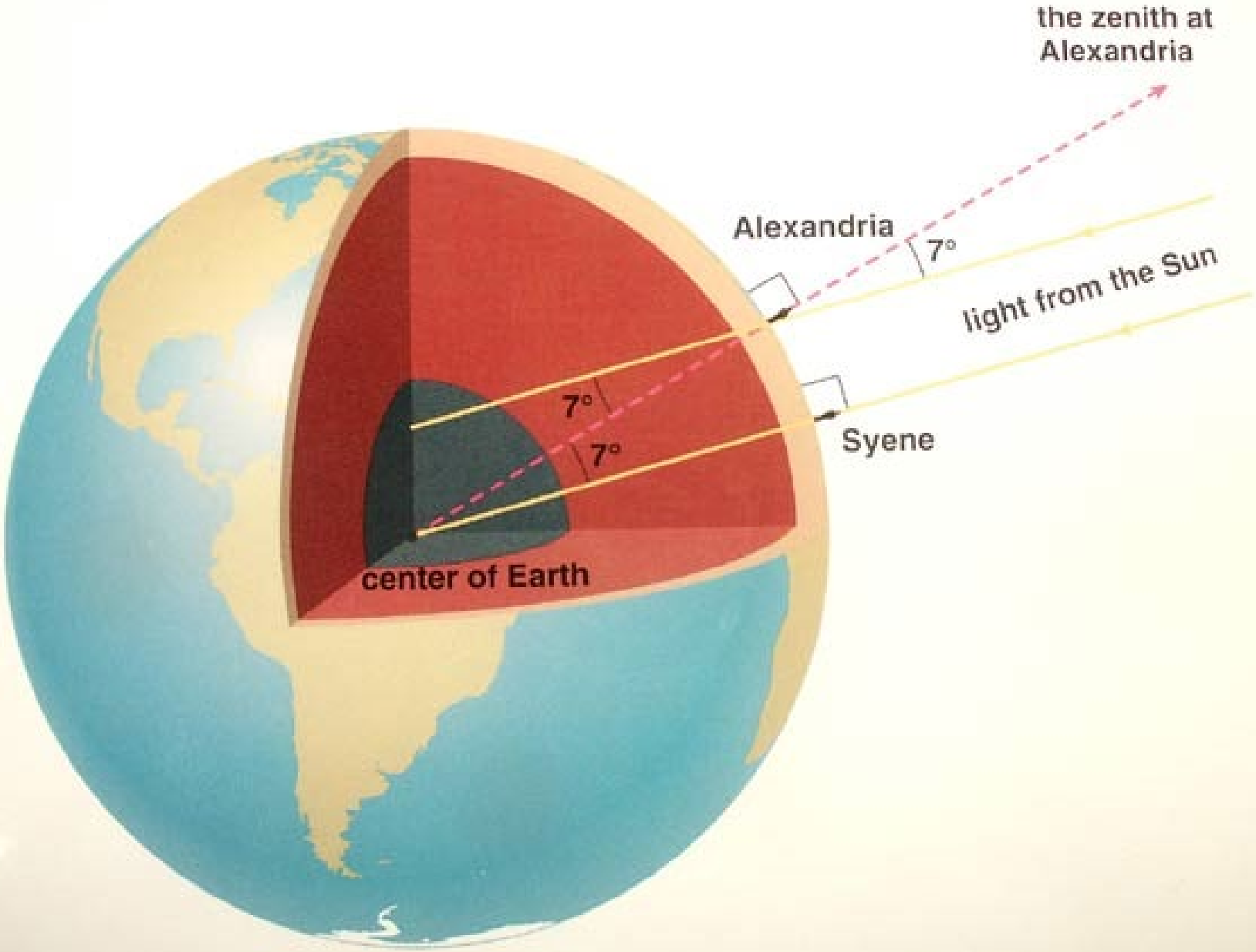
Chapter 3: Historical Astronomy and the Discovery of Natural Law

- Ptolemy vs. Copernicus: Earth in a natural vs central position
- Tycho Brahe's observations of planets; the basis for Kepler's reasoning
- Galileo: the telescope, disproof of the Ptolemaic and Church-approved cosmology
- Kepler and the planetary laws of motion

Erotosthenes: Measured Diameter of Earth

- If you pace off the “as the crow flies” distance from Syene to Alexandria…
- And you measure the angle of the sun above the horizon at noon from those two places on the same day of the year…
- A simple ratio tells you what important measure of the size of the Earth?

Figure 3.13 Method of Eratosthenes



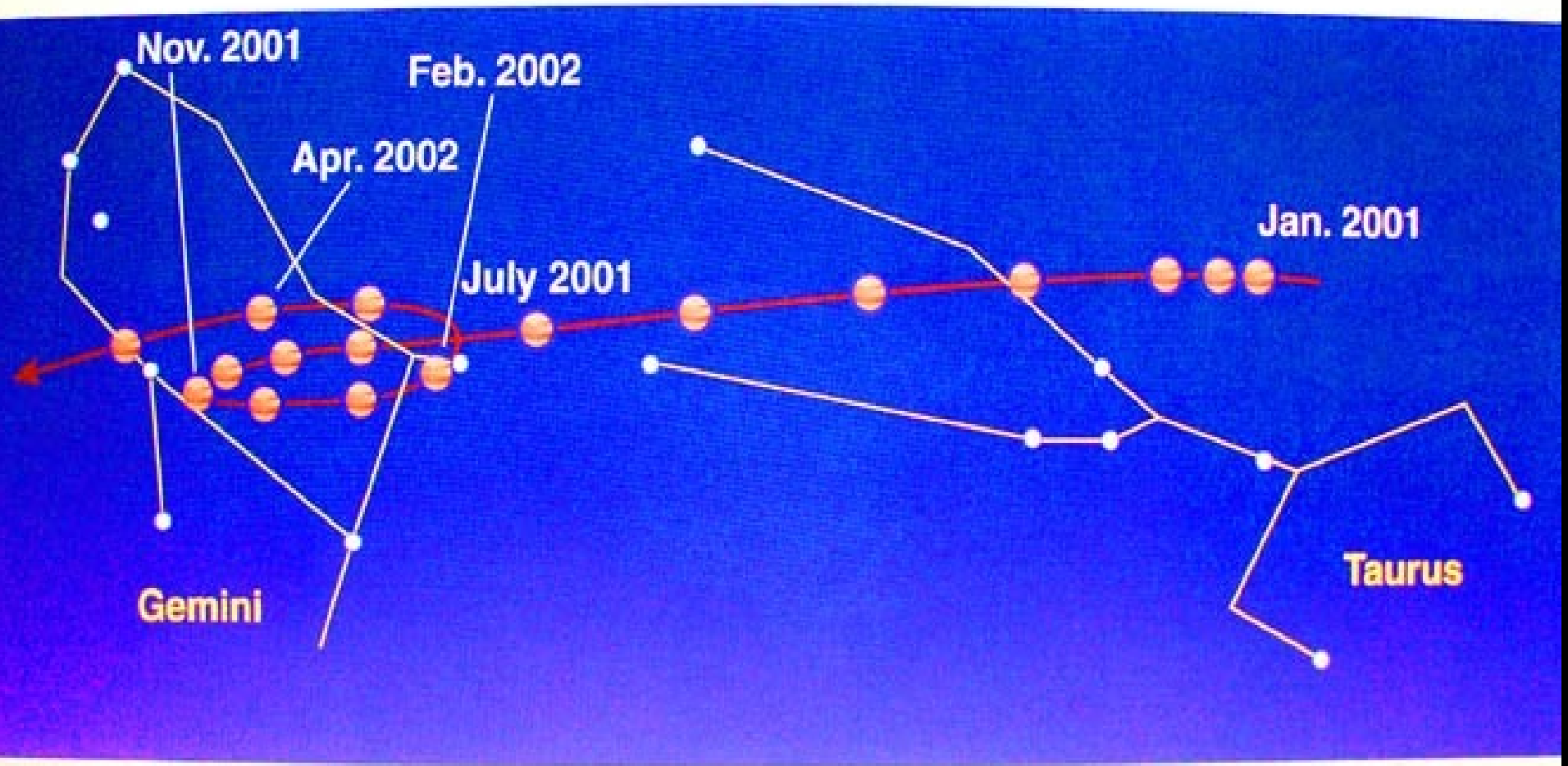
So The Greeks Knew the Earth was a Sphere and it's right size.

- Aristarchus even taught the planets orbited the sun, although we don't know his reasonings. This was during BC times!
- Next, figure out the motions of the planets…

Motions of the Planets

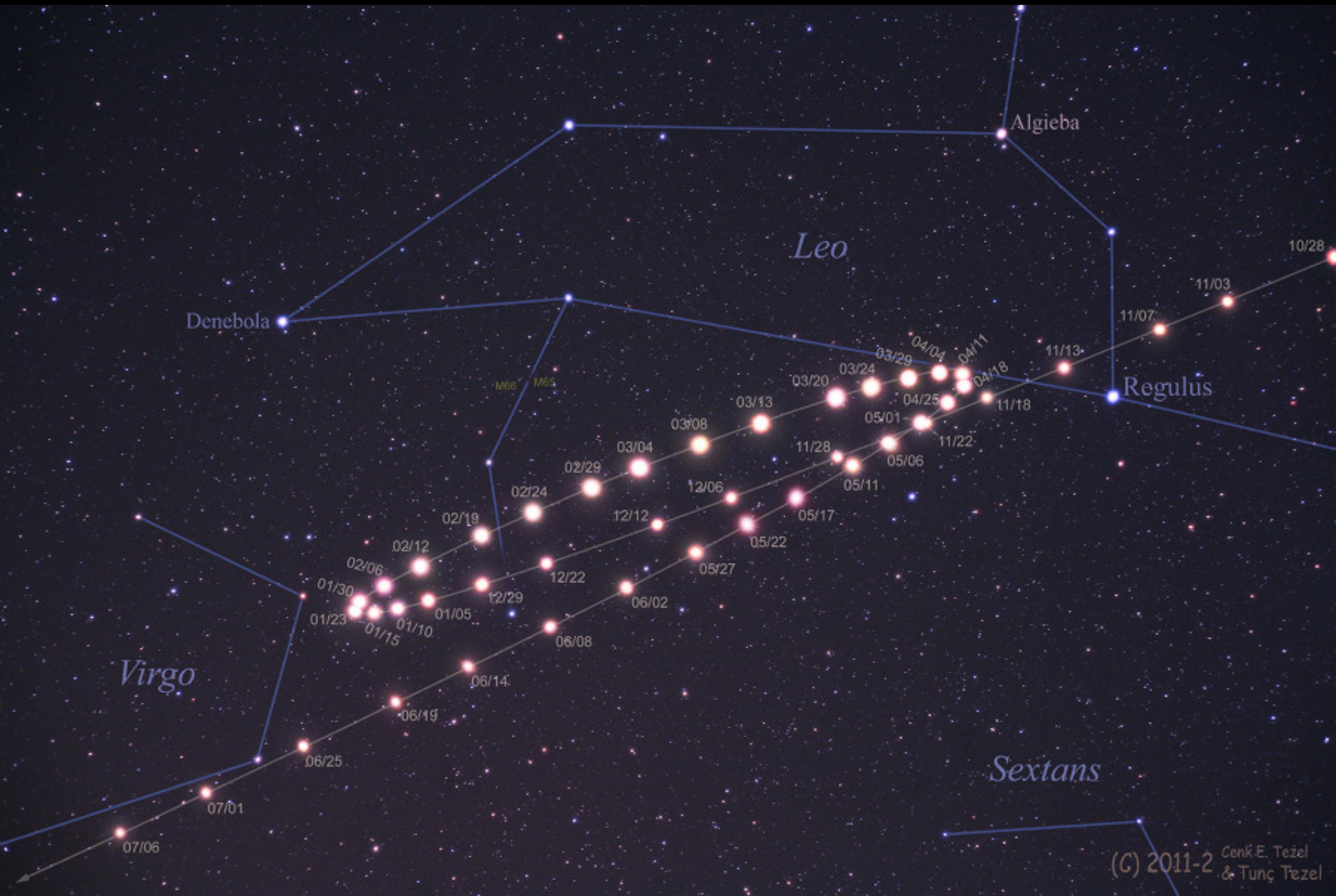
- Back in the old days, planets pretty much WERE astronomy. Stars didn't seem to DO anything, except rise and set. And galaxies, nebulae… invisibly faint and undiscovered.
- Greeks LOVED circles. Even made a semi-religion out of them. The Pythagoreans - insisted the Universe was based on the perfect circle and integer numbers.
- **But then…**

What's up with retrograde motion?



Dots represent Jupiter's position at 1-month intervals.

A Sequence of Images of Mars' Retrograde loop



Retrograde Motion: About once a year, the planets go backwards seen against the background stars

- For fans of simple, uniform, circular motion, this was a problem.
- But many Greeks were true scientists – they didn't sweep inconvenient facts under the rug.
- How to account for this while preserving the appeal of an Earth-centered universe?
- There were actually some good observationally-based reasons initially to favor an earth-centered solar system…

If the Earth were in fact moving around something else…

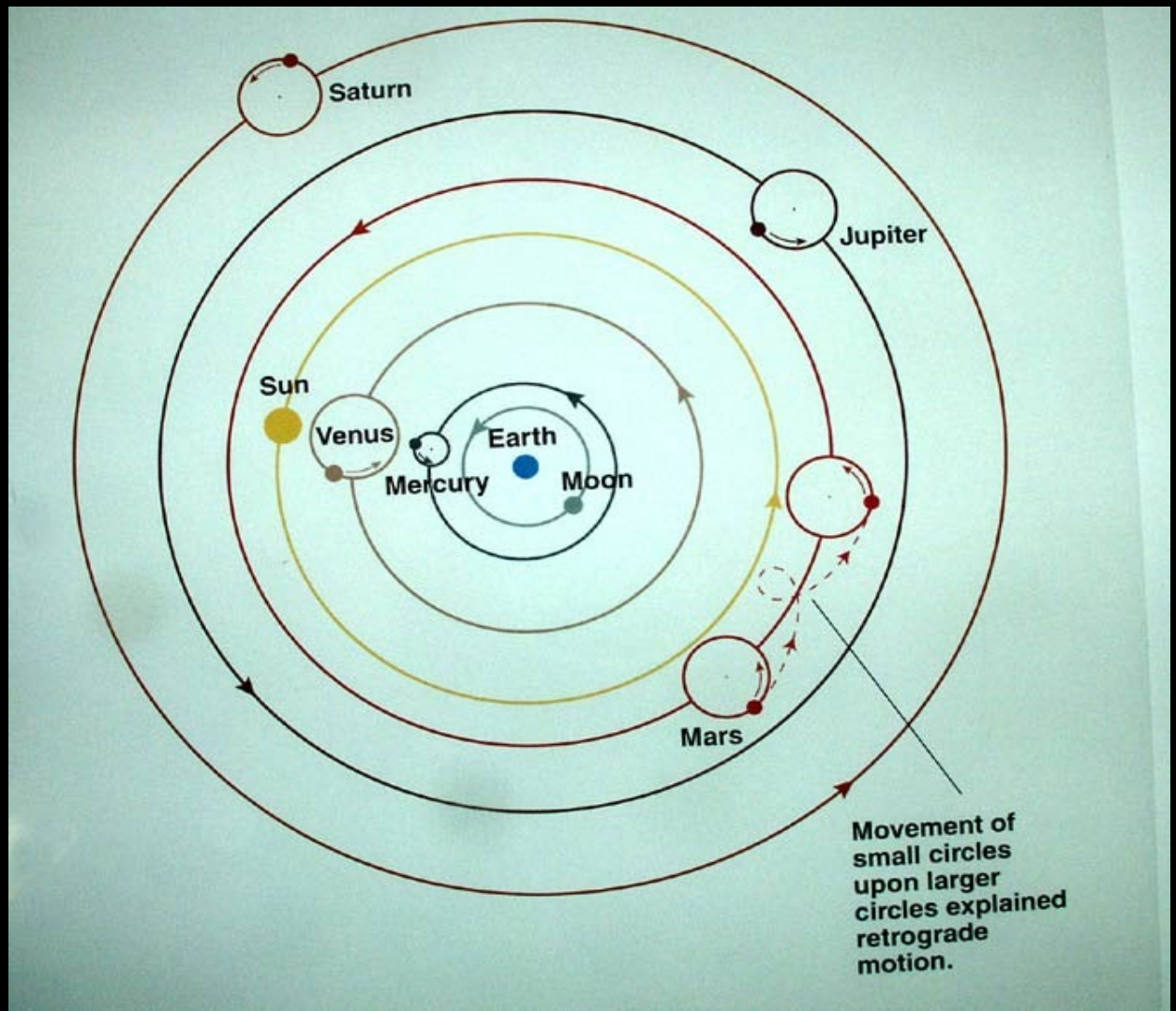
- … we'd see the stars undergoing a reflex motion called "parallax".
- Careful (but crude by today's standards) observations showed no parallax motion during the year.
- So: Either (1) the earth is motionless with respect to the apparently fixed stars, or (2) the stars are so vastly far away that their parallax motion is undetectably small.
- The Greeks went with (#1). **Doh!….** They were wrong! – they should've gone with door #2!!

- Let's continue with the historical progression and explore how the earth-centered model persisted for a *really unfortunately* long period of time…

Ptolemy – Greek (Egyptian) Astronomer 100AD made first decent quantitative model of the planets' motion

- It had the Earth at the center
- Accounted for retrograde motion with epicycles. Then needed to offset the center of epicycles. Then needed epicycles on top of epicycles…
- Taken *literally*, it was ugly. But mathematically, it was *brilliant*!

This conceptual layout isn't correct in literal scaled epicycle size and position, since Mercury's greatest solar elongations are 27 degrees, and Venus' is 47 degrees. The whole system doesn't bear too close a scrutiny because again, epicycles on top of epicycles are needed as observations improved. But the basic idea of non-crossing epicycles and orbits is part of the essence of the Ptolemaic Model



Ptolemy: Dogmatic, or Innovative Mathematical Modeler?

- We don't know for sure.
- Some evidence suggests that he was agnostic on where the center of the solar system was.
- He just wanted the simplest, most concise calculation device for determining the positions of the planets…. And for that limited purpose, his model was mathematically simple and successful!

Of course, one can jam a nail through the Earth and COMPEL the rest of the Solar System to do ALL of the moving and then you WOULD have epicyclic motion

- As observations improved after Ptolemy's death, matching to observations forced epicycles on top of epicycles, and deferrents away from the centers.
- Ptolemy's construction is essentially what we would call today a ***Fourier de-composition*** of the motions of the planets, and this is still to this day the most efficient way to calculate planetary positions for many moderate-accuracy needs.
- But we do know – History took things in a bad direction, enforcing the Earth-centered original Ptolemy model as a literal fact and key piece of Christian dogma.

But! Aristarchus ~270 BC first deduced the planets orbited the sun, not the Earth

- His reasoning is not known – original writings were lost when religious zealots burned the great Library of Alexandria.
- Now, the Greeks had no authoritarian religious problem with a sun-centered universe. But,
- They reasoned if the earth orbited the sun we should see parallax motion in the stars.
- They saw no parallax, and so thought the earth must be at the center.

The Ptolemaic Model Became the Official Dogma for Many Centuries

- Why?
- What else was going on around ~100AD.....?

The Rise of the Christian Church and their Power

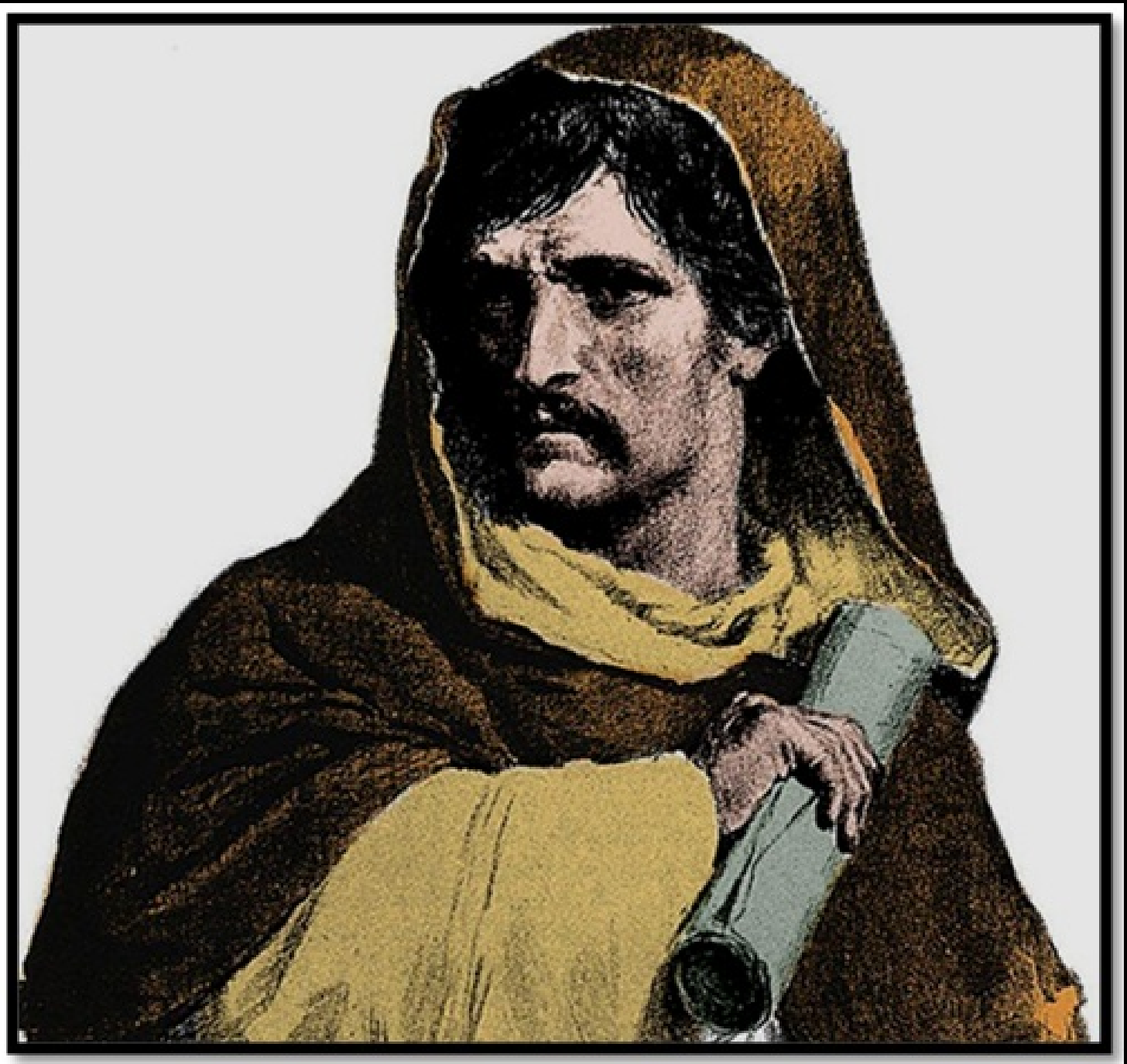
- Ptolemy introduced his model at the time of the rise to power of the Christians in western civilization.
- The Earth-centered model was in line with their belief that the Earth is the center of God's universe and God's attentions. It became dogma… eventually to be challenged only at the risk of being sent to the dungeons of the Inquisition
- Fear is a bad ingredient to introduce into the quest for knowledge. Scientific progress in the western world… stopped.

There followed 1,500 years of intellectual stagnation in the West

- Then in the 1500's ***Nicholas Copernicus*** challenged the Church with his realization that the motions of the planets could be understood much more simply if all planets revolved around the sun…
- His treatise on this was, at his request, to be published only upon his death, in 1543. It became an "underground" hit.

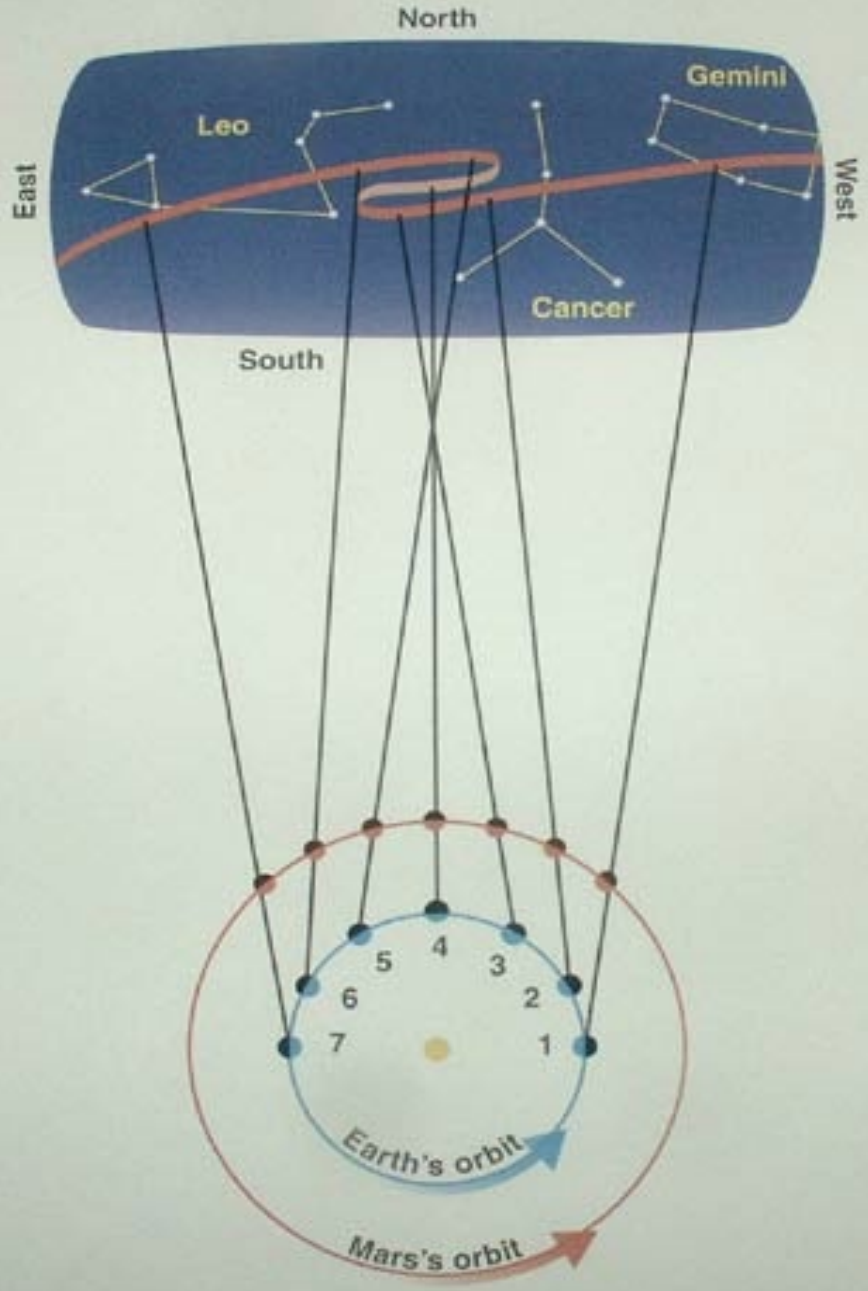
Giordano Bruno

- Astronomer, mathematician, and poet of the late 1500's, Bruno openly advocated the idea that the stars were sun's like ours, likely with planets, some of which perhaps had life. Brilliantly insightful for that early time!
- How was he rewarded? Imprisoned for 8 years by the Catholic Church, tried by the Inquisition, and burned at the stake in 1600, in Italy.
- Very tough to get good science done in this environment… this is the environment in which Galileo found himself.



Copernicus, rediscovered what the ancient Greeks knew – the sun-centered model of the universe explained planet motions much more simply

Figure 2.29 The explanation for apparent retrograde motion



He realized a much simpler explanation for retrograde motion was having (A) the sun at the center, and (B) closer planets move faster

Note that in the middle of retrograde Motion the planet is closest to Earth

- So does this suggest a test that could be done, to see if the Copernican *vs.* Ptolemy model is correct?
- Not really; you might think you could look through a telescope and see the angular size of the planet being maximum at this moment (if they had telescopes!).
- But, compare to the Ptolemy Earth Centered model - is that fact any different?
- If they had no telescopes, is there another obvious clue that is related, which could be used?

Was it just a matter of symantics as to what got to be called “the center of the solar system?”

- Or, is there an observational test which rules conclusively one way or the other?
- Enter… ***Galileo***

Galileo's original telescope. Ornate, but tiny lenses of poor quality, alas.

Galileo's Telescopic Discoveries

- He heard about the invention of the telescope by Hans Lippershey in 1610, and immediately ground his own lenses and built the first astronomical refracting telescope.
- Got him into MAJOR trouble with the Catholic Church, which pretty much ruled western civilization at this time and for a millennium prior.
- He looked through his telescope and saw…

Mountains and Craters on the Moon

- But, the church taught the moon was a perfect orb placed by God to light our nights.
- Many religious authorities considered this…*Heresy!*
- How dare Galileo claim it was scarred with pox marks and mountains like this sinful Earth?

Sunspots!

- Black spots with irregular borders that grew and changed, much like malignant melanoma (skin cancer).
- But, the Church said the sun was this perfect orb placed by God to light and warm our days. How dare Galileo claim it was scarred by ugly spots!
- Many religious authorities considered this…

- ***Heresy!***

Four Moons Orbiting Jupiter

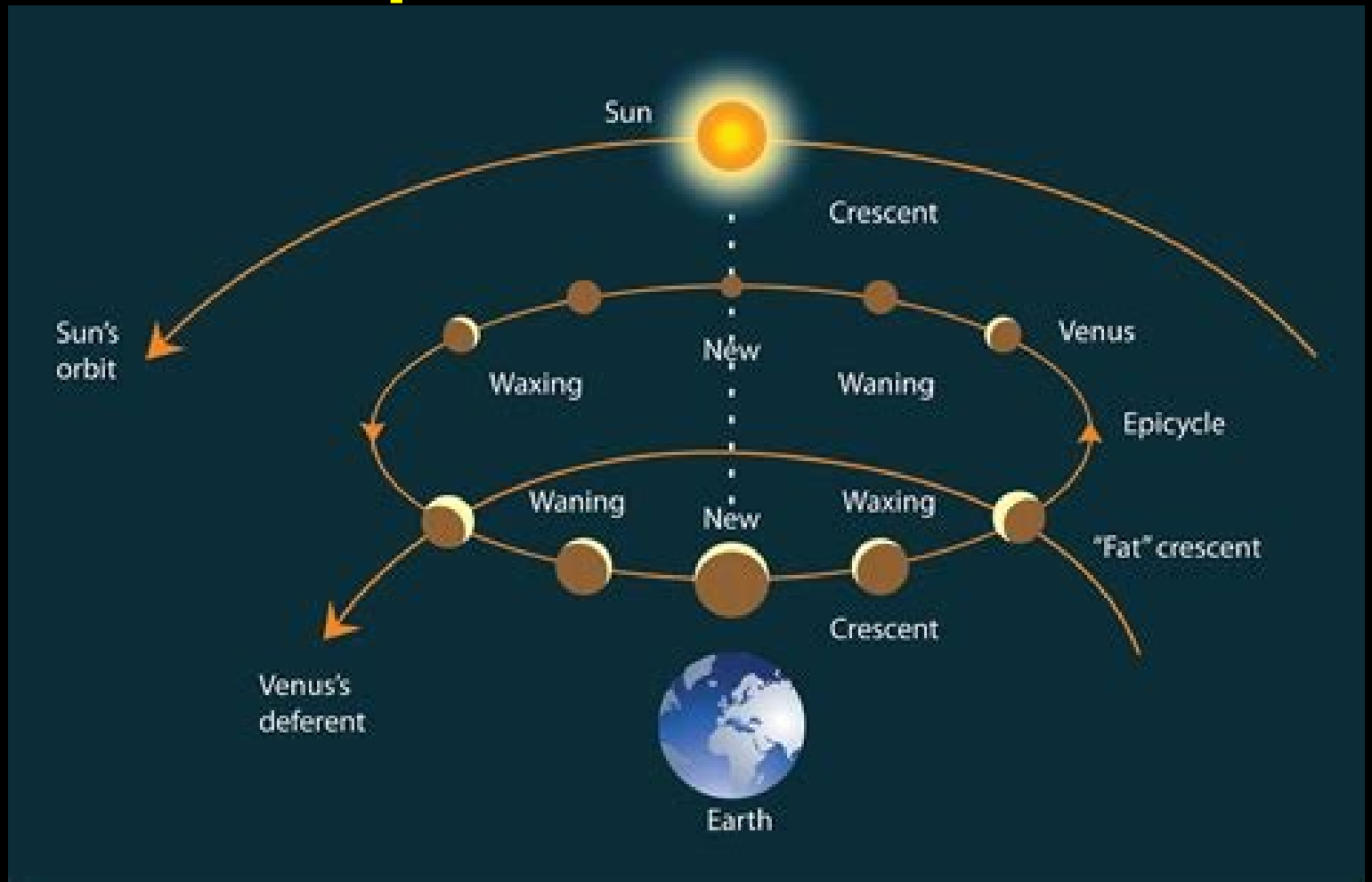
- Orbiting Jupiter?! But the Church taught that the EARTH was the center of the Universe…
- How dare Galileo claim these moons circle Jupiter and not us!
- Many religious authorities considered this…

- ***Heresy!***

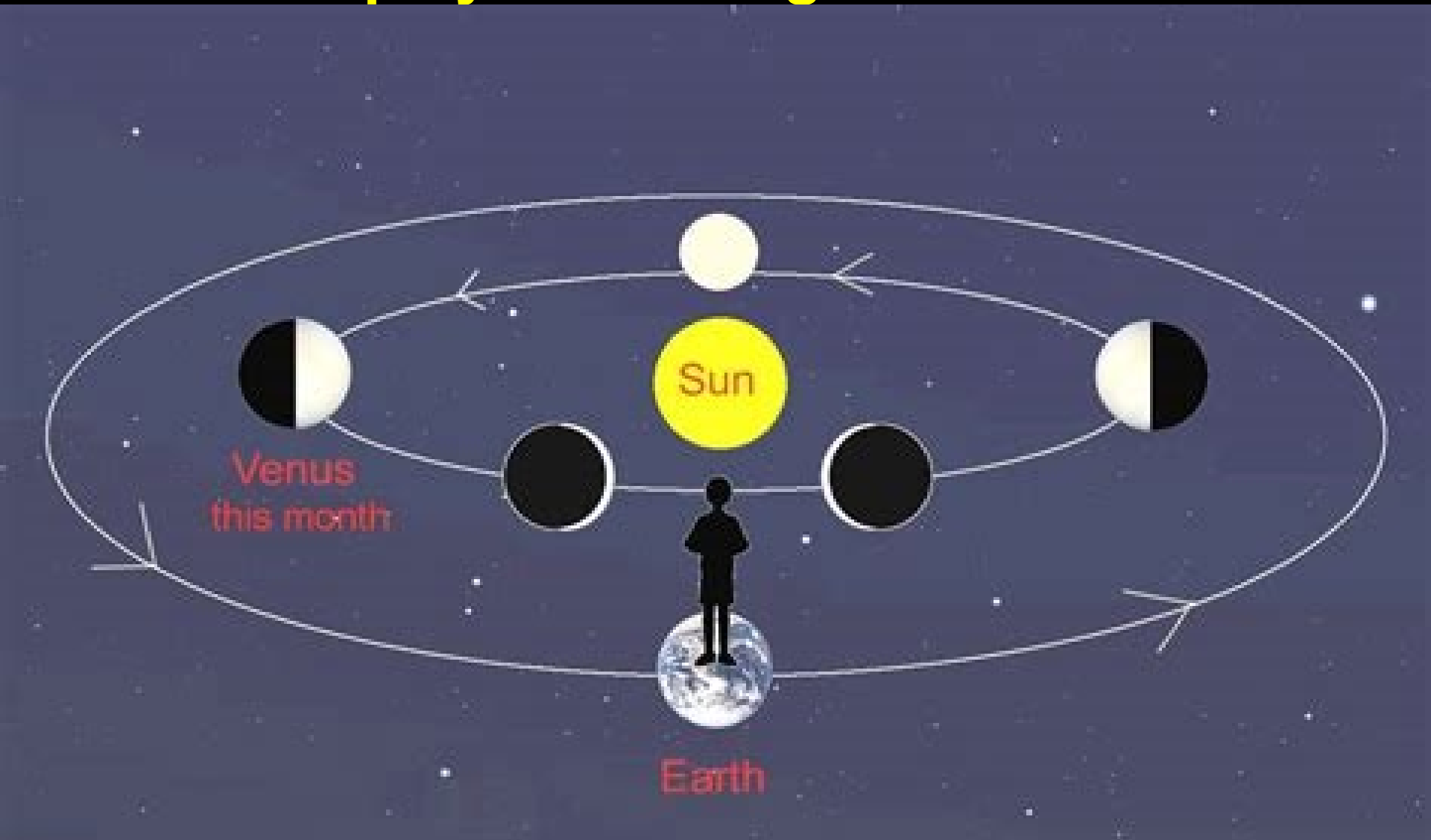
Venus Showed All the Phases that the Moon Did

- The Church wasn't as upset with this. But, they should've been –
- …since it's the most fatal of all his observations to the Church's cosmology, as Galileo knew.
- Let's see why, on the white board…

If Venus follows an epicycle in an orbit around the Earth, as the Church demanded, it always shows a crescent phase, or New.



Venus shows all the phases from new to full, but only if it orbits the sun, not on an epicycle circling the Earth



Bottom Line:

Galileo's observations showed that Venus must circle the Sun, and the Earth must be outside of Venus' orbit.

This Disproves the Ptolemaic Earth-Centered Model

- Still, Galileo had been a friend of the man who later became Pope Urban for many years, and this gave him certain shelter from the wrath of the Church.
- But Galileo's masterful and devastating critique of Jesuit positions on science alienated that large segment of the Catholic Church, and when the political position of Pope Urban weakened, Galileo was sent to the Inquisition and threatened with torture if he did not recant his scientific positions.

At his trial in 1633, under threat of torture, he proclaimed he rejected these scientific positions

- **The Inquisition** was not impressed, sentenced him to prison, later commuted to house arrest, where he spent the remainder of his life.
- All of his works, including any he might write in the future, were declared officially banned.
- He died in 1642.

This Church attitude, unfortunately, is not just ancient history

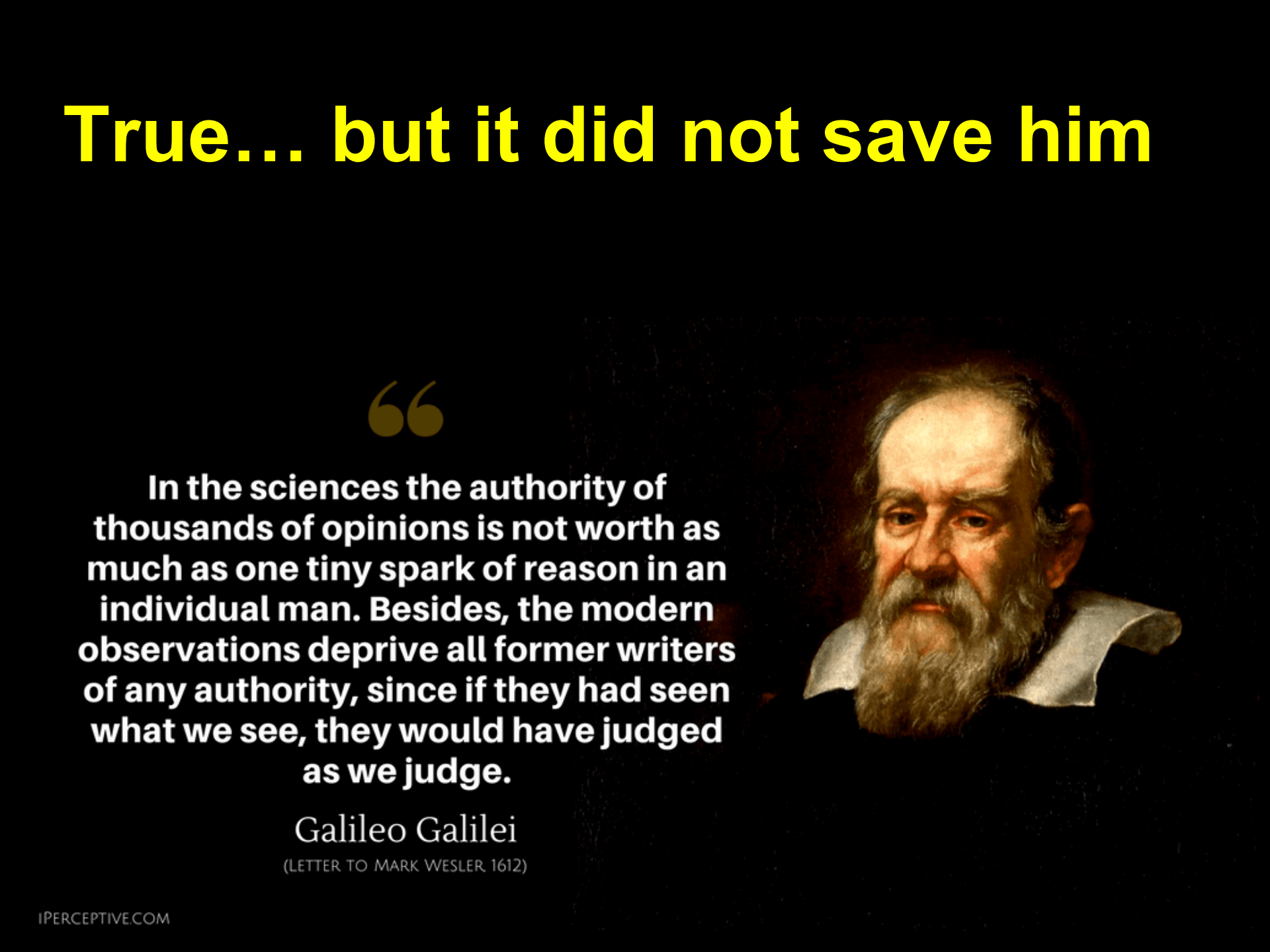
On **February 15, 1990**, in a speech delivered at La Sapienza University in Rome,[78] Cardinal Ratzinger (later Pope Benedict XVI) cited some current views on the Galileo affair as forming what he called *"a symptomatic case that illustrates the extent to which modernity's doubts about itself have grown today in science and technology".*[79] As evidence, he presented the views of a few prominent philosophers including Ernst Bloch and Carl Friedrich von Weizsäcker, as well as Paul Feyerabend, whom he quoted as saying: (Note below: "she" refers to the Catholic Church)

The Church at the time of Galileo kept much more closely to reason than did Galileo himself, and she took into consideration the ethical and social consequences of Galileo's teaching too. Her verdict against Galileo was rational and just, and the revision of this verdict can be justified only on the grounds of what is politically opportune.[80]

From the same Wikipedia Article on Galileo…

- In January 2008, students and professors protested the planned visit of Pope Benedict XVI to La Sapienza University, stating in a letter that the pope's expressed views on Galileo *"offend and humiliate us as scientists who are loyal to reason and as teachers who have dedicated our lives to the advance and dissemination of knowledge".*[82] In response the pope canceled his visit.[83]

True… but it did not save him



But it was too late to stop the Renaissance in science

- Copernicus' "De Revolutionabus" in 1543 had become an underground hit!
- Now the race was on – perfect uniform circular motion, even in the sun-centered model, didn't reproduce the measured positions of the planets accurately.
- What is the true shape and true motion of the planets? To answer, we first need GOOD DATA!
- Enter… ***Tycho Brahe***

Tycho Brahe, with his silver nose, cut off in a duel

Tycho Brahe – Danish Astronomer of late 1500's

- Discovered the supernova of 1572, showed it was far beyond the planets – the first non-planet to be shown to be something other than fixed and constant.
- King of Denmark impressed, gave him an island and money for the best scientific instruments of his day
- He read Copernicus. Brahe's goal: find the true orbits of the planets.
- He was an OUTSTANDING observer. Measured the precise positions of the planets, especially Mars, every clear night for 20 years, with an accuracy of +- 1 arcminute (!)
- But he was not a great mathematician. No problem – he had the money – he hired one!

Johannes Kepler. Very talented with the pen and pencil, and mathematics, hired by Tycho Brahe to help him solve the problem of how the planets moved

How did Kepler determine the shape of the planetary orbits? He was Very Clever!

- Kepler's data was a table of **times** and **positions** of the planets.
- He figured, let's start with a promising planet and once we've figured it out we can then streamline the work on the other planets.
- Let's try and decide which would be a good choice for a first planet to tackle…

Which Planet to Choose?

- Mercury? Too close to the sun and never on the meridian except in daylight
- Venus? Same problem
- Saturn? Took 29 years to go around the sun and with only 20 years of data, that's not even 1 orbit
- Jupiter? Took 12 years, not enough to make sure it travelled the SAME orbit each time

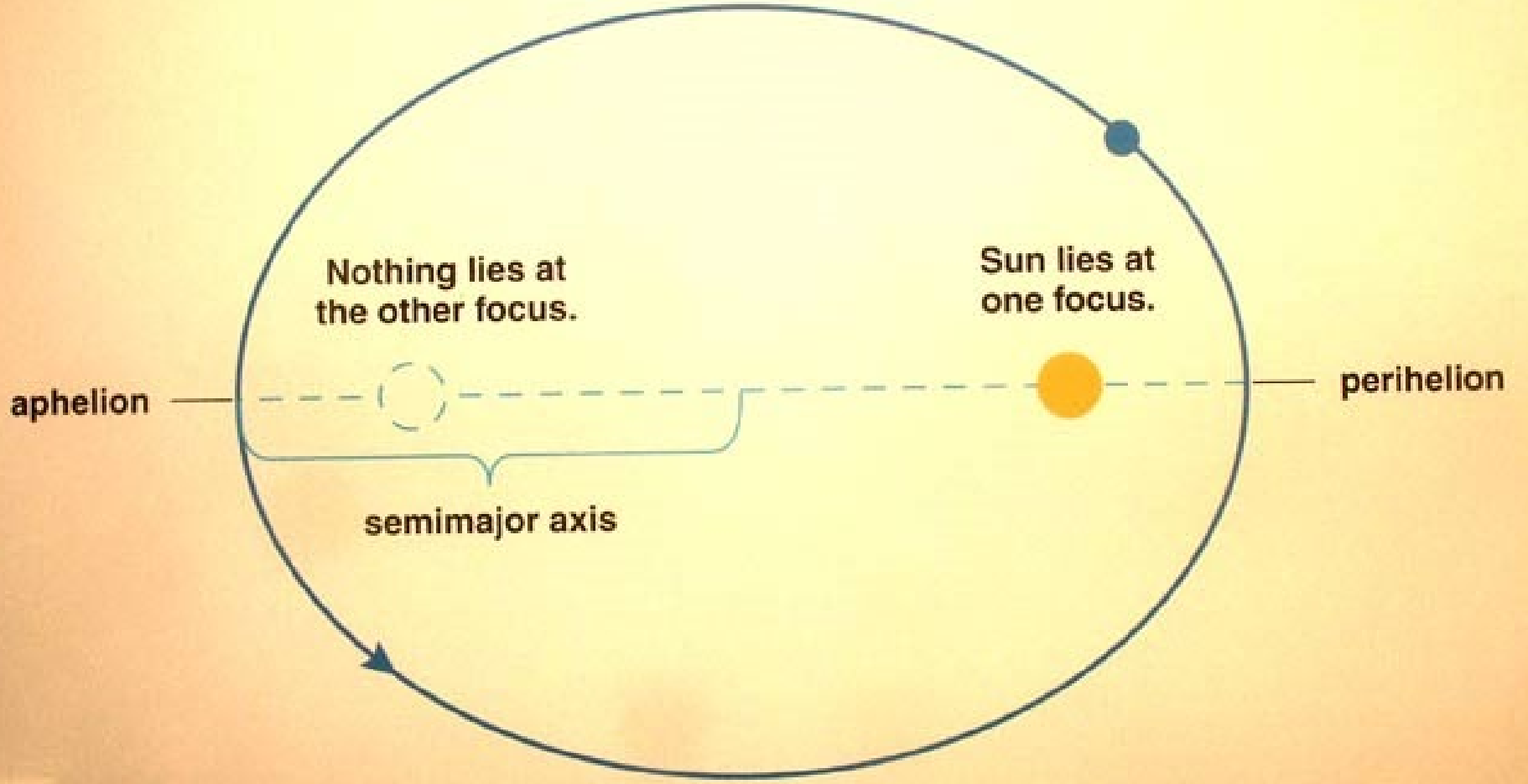
The Obvious Choice was Mars

- It needed 37 epicycles to even just agree with naked eye data, let alone more precise telescope data. Whatever non-circular motion was going on, Mars was doing it big.
- And it took less than 2 years to circle the sun, so 20 years was plenty of time to make sure it did the same orbit each time.
- And it was usually visible due south (on the meridian), as Brahe's observatory required, at night.

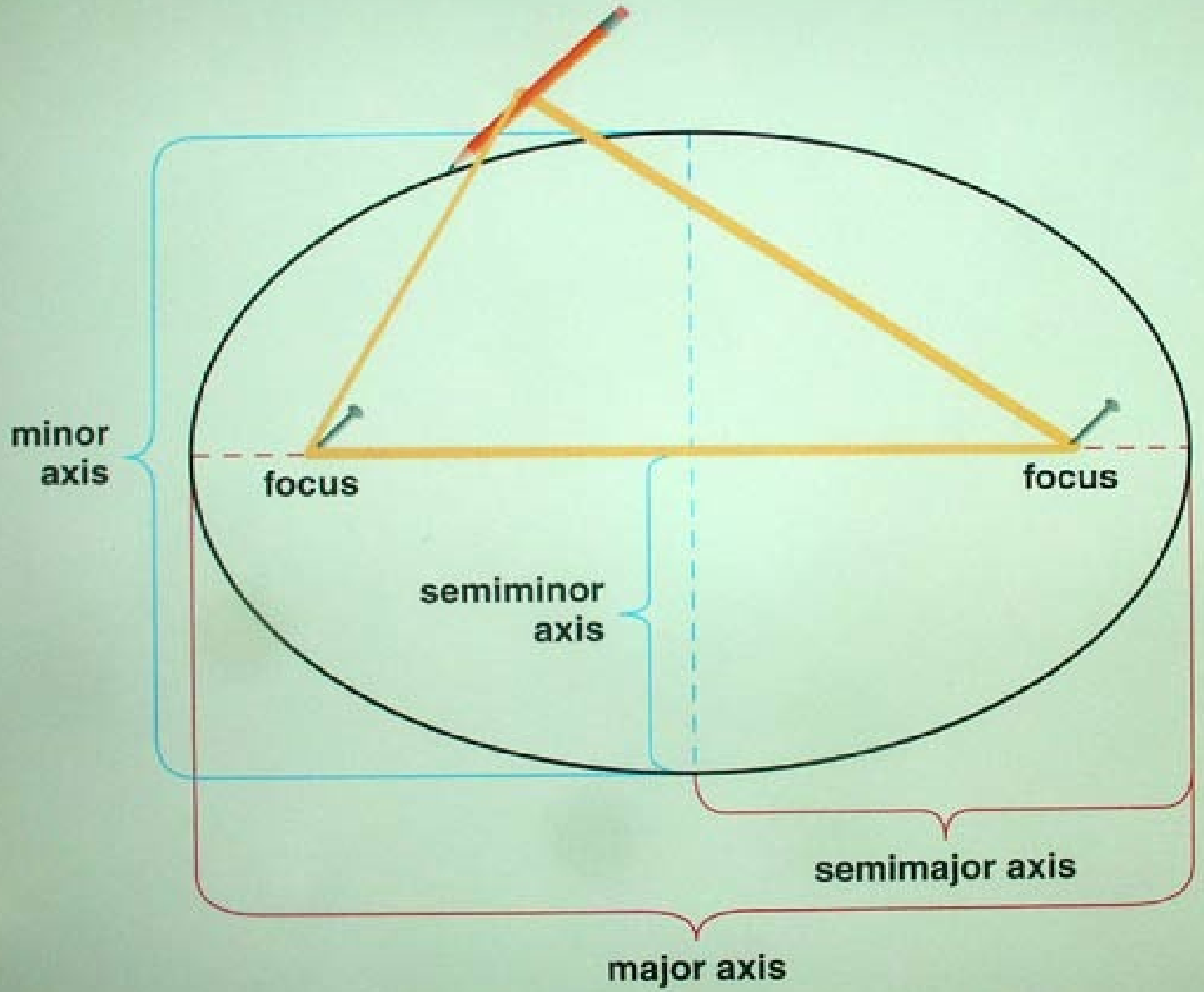
Kepler's 1st Law

- ***Planets orbit in ellipses, with the sun at one focus***
- OK… so what's an ellipse, and what's a focus??...

Figure 5.8 Kepler's first law



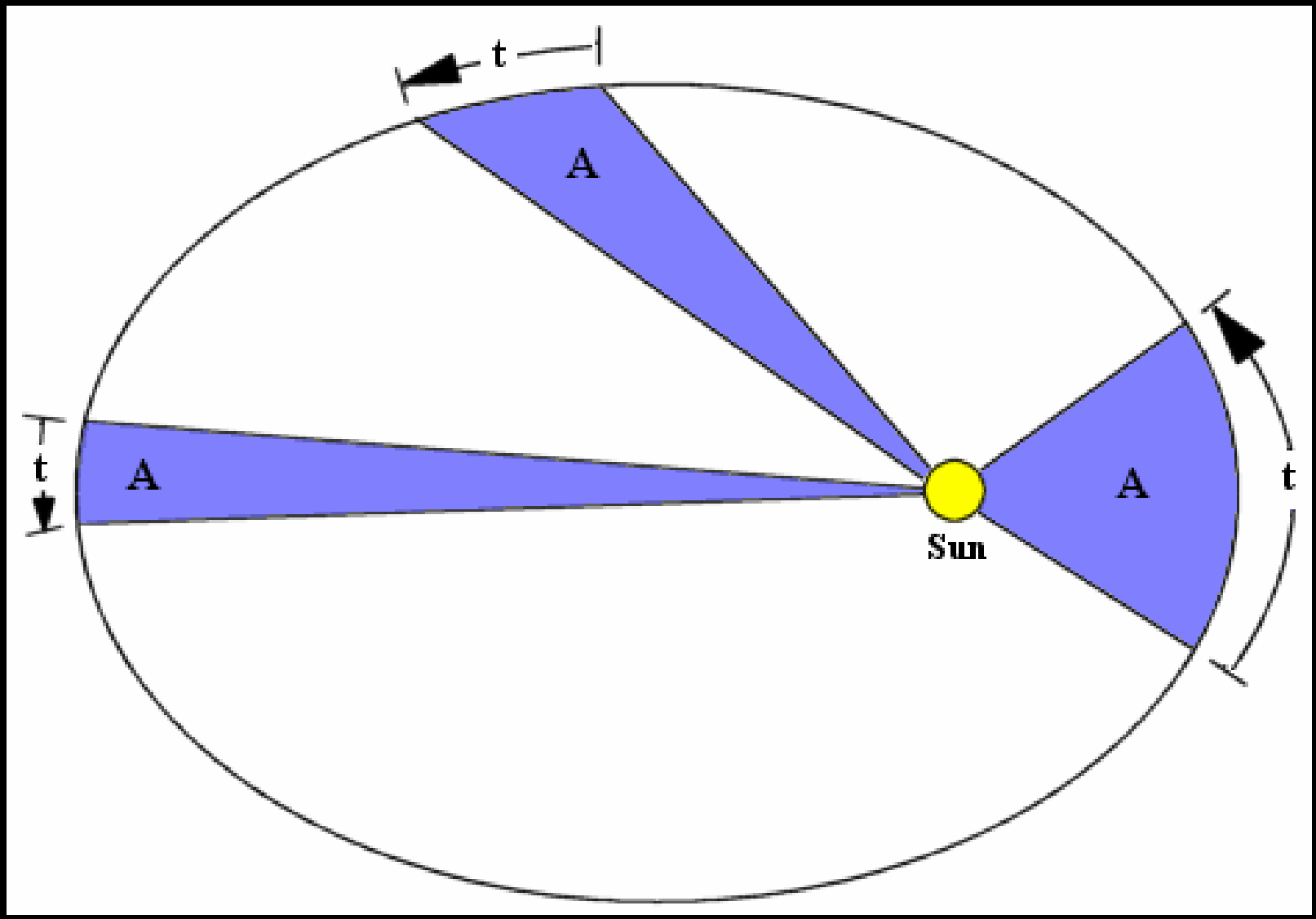
Drawing an ellipse



Kepler's 2nd Law

- Often called the "Equal Area Law"
- The sun-to-planet line sweeps out equal areas in equal times
- Pick any time interval you want. The sun-planet radius sweeps through the same area during that time interval, regardless of where it is in the orbit.
- This law is an example of a more general rule – *Conservation of Angular Momentum*

Kepler's 2nd Law: Equal Area Law



- For a given time interval, **t**, the area swept out in that time is the same no matter where in the orbit. **All blue wedges have the same area**

An Animation showing the Meaning of Kepler's 2nd Law: "The Sun-to-Planet Line Sweeps Out Equal Areas In Equal Times"

- http://en.wikipedia.org/wiki/File:Kepler-second-law.gif
- And a YouTube 9 sec video
- And a tune-able animation
- This law is an example of a more general rule – *Conservation of Angular Momentum*

Kepler's 3rd Law

- This law was a pattern in the numbers that he noticed after he'd solved for the orbits of all 5 known planets.
- He noticed that the **larger the orbit**, the **longer the planet took to do one full orbit of the sun (=Period)**
- He felt sure there must be, again, some wonderful mathematical simplicity which gave exact answers to exactly how the size and period related…

How Might You Quantify a Fuzzy Idea like “Size”?

Give me examples of different ways to talk about the “size” of an elliptical orbit, and that all have the dimension of “length”

Your turn…

Here's Some that Occur to Me

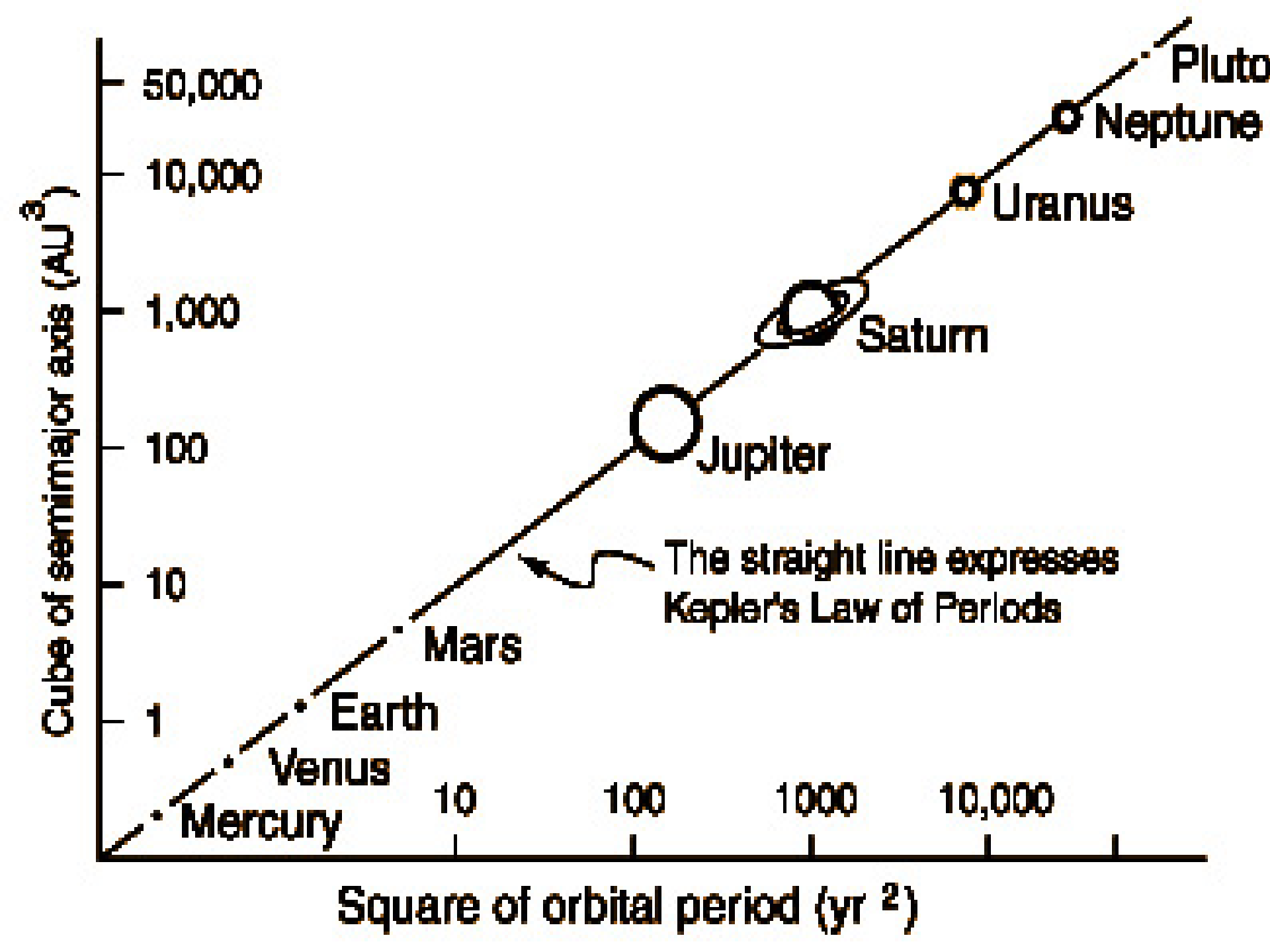
- Shortest diameter (=minor axis)
- Longest diameter (=major axis)
- Sqrt[major * minor]
- Time-averaged distance from sun
- Spacially averaged distance from sun
- Sqrt[area inside the ellipse]

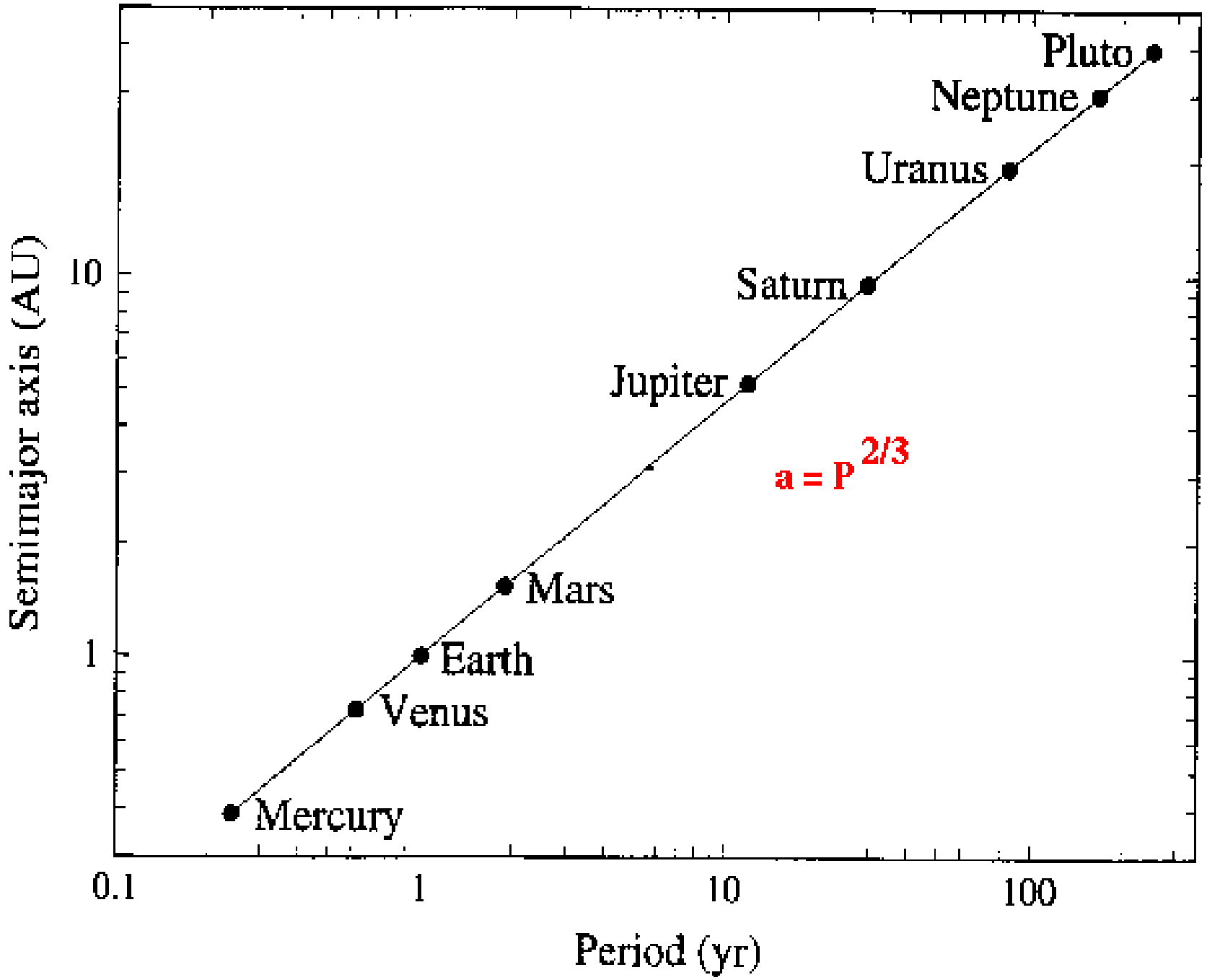
He look for mathematical patterns long and hard with pencil and paper…

- …he tried many ideas for relating size to Period, and none showed any pattern… until
- He tried using "longest diameter" also called the Major Axis = **a**
- Then he discovered…

- **$P^2 = ka^3$ where *k* is just a single "constant" number, the same for all planets or indeed, anything orbiting the sun**
- ***k* is the slope of the line on these following graphs**

$$\frac{P^2}{a^3} = \text{constant}$$


Cube of semimajor axis (AU^3)
50,000
10,000
1,000
100
10
1
Square of orbital period (yr^2)
10
100
1000
10,000
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Pluto
The straight line expresses
Kepler's Law of Periods


Pluto
Neptune
Uranus
Saturn
Jupiter
Mars
Earth
Venus
Mercury
a = P 2/3
Semimajor axis (AU)
10
1
0.1
1
10
100
Period (yr)

Kepler's Laws: These are just numerical patterns at this point

- Kepler supplied no fundamental THEORY of why planets orbit at all, or what should determine their shapes and sizes and the sublime laws he had discovered.
- That was going to be up to Newton, building on the gravity experiments of Galileo, and his own reasonings

Chap 3 - Key Points

- 250 BC Aristarchus first realized sun-centered model was simplest explanation of Retrograde Motion. And, Earth was sphere
- Erotosthenes and how he measured the size of the Earth using the angle above the horizon of the noon sun, from two different places in Egypt. Ponder how that angle changes if the size of Earth changes
- Ptolemy's Earth-centered model of circles was a calculation device for planet positions in the sky, but turned into dogma by Church. Complicated by epicycles on top of epicycles needed to match observations because planets do NOT orbit in circles around the Earth.
- Giordano Bruno in 1600 burned as a heretic for proposing the stars were other suns with solar systems that might be inhabited
- Tycho Brahe: 20 years of precise planet position measurements, used by Kepler and found 3 patterns – Kepler's 3 laws (know all 3!)
- Copernicus, on death bed, had published his treatise on the sun-centered model for the solar system in 1543.
- Galileo: telescope discoveries in 1610 disproved Ptolemy model, imprisoned by Inquisition
- Galileo's observations of the phases of Venus showed Venus went around the sun, not the Earth
- Know the order of the planets
- Know the meaning of the eccentricity of an ellipse