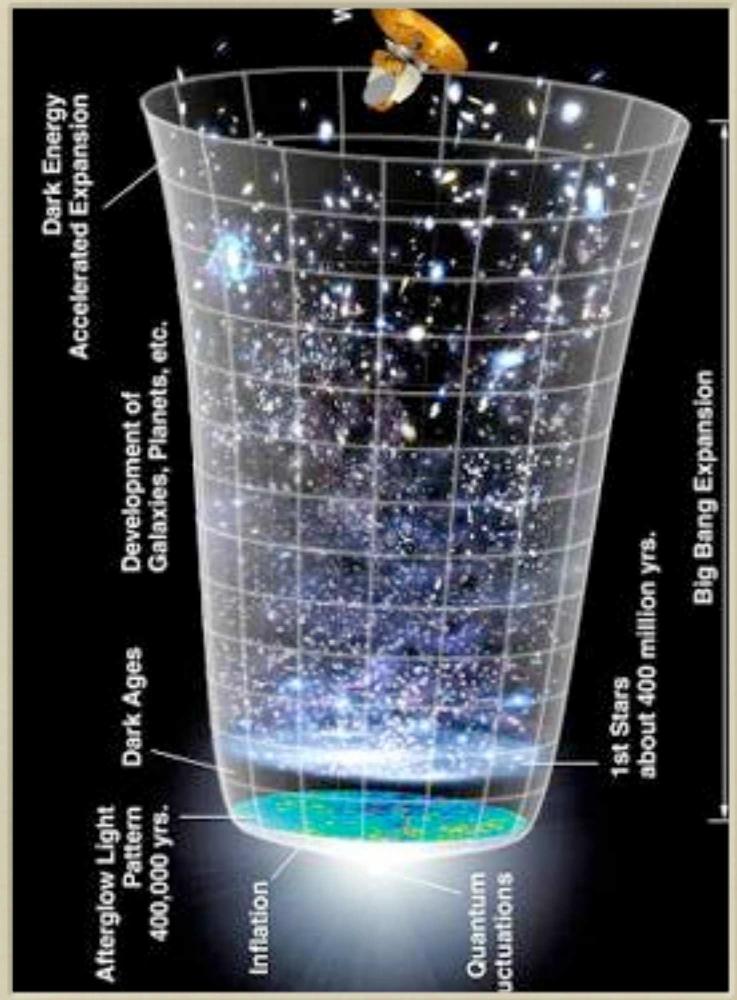
Today

- Galaxy Types Including Active Galaxies
- The Great Debate
- Expansion of the Universe
    - Hubble Law



Types of Galaxies

- Spiral galaxies (like Milky Way): active star formation, most stars in a disk

Types of Galaxies

- Elliptical galaxies: little gas, so little star formation; no disk, all bulge; very big ones found in the centers of galaxy clusters

Types of Galaxies

- Irregular galaxies: lots of gas, lots of star formation, but irregularly shaped so no obvious disk; these are small galaxies

Galaxies like each other!

- If you see a galaxy there is likely to be another one nearby
- Many galaxies (like MW!), are in groups: collections of ~tens of galaxies

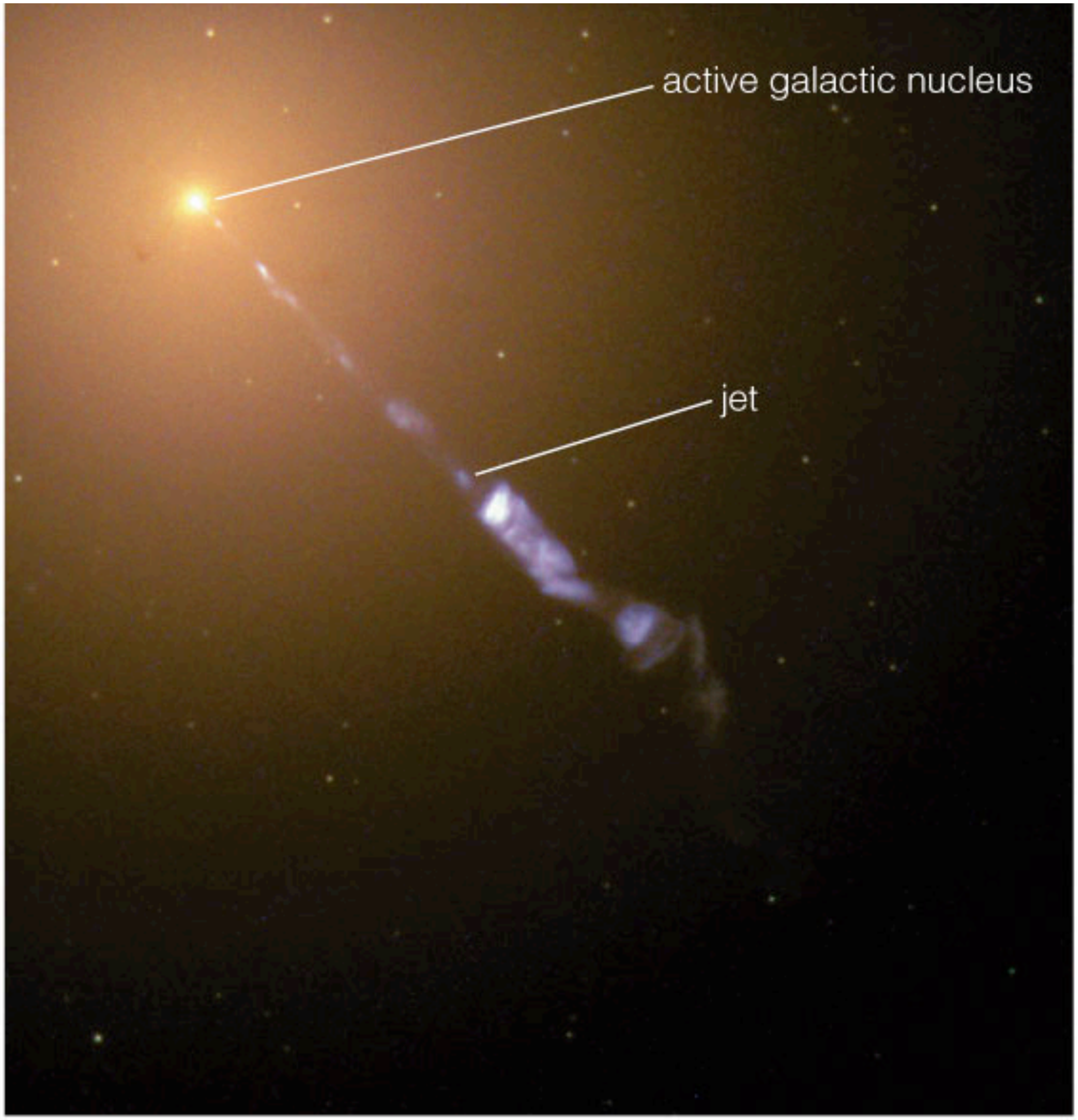
Hickson 44 compact group

Galaxy Clusters

- Some collections of thousands of galaxies within same size as our local group
- Many more ellipticals in these clusters; ellipticals form from collisions between galaxies!

Perseus Cluster:
250 million lyr away,
more than 1000 galaxies

Movie

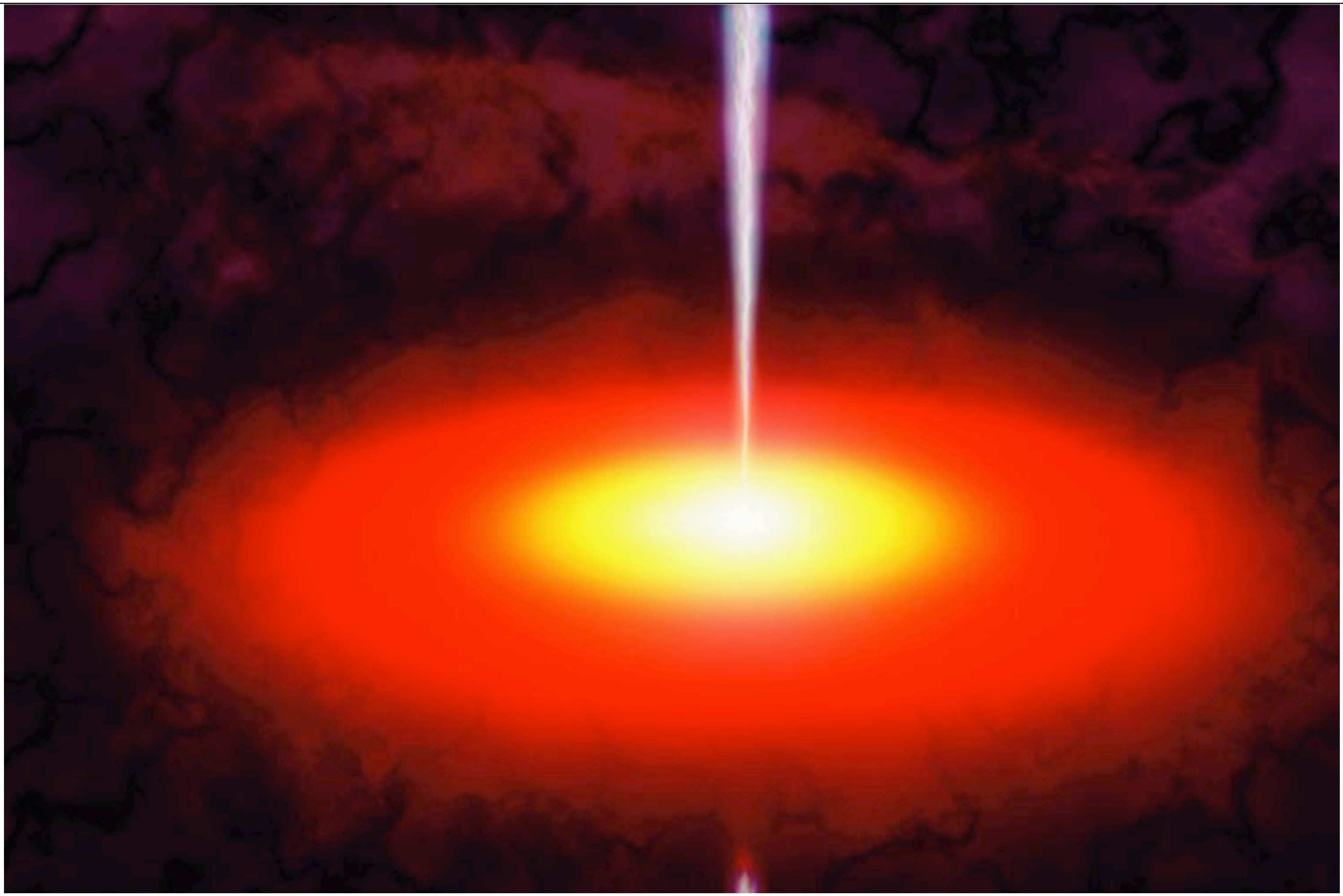


Active Nucleus in M87

If the center of a galaxy is unusually bright, we call it an ***active galactic nucleus (AGN).***

Quasars are the most luminous examples; can be a million times brighter than a normal galaxy!

Power source would fit inside our solar system; what could it be?



The accretion of gas onto a supermassive black hole appears to be the only way to explain all the properties of quasars.

Other Galaxies - The Great Debate

- Is the Milky Way a lonely "Island Universe?"
- Or are there many galaxies like it?
- What is the nature of the "spiral nebulae?"
- Curtis-Shapley Debate (1920)

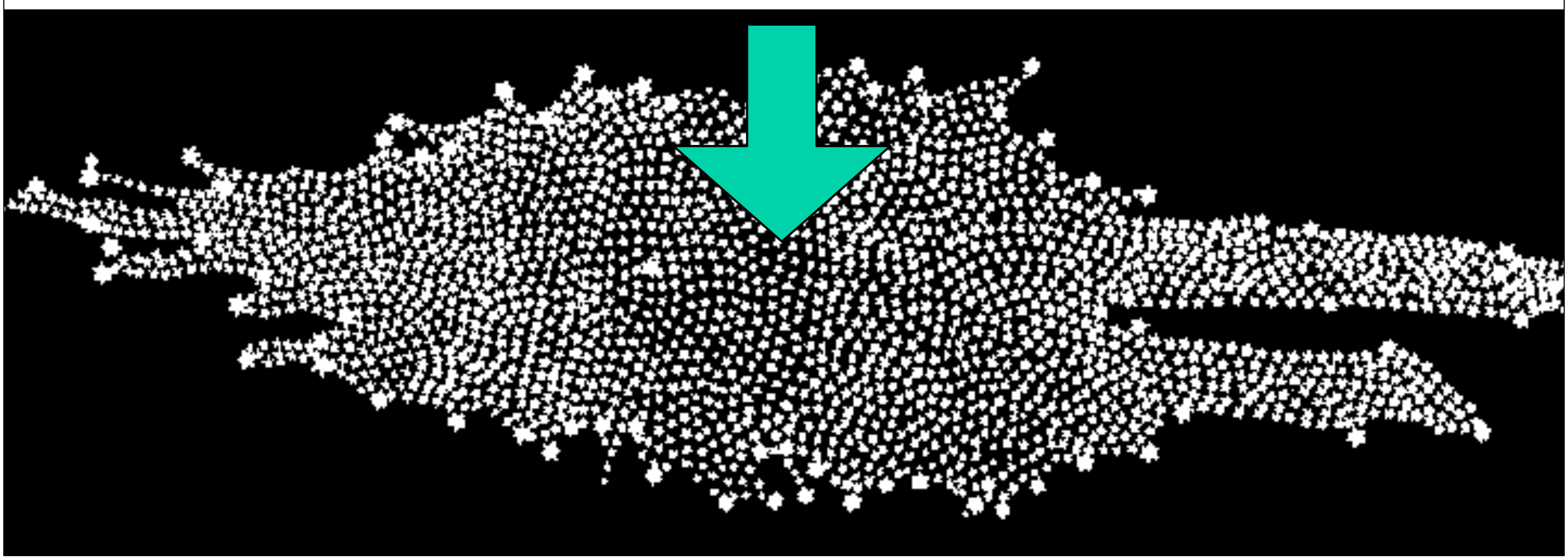
The Great Debate

- <u>CURTIS</u>
- Spiral nebulae are external galaxies comparable to our own Milky Way
- Milky Way small; we're near its center

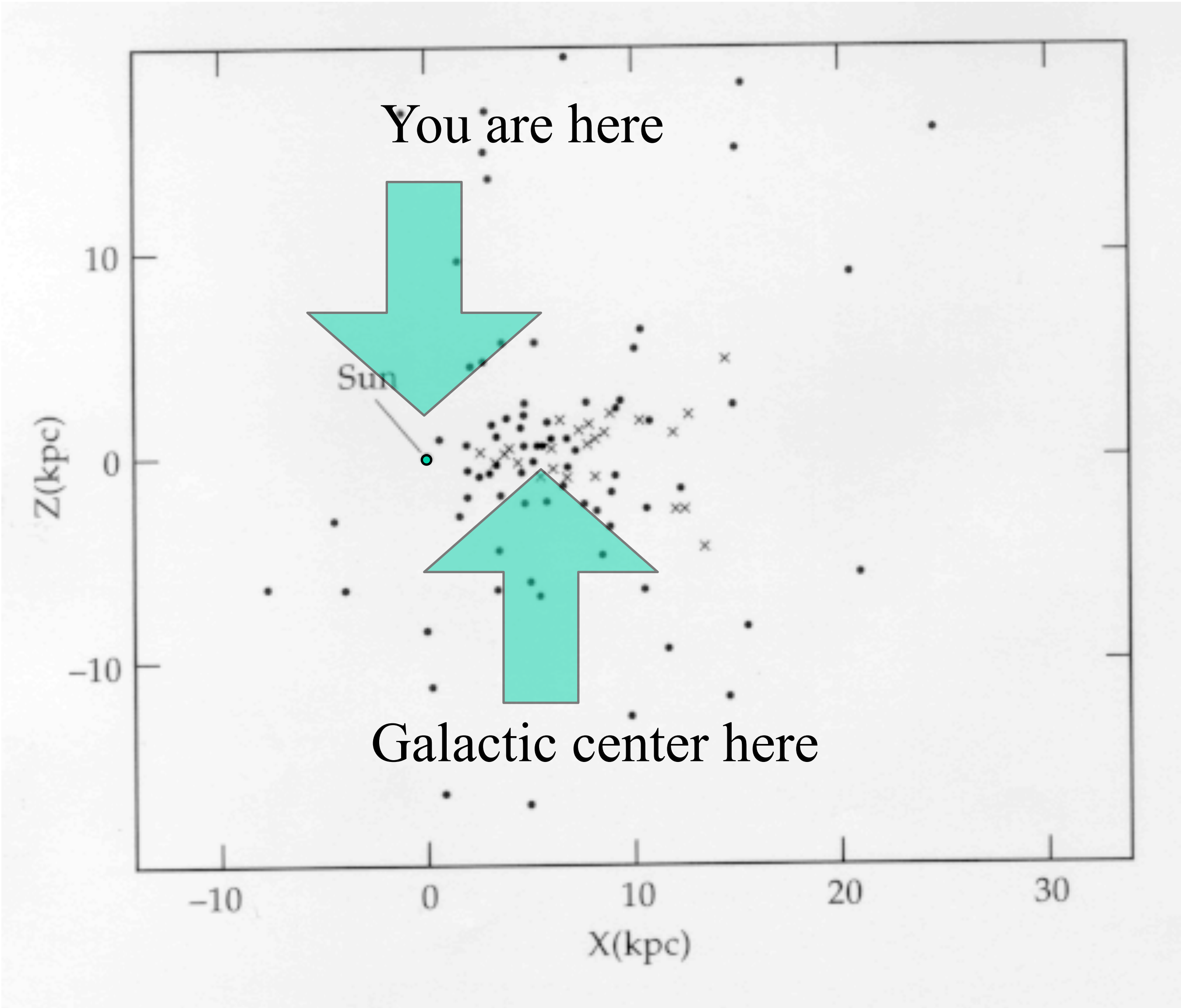
- <u>SHAPLEY</u>
- Spiral nebulae are small gas clouds contained within the Milky Way
- Milky Way big; we're not at its center

Based on star counts made in the ignorance of dust,
Curtis argued that the Milky Way was small.
We just happened to be near its center.

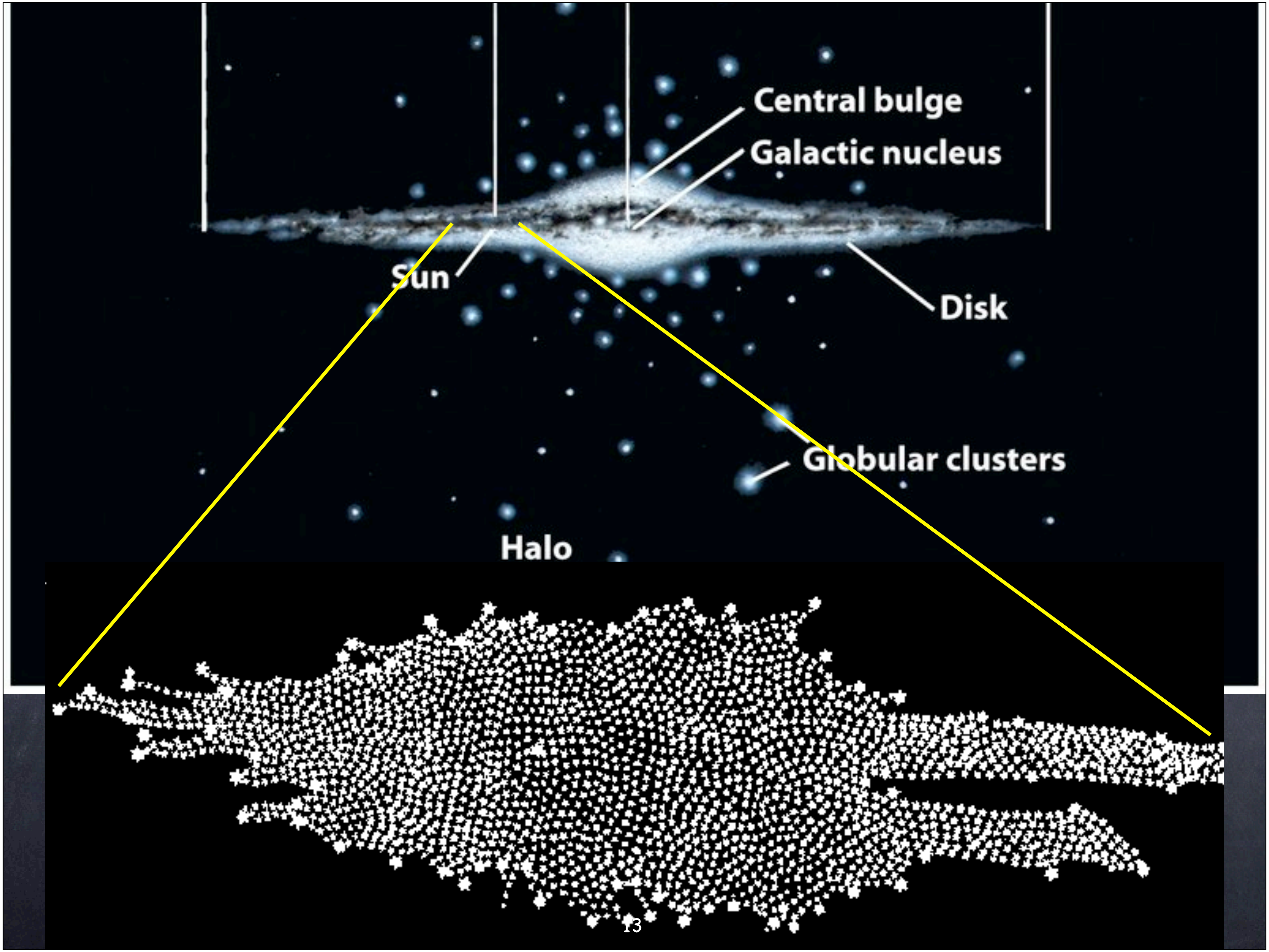
You are here



Shapley argued that we were unlikely to be near the center - the Copernican Principle. The center of the galaxy was likely in the direction where all the globular clusters were.



Curtis's map was incomplete because of dust


Central bulge
Galactic nucleus
Sun
Disk
Globular clusters
Halo

The Great Debate

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Shapley argued that the spiral nebulae were just pinwheels of gas within the Milky Way.

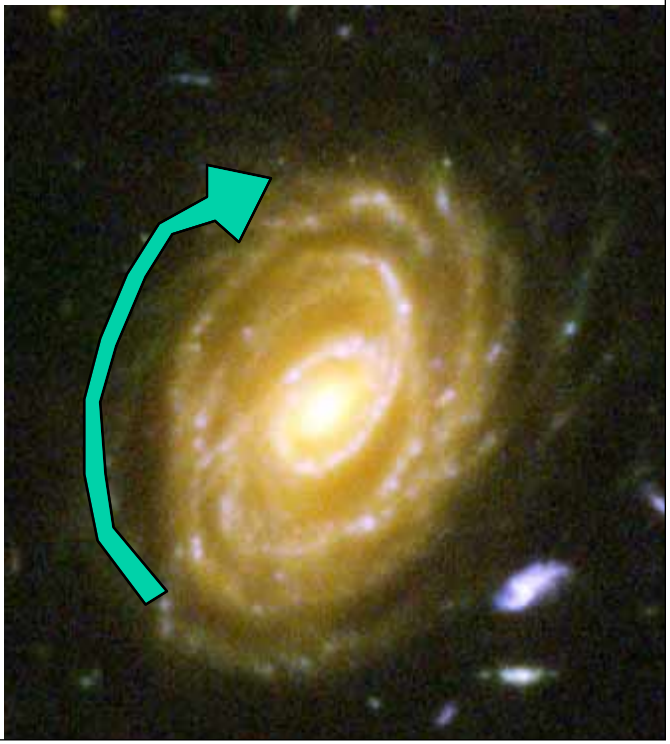
Two critical observations:

(1) spiral galaxies seen to rotate

Just plain wrong.

(2) a nova in Andromeda suggested a distance closer than the globulars.

Really was a supernova (unknown at the time).



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Necessary measurement?

What is the most important measurement we could make about the spiral nebulae to establish whether they are like our MW or much smaller?

A. The shapes of the spiral nebulae

B. The colors of the spiral nebulae

C. The distances to the spiral nebulae

D. The directions to the spiral nebulae

E. I don't know

How can we measure distances in astronomy?

- Start with everyday question: what are some distinct ways we can measure distance in normal life?
- For example, suppose you saw a friend walking down the street towards you; what distinct ways might you use to find out how far your friend is?

How can we measure distances in astronomy?

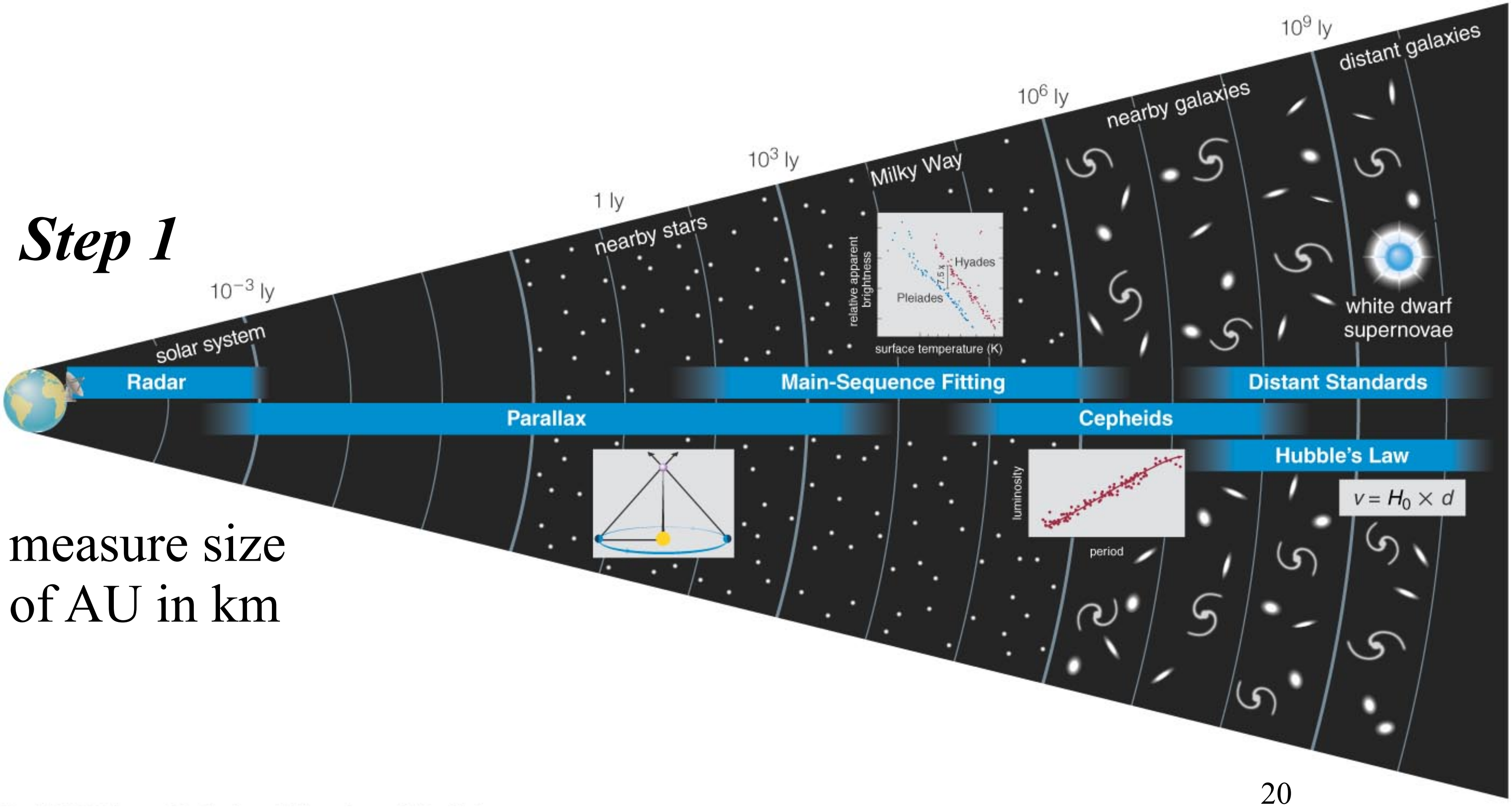
- Direct measurement, e.g., number of blocks away
- Parallax, using your eyes
- "Angular diameter distance"; if you know how tall your friend is and the angle your friend subtends, geometry gives distance
- "Luminosity distance": if your weird friend likes to carry lit 100 watt light bulbs, you can tell from how bright the bulb appears to be, how far away it is (this is the most practical measure for most astronomical purposes)

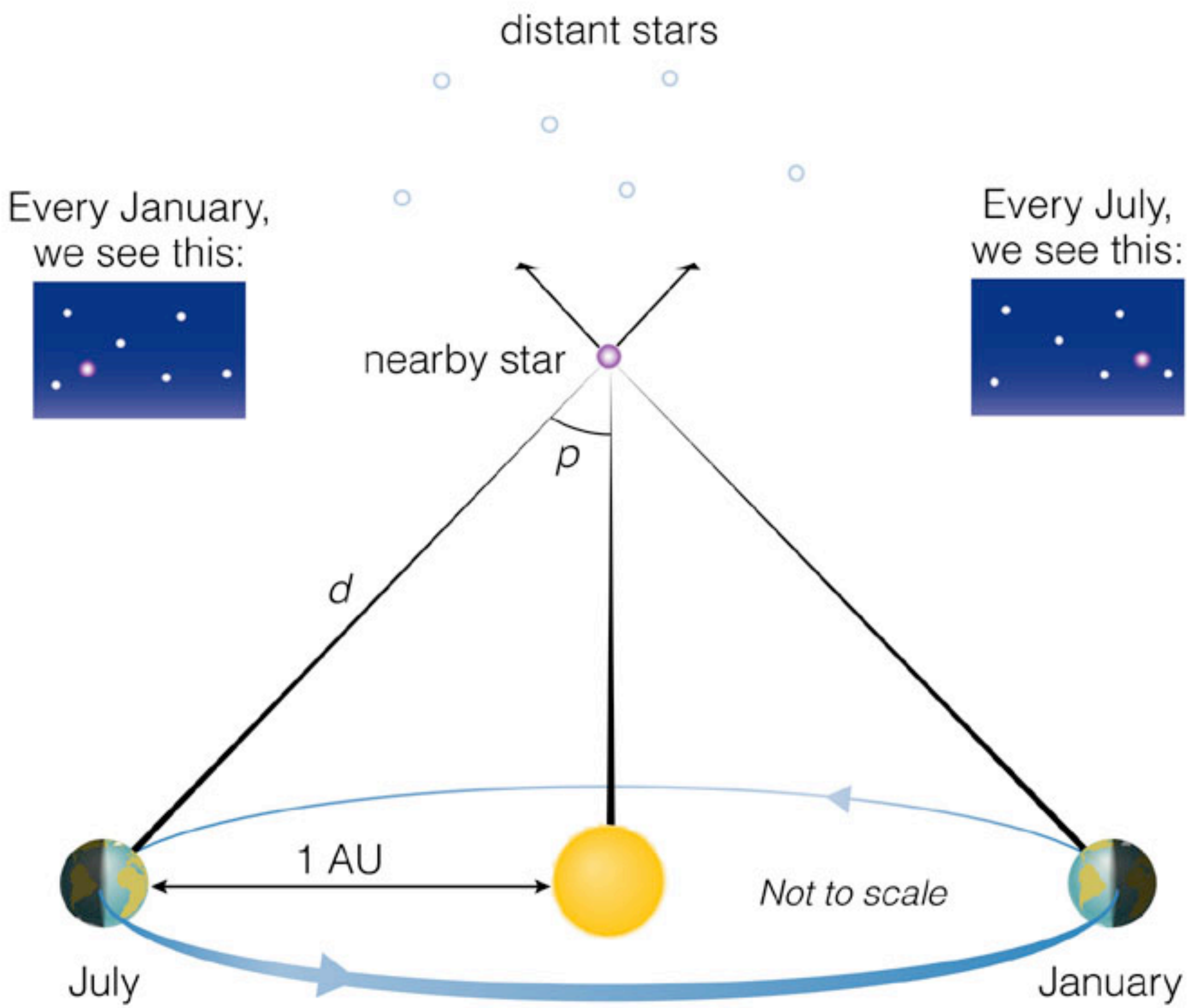
In everyday life, all these distances are equivalent; at distances a decent fraction of the size of the visible universe they need not be, so you have to be careful!

The distance scale ladder

Step 1

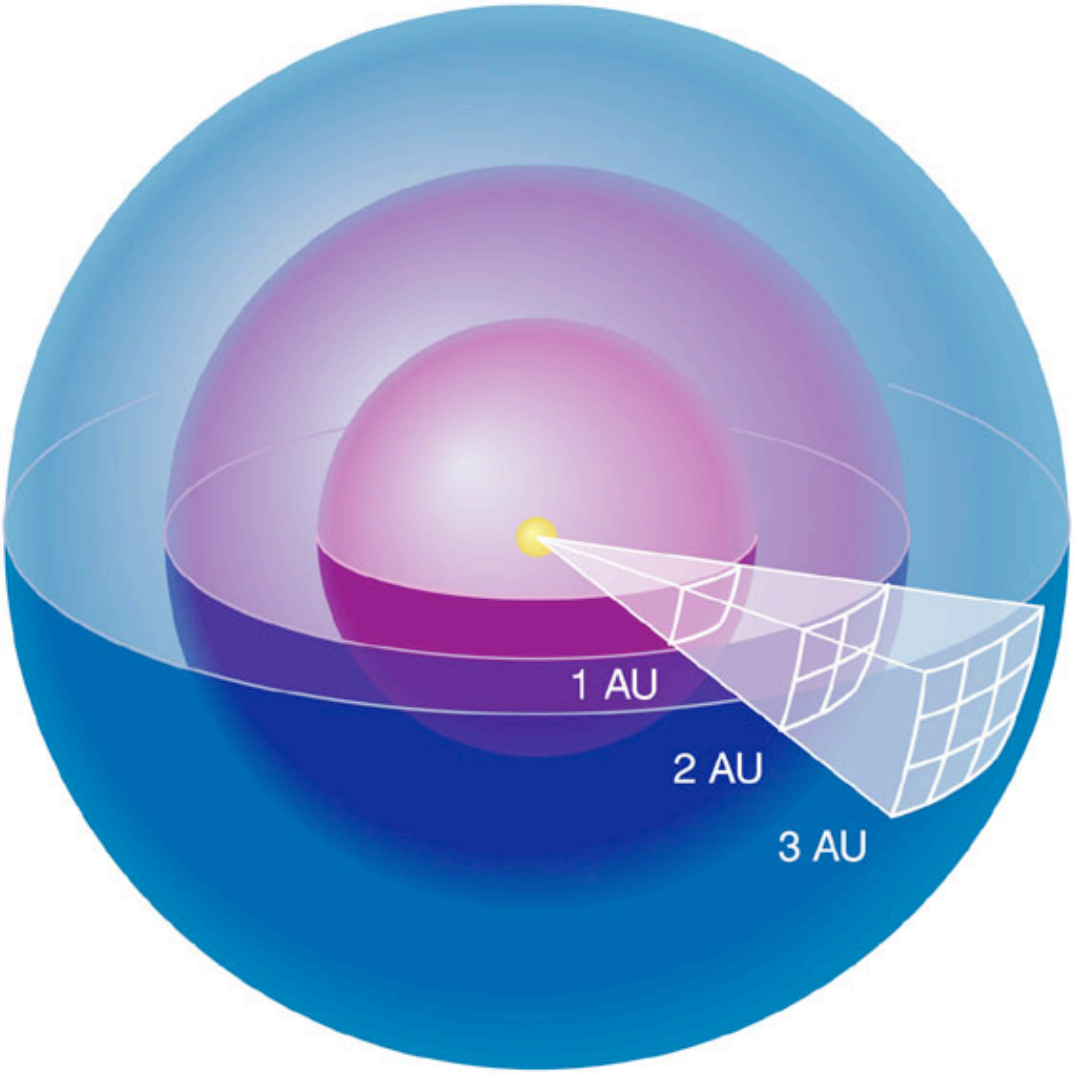
measure size of AU in km





Step 2

Determine distances of stars out to a few hundred light-years using parallax



Luminosity passing through each sphere is the same

Area of sphere:

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

Divide luminosity by area to get brightness

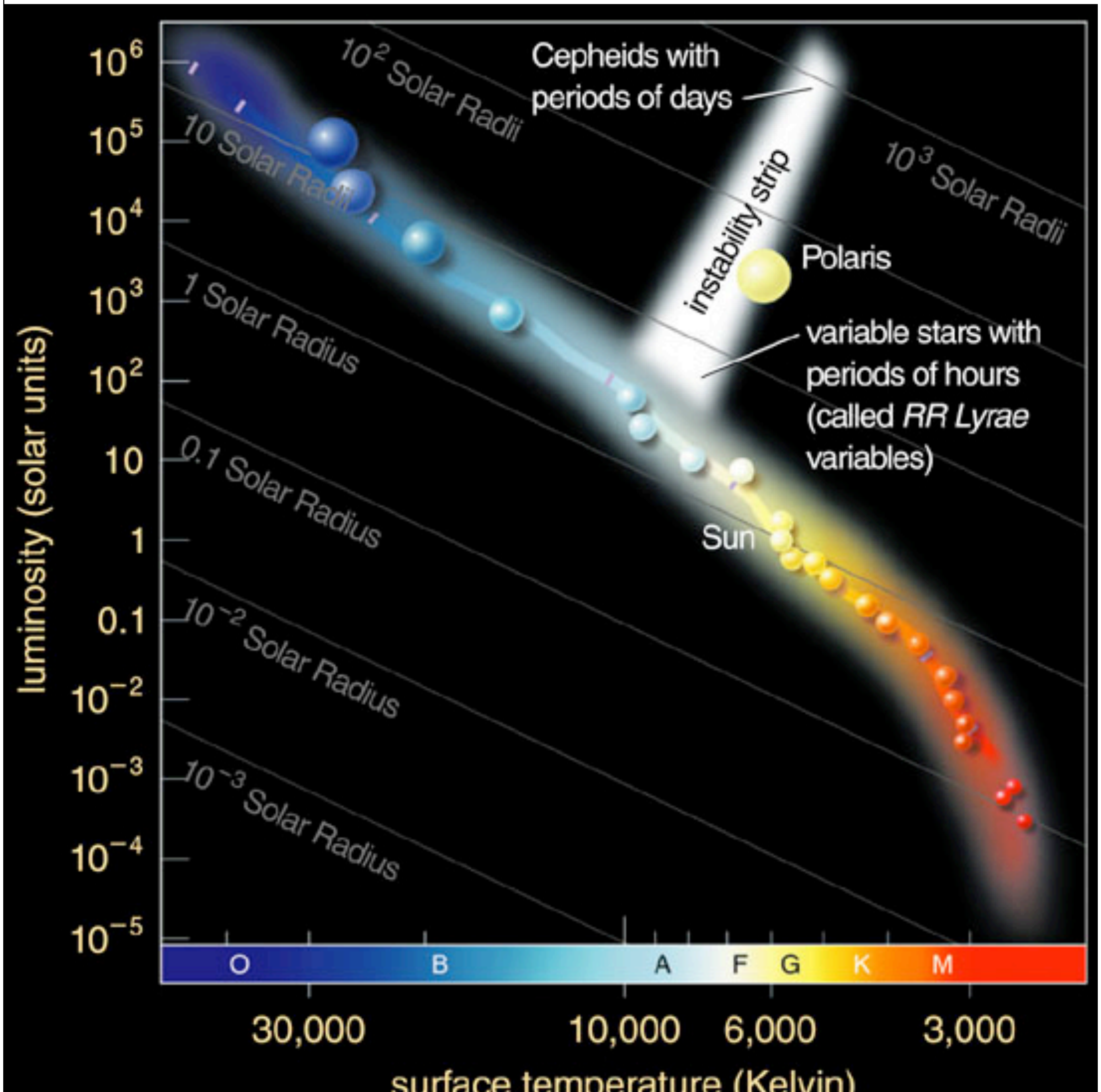
The relationship between apparent brightness and luminosity depends on distance:

$$L = 4\pi d^2 b$$

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

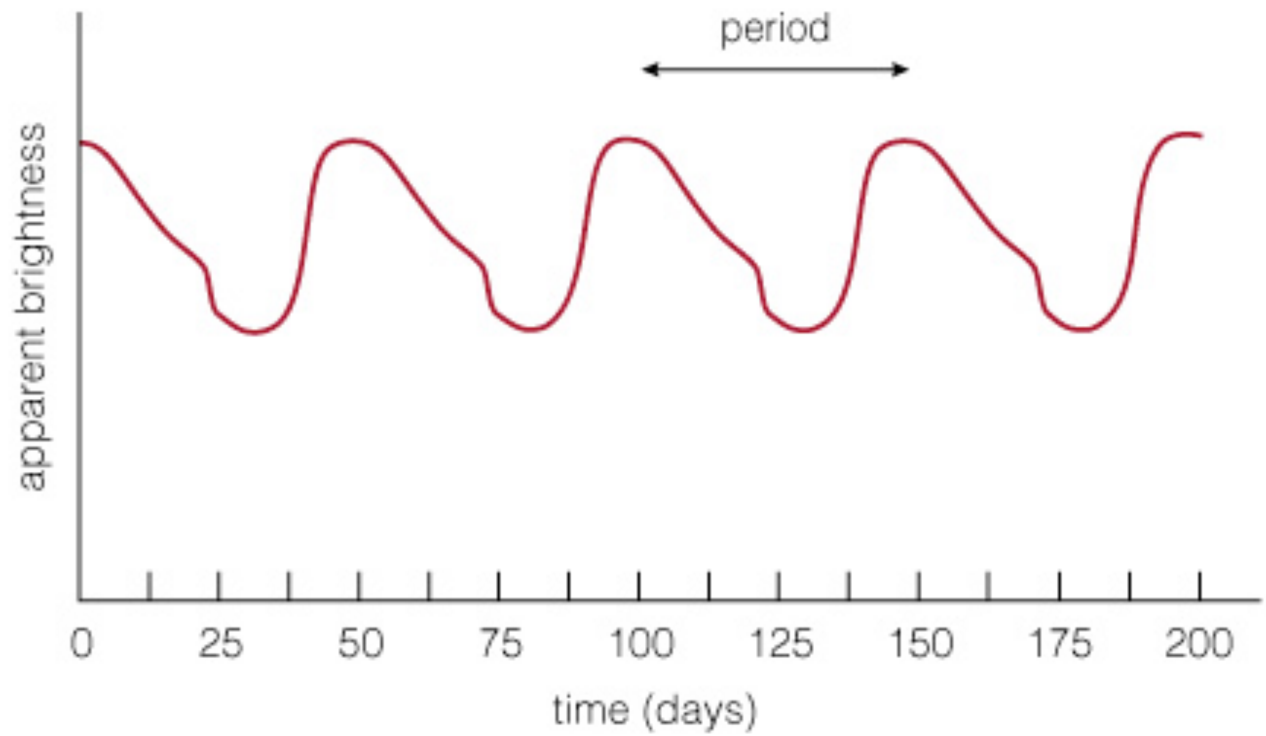
$$d = \sqrt{\frac{L}{4\pi b}}$$

A ***standard candle*** is an object whose luminosity we can determine without measuring its distance.

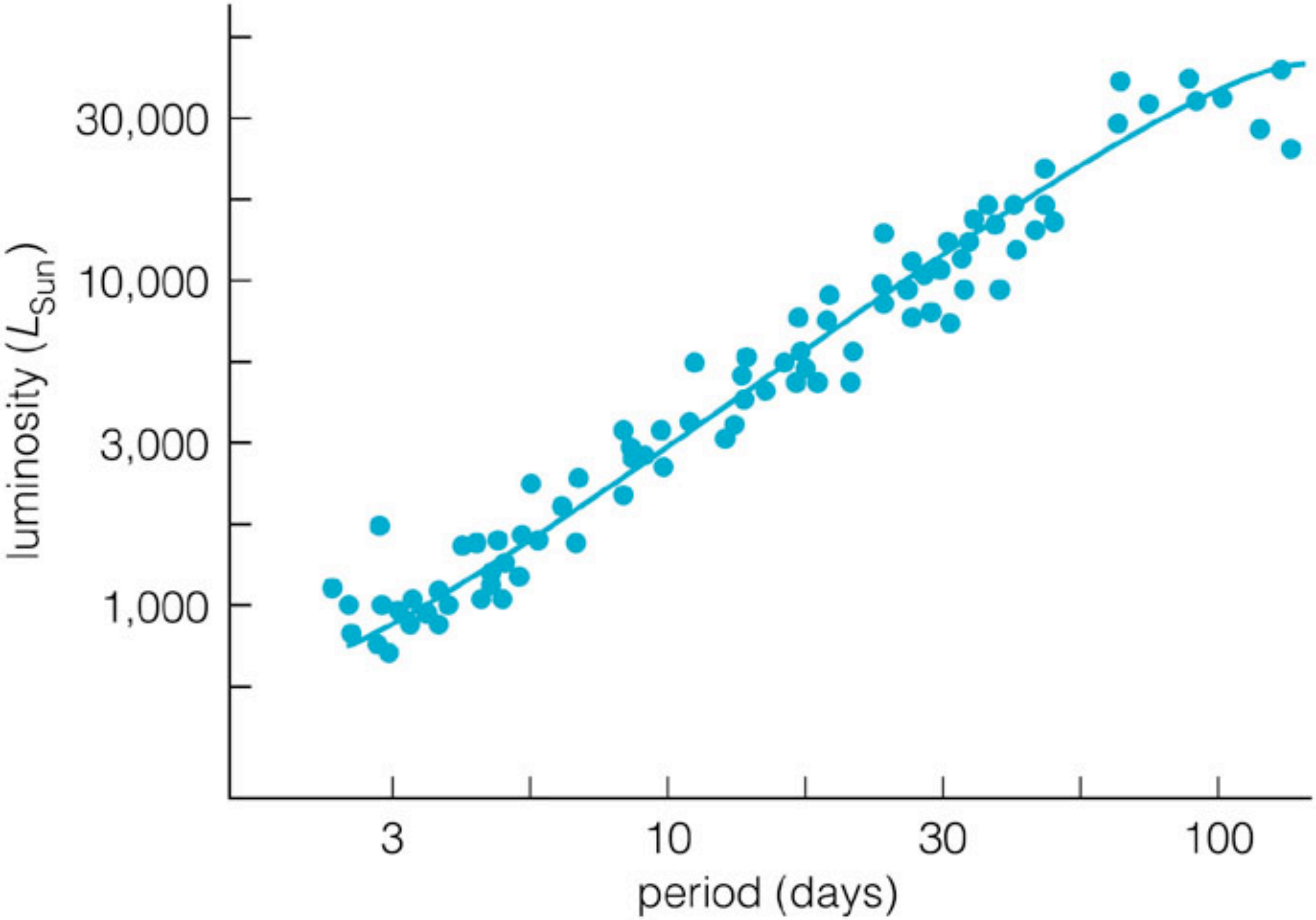


Cepheid variable stars are special examples of standard candles. They are very luminous, so can be seen from far away.

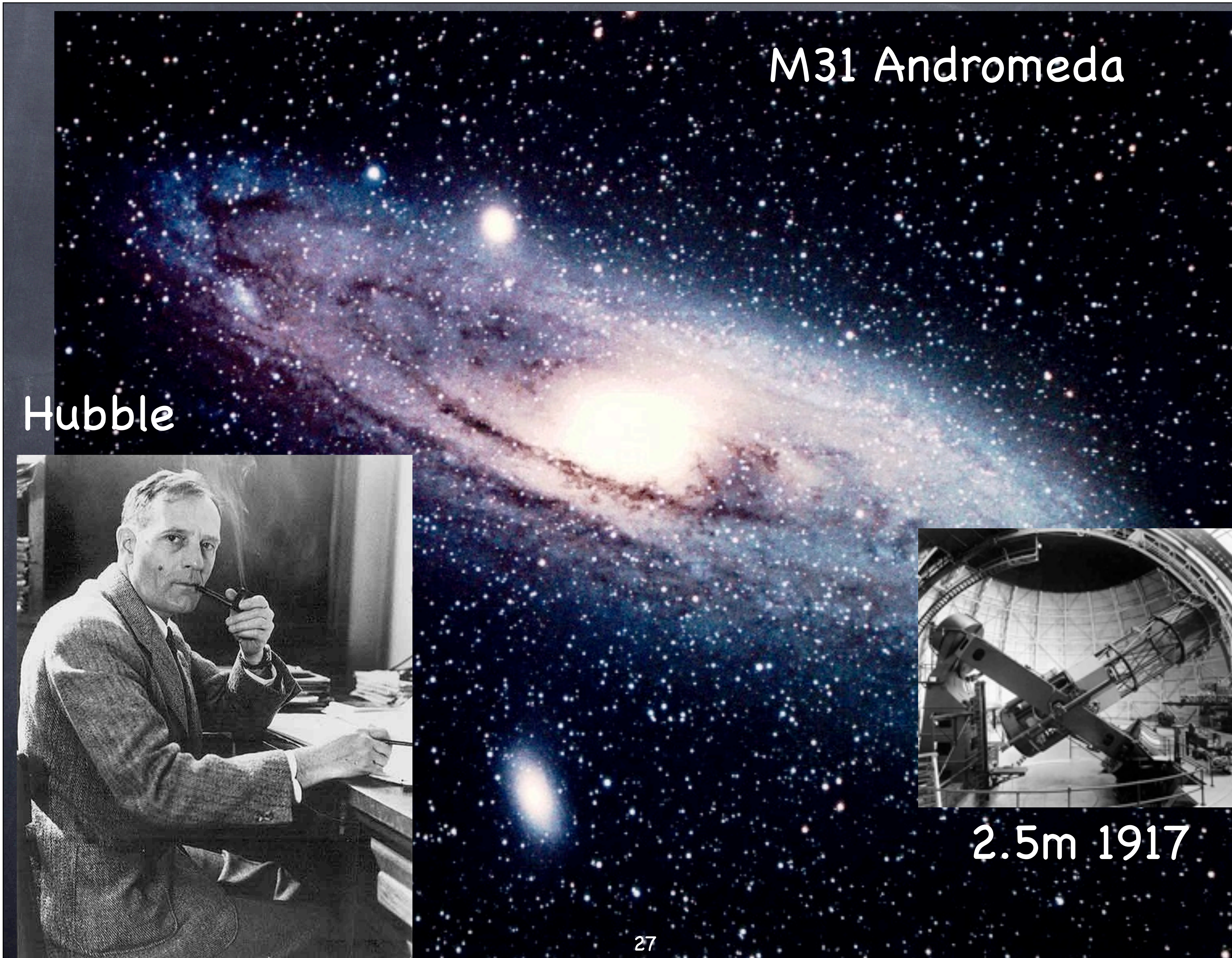
Cepheid Variable Stars

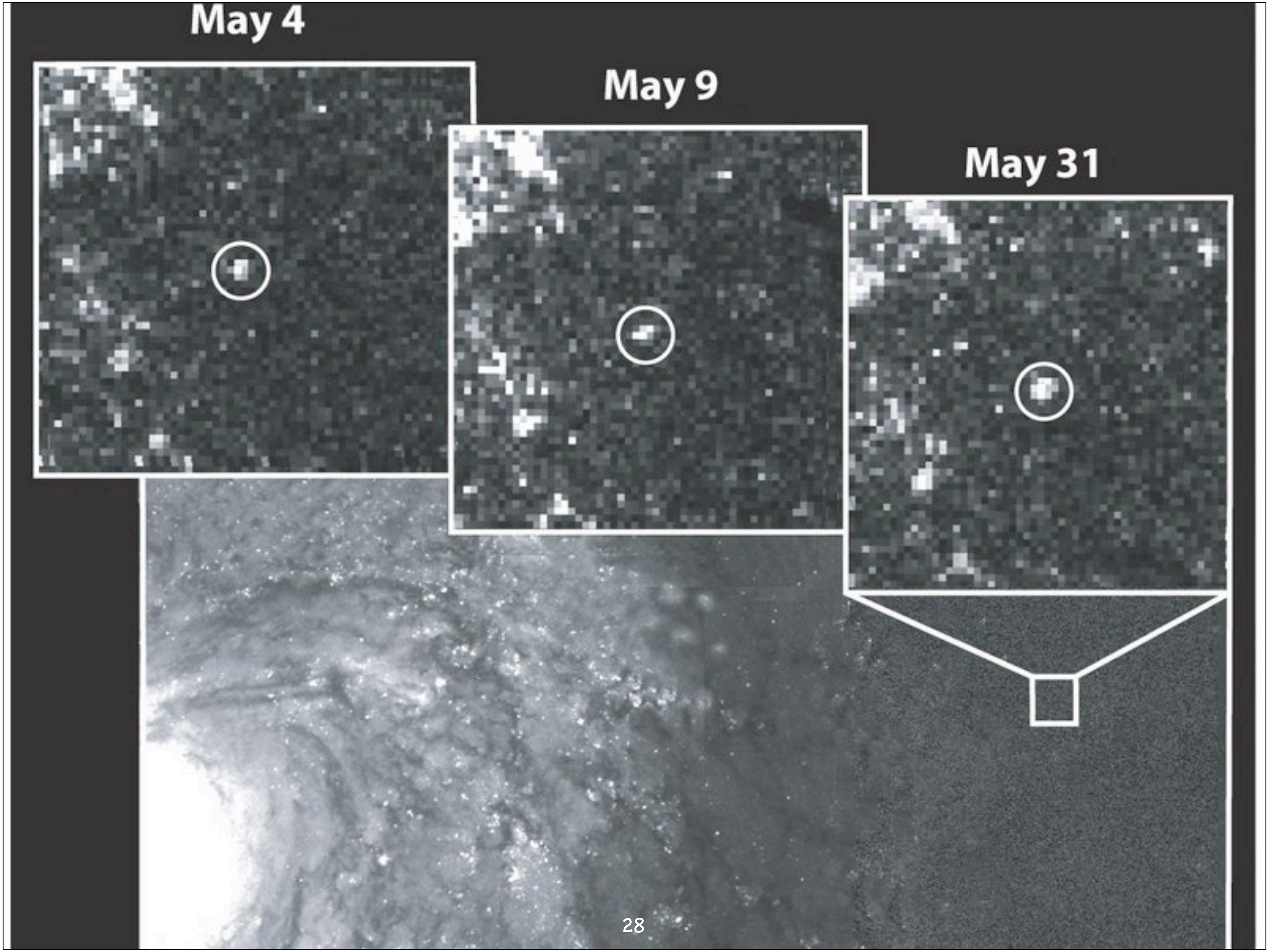


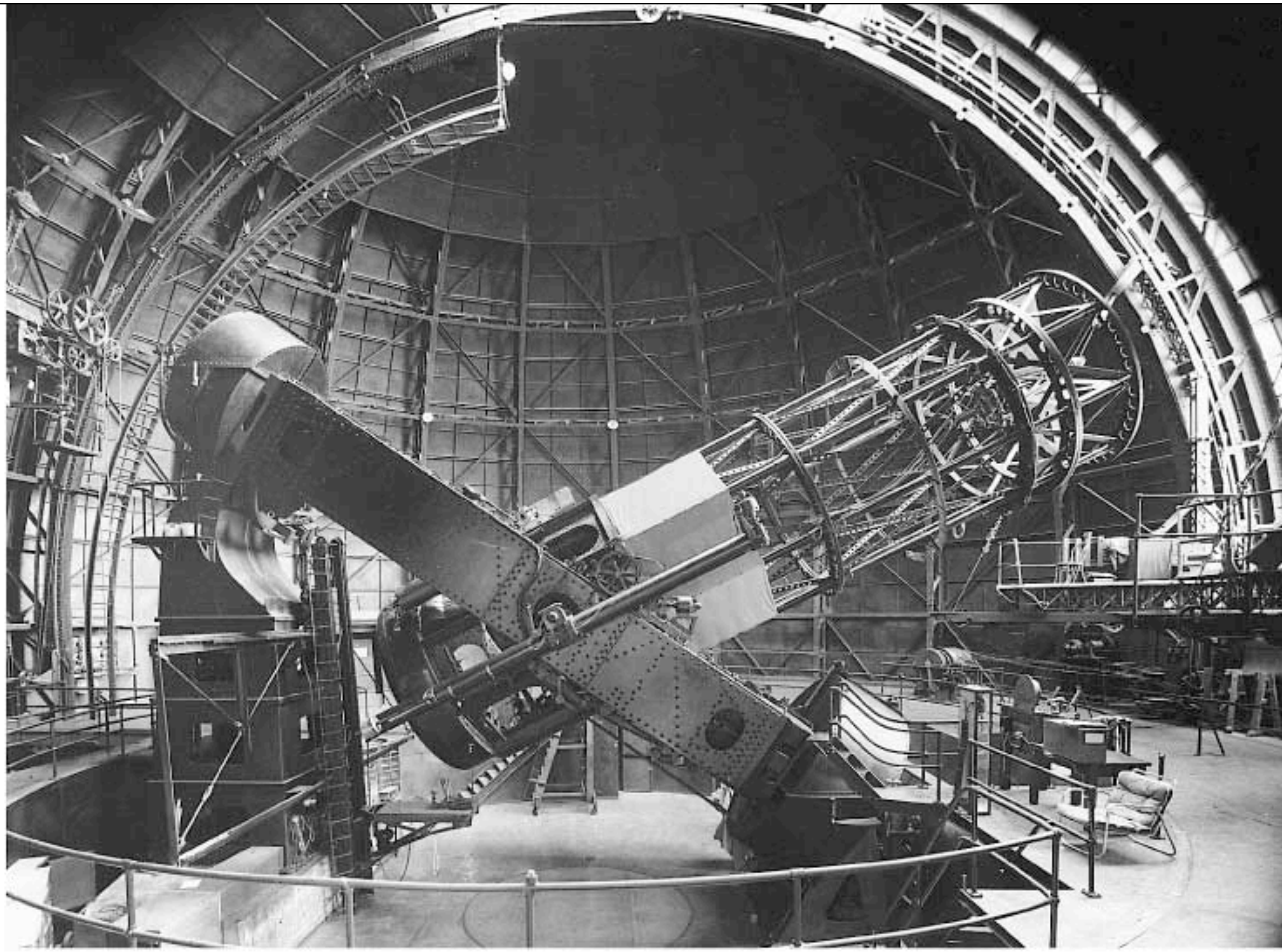
The light curve of this *Cepheid variable star* shows that its brightness alternately rises and falls over a 50-day period.



Cepheid variable stars with longer periods have greater luminosities: measuring the period tells us the luminosity!


M31 Andromeda
Hubble
2.5m 1917


May 4
May 9
May 31



Hubble settled the “Great Debate” by measuring the distance to the Andromeda Galaxy using Cepheid variables as standard candles.

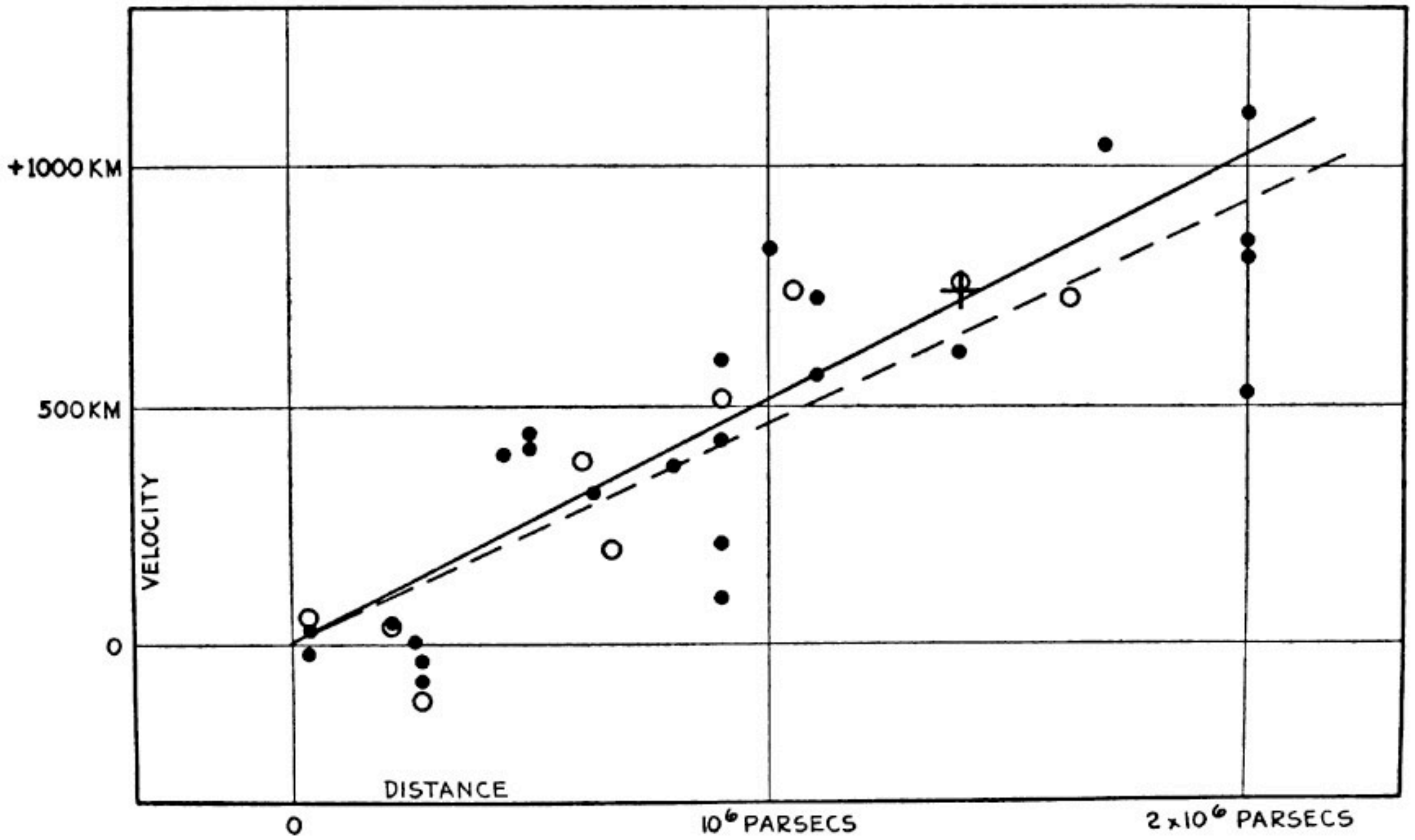
Hubble

- Showed that galaxies were distant systems, comparable in size to the Milky Way
  - settled Great Debate after ten years.

- Classified galaxy morphology (types)

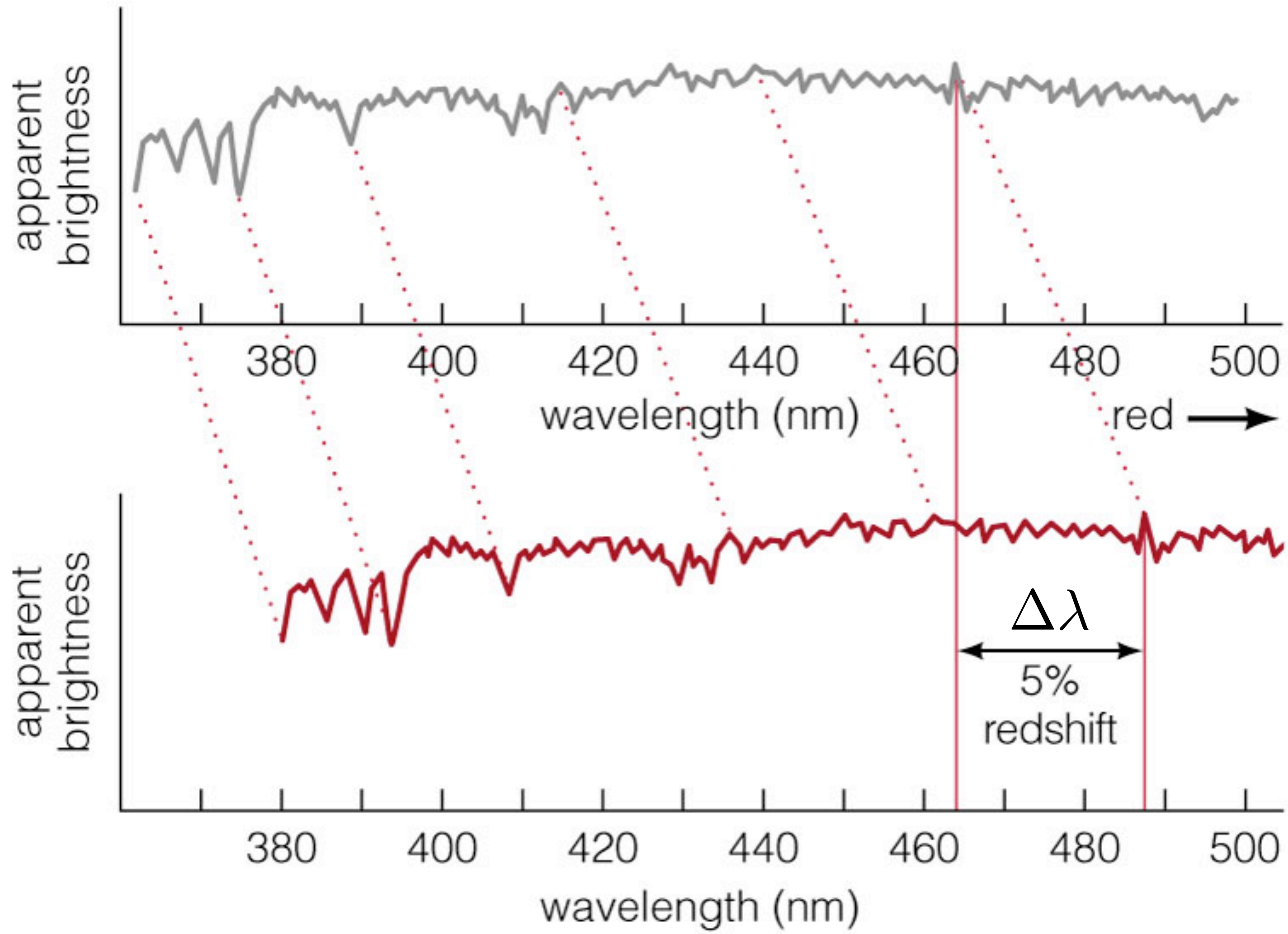
- Discovered expansion of the Universe.

Hubble's law



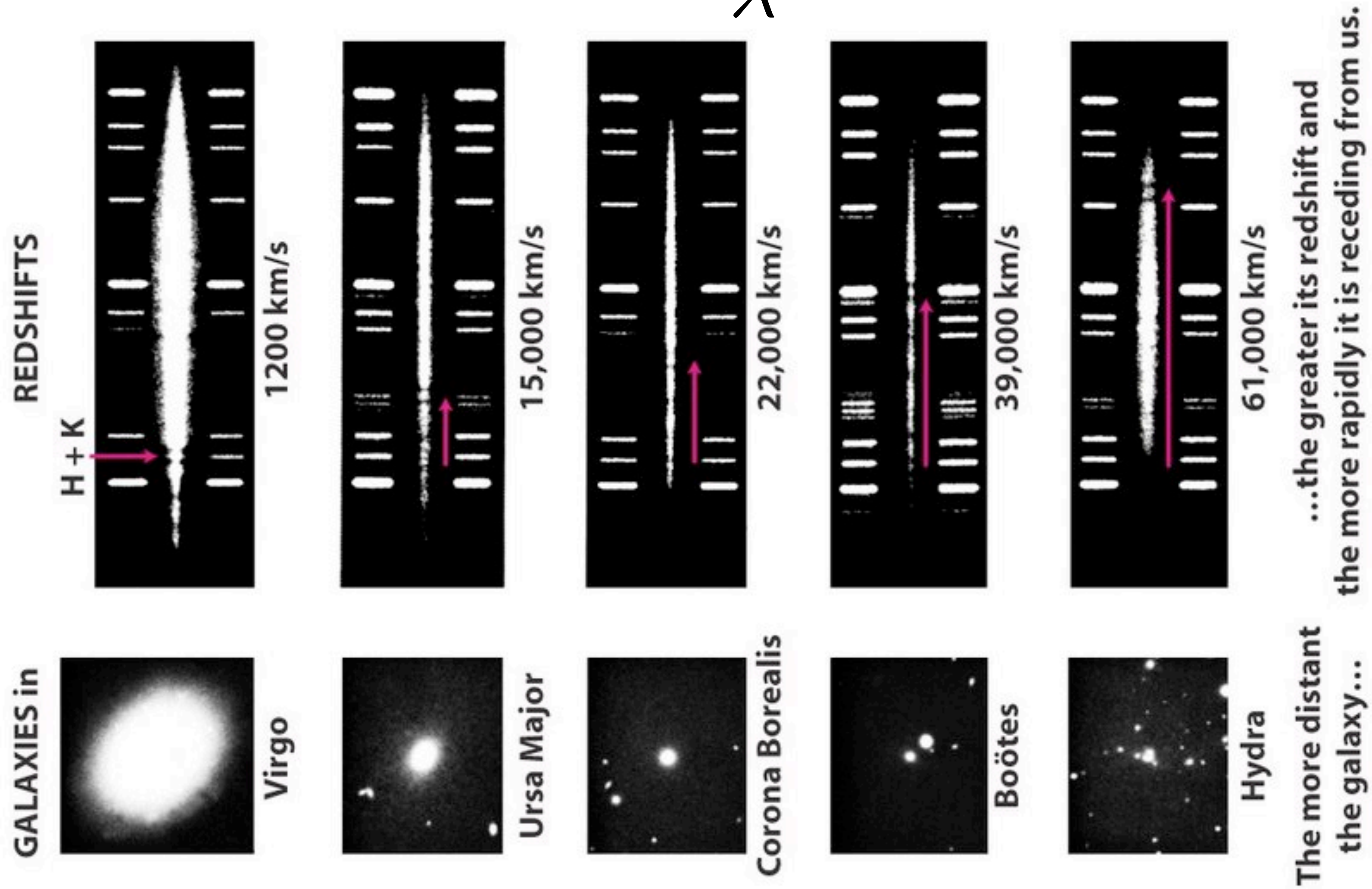
redshift

distance

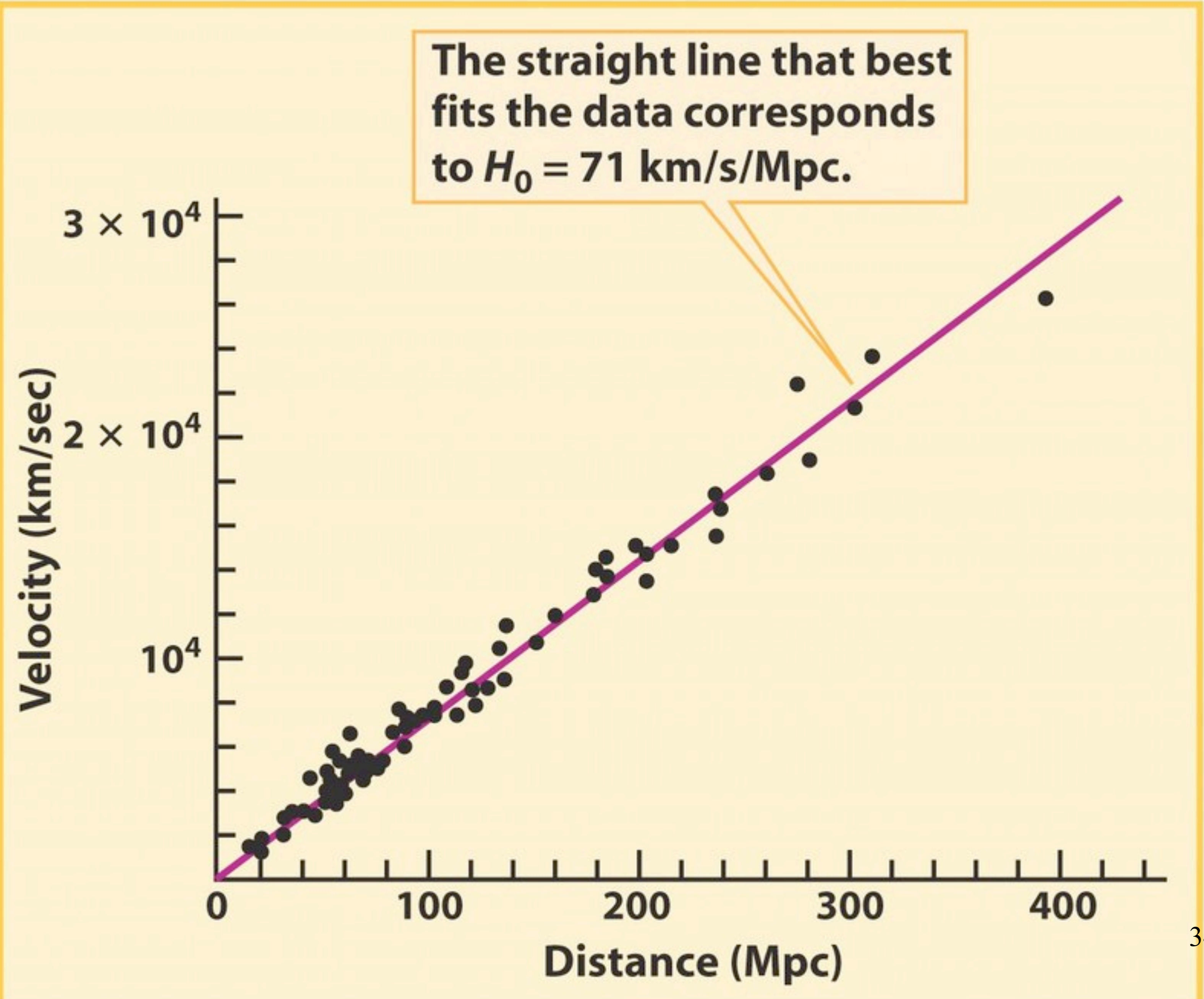


Hubble knew from Slipher's work that the spectral features of virtually all galaxies are ***redshifted*** $\Rightarrow$ they're all moving away from us.

$$V = \frac{\Delta\lambda}{\lambda} c$$



Hubble's law: $V = H_0 d$



Each point represents one galaxy

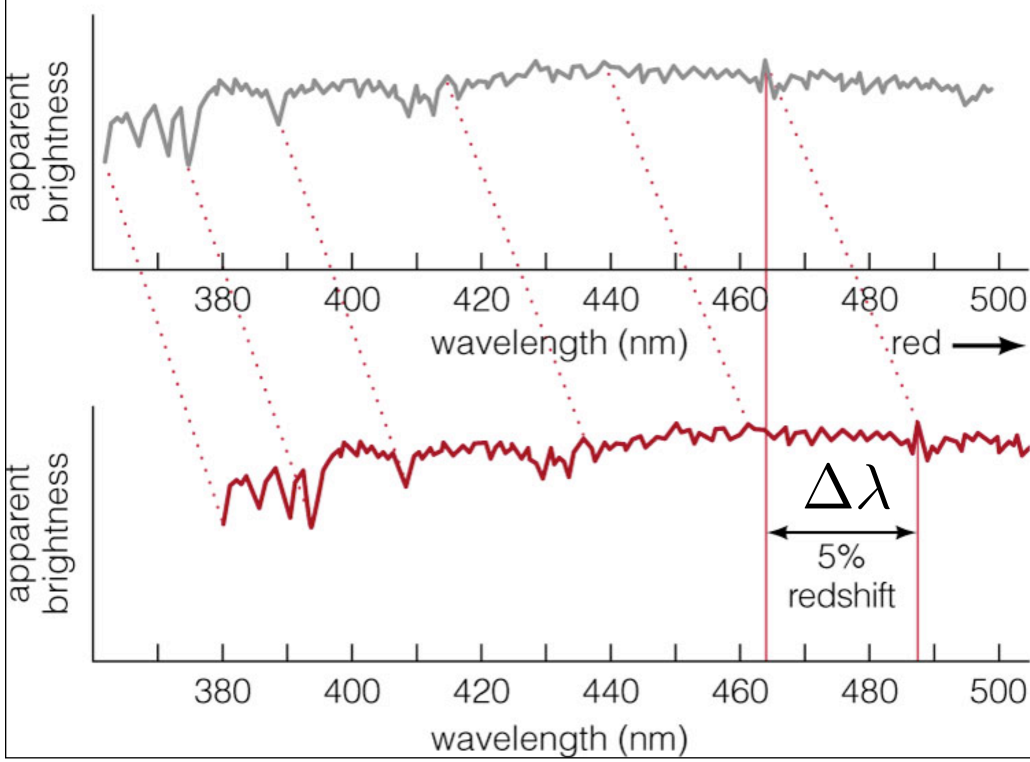
Hubble's law: $V = H_0 d$

apparent recession velocity from Doppler effect

distance

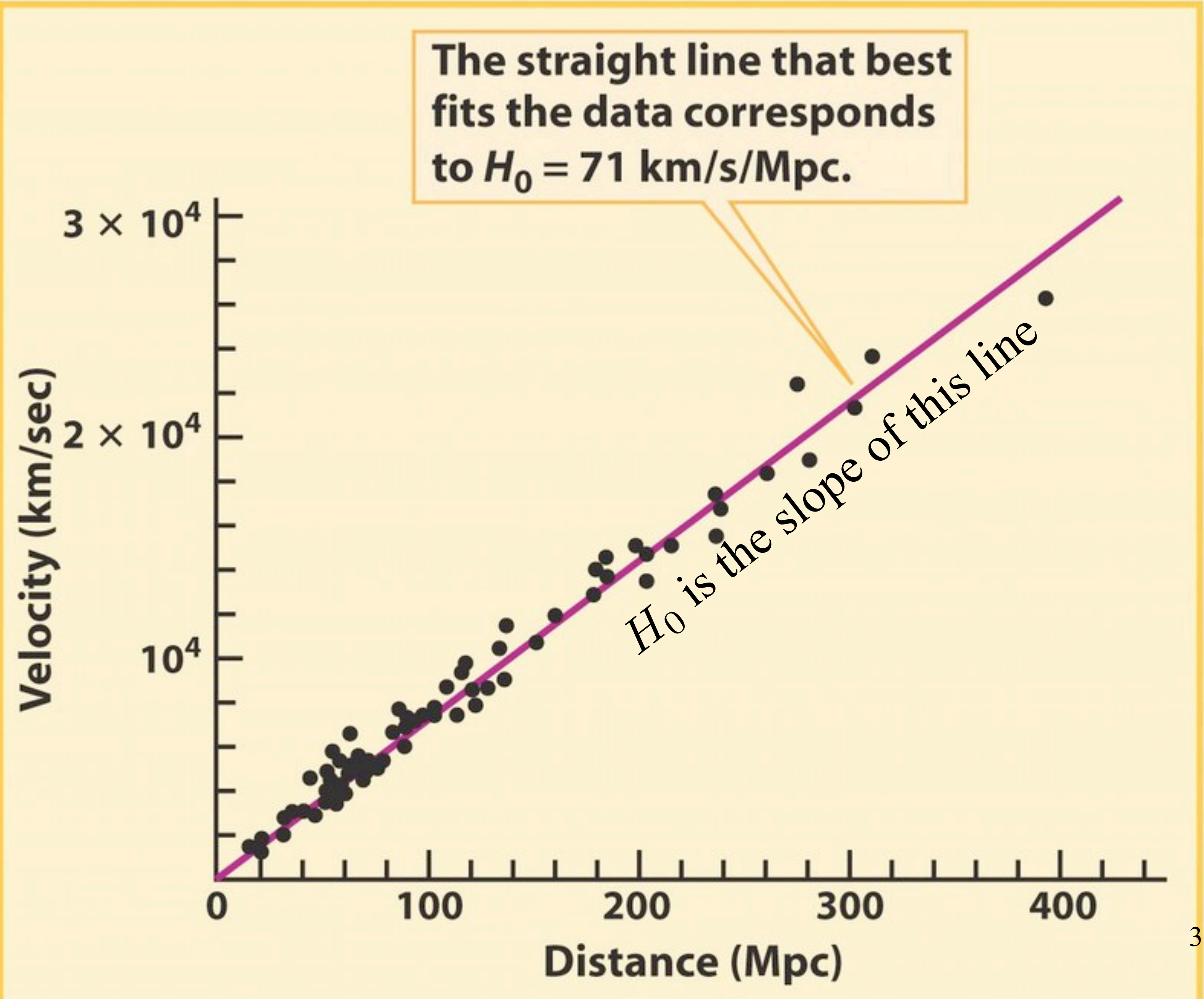
Hubble's constant H_0

$$V = \frac{\Delta\lambda}{\lambda} c$$



$$\Delta\lambda = \lambda_{obs} - \lambda_{em}$$

Hubble's law: $V = H_0 d$

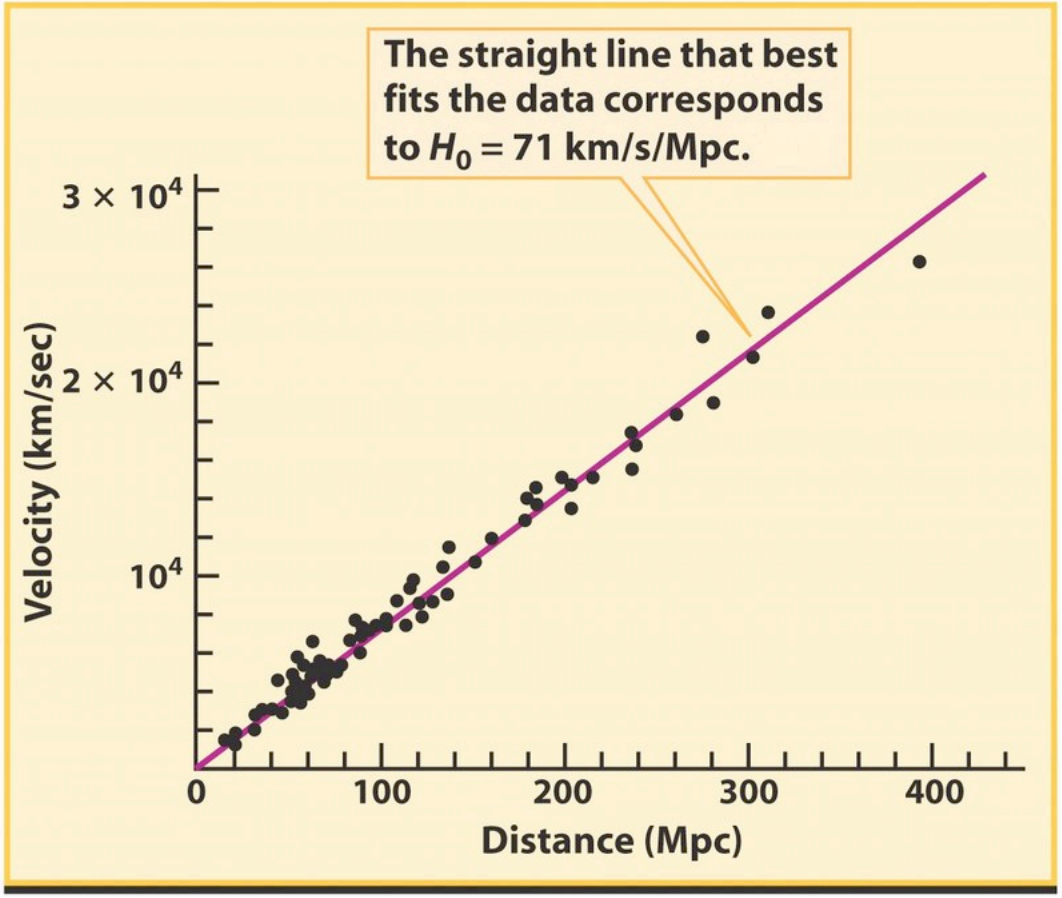


Each point represents one galaxy

What does it mean?

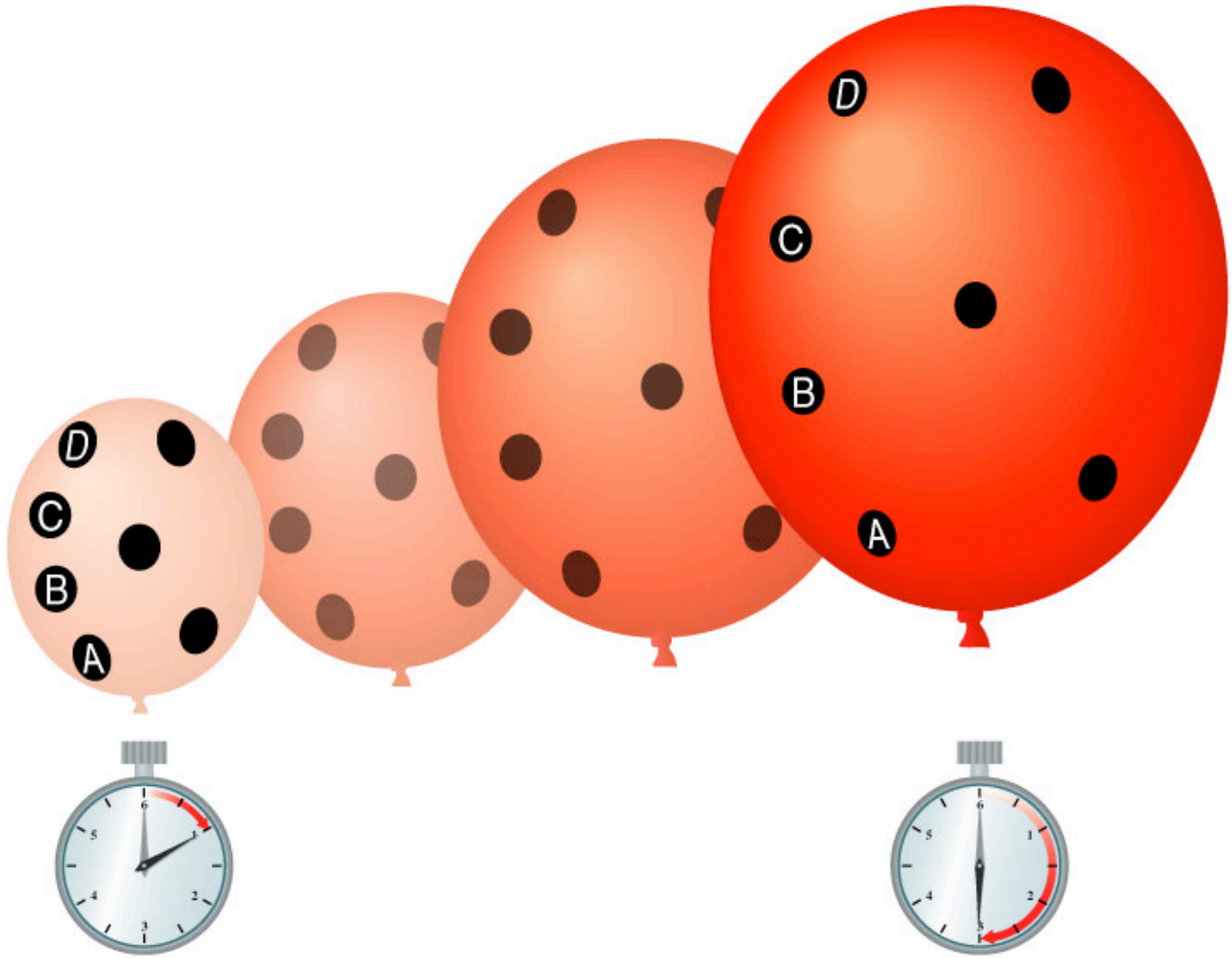
- The universe is expanding
  - galaxies are receding from one another
  - it is *not* like an explosion
  - the space between galaxies is getting stretched
- The expansion has no “center”
- The age of the universe is finite

Expansion age of the universe



size ⟶ zero in finite past: age $\sim \dfrac{1}{H_0}$

E2-63



One example of something that expands but has no center or edge is the surface of a balloon.
The “center” is the beginning of time - the “4th dimension”

Cosmological Principle

The universe looks about the same no matter where you are within it.

Homogeneous and *Isotropic*

- Matter is evenly distributed on very large scales in the universe (*homogeneity*)
- Looks the same in all directions (*isotropy*)
  - No center and no edges
  - Not proven, but consistent with all observations to date