Astronomy 19
Celestial Distances

Hiền Phan
Hà Nội, 09/11/2023

Thinking Ahead

Figure 19.1 Globular Cluster M80. This beautiful image shows a giant cluster of stars called Messier 80, located about 28,000 light-years from Earth. Such crowded groups, which astronomers call globular clusters, contain hundreds of thousands of stars, including some of the RR Lyrae variables discussed in this chapter. Especially obvious in this picture are the bright red giants, which are stars similar to the Sun in mass that are nearing the ends of their lives.
(credit: modification of work by The Hubble Heritage Team (AURA/ STScI/ NASA))

Chapter Outline

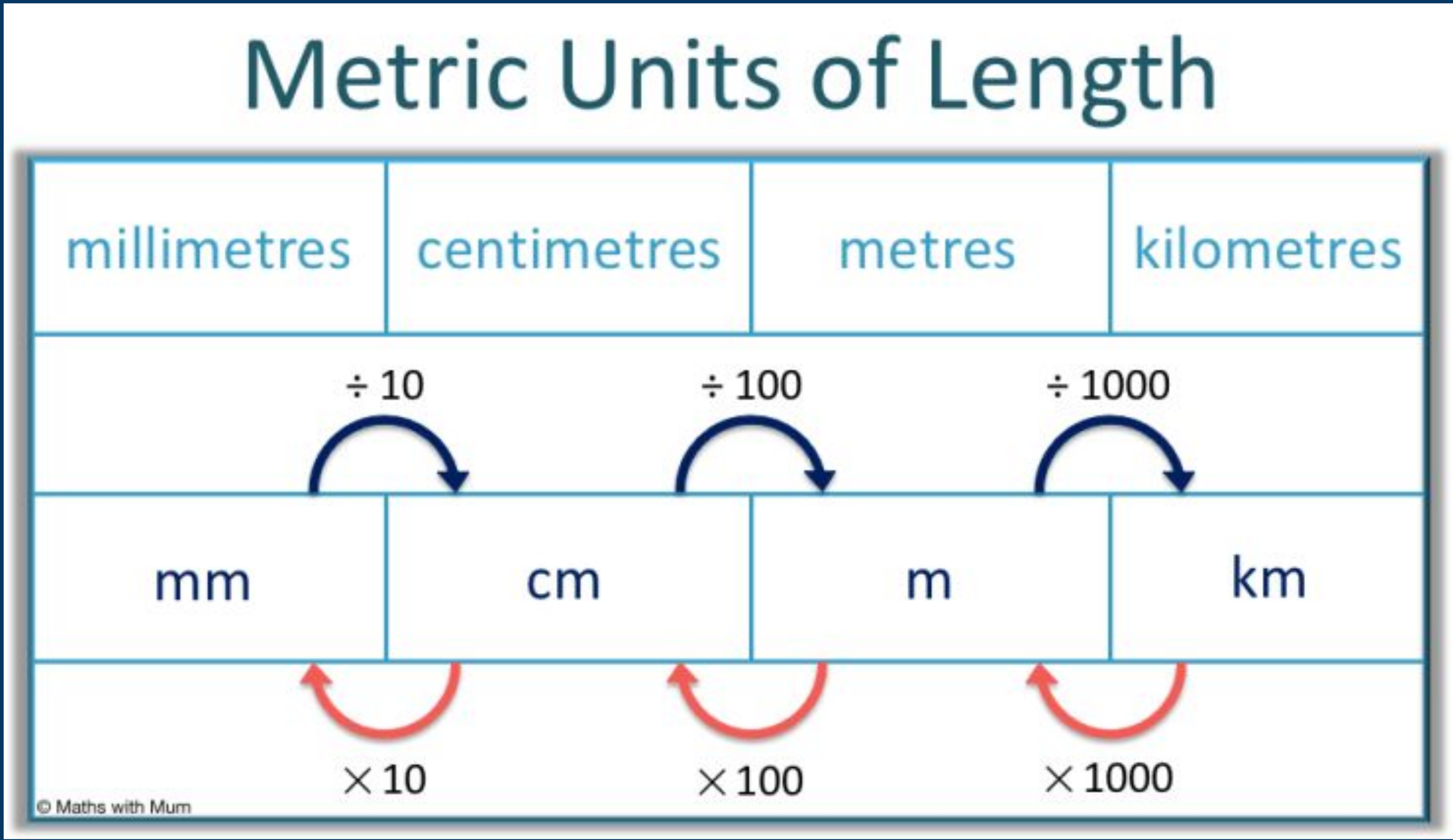
19.1 Fundamental Units of Distance
19.2 Surveying the Stars
19.3 Variable Stars: One Key to Cosmic Distances
19.4 The H–R Diagram and Cosmic Distances

19.1 Fundamental Units of Distance

LEARNING OBJECTIVES

By the end of this section, you will be able to:

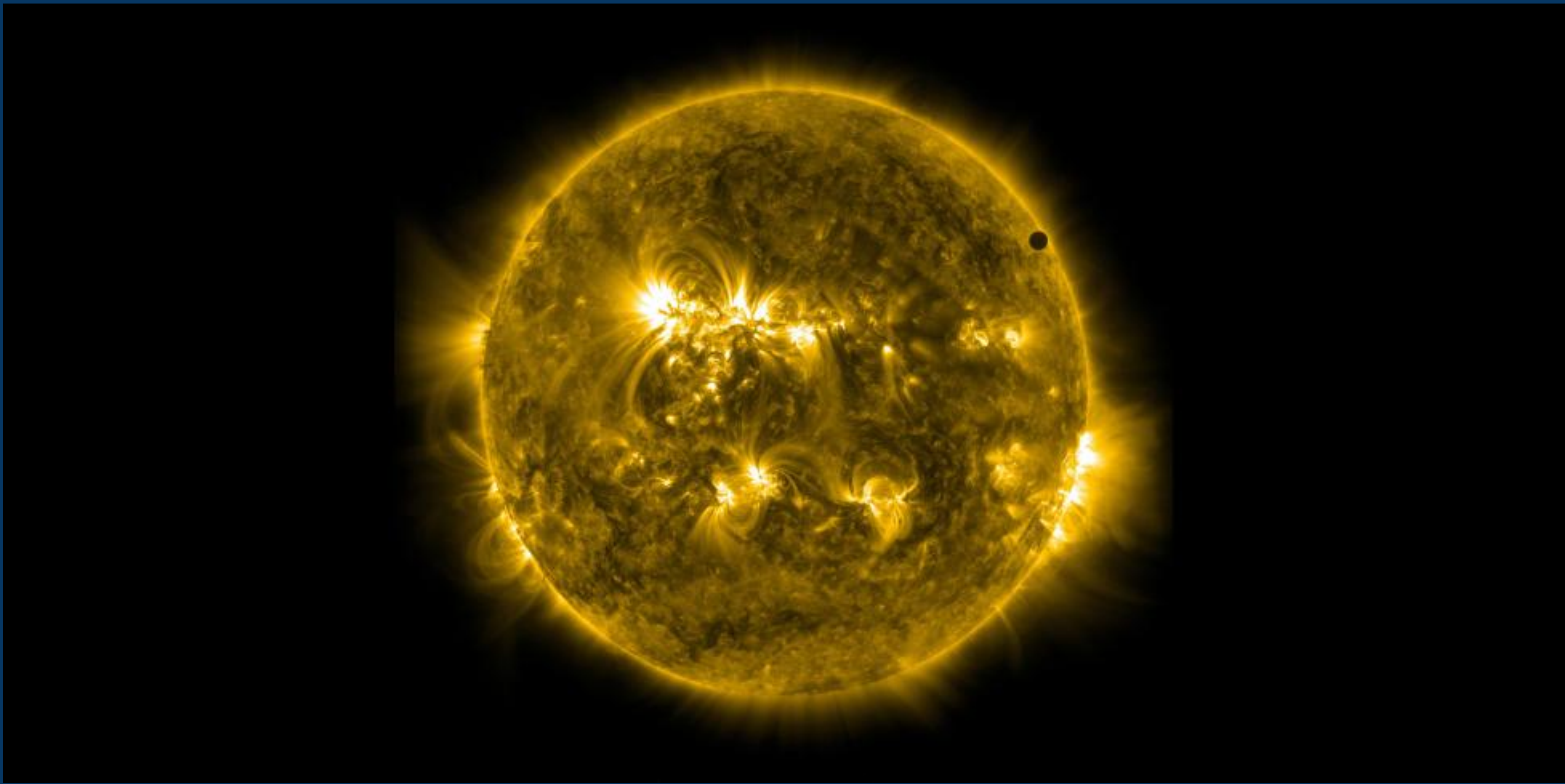
- Understand the importance of defining a standard distance unit
- Explain how the meter was originally defined and how it has changed over time
- Discuss how radar is used to measure distances to the other members of the solar system



The Metric System

The metric system of units, officially adopted in France in 1799 and now used in most countries around the world. The fundamental metric unit of length is the meter, originally

the meter was redefined to equal 1,650,763.73 wavelengths of a particular atomic transition in the element krypton-86.



Distance within the Solar System

Figure 19.2 Venus Transits the Sun, 2012. This striking "picture" of Venus crossing the face of the Sun (it's the black dot at about 2 o'clock) is more than just an impressive image. Taken with the Solar Dynamics Observatory spacecraft and special filters, it shows a modern transit of Venus. Such events allowed astronomers in the 1800s to estimate the distance to Venus. They measured the time it took Venus to cross the face of the Sun from different latitudes on Earth. The differences in times can be used to estimate the distance to the planet. Today, radar is used for much more precise distance estimates.

(credit: modification of work by NASA/SDO, AIA)

Figure 19.3 Radar Telescope. This dish-shaped antenna, part of the NASA Deep Space Network in California's Mojave Desert, is 70 meters wide. Nicknamed the "Mars antenna," this radar telescope can send and receive radar waves, and thus measure the distances to planets, satellites, and asteroids.
(credit: NASA/JPL-Caltech)

The astronomical unit (AU)

The length of 1 AU can be expressed in light travel time as 499.004854 light-seconds, or about 8.3 light-minutes. If we use the definition of the meter given previously, this is equivalent to 1 AU = 149,597,870,700 meters.

speed of light: $c=3\times10^8 m/s=3\times10^5 km/s$
length of light-second: $ls=3\times10^8 m=3\times10^5 km$
astronomical unit: $AU=1.50\times10^{11} m=1.50\times10^8 km=500$ light-seconds

Activity 19.1 If the Moon were only 1 pixel

The distances between the celestial bodies in our solar system are sometimes difficult to grasp or put into perspective. This interactive website provides a “map” that shows the distances by using a scale at the bottom of the screen and allows you to scroll (using your arrow keys) through screens of “empty space” to get to the next planet—all while your current distance from the Sun is visible on the scale.

https://joshworth.com/dev/pixelspace/pixelspace_solarsystem.html

Please make a short presentation (5’) introducing this interactive simulation.

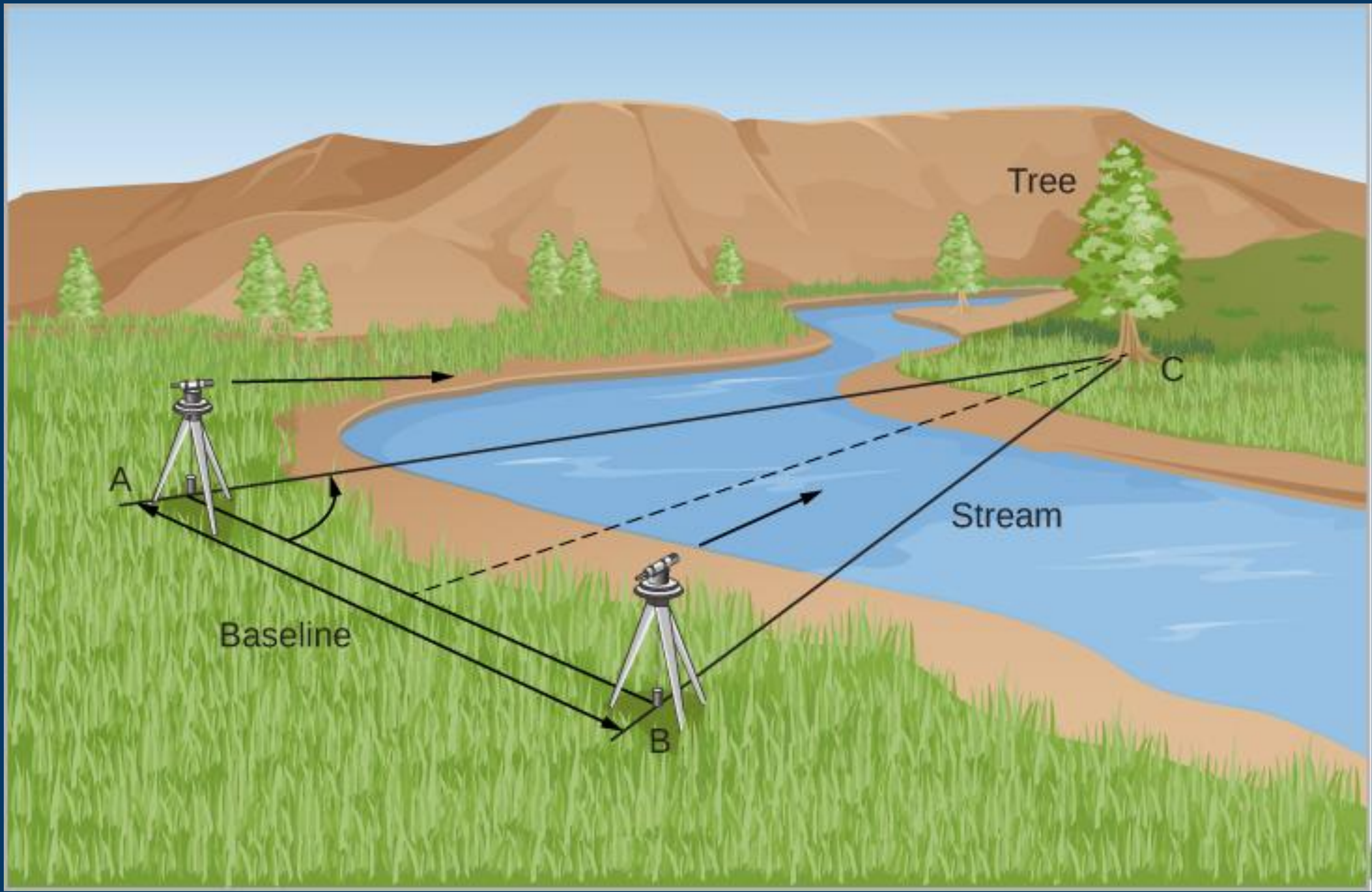
Assigned to:

19.2 Surveying the Stars

LEARNING OBJECTIVES

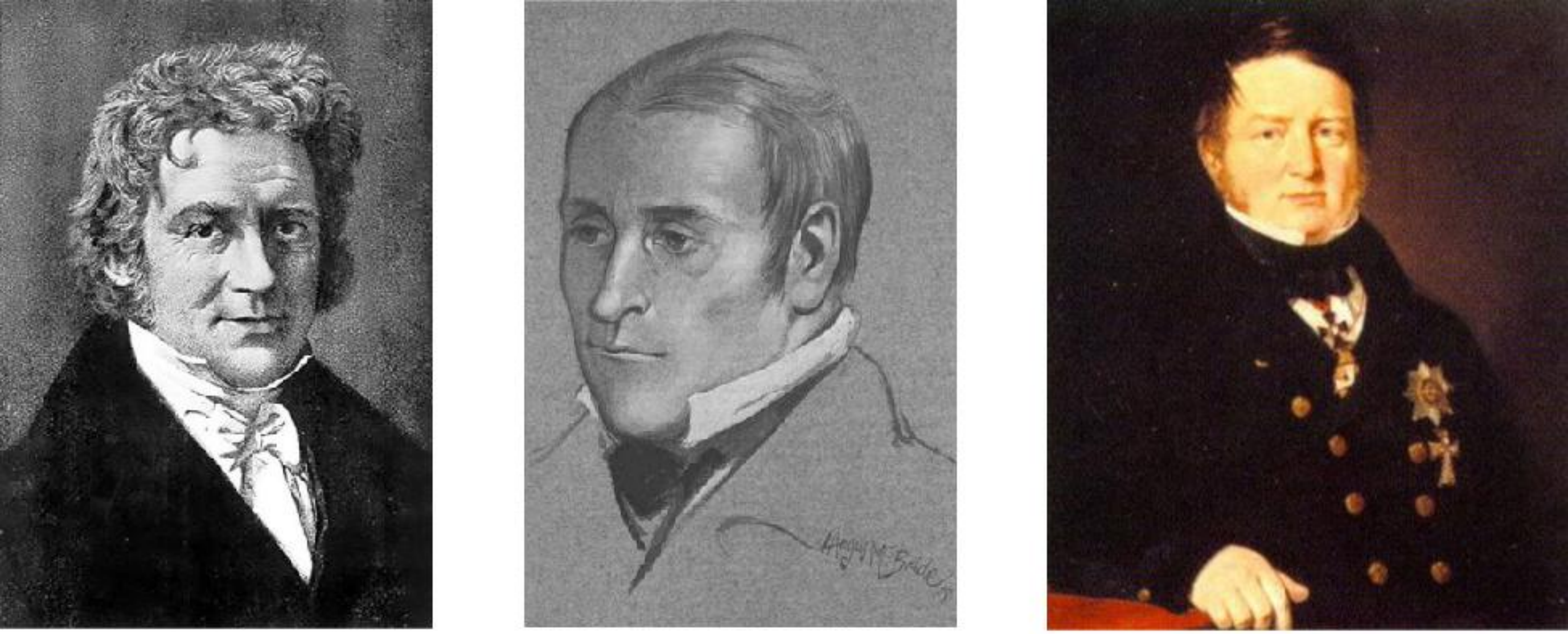
By the end of this section, you will be able to:

- Understand the concept of triangulating distances to distant objects, including stars
- Explain why space-based satellites deliver more precise distances than ground-based methods
- Discuss astronomers' efforts to study the stars closest to the Sun



Triangulation in Space

Figure 19.4 Triangulation. Triangulation allows us to measure distances to inaccessible objects. By getting the angle to a tree from two different vantage points, we can calculate the properties of the triangle they make and thus the distance to the tree.



(a) (b) (c)

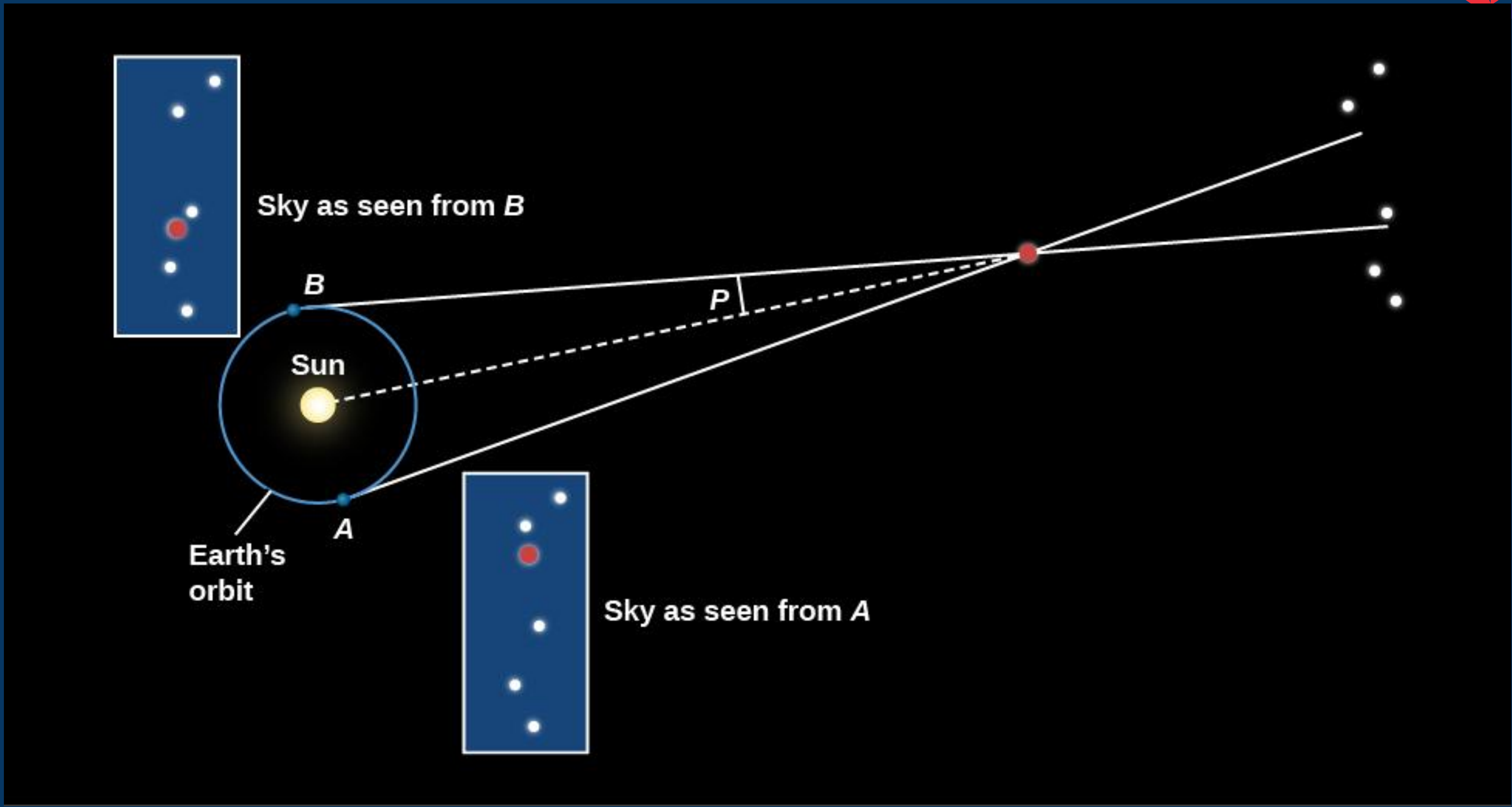
Distances to Stars

Figure 19.5 Friedrich Wilhelm Bessel (1784–1846), Thomas J. Henderson (1798–1844), and Friedrich Struve (1793–1864).

(a) Bessel made the first authenticated measurement of the distance to a star (61 Cygni) in 1838, a feat that had eluded many dedicated astronomers for almost a century. But two others,

(b) Scottish astronomer Thomas J. Henderson and

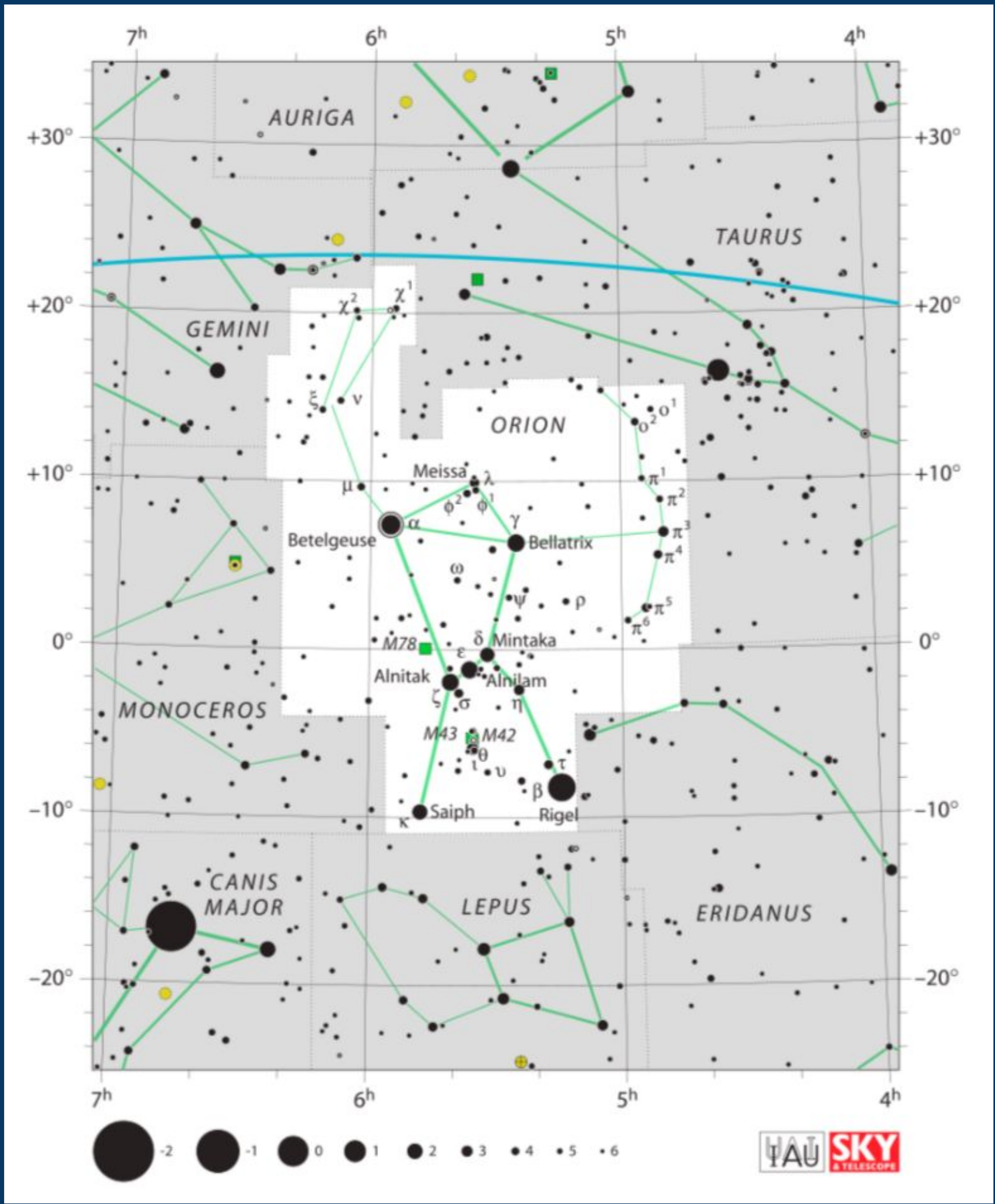
(c) Friedrich Struve, in Russia, were close on his heels.



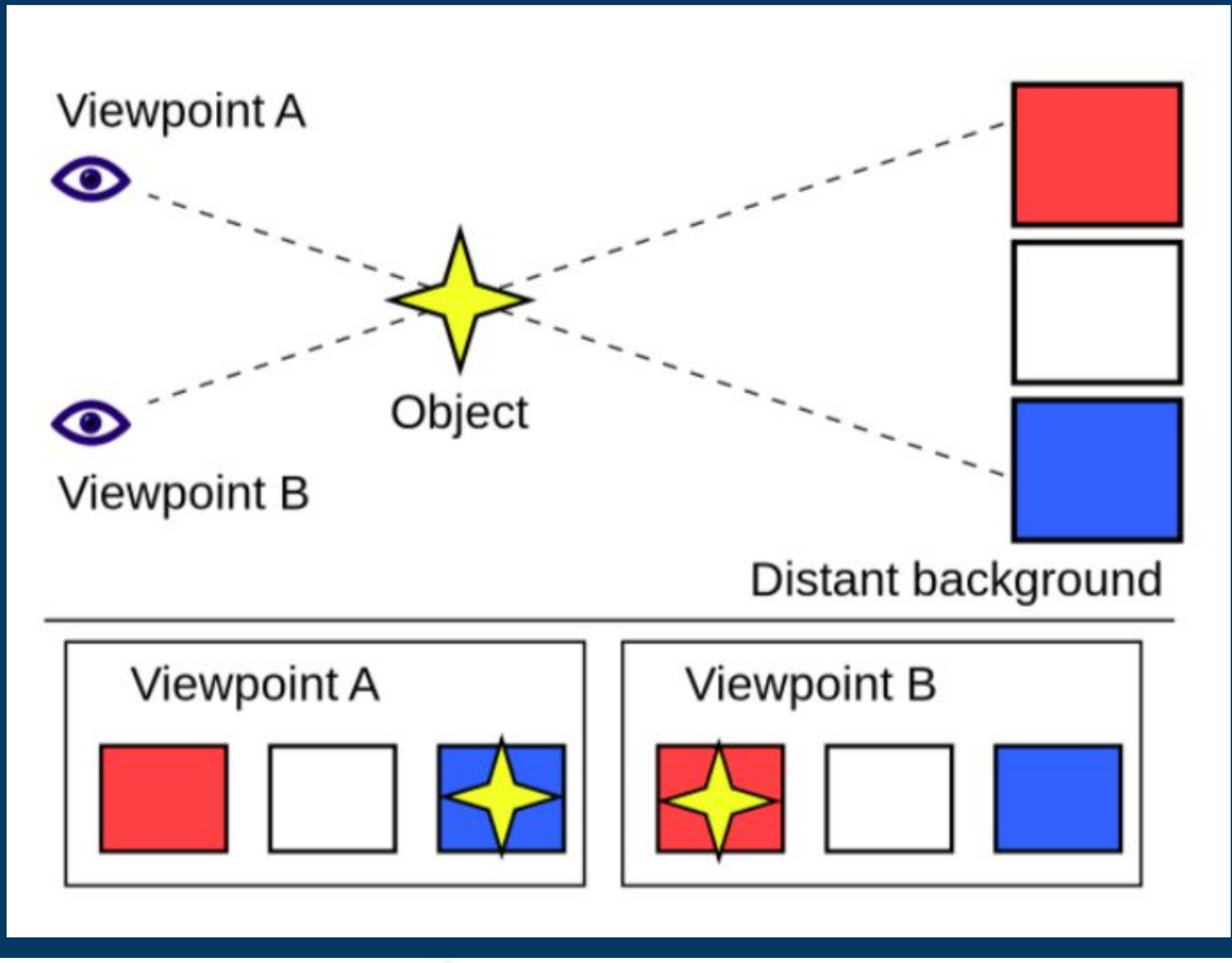
Parallax

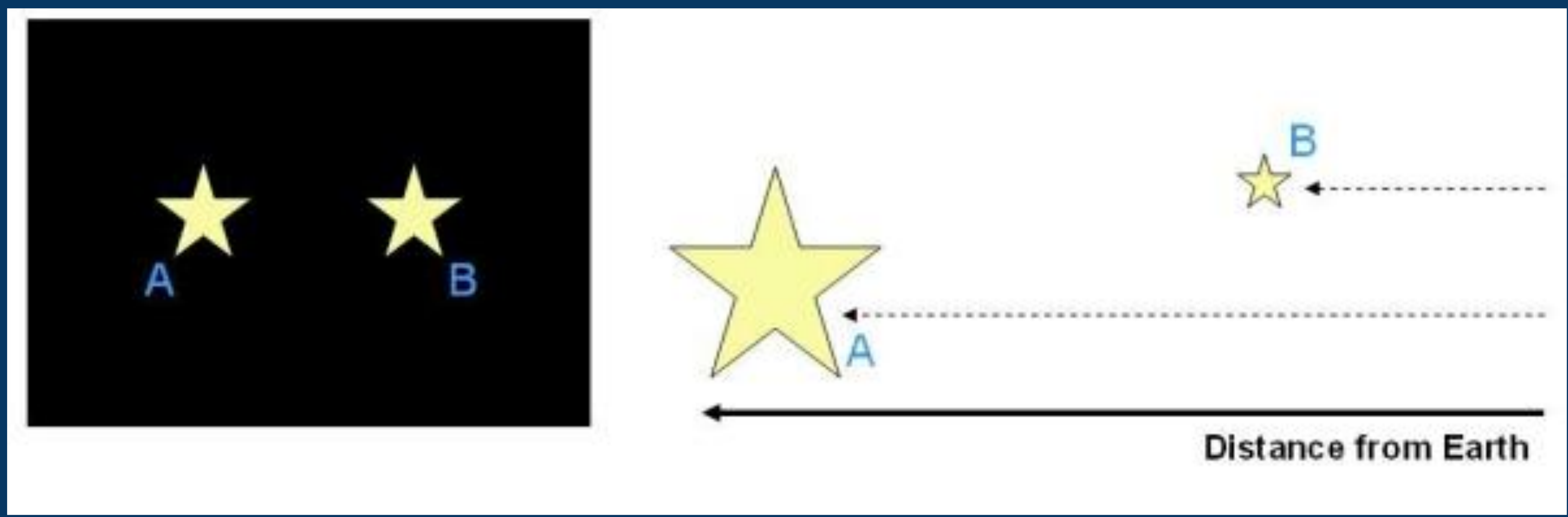
Figure 19.6 Parallax. As Earth revolves around the Sun, the direction in which we see a nearby star varies with respect to distant stars. We define the parallax of the nearby star to be one half of the total change in direction, and we usually measure it in arcseconds.

Why do we need to know the distance of a star?



Name	Apparent magnitude	Approx. distance (light years)	Radius ($R_\odot$)
Betelgeuse	0.0 - 1.3	643	887
Rigel	0.05 - 0.18	860	78.9
Bellatrix	1.59 - 1.64	250	5.75
Mintaka	2.23 (3.2/3.3)	1200	16.5
Alnilam	1.64 - 1.74	2000	42
Alnitak	1.77 (2.08/4.28/4.01)	1260	20
Saiph	2.09	650	22.2





Why do we need to know the distance of a star?

- Same magnitude doesn't mean same distance
- Brighter doesn't mean closer

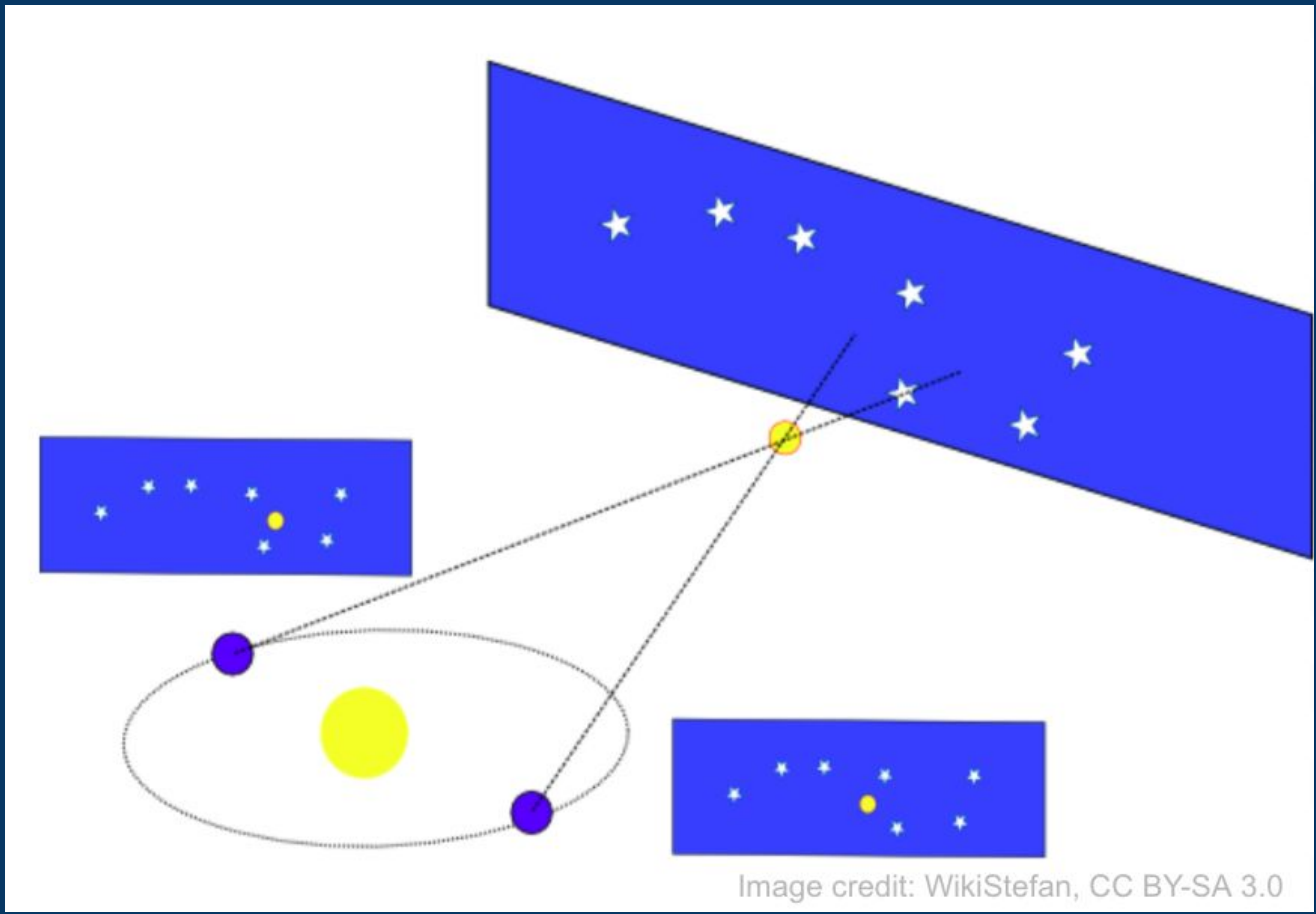
But what happened if we look at a star at different positions?

Imagine: Look at your finger in front of your face by your left eye, then by your right eye.

What do you say about the position of your finger relative to the background?

→ Parallax

(Vietnamese: Thị sai)



Parallax

Parallax is the different in the apparent position of an object when it is viewed along two different lines of sight.

→ By looking at the apparent motion of an object against a distant background from two advantage points, we are able to calculate the distance of that object with a known baseline.

Since stars are far, we need **a baseline as big as possible**.

→ the easiest way is observing from two opposite positions of the Earth's orbit.

→ the biggest baseline: 2 AU.

Stellar parallax

(Vietnamese: Tinh sai, thị sai sao)

Stellar parallax is the apparent displacement of a nearby star on a background of distant objects when it is observed along two different lines of sight.

⟶ Observing haft year apart.

If we have:

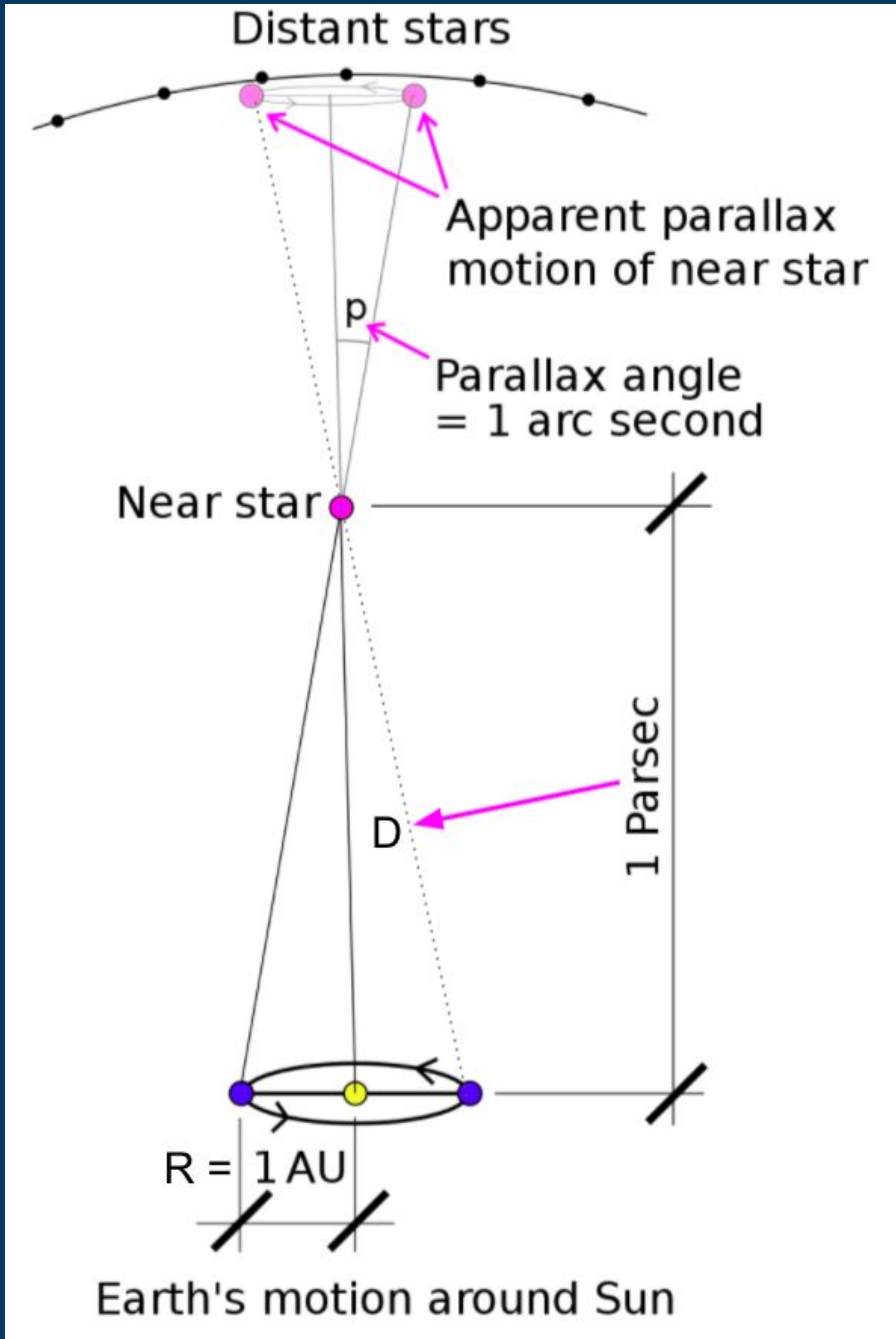
- Parallax angle: *p (arcsecond)*
- Baseline R = 1 (AU)

Then the distance D can be calculated:

$$\Rightarrow D = \frac{R}{tan(p)} \approx \frac{1}{p}$$

- Unit: **Parallax Second = Parsec (pc)**

"A star with a parallax of 1 arcsecond has a distance of 1 Parsec."



Stellar parallax

1 arcsec ≈ 4.84814×10^{-6} radians

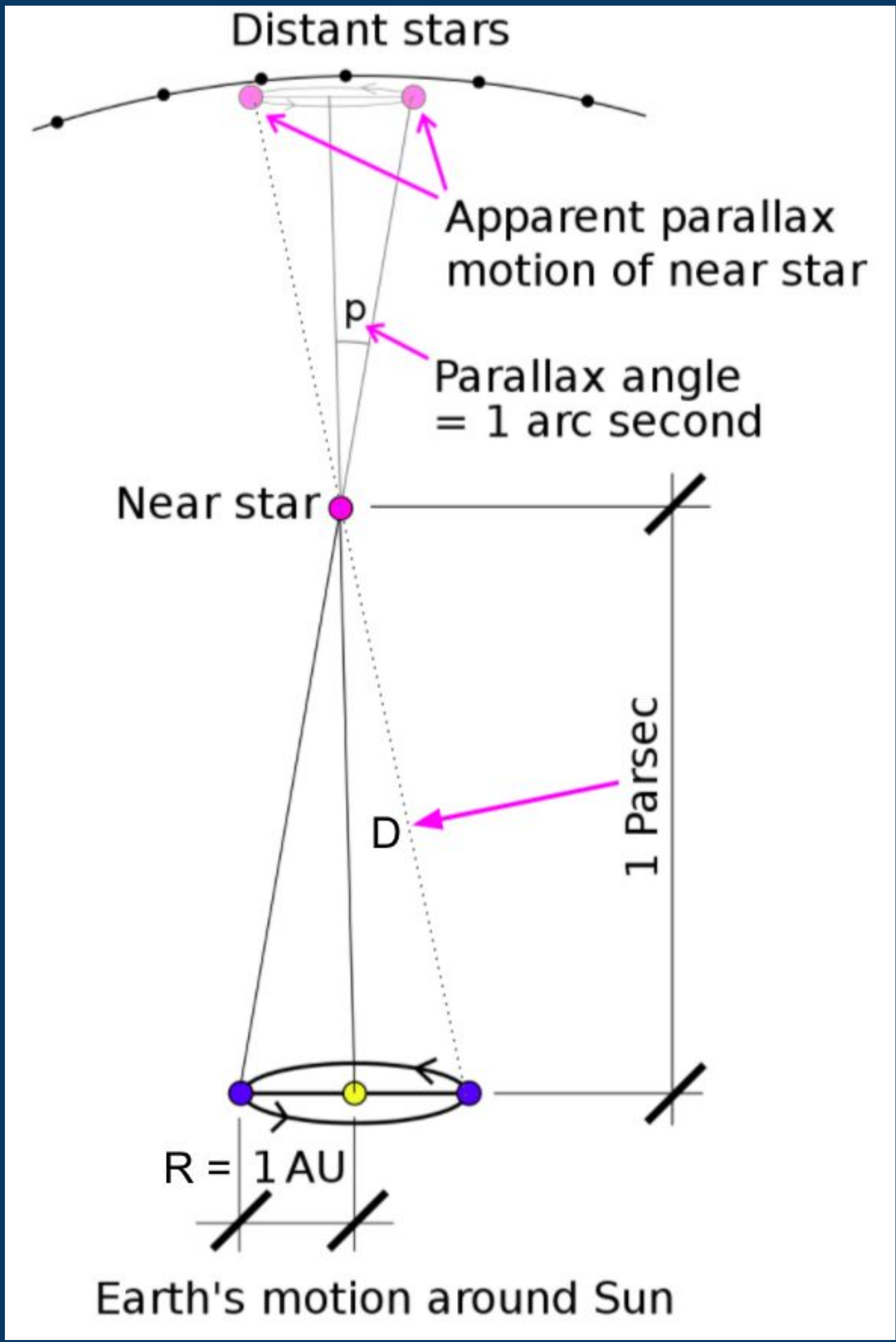
$$\Rightarrow D = \frac{R}{tan(p)} \approx \frac{1(AU)}{4.84814 \times 10^{-6}(rads)} = 206265(AU)$$

1 parsec (pc) is equivalent to:

- 206,265 AU
- 3.26 light years
- 3.086×10^{13} km

The nearest star to the Sun:

- Proxima Centauri (4.3 ly or 1.301 pc)



Example: Alpha Centauri star

1. The parallax of the star Alpha Centauri is 0.742 arcsec. What is the distance of it?
2. If a star has a parallax of 0.02 arcsec, can you estimate its distance?

Example: Alpha Centauri star

1. The star Alpha Centauri has a parallax of 0.742 arcsec. What is the distance of it?

$$D = \frac{1}{p} = \frac{1}{0.742} = 1.35\, pc$$

2. If a star has a parallax of 0.02 arcsecs, can you estimate its distance?

$$D = \frac{1}{p} = \frac{1}{0.02} = 50\, pc$$

Example: calculate the diameter of the Sun

The Sun spans about 0.5° in the sky. Knowing the distance of the Sun to the Earth is 1 AU ≈ 150×10^6 km, can you calculate the diameter of the Sun?

Example: calculate the diameter of the Sun

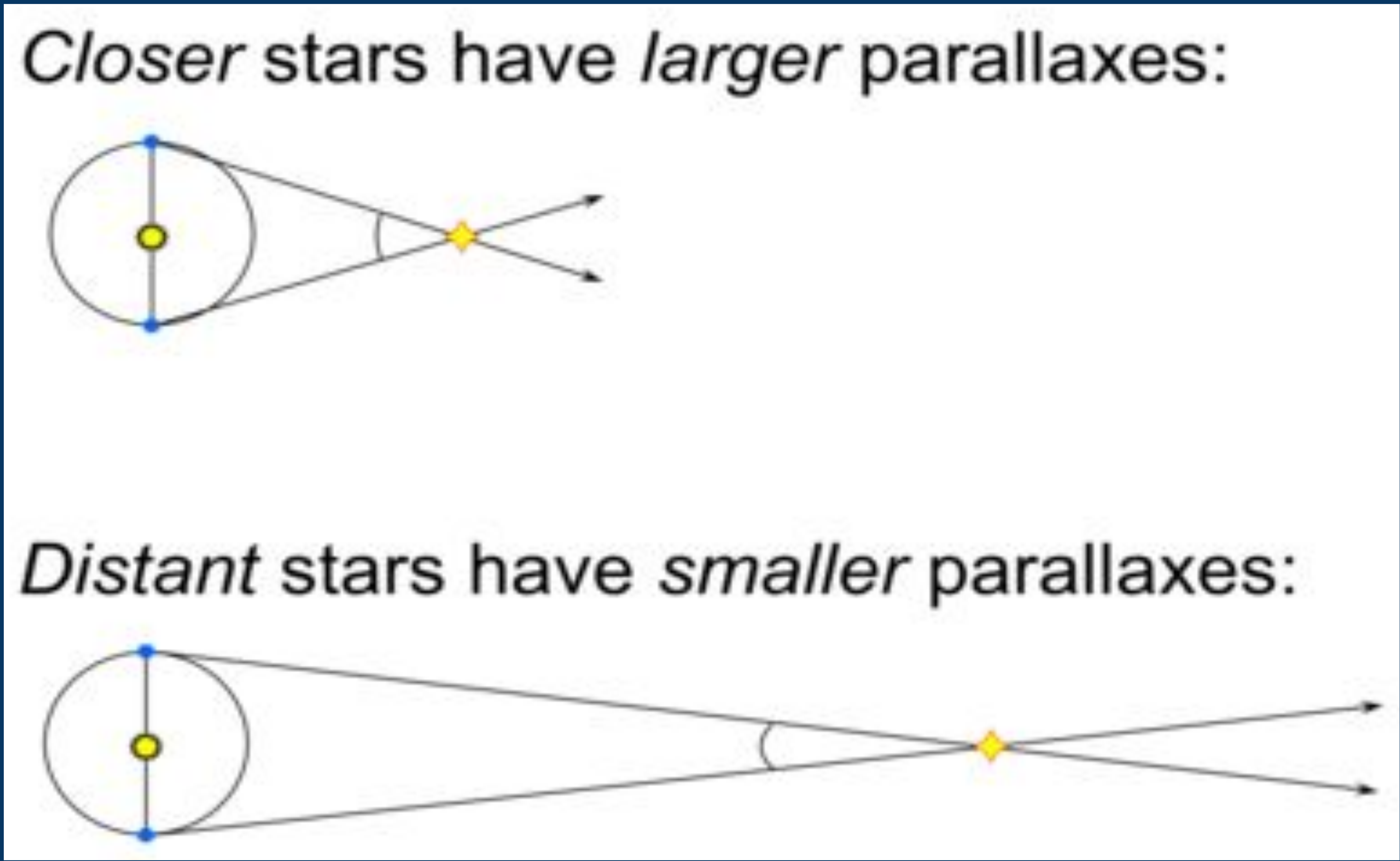
The Sun spans about 0.5° in the sky. Knowing the distance of the Sun to the Earth is 1 AU ≈ 150×10^6 km, can you calculate the diameter of the Sun?

with 0.5° = 0.00872665 rads, we have the distance to the Sun:

Very close to the true value: 1.391×10^3 km.

$$d = 150 \times 10^6 \approx \frac{D_{Sun}}{p(rad)} = \frac{D_{Sun}}{0.00872665}$$

$$\Rightarrow D_{Sun} = 0.00872665 \times 150 \times 10^6 = 1308997.5(km)$$



Limitations

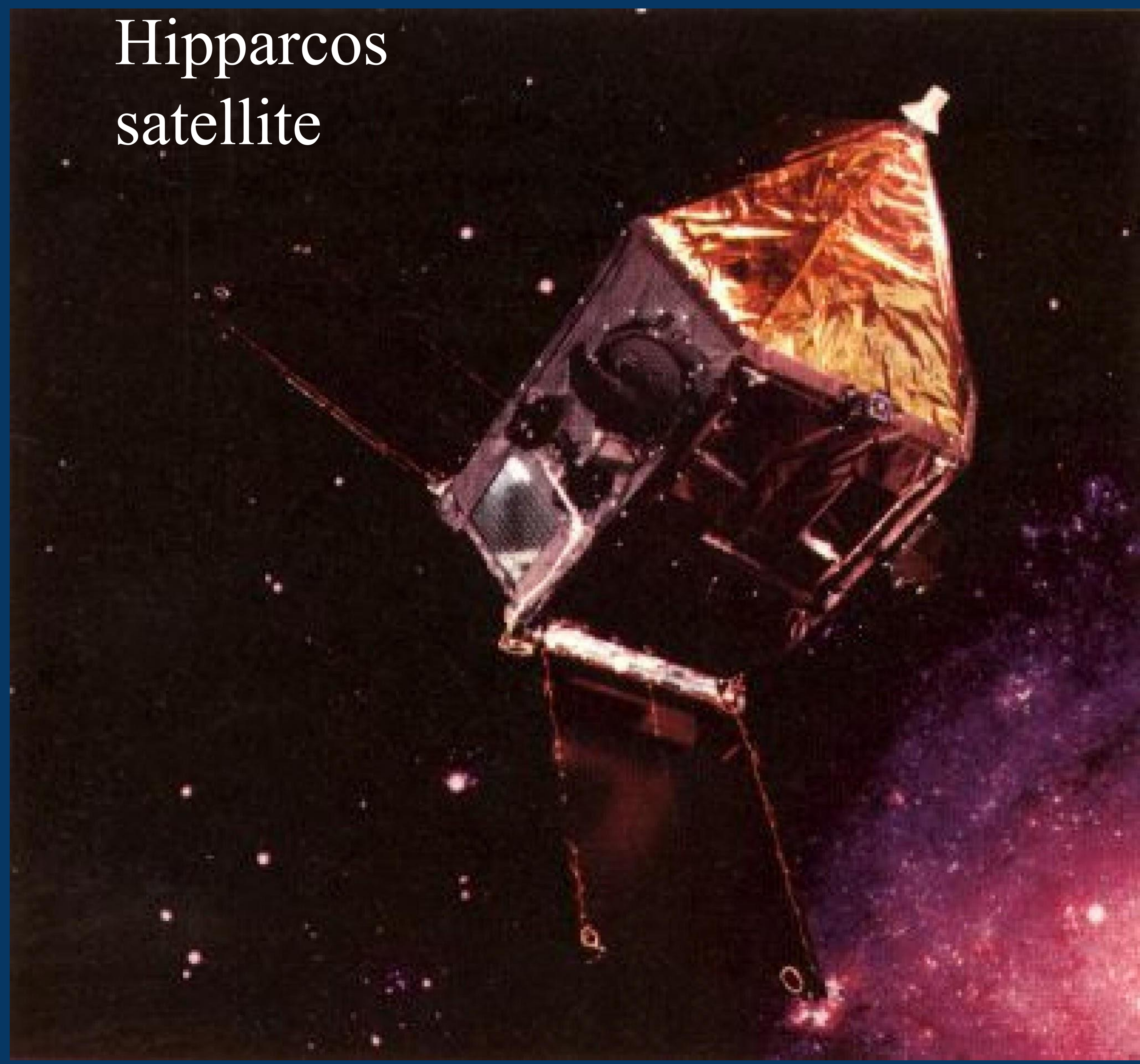
If the stars are too far away: the accuracy of the parallax method will be affected since it can be too small.
The greater distance, the smaller parallax and less accuracy.
On Earth, the smallest parallax can be measure is about 0.01 arcsec:

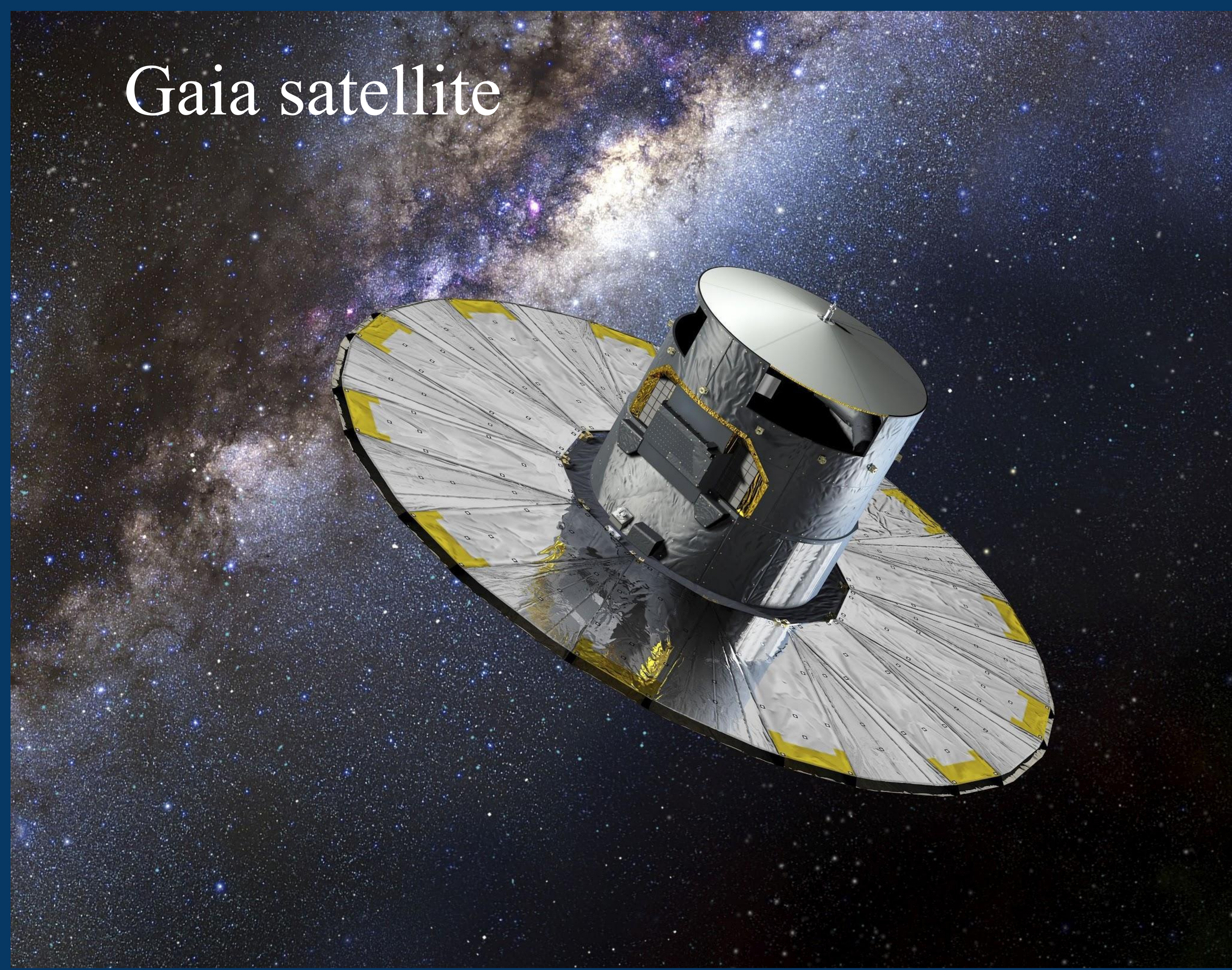
- Limited to 100 pc.
- 10% accuracy distance out to a few parsecs.
- Only few hundred stars are this close

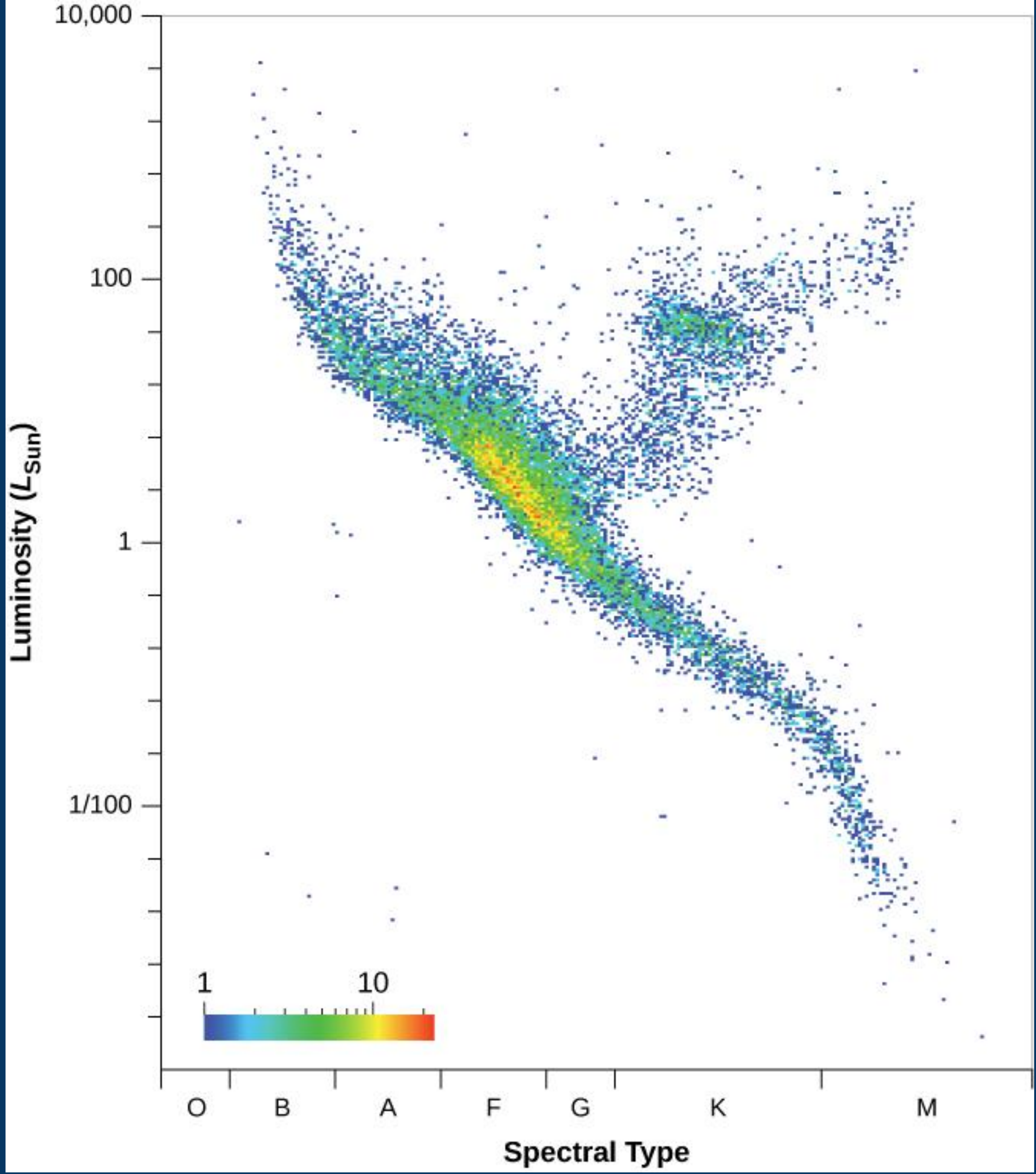
⇒ need to measure in space to improve accuracy.

Parallax measurements in space

- **Hipparcos** satellite (launched in 1989): precision parallax to an accuracy of about 0.001 arcsecs.
    - Can measure parallaxes for 100,000 stars.
    - 10% accuracy distances out of 100 pc.
    - Good measurement for bright star up to 1000pc.
- **Gaia** (launched in 2013): undertaking all-sky-survey at the Earth/Sun L2 point. The catalog will be completed in 2020 with the max precision of 10 microarcseconds.
    - 10% accuracy distances out to 10,000 pc.
    - Measure parallaxes for > 200 million stars.
    - Measure positions and motions for about 1 billion stars.







H–R Diagram of Stars Measured by Gaia and Hipparcos

This plot includes 16,631 stars for which the parallaxes have an accuracy of 10% or better. The colors indicate the numbers of stars at each point of the diagram, with red corresponding to the largest number and blue to the lowest. Luminosity is plotted along the vertical axis, with luminosity increasing upward. An infrared color is plotted as a proxy for temperature, with temperature decreasing to the right. Most of the data points are distributed along the diagonal running from the top left corner (high luminosity, high temperature) to the bottom right (low temperature, low luminosity). These are main sequence stars. The large clump of data points above the main sequence on the right side of the diagram is composed of red giant stars. (credit: modification of work by the European Space Agency)

Activity 19.2 Astronomical Parallax model

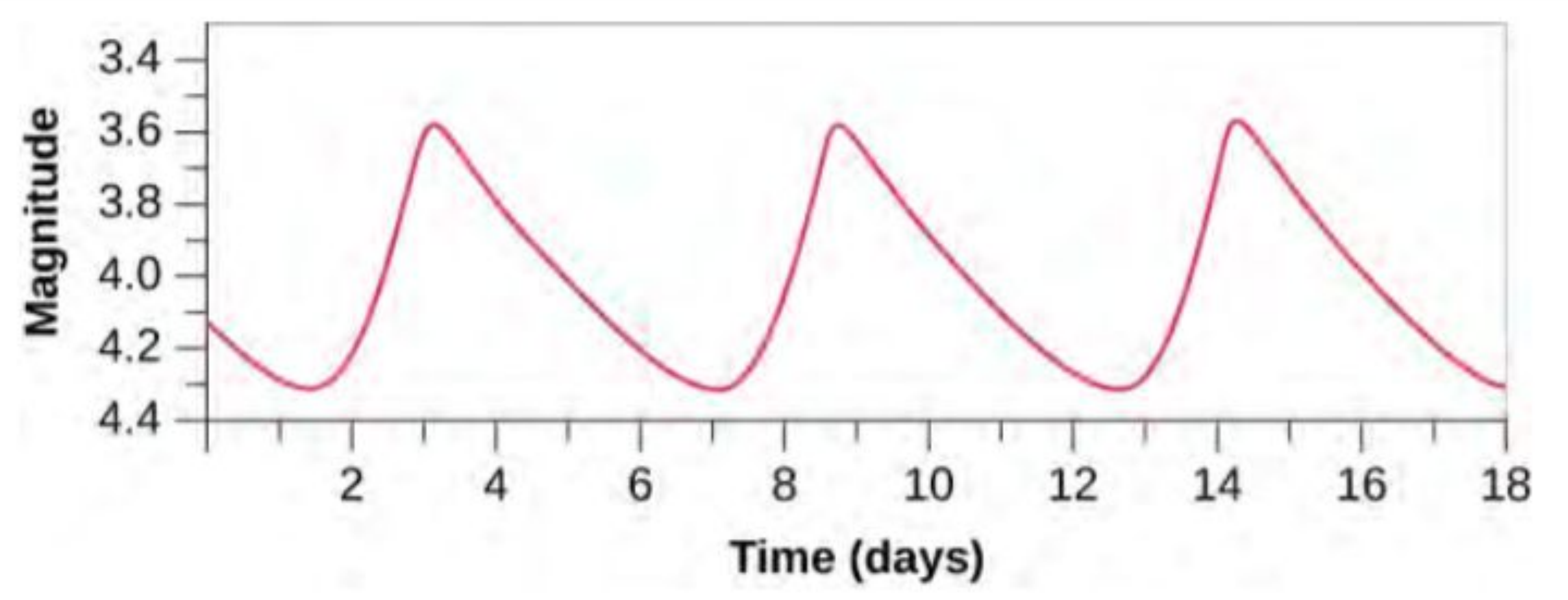
Use the Astronomical Parallax model to explore how the Earth's motion around the Sun causes nearby stars to appear to "wobble" back and forth compared to background stars. Click on the Orbit box, and use the view along the bottom to see the apparent motion of the nearby object.

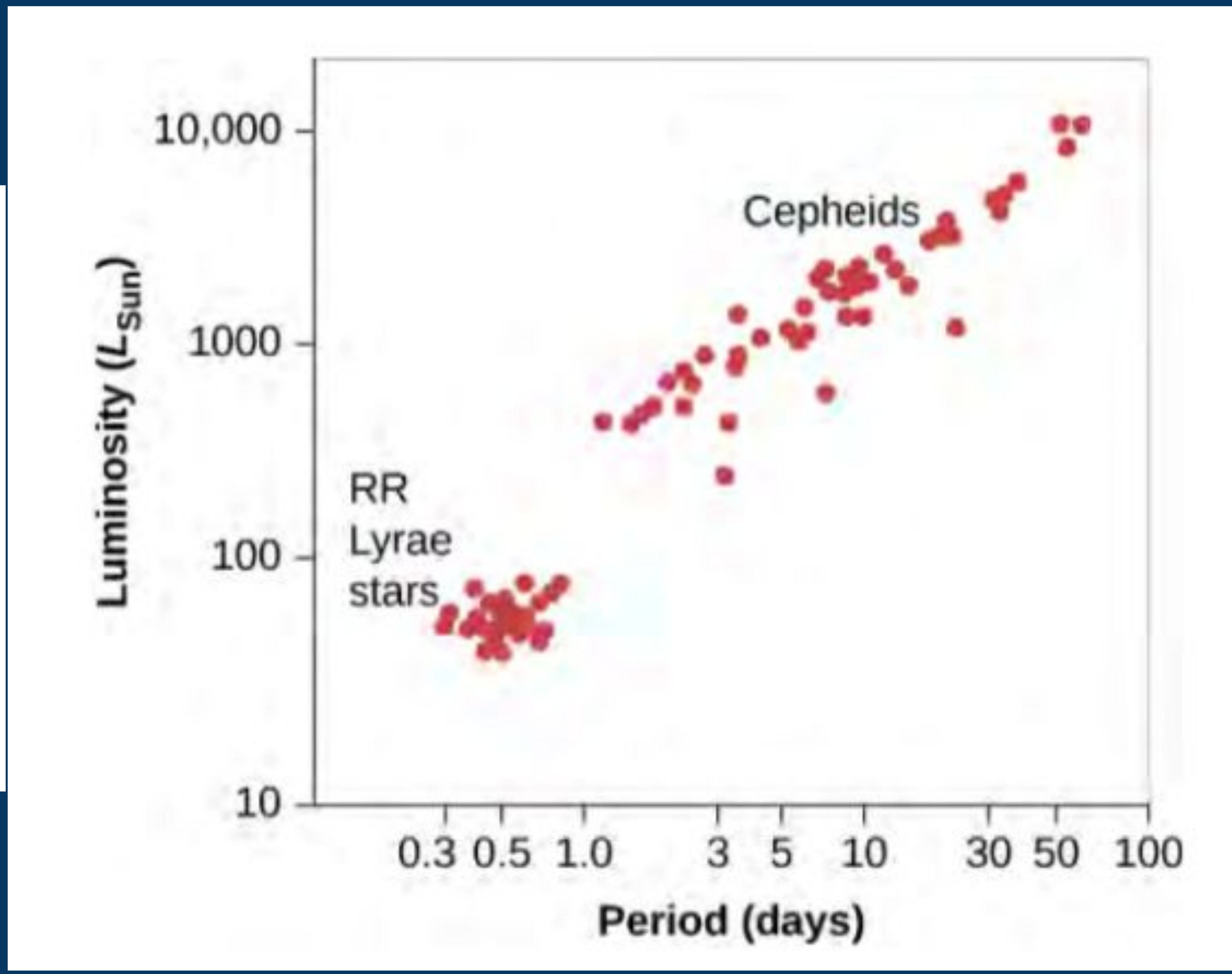
https://www.compadre.org/osp/EJSS/3571/9.htm

Please make a short presentation (5') introducing this interactive simulation.

Assigned to:

19.3 Variable Stars: One Key to Cosmic Distances





Using Variable stars

Most stars are constant in their luminosity.
Some stars are seen to be vary in brightness ⟶ *variable stars*.
Many variable stars vary on a regular circle:

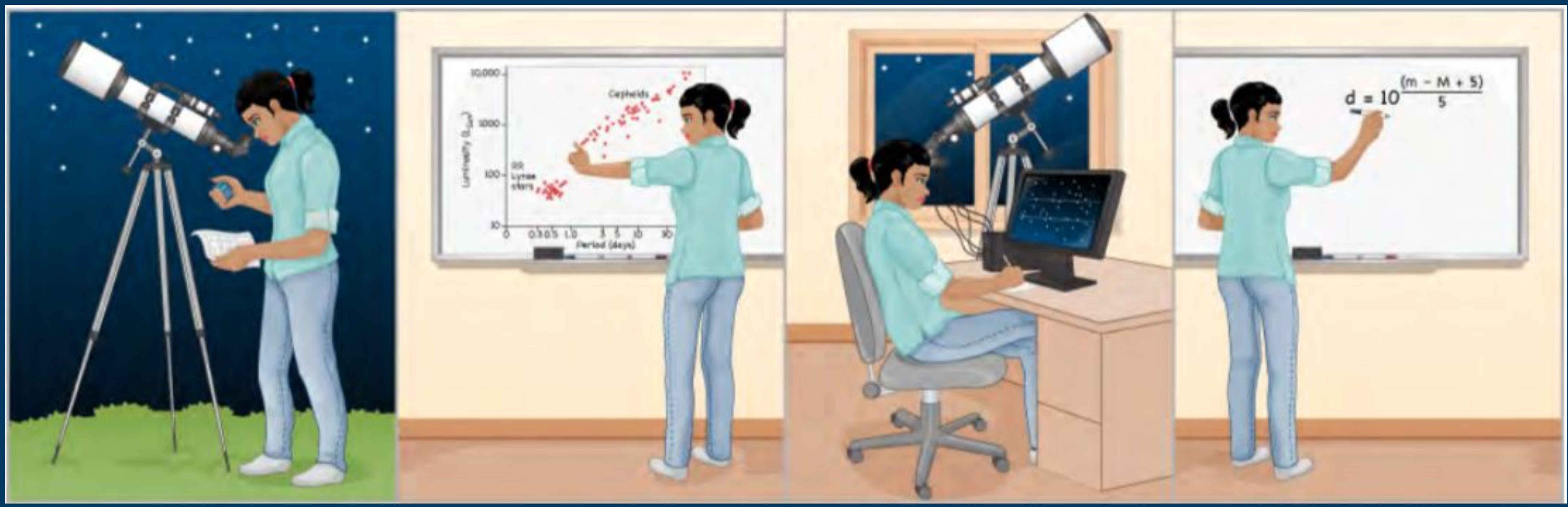
- There is a period when the star is faintest and brightest ⟶ *period of the star*.

⇒ Pulsating variable stars

Two types of variable stars: Cepheid and RR Lyrae variables

Large Magellanic Cloud

The Large Magellanic Cloud (so named because Magellan's crew were the first Europeans to record it) is a small, irregularly shaped galaxy near our own Milky Way. It was in this galaxy that Henrietta Leavitt discovered the cepheid period-luminosity relation. (credit: ESO)



Using Variable stars

Four steps:

1. Find a cepheid variable star and measure its period.
2. Use the period- luminosity relation to calculate the star's luminosity (L).
3. Measure the star's apparent brightness (b).
4. Compare the luminosity with the apparent brightness to calculate the distance (d).

$$b = \frac{L}{4\pi d^2} W/m^2$$

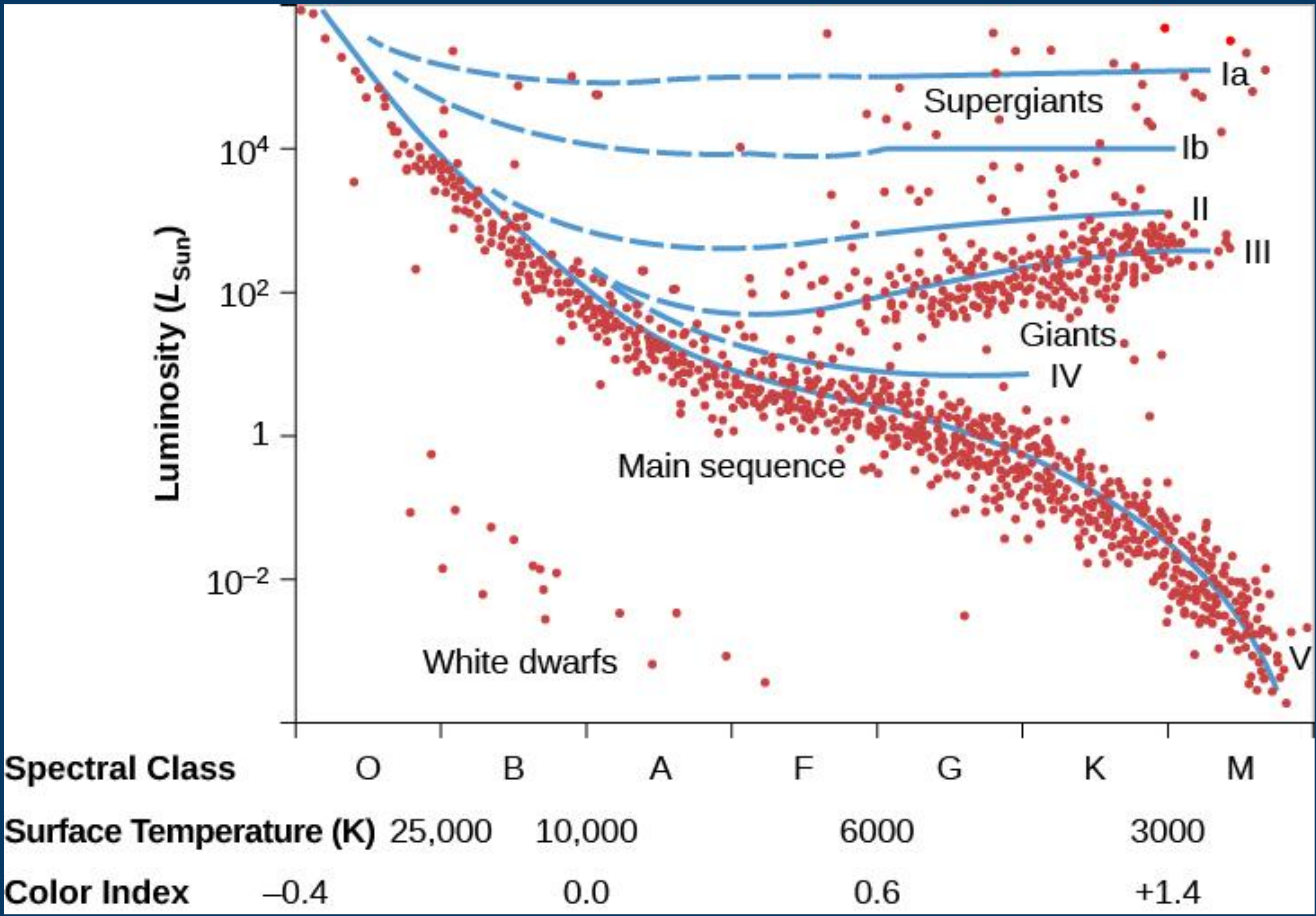
Readmore: https://www.astro.rug.nl/EDUCATION/Tutorial_5.pdf

19.4 The H–R Diagram and Cosmic Distances

Luminosity classes

The most widely used system of star classification divides stars of a given spectral class into six categories called **luminosity classes**. These luminosity classes are denoted by Roman numbers as follows:

- Ia: Brightest supergiants
- Ib: Less luminous supergiants
- II: Bright giants
- III: Giants
- IV: Subgiants (intermediate between giants and main-sequence stars)
- V: Main-sequence stars



Luminosity Classes

Stars of the same temperature (or spectral class) can fall into different luminosity classes on the Hertzsprung-Russell diagram. By studying details of the spectrum for each star, astronomers can determine which luminosity class they fall in (whether they are main-sequence stars, giant stars, or supergiant stars).

Method	Distance Range
Trigonometric parallax	4–30,000 light-years when the Gaia mission is complete
RR Lyrae stars	Out to 300,000 light-years
H–R diagram and spectroscopic distances	Out to 1,200,000 light-years
Cepheid stars	Out to 60,000,000 light-years

Thank you!