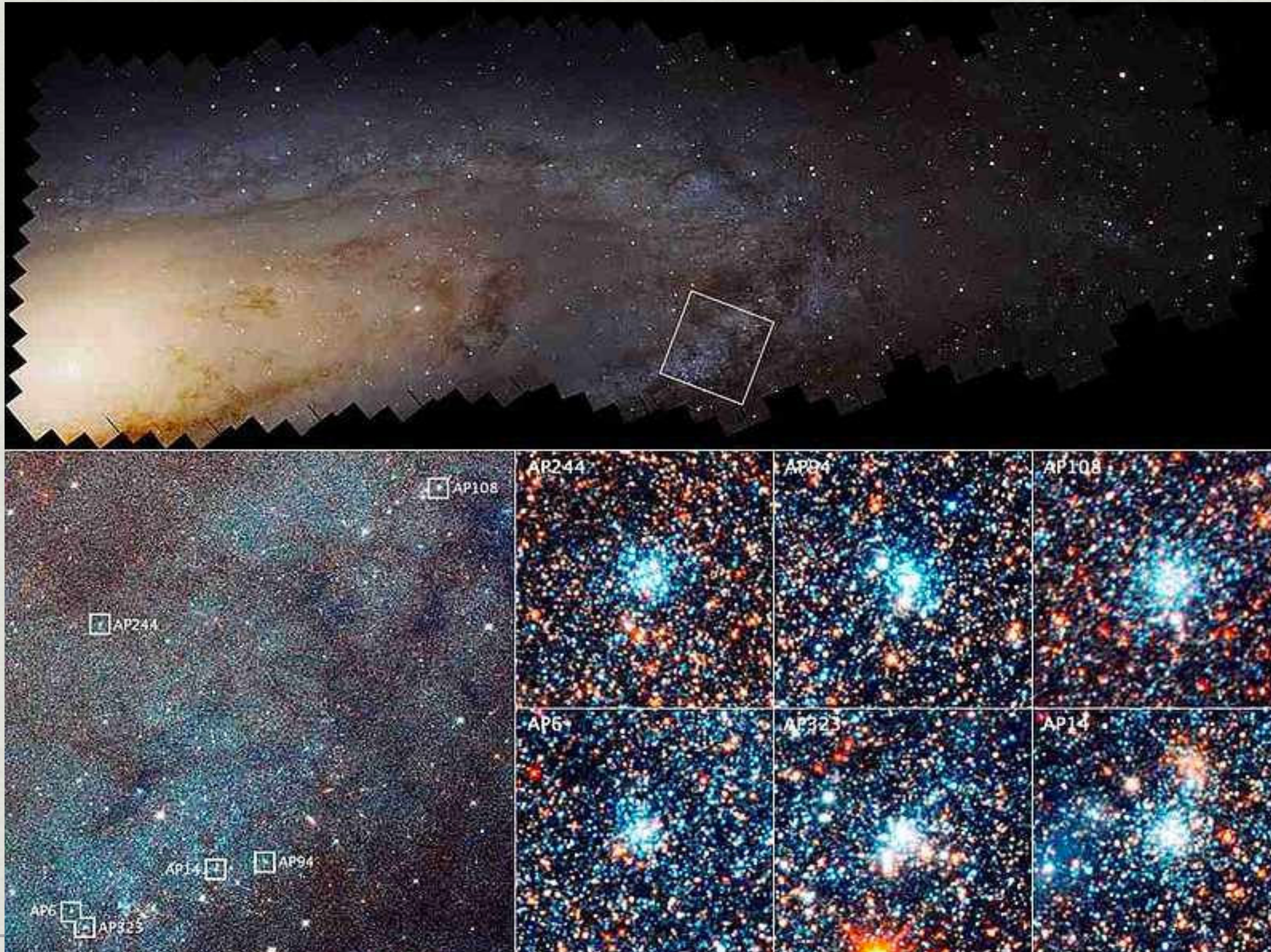
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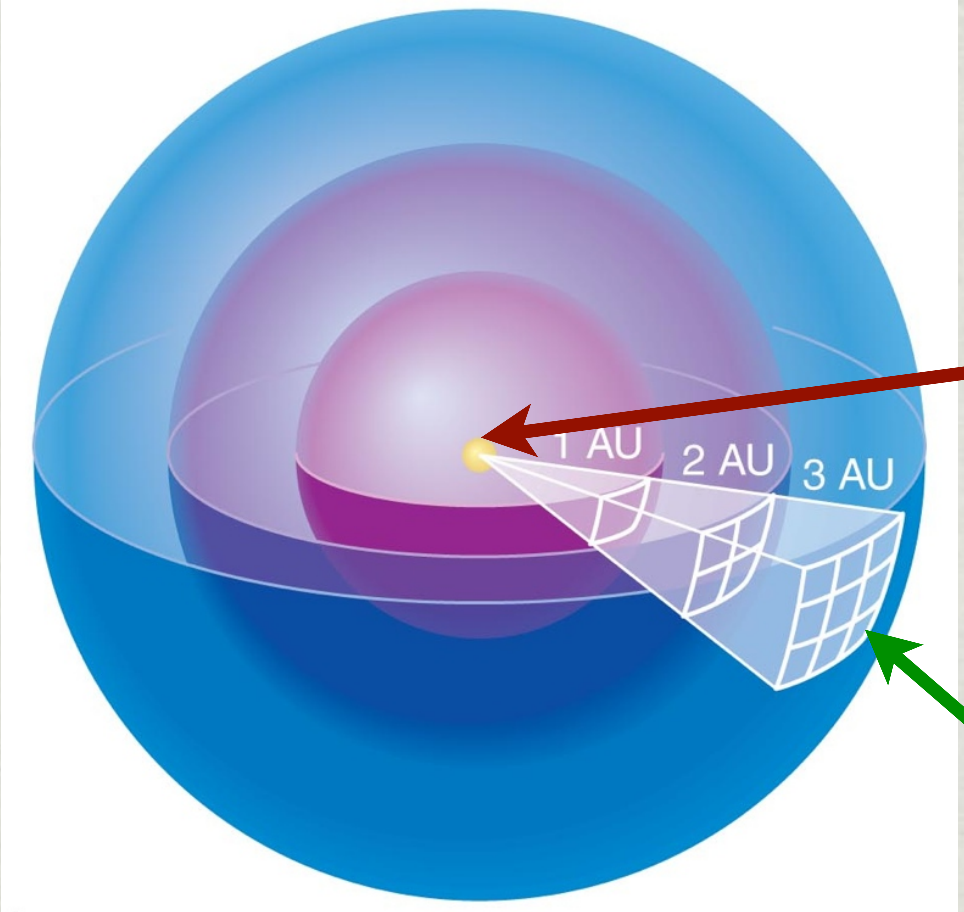
Measuring the Stars

- The Luminosity of a star, total energy output per second, is related to the brightness and distance: $\text{Brightness} = \frac{L}{4\pi d^2}$
  - $10^{-4}\ L_{sun}$ - $10^{6}\ L_{sun}$
- Temperature: from color (wavelength of max photon emission) and lines in the spectrum: Wein's law, spectral classification (OBAFGKM)
  - 3000 K - 50,000 K
- Composition: matching chemical fingerprints of different atoms to lines in the spectrum
  - 10^{-5} - 2 × the metal abundance of the sun
- Mass: period and separation of binary star orbits, Newton's version of Kepler's 3rd Law
  - 0.08 Msun - 150 Msun
- Size: measure Luminosity and Temperature, use Stefan-Boltzmann law
  Luminosity = Total surface area × σT^4 = $4\pi R_{sun}$ x σT^4
  - $0.001\ R_{sun}$ - $1000\ R_{sun}$

Measuring Luminosity



Luminosity = total energy output of the sun in some chunk of time (seconds, weeks, months, etc.) Joules/sec = Watts

You can calculate the luminosity if you the surface area and the temperature.

Stefan-Boltzmann Law:
Luminosity = Total surface area × σT^4

You can learn the luminosity by measuring the brightness and the distance to the object:

$$\text{Brightness} = \frac{L}{4\pi d^2} \rightarrow L = \text{Brightness} \times (4\pi d^2)$$

Measuring Luminosity

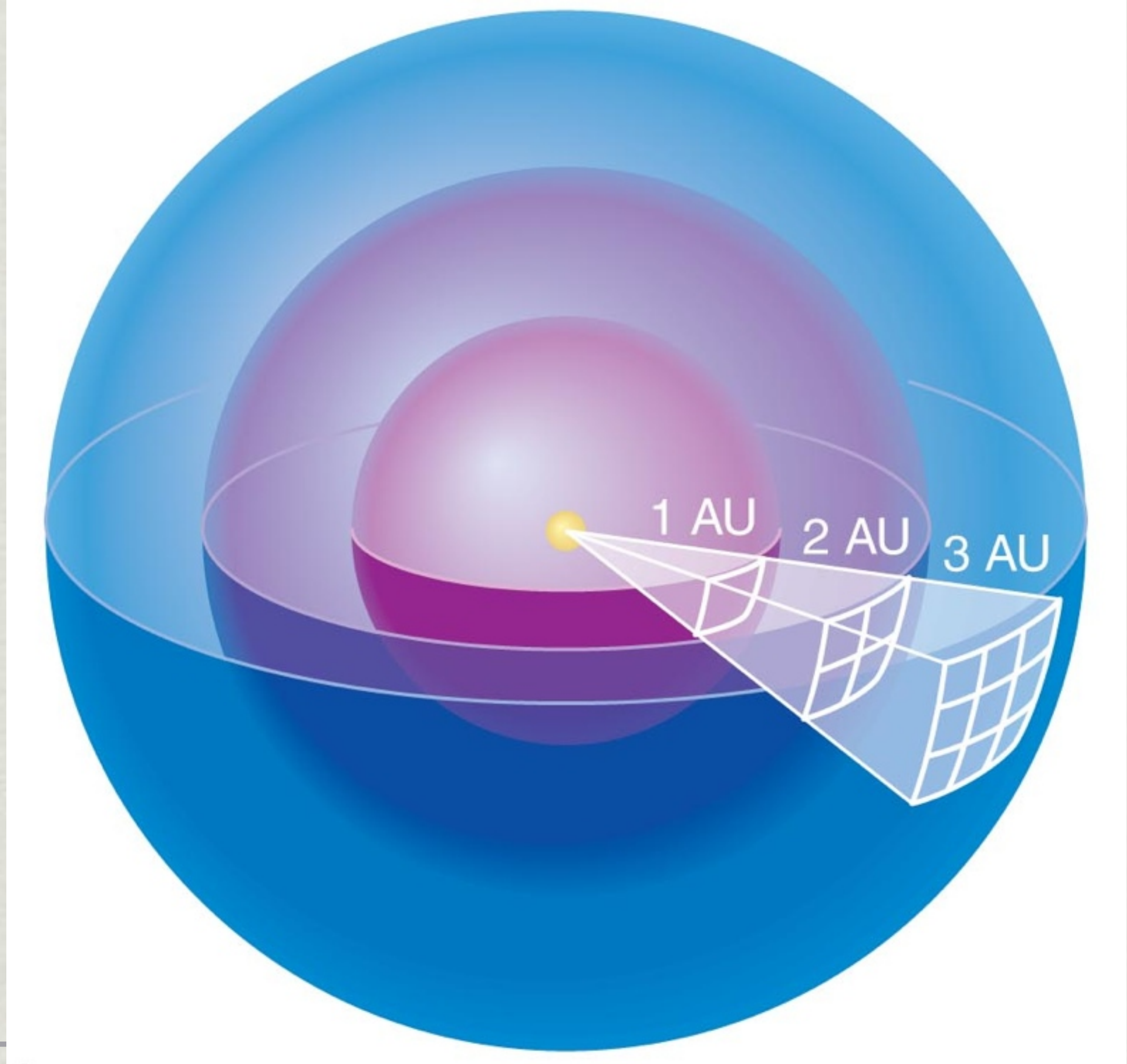
$$\text{Brightness} = \frac{L}{4\pi d^2} \rightarrow L = \text{Brightness} \times (4\pi d^2)$$

Energy output per second in some patch of area

Measure brightness of a star, like the sun.

Then need to know distance to add up the energy ouptput per second over the entire sphere surrounding the object.

That gives the luminosity.



Measuring Luminosity

$$\text{Brightness} = \frac{L}{4\pi d^2} \rightarrow L = \text{Brightness} \times (4\pi d^2)$$

Energy output per second in some patch of area

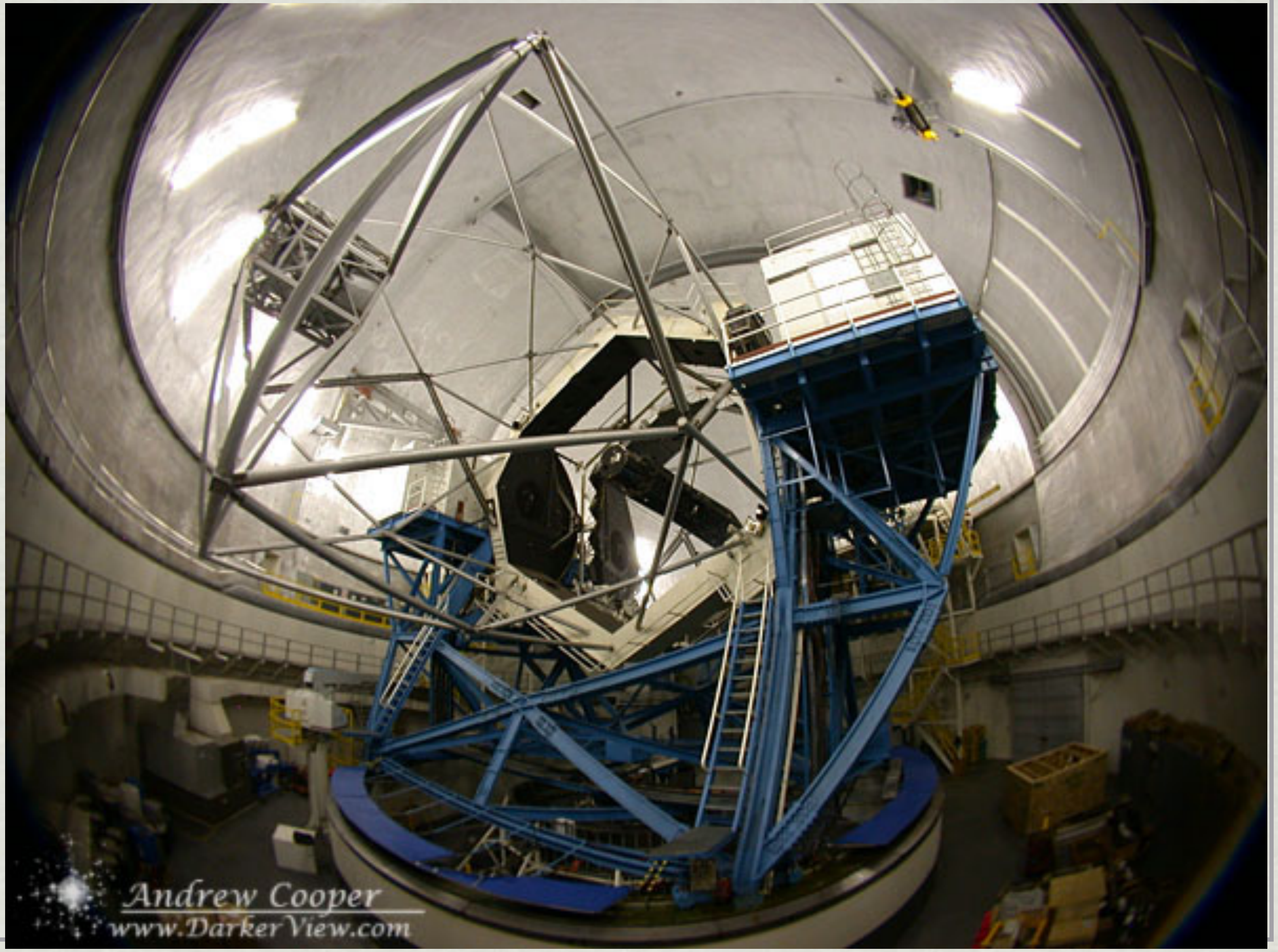
Bigger collecting area, collect more energy per second

Measuring Luminosity

$$\text{Brightness} = \frac{L}{4\pi d^2} \rightarrow L = \text{Brightness} \times (4\pi d^2)$$

Energy output per second in some patch of area

Bigger collecting area, collect more energy per second



Measuring Luminosity

$$\text{Brightness} = \frac{L}{4\pi d^2} \rightarrow L = \text{Brightness} \times (4\pi d^2)$$

Energy output per second in some patch of area

If a star with the same Luminosity as the sun is farther way (larger d), we measure a smaller brightness

Luminosity, Brightness, Distance:

We can always measure Brightness.

Need to know one of Luminosity of Distance to learn the other

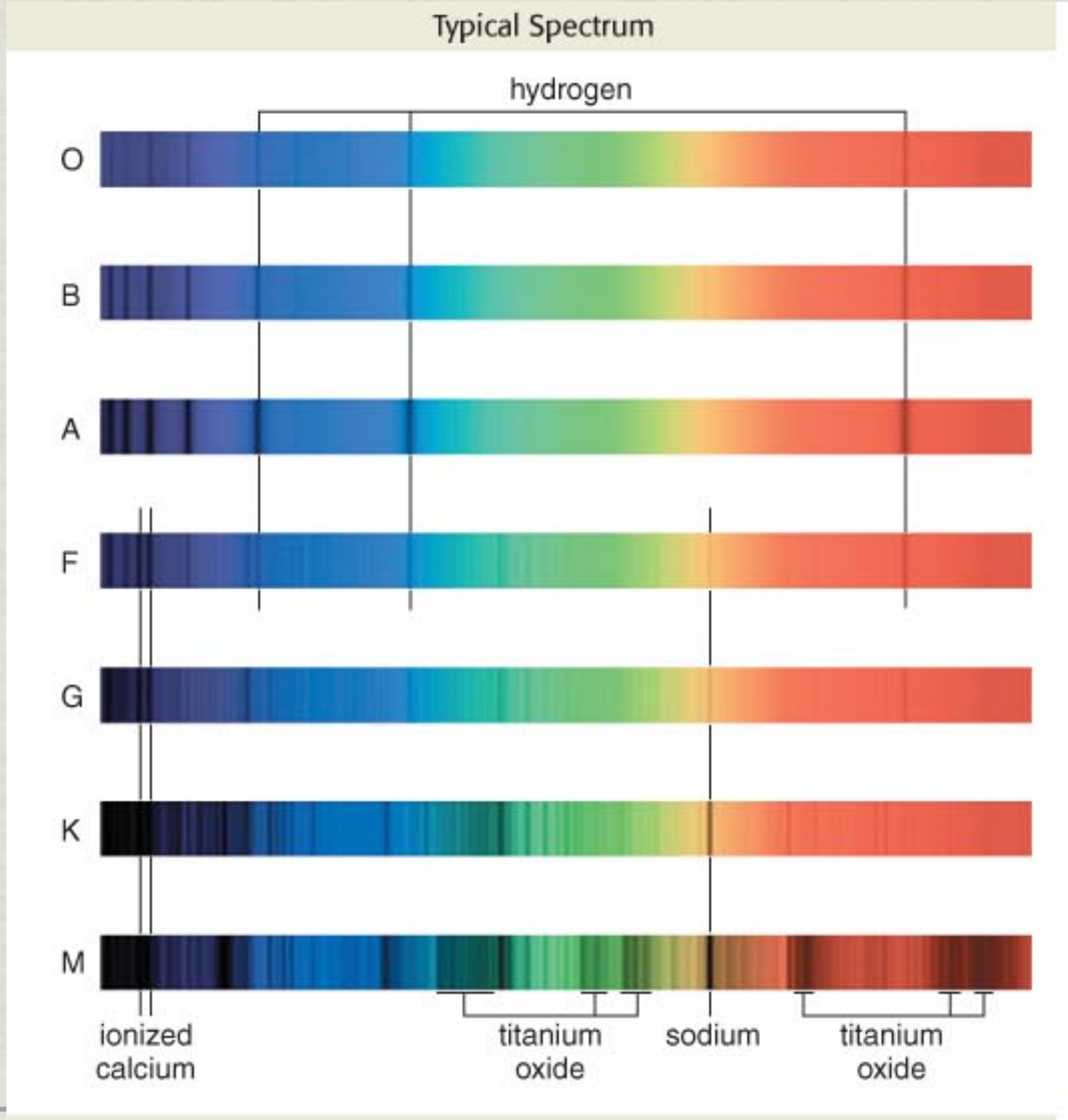
Use other clues about stars, like their spectra, to guess Luminosity.

Remember, spectral sequence OBAFGKM depends on temperature.

We'll see that temperature and luminosity of a star are related.

Temperature and Chemical Composition

O,B,A,F,…classification of spectra using absorption lines is a temperature sequence



O hottest -- no lines, all ionized
B
A strongest Hydrogen lines
F
G
K
M very cool -- molecules form

Measuring Luminosity

Brightness = $\frac{L}{4\pi d^2}$ → L = Brightness × ($4\pi d^2$)

Energy output per second in some patch of area

If a star with the same Luminosity as the sun is farther way (larger d), we measure a smaller brightness

Luminosity, Brightness, Distance:

We can always measure Brightness.

Need to know one of Luminosity of Distance to learn the other

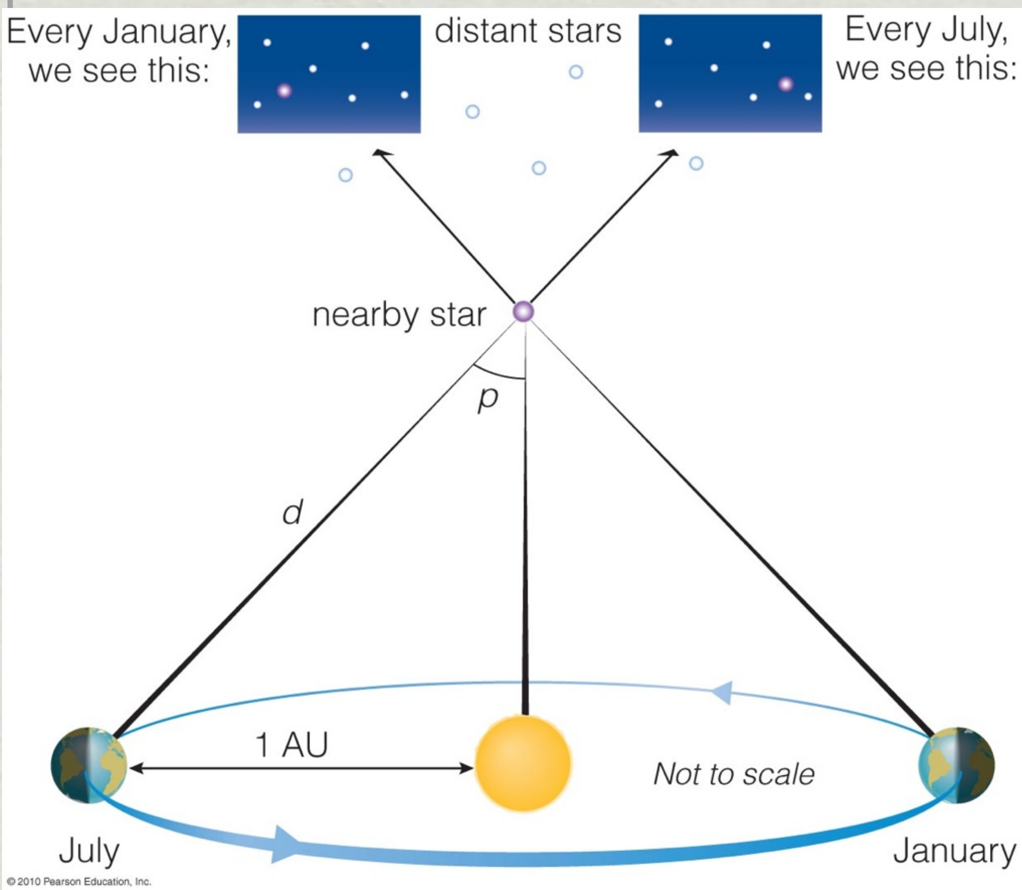
Use other clues about stars, like their spectra, to guess Luminosity.

Remember, spectral sequence OBAFGKM depends on temperature.

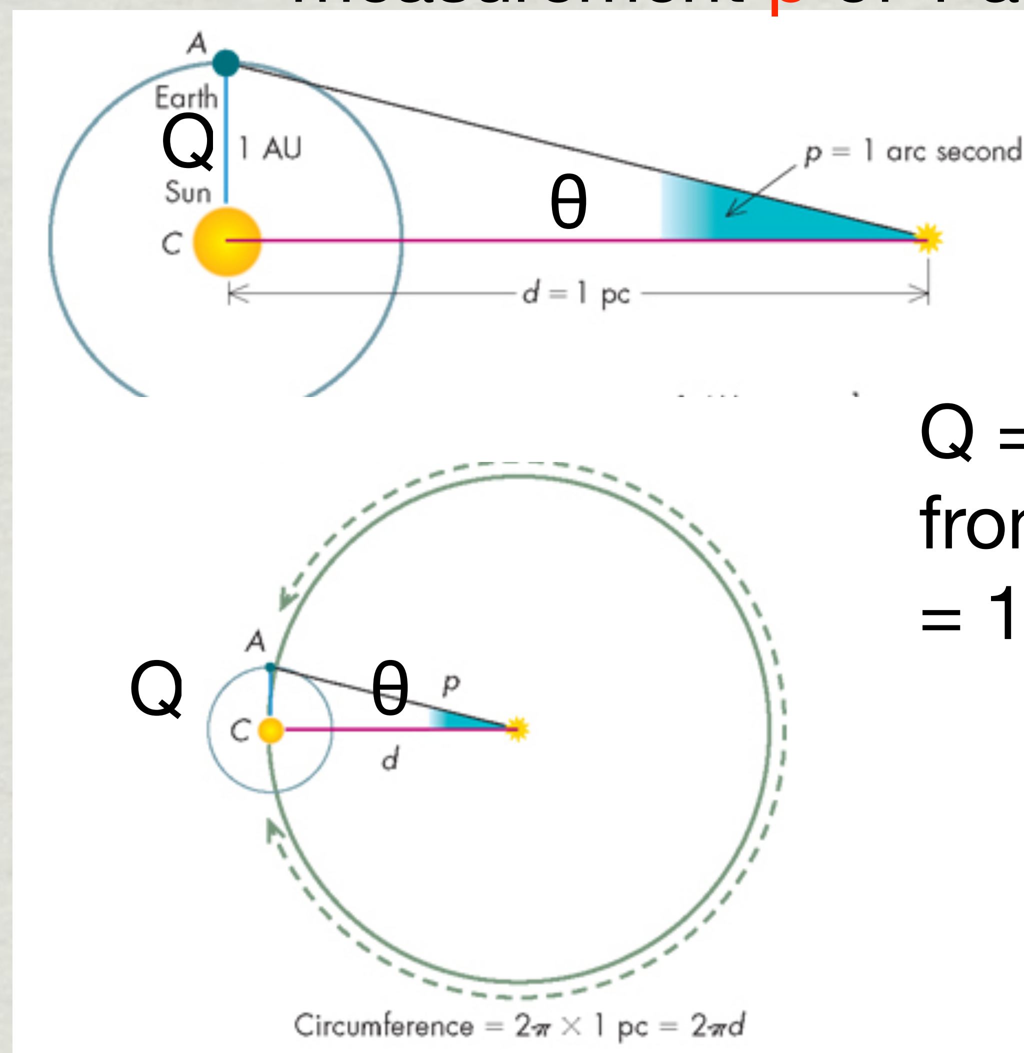
We'll see that temperature and luminosity of a star are related.

Use some other technique, like parallax, to measure distance

Measuring Distance with Parallax



Distance **d** to a star with a parallax measurement **p** of 1 arc second



Q = distance from earth to sun = 1 AU

Use angular-diameter distance relation:

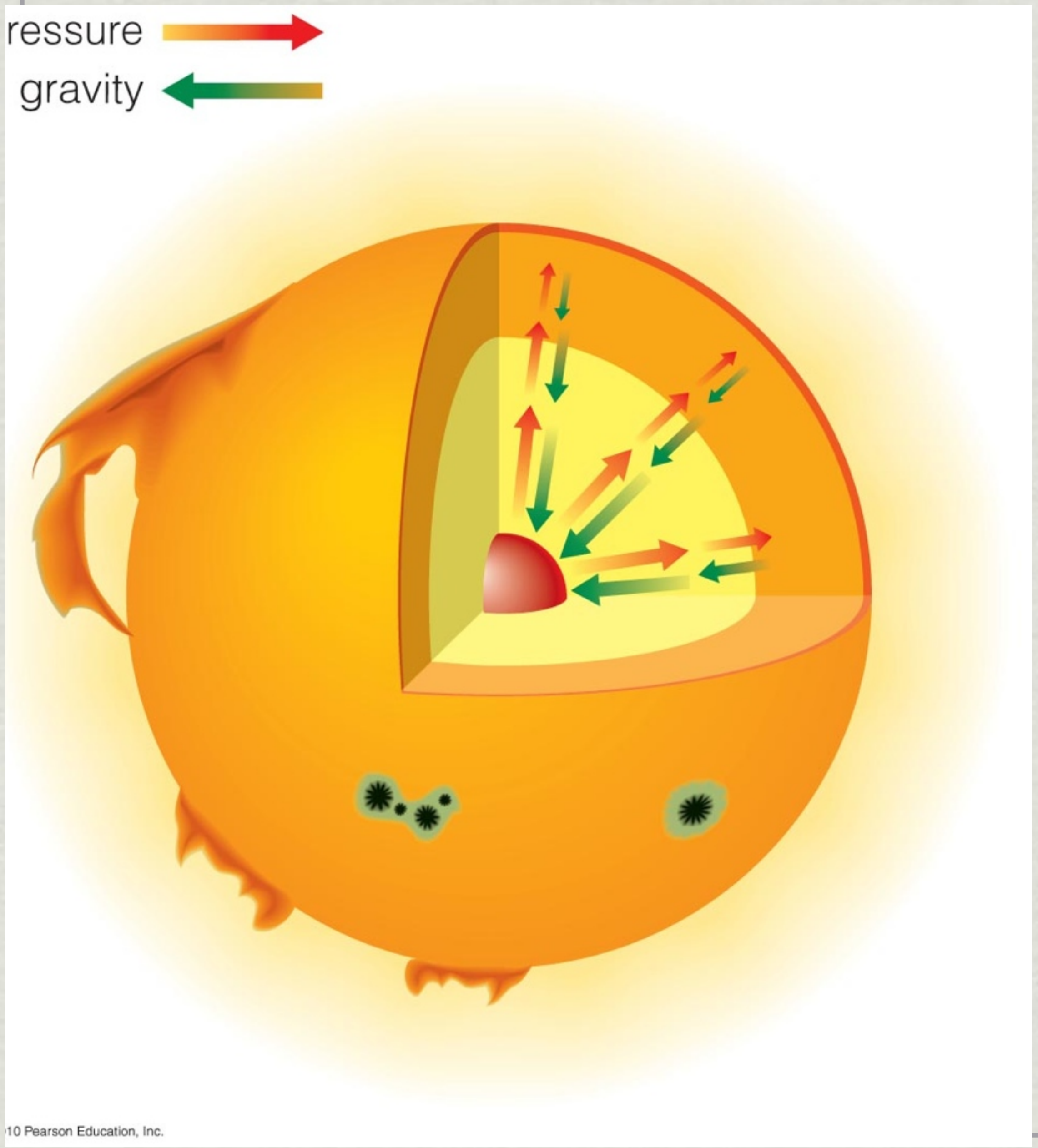
$$\frac{2\pi d}{Q} = \frac{360^\circ}{\theta}$$

distance **d** in parsecs = $\dfrac{1}{\textbf{p}\text{ (arceconds)}}$

1 Parsec = 206265 AU = 3×10^{16} m

Energy Generation and Gravitational Equilibrium in the Sun

A short recap from Lecture 8



- Stars are very, very massive: $M_{sun} = 2 \times 10^{30}$ kg
- Pressure at the deepest layers, near the core, is highest: that's where the most mass above is pushing down
- Gravitational force needs to be balanced everywhere by internal pressure force
- If it weren't, the sun would collapse!

Gravitational Equilibrium in the Sun

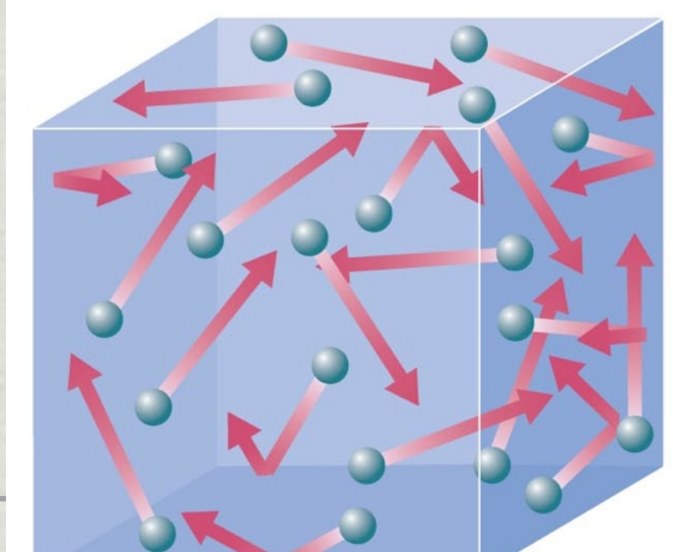
$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

Which would you rather lean on?  or  ?

Same force: (some of) your weight!
But smaller area = higher pressure

That force can come from gravity, or from atoms and molecules bouncing off a boundary. When they change direction, they accelerate → Force!

The boundary exerts force on the molecules (to change their direction), the molecules exert force on the boundary (Newton's 3rd law).



Lots of molecules bouncing off a boundary (like the wall of a balloon) and exerting force on its area → Pressure!

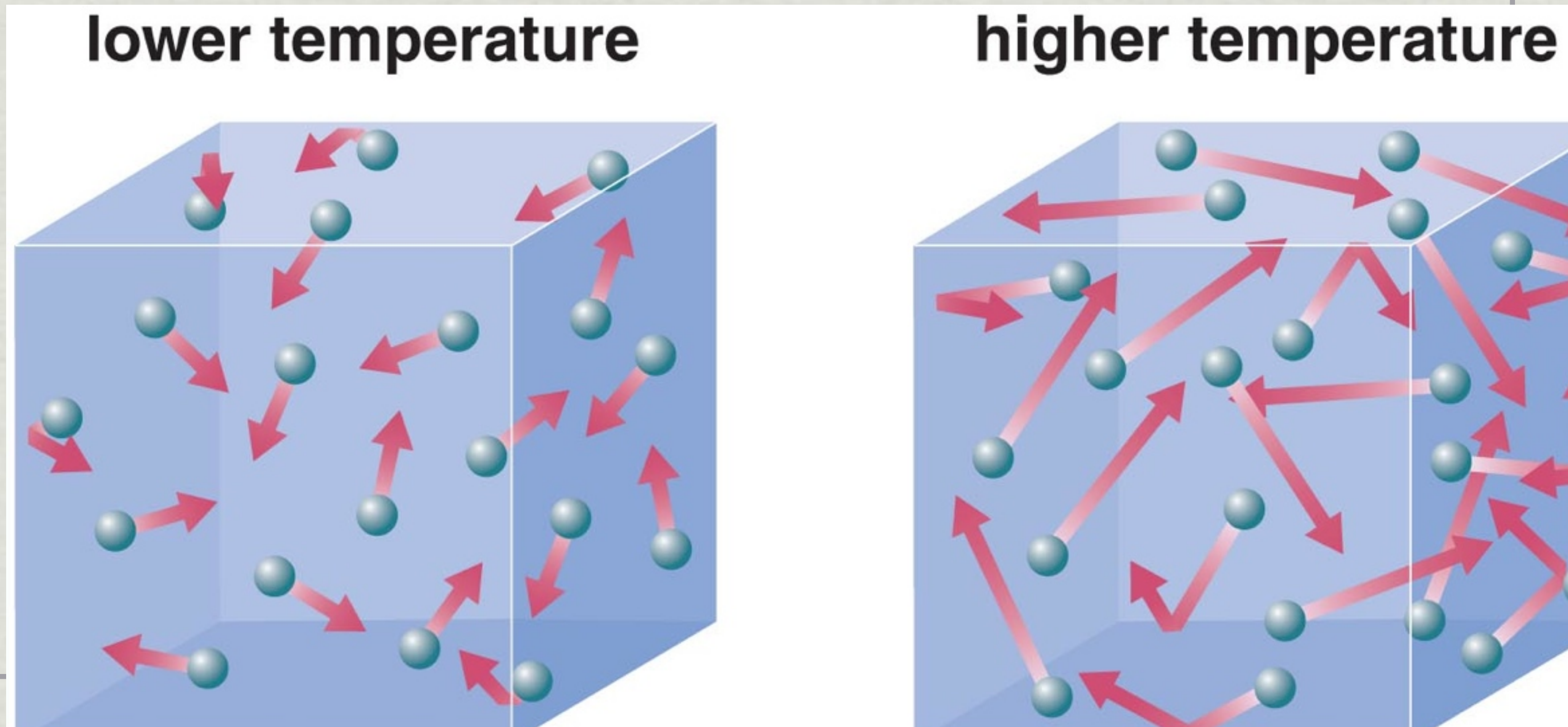
Gravitational Equilibrium in the Sun

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

For a gas (like the earth's atmosphere or the inside of the sun) two things matter for pressure: density and temperature

High temperature (hot):
molecules and atoms have lots of kinetic energy ($1/2\ mv^2$), so every time an atom changes direction it gets a big acceleration. Lots of force per bounce → high pressure.

Low temperature (cool):
less kinetic energy, less acceleration from every bounce → lower pressure



Gravitational Equilibrium in the Sun

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

For a gas (like the earth's atmosphere or the inside of the sun) two things matter for pressure: density and temperature

Many molecules (high density): many collisions = high pressure

Few molecules (low density): few collisions = low pressure

Gravitational Equilibrium in the Sun

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

Perfect Gas Law:

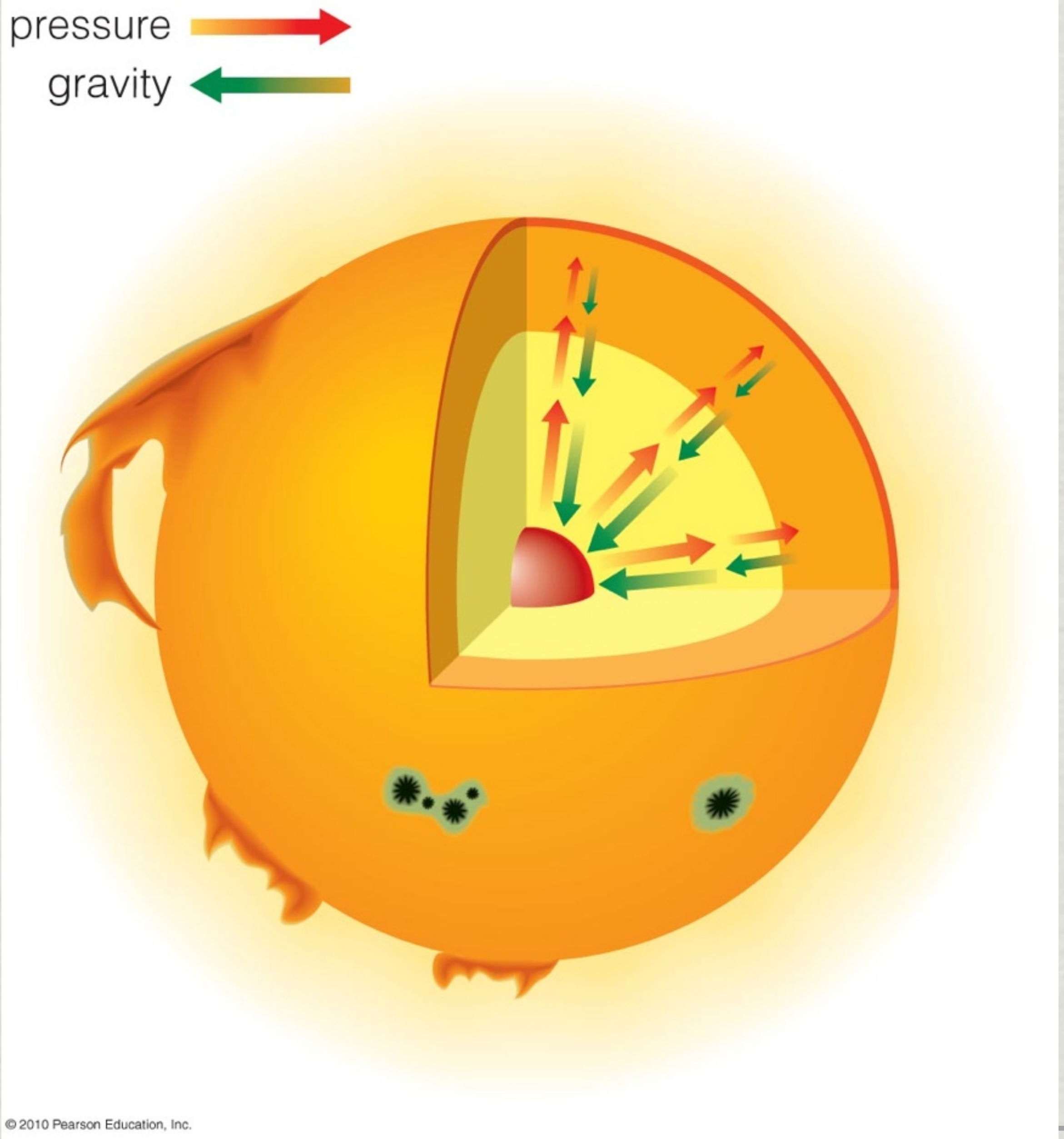
Pressure = k × density x temperature

k is a universal constant (yes, another one), like G

“perfect”: assumes molecules and atoms bounce perfectly in every collision. Chemistry tells us that doesn’t always happen: sometimes they stick together and make molecules! In AY2, you can always assume a gas is “perfect”

Energy Generation and Gravitational Equilibrium in the Sun

A short recap from Lecture 8



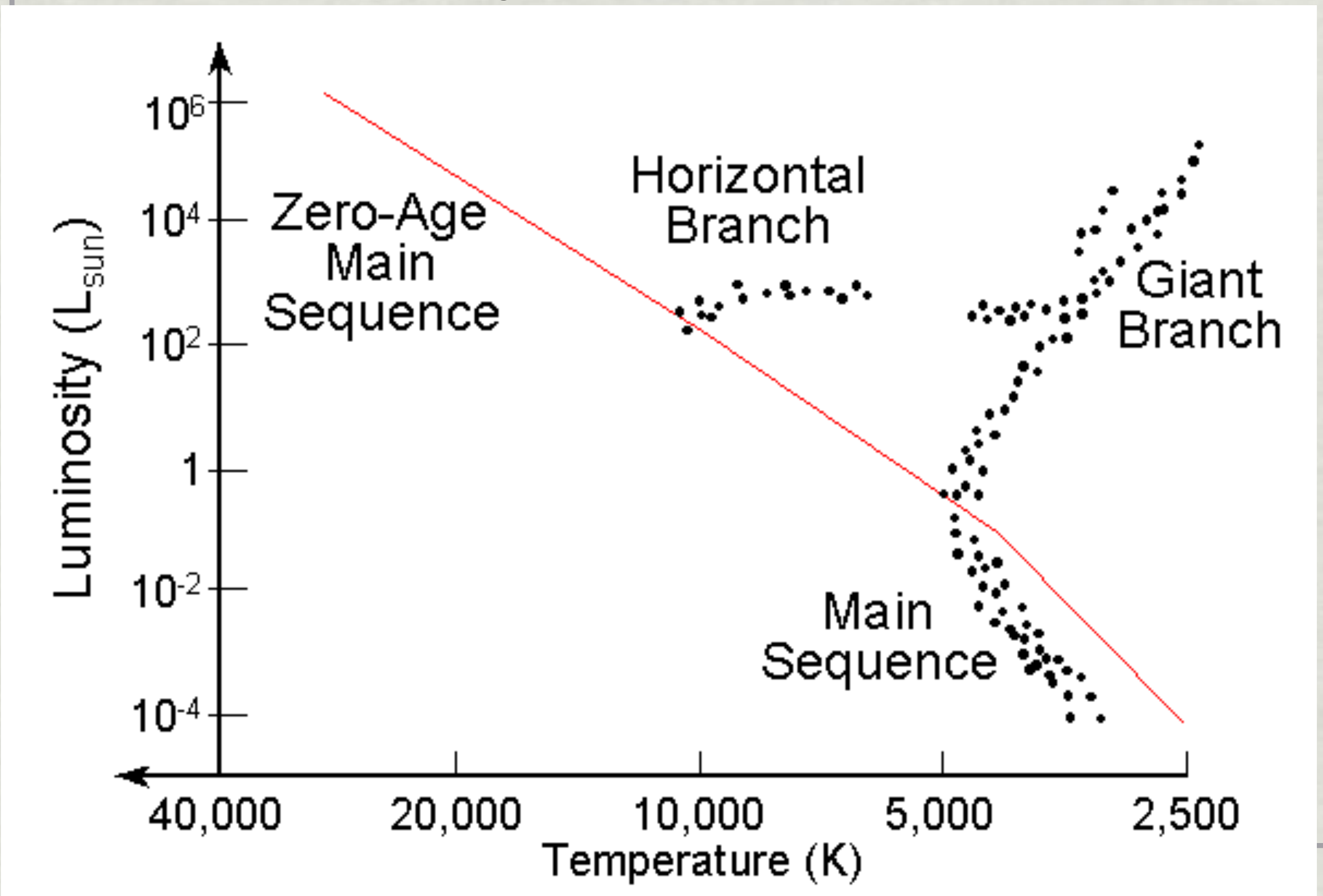
- Stars are very, very massive: $M_{sun} = 2 \times 10^{30}$ kg
- Pressure at the deepest layers, near the core, is highest: that's where the most mass above is pushing down
- Gravitational force needs to be balanced everywhere by internal pressure force
- If it weren't, the sun would collapse!
- Energy produced near the center (in the core) by nuclear fusion heats gas atoms in the core, maintains high gas pressure.
  - More energy generated at higher temperature and pressure.

Lives of Stars: Mass, Luminosity and the Main Sequence

We know how to measure luminosity, mass, size, temperature, composition.

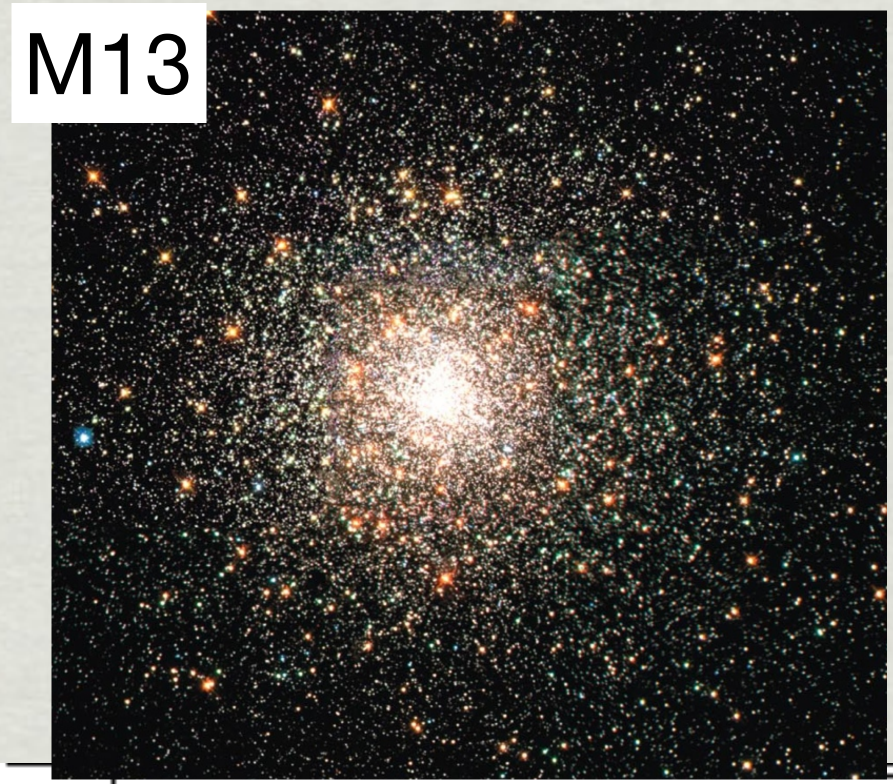
Star clusters:
gravitationally bound group of stars
all at the same distance from Earth
all the same age

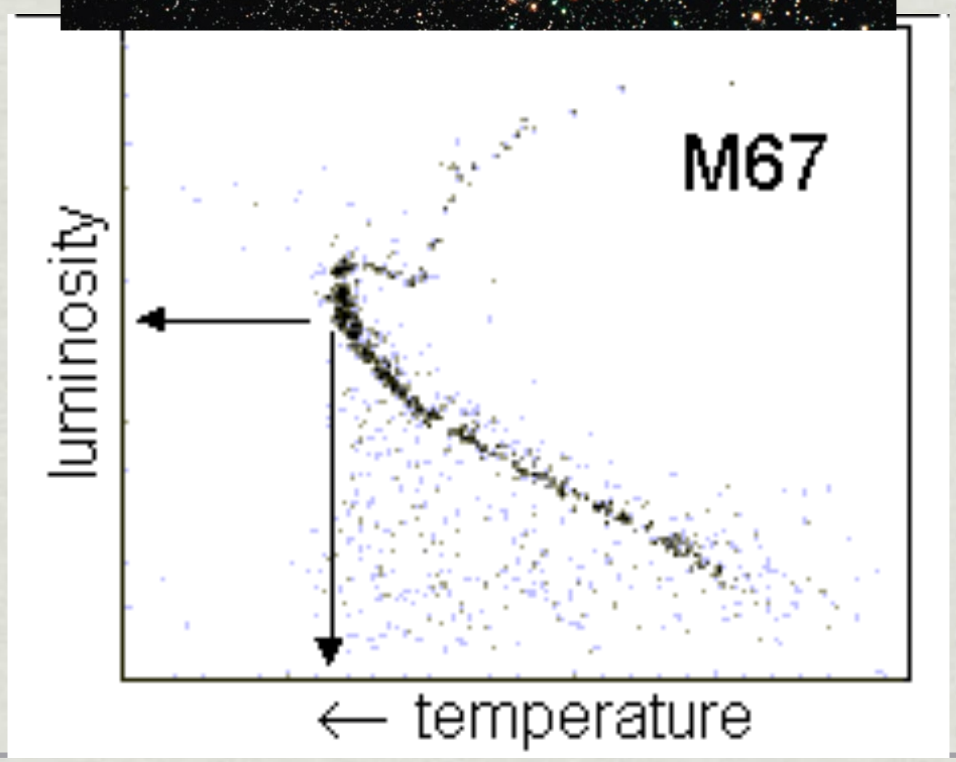
Plot luminosity and temperature:

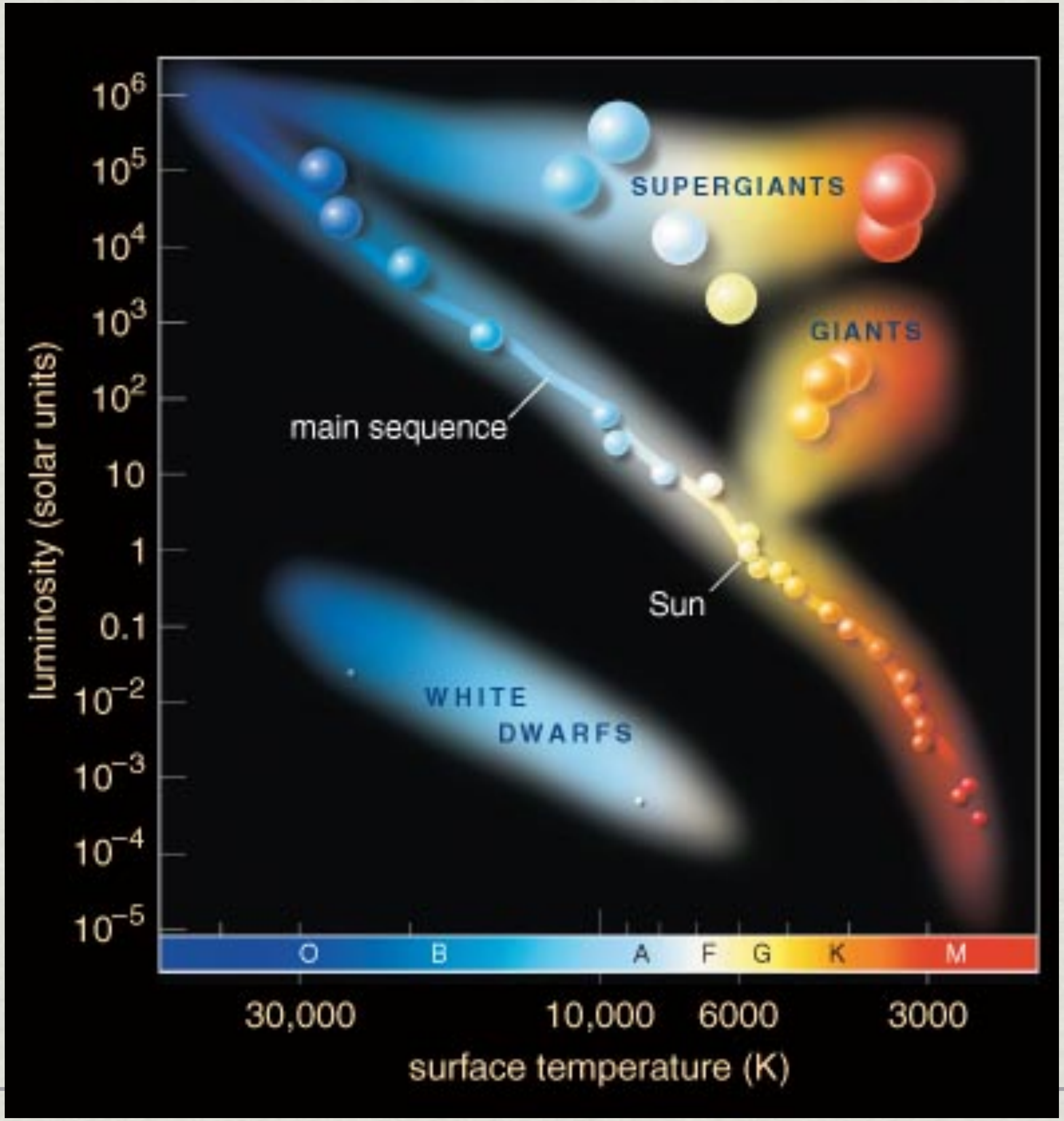


Hertzsprung-Russell (H-R) Diagram

Relations between luminosity, and temperature of stars.







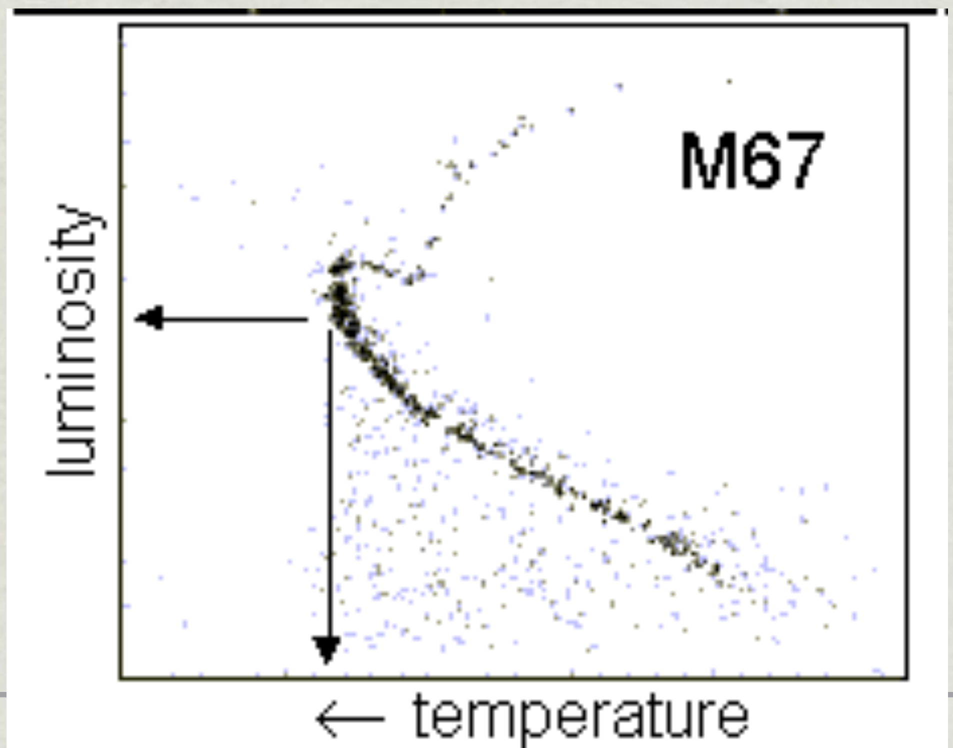
Hertzsprung-Russell (H-R) Diagram

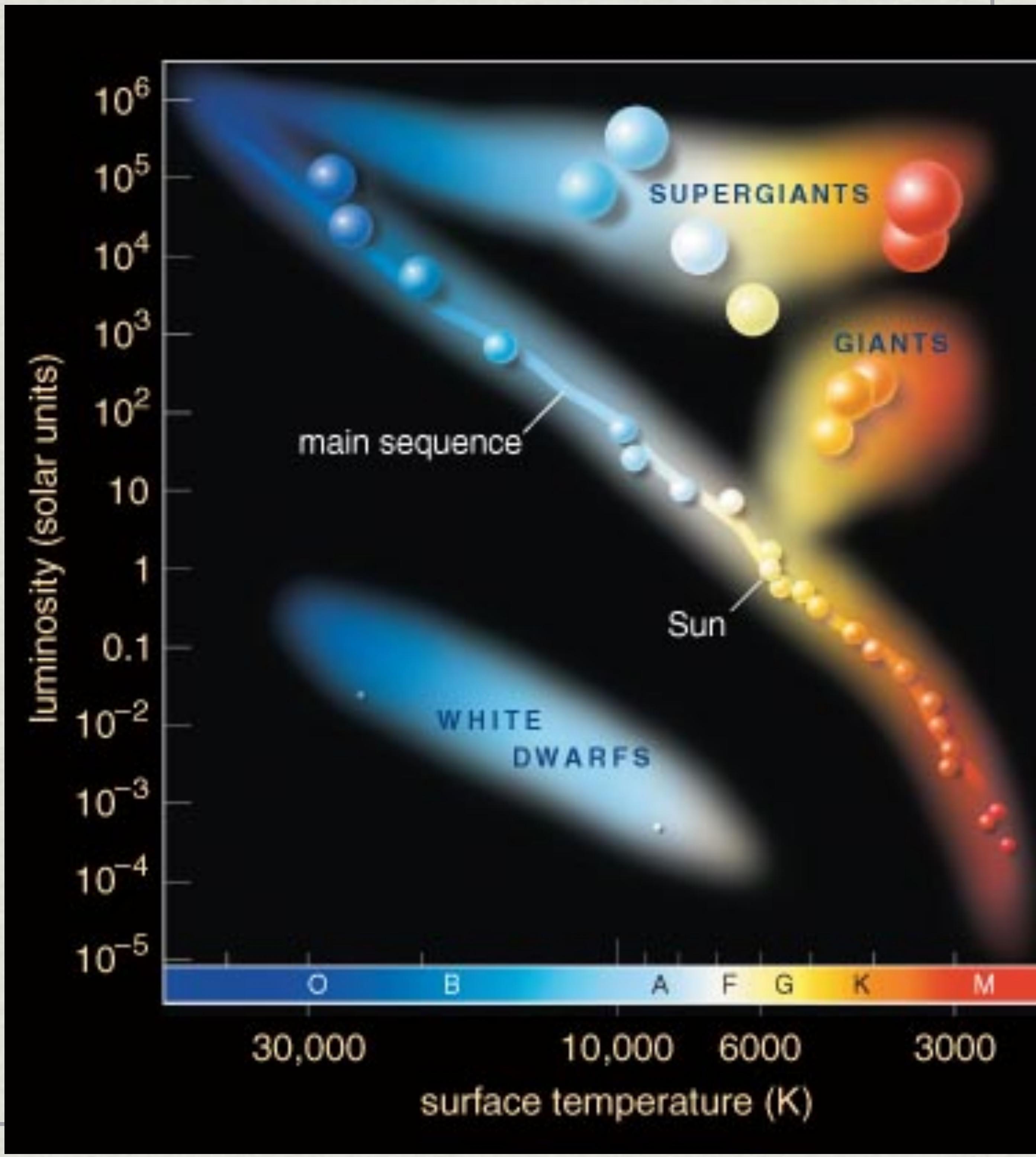
Relations between luminosity and temperature of stars.

Note: stars with similar temperatures have different luminosity.

Stephan-Boltzmann Law:
Luminosity = $\sigma T^4 \times 4\pi R_{star}^2$

Same temperature, different luminosity = different radius, too

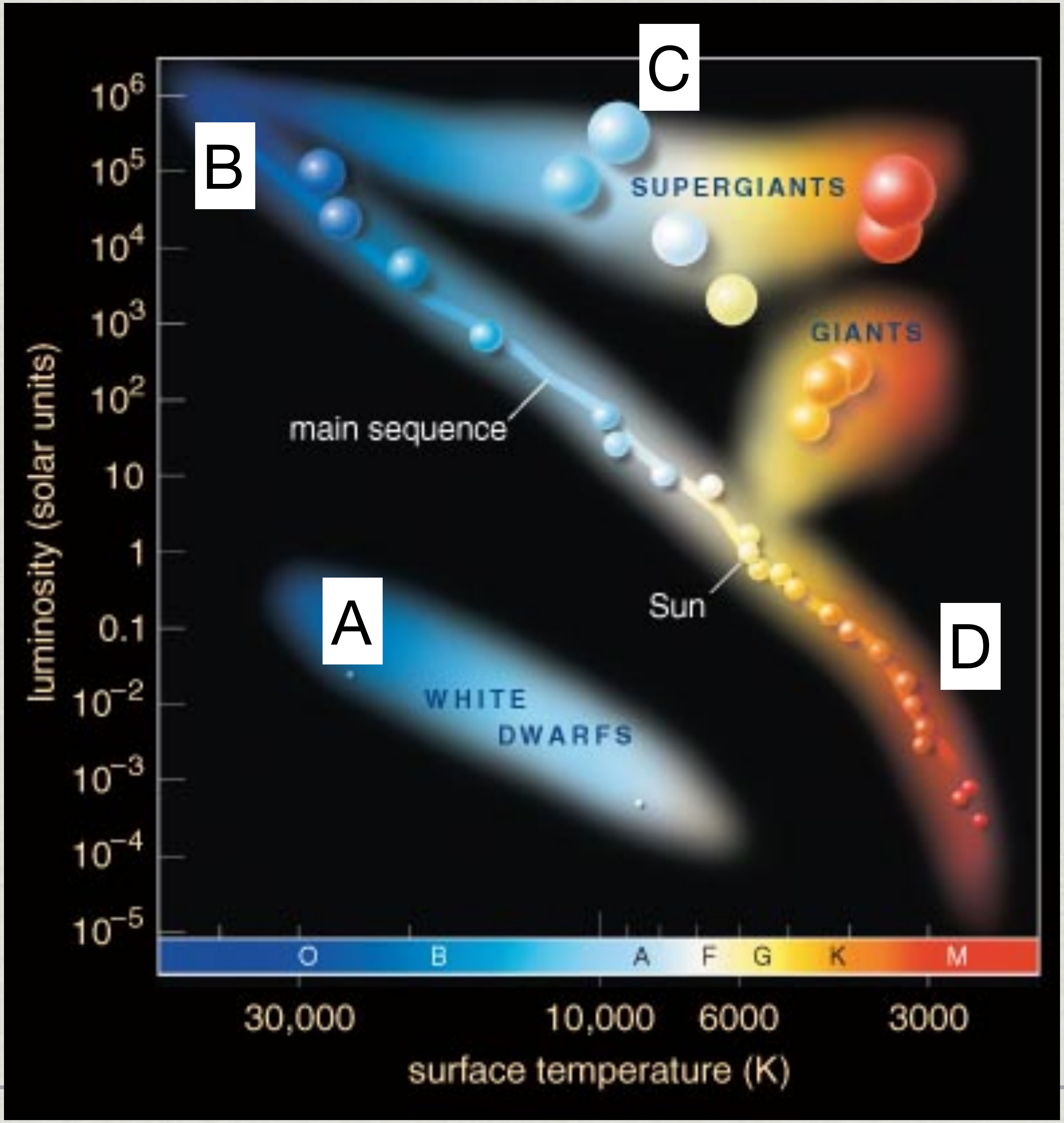




Hertzsprung-Russell (H-R) Diagram

Relations between luminosity, mass, size, temperature of stars.

Which star is hottest?

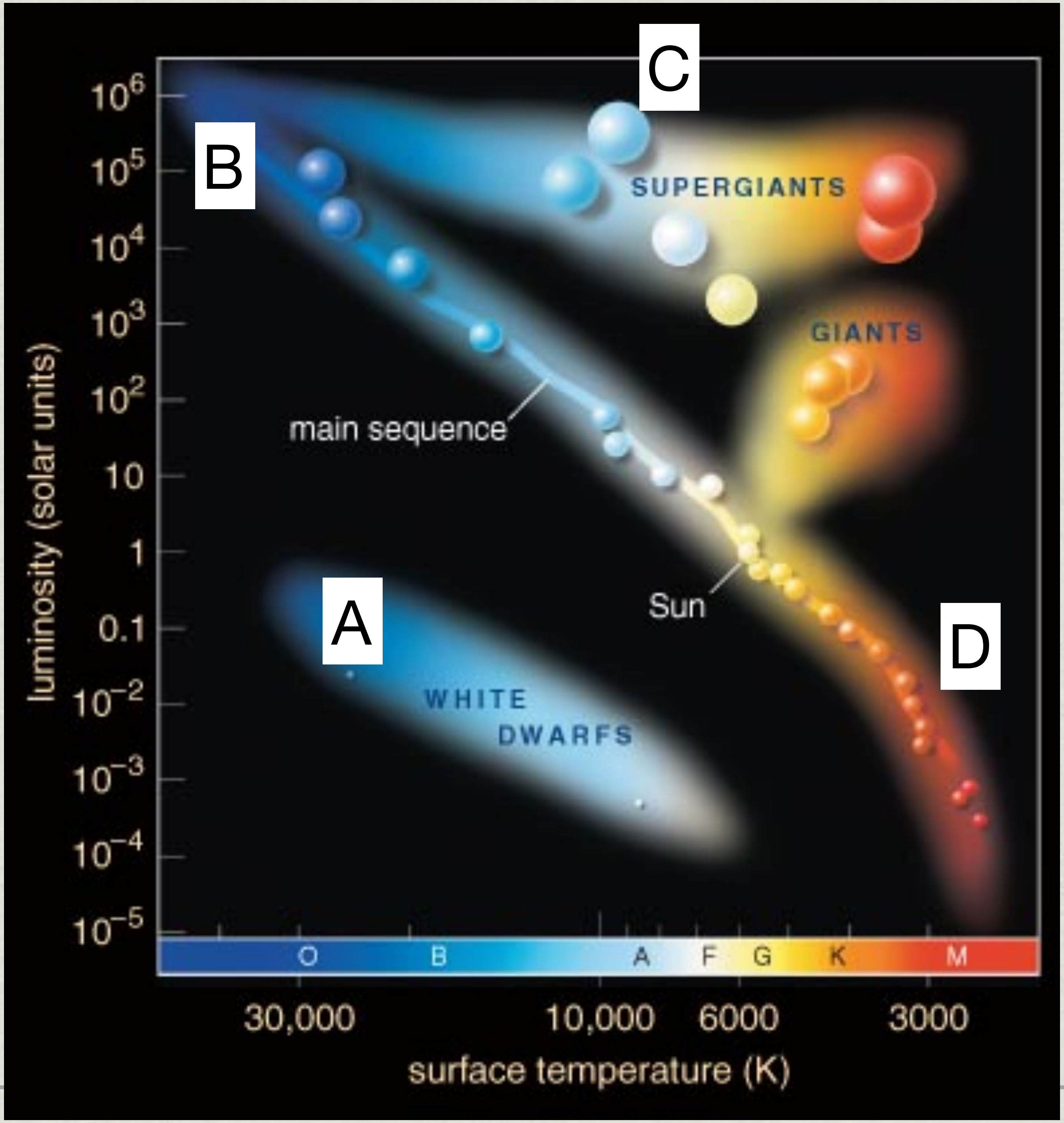


Hertzsprung-Russell (H-R) Diagram

Relations between luminosity, mass, size, temperature of stars.

Which star is hottest?

A (the bluest one; Wien's Law)

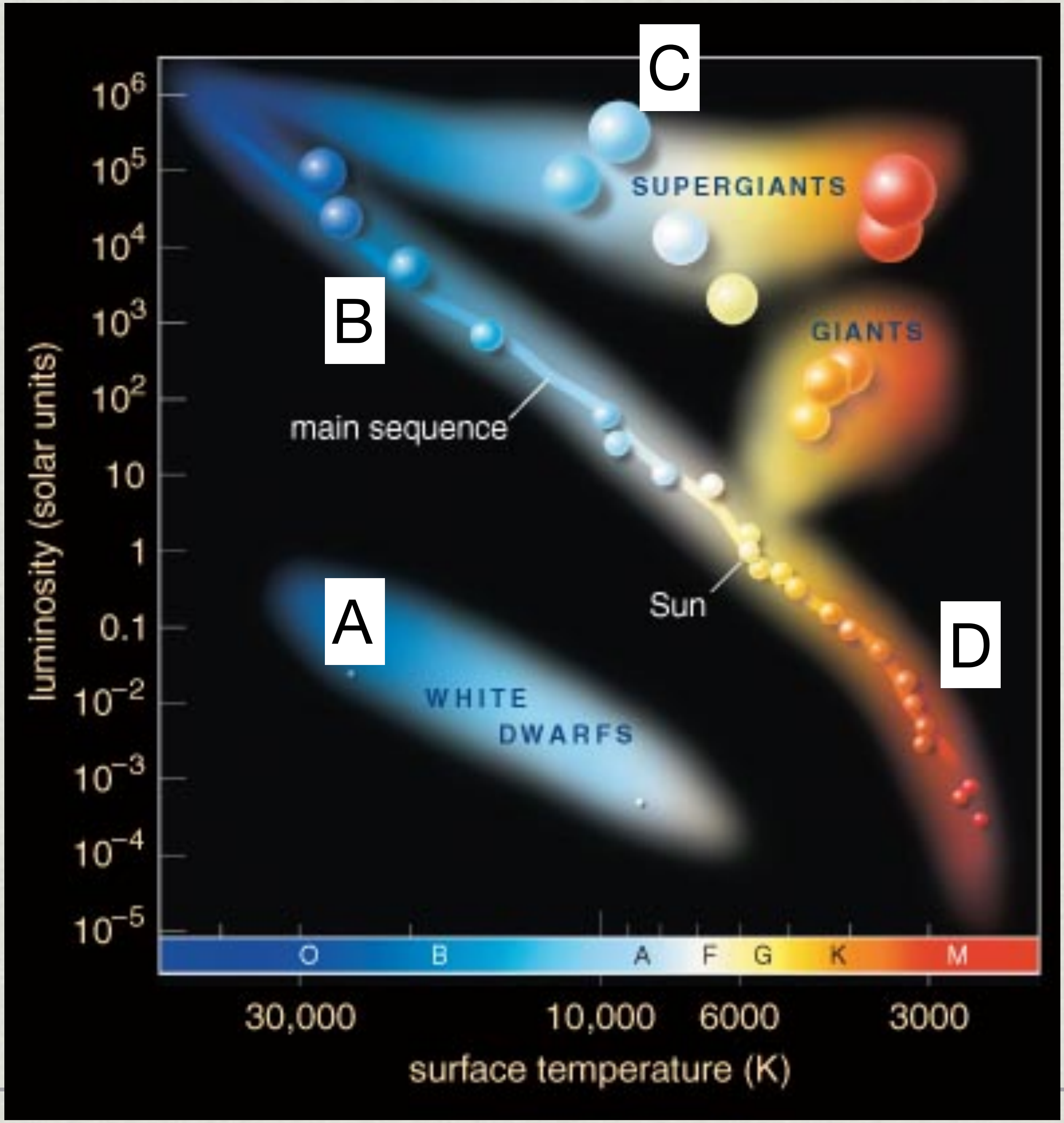


Hertzsprung-Russell (H-R) Diagram

Relations between luminosity, mass, size, temperature of stars.

Which star is hottest?

Which star is most luminous?

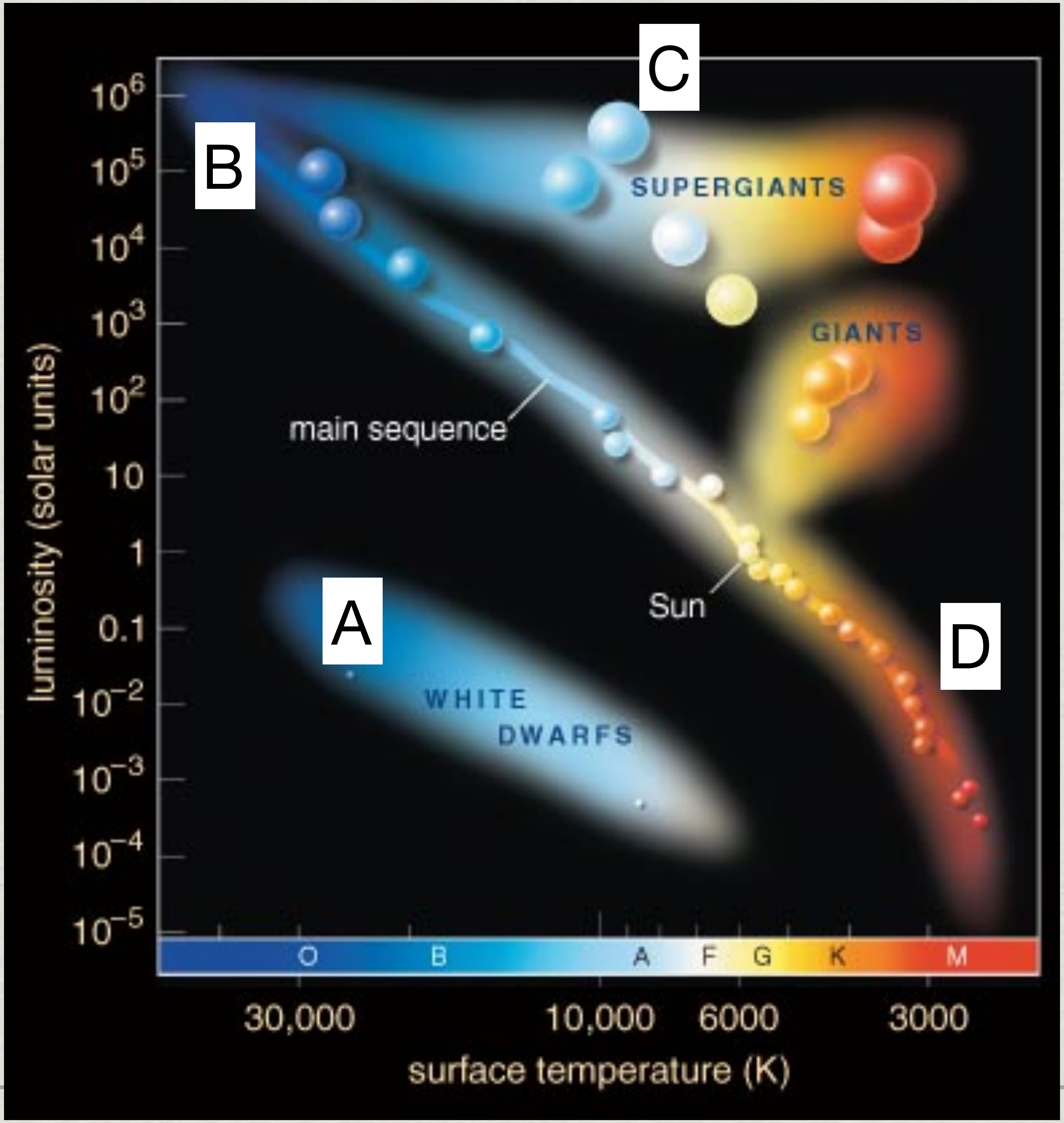


Hertzsprung-Russell (H-R) Diagram

Relations between luminosity, mass, size, temperature of stars.

Which star is hottest?
A (the bluest one; Wien's Law)

Which star is most luminous? C

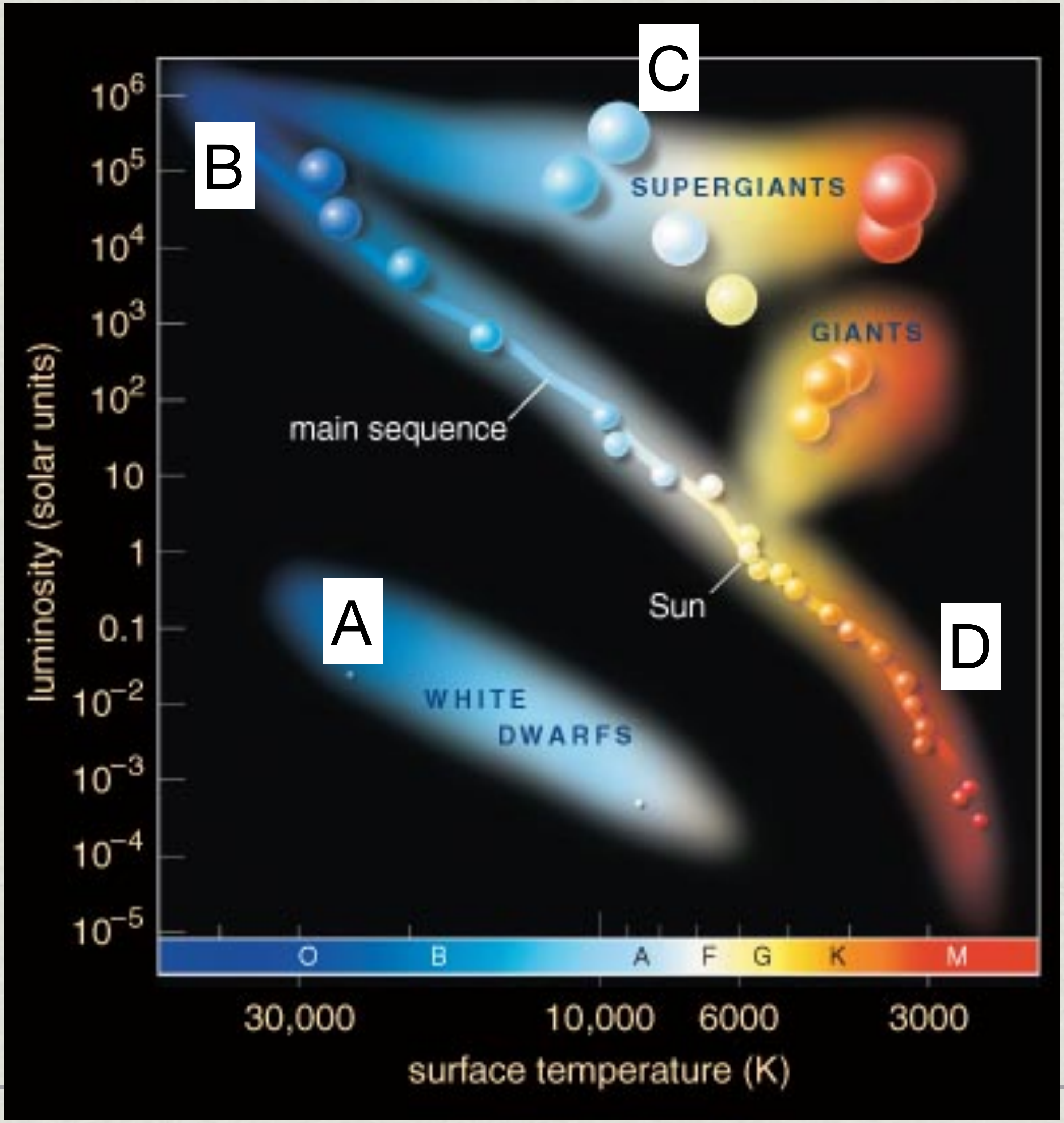


Hertzsprung-Russell (H-R) Diagram

Relations between luminosity, mass, size, temperature of stars.

If B and C have the same luminosity, which has the largest radius, B or C?

Remember S-B Law:
$L = \sigma T^4 \times 4\pi R^2$



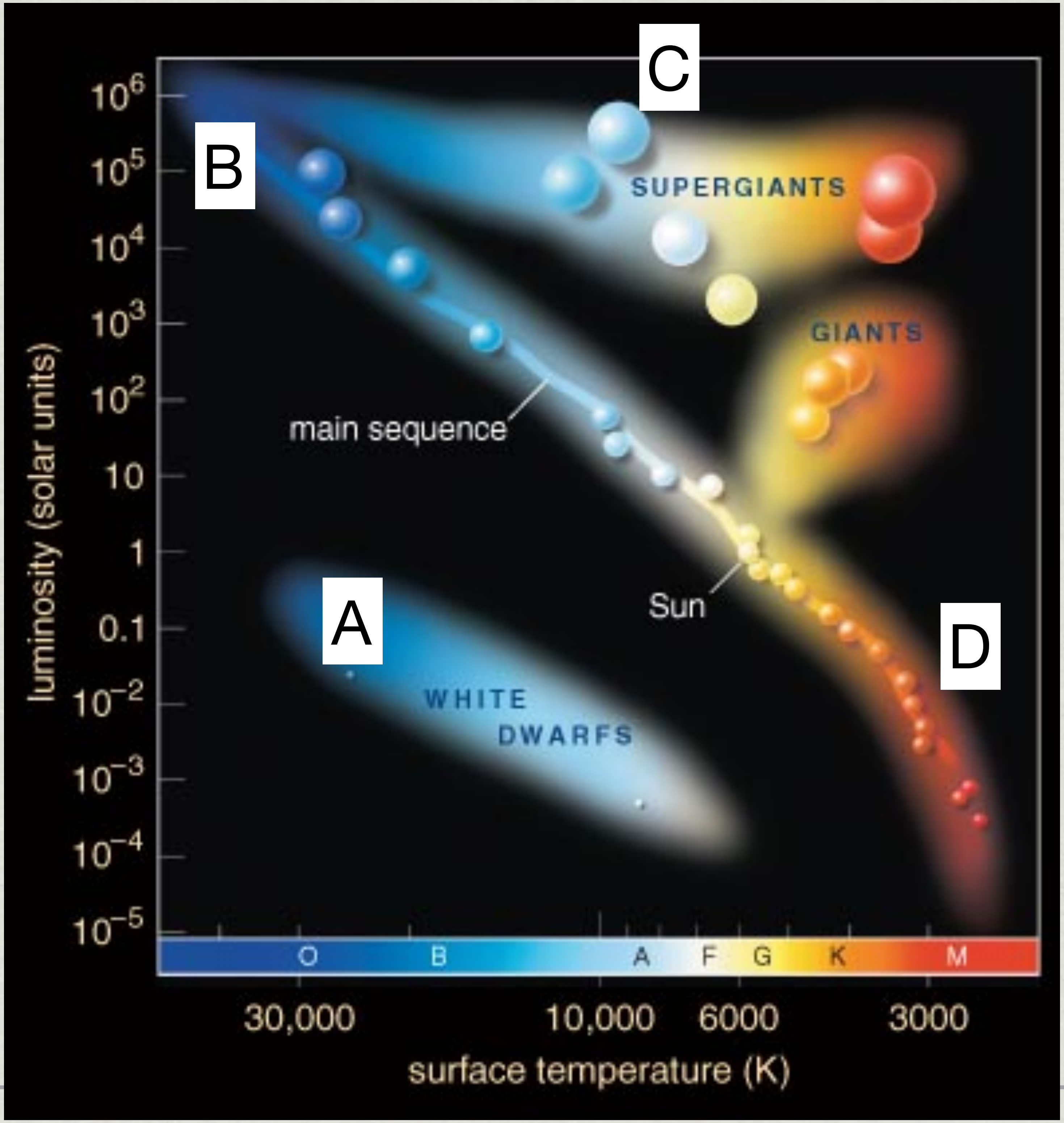
Hertzsprung-Russell (H-R) Diagram

Relations between luminosity, mass, size, temperature of stars.

If B and C have the same luminosity, which has the largest radius, B or C?

Remember S-B Law:
$L = \sigma T^4 \times 4\pi R^2$

B and C have the same luminosity. C is cooler, so it must have a larger radius



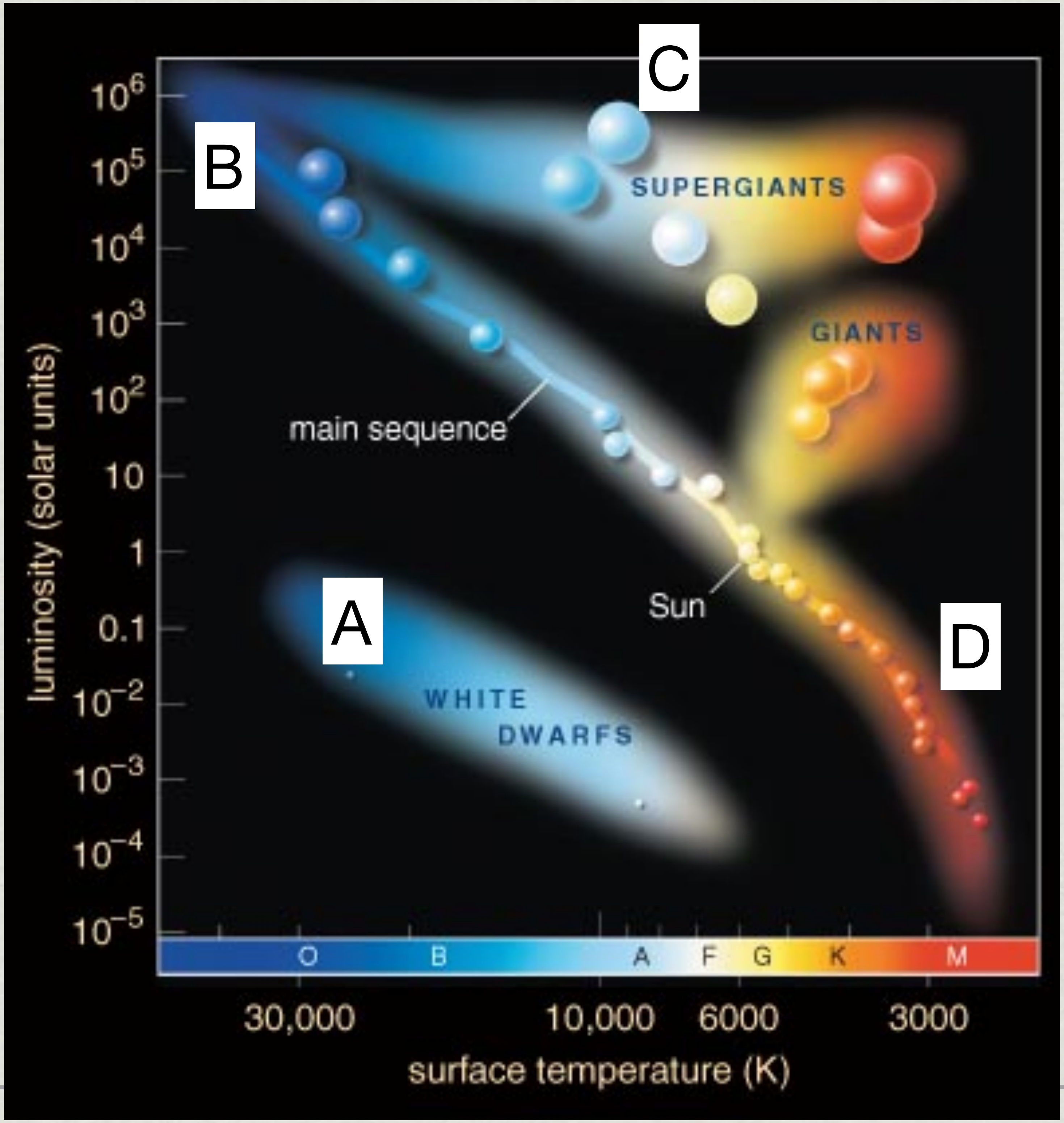
Hertzsprung-Russell (H-R) Diagram

Relations between luminosity, mass, size, temperature of stars.

If B and C have the same luminosity, which has the largest radius, B or C?

S-B Law: $L = \sigma T^4 \times 4\pi R^2$

High luminosity, low temperature = large radius

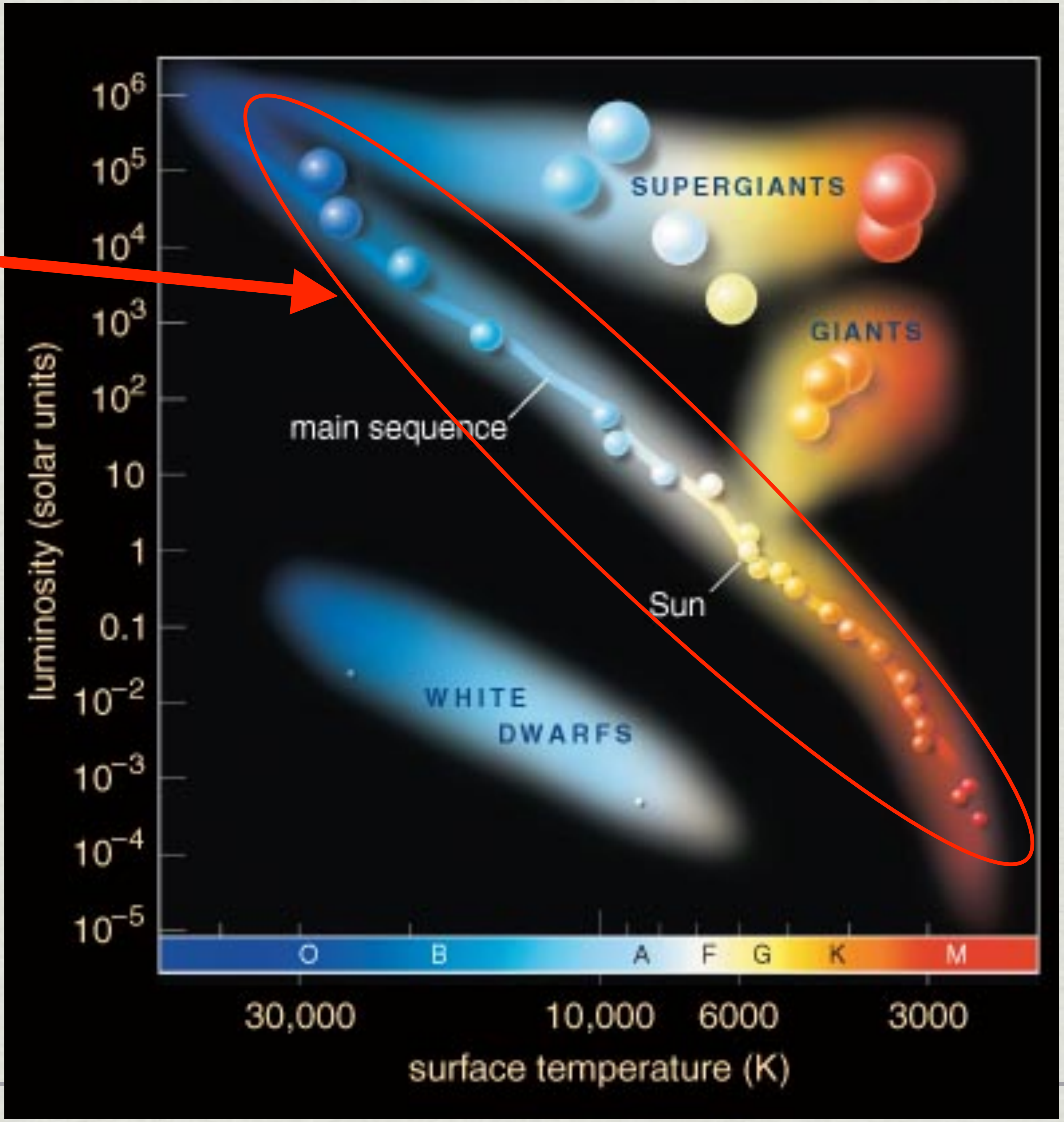


Hertzsprung-Russell (H-R) Diagram

Relations between luminosity, mass, size, temperature of stars.

Where are all the stars?

On the **Main Sequence**



Hertzsprung-Russell (H-R) Diagram

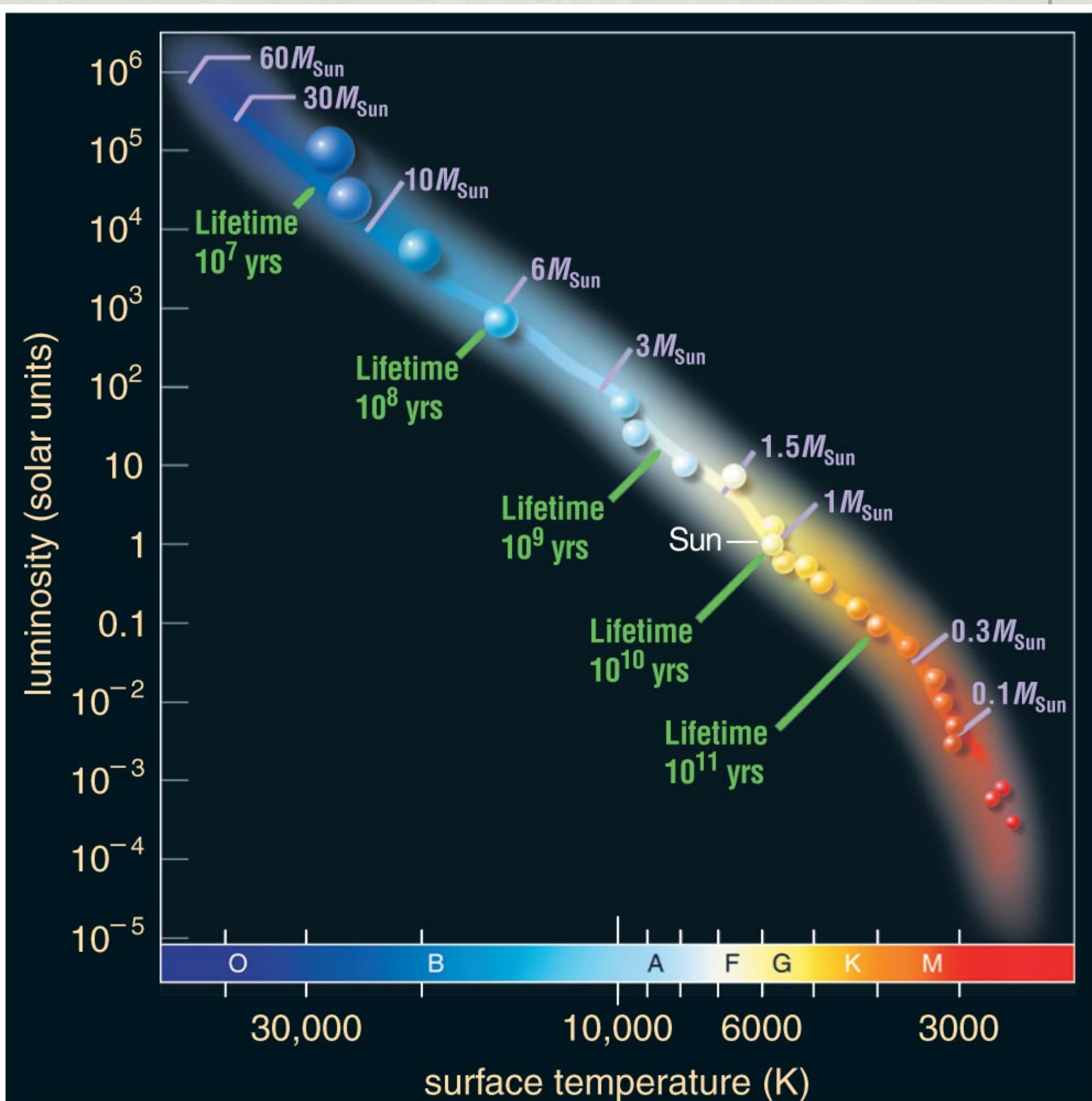
Relations between luminosity, mass, size, temperature of stars.

Where are all the stars?

On the Main Sequence.

Main sequence is a
sequence in mass:
  Hot,bright massive stars
    at top left
  Cool, faint low-mass stars
    at bottom right

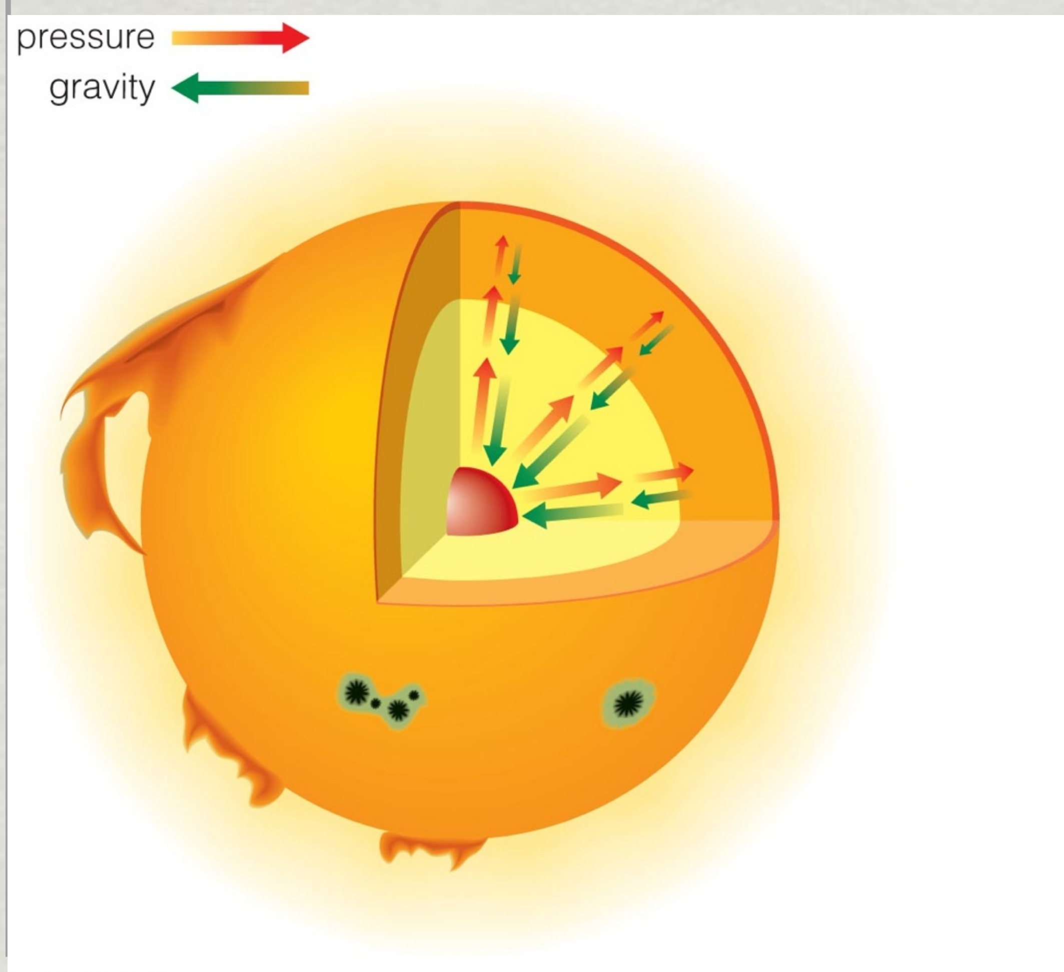
Why?

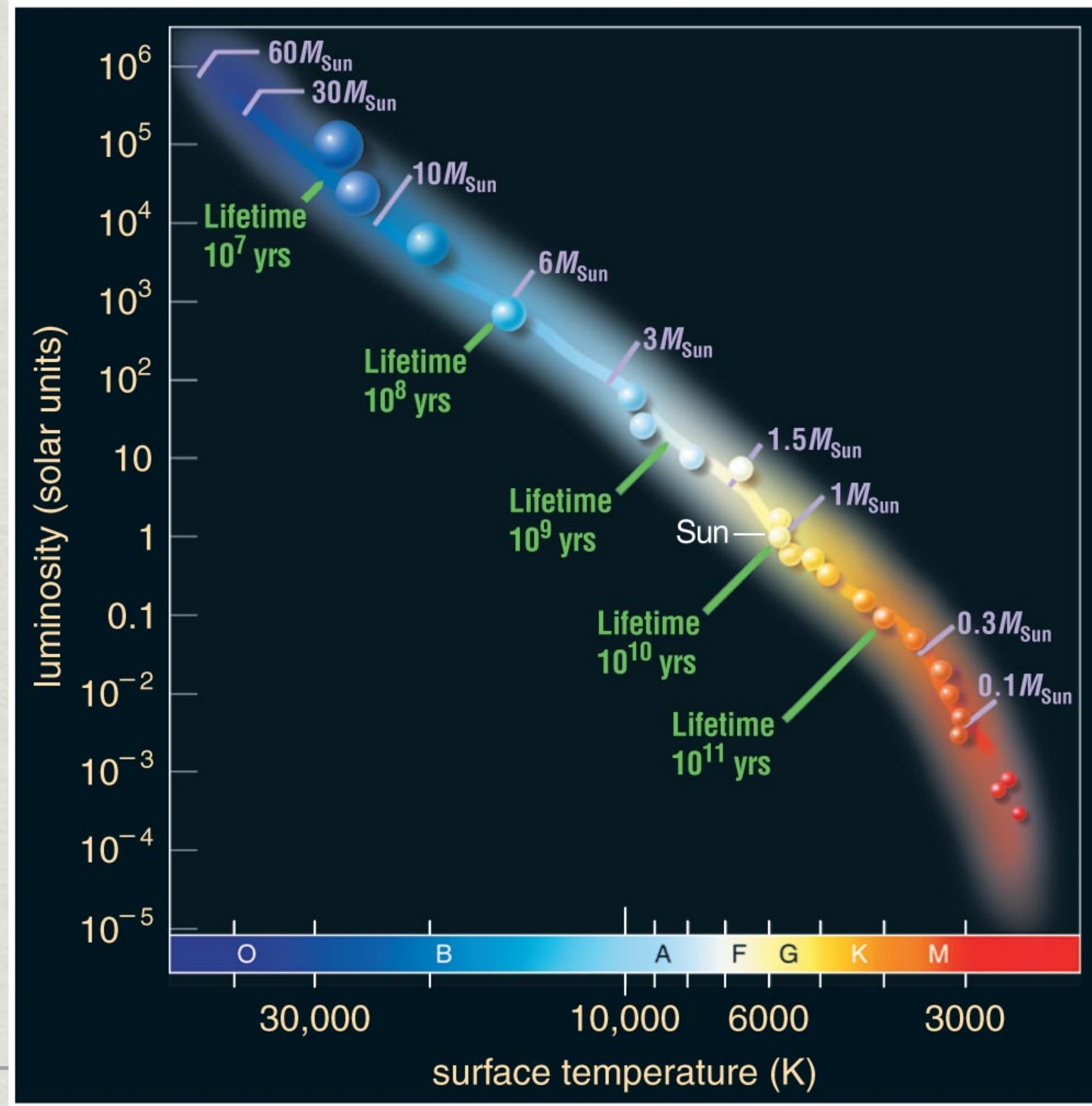


Hertzsprung-Russell (H-R) Diagram

Higher mass = more pressure from gravity

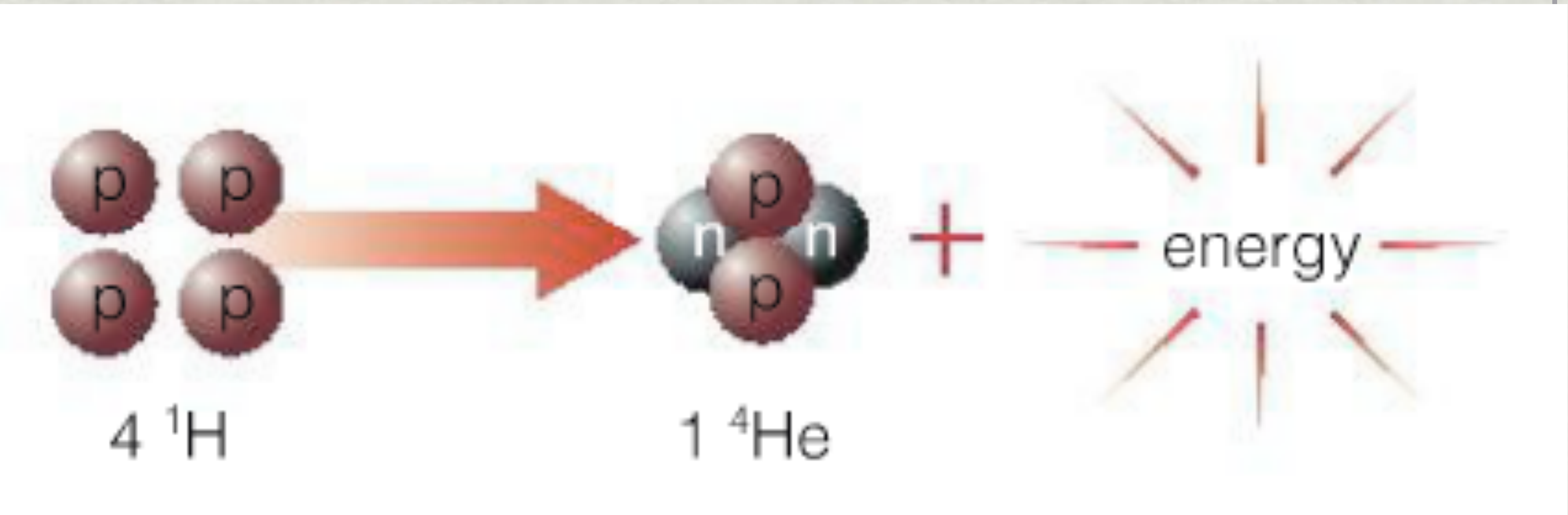
Star has to generate more energy from nuclear fusion to create more thermal pressure to hold itself up against gravity





Powering the Sun: Nucleosynthesis

The Hydrogen-to-Helium fusion process is called: the Proton-Proton Chain



In: 4 protons

Out: 1 ^{4}He nucleus
2 gamma rays (photons)
2 neutrinos (particles with no charge, lots of energy)
2 positrons (like electrons, but positive charge)

Total mass (He nucleus + positrons + neutrinos) is 0.7% lower

Powering the Sun: Nucleosynthesis

Proton-Proton Chain

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Out: 1 ^{4}He nucleus

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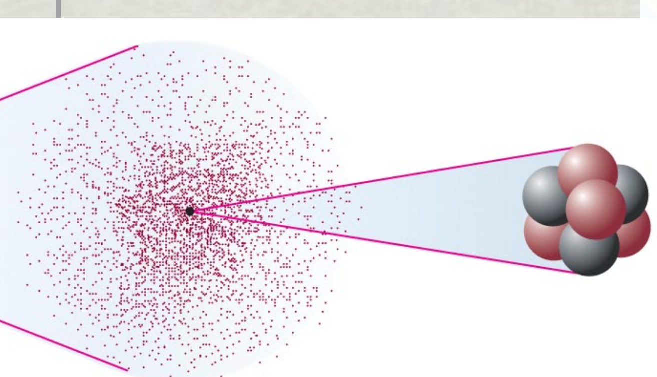
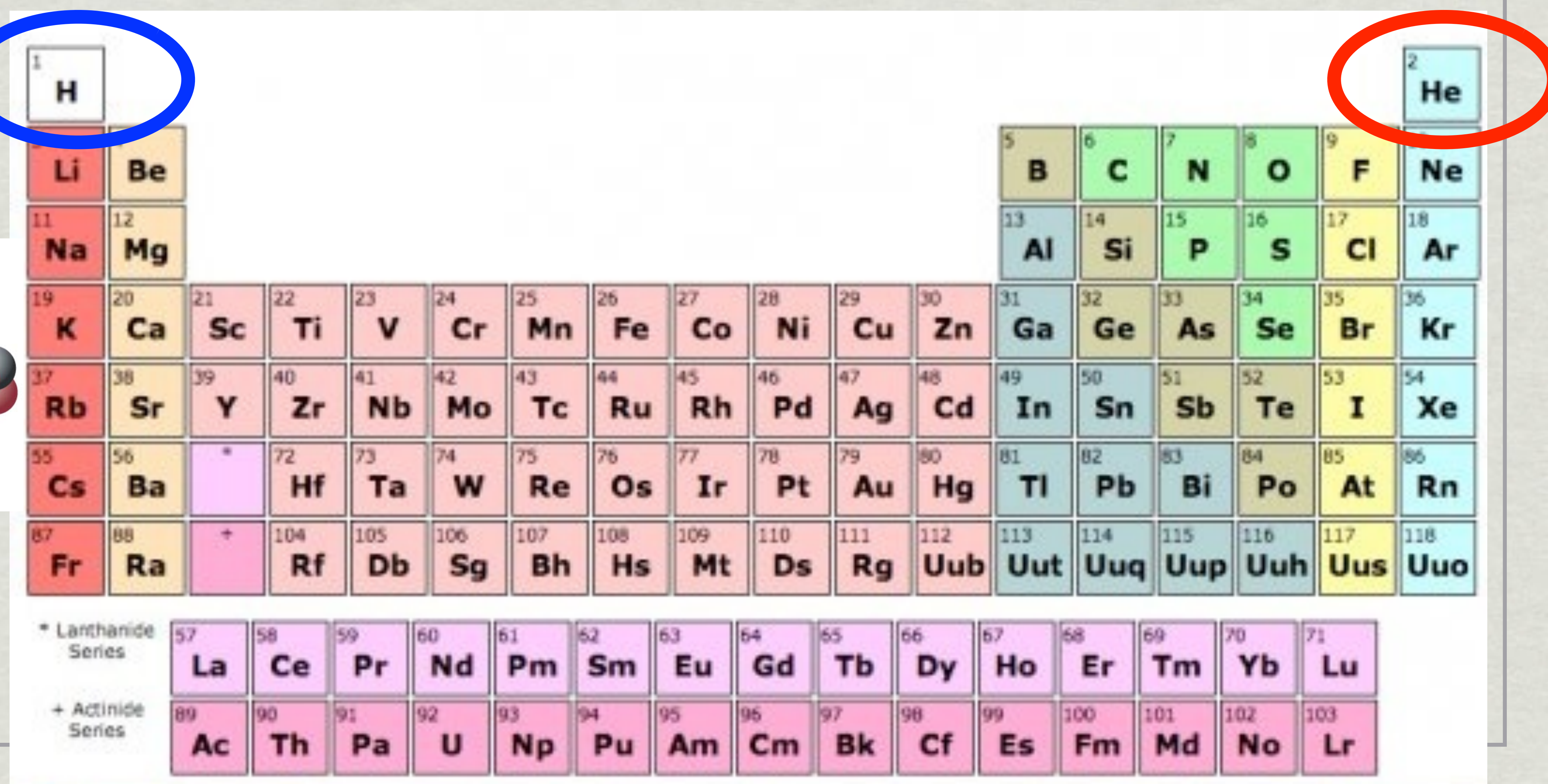
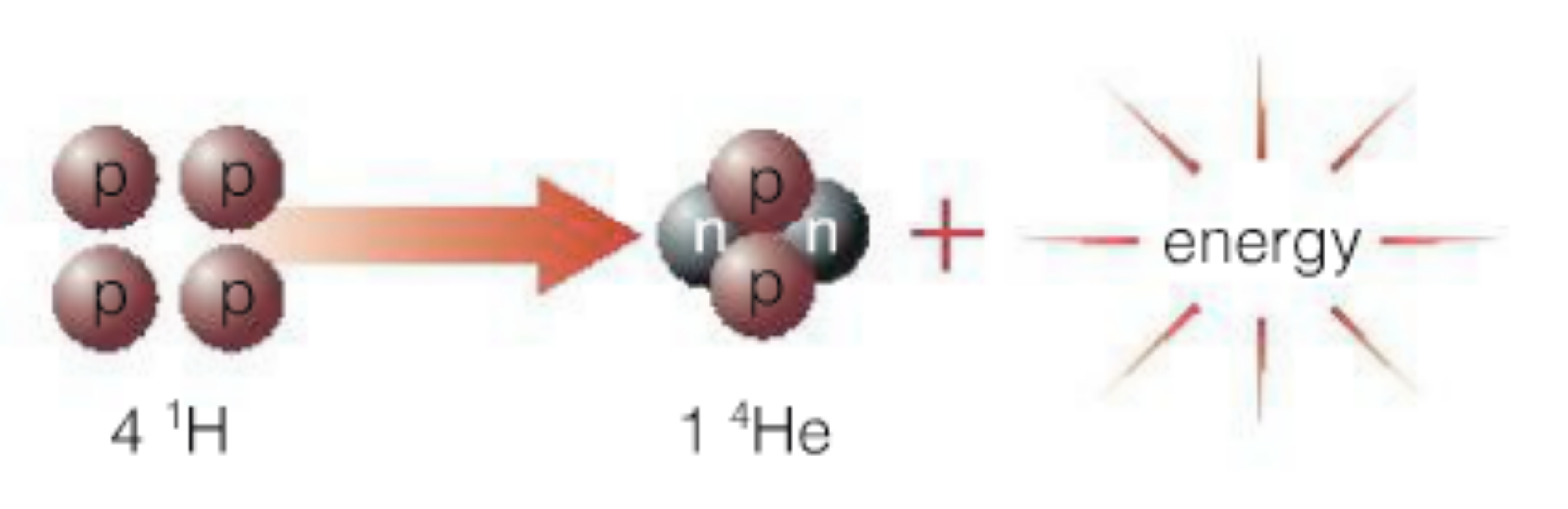




Powering the Sun: Nucleosynthesis



Total mass out (He nucleus + positrons + neutrinos) is 0.7% lower than the 4 protons that go in.

If you stick together Hydrogen atoms to make Helium, the extra mass has to go somewhere.

It becomes energy: **$E = mc^2$**

Mass and energy are the same thing, and transform back and forth using this equation.

Fusing Hydrogen into Helium must release energy

Powering the Sun: Nucleosynthesis

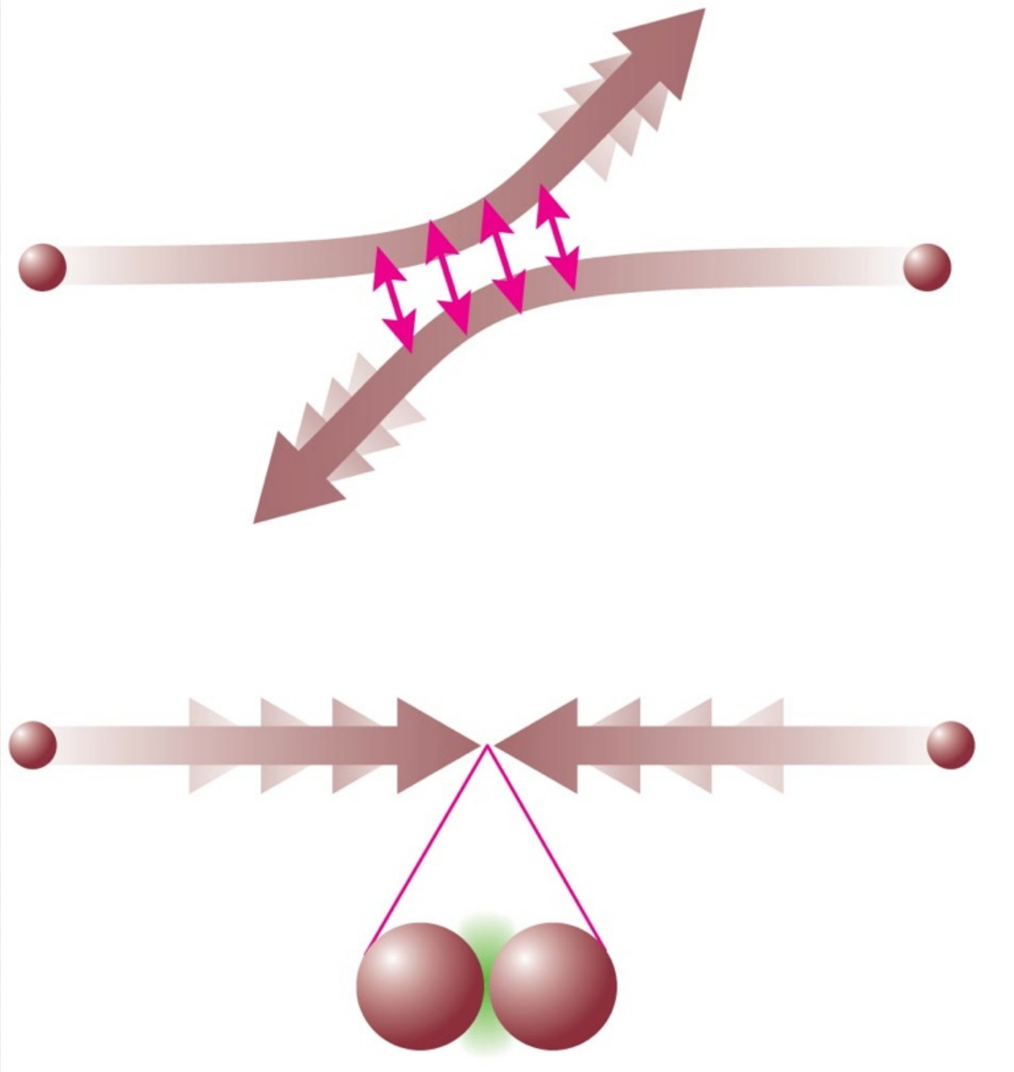
Fusion works at high pressure: high temperature and density.

The nuclei of atoms like Helium are held together by the strong nuclear force:

Works like velcro.

Really strong, way stronger than the electromagnetic force

But works ***only*** at very close range.

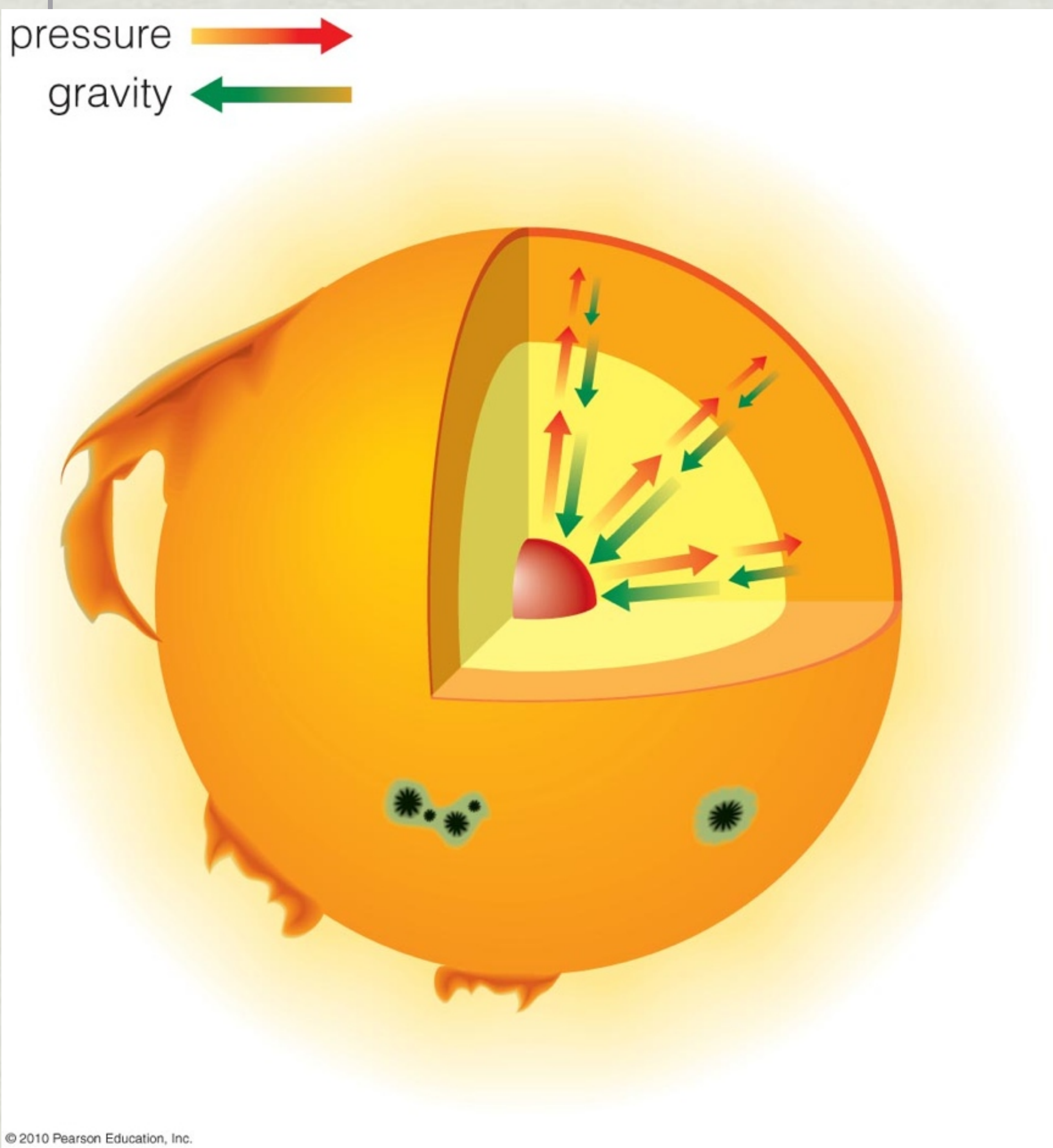


At low pressure (low temperature and density): Electromagnetic force takes over → protons repel each other

At high pressure (high speeds and density): particles get close enough together for the "velcro" effect of the strong nuclear force to win. Particles with same change can stick together → nuclear fusion can happen

Energy Generation and Gravitational Equilibrium in the Sun

A short recap from Lecture 8



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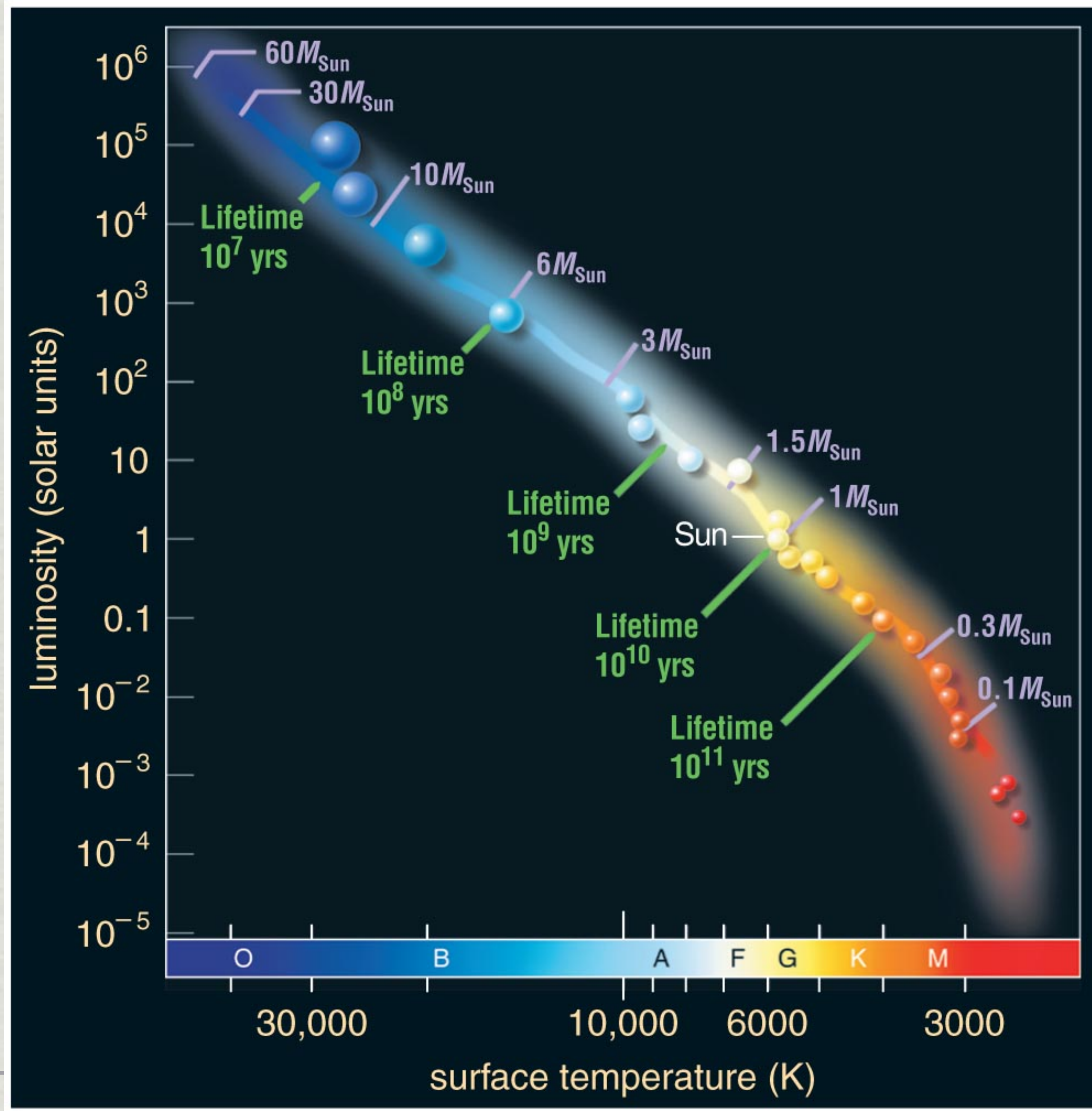
- If it weren't, the sun would collapse!
- Energy produced near the center (in the core) by nuclear fusion heats gas atoms in the core, maintains high gas pressure.
  - More energy generated at higher temperature and pressure.

Hertzsprung-Russell (H-R) Diagram

Higher mass = more pressure from gravity

Higher mass:
Higher core pressure, need Higher core temperature. Need larger rate of energy generation from fusion to hold the star up

Lower mass: lower core pressure, lower core temperature. Can counter-act the pressure from gravity with a lower energy generation rate from nuclear fusion.



Hertzsprung-Russell (H-R) Diagram

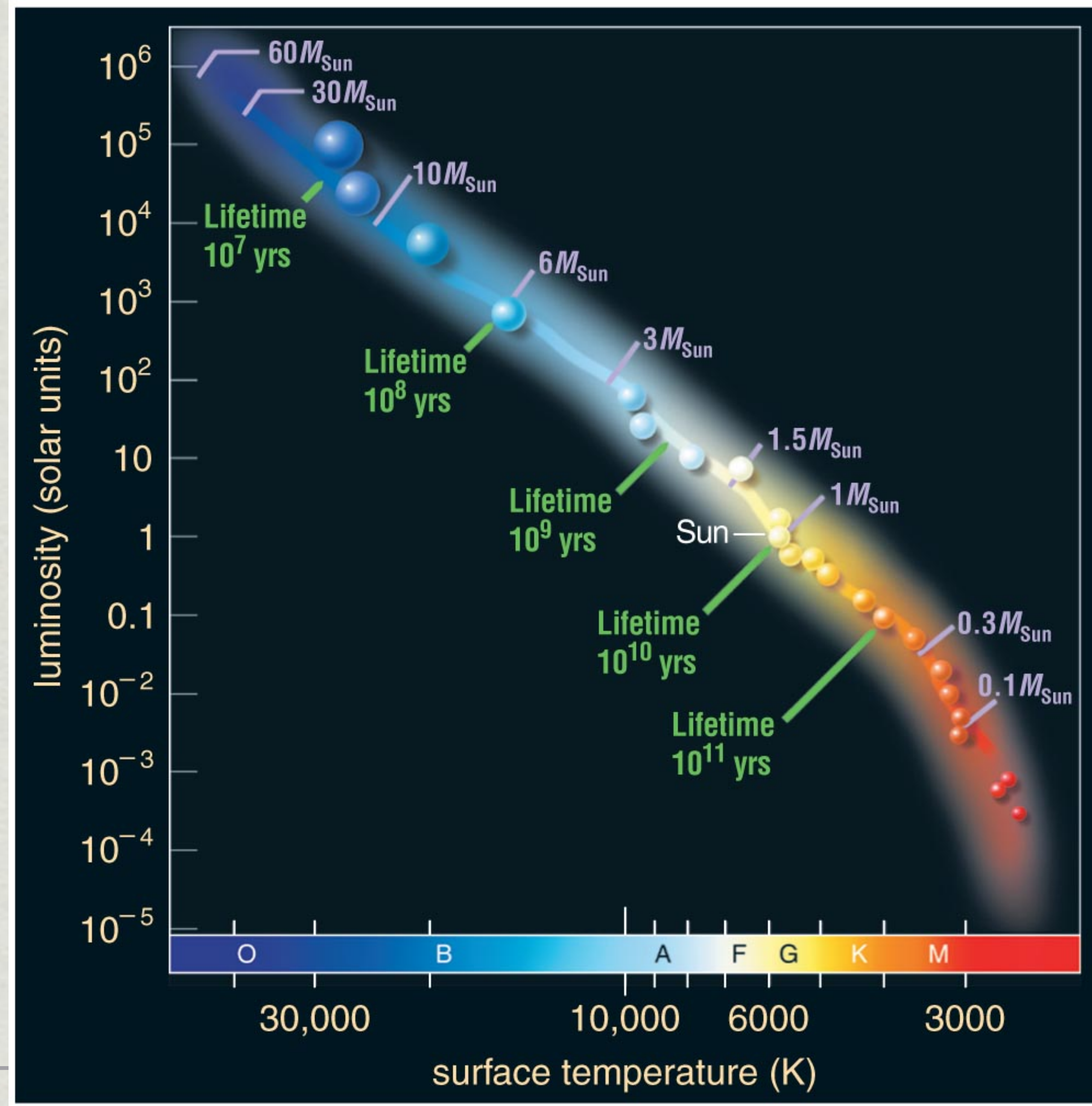
Higher mass = more pressure from gravity

Higher mass: Need larger rate of energy generation from fusion to hold the star up

Lower mass: lower energy generation rate from nuclear fusion.

Energy generated in the core comes out at the surface as luminosity

Energy generation rate from nuclear fusion in the core sets the luminosity output of the star



Hertzsprung-Russell (H-R) Diagram

Higher mass = more pressure from gravity

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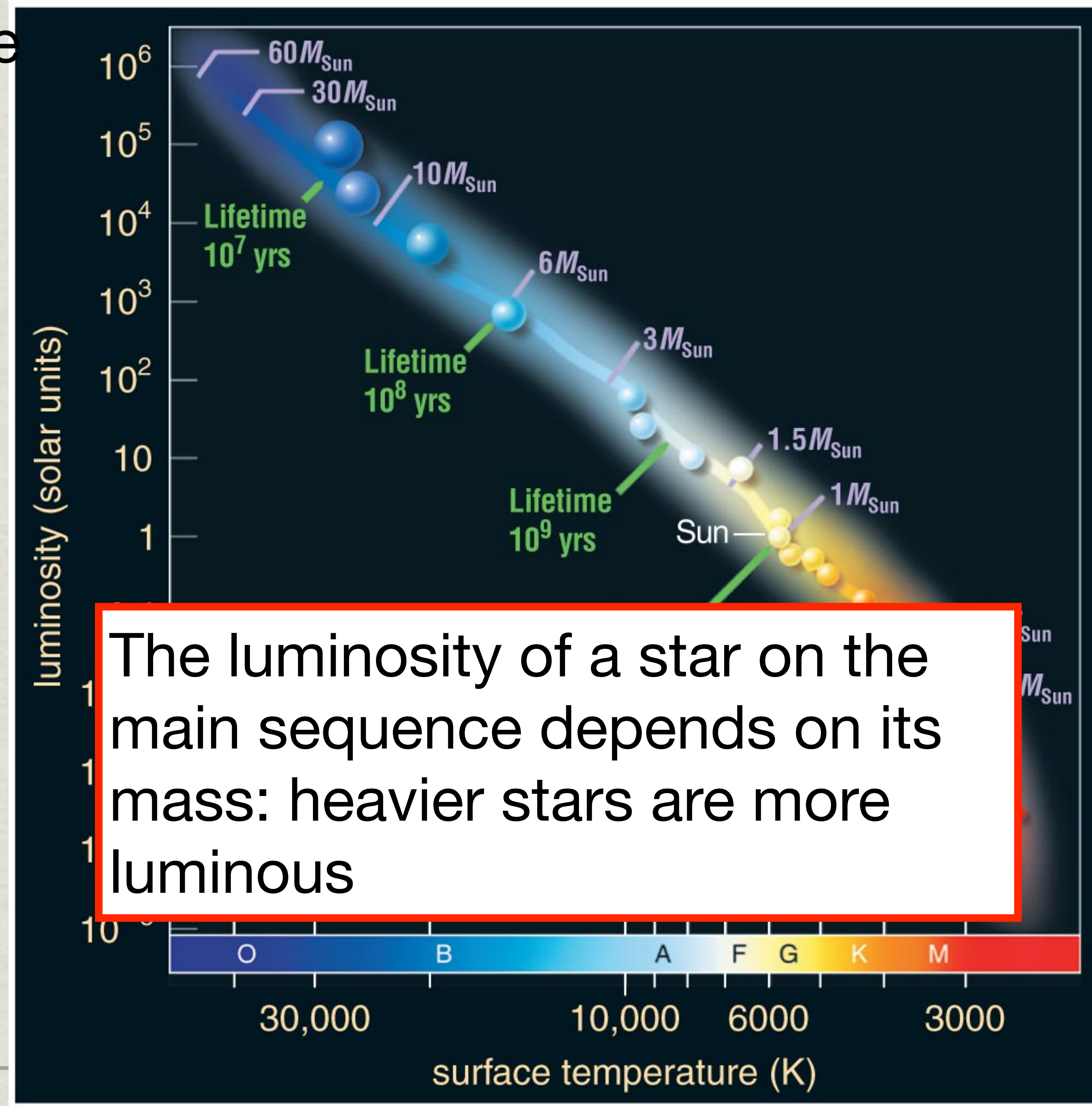
Energy generation rate from nuclear fusion in the core sets the luminosity output of the star

That rate depends on the mass of the star



The luminosity of a star on the main sequence depends on its mass: heavier stars are more luminous

Hertzsprung-Russell (H-R) Diagram

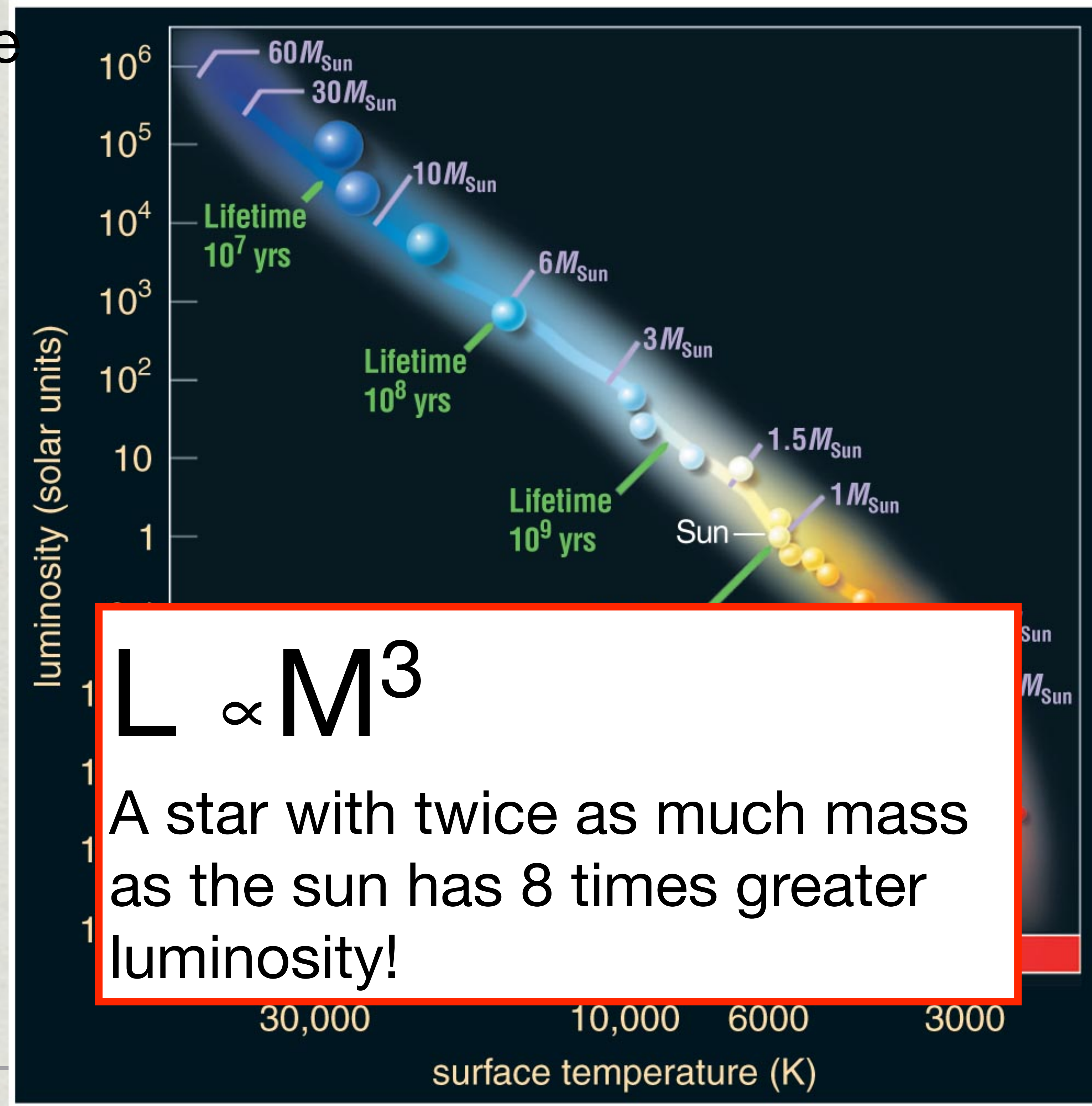
Higher mass = more pressure from gravity

Higher mass: Need larger rate of energy generation from fusion to hold the star up

Lower mass: lower energy generation rate from nuclear fusion.

Energy generation rate from nuclear fusion in the core sets the luminosity output of the star

That rate depends on the mass of the star



$$L \propto M^3$$

A star with twice as much mass as the sun has 8 times greater luminosity!

Hertzsprung-Russell (H-R) Diagram

How are stellar mass and lifetime related?

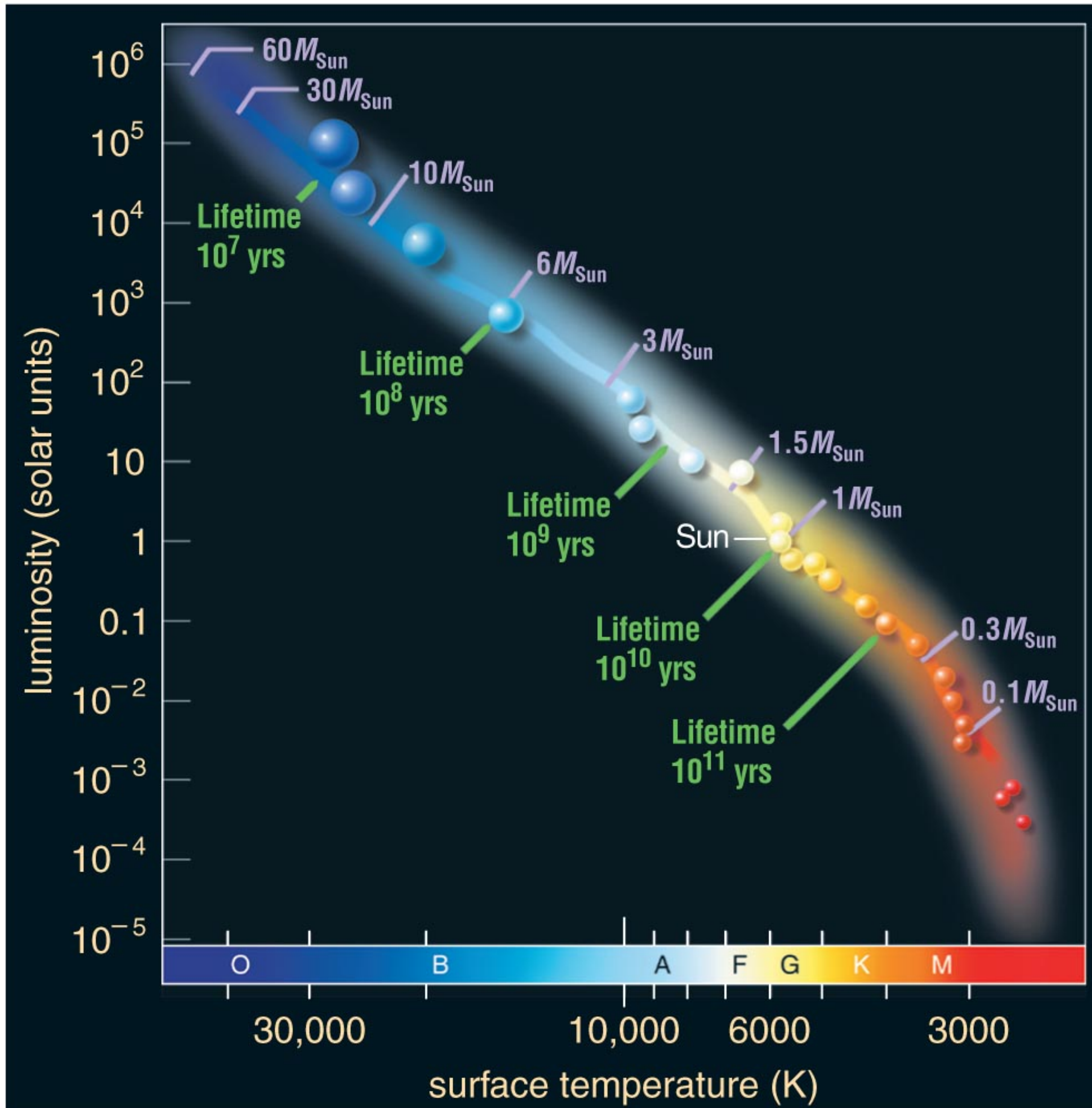
Lifetime: how long fuel lasts.

$$\frac{\text{Amount of fuel}}{\text{Rate fuel is used}} = \frac{\text{Amount of fuel}}{\text{energy generation rate}}$$

Amount of fuel: Mass

Energy generation rate: Luminosity

$$\text{So: Lifetime} = \frac{\text{Mass}}{\text{Luminosity}}$$



Powering the Sun: Nucleosynthesis

Energy released per 1 kg of Hydrogen fused into Heluim:
0.7% of the Hydrogen mass is released: **$0.007 * M_{Hydrogen}$**

$E = mc^2 = \mathbf{0.007 \times 1\ kg} \times (3 \times 10^8\ m/s)^2$
$= \mathbf{6.3 \times 10^{14}}$ **Joules for 1 kg** Hydrogen → Helium

Total energy available in fuel: Mass of sun (kg) × energy per kg of fuel

Mass of the sun: **2×10^{30} kg**

Total energy available: M_{sun} x (Energy/kg) = **2×10^{30} kg** x **6.3×10^{14} Joules/kg**
= **1.3×10^{45} Joules**

Powering the Sun: Nucleosynthesis

Energy released per 1 kg of Hydrogen fused into Heluim:
0.7% of the Hydrogen mass is released: $0.007 * M_{Hydrogen}$

$E = mc^2 = \mathbf{0.007 \times 1\ kg} \times (3 \times 10^8\ m/s)^2$
$= \mathbf{6.3 \times 10^{14}}$ **Joules for 1 kg** Hydrogen → Helium

Total energy available: $M_{sun} \times$ (Energy/kg) = $\mathbf{2 \times 10^{30}}$ **kg** x $\mathbf{6.3 \times 10^{14}}$ **Joules/kg**
= $\mathbf{1.3 \times 10^{45}}$ **Joules**

Lifespan of sun: $\frac{\text{Total energy available in fuel}}{\text{Energy generated per second}}$

Energy generated per second: **Luminosity of sun**, energy output per second
= $\mathbf{4 \times 10^{26}}$ **Joules/sec**

Powering the Sun: Nucleosynthesis

Energy released per 1 kg of Hydrogen fused into Heluim:
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$E = mc^2 =$ **0.007 × 1 kg** $\times (3\times10^8 \text{ m/s})^2$
$=$ **6.3×10^{14} Joules for 1 kg** Hydrogen → Helium

Total energy available: M_{sun} x (Energy/kg) = **2×10^{30} kg** x **6.3×10^{14} Joules/kg**
= **1.3×10^{45} Joules**

Lifespan of sun: $\dfrac{\text{Total energy available in fuel}}{\text{Energy generated per second}}$

Energy generated per second: **Luminosity of sun**, energy output per second

Lifetime of sun: $\dfrac{\mathbf{1.3 \times 10^{45} \text{ Joules}}}{\mathbf{4\times10^{26} \text{ Joules/sec}}} = 3.25 \times 10^{18} \text{ sec} \times \dfrac{(1 \text{ year})}{(3.15 \times 10^{7} \text{ sec})}$

$= 1.0 \times 10^{11}$ years. That's 100 billion years. The Universe is "only" 13.7 billion years old. **Stars like the sun last a long time!**

Hertzsprung-Russell (H-R) Diagram

How are stellar mass and lifetime related?

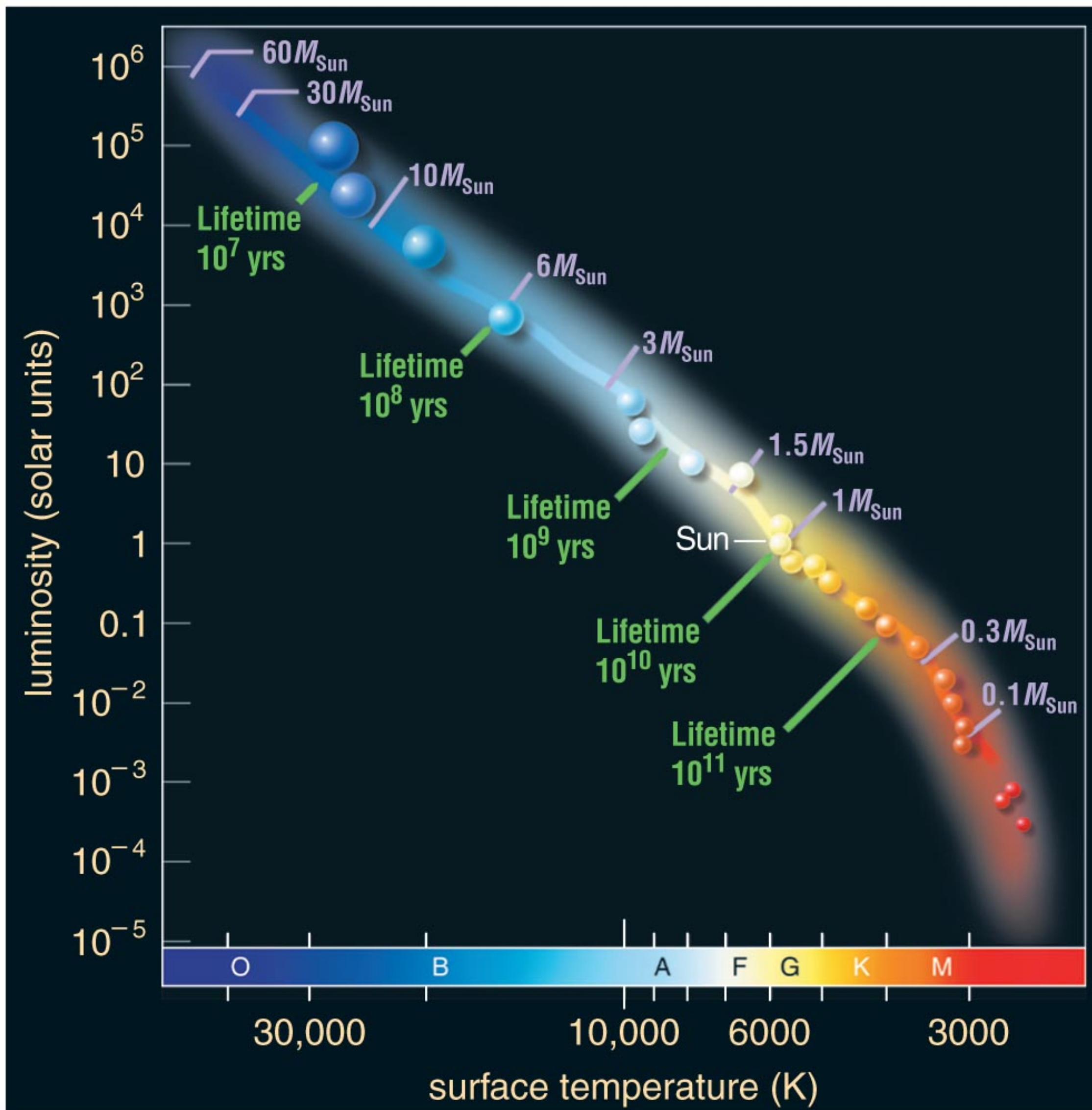
Lifetime: how long fuel lasts.

Amount of fuel: Mass
Energy generation rate: Luminosity

$$\text{So: Lifetime} = \frac{\text{Mass}}{\text{Luminosity}}$$

Lifetime of sun: 10 billion years (we'll see later it can't use all its hydrogen)

What about stars with other masses?



Hertzsprung-Russell (H-R) Diagram

How are stellar mass and lifetime related?

$$\text{Lifetime} = \frac{\text{Mass}}{\text{Luminosity}}$$

$L \sim M^3$ so:

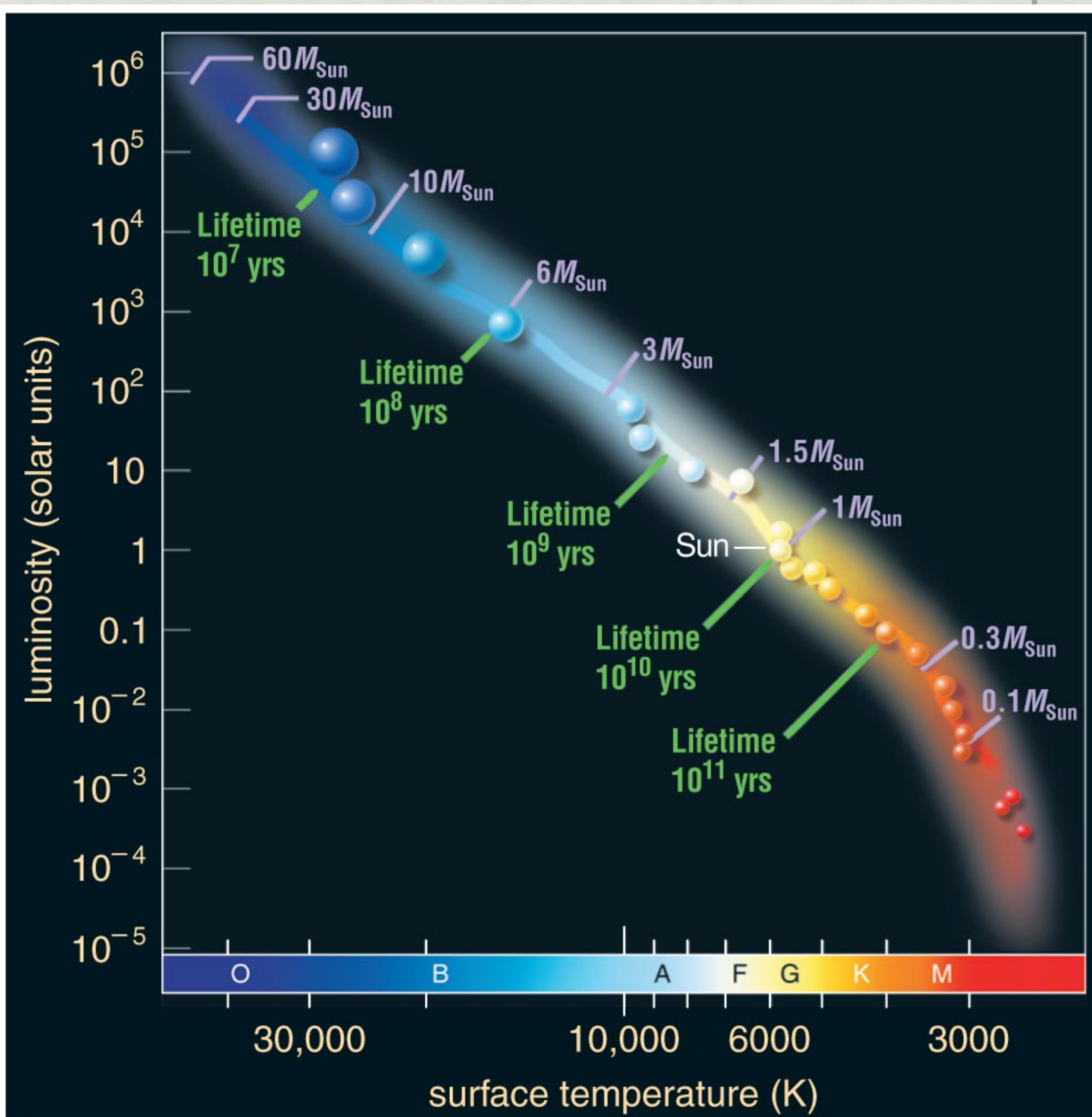
$\text{Lifetime} \sim M/M^3 \sim 1/M^2$

Life expectancy of star with 10 M_{sun}:

$L_* \sim M_*^3 \rightarrow L_* \sim (10\ M_{sun})^3 \sim 10^3\ L_{sun}$

$\text{Lifespan} = M^*/L^* = 10\ M_{sun}/10^3\ L_{sun}$

$= 1/10^2 = 1/100$ sun's lifetime



Hertzsprung-Russell (H-R) Diagram

How are stellar mass and lifetime related?

Lifespan: how long fuel lasts

Lifetime = (constants) × Mass/Luminosity

$L \sim M^3$ so:

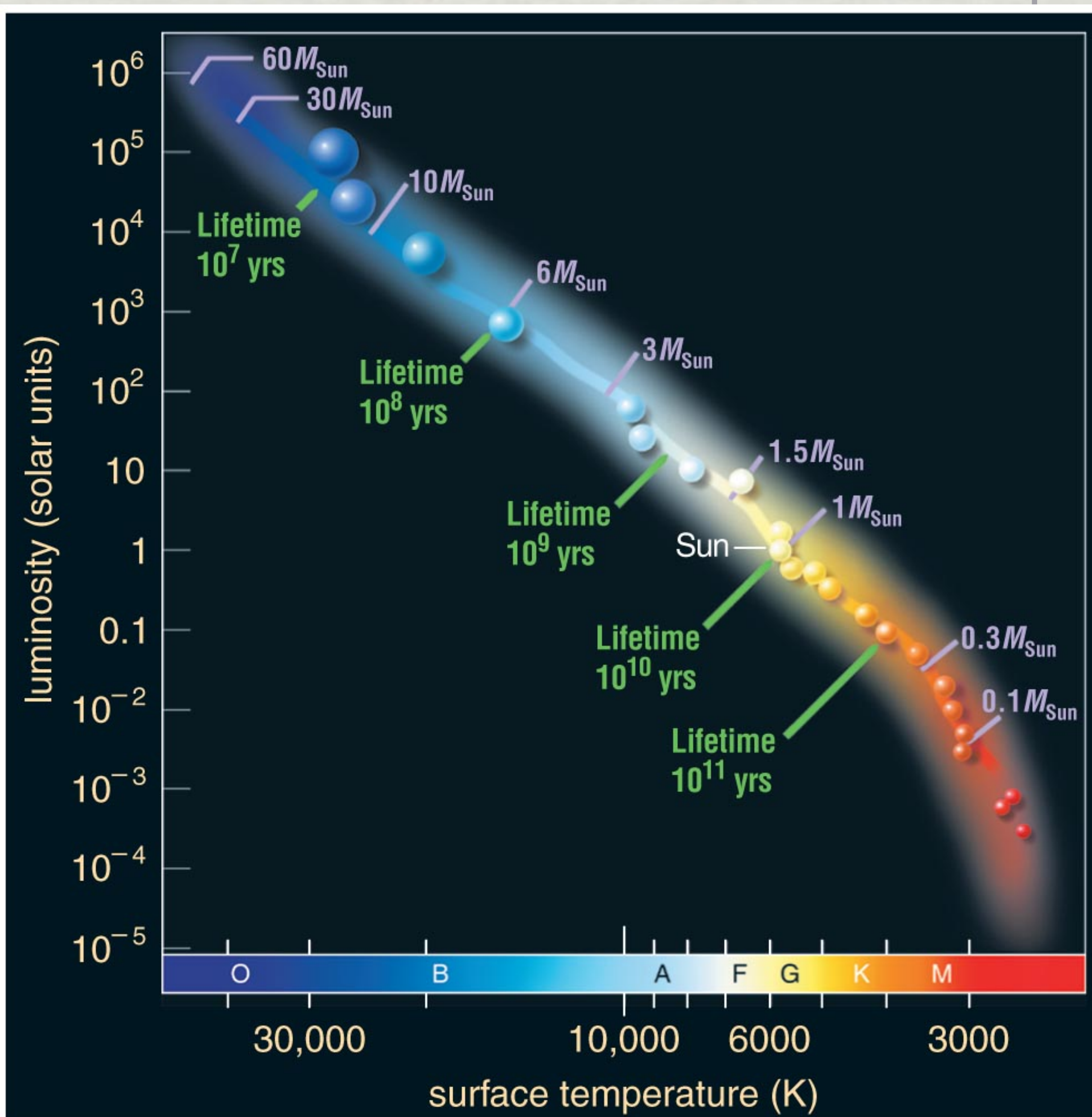
Lifetime $\sim M/M^3 \sim 1/M^2$

Life expectancy of star with 0.1 M_{sun}:

$L_* \sim M_*^3 \rightarrow L_* \sim (0.1\ M_{sun})^3 \sim 0.001\ L_{sun}$

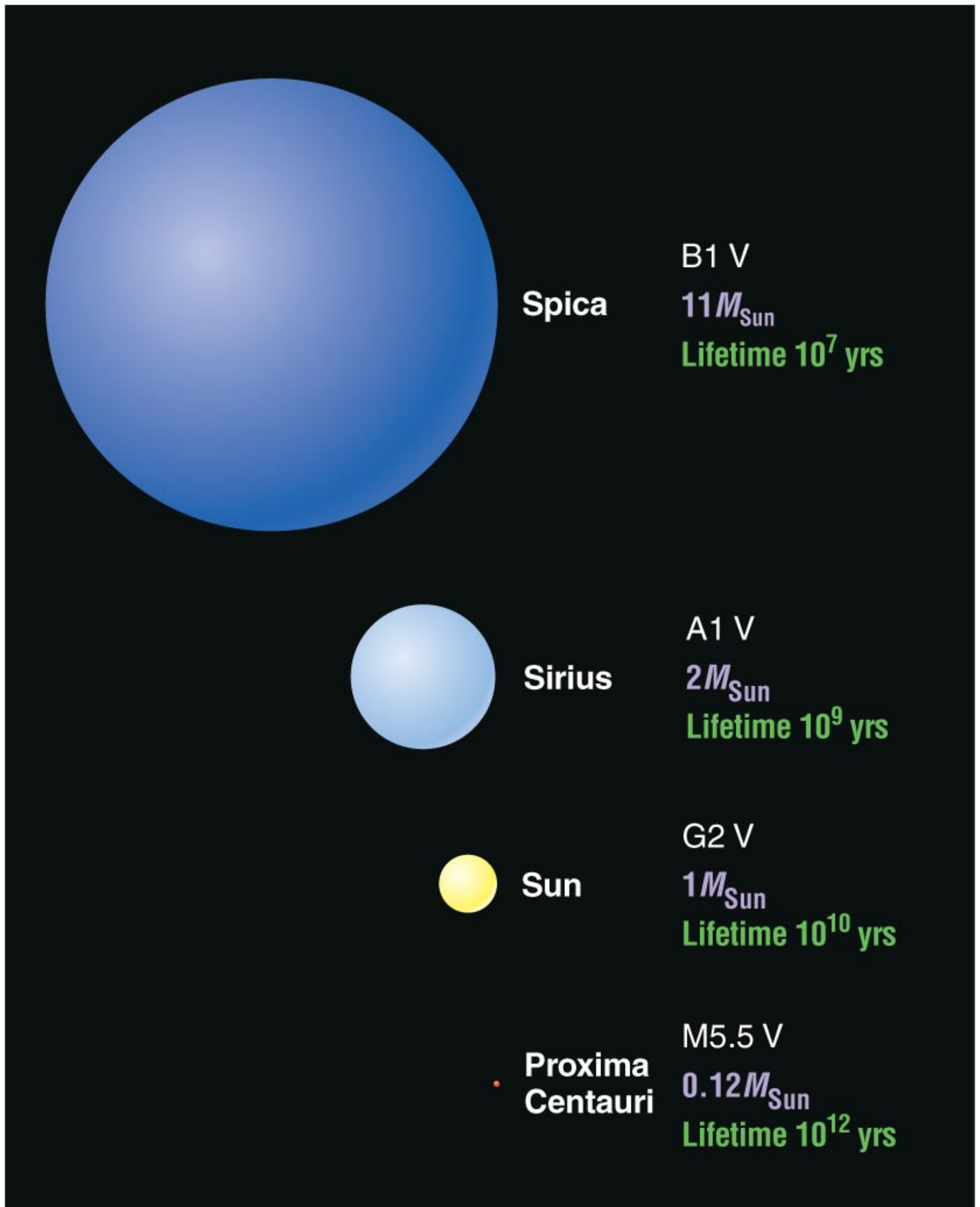
Lifespan = $M^*/L^* = 0.1\ M_{sun}/0.001\ L_{sun}$

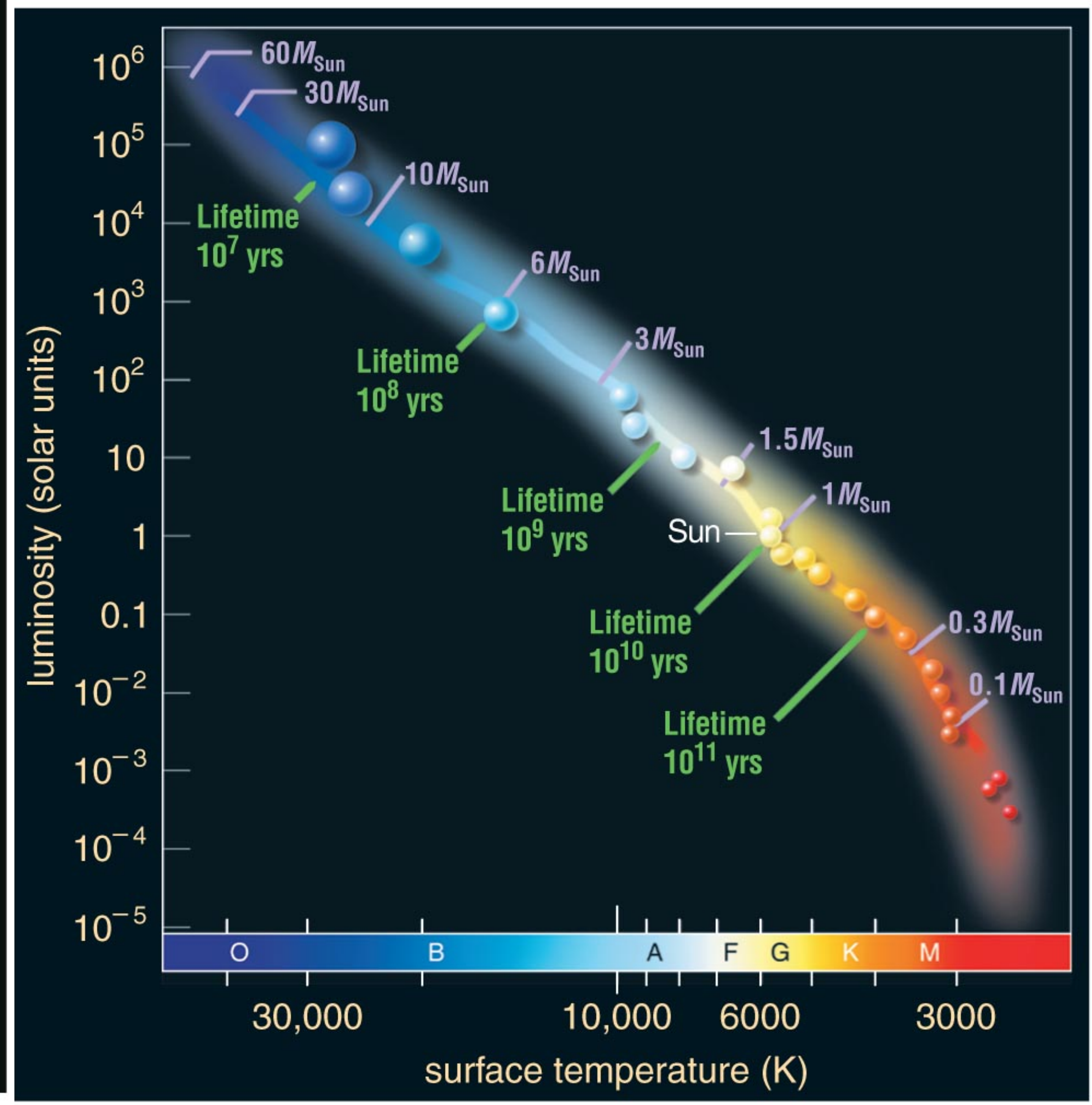
= 100 × sun's lifetime



Hertzsprung-Russell (H-R) Diagram

Stellar mass, temperature, lifetime and radius on the main sequence





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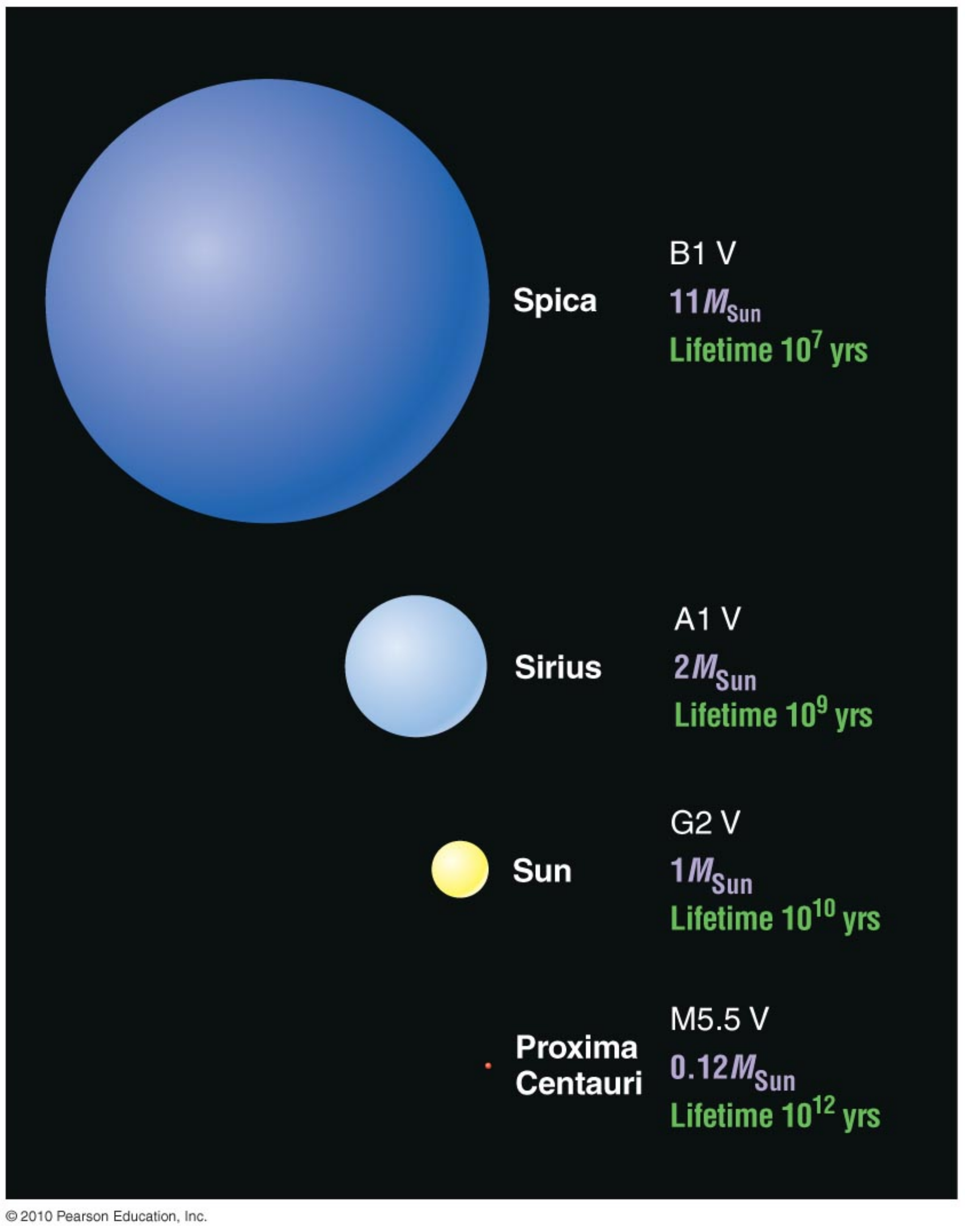
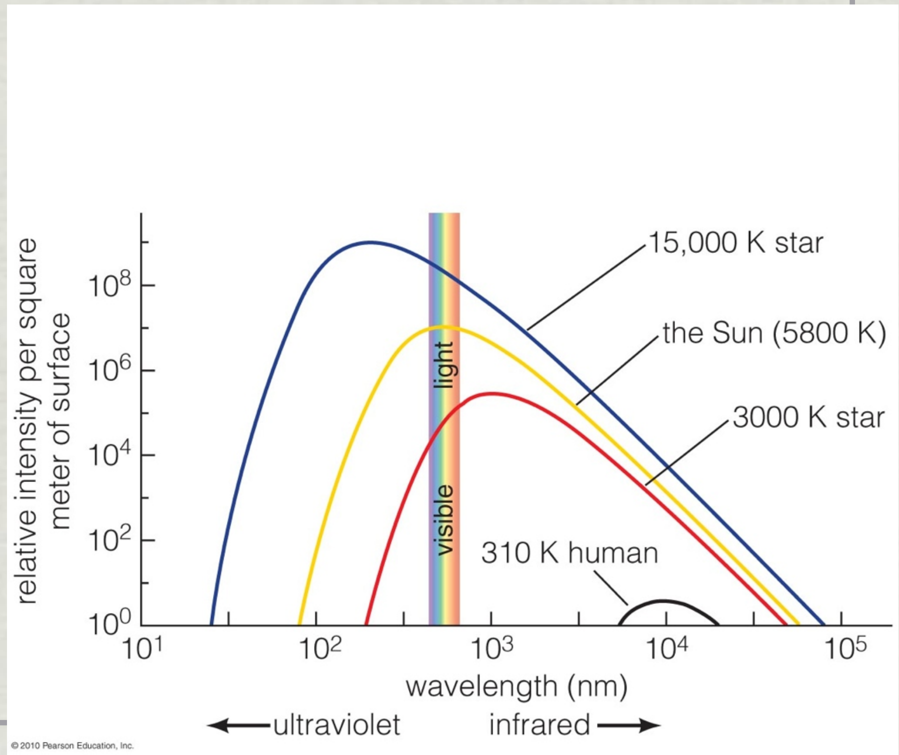


High mass:
- High luminosity
- Blue = high temperature (Wein's Law!)
- Large radius
- Short lifetime



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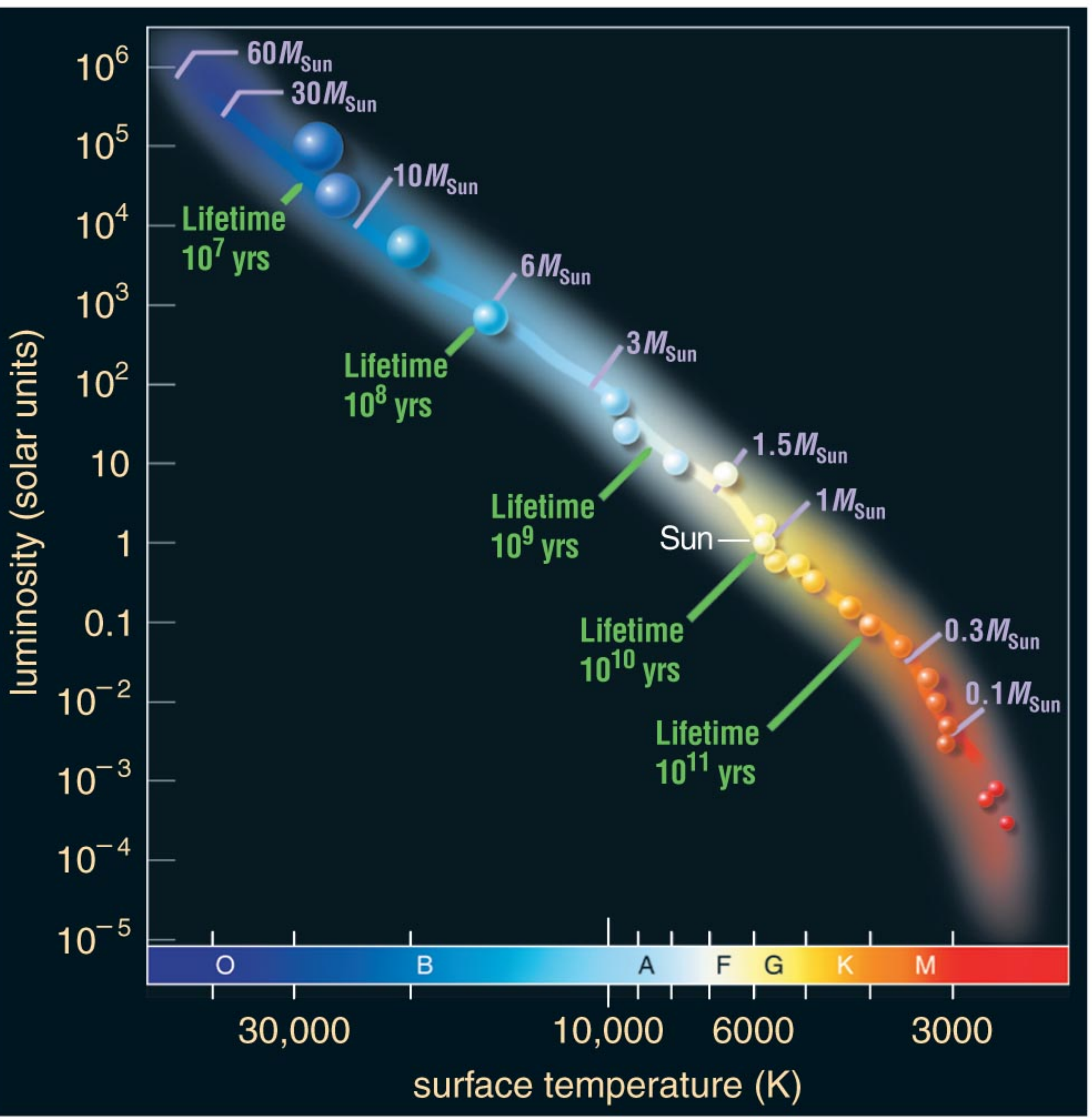

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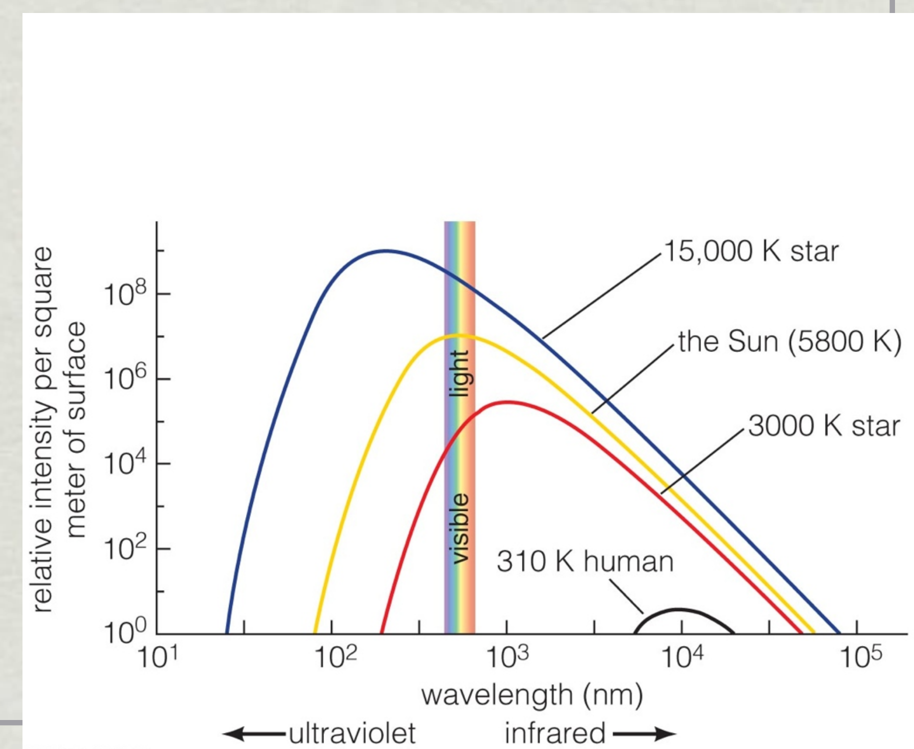

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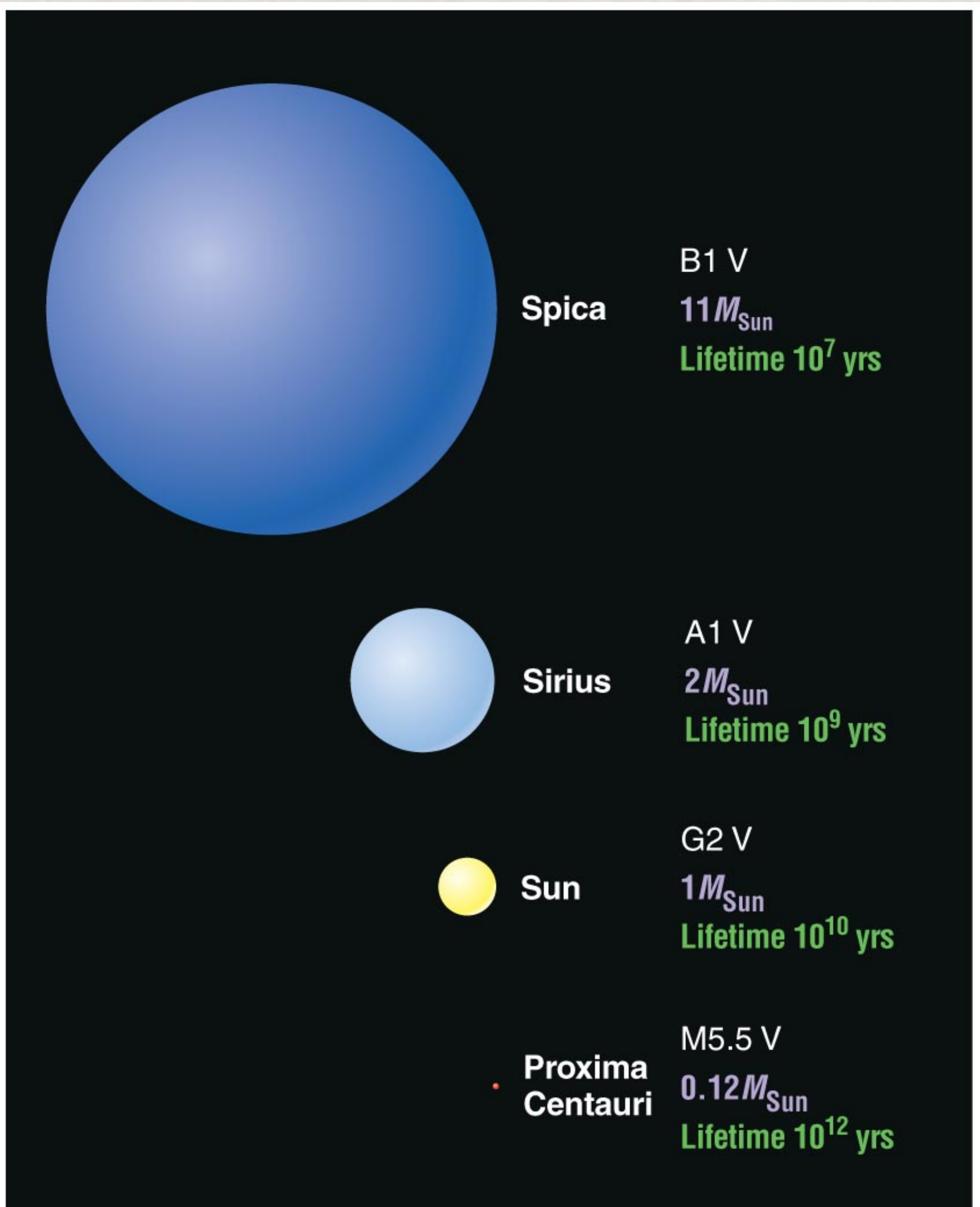


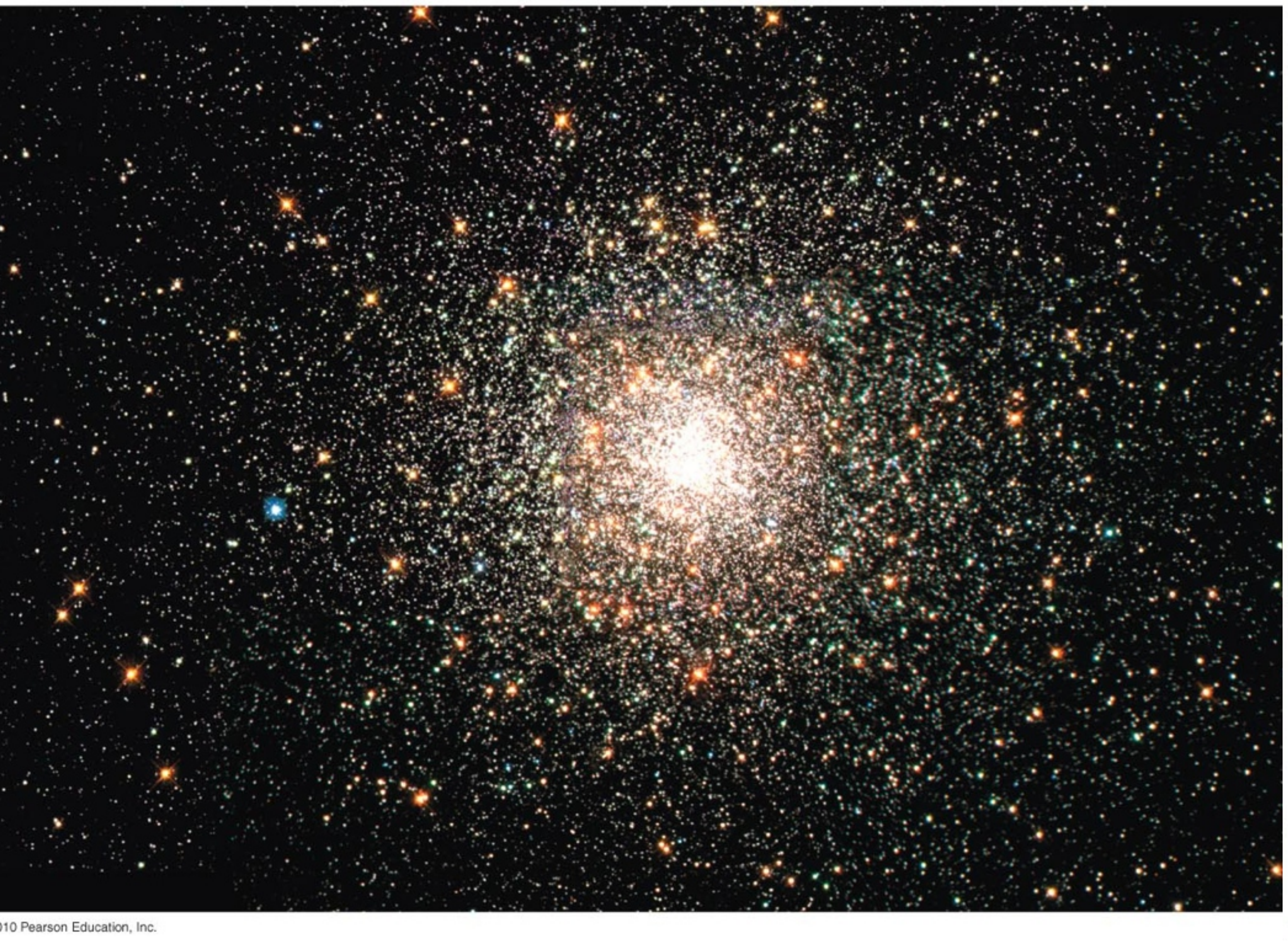
High mass:
- High luminosity
- Blue = high temperature (Wein's Law!)
- Large radius
- Short lifetime

Low Mass:
- Low luminosity
- Red = cool temperature
- Small radius
- Long lifetime

Star Clusters

Star clusters:

- Gravitationally bound group of stars
- All at the same distance from Earth
- All the same age



M80
"Globular" cluster: old, dense

Pleiades
"Open" Cluster: young, sparse

Star Clusters

Star clusters:

- Gravitationally bound group of stars
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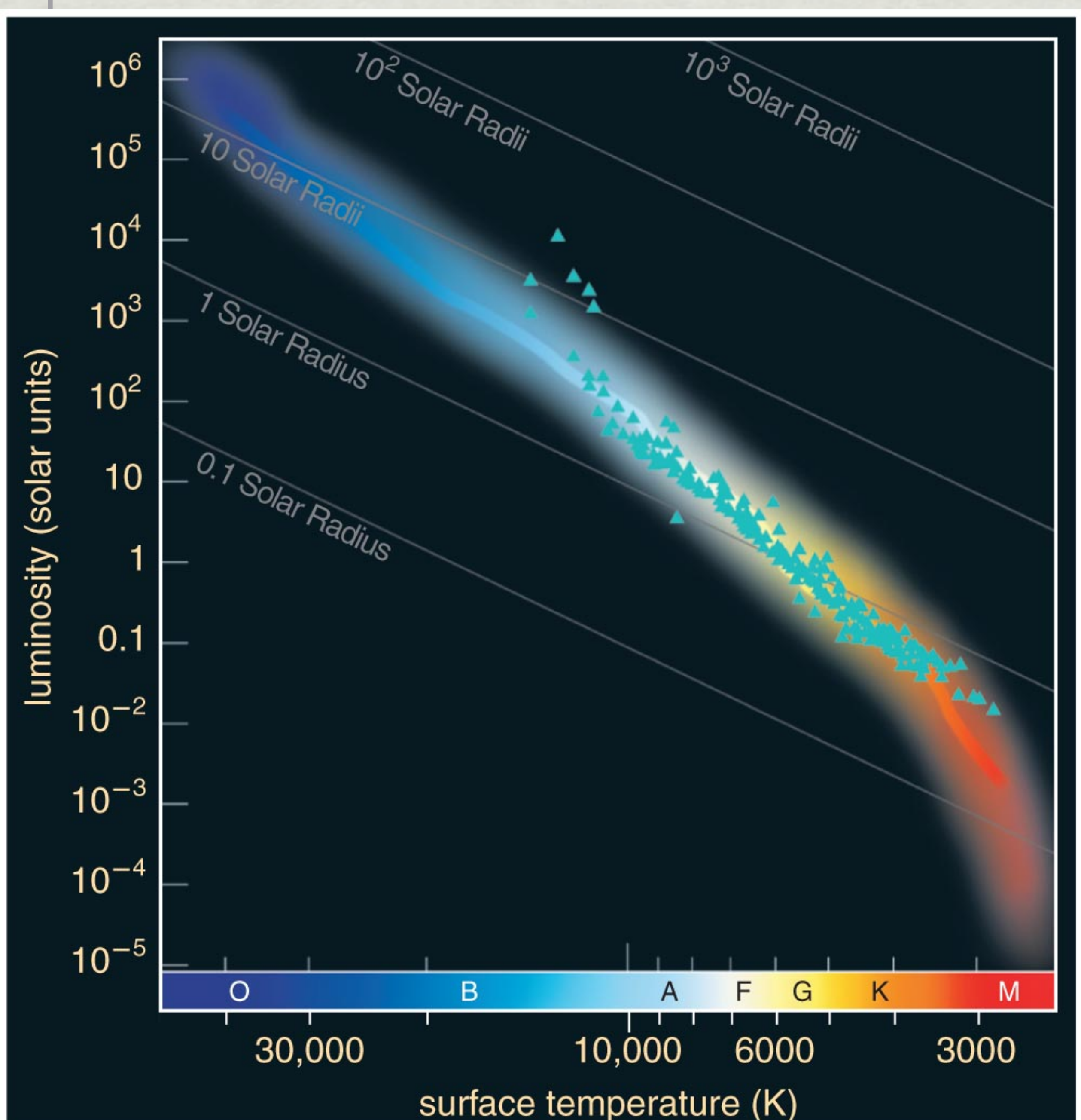
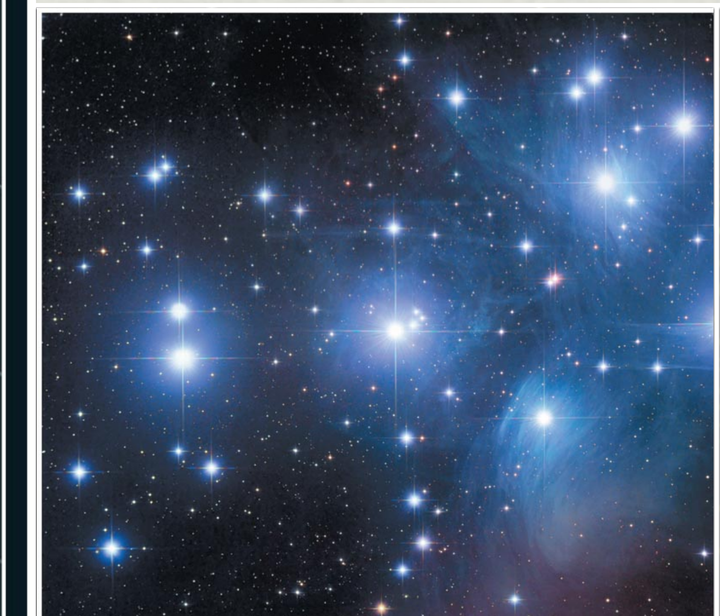
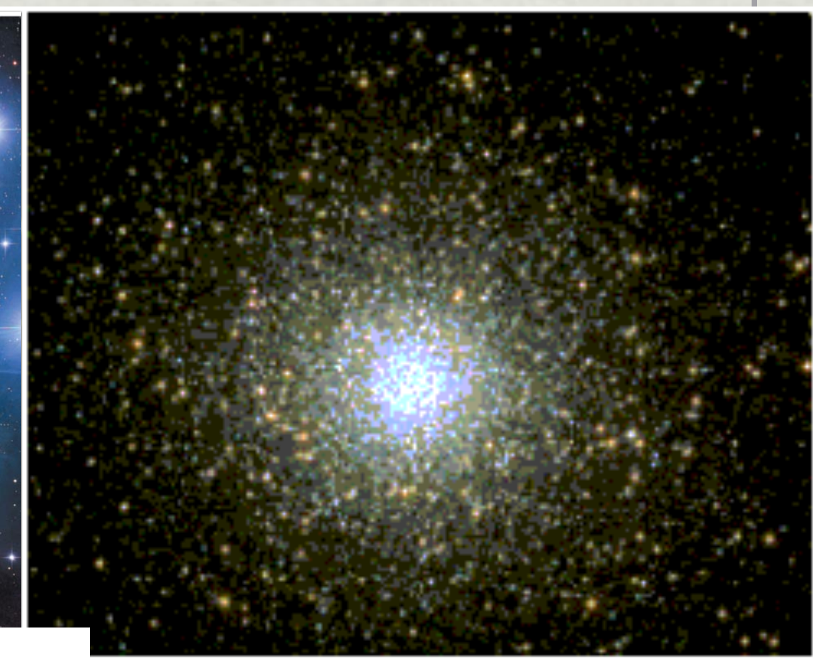
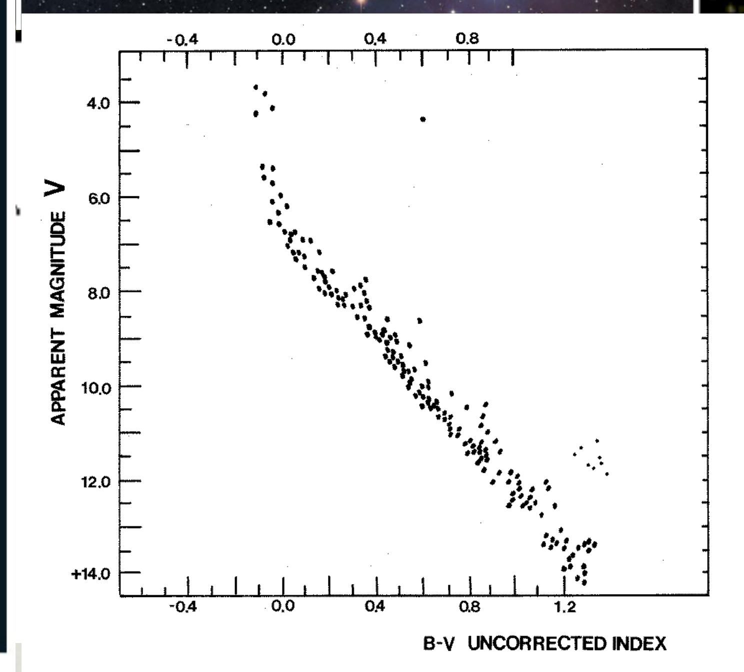
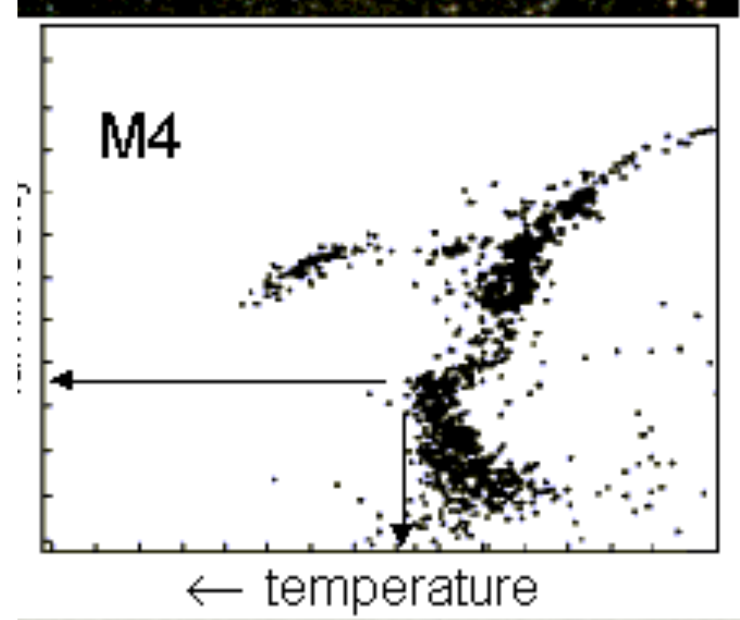
- All the same age









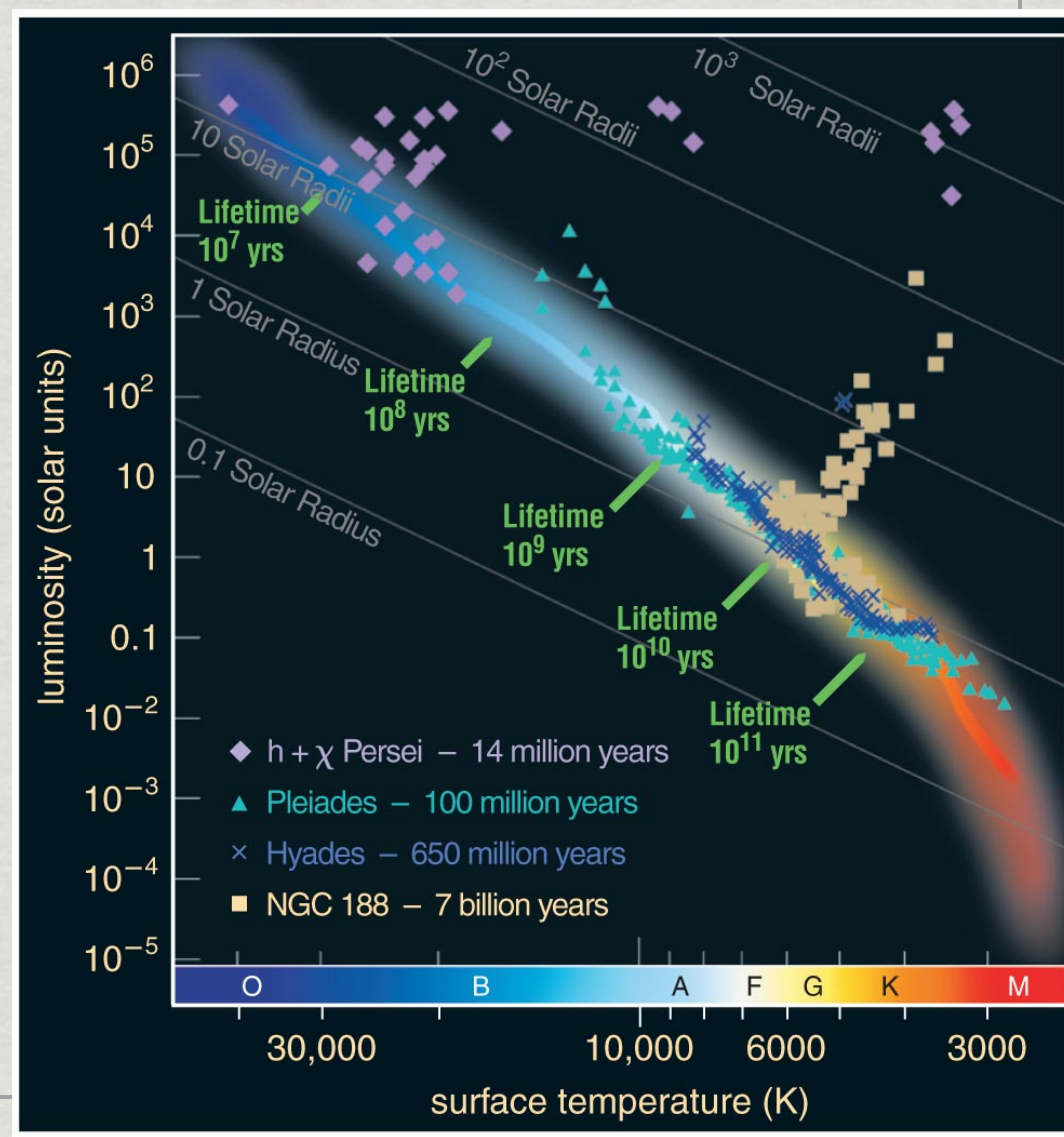


Star Clusters

Remember, lifespan shorter for hot, massive, blue stars

Stars in a cluster form all at the same time.

Hottest, bluest most massive stars run out of fuel in their cores first



Star Clusters

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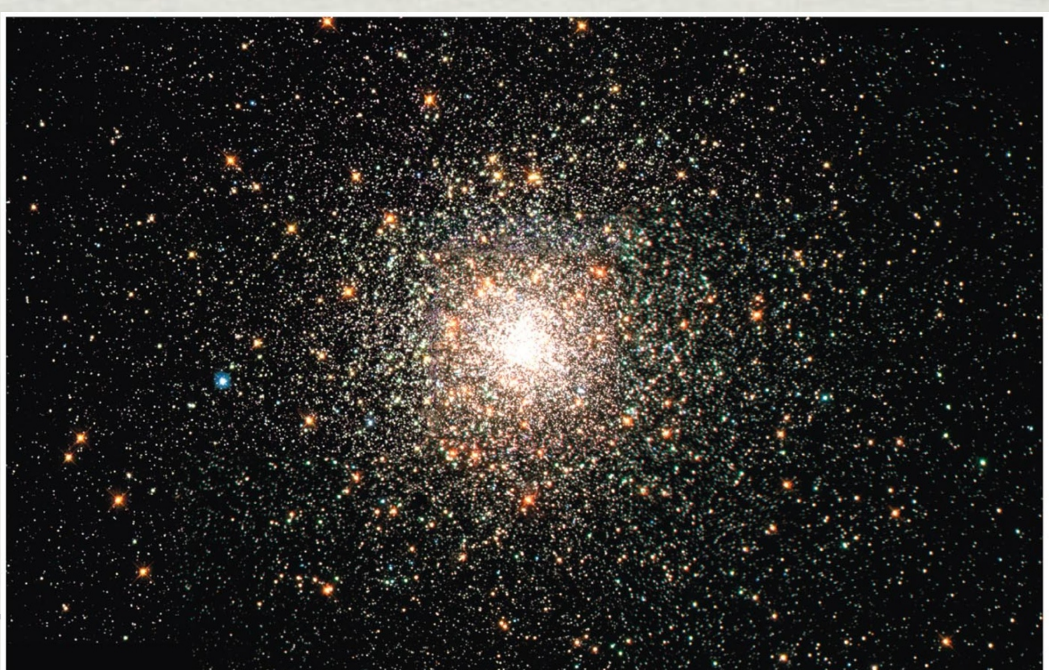
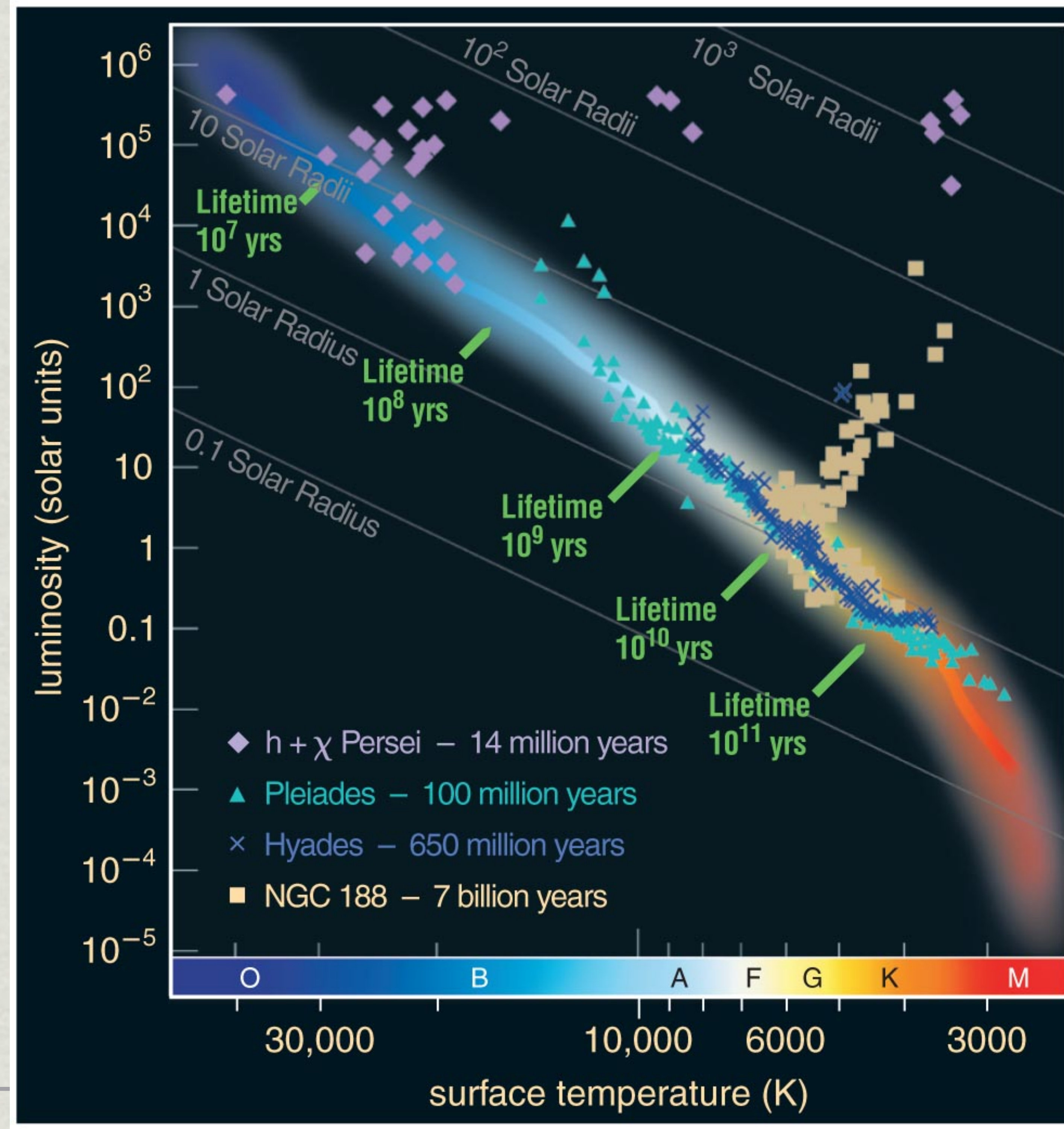
Then the lower mass (yellow) ones





Star Clusters

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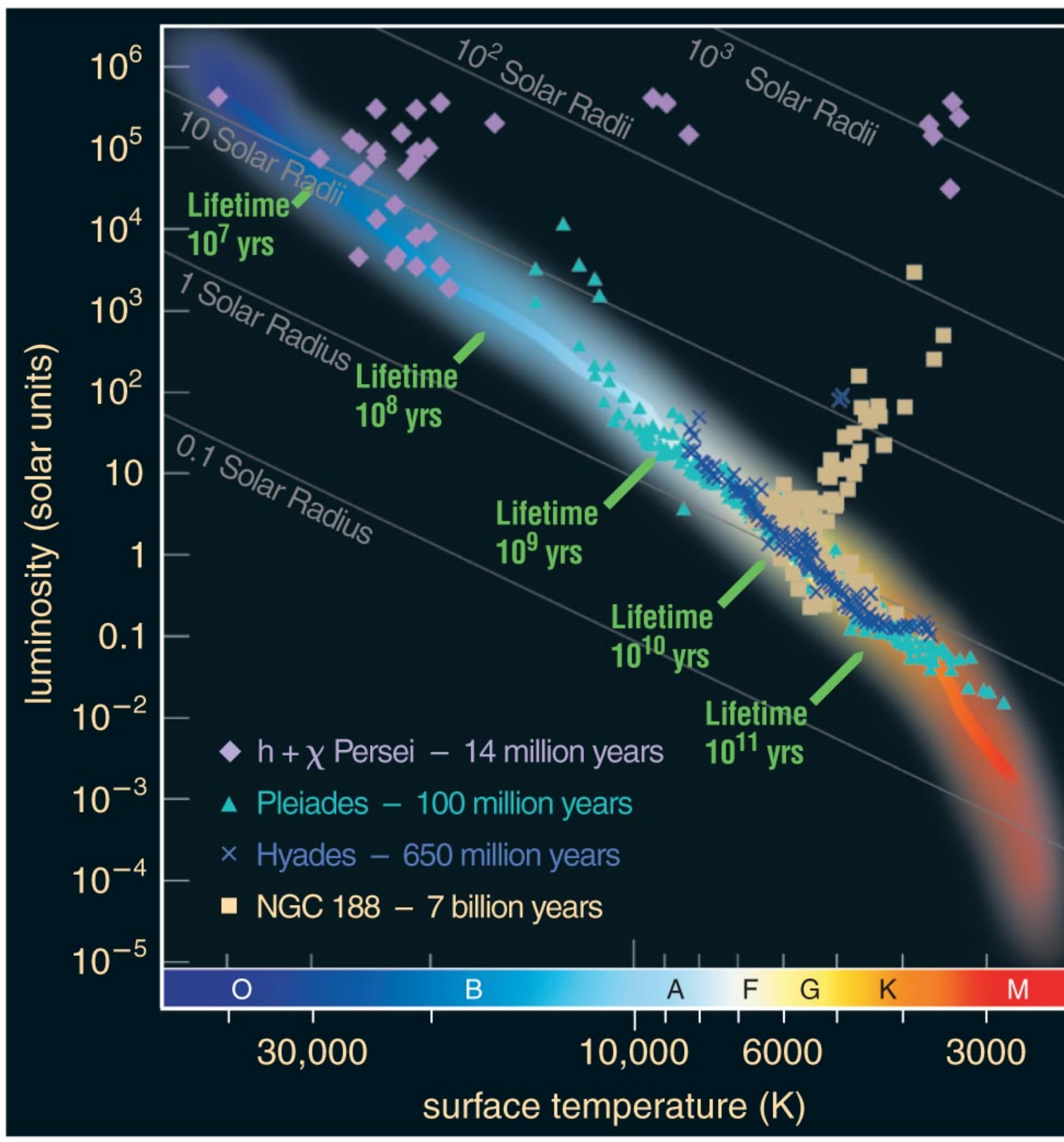
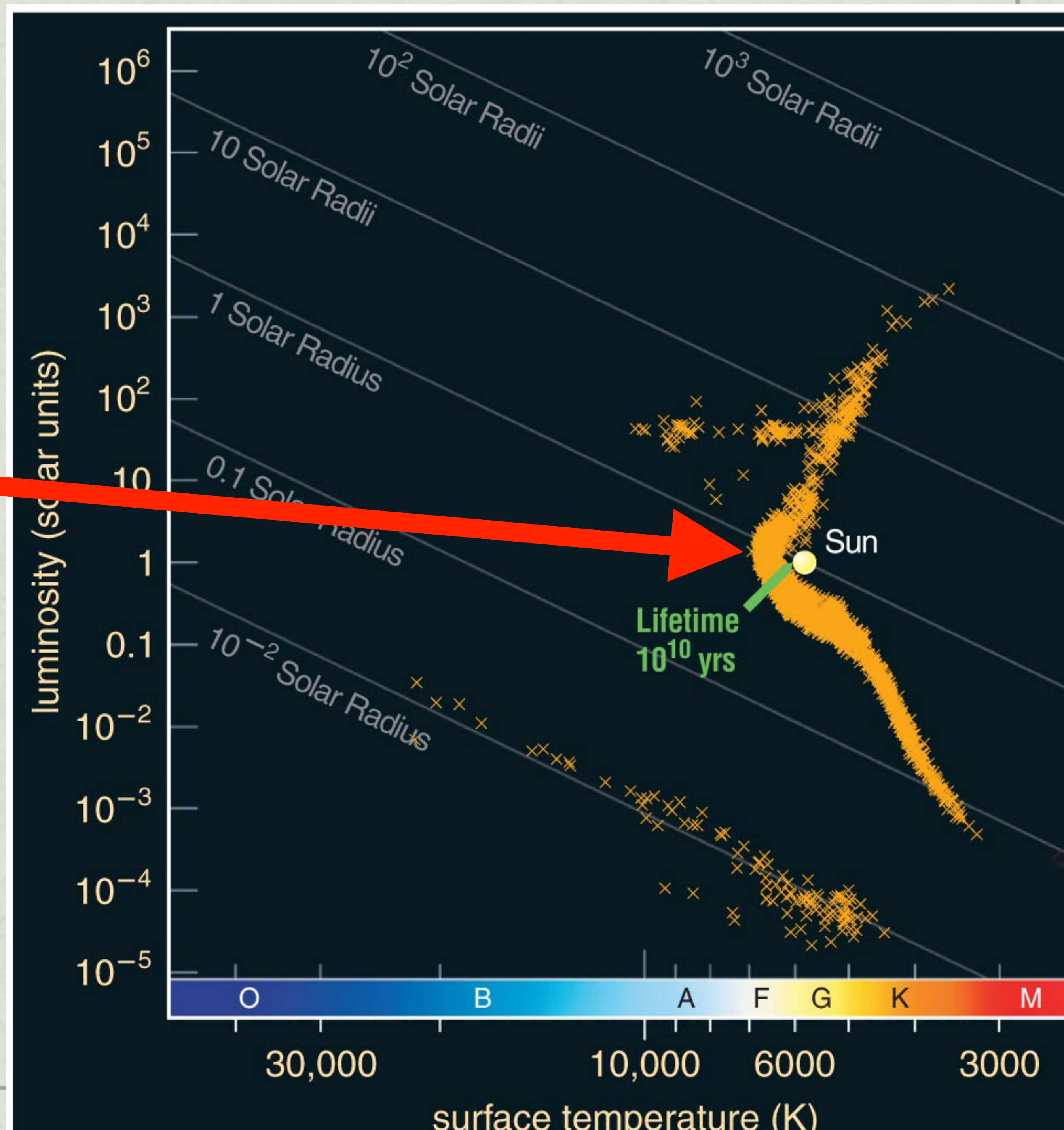
Longest lived are the lowest mass, coolest (reddest) stars.



Star Clusters

Measure luminosity and temperature of the most massive star in a cluster still on the main sequence, just about to exhaust Hydrogen fuel in its core:

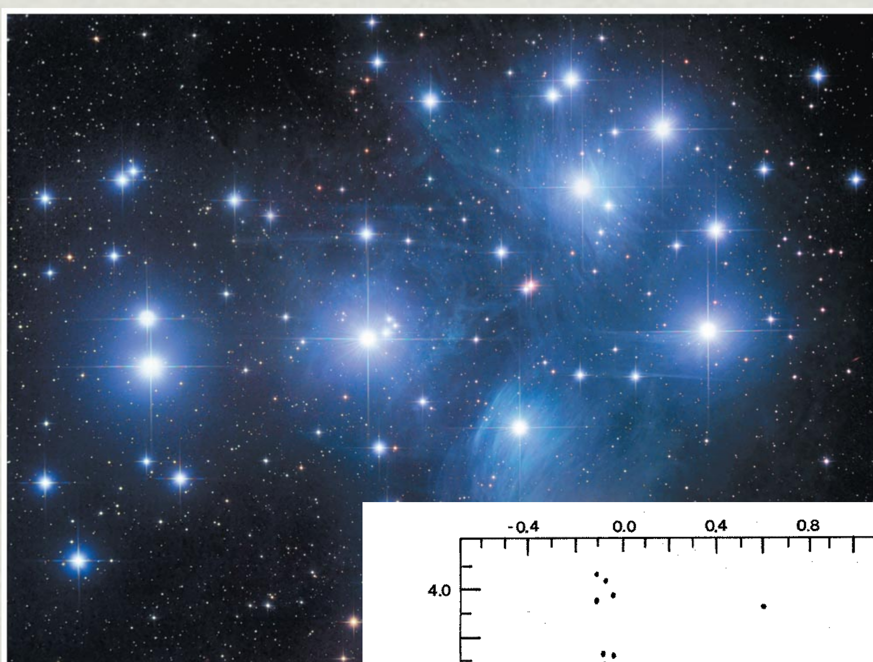
This is called the Main Sequence Turnoff.

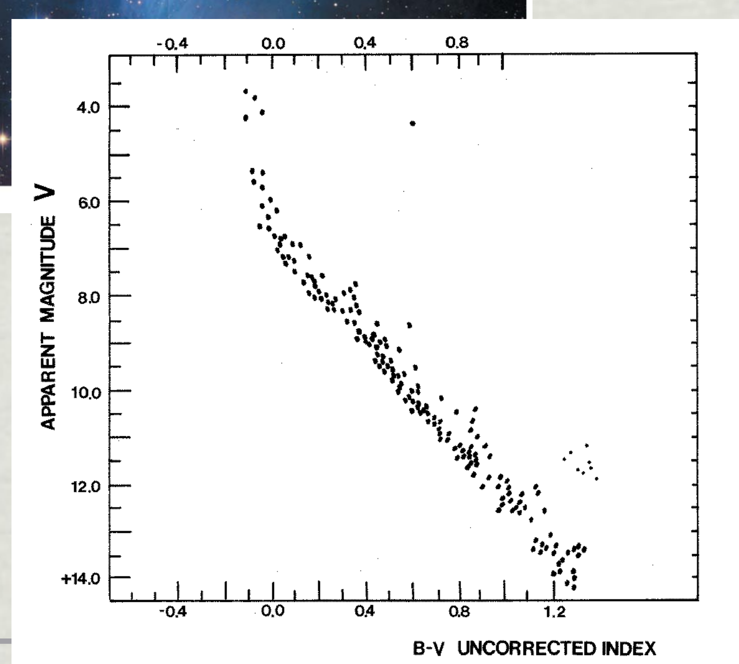


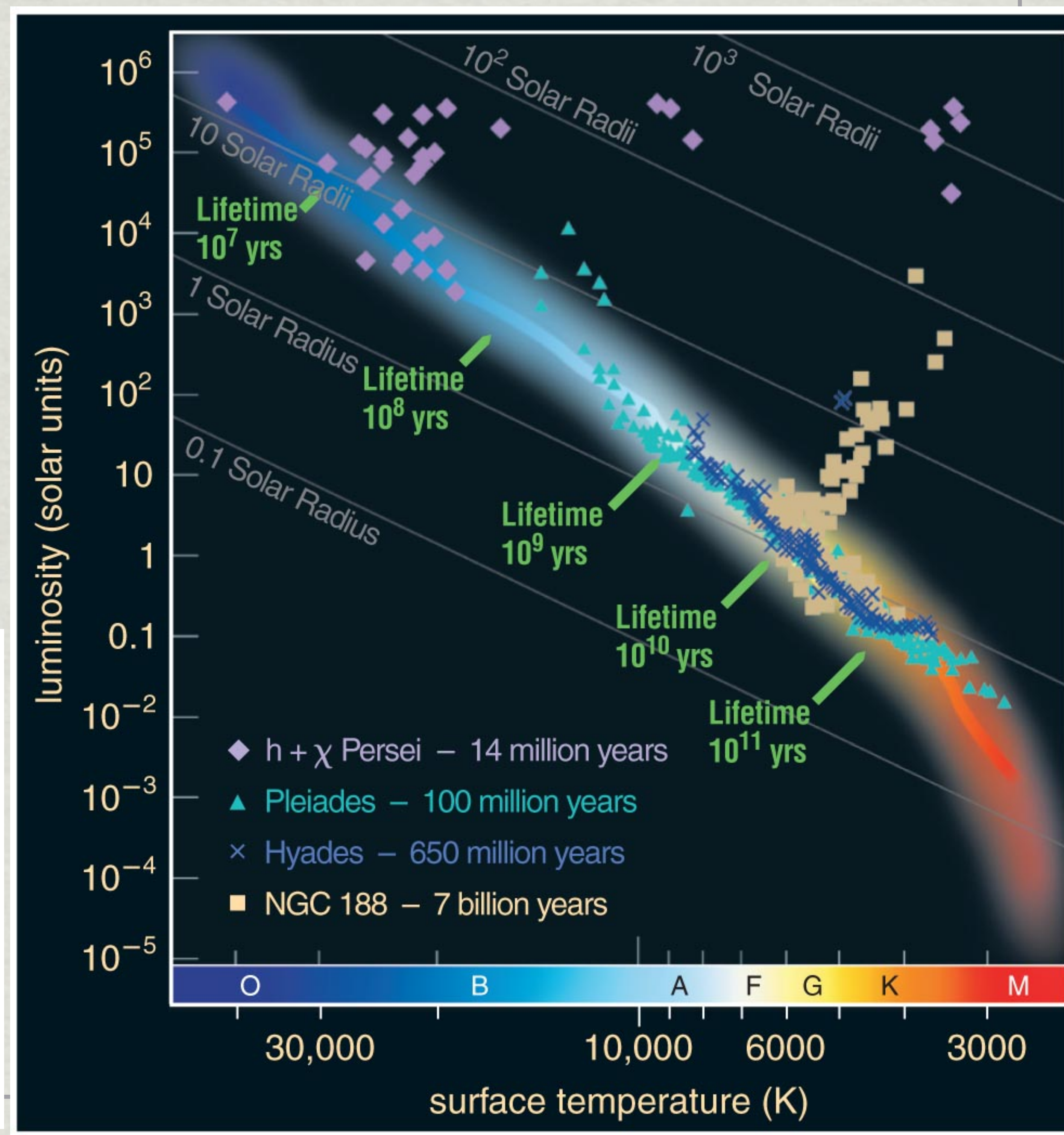
Star Clusters

Stars in a cluster form all at the same time.

Hottest, bluest most massive stars turn off the main sequence first







Star Clusters

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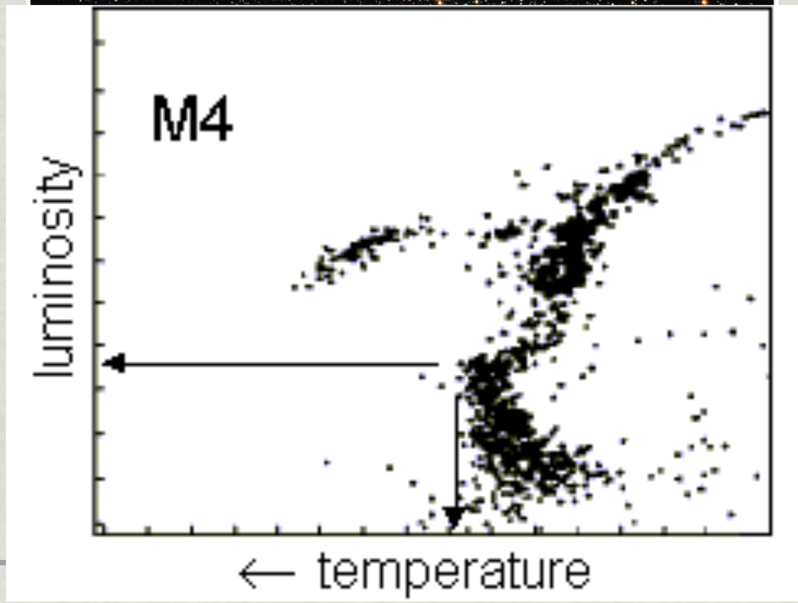
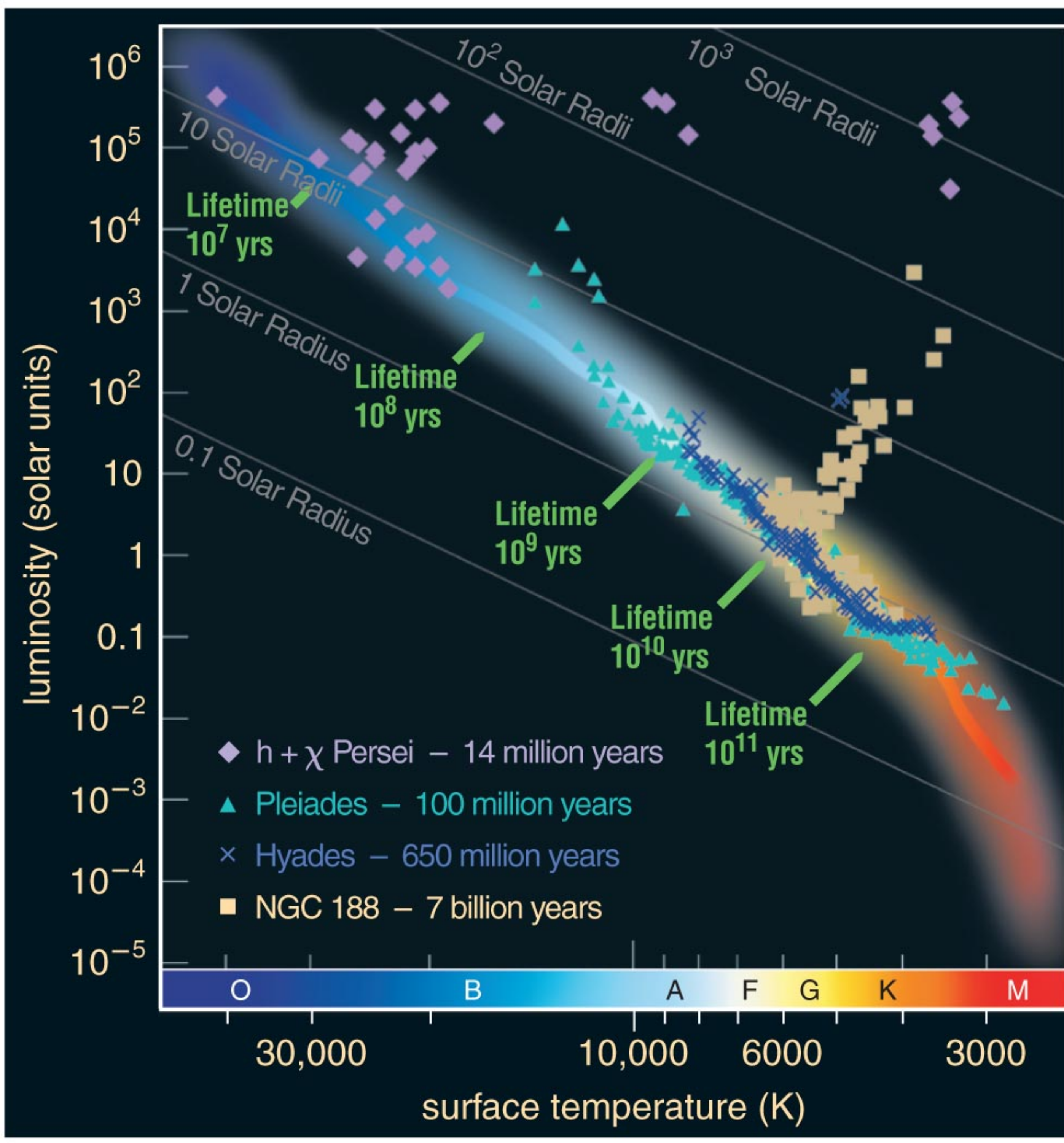




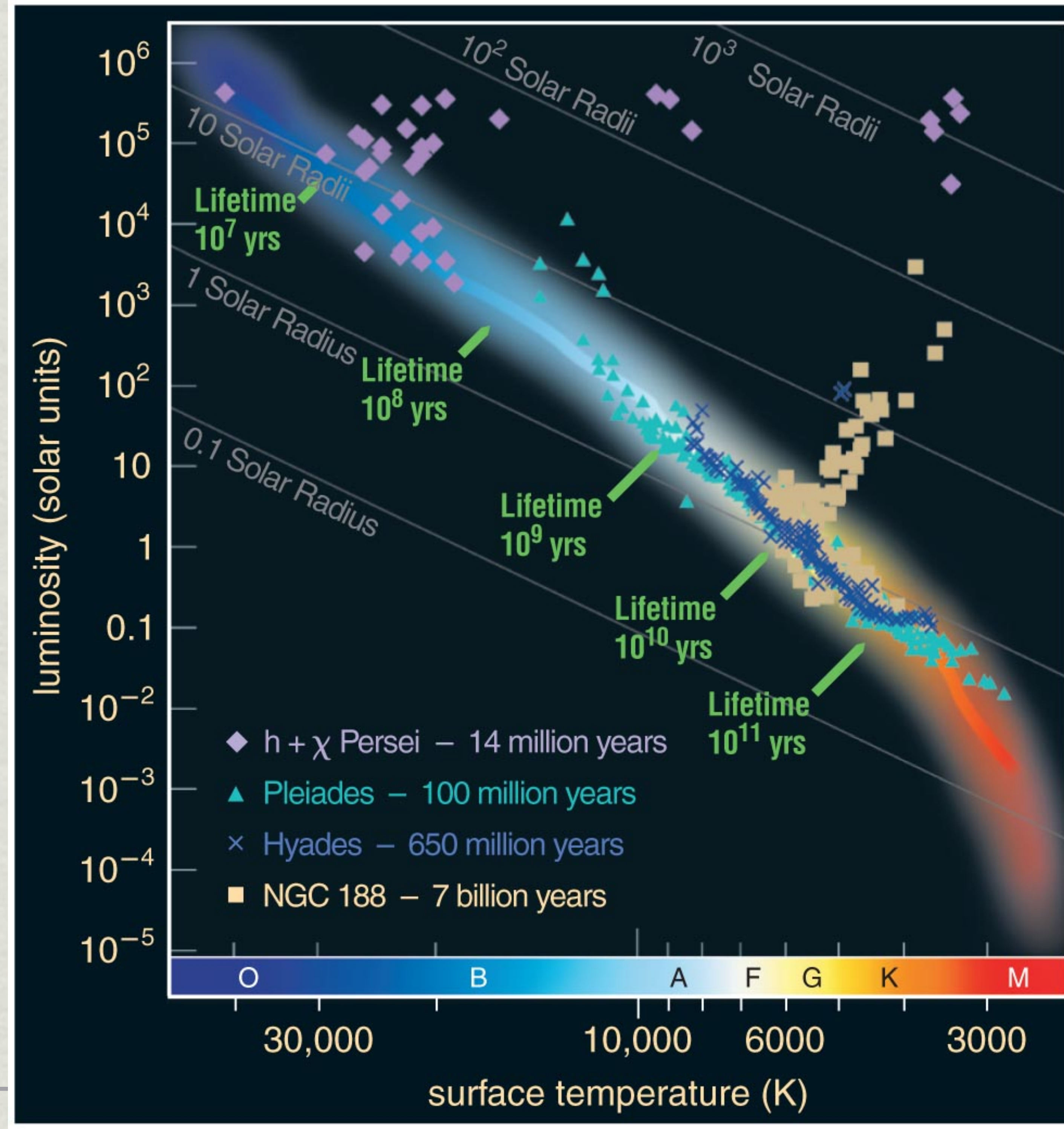
Star Clusters

Measure luminosity, temperature mass of the most massive star on the main sequence, just about to exhaust Hydrogen fuel in their core:

This is called the Main Sequence Turnoff.

What happens then?
Stars then become giants or supergiants.   Then what?

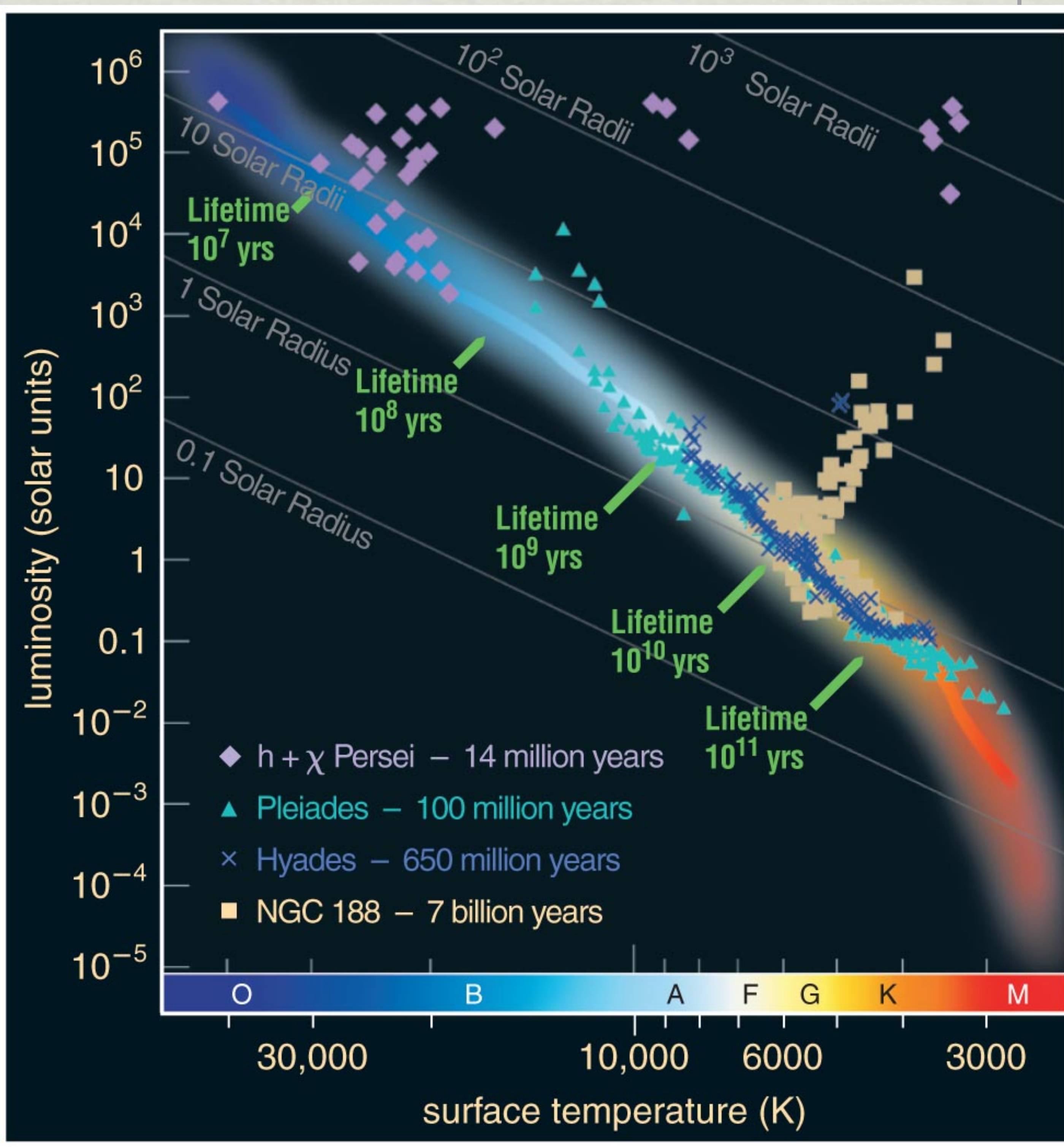
Some fade away, some end in spectacular explosions. We'll get to that....



Star Clusters

Remember, lifespan shorter for hot, massive, blue stars

Measure luminosity, temperature mass of the most massive star on the main sequence, just about to exhaust Hydrogen fuel in their core: Main Sequence Turn-Off

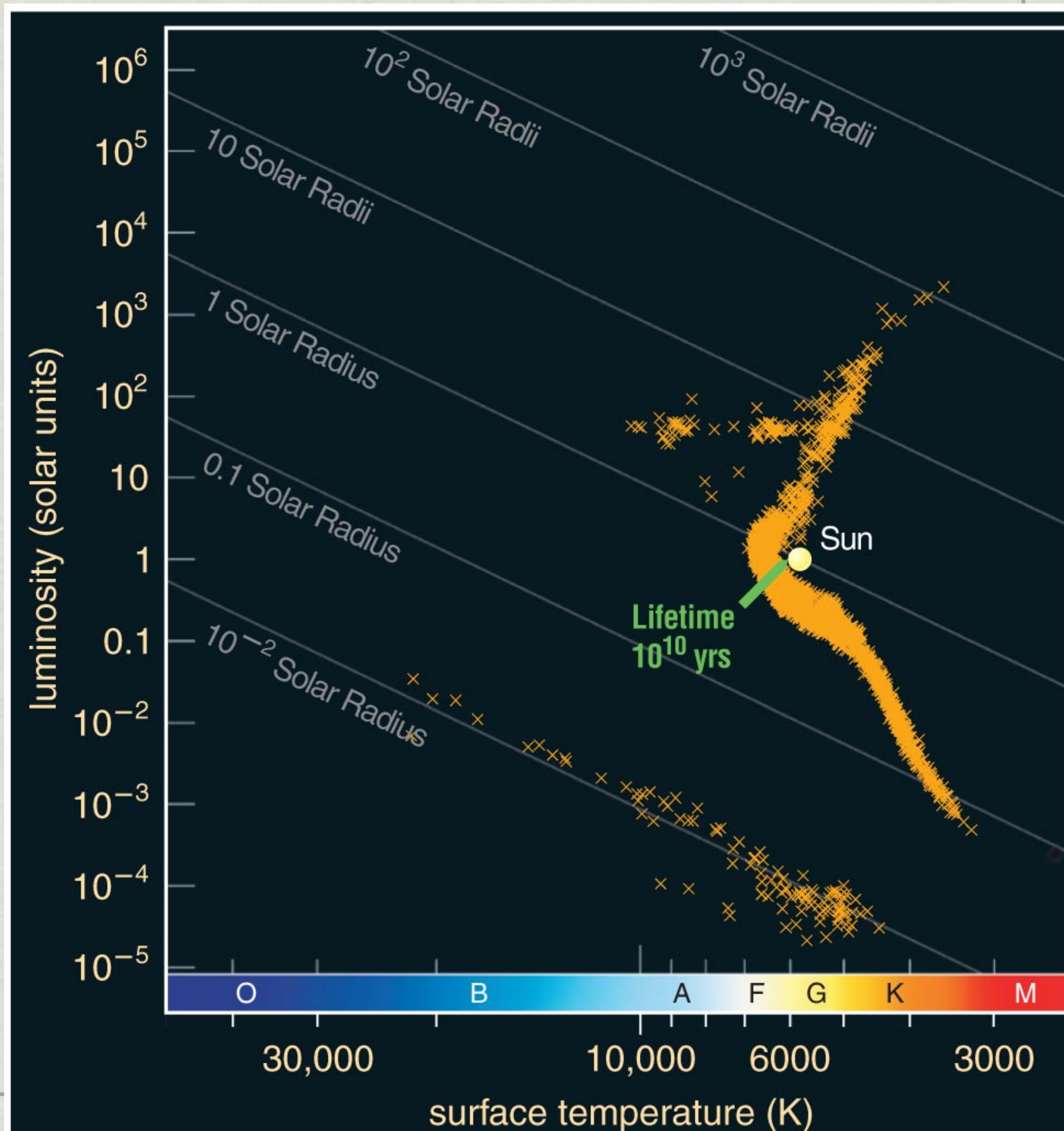


Star Clusters

Remember, lifespan shorter for hot, massive, blue stars

If the 1 M_{sun} stars are just exhausting their Hydrogen supply:

How old is the cluster?



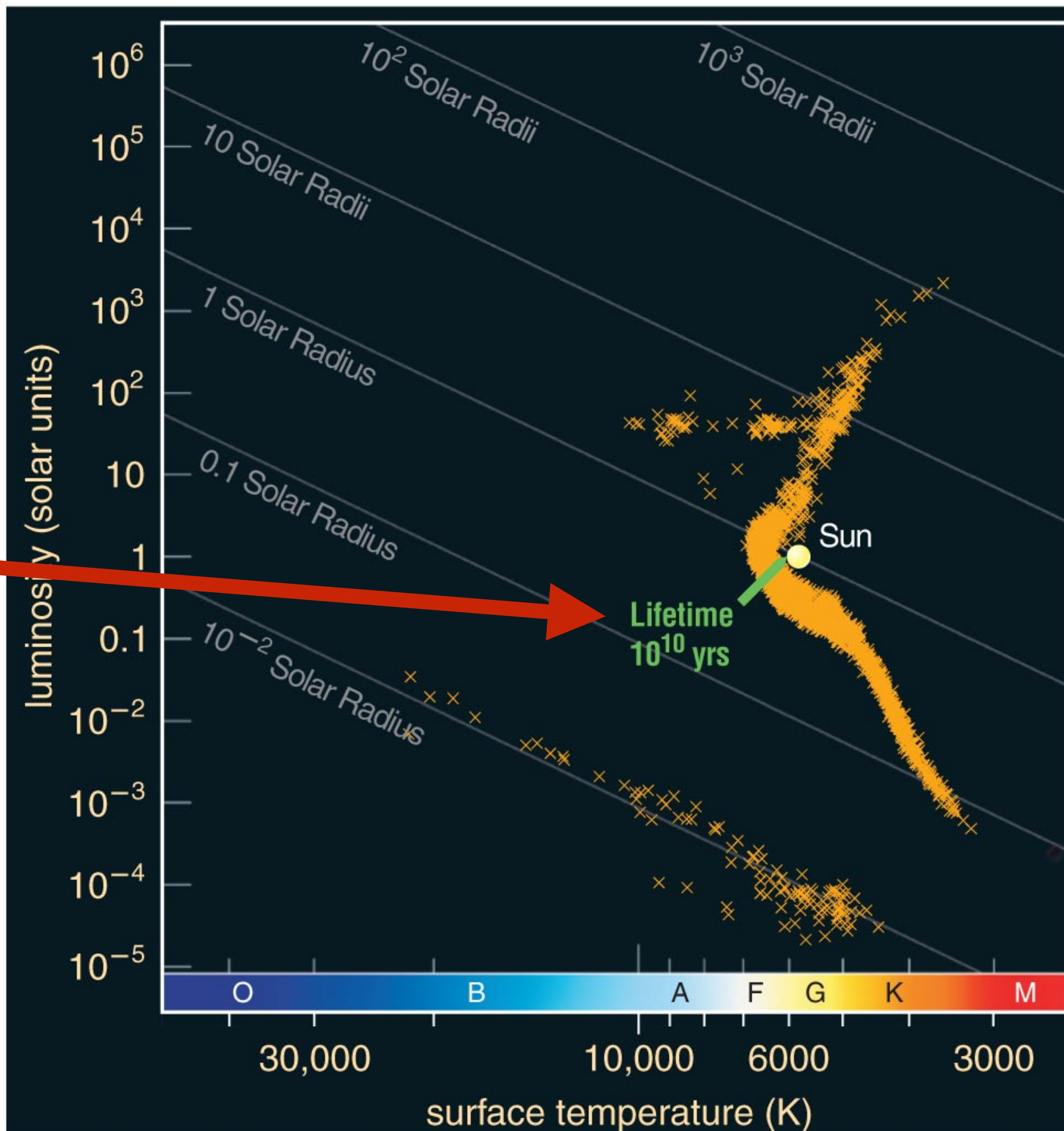
Star Clusters

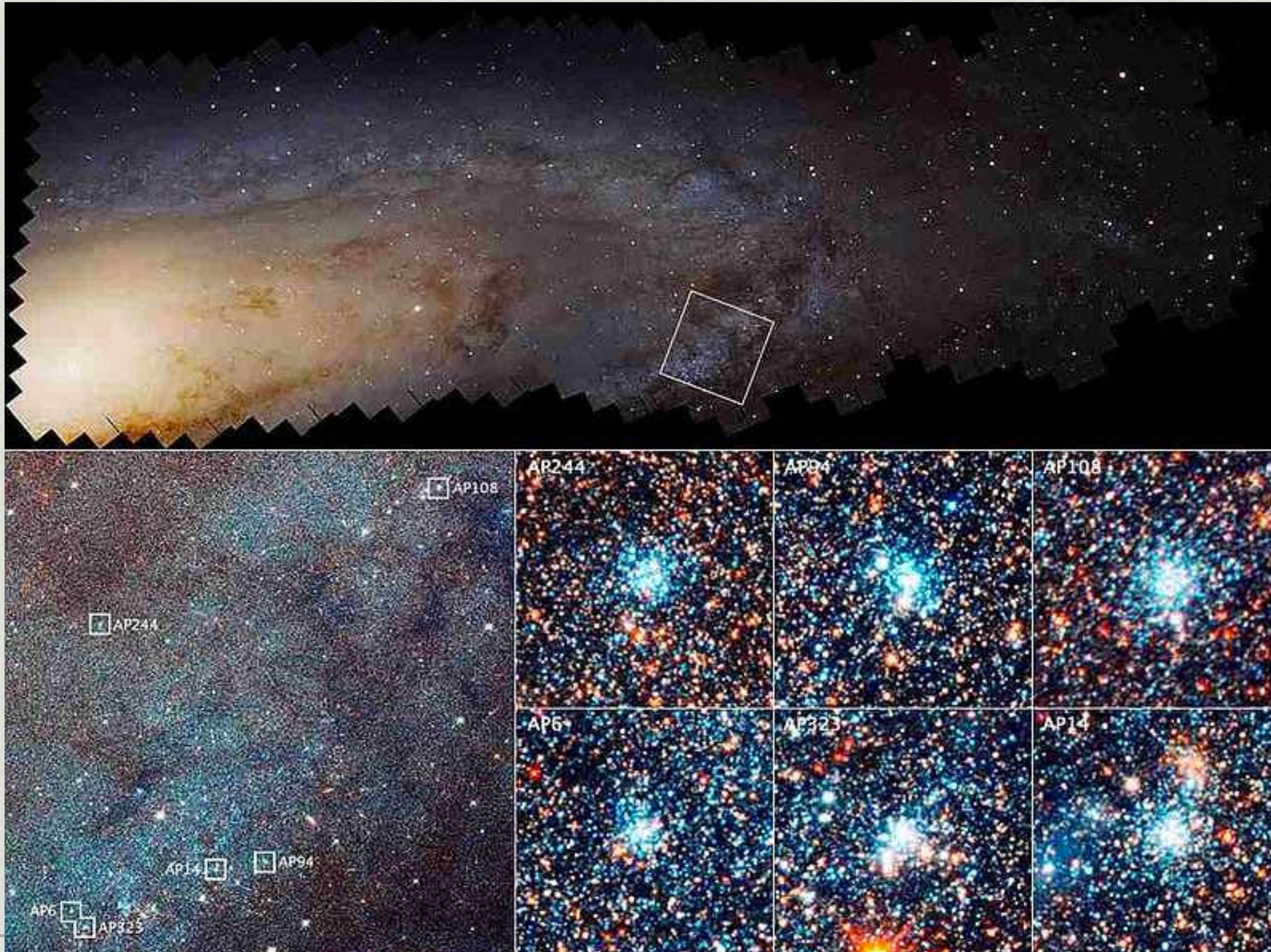
Remember, lifespan shorter for hot, massive, blue stars

If the 1 M_{sun} stars are just exhausting their Hydrogen supply:

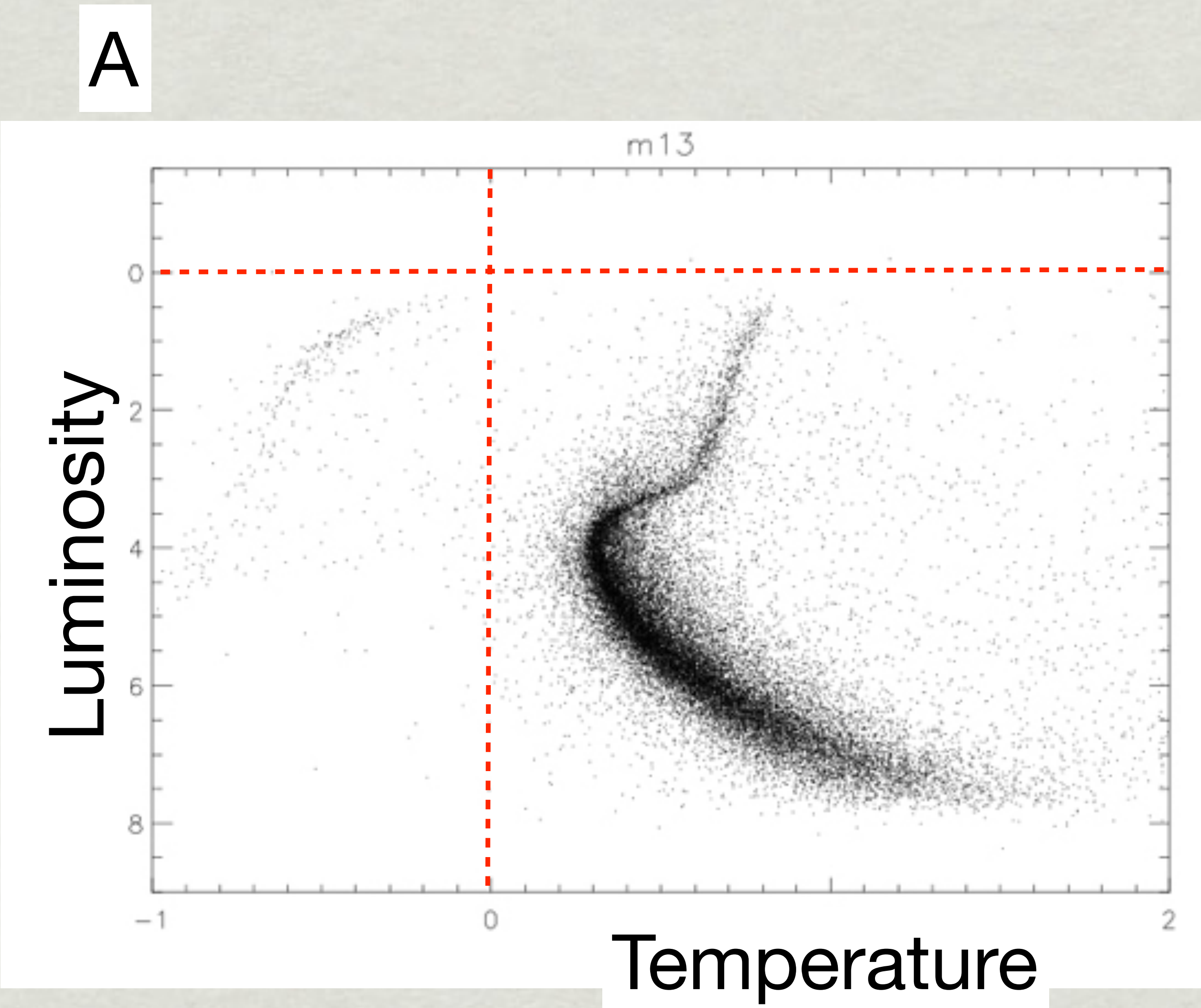
How old is the cluster?

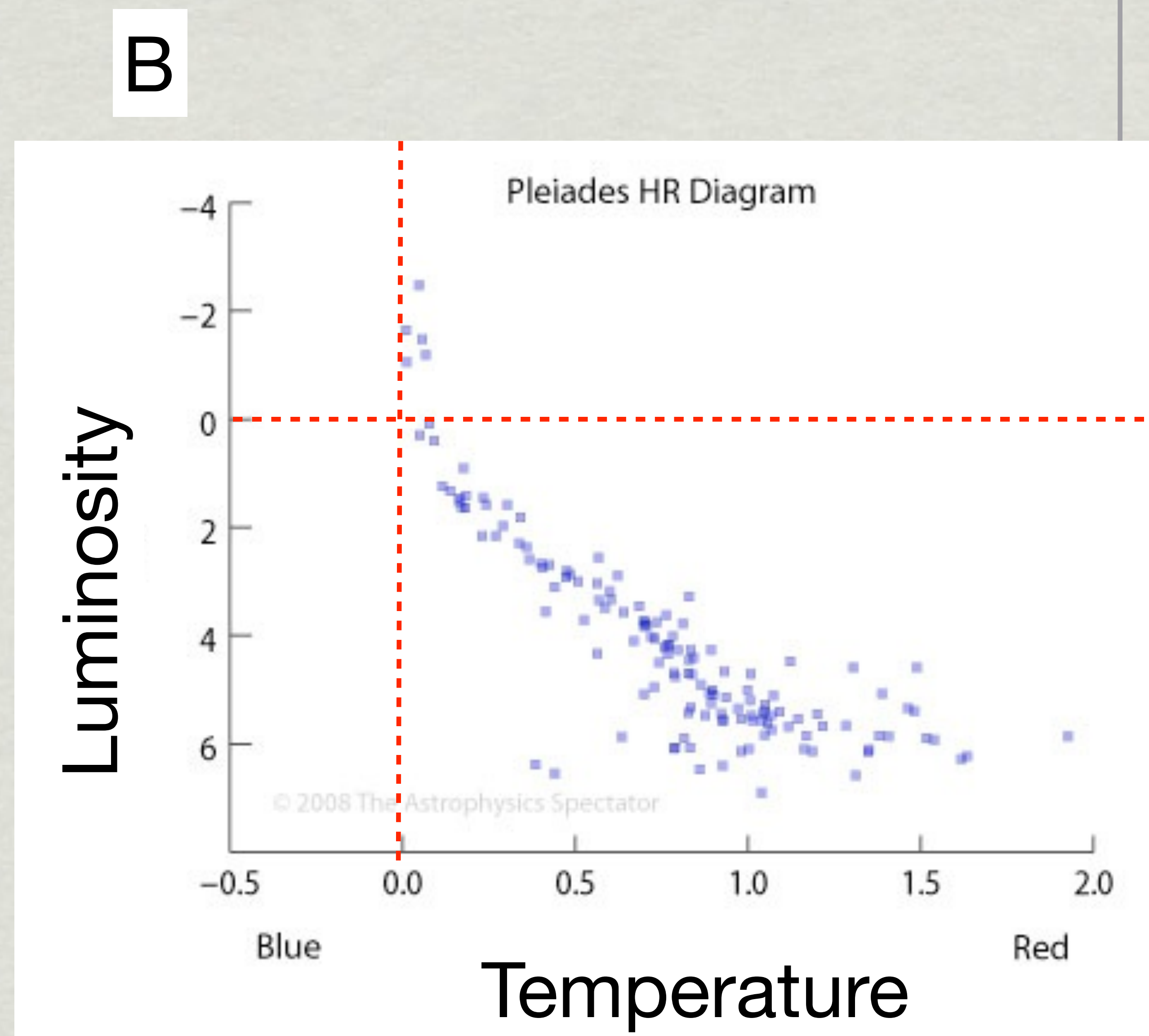
10 billion (10^{10}) years




AP108
AP244
AP14
AP94
AP6
AP323
AP244
AP94
AP108
AP6
AP323
AP14

Clicker quiz: two cluster CMDs of Temperature vs. Luminosity.
The clusters are different ages. The dotted lines cross at the same values of Temperature and luminosity in both plots.
Which is older?





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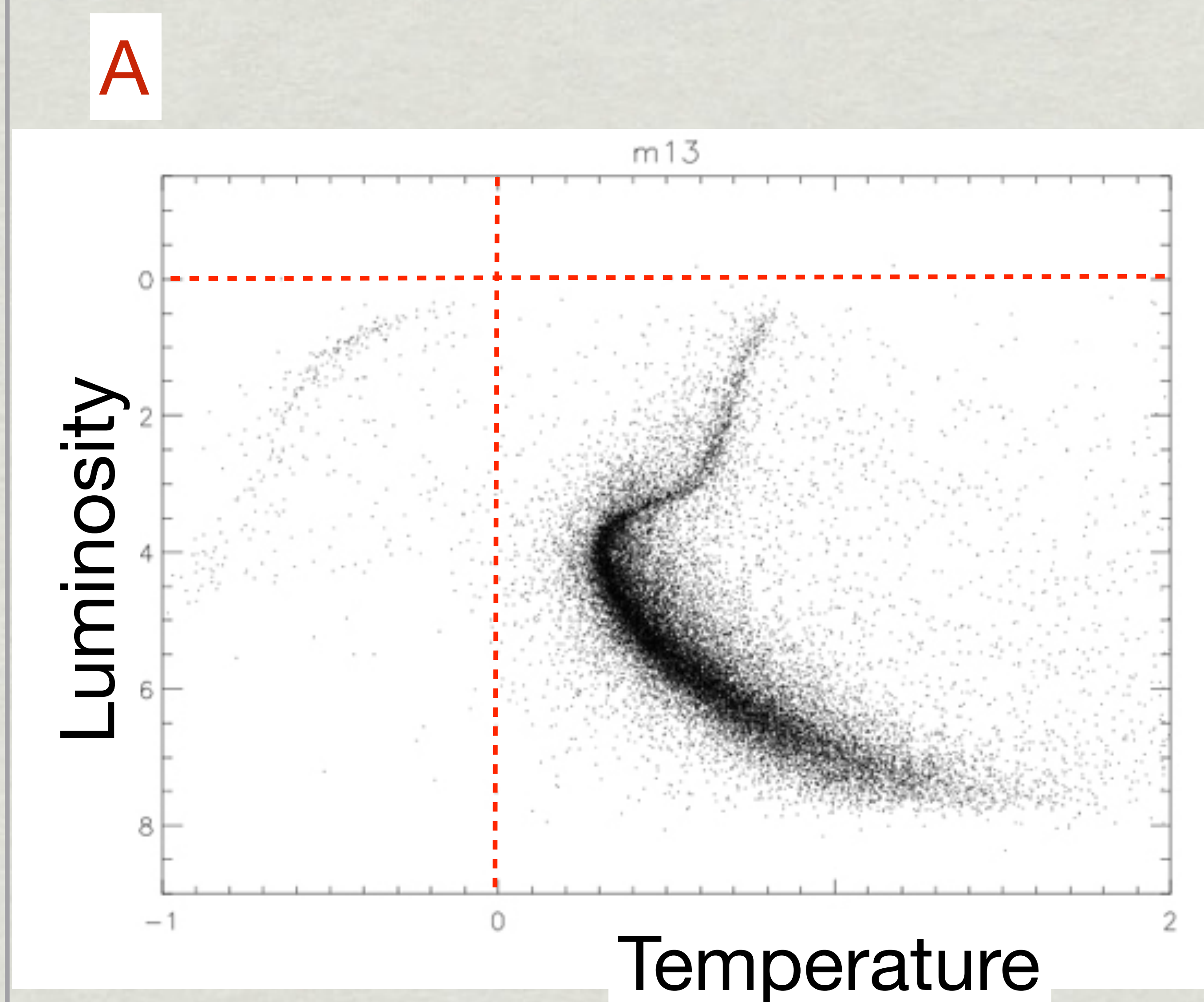
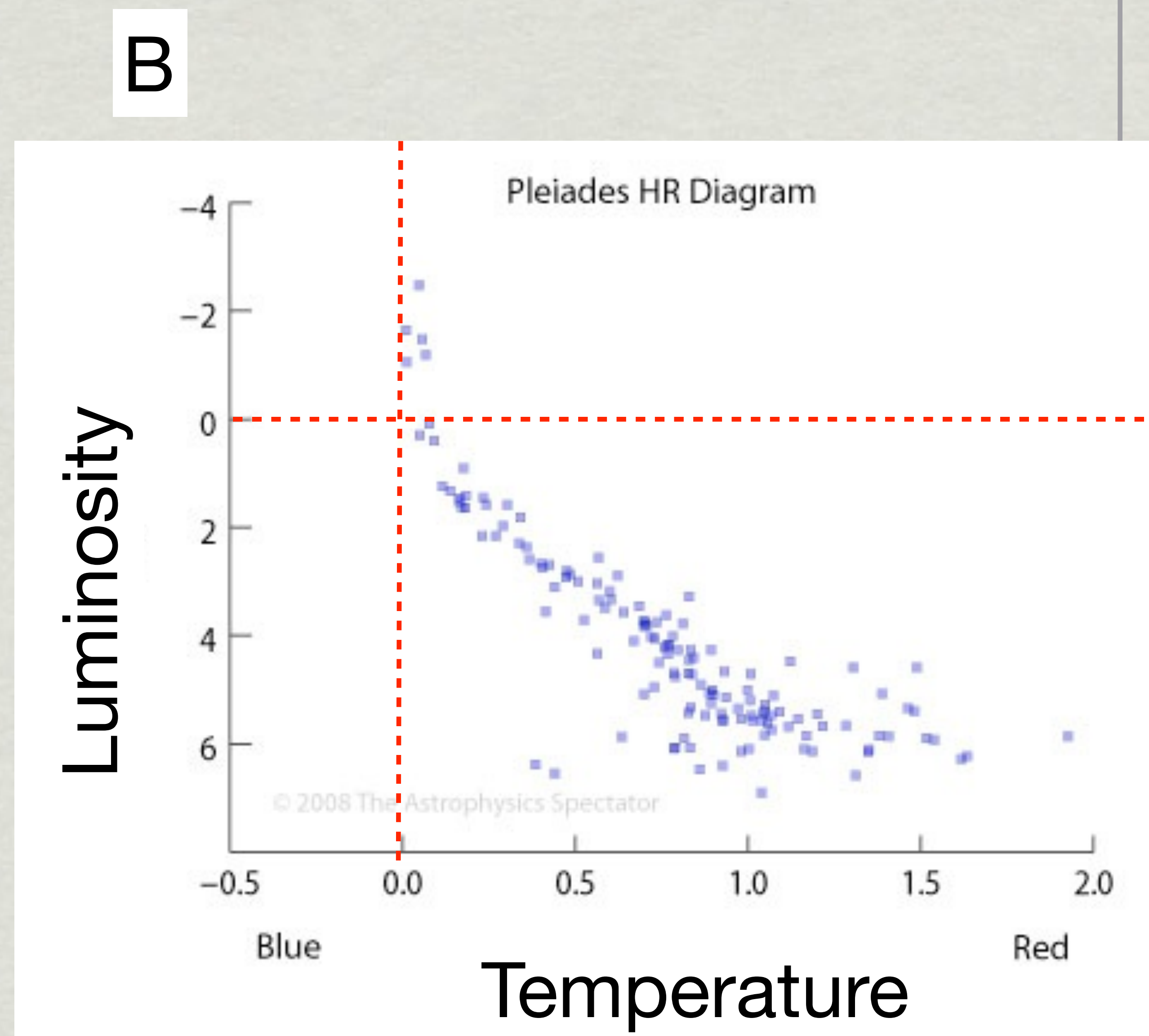
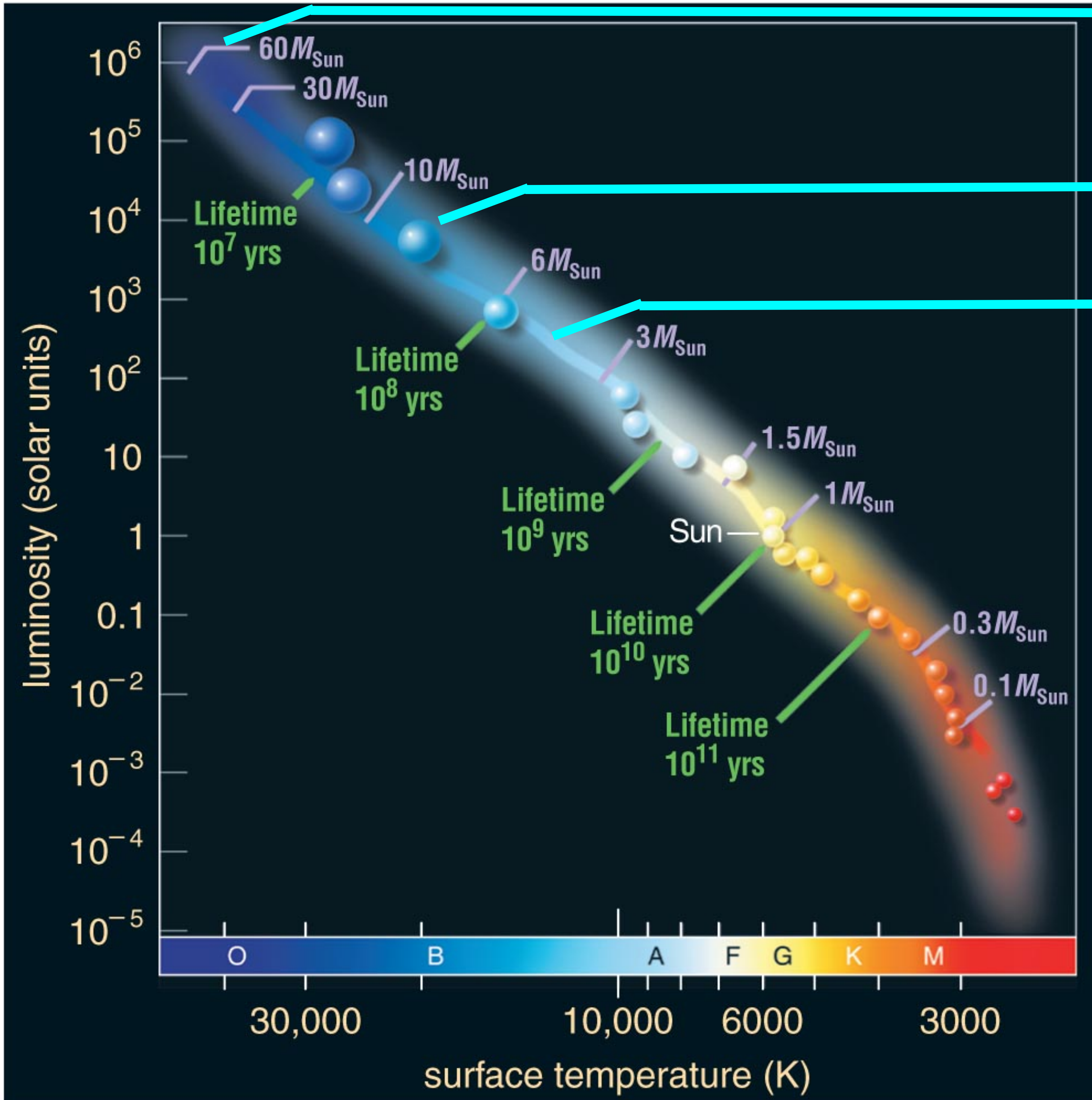




What Happens After the Main Sequence ?

Everything depends on mass.



Some definitions:

High mass stars:
$M > 8\ M_{sun}$

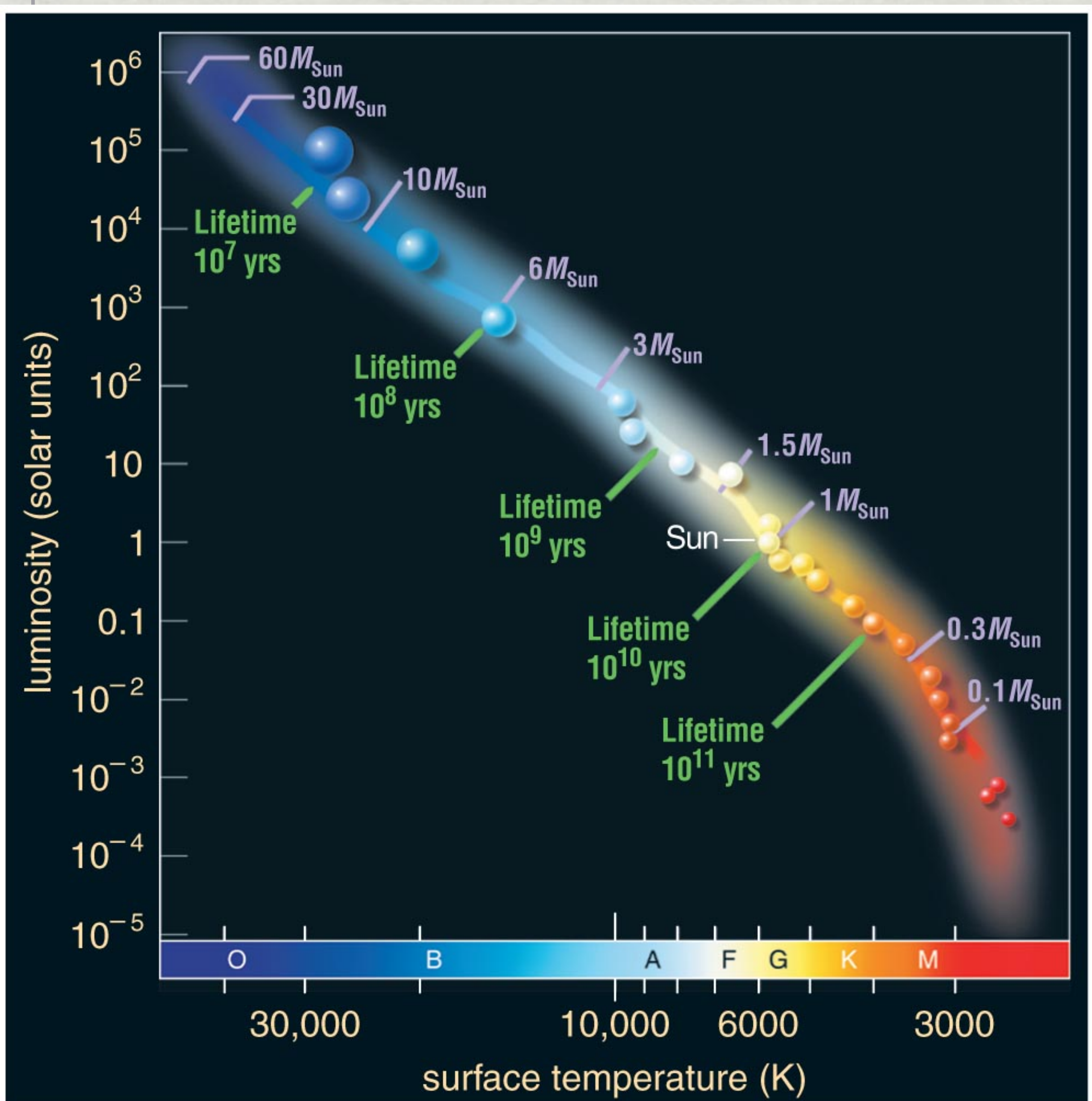
Intermediate mass:
$2 < M < 8\ M_{sun}$

These have similar evolution

Low mass stars:
$M < 2\ M_{sun}$

What Happens After the Main Sequence ?

Everything depends on mass.



Higher mass:
- Higher core temperature
- Higher fusion rate
- More luminous
- Shorter lifetime

Lower mass:
- Lower core temperature
- Lower fusion rate
- Less luminous
- Longer lifetime

Also different evolutionary rates and paths.

What Happens After the Main Sequence ?

Everything depends on mass.

Different evolutionary rates and paths:

Low mass stars:
- Slow
- Distinct nuclear fusion energy generation ("burning") phases, distinct transitions between those phases
- Slowly fade away

High mass stars:
- Rapid
- Messy: multiple burning phases at once
- Ends in a huge explosion

Low Mass Stars: Post Main Sequence Evolution

After the main sequence: Hydrogen supply in the core is used up.

Fusion ends (no fuel!)
Temperature drops → thermal pressure drops

What happens?

http://www.youtube.com/watch?feature=player_detailpage&v=X6gBTT1VJgQ

Low Mass Stars: Post Main Sequence Evolution

After the main sequence: Hydrogen supply in the core is used up.

Fusion ends (no fuel)
Temperature drops → thermal pressure drops

What happens?

Like a balloon in the freezer — pressure goes down.

Collapse!

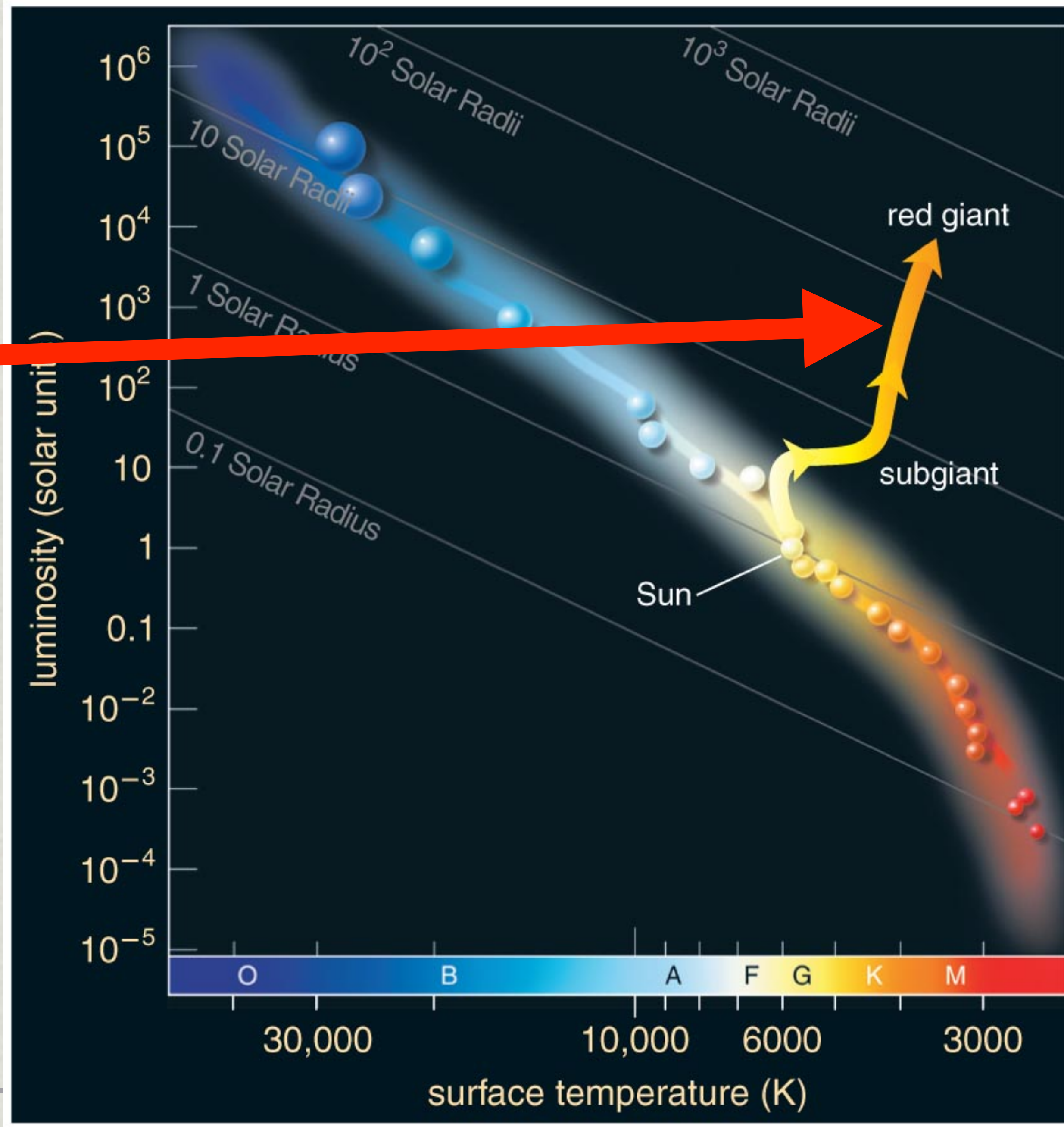
Low Mass Stars: Post Main Sequence Evolution

After the main sequence: Hydrogen supply in the core is used up.

Fusion ends (no fuel)
Temperature drops → thermal pressure drops

What happens?   Collapse!

But what we see is a new track on the H-R diagram



Why?

And what is happening to the star?

Low Mass Stars: Post Main Sequence Evolution

After the main sequence: Hydrogen supply in the core is used up.

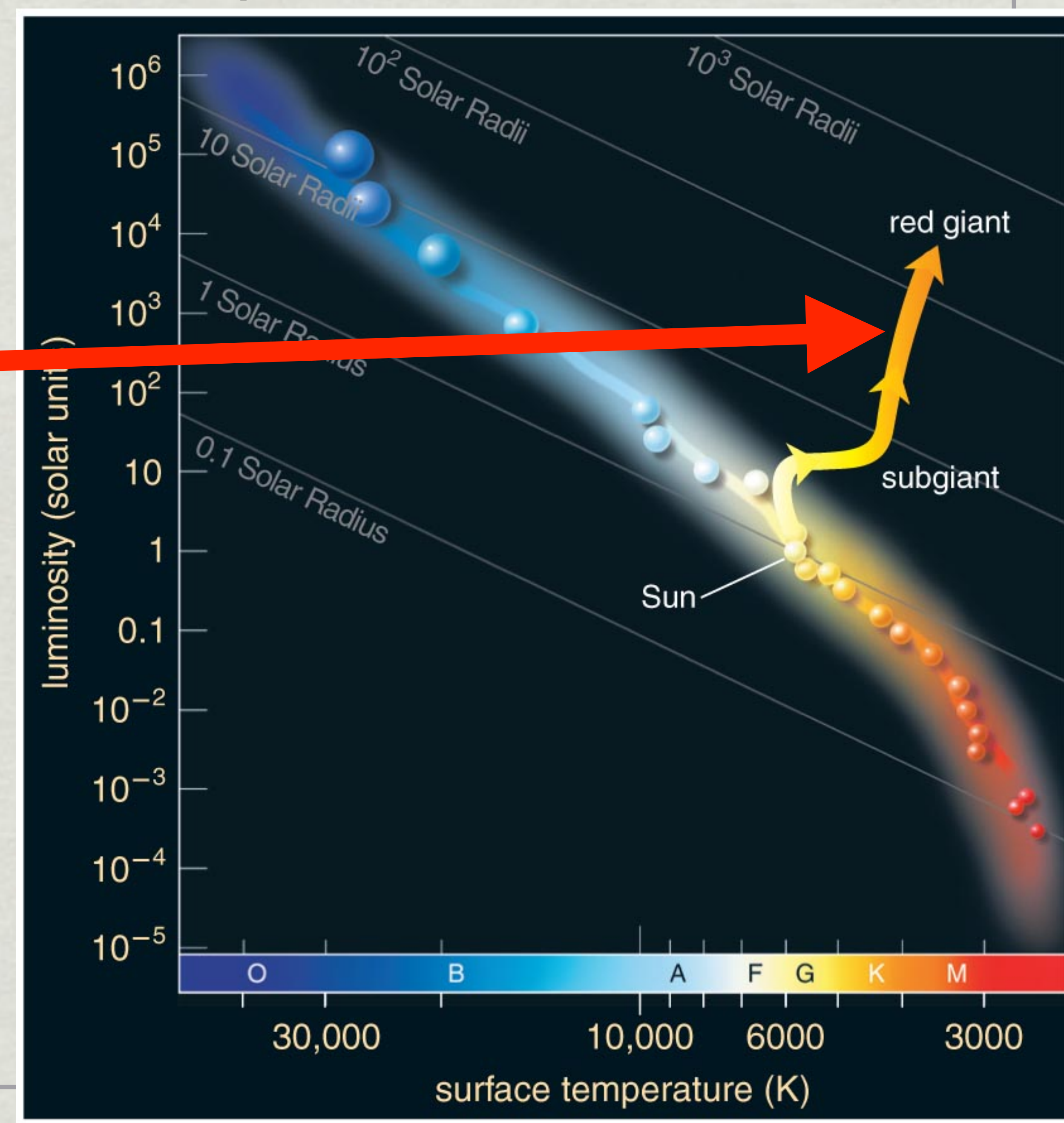
Fusion ends (no fuel)
Temperature drops → thermal pressure drops

What happens?   Collapse!

But what we see is a new track on the H-R diagram

Why?

What stops the collapse?

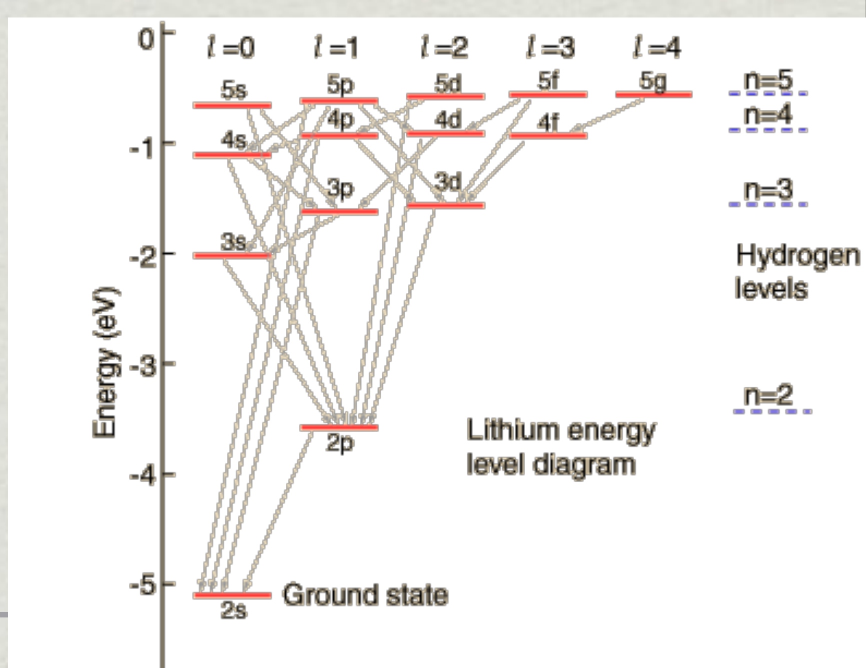


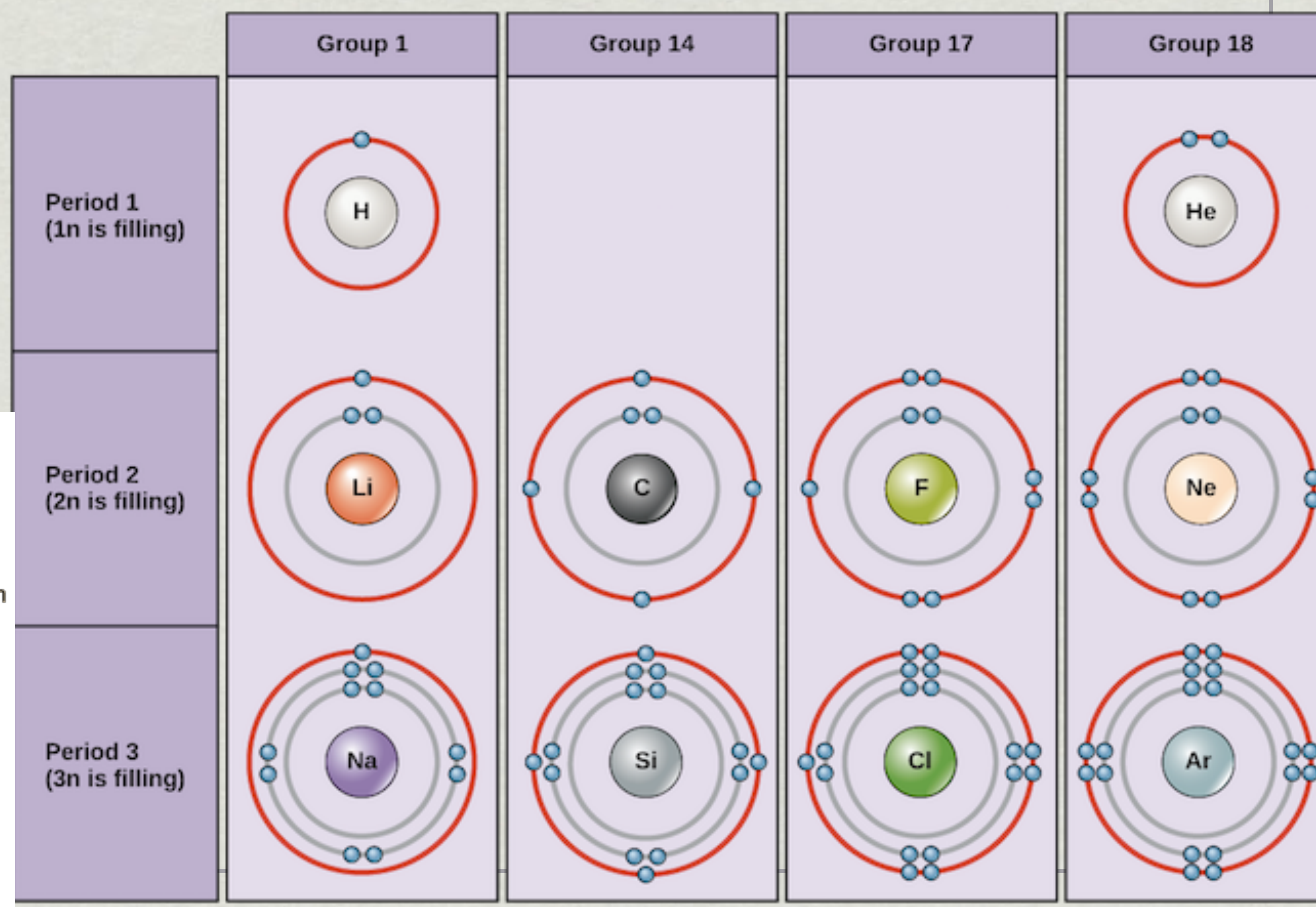
Degeneracy Pressure

The density of matter is limited by two fundamental laws of quantum mechanics.

1) Particles can’t be in the same configuration (same energy, velocity and “spin”) and the same place simultaneously

This is why electrons fill up energy levels in an atom. They can’t all be in the same level.





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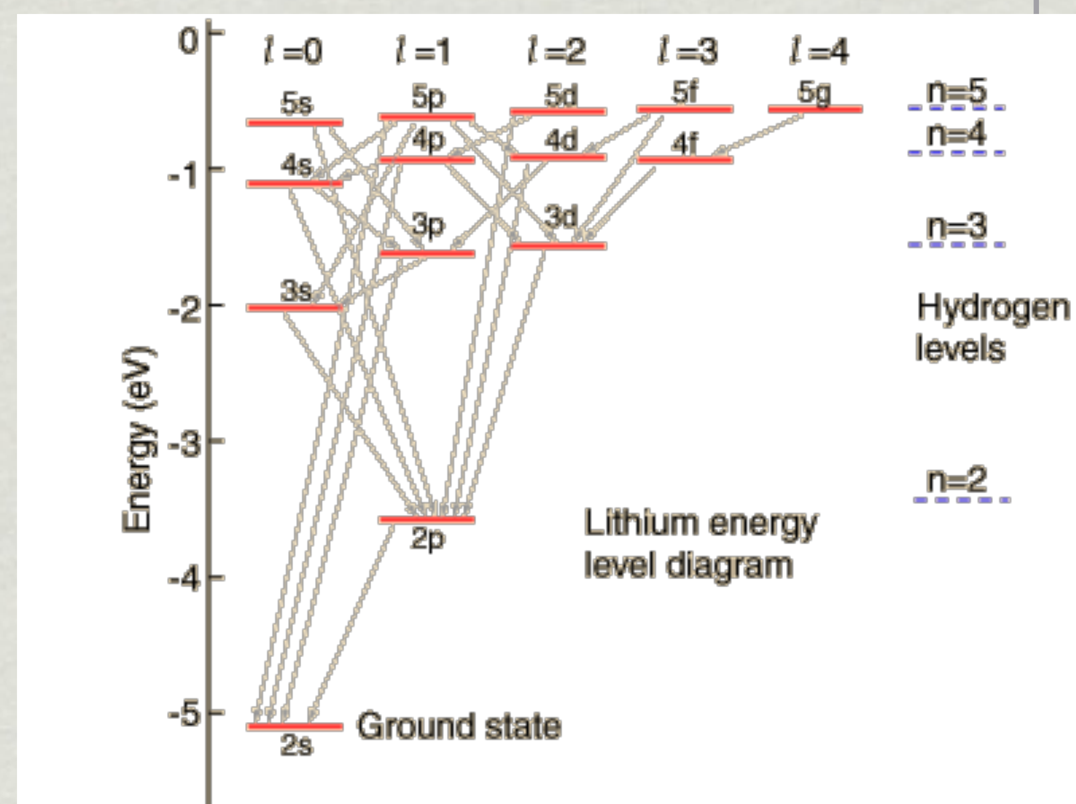
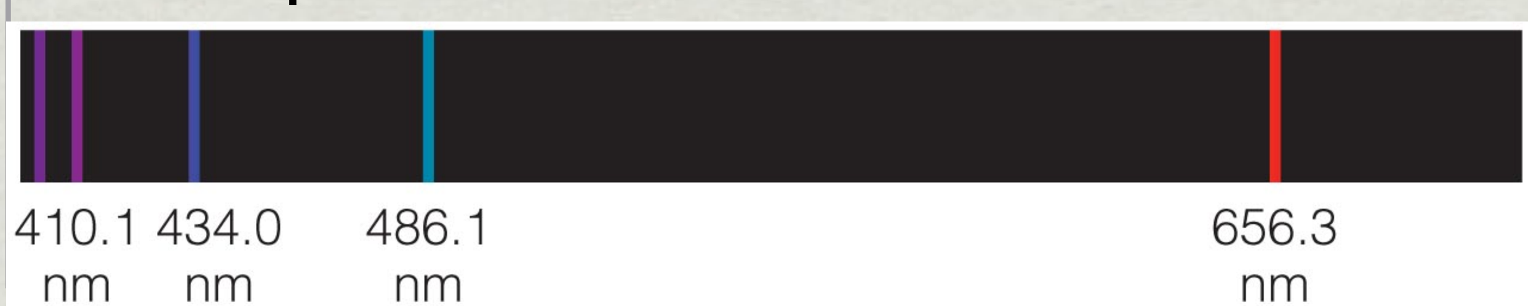


Electrons in many different energy levels give atoms complex emission line spectra



Degeneracy Pressure

The density of matter is limited by two fundamental laws of quantum mechanics.

2) Heisenberg Uncertainty Principle: for a system of particles (gas molecules in a balloon, atomes in a star, etc.)

Uncertainty (spread) in momentum × Uncertainty (spread) in position > Planck's constant

$\Delta p \times \Delta x > h$ (same h as photon energy equation)

Can't squish too many particles into too a small space Δx

Remember: momentum p = mass x velocity

The closer you try to squish the particles in space (Δx) the bigger their range in p (mass and/or velocity, Δv)

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A) it increases B) it decreases C) hunh?

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(same h as photon energy equation)

Can't squish too many particles into too a small space Δx

Remember: momentum p = mass x velocity

The closer you try to squish the particles in space (Δx) the bigger their range in p (mass and/or velocity)

If you squish many particles into a very small space, their velocity goes up! (if their masses stay the same, which is usually the case)

Degeneracy Pressure

The density of matter is limited by two fundamental laws of quantum mechanics.

2) Heisenberg Uncertainty Principle: for a system of particles (gas molecules in a balloon, atomes in a star, etc.)

Uncertainty (spread) in momentum × Uncertainty (spread) in position > Planck's constant

$$\Delta p \times \Delta x > h$$

(same h as photon energy equation)

Can't squish too many particles into too a small space Δx

The closer you try to squish the particles in space (Δx) the bigger their range in p (mass and/or velocity).

Remember: Energy of a photon = $\frac{hc}{\lambda}$

h = Planck's constant
6.626×10^{-24} Joule sec

h is ***tiny***, so particles have to be ***really squished*** for this to matter.

Like 10^{30} kg pushing down on them, like in the core of a star

Degeneracy Pressure

2) Heisenberg Uncertainty Principle:

Uncertainty (spread) in momentum × Uncertainty (spread) in position > Planck's constant

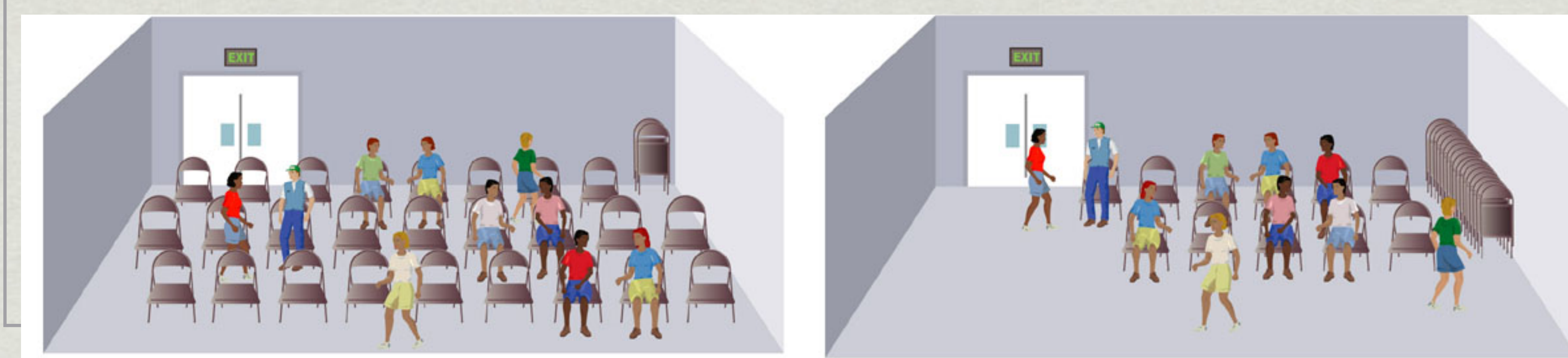
$\Delta p \times \Delta x > h$ Can't squish too many particles into too a small space.

Remember: momentum p = mass x velocity

As star collapses the density increases, available volume Δx decreases.

Particle mass stays the same, so velocity (random motions) increase.

Like not having enough chairs at a party: people have to move around, can't sit still



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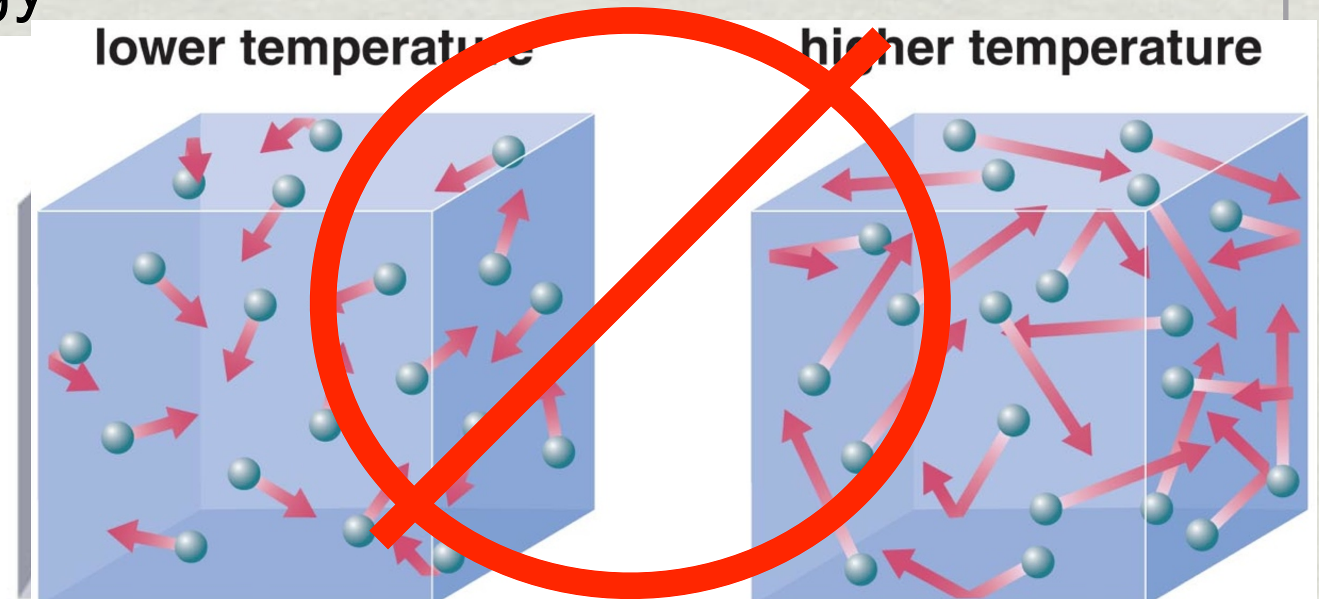
Random motions can create a pressure force, but the motion is caused by the uncertainty principle, not thermal energy



Degeneracy Pressure

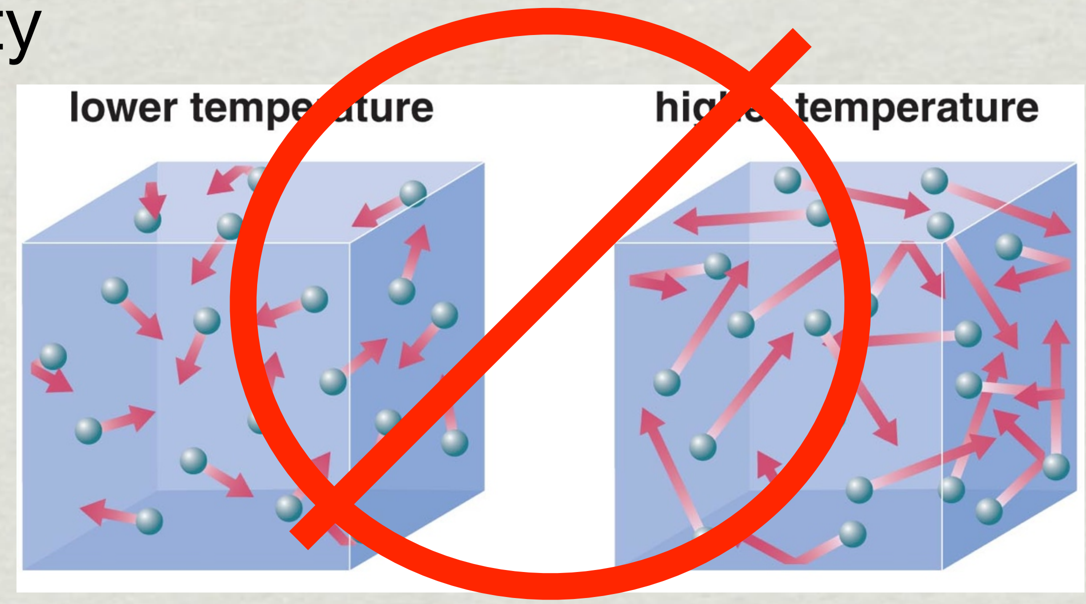
2) Heisenberg Uncertainty Principle:
Uncertainty (spread) in momentum × Uncertainty (spread) in position > Planck's constant

$$\Delta p \times \Delta x > h$$

As Δx goes down, volume decreases: smaller space available for each particle

Δp must go up: particles must spread out over more values of momentum
→ particles keep same mass, gain velocity
→ pressure goes up

This pressure does not depend on temperature!



Remember the perfect gas law:
thermal pressure = (density of particles) × (constant) × T

This pressure from the Uncertainty Principle is ***not*** like the ideal gas law pressure! It doesn't depend on temperature!