

History of Astronomy

Astronomy 101: Exploring the Night Sky

January, 2018

Archaeoastronomy

The Calendar

When should you plant your crops? When does the cold weather start?
How long is a year?

In what direction should I travel if I am lost on the ocean?

If you woke up on an unknown planet, how would you figure these out?

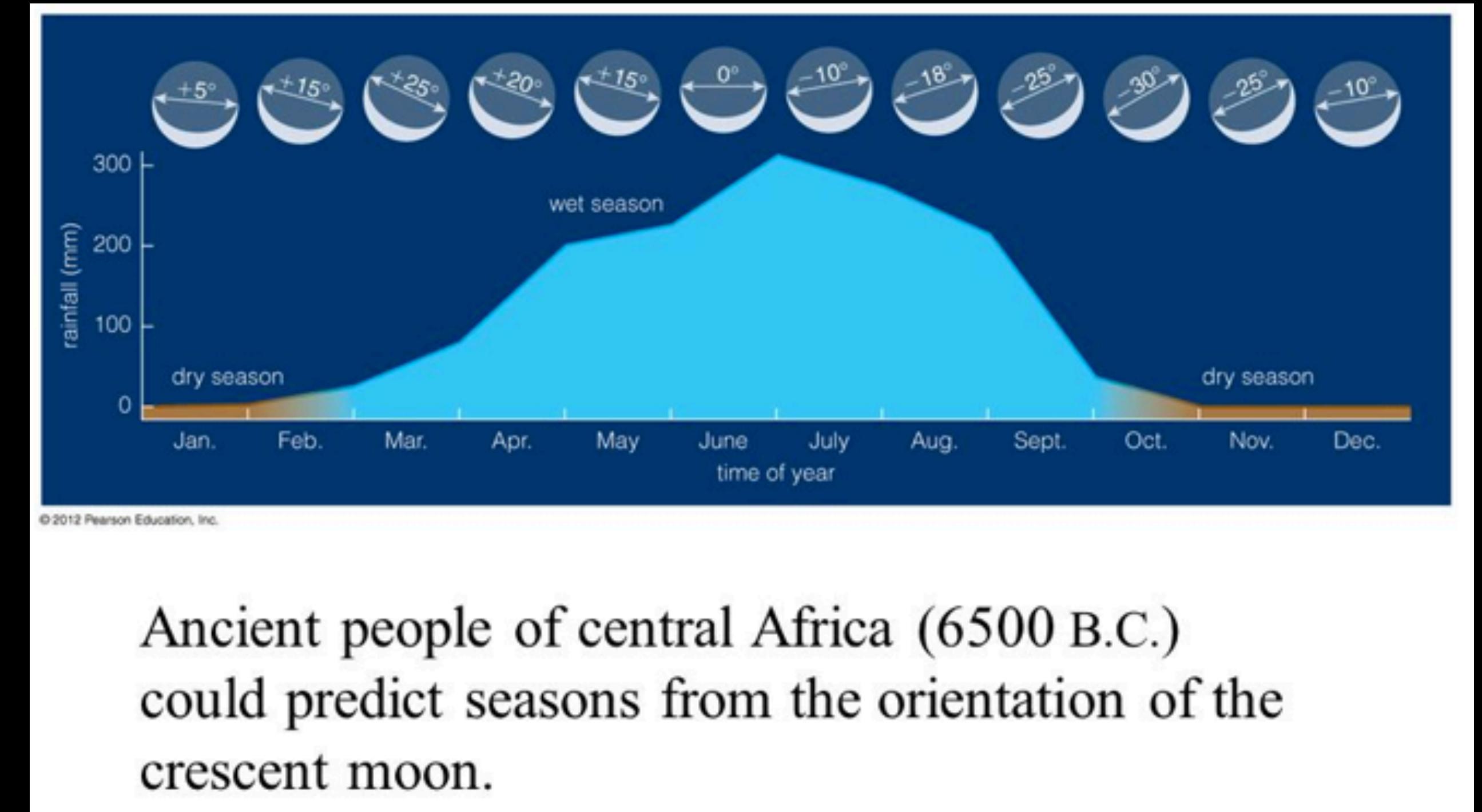
What did ancient people do?

Purposes of ancient astronomy

1. Predict weather patterns

The seasons are tied into our orbit and axial tilt.

Ancient peoples recognized that recurring weather patterns matched celestial events.



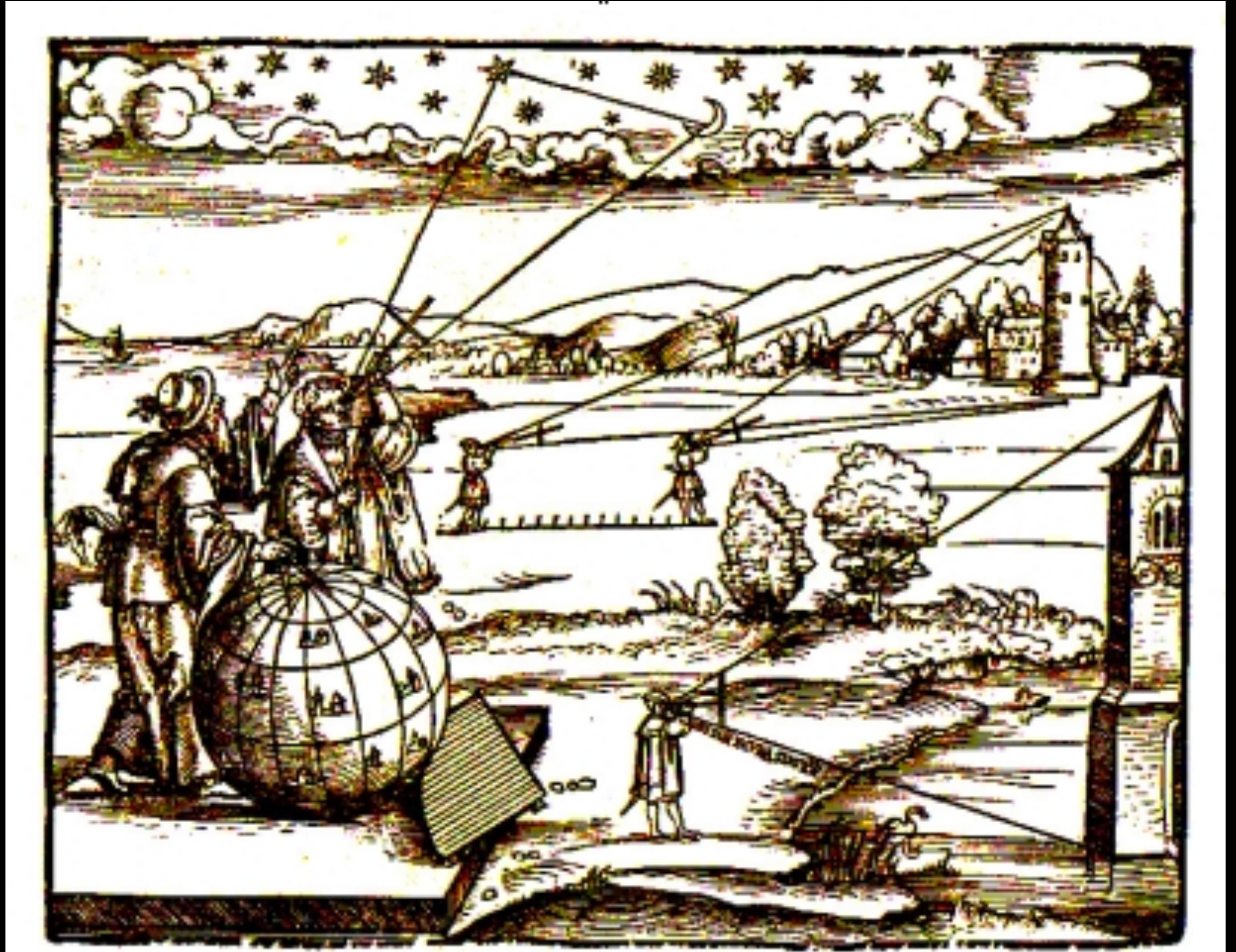
Some used the position of the Sun, some used position of stars, others used the orientation of the Moon.

Purposes of ancient astronomy

2. Assist travelers

Unless you know the time of day or the North direction, the Sun is not a good key to direction.

The North Star and the constellations can orient a traveler much better!



Tools of ancient astronomy

Many cultures built structures to make astronomical measurements.

The use of these tools are well known to have involved rituals.

It is unclear whether they believed these rituals were effective, or whether the rituals were used to disguise the knowledge. (like a magician!)



“Ancient Knowledge” Trope

Stonehenge Apocalypse

From Wikipedia, the free encyclopedia

Stonehenge Apocalypse is a 2010 made-for-TV Canadian science fiction movie starring Misha Collins, Torri Higginson and Peter Wingfield. The movie follows a series of deaths, natural disasters, and strange energy readings that seem to be mysteriously connected to Stonehenge.

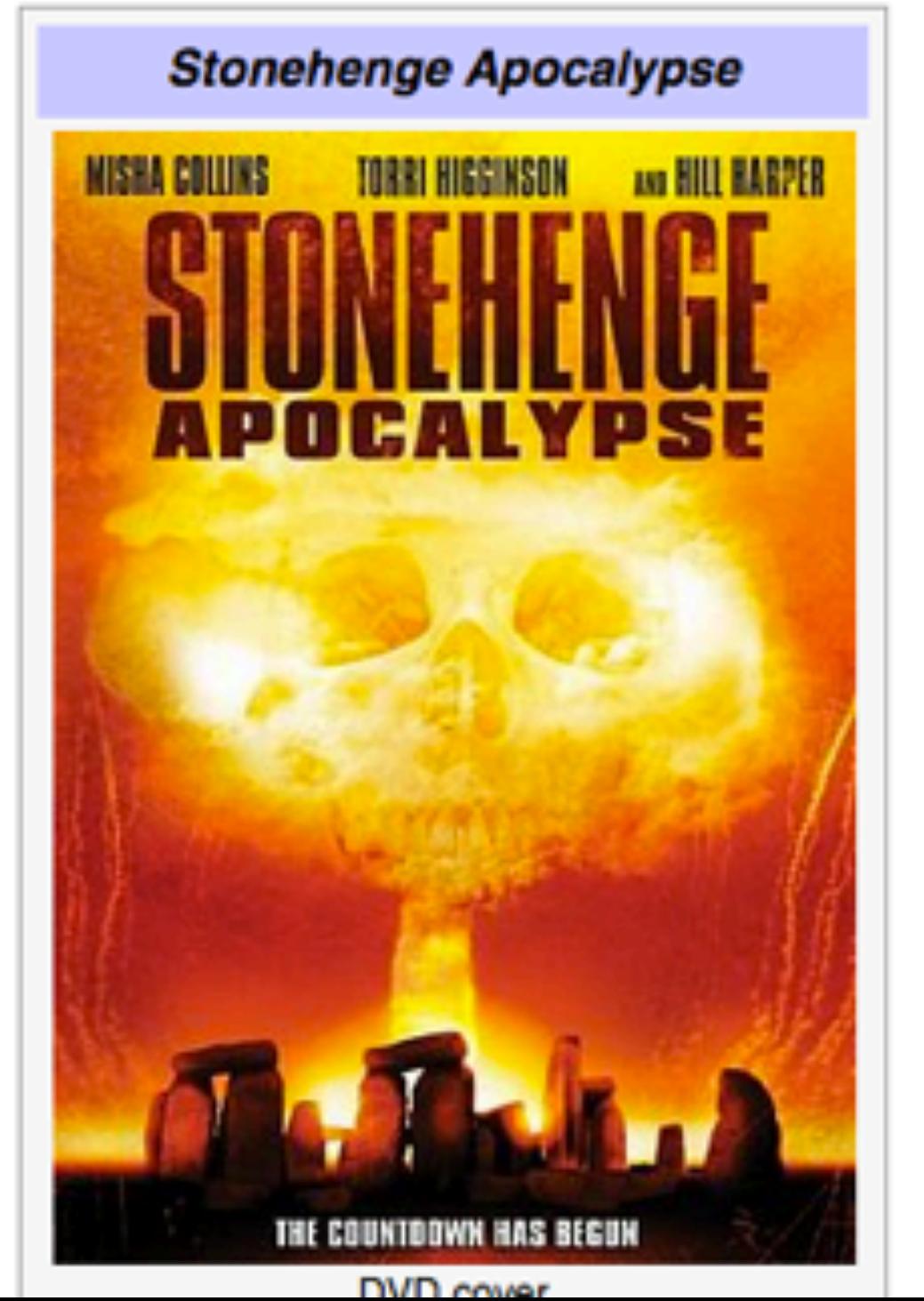
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- 1 Plot
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Plot [edit]

An ancient prophecy comes to pass when archeologists unearth an Egyptian chamber in England, sparking a devastating electromagnetic pulse that originates at Stonehenge and sends destructive shockwaves around the globe. When the Aztec pyramids crumble and the stones take on a life of their own, a renegade radio host, a team of scientists, and a team of British commandos race to prevent the same force responsible for creating life on Earth from cleansing the planet in order to herald the dawn of a new age^[1]

Cast [edit]



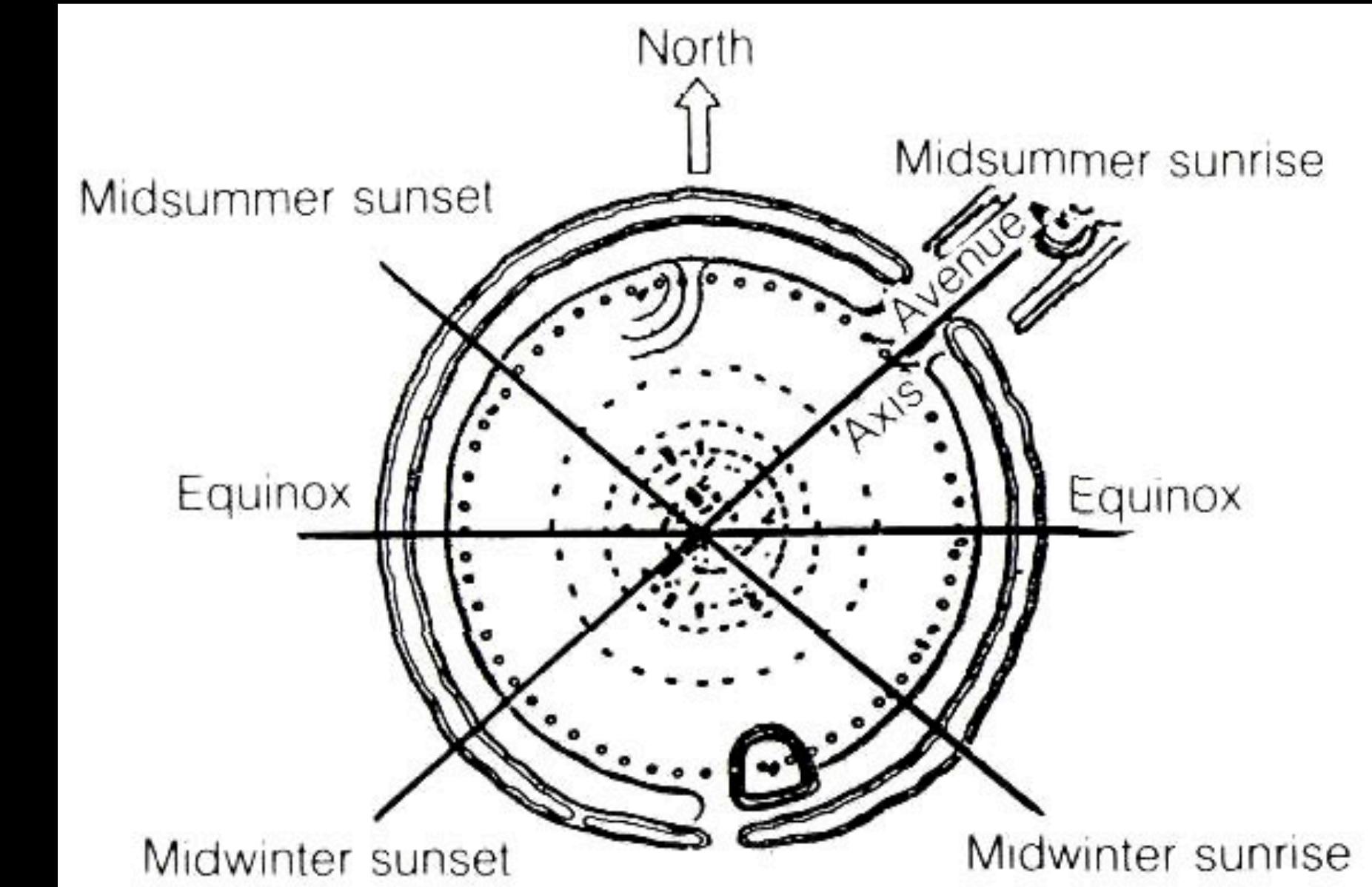
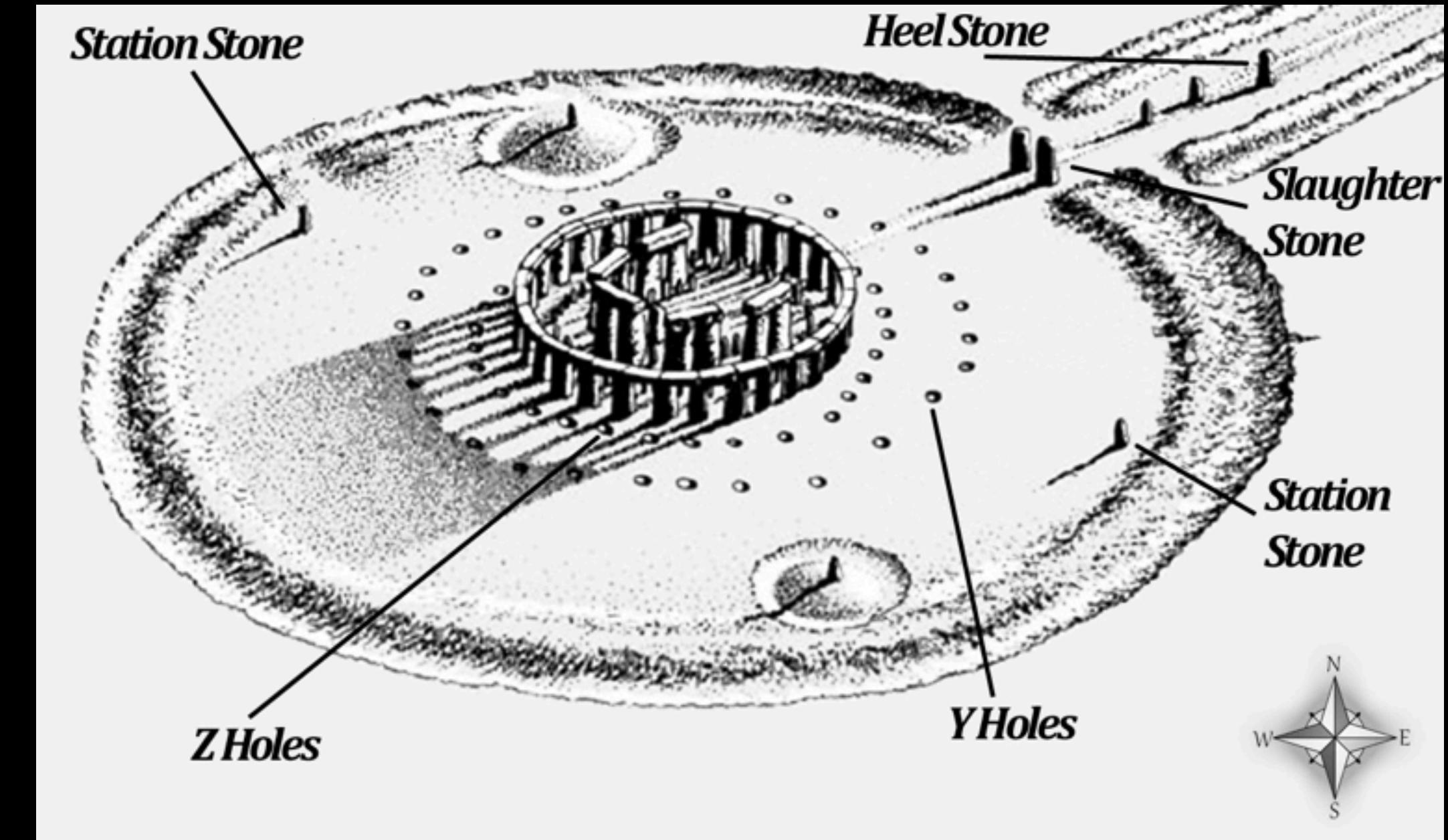
Common fiction trope that ancient people had knowledge that has been lost.
The intermingling of science with ritual may be responsible.

Stonehenge

Built/modified over 1700 years
(2800 BC - 1100 BC)

50 tonne stones moved 200 km to construct.

Summer solstice sunrise aligns with heel stone. Equinox and winter solstice alignments also evident.



Other ancient calendars



Big Horn Medicine Wheel, Wyoming



14 other stone/wood circles in the UK

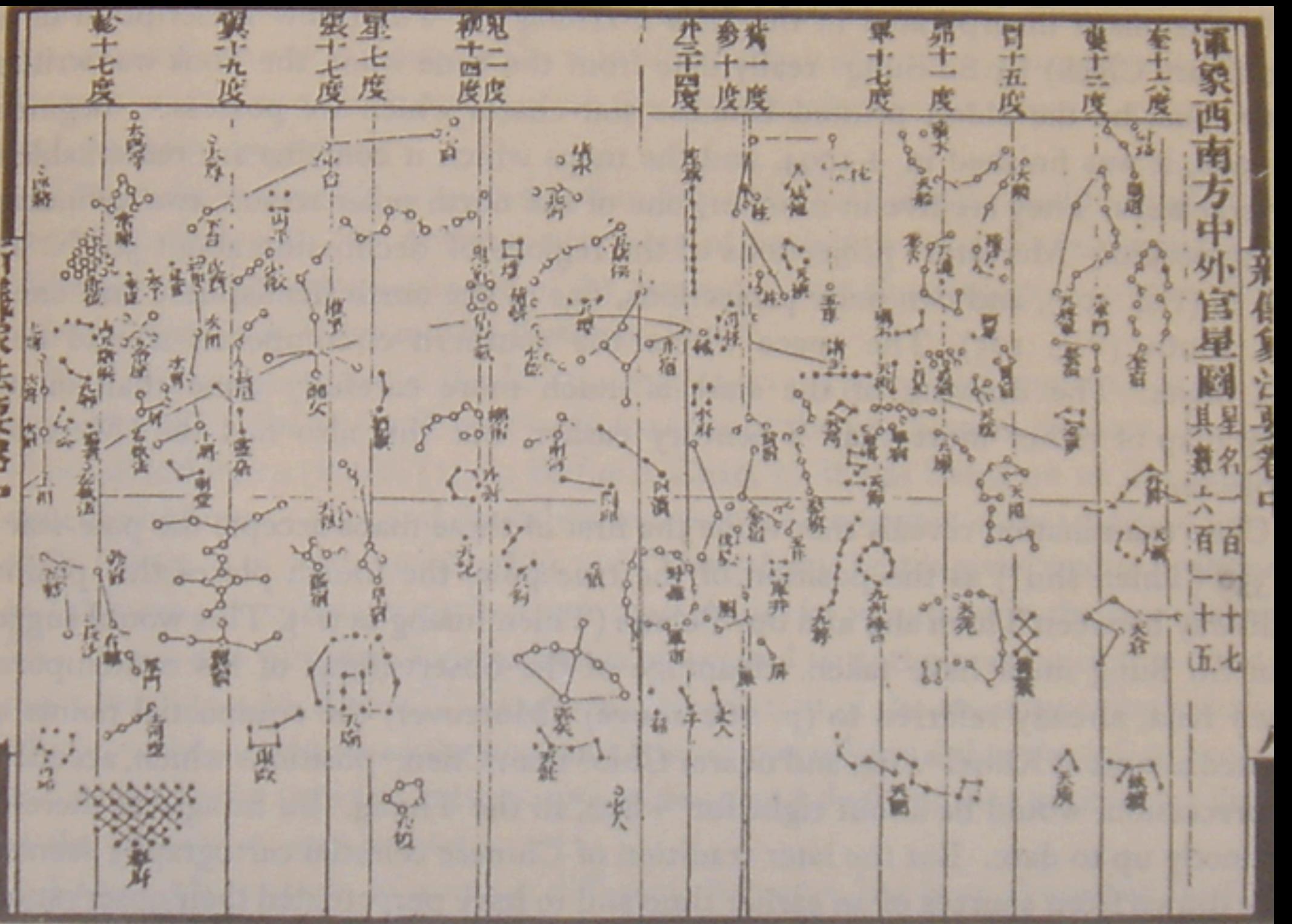


Chaco Canyon Sun Dagger



Ancient Chinese Astronomy

Chinese astronomers created detailed maps of the stars - used for prophetic purposes also.

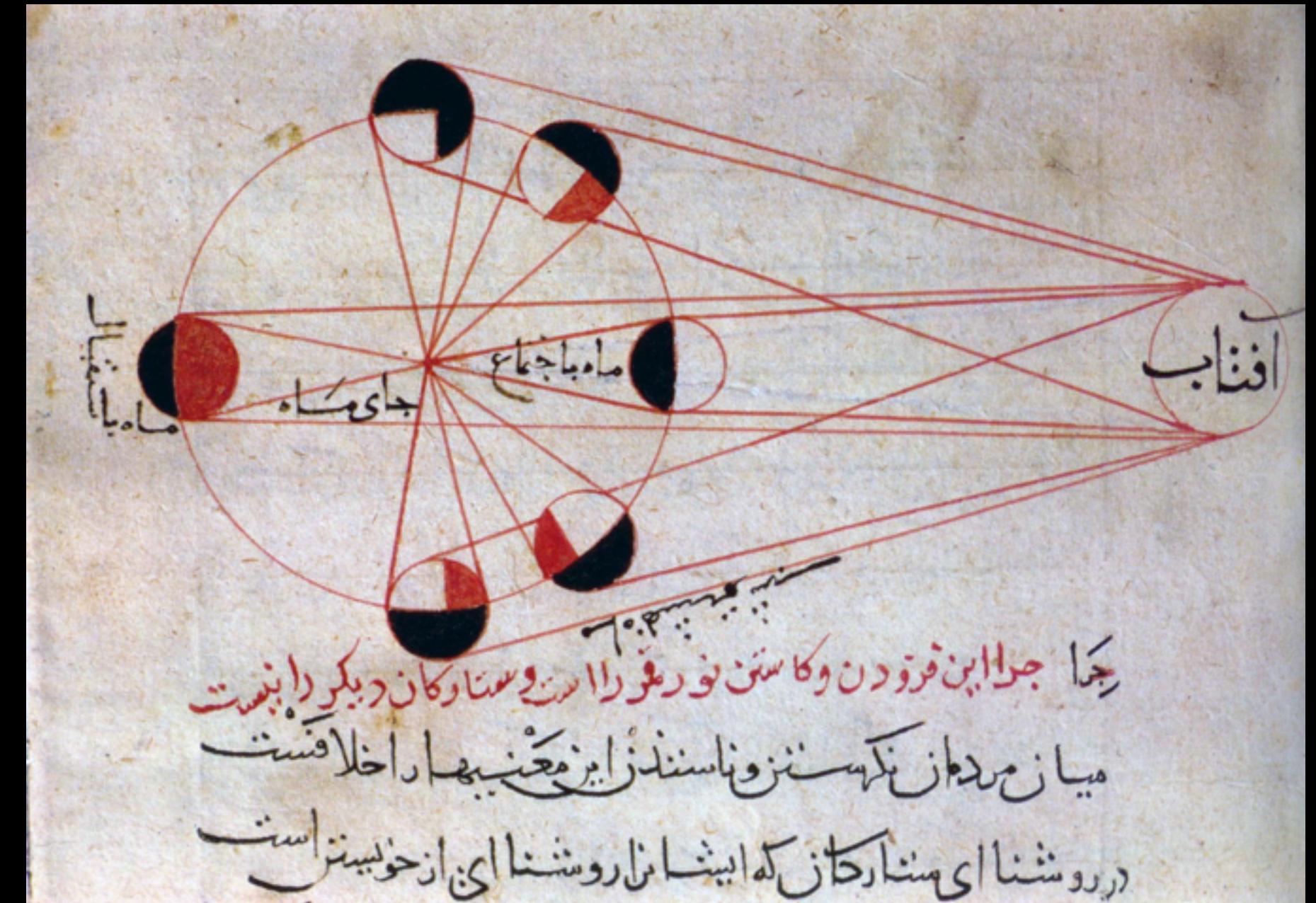


Chinese astronomers noted “guest stars” such as SN-1054. After a thousand years, it now appears to us as the Crab Nebula.

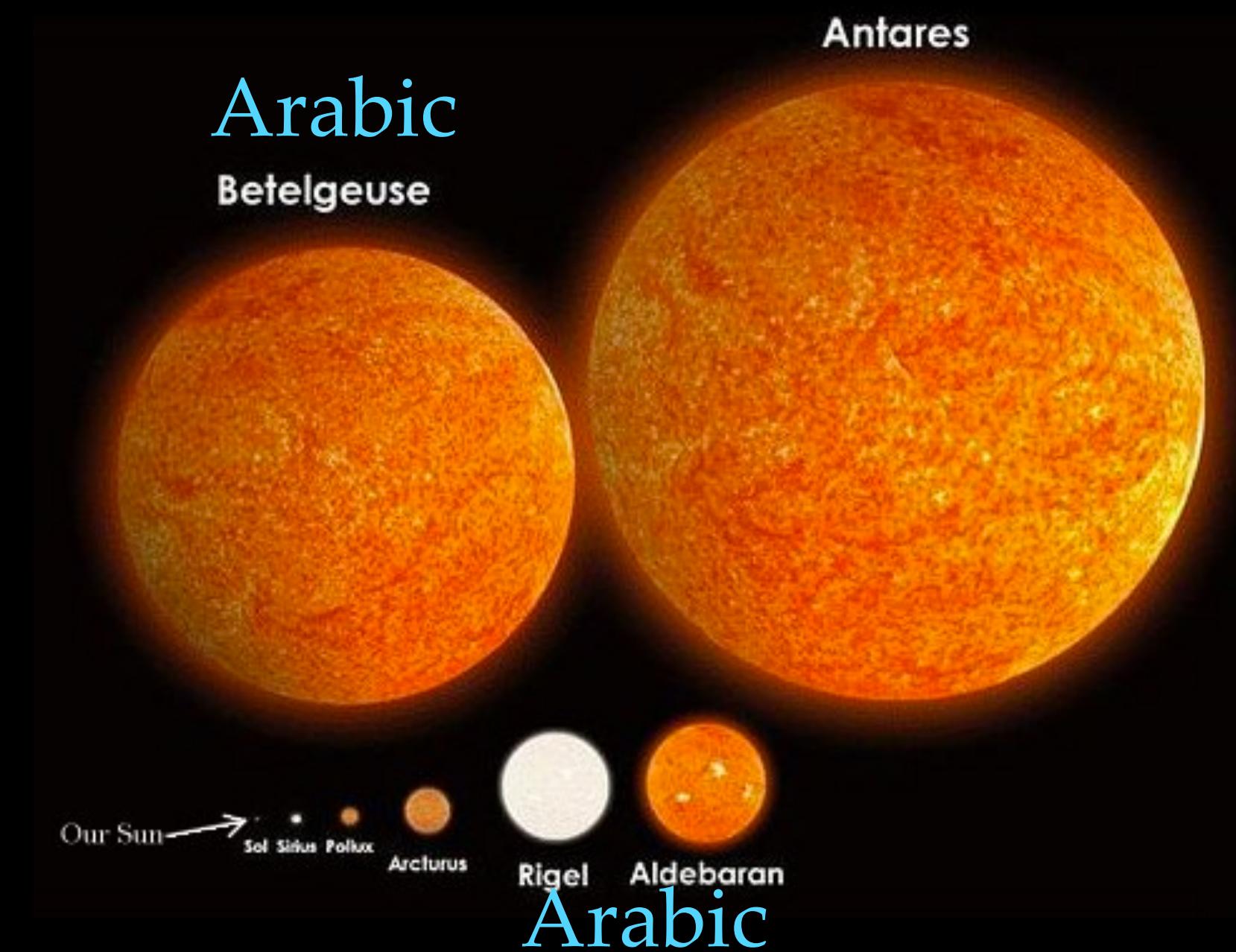


Middle Eastern Astronomy

Astronomers in the Middle East were the most advanced at one point, building upon the understanding of the Greeks.



Terms such as “Zenith” and “Azimuth” as well as the naming of many stars come from Arabic astronomers.



Origins of Geocentric Model

Question: Which of these space objects do you think was NOT catalogued by ancient astronomers?

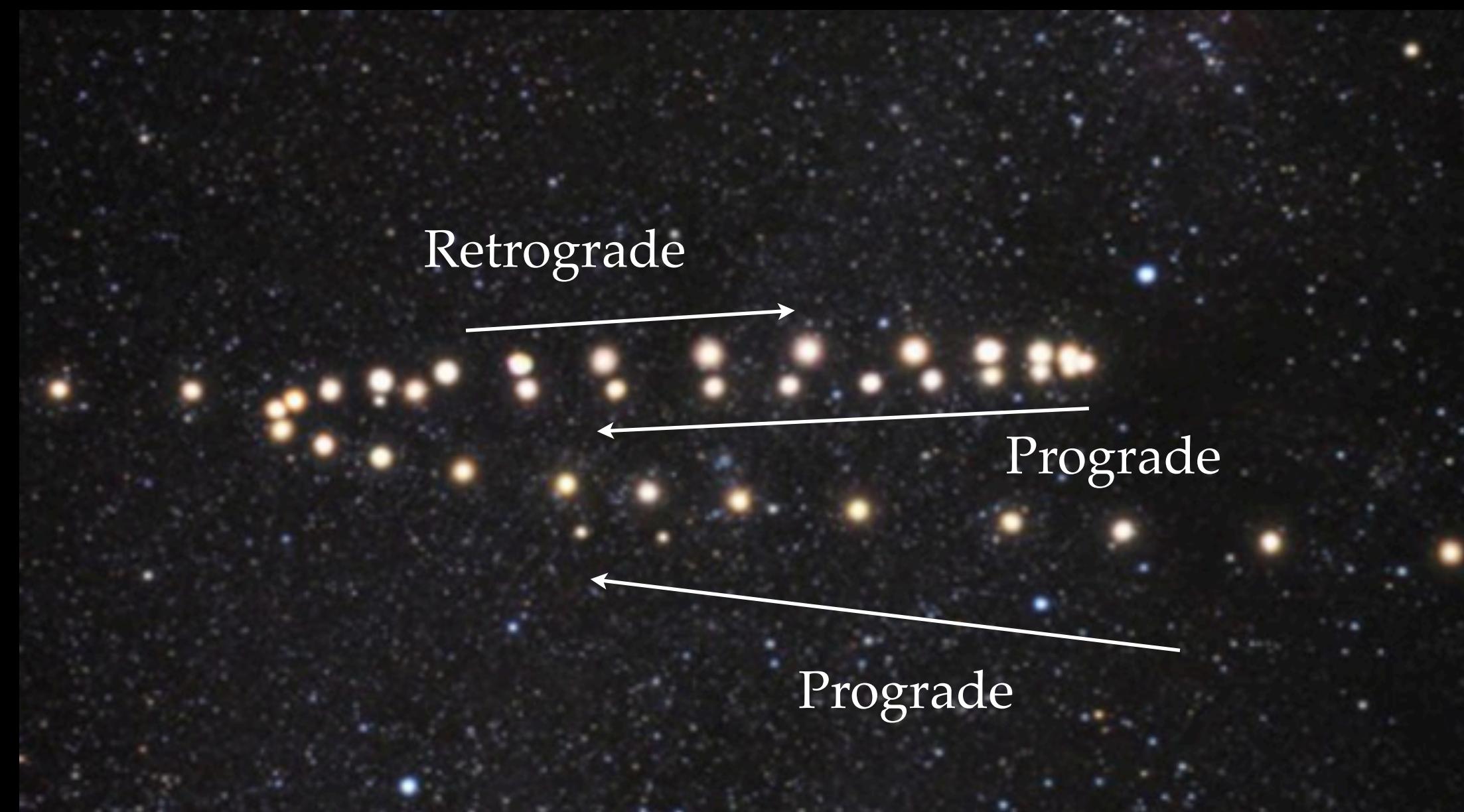
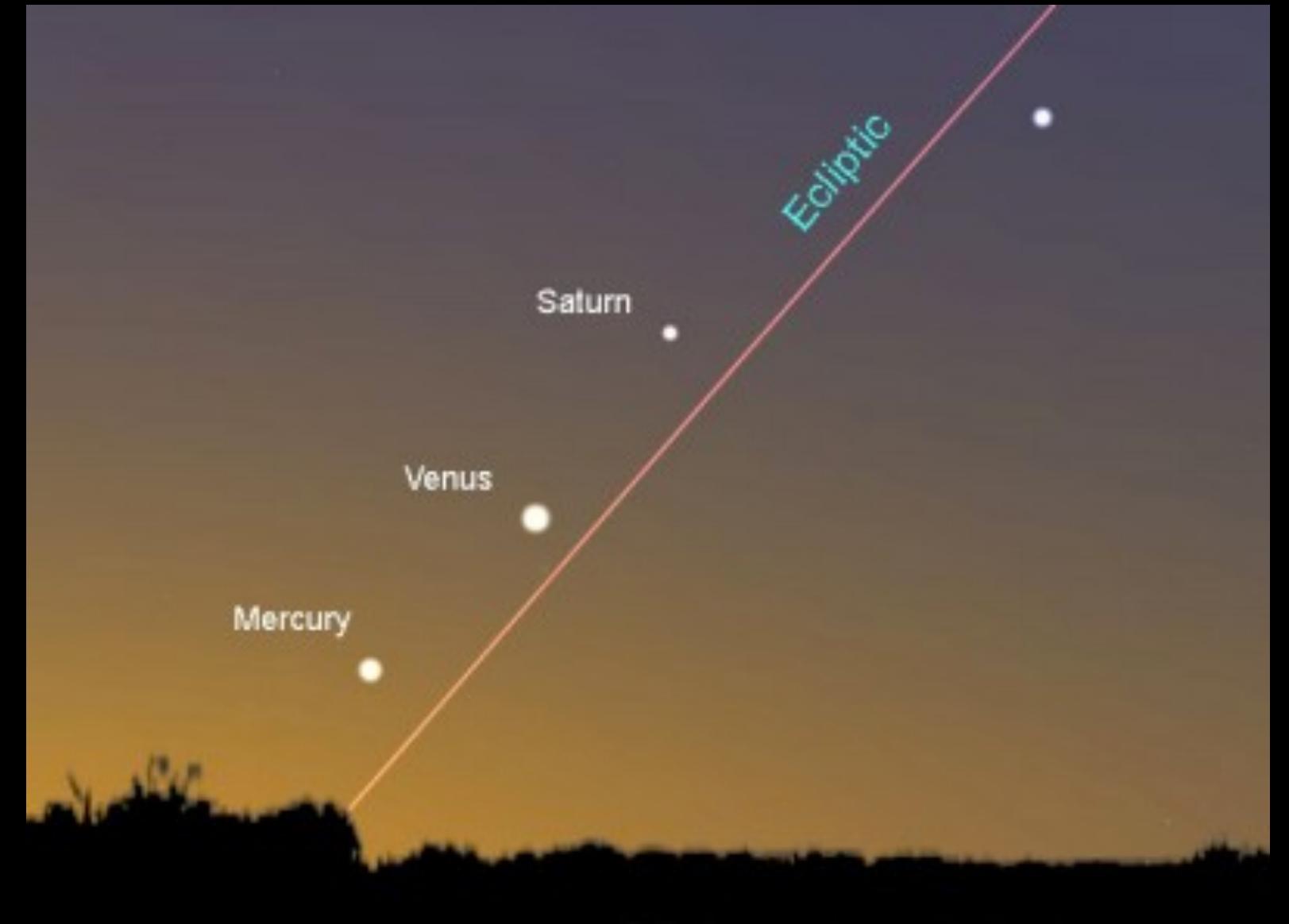
- A. Planets
- B. Asteroids
- C. Supernova
- D. Stars
- E. Comets

Ancient Greece

Greeks distinguished Sun, Moon, planets and stars as distinct types of objects.

The Sun and Stars move from East to West in the night sky.

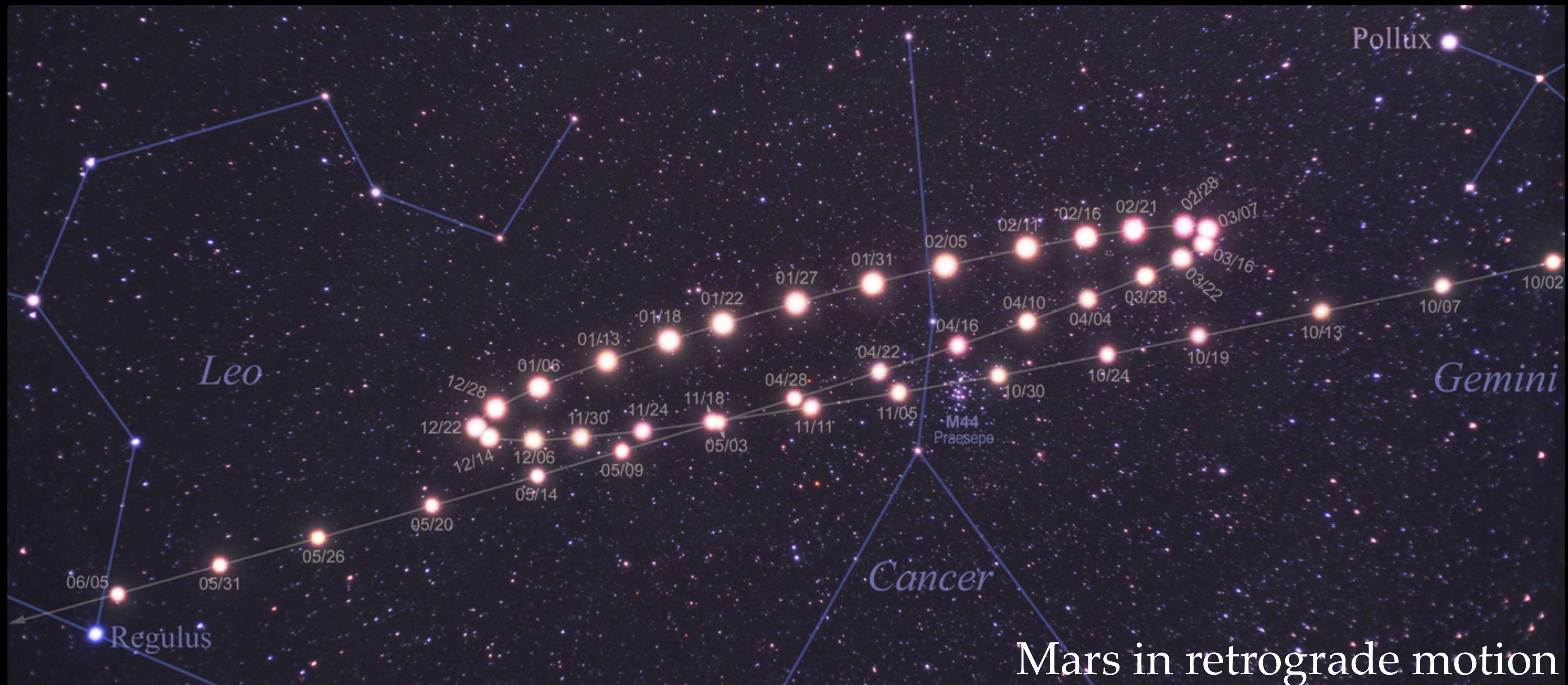
Planets follow the ecliptic (the path of the Sun) but sometimes move in retrograde.



Retrograde and Prograde

Prograde - motion in same direction as other object(s)

Retrograde - motion in opposite direction to other object(s)

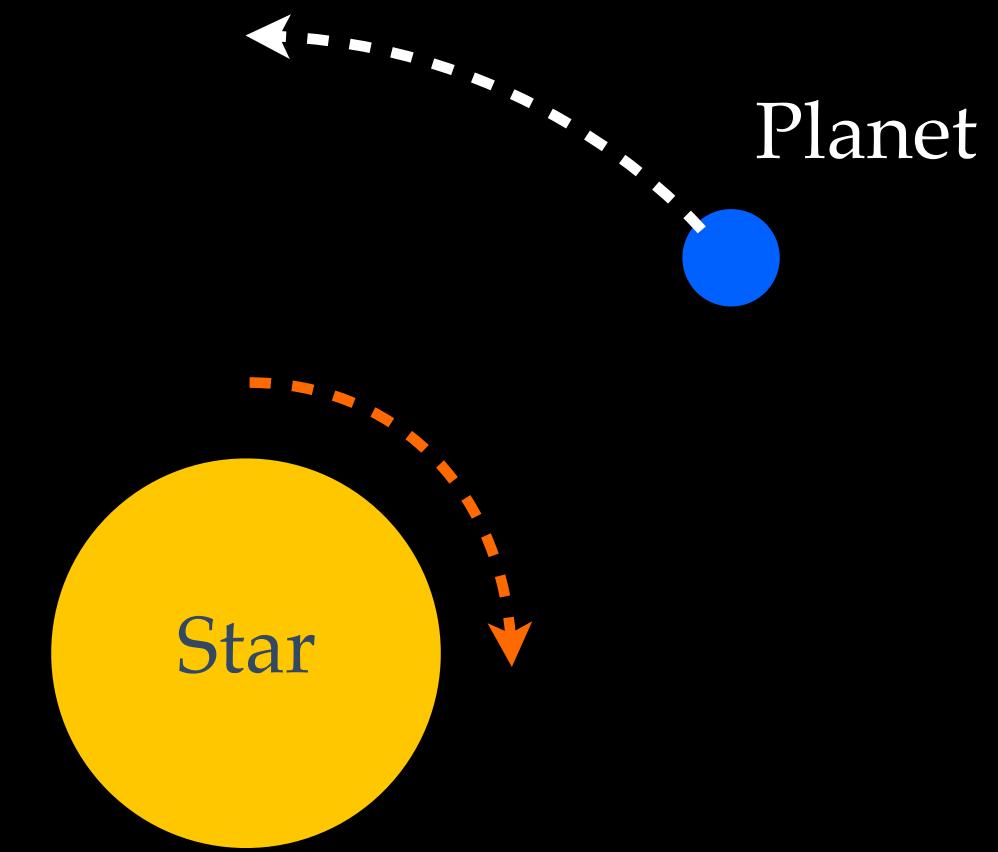


Aside on Retrograde and Prograde

Retrograde and Prograde can refer to MOTION, ROTATION or ORBIT

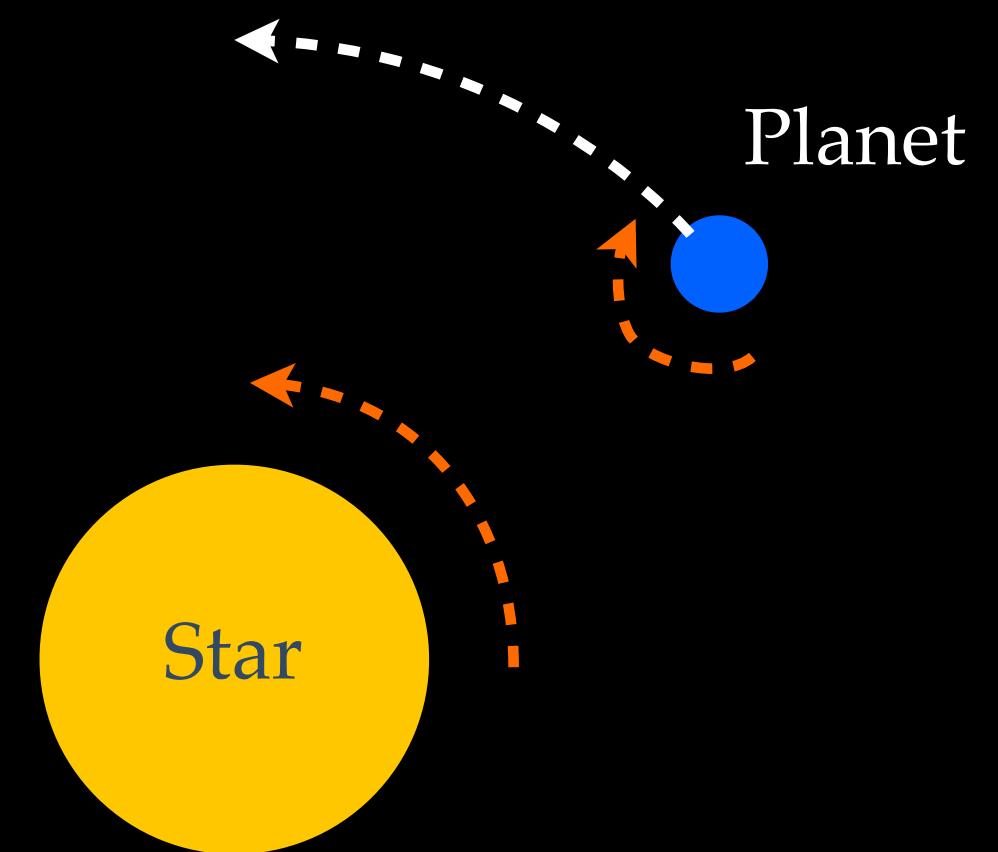
Retrograde orbit

(No planet in our solar system orbits this way)



Retrograde rotation

(Venus and Uranus rotate in retrograde)



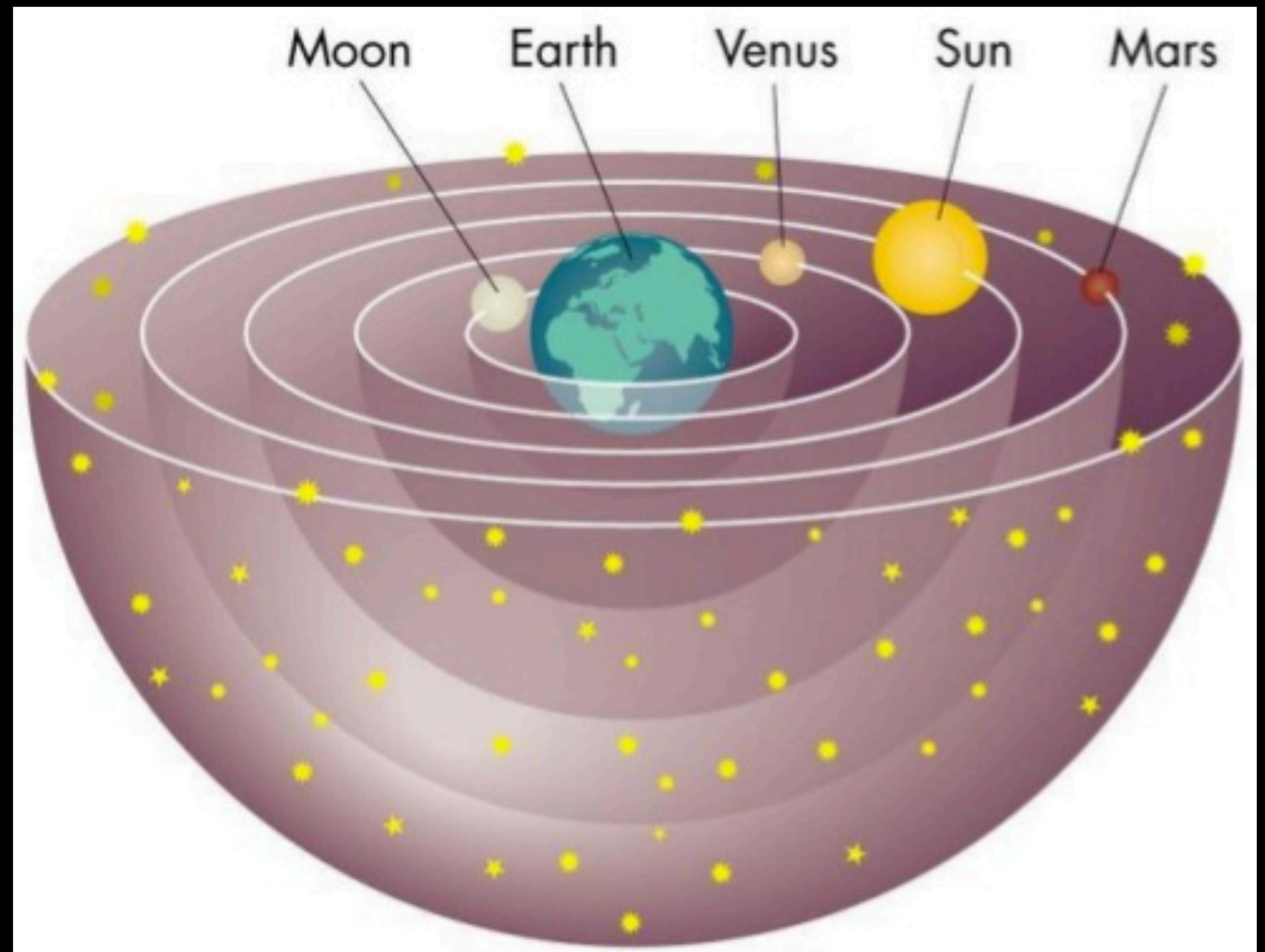
Ancient Greece

Plato (424-347 BCE): Path to truth through pure thought (not experiment!)

Perfection of the Heavens:
all heavenly objects must be perfect circles,
traveling in perfect paths.

No beginning, no end, no change.

Plato's student, Eudoxus, developed
system of 27 spheres to describe motion of
heavens.



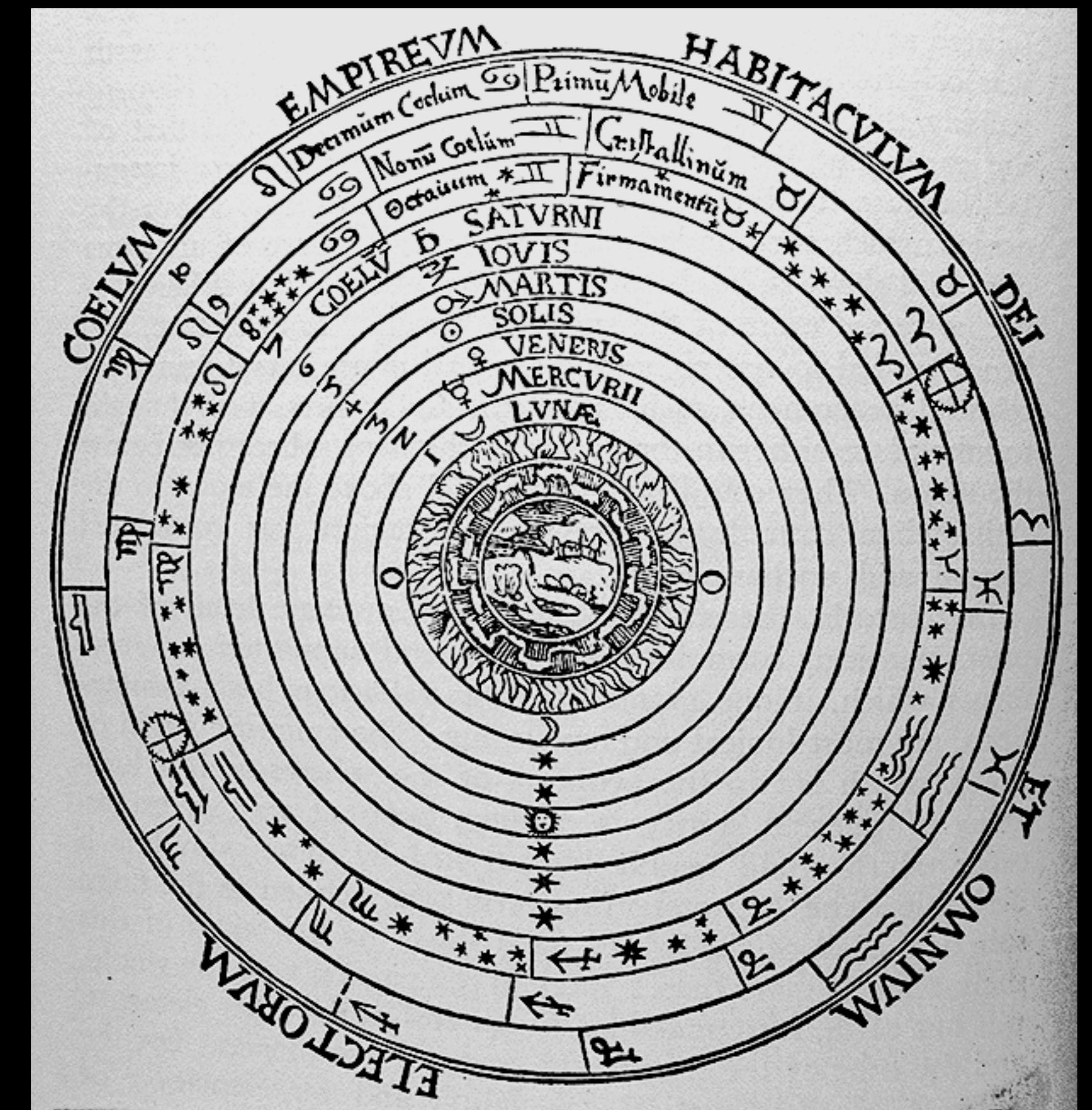
Ancient Greece

Aristotle (384-322 BCE): greatest authority in antiquity, expert on philosophy, politics, ethics, poetry, drama...

All arguments stem from “first principles” - beliefs that are obviously true.

Perfection of heavens was a “first principle”. Natural state of all objects is to be *at rest*, motion of Earth could not be seen (parallax).

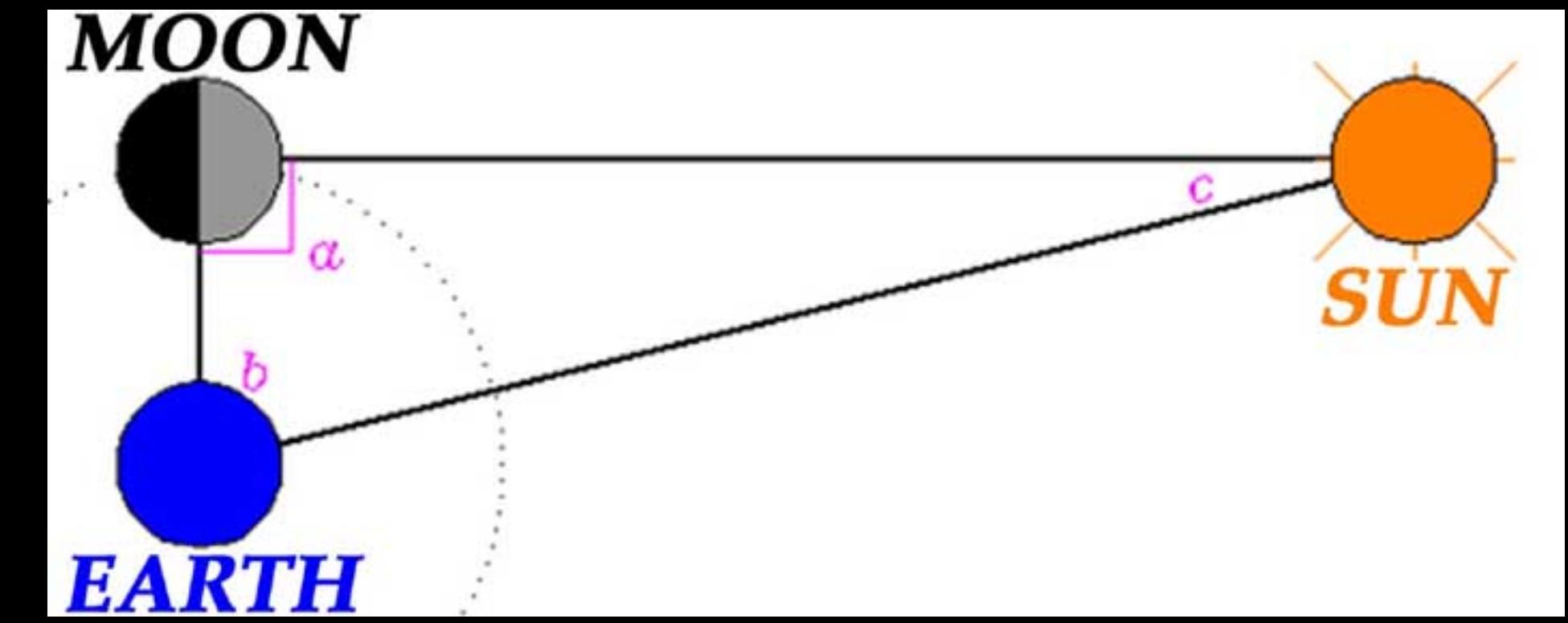
Modified Eudoxus model to 55 spheres.



Ancient Greece

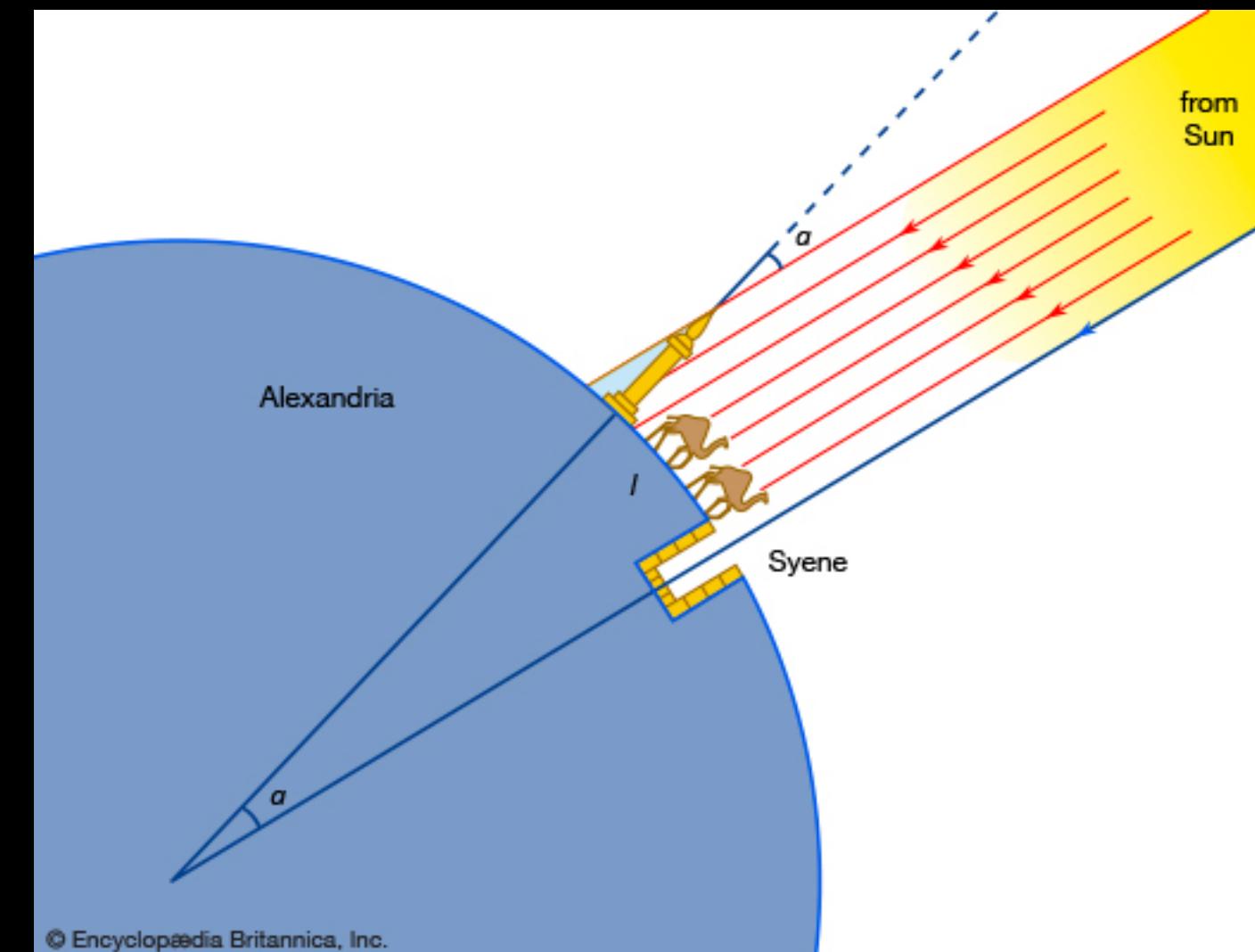
Aristarchus (~310-230 BCE): Proposed idea that Earth rotates around the Sun

Used triangulation to estimate distance to the Sun. (Was way off.)



Ignored due to Aristotle's authority.

Eratosthenes (276-195 BCE): Calculated radius of Earth by measuring angle of shadow in two different cities.
(Accurate to ~10%)



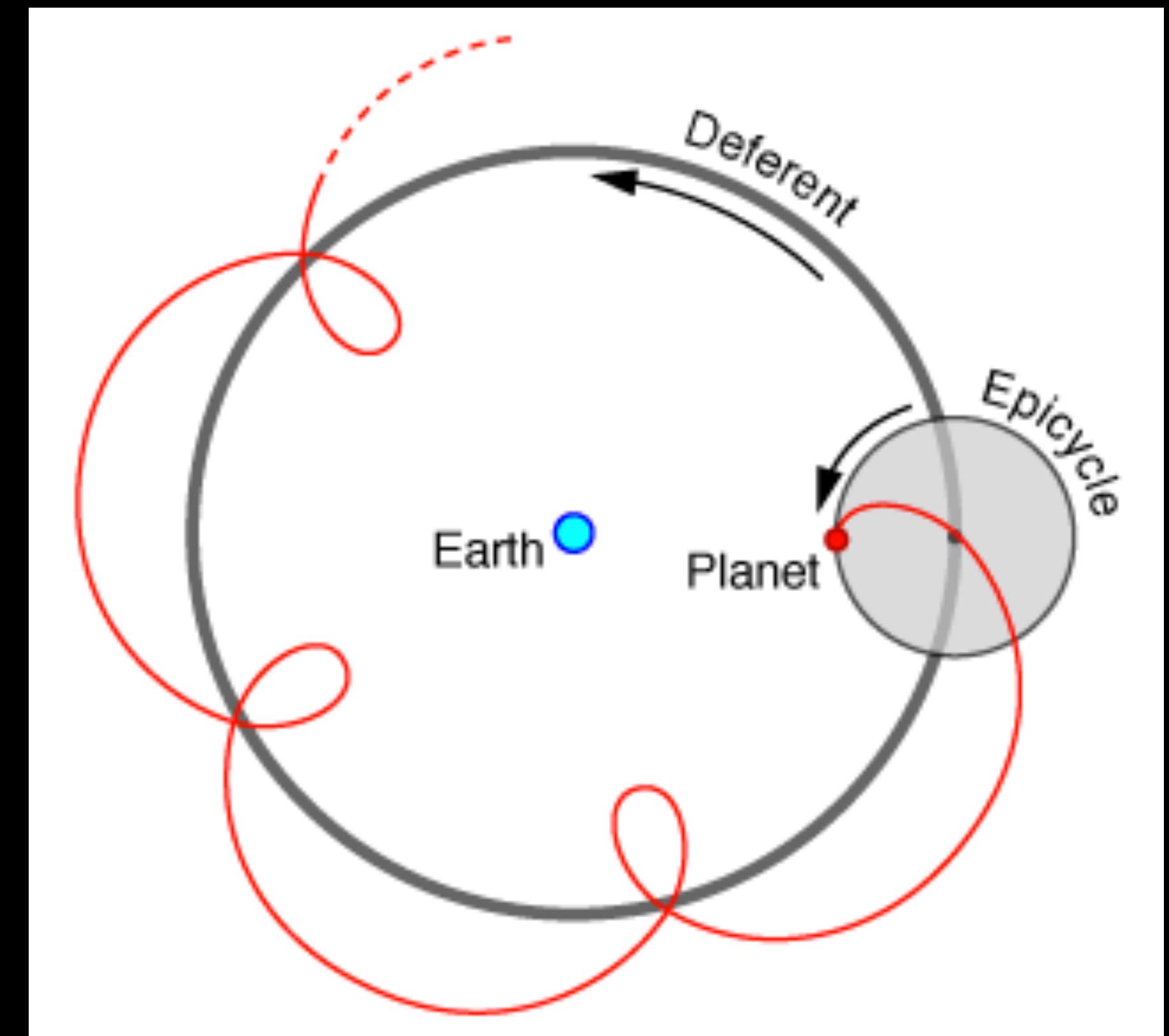
Ancient Greece

Ptolemy (~140 CE): Developed advanced mathematical model of geocentric universe in *Almagest*.

All objects had a primary path: Diferent

Planets moved on epicycles to account for retrograde motion.

Needed 80 spheres to describe motion of the heavens.



<https://www.youtube.com/watch?v=KT3PmGVf6DU>

Ptolemaic Model

Astronomers were scientists - models of heavens predicted future positions of celestial objects.

If your watch is off by 5 second per day, how long does it take for you to miss a job interview by 5 minutes?

Ptolemaic model was successful for centuries.

Alfonsine Tables (13th c.) - last attempt to fix model.

The image shows two pages from a medieval manuscript. The left page contains a table titled 'Tabula equationis' with columns for 'dierum', 'ann', 'noctis', and 'suis'. The right page contains a table titled 'Tabula equationis additione dies longioris et aliquid ante axis in qualibet villa'. Both tables are filled with numerical data in a grid format, likely representing astronomical constants or predictions. The script is in a Gothic hand, and some headings are written in red ink.

Question: Which of these is not incorporated into Ptolemy's geocentric model?

- a. The noon Sun changes position/height in the sky with the seasons
- b. The Earth appears to be flat
- c. Sun, Moon and stars follow smooth paths
- d. The planets periodically travel in retrograde
- e. The Earth feels like it is stationary

Transition to Heliocentric Model

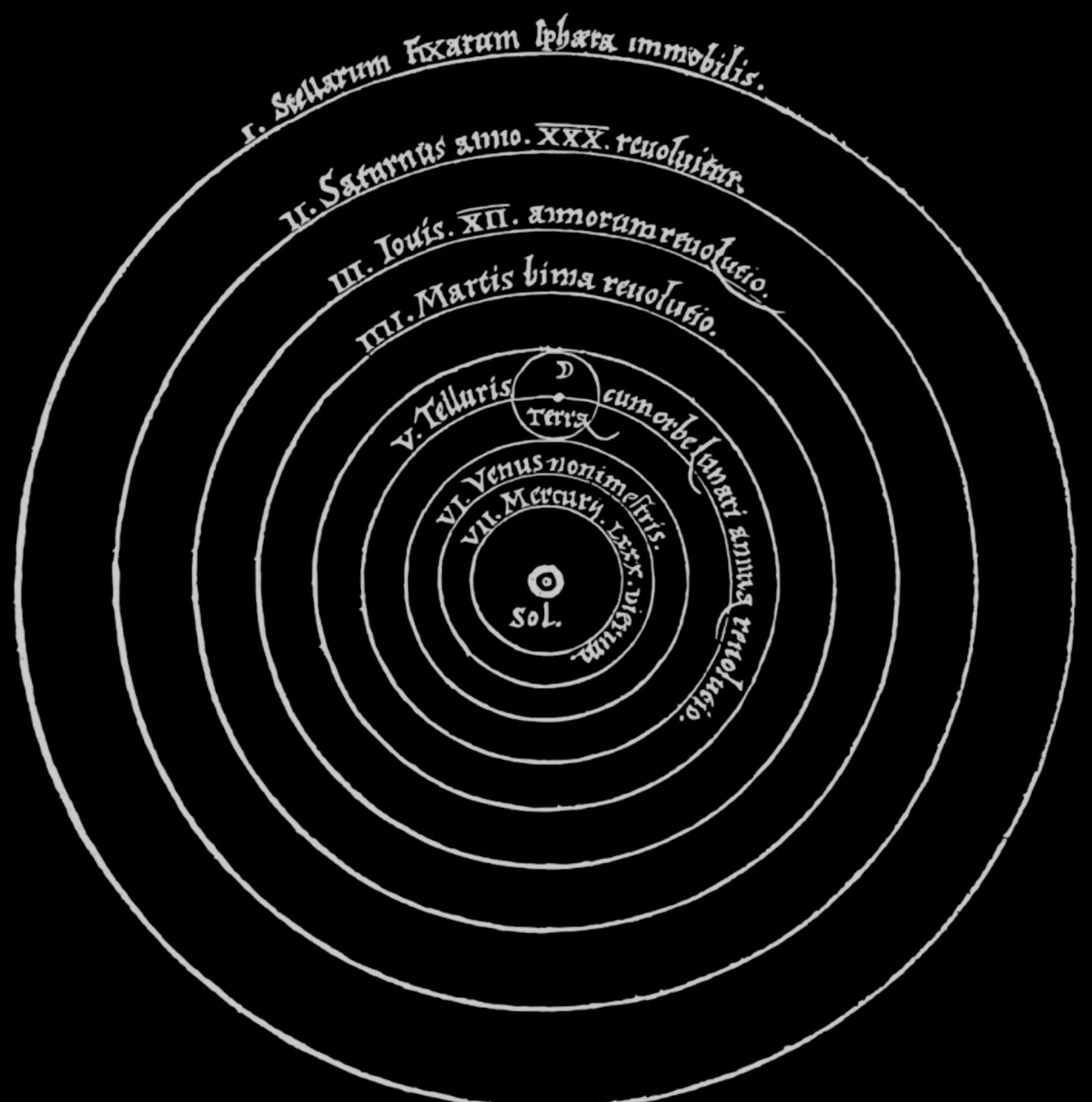
Copernicus

Copernicus (1473-1543) - a Church administrator - rediscovered the writings of Aristarchus.

Developed heliocentric (Sun-centred) model

Could not predict planetary motion

Ptolemaic model was still superior,
but Copernican model did not need
epicycles to explain retrograde!



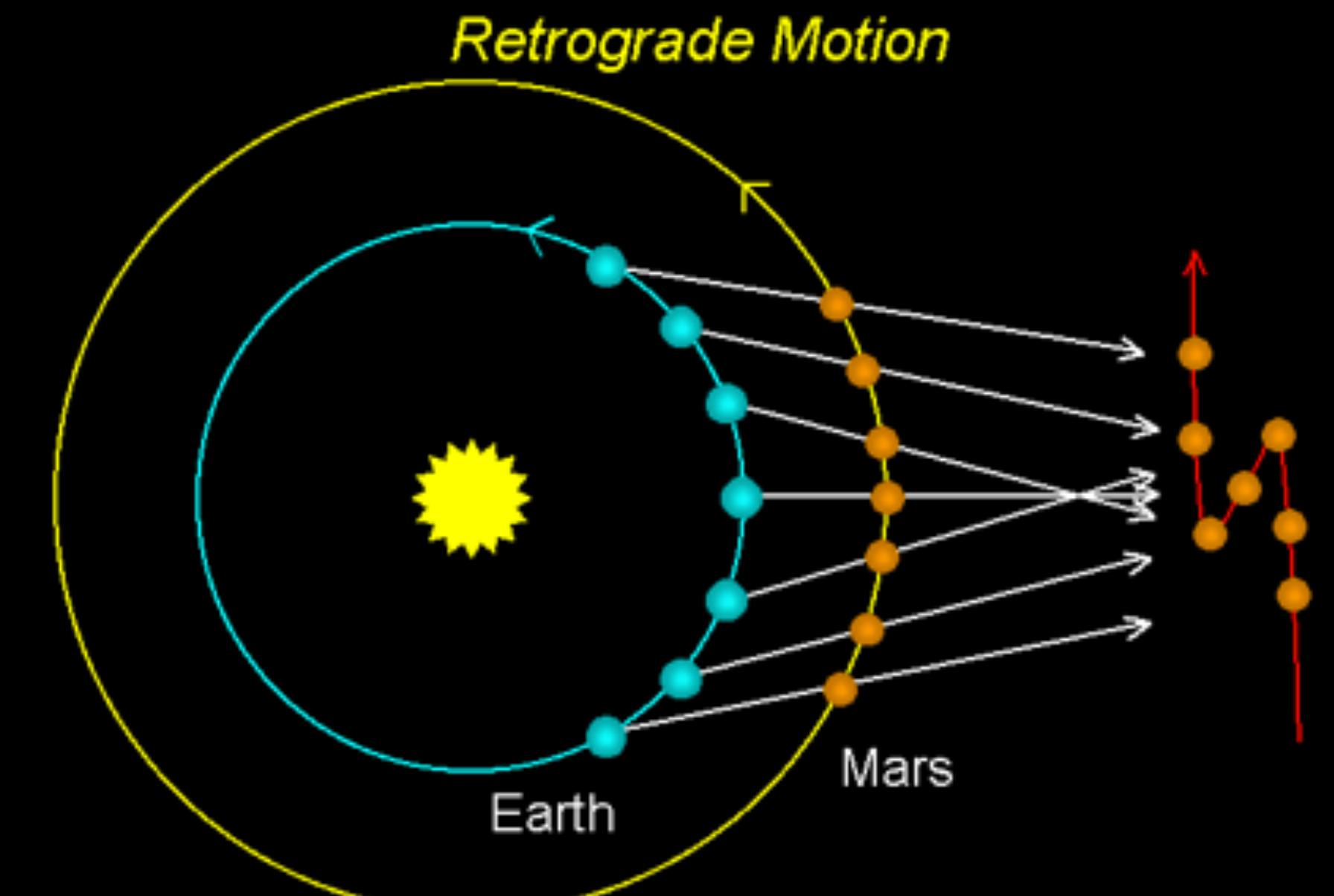
Principles of Copernican Model

1. All orbits are circular, the perfect form.
2. There isn't one common centre of orbit.
3. The Earth is centre of gravity, and moon's orbit. The planets orbit the Sun.
4. The stars are much, much further away.
5. The motion of the stars and Sun is due to rotation of Earth on its own axis.
6. The retrograde motion of the planets is due to Earth's orbit.

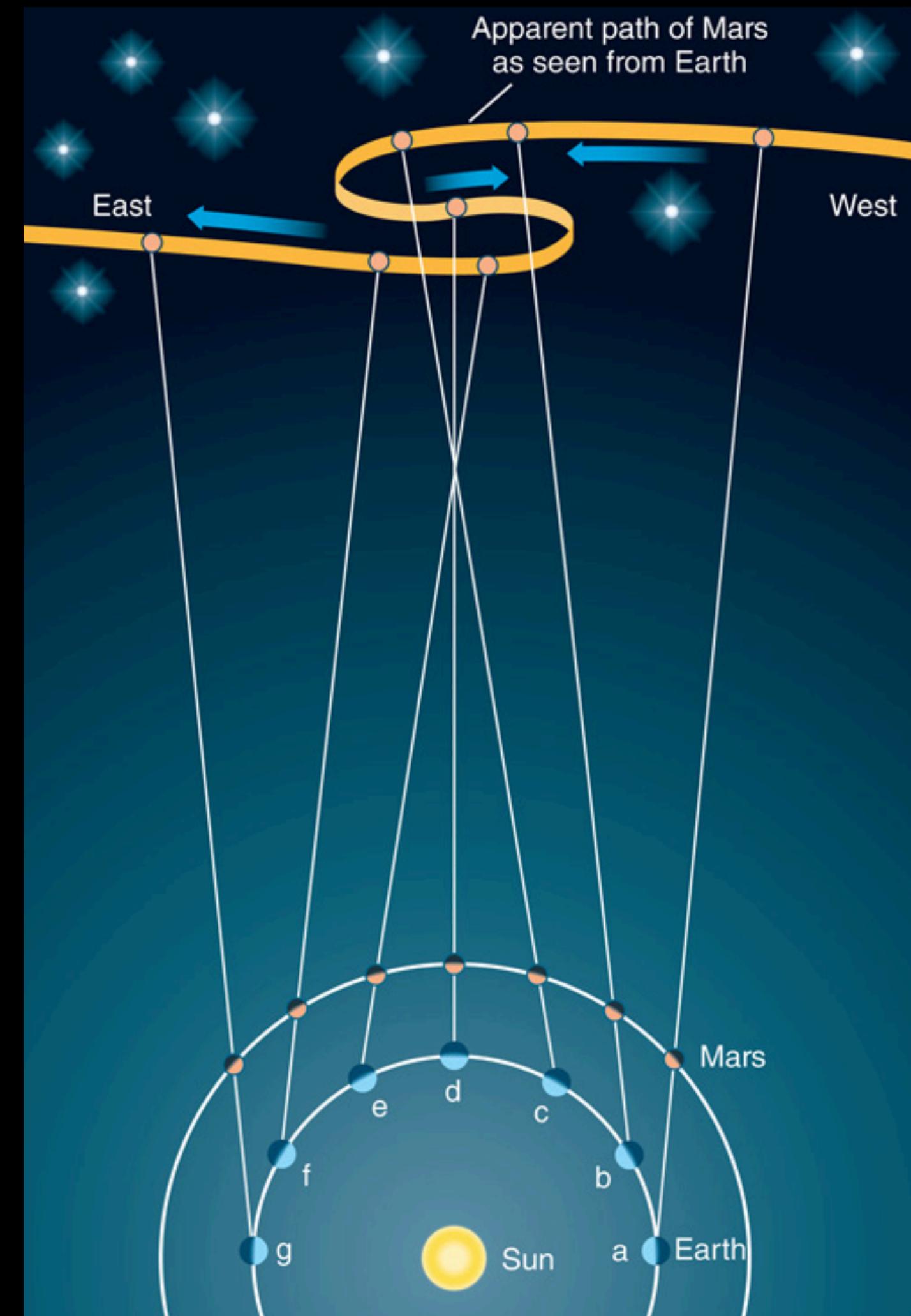
Copernican Retrograde Motion

80 spheres needed for Ptolemaic model, most of which account for retrograde motion

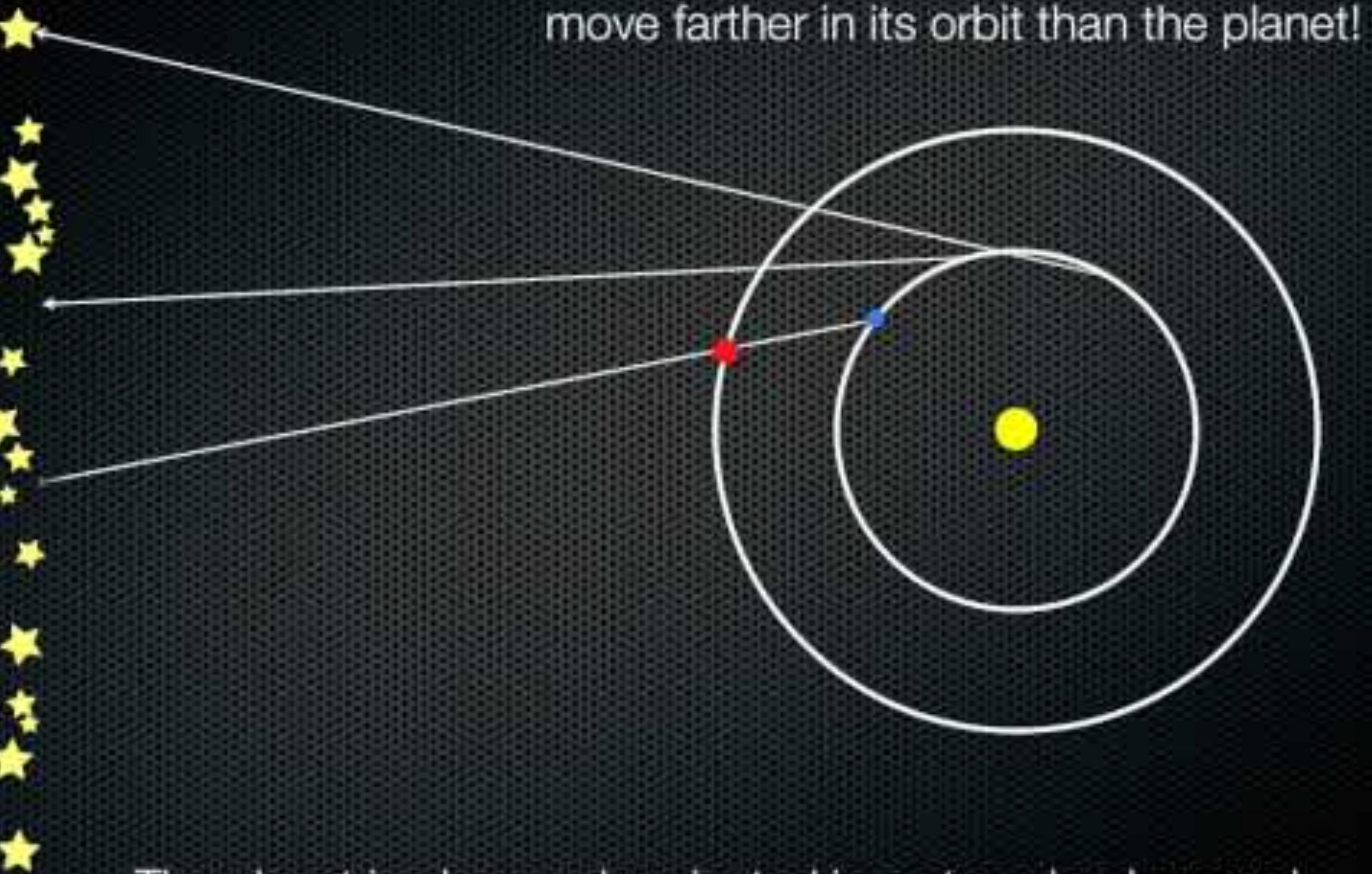
Copernican model could use 9 spheres!



https://www.youtube.com/watch?v=72FrZz_zJFU



In a given time interval, the Earth will move farther in its orbit than the planet!



The planet is observed projected in a starry background

Galileo's Observations

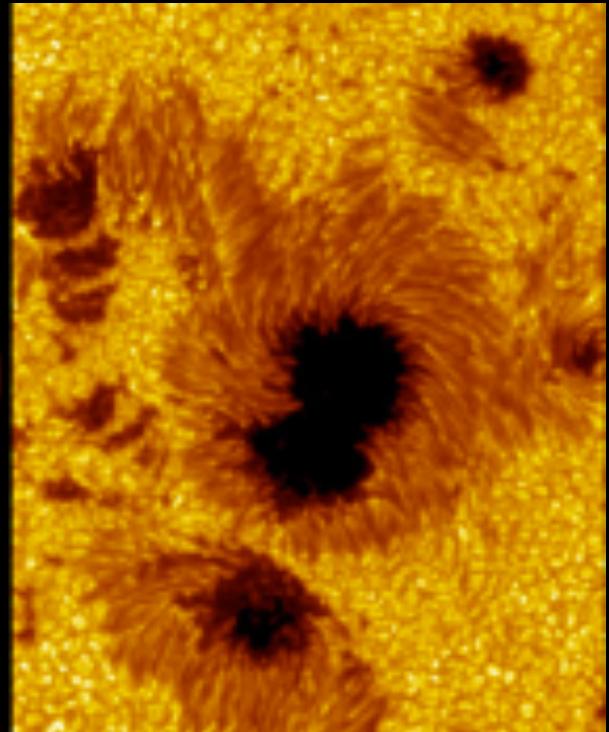
Galileo (1564-1642) - first to use a telescope to increase accuracy of astronomical measurements

Made a series of revolutionary observations:

1. Moon had craters

2. Sun had spots

(Undermined the “perfection” of Aristotle)

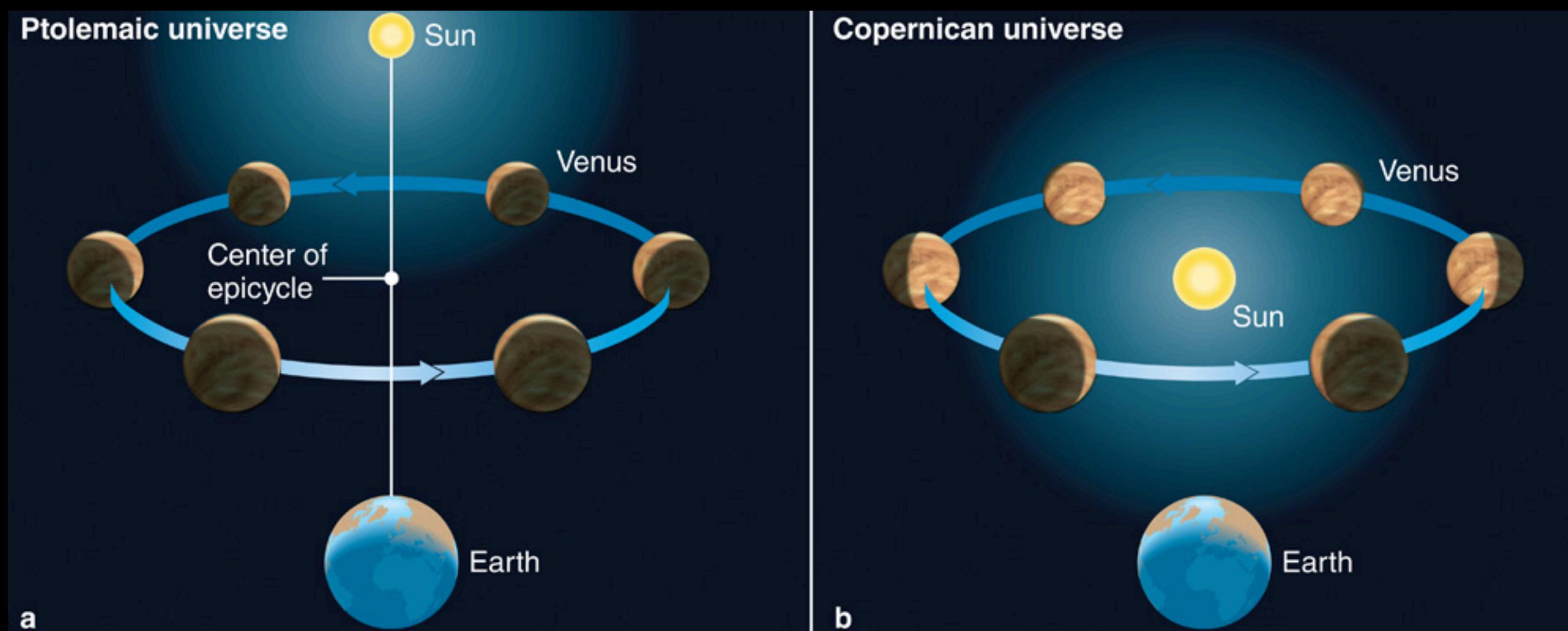


Galileo's Observations

3. There were 4 dots of light that moved back and forth across Jupiter - moons that clearly orbit something OTHER than Earth.

Observationes Iunianae	
2. I. 1610	○ **
3. mense	** ○ *
2. xbn:	○ *** *
3. mense	○ * *
3. Ho. 5.	* ○ *
4. mense	* ○ **
6. mense	** ○ *
8. mense 13.	* * * ○
10. mense	* * * ○ *

4. Venus's phases do not match a geocentric model



Tycho Brahe (1546-1601)

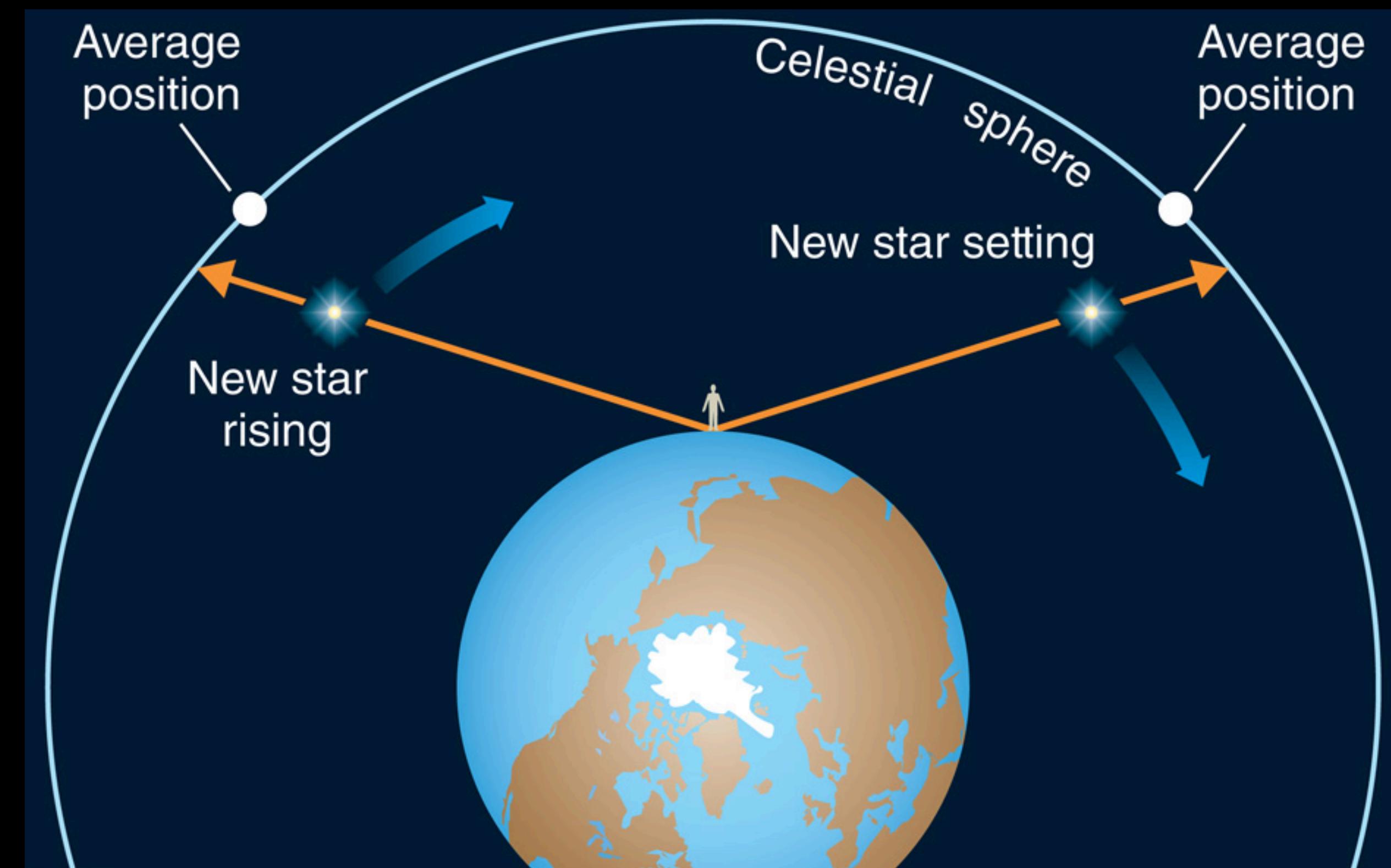
Tried to develop a new geocentric model to replace Ptolemaic model.

His model was geocentric, but all other planets orbited the Sun.

Observed a guest star (supernova) that showed no parallax.

Thus, it had to be part of the celestial sphere.

Thus, the celestial sphere was NOT unchanging, as Aristotle said!



Tycho Brahe's Legacy

Built giant equipment to measure angular positions of celestial objects.

Recorded date - time - positions of planets, stars, comets, and a supernova; accurate to 1' (most accurate to date).

Invited Johannes Kepler to join him in study a year before he died.



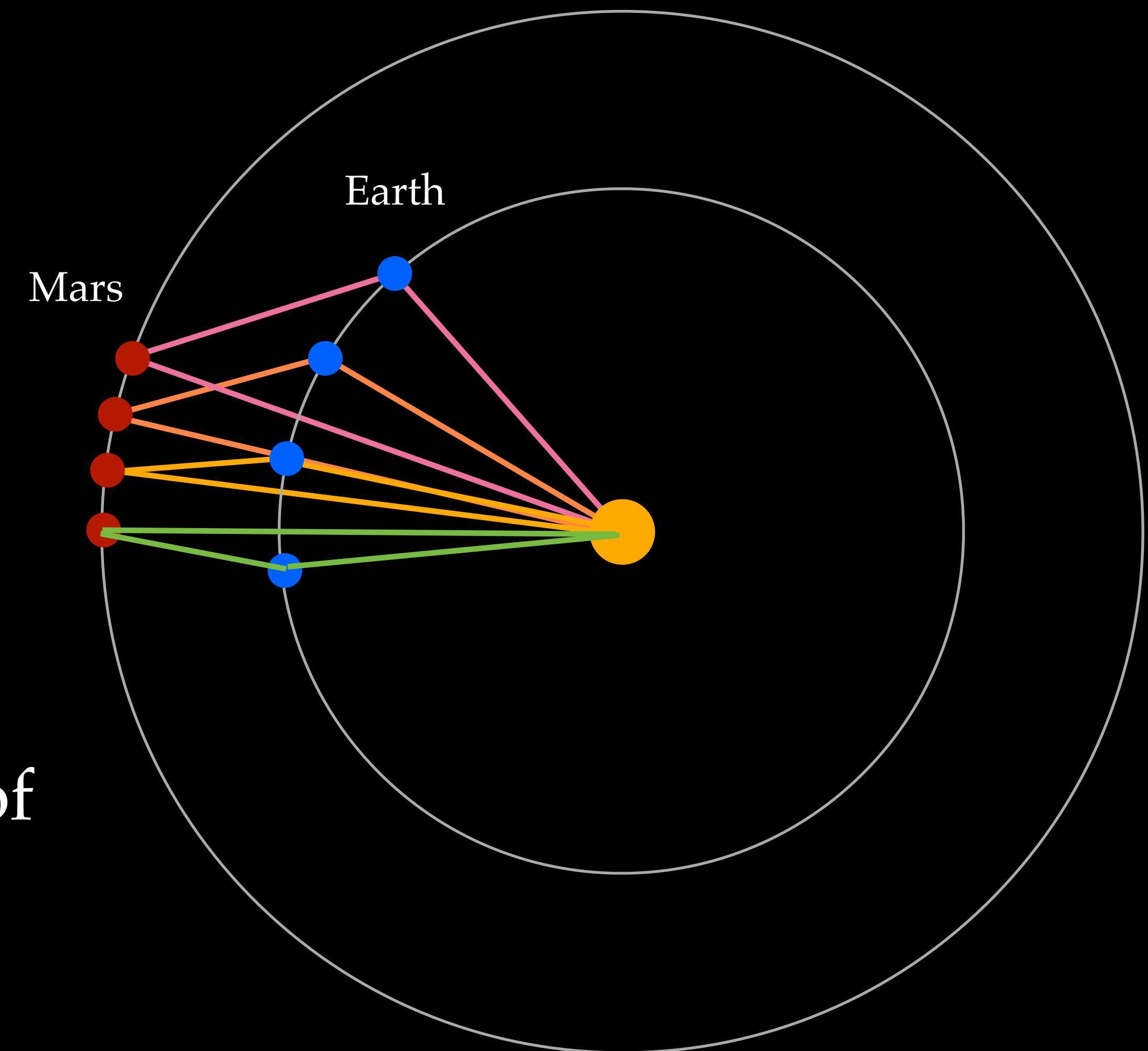
Giant Sextant

Kepler's Works

Kepler (1572-1630) spent 29 years using triangulation techniques to find patterns among Tycho's data.

Kepler's key technique:

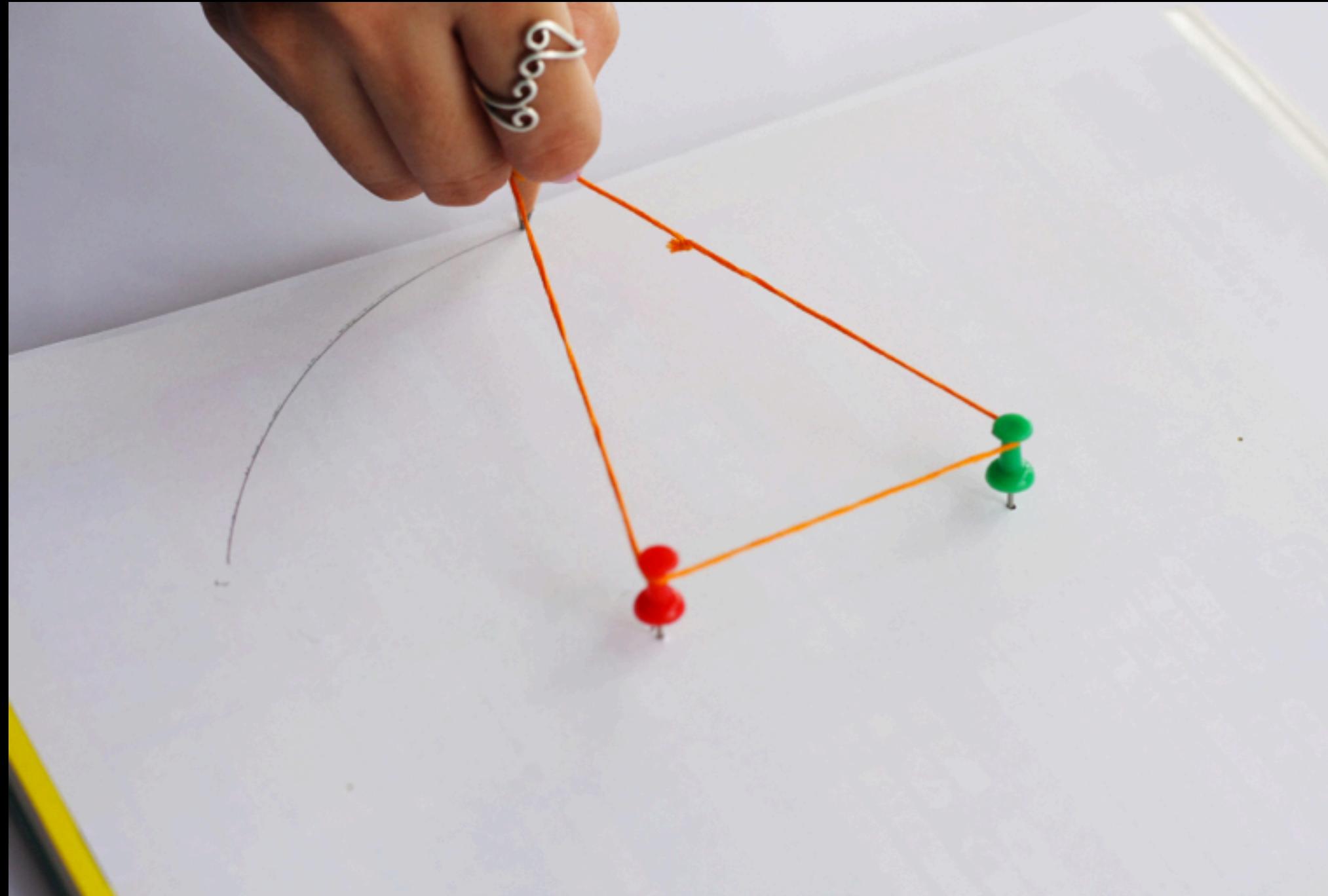
1. All distances referenced as multiples of Earth's orbit.
2. Accounted for the Sun moving about Earth at $360/365^\circ$ per day (Tycho's model).



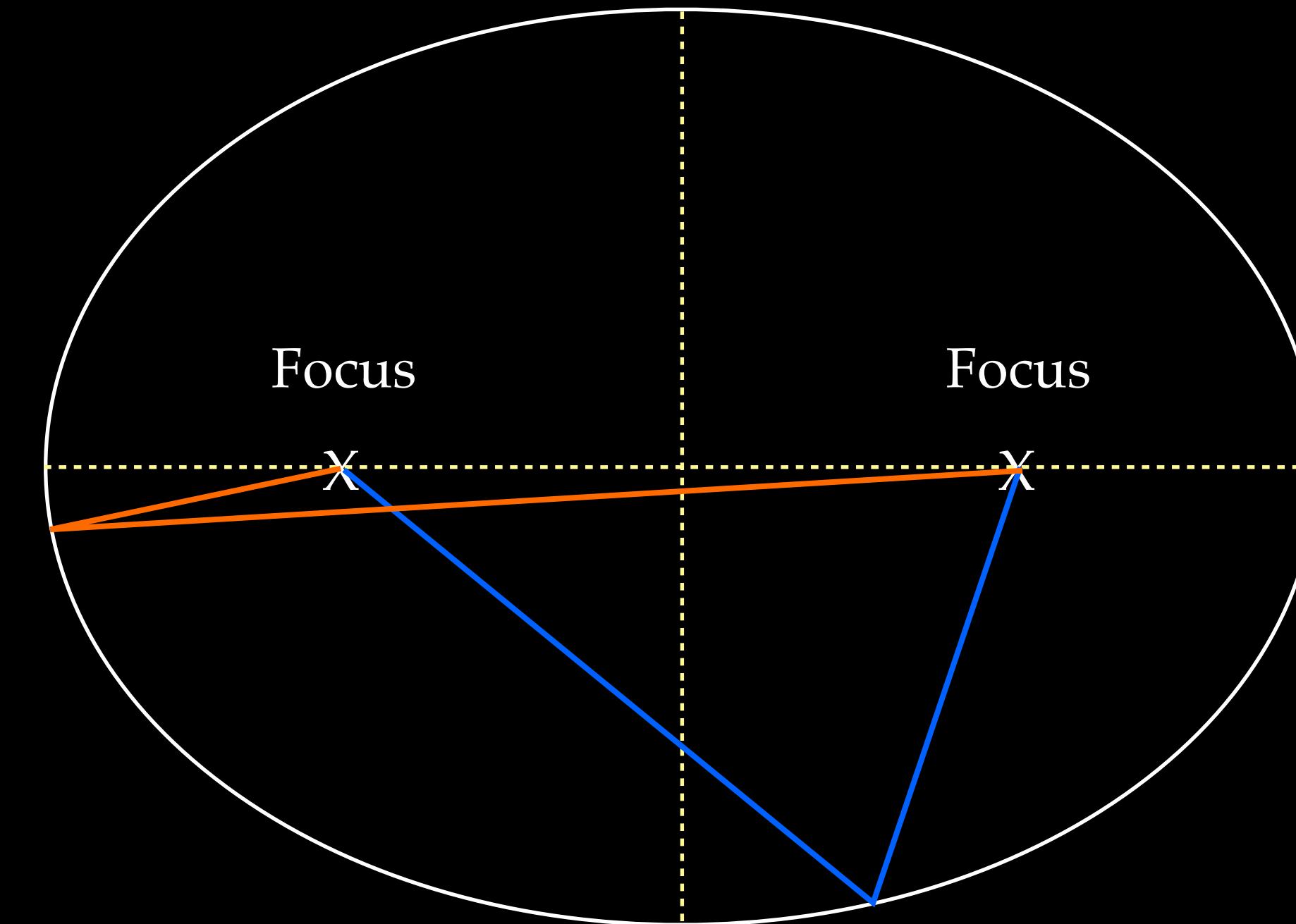
This drawing is heliocentric. The triangles are the same, whether you assume geo- or helio-centric.

Kepler's Laws

1. The orbits of the planets are ellipses with the Sun at one focus.

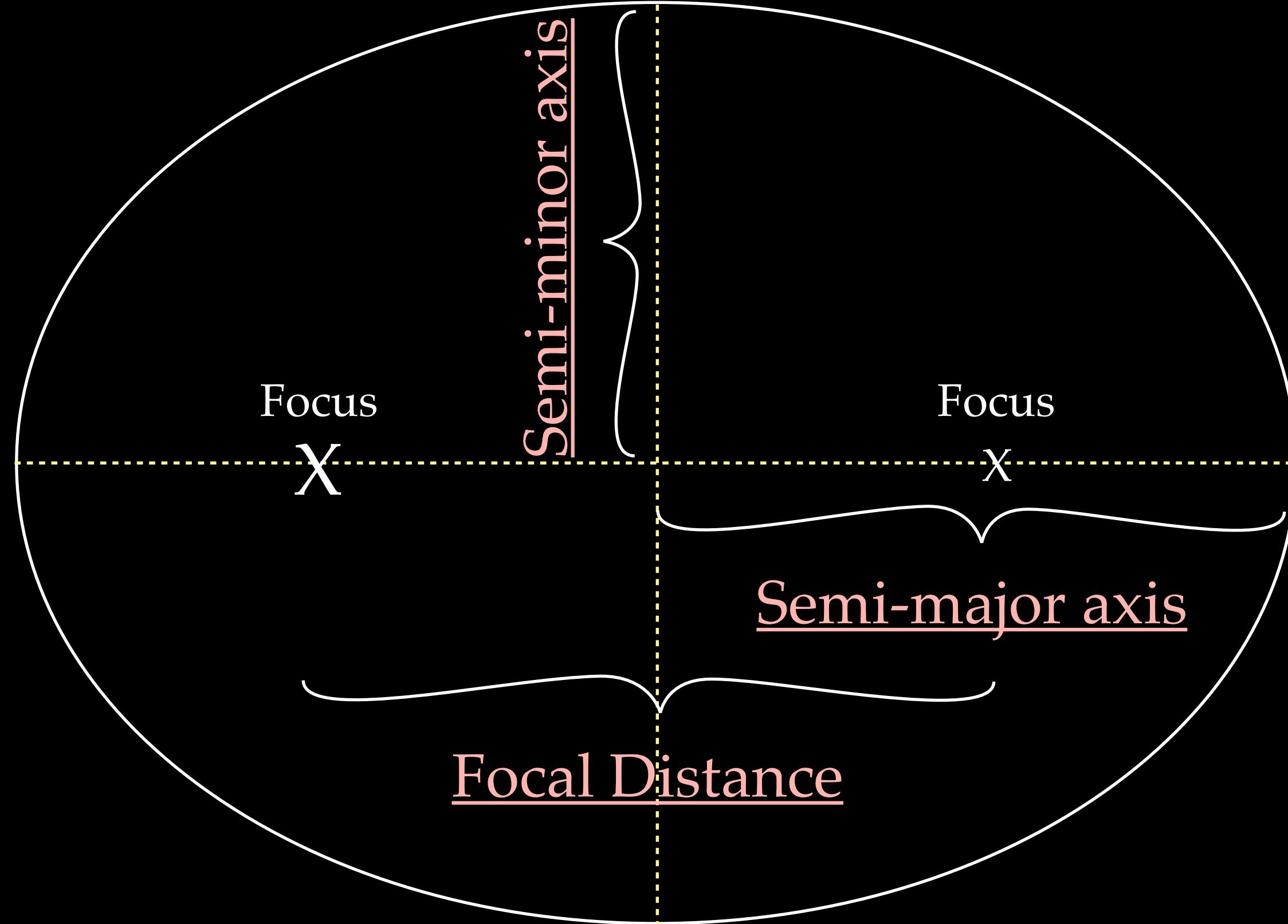


Ellipses are drawn with two focal points
- the sum of the distance from any point
to each focus is a constant.

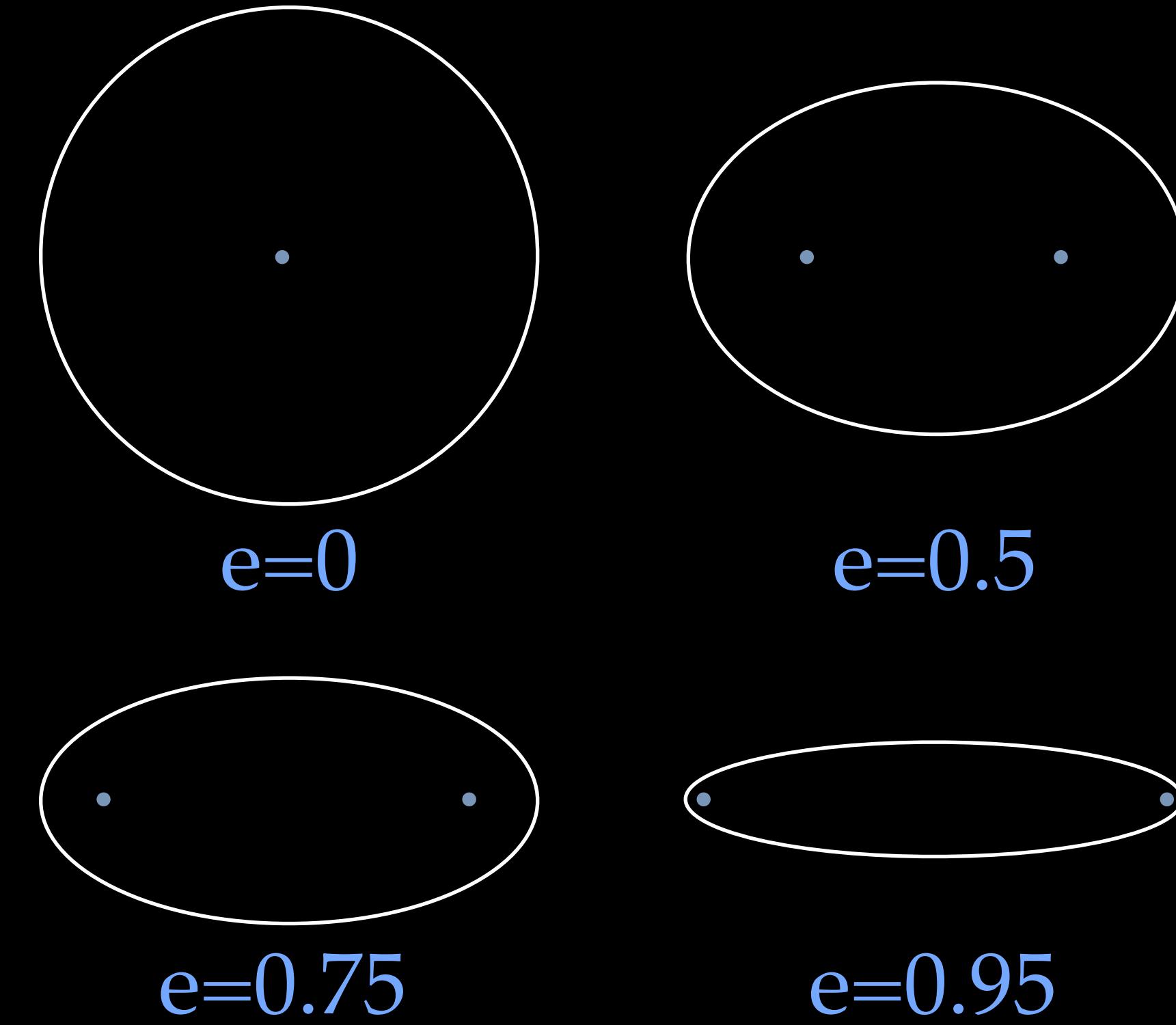


Length of orange &
blue are the same

Ellipses



Three distances are noteworthy on an ellipse: (semi)major axis, (semi)minor axis, and focal distance.



Ellipses are characterized by eccentricity - how elongated they are.

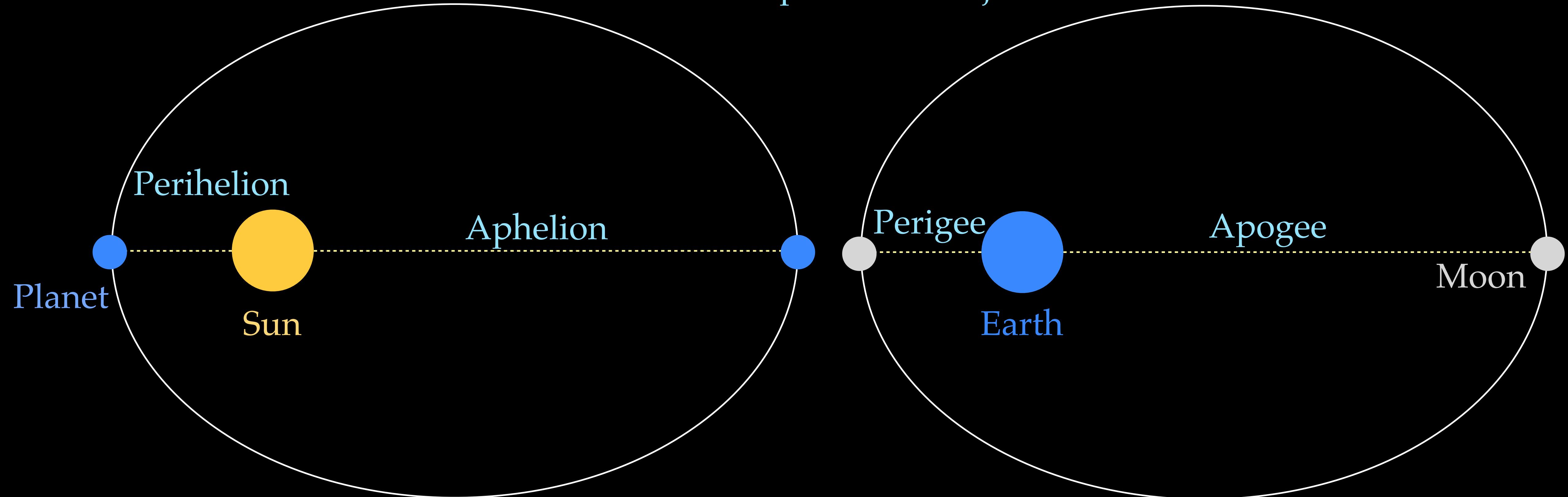
$$e = \frac{\text{Focal Distance}}{\text{Major Axis}}$$

Note: The semi-major axis is also approx. the average orbital distance.

Orbits

Aphelion - Perihelion = Focal Distance

Perihelion + Aphelion = Major Axis



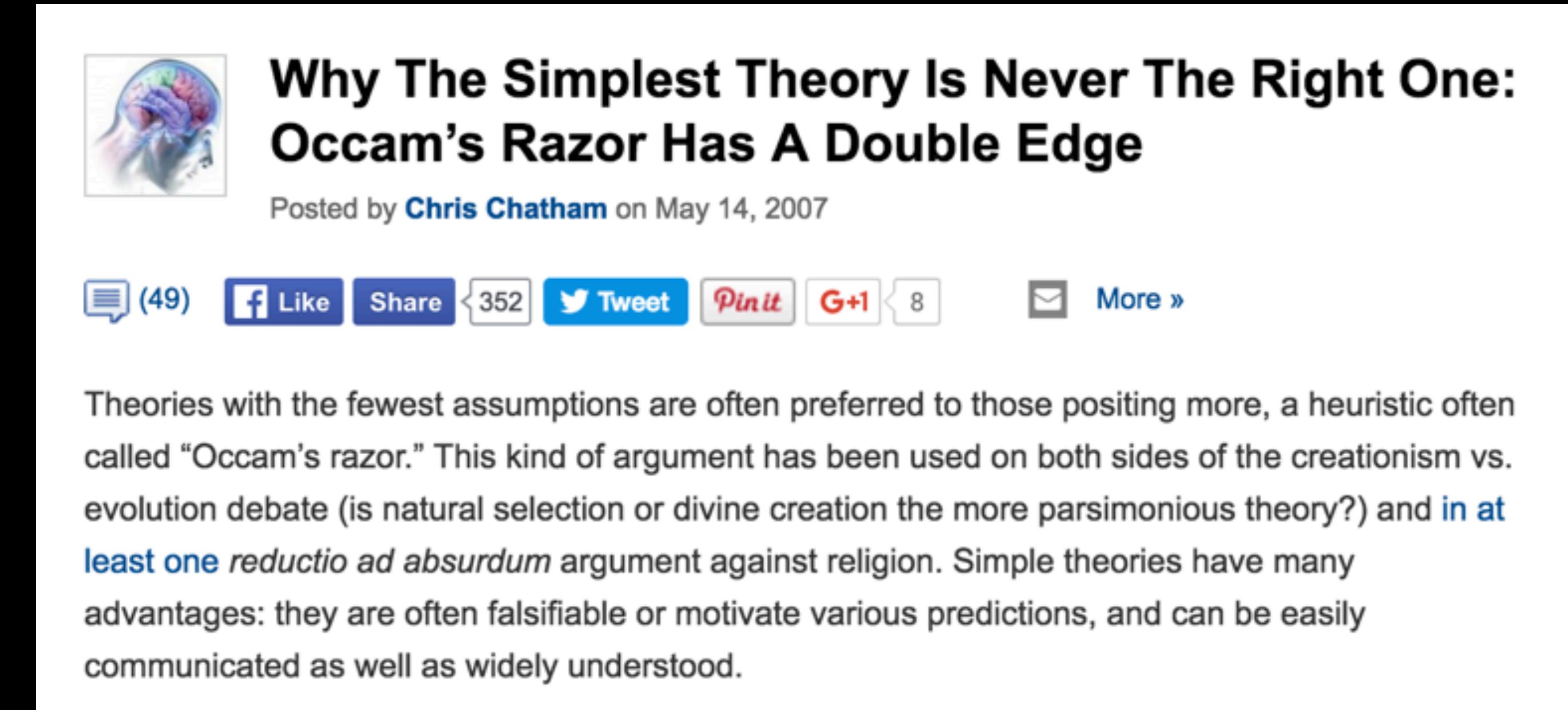
For the Sun, the distance of closest approach is the Perihelion, distance of furthest approach is Aphelion.
For the Earth/Moon system, it is Perigee and Apogee.

The general terms for ANY orbit are:
Periapsis and Apoapsis
(apsis = extreme point of an orbit)

Aesthetic Bias

Plato/Aristotle asserted the aesthetic bias of the “perfect form” (circle) that lasted for thousands of years. Reality is not subject to science. Science is subject to reality.

Simplicity and Elegance! Aesthetic biases typically creep in as a result of desire for simplicity and elegance
- two aesthetic principles.



**Why The Simplest Theory Is Never The Right One:
Occam's Razor Has A Double Edge**

Posted by [Chris Chatham](#) on May 14, 2007

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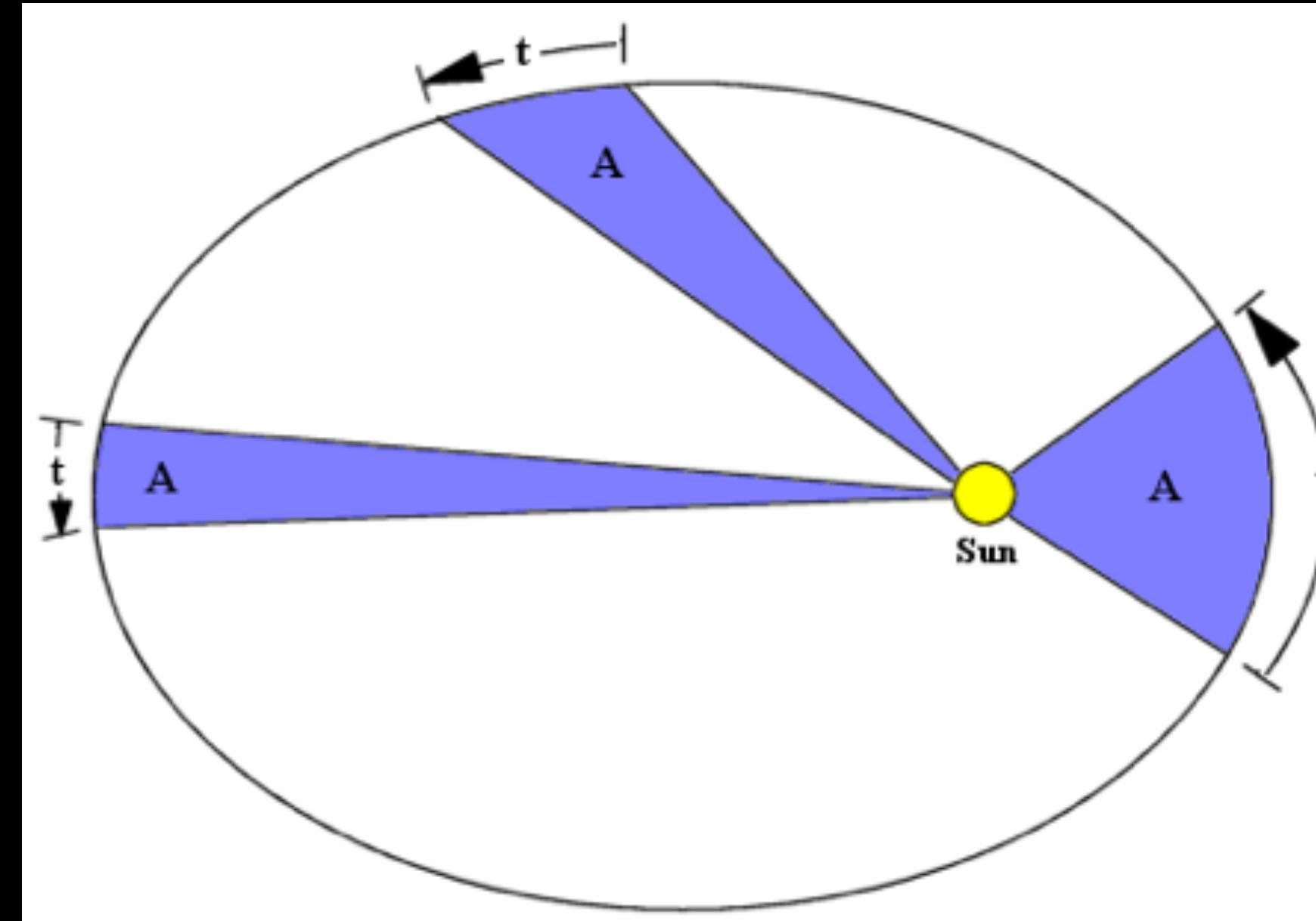
Theories with the fewest assumptions are often preferred to those positing more, a heuristic often called “Occam’s razor.” This kind of argument has been used on both sides of the creationism vs. evolution debate (is natural selection or divine creation the more parsimonious theory?) and [in at least one reductio ad absurdum argument against religion](#). Simple theories have many advantages: they are often falsifiable or motivate various predictions, and can be easily communicated as well as widely understood.

The changing heavens (supernova) observed by Tycho and Kepler's realization of the imperfect orbits was finally enough to reject geocentricity!

Kepler's Laws

2. As a planet orbits the Sun, it sweeps out equal area wedges in equal amounts of time.

Planet moving
slower here



Planet moving
faster here

Each blue shaded region has the exact same area. The time taken to transit the shown distances is the same for all three regions. Larger distance from the Sun results in slower orbital speeds.

Kepler's Laws

3. The SQUARE of a planet's orbital period (T) is equal to the CUBE of its semimajor axis (a).

Period (T) is time taken to complete 1 full orbit.

$$T^2 = a^3$$

Kepler's Laws were developed in reference to Earth's orbit, so this only works when measuring in Earth years and astronomical units.

Using years and AU, this tells us $1^2 = 1^3$ for Earth.

Kepler's Laws

Law 1 and 2 were determined using only Mars data. Needed 10 years to include other planets and see the pattern that gave Law 3.

Planet	Distance (AU)	Period (y)	Eccentricity	T^2/a^3
Mercury	0.387	0.241	0.2056	1.0022
Venus	0.723	0.615	0.0068	1.001
Earth	1	1	0.0167	1
Mars	1.524	1.881	0.0934	0.9996
Jupiter	5.203	11.862	0.0484	0.999
Saturn	9.537	29.457	0.0542	0.998
(Uranus)	19.191	84.011	0.0472	0.993
(Neptune)	30.069	164.79	0.0086	0.986

Semi-minor axis <0.1% smaller than semi-major axis!

Question: An asteroid is observed to orbit the Sun every 8 years - what is its semi-major axis?

a. 8 a.u.

b. 4 a.u.

c. 10 a.u.

d. 64 a.u.

e. 2 a.u.

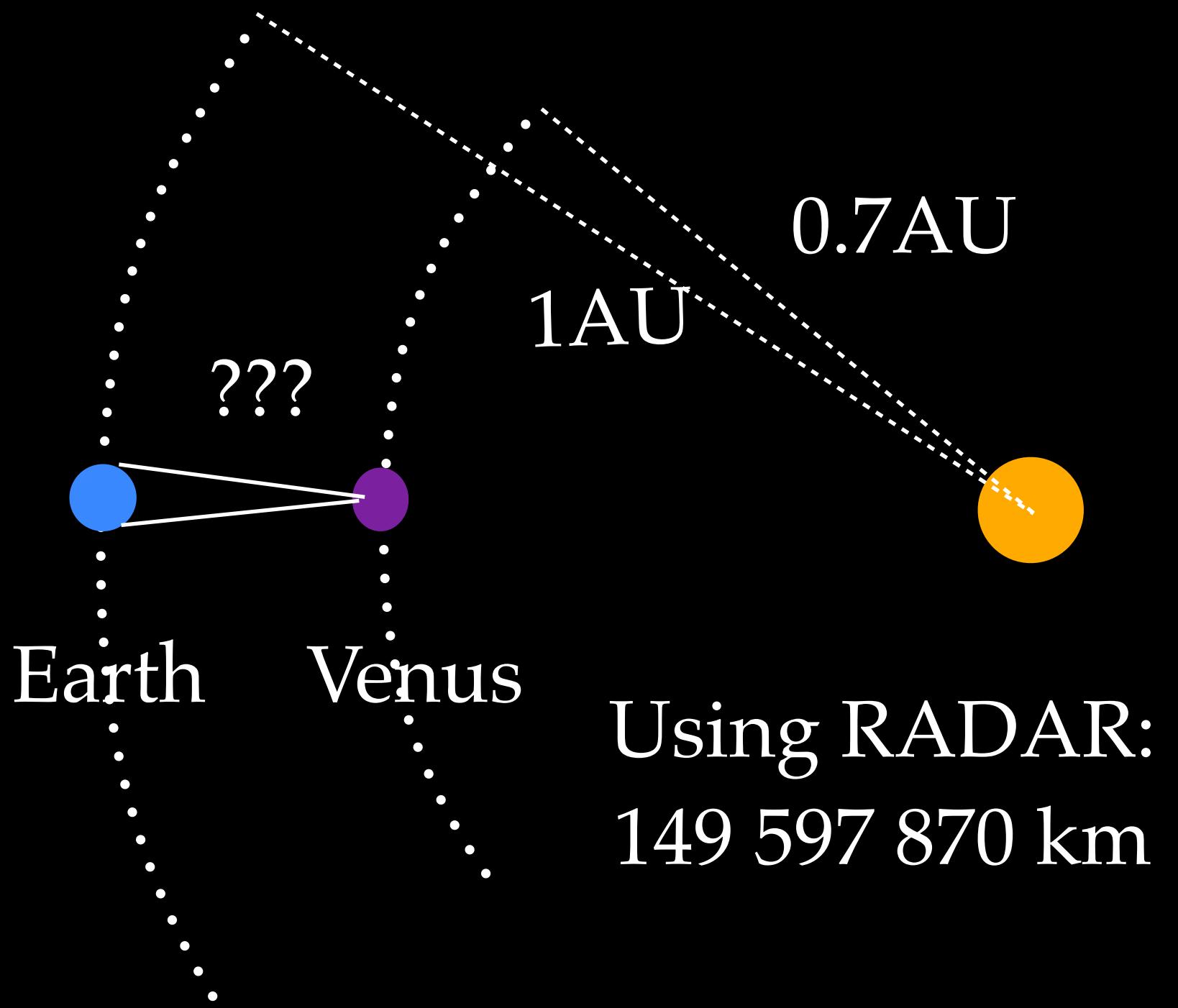
Determining the AU

With Kepler's Laws, only one distance needs to be determined in Earth-based units (km, miles, etc) to determine ALL orbital distances in that unit.

Various attempts had been made since the time of Aristarchus.

Shortly after Kepler's death, a parallax measurement was performed as Venus transited the Sun. This was off by 50%.

It wasn't until 1896 that a decent measurement was made.



Descriptive Laws

Kepler's Laws work for the planets in our solar system - they need to be modified to work for our Moon, Jupiter's moons.



Copernicus, Kepler and Galileo *described* what they saw, but did not explain why it was like that.

Prescriptive Laws

Why do the planets orbit with those periods?

Why does the Moon orbit as it does?

Recall that planetary orbits can be >150 y long! If we found a planet orbiting very distantly from a star, how can we determine the orbital period without having to wait that long?

These questions can be answered with prescriptive laws that explain *why* and *how* all orbits work, without reference to our solar system.

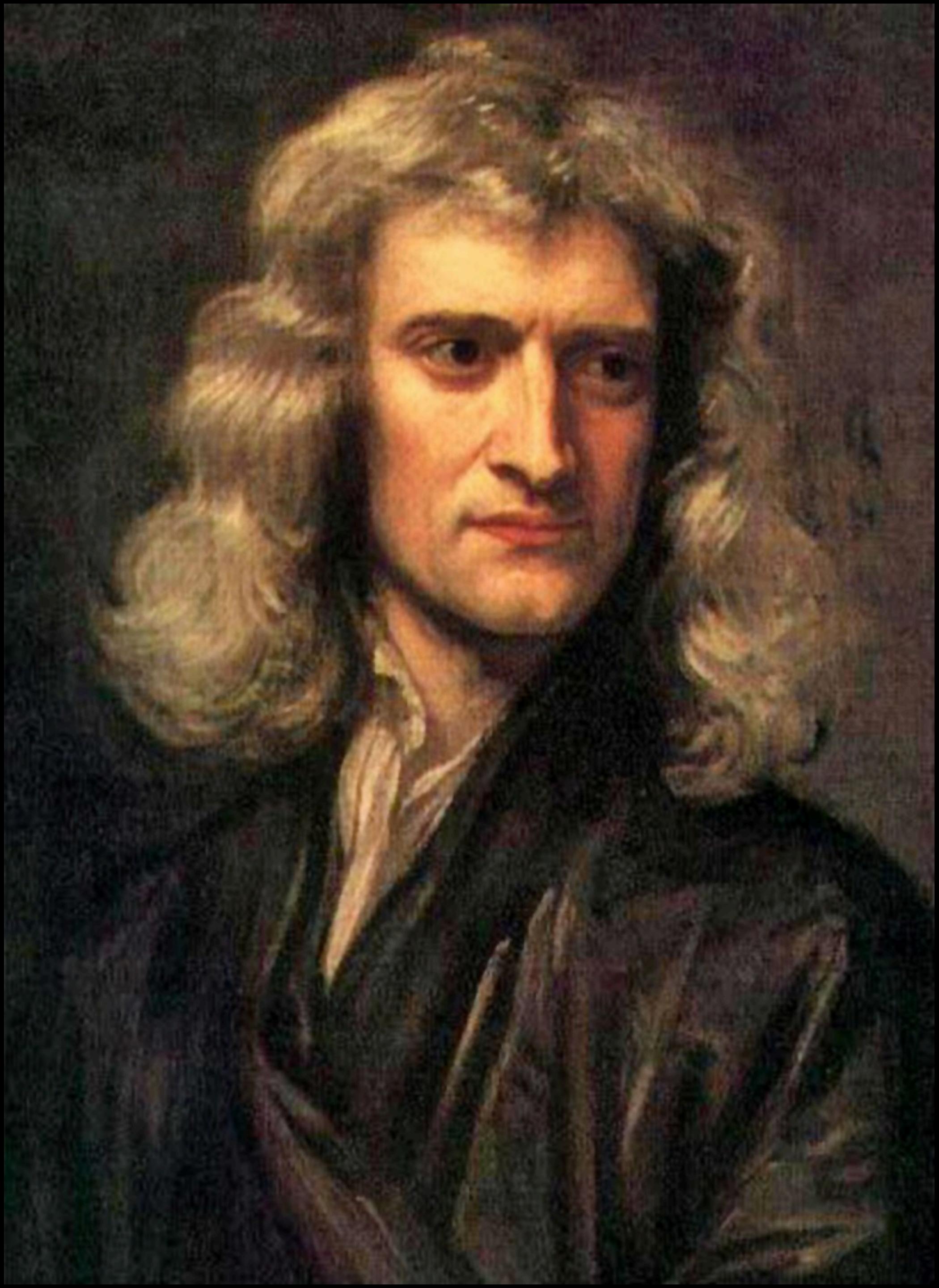
Newton's Laws

Isaac Newton (1643-1727)

Published *Philosophiae Naturalis Principia Mathematica*

Natural science was secondary - searched for philosopher's stone (alchemy) and studied biblical interpretation (apocalypse).

“Newton was not the first of the age of reason, he was the last of the magicians.”
- John Maynard Keynes



Newton's Laws

1. Everything in motion, or at rest, continues on in that state until acted upon by an external force. (Now understood as “inertia”.)



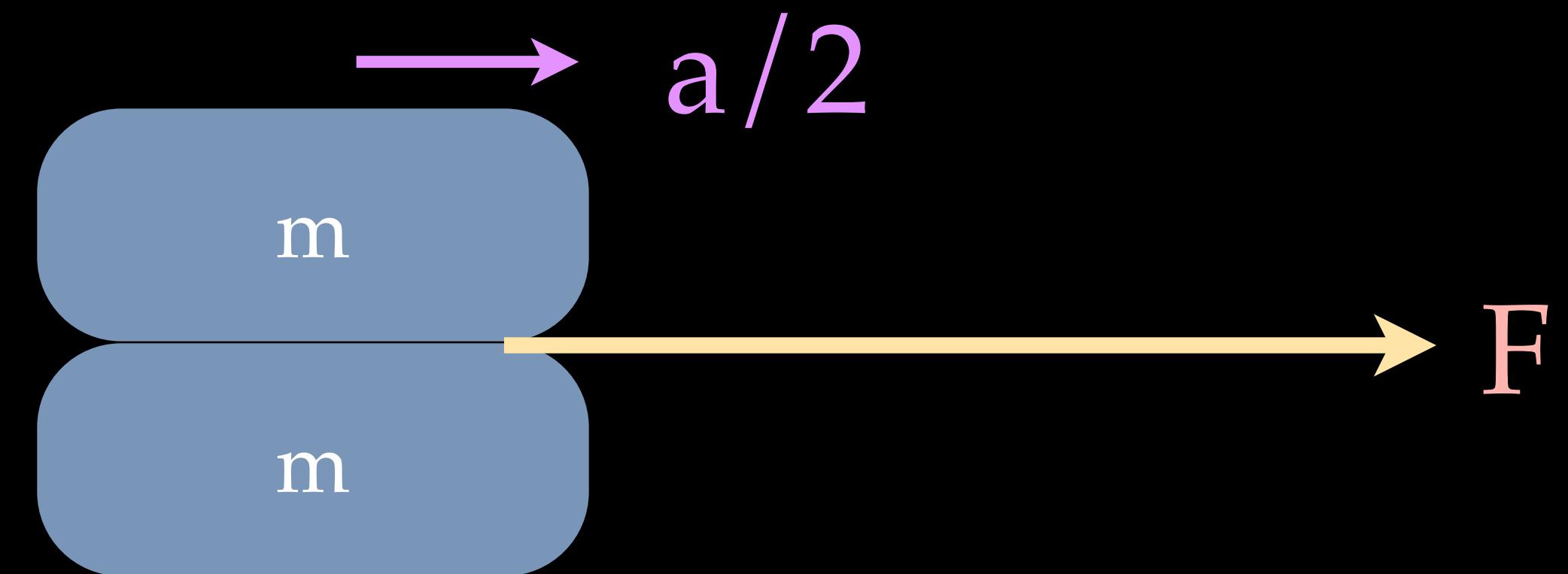
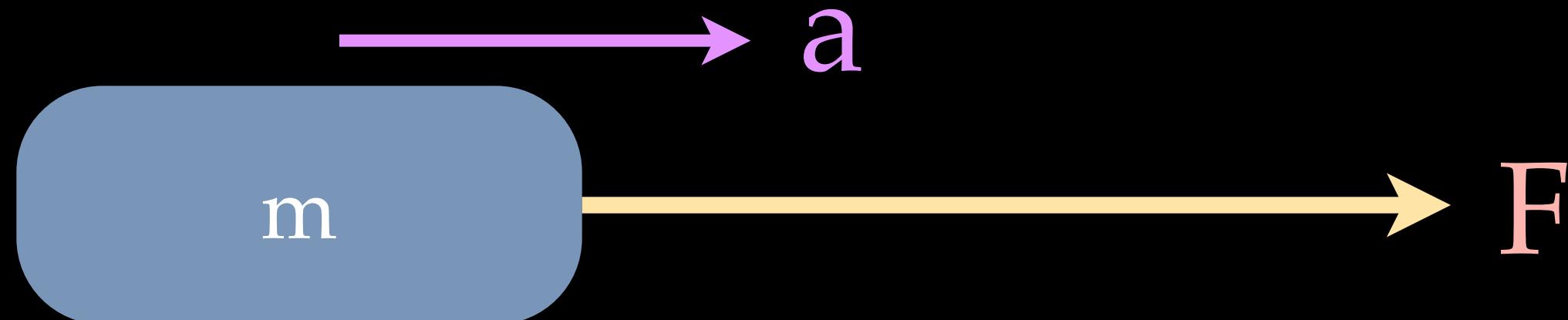
(Recall Aristotle: “Natural state of things is at rest.”)

Newton's Laws

2. When an object is affected by an unbalanced force, there results an acceleration inversely proportional to the mass of the object.

$$\sum F = ma$$

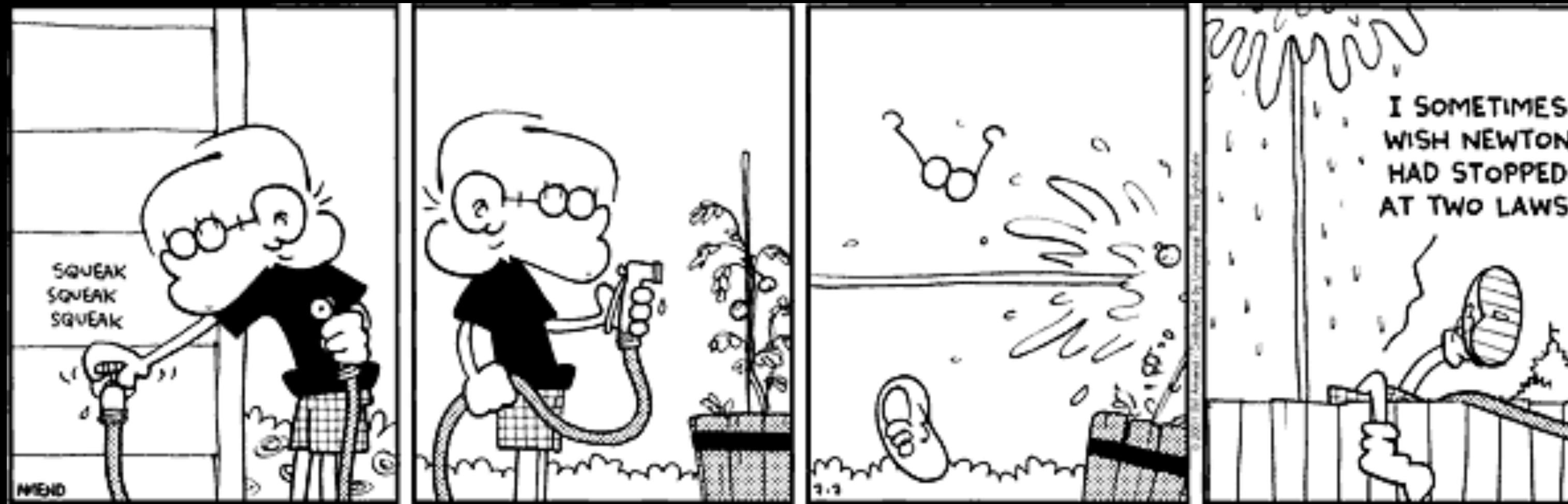
Force is measured in Pounds (lb) or Newtons (N).
This is different from mass, which is measured in kg.



N.B.: Mass does NOT increase force! Mass is the resistance to change in motion!

Newton's Laws

3. For every action (i.e. Force), there is an equal and opposite *REaction*.



Forces do not occur in isolation!

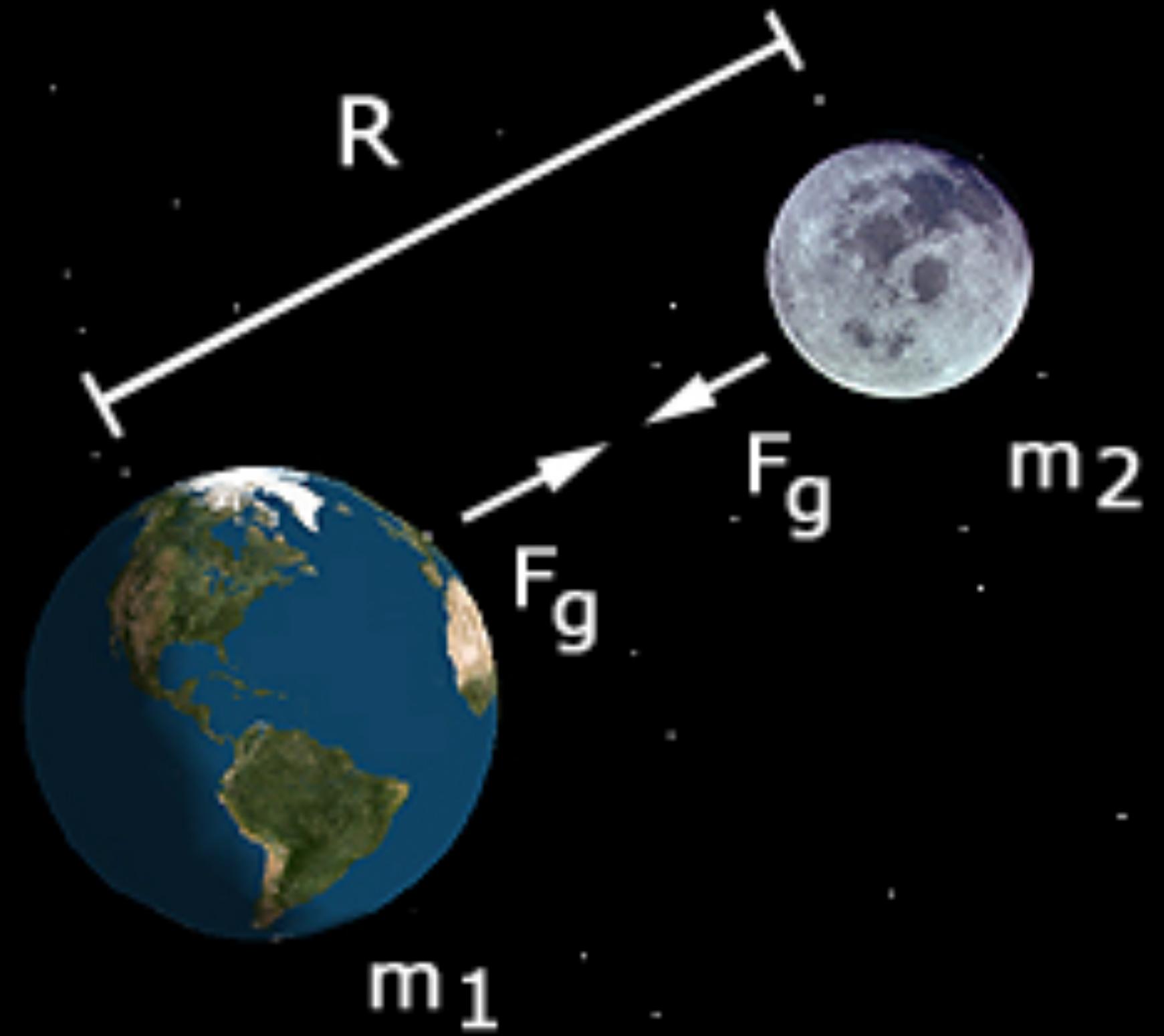
Every force occurs in pairs.



Gravitation

Newton also explained gravity as being connected to mass.

- a) Any object with mass exerts a gravitational force on any other object with mass.



- b) Gravitational forces are always attractive (its the ONLY one!).



Inverse Square Law

Newton proposed the form of the gravitational force (also known as weight)

$$F = \frac{G m_1 m_2}{r^2}$$

Force depends on the mass of both objects.

Also the INVERSE of the SQUARE of the DISTANCE between them.
(Inverse Square Law)

We will see this again when we talk about light!

Kepler's Laws Revisited

1. Orbits are elliptical. Objects continue in a straight path until affected by an external force - the Sun's gravity!
2. Orbits sweep equal areas in equal amounts of time. Newton's laws give us conservation laws: conservation of angular momentum.

$$L = r (mv) \quad \text{or} \quad v = L / rm$$

Objects will speed up as their distance decreases! The “area” issue is just a consequence of this, not a cause.

Conclusive Evidence

Some people still held to the Aristotelian/Ptolemaic view of the perfection of the heavens even after Newton developed his laws.

In 1728, James Bradley claimed to observe stellar parallax - a star in a different position depending on the time of the year.

Did you see it in this slide? If not, you might be just as skeptical as Bradley's colleagues were - the technology of the time was just not precise enough.

Stellar parallax was confirmed in 1838 by Freidrich Bessel.

Question: Right now, the Moon is in free-fall towards the Earth.

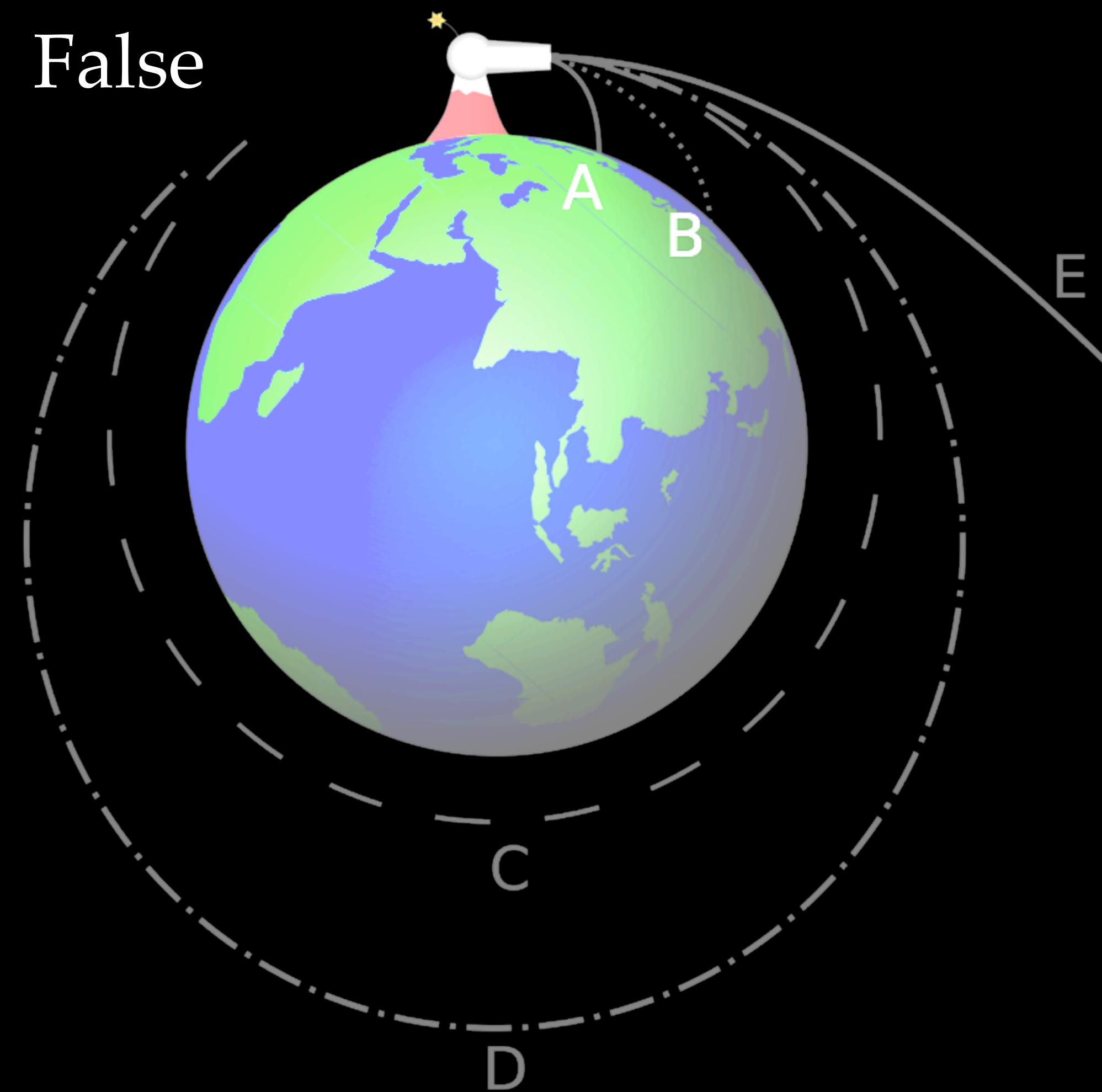
a. True

b. False

Question: Right now, the Moon is in free-fall towards the Earth.

a. True

b. False



Any object in orbit around another is in perpetual free-fall.

The only force acting in space is gravitational, which results in an unbalanced force.

Newton's 2nd Law tells us that there MUST be a net acceleration when there is an unbalanced force - this is colloquially known as "free-fall".

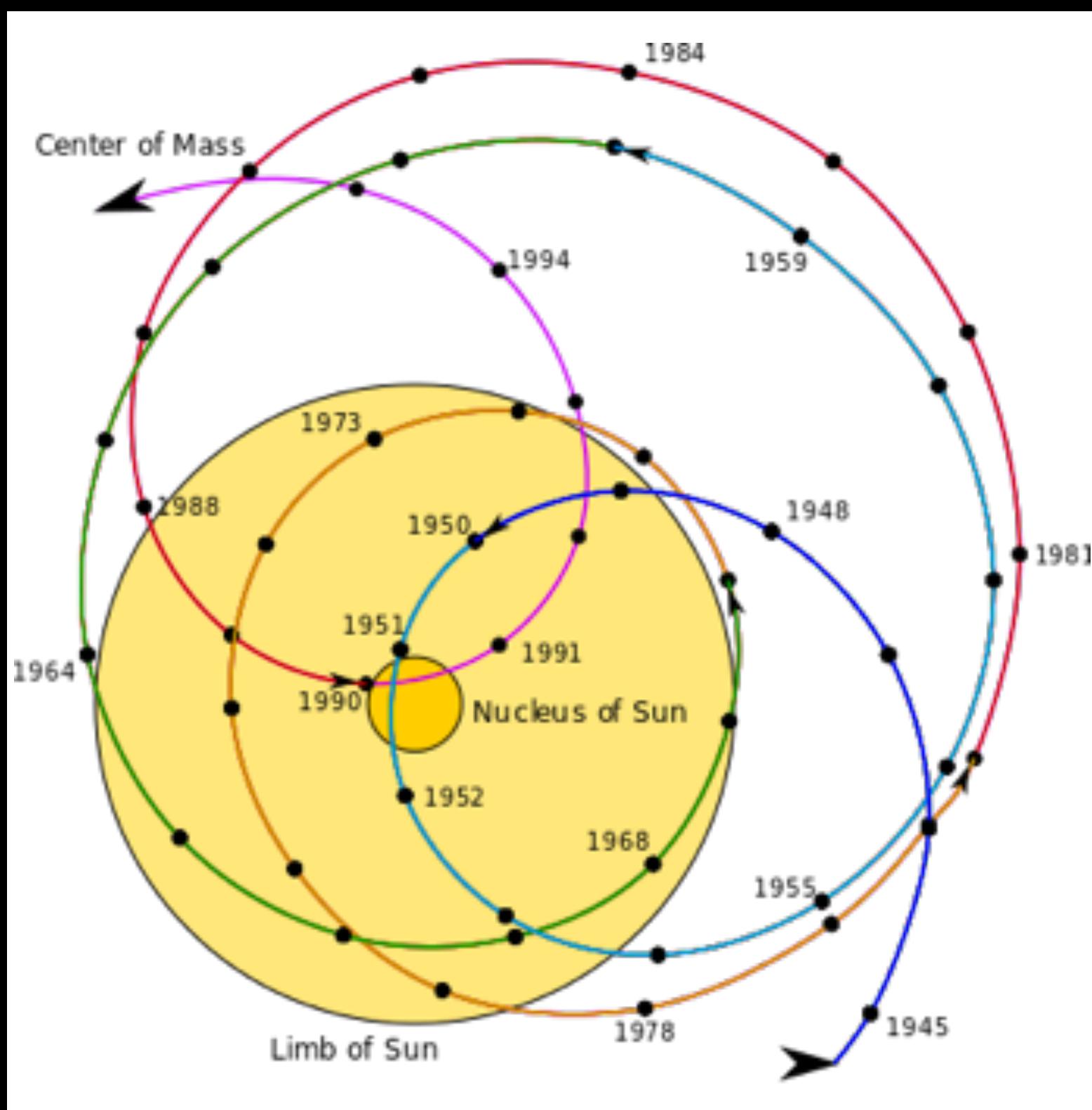
Orbit means something is in free-fall but perpetually missing the target.

Kepler's Laws Revisited

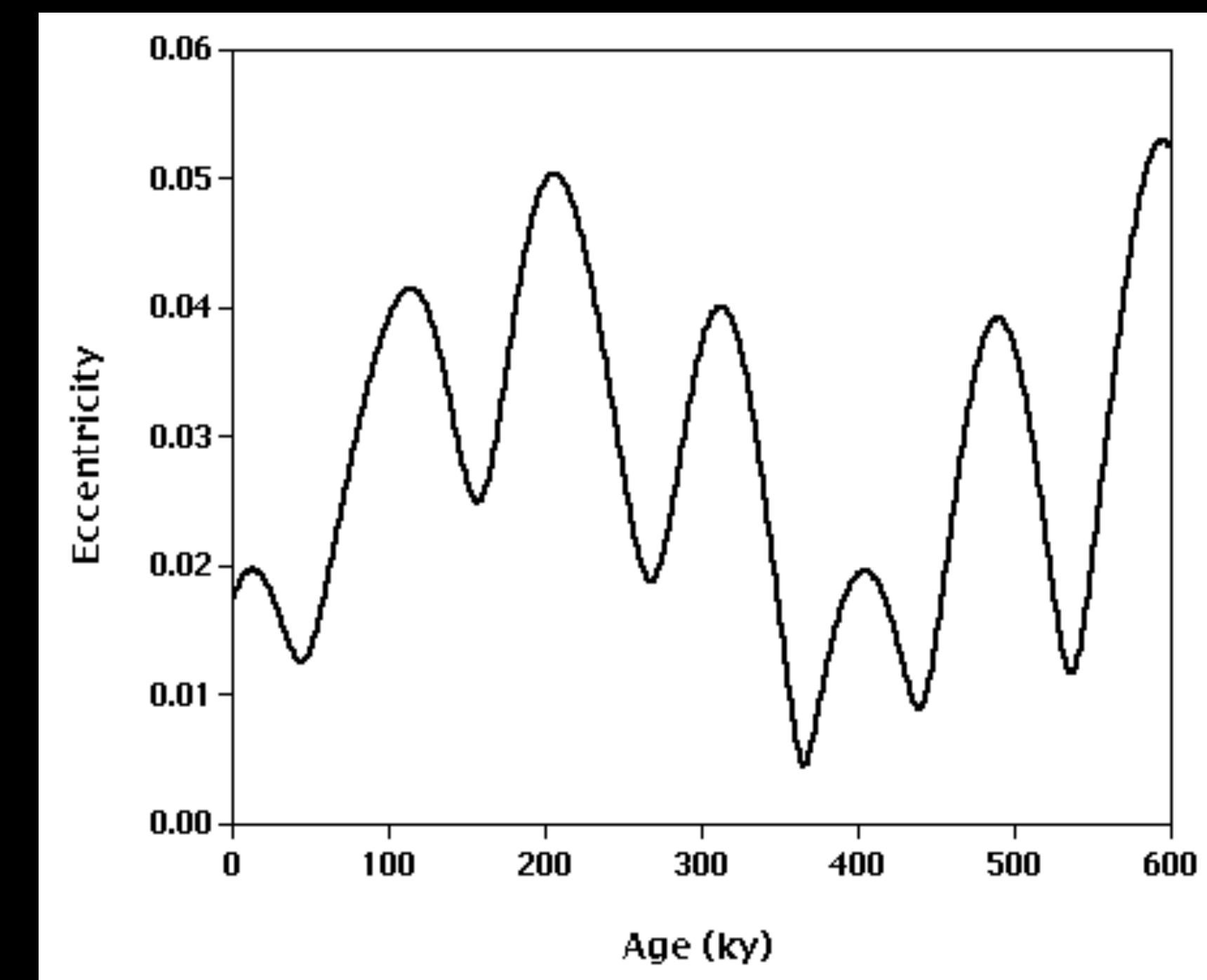
Law 3 turns out to be incorrect! Newton's Laws explain this. The focus of the ellipse is the *centre of mass*, which is affected by the other planets!

Planet	T^2/a^3
Mercury	1.0022
Venus	1.001
Earth	1
Mars	0.9996
Jupiter	0.999
Saturn	0.998
(Uranus)	0.993
(Neptune)	0.986

$$T^2 = a^3 / M_{\text{total}}$$



Centre of Mass of Solar System

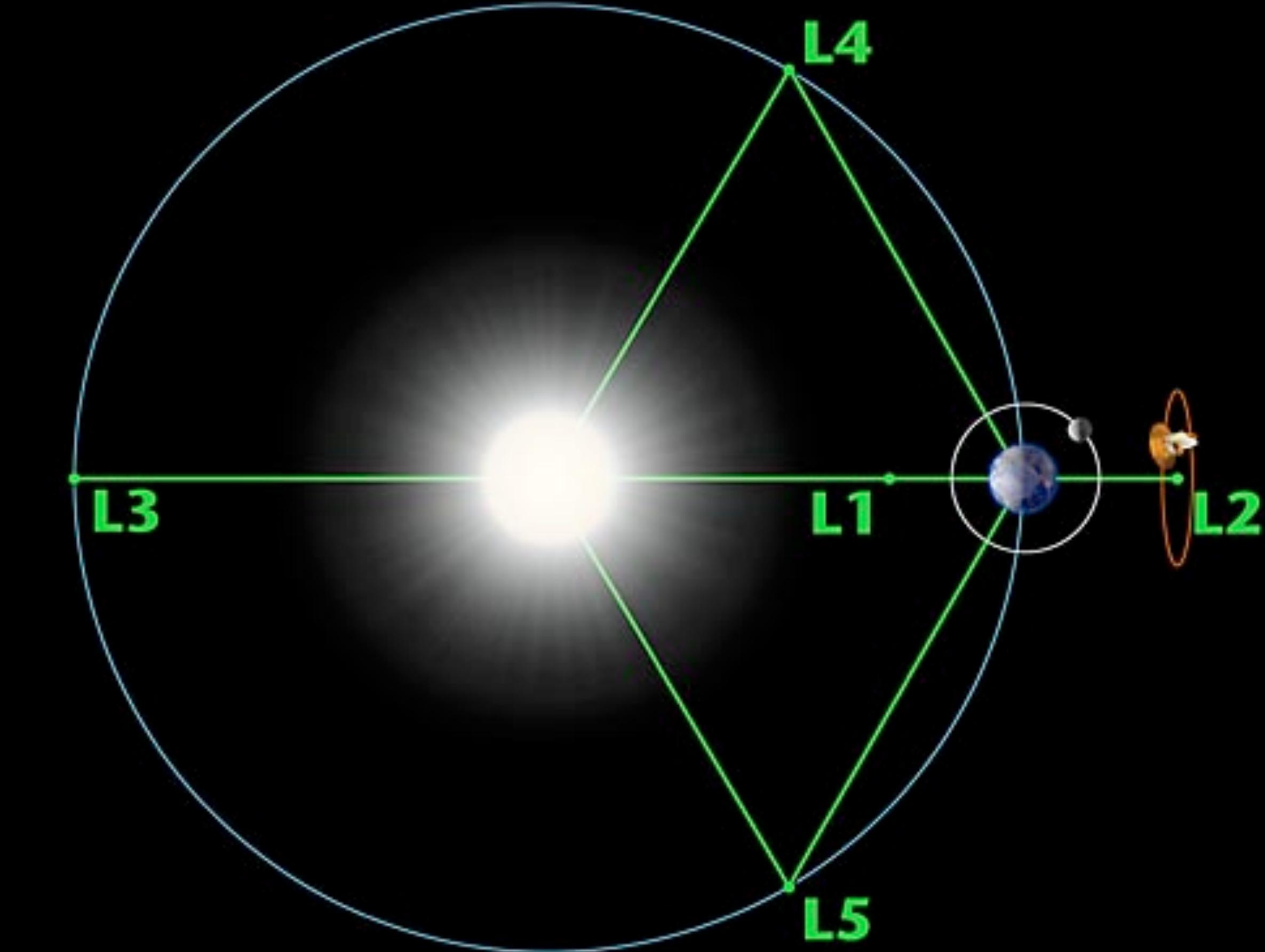


Eccentricity of Earth's Orbit

Lagrange Points

Newton's Laws have lead to space exploration, where Kepler's couldn't.

Example: We now understand Lagrange points - locations with the same orbital period but different locations from an orbiting body!



Consider L1 - it is closer to the Sun, so its orbital period should be less than Earth's. But due to Earth's gravity, the orbital period is the same!

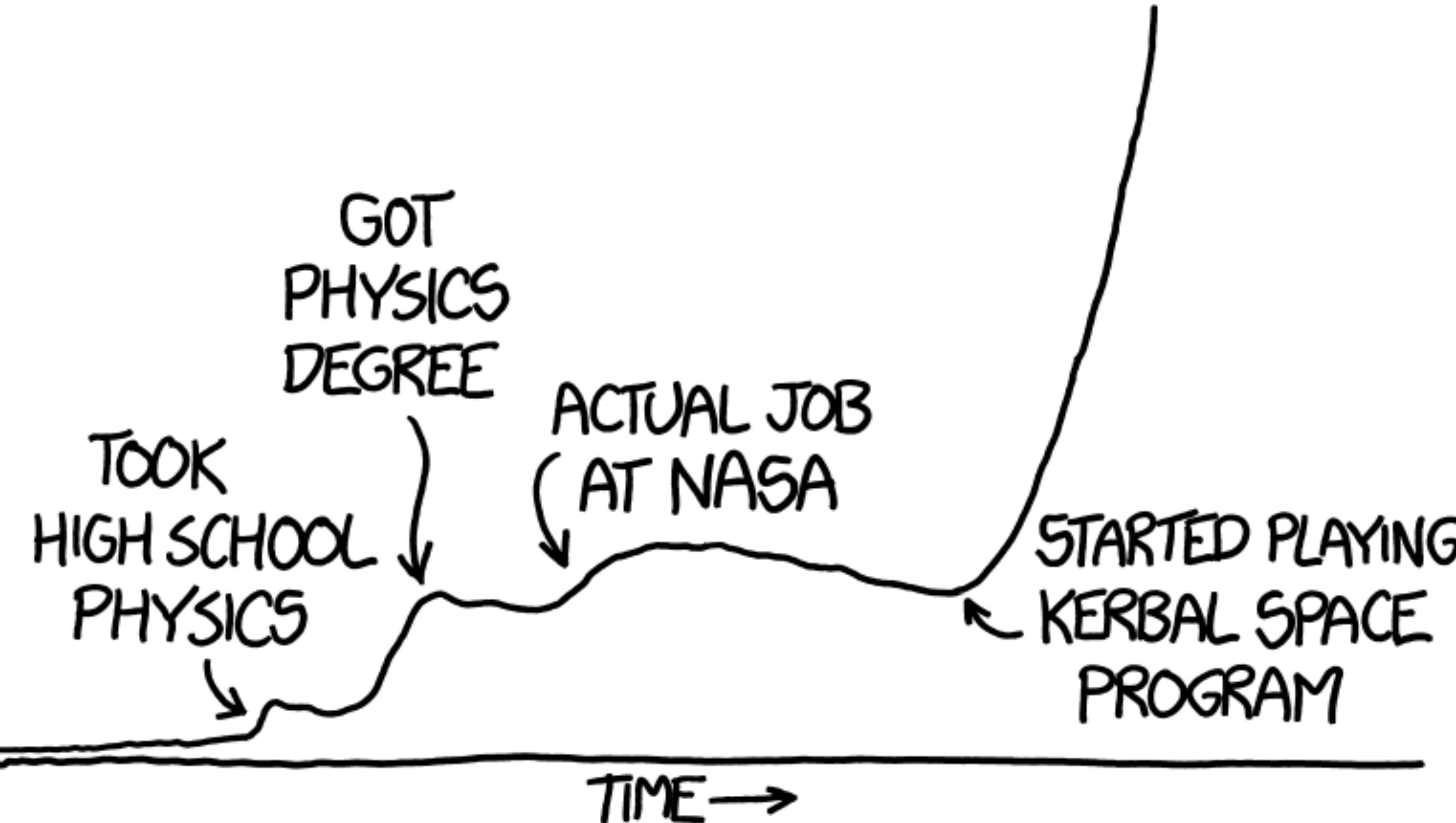
Kerbal Space Program

If you want a fun way to explore orbits, try Kerbal Space Program.

You can explore the math for years and never develop an intuition about orbits as well as you will from spending a few hours with this game.



HOW WELL I UNDERSTAND ORBITAL MECHANICS:



From XKCD by Randall Munroe

Einstein's Revolution

Question: A space ship is flying past Earth at $0.2c$ and shoots a laser in the forward direction. How fast is the laser traveling as measured by someone on Earth and how fast is it traveling as measured by someone on the space ship?

- a. Earth: $1.0c$ Ship: $1.2c$
- b. Earth: $1.2c$ Ship: $1.0c$
- c. Earth: $1.0c$ Ship: $1.0c$
- d. Earth: $1.0c$ Ship: $0.8c$

Equivalence of Frame of Reference

How can you tell you are moving?

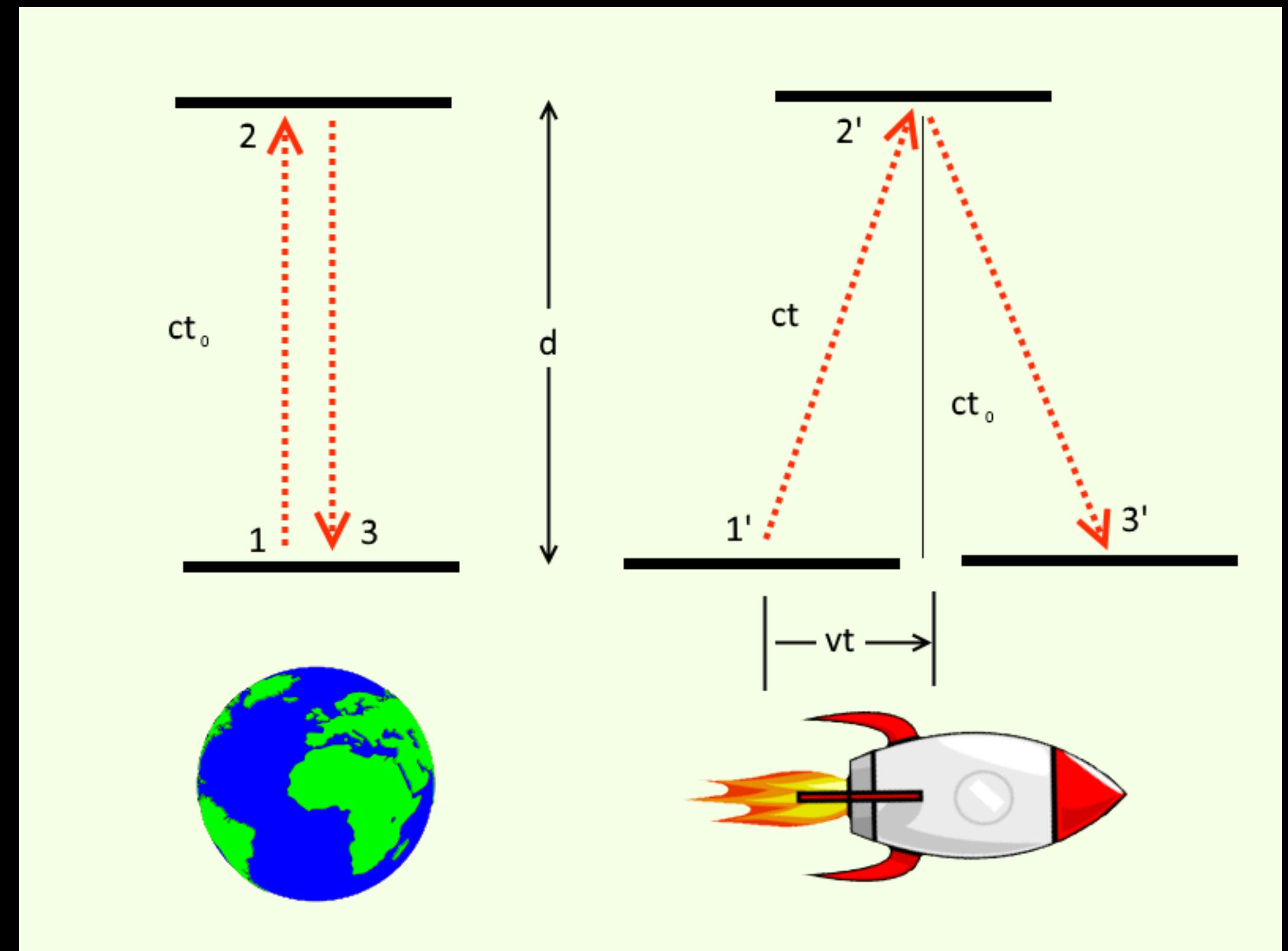
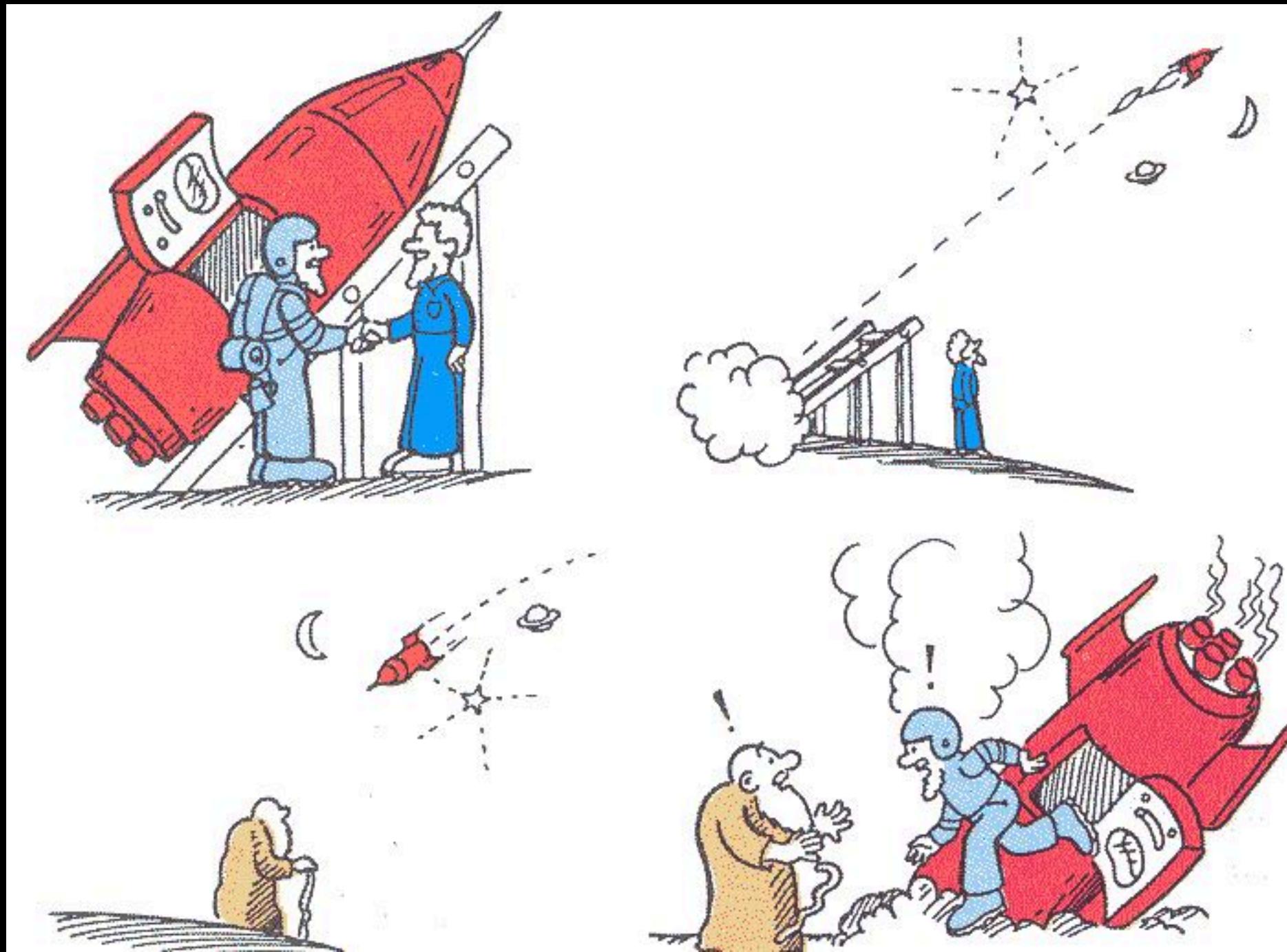
If an experiment is performed elsewhere in the universe, are the results the same as they would be on Earth?

If I am on a space ship and I shine a laser in front of me, how fast does the laser light travel relative to someone on Earth?

These are the hard questions that were faced in the aftermath of Newton's revelations about gravity and space.

Einstein's Theories

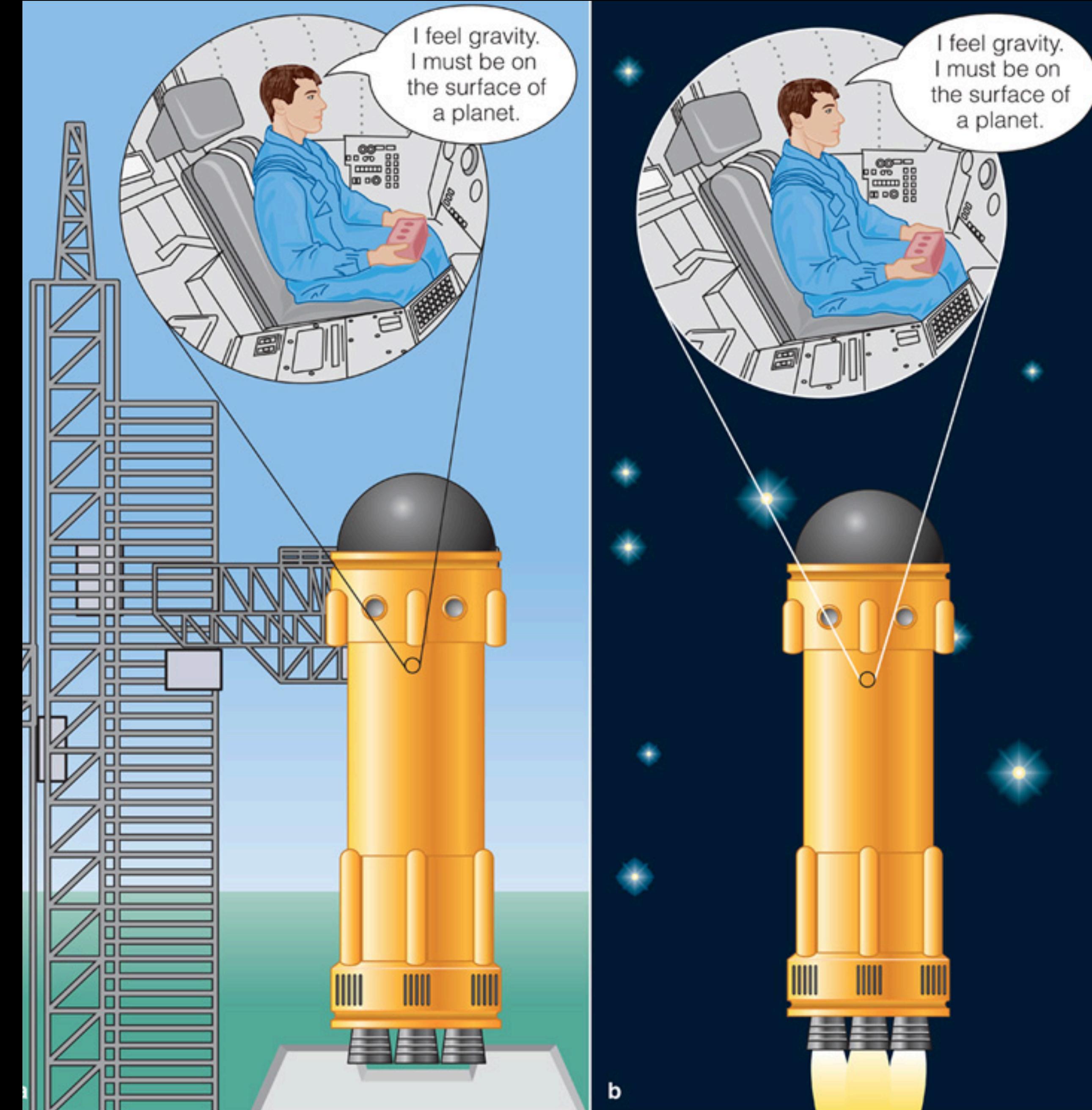
Special Relativity: The speed of light in a vacuum is the same in all frames of reference, and is the maximum possible speed in the universe.



Einstein's Theories

General Relativity: Gravity doesn't produce a force, but instead it curves/warps space-time, resulting in an acceleration towards the centre of gravity.

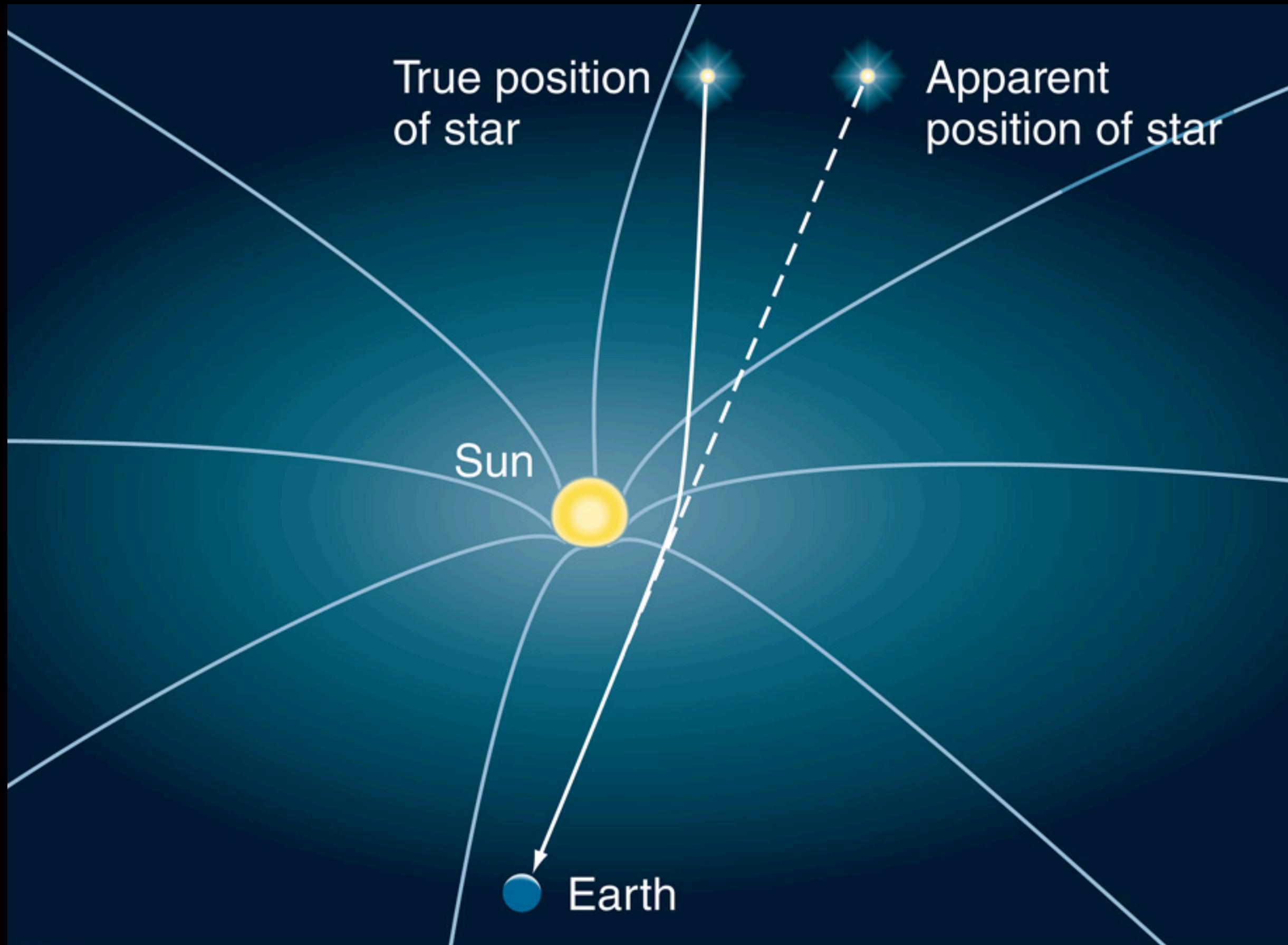
How is this different? Newton says gravity affects things with mass.
Light has no mass, is it affected by gravity?



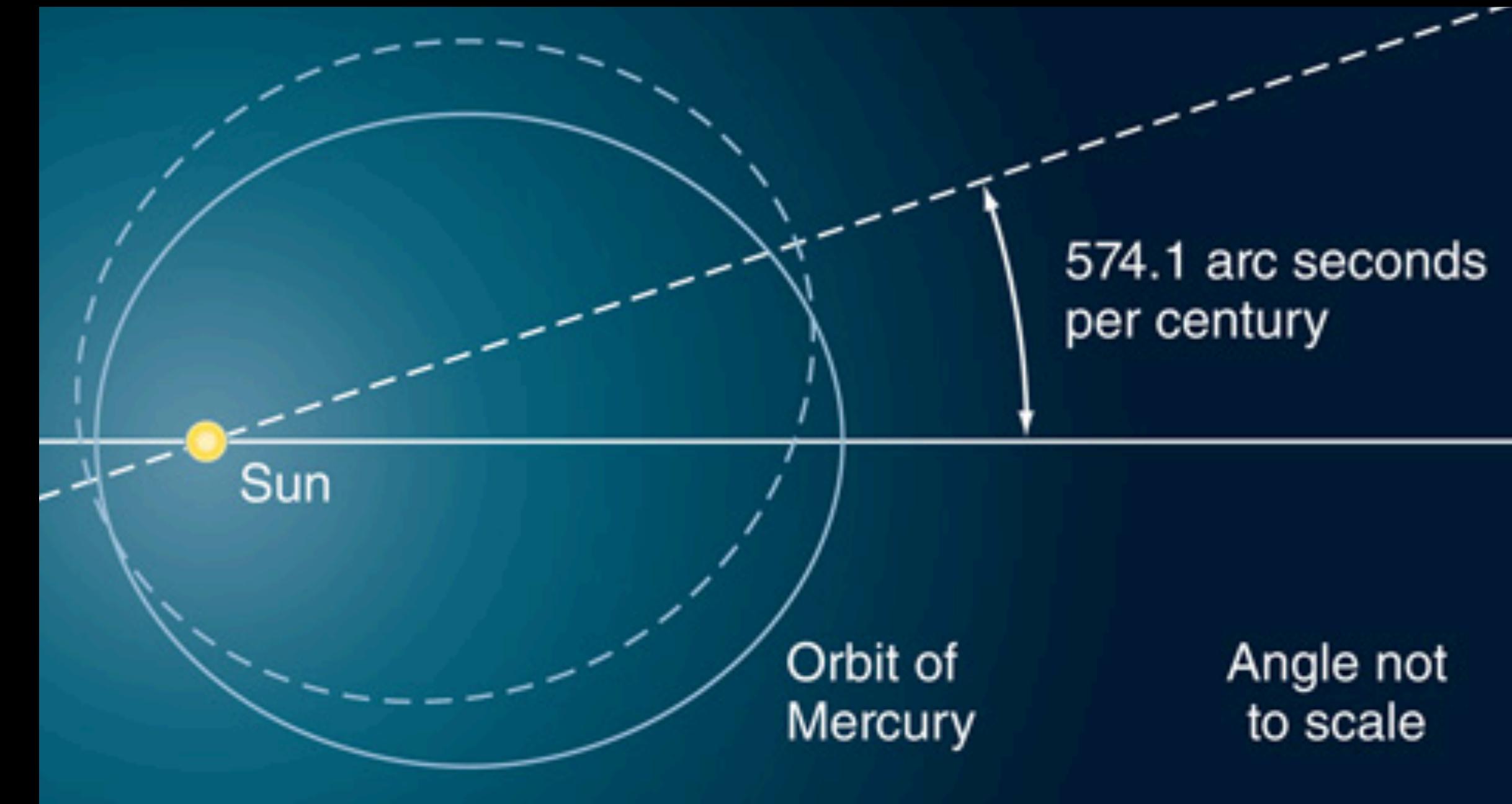
Summary of Relativistic Effects

1. Time slows down if you travel fast or are in a gravitational field
2. Distances shrink if you travel fast or are in a gravitational field
3. The effect of traveling fast is due to perception, the effect of the gravitational field is actual warping of space-time.
4. It is impossible to tell the difference between a gravitational field and normal acceleration, therefore they have the same effect.

Proof of Einstein's Theories



Light bends around the Sun!



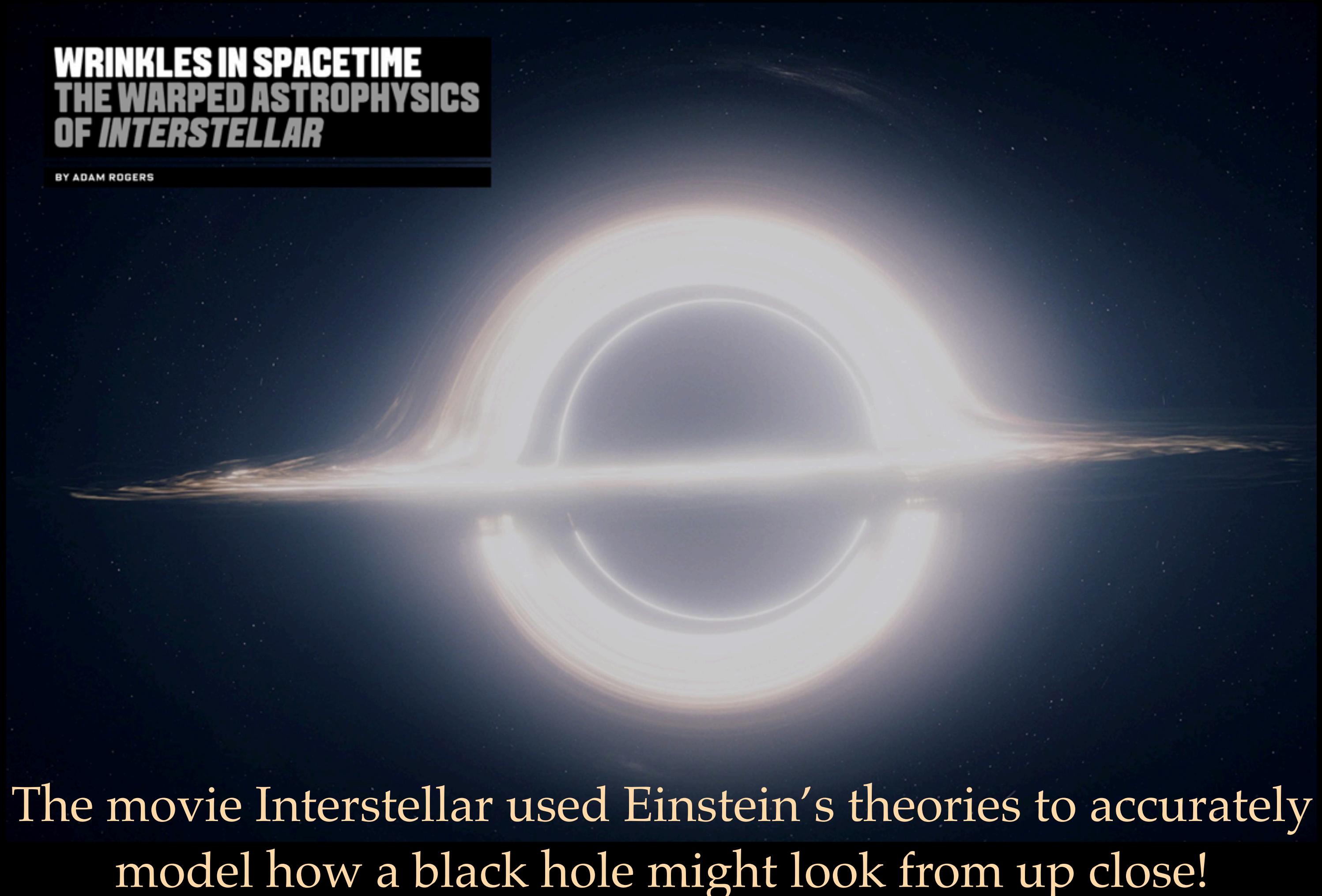
Mercury's orbital precession is $43''$ more per century than predicted by Newton's Laws due to gravitational warping of space-time.

What does this mean for astronomy?

Einstein's theories won't affect much of this course.

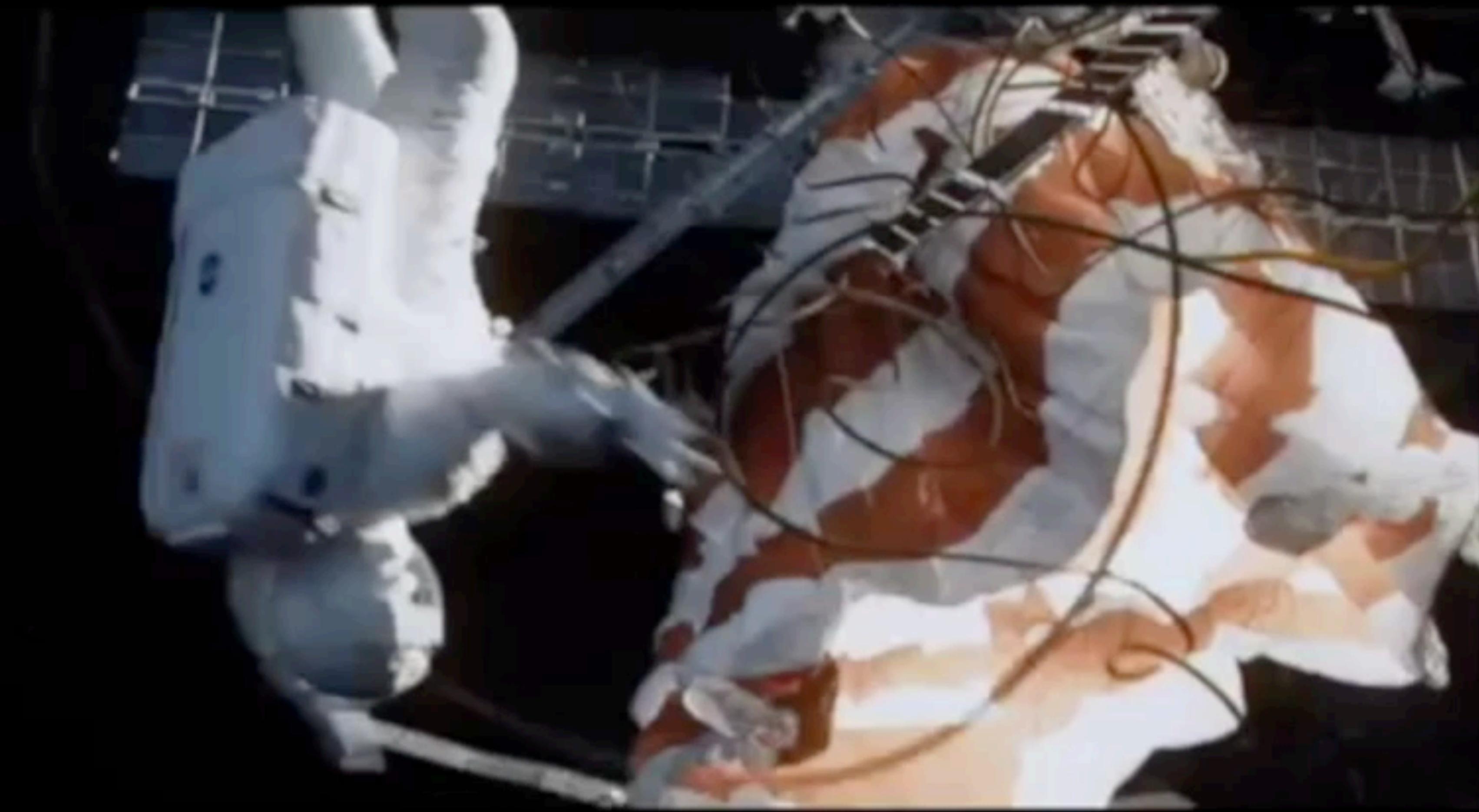
But they are critical for understanding black holes, galaxies, the big bang theory, and other important aspects of astronomy.

Many of these are discussed in Astr 102.



The movie Interstellar used Einstein's theories to accurately model how a black hole might look from up close!

Question: What is wrong with this scene from the movie Gravity?



Question: What is wrong with this scene from the movie Gravity?

<https://www.youtube.com/watch?v=DYDaIyfitn8>

- a. In reality, Earth's gravity is larger than depicted in the movie.
- b. Bullock shouldn't fly backwards as Clooney let go.
- c. Clooney shouldn't accelerate away from Bullock.
- d. The Earth appears too large for the perspective of that orbit.