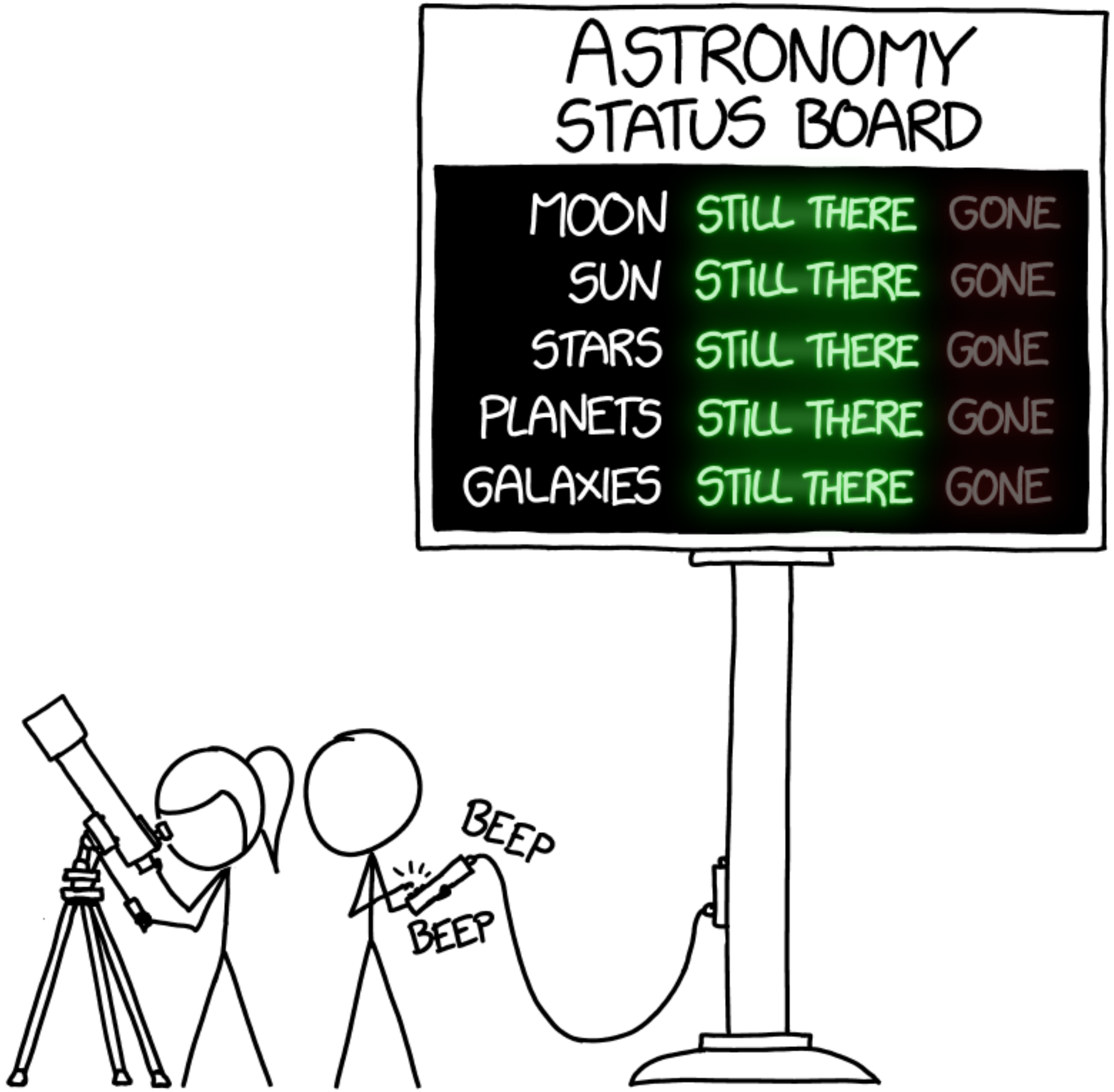
ASTR20A:
Introduction to Astrophysics I

Dr. Devontae Baxter
Lecture 4
Tuesday, October 7, 2025

Credit: *Don Petite/NASA*

Announcements

- Homework #2 will be released on Wednesday, October 8th.
- Coding exercise #2 will be released on Friday, October 10th.



Recap of Lecture 3

We've seen that progress in early astronomy was slow for two major reasons:

1. **Unwillingness to abandon entrenched assumptions** (e.g., geocentric model, circular orbits, etc.)
2. **Lack of technology or new data** (e.g., without telescopes, stellar parallax could not be measured)

We also saw that even if our "standard models" can explain a lot of observations, they may still fail to describe the true nature of reality — for example, epicycles, geocentrism, or the concept of the "eccentric."

Importantly, we found that major advancements in astronomy were made by those who either challenged widely accepted assumptions or used new data to disprove them (e.g., Copernicus, Kepler, and Galileo).

Questions from Lecture 3

Q1: Did the ancients know that Earth was larger than the Moon?

Yes, Aristarchus inferred that the Moon is *smaller* than the Earth by measuring how long it took the Moon to pass through Earth's shadow during a lunar eclipse.

Q2: Can stellar parallax be measured for stars near the celestial poles?

Yes, measuring stellar parallax only requires that the star is close enough to Earth for its shift to be detectable — the closet stars have parallaxes less than 0.75"!

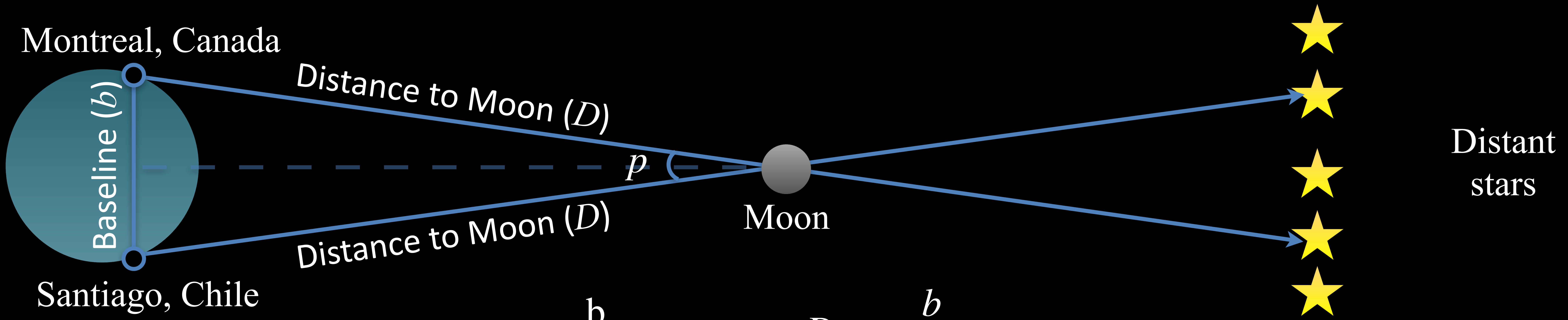
Q3: What is the convention for assigning "east" and "west" for quadratures & elongations?

The convention relates to the definition that Right Ascension (RA) increases ***east*** of the **Vernal Equinox**. At **eastern quadrature**, the superior planet has an RA $\sim 90°$ greater than that of the Sun, so **it lies "more east"** of the Sun. The opposite applies for **western quadrature**.

Questions?

Q4: How is the Geocentric Parallax measured?

To measure the geocentric parallax, the position of a nearby object (e.g., the Moon) relative to the distant stars needs to be measured *simultaneously* at **two different locations on Earth.**



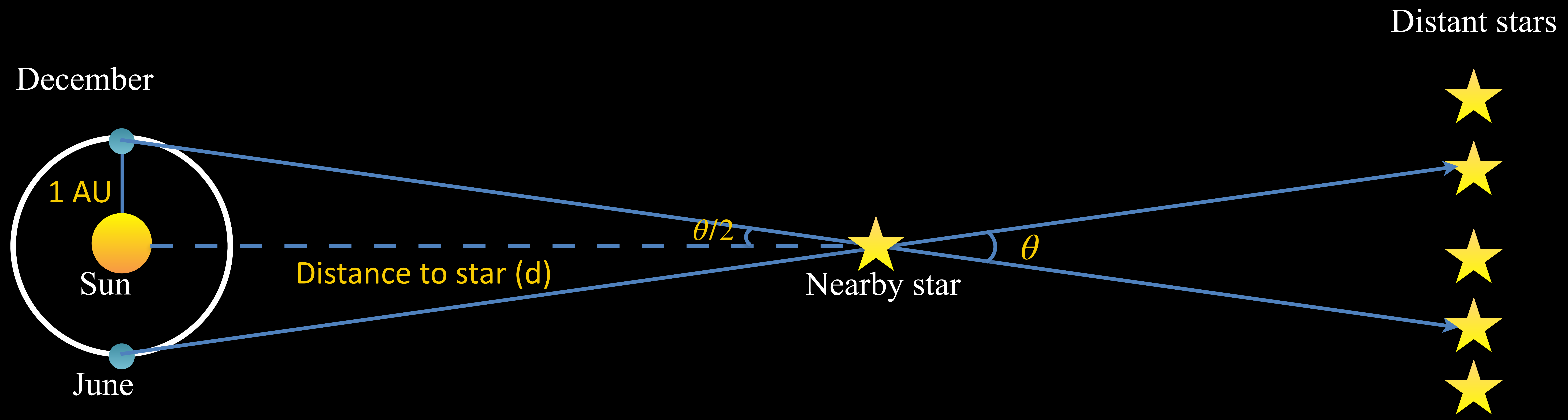
$$\sin(\mathrm{p}) = \frac{\mathrm{b}}{\mathrm{D}} \quad \Rightarrow \quad D = \frac{b}{\sin(\mathrm{p})}$$

By using the known baseline and measuring the parallax (p) one can determine the distance to the Moon.


Questions?

Review: Defining 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

Defining 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

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

Converting the parallax from arcseconds to radians, we find:

$$d = 1 \text{ parsec} = \frac{1 \text{ AU}}{1''}\left(\frac{3600''}{1 \text{ degree}}\right)\left(\frac{180 \text{ degree}}{\pi \text{ rad}}\right) = 206{,}265 \text{ AU} = 2.06\text{x}10^5 \text{ AU}$$

For example, the closest star to Earth, Proxima Centauri, has a parallax of $0.76''$, and hence is at a distance $d = 271{,}401 \text{ AU} = 1.3 \text{ parsecs}$.

Can you spot **the science blunder** in this scene from Star Wars Episode IV?


Questions?

Proof of Earth's Motion

Despite Galileo's discoveries undermining the geocentric model, *definitive proof* that the **Earth rotates on its axis** and **revolves around the Sun** was not provided until much later.

1. The former was demonstrated by detecting the "Coriolis Effect".
2. The latter was demonstrated by measuring the "aberration of star light", with later confirmation provided by the first measurements of stellar parallax.

Rotation of the Earth

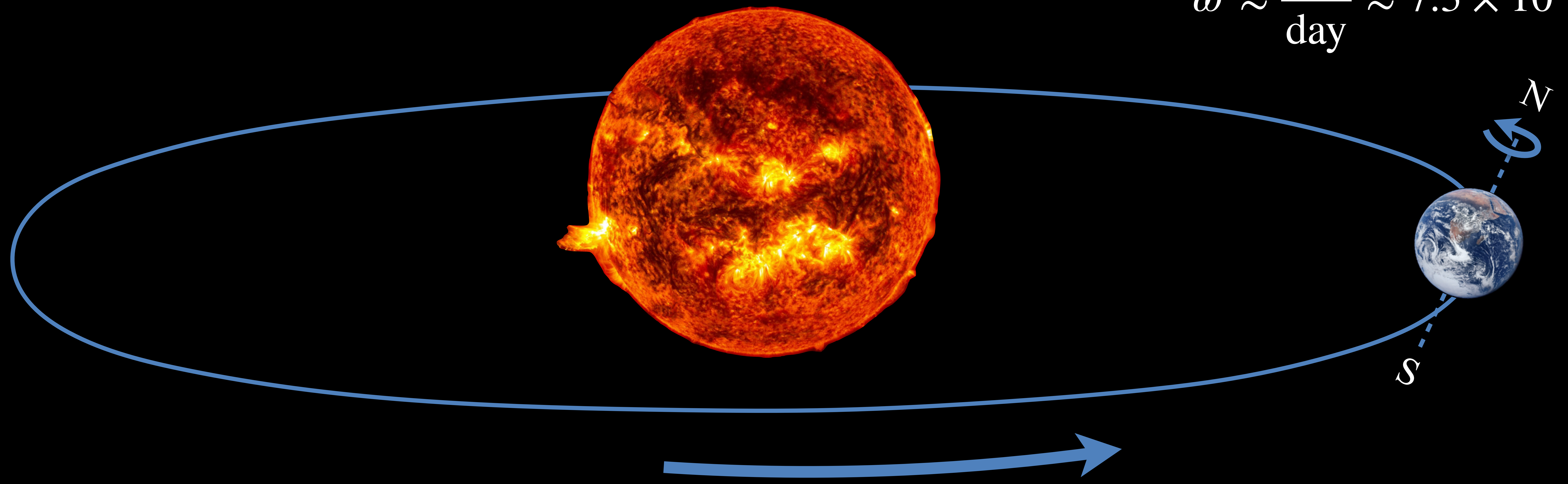
The Earth's surface is rotating with an angular velocity

$$\overrightarrow{\omega} \approx \frac{2\pi}{\text{day}} \approx 7.3 \times 10^{-5}\ \frac{\text{rad}}{\text{s}}$$

$\overrightarrow{\omega}$ is pointing south to north (right hand rule), parallel to the Earth's axis of rotation.

Rotation of the Earth

$$\vec{\omega} \approx \frac{2\pi}{\text{day}} \approx 7.3 \times 10^{-5}\ \frac{\text{rad}}{\text{s}}$$



Because the Earth rotates, a projectile launched on its surface will follow a path that differs from the path it would take if Earth were not rotating.

Rotation of the Earth

For a *non-rotating reference frame*, the object would experience the following acceleration:

Non-rotating:

$$\vec{a} = \frac{\vec{F}}{m}$$

$\vec{a}$ = acceleration

$\vec{F}$ = net force

m = object's mass

For a *rotating reference frame*, the object would experience the following acceleration:

Rotating:

Centrifugal acceleration†

$$\vec{a} = \frac{\vec{F}}{m} + \boxed{2(\vec{v} \times \vec{\omega})} - \boxed{\vec{\omega} \times (\omega \times \vec{r})}$$

Coriolis Effect

$\vec{v}$ = object's velocity

$\vec{\omega}$ = Earth's angular velocity

$\vec{r}$ = object's position

†The centrifugal acceleration points *away* from the axis of rotation!

Rotation of the Earth

The magnitude of centrifugal acceleration is,

$$a_{\mathrm{cent}} = |\,\vec{\omega} \times (\vec{\omega} - \vec{r})\,| = \omega^2 R$$

R = Distance of object from rotation axis

Where on Earth do you expect this acceleration to be greatest?

$$a_{\mathrm{cent}} \approx \left(7.x \times 10^{-5} \frac{\mathrm{rad}}{\mathrm{s}}\right)^2 \left(6.4 \times 10^6 \ \mathrm{m}\right) \approx 0.034 \frac{\mathrm{m}}{\mathrm{s}^2}$$

How does this acceleration compare to gravity?

Answer: The centrifugal acceleration is greatest at the equator (i.e., where $R \approx 6.4 \times 10^6$ m)

Rotation of the Earth

The magnitude of Coriolis Acceleration is,

$$a_{cor} = |2(\vec{v} \times \vec{\omega})| = 2v\omega\sin\theta$$

θ = angle between $\vec{v}$ & $\vec{\omega}$

What happens if an object moves parallel to the Earth's rotation axis?

Thus, for motion at angles that are neither parallel nor perpendicular to the Earth's rotation axis, the Coriolis acceleration can be ***roughly*** approximated as:

$$\boxed{a_{cor} \sim v\omega}$$

Answer: The Coriolis acceleration vanishes, because it depends on the component of velocity perpendicular to the rotation axis

Rotation of the Earth

For a particle in flight for time Δt, its velocity is altered by the Coriolis acceleration according to:

$$\Delta v \approx a_{cor}\Delta t \sim v\omega\Delta t$$

Therefore, the *fractional change* in velocity of the particle is:

$$\frac{\Delta v}{v} \sim \frac{a_{cor}\Delta t}{v} \sim \omega\Delta t$$

For what flight times Δt will the Coriolis-induced change in velocity remain small?

$$\Delta t \ll \frac{1}{\omega} = \frac{1}{2\pi}\ \text{days} \ \sim 4\ \text{hr} \sim 14{,}000\ \text{seconds}$$

Therefore, The Coriolis Effect *can be ignored* for **short distances** & **short timescales!**

Rotation of the Earth

Using the equations of projectile motion, we find that the Coriolis Effect deflects objects by a distance:

$$\Delta d \sim \frac{1}{2}a_{cor}(\Delta t)^2 \sim \frac{1}{2}v\omega(\Delta t)^2$$

Example: The Red Hair Pirates launch a cannon ball due North a distance of 120 km with an initial velocity of $v = 1.6\ \frac{km}{s}$ on a parabolic trajectory with a maximum altitude of 40 km and a time of flight of $\Delta t = 170\ s$. By how much is the cannon ball deflected due to the Coriolis Effect?

$$\Delta d \sim \frac{1}{2}(1.6\frac{km}{s})(7.3 \times 10^{-5}\ \frac{rad}{s})(28{,}900\ s^2)\ \sim 2\ km\ (1.2\ miles)!$$

Questions?

Foucault Pendulum

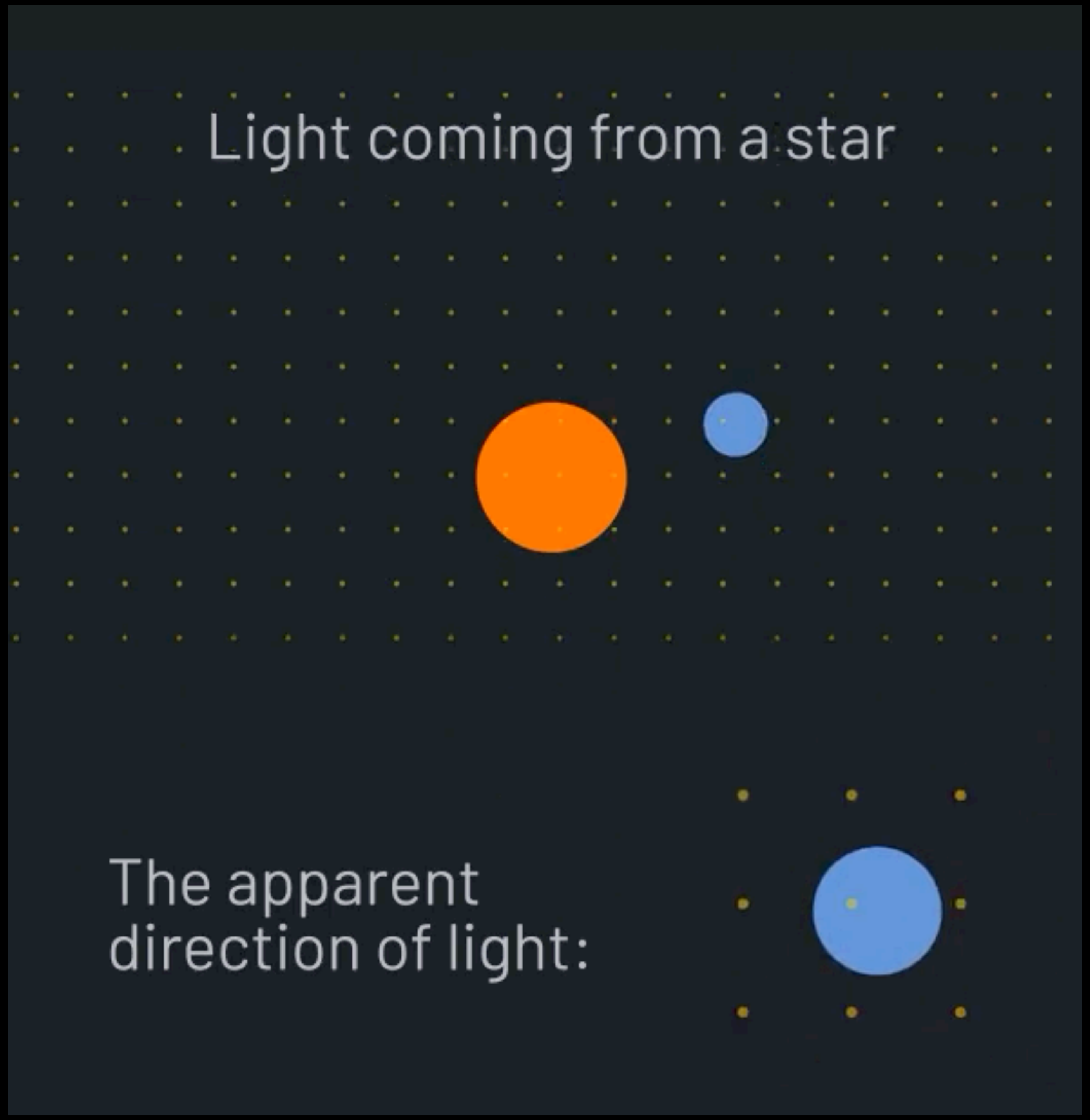
Watch the world turn at the San Diego Museum of Natural History

Cool visualization showing how the Foucault Pendulum behaves at different latitude.

Revolution of Earth

The astronomer James Bradley confirmed the revolution of Earth by detecting and explaining the ***"aberration of starlight"***

Stellar aberration is the a**pparent shift of stars** about their true position depending on the direction Earth is moving in its **orbit around the Sun**. It occurs because the **speed of light is finite** —i.e., it takes time for light to reach the observer.

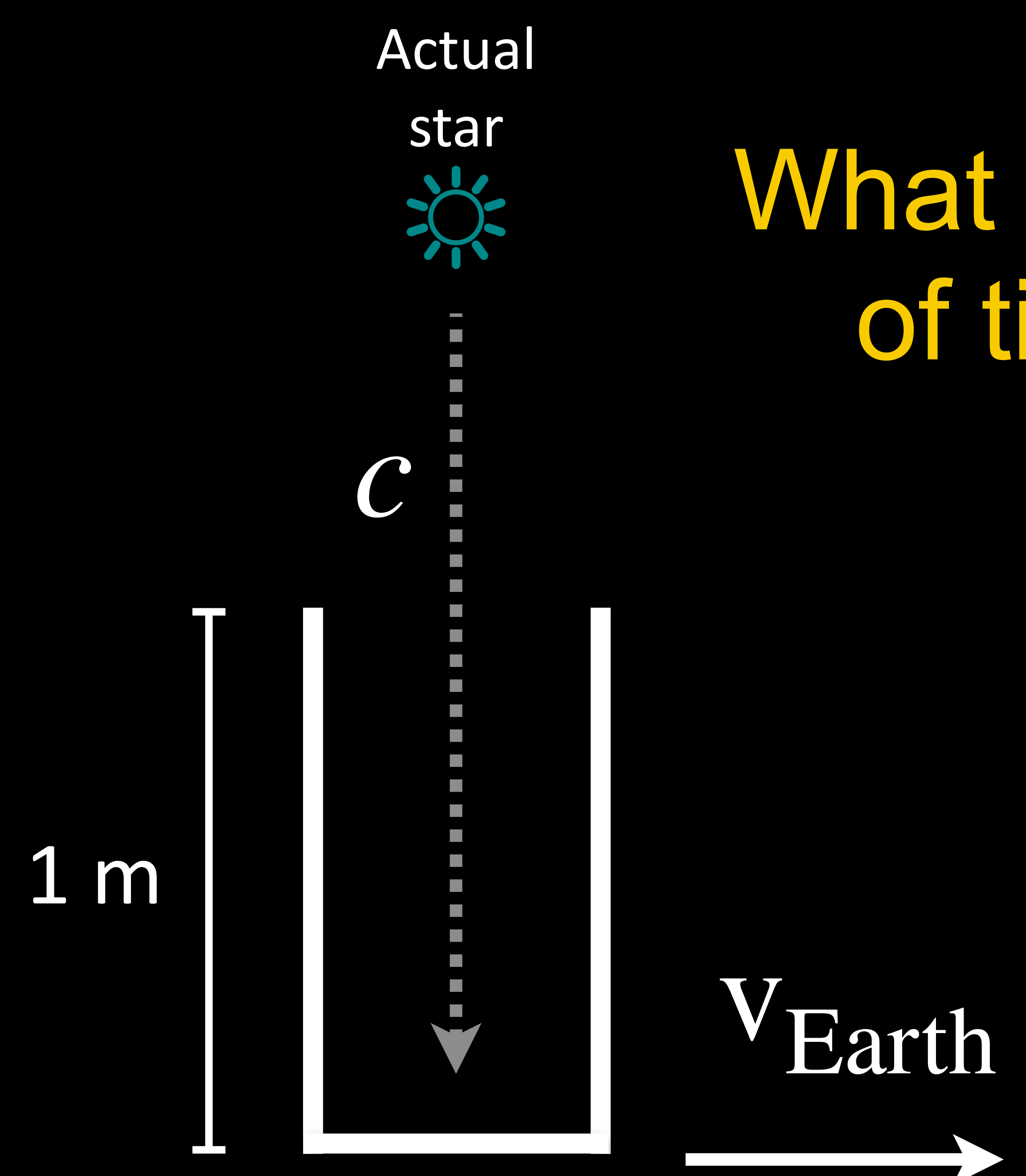


This is analogous to how, when running in the rain, you must tilt your umbrella to avoid getting wet.

James Bradley (1692–1762)

Revolution of Earth

Example: If you have a telescope that is 1 meter long, by how much will the Earth's motion displace the telescope while light travels its length?



What equation should we use to find the amount of time it takes light to travel a distance (d)?

$$d = vt \longrightarrow t = \frac{d}{v}$$

$$t = \frac{d}{c} = \frac{1 \times 10^{-3}\ \text{km}}{3 \times 10^{5}\ \frac{\text{km}}{\text{s}}} = 3.3 \times 10^{-9}\ \text{s}$$

<u>Speed of Light</u>

$$c = 3 \times 10^{5}\ \frac{\text{km}}{\text{s}}$$

<u>Earth's Orbital Speed</u>

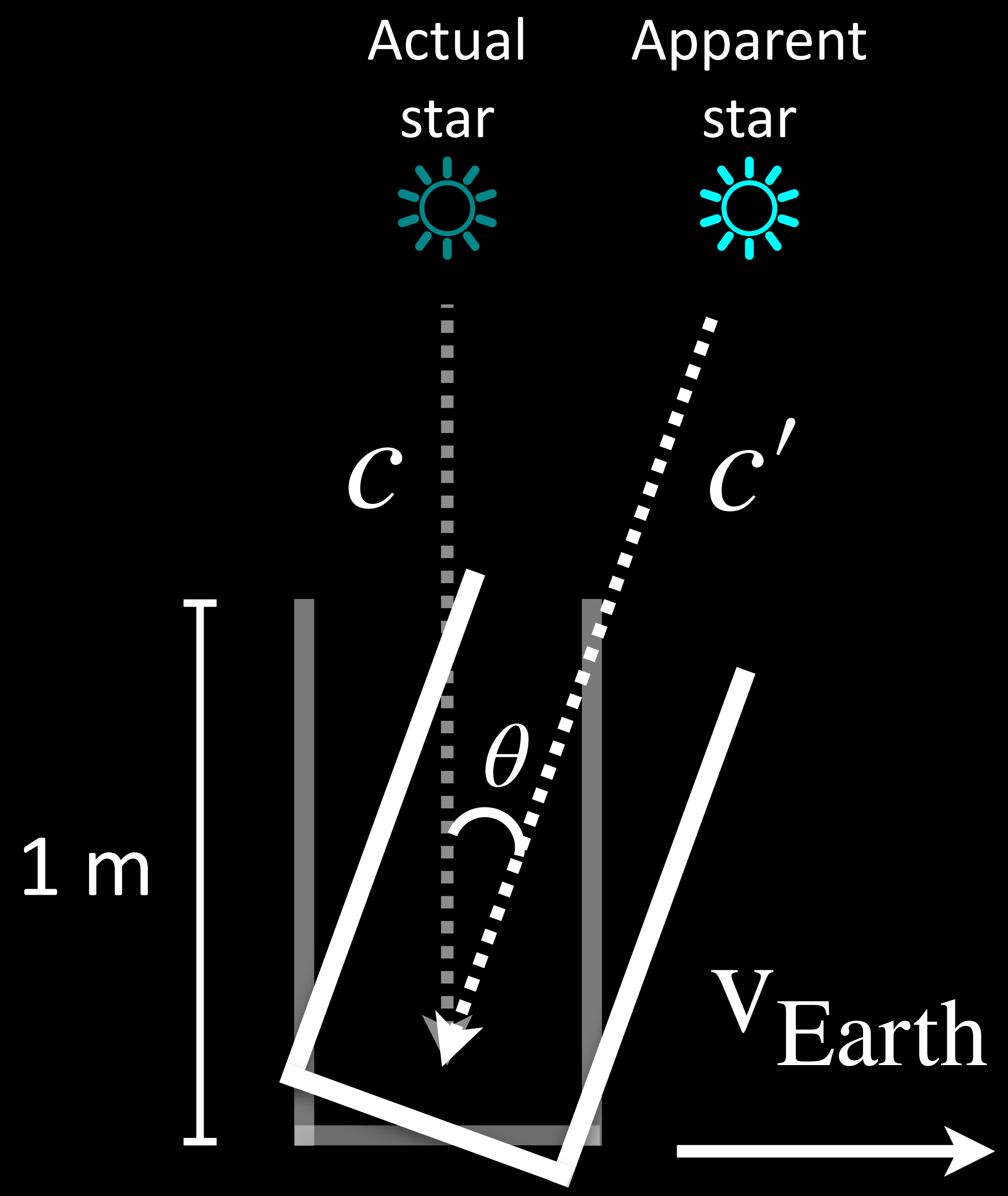
$$v_{Earth} = 29.8\ \frac{\text{km}}{\text{s}} \sim 1 \times 10^{-4}\ c$$

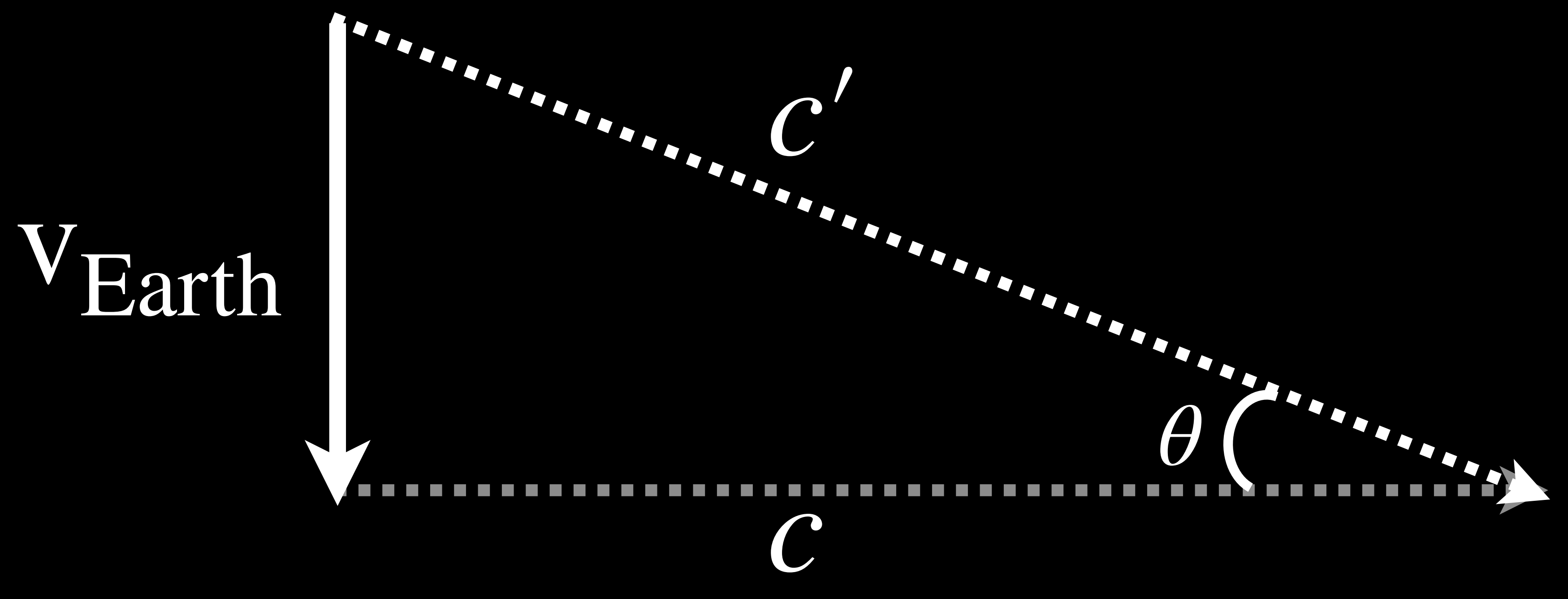
Therefore, the Earth's motion will have translated the telescope through a distance

$$d = vt = \left(29.8\ \frac{\text{km}}{\text{s}}\right)\left(3.3 \times 10^{-9}\ \text{s}\right) \approx \boxed{0.1\ \text{mm}}$$

Revolution of Earth

Example: By what angle must the telescope be tilted to capture light from the distant star, given the Earth's orbital motion?





$$\tan\theta = \frac{v_{\text{Earth}}}{c} \quad \longrightarrow \quad \theta \approx \frac{v_{\text{Earth}}}{c}$$

Small angle approximation
(θ must be in radians)

<u>Speed of Light</u>

$$c = 3 \times 10^5 \, \frac{\text{km}}{\text{s}}$$

<u>Earth's Orbital Speed</u>

$$v_{\text{Earth}} = 29.8 \, \frac{\text{km}}{\text{s}} \sim 1 \times 10^{-4} \, c$$

$$\theta \approx \frac{v_{\text{Earth}}}{c} \approx \frac{1 \times 10^{-4} c}{c} \left(\frac{180 \text{ deg}}{\pi}\right)\left(\frac{3600''}{1 \text{ deg}}\right) \approx 20.5''$$

Note: The maximum aberrational shift of 20.5'' is *independent of the star's distance from the Earth. It is also much larger* than the parallax shift of even the nearest stars (less than 0.75'')

Brain Break – Think-pair-share

The aberration of starlight causes the positions of stars in the sky to follow an annual path that is the projection of the Earth’s motion onto the sky:

- For stars that lie along the Zodiac, what shape does this path take?
- What about for stars located 90° from the plane of the Zodiac?
- More generally, how does the shape of the aberration path depend on a star’s position relative to the Zodiac?

Isaac Newton

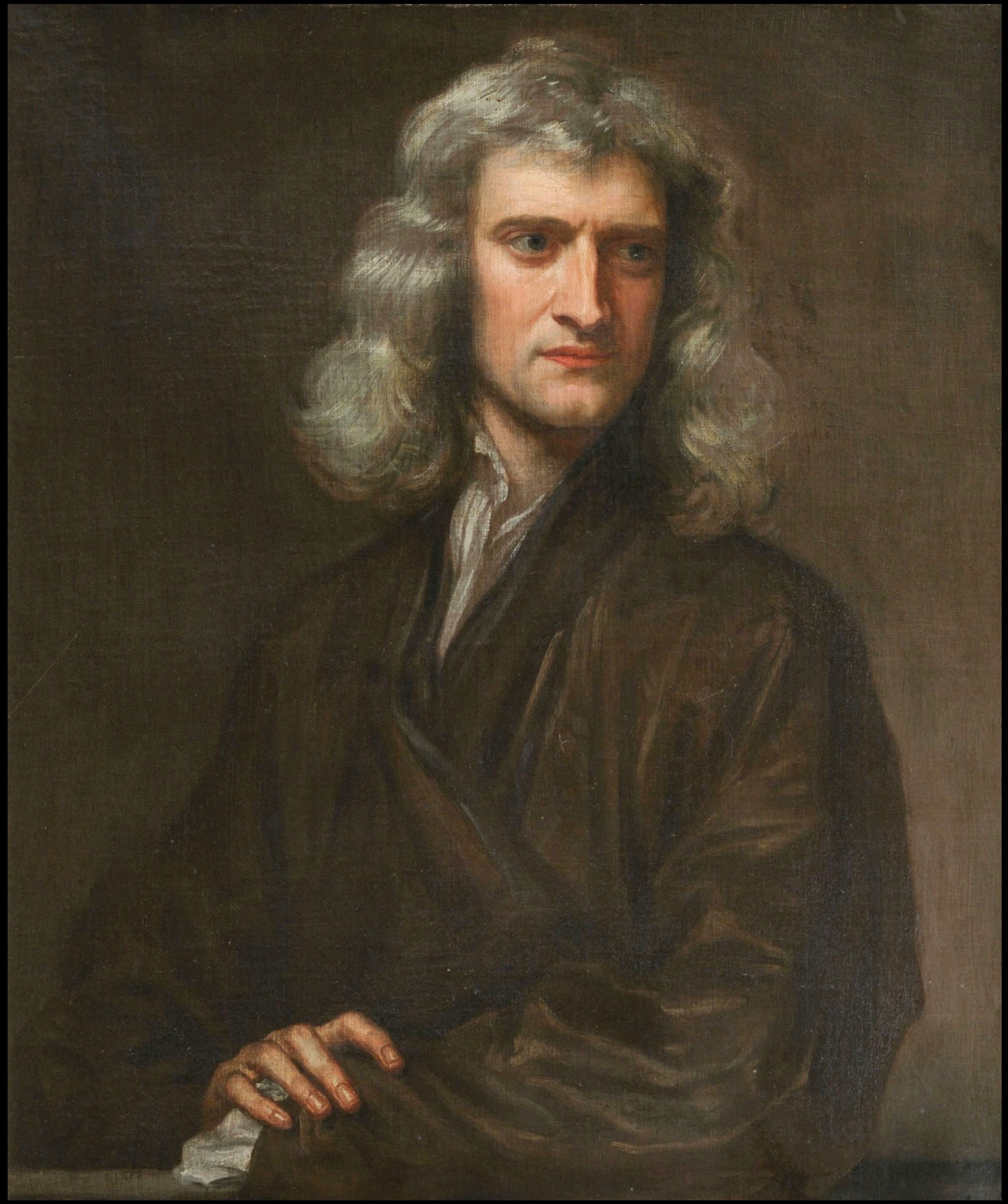
Isaac Newton is the Father of Classical Physics

What you probably know:

- Developed the **3 laws of motion**
- Developed the **law of universal gravitation**

What you might not know:

- Born on December 25 (had a real god complex)
- Did *not* develop the widely used notation for calculus (although Leibniz paid the price).



Isaac Newton (1642-1727)

Three Laws of Motion

1. **Law of Inertia:** An object at rest stays at rest, and an object in motion continues in a straight line at constant speed unless acted upon by an external force.

2. **Law of Acceleration:** The net force on an object is proportional to its mass and the resulting acceleration:

$$\overrightarrow{\mathrm{F}}_{\mathrm{net}} = m\vec{\mathrm{a}}$$

3. **Law of Action and Reaction:** For every action, there is an equal and opposite reaction; in other words, forces always come in pairs.

Law of Universal Gravitation

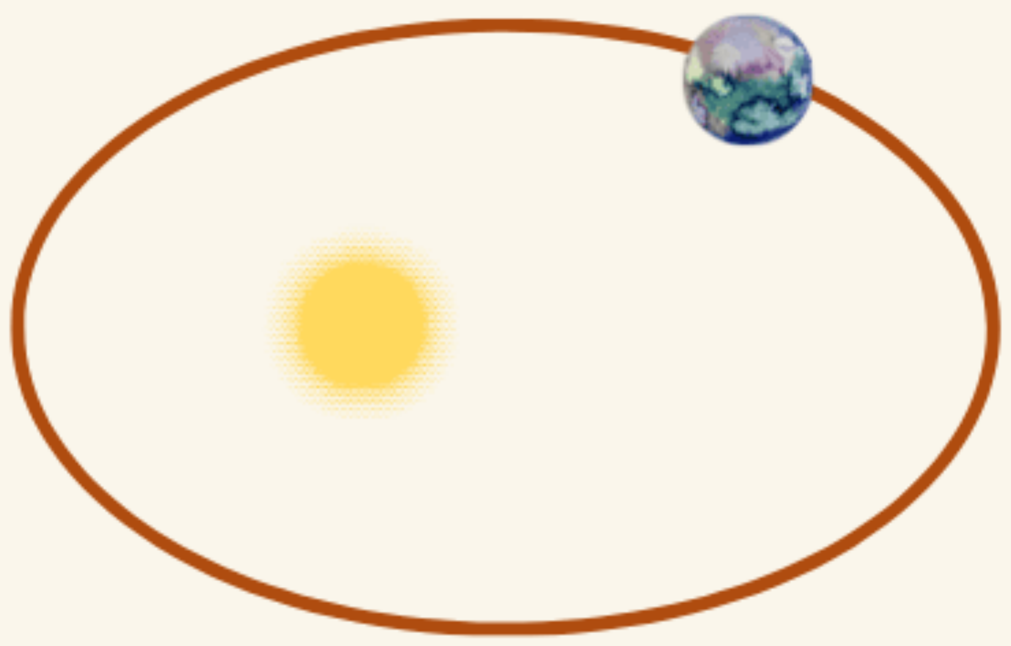
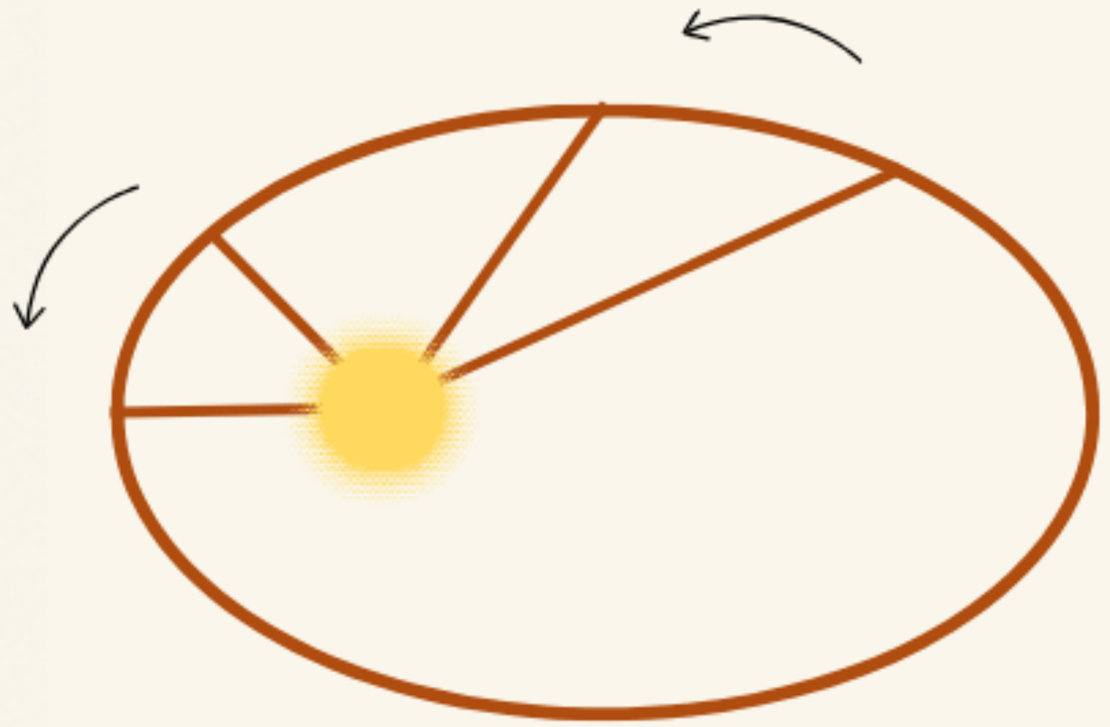
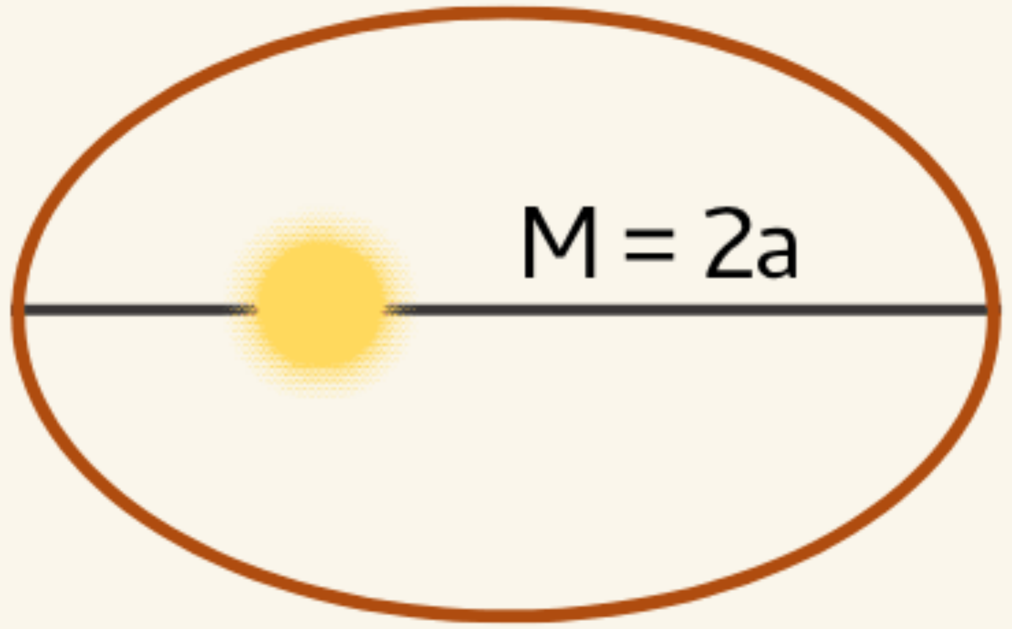
The gravitational force of attraction between two spherical objects, of mass M and m, separated by a distance r, is given by,

$$F = -\frac{GMm}{r^2}$$

Note: The negative sign indicates that it is an *attractive* force.

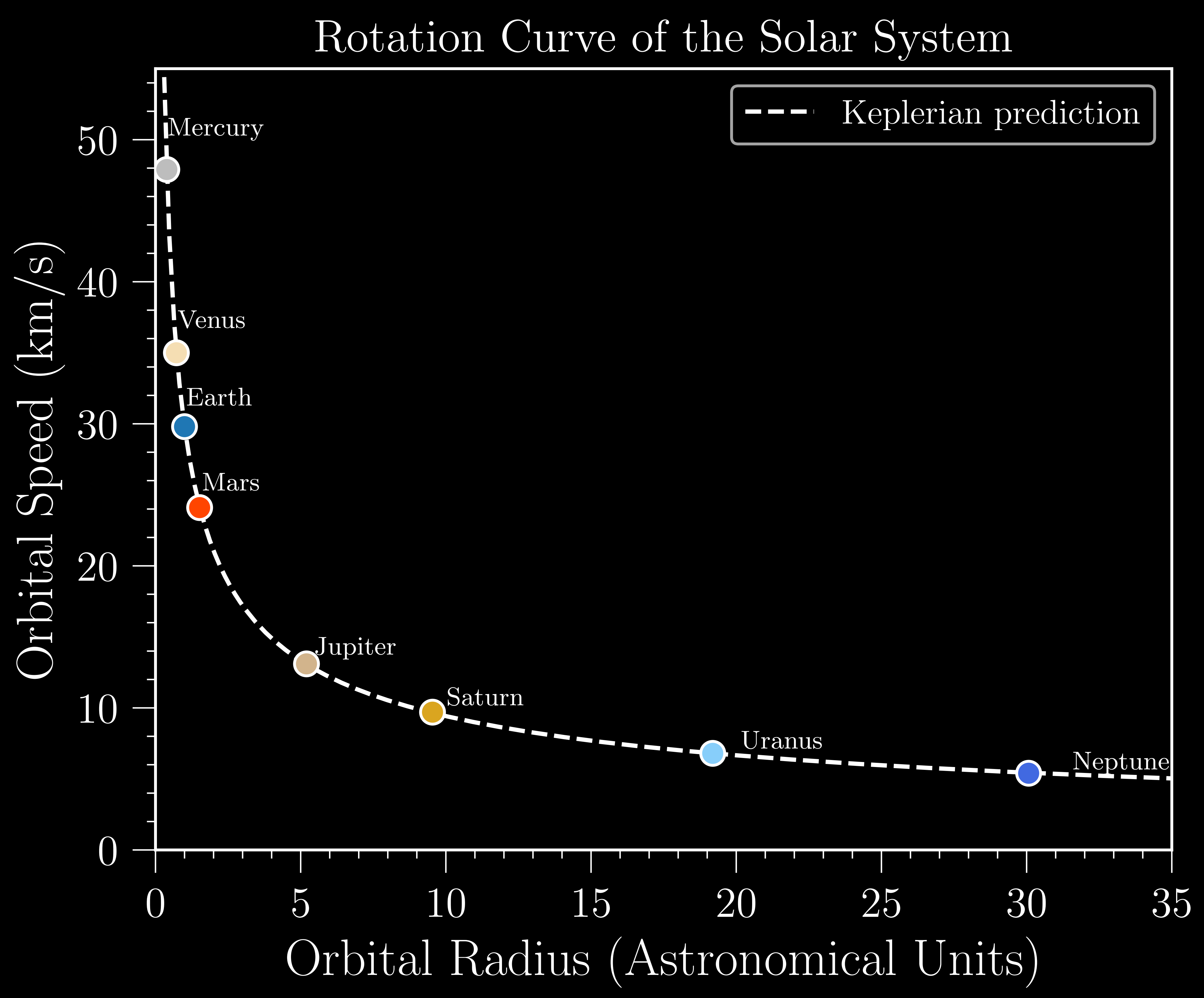
G = gravitational constant $= 6.67 \times 10^{-11} Nm^2kg^{-2}$

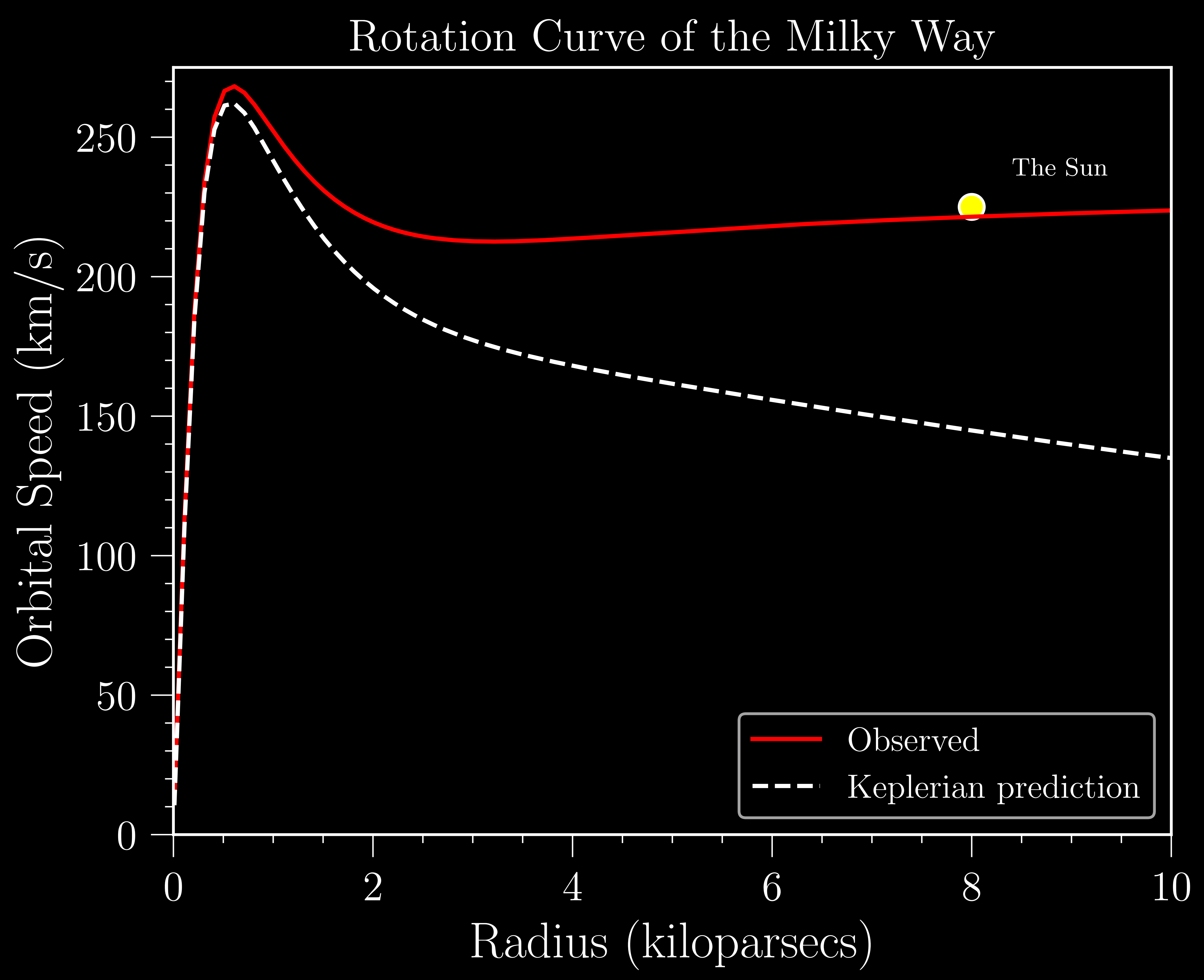
Kepler’s Laws of Planetary Motion

First Law	Second Law	Third Law
 ellipse		P: period (time for one cycle) 2a: length of major axis  $P^2 \propto a^3$
Planets orbit in ellipses with the Sun at one focus.	Planets sweep out equal areas in equal times.	The square of the orbital period is proportional to the cube of the semi–major axis

Recall. The foci are defined used c = a*e, where a is the semi-major axis and e is the eccentricity.

Brain Break: Rotation Curves

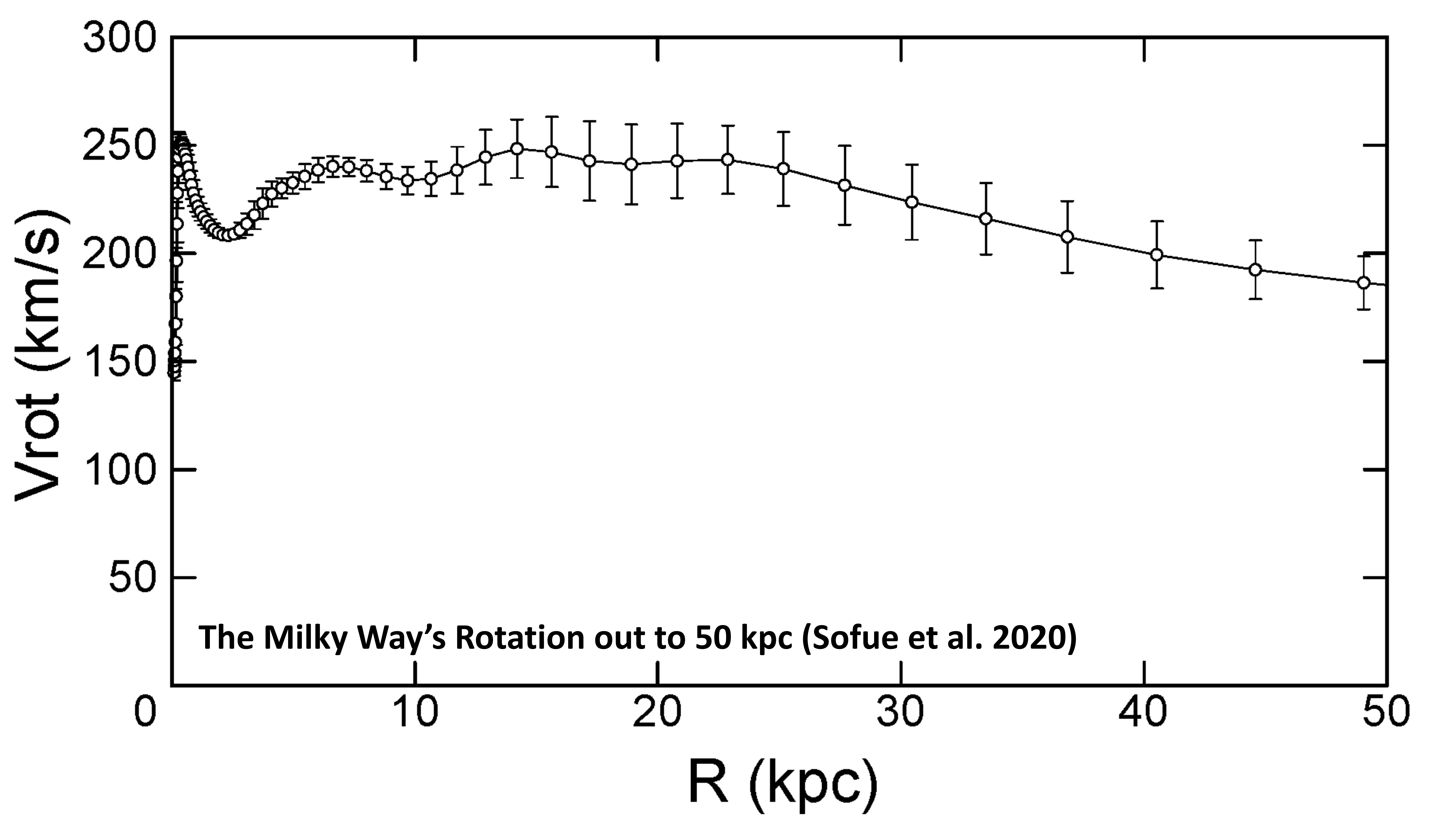




Consider these two plots showing orbital speed vs. distance from the center of the Solar System (left) and the Milky Way (right):

- In what ways are these two “rotation curves” similar/different?
- What are some possible reasons for their differences?

Brain Break: Rotation Curves



Questions?

Reminders

- Homework #2 will be released on Wednesday, October 8th.
- Coding exercise #2 will be released on Friday, October 10th.
- Log into canvas and submit your answer to the discussion question <u>by the end of the day</u> to receive participation credit.