ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 2 • Ancient steps towards a scientific cosmology

09/02/2021

Today

- Logistics
- The scientific method
- The Ancient Greeks
- The Ancient Greeks revisited: Renaissance (part 1)

Comic: Sidney Harris

Office hours

Attempts: 61 out of 61

Which of the current office hour slots can you attend?

Wednesday 3-4pm	42 respondents	**69 %**	✓
Thursday 11am-12pm	33 respondents	**54 %**	✓
Neither	10 respondents	**16 %**	✓

0% answered correctly

Attempts: 61 out of 61

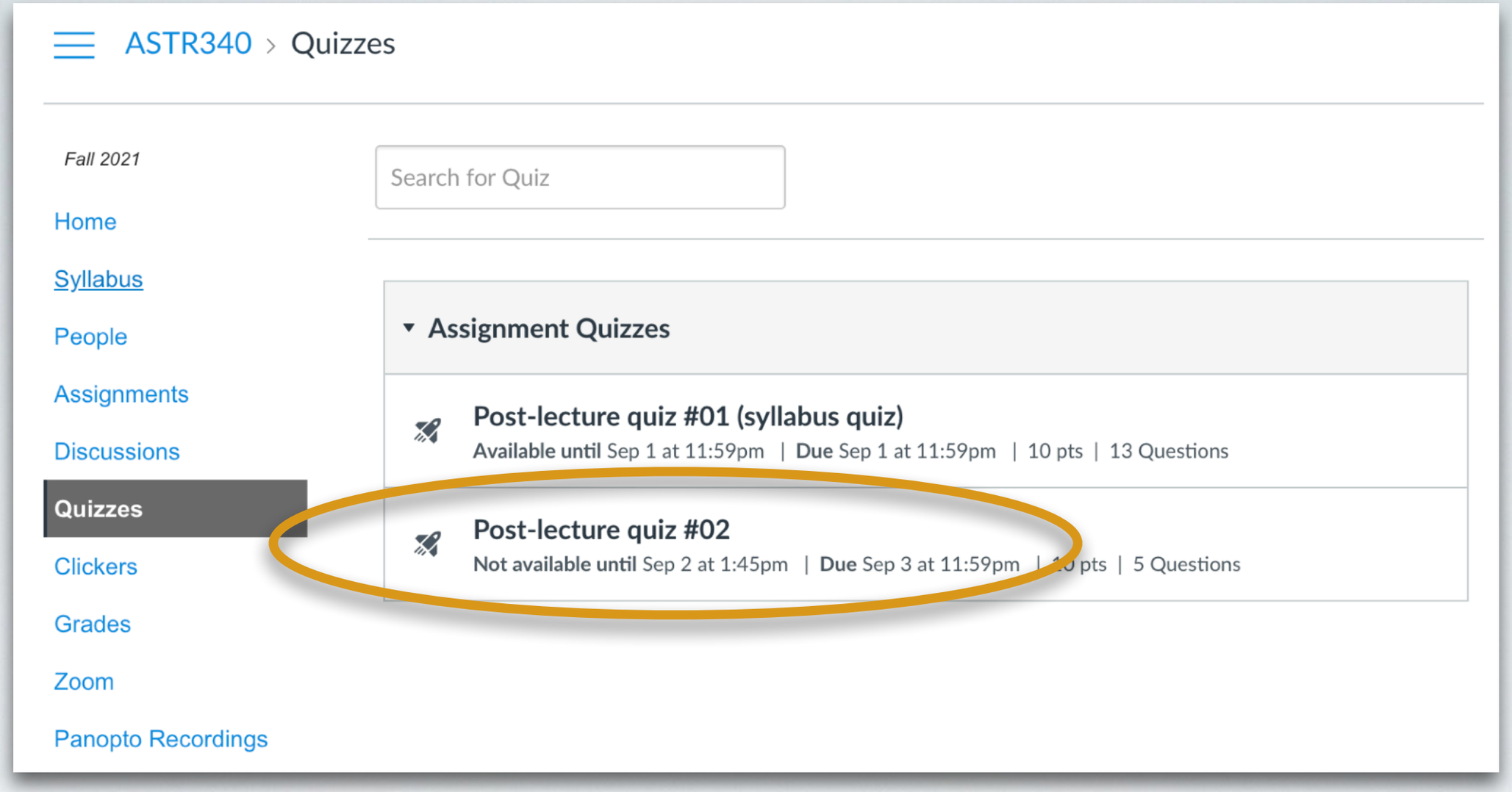
Which mode of office hour would work for you?

In person (in PSC 1107)	46 respondents	**75 %**	✓
On zoom	53 respondents	**87 %**	✓
	1 respondent	2 %	

64% answered correctly

Let's do office hours on zoom (see Canvas for links)

Post-lecture quiz



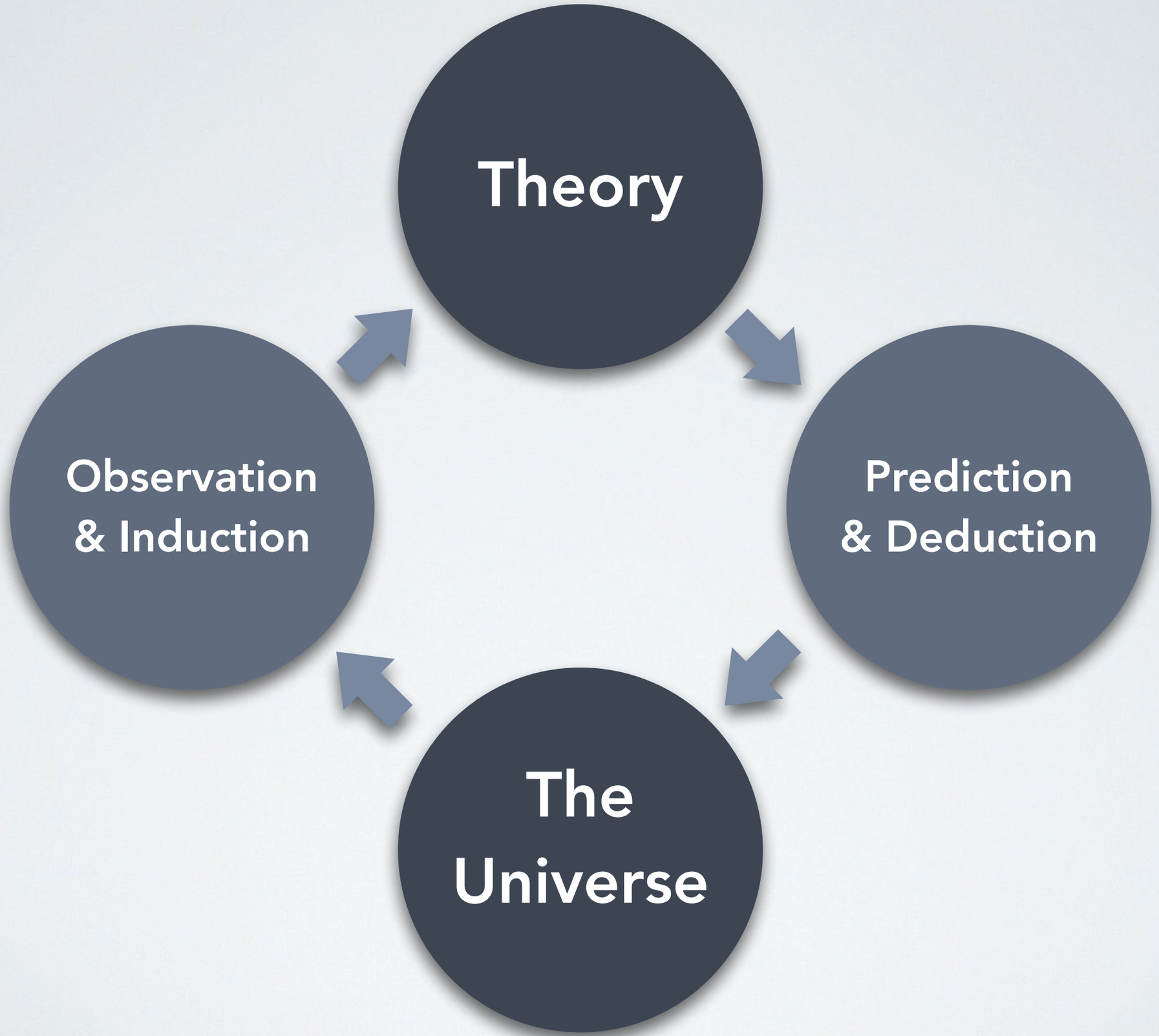
- Due Friday night
- 2 attempts, see correct answers after submitting
- 5 questions, 10 points per quiz

Part 1: The scientific method (again)

The scientific method

- A systematic, **empirical process** for deriving knowledge
- Conditions for a scientific **hypothesis/theory:**
  - **Relevant** (explanatory power)
  - **Consistent** (within and without)
  - **Predictive** (qualitative and quantitative)
  - **Testable** (falsifiable)
  - **Simple** (Occam's razor)
- If a hypothesis survives significant tests of many of its predictions, it **becomes** a theory

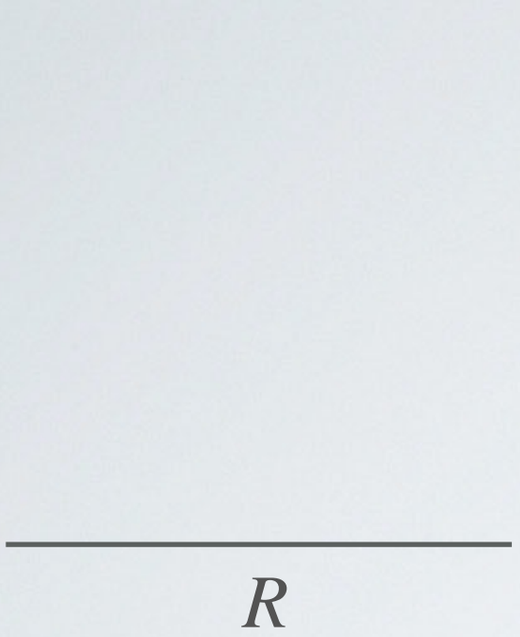
The scientific method



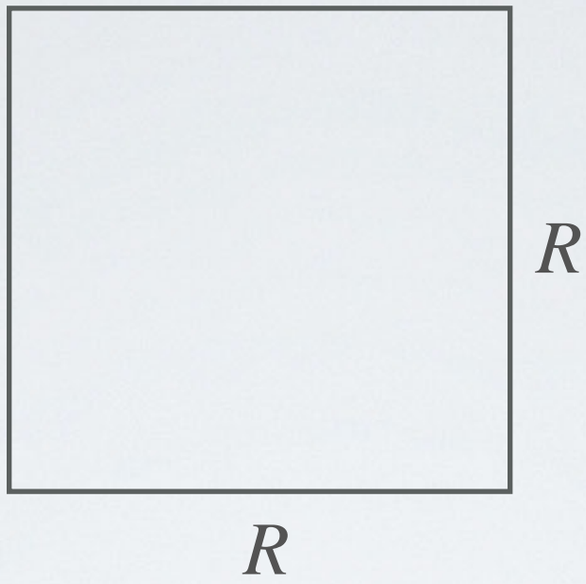
What can we say about infinity?

Night sky in Maryland

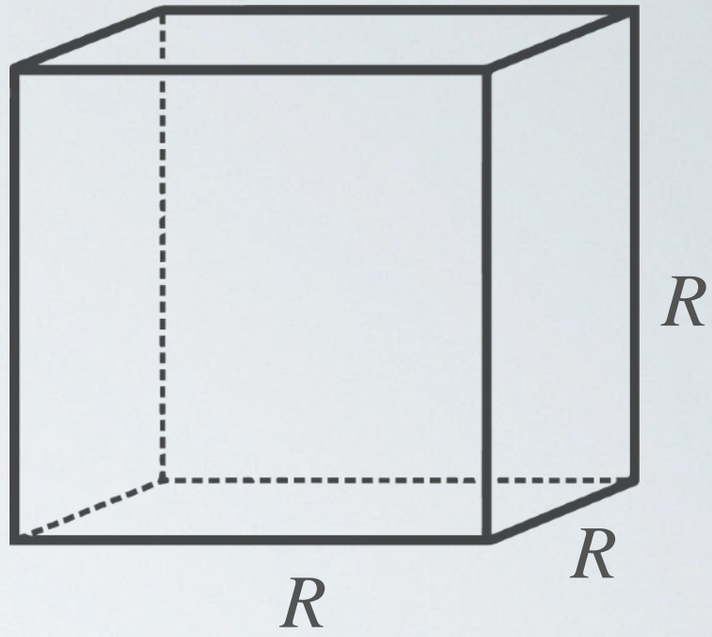
Evolution of length / area / volume



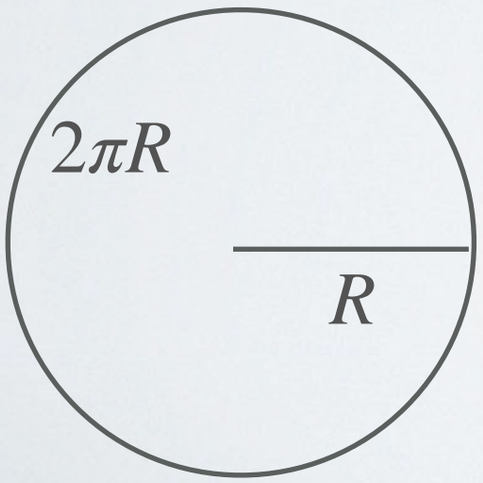
length $\propto R$



area $\propto R^2$

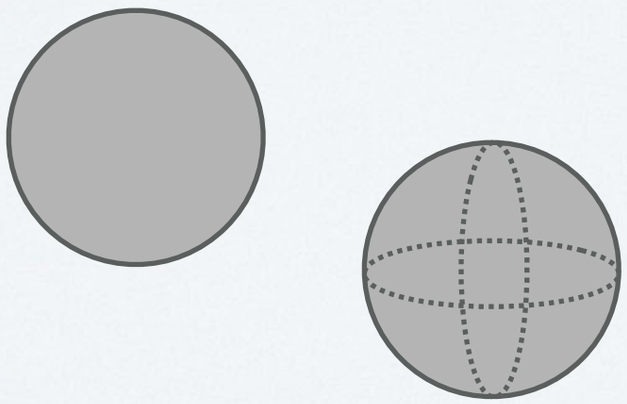


volume $\propto R^3$

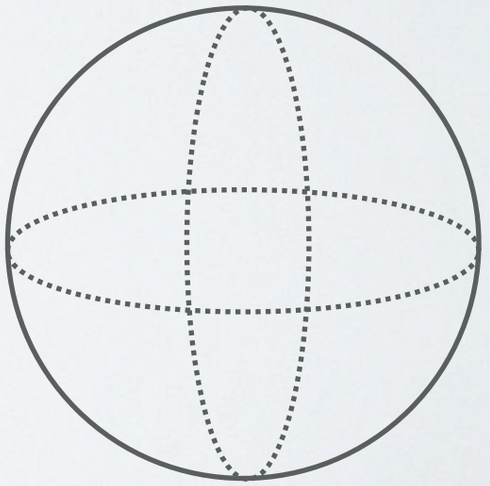


circumference

area $= \pi R^2$

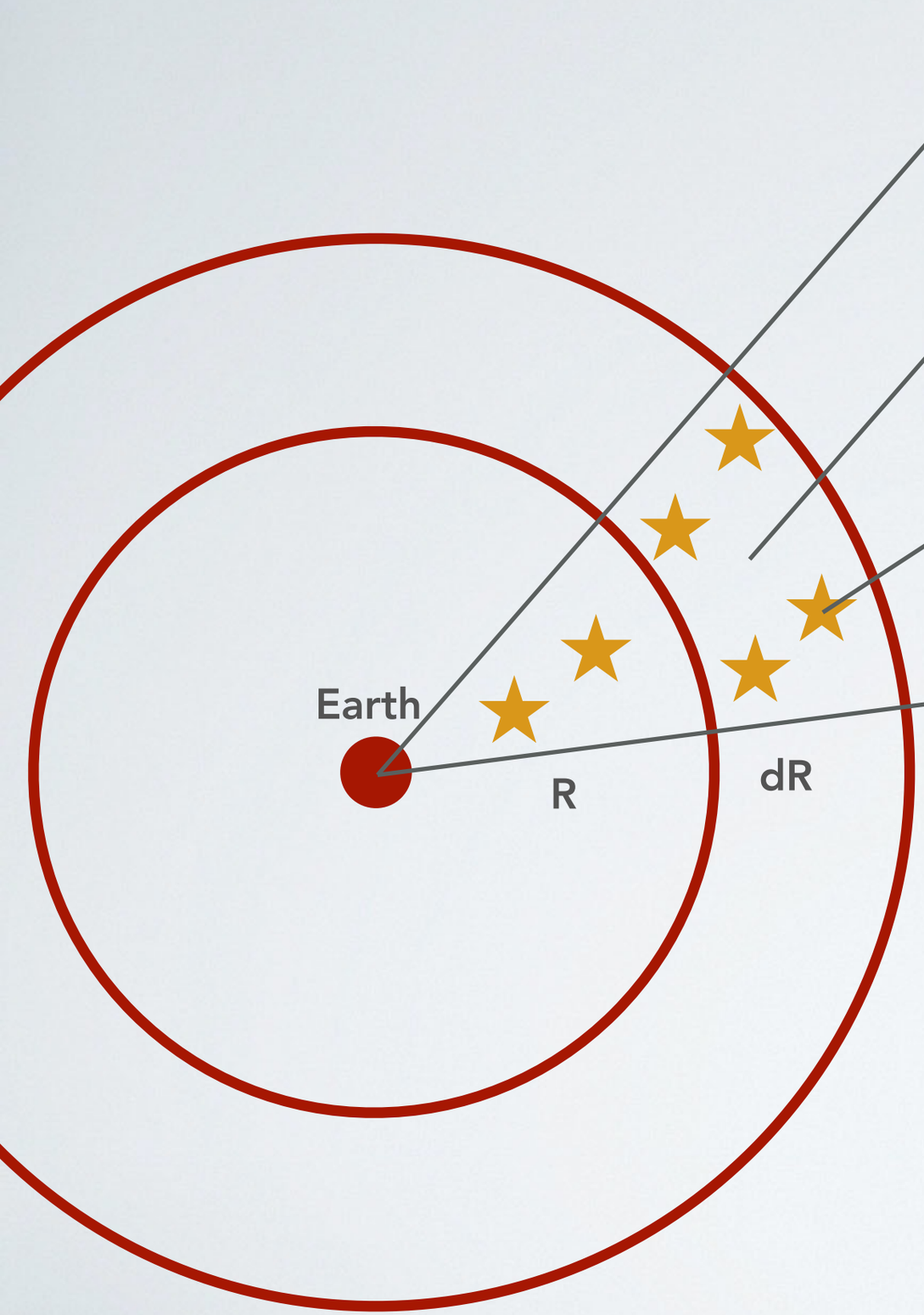


surface area $= 4\pi R^2$



volume $= \dfrac{4\pi}{3} R^3$

Olber's Paradox



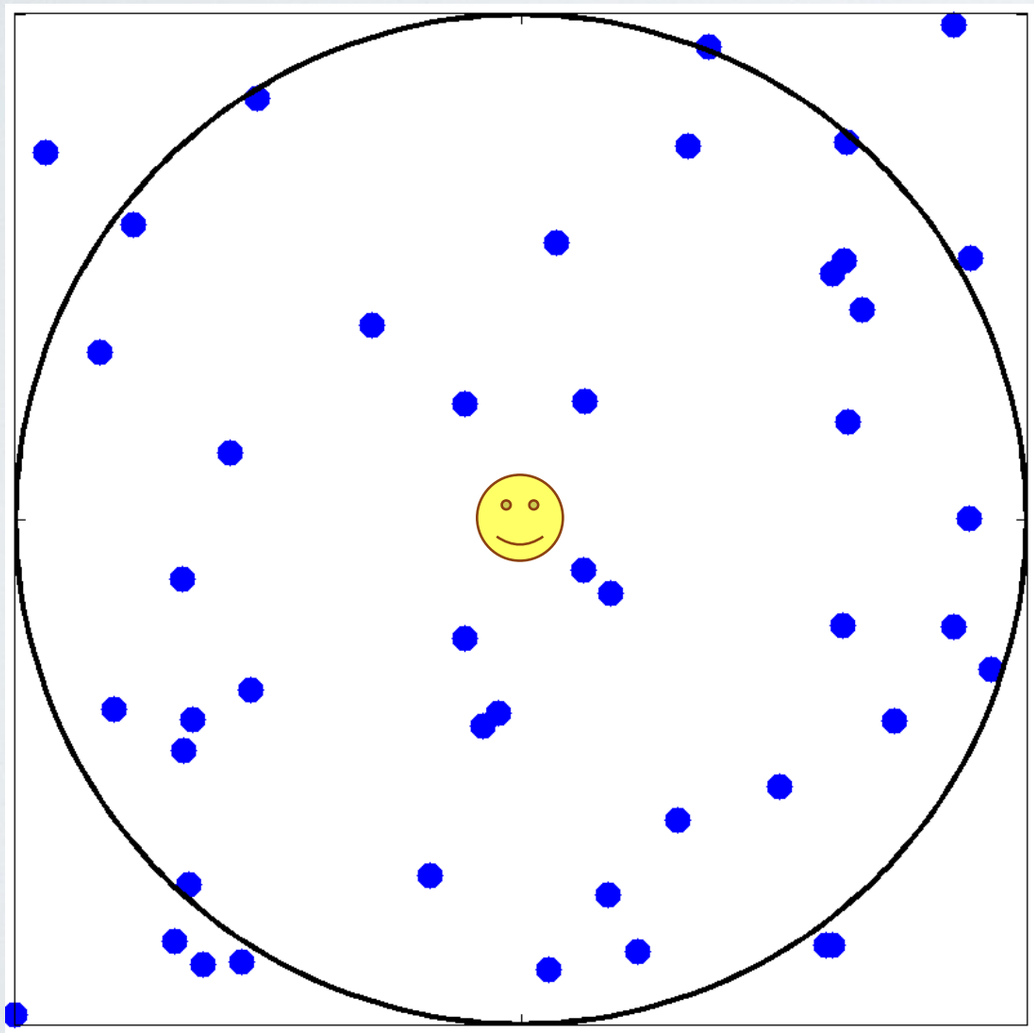
volume of shell $V = 4\pi R^2 \times dR$

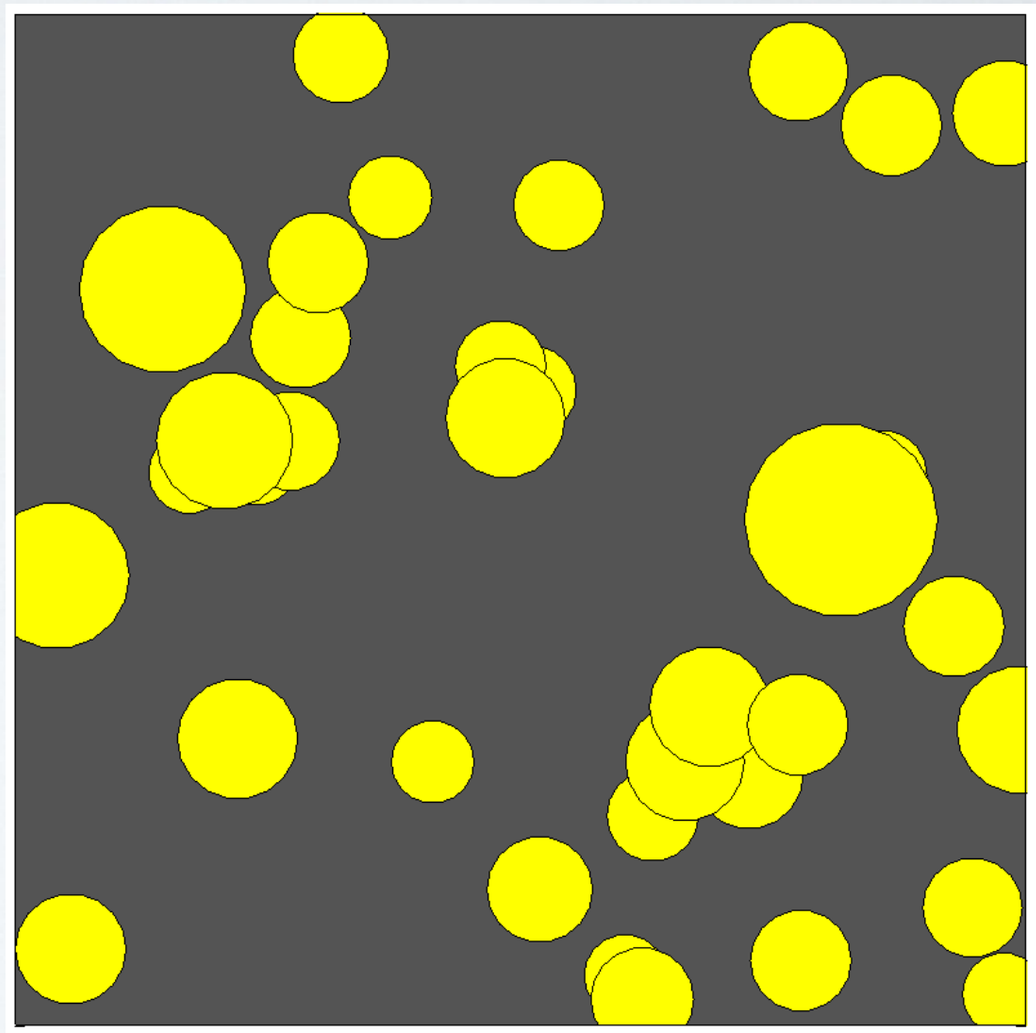
number of stars $\propto V$

brightness $L \propto 1/\text{area} \propto 1/R^2$

$\rightarrow L$ per shell $\propto$ constant!

Why is the night sky dark?





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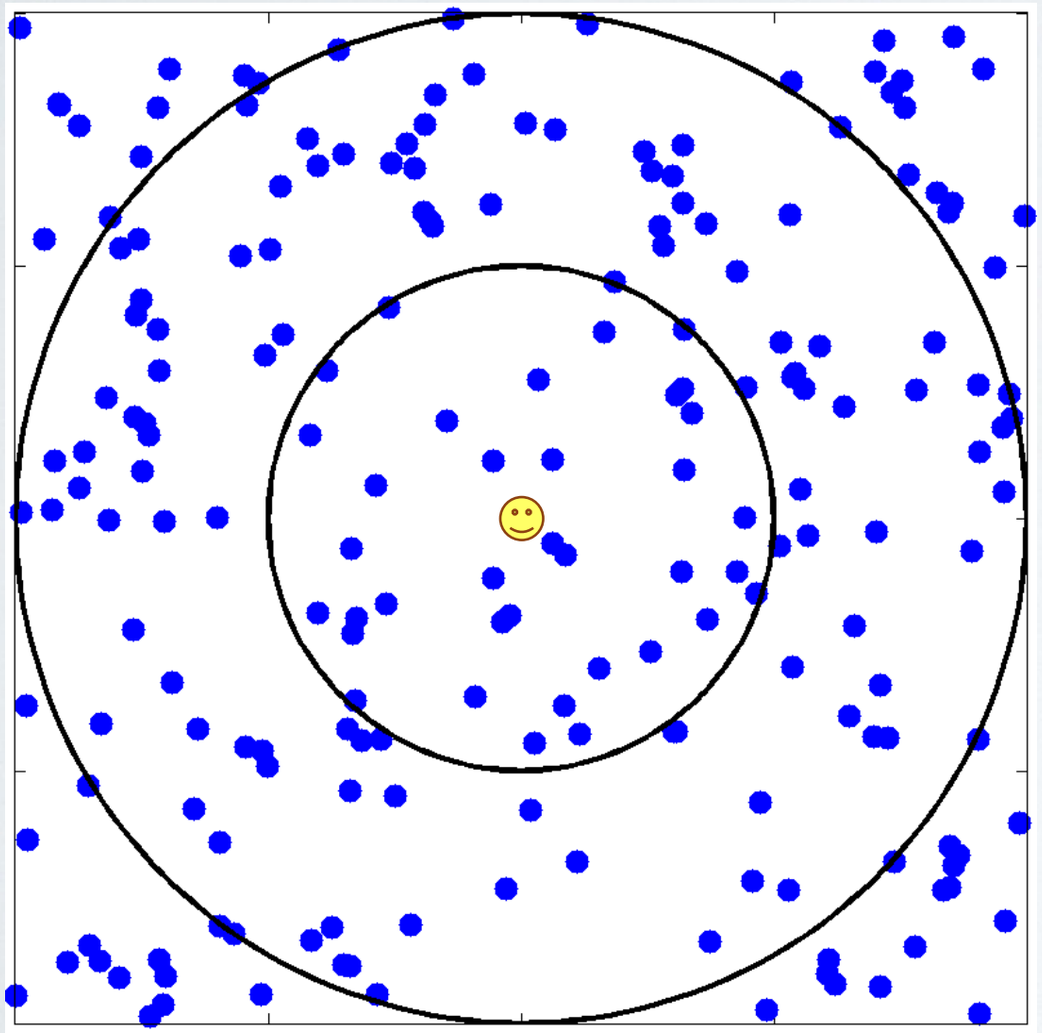

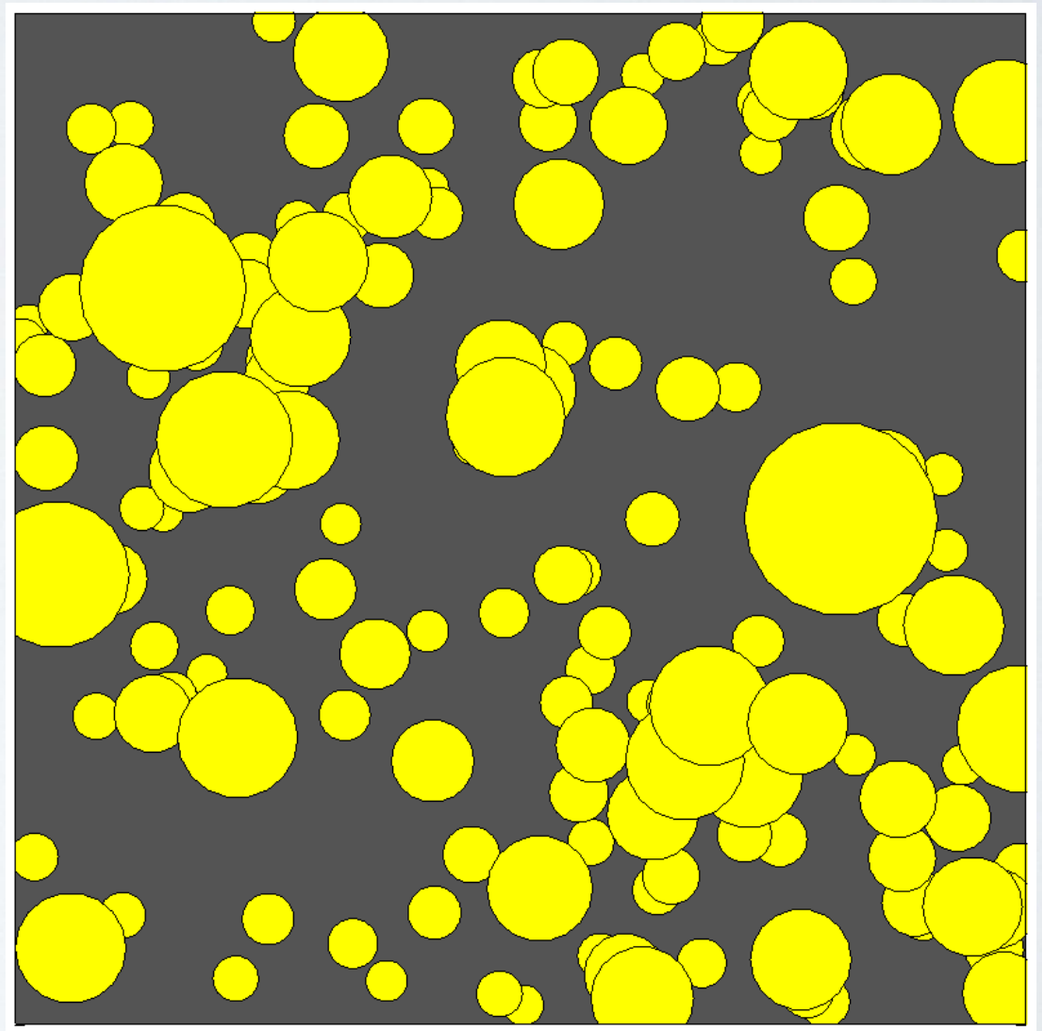

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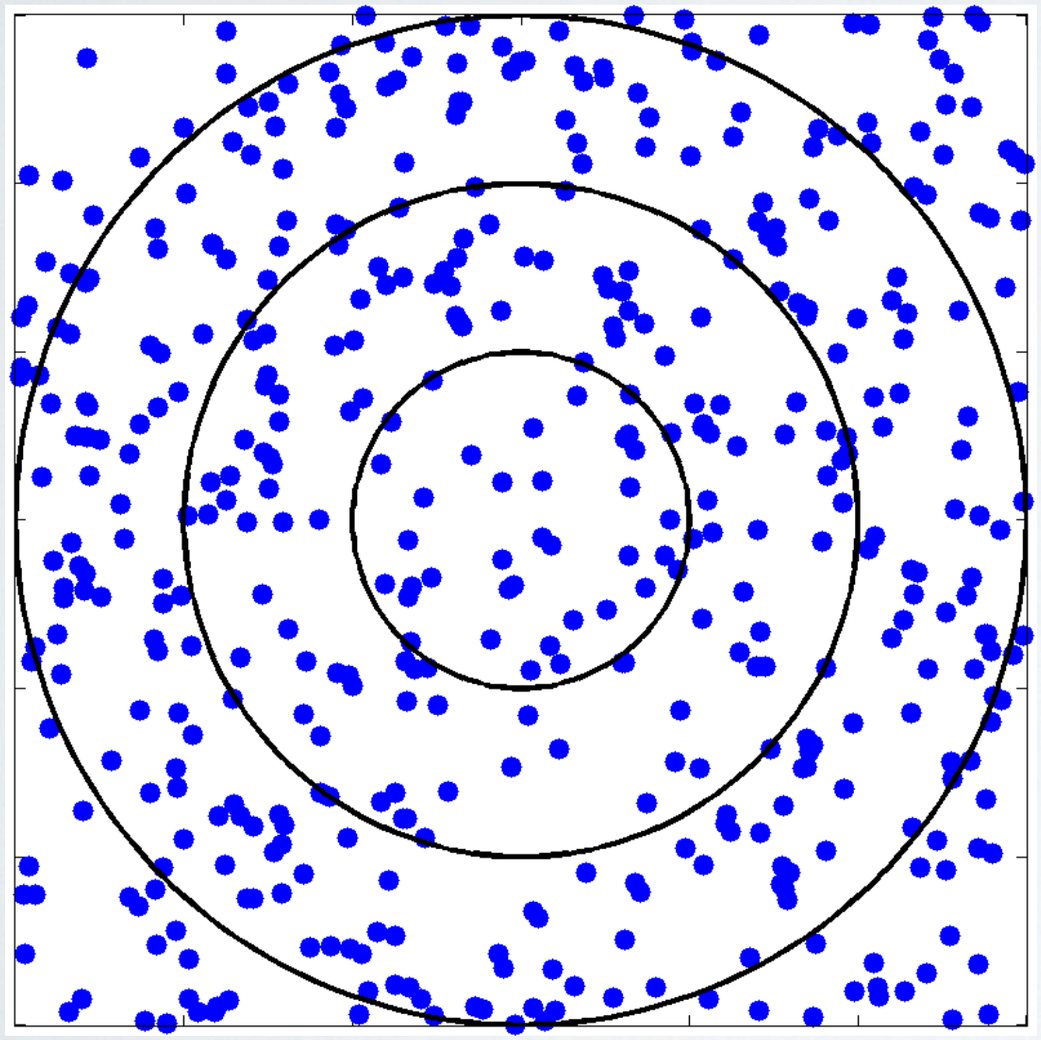

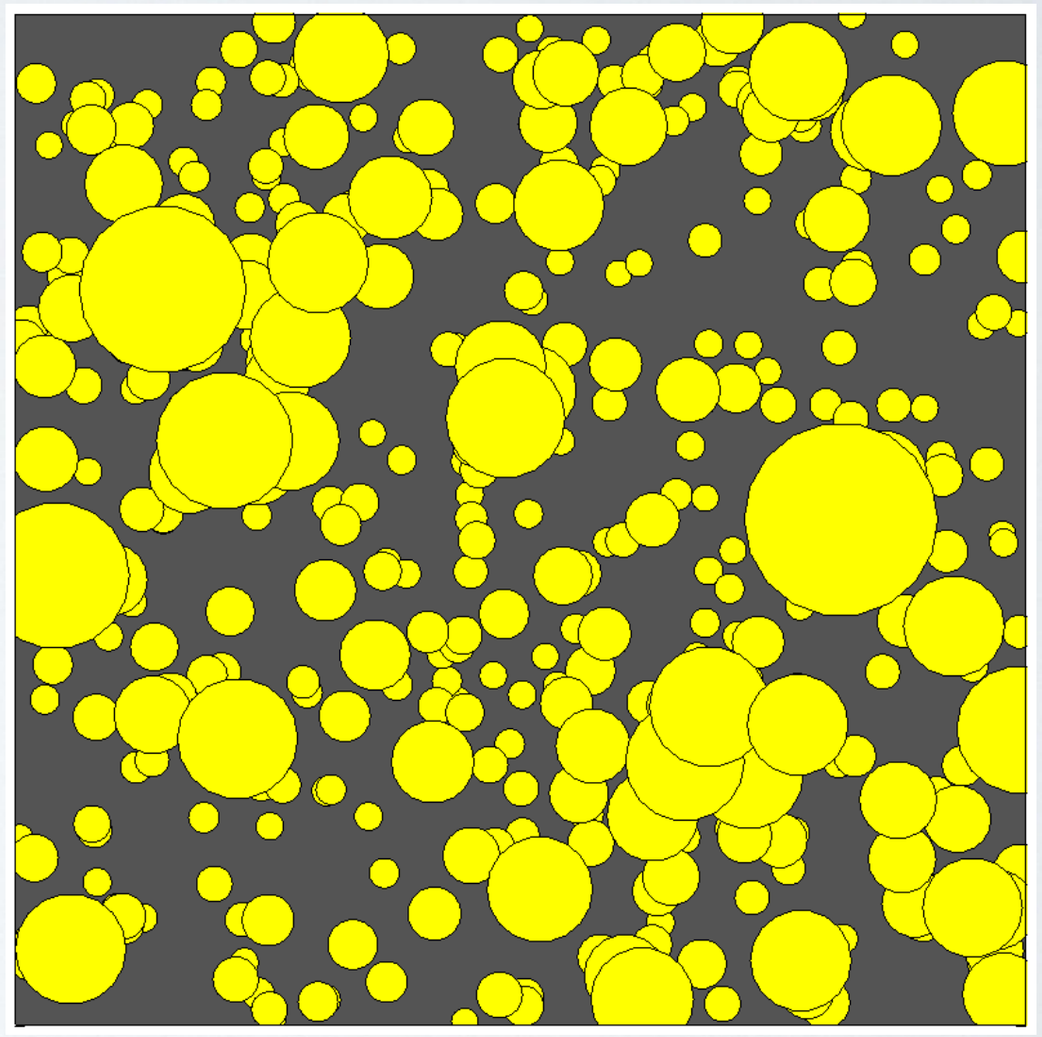

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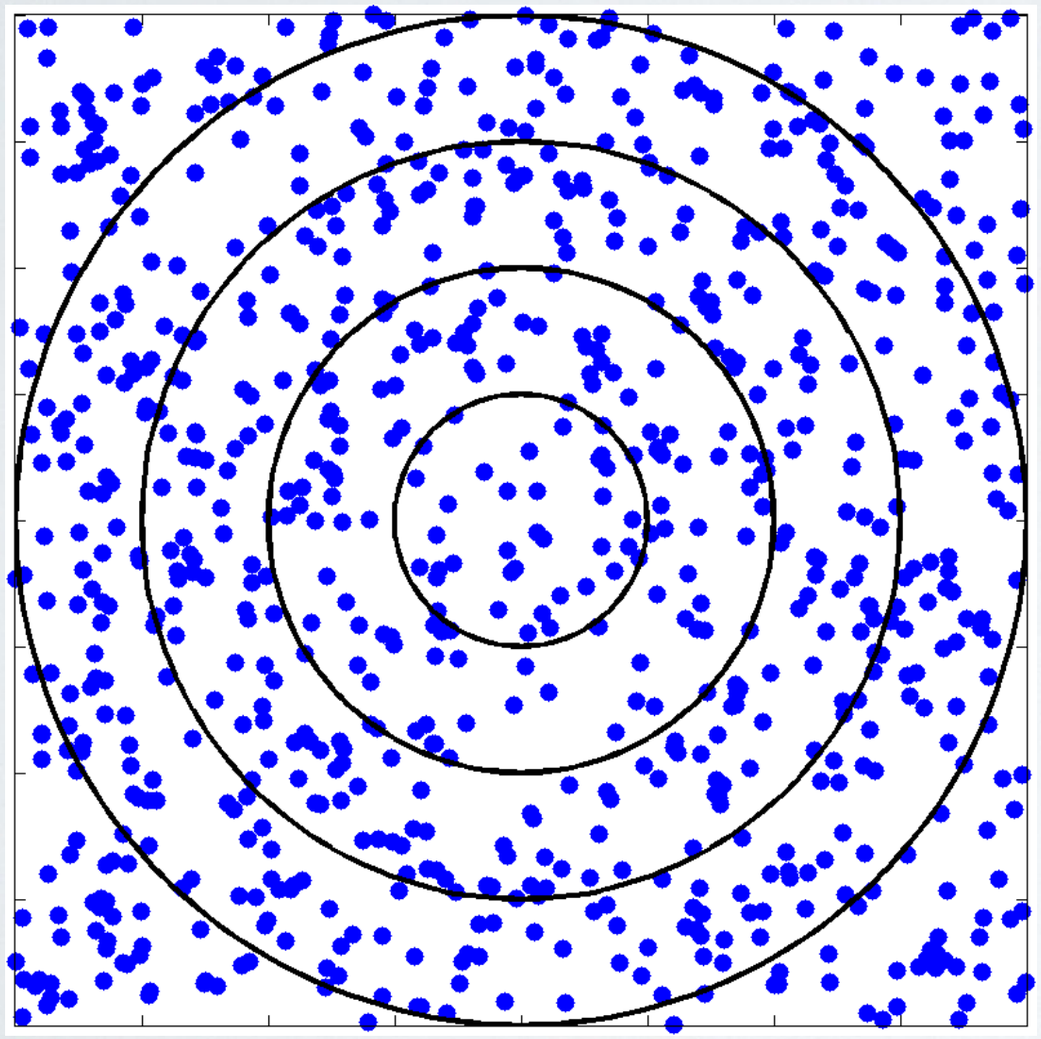

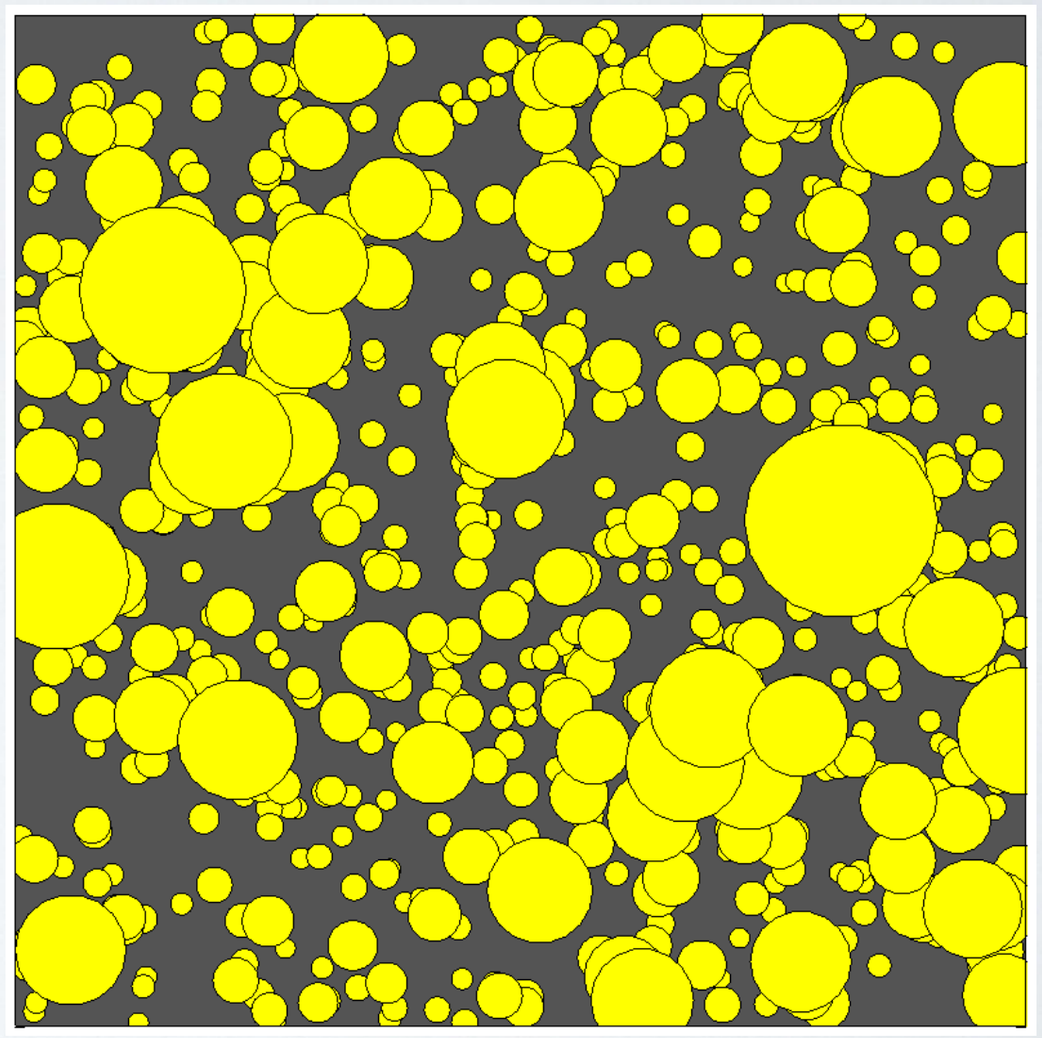

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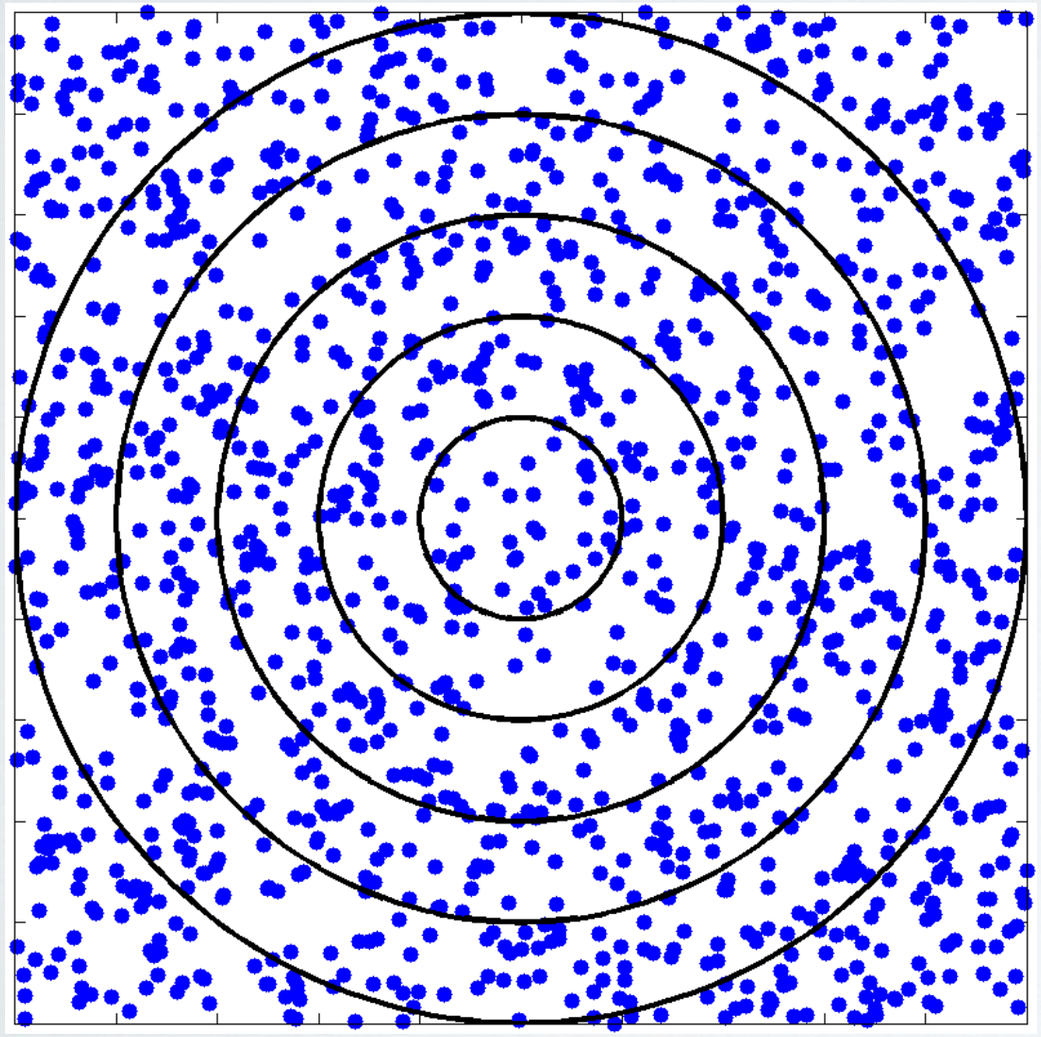

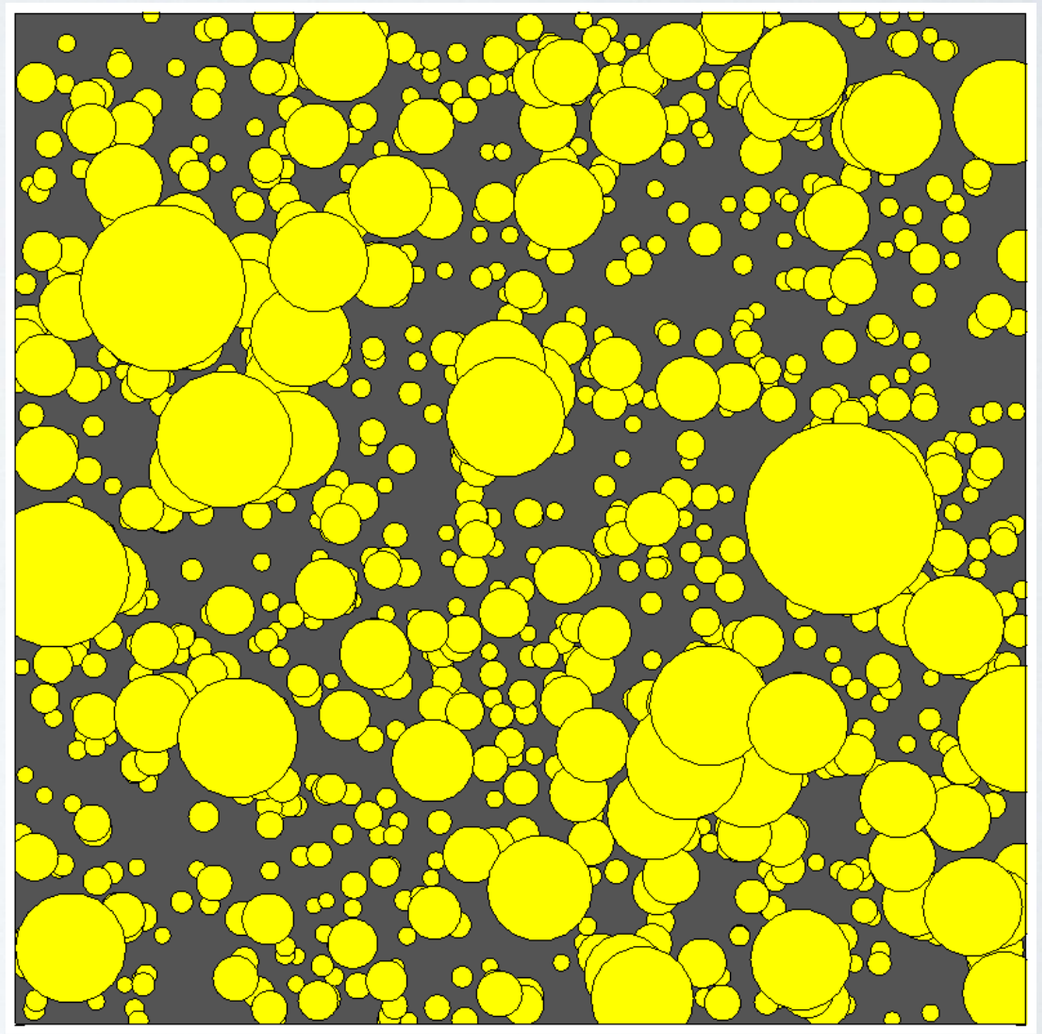

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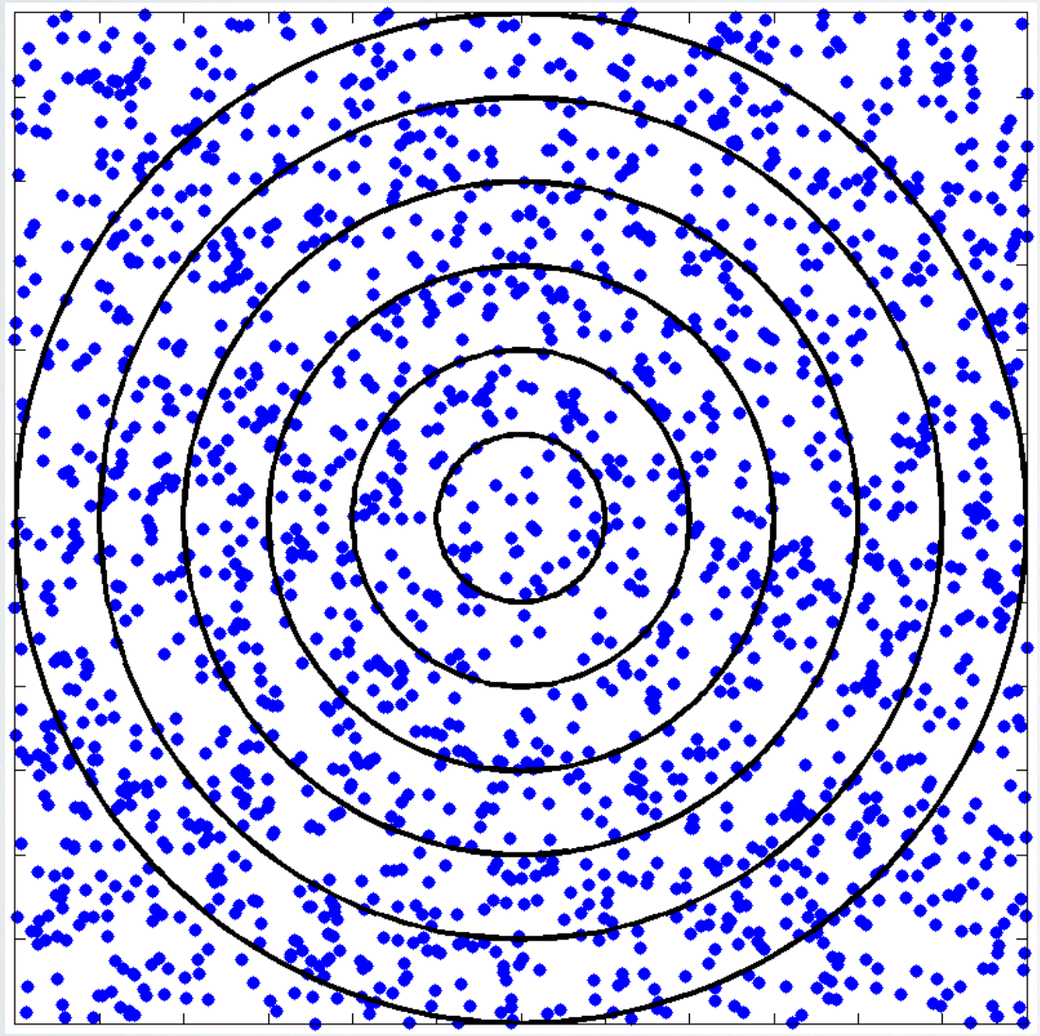

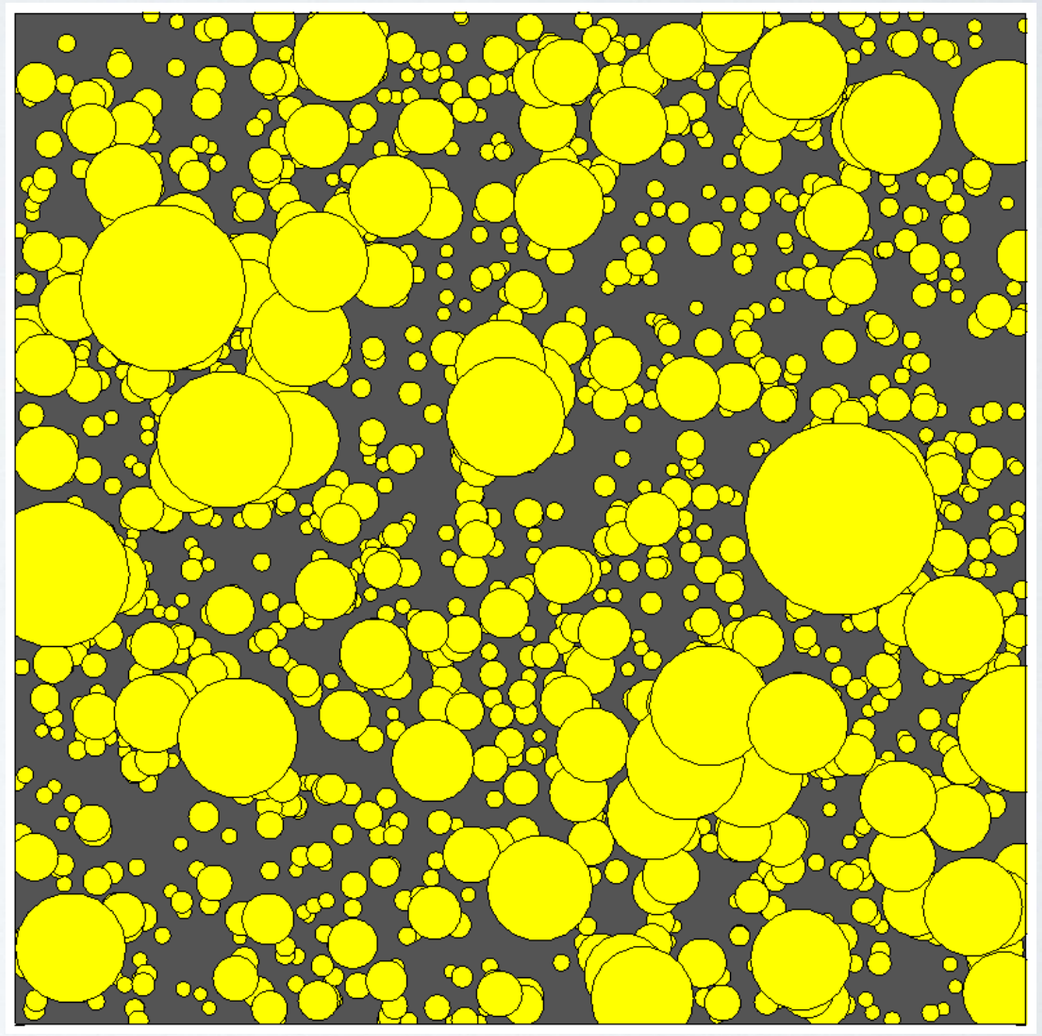

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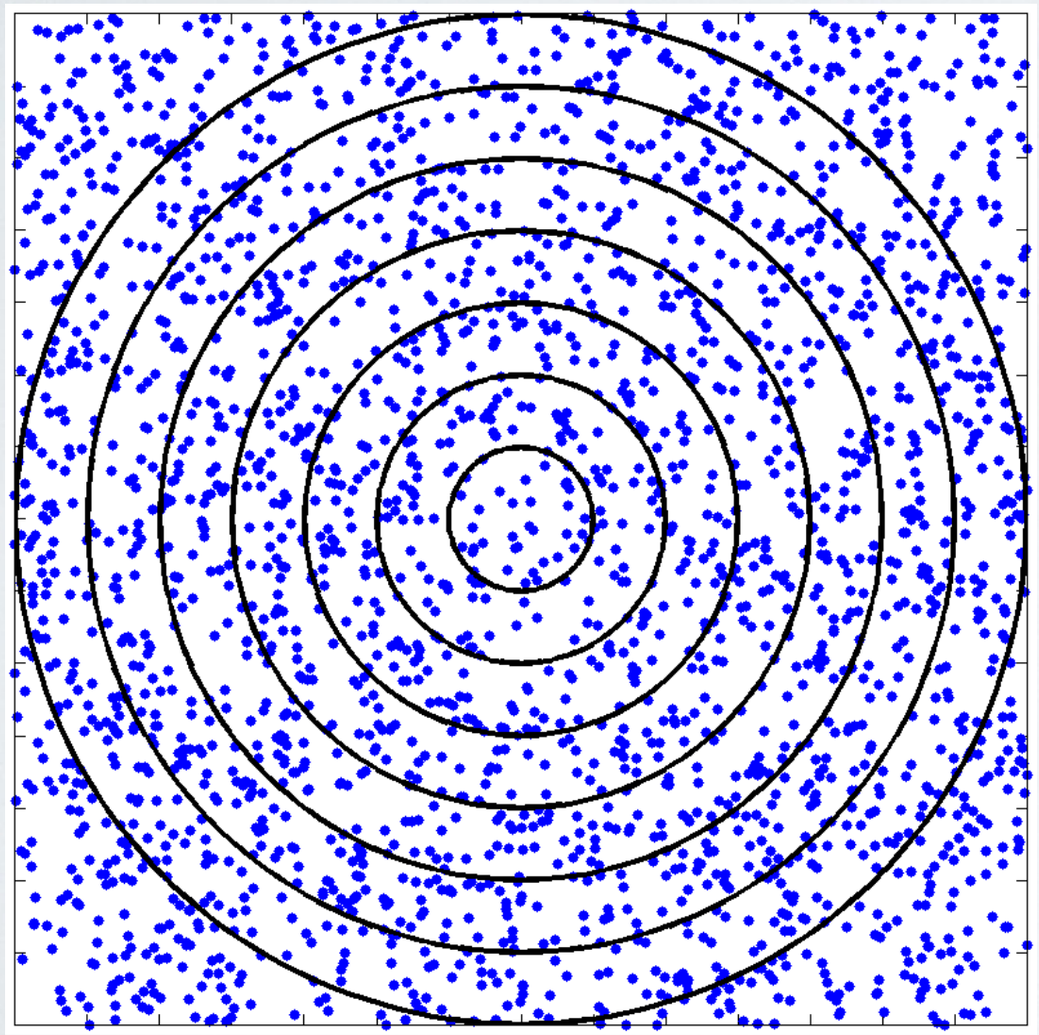

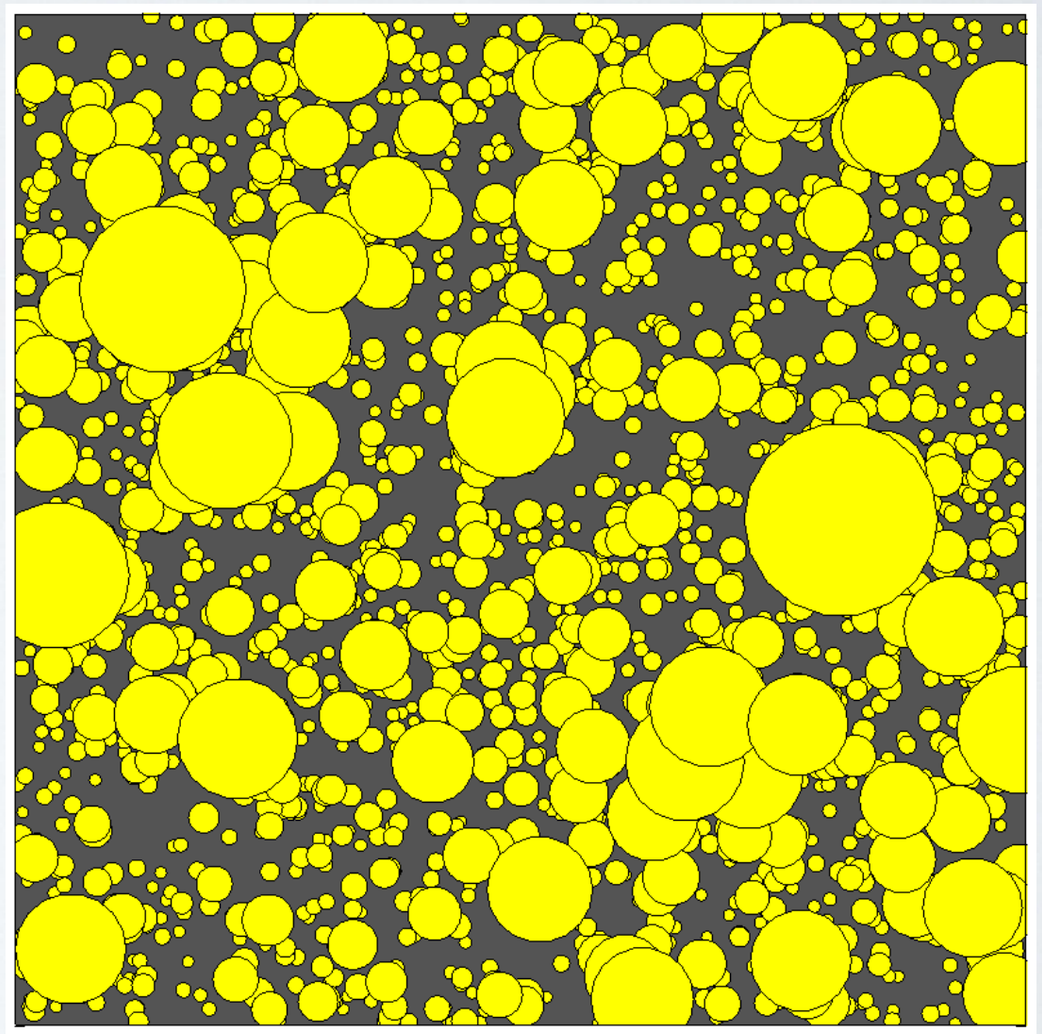

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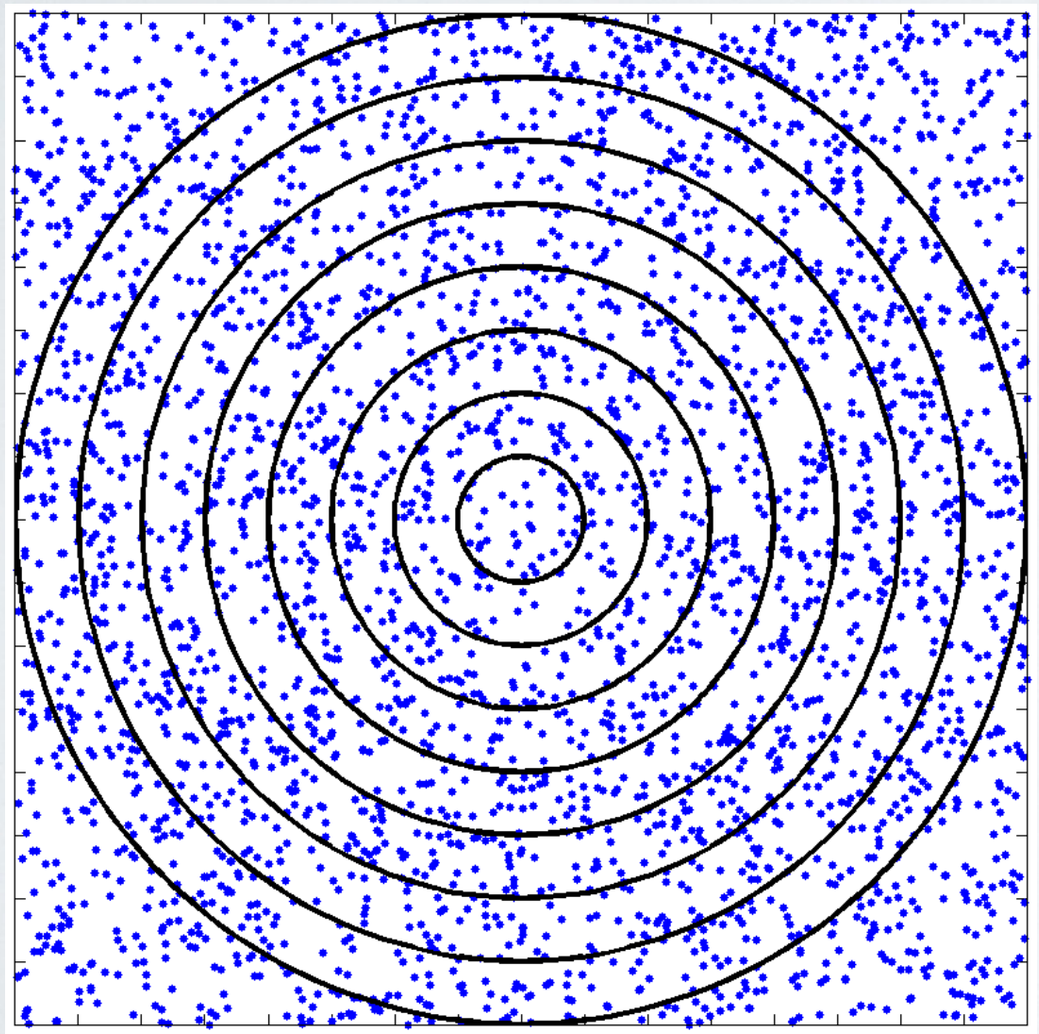

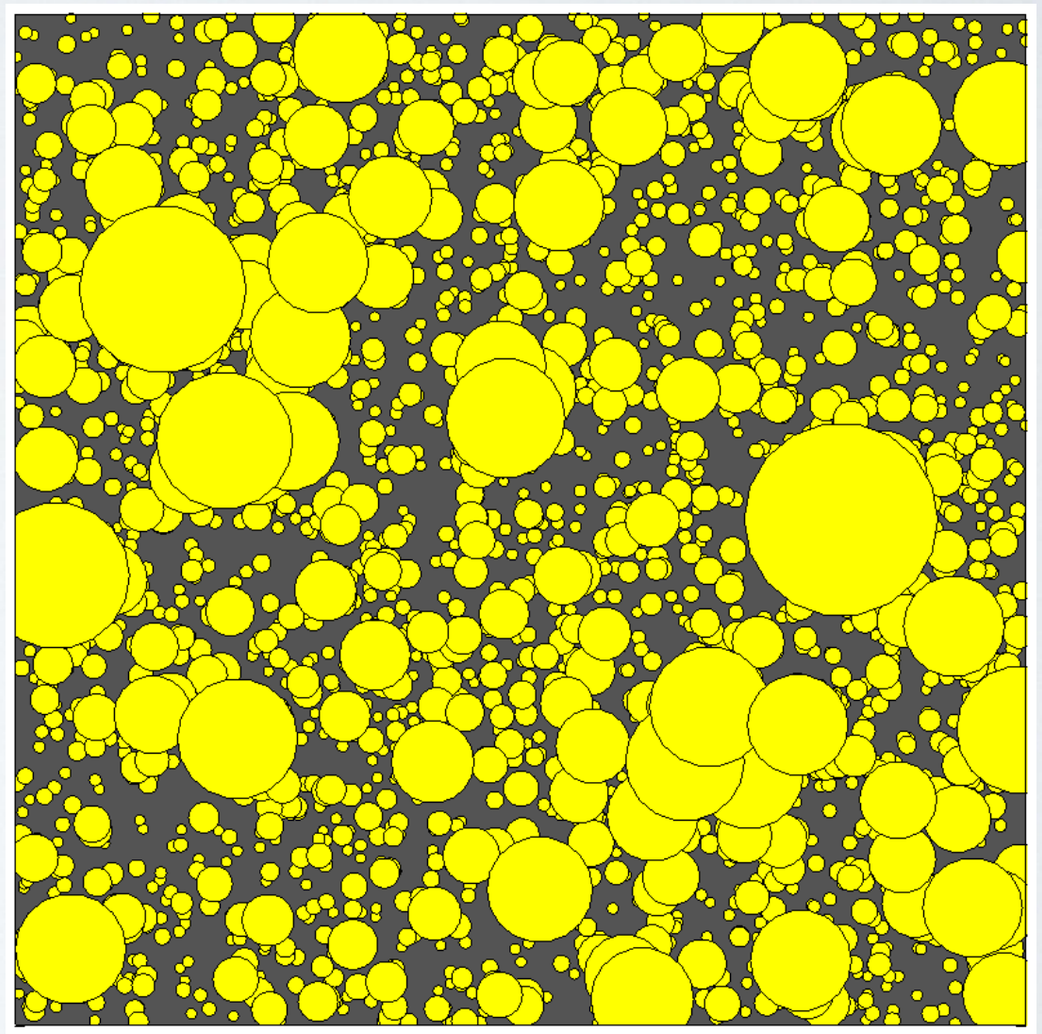

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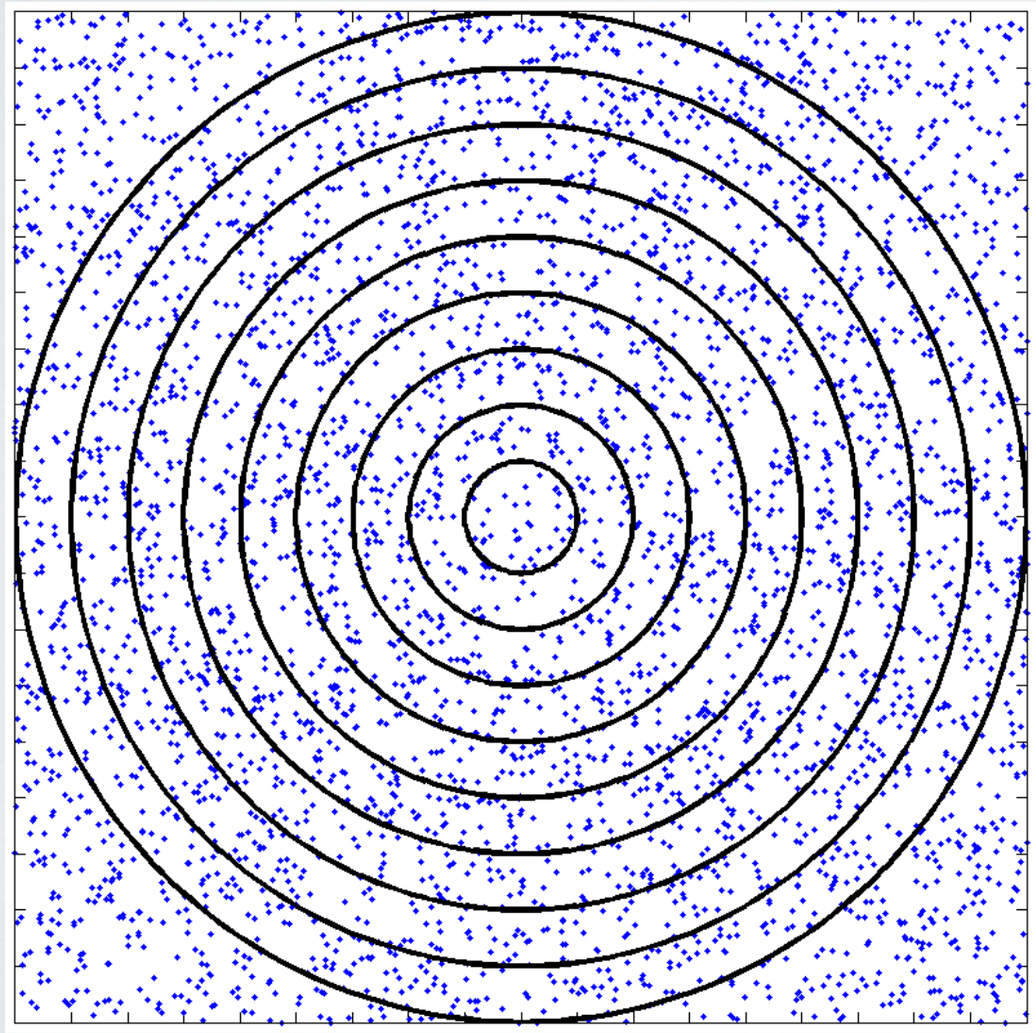

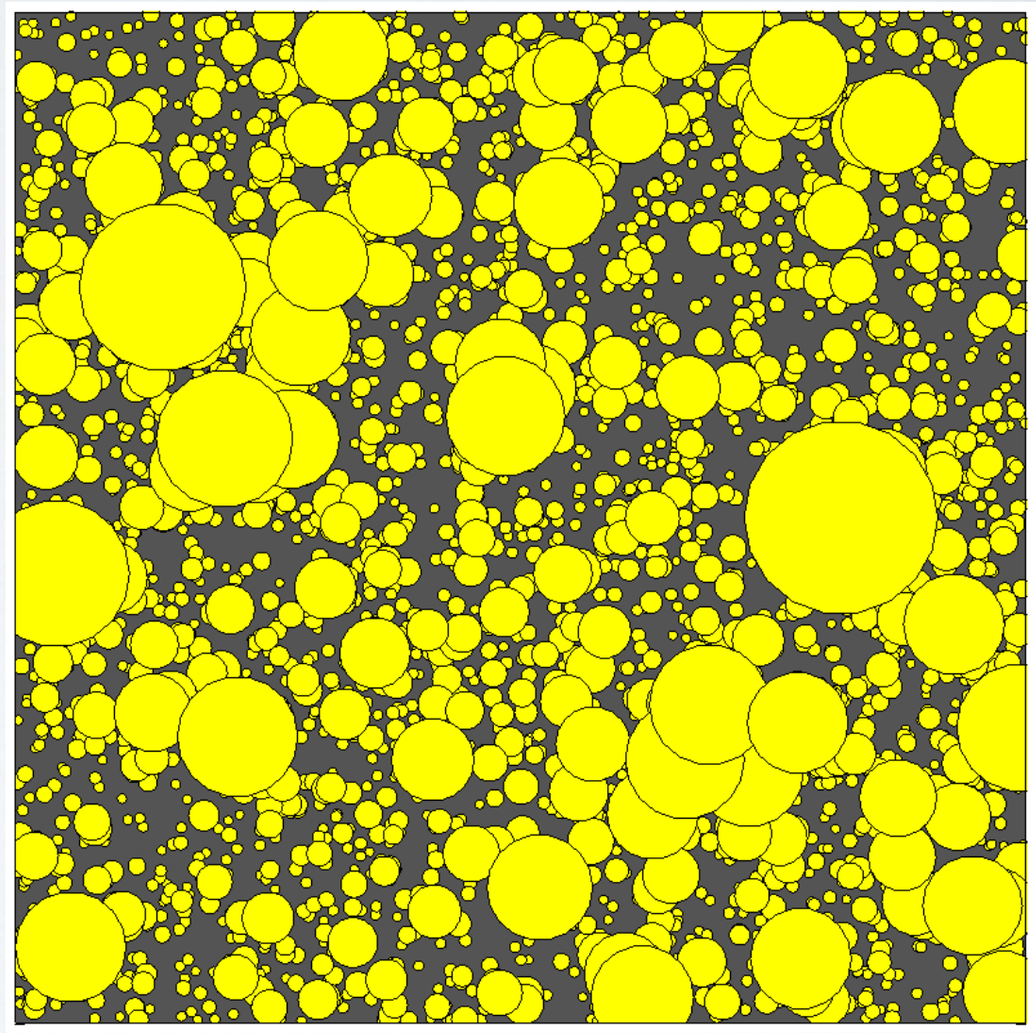

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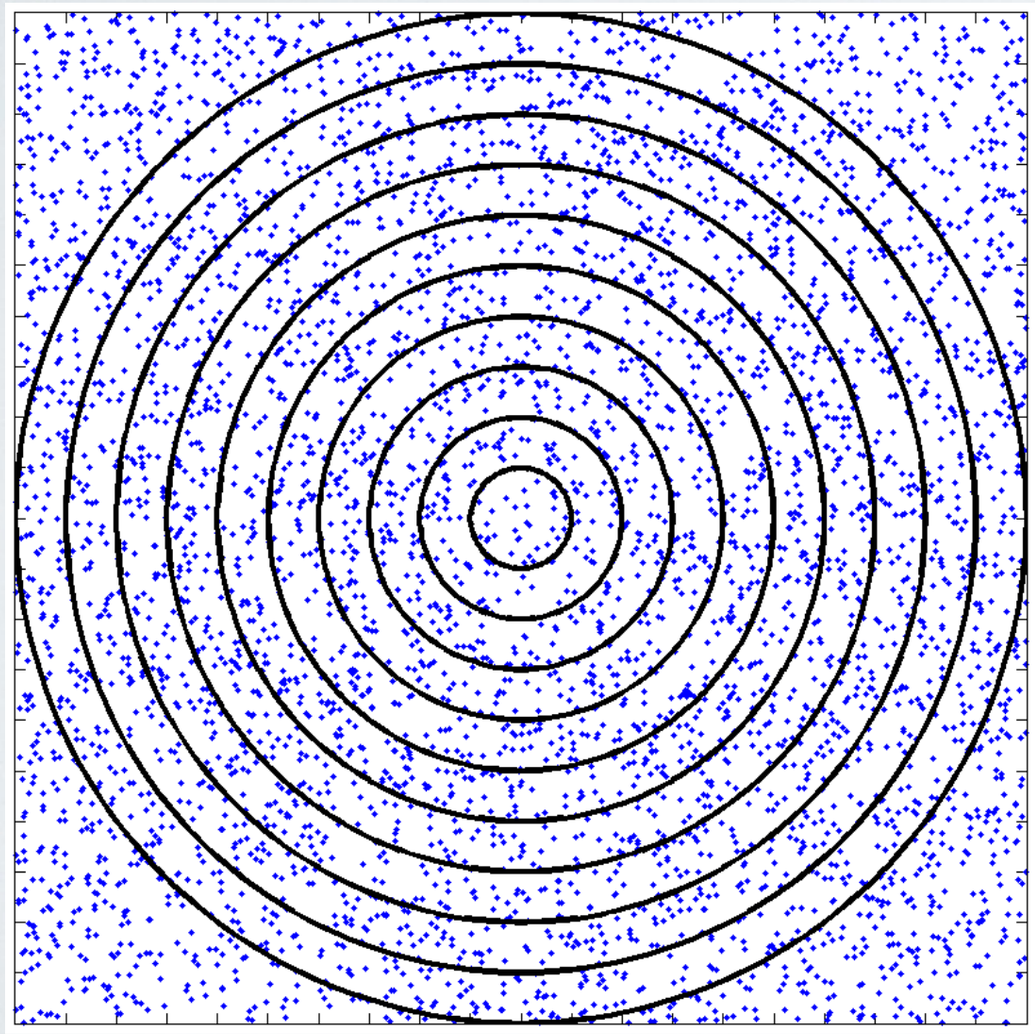
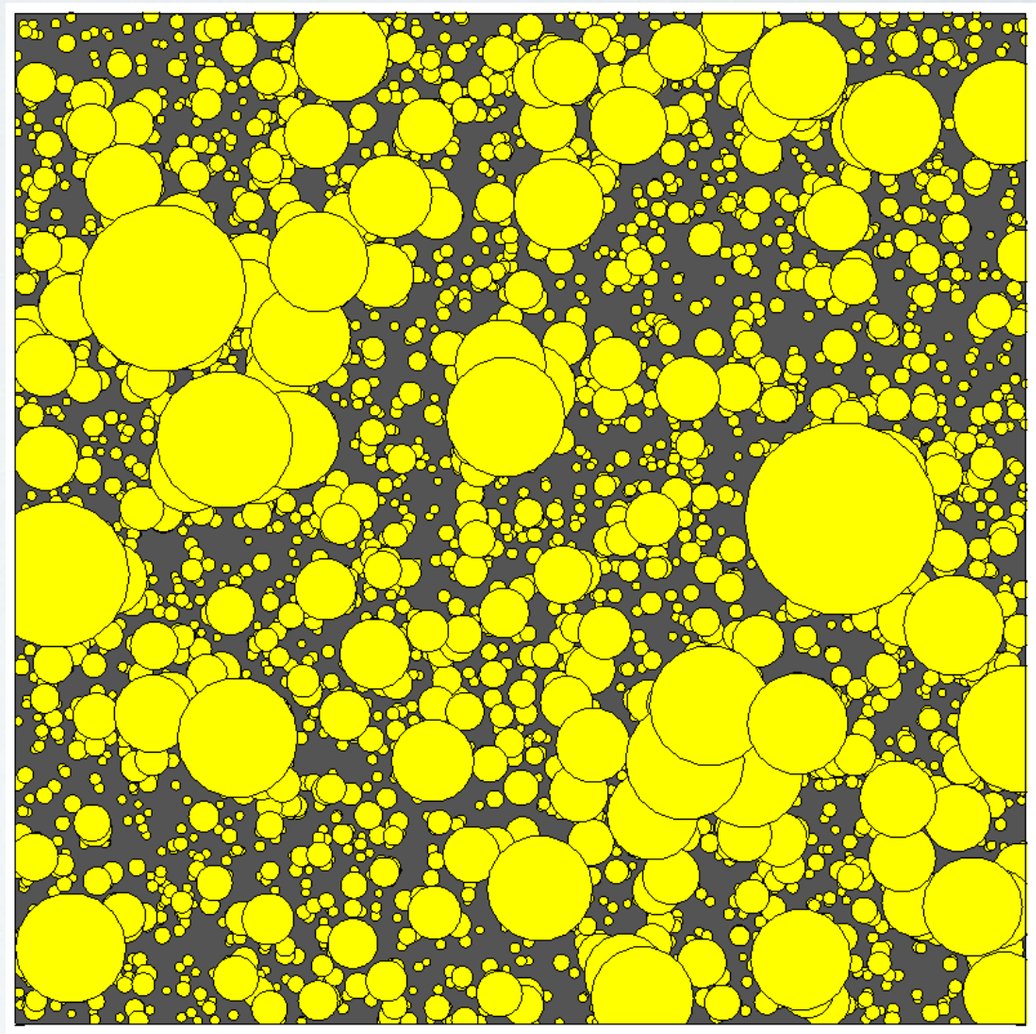
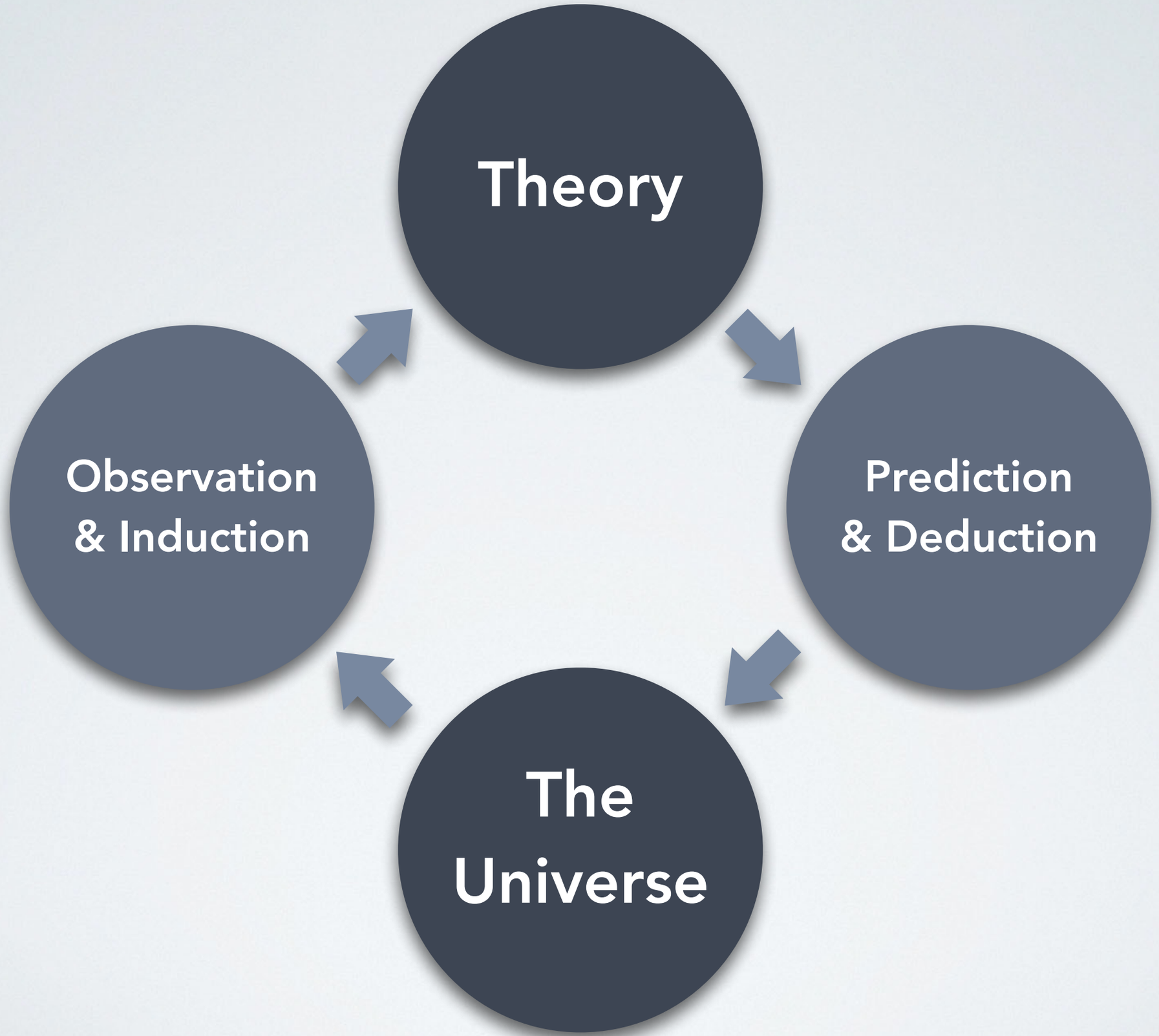




Olber's Paradox

- The Universe **cannot be**
  - static,
  - infinitely old,
  - and full of stars that live forever.

The scientific method



Participation: Video & Discussion #2

Watch *The eBOSS 3D map of the Universe* and write down one example each (!) of what sounds like a:

- **Hypothesis or theory**
- **Observation**
- **Concept that doesn't make sense yet** (by the end of the class we'll be able to fully get this movie!)

 10 minutes

Participation: Video & Discussion

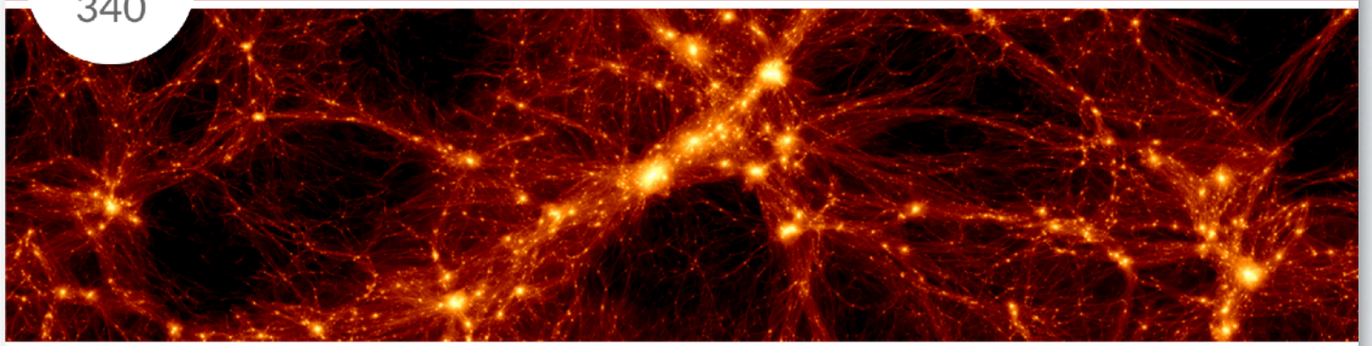
ASTR340

Fall 2021

- **Home**
- Syllabus
- People
- Assignments
- Discussions
- Quizzes
- Clickers
- Grades
- Zoom
- Panopto Recordings

ASTR 340

ORIGIN OF THE UNIVERSE



Syllabus

Lecture slides

Questions & Feedback

Resources

Welcome to *Origin of the Universe*! The goal of this course
study of the cosmos. We'll start right at home in our own
galaxy and to the Universe as a whole - how it started, ho
way, we'll encounter all kinds of bizarre physical and astro
Big Bang, dark matter, dark energy, and gravitational wav

As first step, please carefully read the syllabus .

ASTR340 › Pages › Resources

Fall 2021

- Home
- Syllabus
- People
- Assignments
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Resources

General resources

- World Wide Telescope (link)

Lecture 2

- Video of observed galaxies in the Universe from eBOSS (youtube, download)
- Behind the curve (on IMDB; documentary about flat-Earth movement; I thought i
- World map from the time of Eratosthenes (wikipedia)
- Movie of Eudoxus / Aristotle / Ptolemy type cosmology (youtube)
  - A similar model, built in real life (youtube)
- Movie of drawing Homer with epicycles (youtube)
- Movie of geocentric and heliocentric orbits (malinc.se)

Part 2: The Ancient Greeks

Night sky in Maryland

Participation: What can we see in the sky?

Respond to the poll on TurningPoint

Session ID: diemer

2 minutes

Naked-eye observers

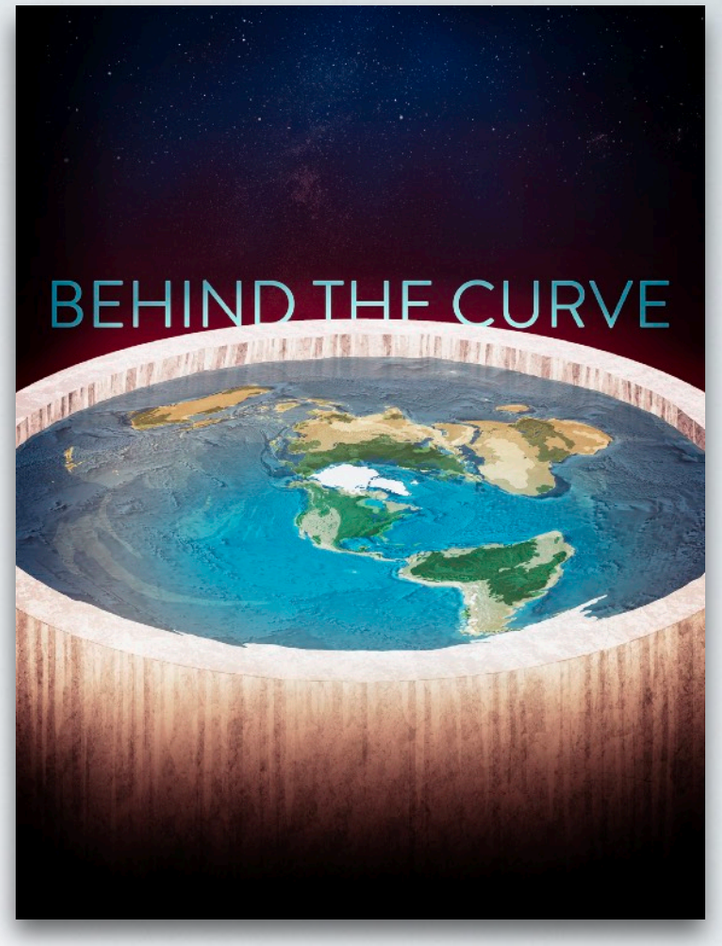
- What do we **see?**
  - Sun, moon, Planets
  - Stars (our immediate neighborhood)
  - Glow from the Milky Way disk
  - Meteorites, Comets, Supernovae
  - Large/small Magellanic clouds
- What would you **conclude?**
  - Earth is at rest (i.e., motionless)
  - Sun, Moon, planets, stars move in the sky (from East to West)
  - Occasional bizarre things happen

Greek Cosmology

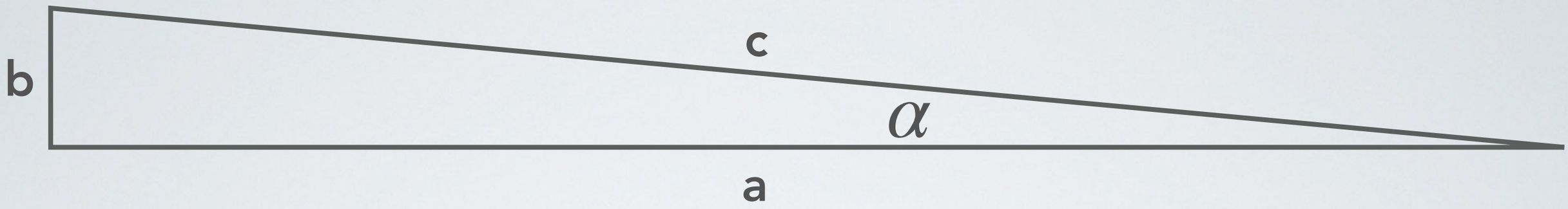
- First culture to look at world in the "modern scientific way":
  - Understood the idea of **cause and effect**
  - Applied **logic** to try to understand the world
  - Assumed that the Universe is fundamentally **knowable**
  - Sought to describe the Universe **mathematically**
  - Understood the importance of comparing theory with **data**
- However, one big roadblock…
  - **Theoretical principles** (especially geometric symmetry) **dominated over data**

Is the Earth flat?

- **Greeks knew the Earth is a sphere!**
  - View of constellations changes from north to south
  - Observations of ships sailing over the horizon (mast disappears last)
  - Observations of the Earth's shadow on the Moon during lunar eclipses



Recap: Trigonometry



Normally: $c^2 = a^2 + b^2$ $\sin(\alpha) = \frac{b}{c}$ $\cos(\alpha) = \frac{a}{c}$

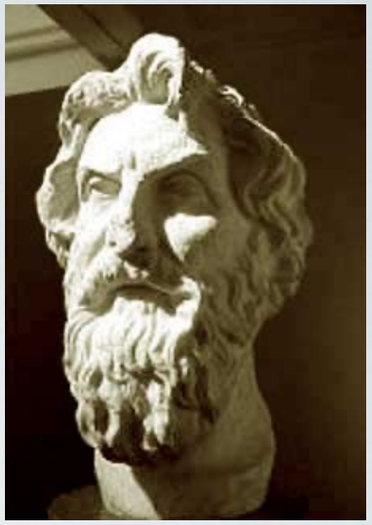
For small angle: $a \approx c$ $\sin(\alpha) \approx \alpha \approx \frac{b}{c}$

Angle must be expressed in radians!

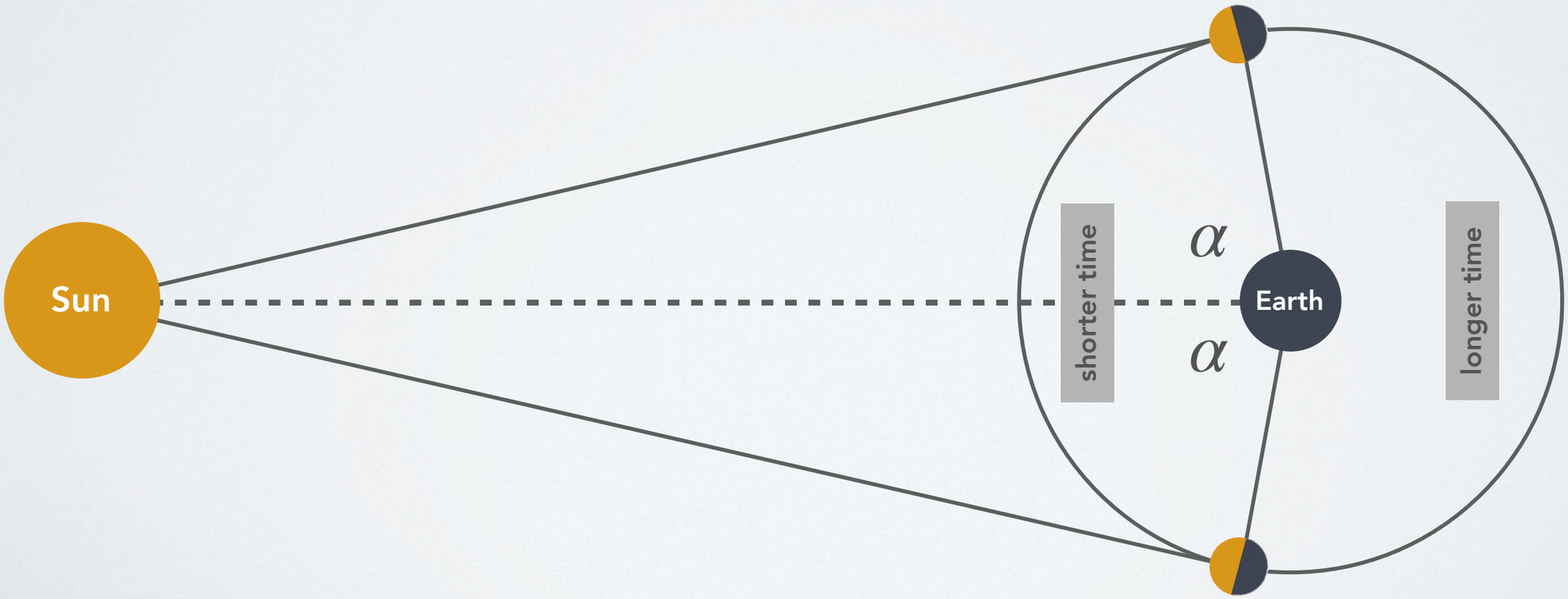
$$\text{radians} = \text{degrees}\frac{\pi}{180}$$

Aristarchus & The Earth-Sun distance

- How can we find the distance to the Sun?
- Idea: use the **phases of the moon**



Aristarchus
(~310-230 BC)



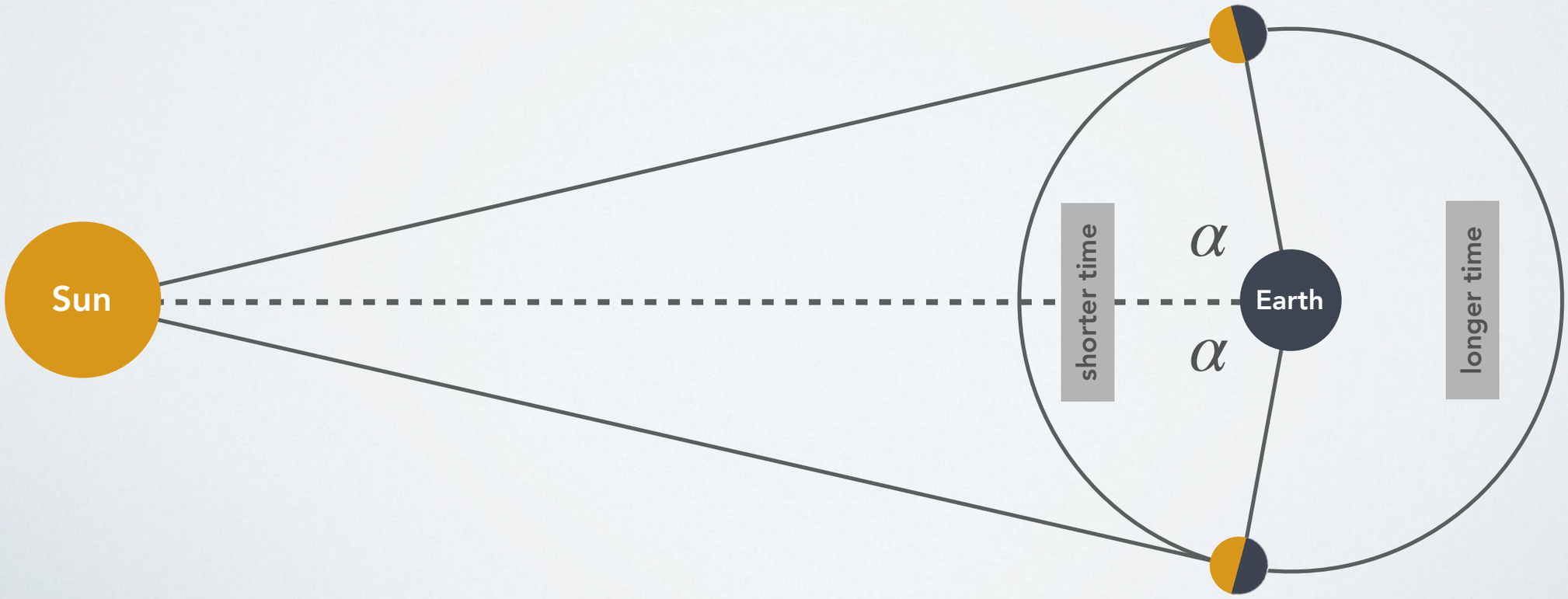
Aristarchus & The Earth-Sun distance

- **Step 1:** Get size of the moon
  - From Earth's shadow during eclipse
  - $R_{earth} \sim 4\ R_{moon}$
- **Step 2:** Get distance to moon
  - $$\frac{\text{duration of eclipse}}{1\ \text{month}} = \frac{2R_{\text{earth}}}{2\pi d_{\text{moon}}}$$
- **Step 3:** Measure times between half-moon epochs

Image: ESA

Aristarchus & The Earth-Sun distance

- Hard to measure in practice (angle is very close to 90 degrees!)
  - Measured angle was too small (87°), thus Sun is ~20 times more distant than moon (true: 89° 50’, 390 times more distant)
  - BUT that still means that the **Sun is larger than the Earth!**
- Proposed **heliocentric** picture, but was never accepted
  - Inconsistent with apparent perception of stationary Earth
  - No apparent shift in stellar positions could be observed
  - Uncomfortable with the idea that Earth was not central to the Cosmos



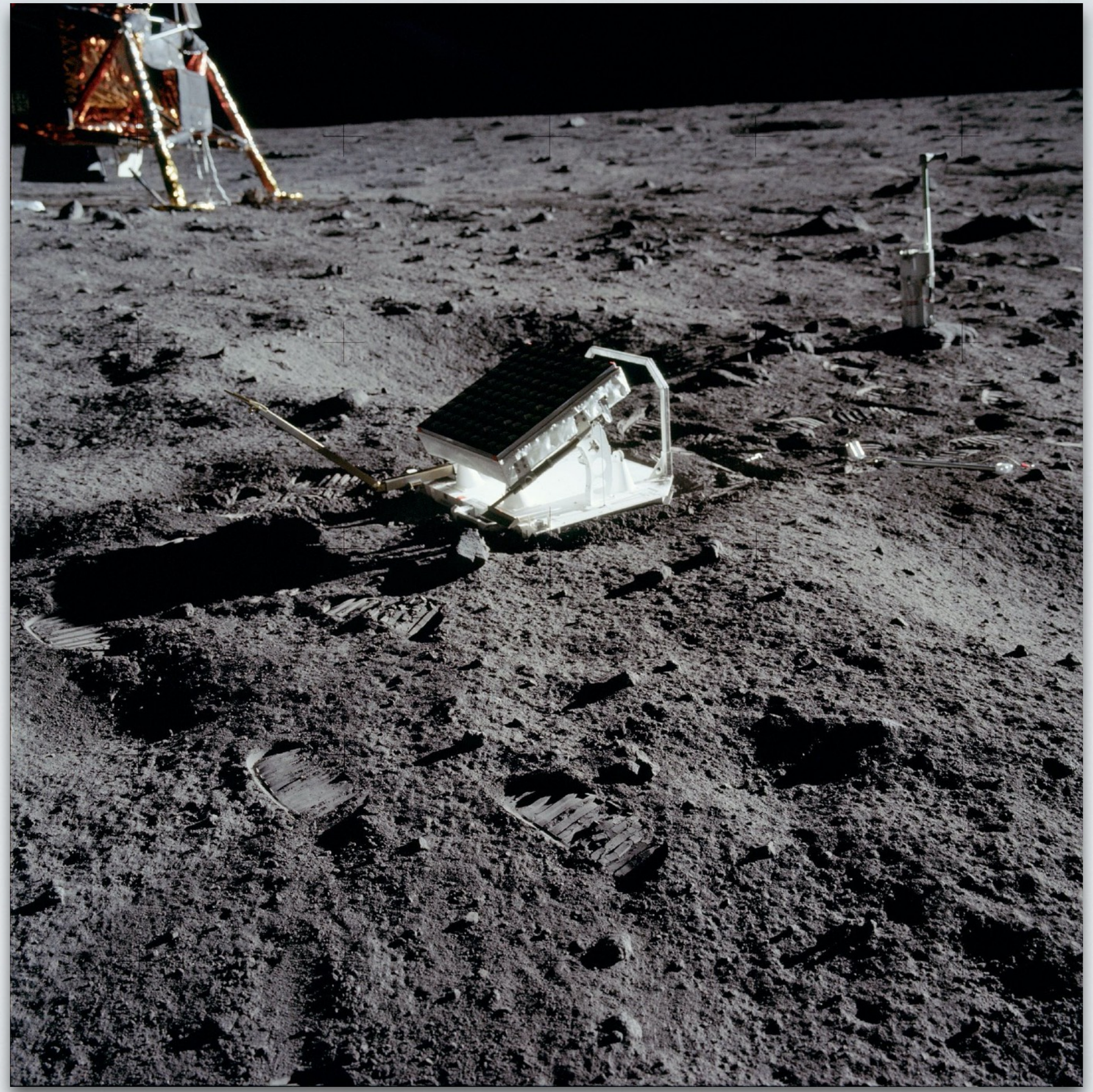
Participation: How well do we know d_{moon} today?

Respond to the poll on TurningPoint

Session ID: diemer

30 seconds

Aside: Lunar laser ranging



Eratosthenes & The size of the Earth

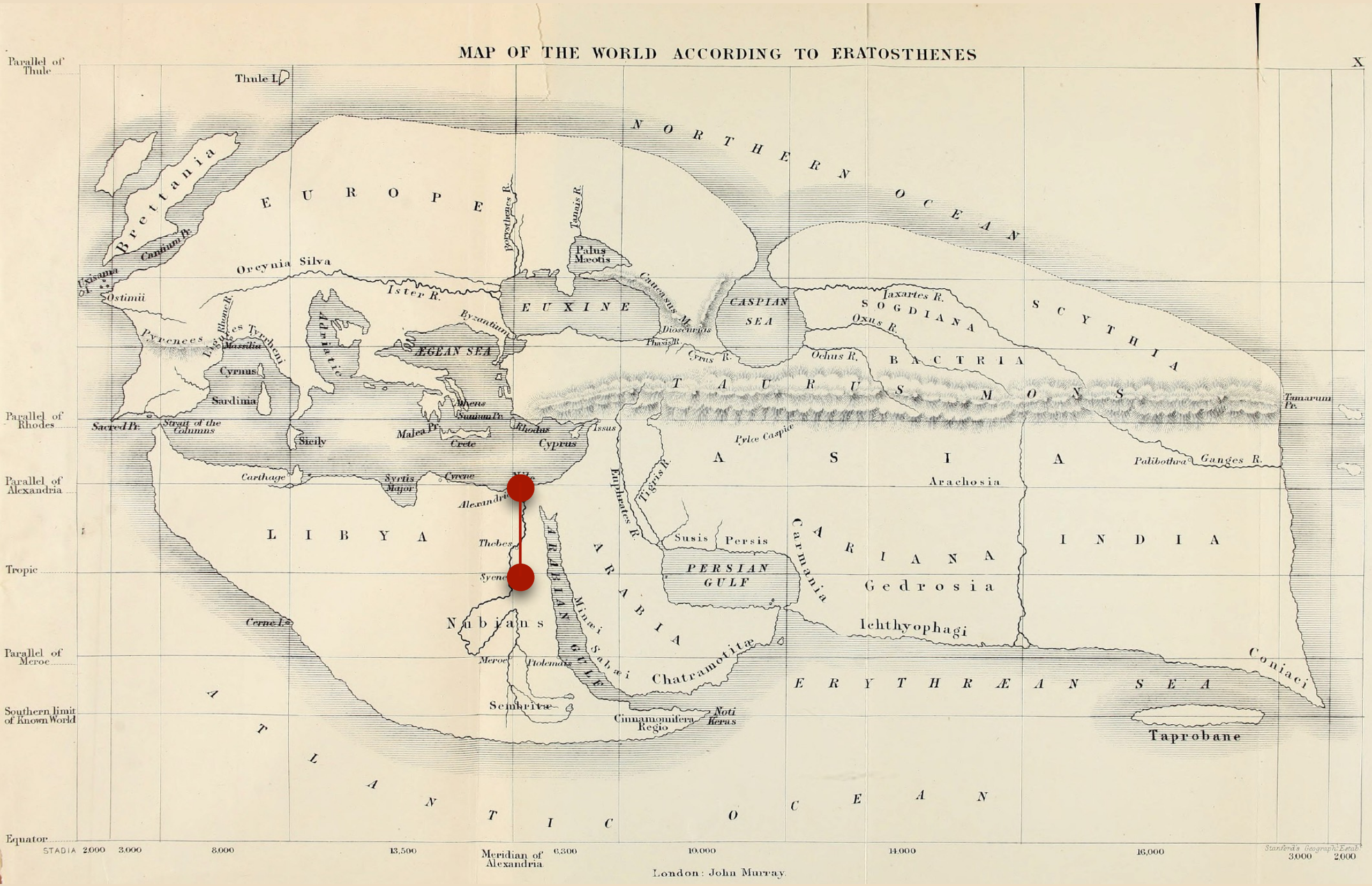
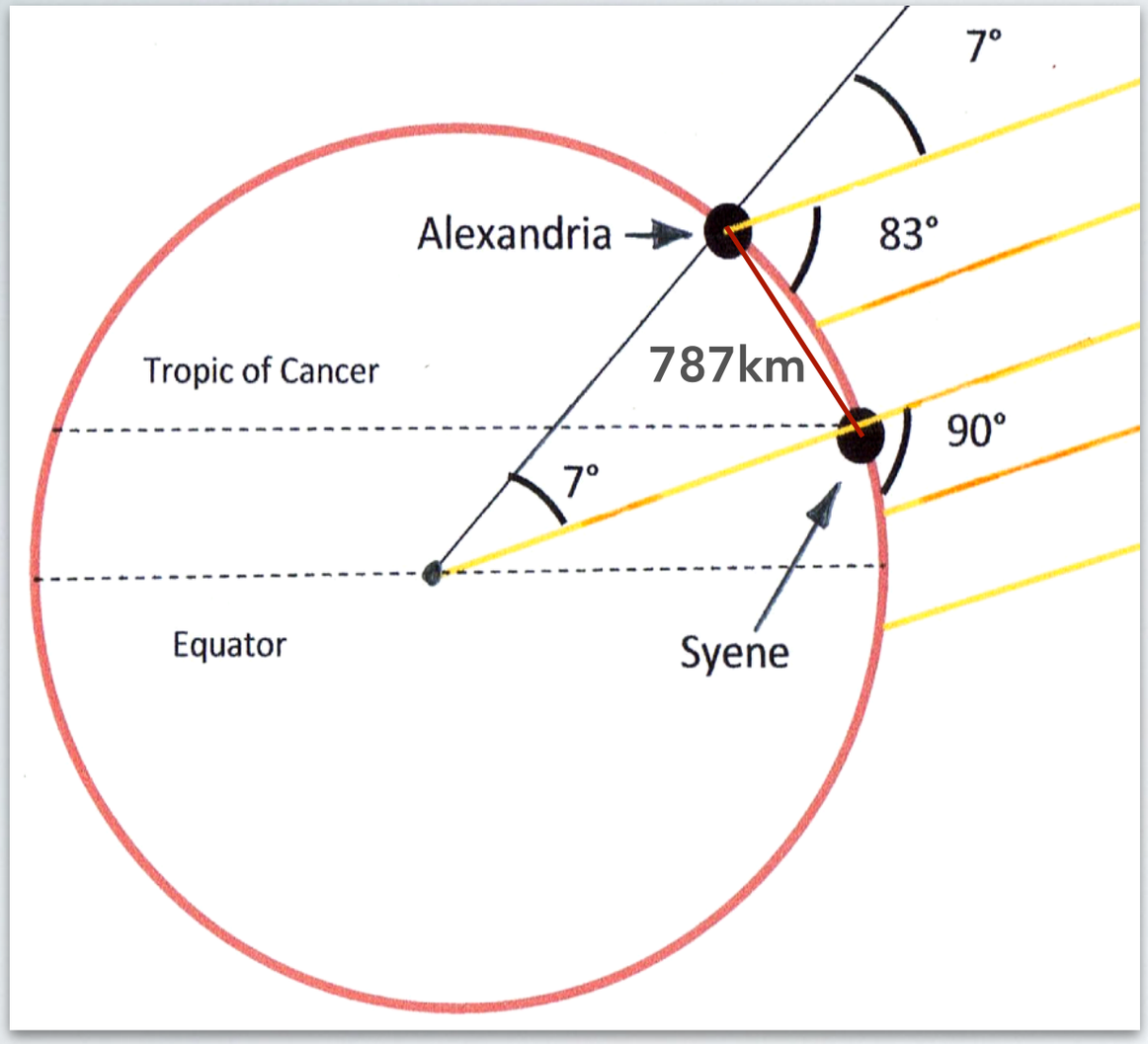


Image: Edward Bunbury

Eratosthenes & The size of the Earth



- Astronomer/mathematician in Hellenistic Egypt (c. 276-195 BC)
- This is a **simplified version** (the original is not preserved)
- **Assumption:** Syene is on the Tropic of Cancer (= sun vertical once a year on 6/21)

$$D = \frac{360^\circ}{7.2^\circ} \times 787\ \text{km} = 39350\ \text{km} \rightarrow \text{within}\ 1.4\,\%$$

Cosmology of Eudoxus and Aristotle

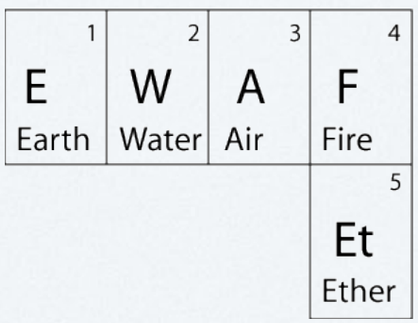
- Fundamental principles:
  - Earth is motionless
  - Sun, Moon, planets and stars **move around the Earth** (geocentric)
- Eudoxus (408-355 BC) & Aristotle (384-322 BC)
  - Proposed that all heavenly bodies are embedded in **giant, transparent spheres** that revolve around the Earth.
  - Eudoxus needed a complex set of **27 interlocking spheres** to explain observed celestial motions
    - e.g., need to have 24-hr period (=day) and 365-day period (=year) for the Sun

Cosmology of Eudoxus and Aristotle

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

Aristotle's terrestrial physics

- Four basic elements: **earth, water, air, fire**
  - Each element tends to move toward its "natural" place: Rock (earth) in air falls, air bubble in water rises
- "Natural motions" of earthly objects are **straight lines toward center of Earth**
  - Bodies in motion naturally tend to come to rest on Earth
  - An applied force can cause deviation from natural motion
  - A body at rest on Earth will remain so unless a force is applied
- **Continual application of force** is needed to sustain any motion other than natural motion (!)



Aristotle's celestial physics

- Heavens are governed by **different laws** from Earth
  - Celestial bodies are composed of "**ether**," a fifth element not present on Earth
  - "Natural motions" of celestial spheres are different from terrestrial motions: **circular, constant, and eternal**
- Aristotle needed **55 spheres** to explain observed motions
- **Space is finite**, bounded by outer sphere
  - But the edge is unreachable: motions become circular in the ethereal domain
  - Time is infinite
- Questions
  - **Is this consistent?**
  - **Why is this important?**

Ptolemy & Epicycles

- Worked at observatory in Alexandria, both as observer and theorist
- Developed theory to accommodate **detailed planetary observations**:
  - Variations in observed brightness over months
  - Retrograde motions
  - Variations in observed orbital speed
- Theory: motion along **small circles superposed** on top of motion **large circles**

Ptolemy (100-170 AD)

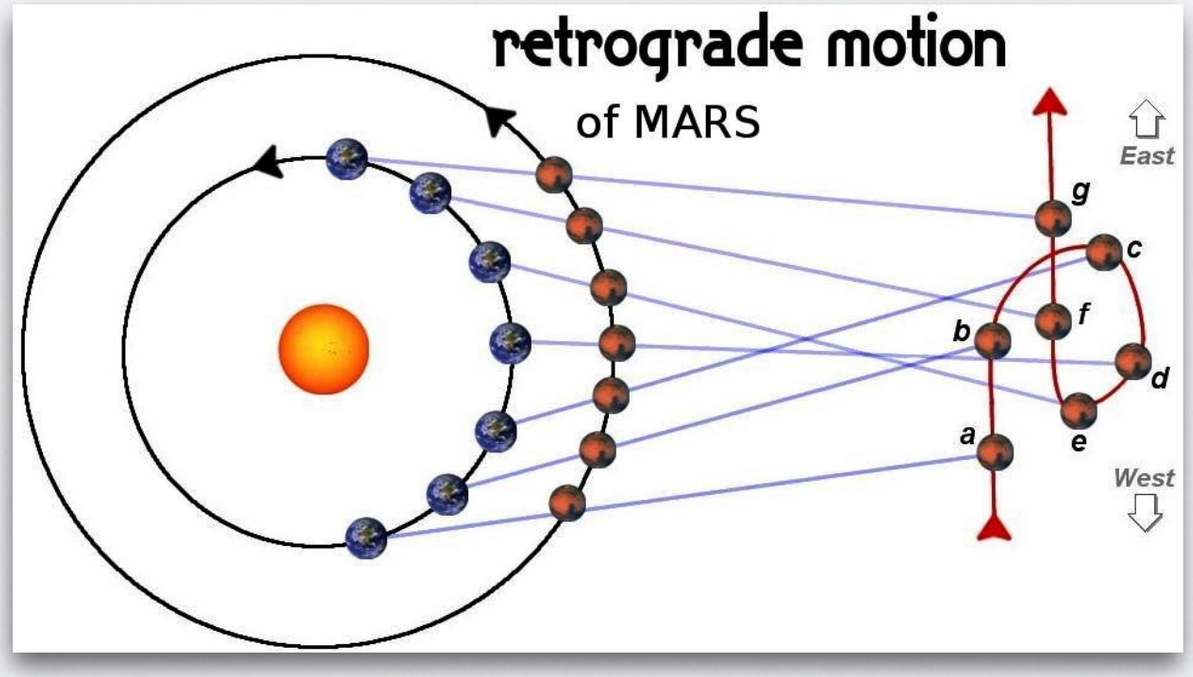
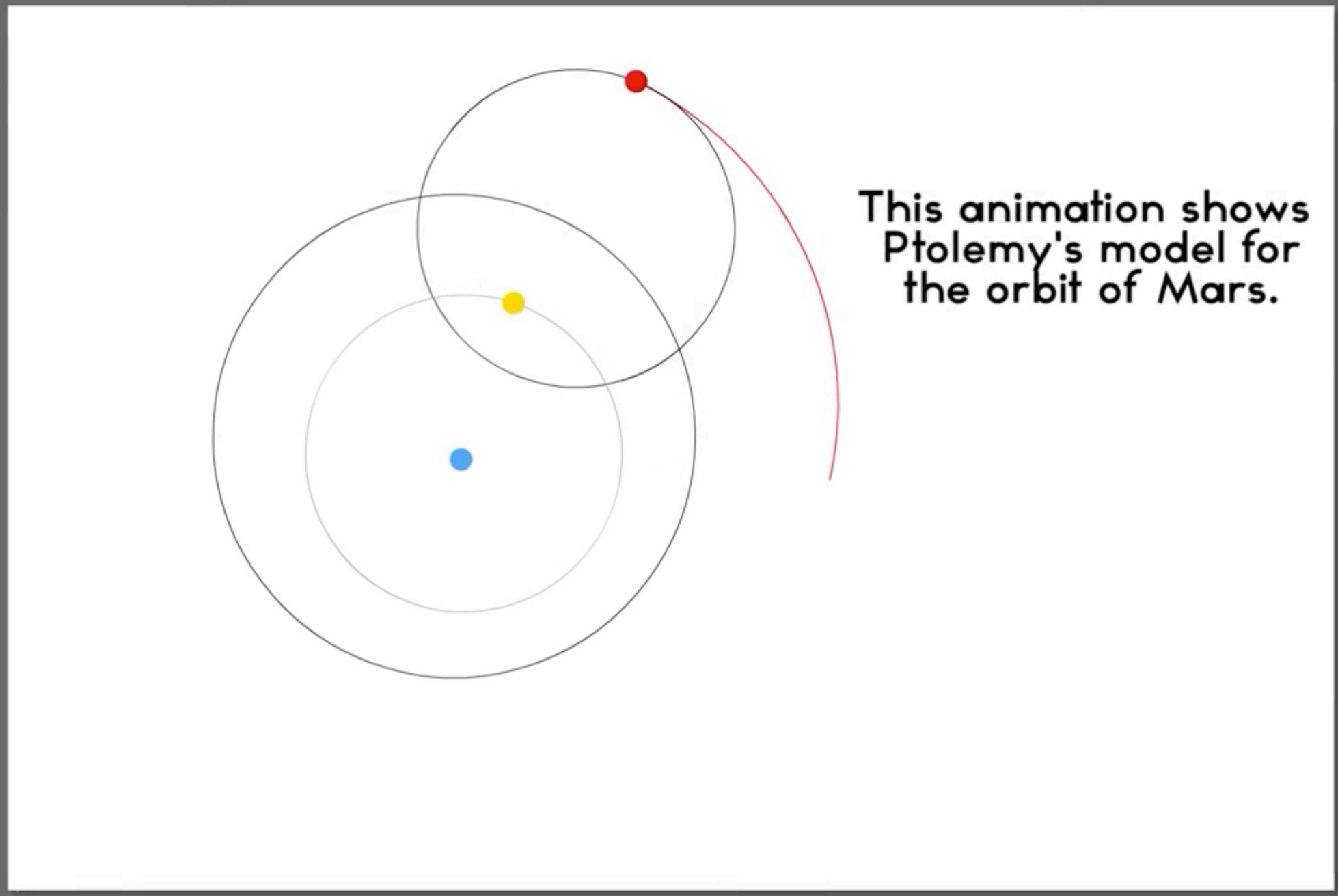


Image: astrogle.com

Epicycles of Ptolemy

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

Ptolemy & Epicycles



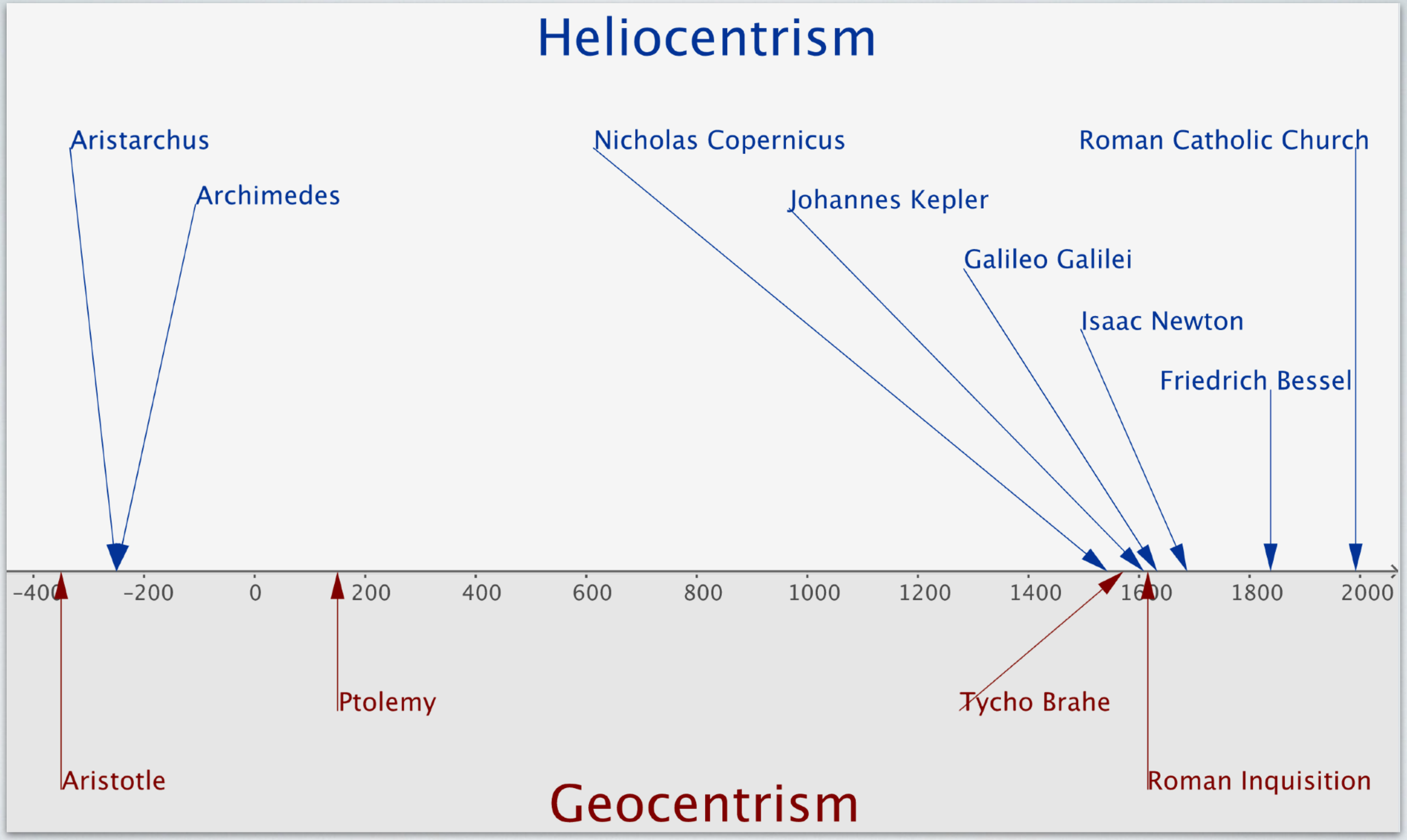
Video: AU Astronomy Demonstrations / https://www.youtube.com/watch?v=1nVSzzYCAYk

Ptolemy & Epicycles

Carman & Serra • youtube.com/watch?v=QVuU2YCwHjw

Part 3: Renaissance

Why Renaissance?

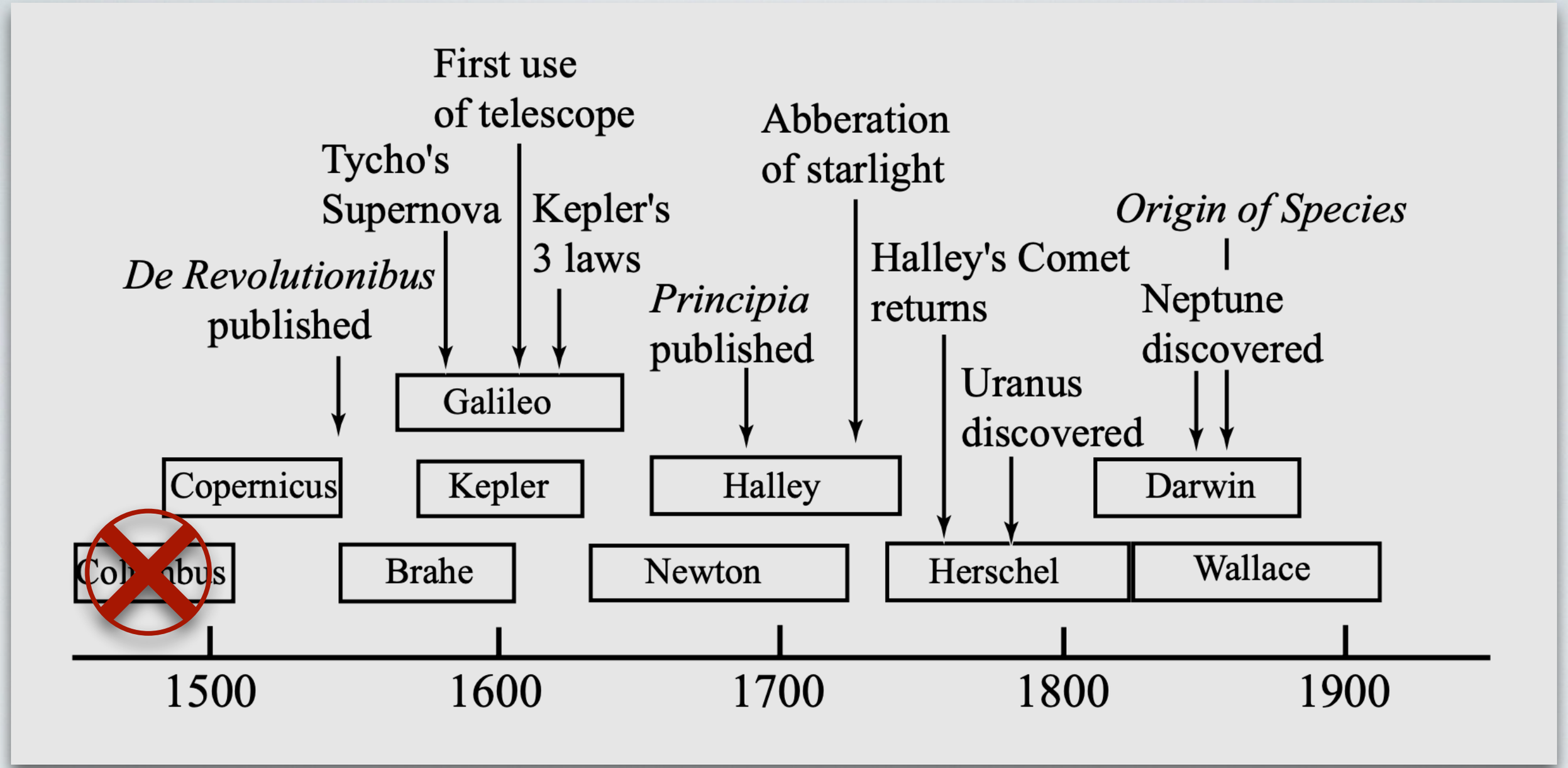


Why Renaissance?

- The European **dark ages** were serious!
  - About 1300 years of no progress
  - For example, Archimedes had understood integration (i.e., calculus), but it was forgotten and not rediscovered until Newton/Leibniz
- **Arab astronomers** preserved and extended Ptolemy's work
- Aristotelian/Ptolemaic view prevailed through 1400's
- **Geocentric** model
- Creation at **finite time** in past (to satisfy Christian theology)
- Earth known to be round

Image: St. Peter's Basilica, Rome

Timeline



Hawley & Holcomb, Foundations of Modern Cosmology

Participation: Center of the Universe

Respond to the poll on TurningPoint

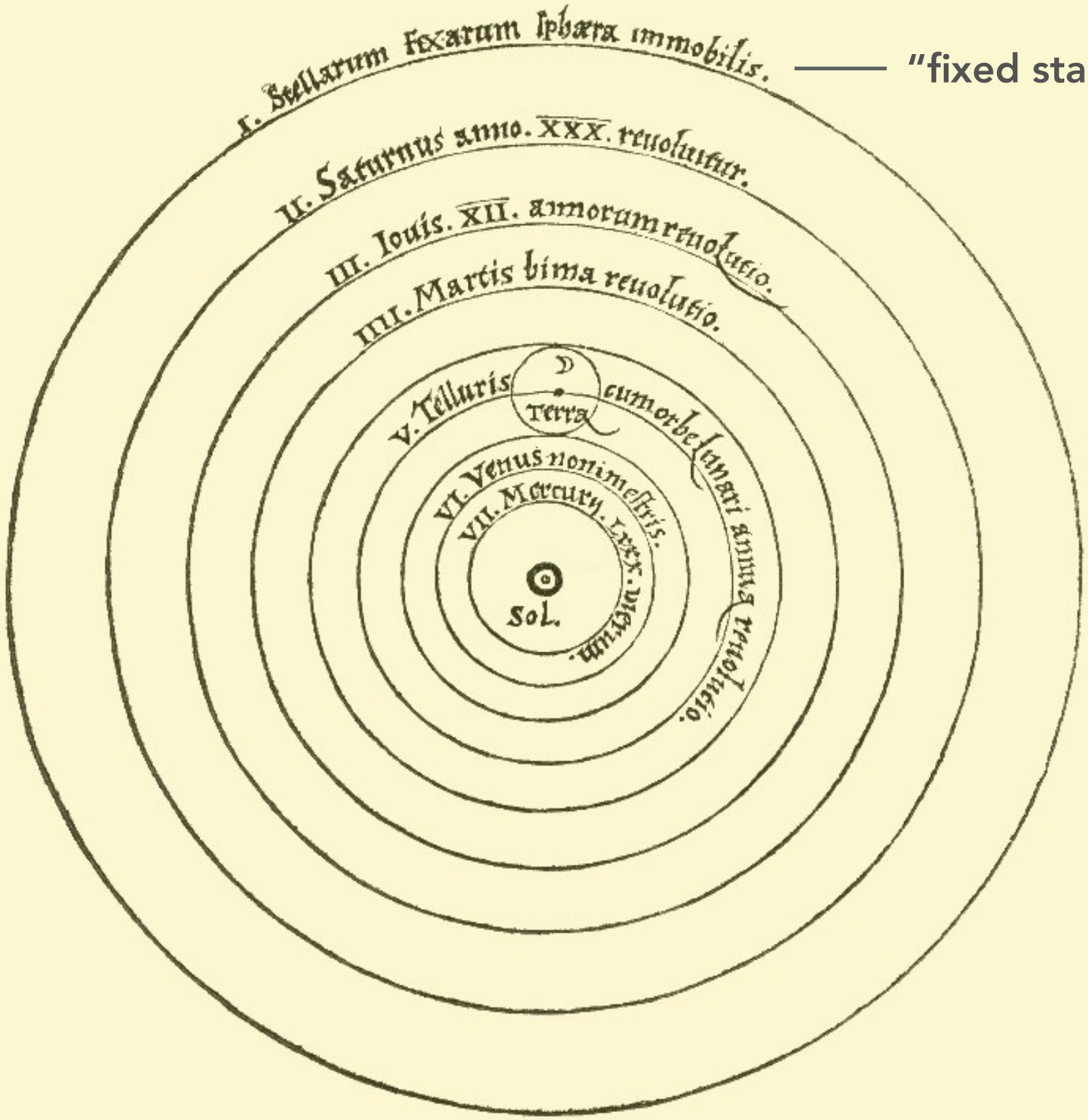
Session ID: diemer

 30 seconds

Copernicus & Heliocentricism

- Copernicus was born in Poland
- Studied in Krakow, Bologna, Padua, Ferrara
  - Canon law, medicine, mathematics, astronomy
  - Worked as church canon, physician
- Rejected Ptolemy's geocentric model because it was too complicated
- Preferred **heliocentric model with perfect circular motions**

Heliocentric solar system



"fixed stars"

From Copernicus, *De Revolutionibus Orbium Coelestium*

Heliocentric solar system

Heliocentrism

Geocentrism

Malin Christersson / malinc.se

Copernicus & Heliocentricism

- Main ideas were already in *Little Commentary* (1514)
  - The Earth's center is not the center of the universe
  - There is **no one center** in the universe
  - The Earth and planets **revolve around the Sun**
  - The distance from the Earth to the Sun is **imperceptible compared with the distance to the stars**
  - The **rotation of the Earth** accounts for the apparent daily rotation of the stars
  - The apparent annual cycle of movements of the Sun is caused by the Earth revolving round it
  - The apparent **retrograde motion** of the planets is caused by the motion of the Earth from which one observes

The Copernican Principle

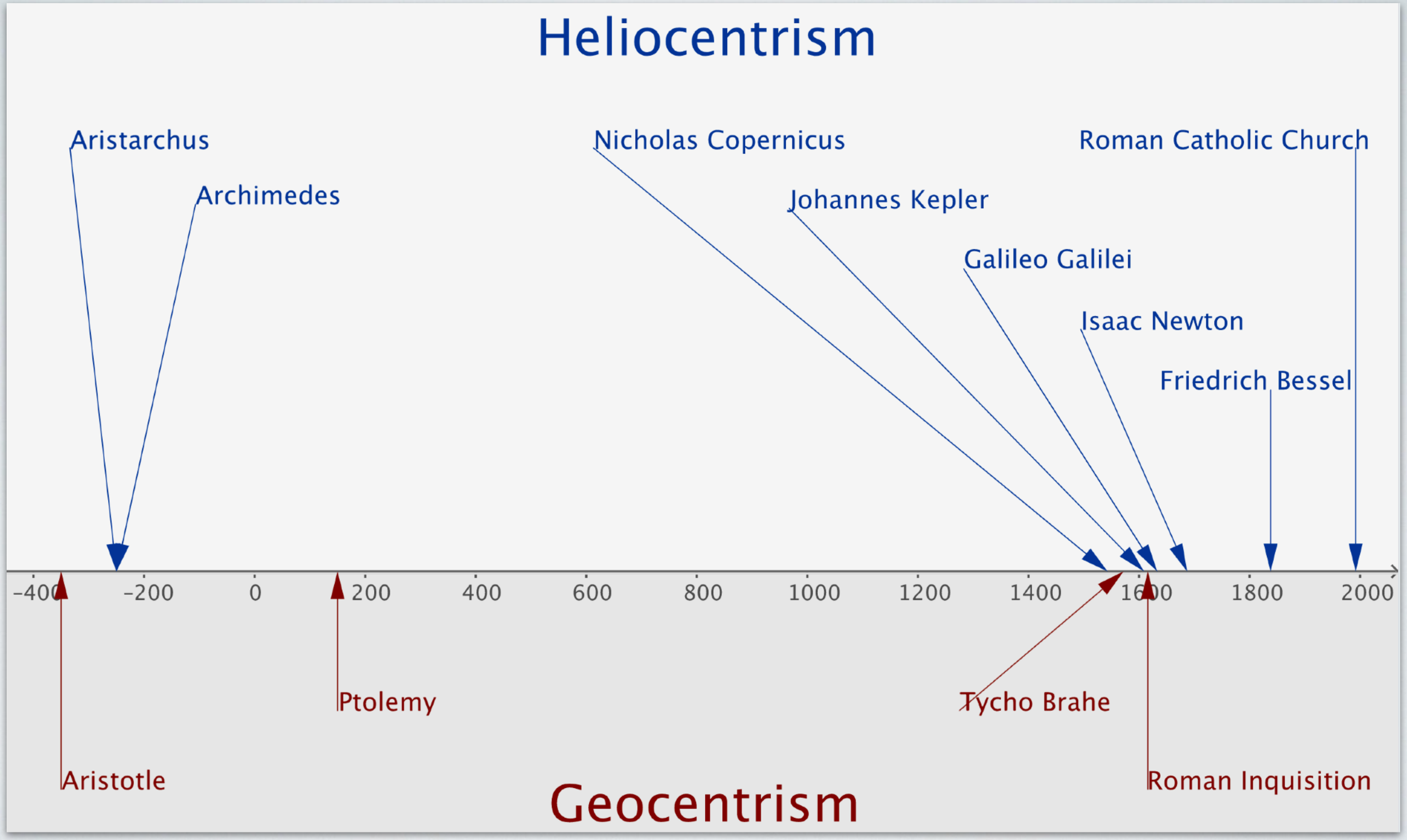
- **Copernican Principle:** The Earth is not at a special location in the Universe

- **Generalized Copernican Principle:** There is no special place (or center) in the universe

Copernicus & Heliocentricism

- Full title: *De Revolutionibus Orbium Coelestium*
  - Printed Nuremberg, 1543, in last year of life
  - Spelled out, using observations and mathematics, evidence for his heliocentric model
  - Simple and natural explanation for retrograde motion of planets
  - Included accurate relative spacings of planetary orbits
  - Showed that **planetary speeds decrease outward from Sun** (implicit prediction for new planets)
- **Not as accurate as Ptolemy** in matching planetary motions; had to include some epicycles to improve agreement with observations (we'll see why)
- Book was **widely read** and appreciated by 16th century astronomers
  - Some believed in Copernicus's heliocentric physical model
  - Others considered Copernicus's approach superior for calculating orbits, but believed in geocentric Universe
  - Opposition with the Catholic church forms, official in 1616

Copernicus & Heliocentricism



Take-aways

- Coming up with a good **model of the solar system** is not easy, especially without telescopes

- The **ancient Greeks** got amazingly far, but their progress was largely forgotten until the **Renaissance**

- Heliocentric models are **much simpler** than geocentric ones

Next time…

We'll talk about:

- The scientific revolution: Brahe, Kepler, Galileo, Newton

Assignments

- Post-lecture quiz (by tomorrow night)

Reading:

- H&H Chapter 2 (continued)