ASTR20A:
Introduction to Astrophysics I

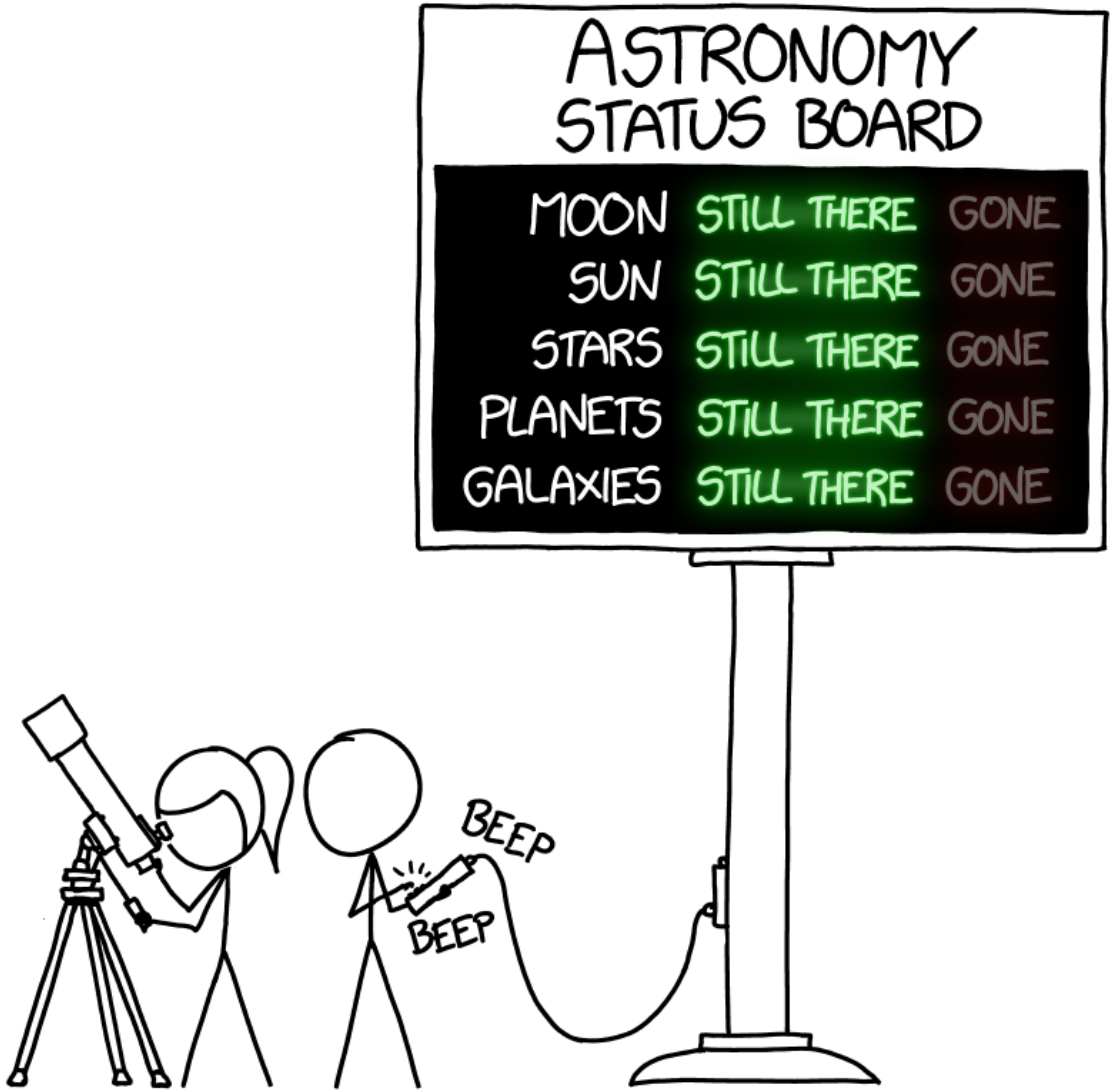
Dr. Devontae Baxter

Lecture 3

Thursday, October 3, 2025

Announcements

- HW1 is due Sunday, 10/5 by 11:59 pm via Canvas
- Coding exercise #1 due 10/5 by 11:59 pm via DataHub.
- Remember that SERF 383 is reserved for ASTR 20A study session on Mondays from 4-6pm.
  - Consider using this space to work together on future homework.



Greek Astronomy

Greeks were considered some of the earliest astronomers.

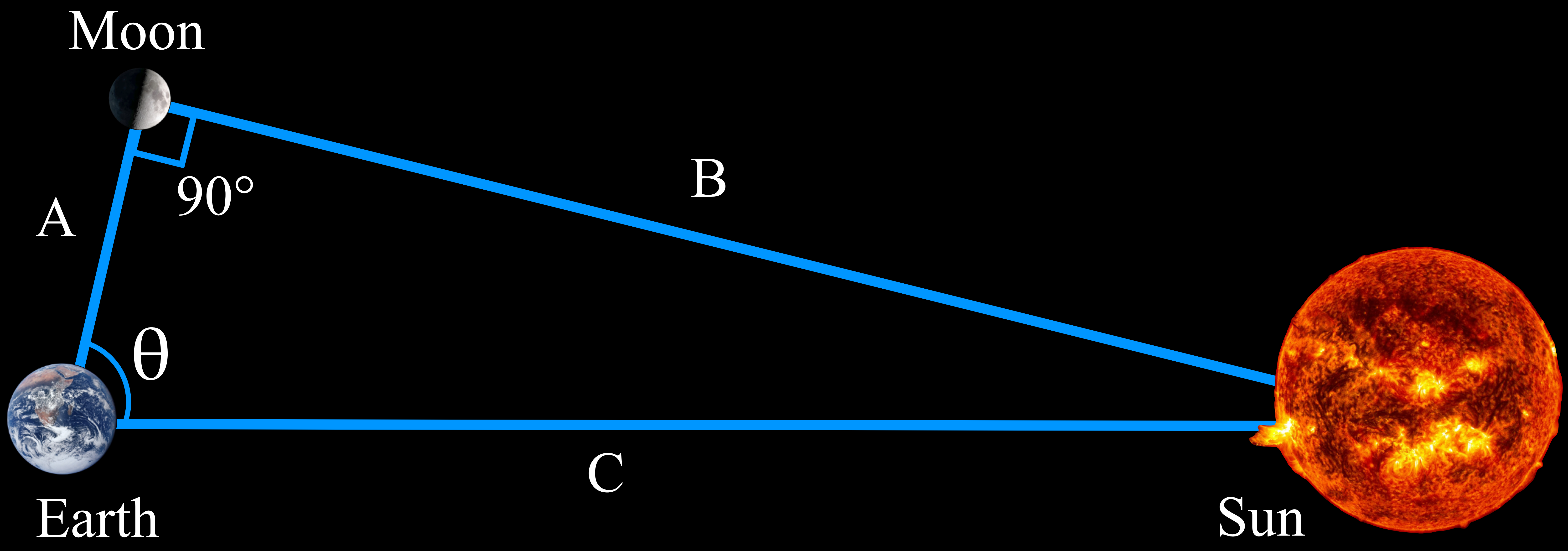
- They correctly **explained the phases of the Moon** — we'll revisit this later.
- They also **understood what causes eclipses** — another topic we will revisit later.
- Aristotle holds the earliest written record **explaining why the Earth is spherical.**
  - He gave four physical reasons, based on observations, why this must be true:

1. **Gravity squeezes the Earth into a compact object.**
2. **Partial lunar eclipses always form an arc of a circle**
3. **New stars appear on the horizon if you head south**
4. **Elephants (see the book for more information.)**

Aristotle of Stagira (384–322 BCE)

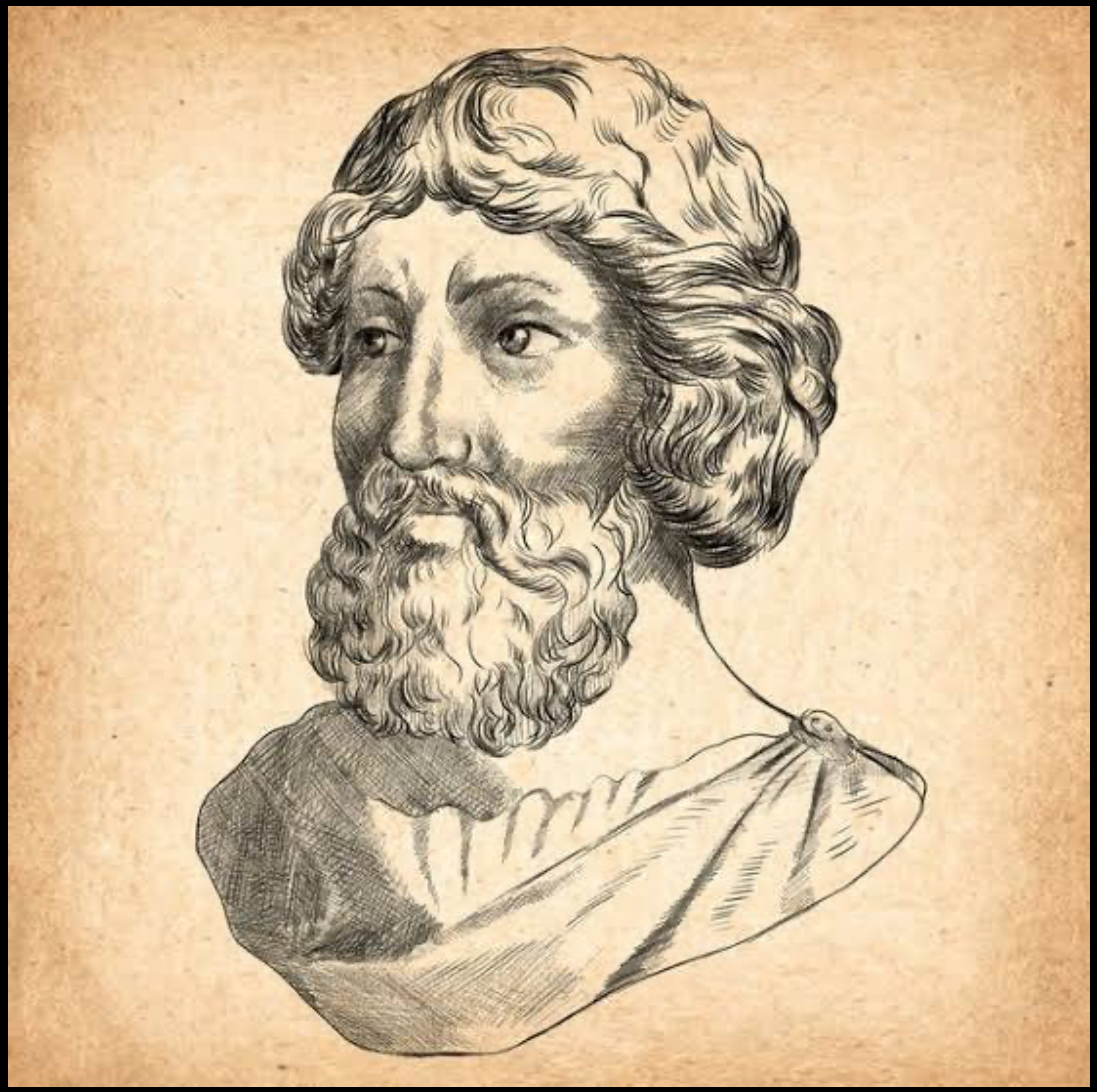
Greek Astronomy

Aristarchus was well known for claiming the Earth orbited the Sun! How did he figure it out?



When the Earth-Moon Sun angle is 90° then the ratio of the Earth-Moon distance (A) to the Earth-Sun distance (C) is:

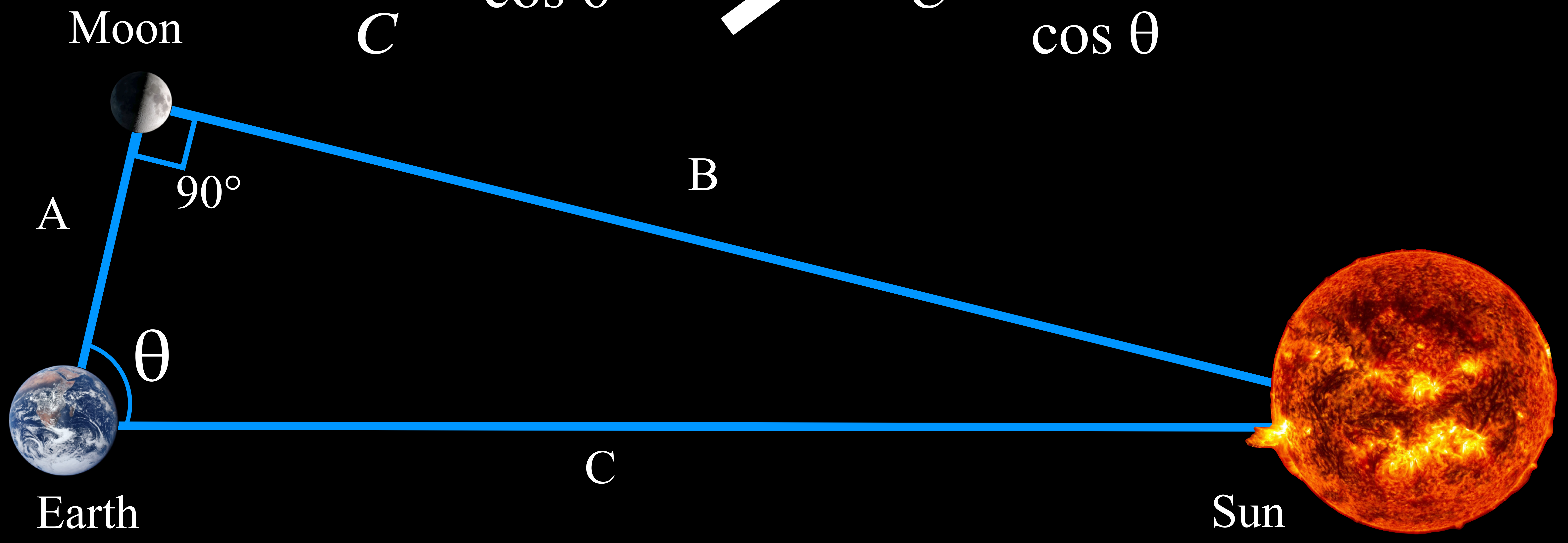
$$\frac{A}{C} = \cos\theta$$



Aristarchus of Samos (310-230 BCE)

Greek Astronomy

$$\frac{A}{C} = \cos\theta \;\Rightarrow\; C = \frac{A}{\cos\theta}$$



We can measure θ, the angle between the Sun and the Moon as seen from Earth. *But* it's **really really** close to 90°, making it's hard to measure accurately.

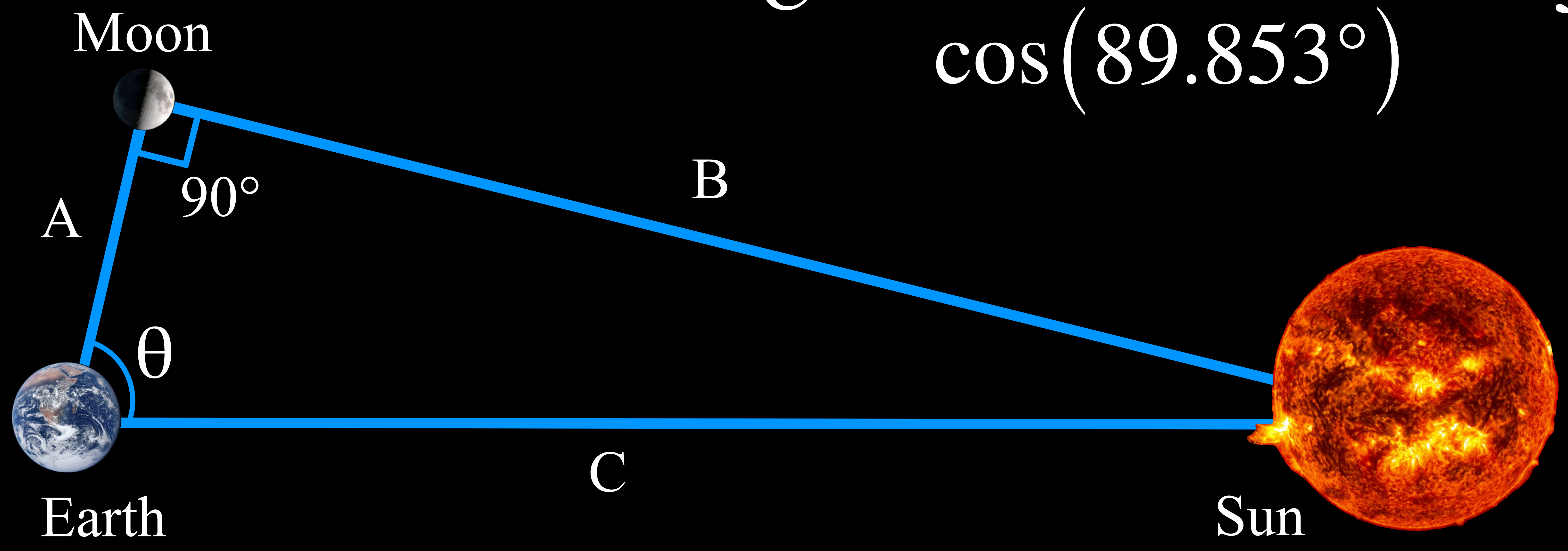
Greek Astronomy

Aristarchus measured 87° so we can plug that in and get:

$$C = \frac{\text{A}}{\cos(87°)} = 19\ \text{A}$$

However, the actual value is 89.853°, which gives us

$$C = \frac{\text{A}}{\cos\left(89.853°\right)} = 390\ \text{A}$$



So Aristarchus was ***off* by about a factor of 20** in the *distance* to the Sun relative to the Moon!

Greek Astronomy

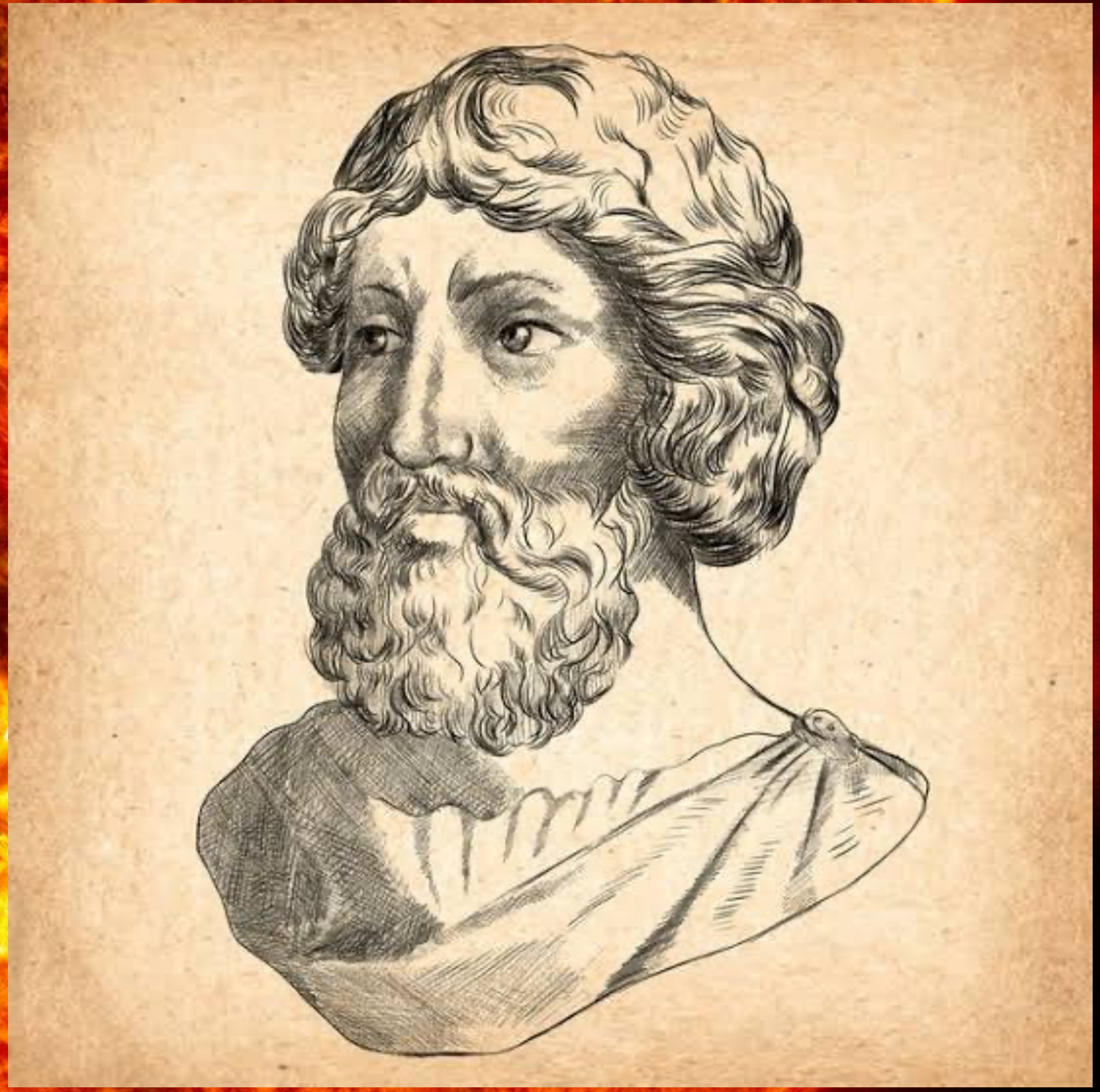
Aristarchus knew from eclipses that the Sun and Moon have similar angular sizes on the sky, **so he was correct in saying the Sun was farther way.**

He also used similar triangles to deduce that the *relative size* of the Sun to the Moon was 19 times bigger, **but it is really 390 times bigger!**

Relative sizes of the Sun and Moon based on Aristarchus' measurements

Moon Sun

Actual relative sizes of the Sun and Moon!



Aristarchus of Samos (310-230 BCE)

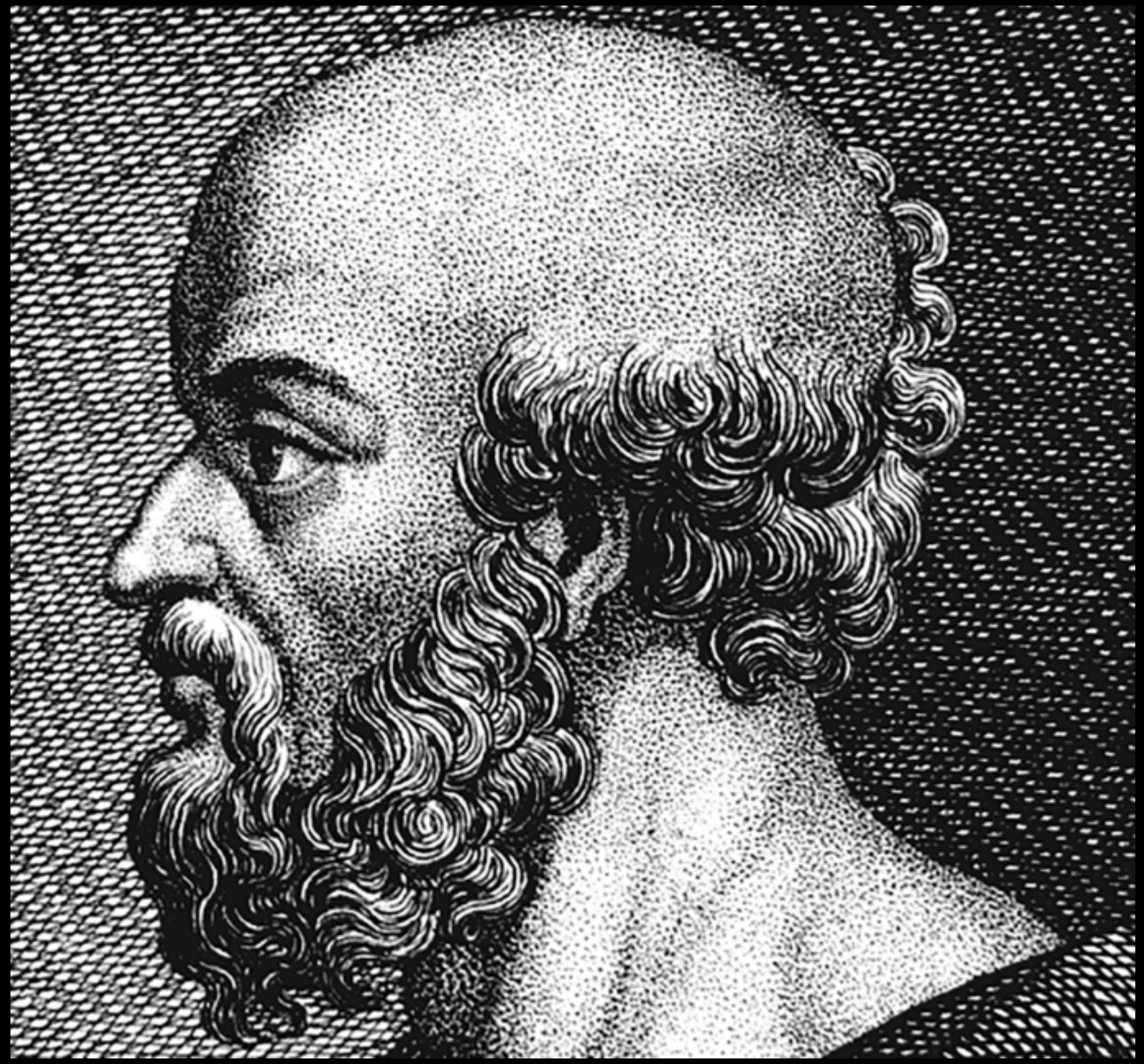
Greek Astronomy

While Aristarchus made progress towards deducing the relative sizes for the Moon, Earth, and Sun, it was **Eratosthenes** that figured out *physical* sizes.

Being the chief librarian for the Library of Alexandria, he spent a lot of time reading papyrus books…

One day, he came across a passage in a book that mentioned something curious:

> *"On June 21st in Syene (modern Aswan, Egypt), as the Sun rises in the sky, shadows cast by temple columns grow shorter and shorter. At midday, when the sun reaches its highest point in the sky, all* ***shadows disappear, and sunlight shines directly down into deep wells, illuminating the water at the bottom."***

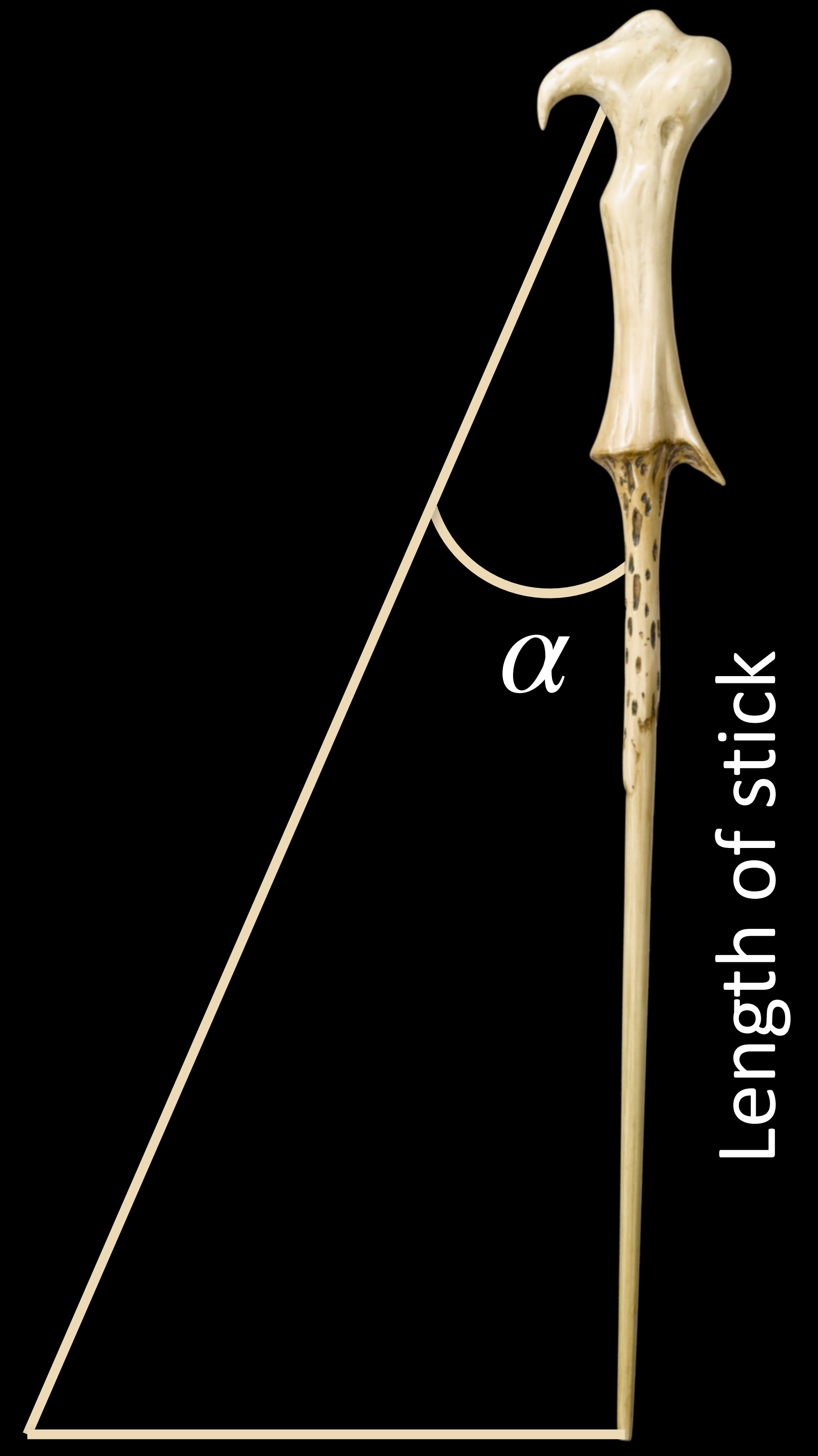


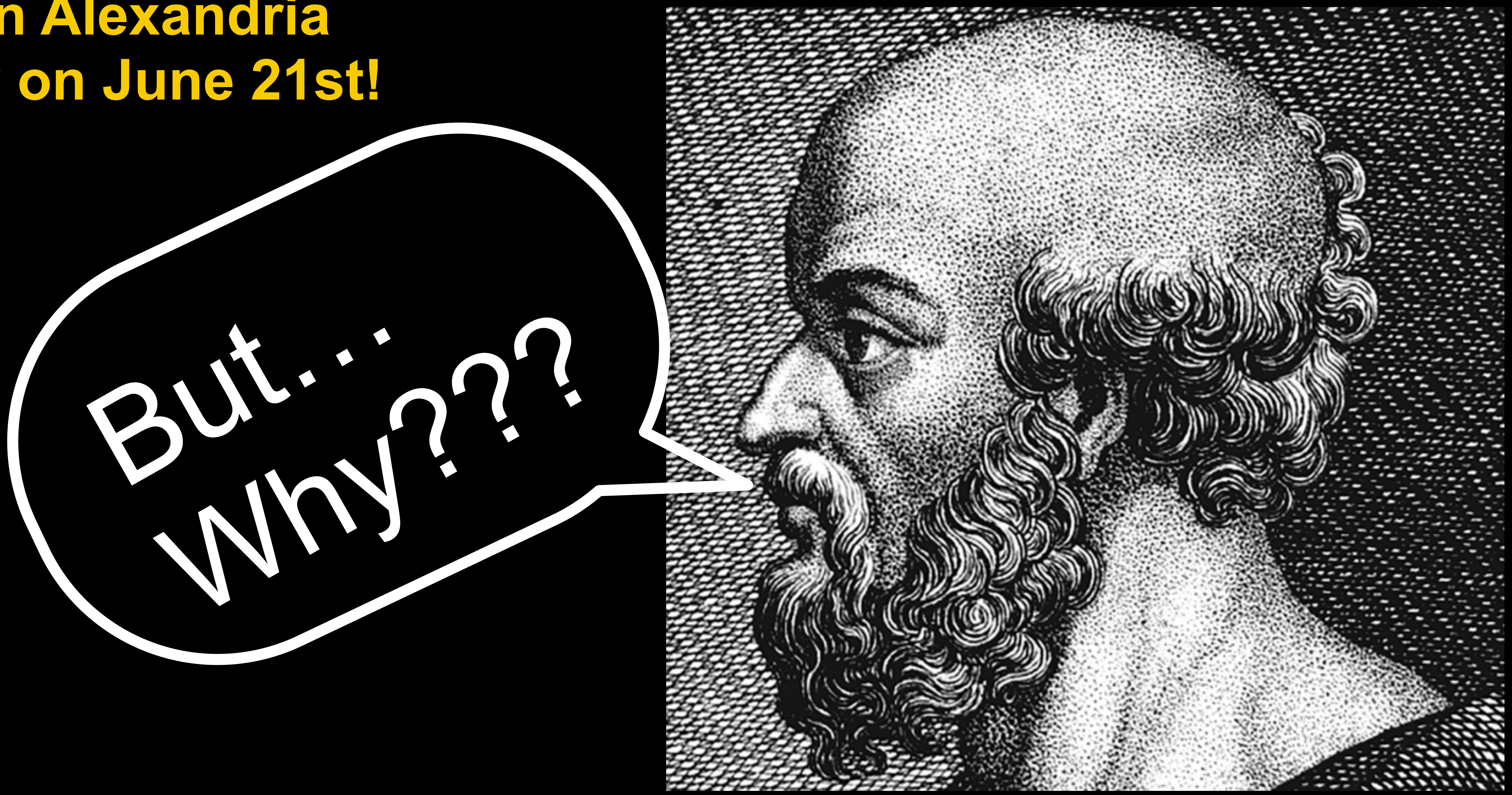
Eratosthenes of Cyrene (276-194 BCE)

Greek Astronomy

Eratosthenes peformed an experiment by placing a *stick* in the ground in Alexandria to see if it cast a shadow at the same day & time the book claimed there was no shadow in Syene.

He discovered that the **stick in Alexandria *did* cast a shadow at midday on June 21st!**

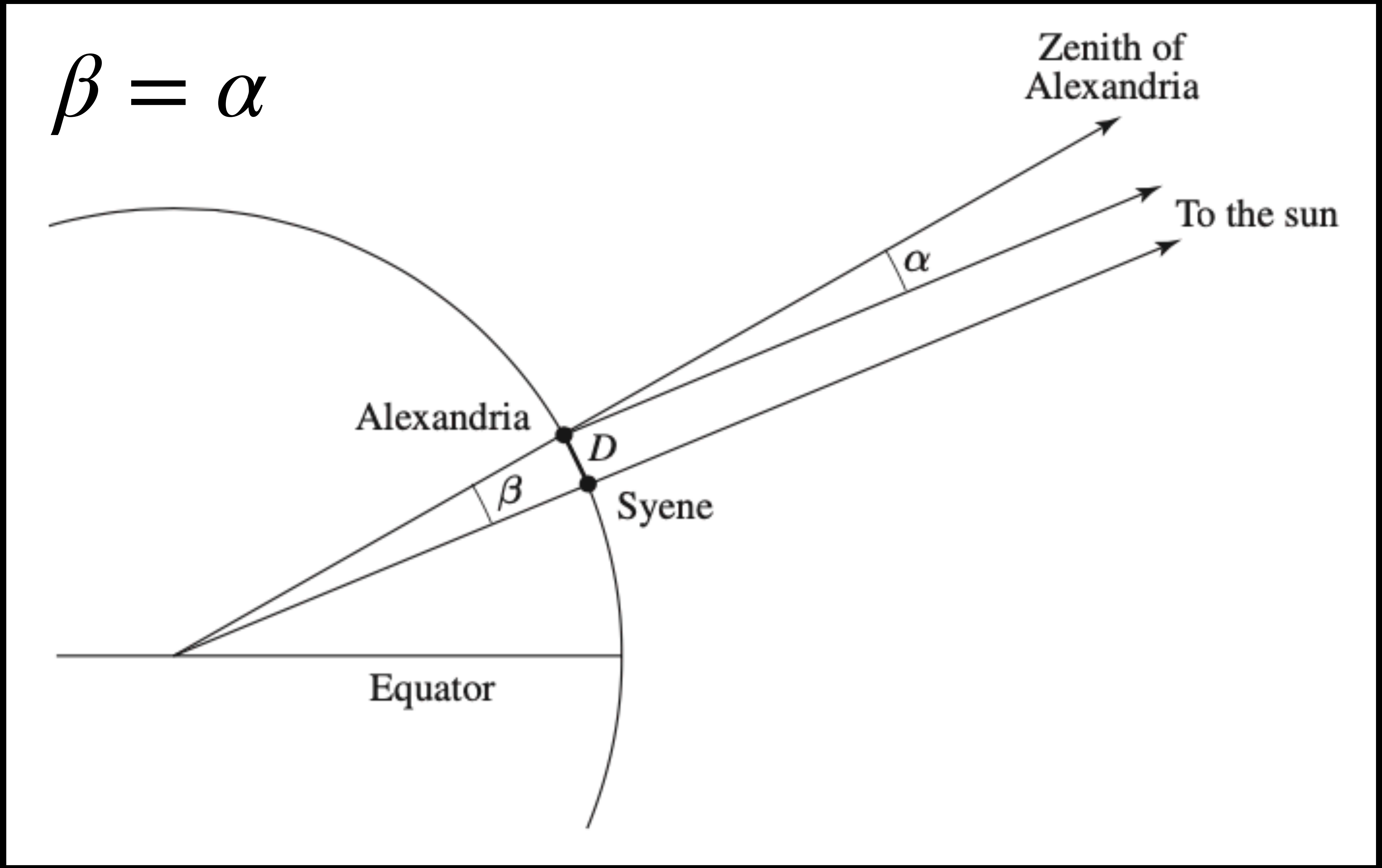


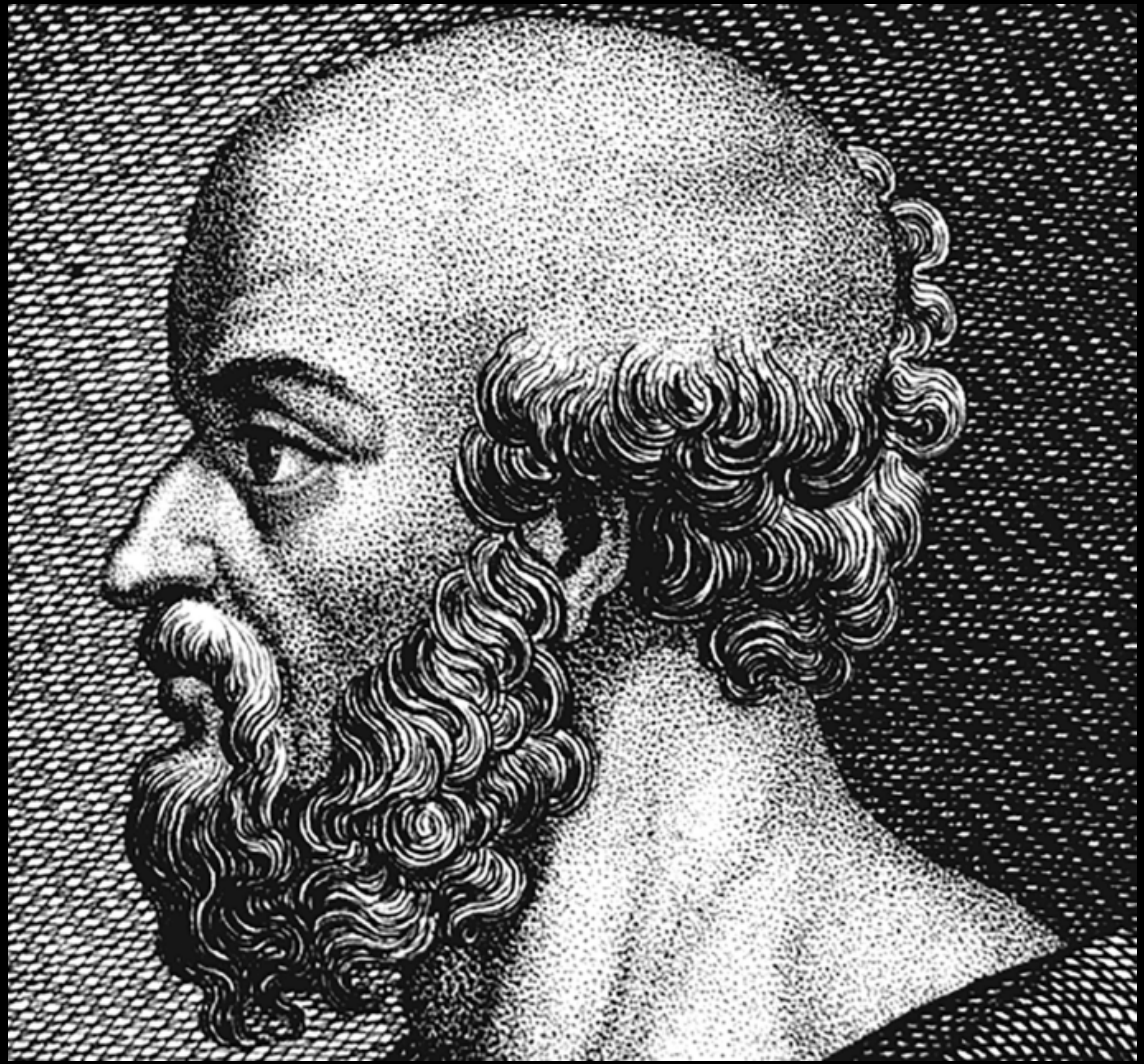


Eratosthenes of Cyrene (276-194 BCE)

Greek Astronomy

After doing a bit of triogonometry, **Eratosthenes** determined that the angle the $\alpha = 7°12'$ (approximately 1/50th of a circle).



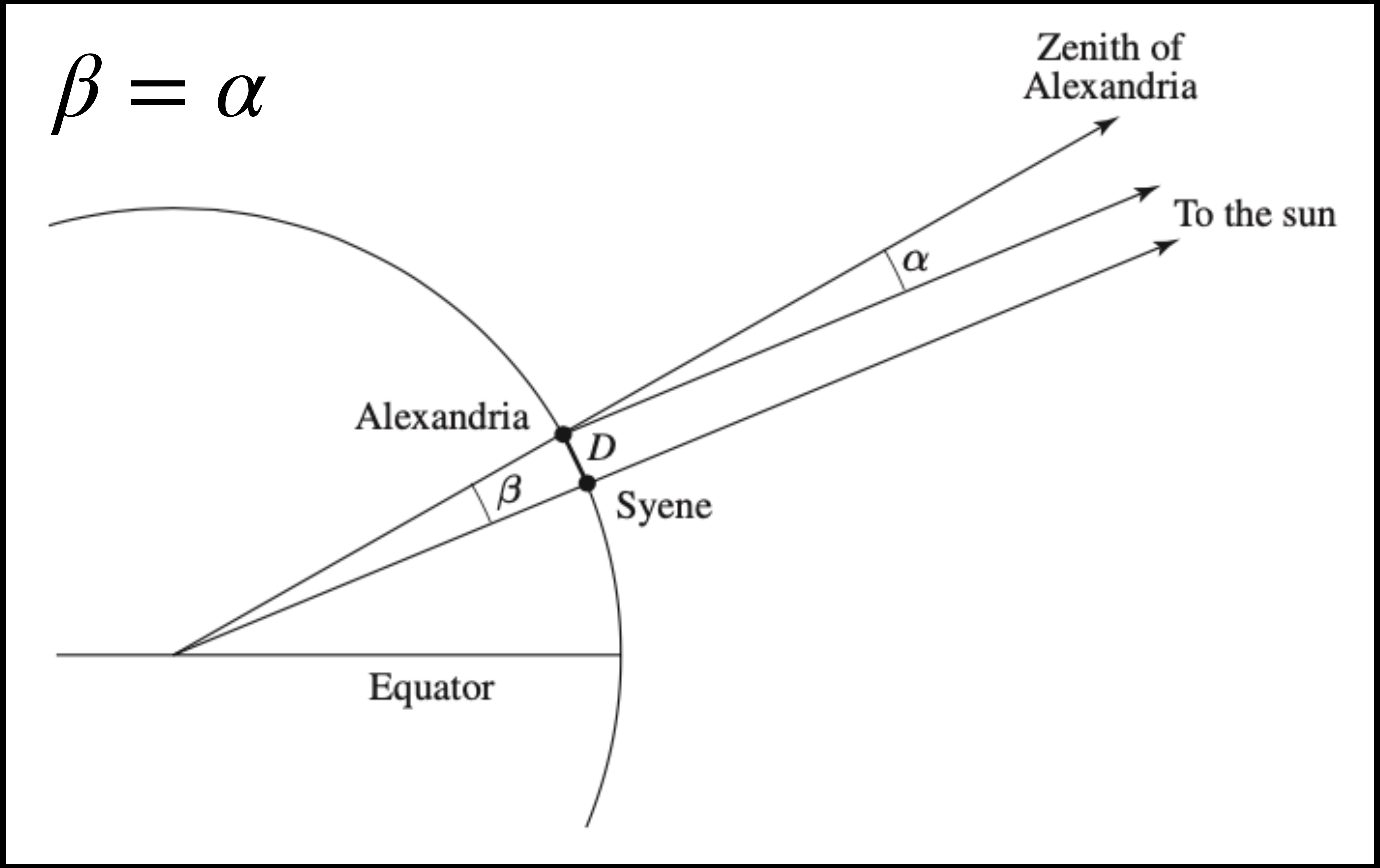


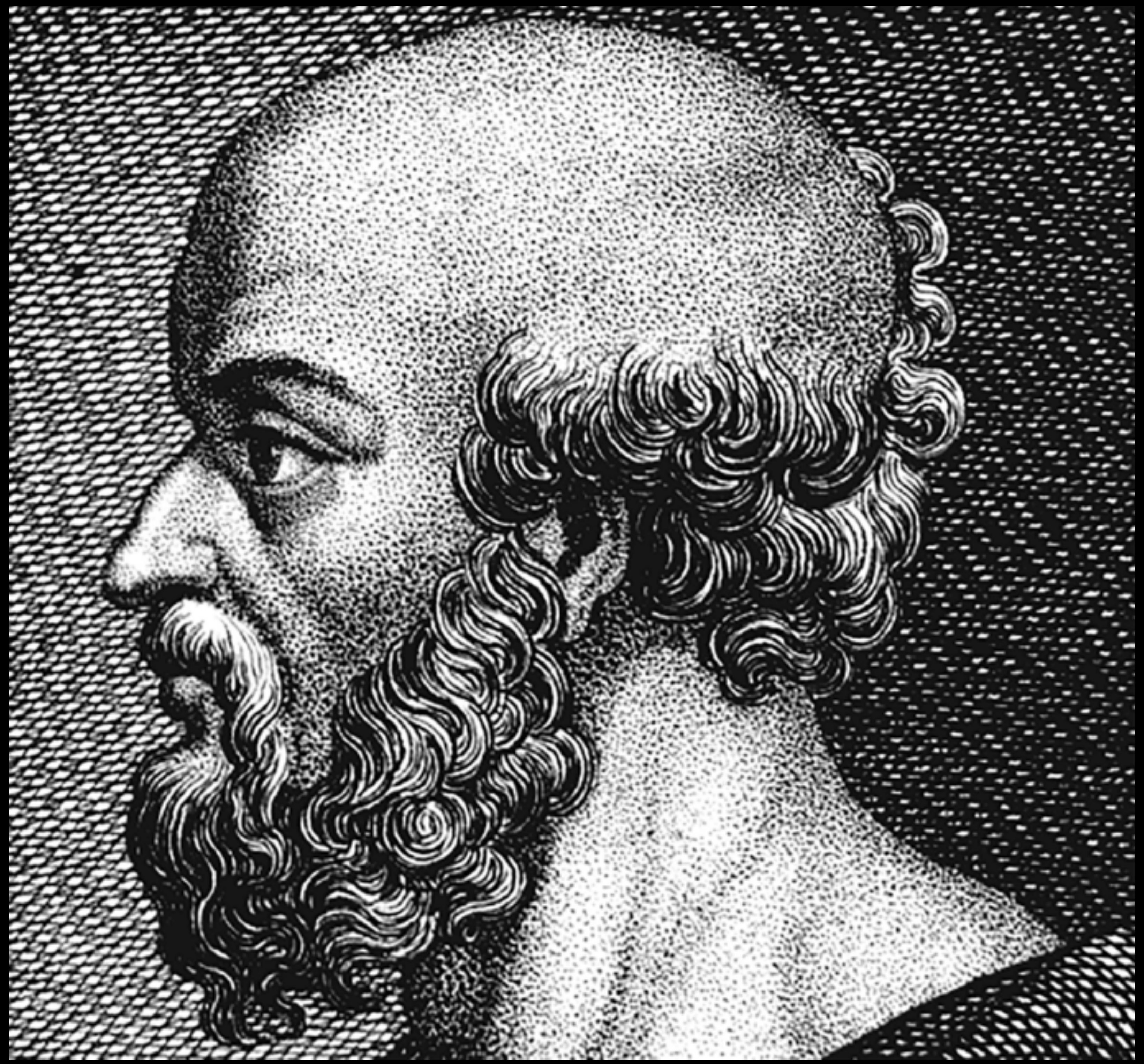
Eratosthenes of Cyrene (276-194 BCE)

He concluded that the total circumference of the Earth must be $C = 50D$

Greek Astronomy

In other words, by measuring the the distance between Alexandria and Syene (D) *one could derive* the circumference of the Earth, and then use $C = 2\pi R$ to get the radius (R)!



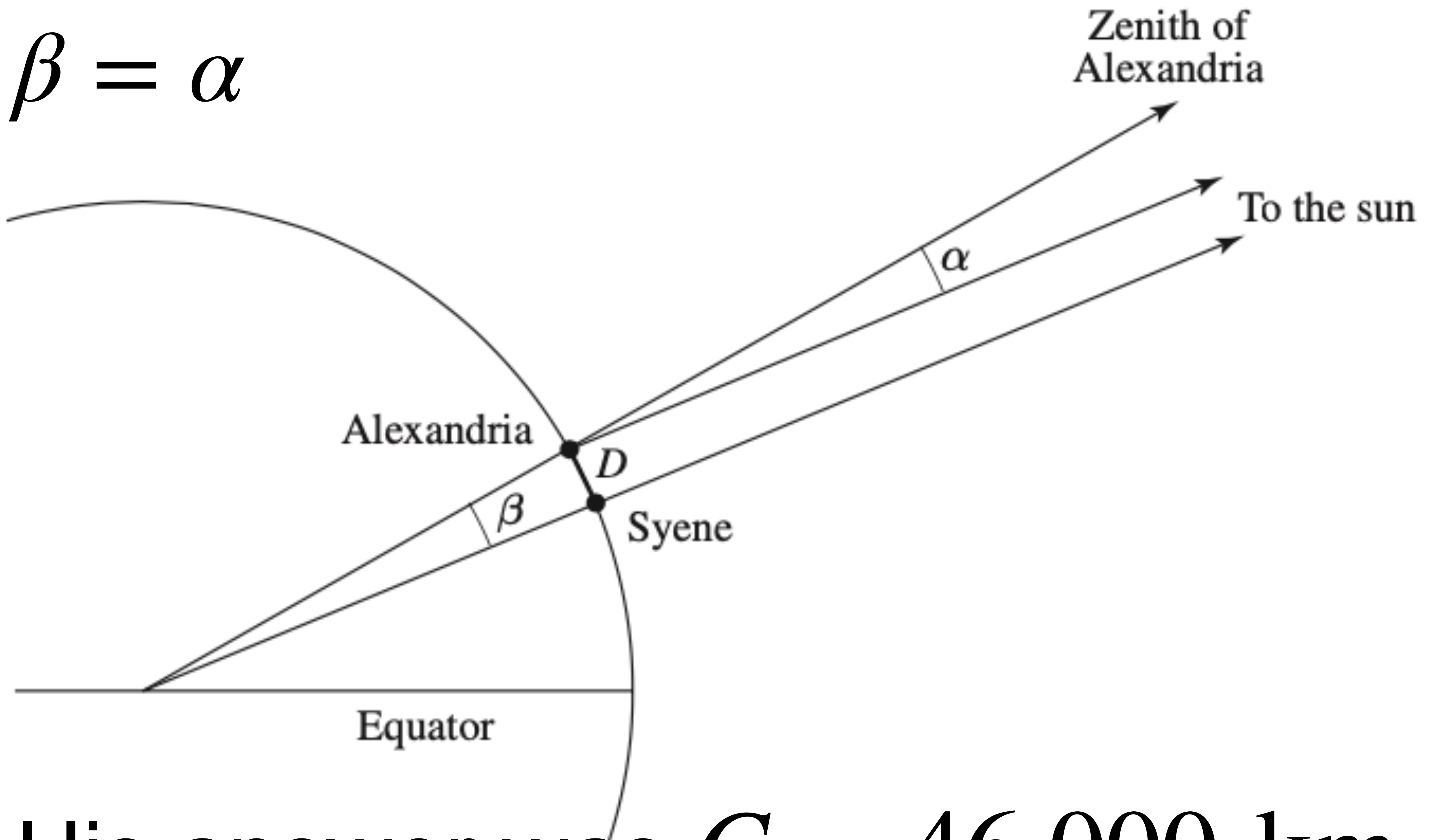


Eratosthenes of Cyrene (276-194 BCE)

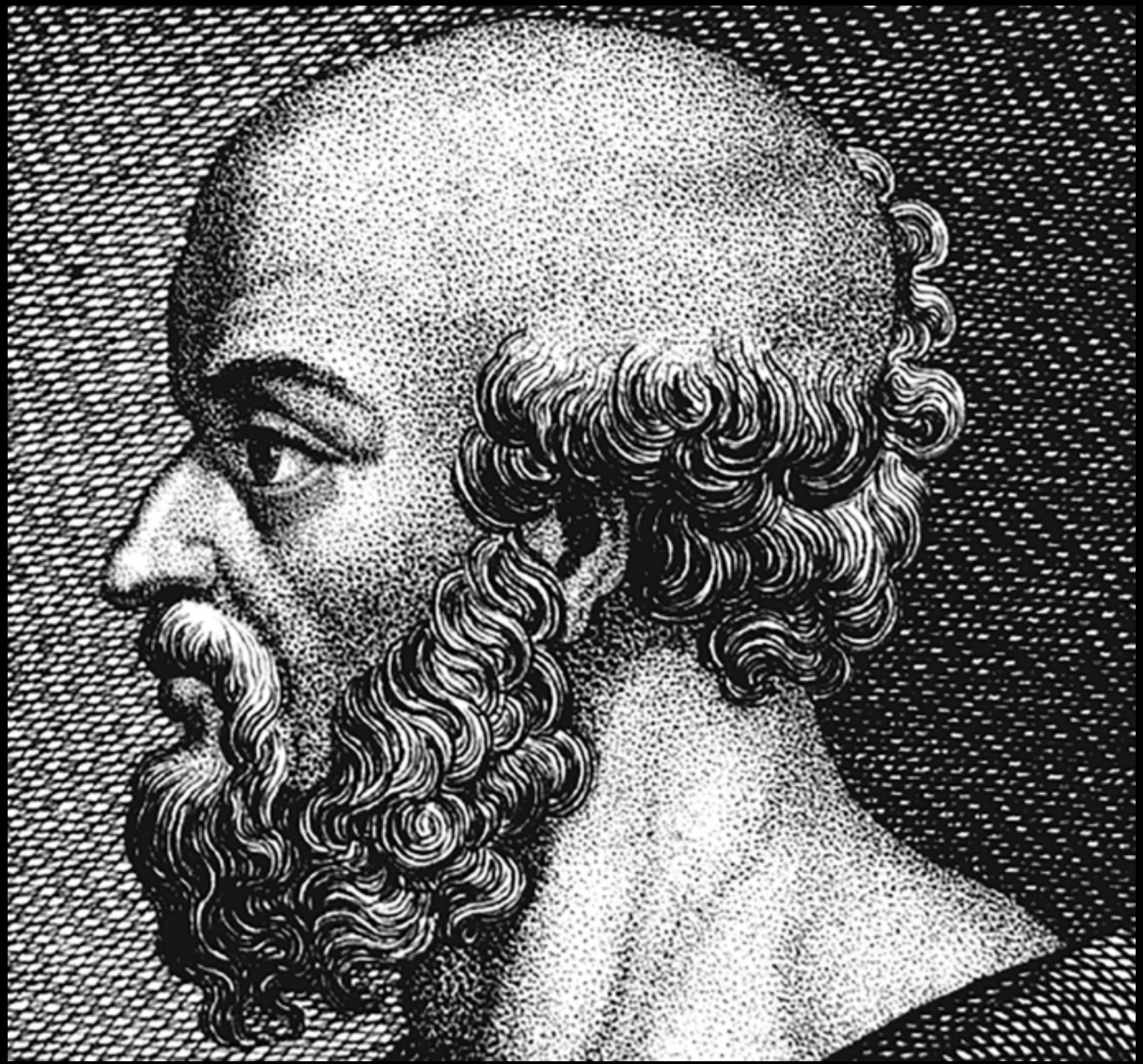
Greek Astronomy

After hiring a man to walk from Alexandria to Syene (and back), he calculated that the distance D was *around* 5000 *stades* (or 915 km).

$\beta = \alpha$



His answer was $C = 46{,}000\ \mathrm{km}$



Eratosthenes of Cyrene (276-194 BCE)

The correct value is $\sim 40{,}000\ \mathrm{km}$ (he was off by 15%!)


Questions?

Greek Astronomy

Ptolemy is best known for his astronomical work, *The Almagest*, which presented the Ptolemaic Model of the Universe.

The Ptolemaic Model attempted to explain:

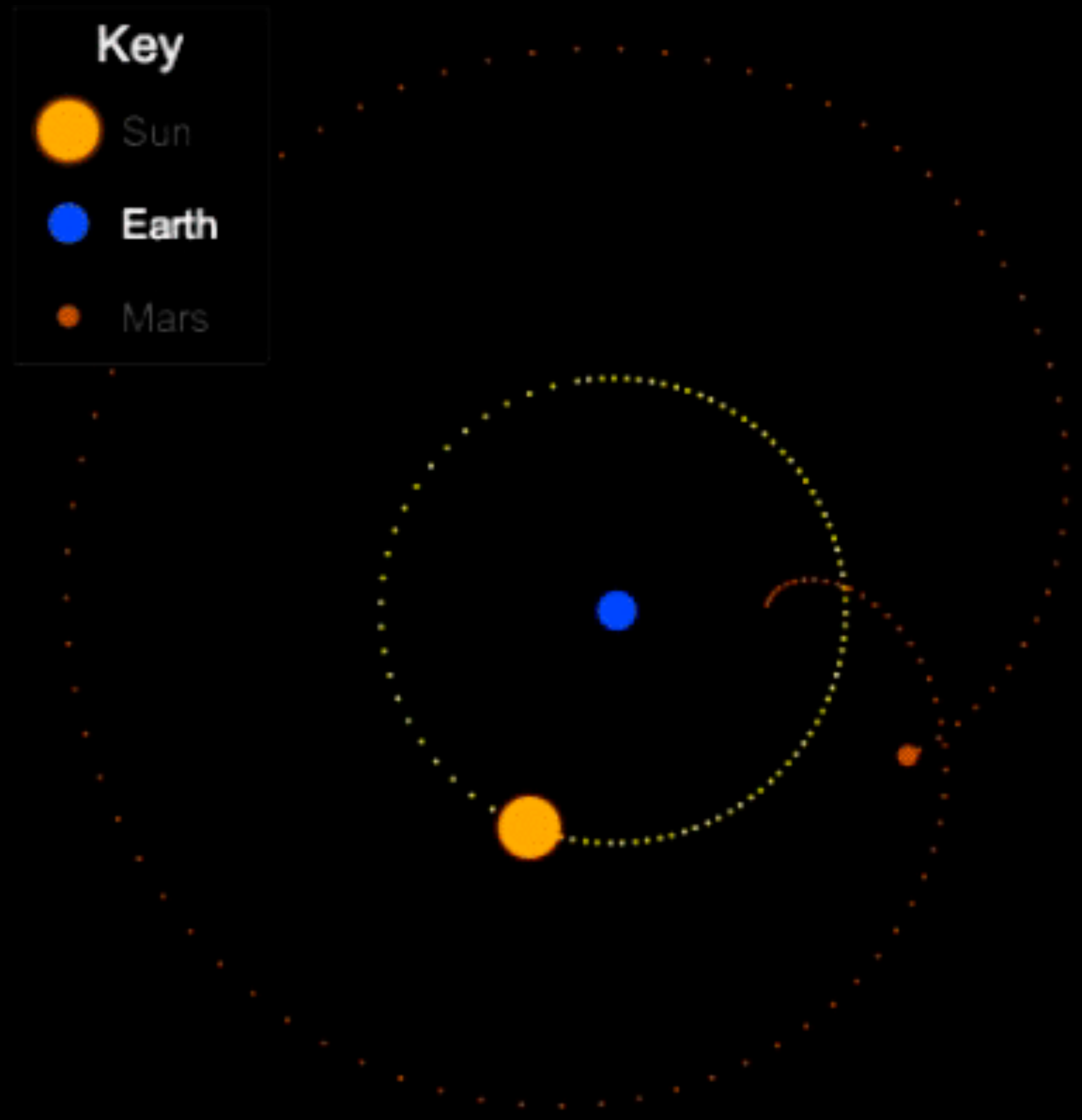
1. Why stars move in diurnal circles about the celestial poles.
2. Why the Sun moves eastward relative to stars.
3. Why the Moon moves eastward relative to stars.
4. Why the (visible) planets moving eastward, but sometimes moving westward (retrograde motion).

His model include two assumptions:

1. Earth was at the center of the Universe
2. Everything moved in perfect circles.

Claudius Ptolemy (100-170 CE)

Ptolemy’s Model vs. Retrograde Motion



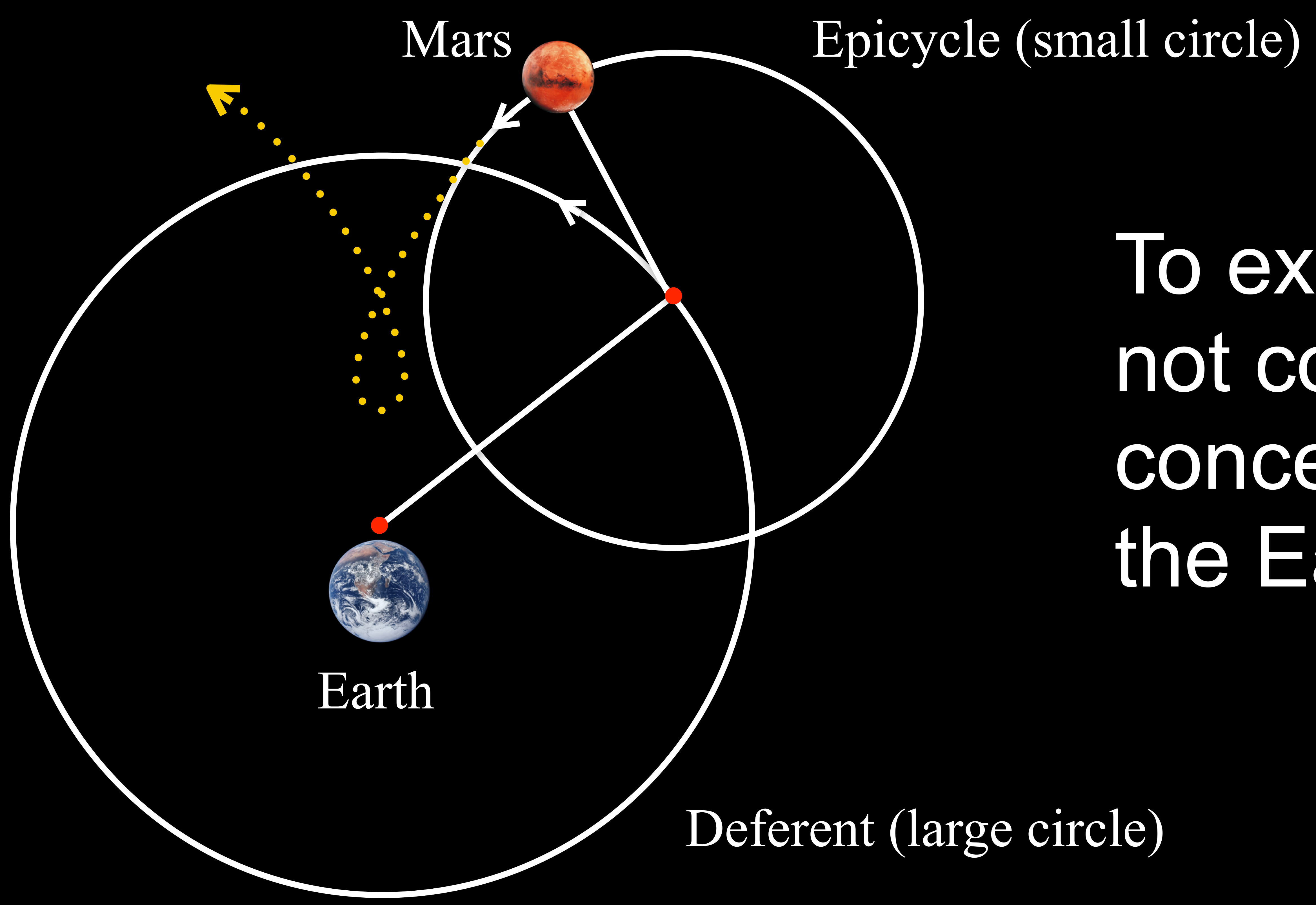
Credit: Rob Kerby Guevarra/IAU OAE

The most significant problem with Ptolemy’s model was its difficulty in explaining why the planets occasionally appeared to reverse direction in the sky — i.e., **retrograde motion**

Ptolemy’s Model vs. Retrograde Motion

What was Ptolemy’s solution to the puzzle of retrograde motion?

Circles! He added more perfect circles to his model.



To explain why the Sun’s speed was not constant, his model introduced the concept of an *eccentric** — offsetting the Earth from the center of its orbit.

*The word “eccentric” literally means “away from center.”

The Persistence of Ptolemy's Model

Despite being overly complicated, Ptolemy's model persisted for centuries.

But why was his static, geocentric model accepted for so long?

- **Predictive power:** It did a remarkably good job of predicting the positions of the Sun, Moon, and planets.
- **Cultural appeal:** Since Earth was home to humans, it must be an extremely important place — naturally fitting the belief that it should sit at the center of the Universe.
- **No sensation of motion:** People could not feel the Earth spinning or moving through space.
- **No observed stellar parallax:** The stars appeared fixed, showing no noticeable shift, which one would expect if Earth were in motion.

Parallax

1. Hold your hand out at arm’s length with your thumb sticking up.
2. Close one eye and line your thumb up with something in the background.
3. Now close the other eye.
4. What do you notice?

Your thumb seems to jump side to side compared to the background!

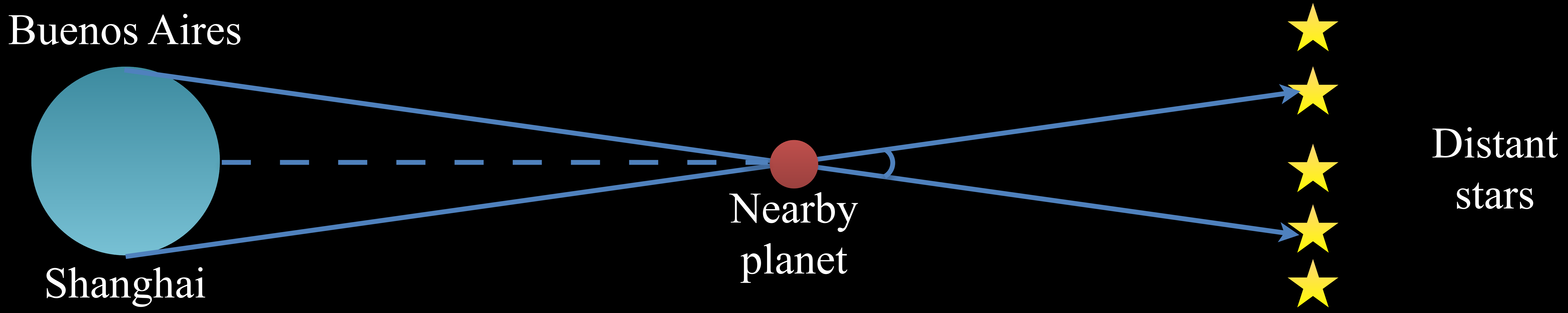
*That “jump” is about **5°**—roughly **ten times the apparent size of the Moon in the sky** (the Moon is about 0.5° across as seen from Earth).*

This effect is called **parallax**: the apparent shift in the position of an object when viewed from two different vantage points.

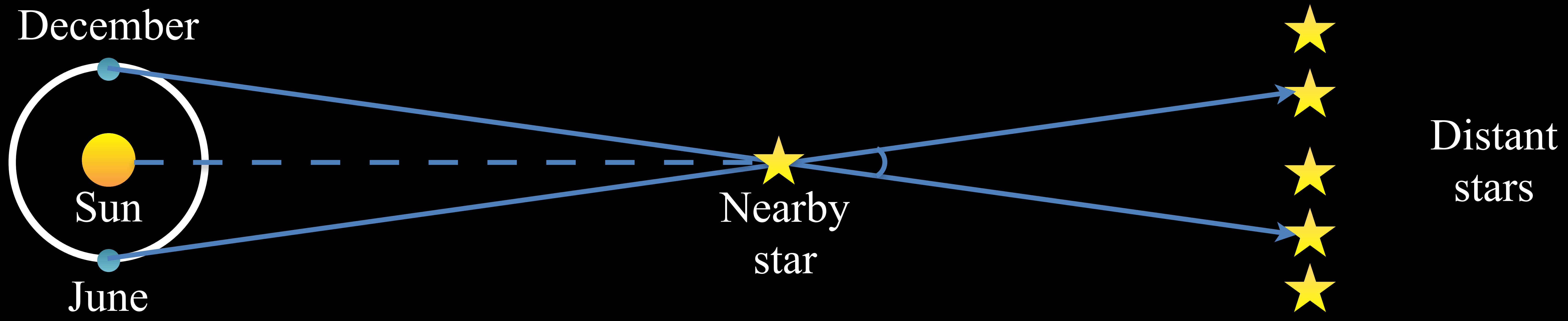
Parallax

In astronomy, we typically distinguish **two types of parallax**:

Geocentric (diurnal) parallax: The apparent shift seen when the same object is observed from two different places on Earth.



Heliocentric parallax: The apparent shift seen when Earth's motion around the Sun provides two different vantage points (e.g., six months apart in orbit).



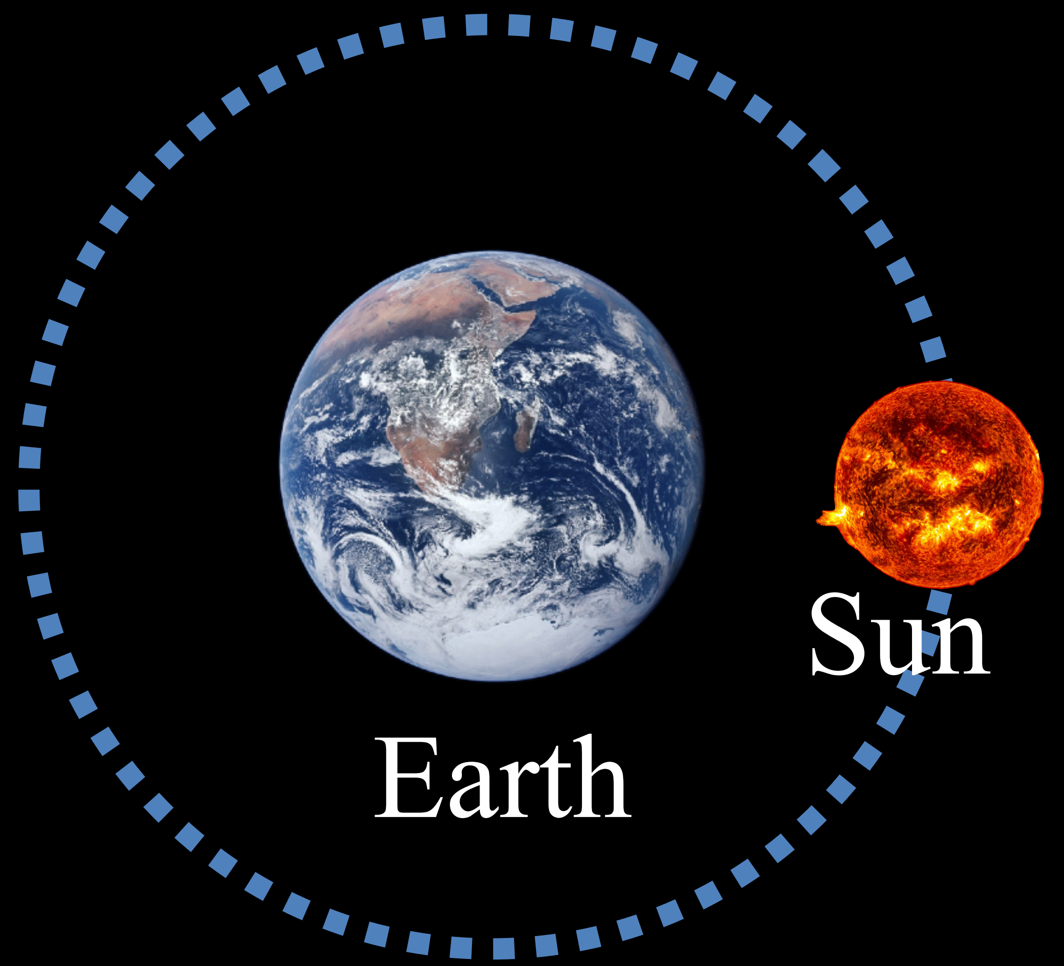

Questions?

The *Copernican Revolution*

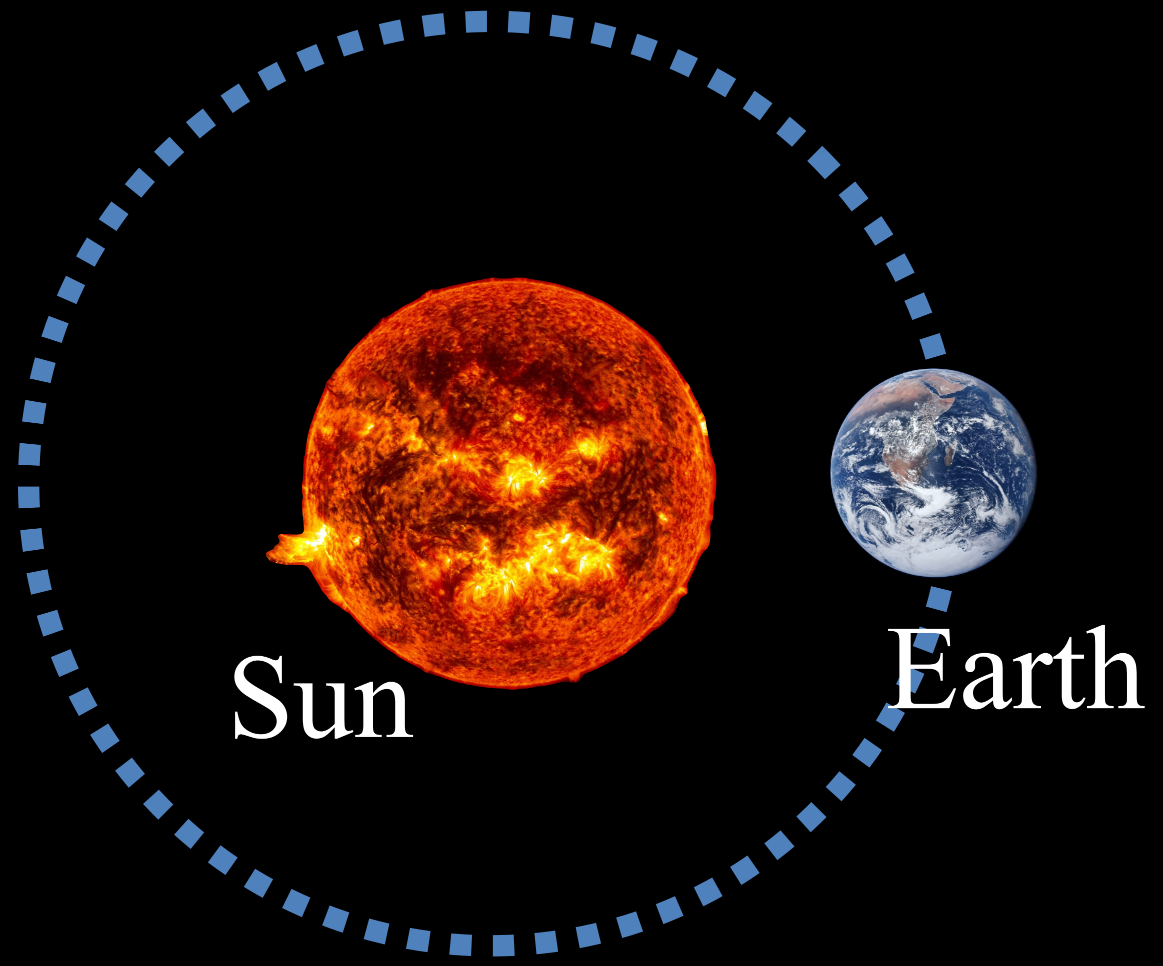
Copernicus is best known for his magnum opus, *De Revolutionibus Orbium Coelestium* (On the Revolutions of the Celestial Spheres).

In this work — which was not published until he was on his deathbed — Copernicus proposed the **heliocentric model,** placing the Sun at the center and Earth as one of several planets orbiting it.

Ptolemy's Geocentric Model



Copernicus' Heliocentric Model



Nicolaus Copernicus (1473-1543 CE)

His model include two major assumptions:

1. **Heliocentrism:** The Sun is at the center of the Solar System.
2. **Circular motion:** Planets move in **perfect circles** around the Sun

The *Copernican Revolution*

In Copernicus' model, some things changed while others stayed the same…

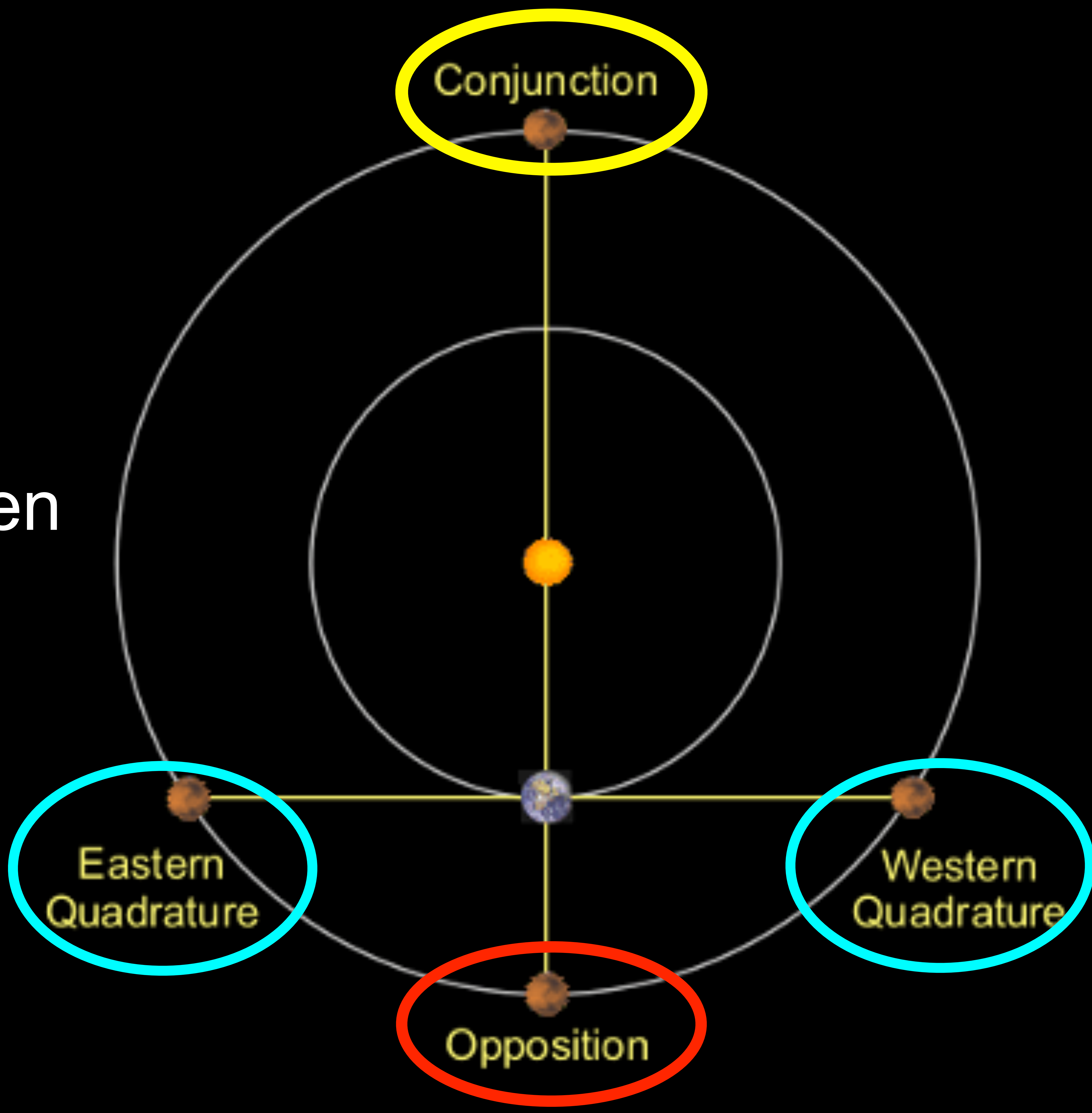
- **Epicycles and eccentrics remained:** His model used these to maintain **circular motion** while explaining planetary motion.
- **Planetary speeds:** Inner planets moved faster than outer planets.
- **Sun-centered:** The Sun was at the center, not the Earth.
- **New Categories for Planets:**
  - **Inferior planets:** Orbits *smaller* than Earth's (Mercury, Venus).
  - **Superior planets:** Orbits *larger* than Earth's (Mars, Jupiter, Saturn).

Nicolaus Copernicus (1473-1543 CE)

The *Copernican* Revolution

New terms introduced in Copernicus' model:

- **Opposition:** When Earth lies directly between the Sun and a superior planet.
- **Conjunction:** When the Sun lies directly between Earth and a superior planet.
- **Quadrature:** When a superior planet appears 90° from the Sun as seen from Earth.



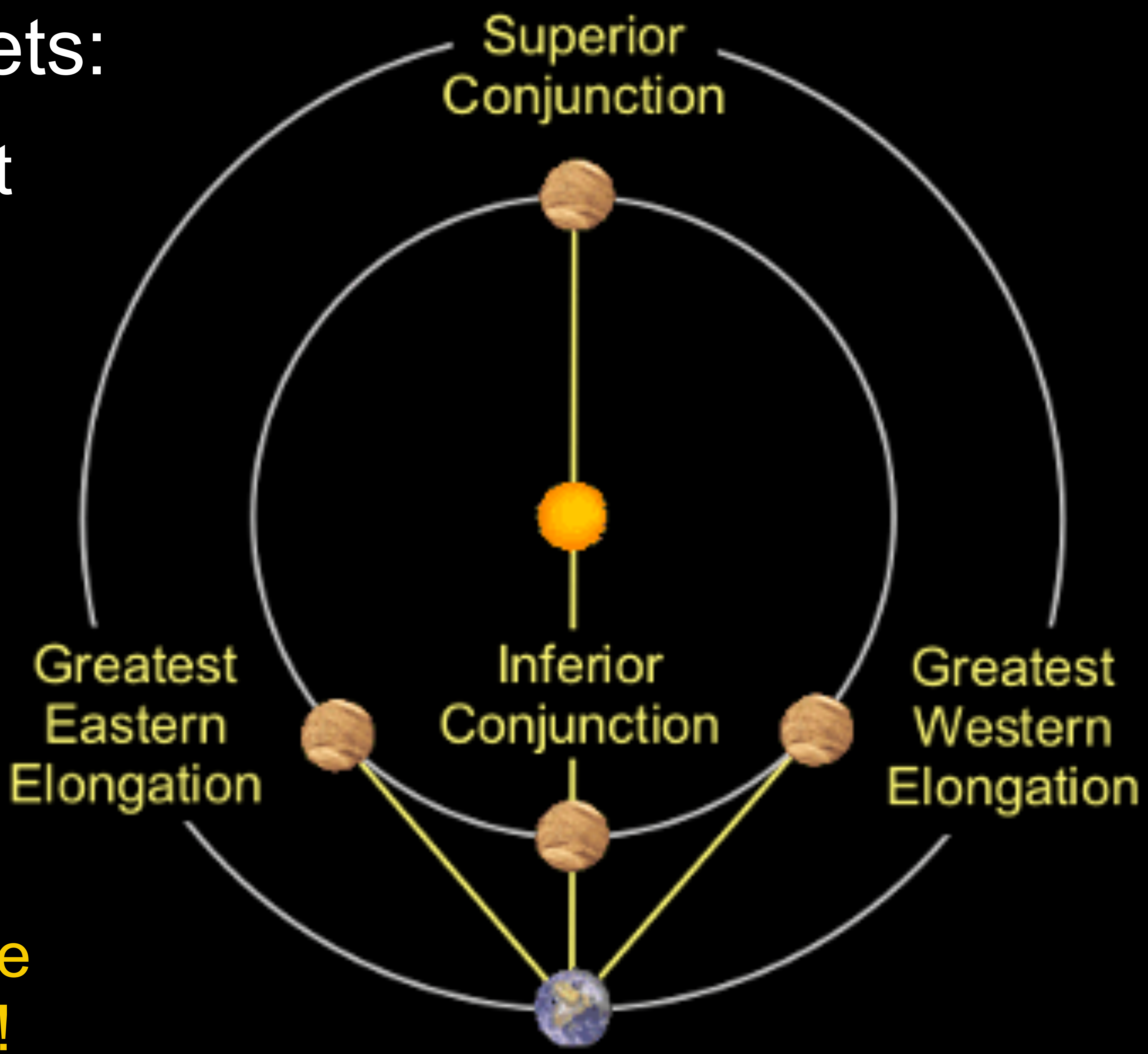
The *Copernican Revolution*

2 types of conjunctions for inferior planets:

- **Inferior Conjunction:** The inferior planet lies between Earth and the Sun.
- **Superior Conjunction:** The Sun lies between Earth and the inferior planet.

His model also introduced *"elongation"*, which is the **angle between the Earth-Sun and Earth-planet lines.**

By measuring elongations, Copernicus could deduce the orbital periods of planets *relative* to Earth's orbit!

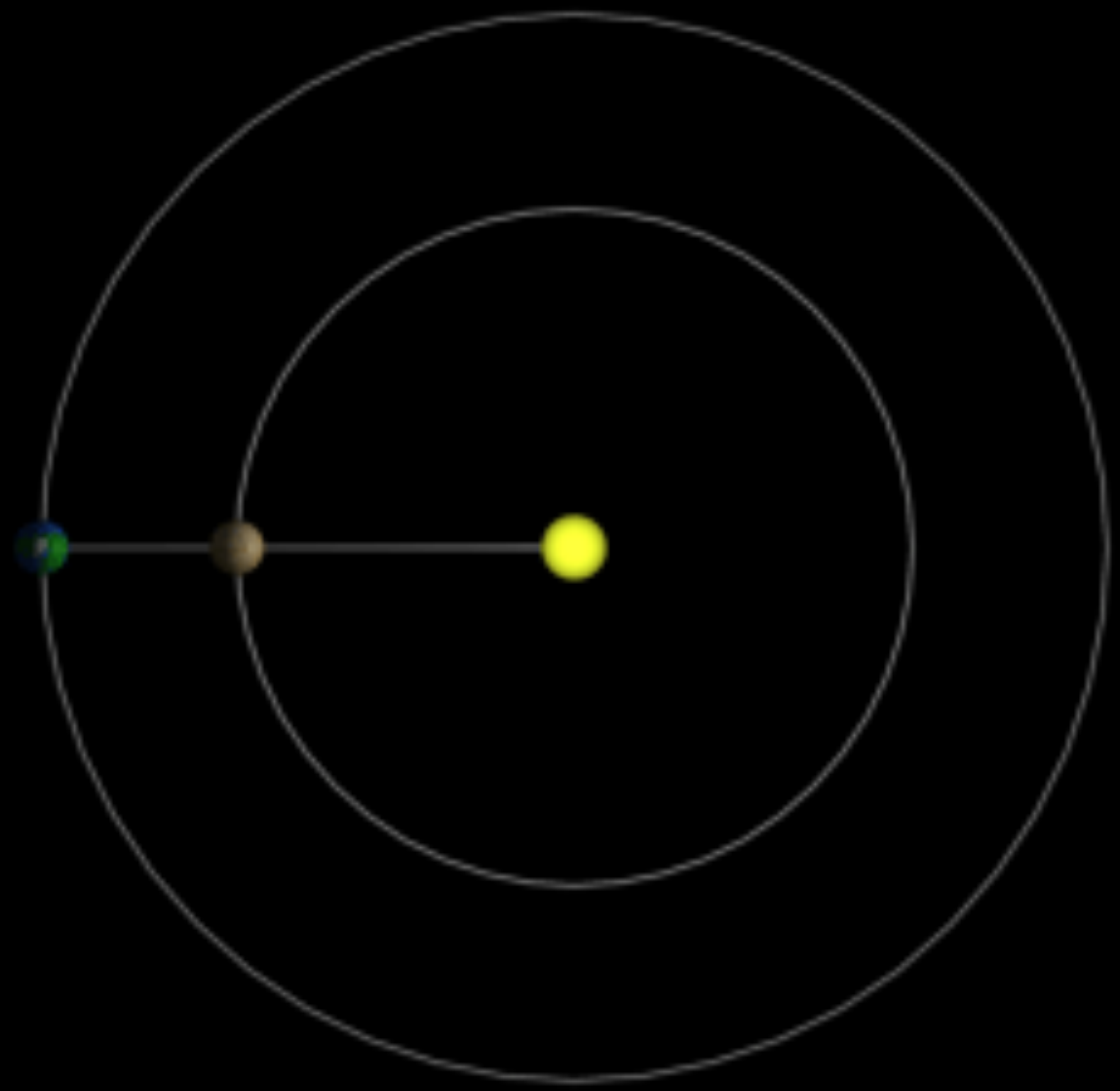


Synodic Period

Synodic Period: The time it takes for a planet to return to the same position relative to the Sun and Earth.

The synodic period is defined differently for **superior** and **inferior** planets.

- **Synodic Period of Superior Planets:** The time between successive conjunctions of a superior planet.
- **Synodic Period of Inferior Planets**: The time interval between successive inferior conjunctions.



Venus Synodic Period

*The term “synodic” comes from the Greek **synodos**, meaning a “coming together.”

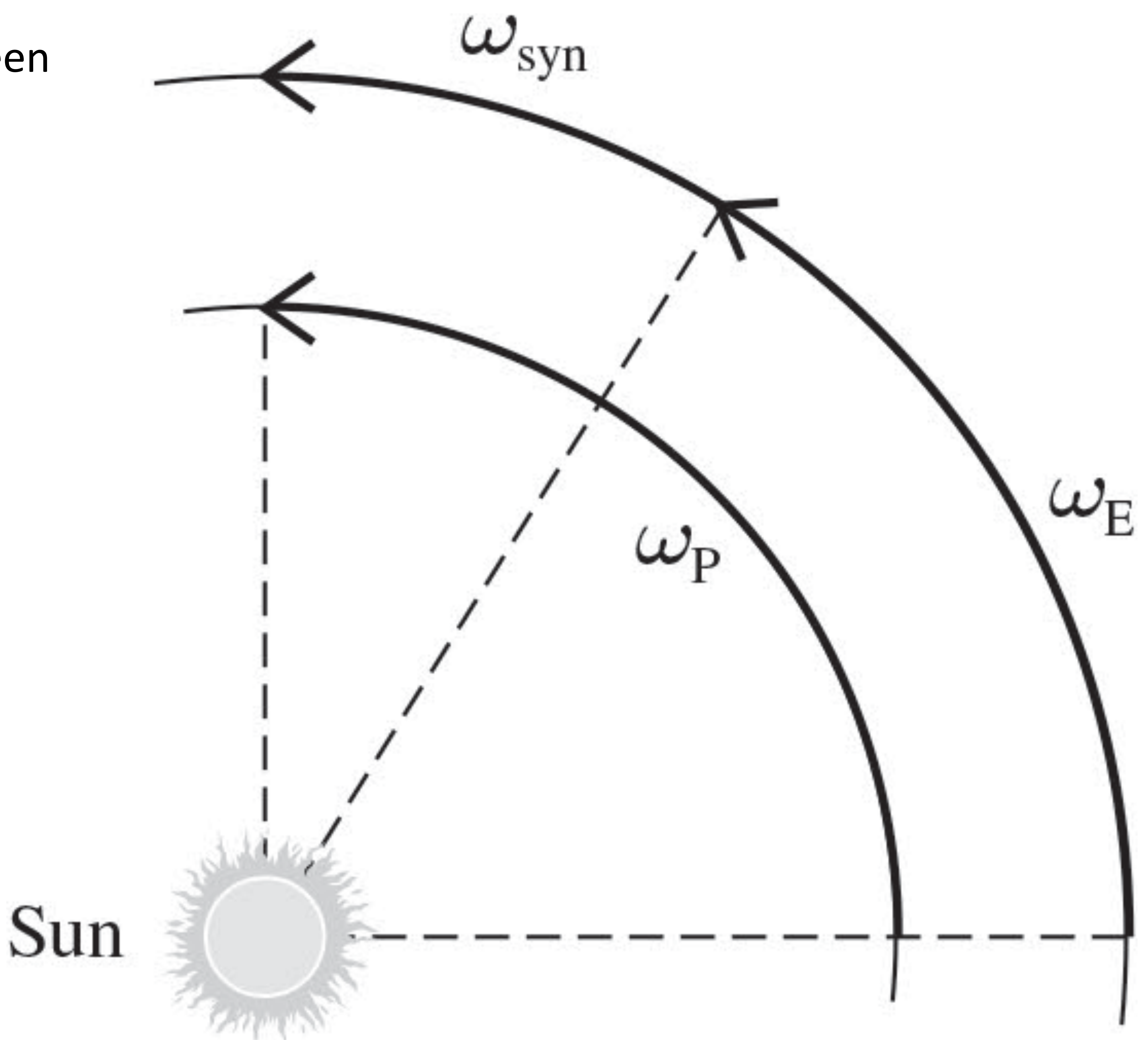
Angular velocity for an inferior planet

Ang. vel. of planet's orbital motion

Ang. vel. of Earth's orbital motion

Difference between ang. velocities

$$\vec{\omega}_{\mathrm{P}} = \vec{\omega}_{\mathrm{E}} + \vec{\omega}_{\mathrm{syn}}$$



$\omega =$ angle per unit time

Angular velocity for an inferior planet

Ang. vel. of planet's orbital motion

Ang. vel. of Earth's orbital motion

Difference between ang. velocities

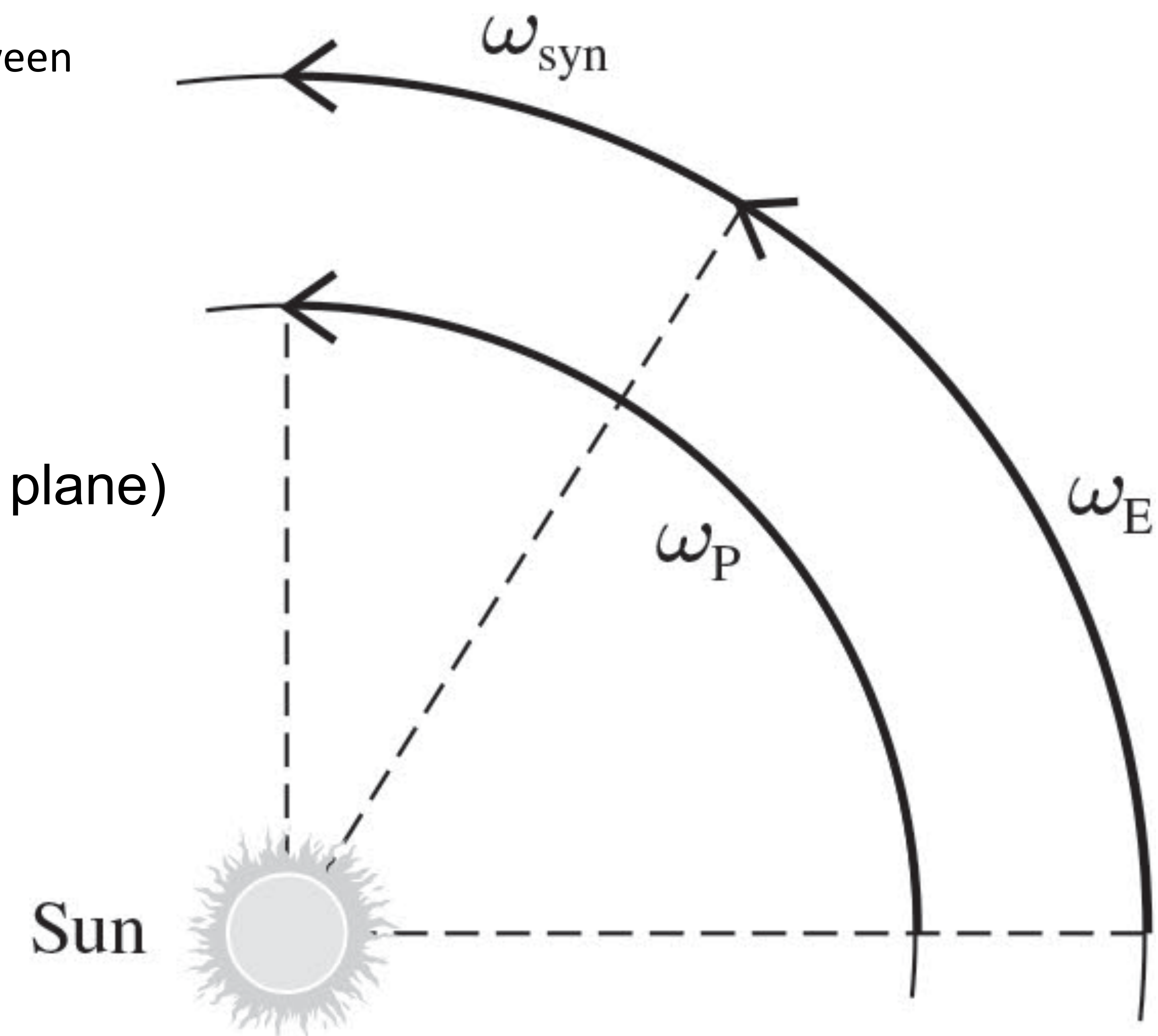
$$\vec{\omega}_{\mathbf{P}} = \vec{\omega}_{\mathbf{E}} + \vec{\omega}_{\mathbf{syn}}$$

Again assume orbits are parallel (in the same plane)

$$\omega_\mathrm{P} = \omega_\mathrm{E} + \omega_\mathrm{syn}$$

$$\frac{2\pi}{P_\mathrm{P}} = \frac{2\pi}{P_\mathrm{E}} + \frac{2\pi}{P_\mathrm{syn}}$$

$$\frac{1}{P_\mathrm{P}} = \frac{1}{P_\mathrm{E}} + \frac{1}{P_\mathrm{syn}}.$$



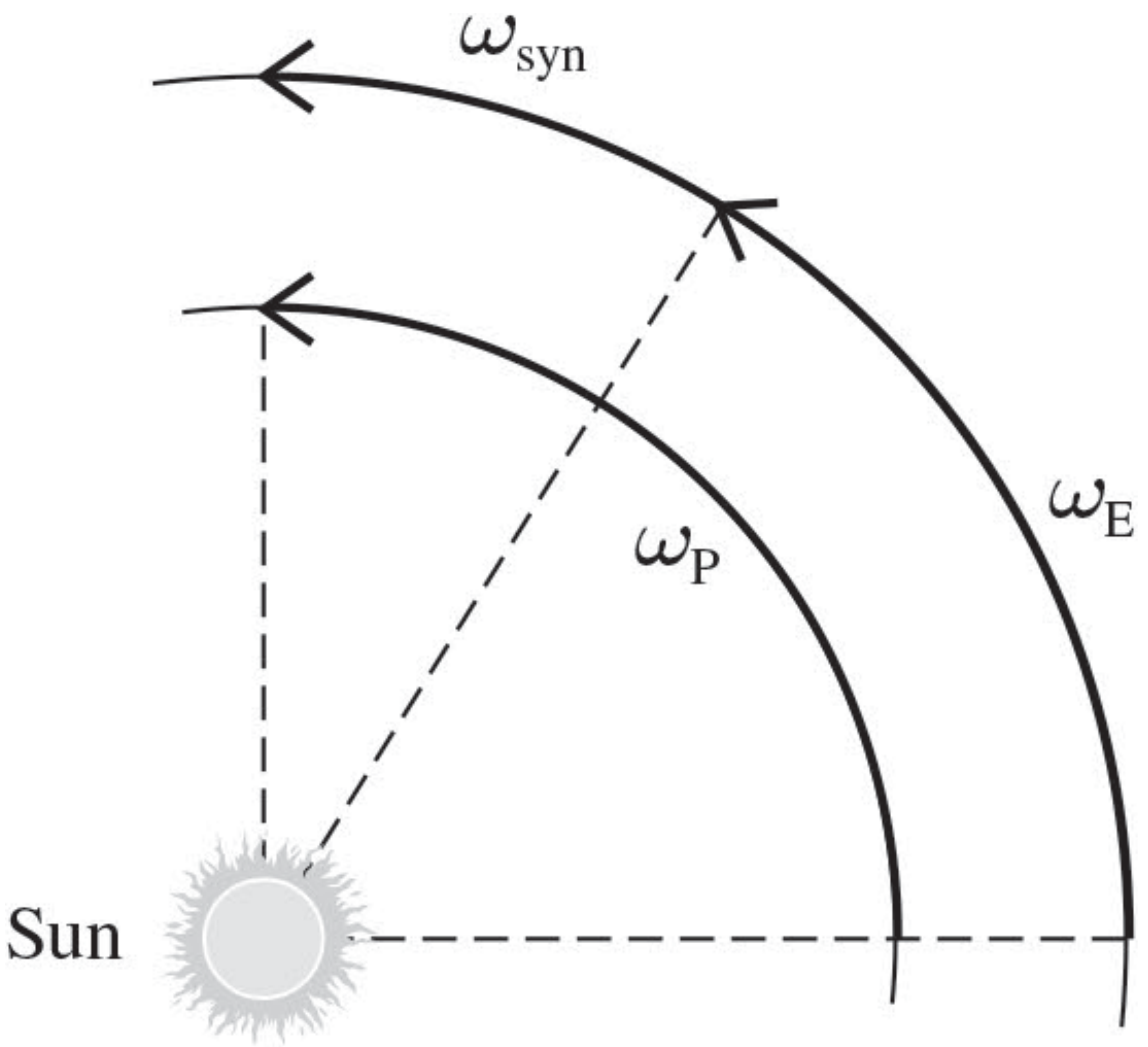
$\omega =$ angle per unit time

Angular velocity for an inferior planet

$$\omega_{\mathrm{P}} = \omega_{\mathrm{E}} + \omega_{\mathrm{syn}}$$

$$\frac{2\pi}{P_{\mathrm{P}}} = \frac{2\pi}{P_{\mathrm{E}}} + \frac{2\pi}{P_{\mathrm{syn}}}$$

$$\frac{1}{P_{\mathrm{P}}} = \frac{1}{P_{\mathrm{E}}} + \frac{1}{P_{\mathrm{syn}}}.$$



P_E = *sidereal* orbital period of the Earth.

P_{syn} = *synodic* orbital period of the inferior planet as seen from Earth.

P_P = *sidereal* orbital period of the inferior planet.

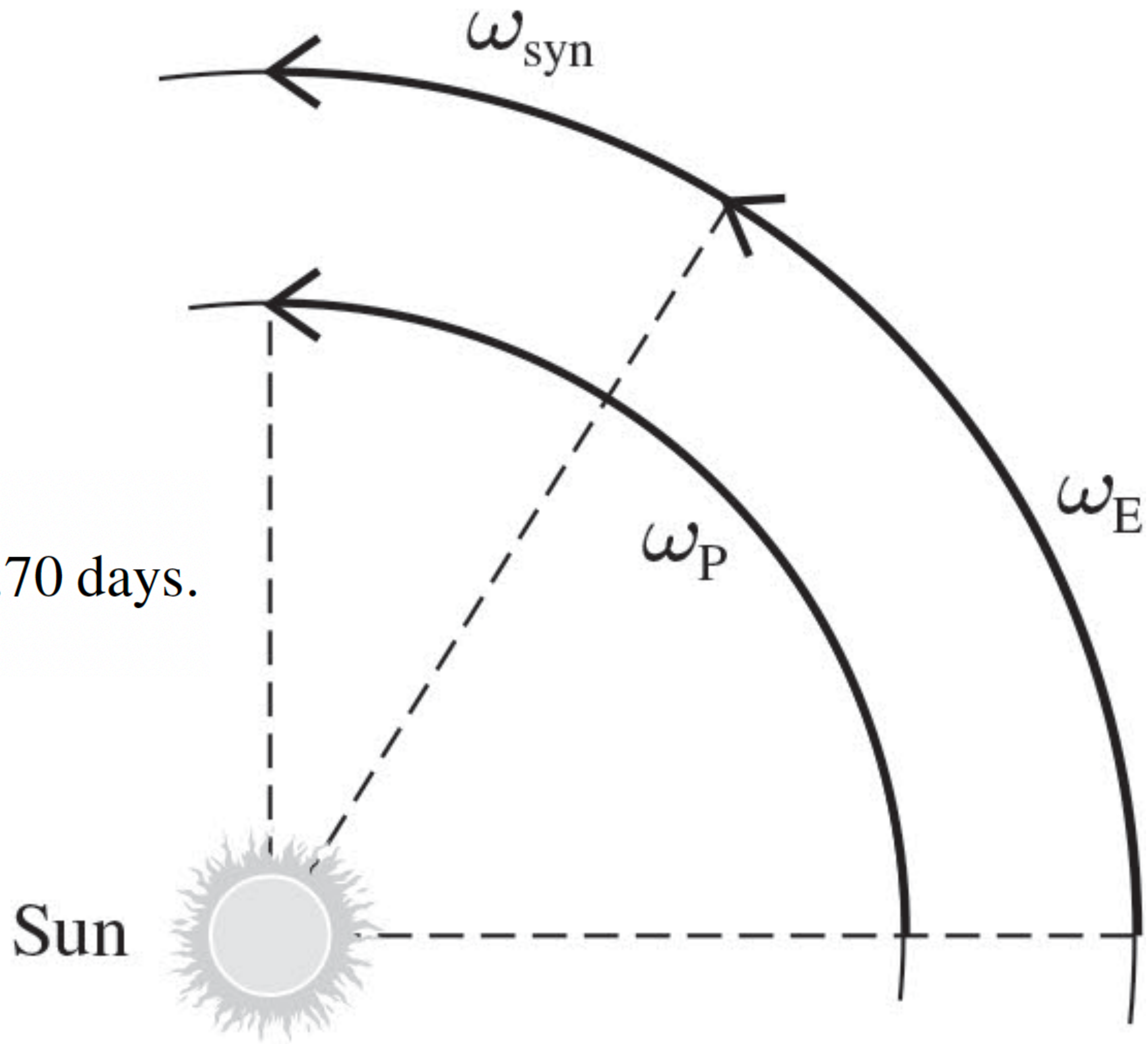
$\omega =$ angle per unit time

Angular velocity for an inferior planet

For the planet Venus,

$$P_{syn} = 583.92 \text{ days}$$
$$P_E = 365.256 \text{ days}$$

$$P_{\text{Venus}} = \left[\frac{1}{365.256 \text{ days}} + \frac{1}{583.92 \text{ days}}\right]^{-1} = 224.70 \text{ days}.$$



P_E = *sidereal* orbital period of the Earth.
P_{syn} = *synodic* orbital period of the inferior planet as seen from Earth.
P_P = *sidereal* orbital period of the inferior planet.

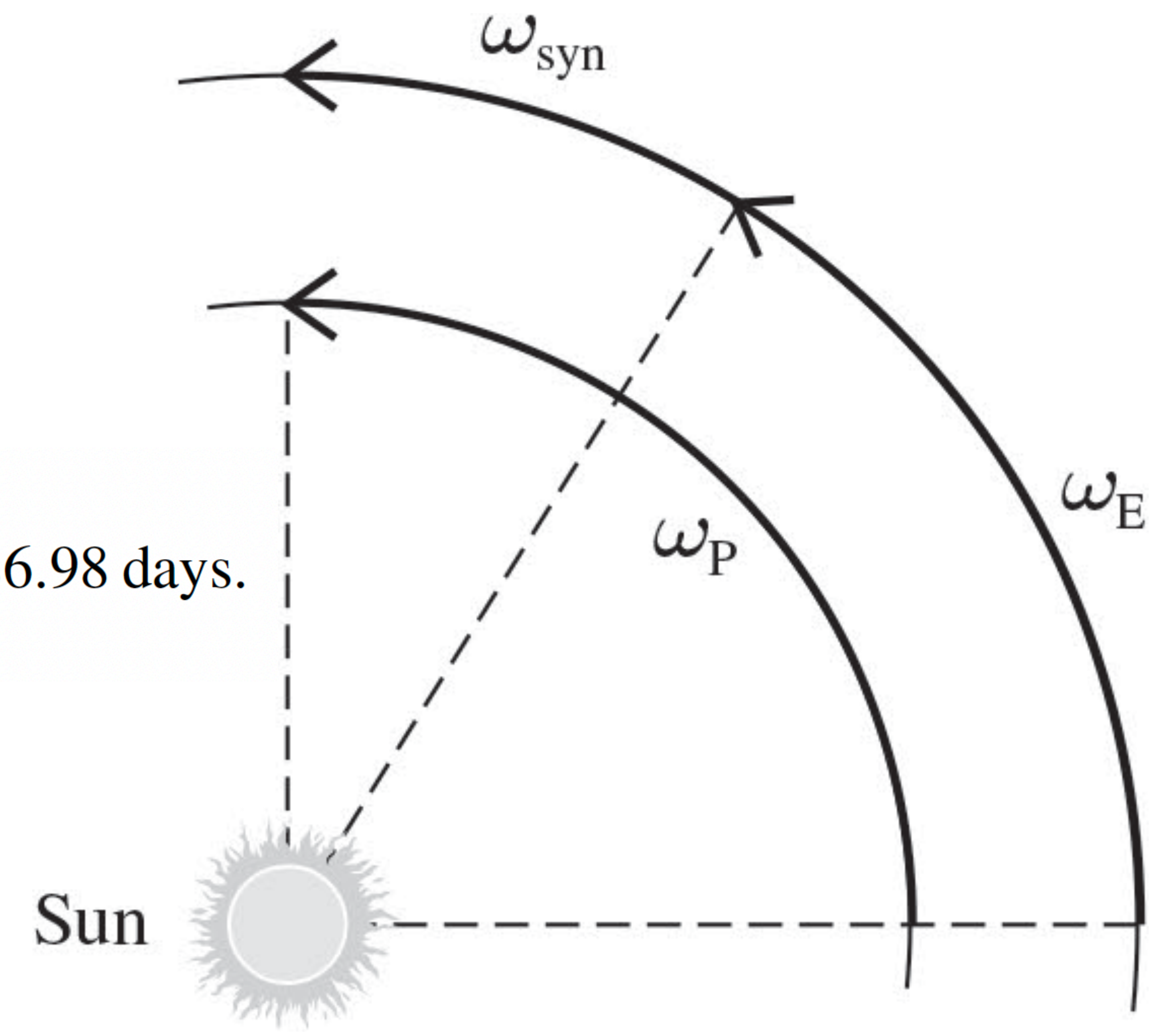
$\omega =$ angle per unit time

Angular velocity for a superior planet

For the planet **Mars**,

$$P_{syn} = 779.95 \text{ days}$$
$$P_E = 365.256 \text{ days}$$

$$P_{\text{Mars}} = \left[\frac{1}{365.256 \text{ days}} - \frac{1}{779.95 \text{ days}}\right]^{-1} = 686.98 \text{ days.}$$



P_E = *sidereal* orbital period of the Earth.
P_{syn} = *synodic* orbital period of the inferior planet as seen from Earth.
P_P = *sidereal* orbital period of the inferior planet.

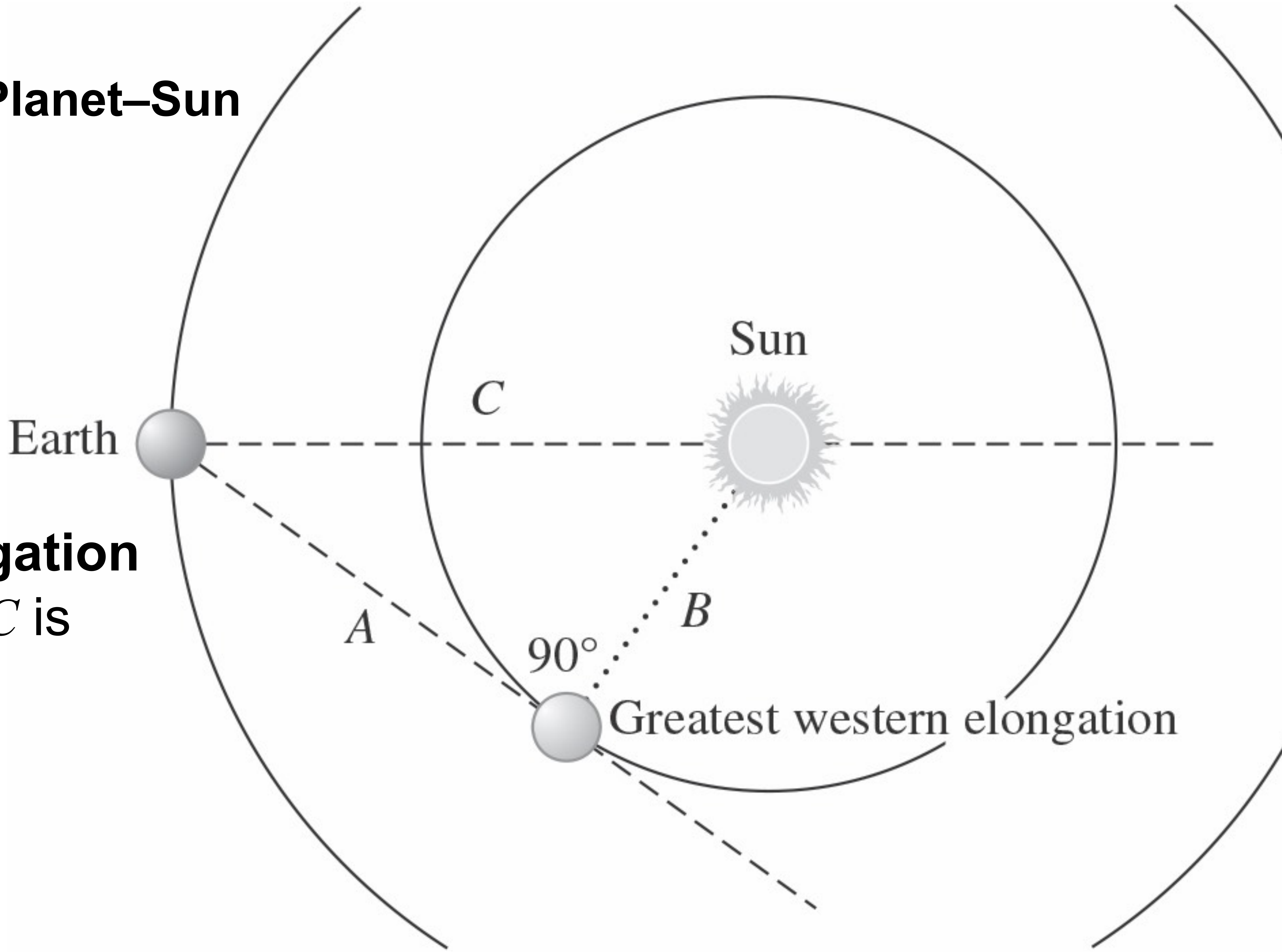
$\omega =$ angle per unit time

Determining the Greatest Elongation: Inferior Planets

Using the right triangle formed by **Earth–Planet–Sun**

$$\frac{B}{C} = \sin\theta$$

Here, θ is the **Greatest western elongation** of the planet as seen from Earth, and C is defined as the **astronomical unit.**



Note that this equation gives the planet's distance **in terms of the Earth–Sun distance!**

Determining the Greatest Elongation: Superior Planets

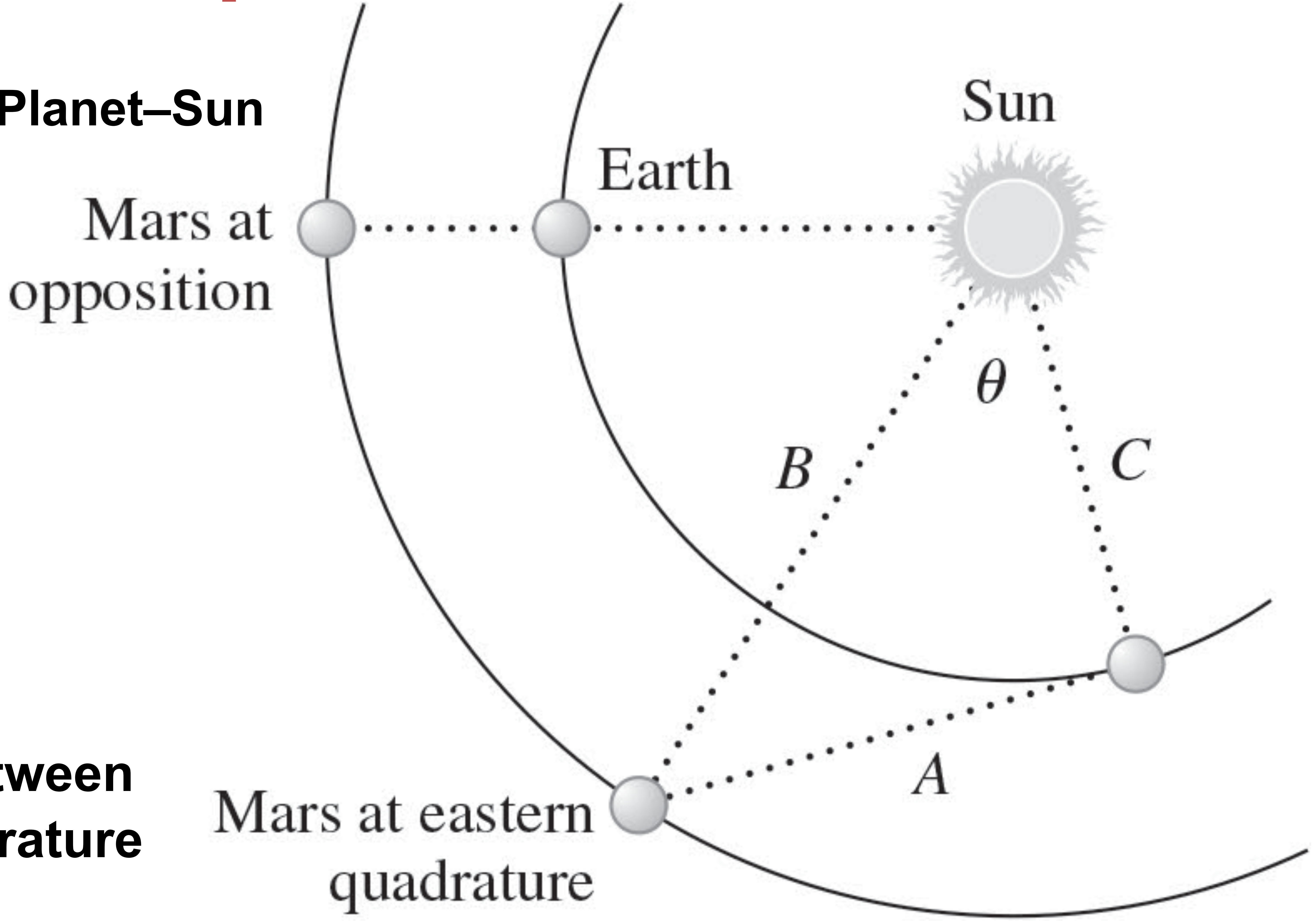
Using the right triangle formed by **Earth–Planet–Sun**

$$\frac{C}{B} = \cos\theta$$

Where,

$$\theta = (\omega_E - \omega_P)\tau$$

Here, τ is the time **interval between opposition and eastern quadrature**



Note that this equation gives the planet's distance **in terms of the Earth–Sun distance!**


Questions?

Galileo Galilei

Galileo used the newly invented telescope (1608) to make several revolutionary discoveries:

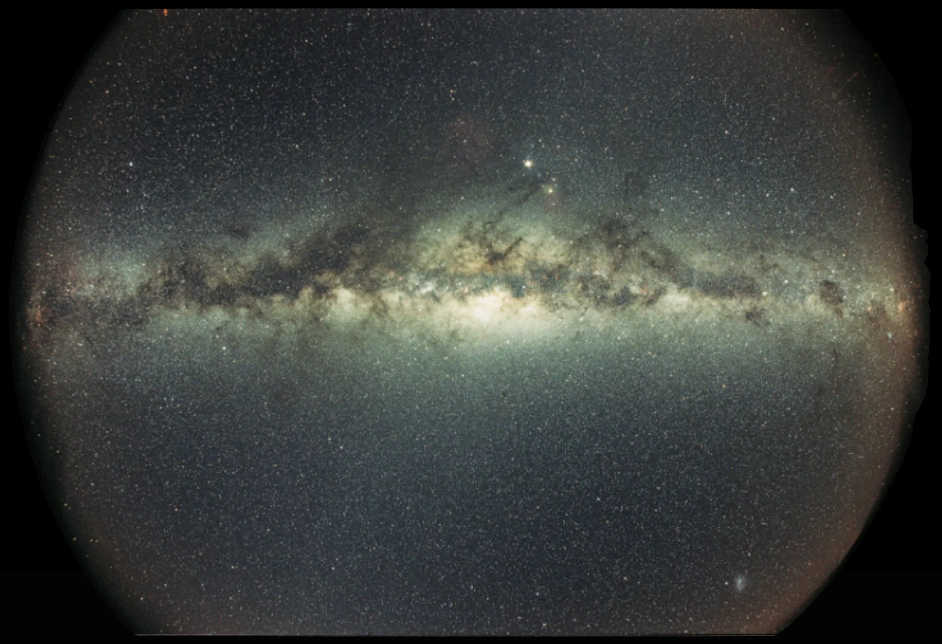
Galileo’s Discoveries

1. **Moon’s surface:** The Moon is not smooth — it has mountains and craters.

2. **Milky Way:** What appears as a fuzzy band is actually made up of countless individual stars.

3. **Stars vs. planets:** Stars remain unresolved points in telescopes, while planets appear as small disks.

4. **Jupiter’s moons:** Jupiter has four large moons (Io, Europa, Ganymede, Callisto) orbiting it.



Galileo Galilei (1564-1642)

Tycho Brahe

Tycho Brahe was a Danish aristocrat and astronomer.

- **Brass nose:** Lost part of his nose in a duel and wore a prosthetic.
- **Royal support:** Funded by the King of Denmark to build an observatory on the island of Hven.
- **Precise observations:** Spent 20 years measuring positions of stars and planets with extraordinary accuracy.
- **Geoheliocentric model:** Proposed the Earth at the center, with the Sun orbiting Earth and other planets orbiting the Sun—because stellar parallax had not been observed.
- **Kepler:** Hired Johannes Kepler as his assistant.
- **Death:** Allegedly died from not going to the bathroom.

Tycho Brahe (1546-1601)

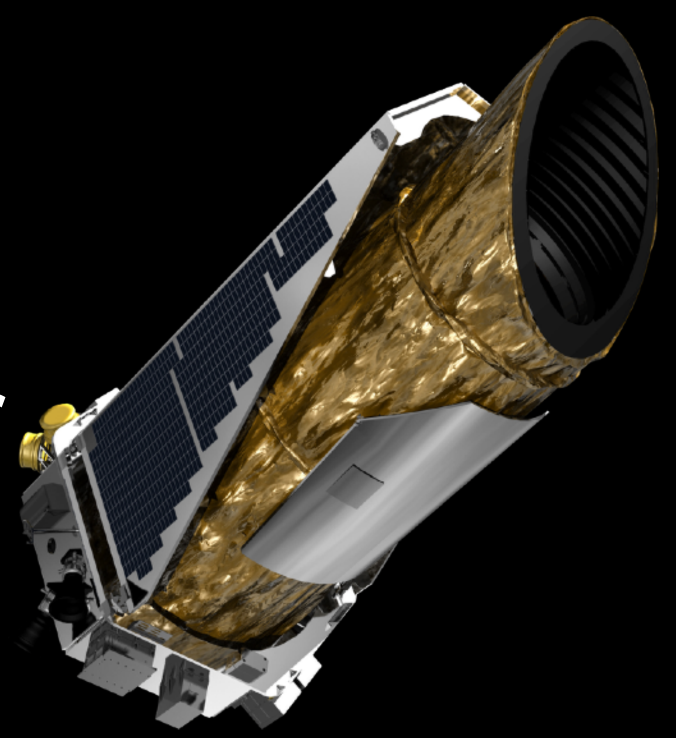
Johannes Kepler

Johannes Kepler was a German astronomer and mathematician

- **Had access to Tycho's data:** Tycho didn't like to share, but eventually gave Kepler his data (good thing because Tycho died 2 years after Kepler started!)

- **Planetary motion:** Kepler used Tycho's precise data to develop the three laws of planetary motion!

- **Legacy:** These laws explained planetary orbits before gravity was fully understood; Newton later refined them.



Johannes Kepler (1571-1630)

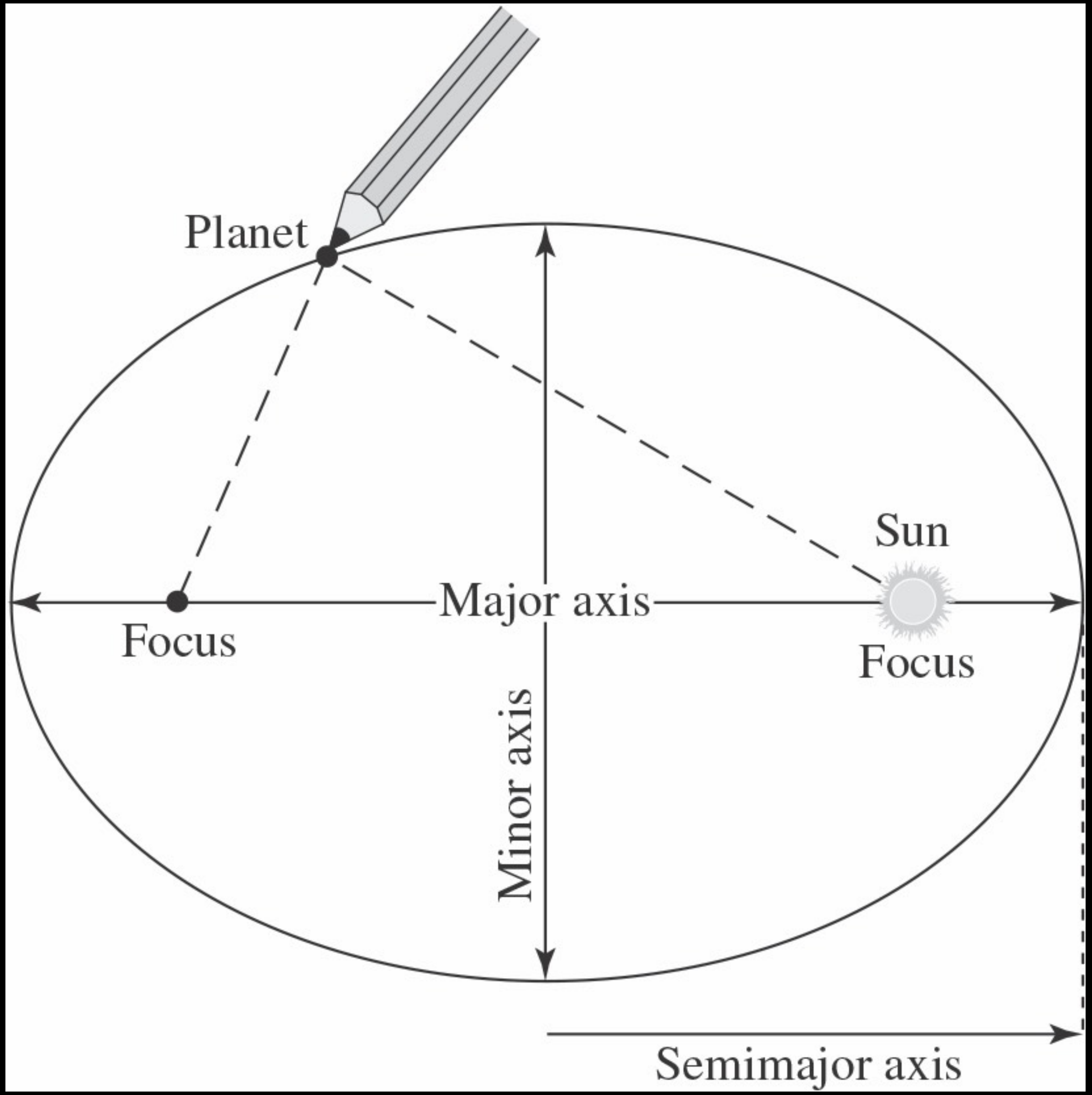
Kepler's 1st Law

Planets travel on elliptical orbits with the Sun at one focus

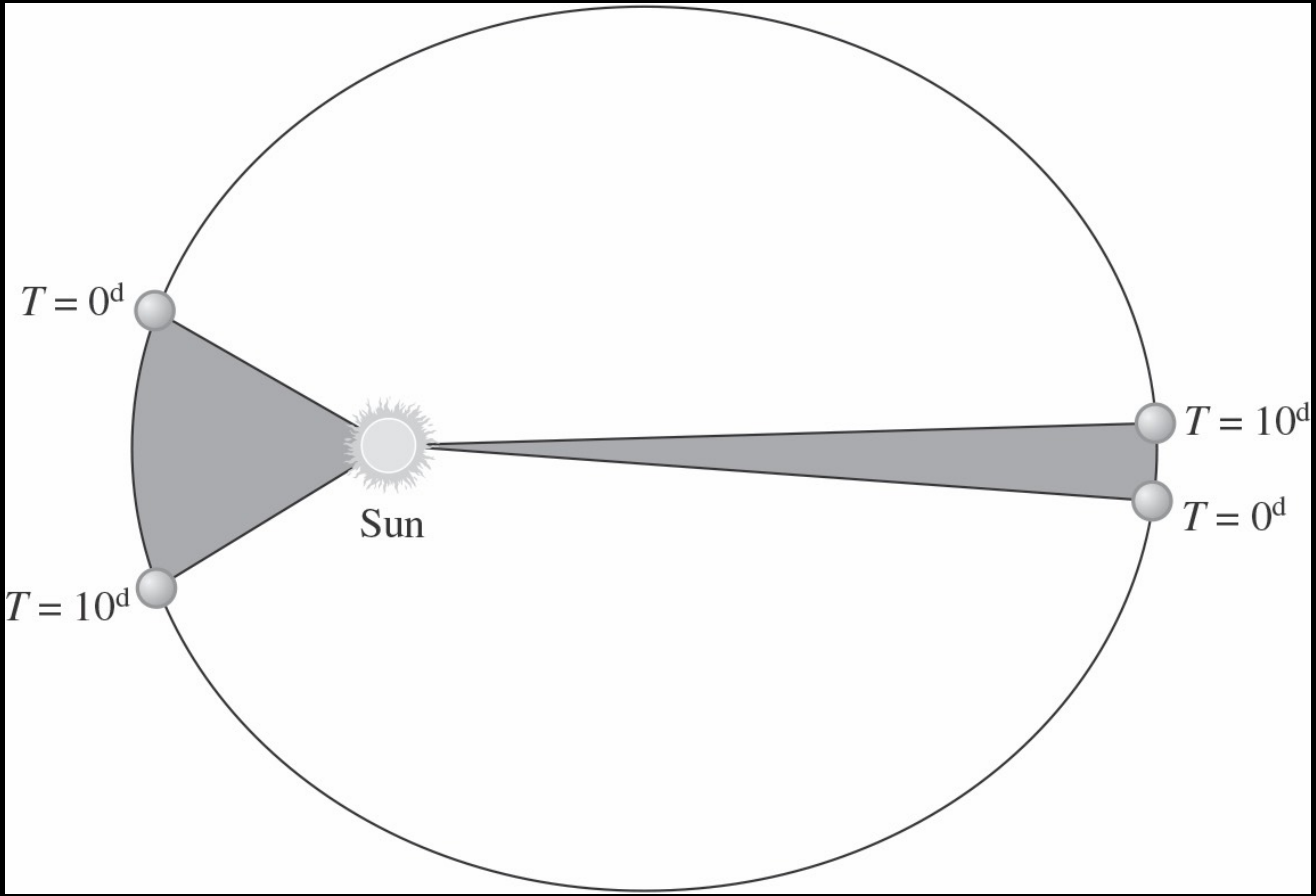
The "eccentricity" of the ellipse (orbit) is the distance between the foci divided by the length of the major axis

e = 0 is a circle

The eccentricity of the Earth's orbit is ~0.0167

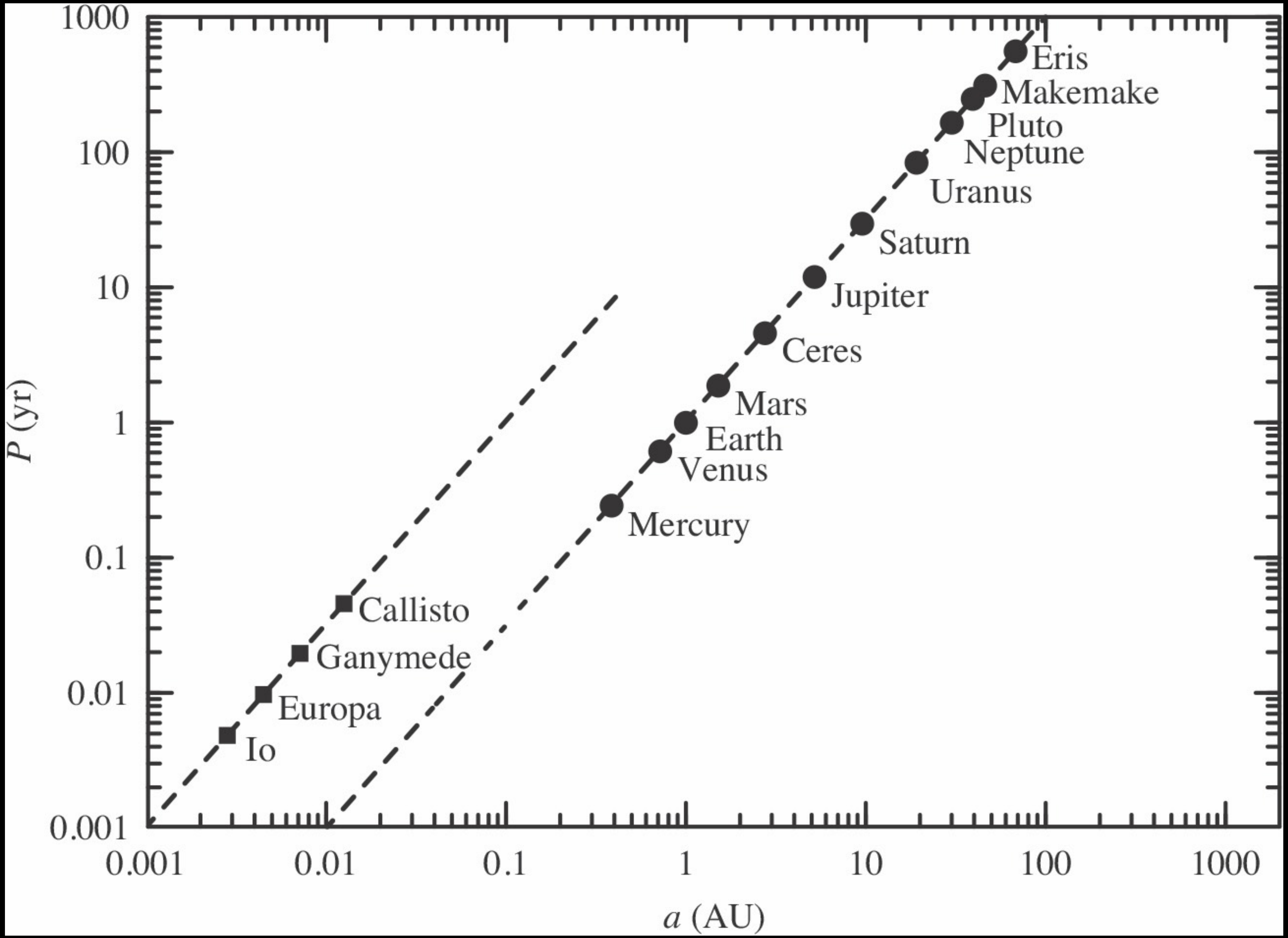


Kepler's 2nd Law



A line drawn from the Sun to a planet sweeps out *equal areas* in *equal intervals of time*

Kepler's 3rd Law



$$P^2 = Ka^3$$

where

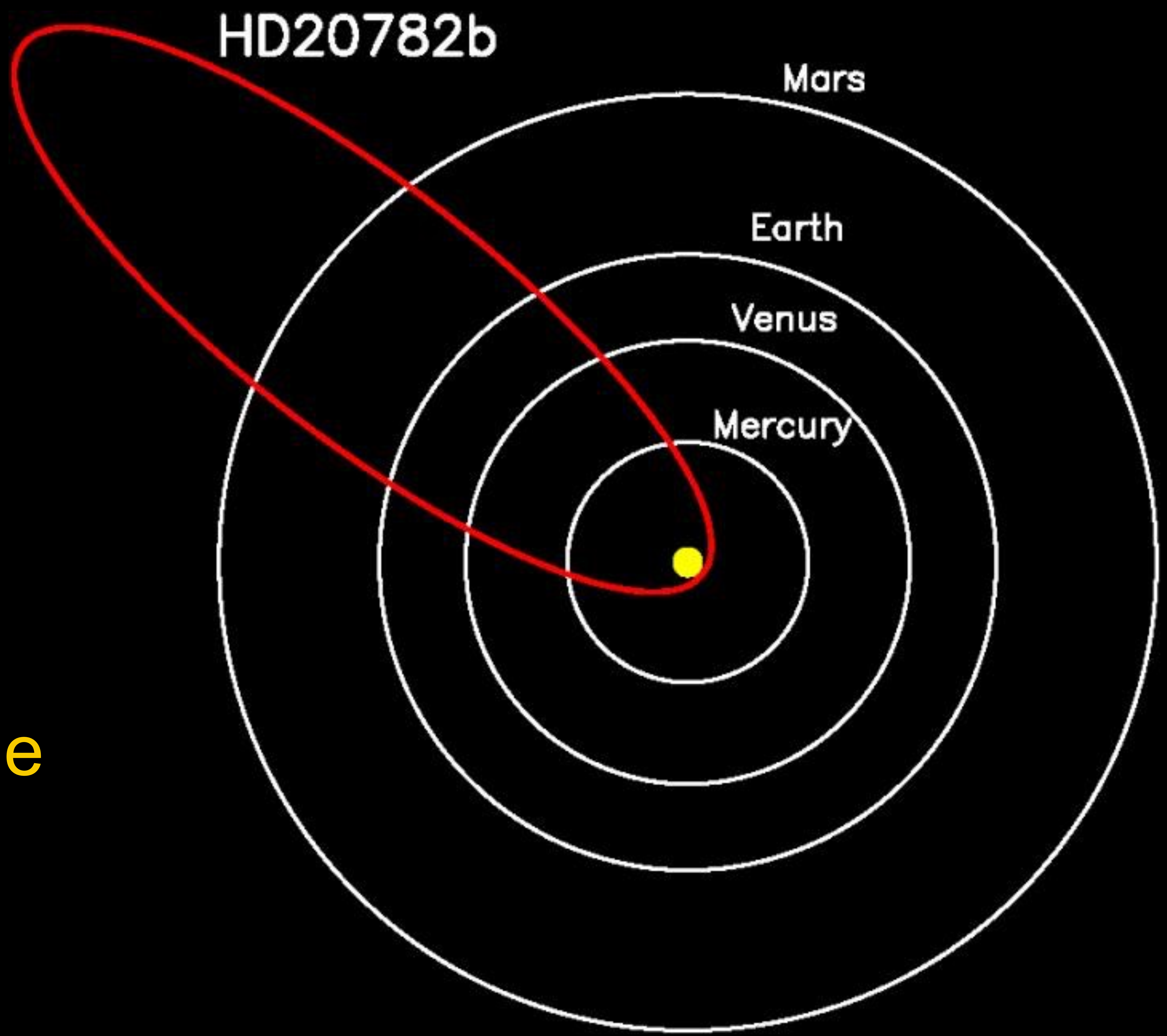
$$K = 1\ yr^2\ AU^{-3}$$

The squares of the sidereal orbital periods of the planets are proportional to the cubes of the semimajor axis of their orbits

Brain Break – Think-pair-share

Imagine if the Earth's orbit had a much higher eccentricity (more elliptical) than it does now.

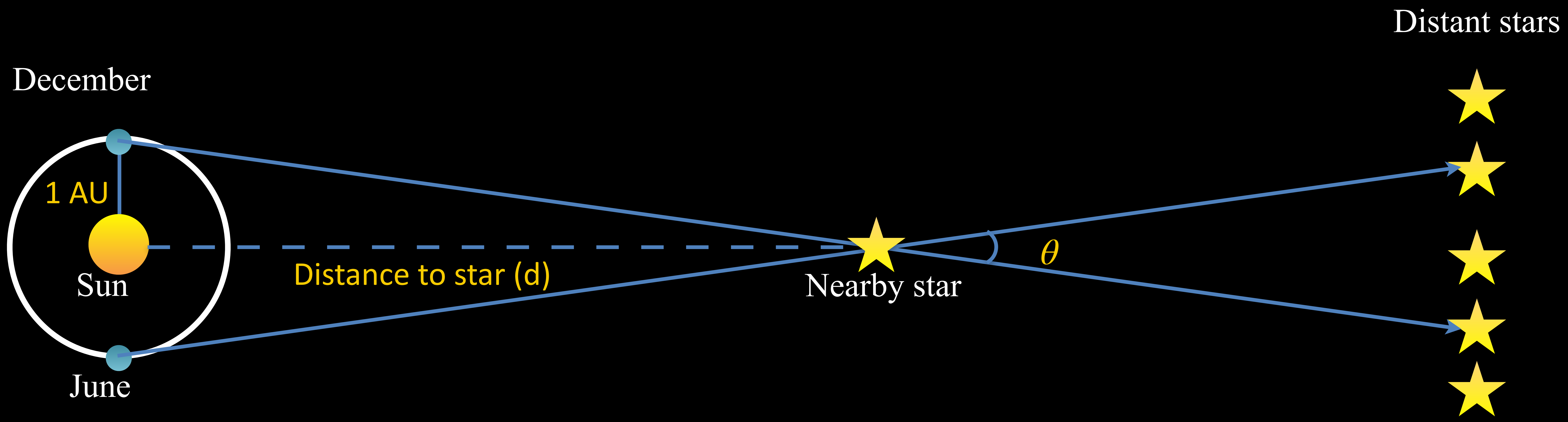
How would this affect the seasons, climate, and overall habitability of the planet?




Questions?

Defining Stellar Parallax

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



We can write,

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

Applying small angle approximation…

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

$$p = \frac{1\ \text{AU}}{d}$$


Questions?

Reminders

- The first coding exercise is due Sunday at 11:59pm.
- The first homework assignment is due Sunday at 11:59pm
- Log into canvas and submit your answer to the discussion question by the end of the day to receive participation credit.