ASTR20A:
Introduction to Astrophysics I

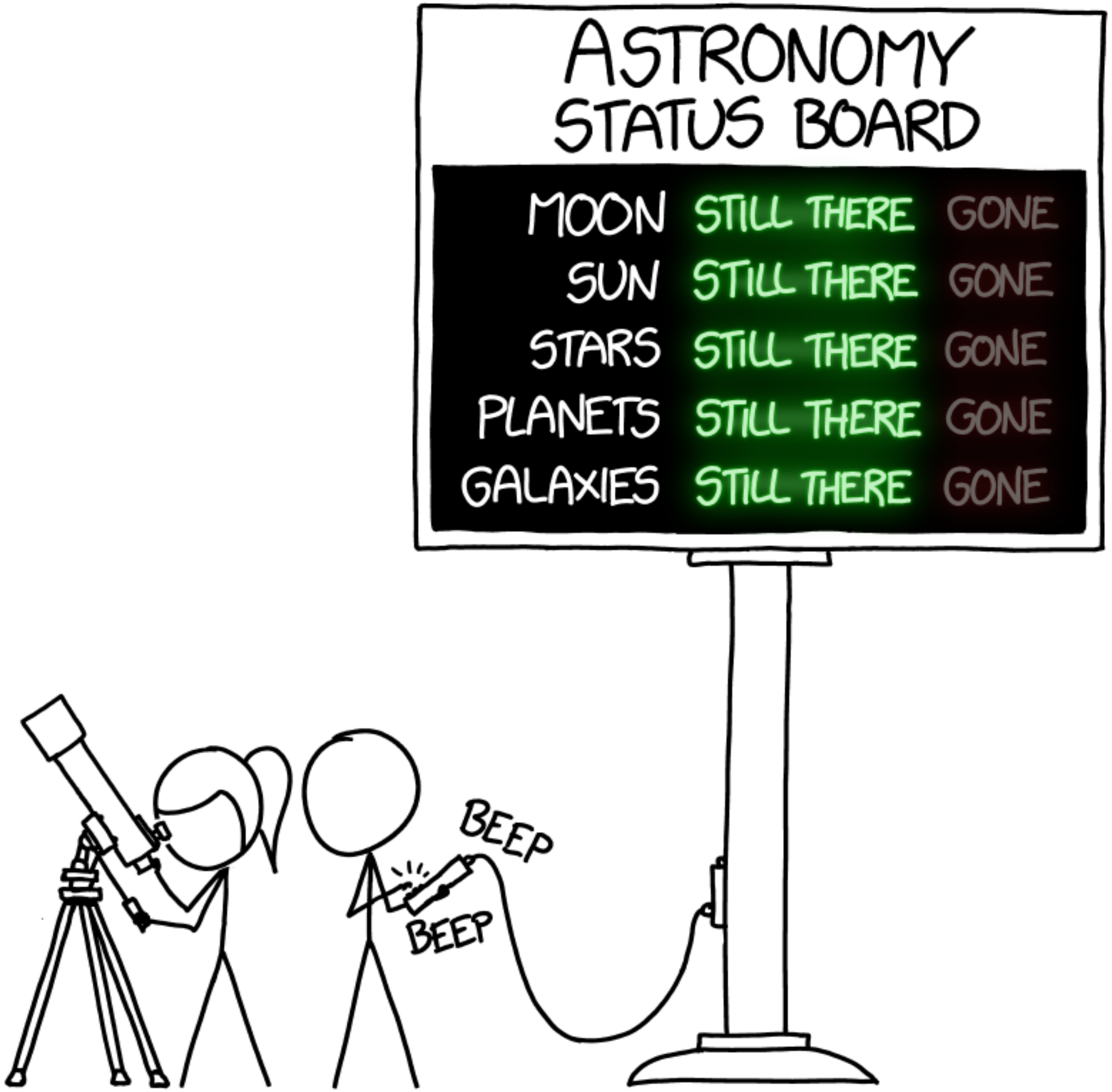
Dr. Devontae Baxter

Lecture 15 | Star Properties

Tuesday, November 25, 2025

Announcements

- HW #7 is due Wednesday, 11/26, by 11:59 pm.
- Coding project is due Sunday, 11/30 by 11:59 pm.
- HW #8 is due Thursday, 12/04, by 11:59 pm.
- Course evaluations are now available!



Questions?

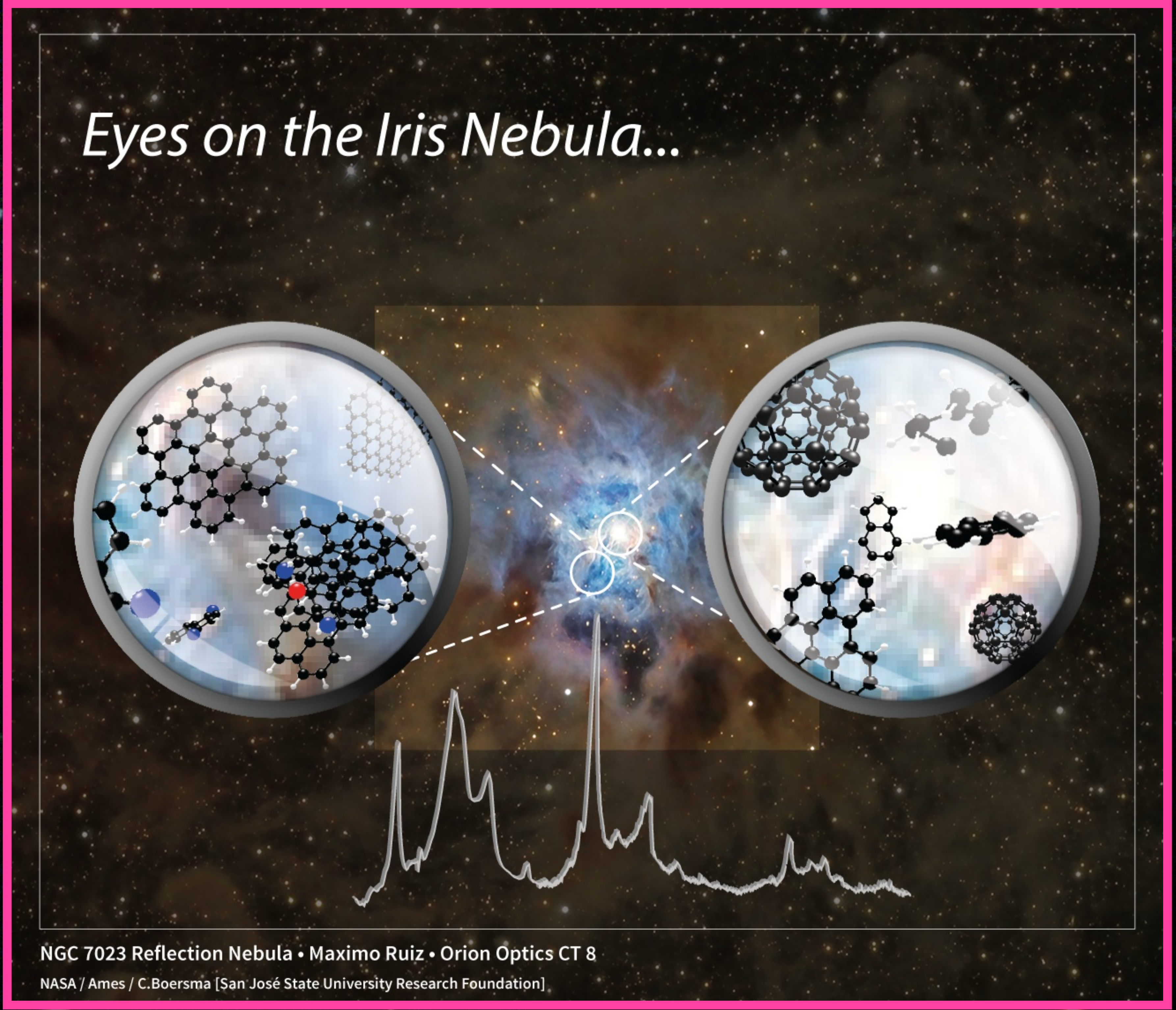
Learning Objectives

By the end of today's lecture you will be able to:

- Explain the difference between the *intrinsic* and *apparent* brightness of a star.
- Describe the stellar magnitude scale and its *logarithmic nature*.
- Calculate a star's absolute magnitude from its apparent magnitude and distance.
- Describe the relationship between stellar color index and surface temperature.
- Explain methods used to measure stellar radii (e.g., direct imaging, interferometry).
- Differentiate between visual, spectroscopic, and eclipsing binaries.
- Describe the stellar mass–luminosity and stellar mass–radius scaling relations.
- Calculate the approximate lifetime of a star from its mass–luminosity relationship.

Stars are the building blocks of astronomy

As we discussed in Lecture 1, modern astronomy spans an enormous range of objects — from tiny dust grains to vast galaxy clusters!



However, progress in all of these areas depends on understanding the fundamental physics that governs how stars form, evolve, and interact with their surroundings.

When poll is active respond at **PollEv.com/busygalaxy520**

What is a star? How do stars differ from other celestial objects?

undergo sizes opposing spheroid
self lifecycles gravitating hydrostatic main stars
illuminates during hydrogen elements heavy much there's
gravity block itself massive equilibrium
older fusion
starts heat nuclear ball star light
condensed internal
thermal large binary body energy
temperatures going helium plasma building self-sustain
release gaseous celestial emits remains
source amounts
reactions different criterion grow lifetime spherical
systems releasing luminous neutrino production
schrwarzchild universe

Twinkle, Twinkle little star,

How I wonder

how distant you are….

Review of Stellar Parallax

"**par**allax of one arc**sec**" – the parsec (distance corresponding to 1")

Using trigonometry, we see that,

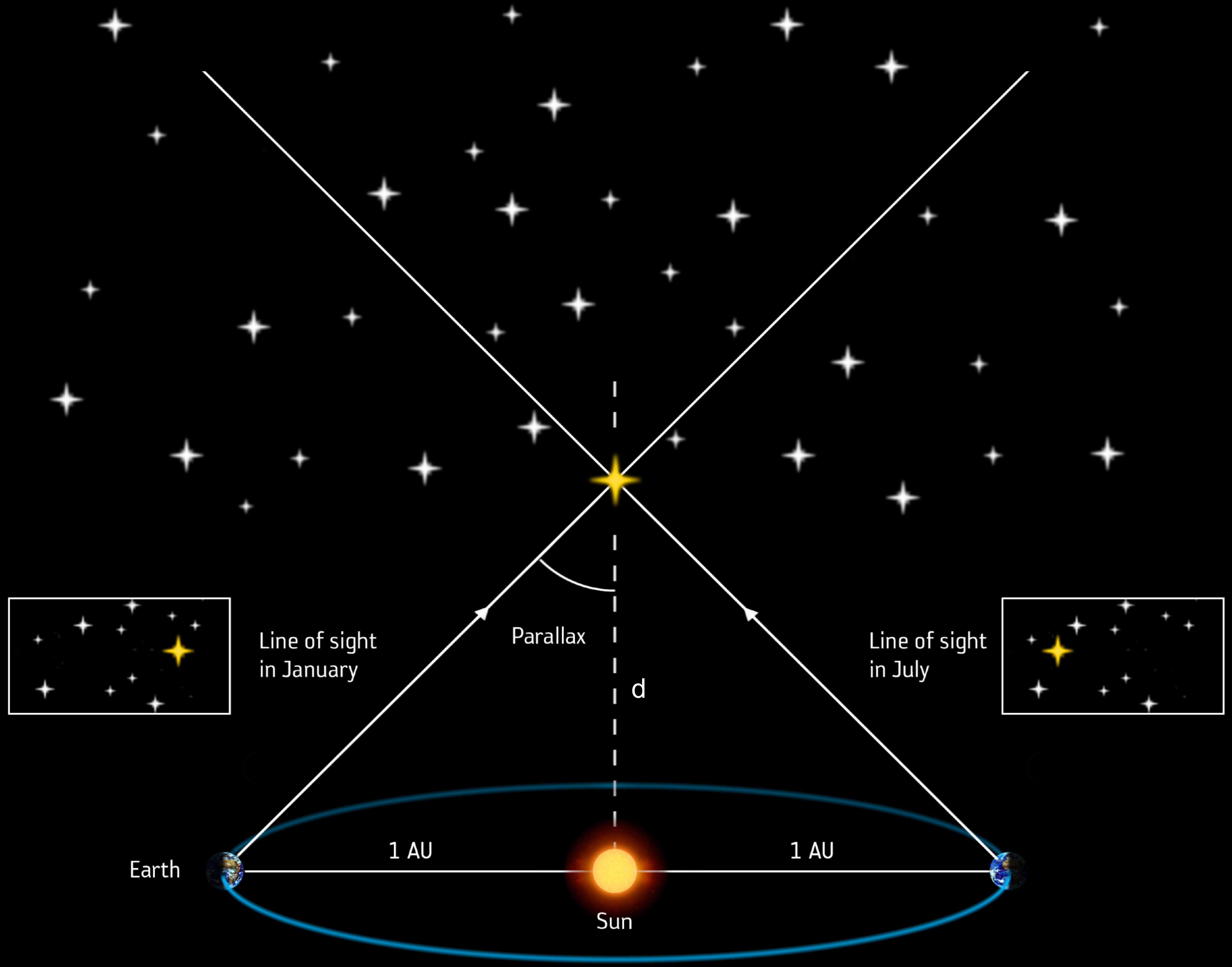
$$\tan(\theta/2) = \frac{1\ \mathrm{AU}}{\mathrm{d}}$$

Applying the small angle approximation† we get…

$$\tan(\theta/2) \approx \theta/2 \equiv p$$

Thus, the parallax (p) is simply defined as:

$$p \equiv \frac{1\ \mathrm{AU}}{d}$$



†Assumes the angle θ is in radians

Review of Stellar Parallax

"**par**allax of one arc**sec**" – the parsec (distance corresponding to 1")

We set the parallax equal to 1 arcsecond to define the distance of 1 parsec

$$p = 1'' \quad \longrightarrow \quad d = 1 \text{ parsec} \equiv \frac{1 \text{ AU}}{1''}$$

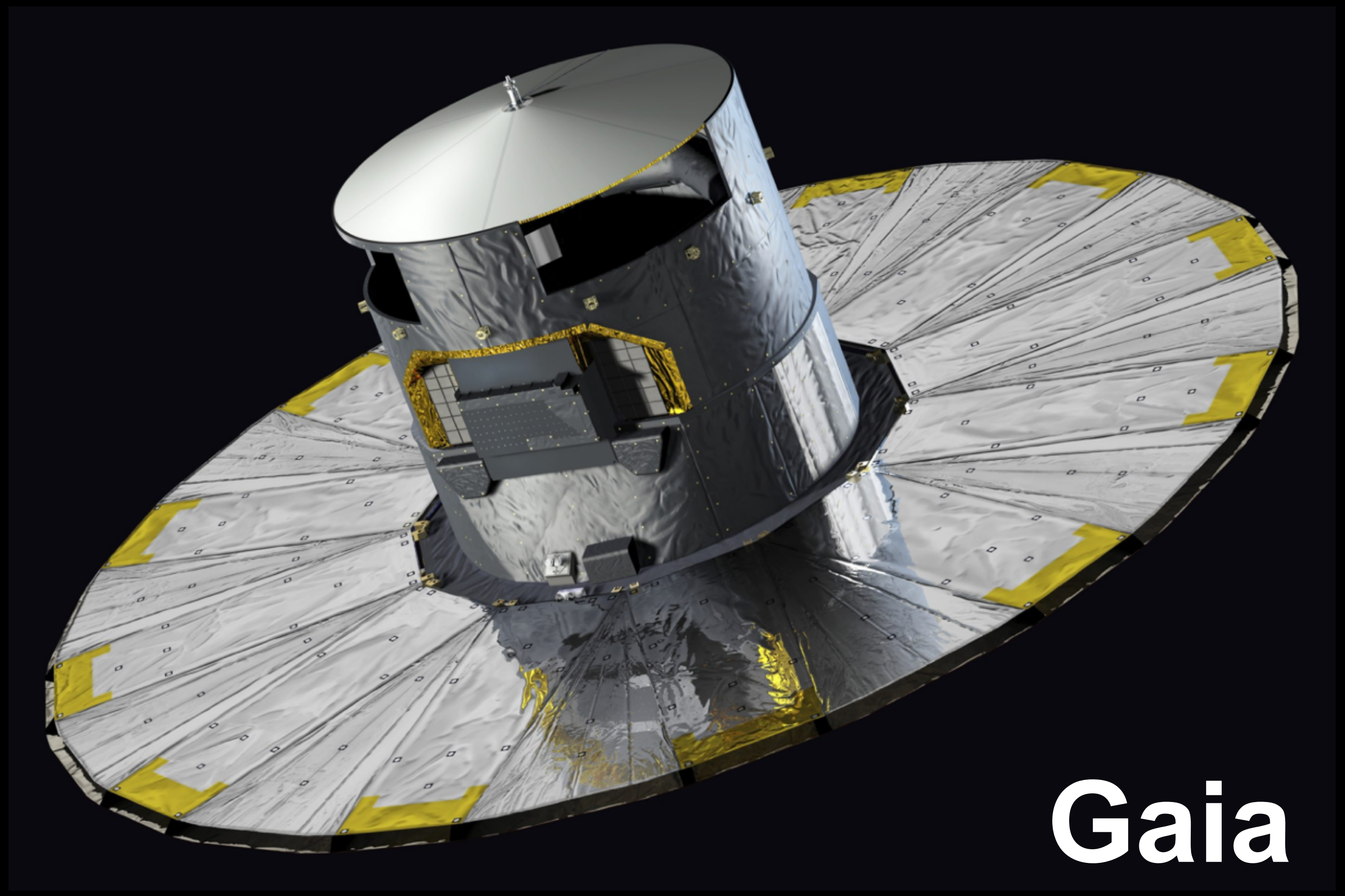
For example, the closest star to Earth, Proxima Centauri, has a parallax of $0.76''$, and hence

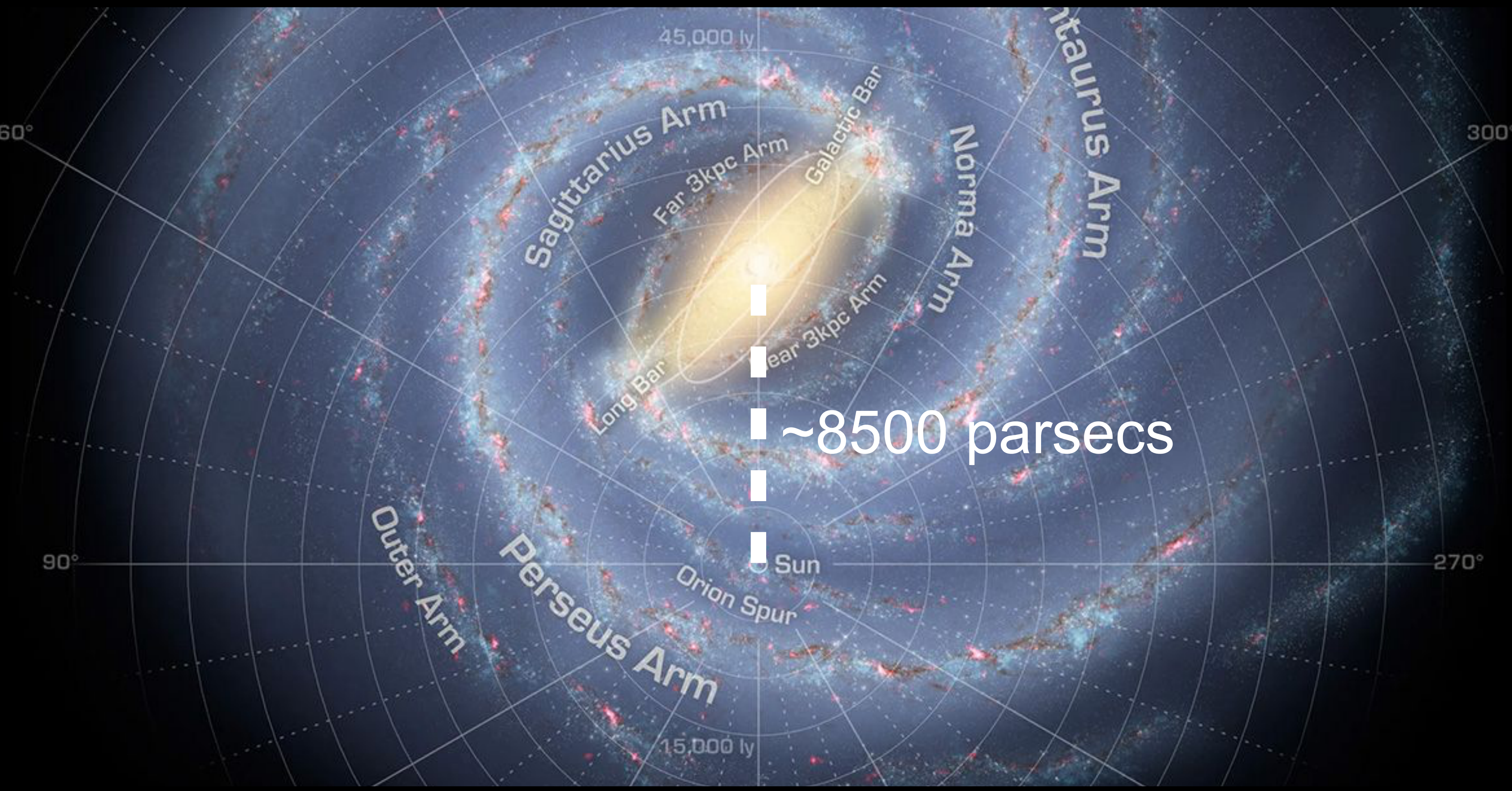
$$\text{distance to Proxima Centauri[parsecs]} = \frac{1 \text{ AU}}{0.76''} = 1.3 \text{ parsecs}$$

Limitation of Stellar Parallax

The main limitation of the stellar-parallax method is that it becomes increasingly difficult to measure accurately for more distant stars, **because the parallax angle becomes very small.**

Even the Gaia spacecraft, which has achieved *the most precise astrometric positions to date*, could only measure stars out to around 8,500 parsecs (roughly the distance from the Sun to the Galactic centre) with an accuracy of about 20%.





Clearly, we need alternative distance-measuring methods for stars that lie farther away.

Twinkle, Twinkle little star,

How I wonder

how bright you are….

Luminosity

In general, what we measure when we look at a star is the **apparent brightness** (how bright it is in the sky), but what we really want to know is its **intrinsic brightness**, or ***luminosity***.

The luminosity of a star is **the rate at which it emits energy in the form of electromagnetic radiation.**

For example, the Sun has a luminosity of

$$L_\odot = 3.86 \times 10^{33}\ \mathrm{erg\,s^{-1}} = 3.86 \times 10^{26}\ \mathrm{W}\,.$$

This luminosity includes all electromagnetic radiation emitted by the Sun, from radio waves to gamma rays.

Flux

The *apparent brightness* is known as the **flux** (F). It is related to the luminosity through the *inverse square law*

$$F = \frac{L}{4\pi d^2}$$

At Earth, we receive a flux of

$$F = \frac{L_\odot}{4\pi(1\ \mathrm{AU})^2} \approx \frac{3.9 \times 10^{26}\ \mathrm{W}}{4\pi(1.5 \times 10^{11}\ \mathrm{m})^2} = 1370\ \mathrm{W\,m^{-2}}$$

In general,

$$F = \frac{4\pi R^2 \sigma T^4}{4\pi d^2} = \sigma T^4 \left(\frac{R}{d}\right)^2$$

Flux

In practice, we compute a star's **luminosity** after measuring its **flux** and **distance**.

Let's consider **Sirius (α CMa)** – the brightest star in our night sky:

- $F_{\text{sirius}} = 1.2 \times 10^{-7}\ \text{W m}^{-2}$
- $d_{\text{sirius}} = 2.637\ \text{pc} = 8.14 \times 10^{16}\ \text{m}$

Therefore, the luminosity of Sirius:

$$L_{\text{sirius}} = 4\pi d_S^2 F_S \approx 1.0 \times 10^{28}\ \text{W} \approx 26\ L_\odot$$

Sirius (Alpha Canis Majoris)

Takeaway: Stars don't all have the same luminosity!

Flux

Historically, measuring a star's *total flux over all wavelengths* has been **challenging**…

- Humans can only see a **tiny slice of the electromagnetic spectrum**: 400–700 nm (not even a full octave 😩).

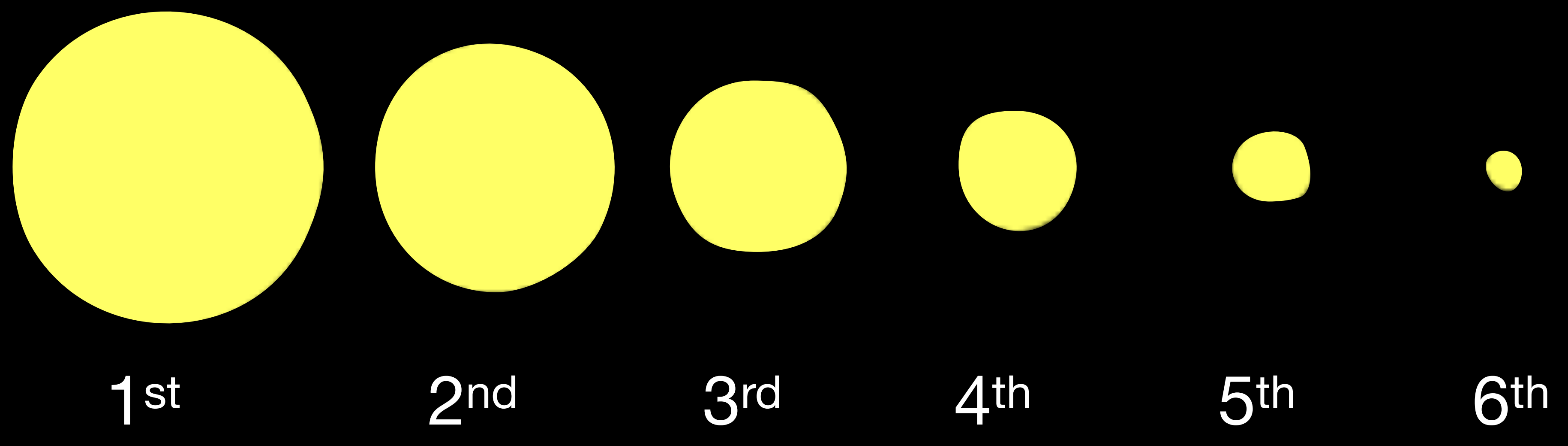
- Simply saying that a star is "bright" is not quantitative.

The first recorded attempt to *quantify* stellar flux at visible wavelengths was made the Greek astronomer Hipparchus in the second century BC.

Magnitudes

Hipparchus invented the first “magnitude” system and slassified stars into **six magnitudes** based on apparent visible brightness:

- 1st magnitude → brightest stars.
- 2nd magnitude → next brightest.
- …
- …
- …
- 6th magnitude → faintest visible to the human eye.



After the invention of the telescope, Hipparchus’s *apparent magnitude scheme* was extended to even fainter stars!

This means ***<u>BIGGER numbers correspond to FAINTER objects!</u>***

Hipparchus of Nicaea (190-120 BCE)

Magnitudes

This madness was attempted to be placed on a firm mathematical basis by Norman Pogson in the 19th century.

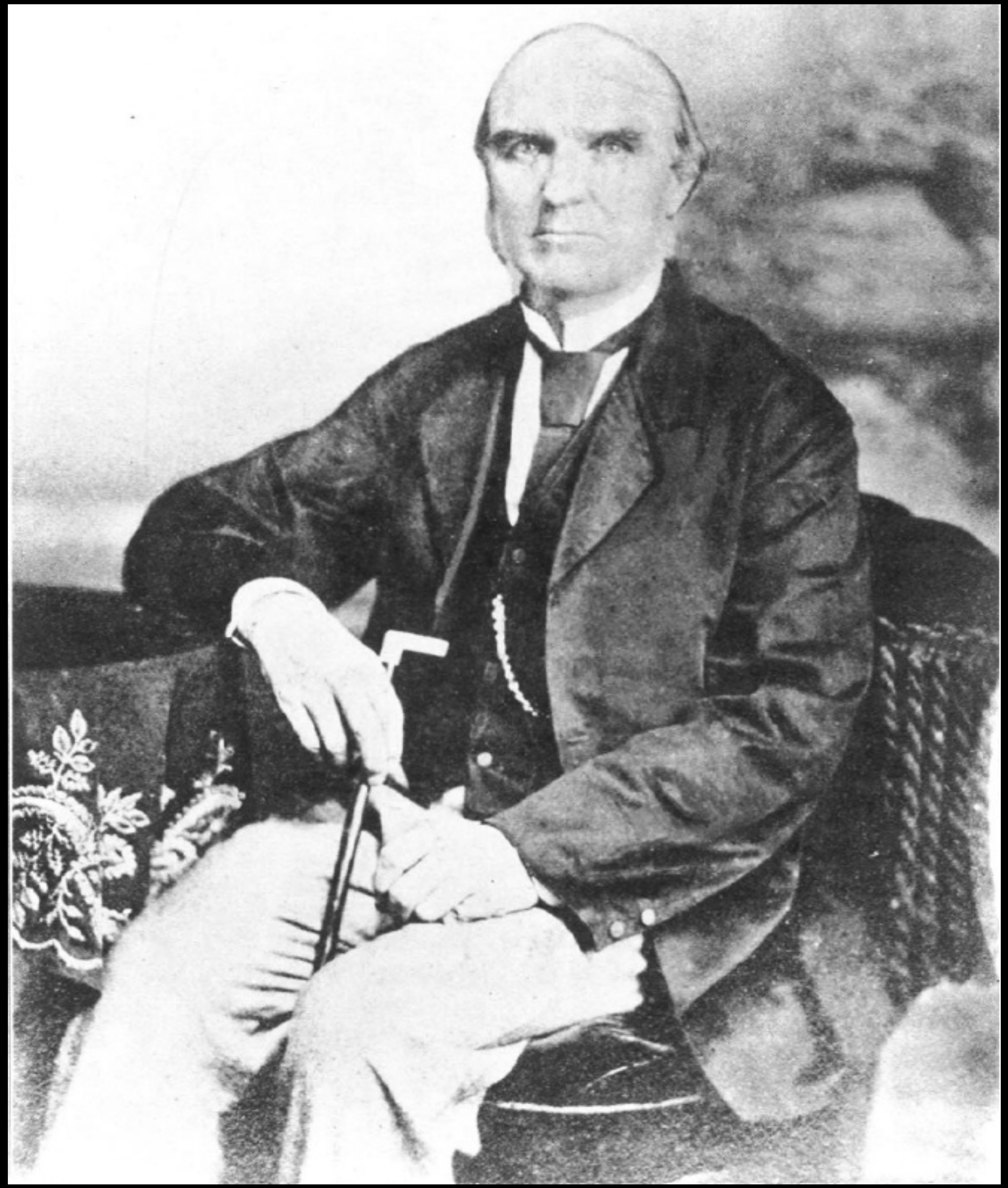
He noticed that 1st magnitude stars are ~100 times brighter than 6th magnitude stars.

Let's take m_1 and m_2 to be 6th and 1st magnitude stars, respectively.

We can write two expressions:

$$m_1 - m_2 = 5 \text{ mag}$$

$$\frac{\text{Flux}_1}{\text{Flux}_2} = \frac{F_1}{F_2} = 100$$



Norman Pogson (1829 - 1891)

Magnitudes

Now if $m_1 - m_2 = 1$ the ratio is

$$\frac{F_1}{F_2} = 100^{1/5} = 10^{0.4} \approx 2.512$$

Each unit change in magnitude is a difference of ***2.5 times in brightness.***

The general form of this equation is

$$\frac{F_1}{F_2} = 100^{(m_2-m_1)/5} = 10^{2(m_2-m_1)/5} = 10^{0.4\,(m_2-m_1)}$$

We can also write this as a difference in magnitudes,

$$m_2 - m_1 = 2.5\log_{10}\left(\frac{F_1}{F_2}\right) = -\,2.5\log_{10}\left(\frac{F_2}{F_1}\right)$$

A star of magnitude 15 is observed at visible wavelengths. How many times fainter is it compared to the faintest star visible to the naked eye (magnitude 6)?

- 500
- 6000
- 4000
- 10000

A star of magnitude 15 is observed at visible wavelengths. How many times fainter is it compared to the faintest star visible to the naked eye (magnitude 6)?

500	0%
6000	0%
4000	100%
10000	0%

Magnitudes

We can think of "**apparent magnitude**" as a logarithmic measure of the flux

$$m = C - 2.5\log(F)$$

The constant C exists because a log scale needs a defined reference level.

where the constant C has historically been calibrated so that the star Vega has an apparent magnitude of 0.

$$C = 2.5\log\left(F_{\mathrm{Vega}}\right)$$

In this system every star would be measured relative to Vega. For example, the nearest star, Proxima Centauri, has $m = 10.7$

$$\frac{F_{\mathrm{Vega}}}{F_{\mathrm{Proxima}}} = 10^{0.4\,(10.7-0.0)} \approx 19{,}000$$

Magnitudes

We also define an **absolute magnitude** (M) as a way to normalize stars to the same scale. The absolute magnitude is the apparent magnitude of a star placed at **10 parsecs.**

$$m - M = 2.5\log_{10}\frac{F_{10\,\mathrm{pc}}}{F_d} = 2.5\log_{10}\frac{L/(4\pi(10\,\mathrm{pc})^2)}{L/(4\pi d^2)}$$

$$m - M = 2.5\log_{10}\frac{d^2}{(10\,\mathrm{pc})^2} = 2.5\log_{10}\left(\frac{d}{10\ \mathrm{pc}}\right)^2$$

$$\Rightarrow m - M = 5\log_{10}\frac{d}{10\ \mathrm{pc}}$$

The difference between the absolute and apparent magnitude of a star is known as the **distance modulus**, a logarithmic measure of its distance.

If an astronomer says, "That star has a distance modulus of 50," how far away is the star?

10^8 parsecs

10^{10} parsecs

10^{11} parsecs

10^4 parsecs

If an astronomer says, "That star has a distance modulus of 50," how far away is the star?

10^8 parsecs	0%
10^{10} parsecs	0%
10^{11} parsecs	100%
10^4 parsecs	0%

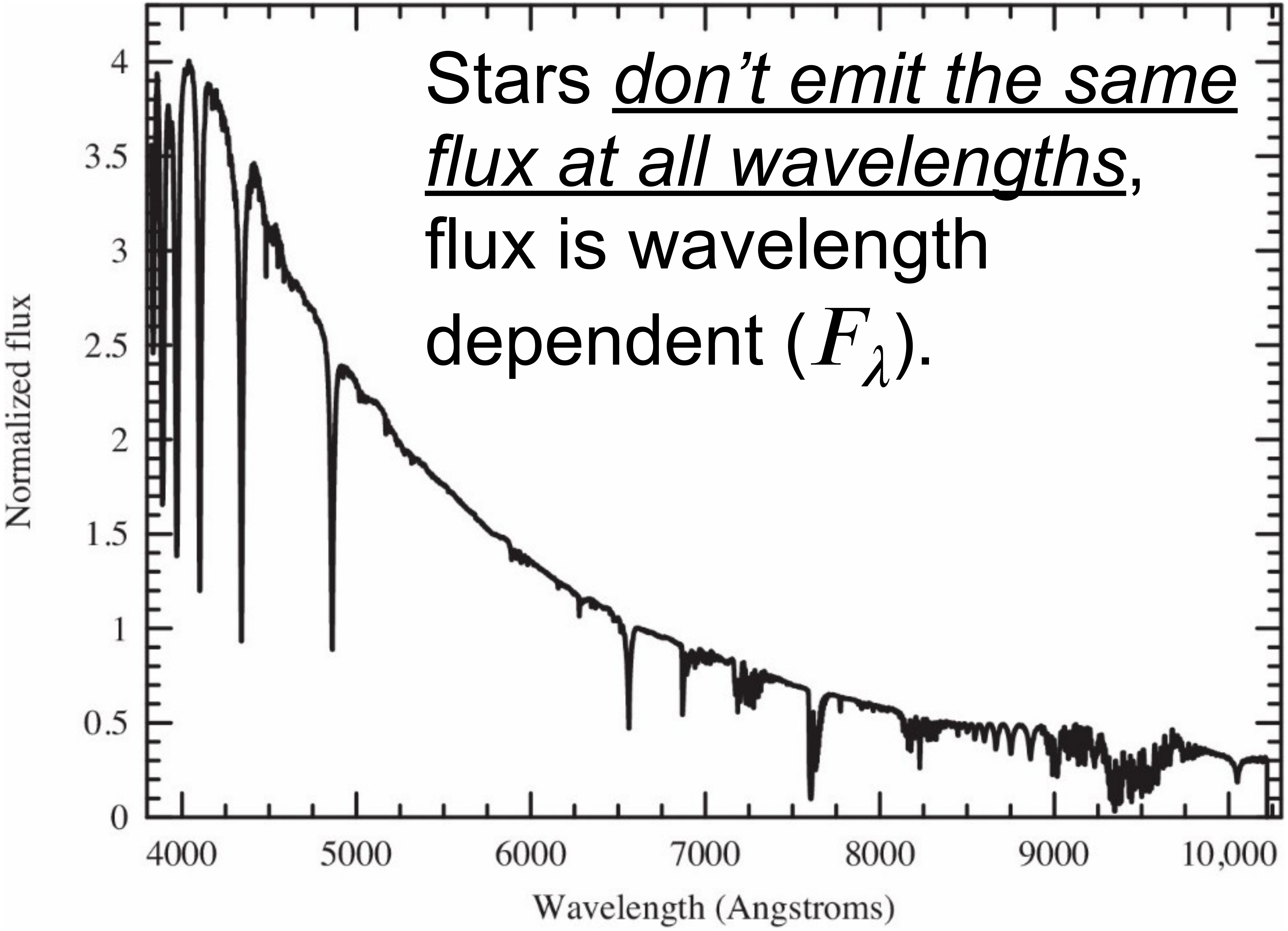

Pause

Twinkle, Twinkle little star,

How I wonder

How hot you are….

More on Fluxes



Stars *<u>don't emit the same flux at all wavelengths</u>*, flux is wavelength dependent (F_λ).

To get a star's total flux (or **bolometric flux)**, you need to integrate the star's F_λ over all wavelengths,

$$F_{\text{bol}} = \int_0^\infty F_\lambda d\lambda$$

Filters

We cannot measure *every* wavelength for an object, so we observe through filters, which are defined by their **bandwidth** and **effective wavelength**.

A star's flux through a filter (V for example) is

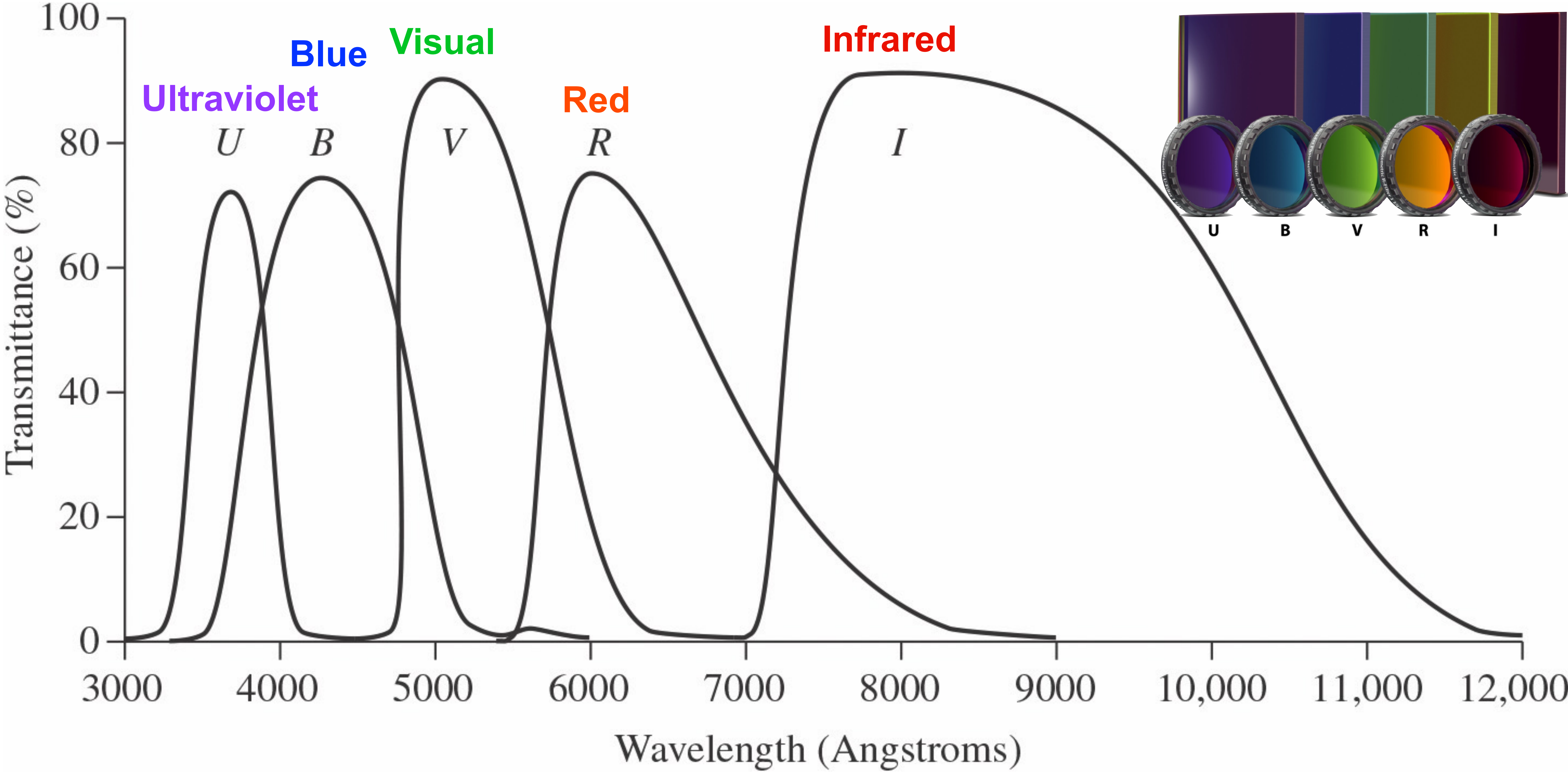
$$F_V = \int_0^\infty F_\lambda S_V(\lambda) d\lambda$$

where $S(\lambda)$ is the spectral sensitivity of the filter.

The apparent magnitude of a star through the V filter is

$$m_V = C_V - 2.5 \log F_V$$

Spectral sensitivity, $S(\lambda)$, of the **Johnson–Cousins** filters



UBVRI magnitudes are normalized so that Vega has an apparent magnitude *close to zero.*

Brain Break – Think-pair-share

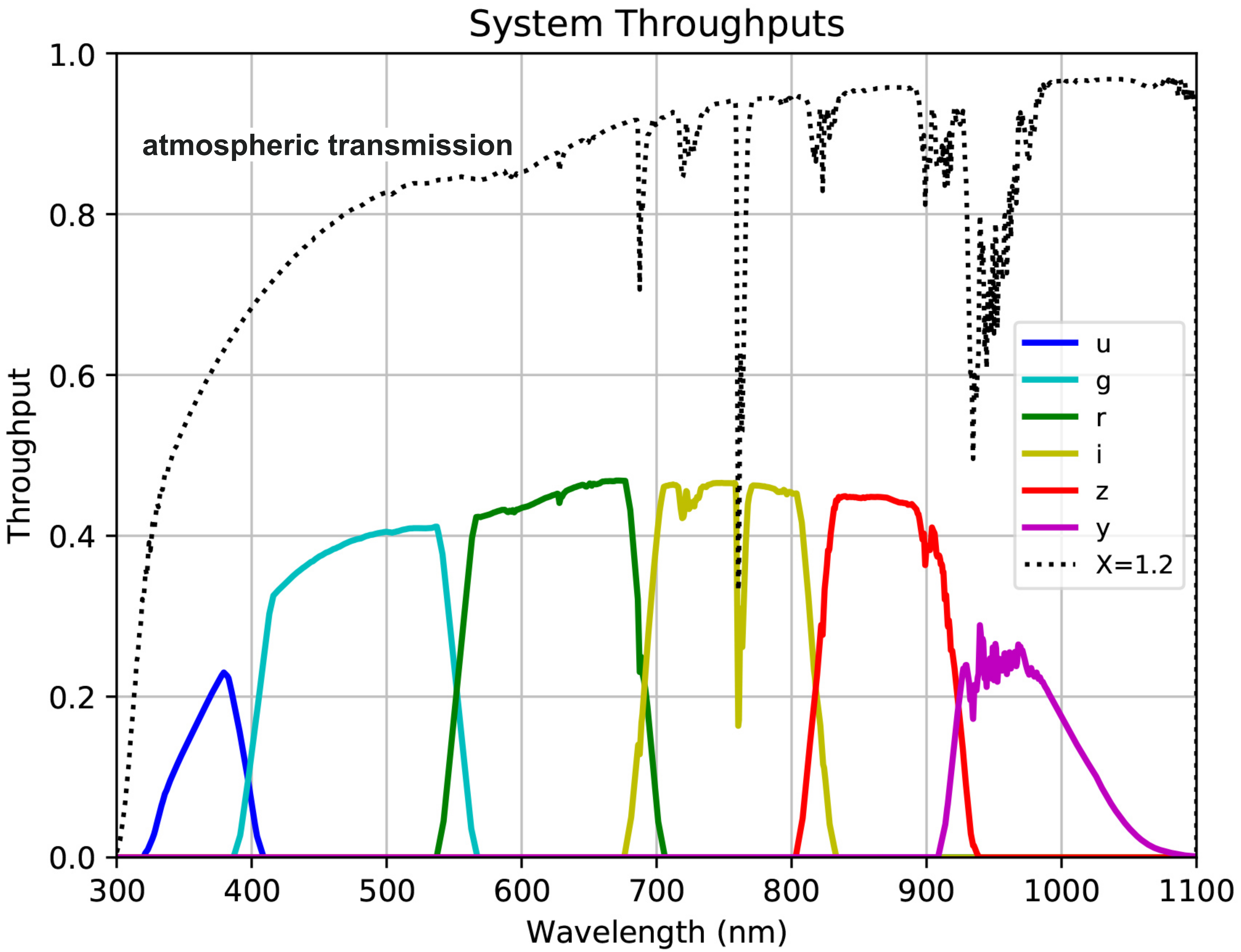
The Rubin Observatory has begun its 10-year survey of the night sky using filters like those shown below.

By combining many repeated images over time, Rubin will be able to detect objects as faint as $m \approx 27.5$ in the *g* and *r* filters!

1. About **how many times fainter** is a magnitude 27.5 object compared to the limit of the unaided human eye?

2. What kinds of **extremely faint objects** do you think Rubin will reveal that are difficult or impossible to detect today?

3. How might Rubin **change our understanding of the Universe?**



Source: https://rubinobservatory.org/for-scientists/rubin-101/key-numbers

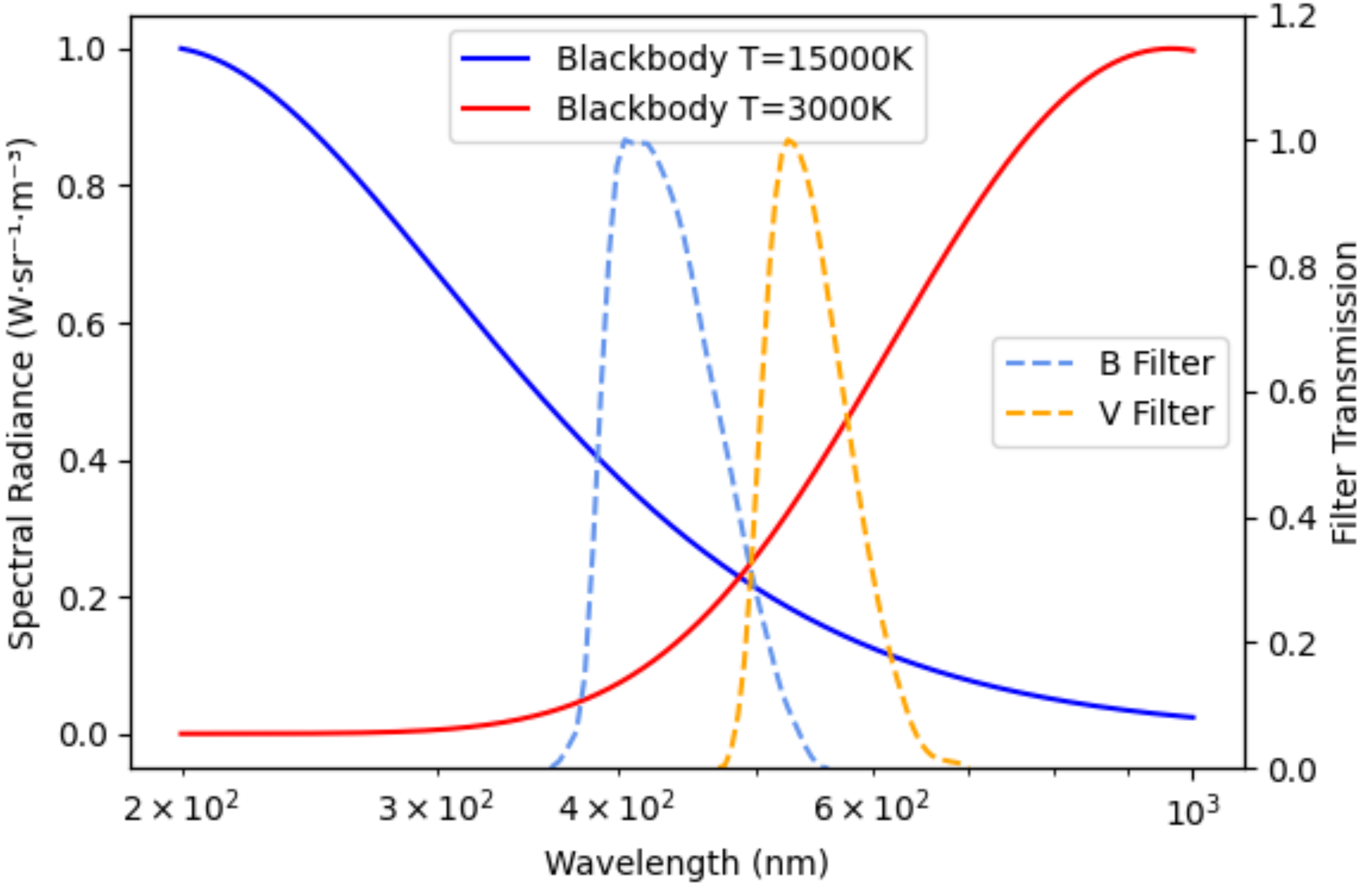
Colors

One way to characterize stars is by measuring their color.

- The **color** of a star is determined by comparing its brightness in two different filters.
- Practically, this is measured as the **difference in magnitudes** (or equivalently, the ratio of fluxes) between those filters.
- We define the **color index** between two filters (e.g. B and V) as:

$$B - V = m_B - m_V$$

By convention, the filter with the **shorter effective wavelength** (here, B) comes first.



Smaller (**larger**) color indices correspond to **bluer** (**redder**) stars.


Main Sequence
Stars

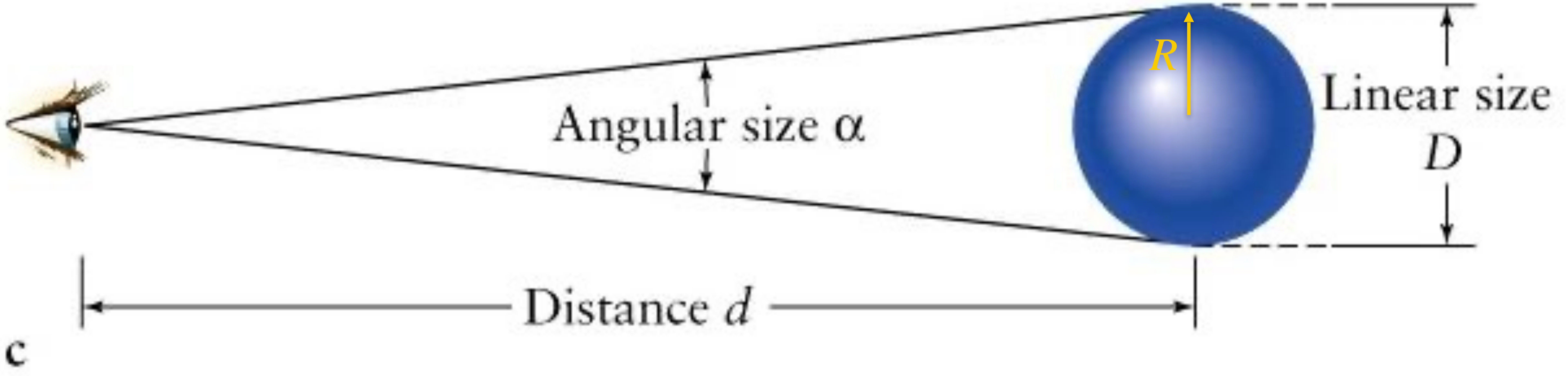
Twinkle, Twinkle little star,

How I wonder

What size you are….

Radius

If you know the distance to a star, measuring its radius R can be determined with a little trig.



$$\tan\left(\frac{\alpha}{2}\right) = \frac{R}{d} \;\rightarrow R = d\,\tan\left(\frac{\alpha}{2}\right) \approx \frac{d\,\alpha}{2}$$

Radius

The Sun has an average distance of $d = 1\ \text{AU} = 1.496 \times 10^8\ \text{km}$ and average angular diameter of $\alpha = 1919'' = 9.30 \times 10^{-3}\ \text{rad}$, so

$$R_\odot = \frac{(1.496 \times 10^8\ \text{km})(9.30 \times 10^{-3})}{2} = 696{,}000\ \text{km}$$

Stars other than the Sun have angular diameters that are very small, and hence **difficult to measure.**

For instance, if we were to view the Sun from the location of Proxima Centauri, $d = 1.295\ \text{pc} = 2.67 \times 10^5\ \text{AU}$, its angular size would be

$$\alpha = 1919'' \times \frac{1\ \text{AU}}{2.67 \times 10^5\ \text{AU}} \approx 7.2 \times 10^{-3}\ \text{arcsec}\,.$$

Measuring an angular size of 7 milliarcseconds is **difficult**!

Radius

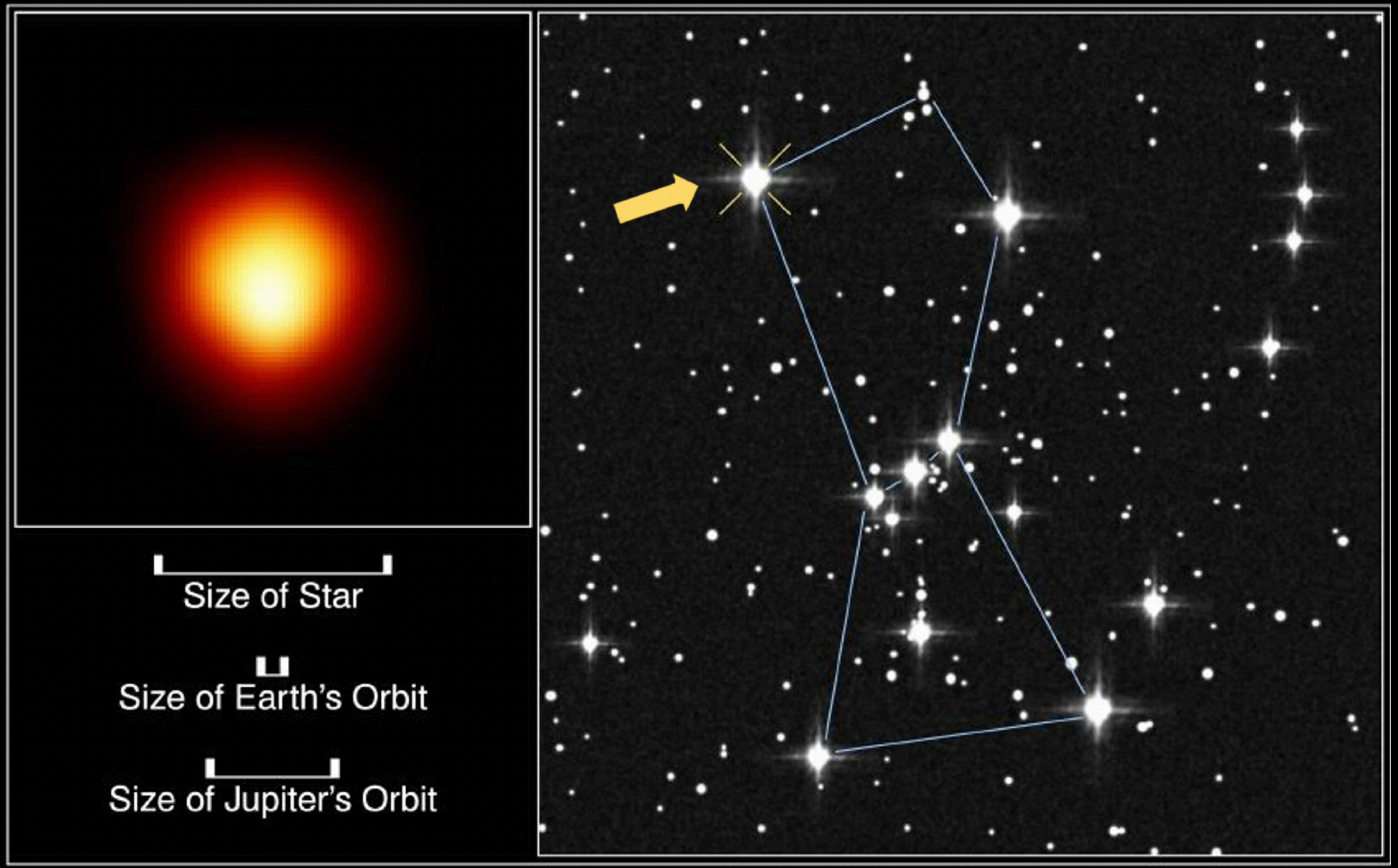
Only one star other than the Sun, Betelgeuse (Alpha Orionis, α Ori), has had its angular diameter resolved through **direct imaging!**

The distance to Betelgeuse, determined from its parallax, is

$$d_B = 131\ \text{pc} = 2.70 \times 10^7\ \text{AU}\,.$$

The angular diameter of Betelgeuse, measured at ultraviolet wavelengths using the Hubble Space Telescope, is

$$\alpha_B = 0.125\ \text{arcsec} = 6.06 \times 10^{-7}\ \text{rad}\,.$$



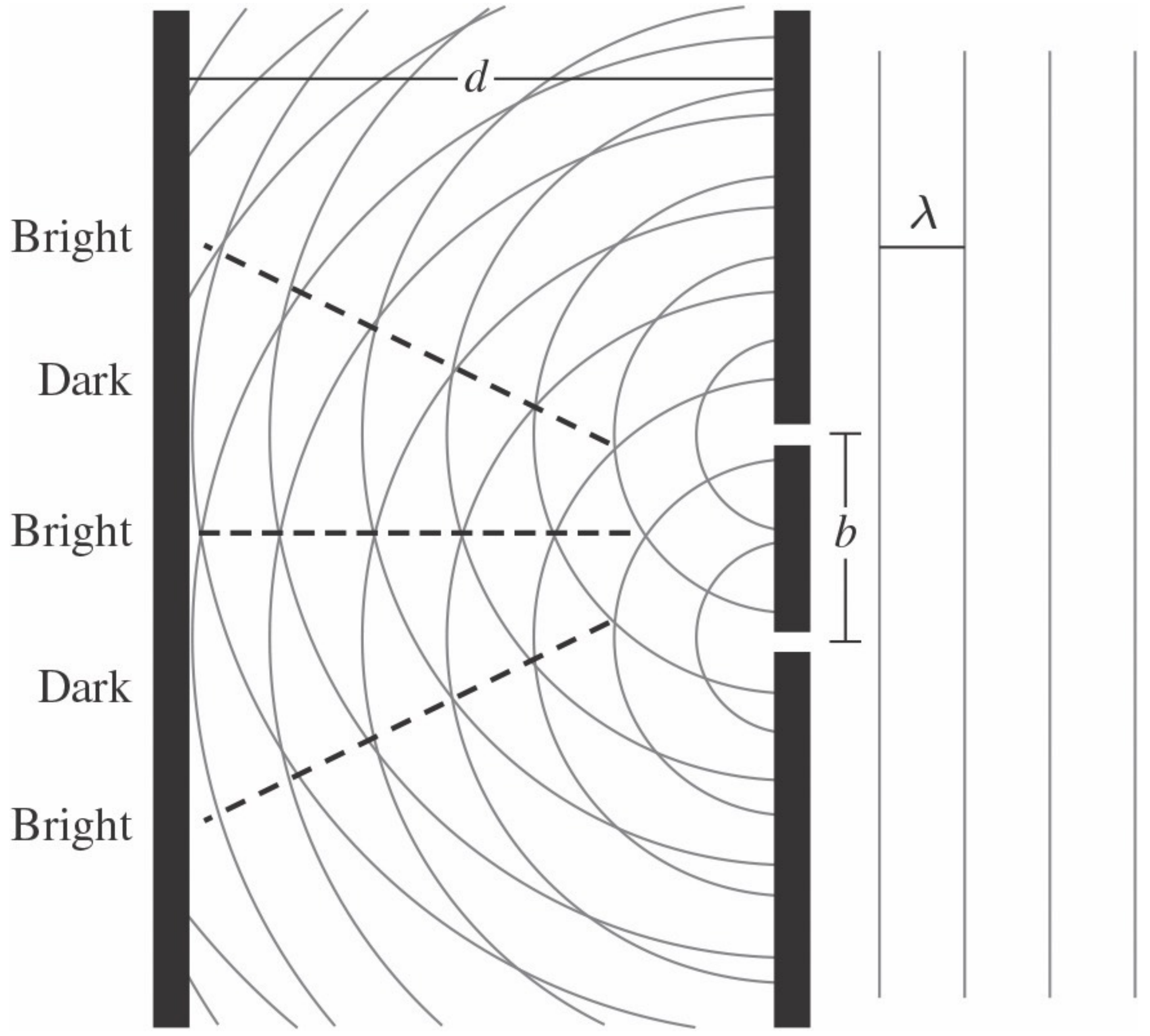
Thus, its radius is

$$R_B = \frac{d_B \alpha_B}{2} = 8.2\ \text{AU} = 1.2 \times 10^9\ \text{km} \approx 1800\ R_\odot\,.$$

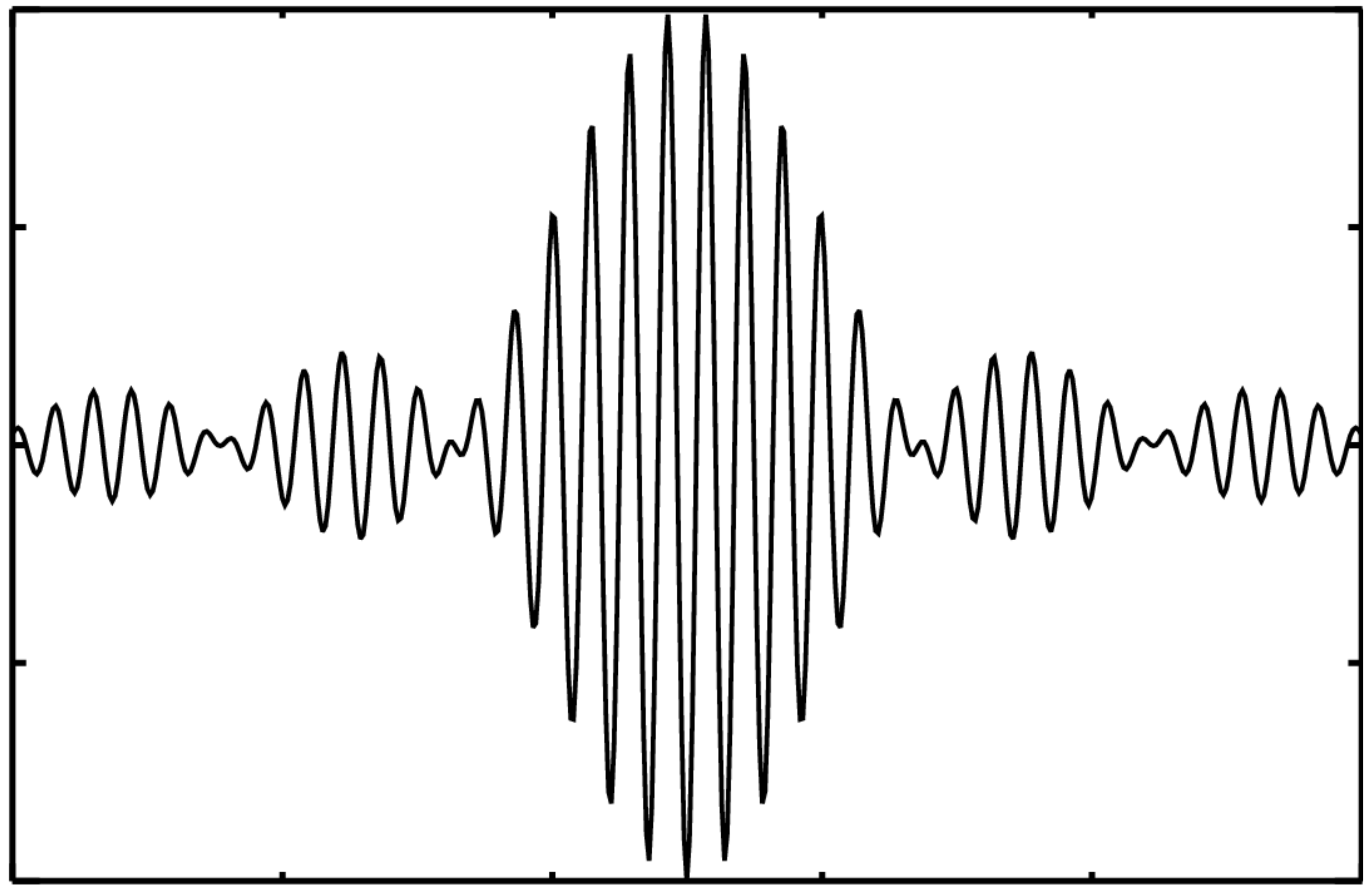
Interferometry

Stars smaller than Betelgeuse can have their radii measured using **interferometry**.

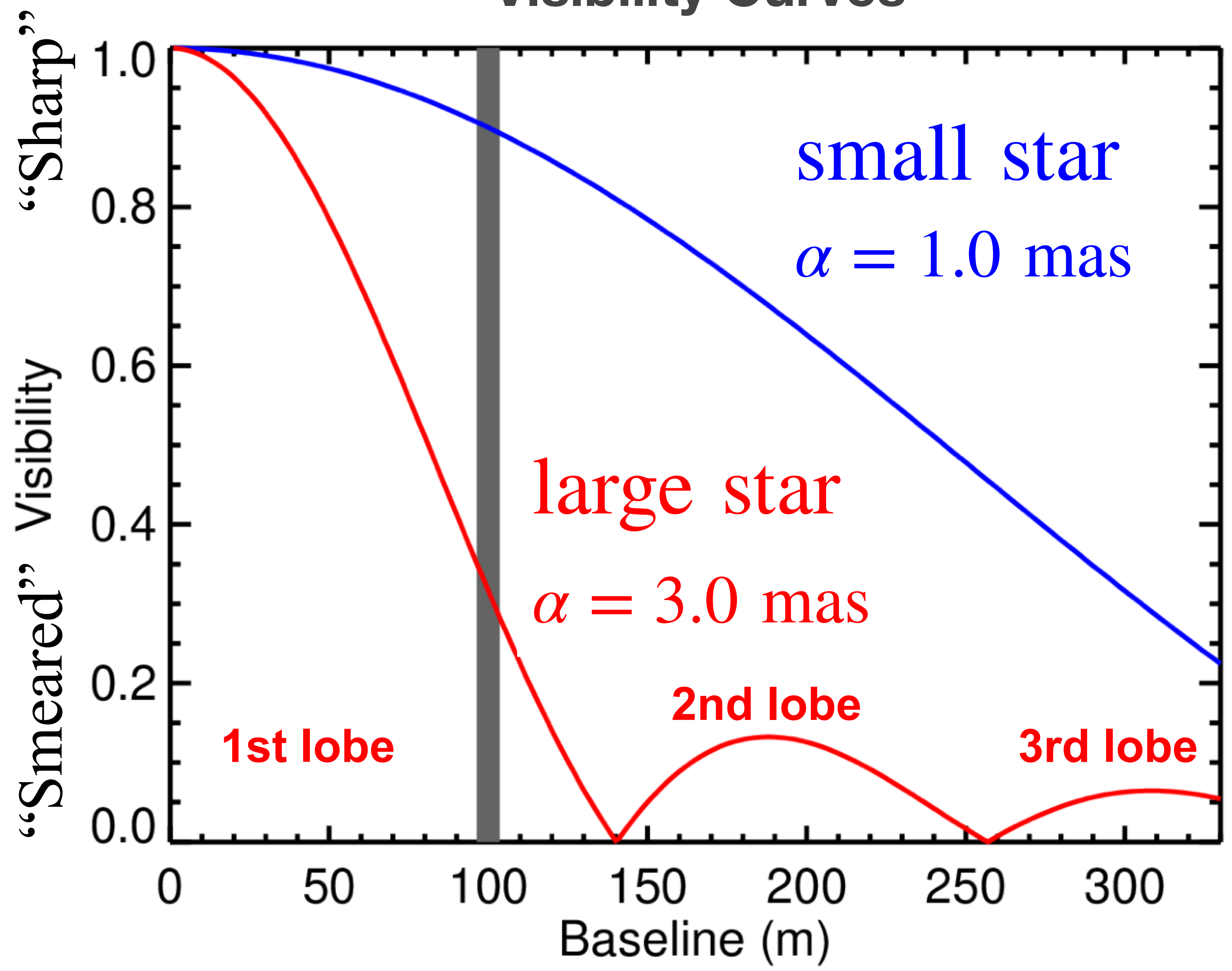
Two-slit Interference



interference pattern



Visibility Curves



By combining the light from <u>two telescopes observing the same star</u>, we can detect patterns of *constructive and destructive interference*, which provide information about the star's angular size.

Interferometry

As the baseline changes you get different interference patterns. The interference pattern produced by a star of angular diameter (α) will be "smeared out" when

$$\alpha\,[\text{radians}] > \frac{\lambda}{b},$$

where λ is the wavelength and b is the baseline — i.e., the distance between two telescopes.

If you observed a star of angular diameter r (α) will be "smeared out" when

$$b > \frac{\lambda}{\alpha}$$

Scaling to a plausible angular diameter for a nearby star:

$$b > 10\ \text{m}\left(\frac{\lambda}{5000\ \text{Å}}\right)\left(\frac{\alpha}{0.01\ \text{arcsec}}\right)^{-1}$$

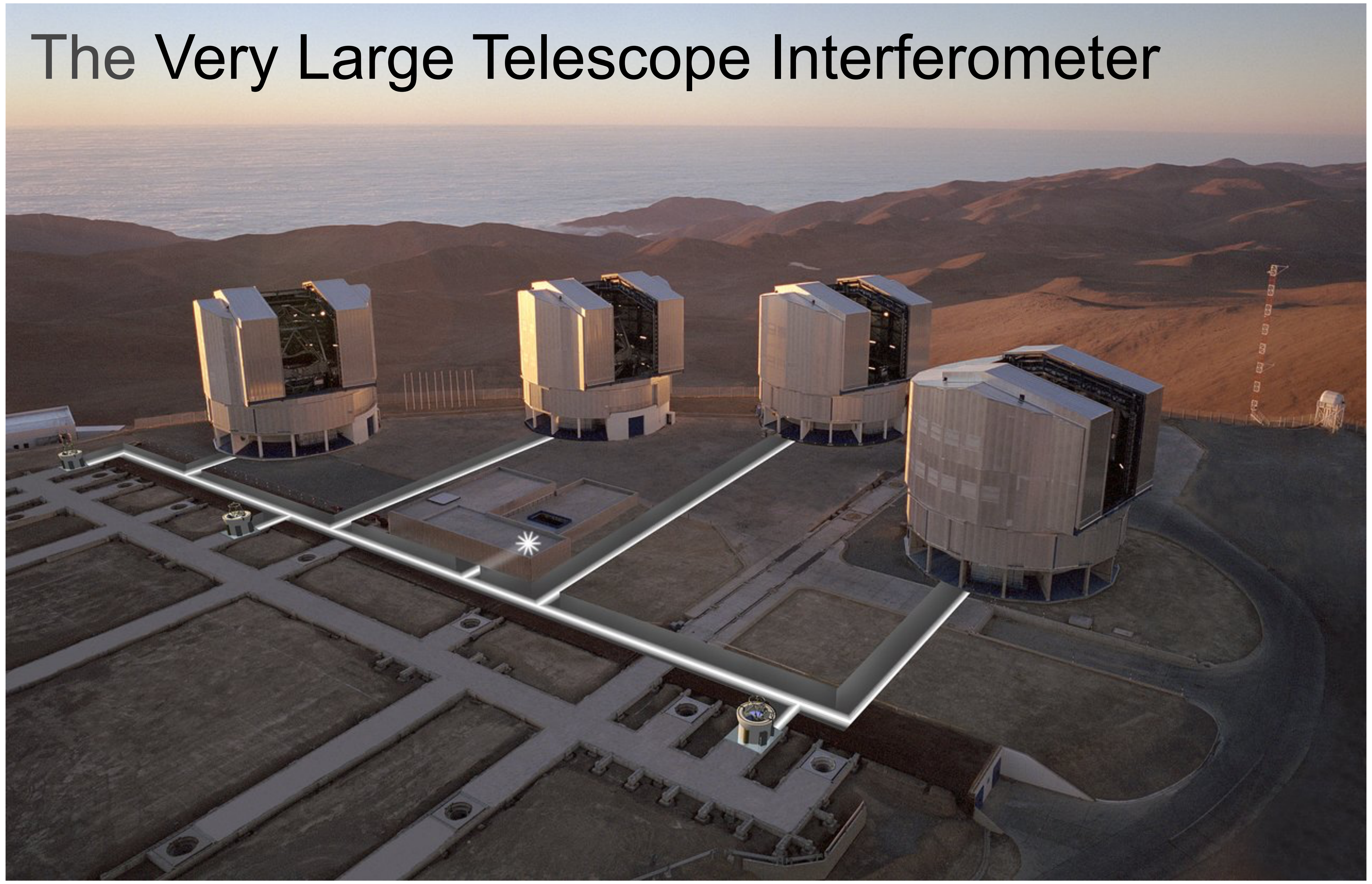
Interferometry

The interferometer at the Very Large Telescope (VLT) in Chile, with a baseline of 140 meters, has been used to measure the angular diameters of the stars in the Alpha Centauri system:

Alpha Centauri A: $\alpha = 8.5 \times 10^{-3}$ arcsec, $R = 1.23\, R_{\odot}$

Alpha Centauri B: $\alpha = 6.0 \times 10^{-3}$ arcsec, $R = 0.87\, R_{\odot}$

Proxima Centauri: $\alpha = 1.0 \times 10^{-3}$ arcsec, $R = 0.14\, R_{\odot}$



Knowing both a star's radius and luminosity allows us to estimate its effective temperature using the Stefan–Boltzmann relation:

$$L = 4\pi R^2 \sigma_{\mathrm{SB}} T_{\mathrm{eff}}^4$$

Comparing this effective temperature to that inferred from the star's spectrum or color index reveals **how closely the star behaves like a blackbody!**


Twinkle, Twinkle little star,
How I wonder
how massive you are….

Mass

Masses can only be measured for objects in binary systems — finding the mass of an isolated star is like recording the sound of one hand clapping.

We call the larger object the **primary**, and the less massive object the **secondary**.

Kepler's 3rd law gives us

$$M_A + M_B = \frac{4\pi^2 a^3}{GP^2}$$

This gives us the *total mass*, but if we can measure each star's individual semi-major axis or maximum radial velocity, we can break the degeneracy and determine the **mass ratio:**

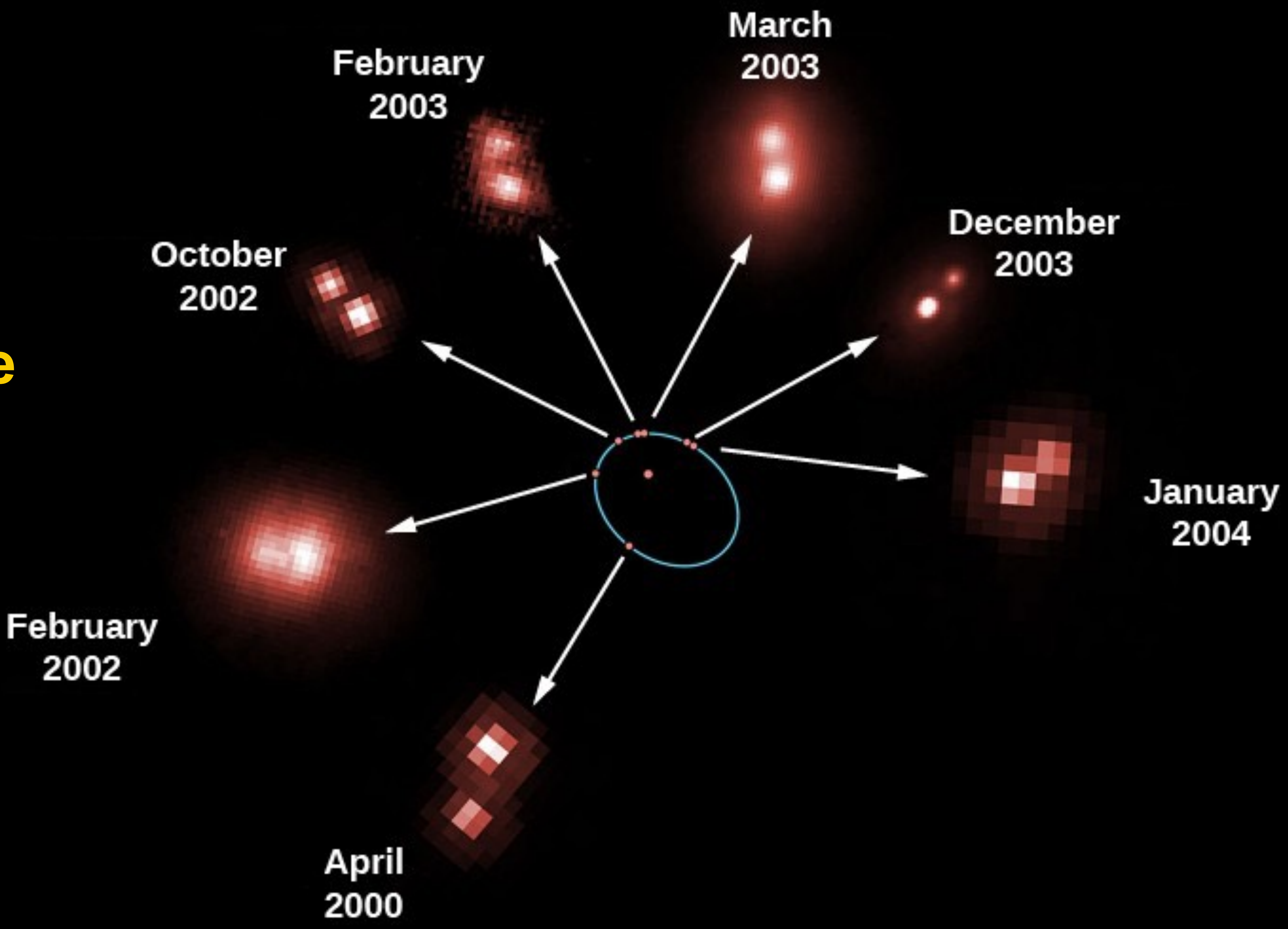
$$\frac{M_A}{M_B} = \frac{a_B}{a_A} = \frac{v_A}{v_B} = \frac{v_A \sin i}{v_B \sin i}$$

There are three main classes of stellar binary systems.

Visual Binaries

If you can **resolve** both components of the binary, it is called a **visual binary**.

- By tracking their positions over time, you can track the orbit and **measure the semi-major axes relative to the center of mass.**
- This allows you to **calculate the mass ratio**, which can then be combined with the total mass from **Kepler's third law to find the individual masses.**
- This method works best for binaries **with relatively short orbital periods.**

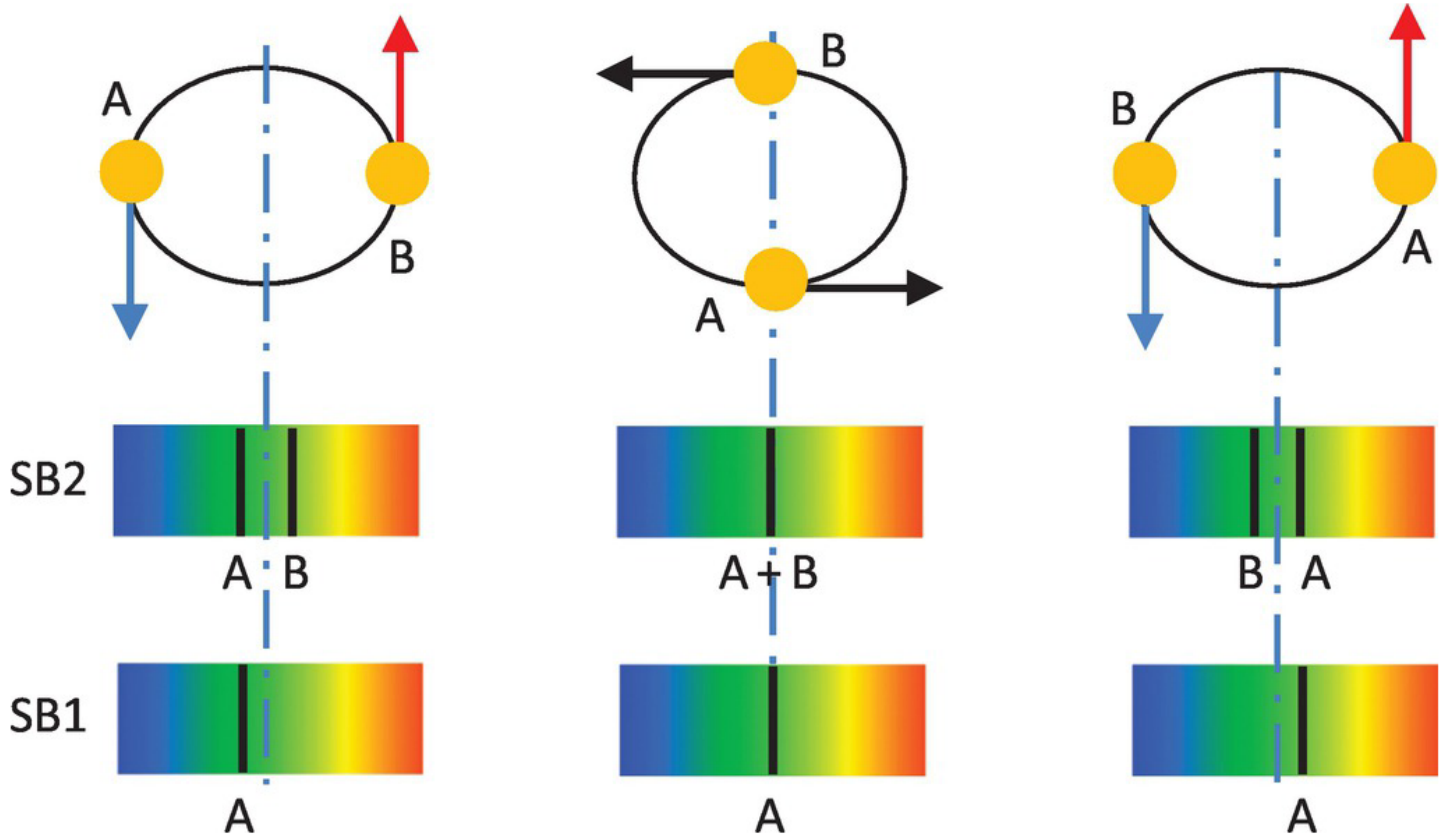


Spectroscopic Binaries

Spectroscopic binaries, which are **unresolved**, are separated into two categories:

-**Double-lined (SB2):** absorption lines from both stars are visible.

- **Single-lined (SB1):** only one star's lines are visible; only a lower limit on the unseen star's mass can be obtained.



-SB2s allow measurement of the **orbital period and radial velocity amplitudes**, from which the **mass ratio** can be inferred and combined with the total mass from Kepler’s 3rd law to **determine individual masses.**

-SB1s only allow us to obtain a lower limit on mass of the unseen star.

Eclipsing Binaries

These are binary star systems that are **unresolved** whose orbital plane is orientated in such a way that **each star is totally or partially eclipsed by the other during the orbital period.**

Light Curve of Eclipsing Binary

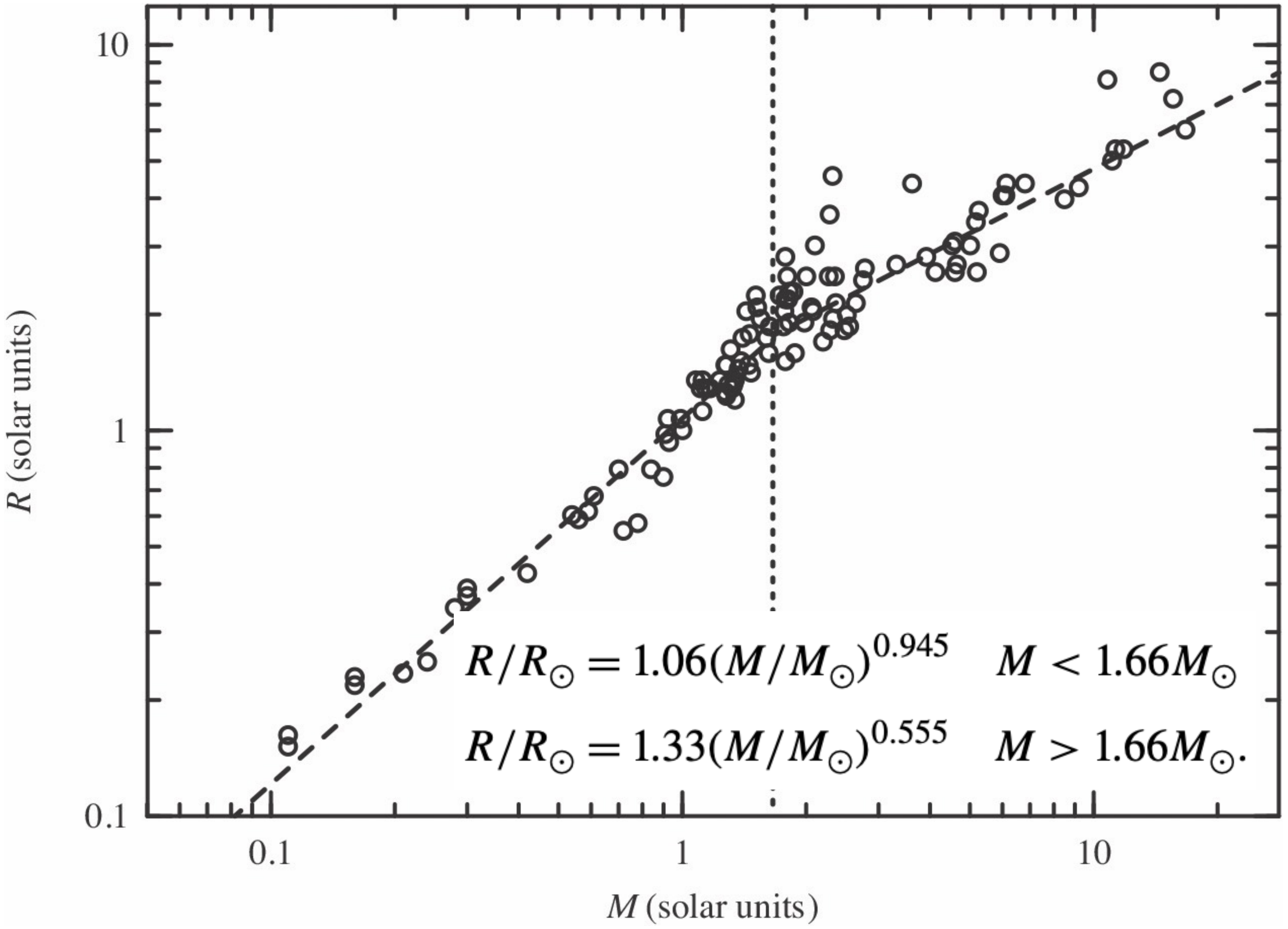
Primary eclipse: This is the deeper dip in the light curve, caused by the larger, cooler star blocking the smaller, hotter star.

Secondary eclipse: This is the shallower dip, which happens when the hotter star passes in front of the cooler star.

Scaling Relations of Main-Sequence Stars

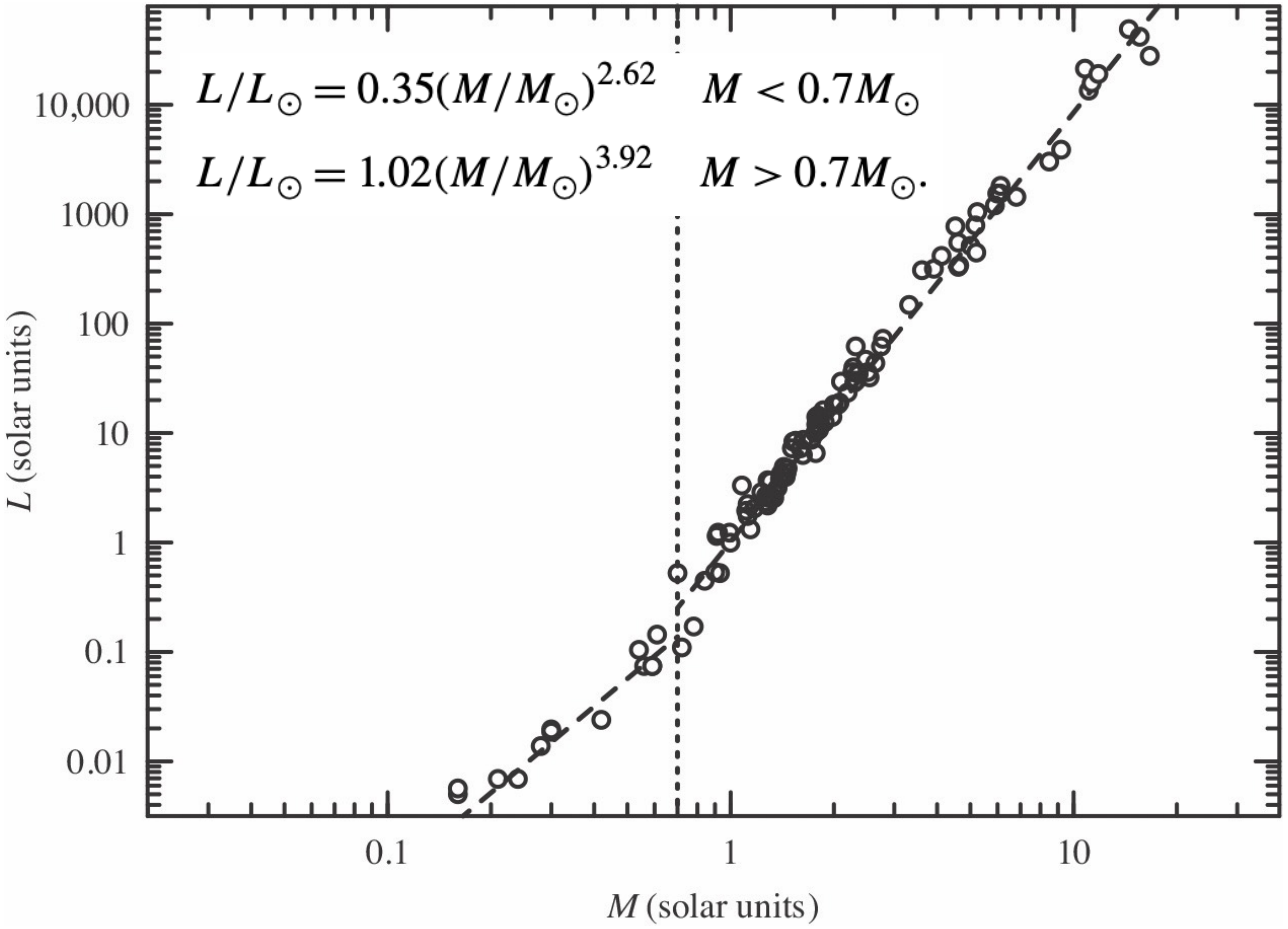
The luminosity and size of a main-sequence star is governed by its stellar mass.

Stellar Radius-Mass Relation



More massive stars are larger.

Stellar Luminosity-Mass Relation



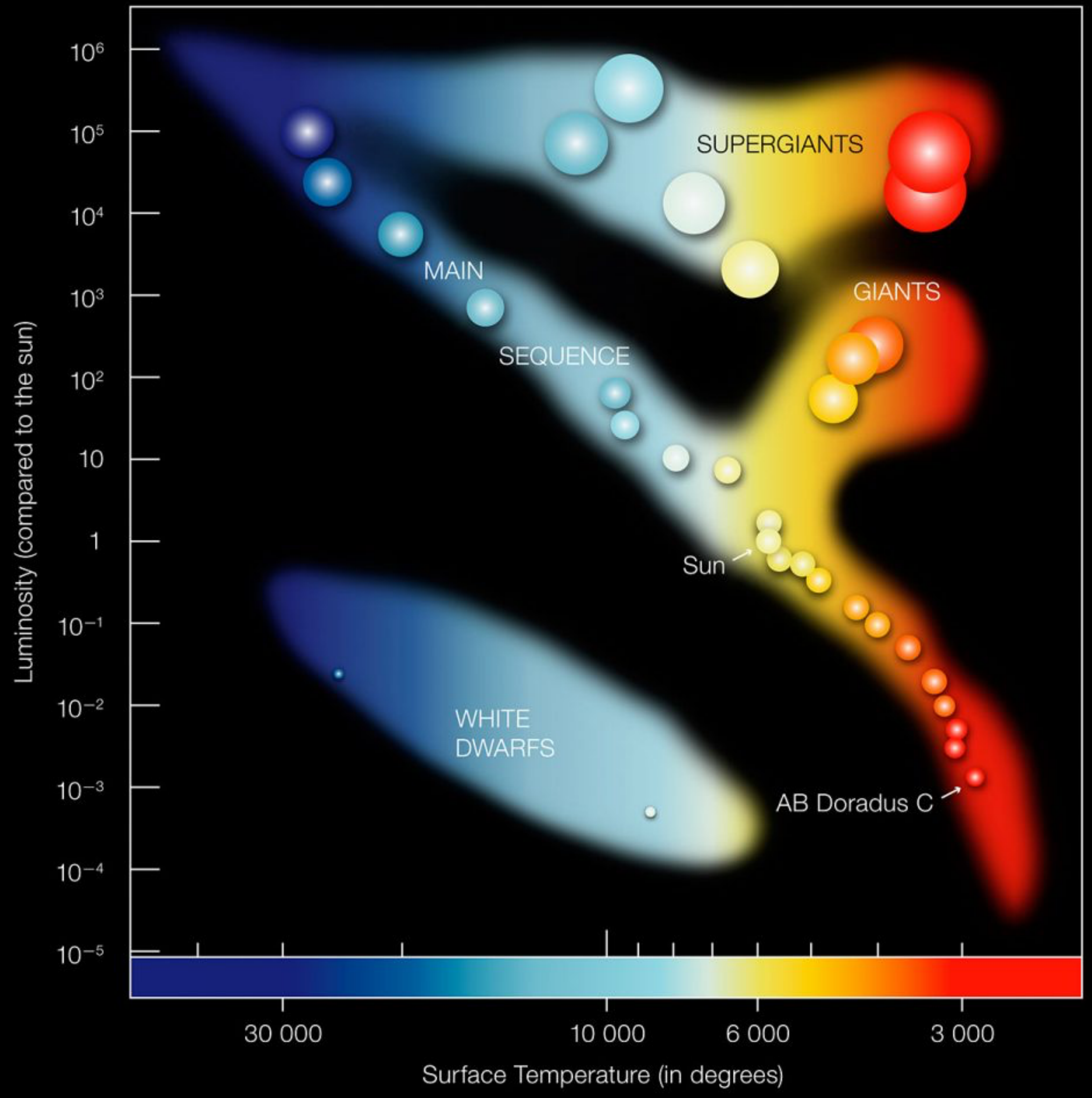
More massive stars are brighter.

Determining how long a star lives

The lifetime of a star on the main sequence is given by the following relation:

$$\tau \propto M/L \propto M^{-1.62} \; (M < 0.7\, M_{\odot})$$

$$\tau \propto M/L \propto M^{-2.92} \; (M > 0.7\, M_{\odot})$$



If a star has a mass of $10\ M_\odot$, roughly how long will it stay on the main sequence?

Nobody has responded yet.

Hang tight! Responses are coming in.

Join by Web **PollEv.com/busygalaxy520**

If a star has a mass of $10\ M_{\odot}$, roughly how long will it stay on the main sequence?

8


Pause

Reminders

- **HW #7 is due Wednesday, 11/26, by 11:59 pm.**
- **Coding project is due Sunday, 11/30 by 11:59 pm.**
- **HW #8 is due Thursday, 12/04, by 11:59 pm.**
- Log into canvas and submit your answer to the discussion question by the end of the day to receive participation credit.