Announcements

- Please fill out an on-line course evaluation
- Final Exam: Wednesday, 3/22, 7:30pm
  - 3 hours
  - same format, rules as midterm: multiple choice with formula sheet, closed book and notes, bring a #2 pencil and a non-internet-enabled calculator
- Cumulative: study the midterm material, too
- Review sessions:
  - Marie Friday 3/17, 4-5pm NatSci2 Annex 101
  - Plato Sunday, 3/20, 3-4pm, NatSci2 Annex 101

Final Exam Review

- Review the midterm. There will be material from the first half of the class on the final. The best way to study for that is to review the midterm.
- Review the homework and reading assignments
- Go to the TA review sessions
- Formula sheet will be available and posted on the course web pages.

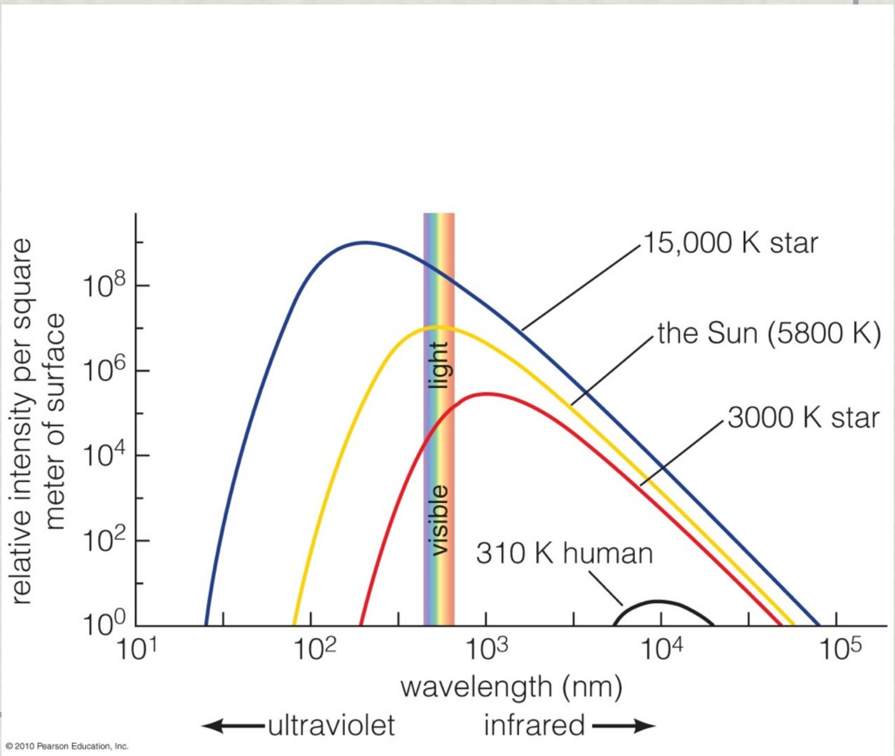
Properties of Thermal Radiation

Stefan - Boltzmann Law: Energy output per second per meter^2 on the surface of an object = σT^4

Luminosity = total energy flow into or out of an object
Units: Energy/sec or Power, Joules/s or Watts

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

Universal constant:
$\sigma = 5.7 \times 10^{-8}$ J/(s m^2 K^4)



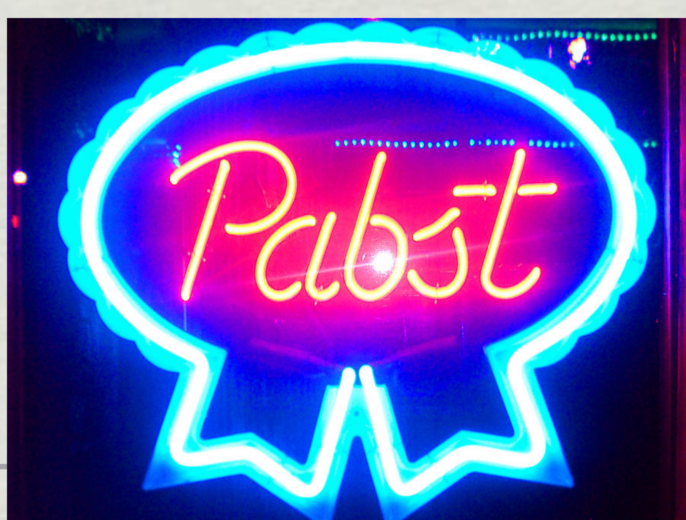
Kirchoff's Laws

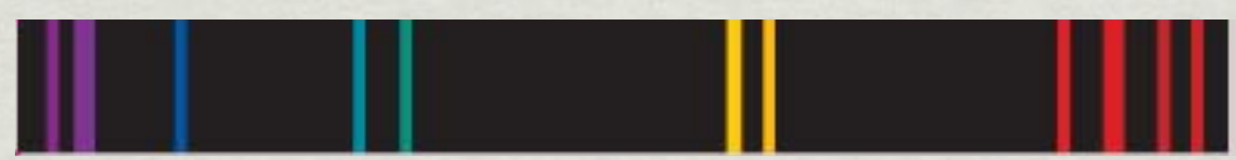
1) Dense, opaque objects: continuous spectrum, thermal emission

Wavelength

2) Transparent, low-density matter:

If too hot to re-absorb photons: emission line spectrum





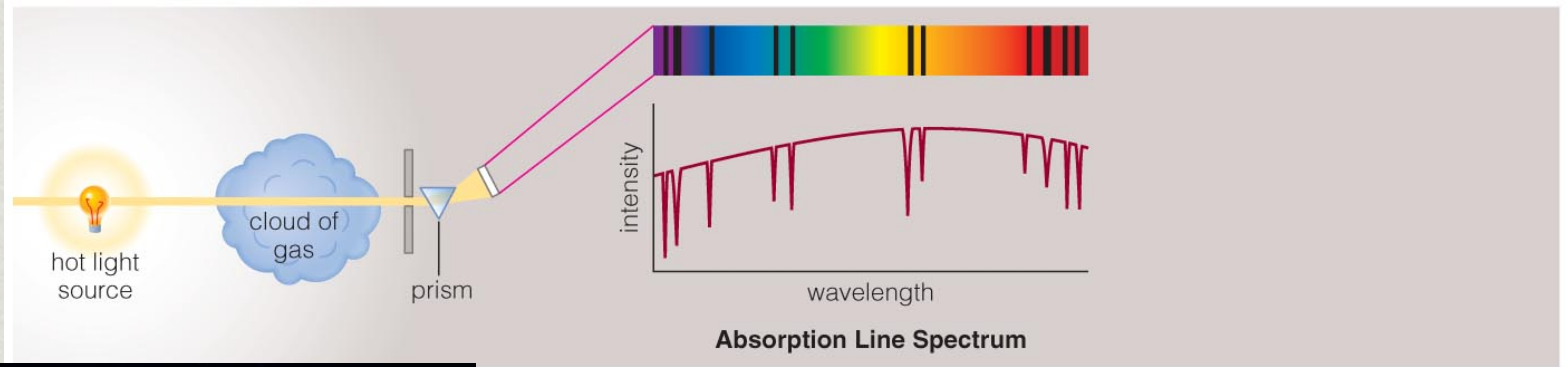
Wavelength

Kirchoff's Laws

3) Thermal emission traveling through some other matter?

Transparent, cool matter: atoms can re-absorb the light

Observe: an absorption line spectrum



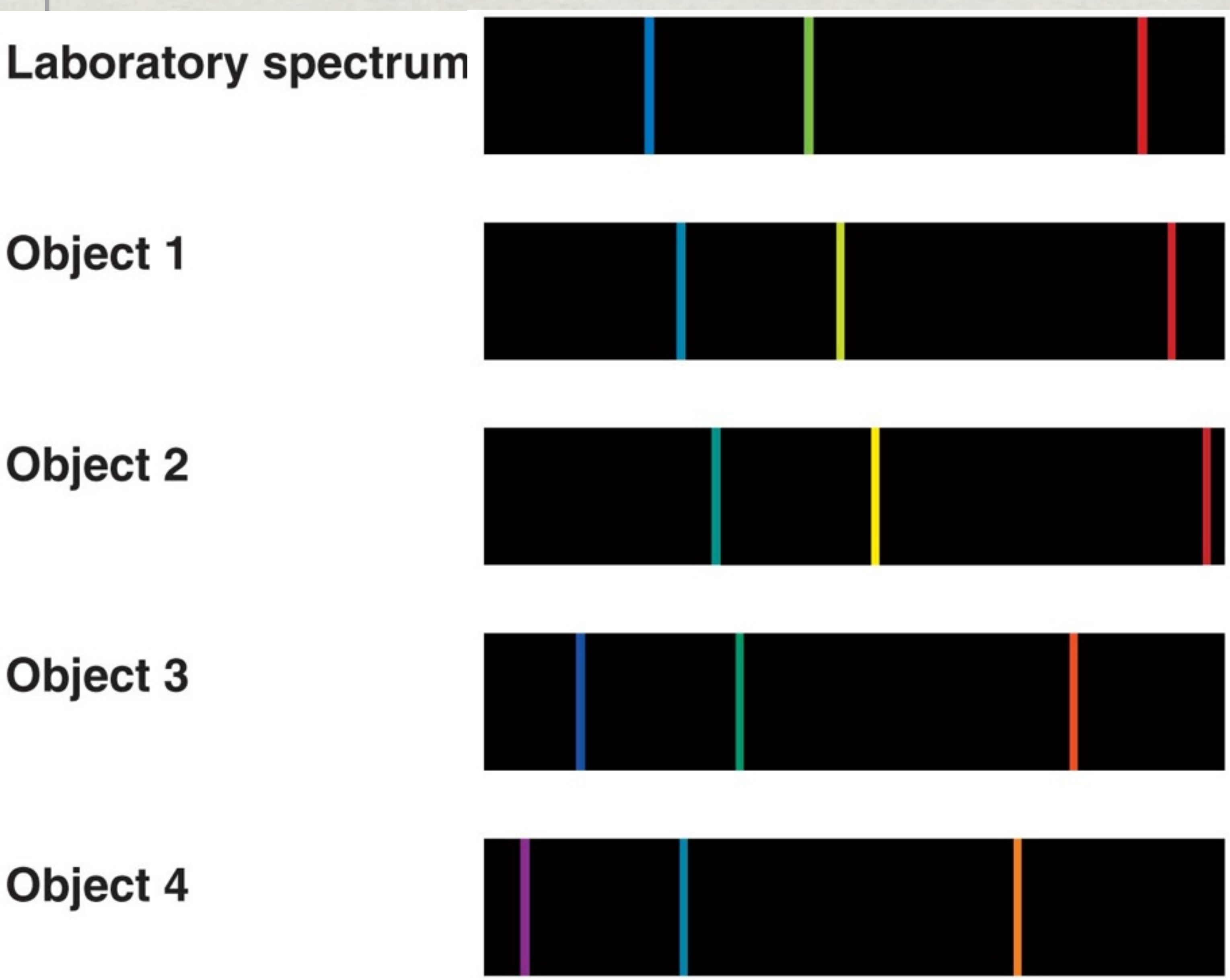
This is often the spectrum we observe from stars and galaxies (which are made of stars)

Exception: hot gas in galaxies, where stars are born or black holes live.

Doppler Shift

$$\frac{V_{radial}}{c} = \frac{\Delta\lambda}{\lambda_{rest}} = \frac{\lambda_{shift} - \lambda_{rest}}{\lambda_{rest}}$$

We can measure the velocity (direction and speed) of a light source from its Doppler Shift.



Rest

Red shift, moving away

Larger red shift, moving away faster

Blue shift, moving toward you

Larger blue shift, moving toward you faster

Recap: Nucleosynthesis

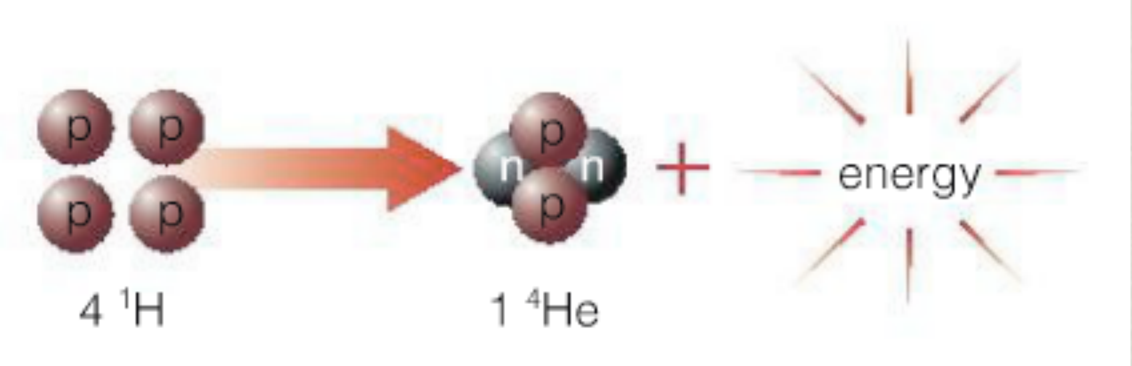
How do you make energy out of 2 x 10^{30} kg of Hydrogen?

One Helium atom is ***less*** massive than 4 Hydrogen atoms?

4 H atoms = 4 protons: 6.693 x 10^{-27} kg
1 He atom = 2 protons + 2 neutrons: 6.645 x 10^{-27} kg (less massive! by 0.7%)

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

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

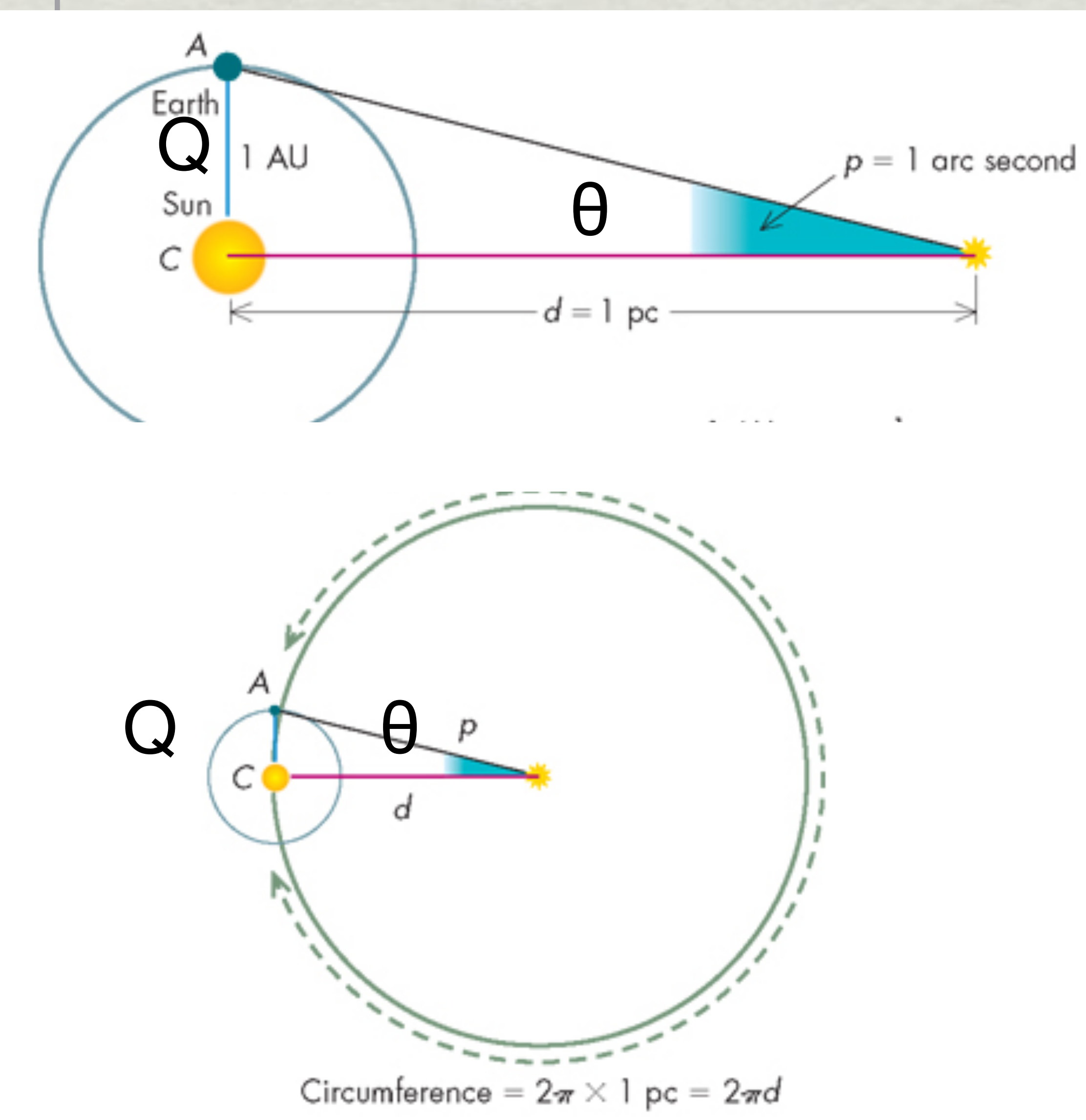


Mass and energy are the same thing, and transform back and forth using this equation.

Fusing Hydrogen into Helium must release energy

Measuring Distance

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



Units for angles:

1 degree = 60 arcminutes = 3600 arcseconds

In symbols: 1° = 60' = 3600"

1' = 60"

$$d = \frac{Q}{p''} \times 206{,}265$$

$$d = \frac{(1\ \text{AU}) \times 206{,}265}{p''}$$

Define a REALLY convenient unit:

1 Parsec = 206265 AU

= 3×10^{16} m

$$\Rightarrow \quad d\ (\text{parsec}) = \frac{1}{p\ (\text{arceconds})}$$

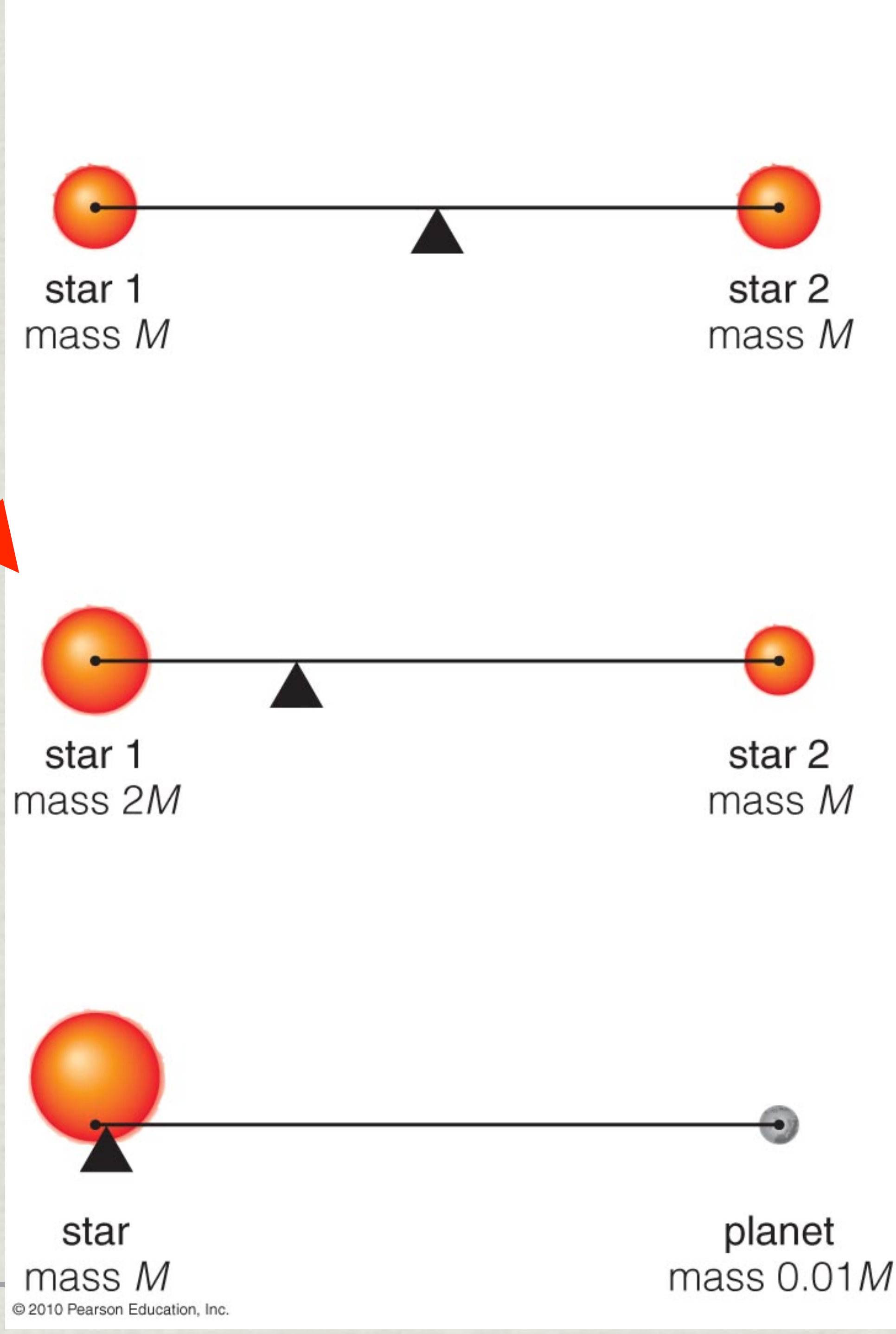
d = distance in parsec, p = parallax angle in arcseconds

Measuring Masses of Stars

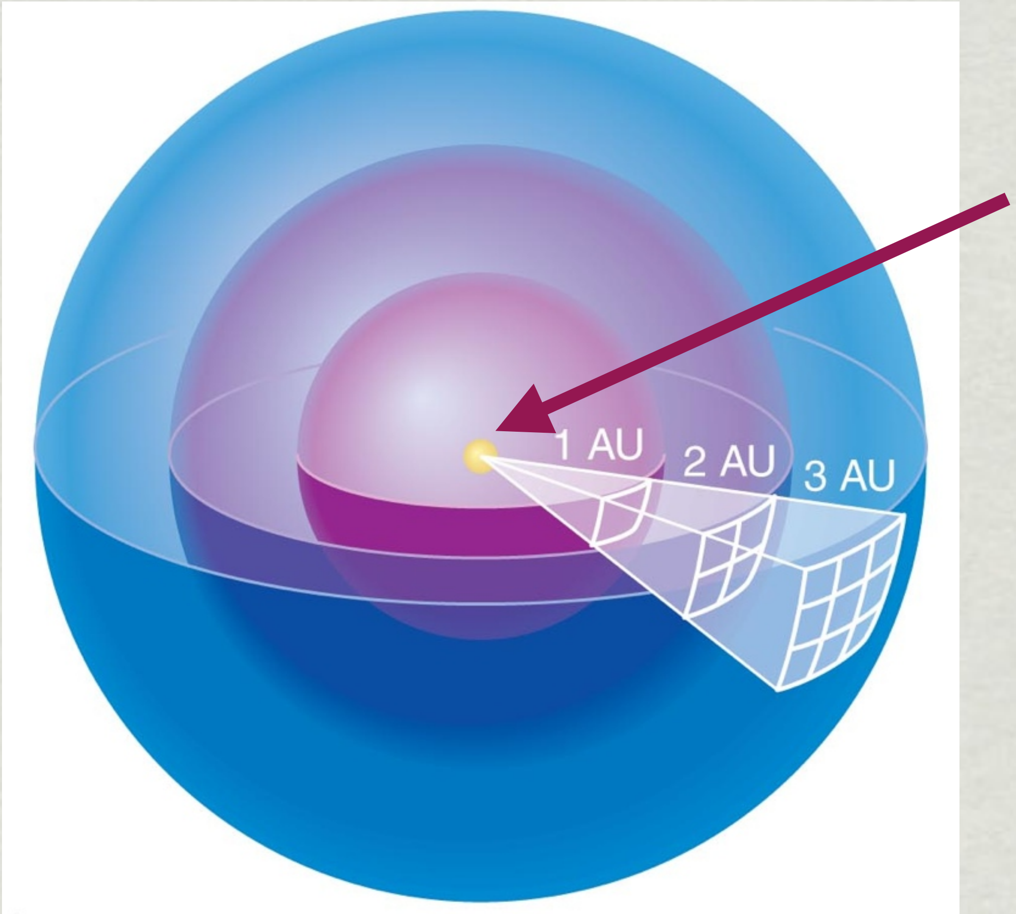
What if M_1, M_2 are both large, like binary stars?
Objects always orbit the Center of Mass.
CM stays still. M_1 and M_2 orbit around it.

Use: $$P^2 = \frac{4\pi^2}{G(M_1+M_2)} A^3$$

Measure P, A, solve for M_1+M_2



Measuring Luminosity



Luminosity: total amount of energy put out by an object. Units: Joules/sec

Always the same, a property of an object (table, me, star, ...)

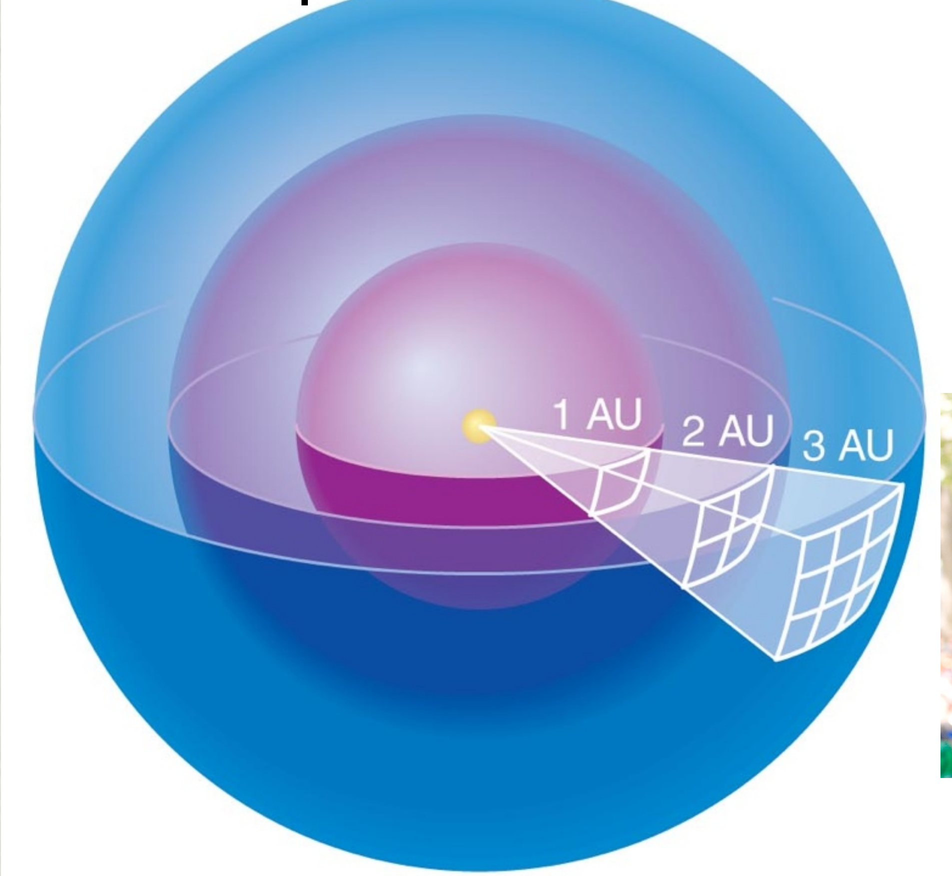
Depends on temperature and surface area of the emitting object

Stefan - Boltzmann Law:

Luminosity = Total surface area × σT^4

Measuring Luminosity

area of sphere: $4\pi d^2$



What can we measure?

Light passing through a patch on the sphere

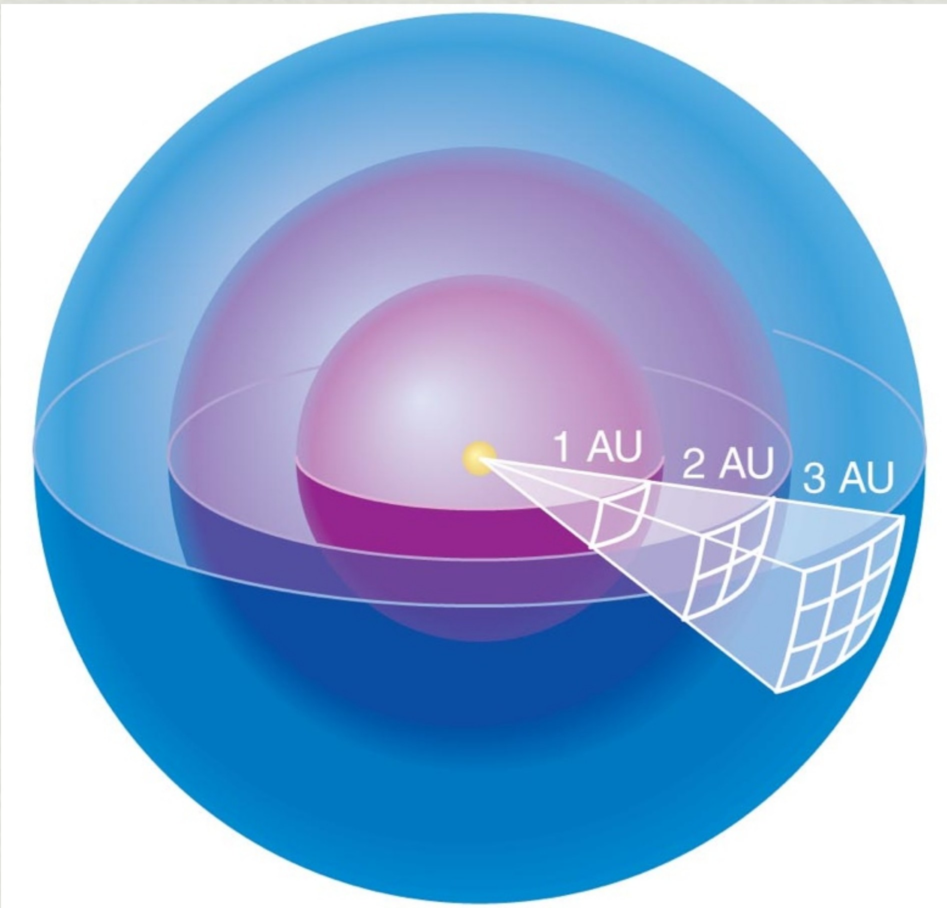
Apparent brightness of an object like a star, etc. $= \frac{\text{Luminosity}}{\text{Surface Area}} = \frac{L}{4\pi d^2}$

Apparent brightness depends on distance to the object.

Objects that are farther away appear fainter: we collect less energy/sec in our eyes,camera, etc. because our eyes,camera are the same size no matter how far away the star is

Luminosity is always the same. It's a property of the star.

Measuring Luminosity



If we can measure the apparent brightness B and the distance to the star d, we can measure the Luminosity of the star L

Measure apparent brightness in some patch of area on the sphere: your eye, a telescope, a camera, ...

Apparent brightness $B = \frac{L}{4\pi d^2}$ rearrange: $\rightarrow L = B \times (4\pi d^2)$

Measuring the Stars

- Measure Luminosity of a star: total energy output per second, by measuring the apparent brightness and distance

$$\text{Apparent Brightness} = \frac{L}{4\pi d^2}$$

- Temperature: from Wein's Law (wavelength of max photon emission)
- Chemical composition: matching chemical fingerprints of different atoms to lines in the spectrum
- Mass: period and distance separation of binary star orbits
- Distance: parallax
- Size: from Luminosity and Temperature, using Stefan-Boltzmann law
  Luminosity = Total surface area × σT^4

Gravitational Equilibrium in the Sun

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

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

Many molecules (high density
many collisions = high pressure

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

Perfect Gas Law:
Pressure = k × density x temperature
k = universal constant

"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!

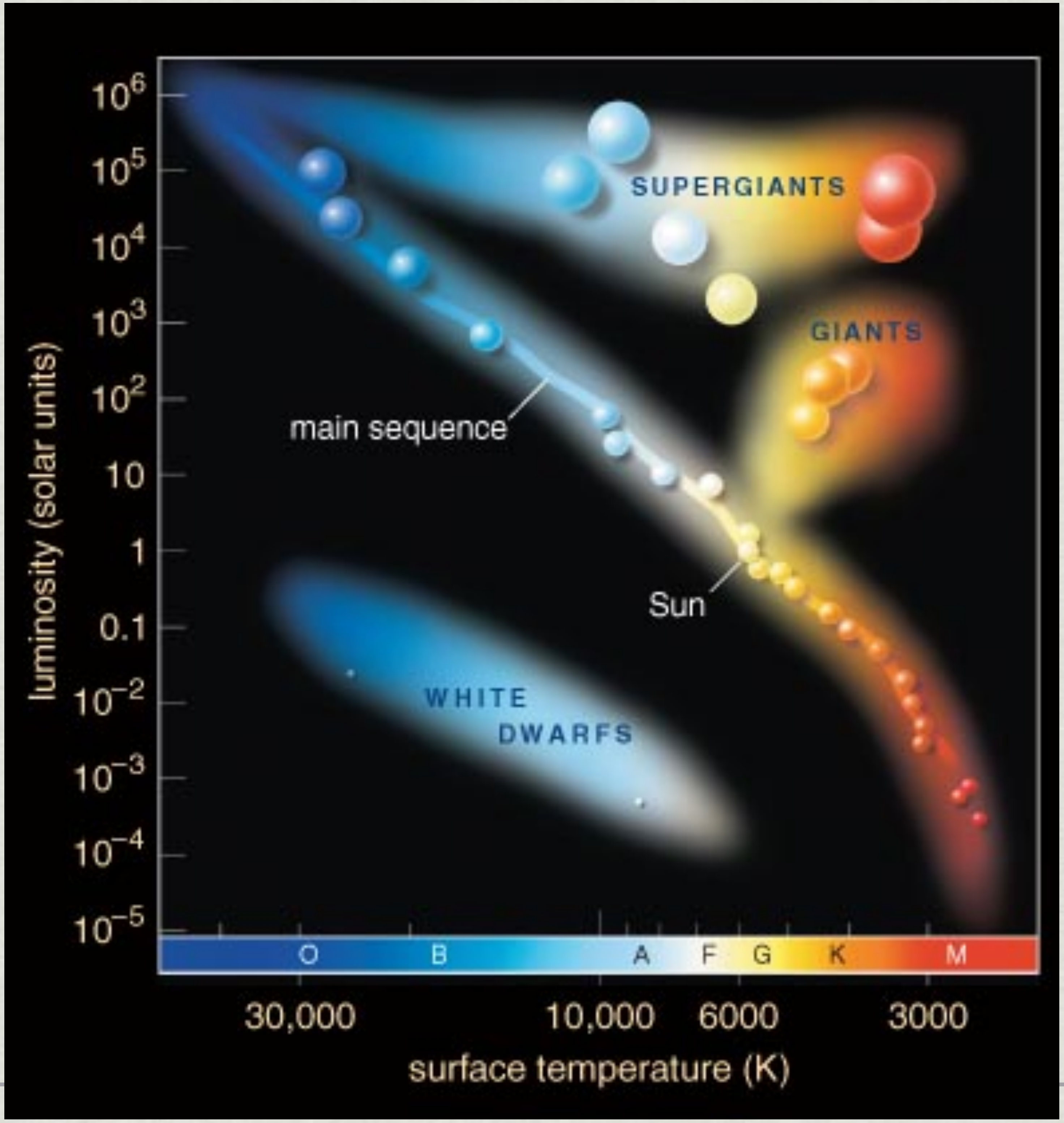
Hertzsprung-Russell (H-R) Diagram

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

Where are most of the stars?

On the Main Sequence.

Maintain gravitational equilibrium, hold themselves up against gravity by generating energy in their core from nuclear fusion of hydrogen to helium:
4H → He + Energy



Hertzsprung-Russell (H-R) Diagram

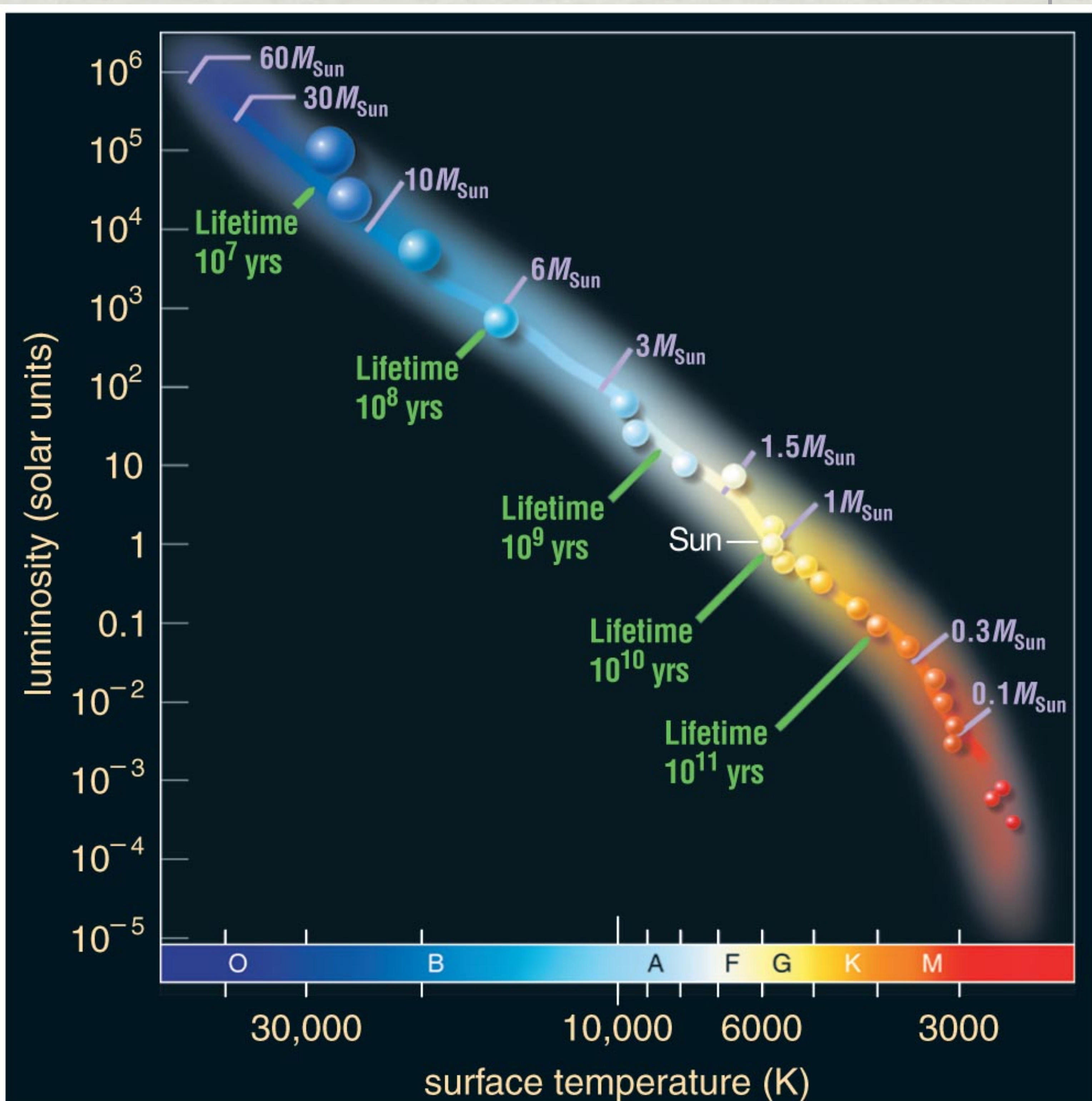
Relations between luminosity, mass, size, temperature of stars.

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

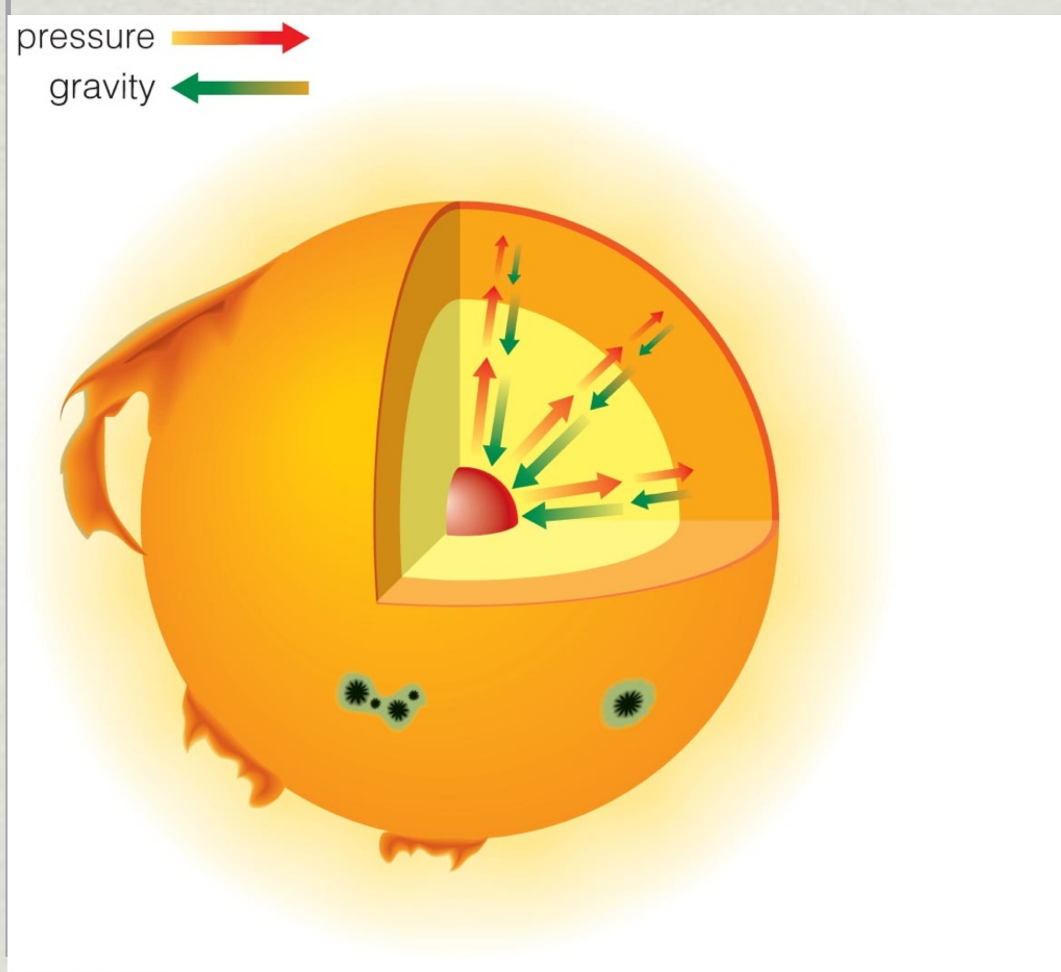
Why?

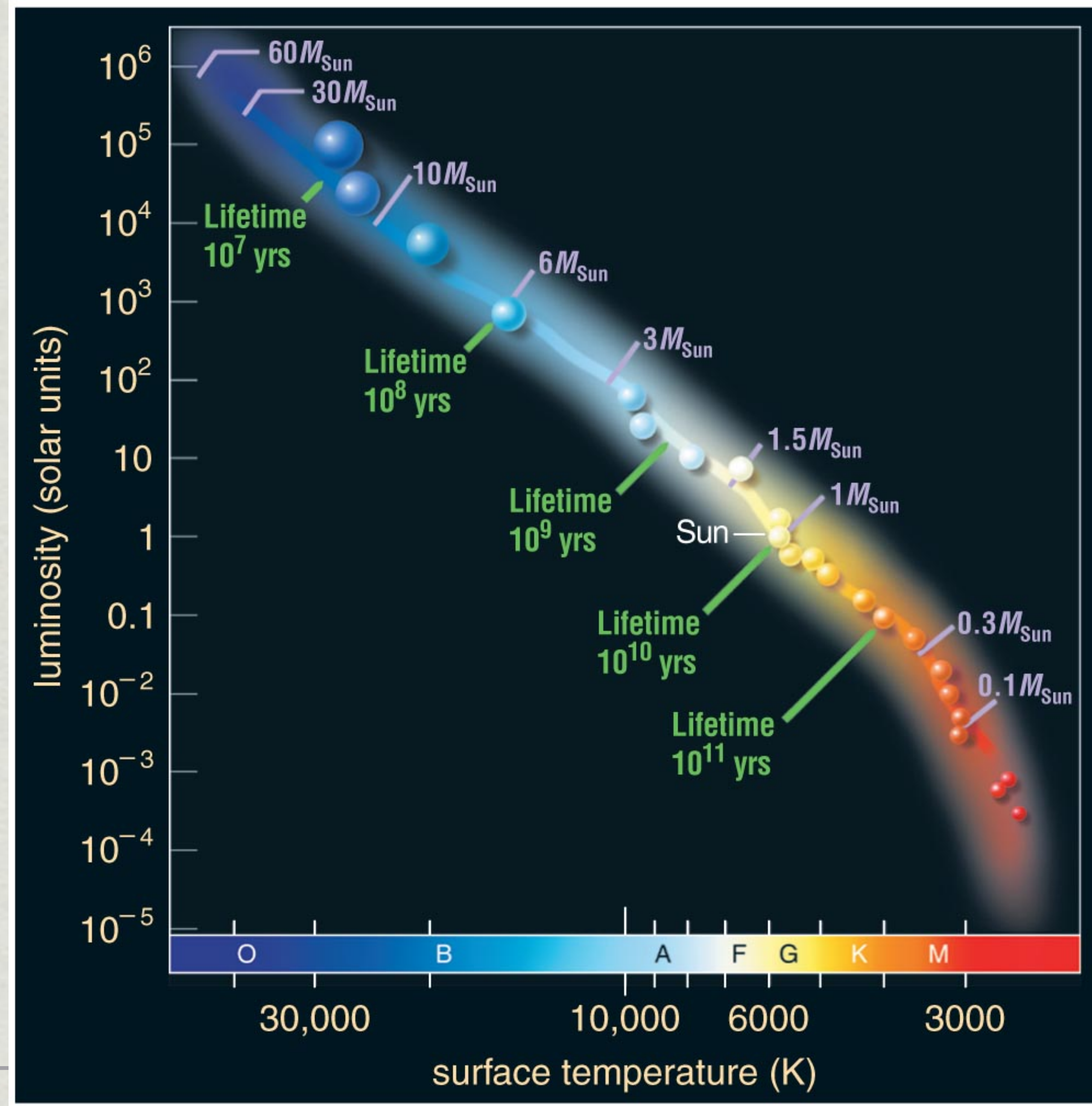


Hertzsprung-Russell (H-R) Diagram

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

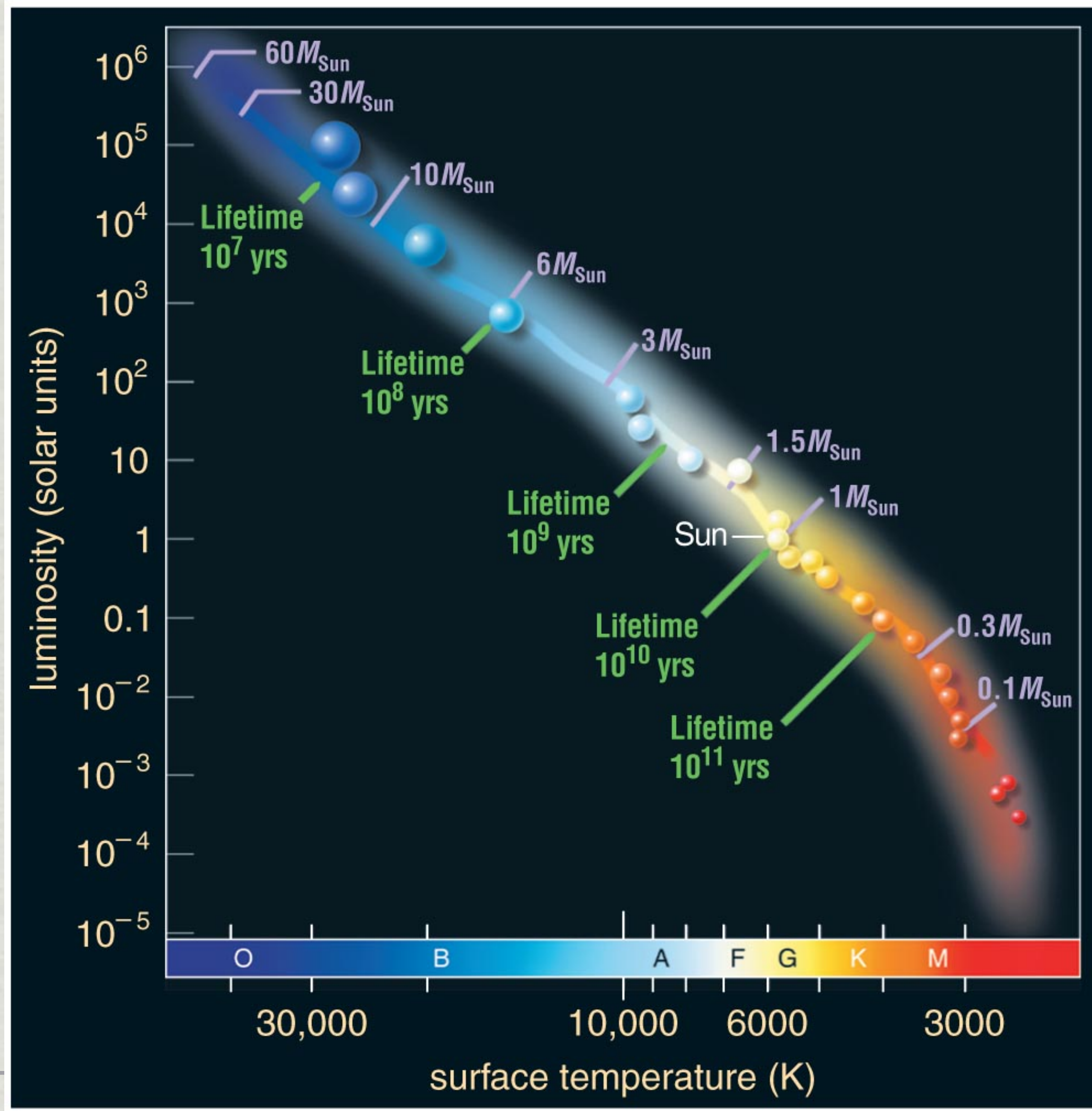




Hertzsprung-Russell (H-R) Diagram

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



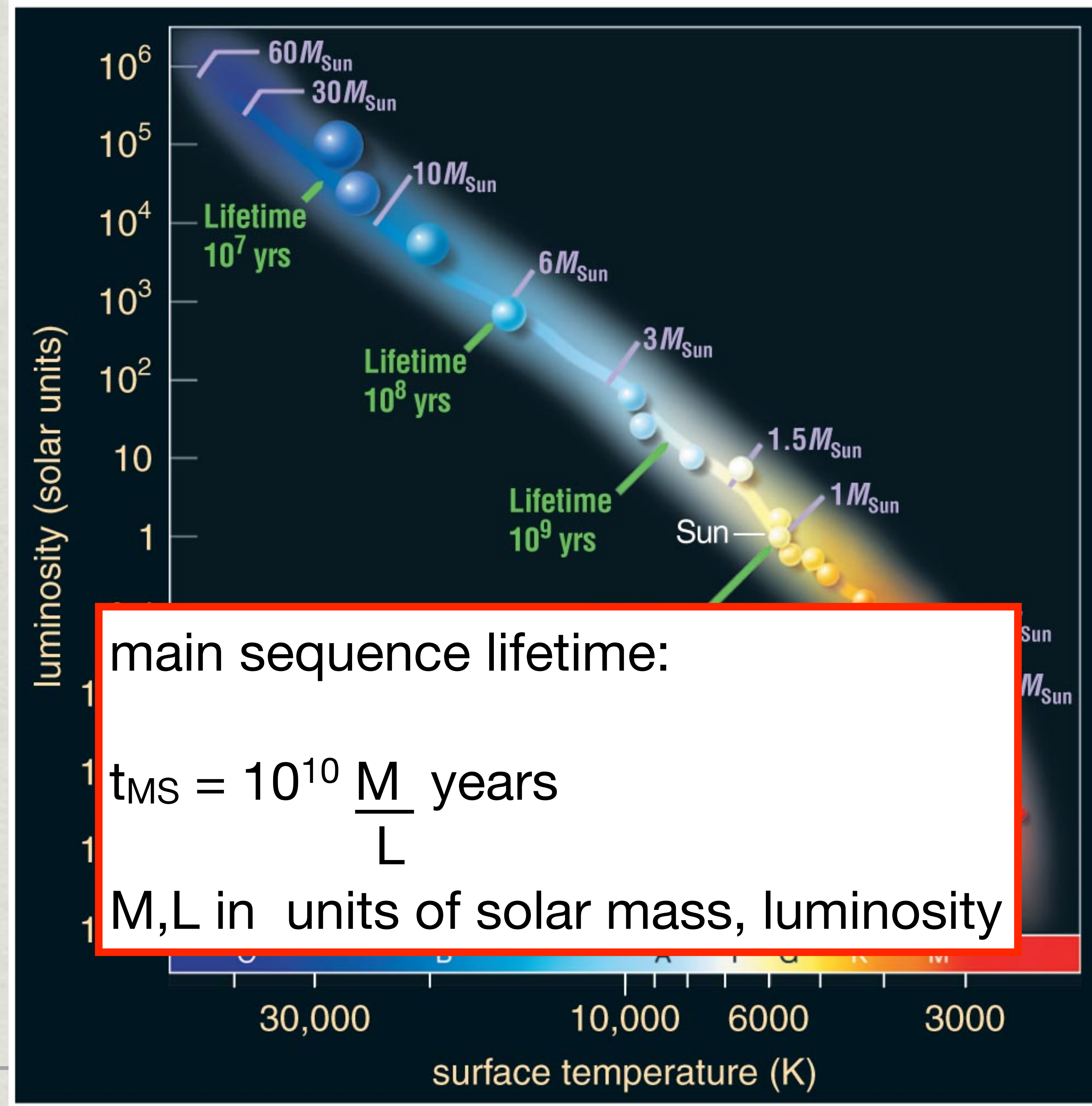
Lower mass: lower core pressure, lower core temperature. Can counter-act the pressure from gravity with a lower energy generation rate from nuclear fusion.

Hertzsprung-Russell (H-R) Diagram

Higher mass = more pressure from gravity

Higher mass:
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.



main sequence lifetime:

$$t_{MS} = 10^{10} \frac{M}{L} \text{ years}$$

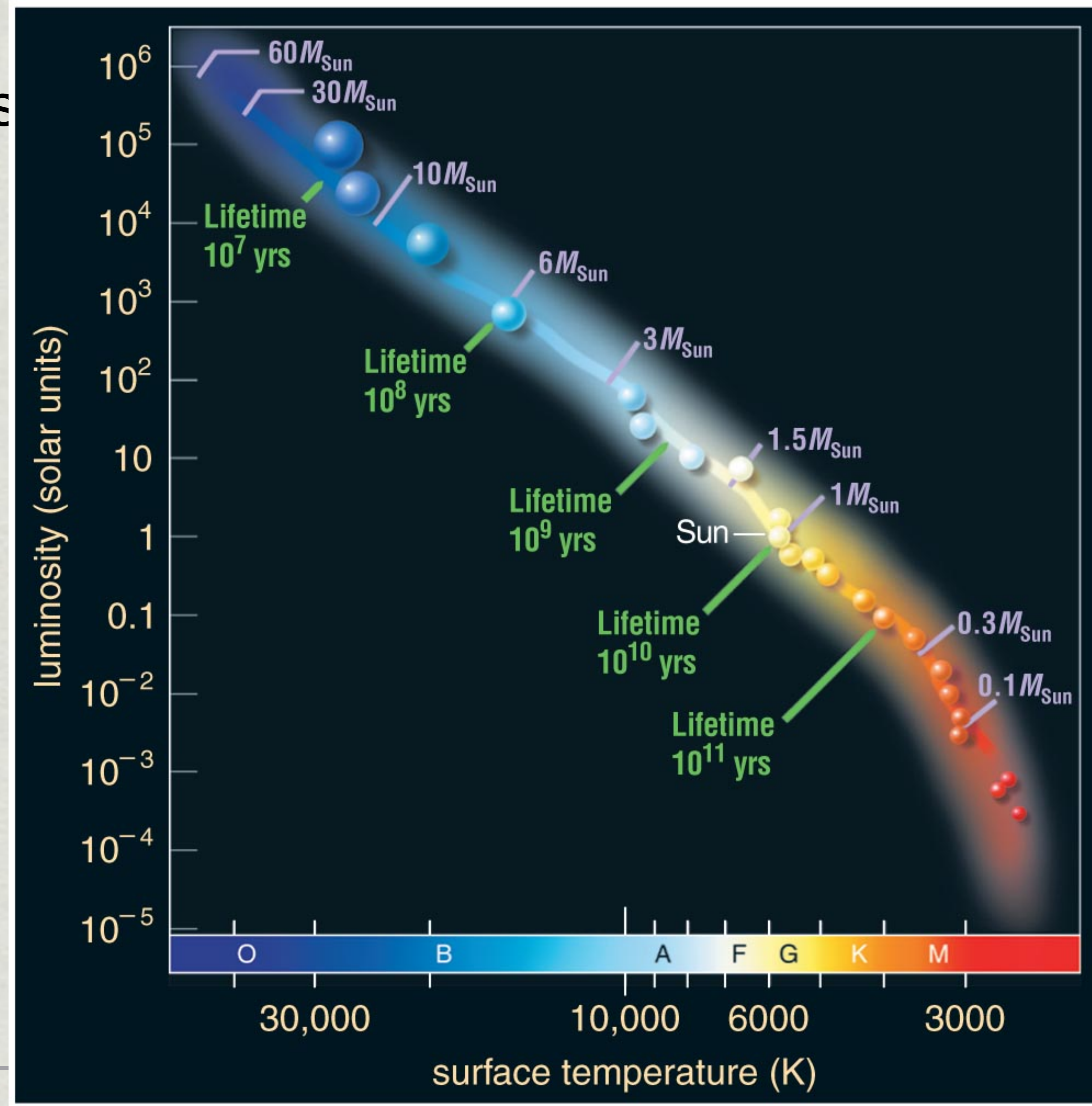
M,L in units of solar mass, luminosity

Hertzsprung-Russell (H-R) Diagram

Higher mass = more pressure from gravity

Main sequence:
- Powered by nucleosynthesis of H to He
- Properties set by mass.

High mass:
  High luminosity
  Blue = high temperature
  Large radius
  Short lifetime
Low Mass:
  Low luminosity
  Red = cool temperature
  Small radius
  Long lifetime



High Mass Stars: Post Main Sequence Evolution

New fusion cycles initiated as core collapses, never becomes degenerate.

Q: When does it stop?
A: When fusion of new elements doesn't release energy

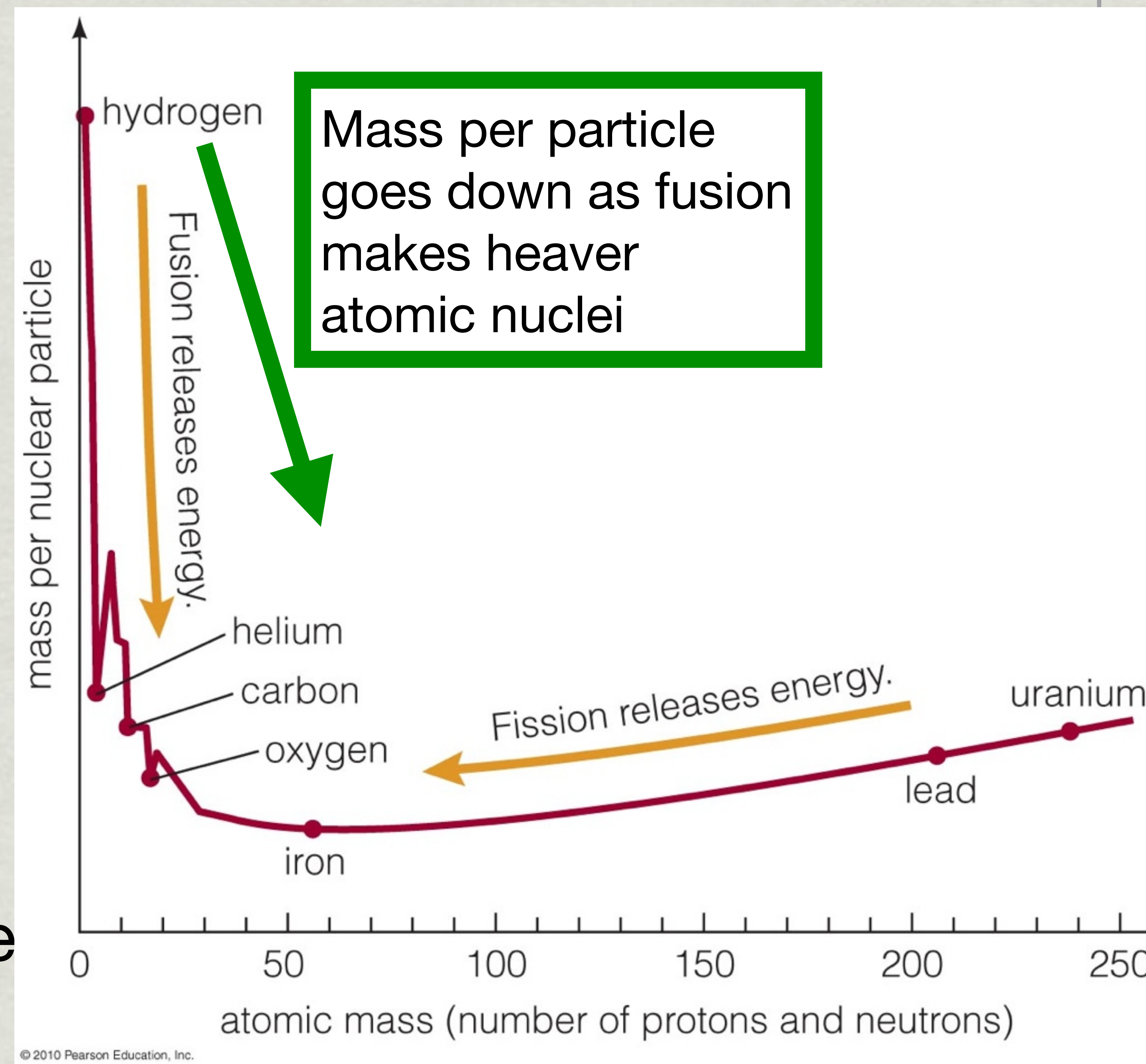
Mass per particle in the nucleus decreases from H to Fe.
Where does it go?

It is converted to energy!

Remember: of 4 H nuclei > 1 He nucleus.

$\Delta m = Mass_{4H} - Mass_{He}$

$E_{out} = \Delta mc^2$



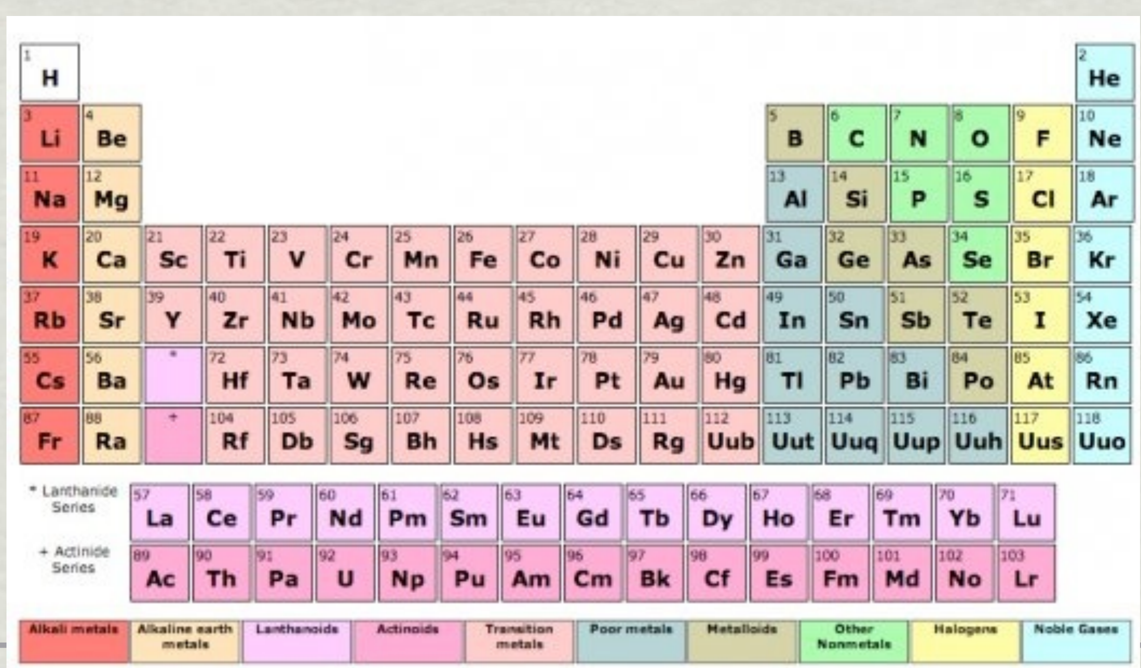
H, He, ... C...Fe...Ag...Pb...U → increasing number of particles in nucleus for elements in the periodic table

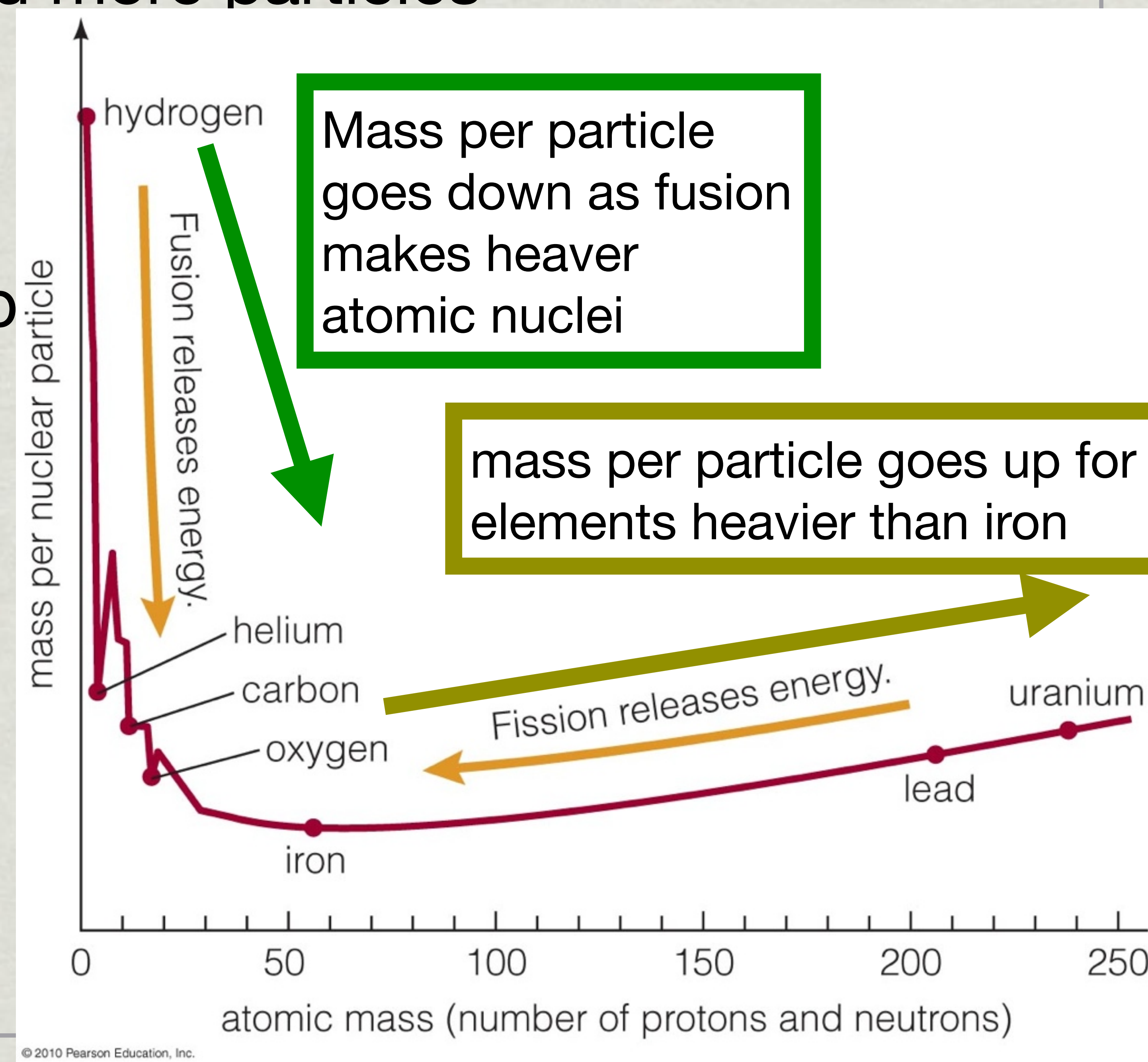
High Mass Stars: Post Main Sequence Evolution

Iron (Fe) is the end of the line for fusion.

Fe nucleus has lowest mass per particle: no conversion of mass to energy when you add more particles

Now gravity can win as the core collapses. Star can't generate energy to hold itself up with thermal pressure.





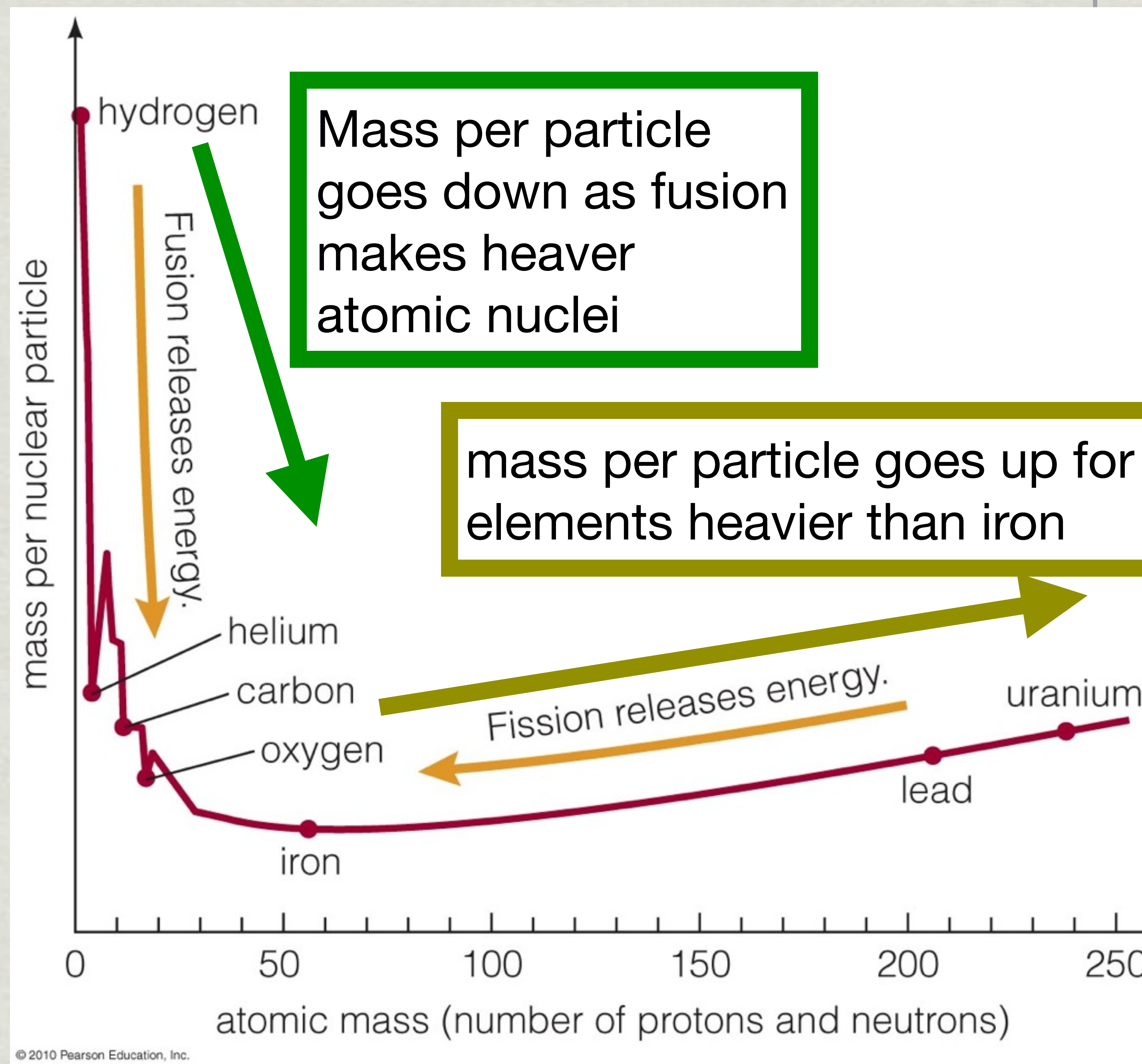
High Mass Stars: Post Main Sequence Evolution

Mass per particle (neutron, proton) in the nucleus increases for elements heavier than Fe.

Mass per particle of a lead nucleus > Mass per particle of an iron nucleus.

$\Delta m = Mass_{Fe} - Mass_{Pb} < 0$
No energy out by fusing nuclei to make lead!

How are these elements made?
Put energy ***in*** during the explosions that end the lives of massive stars

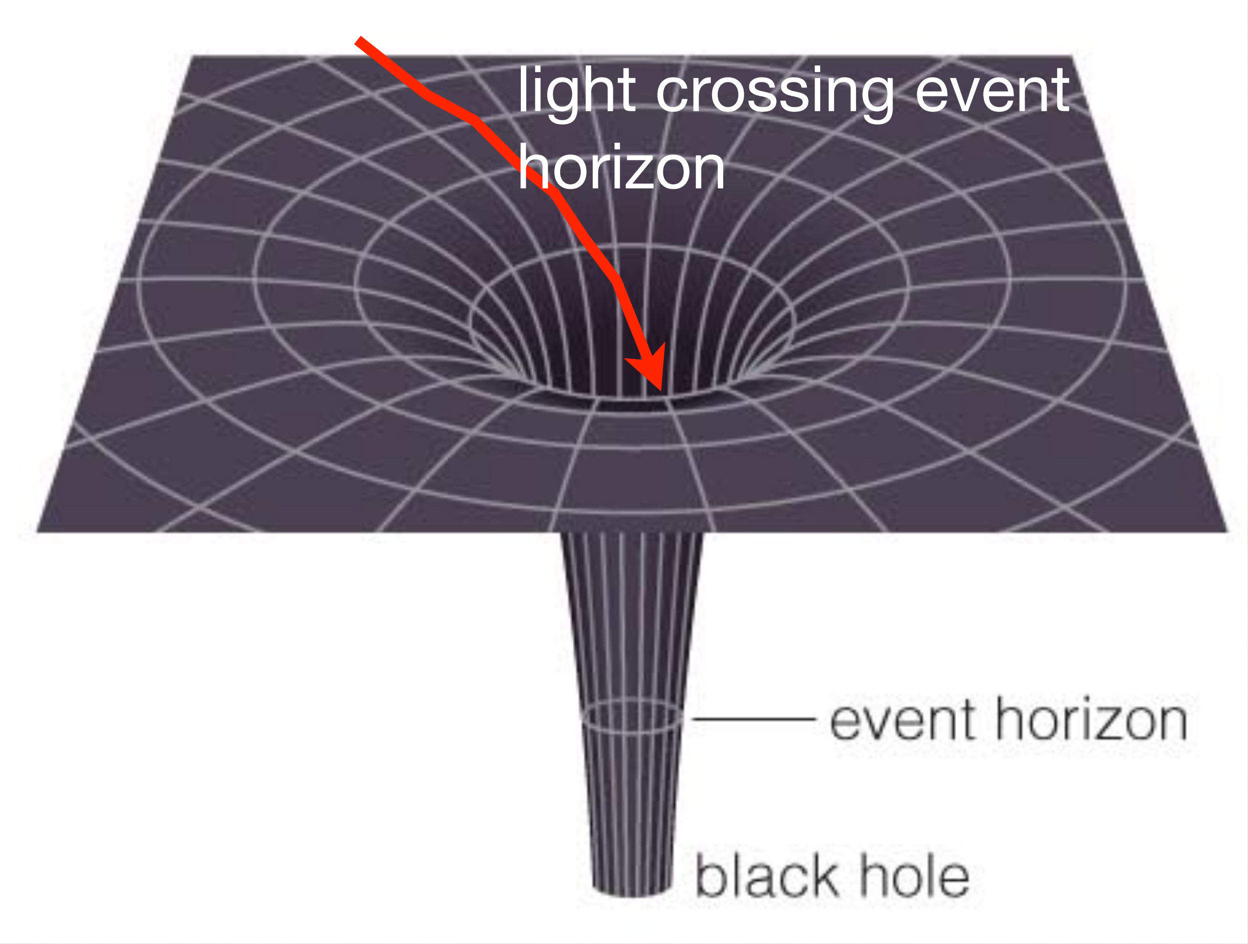


H, He, ... C...Fe...Ag...Pb...U → increasing number of particles in nucleus for elements in the periodic table

General Relativity

Implication #1:
The path of light is always straight, but space is bent by gravity.

Space curved if the sun were a black hole



If mass is dense enough, there is a radius from which light can't escape.

Radius of this "Event Horizon" = Schwarzschild Radius

Black Holes

Escape velocity: velocity needed to get free of an object's gravitational pull.

$$v_{escape} = \sqrt{\frac{2\,G\,M}{d}}$$

M = mass, d = distance from the center of the object you want to escape from

For a star, light is emitted at its surface, so **d** is the radius of the star, **R**

If M is very big and/or R is very small, then $V_{escape} > c$, the speed of light.

NOTHING can have speed > c, so NOTHING can escape, not even light.
Star becomes a Black Hole

Black Holes

For any mass define a radius, the Schwarzschild radius R_s, where $V_{escape} = c$

$$v_{escape} = \sqrt{\frac{2\,G\,M}{R}}$$

Then rearrange:

$$R_s = \frac{2GM}{c^2} = \left(\frac{2G}{c^2}\right) M$$

If $M = M_{sun}$, $R_s = 3$ km

So for any star, $R_s = 3 \text{ km} \times \frac{M_*}{M_{sun}}$

Artist's rendition, not a real picture

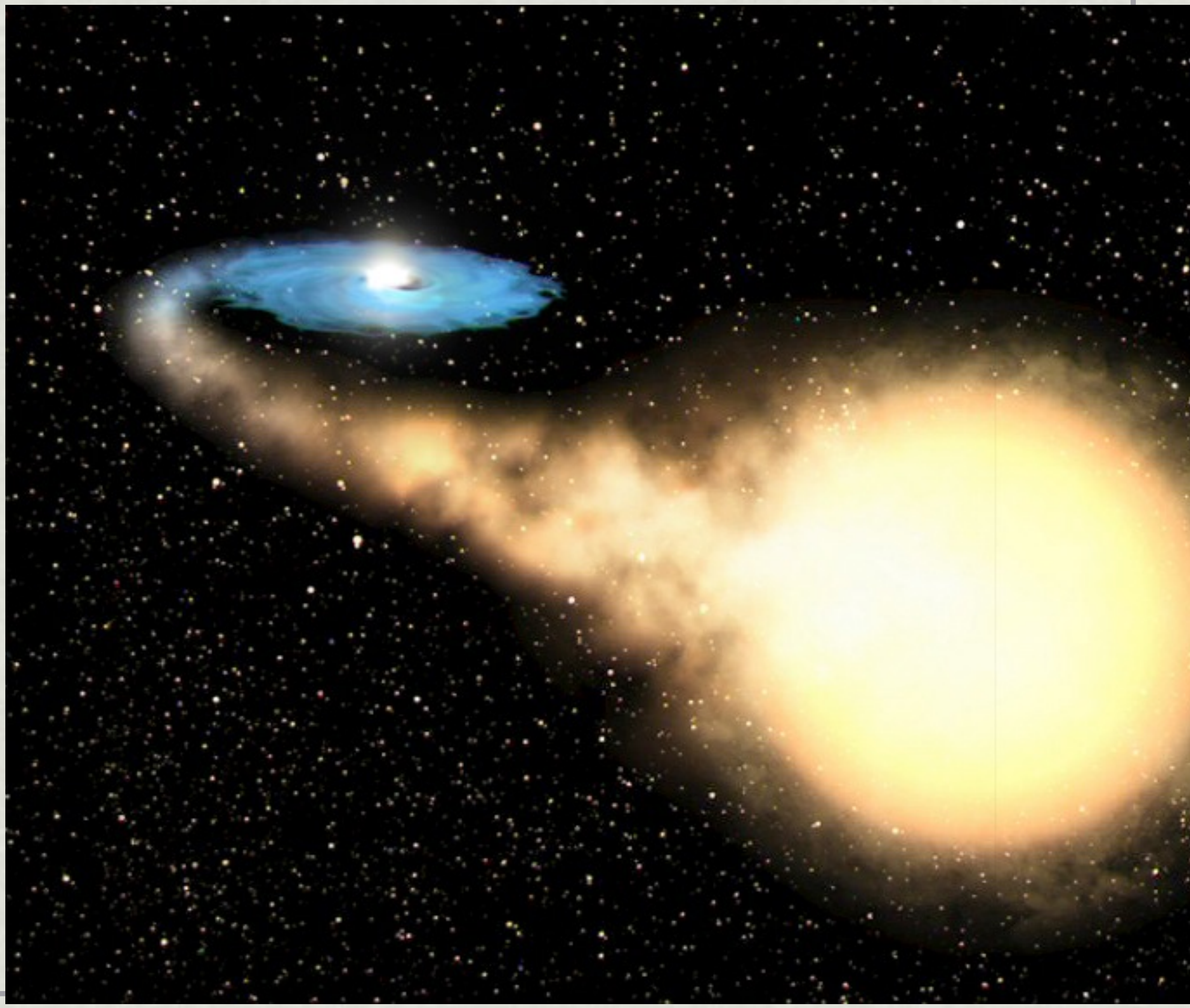
Black Holes

Black holes in the centers of galaxies can pull in gas from the rest of the galaxy.

As the gas falls in the atoms collide. The gas heats up due to friction and the release of gravitational potential energy.

The gas emits radiation, though not a thermal spectrum.

Can be incredibly bright, out-shine an entire galaxy.

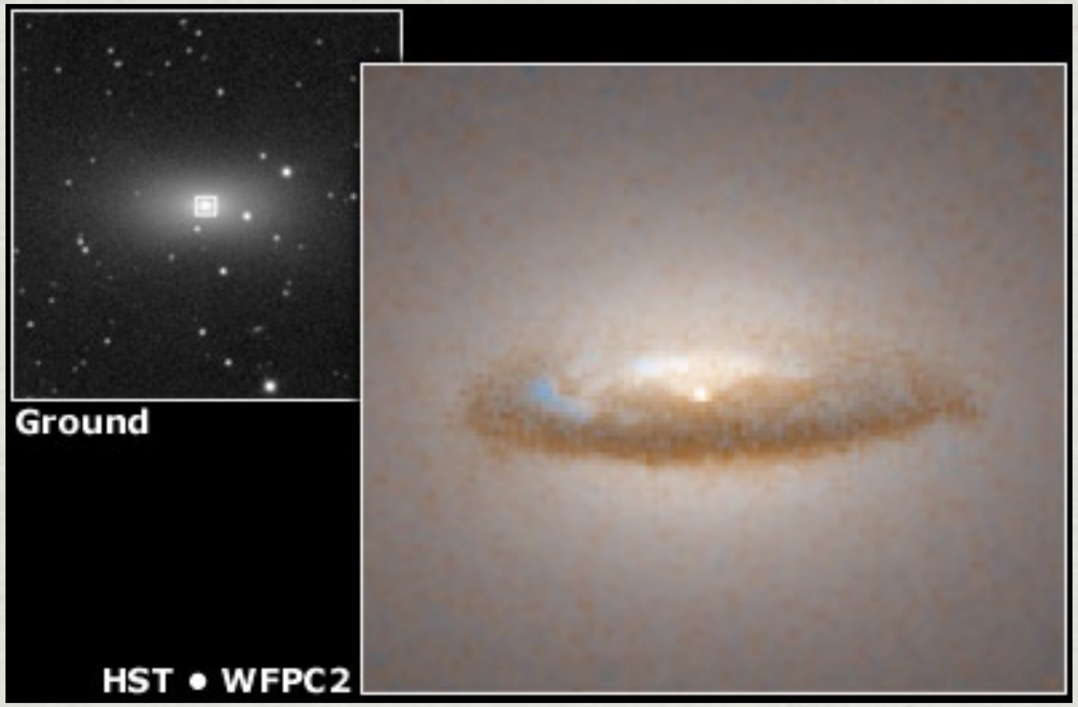


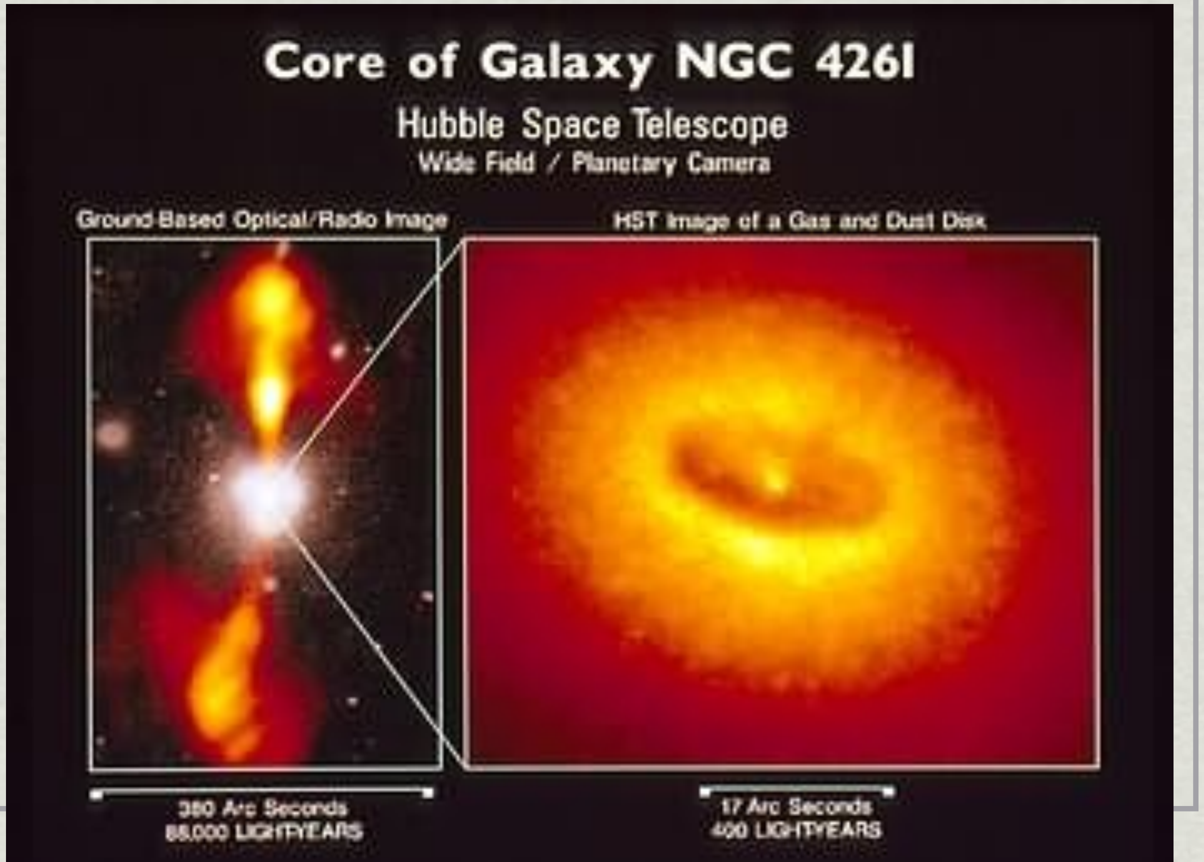
Quasars

Eventually, realized that quasars are black holes in the centers of galaxies.

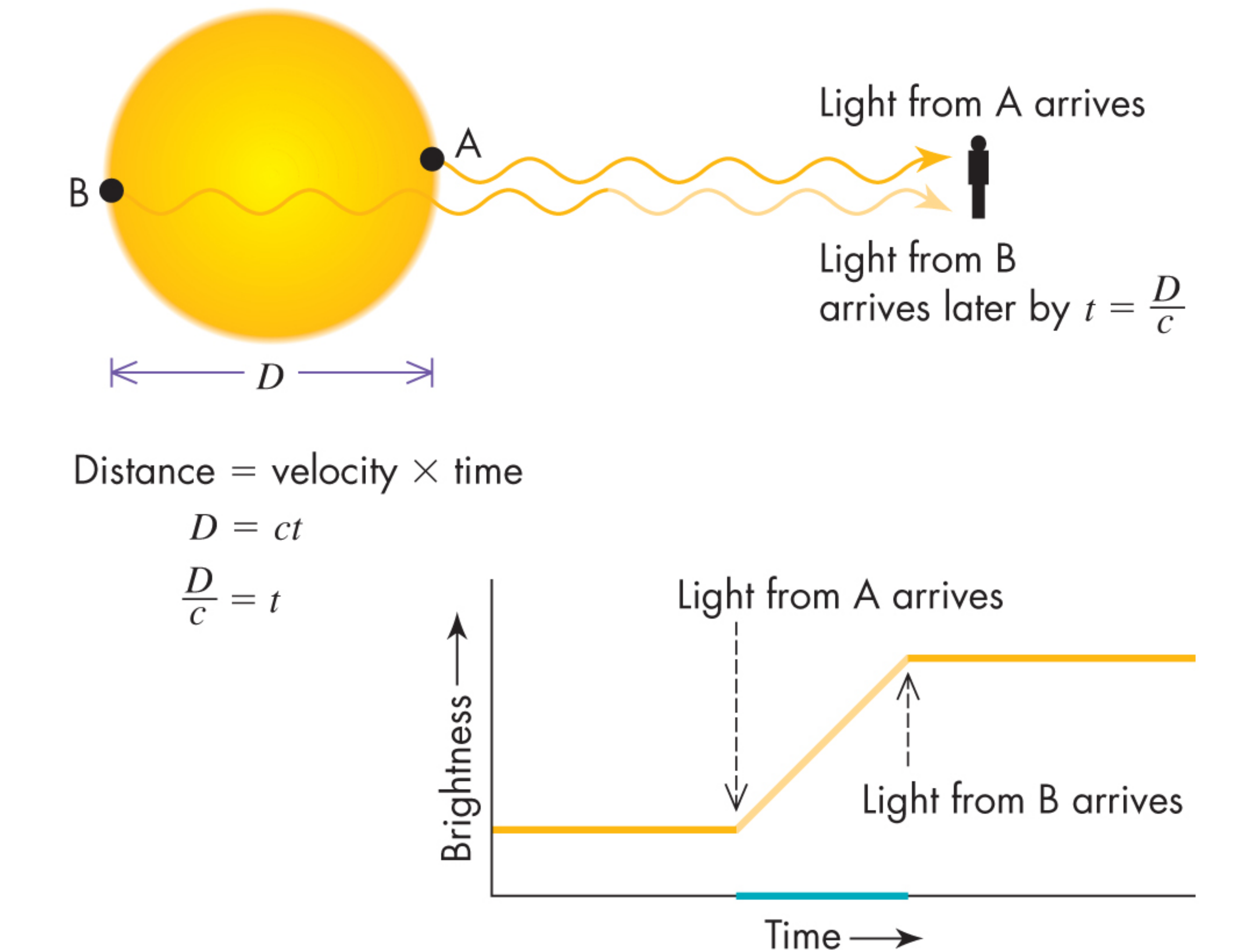
That huge luminosity is the light from gas that is glowing from the energy it gains as it falls in to the black hole.

Infall converts gravitational potential energy to other kinds of energy. Stored in the energy levels of atoms, released as emission line spectra and other interactions

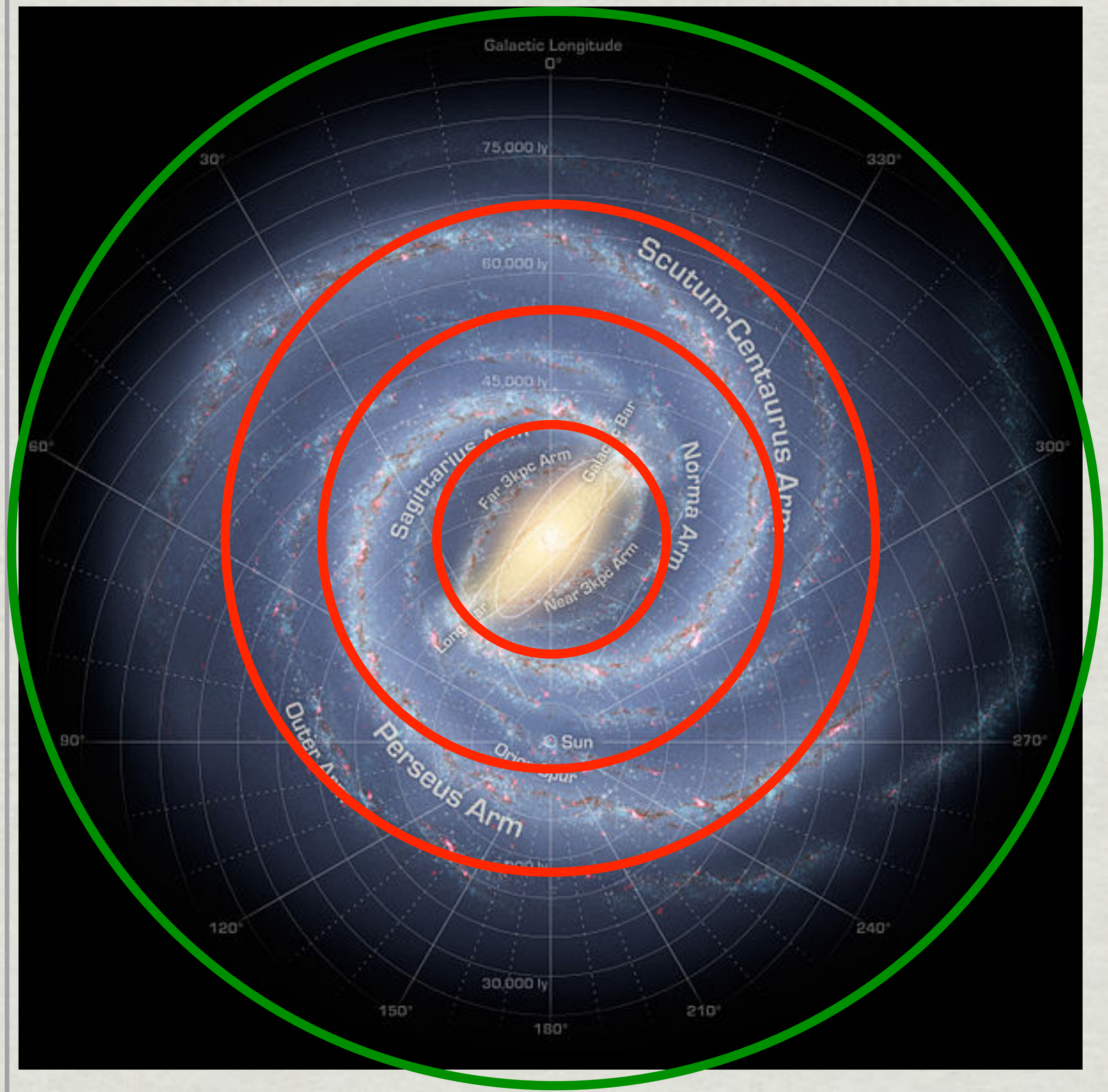




Measuring the Size of Quasars



Milky Way: Mass



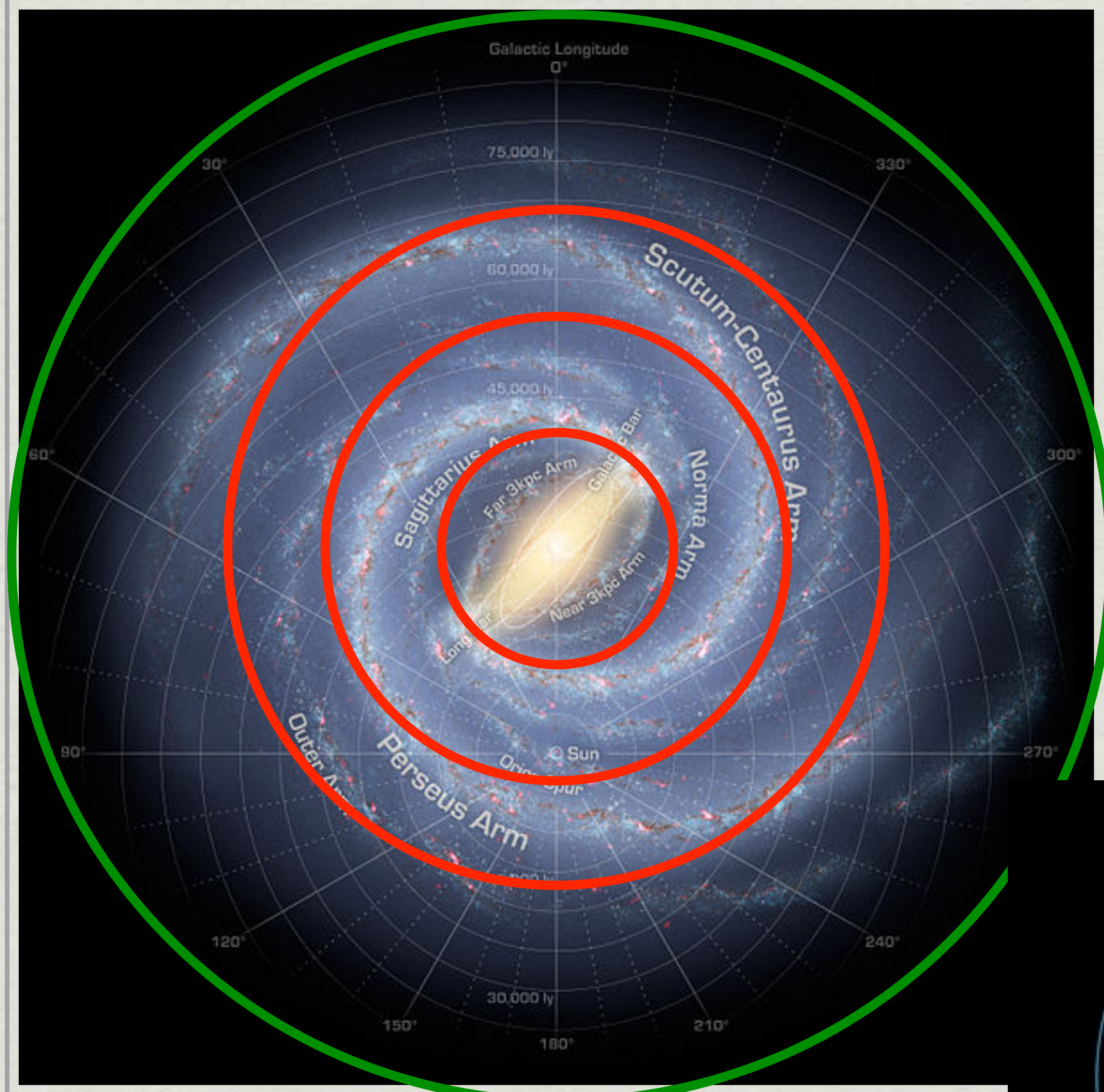
What do you expect will happen to the velocity once the circles get big enough to enclose all the stars?

A) velocity increase as radius gets larger (green circle and beyond)

B) velocity should decrease as radius gets larger (green circle and beyond)

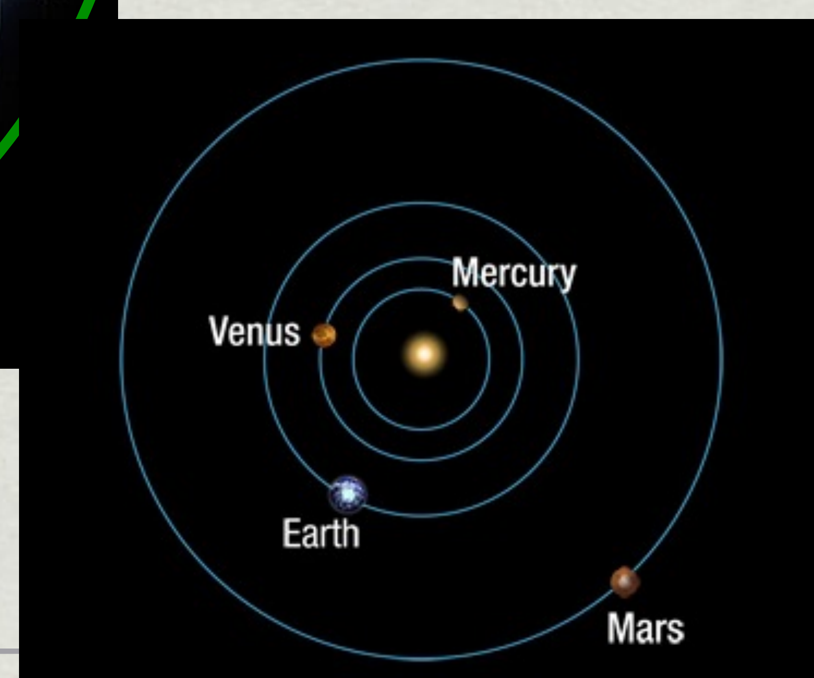
Remember, speed of an orbit around mass M: $v^2 = \frac{GM}{r}$

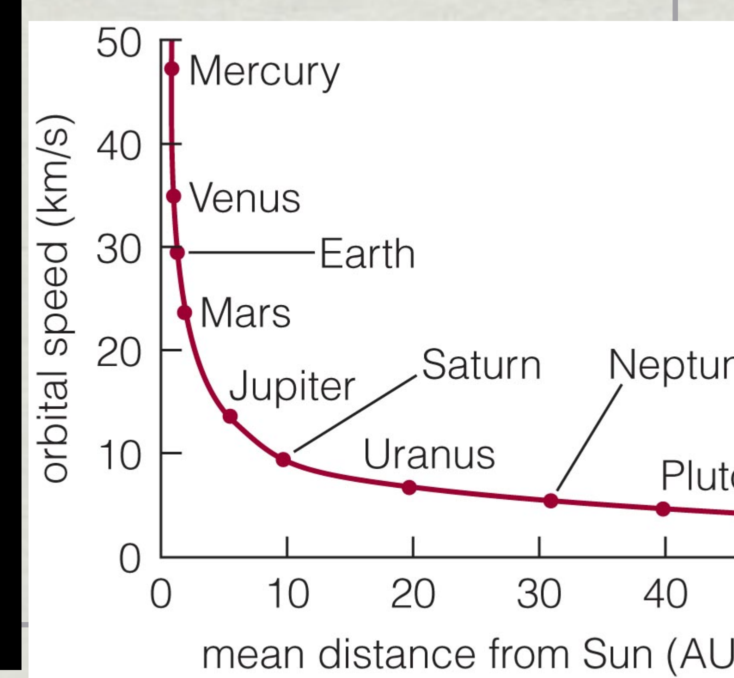
Milky Way: Mass



What do you expect will happen to the velocity once the circles get big enough to enclose all the stars?

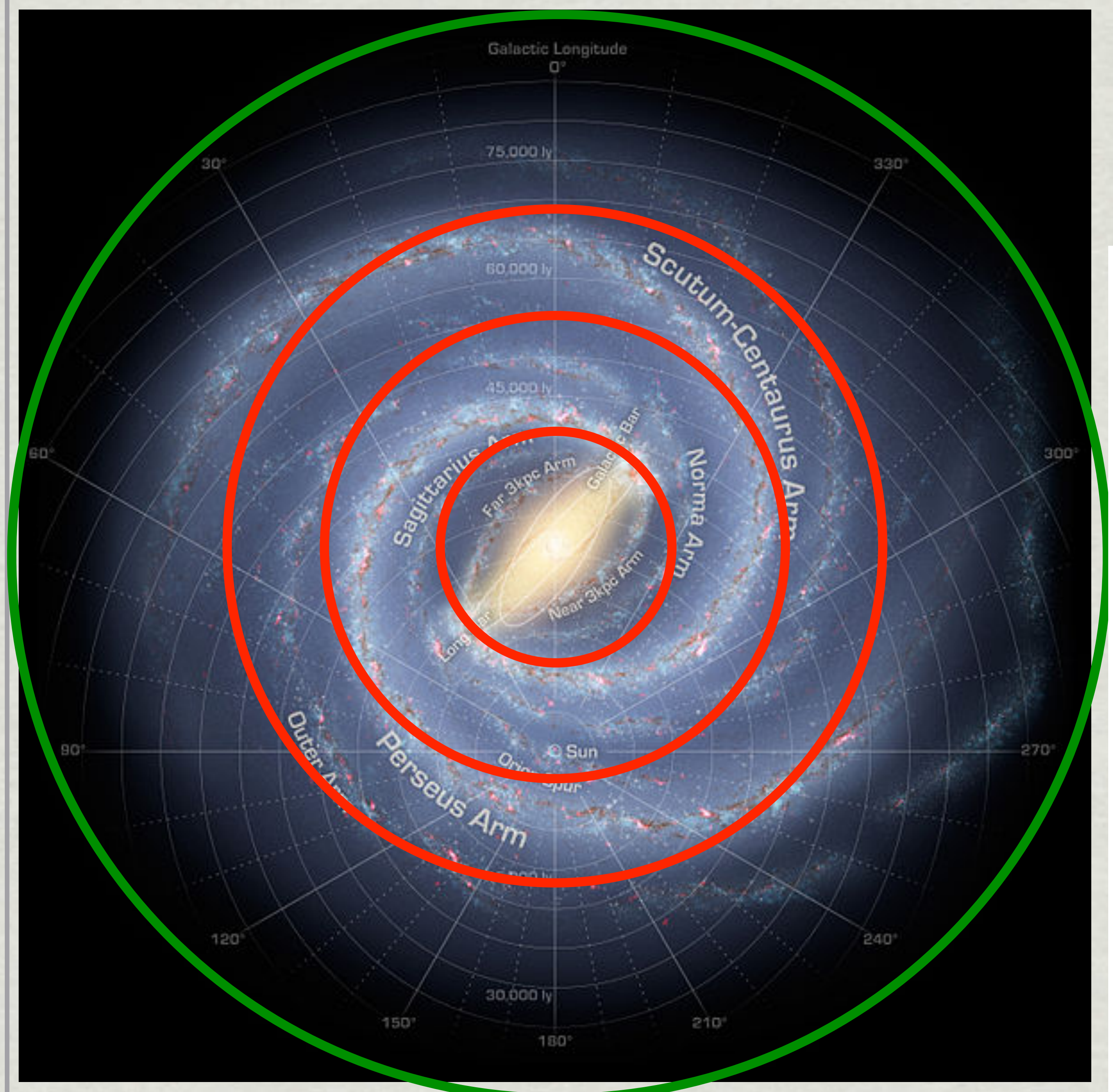
Velocity should decrease at larger radii, just like for the solar system. All the mass is inside the large circles, right?

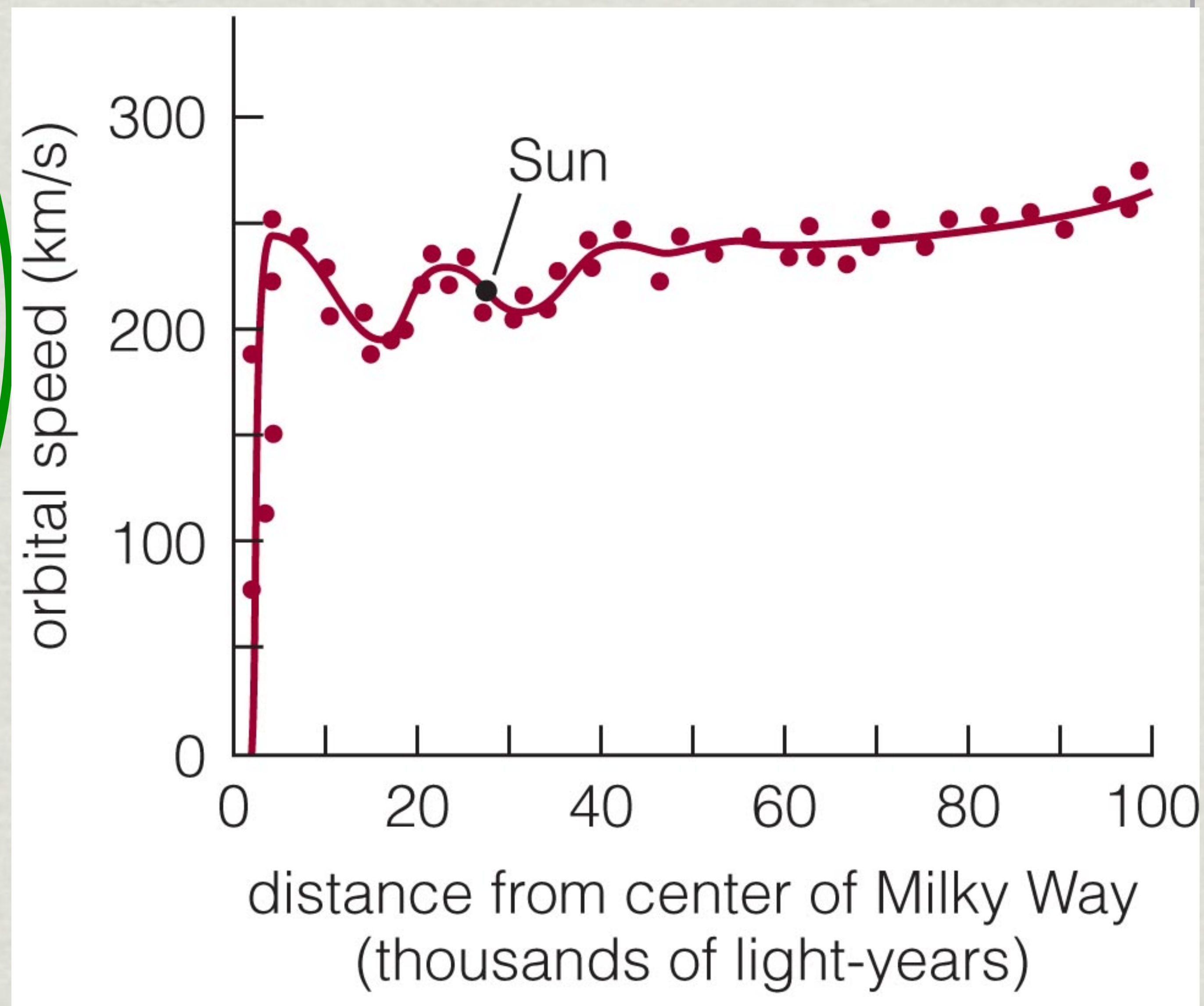




Milky Way: Mass

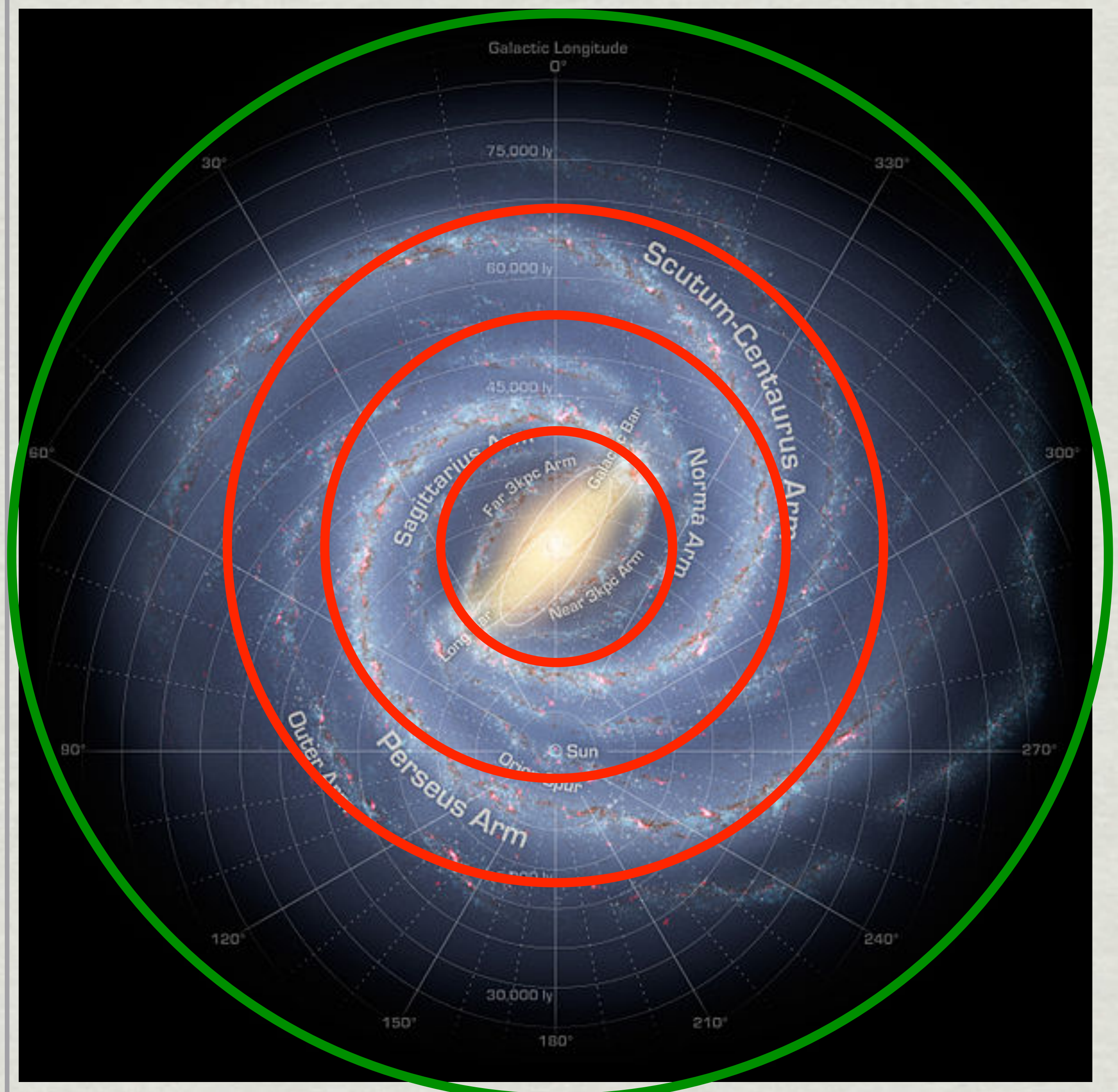
What we measure is wonderfully weird:
the velocity stays constant.



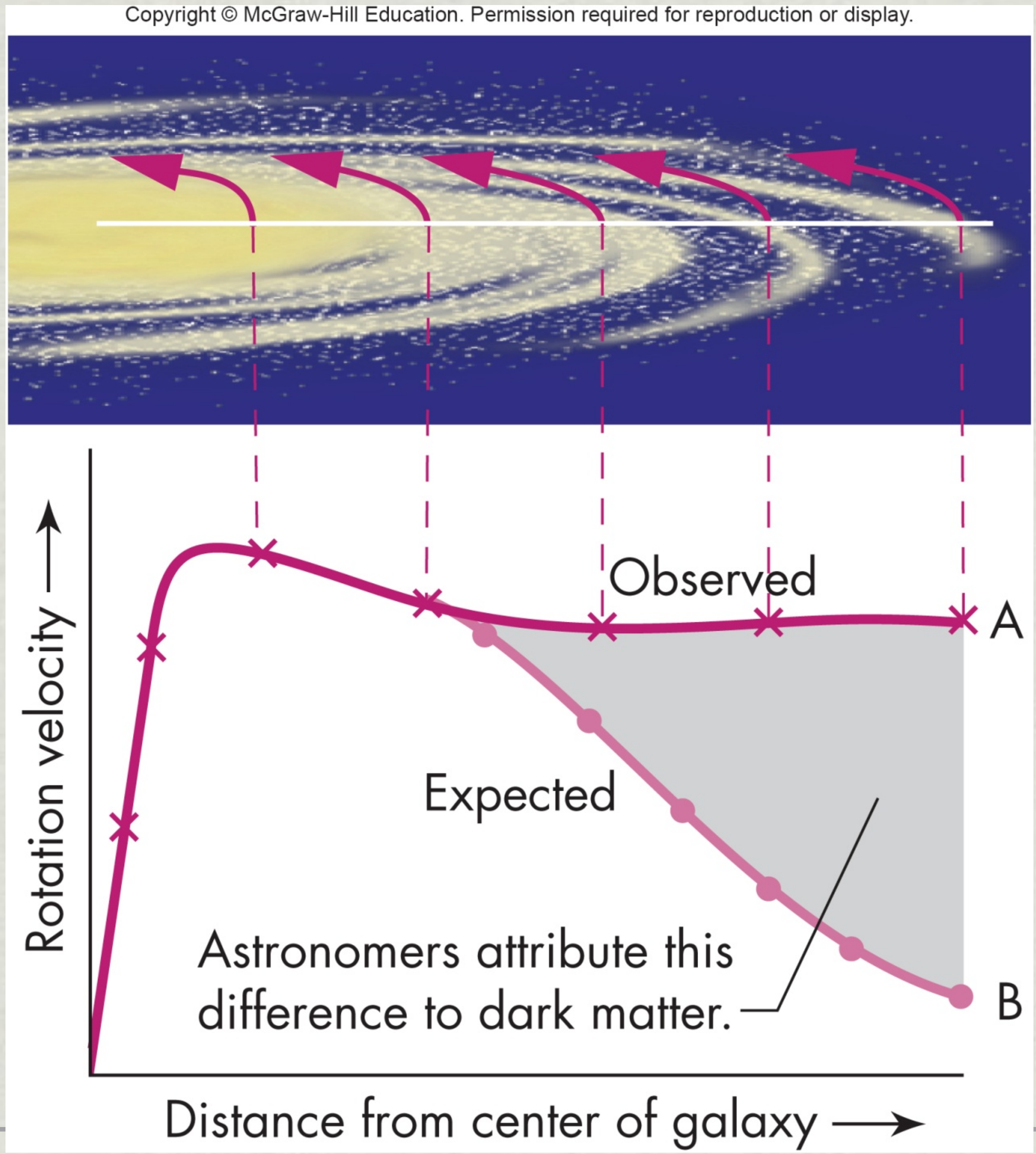


So mass must still be increasing with radius!

Milky Way: Mass



What we measure is wonderfully weird: *the velocity stays constant.*



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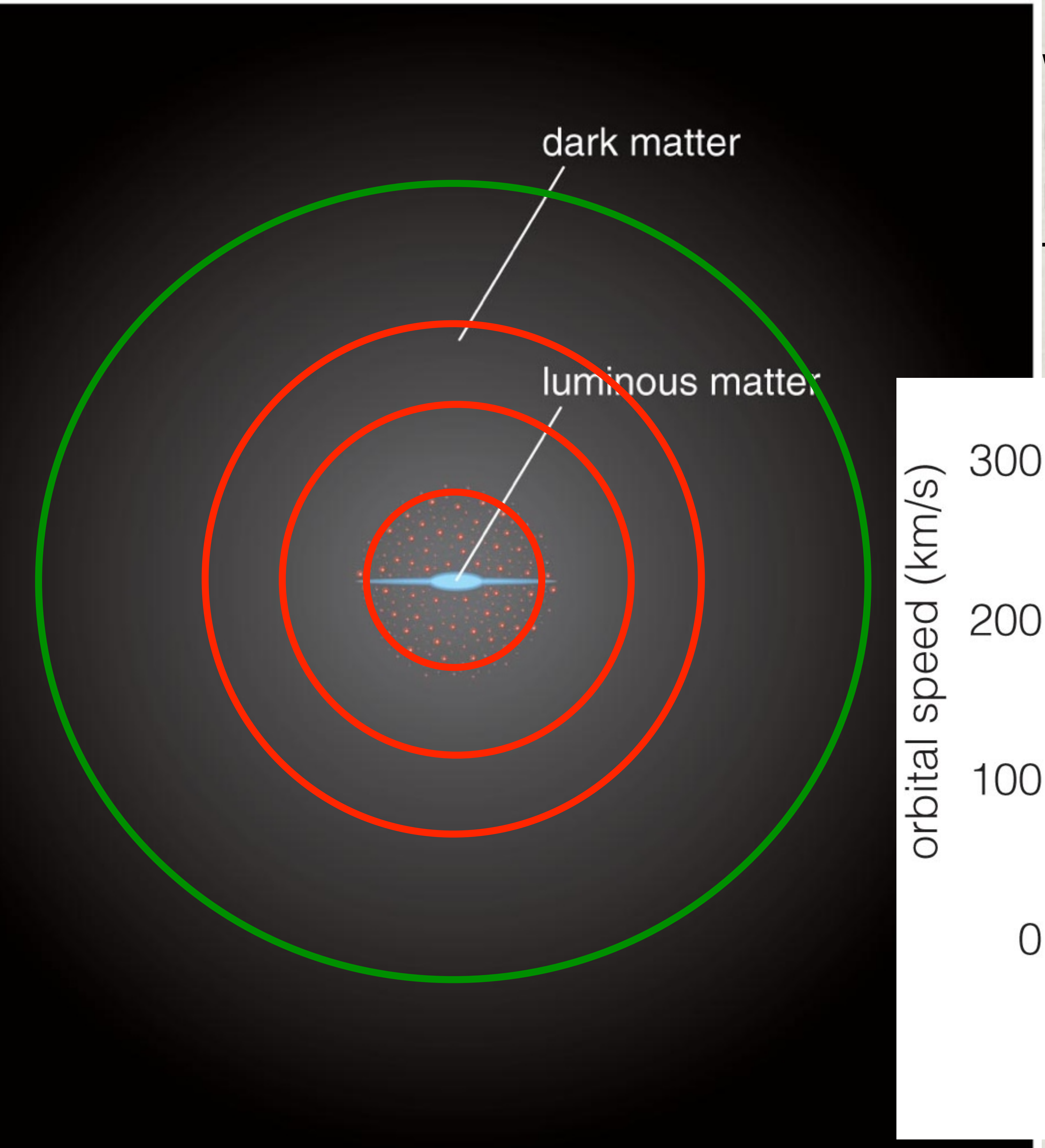
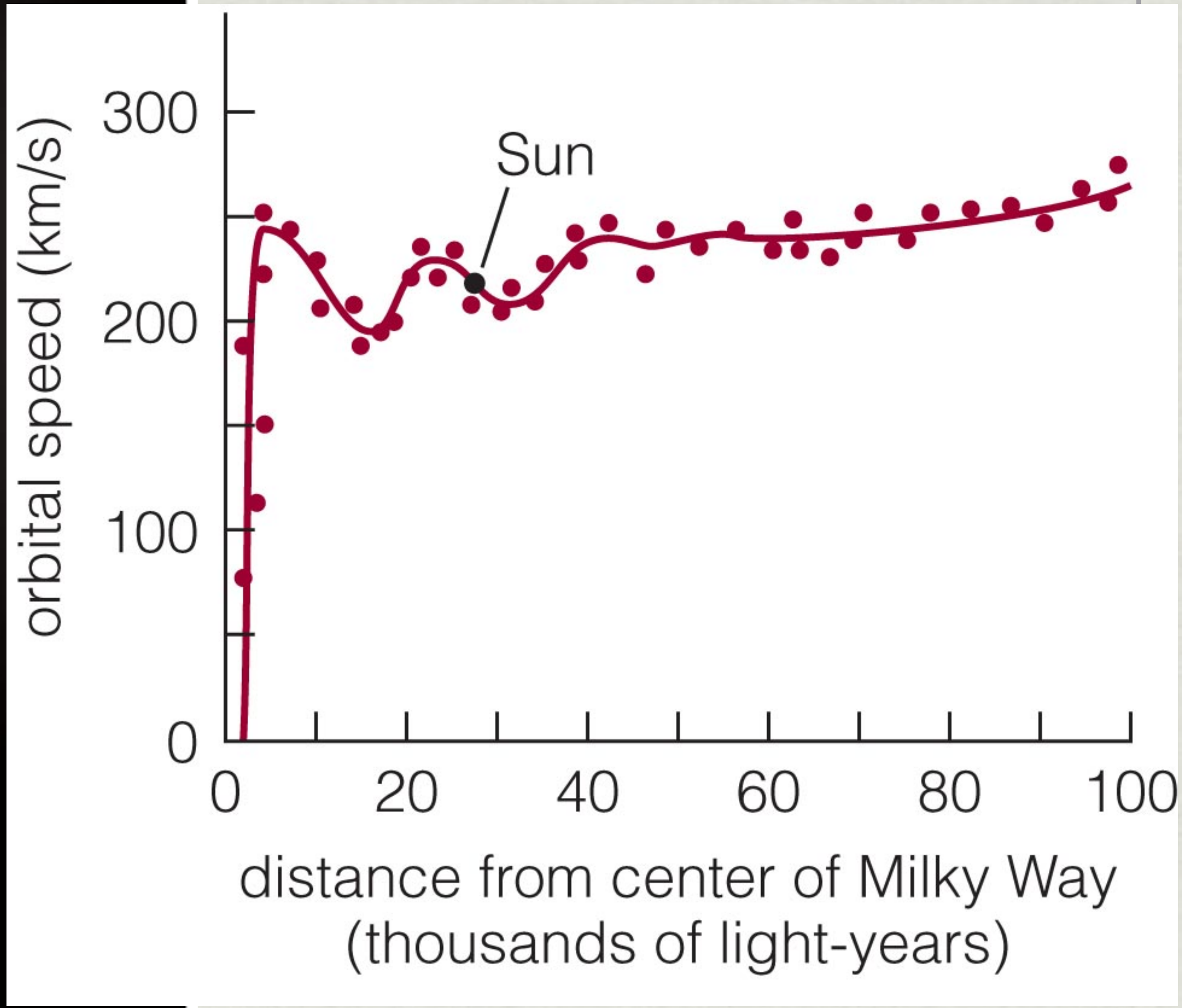
Milky Way: Mass



We can't see it, but the velocity measurements tell us there is mass at larger distances than all the mass we can see



Galaxies in the Universe

- Light travels at a finite speed (300,000 km/s).
- Galaxies at large distances → light left those galaxies a long time ago.
- Large distance = large "look-back time"

The distance to Andromeda, the nearest galaxy to the Milky Way (our galaxy), is 2.5 million light-years.

Stars in the Andromeda galaxy emitted the light we see when we look at Andromeda today 2.5 million years ago.

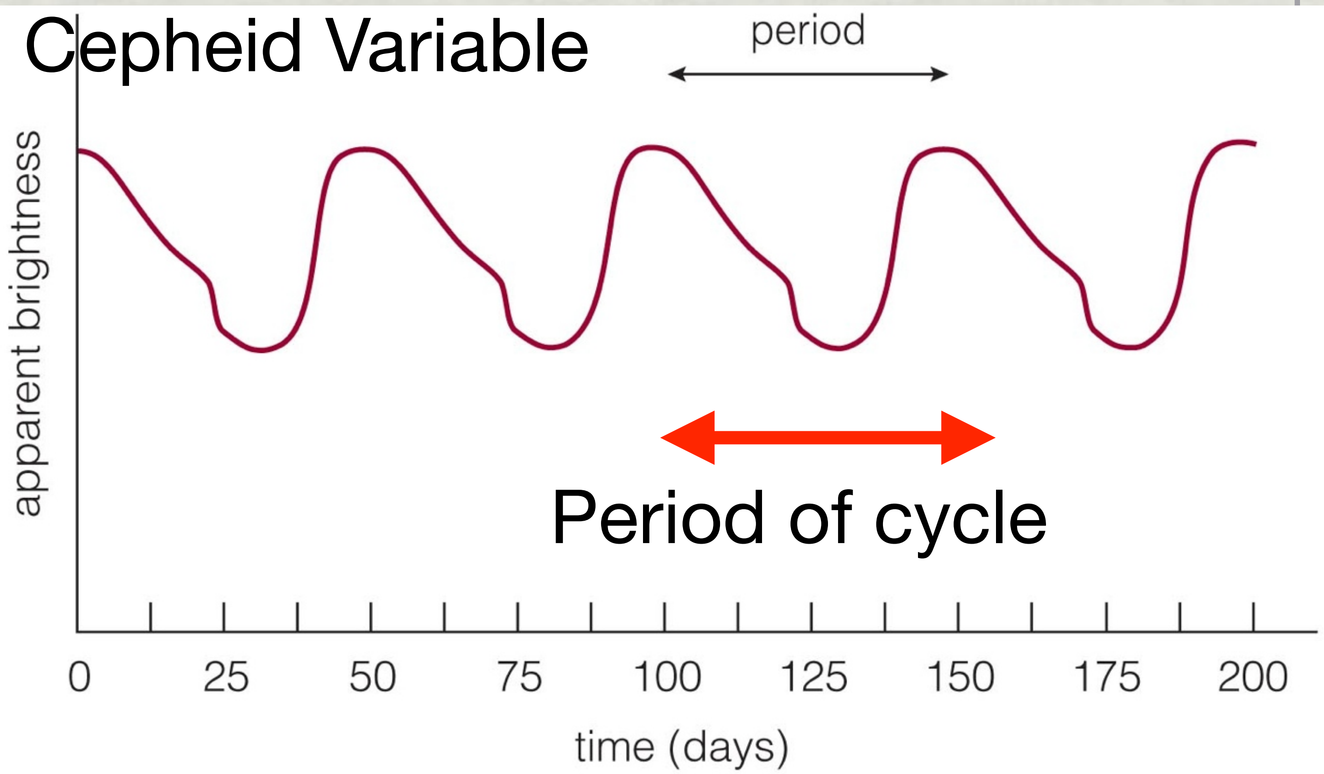
Distances to Galaxies

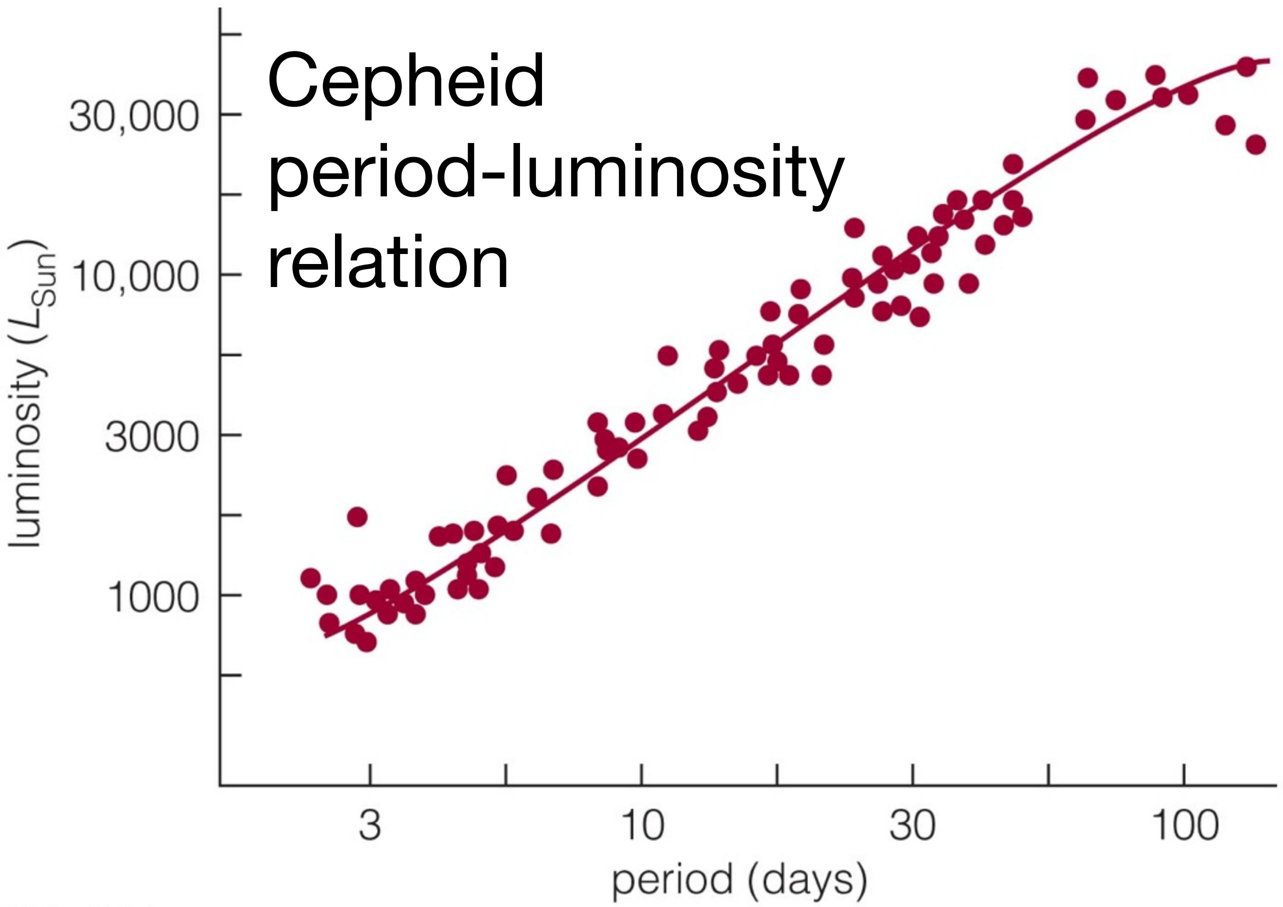
More luminous Cepheids have longer periods

This is ***incredibly useful***: if you can measure period, you can learn luminosity of a Cepheid without knowing its distance!

If you also measure the apparent brightness, you can learn the distance to the Cepheid, and therefore to the star cluster or galaxy it lives in:

$$L = B \times 4\pi d^2$$

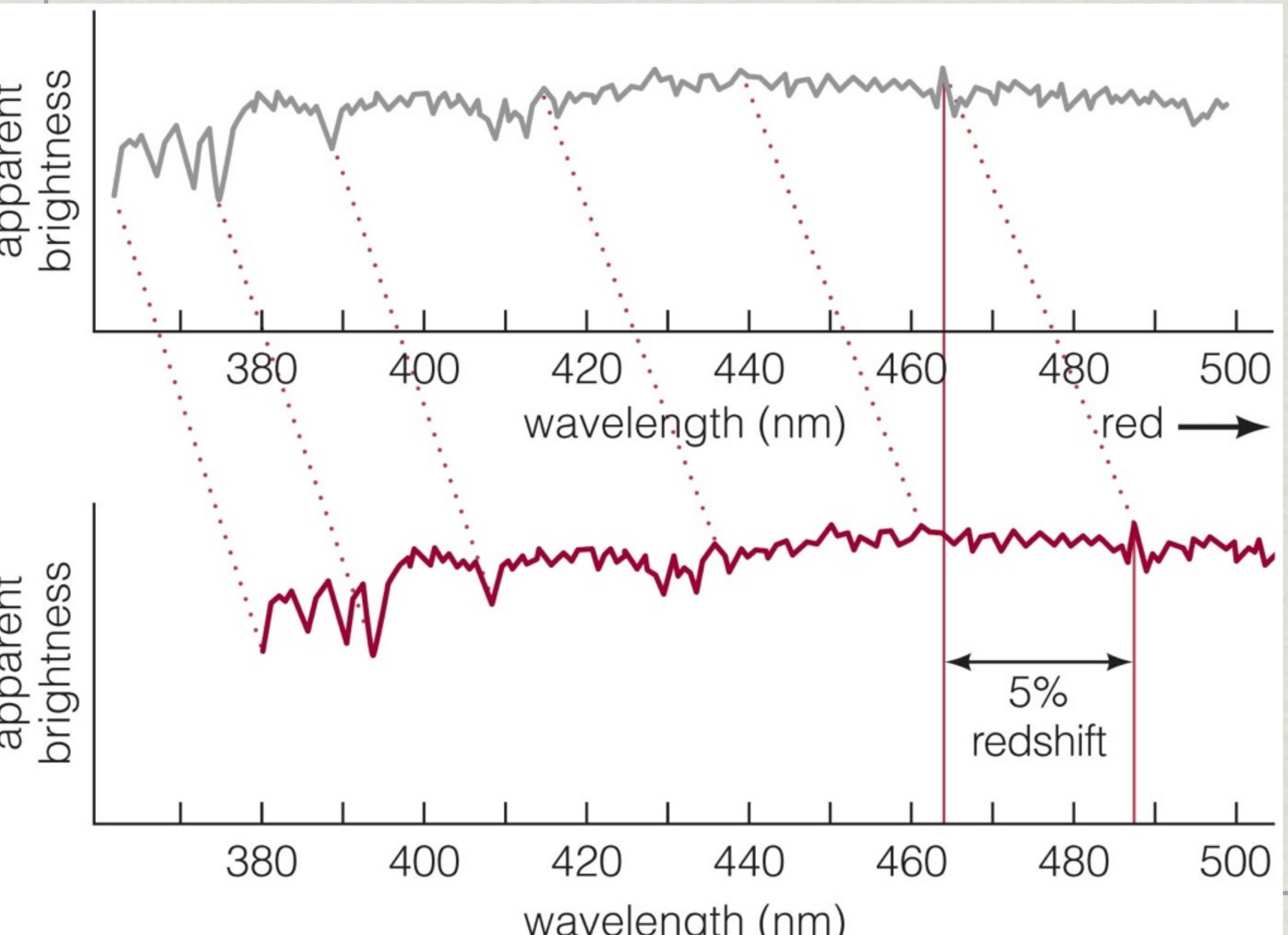




Distances to Galaxies

Edwin Hubble (him again) used the inverse square law for light again to measure the distances to other galaxies.

Astronomers already knew that the spectra of almost all other galaxies is red-shifted.



← normal galaxy spectrum. Looks like the sum of many star spectra. More light from bright stars, less from faint stars.

← This is what we observe.

Redshift (z):

$$z = \frac{v}{c} = \frac{\lambda_{shift} - \lambda_{rest}}{\lambda_{rest}} = \frac{\Delta\lambda}{\lambda}$$

This is just the Doppler formula for light (Chapter 5)

Hubble's Law and the Expanding Universe

Hubble's Law $v = H_0 \times D$

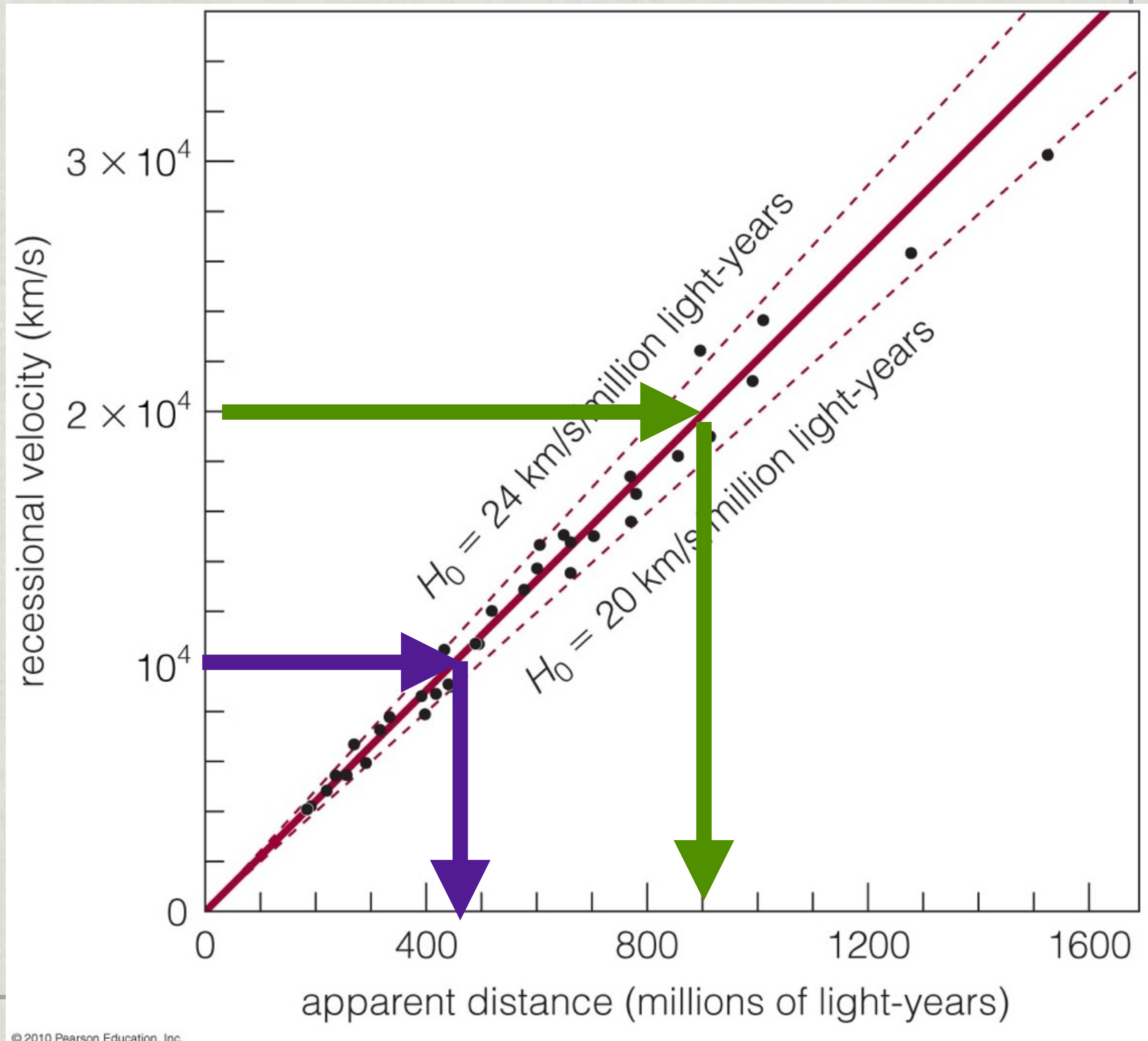
$H_0 = 21$ (km/s)/Mly

H_0 = Hubble's Constant, relates distance and velocity

Looks like all the galaxies are moving away from us
More distant galaxies are moving faster.

Space is expanding, so the distance between galaxies is growing.

Measure a galaxy's Doppler velocity (redshift), know H_0, find its distance from us.



Hubble's Law and the Expanding Universe

Hubble's Law: $v = H_0 \times D$

$\frac{1}{H_0}$ has units of seconds = time!

What time is that? Time since the expansion started.
That's the age of the universe.

Galaxies that are farther away are going faster.

All galaxies take the same amount of time to get where they are now if they all started very close together and the universe expands at a constant rate.