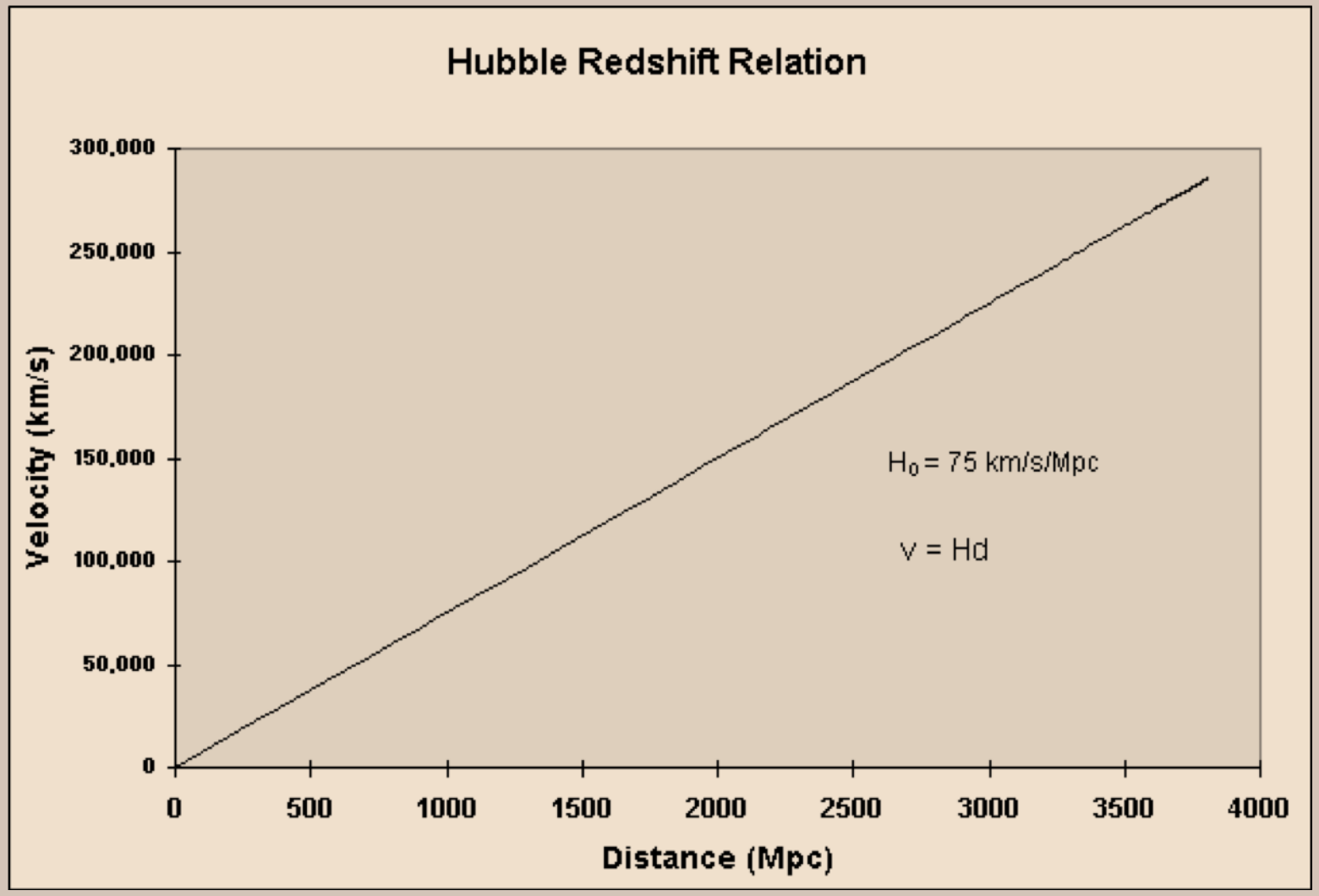
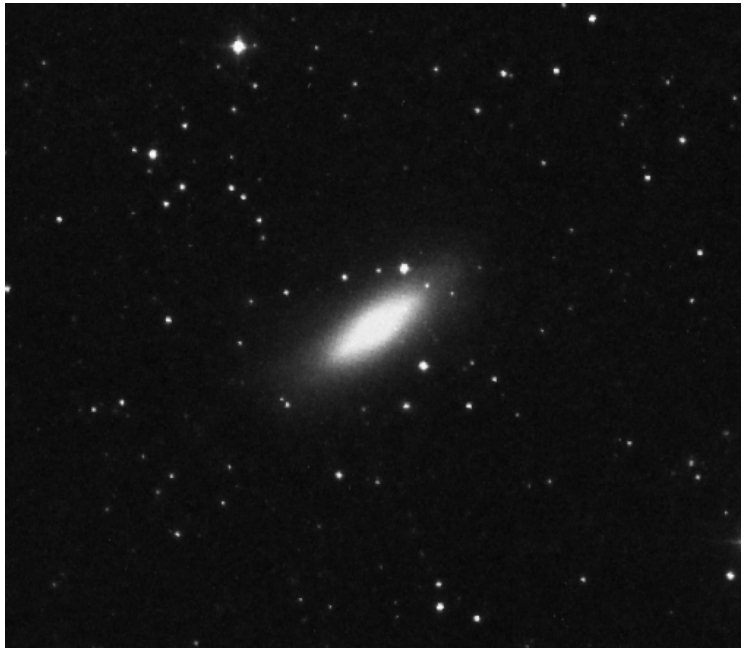
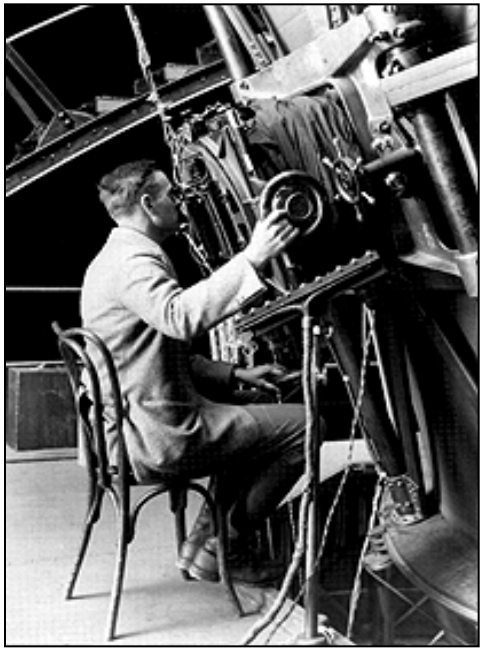
Lecture 23 - Hubble's Law



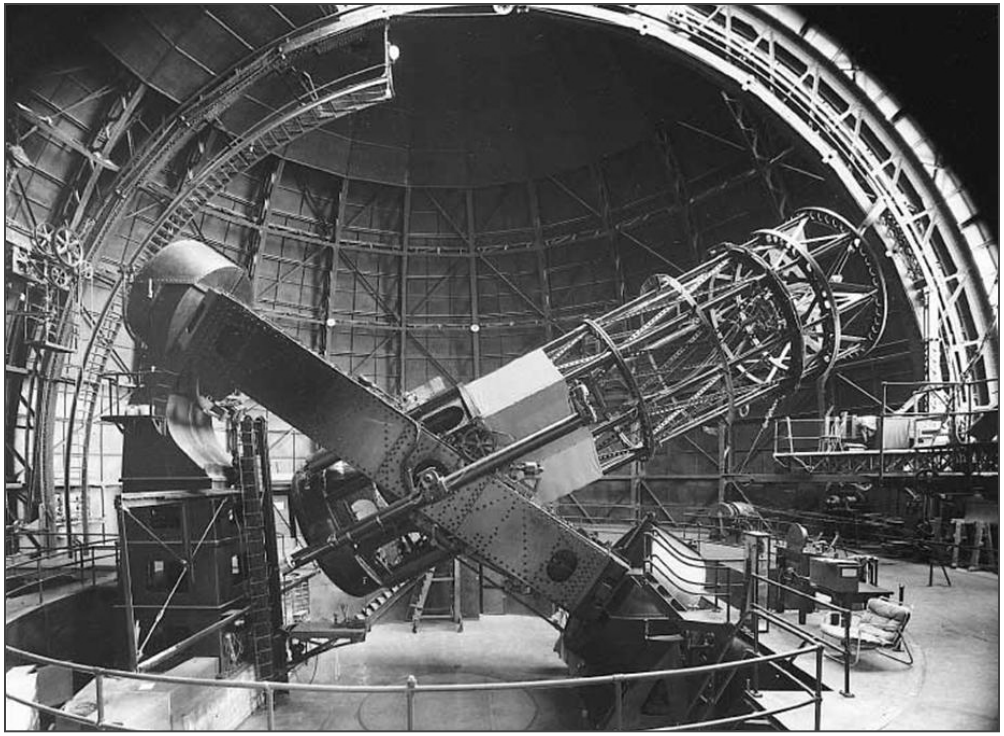
The Puzzle of “Spiral Nebulae”



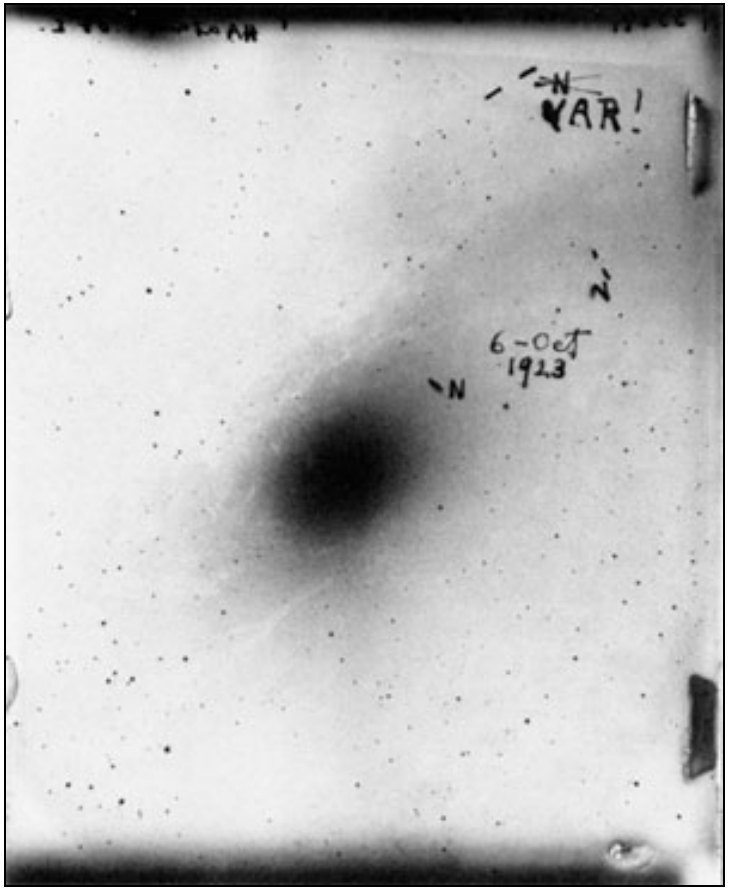


- Were “spiral nebulae” galaxies like our Milky Way - or smaller groups of stars within the Milky Way?
- The debate was settled when Edwin Hubble measured their distances.

The Puzzle of “Spiral Nebulae”

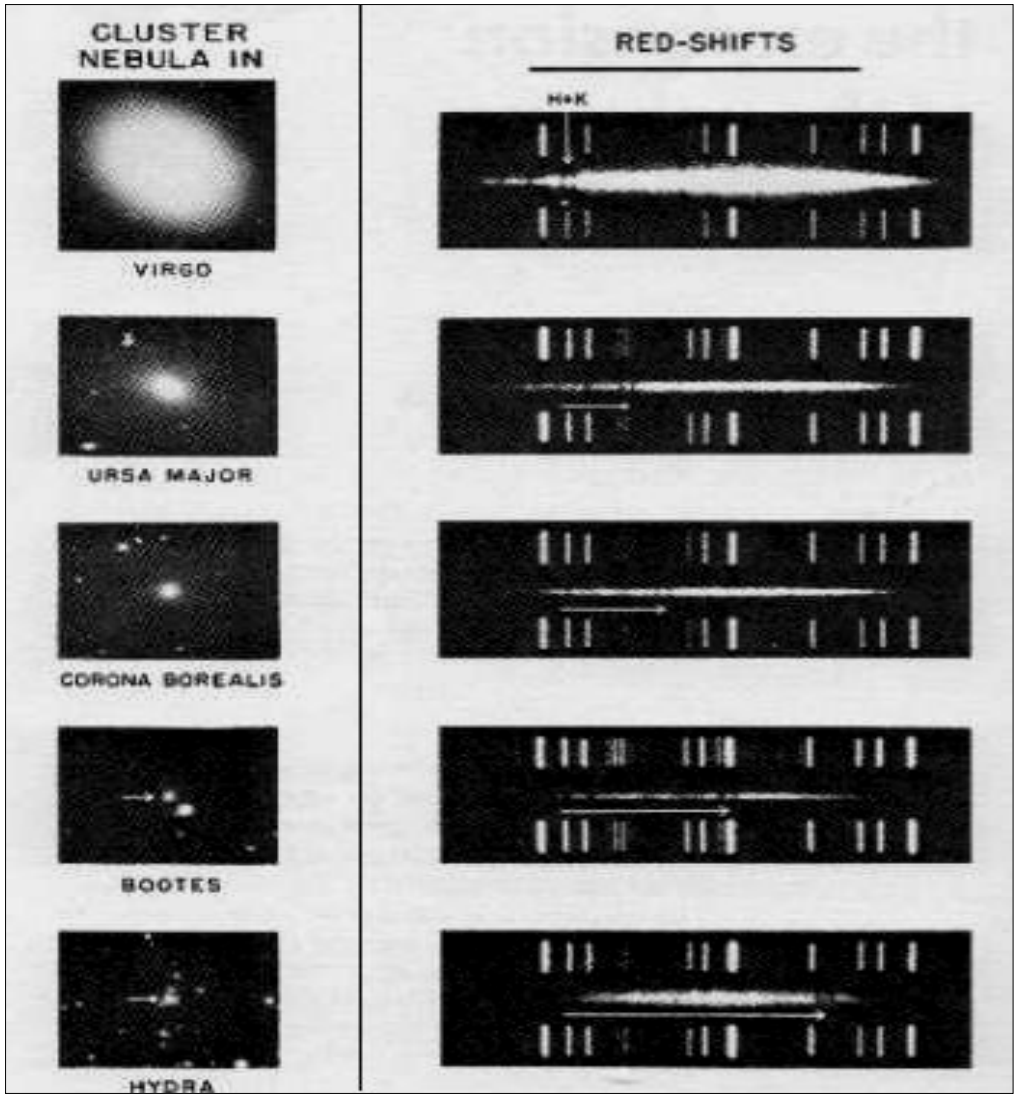


In 1929 Hubble measured the distance to the Andromeda galaxy using **Cepheid variables**; dist >1,000,000 ly!



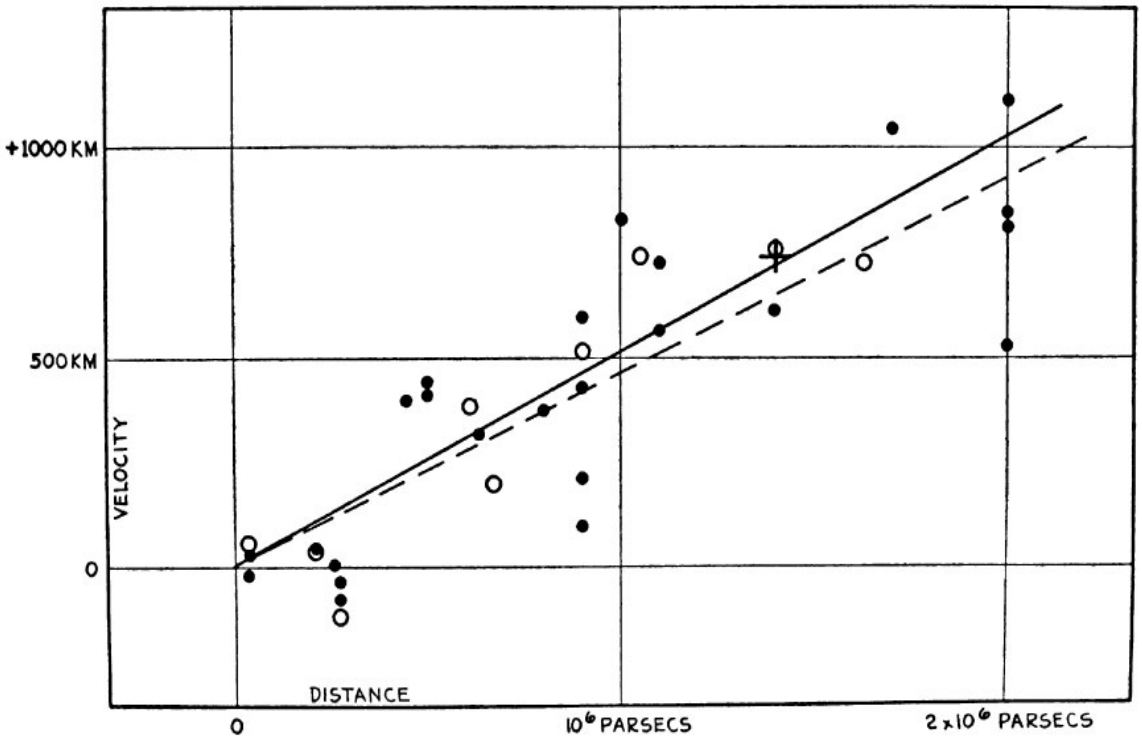
Hubble’s photograph of the Andromeda galaxy showing a Cepheid variable star

Galaxy redshifts



- Hubble next measured distances to 18 more galaxies using Cepheids.
- Most galaxies had spectral lines shifted towards the red (moving away from us)
- *He noticed a correlation between distance and redshift…*

Hubble's Law

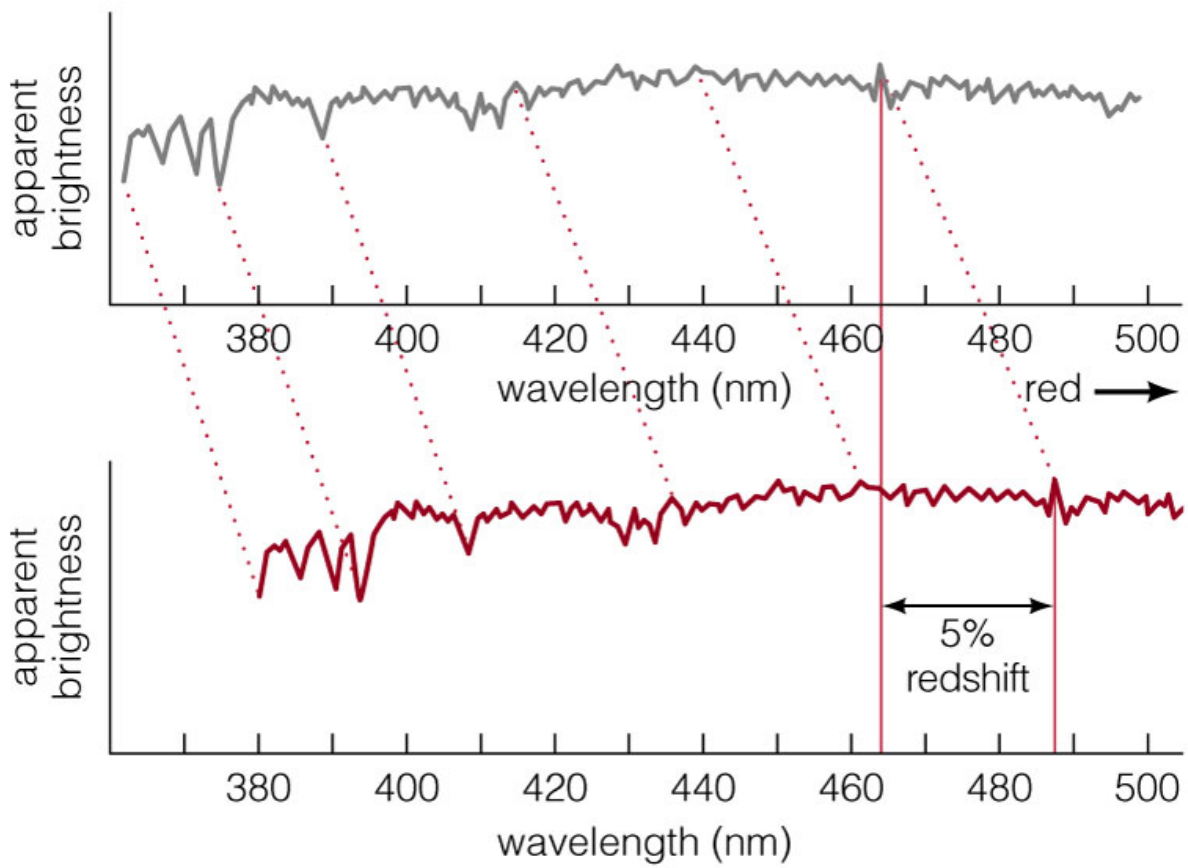


Hubble found that **redshift (or velocity) and distance are related**:

$$H_0 = \text{velocity} / \text{distance}$$

The more distant a galaxy, the greater its redshift (and velocity)

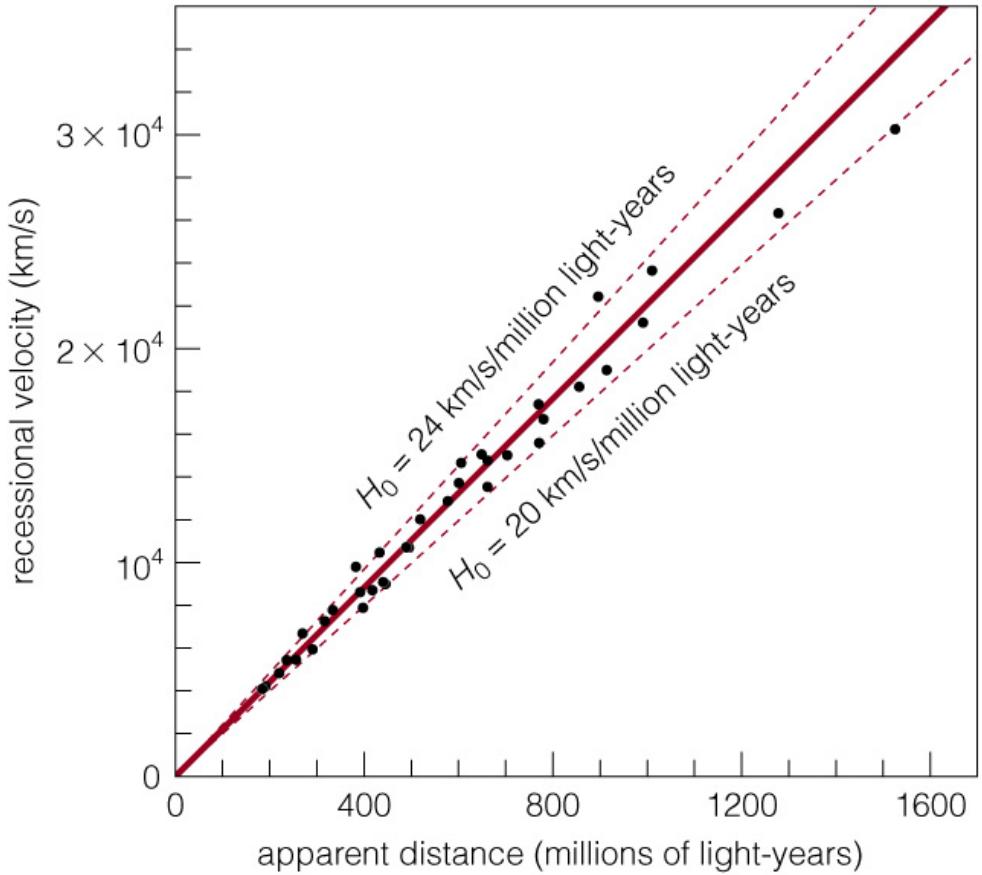
Hubble's Law



The redshift of a galaxy tells us its distance through Hubble's law:

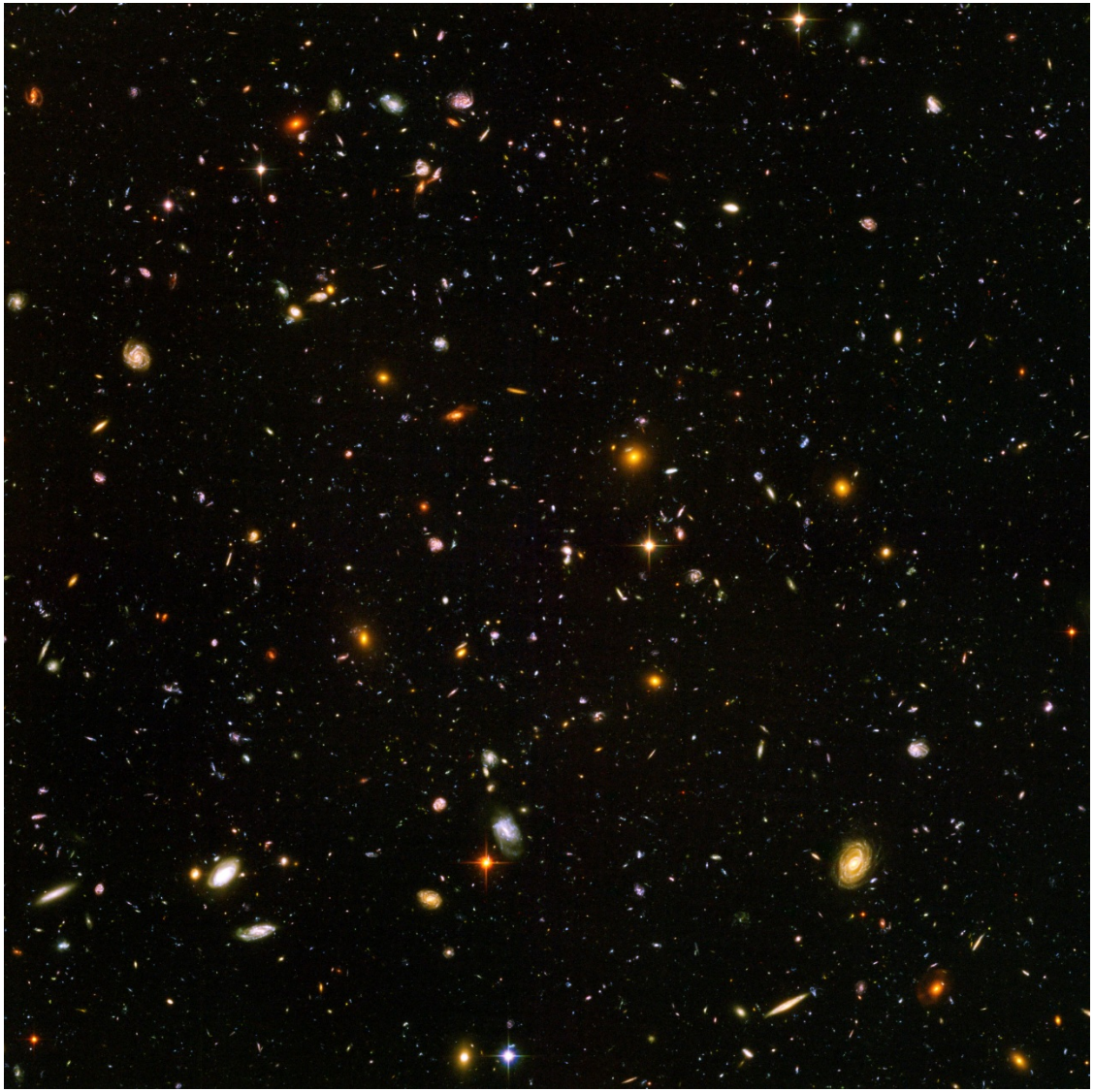
$$\text{distance} = \frac{\text{velocity}}{H_0}$$

Hubble's law



Hubble's law: H_0 = velocity / distance

Measuring distances

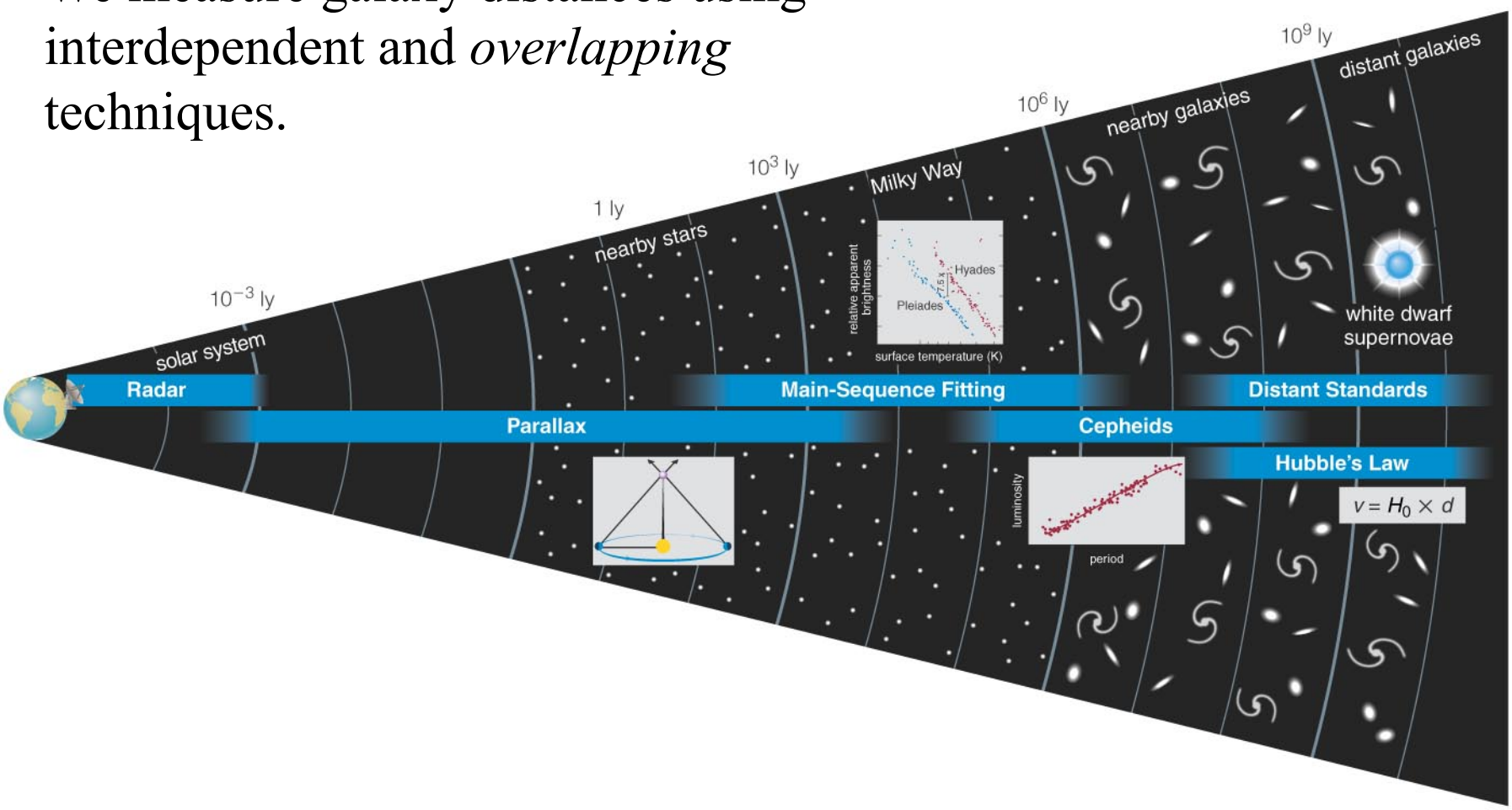


Distance measurement Step 6:

Distances of the farthest galaxies are measured from their **redshifts** or recessional velocities

Measuring distances - summary

We measure galaxy distances using interdependent and *overlapping* techniques.



What have we learned?

Begin 3 minute review

What have we learned?

How did Hubble prove that other galaxies exist beyond the Milky Way?

Hubble used Cepheid variables as distance indicators to establish the Andromeda nebula as a galaxy.

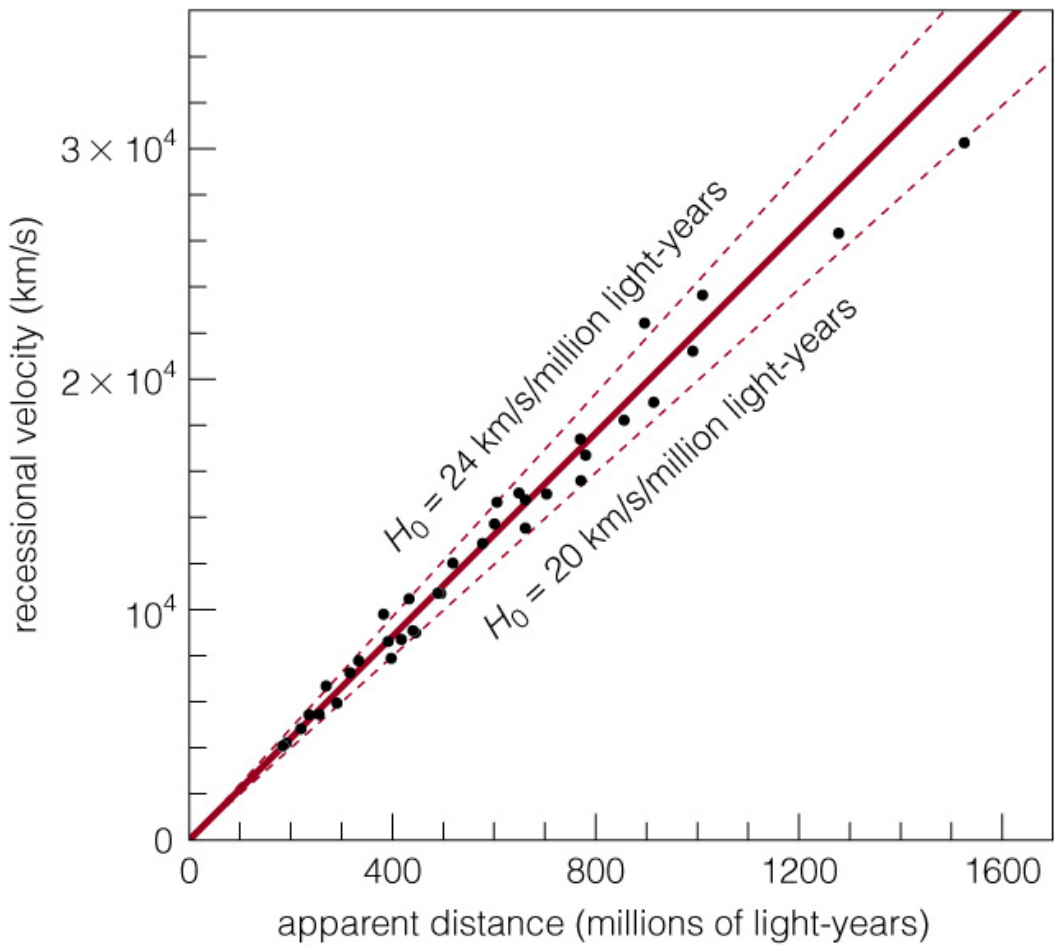
In measuring other galaxies, he found a relationship between redshift (velocity) and distance.

What is Hubble's law?

The faster a galaxy is moving away from us, the greater its distance:

$$\textbf{velocity} = H_0 \times \textbf{distance}$$

How do distance measurements tell us the age of the universe?



Galaxies and Cosmology

- **Cosmology** is the study of the structure and evolution of the universe.
- A galaxy's *distance*, and the *age of the universe* are closely related.

Cosmological Principle

The universe looks the same no matter where you are within it – galaxies all moving apart

- Matter is evenly distributed on very large scales in the universe.
- *No center and no edges to universe.*
- Consistent with all observations to date.

Distance, velocity, time

$$\text{Velocity} = \frac{\text{distance}}{\text{time}} \qquad \frac{\text{distance}}{\text{velocity}} = \text{Time}$$

$$\text{Distance} = \text{velocity} \times \text{time}$$

Thought Question

Your friend leaves your house. She later calls on her cell phone, saying that she's been driving at 60 miles per hour away from you the whole time and is now 60 miles away. How long has she been gone?

A. 1 minute
B. 30 minutes
C. 60 minutes (1 hour)
D. 120 minutes (2 hours)

Thought Question

Your friend leaves your house. She later calls you on her cell phone, saying that she's been driving at 60 miles per hour directly away from you the whole time and is now 60 miles away. How long has she been gone?

A. 1 minute
B. 30 minutes
C. 60 minutes (1 hour)
D. 120 minutes (2 hours)

Thought Question

You observe a galaxy moving away from you at 1 light-year per year, and it is now 10 billion light-years away from you. How long has it taken to get there?

A. 1 million years
B. 10 million years
C. 10 billion years
D. 100 billion years

Thought Question

You observe a galaxy moving away from you at 1 light-year per year, and it is now 10 billion light-years away from you. How long has it taken to get there?

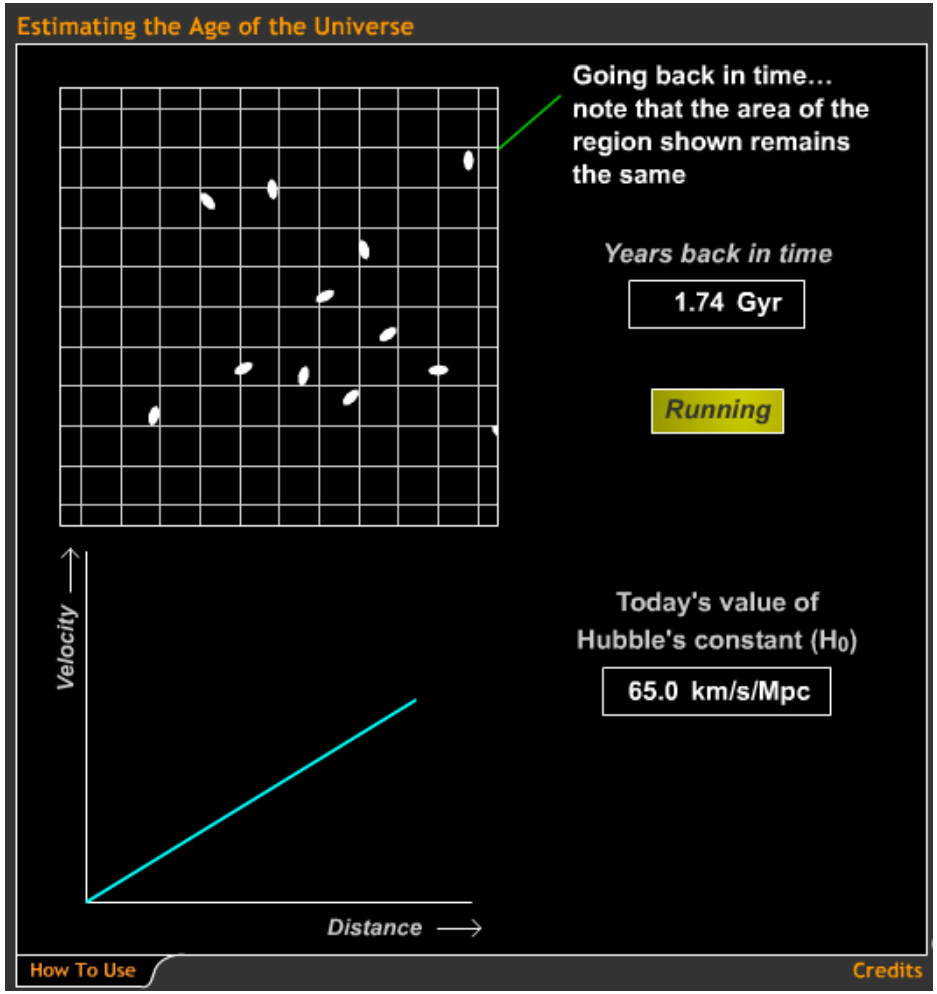
A. 1 million years
B. 10 million years
C. **10 billion years**
D. 100 billion years

Expansion of the universe

- The expansion rate is the same everywhere.
- *Galaxies do not expand into empty space,* ***space itself expands****, carrying the galaxies outward*
- The universe has no center and no edge.

PLAY Two Explanations of the Cause of Hubble's Law

Expansion of the universe



PLAY Estimating the Age of the Universe

What if we ran the expansion backwards? *When did it begin?*

Hubble's constant (**how fast is the expansion**) relates velocities and distances of all galaxies.

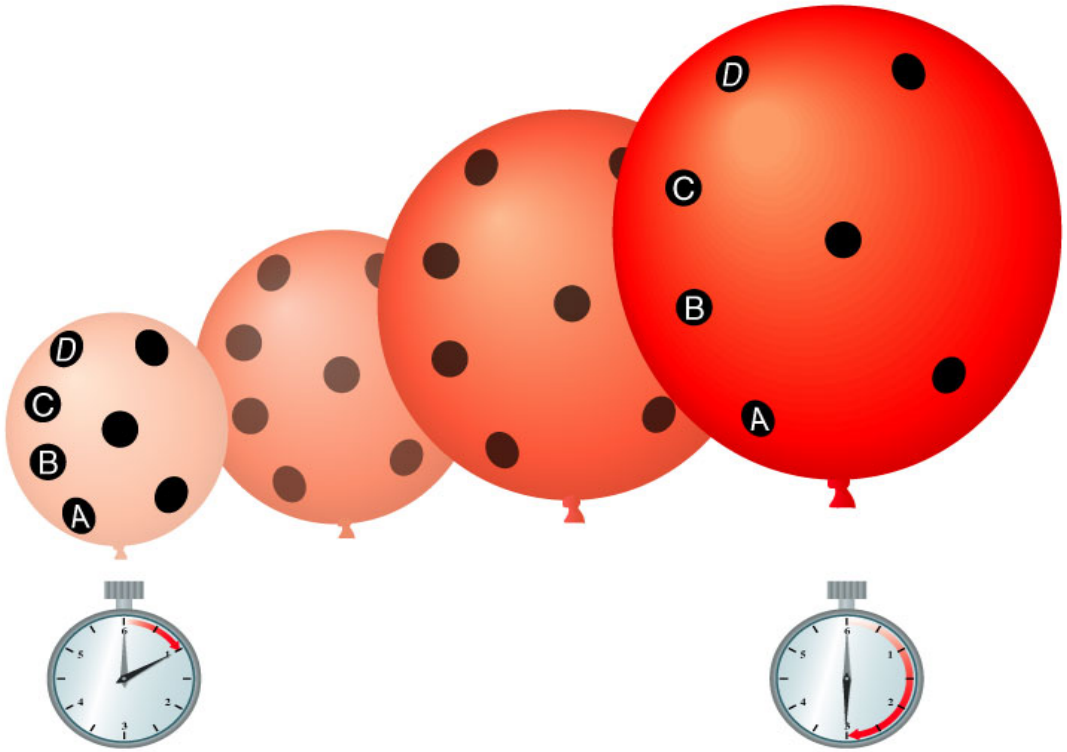
The inverse of H_0 tells us the age of the universe:

$$\text{Age} = \frac{\text{Distance}}{\text{Velocity}}$$

$$\sim 1 / H_0$$

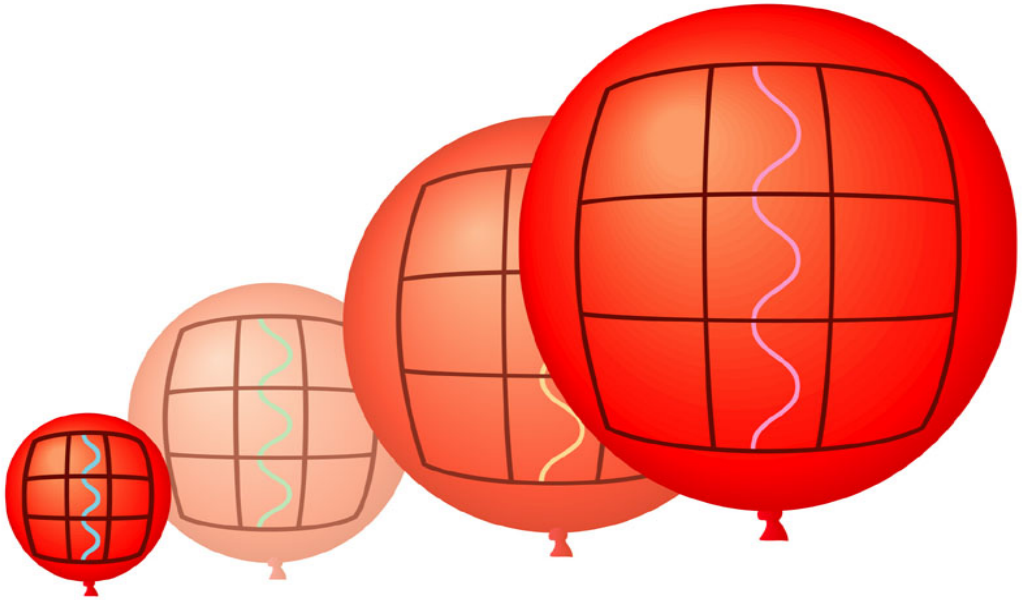
$$\sim \textbf{14 billion yrs}$$

Expansion of the universe



One example of something that expands but has no center or edge is the surface of a balloon.

Expansion of the universe



Expansion stretches photon wavelengths causing a ***cosmological redshift*** directly related to how much space has expanded.

Interactive Figure

Cosmological horizon

How large is the universe?

- We can only observe light that has taken the entire age of the universe to travel to us.
- We can only observe out to where the expansion rate approaches the speed of light.
- These define the *observable (visible)* universe.
- **Is the universe larger than this?**

Think/Pair/Share

If light left a distant galaxy 400 million years ago, how distant is it now?

a. Less than 400 million light-years
b. Exactly 400 million light-years
c. More than 400 million light-years
d. It is impossible to know

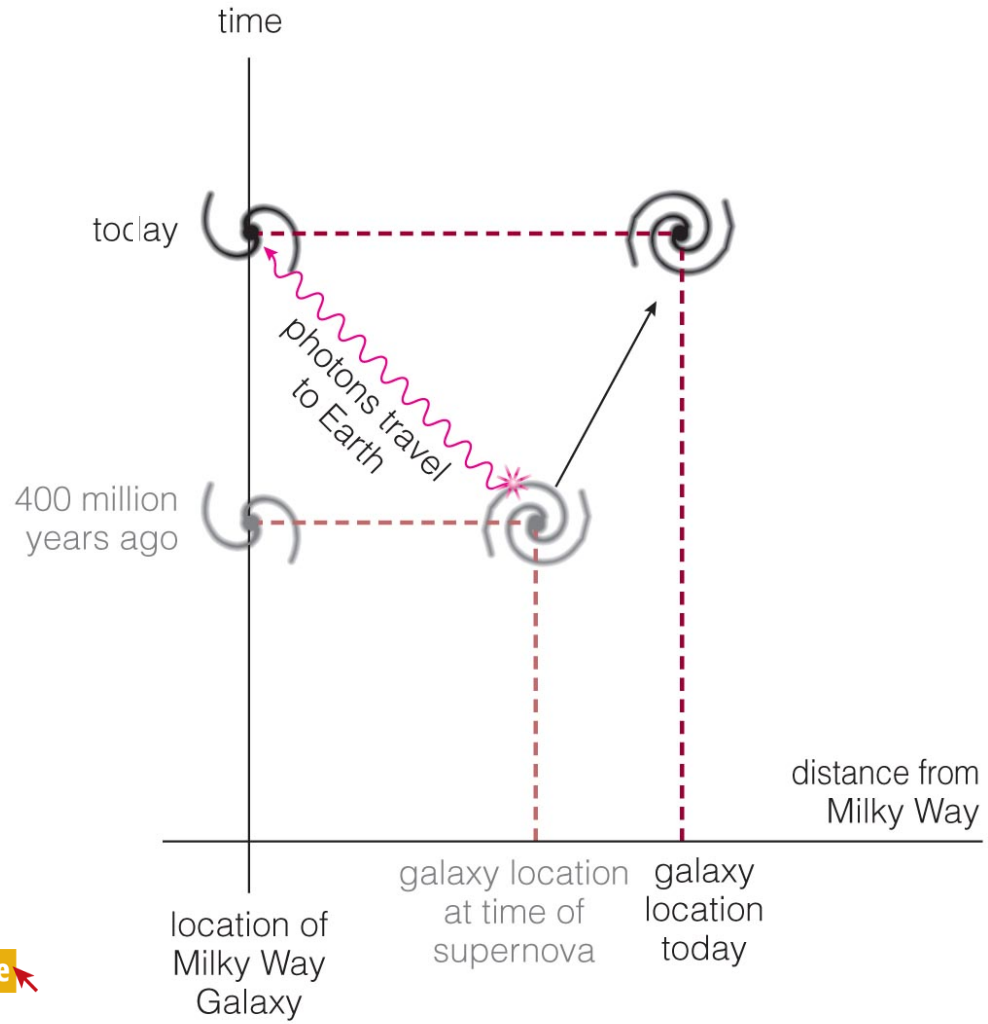
Think/Pair/Share

If light left a distant galaxy 400 million years ago, how distant is it now?

a. Less than 400 million light-years
b. Exactly 400 million light-years
c. **More than 400 million light-years**
d. It is impossible to know

How does the universe's expansion affect our distance measurements?

- Distances between faraway galaxies increase while light travels.
- Objects are actually farther away than we see them now – but will *never* be able to see them as they are now! (Why?)



Interactive Figure

Think/Pair/Share

Astronomers have measured the value of the Hubble constant H_0 to be about 70 km/s/Mpc. If this figure were 140 km/s/Mpc, what would this imply about the age of the universe?

A. It is much younger than currently thought
B. It is much older than currently thought
C. It is the same age as currently thought
D. H_0 doesn't really tell us anything about the age of the universe

Think/Pair/Share

The value of the Hubble constantis H_0 to be 75 km/s/Mpc. If this figure were 150 km/s/Mpc, what would this imply about the age of the universe?

A. **It is much younger than currently thought**
B. It is much older than currently thought
C. It is the same age as currently thought
D. H_0 doesn't really tell us anything about the age of the universe

What have we learned?

Begin 3 minute review

What have we learned?

How do distance measurements tell us the age of the universe?

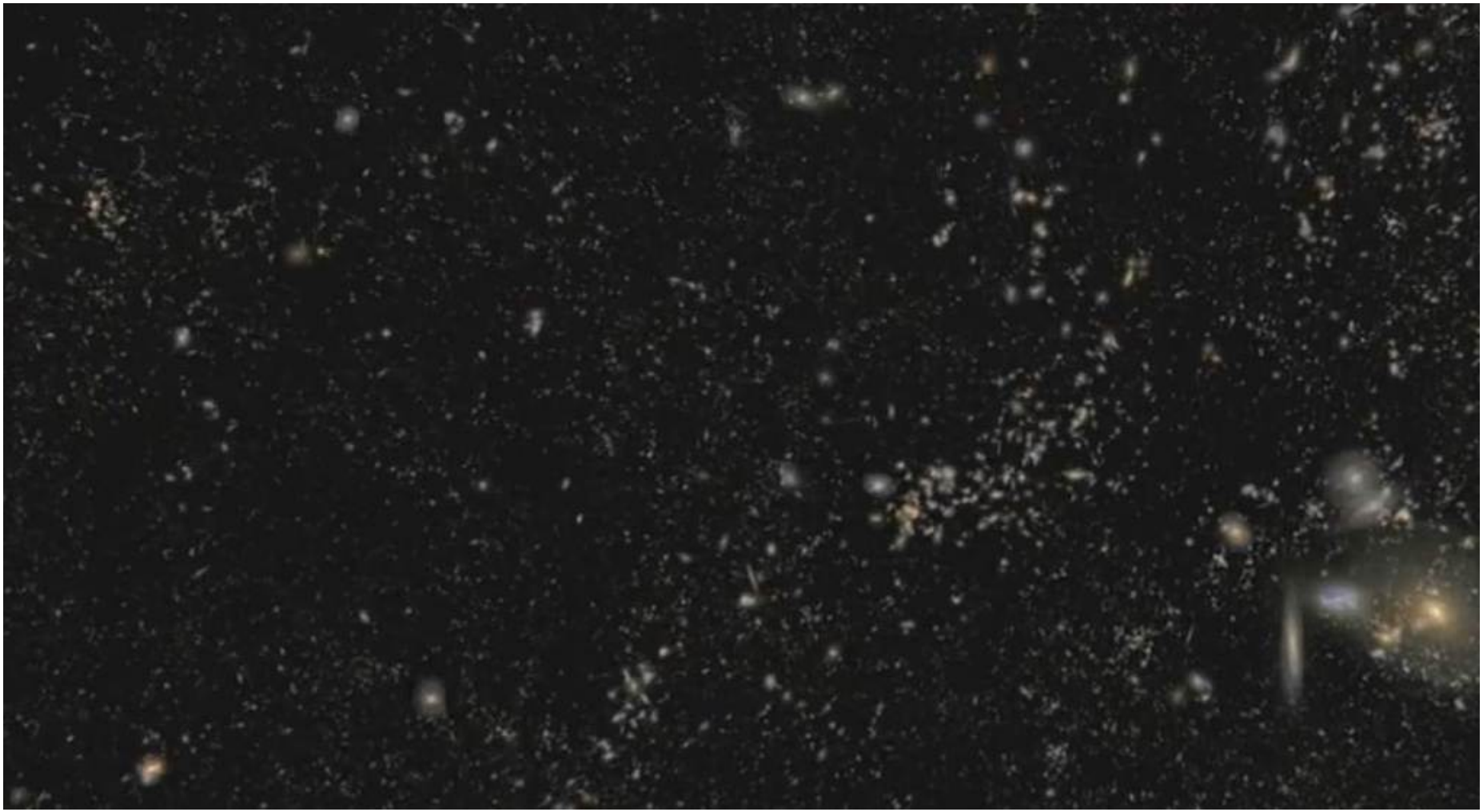
Measuring a galaxy's distance and speed allows us to figure out how long the galaxy took to reach its current distance.

Measuring Hubble's constant (speed of expansion) tells us that amount of time: about **14 billion years**.

Expansion of the universe is due to the **cosmological redshift.**

We can only observe out to about 14 billion light-years.

Flight through the Universe

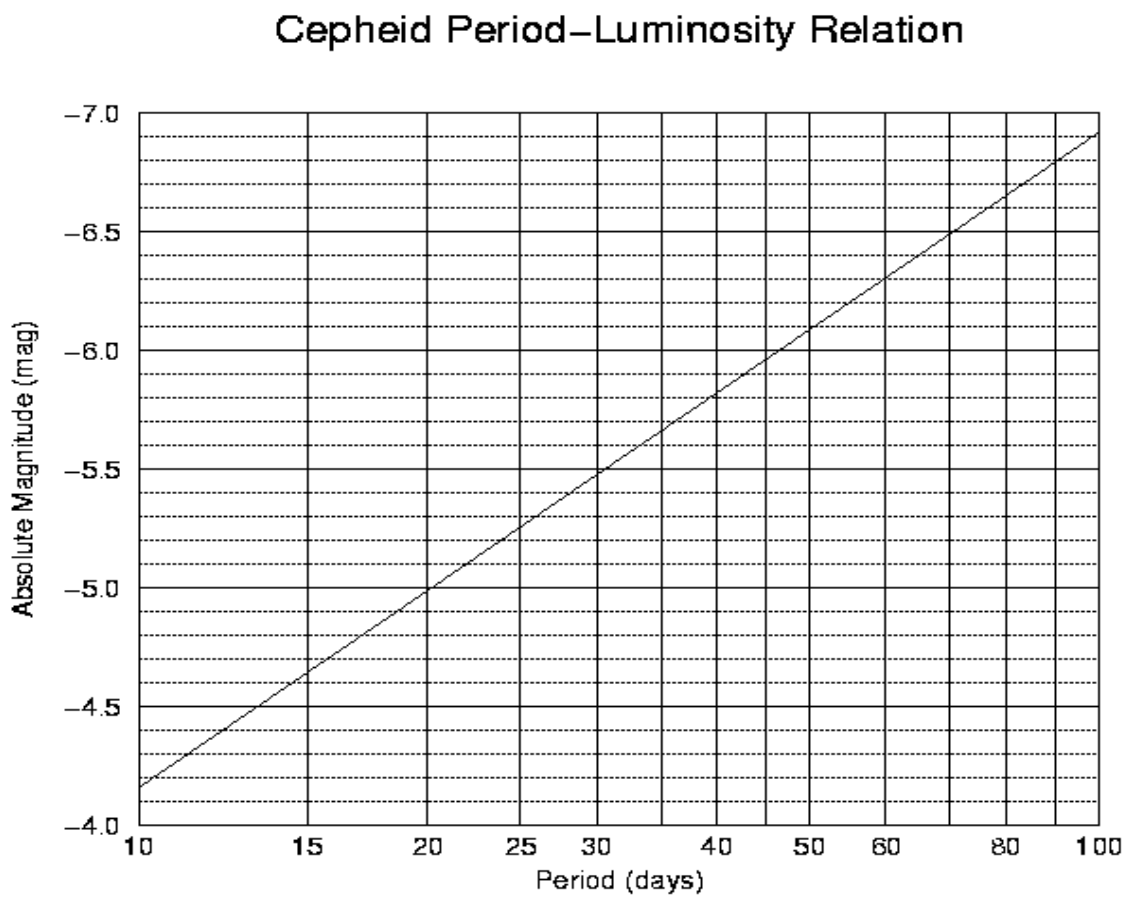


Measuring Astronomical Distances

We can use the period of a Cepheid to determine its absolute magnitude (M) (related to luminosity). The distance to the star can then be calculated using the following formula:

$$d = 10^{[(m-M)+5]/5}$$

where distance (d) is in pc (1 pc = 3.26 ly), **m** is the apparent magnitude and **M** the absolute magnitude.



Measuring Astronomical Distances

Calculating Cepheid variable distances

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1. Measure apparent magnitude m = **18.1**
2. Determine *period* :

   p = 70 days
3. Find *absolute magnitude* M using chart:

   M = -6.5
4. Calculate *distance modulus* :

   $\Delta m = m - M = 24.6$
5. Determine *distance*:

$$\text{distance} = 10^{[(m-M)+5]/5}$$
$$= 10^{5.92}$$
$$= 835{,}000 \text{ pc}$$

Reference spectrum

- Coma
- Leo
- Ursa Major
- Corona
- Bootes
- Virgo