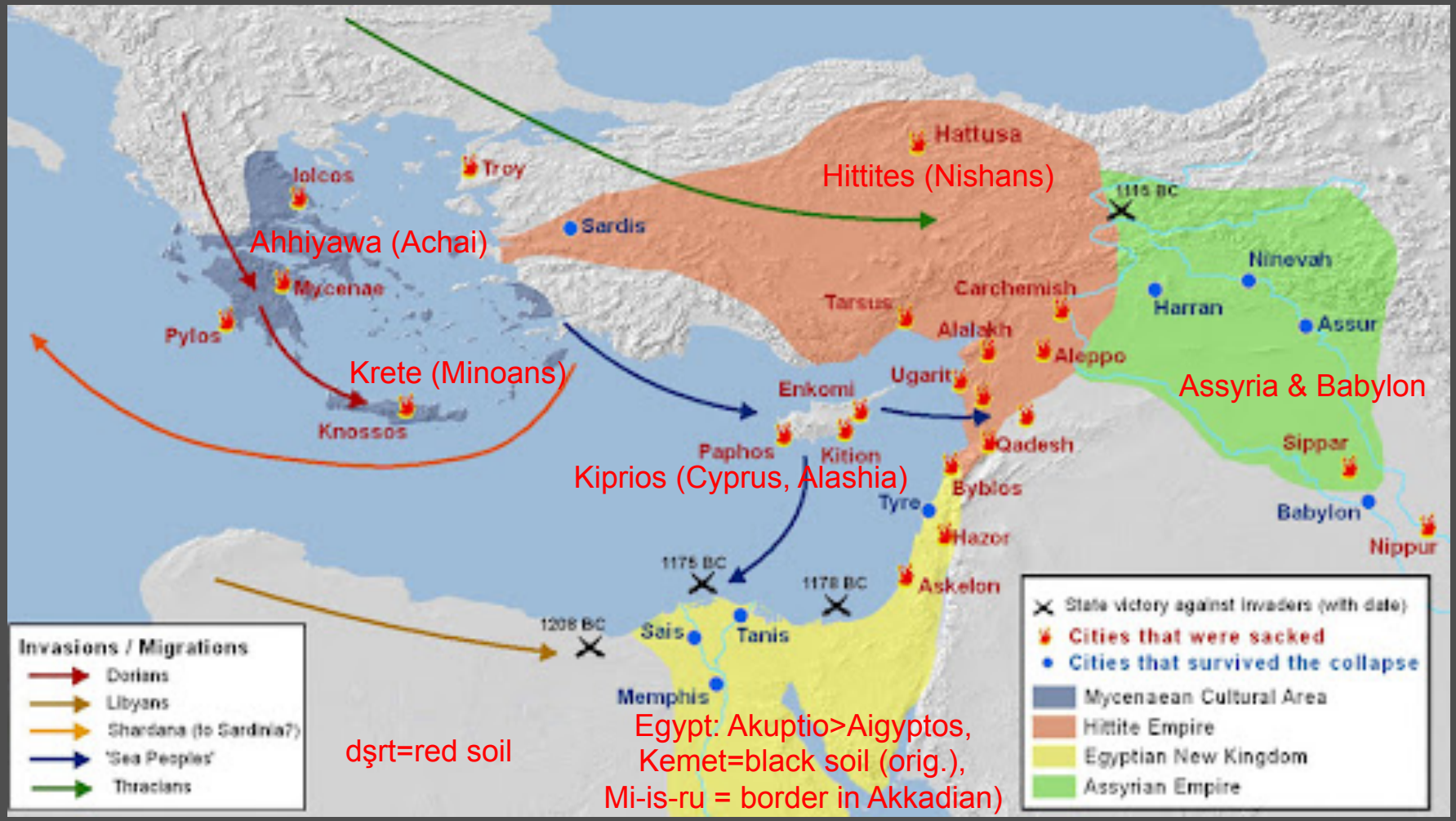
Here's where we ended Lecture 4…

- Pre-scientific astronomy had only involved making observations, recognizing patterns, and making rudimentary predictions. A crucial part of the scientific method – building and testing models and hypotheses – was apparently missing.
- This was about to change in Classic Ancient Greece, civilization which did grew and blossomed on the ashes of earlier, very high-tech civilizations of the Mediterranean region.
- These civilizations lived and traded in a world resembling modern, globalist, interdependent manner: Hittite, Egyptian, Assyrian, Babylonian, Aegean and Minoan, Mitanni, Mycaenian, Cypriot, Ugarit, Amurru, Assuan,Trojan, Canaani kingdoms.
- Following a civilizational catastrophe spurred by environmental changes (Minoan warming for 200 yr), internal unrests, and migrations of warrior nations (Sea People) from the North of the Mediterranean, Late Bronze Age (LBA) ended abruptly around 1177 BC, the time of Egypt invasion soon after the Trojan war.

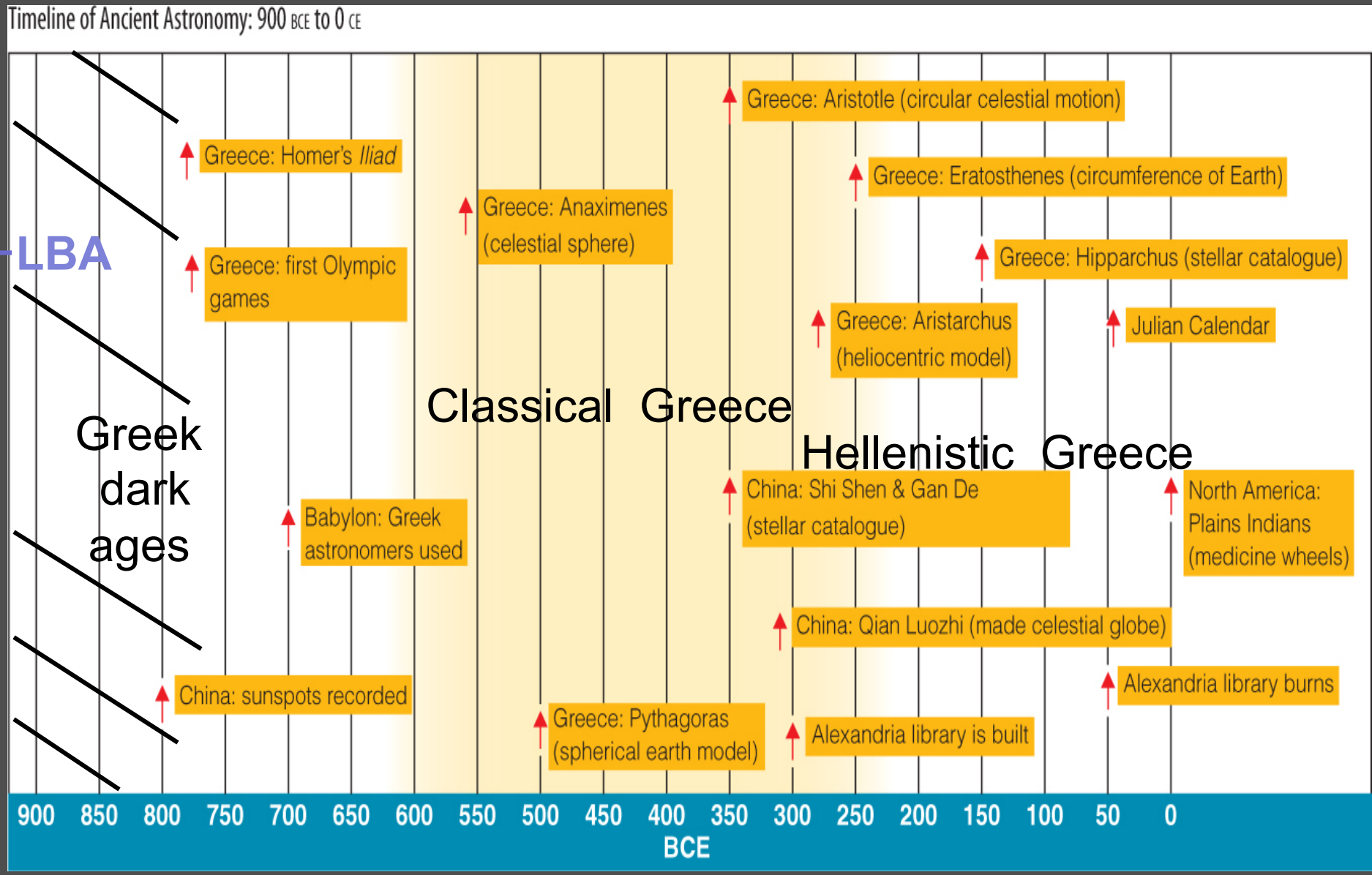
- Invasions of Sea People, tribes called by Egyptians: Peleset(=Phillistines), Tjekker (=?), Shekelesh(=Sicilian), Shardana(=Sardinia). Most palaces, cities, libraries, and temples smashed & burned, abandoned.



Where we stopped in Lecture 4…

- ALL the cities of Late Bronze Age (LBA) civilizations were burned. The ability to read and write cuneiform tablets in Akkadian (widespread like English today) vanished. The period of decline of civilization (1200-750 BC) is called the Greek Dark Ages.

Ancient Greece periods & astronomical moments everywhere



ASTB03 Lecture 5

Great Moments of ancient Greek astronomy:

- Ionian materialists (creators of atomism) Leukippos and Demokritos and their understanding of atoms, and the birth, diversity & evolution of planetary systems
- Master and pupil at the Academia: Platon, Aristoteles (Eng.: Plato, Aristotle)

- The mathematical and mechanical genius: Archimedes, Palimpsest, and mechanical universes
- Antikythera mechanism. A great moment in Astronomy and the beginning of Computer Science

- Astronomer: Claudius Ptolemy's & his *Almagest*. Geocentric world of the hellenistic Greek period.

Greek Atomists

- Greek pre-Socratic philosophy is where the first general theories of Physics started, not only the collection of facts about heaven and earth, calendars or astrology

A materialistic philosophy appeared, which assumed that the universe consists of particles (atoms) able to move in vacuum, with little hooks allowing them to bind into larger objects (molecules, solids, in modern terminology).

From this assumption, Leukippos (Leucippus) and

Demokritos (Democritus) inferred correctly (not in detail! but generally ok) how planetary systems form, live and sometimes die. The idea of evolution was new.

Importantly, they deduced almost infinite *diversity* of planetary worlds (*kosmoi*)

Antique theory #1: Plurality of worlds

Kosmos: unique or multiple (infinite in number?)

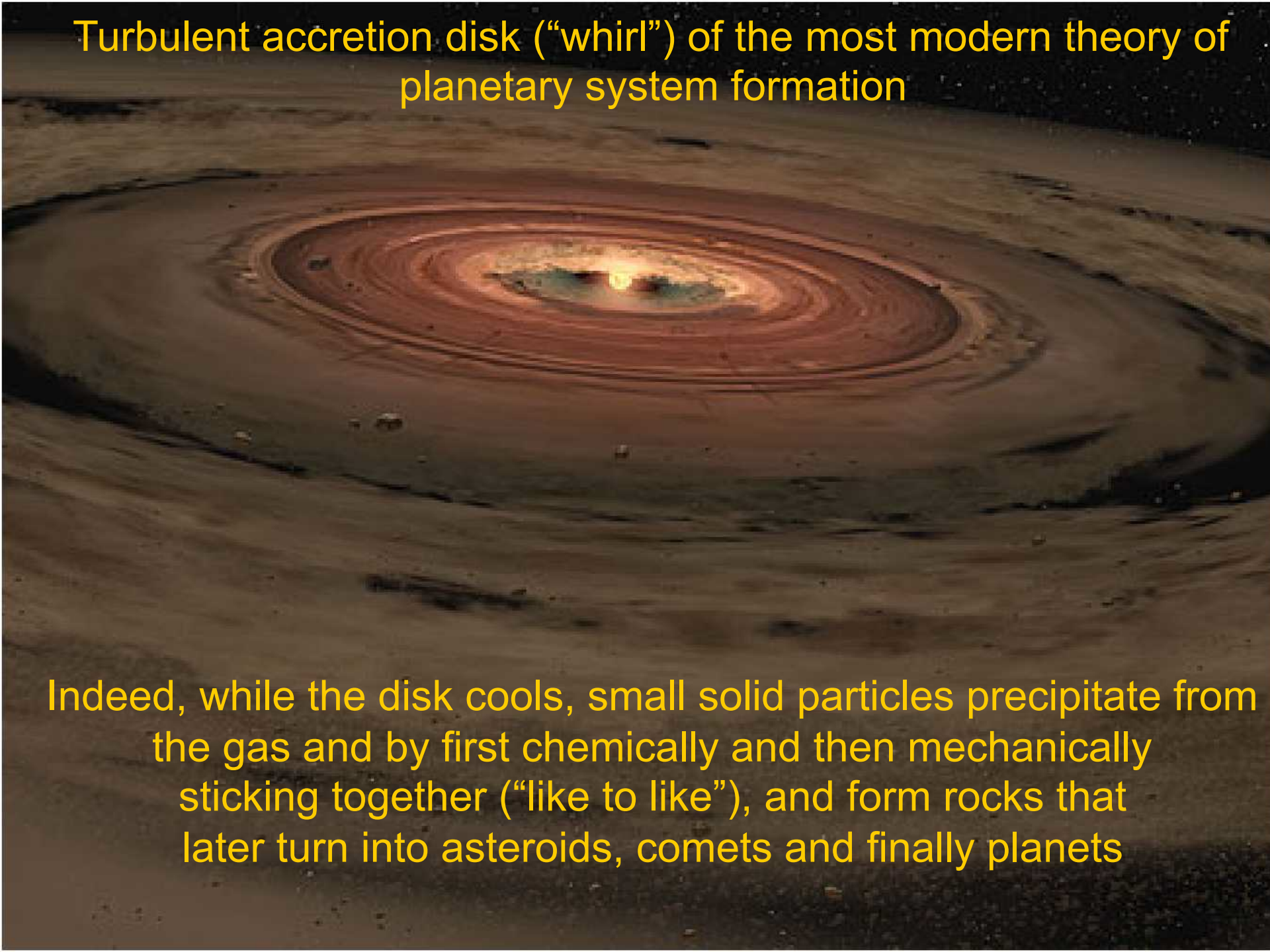
Atomists Leucippus and Democritus considered the world

built of the same (`solar abundance') atomic matter that forms the Earth, subject to constant motion through vacuum, collision, and coalescence (accretion).

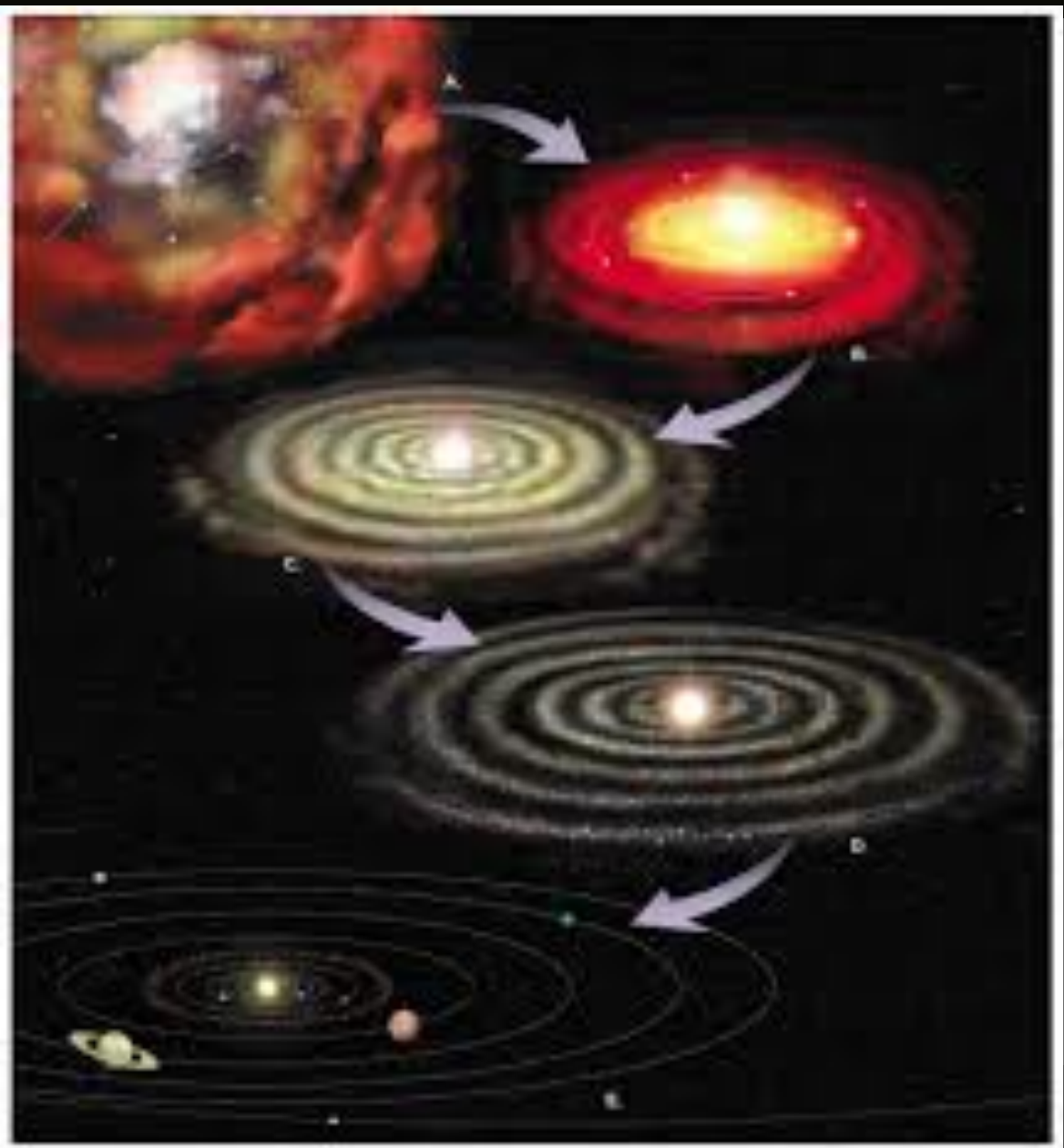
Ancient atomists wrote about what we now call the solar nebula:

> *The worlds come into being as follows: many bodies of all sorts and shapes move from the infinite into a great void; they come together there and produce a single whirl, in which, colliding with one another and revolving in all manner of ways, they begin to separate like to like.*

Leucippus (480-420(?) B.C.), after Diogenes Laertios (3rd c. A.D.)


Turbulent accretion disk (“whirl”) of the most modern theory of planetary system formation
Indeed, while the disk cools, small solid particles precipitate from the gas and by first chemically and then mechanically sticking together (“like to like”), and form rocks that later turn into asteroids, comets and finally planets

Modern “whirls” (schematic stages vs. recent observations)



VIDEO ("HL Tauri: ALMA…")

First detailed picture of a young planetary system HL Tauri (ALMA observatory, 2014)

The following predictions anticipate planets around pulsars and binary stars; evolutionary aspect stressed; hot planets.

In some worlds there is no Sun and Moon, in others they are larger than in our world, and in others more numerous. In some parts there are more worlds, in others fewer (...); in some parts they are arising, in others failing. There are some worlds devoid of living creatures or plants or any moisture.

Democritus (ca. 460-370 B.C.), after Hyppolytus (3rd cent. A.D.)

Plurality and diversity of planetary systems reaffirmed:

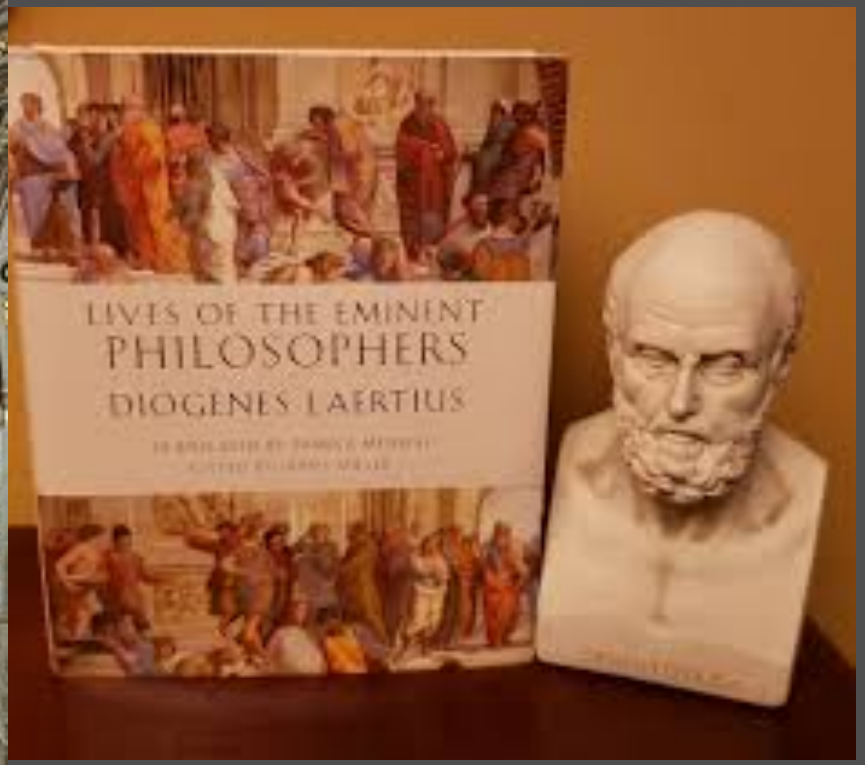
There are infinite worlds both like and unlike this world of ours. For the atoms being infinite in number, as was already proven, (...) there nowhere exists an obstacle to the infinite number od worlds.

Epicurus (341-270 B.C.)

Similar writings by **Lucretius (ca. 99-55 B.C.).**

For more info see a very readable 3rd century A.D. source on those philosophers,

Diogenes Laertios (3rd cent. CE, earliest existing copy from 11th century) “Lives of the Eminent Philosophers”



Antique theory # 2: ideal heavens

Πυθαγόρας (ο Σαμιος)
Pythagoras (of Samos)

The pre-Socratic, materialistic & naturalistic

Philosophy (as opposed to theism) from

Ionia, which achieved so much with the atomic-cosmic world of Leucippus and Democritus, was at odds with a fundamentally different worldview: idealism.

The main representatives were

Pythagoras of Samos (590-475 BCE),

Plato (428-348 BCE), and partly also his famous student

Aristotle (384-322 B.C.)

Antique theory #2: ideal heaven

Pythagoras traveled the world in his youth, and later (~530 BC) founded a somewhat secretive religious sect and school in Croton (currently in southern Italy).

He was the first to call himself philosopher (literally: one loving wisdom).

Pythagorean brotherhood put *integer numbers and ratios* expressed as fractions above all, and made them a mystical basis of everything in the world; also – their closely guarded secret.

"The so-called Pythagoreans, who were the first to take up mathematics, not only advanced this subject, but saturated with it, they fancied that the principles of mathematics were the principles of all things."

Aristotle, *Metaphysics 1–5 , 350 BC*

Antique theory #2: ideal heavens

Pythagoras was the first person known to have

taught the earth was spherical, and that

it *traveled around the sun*

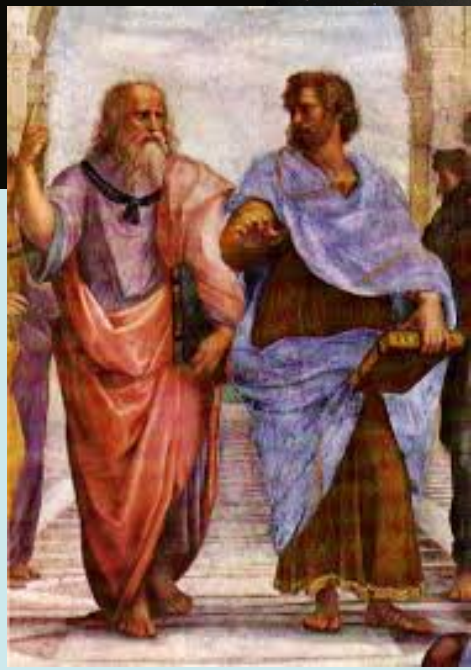
(like Mikołaj Kopernik two thousand years later), although this was based primarily on the mystic not not on astronomical grounds. It is likely that Copernicus adopted parts of Pythagorean worldview.

Pythagoras created the notion of the “Music of the spheres”, the inaudible harmony (accessible to the human mathematical mind) of the revolutions of the heavenly spheres with their attached planets.

Pythagoreans had a hierarchical organization, did not share the knowledge with just anybody and, in general, did not much like democracy, for which they were eventually chased away from Croton (when a tyrant was deposed).

Antique theory # 2: ideal heavens, unique Earth

The atomist worldview was eclipsed by a cohesive system of **Aristotle** (384-322 BC), a student of **Plato** (428-348 BCE) at his Academia and tutor of Alexander the Great.



Aristotle was not really interested in plurality of planetary systems, their formation, or other then-unobservable things.

Plato founded a school in Academia, olive grove of goddess Athena near Athens. He despised all materialism and atomism; his philosophy was idealistic, to a large degree following the Pythagorean spirit.

The ideal forms and their symmetries were different on Earth and in Heaven.

Plato strictly also divided body and soul in a human.

He was not a fan of democracy – enlightened aristocracy should run a city-state, he argued.

Antique theory #2: heaven & earth

Plato proposed pure forms (e.g., the *idea* of a triangle or sphere) as disconnected from and ***superior*** to real world objects, which can only be approximately triangular or spherical & thus are like shadows, less worthy of study than the true objects.

Aristotle disagreed with his teacher on this important point.

For him everything, not only ideal forms and heavenly order were worth of study – everything in Nature, every creature had some beauty and purpose. The essence was in the object we can study and know. We need to experiment, observe and reason in the earthly realm as much as in the heavenly, different as they may be. Today he is acknowledged as a father of most natural sciences.

So that's what the two philosophers discuss in the famous Vatican Palace 1510 fresco *Scuola di Atene* by the Renaissance painter Raphael. See which direction their hands point? Plato's to the heaven, Aristotle's to the earth (or somewhere in-between)!

Antique theory #2: Plato's ideal heavens and the ether

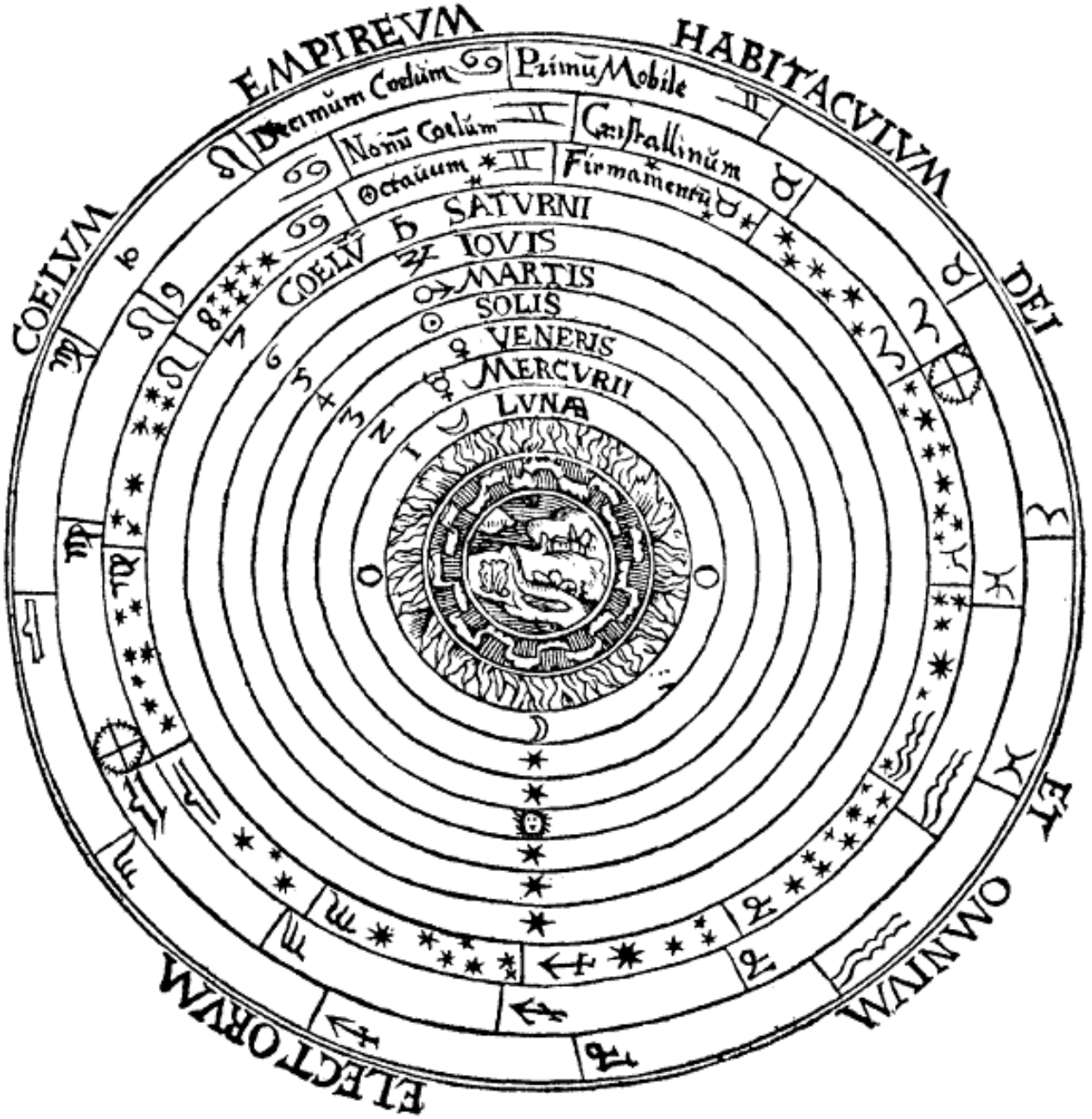
For Plato, that eternal, ideal shapes and ideas created by God were the *quintessence* of the world.

Aristotle considered heavens and bodies therein to be made of a perfect substance of *ether,* also spelled *aether (Gr. α*ἰθήρ).

In fact, *quintessence* is a word from the Aristotelian-Platonic philosophy. It is the "5th element" (*quinta essentia* in Latin), in addition to the 4 accepted ancient elements: earth, water, air and fire.

Those 4 elements Plato and Aristotle associate only with the sub-Lunar world, i.e. regions below the heavenly sphere of the Moon. The supreme, God-like, symmetry of a sphere has led to the conclusion that the universe outside the earthly domain is concentric and made of ideal substance ether.

Schema huius præmissæ diuisionis Sphærarum.



Antique theory #2: Plato's ideal heavens

Plato also maintained that in the heavens the only admissible motion is **uniform** (steady and eternal) – a state of maximum symmetry in time.

The spheres of the Moon, Mercury, Venus, sun, and so on, out to the last one, of the so-called fixed stars, must all be rotating uniformly.

And if they are not moving uniformly across the background of stars, as the ancient well knew, but spend part of the time doing strange loops on the sky chart, then Plato was willing to invoke a model of his pupil Eudoxos of Knidos (408-355 BC): four crystal spheres are assigned to each planet, rotating uniformly around the center of the world on an axis attached to another sphere and so inclined as to satisfy observations.

Earth and Sun are unique - Aristotle

Plato's and Aristotle's world was **geocentric**, **unchanging and unique.** Unfortunately for the history of Physics and Astronomy, this division into terrestrial and extraterrestrial realms, idea of final cause (defined below), and the whole Aristotelian Physics were utterly wrong by today's standards. See for yourself.

None of the following is true:

Motion requires a continuous support (force) to happen.

The four elements move each to their 'natural place' with respect to the center of the world. They are directed by a **final cause** (the purpose, not just the past history or forces). The existence of many such centers is unthinkable: The world would lose the divine spherical symmetry, bodies would not 'know' to which center they should fall, etc. Thus

"There cannot be more worlds than one" Aristotle

[meaning: there is only one planetary system, centered on the Earth]

ARCHIMEDES –& the beginning of modern science

In 3rd century BC, the most famous Greek scientist of antiquity Archimedes (Ἀρχῑμήδης, 287-212 BC) lived in the hellenistic period of history (after the fall of the empire of Alexander of Macedon in 323 BC). He worked in the Greek colonial city of Syracuse, in eastern Sicily (Italy). He was both a mathematician and a physicist, also an applied physicist (engineer) tasked by kings Hiero and Hieronymus to defend Syracuse with his mechanical contraptions during the Roman attacks. The siege of Syracuse lead to the killing of Archimedes, busy with drawing circles in the sand on the beach, by a Roman soldier of the army of general Marcellus (likely against general's orders).

Archimedes directing the defense of Syracuse from Roman army during Rome-Carthage wars (214-212 BC).

ARCHIMEDES AND HIS PALIMSEST

palimpsest = parchment (calves skin) which has been rubbed/erased to make space for a new text (here: for Middle Age prayer book)

Archimedes appears on the world's highest mathematical medal awarded by Fields Institute in Toronto (StG/UofT)

Archimedes created the first laws of mechanics, such as the laws of the lever and pulleys, buoyancy etc.

In mathematics, until recently he was celebrated for his calculation of the area of circle, area under the parabola, area and volume of the sphere and the ratio of volumes of a cylinder and an inscribed sphere.

But in a recent investigation, we found from a previously lost book (Codex C or Archimedes' Palimpsest) that he understood and used infinity, infinitesimals and limits in ways not supposed to have been known for another millenium. Archimedes was using what we call Riemann integral to derive areas and volumes, two thousand years before Georg Riemann.

# Hitory of ARCHIMEDES' PALIMSEST
palimpsest = recycled parchment

- before 213 BCE: Archimedes writes the treatise
- in 10th century CE, monks copy his original treatise
- in 1229 someone erases and recycles it as valuable parchment
- Palimpsest gets deposited in Metochion, Greek library in Constantinople (now Istanbul, Turkey) for many centuries
- in 1880s a catalog mentions a math text in Constantinople
- in 1906 Danish historian Johan L. Heiberg examines the 174-page book after suspecting correctly that it is a treasure
- in 1920s the book disappears from the library, and re-surfaces as private possession in Paris

ARCHIMEDES' PALIMSEST

- During WWII the book disappears again, gets "augmented" by falsified drawings like this one to increase its resale value
- Stored inappropriately, it decays from the relatively good state it was in 1906, due to mold etc.
- Palimpsest is sold at Sotheby's auction in London in 1998 for $2 million to an anonymous buyer, who lets Walters Art Gallery staff (Baltimore, MD) and international experts restore and decipher *The Method of Mechanical Theorems* and other treatises, previously assumed lost.
- It is not obligatory but you may want to see this video in 3 parts The video does not explain the math of the text, but nicely presents the turbulent history of this work.

https://www.youtube.com/watch?v=_rHv3OiaVC8
https://www.youtube.com/watch?v=po-ueHf-mDU
https://www.youtube.com/watch?v=DDPvAOLNXH8

Mysterious mechanism probably from Archimedes's workshop. The first analog-digital computer in the world.

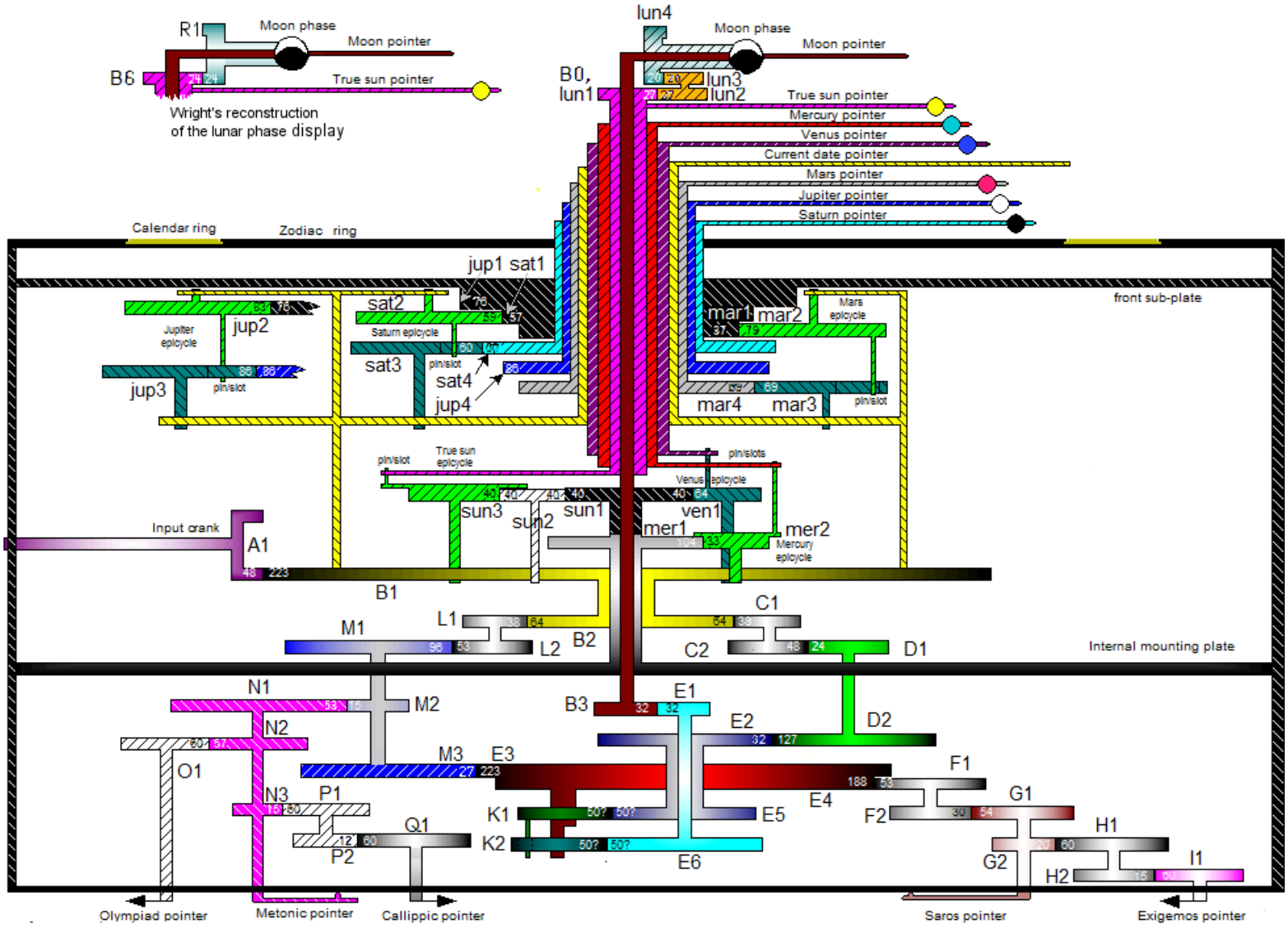
ANTIKYTHERA MECHANISM was recovered from under water around 1900. An ancient shipwreck was found near the Greek island called Antikythera, located south of a bigger island of Kythera. Among the recovered items was a fragile, complicated set of many cogwheels (like in a wrist-watch) that fits within a shoebox. In 2000s it was 3D-scanned with Xrays in a specially built machine, in order to reveal the structure and purpose of the strange thing.

It turned out to be a digital+analog computer of future positions of planets, dates of movable holidays like Olympiads, eclipses of the sun and moon, lunar phases, zodiac signs, etc. It could even show the Saros and other cycles.

It is a complex, special-purpose astronomical calculator!

Parts of the machine are lost, but *functioning* replicas were built.

watch https://www.youtube.com/watch?v=MqhuAnySPZ0



ANTIKYTHERA MECHANISM

Cicero's “De Re Publica”, a 1st-century BC philosophical dialogue, mentions two machines that modern authors consider as a kind of portable planetariums (called orrery) predicting the movements of the Sun, the Moon, and the five planets known at that time.

They were likely built by Archimedes workshop in Syracuse. After Archimedes died at the end of siege in 212 BC, Roman general Marcus Claudius Marcellus brought the contraptions to Rome. Marcellus reportedly had a great respect for Archimedes, and one of these machines was the item he kept from the siege.

How exactly did the mechanism get on the ship and where it was transported is not known.

Models of the Universe

Based on the spherical Earth model, in Alexandria, a contemporary of Archimedes, Eratosthenes (276-195 BC; chief librarian at Alexandria) was able to calculate the Earth's circumference by observing the position of the Sun at noon in two different cities on the first day of summer (summer solstice)

Incredibly, if we are correct in our understanding of his unit of length (stadion) his estimate was very accurate, to within a few percent of the currently known value. Earth's radius corresponding to that circumference is ~6400 km. True mean radius equals 6371 km.

Hipparchus

Hipparcos (190-120 BC)
(a.k.a. **Hipparchus**)

★ made many outstanding visual observations, e.g.

★ very accurate 23º40’ obliquity of Earth (angle of spin axis and orbit),

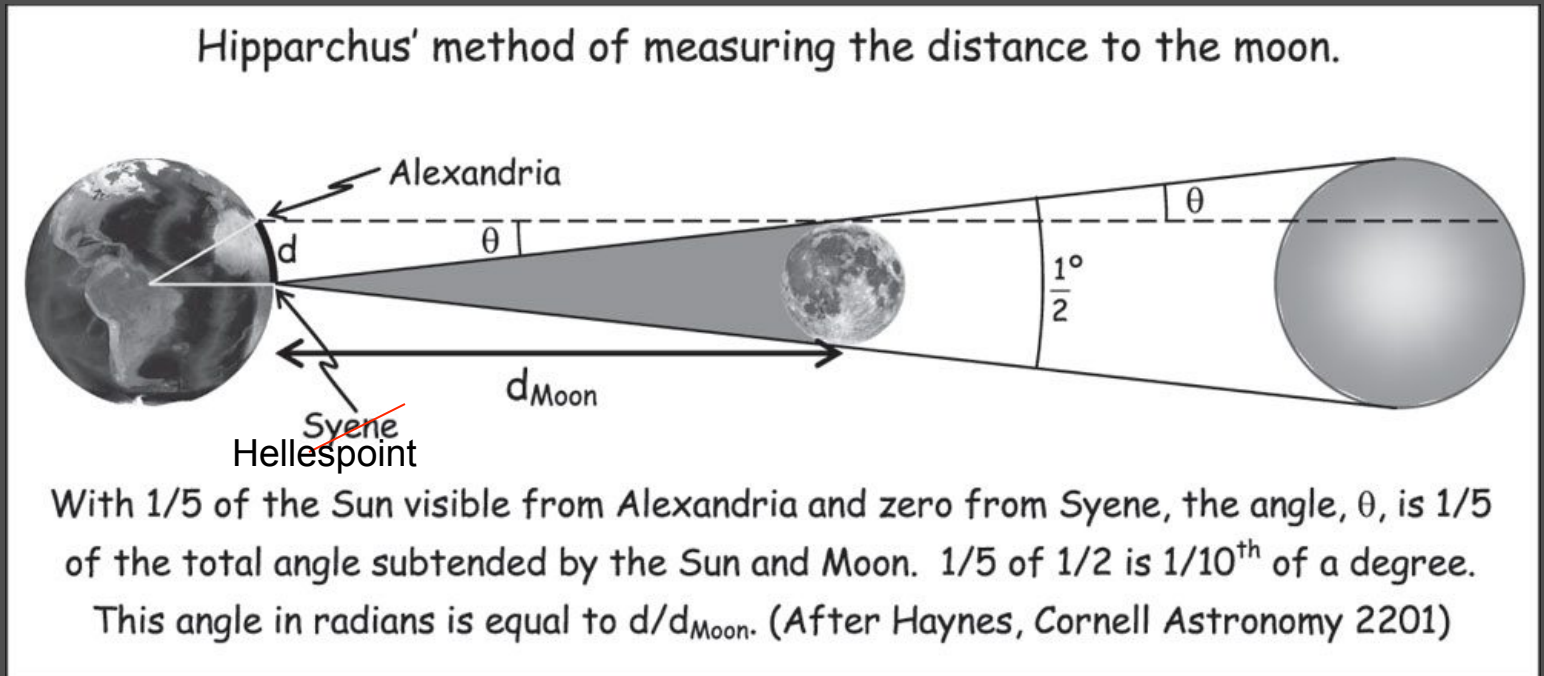
★ published a catalogue of 1080 stars

Hipparchus' discoveries

★ discovered precession of equinoxes, which we now know is caused by the precession of Earth as a spinning top: the spin axis slowly turns in space, moving on a cone with period equal 13000 yr

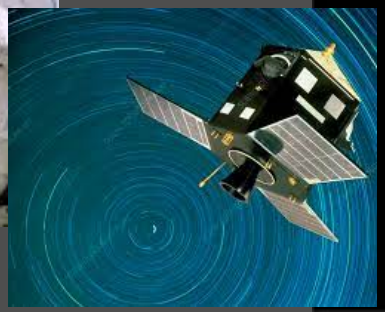
★ parallax of the Moon → distance to the Moon via trigonometry, which he knew very well. If the small side and the small angle (parallax) are known, you can easily find the long sides of a right triangle in this picture:

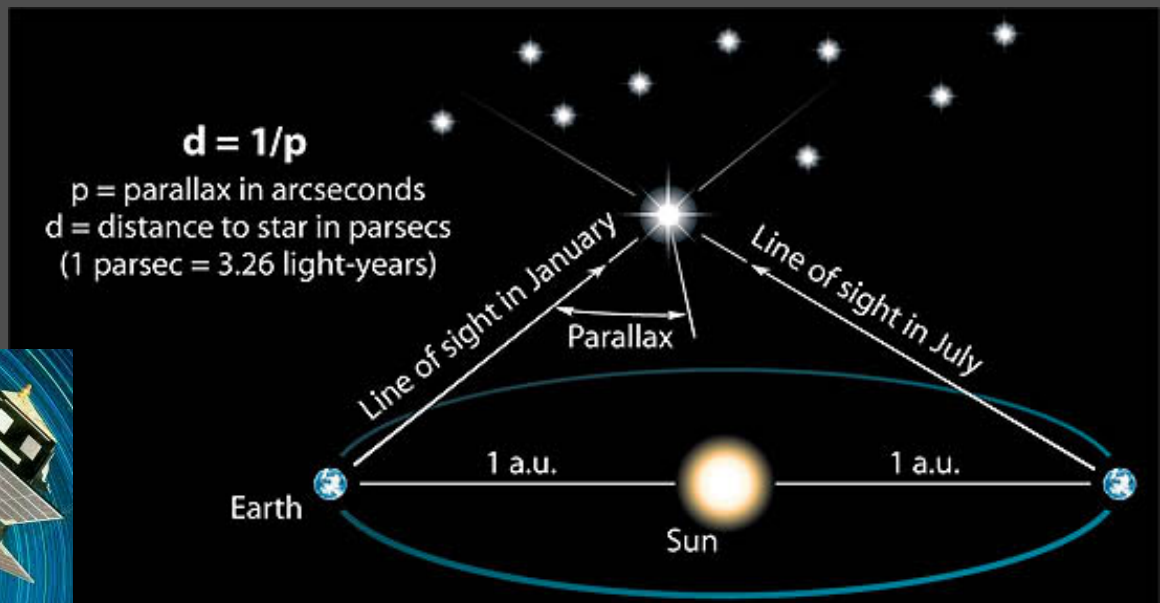
In Alexandria one solar eclipse was partial/ring, while in Hellespoint a total eclipse:



Hipparchus' namesake 2 millenia later found precise distances to a large number of stars by the same method

Satellite Hipparcos launched by ESA (European Space Agency) gave us a Great Moment of modern astronomy by measuring in 1989-1993 extremely precise positions of ~1 mln objects in the sky (±0".001 = 1 milliarcsecond). This allowed precise determination of the distances to the stars. Combining brightness and parallax measurements, the satellite observatory gave luminosities of stars (i.e., energy output in watts) – crucial information for finding what kind of object is observed & of what age. This allowed recalibration of yardsticks with which we measure the universe.





The Geocentric Model of the Universe of

Claudius Ptolemy (Ptolemaeus)

(90-168 AD)

a Greek-Egyptian mathematician living in Roman Alexandria, believed in the basic ideas of Aristotle but was interested in practical not philosophical questions, mainly in accuracy. He set about making an accurate mathematical description (model) of the motions of the planets. He used observations going back 800 years from his times.

- His main book was variously called:

Μαθηματικὴ Σύνταξις (*Mathēmatikē Syntaxis*), Magna Syntaxis,The Almagest, *al–majisṭī* (المجسطي), or the "Great Treatise"

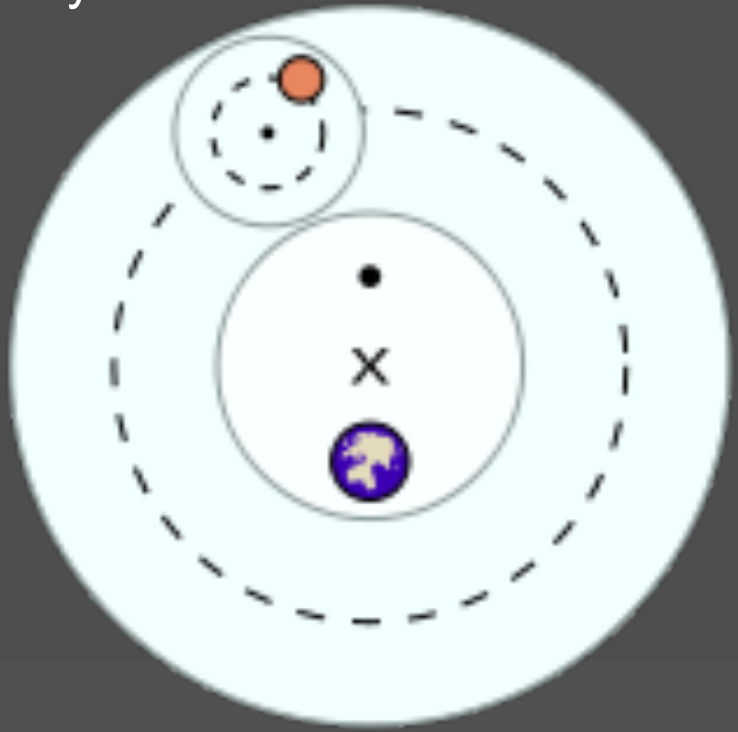
- This was the first major astronomical textbook

The Geocentric Model of Ptolemy

Deferent around the center (x) = the big dashed circle. Epicycle moves on a deferent. Epicycle means „on the circle”.

In addition, the motion on deferent was believed to maintain constant angular speed around not x, but another point called the equant (black dot), and the Earth to be offset w.r.t. the center point (x) anti-symmetrically to equant.

Either one or both devices were employed to explain and predict the motion of planets & sun in the sky.



The Geocentric Model of the Universe

- As viewed by you from Earth, the planets seem to follow complicated paths in the sky, including episodes of "backward" motion that are difficult to explain in terms of motion on circular paths at constant speeds.
- On a sky chart it looks like this (Mars, Saturn, 2016) https://www.youtube.com/watch?v=KVr2MNBPqYU

Ptolemy's ***model*** **explains it** via circular epicycles allowing predictions to be made, https://www.youtube.com/watch?v=EpSy0Lkm3zM&spfreload=10 (Ptolemy's model)

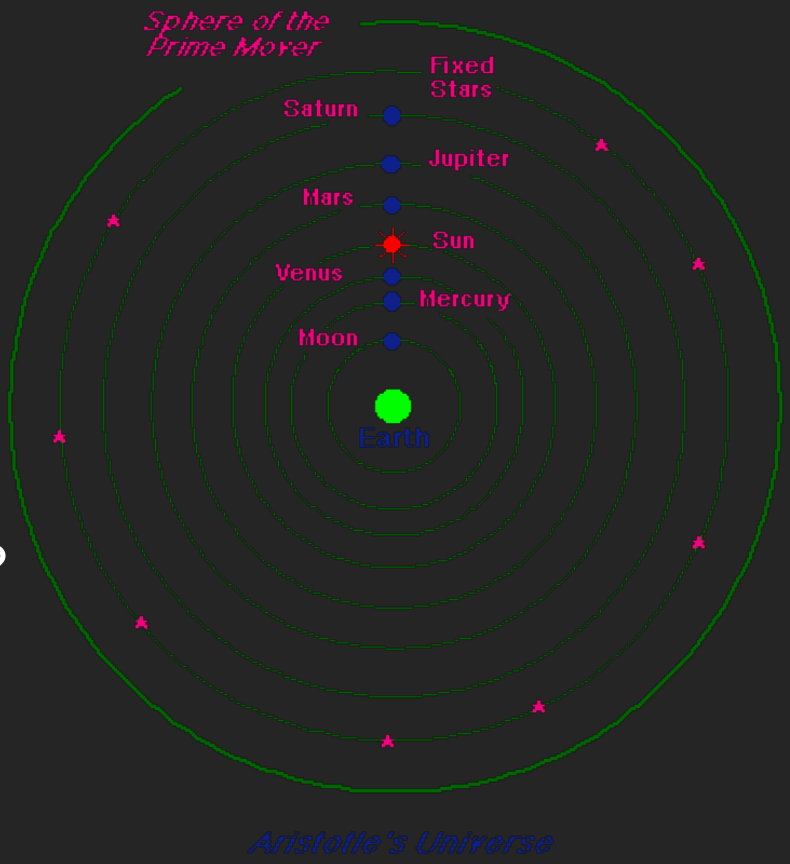
Models and the methodology of science

I said that Ptolemy's ***model explained motion of planets on the backdrop of stars***, allowing predictions of future positions

Two thousand years ago, was his theory right? Is it now?

Did Eudoxus and then Ptolemy get it all wrong and Copernicus right?

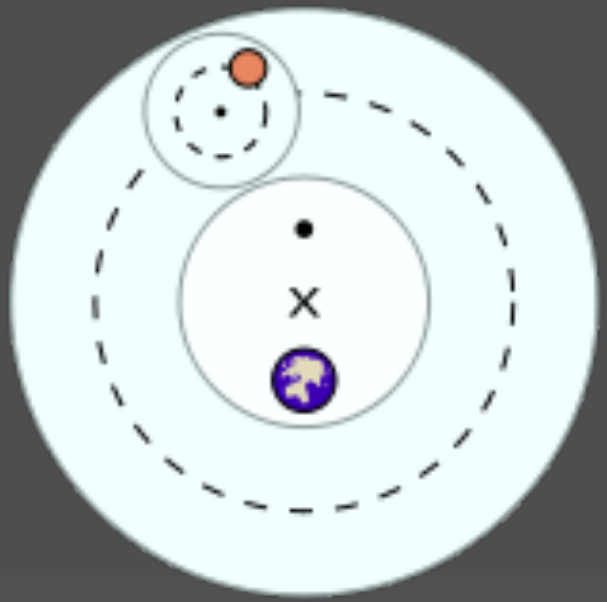
What does it mean that a theory is right?
What does it mean to *explain* the facts?
And are facts always correctly known?
Can one prove a scientific theory?
Falsifiability of a theory as a requirement of scientific method.



The Geocentric Model of the Universe

- Ptolemy weakened the first principles of Aristotle by moving Earth a little off-center in the model and inventing a way to slightly vary the planets' speeds. Motion on deferent was uniform as seen from the so-called equant point (black dot in the figure)
  - This made his model (published around 140 CE) a better match to the observed motions
  - Some people said it is "ugly" and some that it is not truly geocentric but rather geostatic. They didn't like it.

We will return to this issue in the next lecture and argue that the equant was a surprisingly accurate concept/trick.



Almagest reads much like a work of modern science. In fact, Hellenic science was already 'modern' by using scientific method: posing quite abstract theories/models, and then proving/disproving them by observation or experiment.

Library of Alexandria and the decline of Greek science in the Christian Era

- One of Aristotle's students was the military leader Alexander the Great (356 BC – 323 BC). His army conquered much of the Middle East all the way to India creating a huge Greek empire.
- Alexander promoted science and encouraged learning.
- He founded several cities, among them Alexandria in Egypt, on the delta of the Nile river. The city was renowned for its Library. It was a part of Museion (buildings dedicated to 9 Muses) built under the king Ptolemeus II Philadelphus, taking inspiration of older libraries such as in the Sumerian city Uruk.

- The library eventually gathered almost 500,000 papyrus scrolls (books)

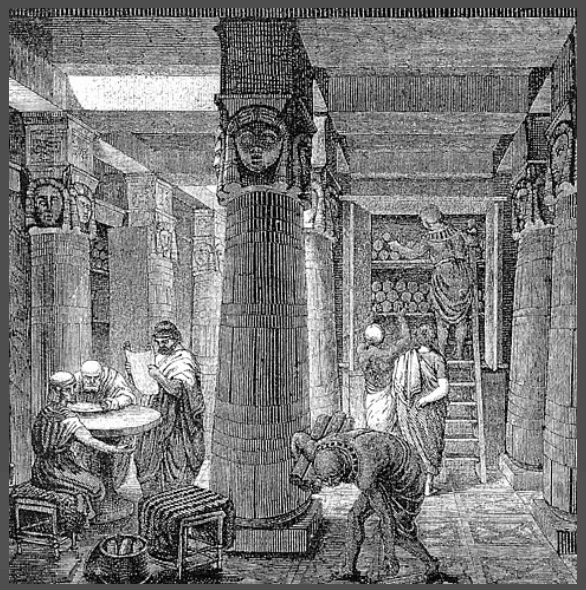
Library of Alexandria served as a major center of knowledge for hundreds of years.

In this illustration, the Muse Clio (of history) reads a papyrus scroll.

Alexander of Macedon

Alexander of Macedon's library & Hypatia

- Every book coming into Egypt through the port had to be copied & the copy deposited in the library
- One of the most famous library scholars was a female astronomer and mathematician Hypatia (~350 AD – 415 AD), whom we would today call the director of the observatory in Alexandria. Her father Theon was a library's resident scholar.
- She was a neo-Platonist philosopher, well-respected scientist and teacher, and wrote several books on algebra, geometry, and astronomy, and perfected astrolabe.
- She may have edited past work by Ptolemy.



Hypatia

- She was eventually killed by a mob of religious fanatics led by Christian monks in 415 CE, during a highly turbulent time of political struggle between the secular Roman governor Orestes and the Christian bishop Cyril.
- The bishop ordered destruction of all pagan temples
- Shortly afterwards the Library of Alexandria was destroyed for good. It already has lost most collections in previous centuries because of wars. In 48 BC Julius Caesar had to burn his own ships attacked by the fleet of Cleopatra; reportedly 40000 scrolls in the library were also destroyed by fire).

Only 1% of the library holdings remain today.

Greek knowledge was preserved and developed

Despite the Alexandria library's destruction, Greek knowledge was preserved in the Islamic world.

- Caliph Abu Jafar Al-Ma'mun's House of Wisdom in Baghdad was a great center of learning around 800 CE
- Tables of observations, geometrical diagrams and ideas of the Persian al-Biruni's (973-1048) & the Damascian astronomer al-Battani's *Zij*

  (tables, charts) were later used by Copernicus
- Ibn-Shatir's and al-Tusi's diagrams were seen and grasped by Copernicus as well (Copernicus did not know Arabic, but one of his diagrams is identical and marked by the same symbols as in the so-called Tusi couple diagram)

Remember the Many World hypothesis of Democritos and Leukippos?

The pendulum of opinion on it starts swinging in the new European institution: Universities.

Aristotle's work was rediscovered in 13th century, soon afterwards starts the epoch of Renaissance.

For 100 years everybody agrees with him on most issues. In support, Roger Bacon (1214-1292) at Oxford cites the argument about the impossibility of vacuum between the planetary systems. Similar thinking prevails at other rising universities, like the Sorbonne in Paris.

Like Aristotle, the Renaissance university scholars were all convinced of the uniqueness and geocentric architecture of the world.

But the Aristotelian insistence on unity and uniqueness began to contradict the Christian doctrine of the omnipotence of God (God can create as many worlds as He wishes), and the Church started enforcing its view.

The Church mandates(!) the many-worlds view in the 13th century

In 1277 Etienne Tempier, the bishop of Paris, with agreement from the Pope, condemned opinions based on 219 statements in Aristotelian writings, among them "that the First Cause cannot make many worlds".

Those paragraphs had to be blanked out in books (censorship).

The many-worlds opinion was hotly contested at the universities but has prevailed, as it was mandated by the Church under a very serious threat of excommunication.

Then, the pendulum swung back: In the 1500s the Church switched back to Aristotelian opinion, while the Renaissance scholars to… the opposite, how else!

* * *

A wandering Dominican->Calvinist friar Giordano Bruno was burned at stake in 1600 by Vatican's Holy Inquisition, although not, as many mistakenly think, for his fervent belief in many inhabited worlds like ours (on stars!). To authorities, he was a heretic: Bruno denied the divinity of Jesus Christ, Saint Mary & doctrine of Trinity.