# Astronomy 100

# Chapter 4:
# Origins of Modern Astronomy

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# Plan for this lesson:

History of astronomy
Retrograde motions
Measuring distances to stars
Kepler's Laws of planetary motion
Galileo's experiments

# Beginnings of astronomy

# Astronomy is as old as humans

- Oldest astronomical artifcts from **Stone Age** (6000 – 20 000 years old) include markings that could be tracking crescent moon.
- **Mayan priest-astronomers** were revered because they could 'predict' the length of the year and times of sunrise and sunset throughout the year.


Fig. 1. The Ishango bone. Based upon an image from the Royal Institute for Natural Sciences of Belgium in Brussels

Ishango Bone, Congo, Africa

The observatory at Chichen Itza

# Greek Astronomy

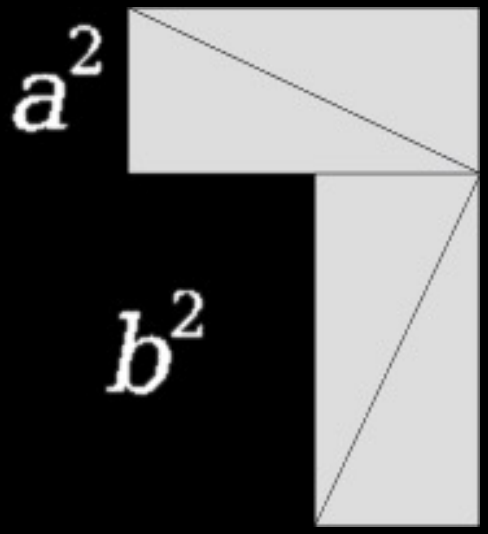
Three major innovations:

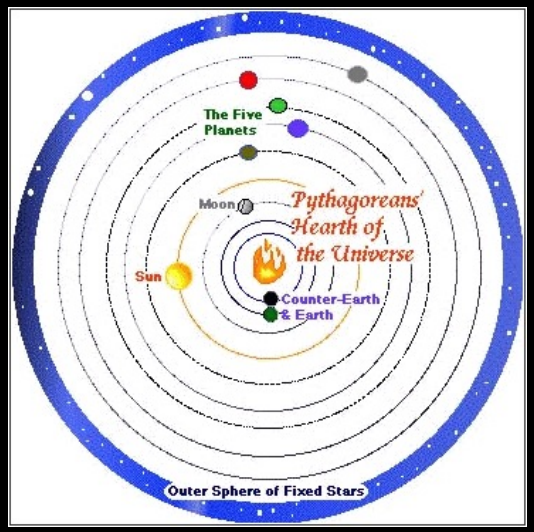
1. Understand nature without relying on super-natural.
2. Express ideas about nature mathematically.
3. Check theories against observations.

# Greek Astronomy

Pythagoras of Samos
(580 BCE to 500 BCE)

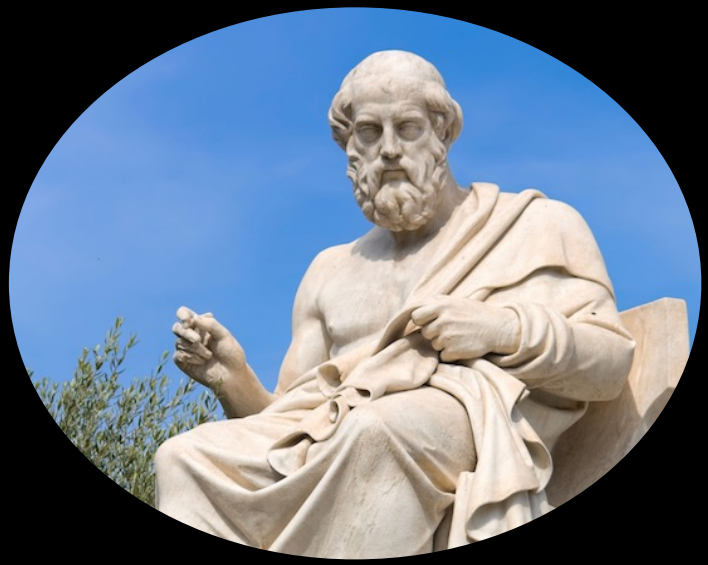
- Nature can be described by mathematics.



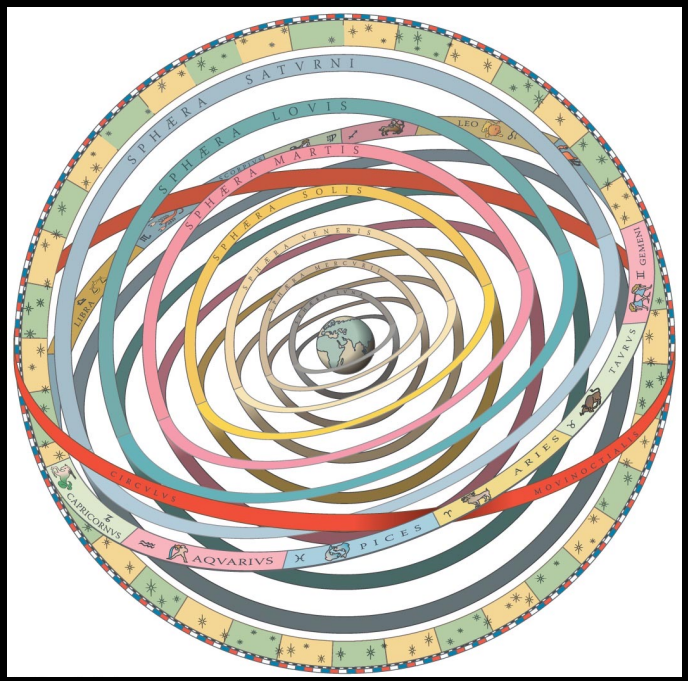



# Greek Astronomy

## Plato
(424 BCE to 347 BCE)



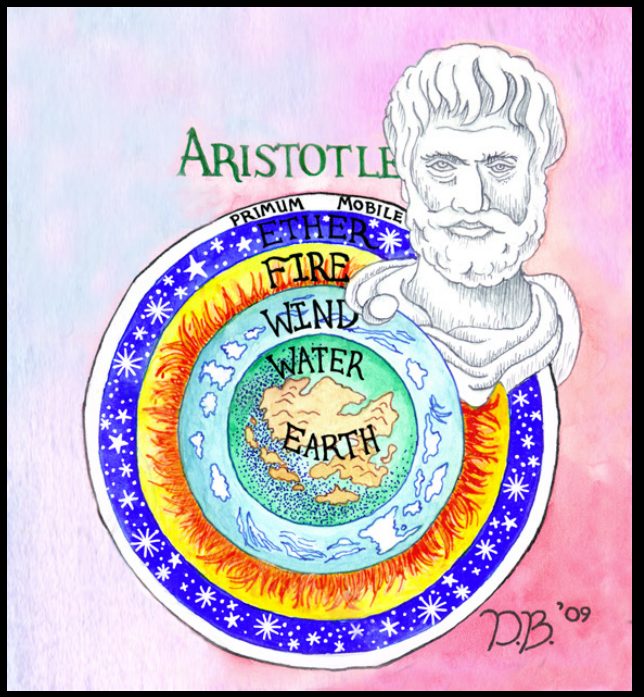
- **Perfection of heavens**: most perfect form was the sphere, so the heavens must be made up of uniformly rotating perfect spheres.
- Earth was the center of the Universe, **geocentric system of the world**.
- The Sun, the Moon, and each of the known planets (Mercury, Venus, Mars, Jupiter, and Saturn) had their own spheres, and the stars were on the outermost sphere.



# Greek Astronomy

## Aristotle
(384 BCE – 322 BCE)

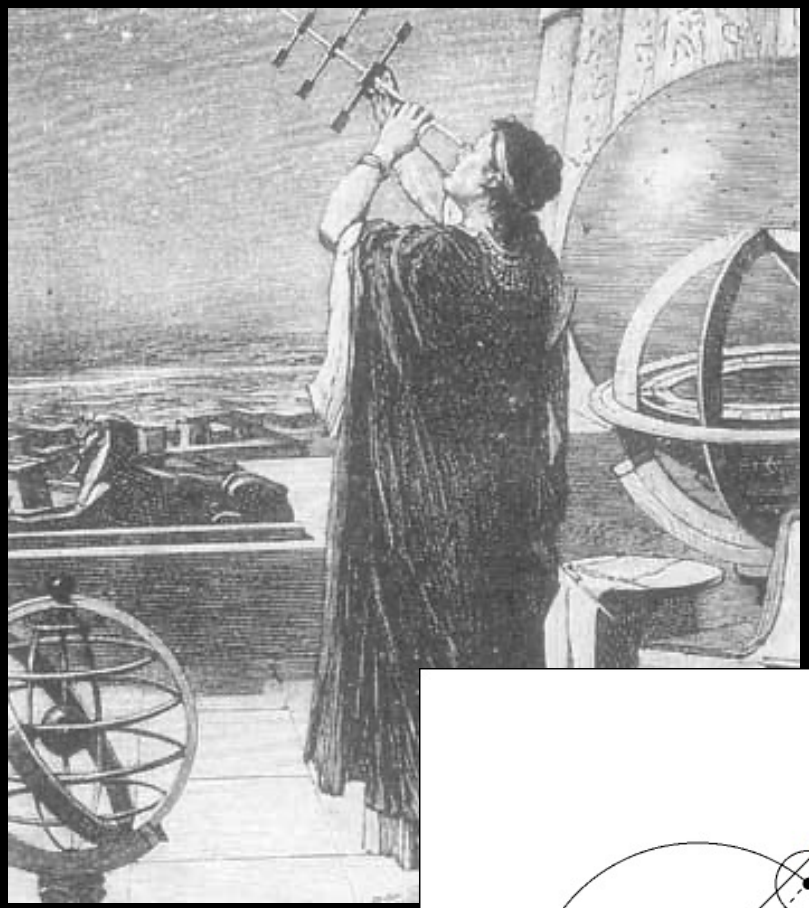
- Earth made of four elements, heavens are made of "quintessence".
- Natural laws did not apply to the heavens.
- Natural state of matter was to be at rest.
- **Earth was the center of the universe.**

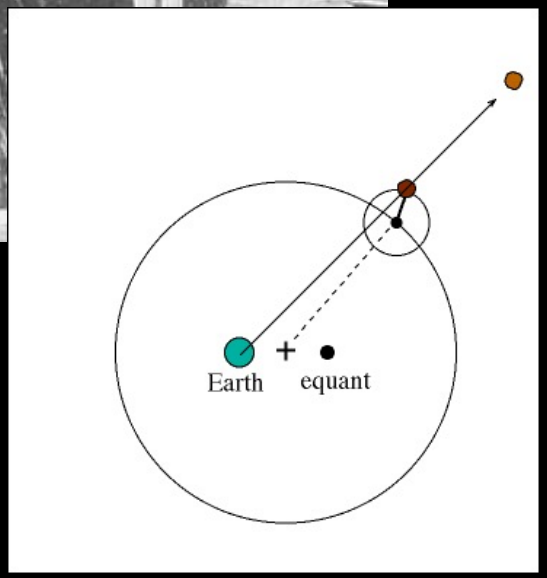


# Greek Contributions to Astronomy

Hipparchus of Nicaea
(194 BCE – 120 BCE)

- Calculated positions and brightness of 1080 stars.
- Discovered **precession**.
- Invented deferent (big circles) and **epicycles** (small circrels) to explain the apparent motion of planets in the sky.





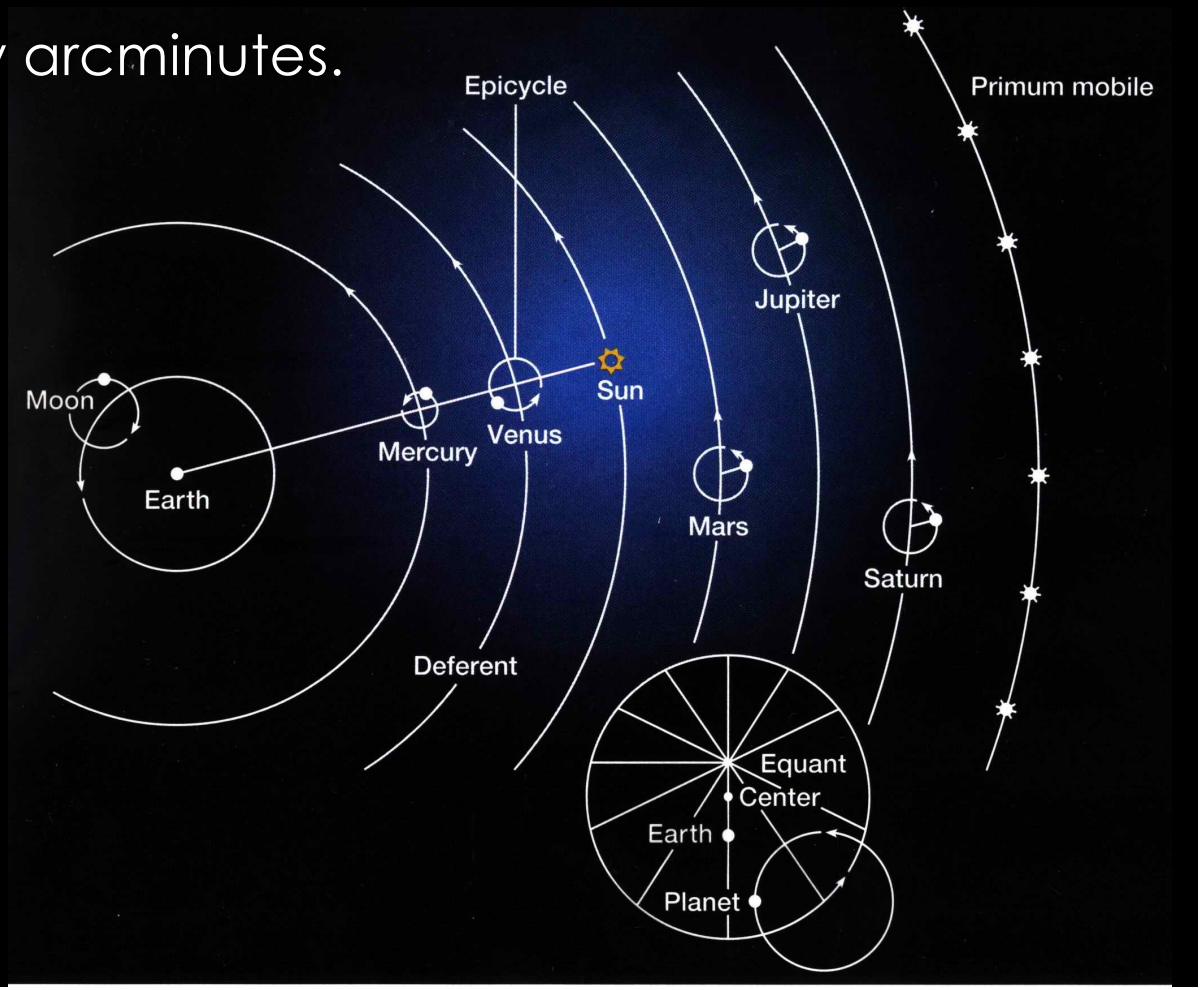
# Greek Contributions to Astronomy

Ptolemy
(100 CE – 170 CE)

- Compiled a 13-volume summary of Greek astronomy, translated into Arabic as ***Almagest*** (The Great Book).
- Refined Hipparchus' idea of epicycles into a full **geocentric model** and made first **predictions**.

# The Ptolemaic System

- Planetary positions predicted based on **uniform circular motion of planets** around a stationary Earth.
- Retrograde motion explained with **epicycles, deferents, and equants**.
- Predictions good to a few arcminutes.



# Islamic (Arab & Persian) contributions to astronomy

- Translated and absorbed astronomical knowledge from India, Persia, Greece, and Rome.
- Invented algebra, algorithms (everything that stars with "al"!)
- Invented the lunar calendar.
- Completely revised Ptolemy's Almagest.
- Argued for a beginning to the Universe.
- **Postulated that the laws of physics also applied to the heavens.**
- Understood the tilt of Earth's axis!

**Before the 16th century, the universe was geocentric.**

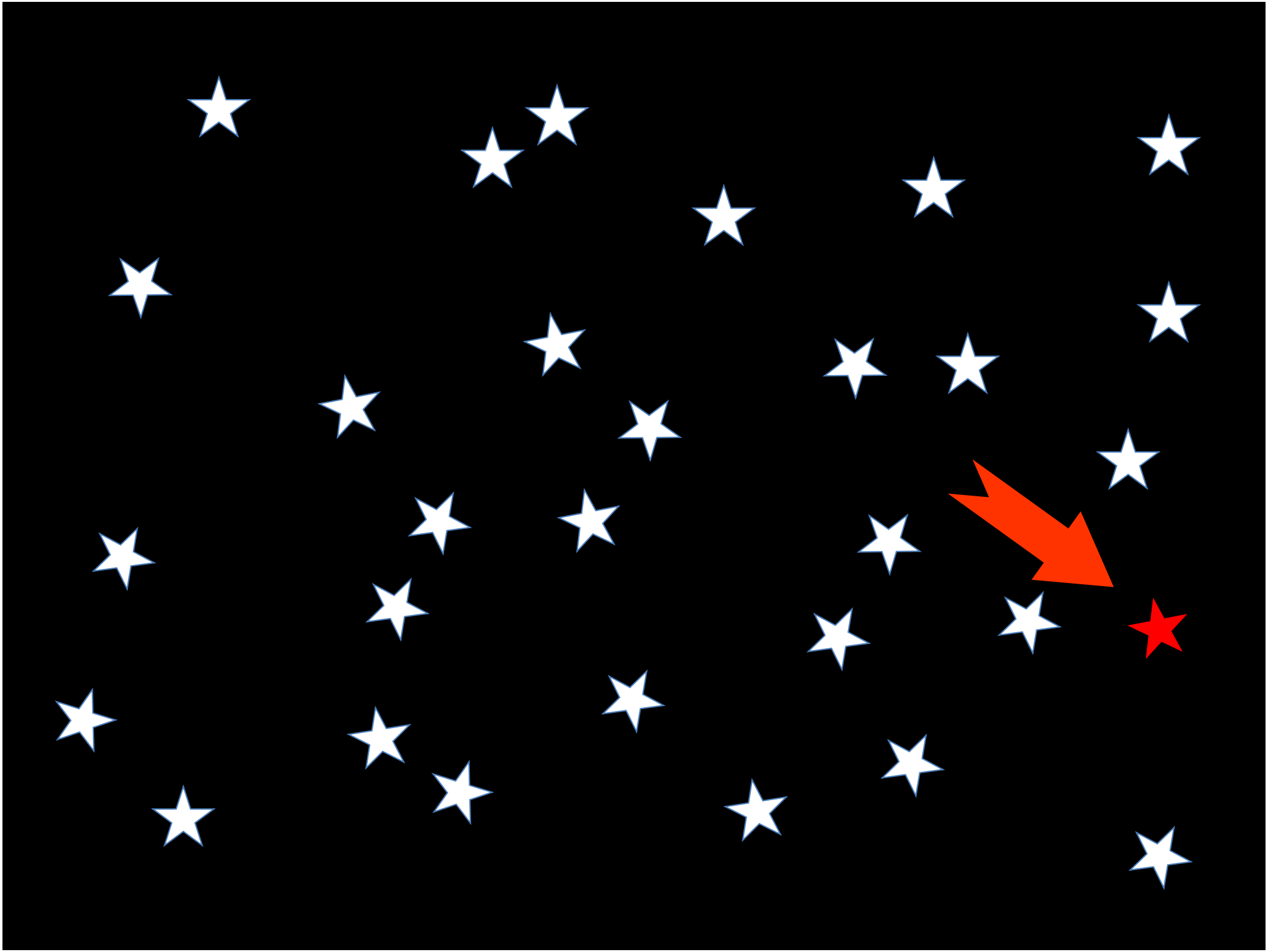
*Advantages*: we don't feel that we're moving, stars don't have parallax, and heavens are perfect (Aristotel's argument).

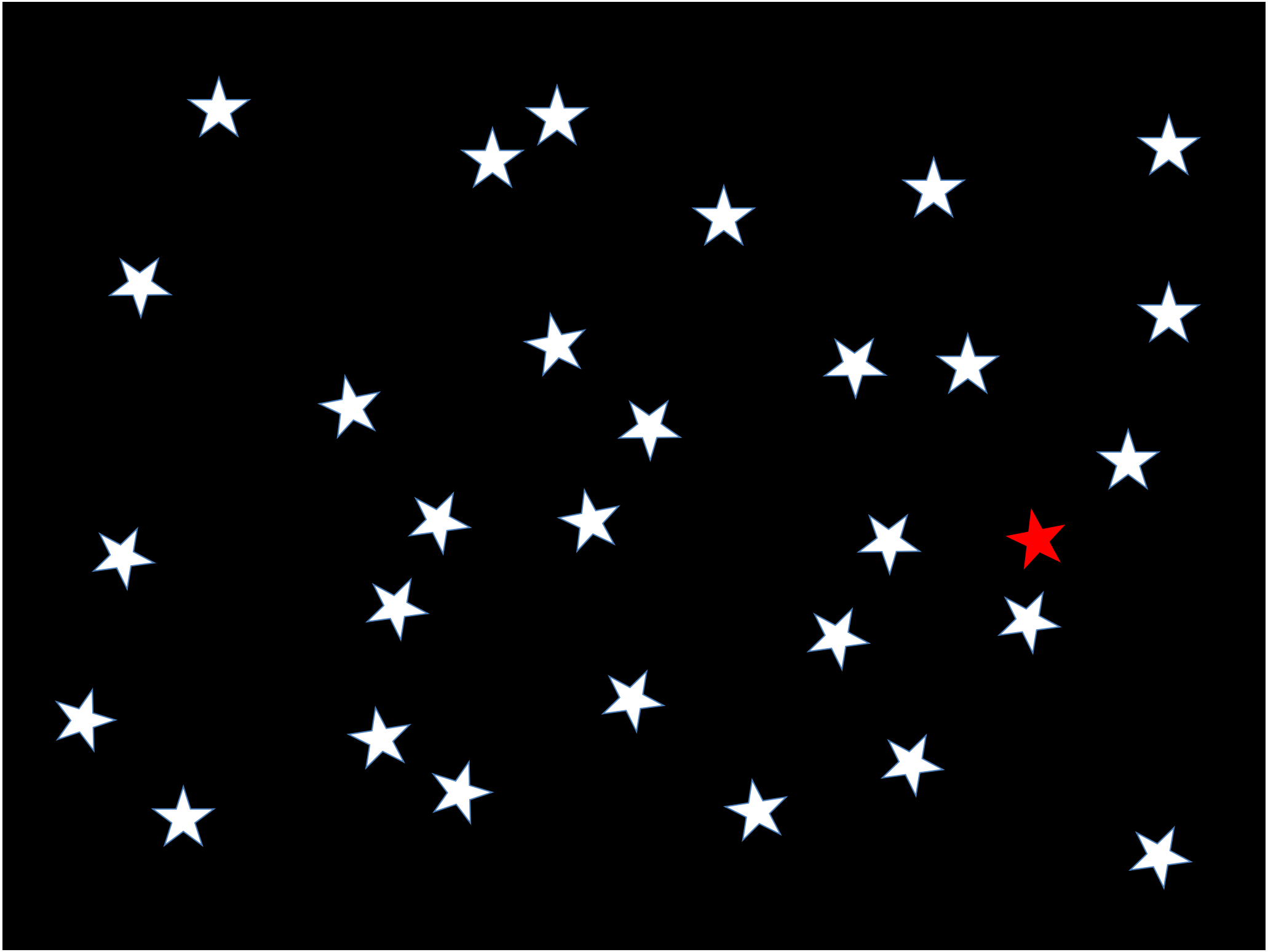
*Problem*: retrograde motions of planets.

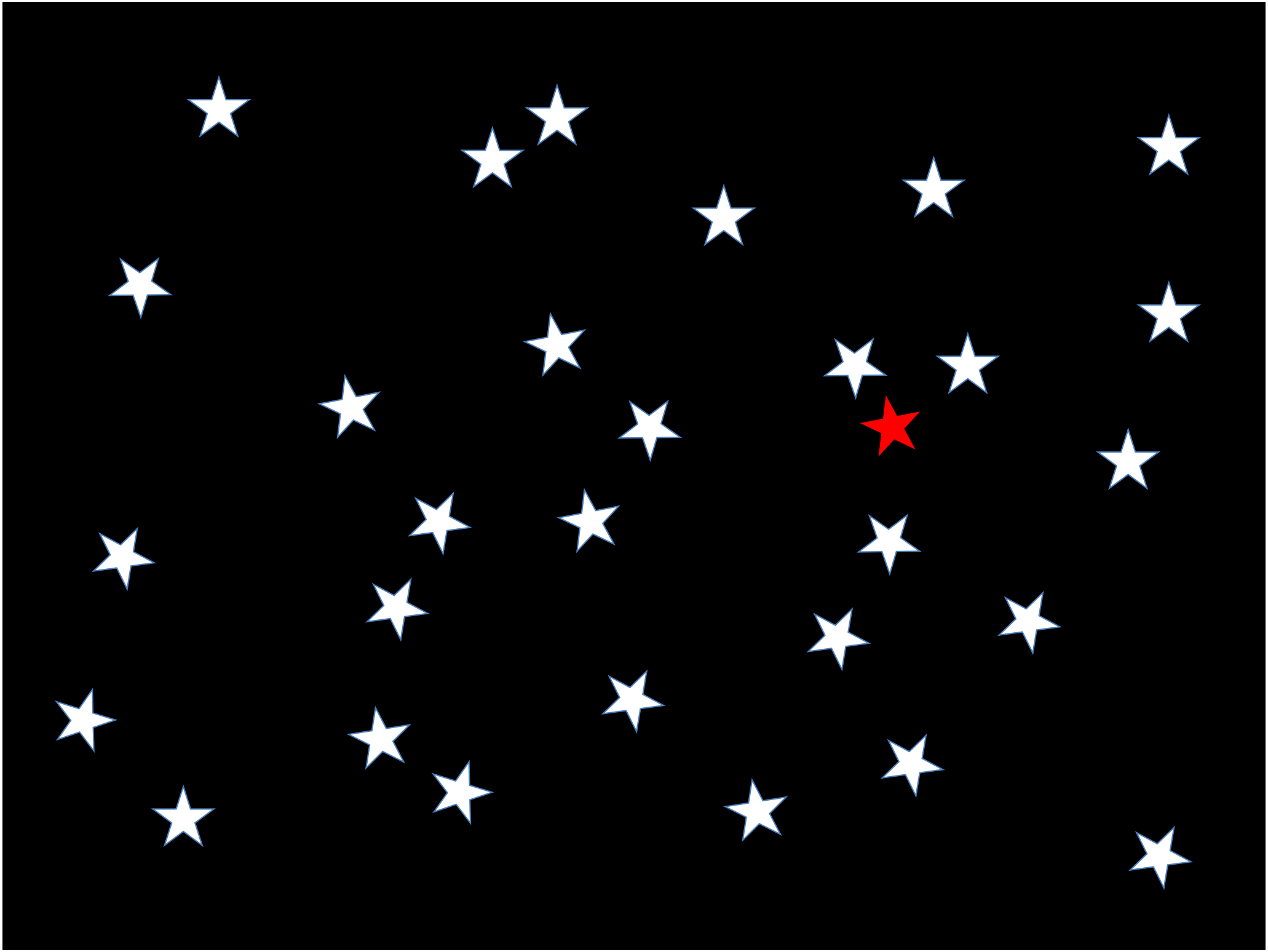
# Retrograde motions of planets

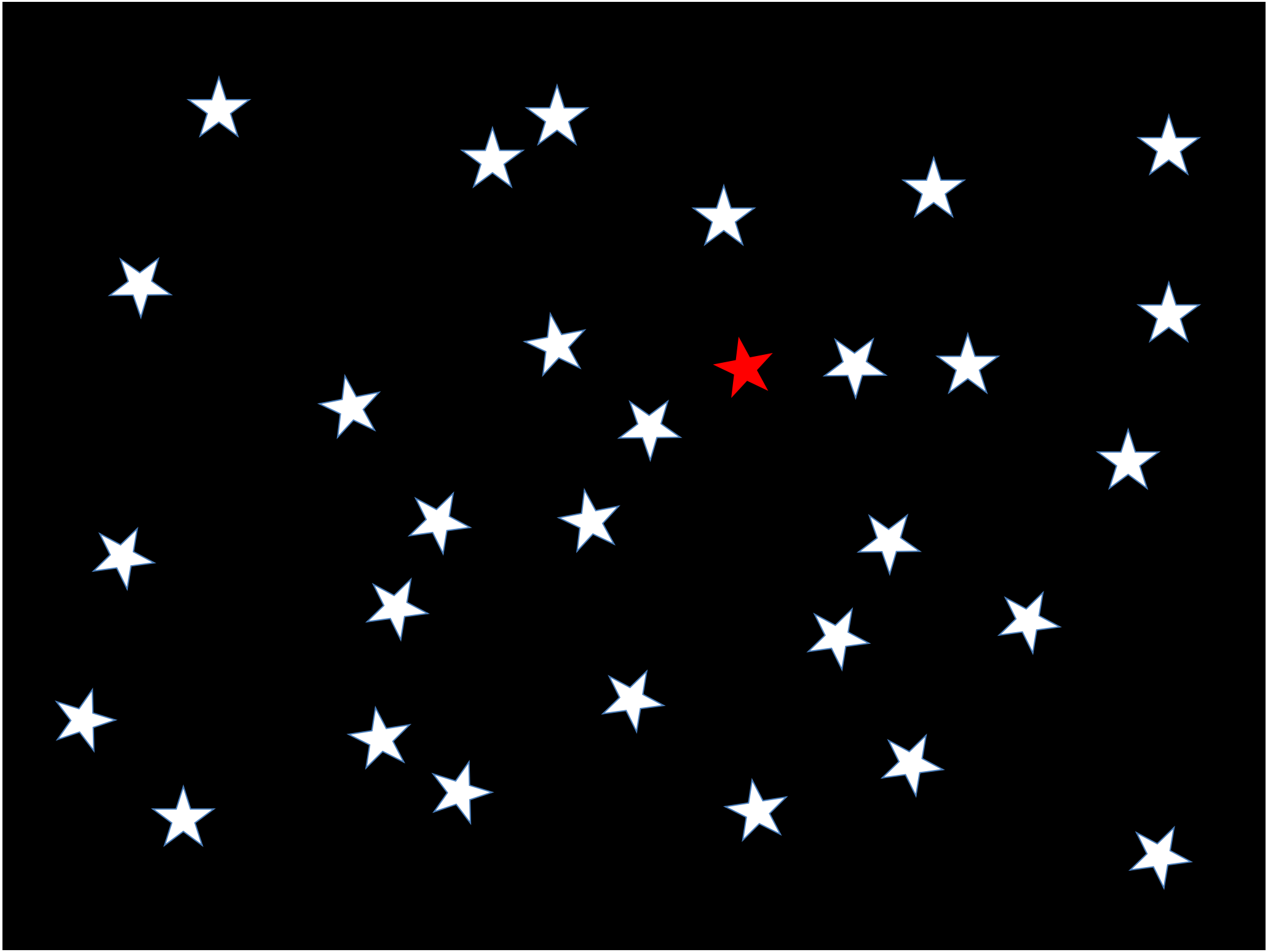
# Planets = “wandering stars”

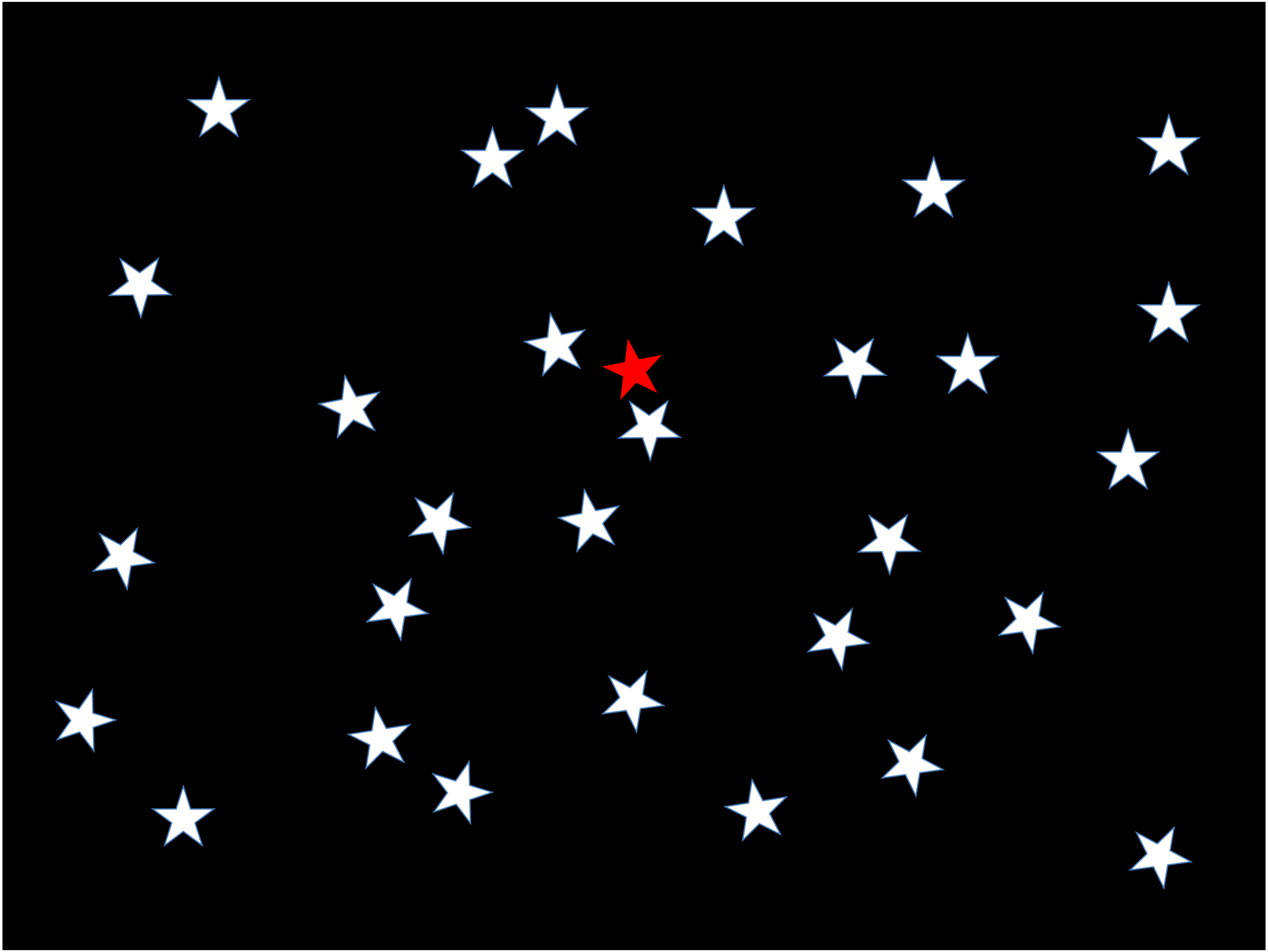
ancient Greeks noticed that planets appear to move across the sky without staying in their respective constellations.

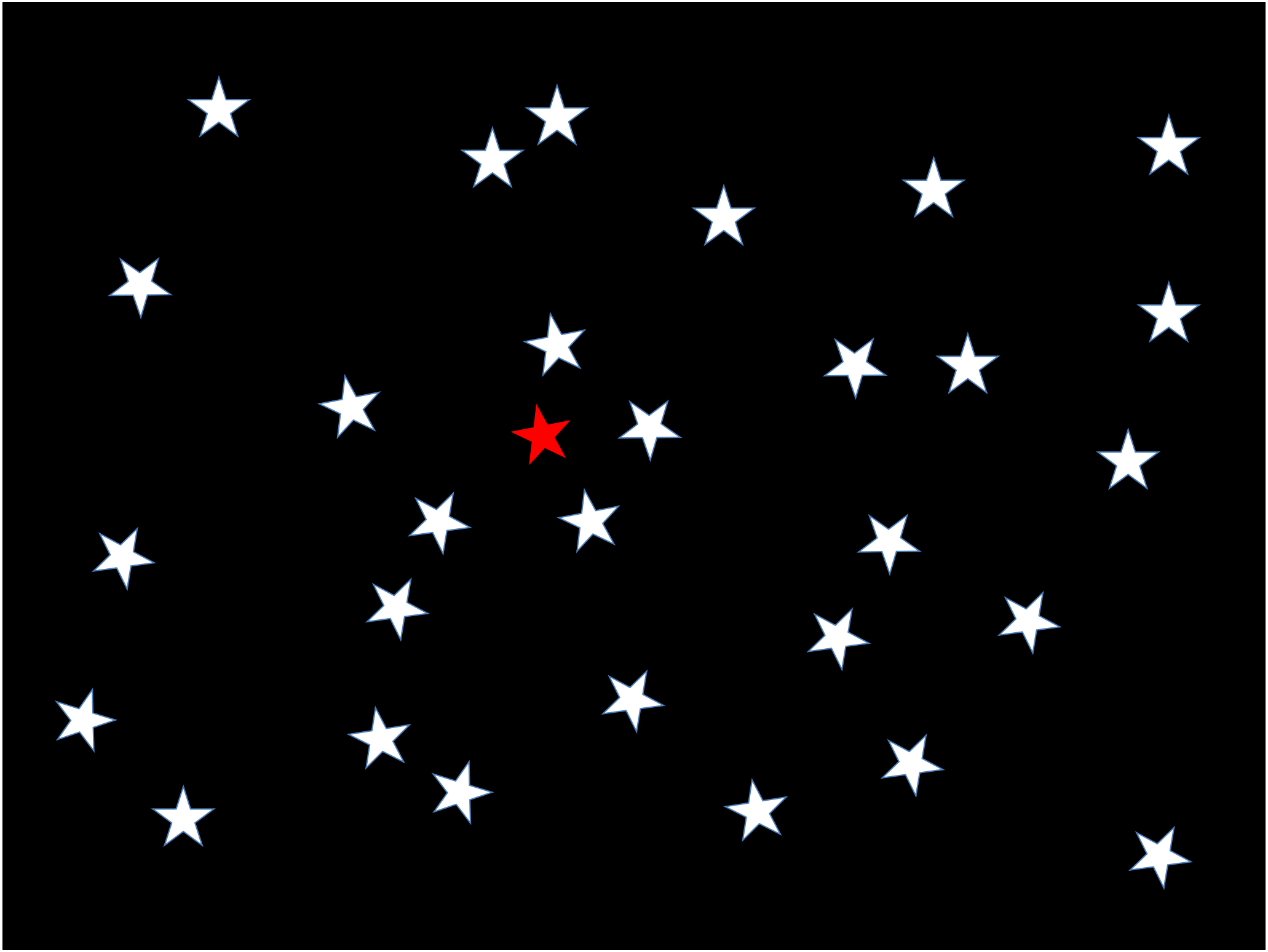


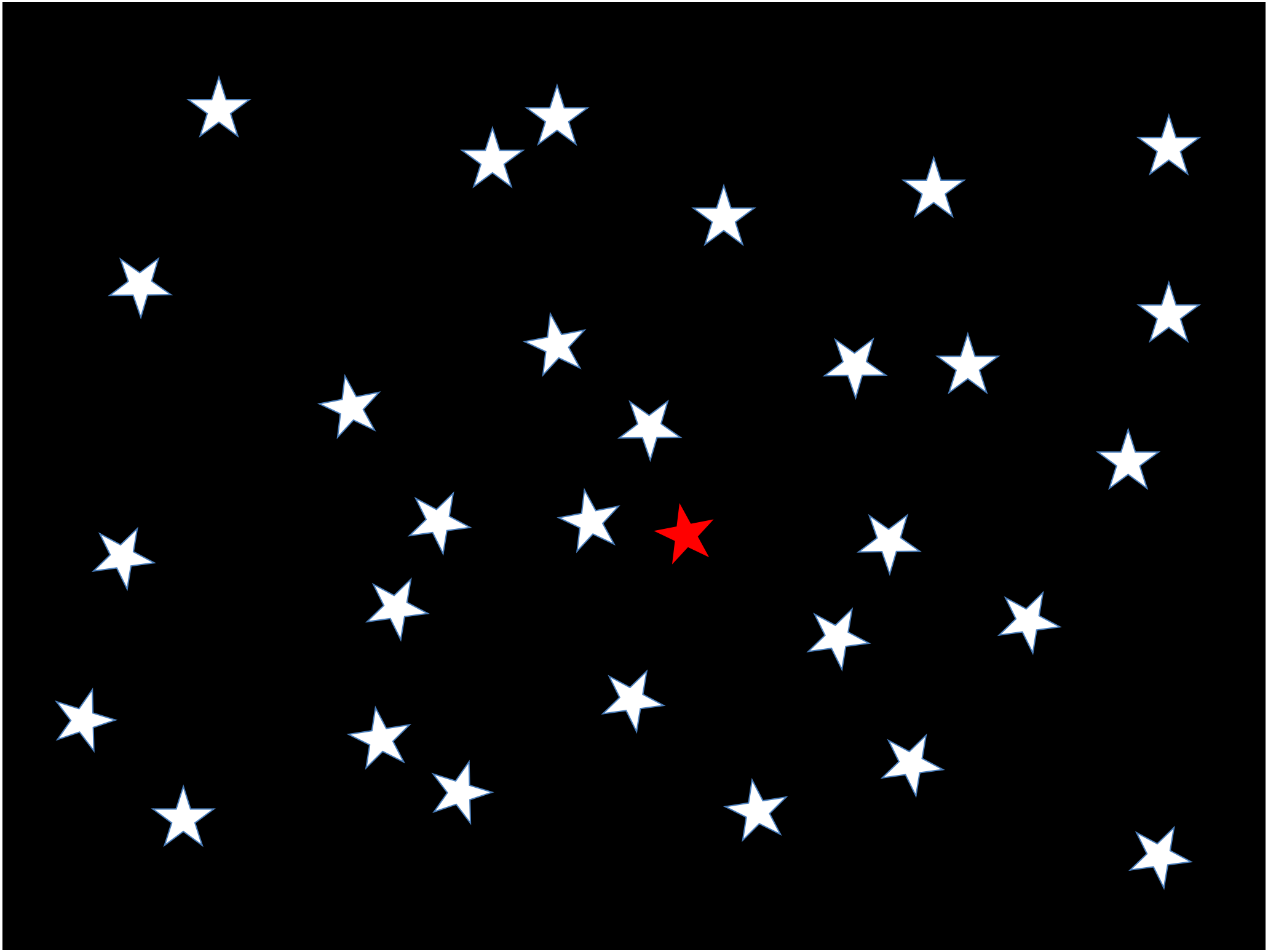


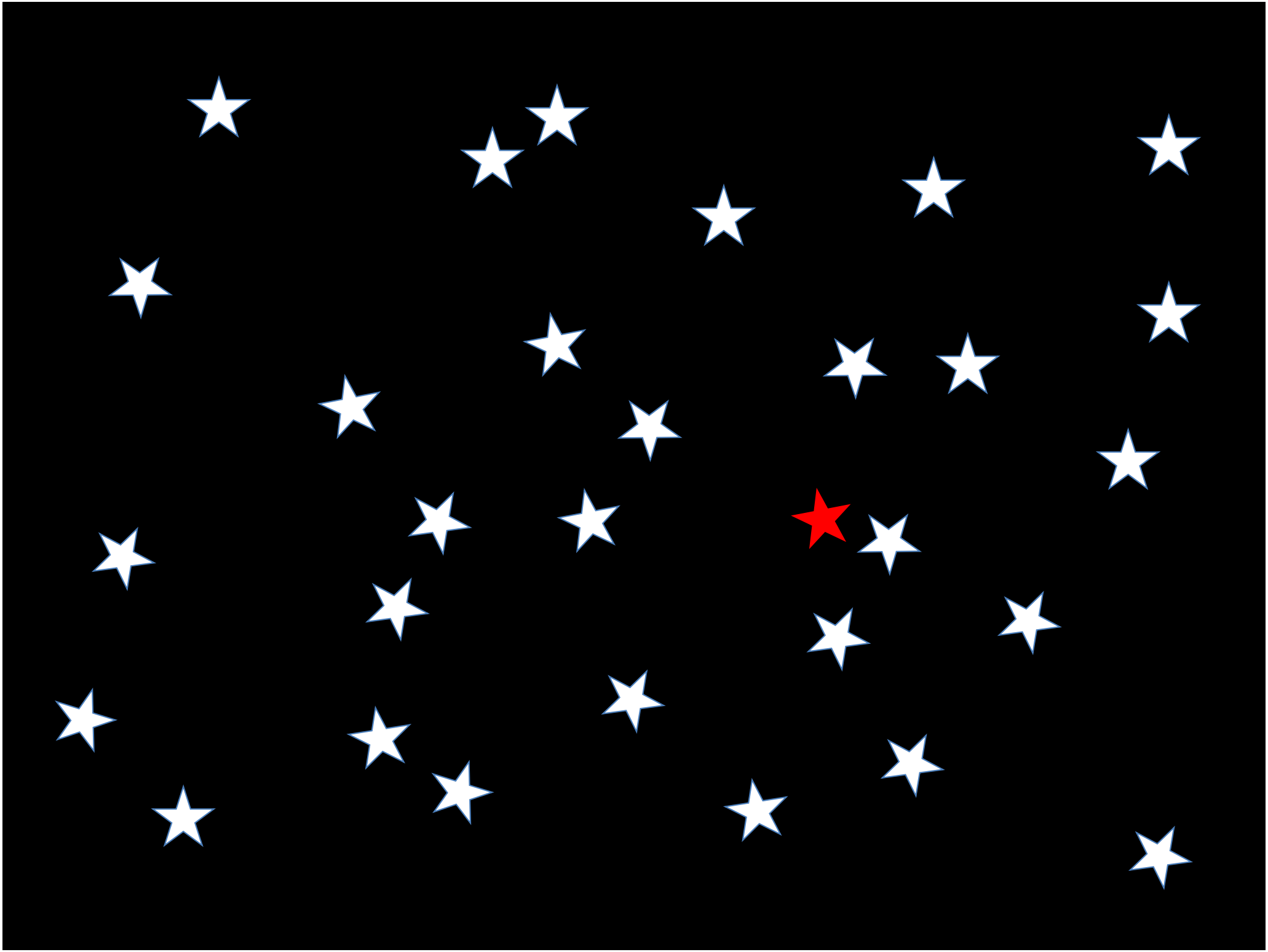


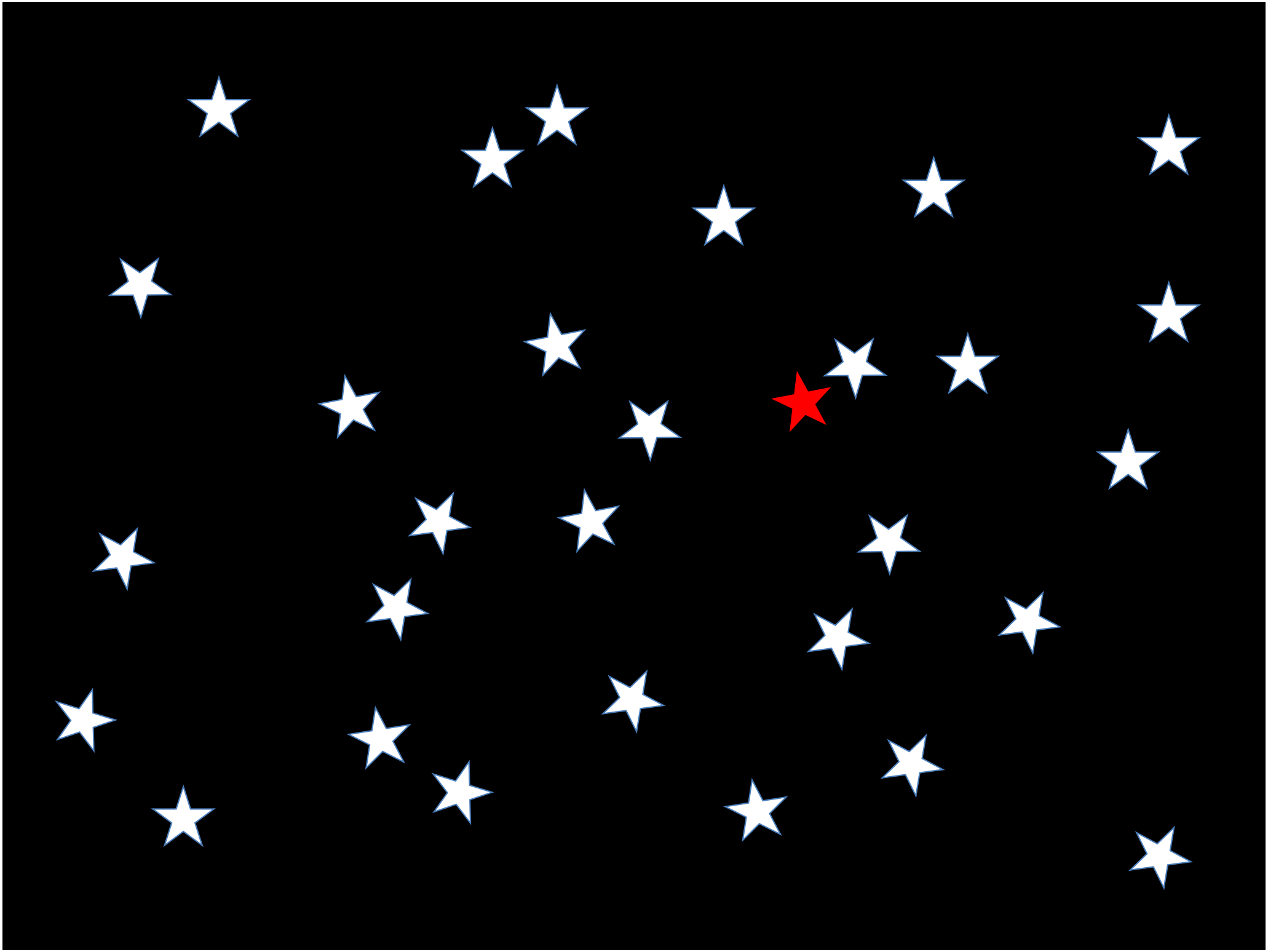


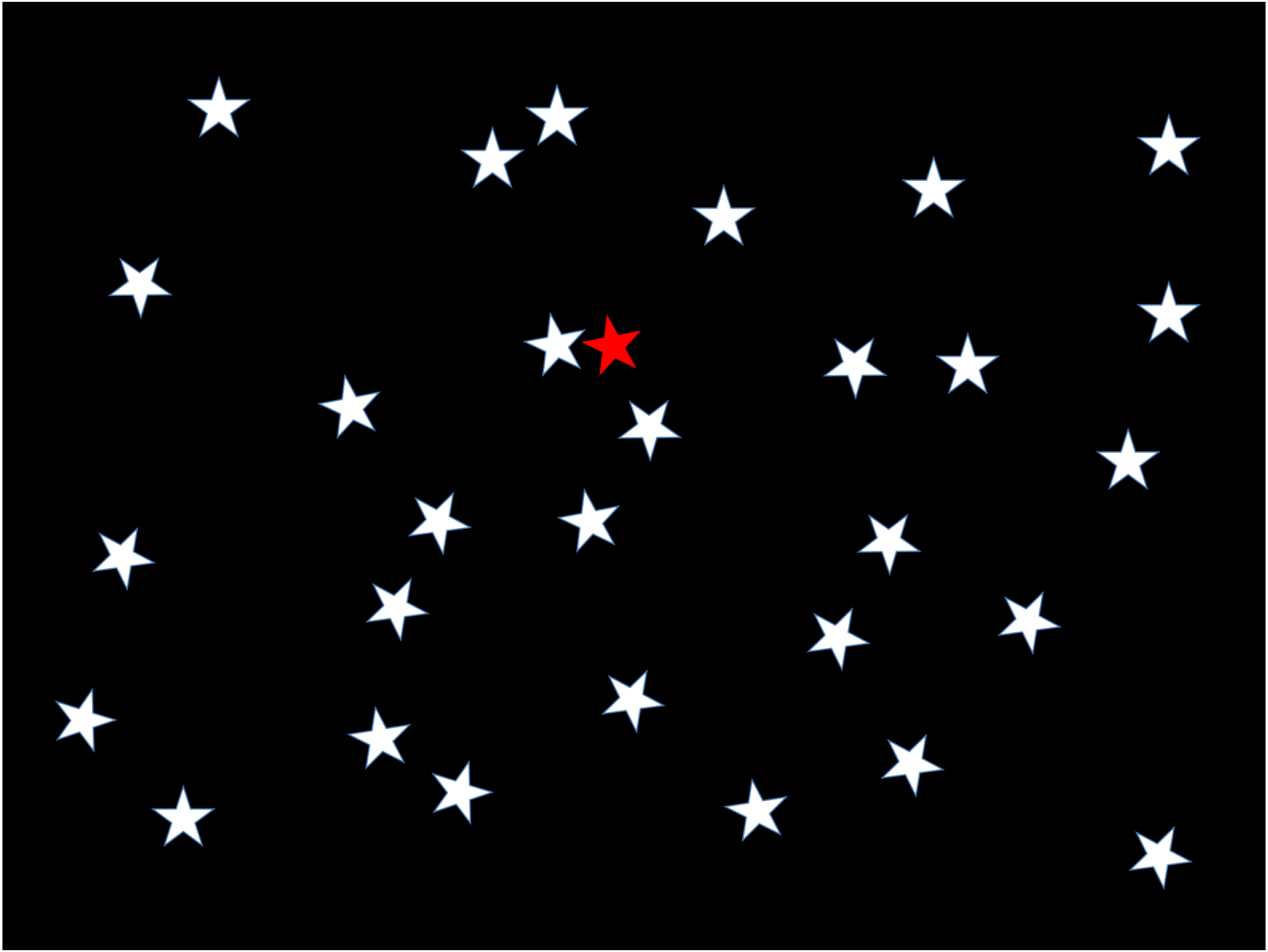


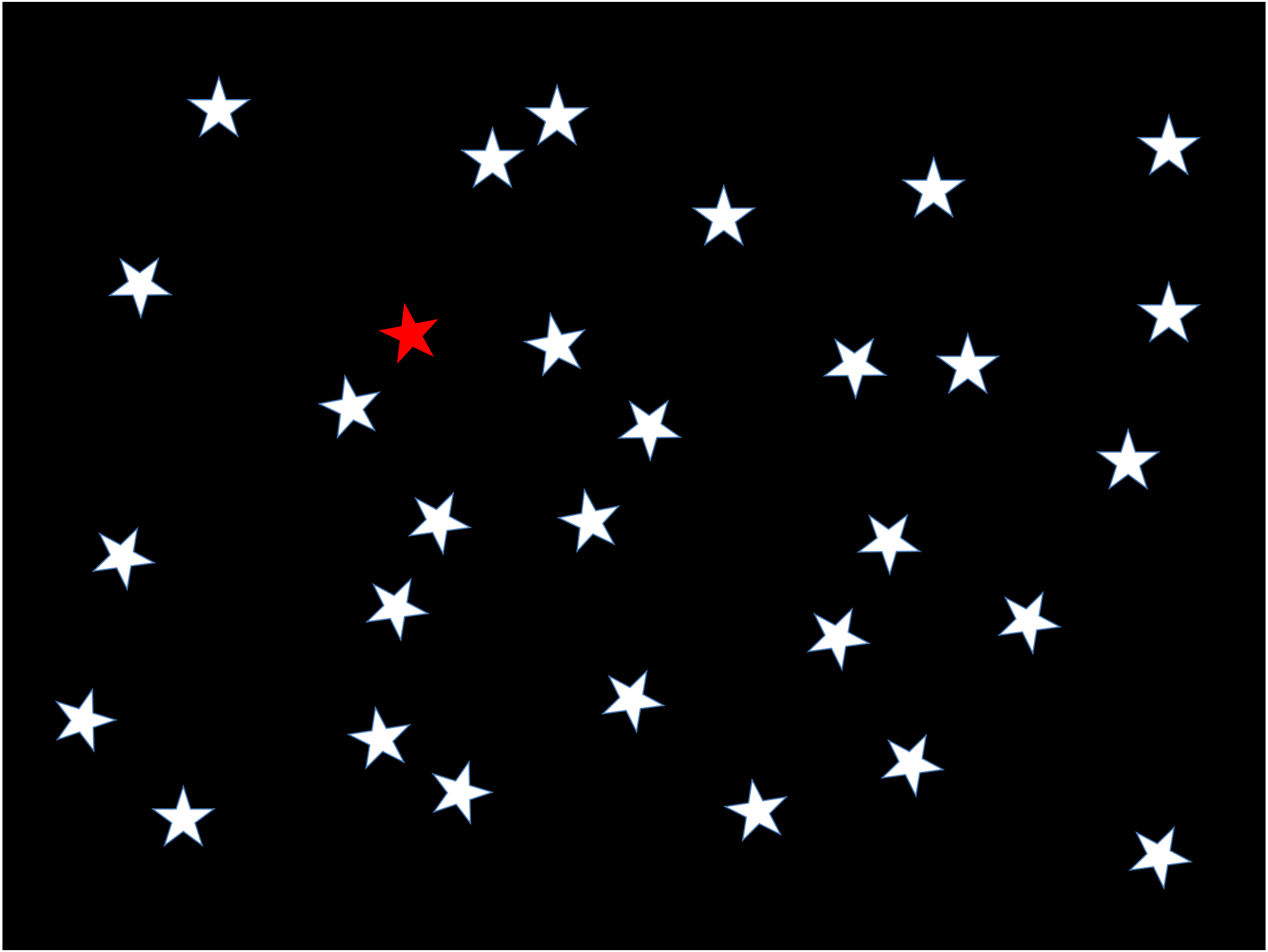


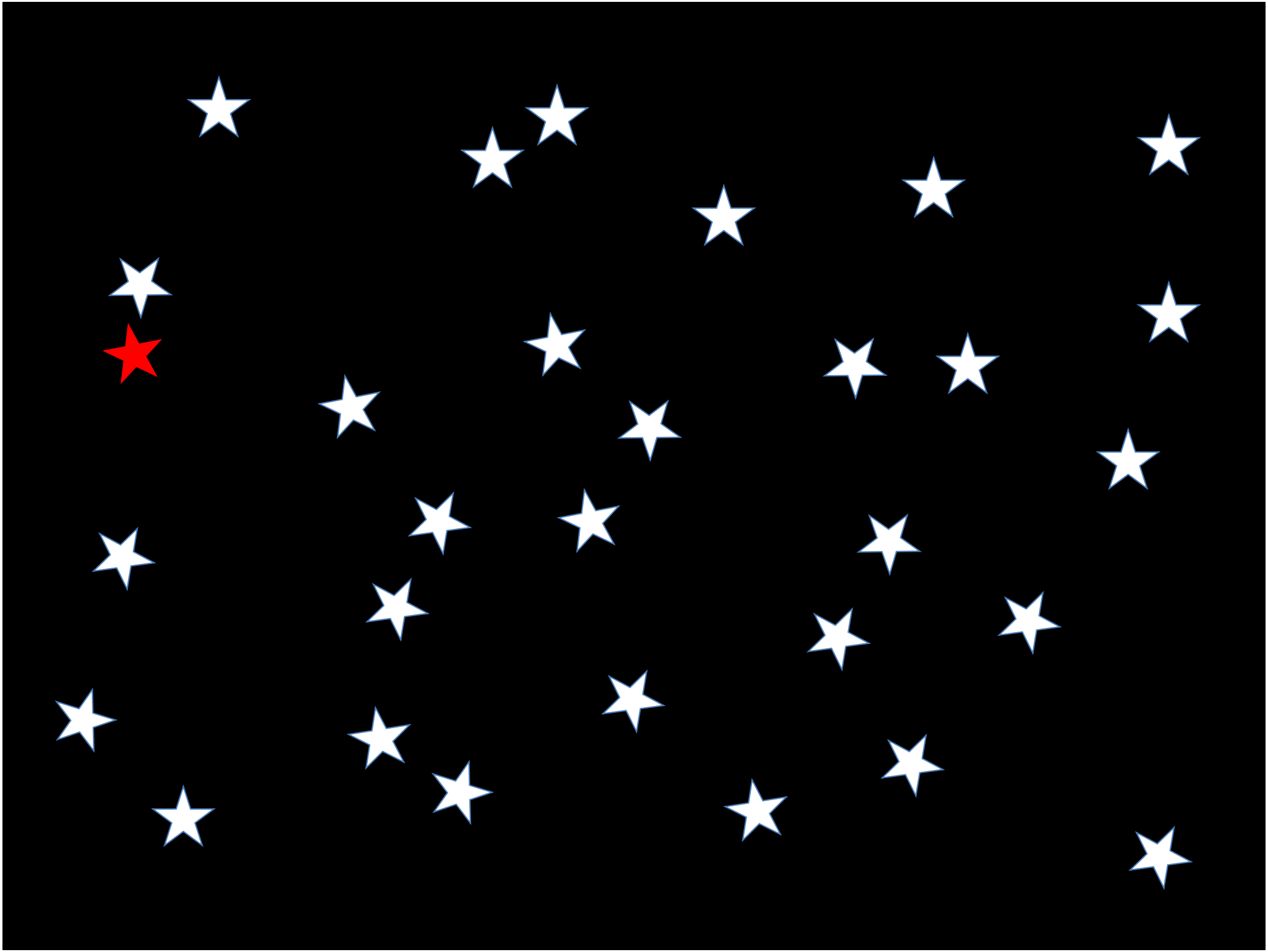


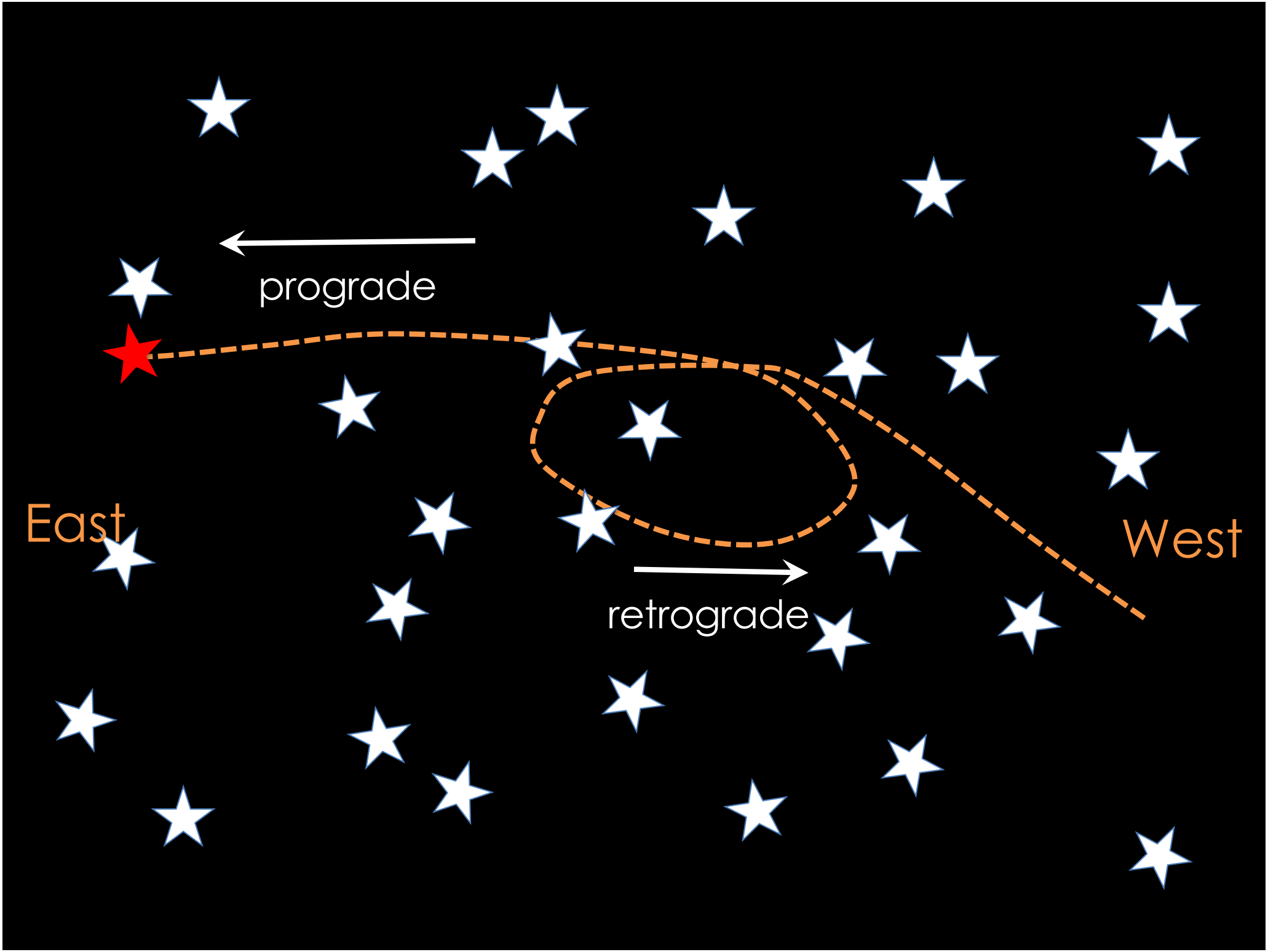




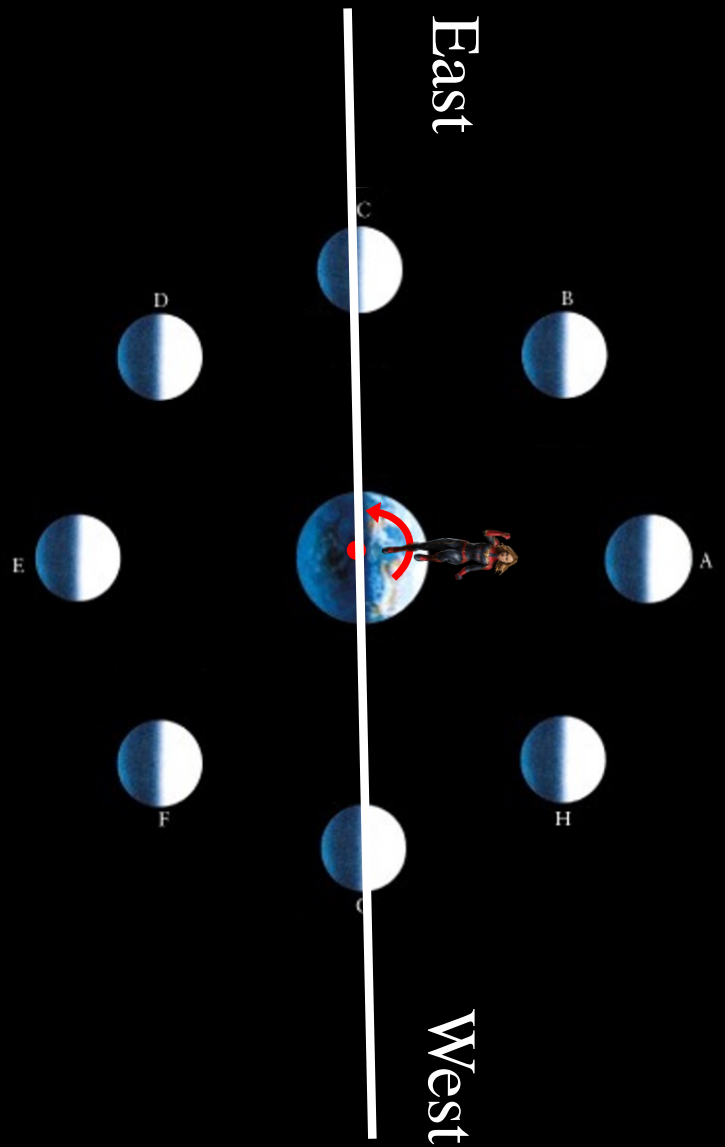







prograde
East
West
retrograde

# Remember:



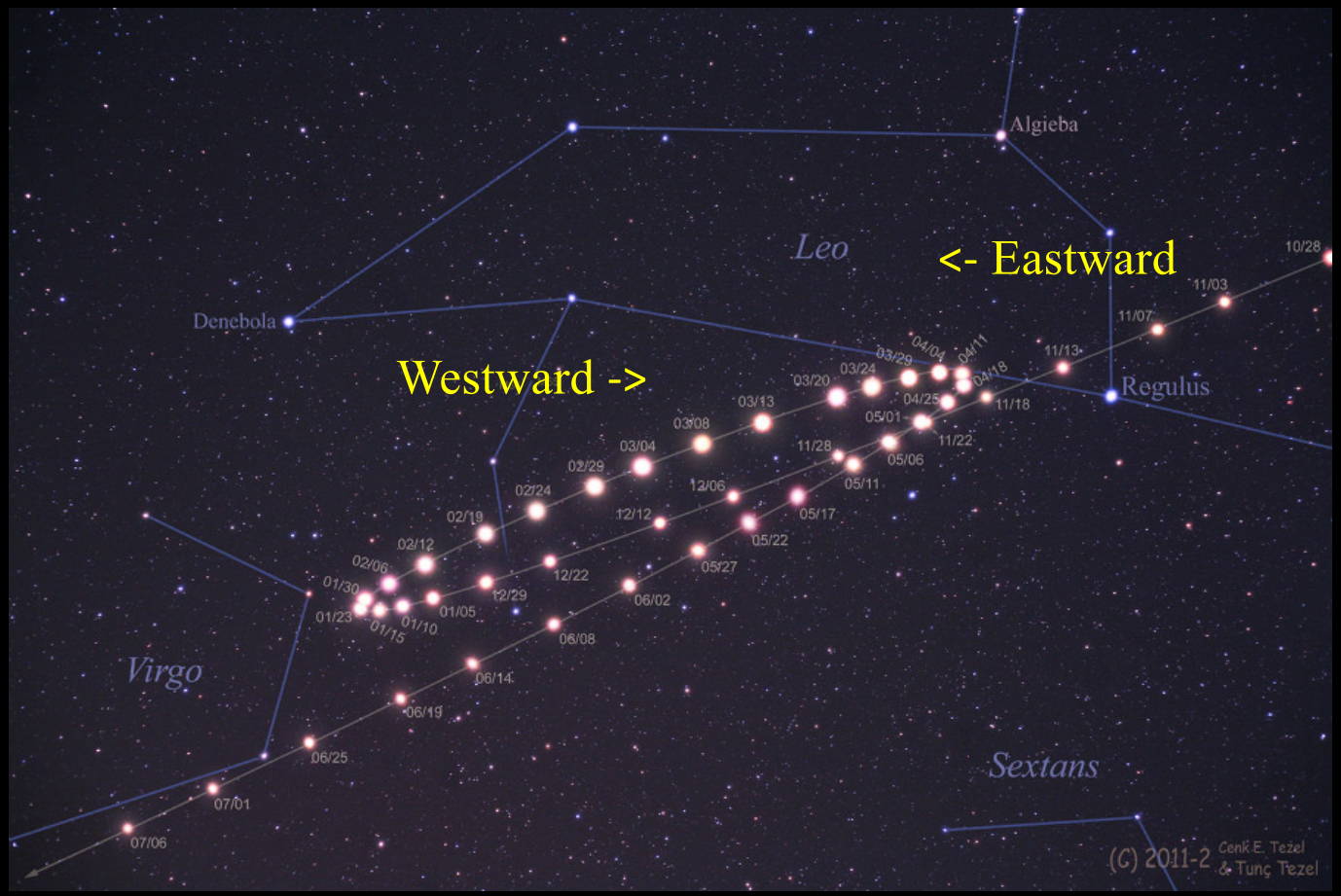

The moon moves W to E slowly, rising 50min later each night, because it orbits the Earth (prograde motion)

- **Prograde Motion** (normal motion): The apparent West to East motion (over many nights) of objects that go around the Earth.

- **Retrograde Motion**: The apparent East to West motion (over many nights) of other planets, which is not explained by the simplest geocentric system.

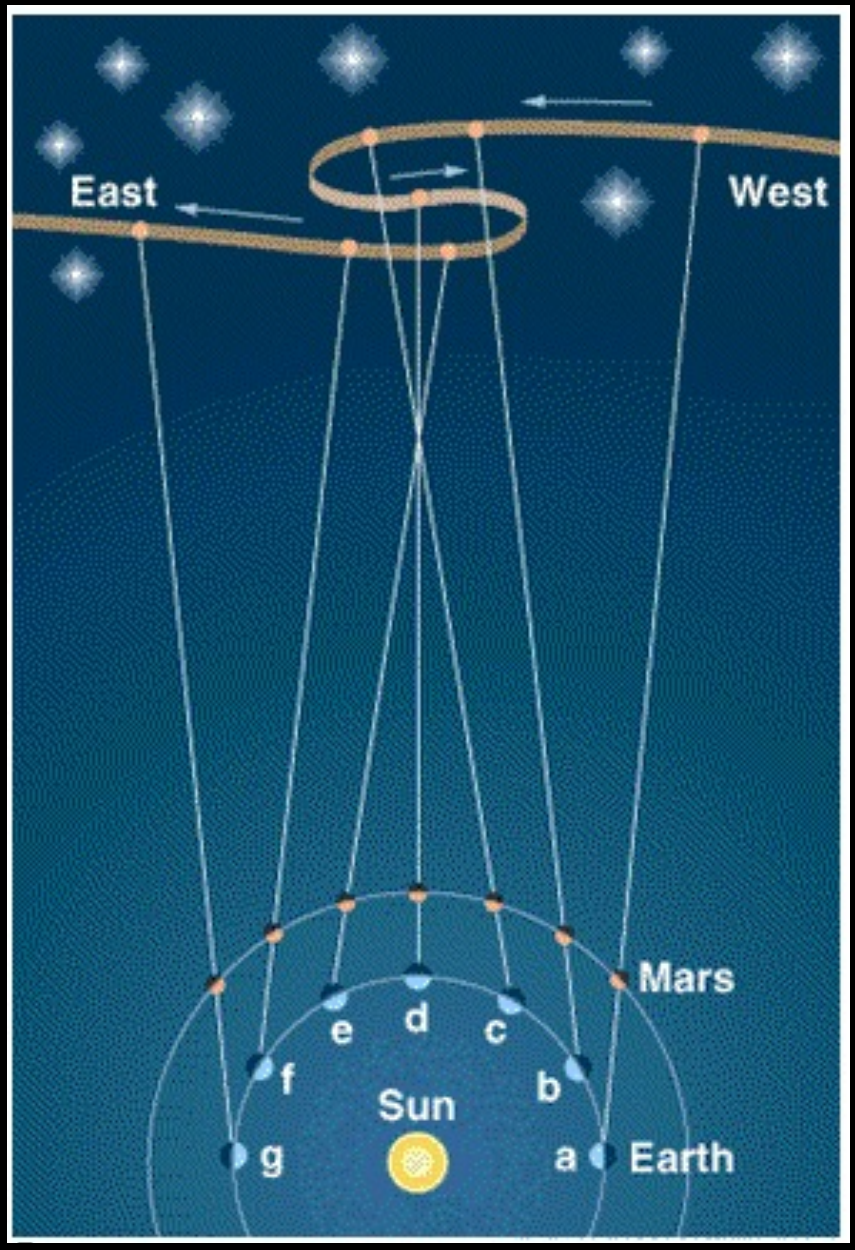
# Retrograde motion of Mars in the sky

Plato could ***not*** explain apparent retrograde motion of Mars, Jupiter, and Saturn.



Plato could ***not*** explain apparent retrograde motion of Mars, Jupiter, and Saturn. Geocentric system needs epicycles.

But heliocentric system can do it simply.

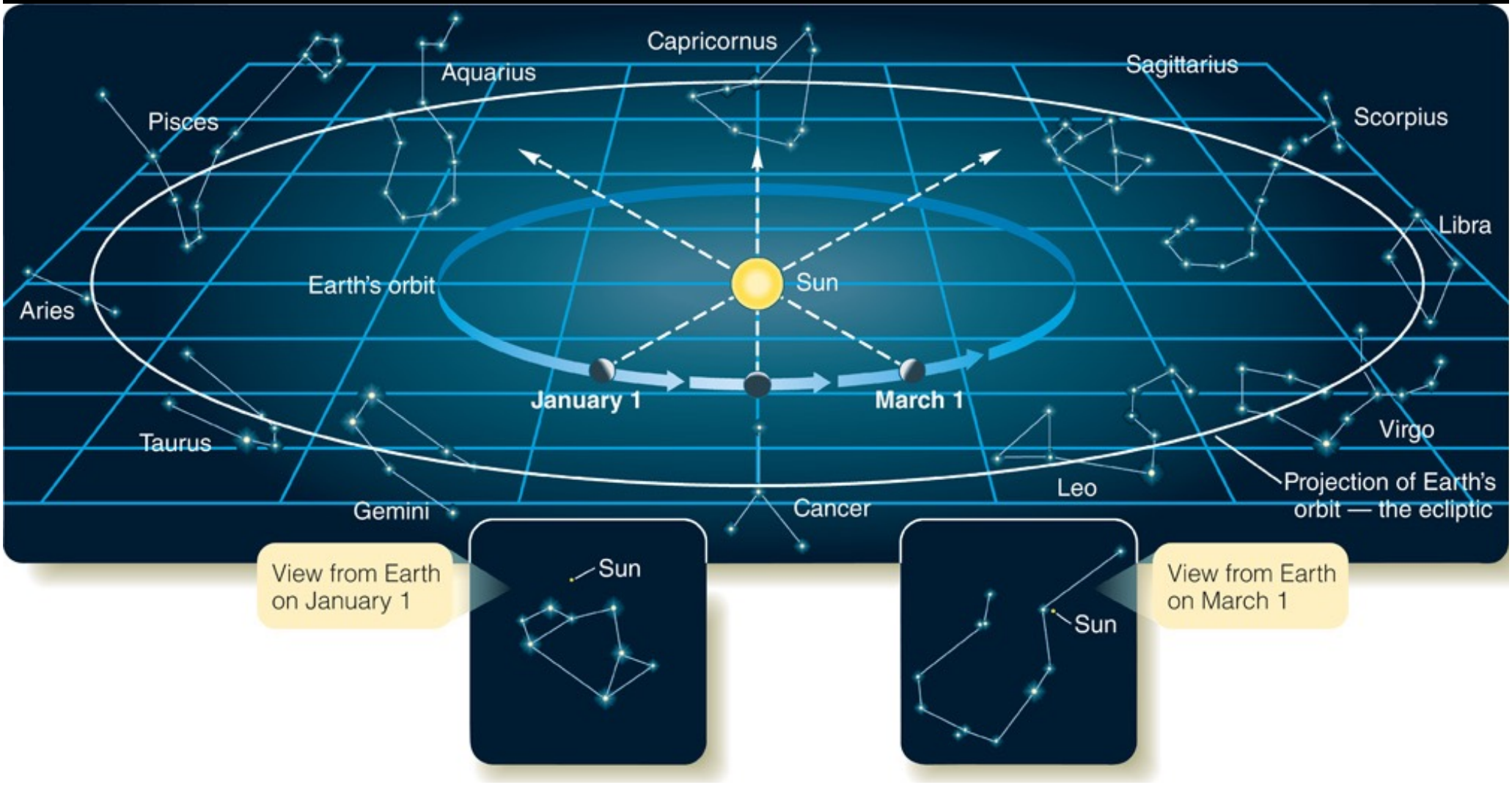


# Measuring distances to stars

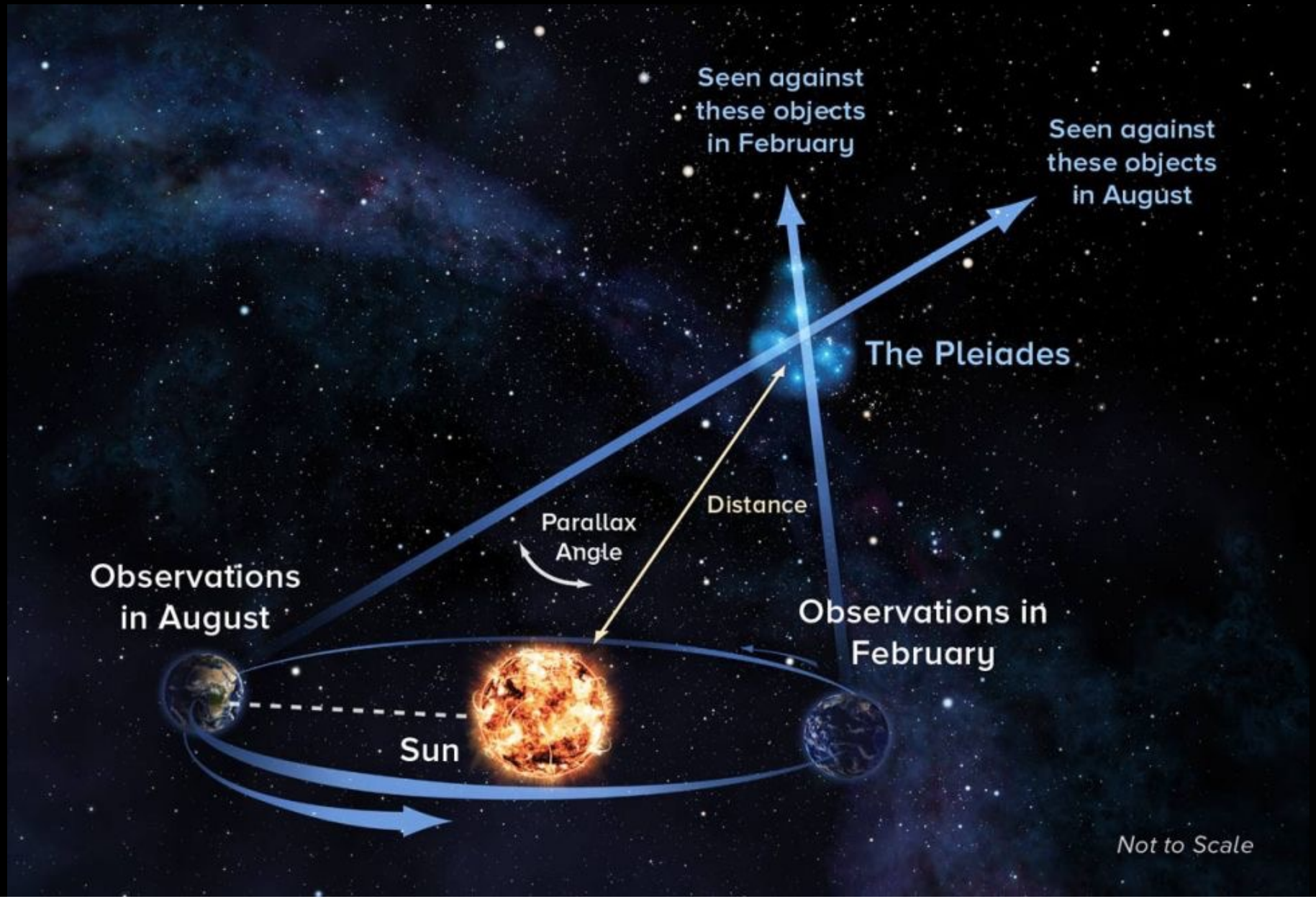
# Parallax

Parallax is a displacement in the apparent position of an object viewed along two different lines of sight.

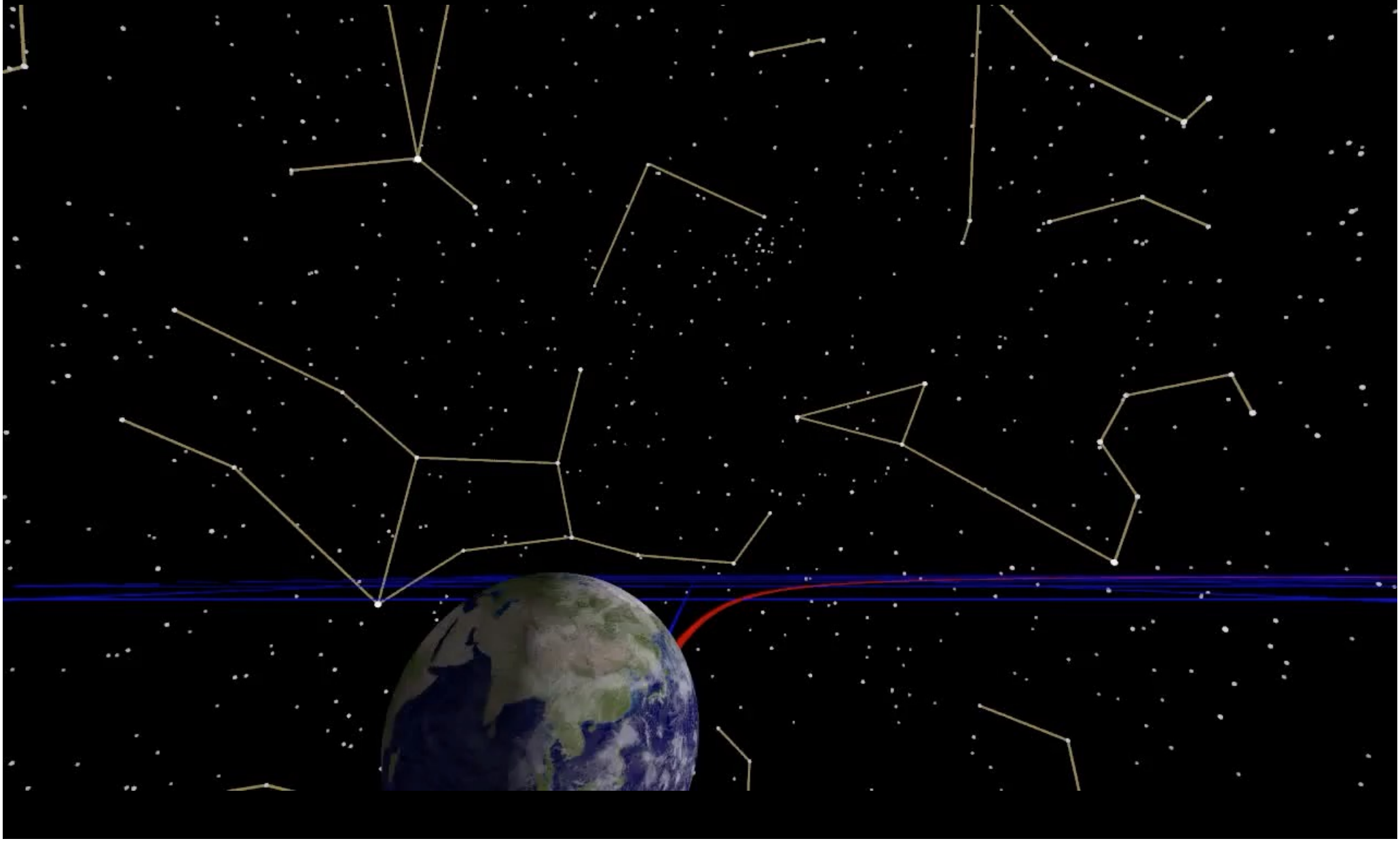
# Sun's parallax



# Stellar Parallax



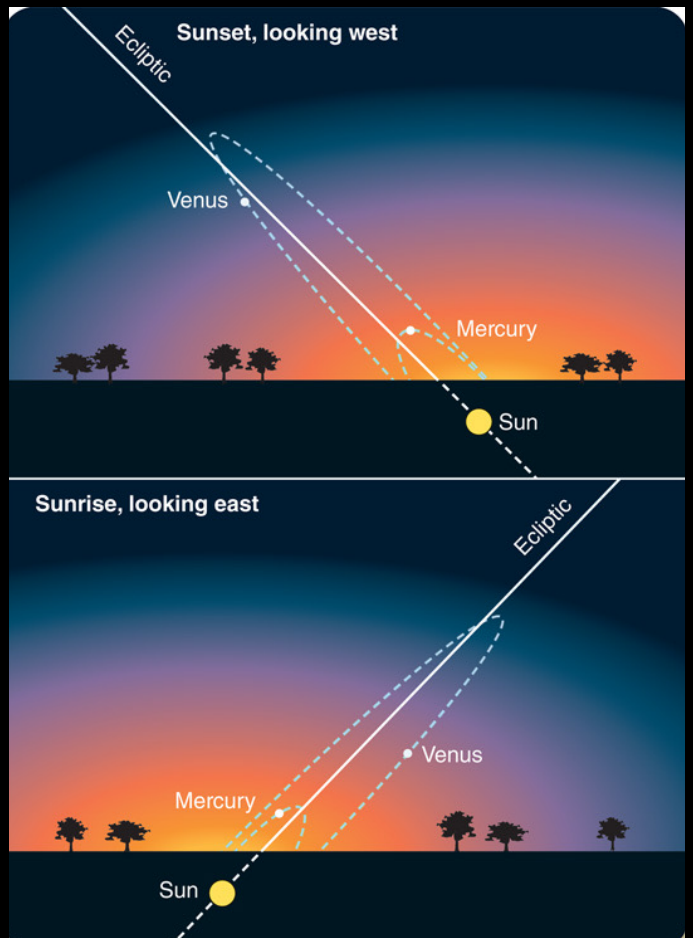
# Stellar Parallax

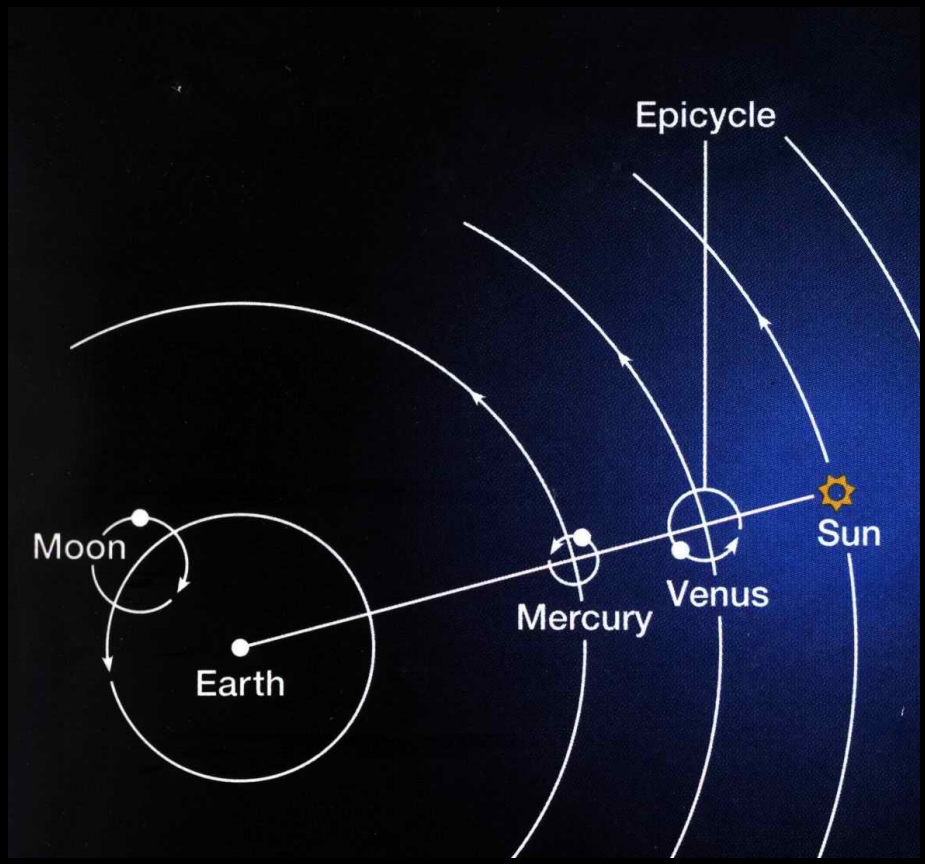


# Mercury and Venus

Mercury and Venus always appear close to the Sun. Ptolemy tied their epicycles to a line stretching from the Earth to the Sun.

In heliocentric system, they are close to the Sun because they are inside of Earth's orbit.

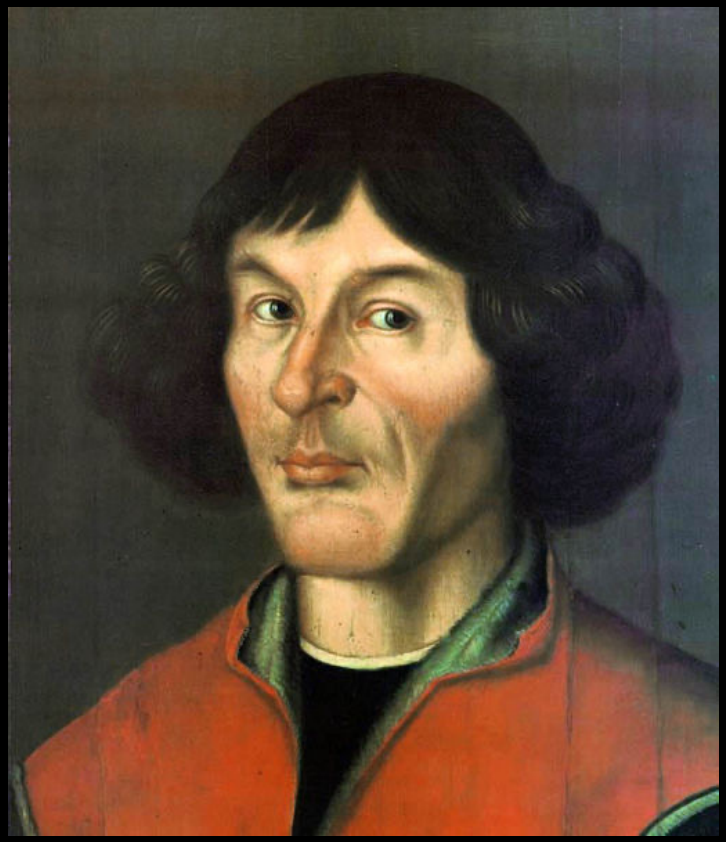


# Rise of modern astronomy

# Nicholas Copernicus
(1473 – 1543)

- Polish polymath (astronomer, astrologist, medical doctor, mathematician, priest)
- Influenced by the work of **Aristarchus** and his own observations.
- Proposed the **Sun as the center of the universe**, but assumed perfect uniform circular orbits, still needed epicycles (though fewer per planet).

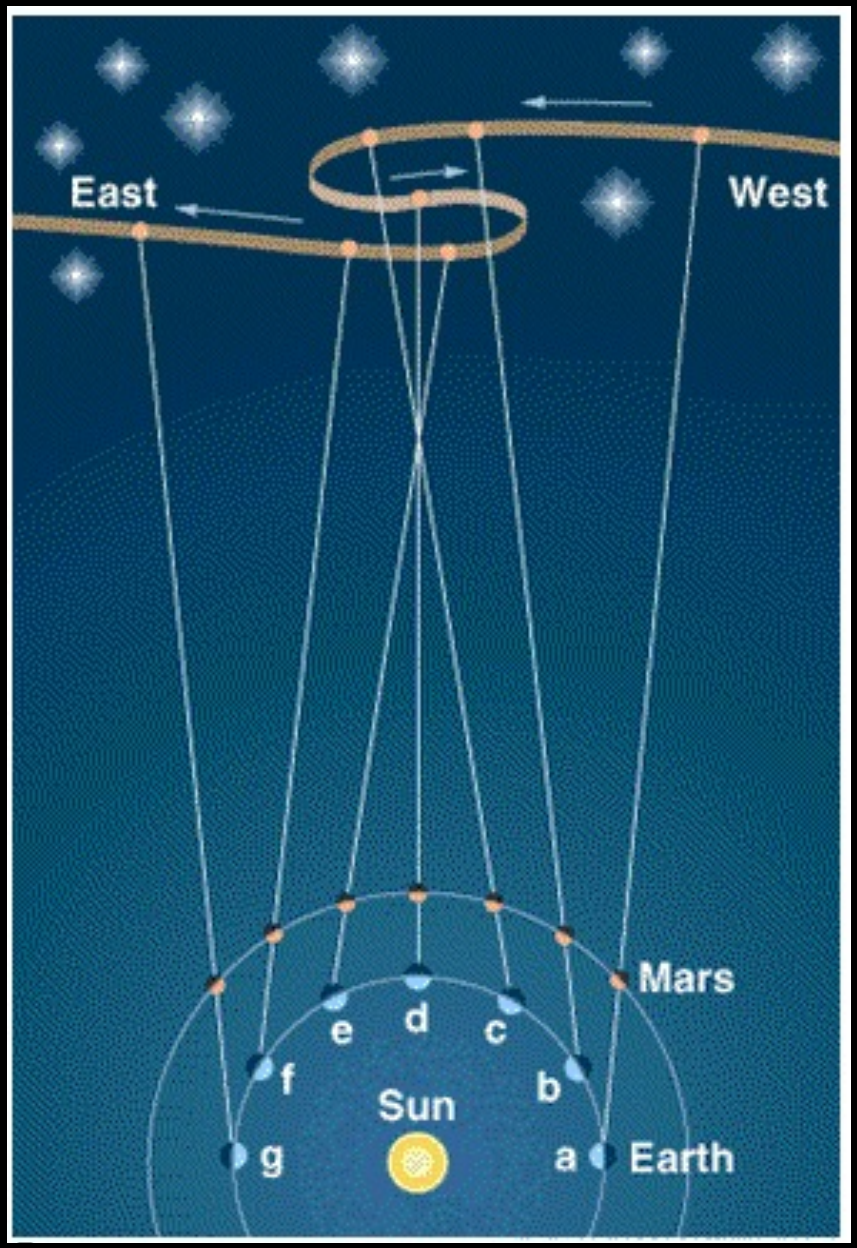


## Nicholas Copernicus
(1473 – 1543)

***De revolutionibus orbium coelestium*** (On the Revolutions of the Celestial Spheres) was published just after he died, presenting his Heliocentric model.

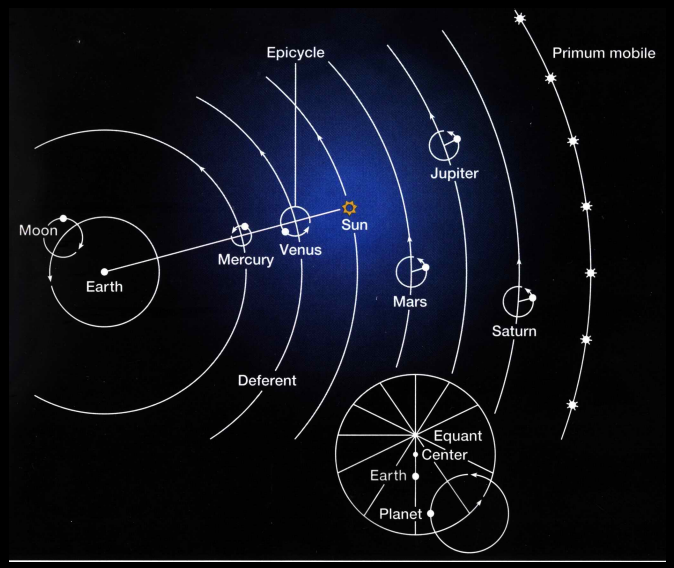
# Copernican System

- Explained retrograde motion: Inner planets move faster, catching up and passing slower outer planets.
- Explained the appearance of Mercury and Venus as **morning and evening stars**.
- Could not explain non-uniform motion without using epicycles…

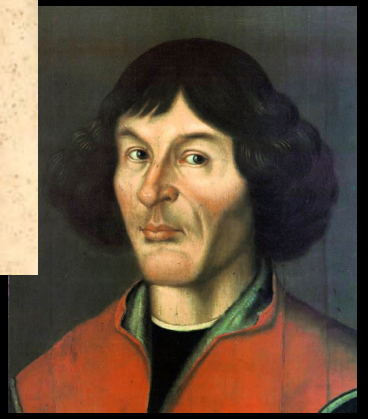


# Who would you trust?

A) Ptolemy

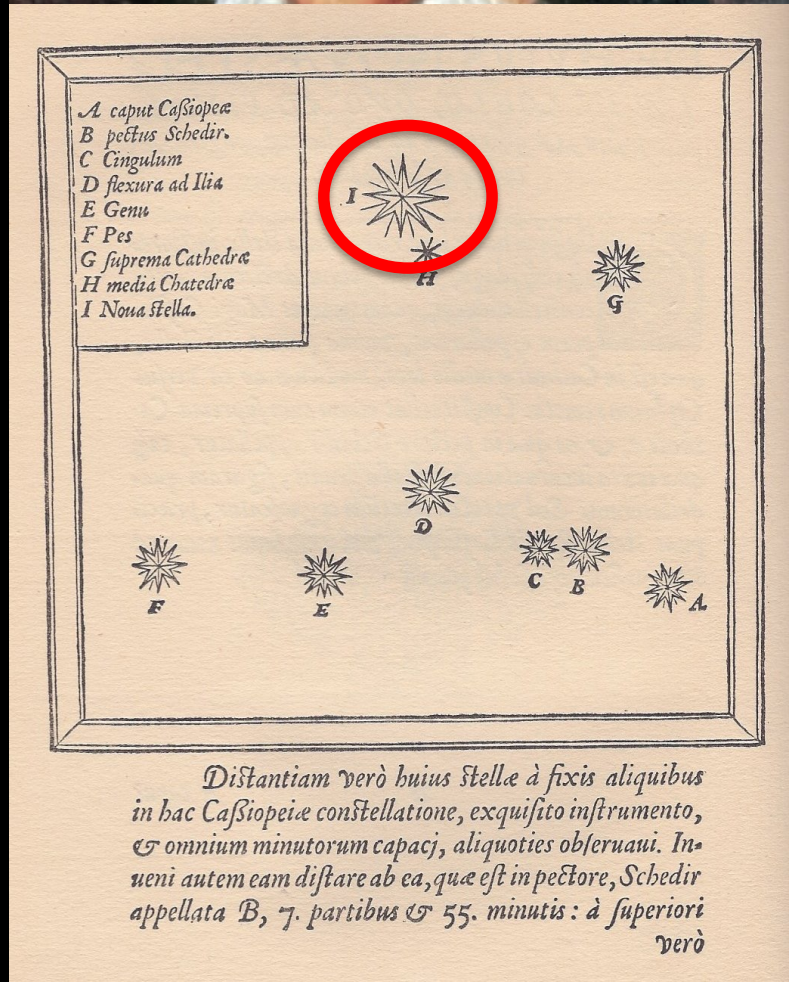



B) Copernicus



# Tycho Brahe
(1546– 1601)

- Danish nobleman with a passion for astronomy.
- Had the most detailed and **accurate observations** of planetary motion.
- Observed supernova of 1573 and refuted Aristotle's claim of an unchanging "Heavens."

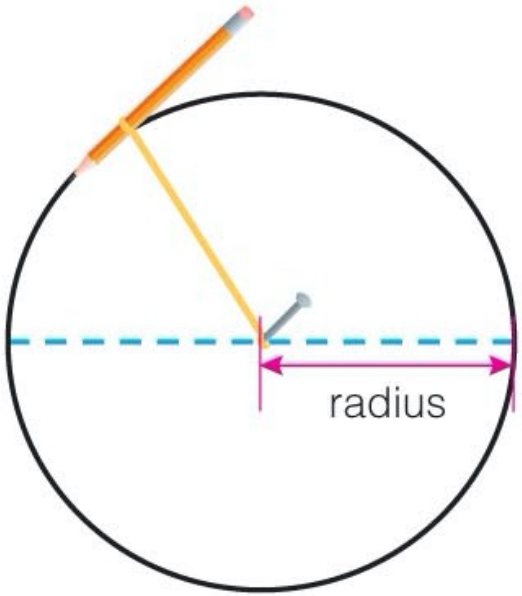


# Johannes Kepler
(1571 – 1630)

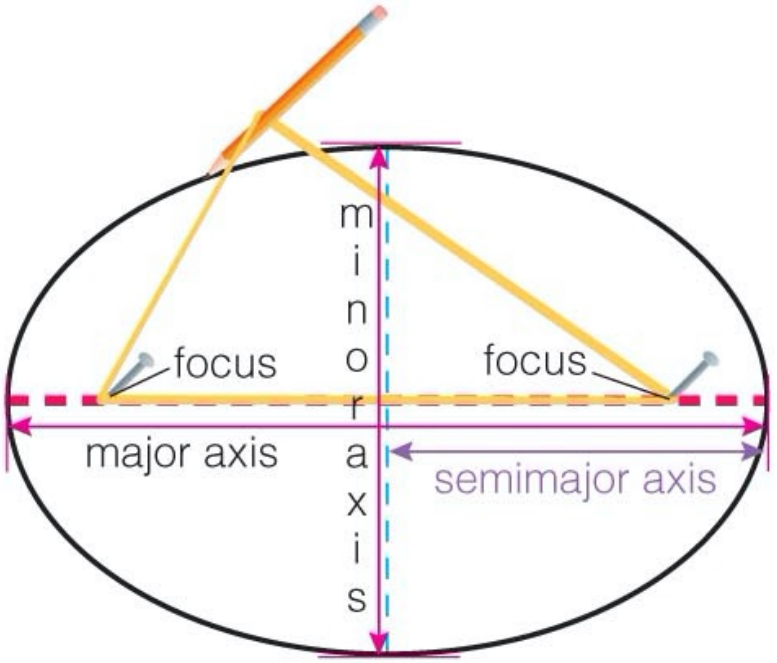
- German astronomer, astrologist, mathematician
- Hired by Tycho Brahe to make sense of his very precise observations of planetary motion.
- Initially hung up on spherical symmetry of the solar system.
- Finally realized planetary **orbits were elliptical.**

# Kepler's Laws

# Circle vs. Ellipse



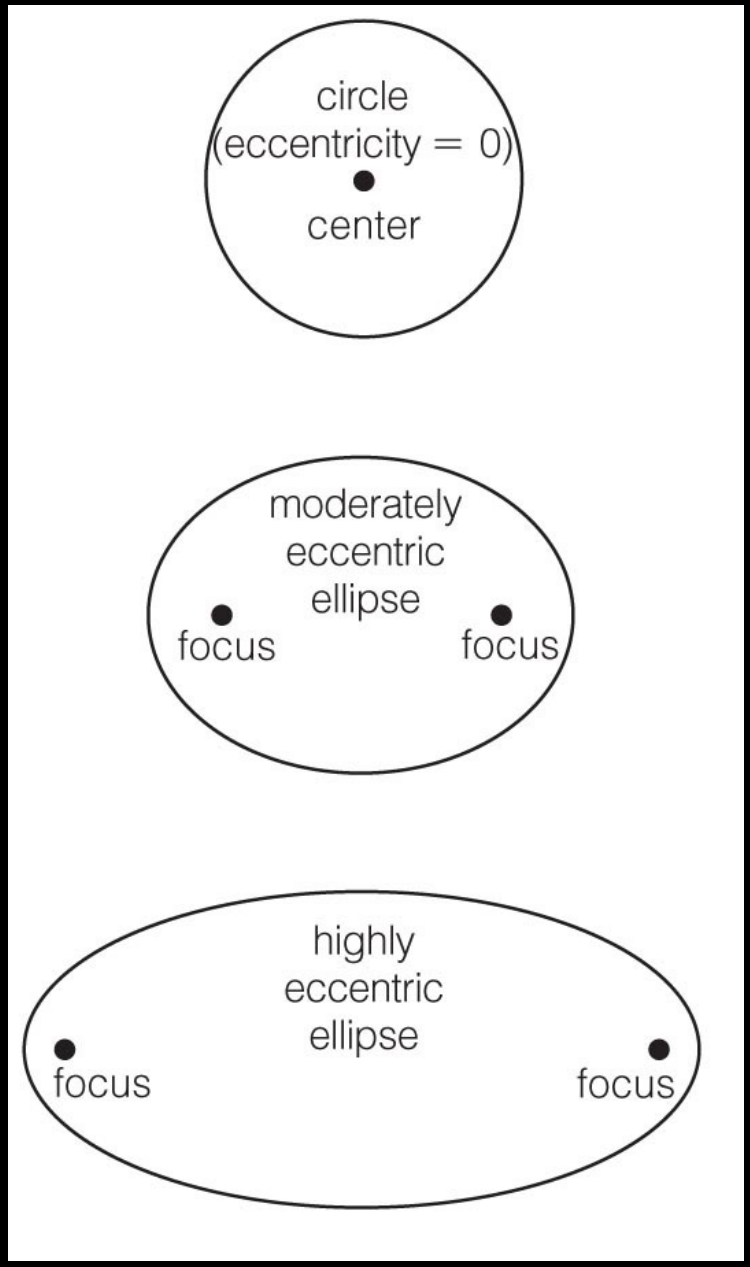

**a** Drawing a circle with a string of fixed length.




**b** Drawing an ellipse with a string of fixed length.

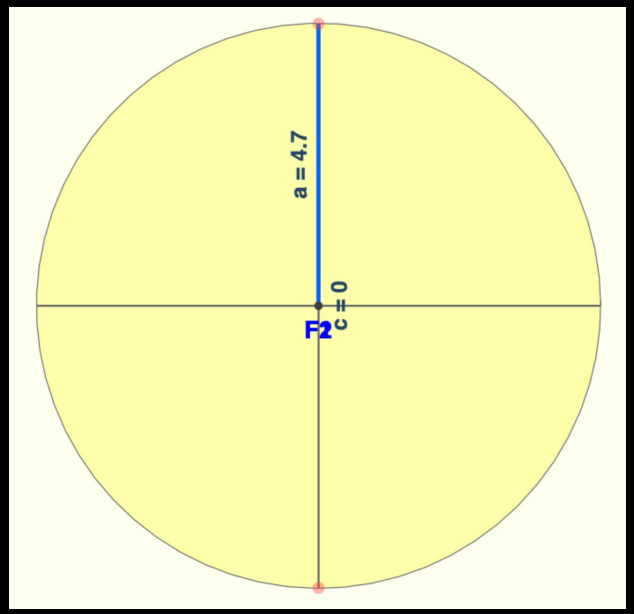
# Eccentricity

- Eccentricity is a measure of **how elongated** is the ellipse, it's a number between 0 and 1.
- A circle has eccentricity zero.

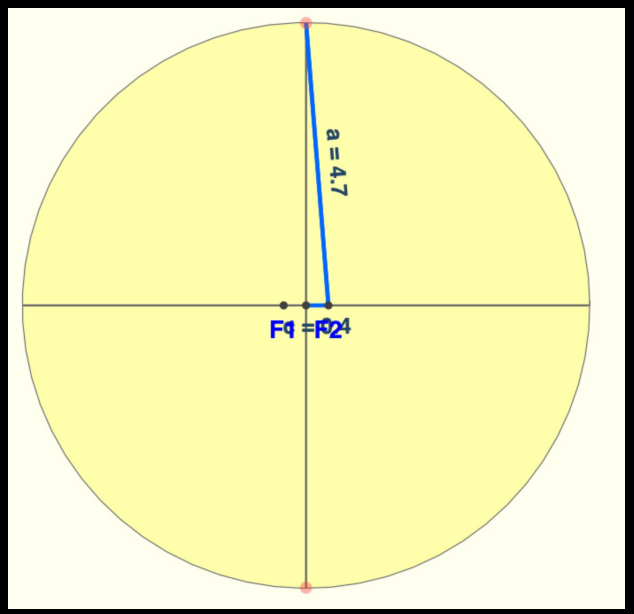


# Eccentricity

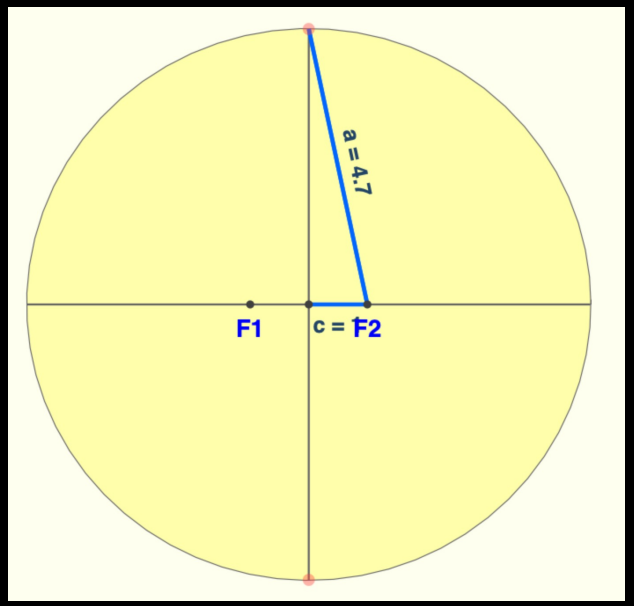
- Earth's orbital eccentricity is 0.0167.
- Mercury (0.2056) and Mars (0.0934) are planets with most eccentric orbits.




Circle




Mars (0.09)

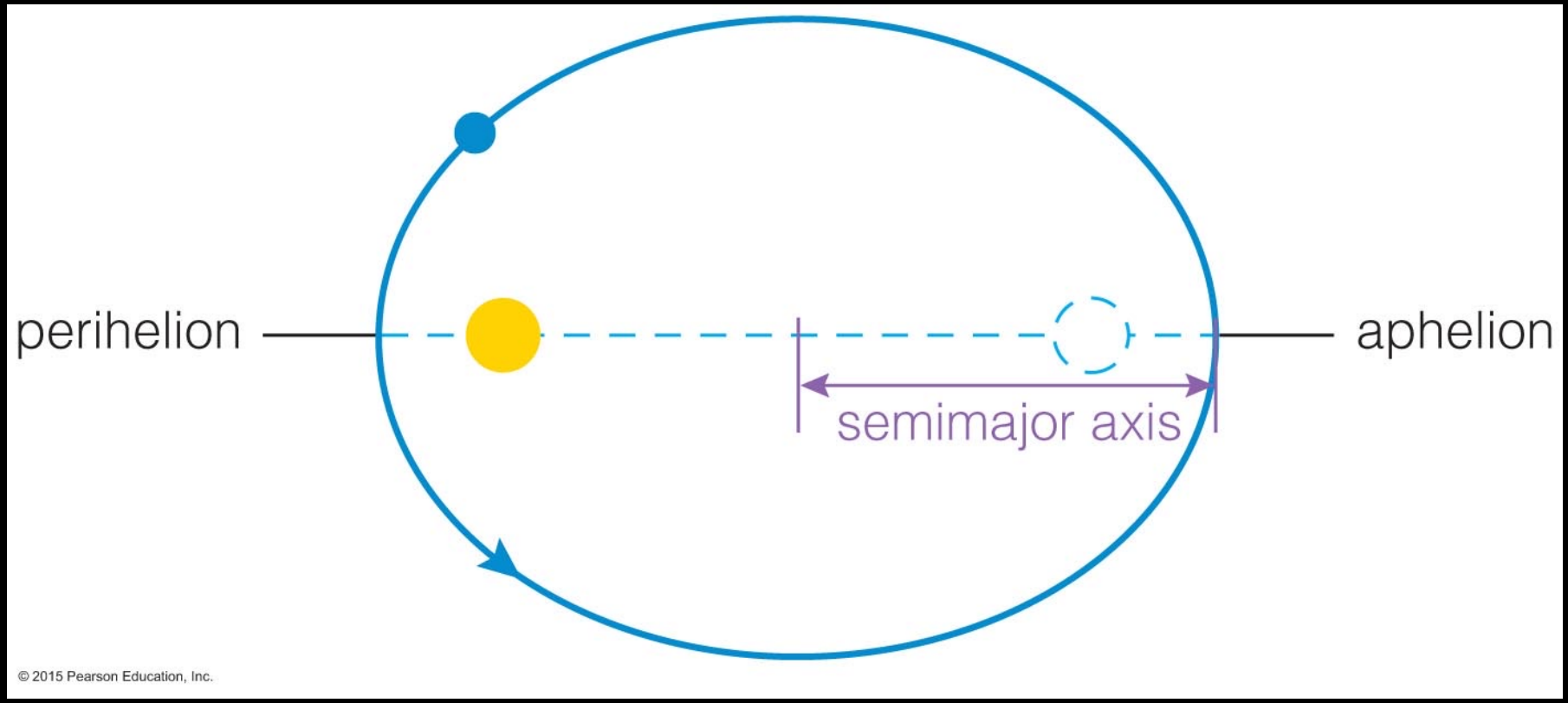



Mercury (0.21)

# Kepler's Laws of Planetary Motion

First Law:

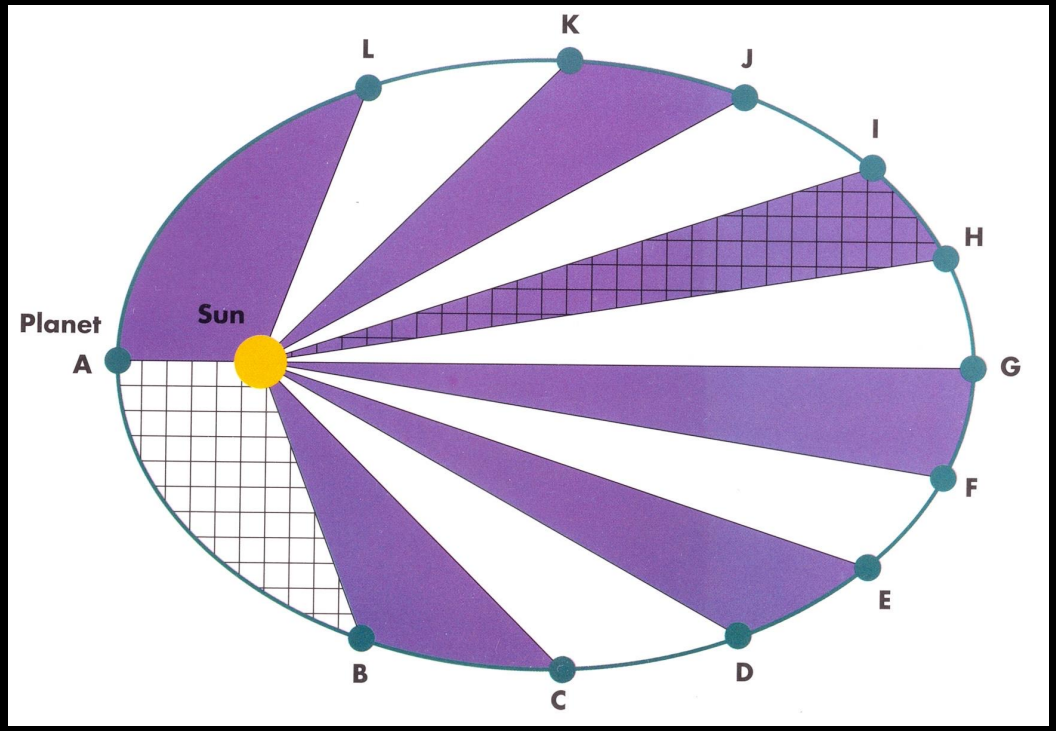
The orbit of each planet around the Sun is an ellipse with the Sun at one focus.



# Kepler's Laws of Planetary Motion

<u>Second Law:</u>

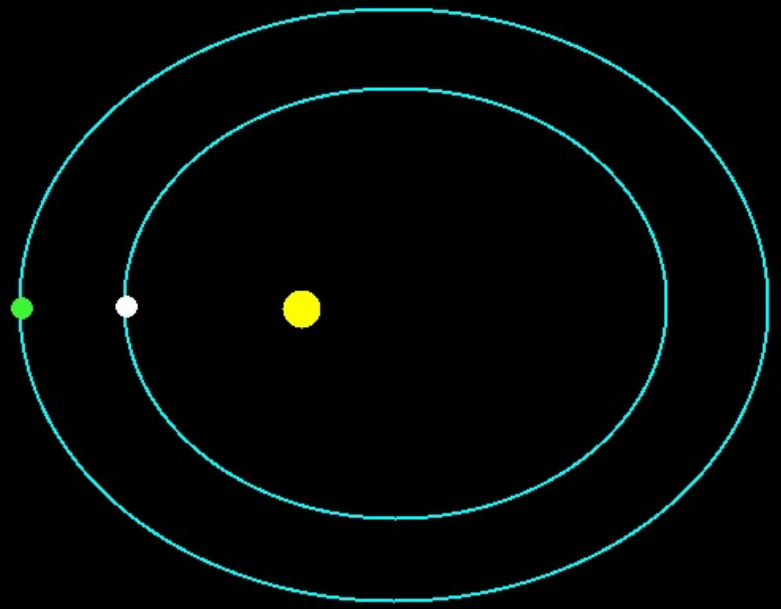
As a planet moves around the Sun in its orbit, it sweeps out equal areas in equal times.



# Kepler's Laws of Planetary Motion

<u>Third Law:</u>

Period and semi-major axis are related (the farther away it is, the slower it orbits): $p^2 = a^3$



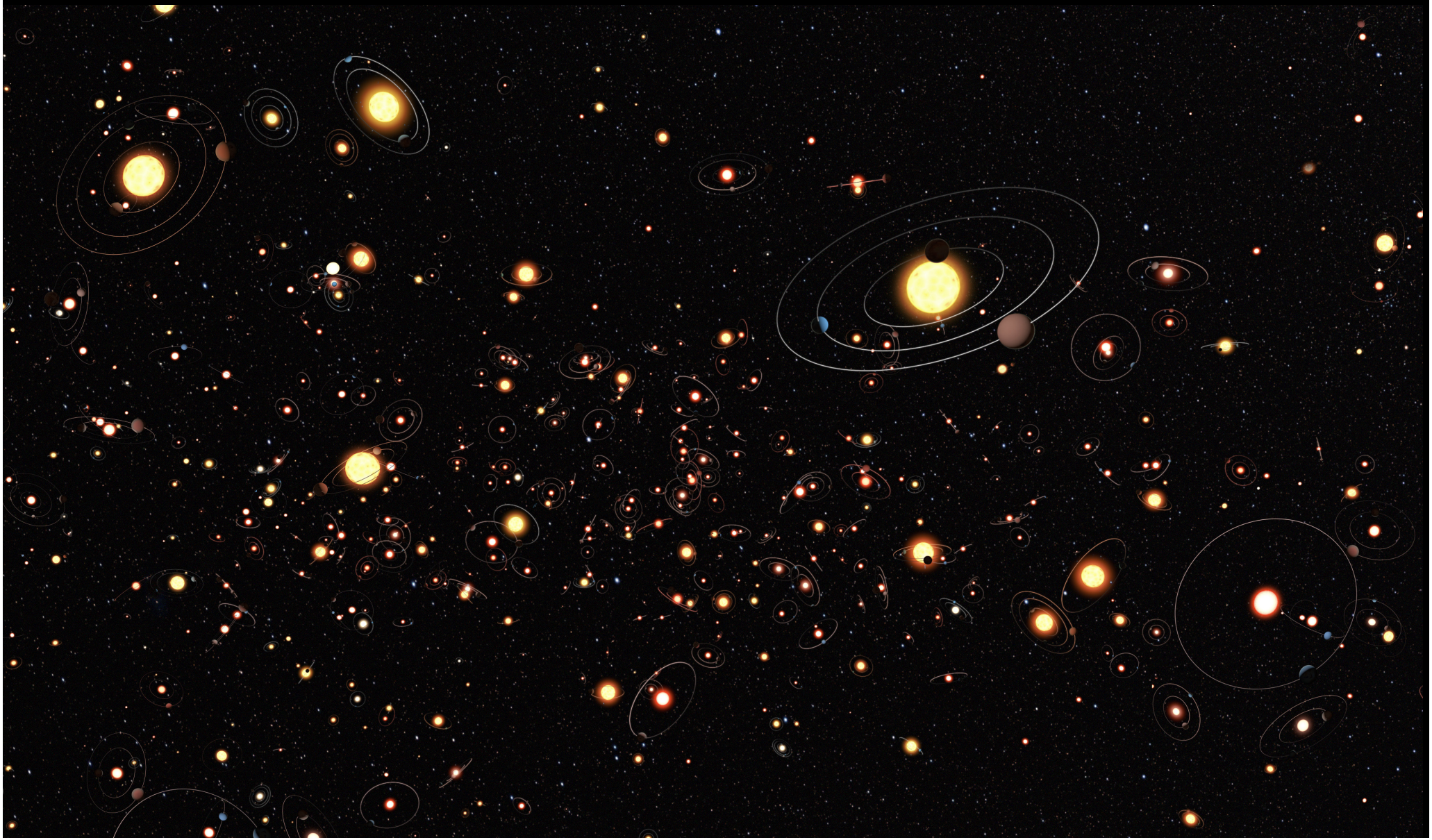
(The farther a planet is from its star, the slower it orbits.)

# Kepler's Third Law – in the Solar System

**TABLE 2-3** A Demonstration of Kepler's Third Law

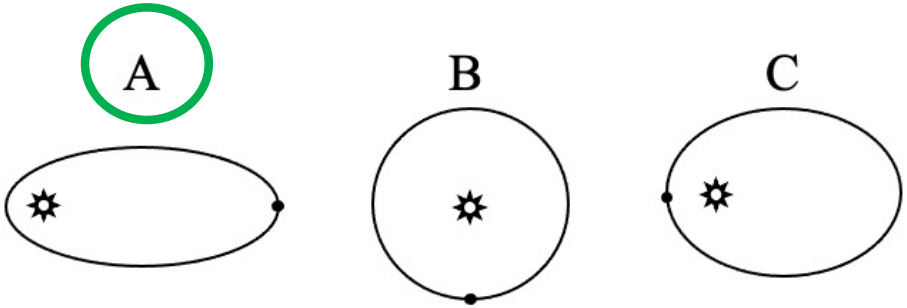
| | Sidereal period $P$ (yr) | Semimajor axis $a$ (AU) | $P^2$ | = | $a^3$ |
|---|---|---|---|---|---|
| Mercury | 0.24 | 0.39 | 0.06 | | 0.06 |
| Venus | 0.61 | 0.72 | 0.37 | | 0.37 |
| Earth | 1.00 | 1.00 | 1.00 | | 1.00 |
| Mars | 1.88 | 1.52 | 3.53 | | 3.51 |
| Jupiter | 11.86 | 5.20 | 140.7 | | 140.6 |
| Saturn | 29.46 | 9.54 | 867.9 | | 868.3 |
| Uranus | 84.01 | 19.19 | 7,058 | | 7,067 |
| Neptune | 164.79 | 30.06 | 27,160 | | 27,160 |
| Pluto | 248.54 | 39.53 | 61,770 | | 61,770 |

Kepler's Third Law is a **consequence of how gravity works**, and it is valid everywhere!



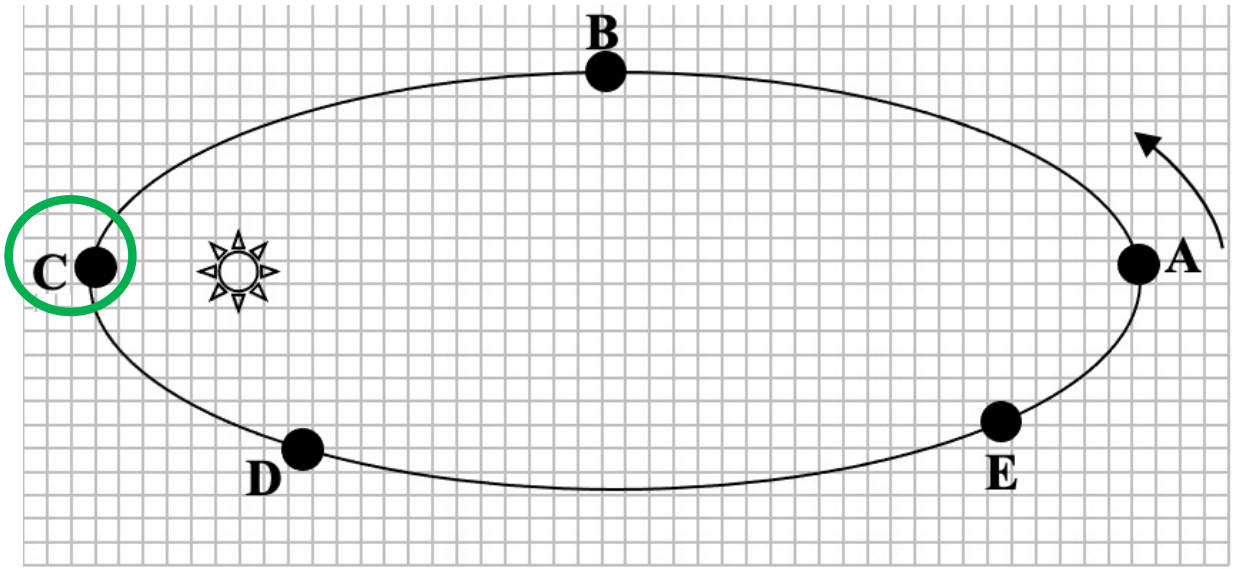
# question for you

The planet in the orbit shown in the drawing obeys Kepler's Laws. Which of the planets shown would experience the greatest change in speed?



# question for you

The planet shown in the drawing obeys Kepler's Second Law. Each lettered position represents the location for the planet during a particular day in a year. During which day (at which lettered position) would the planet move the farthest?

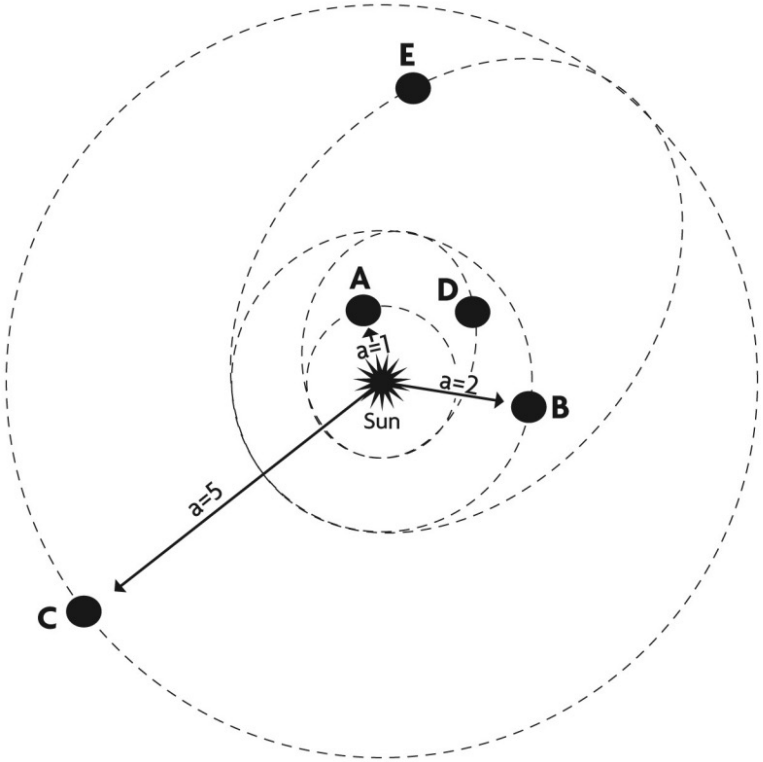


# Handout

- Work with a partner!
- Read the questions carefully.
- Discuss the concepts and your answers with one another.
- Come to a consensus answer you both agree on.
- If you get stuck or are not sure of your answer, ask another group.
- If you get really stuck or don't understand what the question is asking, ask me.

# Question #1

The figure below shows a star and five orbiting planets (A – E). Note that planets A, B and C are in perfectly circular orbits. In contrast, planets D and E have more elliptical orbits. Note that the closest and farthest distances for the elliptical orbits of planets D and E happen to match the orbital distances of planets A, B, and C as shown in the figure. **Rank the orbital period (from longest to shortest) of the planets.**




Ranking Order:
Longest 1 ___ 2 ____ 3 ____ 4 ____ 5 ____ Shortest
Or, the orbital periods of the planets would all be the same. _____ (indicate with check mark).

C>E>B>D>A

# Question #2

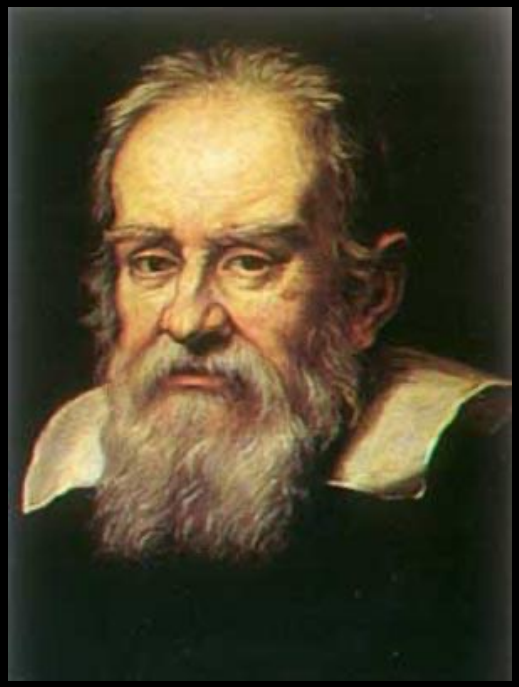
Which of the following best describes what would happen to a planet's orbital speed if its mass were doubled but it stayed at the same orbital distance?

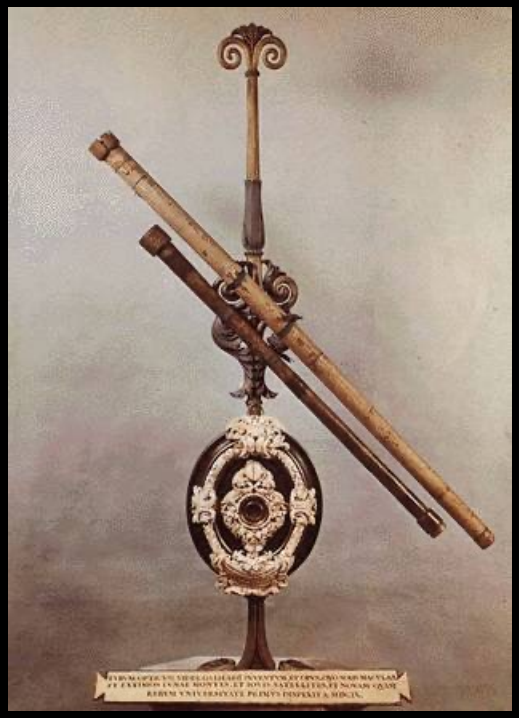
A. It would orbit half as fast.
B. It would orbit about twice as fast.
C. It would orbit more than twice as fast.
D. It would orbit with about the same speed.
E. I have no idea.

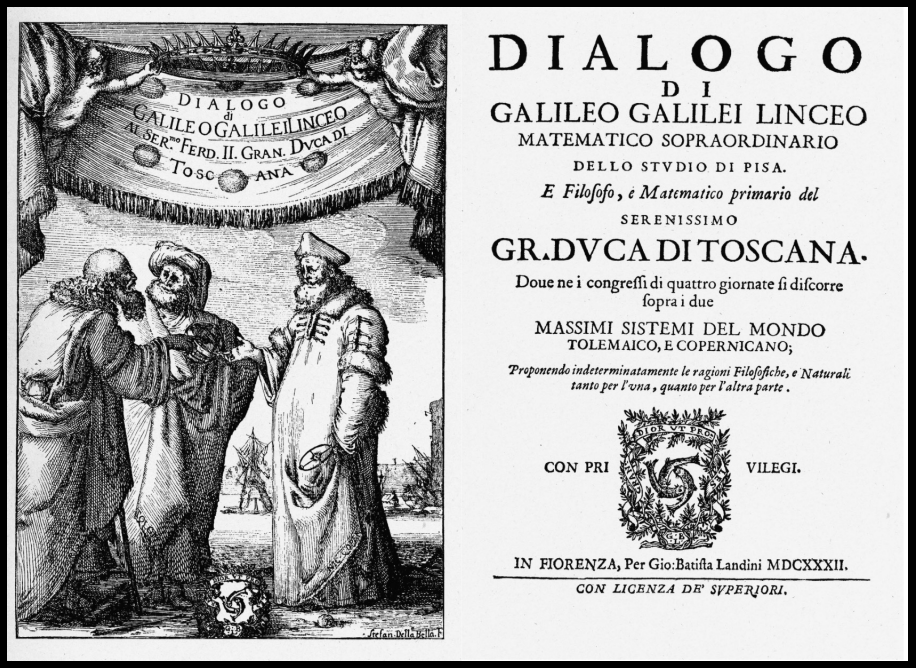
# Galileo's experiments

# Galileo Galilei
# (1564 – 1642)

- Italian astronomer and physicist.
- "Mission in life" to disprove Aristotle's assertions about the Universe.
- Built the **first telescope** for observing the heavens (he was NOT the inventor of the telescope).







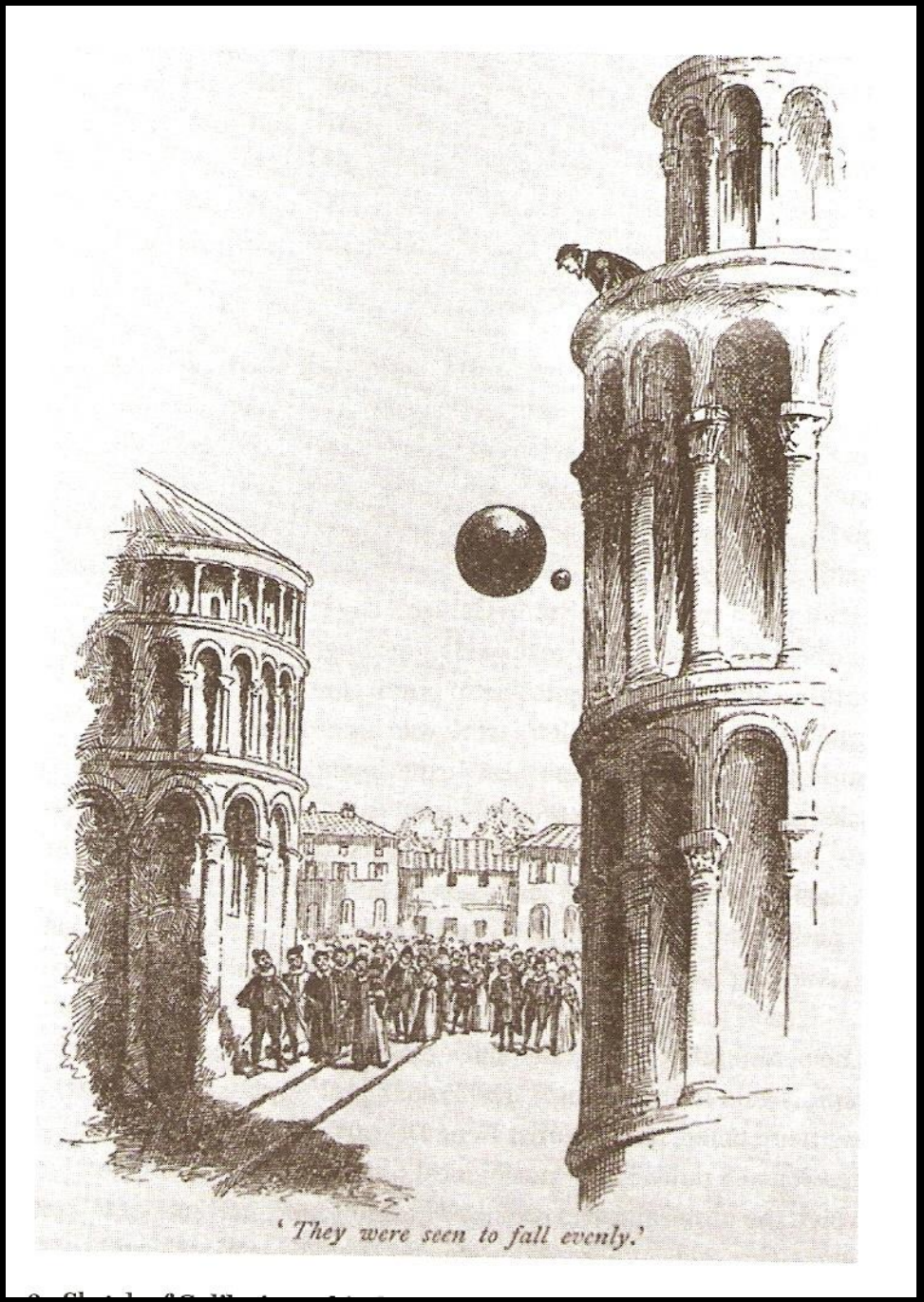

DIALOGO
DI
GALILEO GALILEI LINCEO
MATEMATICO SOPRAORDINARIO
DELLO STVDIO DI PISA.
*E Filosofo, e Matematico primario del*
SERENISSIMO
GR.DVCA DI TOSCANA.
Doue ne i congressi di quattro giornate si discorre
sopra i due
MASSIMI SISTEMI DEL MONDO
TOLEMAICO, E COPERNICANO;
*Proponendo indeterminatamente le ragioni Filosofiche, e Naturali*
*tanto per l'una, quanto per l'altra parte.*

CON PRI VILEGI.

IN FIORENZA, Per Gio: Batista Landini MDCXXXII.
*CON LICENZA DE' SVPERIORI.*

# Observation #1

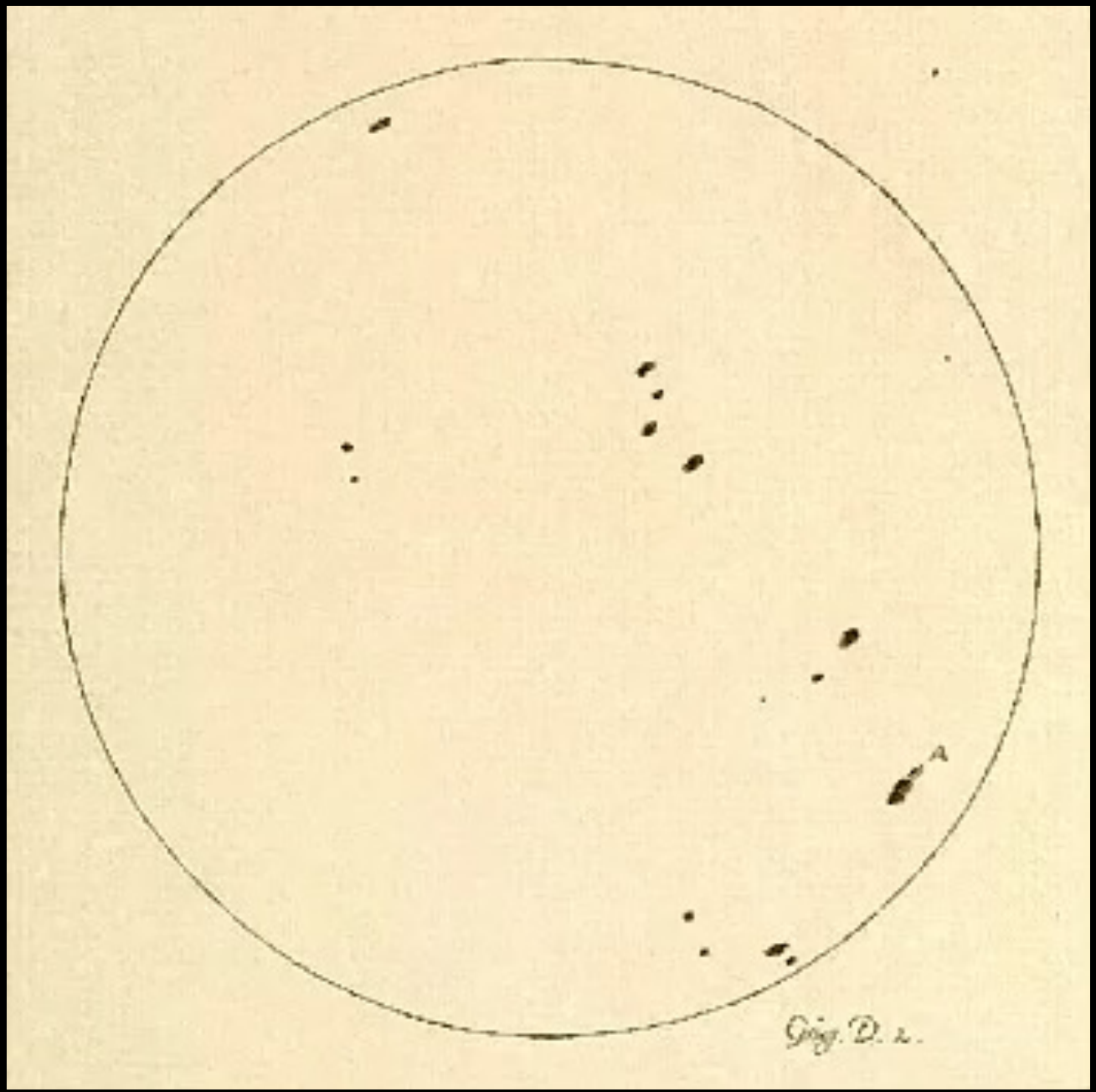
- Falling objects do so at the same rate, regardless of their mass.
- Objects in motion tend to stay in motion unless acted upon by an external force.



# Feather and a bowling ball in free fall

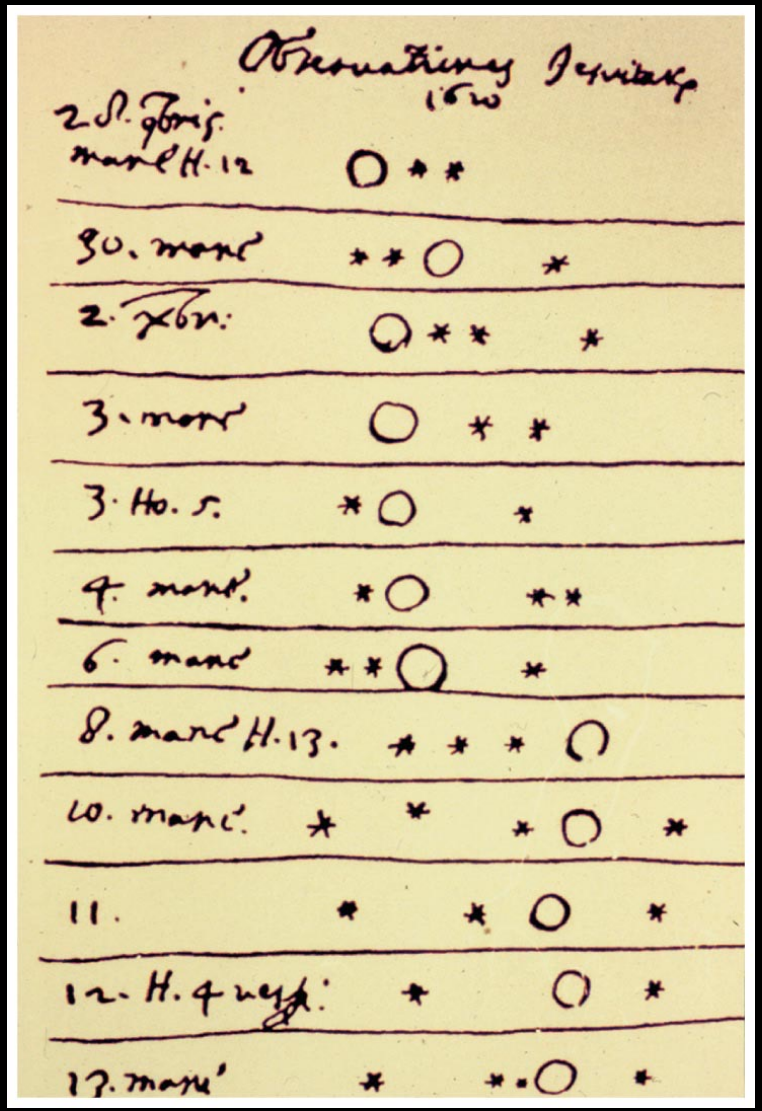
see: https://www.youtube.com/watch?v=E43-CfukEgs

# Observation #2: The Sun is Imperfect



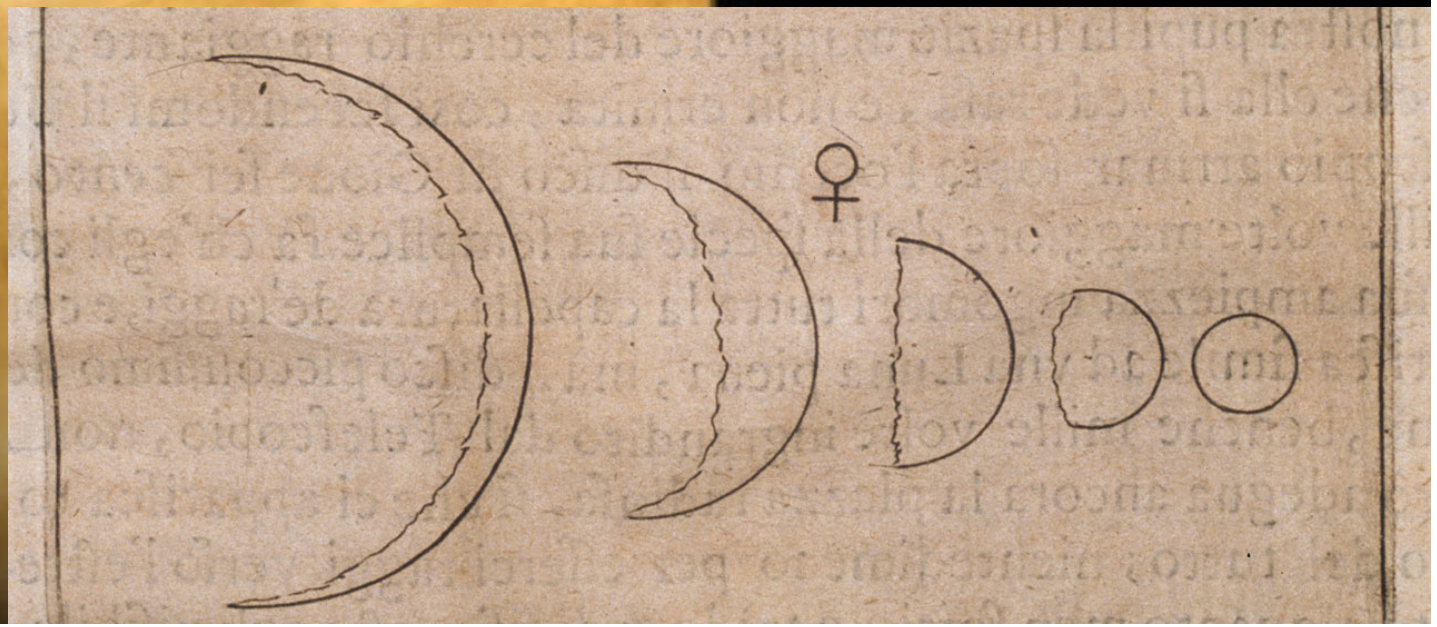
# Observation #3: Stars are really far away!

# More Data: Jupiter has moons.

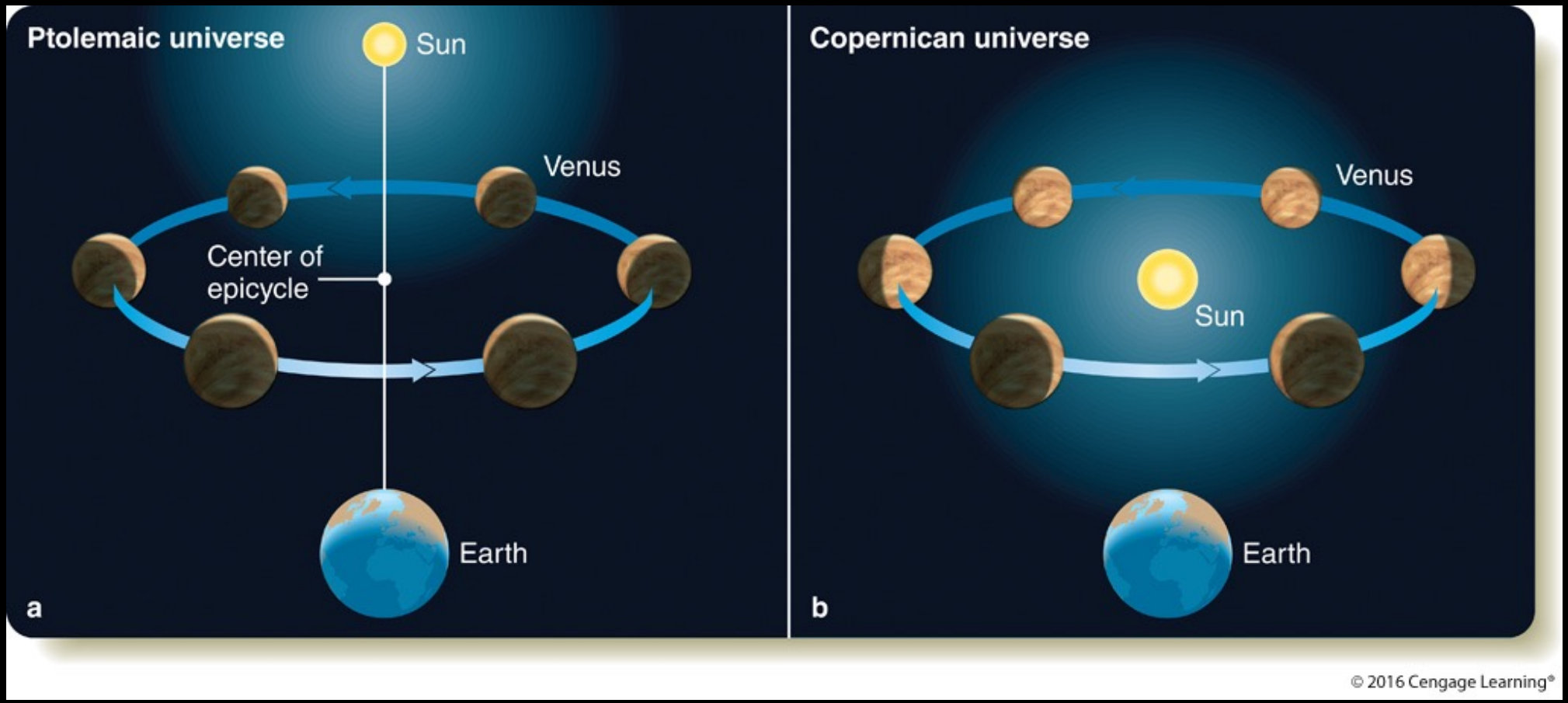


# More Data: The Moon has mountains.

# More Data: Venus has phases.



# Phases of Venus



# The birth of modern science

Ancient Greeks had mostly based explanations on the current cultural sense of what "felt right".

Kepler, Galileo, and later Newton based their assertions on observations.

# What did we learn in Chapter 4?

- Western astronomy originated in Mesopotamia.
- Three Greek innovations:
  - Understanding nature without invoking the supernatural
  - Using mathematics
  - Reasoning from observations
- Greek understanding of Universe:
  - Earth at center of Universe, orbited by Moon, Mercury, Venus, Sun, Mars, Jupiter, Saturn, and the Celestial Sphere containing stars.
  - Could not explain apparent retrograde motion.

# What did we learn in Chapter 4?

- Aristotle's three objections established the basis of the geocentric (Earth-centered) model.
- Ptolemy's geocentric system used epicycles and deferents to account for apparent retrograde motion of planets, but was not too accurate.
- Islamic astronomers responsible for saving Ptolemy's Almagest, naming many stars, computed tilt of Earth's axis.
- Copernican heliocentric system correctly accounted for retrograde motion, but did not gain support because it used circular orbits and epicycles.

# What did we learn in Chapter 4?

- Galileo started the scientific revolution by disproving Aristotle's assertions and using a telescope to observe the "heavens."
- Kepler used Brahe's observations to come up with his three laws:
  1. Planetary orbits are ellipses
  2. Planets sweep out equal areas in equal time
  3. The square of the period of a planet's orbit is proportional to its semimajor axis cubed ($p^2 = a^3$).