

A composite image of the Orion nebula, showing vibrant colors of red, blue, green, and purple, with numerous stars scattered throughout. The nebula's structure is complex, with various filaments and regions of different colors.

The Cosmic Distance Ladder

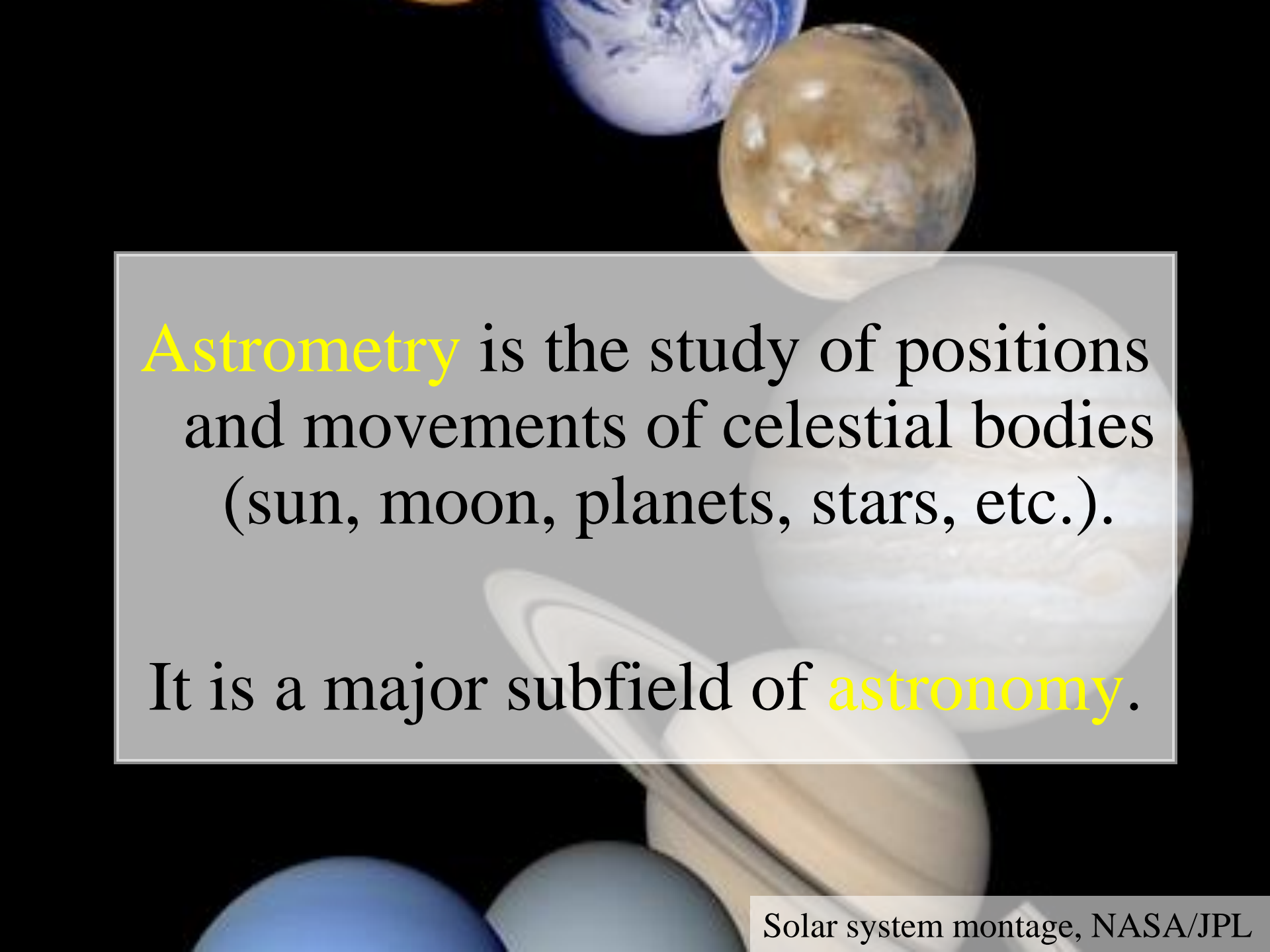
Clay/Mahler lecture series

Terence Tao (UCLA)

A collage of solar system planets including Earth, Mars, Jupiter, Saturn, Uranus, and Neptune. The planets are arranged in a roughly diagonal line from the top left to the bottom right. Earth is at the top left, followed by Mars, Jupiter, Saturn, Uranus, and Neptune at the bottom left. The background is black.

Astrometry

Solar system montage, NASA/JPL

A collage of celestial bodies including Earth, the Moon, Jupiter, Saturn, and Uranus. The background is black, and the objects are arranged in a circular pattern. Earth is at the top left, the Moon is at the top right, Jupiter is in the middle right, Saturn is at the bottom right, and Uranus is at the bottom left.

Astrometry is the study of positions and movements of celestial bodies (sun, moon, planets, stars, etc.).

It is a major subfield of **astronomy**.

A collage of celestial bodies including Earth, the Moon, Saturn, and other planets. The Earth is at the top left, the Moon is at the top right, Saturn is in the middle right, and other planets are at the bottom.

Typical questions in astrometry are:

- How far is it from the Earth to the Moon?
- From the Earth to the Sun?
- From the Sun to other planets?
- From the Sun to nearby stars?
- From the Sun to distant stars?

These distances are far too vast to be measured **directly**.

D_2

D_1

$D_1 = ???$

$D_2 = ???$

Nevertheless, there are several ways to measure these distances **indirectly**.



The diagram shows a field of galaxies with two red arrows originating from a common point at the bottom. One arrow points to a galaxy labeled D_2 , and the other points to a galaxy labeled D_1 . The galaxy D_1 is further away than D_2 .

D_2

D_1

$$D_1 / D_2 = 3.4 \pm 0.1$$

The methods often rely more on **mathematics** than on technology.

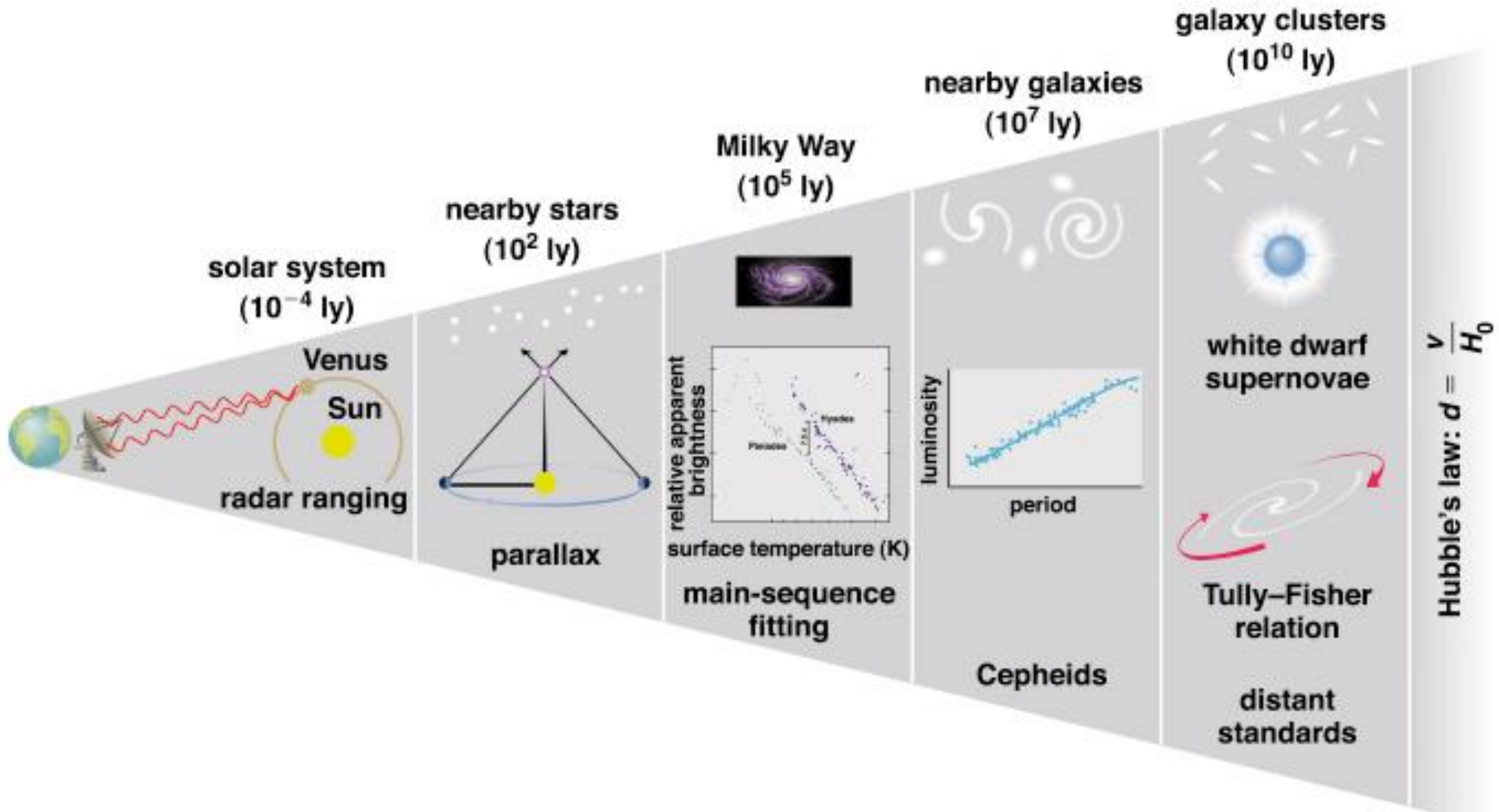
D_2

D_1

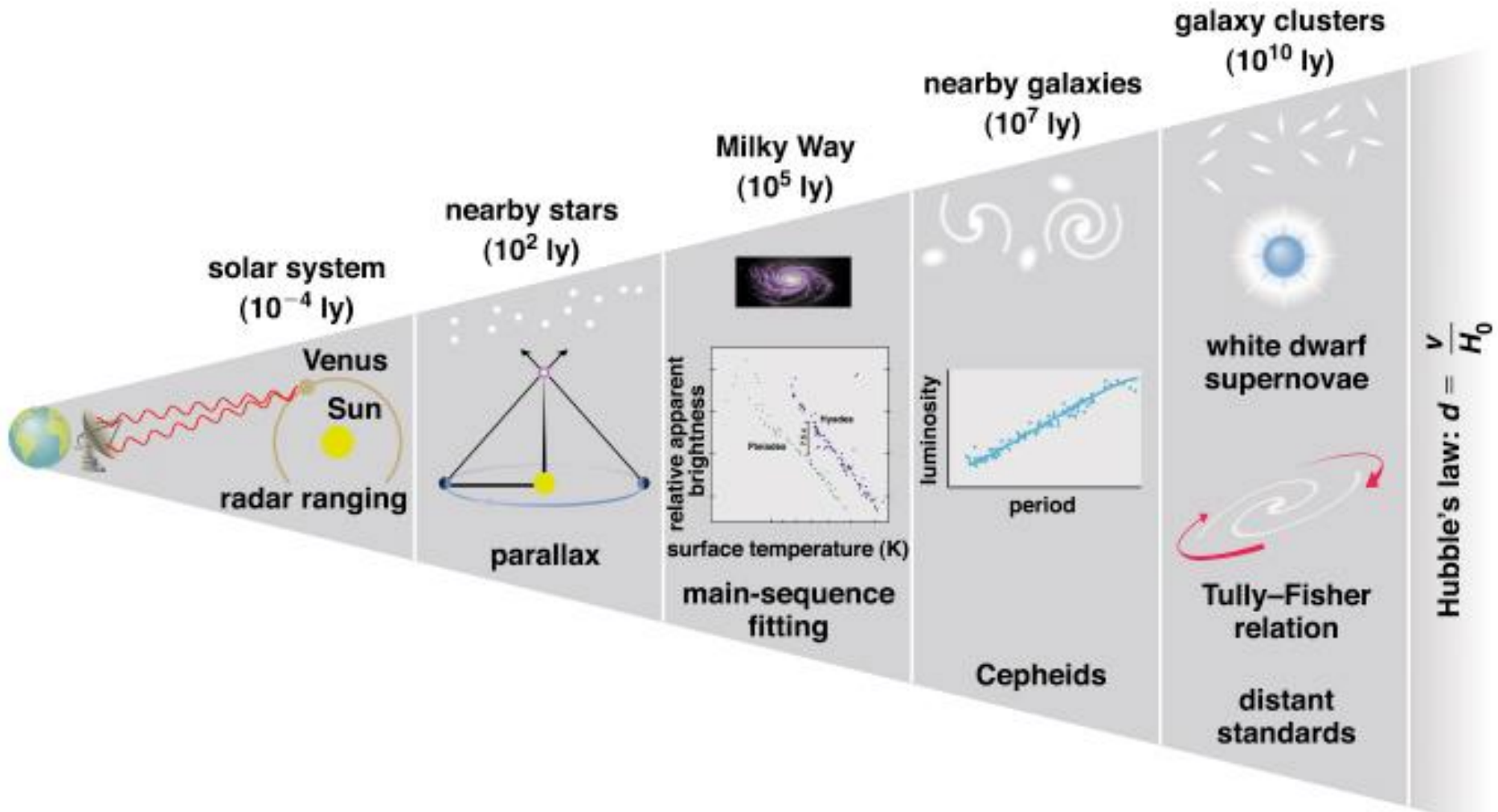
$$\begin{aligned}v_1 &= H D_1 \\v_2 &= H D_2 \\v_1 / v_2 &= 3.4 \pm 0.1\end{aligned}$$

$$D_1 / D_2 = 3.4 \pm 0.1$$

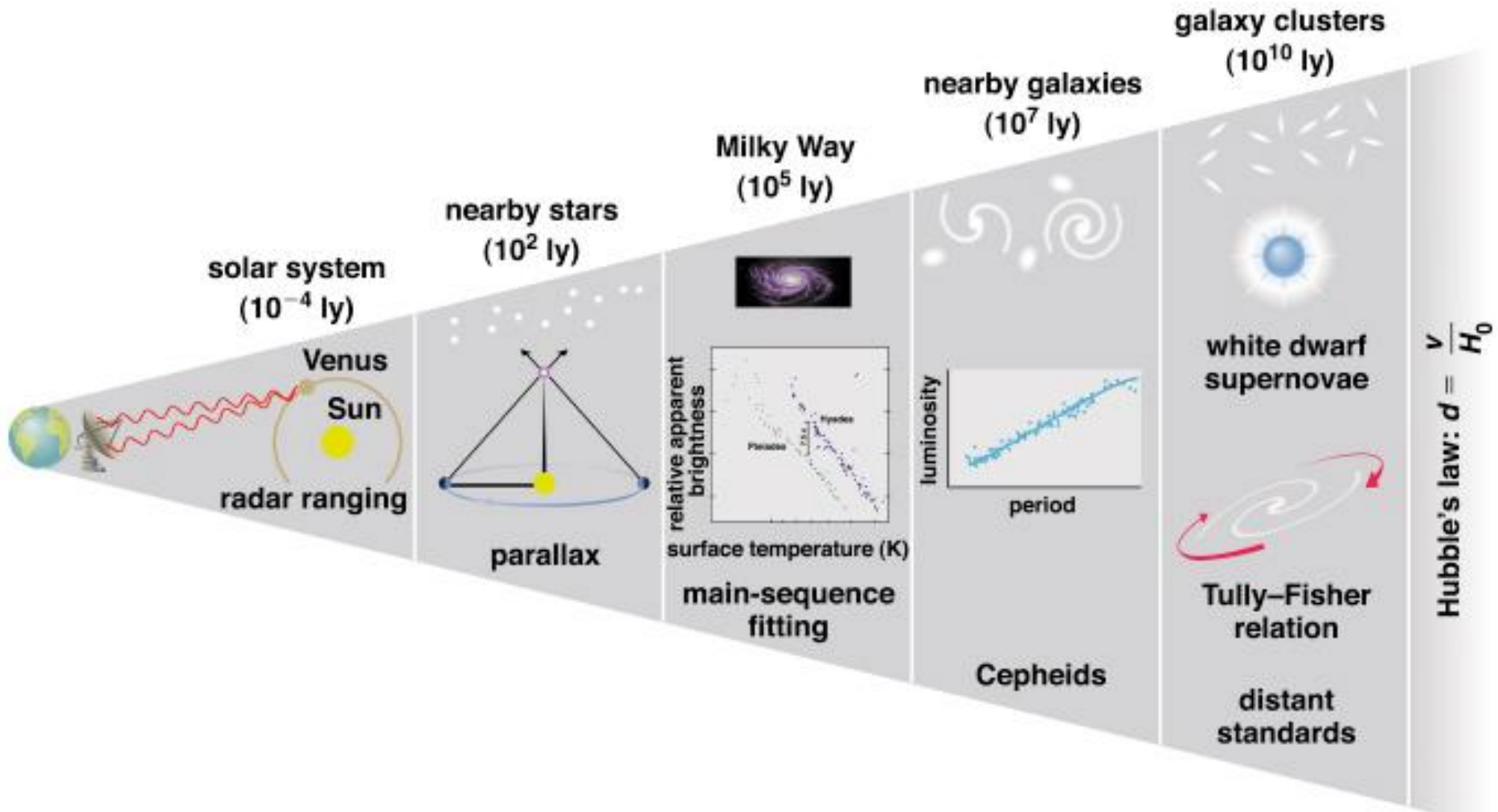
The indirect methods control large distances in terms of smaller distances.



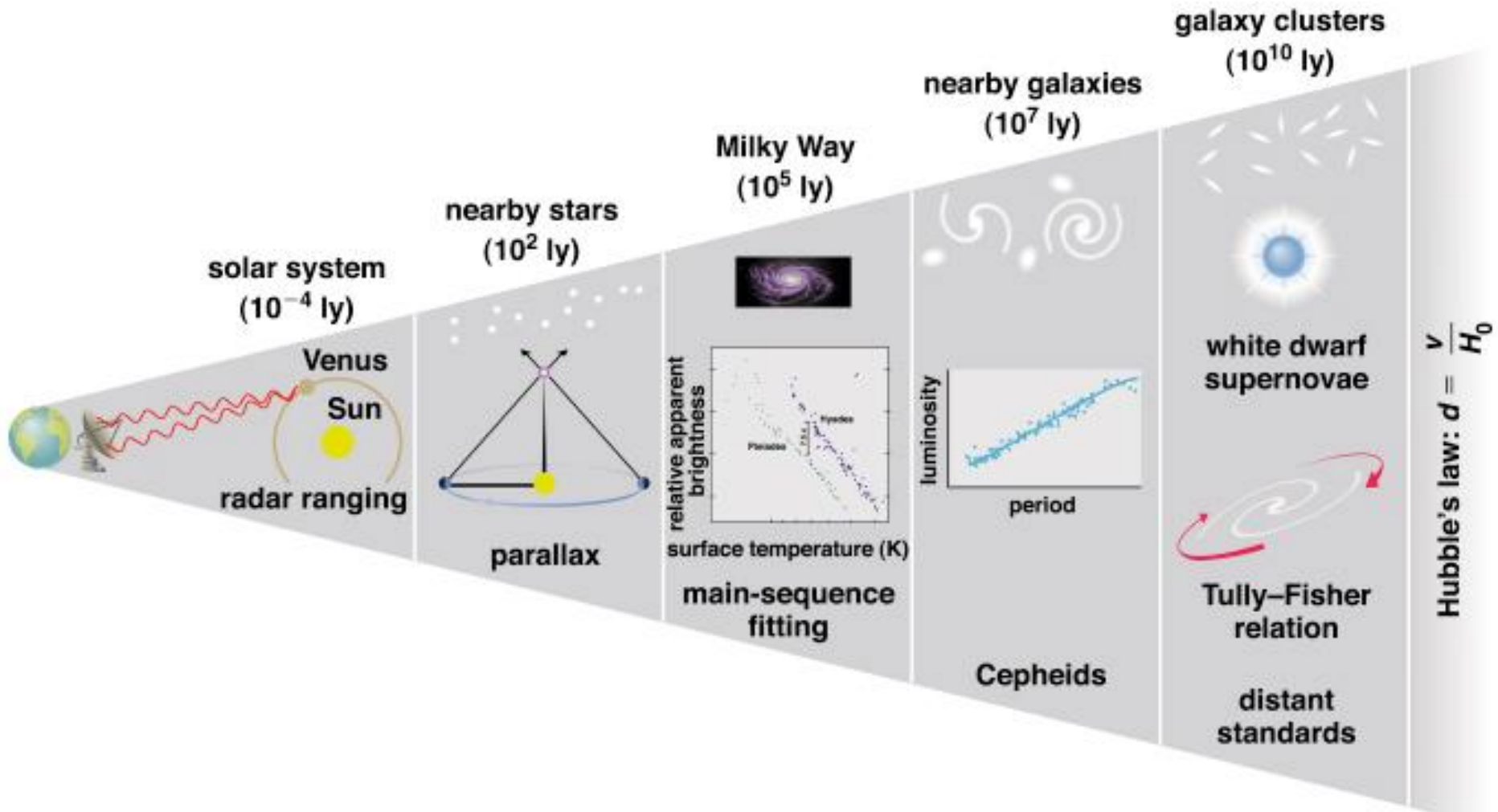
The smaller distances are controlled by even smaller distances...



... and so on, until one reaches distances that one can measure directly.



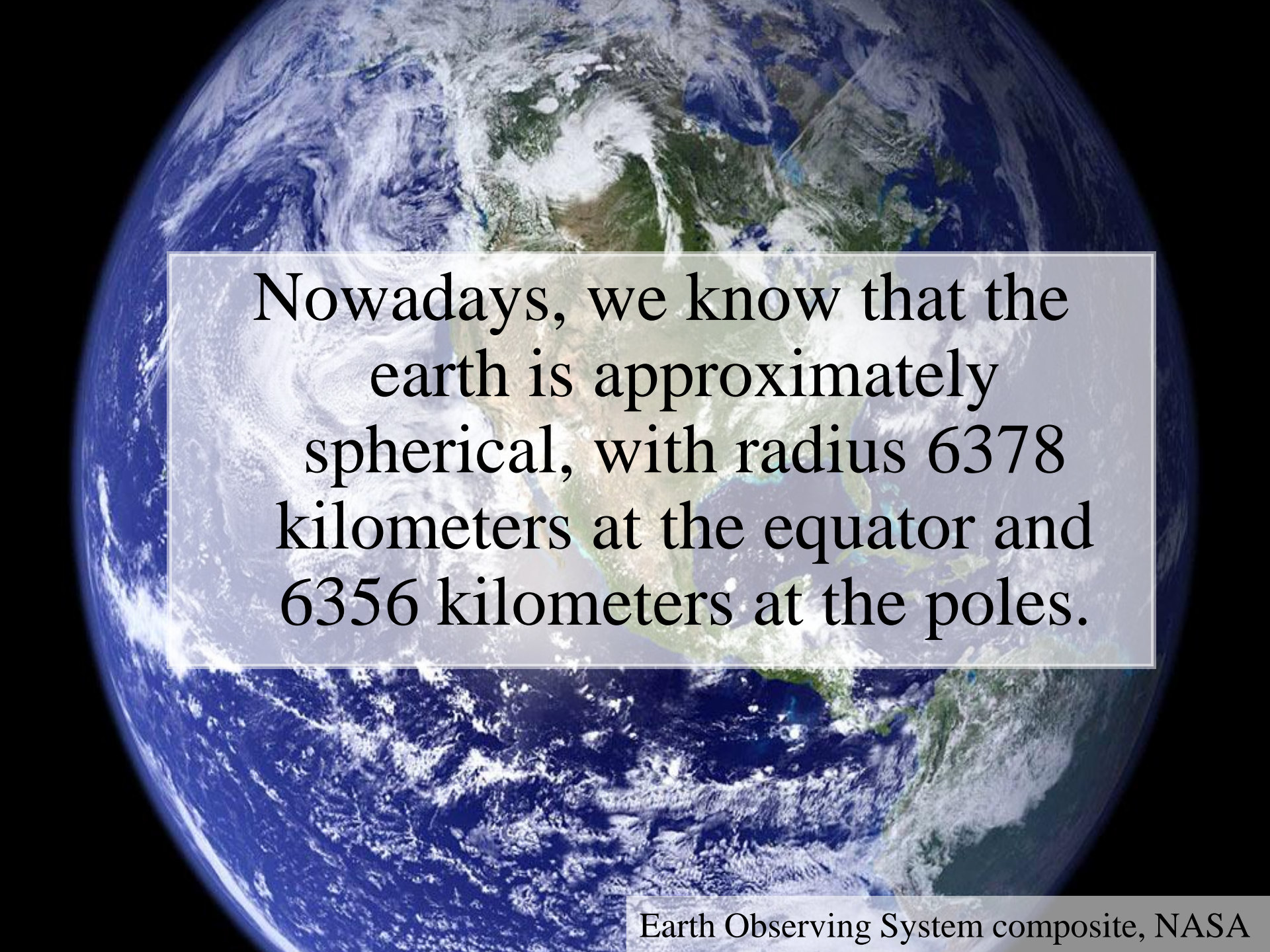
This is the **cosmic distance ladder**.






1st rung: the Earth

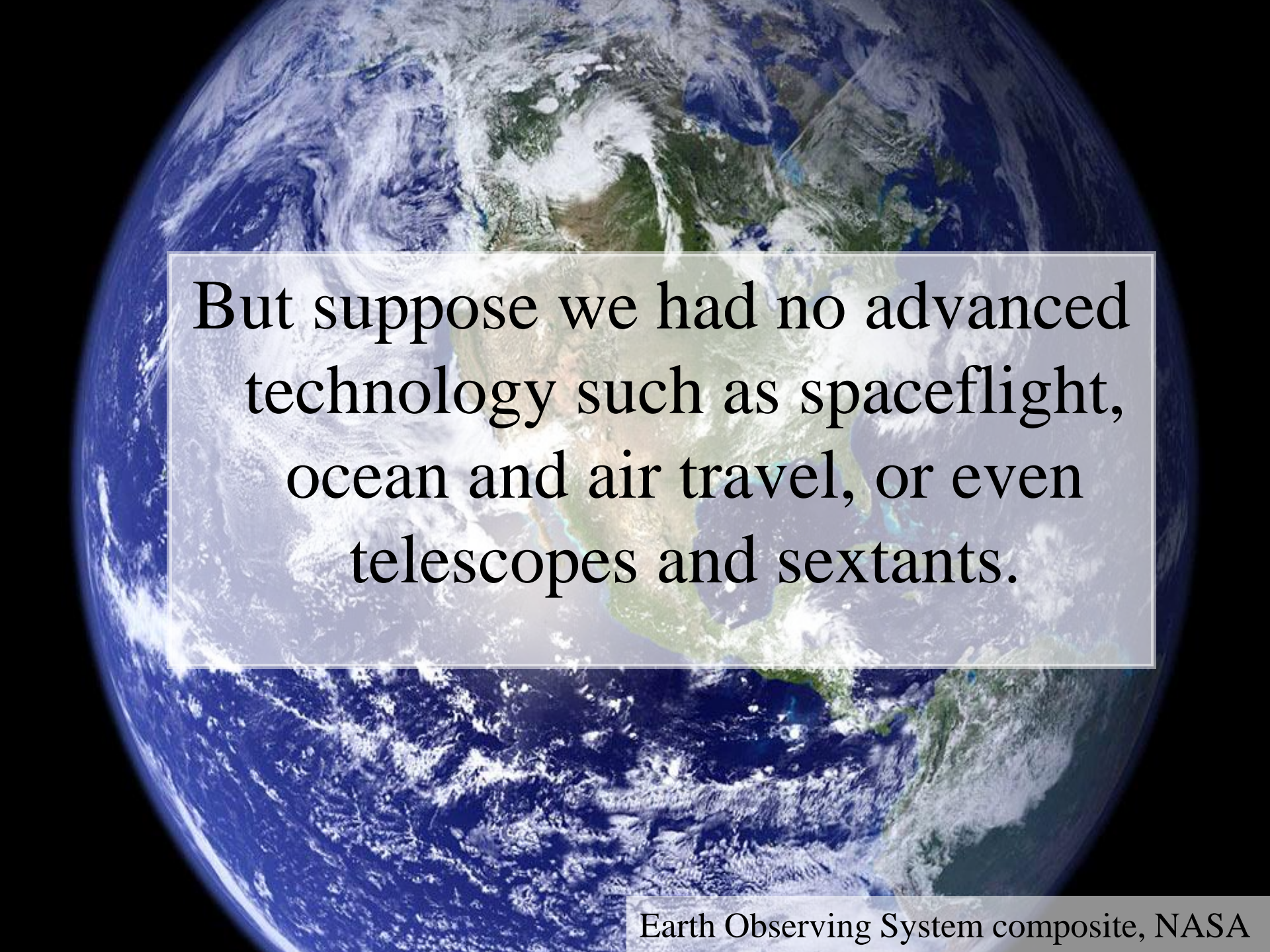
Earth Observing System composite, NASA



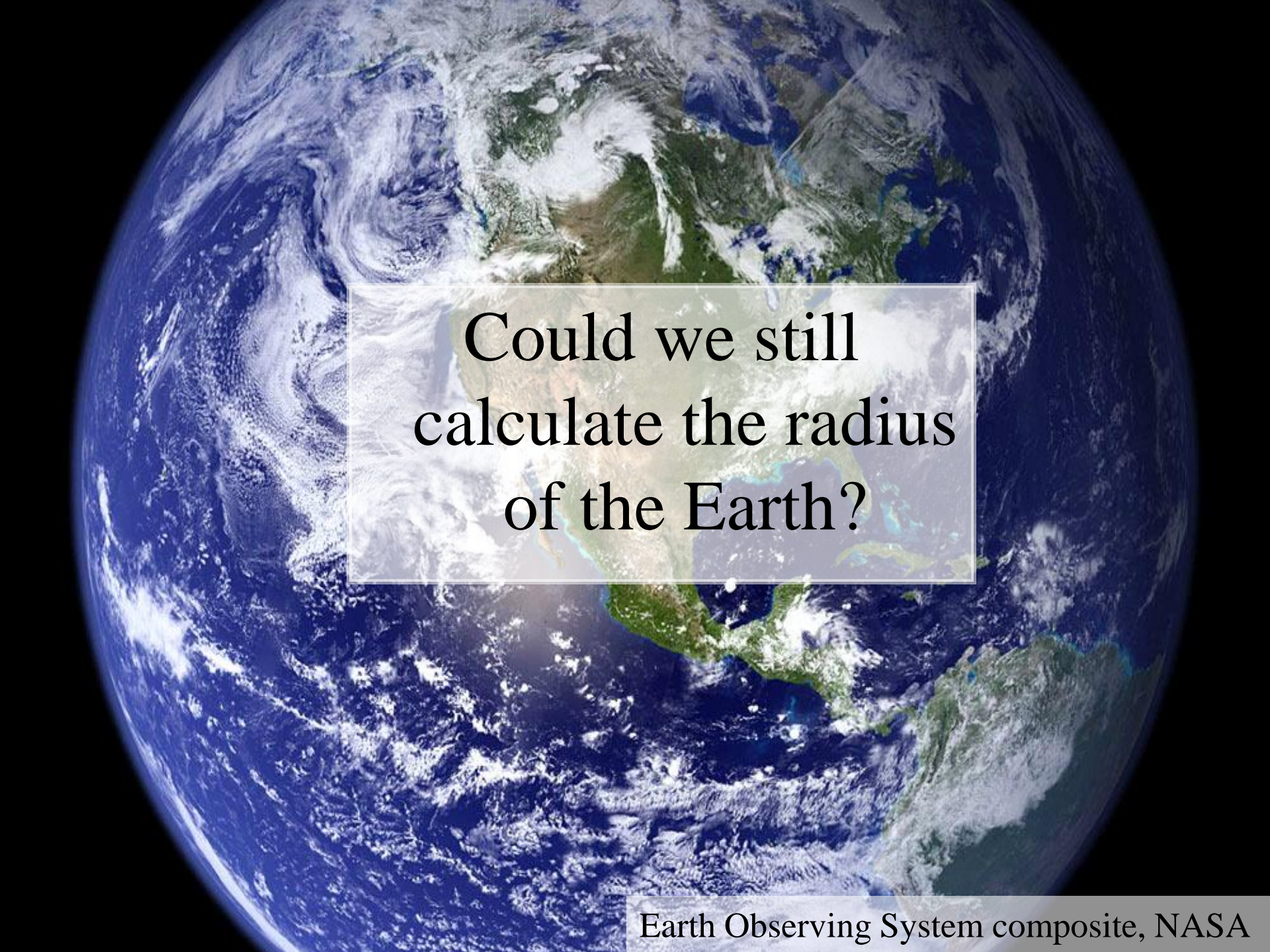
Nowadays, we know that the earth is approximately spherical, with radius 6378 kilometers at the equator and 6356 kilometers at the poles.

A composite satellite image of Earth showing the Americas and surrounding oceans, with a semi-transparent text box overlaid.

These values have now been
verified to great precision by
many means, including modern
satellites.



But suppose we had no advanced technology such as spaceflight, ocean and air travel, or even telescopes and sextants.



Could we still
calculate the radius
of the Earth?

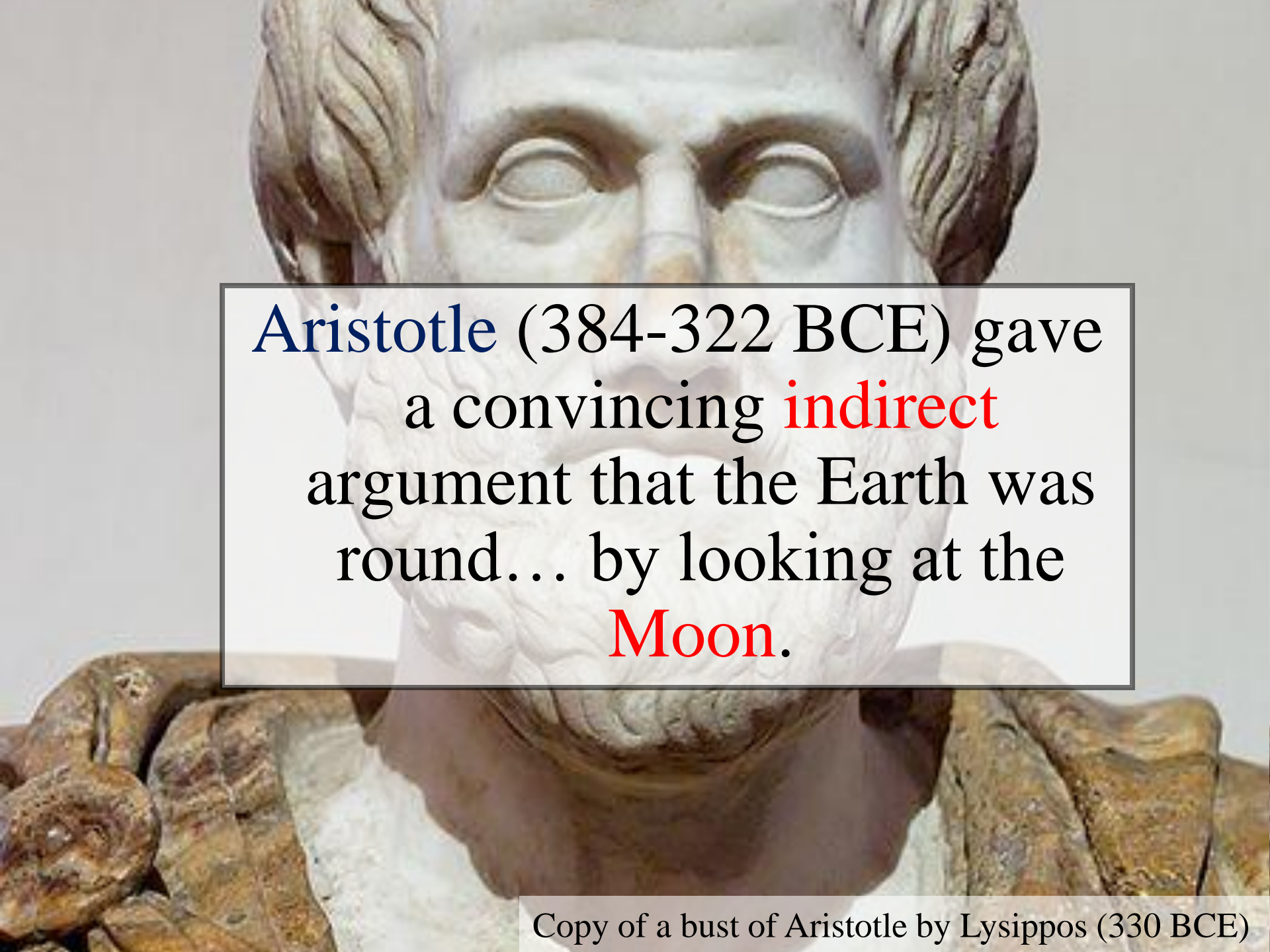
Earth Observing System composite, NASA

A composite satellite image of Earth from the Earth Observing System, showing the Americas and surrounding oceans. The image is a high-resolution view of the planet, with the Americas in the center, surrounded by the Atlantic and Pacific Oceans. The text "Could we even tell that the Earth was round?" is overlaid in a white box with a black border, centered over the continent of North America.

Could we even tell
that the Earth was
round?


Earth Observing System composite, NASA

The answer is **yes** – if one knows some geometry!

A marble bust of Aristotle, showing his face and curly hair. The bust is set against a light background. A white rectangular box with a black border is overlaid on the bust, containing text. The text is in a serif font, with some words in red. The bust is made of white marble and is mounted on a dark, textured base.

Aristotle (384-322 BCE) gave
a convincing **indirect**
argument that the Earth was
round... by looking at the
Moon.

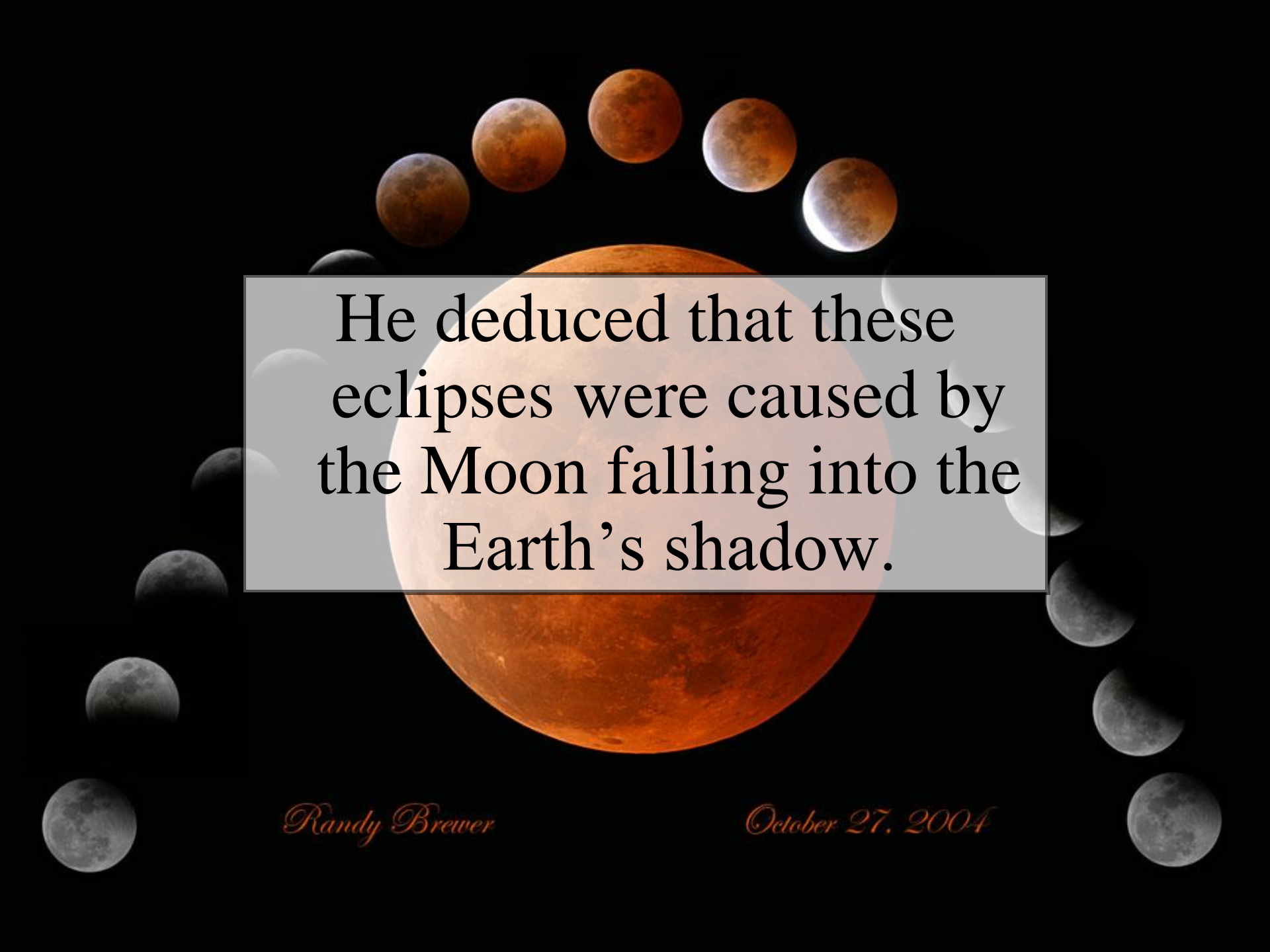
Copy of a bust of Aristotle by Lysippos (330 BCE)



Aristotle knew that **lunar eclipses** only occurred when the Moon was directly opposite the Sun.

Randy Brewer


October 27, 2004



He deduced that these eclipses were caused by the Moon falling into the Earth's shadow.

Randy Brewer


October 27, 2004



But the shadow of the
Earth on the Moon in an
eclipse was always a
circular arc.

Randy Brewer

October 27, 2004

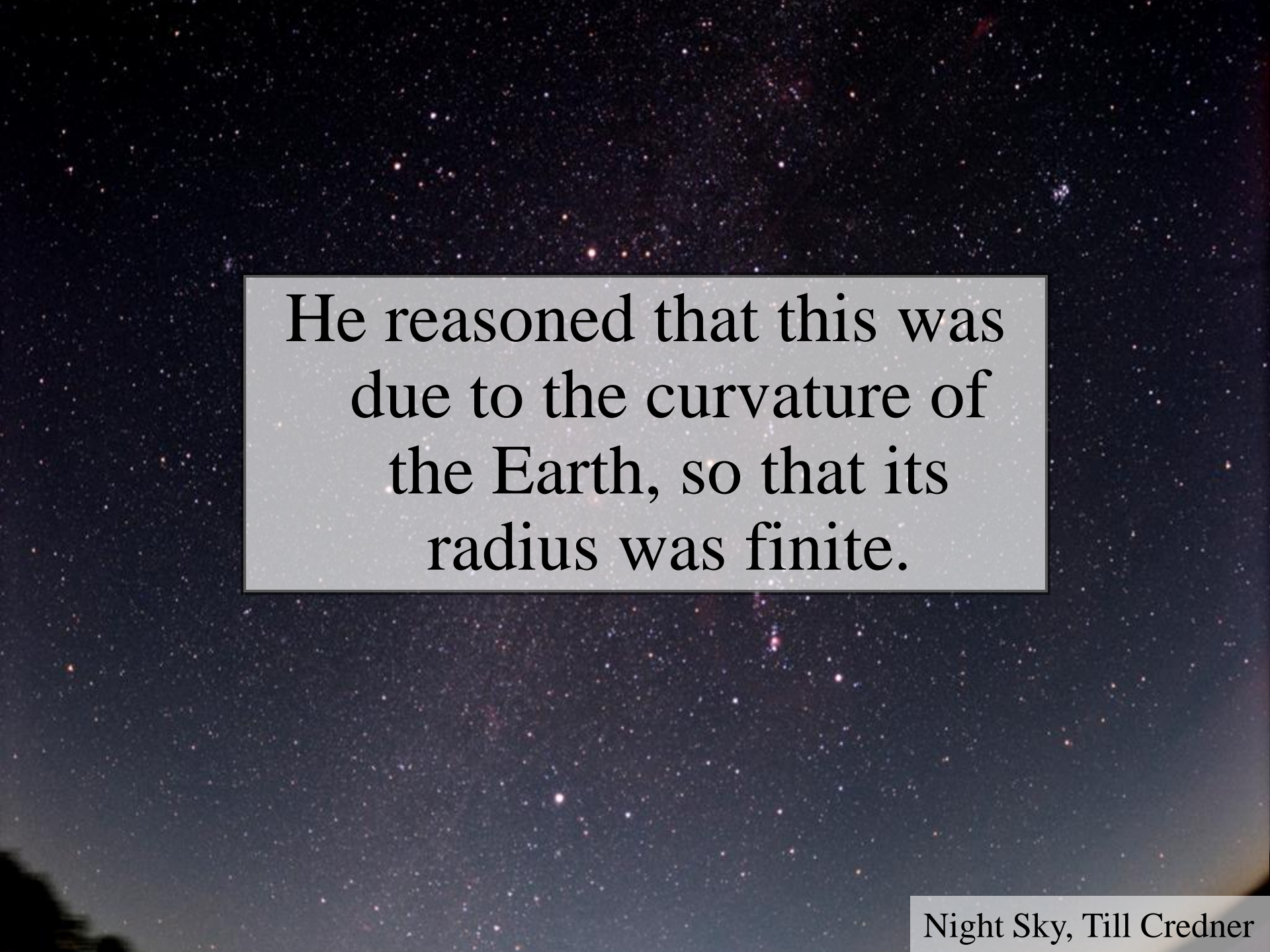


In order for Earth's shadows to always be circular, the Earth must be round.

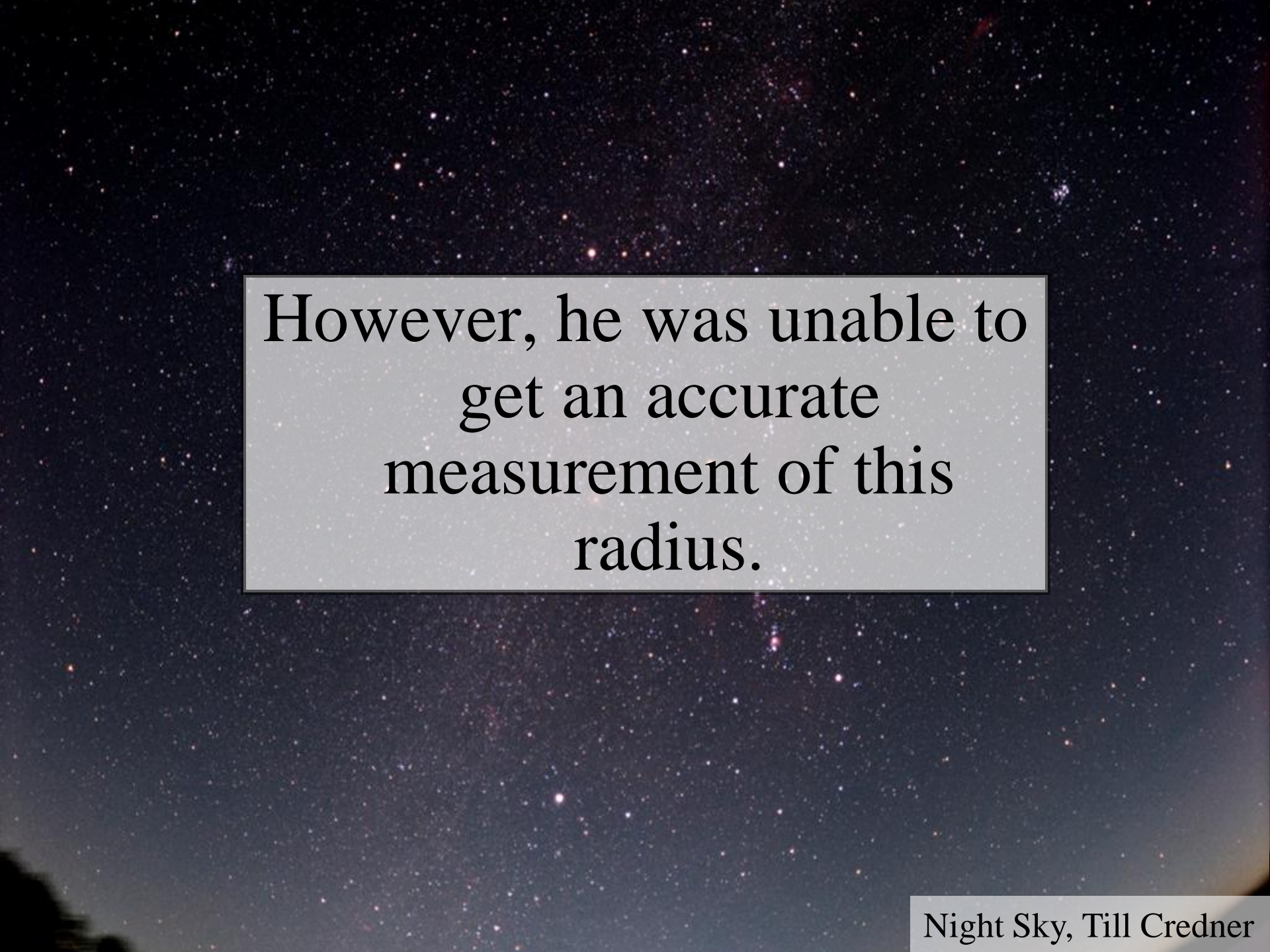
Randy Brewer

October 27, 2004

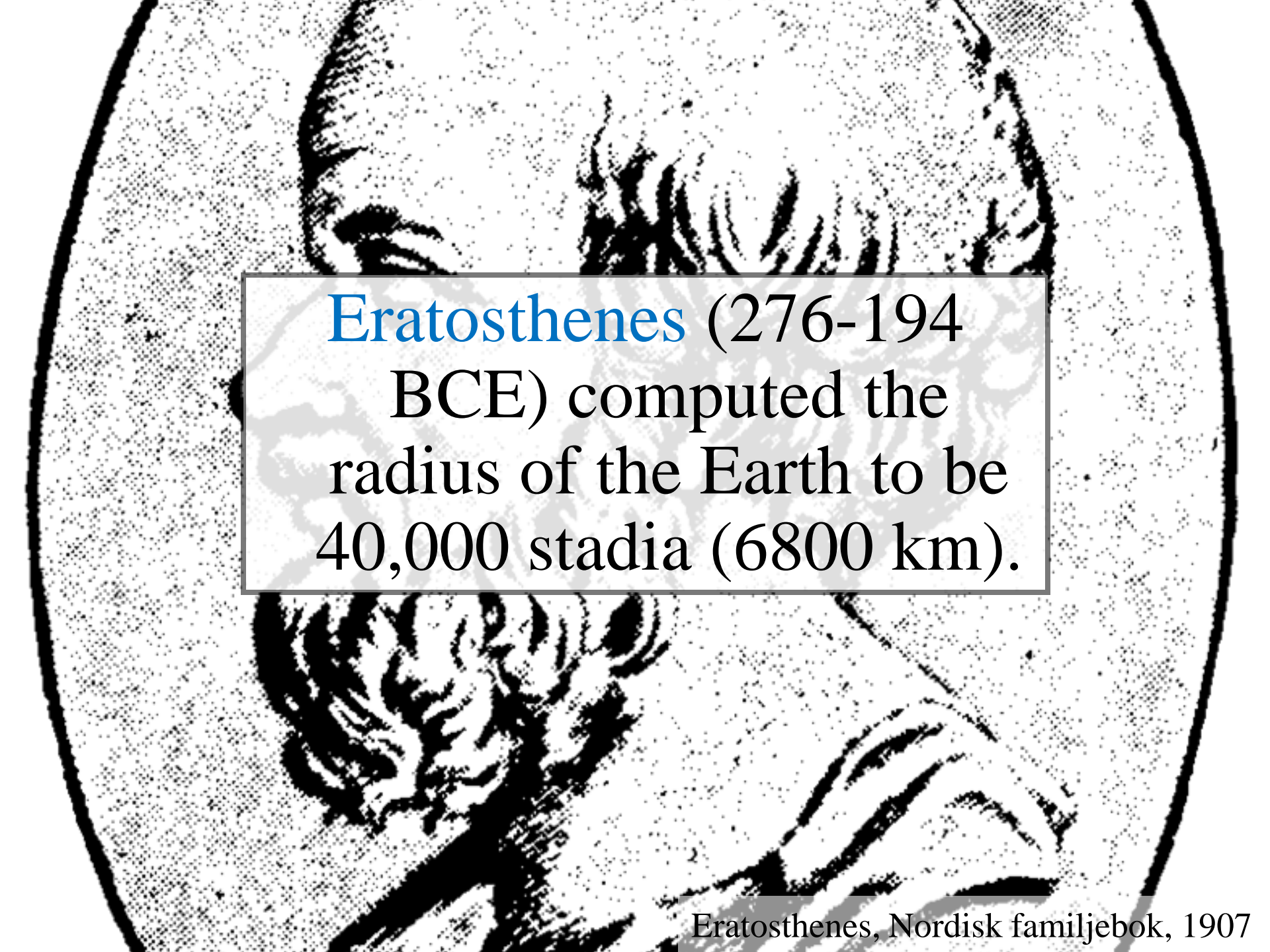
Aristotle also knew there were stars one could see in Greece but not in Egypt, or vice versa.

A dark, starry night sky with numerous stars of varying brightness and colors. A central text box with a light gray background and a thin black border contains the main text. The text is in a black, serif font and is centered within the box.

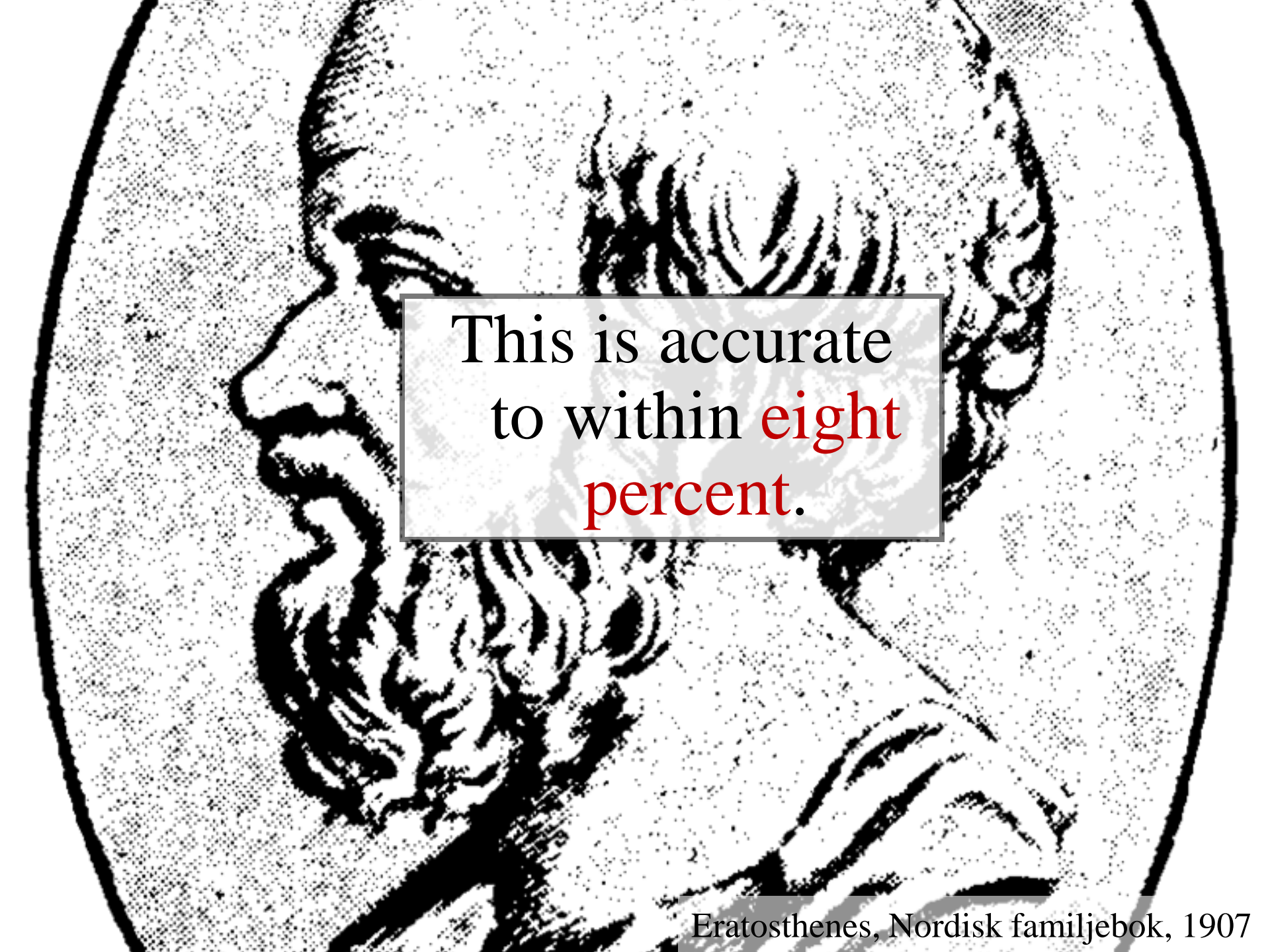
He reasoned that this was
due to the curvature of
the Earth, so that its
radius was finite.

The background of the slide is a deep blue night sky filled with numerous stars of varying brightness and colors, including some reddish and bluish hues. A central white rectangular box with a thin black border contains the main text.

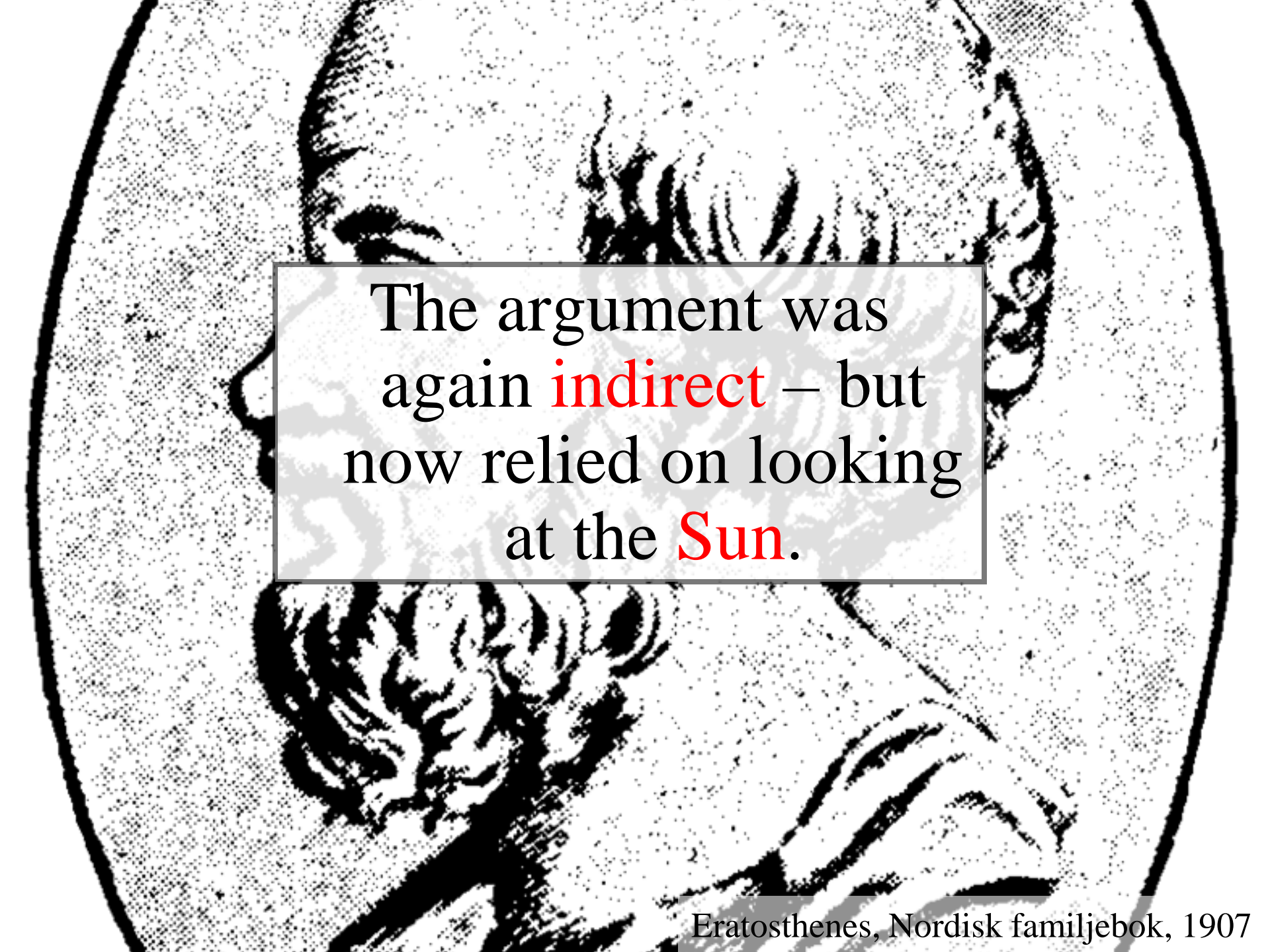
However, he was unable to
get an accurate
measurement of this
radius.



Eratosthenes (276-194 BCE) computed the radius of the Earth to be 40,000 stadia (6800 km).



This is accurate
to within **eight**
percent.



The argument was
again **indirect** – but
now relied on looking
at the **Sun**.

Eratosthenes read of a well in Syene, Egypt which at noon on the summer solstice (June 21) would reflect the overhead sun.



[This is because Syene lies almost directly on the
Tropic of Cancer.]



Eratosthenes tried the same experiment in his home city of Alexandria.



But on the solstice, the sun was at an angle and did not reflect from the bottom of the well.



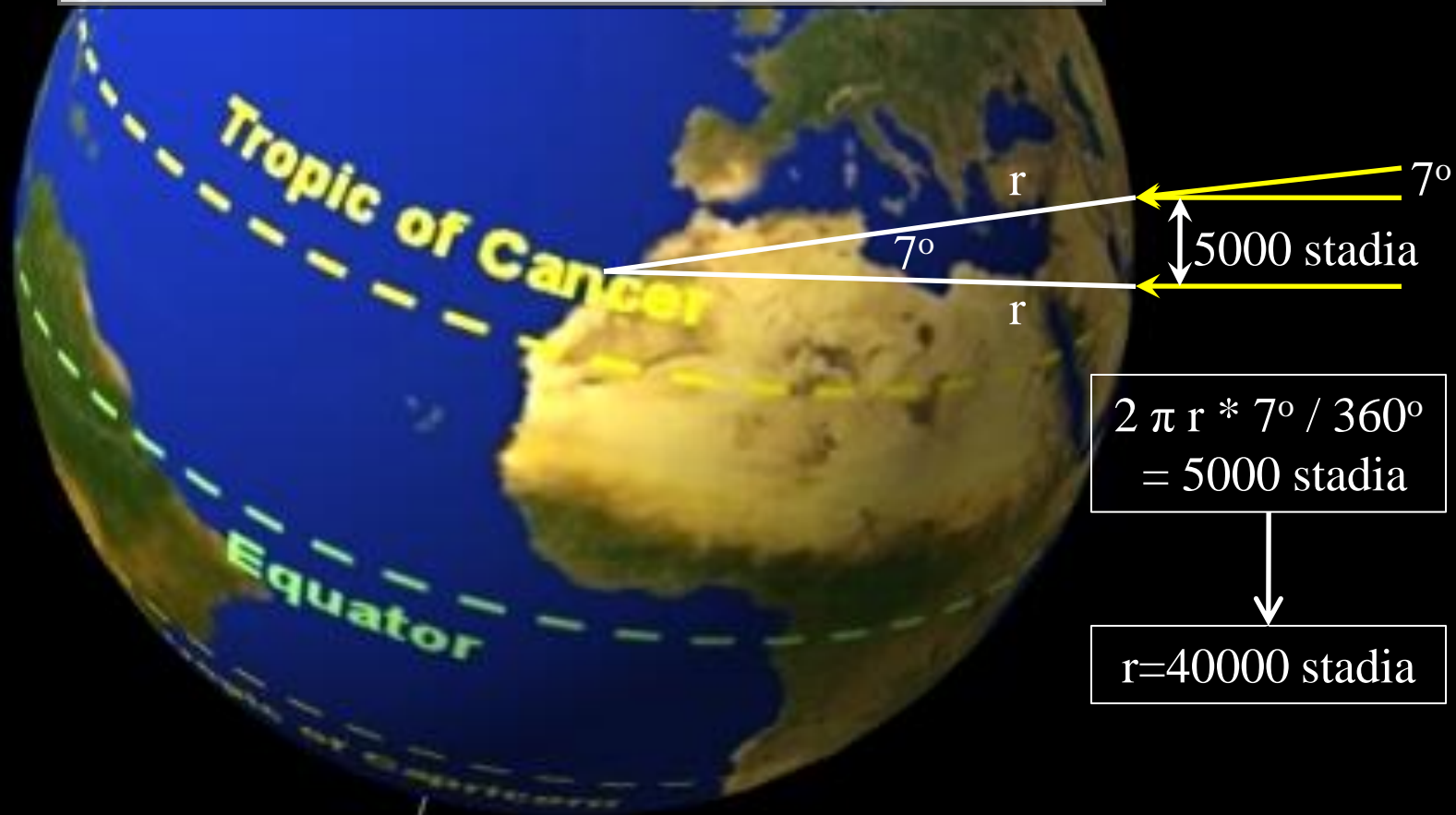
Using a **gnomon** (measuring stick), Eratosthenes measured the deviation of the sun from the vertical as 7° .



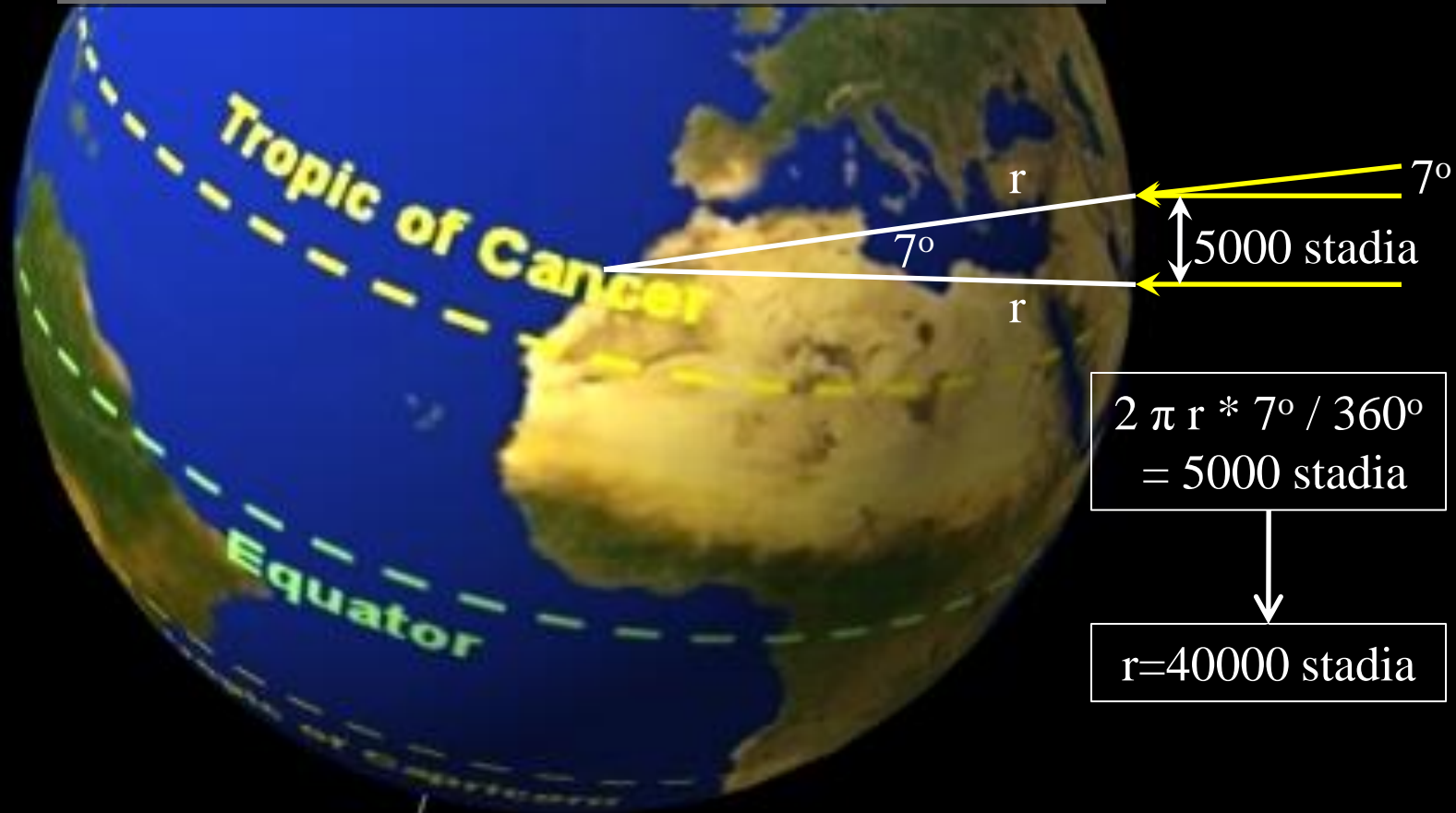
From trade caravans and other sources, Eratosthenes knew Syene to be 5,000 stadia (740 km) south of Alexandria.



This is enough information to compute the radius of the Earth.

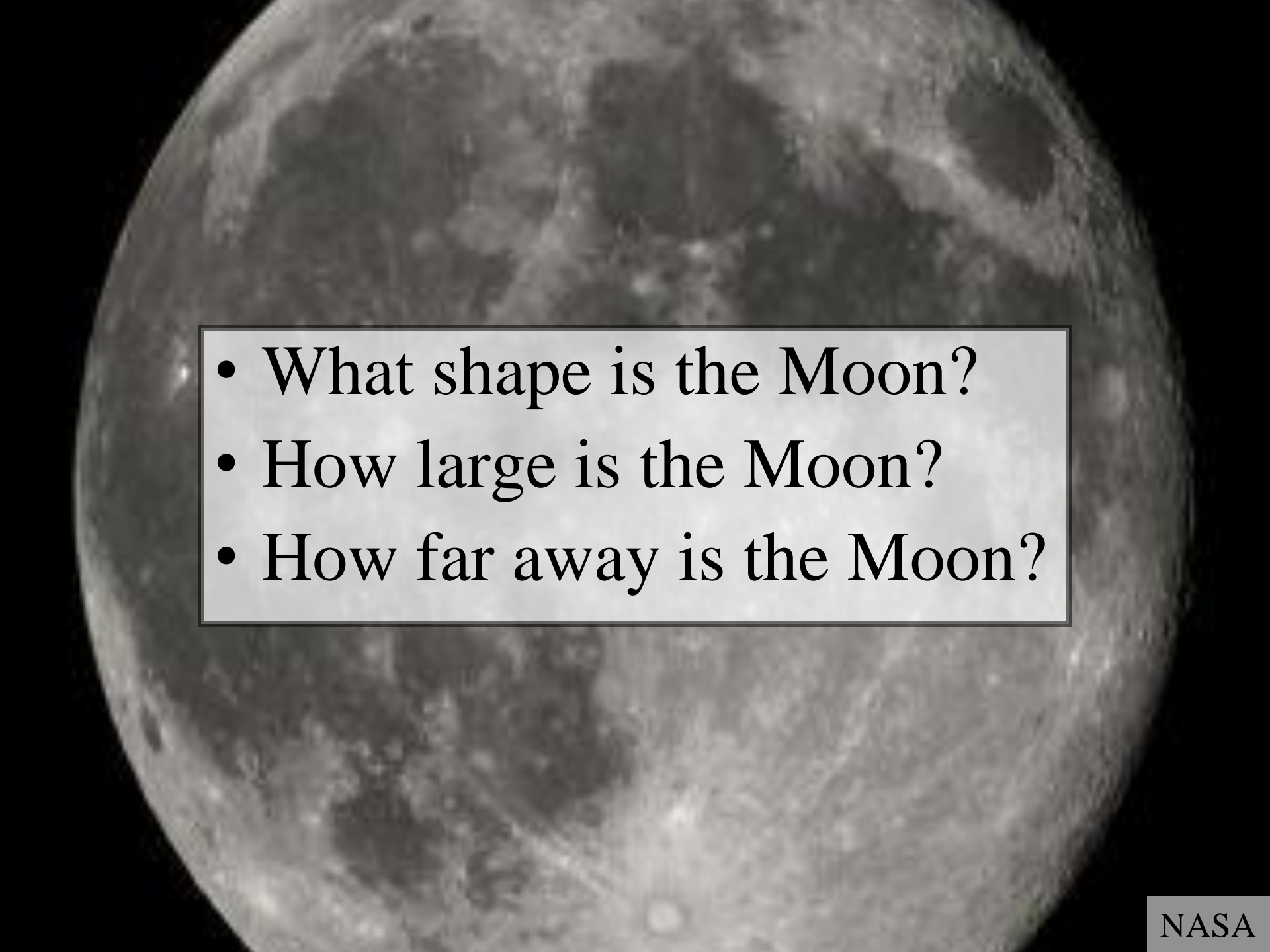



[This assumes that the Sun is quite far away, but more on this later.]



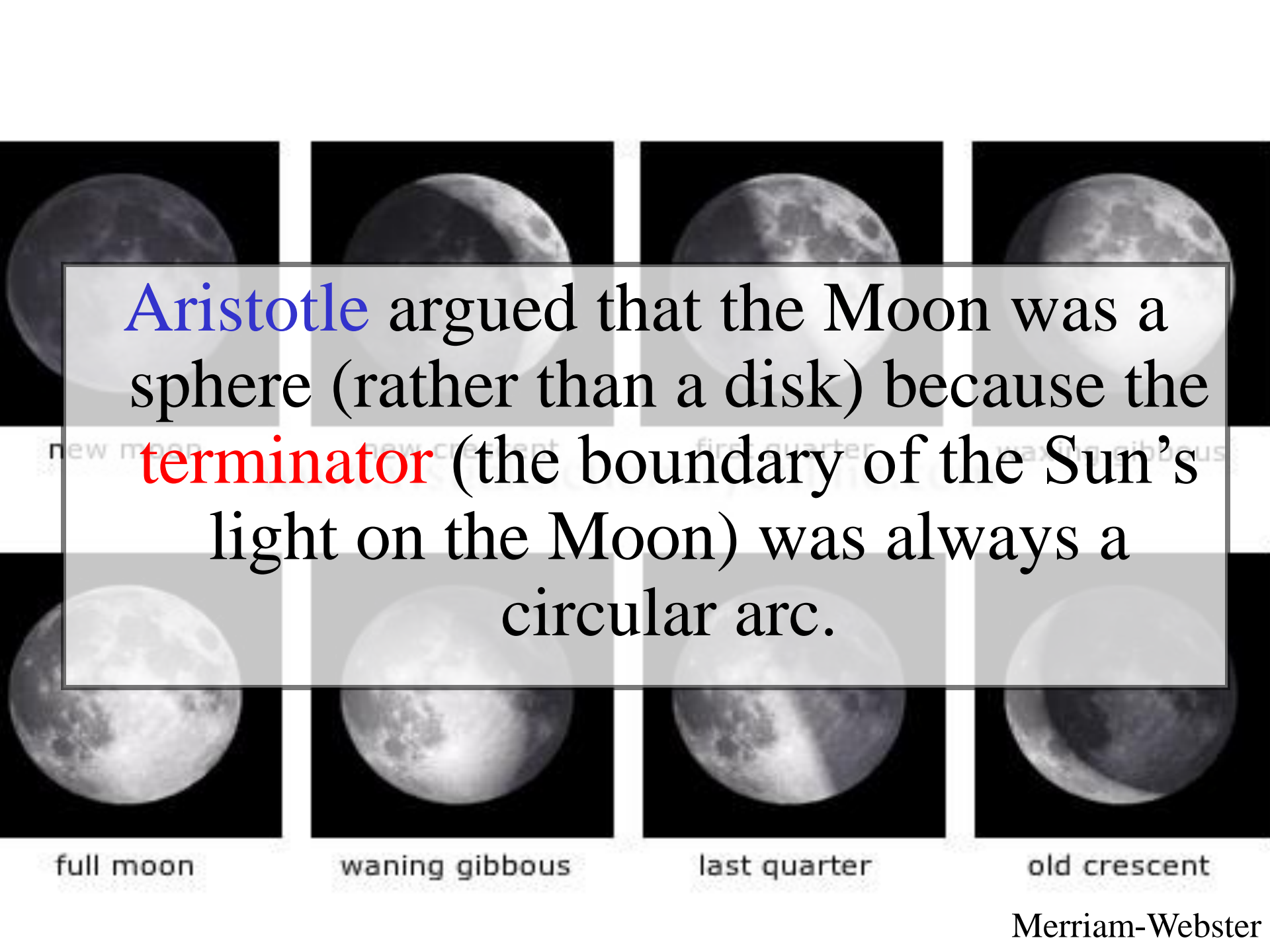


**2nd rung: the
Moon**

- 
- What shape is the Moon?
 - How large is the Moon?
 - How far away is the Moon?



The ancient Greeks
could answer these
questions also.

A grid of eight moon phase images arranged in two rows of four. The top row shows the moon from a waxing crescent to a waxing gibbous. The bottom row shows the moon from a full moon to an old crescent. A central text box is overlaid on the grid.

Aristotle argued that the Moon was a sphere (rather than a disk) because the **terminator** (the boundary of the Sun's light on the Moon) was always a circular arc.

new moon

full moon

waxing crescent

waning gibbous

first quarter

last quarter

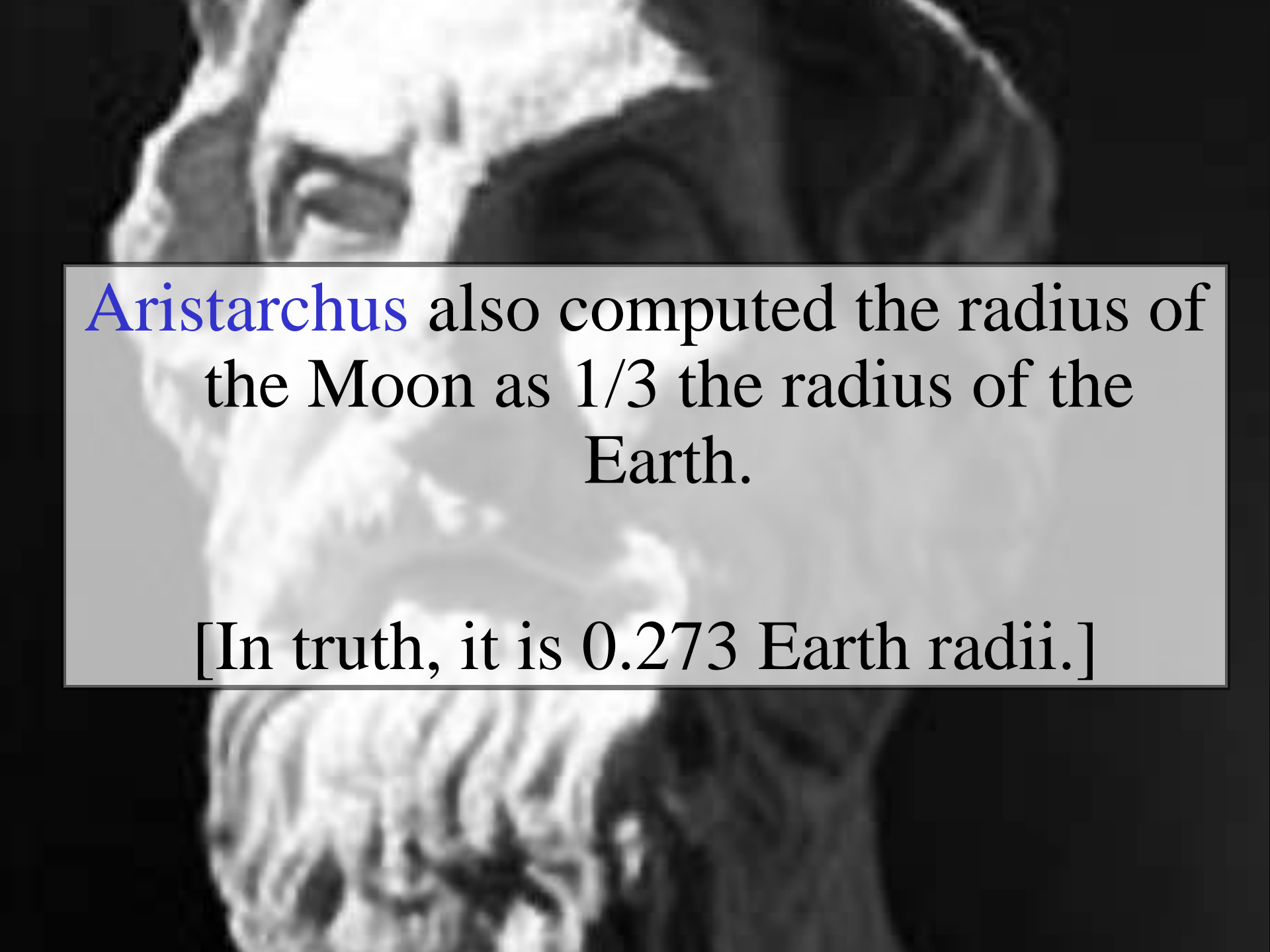
waxing gibbous

old crescent



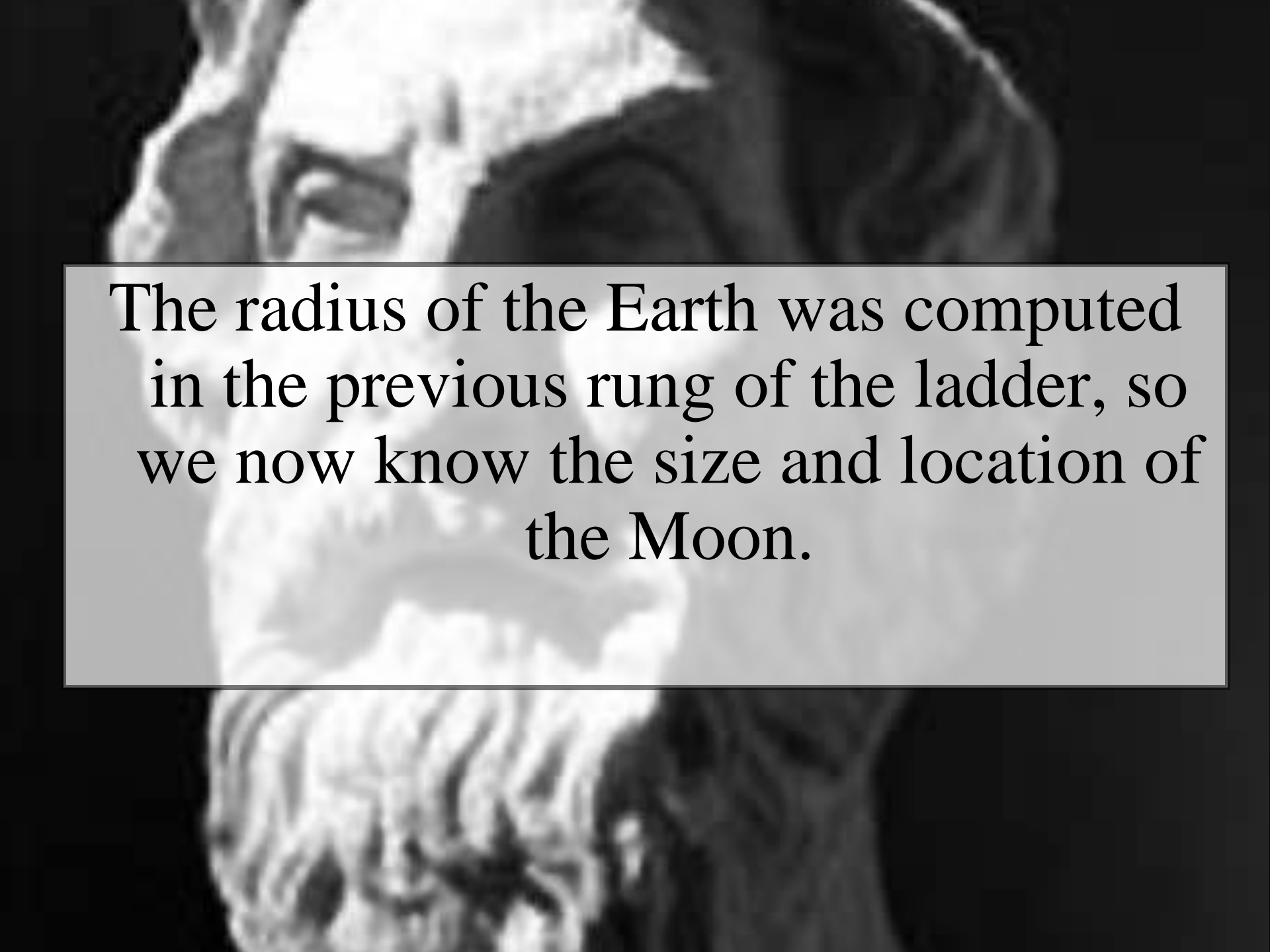
Aristarchus (310-230 BCE) computed
the distance of the Earth to the Moon
as about 60 Earth radii.

[In truth, it varies from 57 to 63 Earth
radii.]

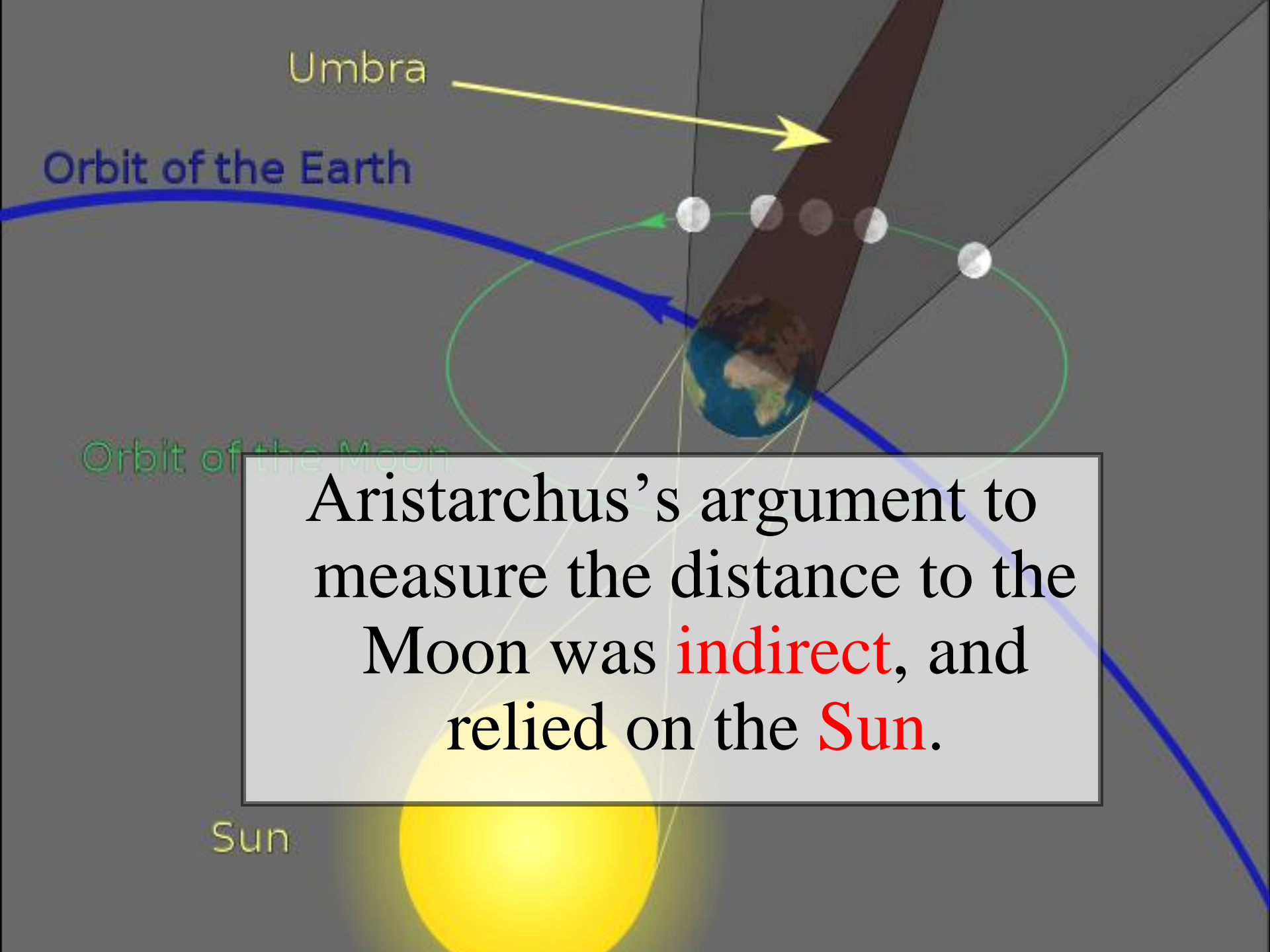


Aristarchus also computed the radius of the Moon as $\frac{1}{3}$ the radius of the Earth.

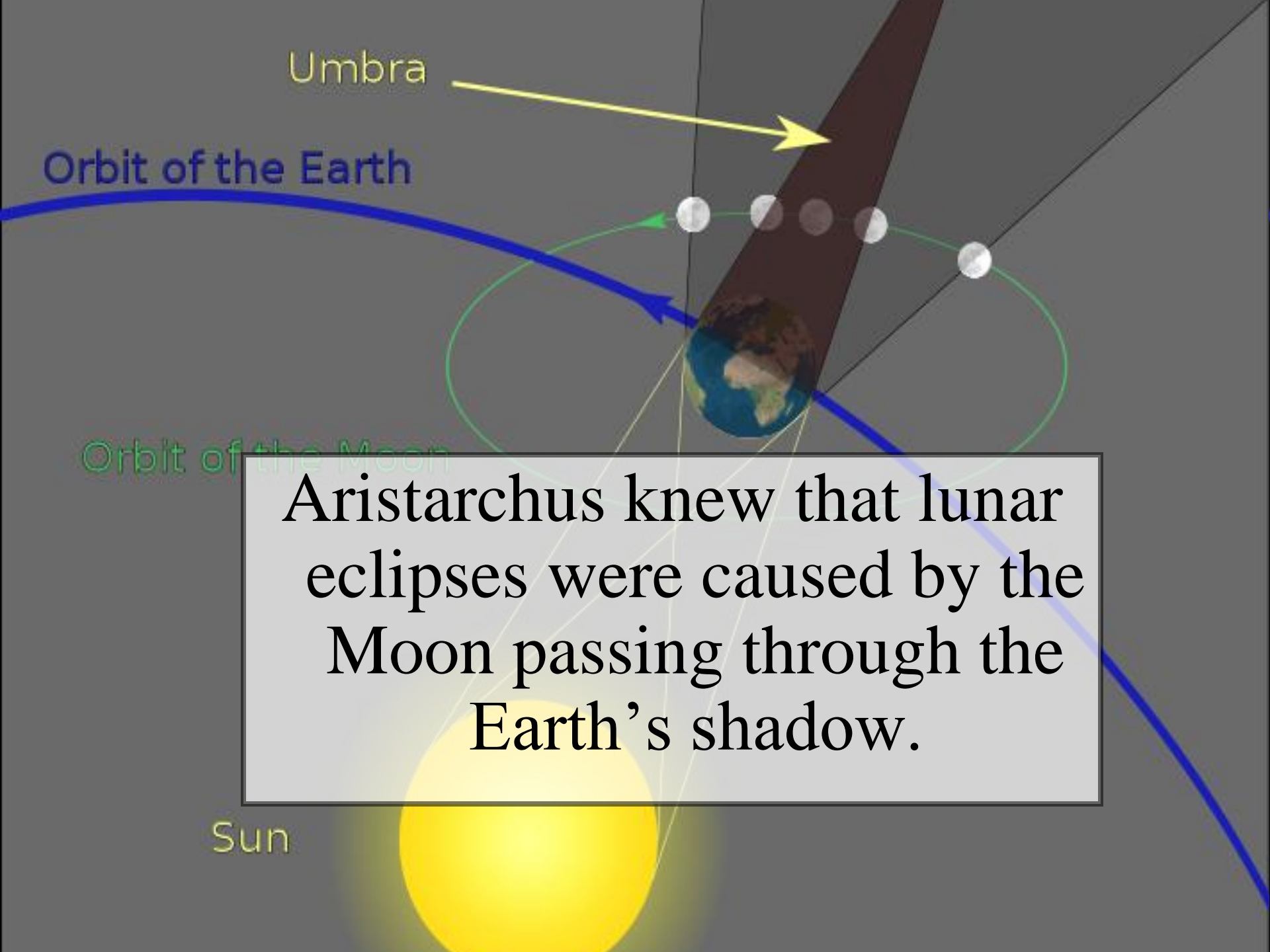
[In truth, it is 0.273 Earth radii.]



The radius of the Earth was computed in the previous rung of the ladder, so we now know the size and location of the Moon.



Aristarchus's argument to measure the distance to the Moon was **indirect**, and relied on the **Sun**.



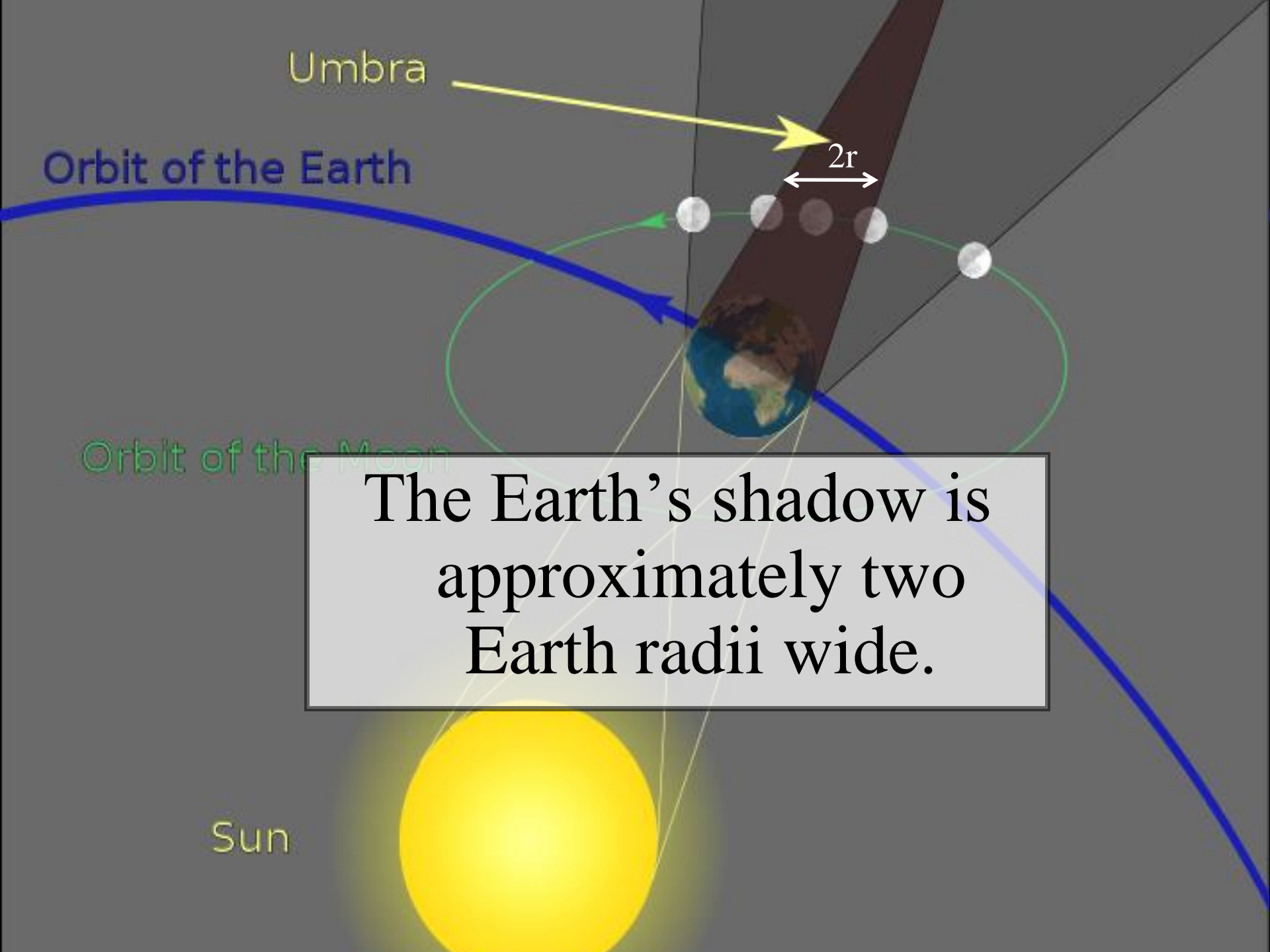
Umbra

Orbit of the Earth

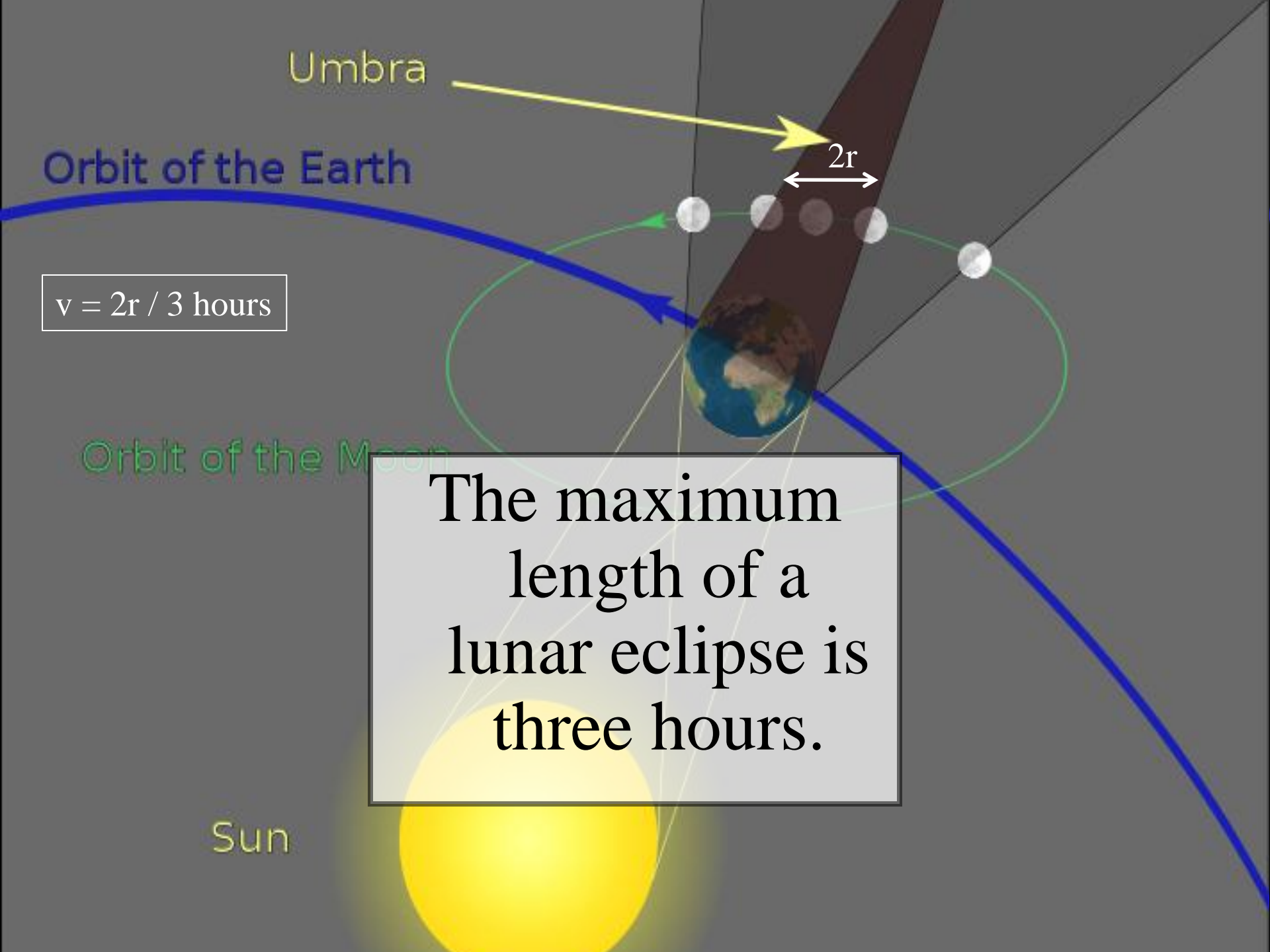
Orbit of the Moon

Sun

Aristarchus knew that lunar eclipses were caused by the Moon passing through the Earth's shadow.



The Earth's shadow is approximately two Earth radii wide.



Umbra

Orbit of the Earth

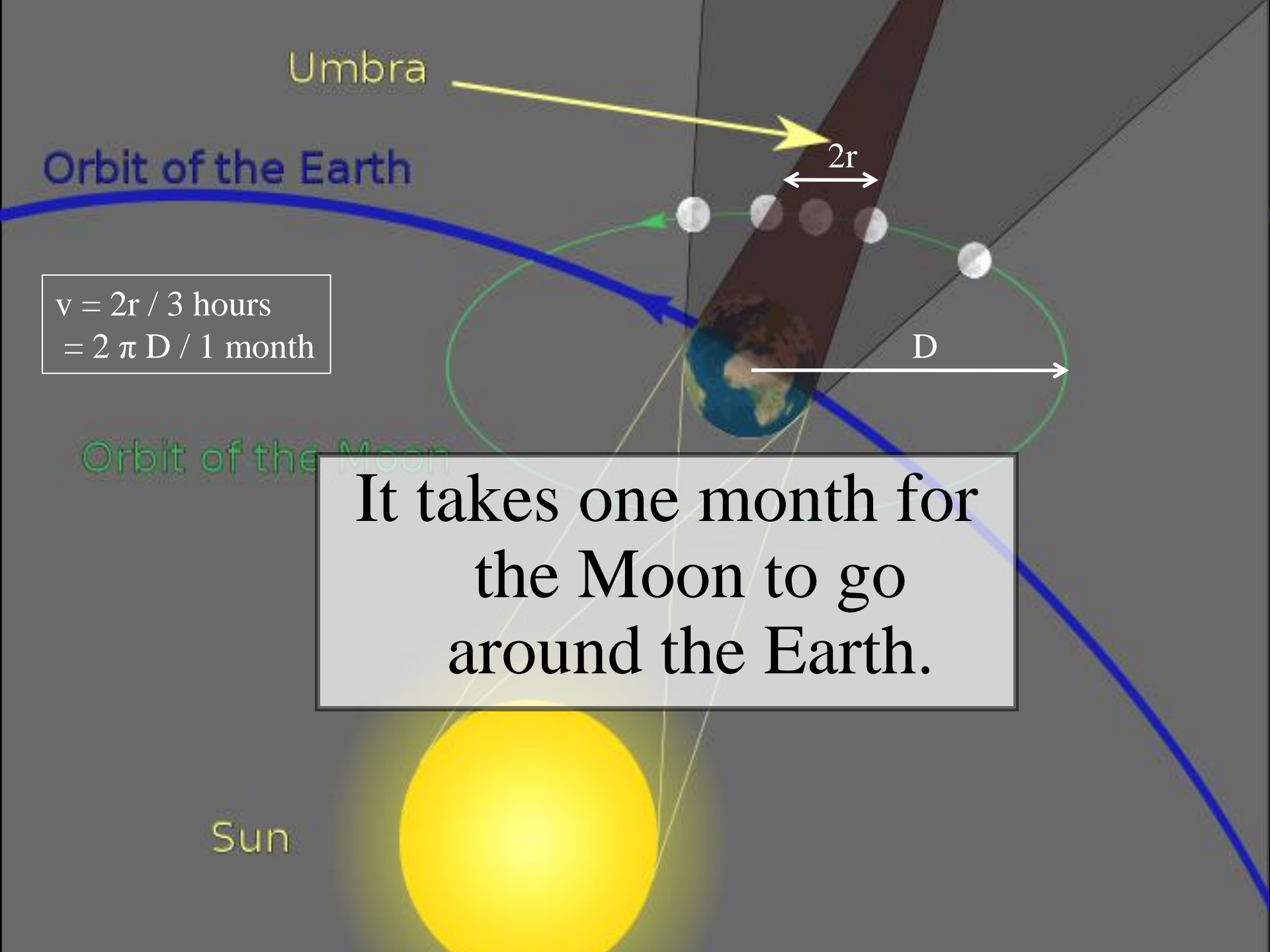
$$v = 2r / 3 \text{ hours}$$

$2r$

Orbit of the Moon

The maximum length of a lunar eclipse is three hours.

Sun



Umbra

Orbit of the Earth

$$v = 2r / 3 \text{ hours}$$
$$= 2 \pi D / 1 \text{ month}$$

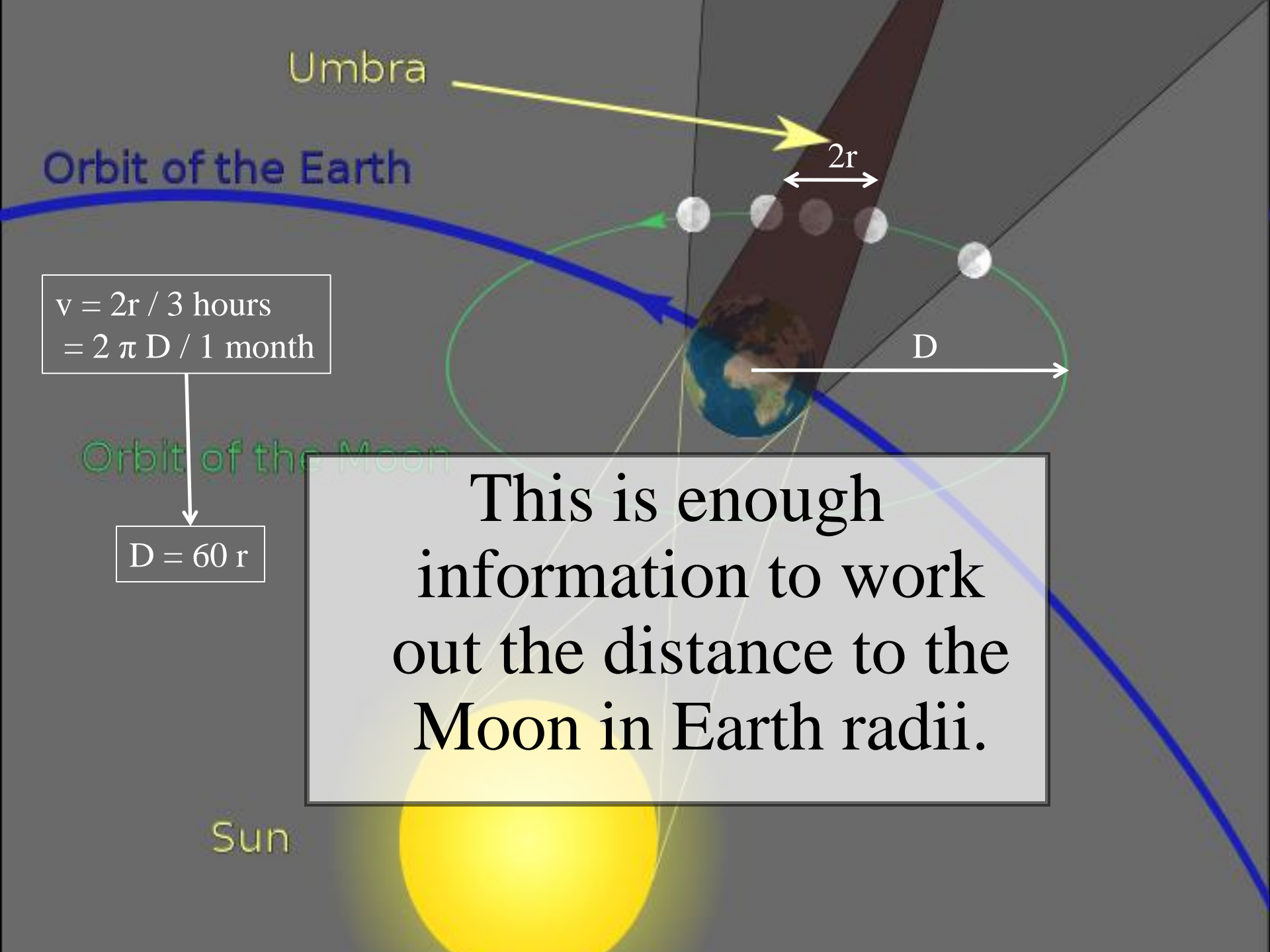
$2r$

D

Orbit of the Moon

It takes one month for
the Moon to go
around the Earth.

Sun



Umbra

Orbit of the Earth

$$v = 2r / 3 \text{ hours}$$
$$= 2 \pi D / 1 \text{ month}$$

$$D = 60 r$$

Orbit of the Moon

This is enough information to work out the distance to the Moon in Earth radii.

Sun

$$V = 2R / 2 \text{ min}$$



Also, the Moon takes
about 2 minutes to
set.

$$V = 2R / 2 \text{ min}$$
$$= 2 \pi D / 24 \text{ hours}$$



The Moon takes 24 hours
to make a full (apparent)
rotation around the Earth.

$$V = 2R / 2 \text{ min} \\ = 2 \pi D / 24 \text{ hours}$$

$$R = D / 180$$

$2R$



This is enough information
to determine the radius of
the Moon, in terms of the
distance to the Moon...

$$V = 2R / 2 \text{ min} \\ = 2 \pi D / 24 \text{ hours}$$

$$R = D / 180 \\ = r / 3$$

$2R$



... which we have
just computed.

$$V = 2R / 2 \text{ min} \\ = 2 \pi D / 24 \text{ hours}$$


$$R = D / 180 \\ = r / 3$$




[Aristarchus, by the way, was handicapped by not having an accurate value of π , which had to wait until **Archimedes** (287-212BCE) some decades later!]




3rd rung: the Sun

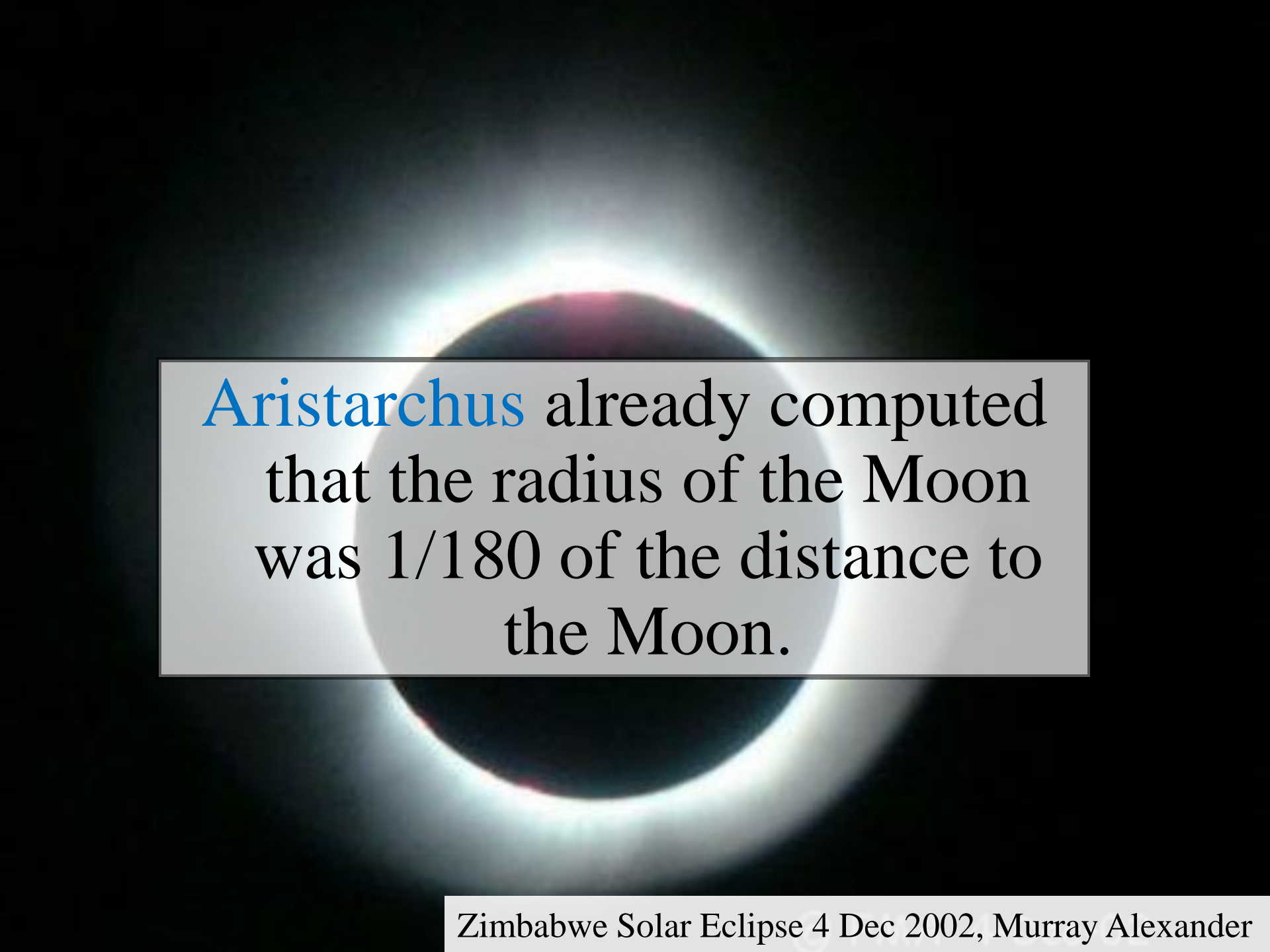
- 
- How large is the Sun?
 - How far away is the Sun?




Once again, the ancient Greeks
could answer these questions
(but with imperfect accuracy).




Their methods were **indirect**,
and relied on the **Moon**.




Aristarchus already computed
that the radius of the Moon
was $1/180$ of the distance to
the Moon.




He also knew that during a solar eclipse, the Moon covered the Sun almost perfectly.



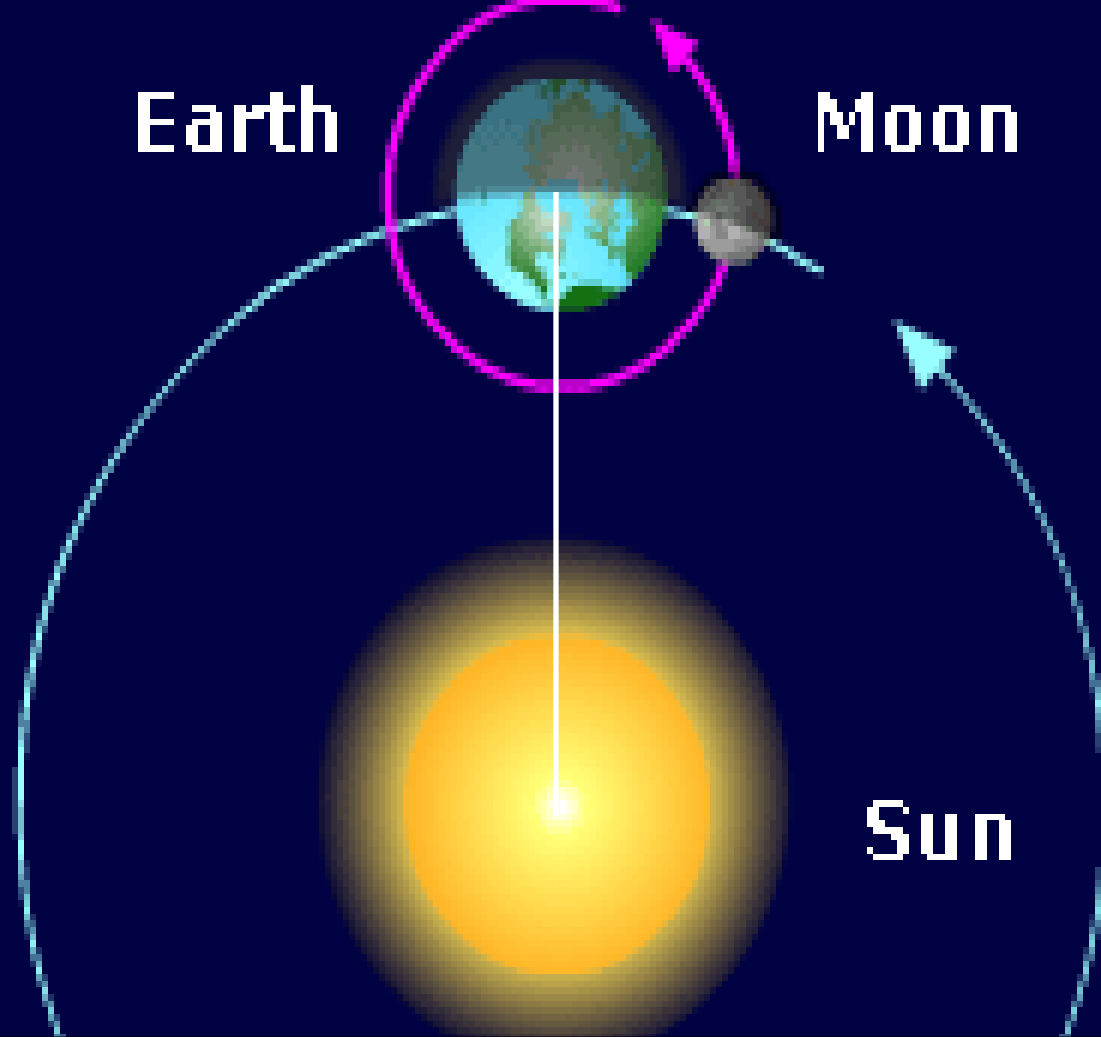
Using **similar triangles**, he concluded that the radius of the Sun was also $1/180$ of the distance to the Sun.

A photograph of a total solar eclipse. The sun is completely obscured by the moon, leaving only a bright white ring of light (the corona) visible against a dark sky. The corona has a soft, ethereal glow. A semi-transparent white rectangular box with a thin black border is centered over the middle of the eclipse. Inside this box, the text "So his next task was to compute the distance to the Sun." is written in a black, serif font, centered horizontally and vertically.

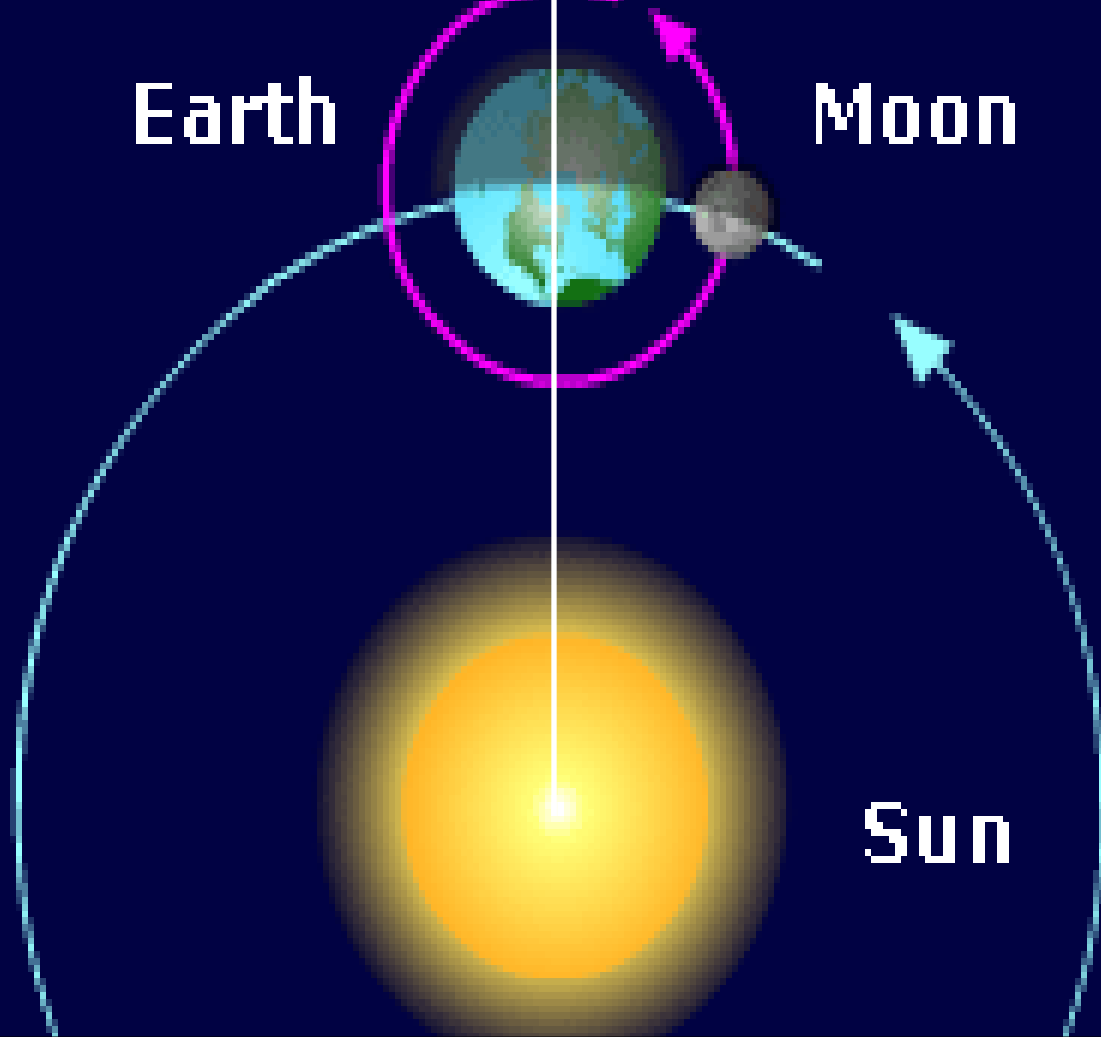
So his next task was to
compute the distance
to the Sun.



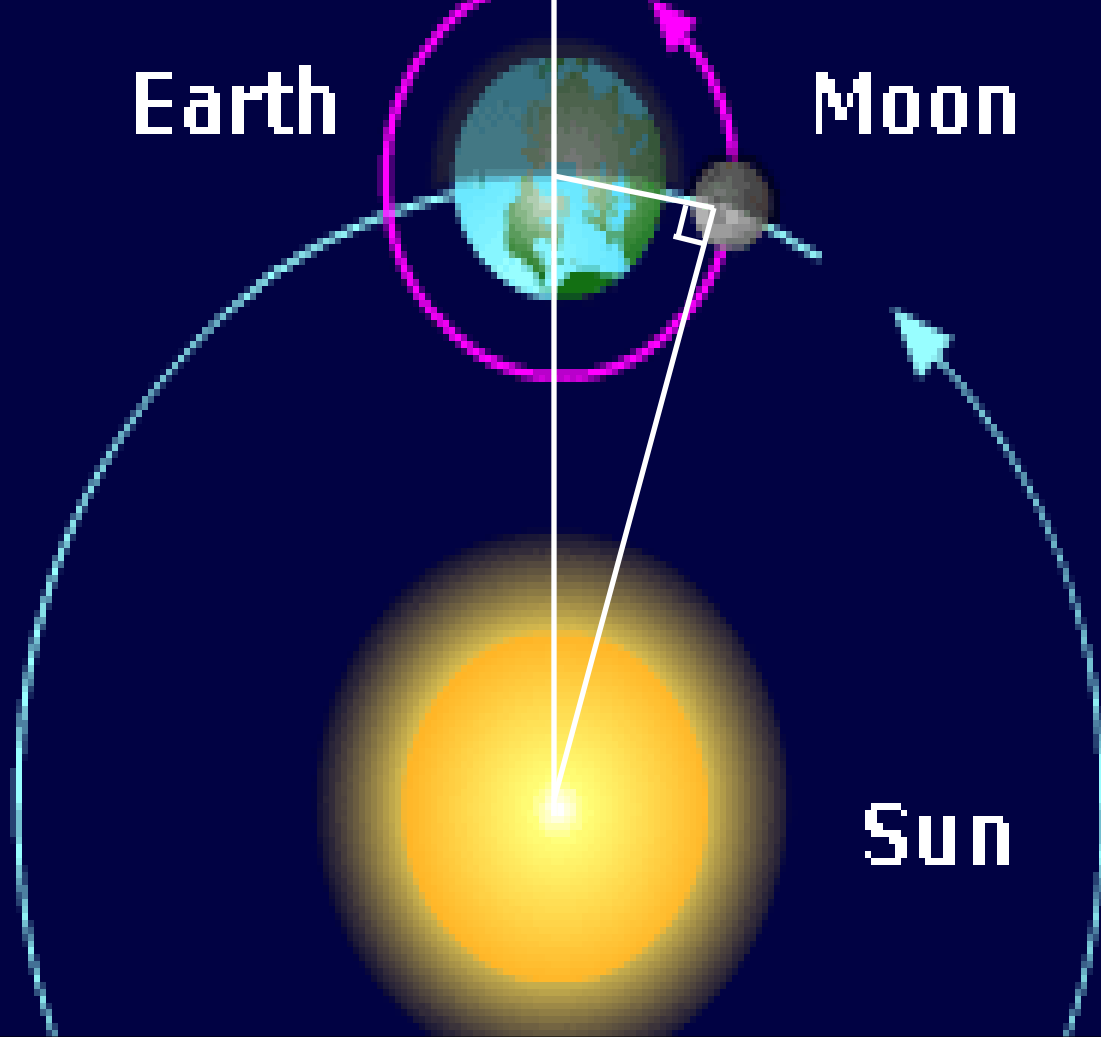
For this, he turned to
the Moon again for
help.



He knew that new Moons occurred when the Moon was between the Earth and Sun...



... full Moons occurred when the Moon was directly opposite the Sun...

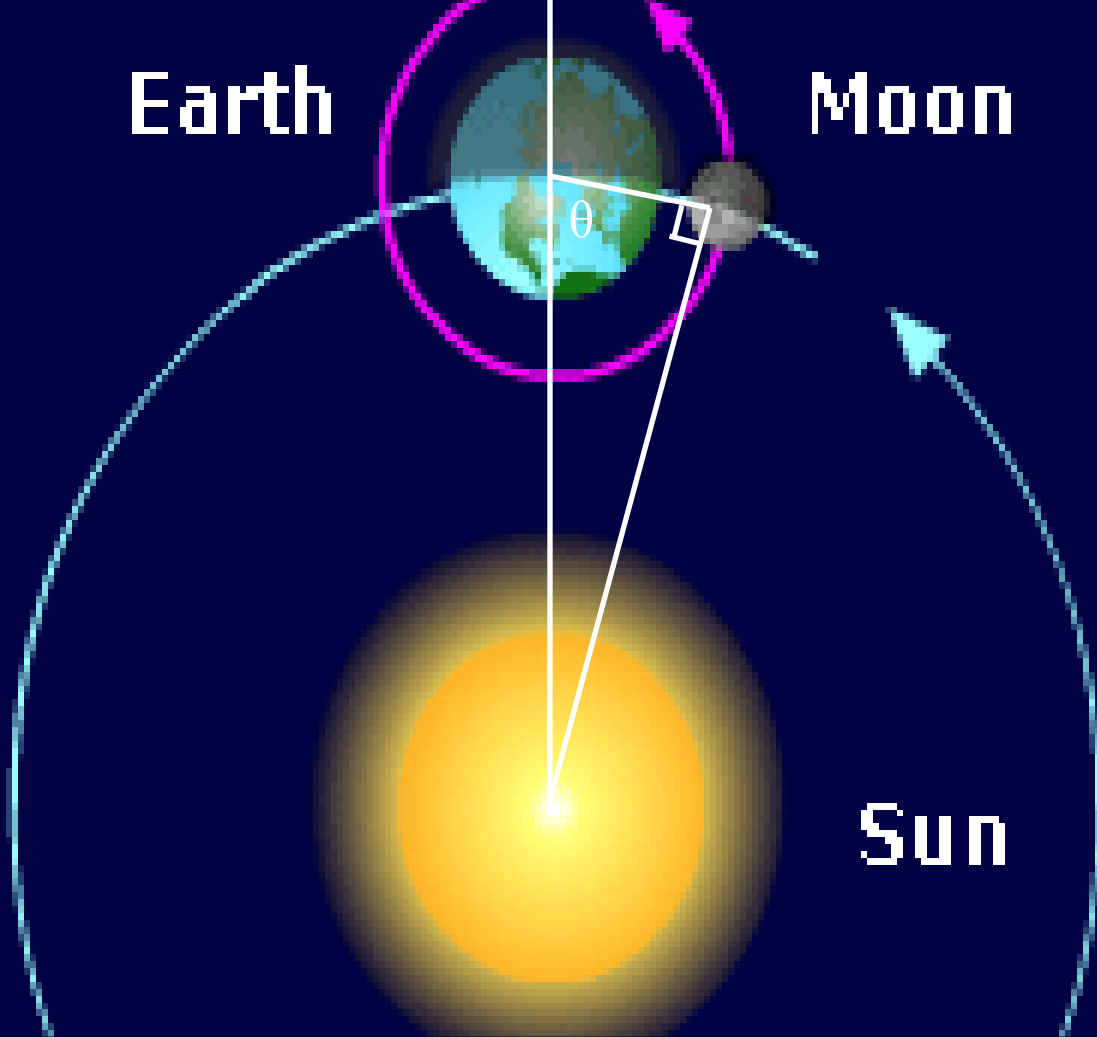


... and half Moons occurred when the Moon made a right angle between Earth and Sun.

$$\theta < \pi/2$$

Earth

Moon

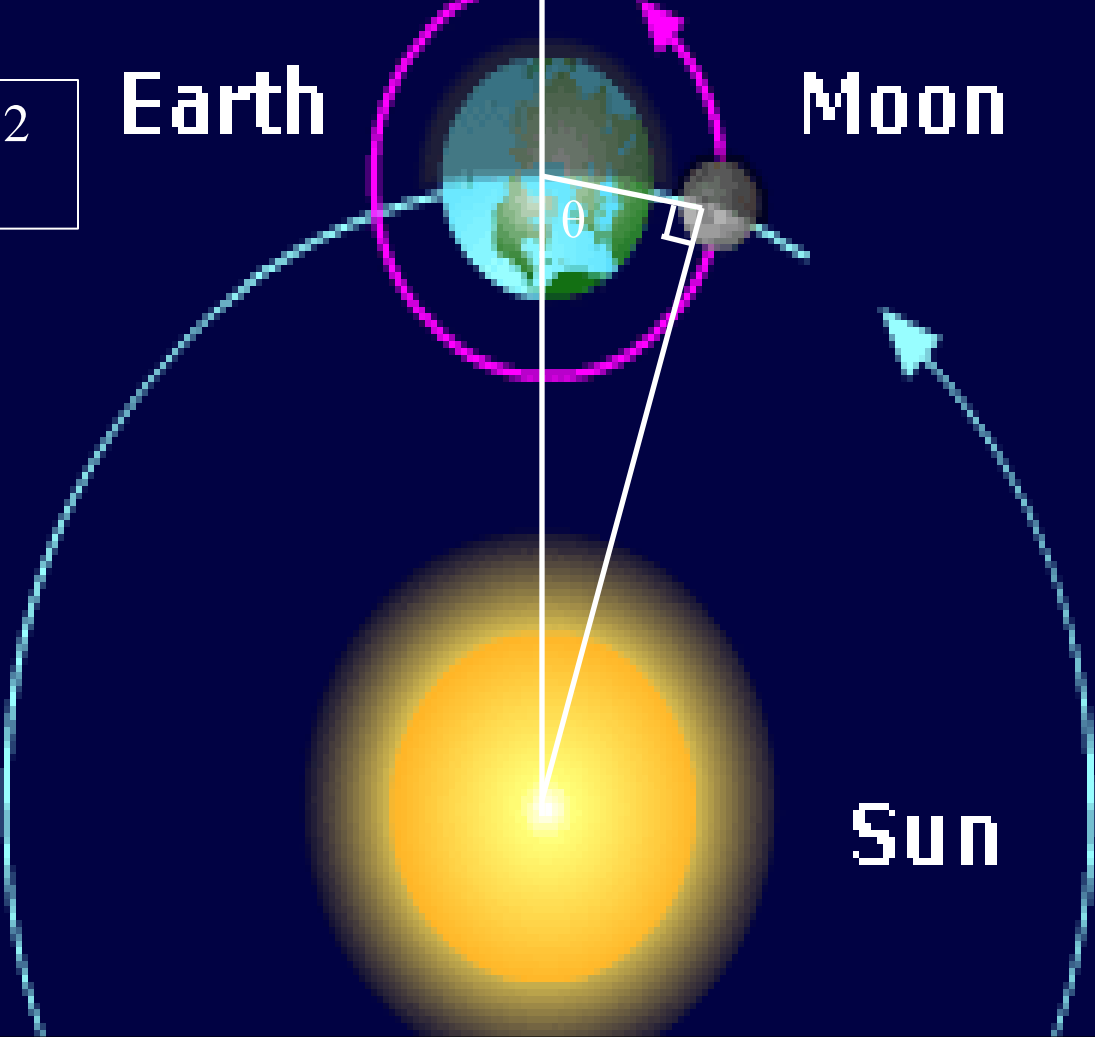


This implies that half Moons occur slightly closer to new Moons than to full Moons.

$$\theta = \pi/2 - 2\pi * 12 \text{ hours/1 month})$$

Earth

Moon

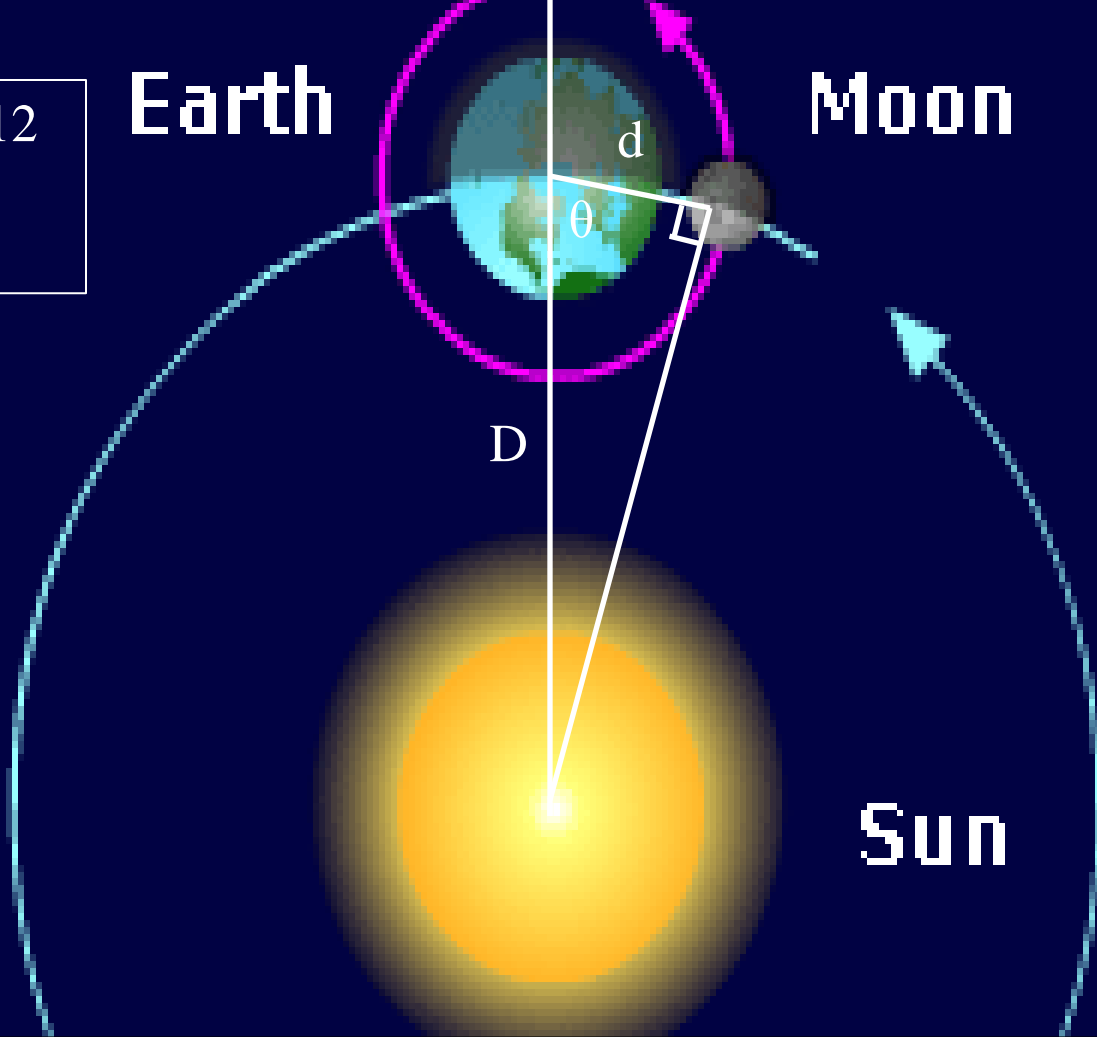


Sun

Aristarchus thought that half Moons occurred 12 hours before the midpoint of a new and full Moon.

$$\theta = \pi/2 - 2\pi * 12 \text{ hours/1 month}$$
$$\cos \theta = d/D$$

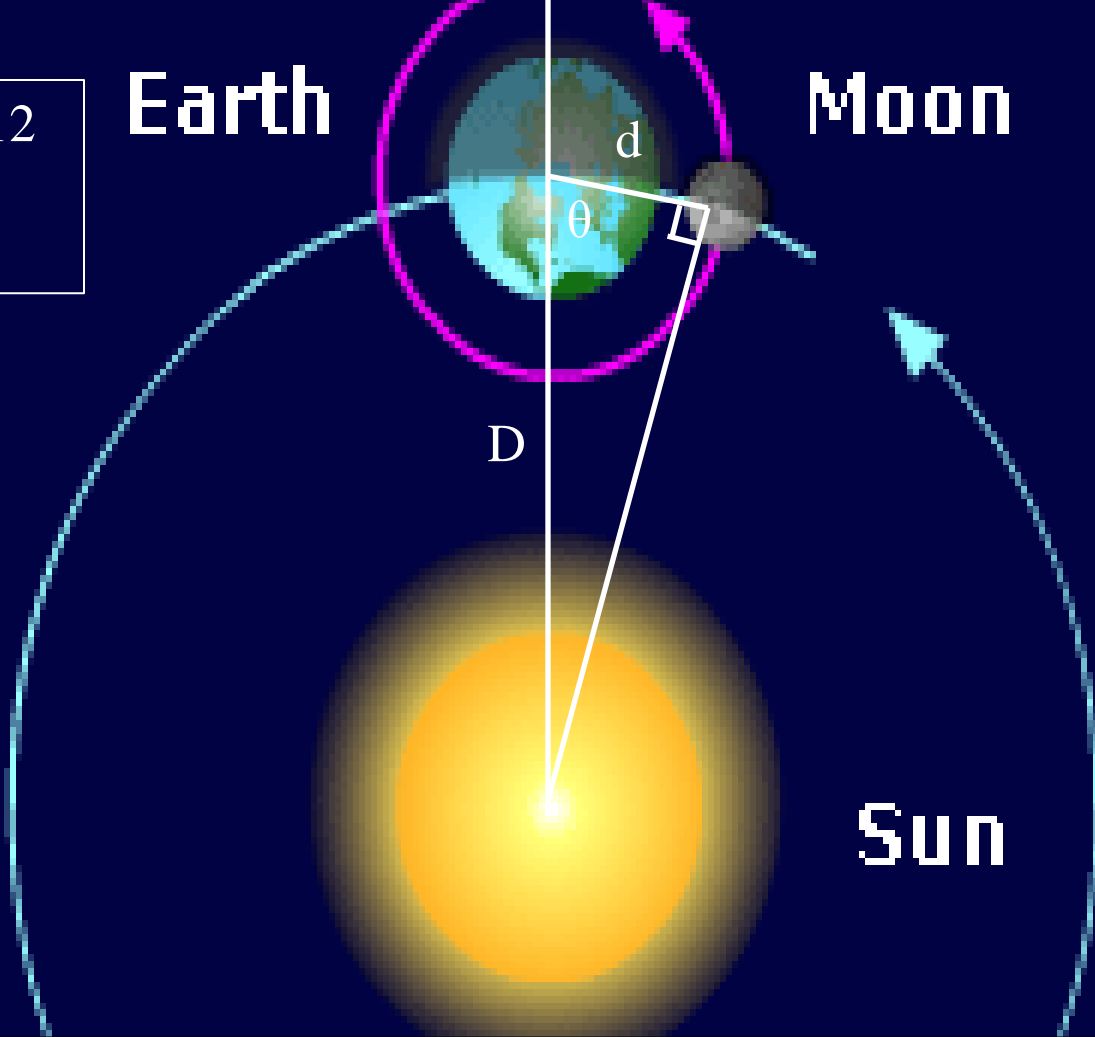
$$D = 20 d$$



From this and trigonometry, he concluded that the Sun was 20 times further away than the Moon.

$$\theta = \pi/2 - 2\pi * 12 \text{ hours} / 1 \text{ month}$$
$$\cos \theta = d/D$$

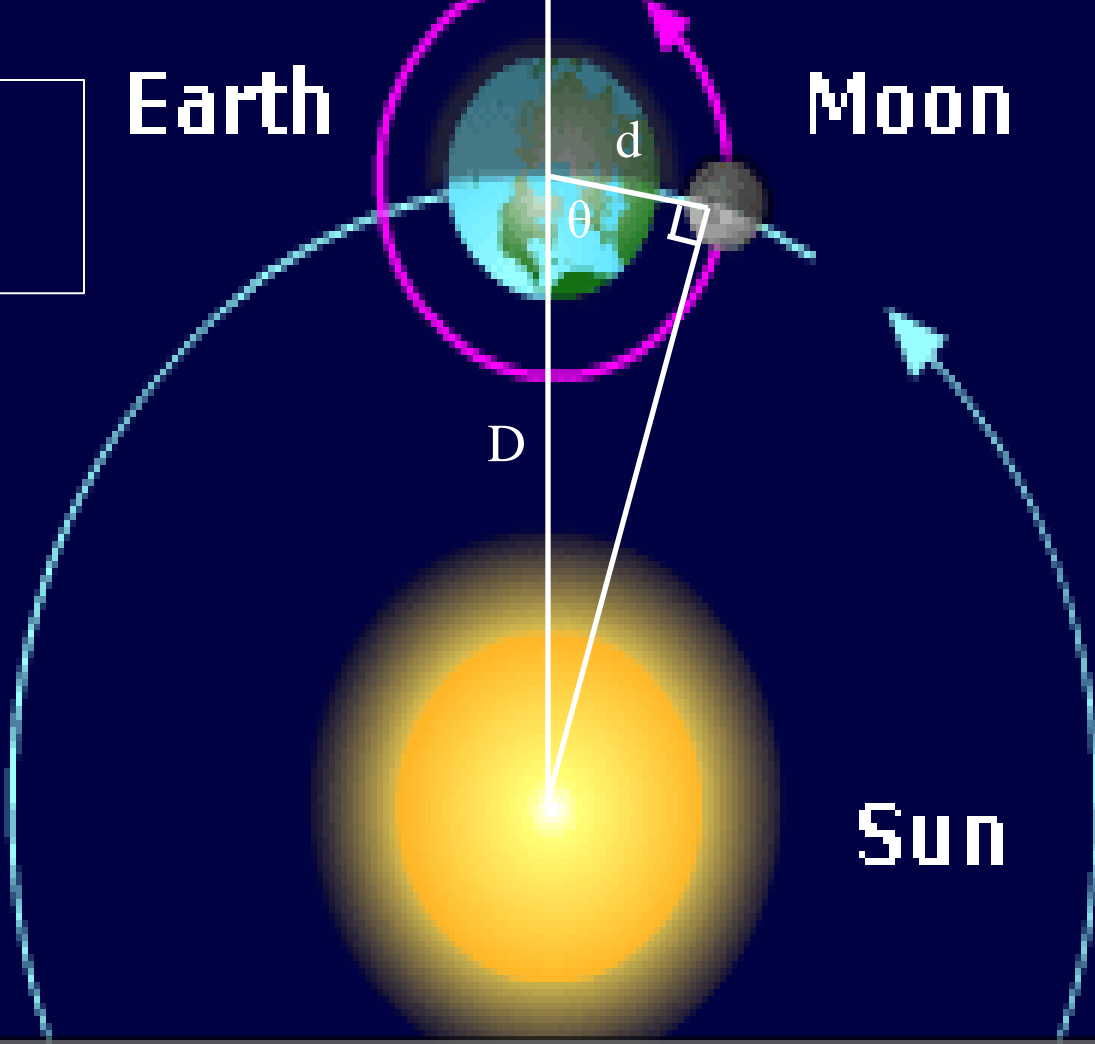
$$D = 20 d$$



Unfortunately, with ancient Greek technology it was hard to time a new Moon perfectly.

$\theta = \pi/2 - 2\pi / 2$
hour/1 month
 $\cos \theta = d/D$

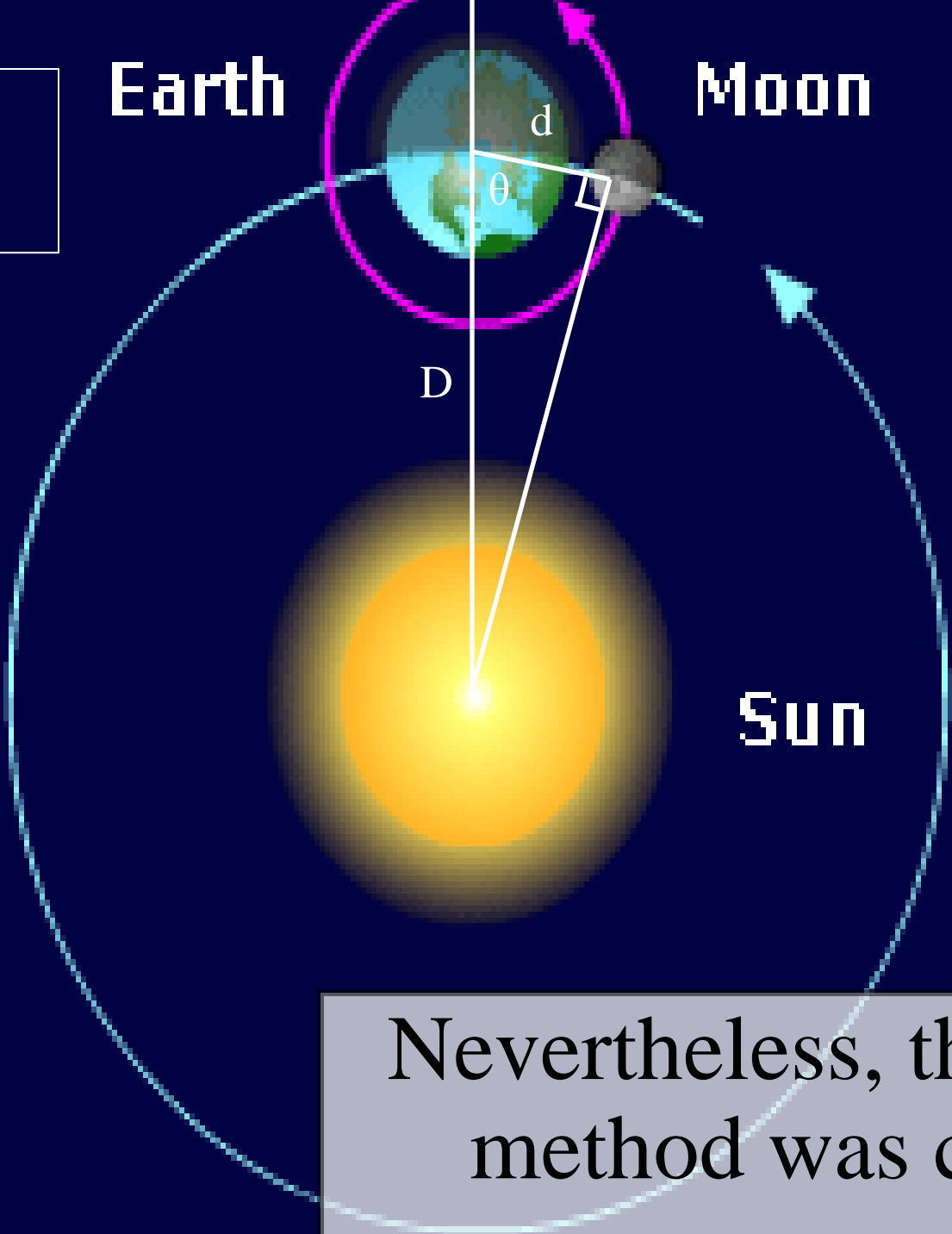
$D = 390 d$



The true time discrepancy is 1/2 hour (not 12 hours), and the Sun is 390 times further away (not 20 times).

$\theta = \pi/2 - 2\pi / 2$
hour/1 month
 $\cos \theta = d/D$

$D = 390 d$

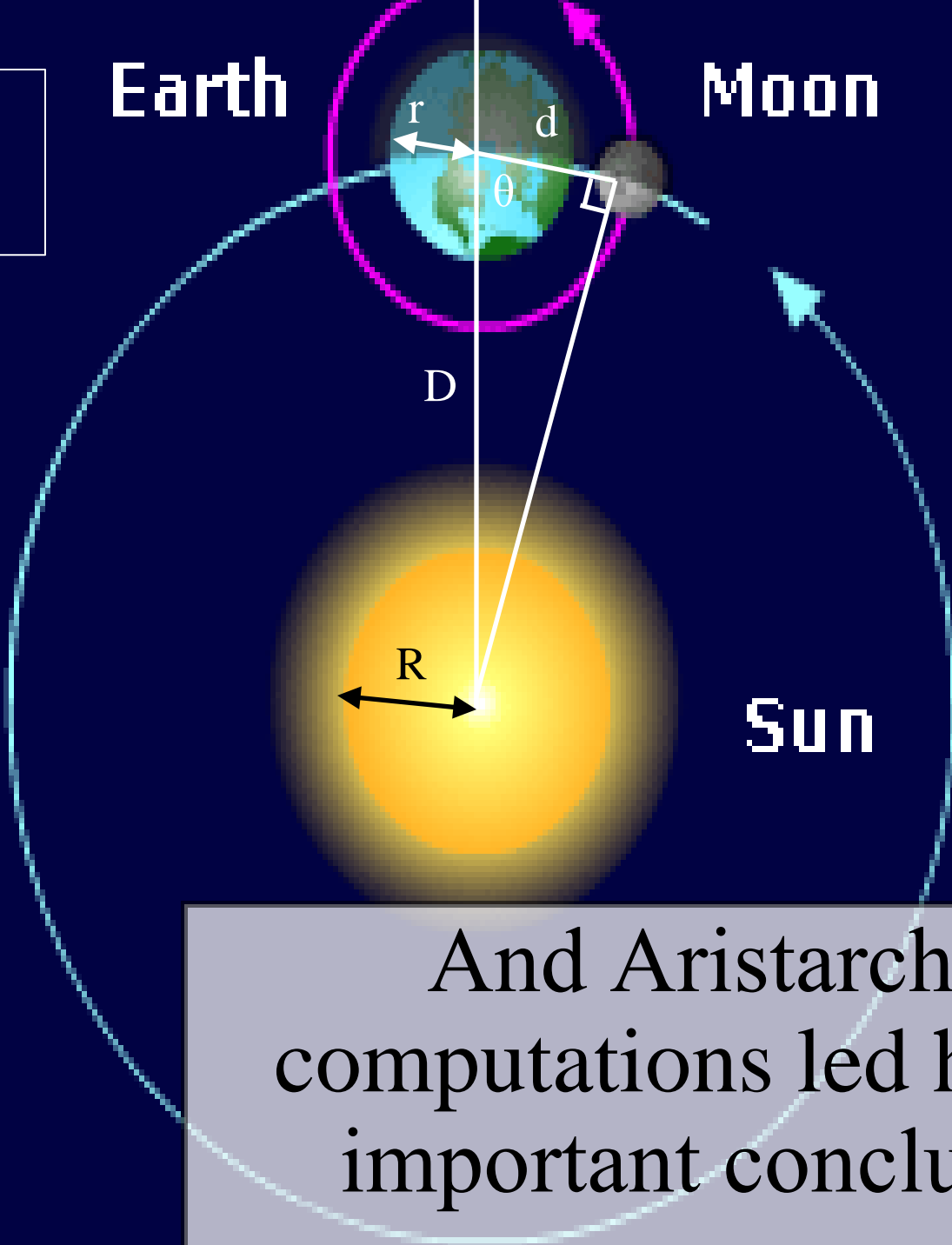


Nevertheless, the basic method was correct.

$d = 60 r$
 $D/d = 20$
 $R/D = 1/180$

Earth

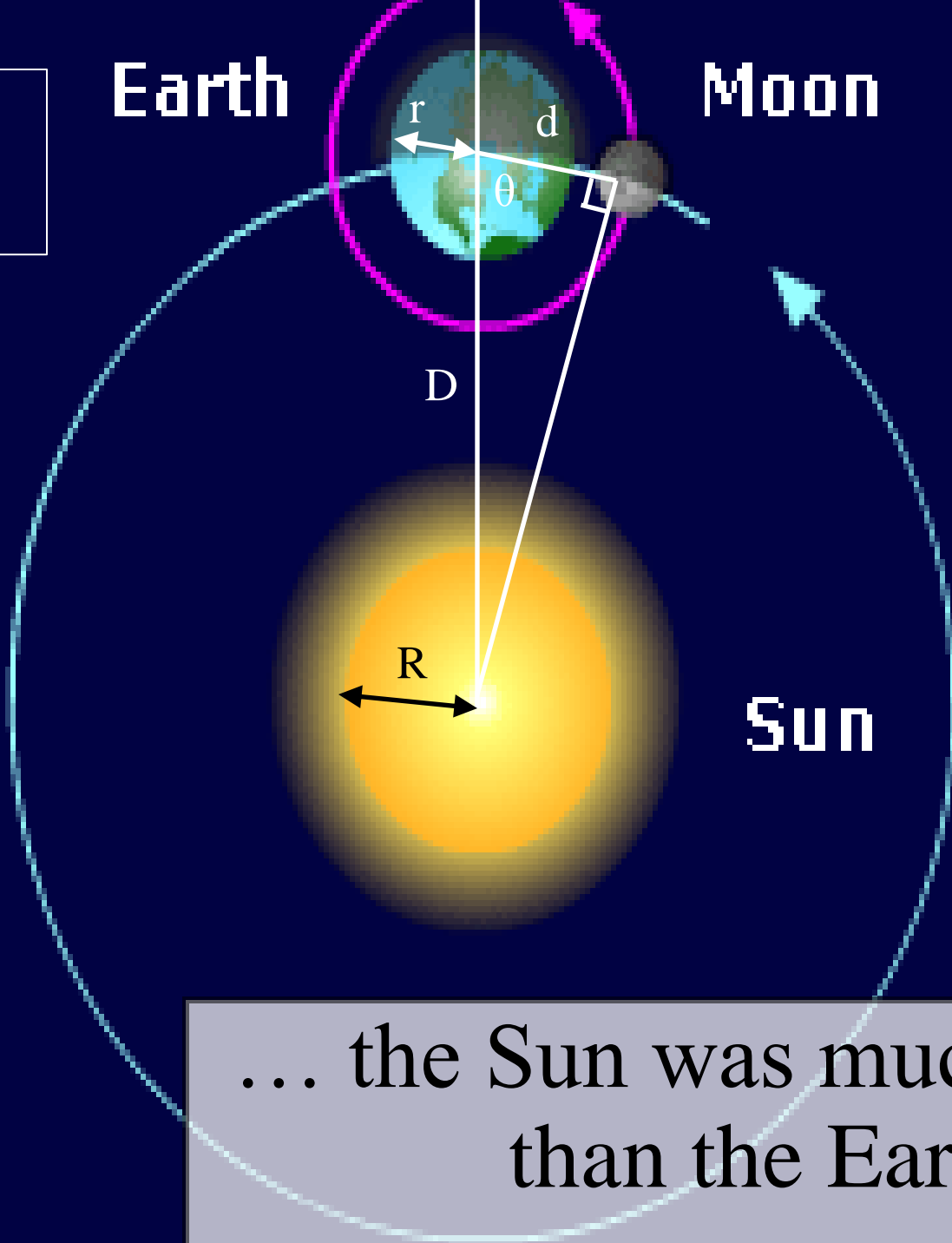
Moon



And Aristarchus' computations led him to an important conclusion...

$d = 60 r$
 $D/d = 20$
 $R/D = 1/180$

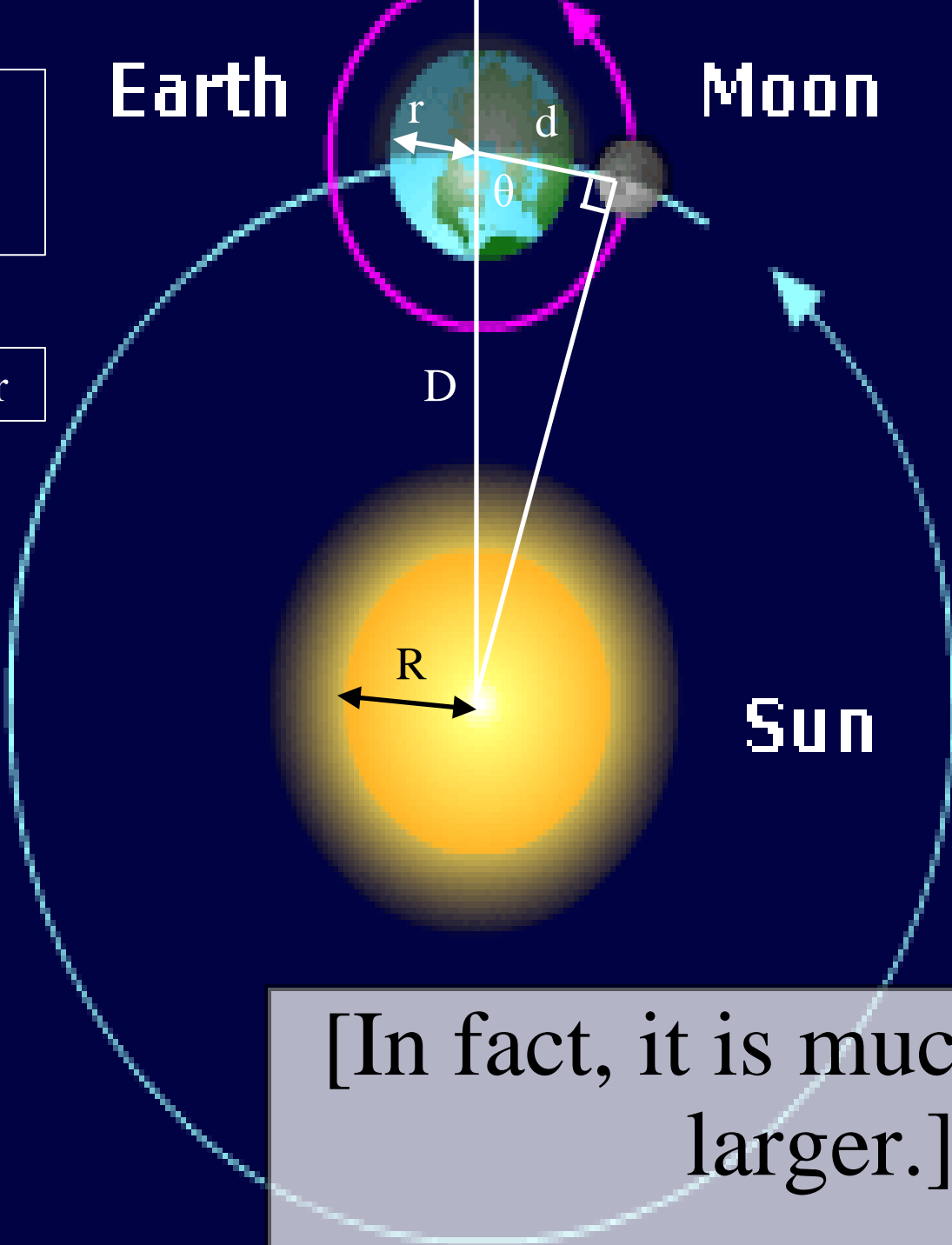
$R \sim 7 r$




... the Sun was much larger than the Earth.

$$d = 60 r$$
$$D/d = 20\ 390$$
$$R/D = 1/180$$

$$R = 7\ 109 r$$




[In fact, it is much, much larger.]




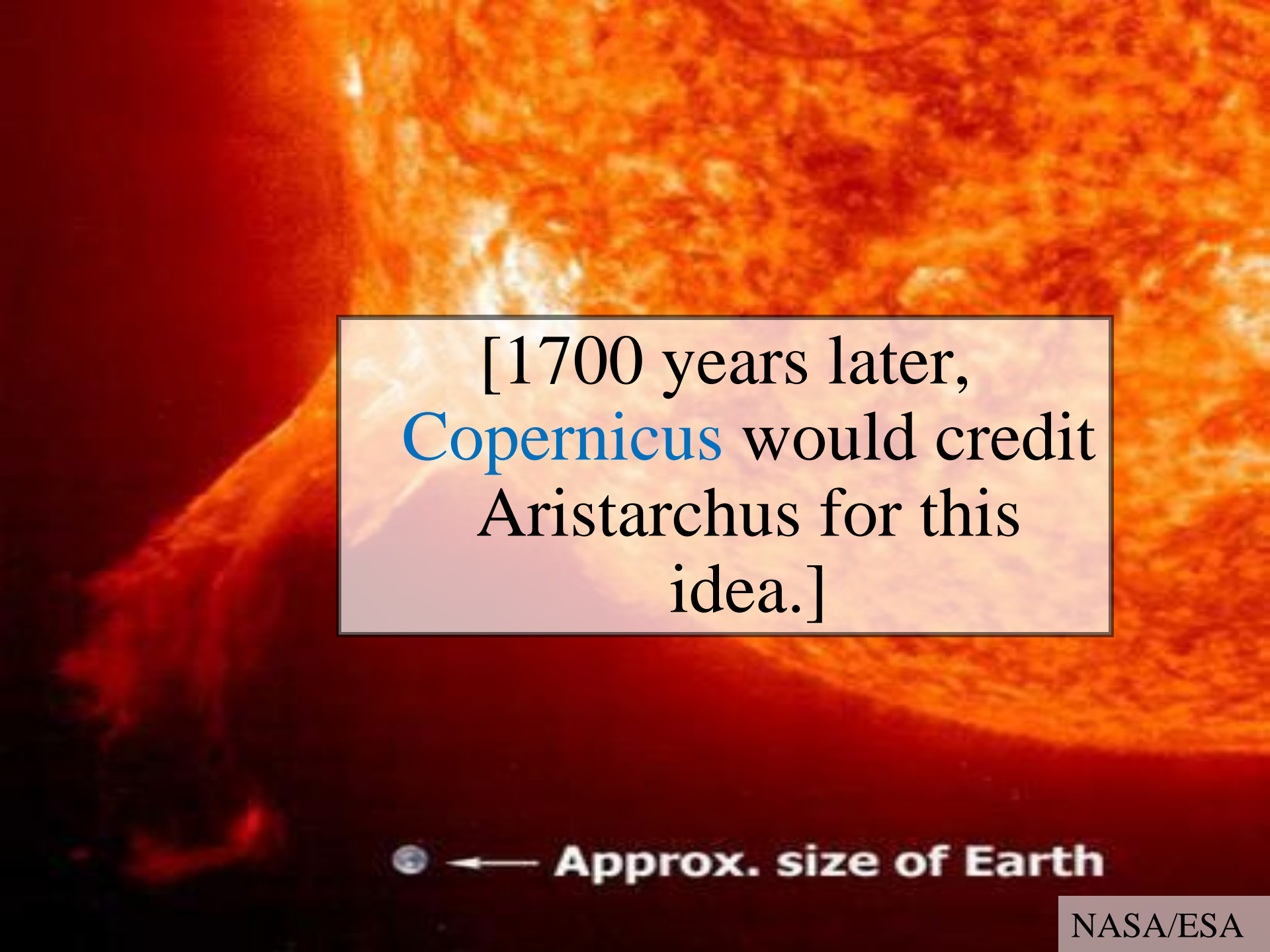
He then concluded it was
absurd to think the Sun
went around the Earth...

 ← **Approx. size of Earth**




... and was the first to propose the **heliocentric model** that the Earth went around the Sun.

 **Approx. size of Earth**





[1700 years later,
Copernicus would credit
Aristarchus for this
idea.]

 **Approx. size of Earth**



Ironically, Aristarchus' theory was not accepted by the other ancient Greeks...

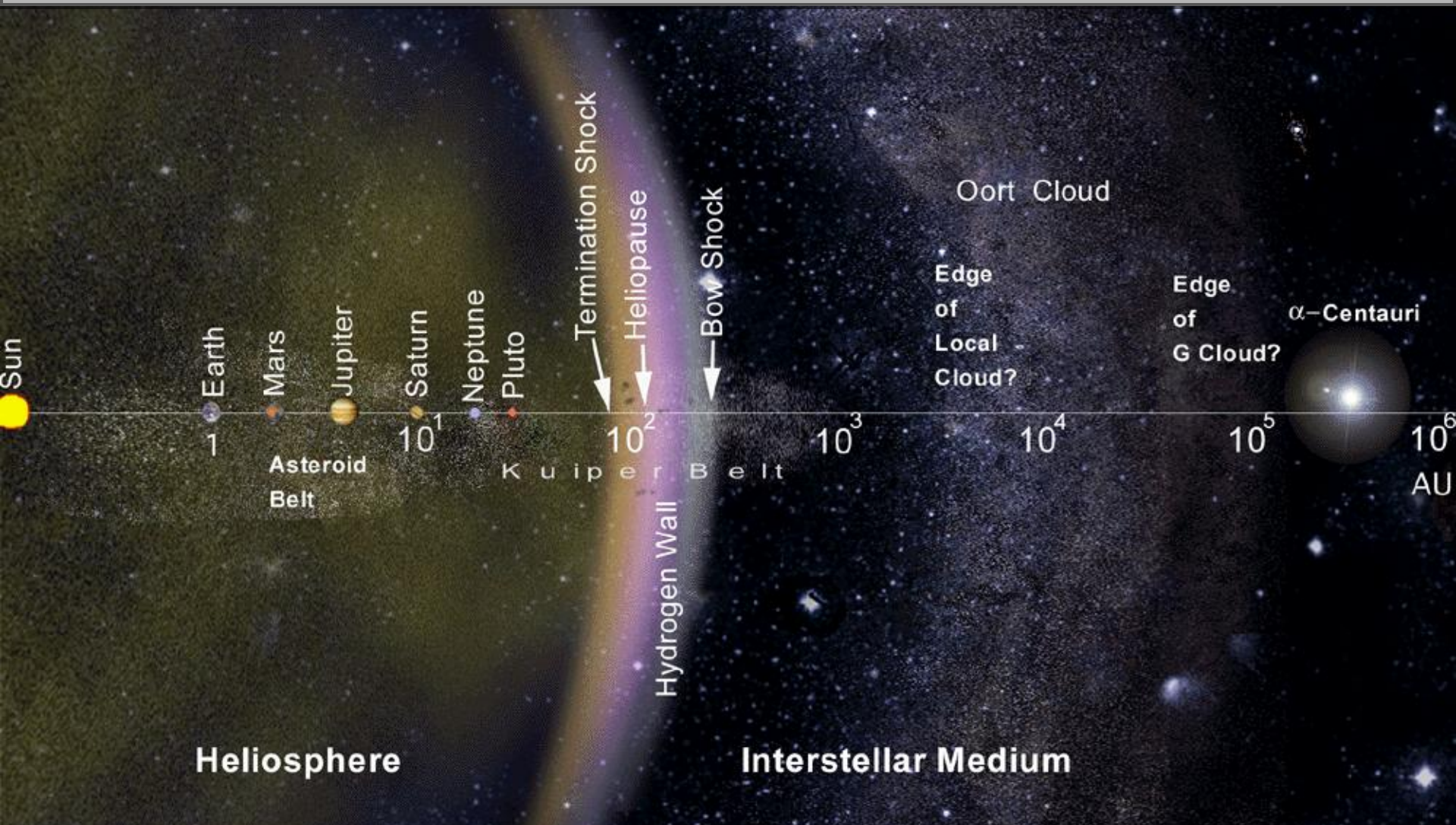
 ← **Approx. size of Earth**



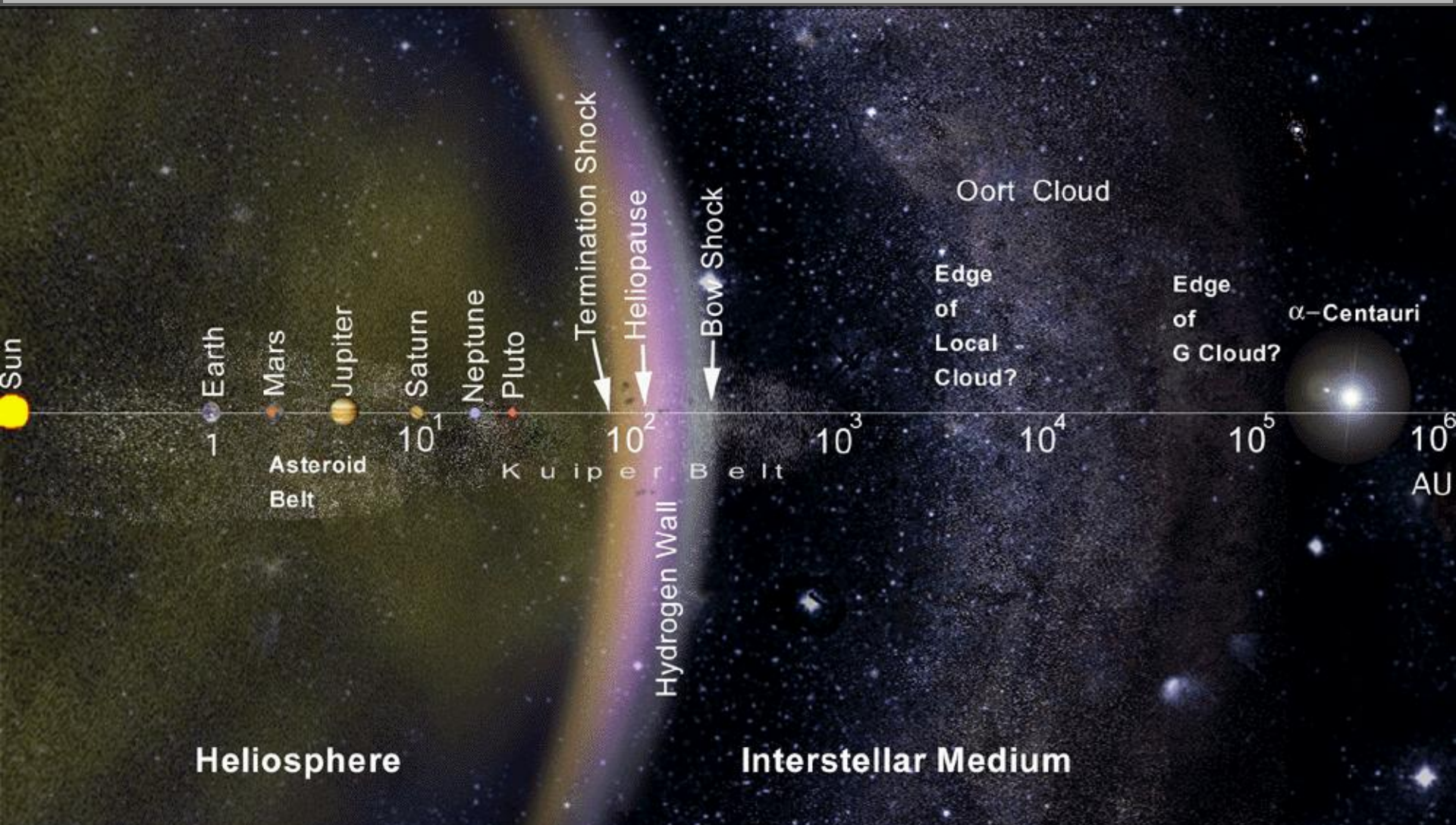
... but we'll explain
why later.

 **Approx. size of Earth**

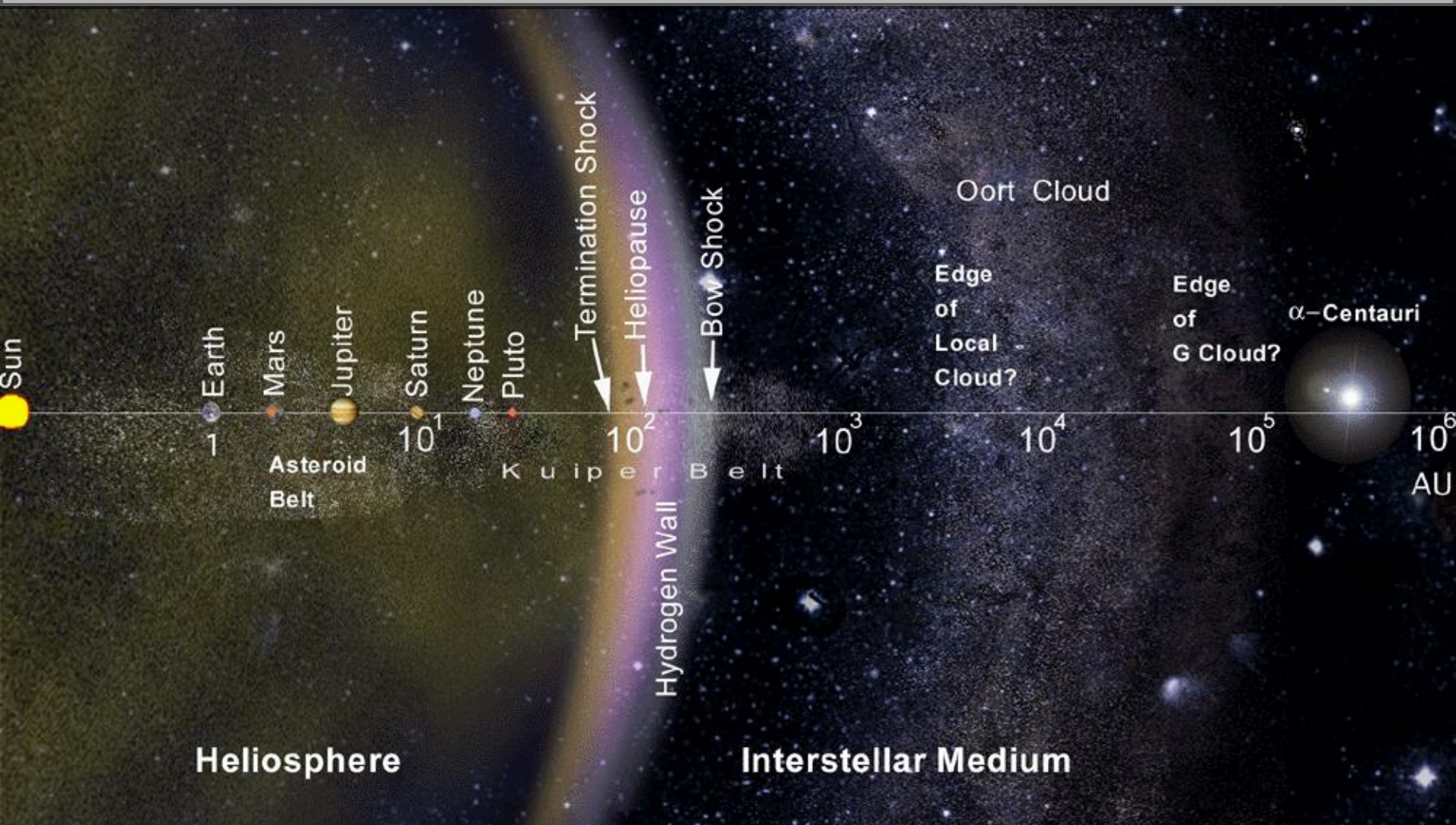
The distance from the Earth to the Sun is known as the Astronomical Unit (AU).



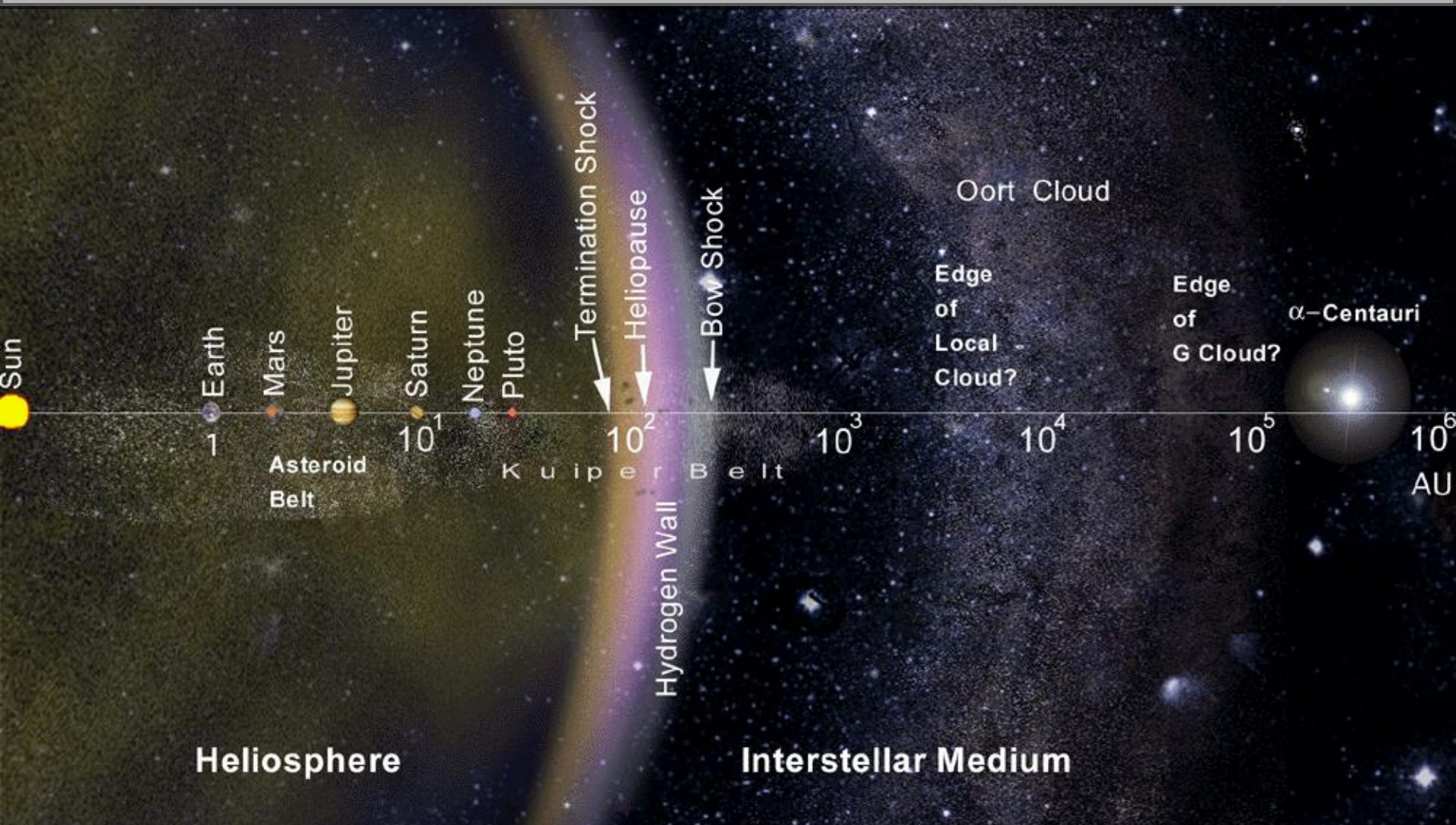
It is an extremely important rung in the cosmic distance ladder.



Aristarchus' original estimate of the AU was inaccurate...

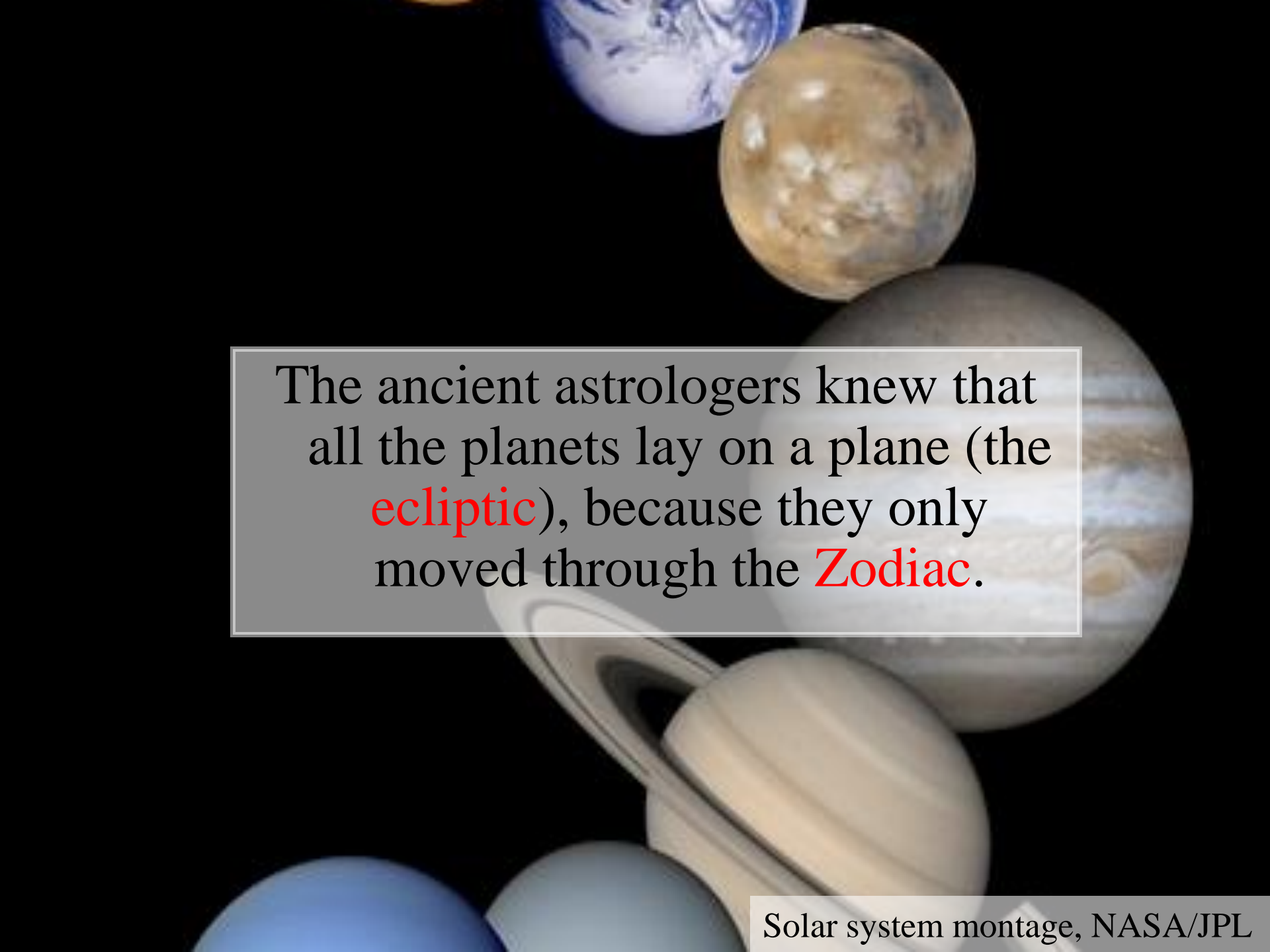


... but we'll see much more accurate ways to measure the AU later on.






4th rung: the planets


A composite image of the solar system planets. At the top left is Earth, showing blue oceans and white clouds. To its right is Mars, a reddish-brown sphere. Below Mars is Jupiter, a large planet with prominent white and brown bands. In the center is Saturn, showing its characteristic rings. Below Saturn are Uranus and Neptune, both appearing as blue spheres. The planets are arranged in a roughly diagonal line from top-left to bottom-right against a black background.

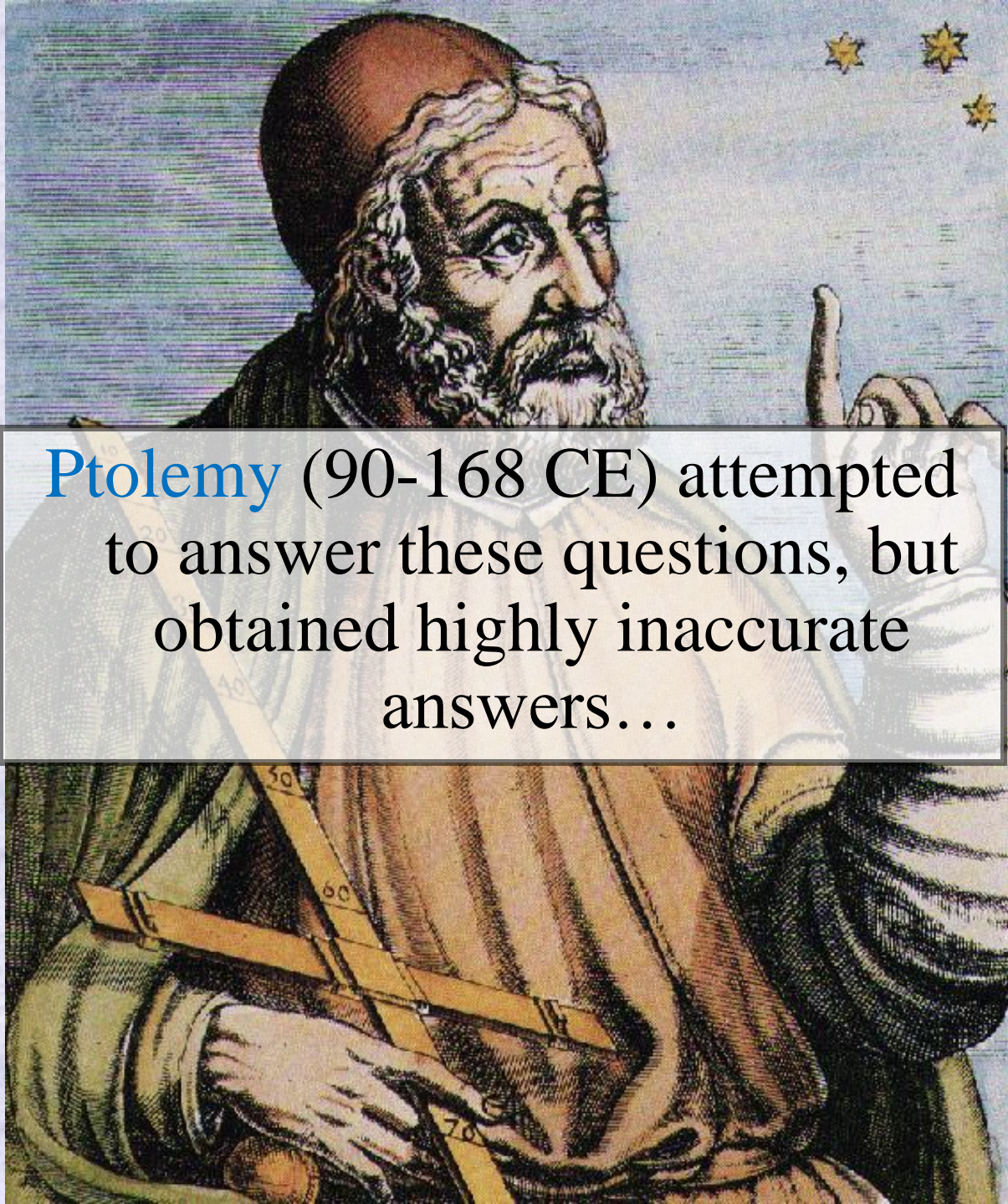
The ancient astrologers knew that all the planets lay on a plane (the **ecliptic**), because they only moved through the **Zodiac**.

A solar system montage featuring Earth, Mars, Jupiter, Saturn, and Uranus against a black background. The planets are arranged in a descending diagonal from top-left to bottom-right. Earth is at the top left, followed by Mars, then Jupiter, Saturn, and Uranus at the bottom left. A semi-transparent grey box with a white border is centered over the image, containing the text "But this still left many questions unanswered:". At the bottom right, there is a white box containing the text "Solar system montage, NASA/JPL".

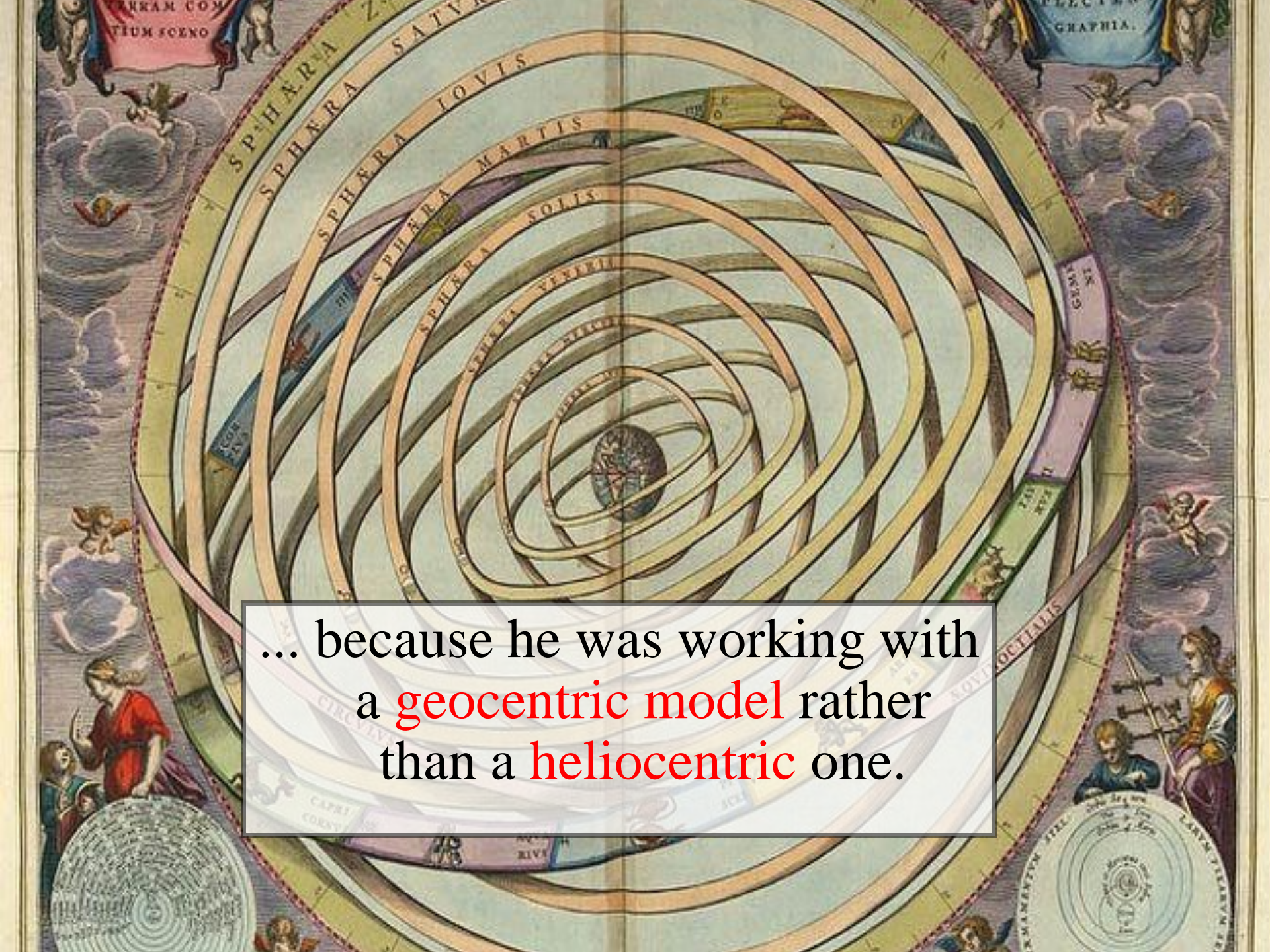
But this still left many
questions unanswered:

Solar system montage, NASA/JPL

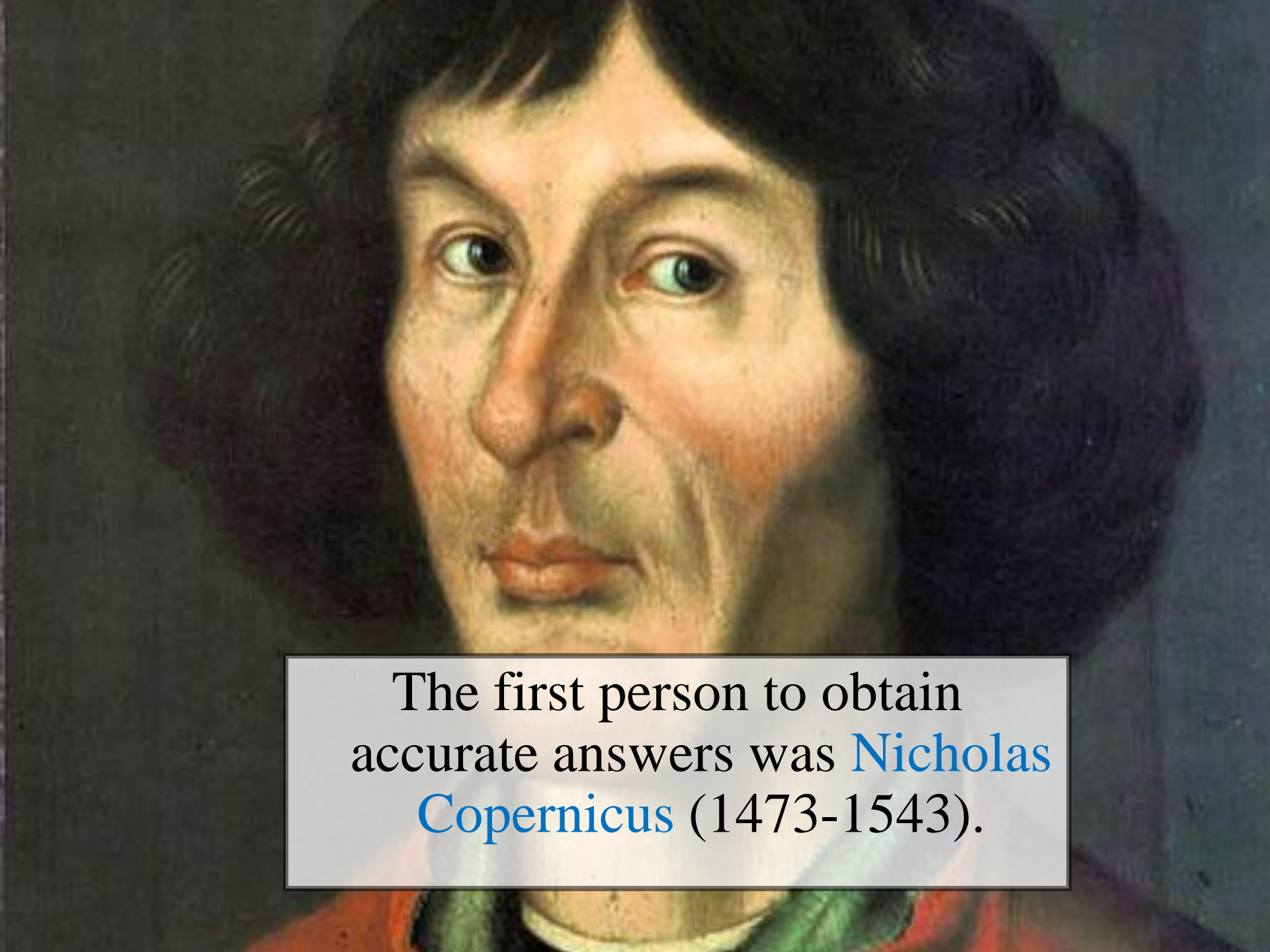
- 
- How far away are the planets (e.g. **Mars**)?
 - What are their orbits?
 - How long does it take to complete an orbit?



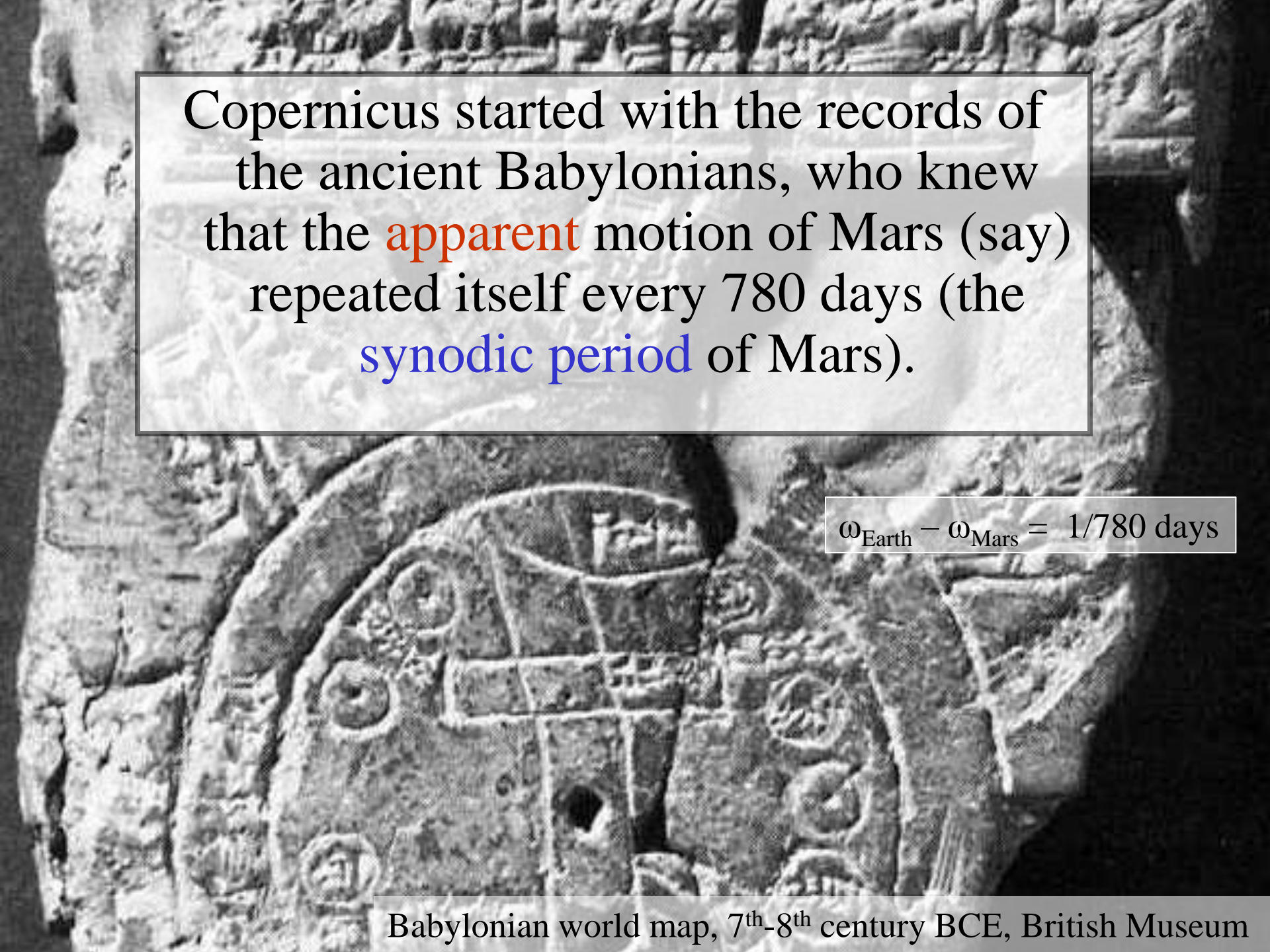
Ptolemy (90-168 CE) attempted to answer these questions, but obtained highly inaccurate answers...



... because he was working with
a **geocentric model** rather
than a **heliocentric** one.

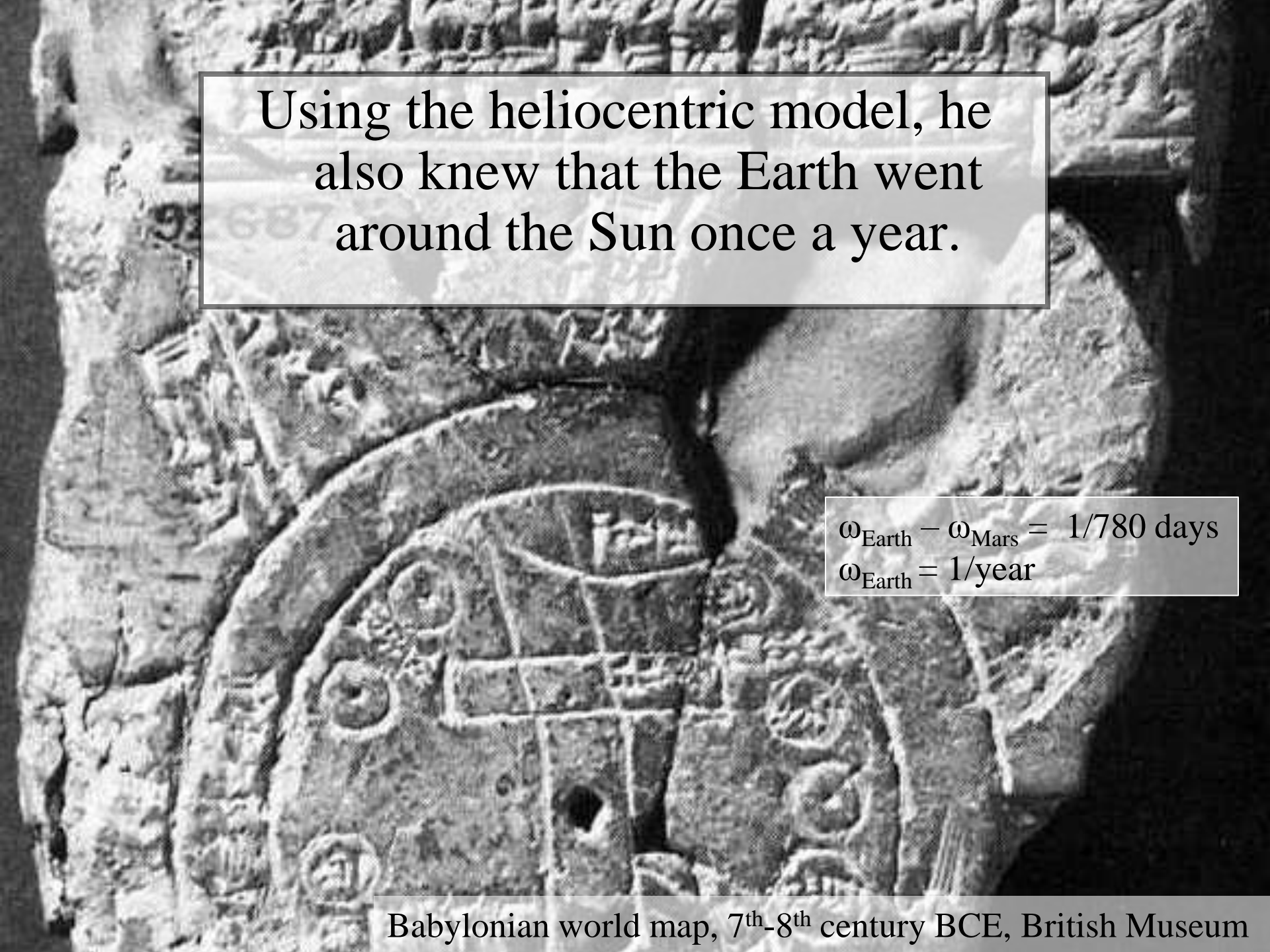
A portrait of Nicholas Copernicus, a Polish astronomer, mathematician, and astronomer. He is depicted with dark, wavy hair, a serious expression, and a white ruff collar. The background is dark and textured.

The first person to obtain accurate answers was **Nicholas Copernicus** (1473-1543).



Copernicus started with the records of the ancient Babylonians, who knew that the **apparent** motion of Mars (say) repeated itself every 780 days (the **synodic period** of Mars).

$$\omega_{\text{Earth}} - \omega_{\text{Mars}} = 1/780 \text{ days}$$



Using the heliocentric model, he also knew that the Earth went around the Sun once a year.

$$\omega_{\text{Earth}} - \omega_{\text{Mars}} = 1/780 \text{ days}$$
$$\omega_{\text{Earth}} = 1/\text{year}$$

Babylonian world map, 7th-8th century BCE, British Museum

Subtracting the implied angular velocities, he found that Mars went around the Sun every 687 days (the **sidereal period** of Mars).

$$\omega_{\text{Earth}} - \omega_{\text{Mars}} = 1/780 \text{ days}$$
$$\omega_{\text{Earth}} = 1/\text{year}$$

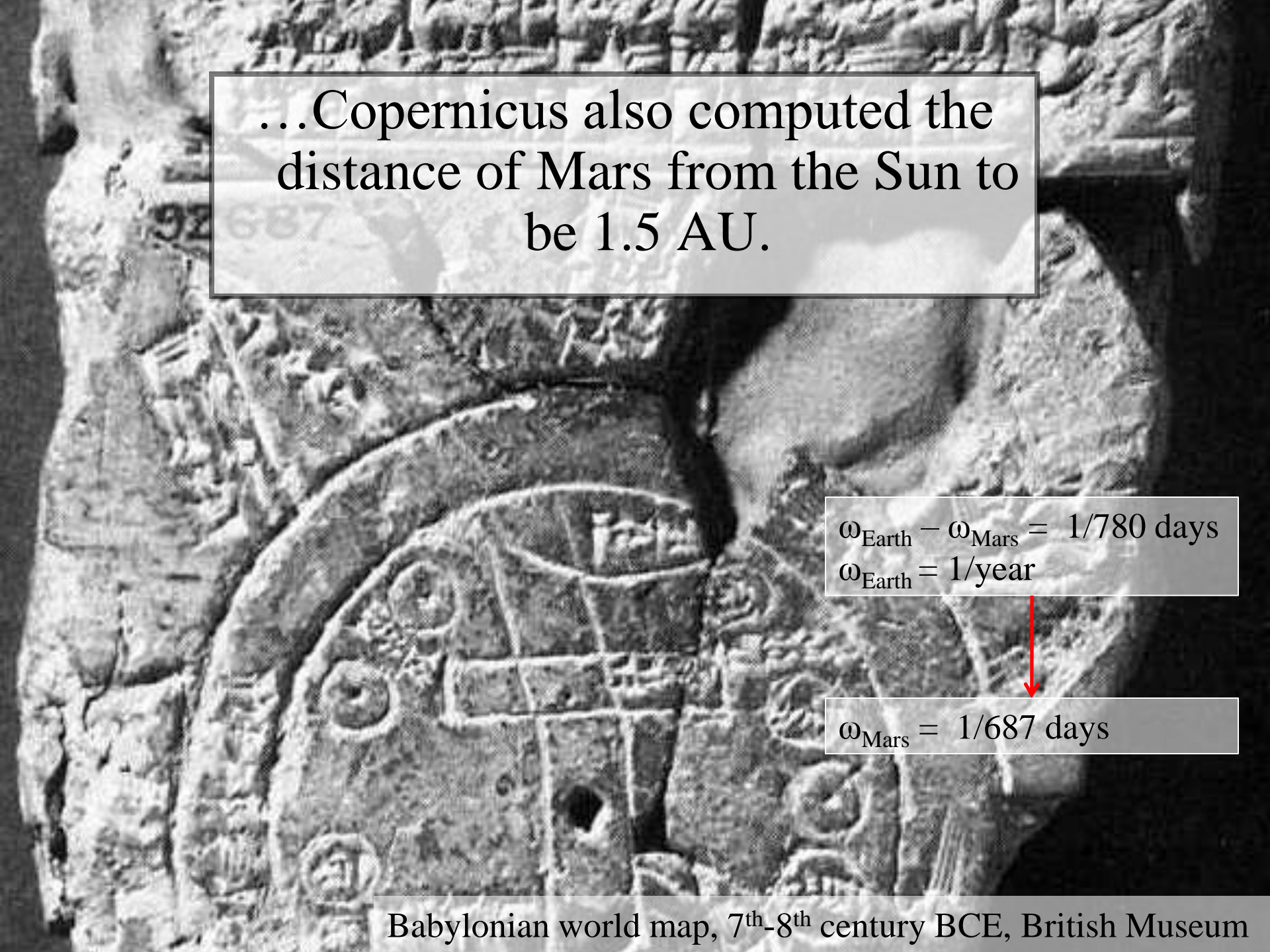
$$\omega_{\text{Mars}} = 1/687 \text{ days}$$

Assuming circular orbits, and using measurements of the location of Mars in the Zodiac at various dates...

$$\omega_{\text{Earth}} - \omega_{\text{Mars}} = 1/780 \text{ days}$$
$$\omega_{\text{Earth}} = 1/\text{year}$$



$$\omega_{\text{Mars}} = 1/687 \text{ days}$$

Babylonian world map, 7th-8th century BCE, British Museum

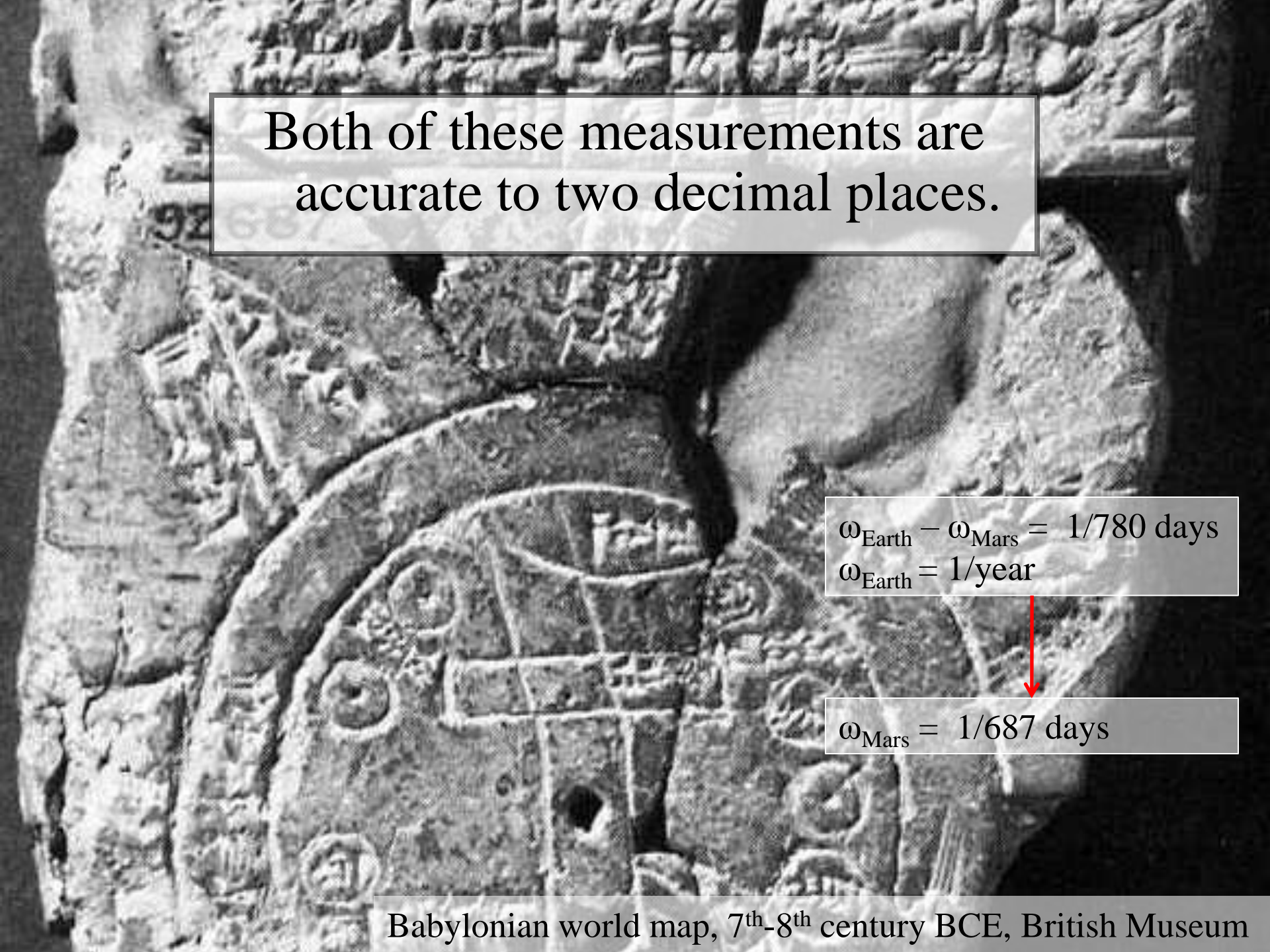


...Copernicus also computed the distance of Mars from the Sun to be 1.5 AU.

$$\omega_{\text{Earth}} - \omega_{\text{Mars}} = 1/780 \text{ days}$$
$$\omega_{\text{Earth}} = 1/\text{year}$$



$$\omega_{\text{Mars}} = 1/687 \text{ days}$$

Babylonian world map, 7th-8th century BCE, British Museum



Both of these measurements are accurate to two decimal places.

$$\omega_{\text{Earth}} - \omega_{\text{Mars}} = 1/780 \text{ days}$$
$$\omega_{\text{Earth}} = 1/\text{year}$$


$$\omega_{\text{Mars}} = 1/687 \text{ days}$$

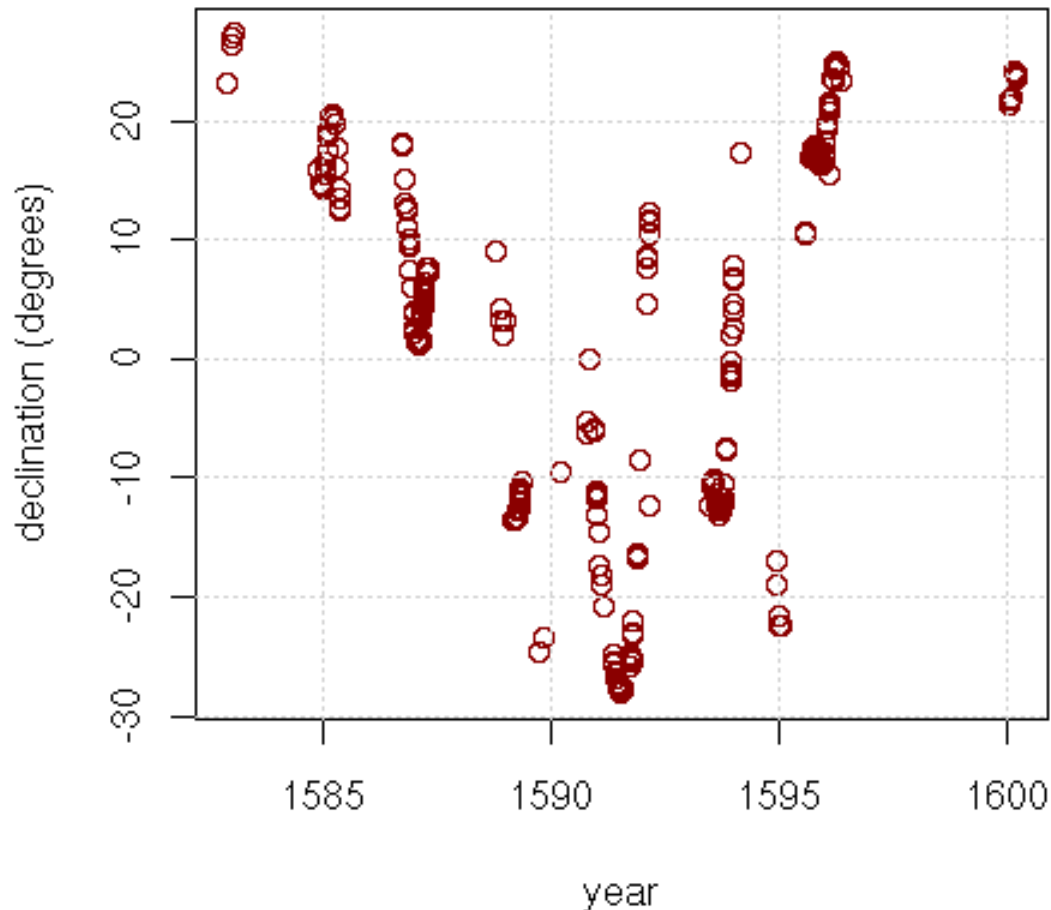
Babylonian world map, 7th-8th century BCE, British Museum



Tycho Brahe (1546-1601) made extremely detailed and long-term measurements of the position of Mars and other planets.

Unfortunately, his data deviated slightly from the predictions of the Copernican model.

Tycho Brahe's Mars Observations



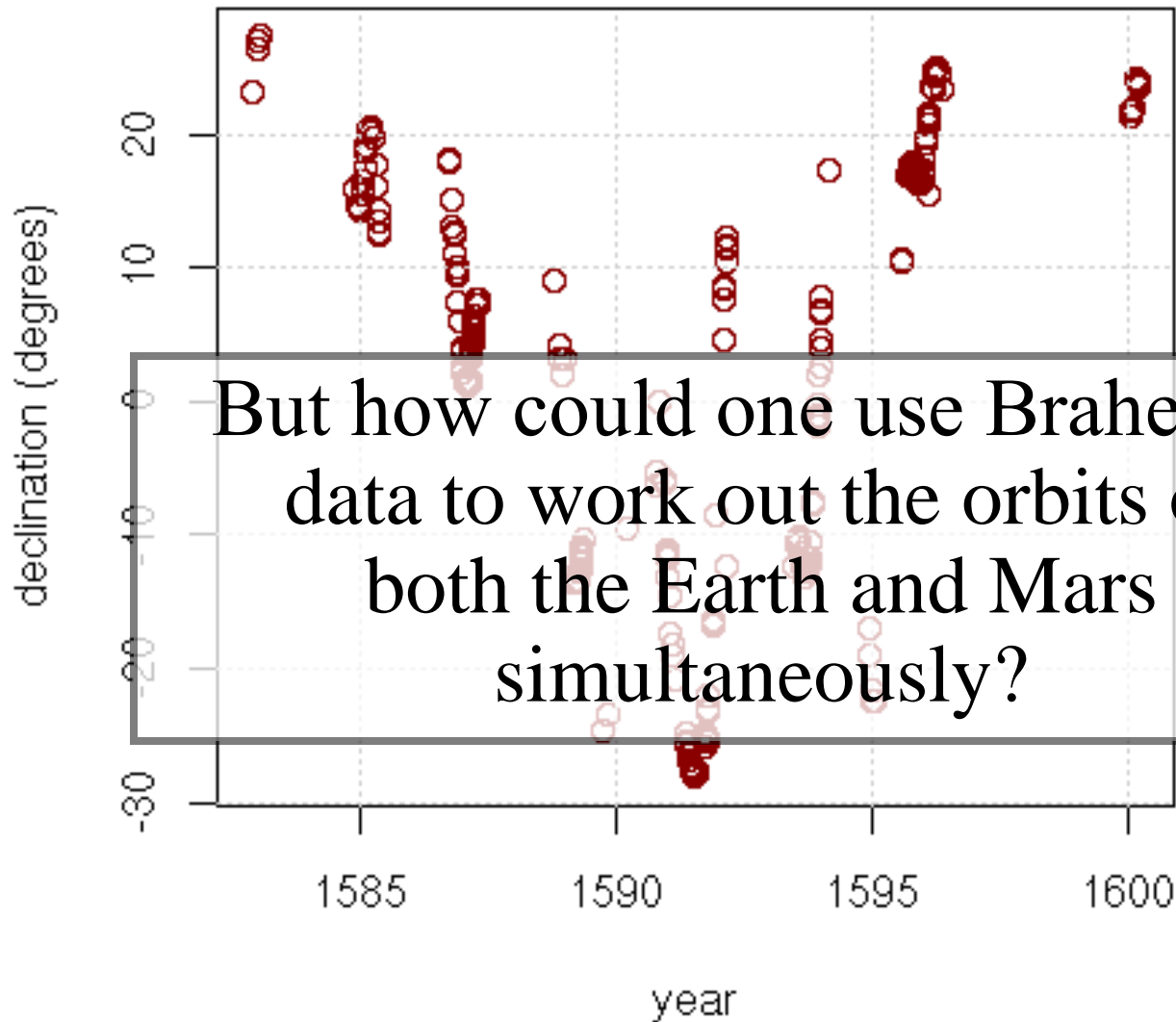
source: Tychonis Brahe Dani Opera Omnia



Johannes Kepler (1571-1630)
reasoned that this was because
the orbits of the Earth and Mars
were not quite circular.

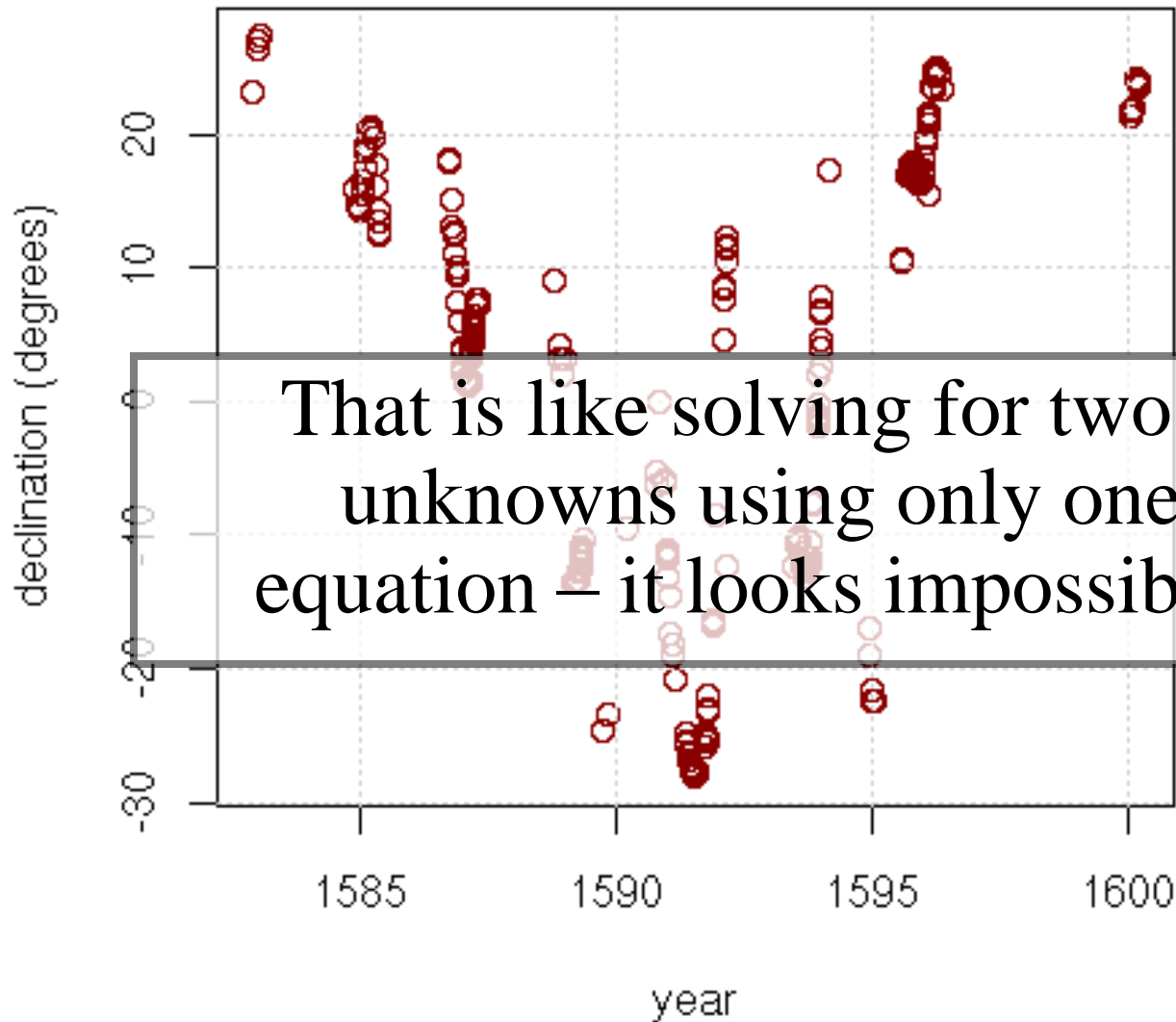


Tycho Brahe's Mars Observations



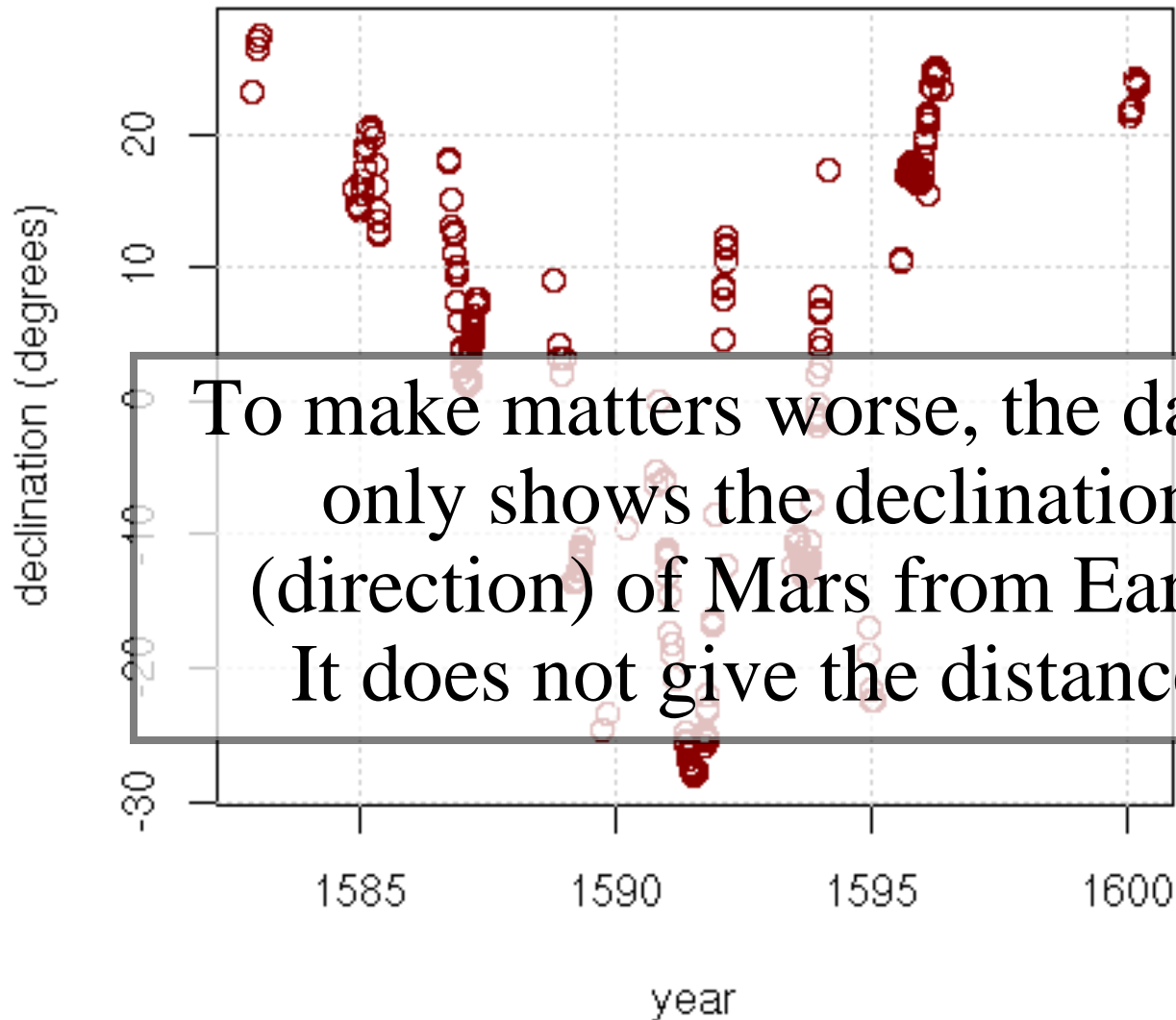
source: Tychonis Brahe Dani Opera Omnia

Tycho Brahe's Mars Observations



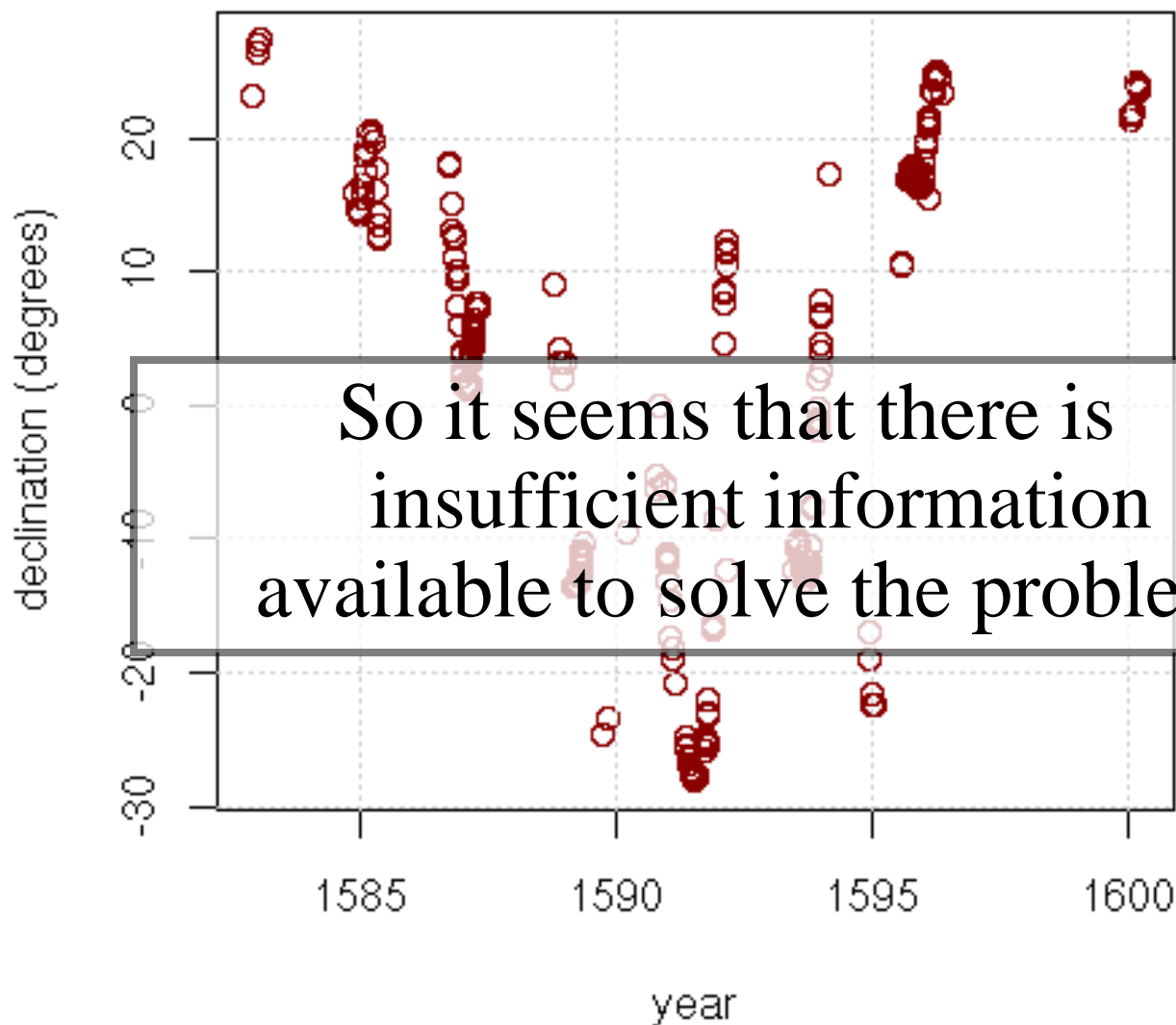
source: Tychonis Brahe Dani Opera Omnia

Tycho Brahe's Mars Observations



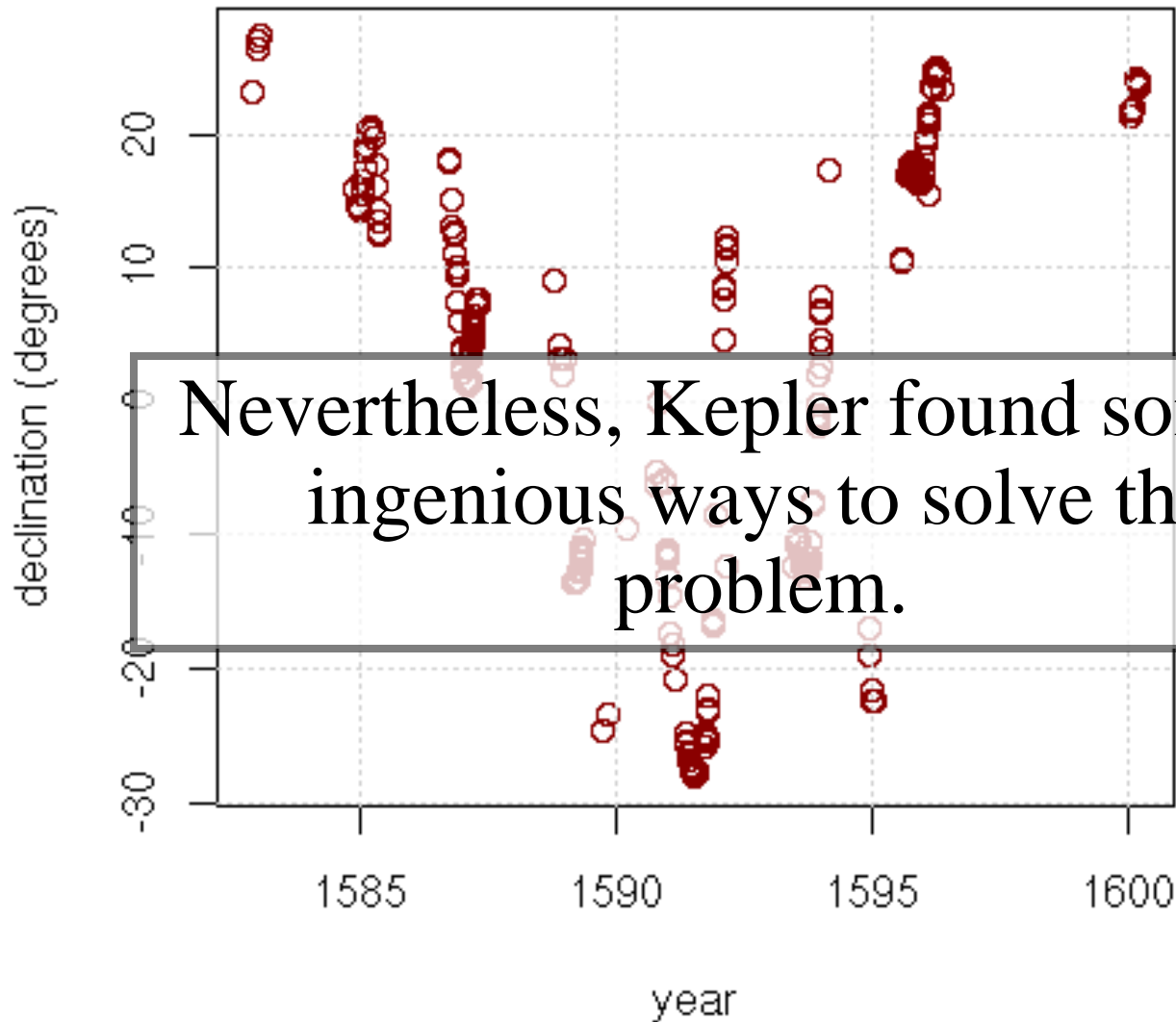
source: Tychonis Brahe Dani Opera Omnia

Tycho Brahe's Mars Observations



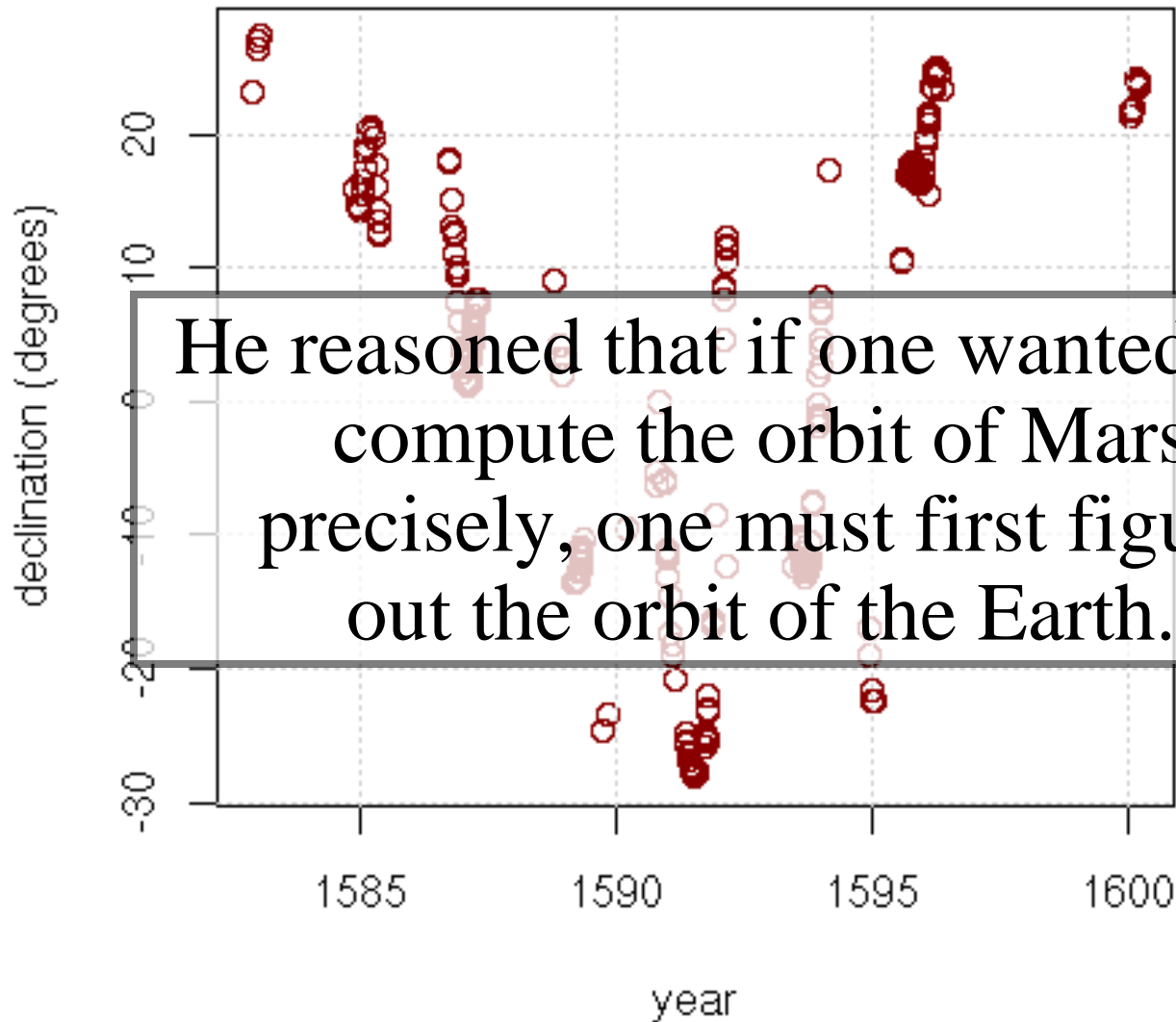
source: Tychonis Brahe Dani Opera Omnia

Tycho Brahe's Mars Observations



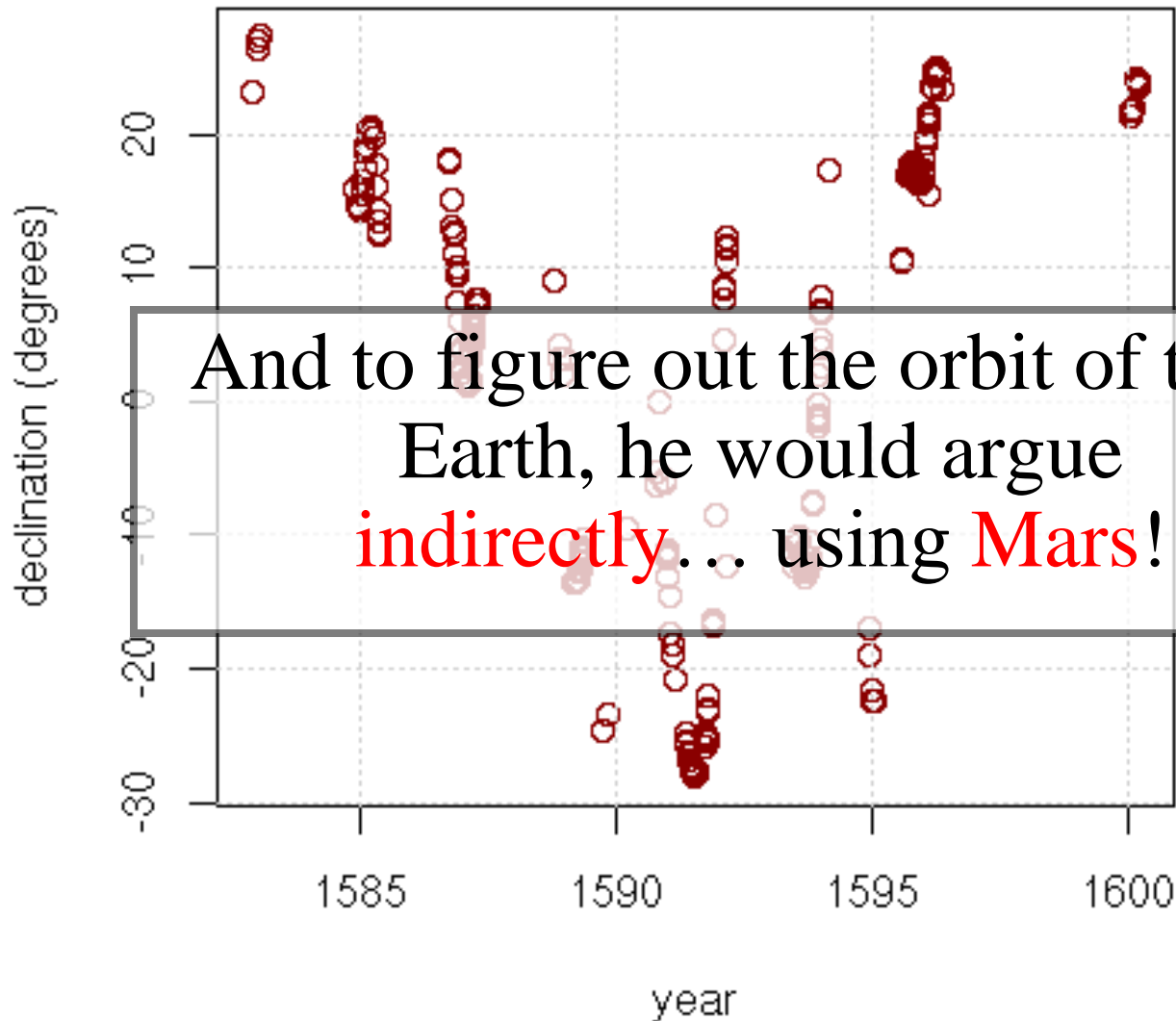
source: Tychonis Brahe Dani Opera Omnia

Tycho Brahe's Mars Observations

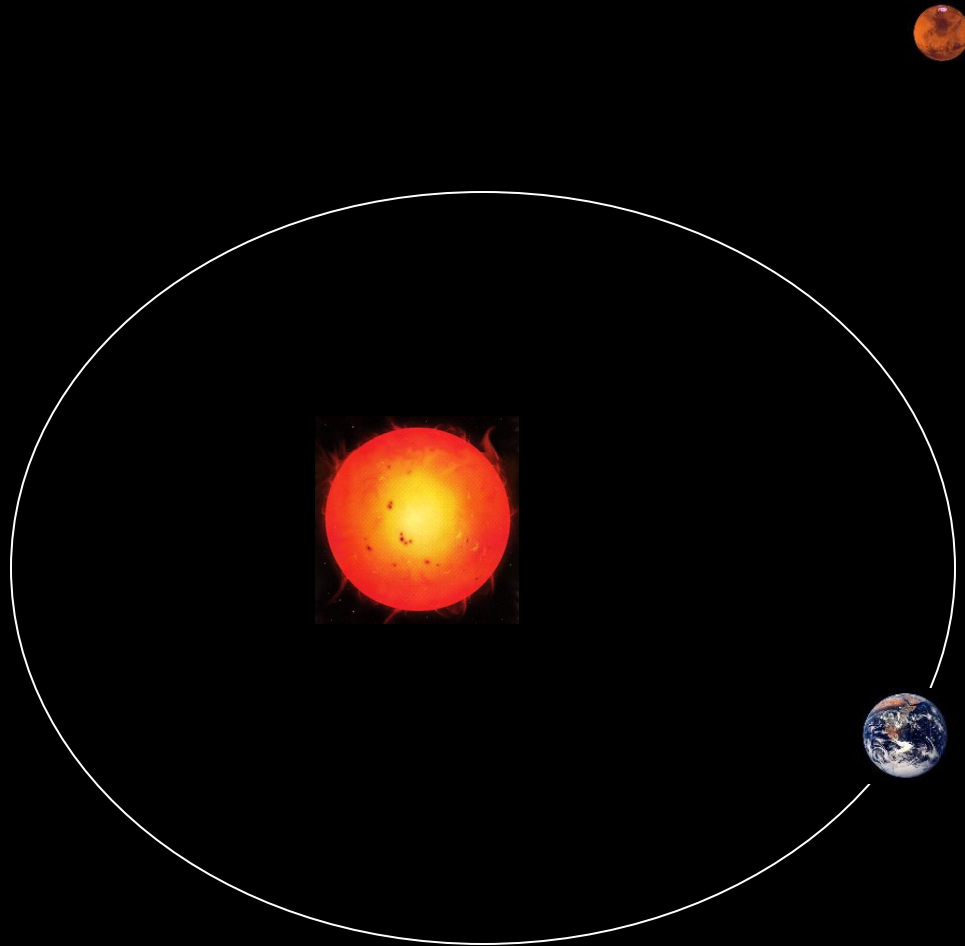


source: Tychonis Brahe Dani Opera Omnia

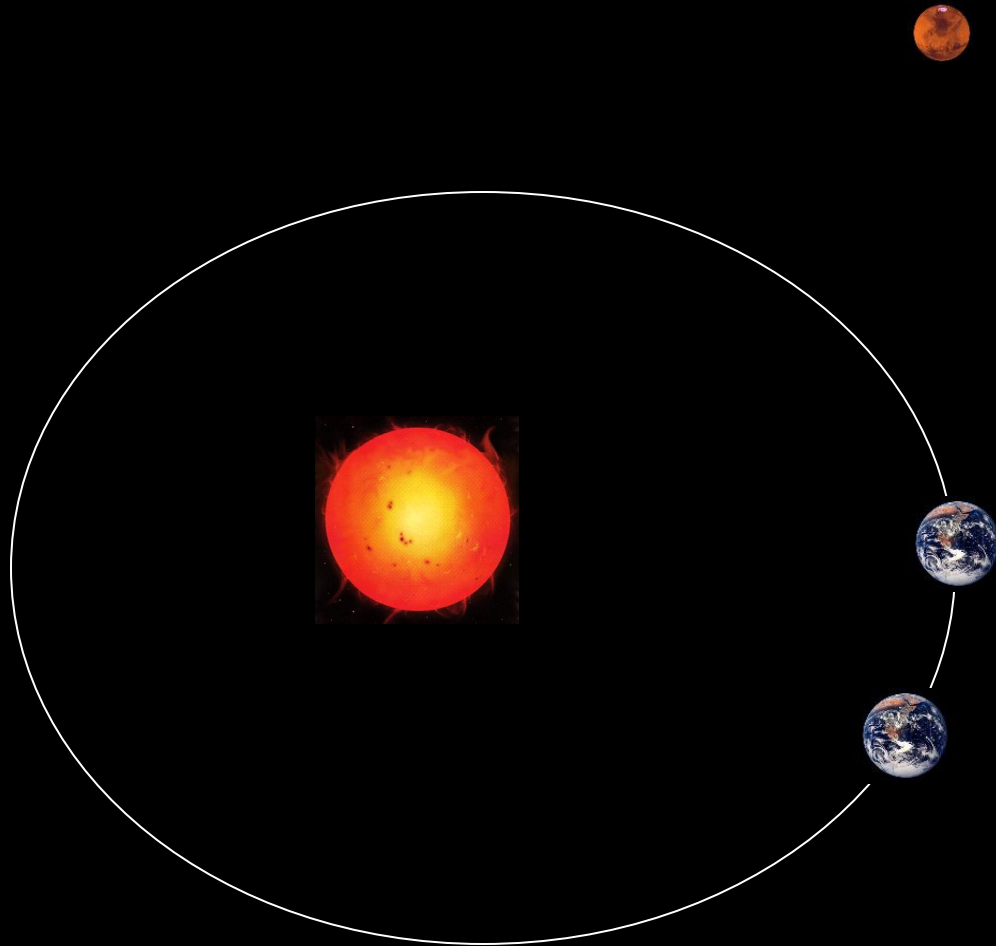
Tycho Brahe's Mars Observations



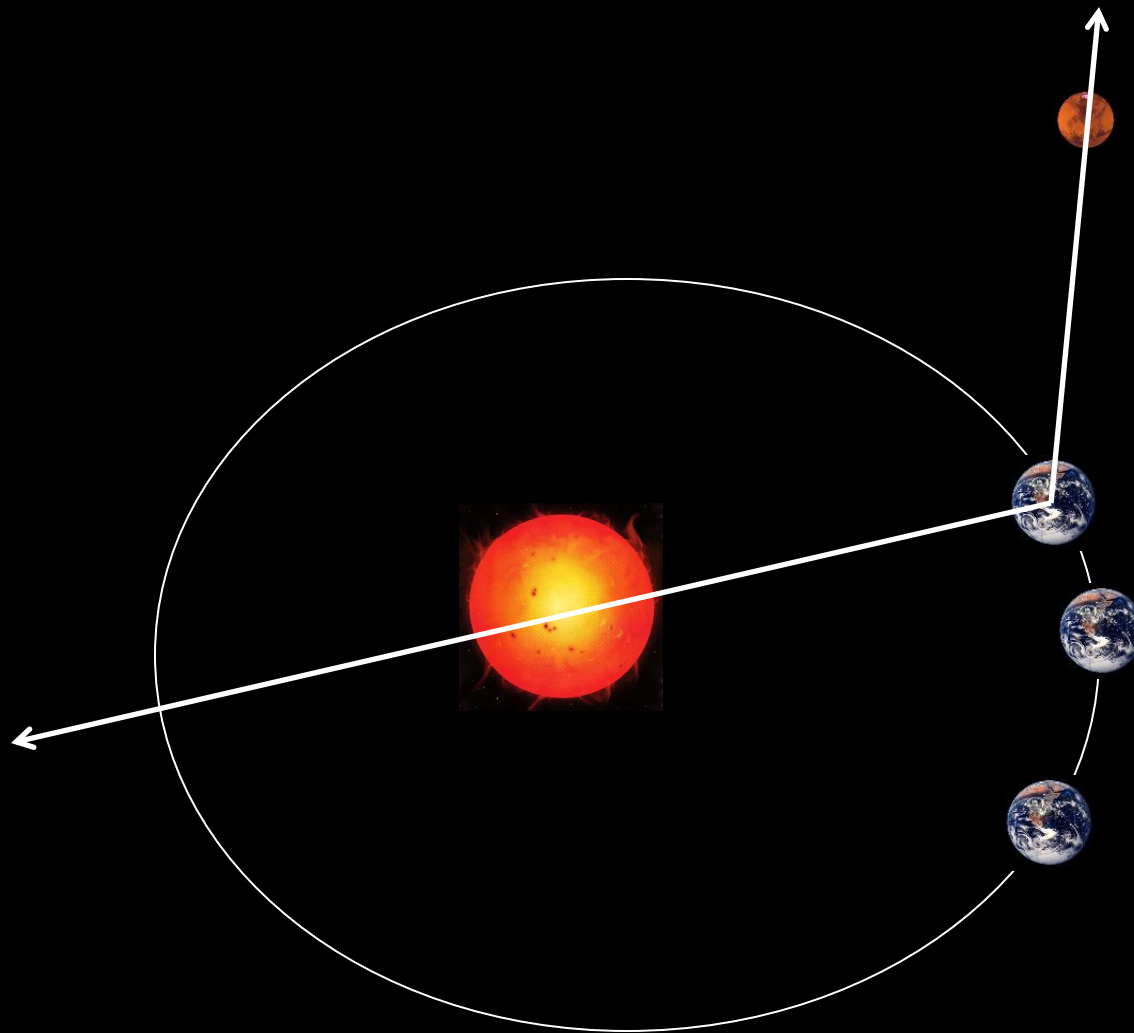
source: Tychonis Brahe Dani Opera Omnia



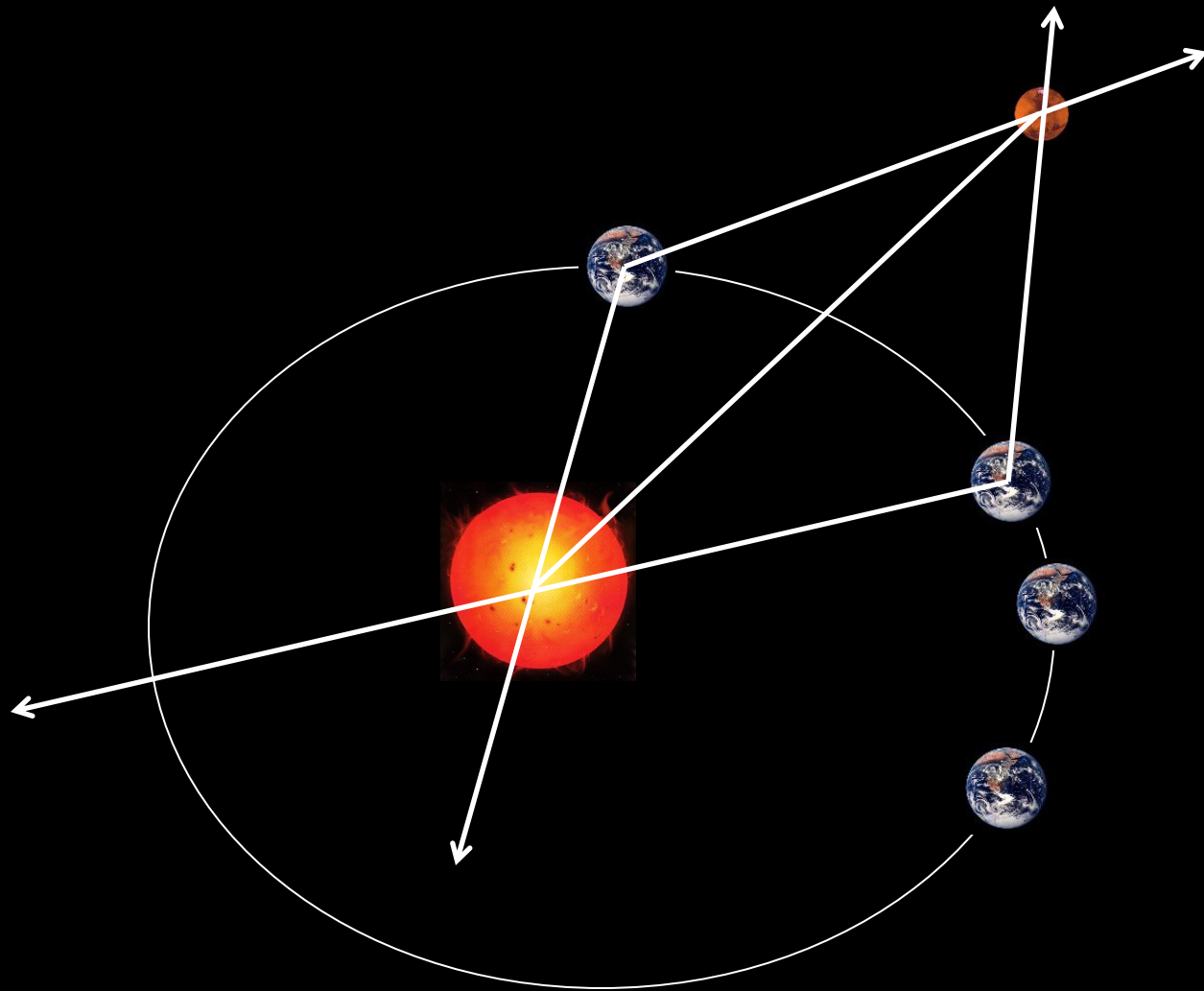
To explain how this works, let's first suppose that Mars is fixed, rather than orbiting the Sun.



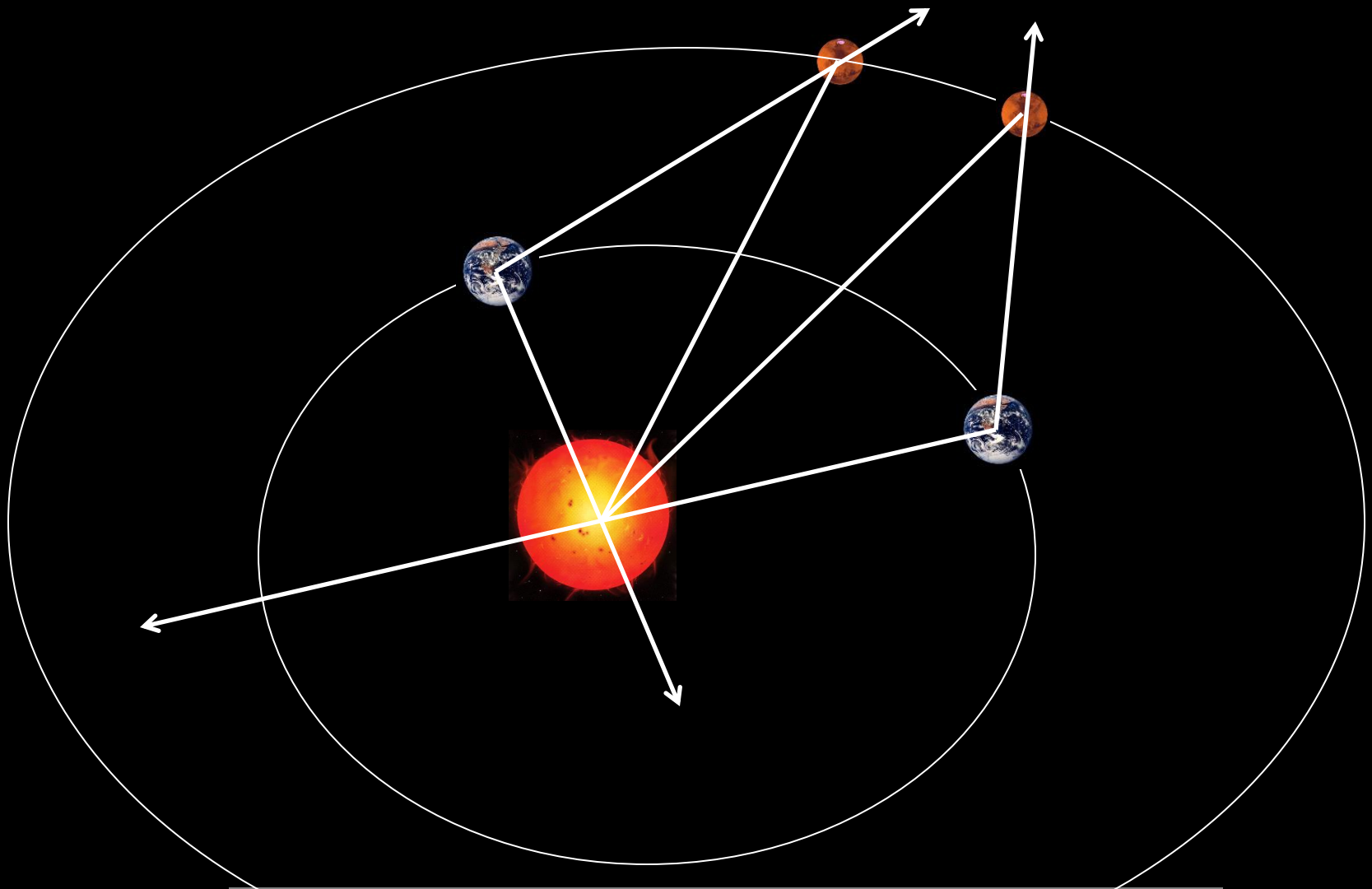
But the Earth is moving in an
unknown orbit.



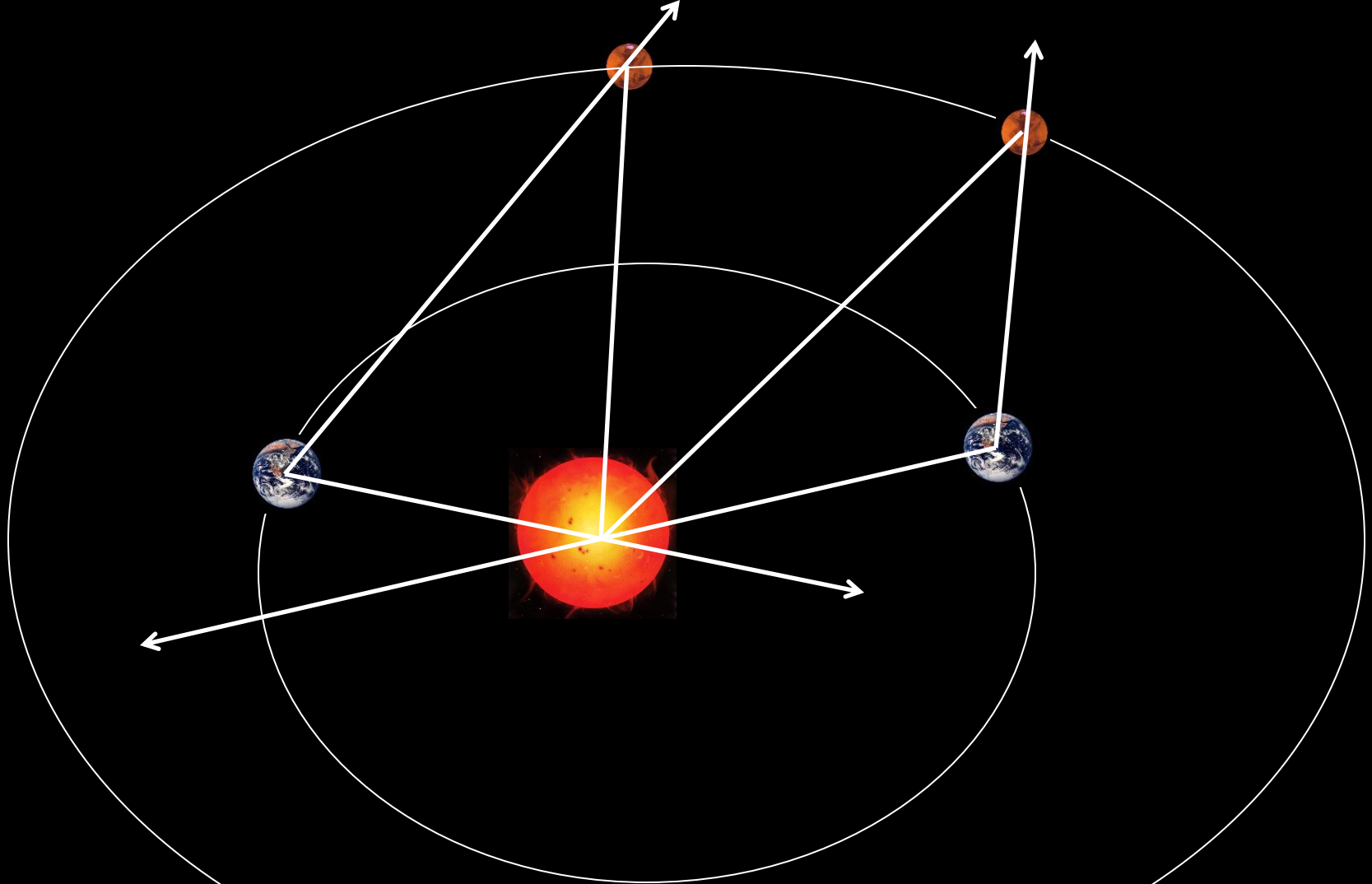
At any given time, one can measure the position of the Sun and Mars from Earth, with respect to the fixed stars (the Zodiac).



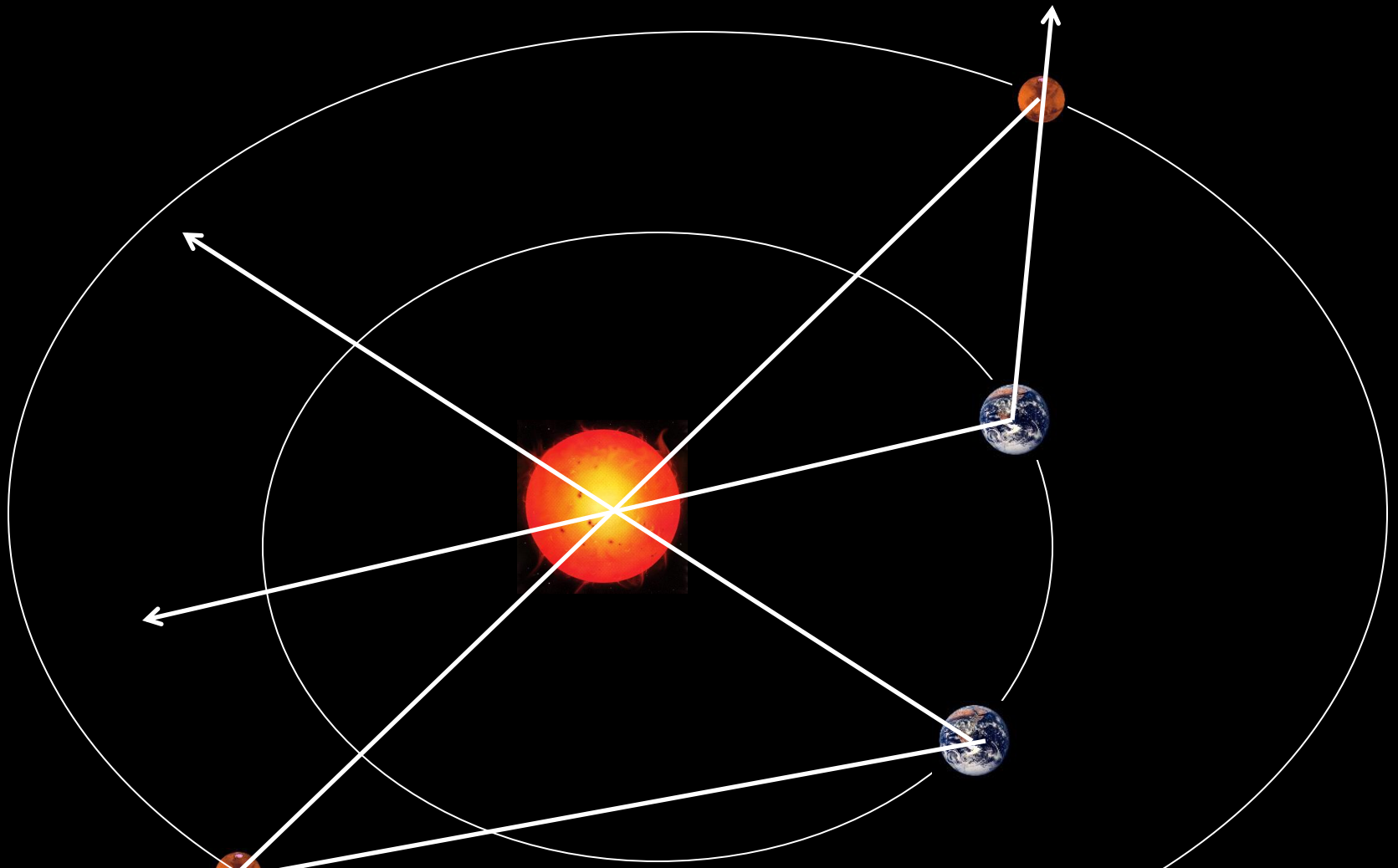
Assuming that the Sun and Mars are fixed, one can then **triangulate** to determine the position of the Earth relative to the Sun and Mars.



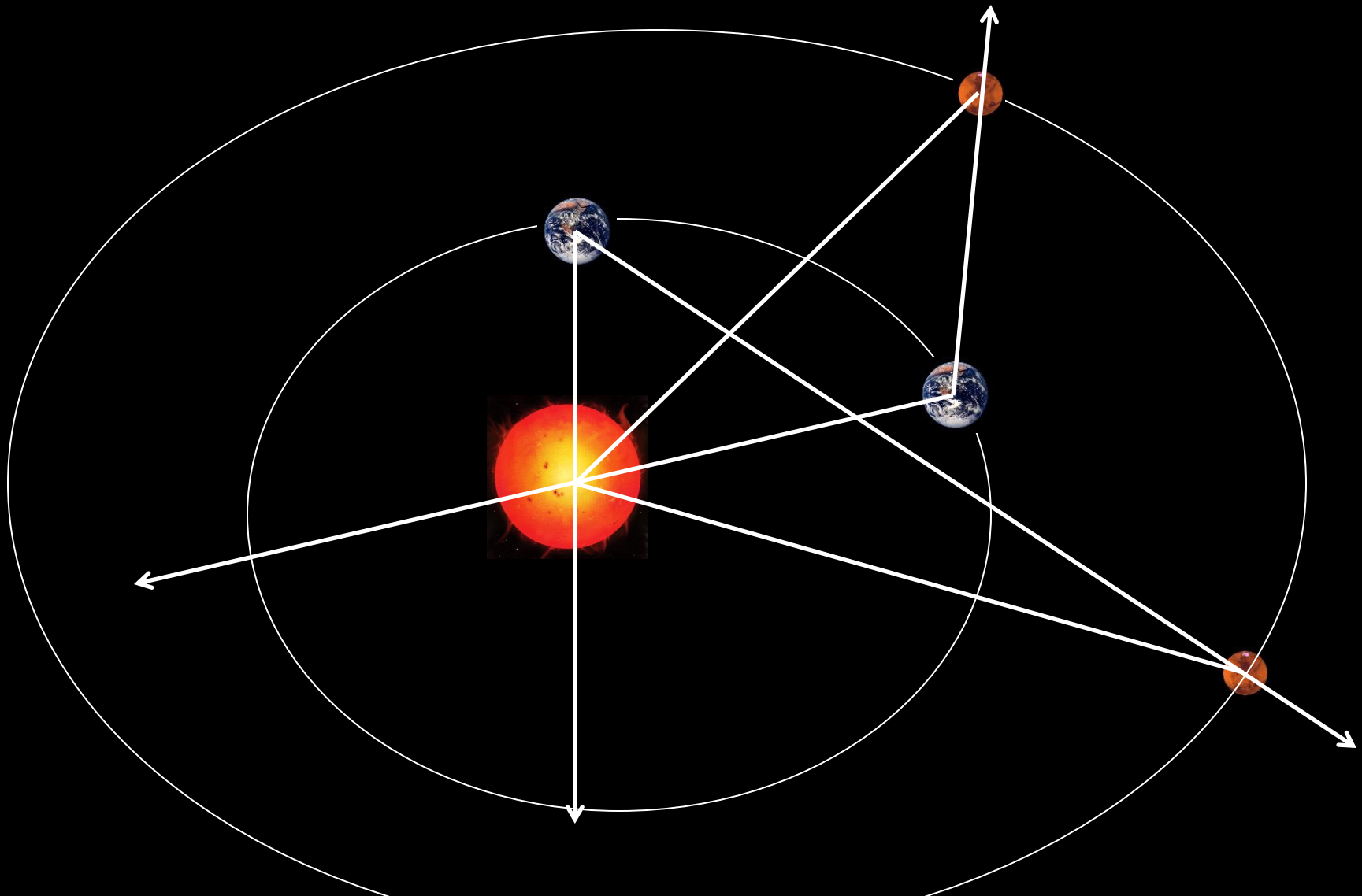
Unfortunately, Mars is not fixed;
it also moves, and along an
unknown orbit.



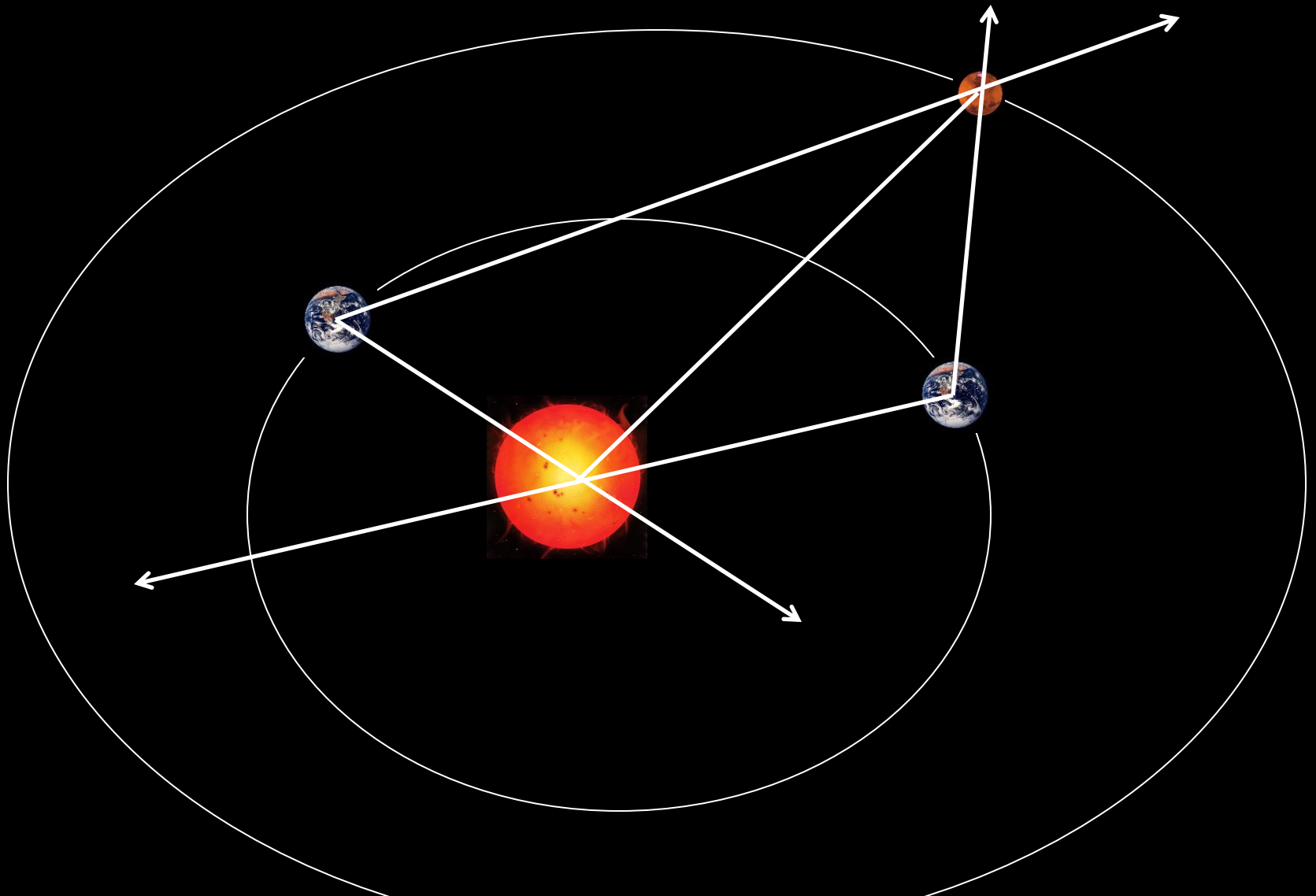
So it appears that
triangulation does not
work.



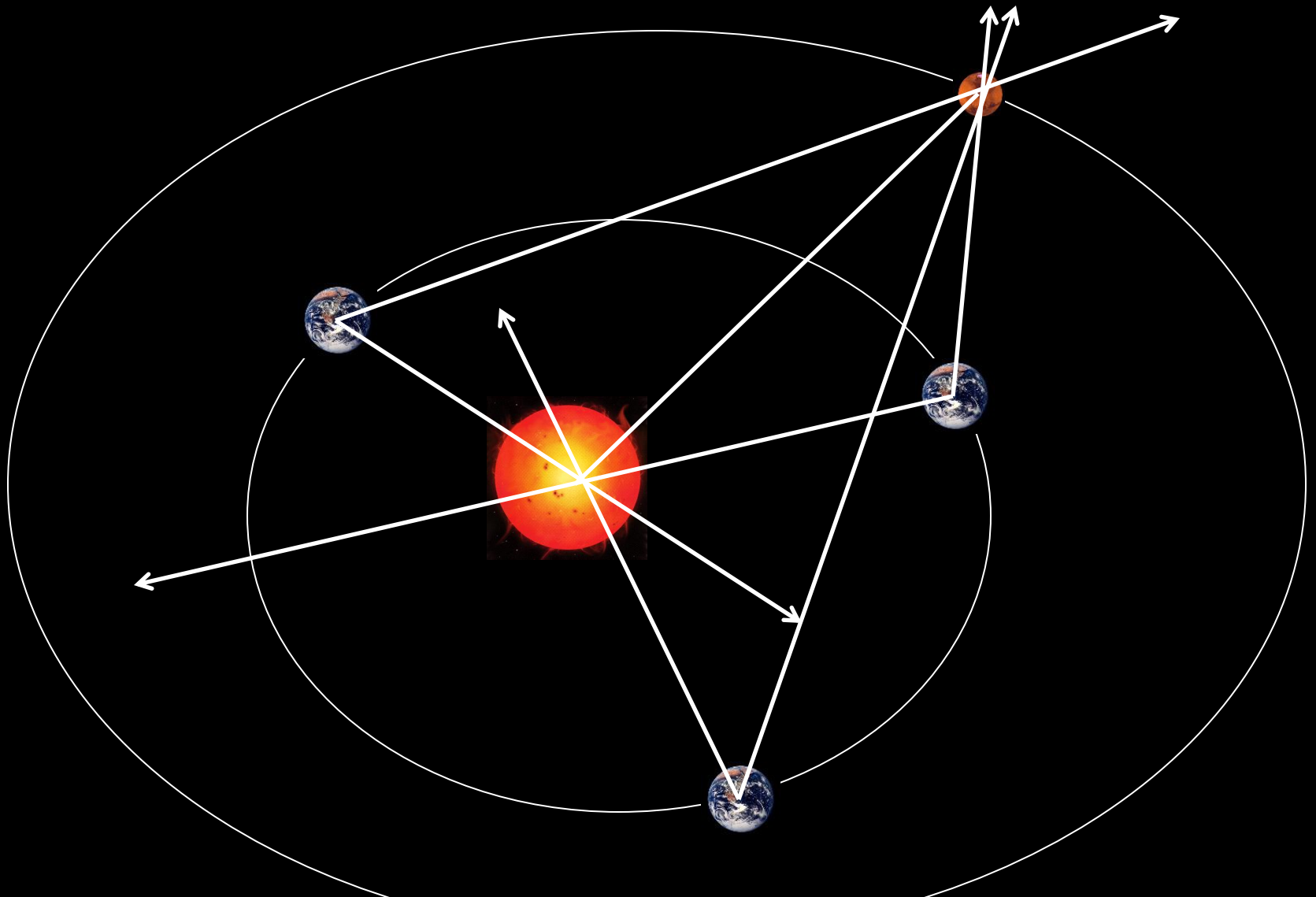
But Kepler had one additional piece of information:



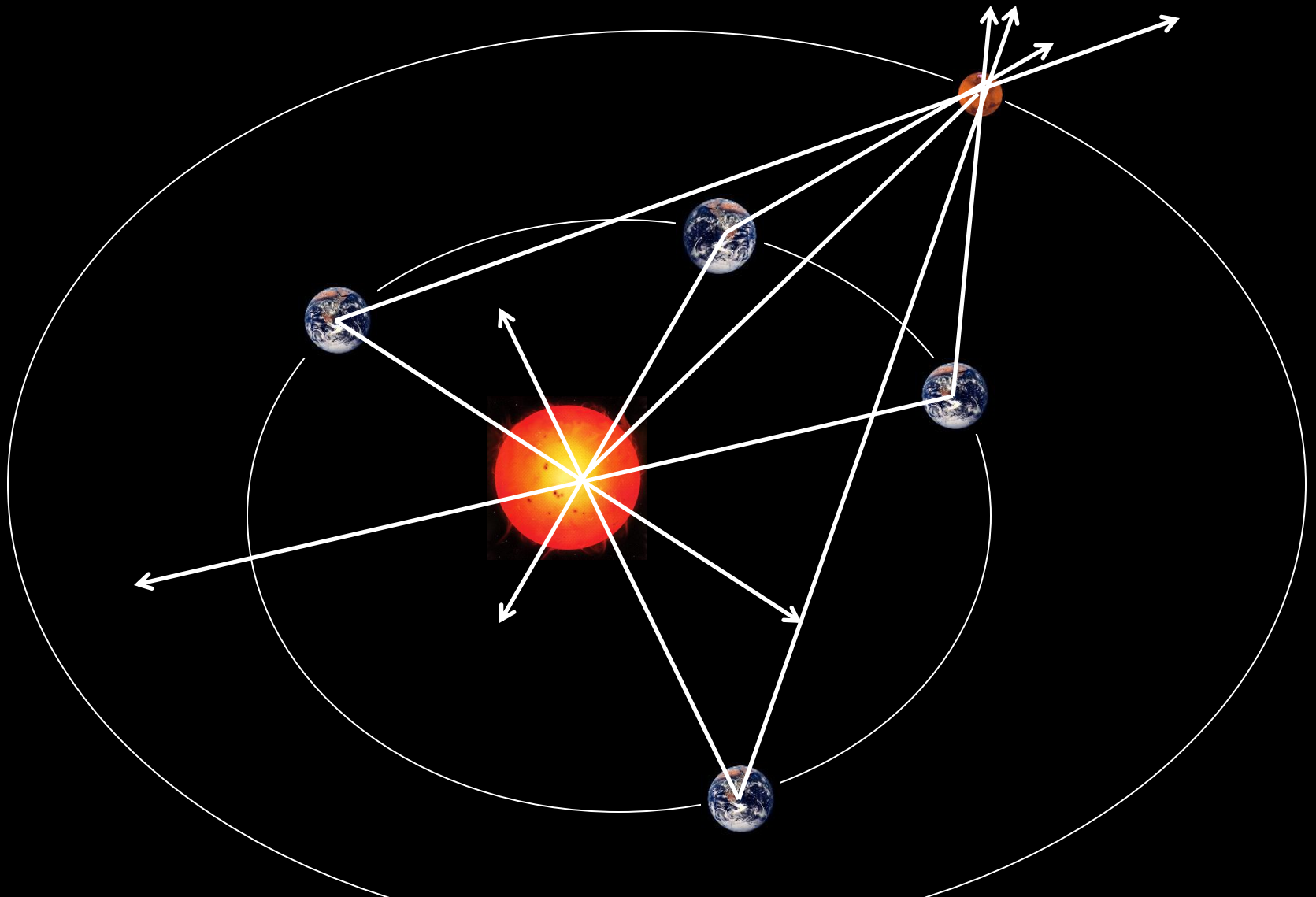
he knew that after every
687 days...



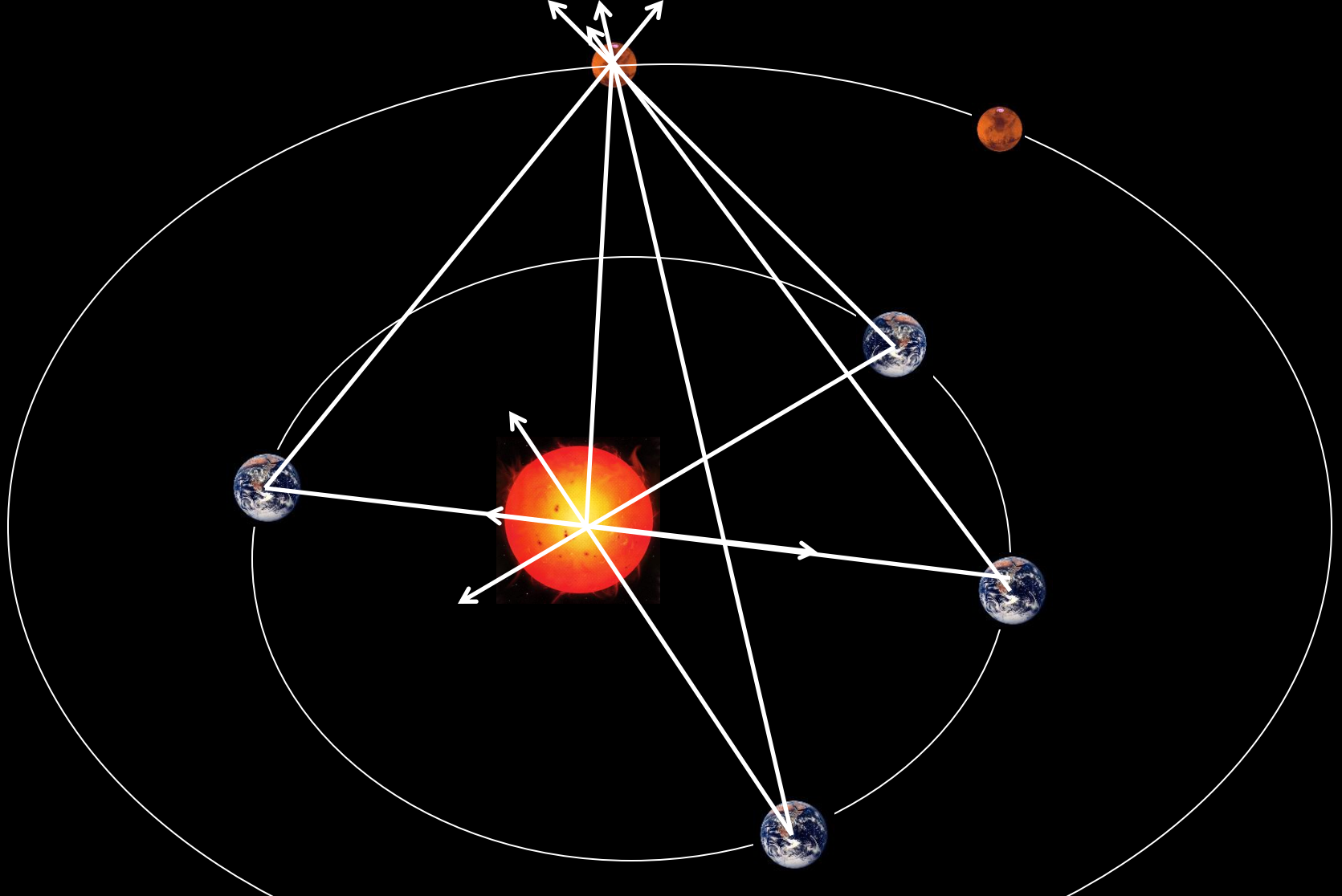
Mars returned to its original position.



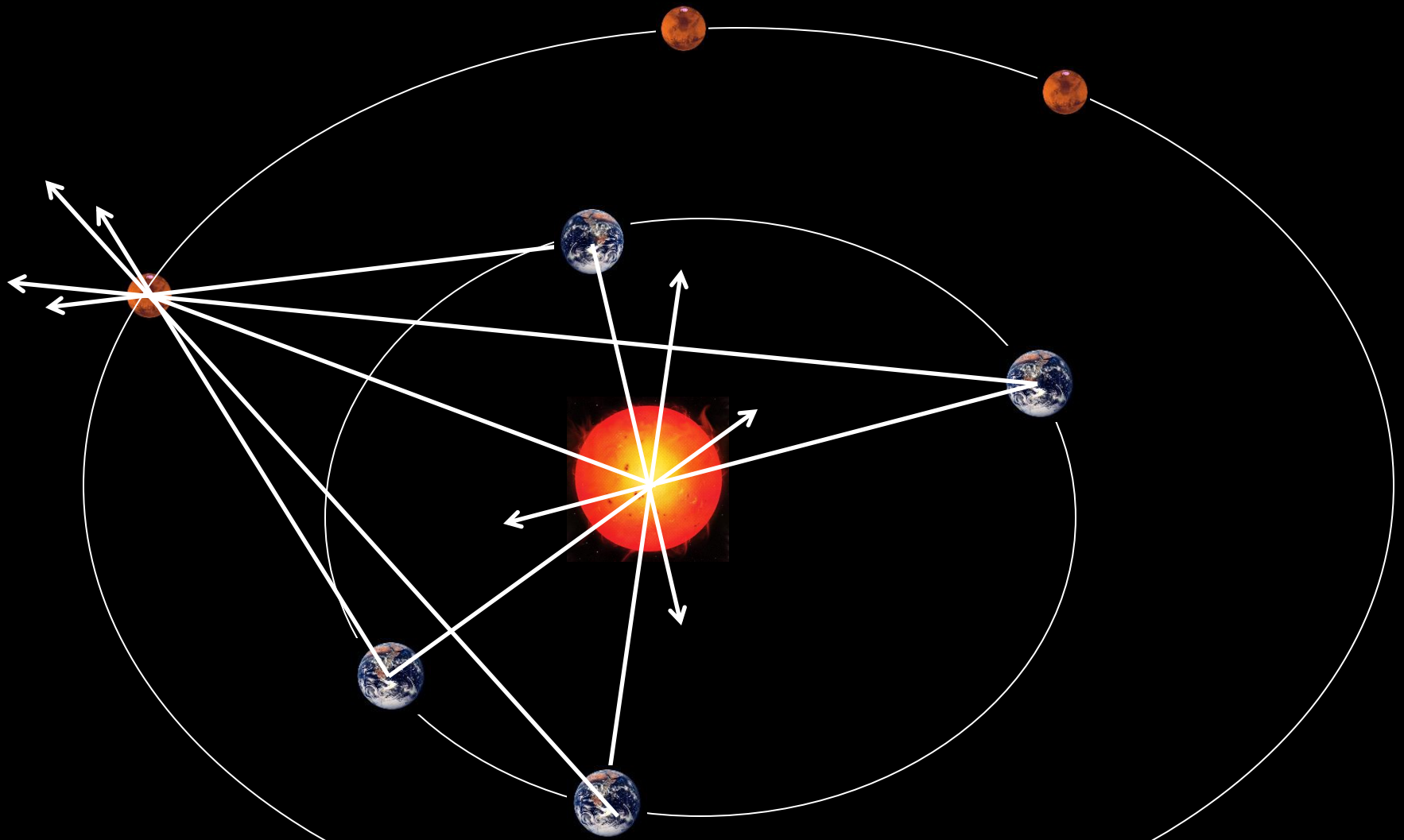
So by taking Brahe's data at intervals of 687 days...



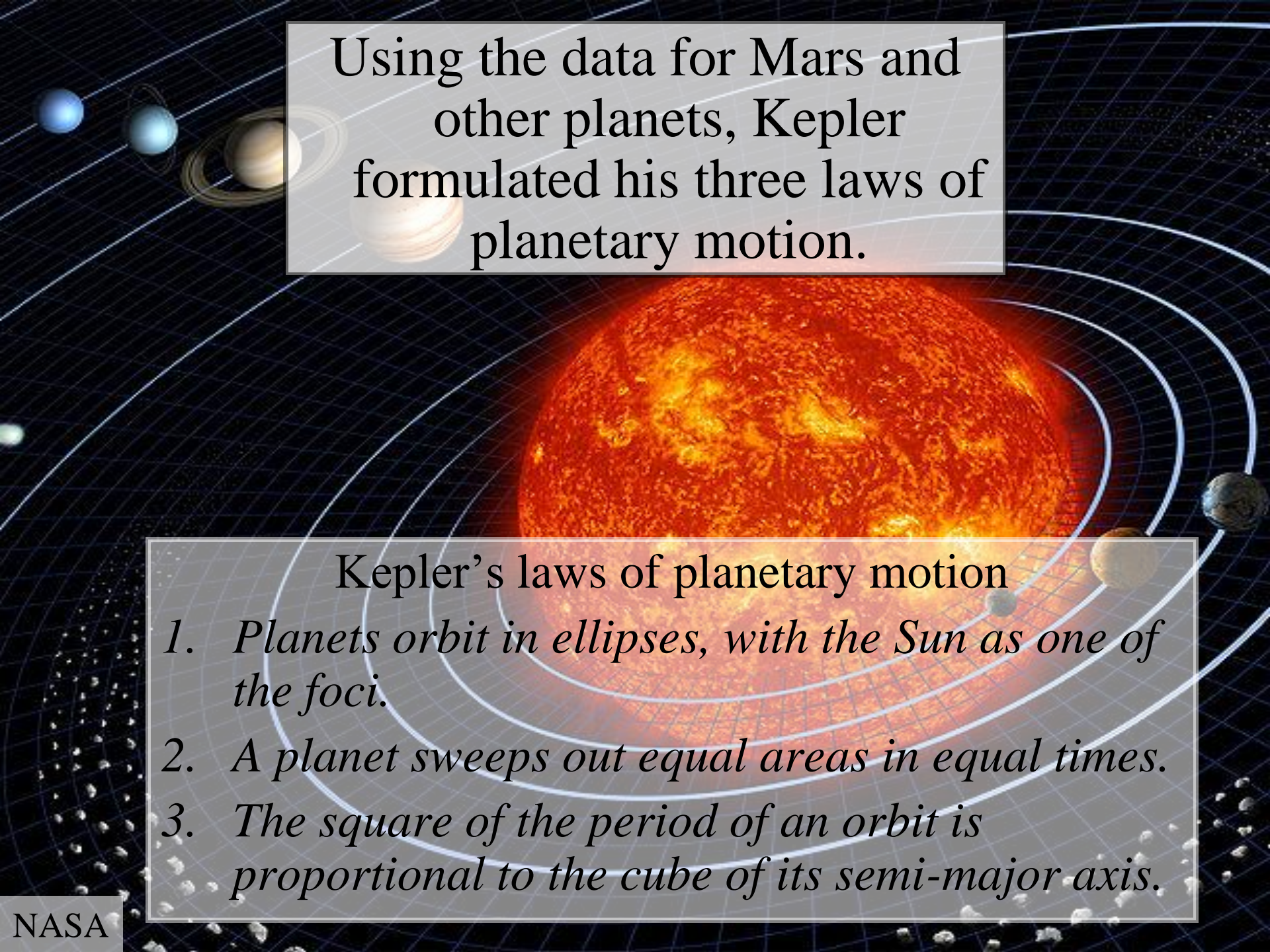
... Kepler could triangulate and compute Earth's orbit relative to any position of Mars.



Once Earth's orbit was known, it could be used to compute more positions of Mars by taking other sequences of data separated by 687 days...



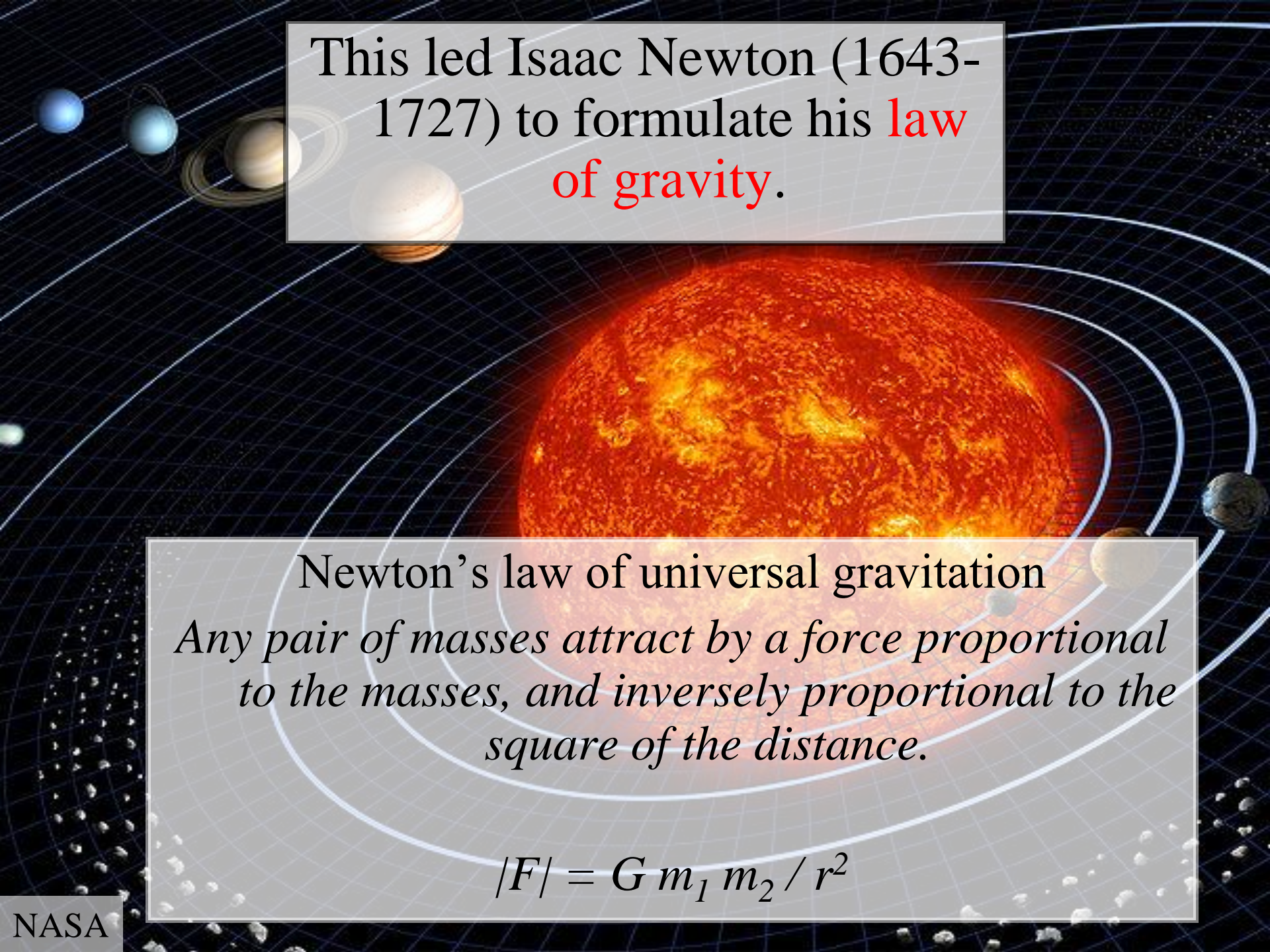
... which allows one to
compute the orbit of Mars.



Using the data for Mars and other planets, Kepler formulated his three laws of planetary motion.

Kepler's laws of planetary motion

1. *Planets orbit in ellipses, with the Sun as one of the foci.*
2. *A planet sweeps out equal areas in equal times.*
3. *The square of the period of an orbit is proportional to the cube of its semi-major axis.*

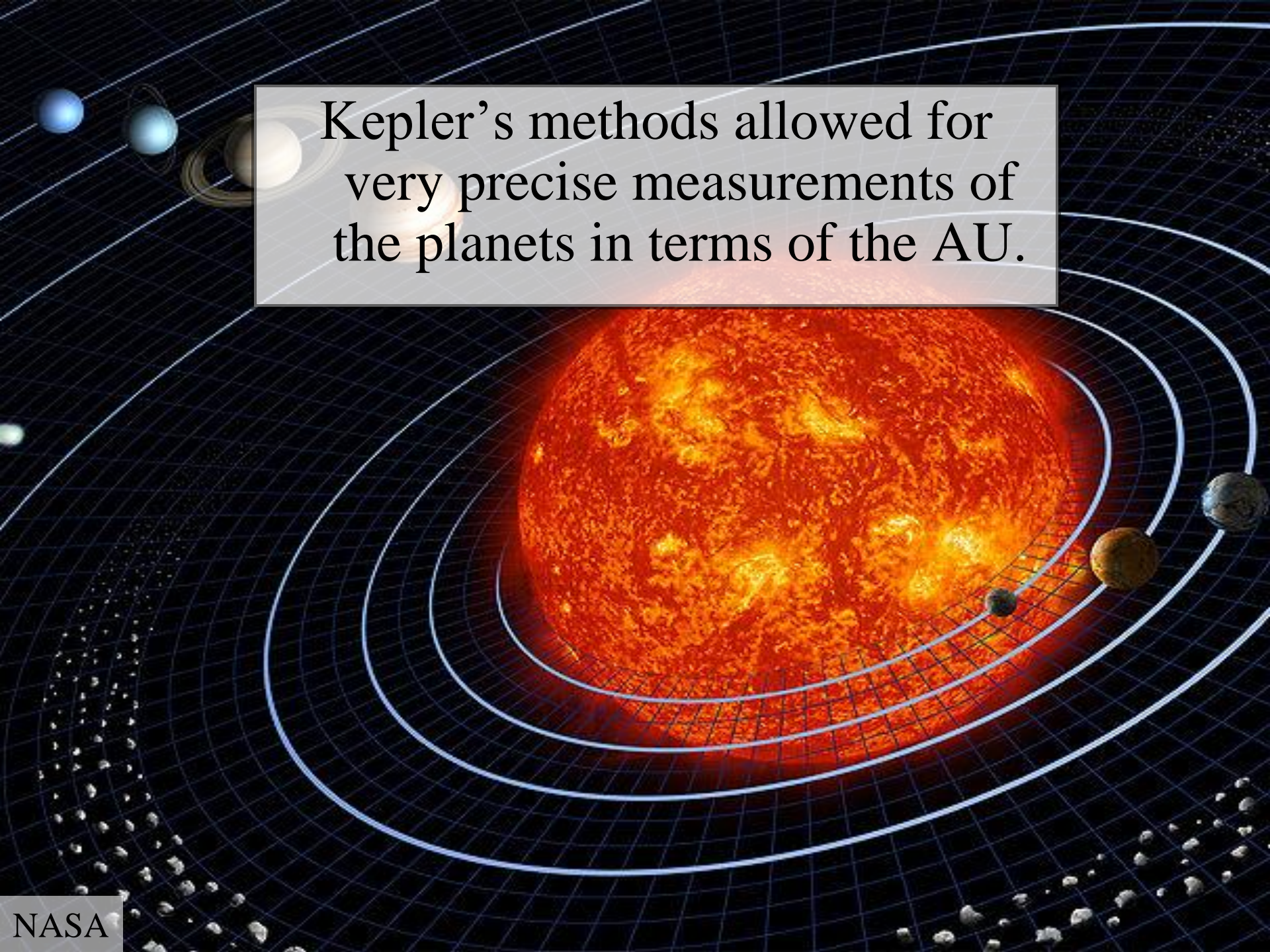


This led Isaac Newton (1643-1727) to formulate his **law of gravity**.

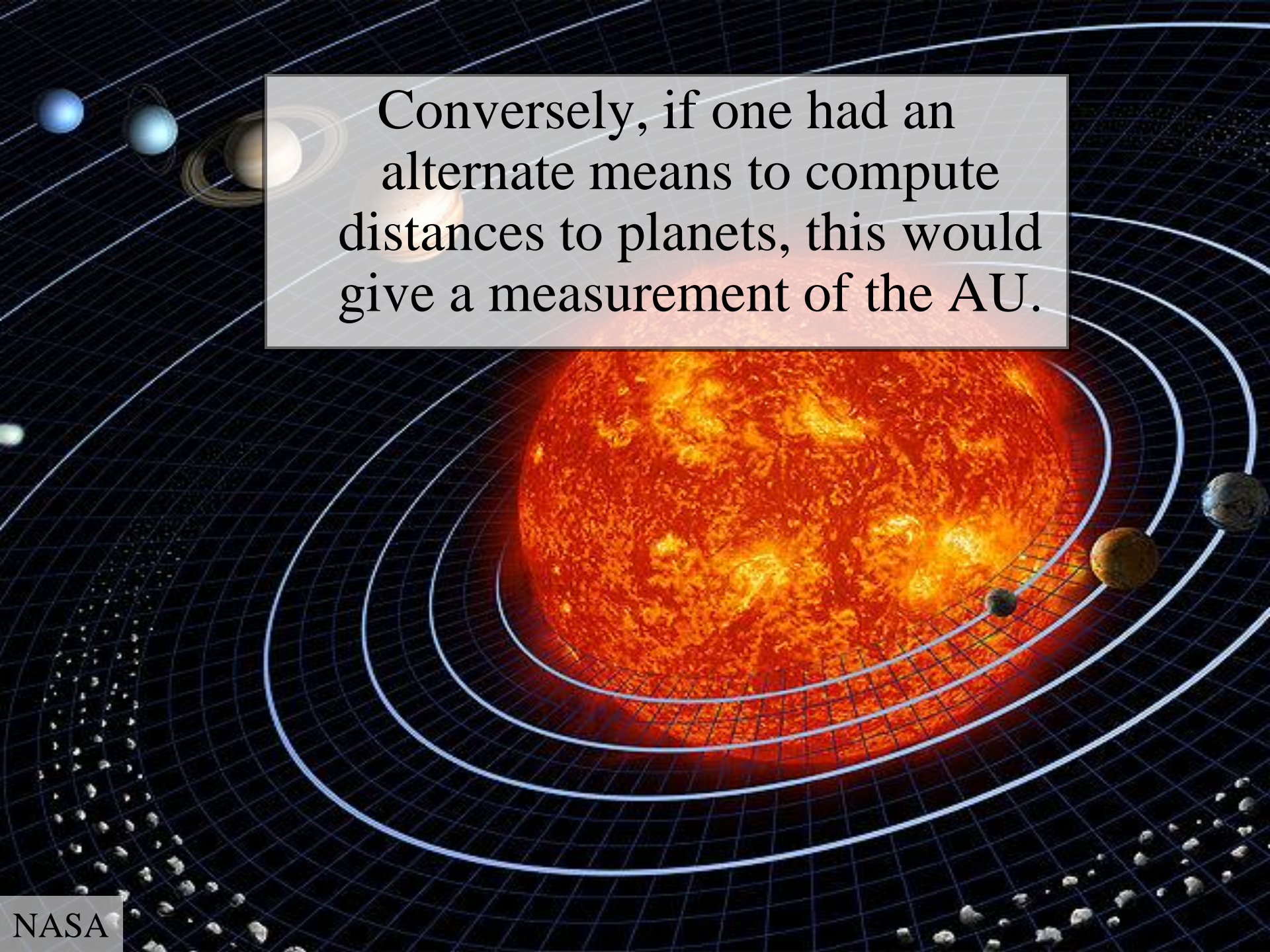
Newton's law of universal gravitation

Any pair of masses attract by a force proportional to the masses, and inversely proportional to the square of the distance.

$$|F| = G m_1 m_2 / r^2$$

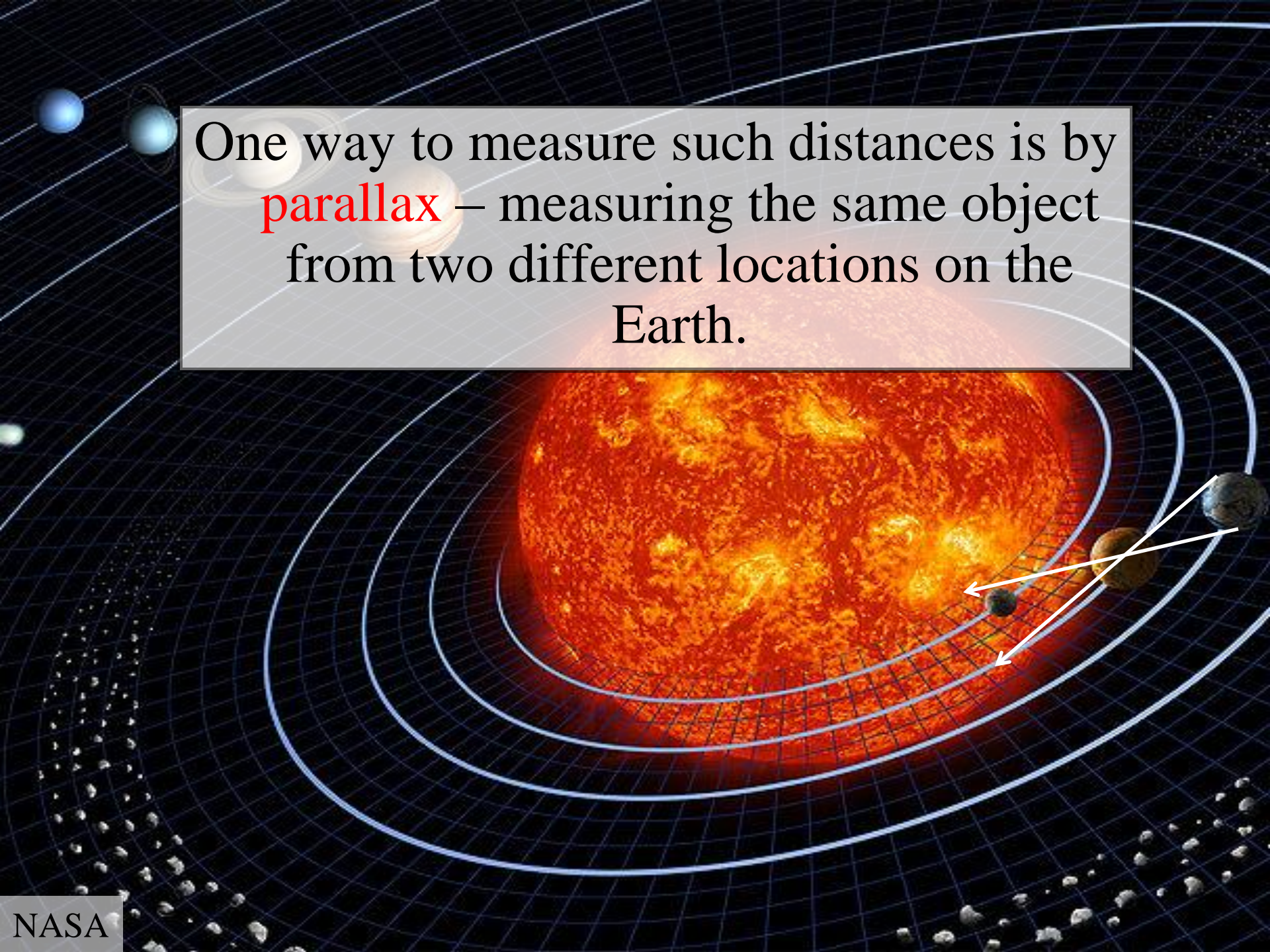


Kepler's methods allowed for very precise measurements of the planets in terms of the AU.

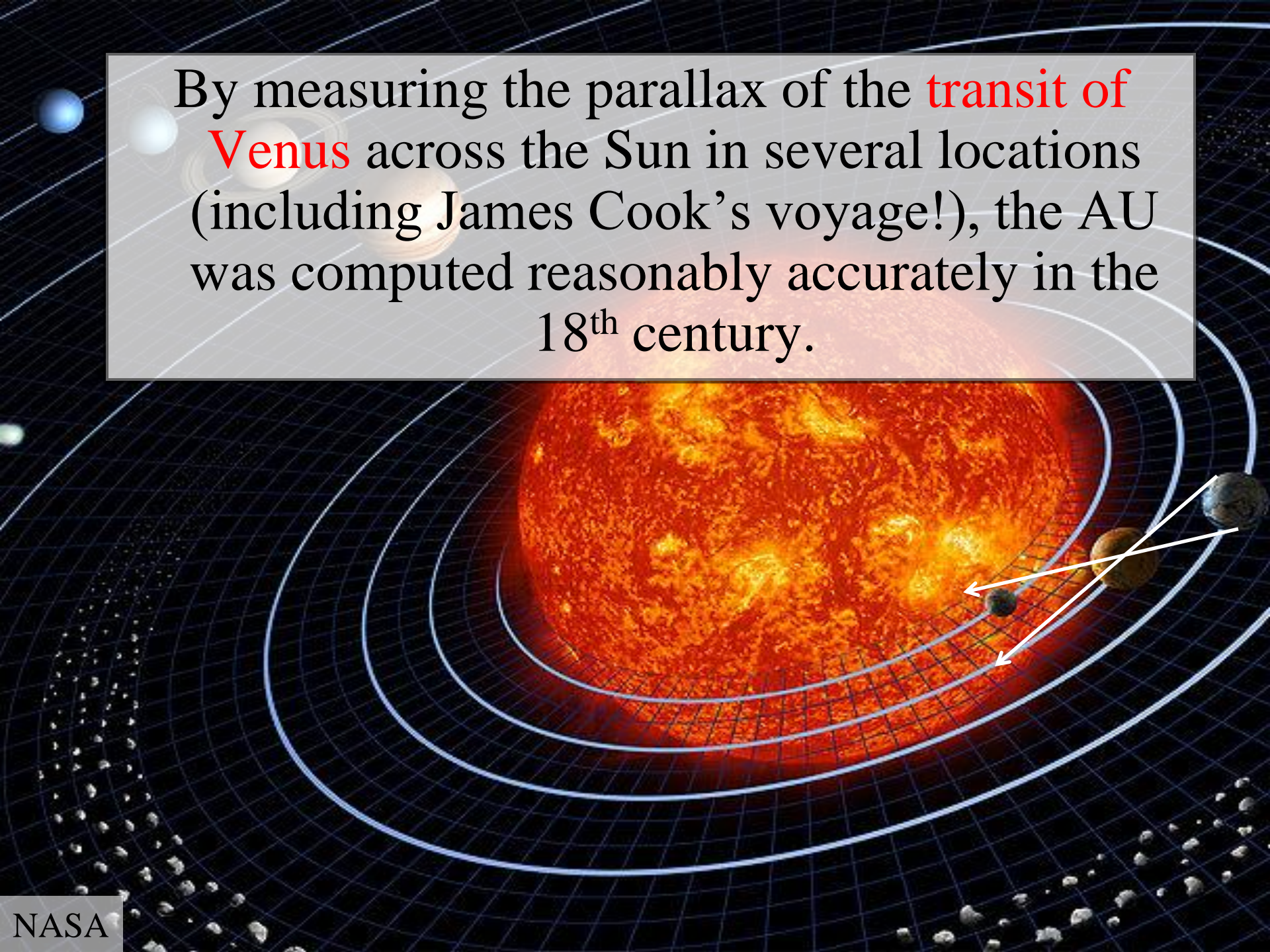
A diagram of the solar system showing the Sun at the center, with planets and their orbits. A text box is overlaid on the image.

Conversely, if one had an alternate means to compute distances to planets, this would give a measurement of the AU.

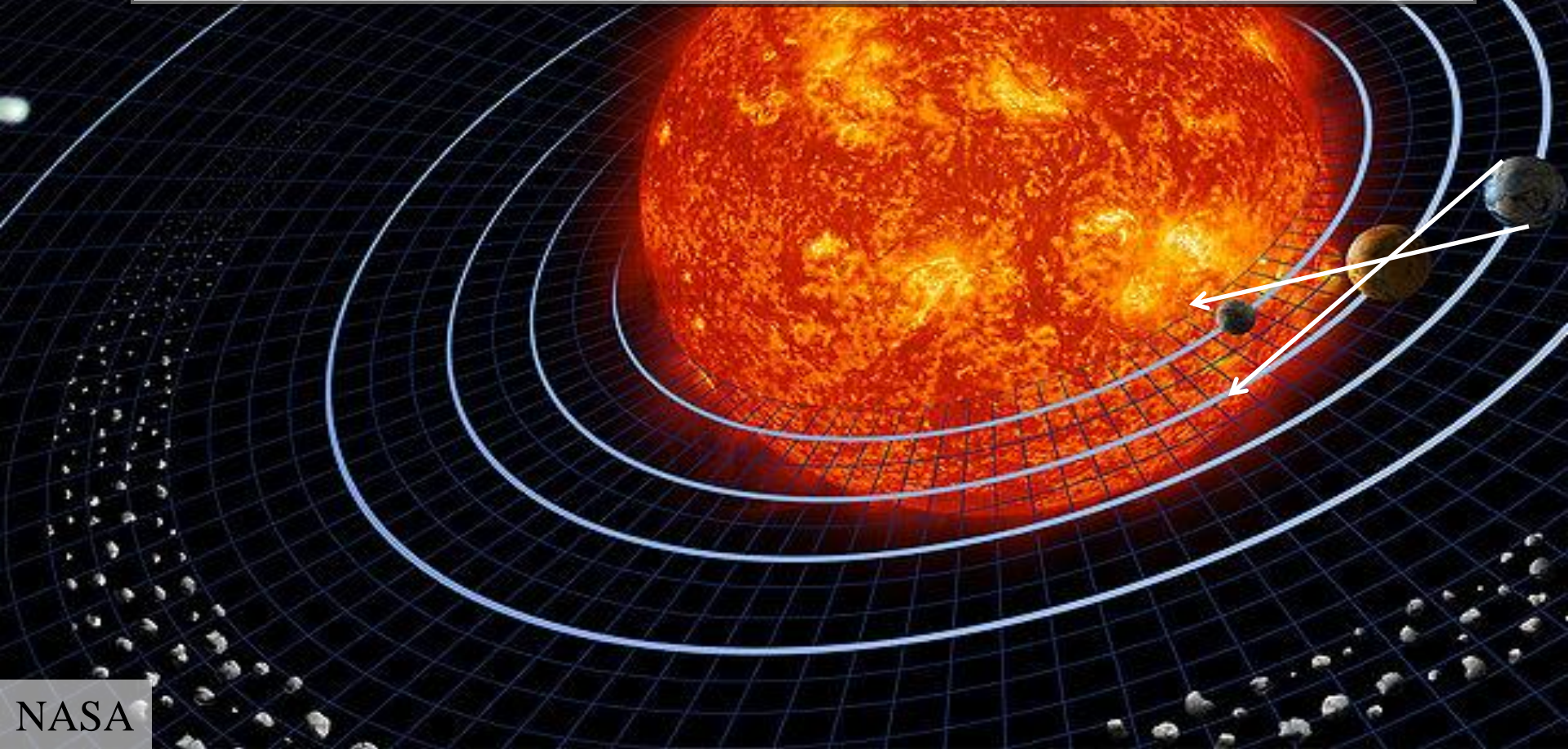
One way to measure such distances is by **parallax** – measuring the same object from two different locations on the Earth.



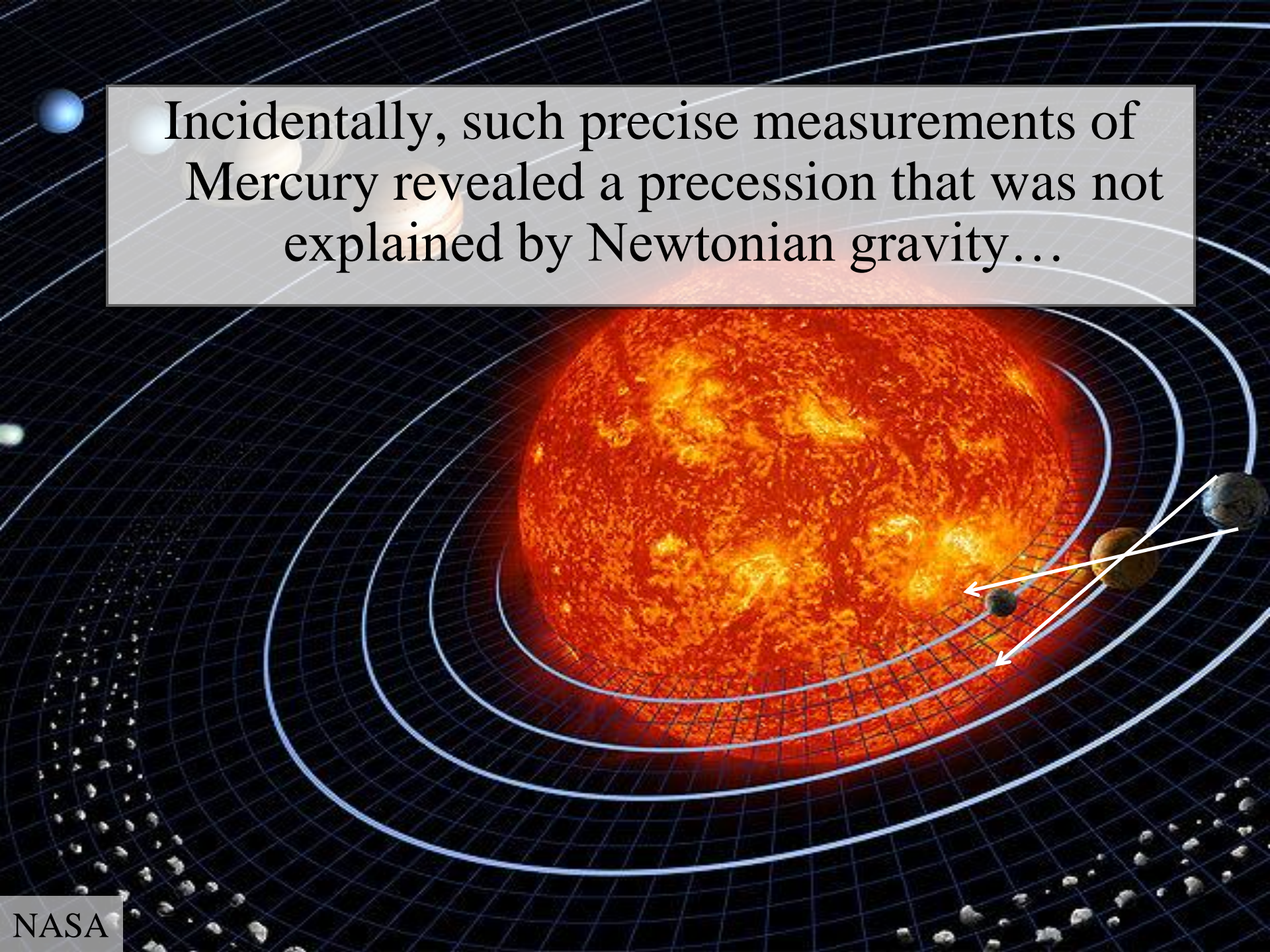
By measuring the parallax of the **transit of Venus** across the Sun in several locations (including James Cook's voyage!), the AU was computed reasonably accurately in the 18th century.



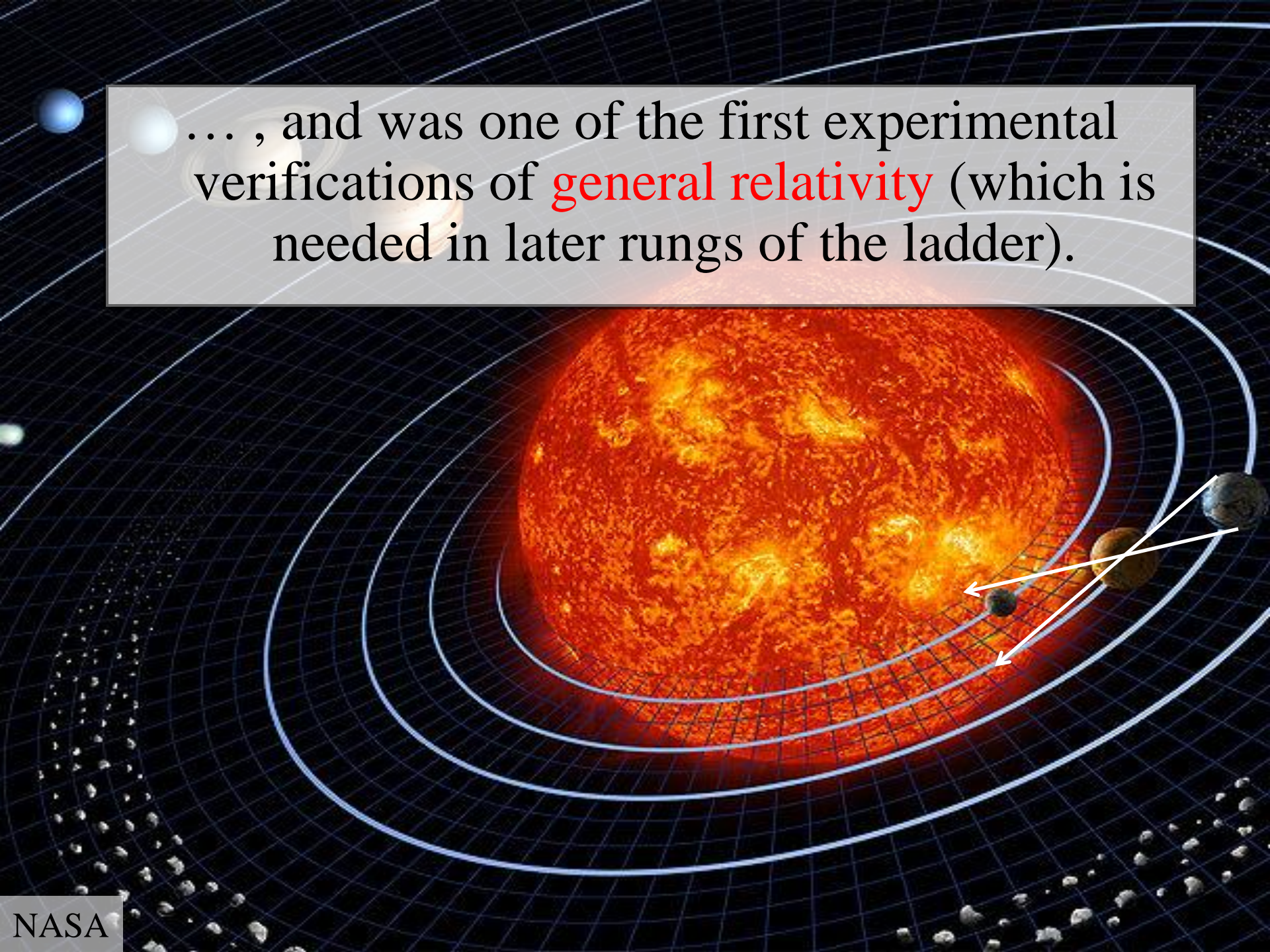
With modern technology such as **radar** and **interplanetary satellites**, the AU and the planetary orbits have now been computed to extremely high precision.



Incidentally, such precise measurements of Mercury revealed a precession that was not explained by Newtonian gravity...




... , and was one of the first experimental verifications of **general relativity** (which is needed in later rungs of the ladder).

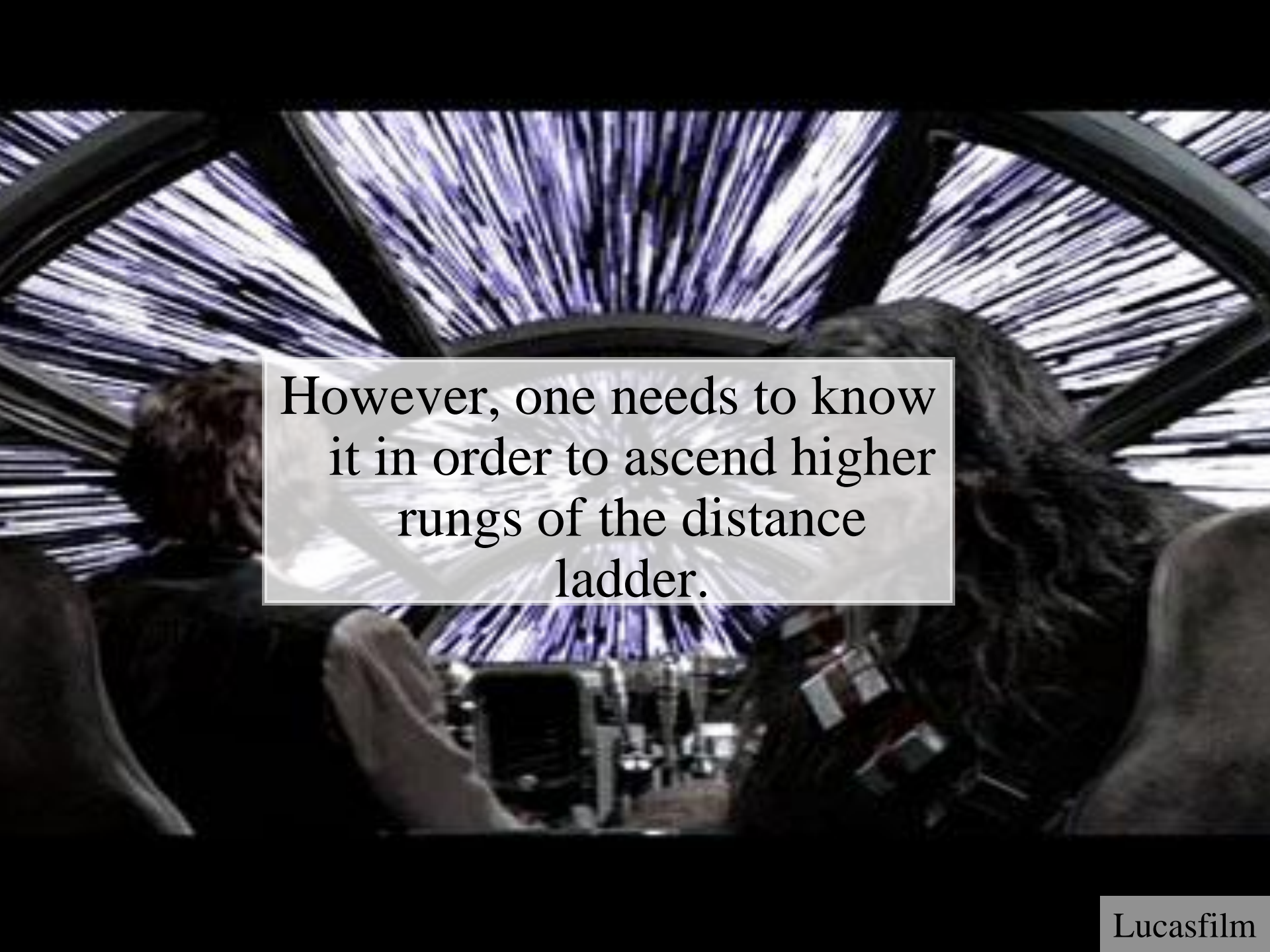


The background image is a scene from the movie Star Wars: The Force Awakens, showing the interior of the Millennium Falcon. The view is from the cockpit, looking forward through the main viewport. The ceiling is a complex, ribbed structure with a central circular opening. The lighting is dramatic, with strong highlights and deep shadows. The text "5th rung: the speed of light" is overlaid in a large, bold, black serif font on a semi-transparent white rectangular background.

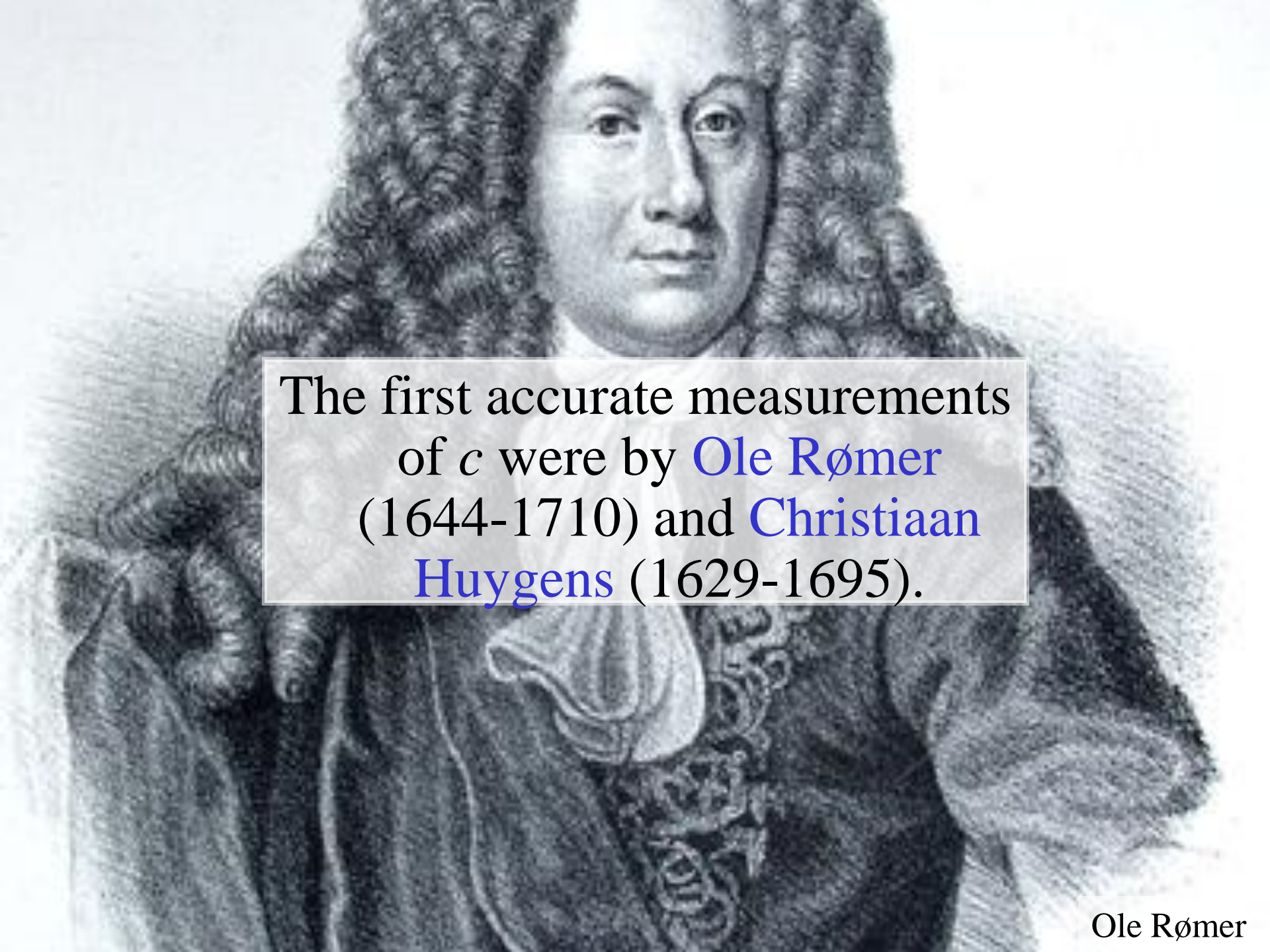
**5th rung: the speed
of light**

A background image showing a perspective from inside a spacecraft cockpit, looking out through a large window. The view outside is a dense field of blue and white streaks radiating from the center, representing the speed of light effect. Two characters are visible in the foreground, seen from behind, looking out the window. The text is overlaid on a semi-transparent white box in the center of the image.

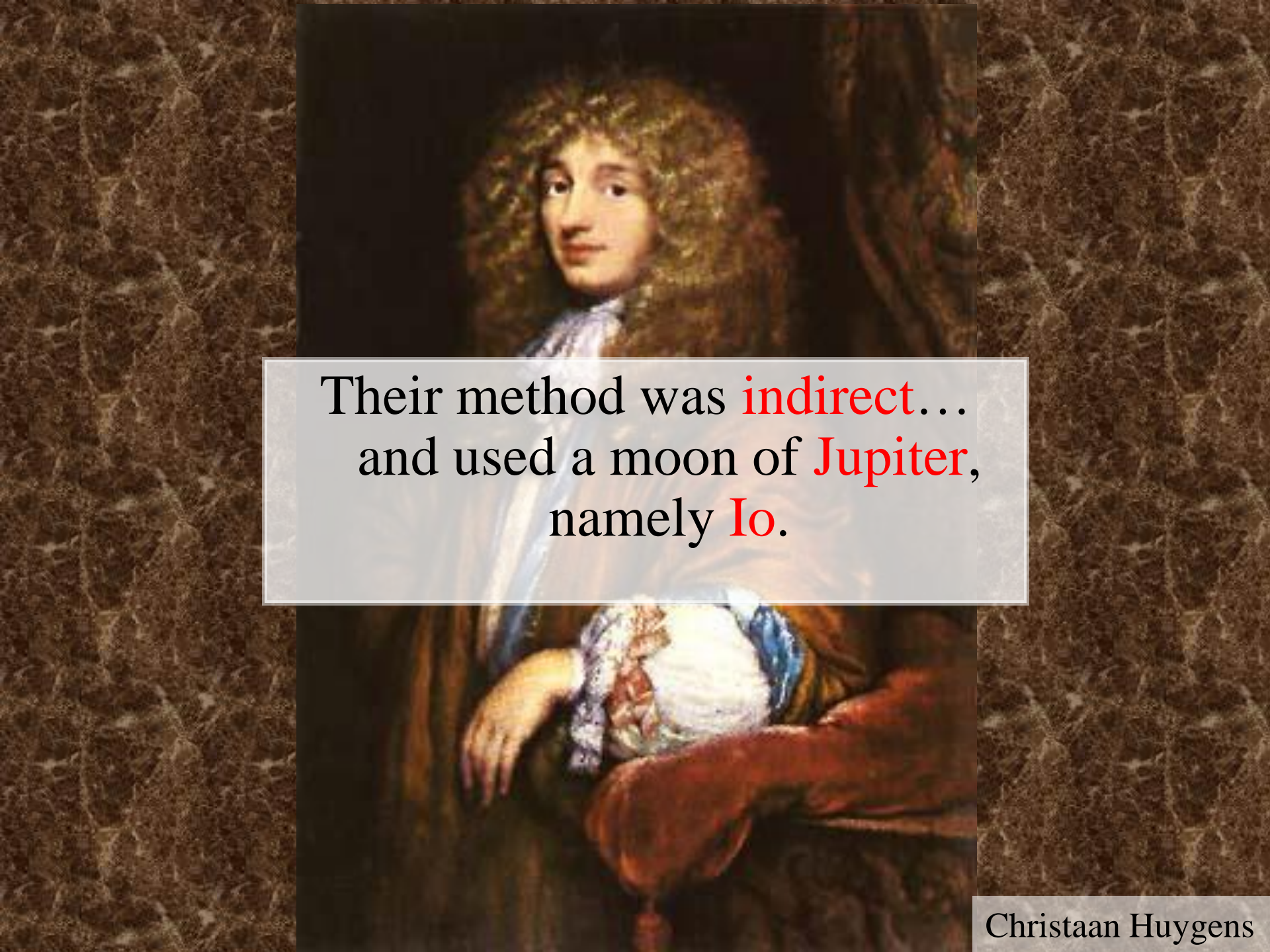
Technically, the **speed of light**, c , is not a distance.



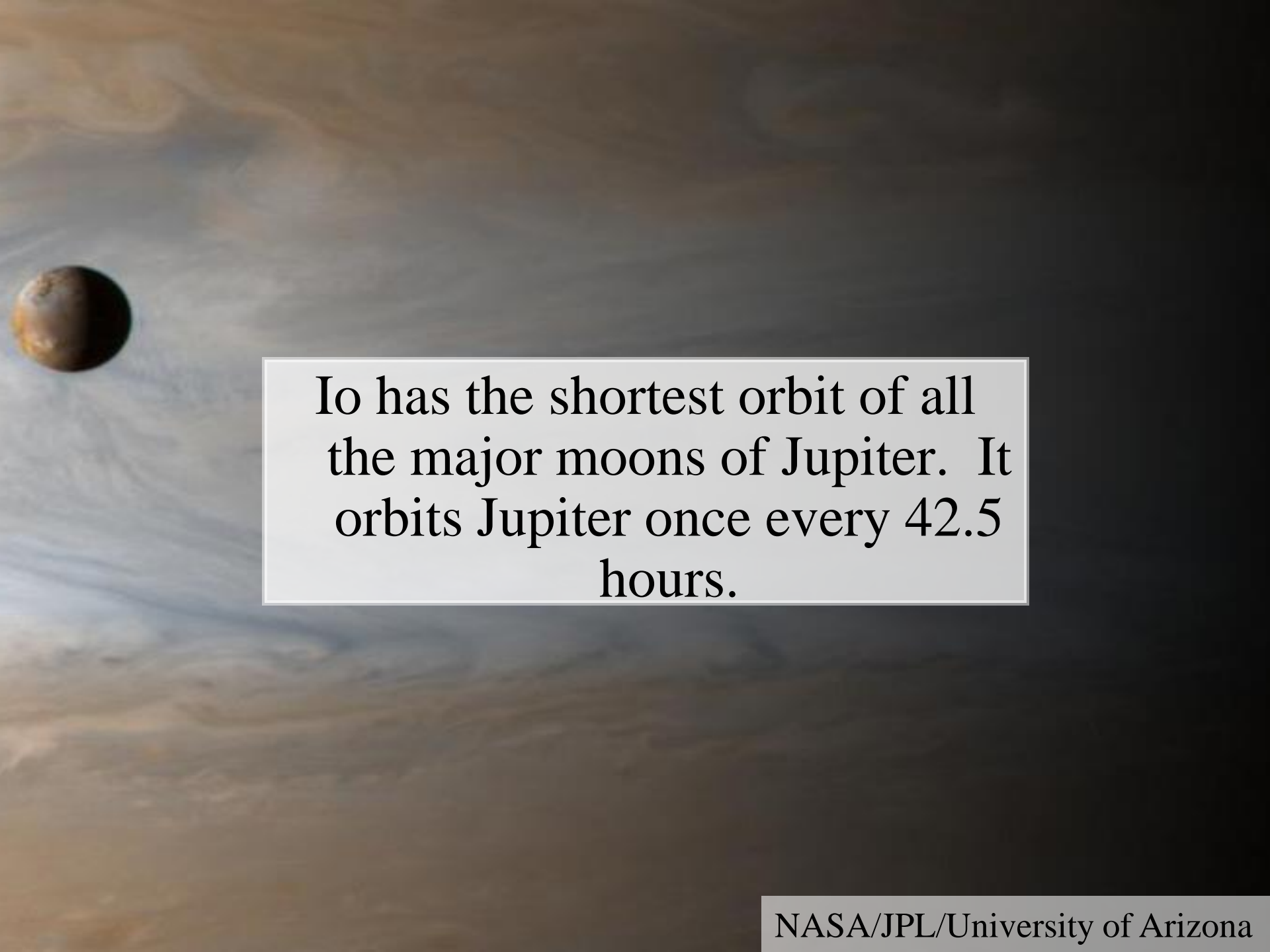
However, one needs to know
it in order to ascend higher
rungs of the distance
ladder.

A black and white engraving of Ole Rømer, a Danish astronomer. He is depicted from the chest up, wearing a large, curly wig and a dark, patterned coat with a white ruffled collar. The background is a light, textured grey.

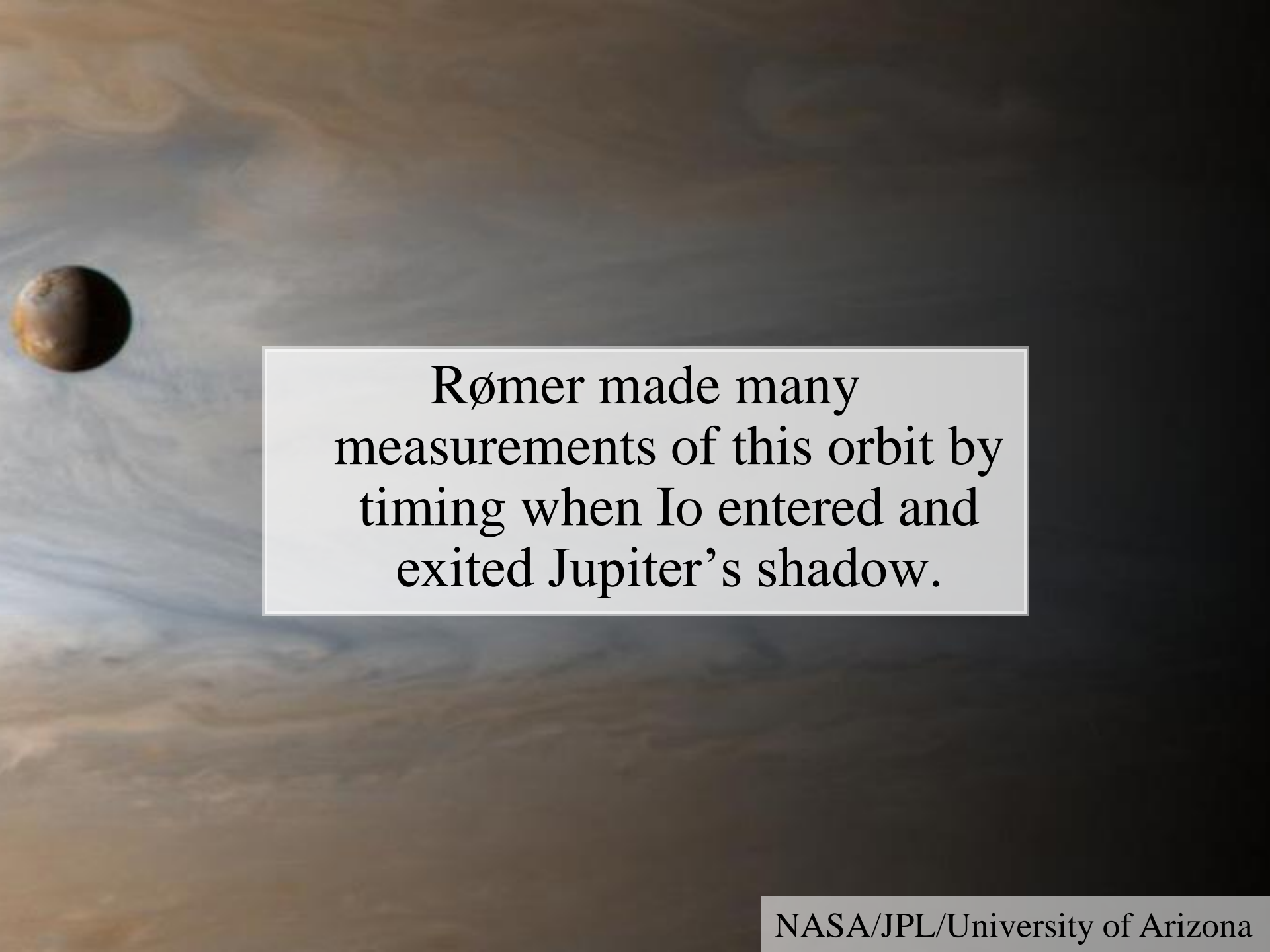
The first accurate measurements
of c were by **Ole Rømer**
(1644-1710) and **Christiaan**
Huygens (1629-1695).

A portrait of Christiaan Huygens, a Dutch astronomer, mathematician, and physicist. He is depicted from the chest up, wearing a large, curly wig and a blue and white striped shirt. He is seated and looking slightly to the right. The background is dark and textured.

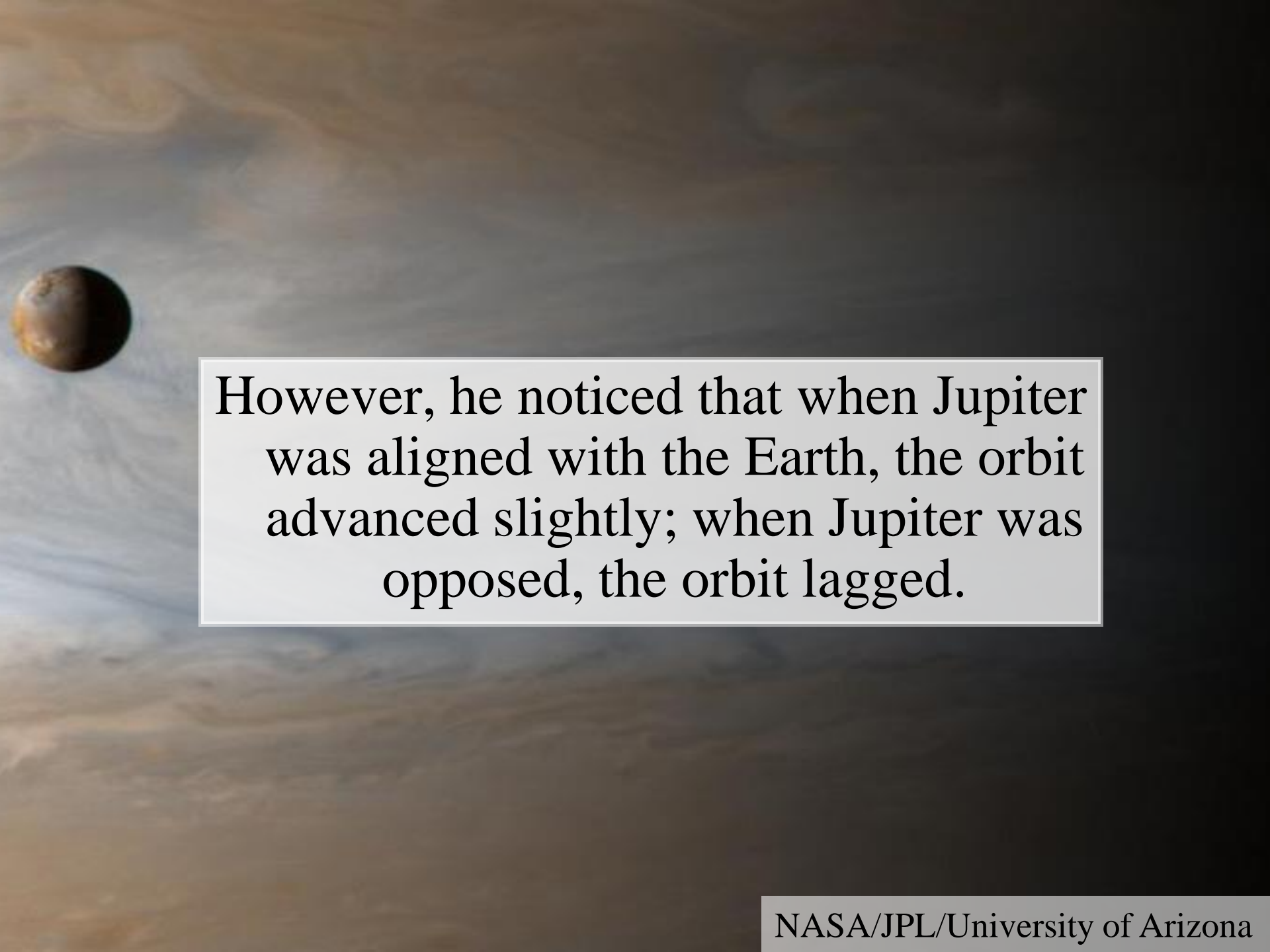
Their method was **indirect**...
and used a moon of **Jupiter**,
namely **Io**.

A photograph of the planet Jupiter with its characteristic bands of orange, brown, and white clouds. In the upper left corner, the moon Io is visible as a small, dark, spherical object. A white rectangular box with a thin black border is centered on the right side of the image, containing text.

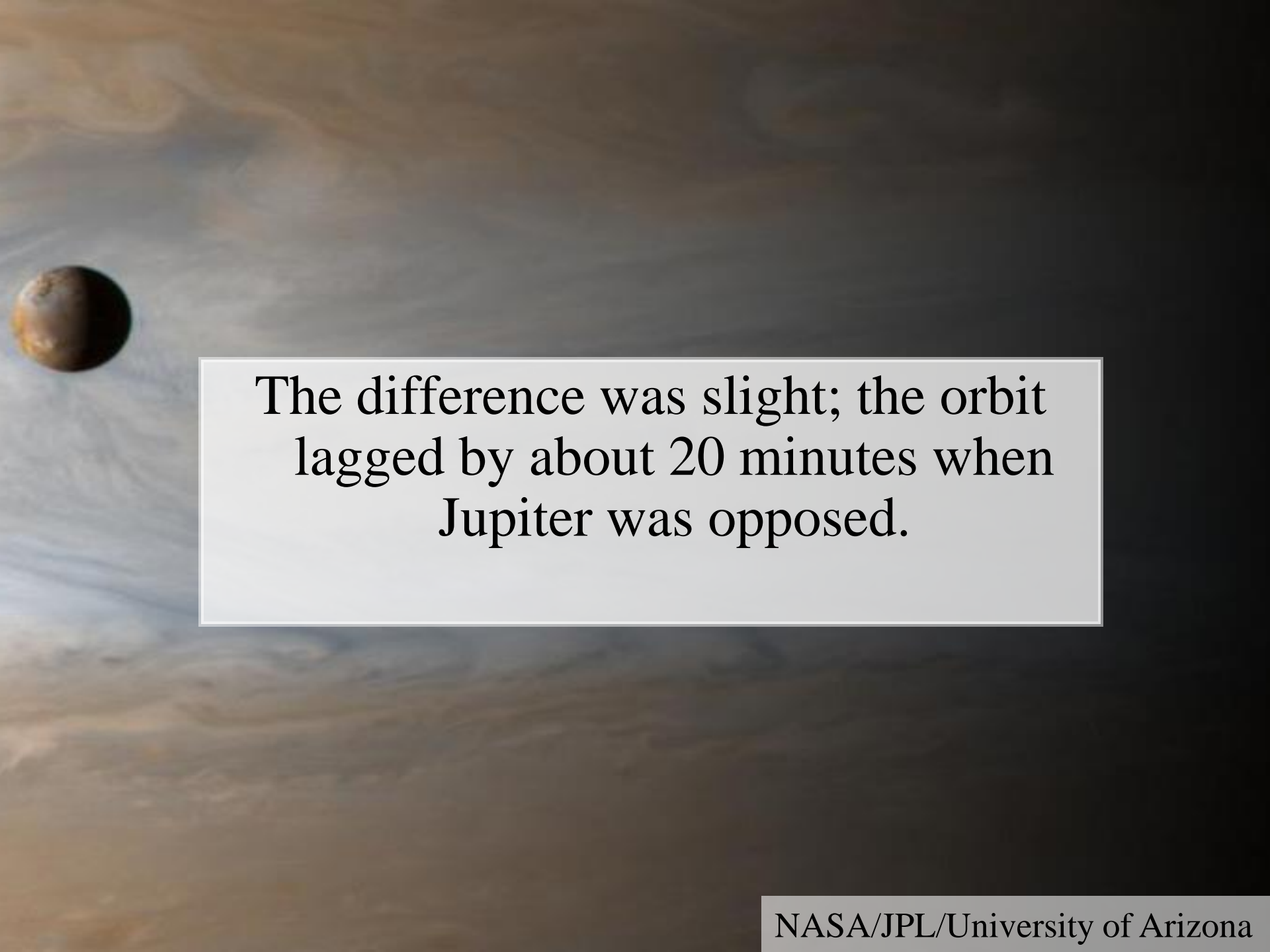
Io has the shortest orbit of all the major moons of Jupiter. It orbits Jupiter once every 42.5 hours.

A photograph of the moon Io in Jupiter's shadow. The moon is a small, reddish-brown sphere on the left side of the frame. The background is a dark, cloudy sky with a faint, lighter-colored band of light, likely representing Jupiter's atmosphere or a nebula. The text is centered in a white box with a thin black border.

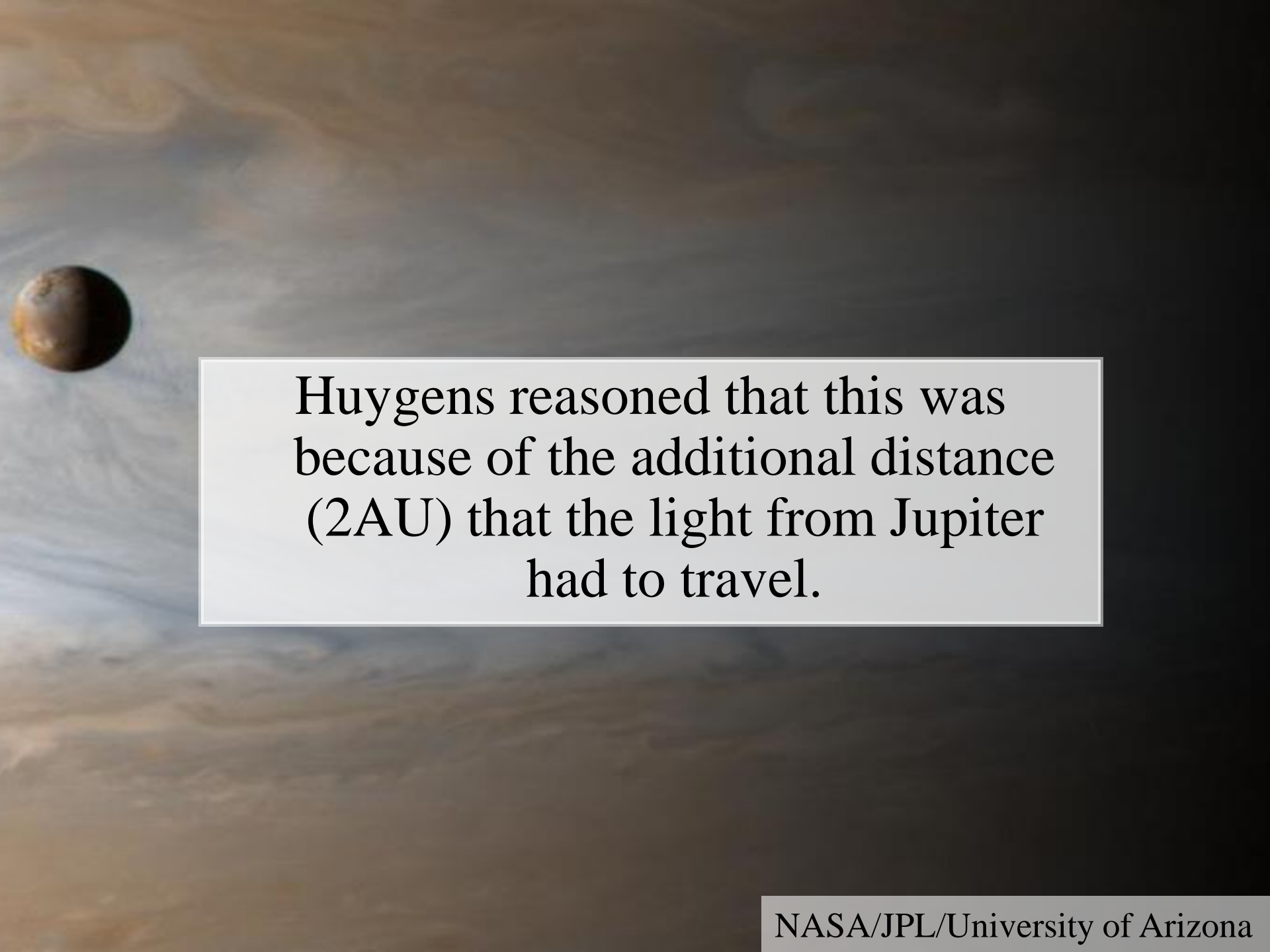
Rømer made many measurements of this orbit by timing when Io entered and exited Jupiter's shadow.

A celestial scene showing a planet with a ring system in the background and a smaller planet in the foreground. The background planet has a brownish-orange surface and a prominent ring system. The foreground planet is smaller, with a brownish-orange surface and a dark shadow. The background is a dark, starry sky.

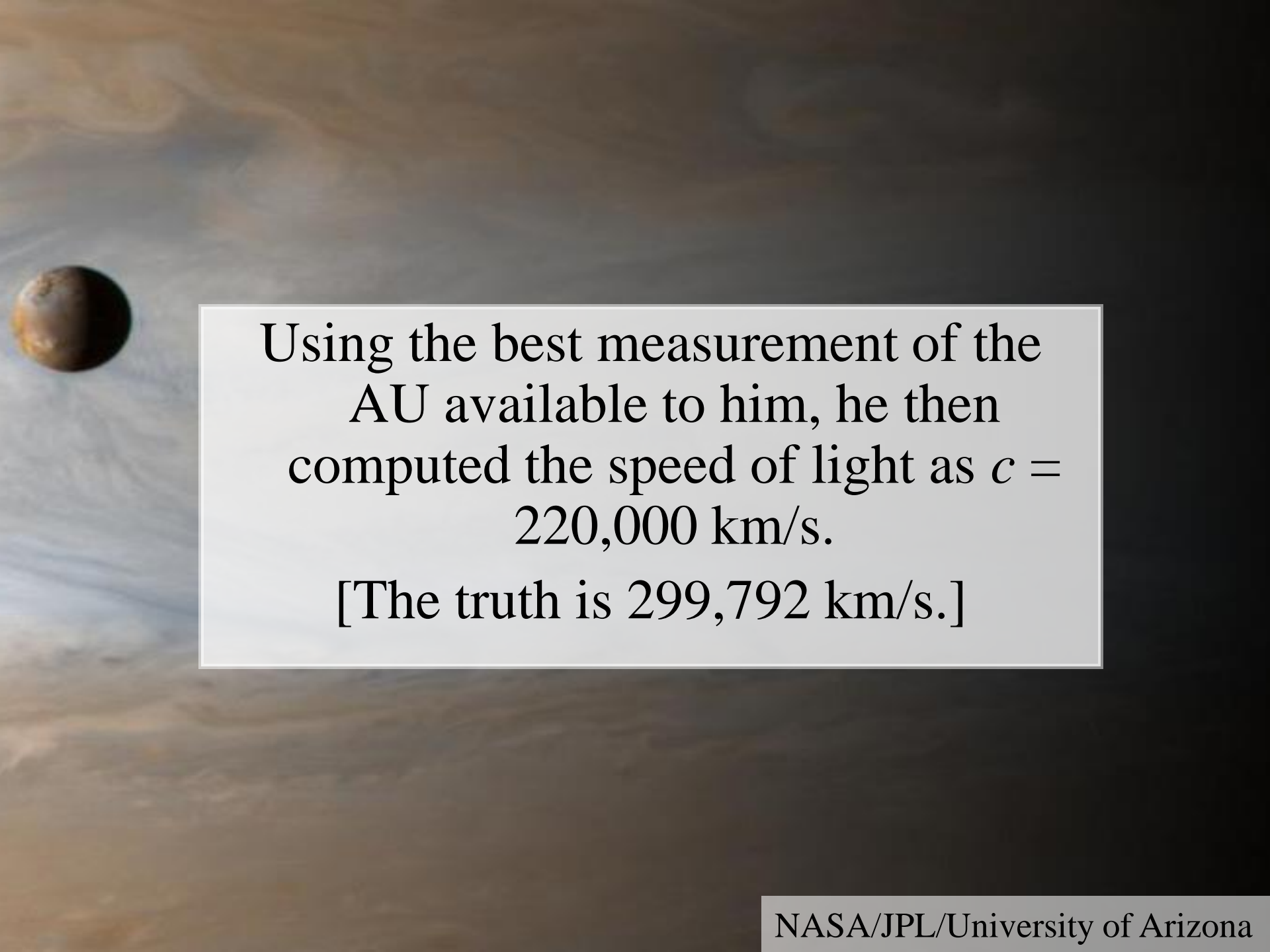
However, he noticed that when Jupiter was aligned with the Earth, the orbit advanced slightly; when Jupiter was opposed, the orbit lagged.



The difference was slight; the orbit lagged by about 20 minutes when Jupiter was opposed.

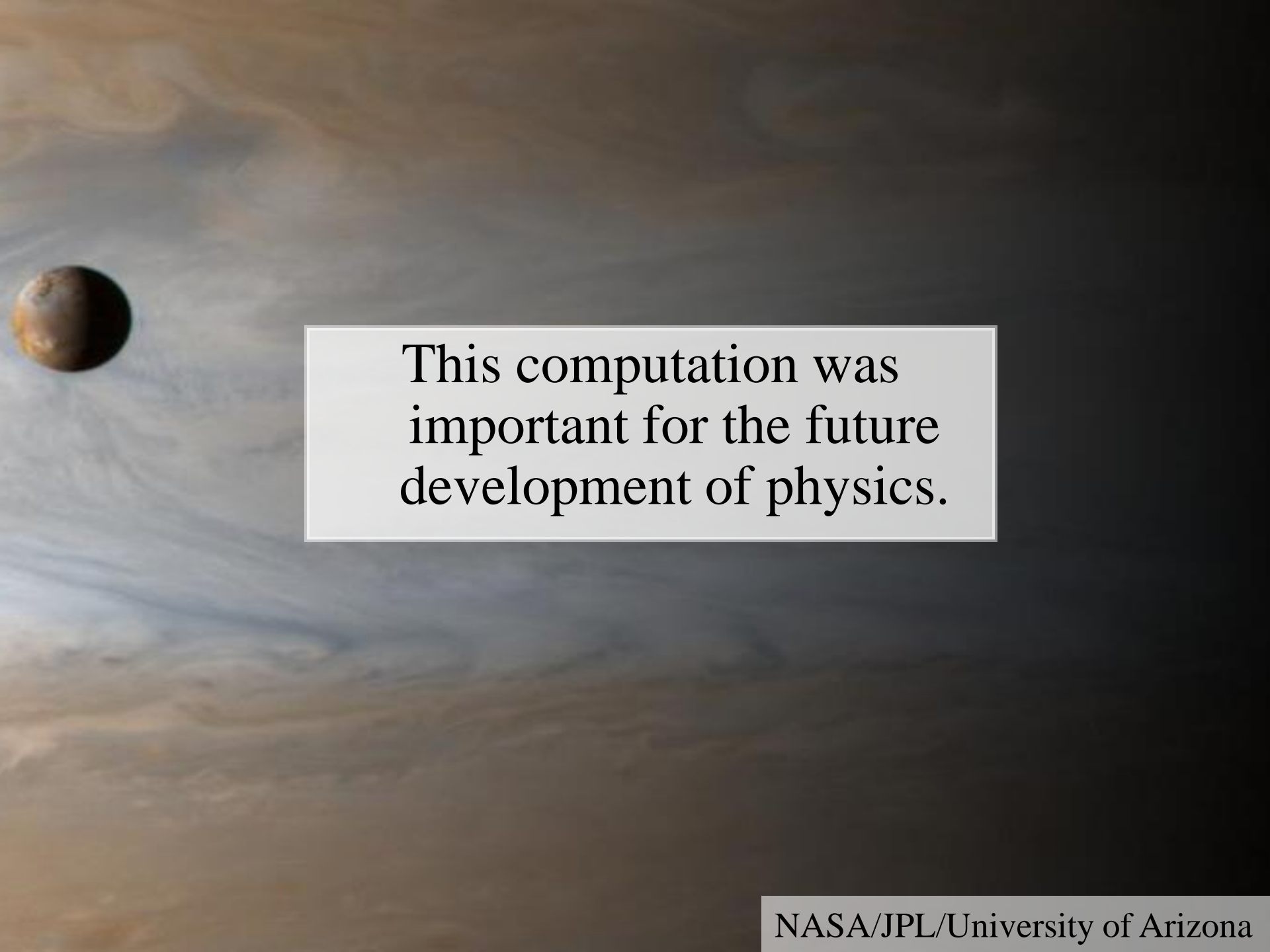


Huygens reasoned that this was because of the additional distance (2AU) that the light from Jupiter had to travel.

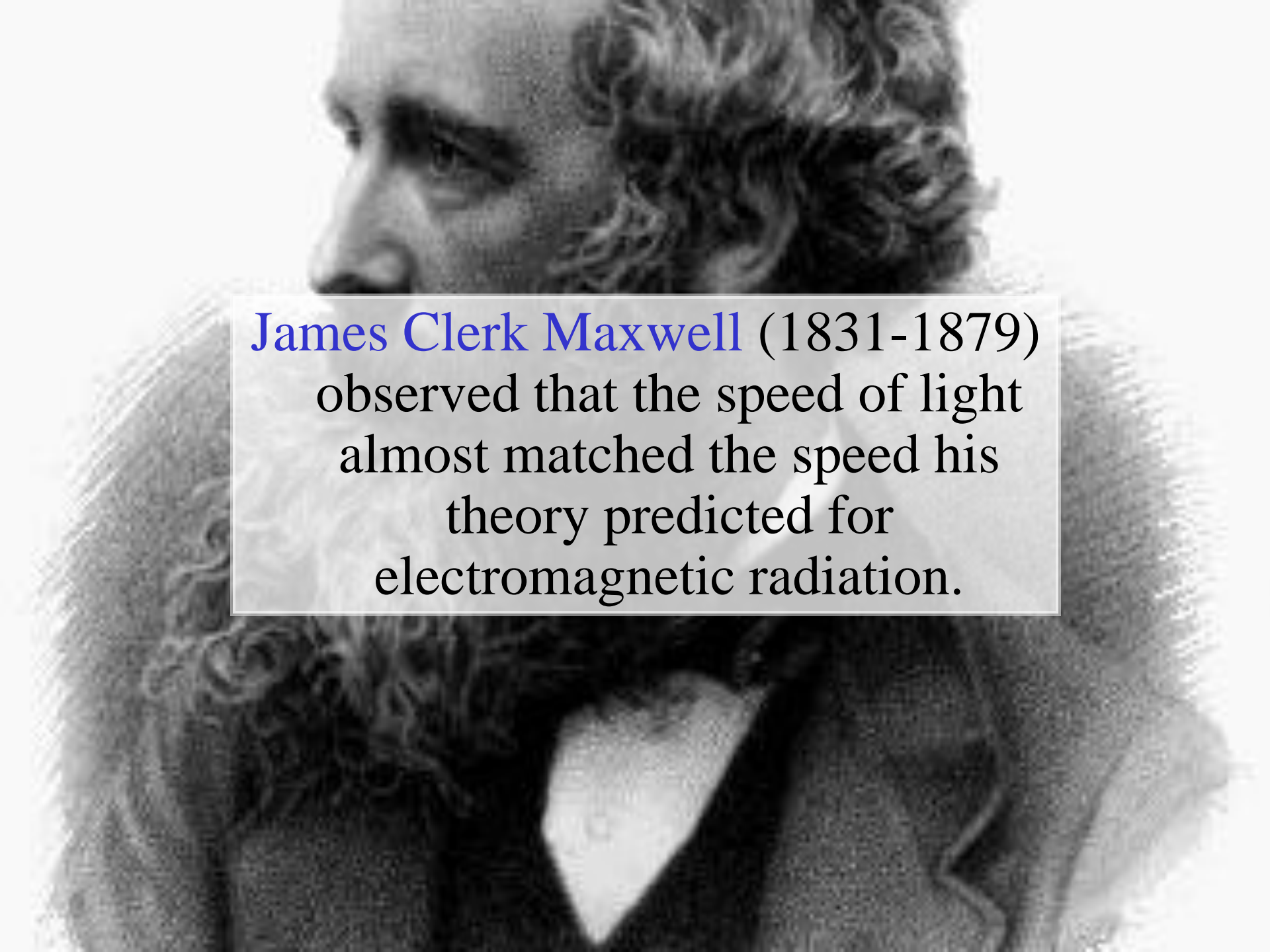


Using the best measurement of the
AU available to him, he then
computed the speed of light as $c =$
220,000 km/s.

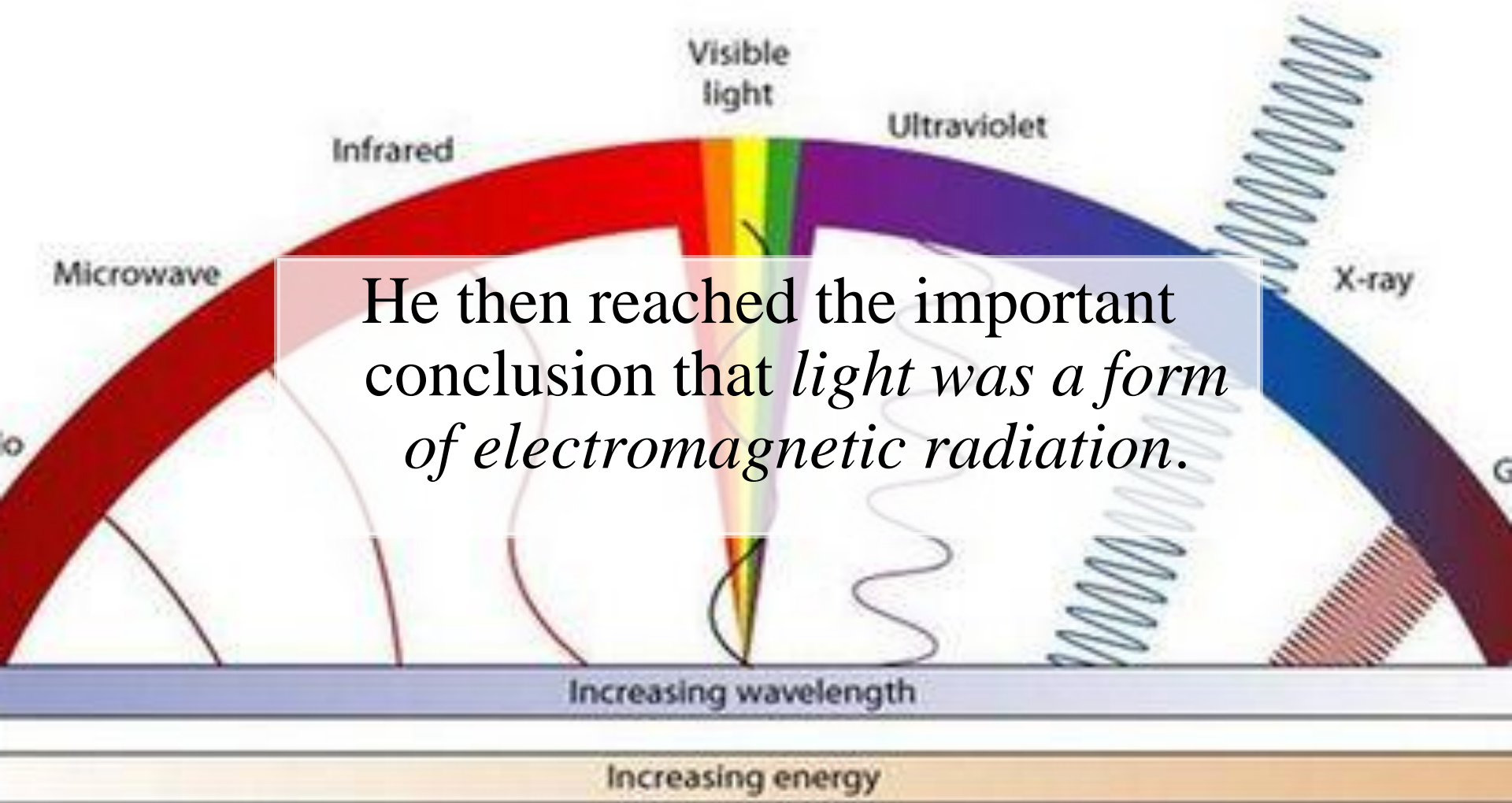
[The truth is 299,792 km/s.]



This computation was
important for the future
development of physics.

A black and white portrait of James Clerk Maxwell, showing his head and shoulders in profile, facing left. He has thick, curly hair and is wearing a dark suit jacket over a white shirt and a dark bow tie. The background is plain white.

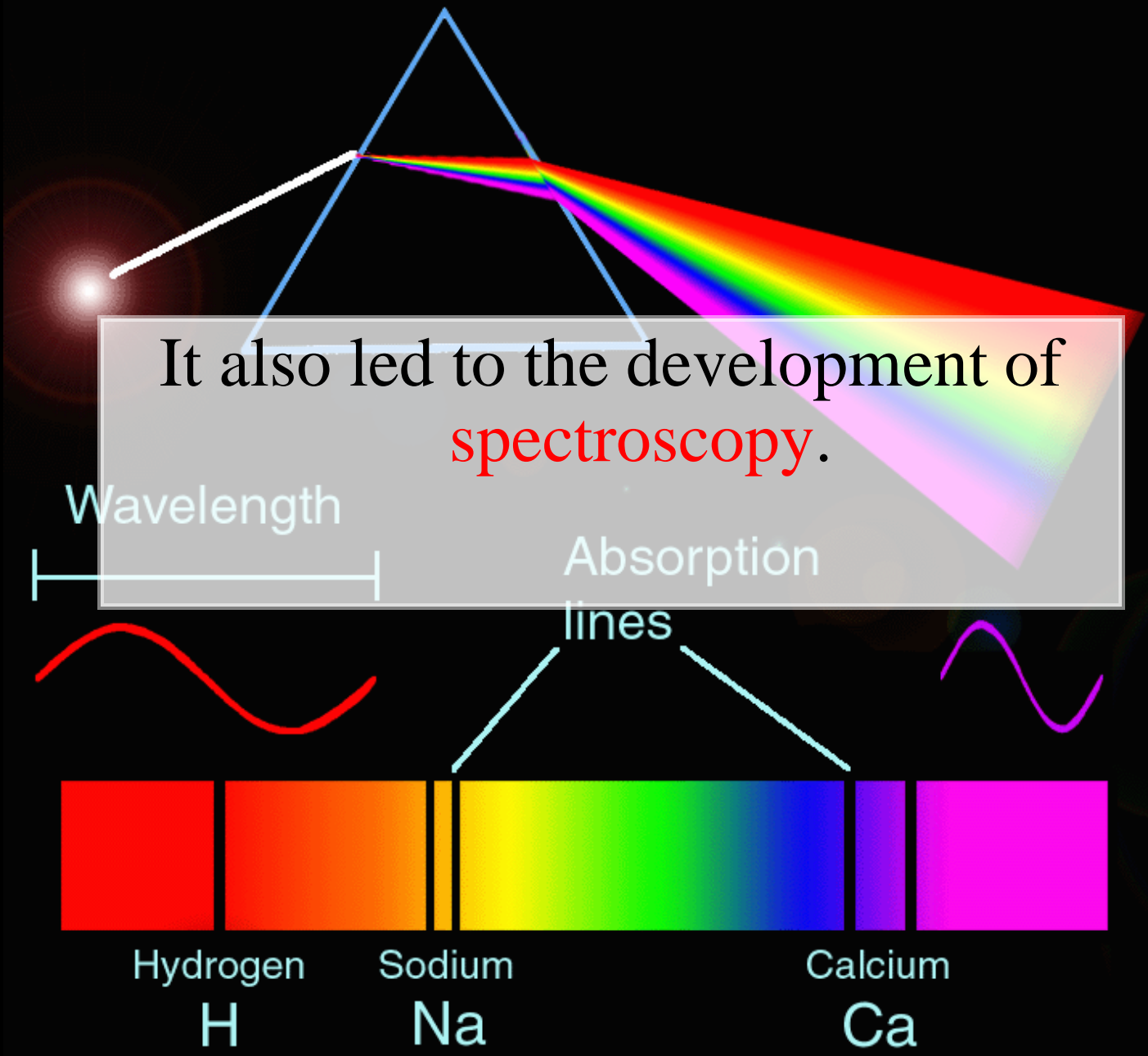
James Clerk Maxwell (1831-1879)
observed that the speed of light
almost matched the speed his
theory predicted for
electromagnetic radiation.

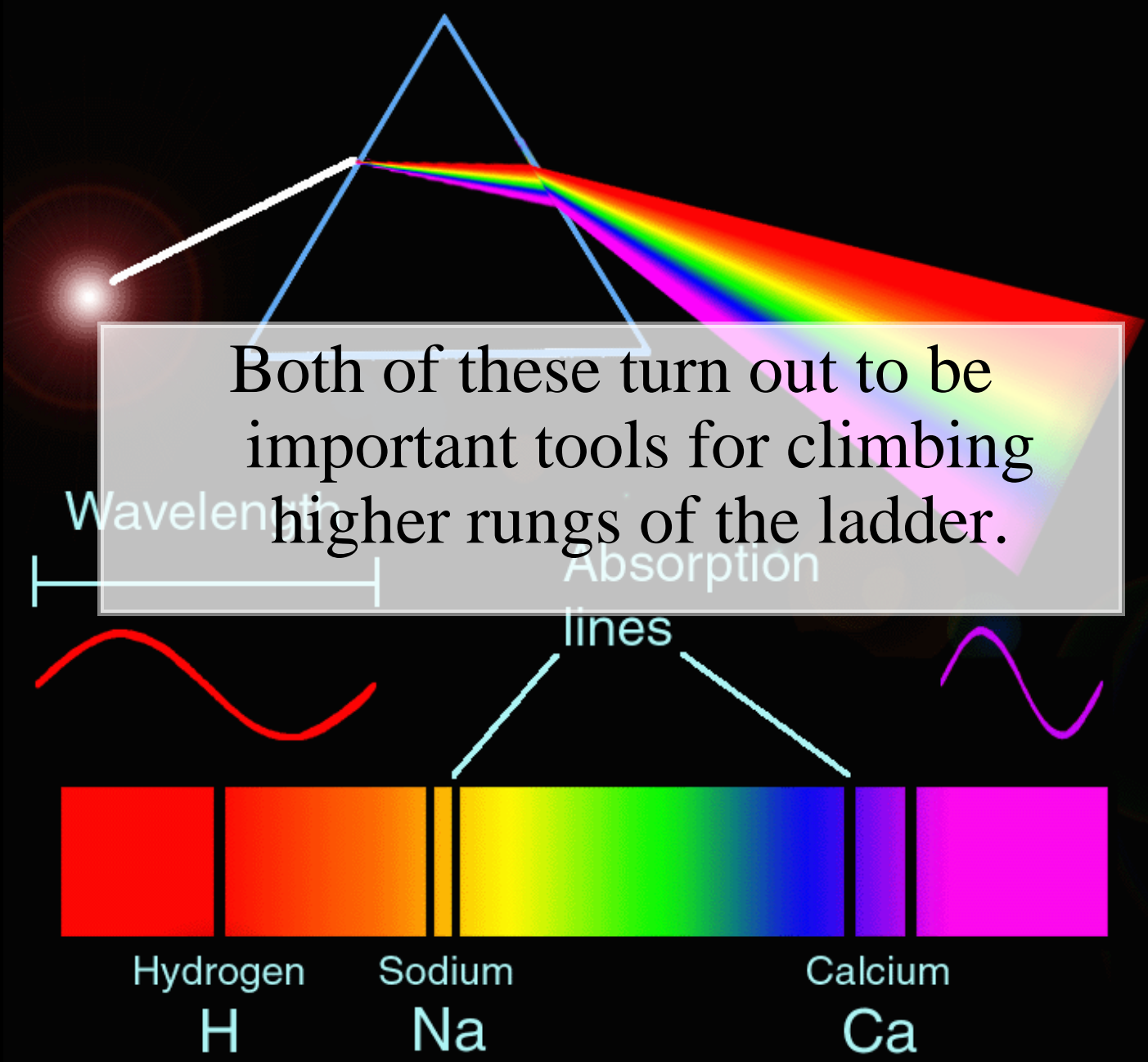


He then reached the important conclusion that *light was a form of electromagnetic radiation.*

A spacetime diagram illustrating the relationship between two reference frames. The background is black with a grid of green and blue lines. A vertical green line represents the worldline of a stationary object in the rest frame. A diagonal red line represents the worldline of an object moving at a constant velocity in the rest frame. A horizontal green line is labeled 'B' at its left end. A vertical red line is labeled 'A' at its top end. Two coordinate axes are shown: a green axis labeled 'x' pointing to the right and a red axis labeled 'x'' pointing up and to the right. The text is centered in a white box with a grey border.

This observation was instrumental
in leading to **Einstein's theory of
special relativity.**





Both of these turn out to be important tools for climbing higher rungs of the ladder.

Wavelength

Absorption

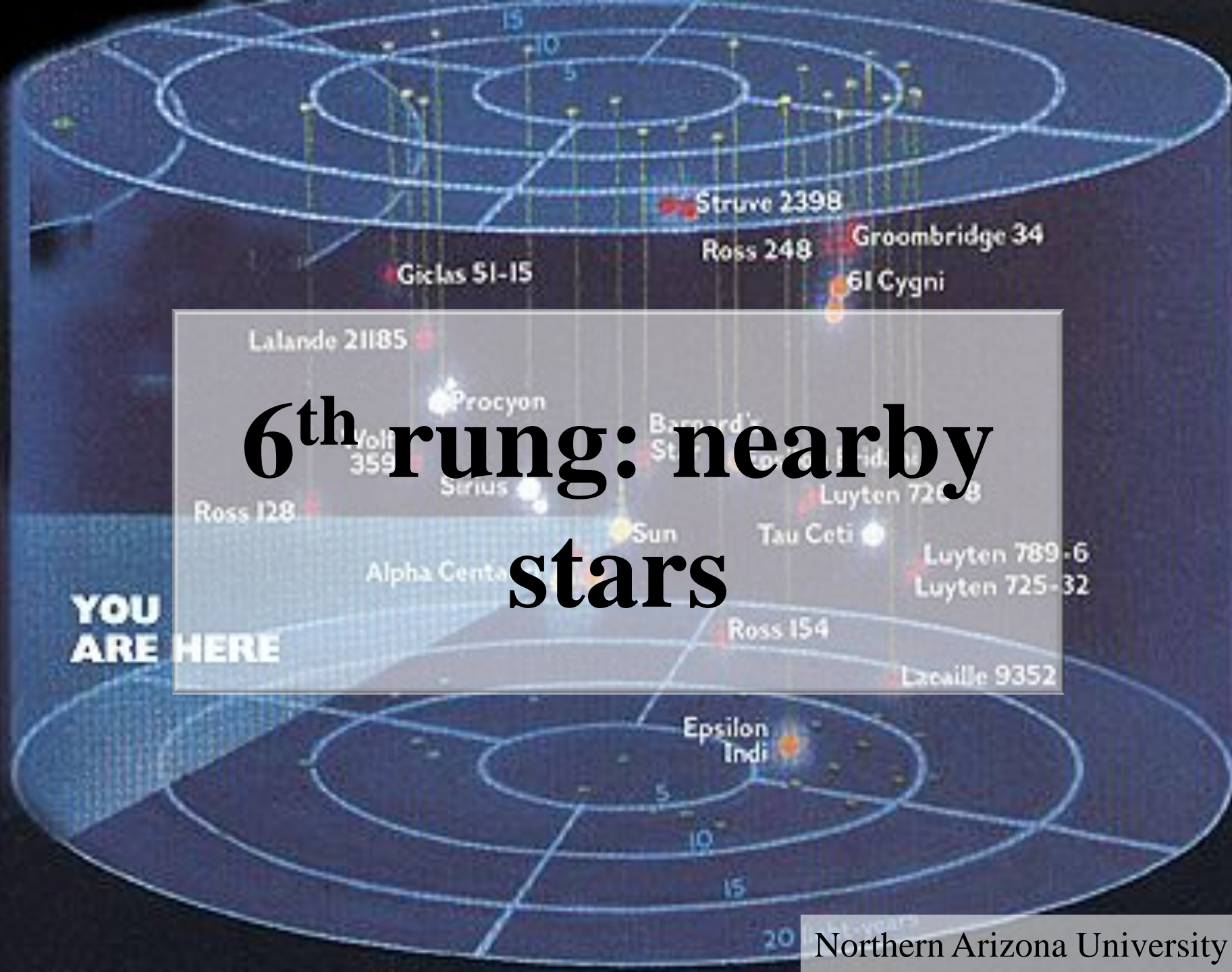
lines



Hydrogen
H

Sodium
Na

Calcium
Ca



6th rung: nearby stars

**YOU
ARE
HERE**

We already saw that **parallax** from two locations on the Earth could measure distances to other planets.

**YOU
ARE HERE**

This is not enough separation to discern distances to even the next closest star (which is about 270,000 AU away!)

**YOU
ARE HERE**

distant stars

Every January,
we see this:



Every July,
we see this:

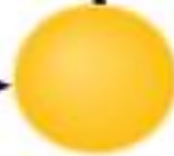


nearby star

However, if one takes
measurements six months apart,
one gets a distance separation of
 2AU ...



1 AU



(not to scale)



July

January

distant stars

Every January,
we see this:



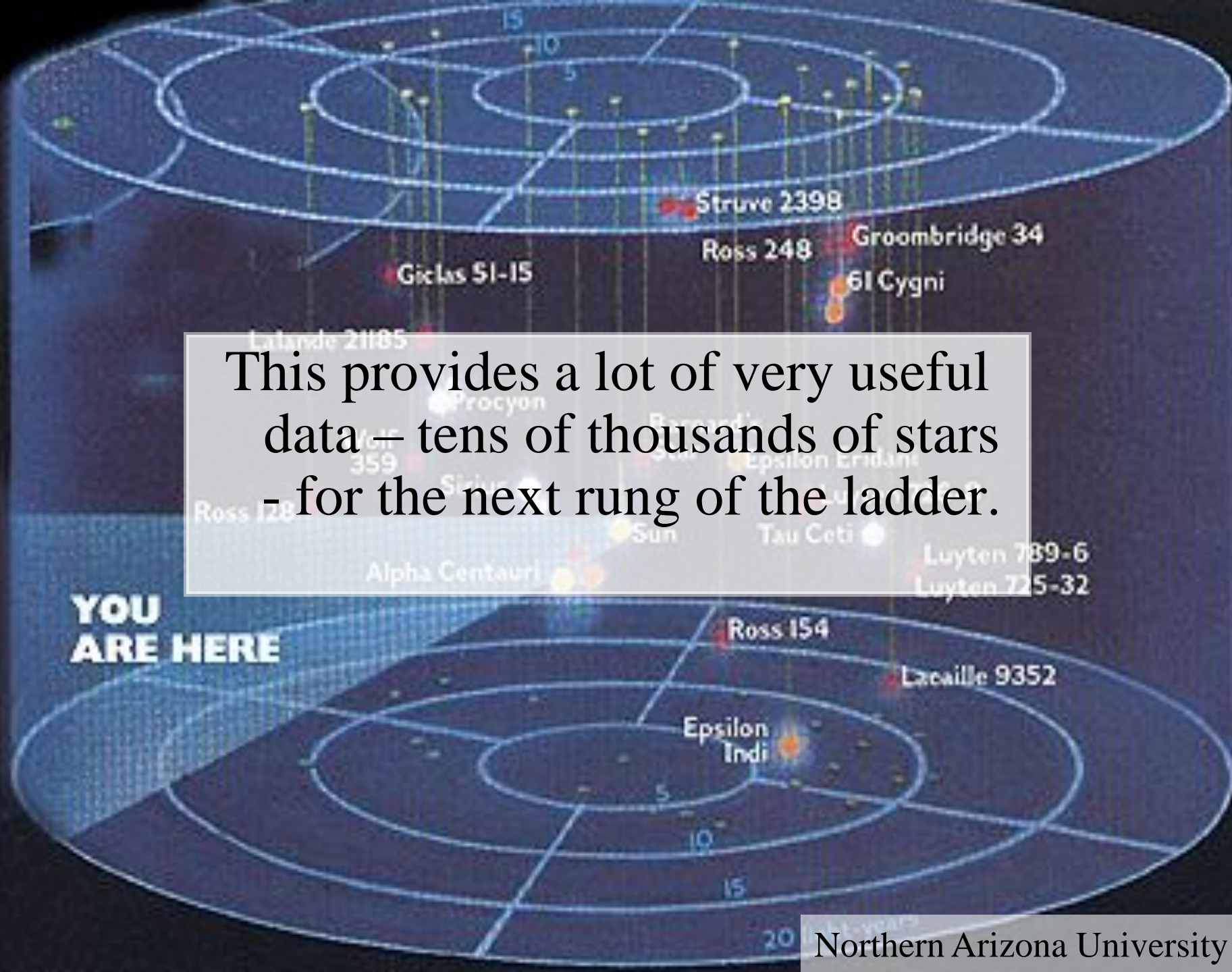
Every July,
we see this:



nearby star


... which gives enough parallax to
measure all stars within about
100 light years (30 parsecs).



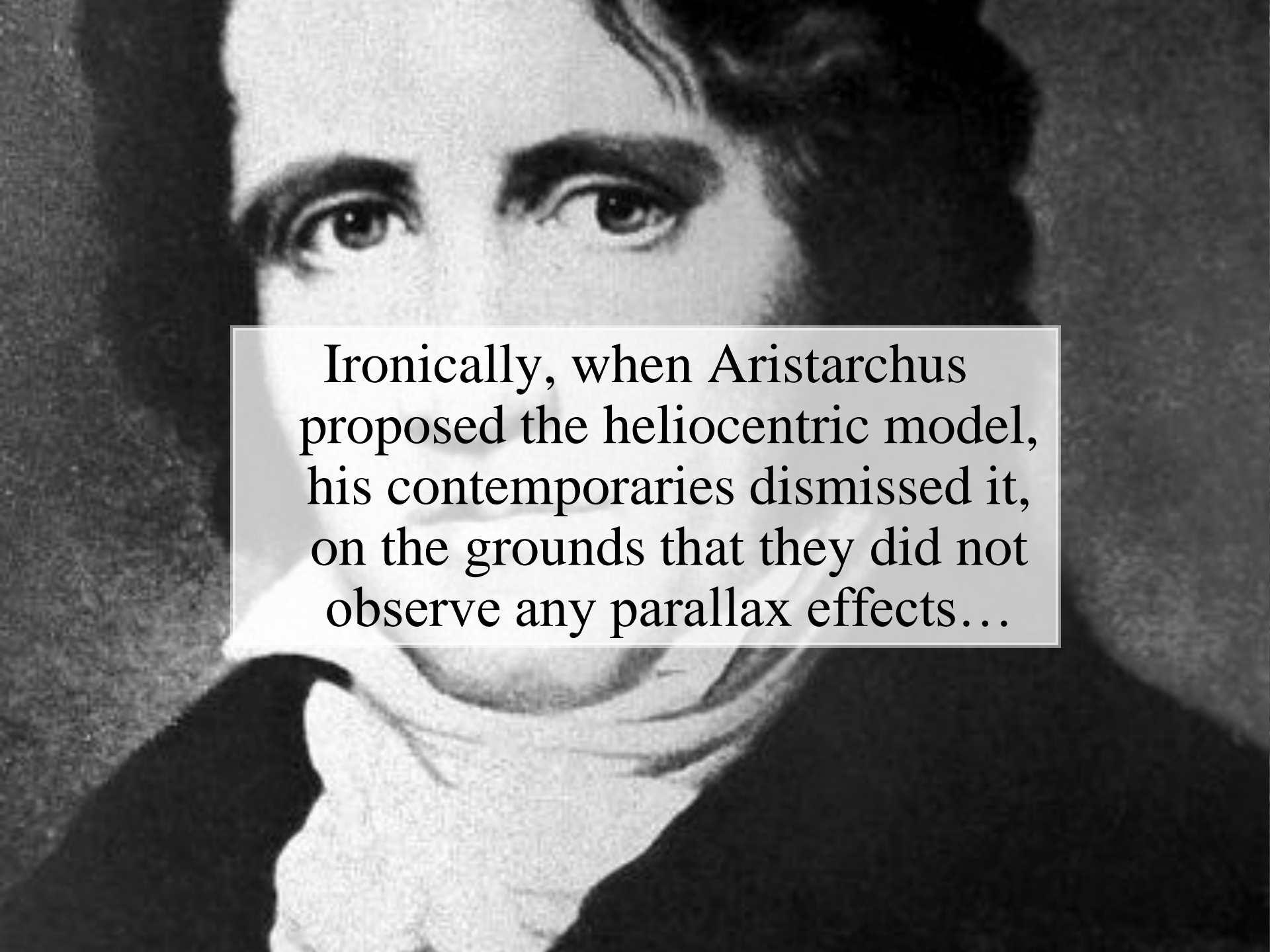


This provides a lot of very useful data – tens of thousands of stars - for the next rung of the ladder.

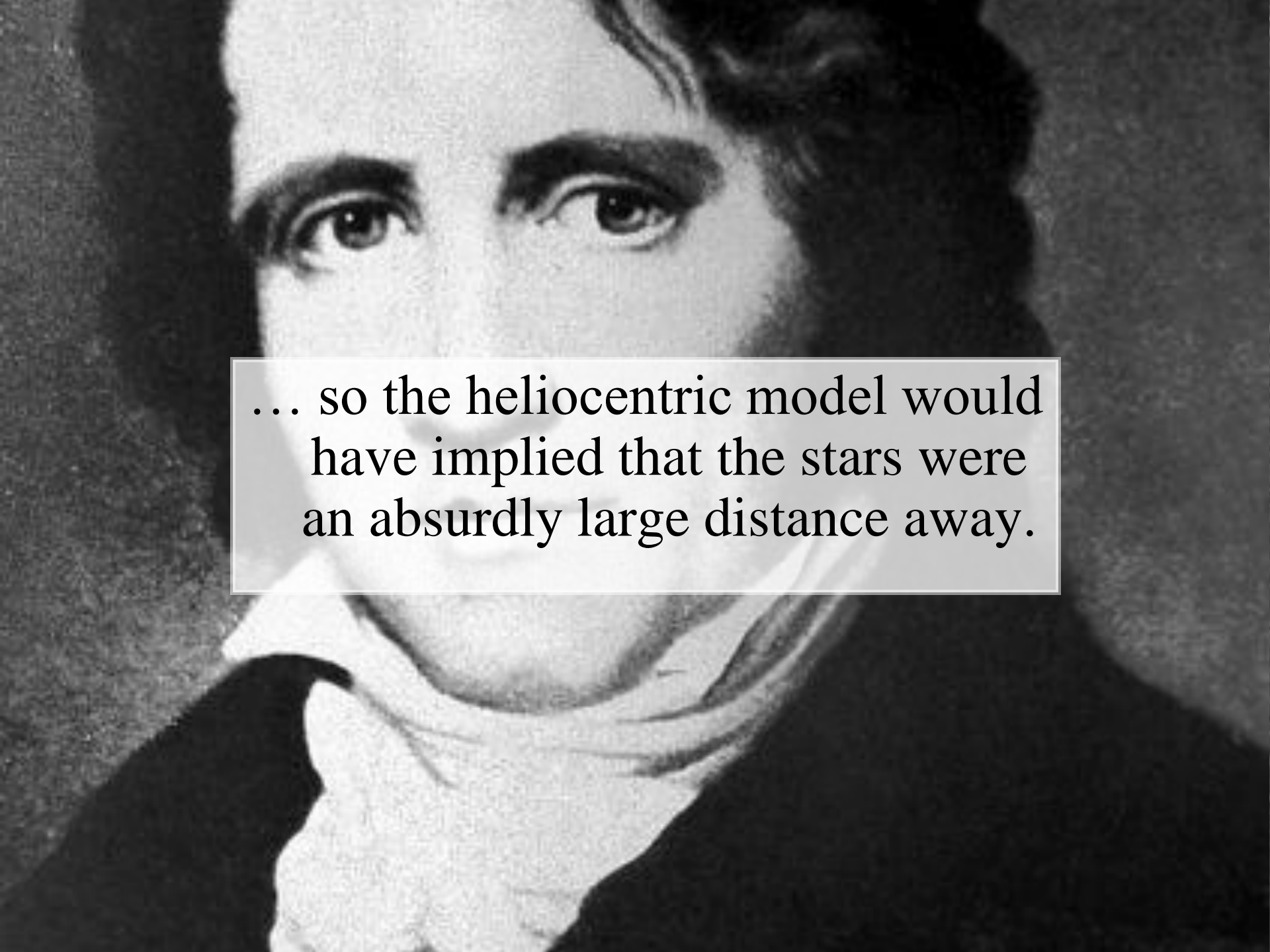
**YOU
ARE HERE**

A black and white portrait of Friedrich Bessel, a German astronomer, physicist, and engineer. He is shown from the chest up, wearing a dark coat and a white cravat. His hair is dark and wavy, and he has a serious expression.

These parallax computations,
which require accurate
telescropy, were first done by
Friedrich Bessel (1784-1846) in
1838.



Ironically, when Aristarchus proposed the heliocentric model, his contemporaries dismissed it, on the grounds that they did not observe any parallax effects...

A black and white portrait of a man, likely a historical figure, with dark, wavy hair and a white cravat. The image is a close-up, focusing on the man's face and upper torso. A semi-transparent white box with a thin black border is overlaid on the lower half of the image, containing text.

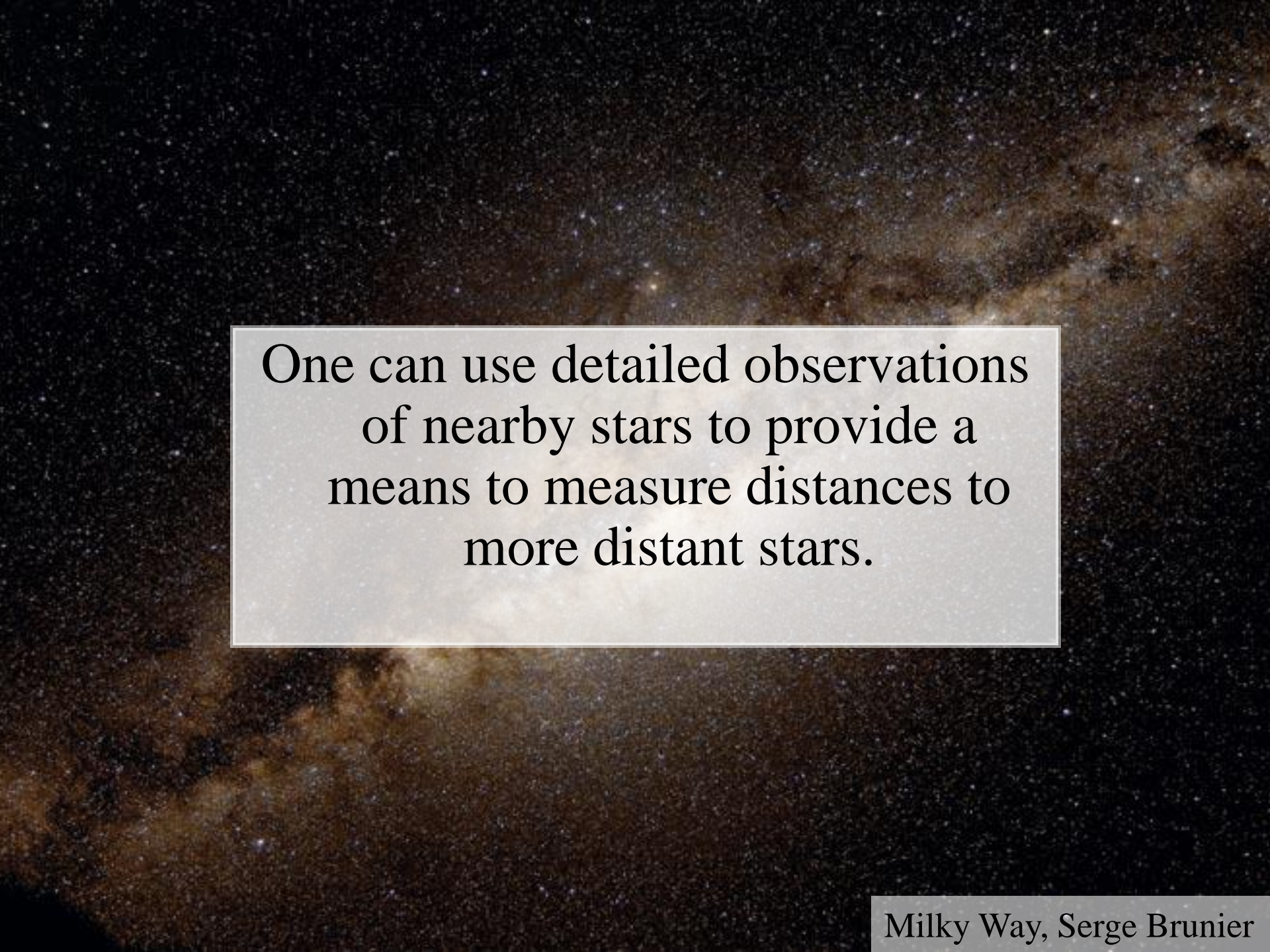
... so the heliocentric model would have implied that the stars were an absurdly large distance away.

A black and white portrait of a man with dark, wavy hair, looking slightly to the right. He is wearing a white cravat and a dark coat. The image has a grainy, high-contrast appearance.

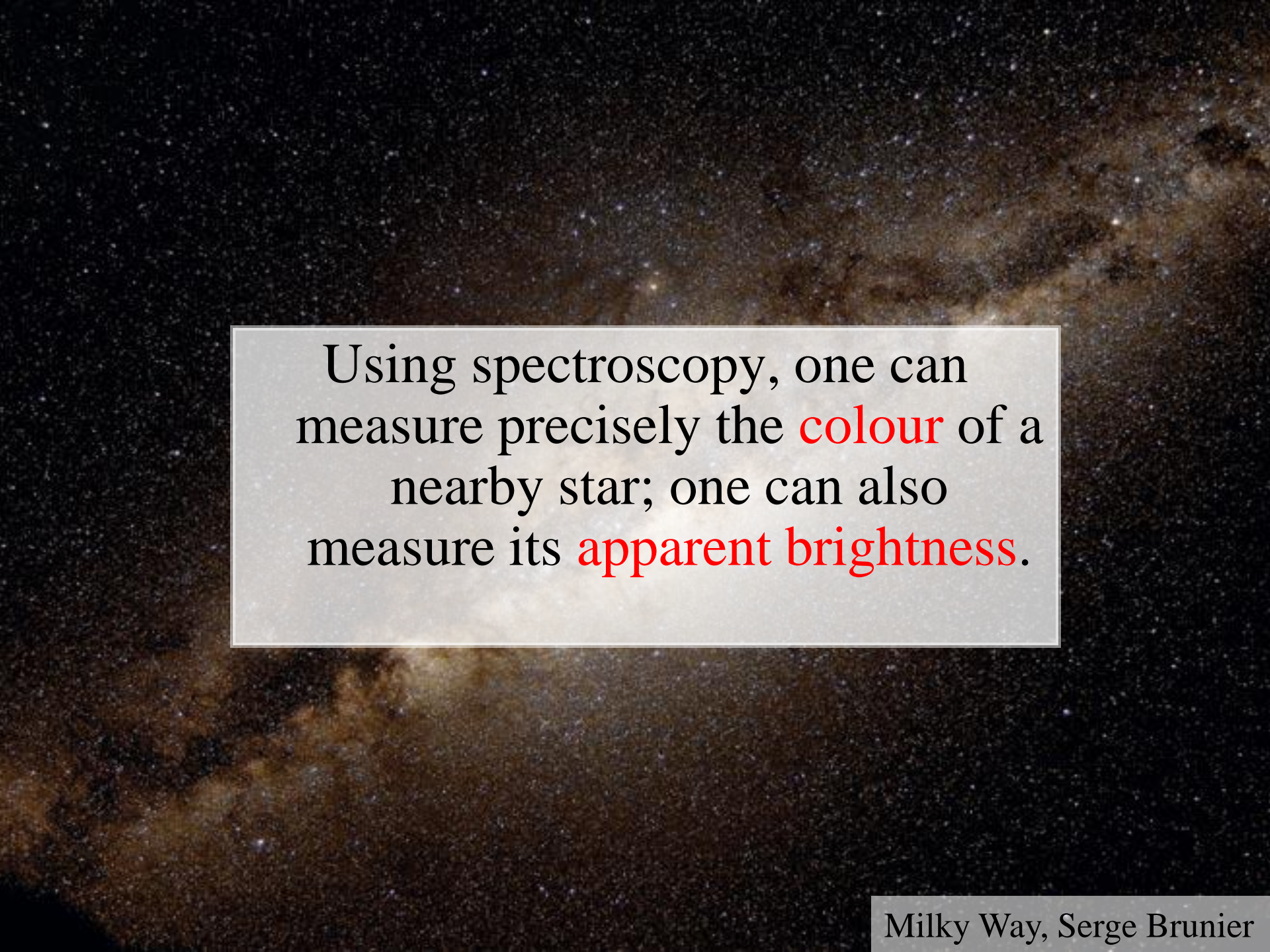
[Which, of course, they are.]




**7th rung: the
Milky Way**



One can use detailed observations of nearby stars to provide a means to measure distances to more distant stars.



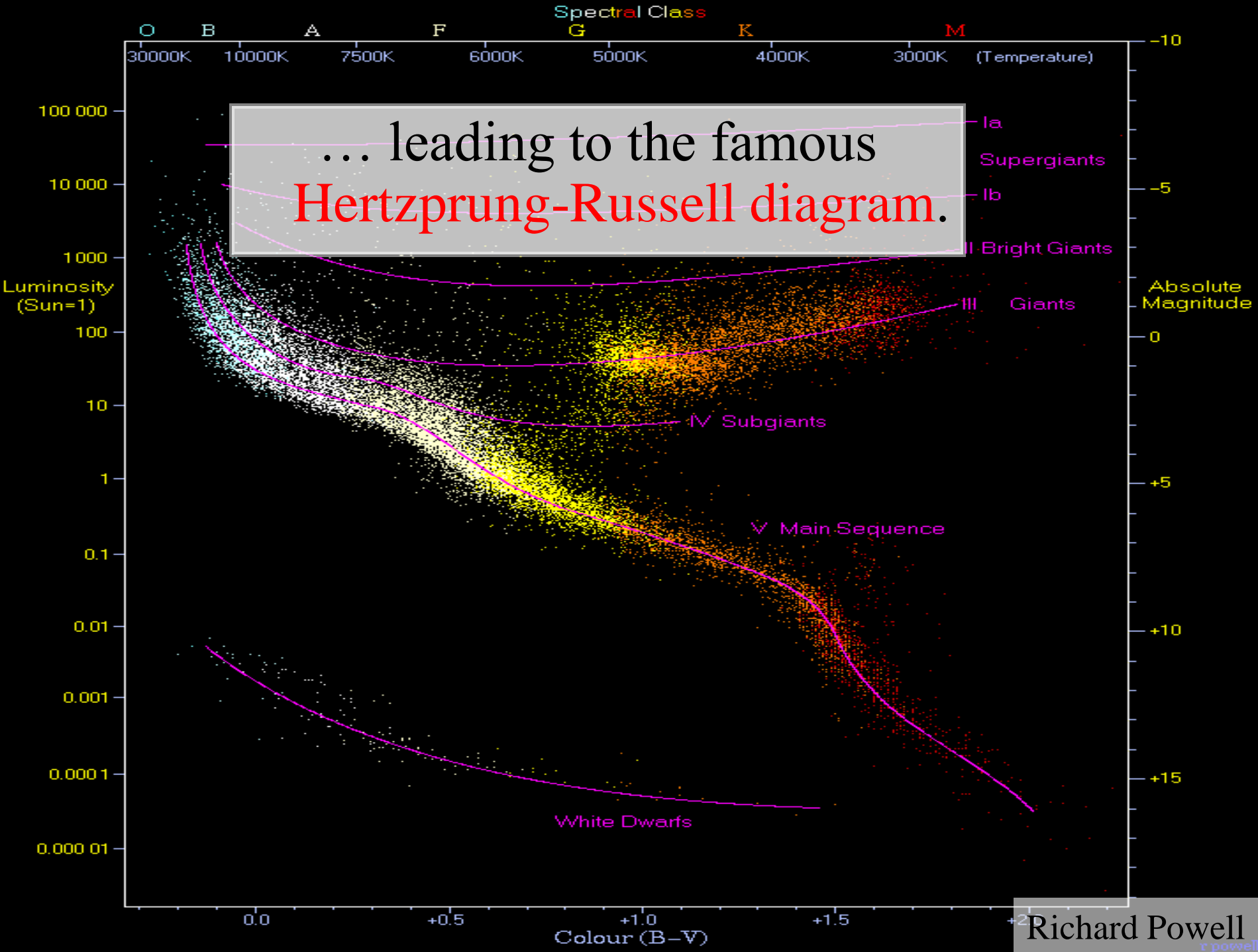
Using spectroscopy, one can measure precisely the **colour** of a nearby star; one can also measure its **apparent brightness**.

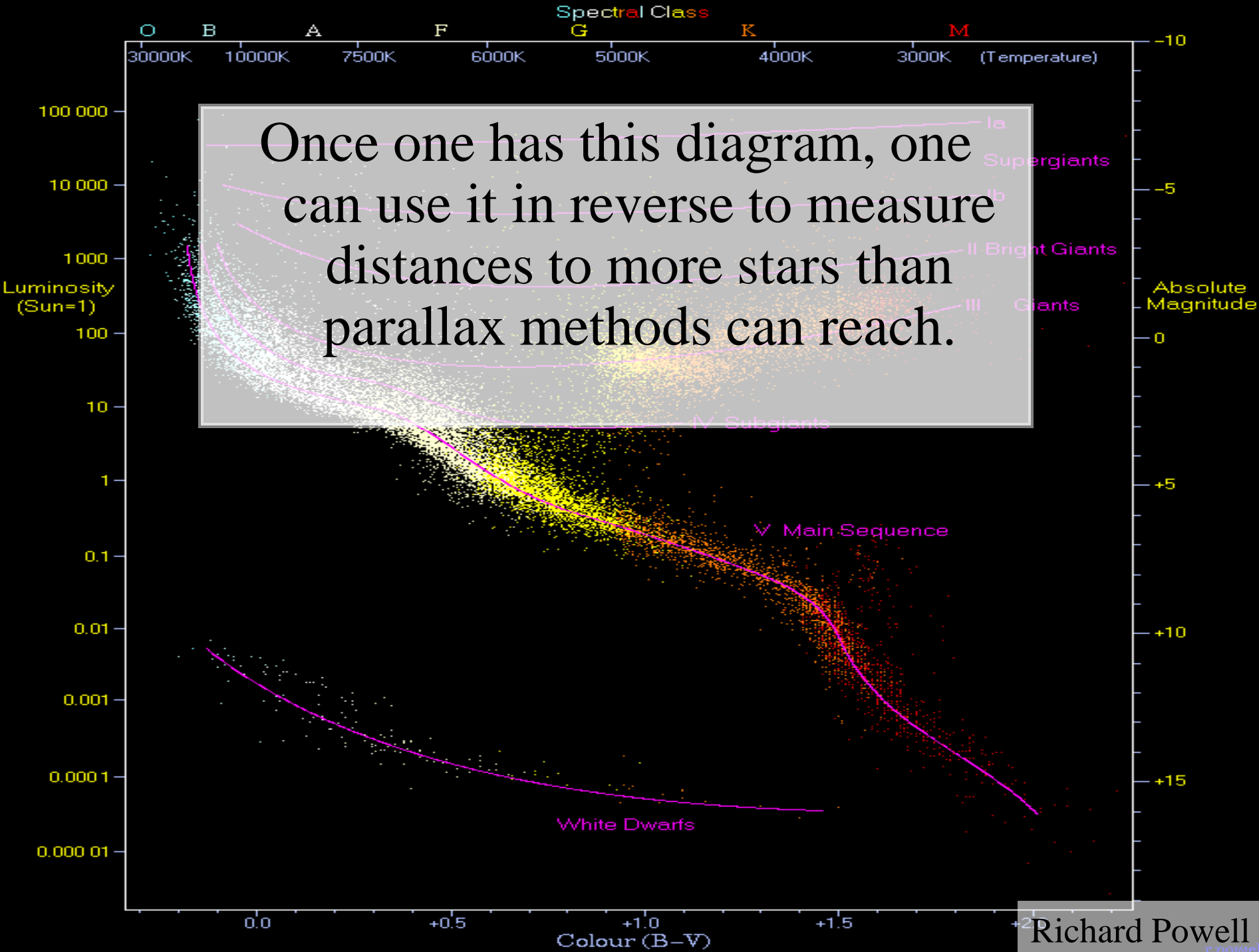


Using the apparent brightness, the distance, and inverse square law, one can compute the **absolute brightness** of these stars.

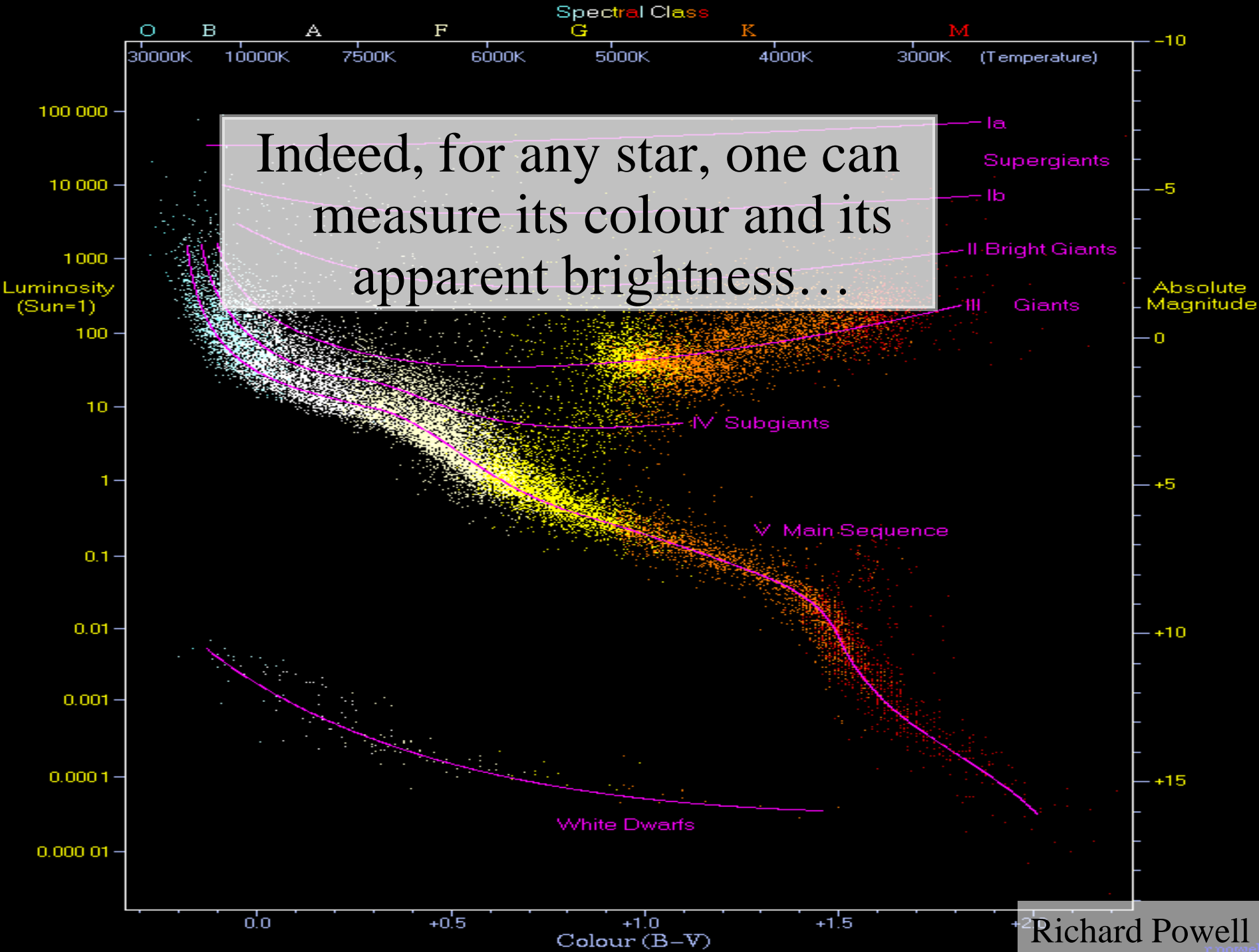


Ejnar Hertzsprung (1873-1967)
and **Henry Russell** (1877-1957)
plotted this absolute brightness
against color for thousands of
nearby stars in 1905-1915...

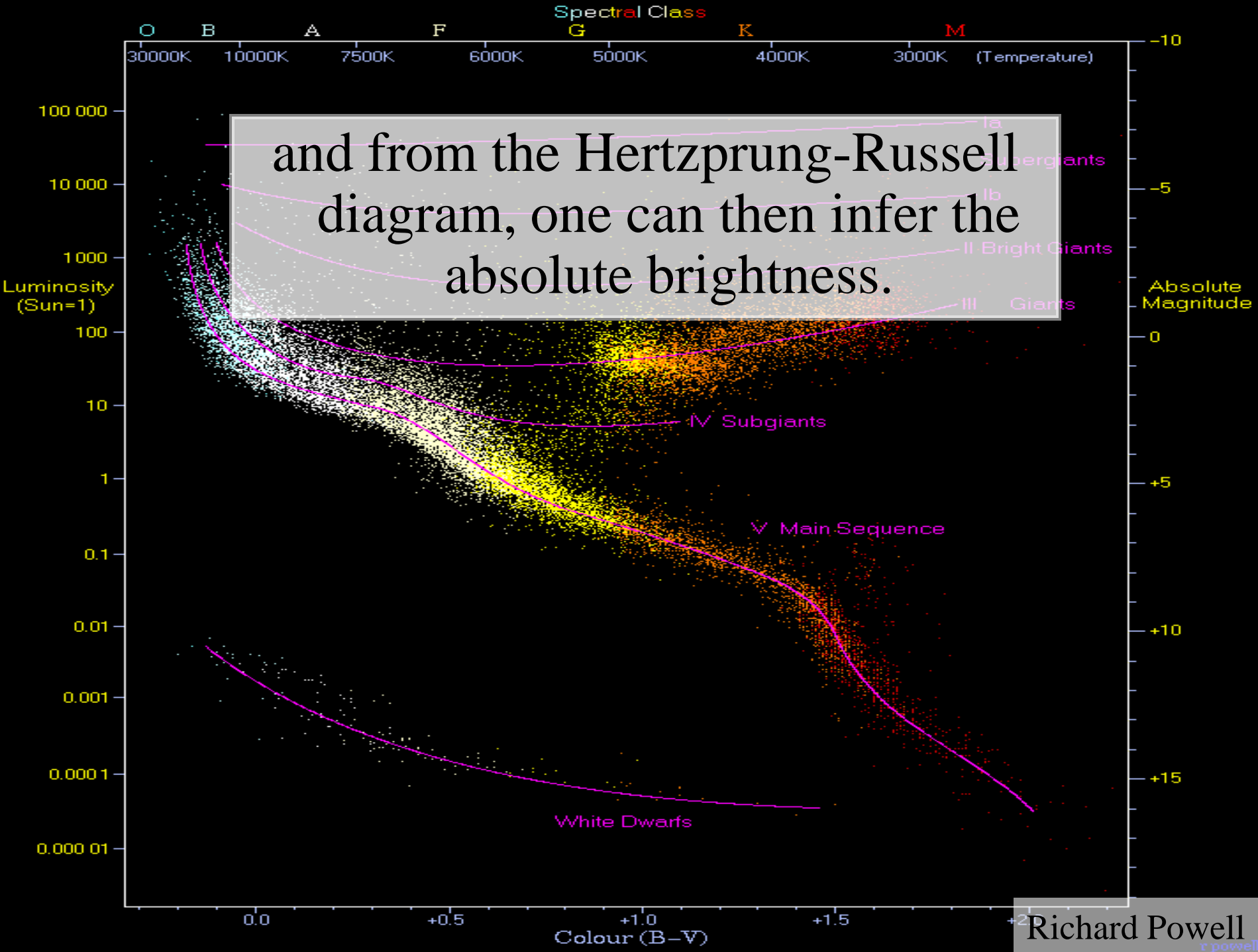


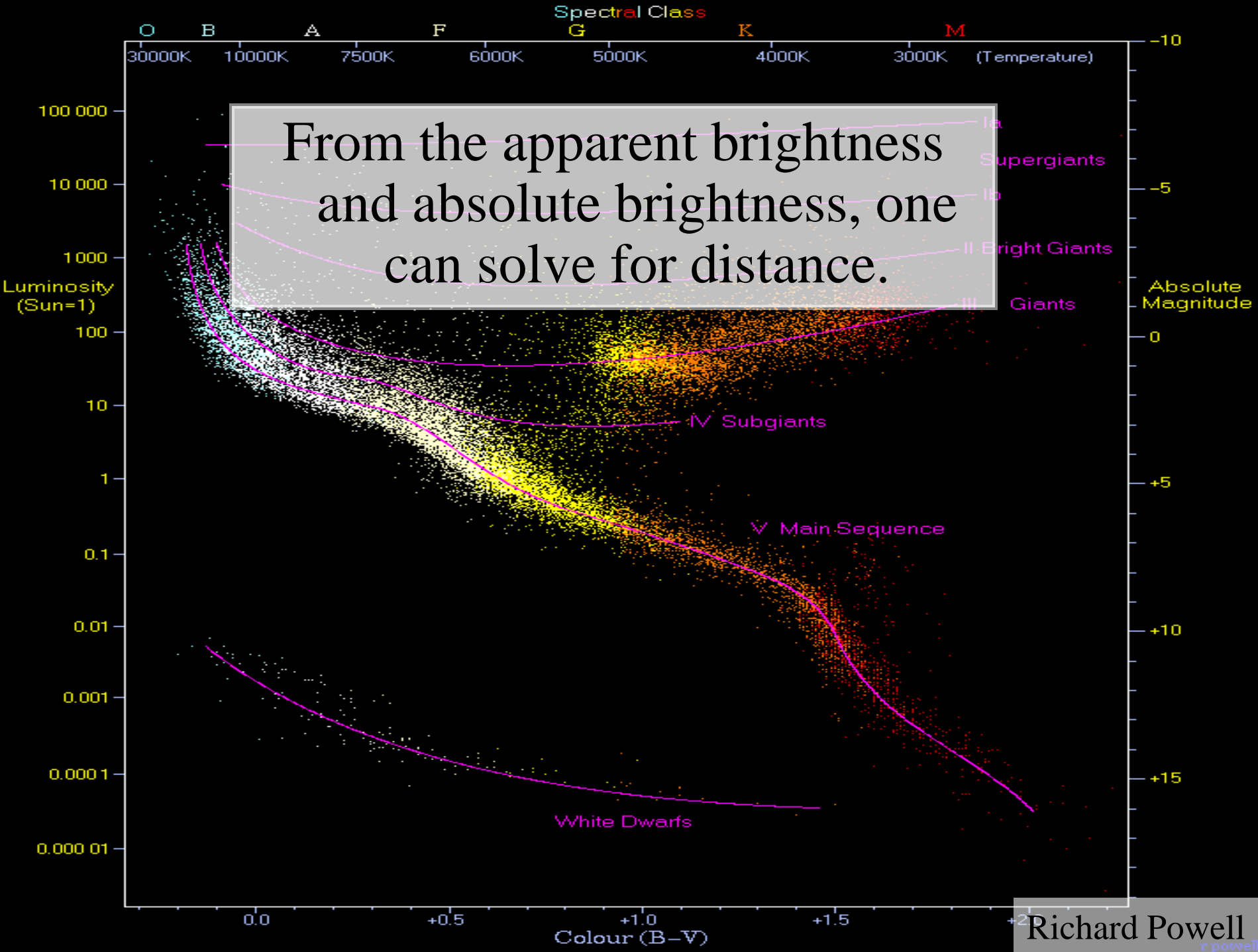


Once one has this diagram, one can use it in reverse to measure distances to more stars than parallax methods can reach.

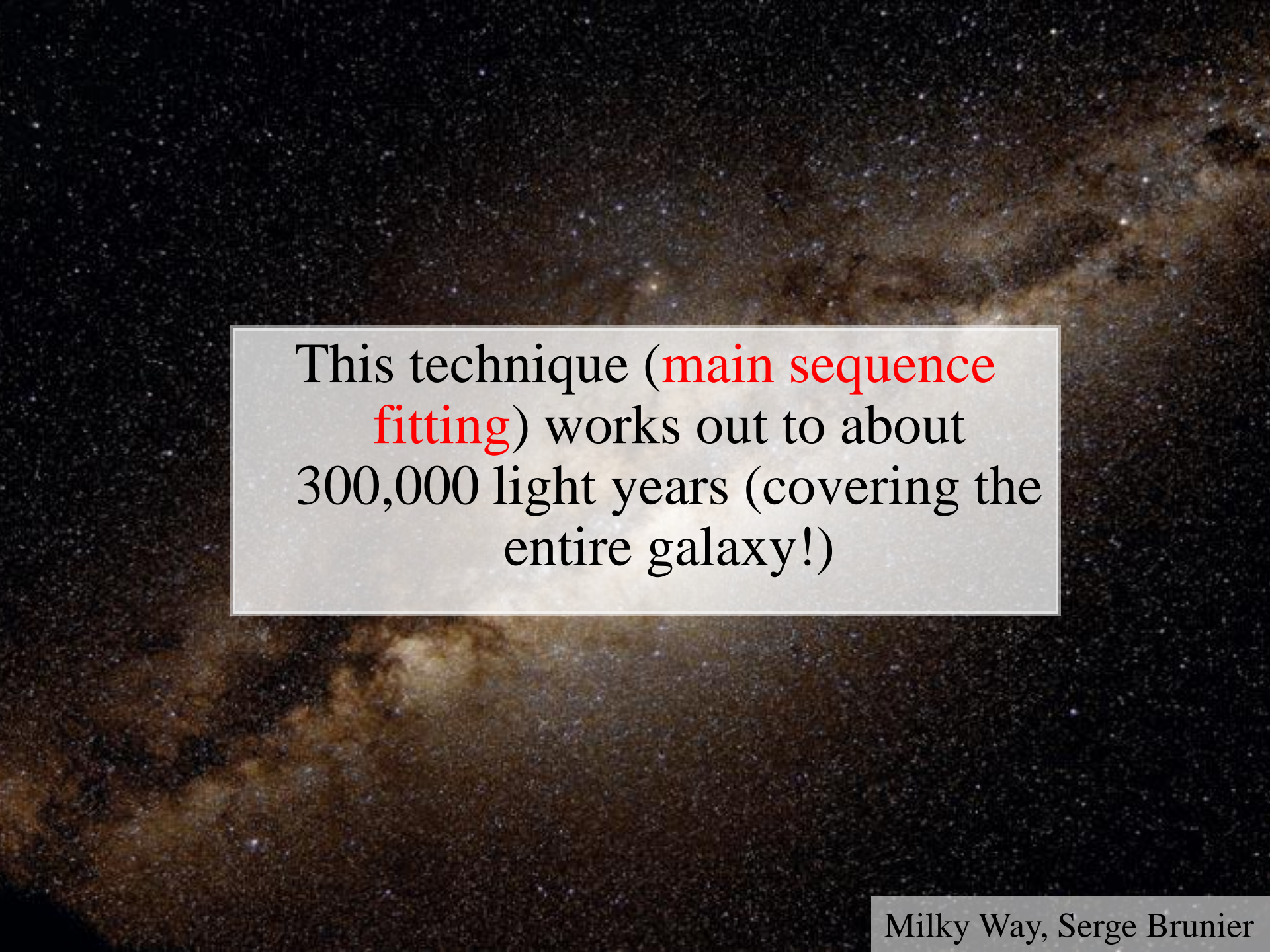


Indeed, for any star, one can measure its colour and its apparent brightness...

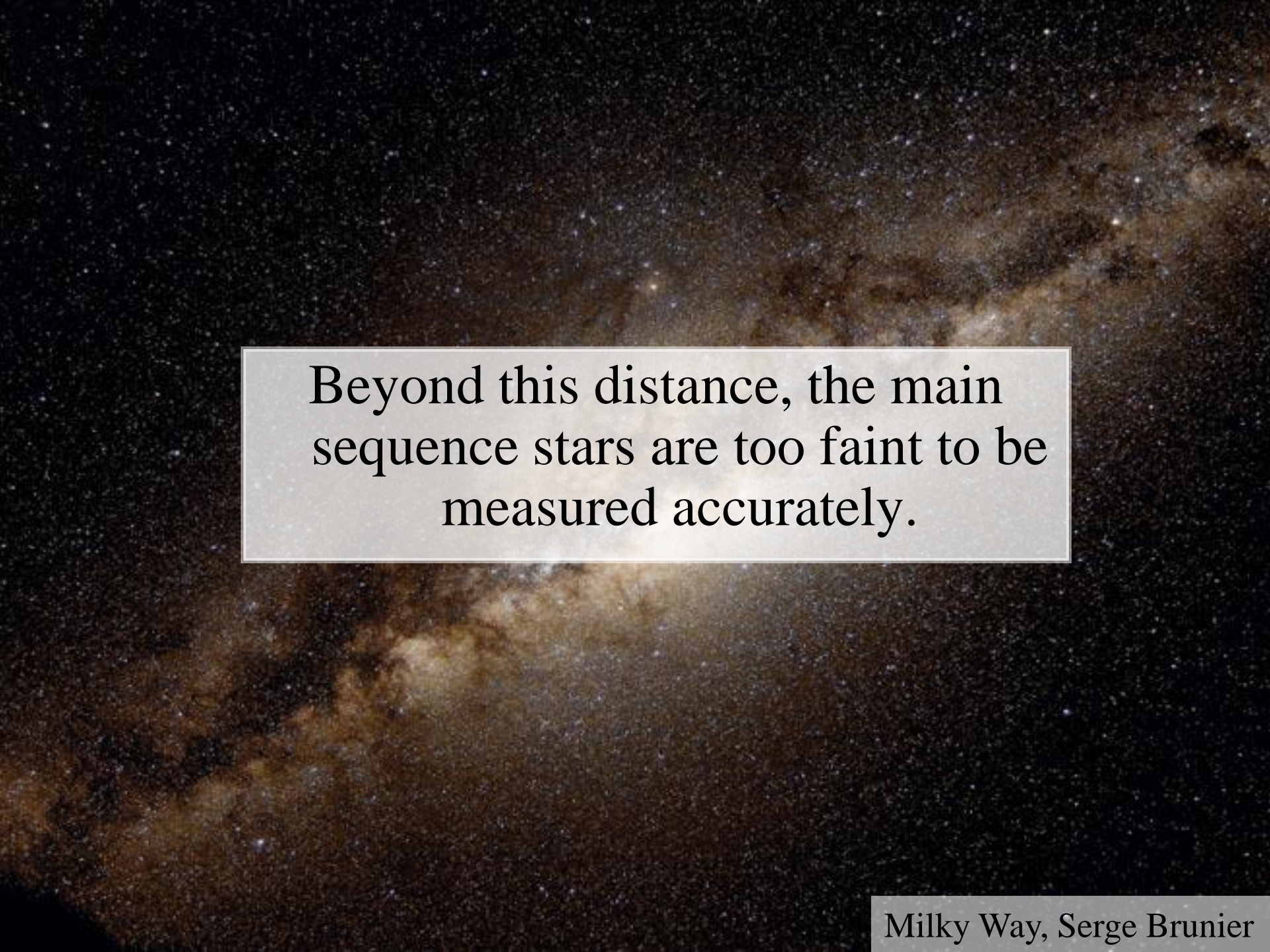




From the apparent brightness and absolute brightness, one can solve for distance.



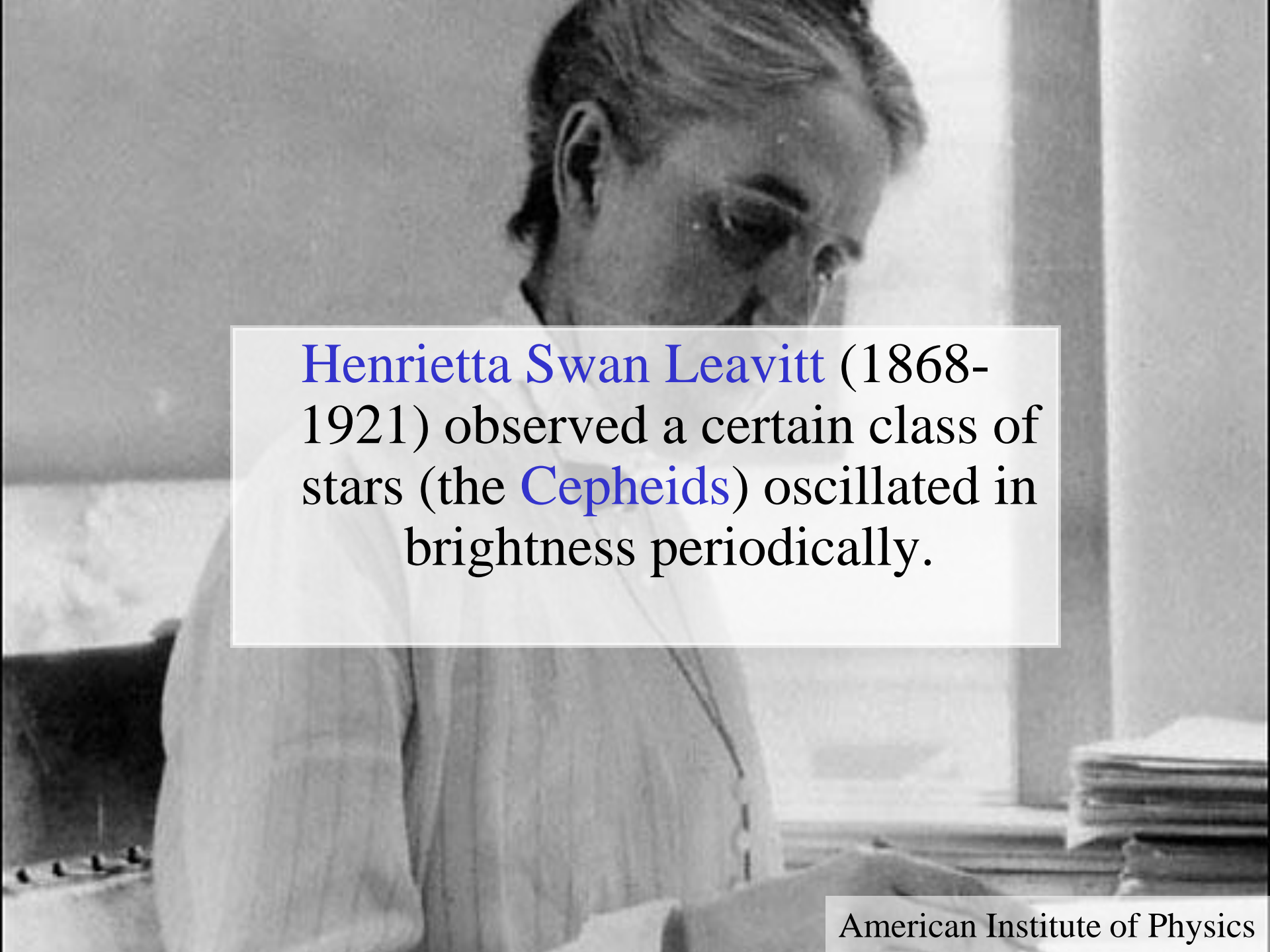
This technique (**main sequence fitting**) works out to about 300,000 light years (covering the entire galaxy!)



Beyond this distance, the main sequence stars are too faint to be measured accurately.

A vast field of galaxies, including spiral, elliptical, and irregular shapes, scattered across a dark cosmic background. The galaxies vary in size, color, and orientation, creating a rich tapestry of celestial objects.

**8th rung: Other
galaxies**

A black and white photograph of Henrietta Swan Leavitt, an astronomer, sitting at a desk and looking down at a document. She is wearing a light-colored, long-sleeved blouse. The background shows a window with a view of a building and a stack of papers on the desk to her right.

Henrietta Swan Leavitt (1868-1921) observed a certain class of stars (the **Cepheids**) oscillated in brightness periodically.

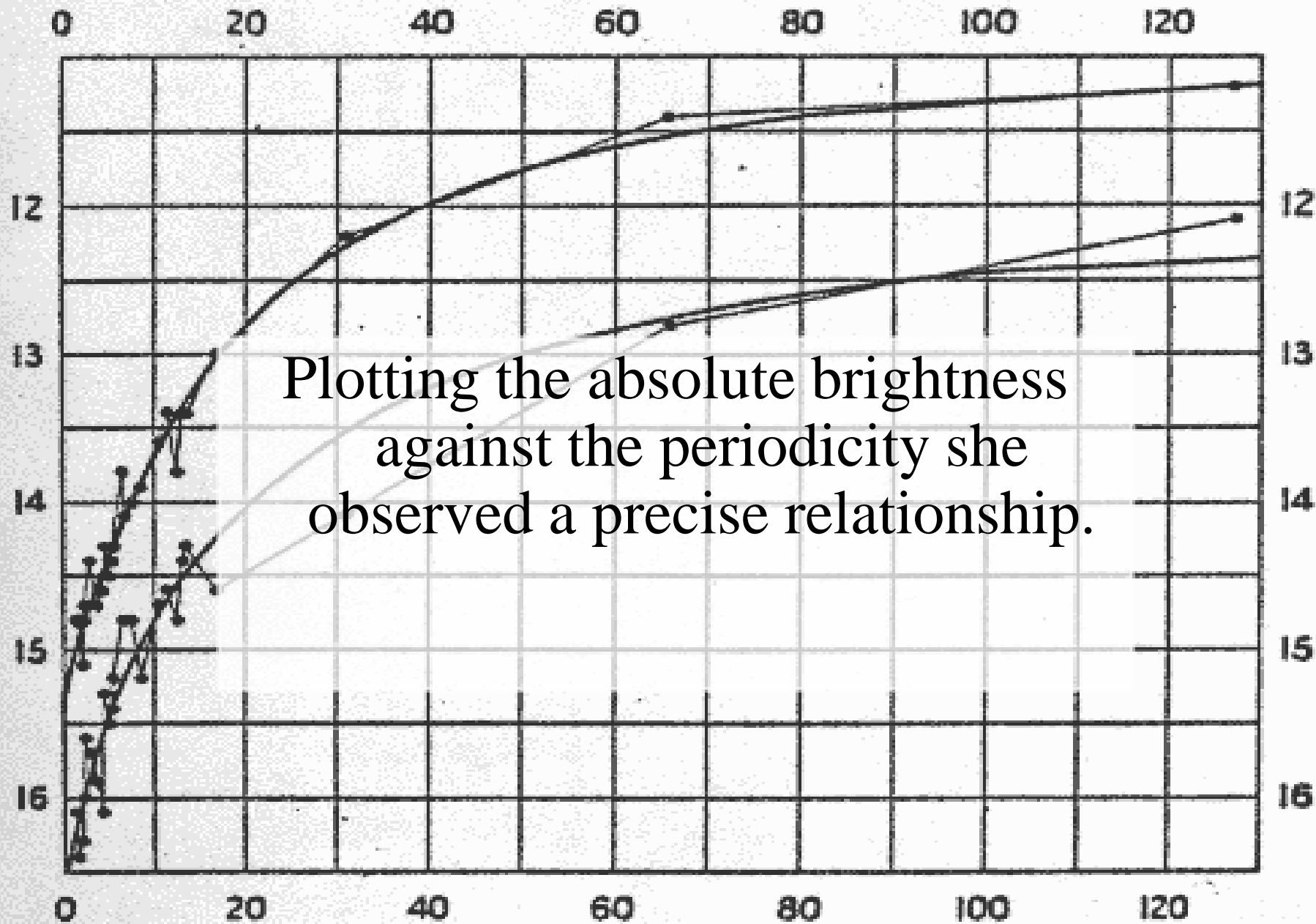
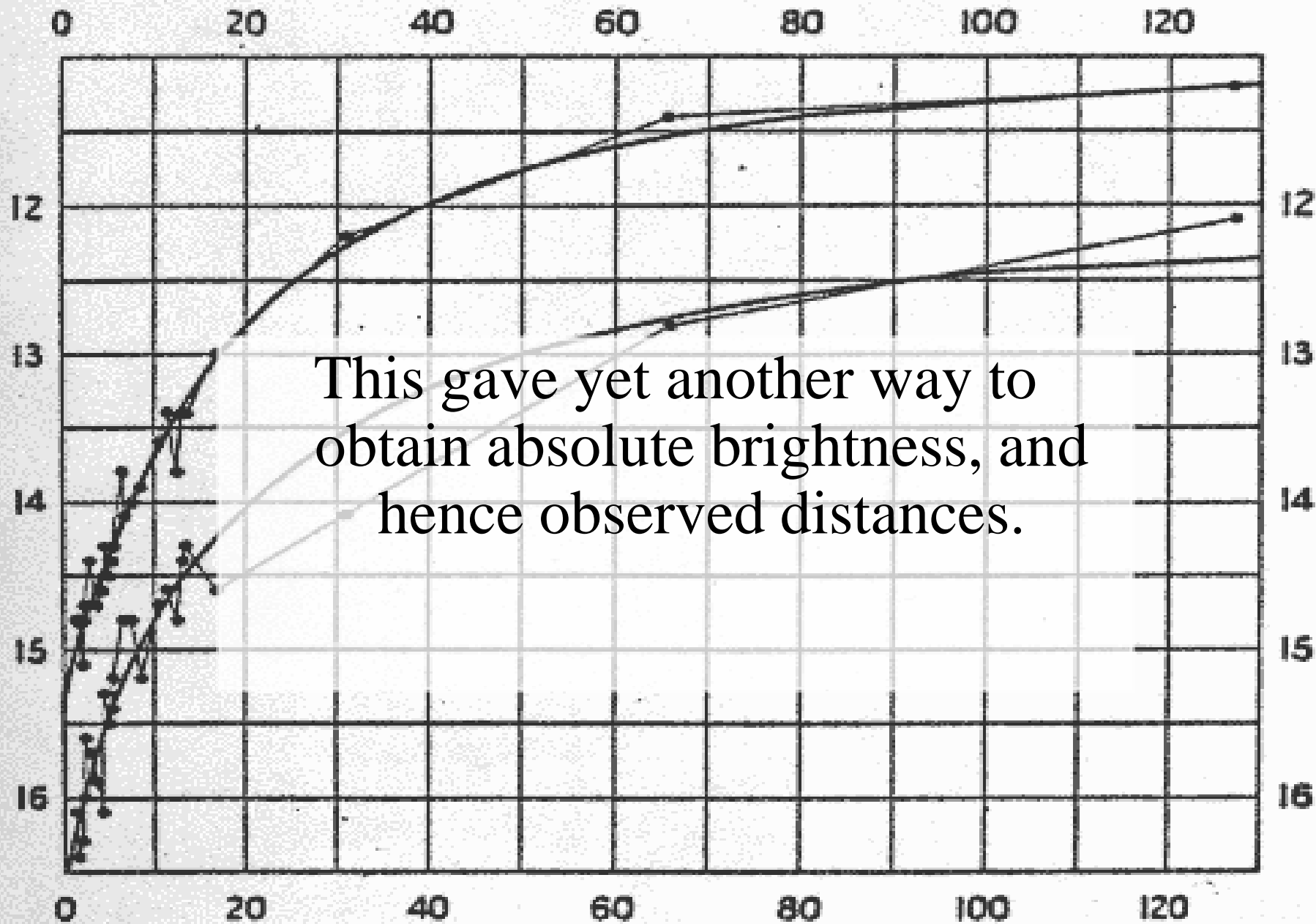


FIG. 1.

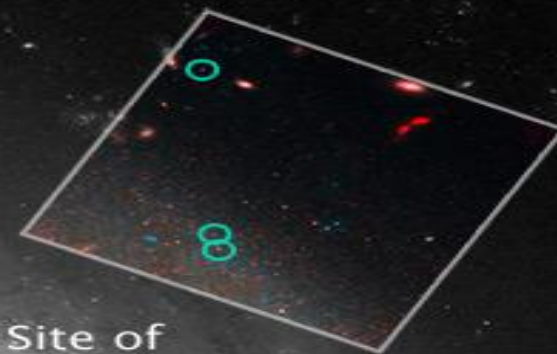
Henrietta Swan Leavitt, 1912



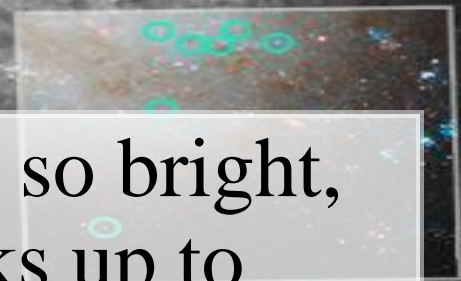
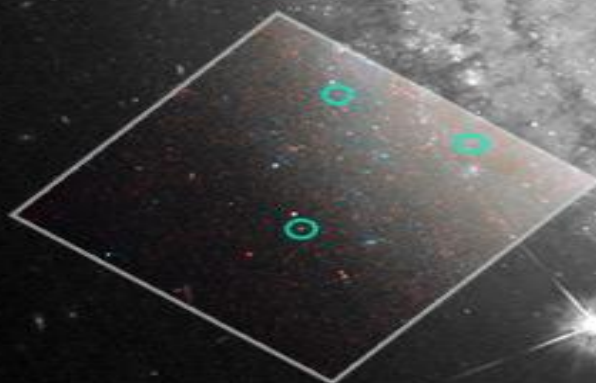
This gave yet another way to obtain absolute brightness, and hence observed distances.

FIG. 1.

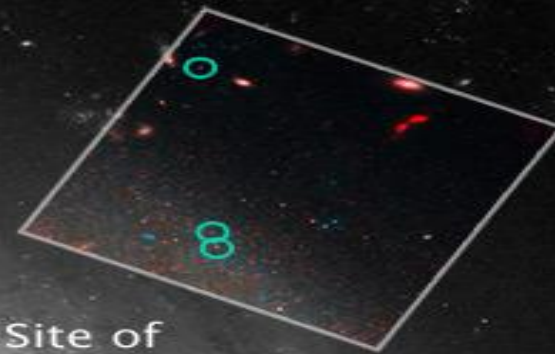
Henrietta Swan Leavitt, 1912



Site of
SN 1995al



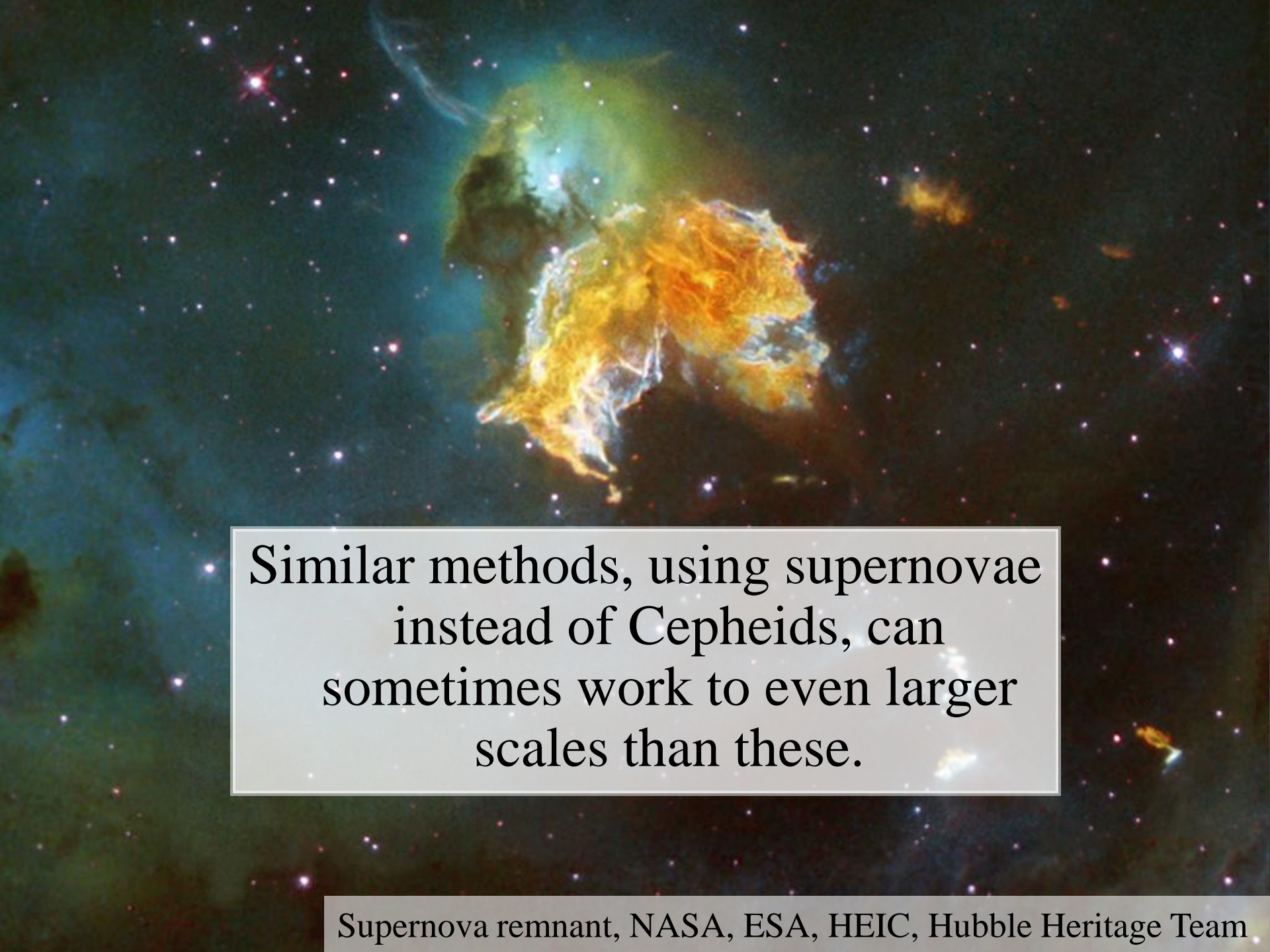
Because Cepheids are so bright,
this method works up to
13,000,000 light years!



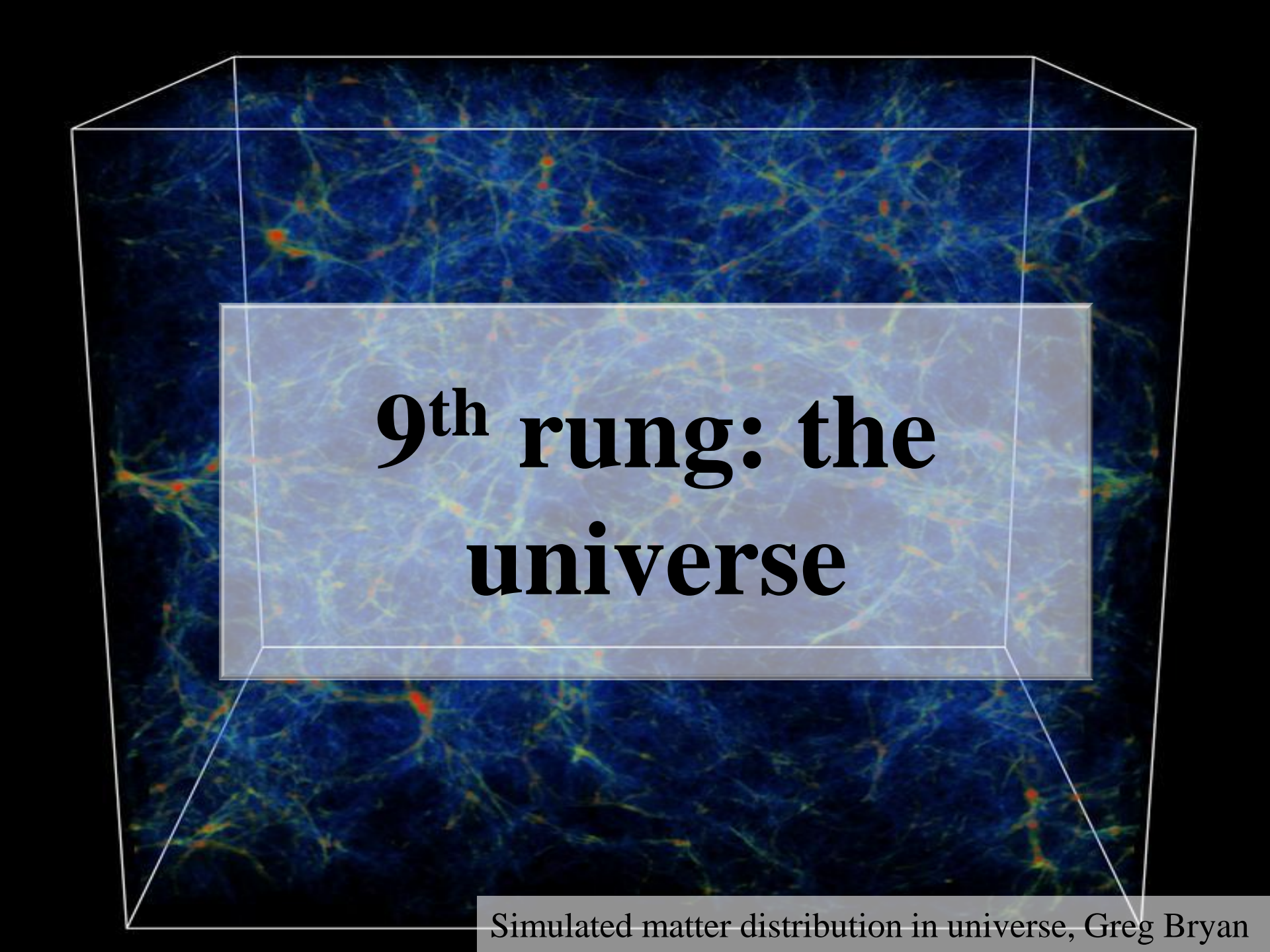
Site of
SN 1995al

Most galaxies are fortunate to have at least one Cepheid in them, so we know the distances to all galaxies out to a reasonably large distance.



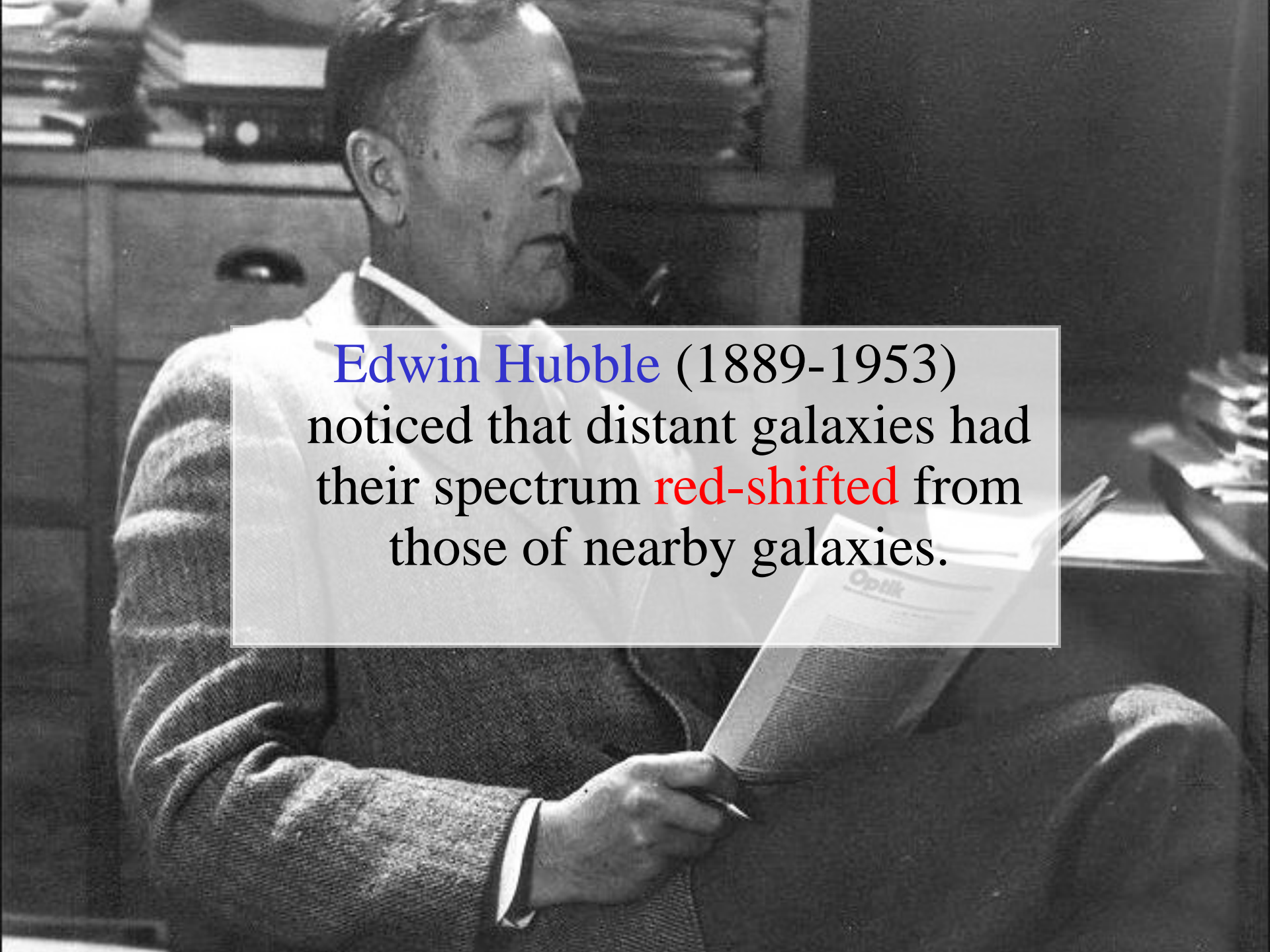


Similar methods, using supernovae instead of Cepheids, can sometimes work to even larger scales than these.

A 3D wireframe box containing a simulated matter distribution in the universe. The background is a dark blue field filled with a complex network of thin, glowing blue and green filaments. Scattered throughout are numerous bright orange and red spots, representing galaxy clusters or individual galaxies. The overall appearance is that of a vast, interconnected web of matter.

9th rung: the universe

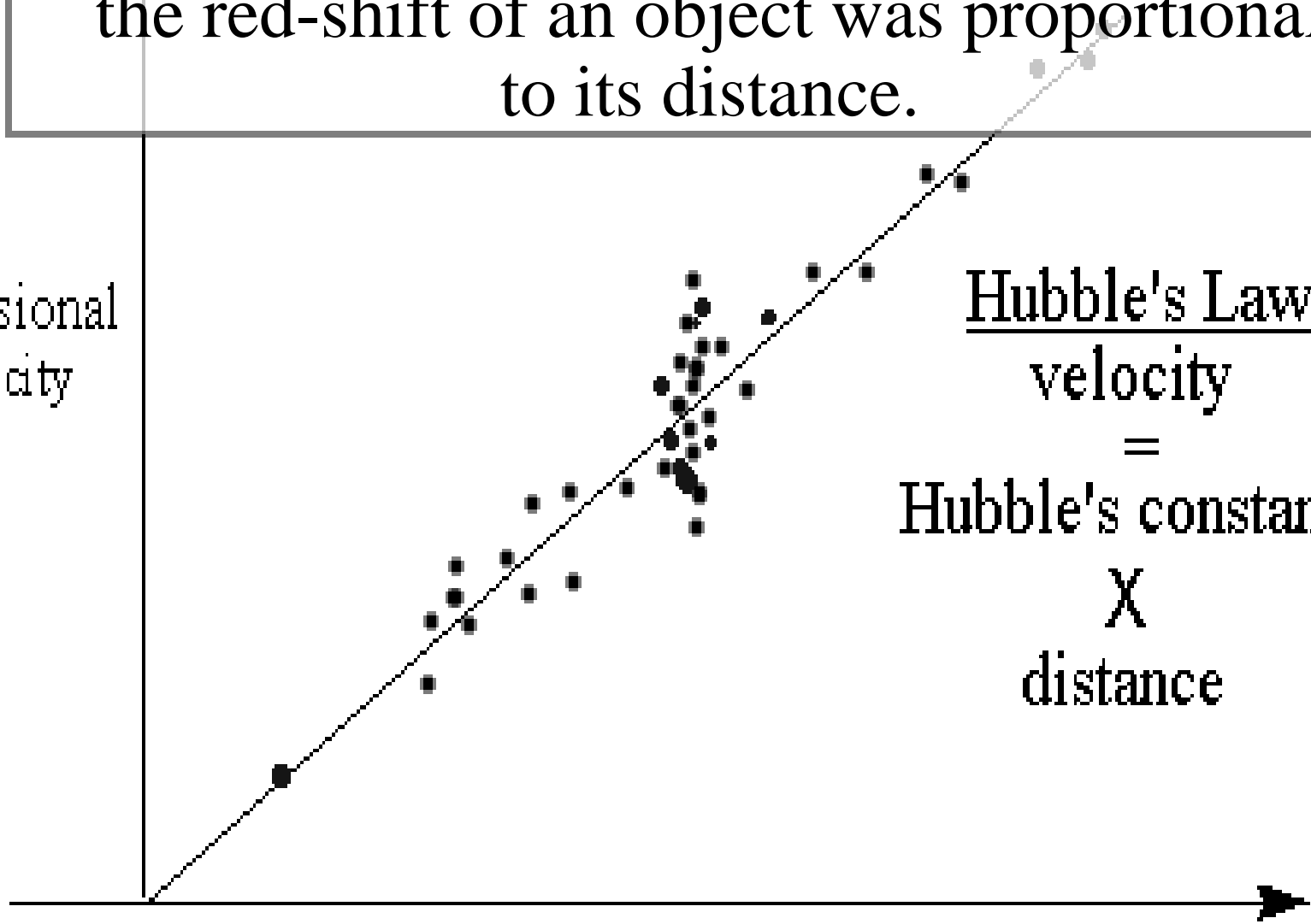
Simulated matter distribution in universe, Greg Bryan

A black and white photograph of Edwin Hubble, an astronomer, sitting at a desk and reading a document. He is wearing a dark sweater over a light-colored collared shirt. The document he is holding has the word "Optik" visible on it. The background shows a desk with various items, including a lamp and some papers.

Edwin Hubble (1889-1953)
noticed that distant galaxies had
their spectrum **red-shifted** from
those of nearby galaxies.

With this data, he formulated **Hubble's law**:
the red-shift of an object was proportional
to its distance.

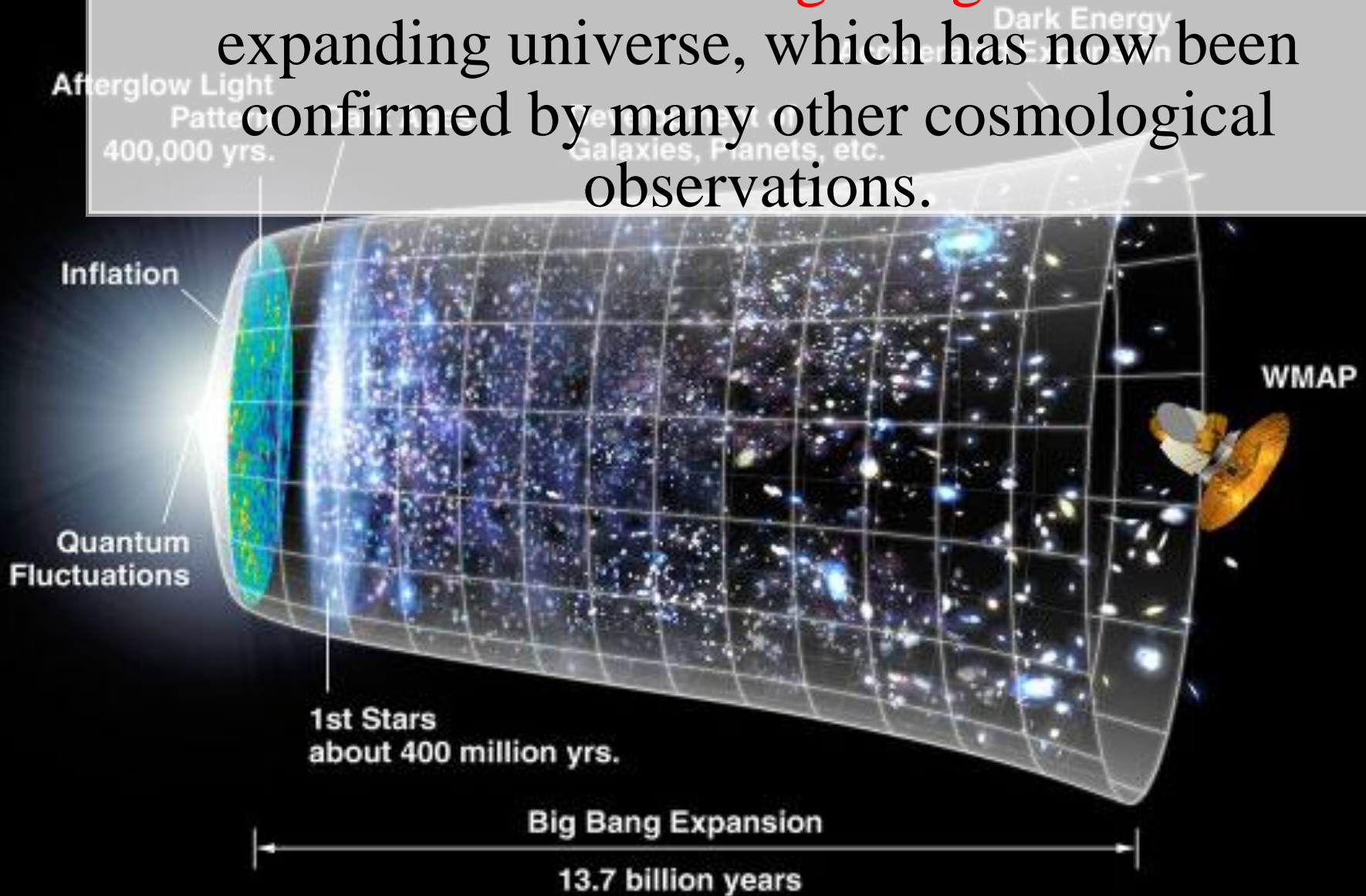
recessional
velocity

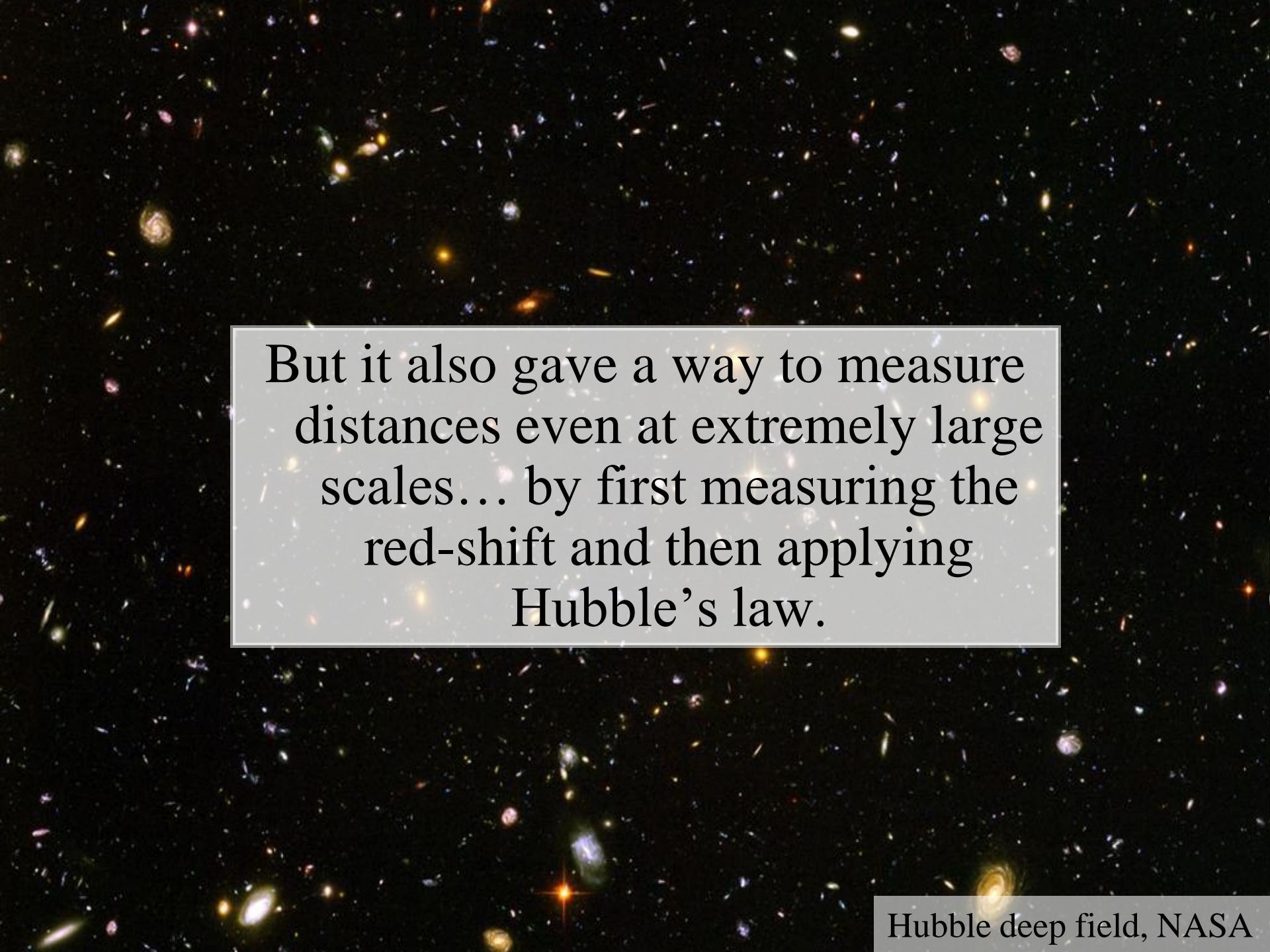


Hubble's Law
velocity
=
Hubble's constant
 \times
distance

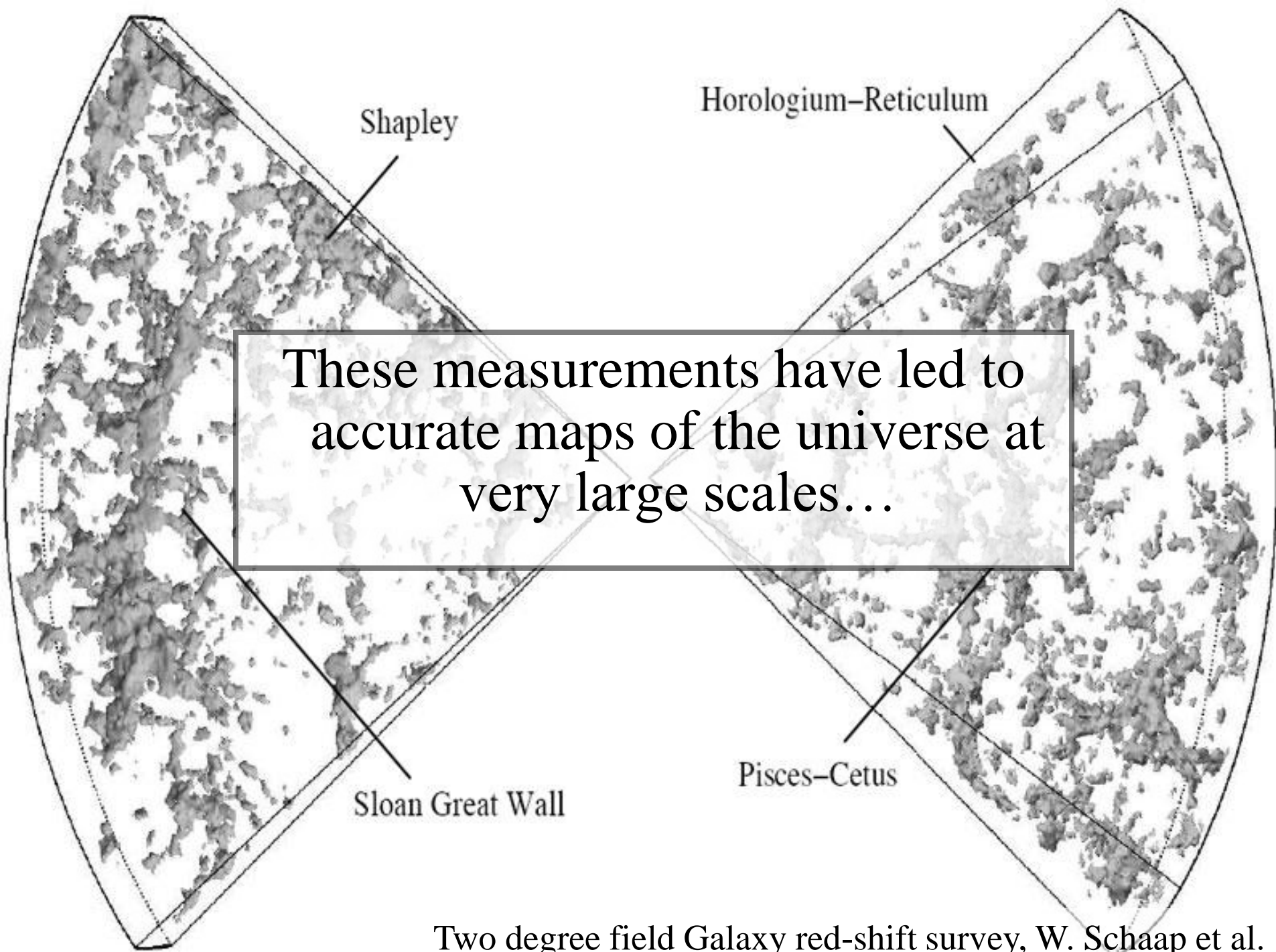
distance

This led to the famous **Big Bang** model of the expanding universe, which has now been confirmed by many other cosmological observations.

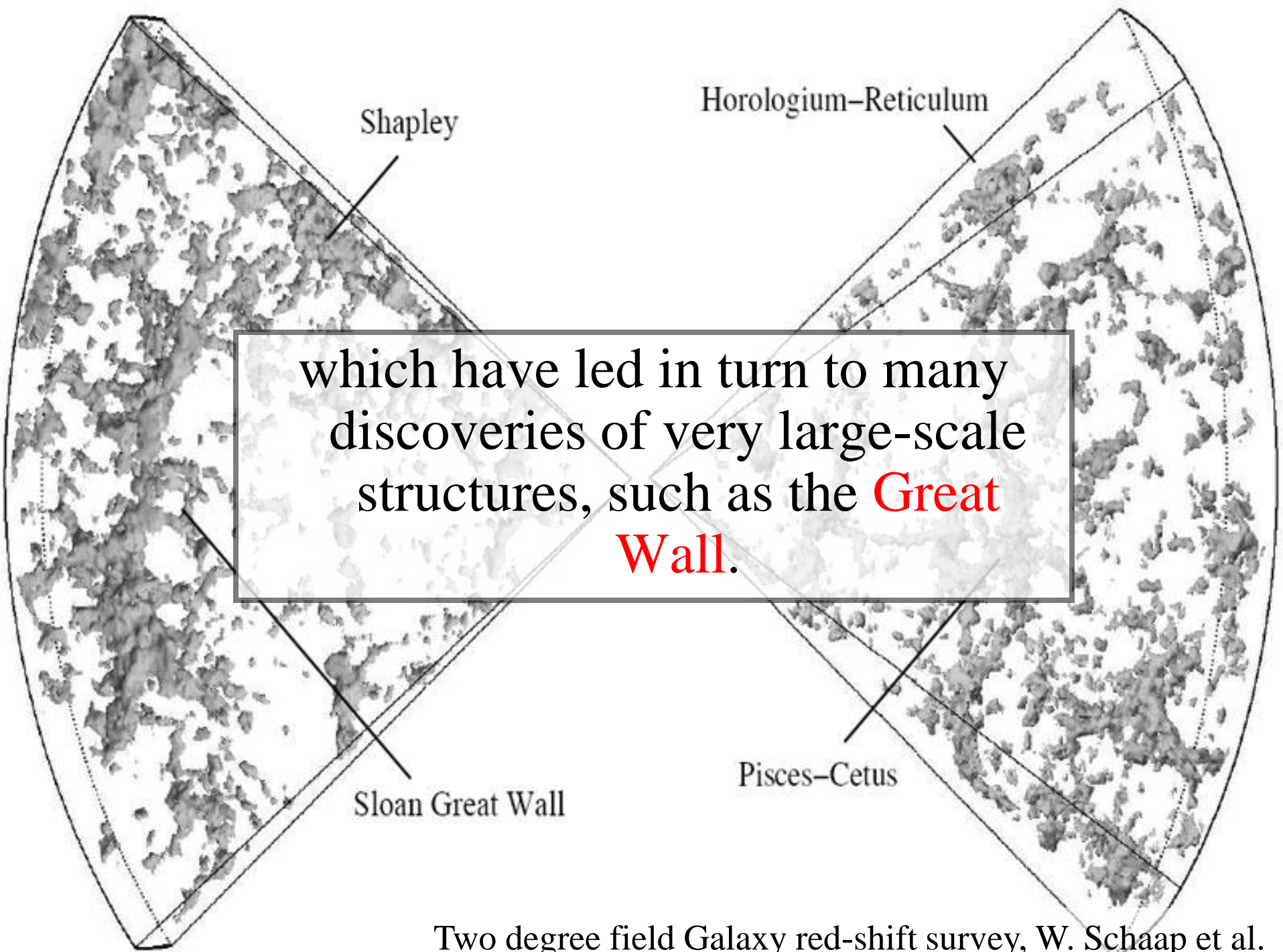


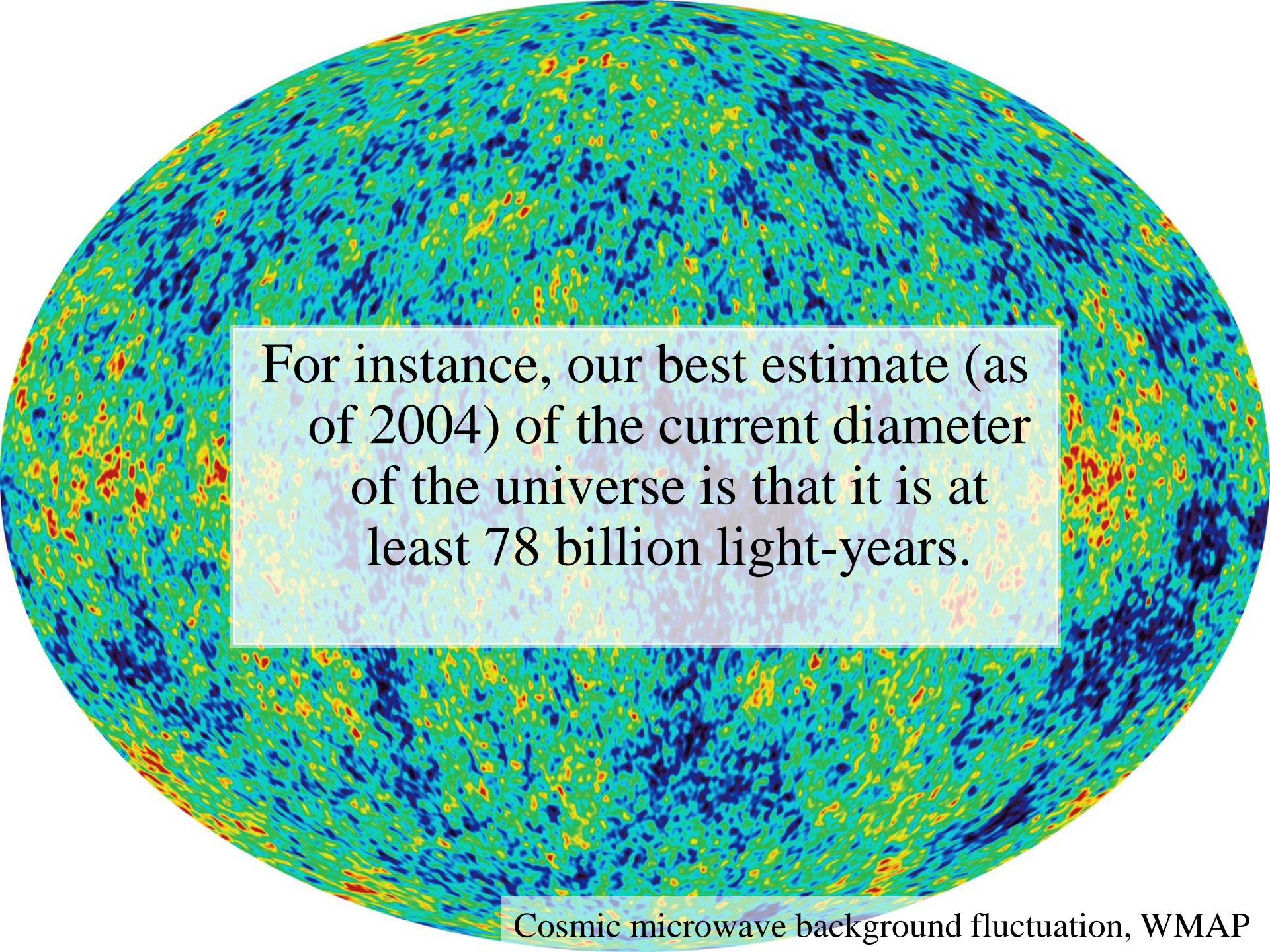
A vast field of galaxies, including spiral, elliptical, and irregular shapes, scattered across a dark cosmic background. The galaxies vary in size, color, and orientation, representing a rich population of distant celestial objects.

But it also gave a way to measure distances even at extremely large scales... by first measuring the red-shift and then applying Hubble's law.



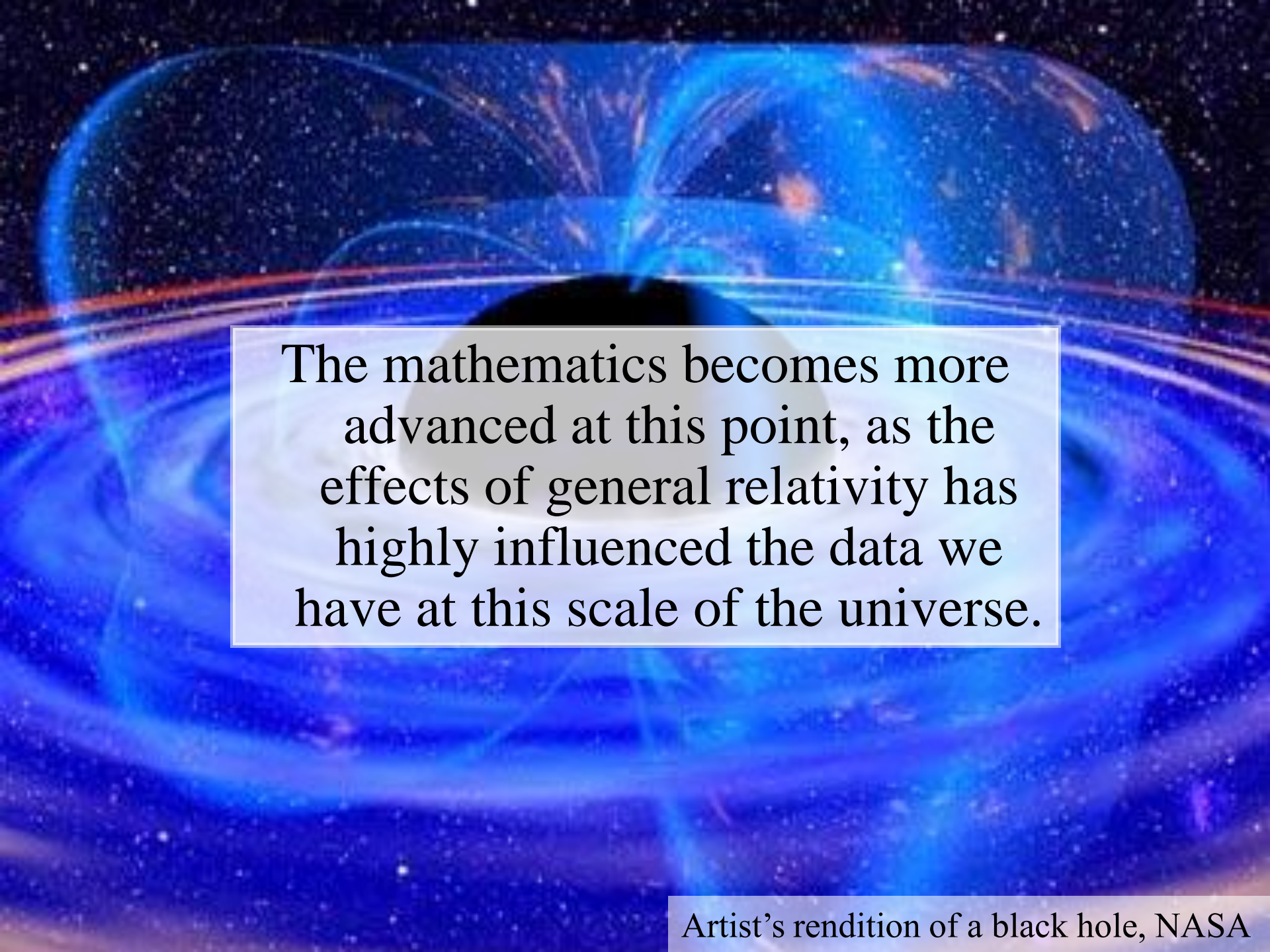
Two degree field Galaxy red-shift survey, W. Schaap et al.





For instance, our best estimate (as of 2004) of the current diameter of the universe is that it is at least 78 billion light-years.

Cosmic microwave background fluctuation, WMAP

An artist's rendering of a black hole, showing a dark central region surrounded by a glowing accretion disk. The disk is composed of blue and purple gas, with bright spots and filaments. The background is a starry space. The text is overlaid on a semi-transparent white box in the center.

The mathematics becomes more advanced at this point, as the effects of general relativity has highly influenced the data we have at this scale of the universe.

Artist's rendition of a black hole, NASA

A photograph of the Hubble Space Telescope in orbit above Earth. The telescope is oriented vertically, with its large cylindrical body and two large solar panel arrays extending outwards. The Earth's surface, showing clouds and landmasses, is visible in the background. A white rectangular box is overlaid on the center of the image, containing text.

Cutting-edge technology (such as the **Hubble space telescope** (1990-) and **WMAP** (2001-)) has also been vital to this effort.

Climbing this rung of the ladder (i.e. mapping the universe at its very large scales) is still a very active area in astronomy today!



