Announcements

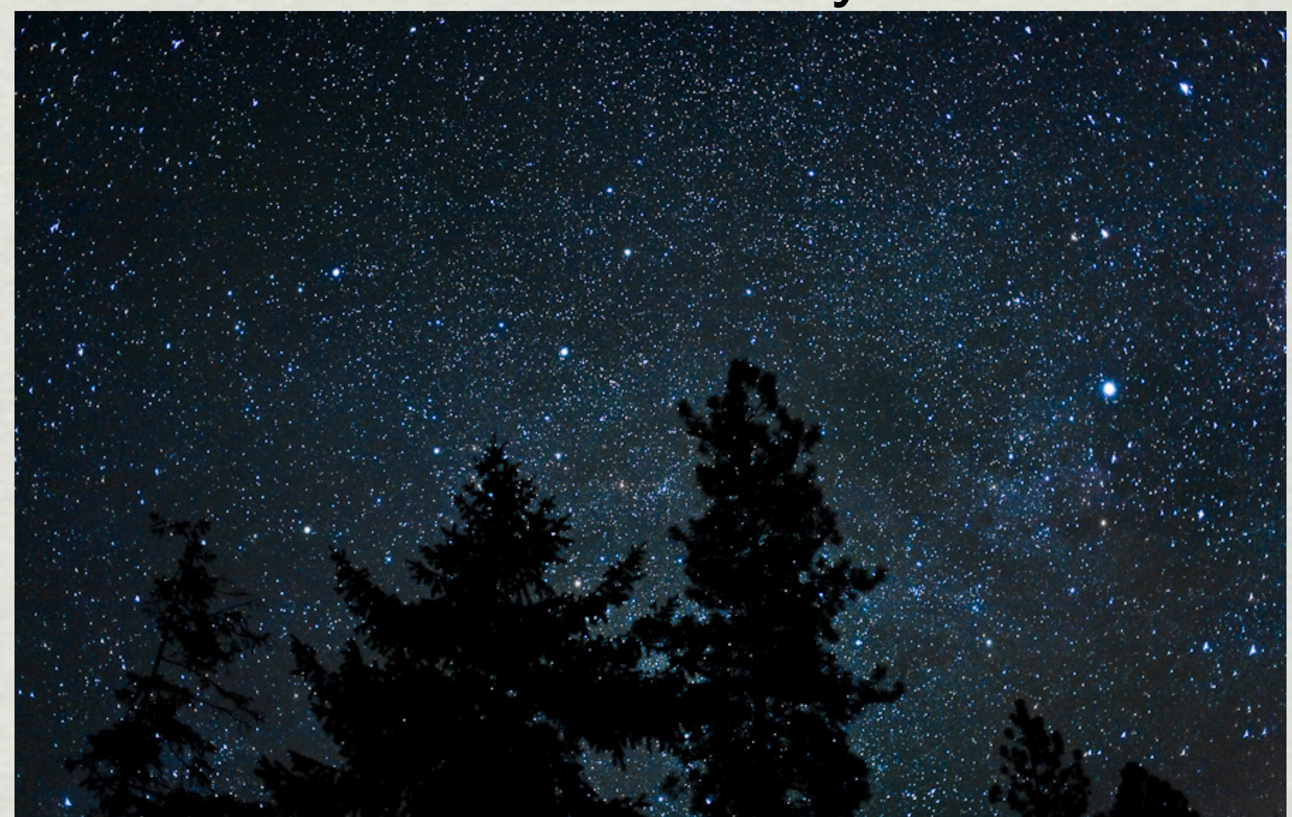
- Please fill out an on-line course evaluation, available today (and sending you annoying email daily!)
- Final Exam: Wednesday, 3/22, 7:30pm, this room
  - 3 hours, same format, rules as midterm: multiple choice with formula sheet, closed book and notes
  - Bring a #2 pencil and a non-internet-enabled calculator. I'll provide the scantrons
- Cumulative: study the midterm material, too. I'll post one of the versions of the midterm with the answer key for you to study
- Review sessions:
  - Marie: Friday, 3/17, 4-5 pm, NatSci2 Annex 101
  - Plato: vote! A) Thursday, 3/16, 8:30 pm

    B) Monday, 3/20, morning

    C) Monday, 3/20, afternoon

Olbers' Paradox

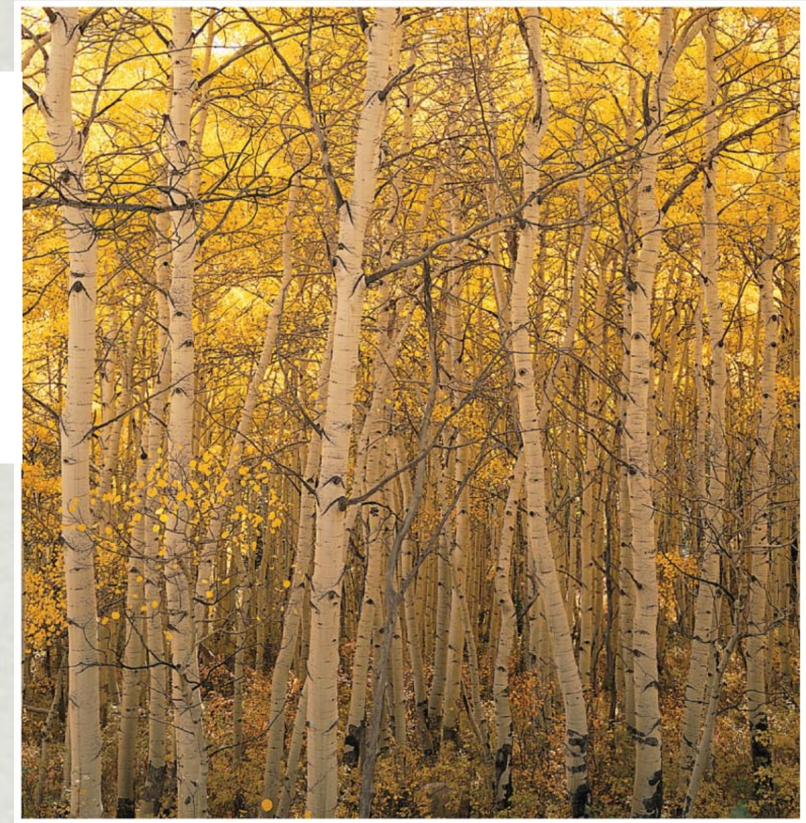
- If you look out from earth, you might see a star in our Galaxy or blank sky.



- If you had a telescope for eyes you could see fainter and more distant objects like other galaxies.
- You would see more stuff, but you would always be able to find blank sky.
- That blank sky tells us something important!

Olbers' Paradox

- The fact that we can always find blank sky tells us something important:
- If the universe were infinite and unchanging and the same everywhere:
  - if you could see far enough you would always (eventually) see a star
  - the sky would be uniformly bright, like the surface of the sun

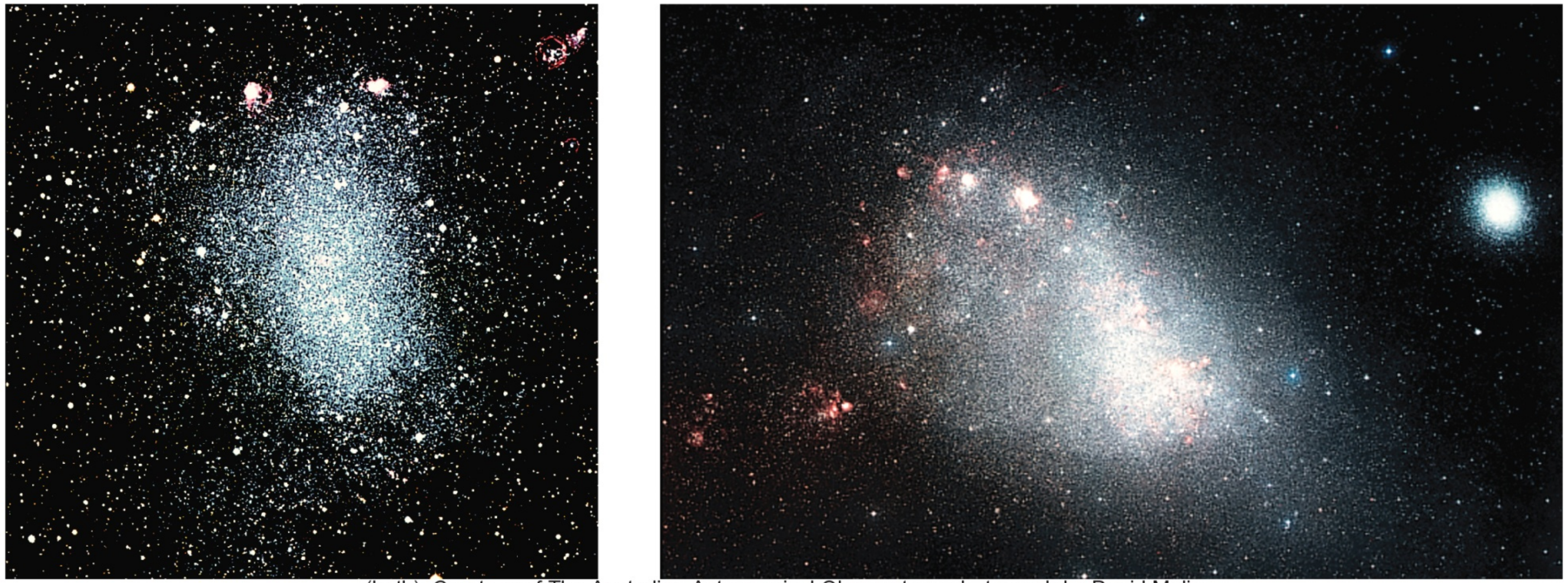


Large Forest, many trees: you see trees everywhere you look

Small Forest, fewer trees: you can see space between the trees

Olbers' Paradox

- That blank sky tells us something important!
  - ***Either*** the universe has a finite number of stars
  - Floating in an infinite black void? Finite, surrounded by a black velvet curtain? But the universe looks the same everywhere, no center, so that isn't it.
  - ***Or*** the universe has changed over time so that we can't see an infinite number of stars
  - Big Bang: universe began 13.7 billion years go, we can only the see objects for which light left 13.7 billion years or less



(both): Courtesy of The Australian Astronomical Observatory; photograph by David Malin

Irregular galaxies.
No neat, tidy disks withs stars moving in circles. But blue, lots of young, hot massive stars. So these galaxies are forming stars now.

Spiral, disk galaxies. Blue, star forming in the disk

“Elliptical” galaxies: balls of stars with random orbits, like gas molecules in a balloon. Red color means all old stars, no ongoing star formation.

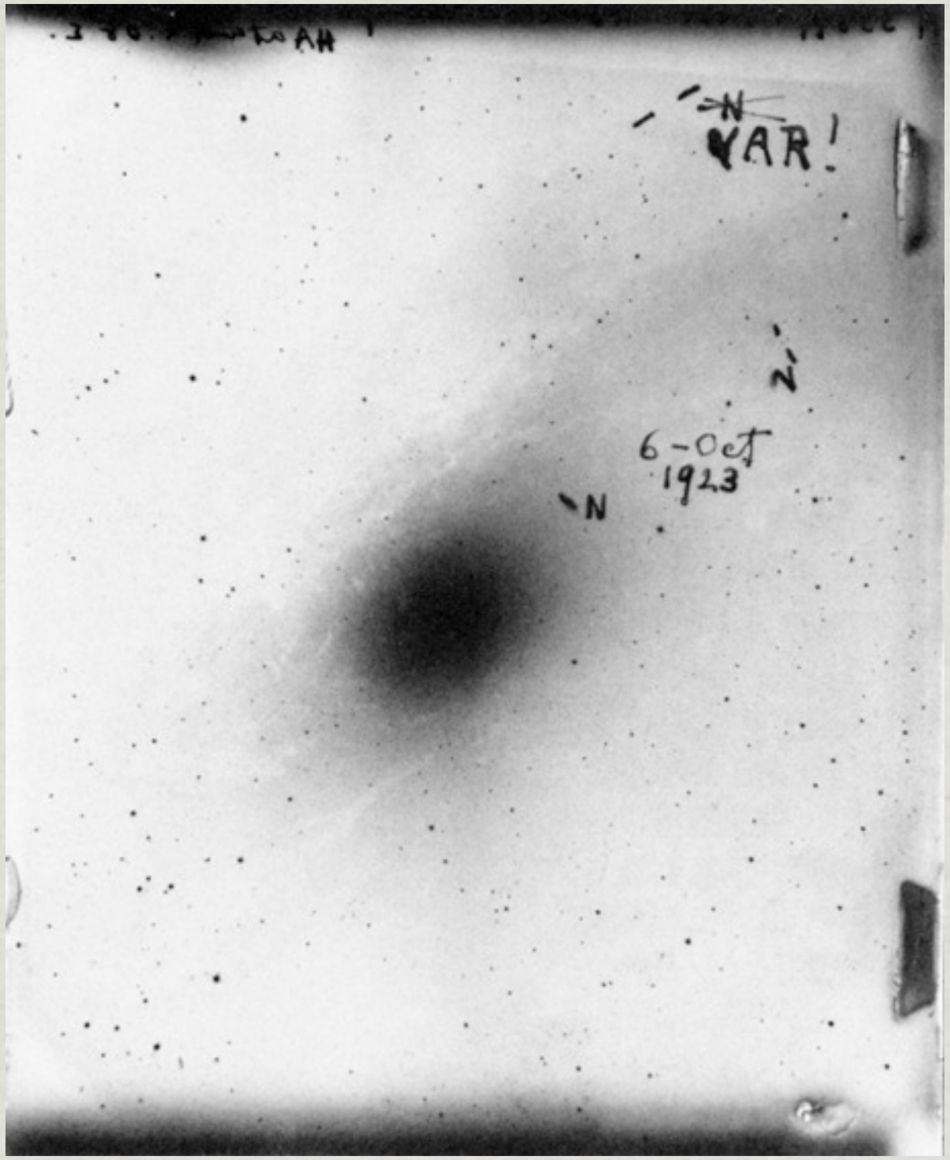
Galaxies in the Universe

- 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”

- Distances:
  - Coma cluster (nearest large cluster of galaxies): 340 million light years
  - Most distant galaxies: 10 billion light years
- Look-back time: light left how many years ago?
  - Coma cluster: 340 million years ago
  - Most distant galaxies: 10 billion years ago

Galaxies in the Universe

It took until the early 20th century just to realize that the fuzzy blobs (called "spiral nebulae" at the time) seen from Earth are other galaxies.



Our nearest neighbor, the Andromeda galaxy, as photographed by Edwin Hubble using the then-new 100 inch telescope on Mt. Wilson, outside LA. World's largest at the time.

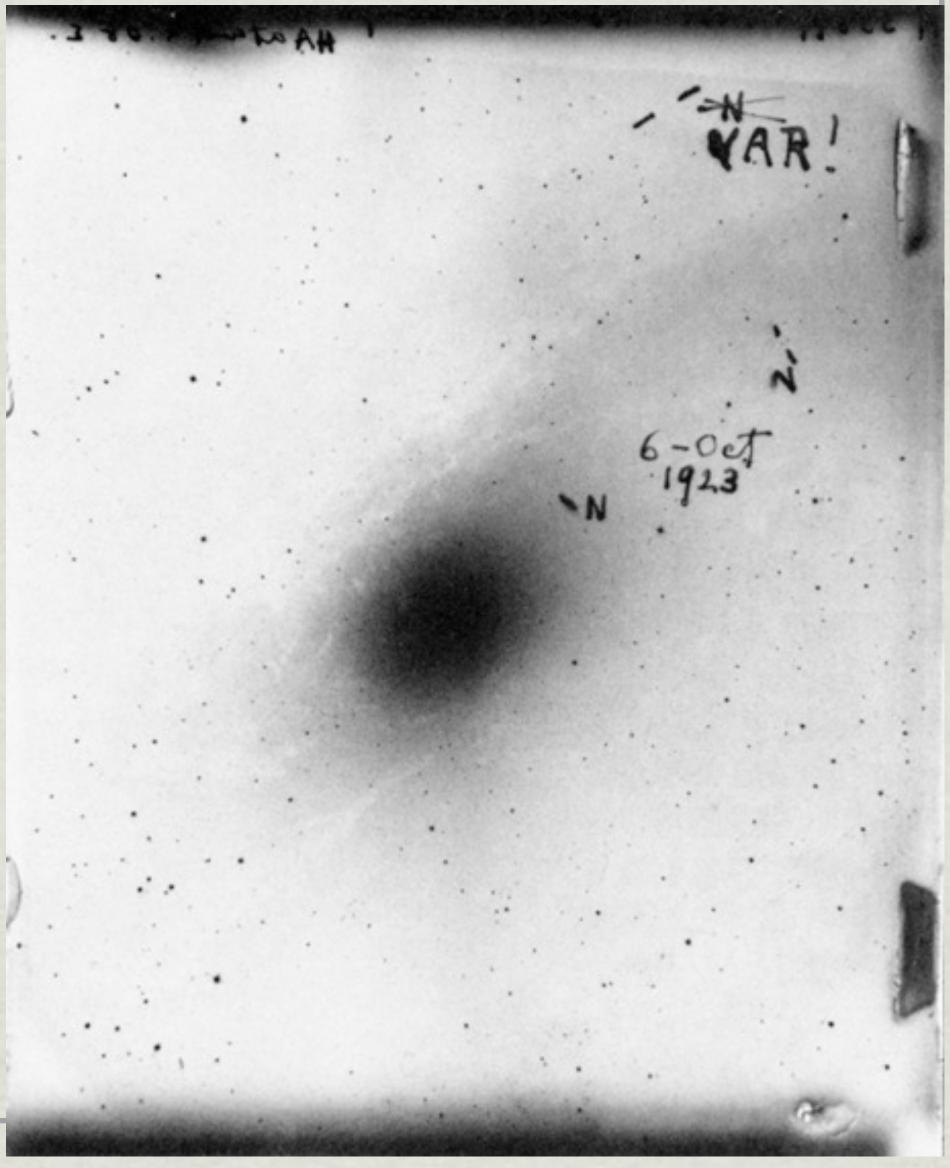
A modern photo of Andromeda

Distances to Galaxies

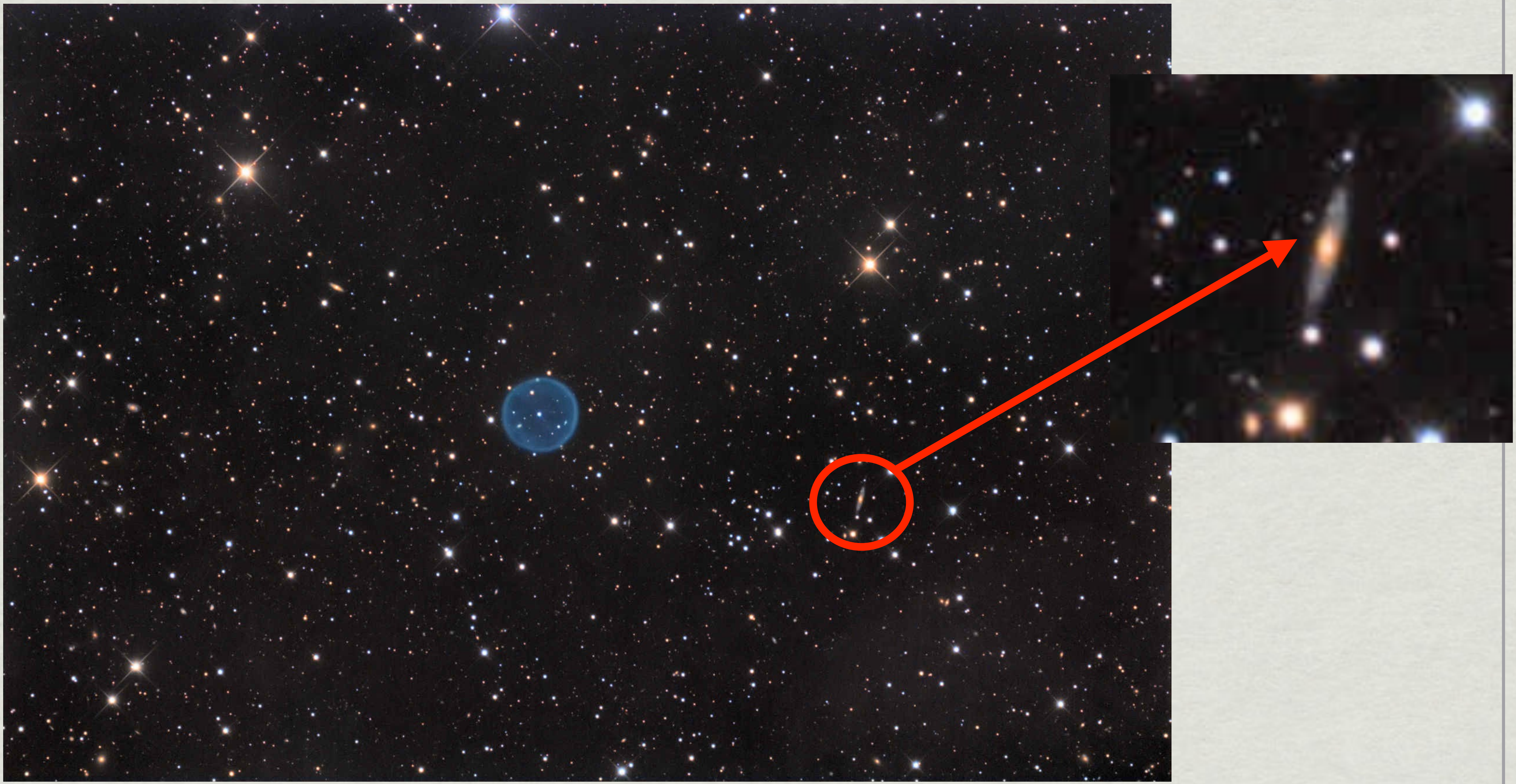
How did anyone figure out what this blob is?

Edwin Hubble (remember the galaxy classification system of ellipticals and spirals from last lecture? Same guy.) measured the distance to Andromeda

Realized it is much farther away than any planetary nebula or supernova remnant in our galaxy.



A Planetary Nebula and a Galaxy: which is bigger?



Angular-diameter distance relation: if two fuzzy blobs are about the same angular size, you don't know if they are the same physical size until you know you know their distances.

Distances to Galaxies

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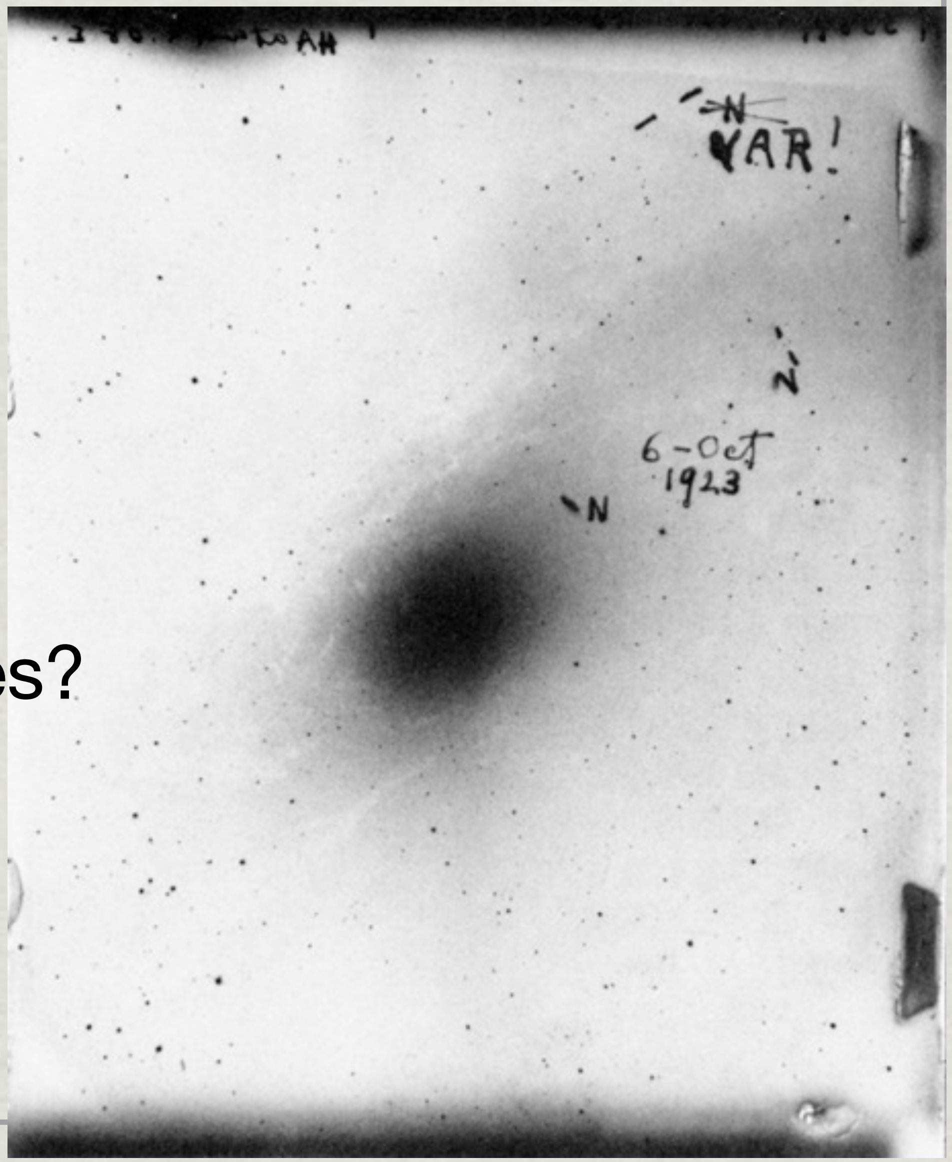


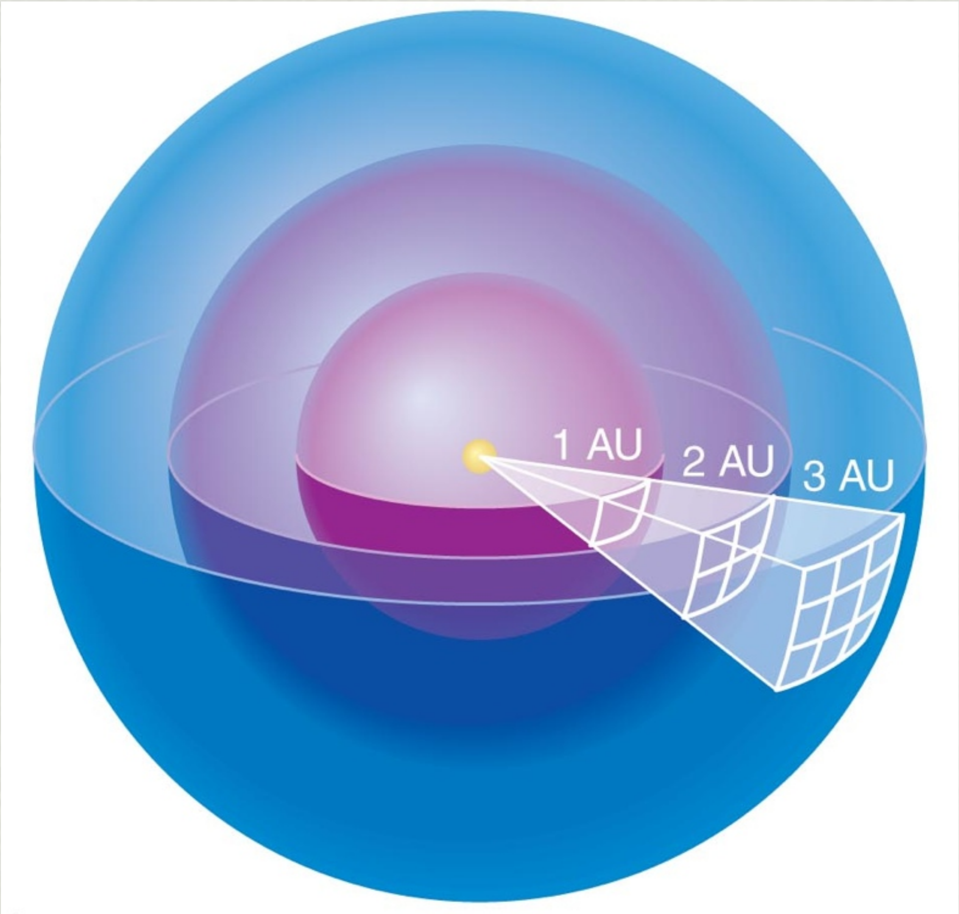
How did Hubble measure the distances to galaxies?

Find an object with known luminosity (L).

Measure apparent brightness, B

Calculate distance (d): $L = B \times 4\pi d^2$

Measuring Luminosity



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

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

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

Distances to Galaxies

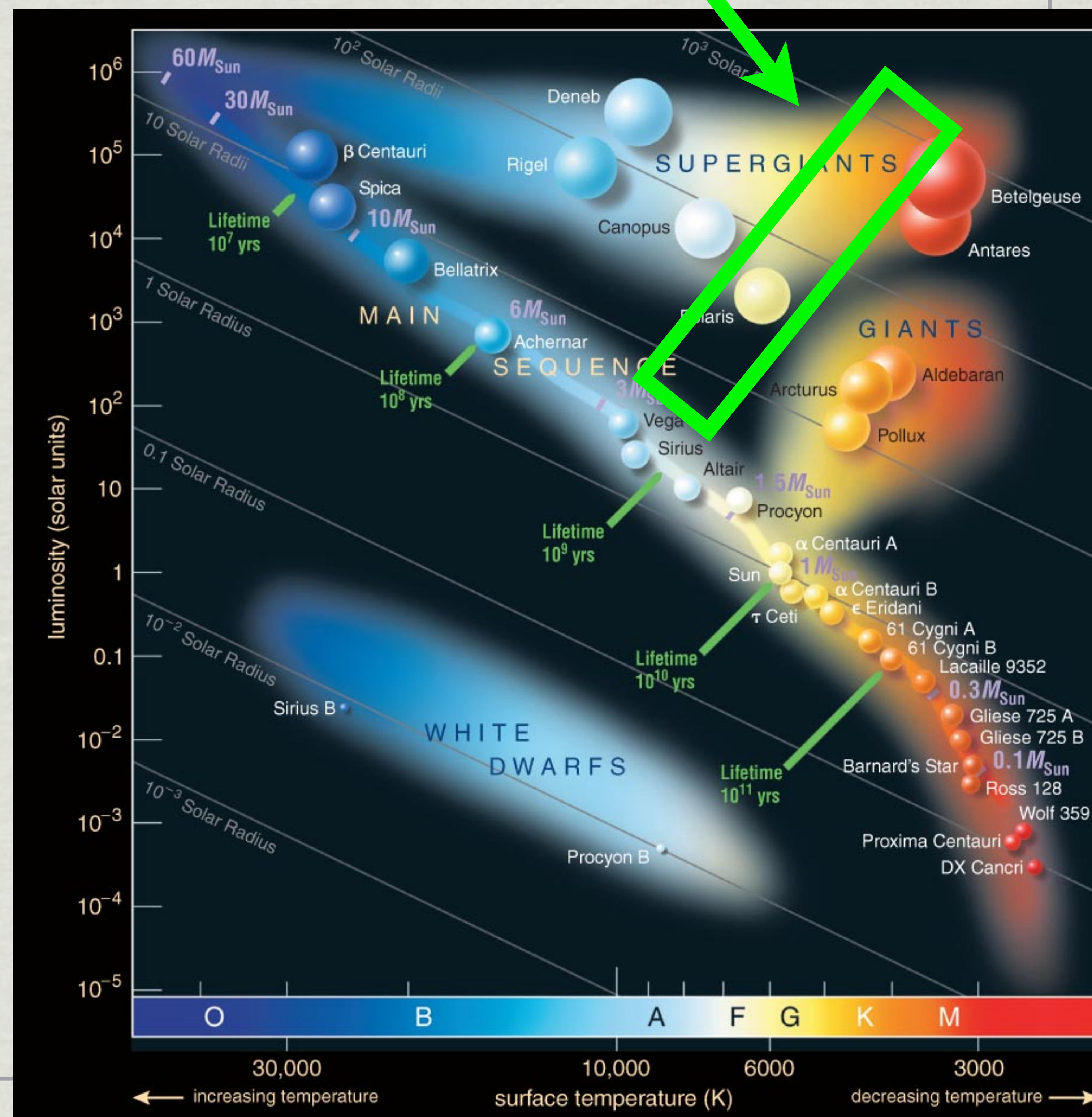
What to measure?
- should be bright so we can see it at large distances
- easy: no other data (like a spectrum) needed.

Stars in the instability strip have variable luminosity.

These are massive stars done burning hydrogen in their cores.

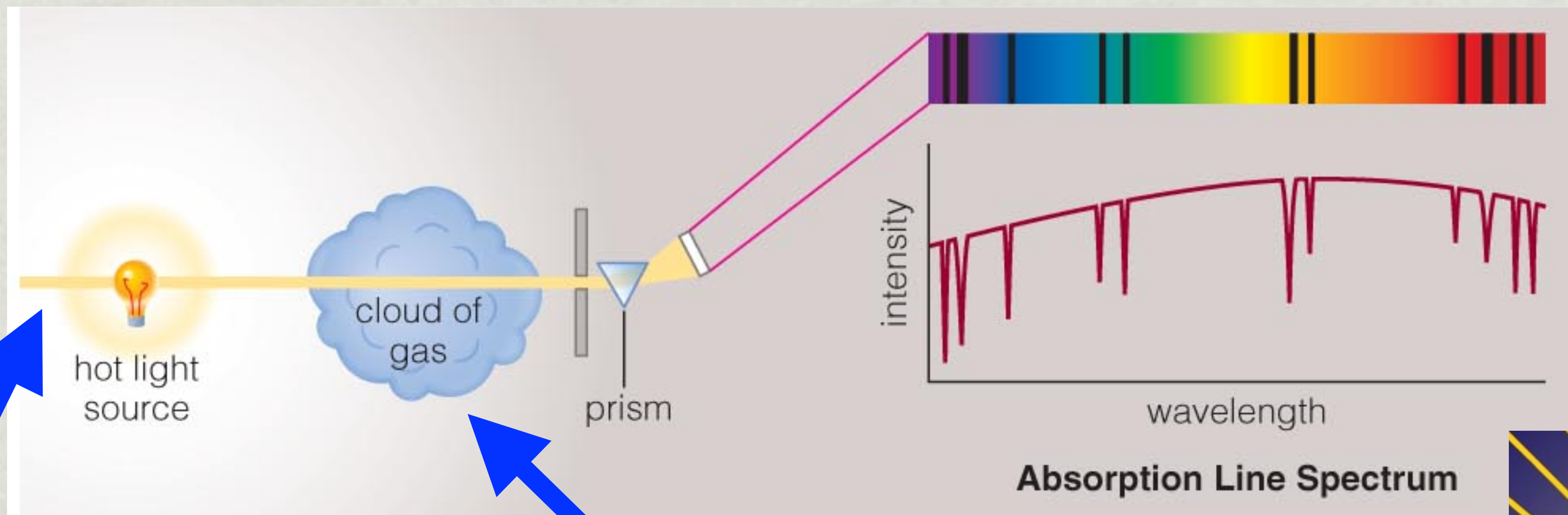
As they cross the HR diagram, they reach special values of temperature and density where the absorption lines in their photospheres trap a significant number of photons coming from core.

Instability strip



Solar Spectrum

- Gas at the photosphere is cooler than the lower layers of the sun.
  - Looks like this cartoon

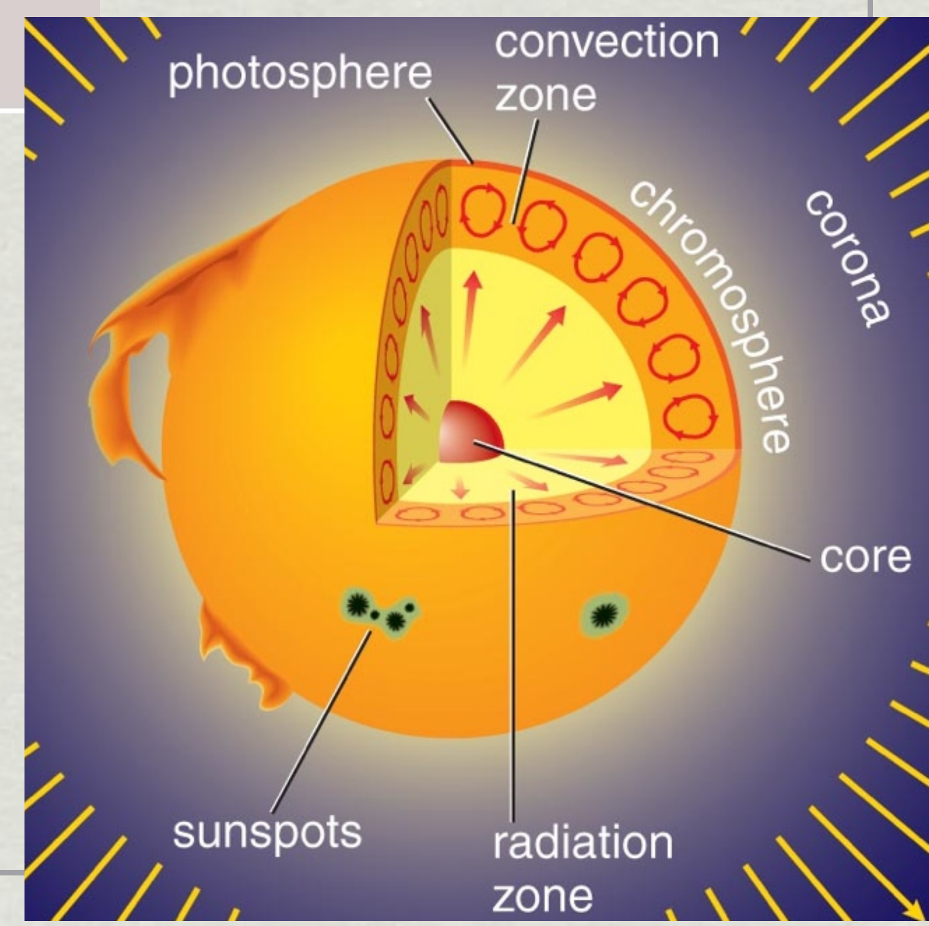


We see an absorption line spectrum from the sun

Thermal source, the inner, opaque layers of the sun

Cooler gas, the photosphere

Cartoon structure of the sun →



Distances to Galaxies

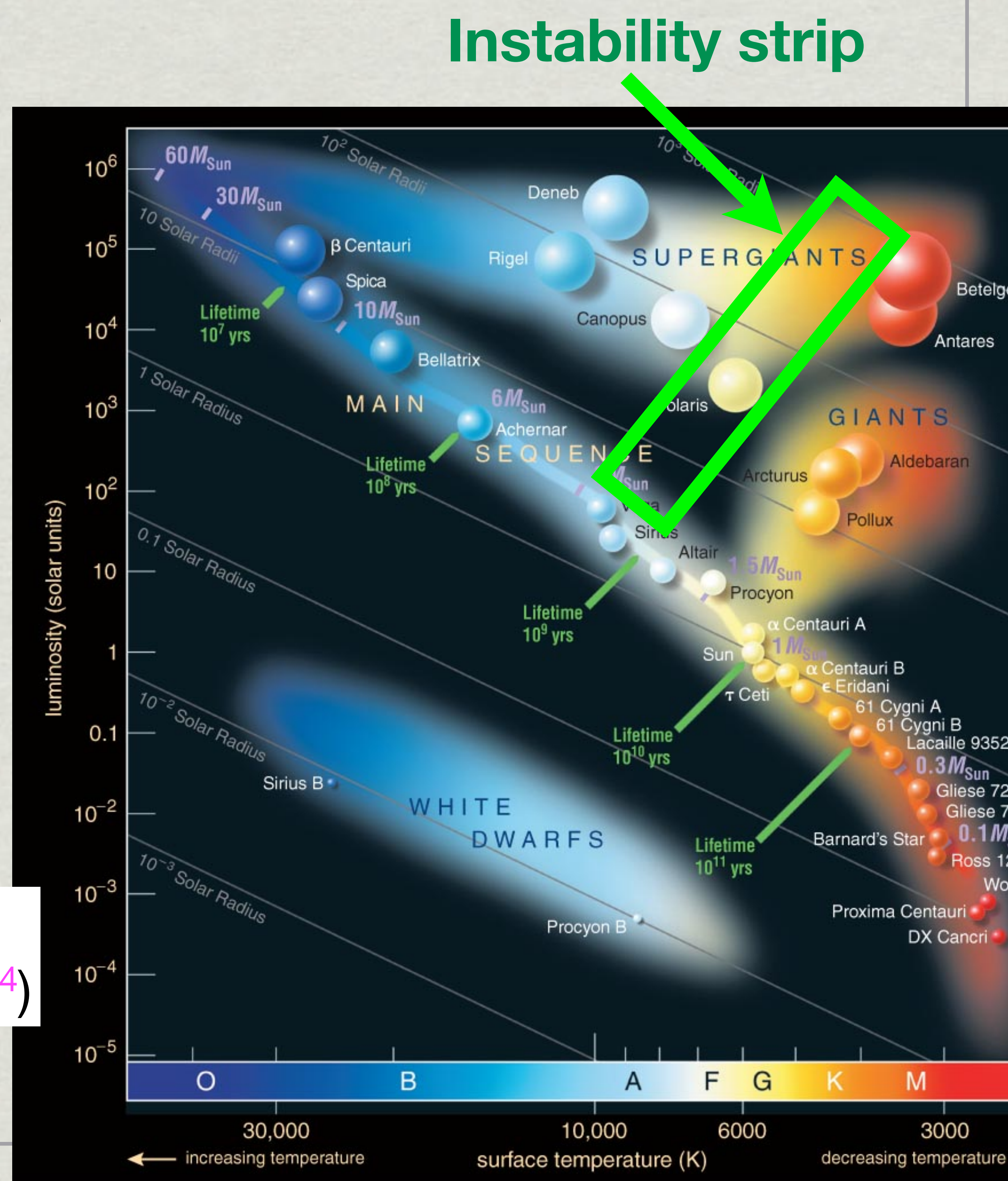
Stars in the instability strip are massive stars done burning hydrogen in their cores.

As they cross the HR diagram, they reach special values of temperature and density where the absorption lines in their photospheres trap a significant number of photons coming from core.

The photons want out, push on the photosphere. Pressure increases, so the star expands

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

and the star's luminosity increases



Distances to Galaxies

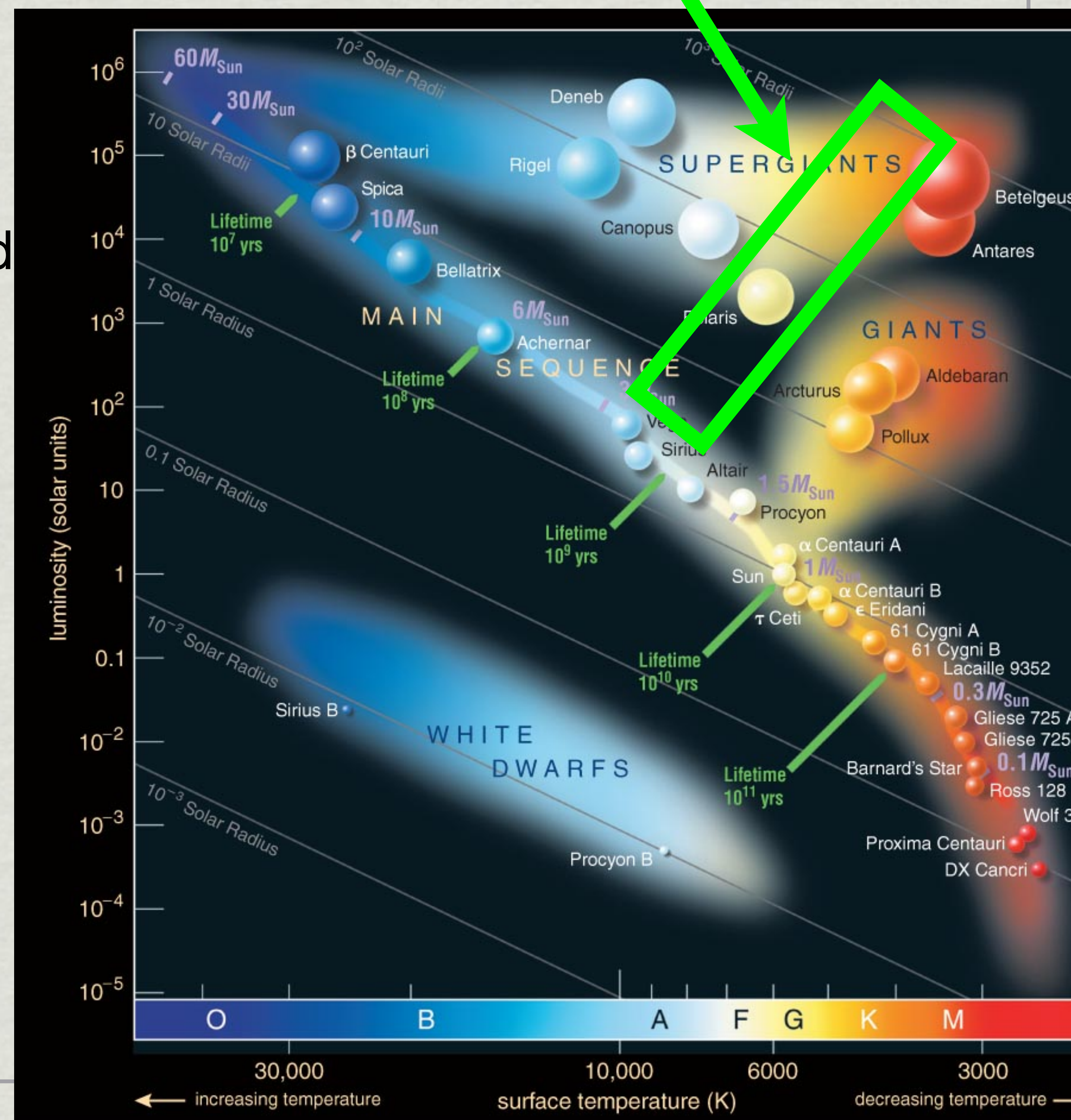
As the star expands and the luminosity goes up the density goes down, and the absorption lines are no longer as good at trapping photons.

The photon pressure decreases and the star "deflates"

Eventually, it is back to the density where the photosphere is good at trapping photons.

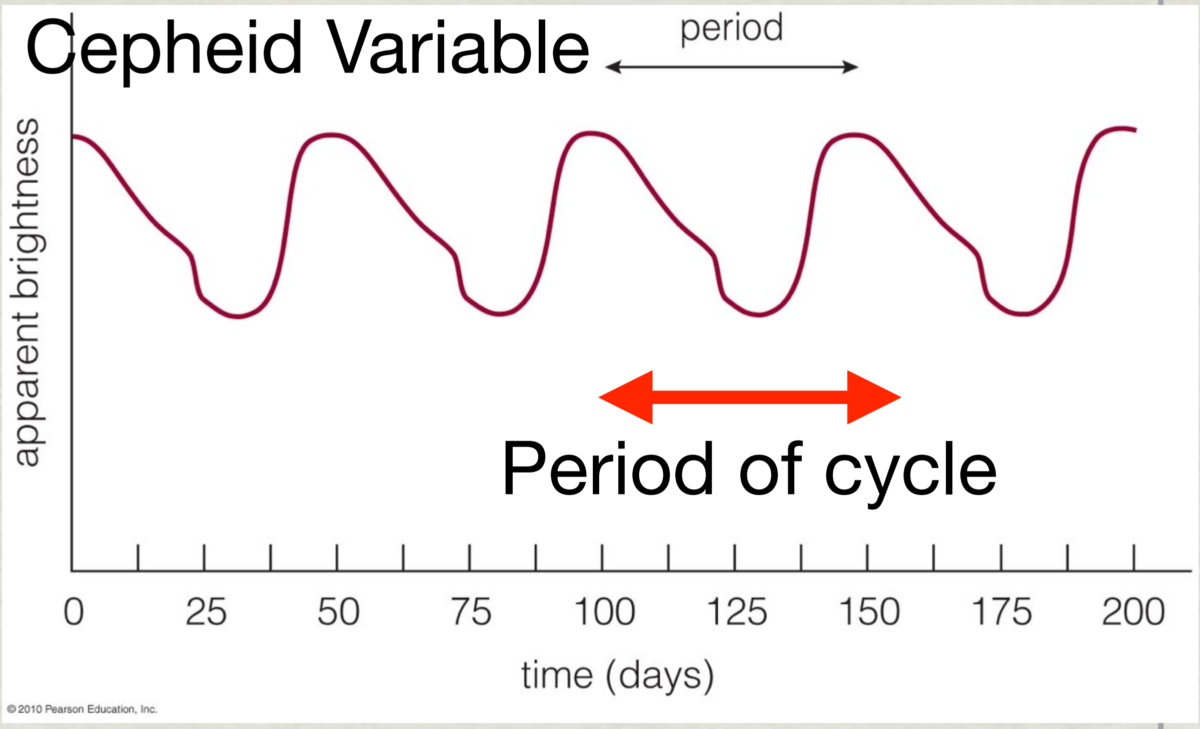
The cycle repeats.

Instability strip



Cepheids

Star changes brightness in a regular cycle as it expands and contracts



We can measure the time it takes to complete a cycle: the period

The stars are called “Cepheid Variables” after the first one discovered, in the constellation Cepheus.

The North (pole) star, Polaris, is a Cepheid Variable

“But I am constant as the Northern Star
Of whose true-fixed and resting quality
There is no fellow in the firmament”
— William Shakespeare, Julius Caesar, 3,1

!!!

Distances to Galaxies

Magellanic Clouds: small satellite galaxies of the Milky Way

Early 1900's: Henrietta Leavitt sees Cepheids in the Magellanic Clouds.

Noticed that brighter Cepheids in the Clouds have longer pulsation periods.

Leavitt realized that because the Clouds are small compared to their distance from the Milky Way, all the Cepheids are at the same distance (close enough). So relative brightness = relative luminosity

Distances to Galaxies

Magellanic Clouds: small satellite galaxies of the Milky Way

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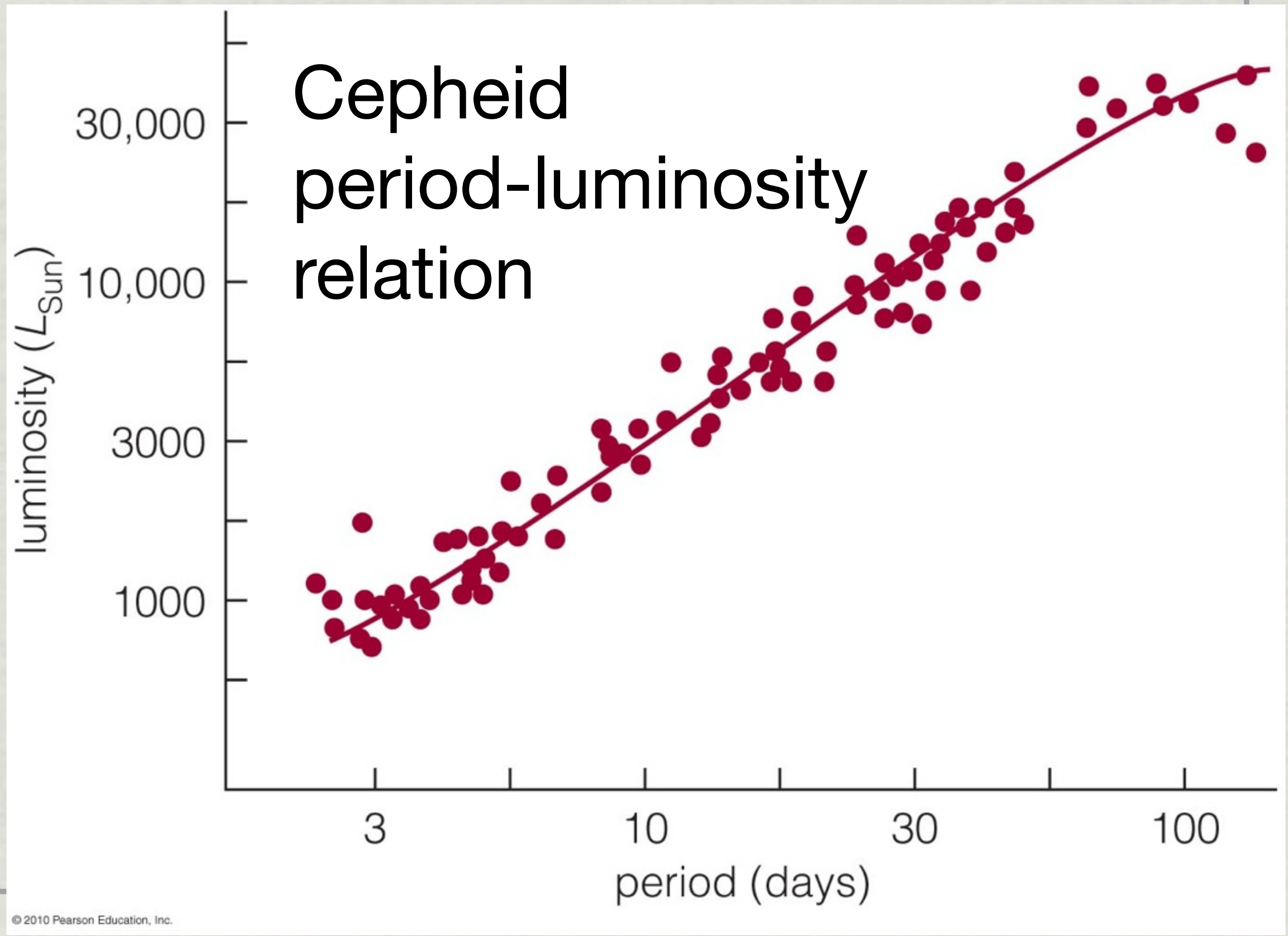
Interpretation: there is a relationship between the luminosity of a Cepheid variable and its period:

More luminous Cepheids have longer periods



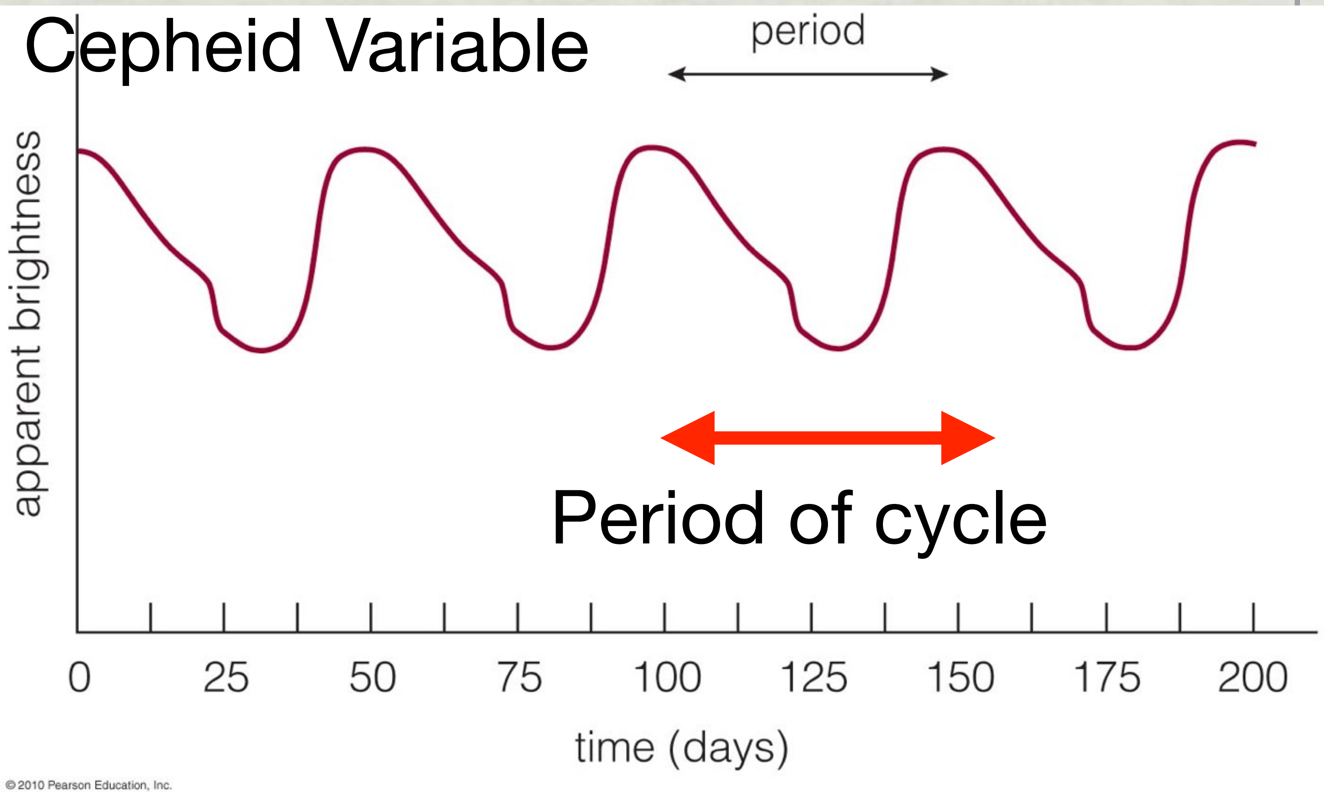
Distances to Galaxies

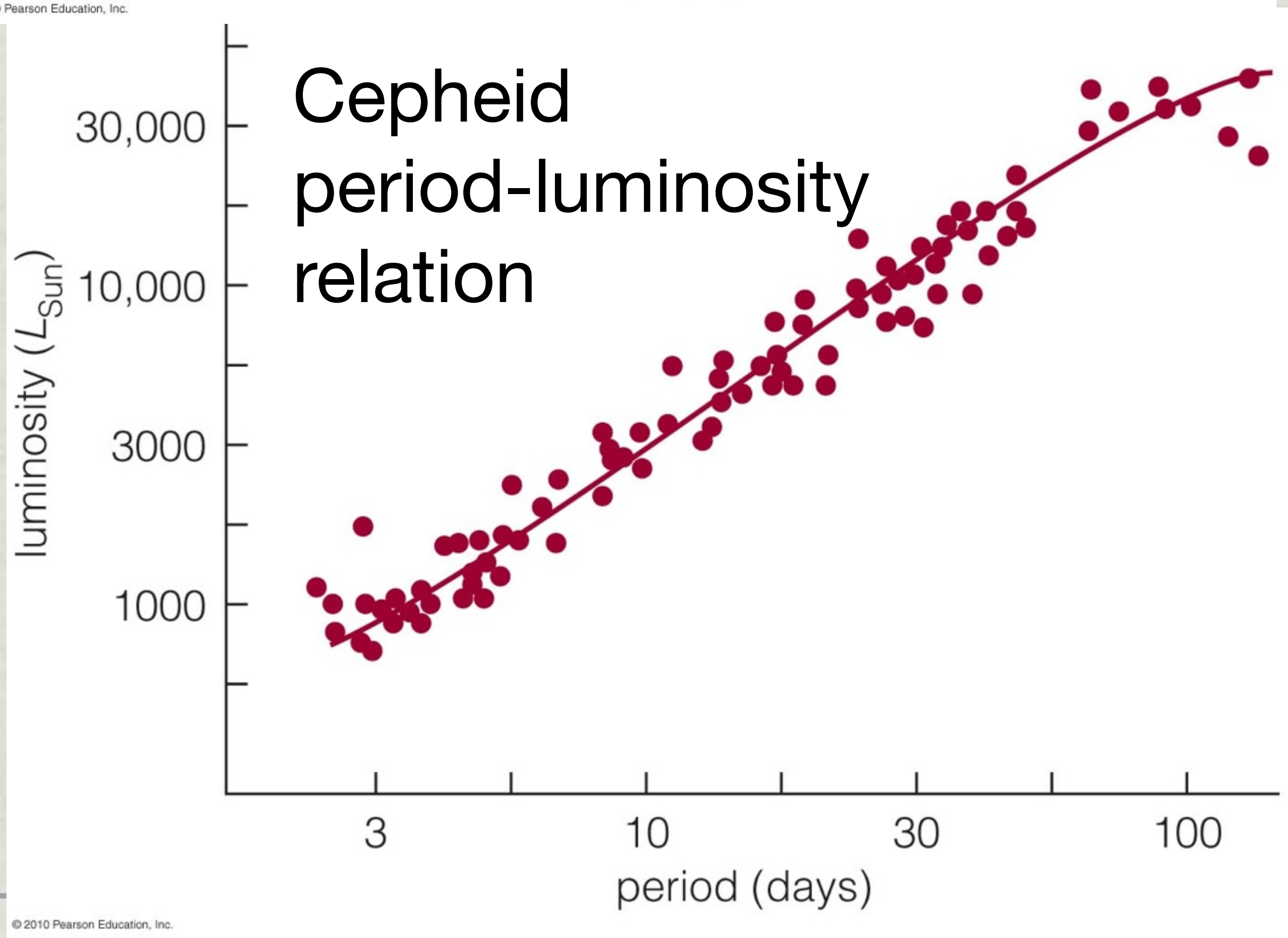
More massive Cepheids are more luminous…

…and take longer to complete an expansion and contraction cycle

That means there is a relationship between the luminosity of a Cepheid variable and its period:

More luminous Cepheids have longer periods





Distances to Galaxies

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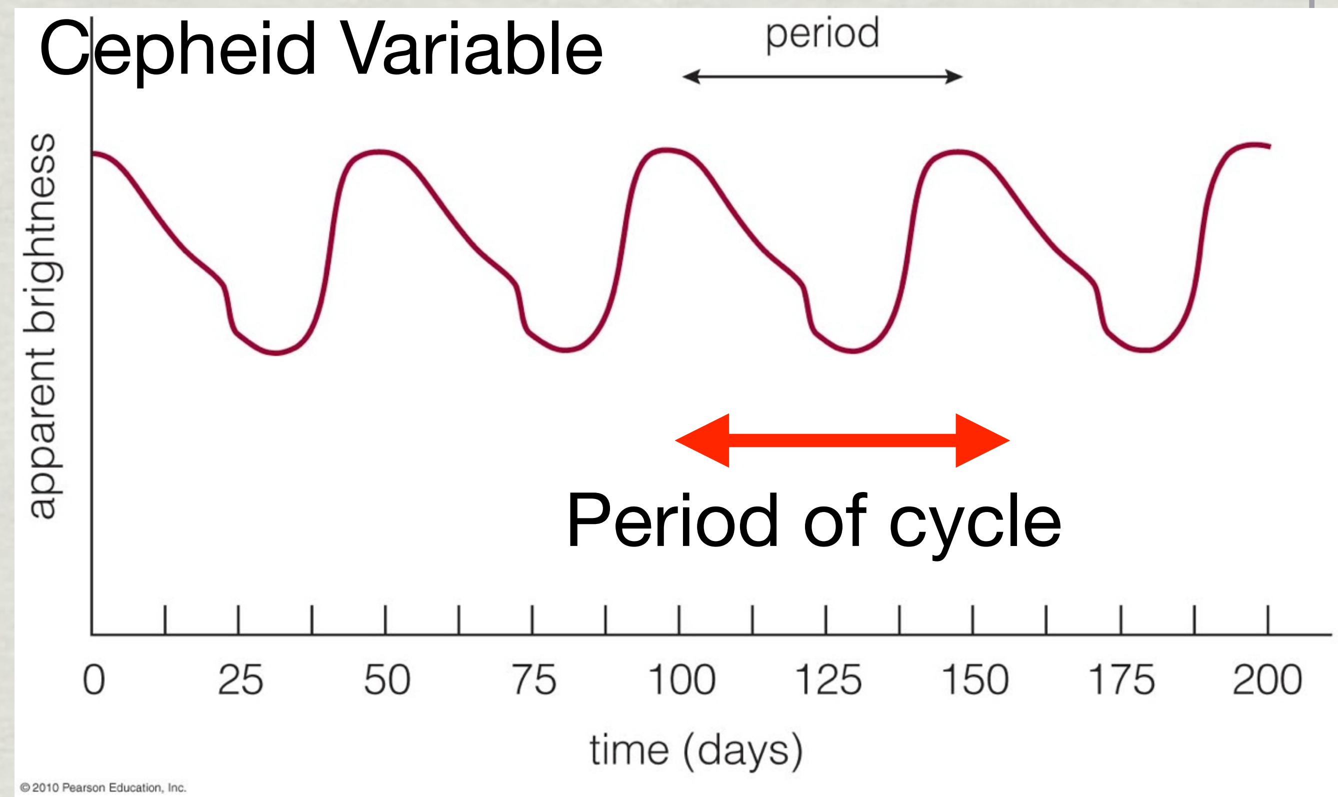
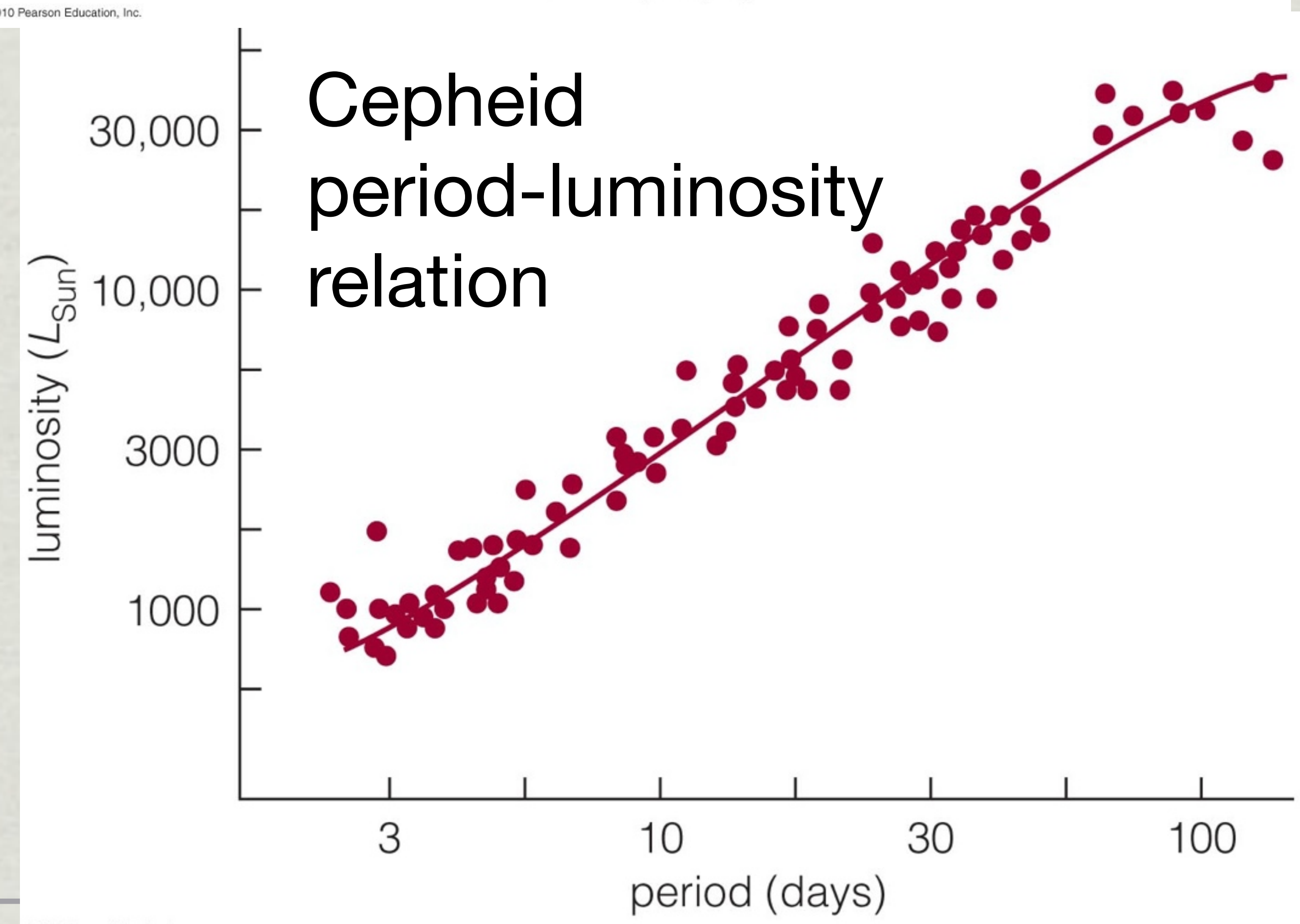
More luminous Cepheids have longer periods

Note: getting the absolute value for the luminosity from the period requires knowing the distance to the Cepheid. That took a while longer!



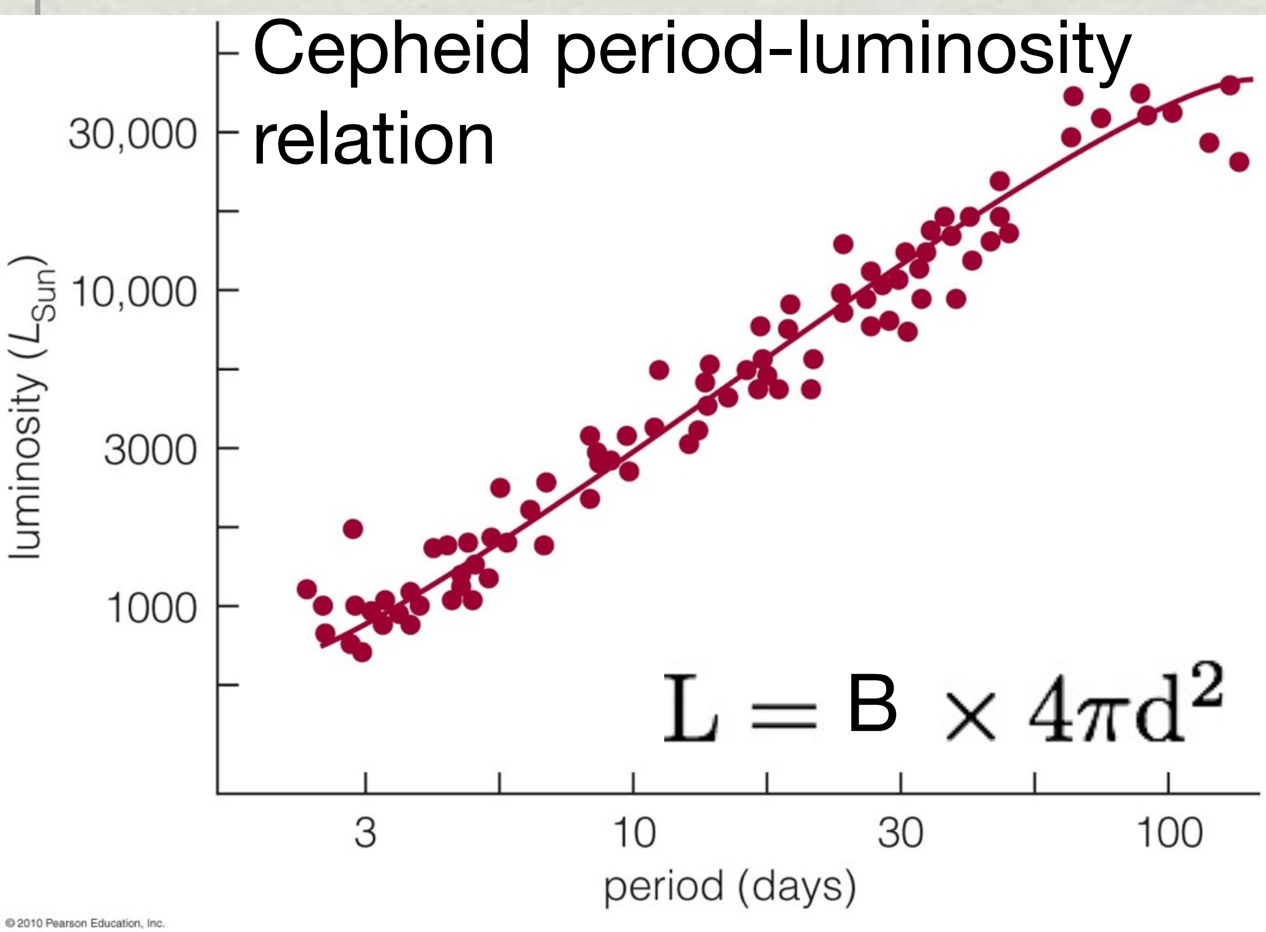


Distances to Galaxies

Why do we have to calibrate the Cepheid Period-Luminosity relation?

Remember Leavitt discovered that brighter Cepheid Variables in the Magellanic Clouds had longer periods.

All she had were relative measurements of the brightness of Cepheids in the Magellanic Clouds. She inferred that brighter Cepheids in the Clouds must be more luminous, since all the Cepheids in the Clouds are at the same distance from us



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

To convert Leavitt's "Period - Relative Brightness" relation to a Period-Luminosity relation, need the distance to the Magellanic Clouds

What we actually use are Cepheids in the Milky Way close enough for parallax measurements.

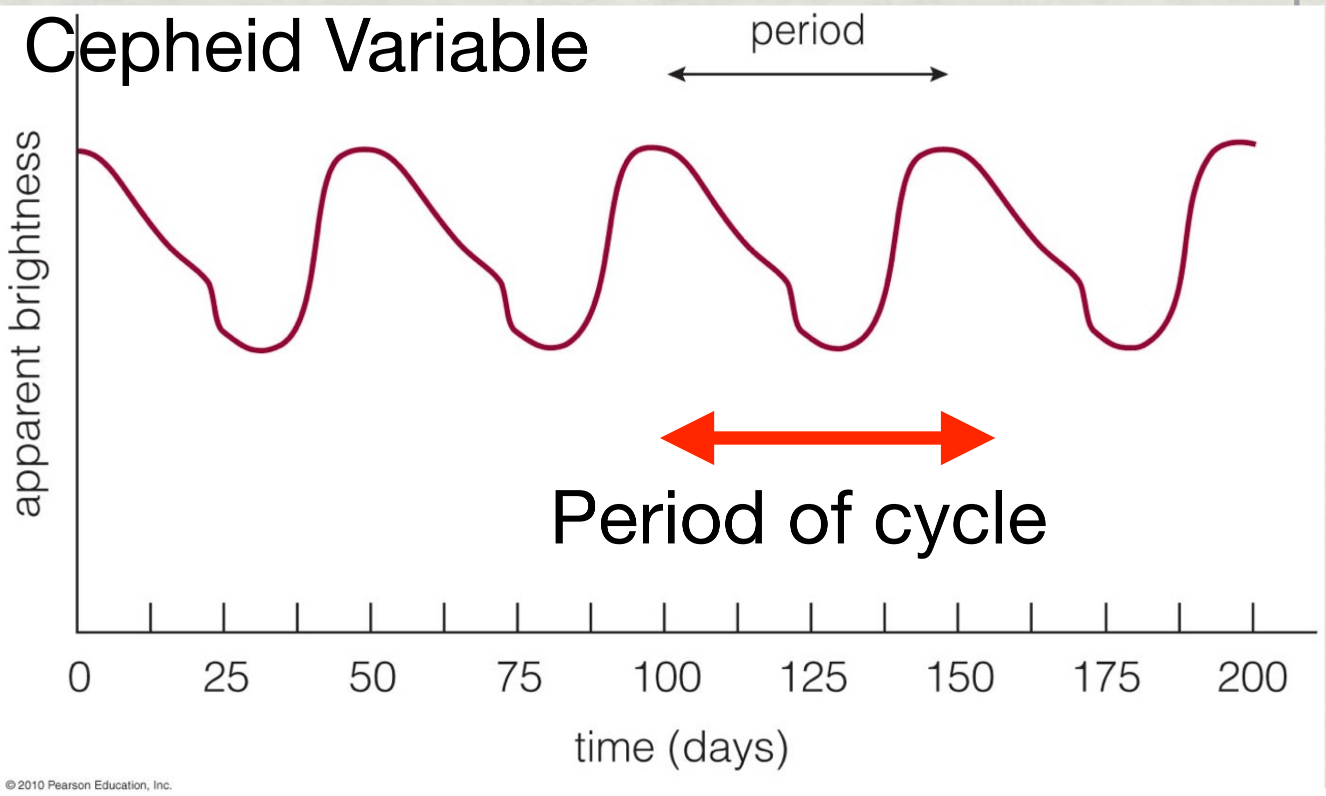
Distances to Galaxies

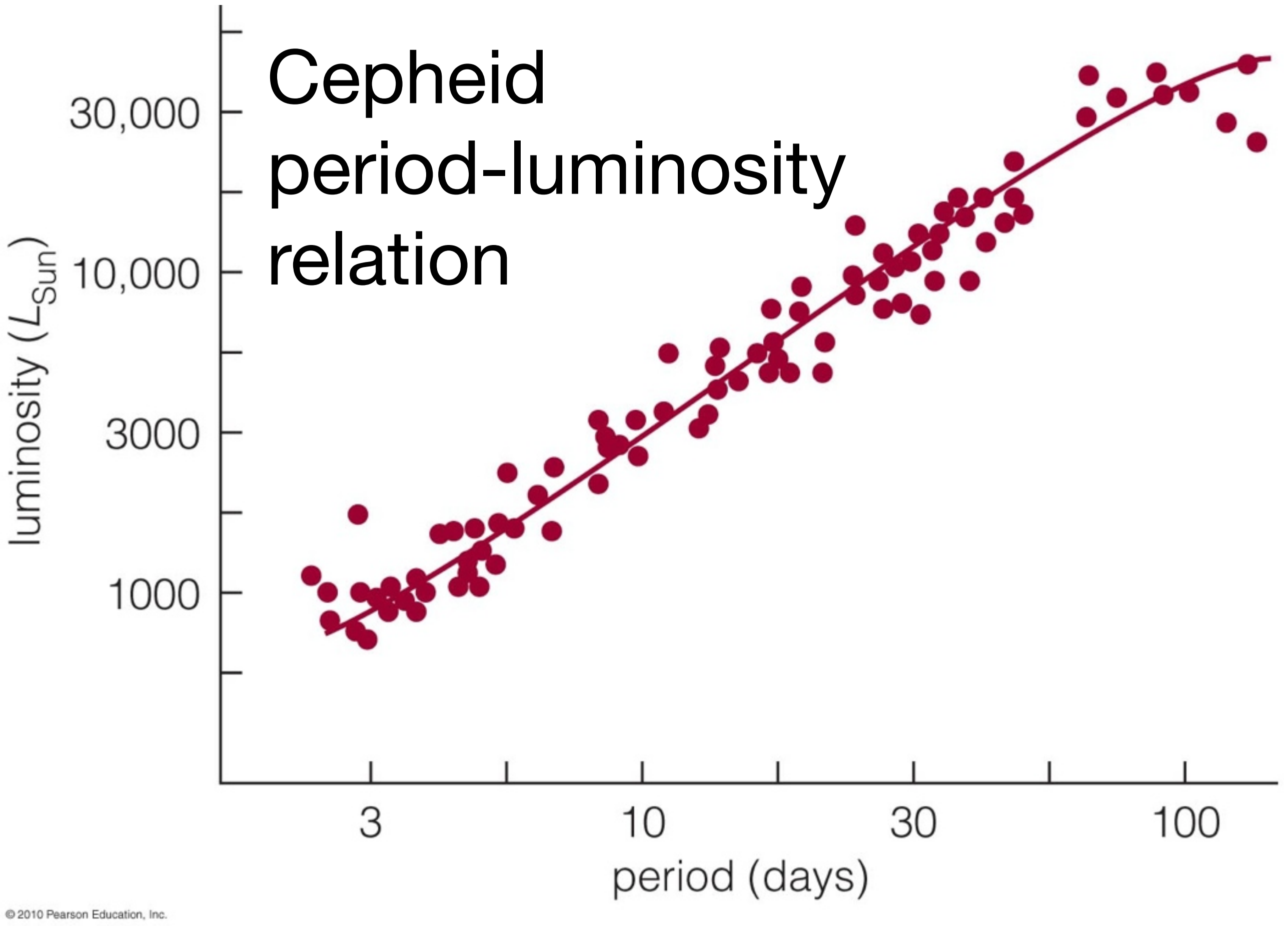
More luminous Cepheids have longer periods

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

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

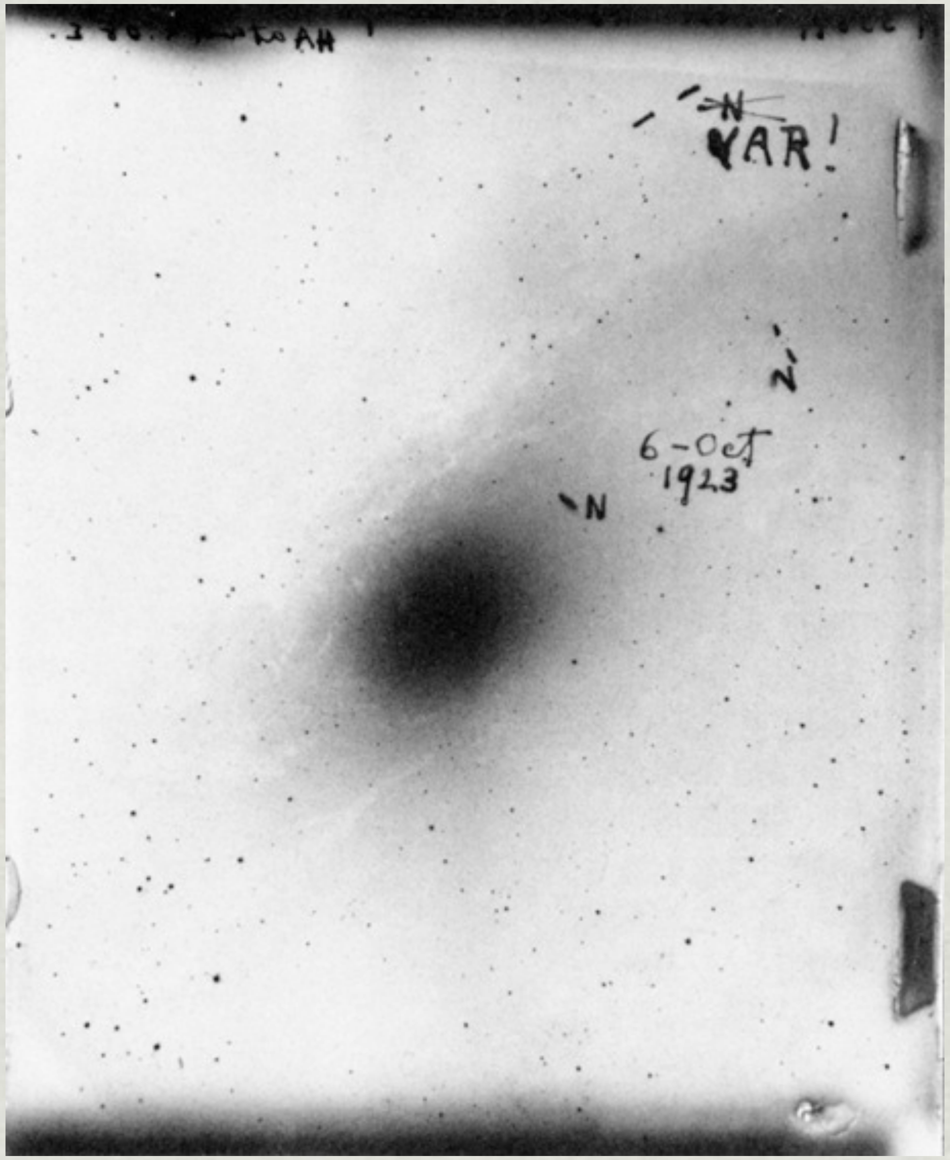
$$L = B \times 4\pi d^2$$





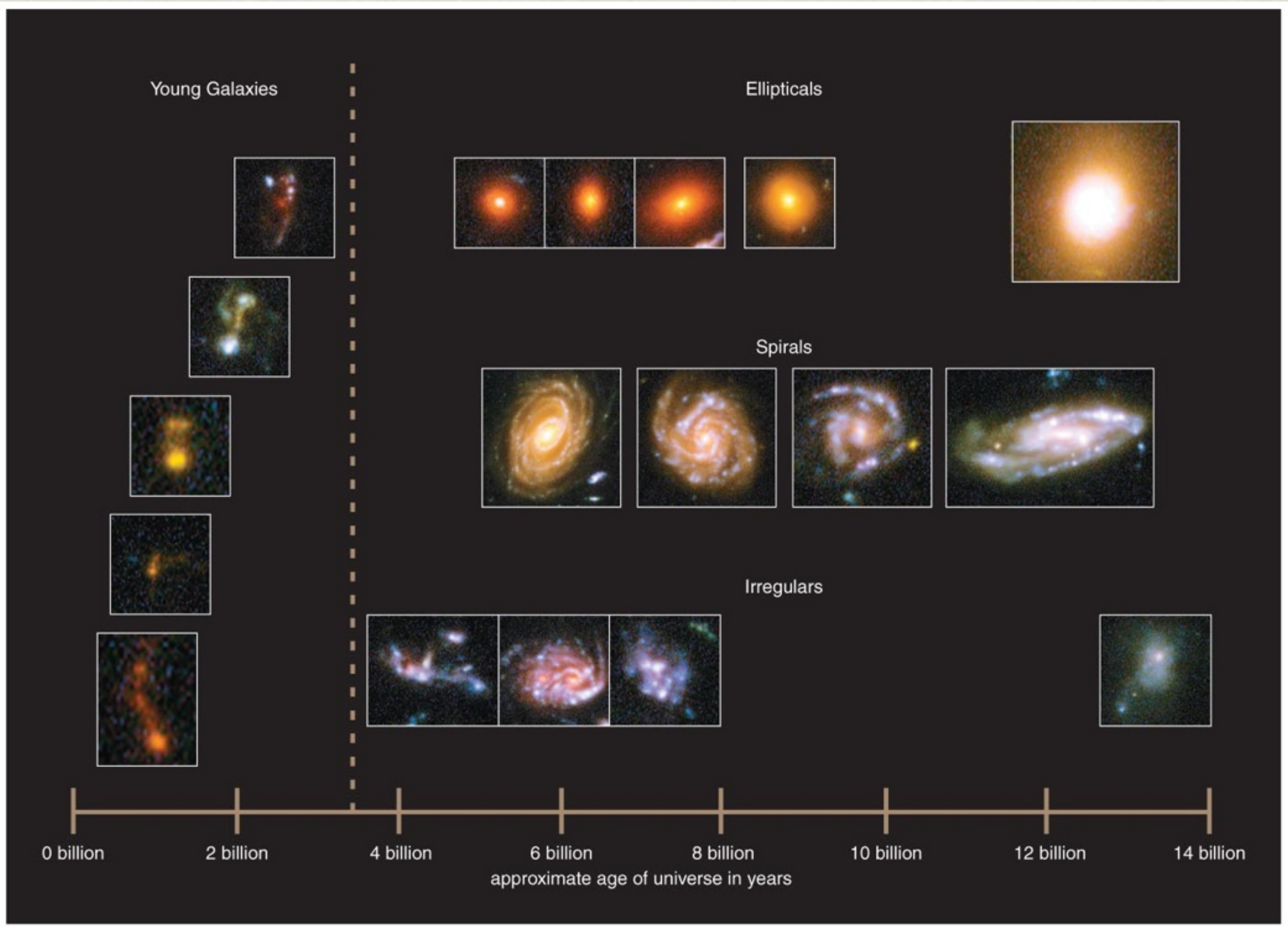
Distances to Galaxies

In the early 1920's, Edwin Hubble found Cepheid Variables in the Andromeda galaxy and showed convincingly that the fuzzy "spiral nebulae" were really other galaxies.



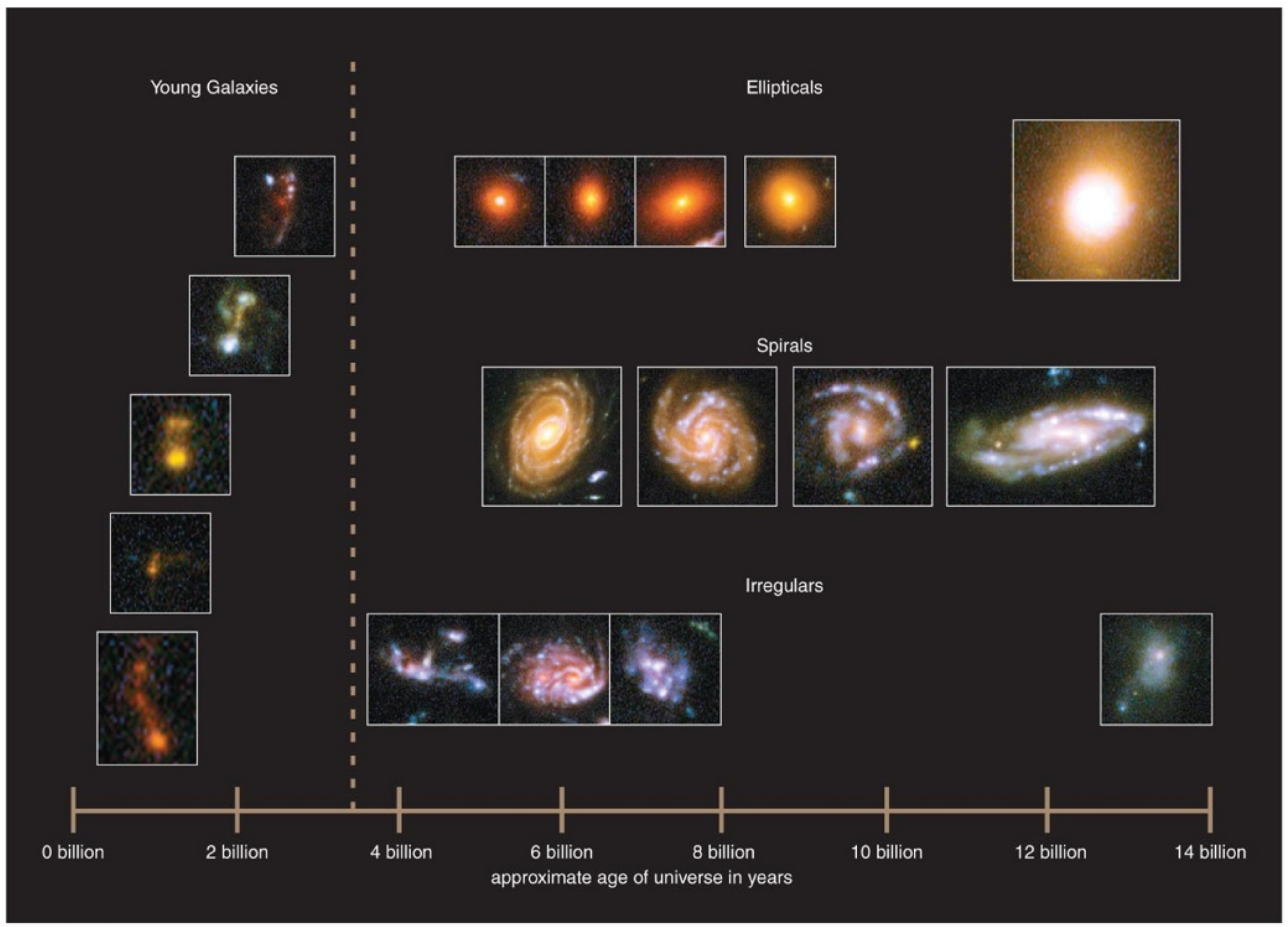
Observing Galaxies as a Time Machine

We see distant galaxies as young galaxies: looking back in time to learn what galaxies were like when they were young.



Observing Galaxies as a Time Machine

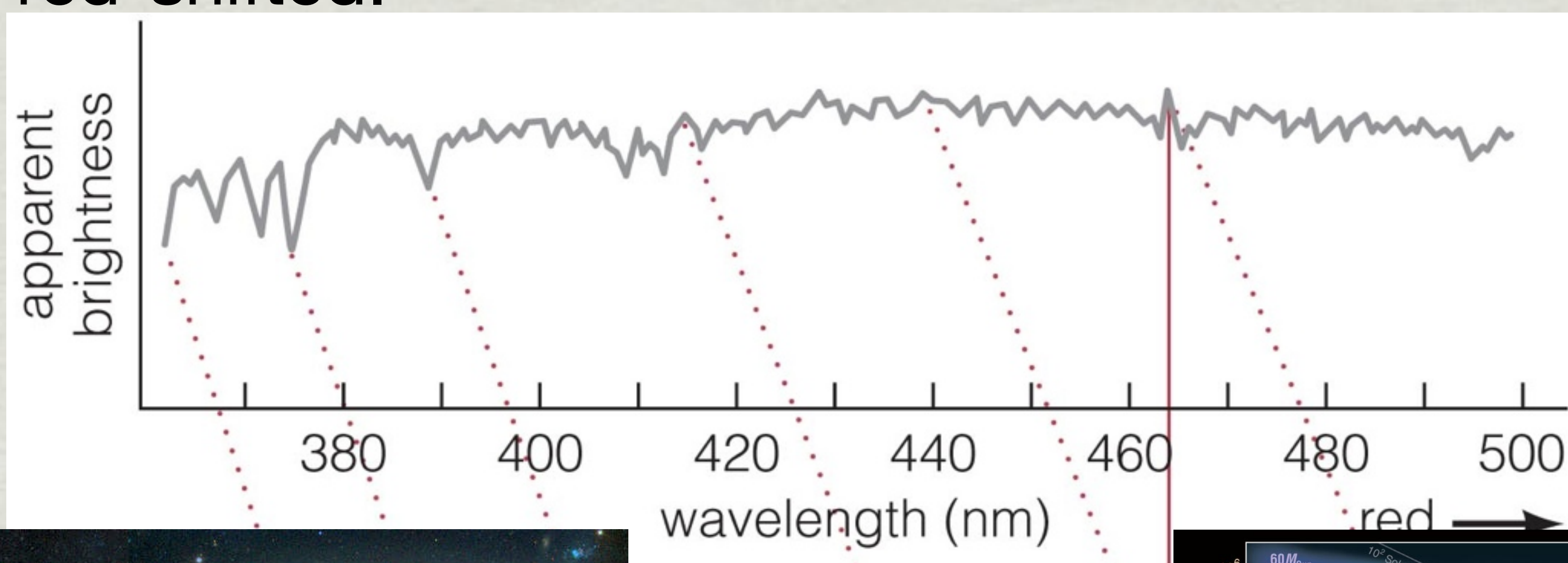
We can also use observations of Galaxies far away to learn what the universe itself was like when it was young



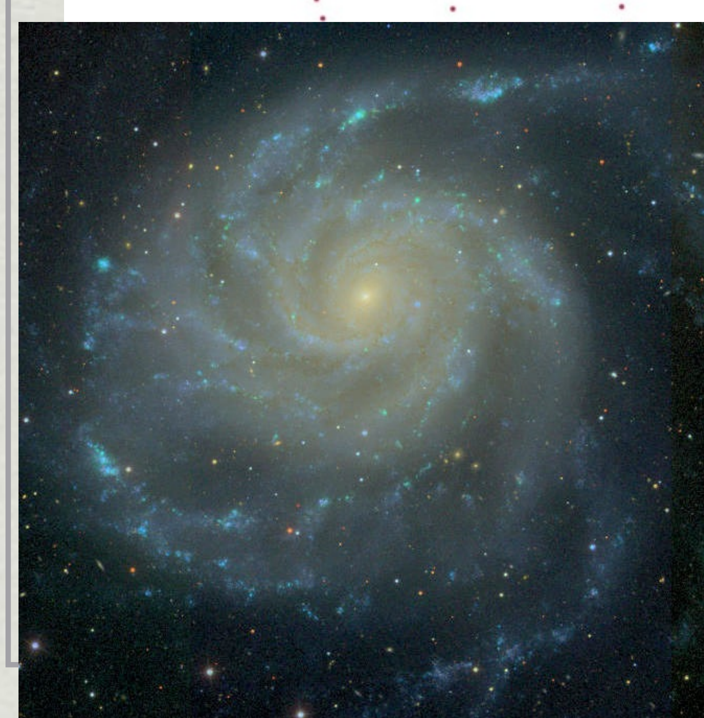
Velocities and Distances to Galaxies

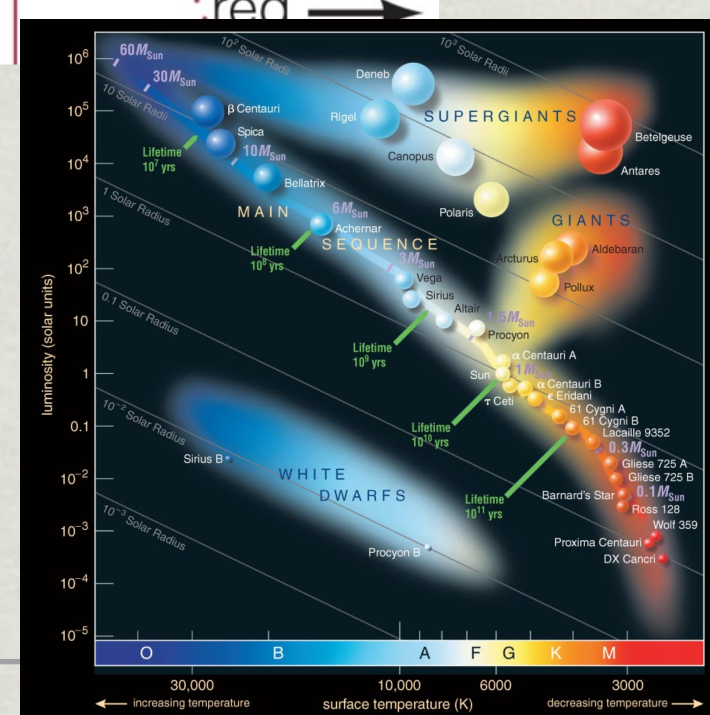
Edwin Hubble (him again) used the inverse square law for light again to measure the distances to many other galaxies besides Andromeda.

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.





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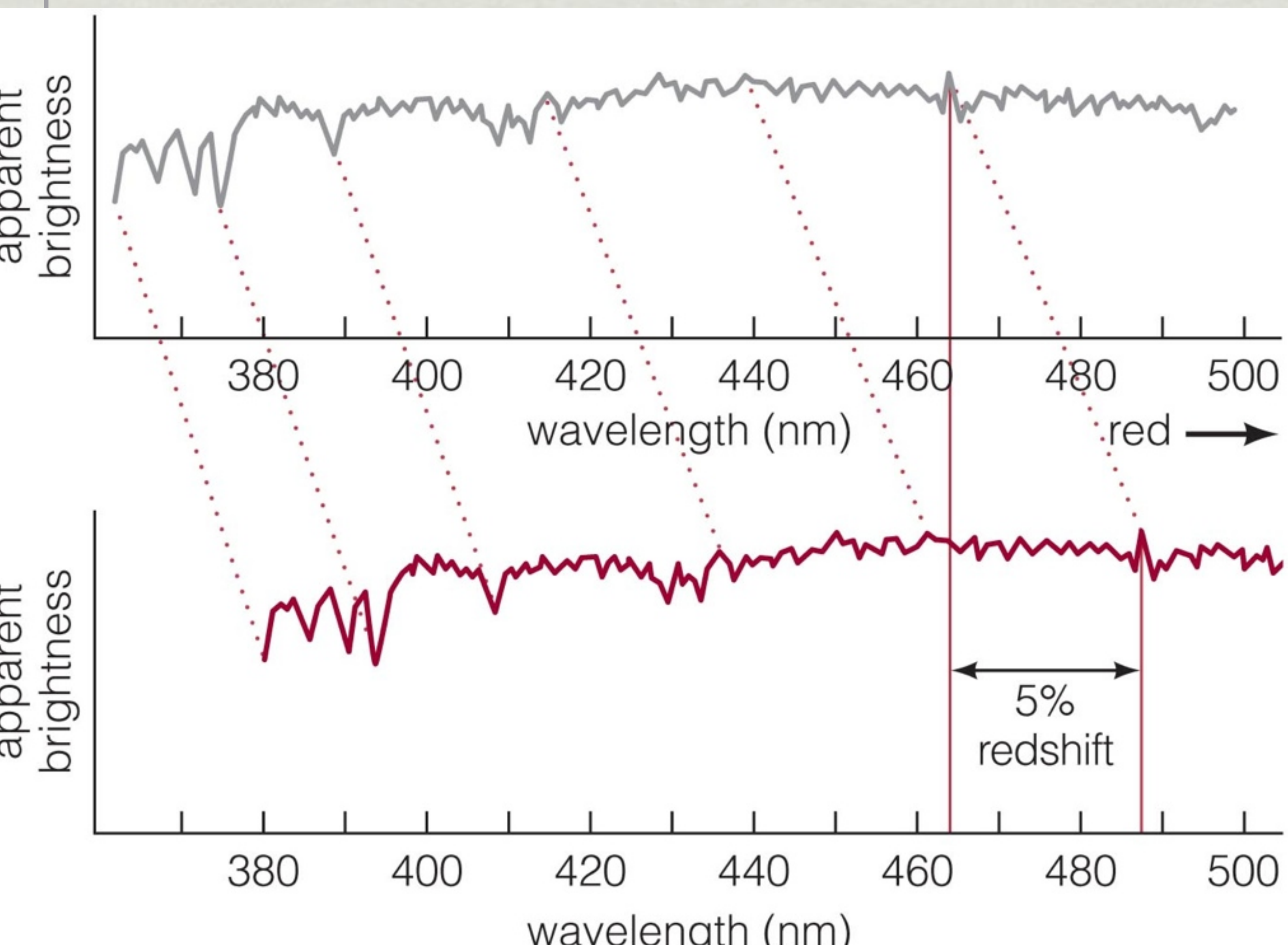


← normal galaxy spectrum. Looks like the sum of many star spectra. More light from bright stars, less from faint stars.

← 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 4)

Velocities and Distances to Galaxies

Andromeda is the galaxy nearest to the Milky Way.

Hubble couldn't identify Cepheid Variables in more distant galaxies, so he took some guesses:

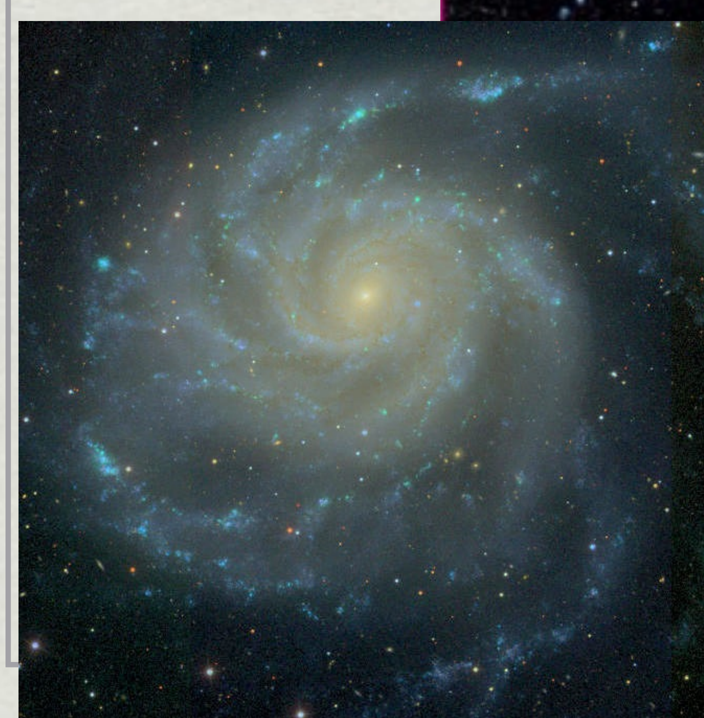
1) the brightest dots in other galaxies are bright stars
2) all those bright stars have the same luminosity

Then he used the Inverse Square Law: $\mathrm{L} = \mathrm{B} \times 4\pi \mathrm{d}^2$

Velocities and Distances to Galaxies

We know Hubble's guess wasn't quite right. Those brightest specs in other galaxies are really clusters of stars, much brighter than single stars.

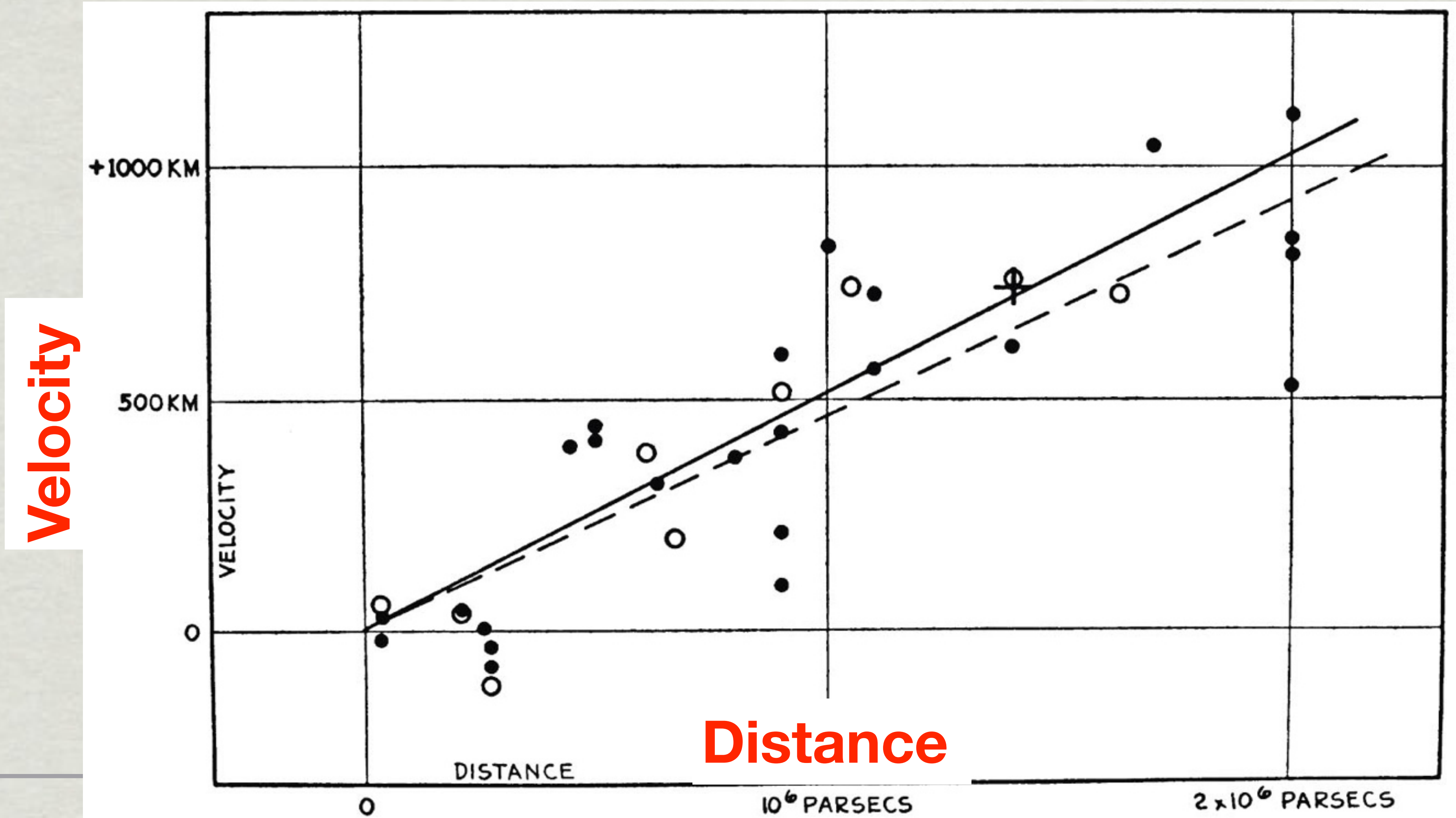
But he was close enough to learn something ***weird, wonderful and important***:



Hubble's Law and the Expanding Universe

Hubble plotted his **distance** measurements (from the inverse square law for light) on the x-axis, **velocity** (from the Doppler shift of the spectra) on the y-axis.

Galaxies at greater distances also have larger velocities.
All galaxies are moving away from us!
And the farther away they are, the faster their velocity appears to be!



Original plot from Hubble's paper announcing his discovery

Hubble's Law and the Expanding Universe

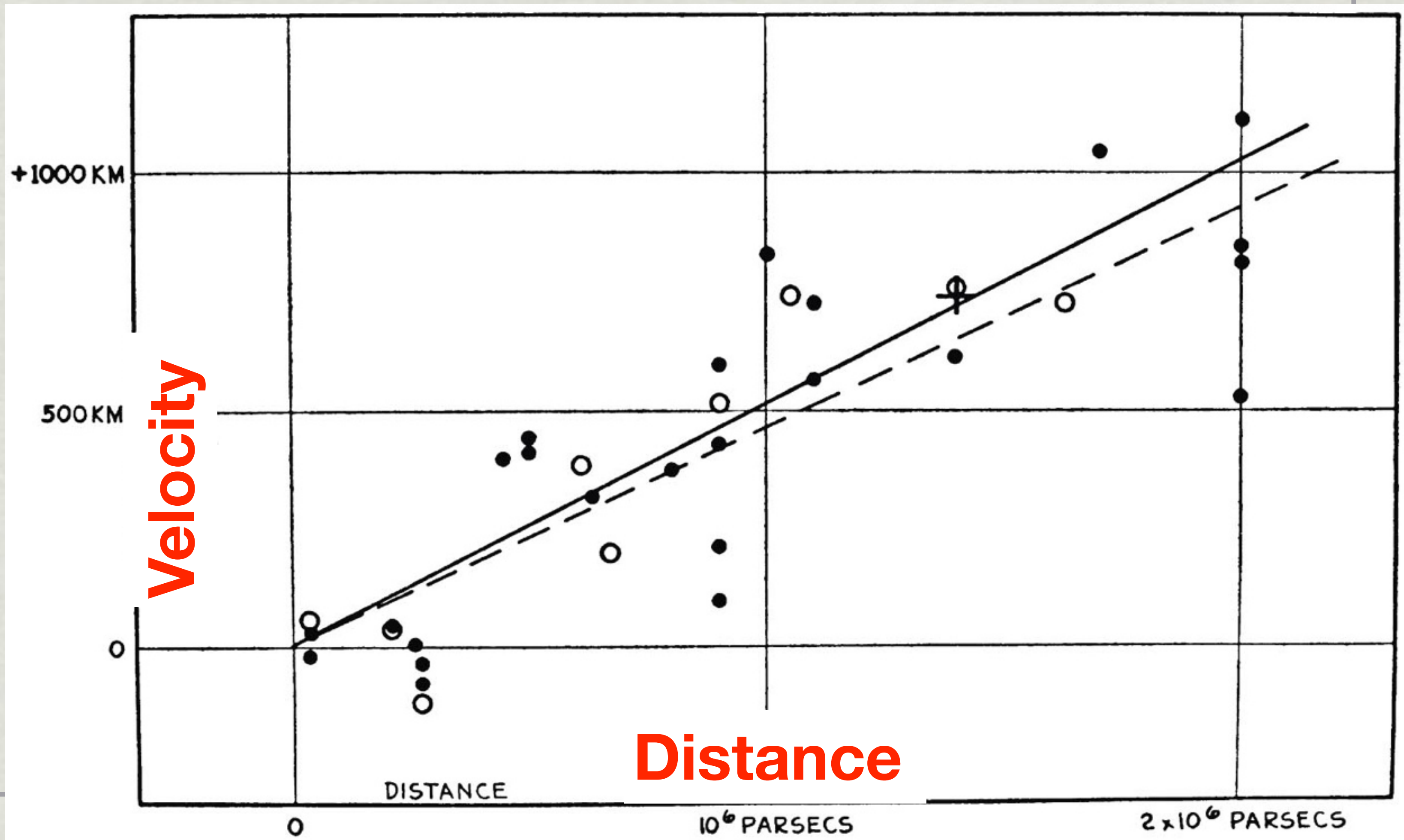
It LOOKS like everything is running away from everything else.

We would see the same thing no matter what galaxy we live in. We are not in a special place in the universe.

Everywhere in space looks like everywhere else: there isn't a "center" or an "edge" to the distribution of galaxies.

There are always about the same number of galaxies in any size box in the universe. And they are always moving away from each other.

This idea that everywhere in the universe is the same (on average) is the ***Cosmological Principle.***



Cosmological Principle

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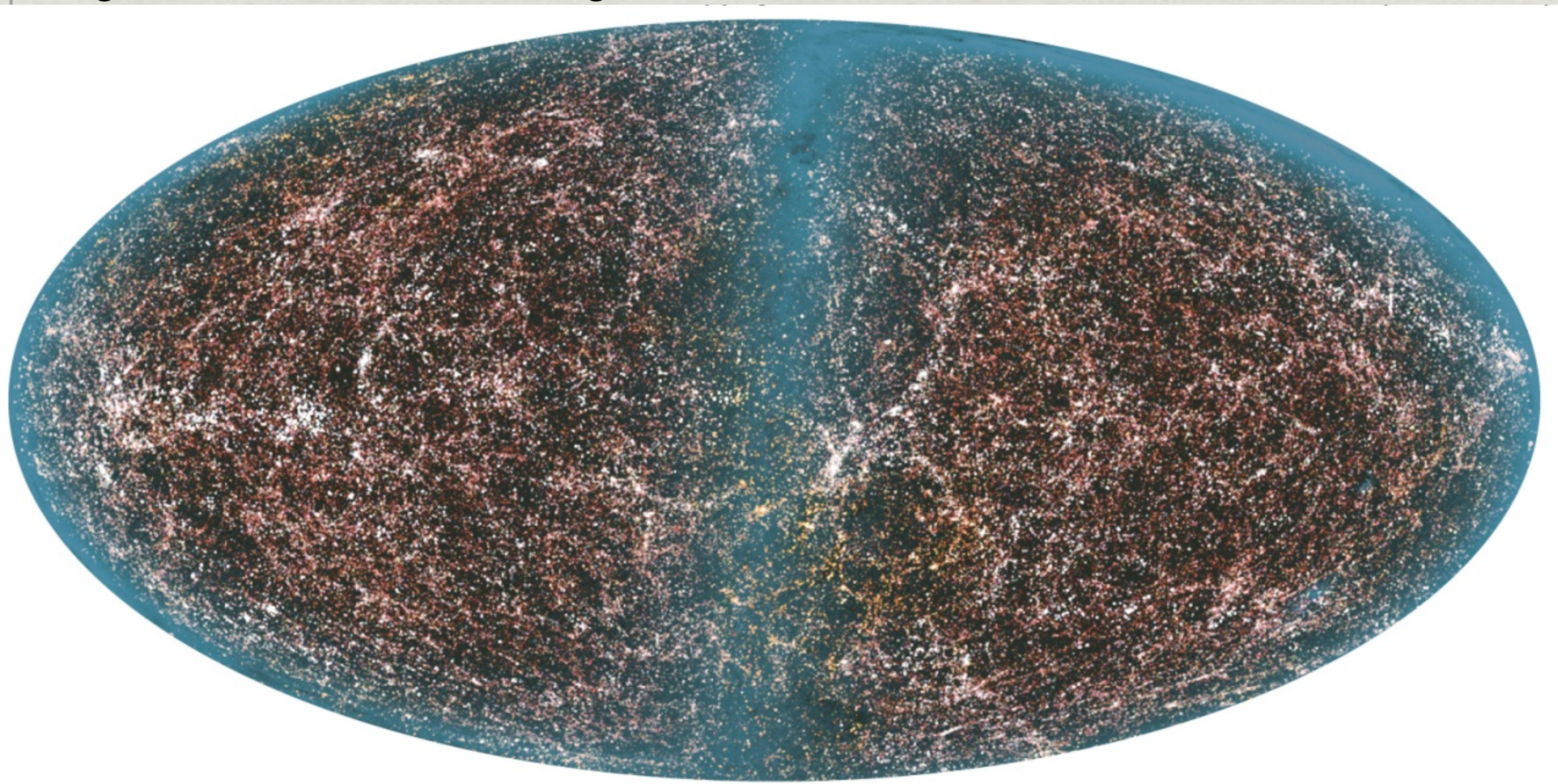
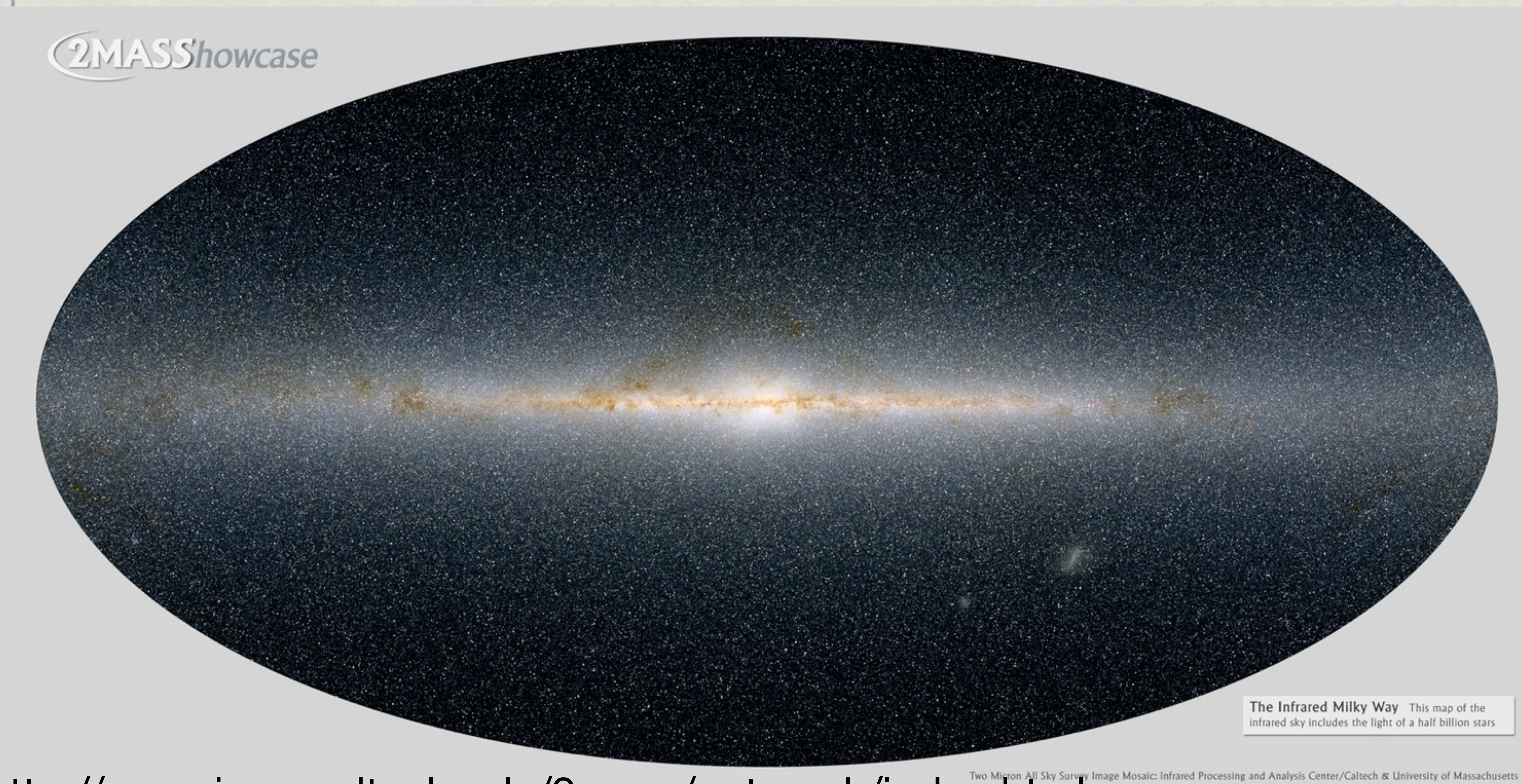


Aitoff projection of galaxies, 2MASS survey. The fuzzy band is dust in our solar system

Compare:

Aitoff projection of stars in the Milky Way, from the 2MASS survey. A map made from real data! Images taken at wavelengths 1-2.2 microns.



http://www.ipac.caltech.edu/2mass/outreach/index.html

Hubble's Law and the Expanding Universe

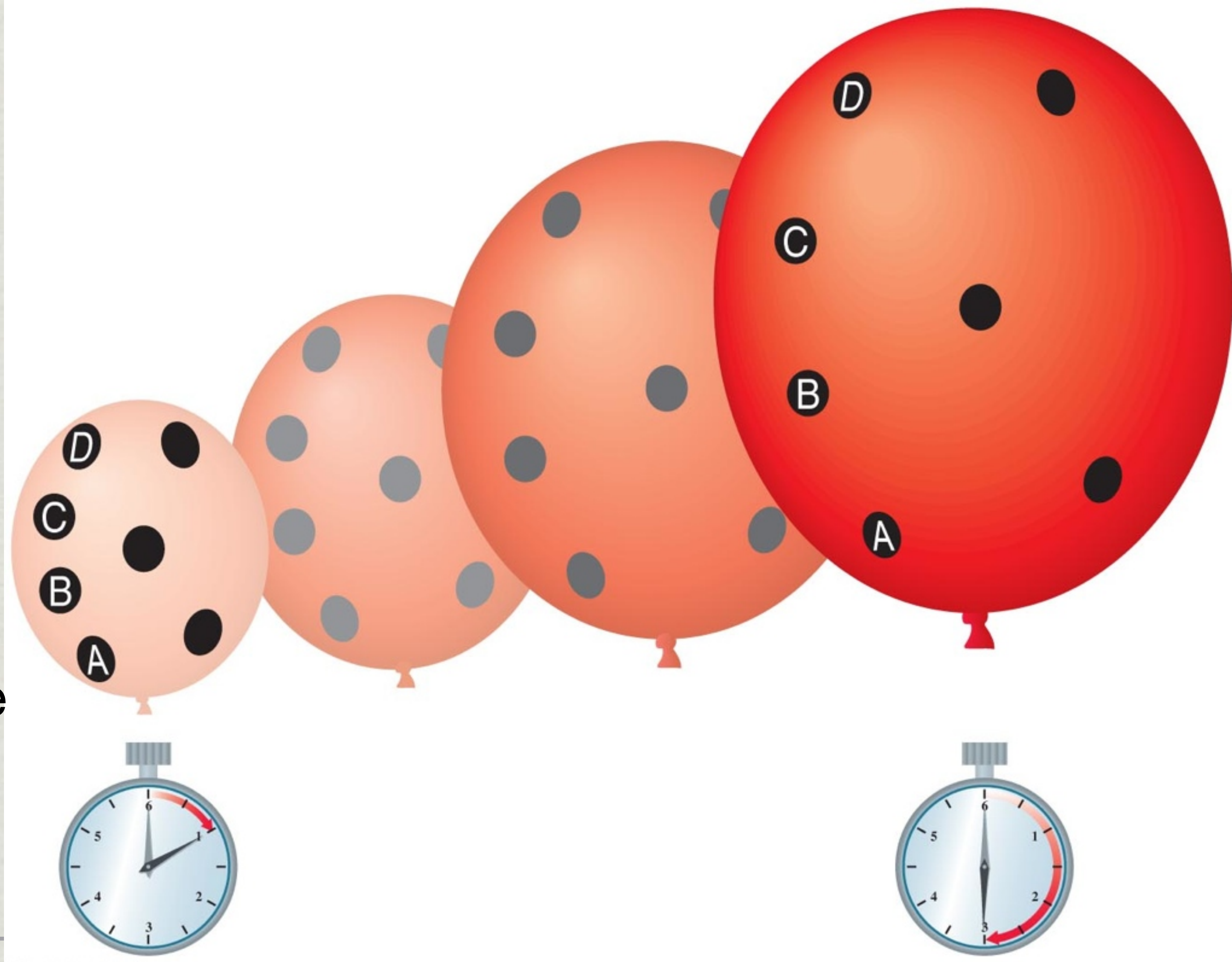
It LOOKS like everything is running away from everything else.

All galaxies look like they are racing away from all other galaxies.

Space is expanding, carrying the galaxies farther apart as it happens.

No center or edge: like the surface of a balloon as it inflates.

The dots get farther apart from each other because the balloon itself is expanding.



Hubble's Law and the Expanding Universe

It LOOKS like everything is running away from everything else.

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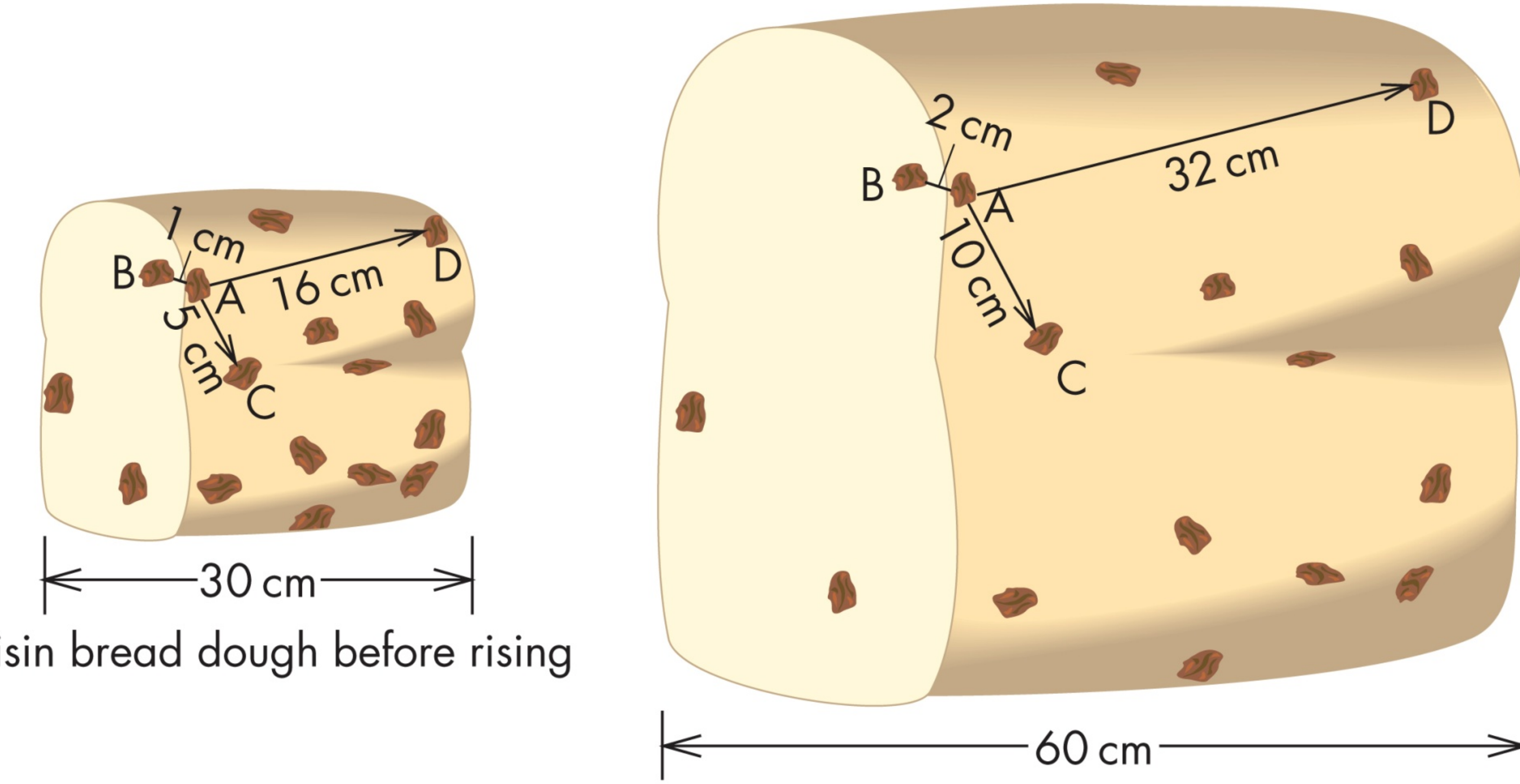
Space is expanding, carrying the galaxies farther apart as it happens.

No center or edge (ignore the crust): the raisins all move apart from each other.

The raisins get farther apart because the dough between them has expanded.

(**not more** dough, **expanded** dough)



Raisin bread dough before rising

Raisin bread dough after rising

Hubble's Law and the Expanding Universe

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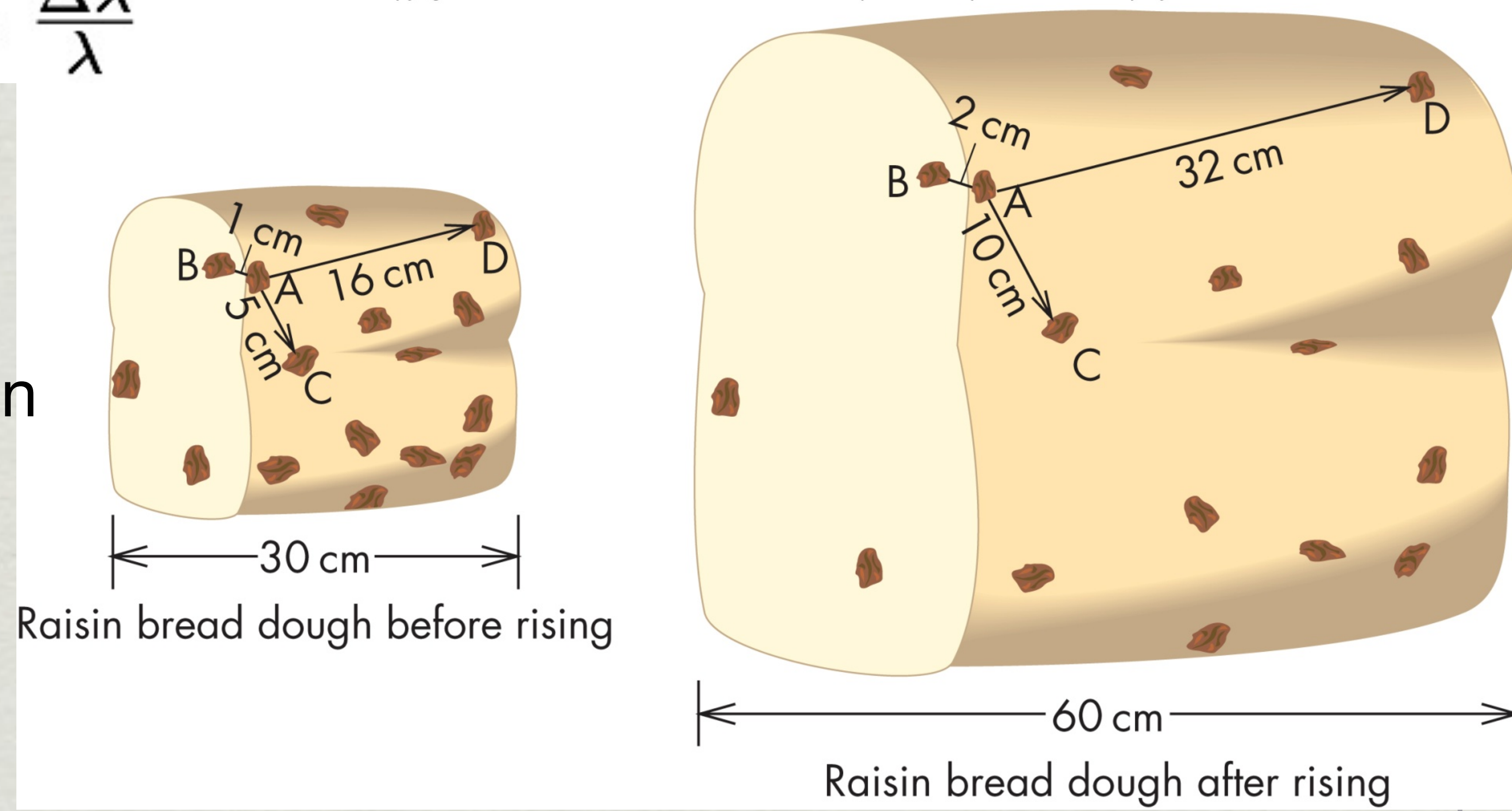
All galaxies look like they are racing away from all other galaxies.

We measure redshift z:

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



$v = zc$

This velocity is the expansion velocity of the universe

v can be > c if z > 1

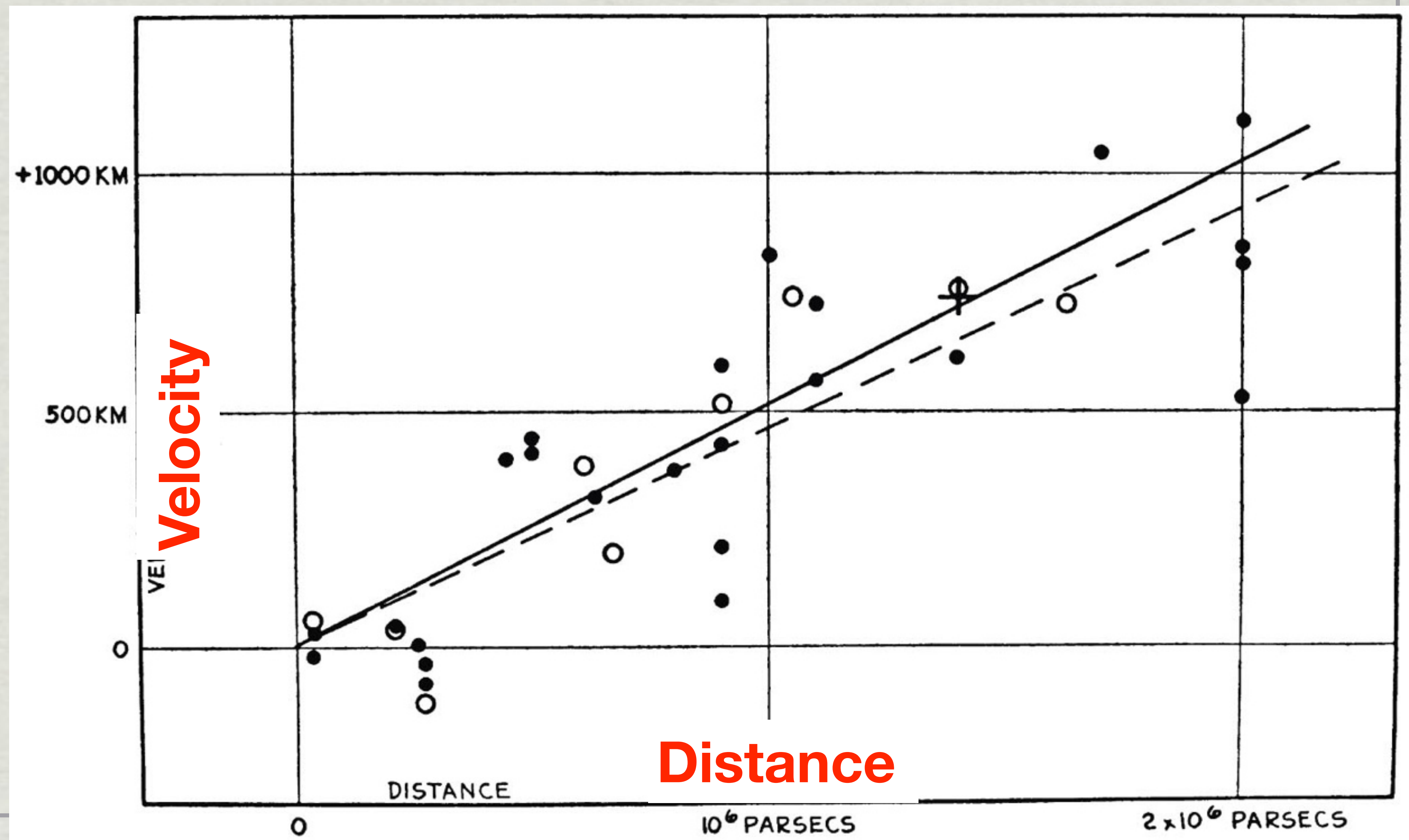
That's OK. Remember it is spacetime itself that is expanding!

Hubble's Law and the Expanding Universe

Suddenly, accurate distances to galaxies seem really important.

Slope of the line in Hubble's diagram: relationship between redshift (Doppler velocity) and distance.

Measure accurate distances to some galaxies, learn the slope of this line.



Hubble's Law and the Expanding Universe

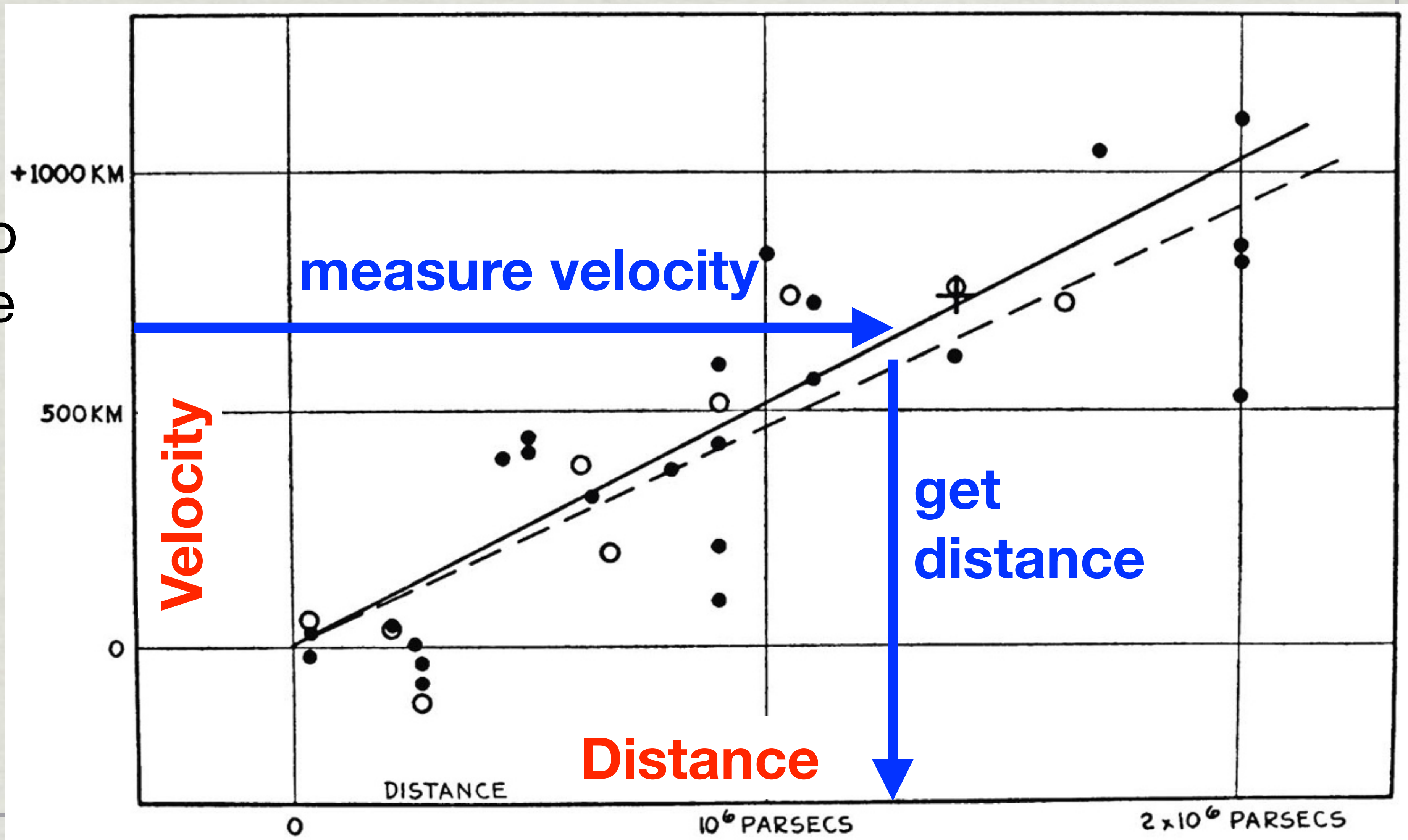
Suddenly, accurate distances to galaxies seem really important.

Slope of the line in Hubble's diagram: relationship between redshift (Doppler velocity) and distance.

Measure accurate distances to some galaxies, learn the slope of this line.

Then we can use it to measure the distance to any galaxy for which we have a redshift.

No need to know the luminosity!

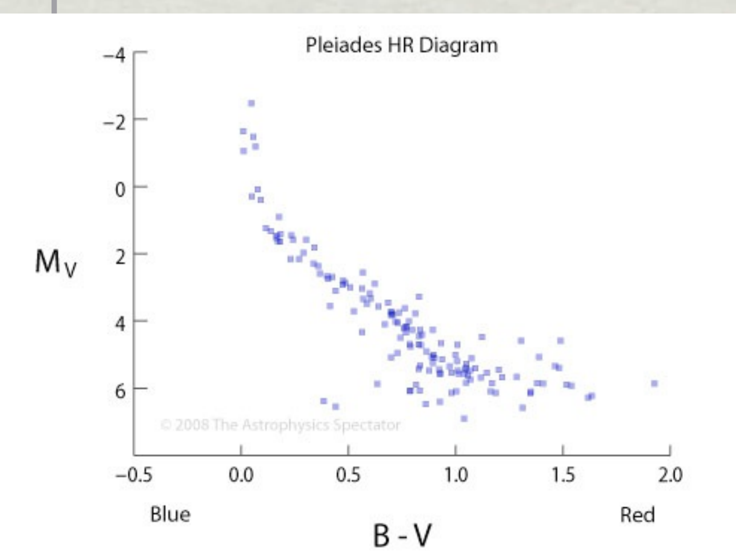


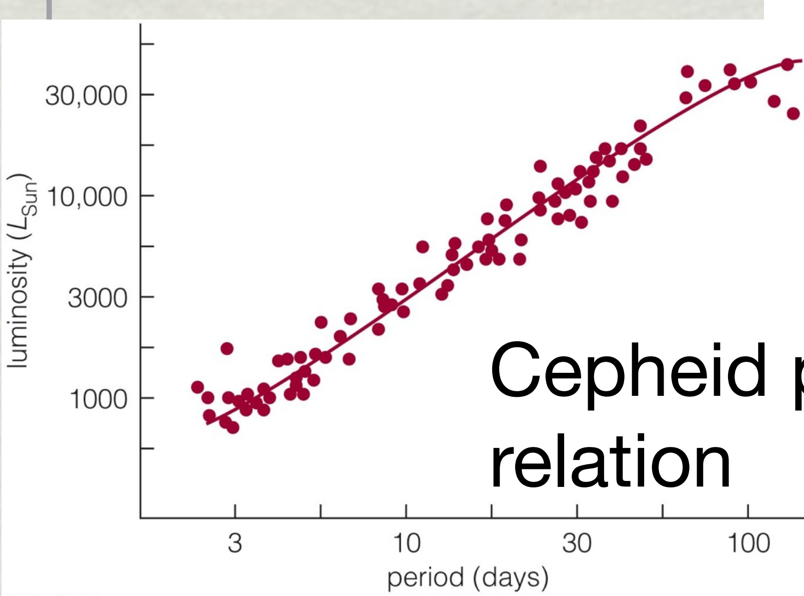
Measuring the Hubble Law Slope: Distances to Galaxies

Parallax: distances to nearby stars and star clusters.

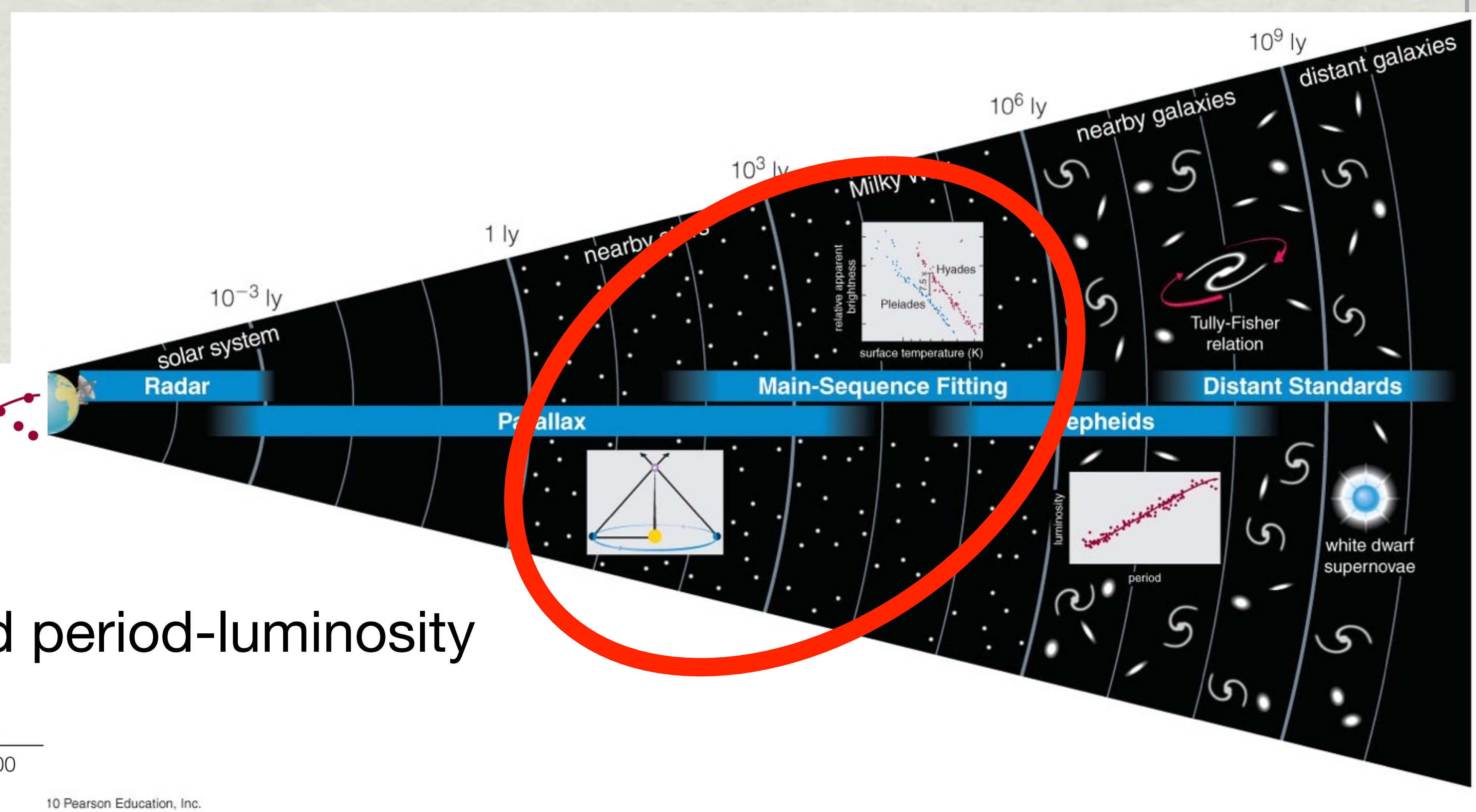
Some of those clusters have Cepheid Variables:

Calibrate relation between period and luminosity.



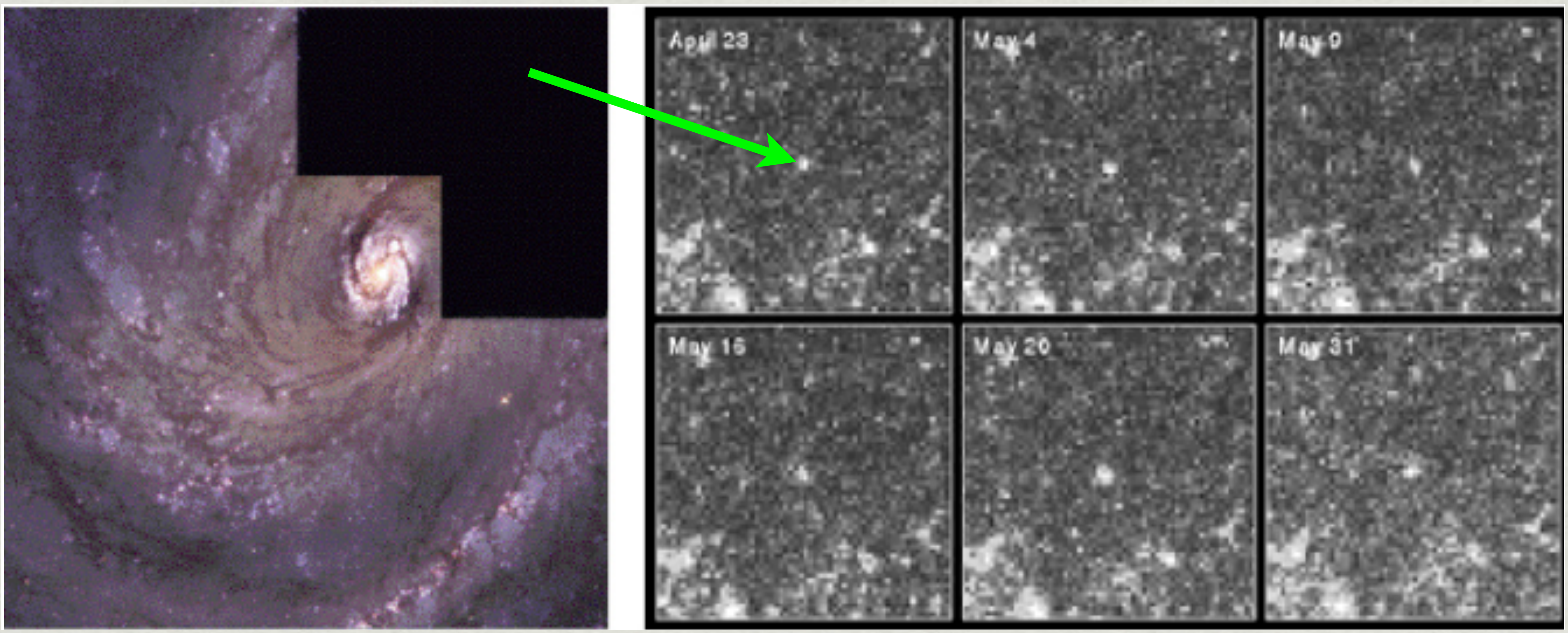


Cepheid period-luminosity relation



Measuring the Hubble Law Slope: Distances to Galaxies

One of the main reasons the Hubble Space Telescope was built was to find and measure Cepheid Variables in nearby galaxies.



Get the luminosity from the Cepheid period-luminosity relation.
Measure distances to those galaxies using the inverse square law for light.

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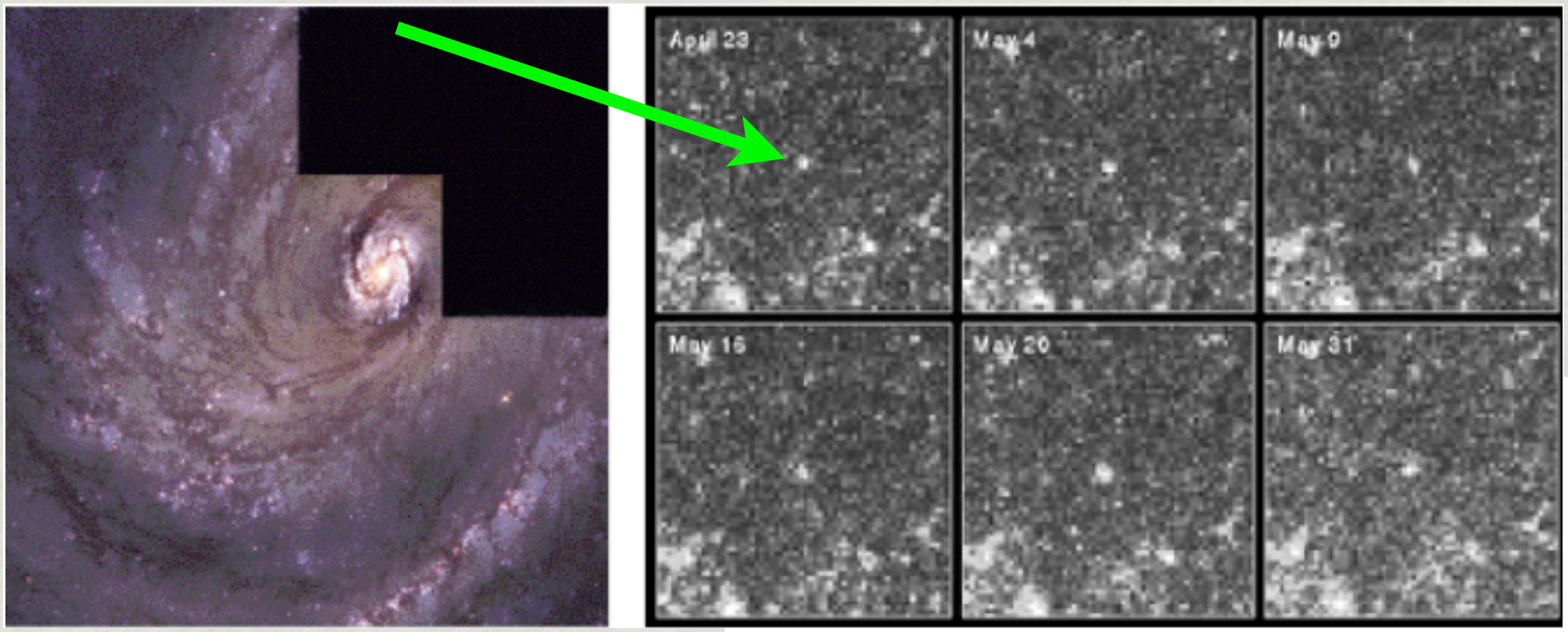
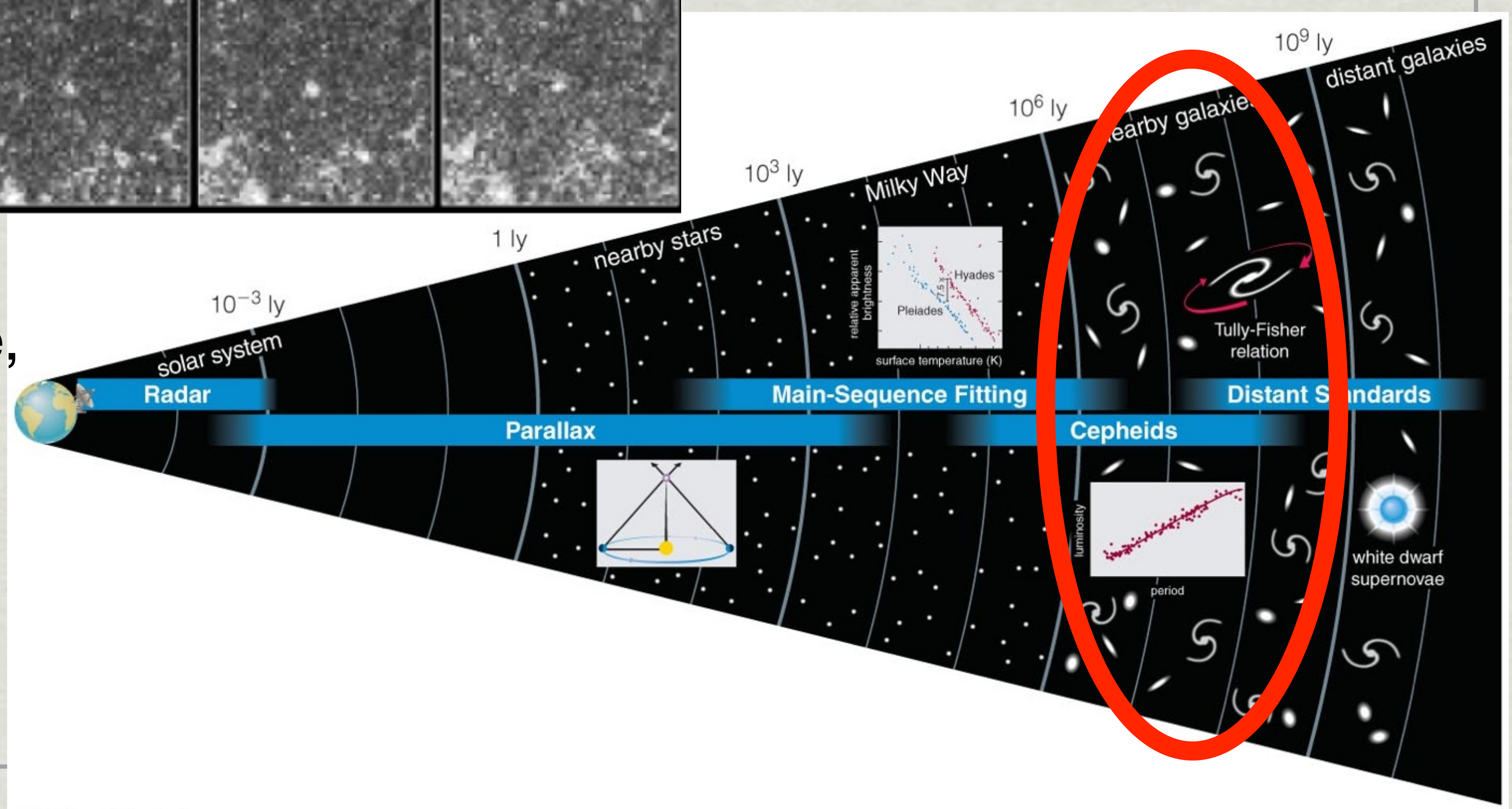


Measure distances to those galaxies using the inverse square law for light.

But even with Hubble, there is a limit to how far away we can see Cepheid Variables.



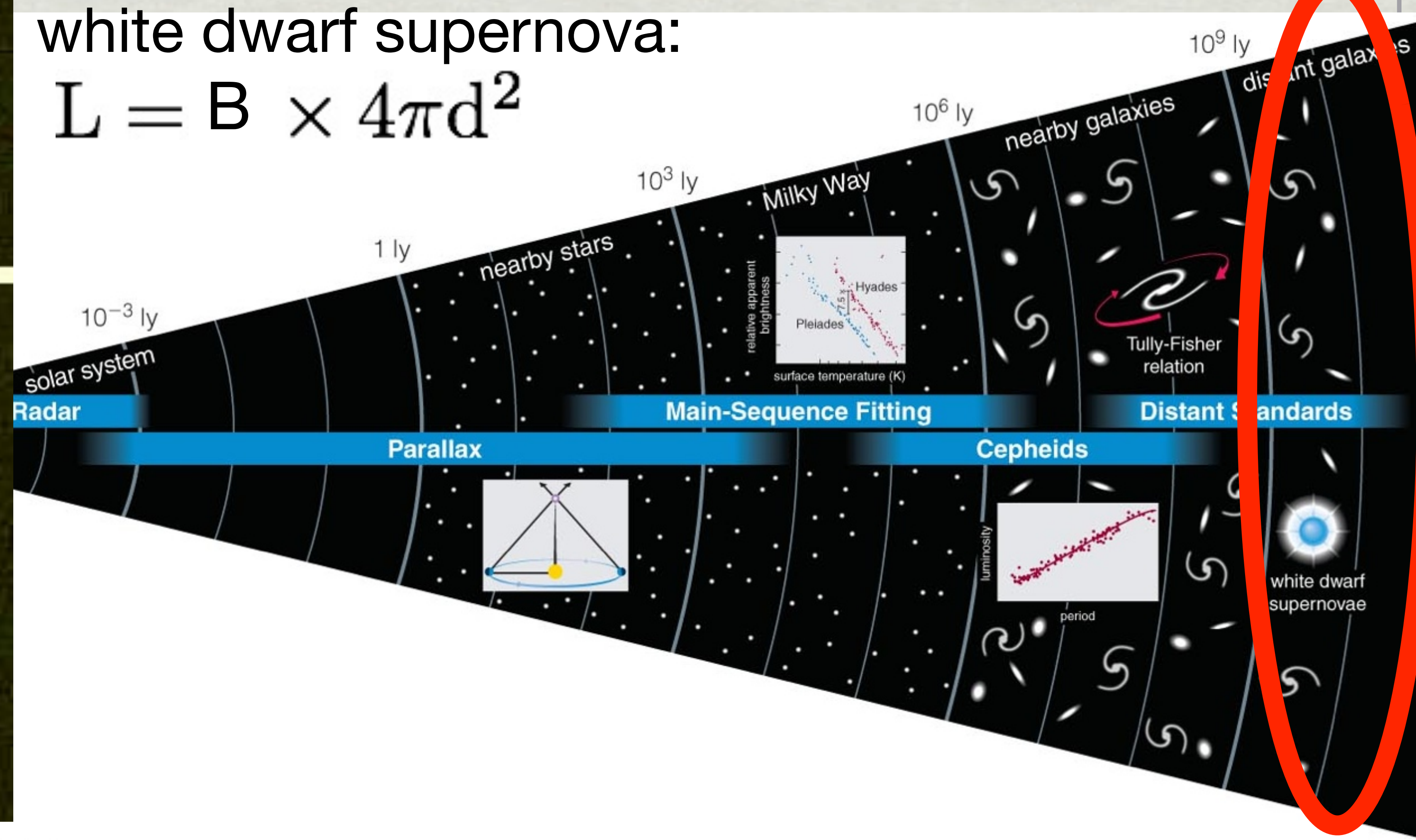
Measuring the Hubble Law Slope: Distances to Galaxies

White dwarf supernovae: 1.4 M_{sun} → Fe by nuclear fusion, so we know how much energy is released.

This means we know the luminosity:
10 billion L_{sun}, about the luminosity of our Galaxy.
Can see these much farther away that Cepheids

Can use the measured flux to get the distance to white dwarf supernova:

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



Hubble's Law and the Expanding Universe

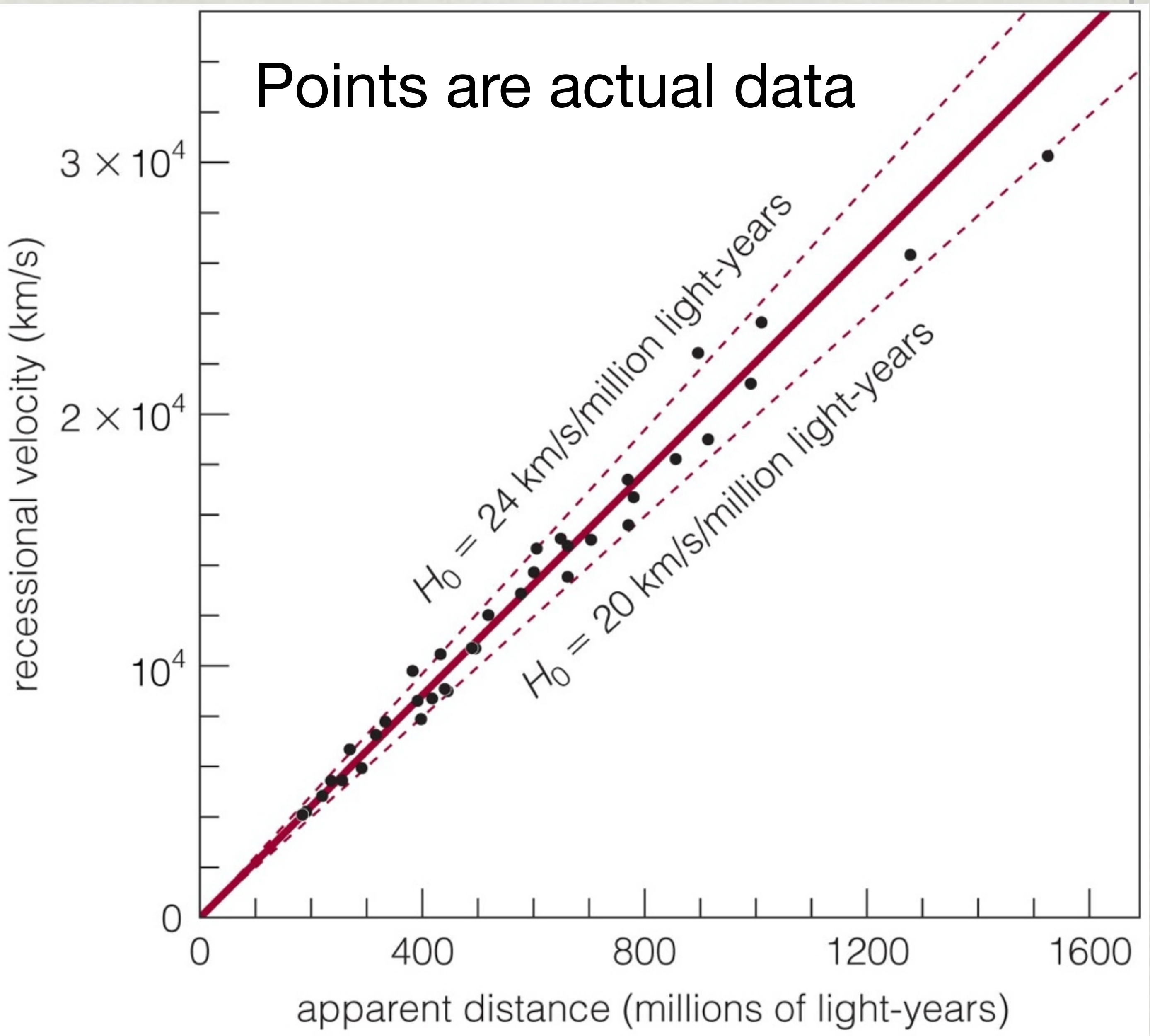
Put together all those distance and velocity measurements.

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

This is just the equation for a line:
$y = mx$

y is the velocity
x is the distance
m, the slope of the line, is H_0

H_0 = Hubble's Constant,
relates distance and velocity



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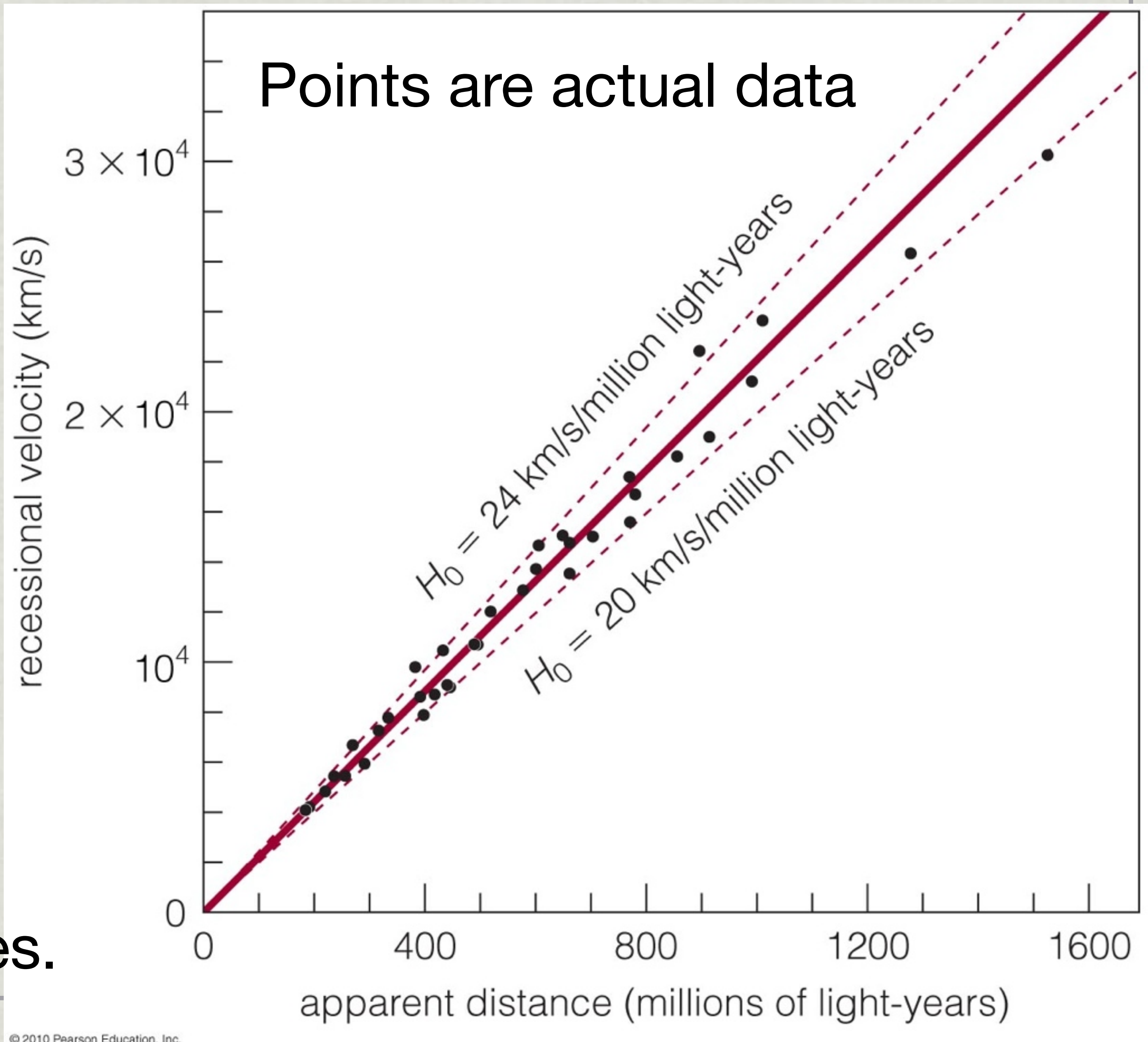
H_0 = Hubble's Constant, relates distance and velocity

H_0 = 21 (km/s)/Mly
or 69 (km/s)/Mpc

Now we can just measure redshift from a galaxy's spectrum and we can learn its distance.

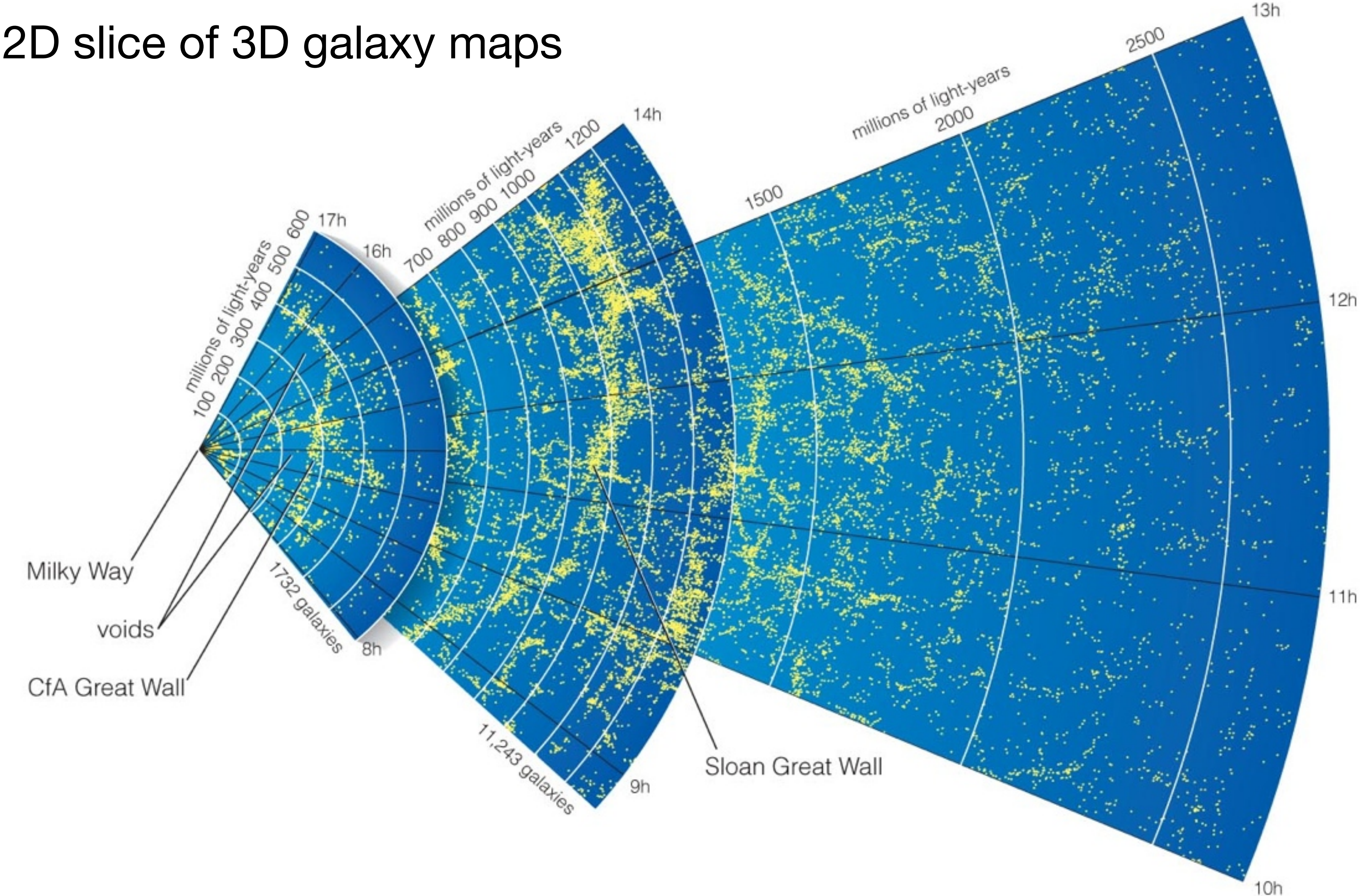
Do not need to know its luminosity, or measure individual stars in galaxies.



Hubble's Law and the Expanding Universe

Why this is useful: we can map the location (in 3D!) of lots of galaxies just by measuring redshift.

A 2D slice of 3D galaxy maps



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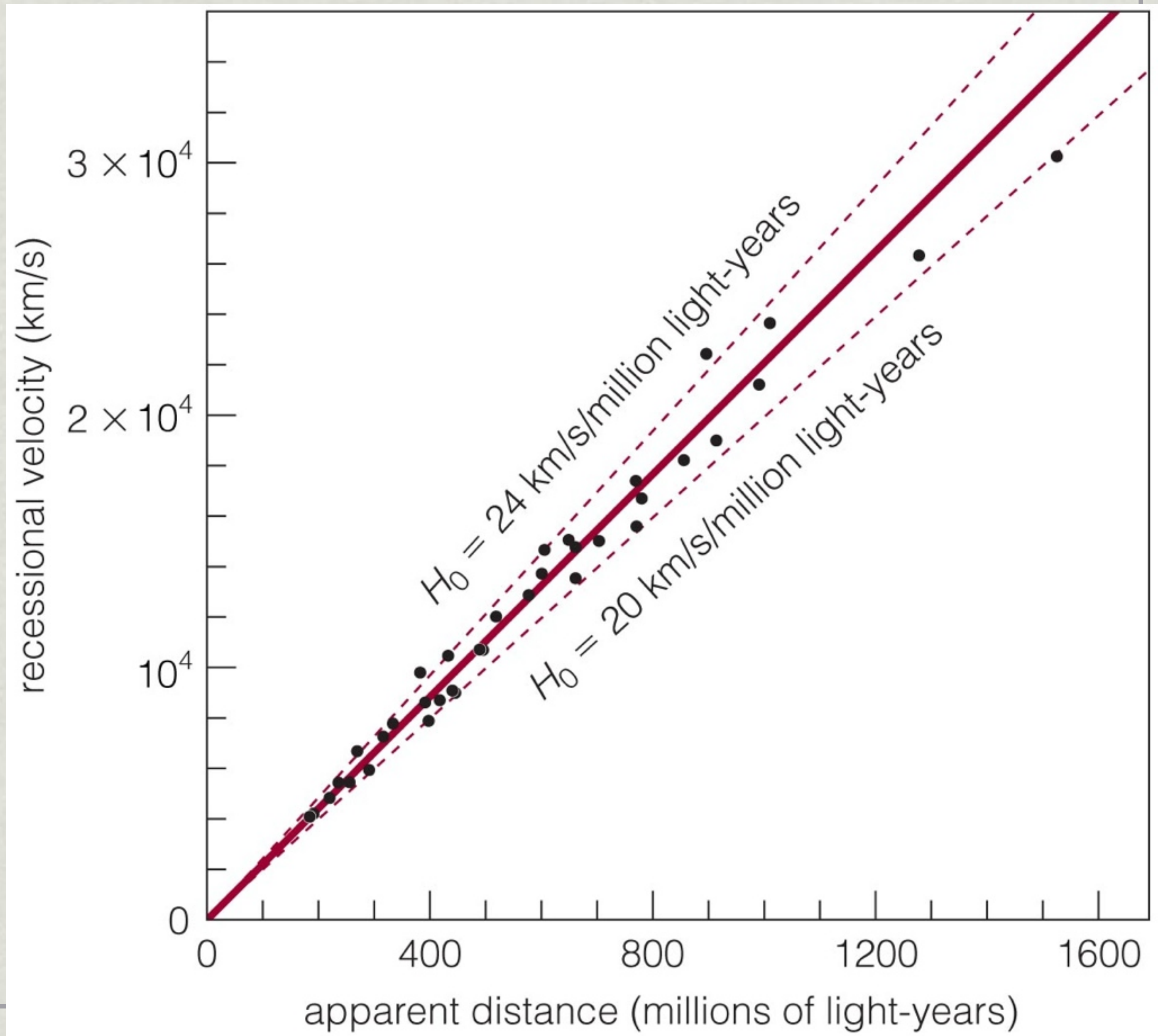
Redshift:

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

If I measure the Doppler velocity of two galaxies:
A 20,000 km/s
B 10,000 km/s

Which one is farther away, A or B?



Hubble's Law and the Expanding Universe

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H_0 = Hubble's Constant, relates distance and velocity

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

Looks like all the galaxies are moving away from us

More distant galaxies are moving faster.

Interpret this

Redshift:

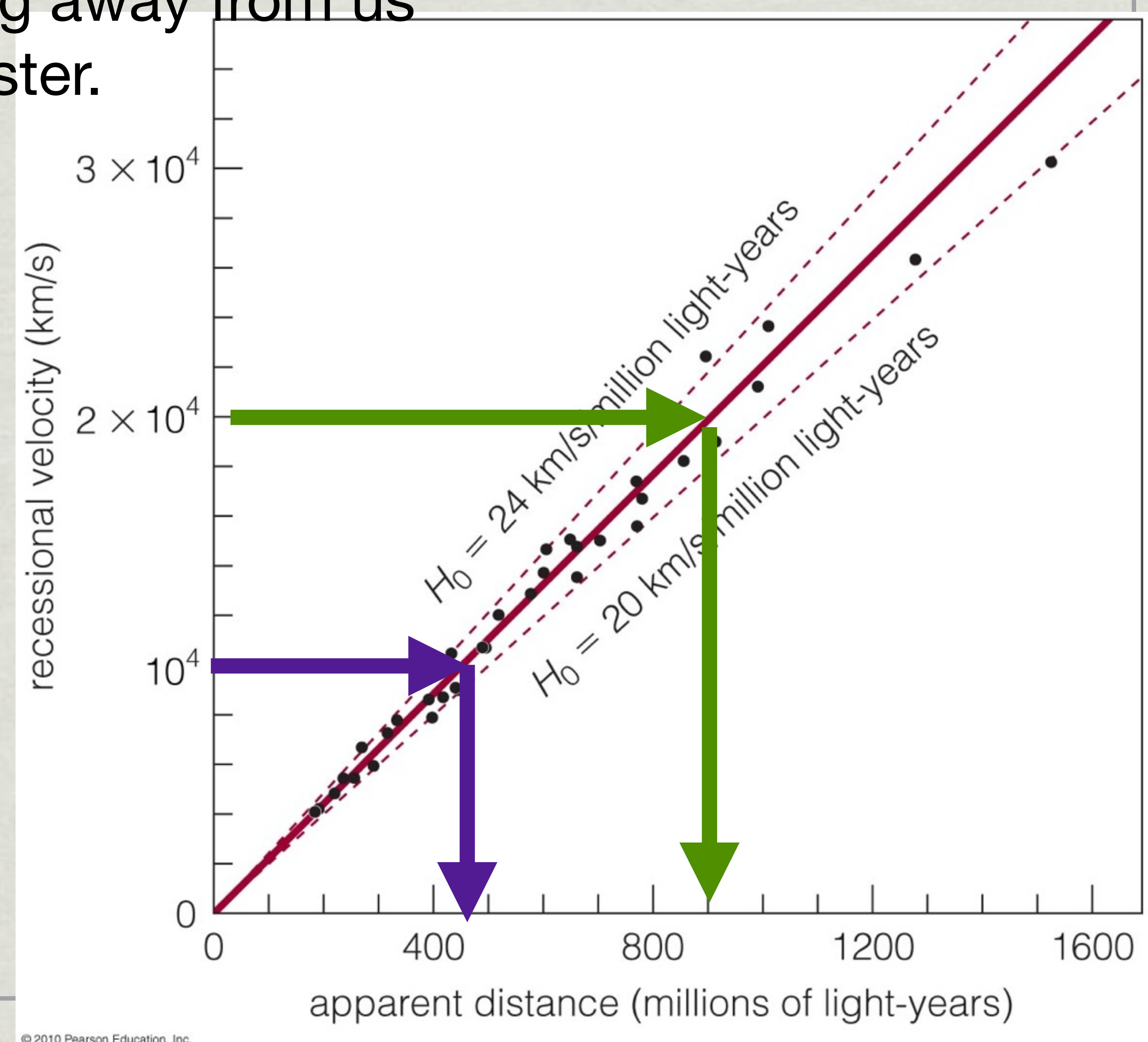
$$z = \frac{v}{c} = \frac{\lambda_{shift} - \lambda_{rest}}{\lambda_{rest}} = \frac{\Delta\lambda}{\lambda}$$

Measure Doppler velocity (redshift), know H_0, find distance.

A 20,000 km/s

B 10,000 km/s

Which one is farther away, A or B?



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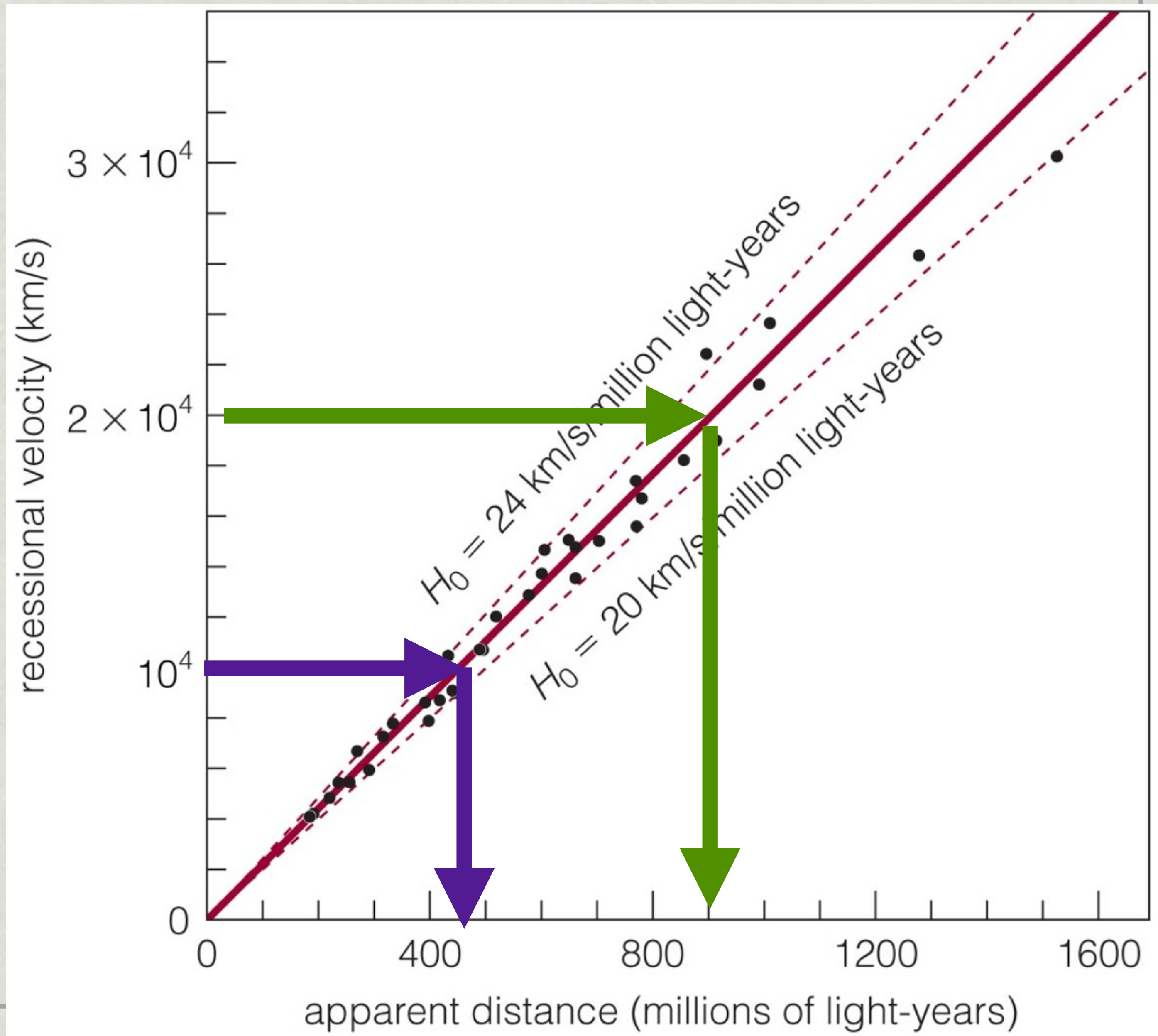

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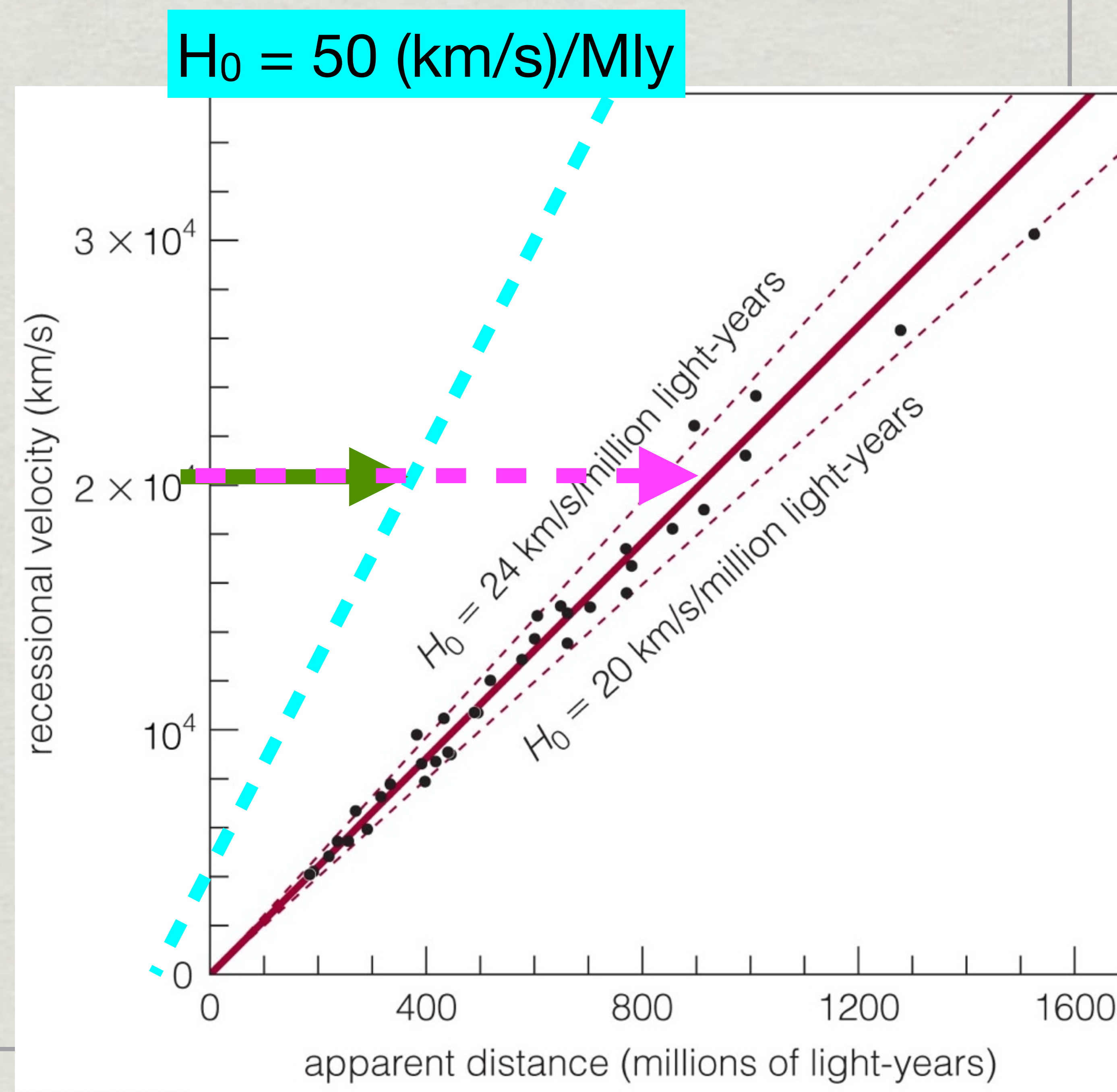
If Hubble's Constant H_0 were 50 (km/s)/Mly:

How would you change your estimate of the distance to a galaxy with velocity 20,000 km/s?

A) You would say it was farther away
B) You would say it was closer



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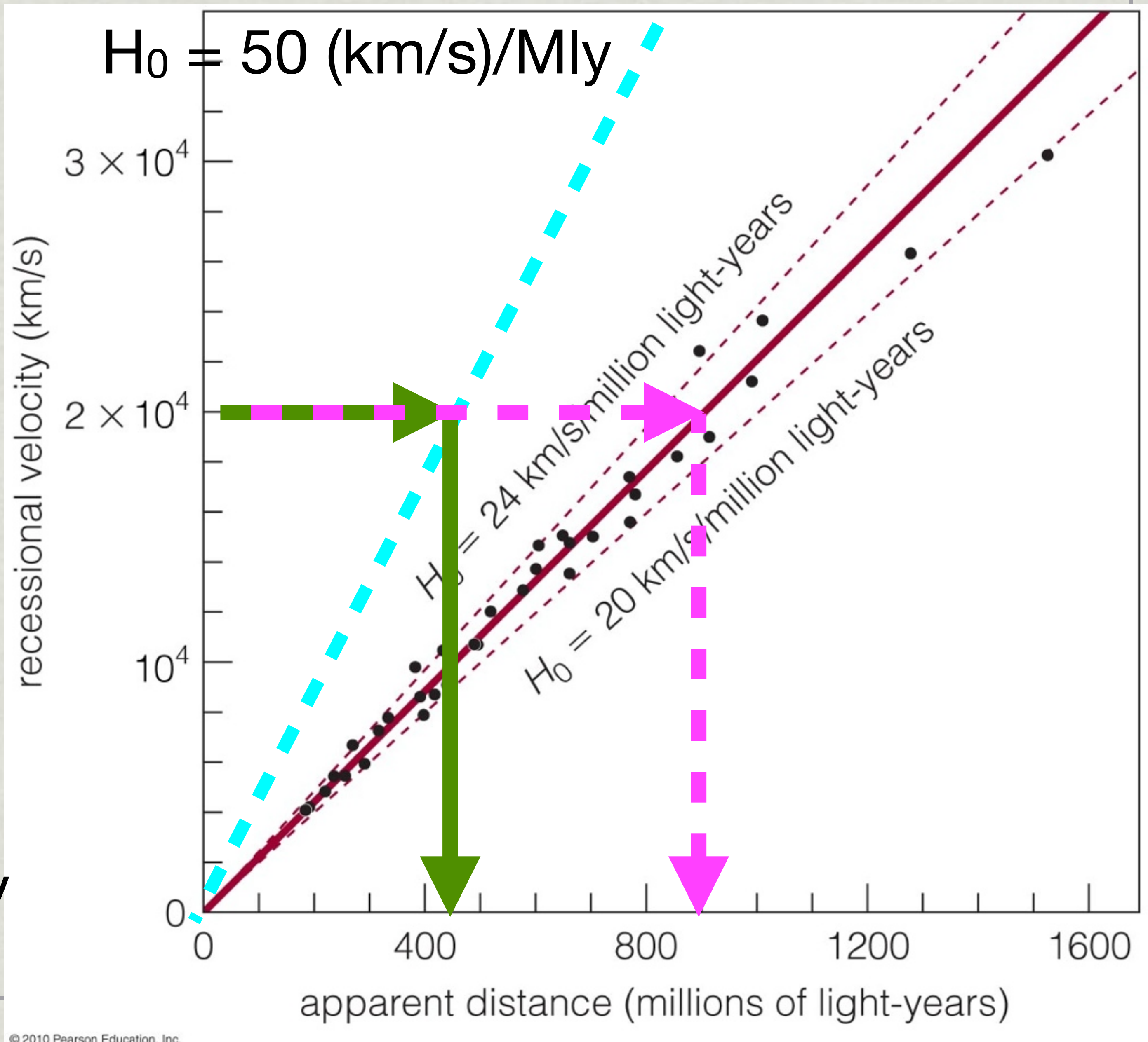

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Redshift:

$z = \frac{v}{c} = \frac{\lambda_{shi}}{}$

If Hubble's Cons
50 (km/s)/Mly:

H_0 is just a number. It sets the relation between redshift (velocity) of galaxies as space expands, and their distance.

Just like G for gravity, σ in the Stefan-Boltzmann law.

It was just a little more difficult to measure, because we had to figure out how to measure distances to galaxies.

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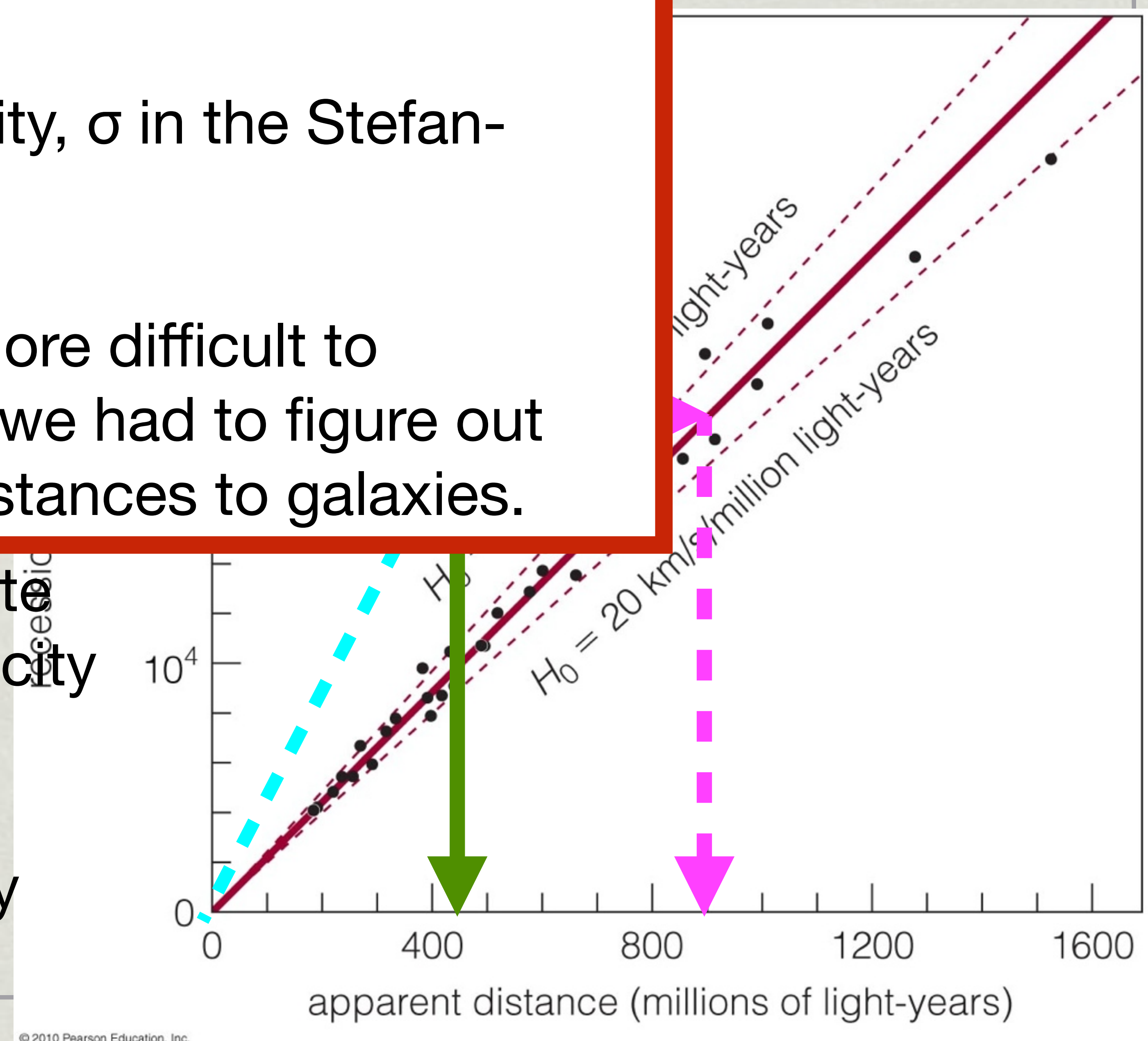


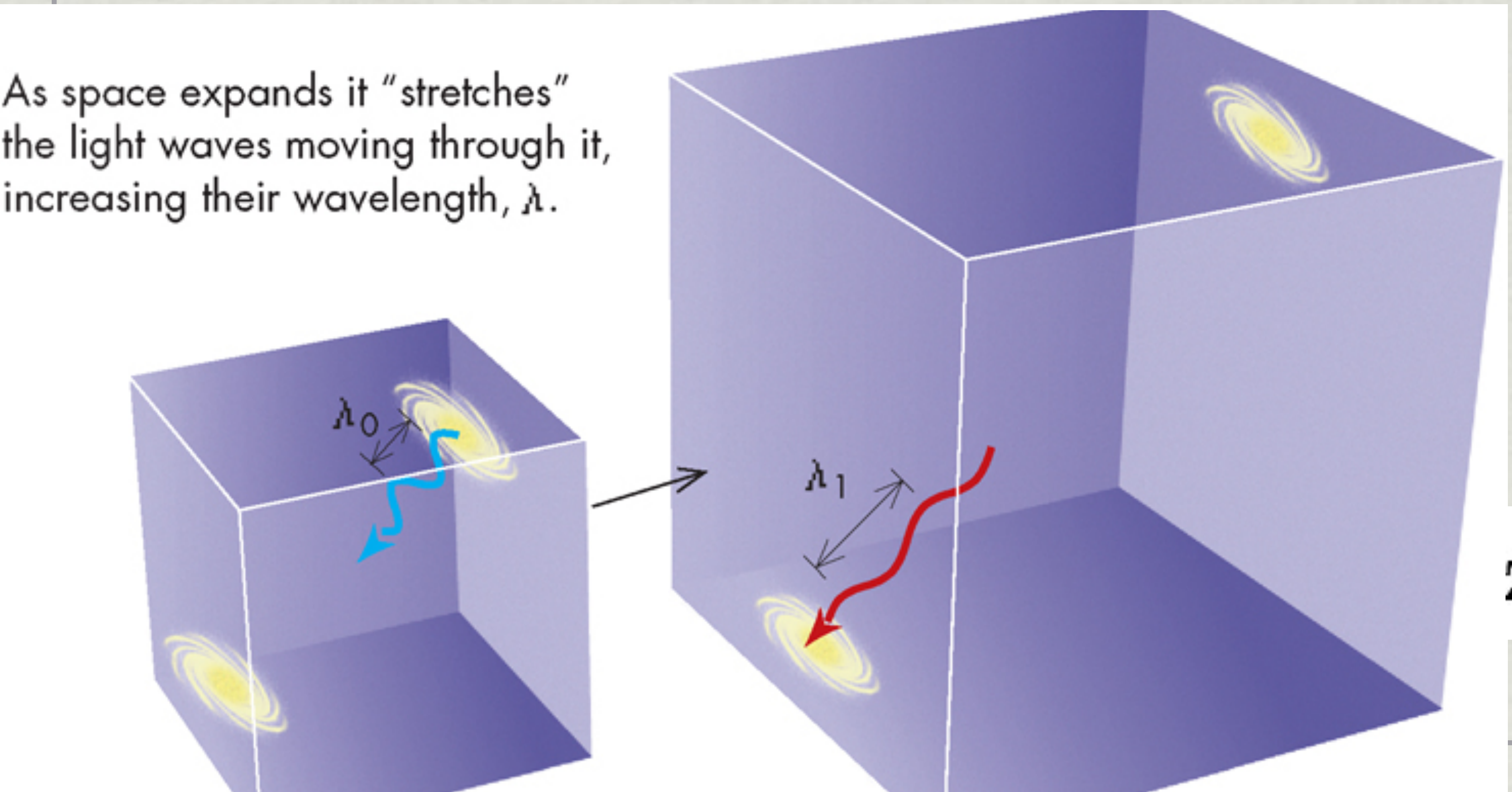
Expansion of the Universe and the Big Bang

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

Another way to look at the redshift due to space expanding:
As space expands, the wavelength of the photons stretches, too.

So the light from a galaxy is redshifted as the space between us and the distant galaxy expands.

More distant galaxies: Light left longer ago.



Space has had more time to expand while the light travels to us.

→ larger redshift. We see a what looks like a larger Doppler shift, larger velocity

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

$v = zc$, v can be $> c$ for $z > 1$

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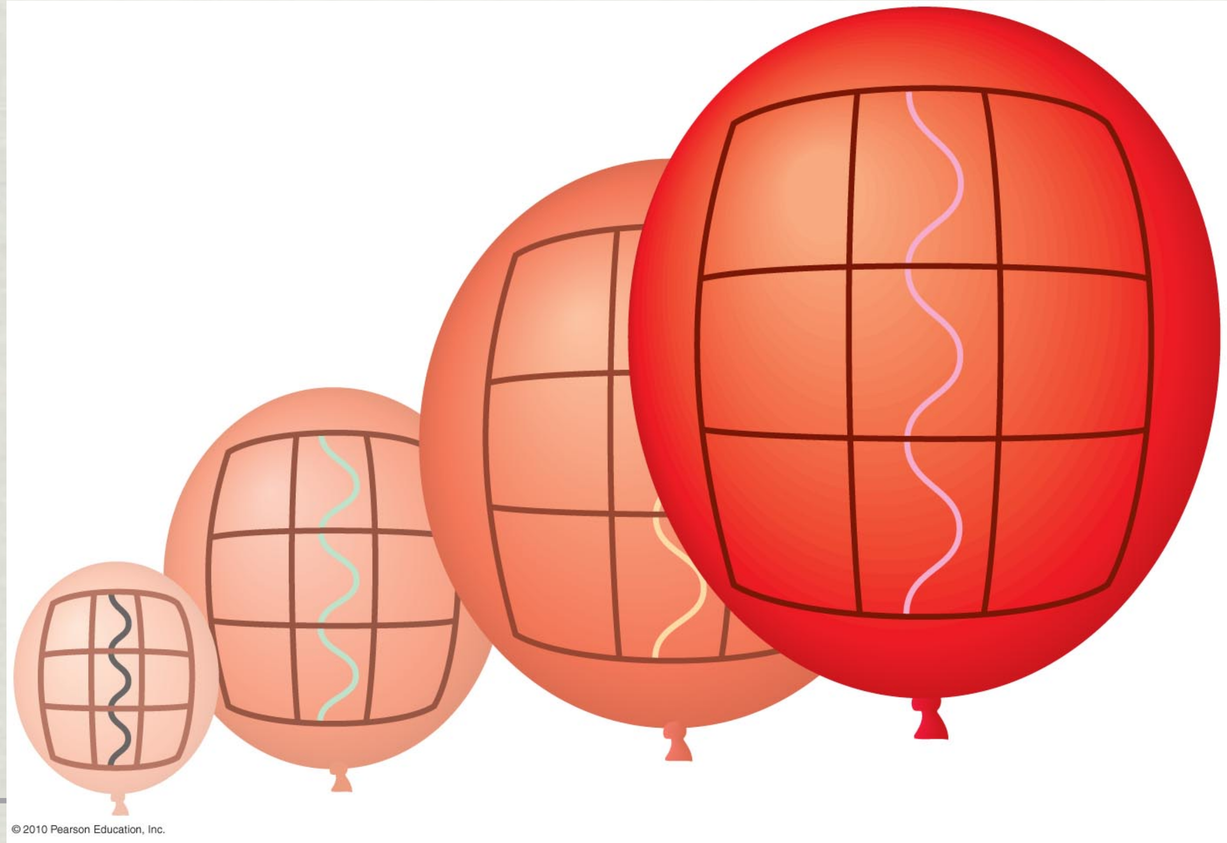

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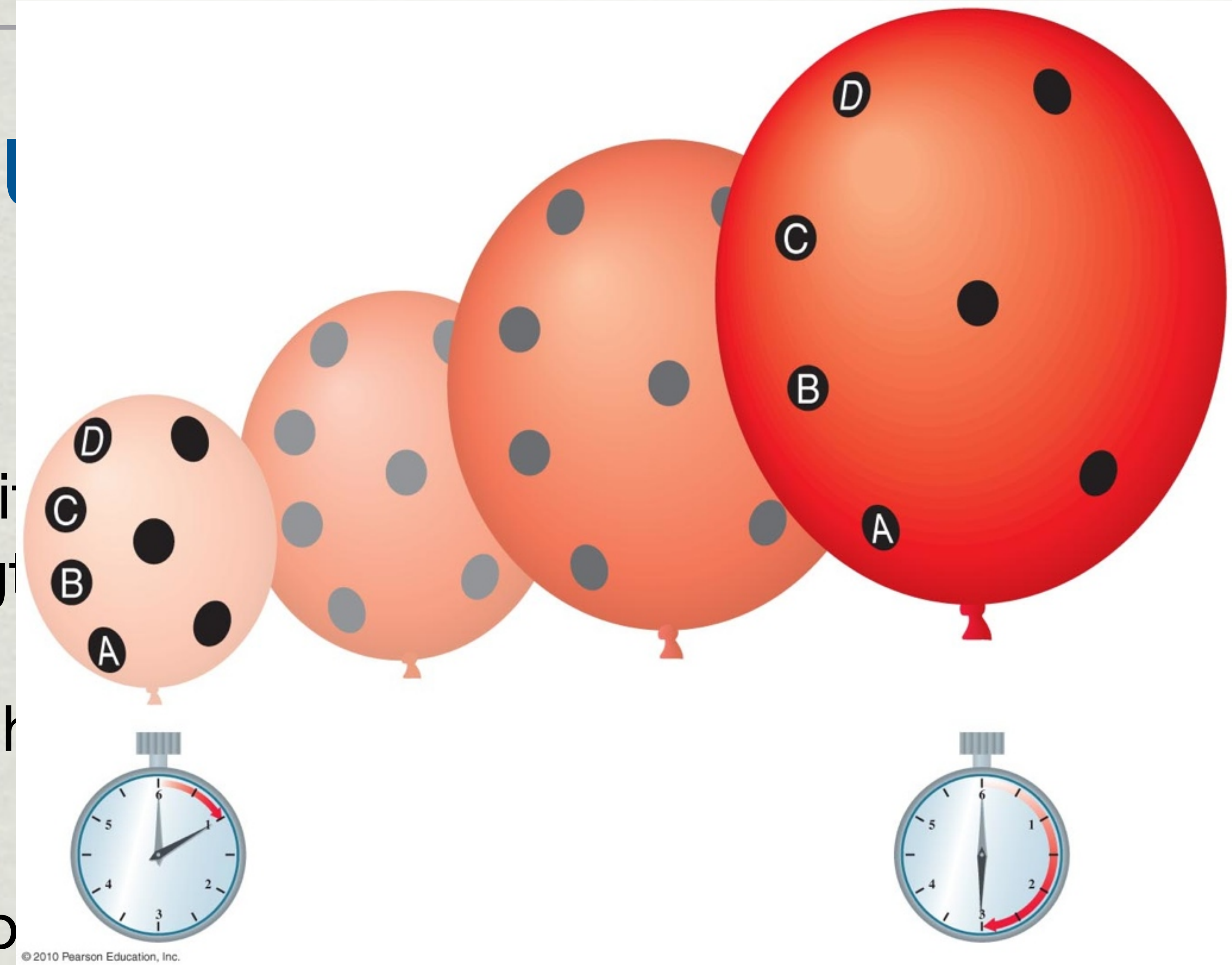

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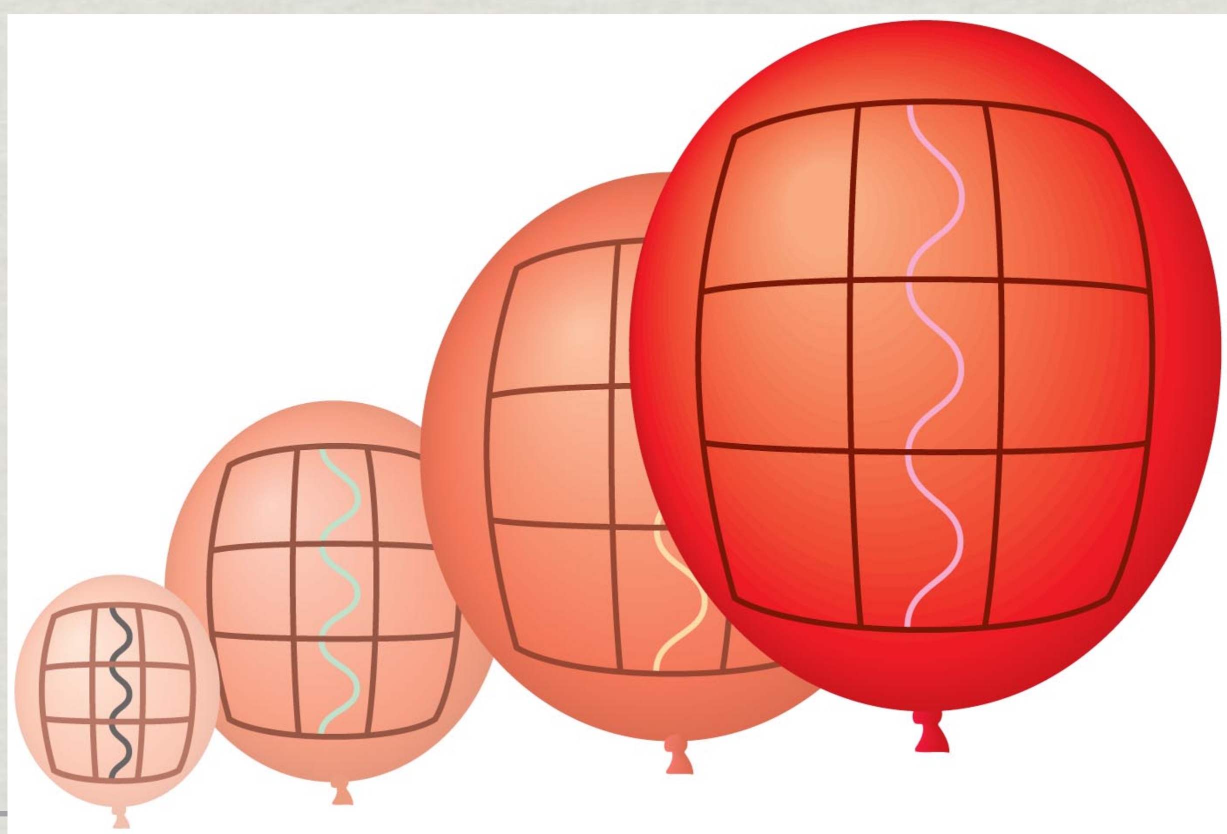

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Hubble's Law and the Expanding Universe

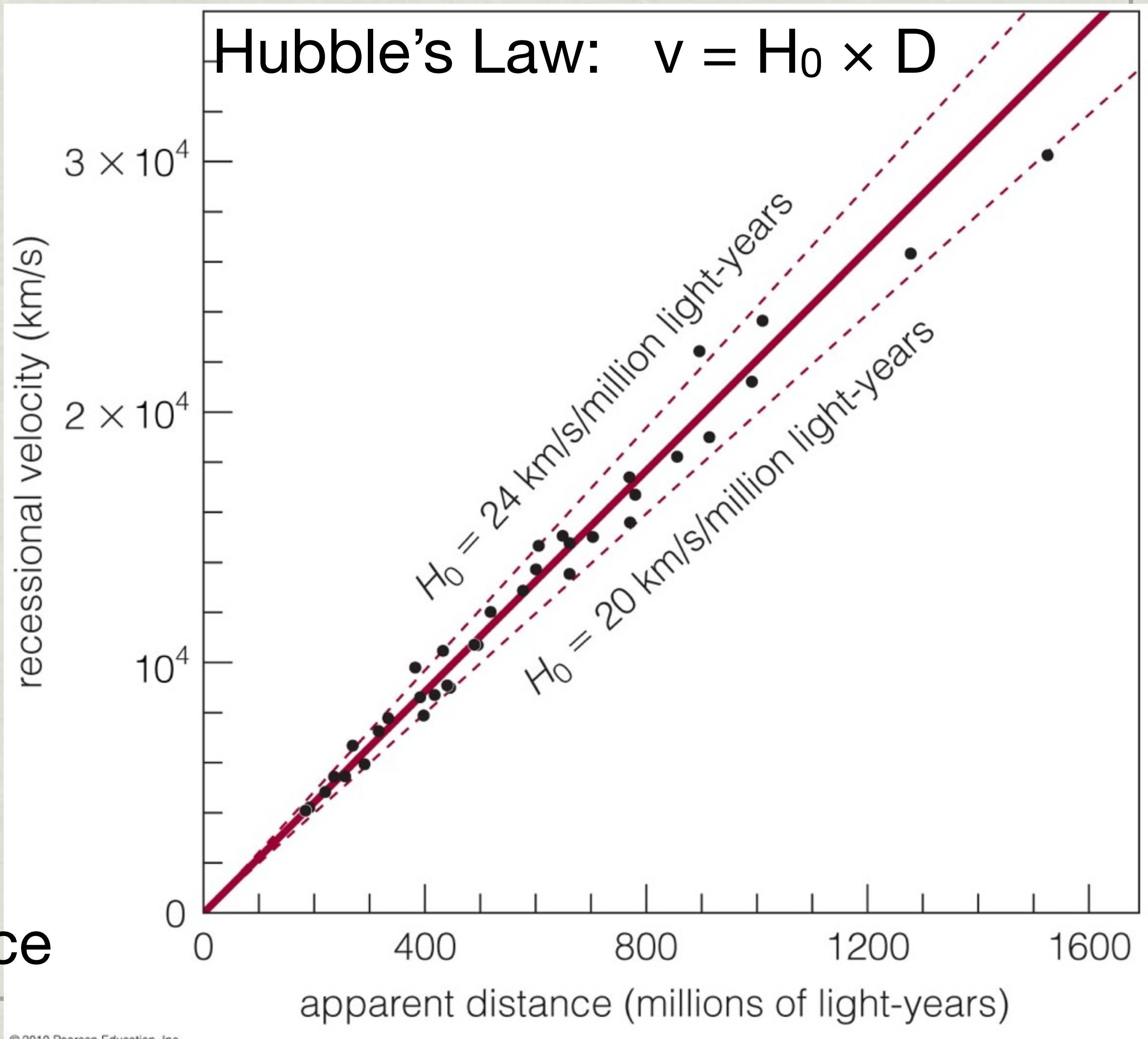
We see all galaxies moving away from us.

Galaxies that are farther away appear to be moving away from us at larger velocities.

H_0 = Hubble's Constant, relates the distance of a galaxy and its recession velocity (velocity moving away from us)

We are not in a special place: observers in other galaxies see the same thing

All galaxies are moving away from each other and follow the same relation between velocity and distance



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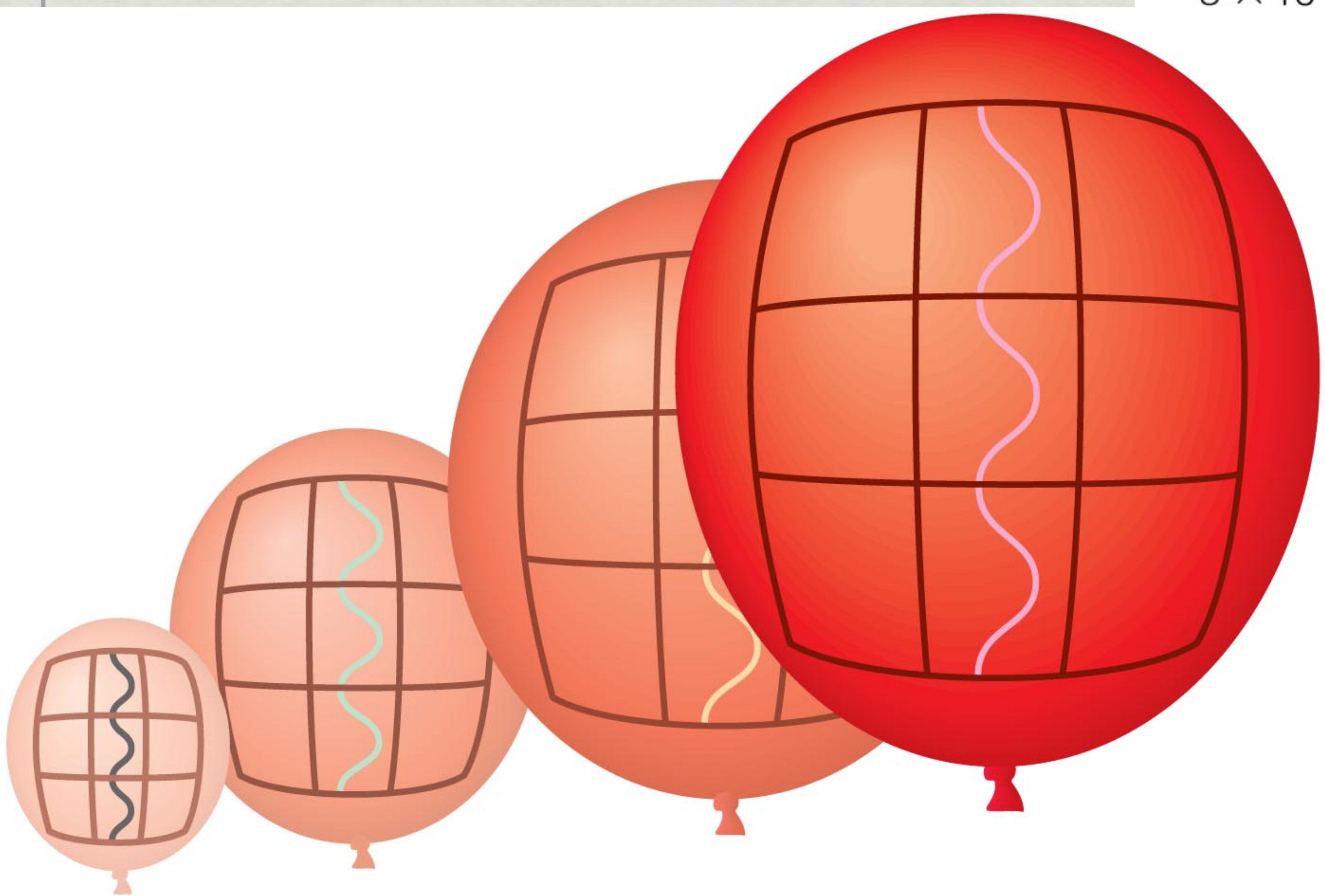
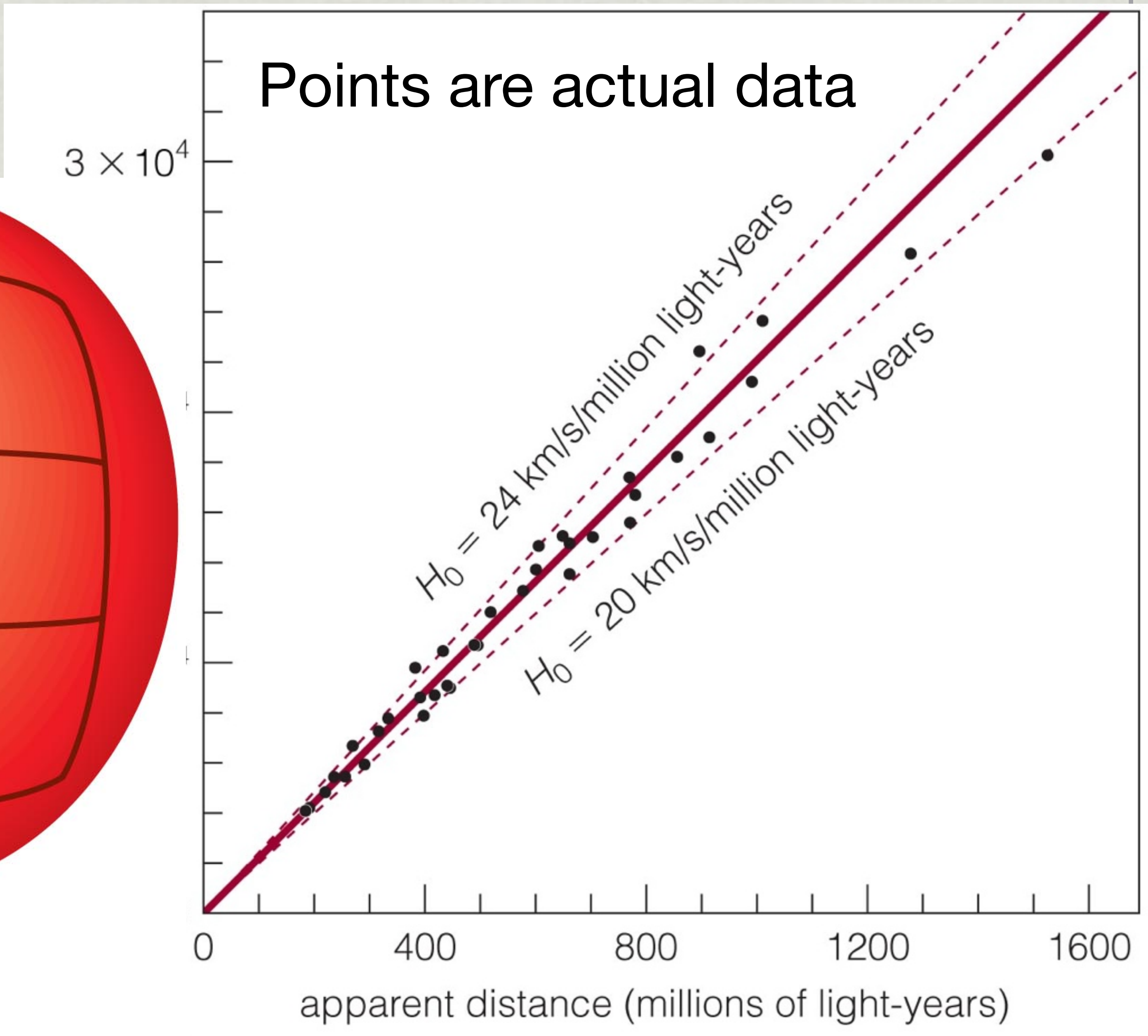
H_0 = Hubble's Constant, relates distance and velocity

H_0 = 21 (km/s)/Mly
or 69 (km/s)/Mpc

That recession velocity comes from the expansion of space, of the universe: the galaxies aren't really racing away from us, space is expanding and carrying them farther away from us (and each other).





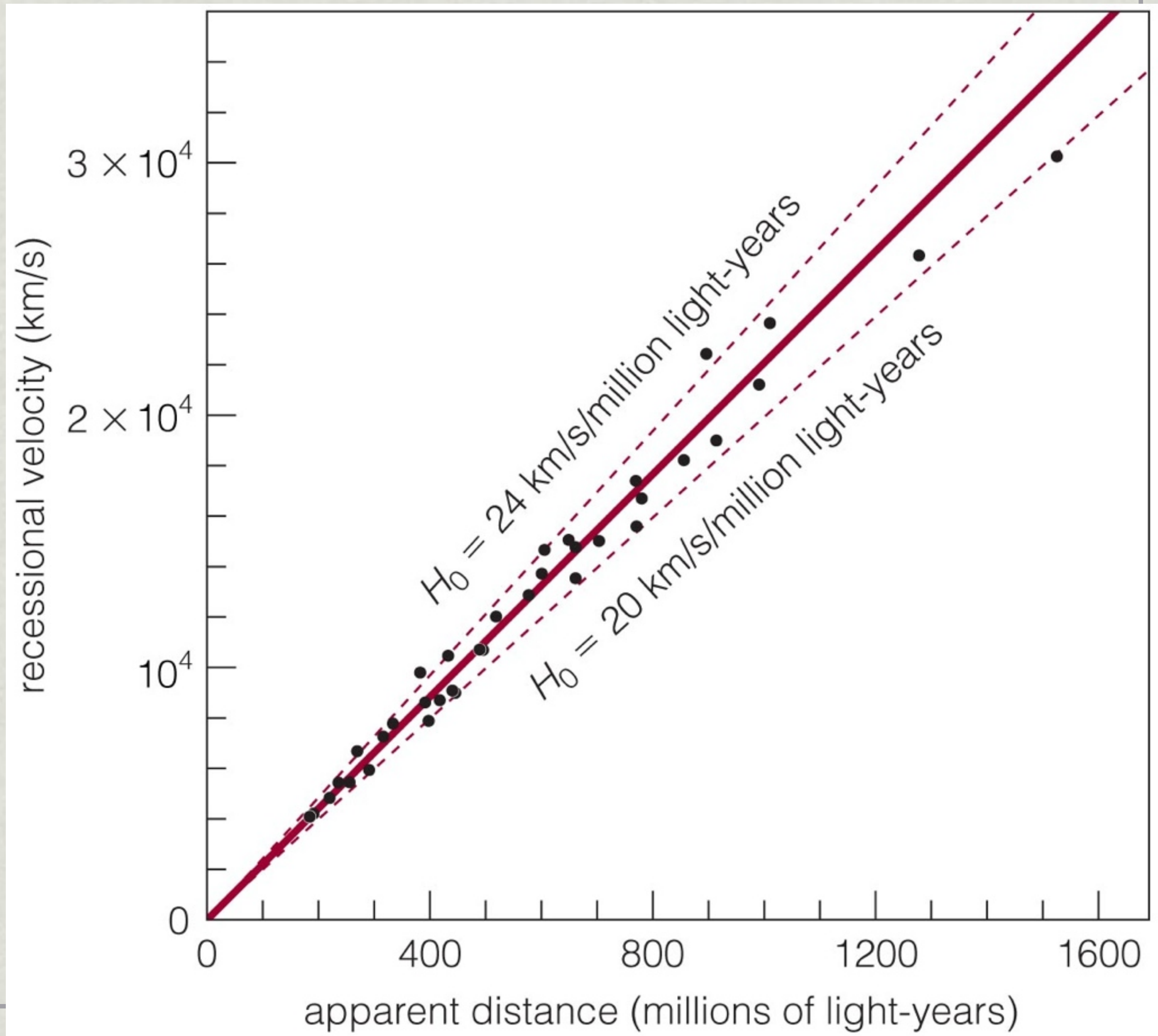
Hubble's Law and the Expanding Universe

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

Galaxies that are farther away are going faster.

All galaxies take the same amount of time to get where they are now if:

1) they all started very close together
2) the universe expands at a constant rate.



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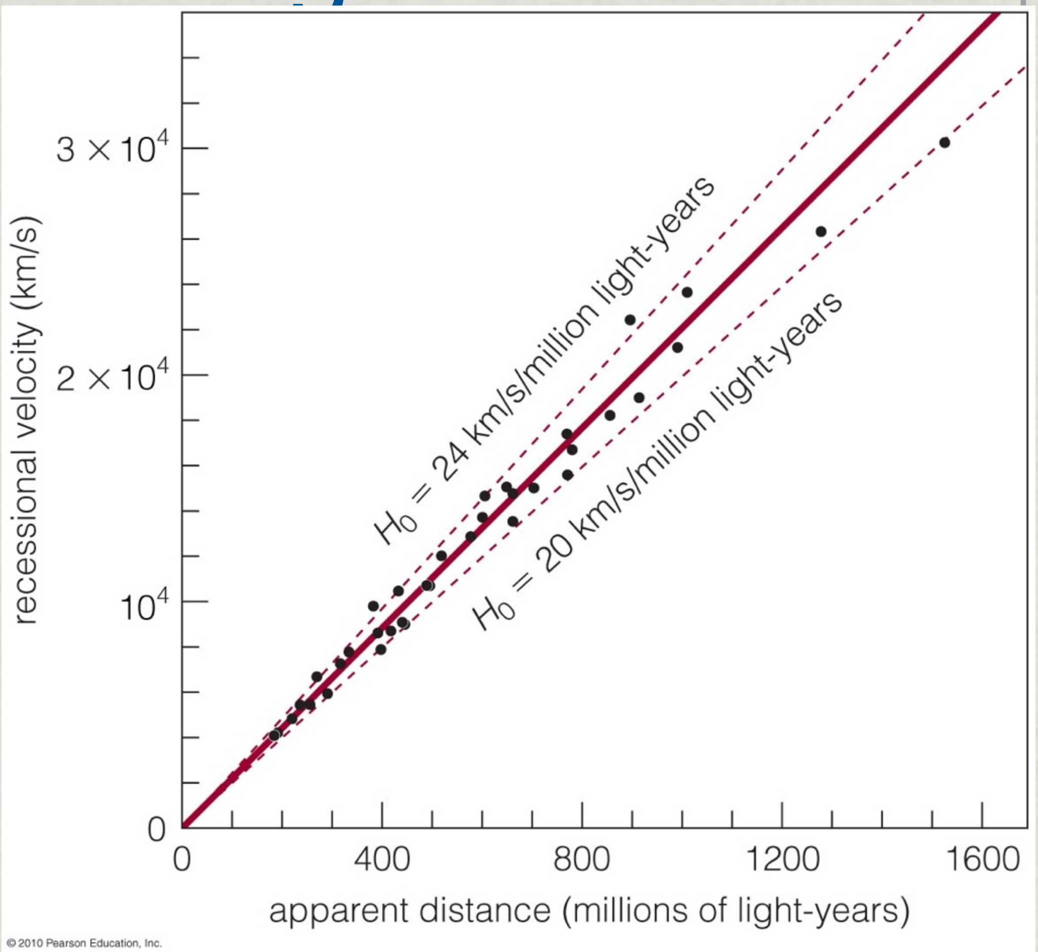
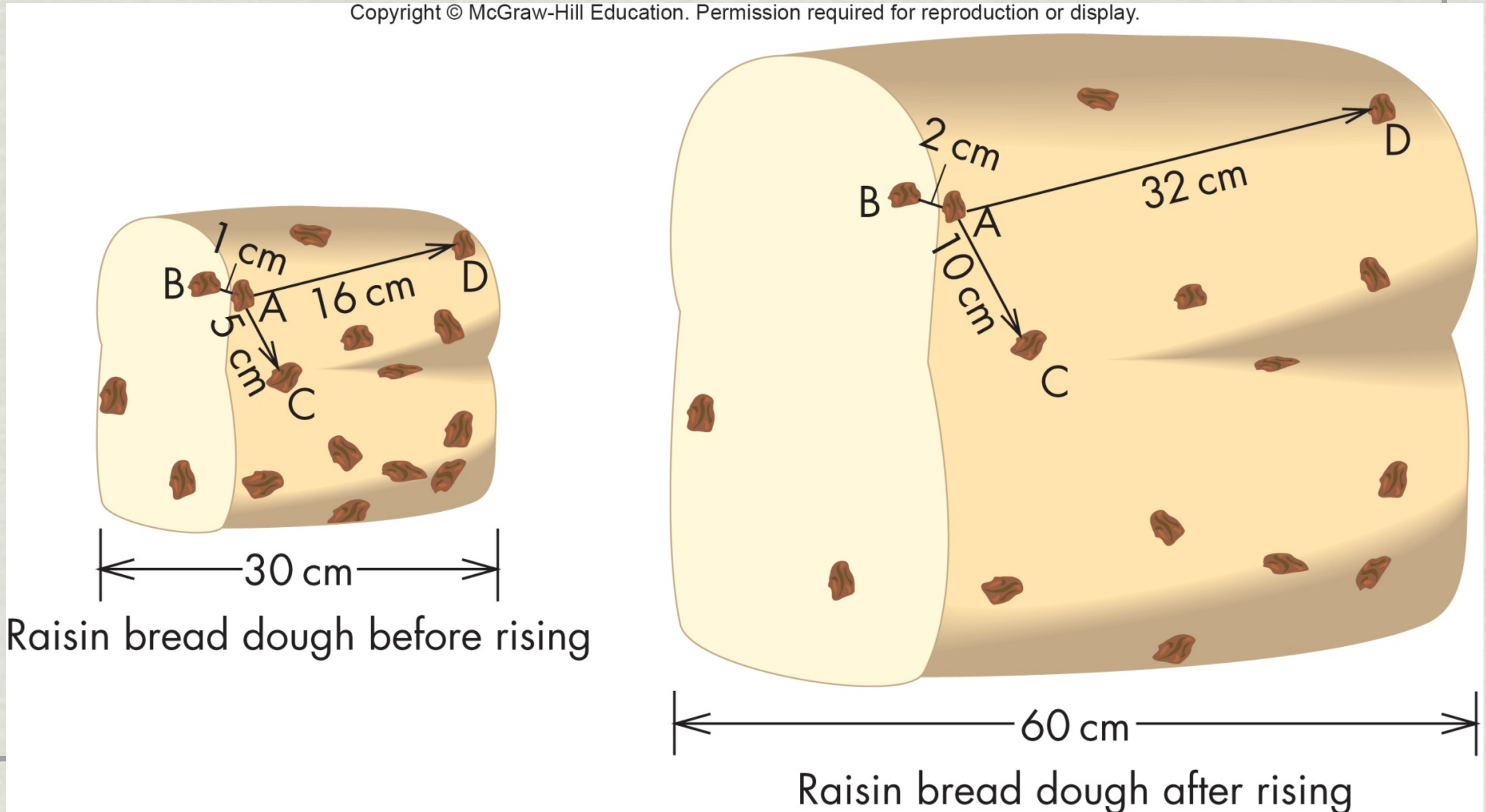
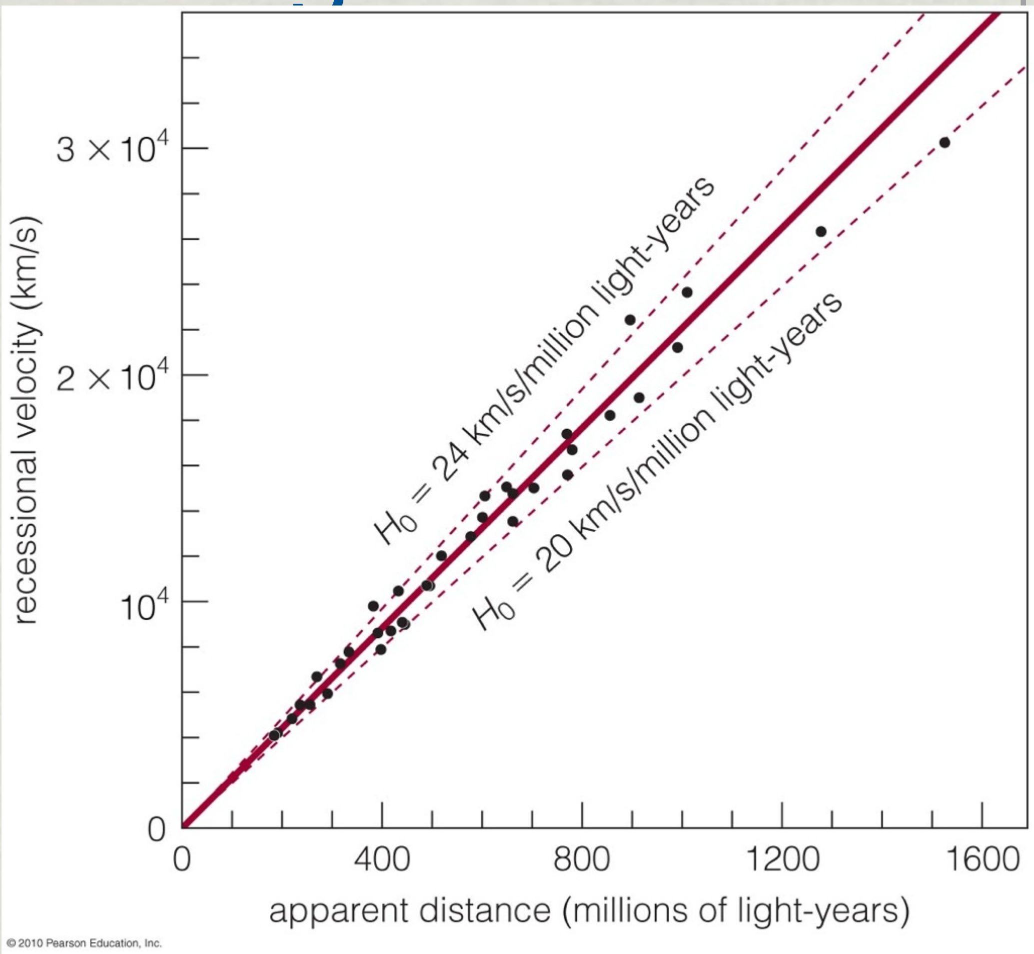


The raisins start close together. All the dough all rises for the same amount of time, at the same rate.

Raisins that are farther away from each other move the largest distance apart during rising = have largest velocity.



Hubble's Law and the Expanding Universe

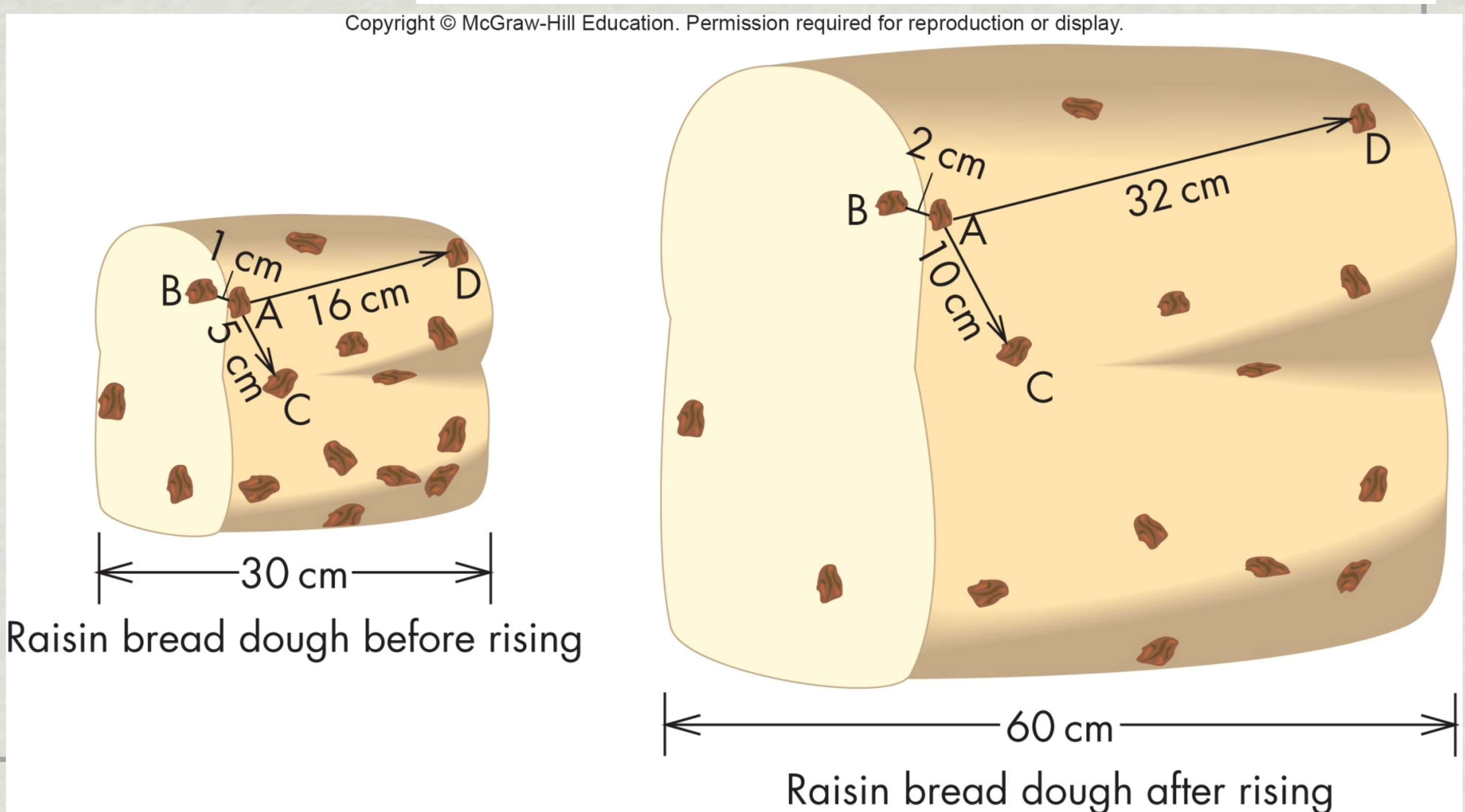


Raisins that are farther away from each other move the largest distance apart during rising = have largest velocity.

Remember: distance = velocity x time

Everything expands for the same amount of time

So two objects at bigger distance must be moving apart faster

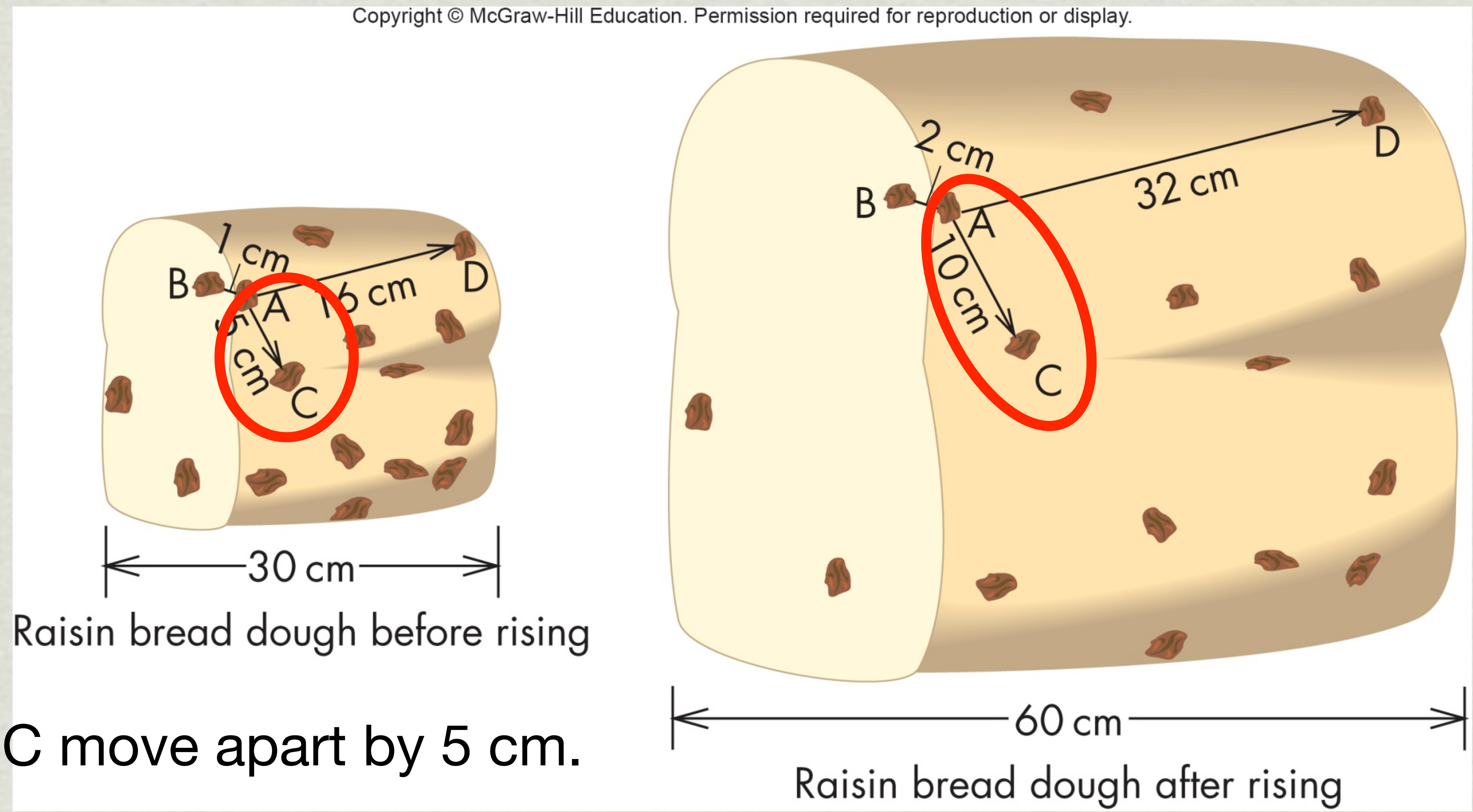


Hubble’s Law, the Expanding Universe and Raisin Bread

Dough rises for an hour.

Expands at the same rate (cm of dough per hour) everywhere

Distance between all the raisins doubles (increases by a factor of 2)



Raisins A and C move apart by 5 cm.

A sees C moving away from it at a speed of 5 cm/hour.

C sees A moving away from it at a speed of 5 cm/hour.

Hubble's Law, the Expanding Universe and Raisin Bread

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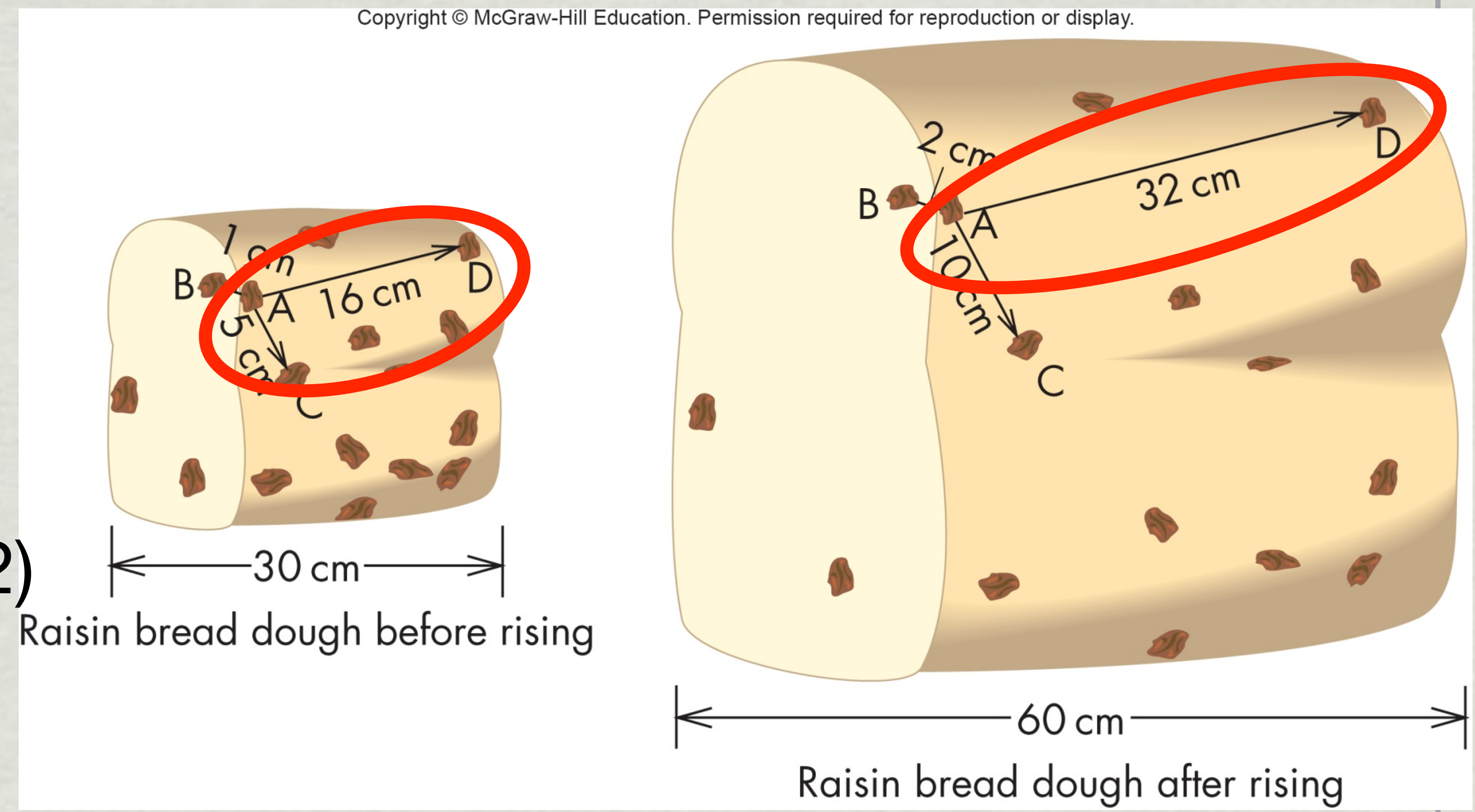

D is farther away from A

A sees D moving away from it at 16 cm/hour.

D sees A moving away from it at 16 cm/hour.

Raisins that are farther away from A are moving away from A at larger speed.

The rate the dough is expanding is the same everywhere.

There is more dough to expand between raisins that are far away from each other

Hubble's Law, the Expanding Universe and Raisin Bread

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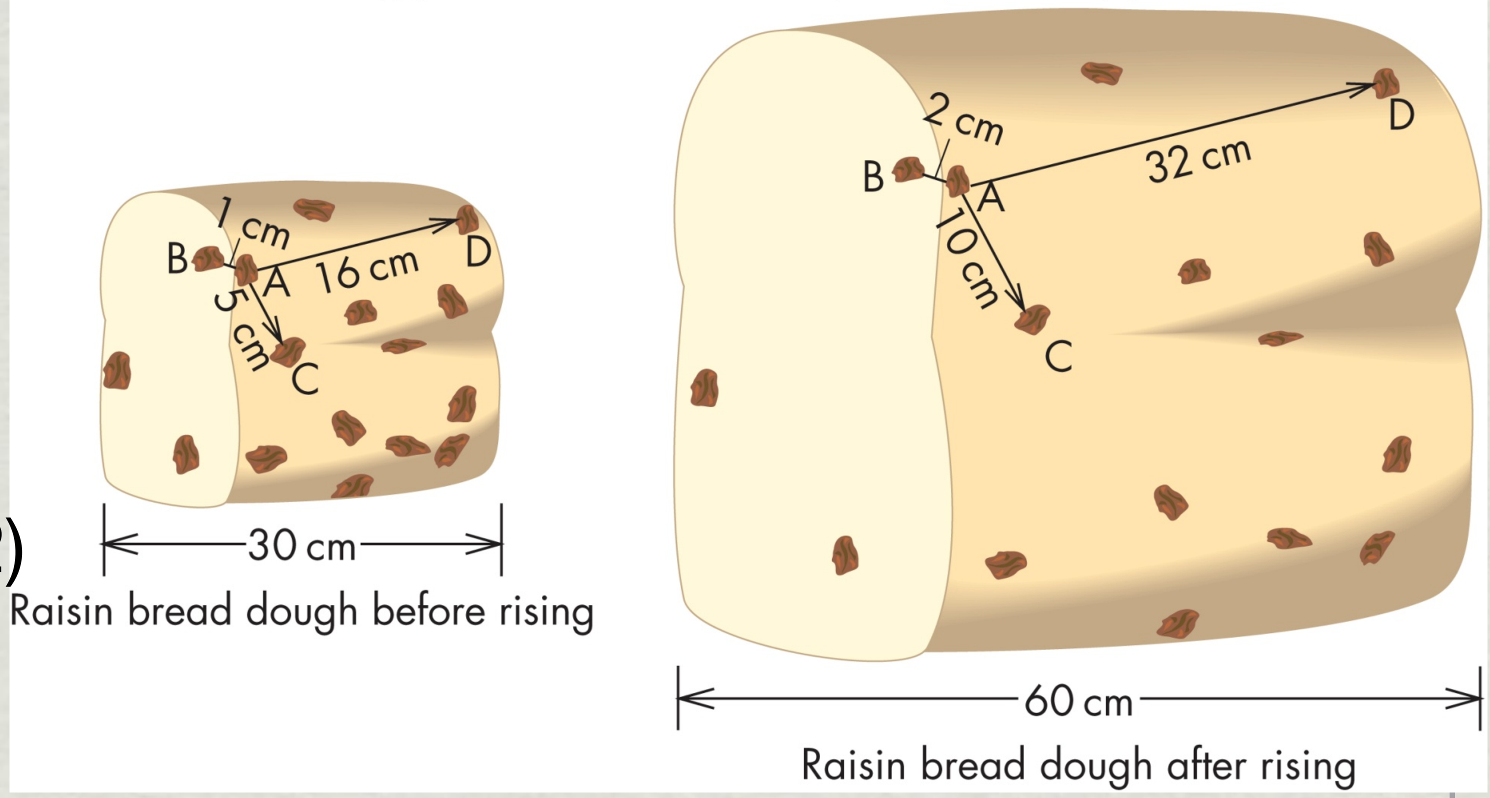
Expands at the same rate (cm of dough per hour) everywhere

Distance between all the raisins doubles (increases by a factor of 2)



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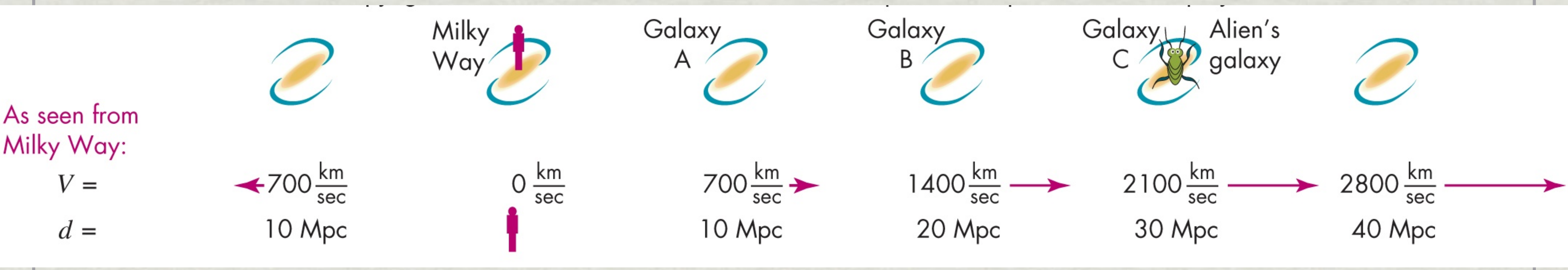
Raisins that are farther away from A are moving away from A at larger speed.

The rate the dough is expanding is the same everywhere.

For the universe, the expansion rate is the same everywhere at any instant in time. We'll see next time that the expansion rate changes with time, was different in the past

Cosmological Principle

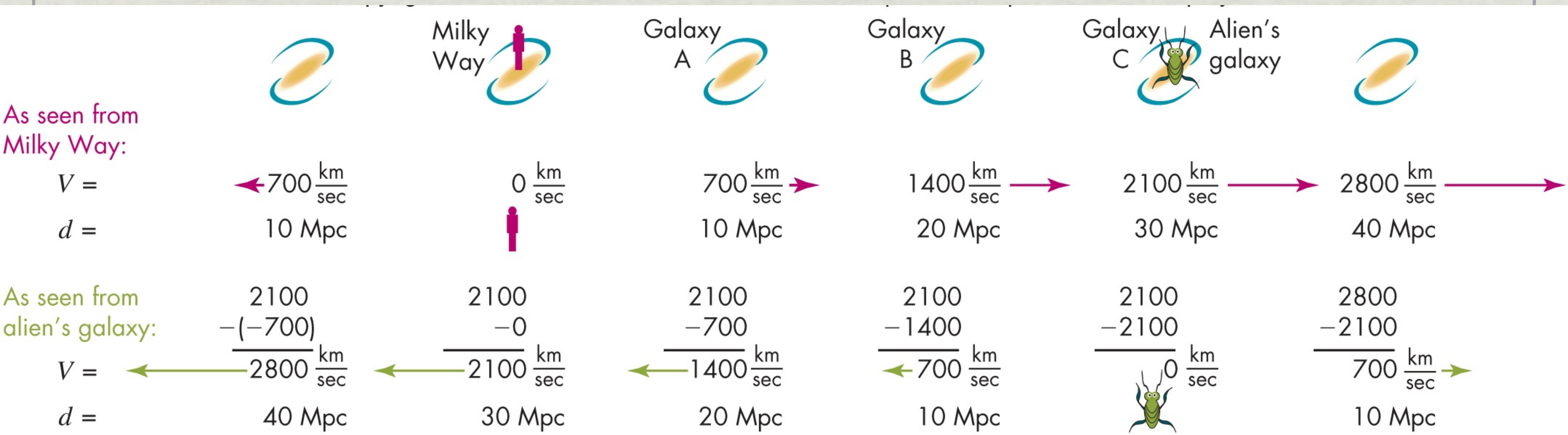


H_0 = Hubble's Constant, relates distance and velocity

H_0 = 21 (km/s)/Mly or 69 (km/s)/Mpc

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

Cosmological Principle



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Expansion of the Universe and the Big Bang

Mrs Felix: Why don't you do your homework?

Allen Felix: The Universe is expanding. Everything will fall apart, and we'll all die. What's the point?

Mrs Felix: We live in Brooklyn. Brooklyn is not expanding! Go do your homework.

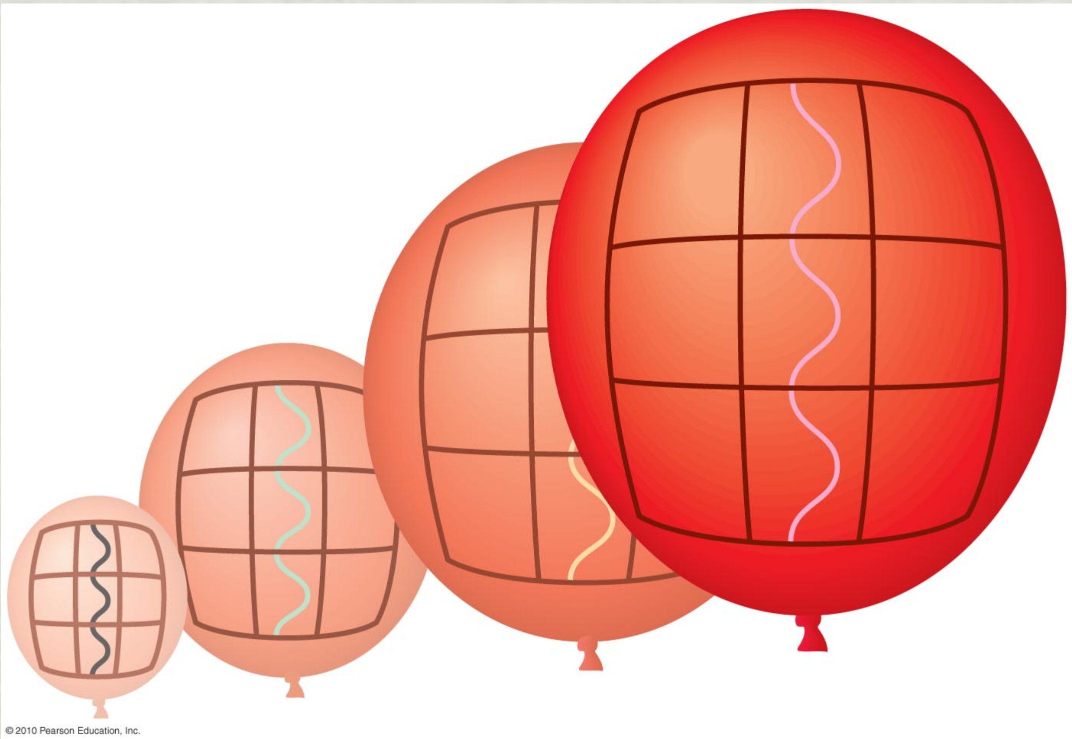
(from Annie Hall by Woody Allen)

Why isn’t Brooklyn (or Santa Cruz, or the solar system, or the Milky Way) expanding?

How can Andromeda be on a collision course with the Milky Way if all galaxies are moving away from each other?

thanks to math.ucr.edu/home/baez/physics/Relativity/GR/expanding_universe.html

Expansion of the Universe and the Big Bang



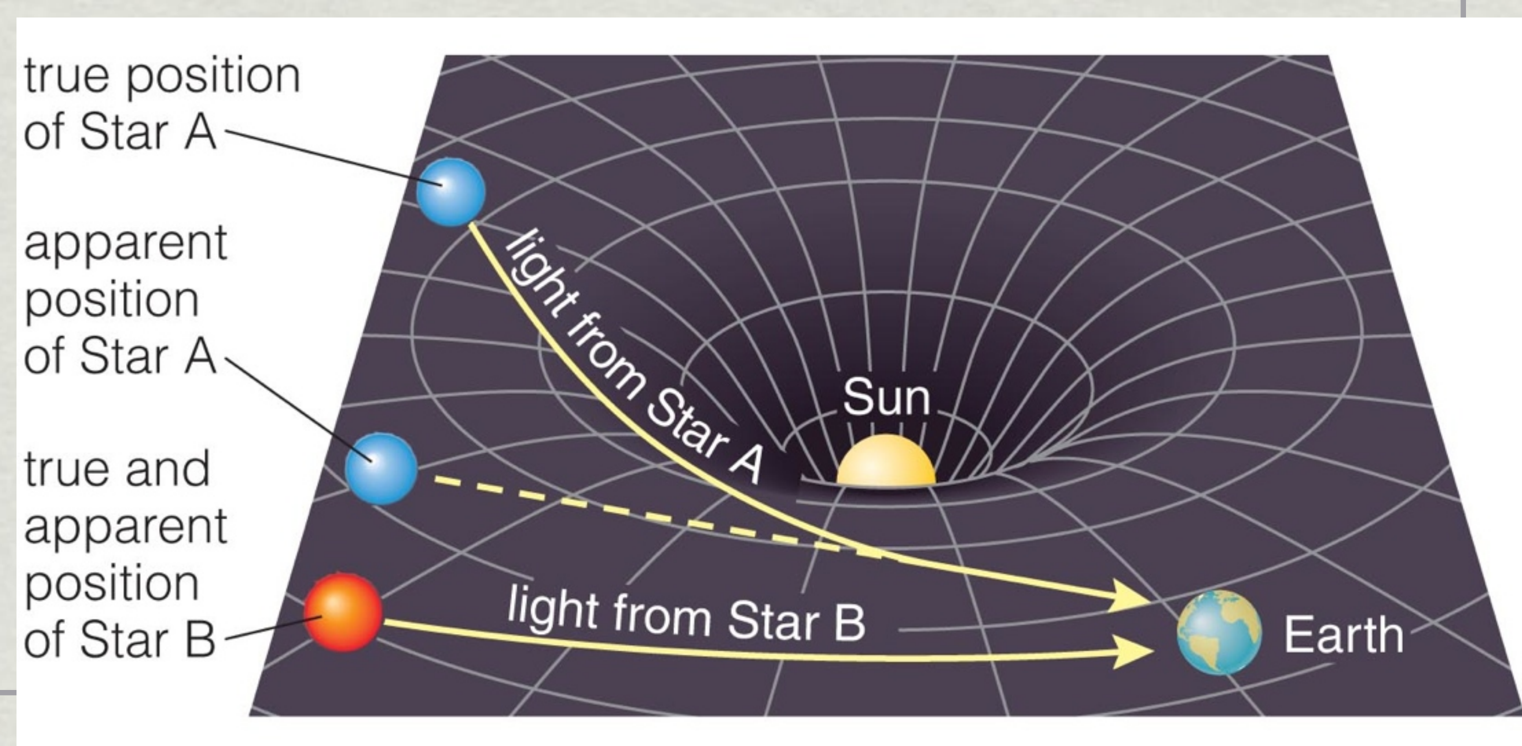
Spacetime is expanding!

But other things, like stars and black holes, can change spacetime, too

Locally, in the solar system, the sun's curvature of spacetime is much stronger than anything cosmology is doing, and the planets stay in orbit

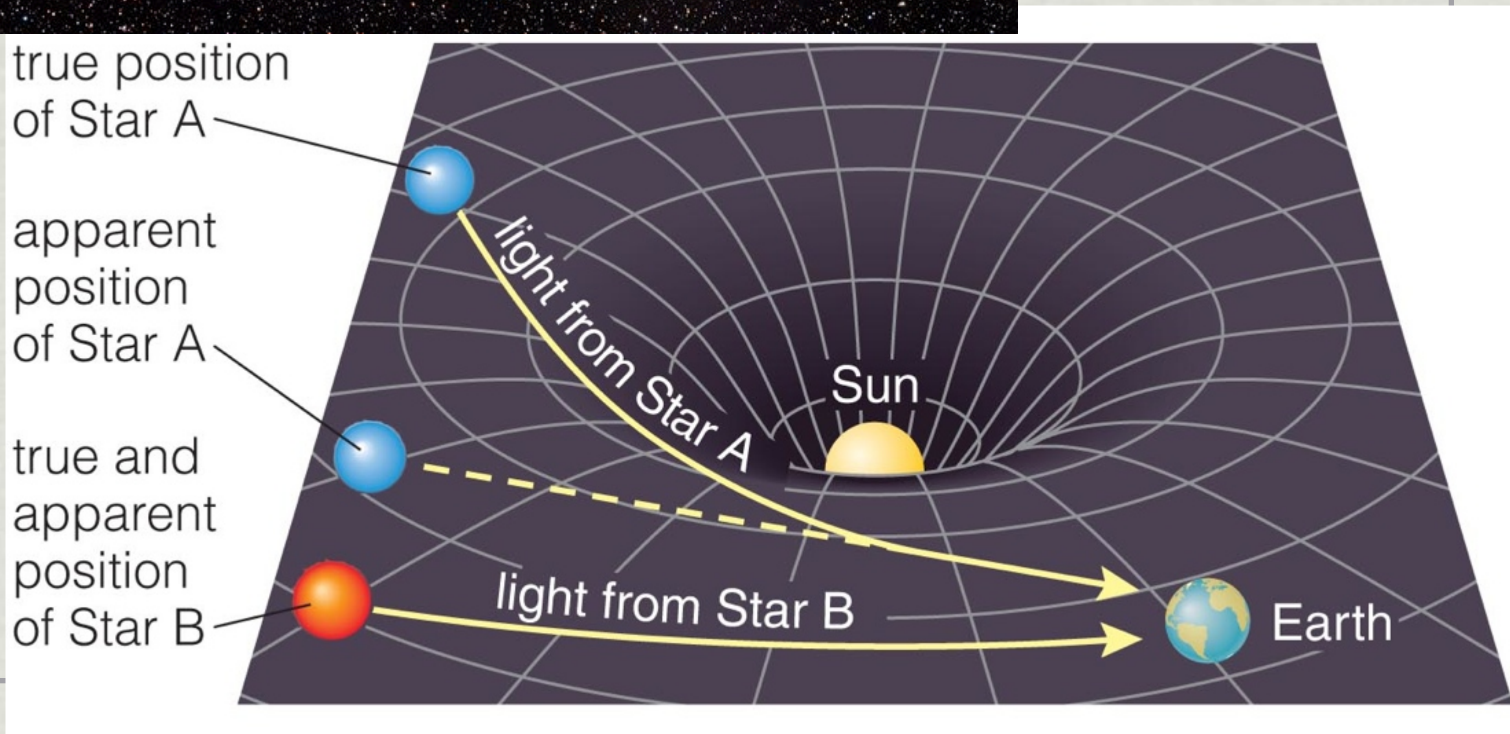
Why isn't Brooklyn (or Santa Cruz, or the solar system, or the Milky Way) expanding?

How can Andromeda be on a collision course with the Milky Way if all galaxies are moving away from each other?



Expansion of the Universe and the Big Bang

The Milky Way and Andromeda together have enough mass to curve spacetime so much that they stay in orbit and the space between them does not expand



Hubble's Constant and the Age of the Universe

Hubble's Constant H_0 = 21 (km/s)/Mly

Let's look at those units:

$$H_0 = \frac{21\ (\text{km/s})}{\text{million light-years}}$$

Mly = million light-years

Remember: a **light-year** is a unit of **distance**

Weird! $\frac{\text{km/s}}{\text{million light-years}}$

For every million light-years away something is, its velocity appears to increase by 21 km/s

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Remember acceleration: $m/s^2 = \dfrac{m/s}{s}$

In earth's gravity, acceleration is 9.8 m/s^2 so for every second an object falls, its velocity increases by 9.8 m/s.

After falling for 1 second, speed is 9.8 m/s
After falling for 2 seconds, speed 2 x 9.8 m/s = 19.6 m/s
After falling for 3 seconds, speed is 3 x 9.8 m/s = 29.4 m/s

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For every million light-years away something is, its velocity appears to increase by 21 km/s

So a galaxy that is 1 million light-years away has a velocity of 21 km/s
A galaxy 2 million light-years away has a velocity of 2 x 21 km/s = 42 km/s
A galaxy 3 million light-years away has a velocity of 3 x 21 km/s = 63 km/s

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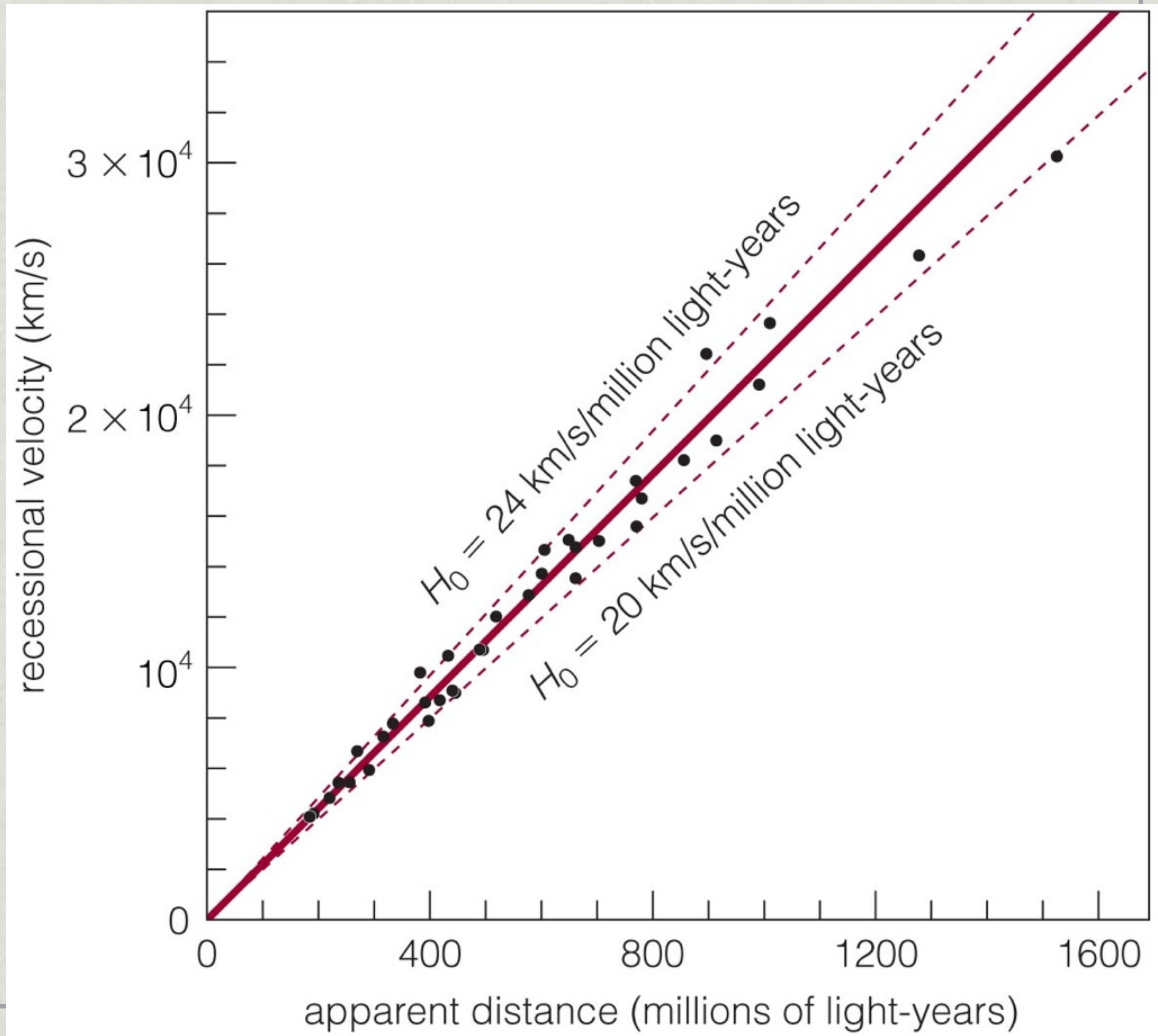

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1 light-year:
Speed of light (c) = 300,000 km/s

1 million light-years: $(1\text{x}10^6 \text{ years}) \times (300{,}000 \text{ km/s}) \times (3.14\text{x}10^7 \text{ seconds/year})$
Units: km

So, units of H_0: $\frac{(\text{km/s})}{\text{km}} = \frac{1}{\text{seconds}}$

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

What time is this?

Hubble's Constant and the Age of the Universe

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

What time is this? **Time since the expansion started!**

If everyone is moving with speed 5 m/s and they have run 5 m, how long ago did the race start?

A) 5 seconds
B) 1 second
C) 10 seconds
D) 0.5 seconds

Hubble's Constant and the Age of the Universe

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

Hubble's Constant H_0 = 21 (km/s)/Mly

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

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Hubble's Constant and the Age of the Universe

Distance = velocity × time: $D = v \times t$

Rearrange: $v = \frac{D}{t}$

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

$\frac{1}{H_0}$ has units of seconds (time)

So Hubble's Law tells us: $v = \frac{D}{t}$ since H_0 has units of $\frac{1}{\text{time}}$

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The time since the expansion of the universe started: its **age**!

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$\frac{1}{H_0}$ has units of seconds (time)

So Hubble's Law tells us: $v = \frac{D}{t}$ s

What time is $\frac{1}{H_0}$?

The time since the expansion of the universe started: its **age**!

Just like:
Everyone is running at 5 m/s and they have run for a distance of 5 m.

$$v = \frac{D}{t}$$

t is 1 second, the time since the start of the race.

Hubble's Constant and the Age of the Universe

$H_0 = \dfrac{21\ \text{(km/s)}}{\text{million light-years}}$ tells us the time since the expansion started: the age of the universe.

Speed of light (c) = 300,000 km/s

1 million light-years: $(1\text{x}10^6\ \text{years}) \times (300{,}000\ \text{km/s})$

$= (1\text{x}10^6\ \text{years}) \times (300{,}000\ \text{km/s}) = 3\text{x}10^{11}\ \text{(km/s)years}$ (yes, that is units of distance, just weird)

So: $H_0 = \dfrac{21\ \text{(km/s)}}{3\text{x}10^{11}\ \text{(km/s)years}} = \dfrac{21}{3\text{x}10^{11}\ \text{years}}$

$\dfrac{1}{H_0}$ = time since expansion started

$= \dfrac{3\text{x}10^{11}\ \text{years}}{21} = 14.3\text{x}10^9$ or about 14 billion years

The true best value is 13.8 billion years. The difference has to do with the accounting between dark matter, dark energy and regular atoms. But this is basically how we measure the age of the universe: $\dfrac{1}{H_0}$

Hubble's Constant and the Age of the Universe

Hubble's Law: $v = H_0 \times D$ in units: $v = \frac{D}{t}$

If v is constant, then when t is small (near the beginning), D must be small, too.

What is D? the distance between any two galaxies, any two places in the universe.

Since space is what is really expanding, D is a measurement of the size of the universe.

So, what was the universe like when t was small?

Hubble's Constant and the Age of the Universe

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Smaller!
Denser!

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Hotter!
Different and very weird!

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Denser!
Hotter!
Different and very weird!

The term "Big Bang" was initially a sarcastic way to refer to the state of the universe just before expansion began.

First used by people who thought this whole idea of expanding space was crazy.

But there turns out to be lots of evidence for it...

Evidence for the Big Bang

Universe was hotter, denser, smaller at early time (small t, small D)

Another hot, dense place in the universe that we've thought about:
Cores of stars

That leads us to some predictions:
1) Nuclear fusion should have been happening.
This is why we think the universe starts out with some Helium (and a tiny amount of Beryllium, Lithium and Boron), not just Hydrogen.

Evidence for the Big Bang

Universe was hotter, denser, smaller at early time (small t, small D)

Another hot, dense place in the universe that we've thought about:
Cores of stars

That leads us to some predictions:

2) Thermal radiation: the universe was dense enough to be opaque, so light interacts with lots of atoms before it can escape. Makes a thermal spectrum.

- "Escape" in this case means that the universe expands enough that the density goes down. Atoms recombine (protons and electrons stick together). Photons stop interacting with atoms so easily.

- Like photons escaping from the outer layers of a star when the density finally is low enough that there are not so many atoms to interact with.

Evidence for the Big Bang

The early universe was hot and dense, just like the core of a star.

→ fuse hydrogen into helium, other light elements

Just like in a star, nuclear fusion is more efficient at higher density.
Density of ***atoms*** is the only thing that matters.
"baryons": normal matter. Protons, neutrons, electrons, atoms, easy chairs, banana slugs, etc.

So this can tell us the total amount of baryonic matter (atoms, normal matter) in the universe.
Gravity: works on ***all*** matter, baryons + dark matter.
Early universe nucleosynthesis: how much baryonic (normal) matter (atoms)

Universe today: 70% Hydrogen, 28% Helium, 2% everything else
But all the stars that have ever lived could have made only 3% Helium.
Where did the rest come from?

The Big Bang!

Evidence for the Big Bang

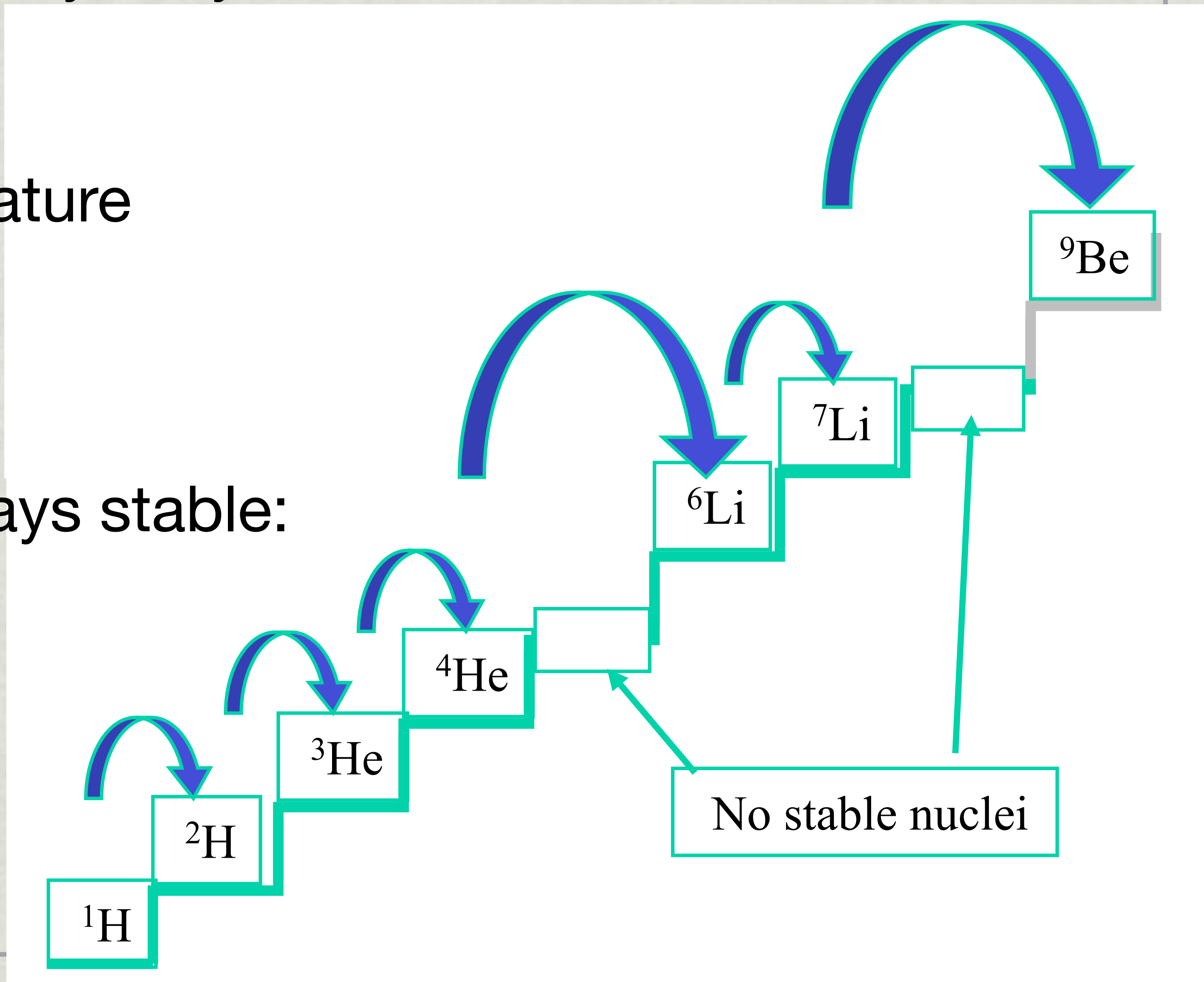
Conditions in the early universe hot and dense enough for nucleosynthesis: universe was 0.001 seconds to 3 minutes old

Protons, neutrons, electrons bouncing around with ***lots*** of kinetic energy

Nuclei form and break apart very quickly, only stable elements survive.

As the universe expands, the temperature and density go down

Nucleosynthesis stops.
Number of atoms of each element stays stable: "freeze-out"

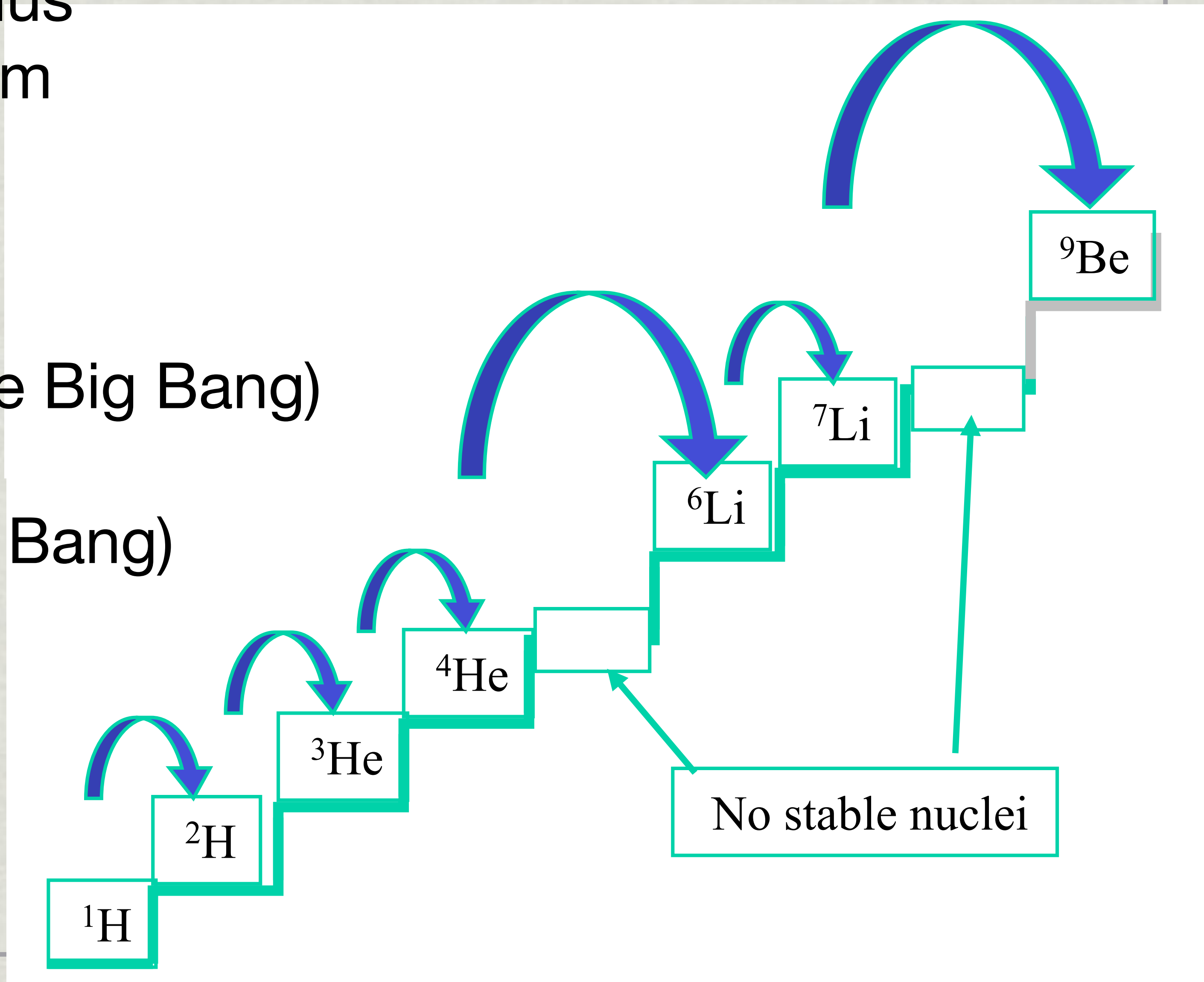


Evidence for the Big Bang

Nucleosynthesis stops.
Number of atoms of each element stays stable:
"freeze-out"

75% Hydrogen
25% Helium
tiny traces of Deuterium (Hydrogen plus one neutron), Lithium, Boron, Beryllium

Universe today:
70% Hydrogen
28% Helium (3% from stars since the Big Bang)
2% everything else
(all made in stars since the Big Bang)



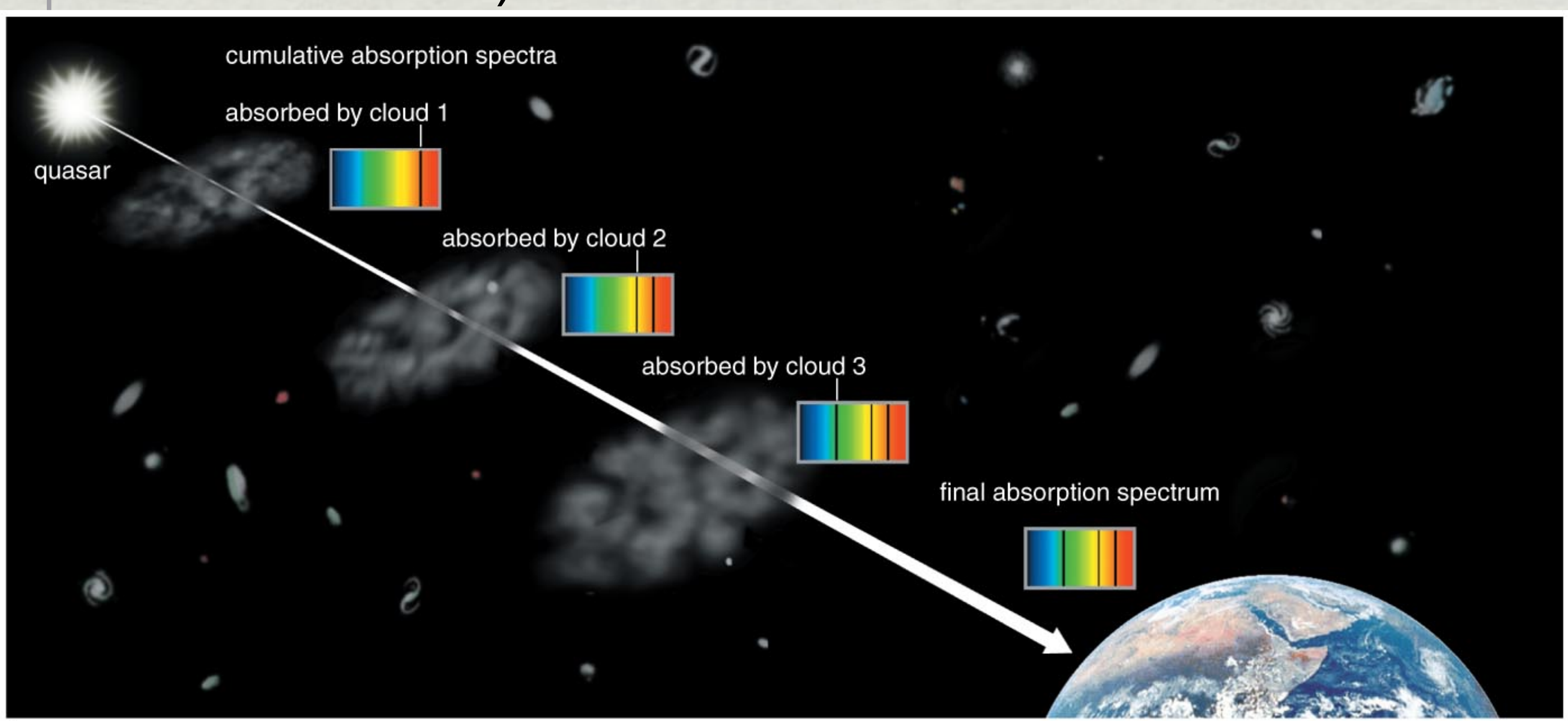
Evidence for the Big Bang

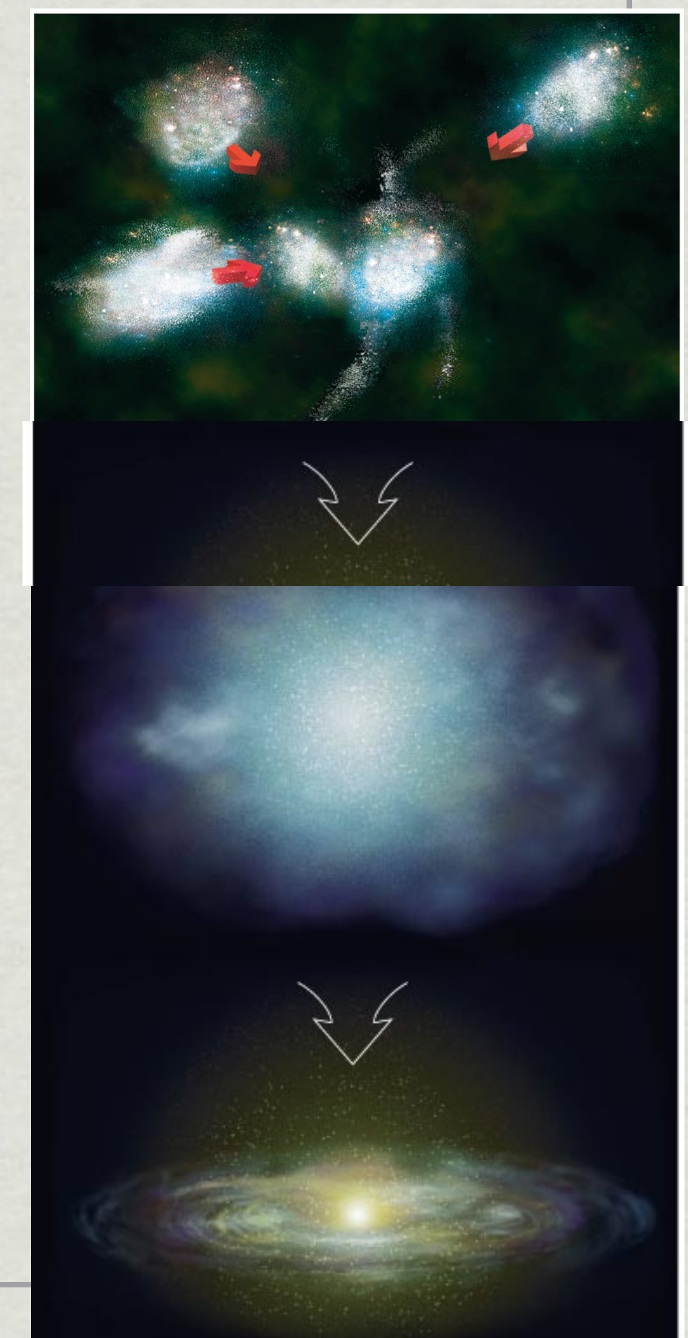
How do we measure the helium and deuterium content of the universe to compare to predictions?

Gas clouds in the distant universe.

These are young overdensities, like the first blobs of gas that we think made the Milky Way.

Not much time for star formation (ideally, no star formation at all) to make helium in stars.





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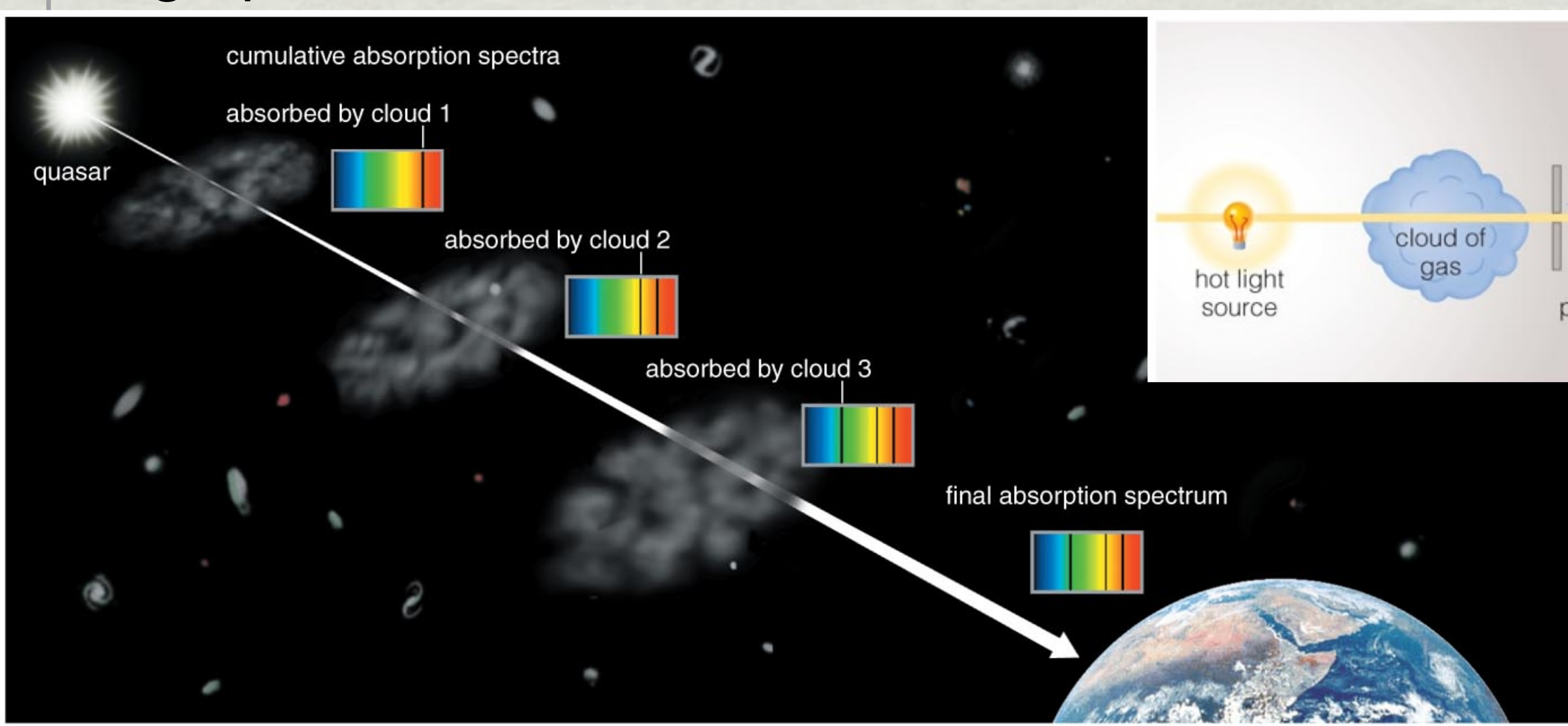
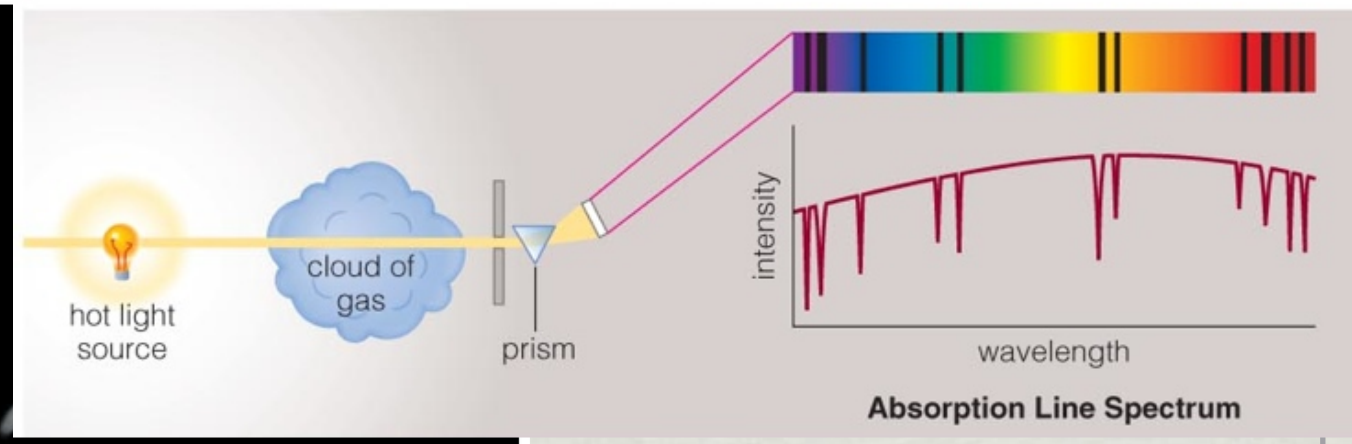
Quasar: hot source behind cool gas. Get an absorption spectrum, look for the fingerprints of deuterium and helium.





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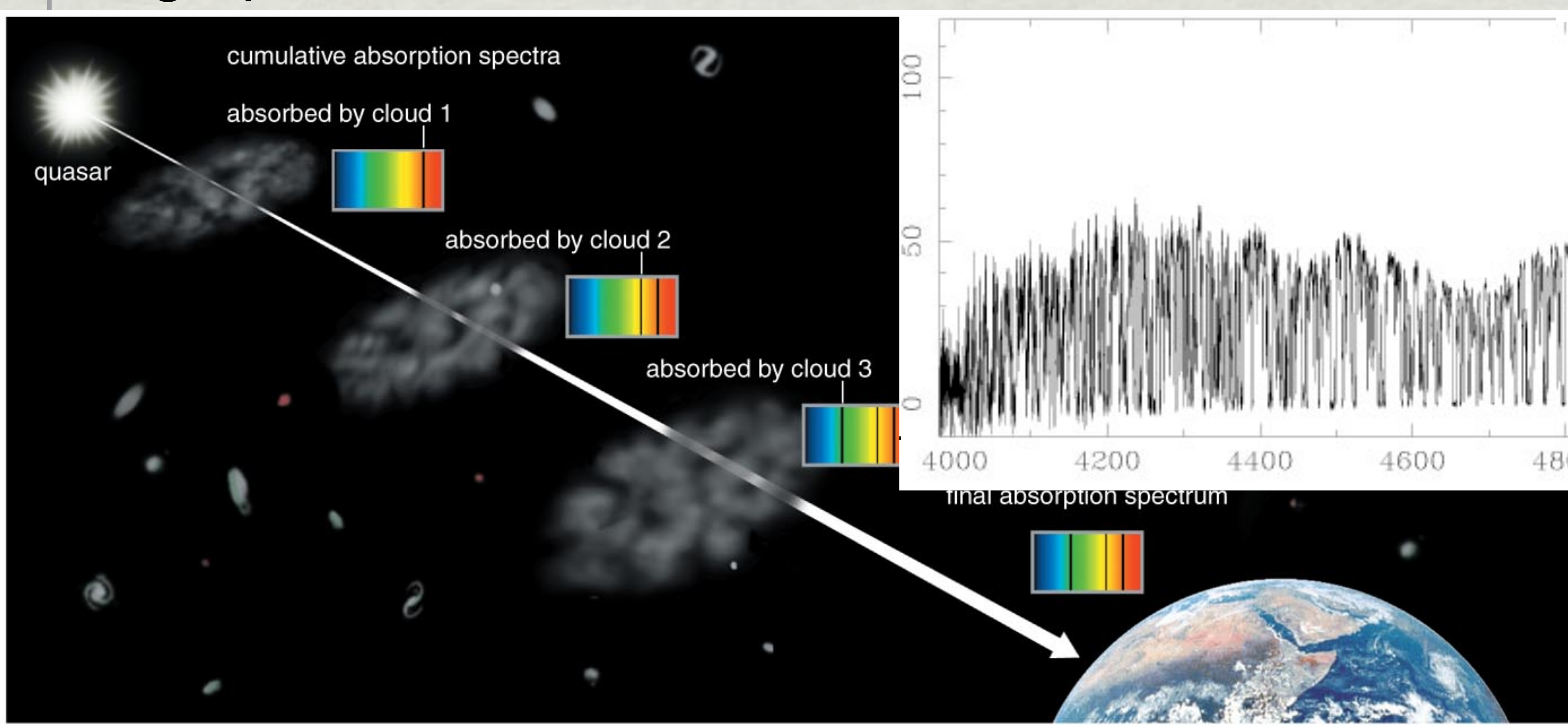
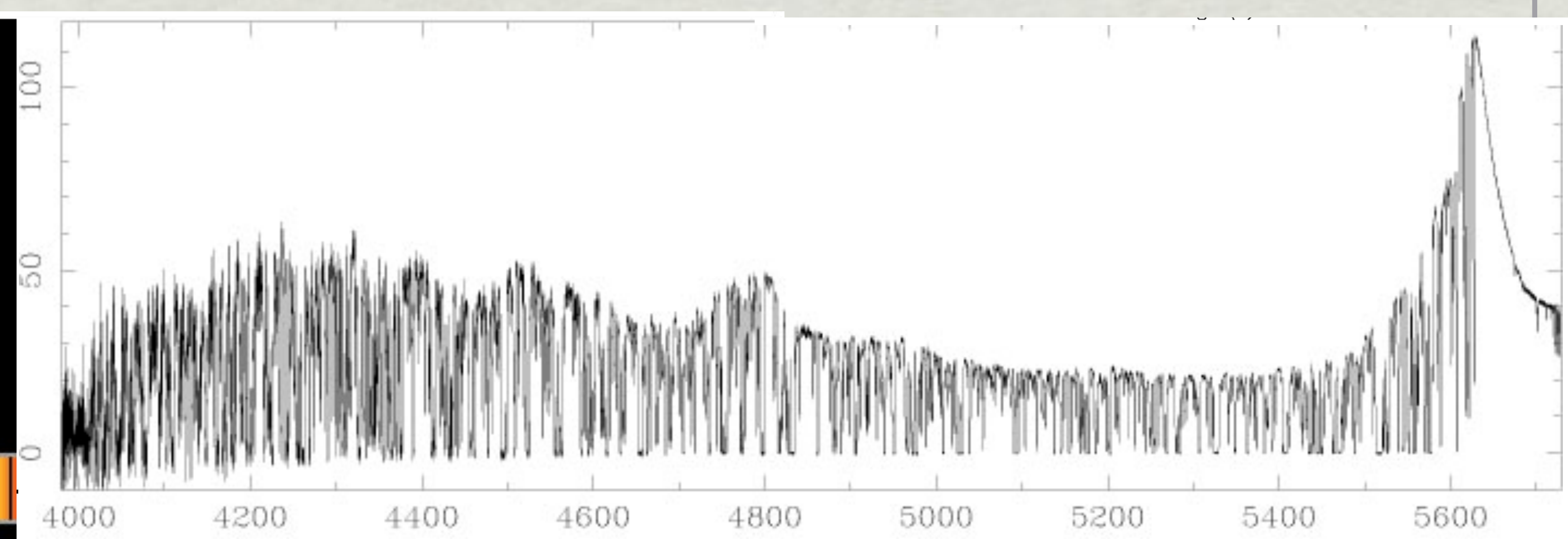




Evidence for the Big Bang

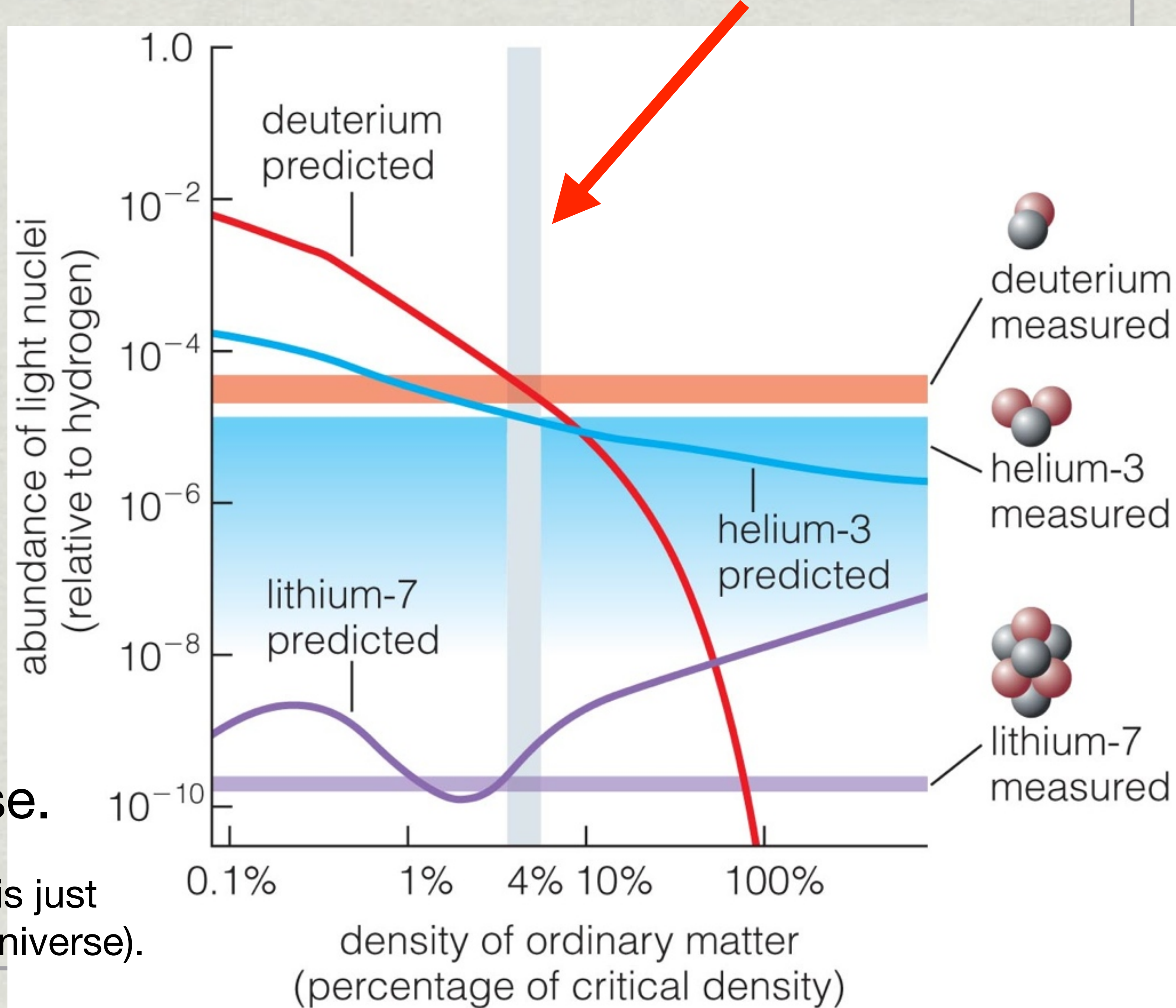
Predicted fraction of the total mass-energy budget of the universe that is Helium, Deuterium and Lithium made in early-universe nucleosynthesis.

Fractions are calculated for different fractions of the "critical density" required for gravity to just stop expansion of the universe.

Early universe nucleosynthesis tells us the amount of baryonic matter (normal matter; atoms, banana slugs, etc.) in the universe.

(We'll get to "critical density" later. For now it is just way to scale to the total mass-energy in the universe).

Measurements agree with predictions for a density of baryons about 4% of the critical density.

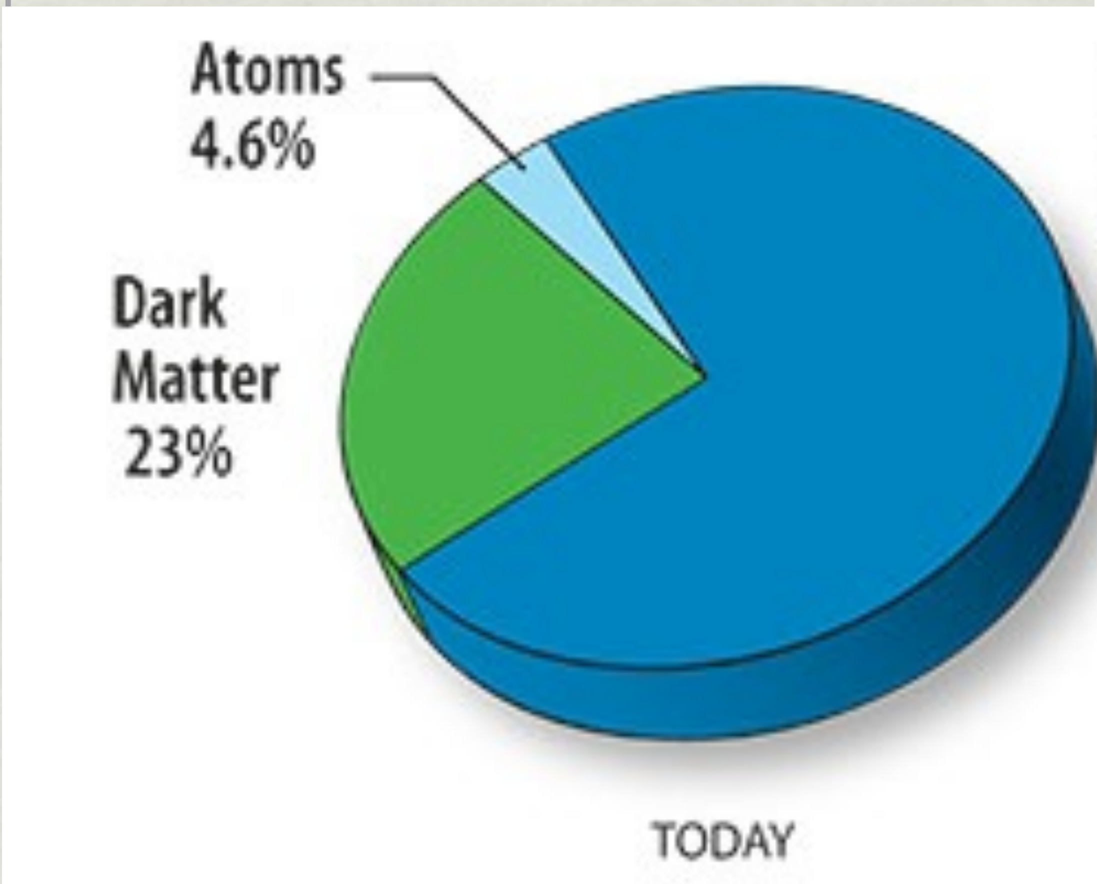


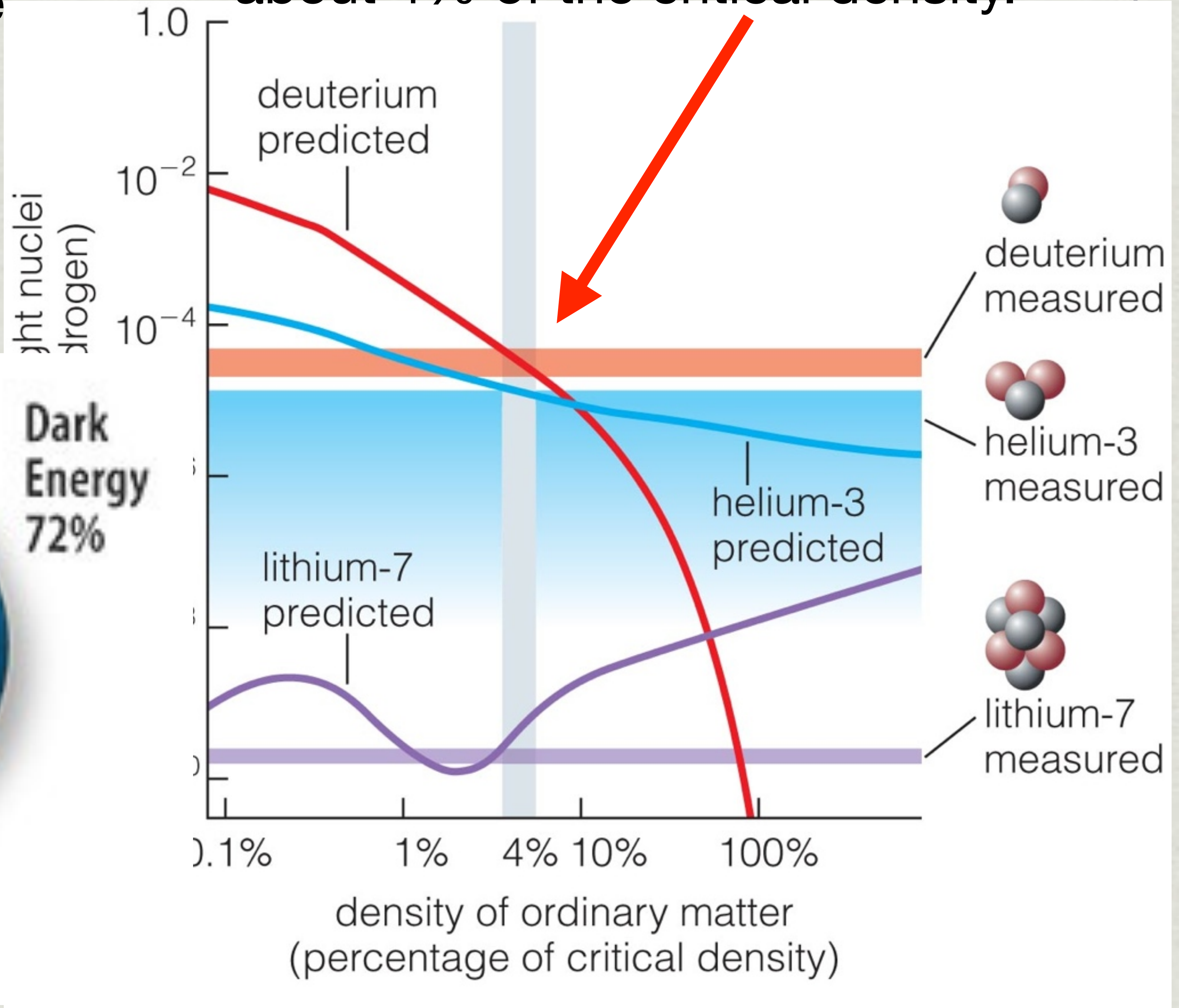
Evidence for the Big Bang

Early universe nucleosynthesis tells us **baryon** density.

This is how we know that all the gravitating matter in the universe is not atoms. We measure more gravitating matter than we measure atoms.

Measurements agree with predictions of density of baryons is about 4% of the critical density.



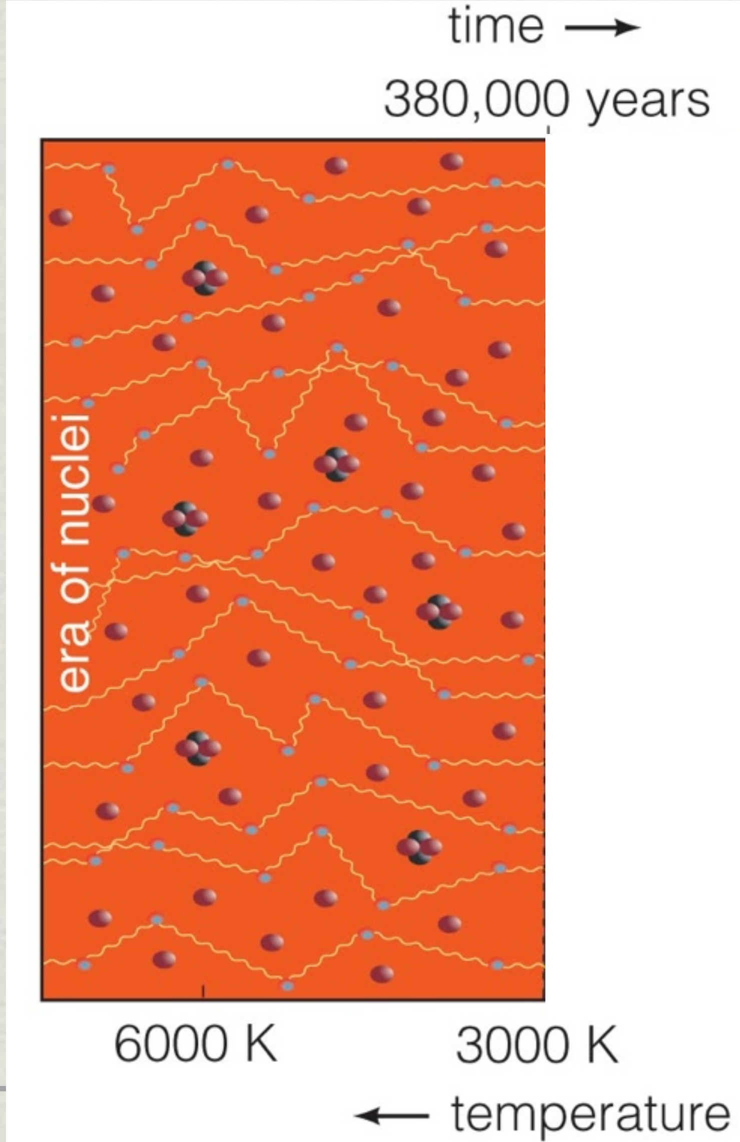


Evidence for the Big Bang

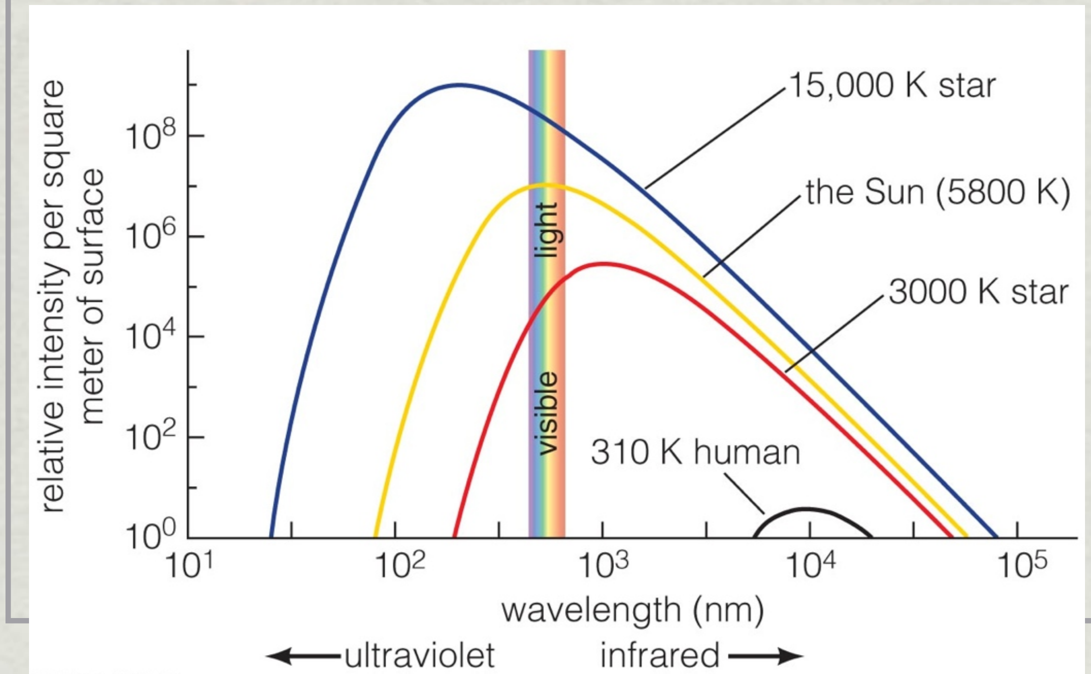
Prediction of the Big Bang:

2) Thermal radiation: dense, opaque matter. Light interacts with lots of atoms before it can escape.

Early universe is hot and dense. Atoms separated into protons and electrons (ionized — too hot (too much kinetic energy) for electromagnetic force to keep them together.



Photons interact with electrons even more readily than with atoms, so dense gas with free electrons is very opaque



Evidence for the Big Bang

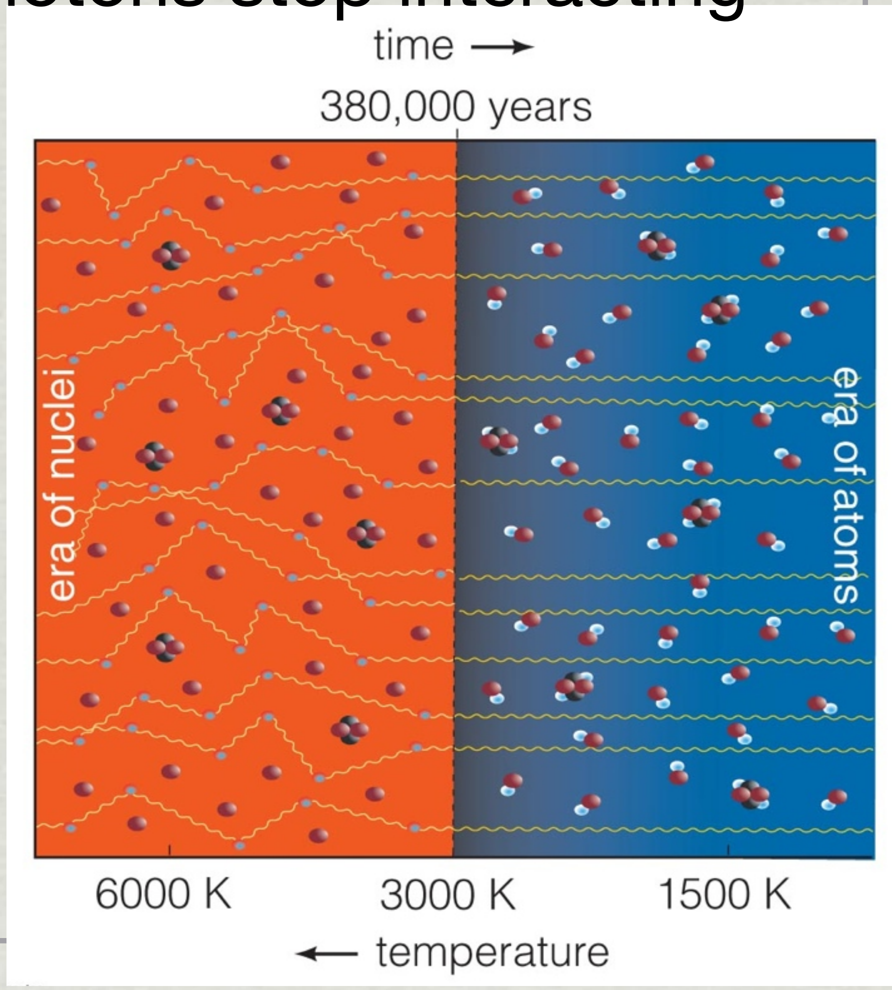
Prediction of the Big Bang:

2) Thermal radiation: dense, opaque matter. Light interacts with lots of atoms, protons and electrons before it can escape.

What do we mean by “Escape” ?

As the universe expands the density goes down and it cools. Atoms recombine, protons and electrons stick together. Photons stop interacting (very much) with atoms.

Universe becomes transparent, photons can move through space uninterrupted.



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What do we mean by "Escape" ?

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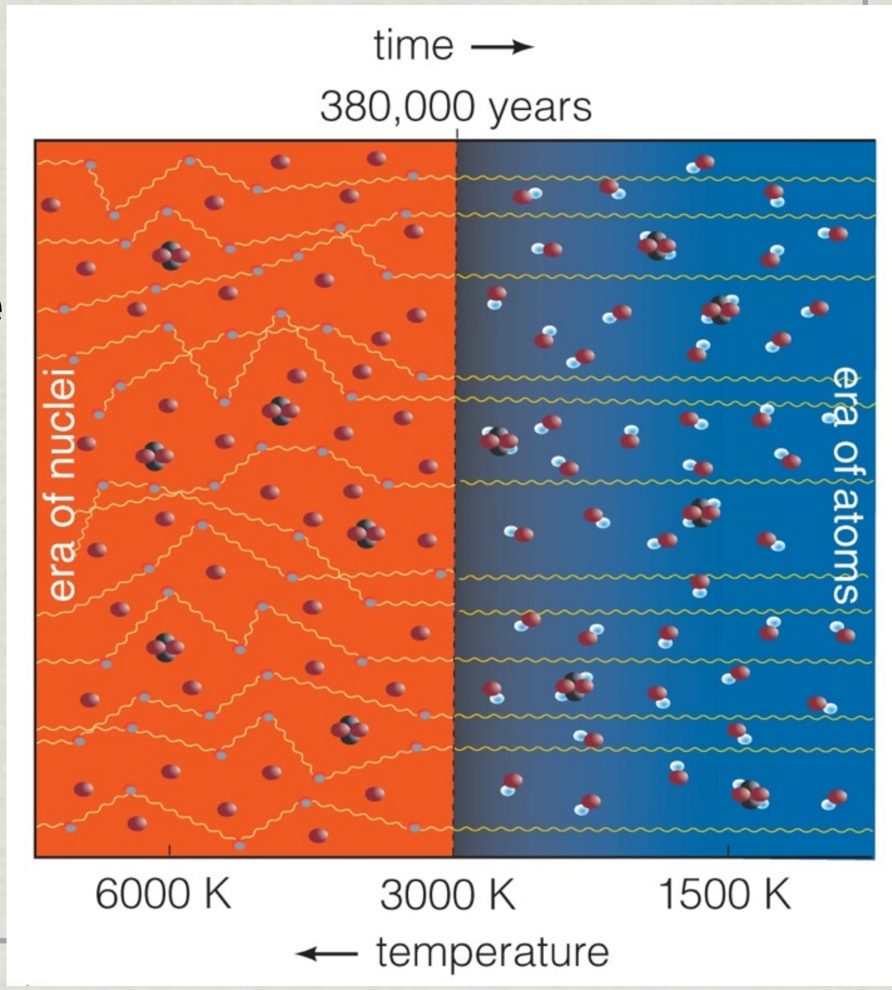
- Like the sun, we see the "surface" where that density drops so photons can escape. Where do they escape to? Into the expanding universe, where we eventually see them.

- Rate of photon interaction with atoms depends on pressure and density. Higher density, more trapped photons, brighter. The thermal radiation gives us a record of the density and temperature in the universe at the time the photons escape.



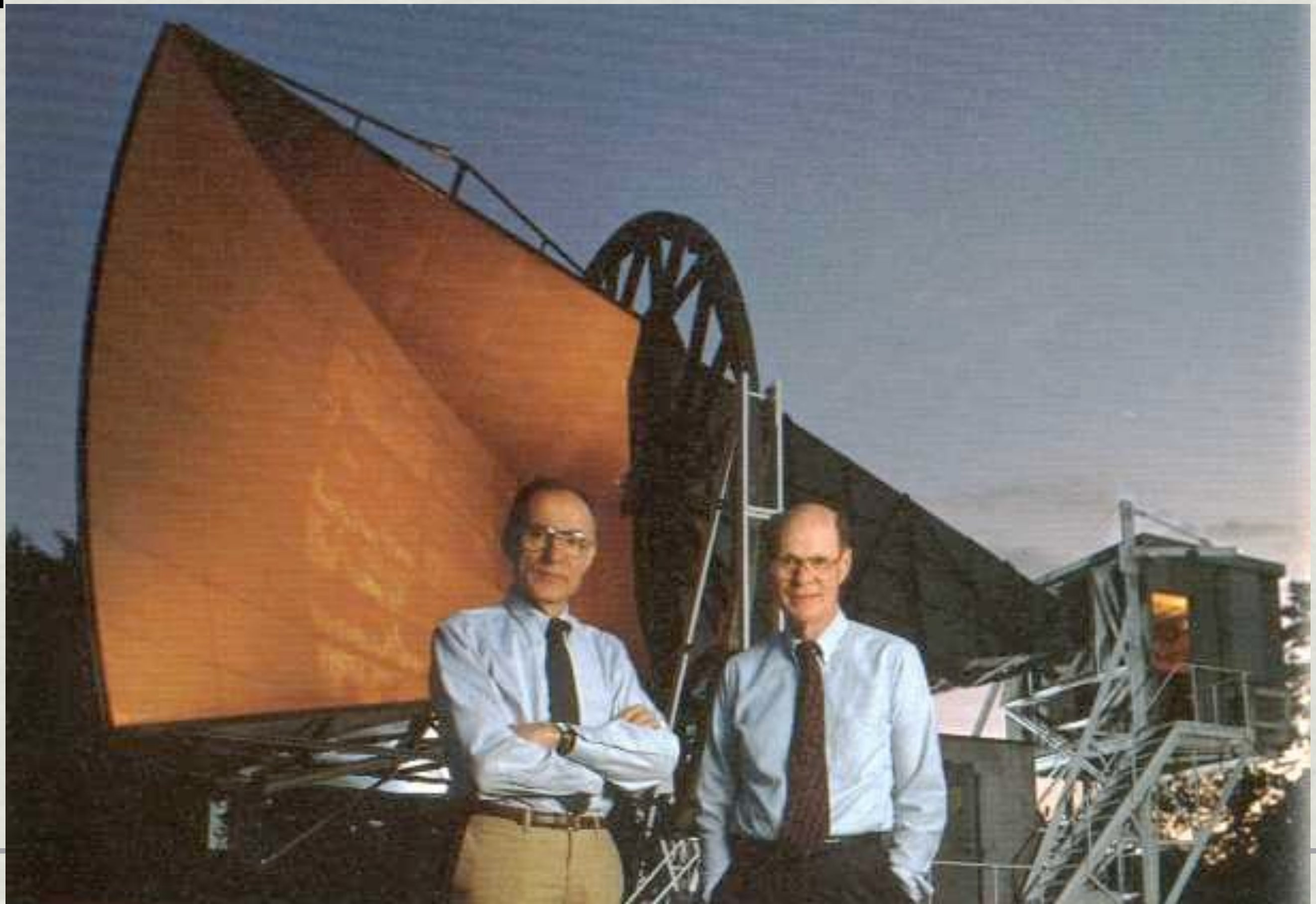
Evidence for the Big Bang

Observation: Penzias and Wilson, 1964, AT&T Bell Laboratories in New Jersey

Trying to receive very faint signals from the first communication satellites

Found an annoying radiation background with a thermal spectrum at a temperature of 3° K

With a little help from Peebles and Dickie at Princeton, who had calculated what T should be at the time the photons escape, it was identified as that thermal radiation spectrum from the Big Bang at exactly the expected temperature.



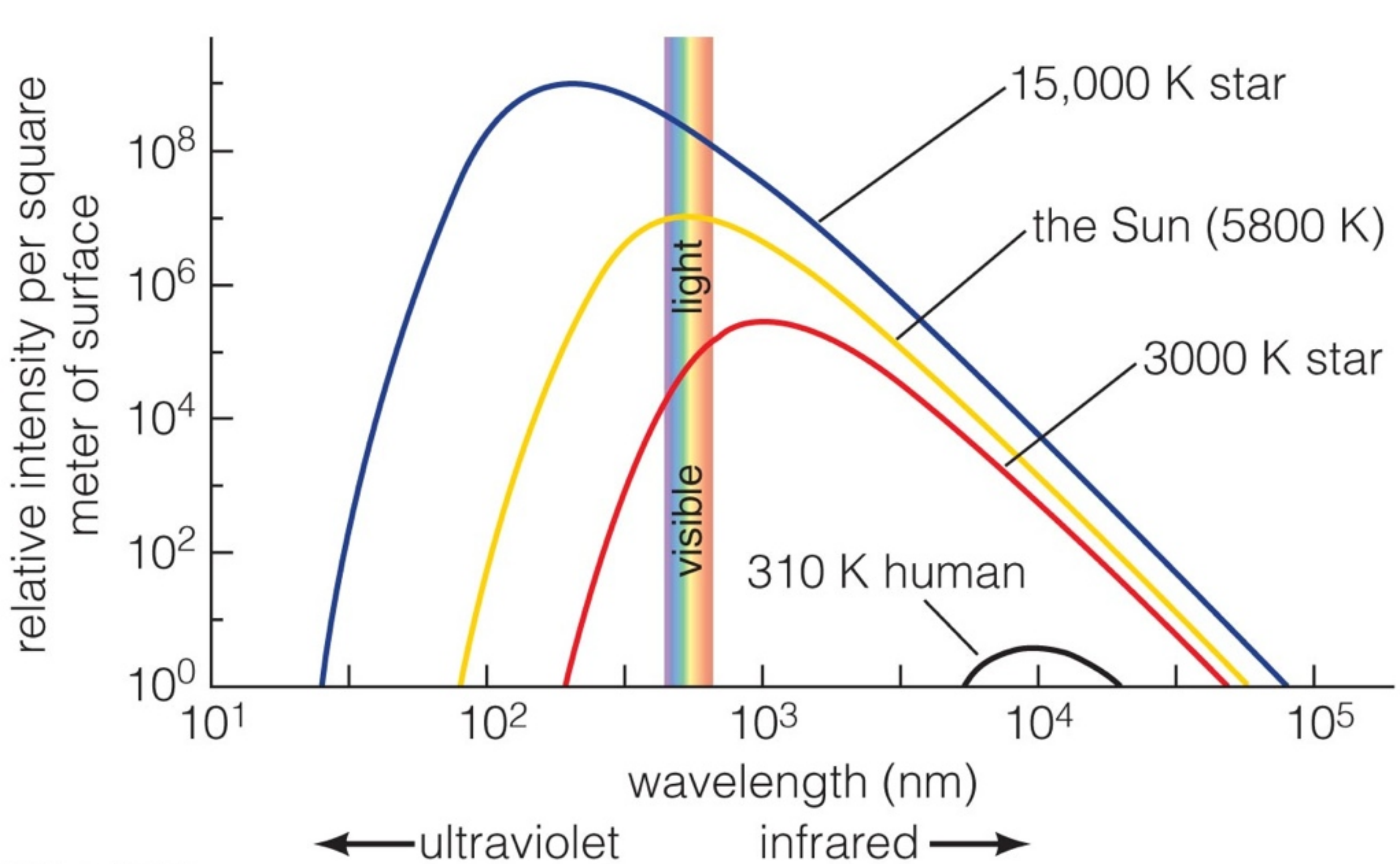
Bird poop?

Cosmic Microwave Background

Penzias and Wilson found that the spectrum matched a Stefan-Boltzmann law perfectly, as well as they could measure, with peak wavelength of about 1 mm (Wein's Law) or 3º K

This is true in every direction.

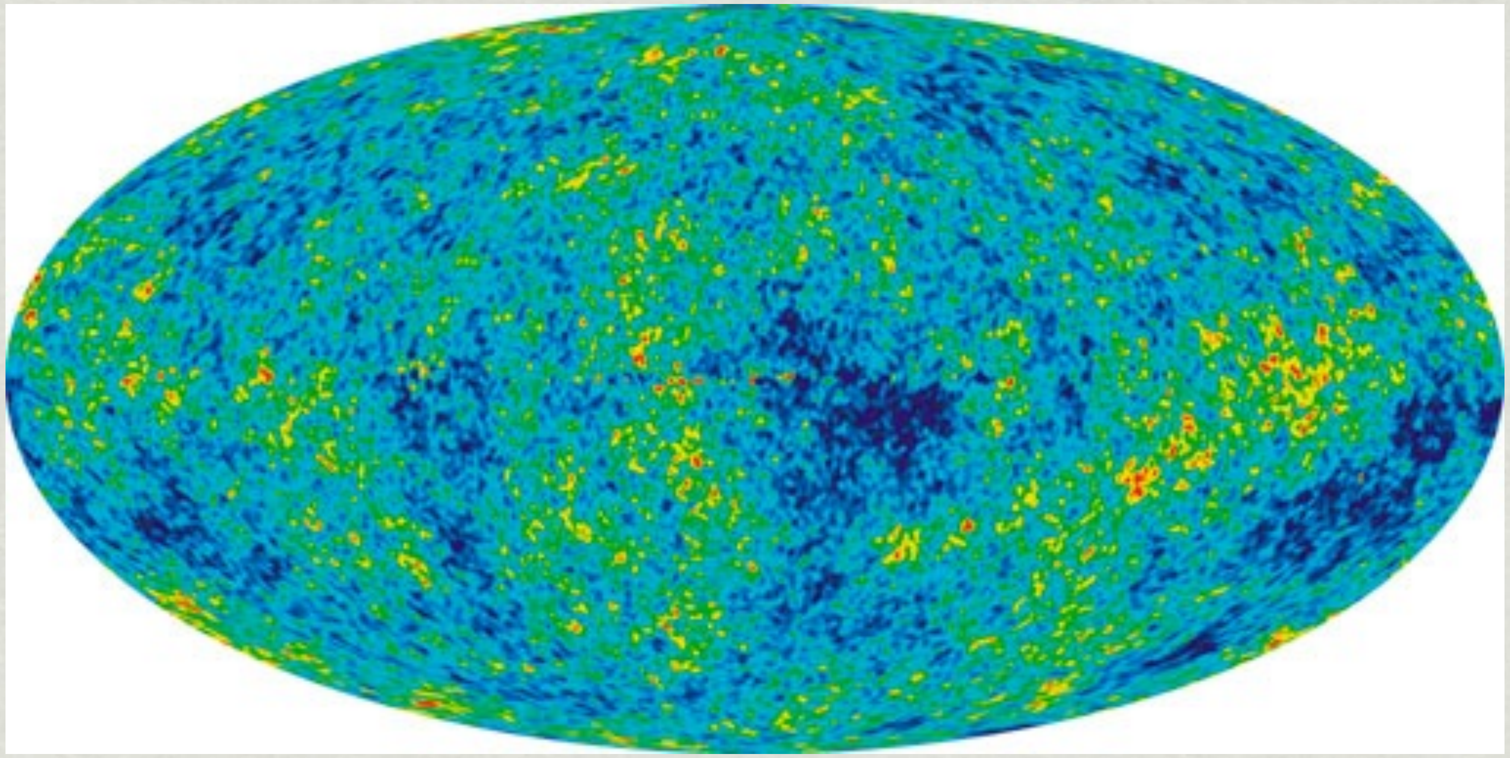
"Cosmic Microwave Background"   (CMB)



Penzias and Wilson's discovery:
Nobel prize in physics, 1978

Cosmic Microwave Background

as seen by WMAP



Variations are temperature are ***tiny*** changes of ± 200 microKelvin

$\pm 200 \times 10^{-6}$ Kelvin!

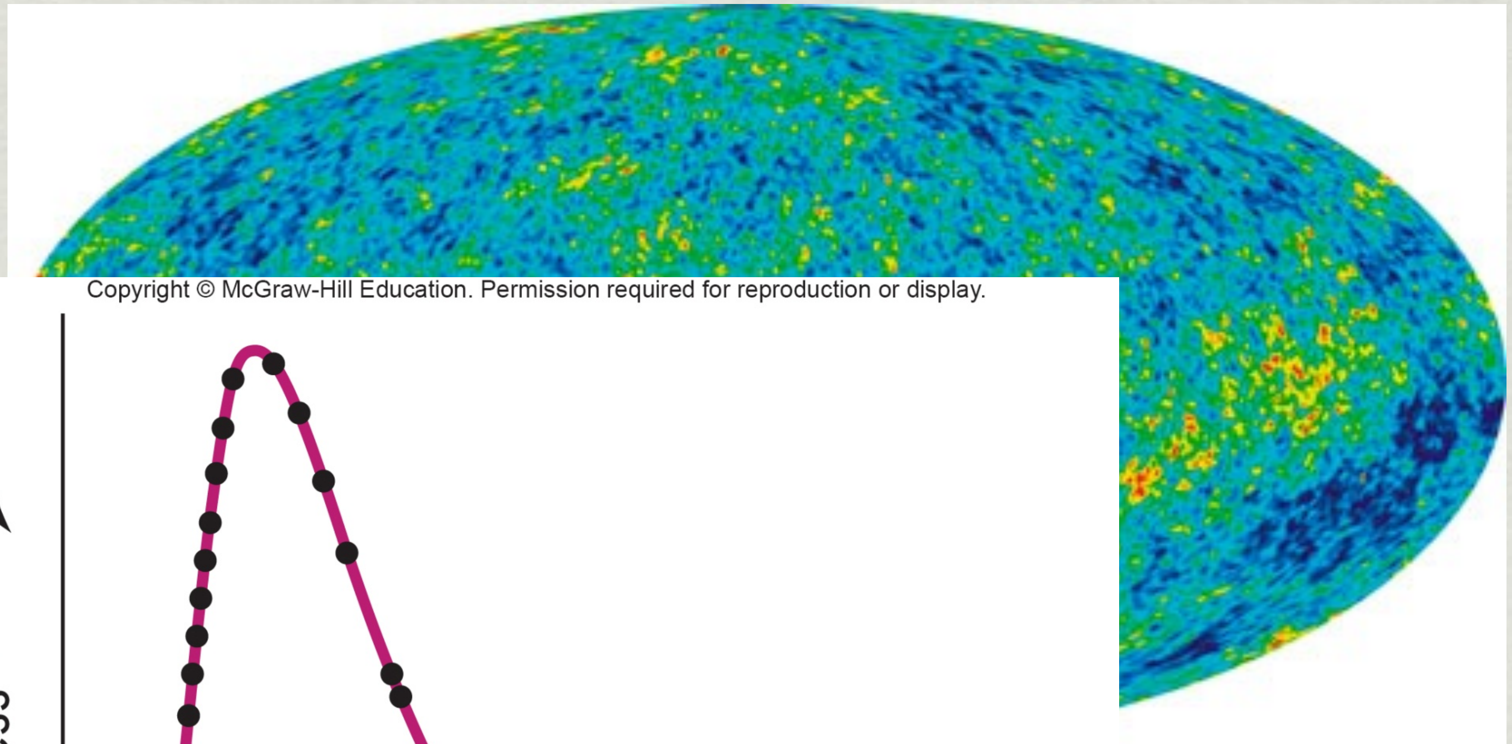
Density and temperature are related, so these are small density variations, too.

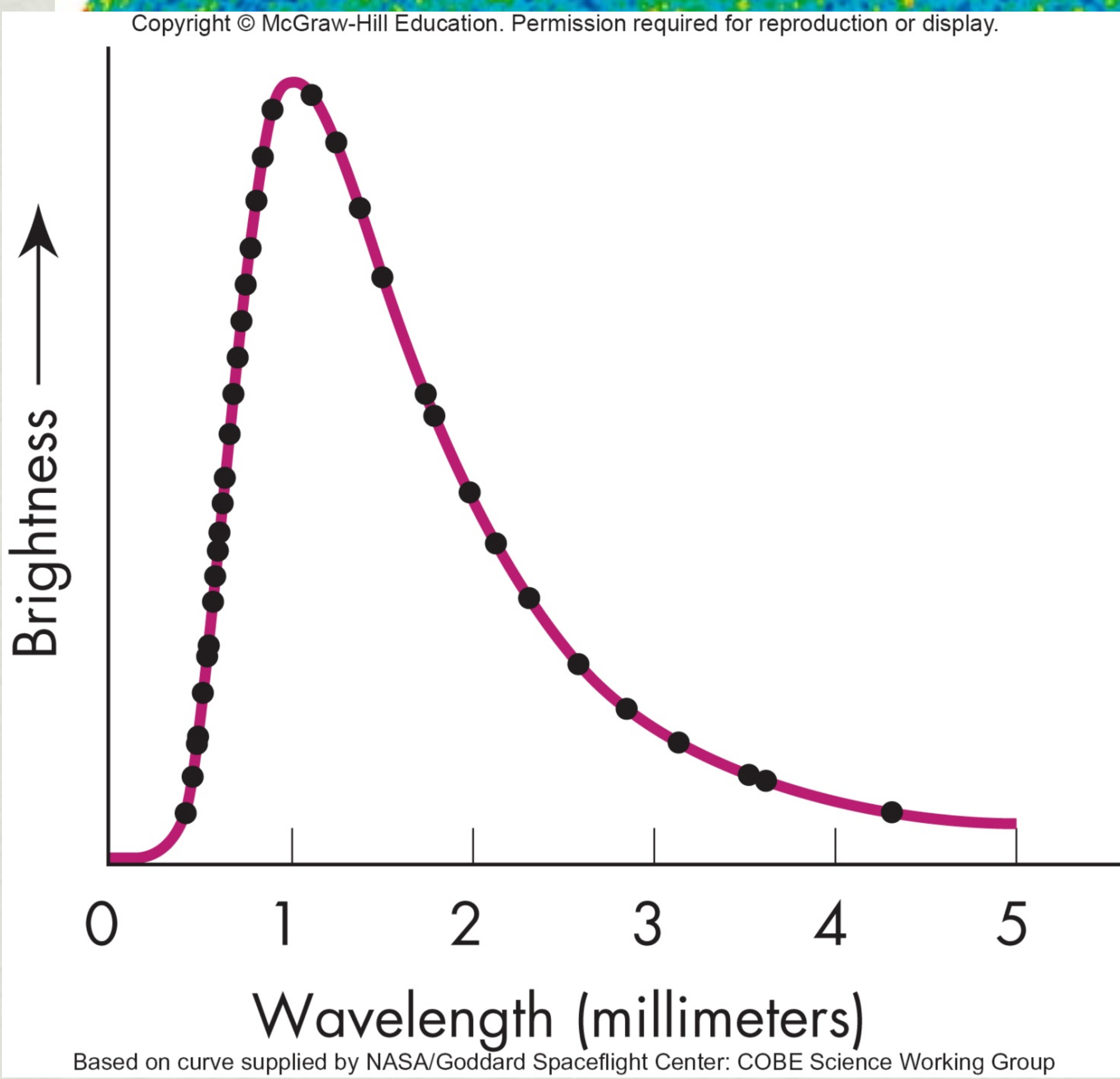
Red: hot, more dense spot
Blue: cool, less dense spot

But mostly the background looks like a thermal spectrum at 3 K

Cosmic Microwave Background

as seen by WMAP





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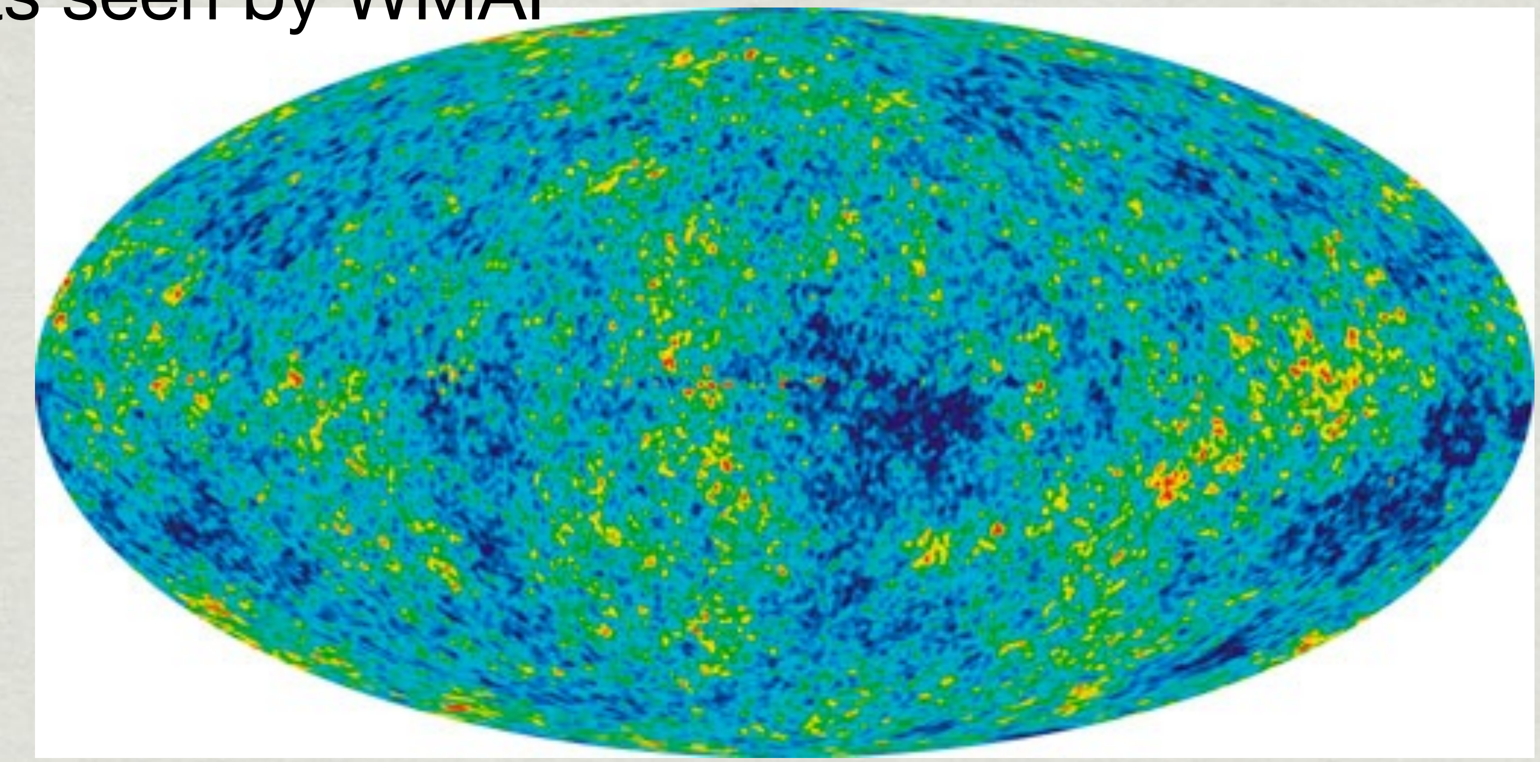
Blue: cool, less dense spot

But mostly the background looks like a thermal spectrum at 3 K

note really long peak wavelength — cold!

Cosmic Microwave Background

as seen by WMAP



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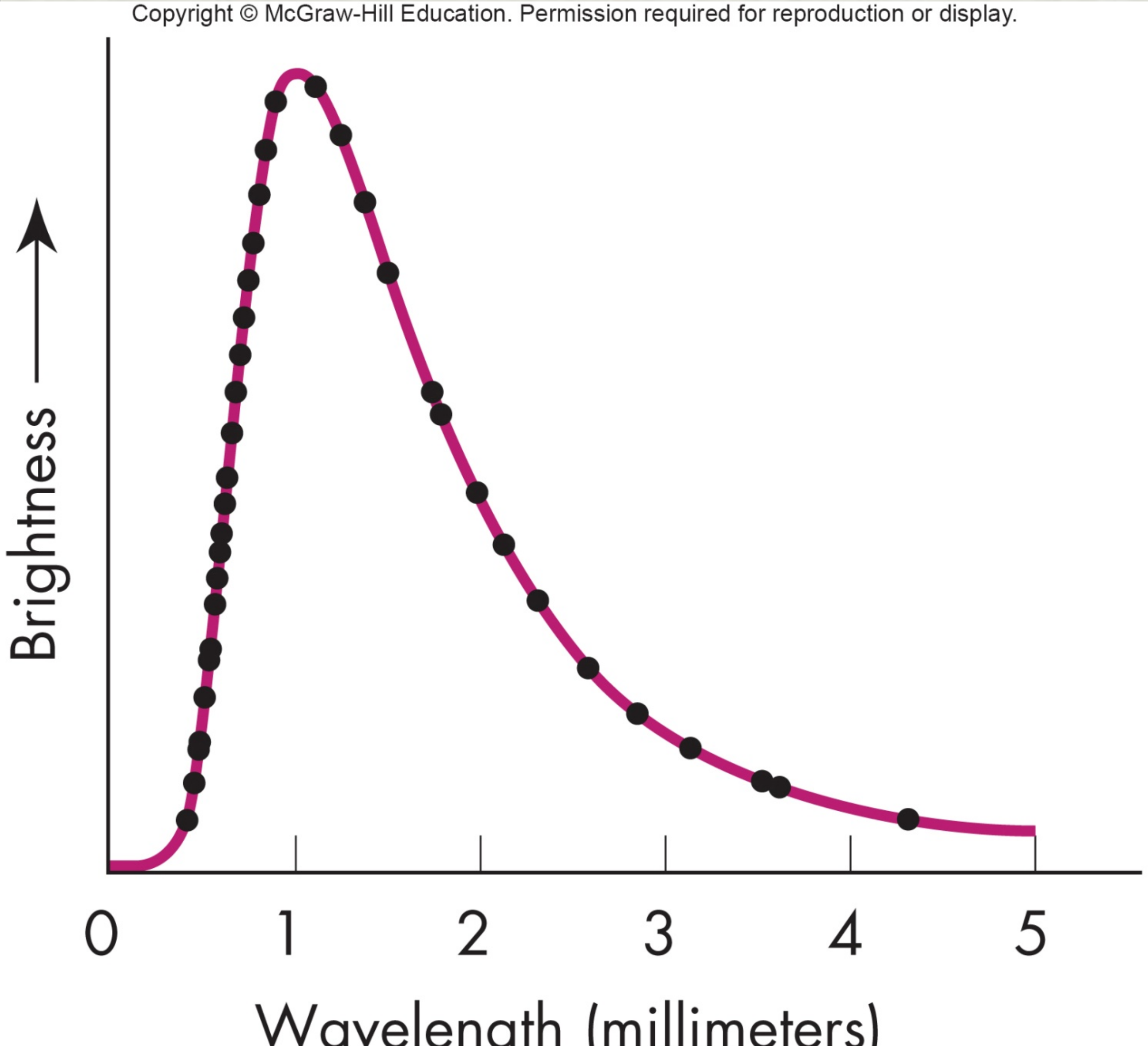
Red: hot, more dense spot
Blue: cool, less dense spot

Another prediction: temperature should not follow a Stefan-Boltzmann law perfectly.

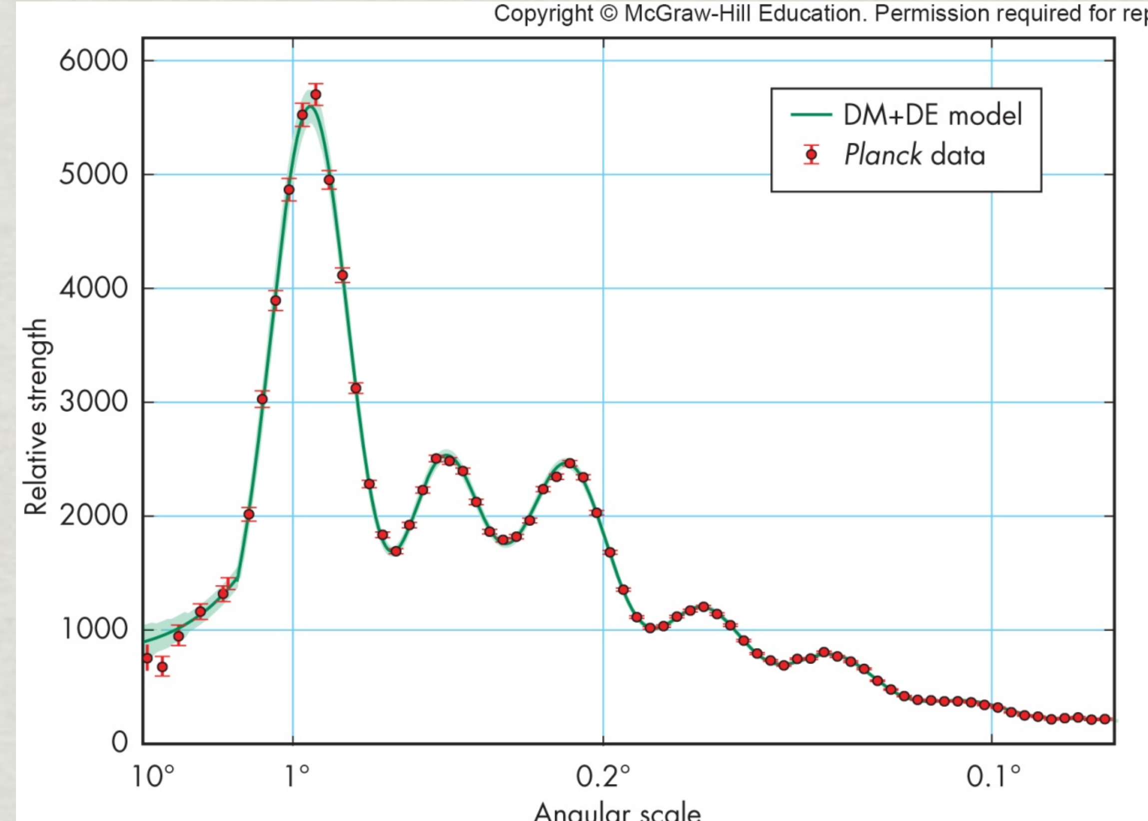
Expect small variations in density and temperature.
Dense patches are what grow by gravity into galaxies!

Cosmic Microwave Background

Two spectacular satellite experiments from NASA and one from ESA: COBE (COsmic Background Explorer) and the Wilkinson Microwave Anisotropy Probe (WMAP) both measured the themal spectrum shape and detected small measured deviations from that perfect thermal spectrum. Whew!

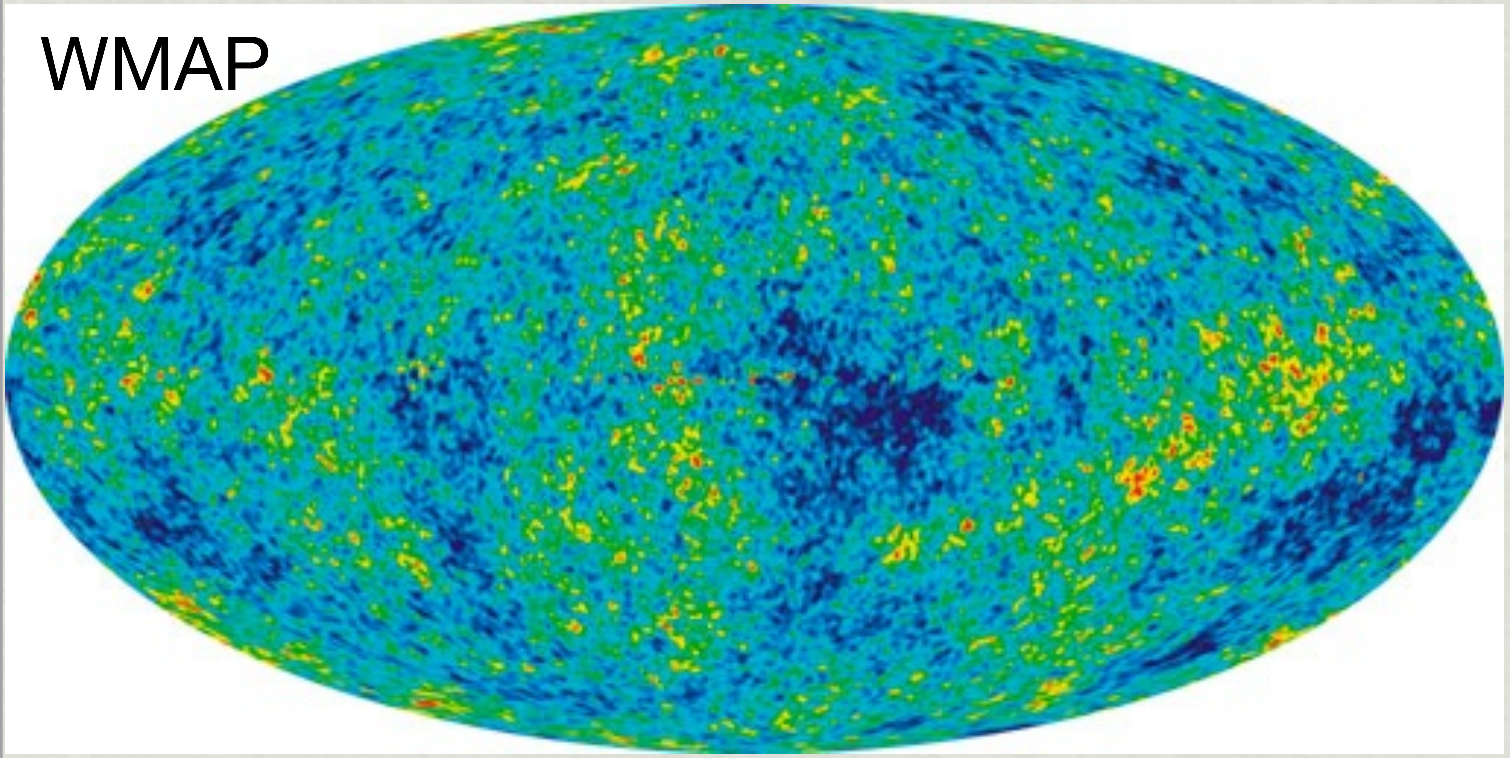


Based on curve supplied by NASA/Goddard Spaceflight Center: COBE Science Working Group



(right): based on Planck 2013 results. I. Overview: Fig. 19, ESA/Planck, a

Evolution of Density



temperature variations:
±200 x 10^{-6} Kelvin

Density variations are similar.

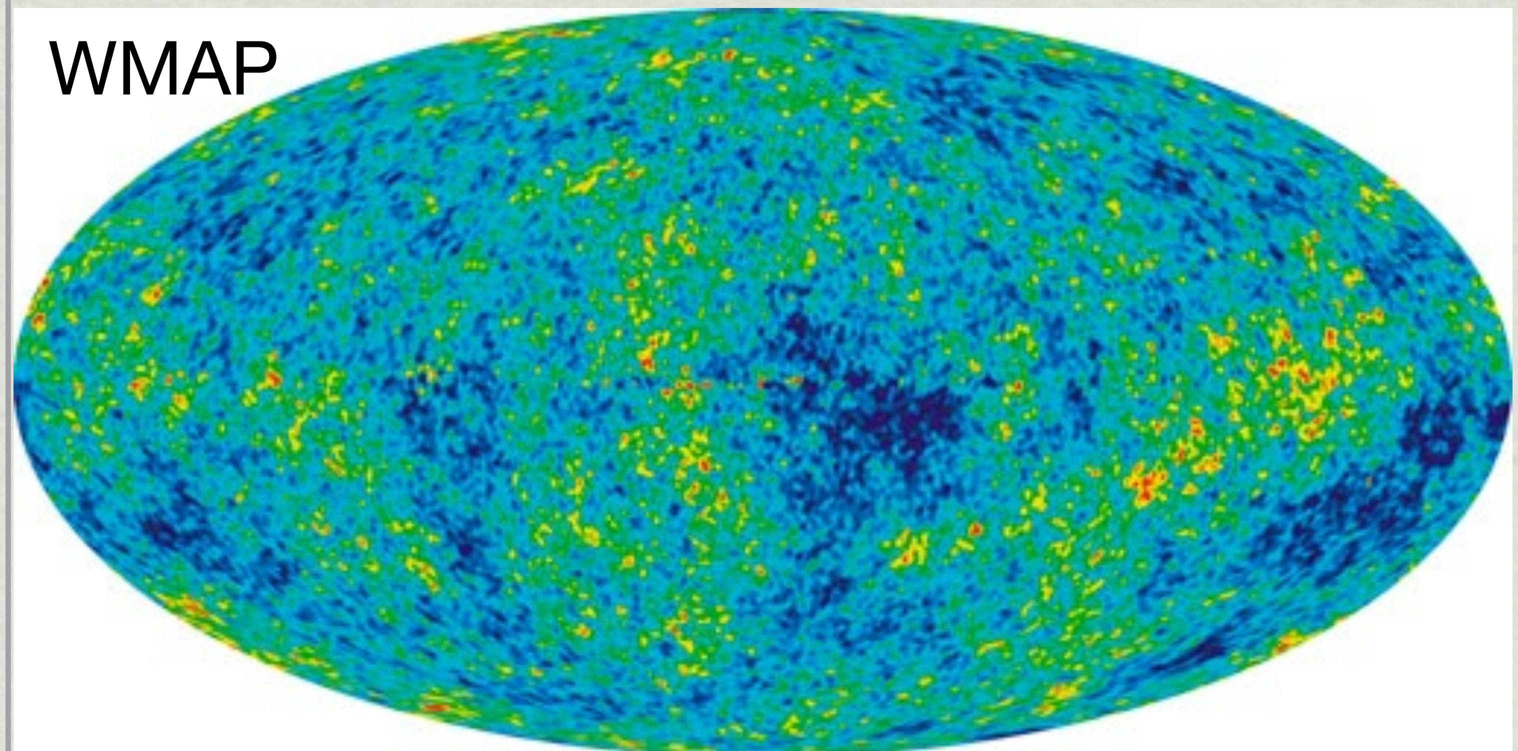
How do we get from (almost) smooth to the lumpy universe we see today?

Gravity!

Hubble Deep Field:
Galaxies in the universe

Much lumpier!
1×10^6 over-dense compared to average density in universe.

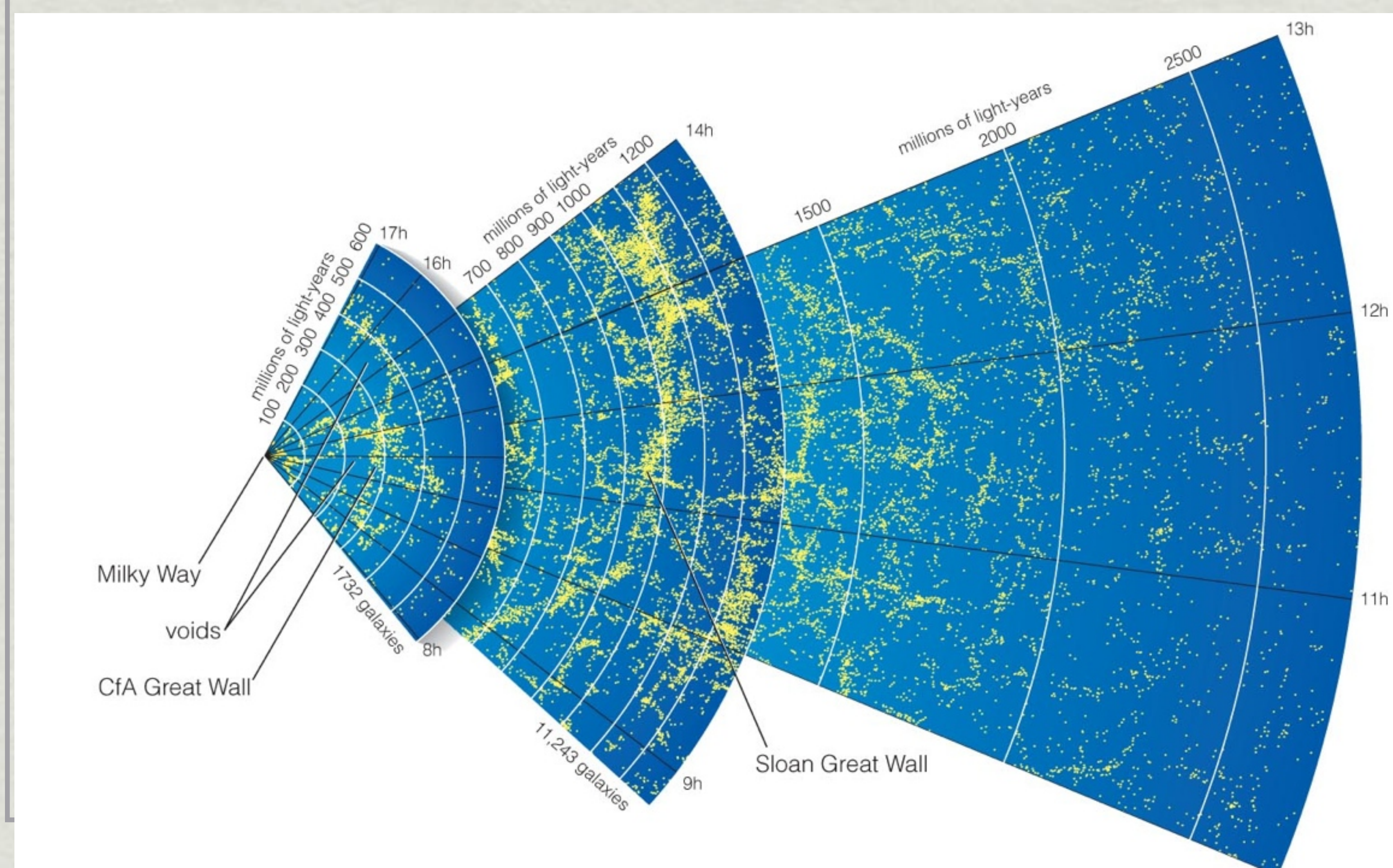
Evolution of Density



How do we get from smooth to lumpy?

Gravity!

The density variations in the Cosmic Microwave Background are the “seeds” of the structure we see today:
Galaxies, groups of galaxies



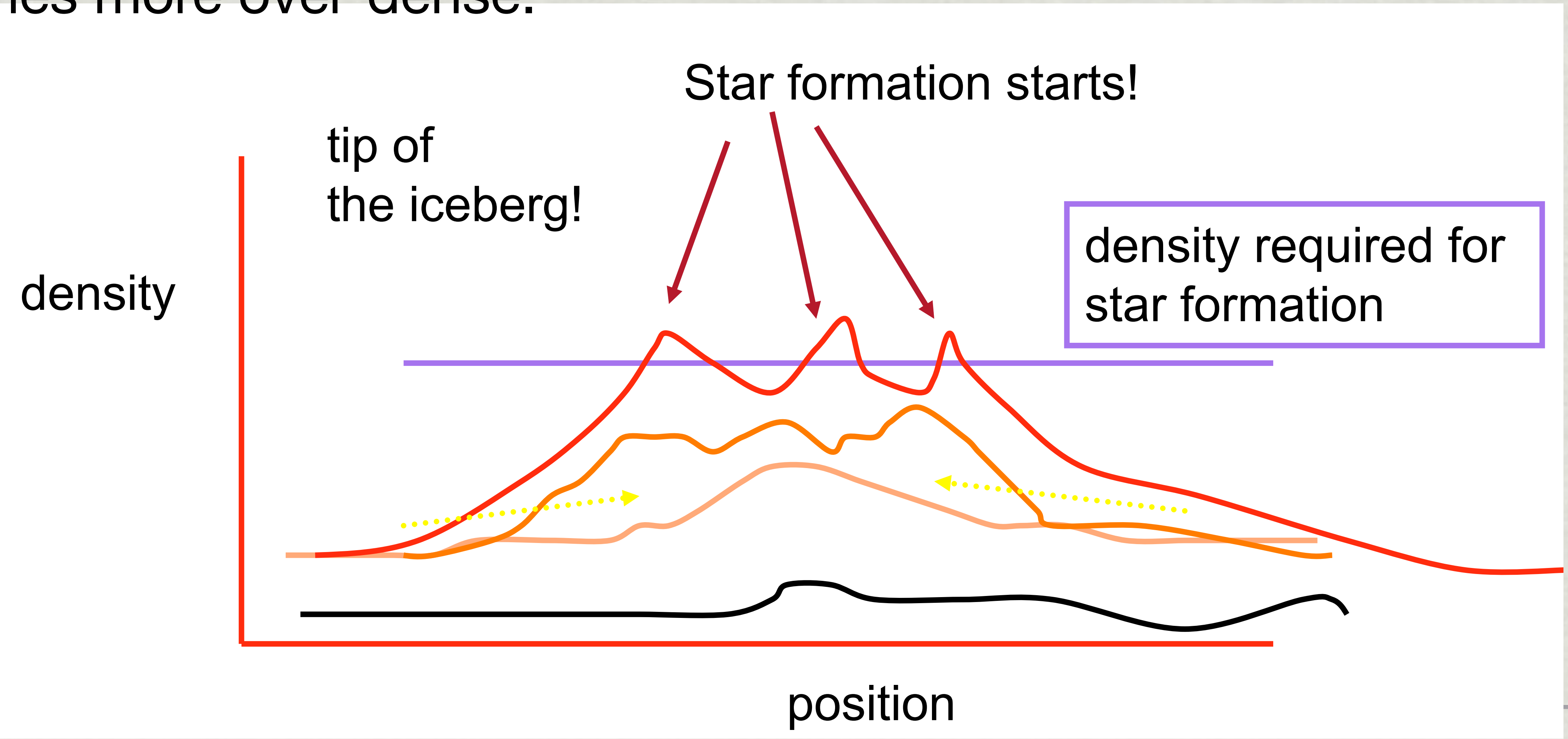
Observed distribution of galaxies seen today: a slice in distance and position along a circle in the sky.

Evolution of Density

How do we get from smooth
to lumpy?   Gravity!

Very small overdensities grow: gravitational attraction of stuff in a dense patch to itself is stronger than pull of gravity from the less-dense stuff outside the patch.

Stuff in the over-dense patch get closer together.
Patch becomes more over-dense.



Evolution of Density

Overdensities grow due to gravity.

The rate at which an overdensity grows depends on the amount of gravitating stuff (normal atoms + dark matter) in the universe.

Computer simulation of density growth in the universe