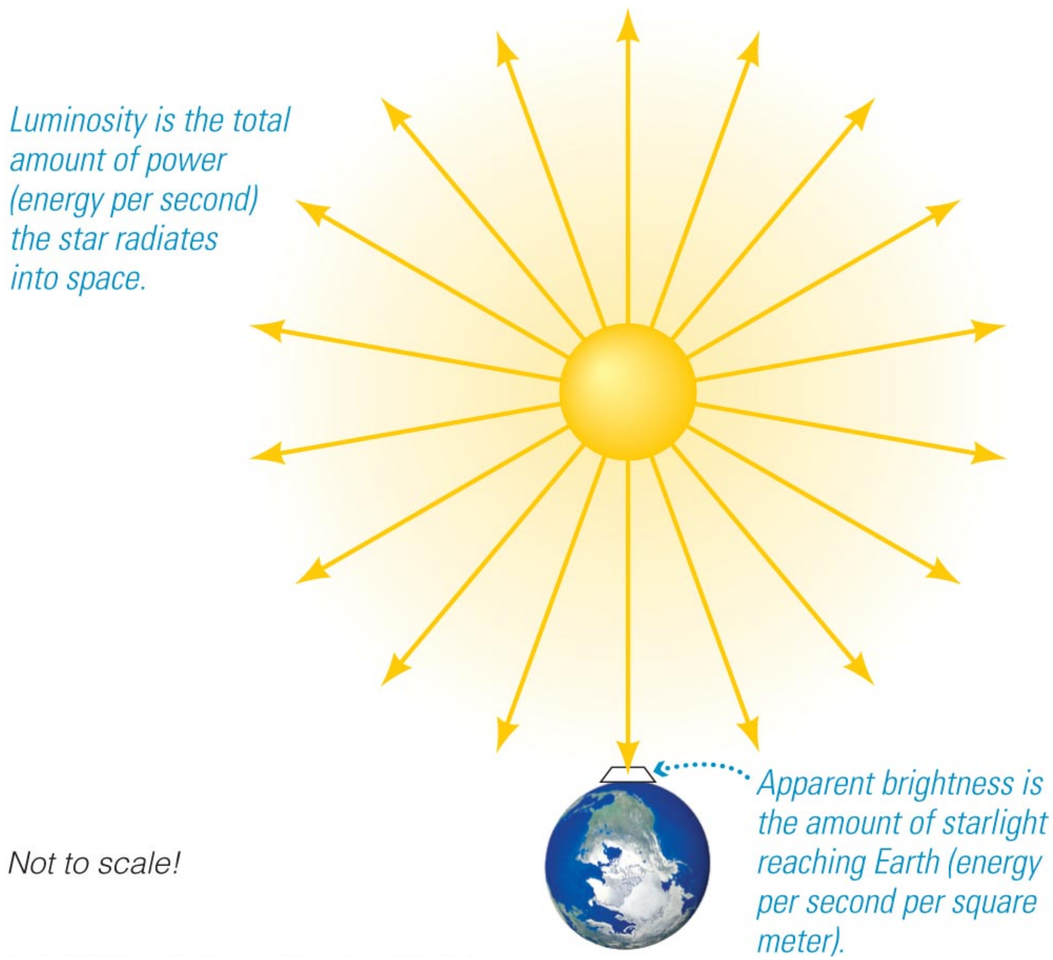
Surveying the Stars



Luminosity:

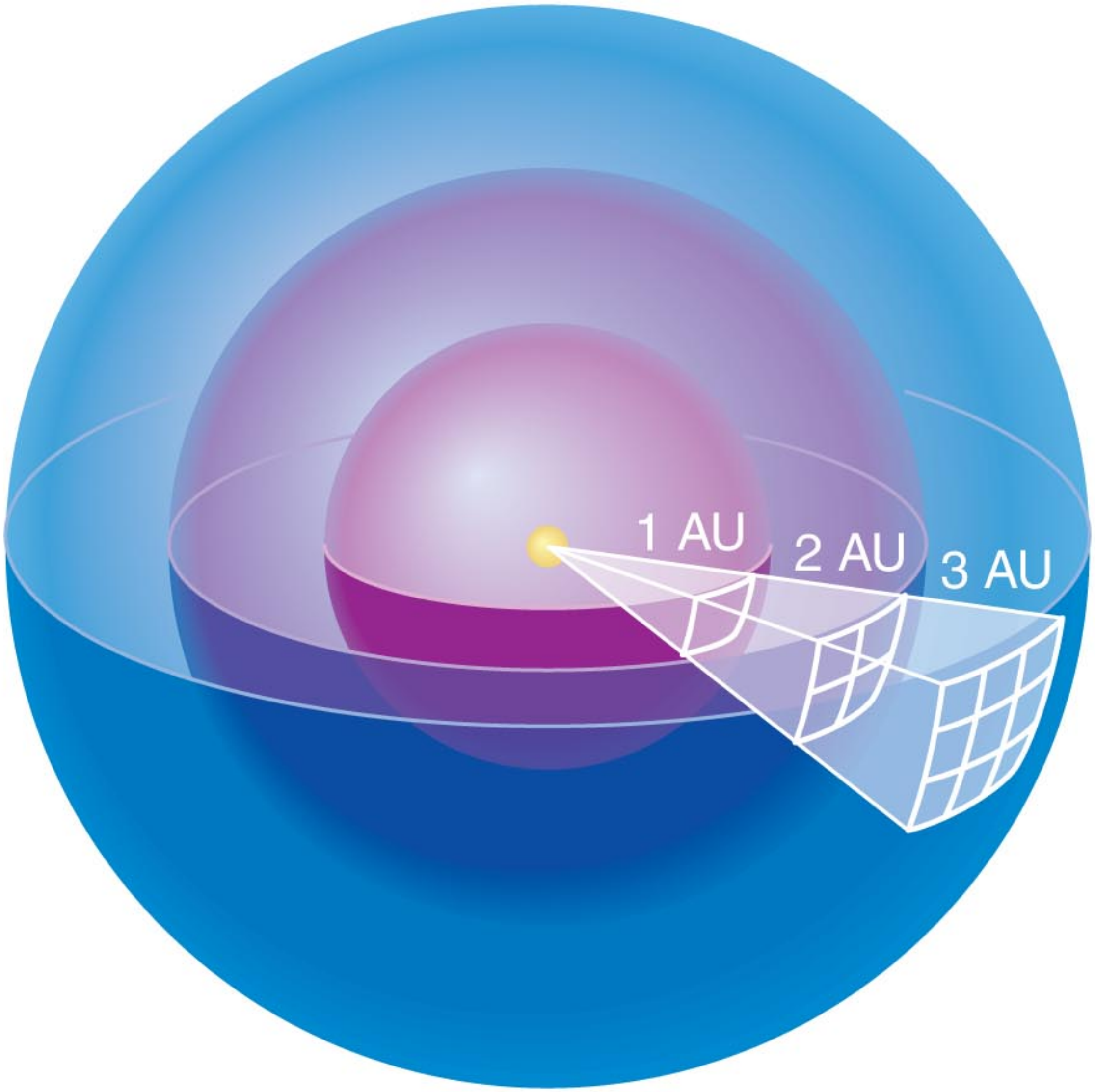
Amount of power a star radiates

(energy per second = watts)

Apparent brightness:

Amount of starlight that reaches Earth

(energy per second per square meter)



Luminosity passing through each sphere is the same

Area of sphere:

$$4\pi\ (\text{radius})^2$$

Divide luminosity by area to get brightness

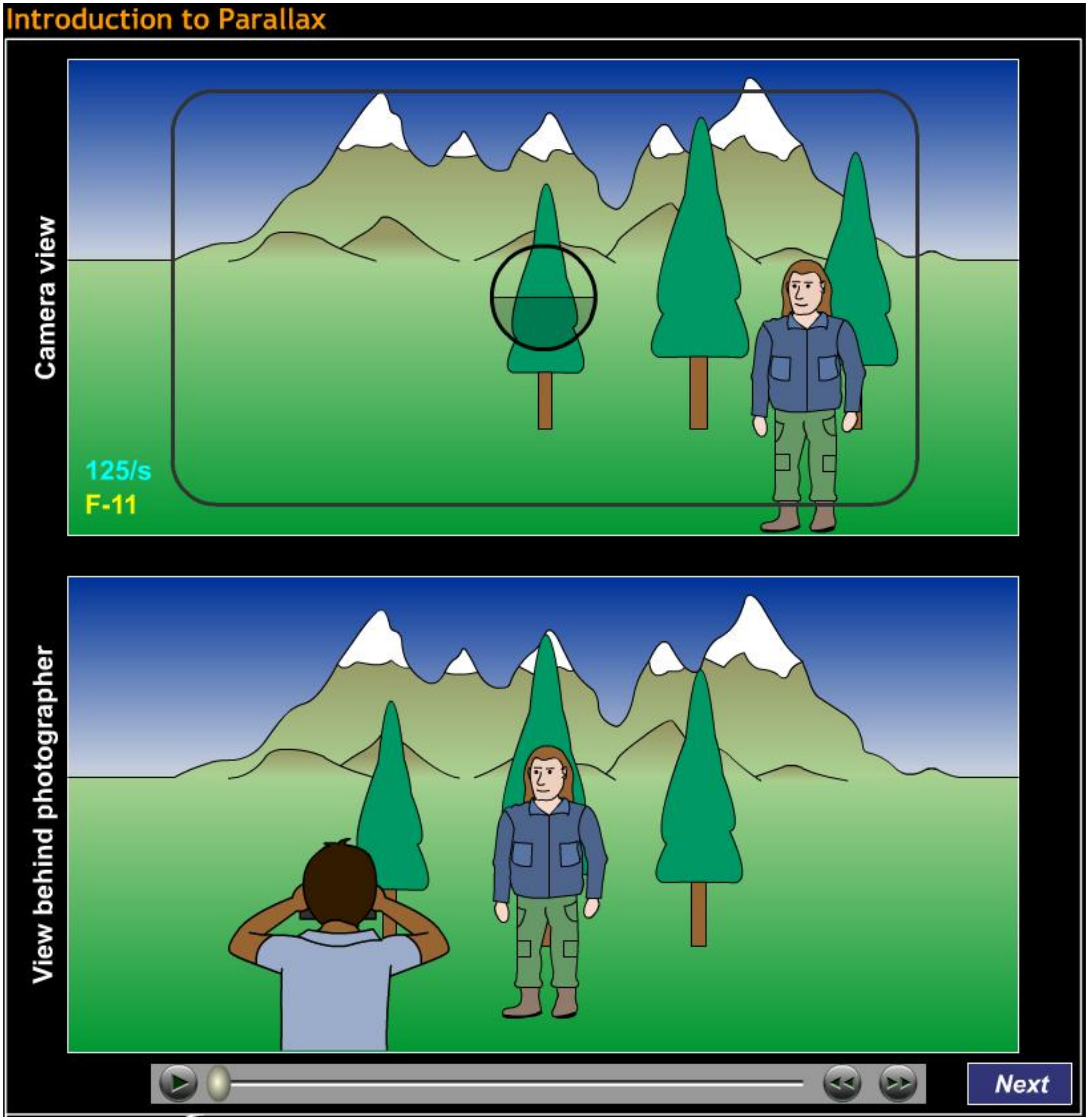
The relationship between apparent brightness and luminosity depends on distance:

$$\text{Brightness} = \frac{\text{Luminosity}}{4\pi\,(\text{distance})^2}$$

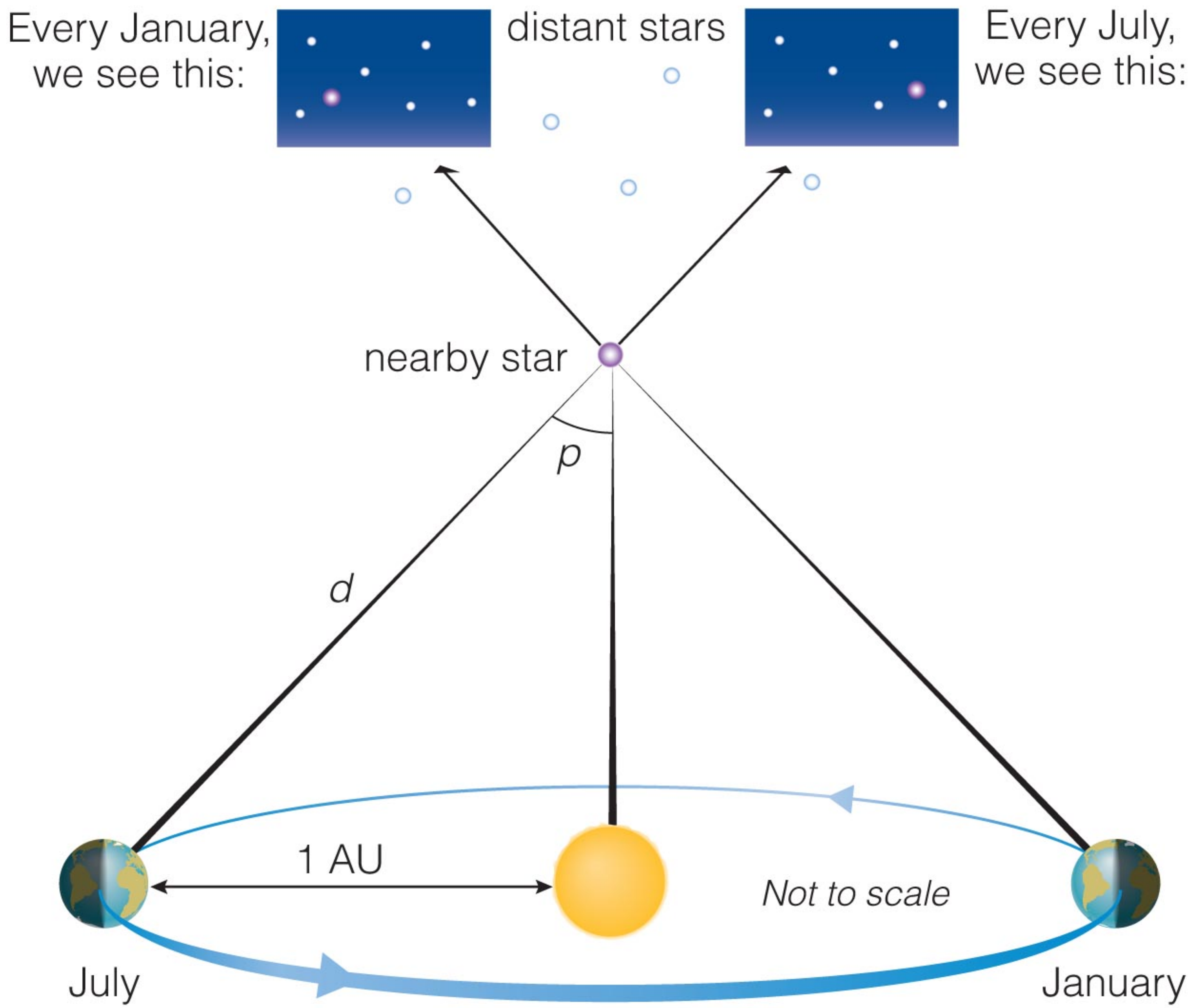
We can determine a star's luminosity if we can measure its distance and apparent brightness:

$$\text{Luminosity} = 4\pi\,(\text{distance})^2 \times (\text{Brightness})$$

Distances to stars



Parallax
is the apparent shift in position of a nearby object against a background of more distant objects


Every January,
we see this:
distant stars
Every July,
we see this:
nearby star
p
d
1 AU
Not to scale
July
January

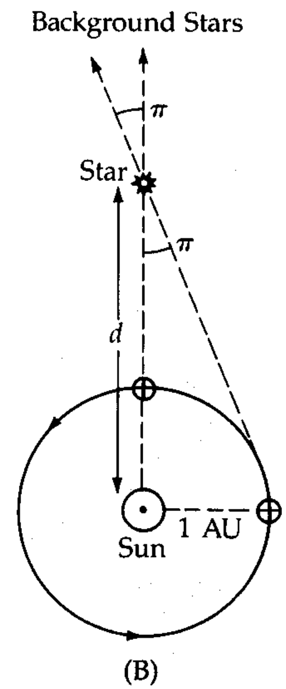
Parallax and Distance

$$p = \text{parallax angle}$$

$$d \text{ (in parsecs)} = \frac{1}{p \text{ (in arcseconds)}}$$

$$d \text{ (in light - years)} = 3.26 \times \frac{1}{p \text{ (in arcseconds)}}$$

Parallax



- (Bessel 1838)
  - π ["] = 1 / d [pc] from π [rad] = 1 / d [AU]

    where 1 pc = 206265 AU (1AU = 1.5E8 km)
    = 3.26 light yr
    = 3.1E13 km

  - 1 parsec = “that distance at which parallax is 1 arcsec”

  - measured w.r.t. sun!
  - parallactic orbits – ellipse in sky
  - nearest star - π =0.76 arcsec (Proxima Centauri), d=???
  - Limits: +-0.001 arcsec

Most luminous stars:

10^6 L_{Sun}

Least luminous stars:

10^{-4} L_{Sun}

(L_{Sun} is luminosity of Sun)

Magnitudes and Fluxes

$$m_1 - m_2 = 2.5\log_{10}(\ell_2/\ell_1)$$

$$\ell_2/\ell_1 = 10^{0.4(m_1 - m_2)}$$

- Backwards, logarithmic, no zeropoint
  - Mag differences correspond to flux ratios
- Origins - Hipparchos "1st-6th mags"
  - Herschel - factor of 100x in brightness
- Each mag is a factor of 2.512…x in brightness
  - 2.5 mag = 10x, 5 mag= 100x, 10mag = 10^4x, …
- Combining mags: convert to flux first
- Small Δm:

$$\Delta\ell/\ell \cong \Delta m$$

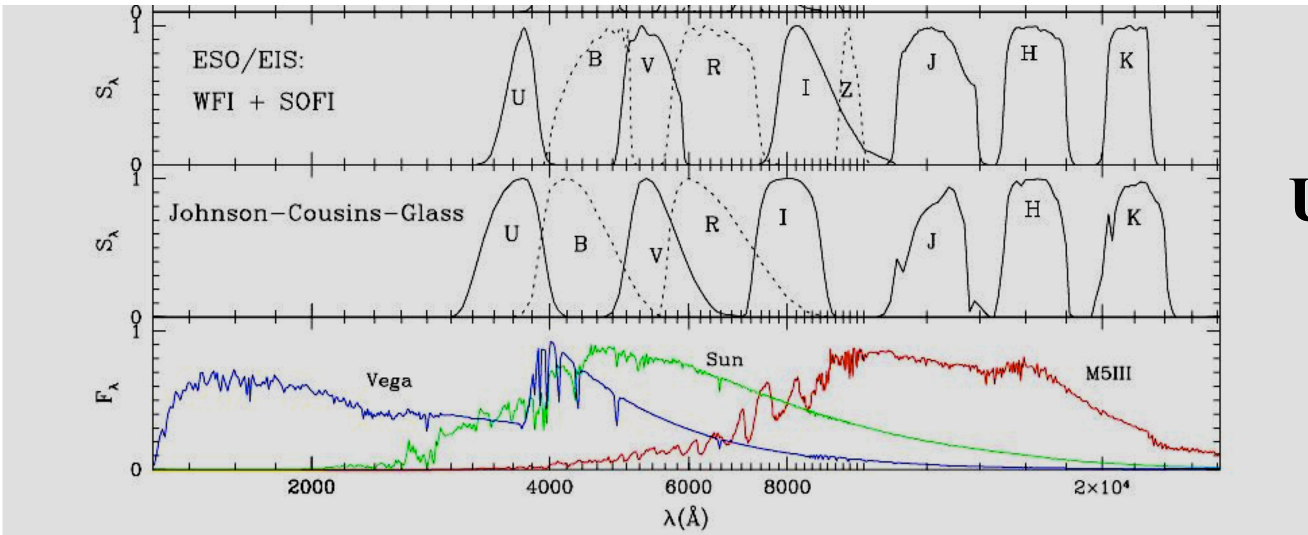
- *Apparent vs. Absolute magnitude*:
  - abs mag is apparent magnitude if the object were at a distance of 10pc
  - From inverse square law (Euclidean space):

$$m - M = 5\log_{10} d_{pc} - 5 = \text{"distance modulus"}$$

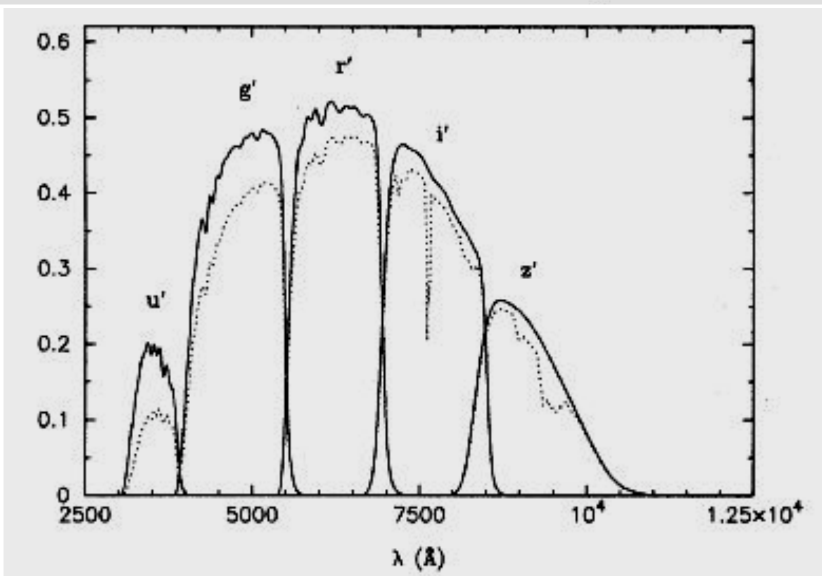
App mag **Abs mag** ***Must*** **be in parsecs, not kpc or Mpc**

- *Magnitude systems* - examples:
  - UBVRIJHK…
  - griz
  - …

Photometric band-passes



UBVRIJHK



Sloan Digital Sky Survey

- Zero points
  - Vega system for UBVRIJK

Table 7.5. *Filter wavelengths, bandwidths, and flux densities for Vega.*[a]

Filter name	λ_{iso}[b] (μm)	$\Delta\lambda$[c] (μm)	F_λ (W m^{-2} μm^{-1})	F_ν (Jy)	N_ϕ (photons s^{-1} m^{-2} μm^{-1})
V	0.5556[d]	...	3.44×10^{-8}	3 540	9.60×10^{10}
J	1.215	0.26	3.31×10^{-9}	1 630	2.02×10^{10}
H	1.654	0.29	1.15×10^{-9}	1 050	9.56×10^{9}
K_s	2.157	0.32	4.30×10^{-10}	667	4.66×10^{9}
K	2.179	0.41	4.14×10^{-10}	655	4.53×10^{9}
L	3.547	0.57	6.59×10^{-11}	276	1.17×10^{9}
L'	3.761	0.65	5.26×10^{-11}	248	9.94×10^{8}
M	4.769	0.45	2.11×10^{-11}	160	5.06×10^{8}
8.7	8.756	1.2	1.96×10^{-12}	50.0	8.62×10^{7}
N	10.472	5.19	9.63×10^{-13}	35.2	5.07×10^{7}
11.7	11.653	1.2	6.31×10^{-13}	28.6	3.69×10^{7}
Q	20.130	7.8	7.18×10^{-14}	9.70	7.26×10^{6}

Notes

[a] Cohen et al. [1] recommend the use of Sirius rather than Vega as the photometric standard for $\lambda > 20$ μm because of the infrared excess of Vega at these wavelengths. The magnitude of Vega depends on the photometric system used, and it is either assumed to be 0.0 mag or assumed to be 0.02 or 0.03 mag for consistency with the visual magnitude.

[b] The infrared isophotal wavelengths and flux densities (except for K_s) are taken from Table 1 of [1], and they are based on the UKIRT filter set and the atmospheric absorption at Mauna Kea. See Table 2 of [1] for the case of the atmospheric absorption at Kitt Peak. The isophotal wavelength is defined by $F(\lambda_{iso}) = \int F(\lambda)S(\lambda)\,d\lambda / \int S(\lambda)\,d\lambda$, where $F(\lambda)$ is the flux density of Vega and $S(\lambda)$ is the (detector quantum efficiency) $\times$ (filter transmission) $\times$ (optical efficiency) $\times$ (atmospheric transmission) [2]. λ_{iso} depends on the spectral shape of the source and a correction must be applied for broadband photometry of sources that deviate from the spectral shape of the standard star [3]. The flux density and λ_{iso} for K_s were calculated here. For another filter, K', at 2.11 μm, see [4].

[c] The filter full width at half maximum.

[d] The wavelength at V is a monochromatic wavelength; see [5].

References

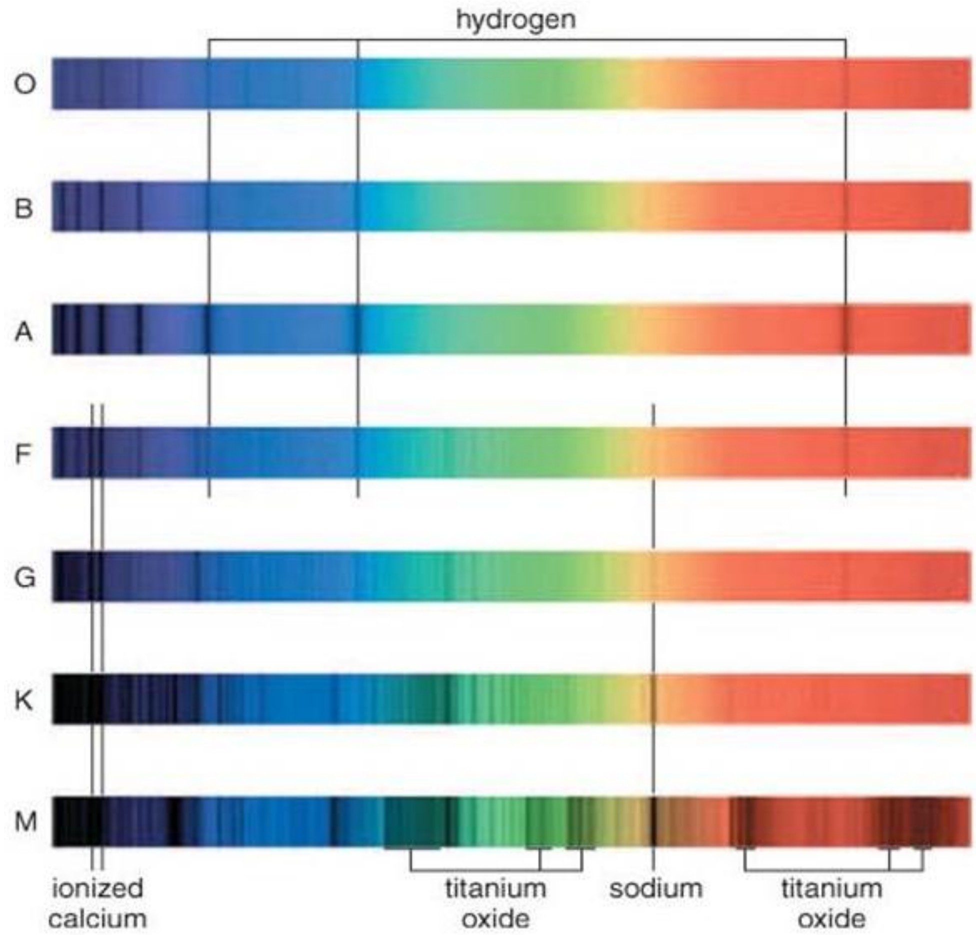
1. Cohen, M. et al. 1992, *AJ*, **104**, 1650
2. Golay, M. 1974, *Introduction to Astronomical Photometry* (Reidel, Dordrecht), p. 40
3. Hanner, M.S., et al. 1984, *AJ*, **89**, 162
4. Wainscoat, R.J., & Cowie, L.L. 1992, *AJ*, **103**, 332
5. Hayes, D.S. 1985, in *Calibration of Fundamental Stellar Quantities*, edited by D.S. Hayes, et al., Proc. IAU Symp. No. 111 (Reidel, Dordrecht), p. 225

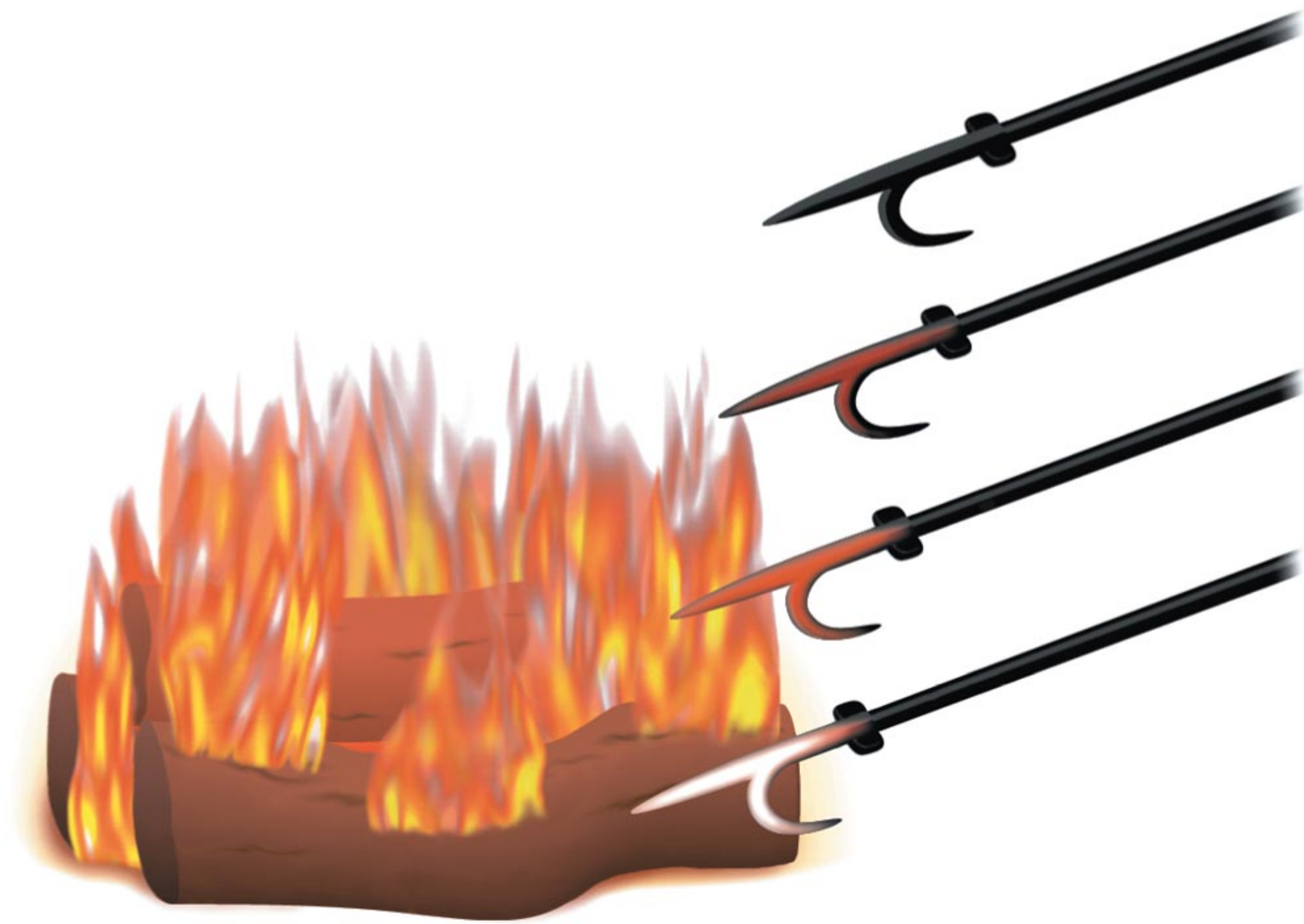
  - AB system for griz…
    - m_{AB}=0 corresponds to 3.63×10^{-20} erg s^{-1} cm^{-2} Hz^{-1}

$$m_{AB} = -2.5\log_{10} f_\nu[\mathrm{erg\ s^{-1}cm^{-2}Hz^{-1}}] - 48.60$$

  - Warning: sometimes UBVRIJHK is in the AB system!!

How do we measure stellar temperatures?

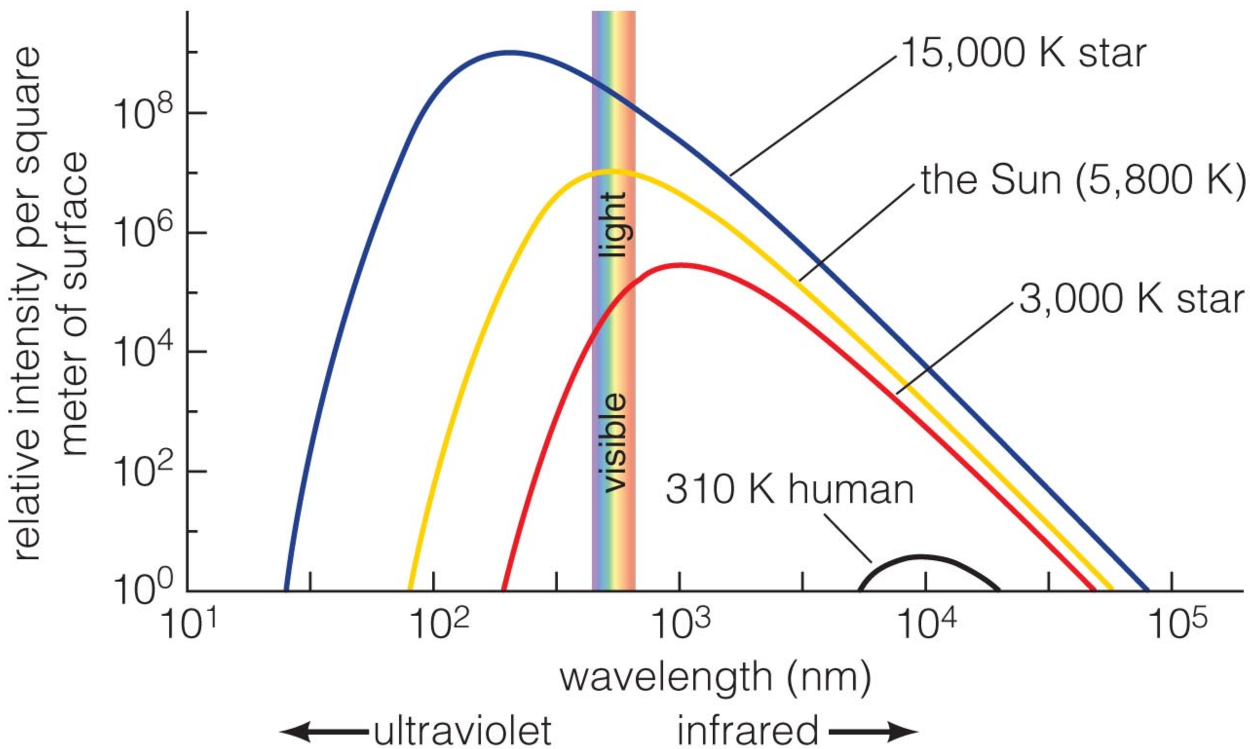




Every object emits ***thermal radiation*** with a spectrum that depends on its temperature

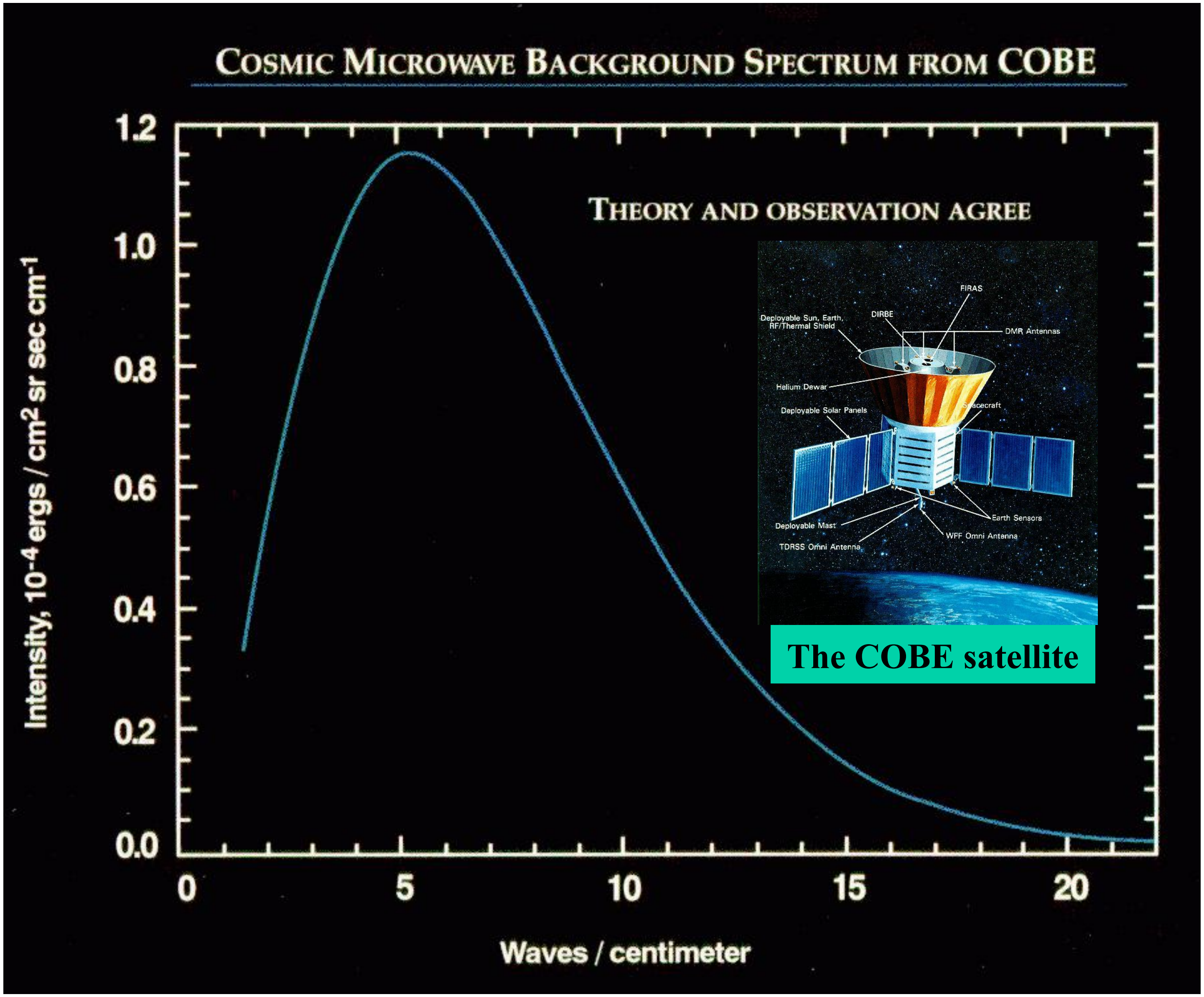
Properties of Thermal Radiation

1. Hotter objects emit more light per unit area at all frequencies.
2. Hotter objects emit photons with a higher average energy.



Energy emitted by a "black body" per unit area depends *only* on temperature.

The Perfect Black Body



$\lambda_{max}=(2.9/T_K)$mm

Wien's displacement law

The Universe has a well-defined temperature: 2.7K

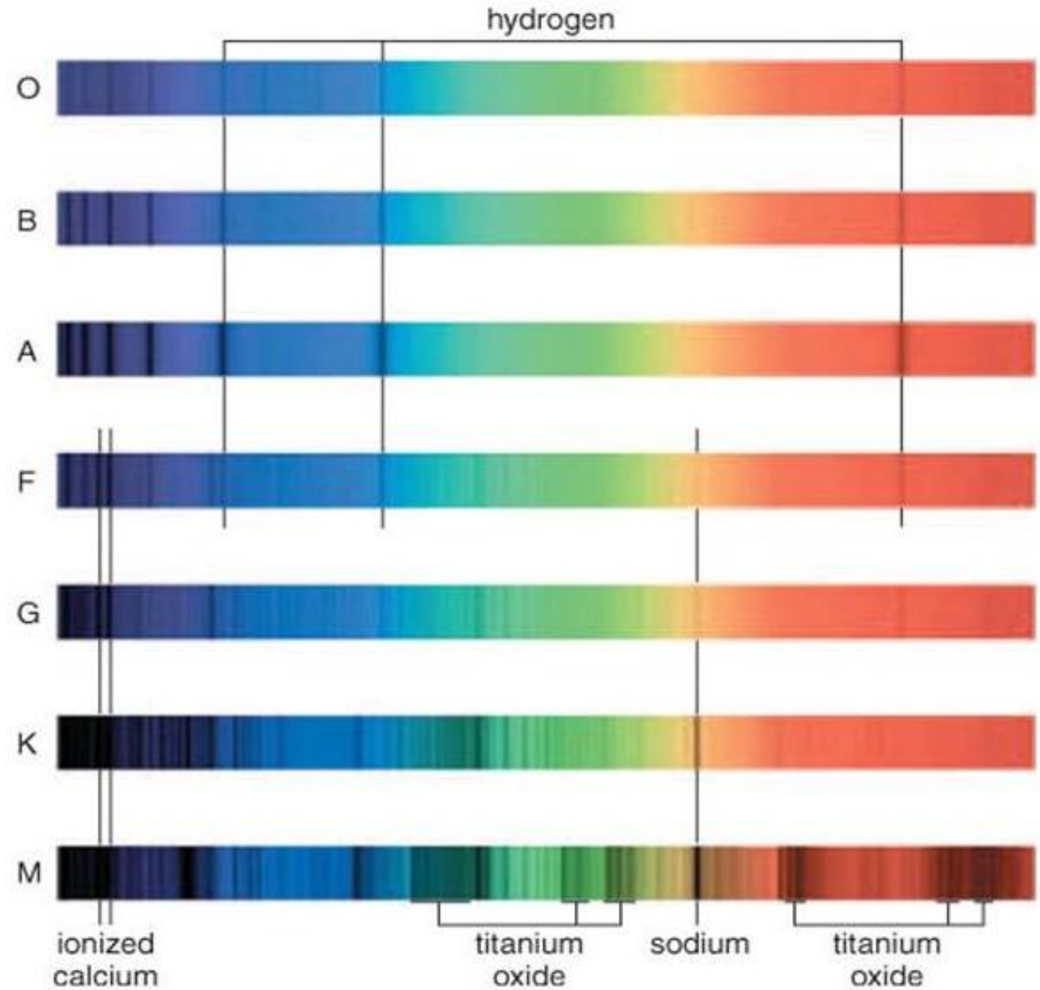
Hottest stars:

50,000 K

Coolest stars:

3,000 K

(Sun's surface is 5,800 K)



Lines in a star's spectrum correspond to a ***spectral type*** that reveals its temperature

(Hottest) O B A F G K M (Coolest)

Pioneers of Stellar Classification

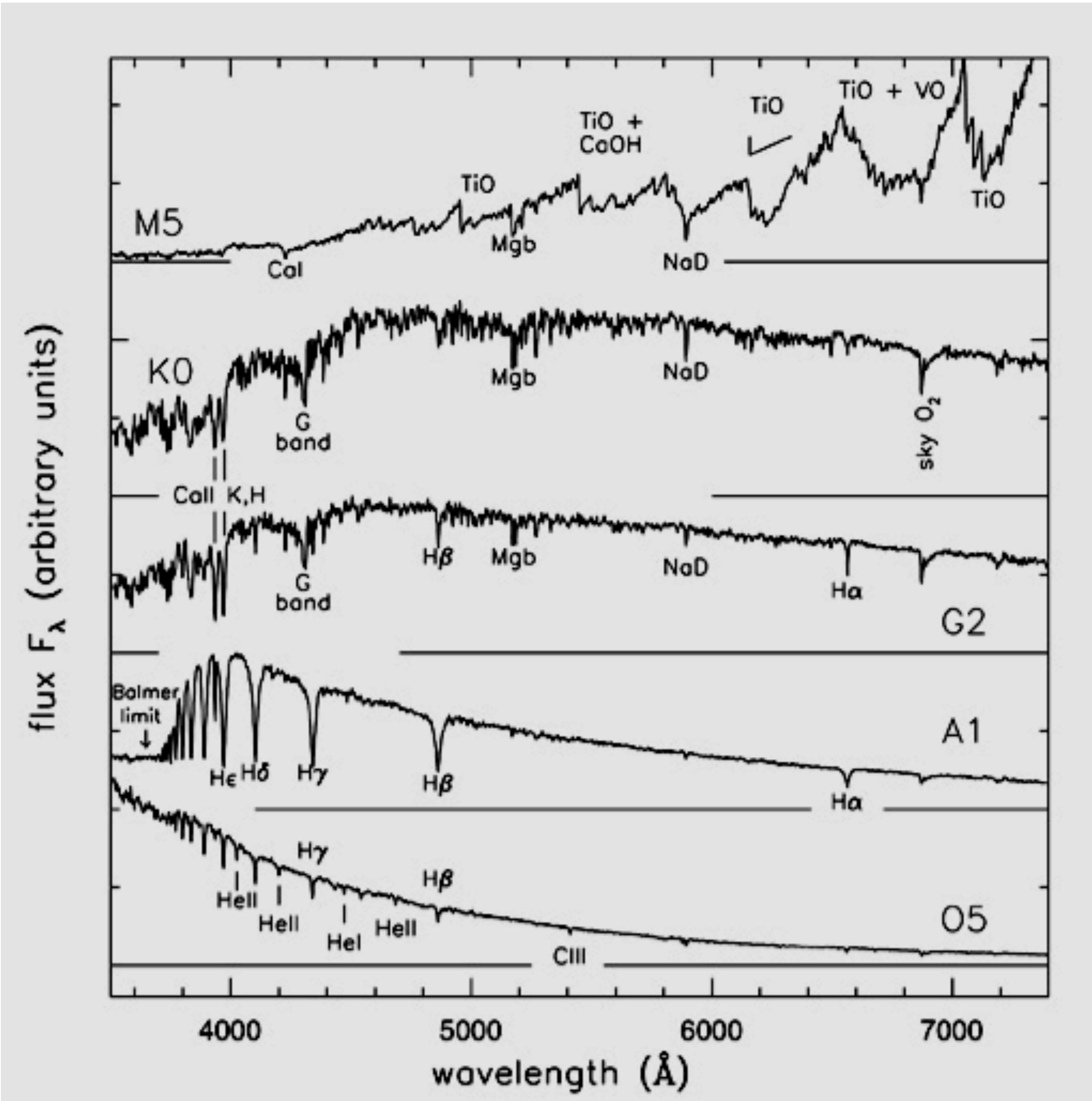
- Annie Jump Cannon and the "computers" at Harvard laid the foundation of modern stellar classification

Remembering Spectral Types

(Hottest) O B A F G K M (Coolest)

- Oh, Be A Fine Girl, Kiss Me
- Only Boys Accepting Feminism Get Kissed Meaningfully

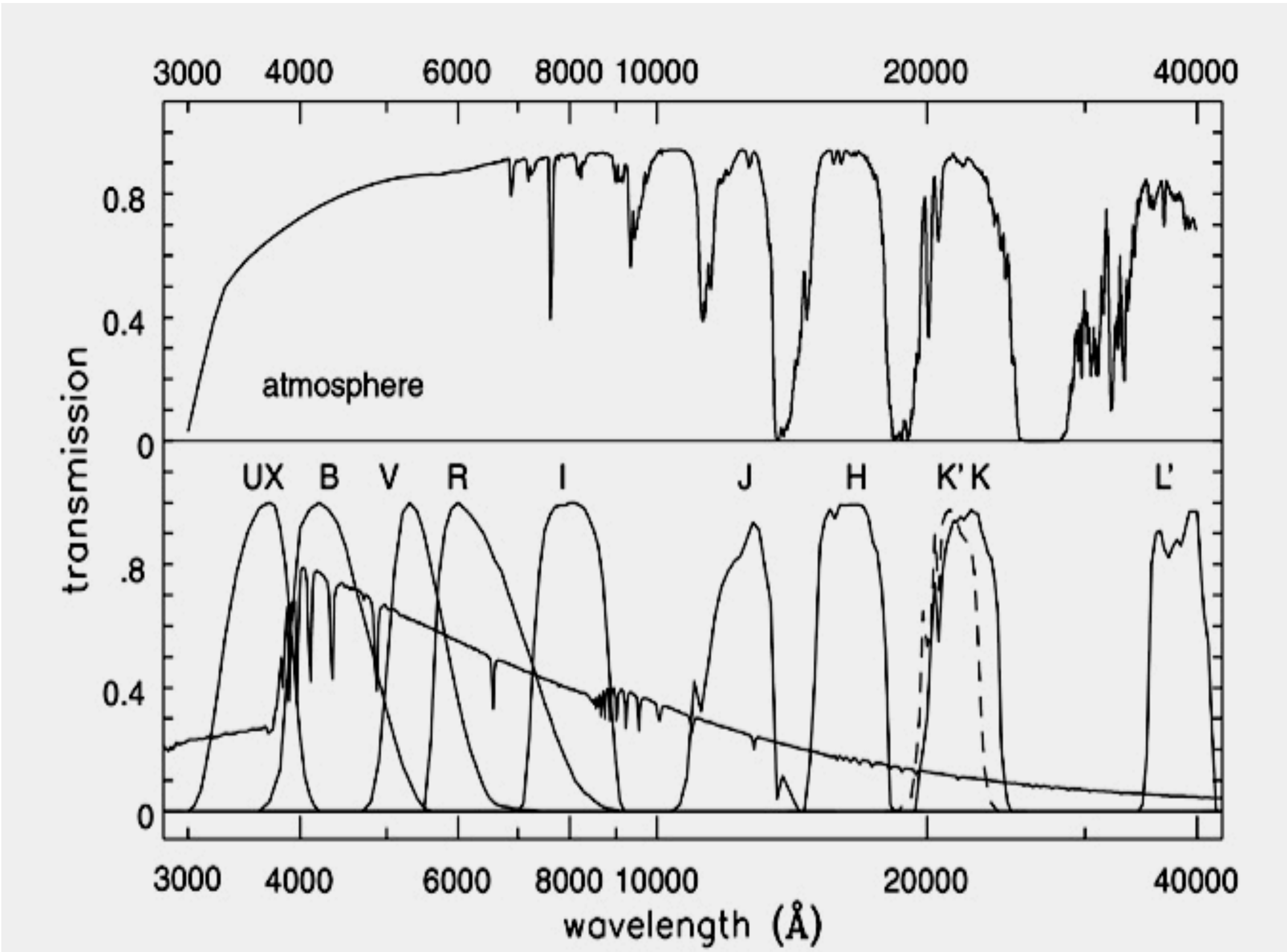
Temperature and Spectral Classification



The shape of the spectrum and its features correlate strongly with the star's temperature.

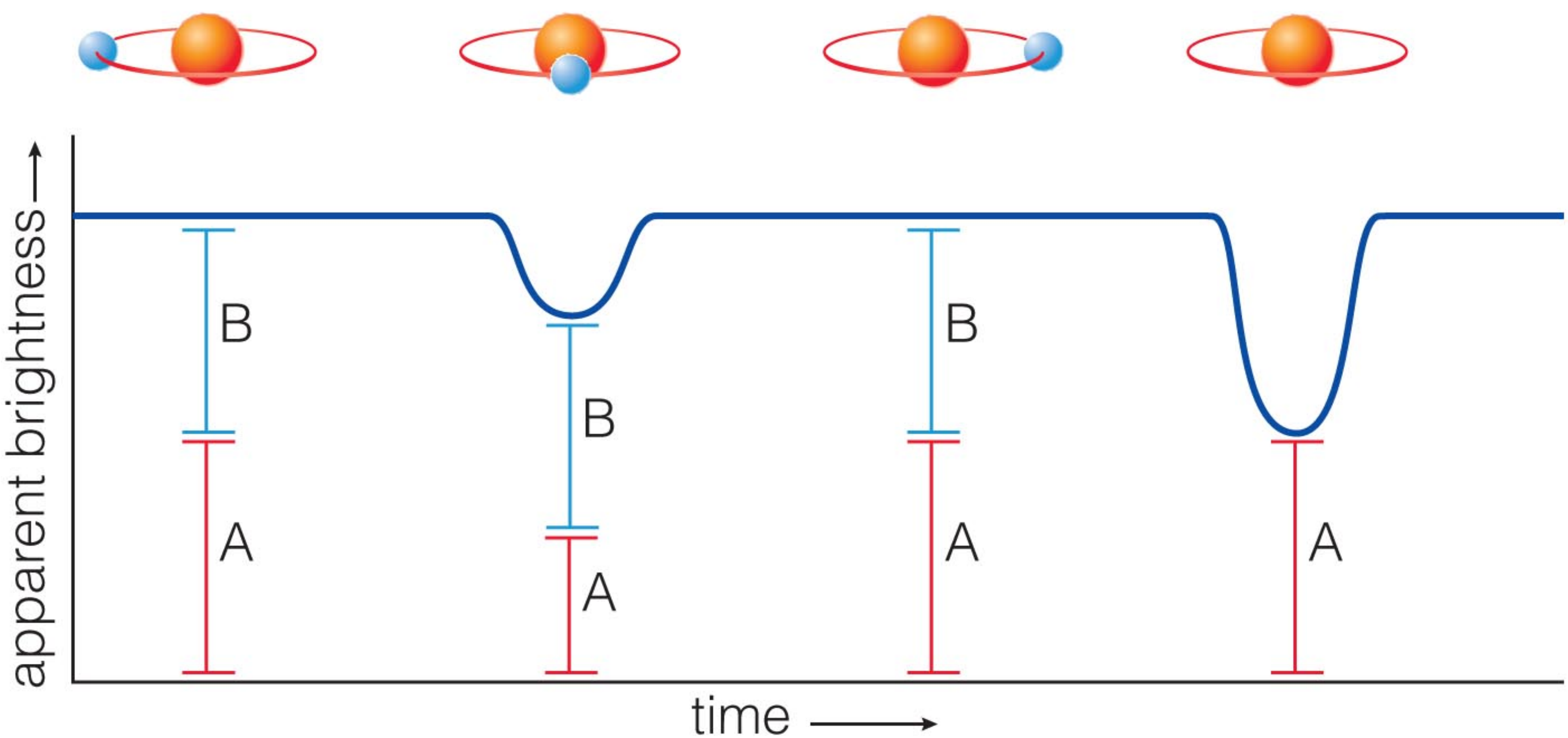
They also depend on a star's composition

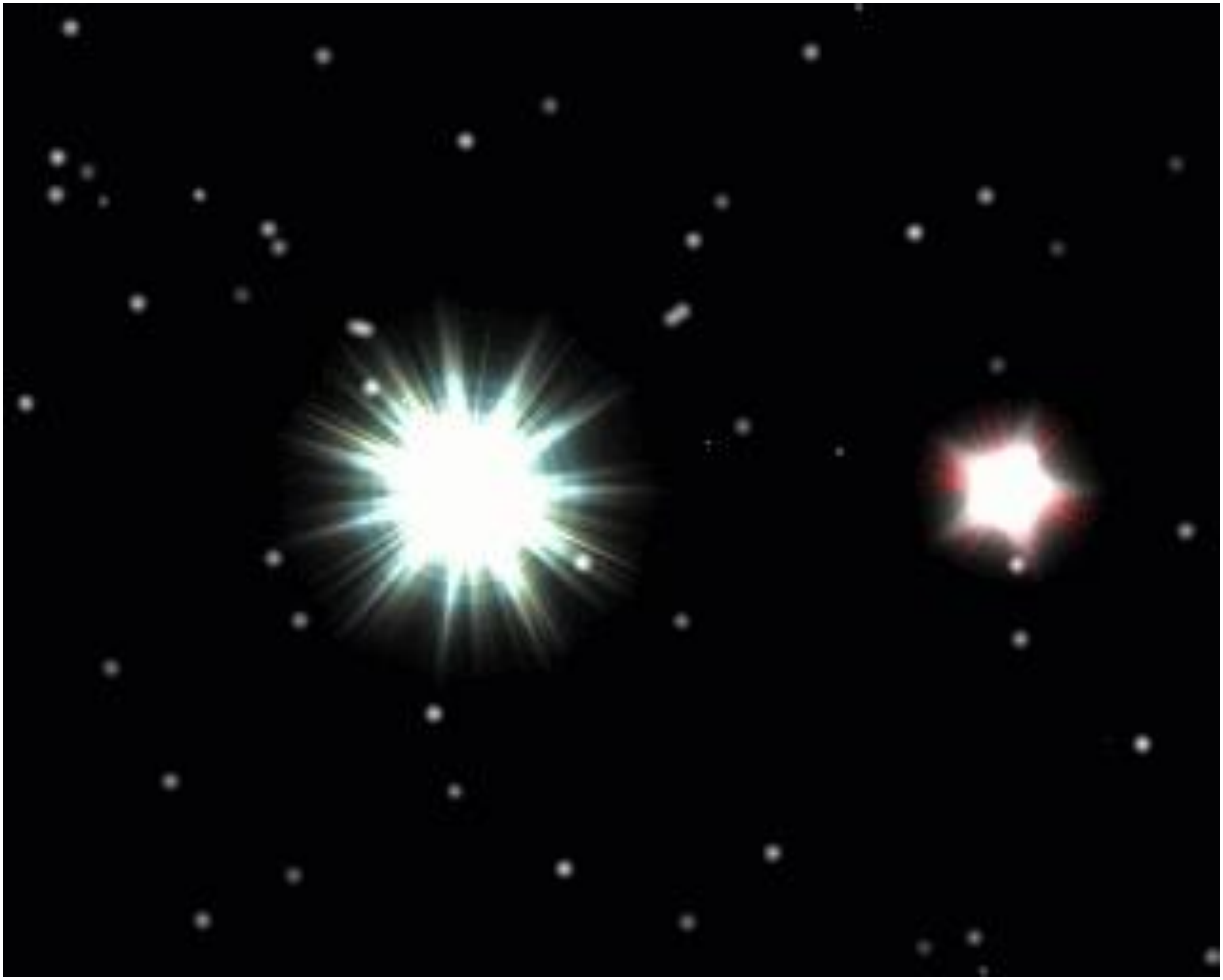
Spectral Classification and Photometric Bandpasses



Bandpasses are chosen to either bracket features in a star's spectrum or to track portions of the spectrum where the Earth's atmosphere is transparent.

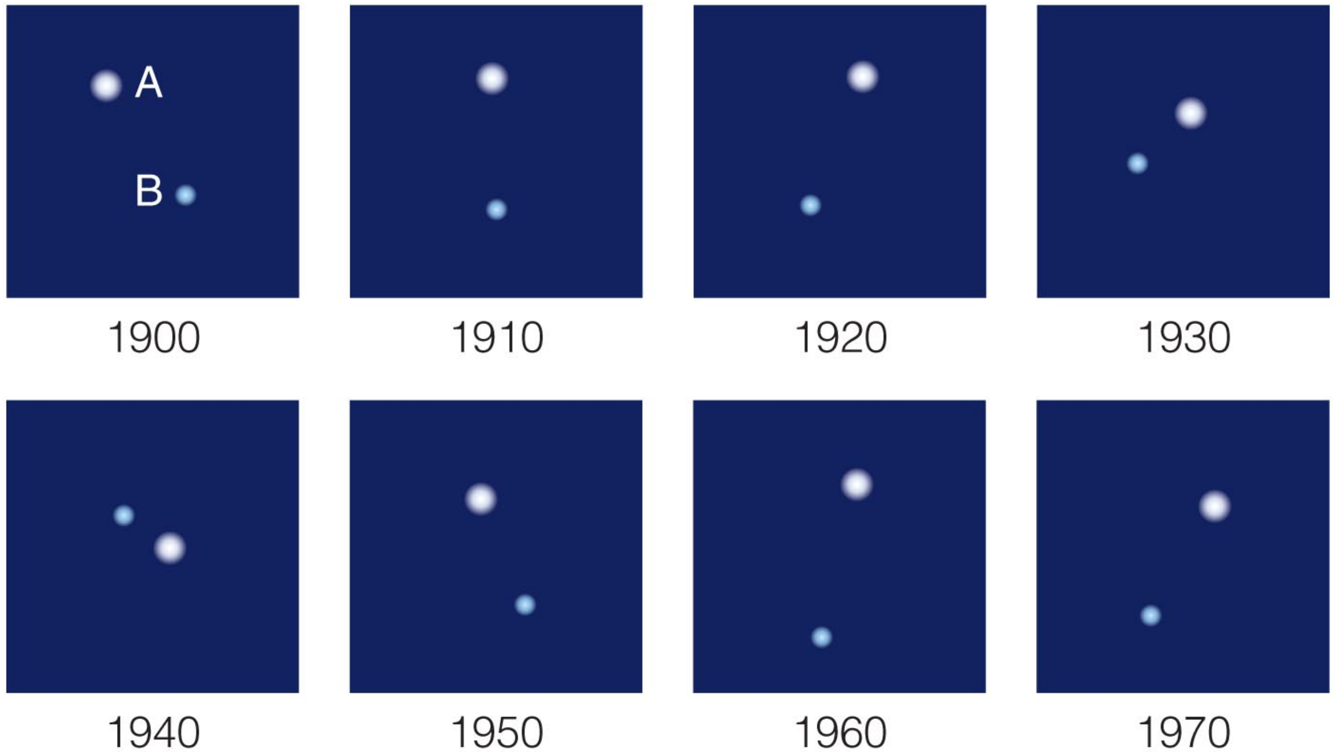
How do we measure stellar masses?





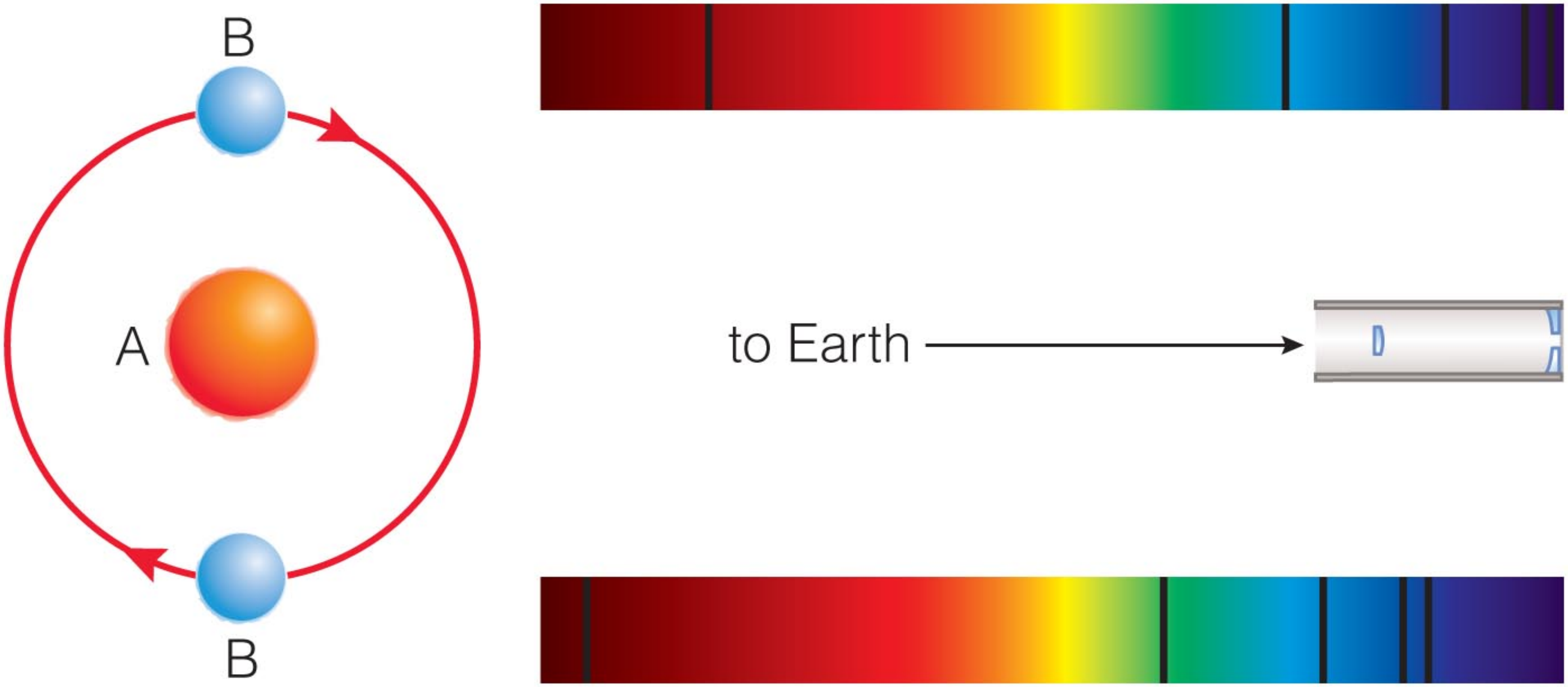
The orbit of a binary star system depends on strength of gravity

Visual Binary



We can directly observe the orbital motions of these stars

Spectroscopic Binary



We determine the orbit by measuring Doppler shifts

Sir Isaac Newton (1642–1727)

We measure mass using gravity

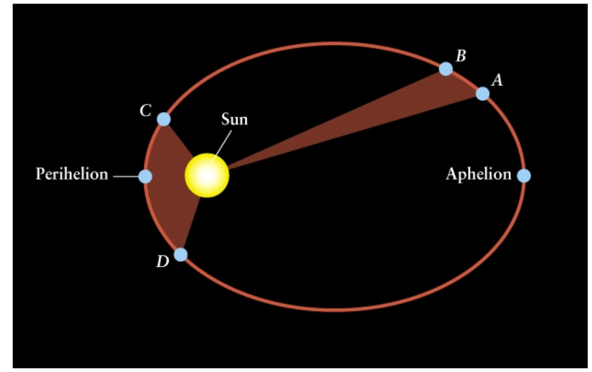
Direct mass measurements are possible only for stars in binary star systems

$$p^2 = \frac{4\pi^2}{G\,(M_1 + M_2)}\,a^3$$

p = period

a = average separation

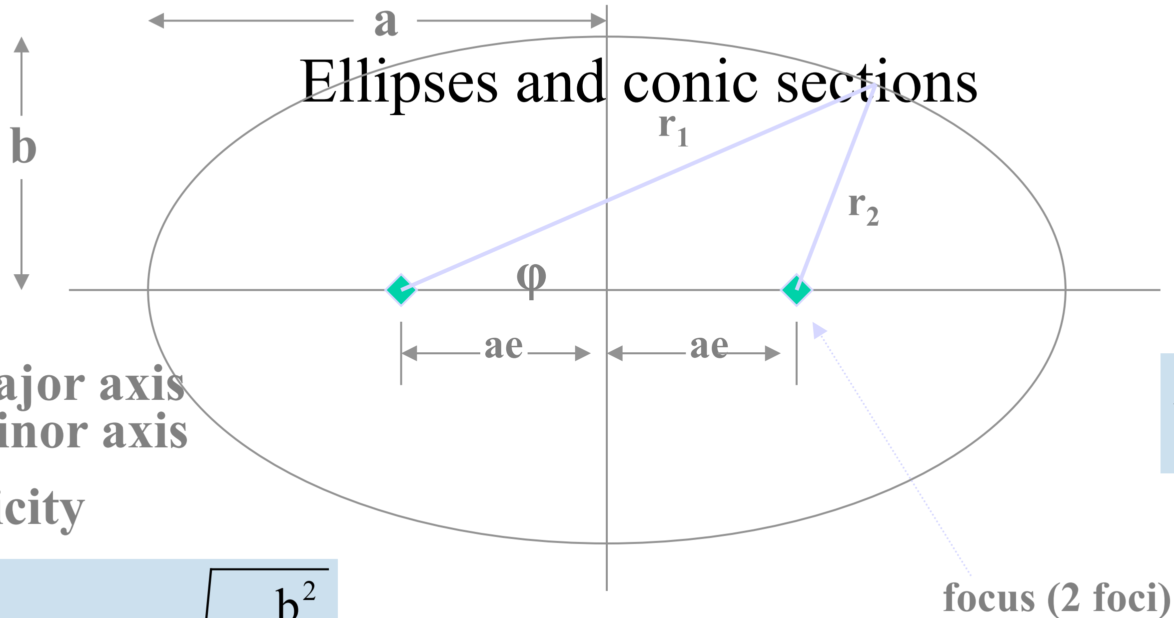
Gravity & Kepler's Laws



From Tycho Brahe's observations …

I. Planets move in elliptical orbits with the sun at one focus.
II. Radius vector between the sun and a planet sweeps out equal areas in equal time.
III. P^2 prop. to a^3 for orbit (P=period, a=semimajor axis)

Ellipses and conic sections



a=semi-major axis
b=semi-minor axis

e=eccentricity

$$\frac{b}{a} = \sqrt{1-e^2} \quad \text{or} \quad e = \sqrt{1-\frac{b^2}{a^2}}$$

$$r_1 + r_2 = 2a$$

Ellipse in x-y: $$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

$$r = \frac{a\,(1-e^2)}{1+e\cos\phi}$$

r=distance <u>from focus</u>
φ=angle from x-axis in r direction

- Kepler's 3rd Law: centripetal force =gravitational force

$$\frac{mv^2}{r} = \frac{GMm}{r^2}, \quad v = 2\pi r/P$$

$$\therefore \frac{4\pi^2 r^2}{r\,P^2} = \frac{GM}{r^2}$$

$$\therefore \; P^2 = \left(\frac{4\pi^2}{GM}\right) r^3 \quad or \quad P^2 \propto a^3$$

for circular orbits

P in yr, a in AU, M in solar masses:

$$P^2 = a^3 / M$$

$M = m_1 + m_2 \cong M_{sun}$ for solar system

Energy Considerations

- Total energy of orbit:

Why is energy conserved?

$$E_{tot} = -\frac{GMm}{2a}$$

- Energy in orbit

$$E_{tot} = -\frac{GMm}{2a} = \frac{mv^2}{2} - \frac{GMm}{r} \quad \text{at any point in orbit}$$

A little algebra gives: $\quad v^2 = GM\left(\frac{2}{r} - \frac{1}{a}\right)$

Most massive stars:

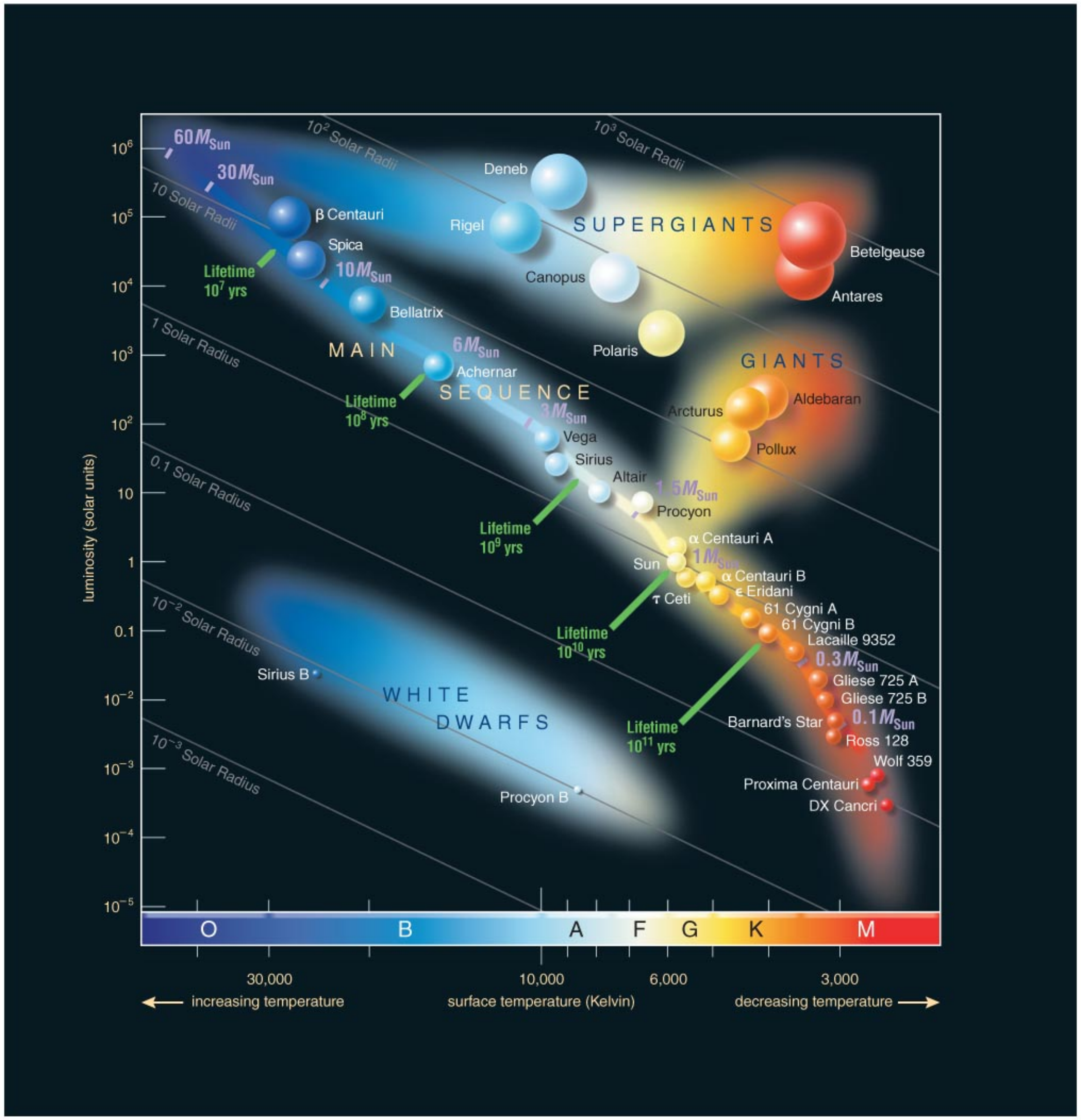
$100\ M_{\text{Sun}}$

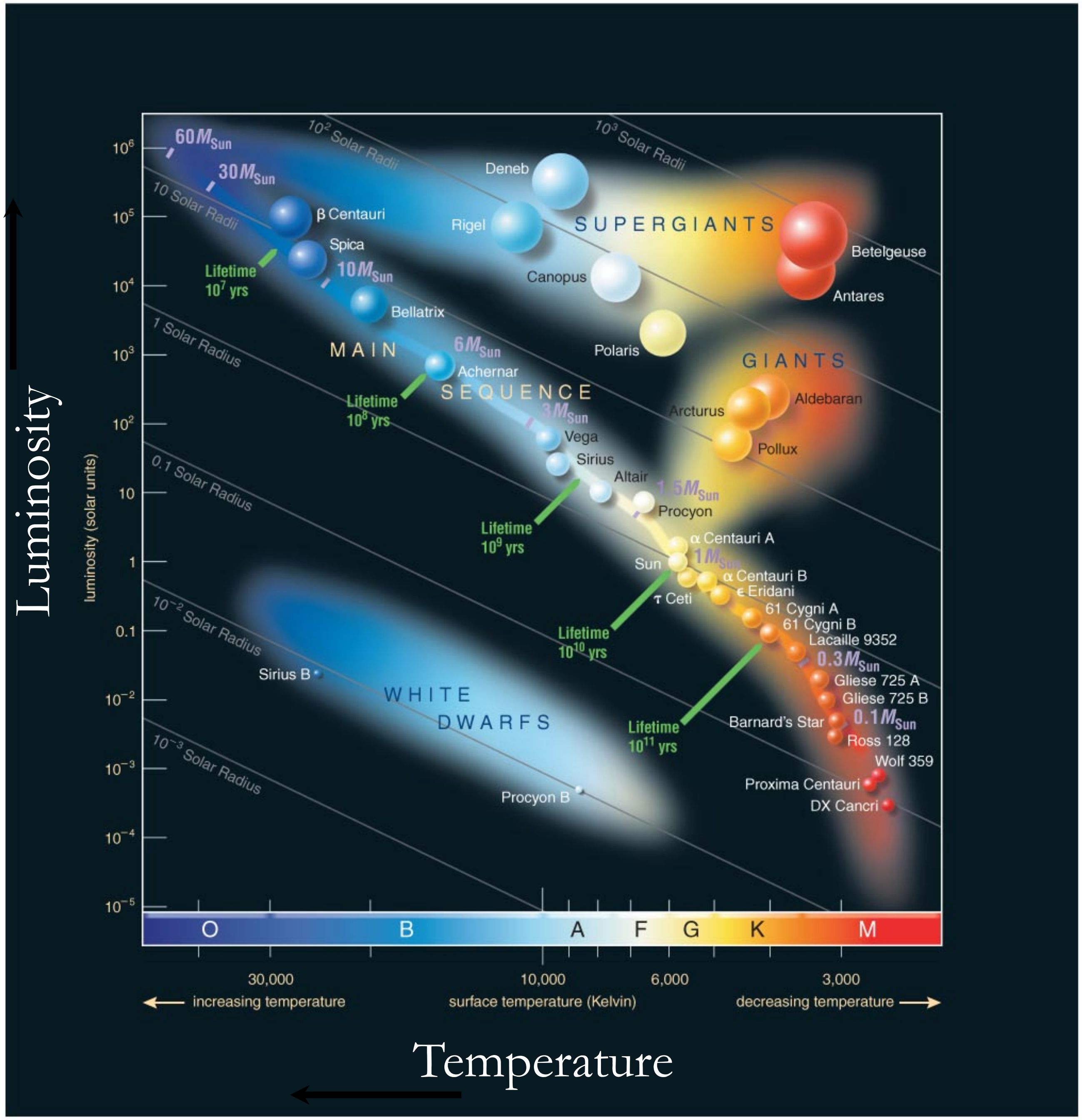
Least massive stars:

$0.08\ M_{\text{Sun}}$

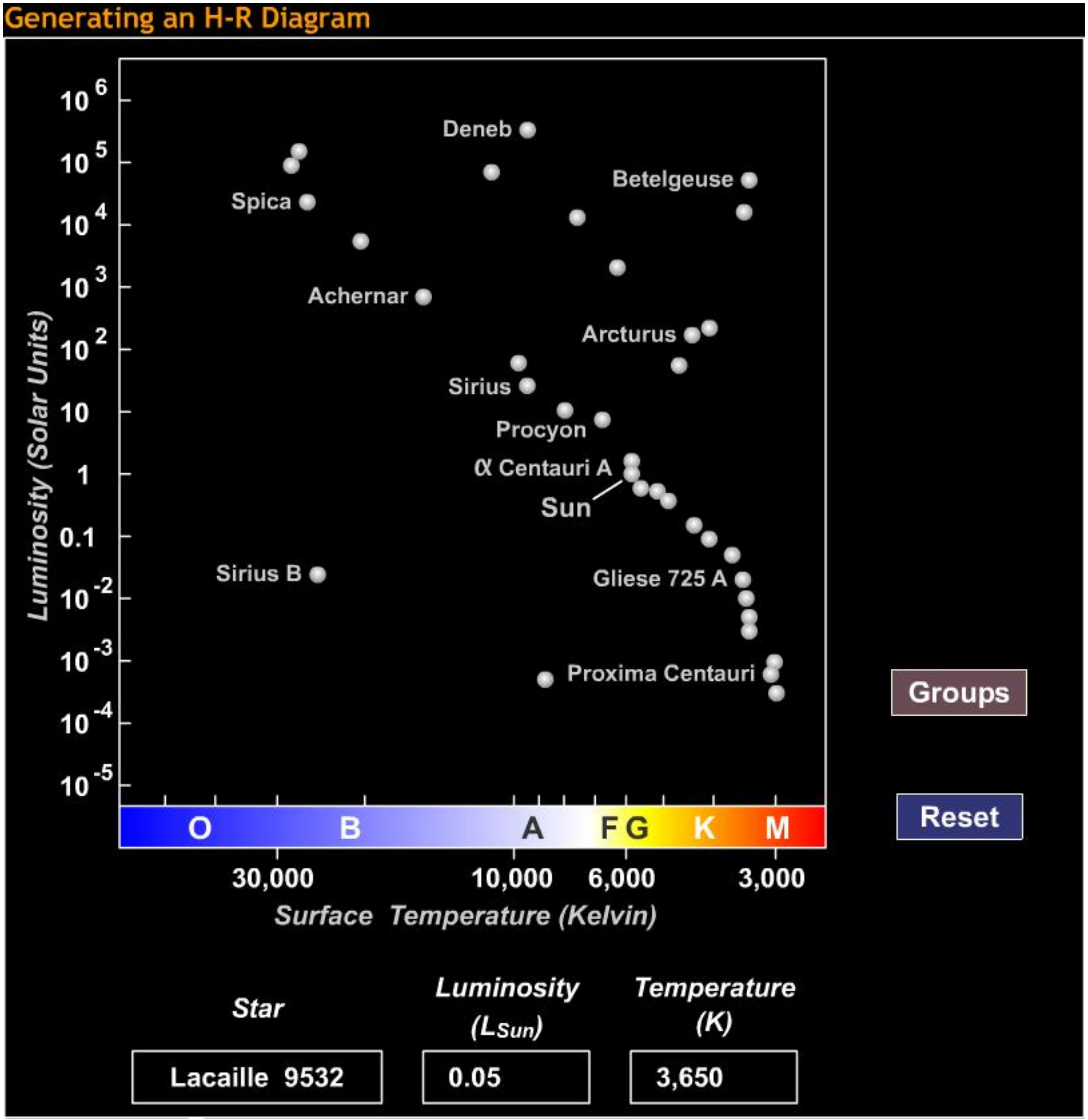
(M_{Sun} is the mass of the Sun)

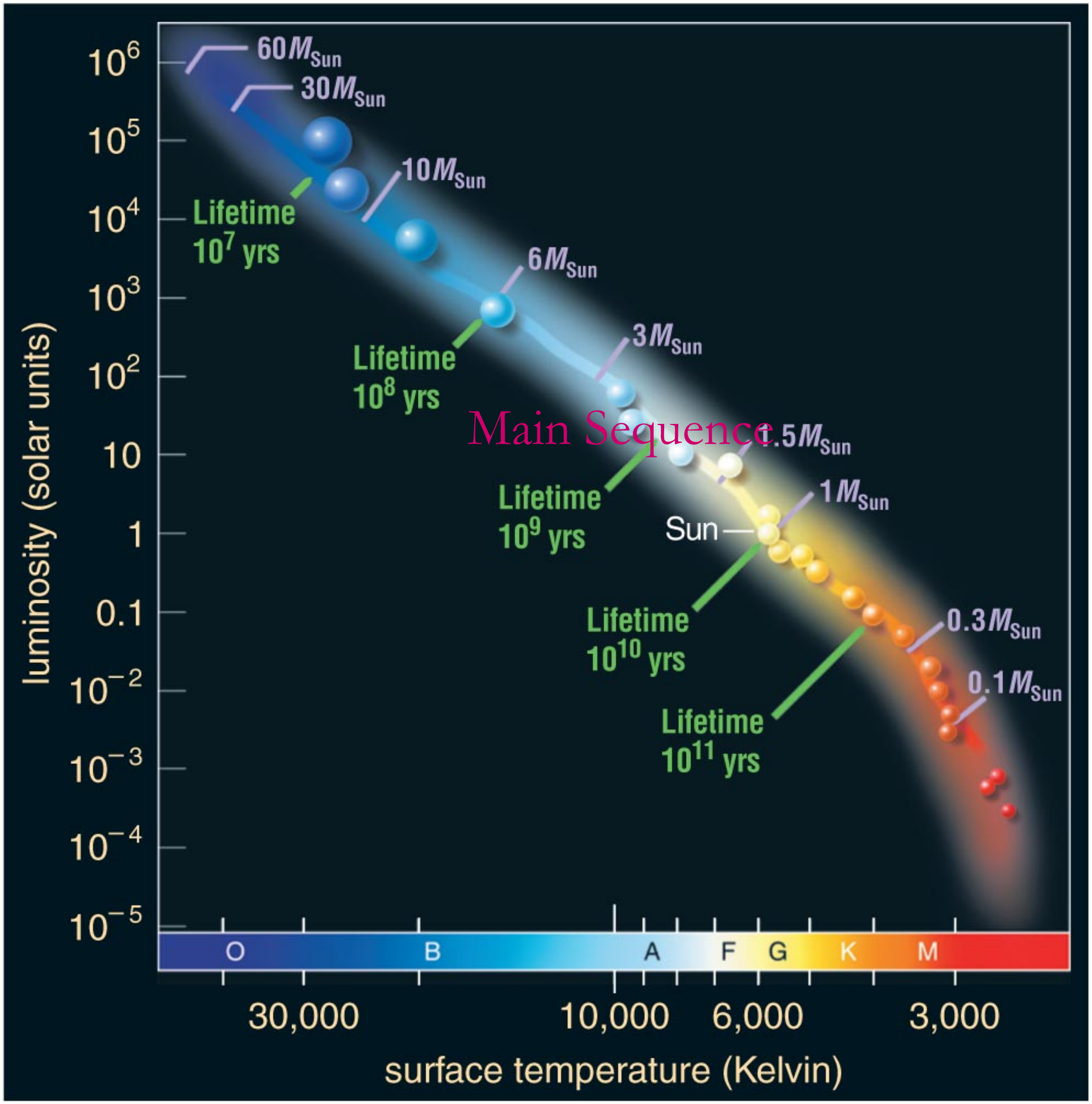
Patterns among stars



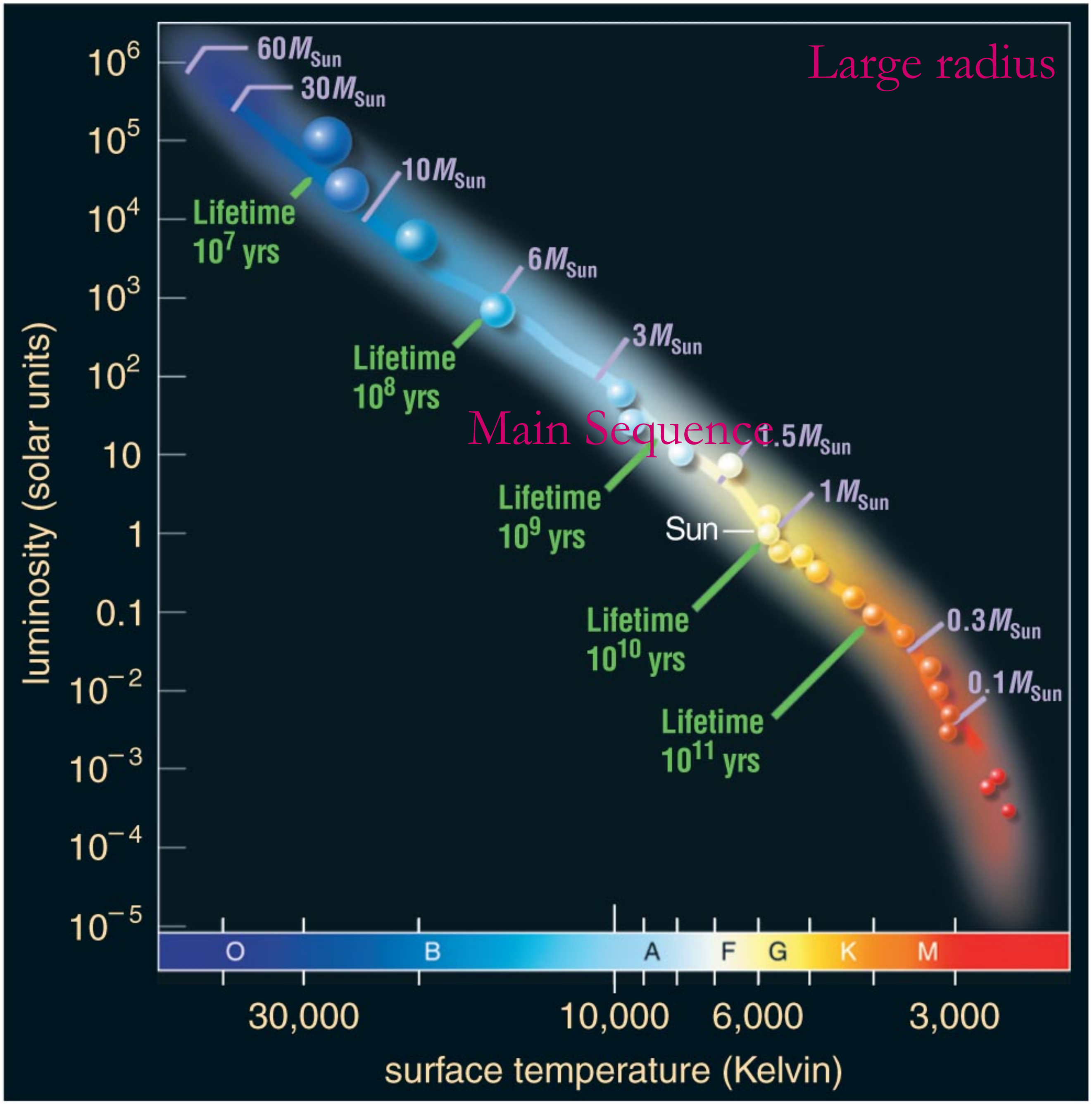


A Hertzsprung-Russell diagram plots the luminosity and temperature of stars


Generating an H-R Diagram
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
Deneb
Betelgeuse
Spica
Achernar
Arcturus
Sirius
Procyon
α Centauri A
Sun
Sirius B
Gliese 725 A
Proxima Centauri
O
B
A
F G
K
M
30,000
10,000
6,000
3,000
Surface Temperature (Kelvin)
Groups
Reset
Star
Luminosity (LSun)
Temperature (K)
Lacaille 9532
0.05
3,650

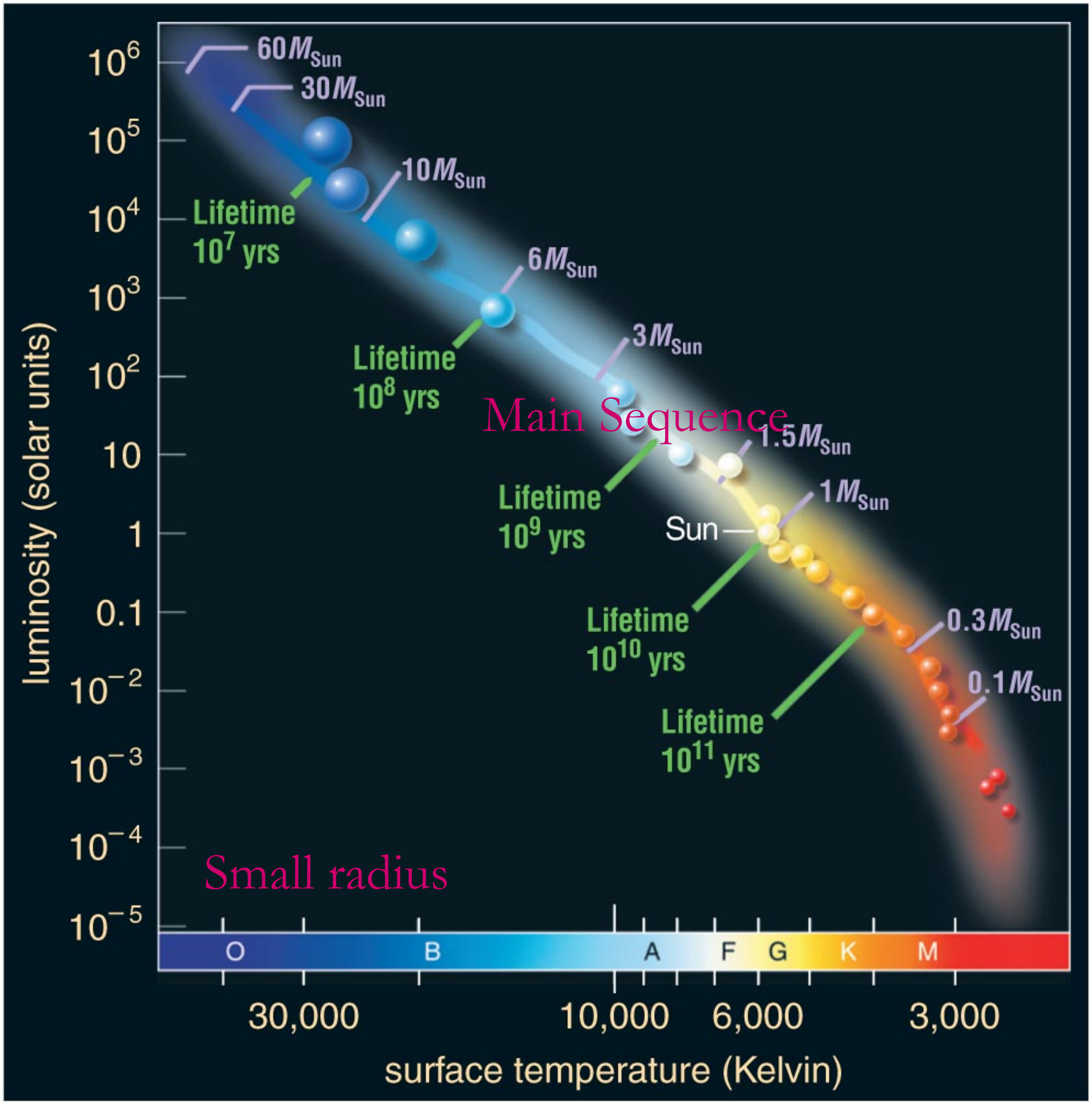


Most stars fall somewhere on the ***main sequence*** of the H-R diagram



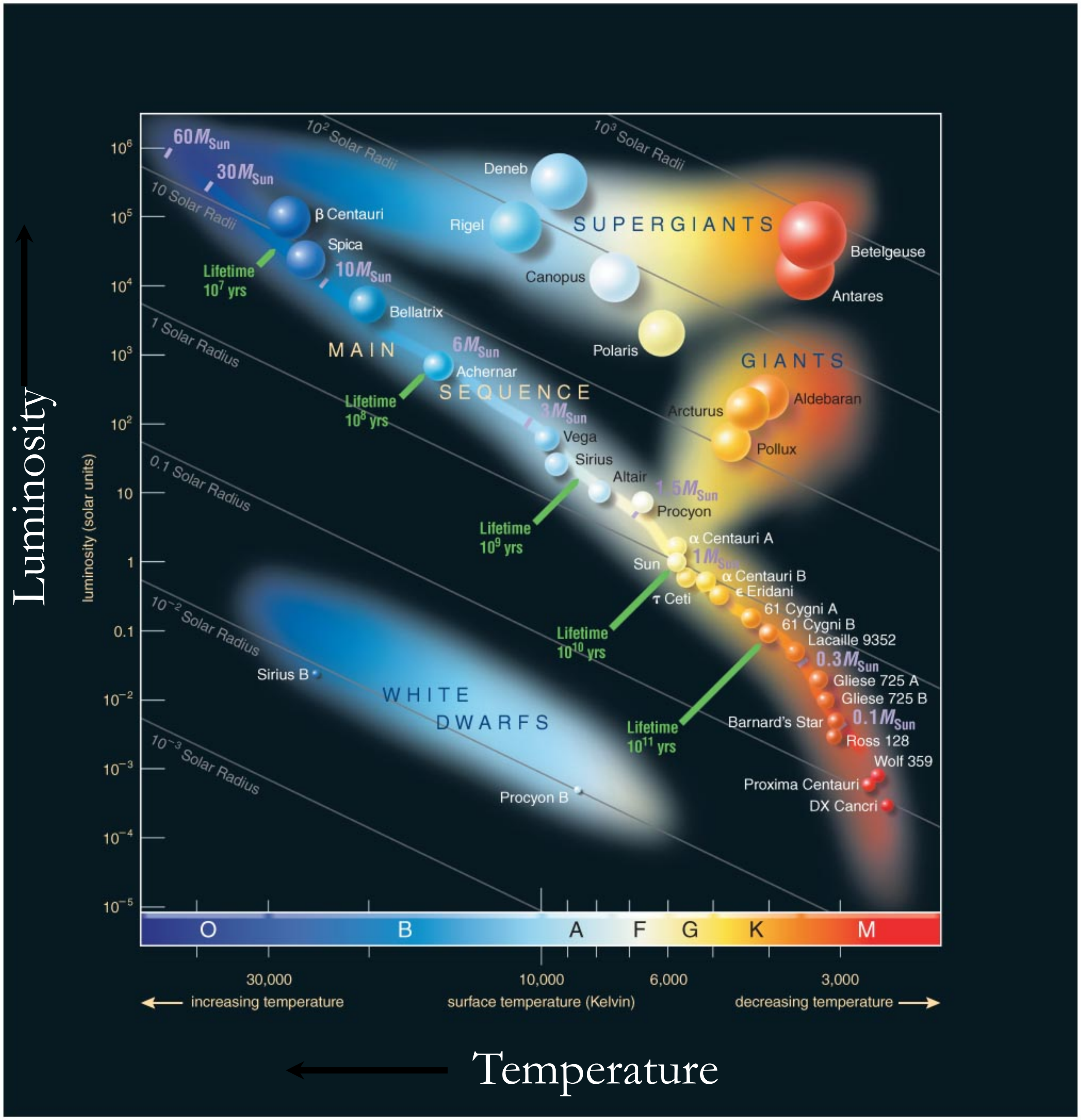
Stars with lower T and higher L than main-sequence stars must have larger radii:

giants and ***supergiants***



Stars with higher T and lower L than main-sequence stars must have smaller radii:

white dwarfs

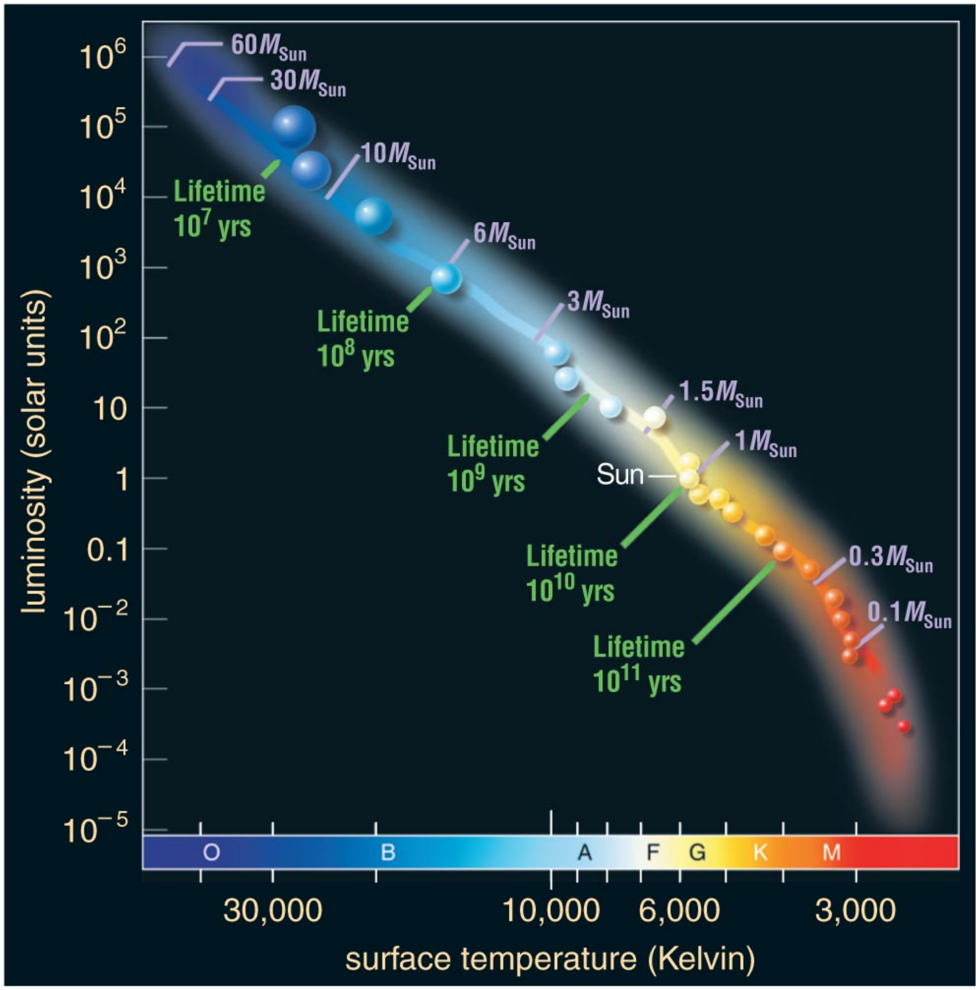


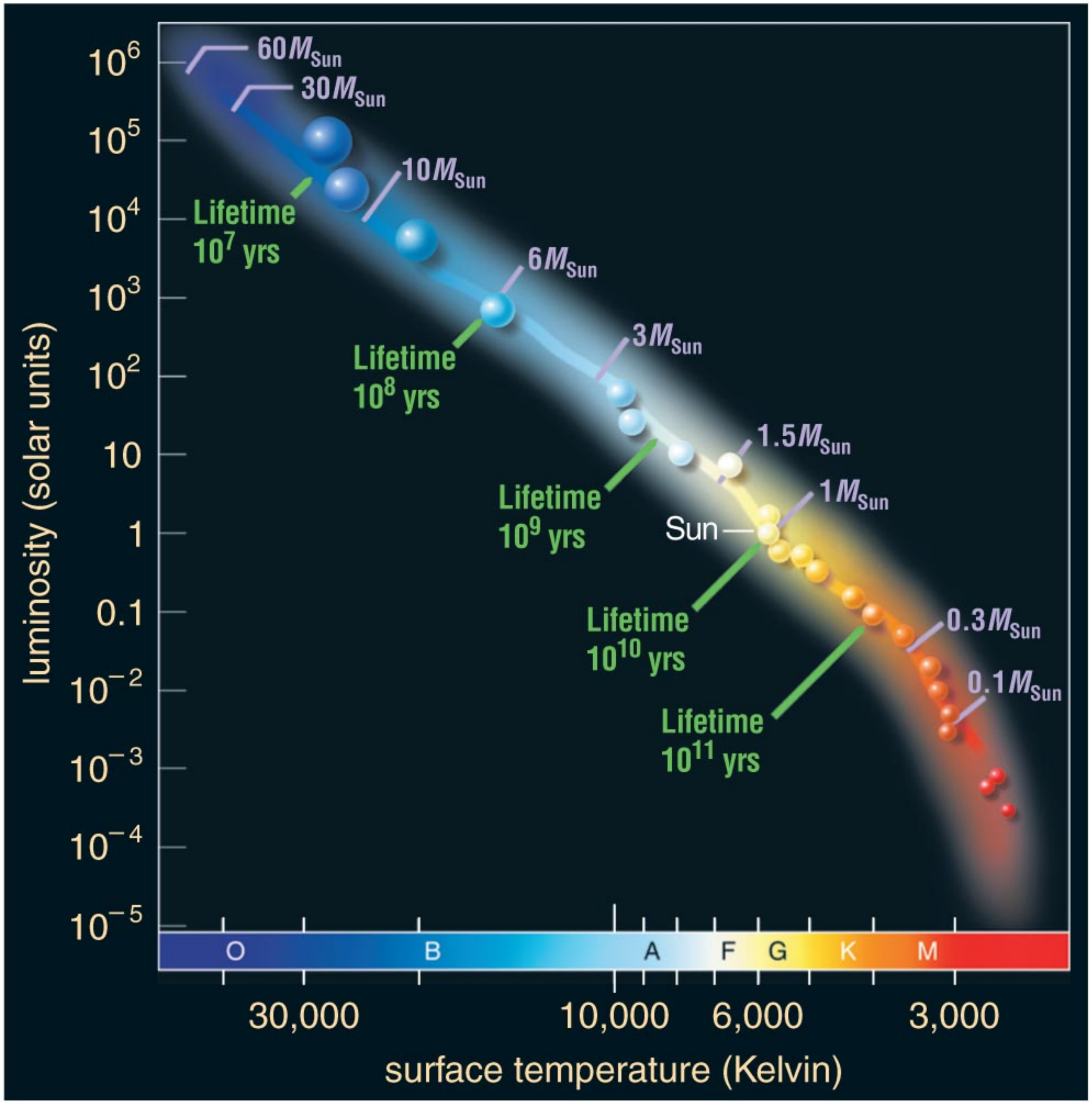
H-R diagram depicts:

- Temperature
- Color
- Spectral Type
- Luminosity
- Radius

$$L \propto r^2 T^4$$

What is the significance of the main sequence?

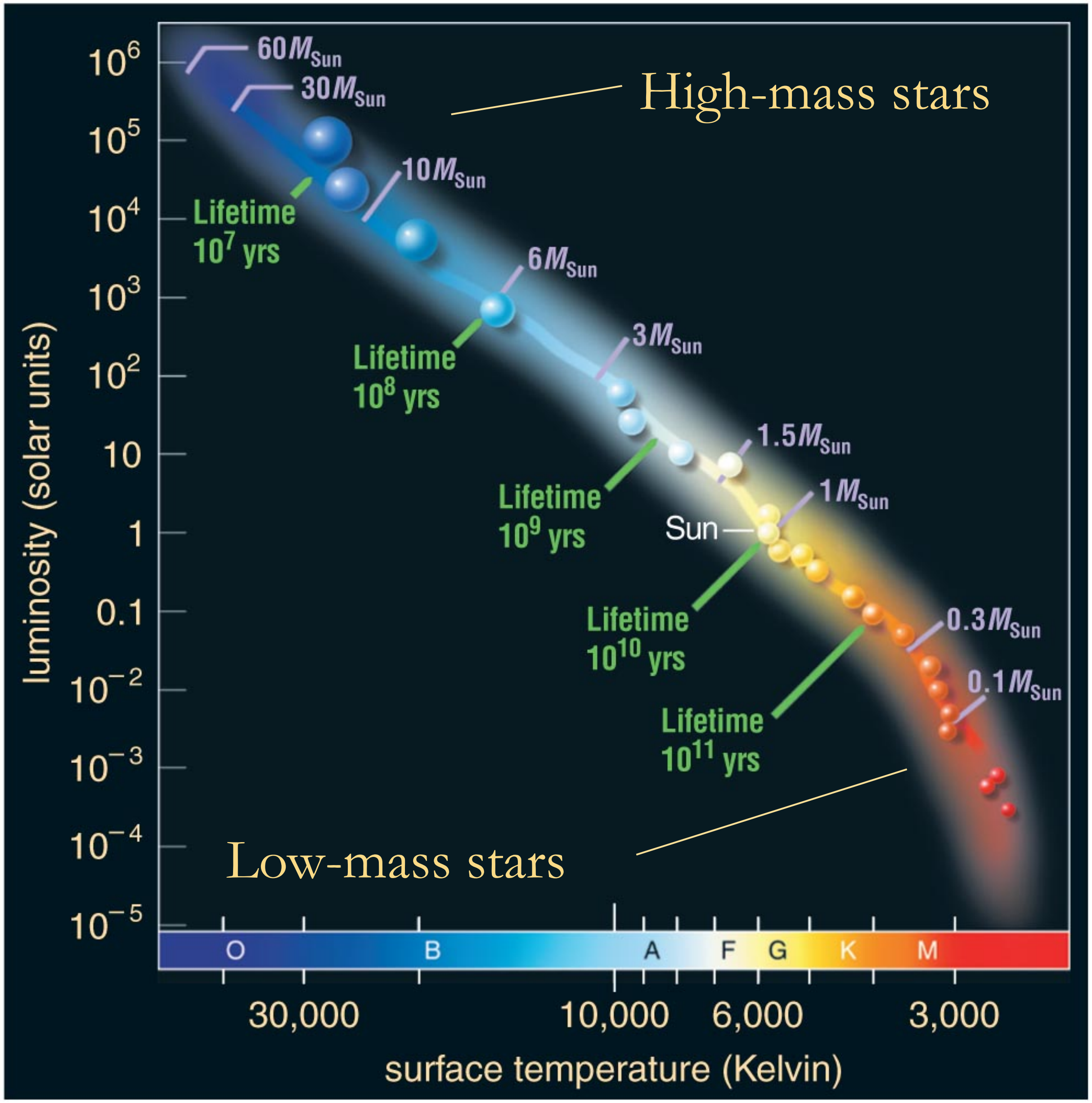




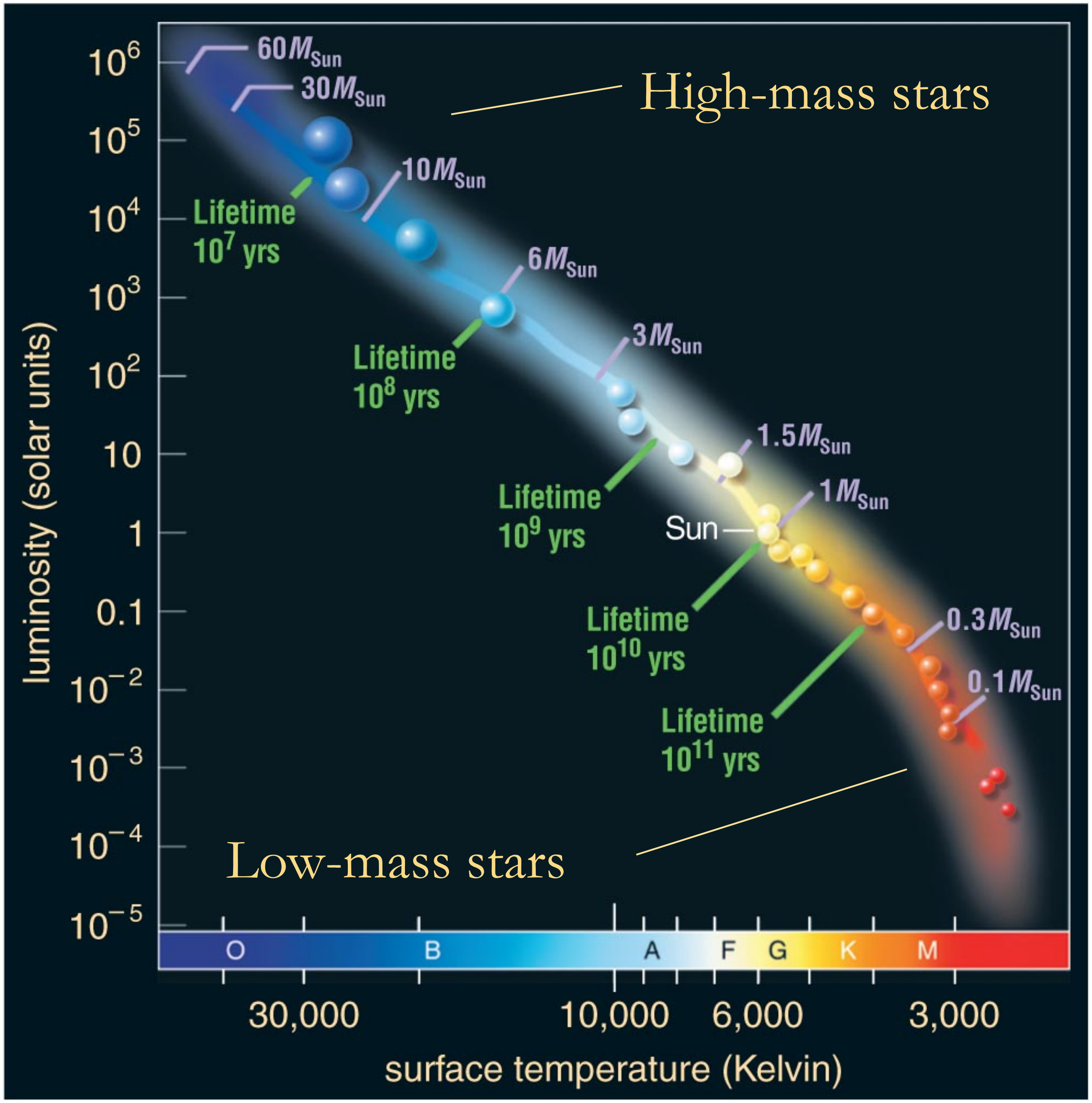
Main-sequence stars are fusing hydrogen into helium in their cores like the Sun

Luminous main-sequence stars are hot (blue)

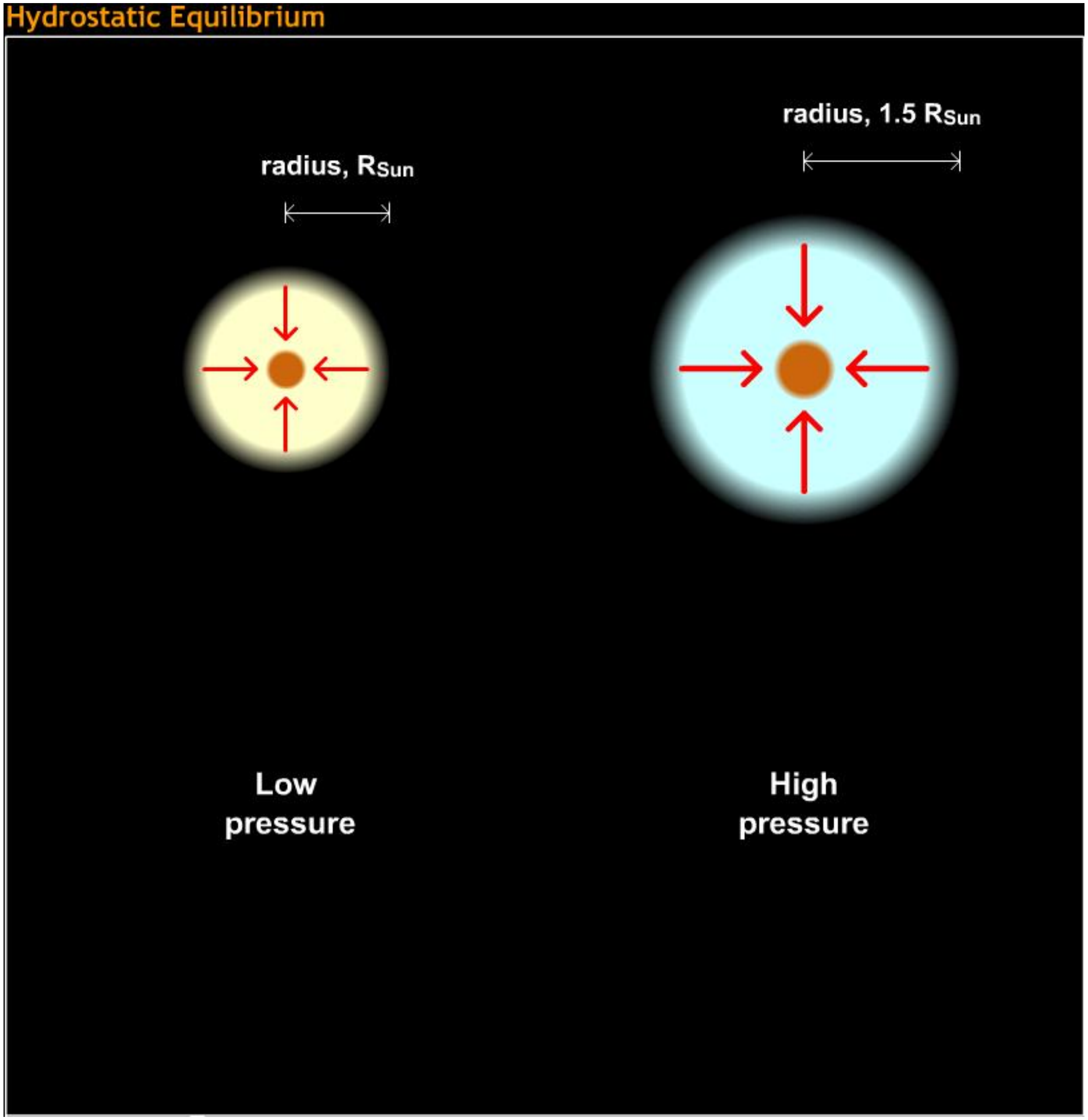
Less luminous ones are cooler (yellow or red)



Mass measurements of main-sequence stars show that the hot, blue stars are much more massive than the cool, red ones



The mass of a normal, hydrogen-burning star determines its luminosity and spectral type!



Core pressure and temperature of a higher-mass star need to be larger in order to balance gravity

Higher core temperature boosts fusion rate, leading to larger luminosity

Mass & Lifetime

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

Sun's life expectancy: 10 billion years

Life expectancy of 10 M_{Sun} star:

10 times as much fuel, uses it 10^4 times as fast

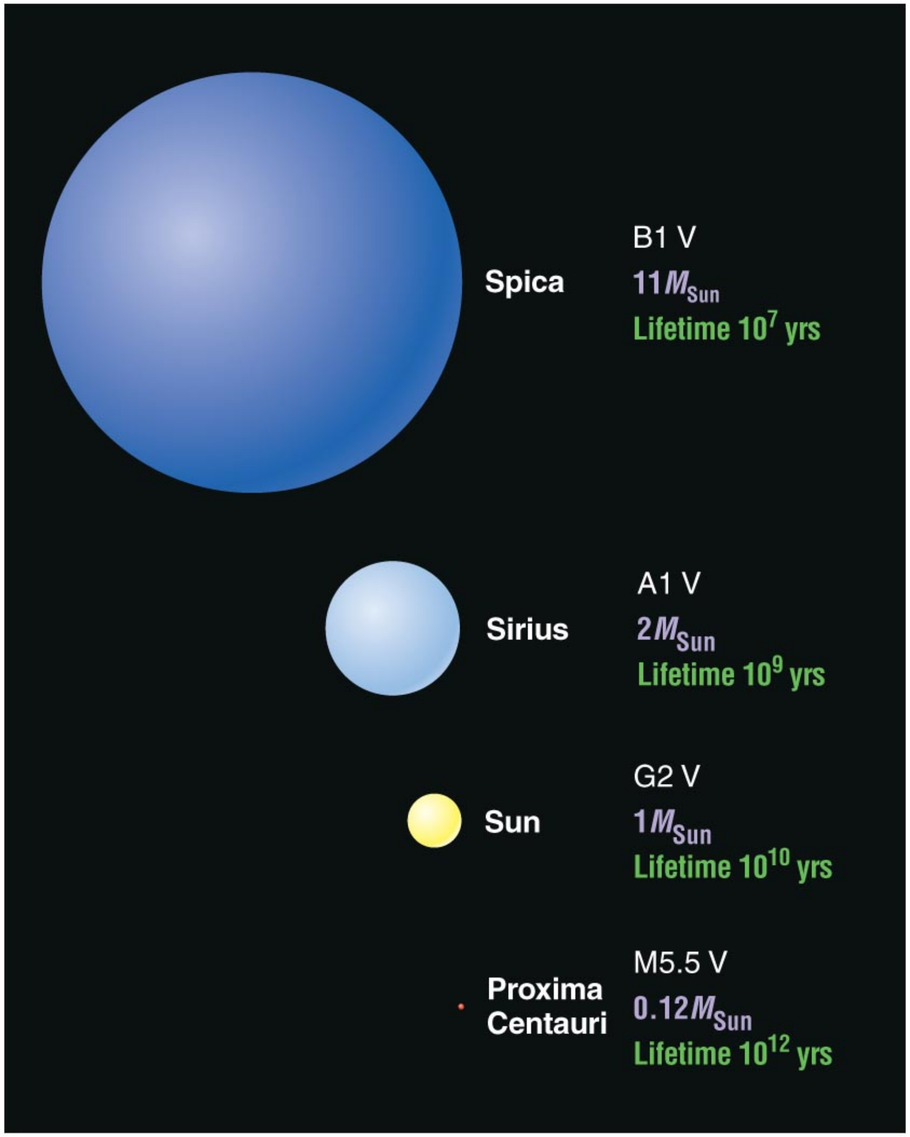
10 million years ~ 10 billion years x 10 / 10^4

Life expectancy of 0.1 M_{Sun} star:

0.1 times as much fuel, uses it 0.01 times as fast

100 billion years ~ 10 billion years x 0.1 / 0.01

Main-Sequence Star Summary



High Mass:

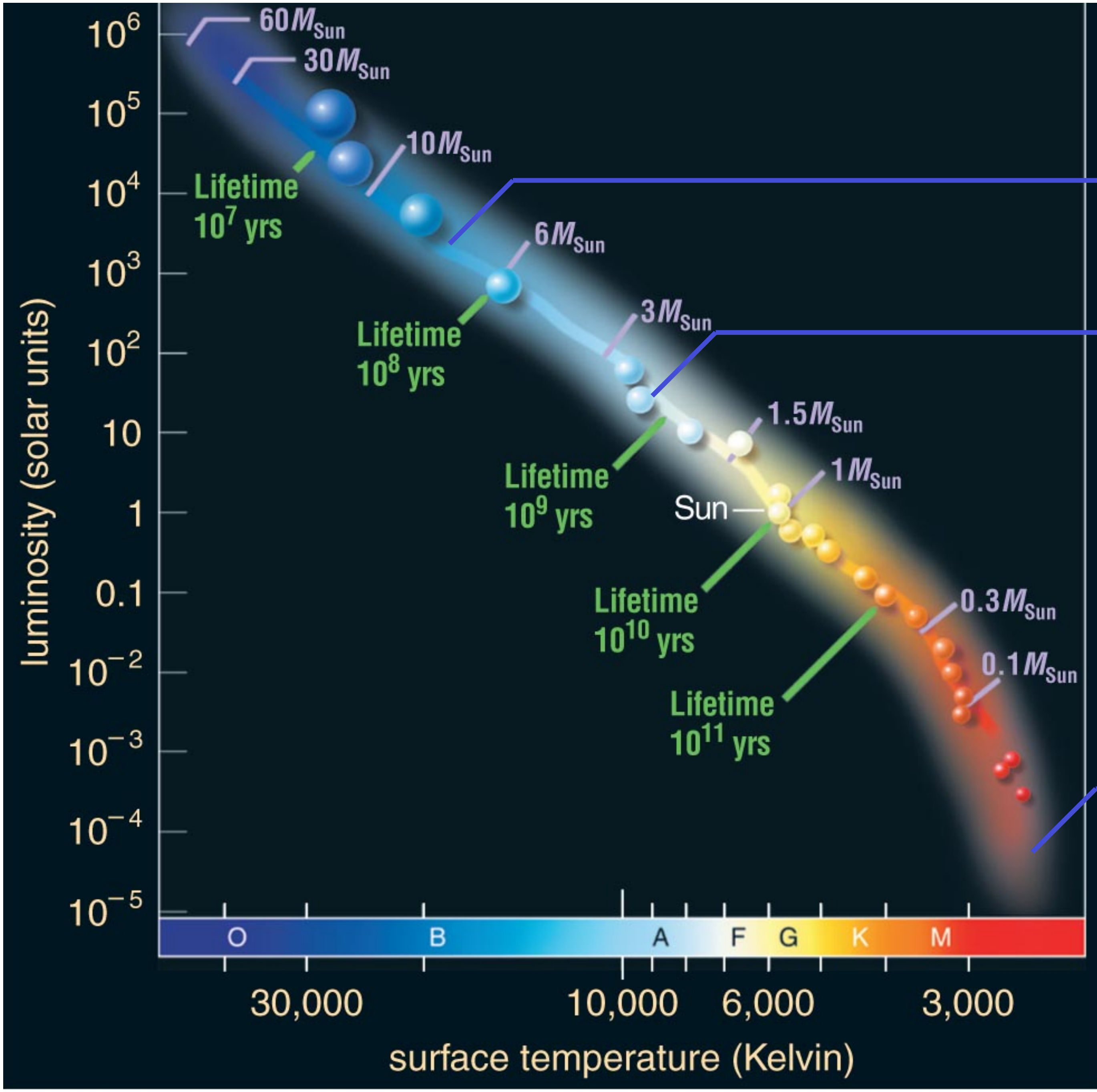
- High Luminosity
- Short-Lived
- Large Radius
- Blue

Low Mass:

- Low Luminosity
- Long-Lived
- Small Radius
- Red

Stellar Mass and Fusion

- The mass of a main sequence star determines its core pressure and temperature
- Stars of higher mass have higher core temperature and more rapid fusion, making those stars both more luminous and shorter-lived
- Stars of lower mass have cooler cores and slower fusion rates, giving them smaller luminosities and longer lifetimes



High-Mass Stars

> 8 M_{Sun}

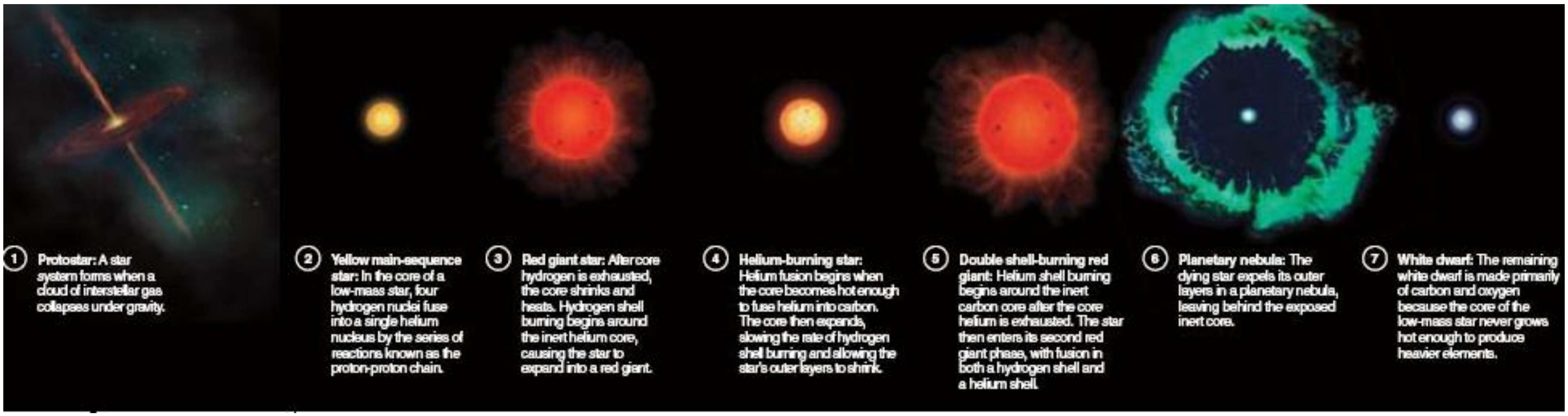
Intermediate-Mass Stars

Low-Mass Stars

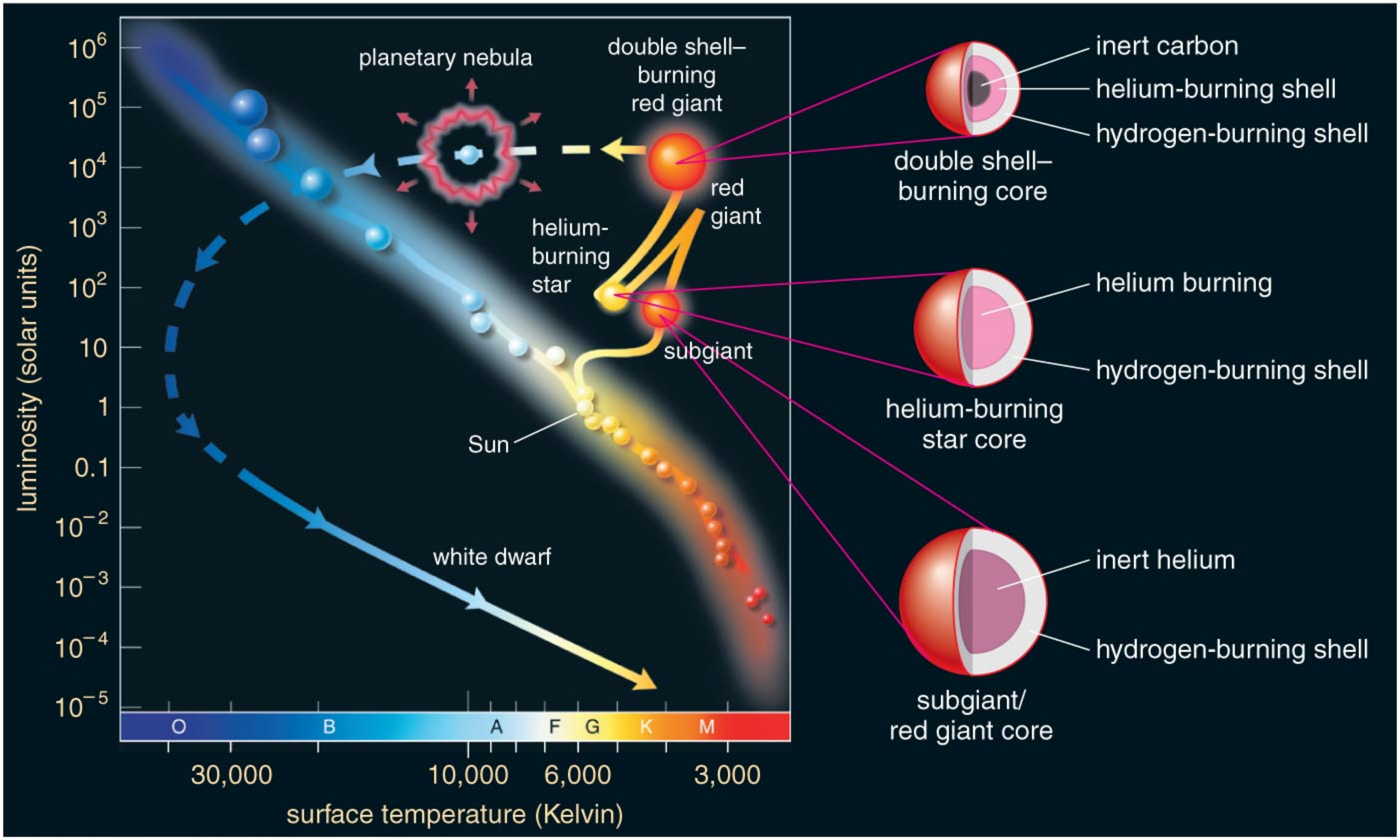
< 2 M_{Sun}

Brown Dwarfs

What are the life stages of a low-mass star?



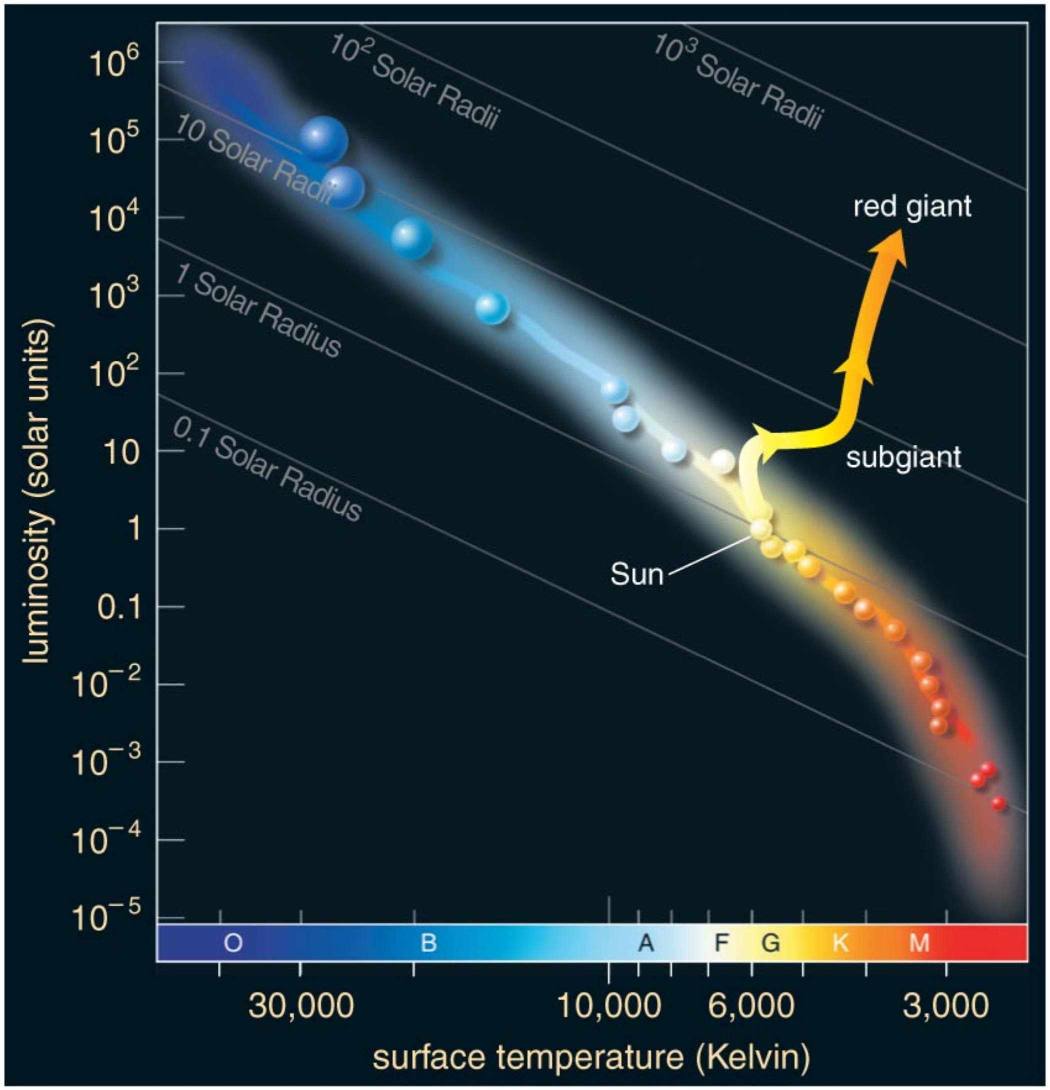
Life Track of a Sun-Like Star



Off the Main Sequence

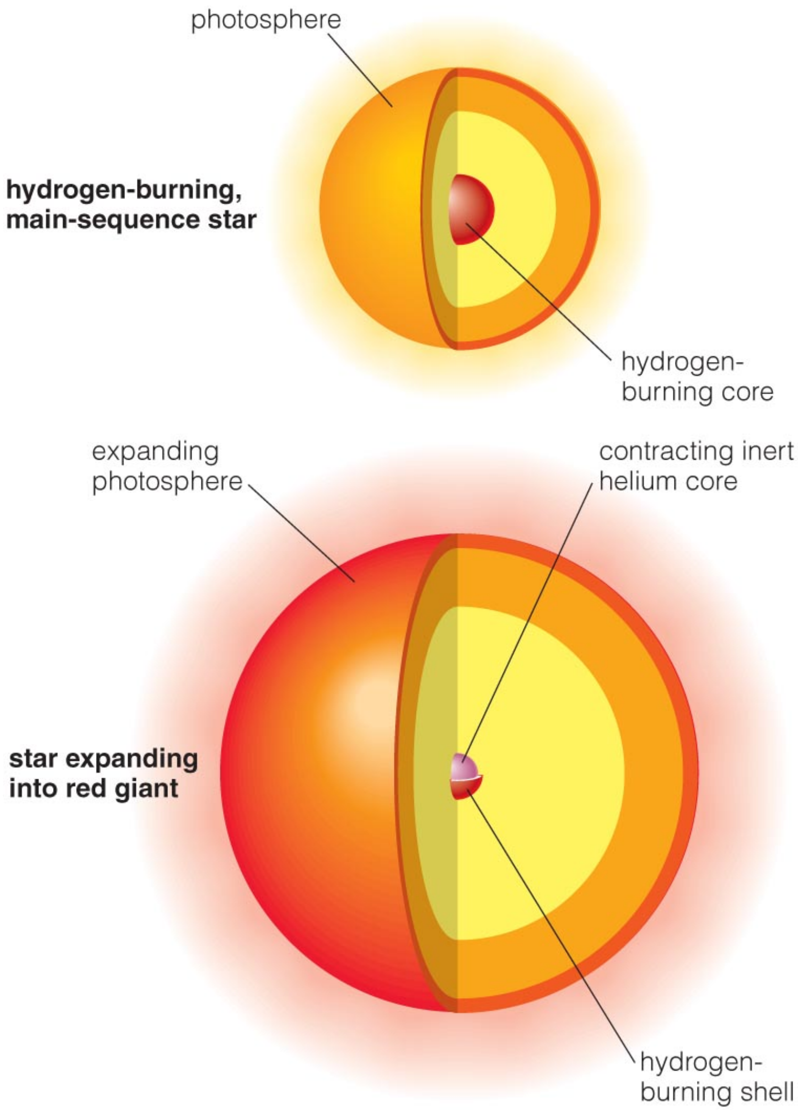
- Stellar properties depend on both mass and age: those that have finished fusing H to He in their cores are no longer on the main sequence
- All stars become larger and redder after exhausting their core hydrogen: **giants** and **supergiants**
- Most stars end up small and white after fusion has ceased: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

Life Track After Main Sequence



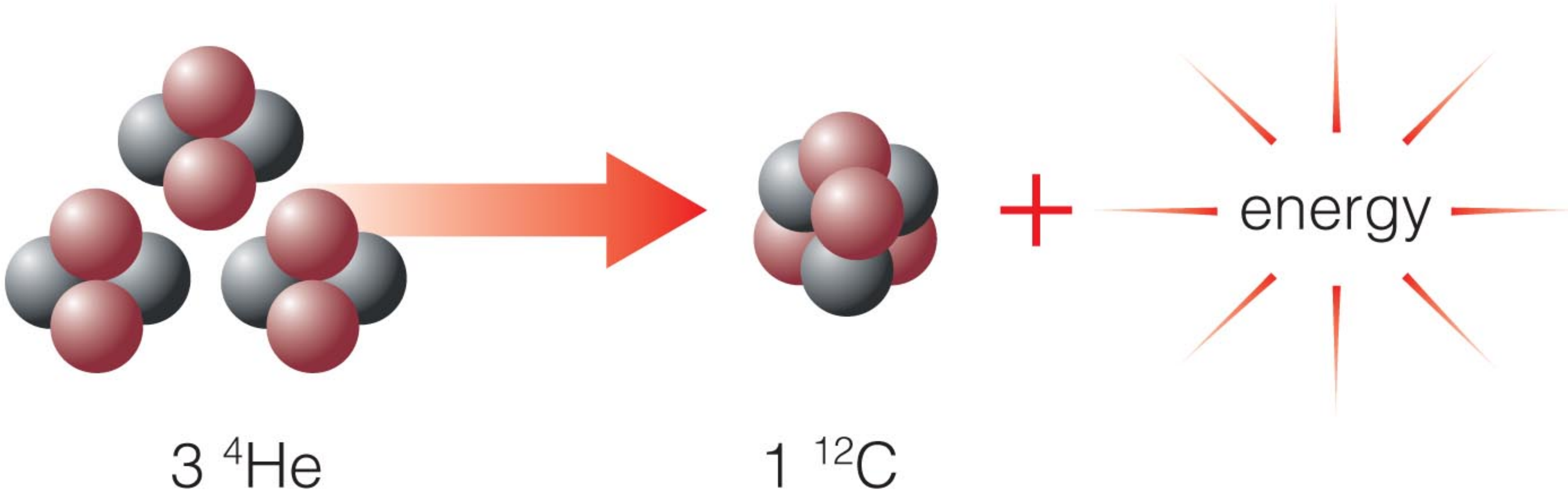
- Observations of star clusters show that a star becomes larger, redder, and more luminous after its time on the main sequence is over

Broken Thermostat
Degenerate Cores



- As the core contracts, H begins fusing to He in a shell around the core

- Luminosity increases because the core thermostat is broken—the increasing fusion rate in the shell does not stop the core from contracting

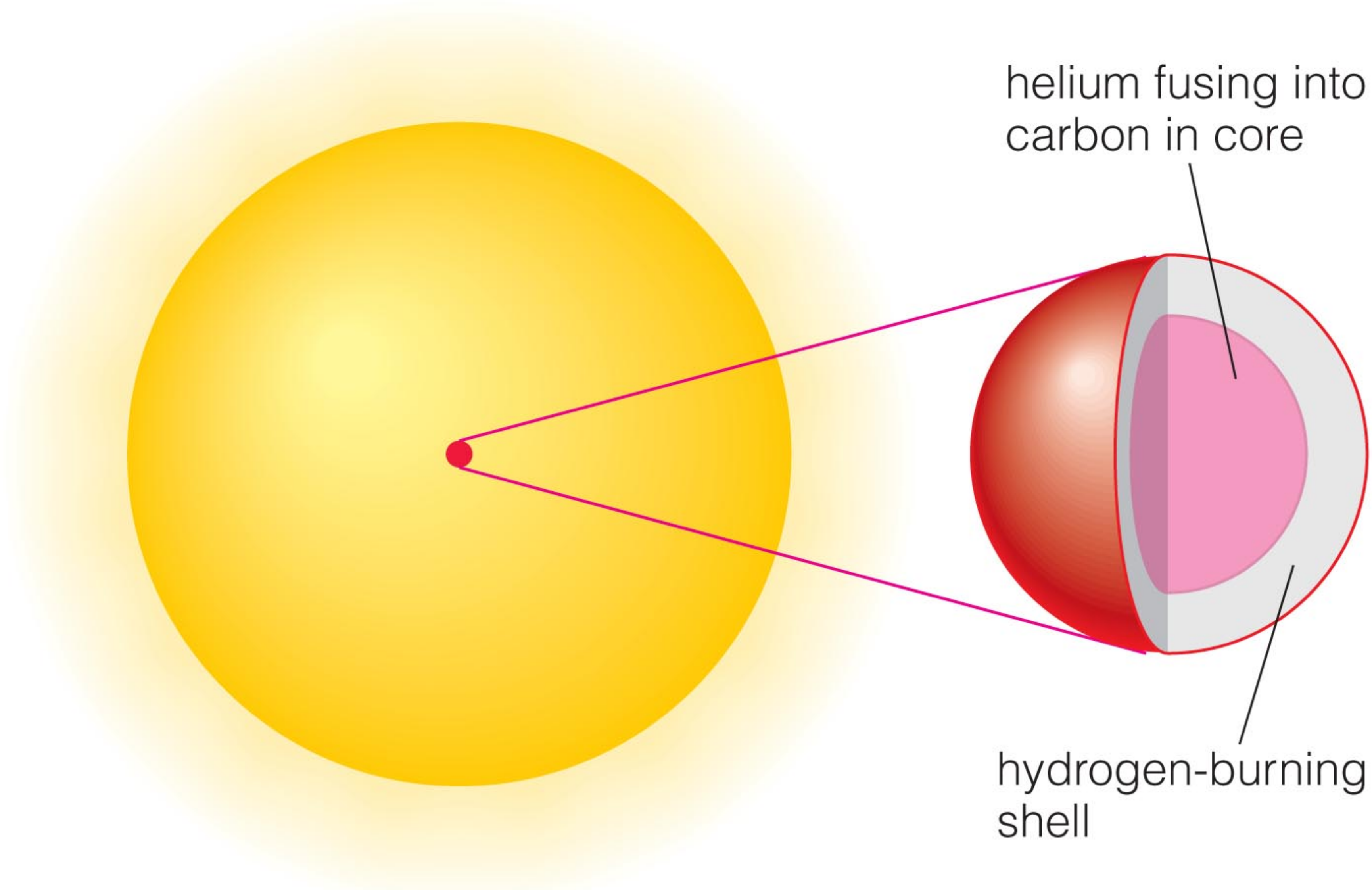


Helium fusion does not begin right away because it requires higher temperatures than hydrogen fusion—larger charge leads to greater repulsion

Fusion of two helium nuclei doesn't work, so helium fusion must combine three He nuclei to make carbon

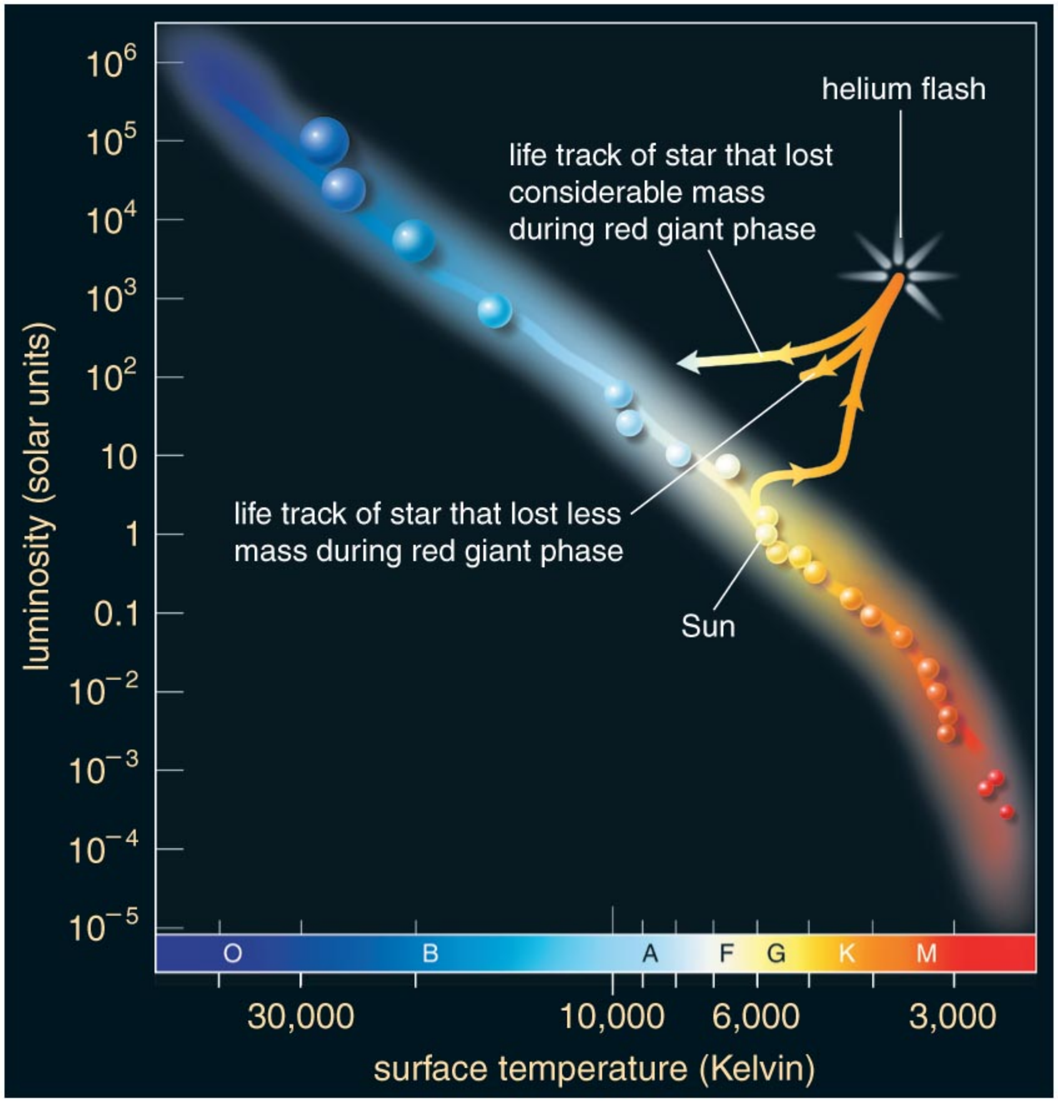
Helium Flash

- Thermostat is broken in low-mass red giant because degeneracy pressure supports core
- Core temperature rises rapidly when helium fusion begins
- Helium fusion rate skyrockets until thermal pressure takes over and expands core again



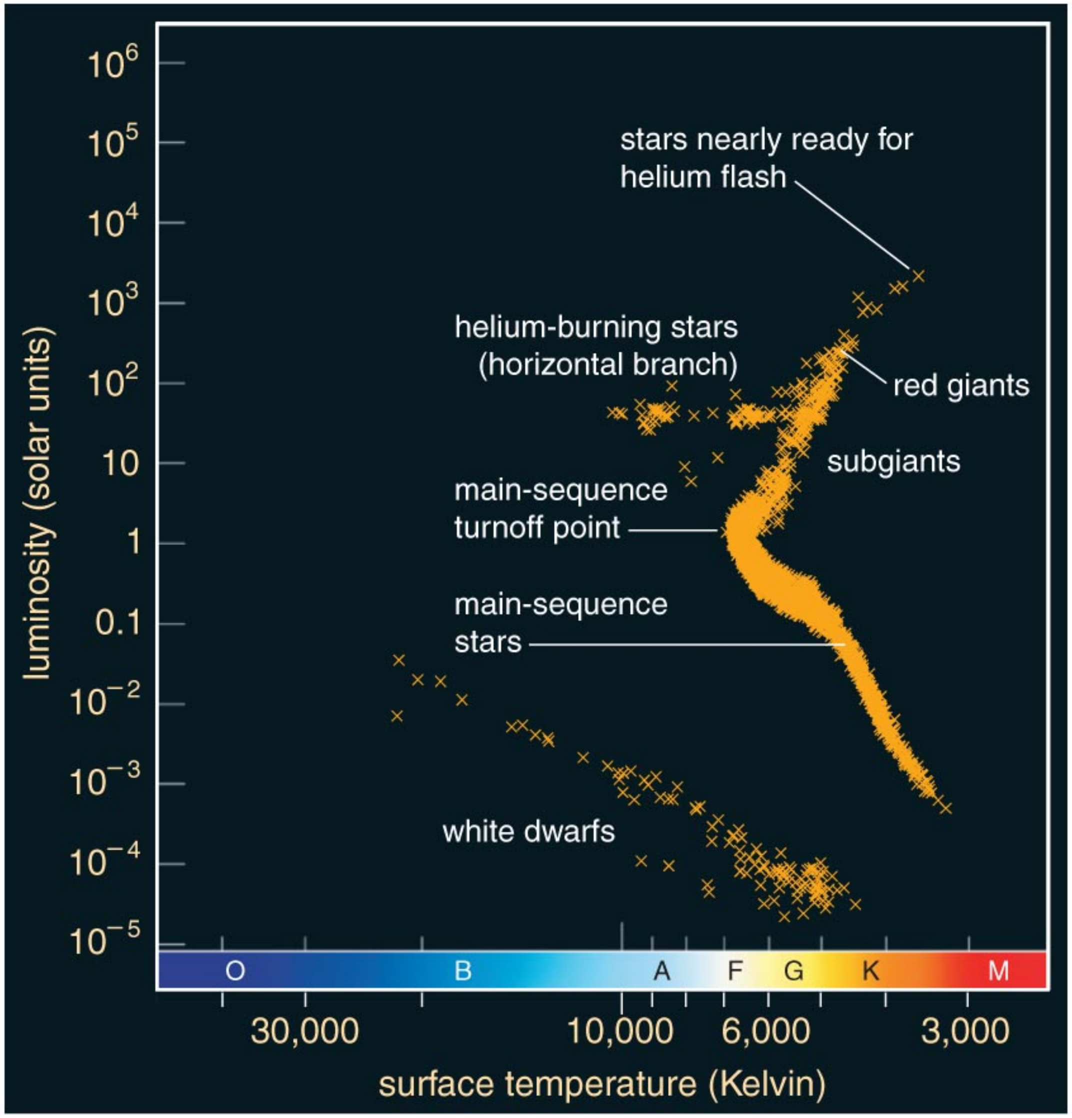
Helium burning stars neither shrink nor grow because core thermostat is temporarily fixed.

Life Track after Helium Flash



- Models show that a red giant should shrink and become less luminous after helium fusion begins in the core

Life Track after Helium Flash

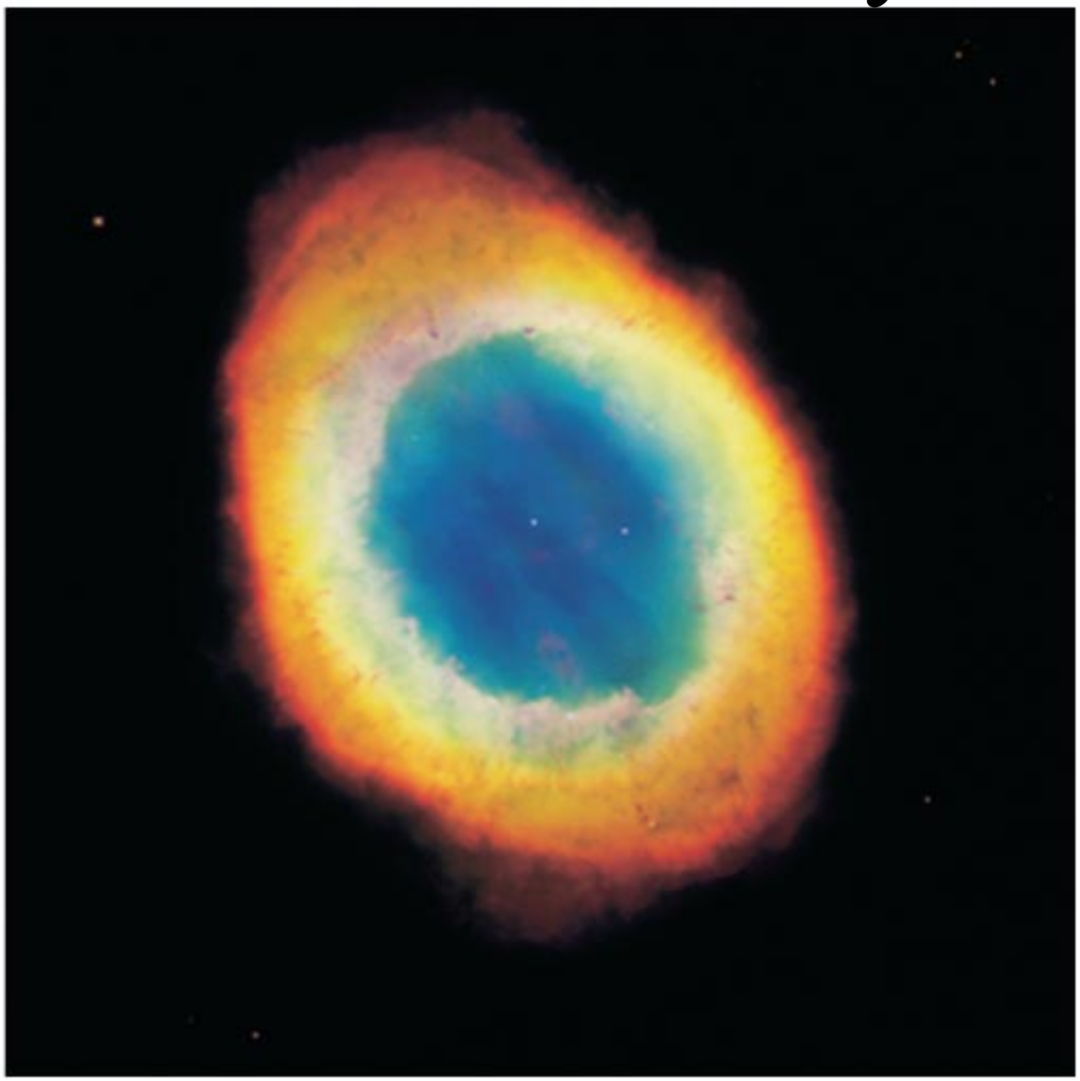


- Observations of star clusters agree with those models
- Helium-burning stars are found in a *horizontal branch* on the H-R diagram

Double Shell Burning

- After core helium fusion stops, He fuses into carbon in a shell around the carbon core, and H fuses to He in a shell around the helium layer
- This double-shell burning stage never reaches equilibrium—fusion rate periodically spikes upward in a series of *thermal pulses*
- With each spike, convection dredges carbon up from core and transports it to surface

Planetary Nebulae



- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*
- The core left behind becomes a white dwarf

Planetary Nebulae

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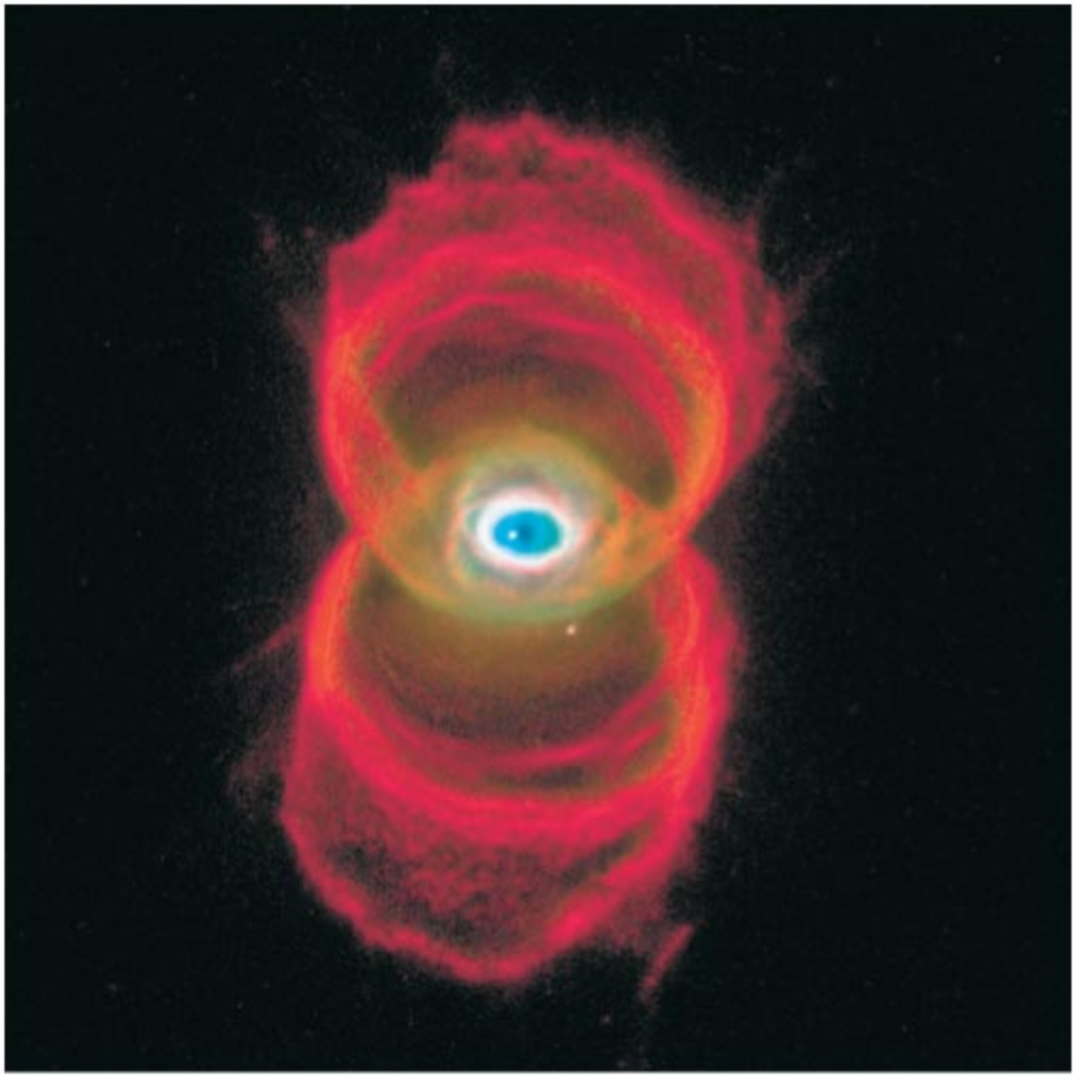
Planetary Nebulae



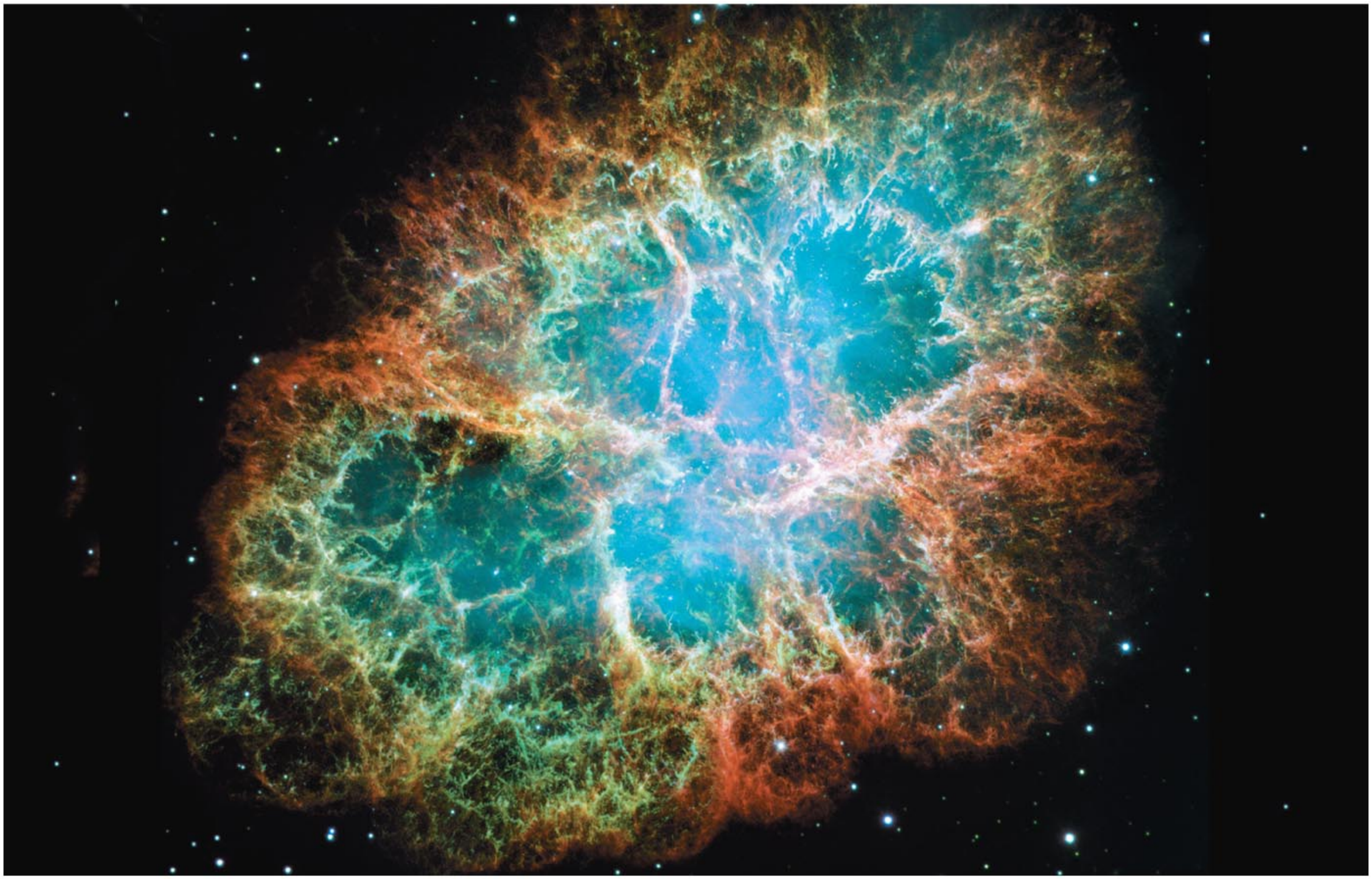
- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*
- The core left behind becomes a white dwarf

End of Fusion

- Fusion progresses no further in a low-mass star because the core temperature never grows hot enough for fusion of heavier elements (some He fuses to C to make oxygen)

- Degeneracy pressure supports the white dwarf against gravity

Stellar Lives



Star Clusters

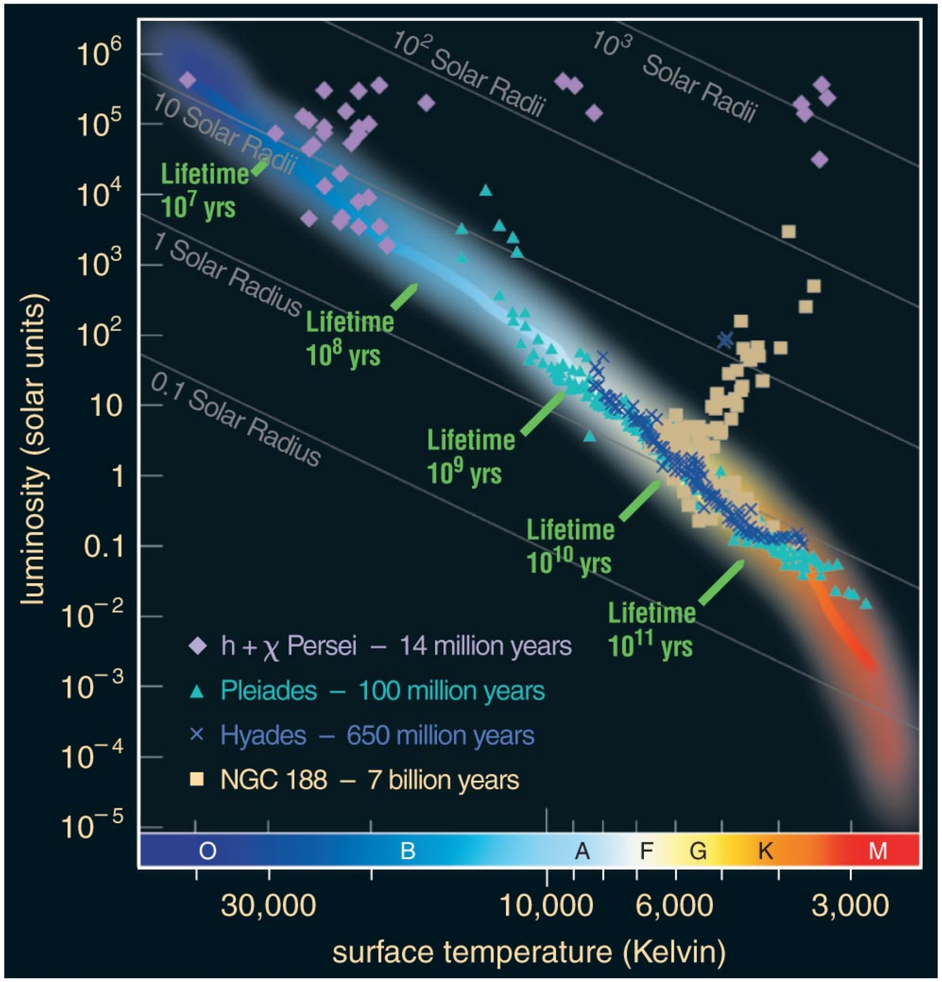
Open cluster: A few thousand loosely packed stars

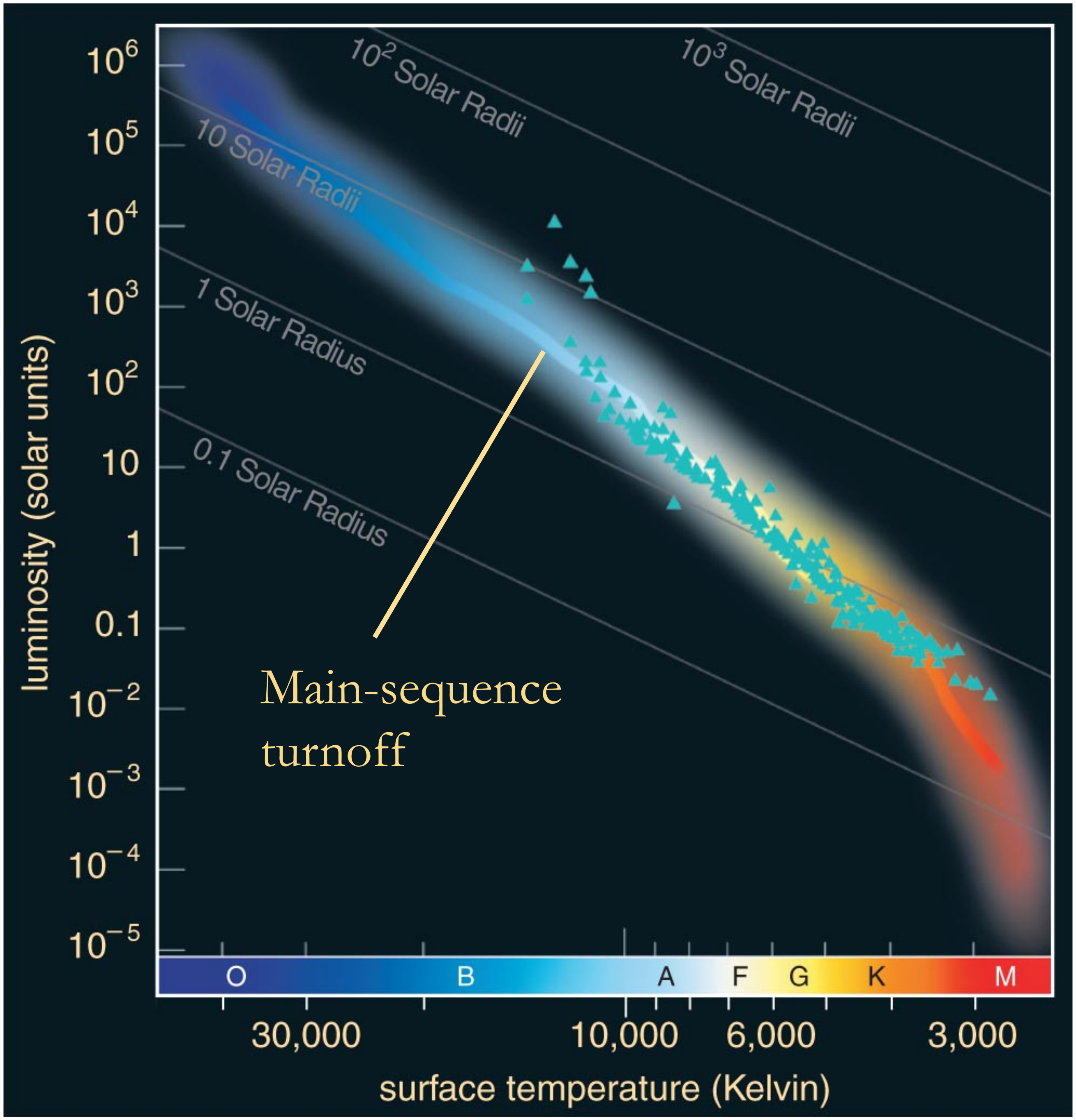
Globular cluster: Up to a million or more stars in a dense ball bound together by gravity

Star Clusters and Stellar Lives

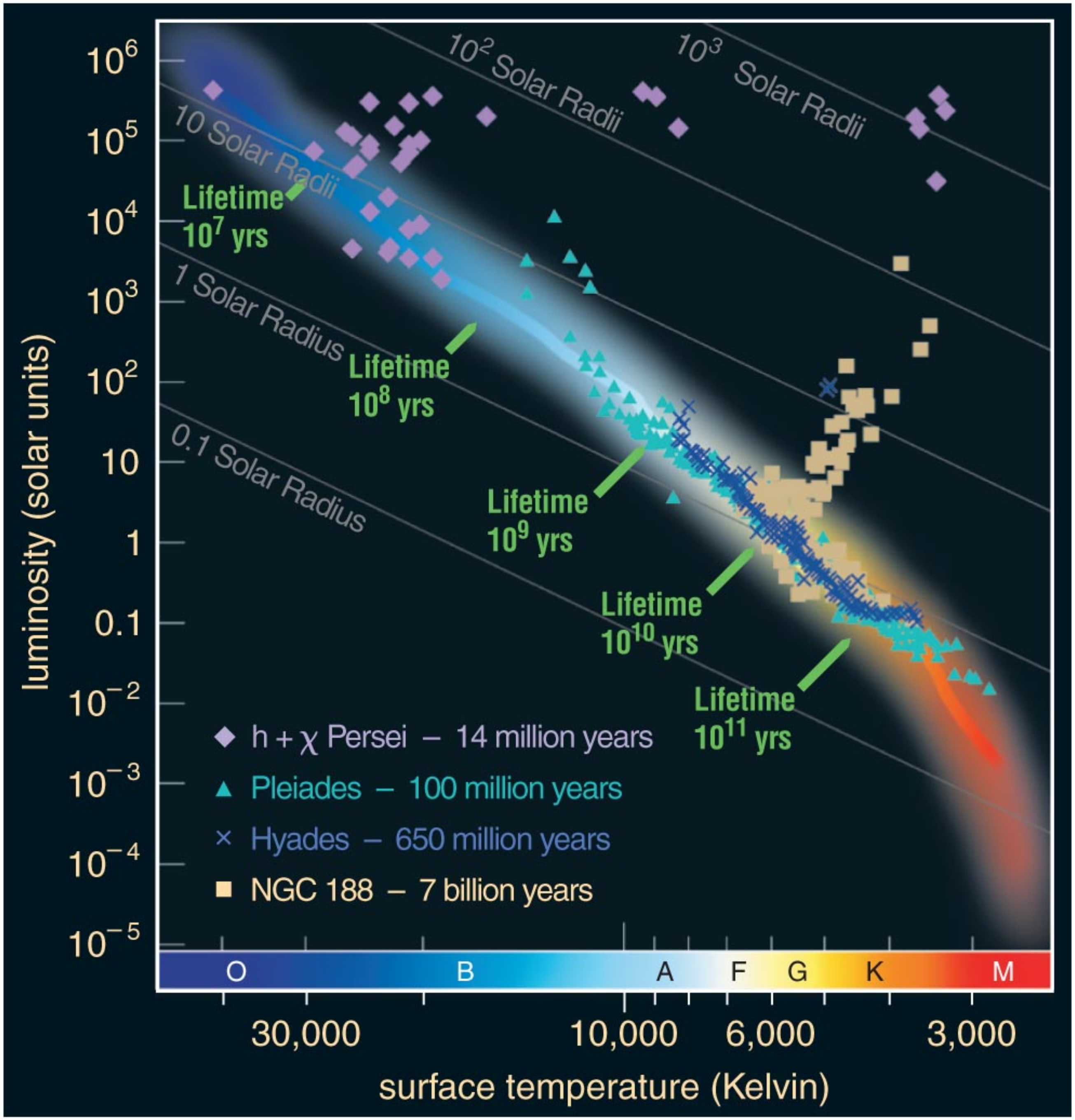
- Our knowledge of the life stories of stars comes from comparing mathematical models of stars with observations
- Star clusters are particularly useful because they contain stars of different mass that were born about the same time

Star Cluster Ages

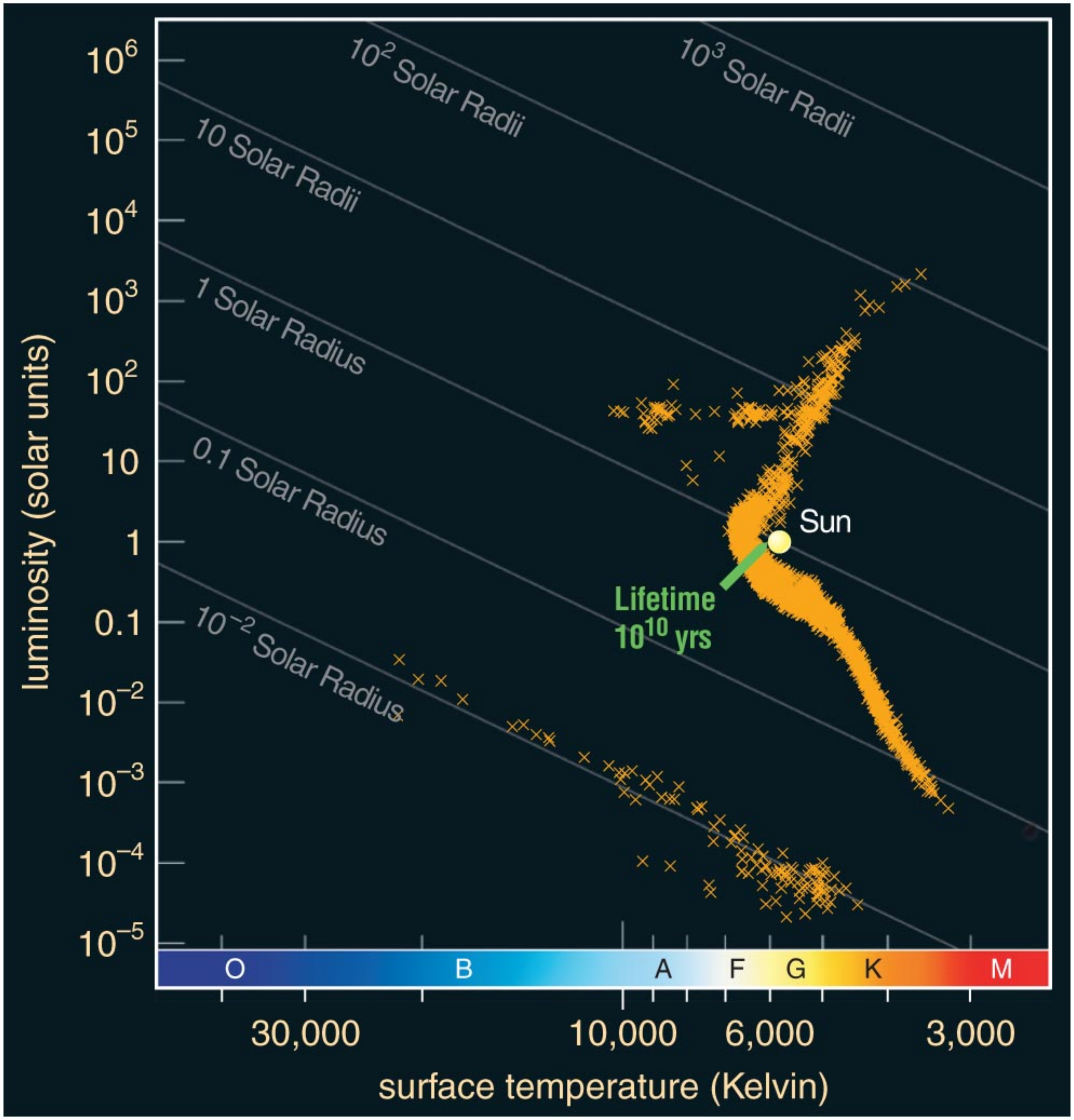




Pleiades now has no stars with life expectancy less than around 100 million years

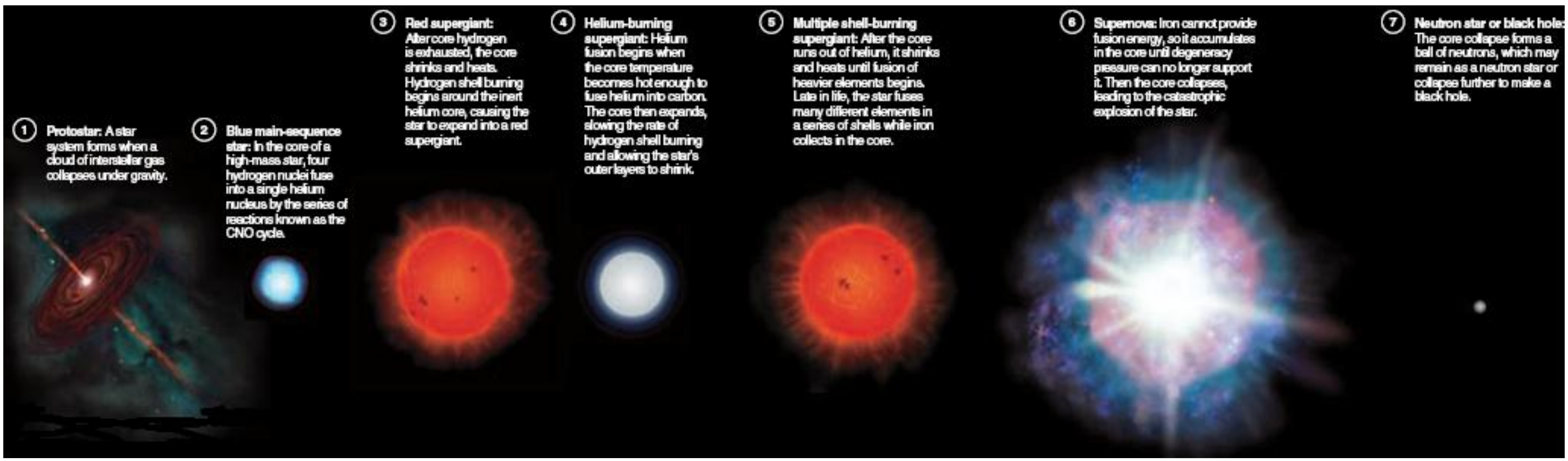


Main-sequence turnoff point of a cluster tells us its age

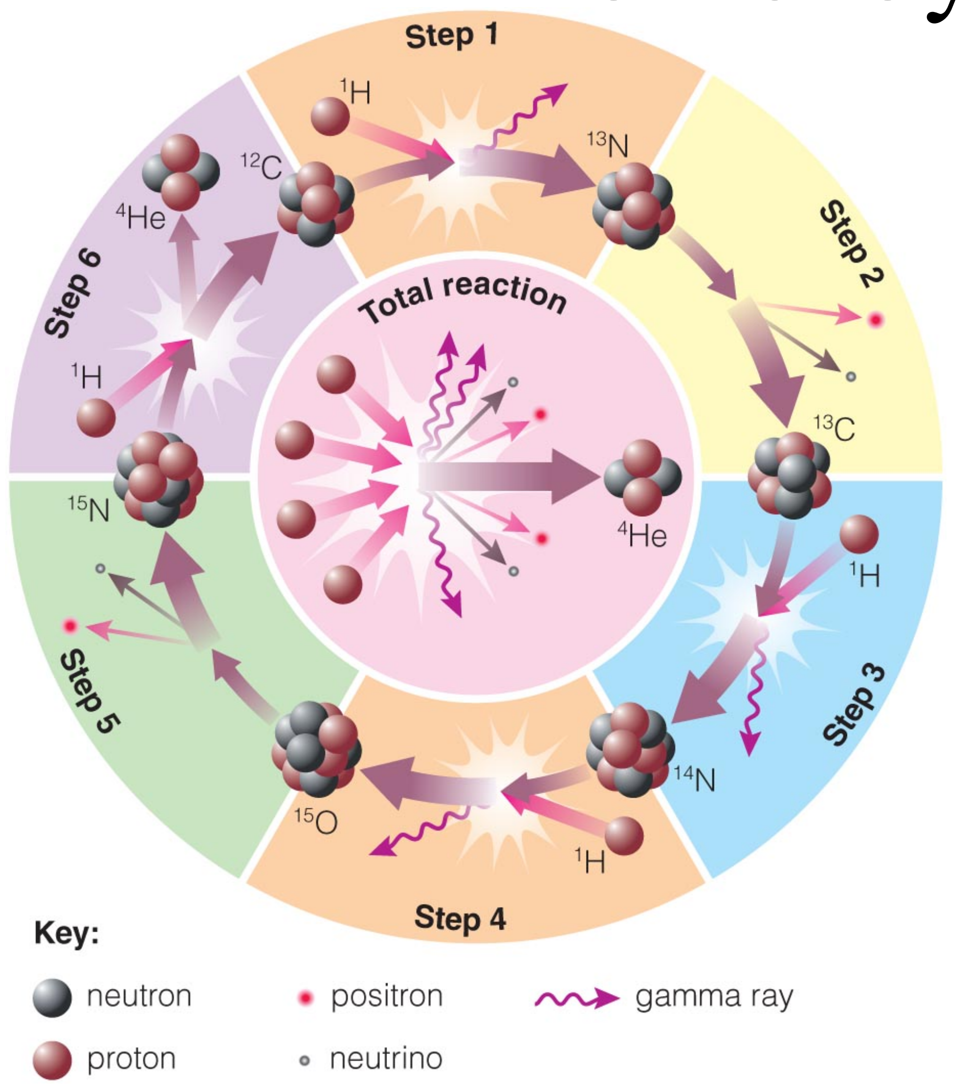


Detailed modeling of the oldest globular clusters reveals that they are about 13 billion years old

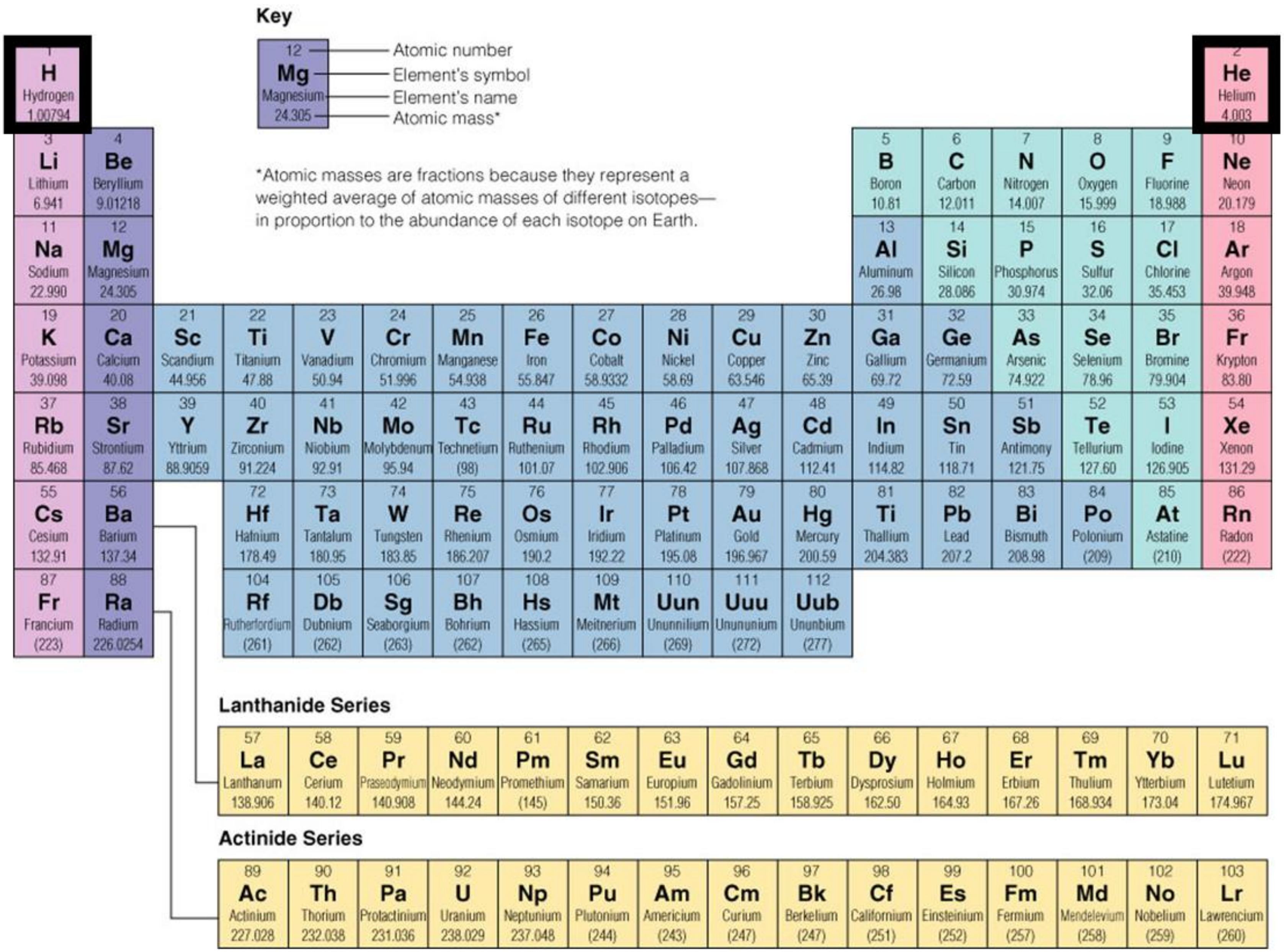
What are the life stages of a high-mass star?



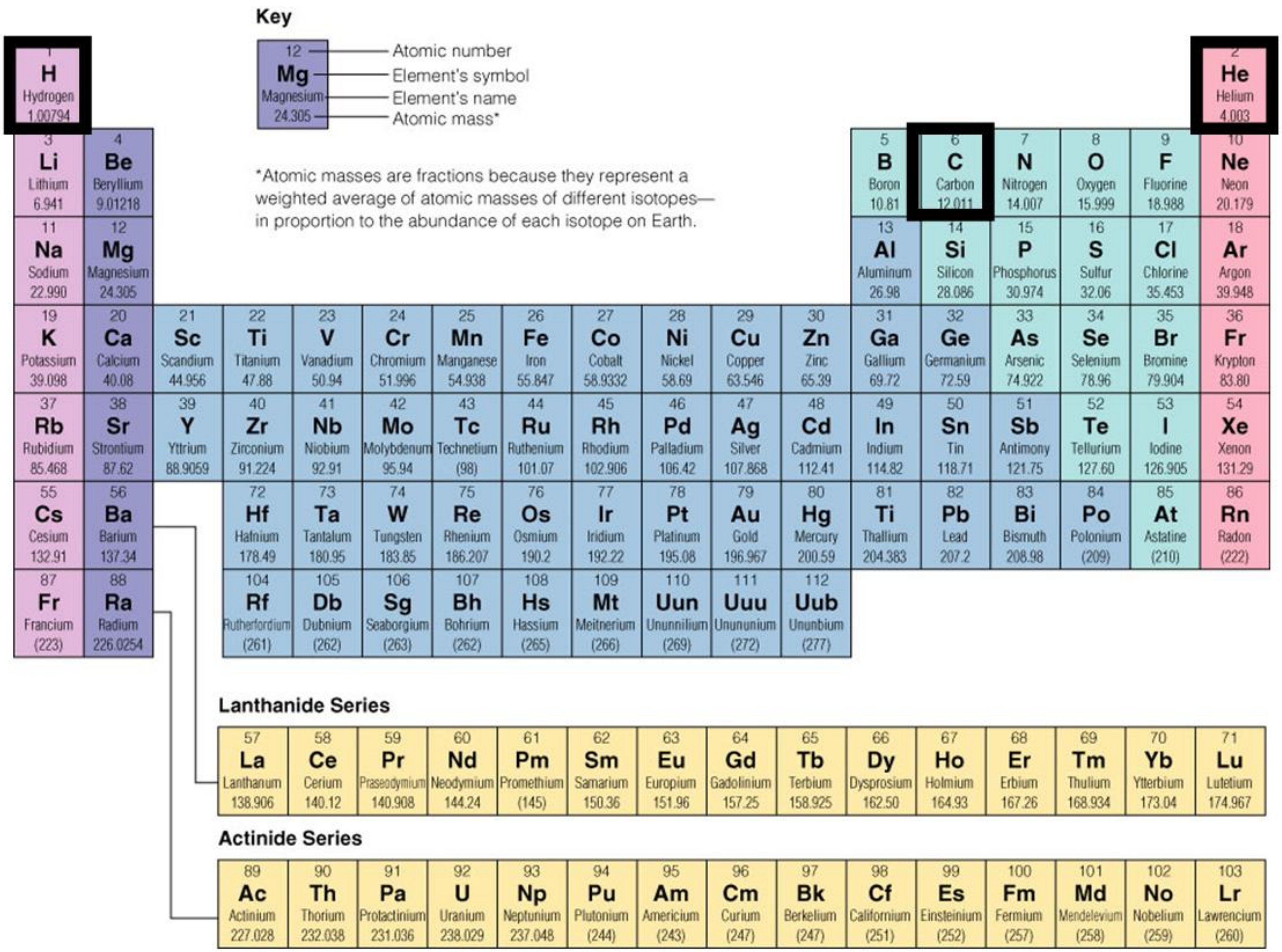
CNO Cycle



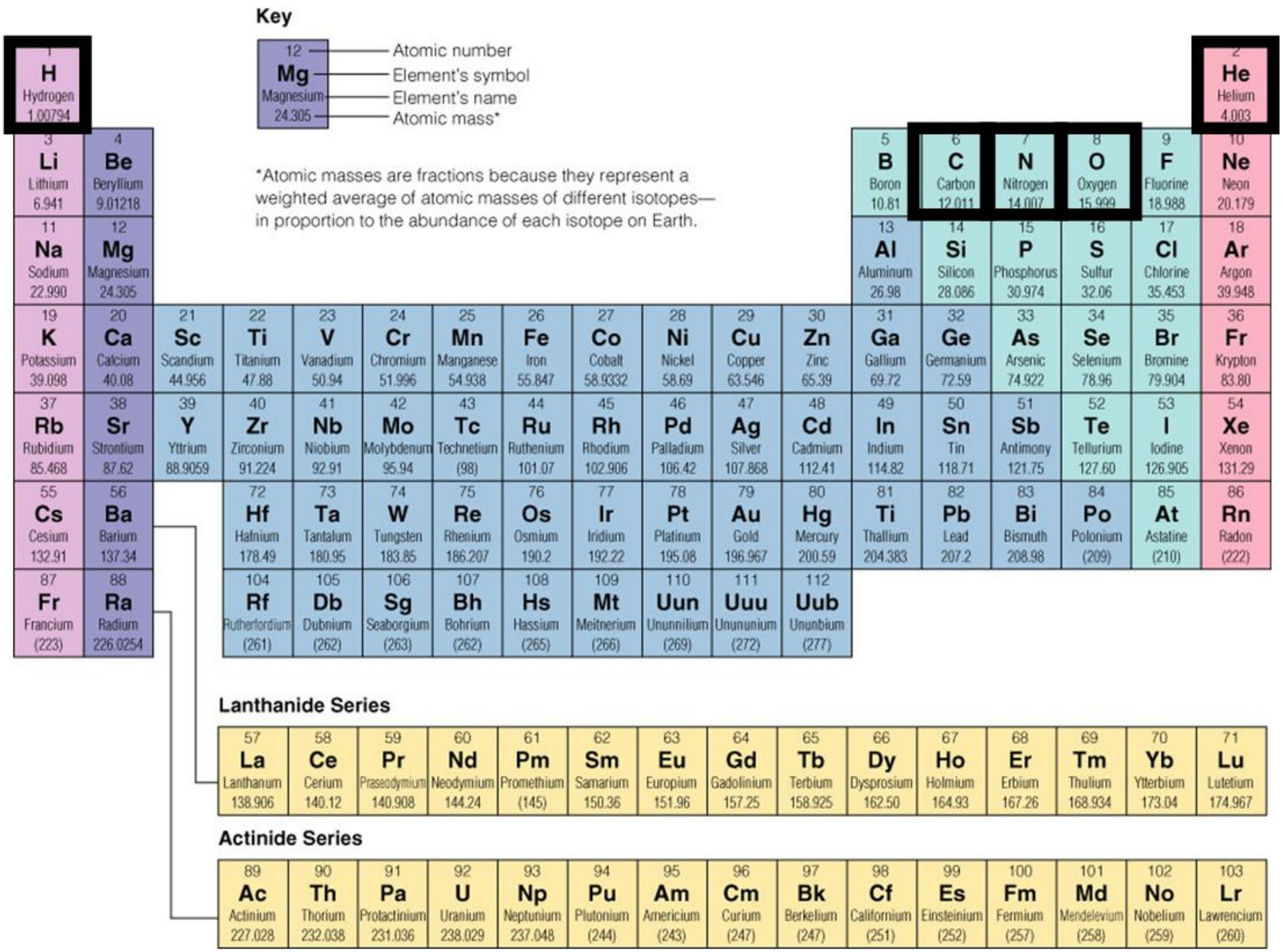
- High-mass main sequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as catalysts
- Greater core temperature enables H nuclei to overcome greater repulsion



Big Bang made 75% H, 25% He – stars make everything else

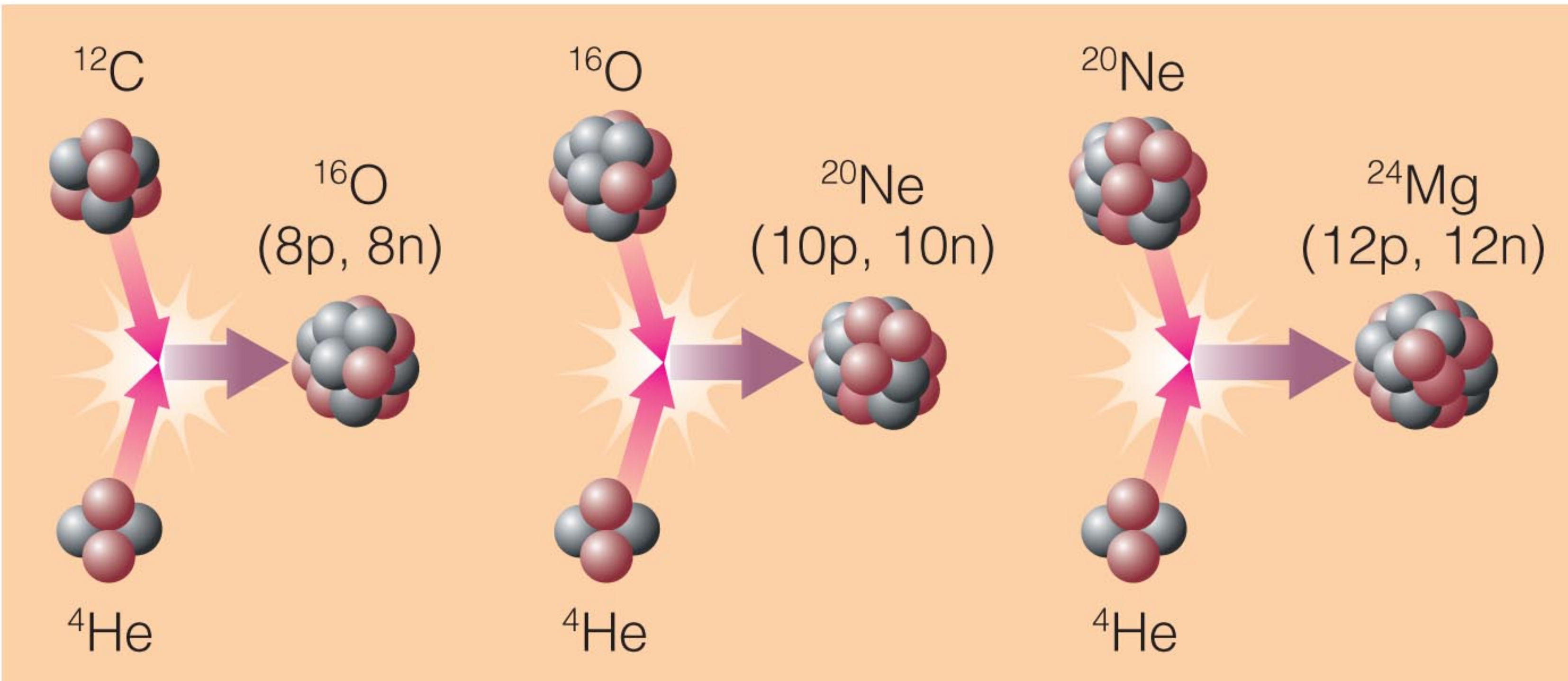


Helium fusion can make carbon in low-mass stars

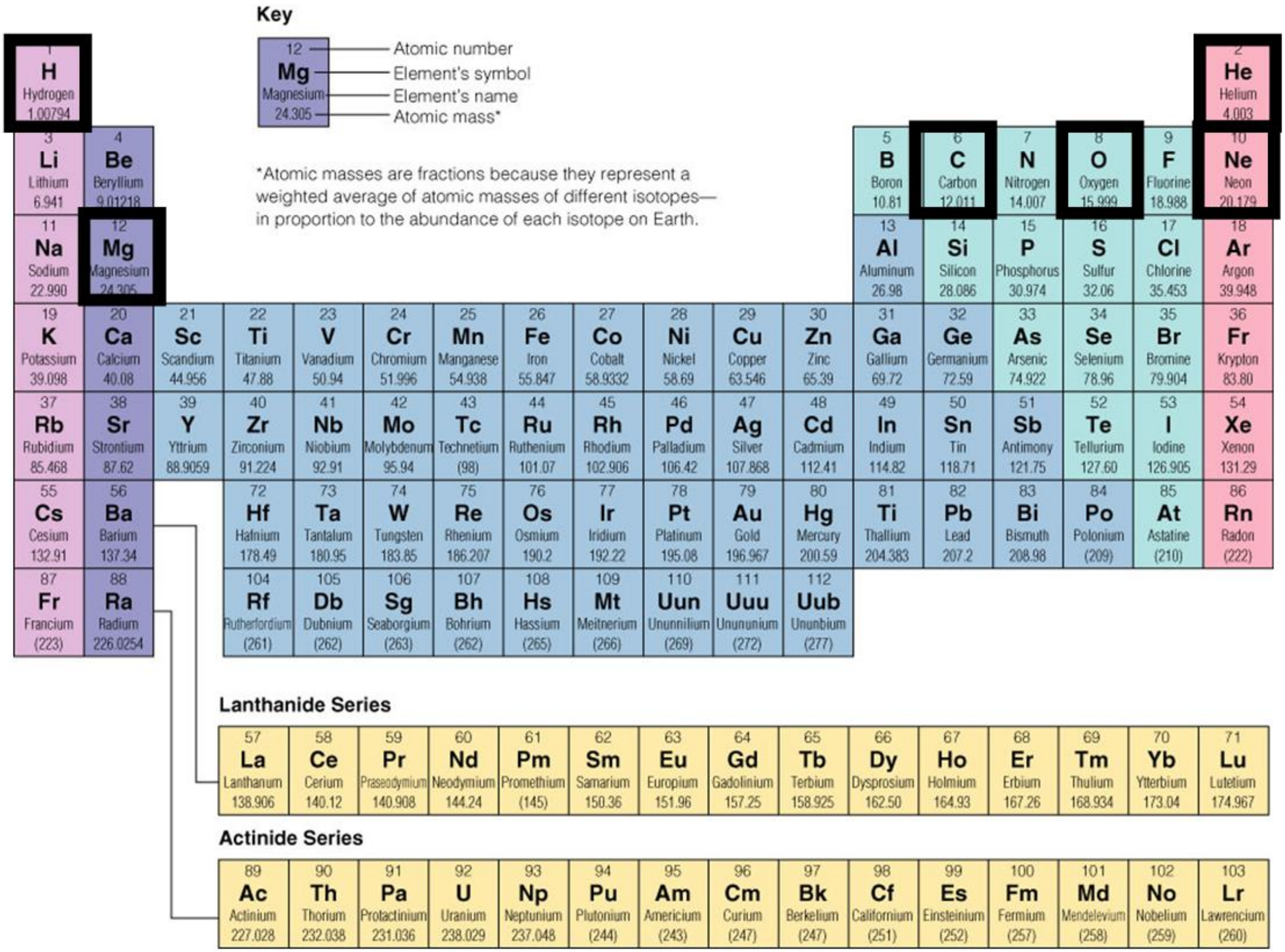


CNO cycle can change C into N and O

Helium Capture

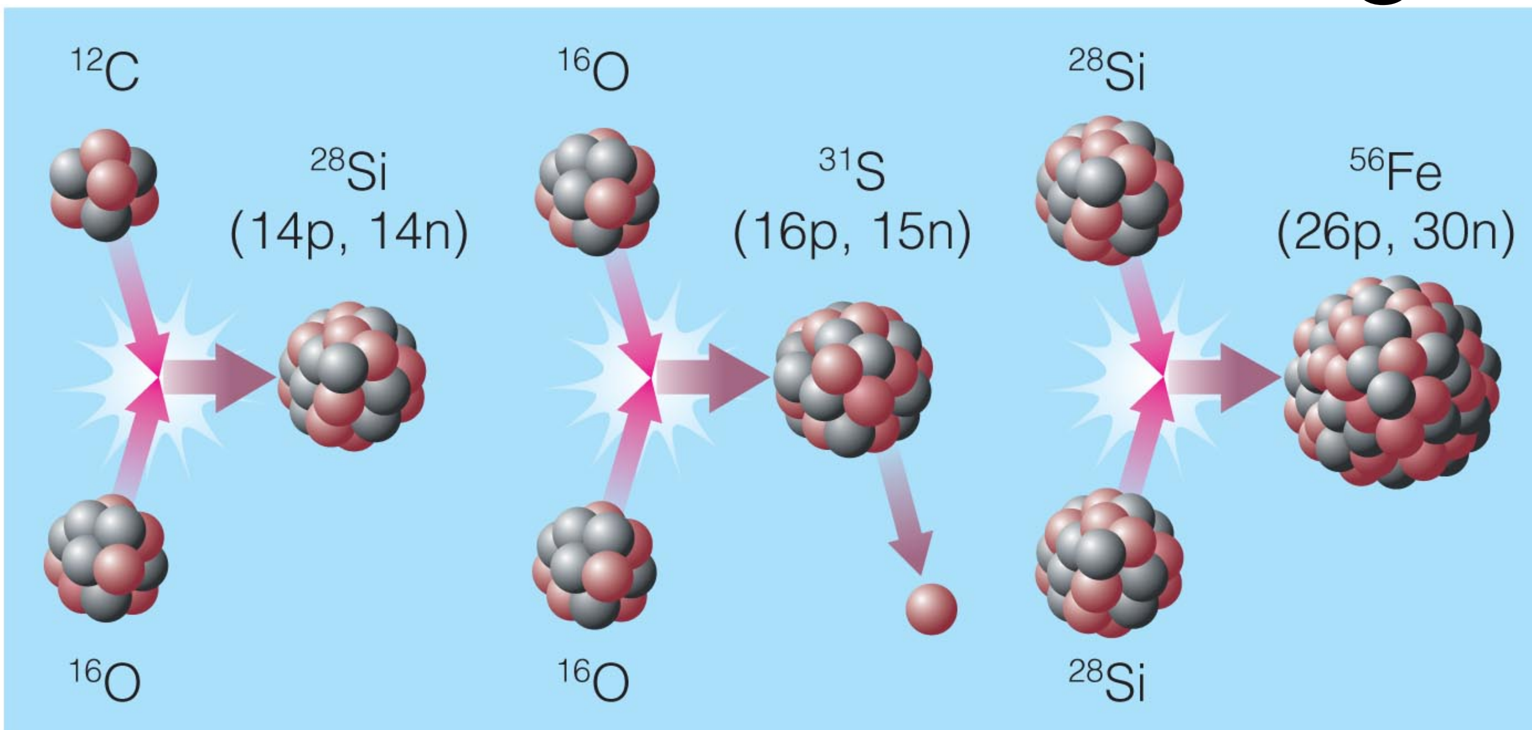


- **High core temperatures allow helium to fuse with heavier elements**

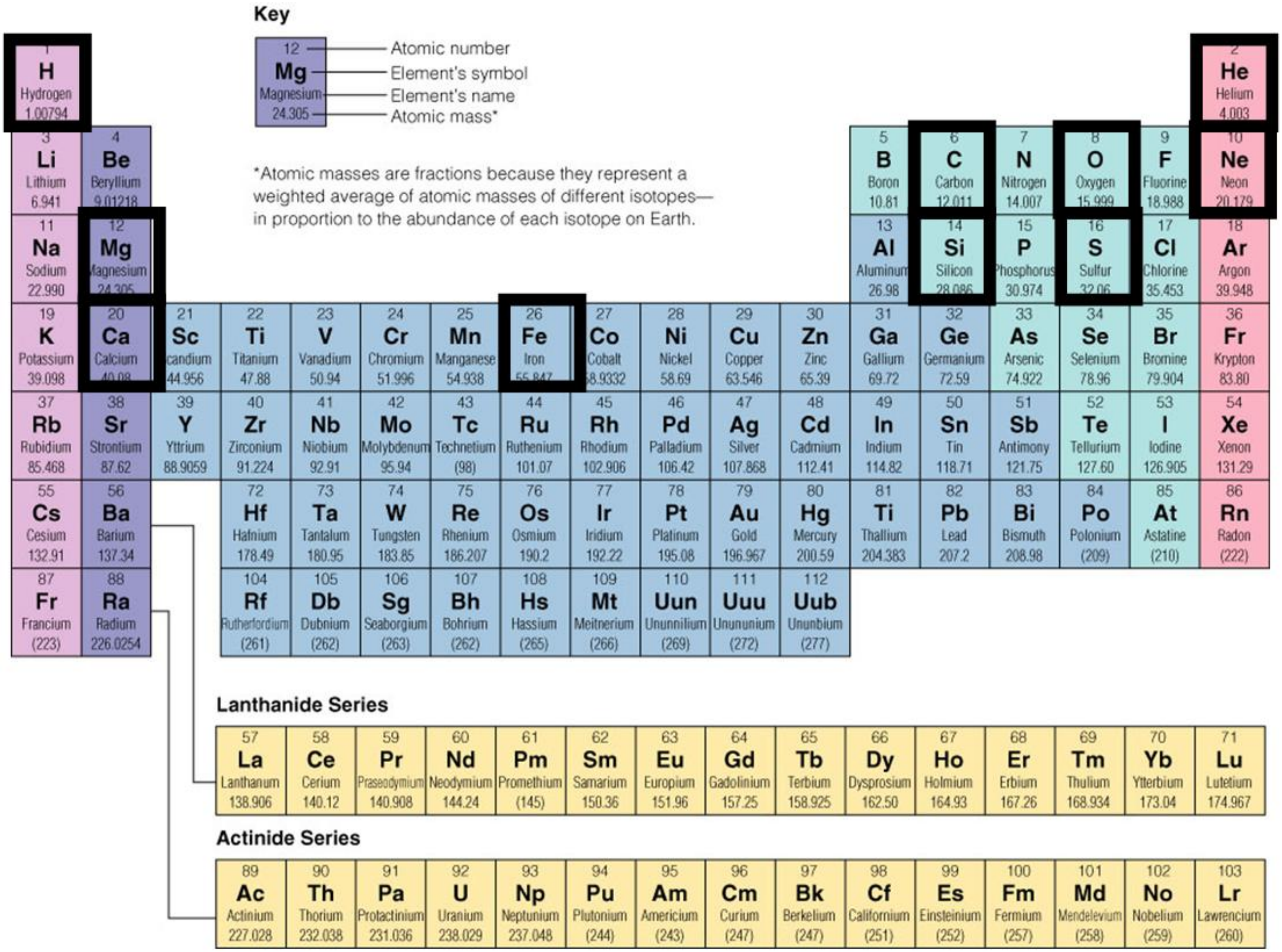


Helium capture builds C into O, Ne, Mg, …

Advanced Nuclear Burning

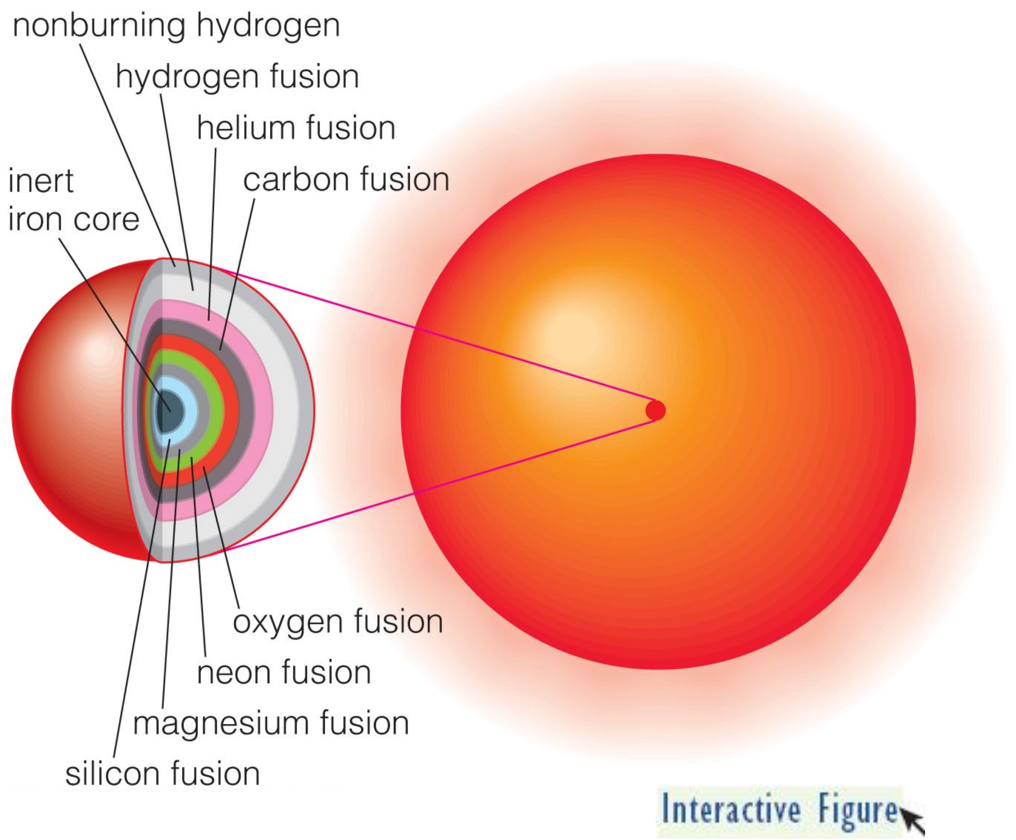


- **Core temperatures in stars with >8M_{Sun} allow fusion of elements as heavy as iron**

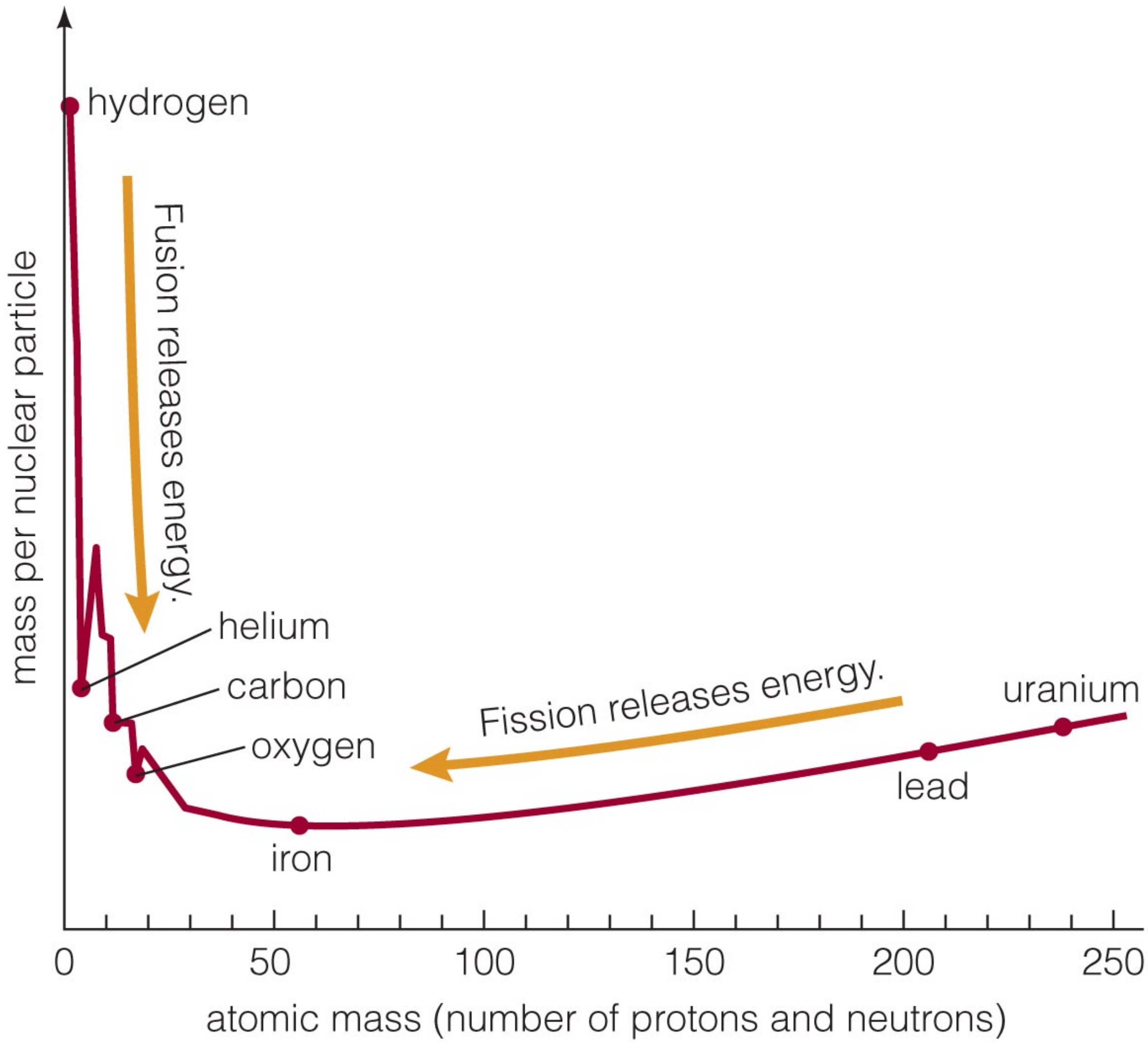


Advanced reactions in stars make elements like Si, S, Ca, Fe

Multiple Shell Burning

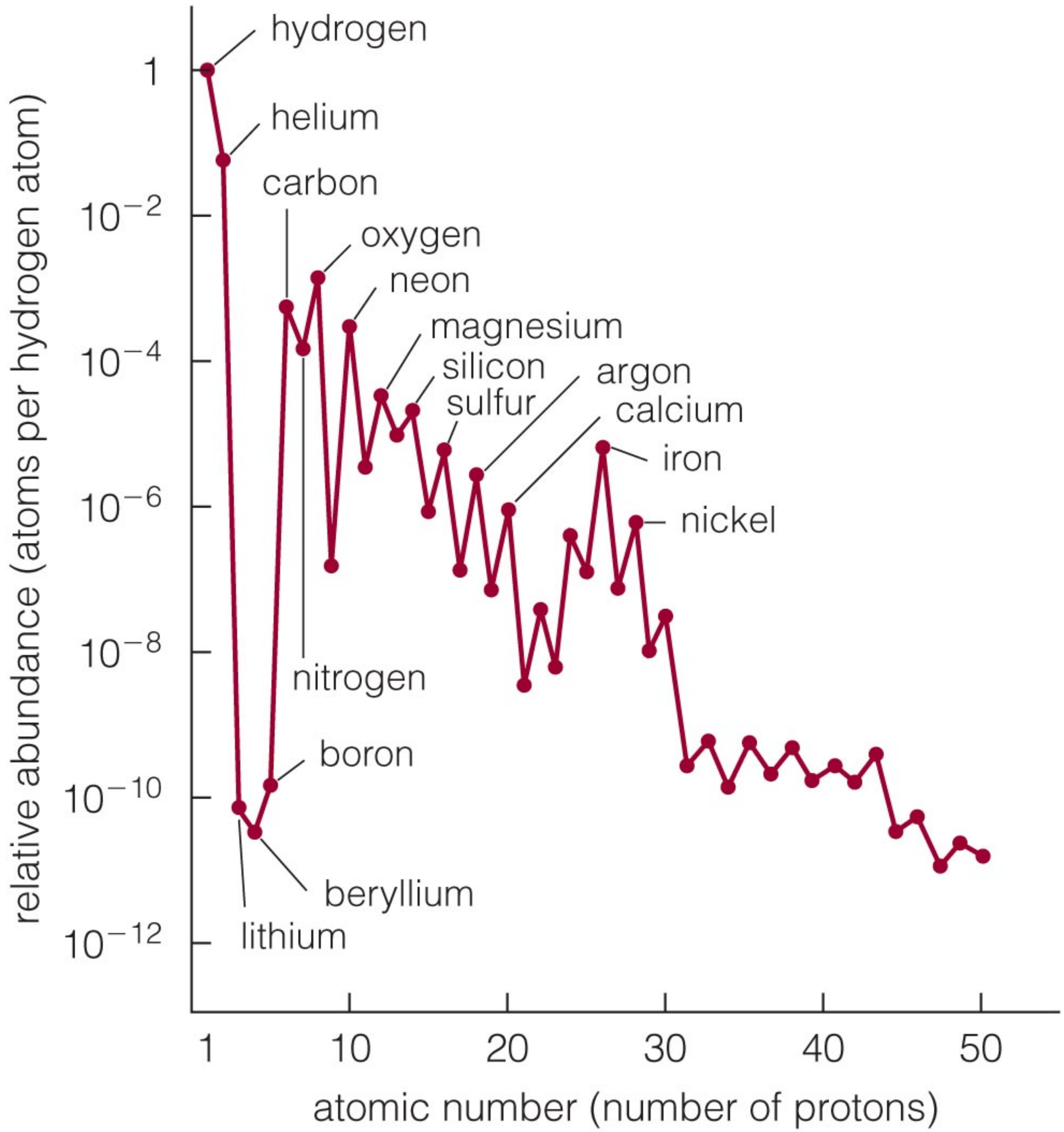


- Advanced nuclear burning proceeds in a series of nested shells



Iron is dead end for fusion because nuclear reactions involving iron do not release energy

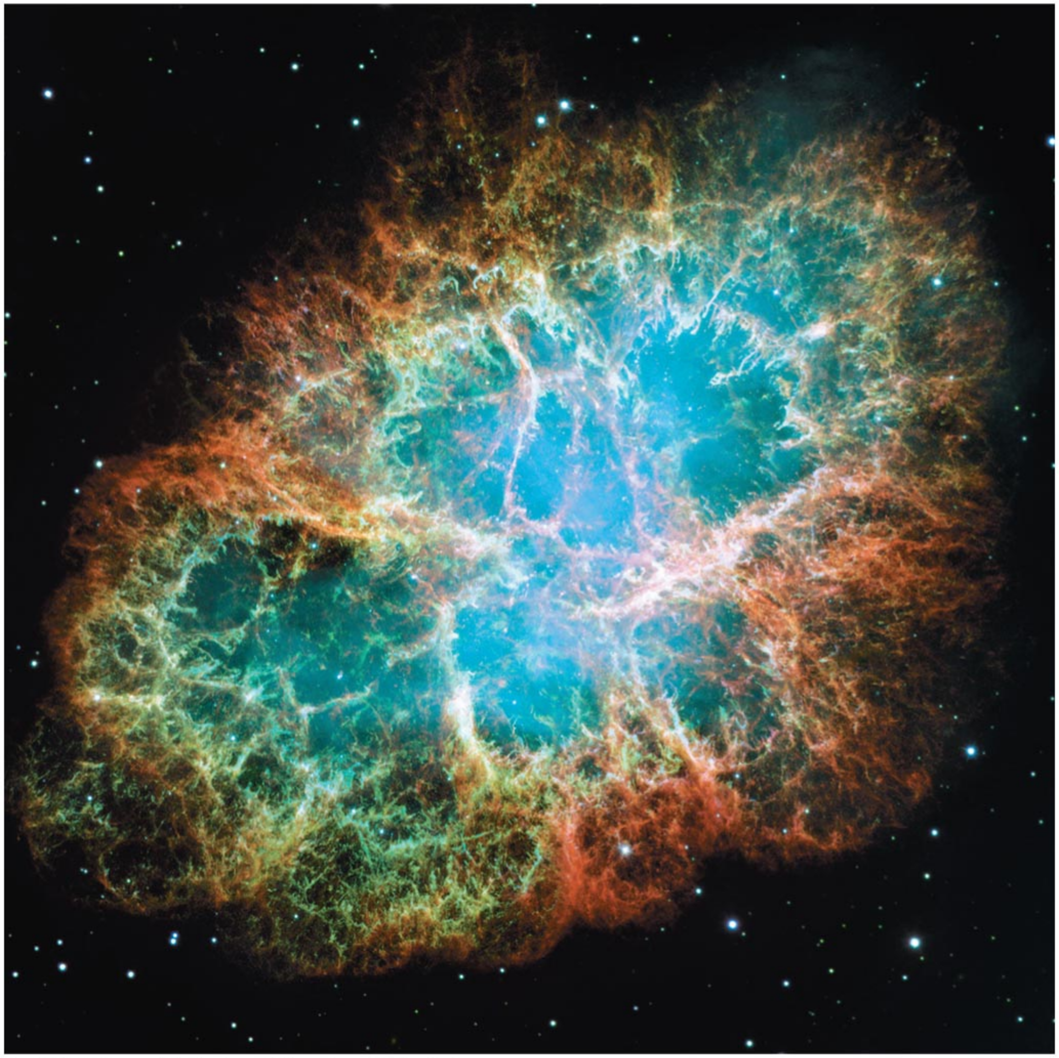
(Fe has lowest mass per nuclear particle)



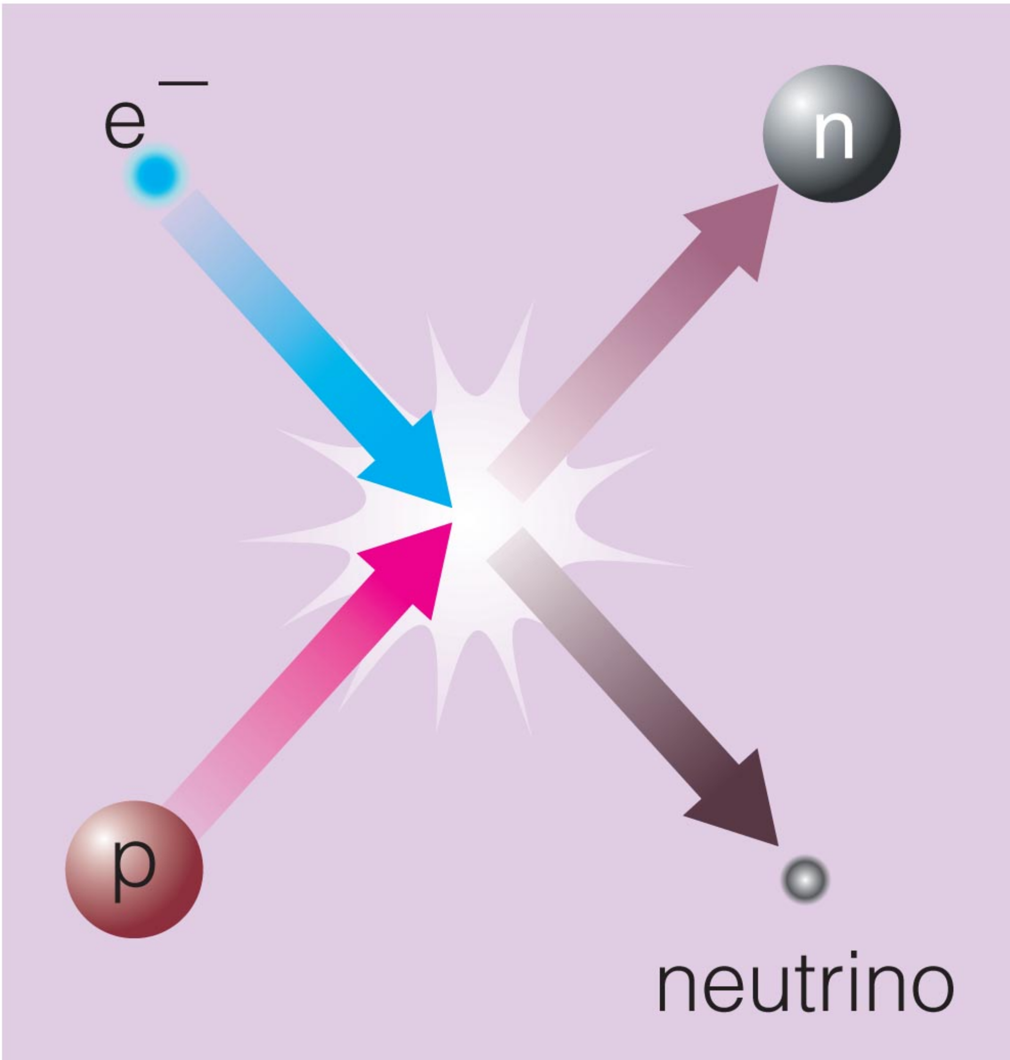
Evidence for helium capture:

Higher abundances of elements with even numbers of protons

How does a high-mass star die?

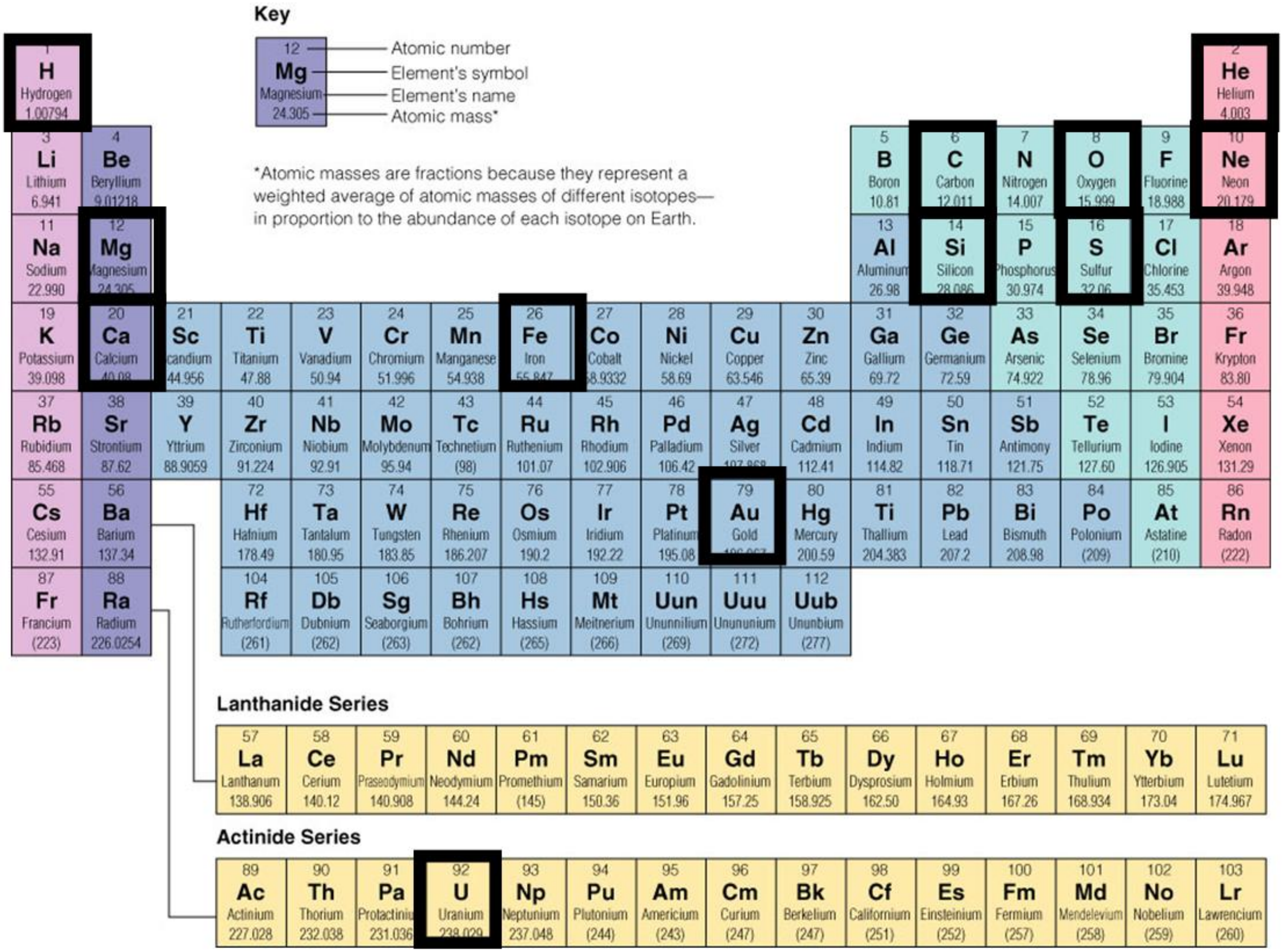


Supernova Explosion



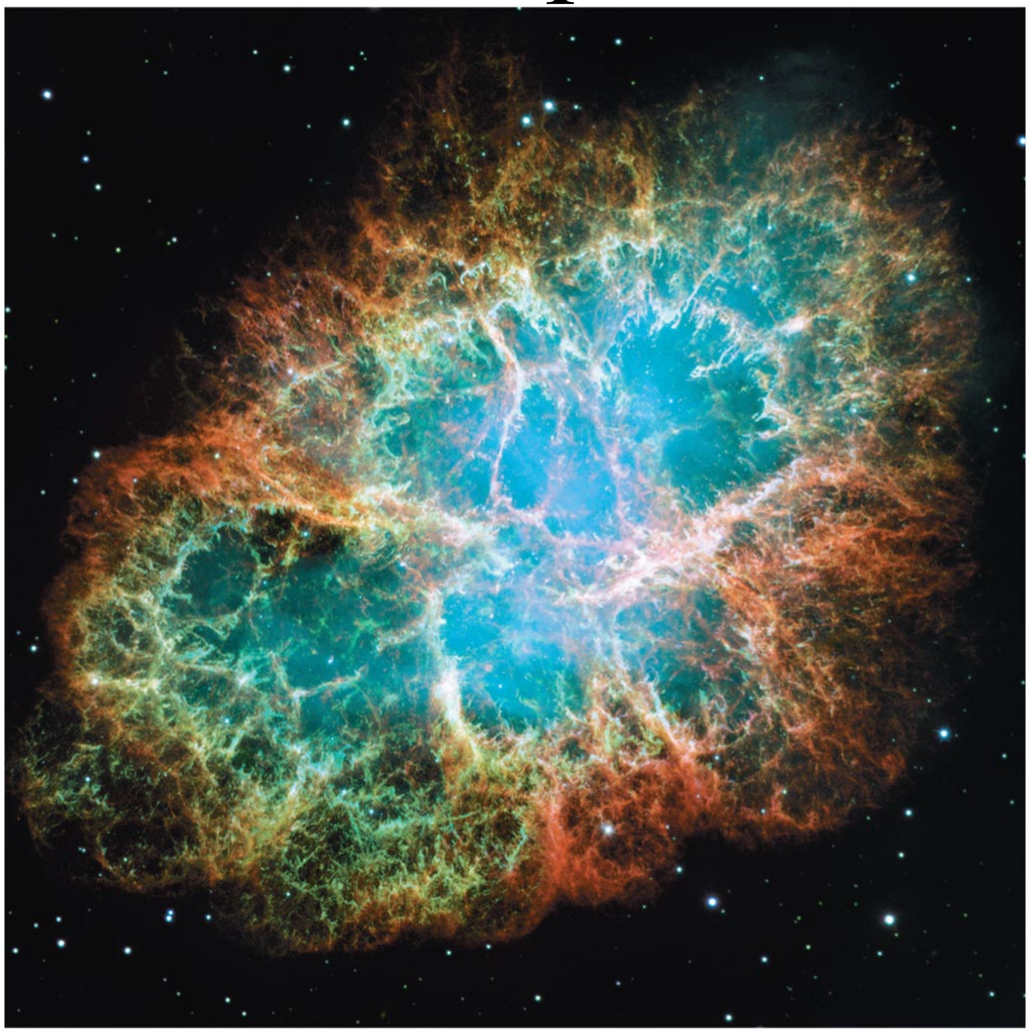
- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos

- Neutrons collapse to the center, forming a **neutron star**



Energy and neutrons released in supernova explosion enable elements heavier than iron to form, including Au and U

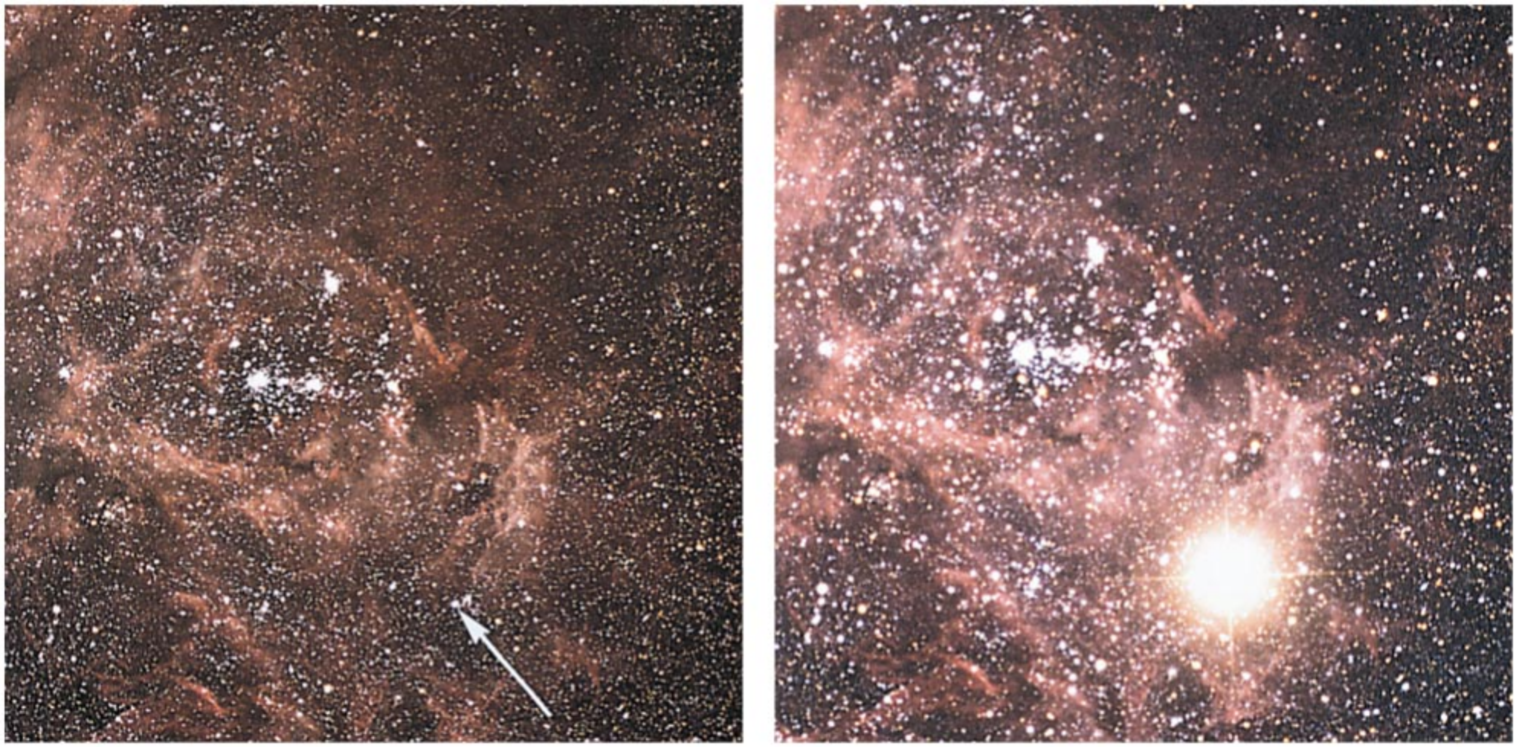
Supernova Remnant



Interactive Figure

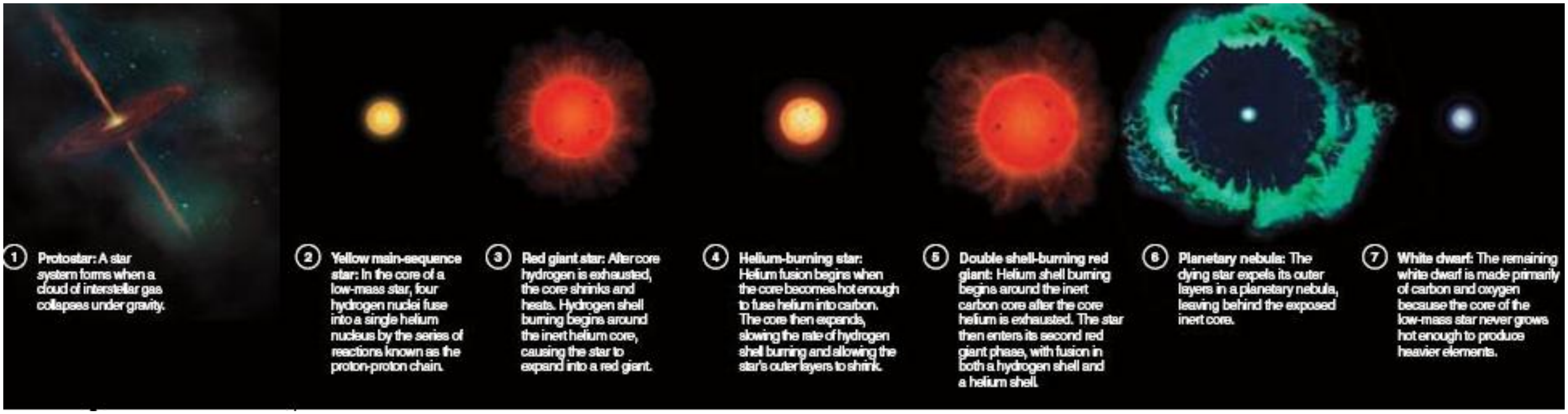
- Energy released by collapse of core drives outer layers into space
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054

Supernova 1987A



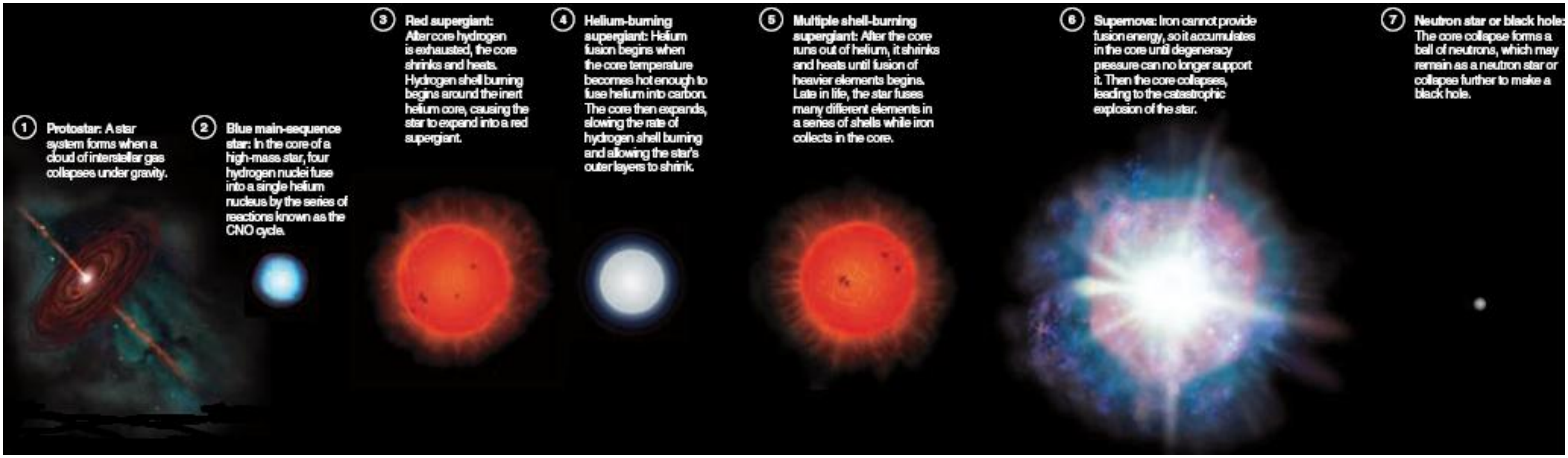
- **The closest supernova in the last four centuries was seen in 1987**

Low-Mass Star Summary



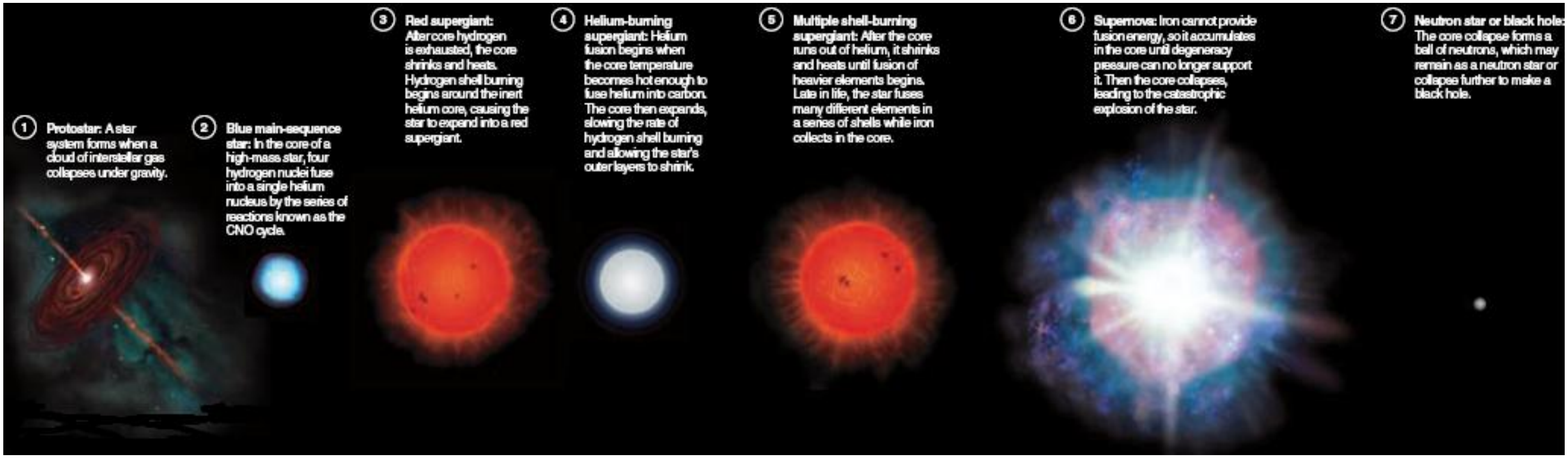
1. **Main Sequence: H fuses to He in core**
2. **Red Giant: H fuses to He in shell around He core**
3. **Helium Core Burning:**
   He fuses to C in core while H fuses to He in shell
4. **Double Shell Burning:**
   H and He both fuse in shells
5. **Planetary Nebula leaves white dwarf behind**

Reasons for Life Stages



- **Core shrinks and heats until it's hot enough for fusion**
- **Nuclei with larger charge require higher temperature for fusion**
- **Core thermostat is broken while core is not hot enough for fusion (shell burning)**
- **Core fusion can't happen if degeneracy pressure keeps core from shrinking**

Life Stages of High-Mass Star



1. **Main Sequence: H fuses to He in core**
2. **Red Supergiant: H fuses to He in shell around He core**
3. **Helium Core Burning:**
   He fuses to C in core while H fuses to He in shell
4. **Multiple Shell Burning:**
   Many elements fuse in shells
5. **Supernova leaves neutron star behind**