ASTR 1P01
Brock University
Prof. Barak Shoshany

Lecture 3:
Ancient astronomy

We will learn about...

- The ancient history of astronomy.
- The geocentric model.
- The “flat Earth” model.
- The scientific method.

The Pleiades
Credits: NASA, ESA, AURA/Caltech, Palomar Observatory

Astronomy and the scientific method

Astronomy and the scientific method

- Astronomy has a long history of replacing old theories with new ones based on scientific evidence.
- Learning about astronomy is also a great opportunity to learn about the scientific method, critical thinking, and skepticism.
- All of these are extremely important for understanding how the universe really works.
- You can also use these tools in your daily life, to tell the difference between what's true and what's not!

Astronomy and the scientific method

- Today, when we look at the sky, we have a very good understanding of what we see:
  - The physical laws that govern the movement of the celestial objects.
  - Details about these objects: distance, size, composition, time evolution, etc.
- We also have telescopes and other tools to measure properties that cannot be seen with the naked eye.

Astronomy and the scientific method

- Modern humans evolved ~300,000 years ago, and recorded history began ~5,000 years ago.
- But we learned essentially everything we know about the universe only in the last few hundred years.
- In fact, there are some very important things we only learned in the last century, or even the last decade.

Astronomy and the scientific method

- We used to think that the Milky Way was the entire universe. But in 1923, we discovered that there are other galaxies, and the Milky Way is just a tiny speck of dust compared to the entire universe.
- Black holes were theorized more than 100 years ago. But only very recently, in 2019, we were able to obtain the first image of a black hole.


Ancient astronomy

Ancient astronomy

- In prehistoric times, for countless years, humans had no idea what the true nature of the celestial bodies was.
- Prehistoric people identified celestial objects with “gods”, as they did with everything else they didn’t understand.
- The first astronomers were actually priests of ancient religions, tens of thousands of years ago.
- They also believed that the celestial objects influenced their lives. This is the origin of astrology.

Ancient astronomy

- Astronomy remained closely tied to religion and astrology for thousands of years, in essentially every single ancient culture we know of, all around the world.
- It took a long time before humans finally understood that the celestial objects are governed by mundane natural laws, just like things down here on Earth.

Ancient astronomy

- Proper astronomy involves collecting and analyzing data.
- Therefore it cannot exist without writing and mathematics, which were only invented ~5,000 years ago.
- Around that time, ancient civilizations such as the Babylonians and the Egyptians noticed that astronomical phenomena are periodic, and could be used to keep track of time.
- They developed calendars that could be used to predict the change of seasons, which was very helpful for agriculture, e.g. to know when to plant and harvest.
- This was one of the main catalysts for developing advanced mathematics in the ancient world.

Ancient astronomy

- Babylonian astronomers measured and recorded the positions of the Moon and planets for hundreds of years.
- By around 400 BC they compiled enough data to be able to find regular patterns.
- Using these patterns, they could predict not only where the celestial bodies will be at any time, but also when lunar eclipses will occur.
    - However, they could not yet predict solar eclipses accurately.

Ancient astronomy

- Ancient Chinese astronomers also recorded astronomical data, and the oldest written record of a solar eclipse, from around 2000 BC, is from China.
- The Chinese astronomical catalogs span 3,000 years and list thousands of eclipses, comets, meteors, exploding stars, and even dark spots on the Sun.
- This historical data is still used by modern astronomers even today.

Axial precession

Hipparchus and axial precession

- The ancient Greek astronomer Hipparchus built an observatory on the Greek island of Rhodes around 150 BC.
- He used it to measure the accurate positions of objects in the sky.
- He composed a star catalog with ~850 entries, with celestial coordinates for each star specifying its position in the sky.

Hipparchus and axial precession

- Hipparchus divided the stars into apparent magnitudes according to their (apparent) brightness.
- The brighter the star, as it appears to us, the smaller the magnitude. Stars of the first magnitude are the brightest.
- Today, we still use the term "magnitude" to describe the brightness of stars, but the modern definition is much more precise.

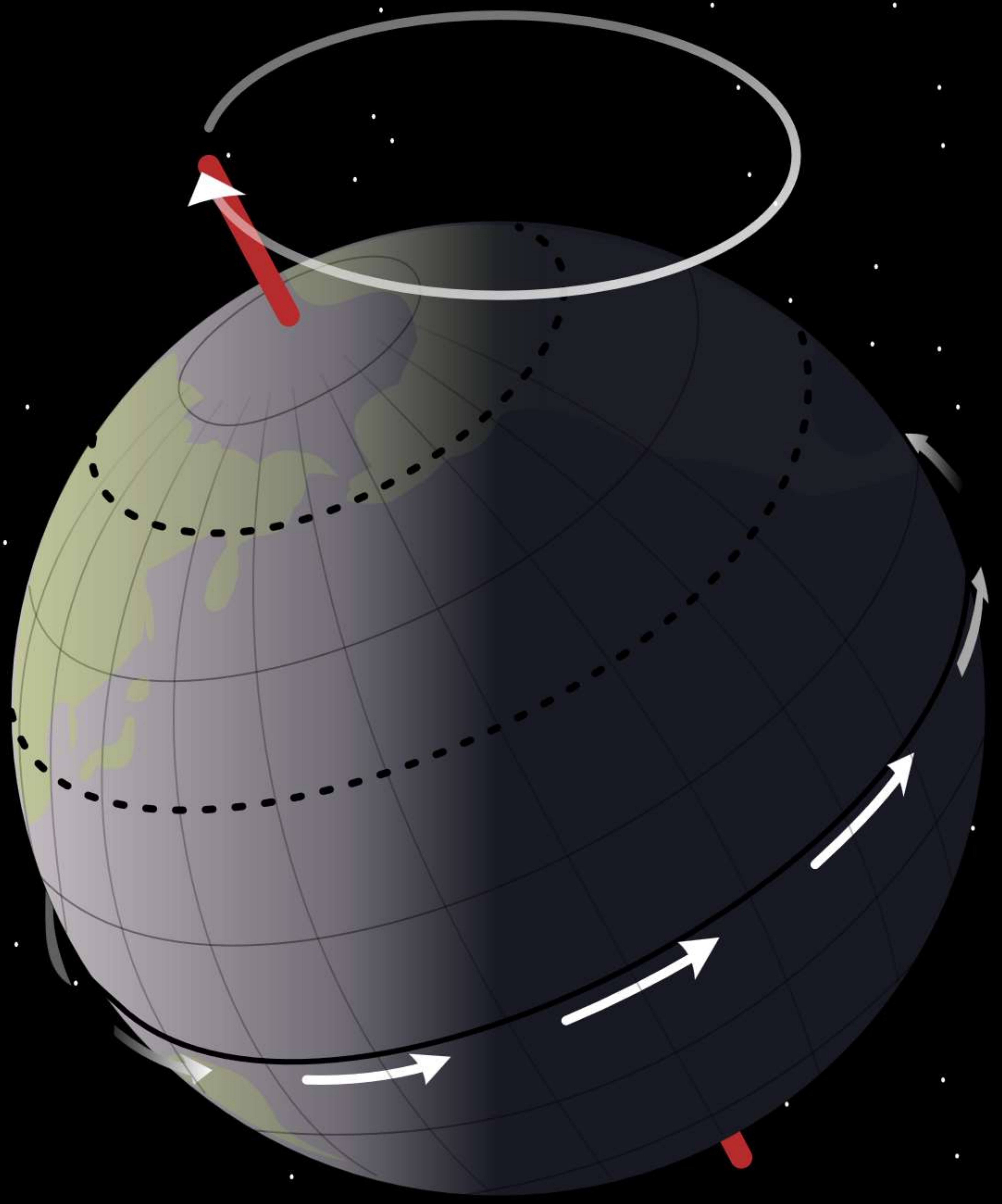
Hipparchus and axial precession

- Note that the apparent brightness of the star isn't the same as its actual brightness or luminosity.
- Two stars of the same luminosity but at different distances from us will have different apparent magnitudes.

Hipparchus and axial precession

- By comparing the data Hipparchus collected with data from older observations, he discovered that the position of the north celestial pole changes over time.
  - Recall that the north celestial pole is the point around which the sky appears to rotate.
- This phenomenon is called axial precession.

The Earth is like a spinning top. There are two types of rotation.



1. Fast spin around the axis.
2. Slow precession of the axis itself.

Precession of Earth's Rotational Axis

Credits: NASA, Mysid (Wikipedia)

Video

Watch the precession of a spinning top.

The video is available at this URL:

https://youtu.be/kbh1Yzzq0Ow

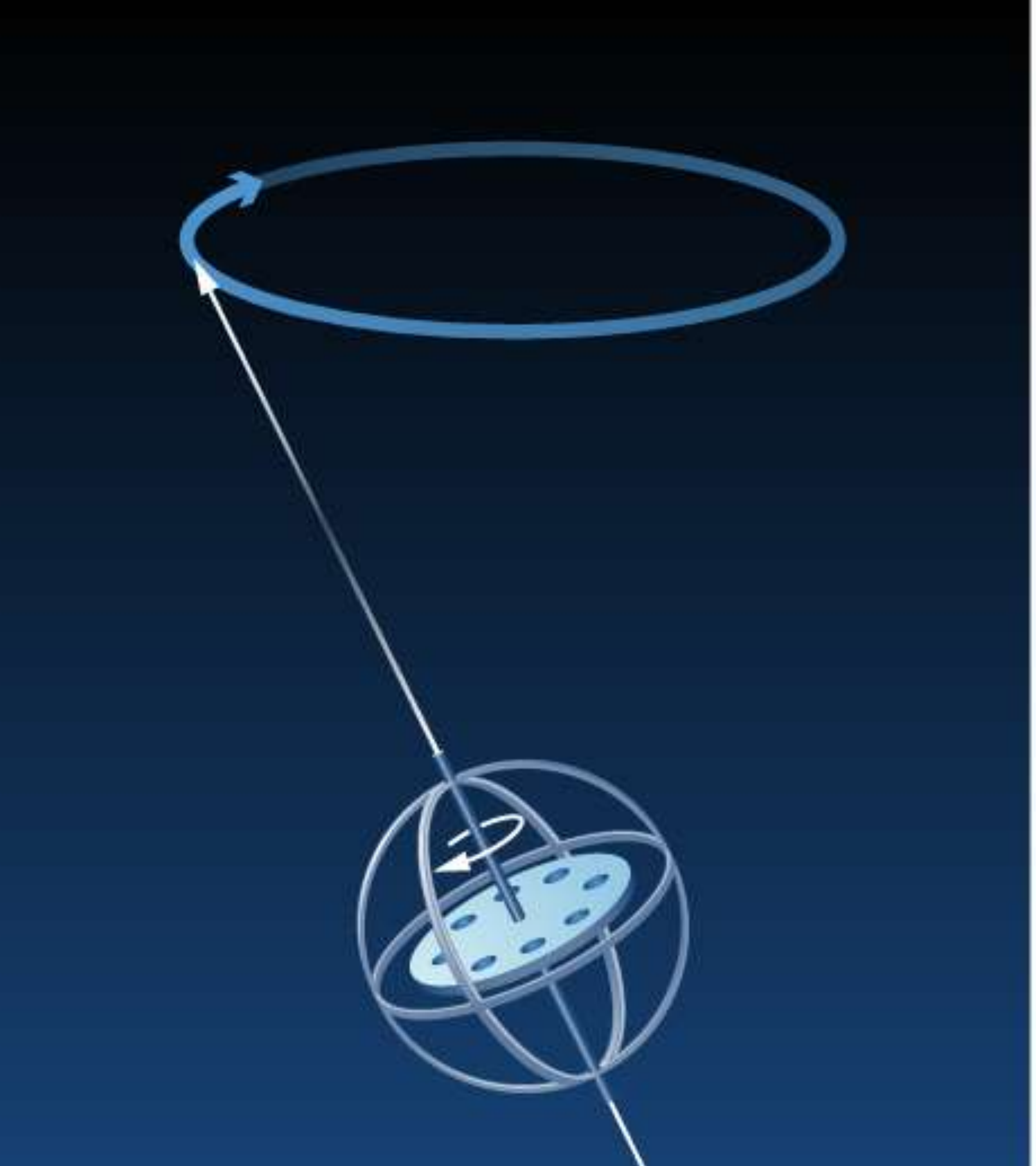
Precession of a Spinning Top
Credits: Iacopo Simonelli, from https://youtu.be/kbh1Yzzq0Ow

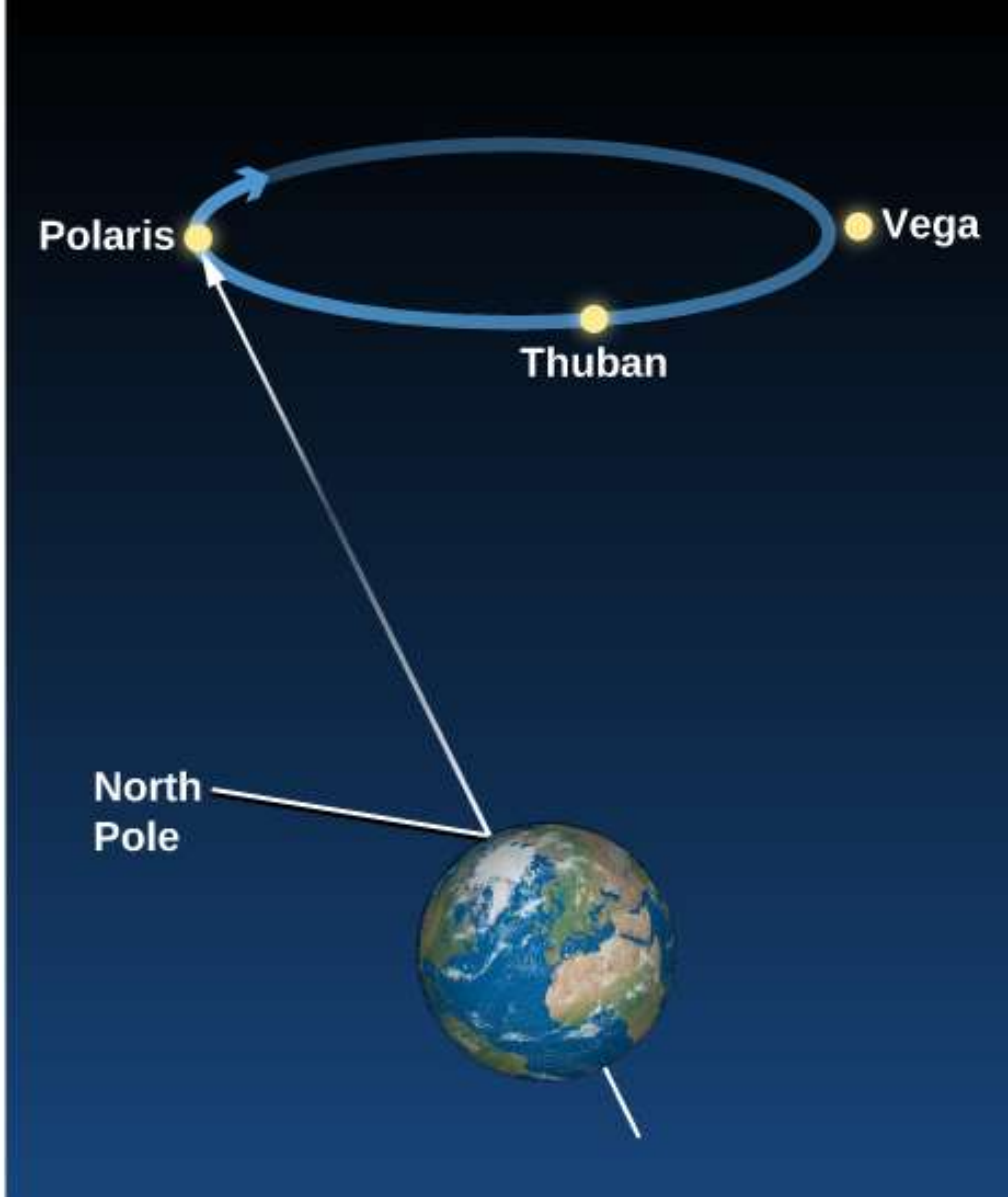
Hipparchus and axial precession

- The Earth is not a perfect sphere, it bulges a bit at the equator.
- The gravitational pull of the Sun and the Moon on this equatorial bulge causes the axis to precess.
- It takes the Earth's axis around 25,700 years to complete a full circle.

Hipparchus and axial precession

- The north and south celestial poles change due to precession.
- Today the north celestial pole is near the star Polaris, which is why we call it the "North Star".
- But around 14,000 years ago, the star Vega was the North Star, and it will become the North Star again in around 11,700 years.





Precession: Spinning Top vs. Earth
Credits: OpenStax Astronomy

The spherical Earth

The spherical Earth

- Many ancient cultures initially believed that the Earth was flat, shaped as a plane or a disk.
- If you stand in an open field and look around, it certainly looks like the Earth is flat!
- But it’s not hard to prove it is actually spherical.
- In fact, it's so easy that the ancient Greeks already knew the Earth was spherical as early as 2,500 years ago, in the time of Pythagoras.

The spherical Earth

- Many of the proofs that the Earth is spherical were collected by the Greek philosopher Aristotle around 330 BC.
- By that time, every Greek scholar accepted the spherical Earth as a fact, and this knowledge gradually spread to the rest of the world.

The spherical Earth

- Let's review some of the evidence, including even some experiments that you can do on your own.
- By doing so, we will learn a bit about how science works.
- Some of the following evidence was already known to the ancient Greeks, but some of it is more modern.

Lunar Eclipse
Credits: Starry Night and Bob King

A lunar eclipse happens when the Moon moves into Earth's shadow.

The shape of the Earth's shadow seen on the Moon is always round.

But the only kind of object that always produces a round shadow is a sphere.

Shadow of the Earth During a Lunar Eclipse
Credits: OpenStax Astronomy

Eclipses

- You can check that for yourself at home using a simple experiment.
- Take objects of different shapes and rotate them in front of a lamp or a flashlight.
- If you do this with a disk-shaped object, such as a plate, you will notice that the shadow it creates can be flat, round, or anything in between, depending on its orientation.

Eclipses

- However, if you do this with a spherical object, such as a ball, you will see that the shadow is always round, no matter the orientation.
- Therefore, the Earth must be a sphere. If it wasn't a sphere, then we would have seen different shapes during lunar eclipses, depending on the relative positions of the Sun and the Earth.

The visibility of stars

- Travelers who travel a significant distance to the south see new stars, that were not visible from the north.
- They also see the height of the North Star in the sky decrease as they go further south.
- The reason for that is that the Earth is a sphere, and therefore we see different portions of the sky from different points on the sphere.
- If the Earth was flat, then everyone would have seen the same stars, because they would all be facing the same direction.

Photos from space

- The previous two proofs were already known to the ancient Greeks, but they are indirect proofs.
- Modern technology allows us to provide direct proof that the Earth is a sphere.
- There are plenty of photos of the Earth taken by satellites and by astronauts.
- Since photos taken from different directions always show that the Earth is round, its shape must be spherical.
  - That’s the same reason its shadows is always round.

Website

NASA's Earth Polychromatic Imaging Camera (EPIC) takes images of the Earth from different angles every day.

The images can be viewed at this URL:

https://epic.gsfc.nasa.gov/

Go to the nearest ocean and watch a ship sail into the horizon.

Ship Disappearing Below the Horizon
Credits: DrGC (StackExchange)

You will see it disappear gradually: first the bottom part disappears, then the middle, then the top.

Disappearing ships

- The reason is that the ship sails far enough from you that it actually goes down the slope of the spherical Earth.
- It's like watching an ant walk on an orange. After a while it's going to disappear because the surface of the orange will block it from view.
- If the Earth was flat, you would have instead seen the entire ship becoming smaller and smaller but not disappearing, just like if the ant was walking on a flat table.

The view from different heights

- A related phenomenon is that you can see farther away the higher you go.
- On a clear day, you climb a mountain and see a city in the distance from the peak of the mountain.
- You then climb back down, but you can't see the city anymore, even if the terrain is completely flat.
- The reason is that the curvature of the Earth blocks your view. If the Earth was flat, you could have still seen the city from the ground (assuming nothing else was blocking your view).

Circumnavigation of the Earth

- Between 1519 and 1522, the Magellan-Elcano expedition performed the first circumnavigation of the world.
- They sailed in a complete circle around the world, sailing west and eventually ending up back where they started. At no point did they find an edge.
- Since then, many other people have also circumnavigated the Earth, some by boat and some by plane.
- The first circumnavigation by plane was done in 1924, in 175 days.
- If the Earth was flat, then a plane going in one direction without turning back would have fallen off the edge.

The circumference of the Earth

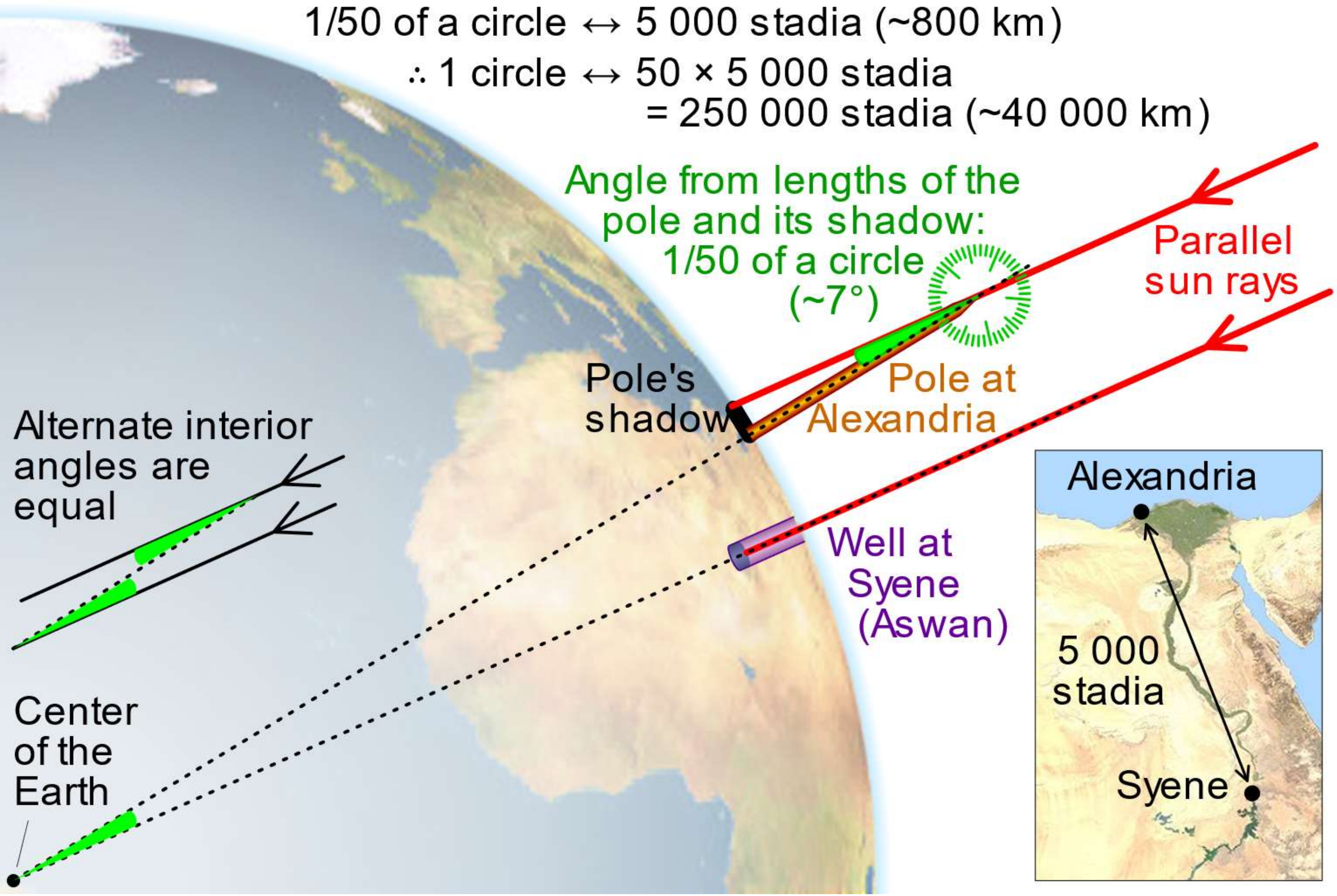
- The ancient Greek Eratosthenes measured the circumference of the Earth around 240 BC.
- He placed two sticks of the same length in two different Egyptian cities, Syene and Alexandria, separated by ~800 km.

The circumference of the Earth

- Because the Earth is spherical, the two sticks had shadows of different lengths at the same time of day.
- Light rays from the Sun shine on the sticks at different angles, because they are located at different points on the sphere.
- If the Earth was flat, then the rays would have hit every point at the same angle, and the shadows would have been of the same length.

The circumference of the Earth

- In Syene, the Sun was at the zenith, so its rays made an angle of 0° with the ground, and no shadow was cast.
- In Alexandria at the same time, the sun was slightly south of the zenith, and its rays made an angle of ~7.2° with the ground.
- There are 360° in a circle, and 360 / 7.2 = 50, so the circumference of the Earth is 50 times the distance between the two cities.
- The result of this measurement was remarkably close to the correct value known today, which is ~40,075 km (at the equator).



Eratosthenes Measures the Earth's Circumference

Credits: Cmglee (Wikipedia)

The geocentric model

We are not the center of the universe

- Until the 17th century, almost everyone believed that the Earth is the center of the universe, and everything revolves around it.
- This is called the geocentric (Earth-centered) view, and it was popular for two reasons:
  1. Even though the Earth does move around the Sun, we don't feel that movement.
  2. Religions usually claim that humans and the Earth have a central role in the universe, and the geocentric view reinforces this claim.

We are not the center of the universe

- It took a lot of time for astronomers to realize that the geocentric view is totally wrong.
- Now we know that the Sun is at the center of the solar system, and the Earth is just one of several planets revolving around it.
- This is called the heliocentric (Sun-centered) view.

We are not the center of the universe

- Today we know that there's nothing special about the Sun and the solar system.
- There are trillions of other stars in the observable universe…

  …and trillions of other solar systems around those stars…

  …with trillions of other planets…

some of which may be homes to other life forms, and even advanced alien civilizations.

We are not the center of the universe

- The Earth and humans turn out to be completely insignificant compared to the universe as a whole.
- We already saw that when we discussed scales in the universe.

The heliocentric model and parallax

- The first known heliocentric model was presented by the ancient Greek astronomer Aristarchus of Samos, who lived between 310 and 230 BC.
- However, most Greek scholars rejected this idea.
- One of their arguments against the heliocentric model was that if the Earth moved around the Sun, nearby stars would shift their positions in the sky relative to more distant stars.

The heliocentric model and parallax

- Imagine driving along a road and looking out the window.
- As you move, objects closer to you, like trees near the road, will appear to move.
- Objects far away from you, like mountains far away, will stay in the same place.
- This phenomenon is called parallax.

The heliocentric model and parallax

- The same thing happens as the Earth moves around the Sun.
- Over the course of a year, more distant stars will stay in place, while closer stars will appear to move relative to them.
- In this context, the phenomenon is called stellar parallax.

Points A and B are 6 months apart.

Stellar Parallax
Credits: OpenStax Astronomy

Video

Animation of stellar parallax.

The video is available at this URL:

https://youtu.be/iwlMmJs1f5o

Parallax

Credits: Alice Hopkinson and Sarah Ragan, Las Cumbres Observatory, from https://youtu.be/iwlMmJs1f5o

The heliocentric model and parallax

- The problem is that even though the ancient Greeks made efforts to observe stellar parallax, they could not detect any.
- If there is no stellar parallax, that can mean one of two things:
    1. The Earth does not revolve around the Sun, or
    2. The stars are so far away that the parallax angle is too small to measure.
- Now we know that option 2 is the correct one. The stars are located many light-years away.
- To the ancient Greeks, such distances seemed inconceivable.

The heliocentric model and parallax

- Stellar parallax does happen, but can only be detected using extremely precise modern measurement devices.
- The first successful measurement of a parallax was only made a couple of millennia later.

In 1838, Friedrich Bessel measured the stellar parallax of 61 Cygni (SIG-nie).

Binary Star 61 Cygni
Credits: Tom Wildoner

He used this to estimate the distance to the star at about 11.4 light-years.

Ptolemy

Ptolemy

- In the 2nd century, the ancient astronomer Ptolemy wrote a treatise called Almagest.
- This is the only surviving comprehensive writing on astronomy from ancient times.
- Ptolemy compiled much of the knowledge about astronomy that existed at the time, including his own work.

Ptolemy

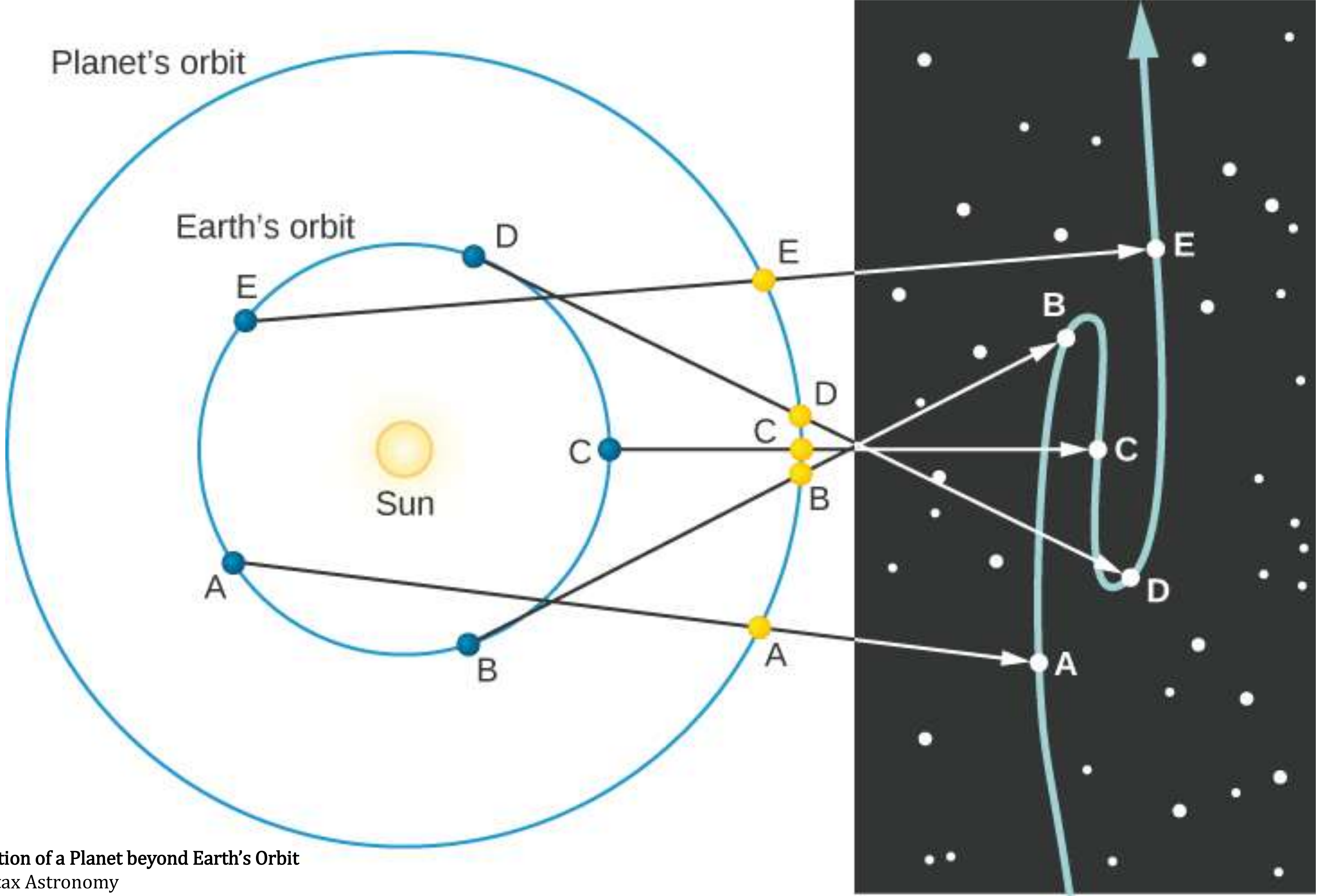
- The book also introduced a geocentric model of the solar system.
- This model predicted the positions of the planets at any date and time.
- To develop this model, Ptolemy used his own observations in addition to data collected by Hipparchus.
- This model remained in use for more than 1,400 years.

Retrograde motion

- Today, we know that the apparent motion of each planet in the sky results from a combination of:
  1. The motion of that planet around the Sun, and
  2. The motion of the Earth around the Sun.
- The planets always move along the zodiac.
- Over a year, the Sun continuously drifts eastward relative to the constellations.
- Planets mostly move eastward, which is called prograde motion.
- But sometimes they seem to stop and go westward for a bit, which is called retrograde motion.

Retrograde motion

- Of course, the planets don't actually move back in their orbits!
- Retrograde motion happens whenever Earth catches up to the planet and moves past it.
- Because the Earth is momentarily moving faster relative to the planet, it looks like the planet is moving "backwards".
- This is similar to what you see when you drive on a road and pass a slower car.
- From your point of view, it looks like the other car is moving backwards, even though both of you are going forward.



Retrograde Motion of a Planet beyond Earth's Orbit
Credits: OpenStax Astronomy

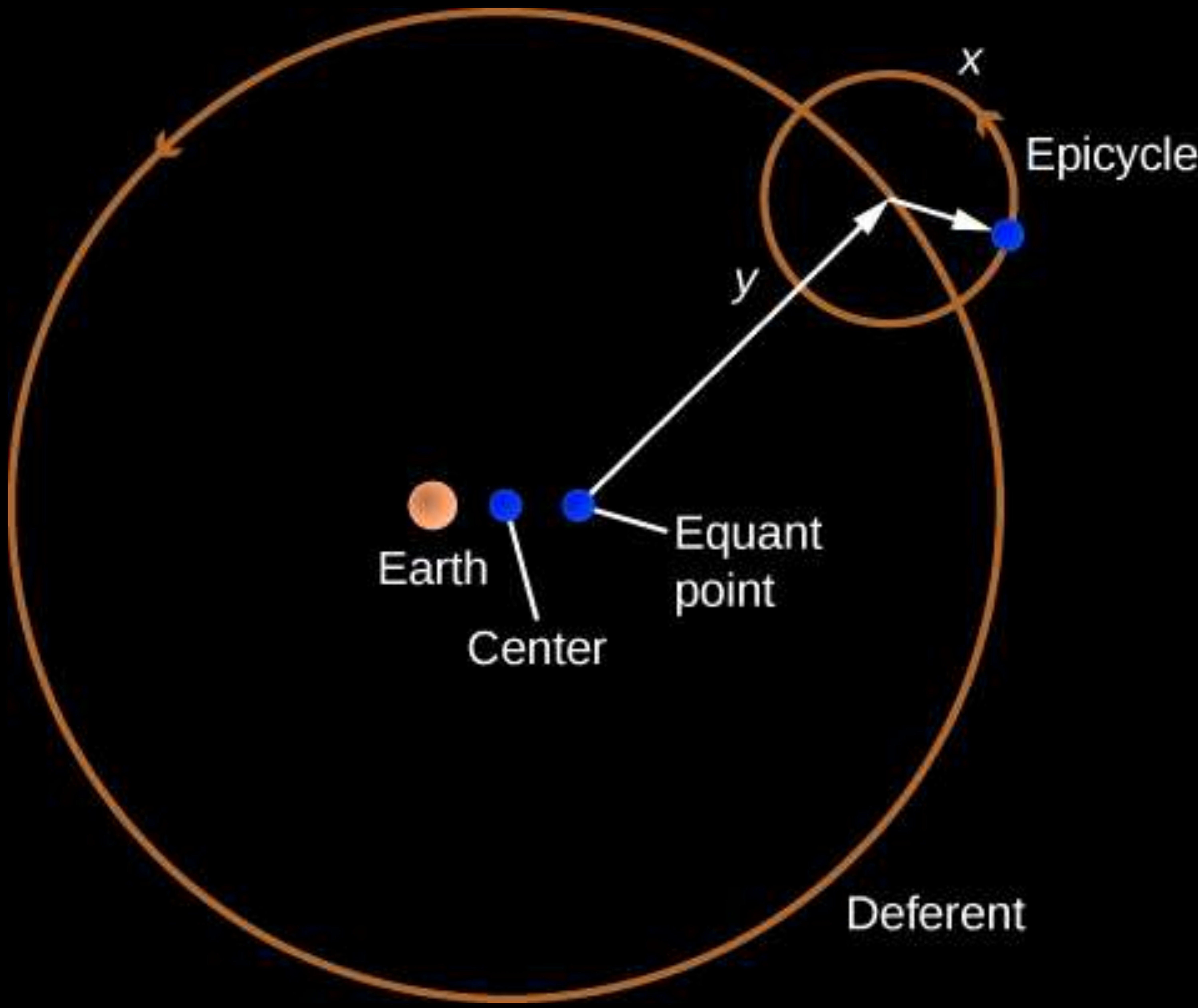
Simulation

The following program simulates the motion of a planet in the Earth's sky compared to the Sun and the constellations of the zodiac.

It is available at this URL:

https://foothillastrosims.github.io/planetary-config-react/

- Explaining retrograde motion in Ptolemy’s model required some assumptions.
- Each planet orbits in a small circle called an epicycle.
- Each epicycle orbits in a large circle called the deferent.
- The Earth is not at the center of the deferent, it's a bit to the side.
- On the opposite side of Earth there is the equant, the point with respect to which the epicycles move at a constant speed.



Simulation

The following program simulates Ptolemy’s epicycle model.

It is available at this URL:

https://foothillastrosims.github.io/Ptolemaic-System-Simulator/

Science and simplicity

- Today we know that the Sun is at the center of the solar system, not the Earth.
- We also know that the planets move in ellipses around the Sun, not in circles, and certainly not in epicycles.
- Therefore, the epicycle model has nothing to do with how the orbits of the planets actually work.
- Yet, it did manage to accurately predict the motion of the planets in the sky! How is that possible?

Science and simplicity

- Using some advanced math, it can be proven that any shape can be approximated using enough epicycles.
- This includes ellipses, so the epicycles were able to approximate the elliptical orbits of the planets.
- Ptolemy was actually creating a mathematical approximation of the heliocentric model with elliptic orbits, he just didn't realize it...

Science and simplicity

- Ptolemy's model is a great example of a model that gives correct predictions, but has no real explanatory power.
- A scientific model is only useful for explaining how things work if it provides a simple mechanism that can explain complicated results.
- Ptolemy described the complicated motion of the planets using a model that is just as complicated.
- He just "moved the complexity around", without providing a real explanation.

Science and simplicity

- The modern heliocentric model with elliptic orbits (plus the laws of gravity) is a very simple model with only a few simple rules.
- Yet, it can predict the complicated motion of the planets in the sky very accurately.
- This makes it much more useful in providing a true explanation for the motion of the planets.

Geocentric:

Complex

↓

Complex

Heliocentric:

Simple

↓

Complex

Science and simplicity

- Occam's razor is a very important scientific principle.
- It says that simple theories should be preferred over complex ones.
- The reason is not that simpler theories are easier to understand. There's no reason to expect that from the laws of nature.
- Instead, Occam's razor says that the simpler the theory is, the more predictive value it has.

Science and simplicity

- We want a scientific theory to generate plenty of output based on as little input as possible.
- The modern heliocentric model gives you a lot of output for just a bit of input.
- Ptolemy's geocentric model requires as much input as it gives output.
- So although it can be used to predict the motion of the planets, it cannot be used to explain it!

Modern "flat-Earthers" and geocentrists

- In this lecture, we saw concrete examples of how science works and how the scientific method allows us to tell truth from fiction.
- We've seen that geocentrism and flat Earth are two hypotheses that were accepted by ancient people, but discarded once we learned how to use science to study the universe.
- Despite all the very conclusive evidence against these hypotheses, some people still believe in one or both of them even today.

Modern "flat-Earthers" and geocentrists

- Like many other anti-scientific beliefs, the main motivation for modern geocentric or flat Earth beliefs is a literal interpretation of religious scriptures.
- These scriptures were written in ancient times, so they reflect the way humans thought the universe works back then, before modern math, science, and astronomy were developed.
- Today we know that religious scriptures are not a reliable source of knowledge.
- In fact, almost everything written in them turned out to be incorrect upon further investigation.

Modern "flat-Earthers" and geocentrists

- A major reason for belief in flat Earth is conspiracy theories which spread misinformation.
- Most of this happens online, for example via YouTube videos.
- In these videos, conspiracy theorists claim that:
  - The Earth is actually flat,
  - This fact is being hidden from the public in an elaborate conspiracy,
  - Every one of the millions of scientists around the world is somehow able to keep this huge secret.
- They never explain why hiding this information would benefit any scientist.

Modern "flat-Earthers" and geocentrists

- Believers in geocentrism or flat Earth are relatively few.
- But there are other beliefs, which are just as irrational, and yet are believed by millions or even billions of people around the world!
- One of these is astrology, and it will be the focus of my next lecture.

Conclusions

- In this lecture we learned about some important concepts in ancient astronomy, such as axial precession and parallax, which are still used today.
- We also learned about some ancient ideas that are no longer used, because modern theories match our observations much better.

- Reading: OpenStax astronomy, section 2.2.
- Exercises: Practice questions are available in the textbook and on the course website.