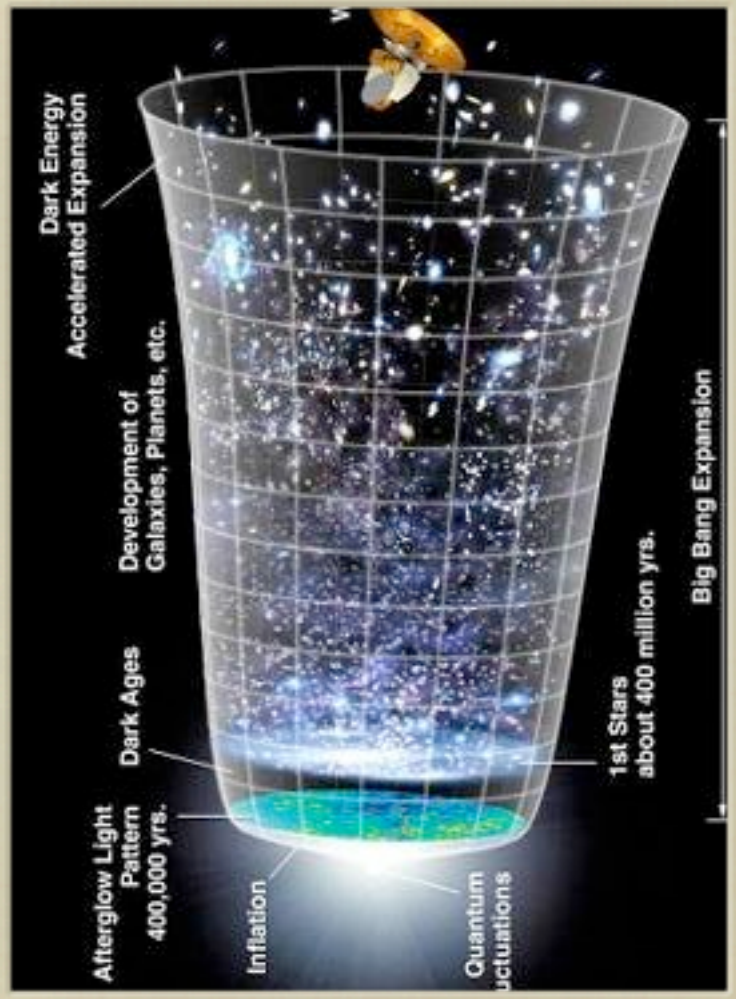
Today

- The Distance Scale
  - The Great Debate
- Expansion of the Universe
  - Hubble Law



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)

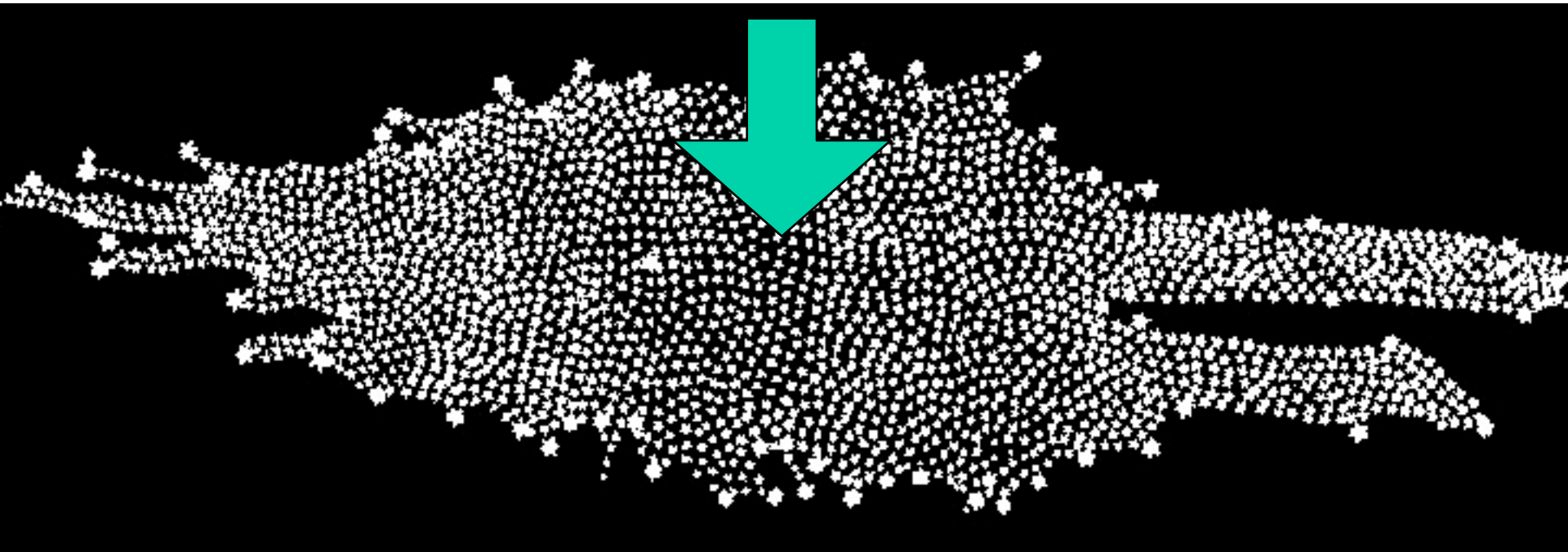
The Great Debate

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

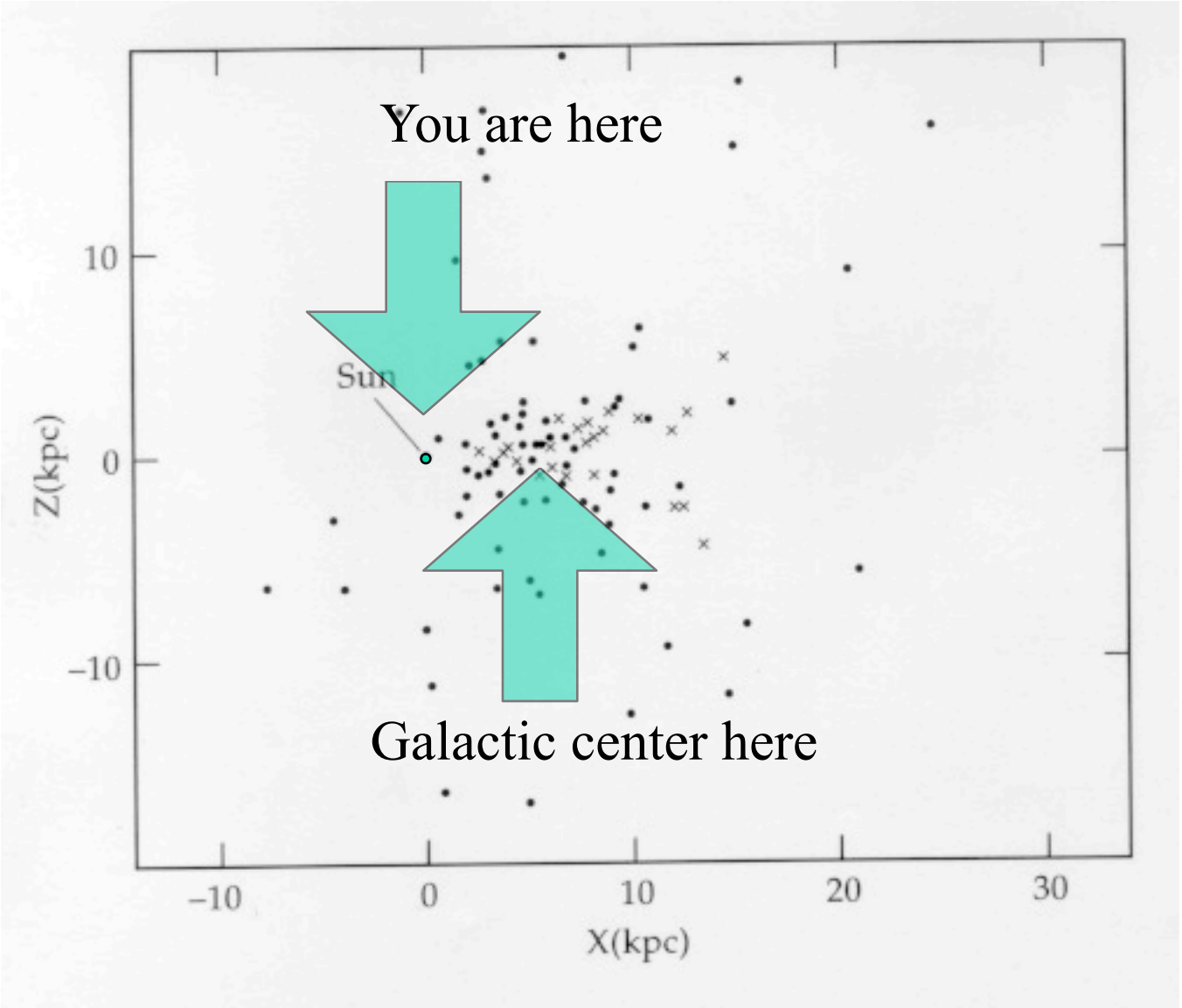
- <u>SHAPLEY</u>
- Spiral nebulae are small gas clouds contained within the Milky Way
- Milky Way big; we're not at its center

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.

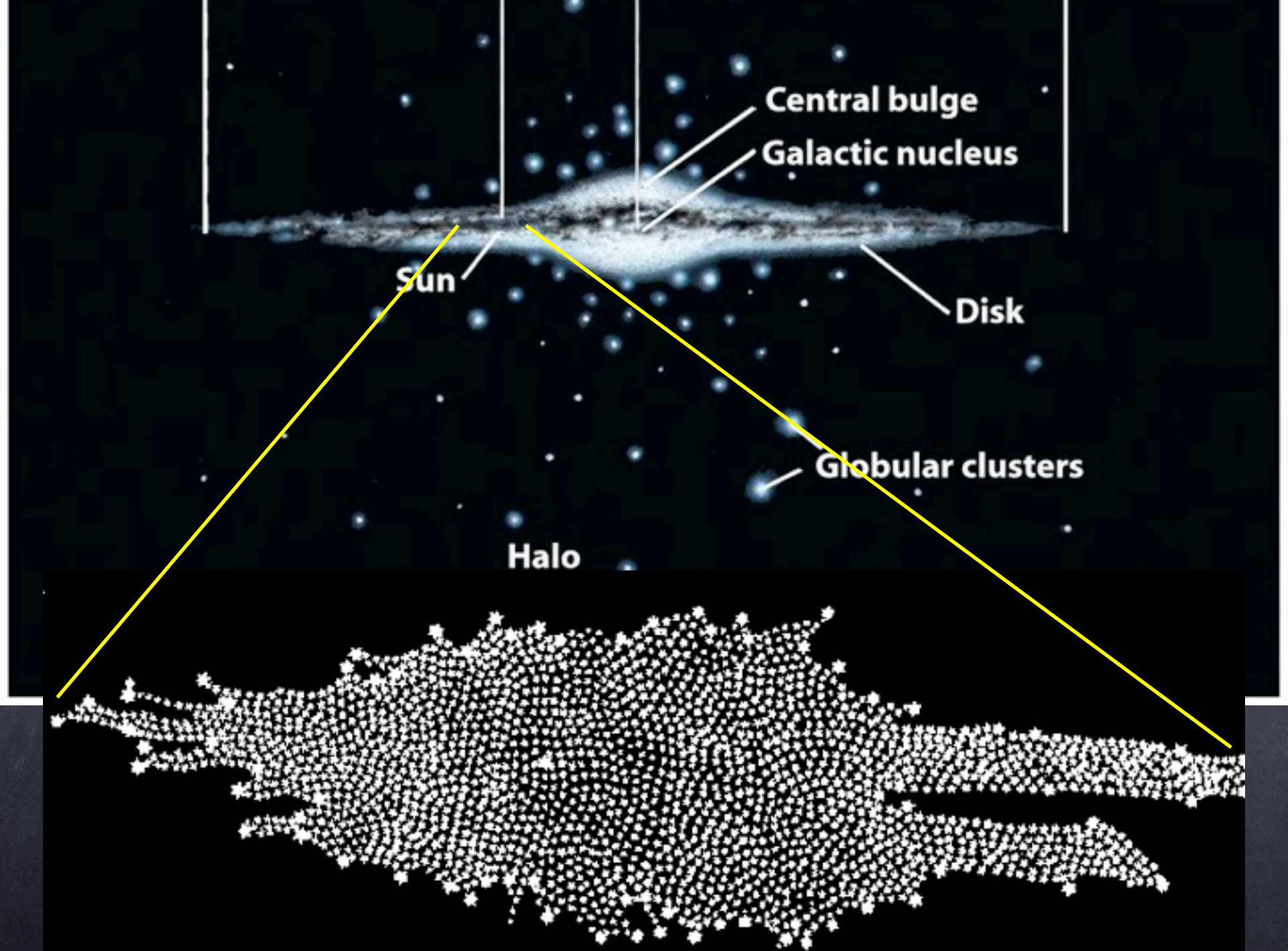
You are here



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

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 globular clusters.

Really was a supernova (unknown at the time).

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

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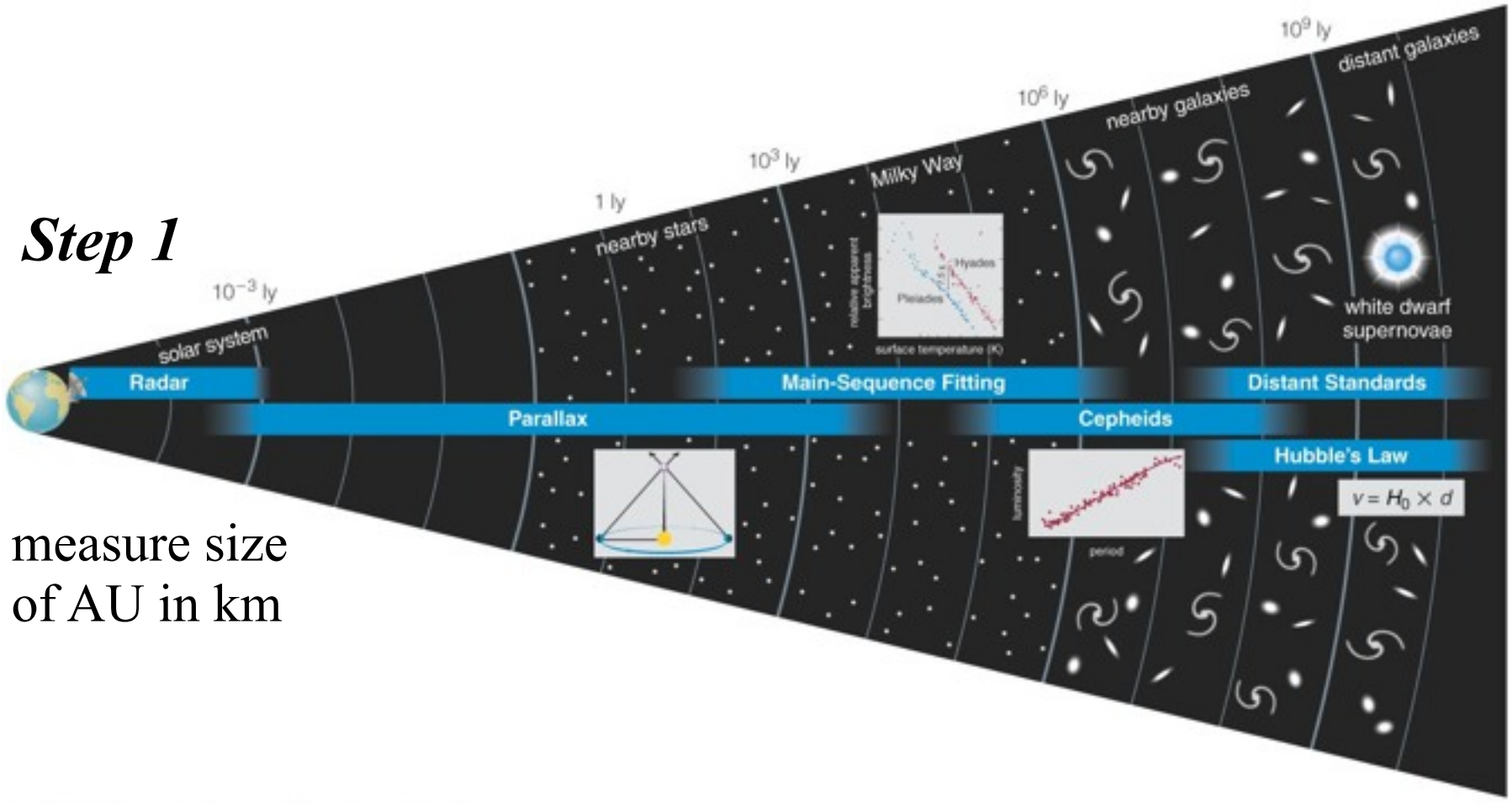
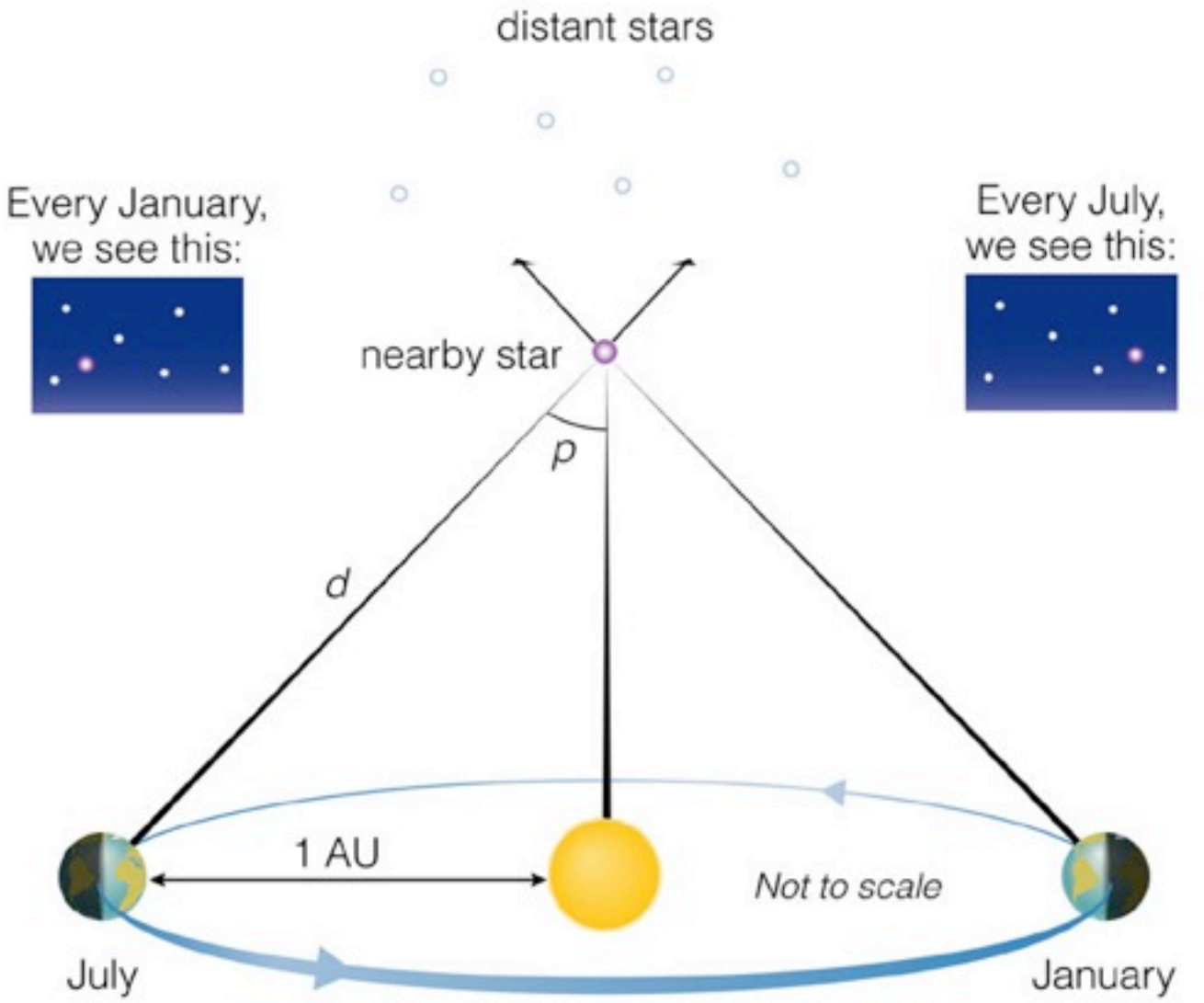
The distance scale ladder



Step 1

measure size of AU in km



Step 2

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

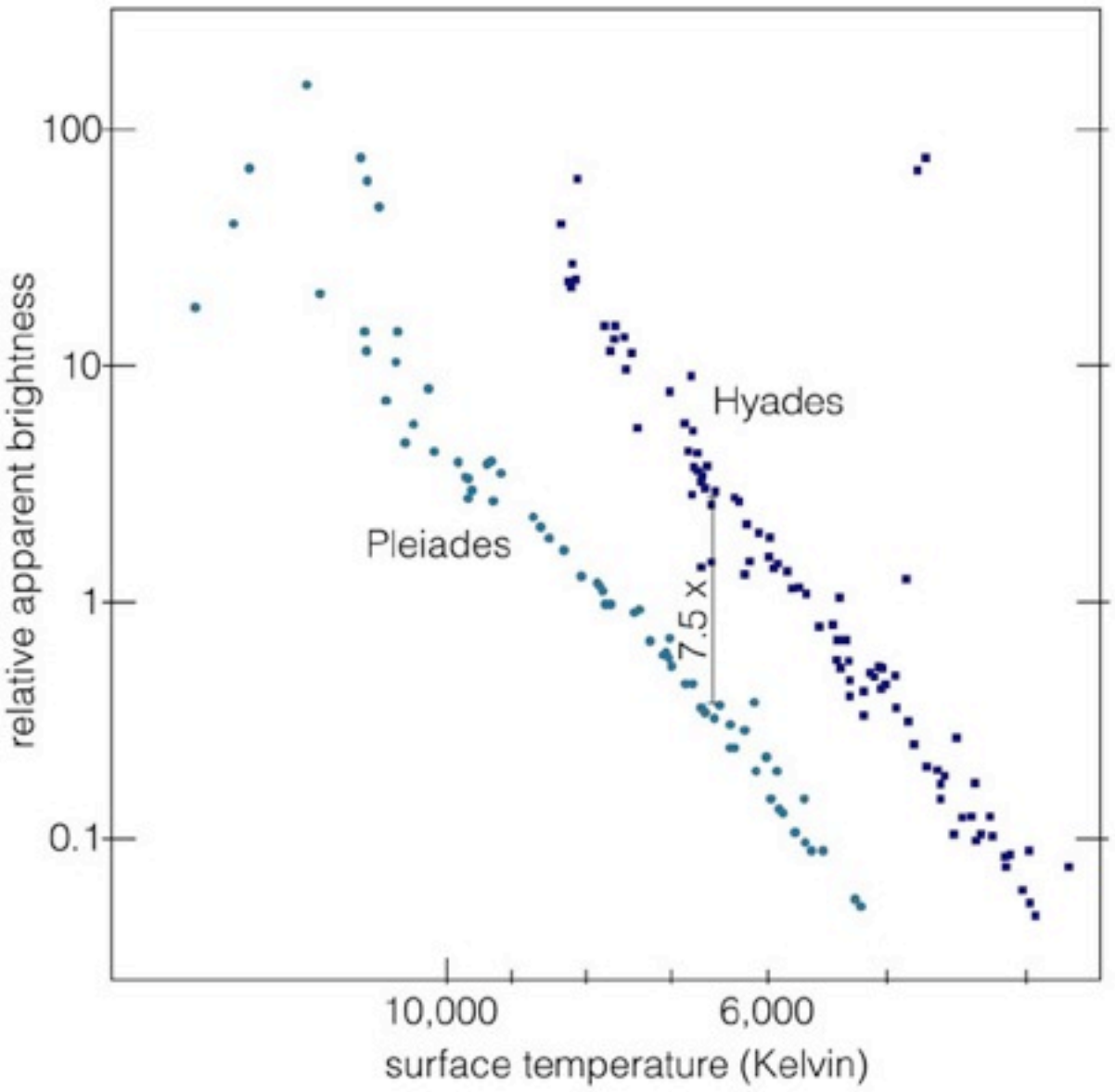
The relationship between apparent brightness and luminosity depends on distance:

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

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

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

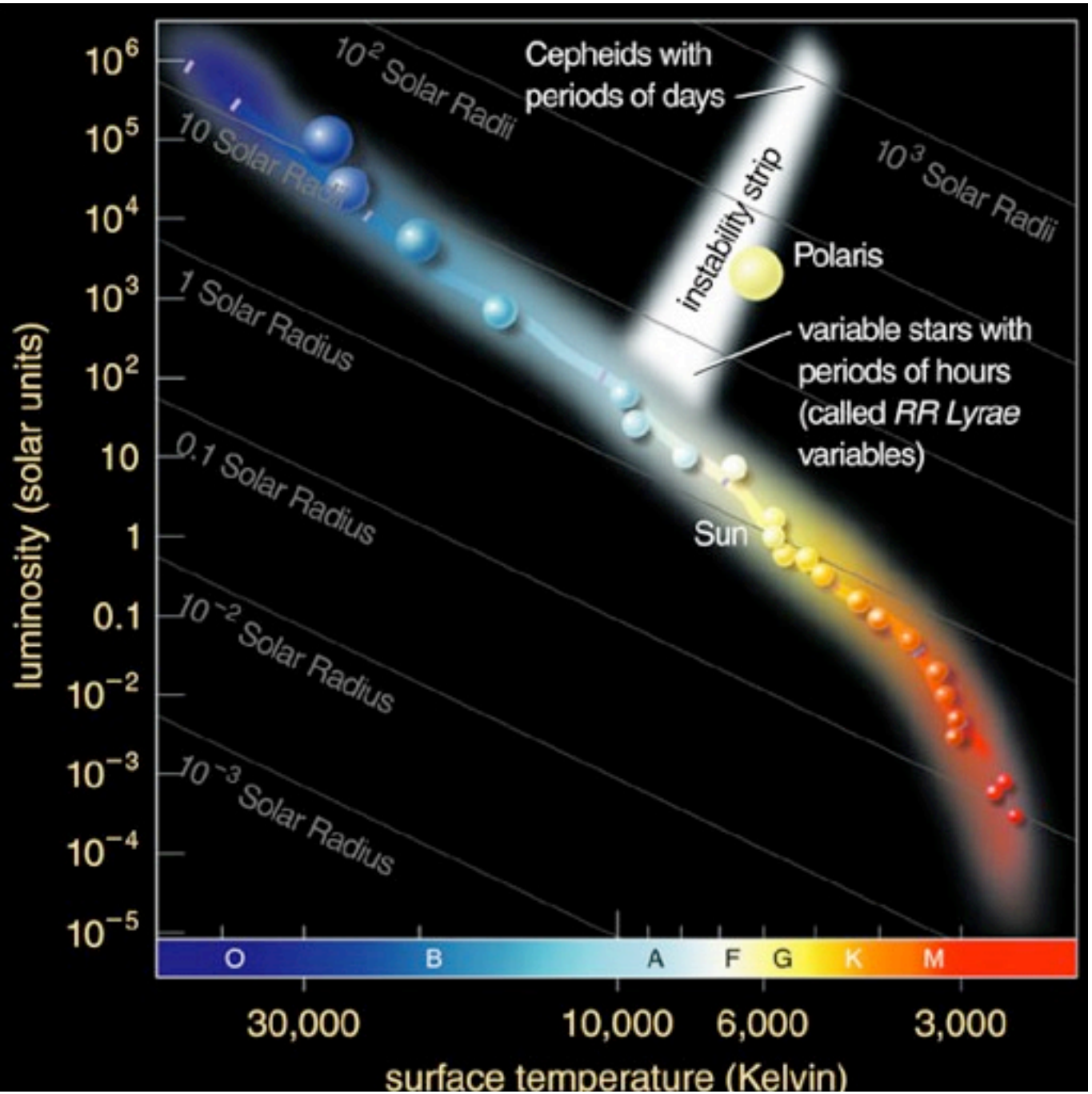
A ***standard candle*** is an object whose luminosity we can determine without measuring its distance.



Step 3

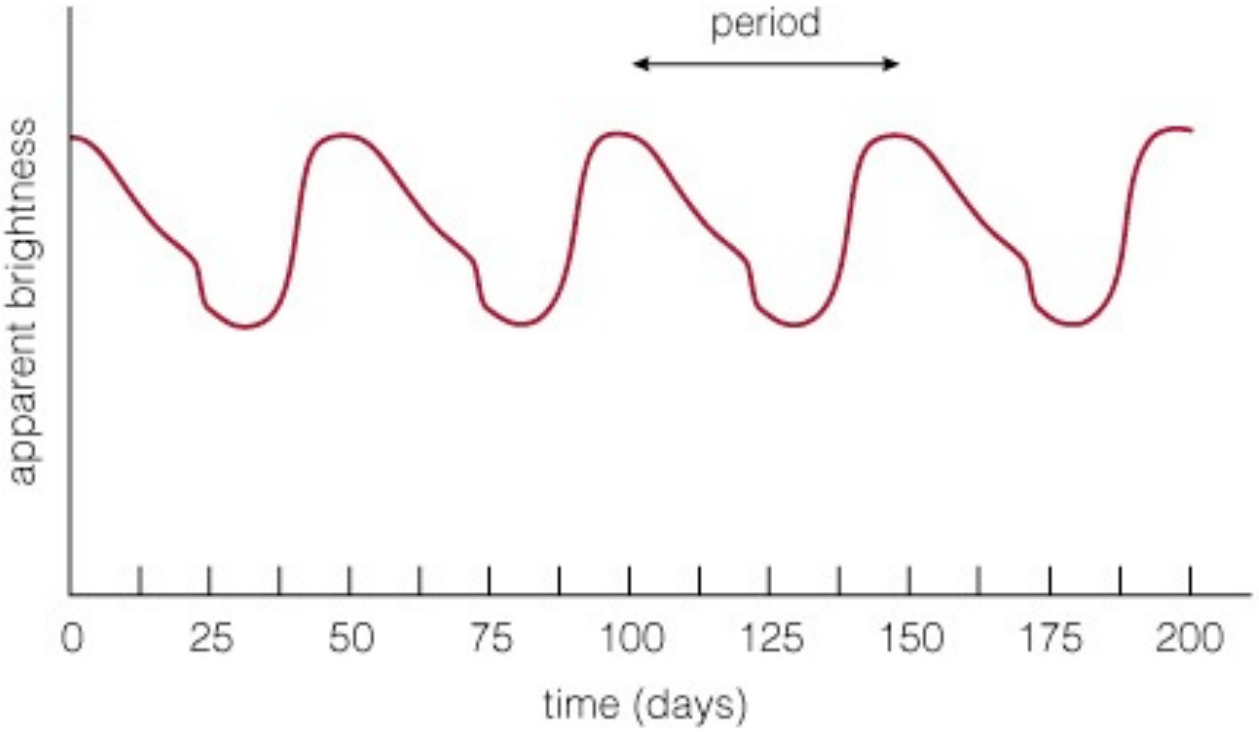
Apparent brightness of star cluster's main sequence tells us its distance

In effect, the main sequence is a standard candle.



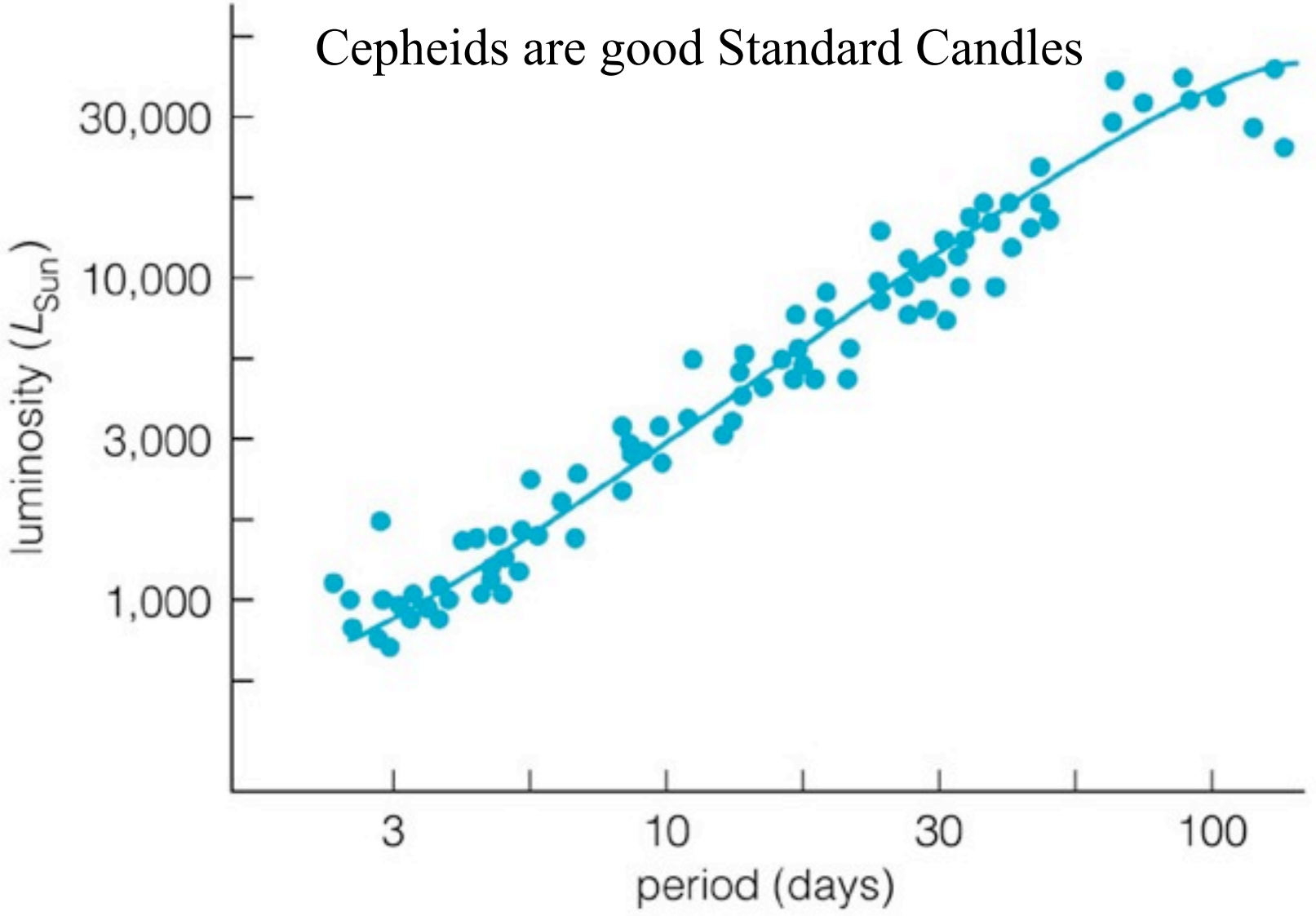
Cepheid variable stars are special examples of standard candles. They are very luminous, so can be seen from far away.

Cepheid Variable Stars



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

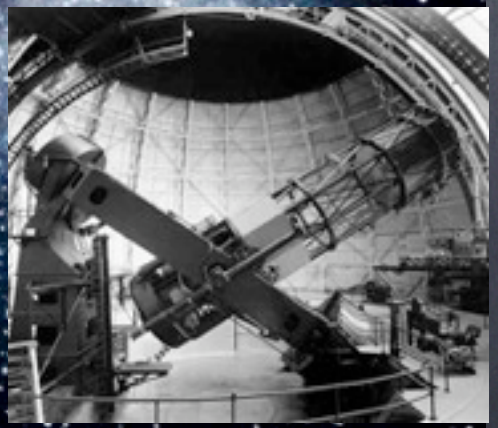
Cepheids are good Standard Candles



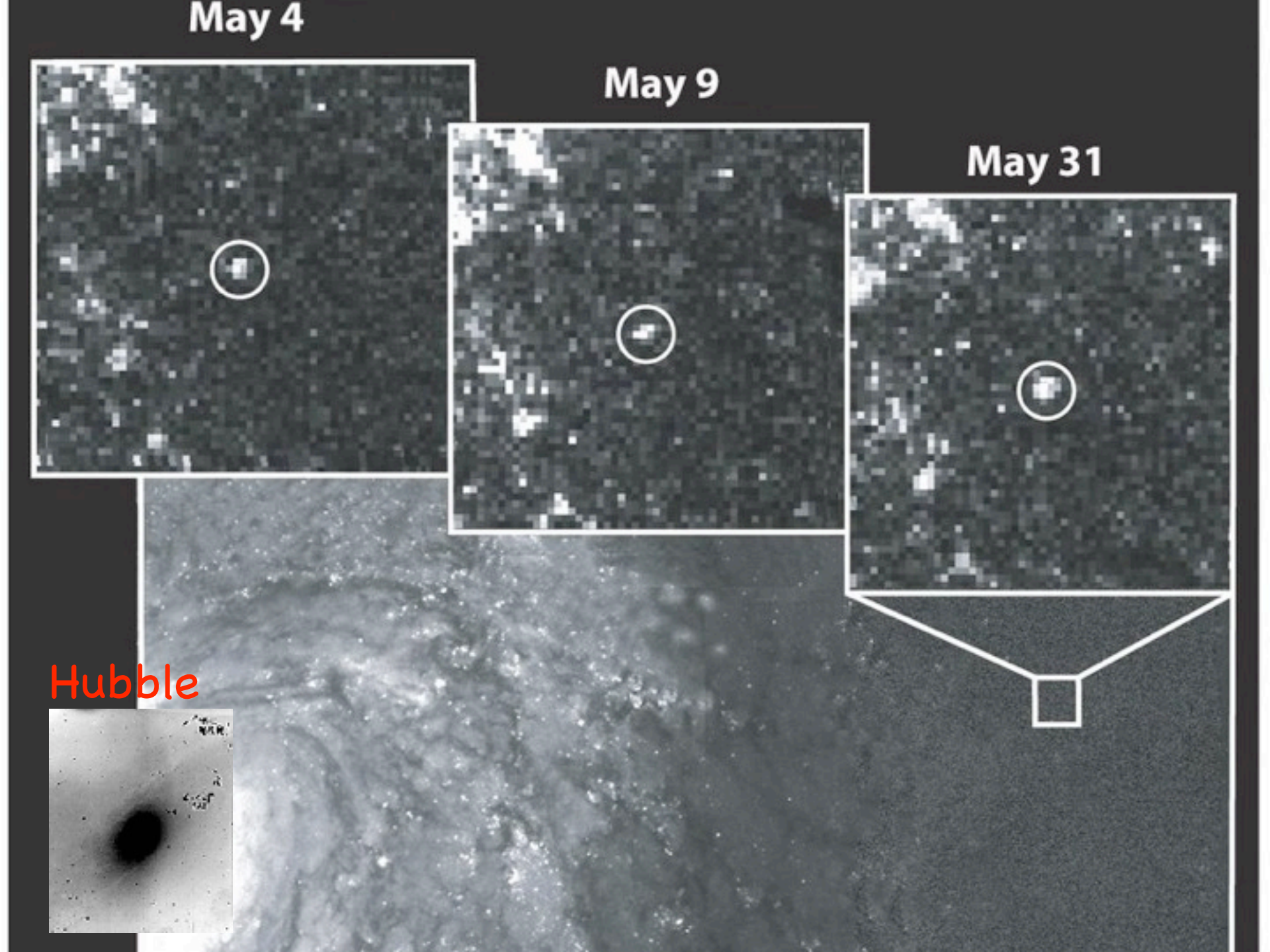
Cepheid variable stars with longer periods have greater luminosities: measuring the period tells us the luminosity!

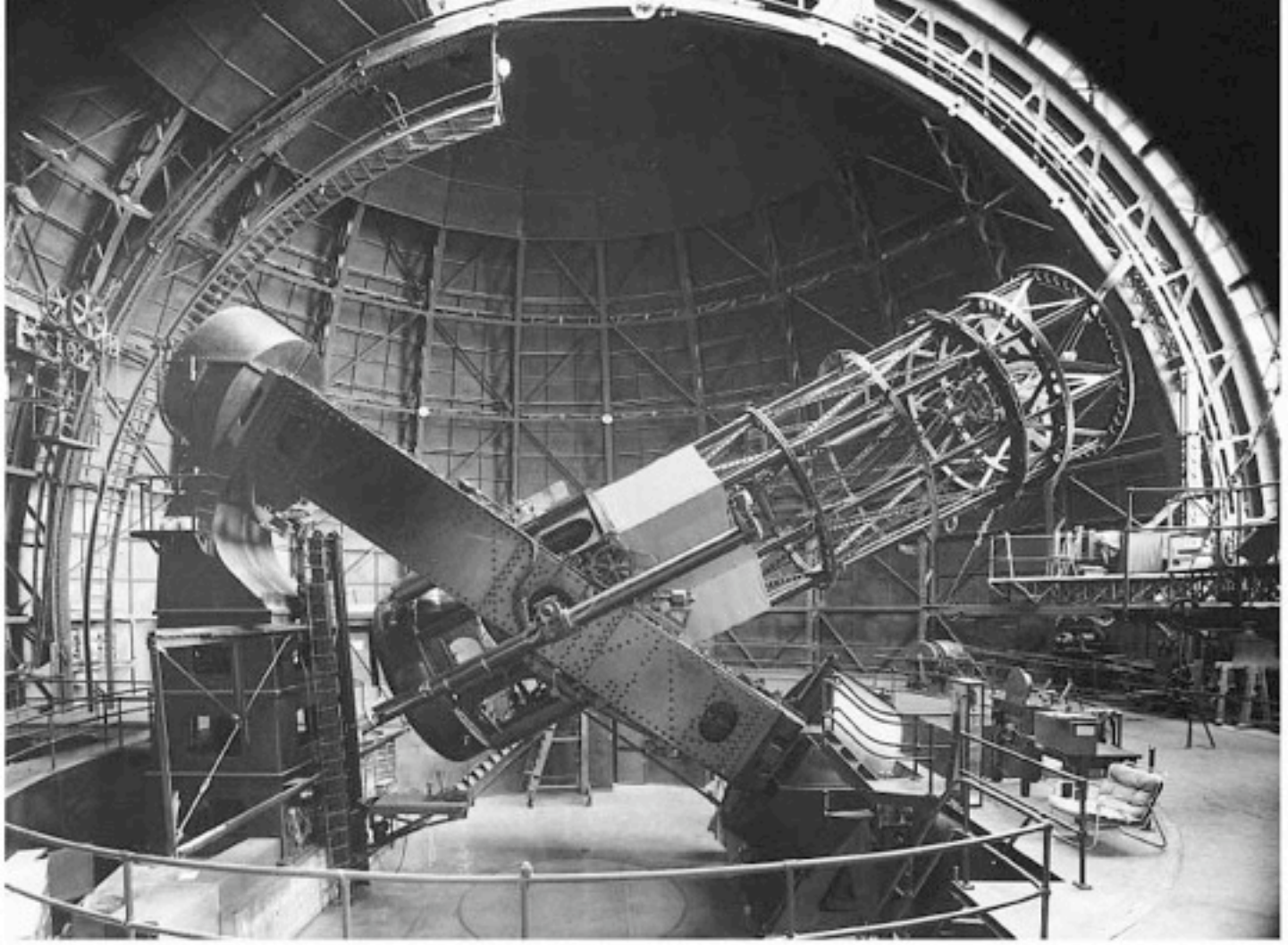
M31 Andromeda

Hubble



2.5m 1917

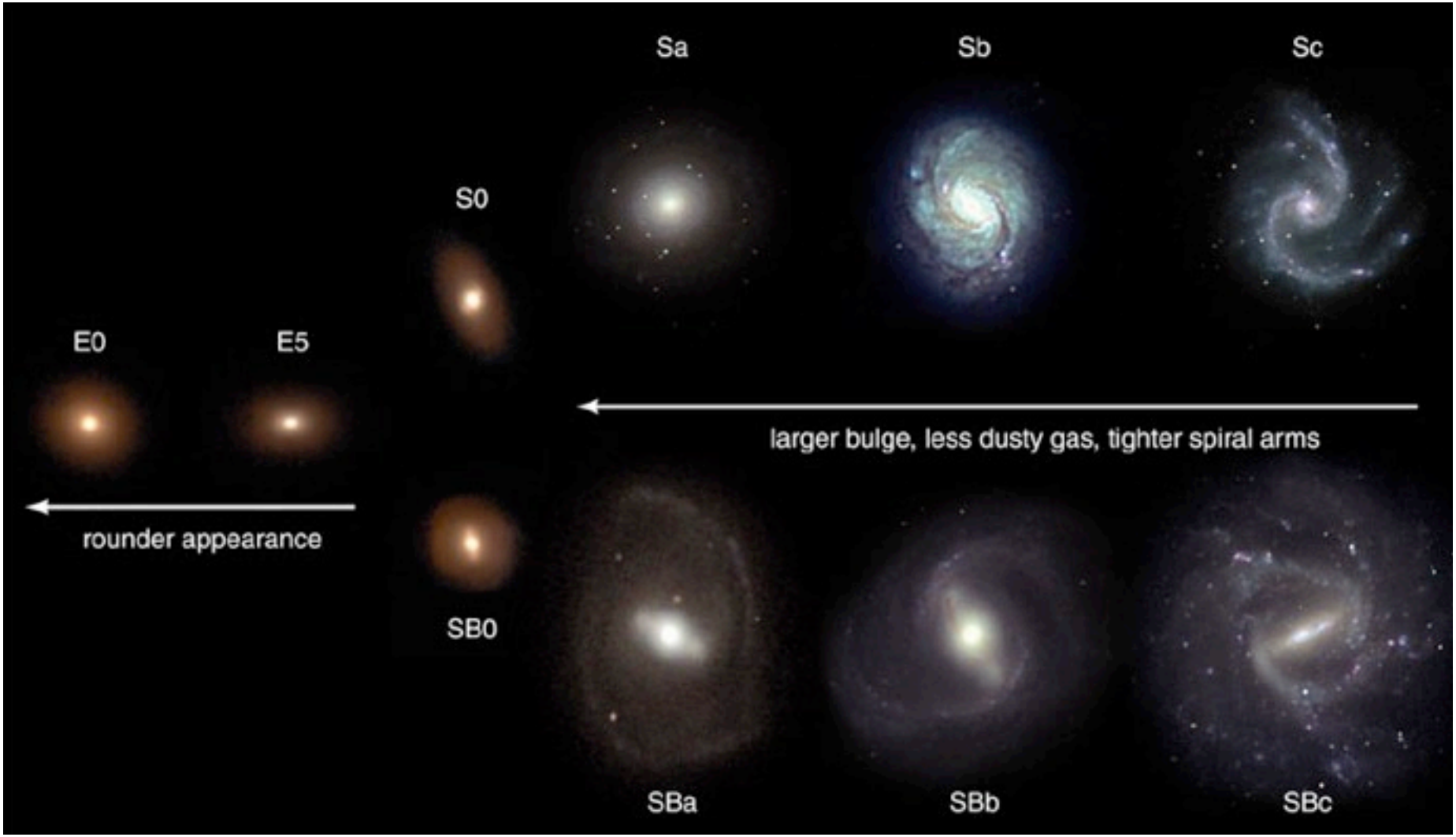

May 4
May 9
May 31
Hubble



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.



Spheroid Dominates

Population II

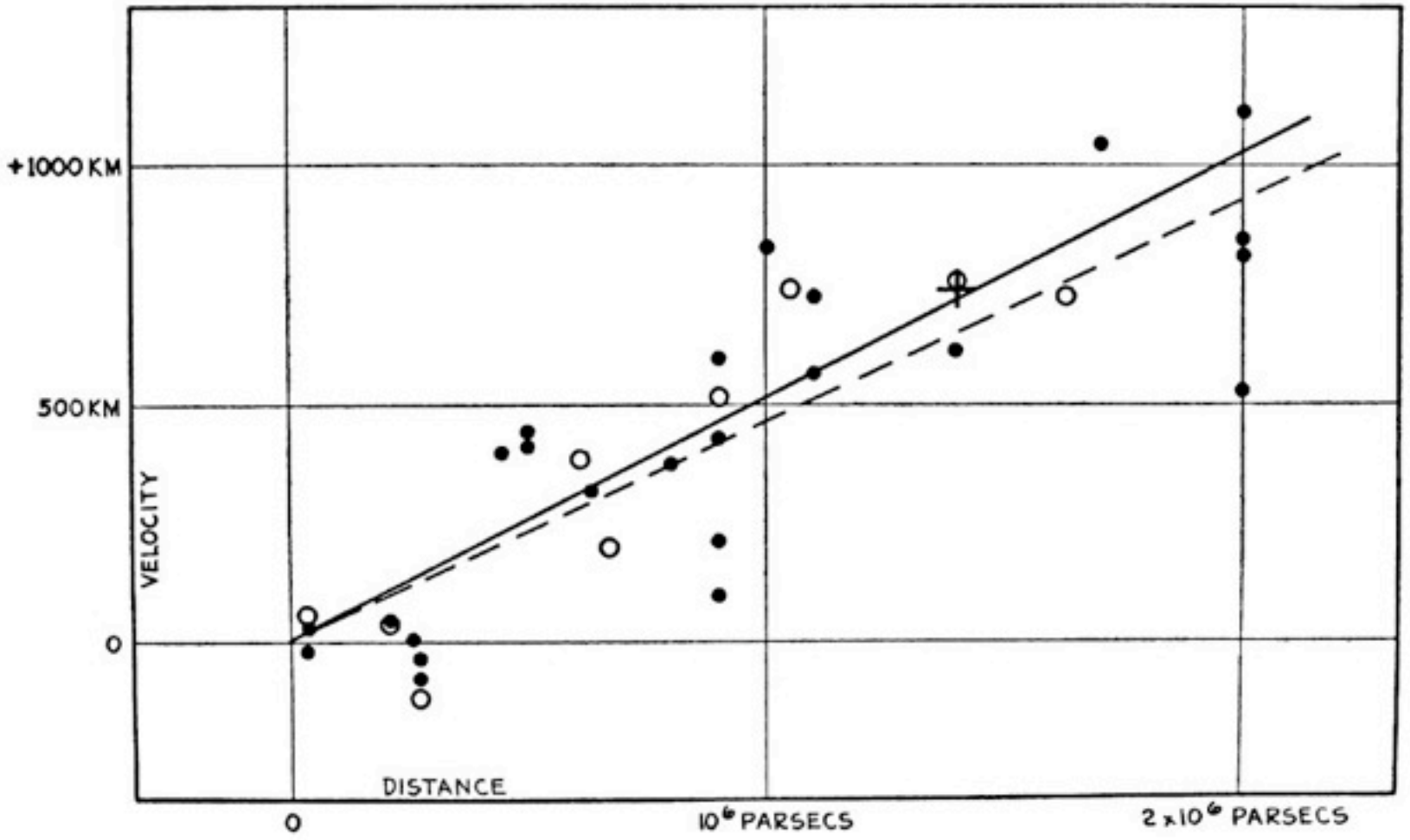
Hubble's galaxy classes

"tuning fork"

Disk Dominates

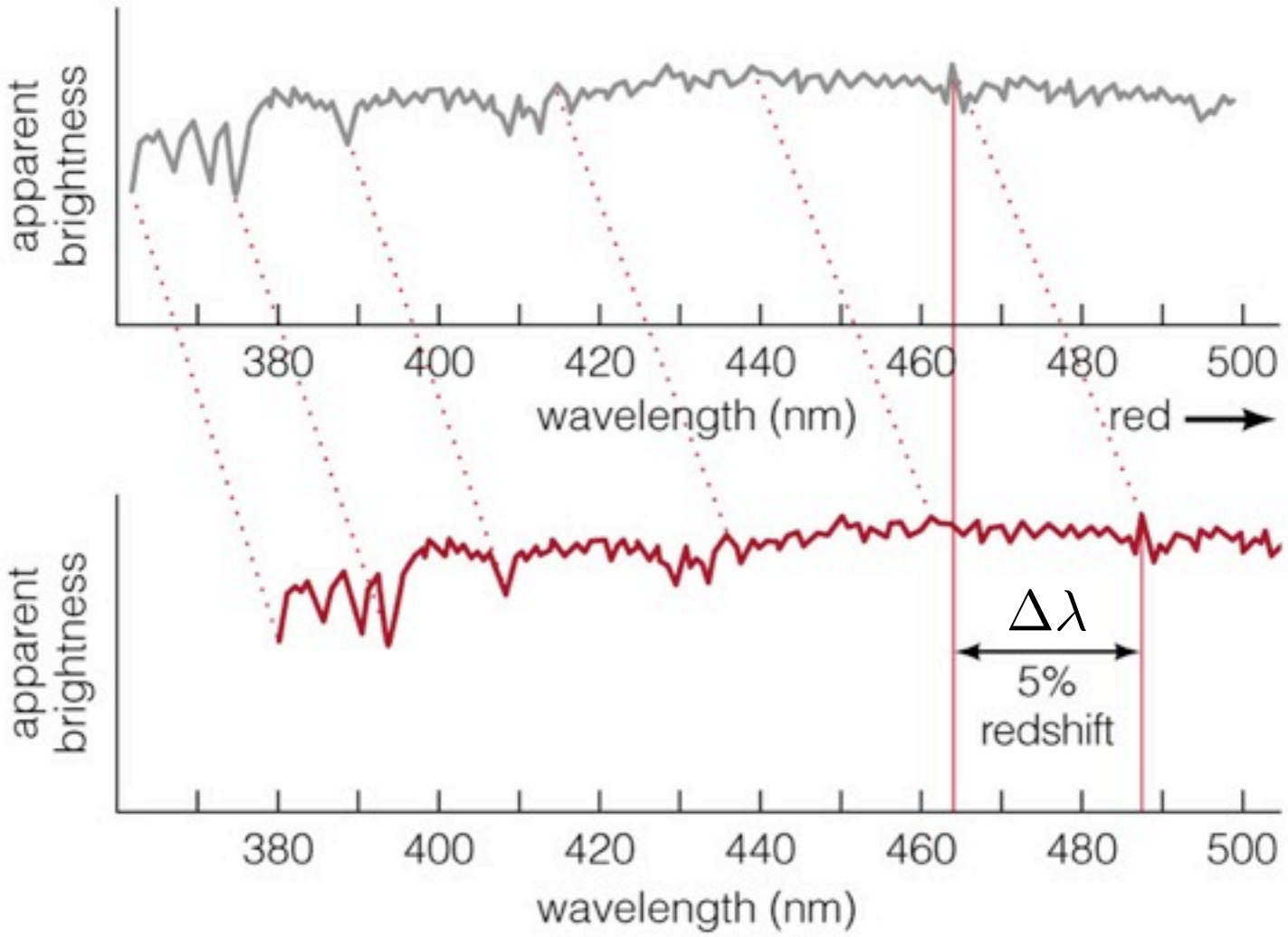
Population I

Hubble's law



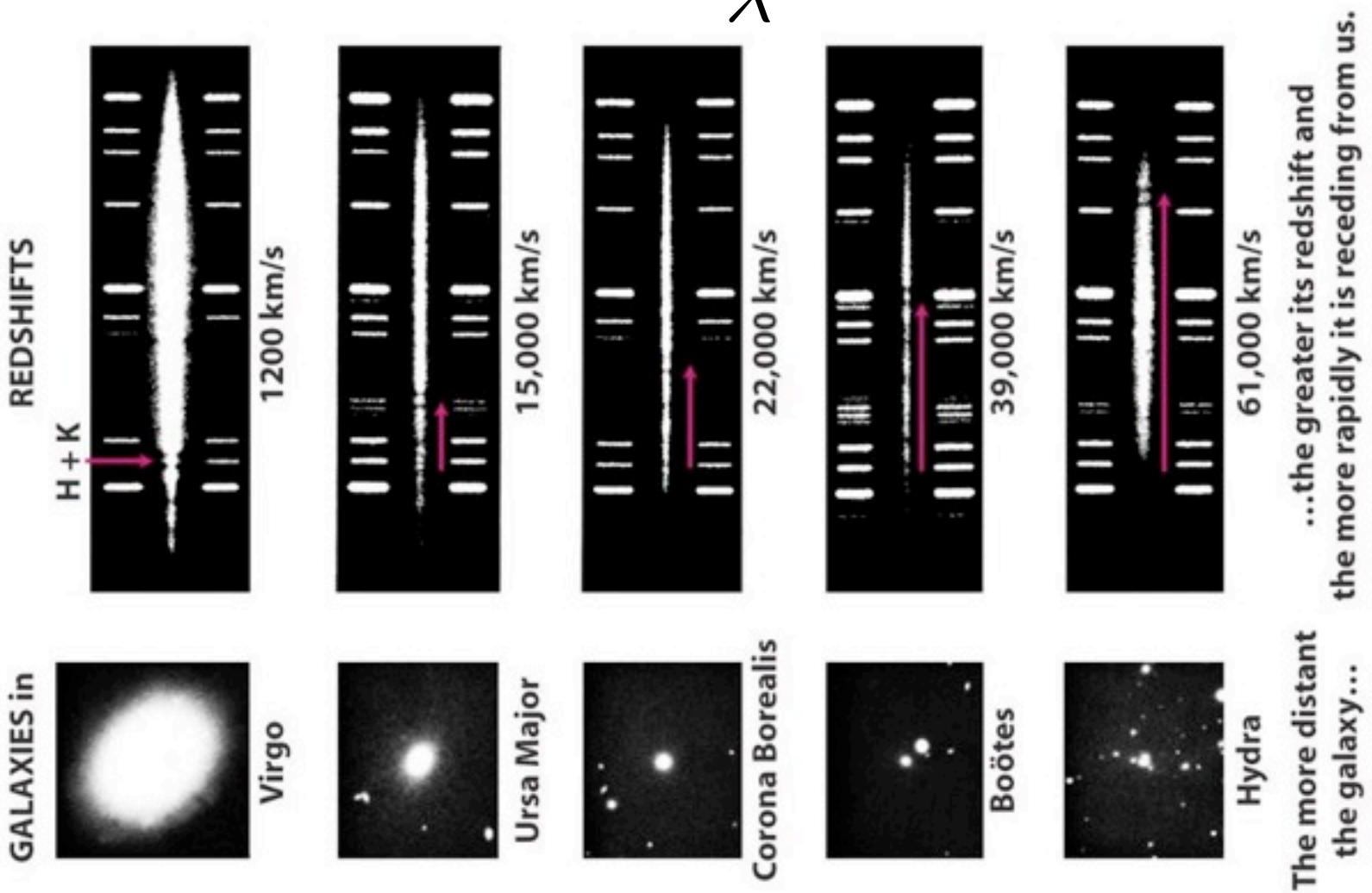
redshift

distance

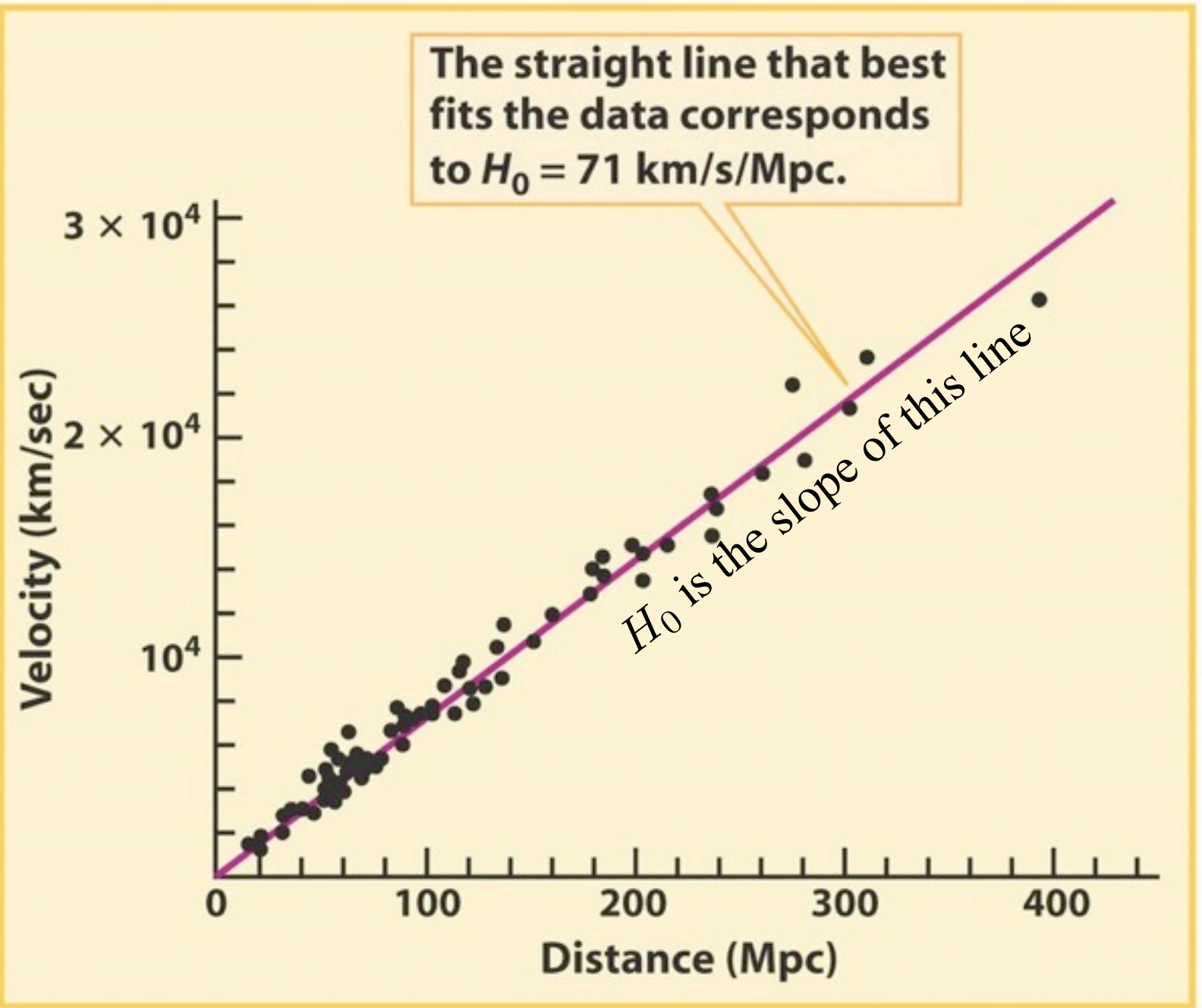


Hubble knew from Slipher's work that the spectral features of virtually all galaxies are ***redshifted*** ⇒ they're all moving away from us.

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



Hubble's law: $V = H_0 d$



Each point represents one galaxy

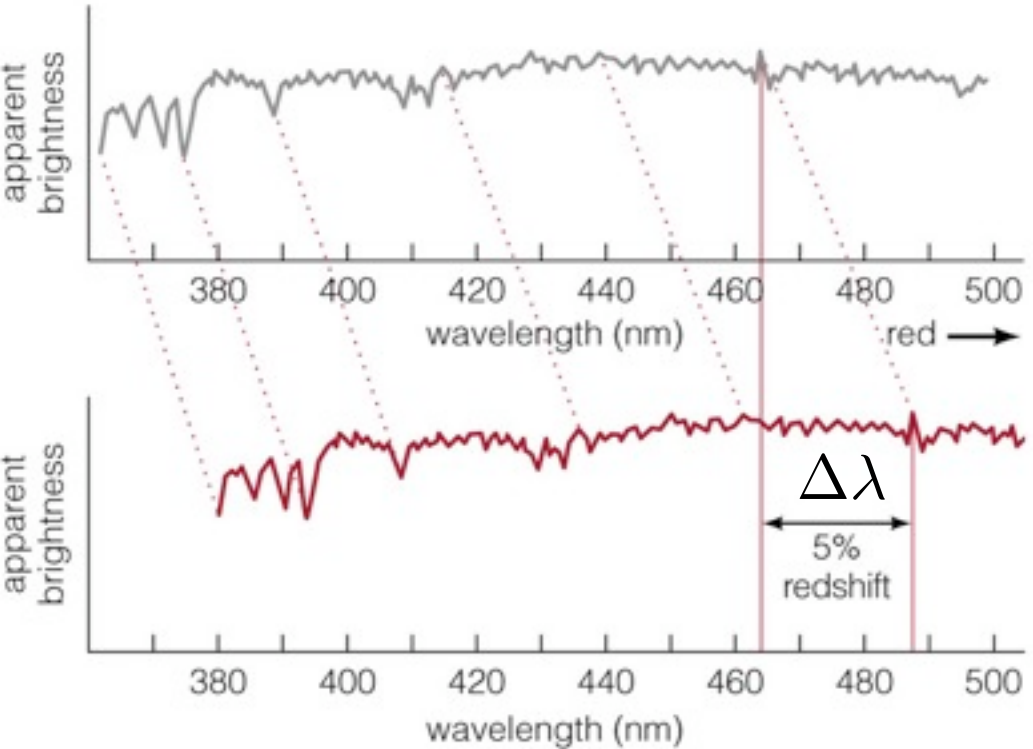
Hubble's law: $V = H_0 d$

distance

apparent recession velocity from Doppler effect

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

Hubble's constant H_0

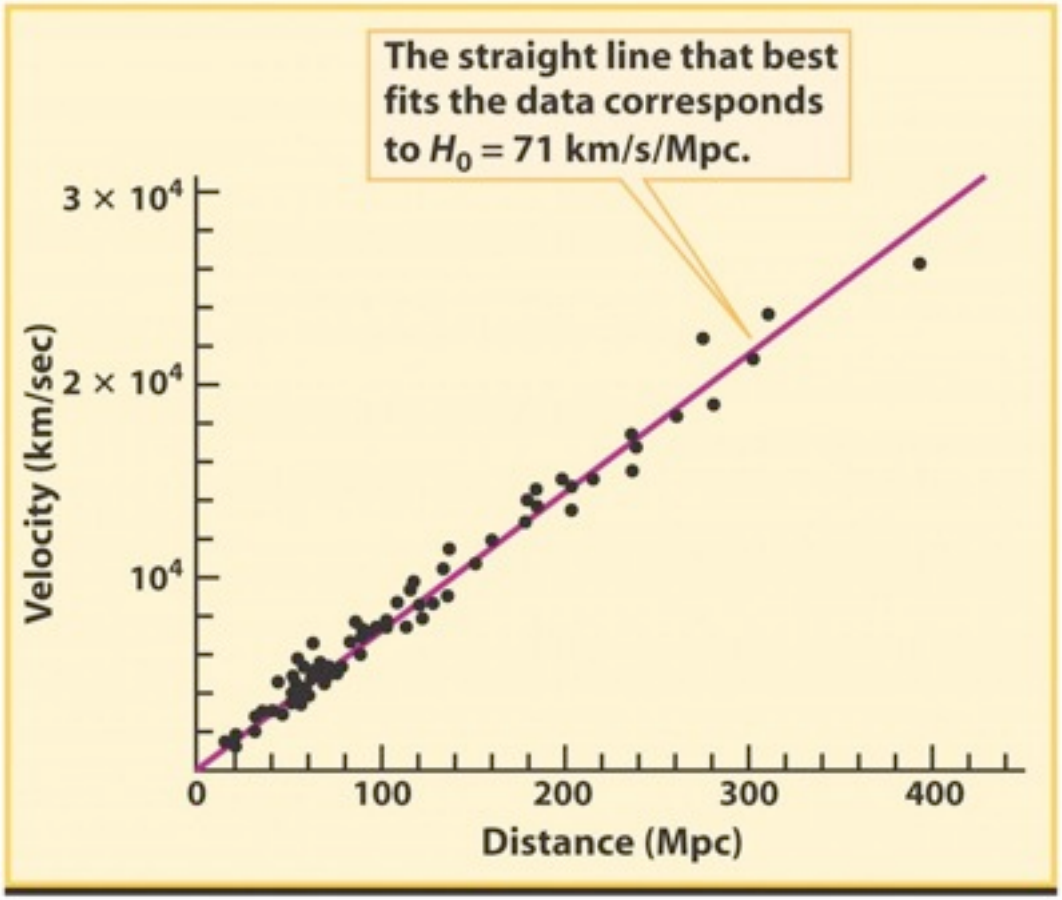


$$\Delta\lambda = \lambda_{obs} - \lambda_{em}$$

What does it mean?

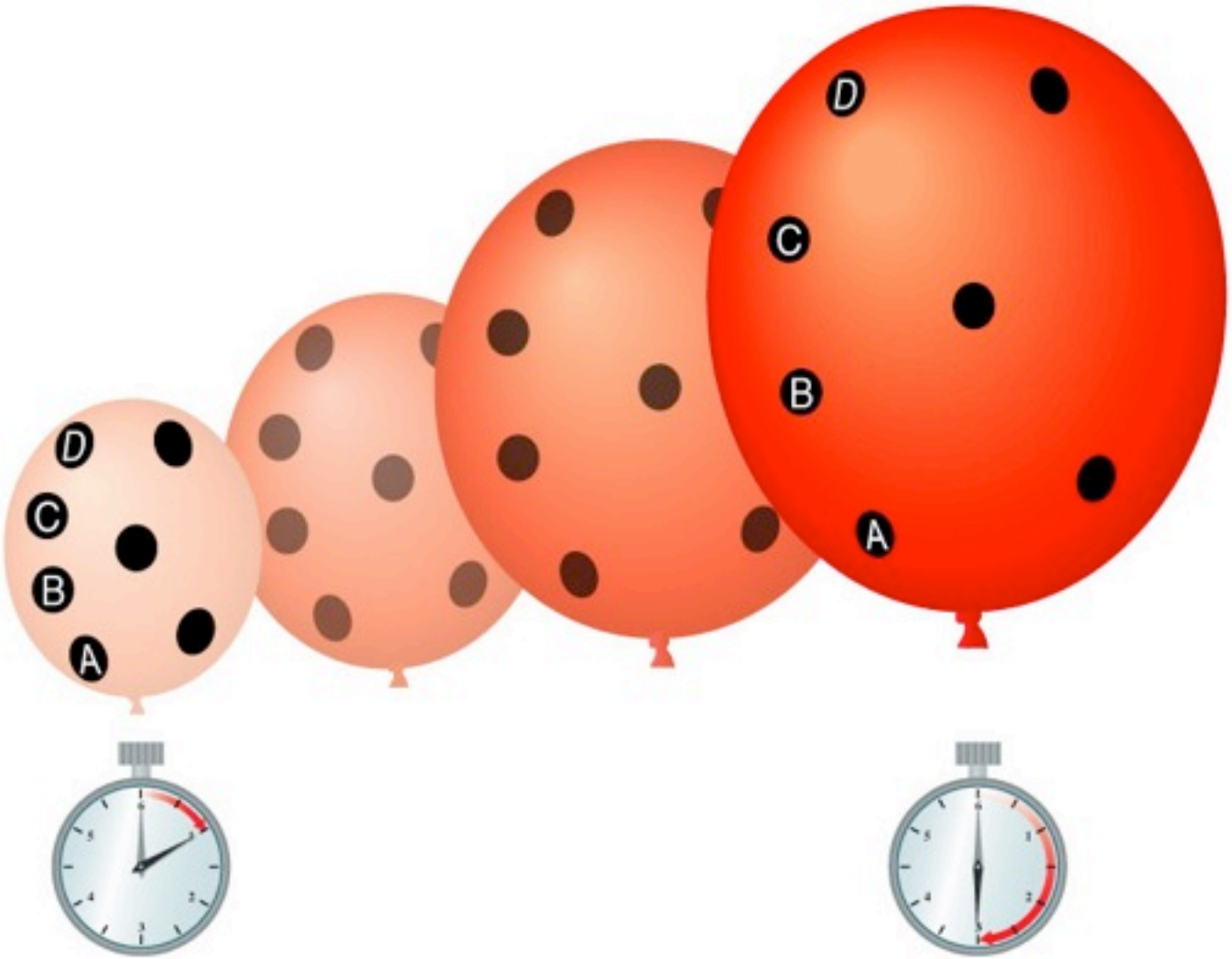
- The universe is expanding
  - galaxies are receding form one another
  - it is *not* like an explosion
  - the space between galaxies is getting stretched
- The expansion has no “center”
- The age of the universe is finite

Expansion age of the universe



size $\longrightarrow$ zero in finite past: age ~ $\dfrac{1}{H_0}$

E2-63



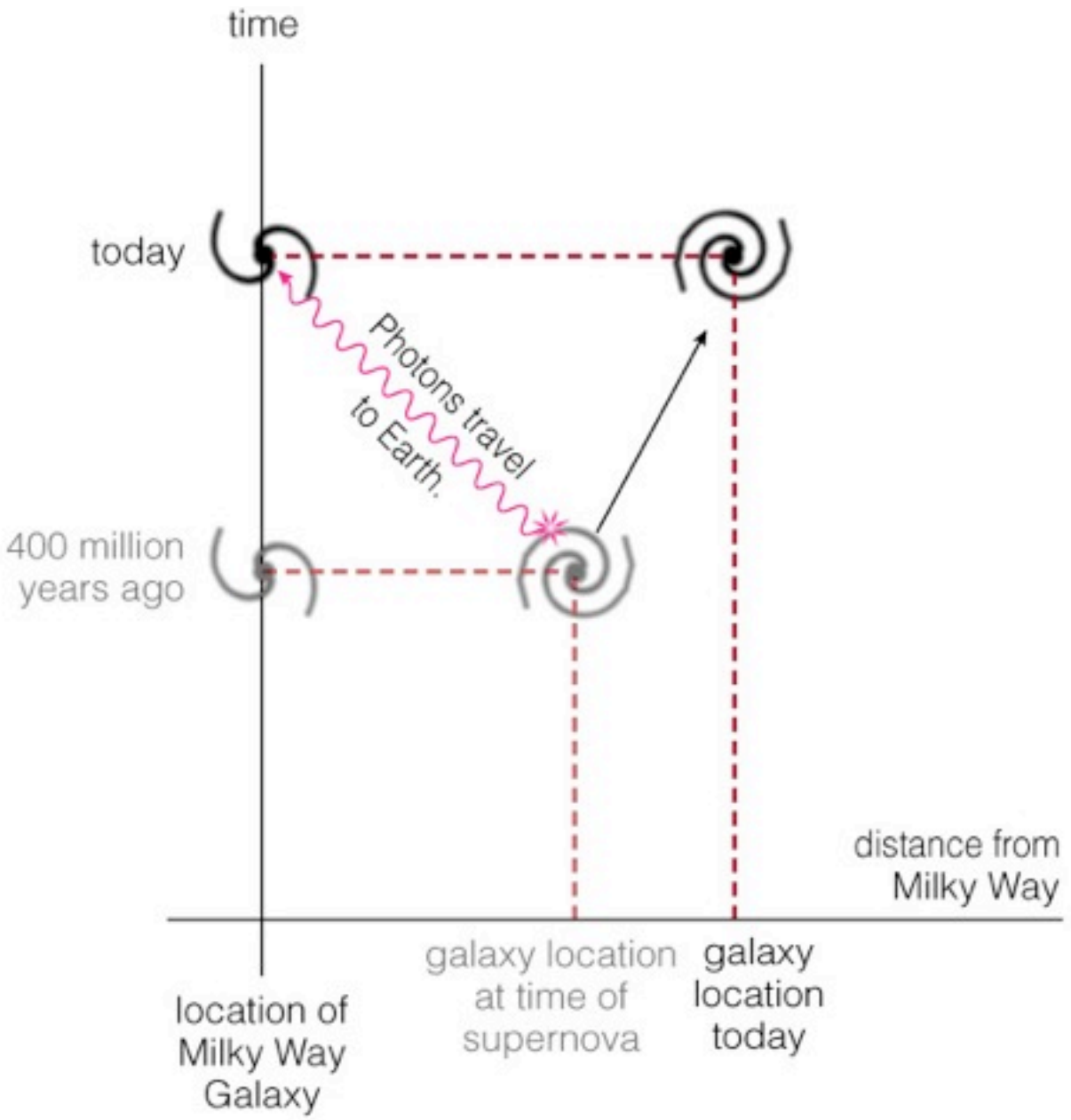
One example of something that expands but has no center or edge is the surface of a balloon.
The “center” is the beginning of time - the “4th dimension”

Cosmological Principle

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

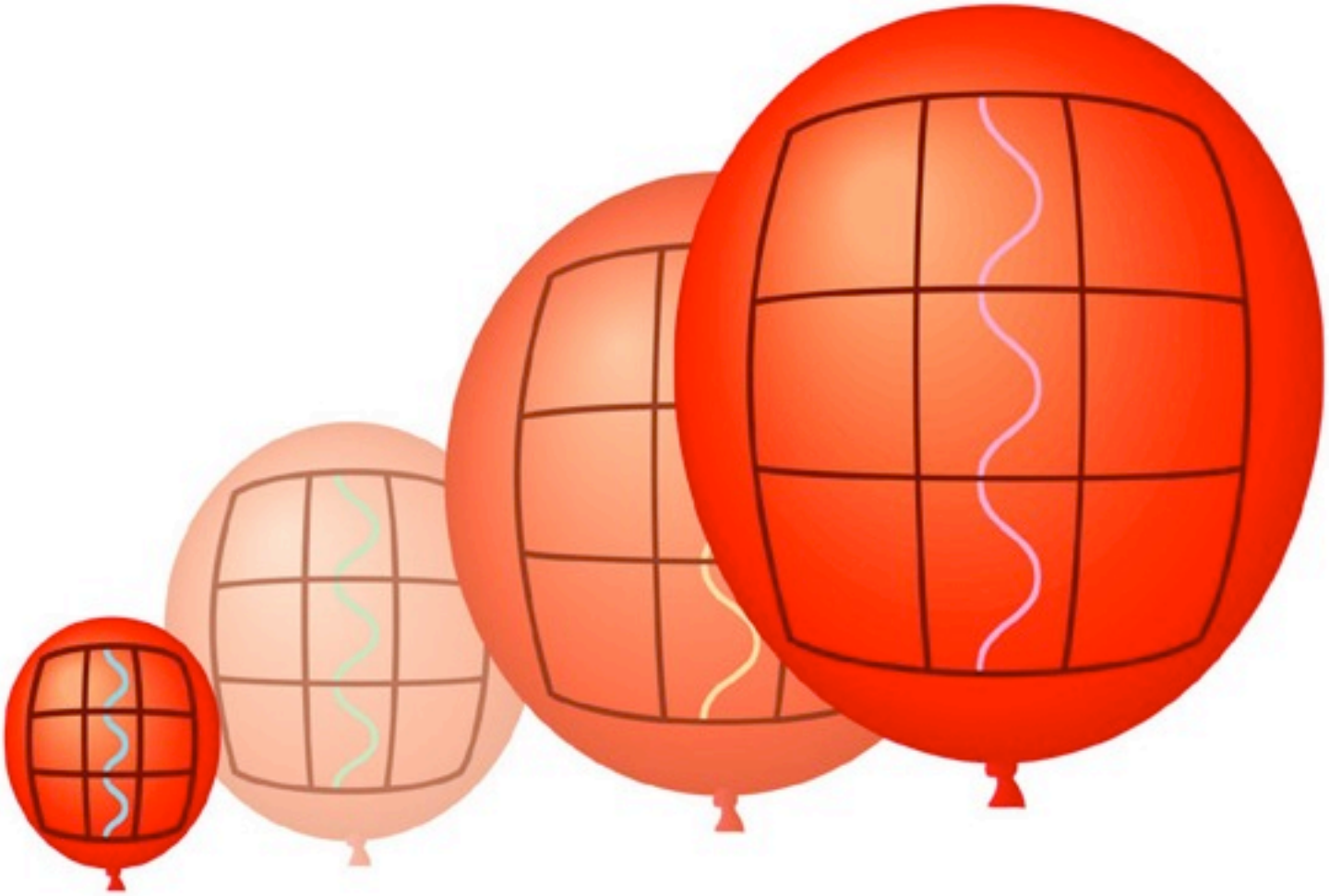
Homogeneous and *Isotropic*

- 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



Distances between faraway galaxies change while light travels.

Looking further away is equivalent to looking back in time.



Expansion stretches photon wavelengths causing the ***cosmological redshift***: stretching of space, *not* explosion.

$$V = H_0 d$$

Modern Cosmology

- We live in an expanding universe
  - The expansion of space causes the wavelengths of photons to stretch
  - more distant objects have larger redshift (Hubble's Law: $V = H_0 d$)
- The universe may be spatially infinite
- The universe has a finite age
  - about 13 or 14 Billion years