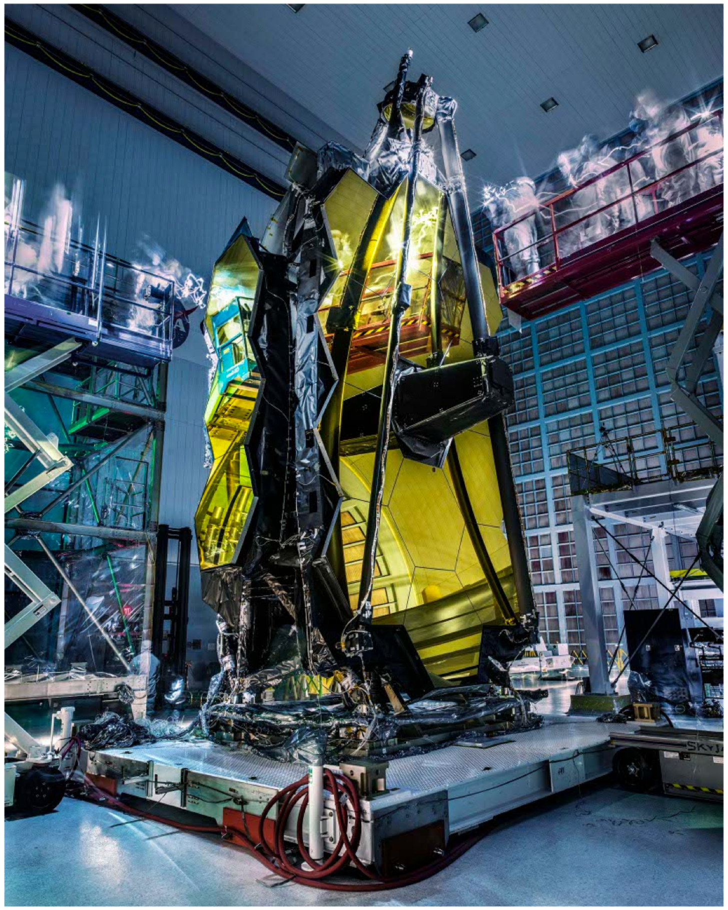
[17] The Cosmic Distance Ladder (4/3/18)

Upcoming Items

1. Homework #4 due today!
   HW #5 due April 24
2. Read Ch. 20.3 for next class and do the self-study quizzes
3. Second midterm next Tuesday, April 10
   Material: from class 12 (Milky Way) through Thursday (class 18, Hubble's Law) inclusive. ***Includes*** prob/stat!
4. Friday's discussion: review
5. Joe will lead review Mon 6-8, in ATL 2400 (last sem's room)
   Please send him Qs by noon Monday; both reviews driven ***entirely*** by your questions

APOD 3/18/17: JWST
Now delayed by >=1 year

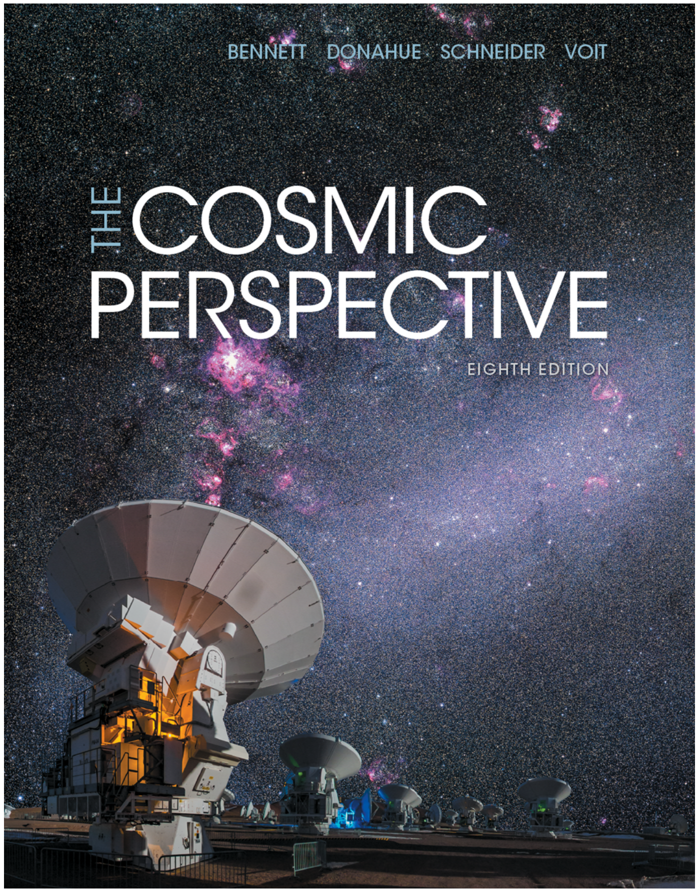


LEARNING GOALS

Ch. 20.2

For this class, you should be able to…

- … *describe the period-luminosity relation of certain variable stars and how it is used to measure distances to nearby galaxies;*
- … *use different techniques that we have seen throughout the semester to estimate distances to objects in the universe, from the nearest to the furthest scales, and explain which techniques are most suitable for which distances.*



Any astro questions?

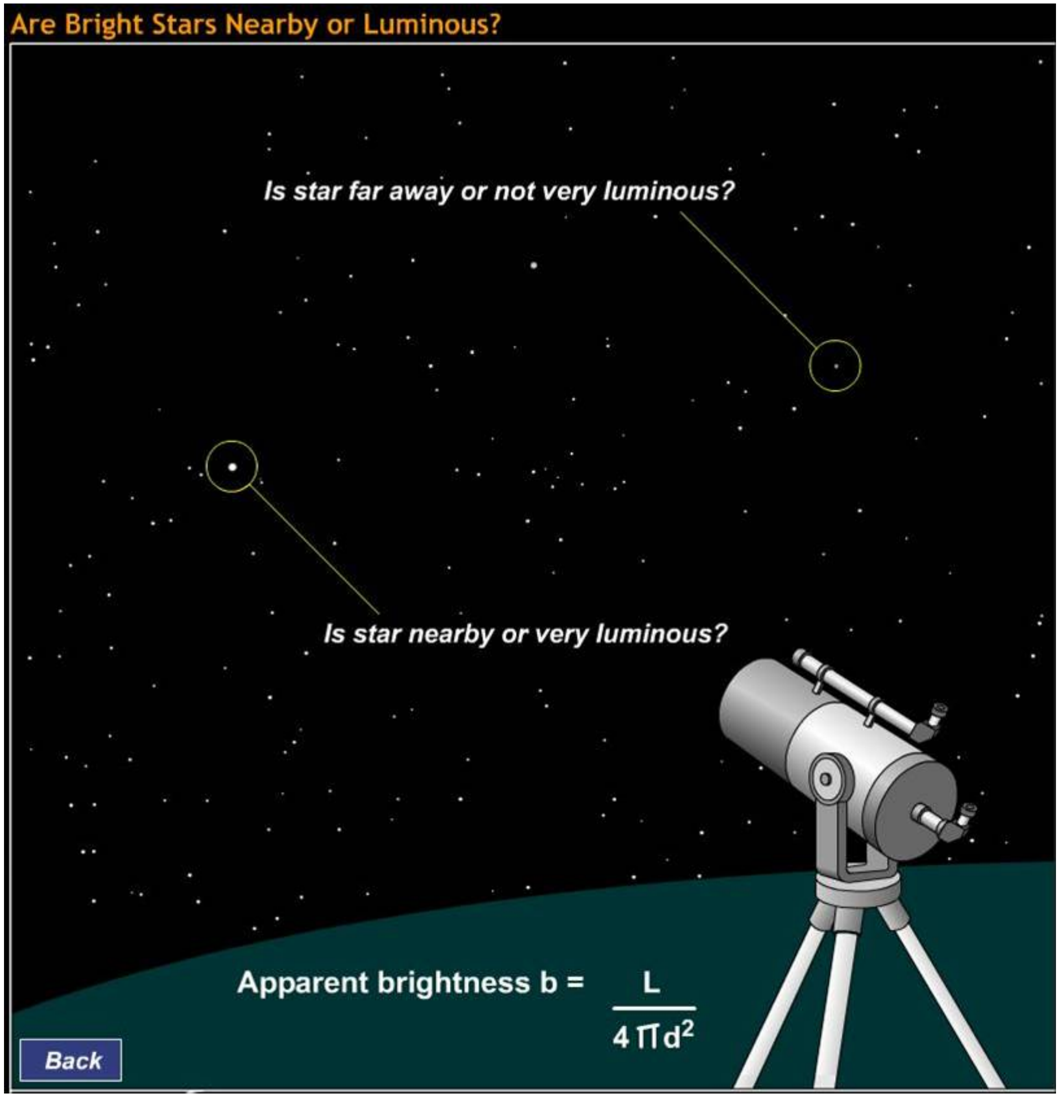
Group Q: Different Distance Measures

- A bit of a repeat, but it’s relevant for today
- You see a friend walking down the sidewalk toward you
- How many conceptually *distinct* ways can you think of measuring your friend’s distance from you?

The Cosmic Distance Ladder

- Astronomers measure distances to objects in the universe using a chain of techniques, many of which rely on the concept of a *standard candle*:
  1. Length of 1 AU using radar.
  2. Nearest stars using parallax (also: “spectroscopic parallax”).
     - Can measure distances to star clusters using main-sequence fitting.
  3. Nearby galaxies using Cepheid variables.
     - Can also use the Tully-Fisher and Faber-Jackson relations.
  4. Distant galaxies using white dwarf supernovae (needs luck!).
  5. Other distant galaxies using Hubble’s law (next lecture).
- Knowing galaxy distance, get luminosity and diameter.

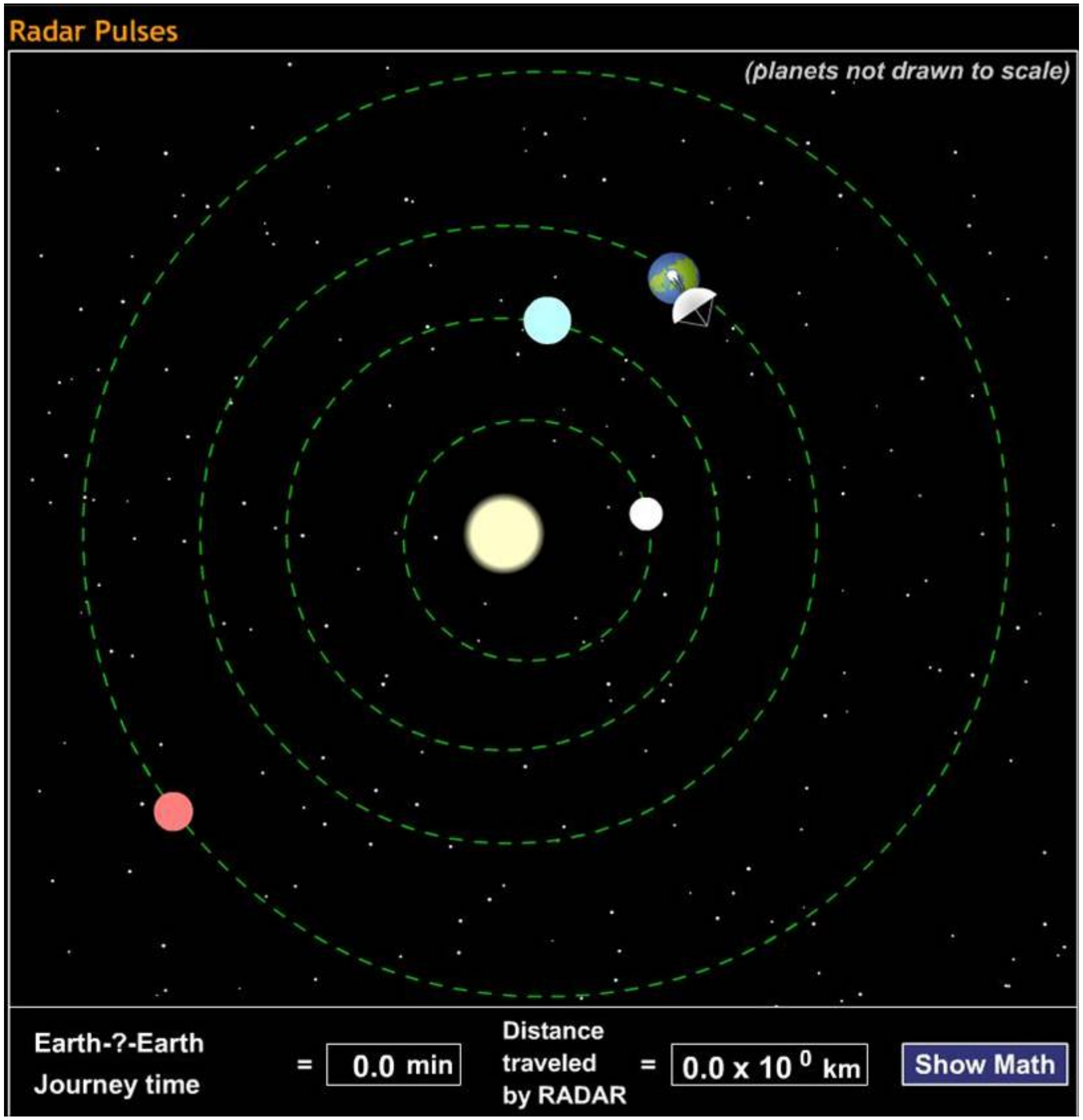
Unknown Distances



Recall: brightness alone does not provide enough information to measure the distance to an object.

The Cosmic Distance Ladder

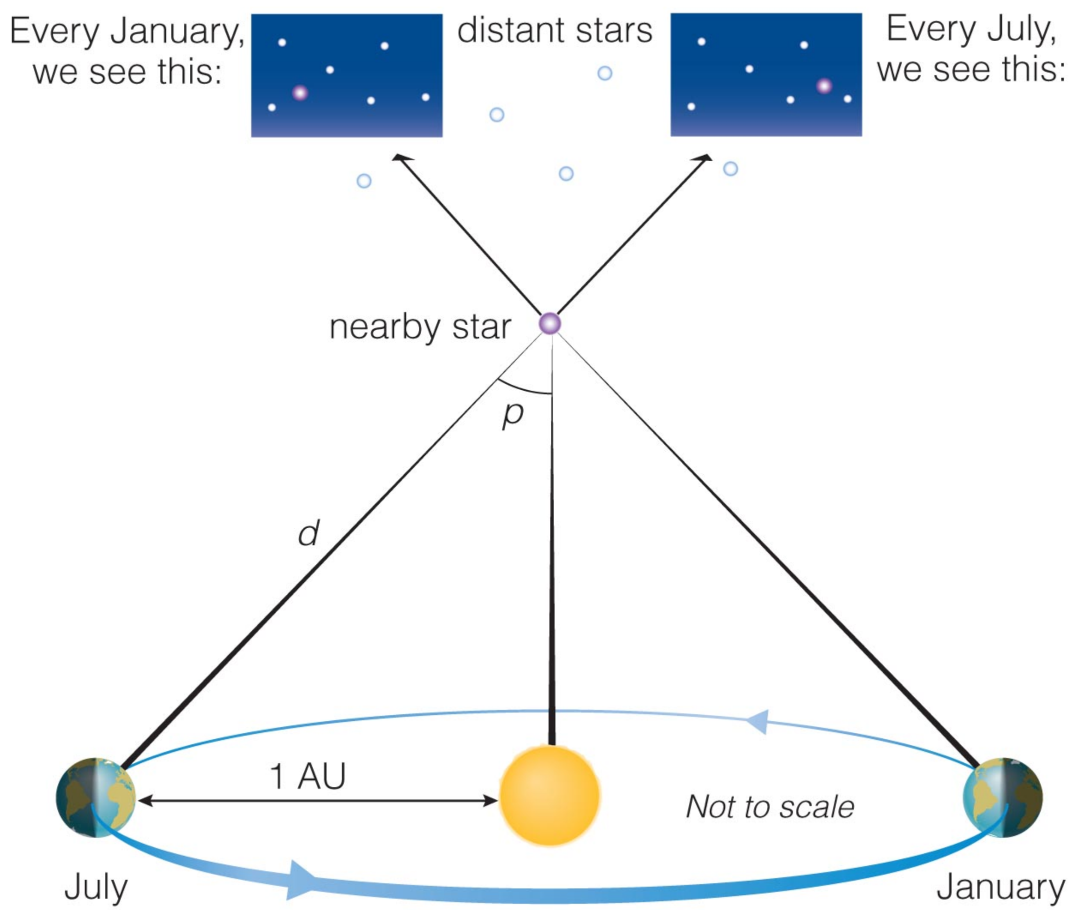
- In the previous lecture, we discussed some basic galaxy properties—composition, shape, color—based on visual appearance.
- But we can't determine other basic properties—size and luminosity—without knowing how far away galaxies are.
- We use a chain of techniques to measures distances to farther and farther objects: the *cosmic distance ladder.*



Step 1

Determine size of the solar system using **radar**.

This gives the length of 1 AU.



Step 2

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

$$d_{\mathrm{pc}} \cong 1/p_{\mathrm{arcsec}}$$

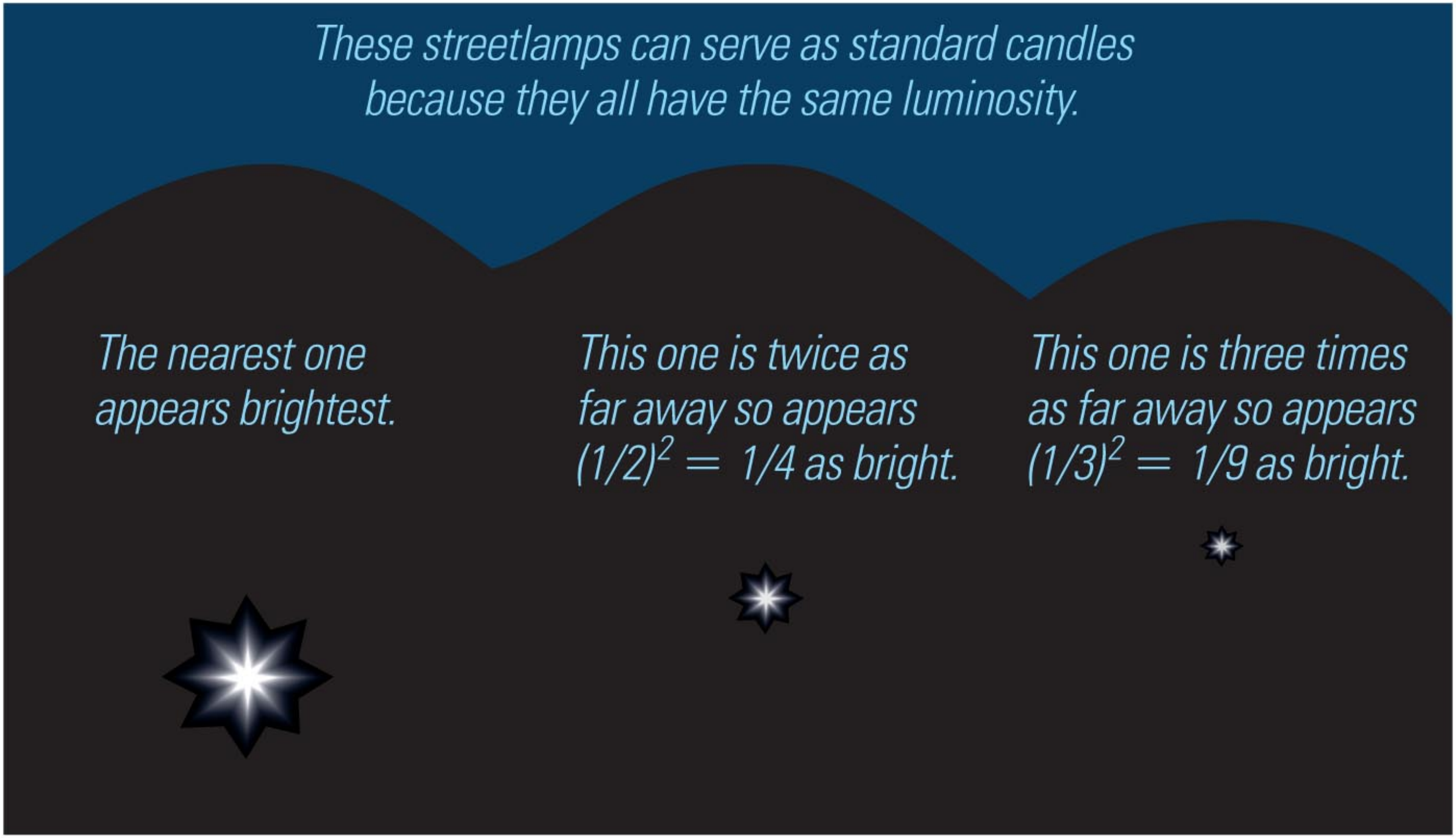
Standard Candles

- Recall, the relationship between apparent brightness (observed flux F) and luminosity L depends on distance d:

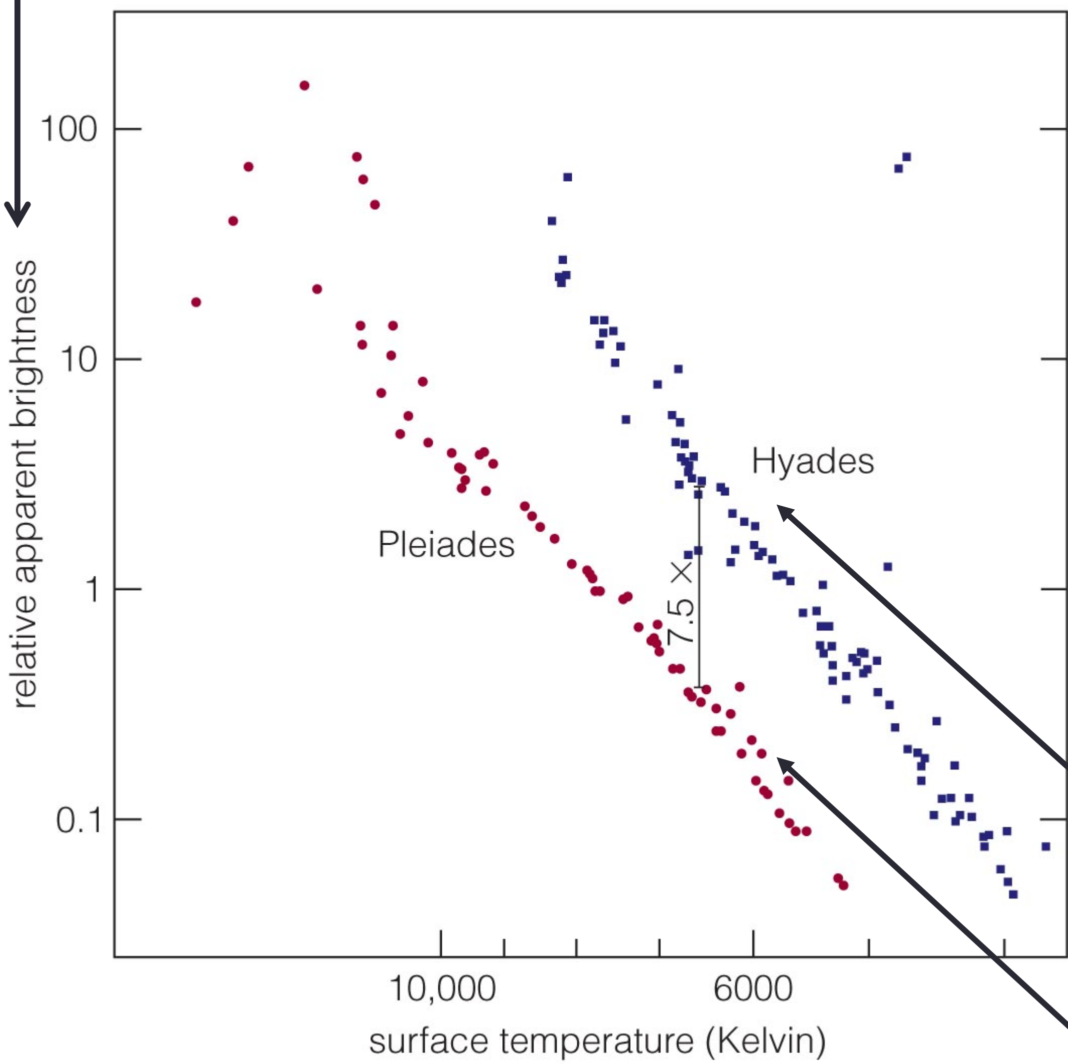
$$F_{\text{obs}} = \frac{L}{4\pi d^2}.$$

- A *standard candle* is an object whose luminosity we know without knowing its distance.
- If we can measure the apparent brightness of a standard candle of known luminosity, we get its distance:

$$d = \sqrt{\frac{L}{4\pi F_{\text{obs}}}}.$$


These streetlamps can serve as standard candles because they all have the same luminosity.
The nearest one appears brightest.
This one is twice as far away so appears $(1/2)^2 = 1/4$ as bright.
This one is three times as far away so appears $(1/3)^2 = 1/9$ as bright.

Apparent brightness—not a standard H-R diagram!



Step 2.5

See Lab 4!

Main-sequence fitting

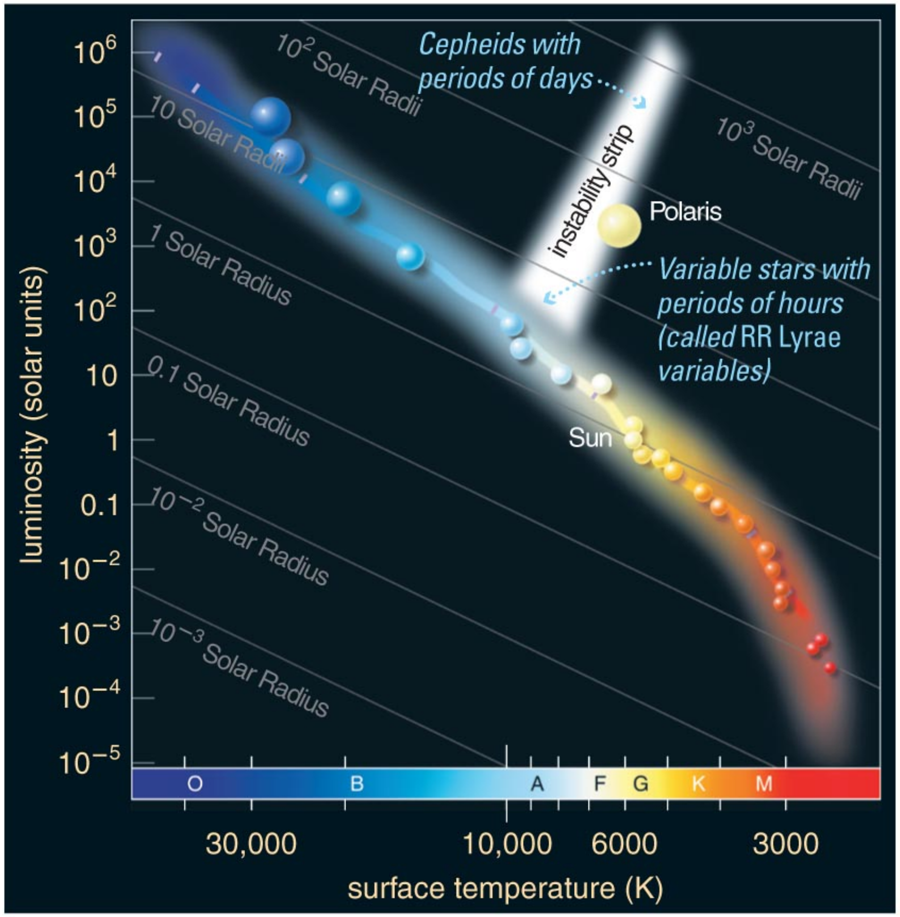
Apparent brightness of star cluster's main sequence tells us its distance.

Distance found by parallax.

2.75 × further away.

Knowing a star cluster's distance, we can determine the luminosity of each type of star within it.

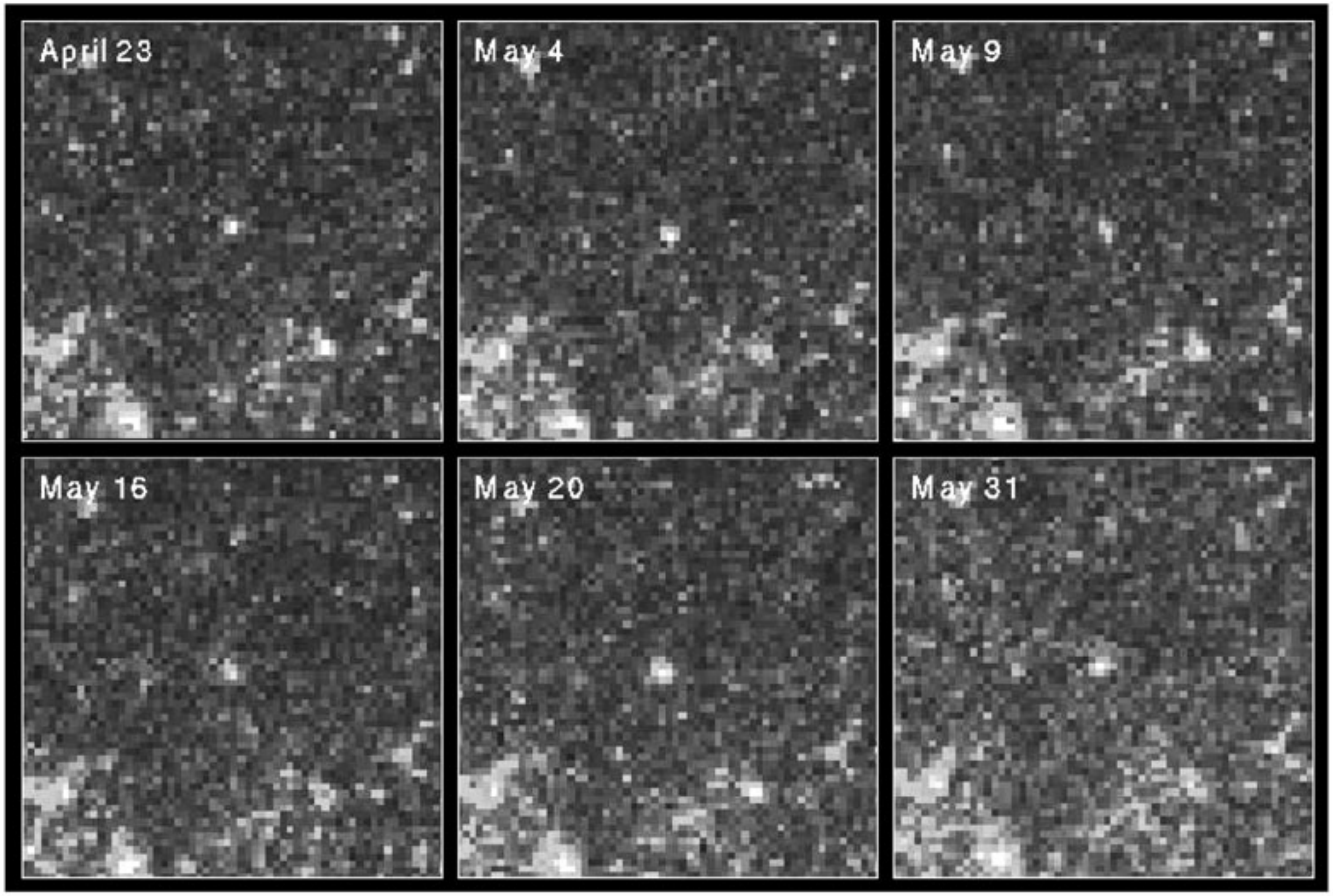
Variable Stars as Standard Candles



- Since brightness fades as distance squared, we need higher-luminosity standard candles to go further.
- Stars on the *instability strip* of the H-R diagram pulsate with a period that depends on the star's luminosity.
- The most luminous ones are known as *Cepheid variables*.

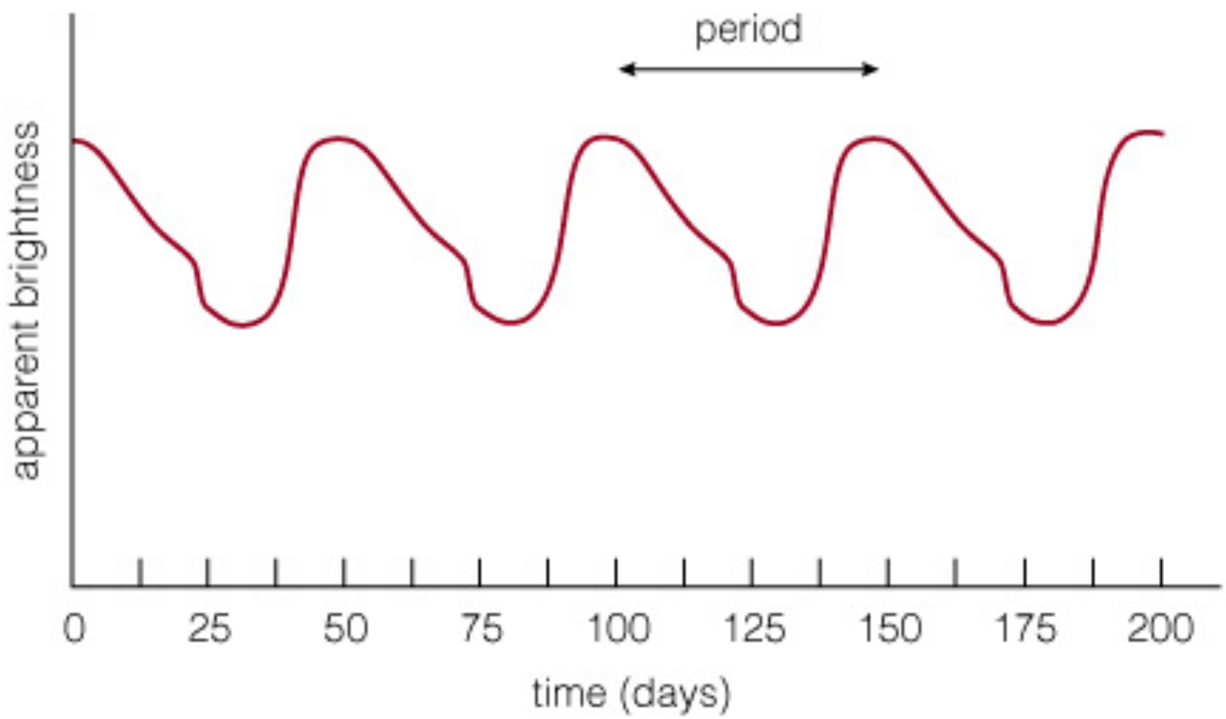
Variable Stars

- Any star that varies significantly in brightness with time is called a *variable star*.
- Some stars vary in brightness because they cannot achieve proper balance between power welling up from the core and power radiated from the surface.
  - *Detail*: For a given temperature, more luminous stars have larger radius. The dynamical time for a star to fall back under its own gravity goes as 1/sqrt(ρ). More massive (and thus brighter!) stars are less dense: temperature at the core T~M/R (virial theorem), T roughly constant, $\rho \propto M/R^3=(M/R)/R^2\sim 1/R^2$, so more luminous Cepheids have longer pulsation periods. (Here ρ is the density.)
- Such a star alternately expands and contracts, varying in brightness as it tries to find a balance.

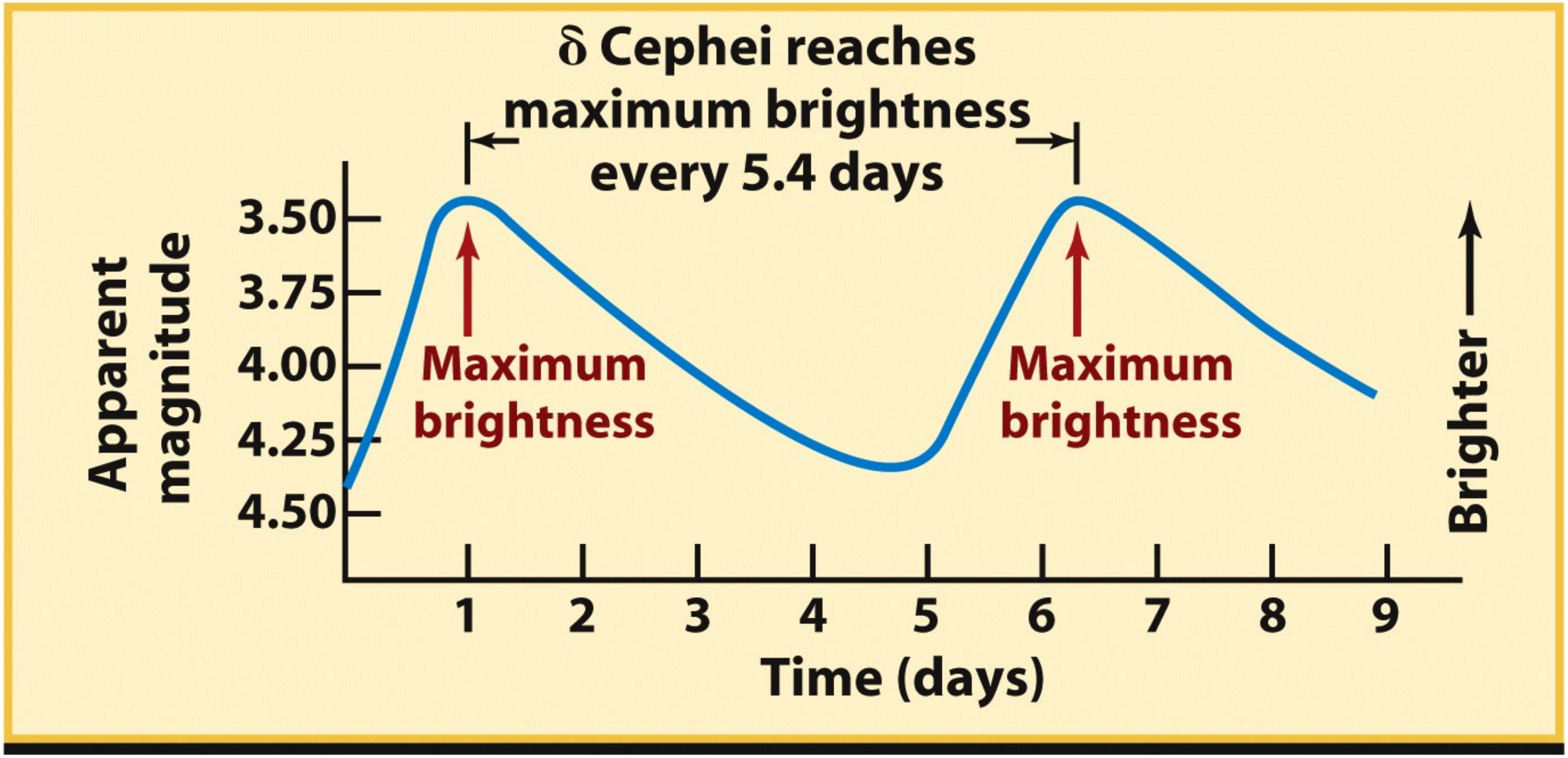


Cepheid variable star in M100 with period ~ one month.

Cepheid Variable Stars

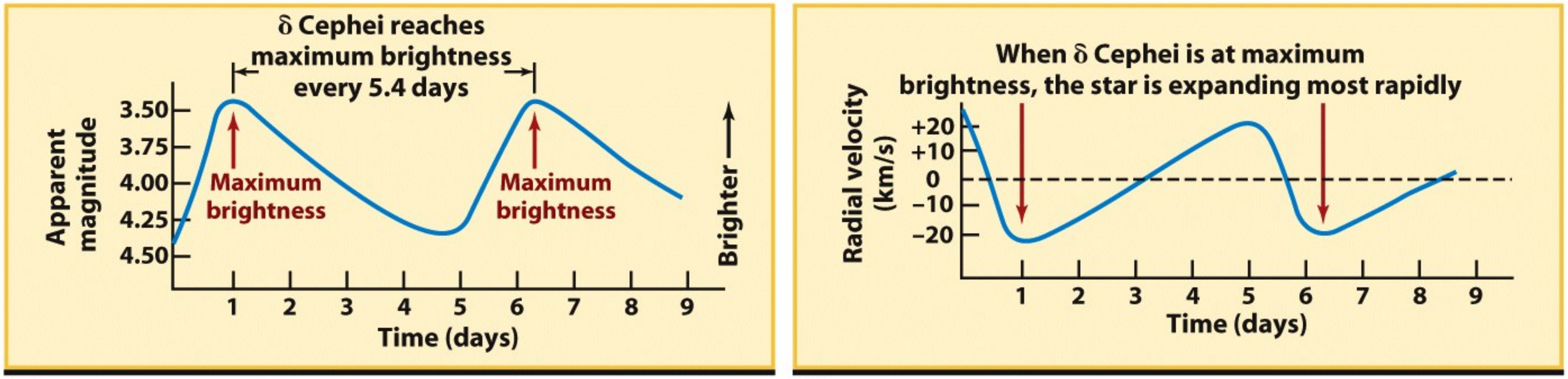


The light curve of this Cepheid variable star shows that its brightness alternately rises and falls over a 50-day period.



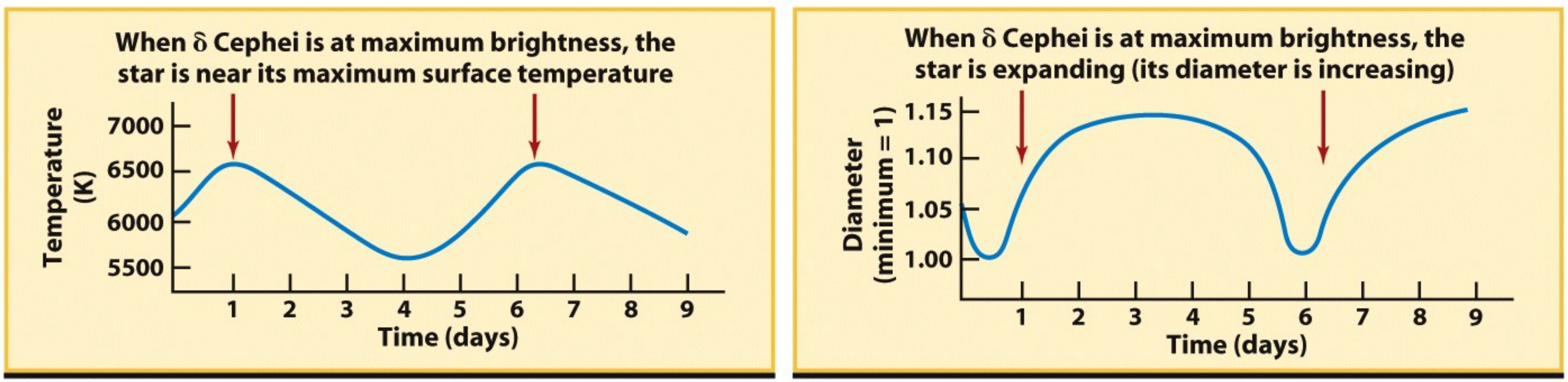
The light curve of δ Cephei (a graph of brightness versus time)

- Variability is caused by the radial pulsation of outer layers of star (due to ionization and deionization of He).



(a) The light curve of δ Cephei (a graph of brightness versus time)

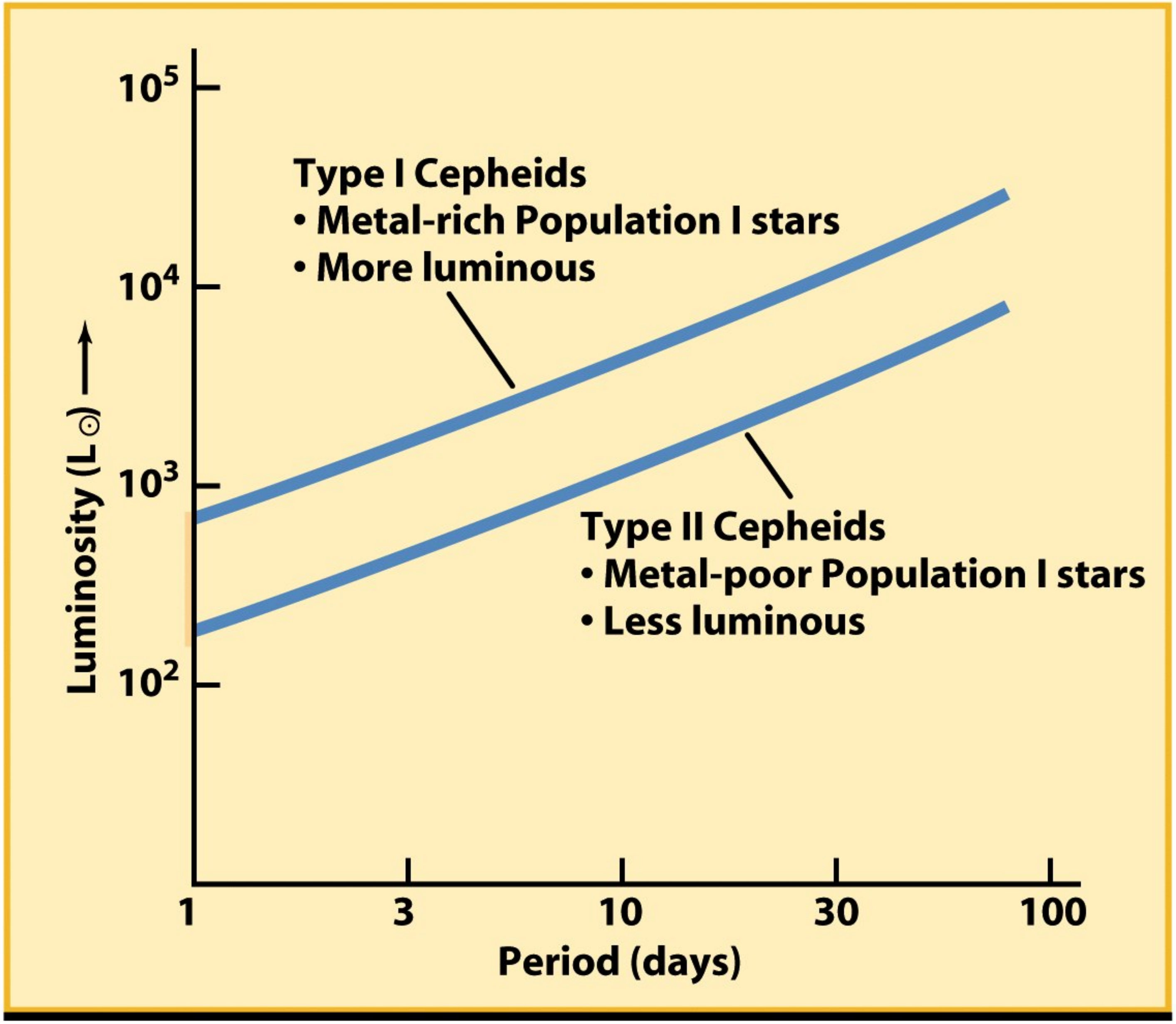
(b) Radial velocity versus time for δ Cephei (positive: star is contracting; negative: star is expanding)

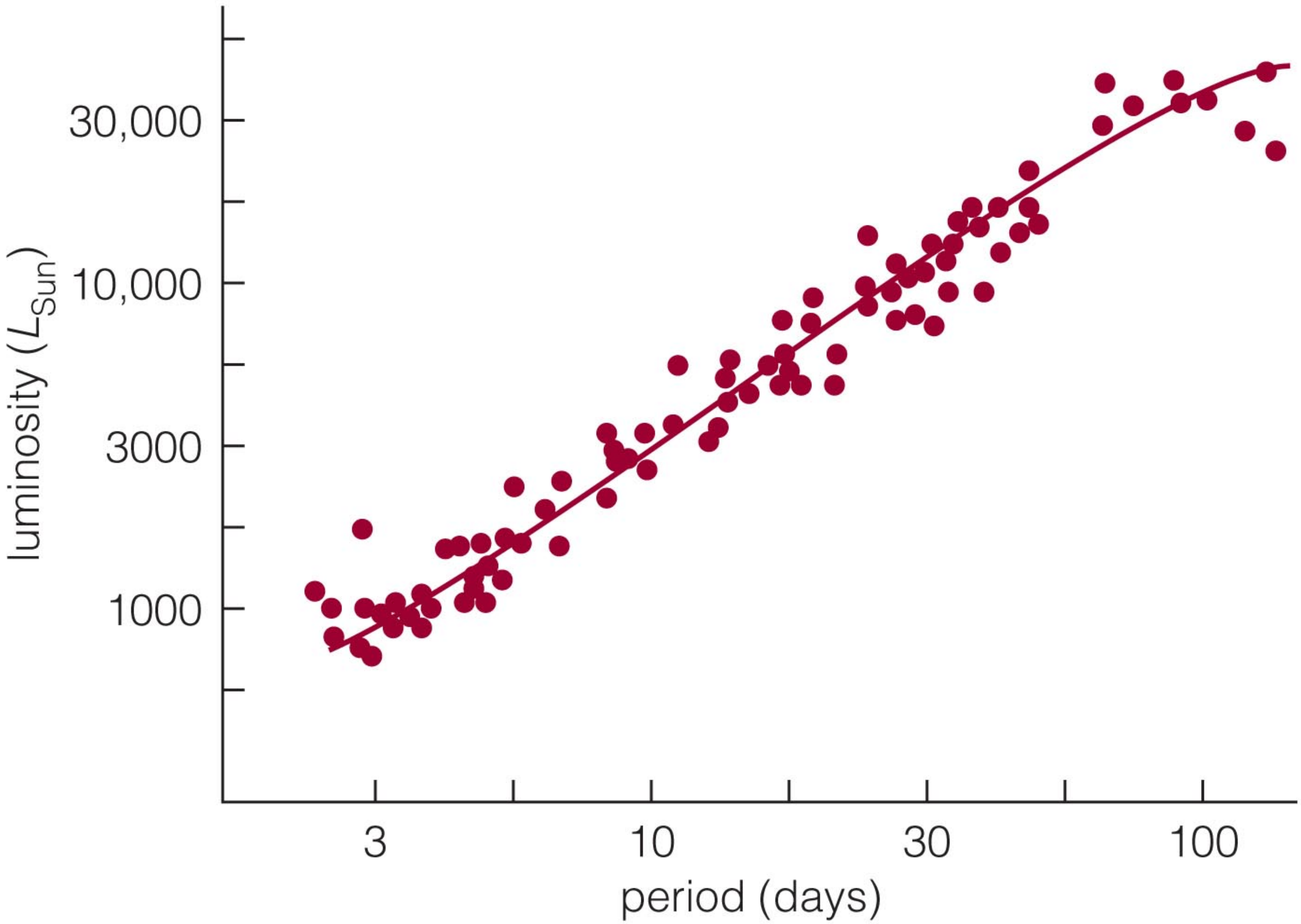


(c) Surface temperature versus time for δ Cephei

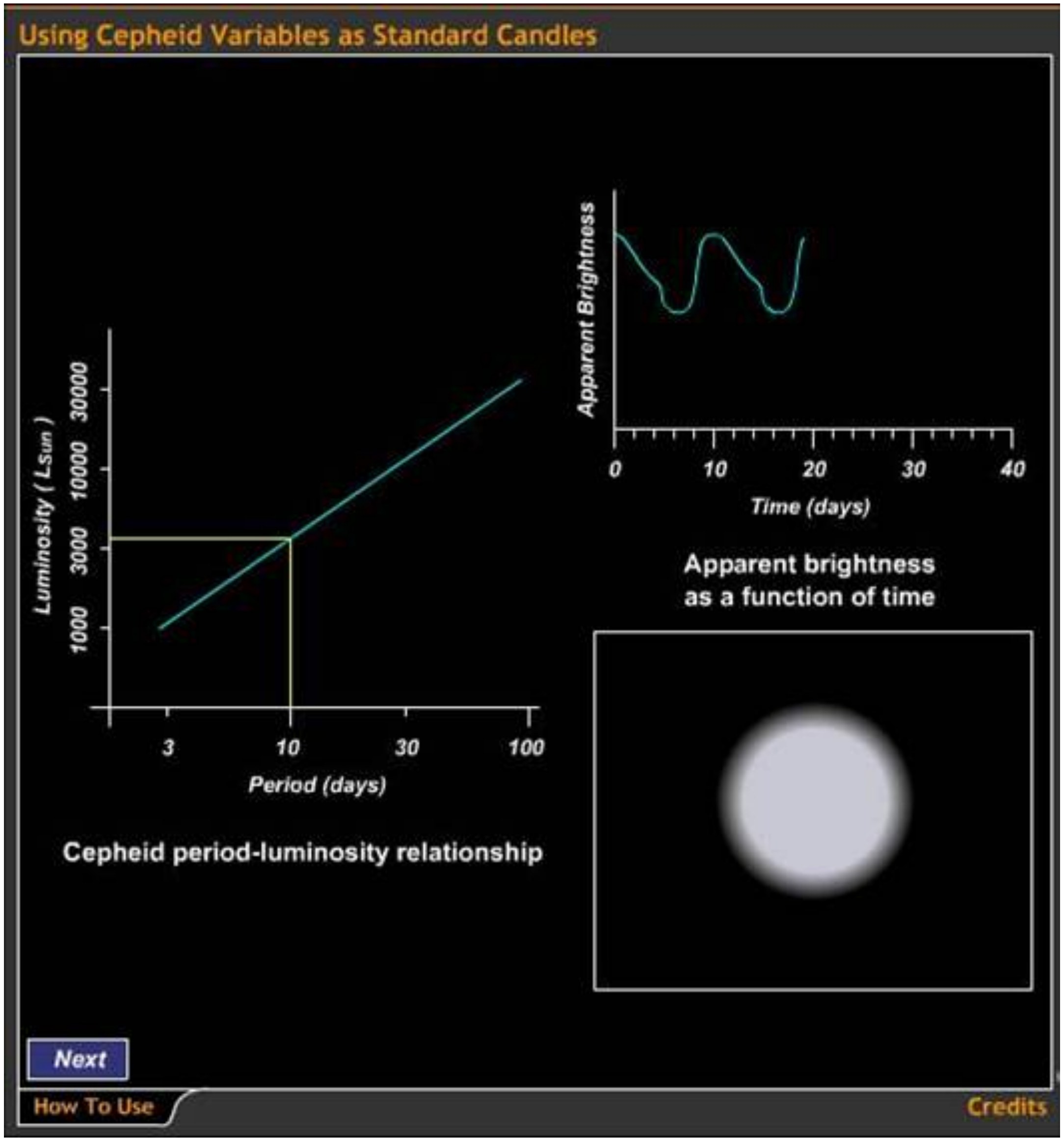
(d) Diameter versus time for δ Cephei

Important to note: the rate of fusion isn't changing significantly! Just the rate at which photons *leave* the star, and their energies


Type I Cepheids
• Metal-rich Population I stars
• More luminous
Type II Cepheids
• Metal-poor Population I stars
• Less luminous
Luminosity (L☉)
10^5
10^4
10^3
10^2
1
3
10
30
100
Period (days)



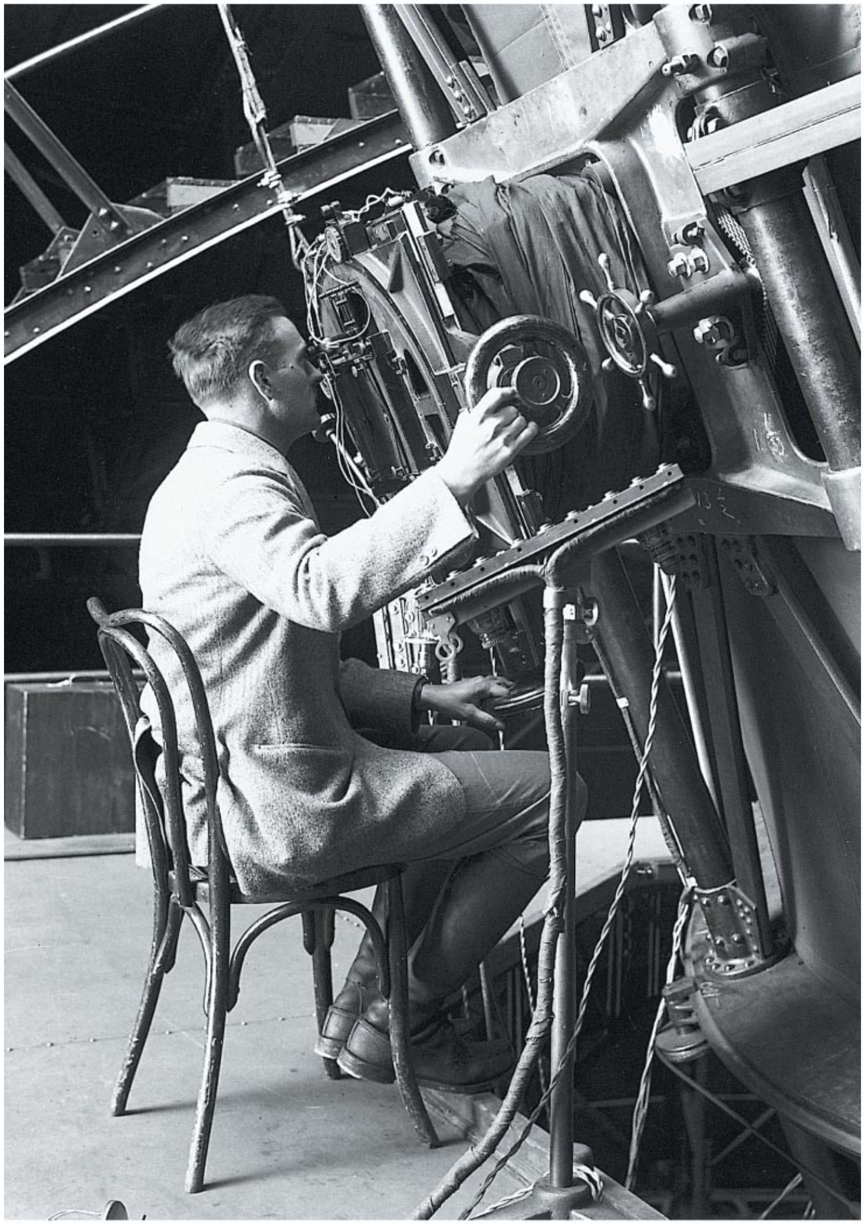
Cepheid variable stars with longer periods have greater luminosities.



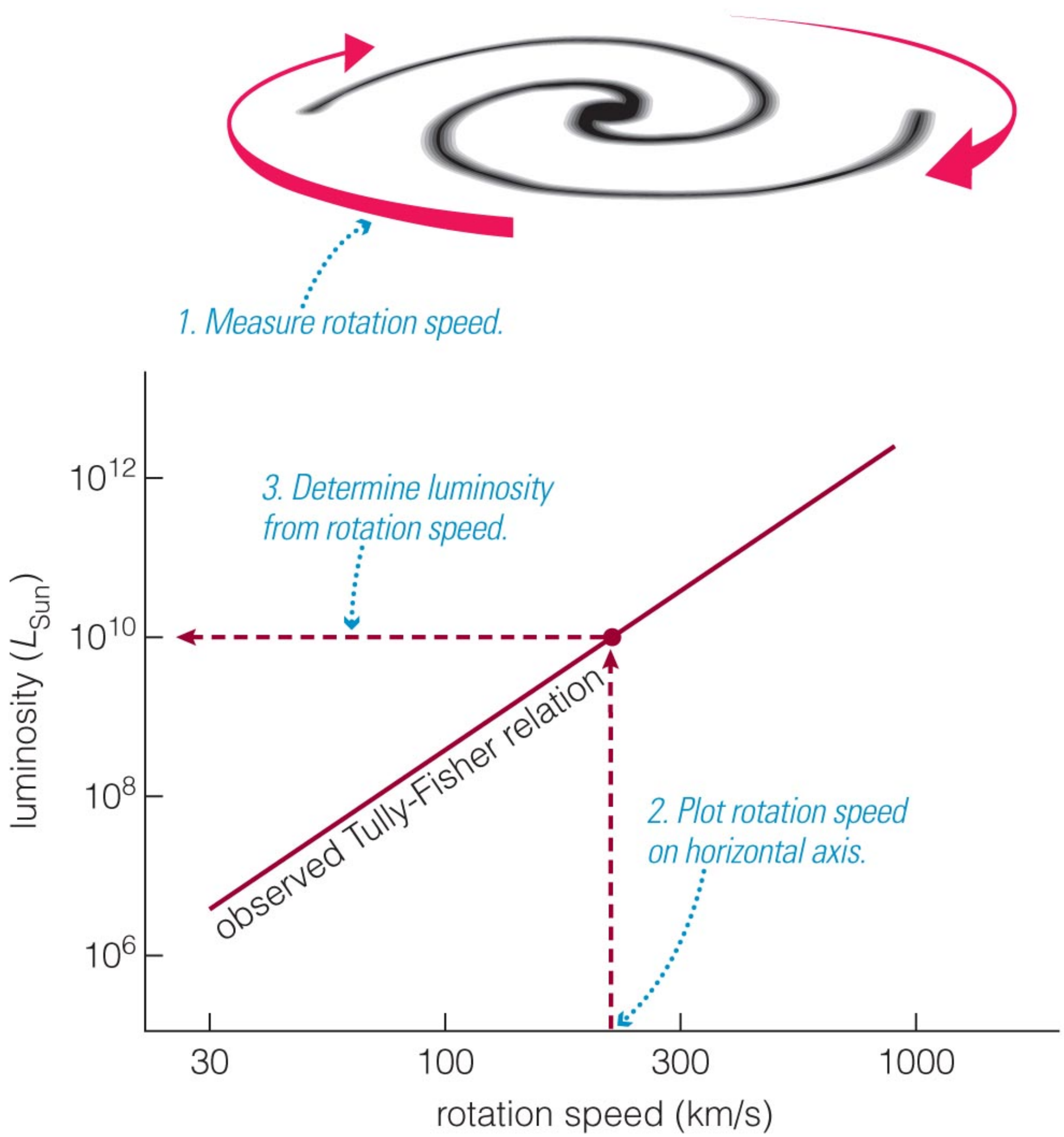
Step 3

Because the period of **Cepheid variable stars** tells us their luminosities, we can use them as standard candles.

Historical note: Henrietta Leavitt is credited with discovering this relation. She did this by looking at stars in the Small Magellanic Cloud; all basically at the same distance from us.



Edwin Hubble, using Cepheids as standard candles, was the first to measure distances to other galaxies.

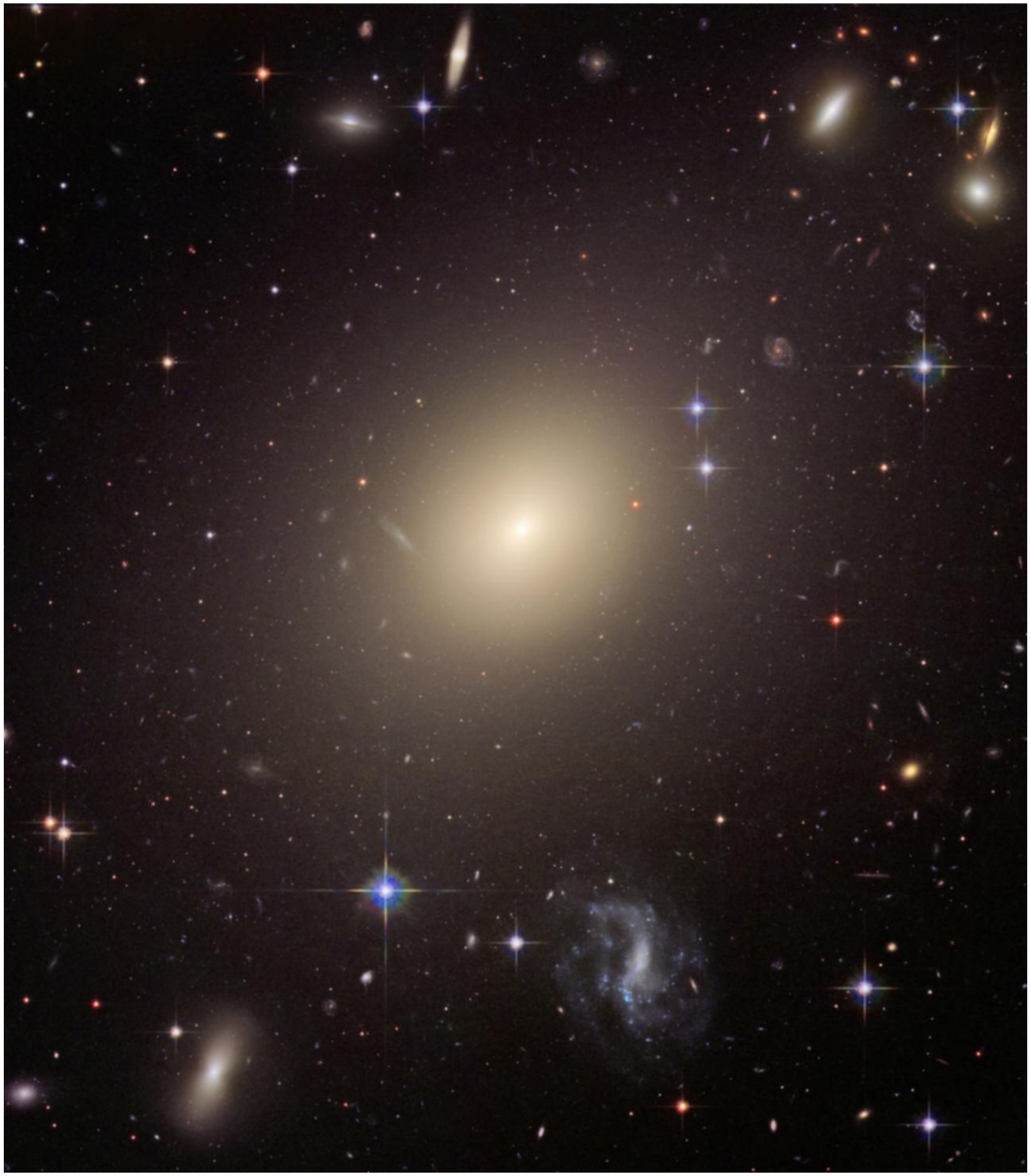


Step 3.5

Tully-Fisher Relation

Spiral *galaxies* can also be used as standard candles because a spiral's luminosity is related to its rotation speed.

$$L \propto v^4$$

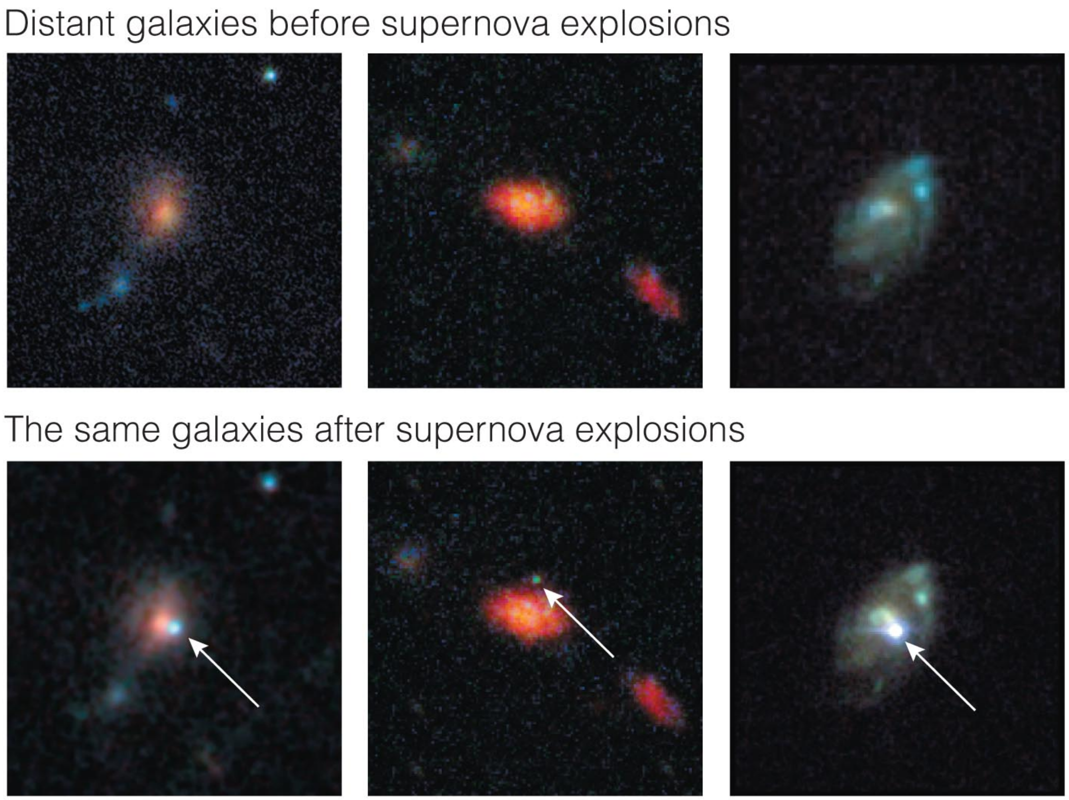


Step 3.5

Faber-Jackson Relation

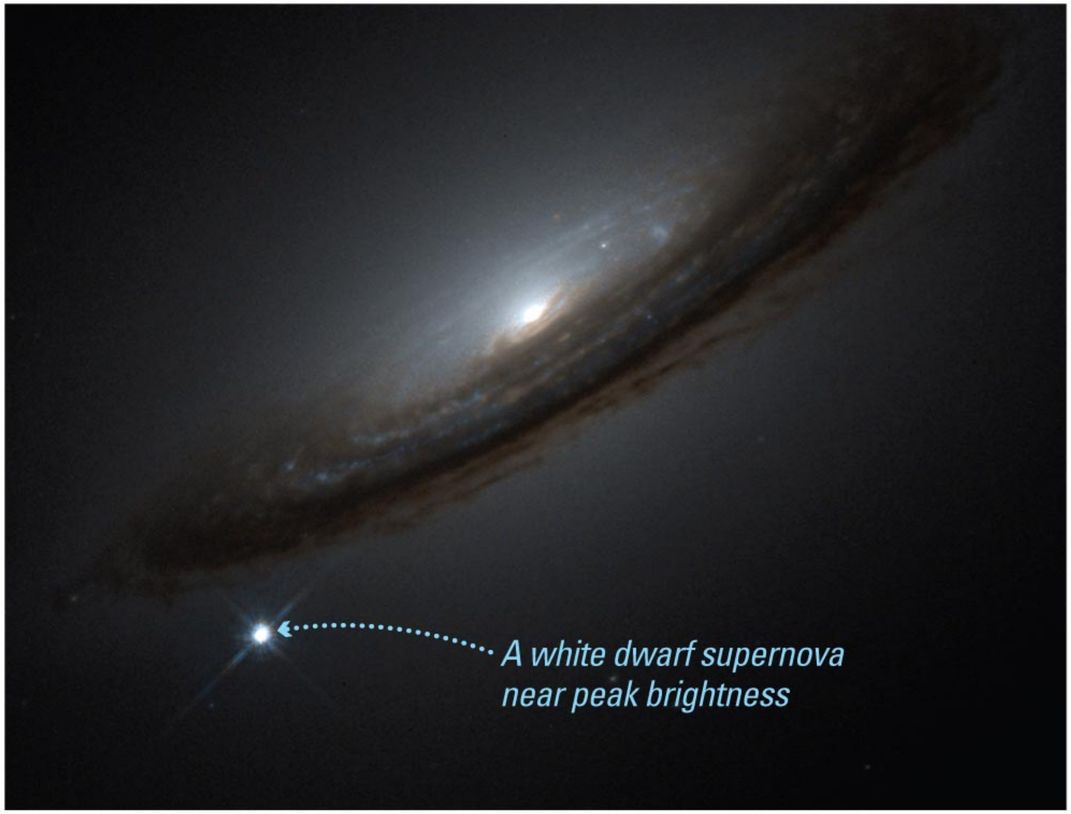
Elliptical galaxies have a similar relation based on their central velocity dispersion σ.

$$L \propto \sigma^4$$



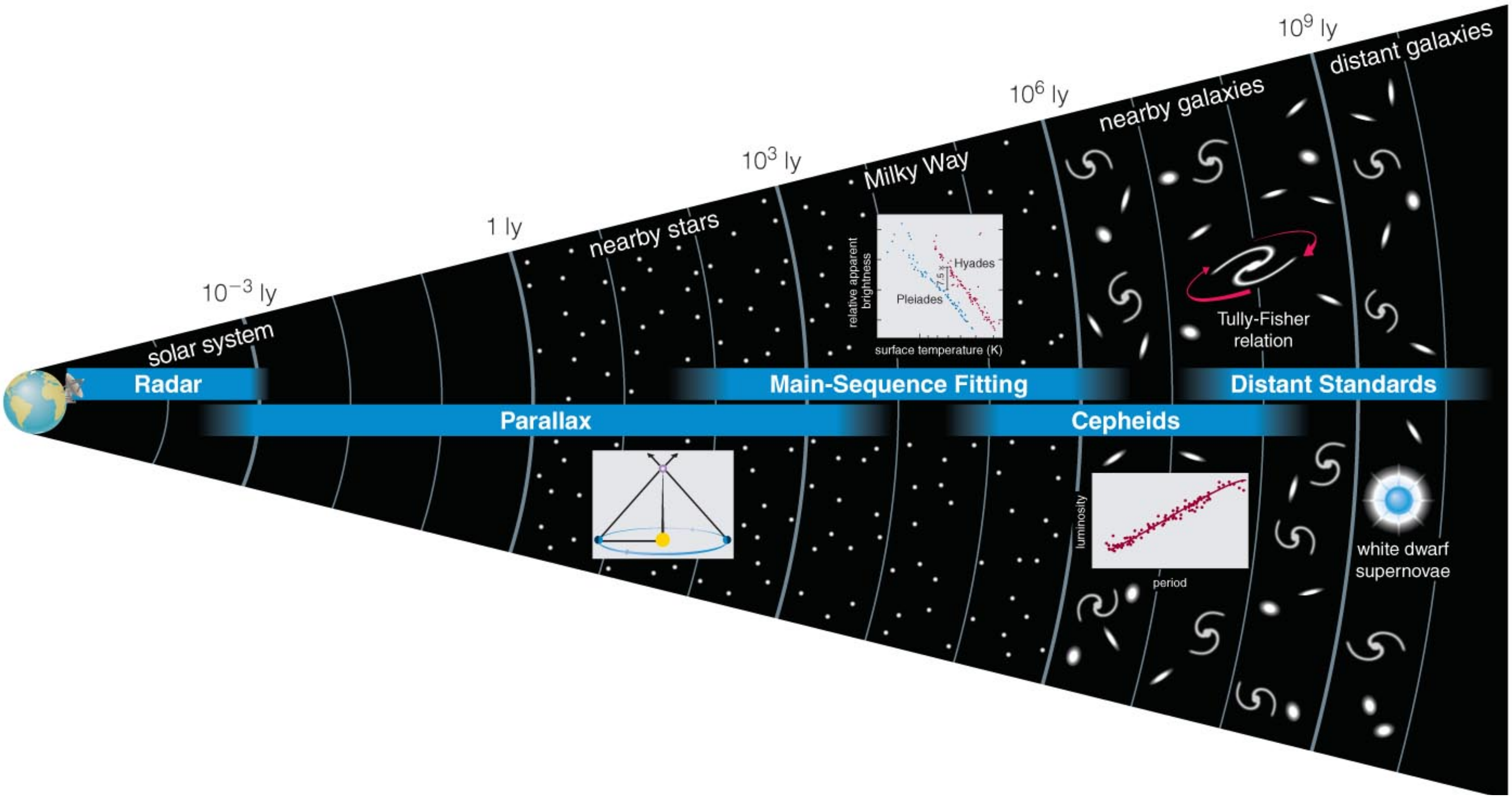
Step 4

The apparent brightness of a **white dwarf supernova** tells us the distance to host galaxy (up to 10 billion light-years).



White-dwarf supernovae can be used as standard candles because their peak luminosities are very strongly related to the time their flux takes to decrease.

We measure galaxy distances using a chain of interdependent techniques.



Measuring Galaxy Properties

- Mass: use rotation curves for spirals, velocity dispersion for ellipticals (broadening of spectral lines).
- Luminosity: given by distance and apparent brightness.
- Size (diameter): given by distance and angular size.
- Summary:

	Spirals	Ellipticals	Irregulars
Mass ($M_\odot$)	$10^{9–12}$	$10^{5–13}$	$10^{8–10}$
Luminosity ($L_\odot$)	$10^8 – 2\times10^{10}$	$3\times10^5 – 10^{11}$	$10^{7–9}$
Diameter (kpc)	5–250	1–200	1–10