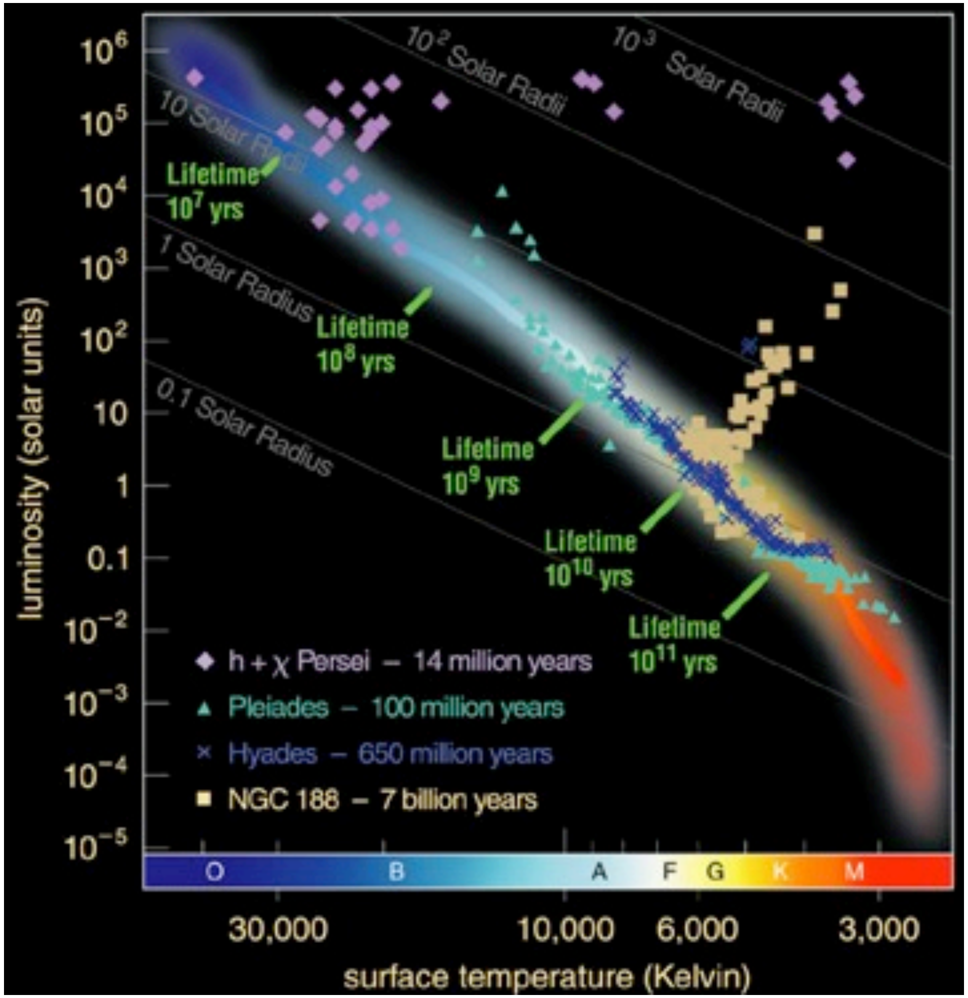
***Open cluster***

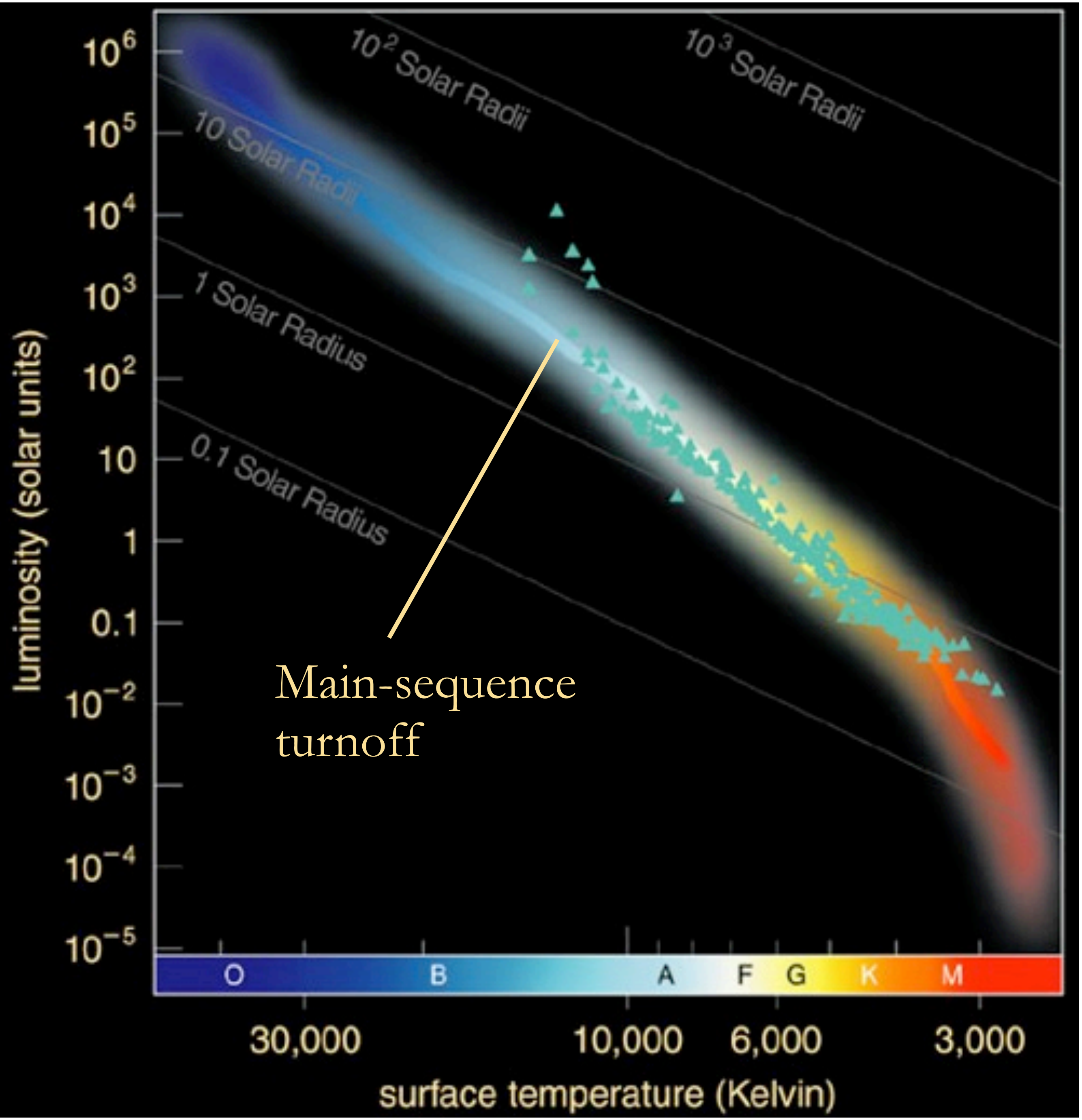
***Globular cluster***

***Open cluster:*** A few thousand loosely packed stars

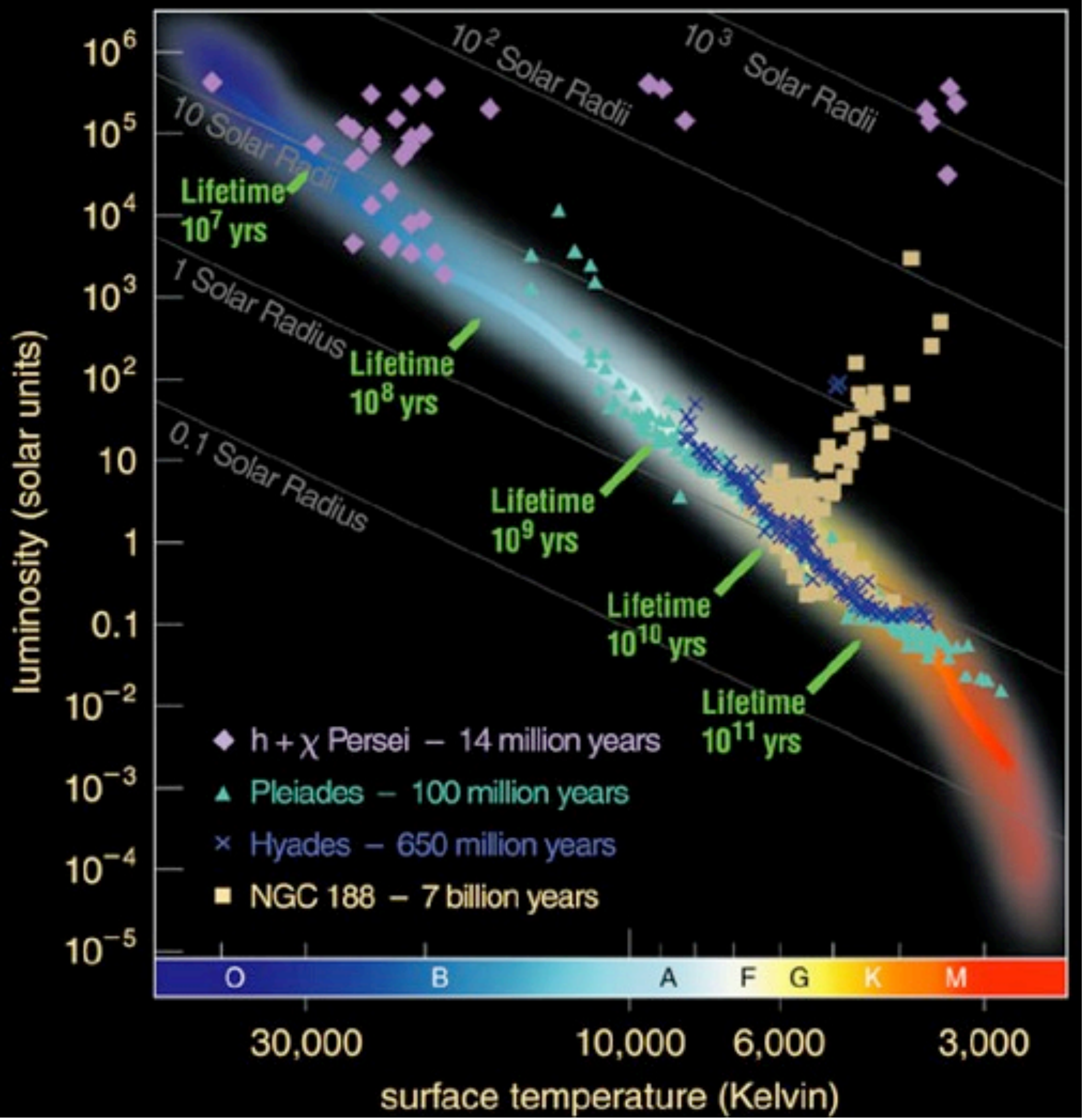
***Globular cluster:*** Millions of stars in a dense ball bound together by gravity

# Measuring the age of a star cluster

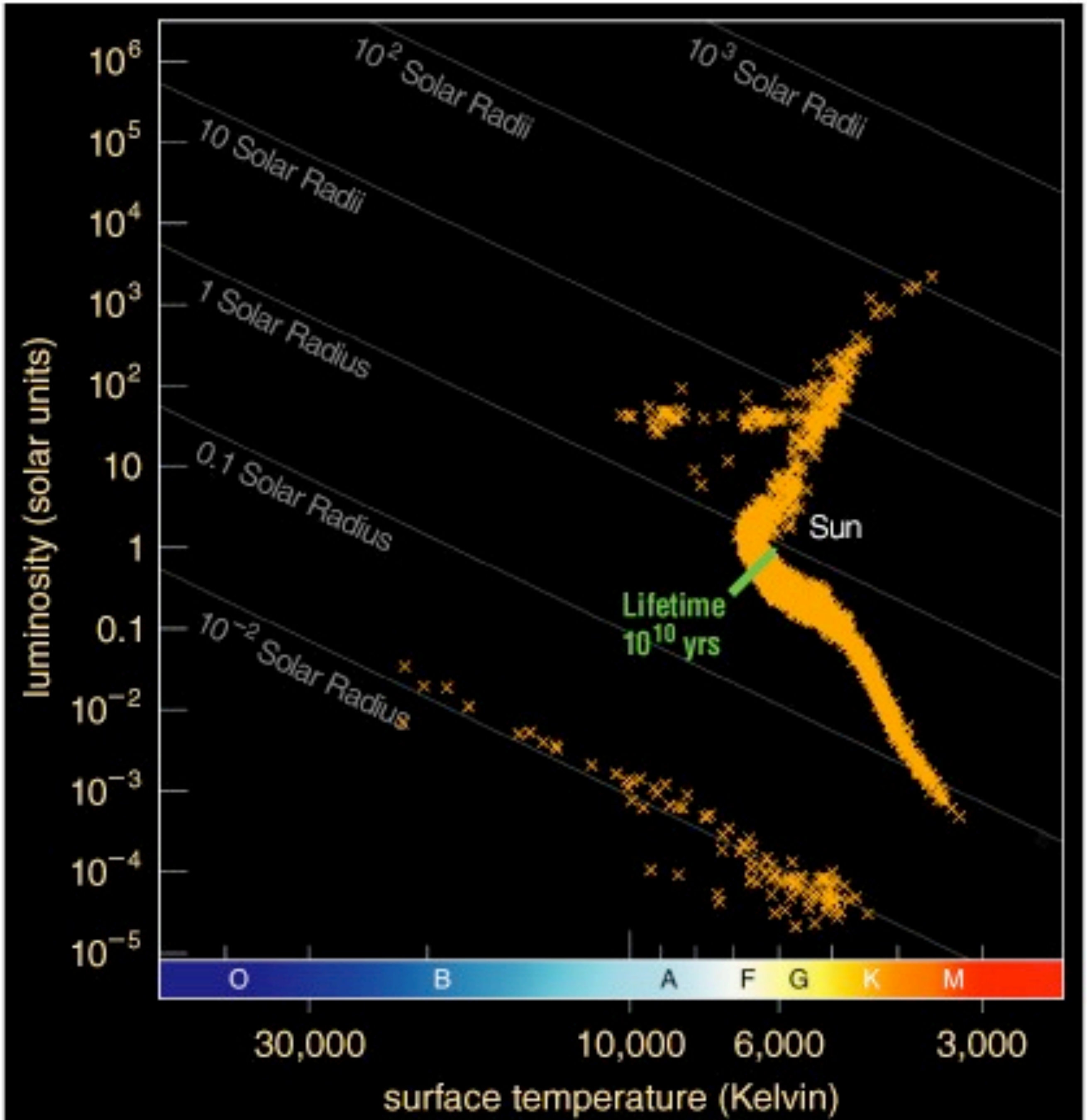





Pleiades now has no stars with life expectancy less than around 100 million years.

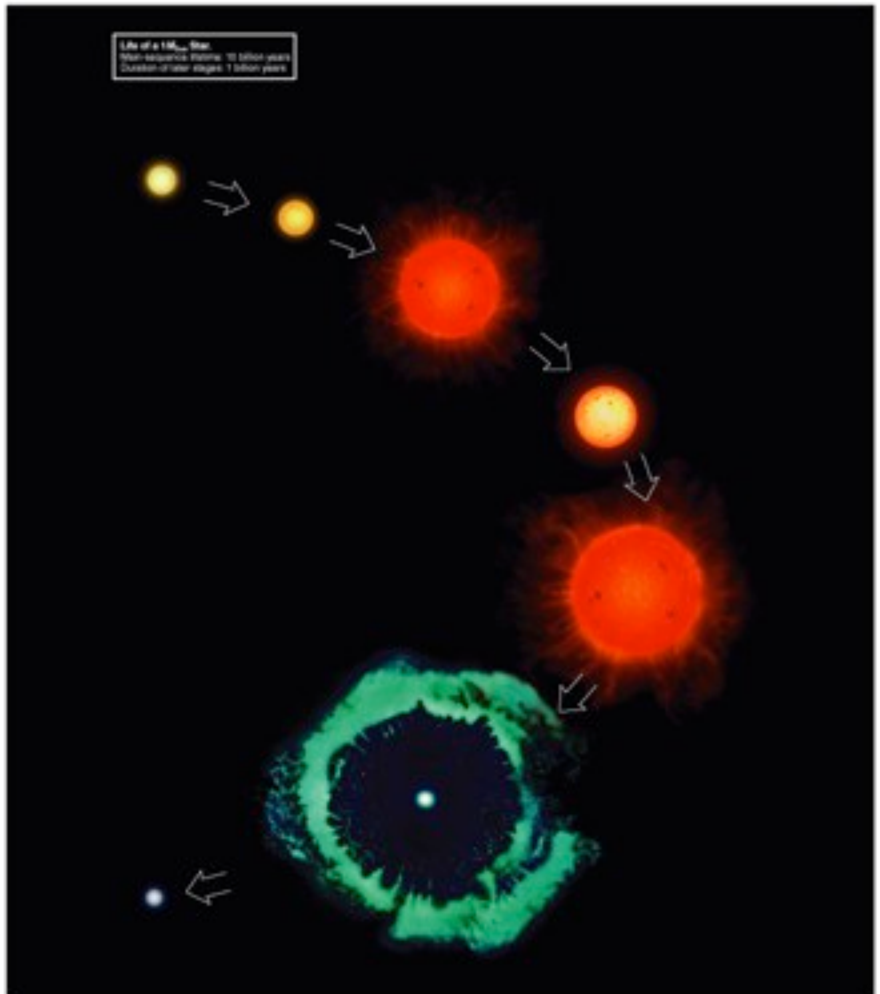



The **main-sequence turnoff point** of a cluster tells us its age.

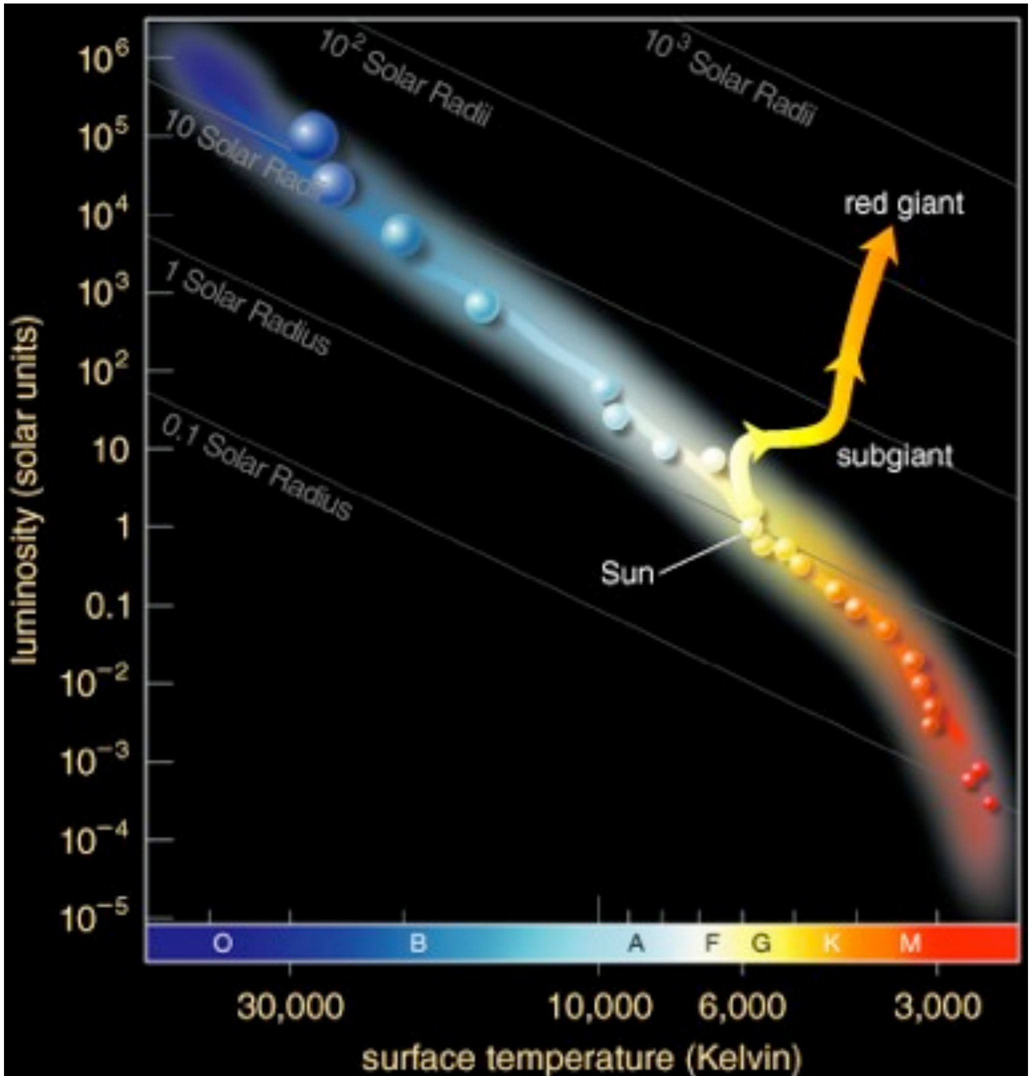



Detailed modeling of the oldest globular clusters reveals that they are about 13 billion years old.

# The life stages of a low-mass star



# Life Track After Main Sequence

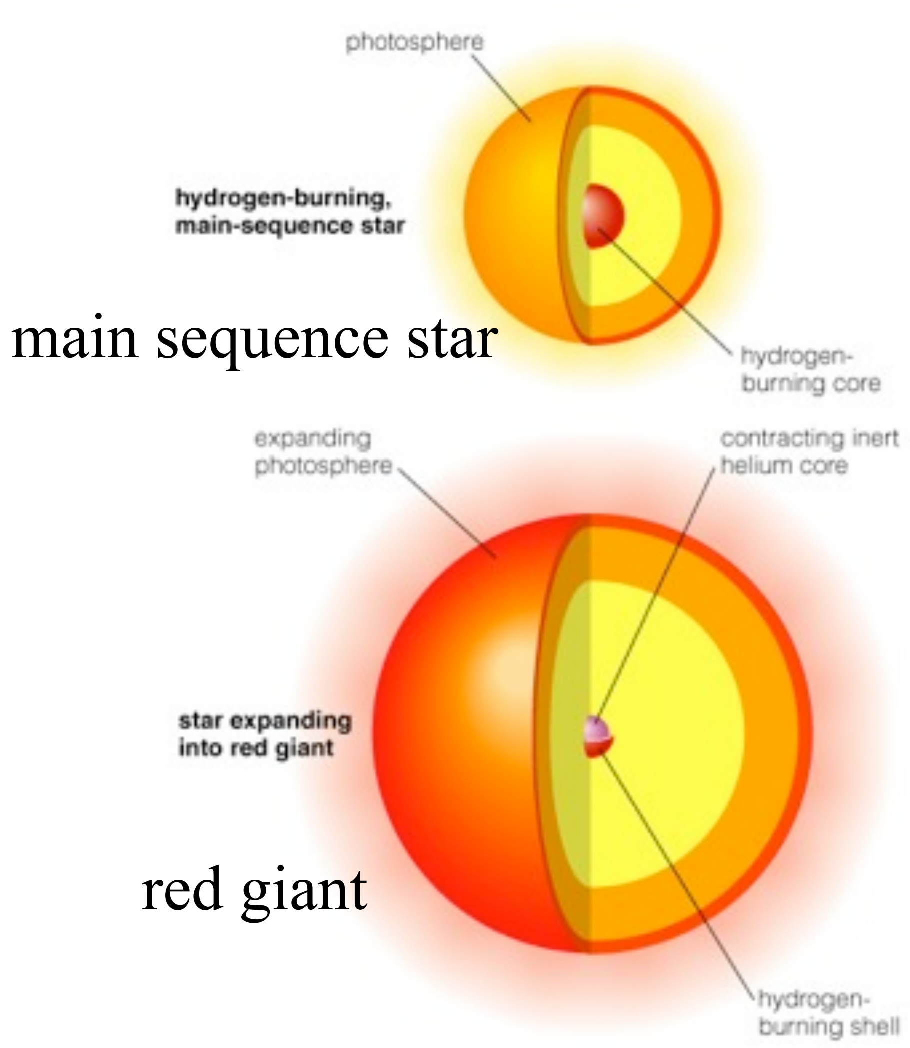





- Observations of star clusters show that a star becomes larger, redder, and more luminous after its time on the main sequence is over.

- 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.