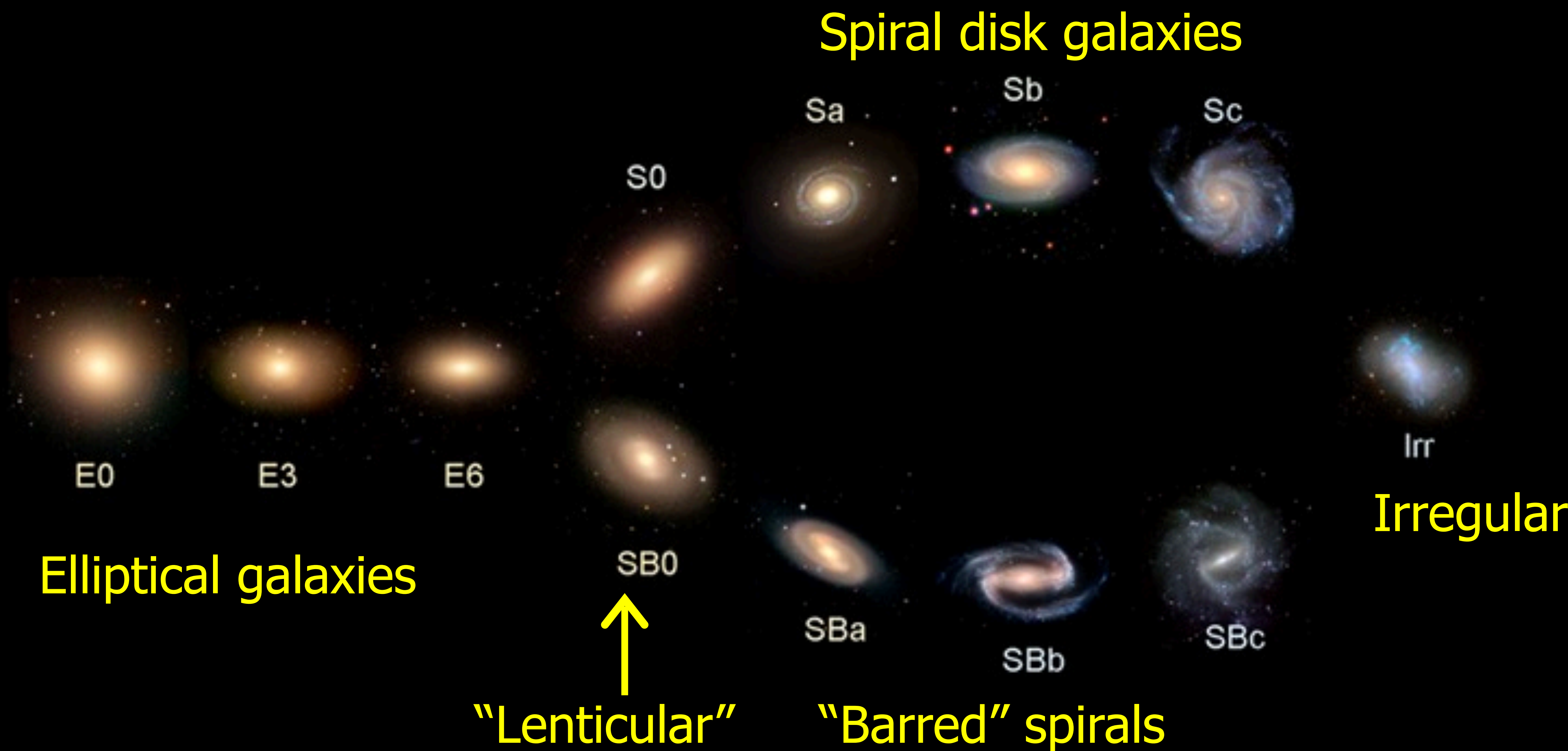
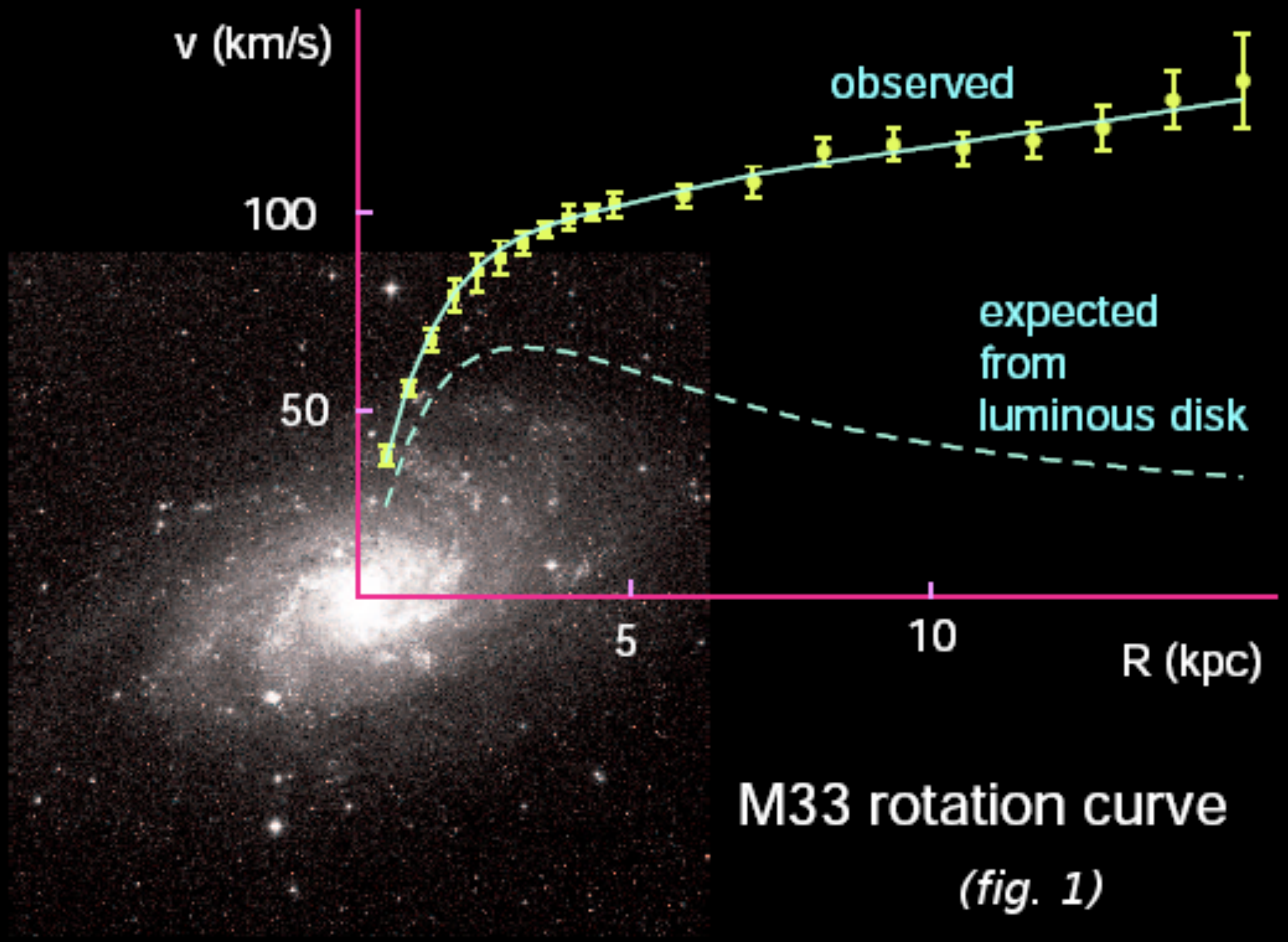
Galaxies and Modern Cosmology

Chapter 20

Recap: Galaxies Classes

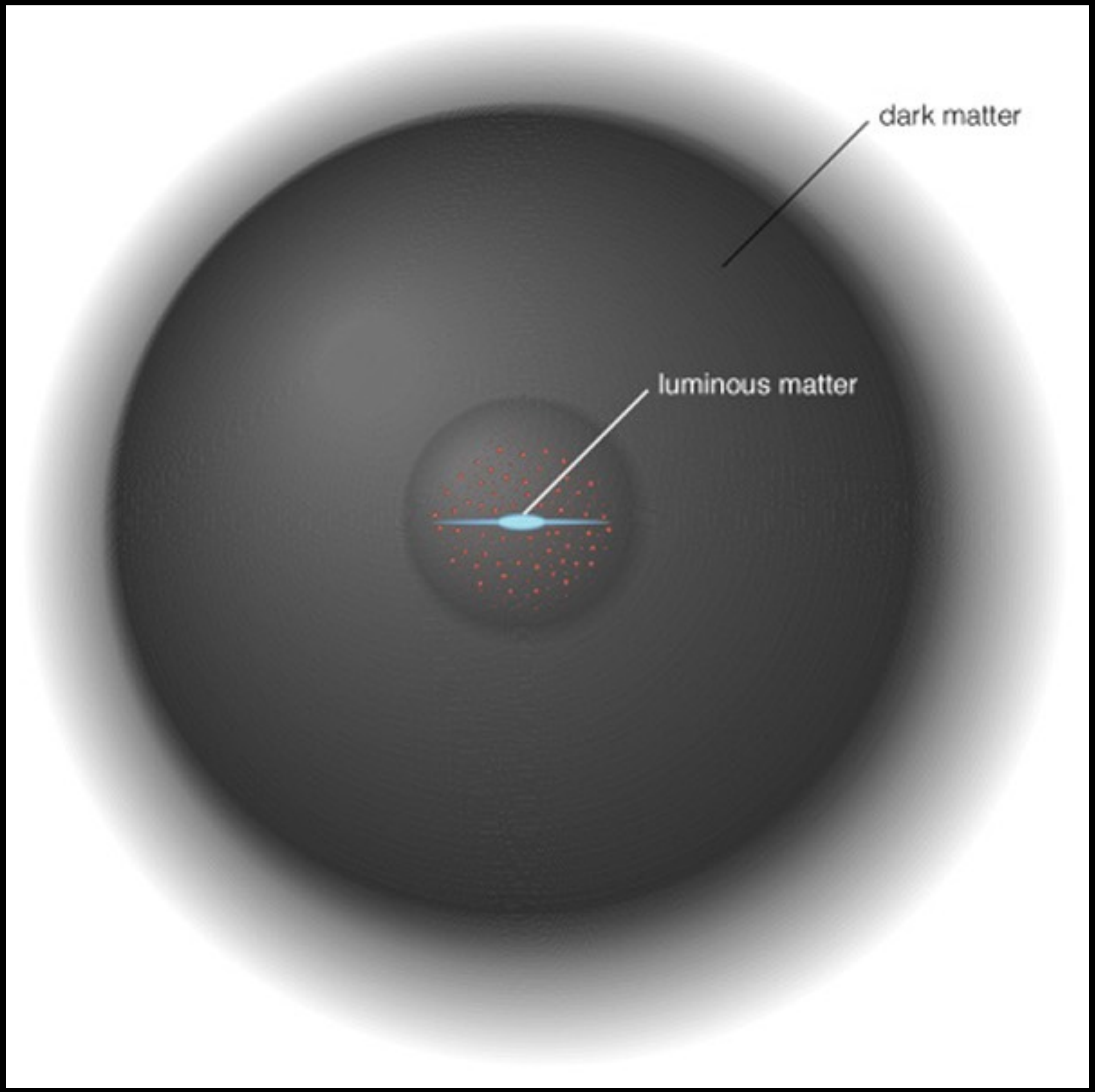


Recap: galaxy “rotation curves” and Dark Matter



M33 rotation curve

(fig. 1)



Rotation curves are usually “flat”.

All galaxies appear to have large amounts of mass well beyond the visible extent of the stars and gas — this is the Dark Matter!

Masses of galaxy clusters

- We have 3 different ways to measure the masses of galaxy clusters
  - The velocities of galaxies in the cluster
    - $M = v^2 r / G$
  - The temperature of the gas (thermal radiation)
    - Kinetic energy (temperature) is directly related to gravitational potential energy (mass)
  - Gravitational lensing
    - Independent method; does not rely on motion!
- All 3 methods say that galaxy clusters are dominated by dark matter
  - Dark matter in galaxy clusters has **50 times more mass** than the stars within the galaxies

Recap: what have we learned?

- **What is “Dark Matter”?**
  - Dark matter is what we call a form of matter which does not interact with light, but which has mass
  - We detect dark matter by its gravitational influence, but we do not know what it is

- **What is the evidence for Dark Matter in the Milky Way and other galaxies?**
  - Rotation velocities of galaxies are approximately constant, indicating that most of their total mass lies beyond the visible regions

- **What is the evidence for Dark Matter in galaxy clusters?**
  - Masses measured from galaxy motions, temperature of hot gas, and gravitational lensing all indicate that the vast majority of matter in clusters is dark

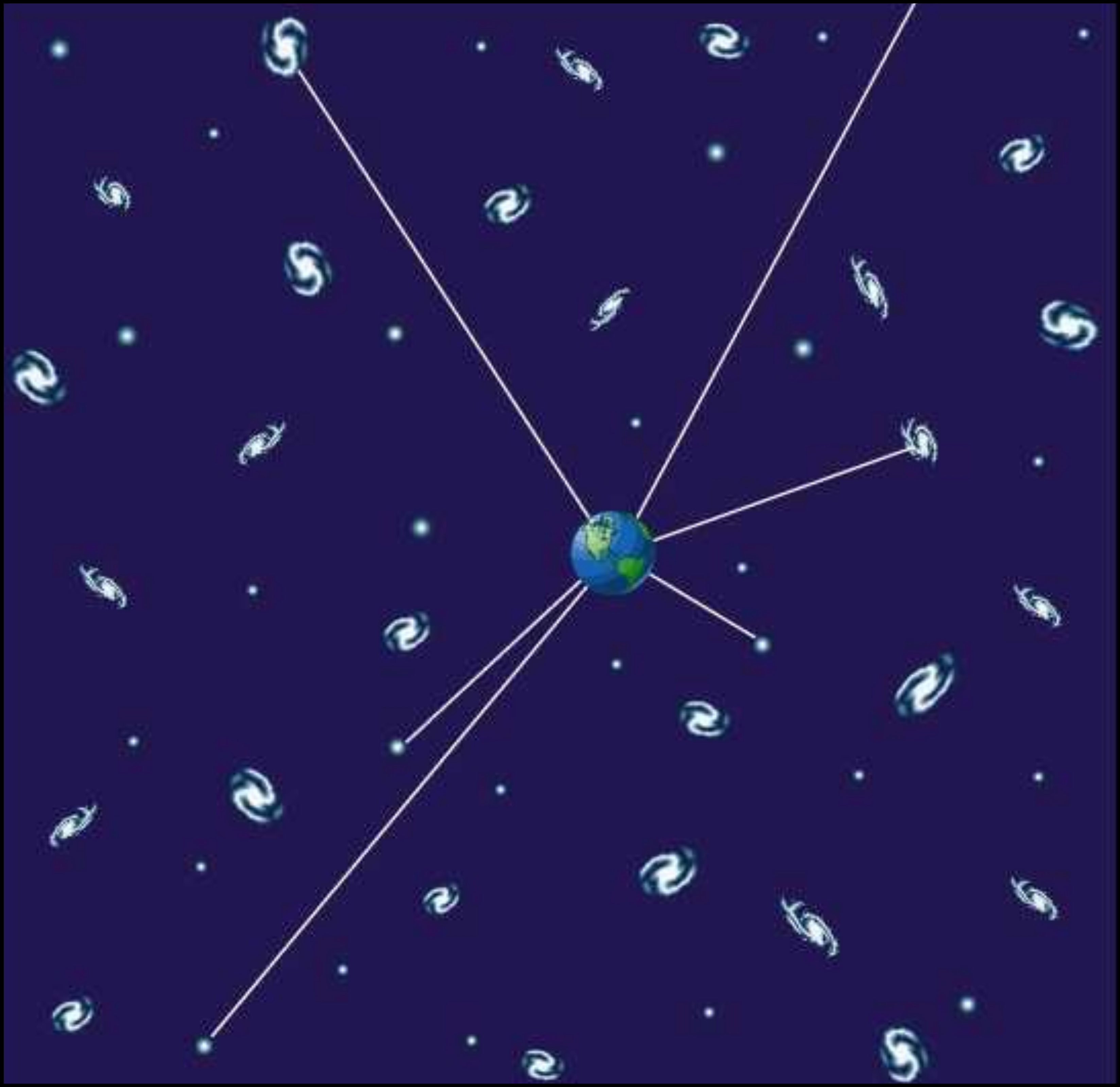
Distances to Galaxies

Chapter 20.2

Questions of the day

- How do we measure distances to galaxies?
- What is Hubble's Law? How does it tell us the age of the Universe?

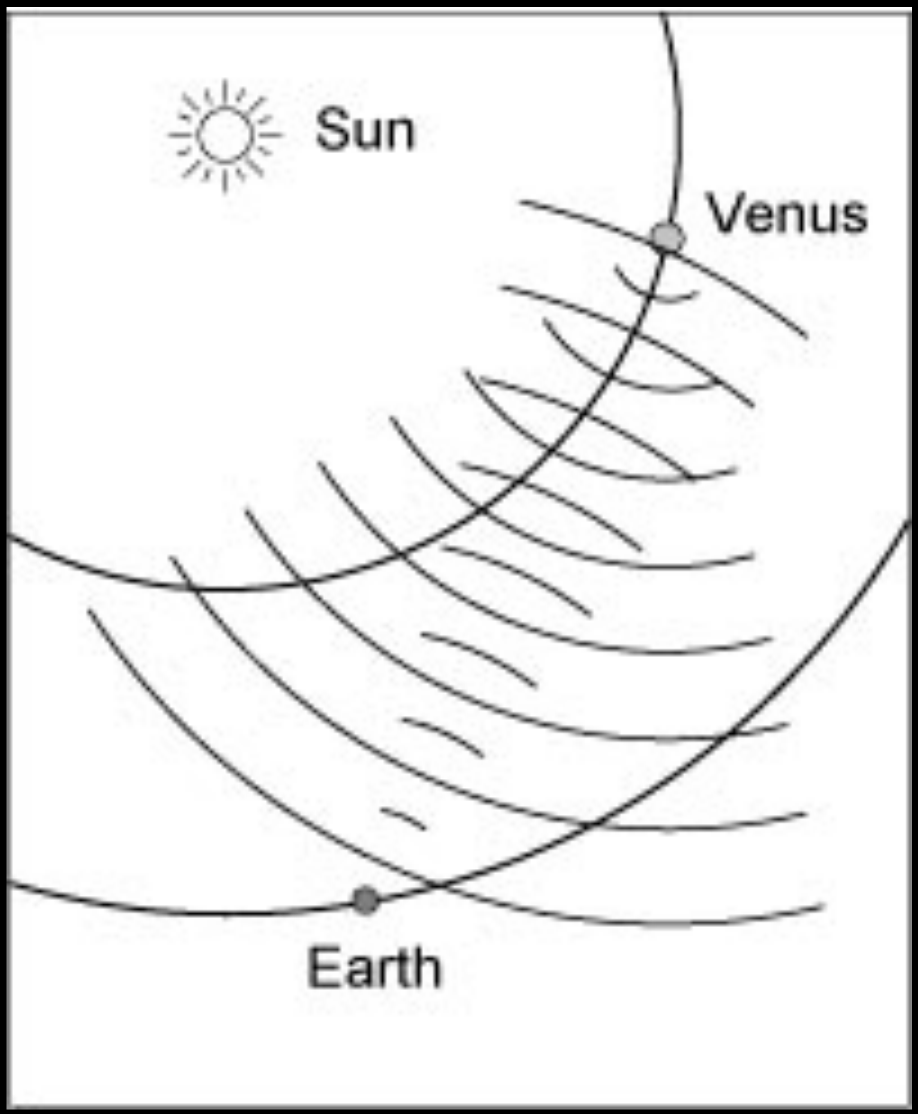
Measuring distances is **super hard!**



We need to know how luminous or how large an object is!

Solar systems distances

Step 1

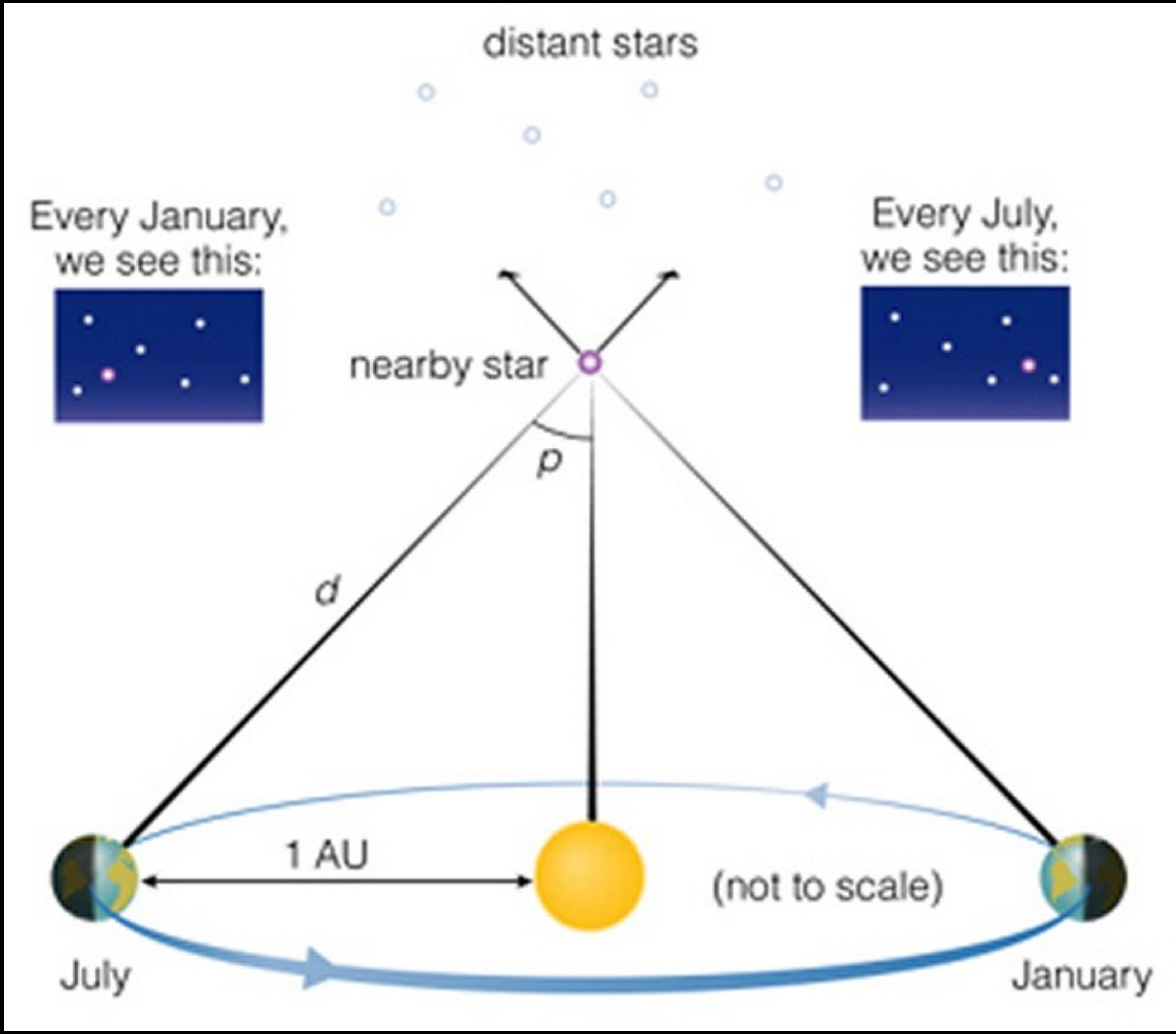


Accurate distances to the nearby planets have been determined by sending radio pulses from Earth to the planet, and timing their return several minutes later.

We know 1 AU in this way

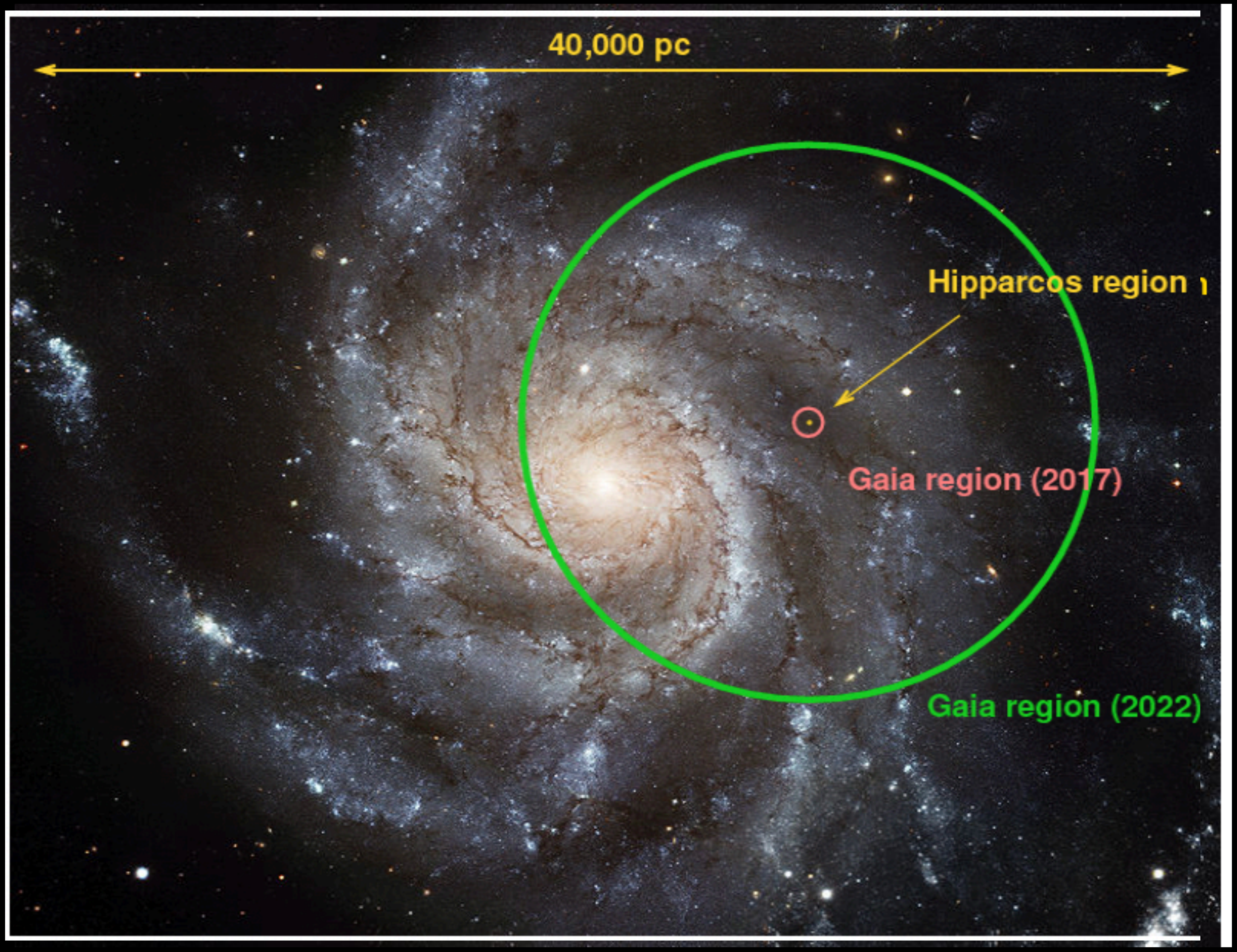
Nearby objects: parallax

Step 2

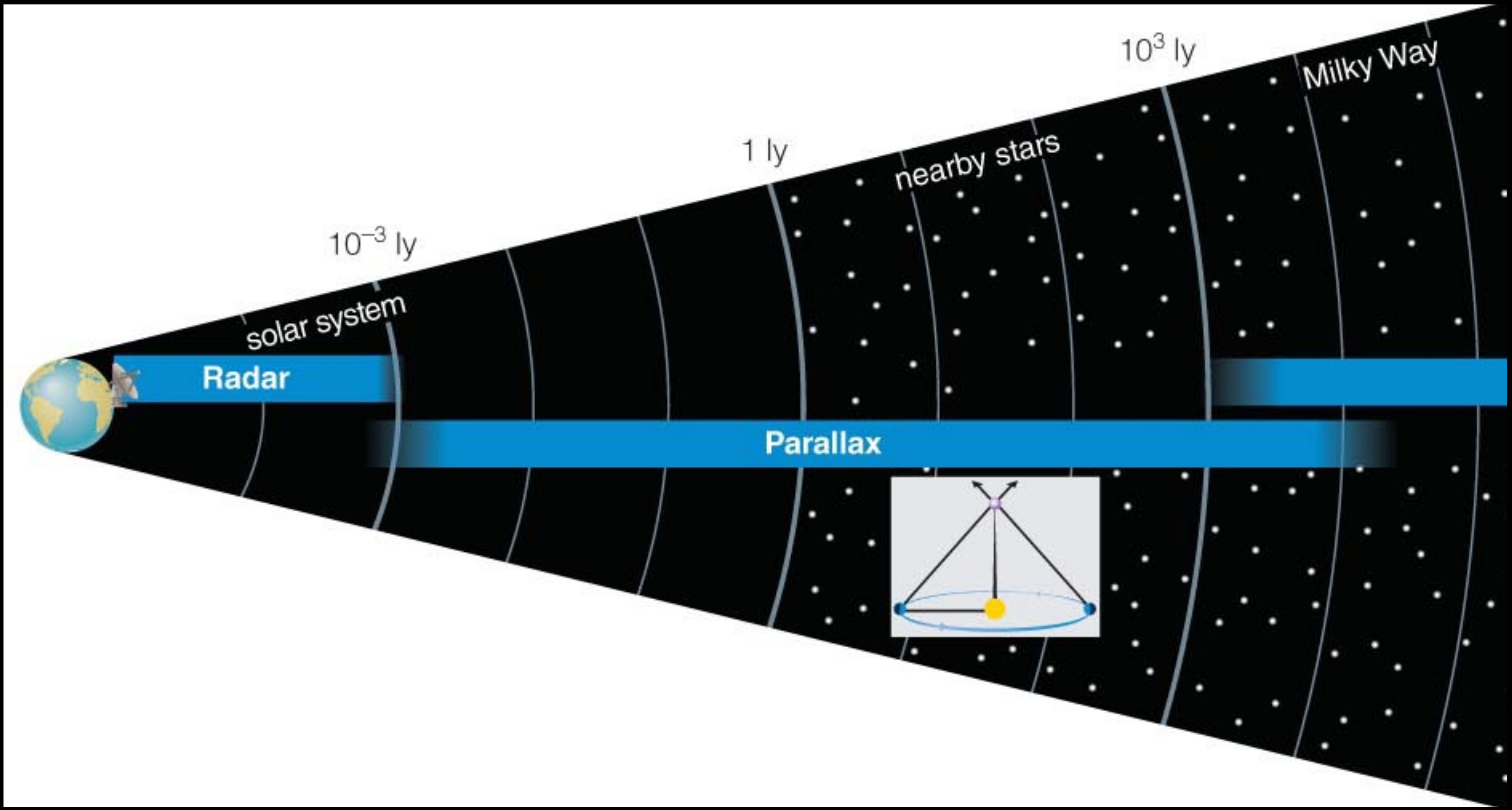


Nearby objects: parallax

Step 2



The “Distance Ladder”



How to measure distances which are too far away for parallax?

2 main distance techniques once you get too far away for parallax

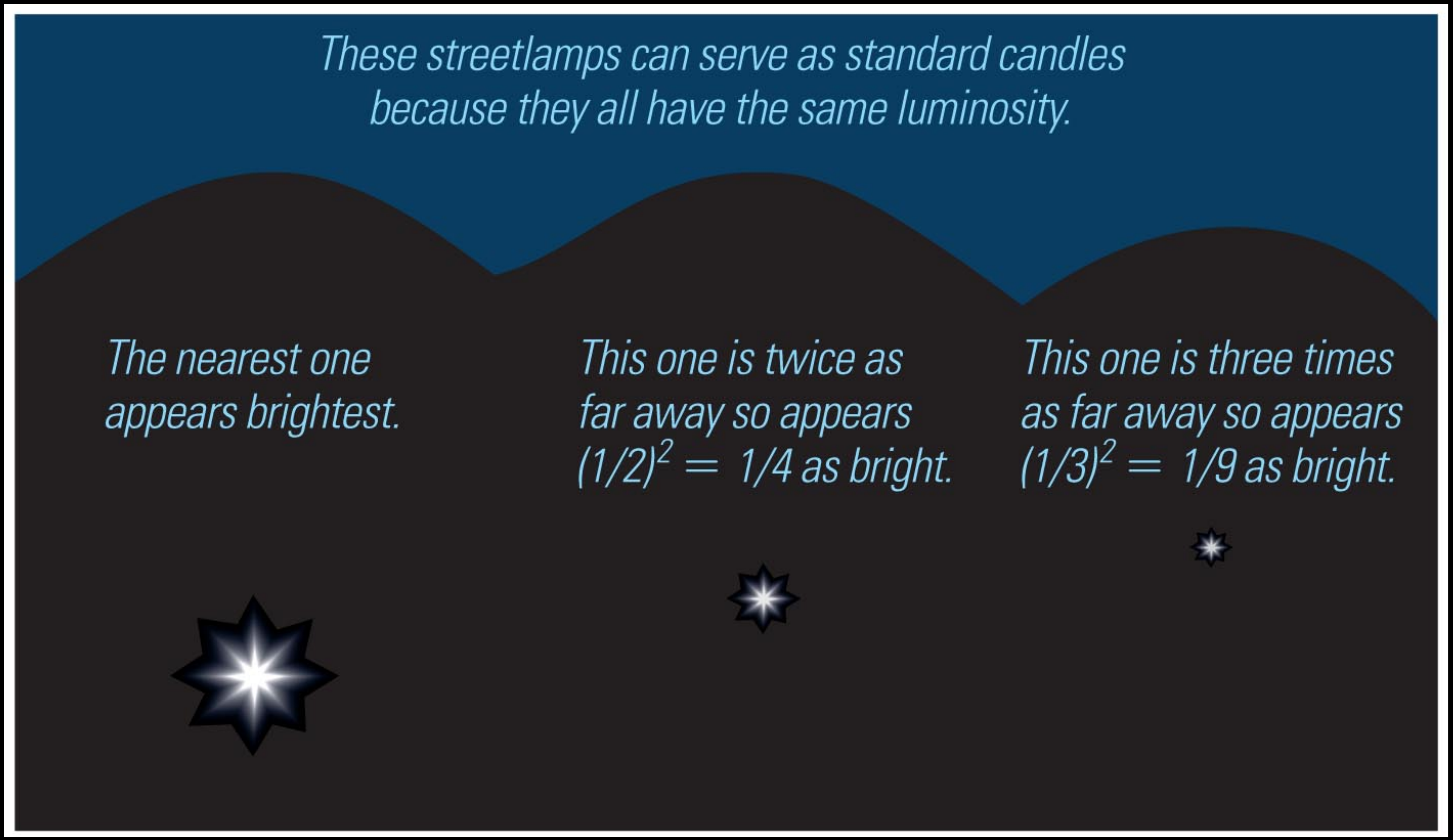
- Standard candles
  - Objects with "known" luminosity (L)
  - You measure the apparent brightness (flux)
  - Calculate the distance: $F = \frac{L}{4\pi d^2}$
- Standard rulers
  - Objects with "known" physical size (x)
  - You measure the angular size
  - Calculate the distance: $x = d \times \theta$

Standard Candles

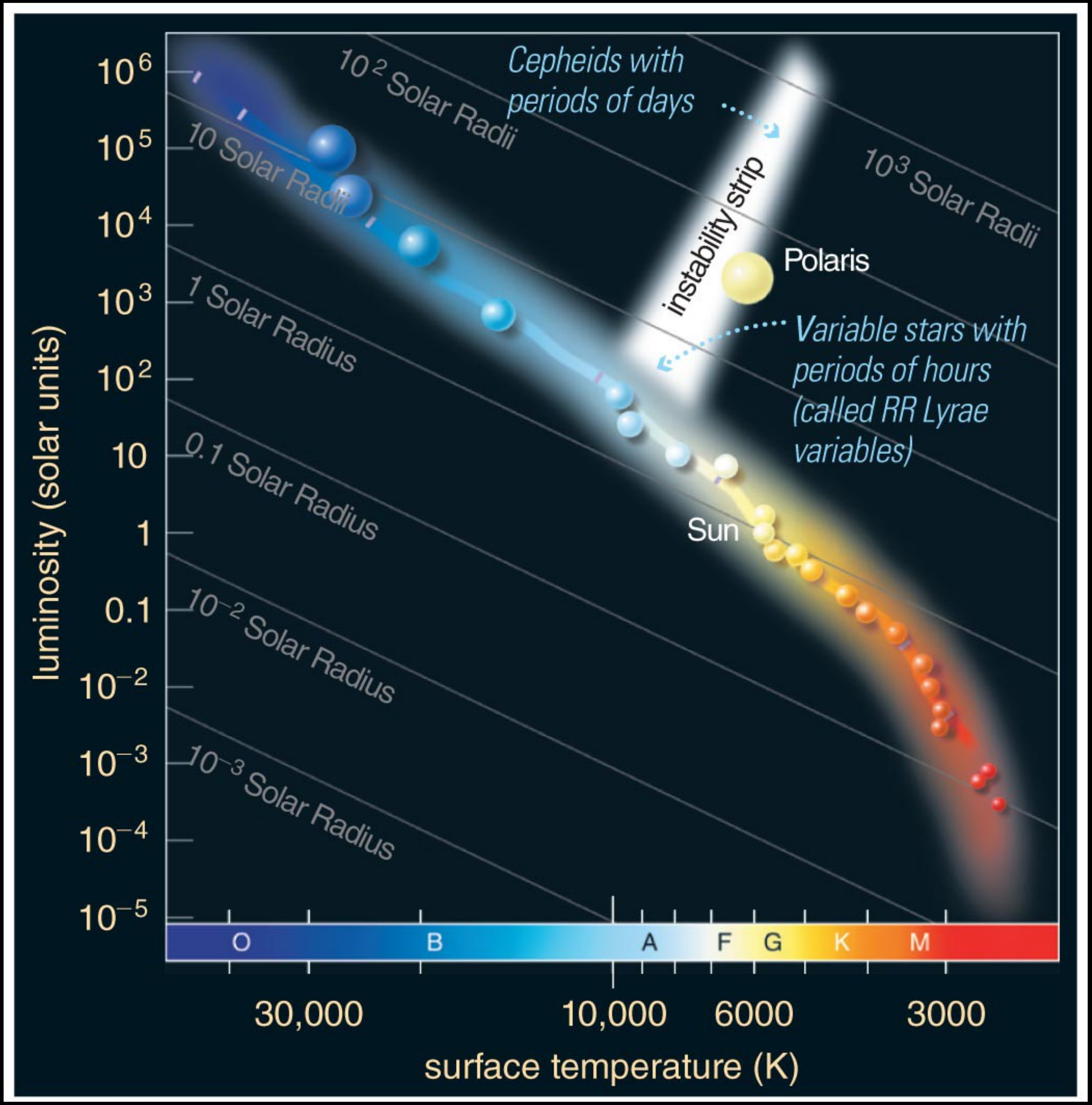
A good standard candle should be:

- Very luminous — bright enough to see at large distances
- Easy to recognize

Standard Candles



Some luminous stars **PULSATE**



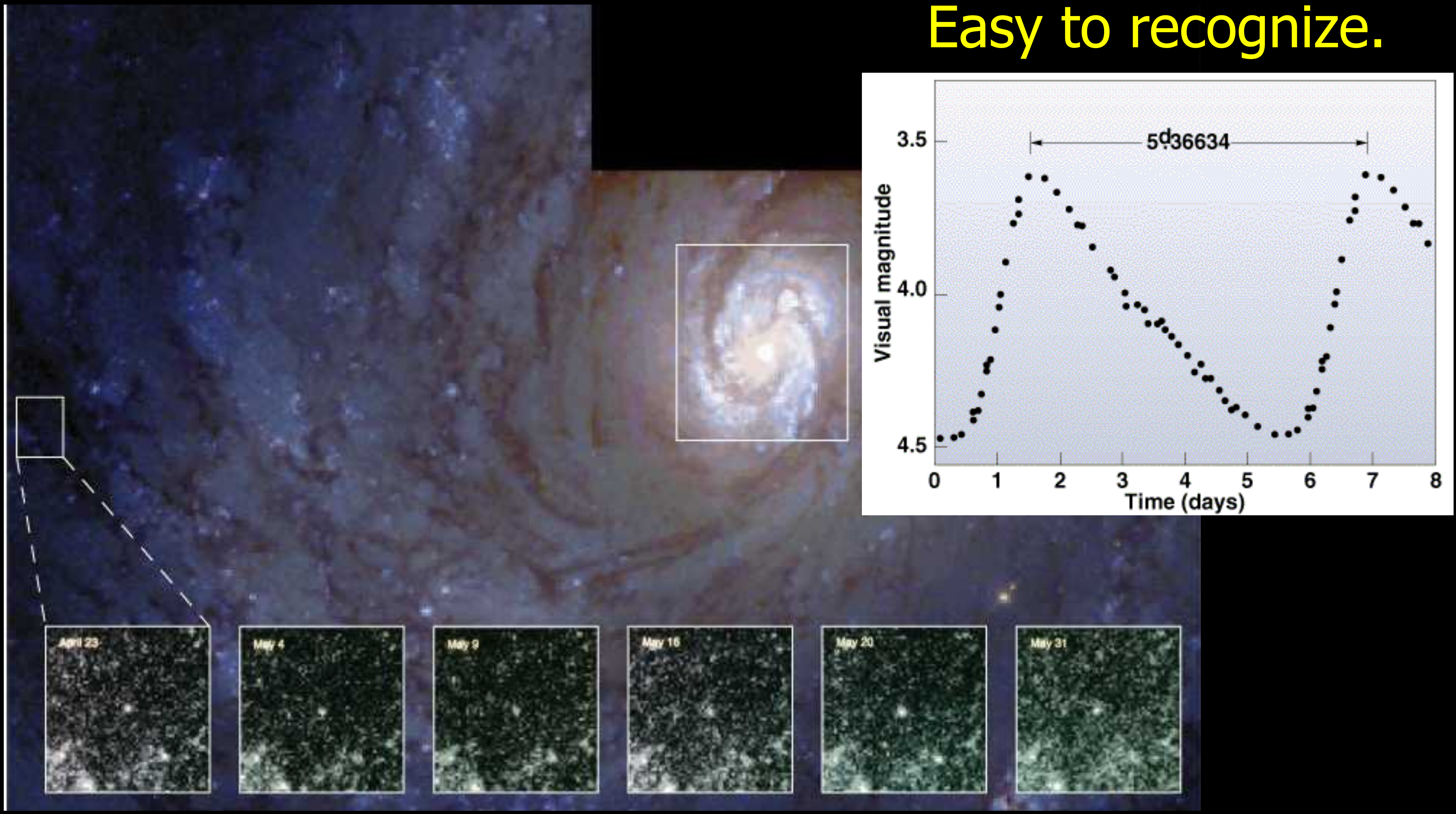
There is an "instability strip" in the H-R diagram, where stars' sizes are not stable

- Luminosity changes with a regular period
- "Variable" stars!
- The brightest such stars are **Cepheids** (or Cepheid variables)

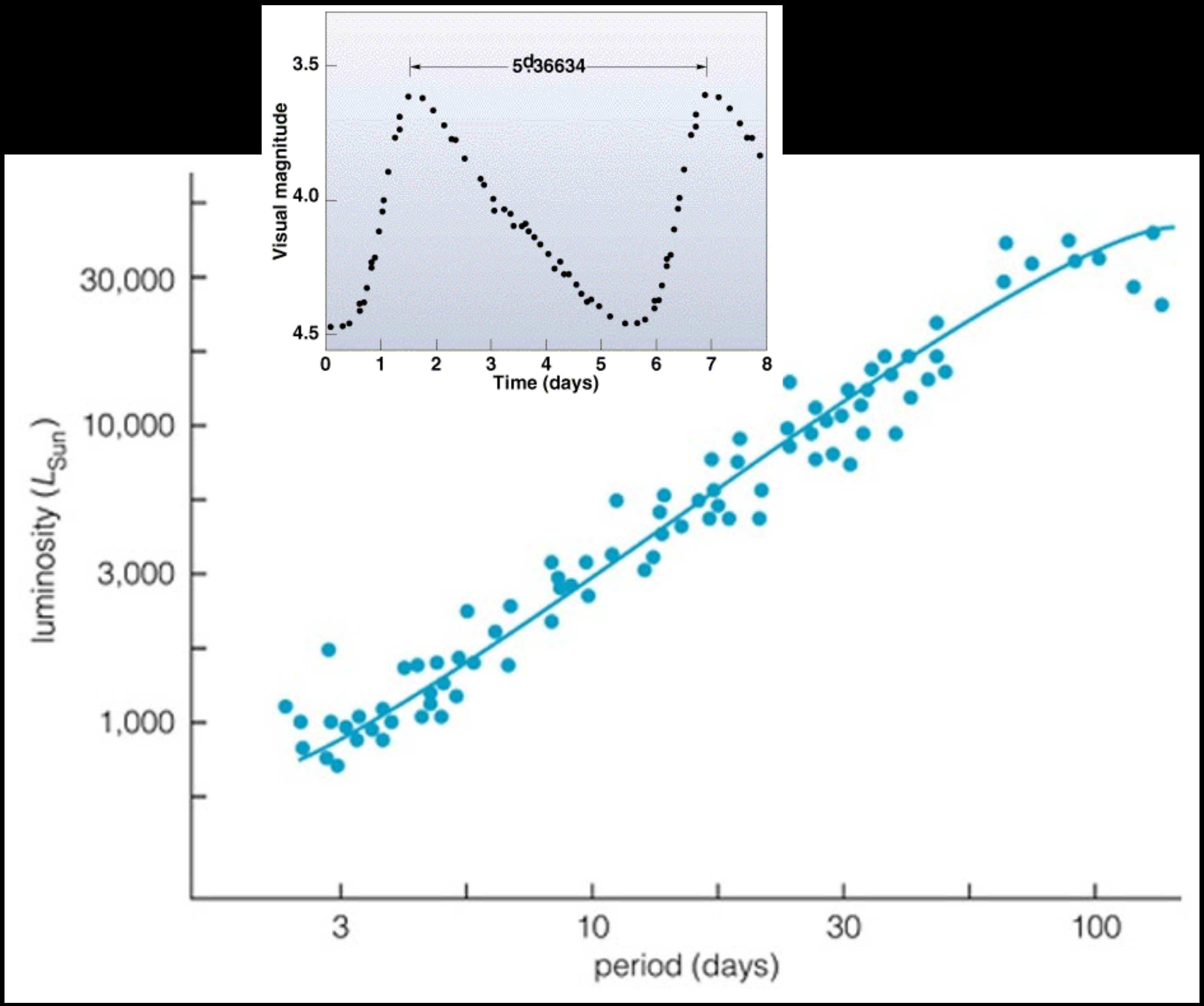
Cepheids get brighter and fainter every few days

Unique pattern!

Easy to recognize.

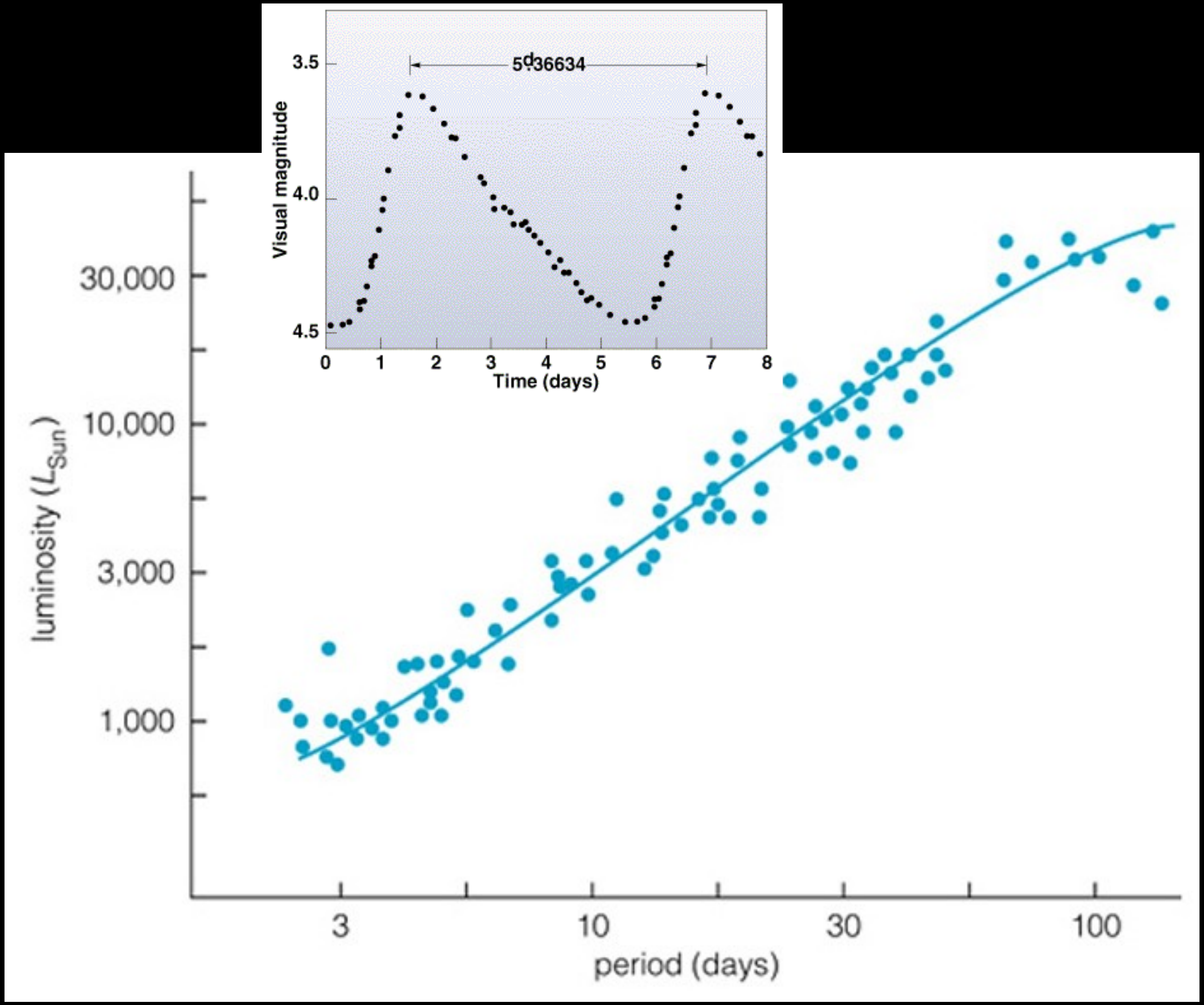


The period (duration) of the pulsation tells you the luminosity of Cepheid stars!



- Periods are easy to measure: observe the brightness changing with time
- Many Cepheids are close enough that we can measure distances with parallax
  - Luminosities are known
  - Longer period = more luminous!

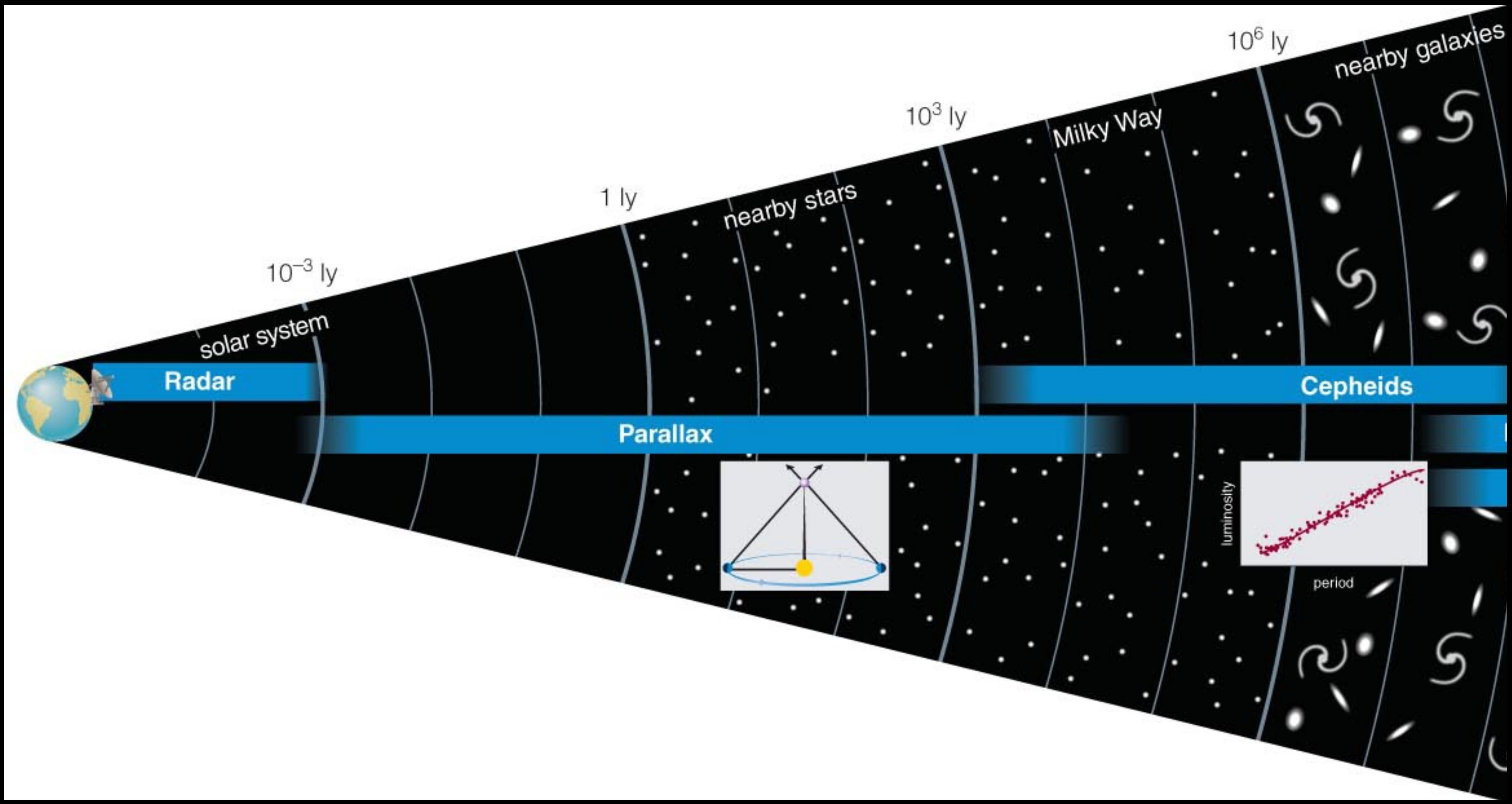
The period (duration) of the pulsation tells you the luminosity of Cepheid stars!



Standard candle!

- Luminosity is known
  - Measure period, which tells you the luminosity
  - Longer period = more luminous
- Measure apparent brightness (flux)
- Calculate distance!

Hubble Space Telescope can detect Cepheids in many nearby galaxies



Another "rung" in the Distance Ladder!

- Radar (solar system)
- Parallax (stars in the Milky Way)
- Standard Candles: Cepheids (nearby galaxies)

Beyond Cepheids

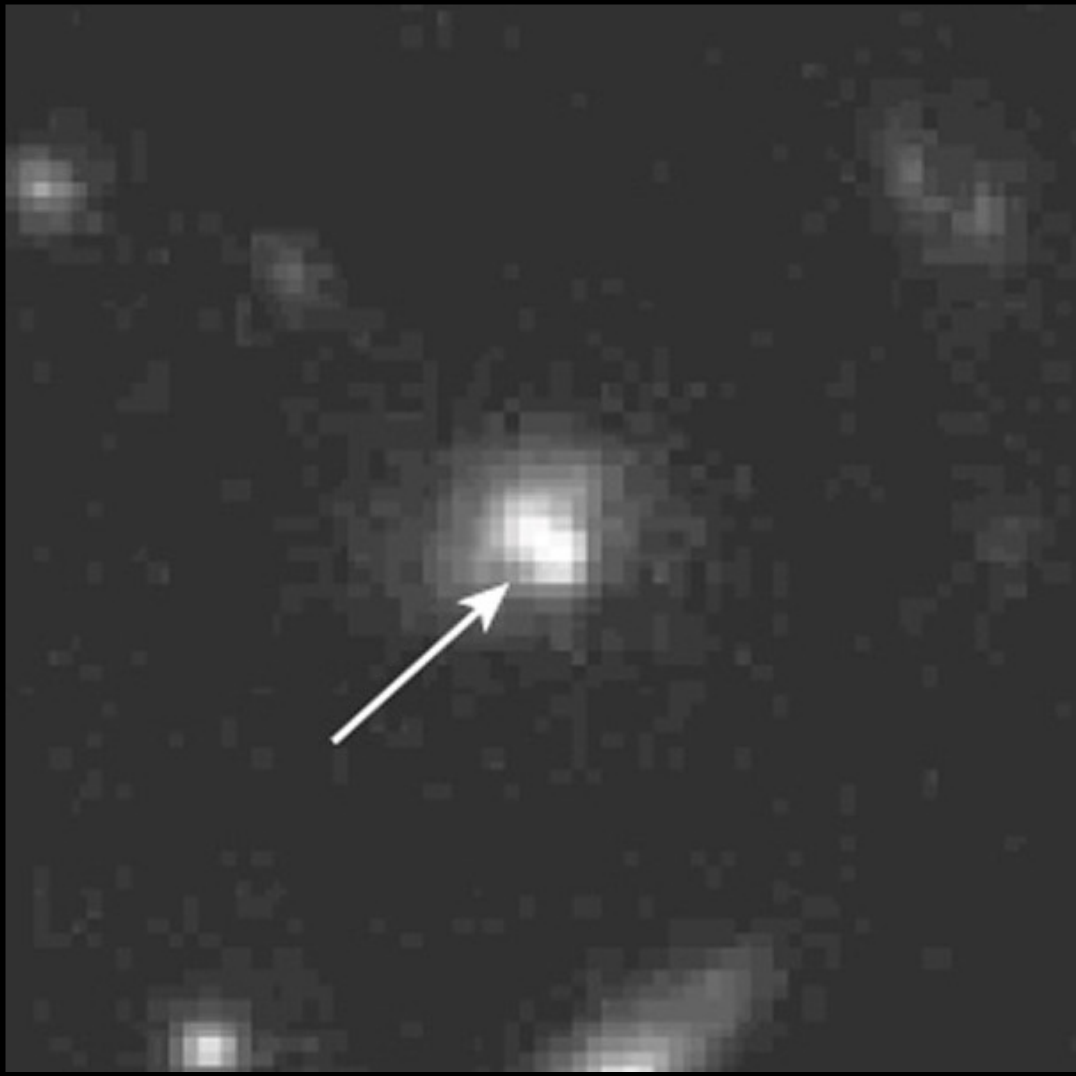
Cepheids only get you as far as 20 Mpc
(60 million lightyears)

- How can we go farther?
- Need standard candles which are **BRIGHTER**

Supernovae!

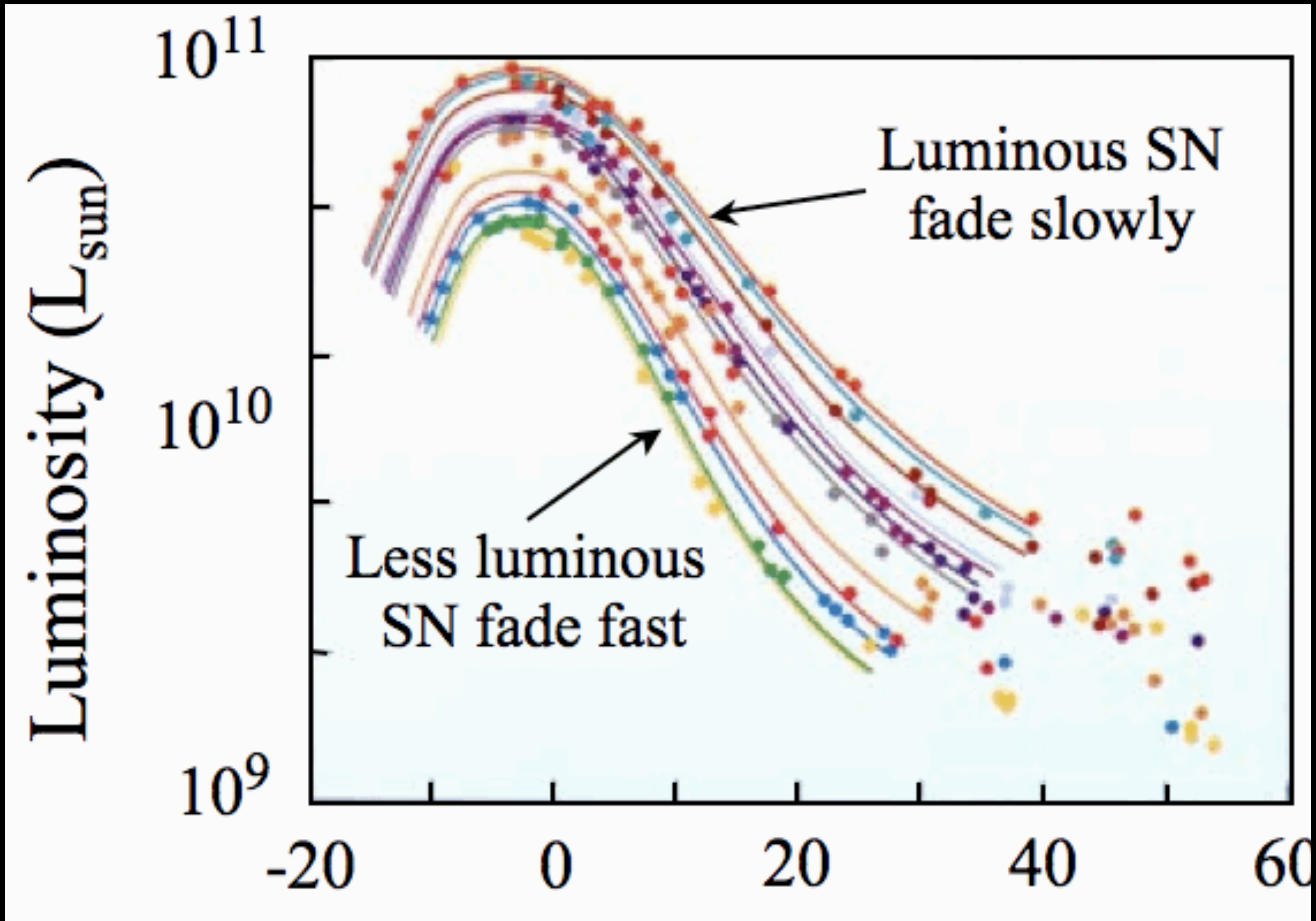
Supernovae as standard candles

- White Dwarf Supernovae ("Type 1a" supernovae)
  - All have nearly the same luminosity!
  - As bright as an entire galaxy!
  - Can see them to HUGE distances (thousands of Megaparsecs)



Supernovae as standard candles

- All have nearly the same luminosity! (almost)



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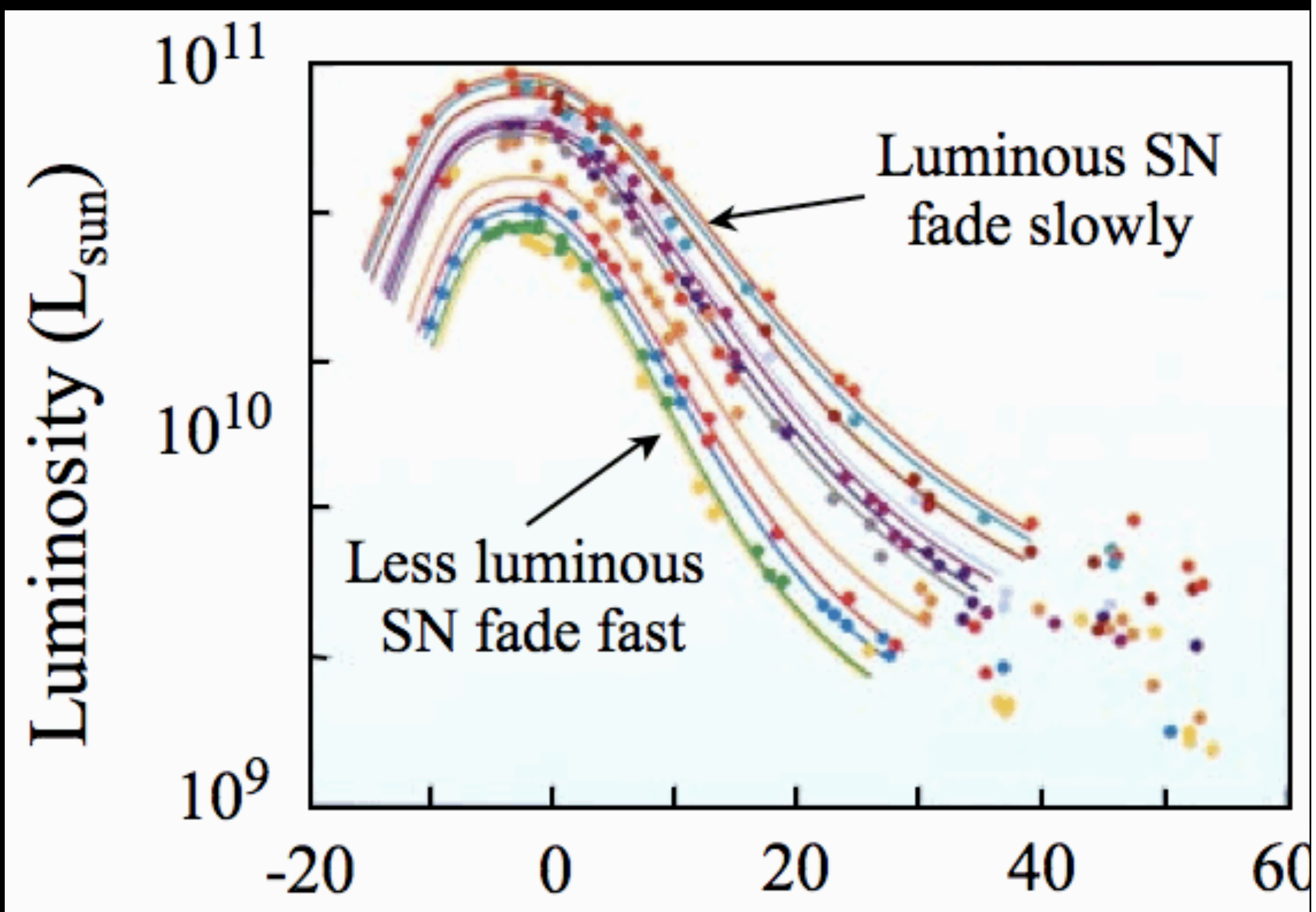
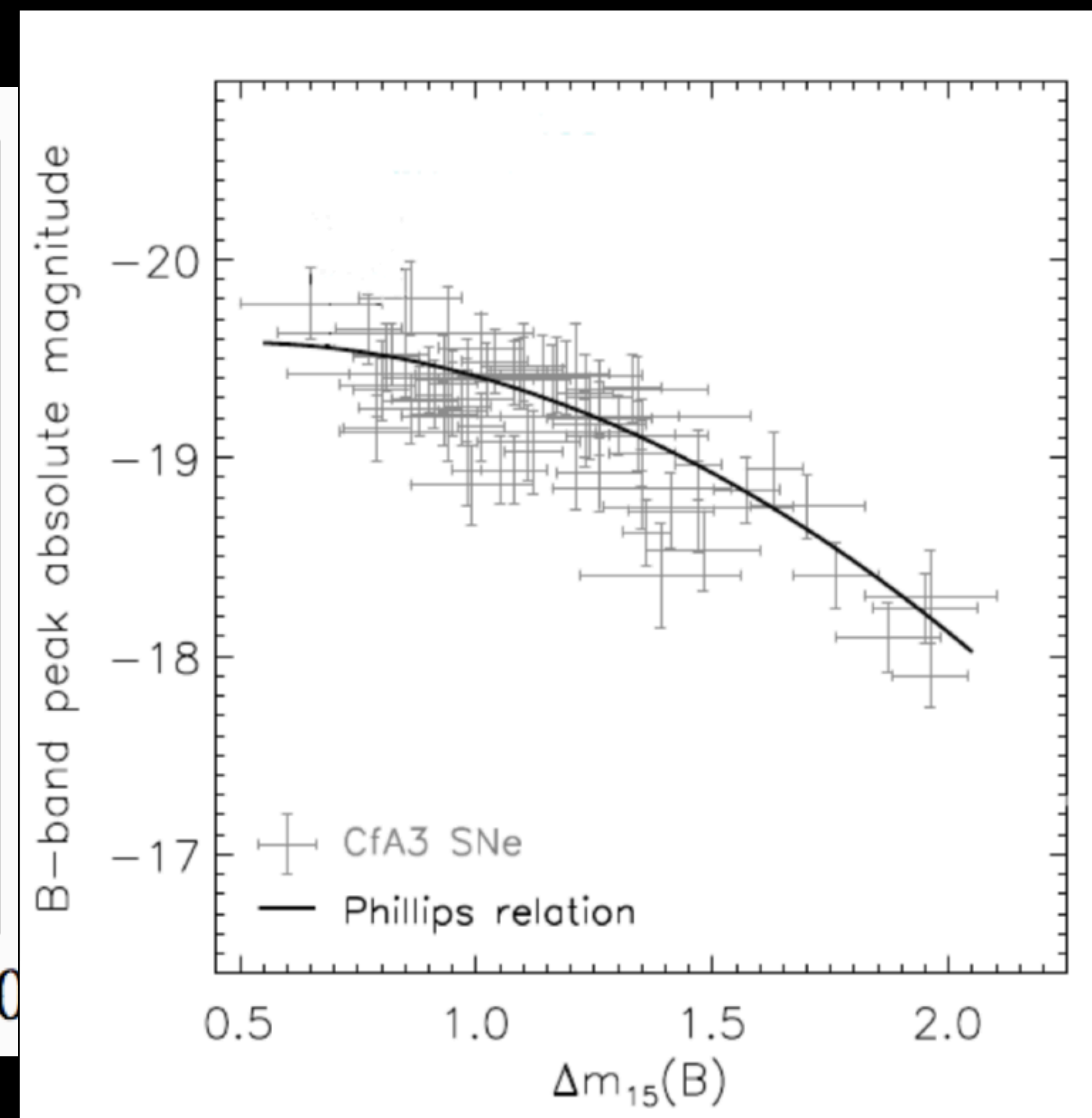
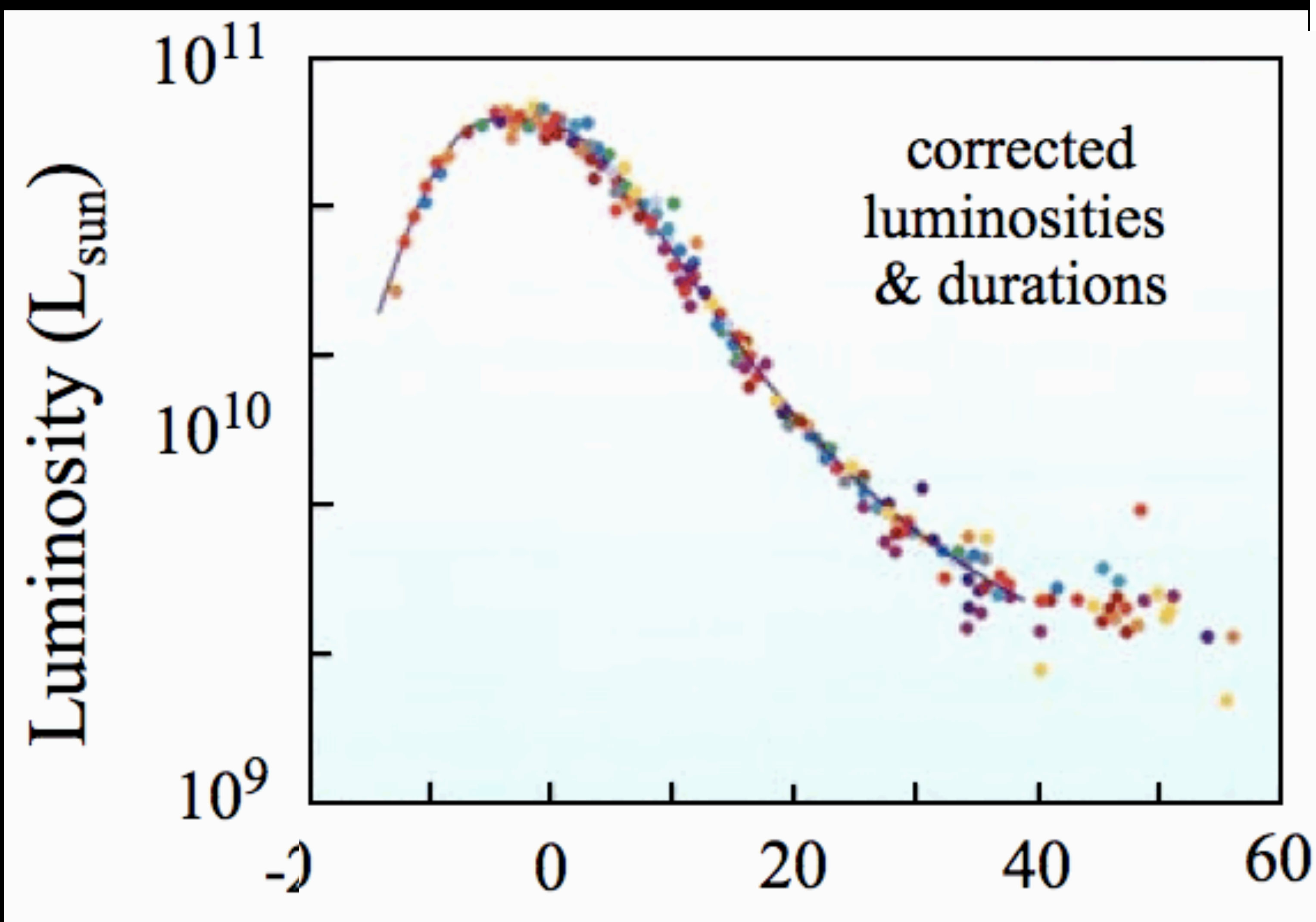
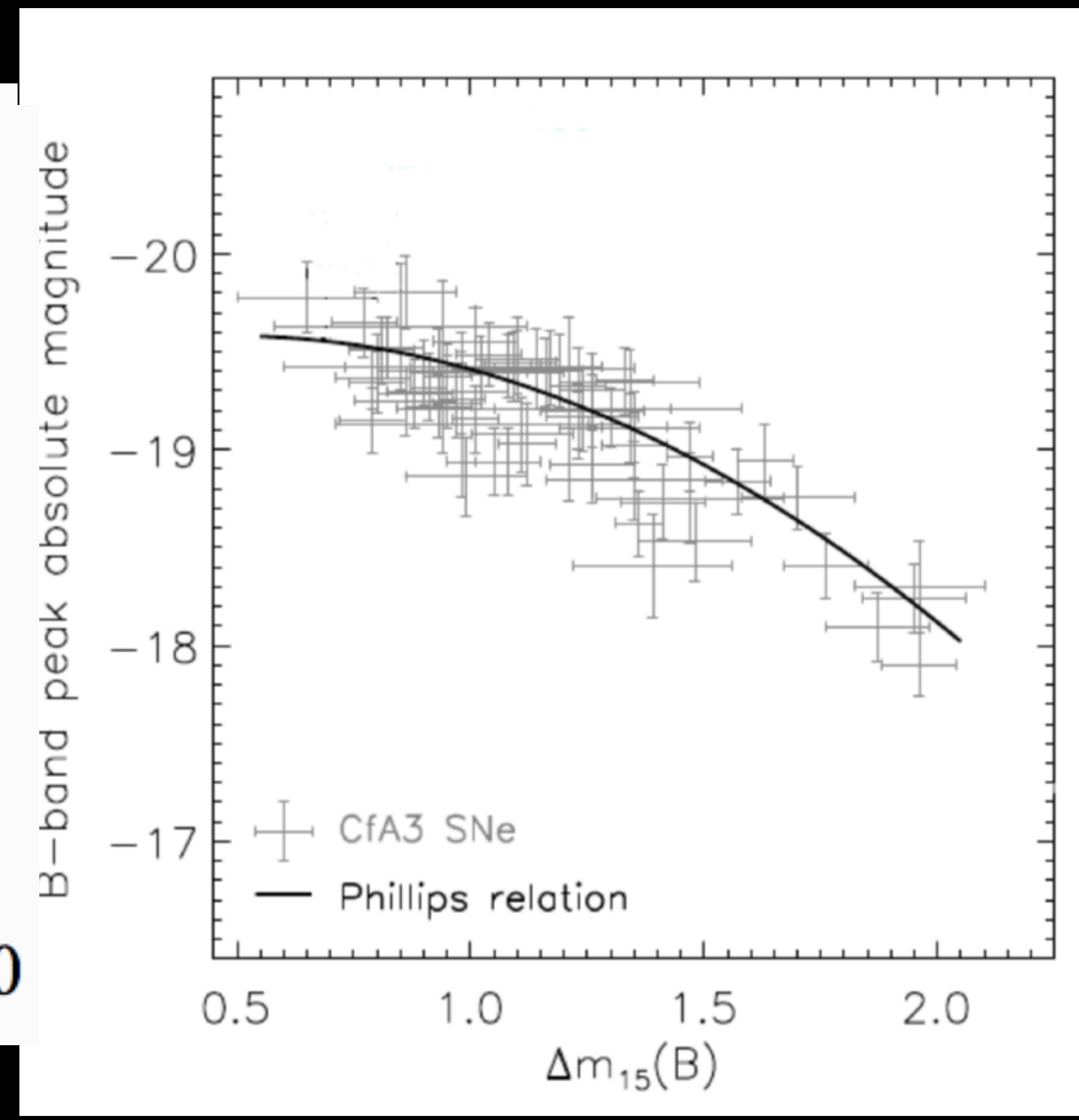




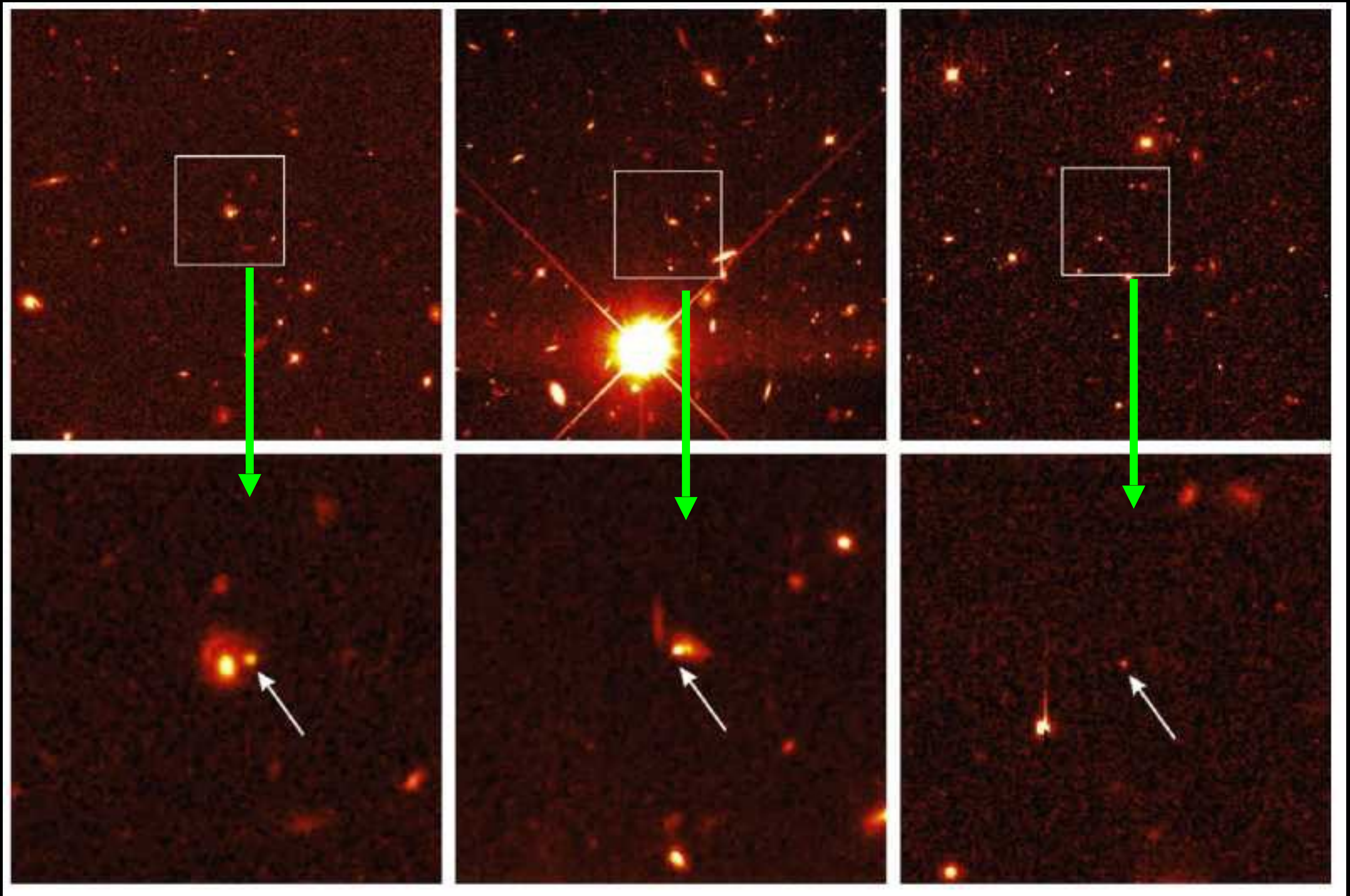
Supernovae as standard candles

- All have nearly the same luminosity! (almost)
- when you take into account light curve stretch

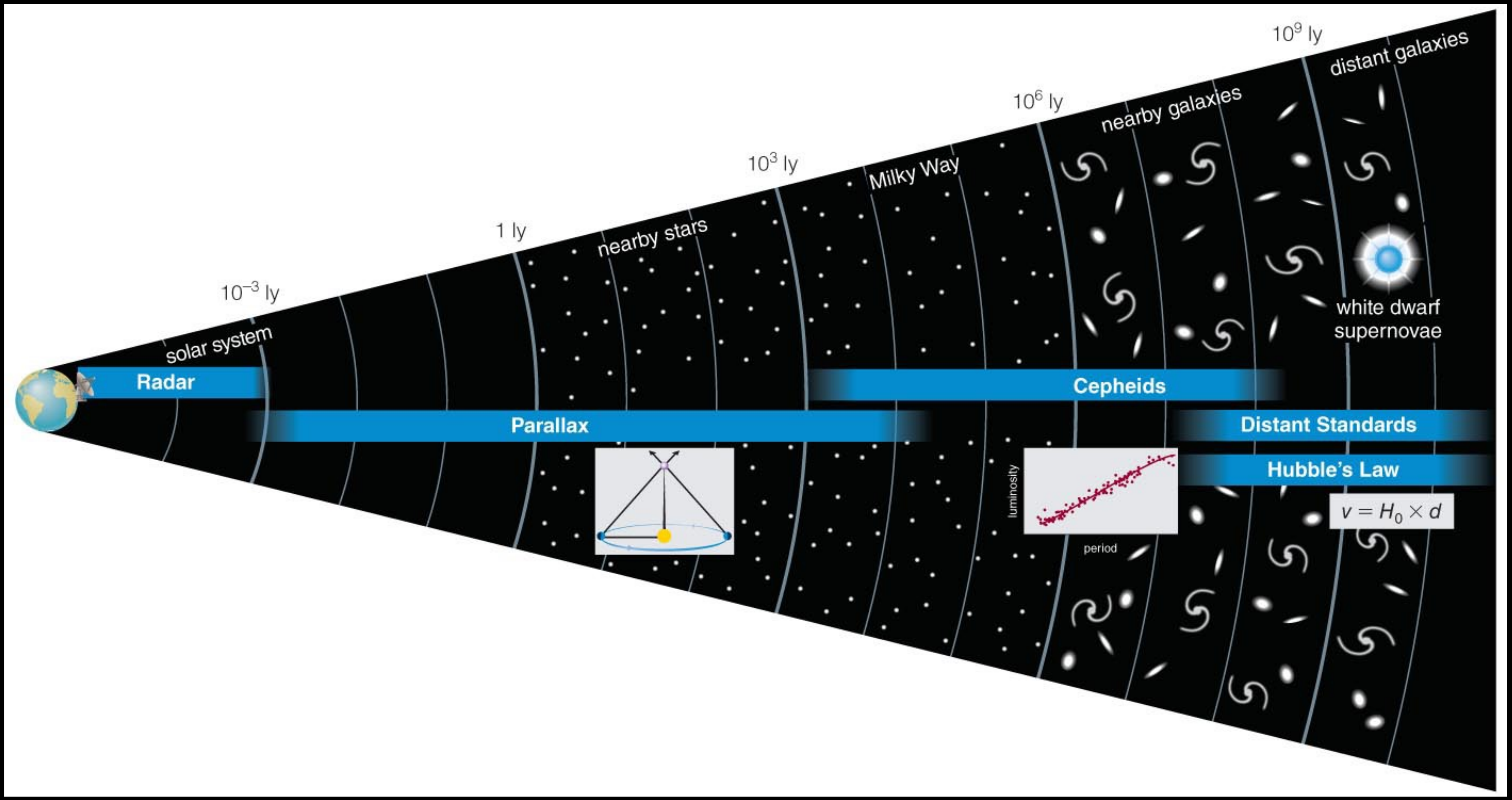




Distant supernovae (up to 10^{10} lyr)



The “distance ladder” is interconnected



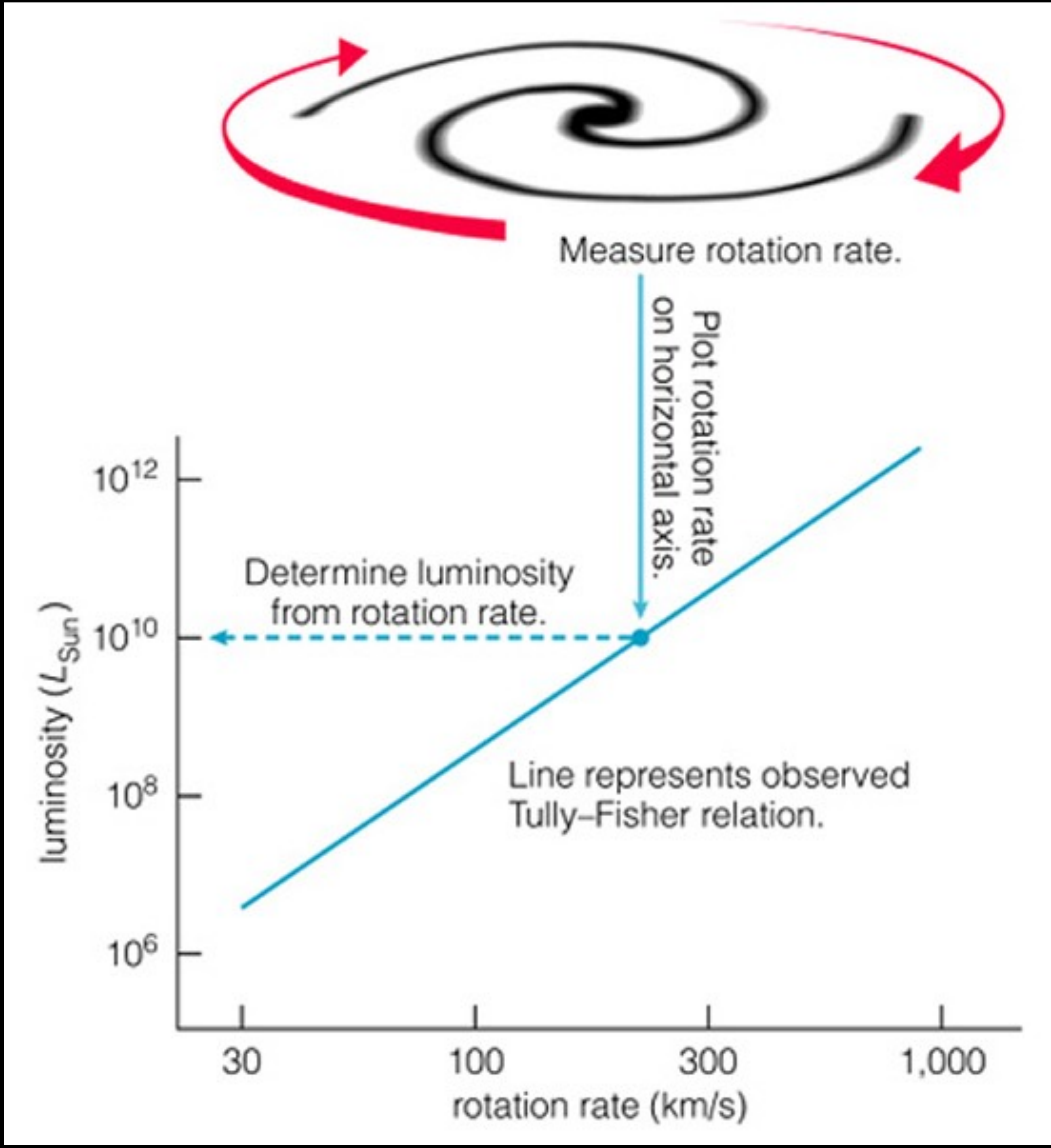
Each “rung” overlaps with the previous one

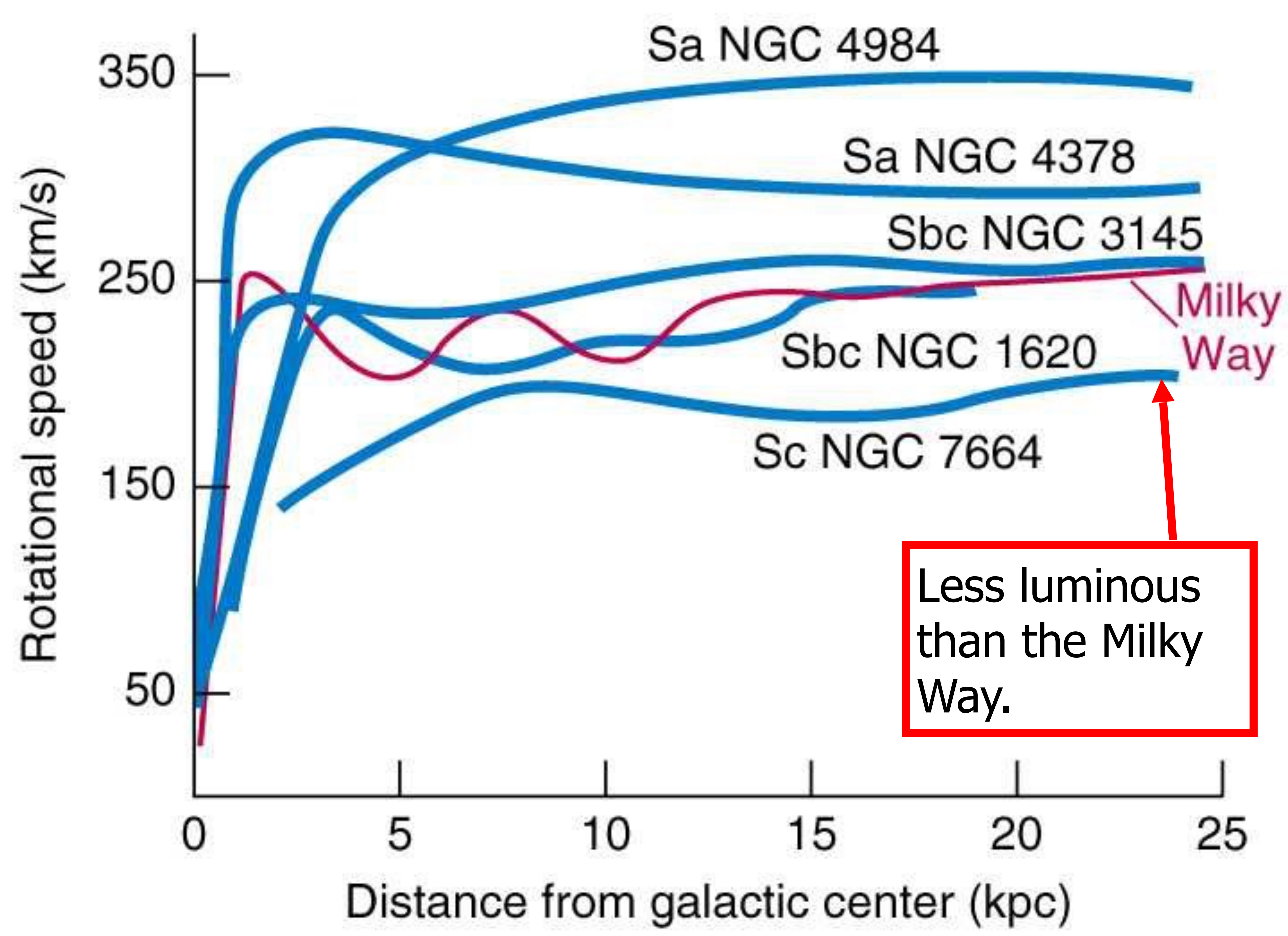
- Measure distances to the same objects with different methods, to make sure they agree

Other “distance ladders”

Tully-Fisher Relation for spiral galaxies

- Fast rotators are much more luminous.
- Easy to measure rotation speed with Doppler Effect

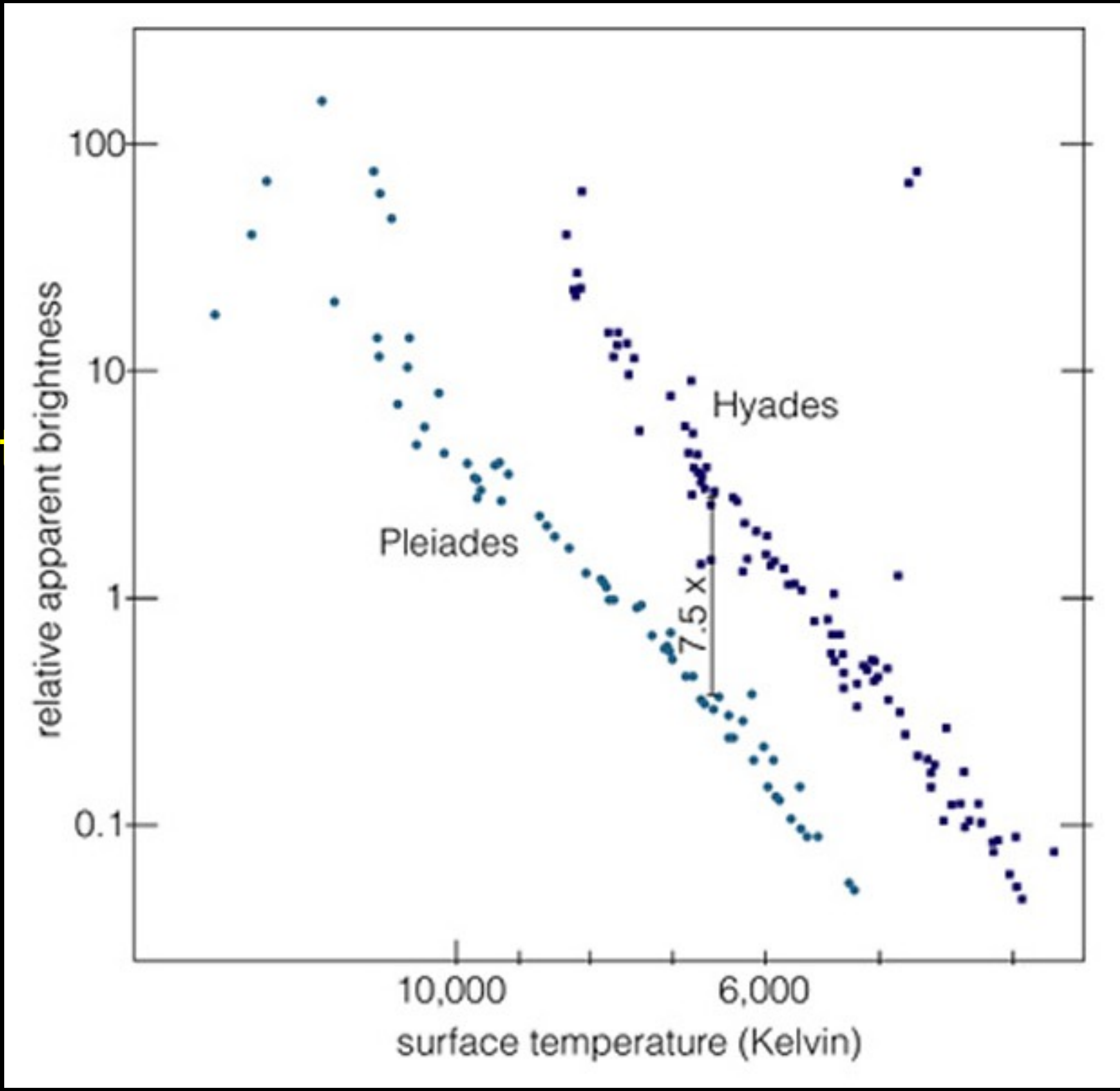




Sa NGC 4984
Sa NGC 4378
Sbc NGC 3145
Milky Way
Sbc NGC 1620
Sc NGC 7664
Less luminous than the Milky Way.
Rotational speed (km/s)
350
250
150
50
0
5
10
15
20
25
Distance from galactic center (kpc)

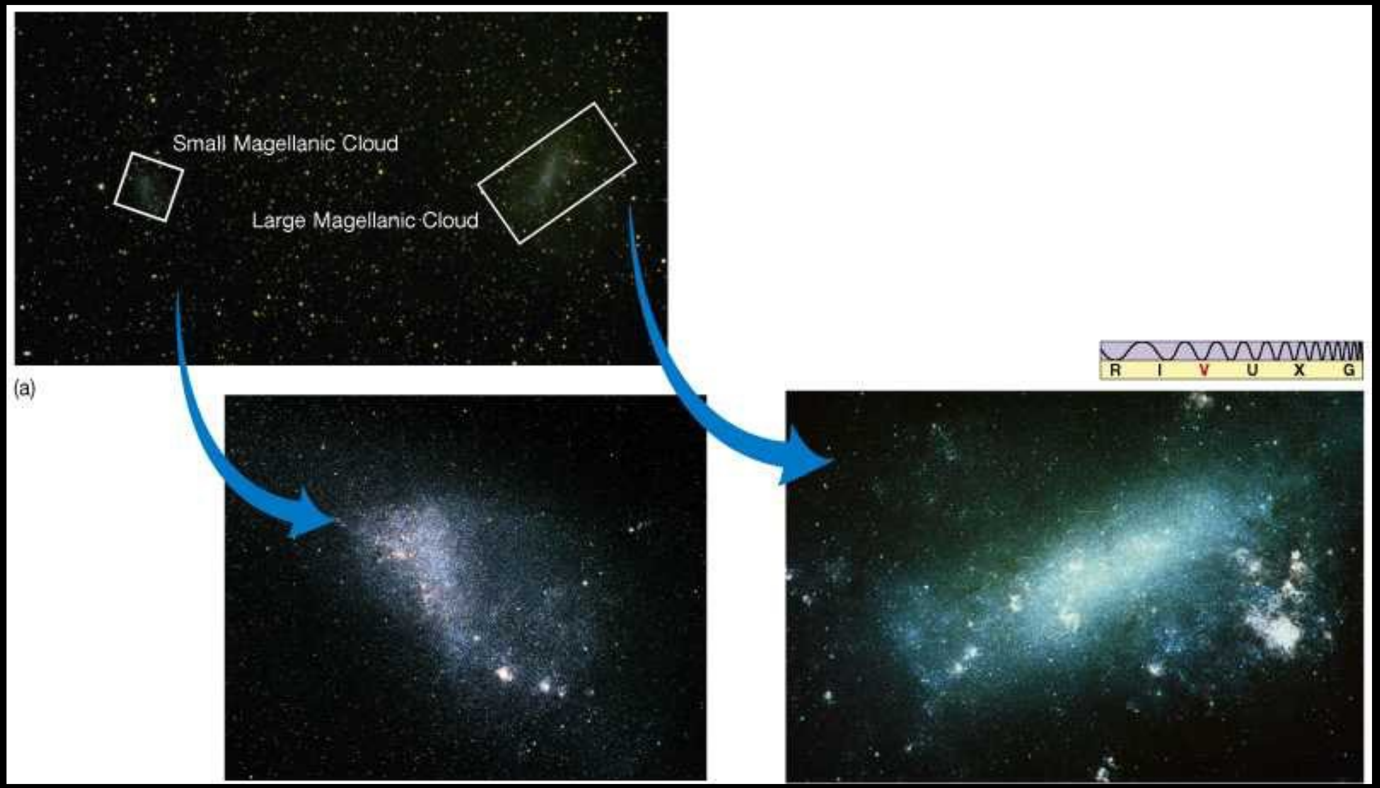
Main Sequence Fitting

- Use main sequence stars as standard candles
  - How?
- Works for larger distances than parallax
- Groups of stars at different distances are "shifted" downwards on the HR diagram of Apparent Brightness versus Surface Temperature
- Pleiades is 7.5x fainter than the Hyades.



Main Sequence Fitting

- Can get distances to anywhere you can **resolve large numbers of individual stars**.
  - Globular Clusters in the Milky Way
  - The Large & Small Magellanic Clouds.



Recap: what have we learned?

- **How do we measure distances to galaxies?**
  - The “distance ladder” connects several methods
    - Radar, within the solar system
    - Parallax, within the Milky Way
    - Bright standard candles (Cepheid stars, White Dwarf Supernovae) allow us to measure distances of galaxies

Let's make our universe bigger…

Courtesy UCO/Lick Observatory

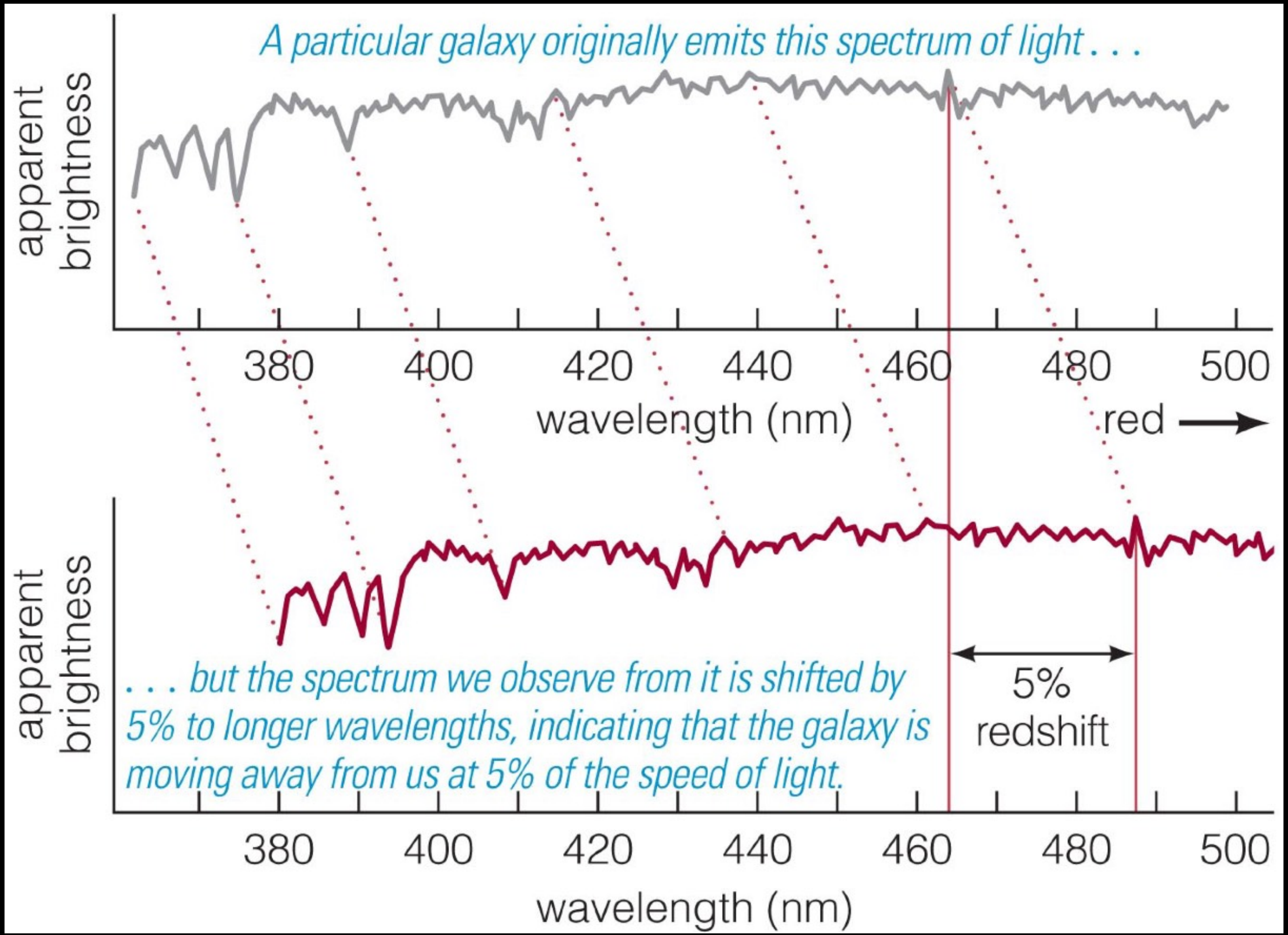
1920's: the mysterious "Spiral Nebulae"

- Some argued that these were entire galaxies, like our own Milky Way, located at great distances
- Others argued they were much smaller and nearby, within the Milky Way, and there is nothing in the universe beyond the Milky Way
- How to tell? Need to measure **distances**!

Edwin Hubble (& Milton Humason)

- Discovered Cepheid variable stars in the Andromeda “nebula” (galaxy), and measured its distance
- Proved that the spiral nebulae were entire galaxies, located far beyond the Milky Way!

We can also measure velocities of galaxies

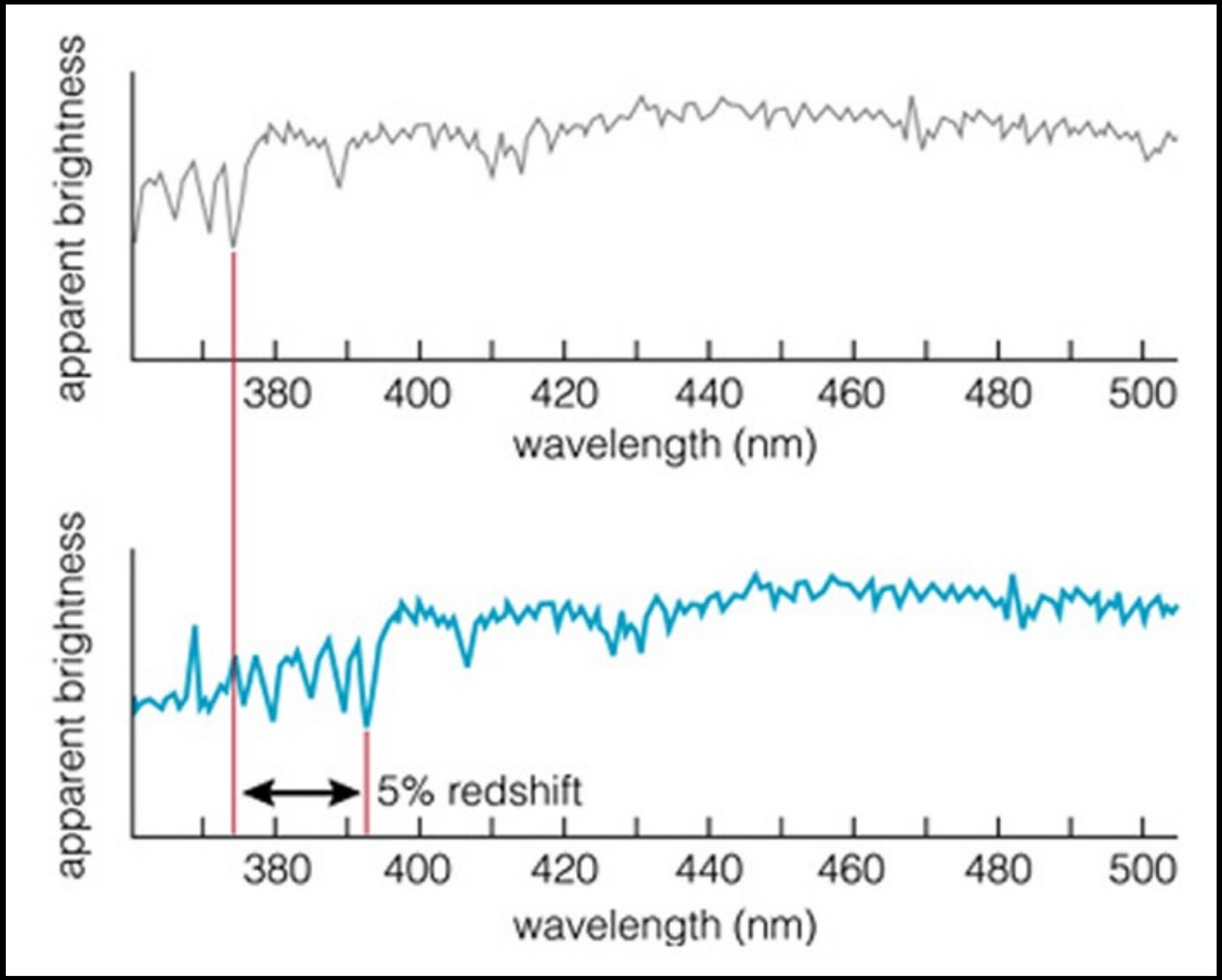


$$\frac{v}{c} = \frac{\Delta\lambda}{\lambda_0}$$

Astronomers define the term **redshift (z)**: $z = \frac{\Delta\lambda}{\lambda_0} \approx \frac{v}{c}$

- Doppler shift! (Recall Lecture 5)
- Note: only tells you the **radial** motion (toward/away from you)
- Measure redshift **z**, get the velocity **v = c z**

Hubble plotted speed vs distance to galaxies, and found that more distant galaxies are **moving away** from us **FASTER**!

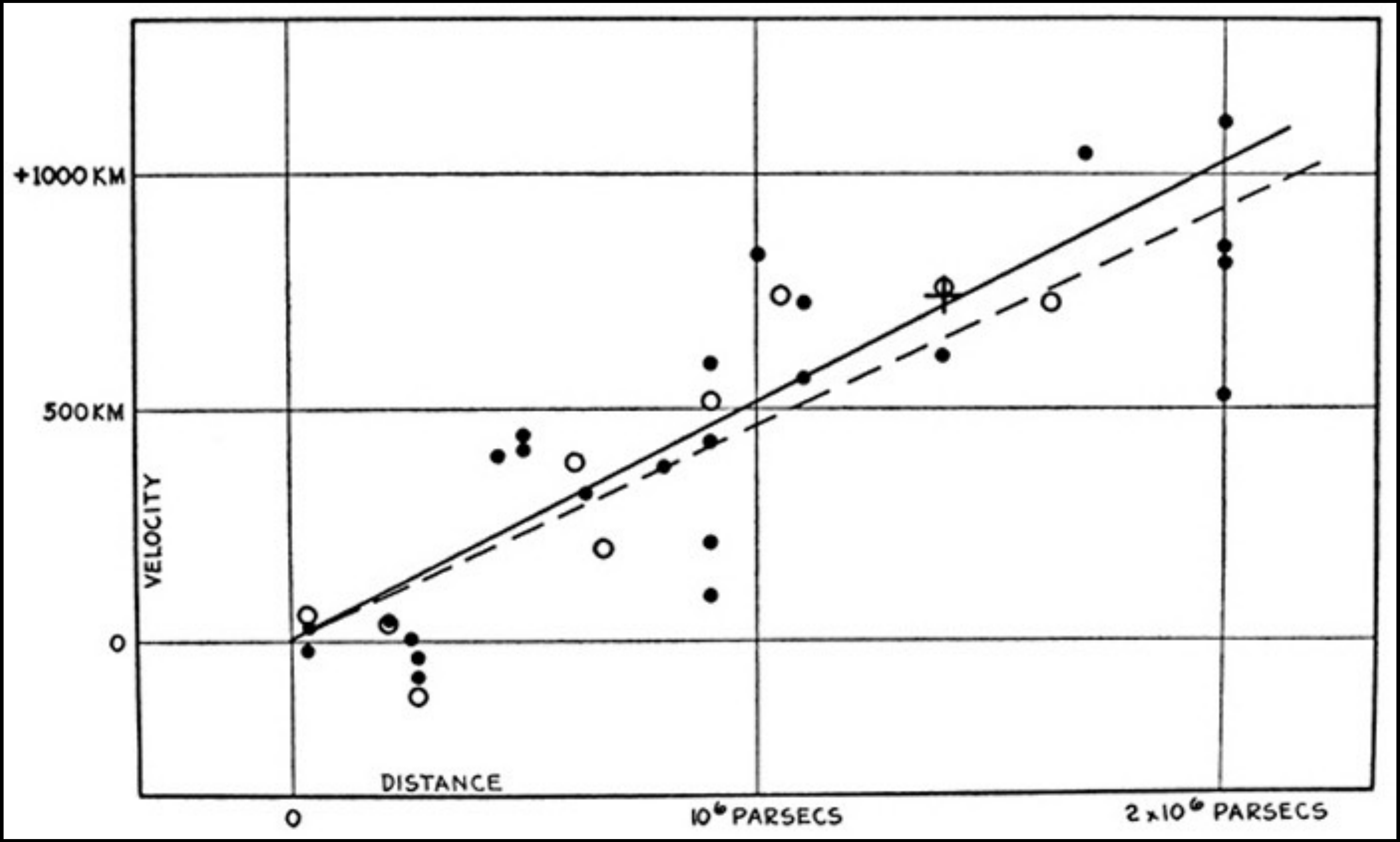


Measure the redshift 'z', derive the 'recessional velocity'

$$z \equiv \frac{\Delta\lambda}{\lambda}$$

$$V = c \times z$$

Hubble's original data

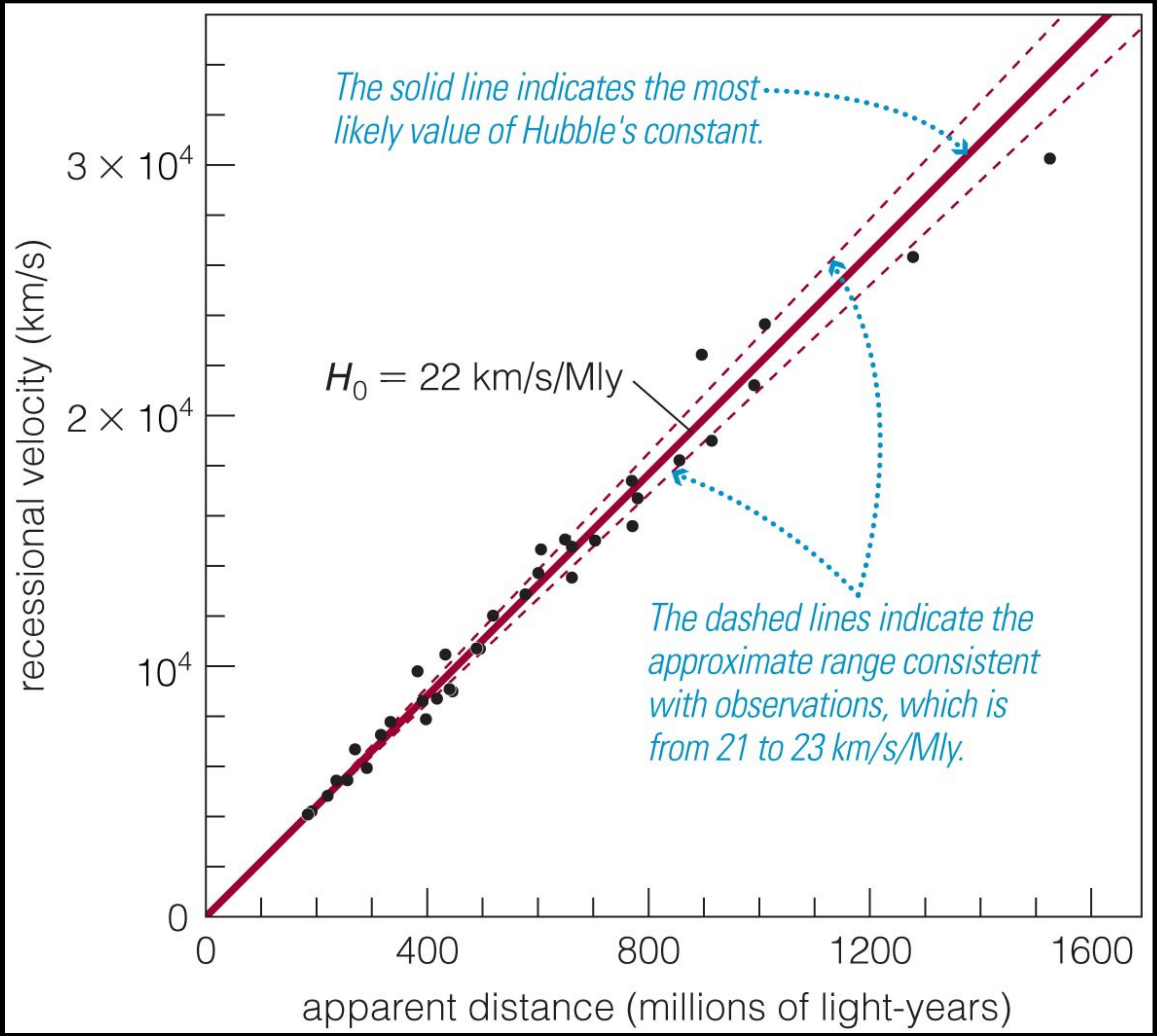


Nearly all galaxies are moving away from us!
Speed is directly proportional to distance

Hubble's x-axis was wrong by a factor of 10!

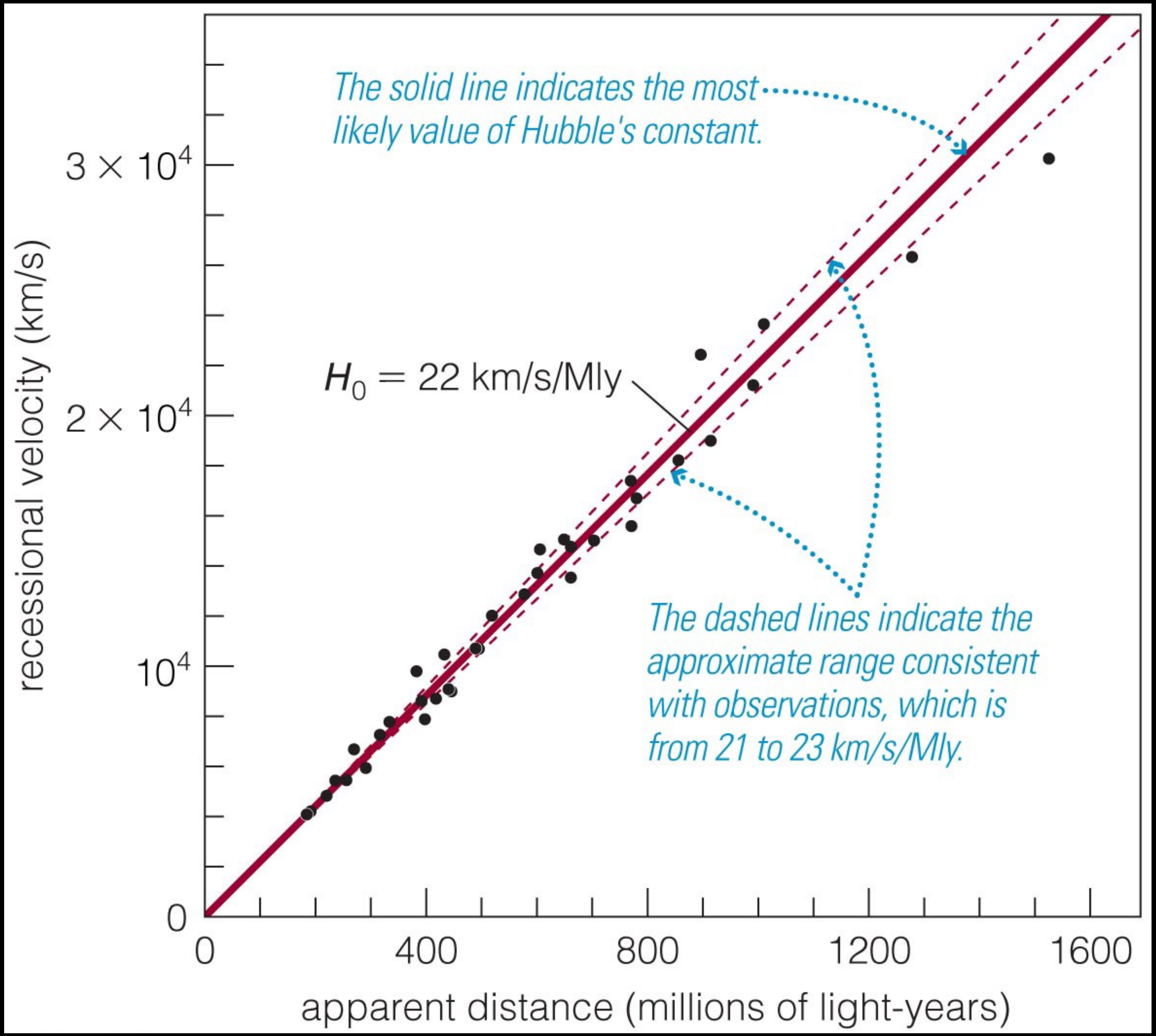
"Hubble's Law"

- Recessional velocity is proportional to distance
- $v = H_0 \times D$
- H_0 is the "Hubble Constant". Units are km/s / Mpc.



Hubble's Law tells us the age of the Universe (sort of)

- Nearly all galaxies are moving away from us
- They must have been closer together in the past
- If we extrapolate into the past, it suggests that all galaxies have a common origin: same place at a certain time
  - "Beginning" of the Universe!



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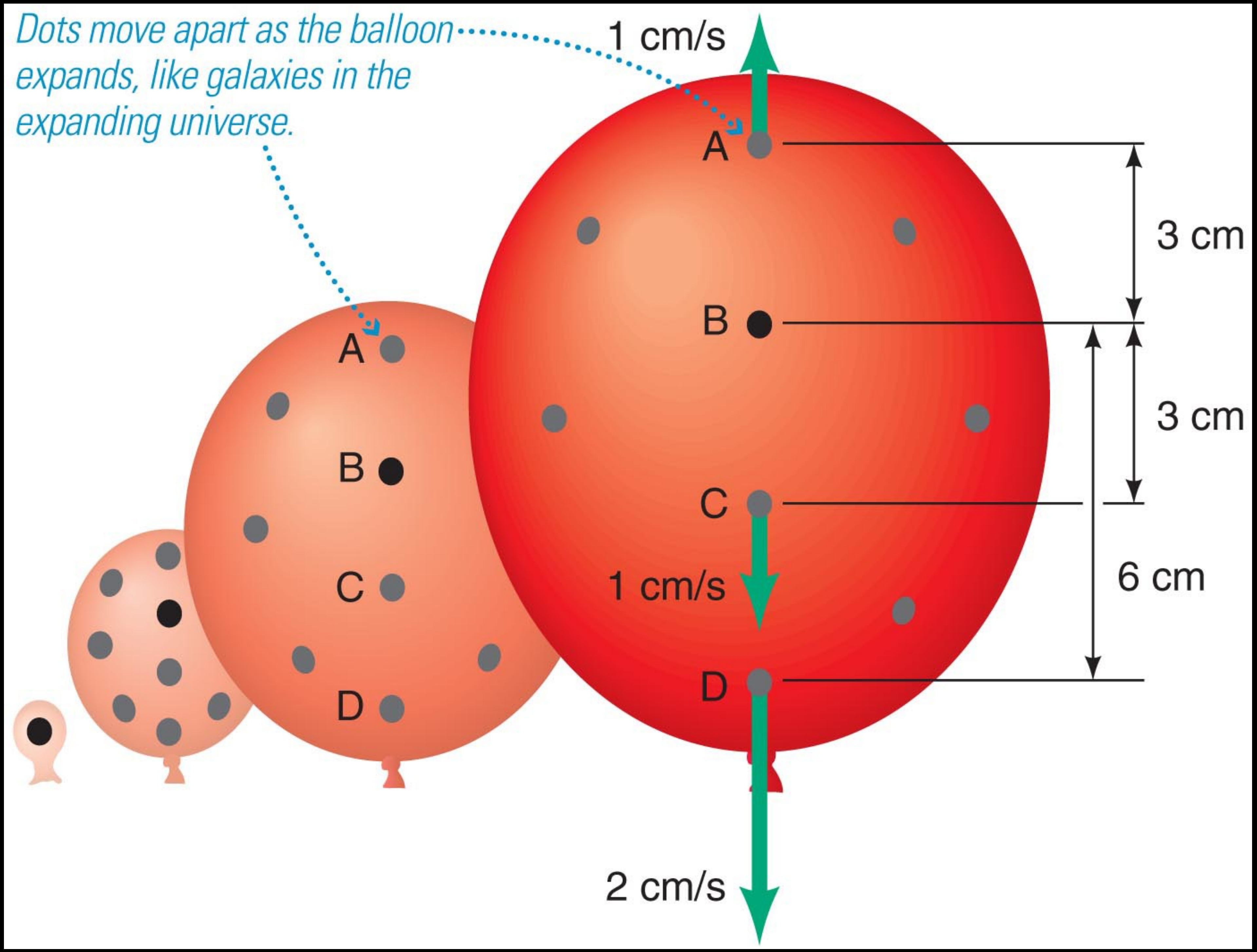


- Galaxies are all moving apart from one another
- Analogous to blowing up a balloon

Thought question

Suppose that your friend left your house, walking at a speed of 4 km/hr. She calls you later and is 2 km away. How long has she been walking?

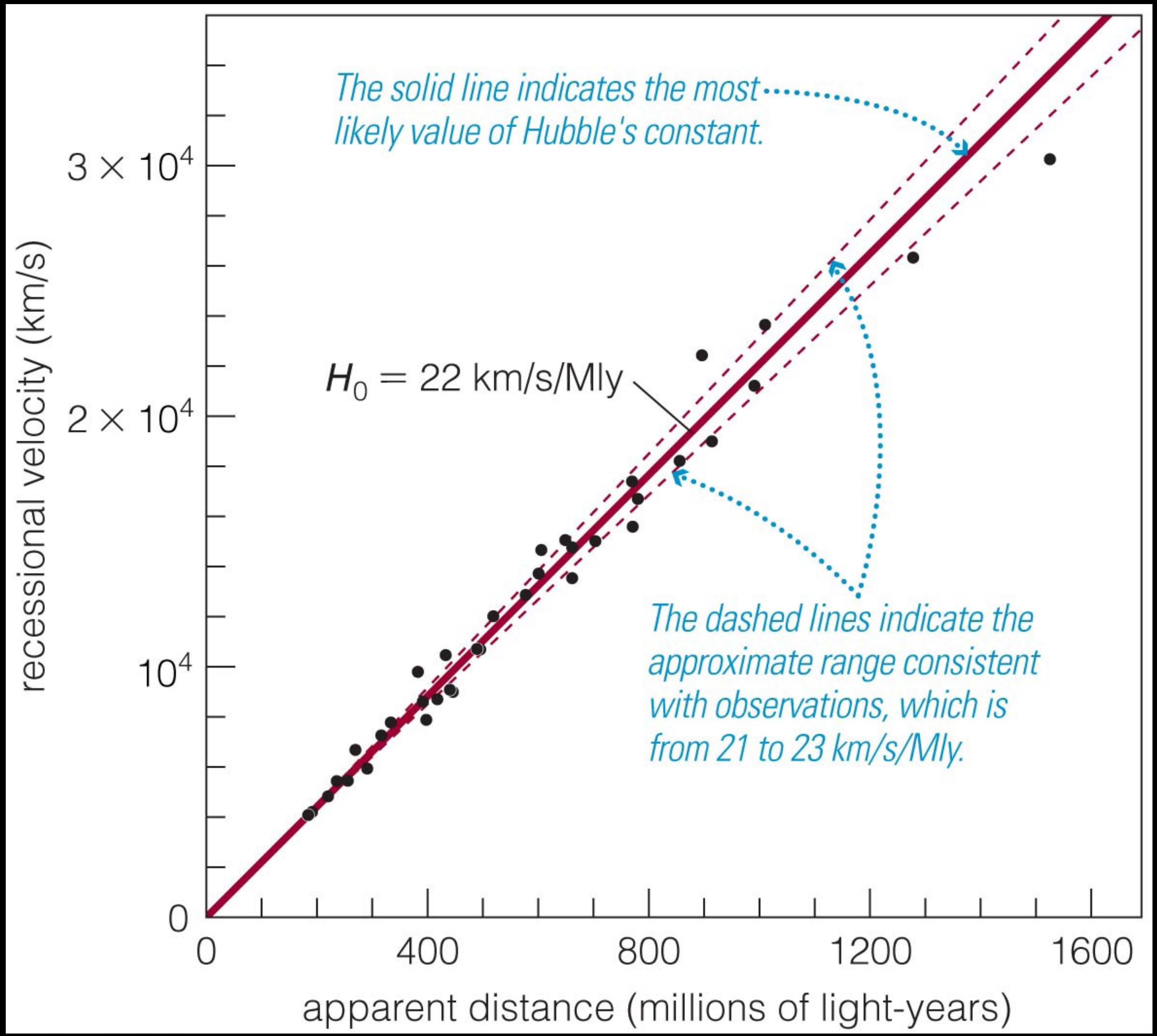
Thought question

Suppose that your friend left your house, walking at a speed of 4 km/hr. She calls you later and is 2 km away. How long has she been walking?

1/2 hour

Distance = speed × time

Hubble's Law tells us the age of the Universe (sort of)



Hubble's Law:

$$v = H_0 \times D$$

Rewrite as:

$$D = v \times \frac{1}{H_0}$$

→ Distance = speed × time

Where here time = $1/H_0$ = amount of time that galaxies have been traveling!

→ This is roughly the "age" of the Universe: 14 billion years!

Recap: what have we learned?

- **What is Hubble's Law?**
  - The faster a galaxy is moving away from us, the greater its distance
    - $v = H_0 \times D$
- **How does Hubble's Law tell us the age of the Universe?**
  - By measuring a galaxy's current distance and speed, we can deduce how long it must have been traveling to reach its current distance
  - Measuring the "Hubble Constant" H_0 tells us the approximate amount of time: 14 billion years