ASTR 1P01
Brock University
Prof. Barak Shoshany

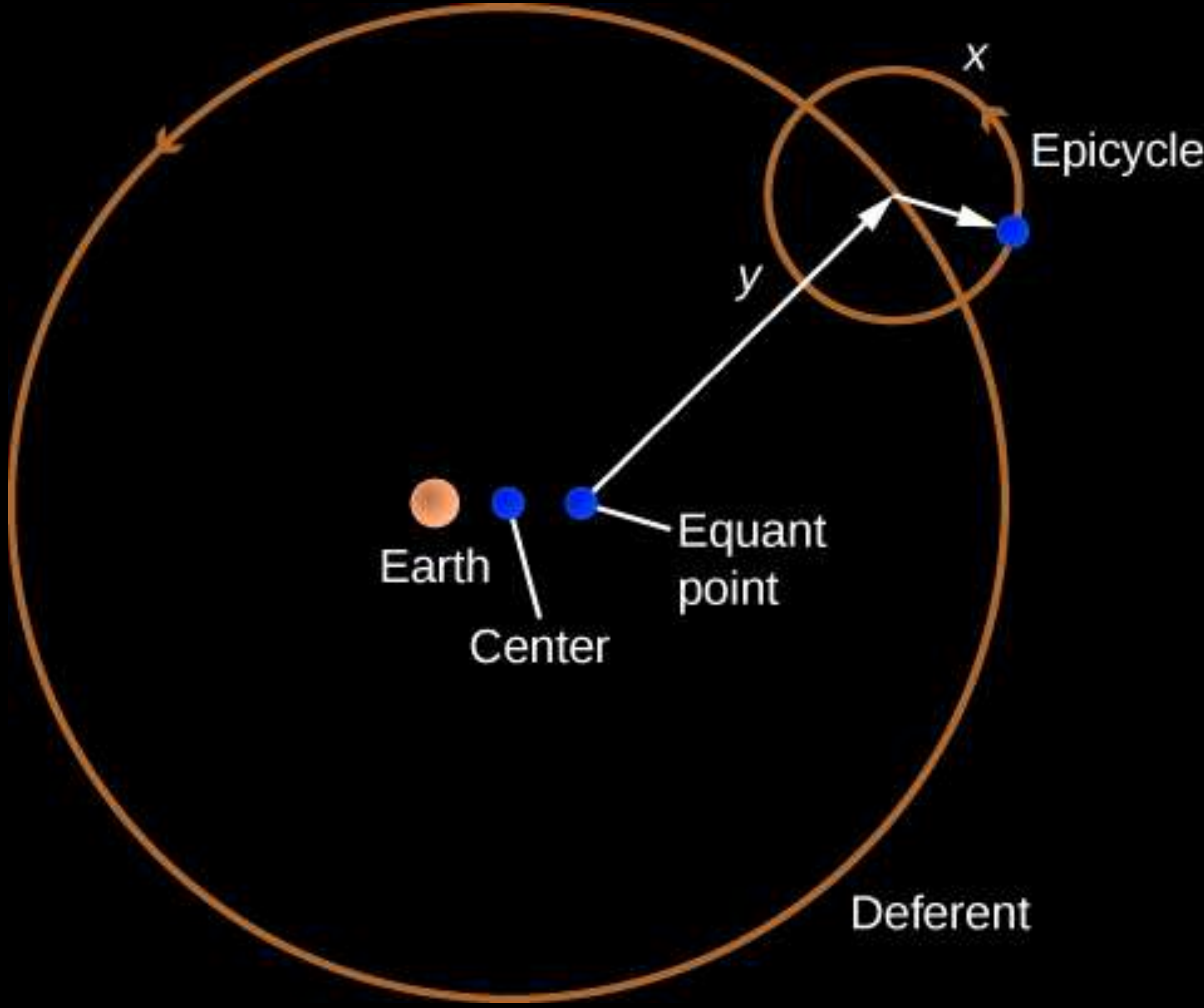
Lecture 5:
Modern astronomy

We will learn about…

- The beginning of modern astronomy in the 16th and 17th centuries.
- One of the most important discoveries in history: heliocentrism.
- Why we don't feel the Earth moving.
- Kepler's laws of planetary motion.

Galaxy IC 5332
Credits: ESA/Webb, NASA & CSA, J. Lee and the PHANGS-JWST and PHANGS-HST Teams

- Let us recall Ptolemy’s geocentric model.
- 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.



After Ptolemy

- Ptolemy’s model was accepted for 1,400 years.
    - Ptolemaic geocentrism: ~150 CE
    - Copernican heliocentrism: ~1550 CE
- During the Middle Ages in Europe, from the 5th to the 15th century, not much progress was made in astronomy.
- People were too busy with plagues, wars, and crusades to worry about scientific advancement.

After Ptolemy

- Meanwhile, Islamic and Persian astronomers and mathematicians made progress.
- They improved many astronomical measurements and developed new mathematical methods.
- They also built the first observatories.

After Ptolemy

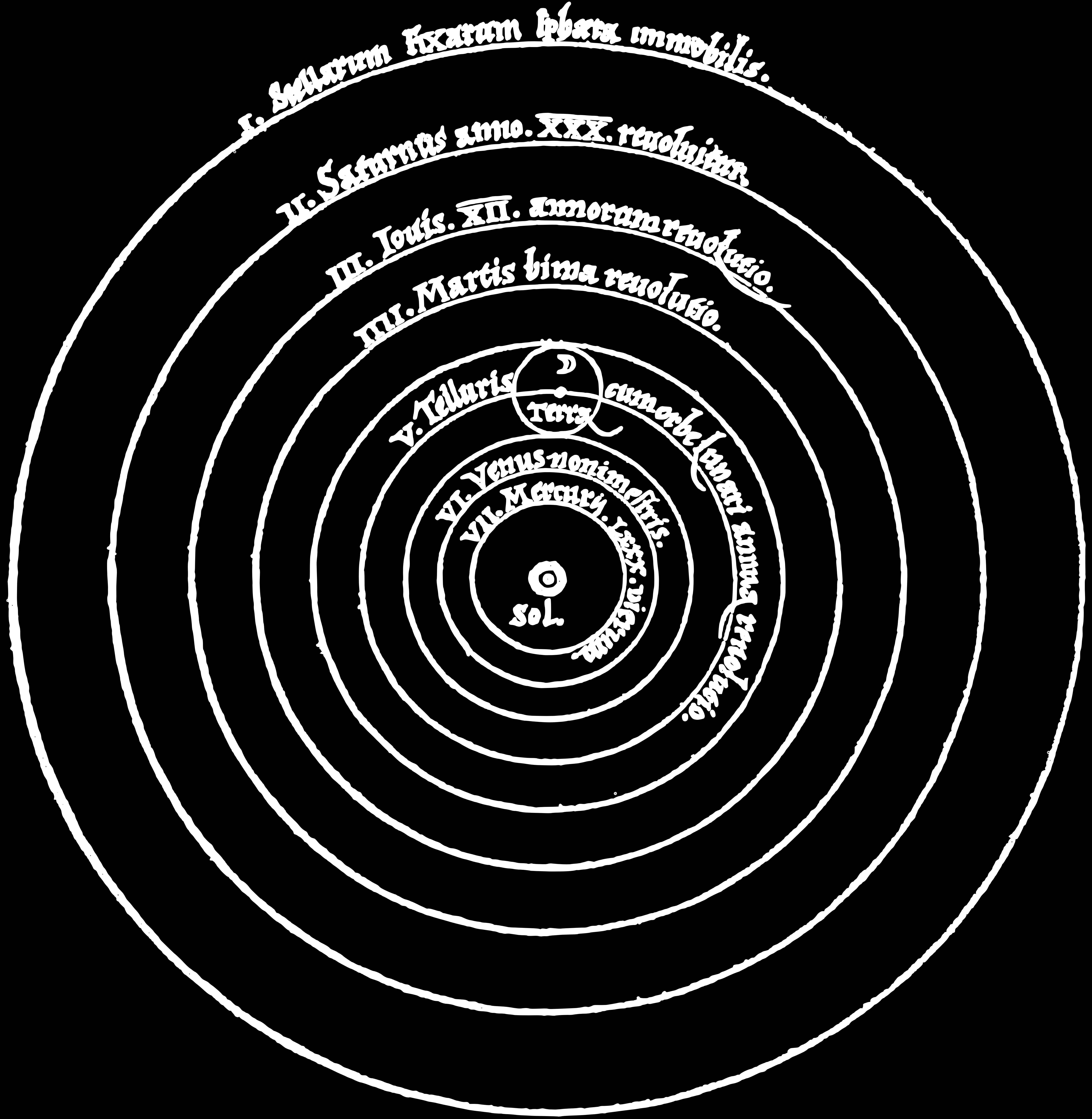
- The first Islamic observatory was built in what is now Iran around 1074.
- The great observatory of Maragheh was built around 1260, also in Iran.
- It contained instruments of very high quality for the time and a huge library of 400,000 manuscripts on astronomy.
- Similar observatories were built in Uzbekistan, in 1420, and Istanbul, in 1575.

After Ptolemy

- Back in Europe, the Renaissance period started in the 15th century.
- Many new developments in mathematics, physics, and astronomy began to appear.
- These developments led to the scientific revolution, which forever changed humanity's understanding of nature and the universe.

Nicolaus Copernicus

- In the 16th century, the Polish astronomer Nicolaus Copernicus developed a new heliocentric model of the solar system.
- The Earth was no longer the center of the universe, just one of several planets orbiting the Sun.
- In 1543, the year of Copernicus's death, this model was published in his book "On the Revolution of the Celestial Spheres".
- This book is often said to be the beginning of the scientific revolution.



The Heliocentric Model from "On the Revolution of the Celestial Spheres“ by Copernicus

Credits: Nicolaus Copernicus

Nicolaus Copernicus

- Copernicus's model correctly placed the Sun at the center, with the Earth and all the other planets orbiting around it.
- It also correctly stated that the celestial sphere stays fixed, and only appears to rotate due to the Earth’s rotation around its axis.

Nicolaus Copernicus

- However, this model wasn't yet fully accurate. It still assumed:
  - The planets were moving in epicycles,
  - The deferents were circles,
  - The epicycles were moving at a constant speed,
  - The celestial bodies were embedded on actual celestial spheres.
- Today we know the orbits of the planets are actually ellipses, there are no epicycles or celestial spheres, and their speed varies along the orbit.

Nicolaus Copernicus

- Heliocentrism wasn't a new idea, it was first suggested in ancient Greece by Aristarchus of Samos.
- Similarly, the idea that the Earth rotates around its axis was already proposed by Heraclides Ponticus, a century before Aristarchus.
- However, these ideas were never taken seriously until Copernicus's time, 1,800 years later.

Nicolaus Copernicus

- Copernicus's work sparked more than a century of scientific progress, known as the Copernican revolution.
- This revolution had two very important outcomes:

1. Practical: After thousands of years, humanity finally had a correct understanding of the structure of the solar system.
2. Philosophical: The idea that humans and the Earth are not special and not the center of the universe, a.k.a. the Copernican principle.
    - We're just one species, on one planet, in one solar system, in one galaxy, among trillions of other galaxies, each of which may contain other forms of life that are no more or less special than we are.

Objections to heliocentrism

- Of course, this heliocentric model raised some objections.
- Some of these objections were religious, because the model contradicts a literal interpretation of the Bible.
- But religious texts are not a reliable source of scientific facts, they only tell us what people believed when they were written, before the scientific method allowed us to determine fact from fiction.
- The reason the Bible is consistent with a geocentric model is that the people who wrote the Bible believed in geocentrism.

Objections to heliocentrism

- Even in Copernicus's time, most people didn't take these religious objections too seriously.
- Copernicus himself wrote in response that the people who claimed his model contradicts the Bible are merely choosing to interpret the Bible in a way that benefits their argument.

Objections to heliocentrism

- On the other hand, objections to Copernicus's model that were scientific in nature were taken seriously.
- One was the absence of stellar parallax, an issue that was already raised by the ancient Greeks in response to Aristarchus.
  - We learned about this in lecture 3.

Stellar Parallax

Credits: OpenStax Astronomy

Objections to heliocentrism

- Perhaps the most important objection was that the claim that the Earth is moving seems to contradict our experience from daily life.
    - Why don't we feel that motion?
    - Why do things that are not bolted down not fly away?
    - Why does a ball dropped from a tall building hit the ground directly below it, instead of in an angle?

Objections to heliocentrism

- The Earth rotates around its axis at a speed of around 0.46 km/s at the equator, and rotates around the Sun at around 30 km/s.
- The ancient Greeks only considered these motions, because in the heliocentric model of Aristarchus, the Sun is the center of the entire universe.

Objections to heliocentrism

- Actually, the situation is much worse than the ancient Greeks thought!
- Today we know that the entire solar system, including the Earth, is moving at 220 km/s around the center of the Milky Way galaxy.
- And the galaxy itself moves at around 1,000 km/s towards the Great Attractor, a mass at the center of the Laniakea Supercluster.

The Flow of Galaxies into the Great Attractor

Credits: Helene M. Courtois, Daniel Pomarede, R. Brent Tully, Yehuda Hoffman, Denis Courtois, from “Cosmography of the Local Universe” (2013).

Objections to heliocentrism

- Copernicus himself didn't have any definitive answers to these objections.
- It his time, people believed in Aristotle's theory that being at rest is the "natural state" of matter.
- This makes sense, because we know that if something is at rest, it tends to remain at rest unless we push it.
- We also know that objects in motion don't keep moving forever, they gradually slow down and eventually stop.
- So it seems that objects indeed "want" to be at rest.

Galileo Galilei

- However, Copernicus's model forced people to think about how motion works.
- This eventually resulted in revolutionizing not only astronomy, but also physics!
- One of those people was **Galileo Galilei**, born in 1564 in Italy.

Galileo Galilei

- Galileo performed experiments, such as rolling balls down inclined planes and studying their motion.
- He deduced that objects don't slow down because they "want" to be at rest, but because they experience friction.
- For example, if I push a box on the floor, it won't move much, because friction from the floor will slow it down.
- But if I push a box on smooth ice, it will move a much longer distance, because it will experience much less friction.
- Theoretically, if I had a perfectly smooth material, with no friction at all, the box would keep moving forever.

Galileo Galilei

- This is due to the law of inertia.
- The inertia of an object is its natural tendency to keep moving at the same speed.
- You need to push or pull the object to make it go slower or faster. Otherwise, it will never change its speed.
- Friction causes the object to slow down and eventually stop, but if there was no friction, the object would keep moving forever at the same speed.

Galileo Galilei

- Galileo used this argument to conclude that being at rest isn't any more natural than being in motion.
- He also formulated the Galilean principle of relativity: the laws of physics are the same in any system that is moving at a constant speed in a straight line.
- This also applies to systems at rest, because being at rest is still moving at a constant speed – that speed being zero.

Galileo Galilei

- Changing your speed requires acceleration.
- As long as there is no acceleration, your speed remains constant.
- So according to Galilean relativity, the laws of physics are the same as long as you're not accelerating.

Galileo Galilei

- What does it mean that "the laws of physics are the same"?
- As long as there is no acceleration, there is no experiment we can do that will tell us at what speed we are moving, or if we are moving or at rest.
- In simpler terms, it means that we can't feel movement at constant speed, we can only feel acceleration.

Galileo Galilei

- Imagine waking up inside a very silent train with no windows.
- If the train is moving at a constant speed, you won't be able to tell if it's moving or at rest relative to the ground.
- You would only feel motion if the train speeds up or slows down (i.e., accelerates).
- This provides an answer to the question of why we can't feel the Earth moving: it's because it's moving at a constant speed.
- If the Earth suddenly changed its speed or stopped moving, we would definitely feel that!

Galileo Galilei

- Galilean relativity also means that all speeds are relative.
- There is no absolute notion of speed. The notion of “speed” of an object is only meaningful relative to another object.
- For example, when we say a car is moving at 100 km/h, we really mean it's moving at 100 km/h relative to the ground. We could also say the ground is moving at 100 km/h relative to the car.
- Both statements are correct and equivalent. There's nothing "special" about the ground, except that it’s something we all secretly agreed to measure speeds relative to.

Galileo Galilei

- The principle of relativity was developed further by Einstein, almost 300 years after Galileo formulated his version. We will learn more about that in the future.

Some more physics

- Going back to objections to heliocentrism, why do things on the ground stay on the ground even if they're not bolted down?
- Intuitively, if you put a box on the roof of your car while it's moving, the box will quickly fly away.
- So the same thing should happen to objects on the surface of the Earth when it moves, right..?
- No, this intuition is wrong. The reason that the box flies away is that there's air resistance causing it to be pushed back.
- The car has its own engine, so it can overcome air resistance, but the box cannot do that on its own.

Some more physics

- What if you put the box on the floor of the car, instead of the roof?
- The box will stay where it is, even though the car is moving.
- That's because the air inside the car moves with it, so there's no air resistance pushing the box back.
- The same thing happens when Earth moves. The air in the atmosphere moves with it, so there's nothing to push objects on the surface away.

Some more physics

- This also explains the other objection, that a ball dropped from a tall building should hit the ground at an angle.
- If you drop a ball from a moving car, then it will fall at an angle due to air resistance pushing it away.
- But if you drop the ball inside the car, it will hit the floor directly below it, even though the car is moving, because both the ball and the air are moving with the car.
- The same happens when you drop a ball from a building. Even though the Earth is moving, the air and the ball are moving with it, so the ball will fall straight to the ground.

Video

This video shows a heavy ball thrown up from a moving truck.
The ball keeps moving with the truck due to inertia.
Later this is repeated with a tennis ball at high speed.
The tennis ball is pushed back due to air resistance.

The video is available at this URL:
https://youtu.be/j1URC2G2qnc

Ball Thrown from a Moving Truck
Credits: Jon White

Some more physics

- Another one of Galileo's important contributions was an experiment demonstrating that falling objects accelerate uniformly.
- If two objects start from rest at the same height, their heights and speeds will be the same at each point in time.
- The two objects will move in exactly the same way.
- Every second, the speed of each object increases by the same amount.

Some more physics

- This contradicts our intuition.
- If we drop a hammer and a feather at the same time, we expect the hammer to fall faster.
- And this is indeed what will happen if you do the experiment, but that result is misleading!
- The feather is very light and will float along any air movements, while the hammer is heavy so the air has almost no effect on it.
- The presence of the air will slow down the feather, but not the hammer.

Some more physics

- However, if this experiment is performed in a vacuum, where there is no air, then both the hammer and the feather will:
  - Fall at the same rate, and
  - Hit the ground at the same time.
- This experiment was even done on the Moon, where there is no atmosphere and no air, and the results were as Galileo predicted.
- This finding again contradicted Aristotle's theory, which was that heavy objects fall faster than lighter objects.

Video

At the end of the last Apollo 15 moon walk, Commander David Scott demonstrated that a hammer and a feather dropped at the same time in a vacuum will fall at the same rate.

The video is available at this URL:

https://youtu.be/oYEgdZ3iEKA

Commander David Scott Dropping a Feather and a Hammer on the Moon
Credits: NASA

Galileo's astronomical observations

- The first telescopes were invented in the Netherlands in 1608.
- At first, they were used only to look at objects on Earth, for example for navigation and military purposes.
- Galileo was one of the first people to use a telescope for astronomical observations, with telescopes he built himself.
- His first telescope had a magnification by a factor of 3, which means it made objects look 3 times larger.

A Telescope Built by Galileo with 3x Magnification

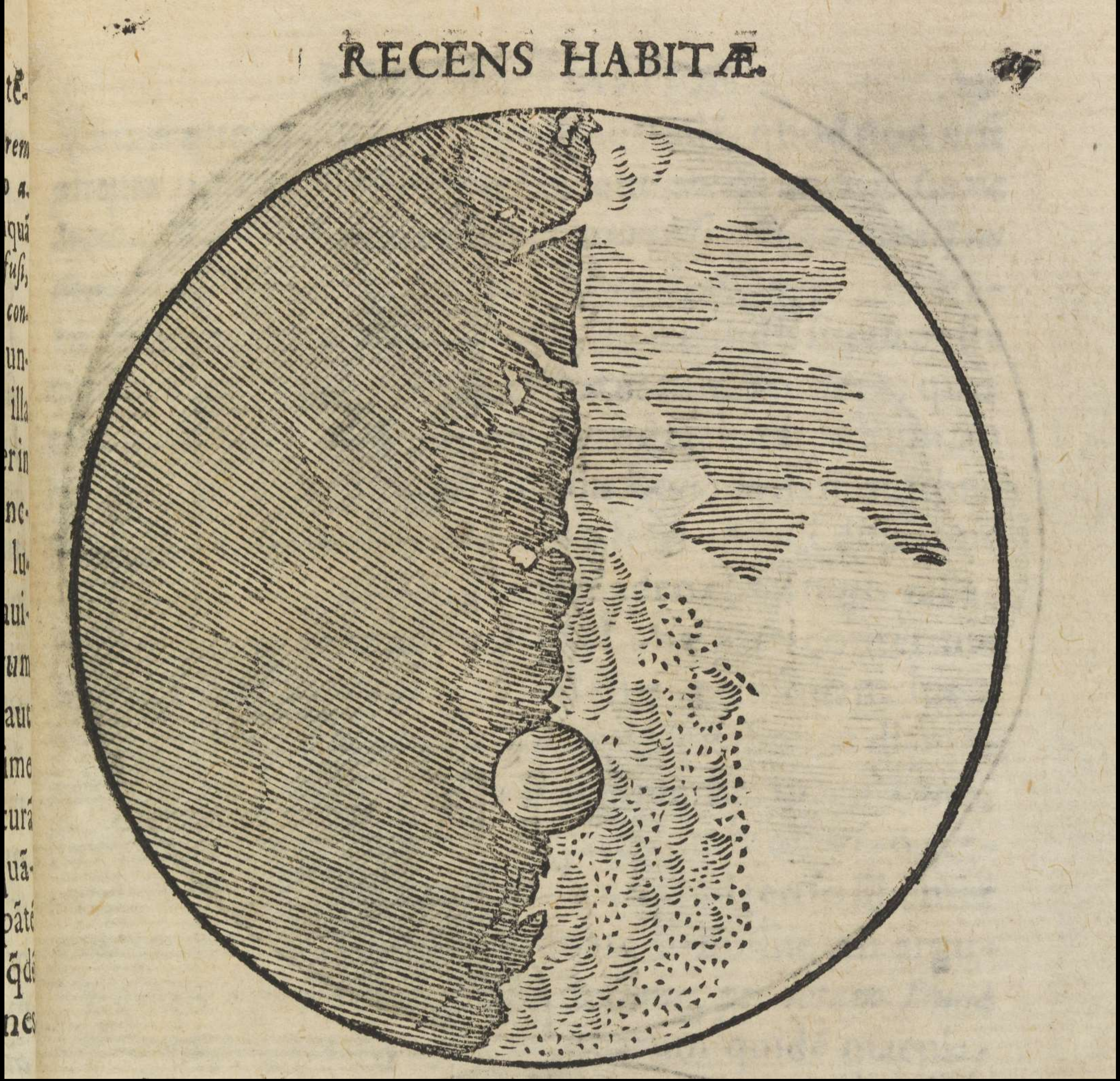
Credits: Openstax Astronomy

Two Telescopes Built by Galileo Around 1609-10

Credits: Sailko (Wikipedia)

Galileo's astronomical observations

- Subsequent telescopes had magnifications up to a factor of 30.
- In 1609, Galileo used his telescope to see mountains and craters on the Moon, and even estimate their height.
- This provided direct evidence against the idea that the Moon was a translucent perfect sphere, which has been accepted since Aristotle.



RECENS HABITÆ.

An Illustration of the Moon, From a Book Published by Galileo in 1610

Credits: Wellcome Images

Galileo's astronomical observations

- This also provided support for heliocentrism.
- If the Moon has mountains and craters as the Earth does, then maybe the Earth and the Moon are not so different.
- And yet, the Moon is a celestial body that moves around in space. So if the Earth is a similar type of object, it can also move in space!

Galileo's astronomical observations

- In 1610, Galileo discovered four of Jupiter's moons: Io, Europa, Ganymede, and Callisto, which are referred to today as the Galilean moons.
- These are the largest of Jupiter's moons, so they were visible using a telescope, but still too small to be visible to the naked eye.
- Today we know Jupiter has (at least) 80 moons, but they were too small to see with Galileo’s telescope.

Jupiter and the Galilean Moons

Credits: Jan Sandberg

Galileo's astronomical observations

- The discovery of Jupiter's moons provided support for the heliocentric model in two ways.
- First, it proved that there are celestial bodies that do not orbit the Earth. So the Earth is no longer the thing that everything orbits.
- Second, one of the objections to heliocentrism was that if the Earth was moving around the Sun, and the Moon around the Earth, then the Moon won't be able to “keep up”, and would be left behind.
- But if the moons of Jupiter can keep orbiting it even though Jupiter is moving, then surely the Earth's Moon can keep orbiting the Earth even if the Earth was moving.

Galileo's astronomical observations

- Galileo also saw with his telescope that Venus has phases, like the Moon.
- This again provided evidence for heliocentrism.
- Venus would have phases whether it orbits the Sun or the Earth, but they would be different phases in each case.
- The phases that Galileo saw were consistent with Venus orbiting the Sun, not the Earth.

Phases of Venus

Credits: OpenStax Astronomy

Galileo's astronomical observations

- Galileo also discovered that there are many more stars than people thought, which are visible only using a telescope.
- Also, he discovered that the Milky Way wasn't a “cloudy strip” in the sky, as was believed at the time, it was made of a huge number of individual stars.
- This meant that the universe was actually much larger and more populous than it seemed until then.

Galileo's astronomical observations

- These discoveries, which contradicted the geocentric model, could be verified by anyone with a telescope.
- Therefore, the vast majority of astronomers of Galileo's time ended up abandoning Ptolemy's geocentric model.
- However, they weren't quite ready to accept the heliocentric model just yet!

Galileo's astronomical observations

- Instead, they created models where the Earth was still at the center, but the other planets were allowed to orbit the Sun.
- These models seemed to explain the new observations, and were easier to accept after believing the Earth is the center of the universe for thousands of years.
- There were even some astronomers who still supported the geocentric model despite all the evidence.
- At least two of them went so far as to literally refuse to look through a telescope and see the evidence!

Religious objections to Galileo

- Unfortunately, the Roman Catholic Church saw Galileo's discoveries as a serious threat.
- As a religious organization, they wanted to maintain the illusion that their holy texts and traditions represented absolute truth that cannot be disputed.

Religious objections to Galileo

- The Church's teachings were compatible with Ptolemy's geocentric model.
- And yet, Galileo presented concrete scientific proof that these religious teachings were wrong.
- If it became known to the public that the Church's teachings about astronomy are wrong, then people might begin to suspect that perhaps the Church's other teachings were wrong too...
- This would, of course, be extremely undesirable, as it could undermine the Church's authority and influence.

Religious objections to Galileo

- The Roman Inquisition was an organization created to prosecute anyone who adopted views different from the Church's religious doctrine.
- In 1616, the Inquisition declared that heliocentrism was heretical due to contradicting the holy scripture.
- Galileo was ordered to stop teaching or defending his scientific discoveries.
- In addition, all books advocating Copernicus's theory were banned, including but not limited to Galileo's own work.

Religious objections to Galileo

- 16 years later, in 1632, Galileo published his book "Dialogue Concerning the Two Chief World Systems", which became quite popular.
- In this book, he presented arguments in support of heliocentrism and against geocentrism, in the form of a dialogue between three characters.
- Galileo was allowed to publish the book under the condition that it presents the Copernican model as "hypothetical".
- He did do that, but he also mocked and ridiculed the geocentric view, and made it clear that the "hypothetical" heliocentric model must be the correct one.

Religious objections to Galileo

- In response, the Inquisition tried Galileo in 1633 and found him guilty of not abandoning his heretical views, as he was previously ordered to do.
- Threatened with torture, Galileo was forced to recant his views, his book was banned, and he spent the rest of his life under house arrest.

Religious objections to Galileo

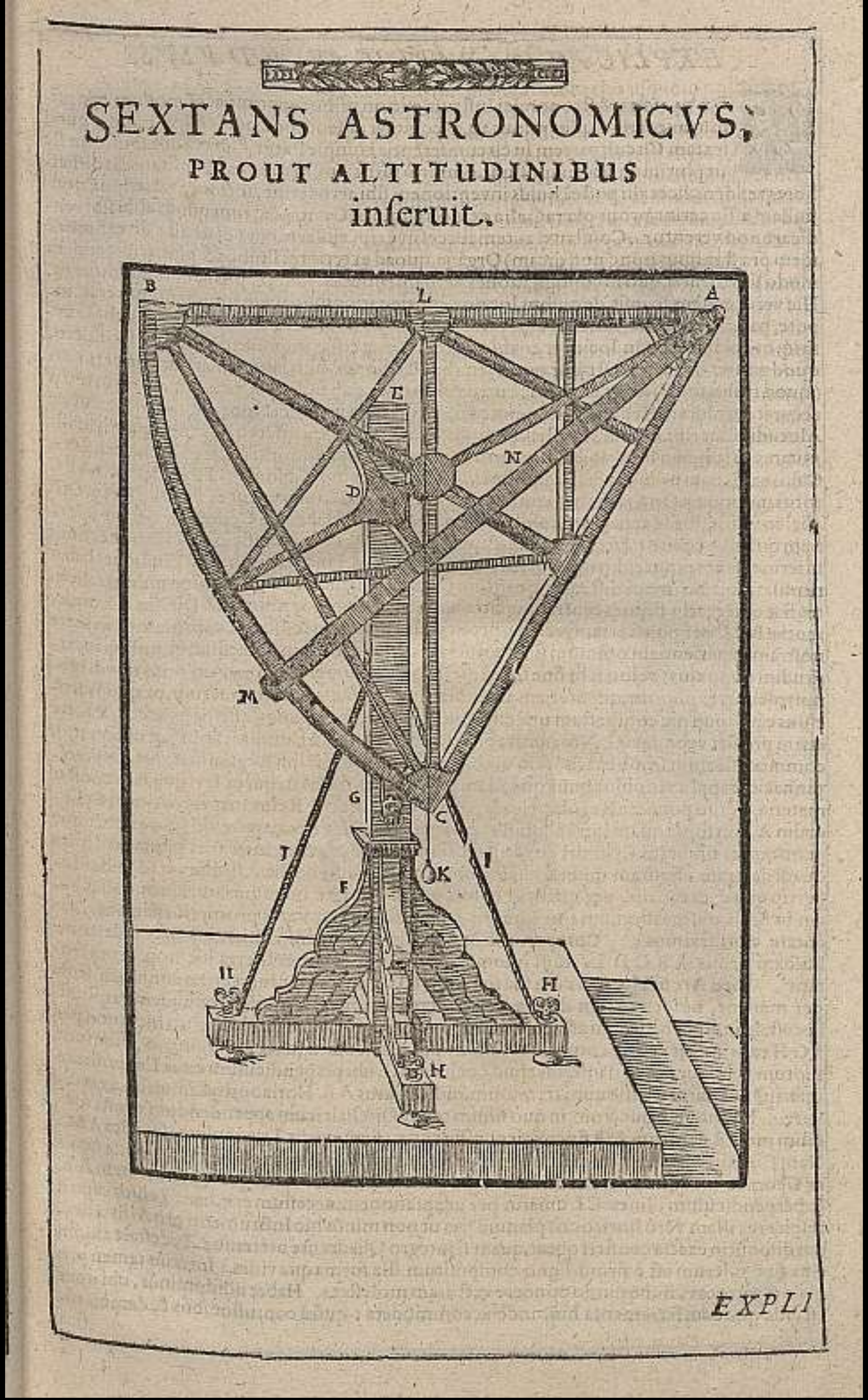
- It was only very recently, in 1992, that the Catholic Church finally admitted that Galileo was right!
- But astronomers have known since the 17th century that Galileo was right, because that's what the scientific evidence says, and anyone with a telescope could repeat the observations and obtain the same evidence on their own.
- Scientific facts are not determined by any organization, no matter how powerful or influential.
- They are determined by performing experiments and observations and collecting evidence to support or refute scientific hypotheses.

Tycho Brahe

- This is why one of the most important parts of the scientific method is collecting empirical data.
- In most fields of science, this data is collected by doing experiments or observing nature.
- In astronomy, this data consists almost exclusively of observations of objects in the sky, mainly through telescopes.

Tycho Brahe

- Tycho Brahe (TY-koh BRAH-he) was a Danish astronomer, born in 1546, 18 years before Galileo.
- He spent most of his scientific career collecting a large amount of accurate astronomical data.
- This was decades before telescopes were invented, so he collected all this data with the naked eye.
- He used instruments such as sextants and quadrants, which he improved to increase their accuracy.



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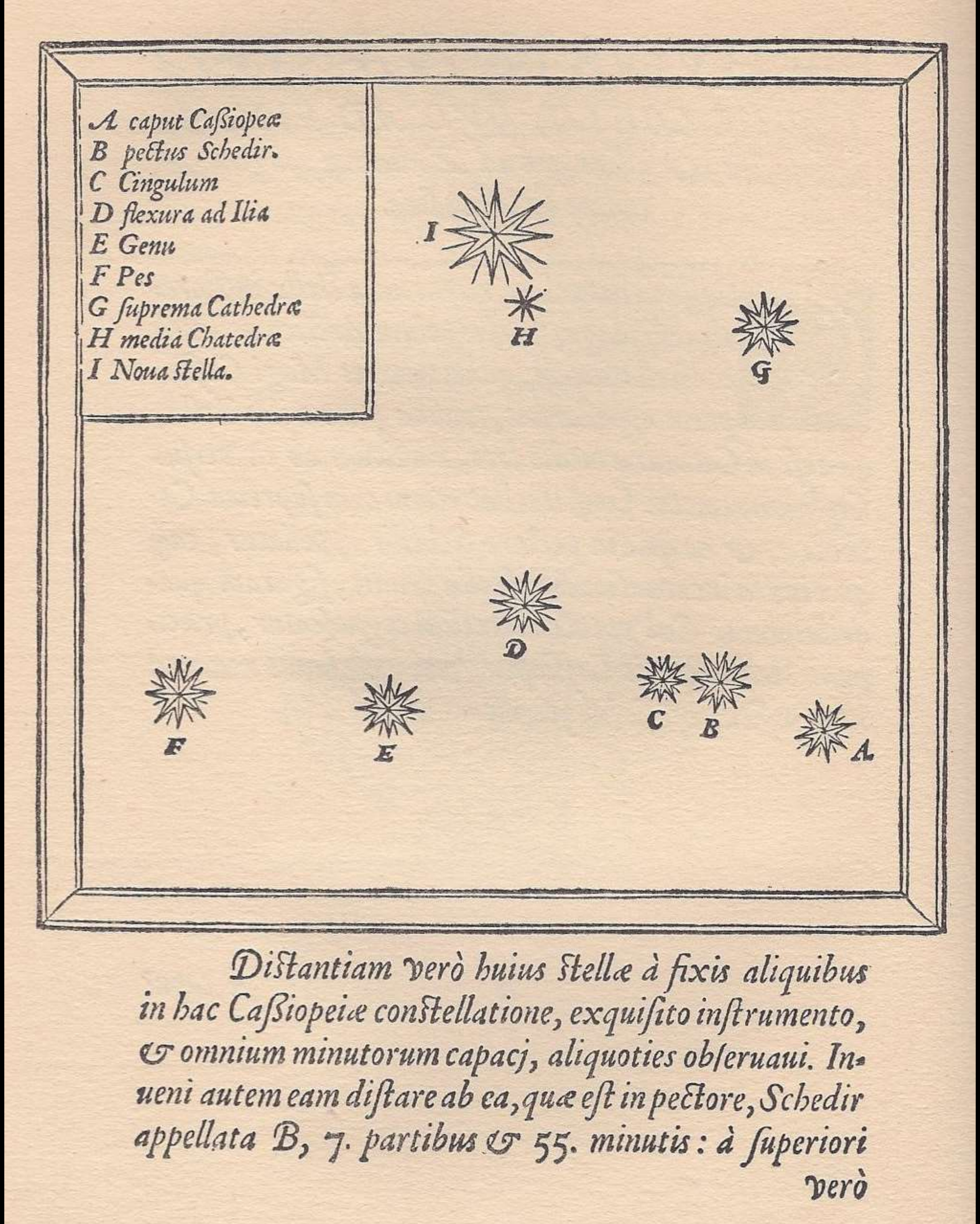
A Large Sextant Used by Tycho Brahe to Measure Angles in the Sky

Credits: Deutsche Fotothek



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Star Map of the Constellation Cassiopeia Showing the Position of the Supernova of 1572

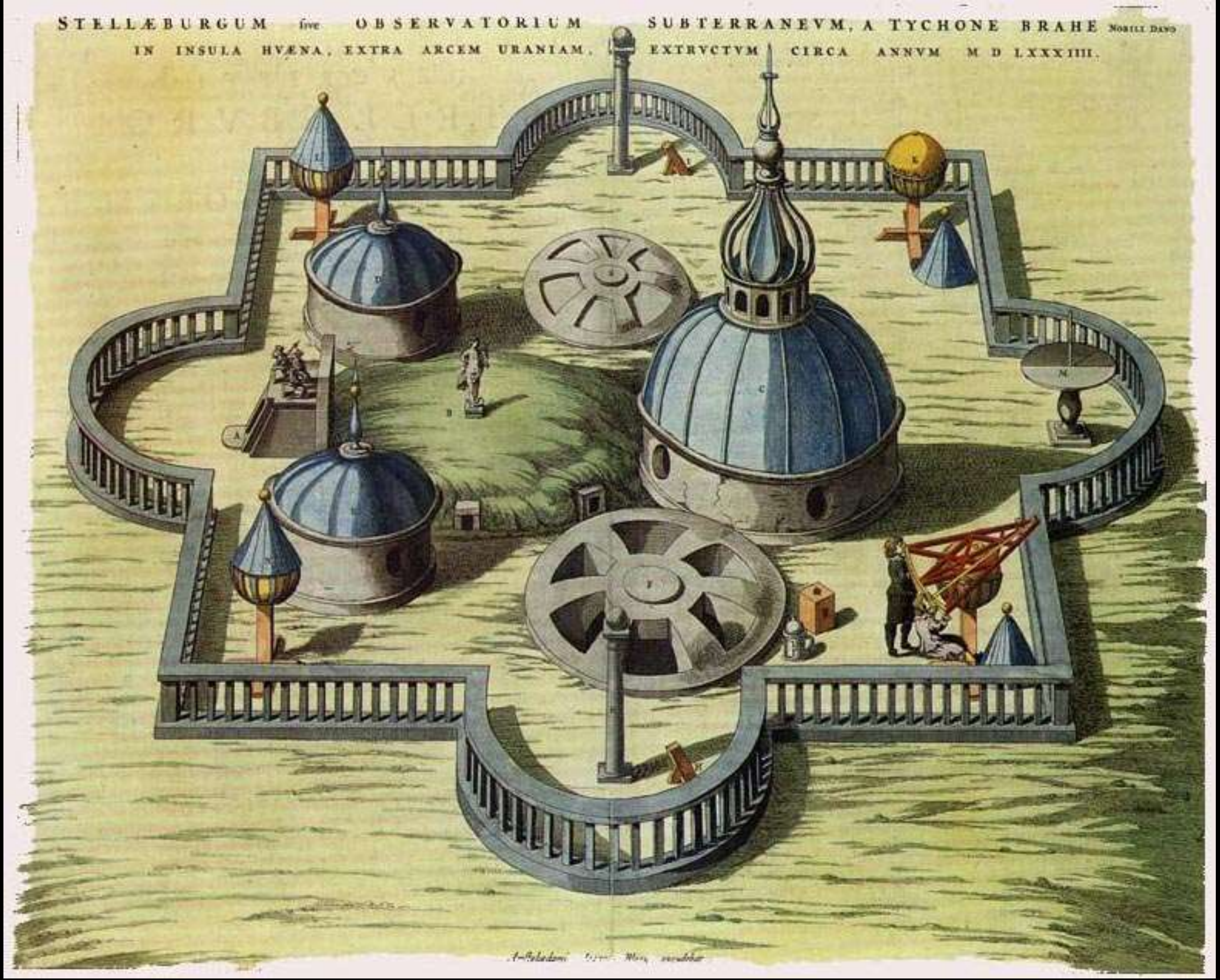
Credits: Tycho Brahe

Tycho Brahe

- Tycho collected data on the positions of the stars, planets, and other celestial bodies at an accuracy of 1 arc minute.
- An arc minute is an angle equal to 1/60 of a degree. So 1 degree equals 60 arc minutes.
- A full circle has 360 degrees, or $360 \times 60 = 21{,}600$ arc minutes.
- That means the data was accurate to 1 part in 21,600, a level of accuracy never seen before.

Tycho Brahe

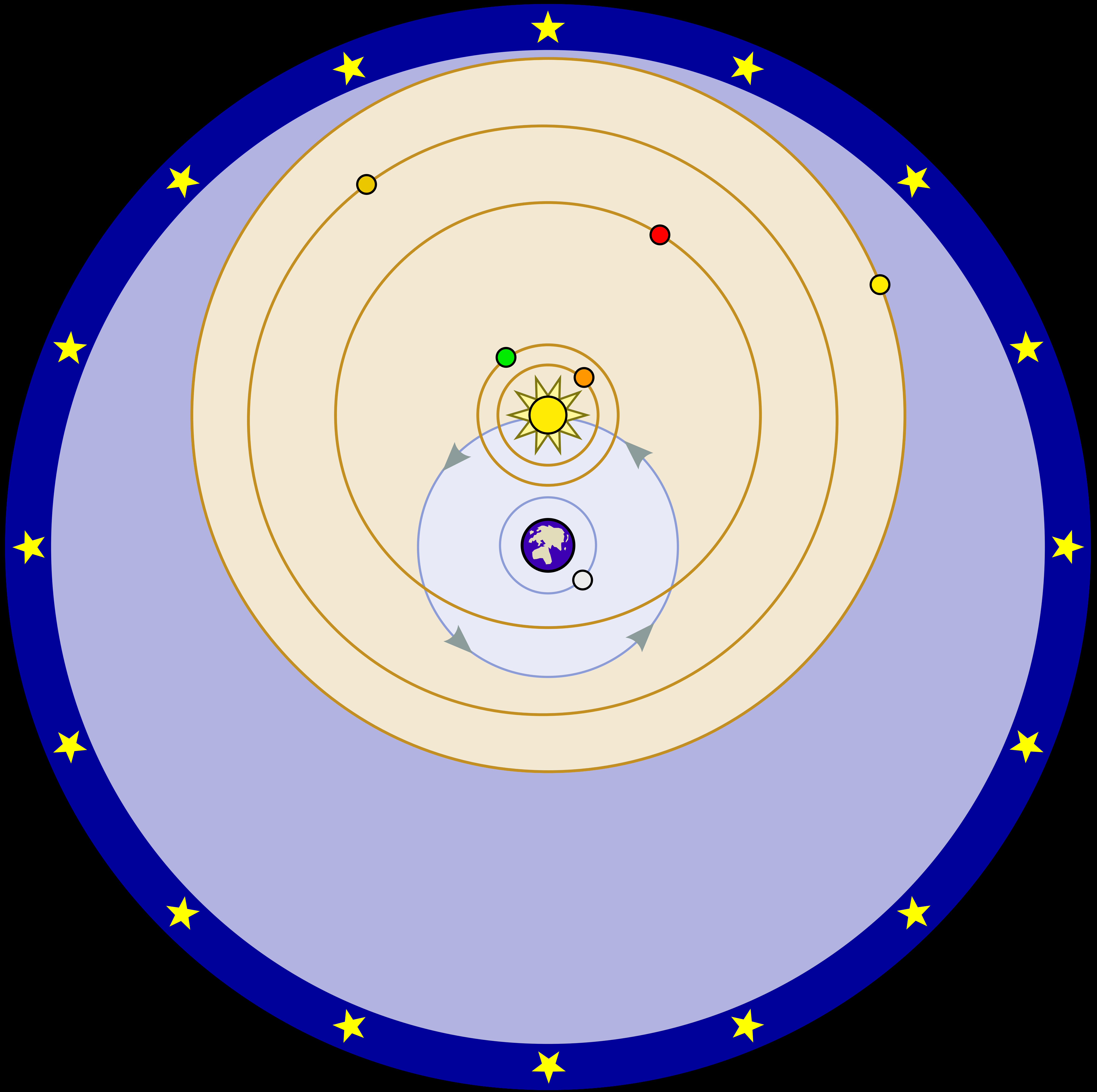
- To achieve this, Tycho developed ways to correct against optical errors.
- He also used new mathematical techniques for facilitating the necessary calculations.
- Over the years he built several observatories and laboratories, where he made his observations and developed new and more precise instruments.



Tycho Brahe's Underground Observatory, "Star Castle"
Credits: Willem Blaeu

Tycho Brahe

- Tycho also created his own model of the solar system, a "geo-heliocentric" model where the Sun and Moon orbited the Earth, and the other planets orbited the Sun.
- It had most of the benefits of the Copernican heliocentric model, while keeping in line with the philosophy of the Ptolemaic geocentric model.
- It's not correct, but at least much closer to correct than the geocentric model.



The Tychonian system

Credits: Fastfission (Wikipedia)

Tycho Brahe

- Tycho's astronomical observations were essential for establishing the necessity of precise and objective measurements as part of the scientific process.
- They were an important contribution to the scientific revolution and to improving our understanding the universe.

Johannes Kepler

- Johannes Kepler was a German astronomer and mathematician, born in 1571, and a key figure in the scientific revolution.
- In 1600 he was hired as Tycho Brahe's assistant.
- He worked on finding a theory of planetary motion based on the data collected by Tycho, in particular the orbit of Mars.
- In 1609, he published his findings in a book called "Astronomia Nova" ("New Astronomy"), one of the most important books in the history of astronomy.

Johannes Kepler

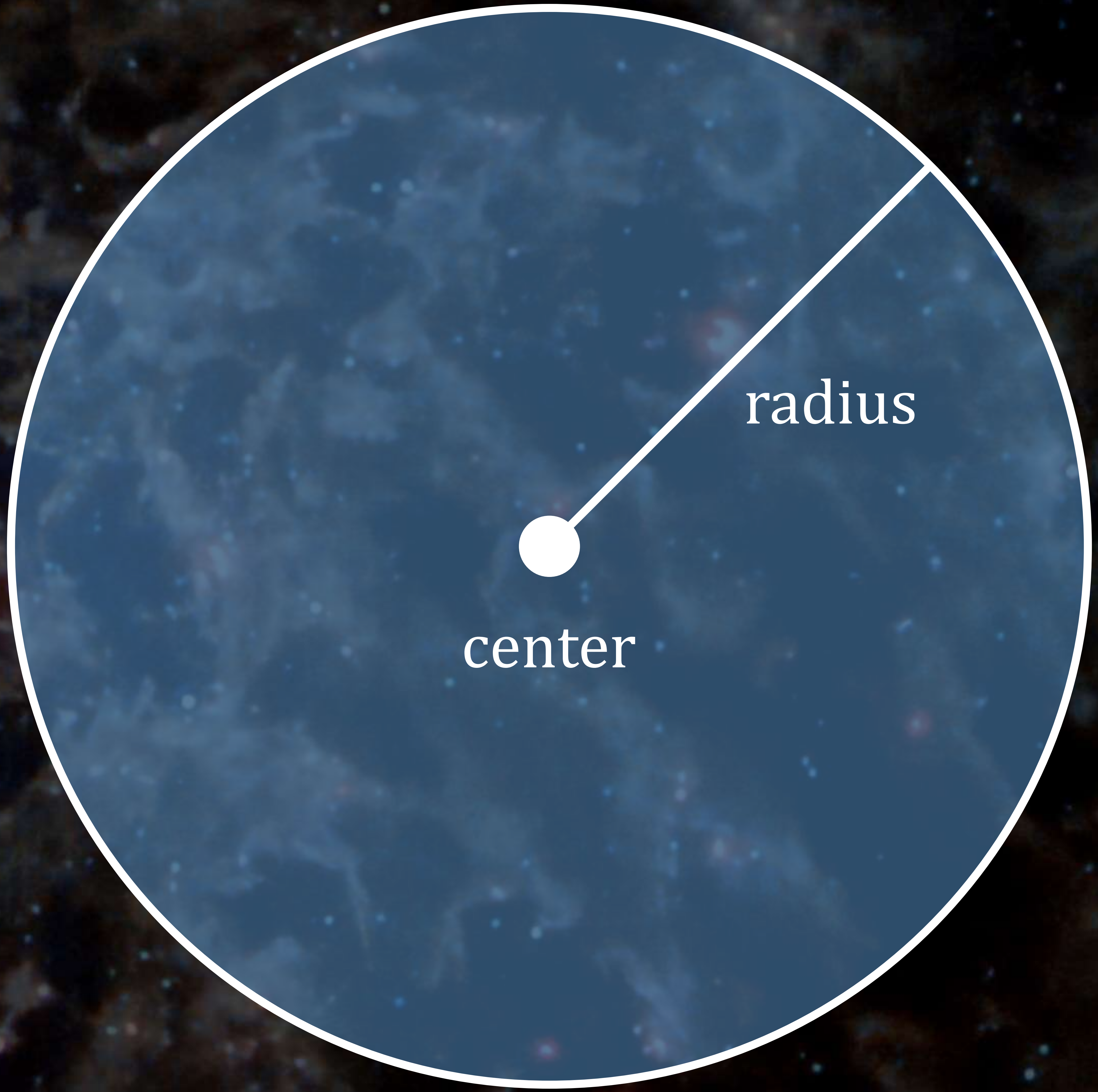
- In his book, Kepler provided evidence for heliocentrism, and improved Copernicus's model by allowing the planets to move along elliptical orbits, instead of circular orbits with epicycles.
- The planets were no longer assumed to be attached to actual celestial spheres, as in Ptolemy's and even Copernicus's models.
- The planets were simply objects moving in space according to certain laws, which we now call Kepler's laws of planetary motion.

Johannes Kepler

- Kepler did not consider elliptical orbits at first.
- He reasoned that since they were so simple, they must have already been considered in the past and found to be unsuitable.
- Therefore, he first tried more complicated oval or "egg-shaped" orbits, which did not fit the data.
- Eventually, in 1604, he found that the data on the orbit of Mars fits an elliptical orbit, and concluded that the other planets must also move in elliptical orbits.

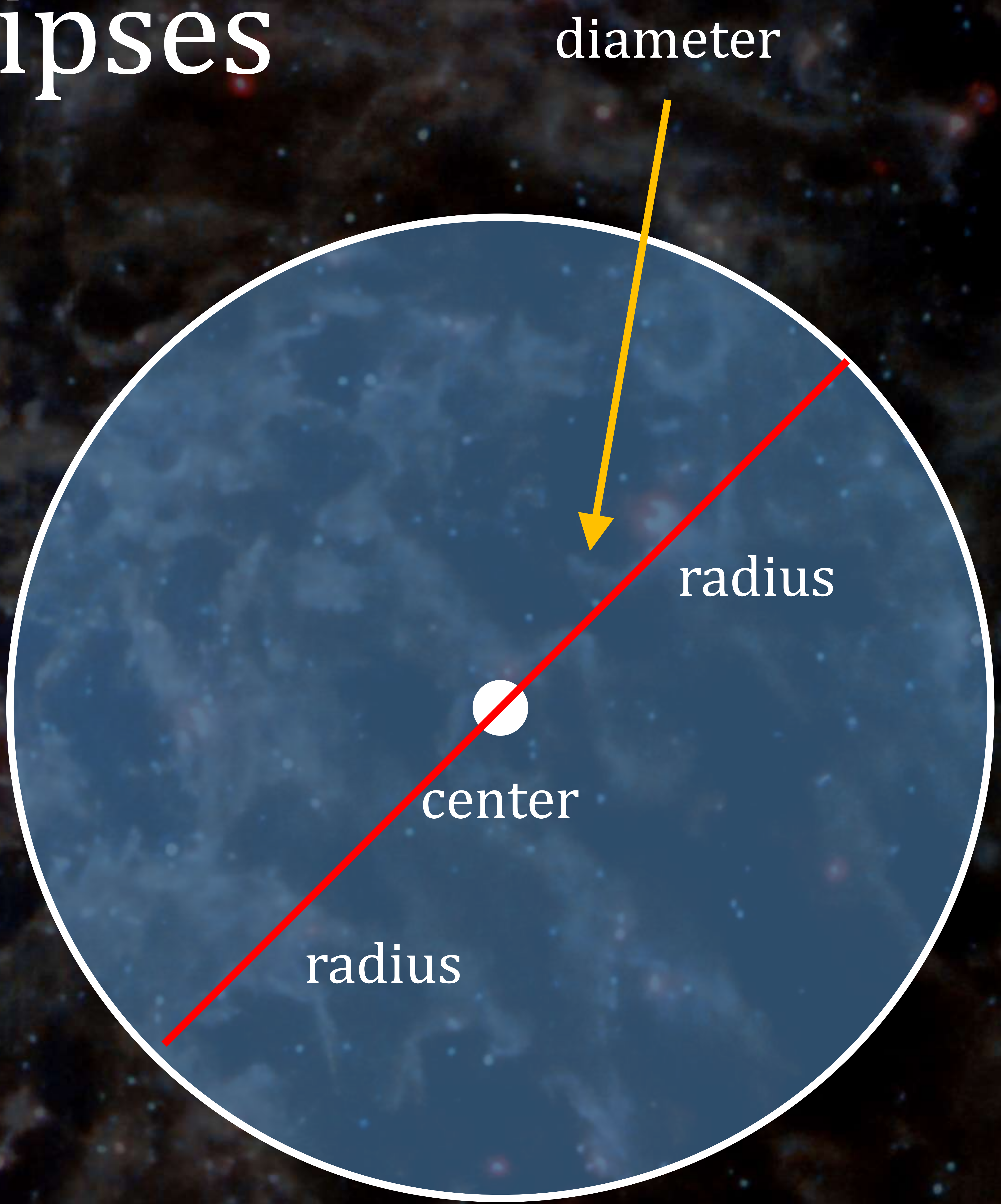
All about ellipses

- To understand Kepler's laws, we must first understand what an ellipse is.
- Let's start by defining a circle. We choose one point as the center of the circle. Then we choose a length as the radius.
- The circle is formed by all the points that are exactly one radius away from the center.



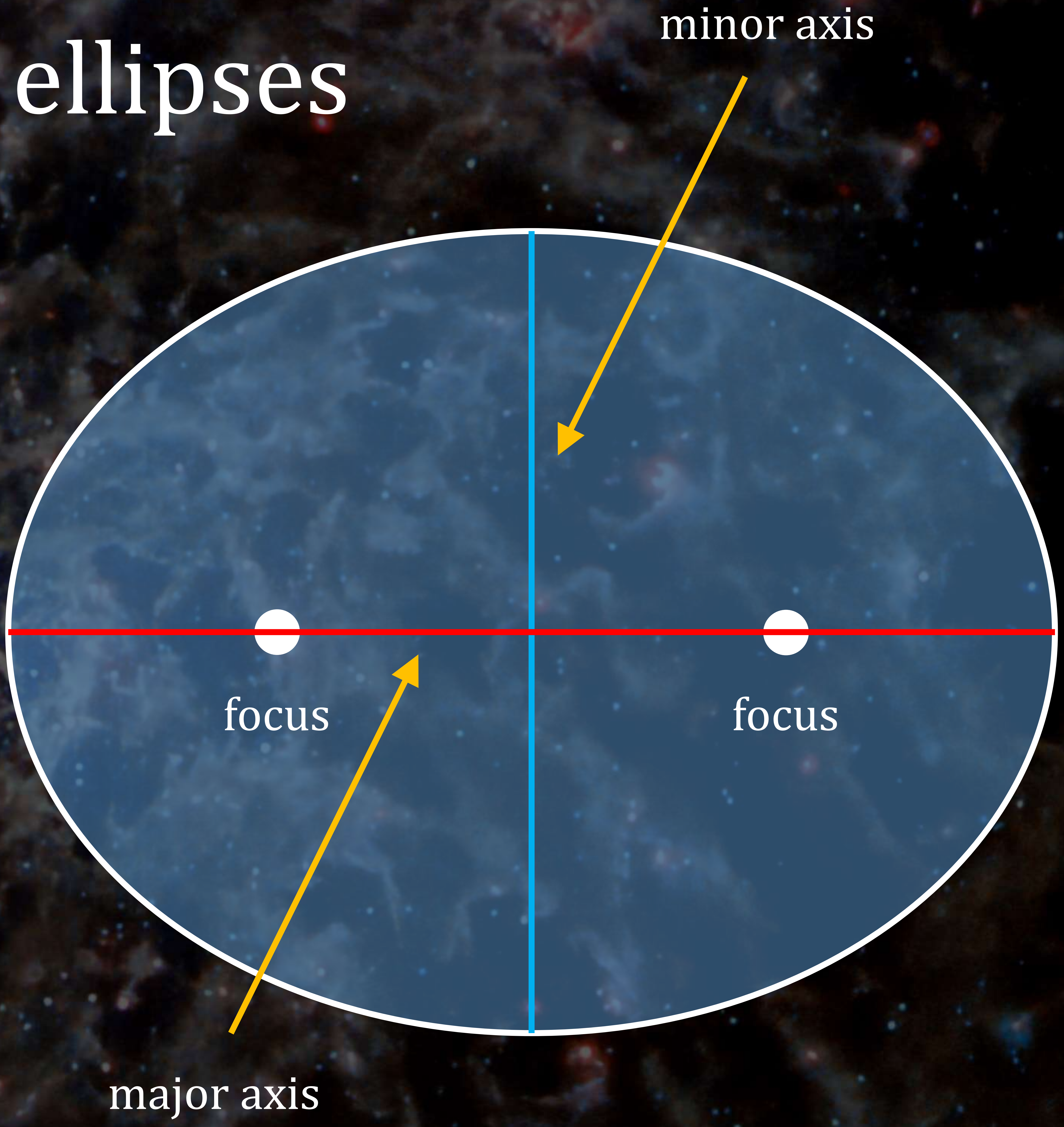
All about ellipses

- The diameter is a line that passes through the center.
- Its length is equal to two radii (plural of radius).
- The diameter is the longest distance between any two points on the circle.



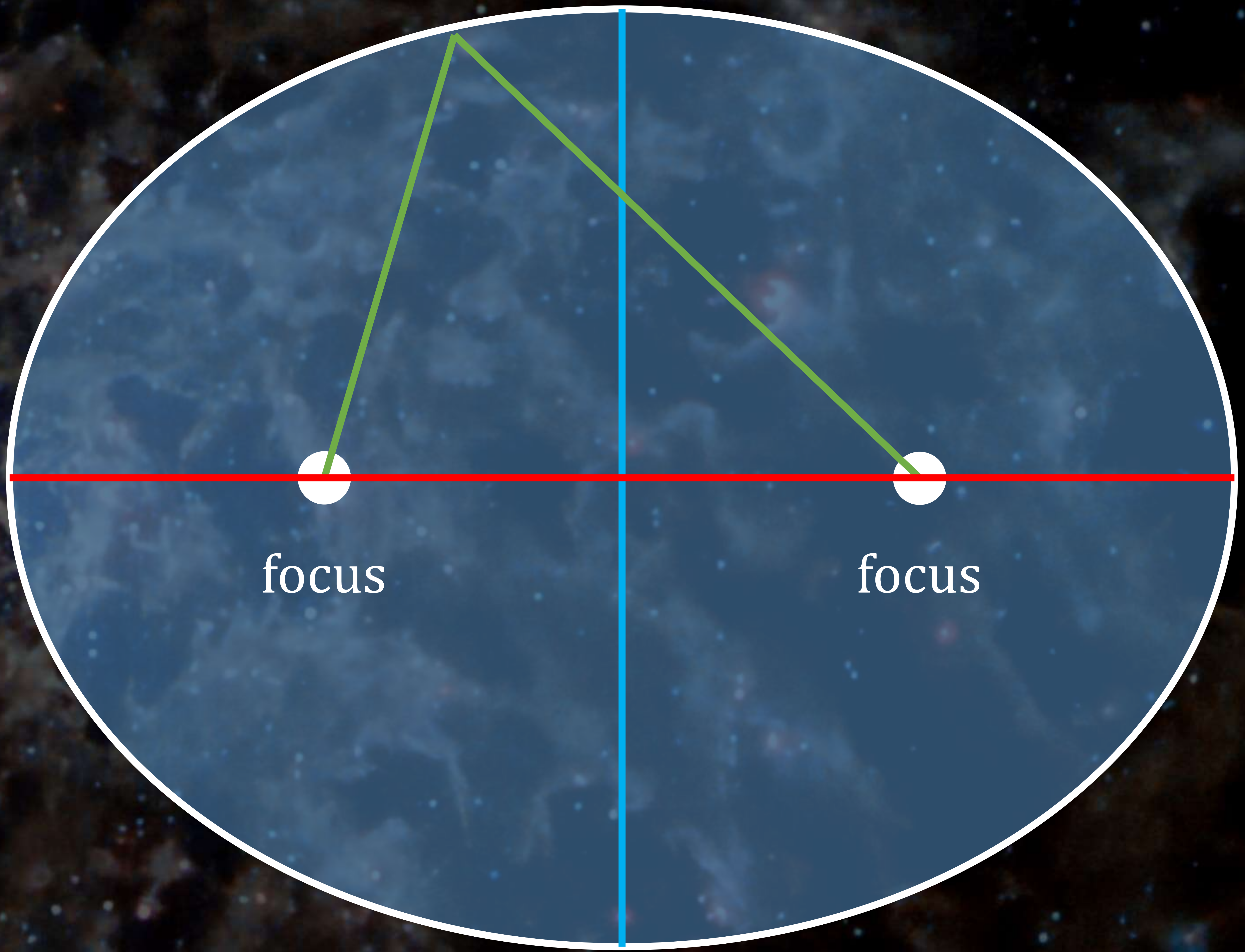
All about ellipses

- An ellipse is basically a circle with two "centers".
- Instead of a center, an ellipse has two focal points (a.k.a. foci).
- Instead of a diameter, it has two axes:
  - Major axis: the line passing through the two focal points.
  - Minor axis: a line perpendicular to the major axis, passing through the center.



All about ellipses

- If we draw two lines connecting any point on the ellipse to the two focal points, then the sum of the lengths of the two lines will be the length of the major axis.
- The ellipse consists of all the points with this property.



Video

This video shows how to draw an ellipse using two pins and a string.
The pins are the foci, and the length of the string is the major axis.

The video is available at this URL:

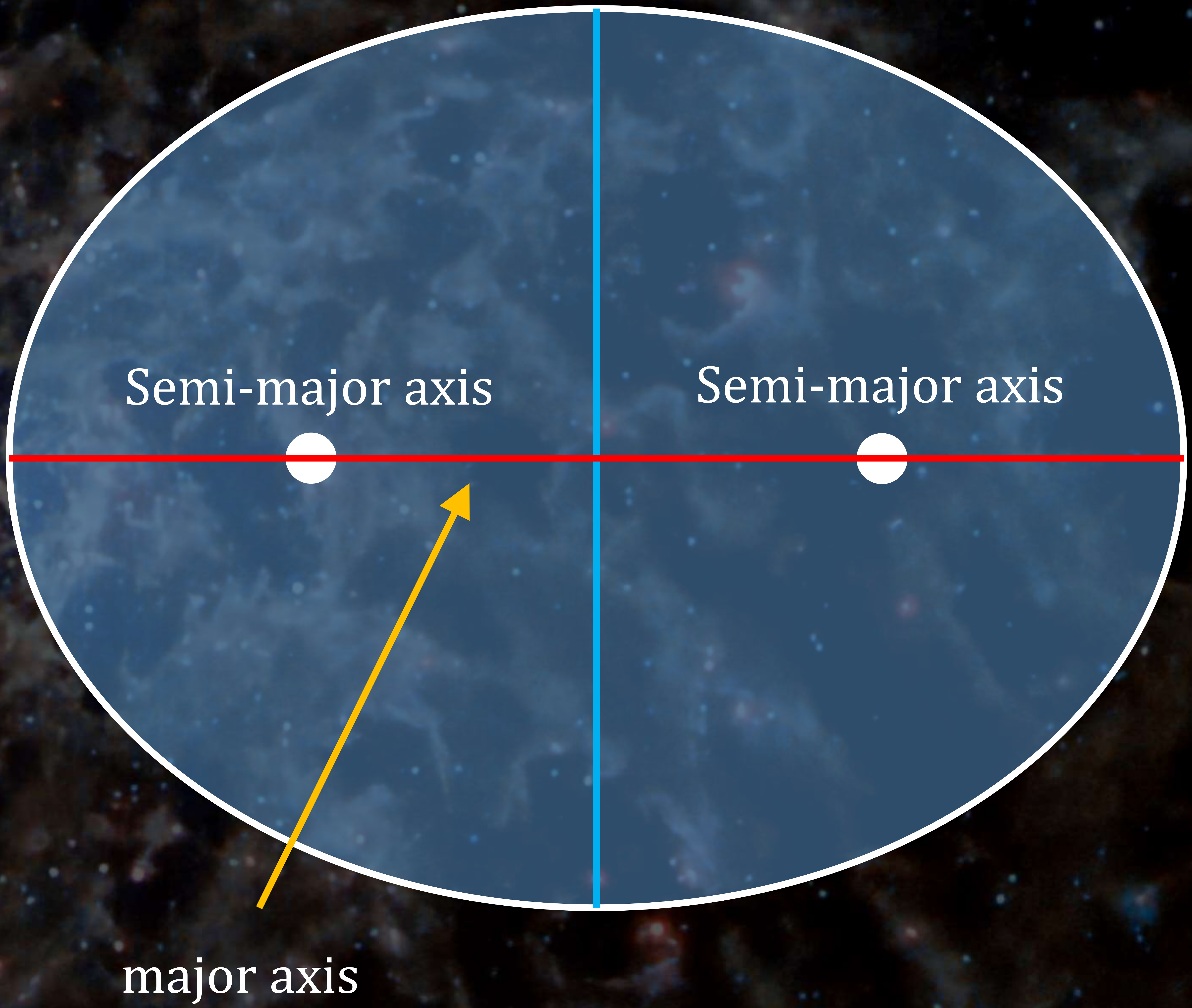
https://youtu.be/Et3OdzEGX_w

Drawing an Ellipse

Credits: TechSquare

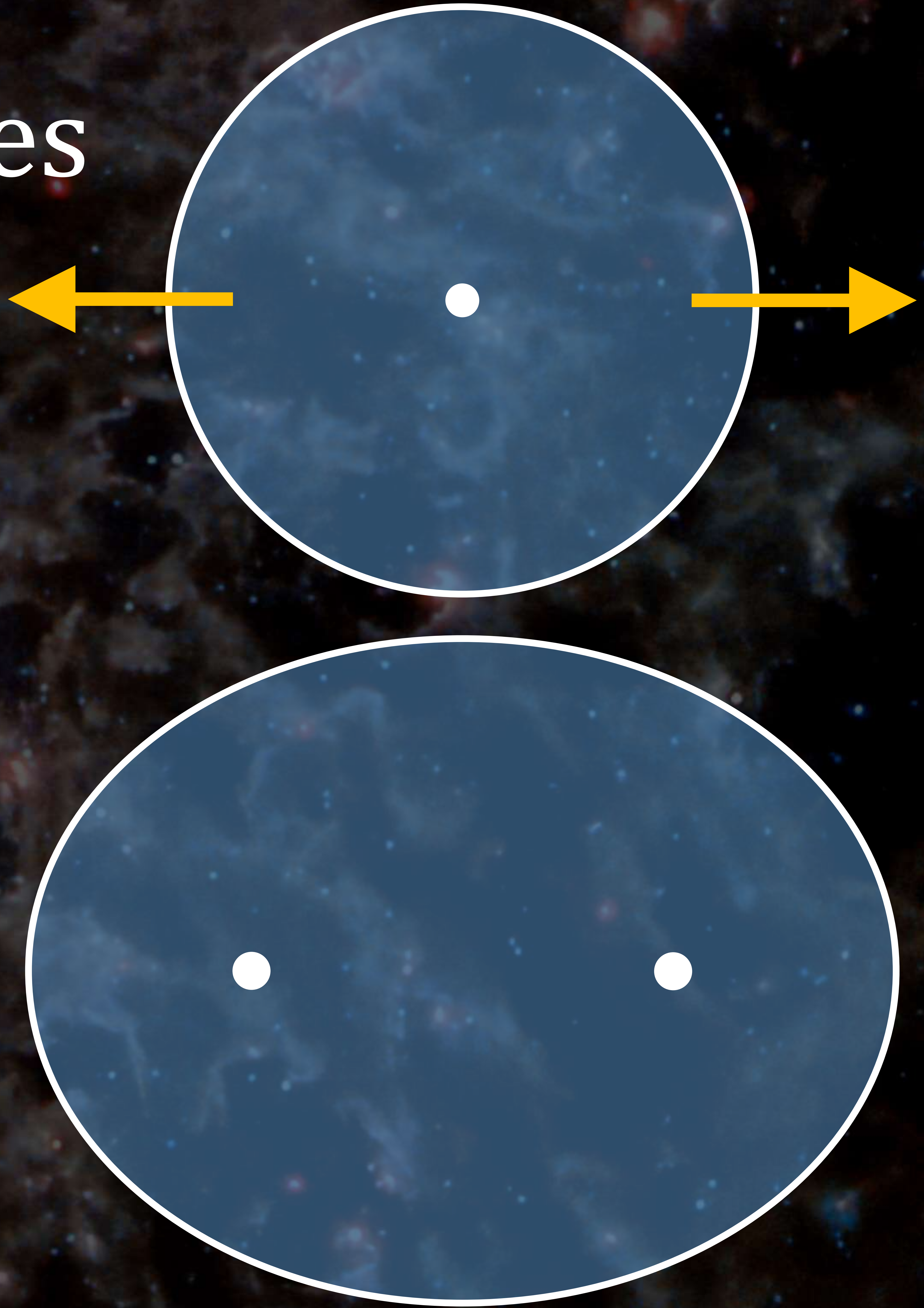
All about ellipses

- The major axis is analogous to the diameter of a circle, which is twice the length of the radius.
- The semi-major axis of an ellipse is half the major axis, and is analogous to the radius of a circle.



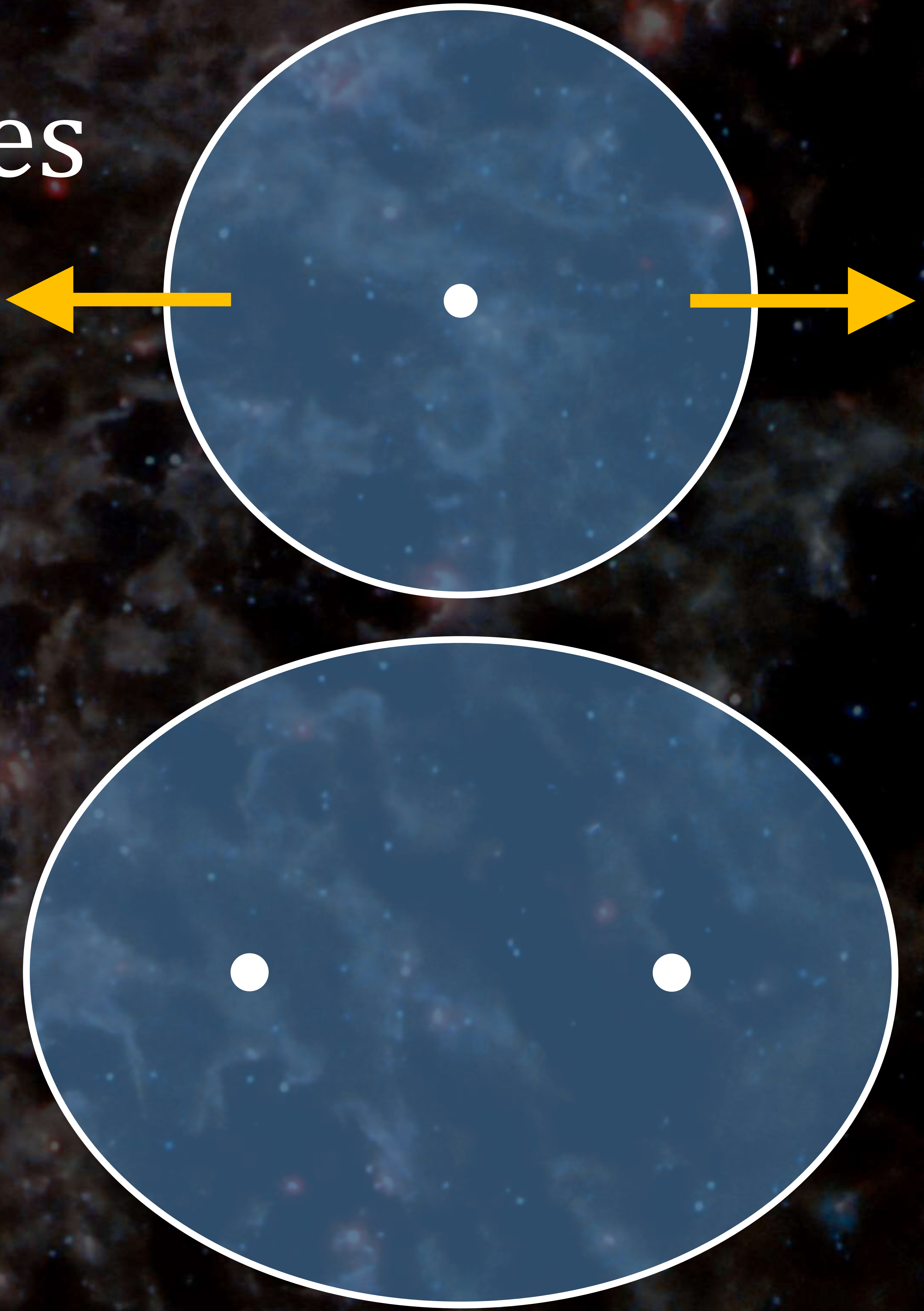
All about ellipses

- Another way to think of an ellipse is as a "stretched" circle.
- Grab a circle at two opposite ends, and pull them apart.
- The ratio of the distance between the two focal points to the length of the major axis is called the eccentricity of the ellipse.
- The wider you stretch the ellipse, the larger its eccentricity.



All about ellipses

- An ellipse with an eccentricity of 0 is just a circle.
    - The two focal points will combine into the circle's center.
    - The semi-major axis will become the circle's radius.
- The maximum possible eccentricity is 1, when the ellipse is stretched so much that it becomes two infinite lines.



Simulation

$(1-c^2)x^2+y^2=1$

$c=0.5$

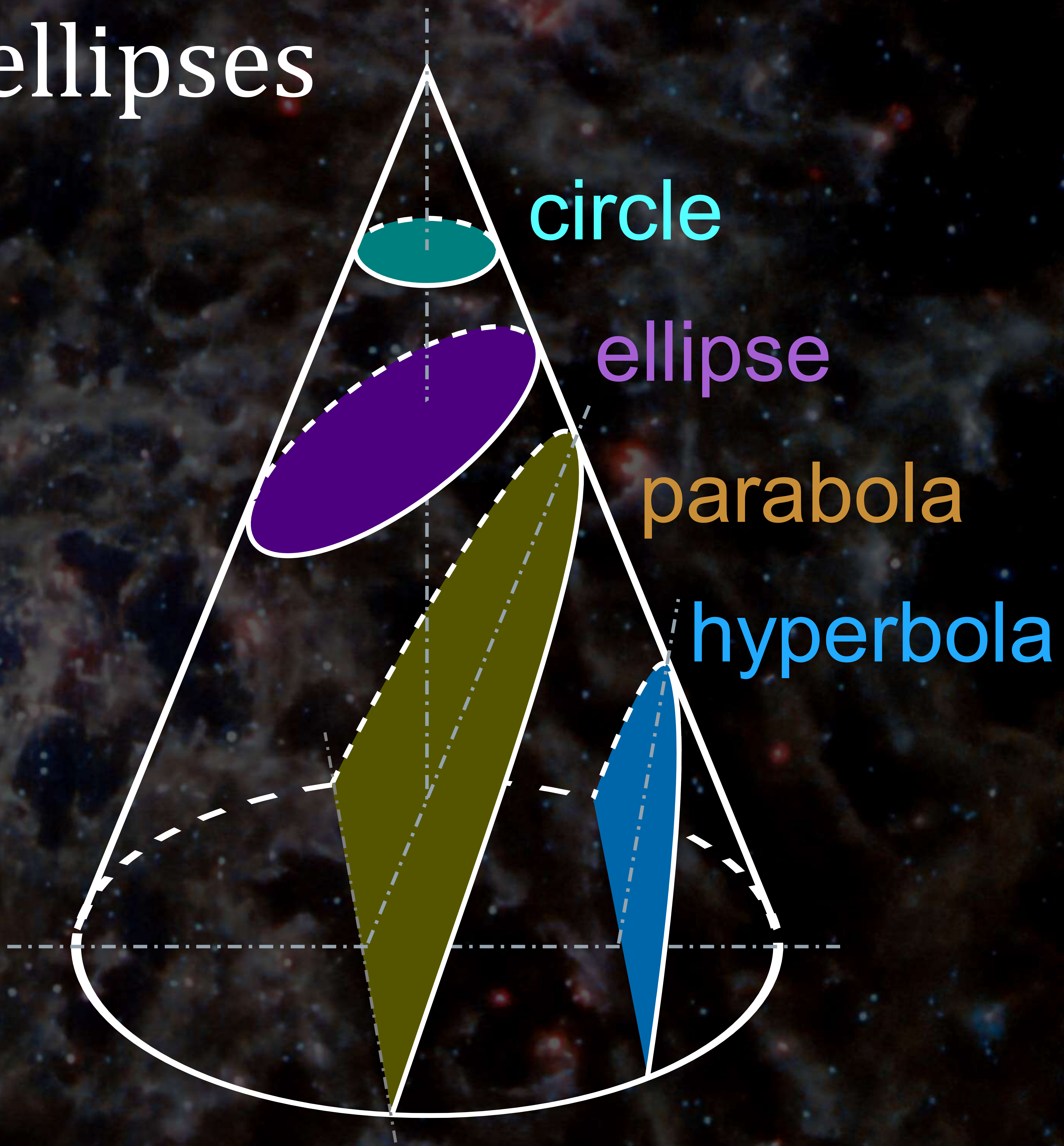
In this simulation you can stretch a circle into an ellipse by increasing its eccentricity.

The simulation is available at this URL:

https://www.desmos.com/calculator/ei1paaik82

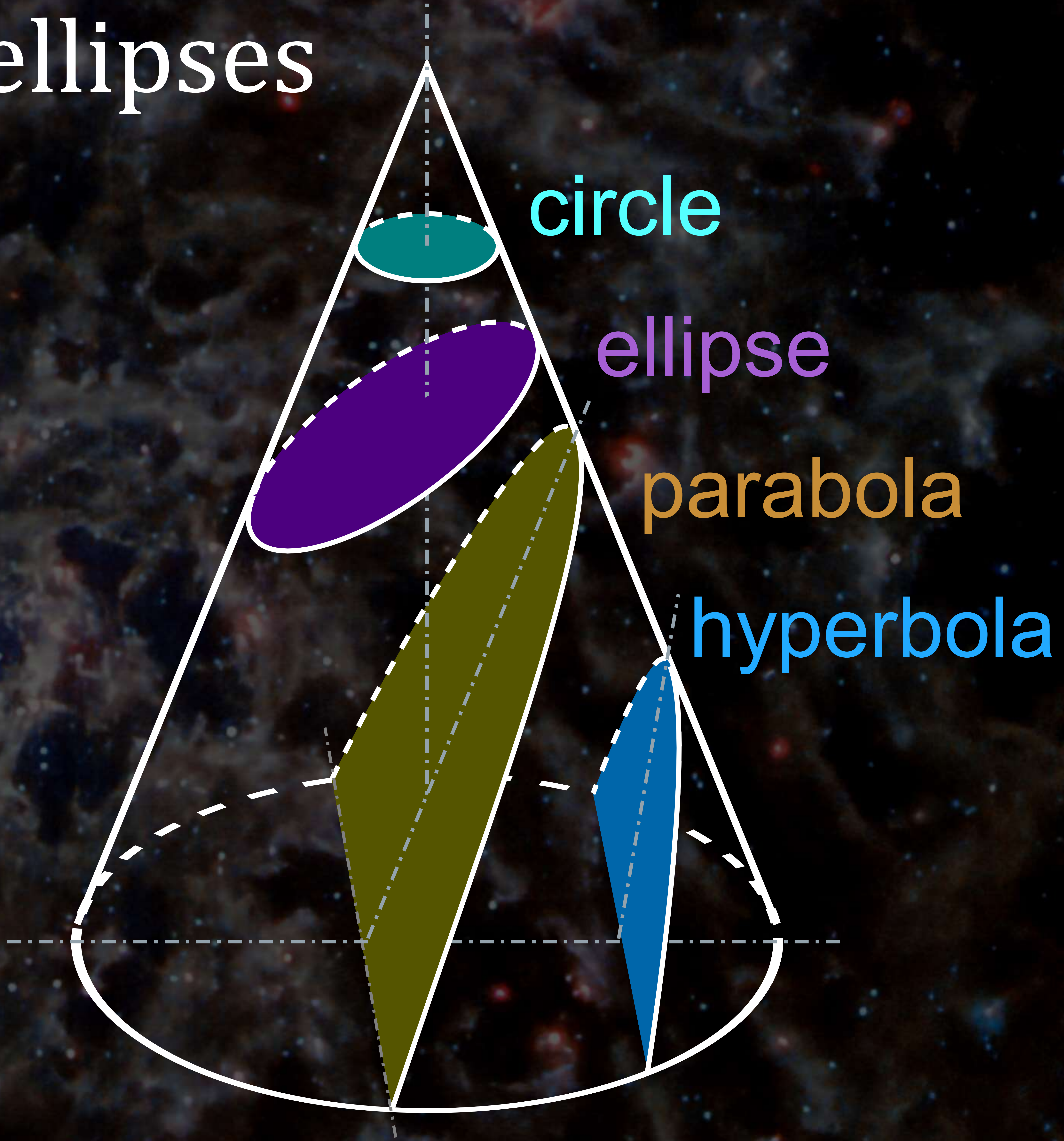
All about ellipses

- Another way to think of an ellipse is as a conic section.
- You can take cross-sections of a cone at different places.
- If the cross-section doesn't touch the bottom of the cone, then it's an ellipse.
- In the special case where the cross-section is parallel to the bottom of the cone, we get a circle.



All about ellipses

- If the conic section does touch the bottom of the cone, it's called a hyperbola.
- In the special case where the cross-section is parallel to the side of the cone, we get a parabola.



Conic Sections

Credits: Magister_Mathematicae (Wikipedia)

Kepler's laws of planetary motion

- Kepler's first law of planetary motion says that the orbit of a planet is an ellipse, with the Sun at one of the two focal points.
- Kepler's second law says that a planet's speed in its orbit is inversely proportional to its distance from the Sun.
- In other words, the planet moves faster along its orbit when it's closer to the Sun and slower when it's farther from the Sun.

Simulation

This is a simulation of a solar system with 1 star and 1 planet, which demonstrates Kepler’s first two laws.

After opening it, go to Physics and increase the Gravitational Constant a bit to make the orbit of the planet more eccentric.

The simulation is available at this URL:

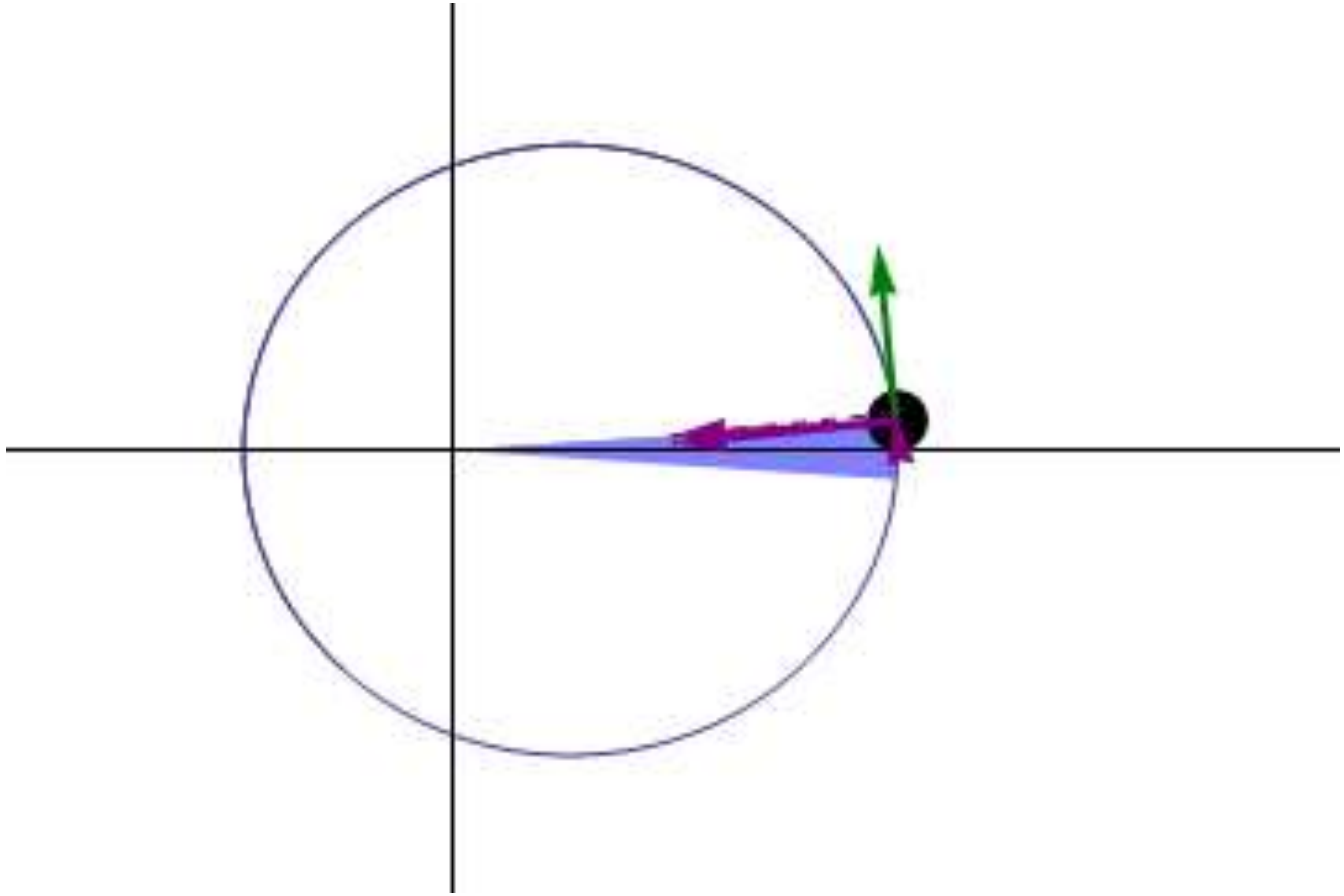
https://gravitysimulator.org/exoplanets/toi-5153-system-with-1-exoplanet

Kepler's laws of planetary motion

- Calculating the speed of the planets at each point on their orbits based on Kepler's second law proved to be very complicated.
- In fact, solving problems like this was one of the reasons behind the development of a new field of mathematics, calculus.
- But since Kepler did not have calculus, he formulated his second law in a geometric way:

“A line segment joining a planet and the Sun sweeps out equal areas during equal intervals of time.”

- The geometrical version of the second law is illustrated in this animation.
- The blue region always has the same area.
- A planet farther from the Sun moves slower, so it sweeps out a smaller portion of the circumference in the same amount of time.
- But this exactly cancels out with the fact that the radius is larger, so in the end the area stays the same.



The animation is available at this URL:

https://en.wikipedia.org/wiki/File:Kepler-second-law.gif

Animation of Kepler's Second Law

Credits: Gonfer (Wikipedia)

Kepler's laws of planetary motion

- Between 1618 and 1621, Kepler published his book “Epitome of Copernican Astronomy”.
- In this book he introduced his third law of planetary motion:

“The square of a planet's orbital period is proportional to the cube of the planet's average distance from the Sun.”

Kepler's laws of planetary motion

- The orbital period is how long it takes the planet to complete a full orbit. This is the length of a year on that planet.
- It can be measured in days. For example, the orbital period of the Earth is 365.25 days.
- The average distance from the Sun is equal to the semi-major axis of the ellipse.
- It can be measured in astronomical units (AU), where 1 AU is the average distance of the Earth from the Sun, which is about 150 million kilometers or 8.3 light-minutes.

Kepler's laws of planetary motion

- In mathematical terms, if:
  - T is the orbital period
  - a is the average distance from the Sun

  Then:

$$a^3 \propto T^2$$

- The constant of proportionality is the same for each planet in the same solar system:

$$\frac{a^3}{T^2} \approx 7.5 \times 10^{-6} \, \frac{\mathrm{AU}^3}{\mathrm{day}^2}$$

Planet	Semi-major axis (AU)	Period (days)	a^3/T^2 (10^{-6} AU^3/day^2)
Mercury	0.38710	87.9693	7.496
Venus	0.72333	224.7008	7.496
Earth	1	365.2564	7.496
Mars	1.52366	686.9796	7.495
Jupiter	5.20336	4332.8201	7.504
Saturn	9.53707	10775.599	7.498
Uranus	19.1913	30687.153	7.506
Neptune	30.0690	60190.03	7.504

Kepler's laws of planetary motion

- When Kepler discovered this law, he attributed it to a sort of musical harmony in the movements of the planets.
- This concept is known as the "music of the spheres", and dates all the way back to Pythagoras.
- However, about 70 years later, in 1687, Isaac Newton showed that this law – and in fact, all three of Kepler's laws – are a consequence of just one simple law, Newton's law of universal gravitation, which we will learn about in the next lecture.

Conclusions

- In this lecture, we learned how the ancient geocentric model was eventually replaced by the modern heliocentric model, which we now know to be the correct model.
- This illustrated an extremely important principle in science: when the data doesn't fit the theory, we must find a better theory.

- Reading: OpenStax astronomy, sections 2.4 and 3.1.
- Exercises: Practice questions are available in the textbook and on the course website.