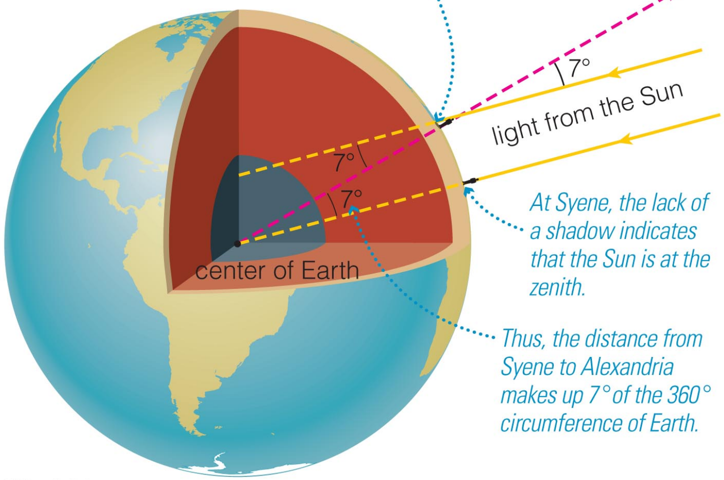
Chapter 3: The Science of Astronomy

3.2 Ancient Greek Science

- Our goals for learning:
  - **Why does modern science trace its roots to the Greeks?**
  - **How did the Greeks explain planetary motion?**

Special Topic: Eratosthenes Finds Spherical Earth and circumference (c. 240 B.C.)

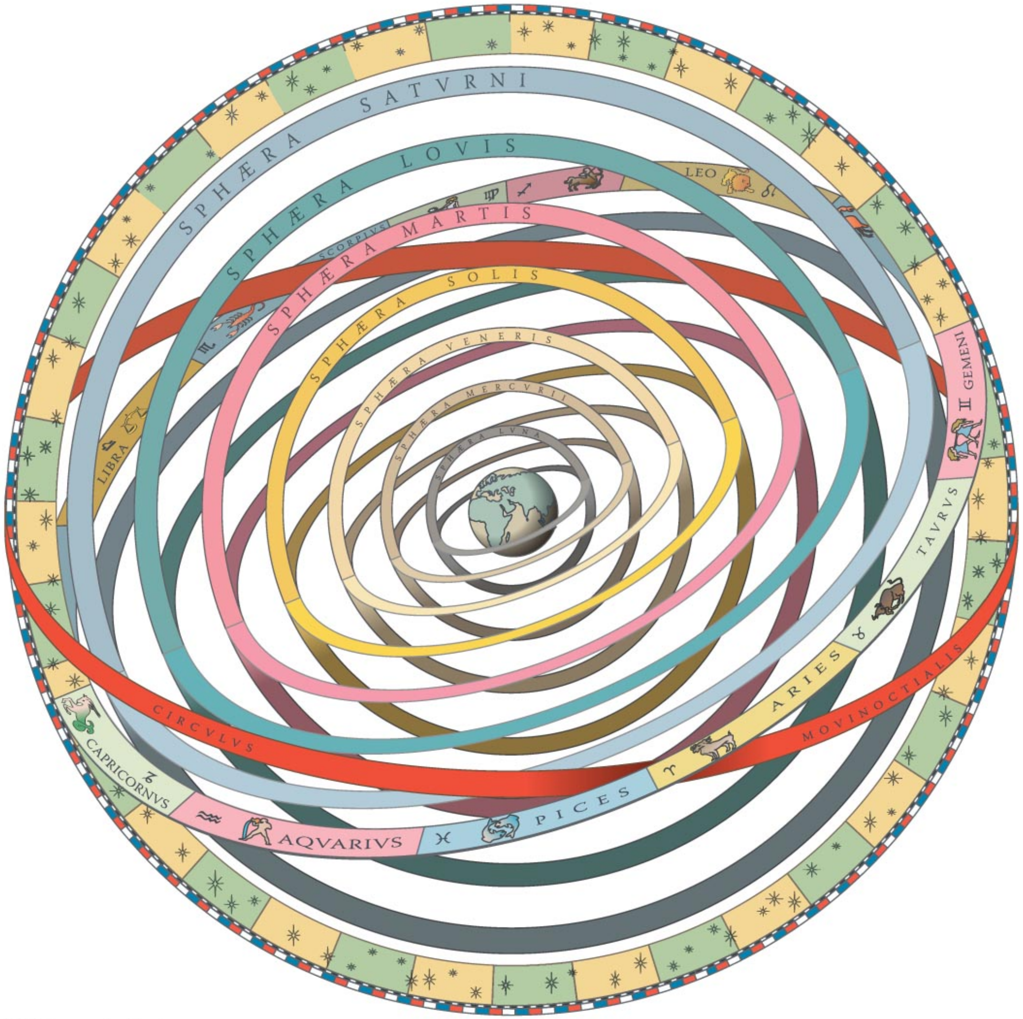
- Measurements:
  - Syene to Alexandria distance ≈ 5000 stadia angle = 7º



  - <u>Calculate circumference of Earth:</u>
    7 : 360 = 5000 stadia : (circum. Earth)
    ⟹ circum. Earth = 5000 × 360 : 7 stadia ≈ 250,000 stadia
  - <u>Compare to modern value (≈ 40,100 km):</u>
    Greek stadium ≈ 1/6 km ⟹ 250,000 stadia ≈ 42,000 km

An error of less than 5%!

Why does modern science trace its roots to the Greeks?



- Greeks were the first people known to make ***models*** of nature.
- They tried to explain patterns in nature without resorting to myth or the supernatural.

- Greek geocentric model (c. 400 B.C.)

How did the Greeks explain planetary motion?

- Underpinnings of the Greek geocentric model:
  - Earth at the center of the universe
  - Heavens must be "perfect": Objects moving on perfect spheres or in perfect circles.

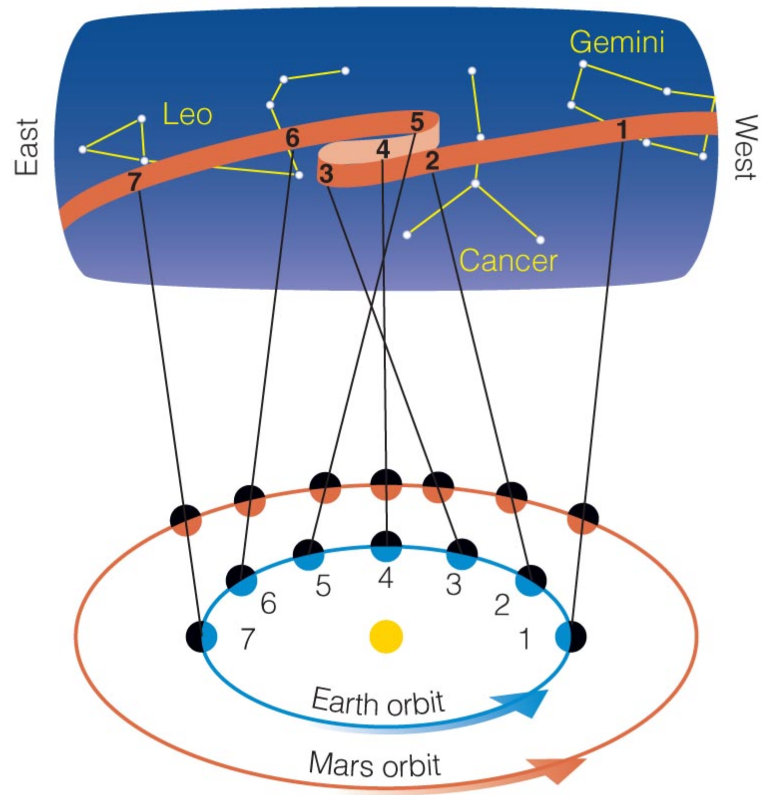
Ptolemy’s model of the Universe

- The most sophisticated geocentric model was that of Ptolemy (A.D. 100–170) — the **Ptolemaic model:**
  - Sufficiently accurate to remain in use for 1,500 years.
  - Arabic translation of Ptolemy's work named *Almagest* ("the greatest compilation")

Ptolemy’s model of the Universe

Source: Andrej Rehak (Principia Universi)

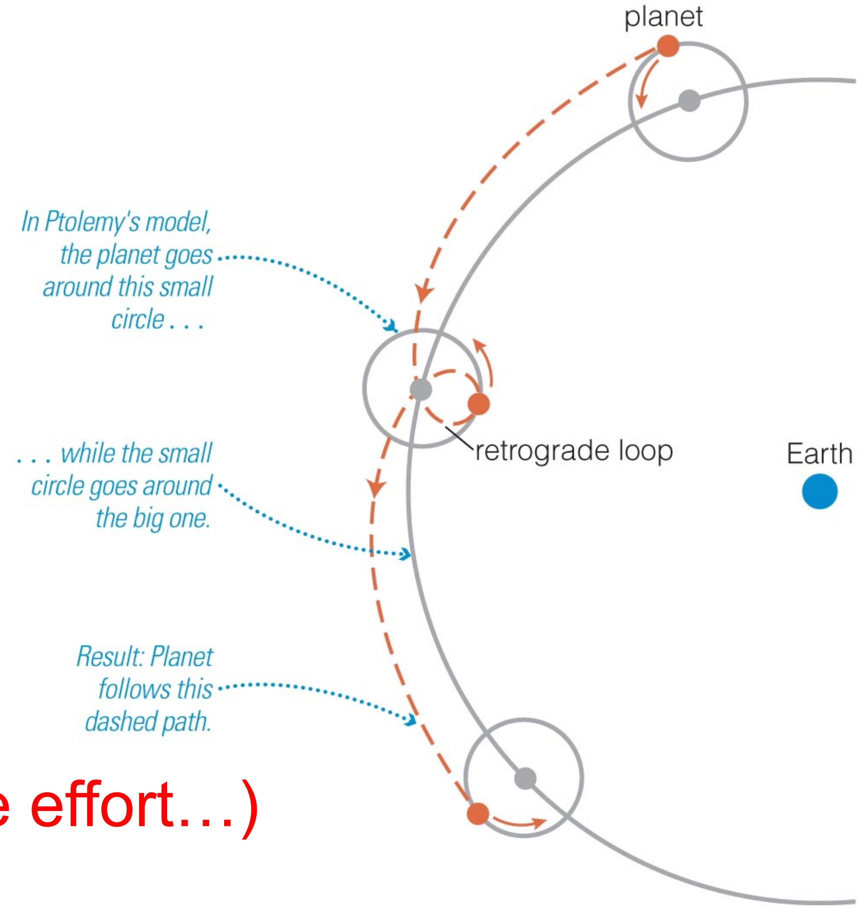
But this made it difficult to explain apparent retrograde motion of planets…



- Review: Over a period of 10 weeks, Mars appears to stop, back up, then go forward again.

But this made it difficult to explain apparent retrograde motion of planets…

- So how does the Ptolemaic model explain retrograde motion?
  Planets *really* do go backward in this model..



(a beautiful, but desperate effort…)

Thought Question

- Which of the following is the prime reason for deciding between the geocentric and the Sun-centered model?

A. Earth is stationary in the geocentric model but moves around Sun in Sun-centered model.
B. Retrograde motion is real (planets really go backward) in geocentric model but only apparent (planets don't really turn around) in Sun-centered model.
C. Stellar parallax is expected in the Sun-centered model but not in the Earth-centered model.
D. The geocentric model is useless for predicting planetary positions in the sky, while even the earliest Sun-centered models worked almost perfectly.

Thought Question

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D. **The geocentric model is useless for predicting planetary positions in the sky, while even the earliest Sun-centered models worked almost perfectly.**

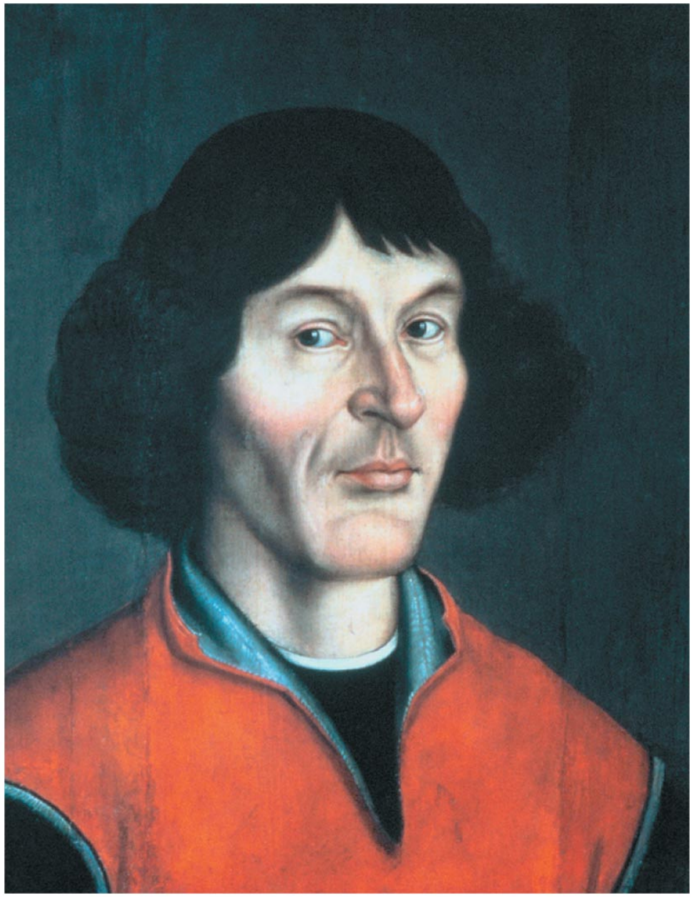
What have we learned?

- **Why does modern science trace its roots to the Greeks?**
  - They developed models of nature and emphasized that the predictions of models should agree with observations.
- **How did the Greeks explain planetary motion?**
  - The Ptolemaic model had each planet move on a small circle whose center moves around Earth on a larger circle.

3.3 The Copernican Revolution

- Our goals for learning:
  - **How did Copernicus, Tycho, and Kepler challenge the Earth-centered model?**
  - **What are Kepler's three laws of planetary motion?**
  - **How did Galileo solidify the Copernican revolution?**

How did Copernicus, Tycho, and Kepler challenge the Earth-centered model?



- Copernicus (1473–1543)

- Proposed a Sun-centered model (published 1543)
- Used model to determine layout of solar system (planetary distances in AU) But . . .
- The model was no more accurate than the Ptolemaic model in predicting planetary positions, because it still used perfect circles.

How did Copernicus, Tycho, and Kepler challenge the Earth-centered model?

- Tycho Brahe (1546–1601)

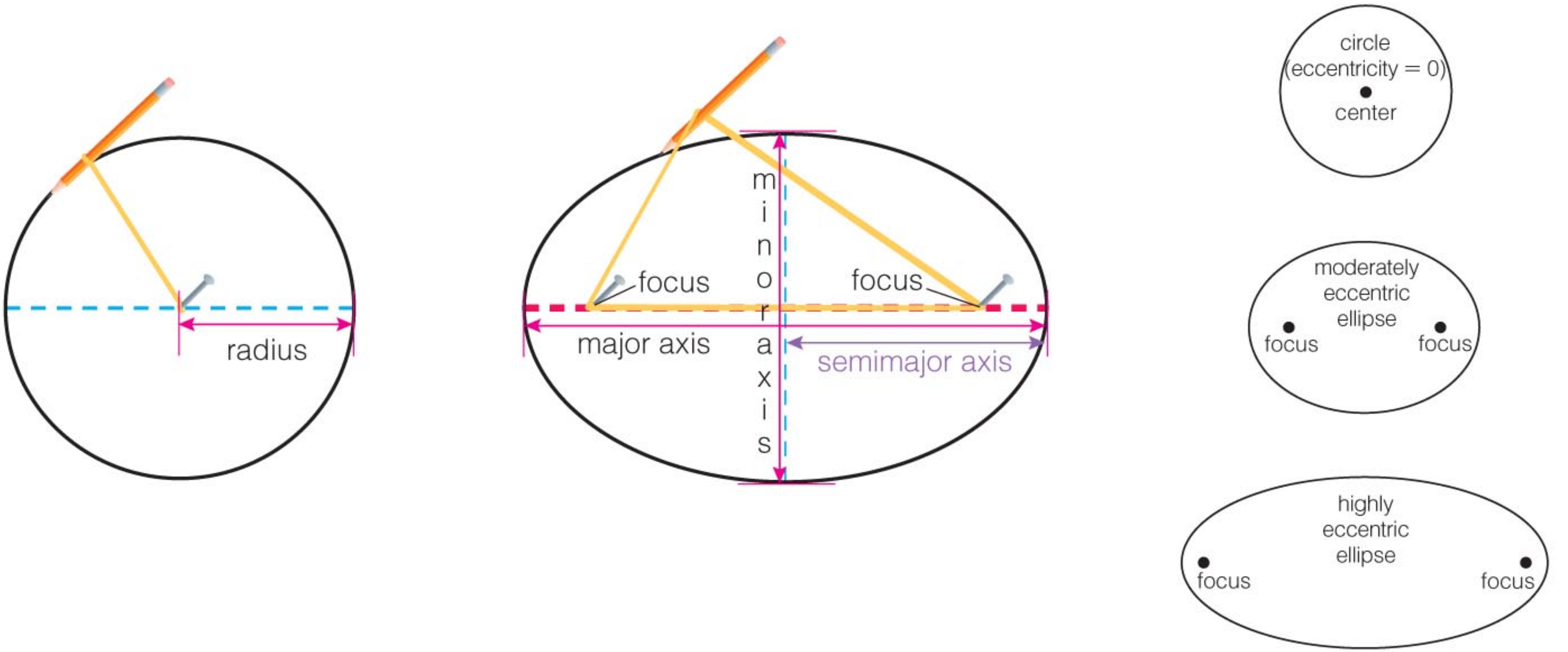
- Compiled the most accurate (one arcminute) naked eye measurements ever made of planetary positions.
- Still could not detect stellar parallax, and thus still thought Earth must be at center of solar system (but recognized that other planets go around Sun).
- Hired Kepler, who used Tycho's observations to discover the truth about planetary motion.

How did Copernicus, Tycho, and Kepler challenge the Earth-centered model?

- Johannes Kepler (1571–1630)

- Kepler first tried to match Tycho's observations with circular orbits
- But an 8-arcminute discrepancy led him eventually to ellipses.
- *"If I had believed that we could ignore these eight minutes [of arc], I would have patched up my hypothesis accordingly. But, since it was not permissible to ignore, those eight minutes pointed the road to a complete reformation in astronomy."*

What is an ellipse?



a Drawing a circle with a string of fixed length.

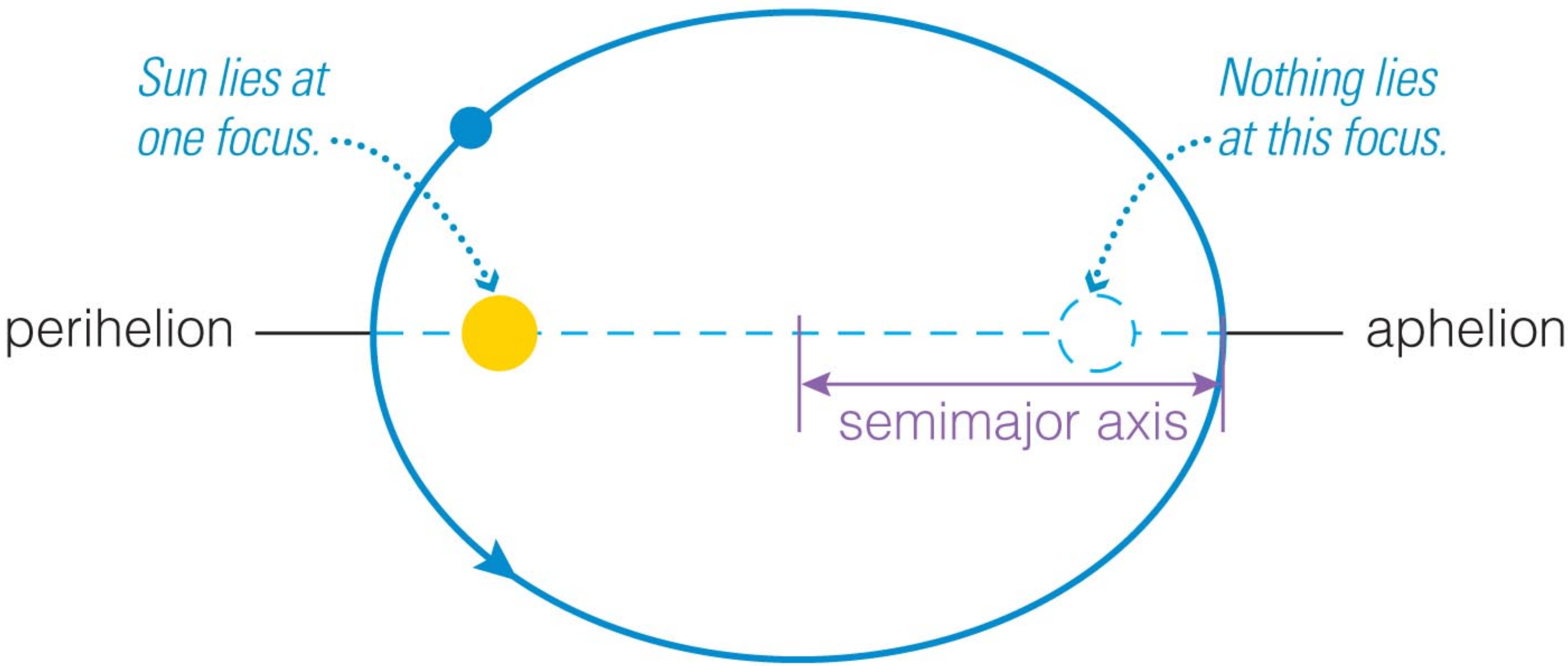
b Drawing an ellipse with a string of fixed length.

c Eccentricity describes how much an ellipse deviates from a perfect circle.

- An ellipse looks like an elongated circle.

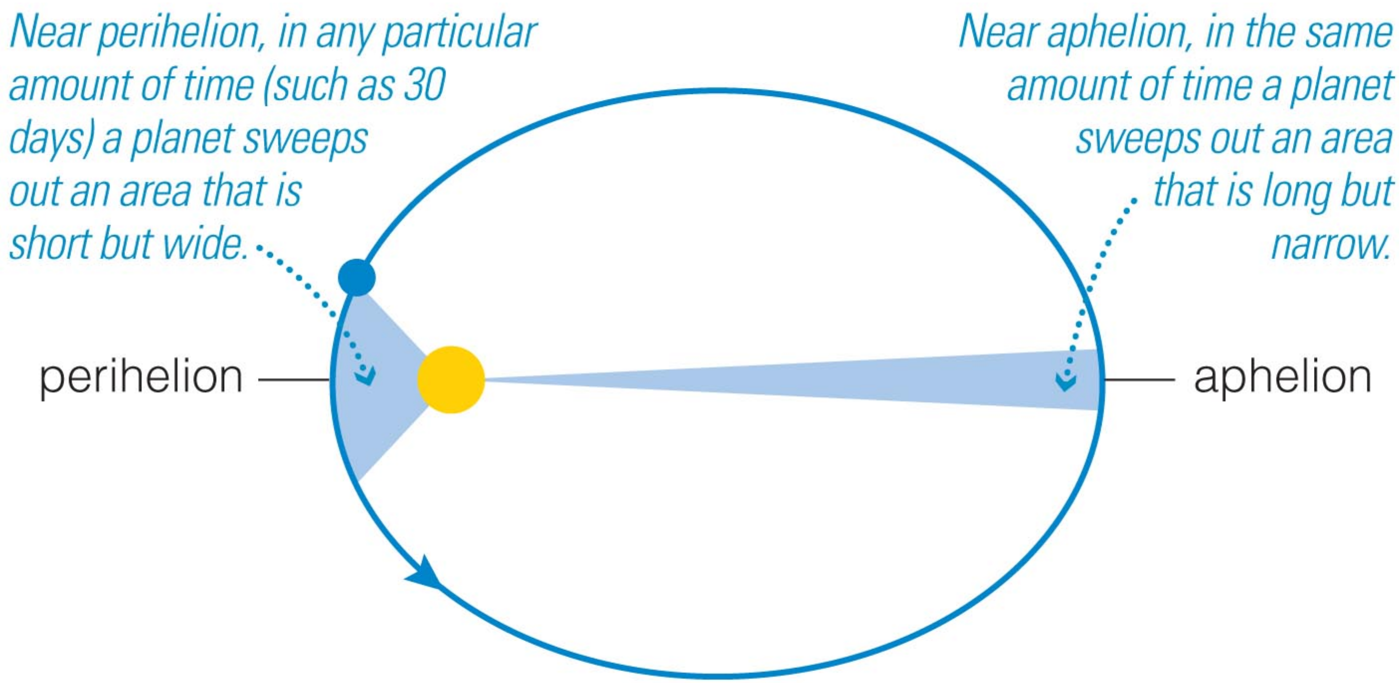
What are Kepler's three laws of planetary motion?

- **Kepler's First Law:** The orbit of each planet around the Sun is an ***ellipse*** with the Sun at one focus.



What are Kepler's three laws of planetary motion?

- **Kepler's Second Law:** As a planet moves around its orbit, it sweeps out equal areas in equal times.



- This means that a planet travels faster when it is nearer to the Sun and slower when it is farther from the Sun.

Kepler's Third Law

- More distant planets orbit the Sun at slower average speeds, obeying the relationship

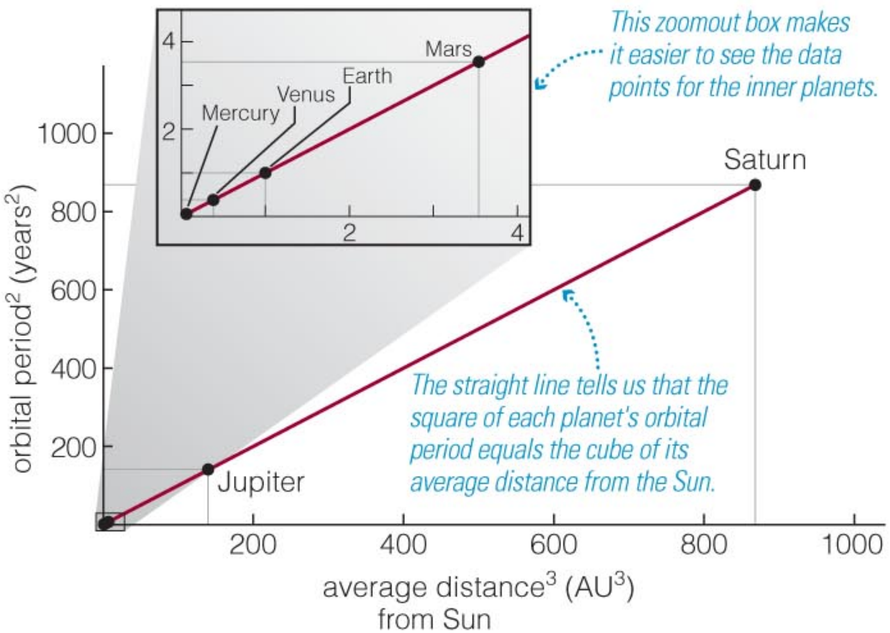
$$p^2 = a^3$$

- p = orbital period in years
- a = average distance from Sun in AU*

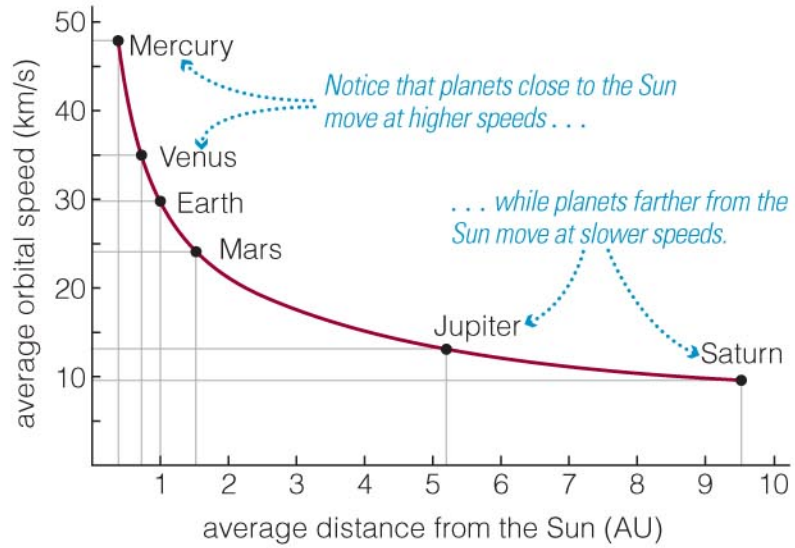
*1 AU$\simeq$ 150,000,000 km = 1.5 x 10^{11} m (~ 93,200,000 miles)
(mean Sun – Earth distance)

Kepler's Third Law

- Graphical version of Kepler's Third Law



a This graph shows that Kepler's third law ($p^2 = a^3$) holds true; the graph shows only the planets known in Kepler's time.



b This graph, based on Kepler's third law and modern values of planetary distances, shows that more distant planets orbit the Sun more slowly.

Thought Question

An asteroid orbits the Sun at an average distance a = 4 AU. How long does it take to orbit the Sun?

A. 4 years
B. 8 years
C. 16 years
D. 64 years

Hint: Remember that $p^2 = a^3$

Thought Question

An asteroid orbits the Sun at an average distance $a = 4$ AU. How long does it take to orbit the Sun?

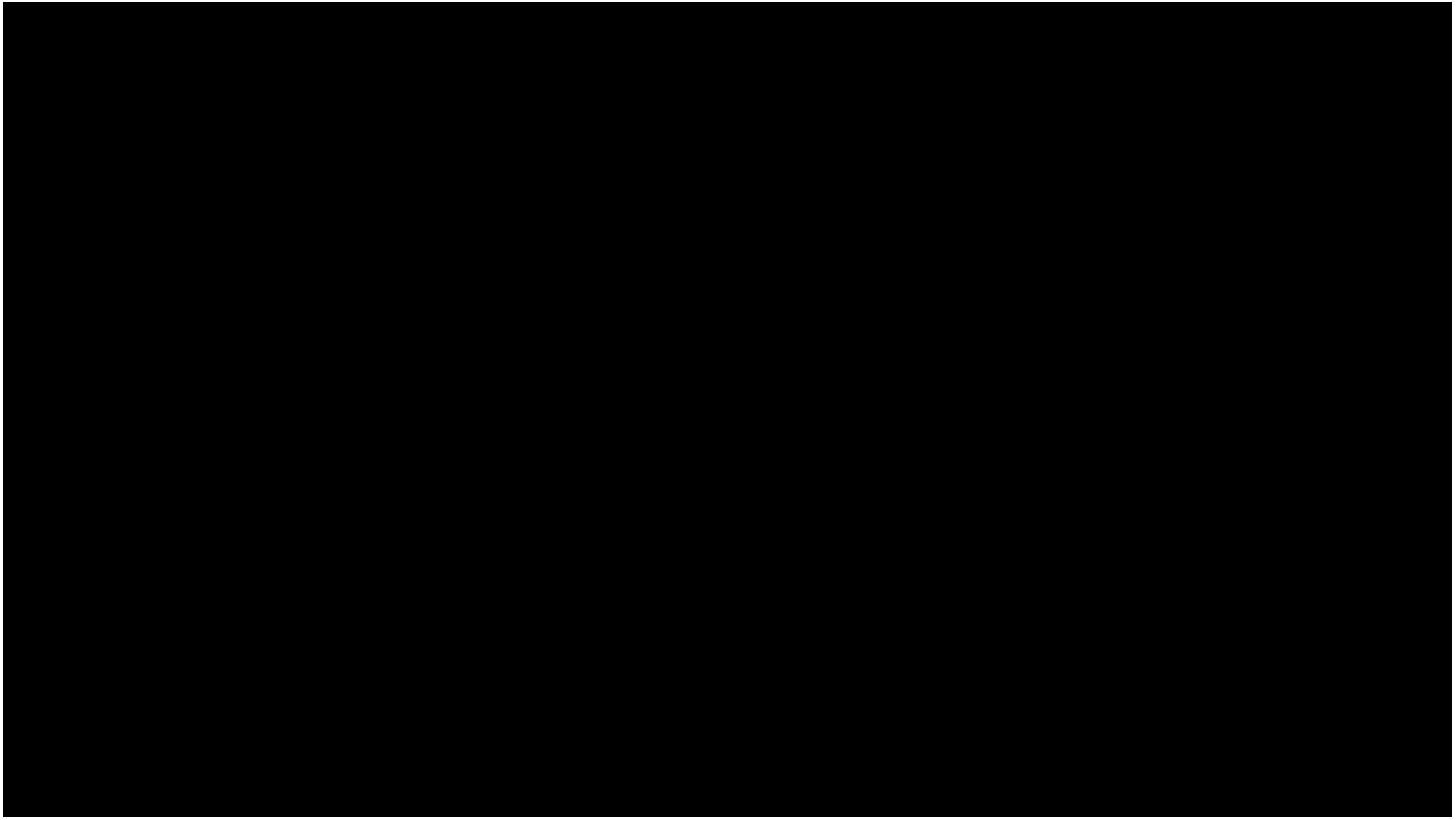
A. 4 years
B. 8 years
C. 16 years
D. 64 years

We need to find p so that $p^2 = a^3$.

Since $a = 4$, $a^3 = 4^3 = 64$.

Therefore, $p = 8$, $p^2 = 8^2 = 64$.

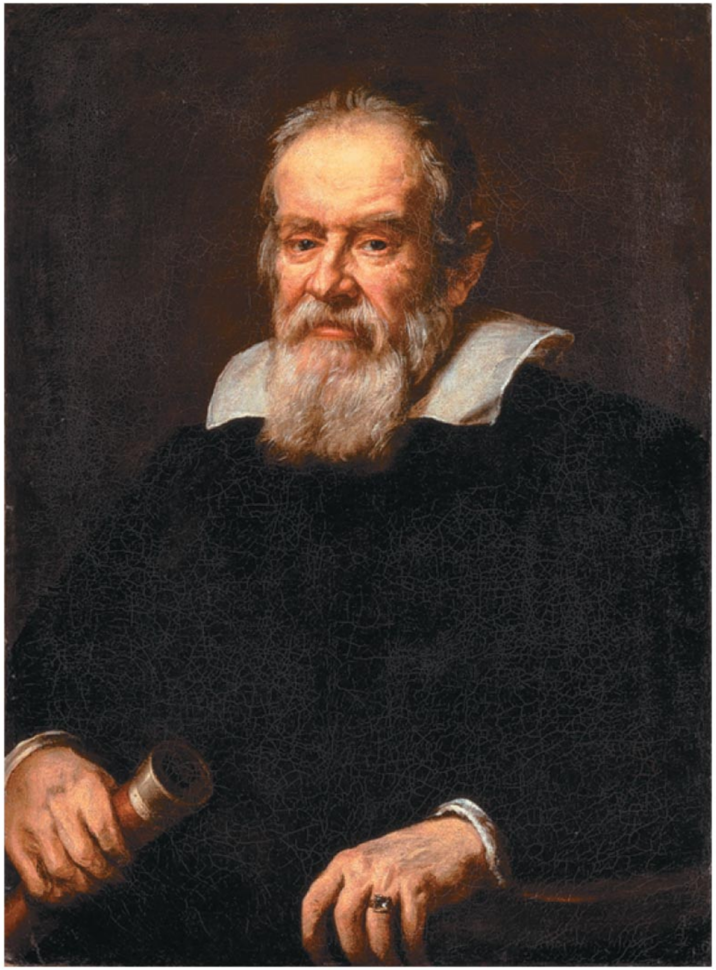
A comet’s orbit around Sun



An extremely high-eccentricity orbit!

Source: NASA Scientific Visualization Studio

How did Galileo solidify the Copernican revolution?



- Galileo (1564–1642)

- Galileo overcame major objections to the Copernican view. Three key objections rooted in Aristotelian view were:
  1. Earth could not be moving because objects in air would be left behind.
  2. Non-circular orbits are not "perfect" as heavens should be.
  3. If Earth were really orbiting Sun, we'd detect stellar parallax.

Overcoming the First Objection (Nature of Motion)

- Galileo's experiments showed that objects in air would stay with Earth as it moves.
  - Aristotle thought that all objects naturally come to rest.
  - Galileo showed that objects will stay in motion unless a force acts to slow them down (Newton's first law of motion).

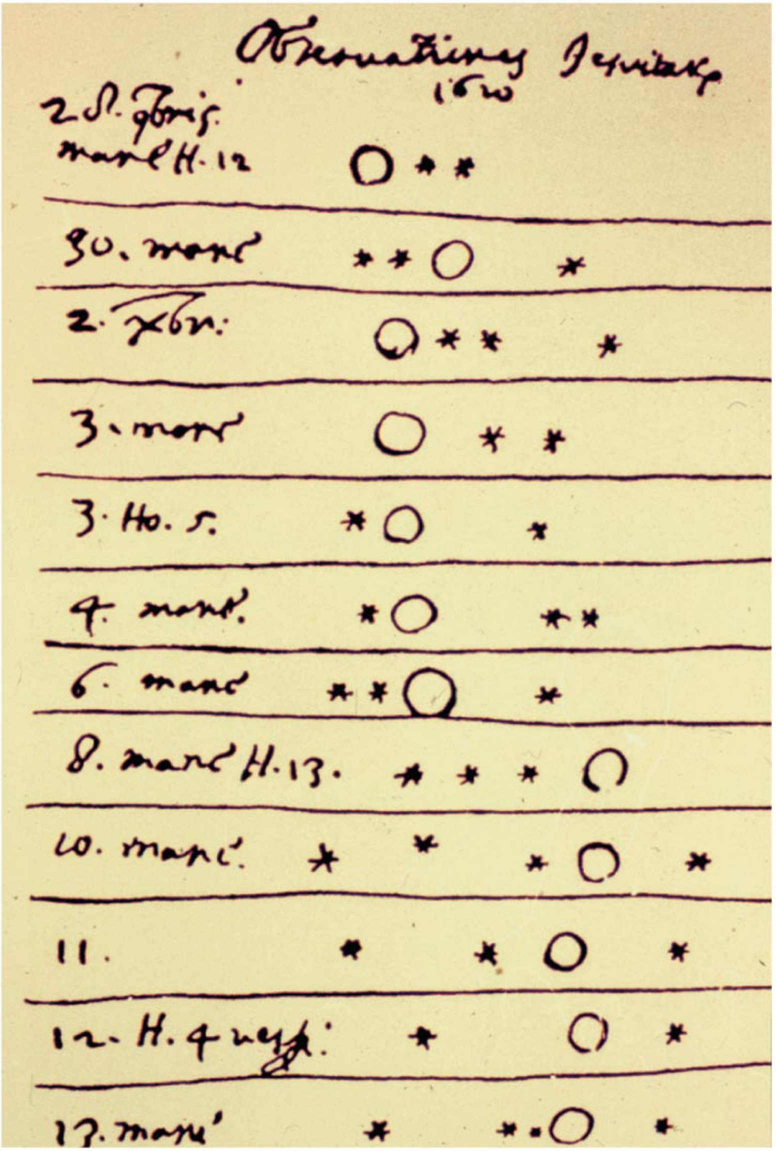
Overcoming the Second Objection (Heavenly Perfection)

- Tycho's observations of comet and supernova already challenged this idea.
- Using his telescope, Galileo saw:
  - Sunspots on Sun ("imperfections")
  - Mountains and valleys on the Moon (proving it is not a perfect sphere)

Overcoming the Third Objection (Parallax)

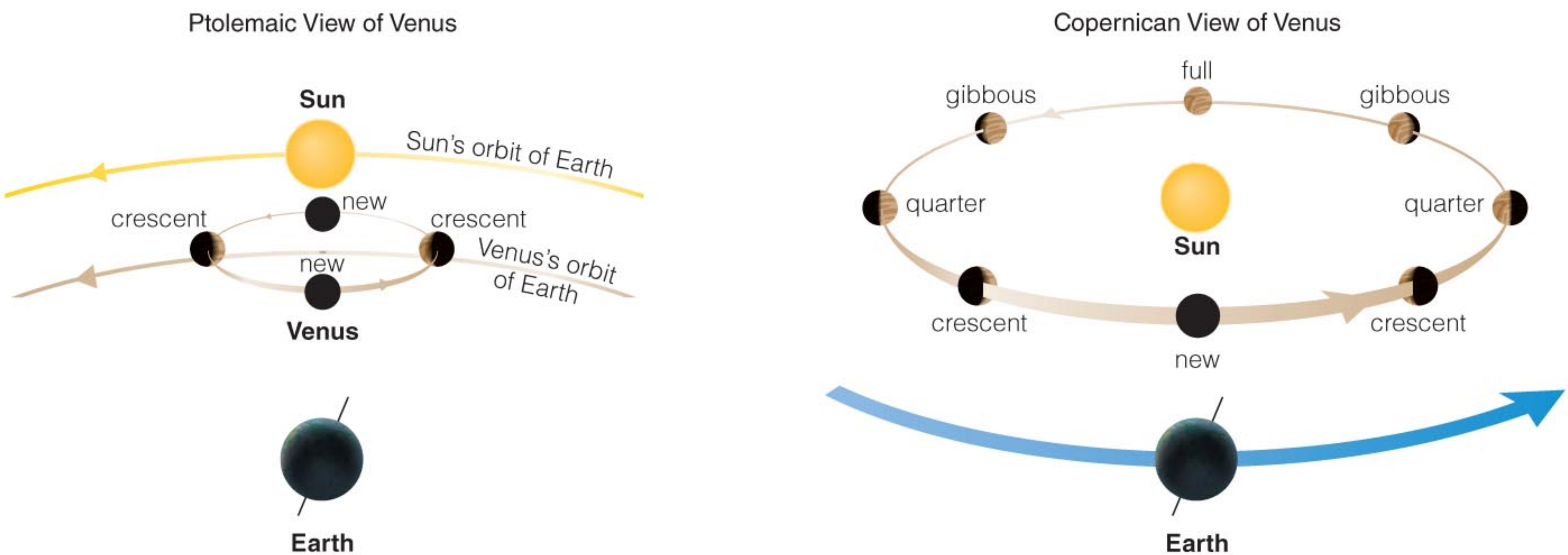
- Tycho *thought* he had measured stellar distances, so lack of parallax seemed to rule out an orbiting Earth.
- Galileo showed stars must be much farther than Tycho thought — in part by using his telescope to see the Milky Way is countless individual stars.
  - ✓ If stars were much farther away, then lack of detectable parallax was no longer so troubling.

Overcoming the Third Objection (Parallax)



- Galileo also saw four moons orbiting Jupiter, showing that not all objects orbit Earth.

Overcoming the Third Objection (Parallax)



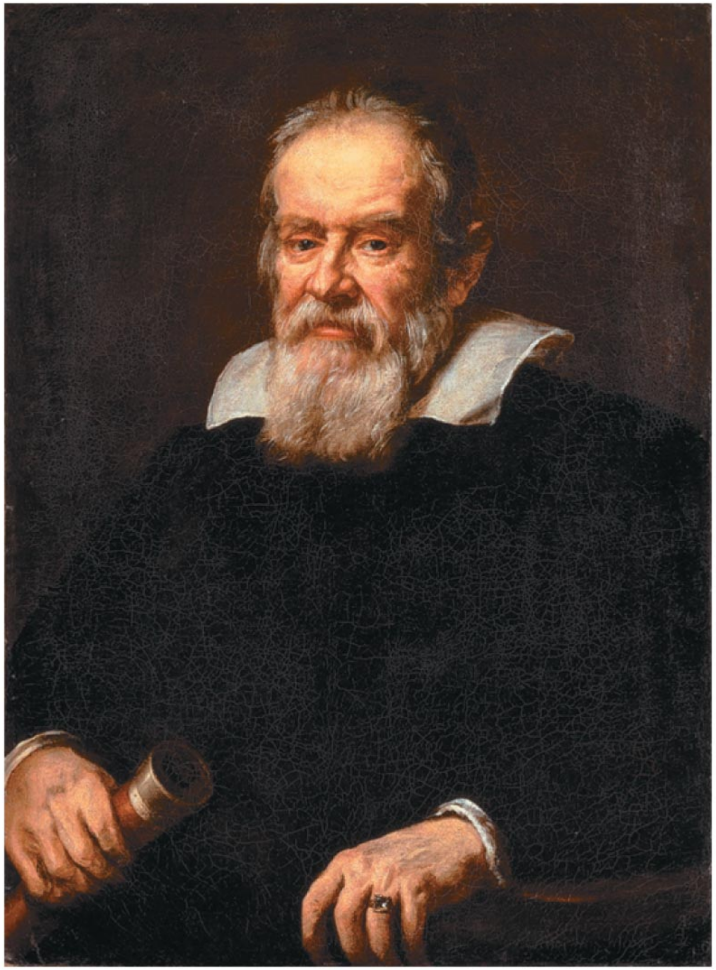
a In the Ptolemaic system, Venus orbits Earth, moving around a smaller circle on its larger orbital circle; the center of the smaller circle lies on the Earth-Sun line. If this view were correct, Venus's phases would range only from new to crescent.

b In reality, Venus orbits the Sun, so from Earth we can see it in many different phases. This is just what Galileo observed, allowing him to prove that Venus orbits the Sun.

- Galileo's observations of phases of Venus showed that it orbits the Sun and not Earth.

Overcoming the Third Objection (Parallax)

- The Catholic Church ordered Galileo to recant his claim that Earth orbits the Sun in 1633.
- His book on the subject was removed from the Church's index of banned books in 1824.
- Galileo was formally vindicated by the Church in 1992.



What have we learned?

- **How did Copernicus, Tycho and Kepler challenge the Earth-centered idea?**
  - Copernicus created a sun-centered model; Tycho provided the data needed to improve this model; Kepler found a model that fit Tycho's data using the Copernican model or rotation around Sun.
- **What are Kepler's three laws of planetary motion?**

1. The orbit of each planet is an ellipse with the Sun at one focus.
2. As a planet moves around its orbit it sweeps out equal areas in equal times.
3. More distant planets orbit the Sun at slower average speeds: p^2 (in years) = a^3 (in astronomical units).

What have we learned?

- **What was Galileo's role in solidifying the Copernican revolution?**
  - His experiments and observations overcame the remaining objections to the Sun-centered solar system model.

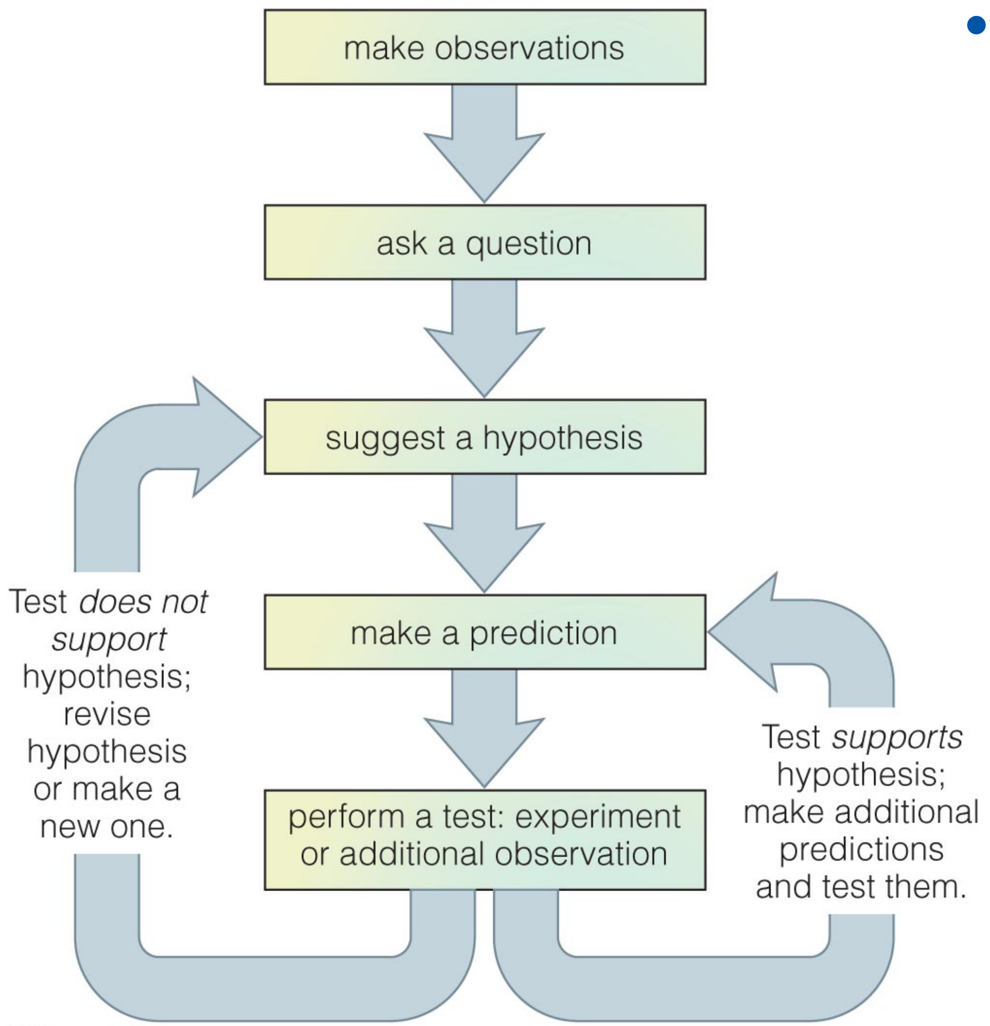
3.4 The Nature of Science

- Our goals for learning:
  - **How can we distinguish science from nonscience?**
  - **What is a scientific theory?**

How can we distinguish science from non-science?

- Defining science can be surprisingly difficult.
- *Science* from the Latin *scientia*, meaning "knowledge."
- But not all knowledge comes from science.

How can we distinguish science from non-science?



- <u>The idealized scientific method</u>
  - Based on proposing and testing hypotheses
  - **hypothesis** = educated guess

How can we distinguish science from non-science?

- But science rarely proceeds in this idealized way. For example:
  - Sometimes we start by "just looking" then coming up with possible explanations.
  - Sometimes we follow our intuition rather than a particular line of evidence.

Hallmark of Science: #1

- Modern science seeks explanations for observed phenomena that rely solely on natural causes.
- (A scientific model cannot include divine intervention)

Hallmark of Science: #1

Science does not include divine intervention!

The Inquisition of Galileo (Wikipedia)

Hallmark of Science: #2

- Science progresses through the creation and testing of models of nature that explain the observations as simply as possible (i.e., without making more assumptions than needed).

(Simplicity = "Occam's razor")

Hallmark of Science: #2

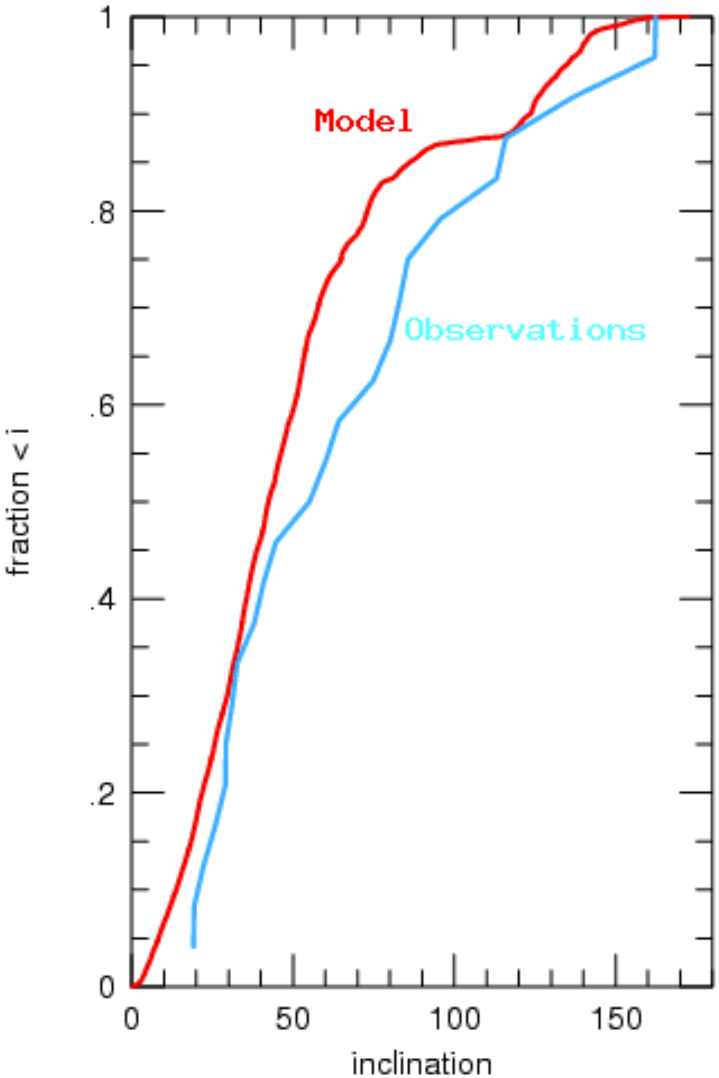
If there was a storm the night before, where would you attribute the tree's fall? – Use only the assumptions you need – not more!

Source: Claremont-courier.com

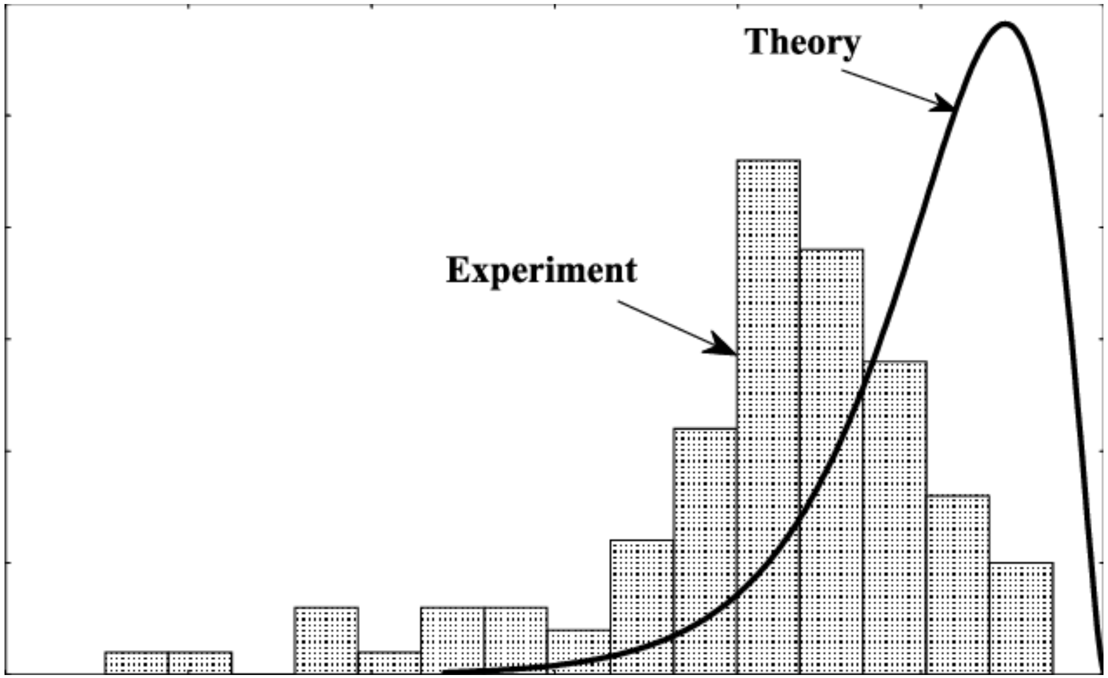
Hallmark of Science: #3

- A scientific model must make testable predictions about natural phenomena that would force us to revise or abandon the model if the predictions do not agree with observations.

Hallmark of Science: #3



Both are imperfect, but it is tendencies that matter!



Agreement between model & observation

Disagreement between model & observation

Plato's Allegory of the Cave: Human Perception

Getty Images

- **BUT**, observations can be erroneous or biased - in this case, so are the theories that fit them!
- **Solution:** Try to think outside the box (or the Cave!)

What is a scientific theory?

- The word theory has a different meaning in science than in everyday life.
- In science, a theory is NOT the same as a hypothesis, rather:
- A ***scientific theory*** must:
  - Explain a wide variety of observations with a few simple principles, AND
  - Must be supported by a <u>large</u>, <u>compelling</u> body of evidence.
  - Must survive, relatively unscathed, crucial tests of its validity.

Scientific vs. Everyday Usage

- Many terms used in science have different or more specific meaning than they do in everyday speech.
- Examples: model, hypothesis, theory, bias, critical, deviation, enhance, enrich, error, feedback, state, uncertainty, values.

Thought Question

Darwin's theory of evolution by natural selection meets all the criteria of a scientific theory. This means:

A. Scientific opinion is about evenly split as to whether evolution really happened.
B. Scientific opinion runs about 90% in favor of the theory of evolution and about 10% opposed.
C. After more than 100 years of testing, Darwin's theory stands stronger than ever, having successfully met every scientific challenge to its validity.
D. There is no longer any doubt that the theory of evolution is absolutely true.

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What have we learned?

- **How can we distinguish science from non-science?**
  - Science: seeks explanations that rely solely on natural causes; progresses through the creation and testing of models of nature; models must make testable predictions
- **What is a scientific theory?**
  - A model that explains a wide variety of observations in terms of a few general principles and that has survived repeated and varied testing

3.5 Astrology vs. Astronomy

- Our goals for learning:
  - **How is astrology different from astronomy?**
  - **Does astrology have any scientific validity?**

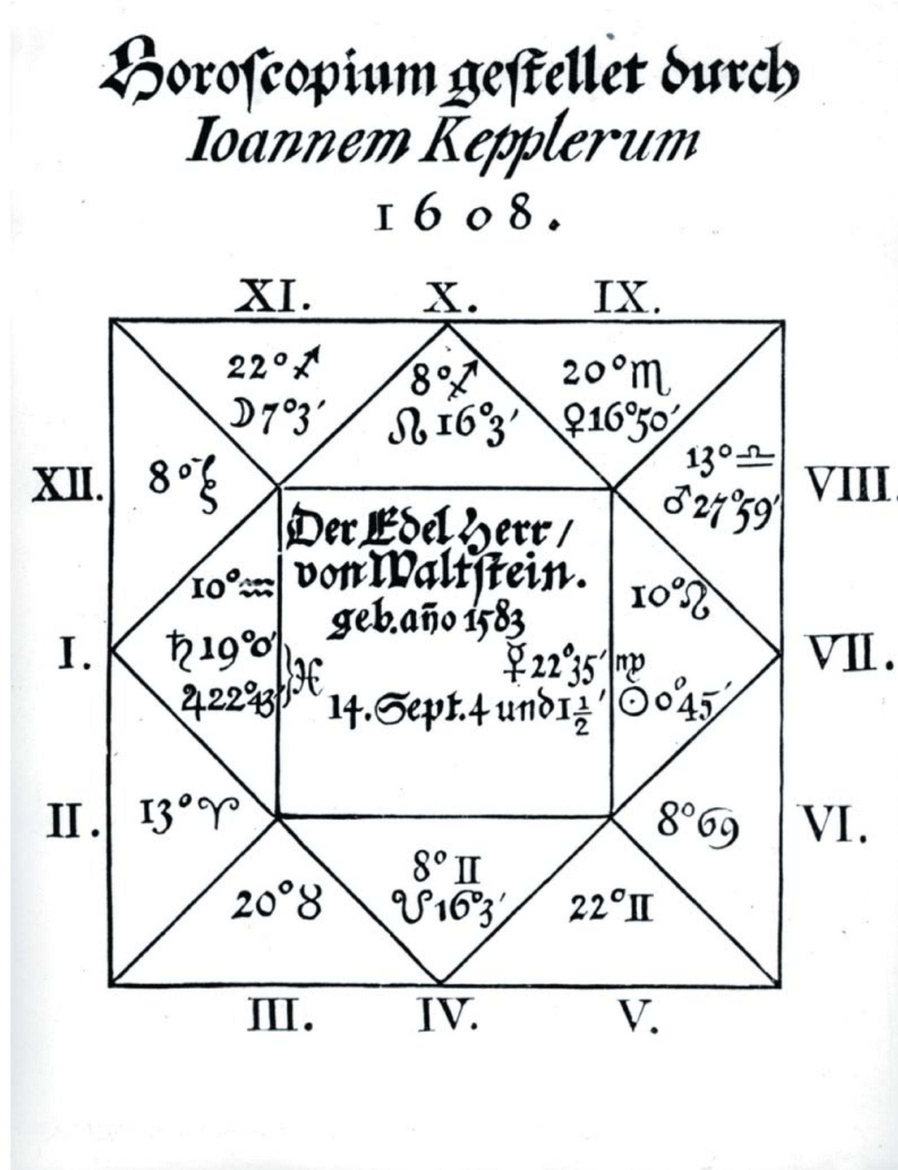
How is astrology different from astronomy?

- Astronomy is a science focused on learning about how stars, planets, and other celestial objects work.
- Astrology is a search for hidden influences on human lives from the positions of planets and stars in the sky.

- **Astrology:** divination of stars (so it fails Hallmark of Science #1)
- **Astronomy:** (observed / interpreted) laws of stars

Does astrology have any scientific validity?

- Scientific tests have shown that astrological predictions are no more accurate than we should expect from pure chance.



What have we learned?

- **How is astrology different from astronomy?**
  - Astronomy is the scientific study of the universe and the celestial objects within it.
  - Astrology assumes that the positions of celestial objects influence human behavior and actions.
- **Does astrology have any scientific validity?**
  - Scientific tests show that the predictions of astrology are no more accurate than pure chance.