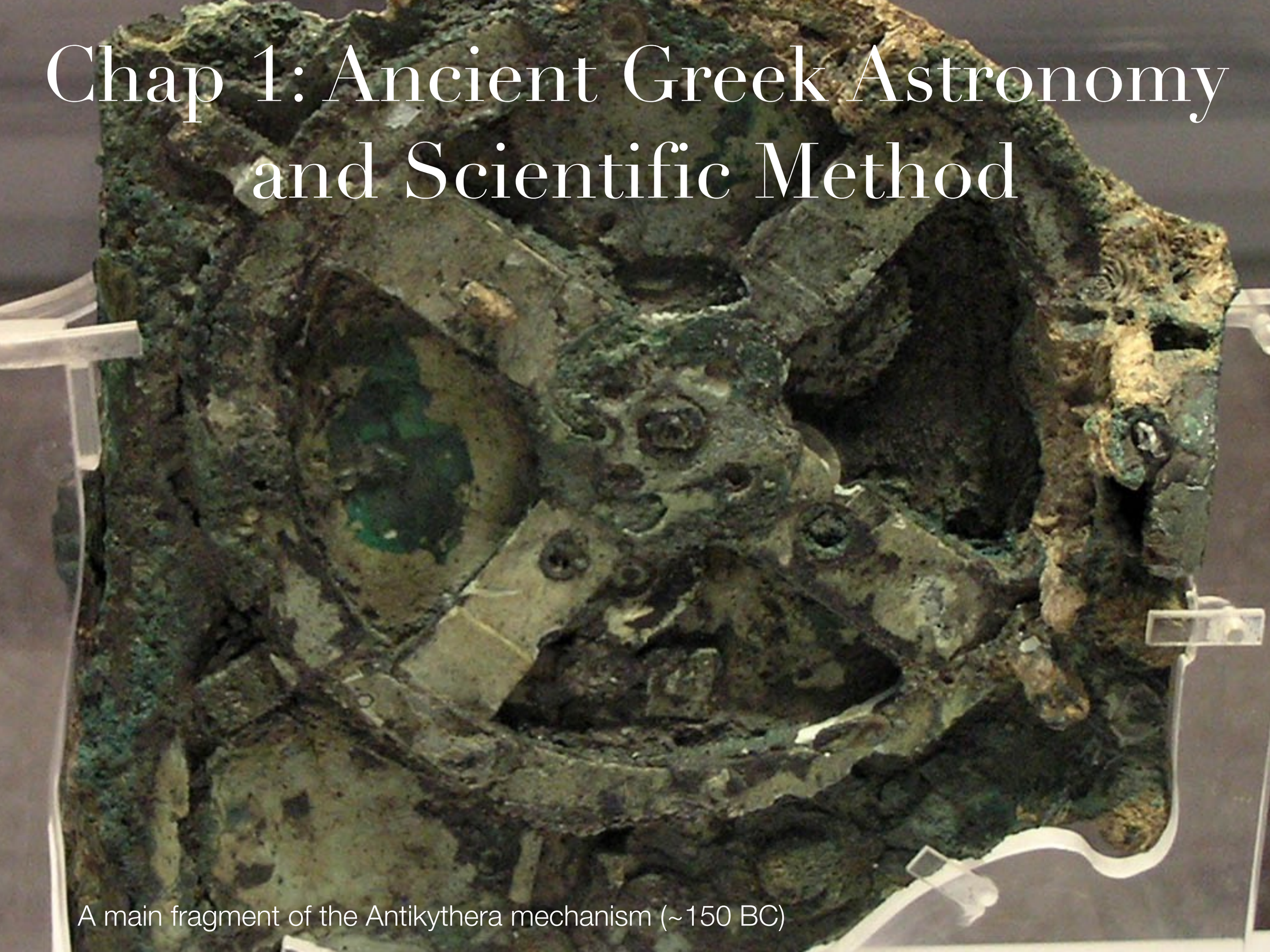
Chap 1: Ancient Greek Astronomy and Scientific Method



A main fragment of the Antikythera mechanism (~150 BC)

The scope of the known Universe

10^{17} Solar Masses, 10^{5} Member Galaxies, 520 million light years across

Laniakea Supercluster

Cygnus Void

PAVO-INDUS SUPERCLUSTER

NGC 6769 Group 185MLY

Teloscopium Group 125MLY

Delphinus Void

CENTAURUS SUPERCLUSTER

NGC 5419/5488 Group 190MLY

NGC 6753 Group 150MLY

Pegasus Cluster 180MLY

Pavo Cluster 180MLY

Local Void

VIRGO SUPERCLUSTER

Virgo III Groups 65-85MLY

A3565 Group 165MLY

Centaurus A/M83 Group 11.9MLY

Sculptor Group 12.7MLY

M94 Group 15MLY

NGC 7172 Group 125MLY

NGC 7329 Group 150MLY

LOCAL GROUP

Canes II Group 22.1MLY

M101 Group 21MLY

Virgo Cluster 59MLY

Centaurus Cluster 170MLY

M81 Group 12MLY

IC 341/Maffei Group 10.7MLY

Coma I Group 47.3MLY

Leo I Group 37MLY

Ursa Major Cluster 60MLY

NCG 2997 Group 24.8MLY

SOUTHERN SUPERCLUSTER

NGC 1023 Group 20.6MLY

Eridanus Void

Leo II Groups 65-90MLY

Corvus Void

Dorado Group 60MLY

Fornax Cluster 62MLY

Leo Void

Hydra Cluster 190.1MLY

Eridanus Cluster 75MLY

Puppis Cluster 95MLY

Antlia Cluster 132.7MLY

HYDRA SUPERCLUSTER

Taurus Void

Gemini Void

NGC 1417 Group 189MLY

Cancer Cluster 200MLY

Chapter 1 Lecture Outline

- Ancient Greek Astronomy & the Scientific Method

  - How did they use Math and the scientific method to understand the natural world?

  - How did they measure the size of the Earth, the distance to the Moon, and the distance to the Sun over 2000 years ago?

  - How did they use scientific method to **reject** the idea that the Earth spins and the Earth orbit around the Sun?

What did Athens look like in 350 BC?

Parthenon on the Acropolis of Athens
built 100 years ago between 447-432 BC,
in the middle of the Golden Age of Greece

Parthenon

An 19th-century reconstruction of the Acropolis, including the Parthenon. Leo von Klenze.

Acropolis of Athens Today, 2400 years later

Parthenon Today, 2400 years later

Expansion of Alexander the Great from Macedonia (334-323 BC)

Empire of Alexander the Great (323 BC)

Average People's Life in Ancient Greece

Terrace farming

The Marketplace

Ancient Greek Astronomy
350 BC to 130 BC
Classical Period to Hellenistic Period

- The spherical shape of Earth & Moon:
  Aristotle, ~350 BC

- Radius of the Earth:
  Eratosthenes, ~240 BC

- *Relative* distances of the Sun and the Moon:
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- Distance to the Moon:
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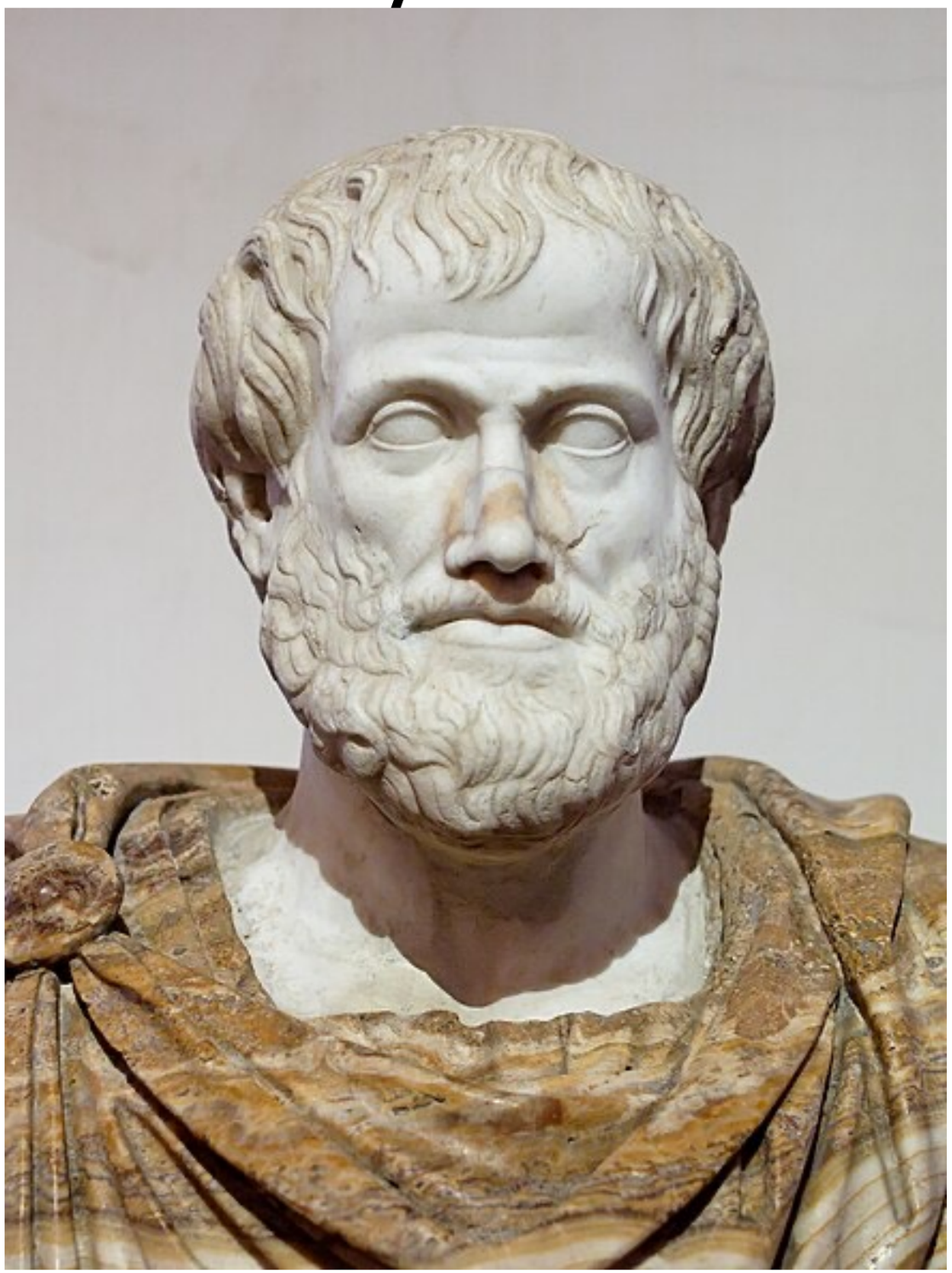
Aristarchus of Samos
310-230 BC

Aristotle (384-322 BC)

"The Earth must be a sphere!"



Aristotle's inference of the spherical shape of the Earth :
the Sun and the Moon have circular shapes, all the time

Aristotle's confirmation of the sphere hypothesis

Total Lunar Eclipse

always full moon, always midnight

Patrick Prokop
Savannah, GA

Eratosthenes of Cyrene (276-195 BC)

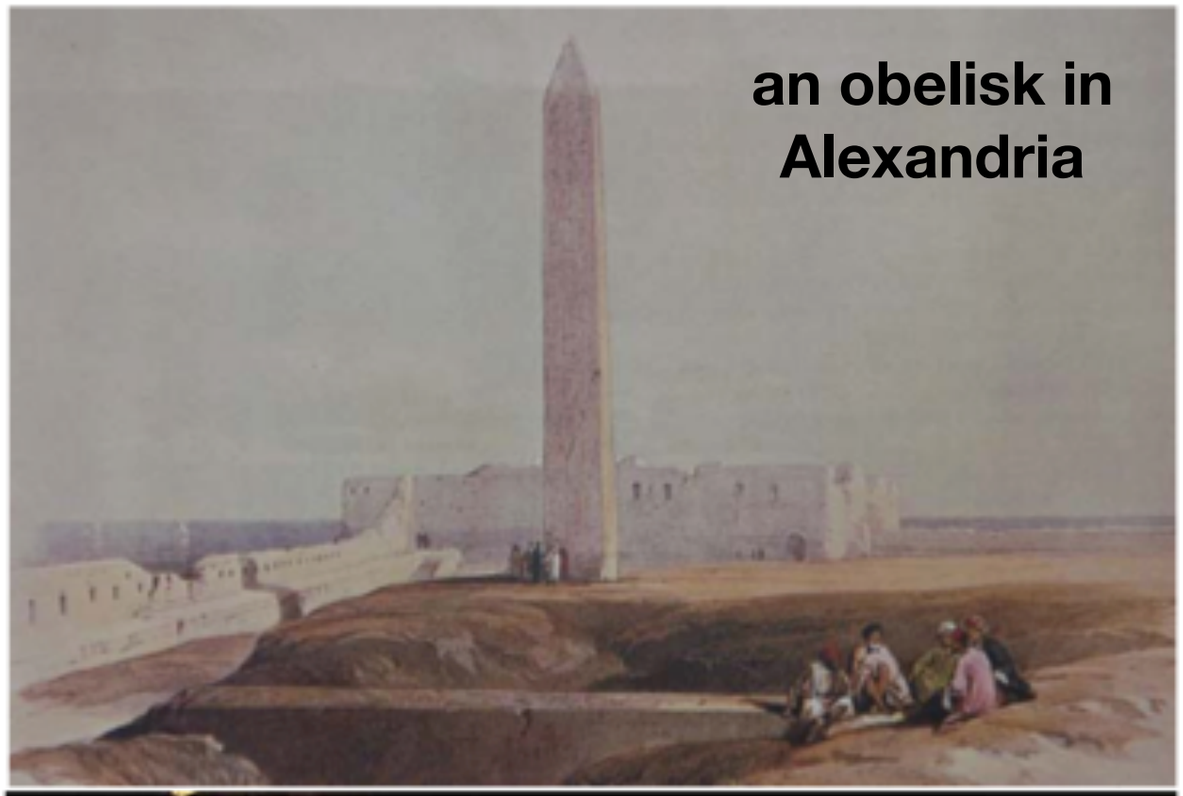
Eratosthenes (~240 BC)

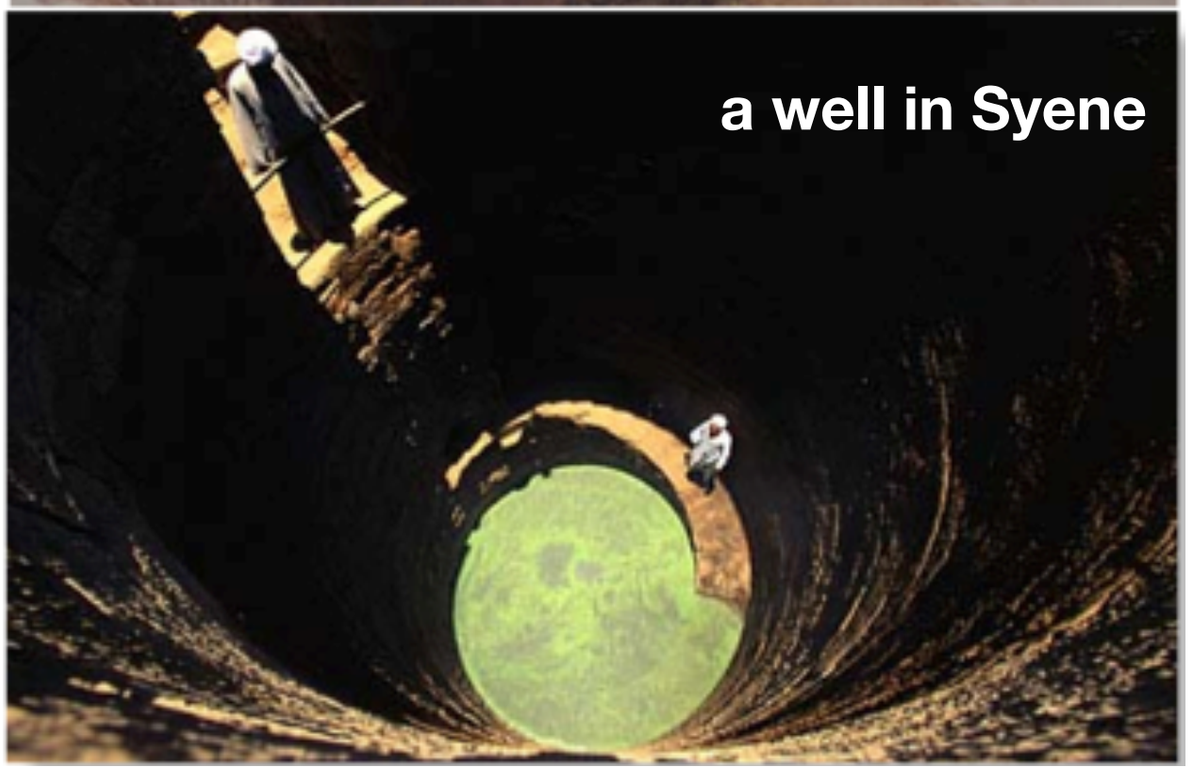
- Measured the circumference of the Earth within 10% of the modern value

- Simultaneous measurements of the Zenith angle of the Sun at two locations in Egypt on Summer solstice

- Syene - directly at zenith, the Sun casts no shadow.

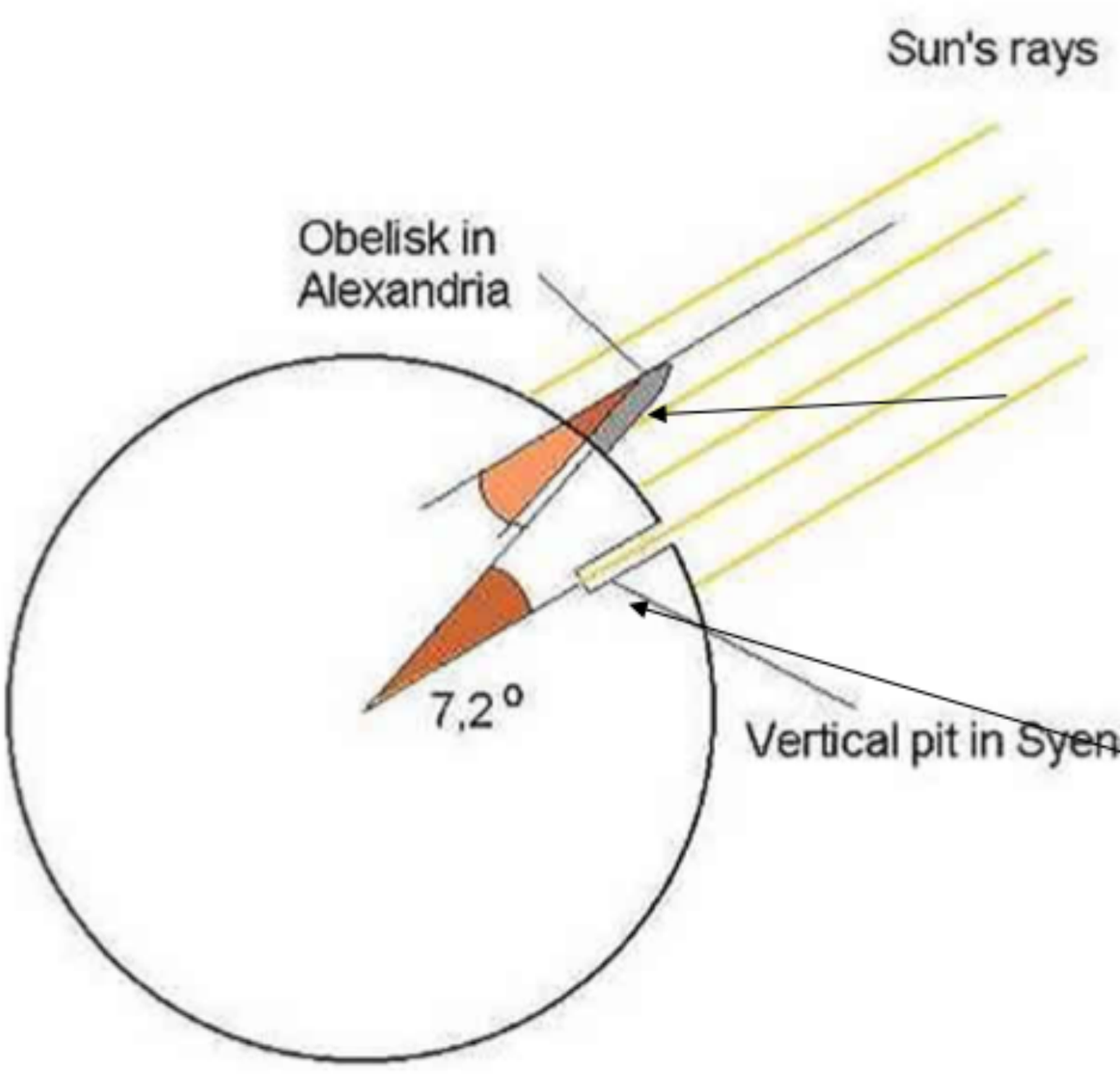
- Alexandria - the sun is 7 degrees from zenith, by measuring the shadow and height of an obelisk.





Syene is almost directly south of Alexandria, so their local noons occur simultaneously

Eratosthenes's Method for Finding the Circumference of the Earth



Note that the two cities in Egypt are on the same meridian (i.e, same longitude), so their local noon occurs simultaneously

1/50 of a circle ↔ 5 000 stadia (~800 km)

∴ 1 circle ↔ 50 × 5 000 stadia
= 250 000 stadia (~40 000 km)

Angle from lengths of the pole and its shadow: 1/50 of a circle (~7°)

Parallel sun rays

Pole's shadow

Pole at Alexandria

Well at Syene (Aswan)

Alternate interior angles are equal

Center of the Earth

Eratosthenes' Method of Measuring Earth radius (240 BC)

What are known?

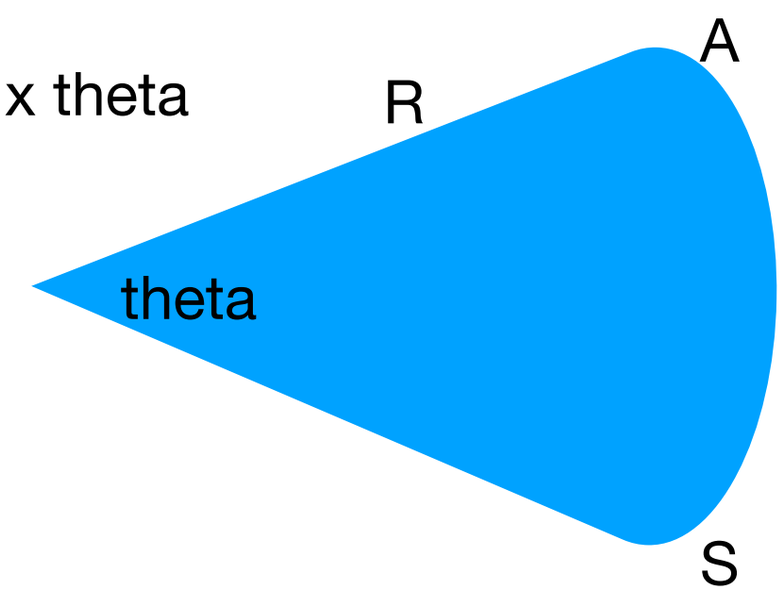
1. distance between Alexandria & Syene (AS) is 5000 stadia (1 stadion = circumference of a stadium = 160 meters)
2. the angle between the two cities seen from the center of the Earth is 7 deg (theta)

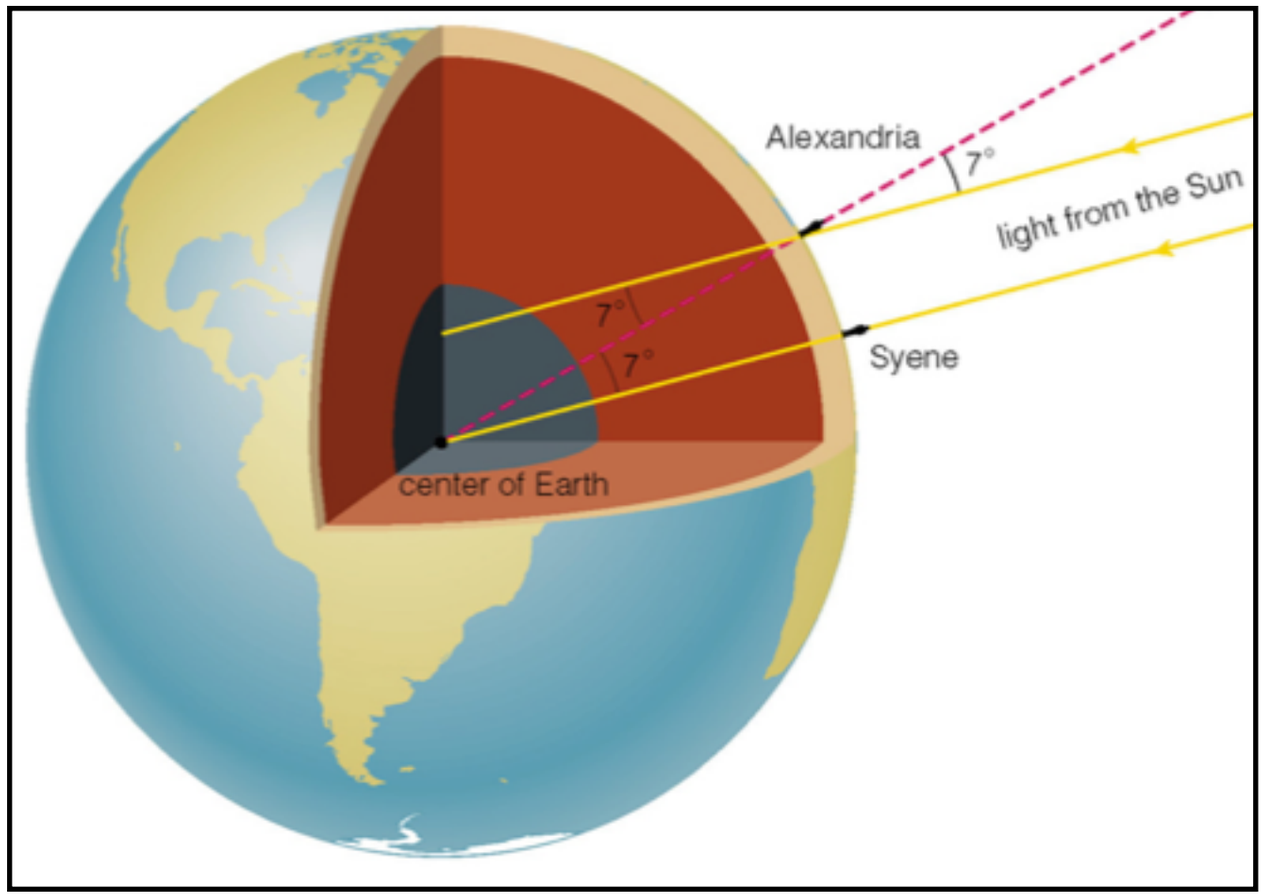
What need to be solved?

The radius of the Earth (R)

What formula to use?

AS = R x theta





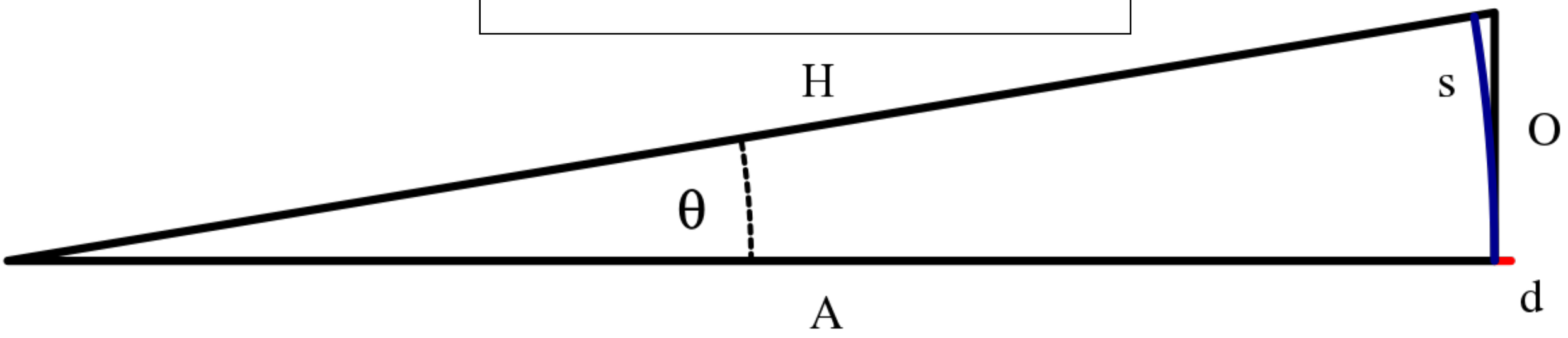
Radian: The Natural Unit of Angles

360 deg = 2π radian
so 1 deg = 1/57.3 radian

arc length on a circle = radius of the circle $\times \theta$

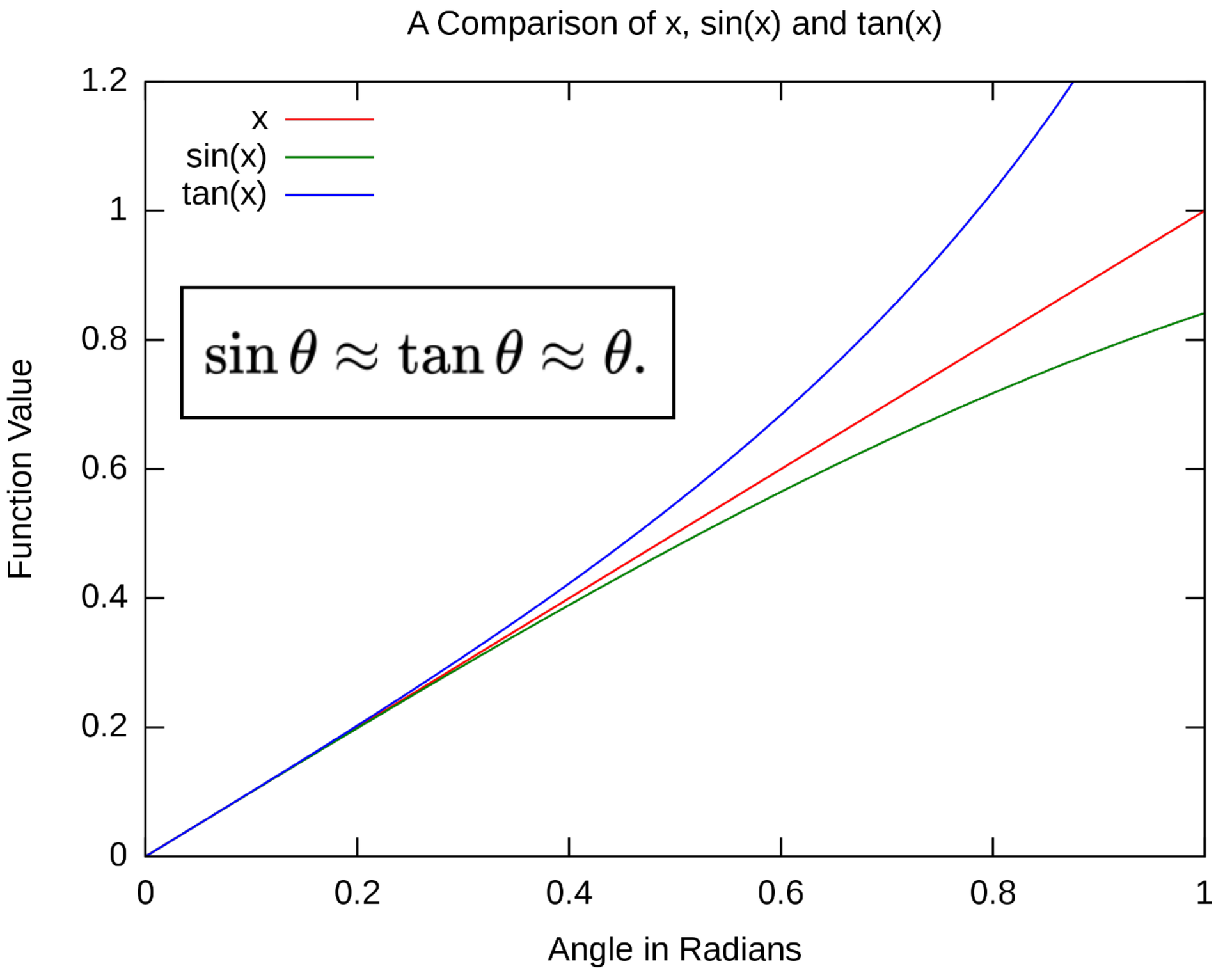
Small angle approximation, θ must be in unit of **radian and $\theta \ll 1$:**

$$\sin\theta \approx \tan\theta \approx \theta.$$



Geometric illustration: *O* ~ *s* when $\theta \ll 1$

Small Angle Approximation: Graphical Illustration



Recap:
Astronomy as a **Science** in Ancient Greece

Aristotle's inference of the spherical shape of the Earth

Total Lunar Eclipse

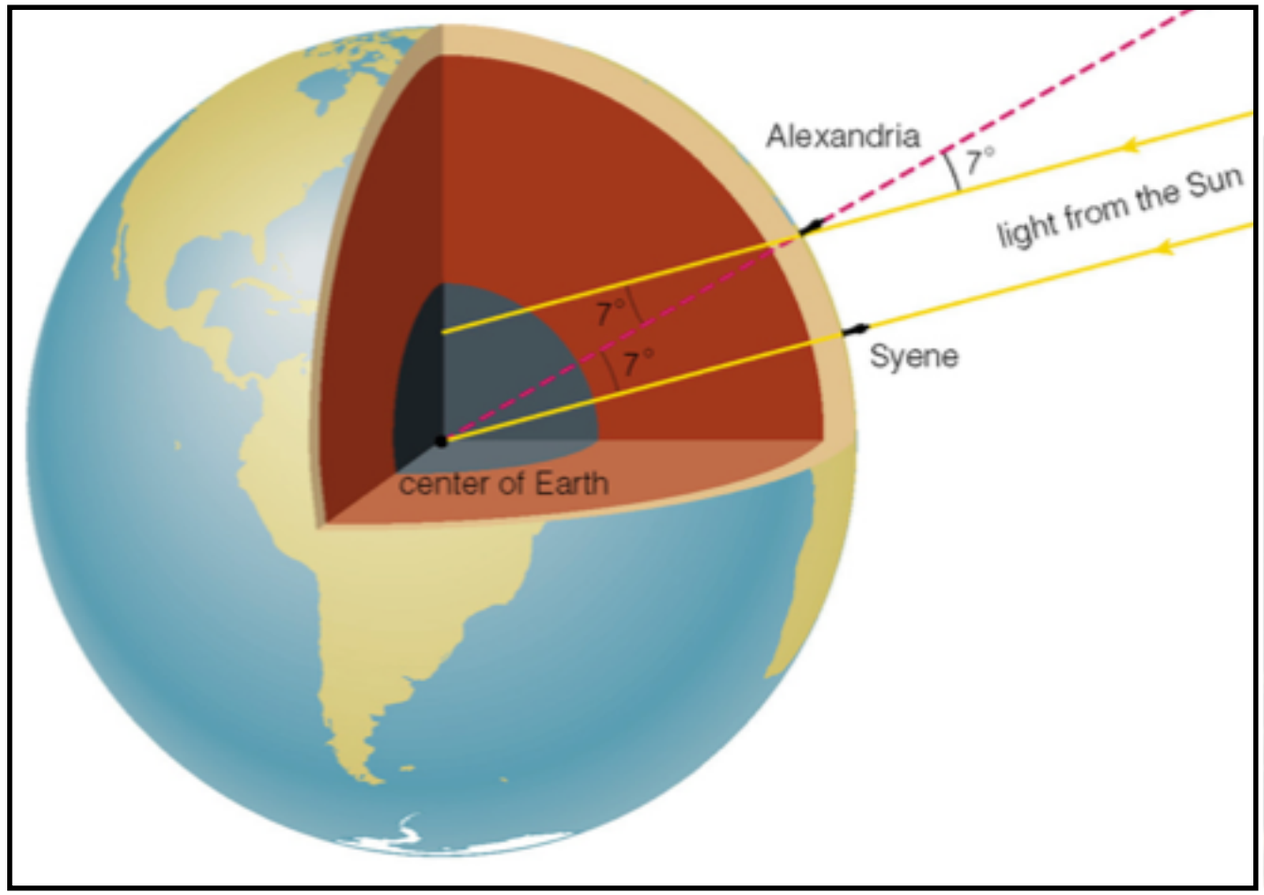
always full moon, always midnight

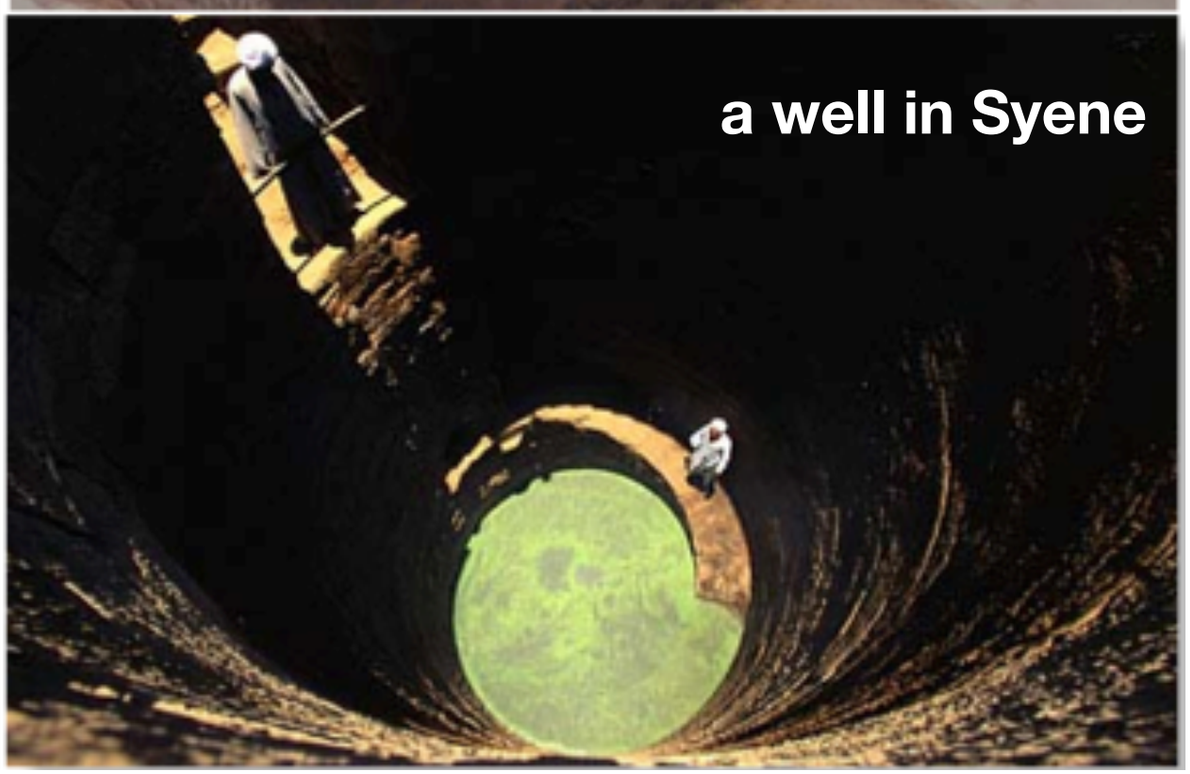
Patrick Prokop
Savannah, GA

Eratosthenes (~240 BC)

- Noon at Syene - the Sun was directly at zenith, the Sun casts no shadow.

- Noon at Alexandria - the Sun is 7 degrees from zenith, by measuring the length of the shadow and the height of an obelisk.





Ancient Greek Astronomy
~350 BC to ~130 BC
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  Hipparchus, ~130 BC

Distance to the Moon

Hipparchus of Nicaea (190-120 BC); Claudius Ptolemy (100-170 AD)

Geological survey method has been used to determine distances before Hipparchus' time

Castillo de San Marcos in St Augustine, Florida. Completed in 1695

Geological Survey Method: Distance Measurements

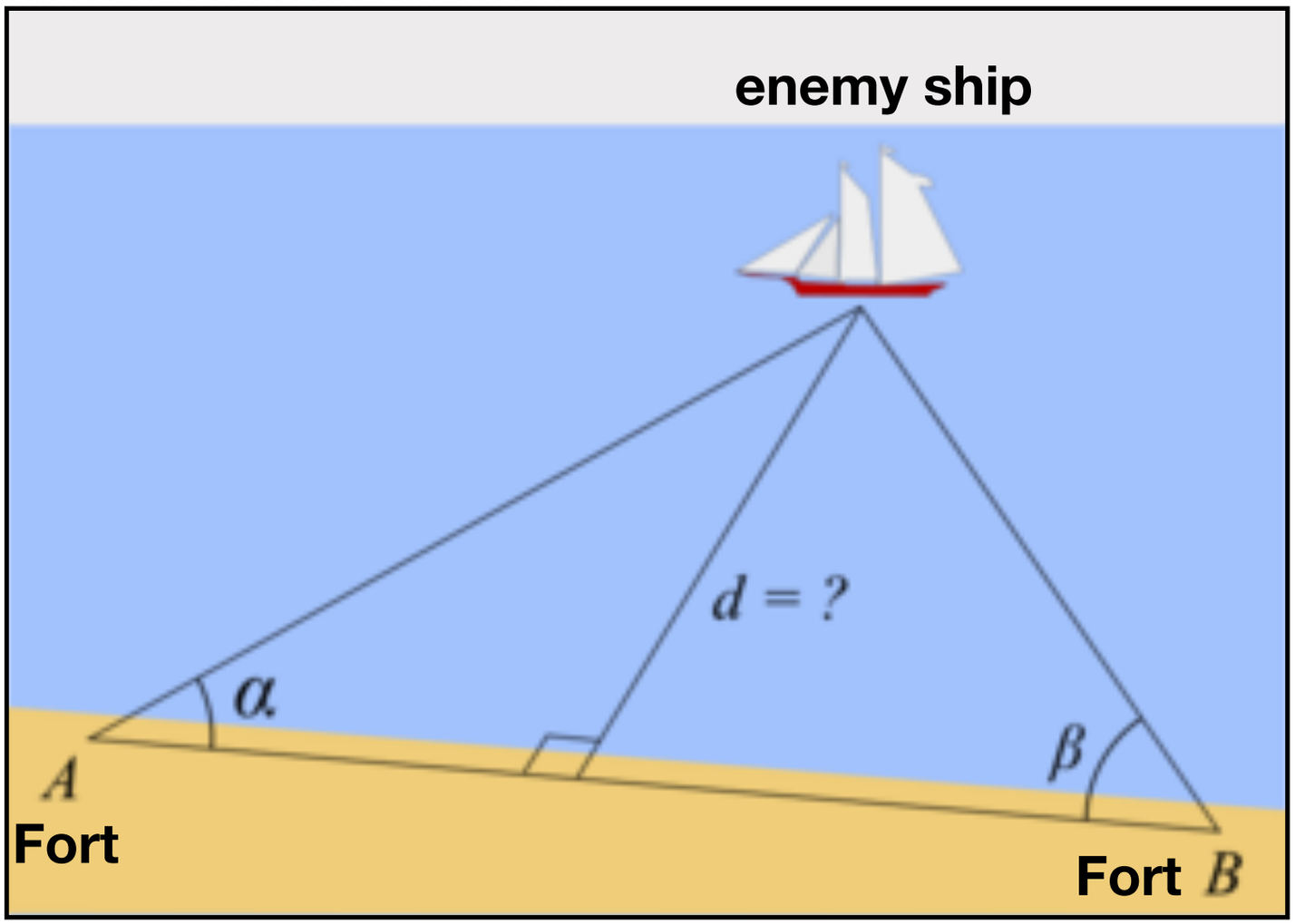
need to know the baseline length ($l = AB$) and the two angles (α, β)

$$\ell = d\left(\frac{\cos\alpha}{\sin\alpha} + \frac{\cos\beta}{\sin\beta}\right)$$

$$\ell = d\,\frac{\sin(\alpha+\beta)}{\sin\alpha\sin\beta}$$

therefore:

$$d = \ell\,\frac{\sin\alpha\sin\beta}{\sin(\alpha+\beta)}$$



The solar eclipse of March 14, 190 BC

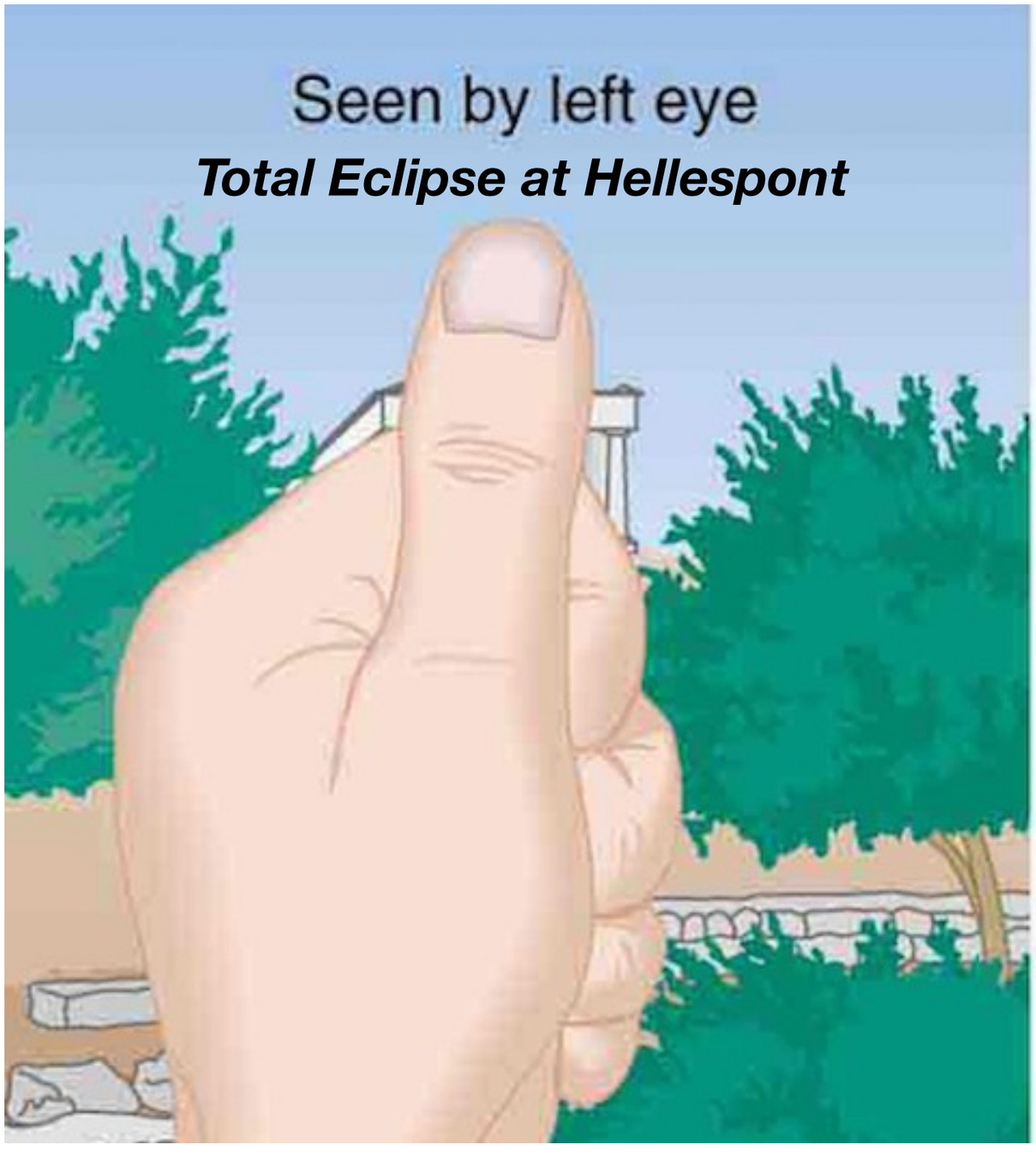
- The eclipse happened the year when Hipparchus was born, so he used historical record instead of his own observations

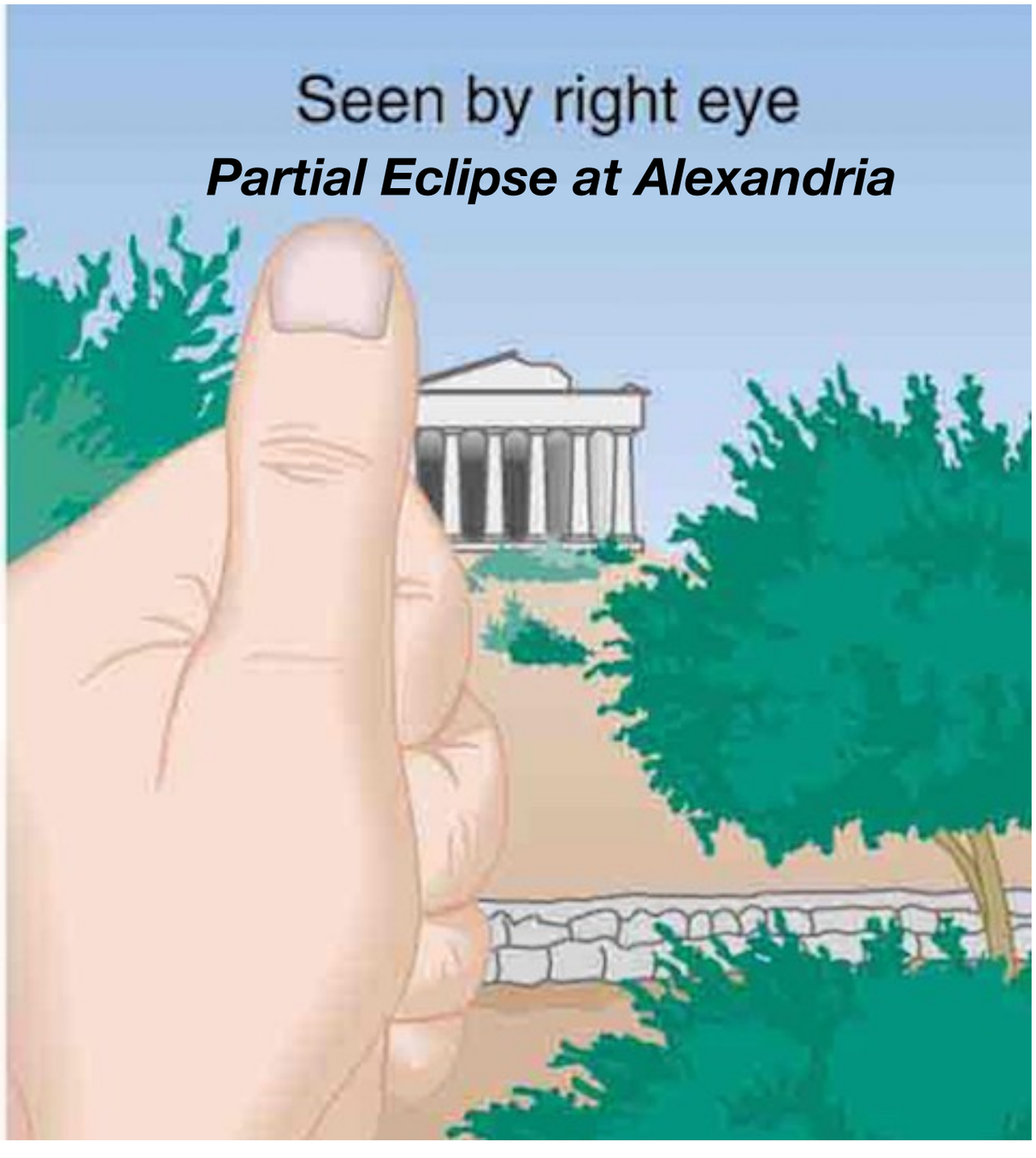
- It was recorded that the sun is fully covered by the moon (total eclipse) in **Hellespont** (40 N in today's Turkey), when the Romans were preparing for war in the area

- The same eclipse was also recorded in **Alexandria** (31 N, in Egypt), where the Sun was obscured 4/5 by the moon at the maximum

- The two cities have roughly the same longitude (i.e., along the same meridian)

Hipparchus' method is called **Parallax**, it uses the same concept as our stereoscopic vision





The solar eclipse of March 14, 190 BC

seen in Hellespont (100% obscured)

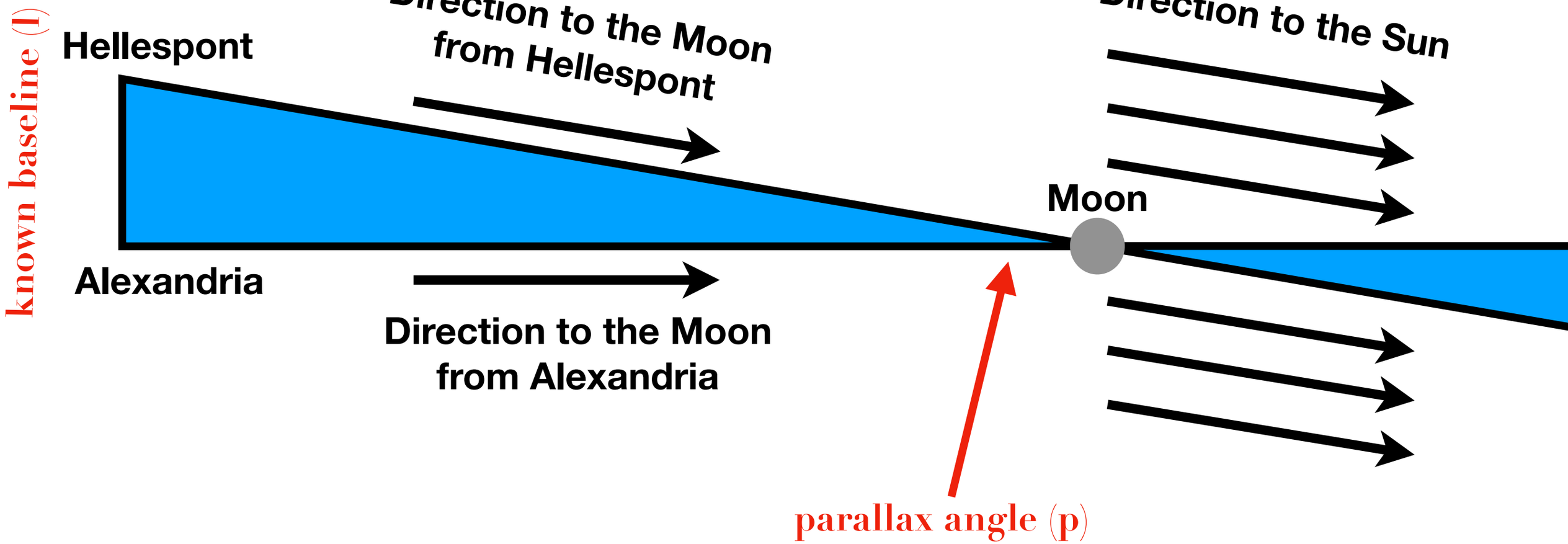
seen in Alexandria (80% obscured)

Both the Sun and the Moon has an angular size of ~0.5 deg in diameter, how much has the moon's direction shifted relative to the direction to the Sun?

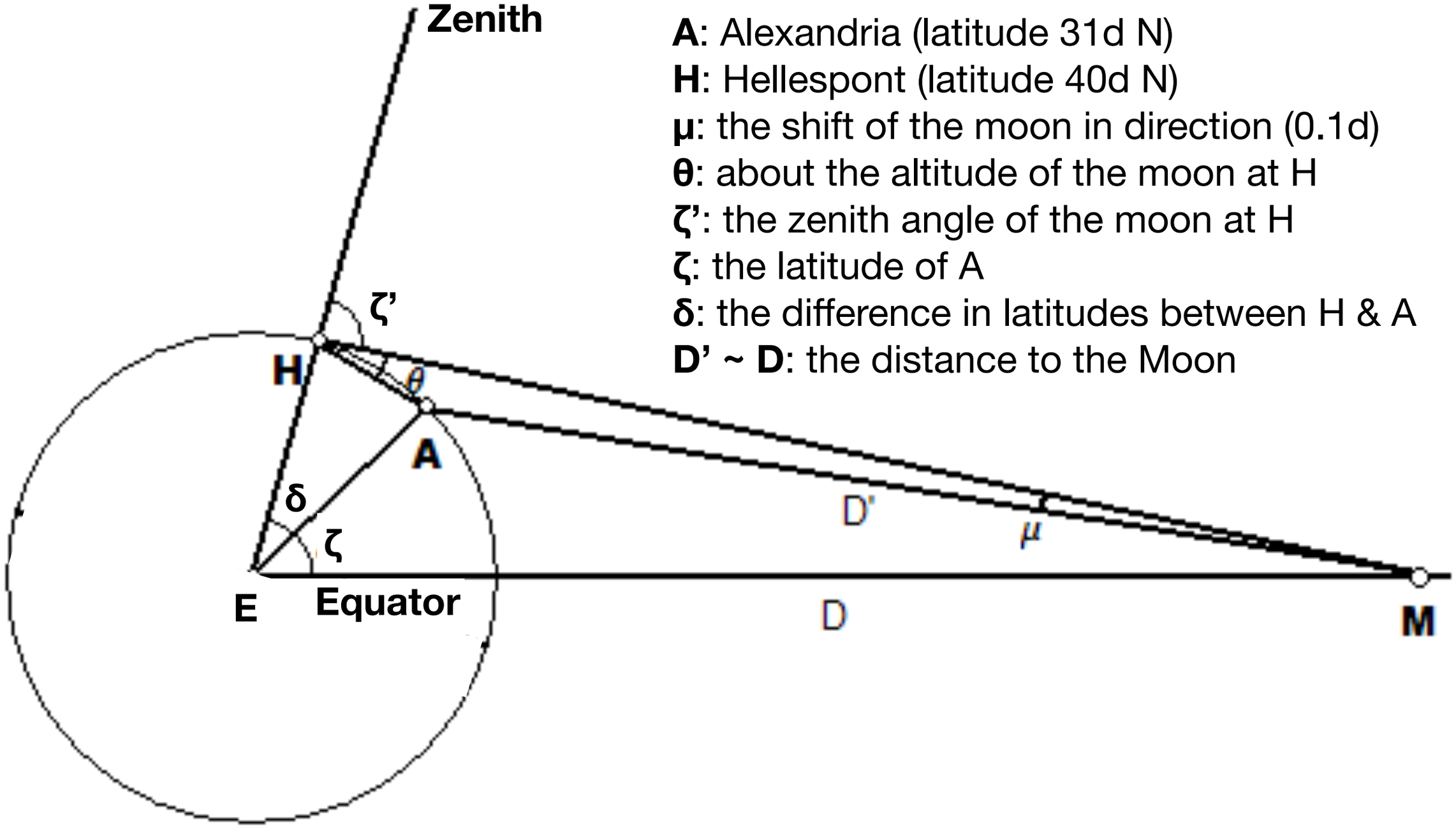
The Simple Geometry of Parallax

$$D_{\text{moon}} = \text{baseline length/parallax angle in radian} = l/p$$

we have used the small angle approximation above

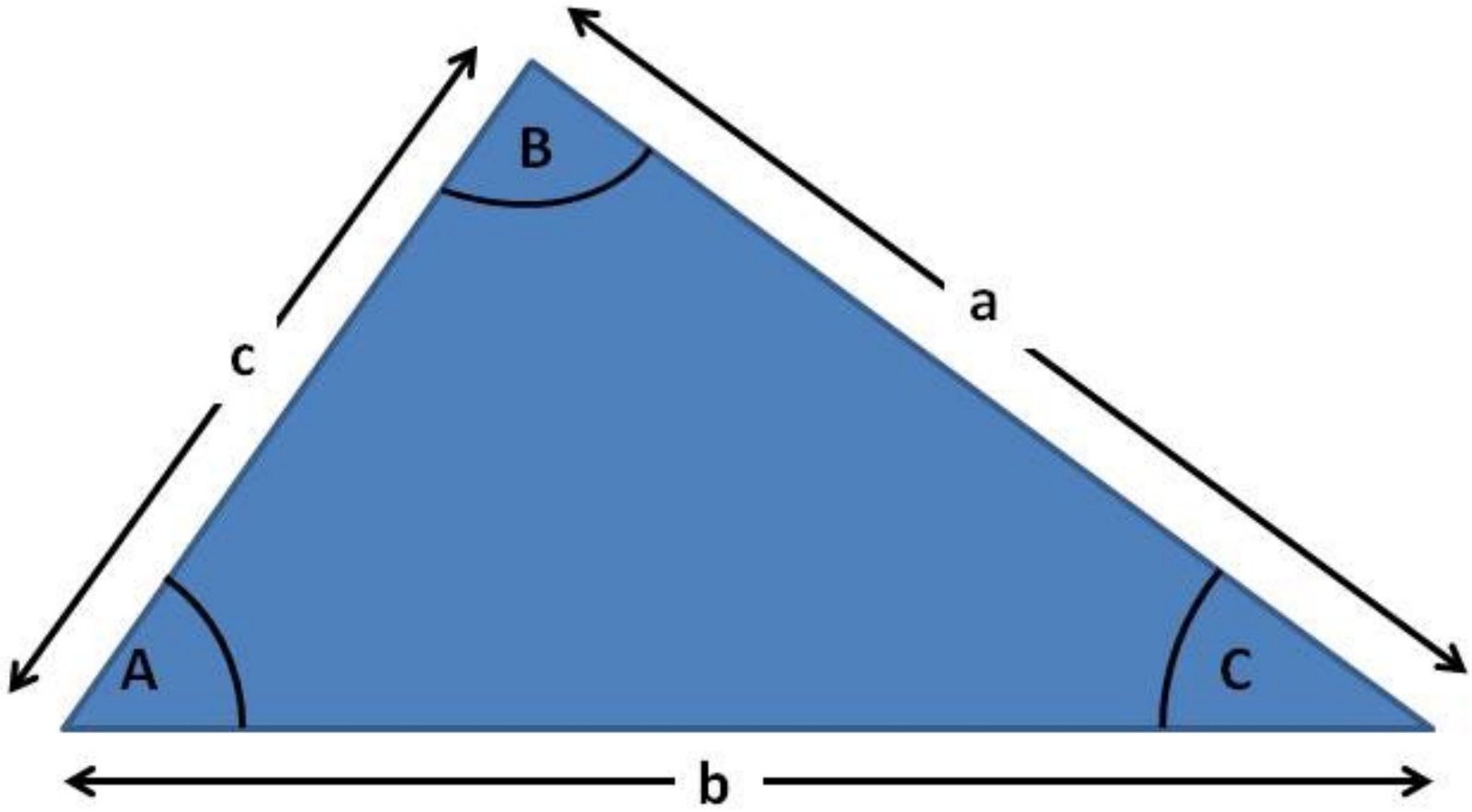


The solar eclipse of March 14 190 BC it was near the Spring Equinox, so the Sun and the Moon are both near the celestial equator



A: Alexandria (latitude 31d N)
H: Hellespont (latitude 40d N)
μ: the shift of the moon in direction (0.1d)
θ: about the altitude of the moon at H
ζ': the zenith angle of the moon at H
ζ: the latitude of A
δ: the difference in latitudes between H & A
D' ~ D: the distance to the Moon

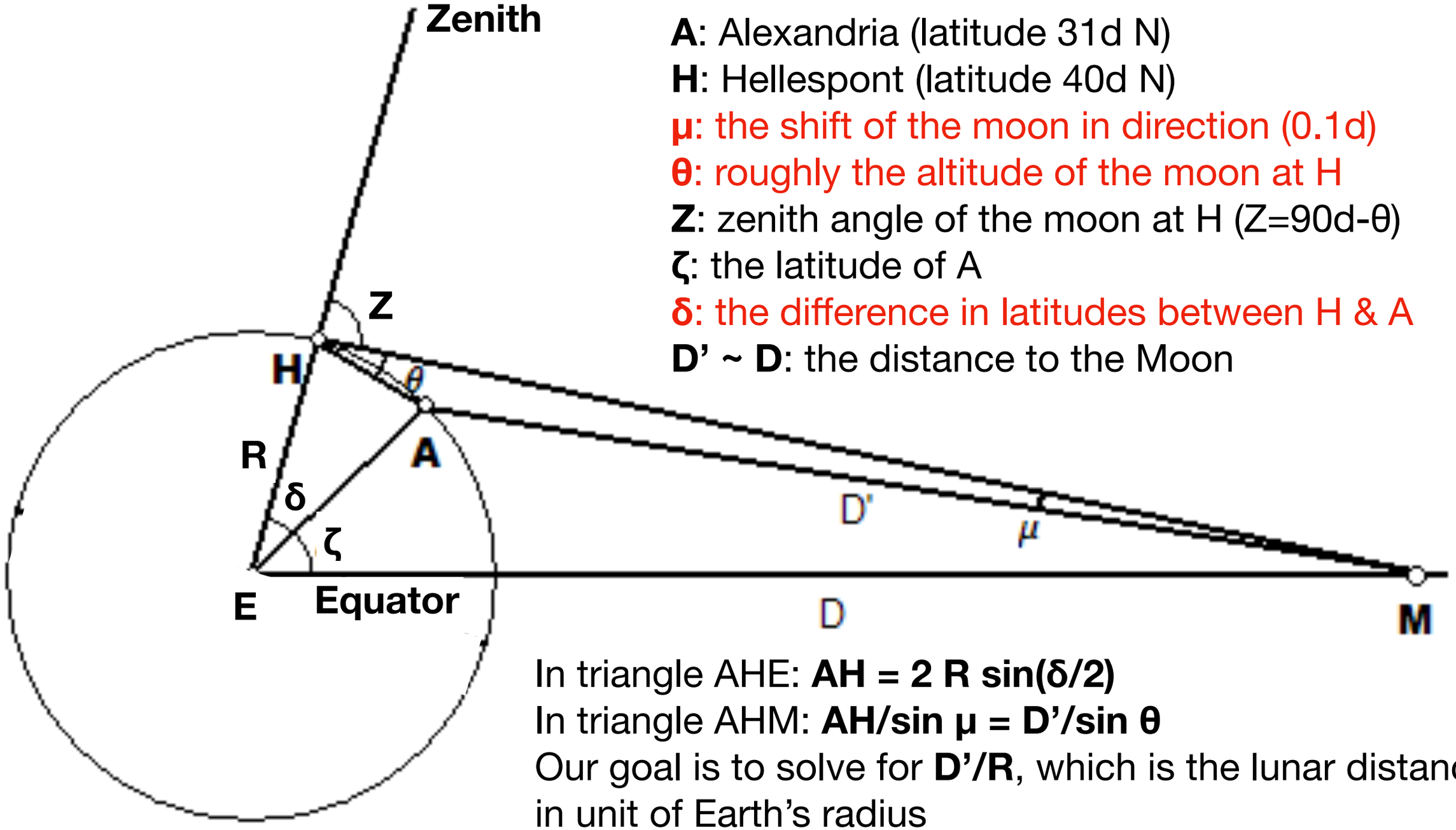
Sine & Cosine rule for a general triangle



Sine Rule: $$\frac{a}{\sin(A)} = \frac{b}{\sin(B)} = \frac{c}{\sin(C)}$$

Cosine Rule: $$c^2 = a^2 + b^2 - 2ab\cos(C)$$

The solar eclipse of March 14, 190 BC
The date was near the Spring Equinox, so the Sun and the Moon were both near the celestial equator



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μ: the shift of the moon in direction (0.1d)
θ: roughly the altitude of the moon at H
Z: zenith angle of the moon at H (Z=90d-θ)
ζ: the latitude of A
δ: the difference in latitudes between H & A
D' ~ D: the distance to the Moon

In triangle AHE: **AH = 2 R sin(δ/2)**
In triangle AHM: **AH/sin μ = D'/sin θ**
Our goal is to solve for **D'/R**, which is the lunar distance in unit of Earth's radius

Hipparchus' measurement of lunar distance (the first parallax based method)

In triangle AHE: **AH = 2 R sin(δ/2)**
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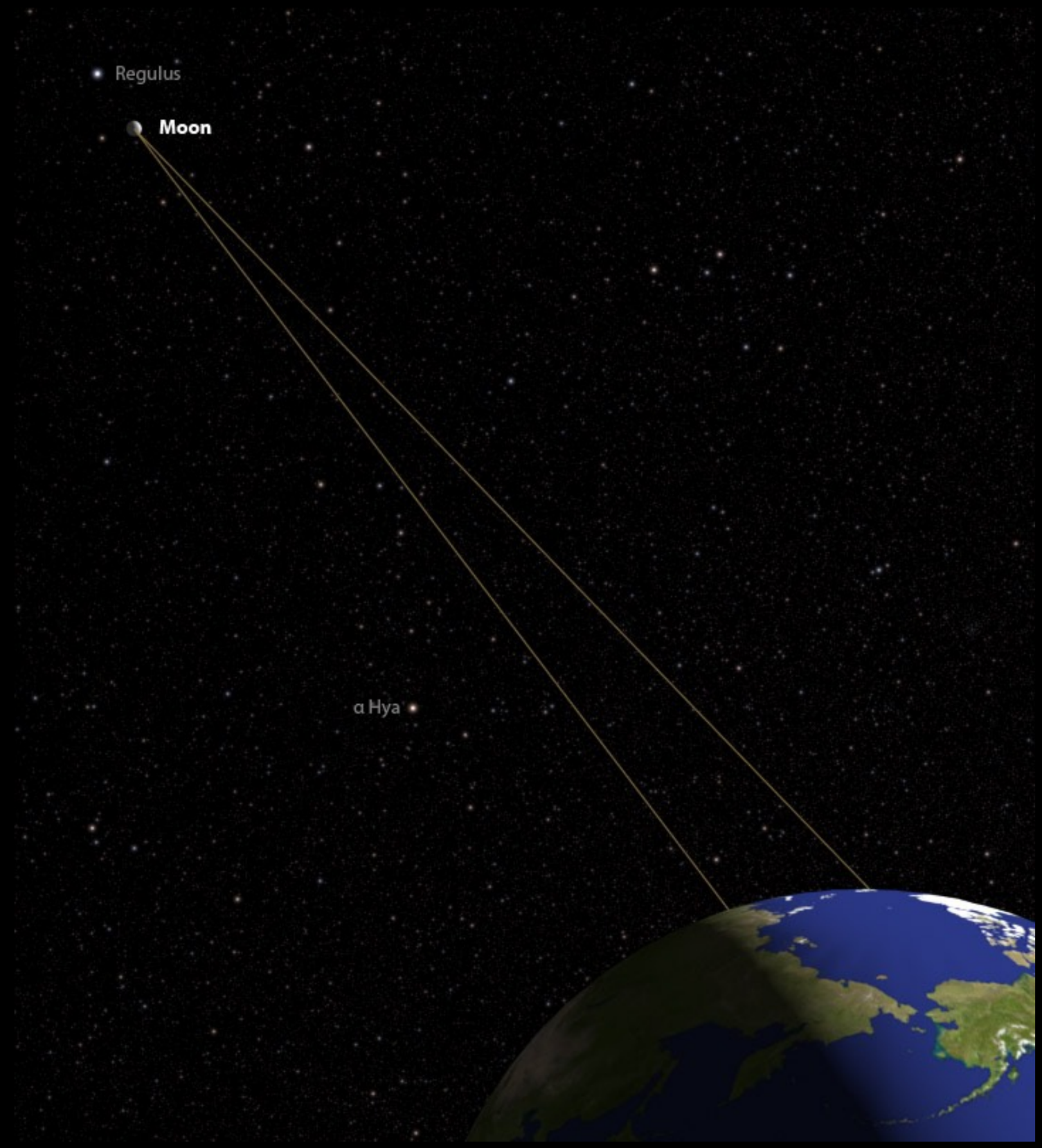
Our goal is to solve for **D'/R**, which is the lunar distance in unit of Earth's radius

$$\frac{D'}{R} = \frac{2\sin(\delta/2)}{\sin\mu}\sin\theta \approx \frac{\delta}{\mu}\sin\theta = \frac{9^\circ}{0.1^\circ}\sin(50^\circ) = 69$$

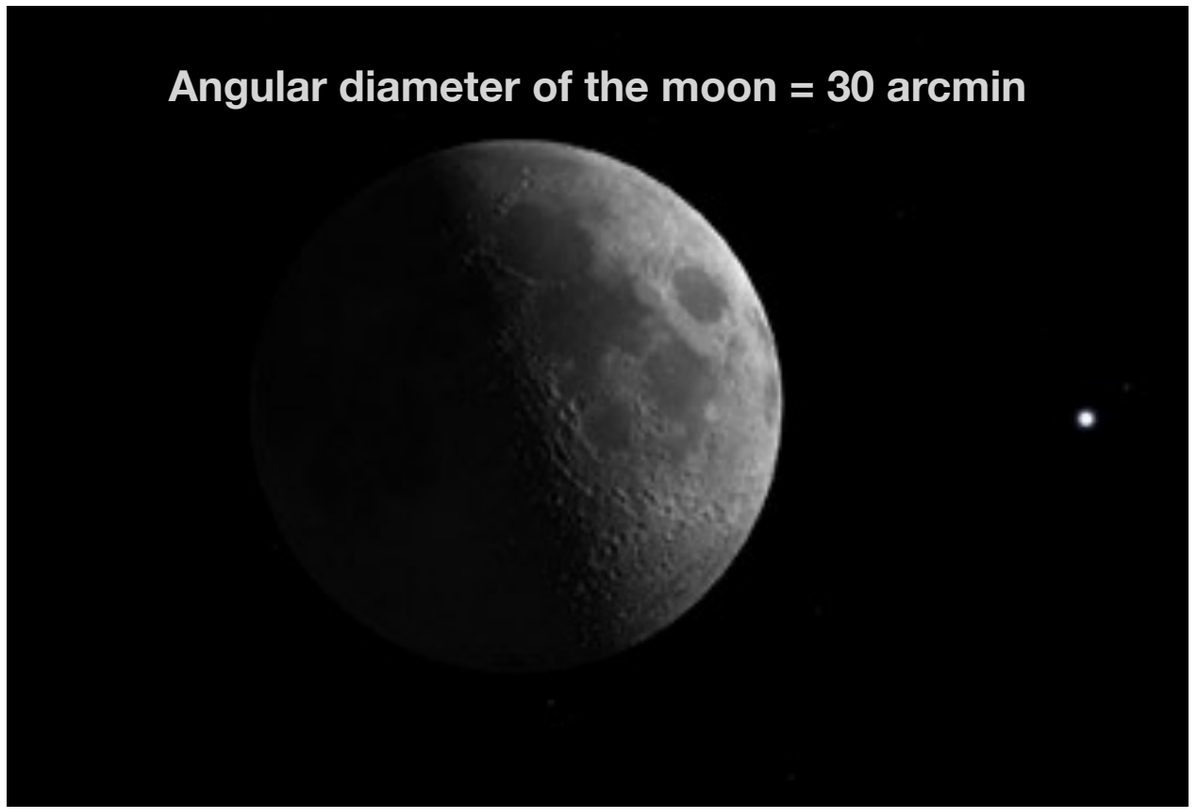
For comparison, the modern day measurements show D/R = 56-64 (elliptical orbit)

Parallax of the Moon using background stars



Simultaneous observations of the Moon at two locations

Selsey, UK



Athens, Greece

On May 23, 2007, at Athens, the moon appears closer to the bright star (**Regulus**) by 18 arcmin compared to the image taken in Selsey. The separation of the two locations is 2360 km. This difference seen in the direction of the moon against distance stars is the parallax.

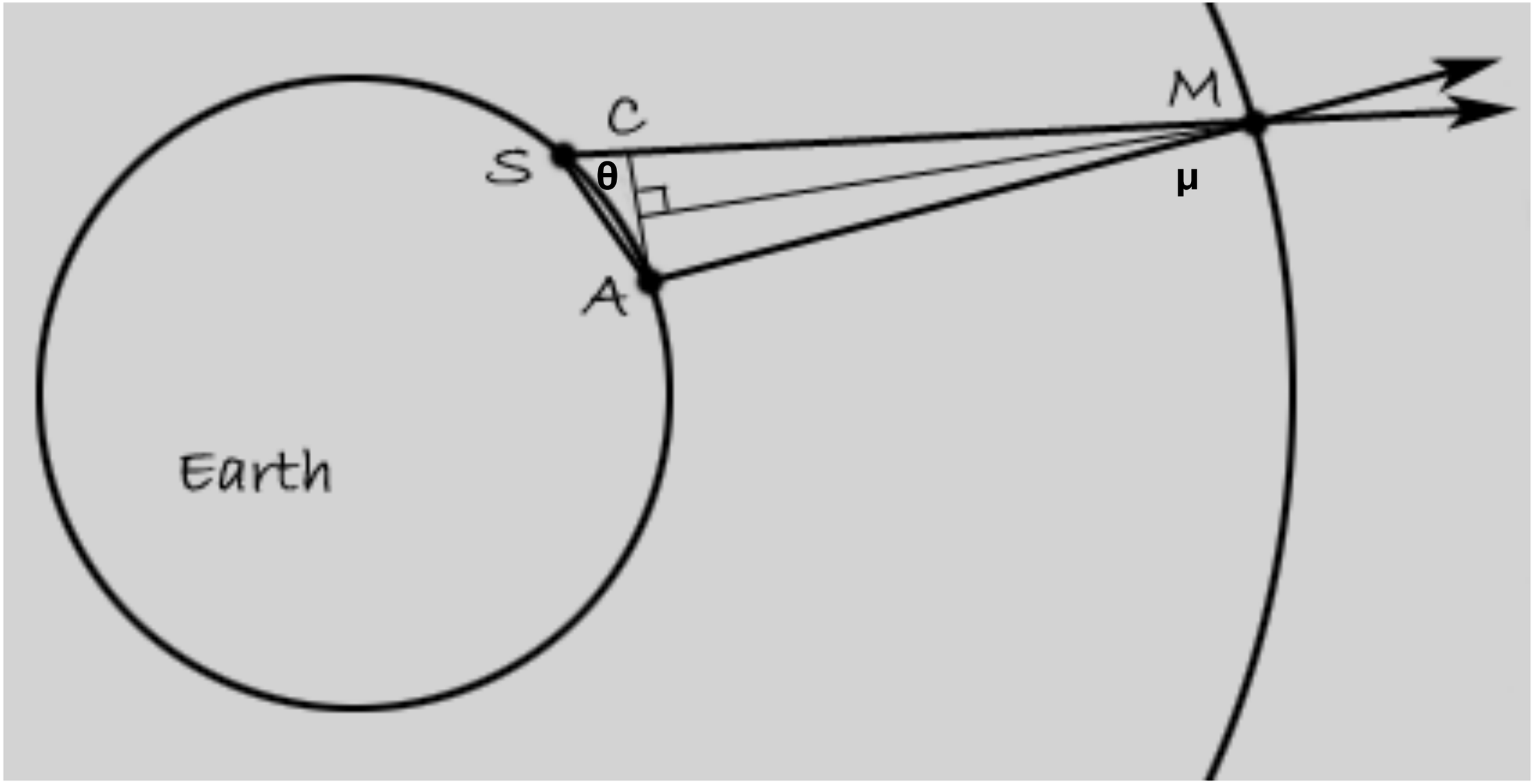
Let’s draw a Geometric Diagram of the Experiment

AC = AS sin(θ) = 2360 km sin(θ), θ = 60 deg

μ = 18 arcmin

Distance to the Moon = AM = AC/μ

AM = AC/μ = 2360 km sin(60 deg) / [(18/60)/57.3] = 3.9e5 km (actual value: 3.8e5 km)



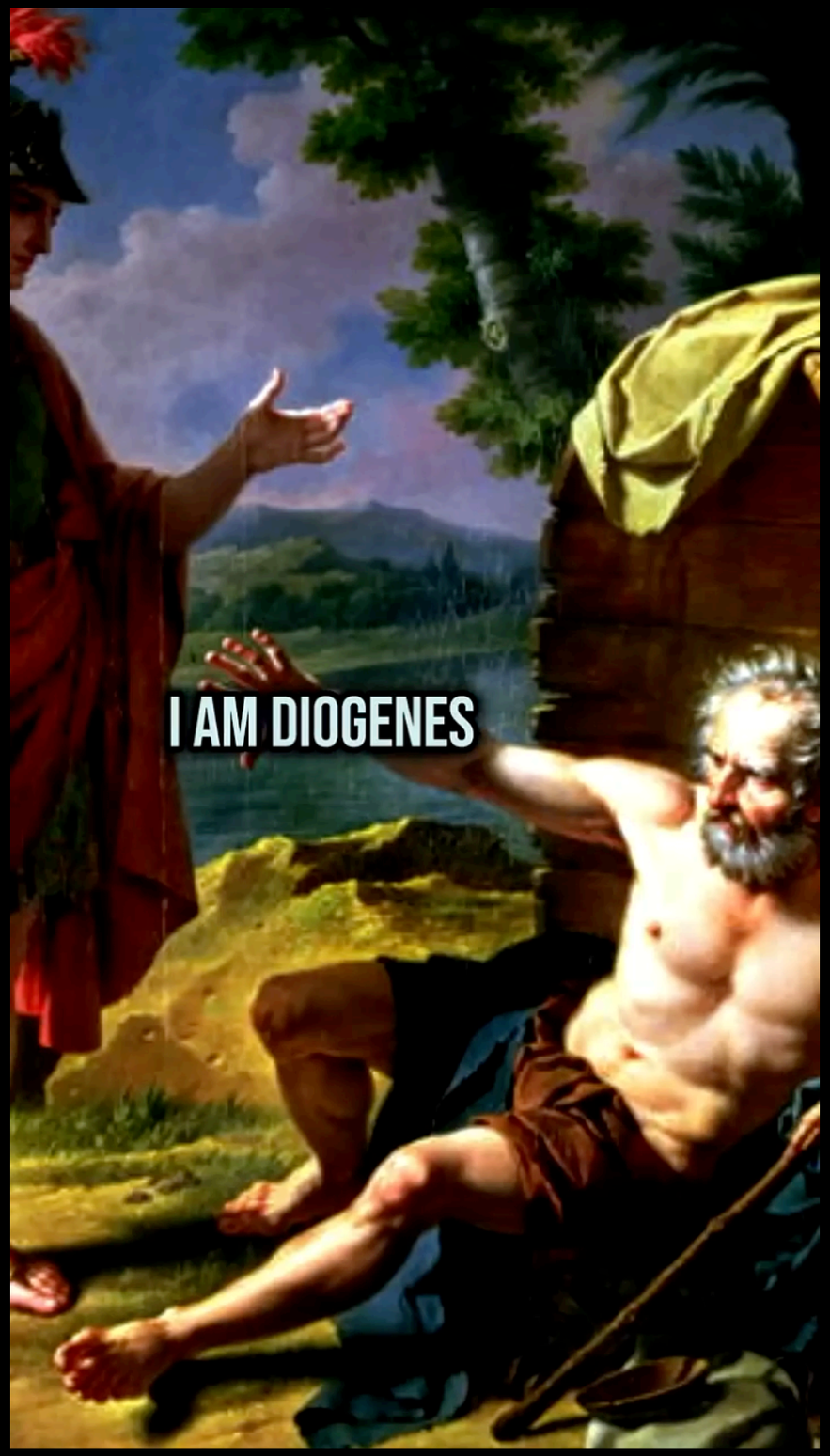
When *Alexander the Great* met *Diogenes* …

- Alexander the Great came to visit the philosopher Diogenes of Sinope. Alexander wanted to fulfill a wish for Diogenes and asked him what he desired.

  Diogenes replied "**Stand out of the sun**."

  Alexander later said, "If I were not Alexander, I wish I were Diogenes."

- Evidence of Diogenes' disregard for **authority, political power, and decorum**



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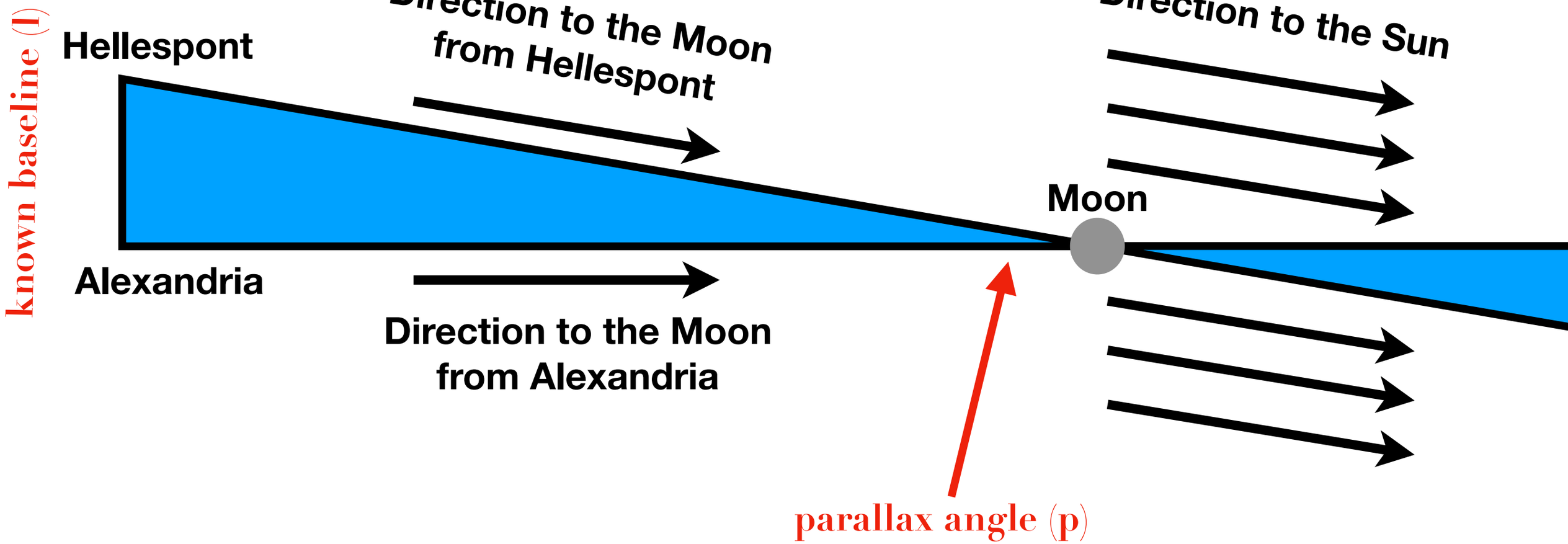

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- **Relative distances of the Sun and the Moon:**
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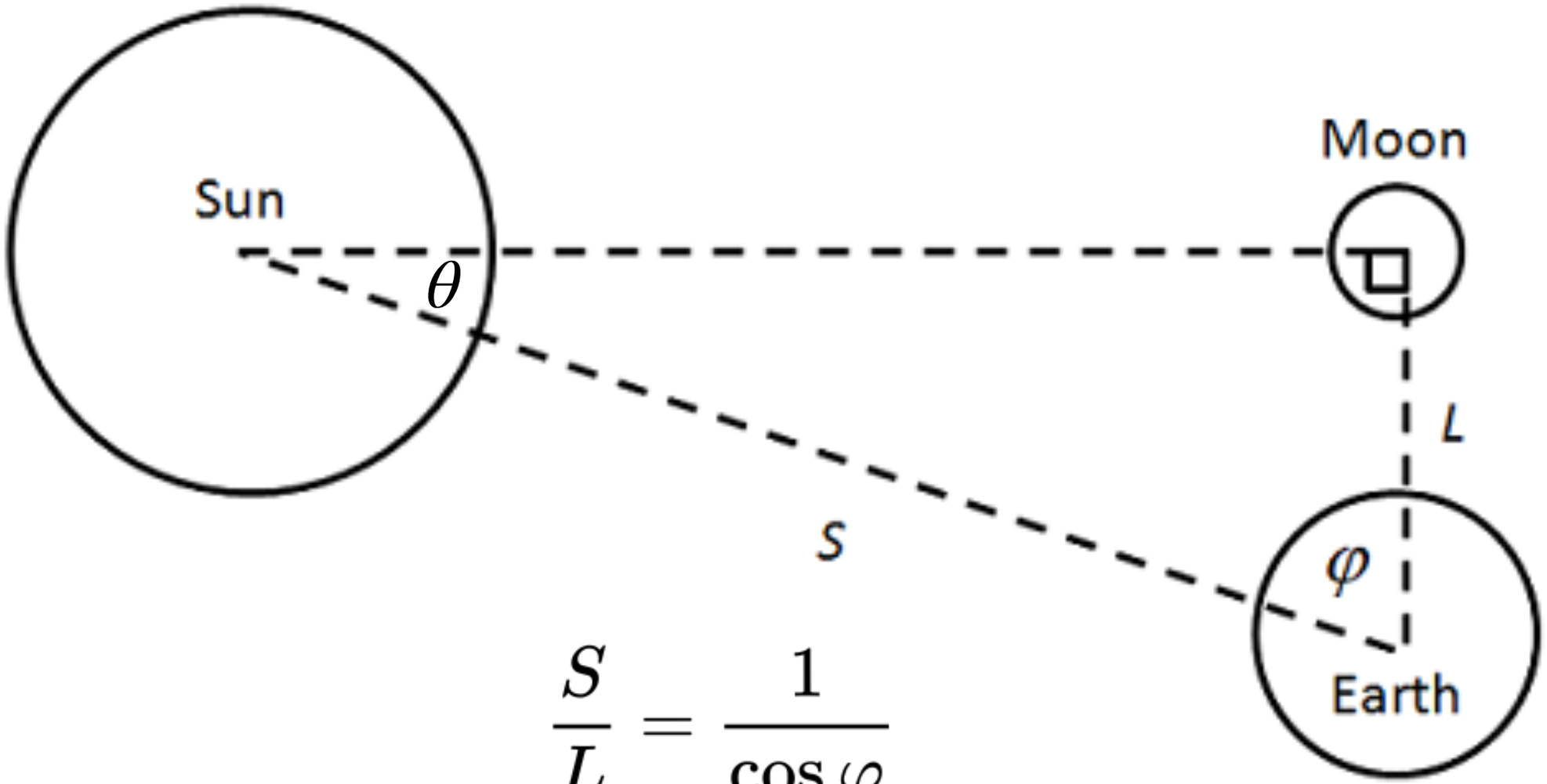
Relative distances of the Sun and the Moon this distance ratio: D_{sol}/D_{luna}

Aristarchus of Samos 310-230 BC

Moon Phases

At the **quarter moon** phase, the Sun-Moon-Earth system forms a right-angle triangle, and the angular separation between the Moon and the Sun at that moment gives the ratio between their distances

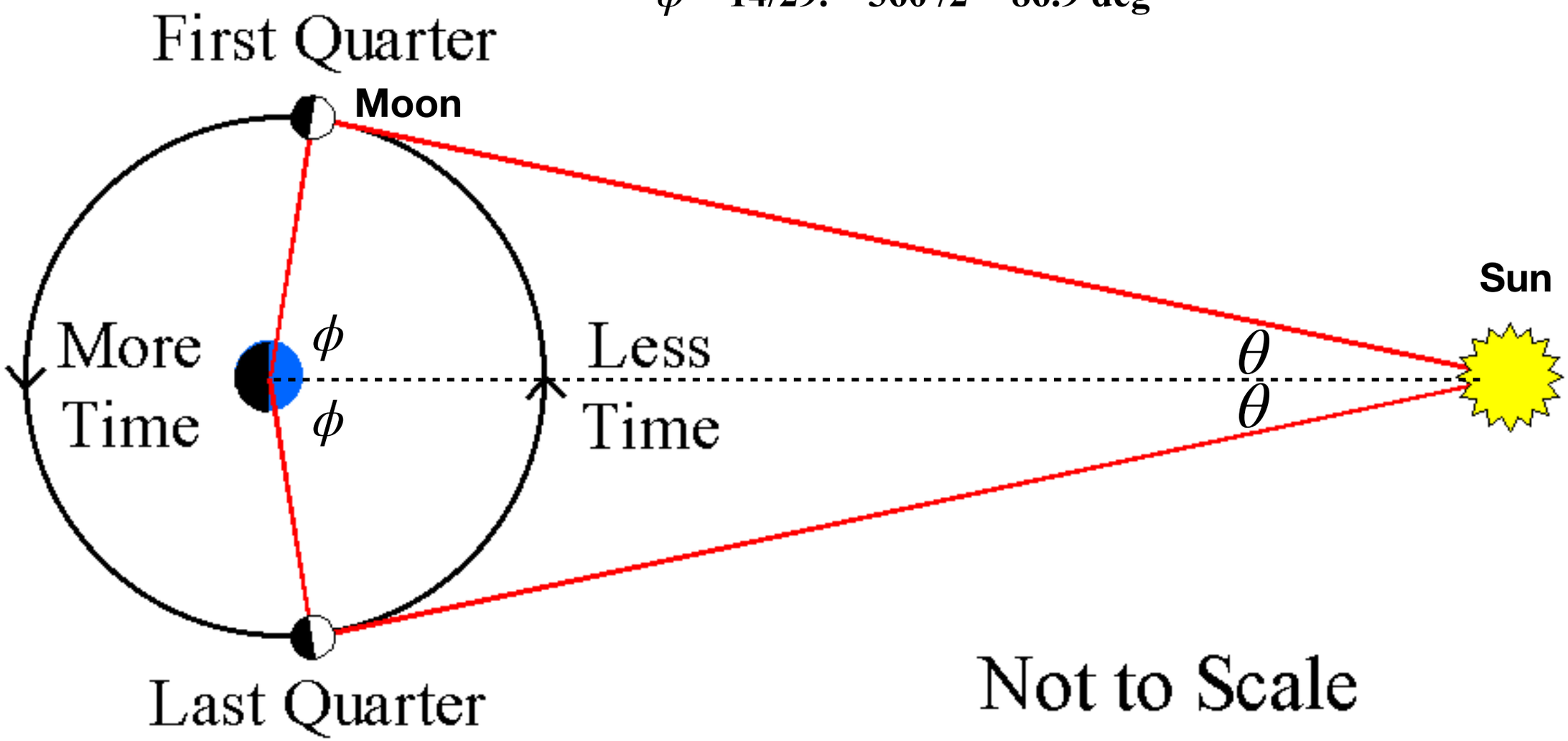


$$\frac{S}{L} = \frac{1}{\cos\varphi}$$

Aristarchus' Timing Method

Suppose the time between first and last quarter moon is 15 days and the time between the last and the first quarter moon is 14 days, what is the angle ϕ?

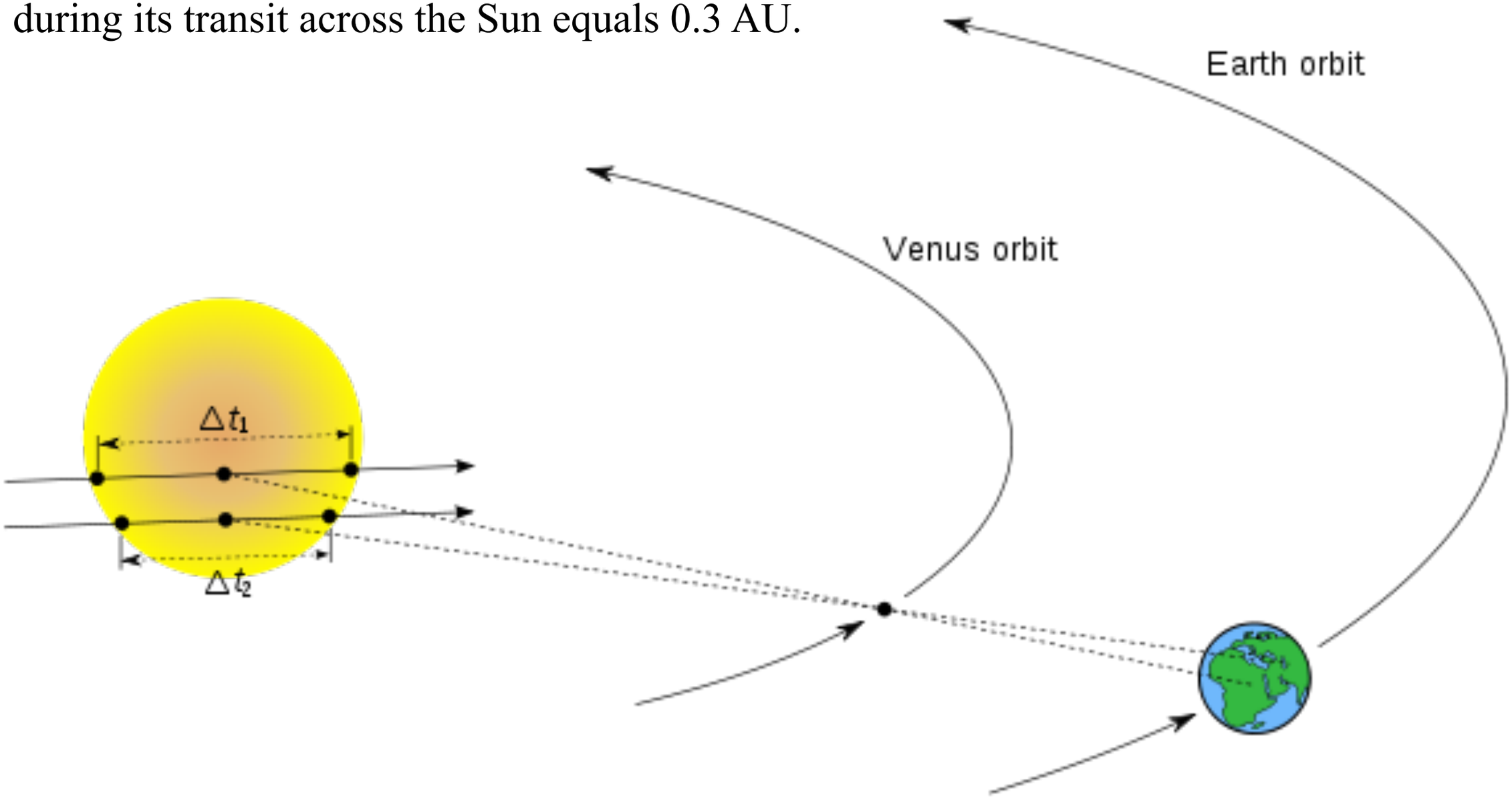
ϕ = 14/29. * 360 /2 = 86.9 deg



Aristarchus found the angle ϕ to be 87 deg (so θ = 3 deg = 0.052 radian), giving Solar distance/Lunar distance = S/L = 19.1 (actual value 390)

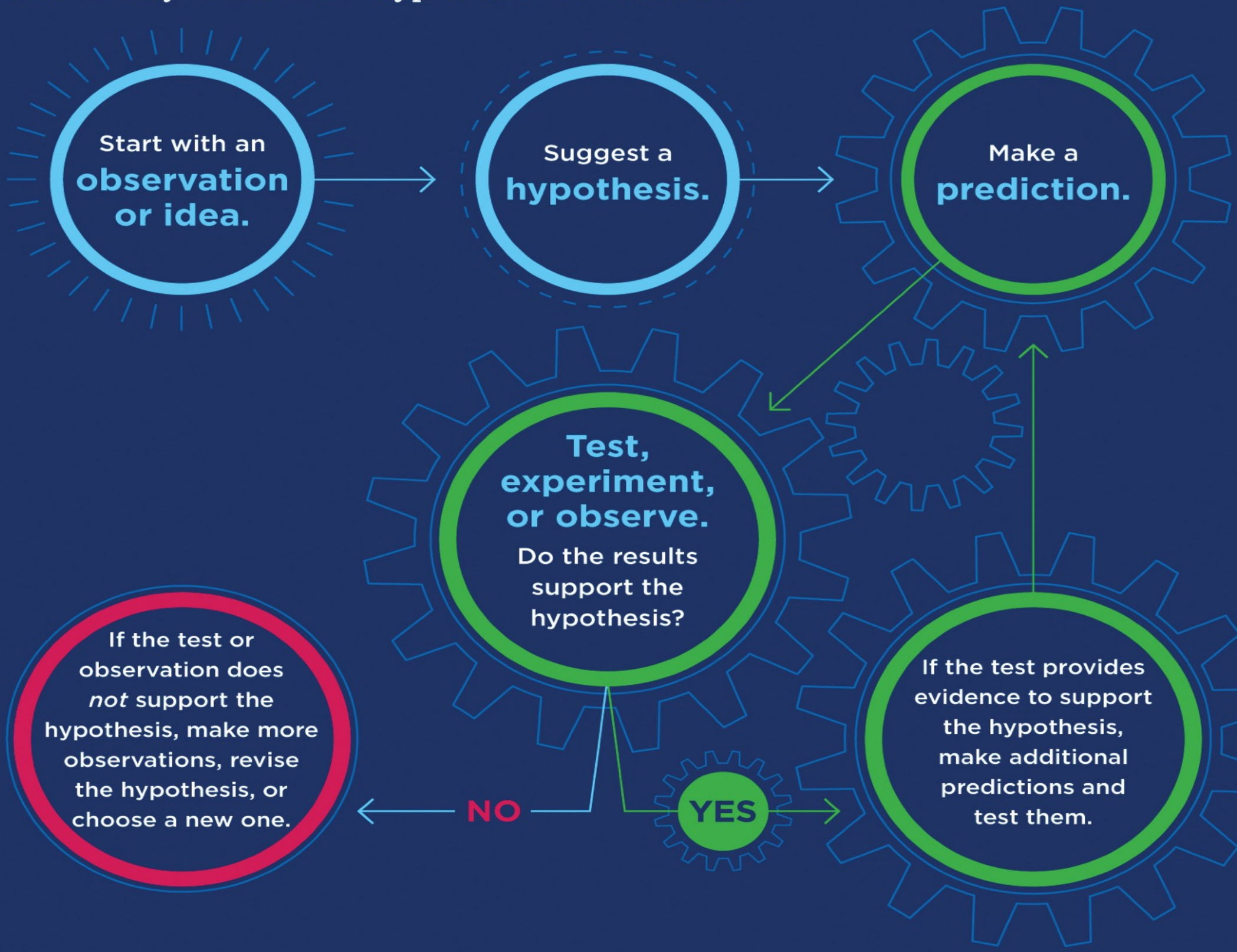
Modern method to measure AU

- By observing the transit of Venus at two locations on Earth, one can measure the distance to Venus using the measured **parallax** and the distance between the two locations.
- Assuming Venus and Earth are both on circular orbits around the Sun, the greatest elongation angle of Venus tells us its orbit has a radius of 0.7 AU.
- Since the Earth's orbit has a radius of 1 AU, the measured parallax distance of Venus during its transit across the Sun equals 0.3 AU.



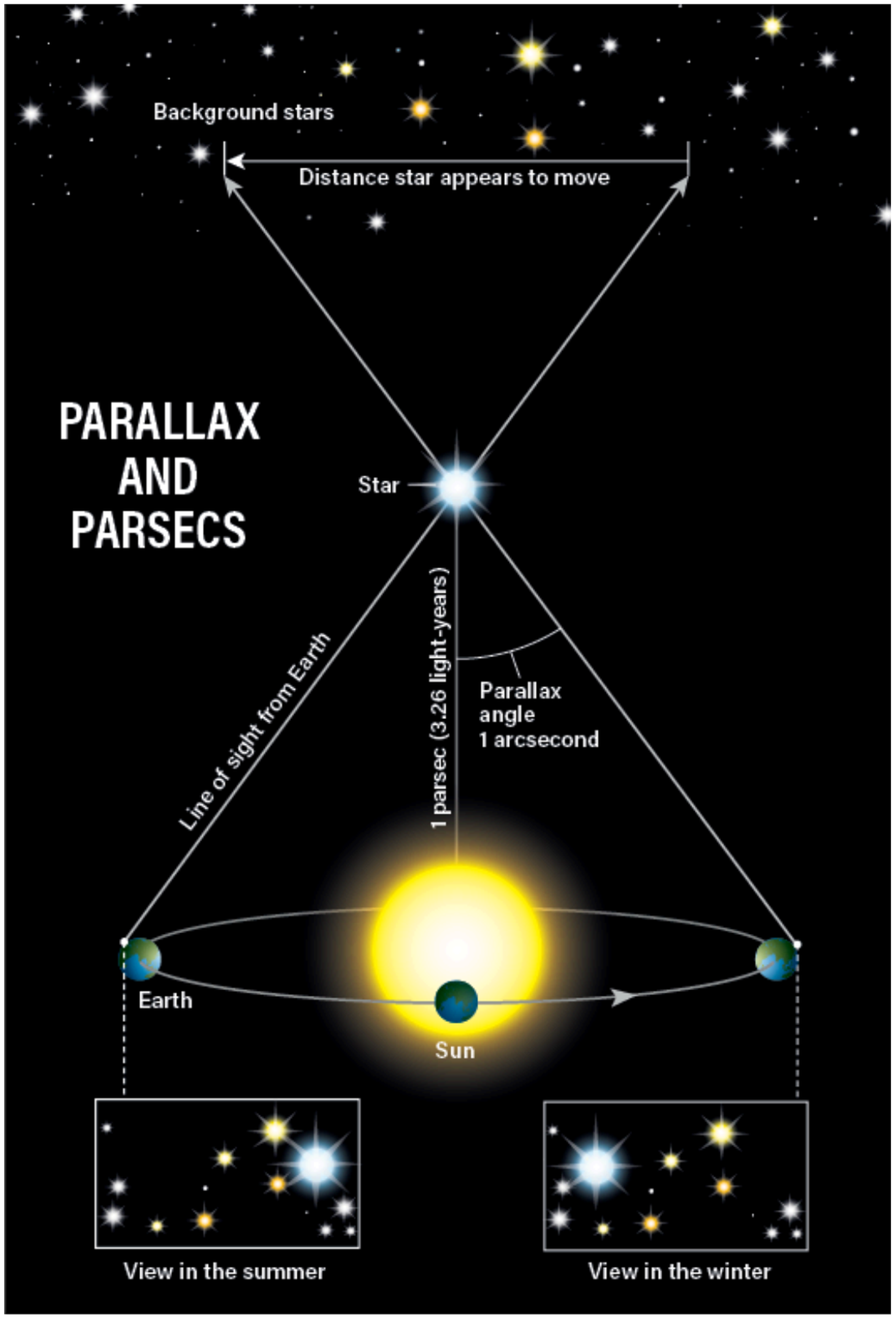
The Scientific Method

The scientific method is a formal procedure used to test the validity of scientific hypotheses and theories.

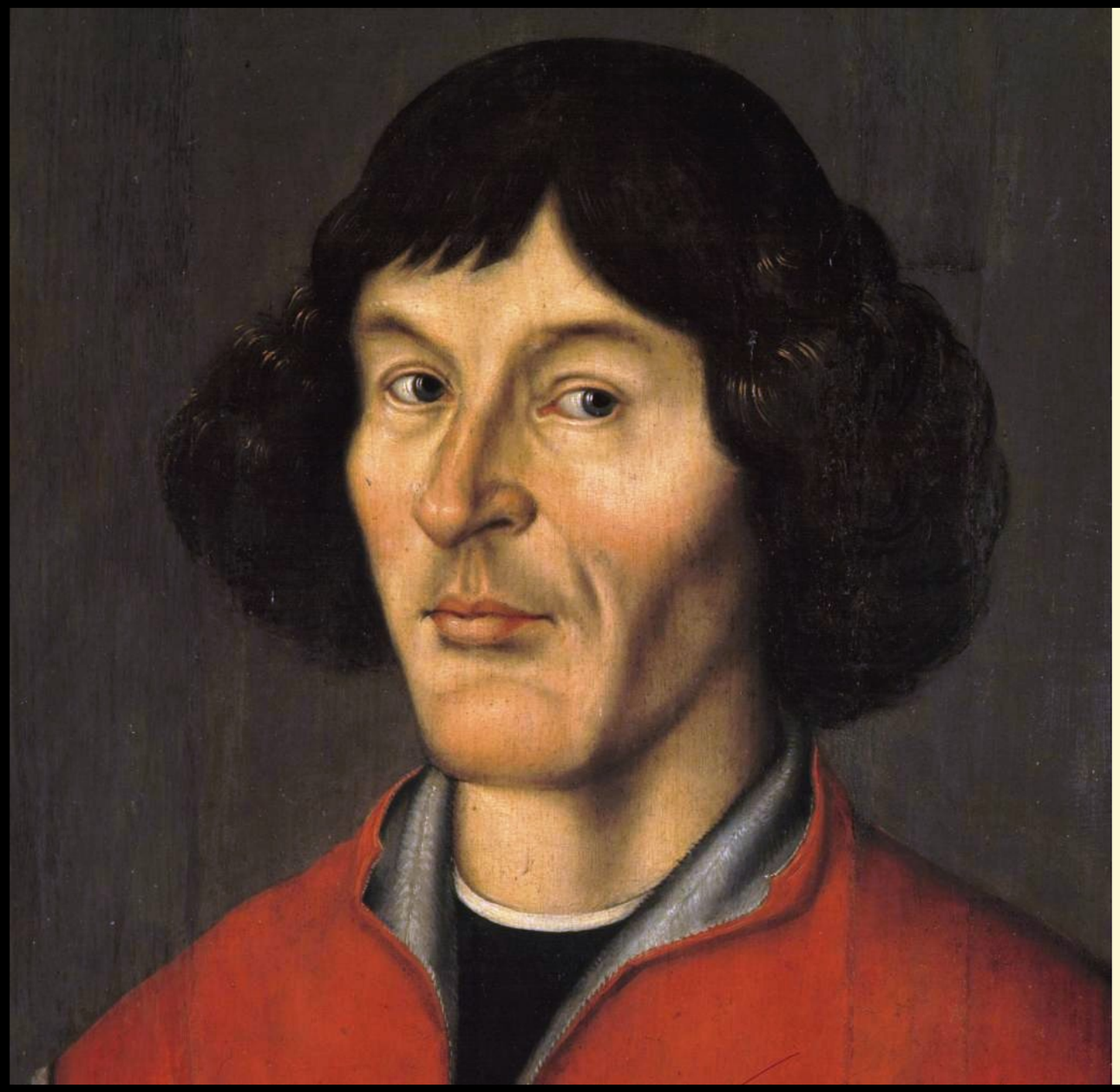


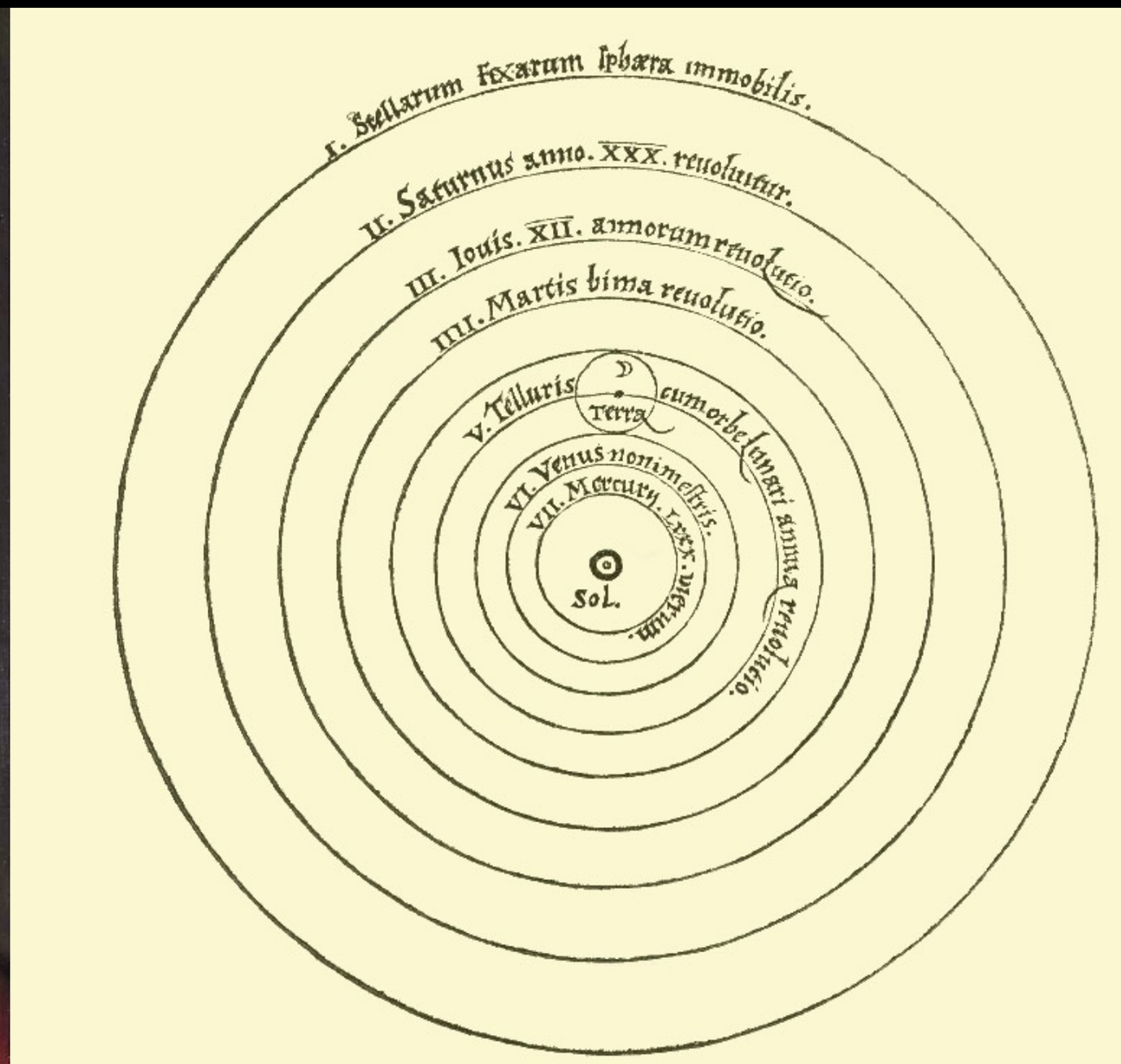
How did ancient Greek astronomers reject the hypothesis the Earth orbit around the sun?

- **Observation**: The Sun moves against background stars on the celestial sphere
- **Hypothesis**: The Earth moves around the Sun (which is much larger)
- **Experiment**: Measuring the expected motion of bright stars due to Earth's orbital motion around the Sun (i.e., **parallax**)
- **Result**: no such yearly motion is detected for any bright stars
- **Updated Hypothesis**: The Earth is stationary and the Sun moves around the Earth

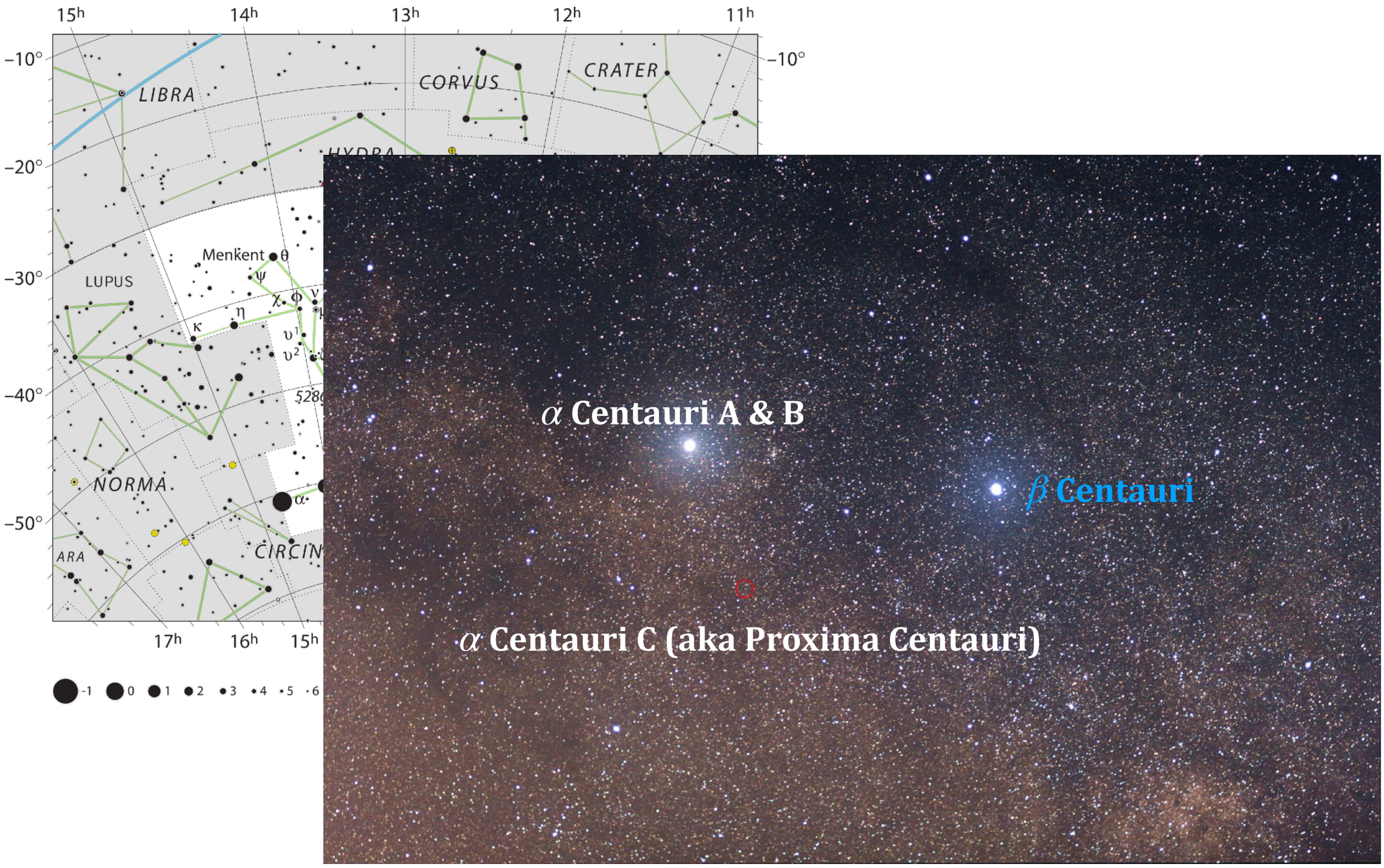


Rejection of the updated Hypothesis "The Earth is not orbiting around the Sun", first by Copernicus in 1543 AD (51 years after the discovery of the "New World")

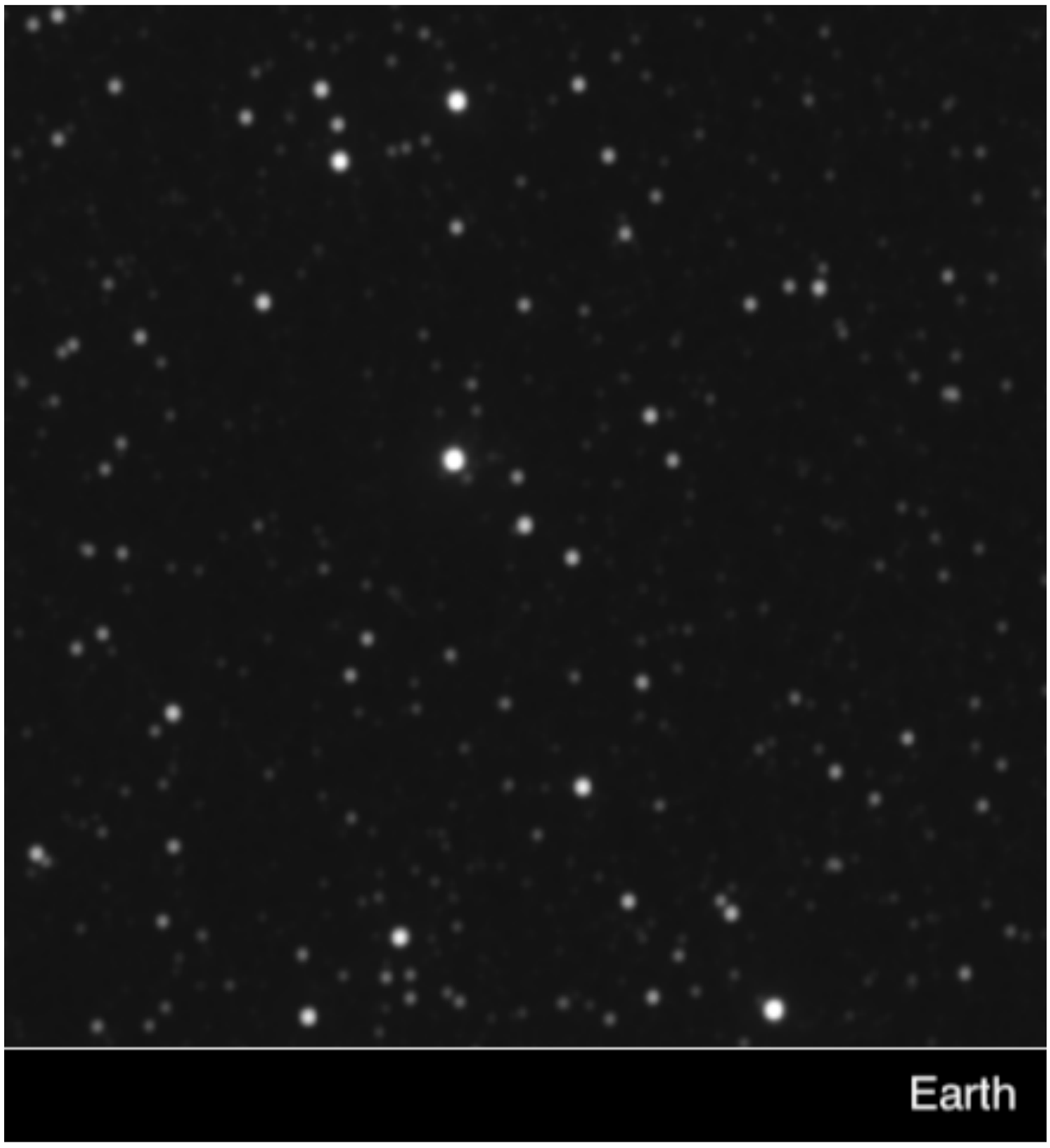




“The Three-Body Problem”: α Centauri Triple Star System



Parallax of Proxima Centauri



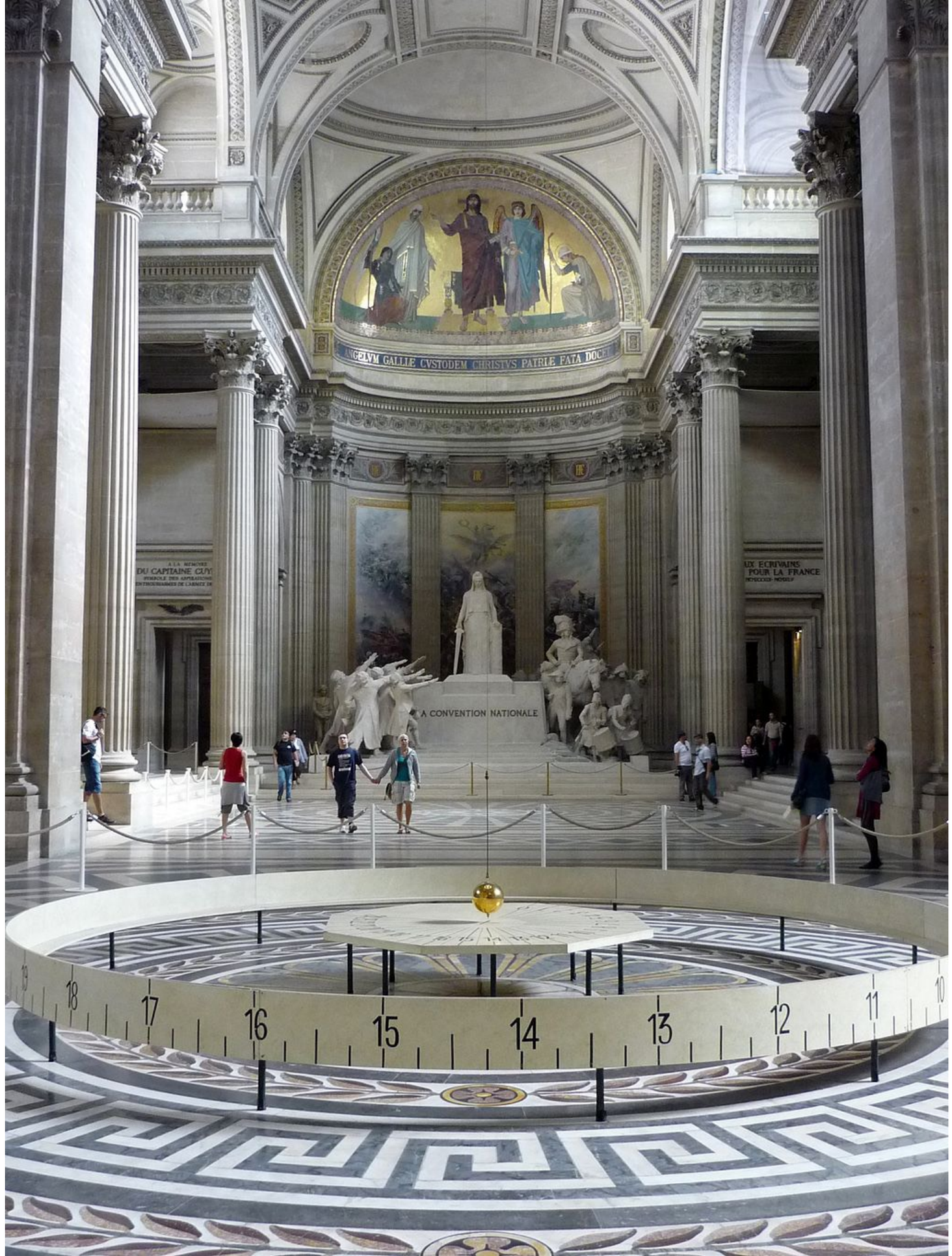
Parallax of Proxima Centauri as observed simultaneously from *New Horizons* at Pluto's orbit and the Earth.

How did ancient Greek astronomers reject the hypothesis that the Earth is spinning with a period of 24 hrs?

- **Observation**: Stars rise from the east, drift across the night sky, and set in the west
- **Hypothesis**: The Earth spins on its poles every 24 hours
- **Experiment**: Measuring the expected motion of air flow caused by this fast spin (1700 km/h on the equator)
- **Result**: no such strong wind is seen.
- **Updated Hypothesis**: The Earth is not spinning

Rejection of the updated Hypothesis

"The Earth is not spinning" by Foucault in 1951

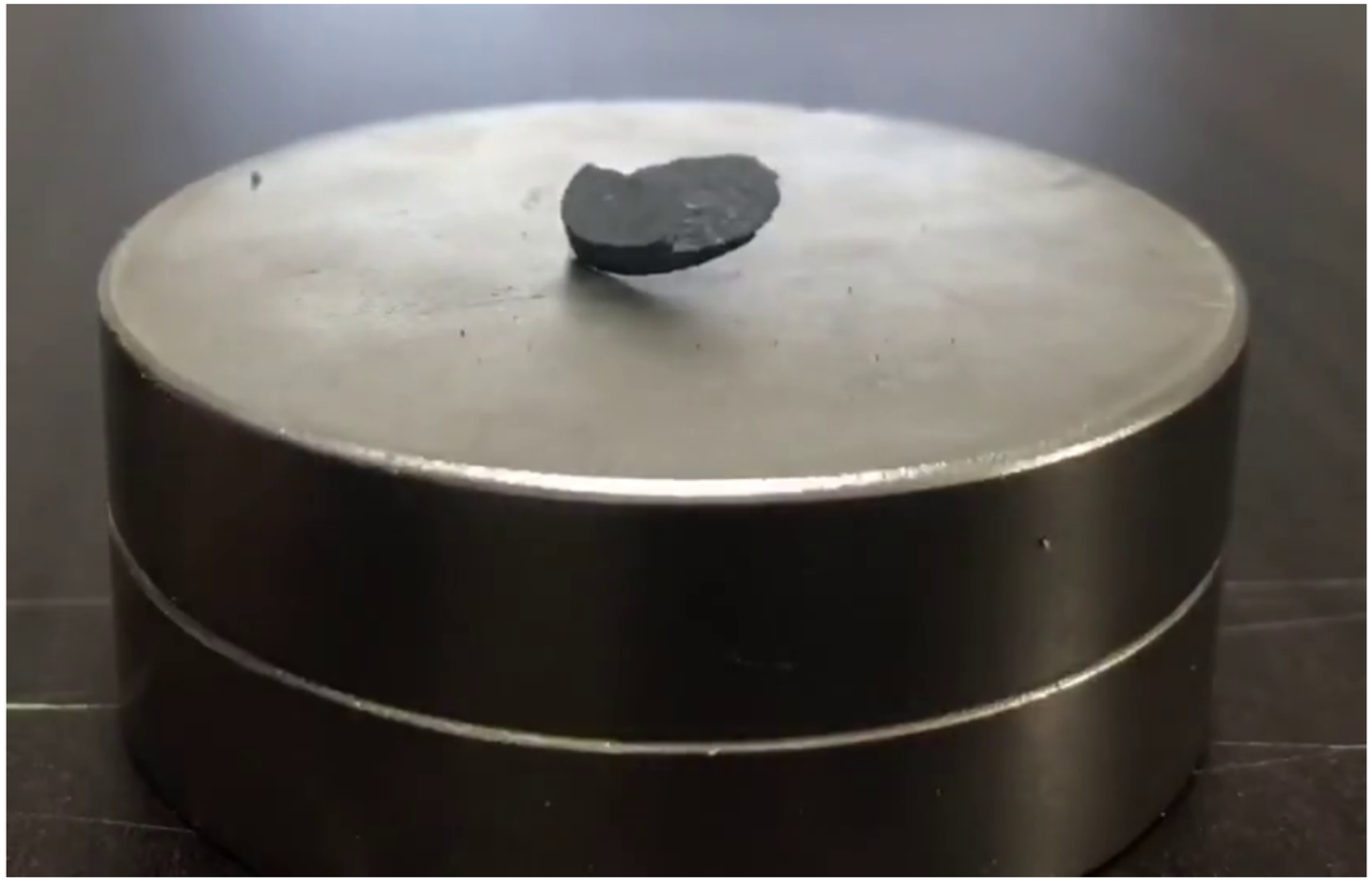


Foucault's pendulum in the Panthéon, Paris (200 ft, 60 lb)

Not the Pantheon in Rome built in 126 AD

“Room-temperature Superconductor” - LK-99

- Low temperature superconductivity (few Kelvin) was discovered in 1911 by Heike Onnes. In 1986, high-temperature superconductors were discovered to have critical T above 90 Kelvin.
- **Hypothesis**: The compound “LK-99” was claimed to be a *room-temperature* superconductor by a group of scientists in Korea in 2023.
- **Experiment**: Based on the recipe given in the preprints, multiple research groups in the world attempted to replicate the compound in their labs so that they can test its properties
- **Result**: LK-99 is **not** a superconductor at any temperature, it’s actually an insulator in pure form. The observed resistivity drop and repulsion to magnetic field is mainly caused by the copper-sulfide impurities in small samples.



Chapter 1 Summary

- Astronomy as a Science in Ancient Greece
  - The size of the Earth - **Zenith Angles** of the Sun
  - The distance to the Moon - **Parallax** of the Moon
  - The distance ratio between the Sun and the Moon - **Timing** of Quarter Moons.

- The Scientific Method
  - **Hypothesis** must be **testable**
  - **Experiments** must be carried out, in attempts to **reject** the hypothesis, **indefinitely**
  - Conclusions must be based on **experimental data**
  - Scientific method does not guarantee correct results, but it has a mechanism to **self-correct**, because it is a process that relies on independent thinkers