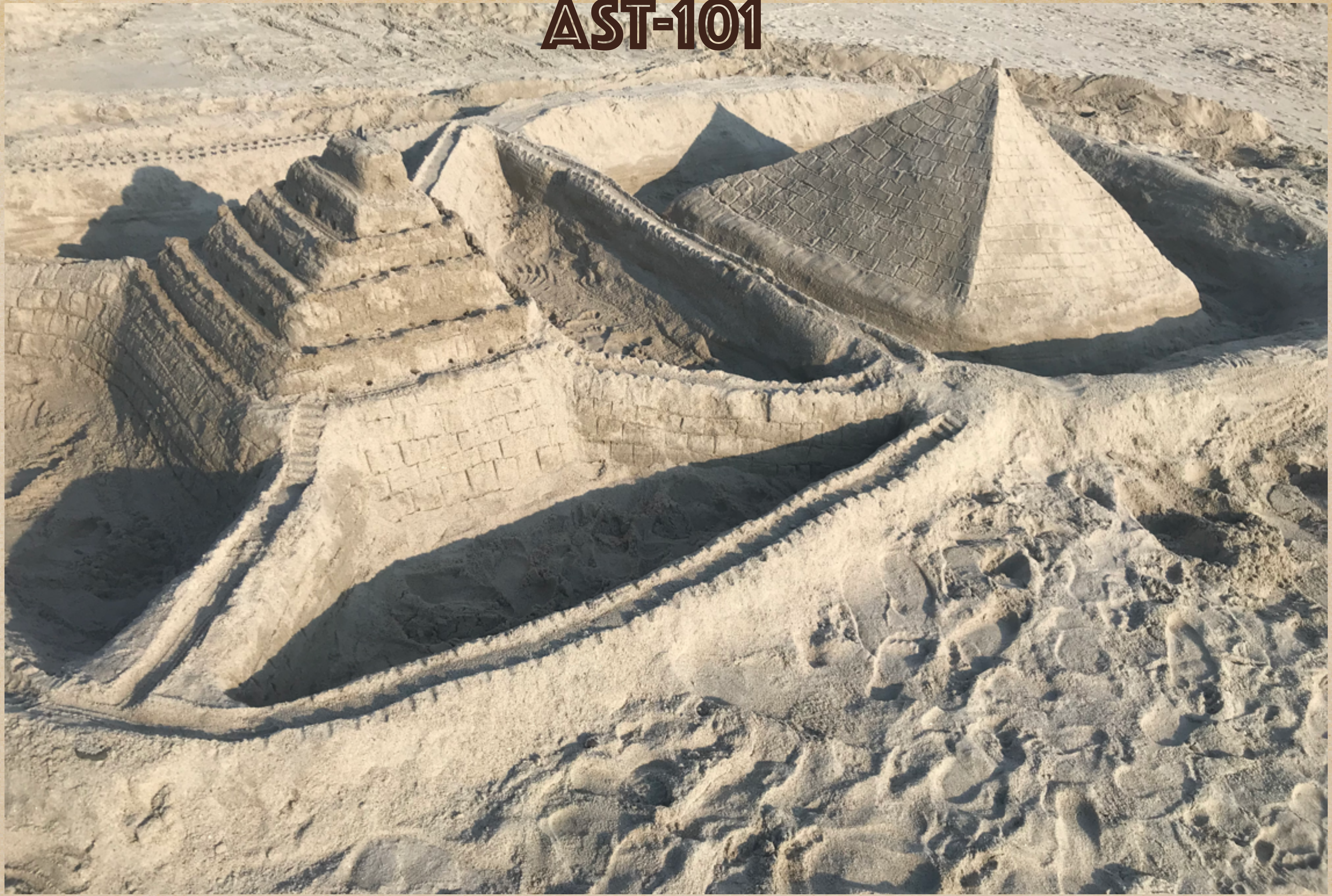
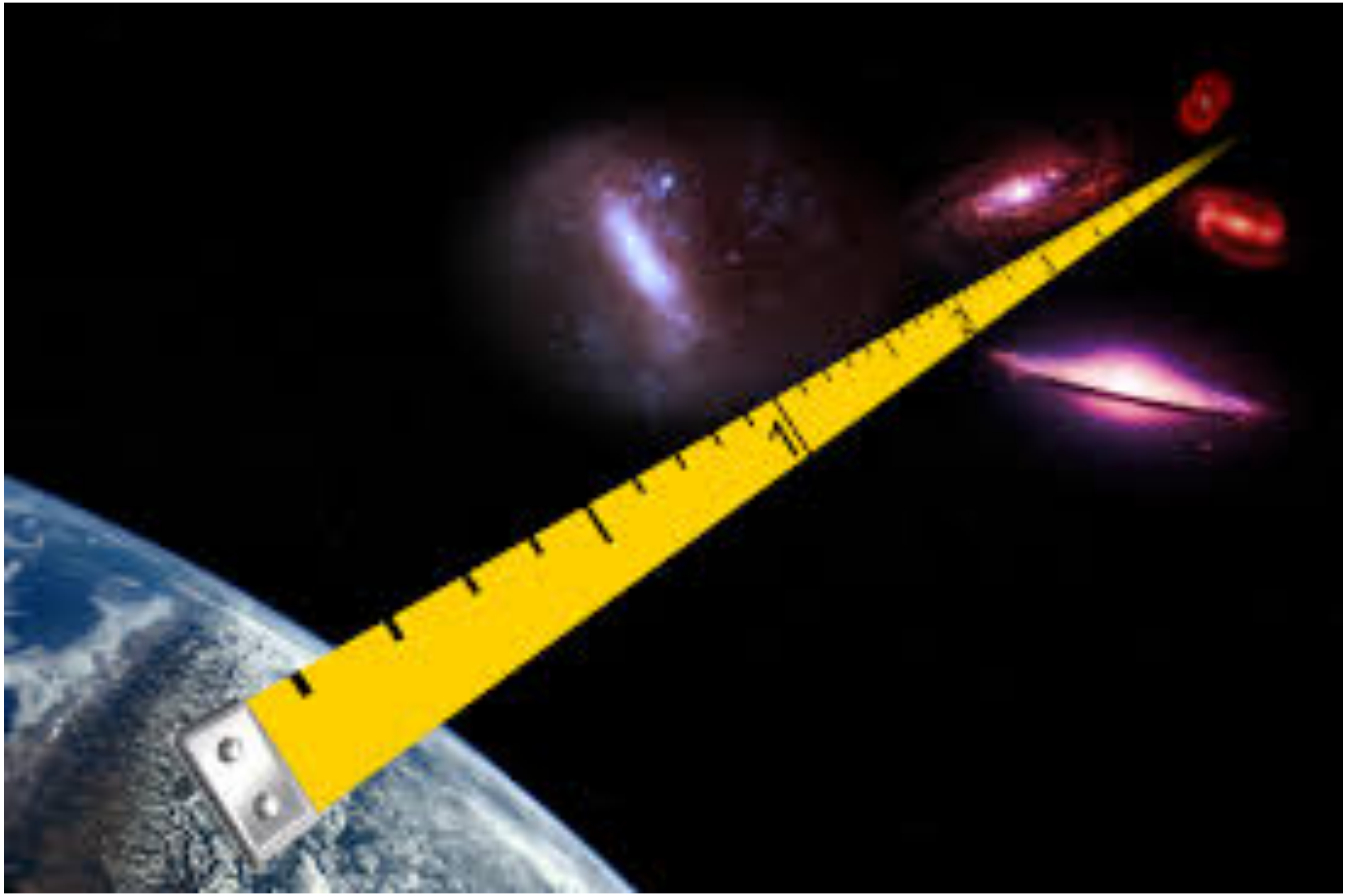
AST-101



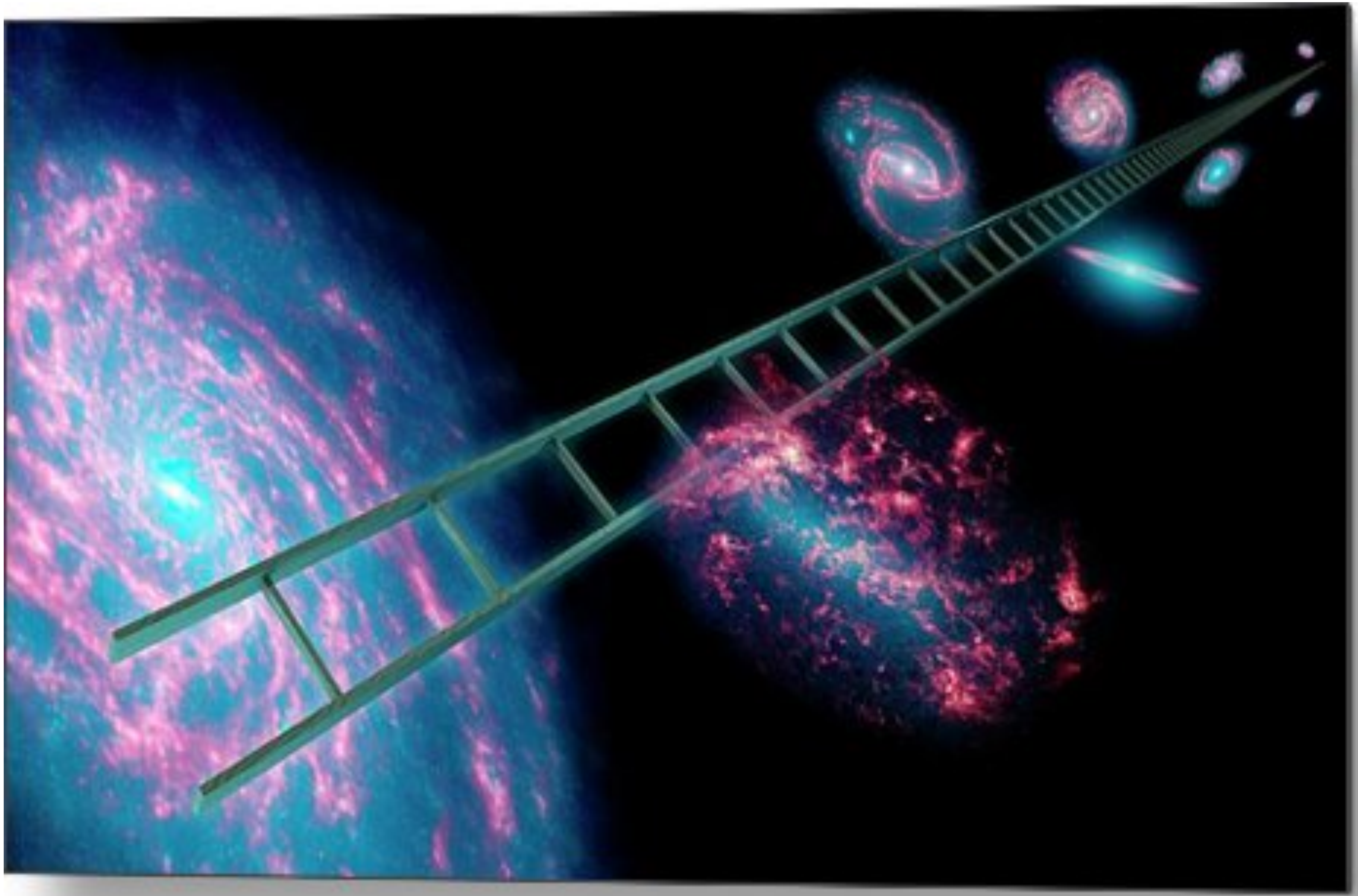
The H_0 Tension

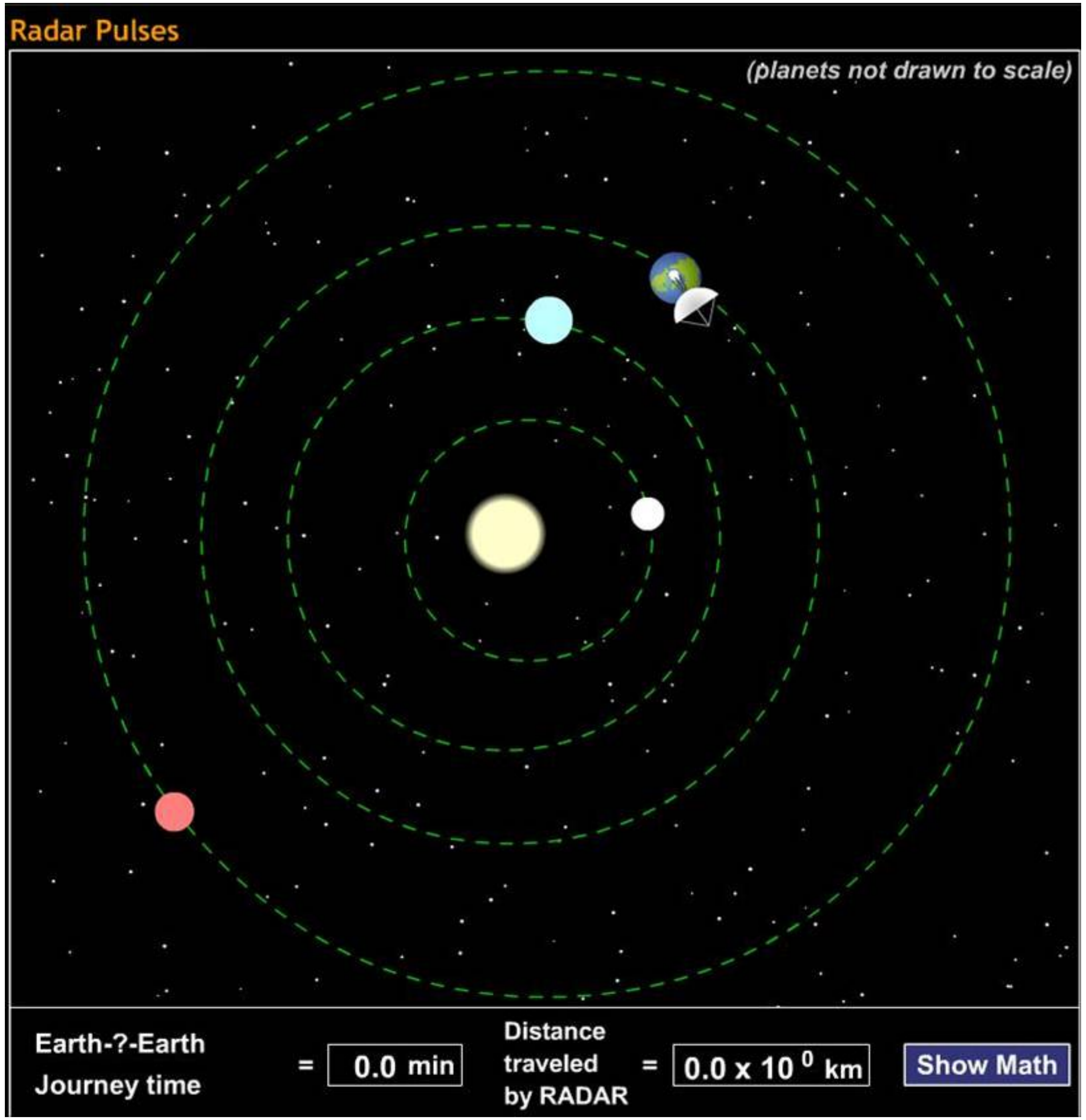
Luis Anchordoqui

HOW DO WE MEASURE THE DISTANCE TO A PLACE WE CANNOT GO?



The Cosmic Distance Ladder

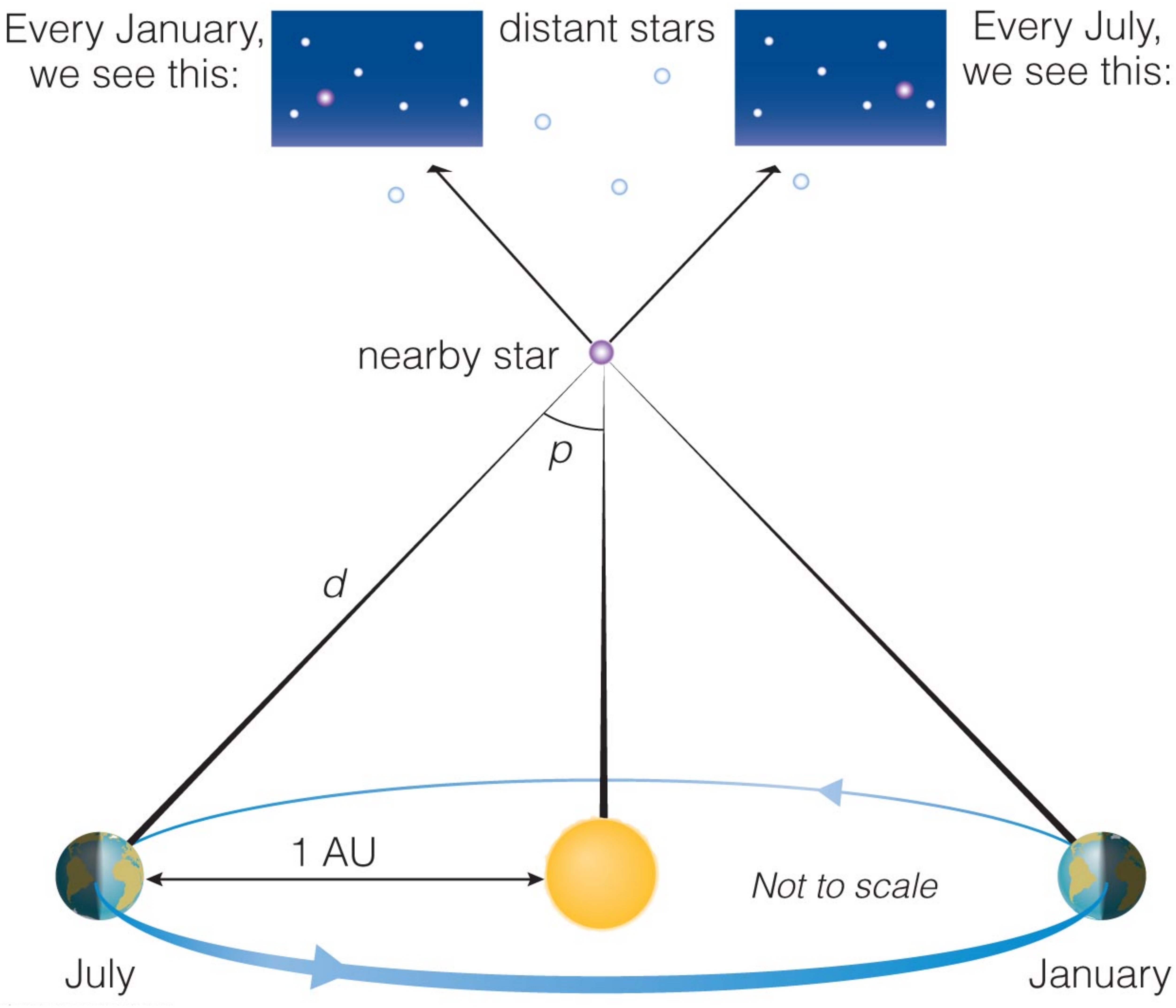




Step 1

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

This gives the length of 1 AU.

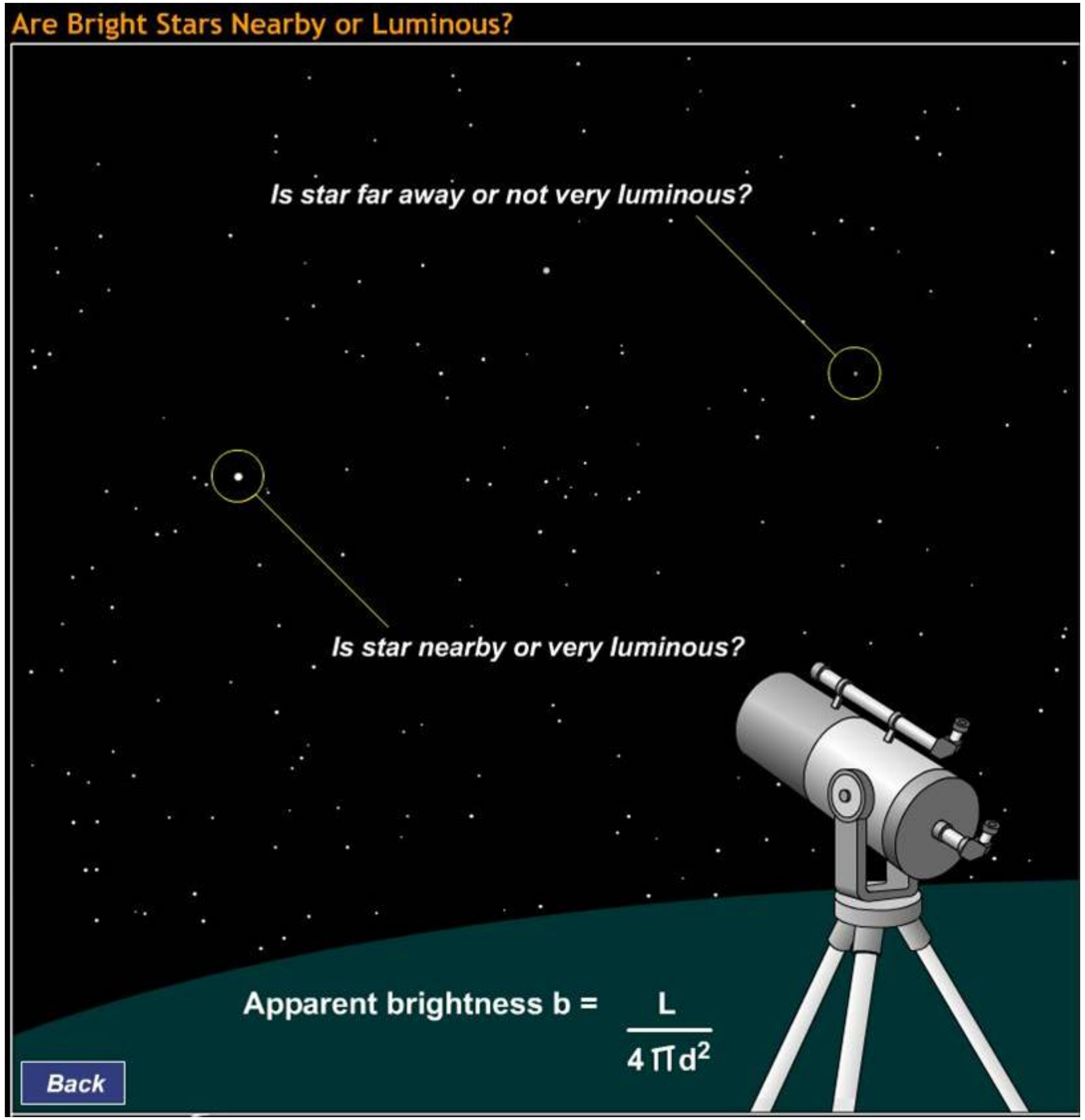


Step 2

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

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

Unknown Distances



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

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.

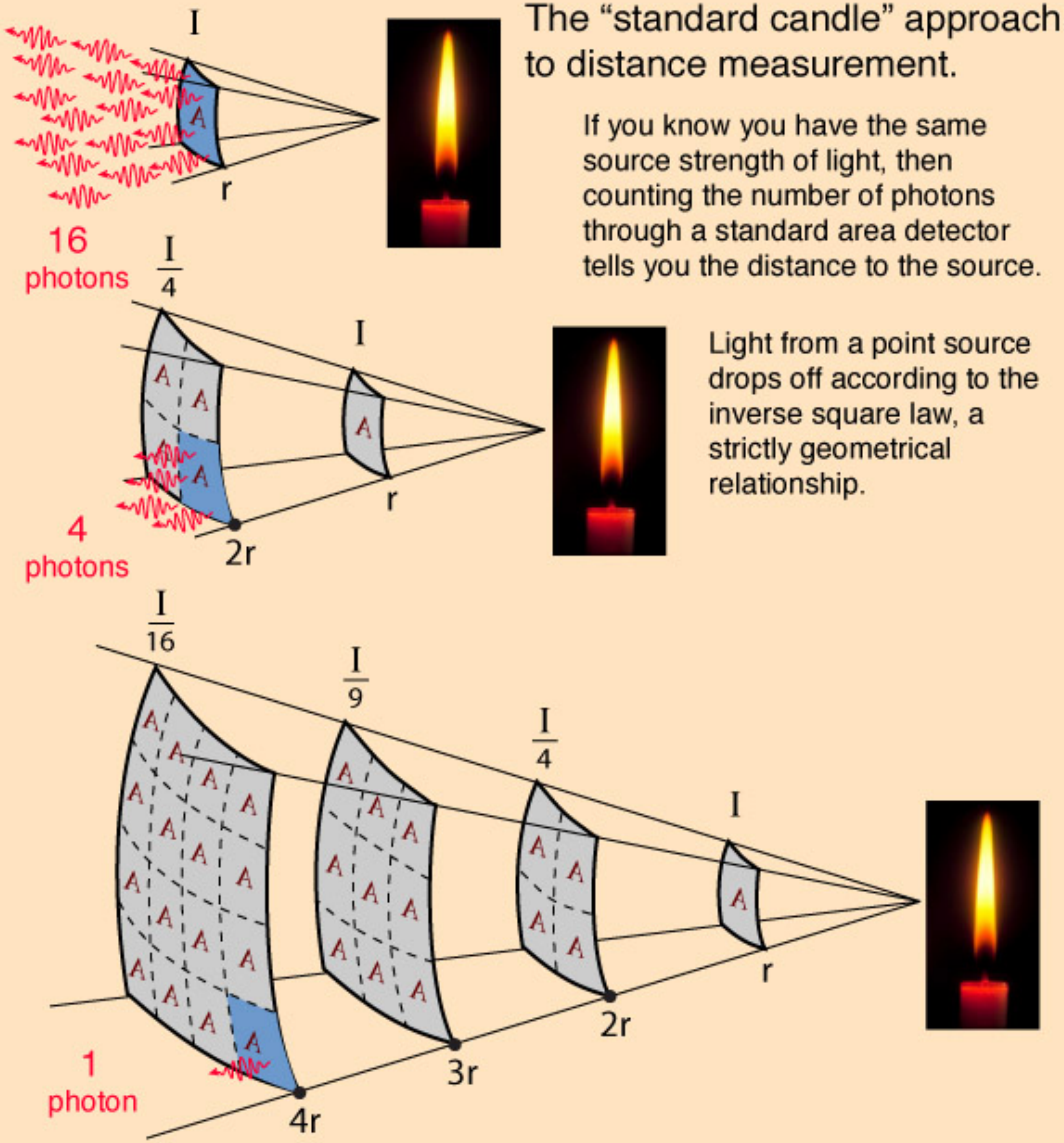
This one is twice as far away so appears $(1/2)^2 = 1/4$ as bright.

This one is three times as far away so appears $(1/3)^2 = 1/9$ as bright.

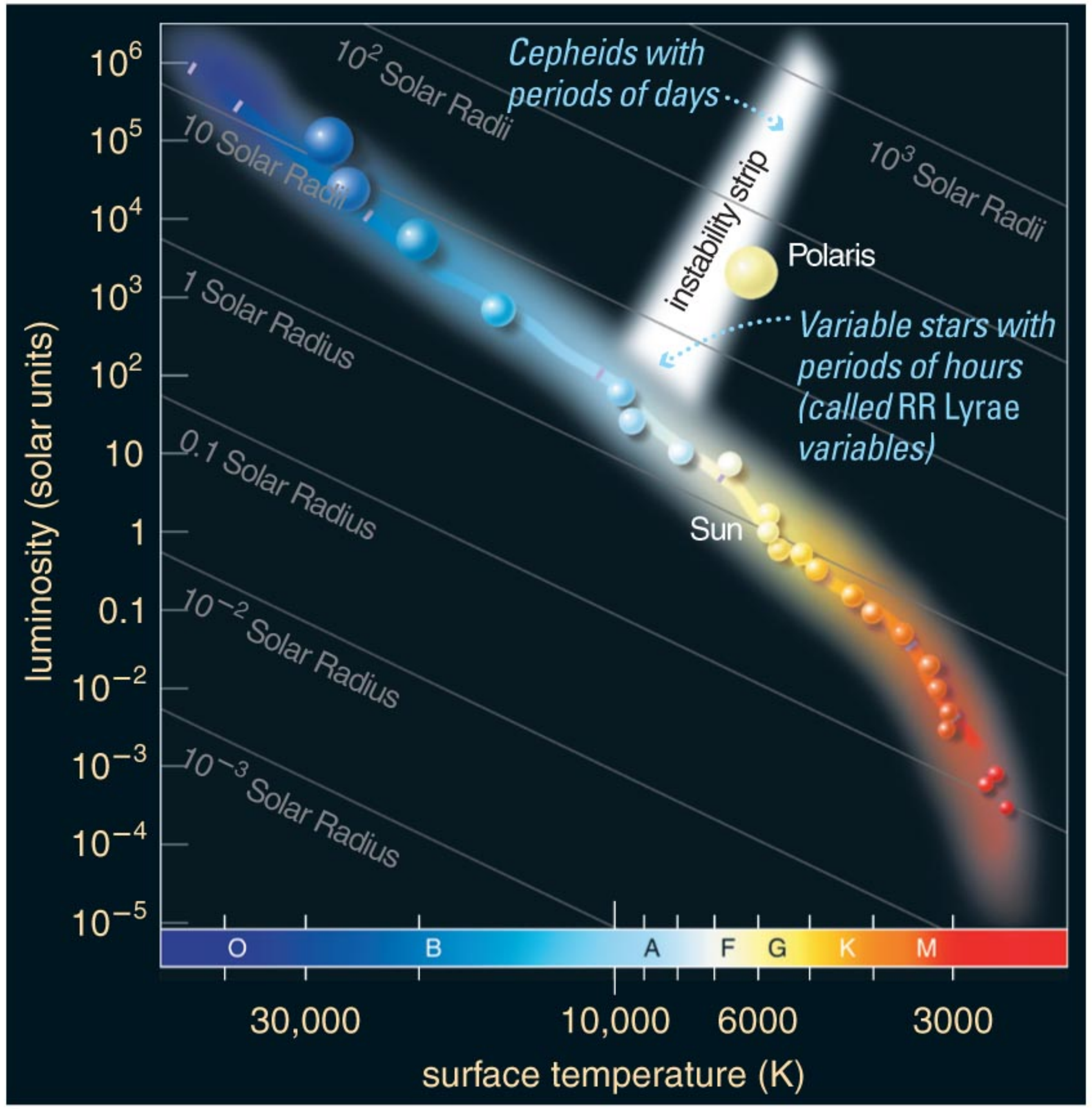
The "standard candle" approach to distance measurement.

If you know you have the same source strength of light, then counting the number of photons through a standard area detector tells you the distance to the source.

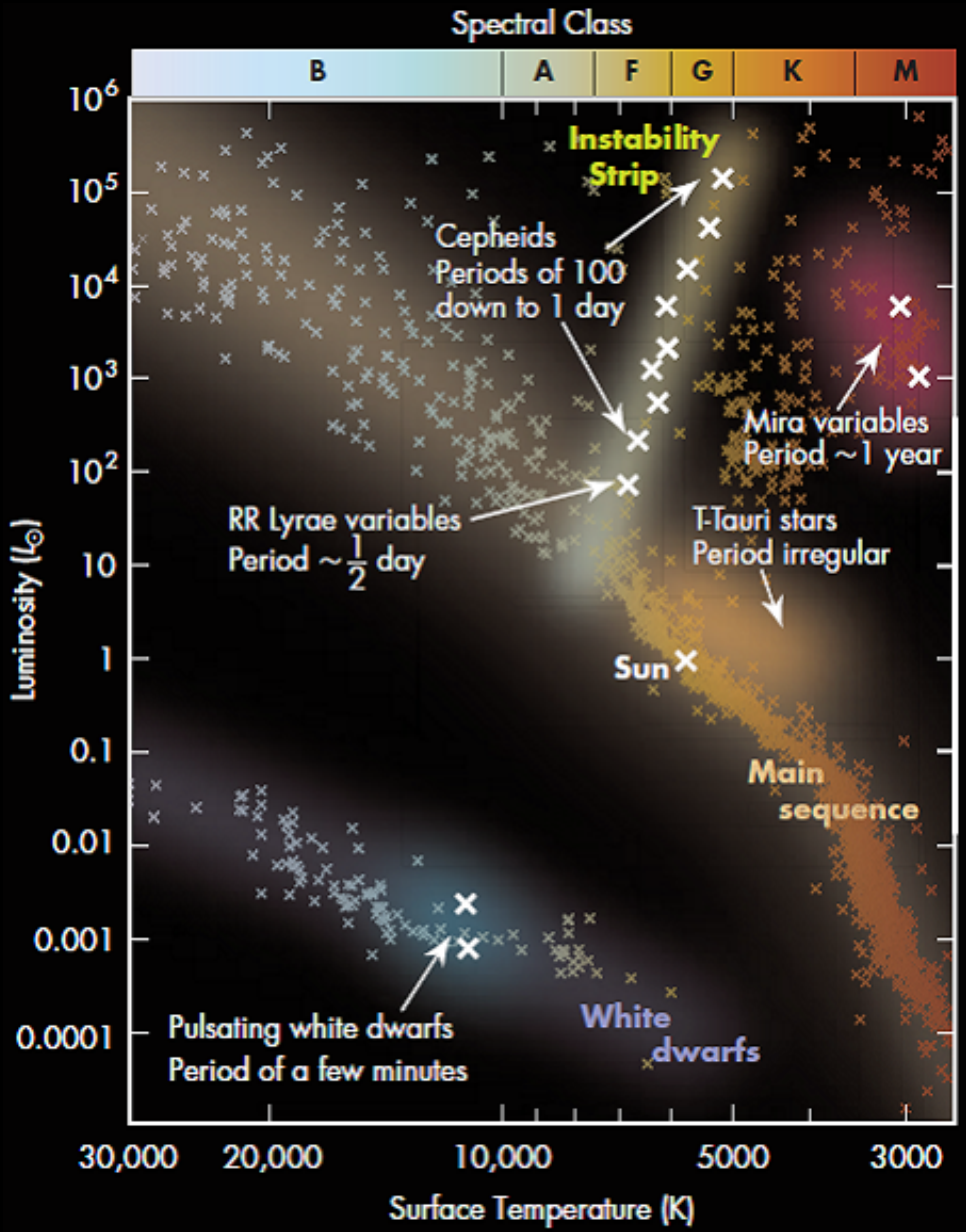
Light from a point source drops off according to the inverse square law, a strictly geometrical relationship.



Variable Stars as Standard Candles

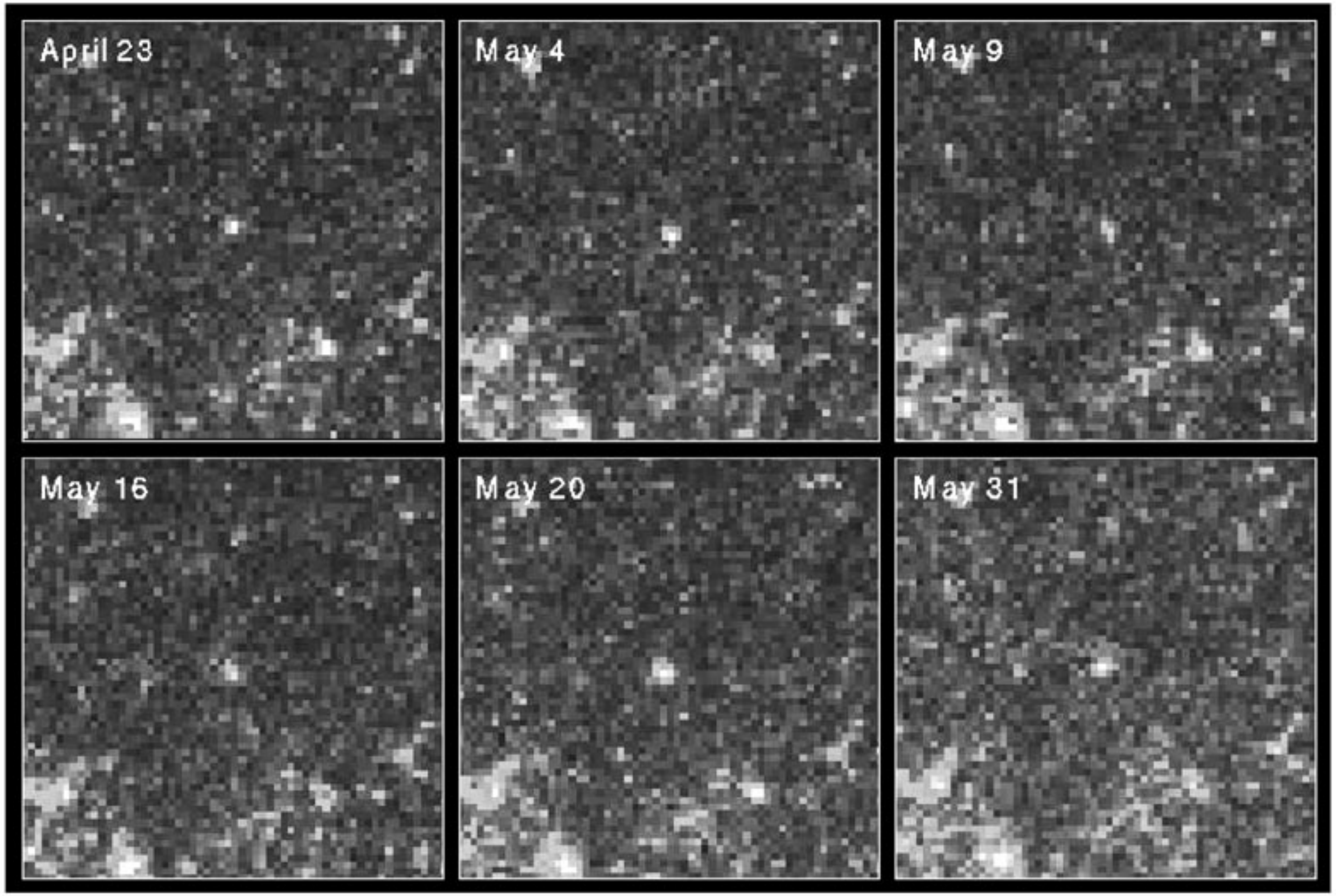


- Since brightness fades as distance squared, we need higher-luminosity standard candles to go further.
- Stars on the *instability strip* of the H-R diagram pulsate with a period that depends on the star's luminosity.
- The most luminous ones are known as *Cepheid variables*.


Spectral Class
B
A
F
G
K
M
Instability Strip
Cepheids
Periods of 100
down to 1 day
Mira variables
Period ~1 year
RR Lyrae variables
Period ~ $\frac{1}{2}$ day
T-Tauri stars
Period irregular
Sun
Main
sequence
White
dwarfs
Pulsating white dwarfs
Period of a few minutes
Luminosity ($L_\odot$)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
0.01
0.001
0.0001
30,000
20,000
10,000
5000
3000
Surface Temperature (K)

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.

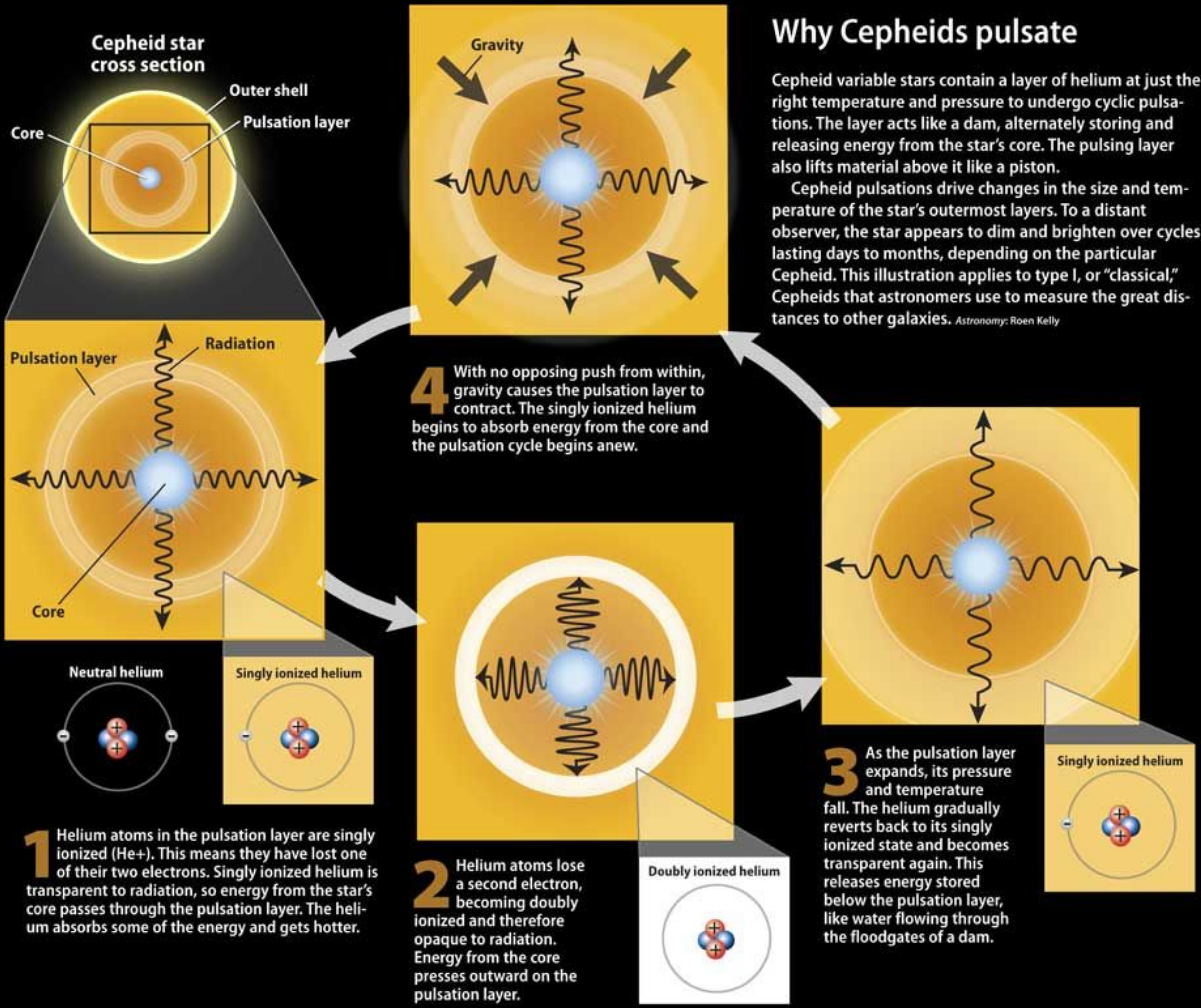


Cepheid variable star in M100 with period ~ one month.

Why Cepheids pulsate

Cepheid variable stars contain a layer of helium at just the right temperature and pressure to undergo cyclic pulsations. The layer acts like a dam, alternately storing and releasing energy from the star's core. The pulsing layer also lifts material above it like a piston.

Cepheid pulsations drive changes in the size and temperature of the star's outermost layers. To a distant observer, the star appears to dim and brighten over cycles lasting days to months, depending on the particular Cepheid. This illustration applies to type I, or "classical," Cepheids that astronomers use to measure the great distances to other galaxies. *Astronomy*: Roen Kelly

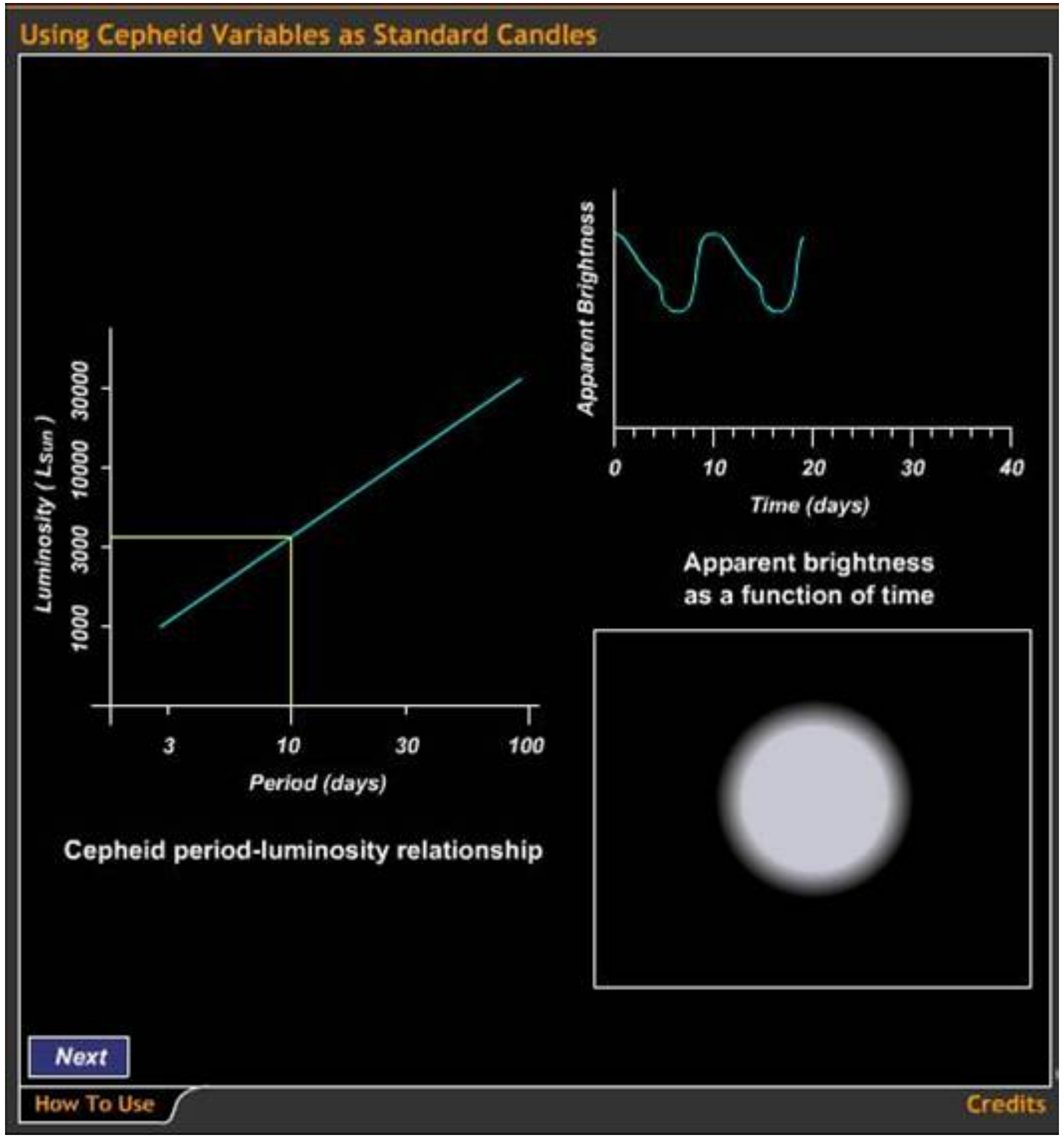


1 Helium atoms in the pulsation layer are singly ionized (He+). This means they have lost one of their two electrons. Singly ionized helium is transparent to radiation, so energy from the star's core passes through the pulsation layer. The helium absorbs some of the energy and gets hotter.

2 Helium atoms lose a second electron, becoming doubly ionized and therefore opaque to radiation. Energy from the core presses outward on the pulsation layer.

3 As the pulsation layer expands, its pressure and temperature fall. The helium gradually reverts back to its singly ionized state and becomes transparent again. This releases energy stored below the pulsation layer, like water flowing through the floodgates of a dam.

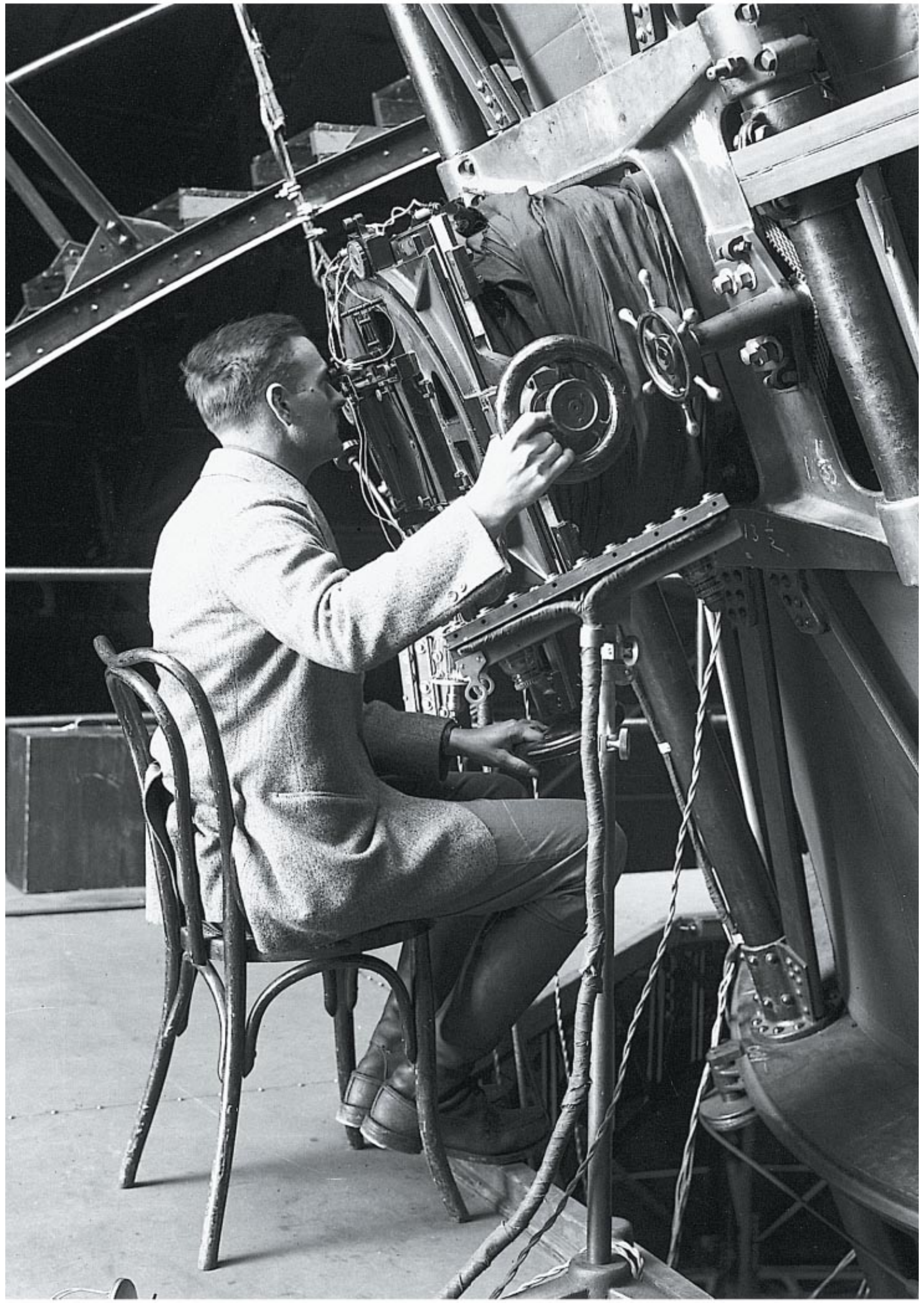
4 With no opposing push from within, gravity causes the pulsation layer to contract. The singly ionized helium begins to absorb energy from the core and the pulsation cycle begins anew.



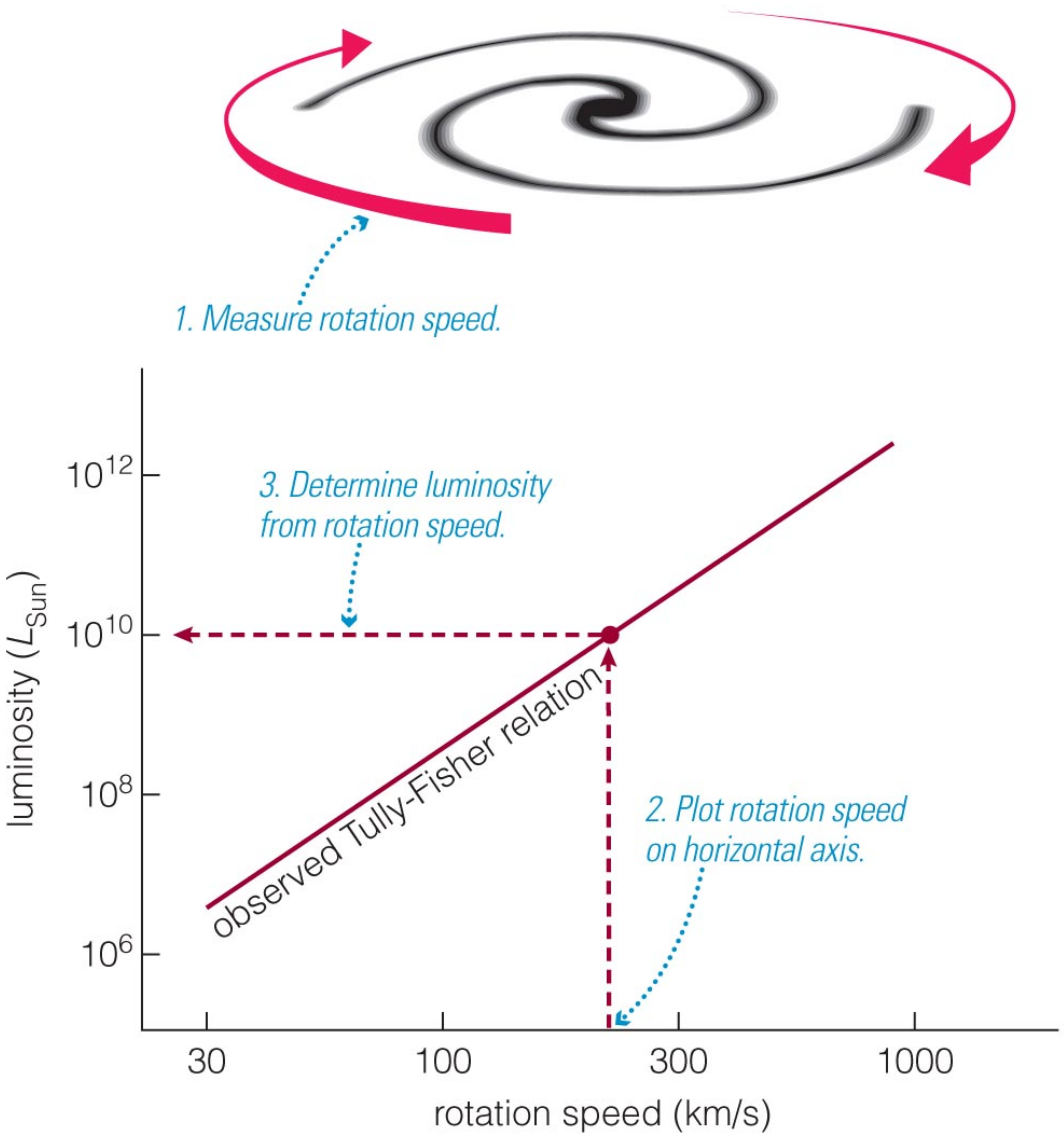
Step 3

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.



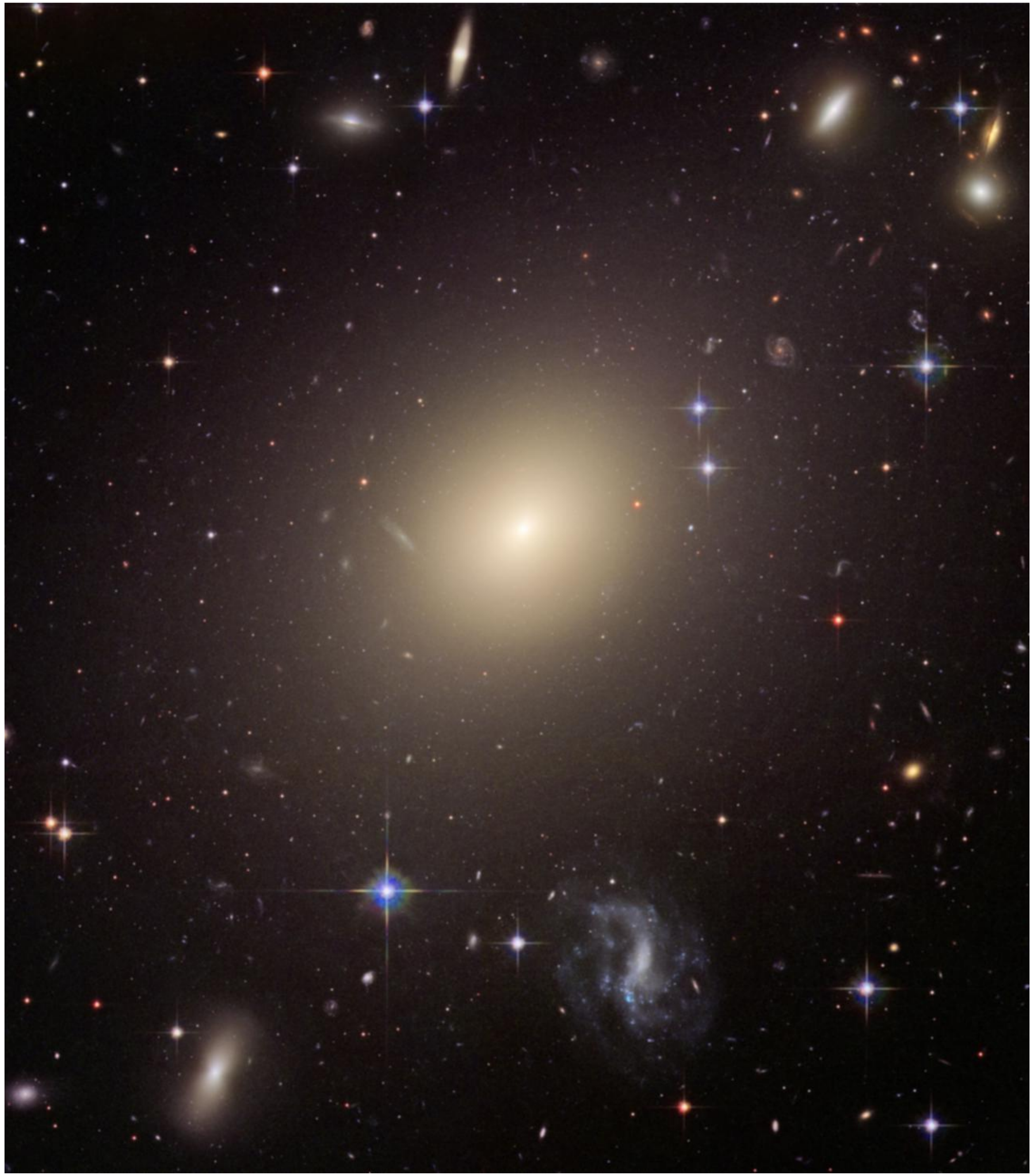
Edwin Hubble, using Cepheids as standard candles, was the first to measure distances to other galaxies.



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.



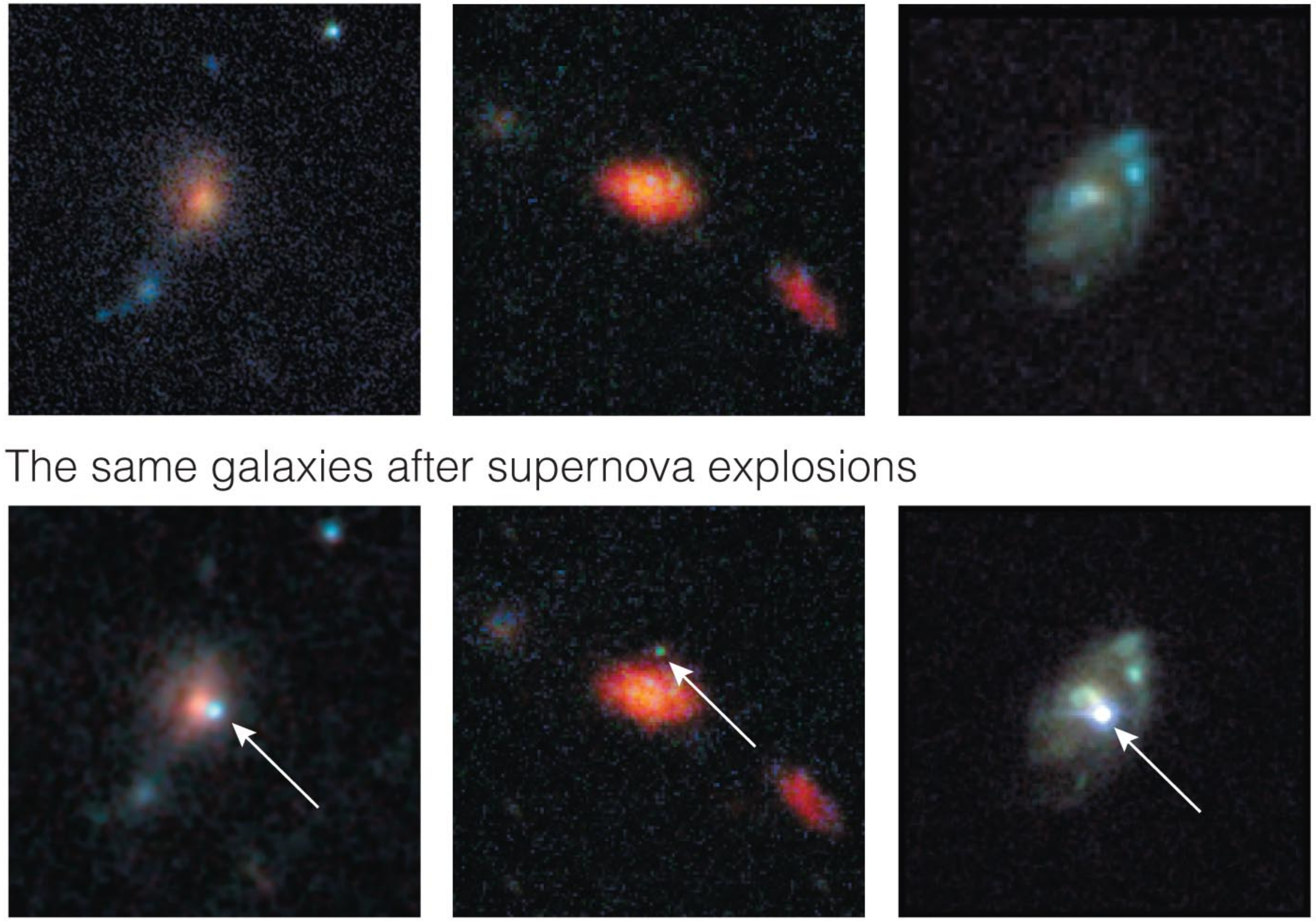
Step 3.5

Faber-Jackson Relation

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

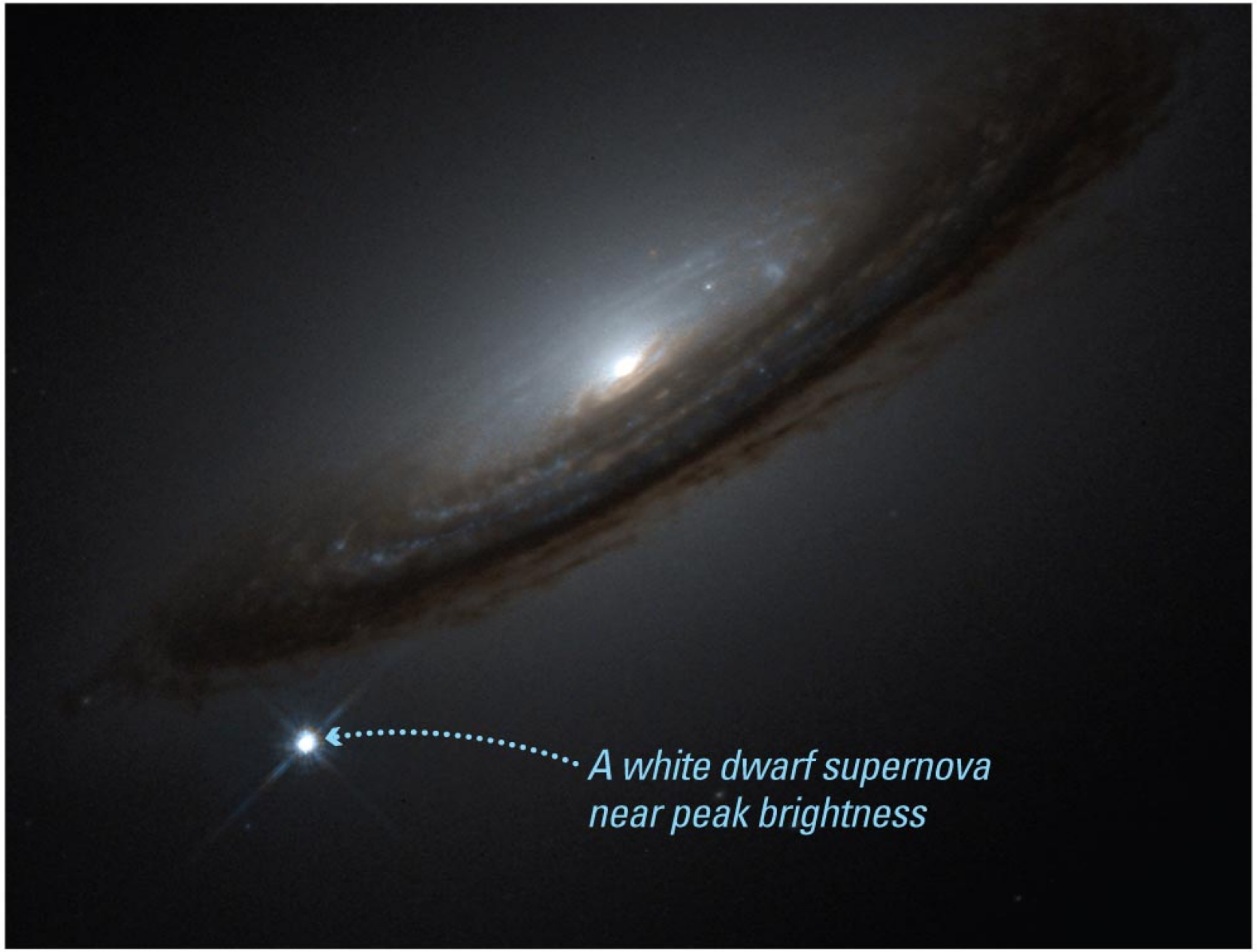
Distant galaxies before supernova explosions

The same galaxies after supernova explosions



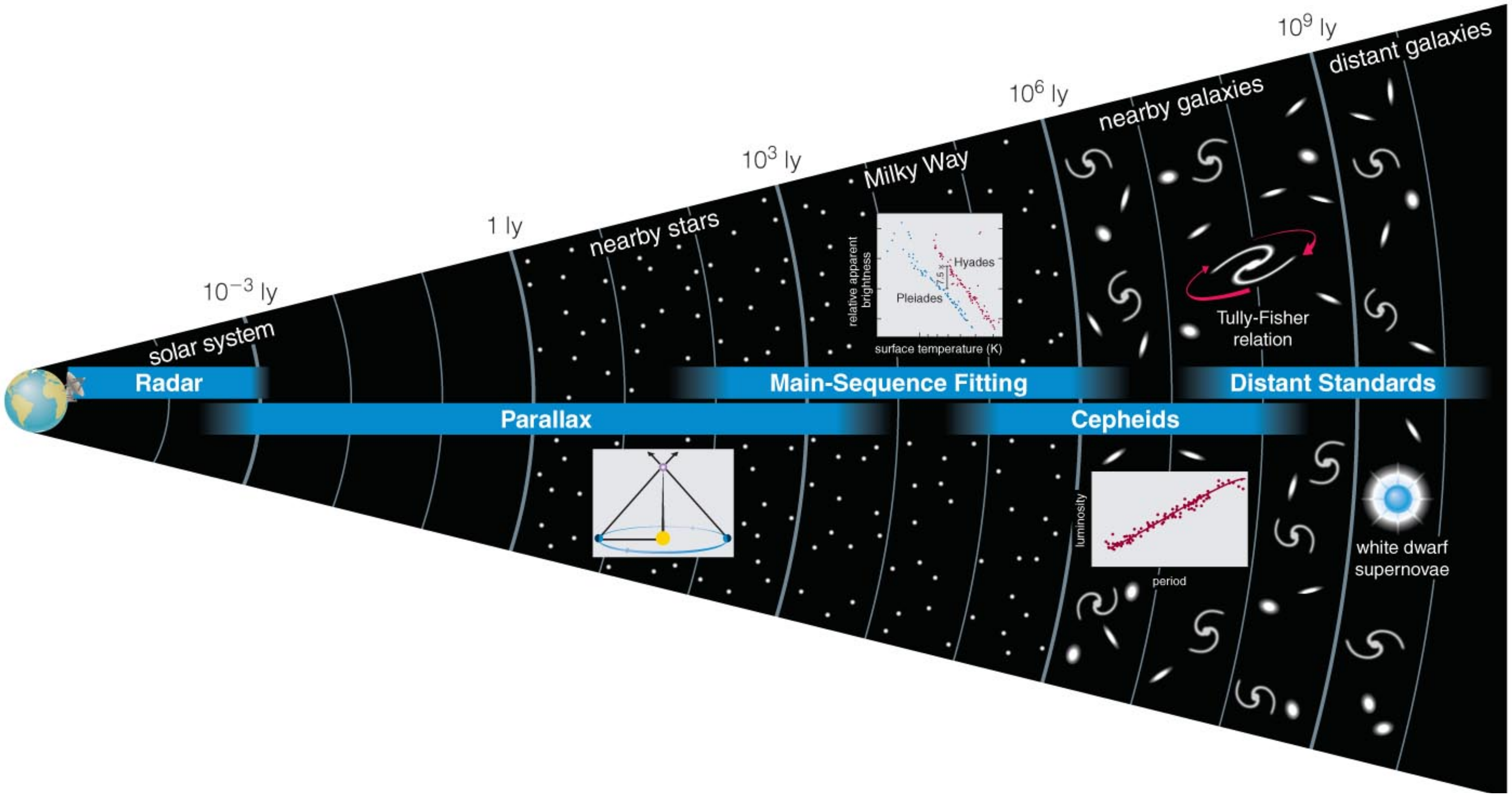
Step 4

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



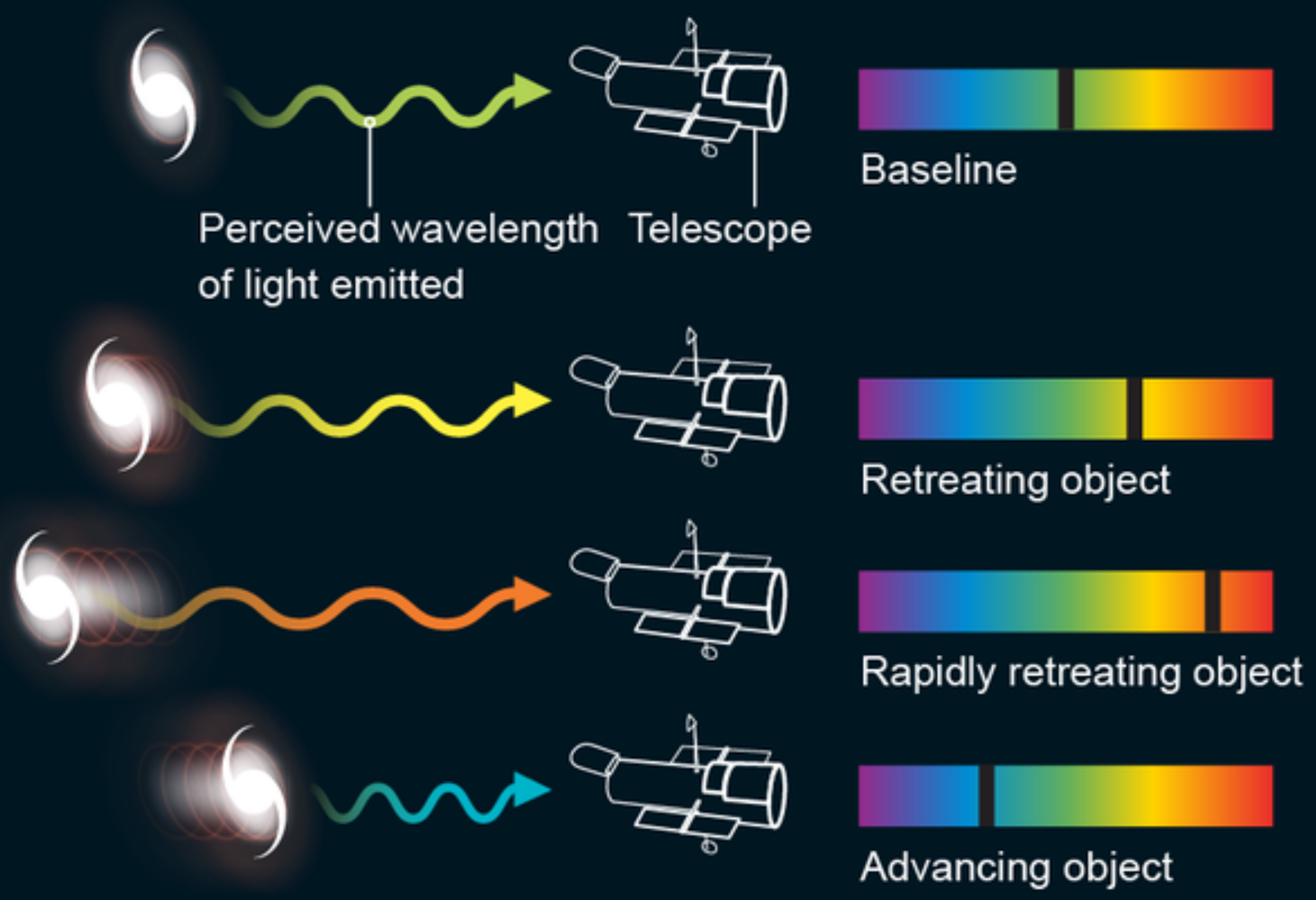
White-dwarf supernovae can be used as standard candles because their peak luminosities are very strongly related to the time their flux takes to decrease.

We measure galaxy distances using a chain of interdependent techniques.



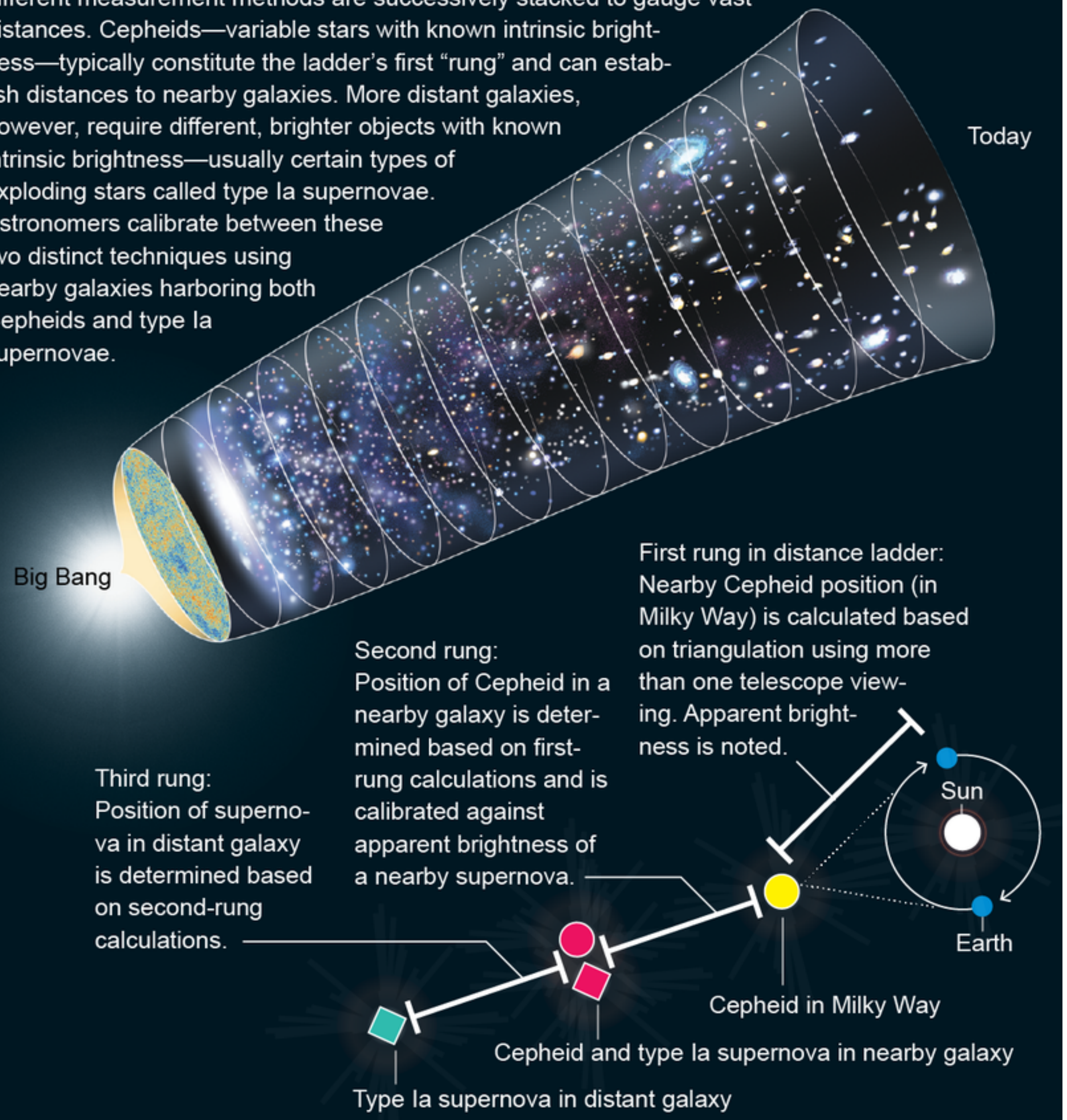
CLOCKING SPEEDING GALAXIES

The classic approach to calculating H_0 in the late universe requires measuring both the velocities and distances of far-off galaxies. Getting a velocity relies on a phenomenon called cosmological redshift—the stretching out, or reddening, of light from objects receding from us as the universe expands. The greater the redshift, the faster an object is receding.



CLIMBING THE DISTANCE LADDER

Reckoning distances to remote galaxies is far harder than measuring their velocities via redshift. Astronomers seeking the late universe value of H_0 do this by ascending what is known as the cosmic distance ladder, in which different measurement methods are successively stacked to gauge vast distances. Cepheids—variable stars with known intrinsic brightness—typically constitute the ladder's first "rung" and can establish distances to nearby galaxies. More distant galaxies, however, require different, brighter objects with known intrinsic brightness—usually certain types of exploding stars called type Ia supernovae. Astronomers calibrate between these two distinct techniques using nearby galaxies harboring both Cepheids and type Ia supernovae.



The distance ladder probes only the background H_0

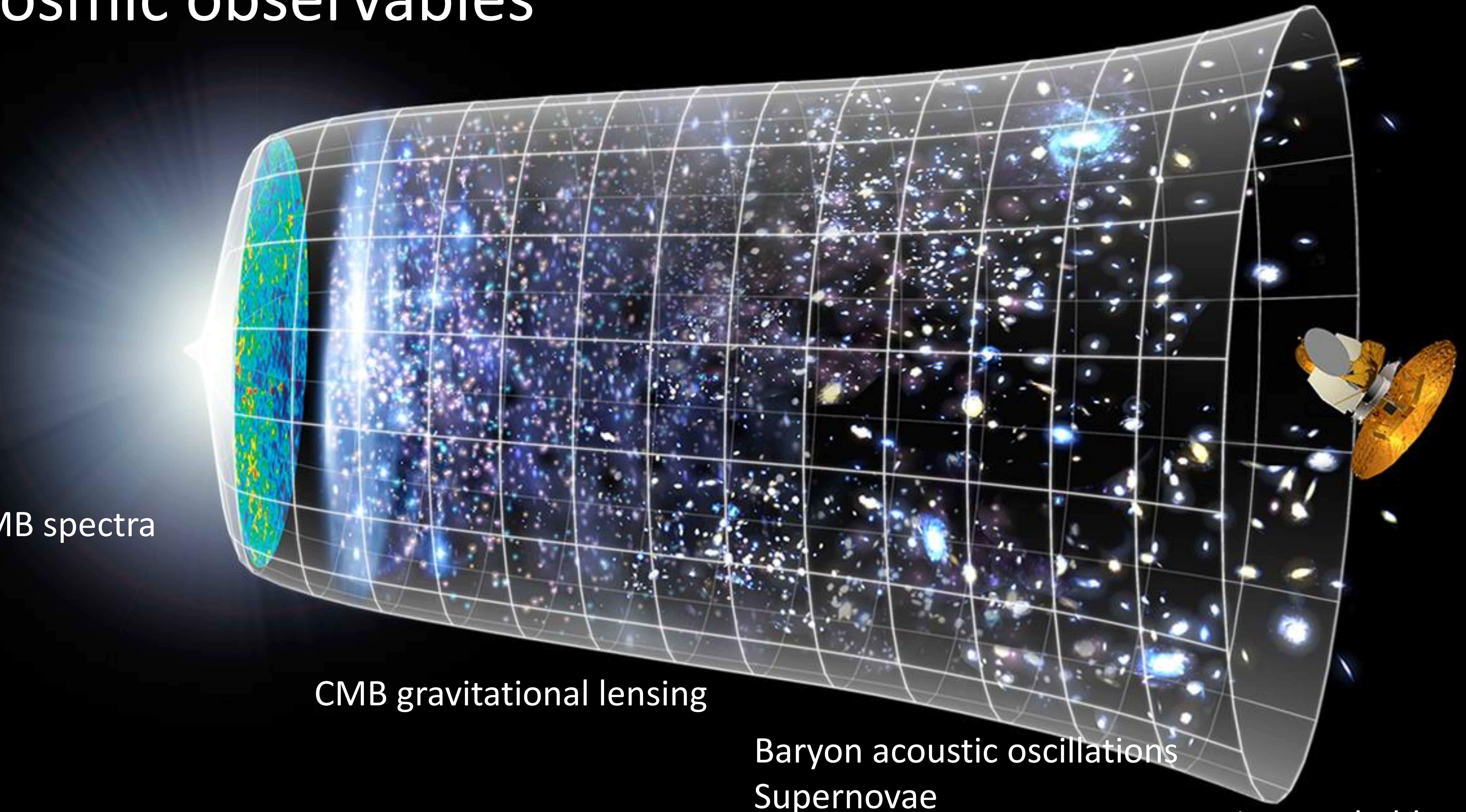
Our own galaxy:
Parallax distance
Calibrate brightness

Nearby galaxies:
Cepheid brightness
Calibrate distance

Faraway galaxies:
Supernova brightness
Calibrate distance
at $z \simeq 0.15$

Source: Hubble Space Telescope

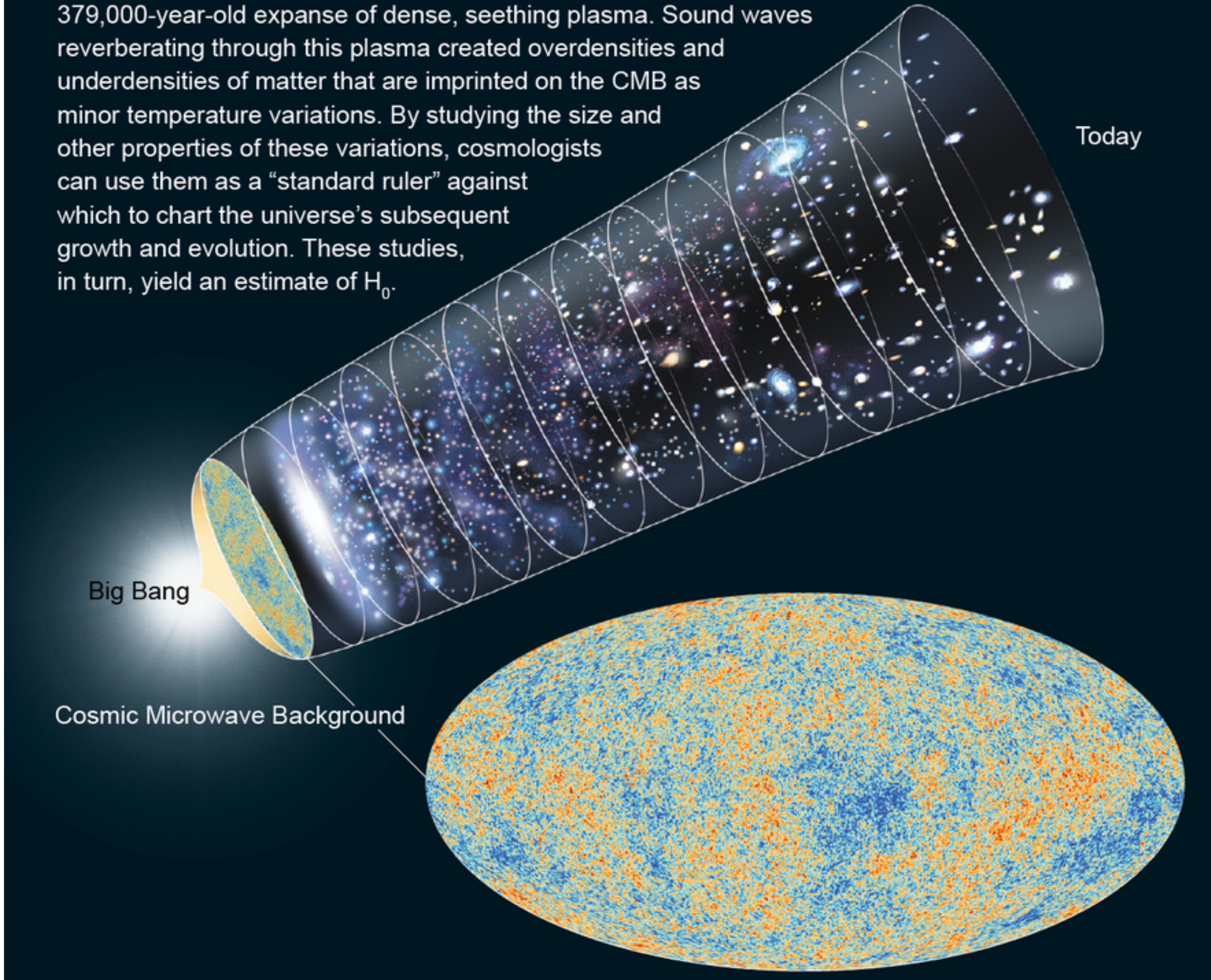
Cosmic observables

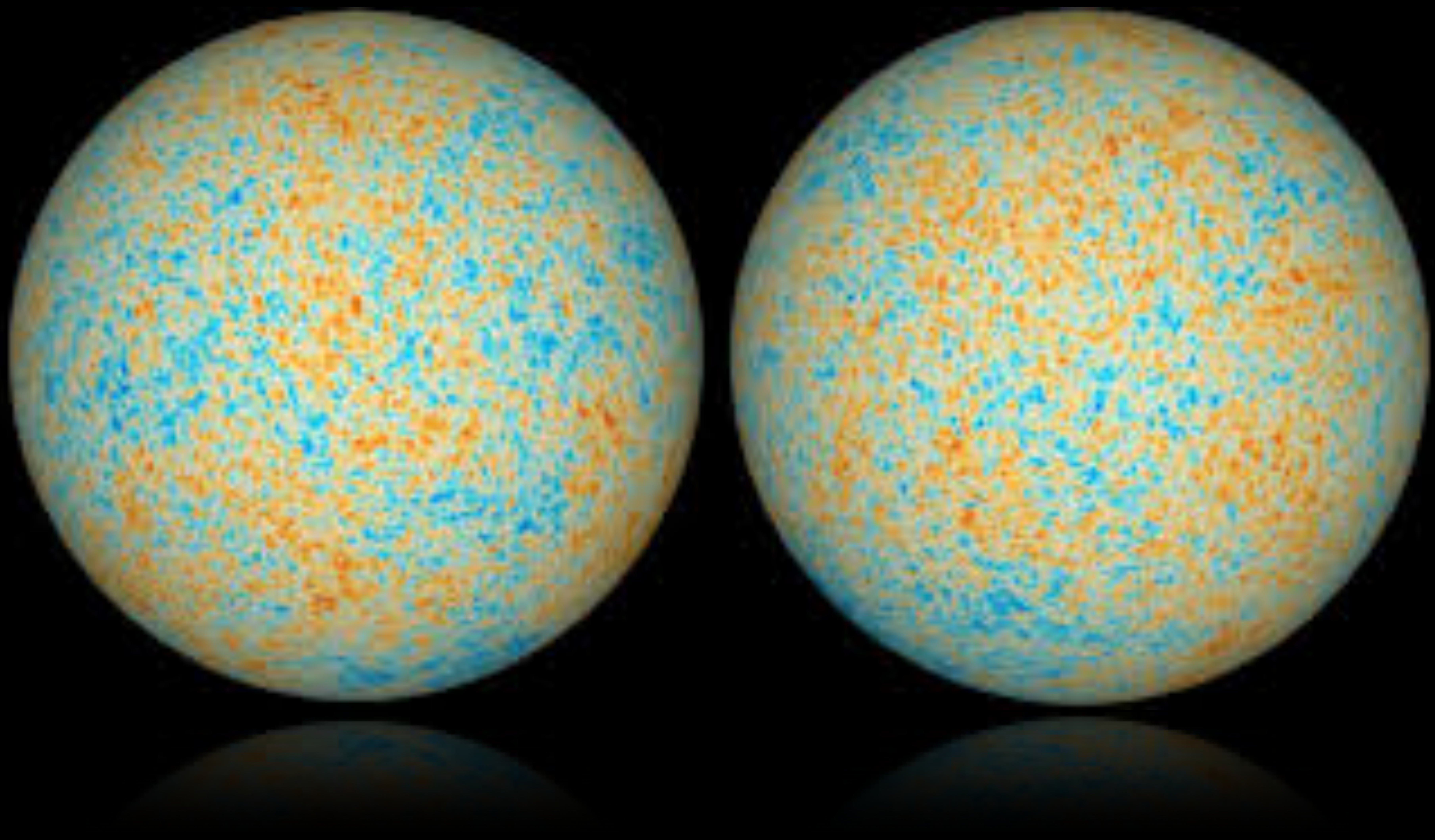


NASA/WMAP Science Team

VIEW FROM THE EARLY UNIVERSE

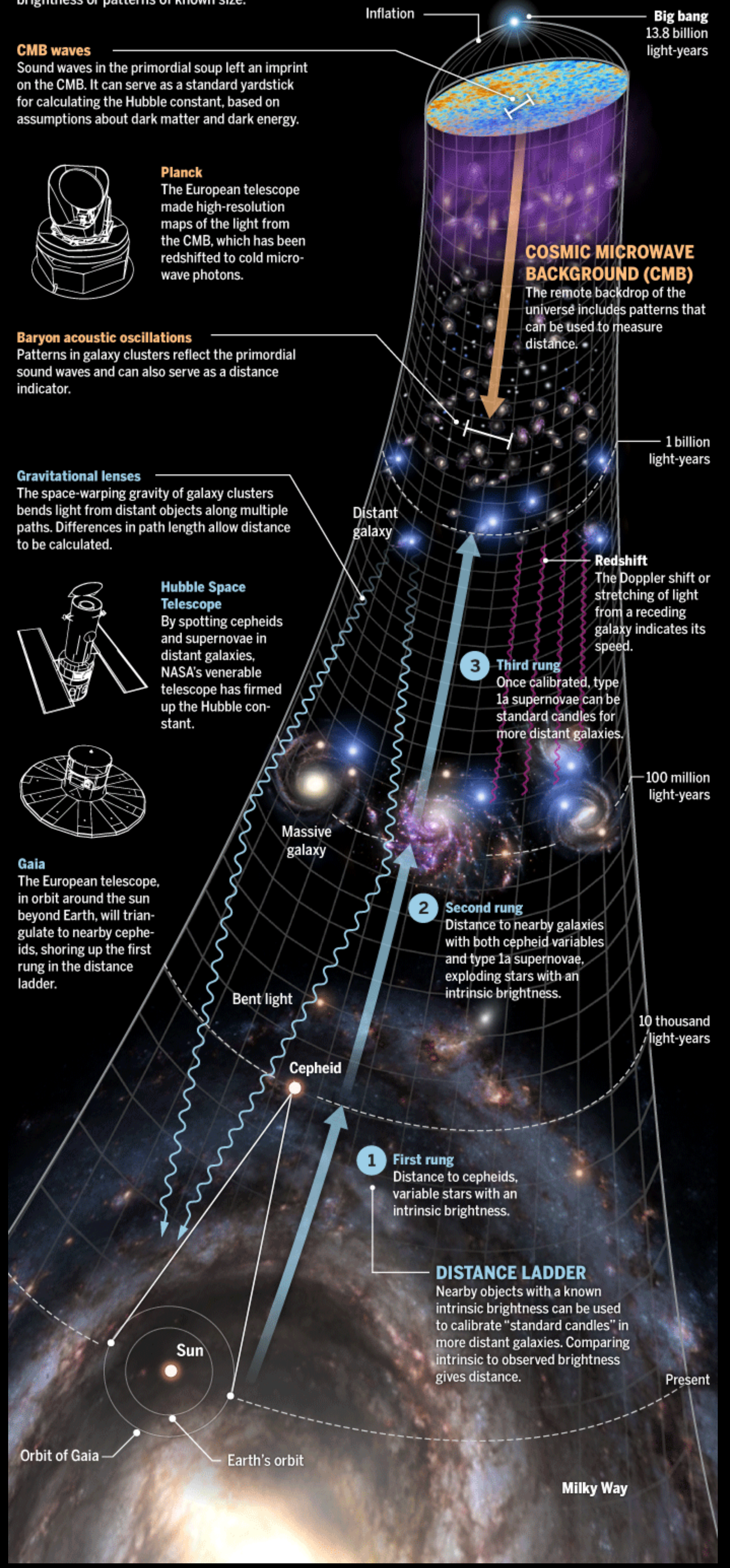
H_0 can also be measured using the cosmic microwave background (CMB), the big bang's all-sky afterglow from when the universe was just a 379,000-year-old expanse of dense, seething plasma. Sound waves reverberating through this plasma created overdensities and underdensities of matter that are imprinted on the CMB as minor temperature variations. By studying the size and other properties of these variations, cosmologists can use them as a "standard ruler" against which to chart the universe's subsequent growth and evolution. These studies, in turn, yield an estimate of H_0.



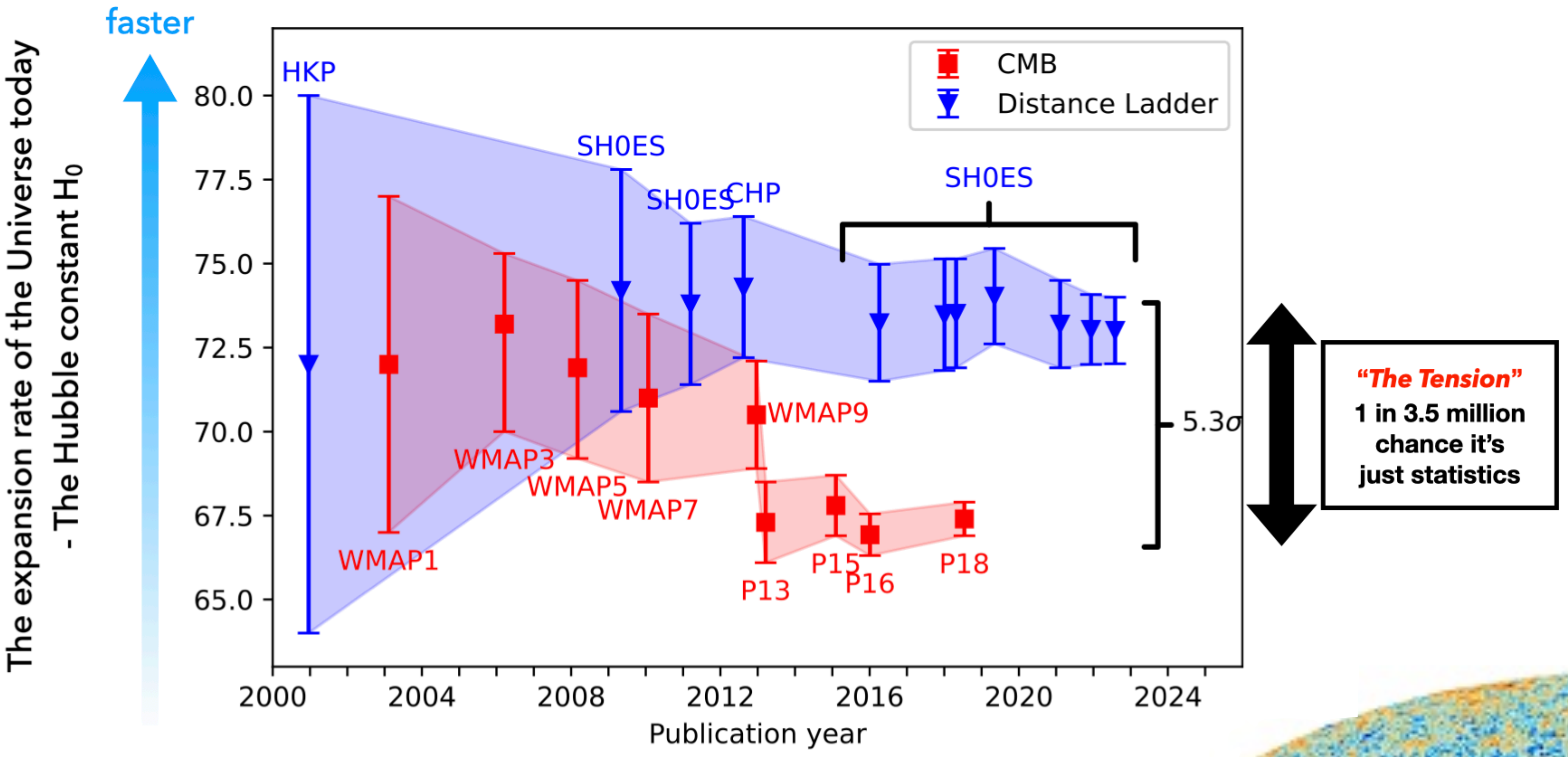


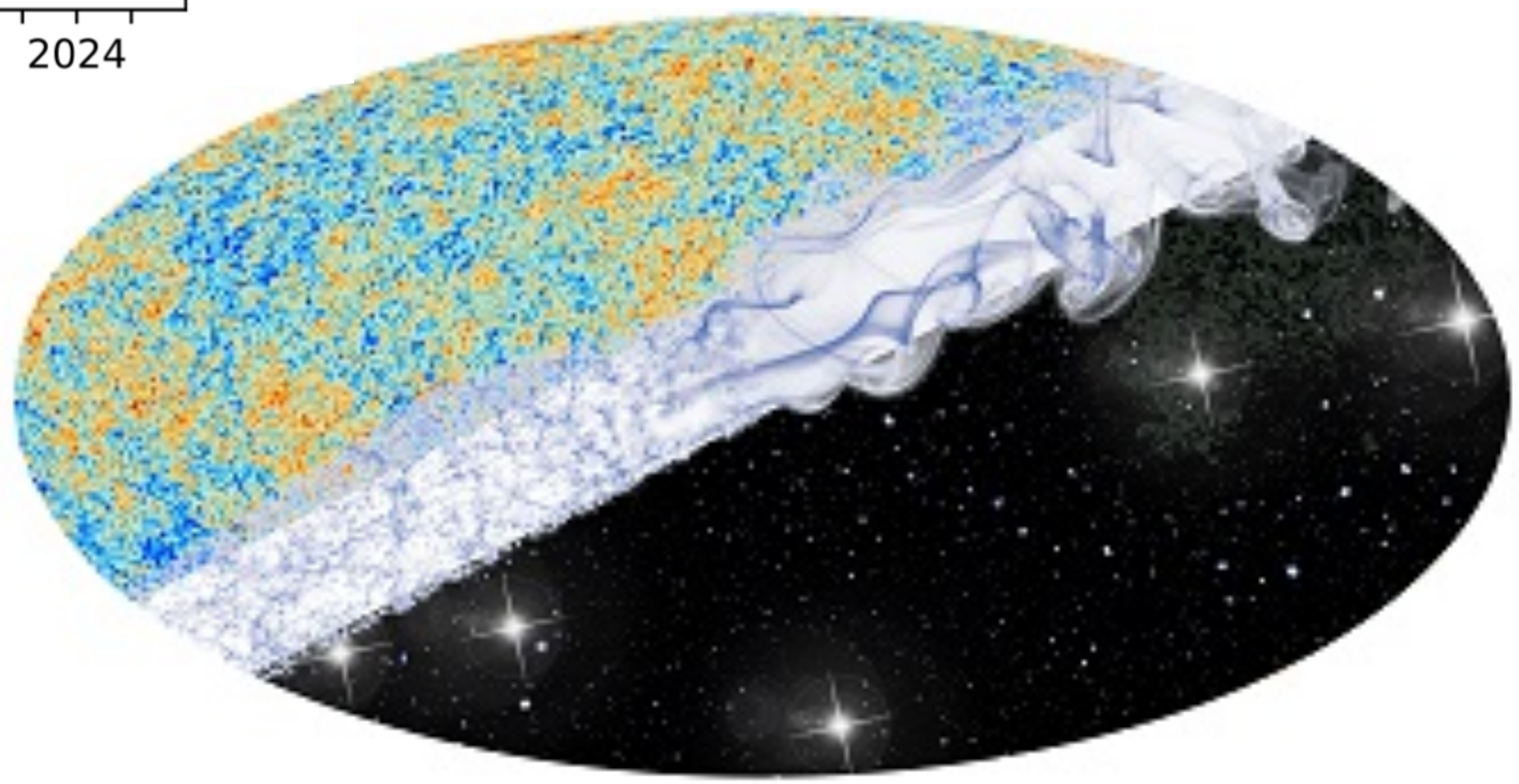
Two ways to clock the cosmos

Determining the Hubble constant requires measuring the speed of receding objects and the distances to them. Speeds are easy, and come from redshifts. Distances are hard and rely on stars of known brightness or patterns of known size.



An emerging problem in Physics





What is the H_0 Tension?

A. The assumption that the age of the Universe is bounded by 1/H0

B. A mismatch in the clustering of matter

C. A long simmering disagreement over the Universe’s present-day expansion rate

D. A flaw in one of the mirrors of the Hubble Space Telescope

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