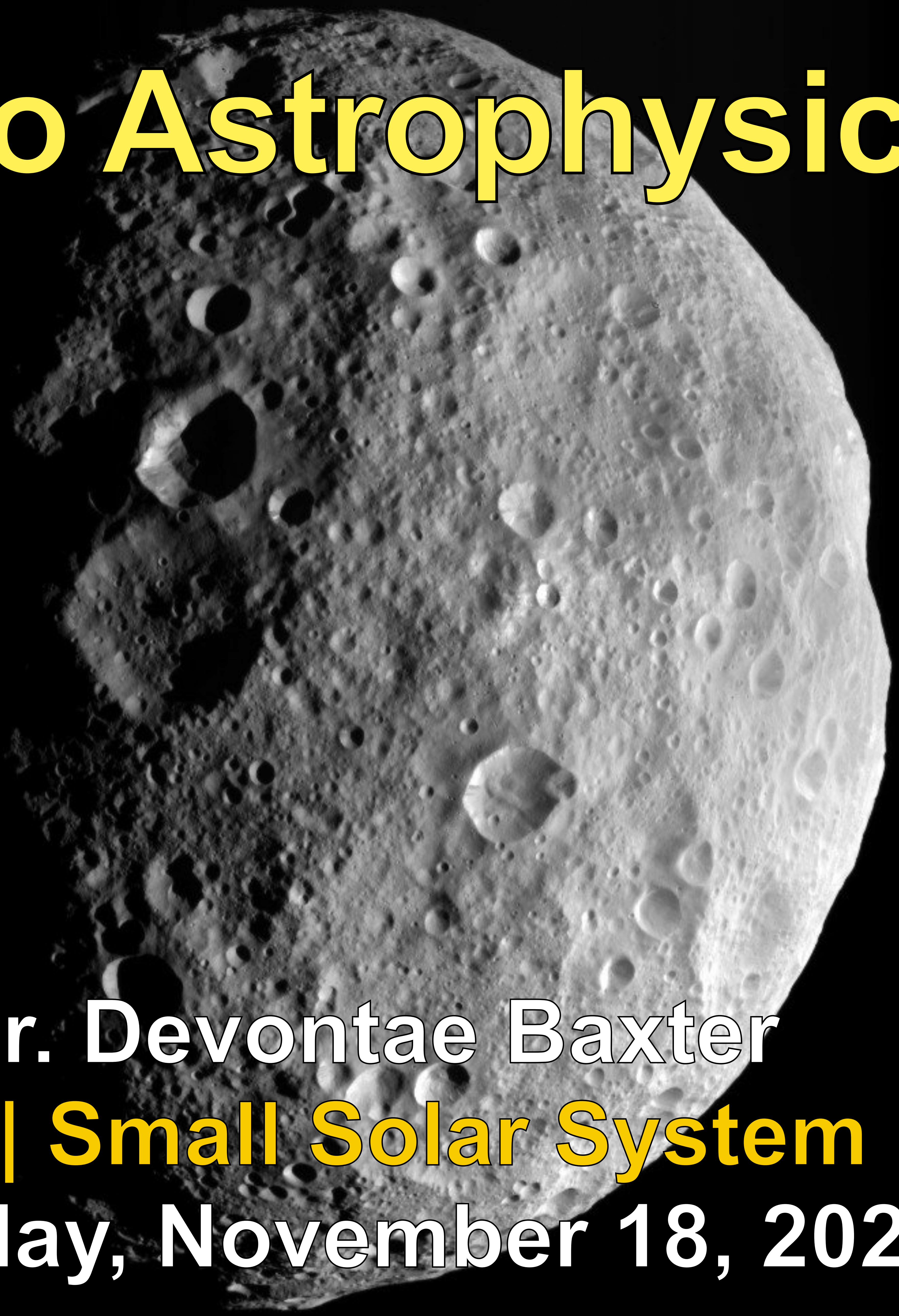
ASTR20A:
Introduction to Astrophysics I



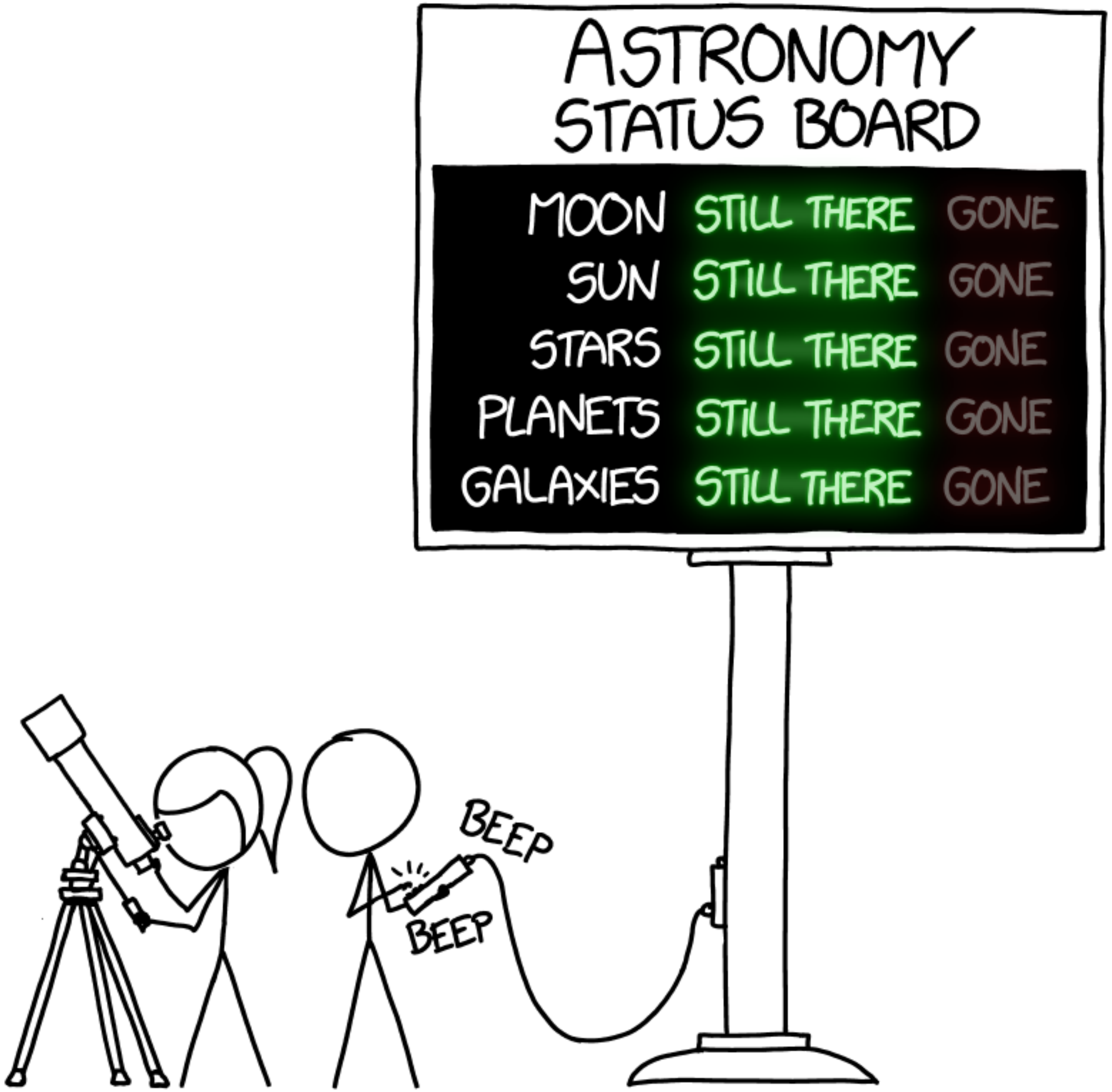
Dr. Devontae Baxter

Lecture 13 | Small Solar System Bodies

Tuesday, November 18, 2025

Announcements

- HW #6 is due **Tuesday, 11/18 by 11:59 pm.**
- HW #7 is due **Tuesday, 11/25, by 11:59 pm.**
- Coding project is due **Sunday, 11/30 by 11:59 pm.**



Survey Results

Thank you all for taking time to complete the survey. Below are a few changes that I will immediately implement going forward:

- **More connection between the homework and lecture.**
  - I'll include hints to the slides which will be relevant for the HW.
  - Include also include HW-style problem in class.
- **Posting lecture slides ahead of class.**
  - I'll post the notes within 24 hours of lecture — cannot promise that this will be the final version.
- **Introduce more pauses, especially for derivations to allow students to process material.**
  - I'll include periodic pauses throughout the lecture to give you time to review the material and ask questions for information that didn't click.

Midterm II

Grades for midterm II are posted. Below are a few common issues/misconceptions that I noticed:

- Relative change **implies taking a ratio between two values.**
  - In general, most math problems on the ASTR 20A exams will involve taking ratios.
- Always **solve symbolically before plugging in numbers.**
  - This is generally the most error proof way to solve a problem. I highly suggest that you adopt this approach going forward.
- Always **include arrows when drawing optical paths.**
- **Read problems carefully!**
  - Some questions can have multiple answers — e.g., question 1b.
  - Some are intentionally misleading — e.g., question 1m.
- Review diffraction-limited seeing.

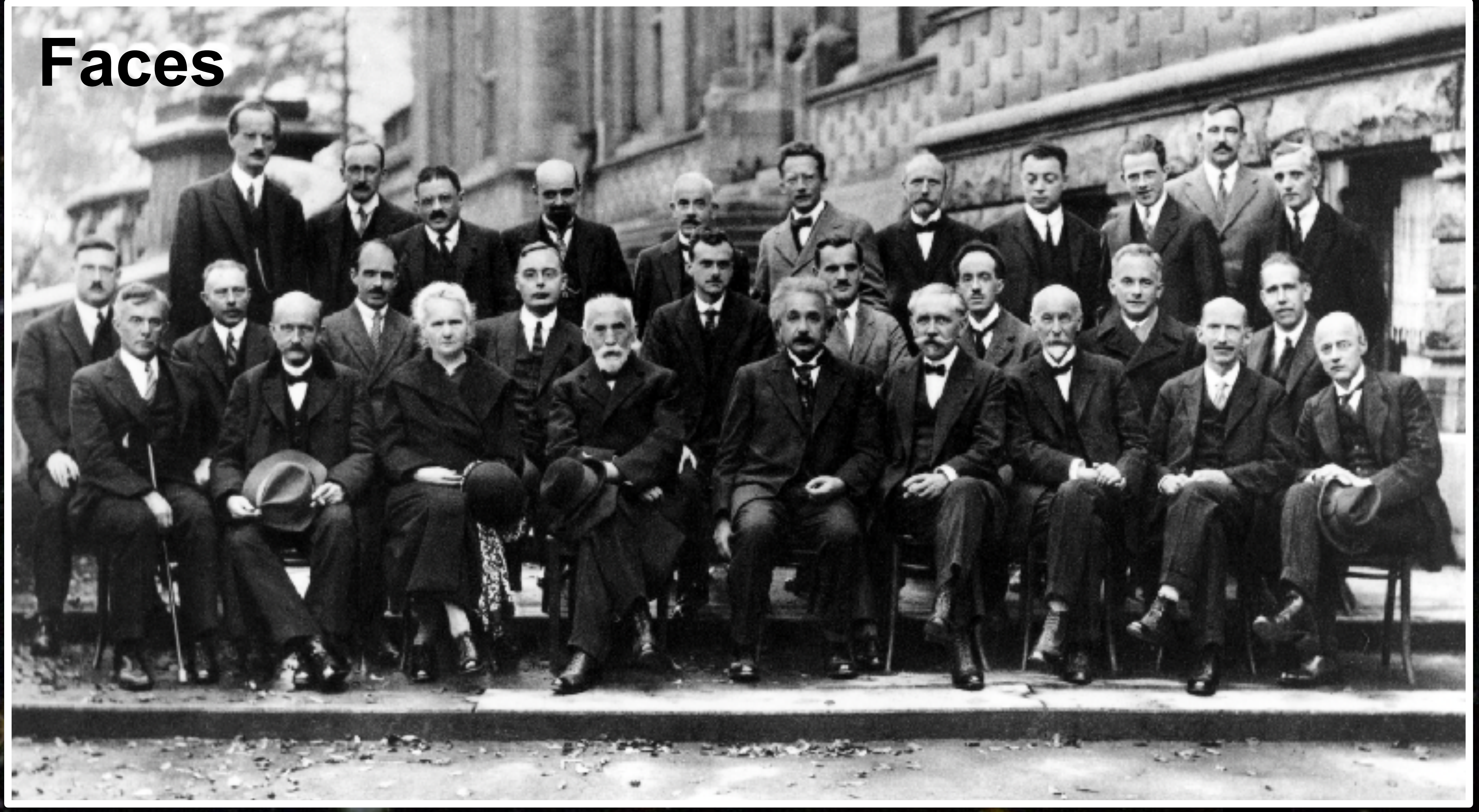

Questions?

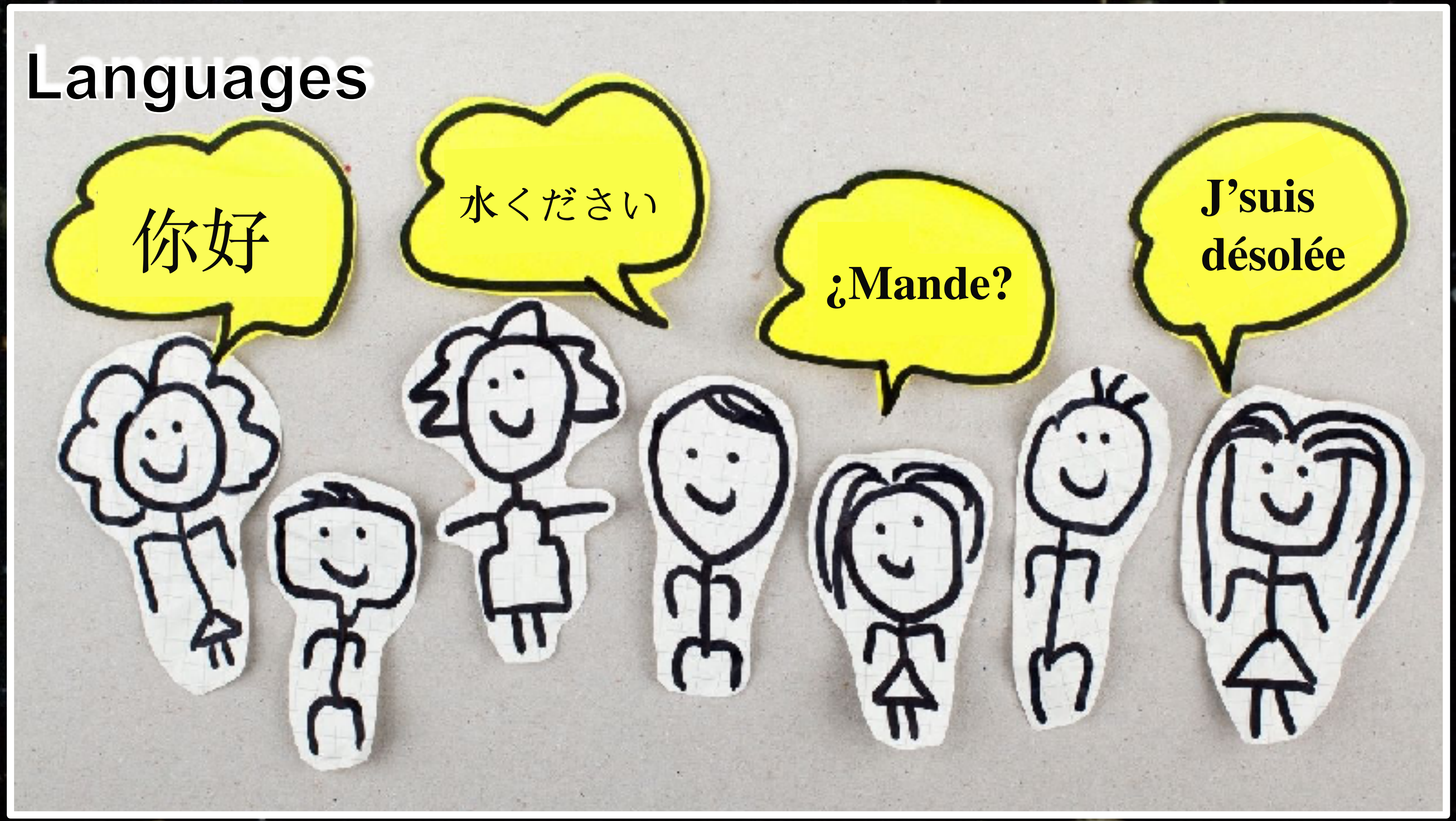
Learning Objectives

By the end of today's lecture you will be able to:

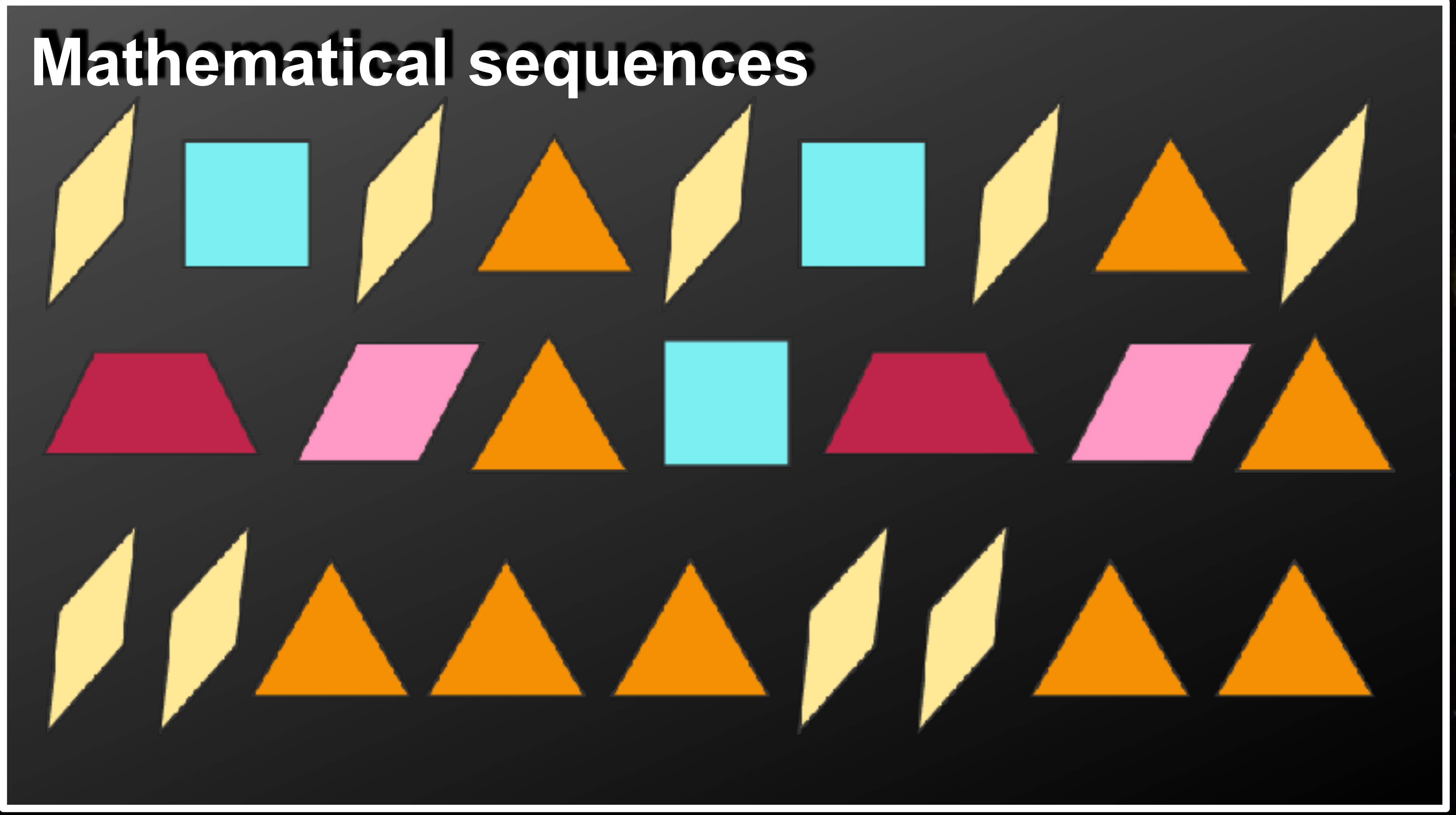
- Describe the difference between Trojan and Hilda asteroids.
- Draw the orbits of the four types of Near-Earth Asteroids.
- Explain the origin of the "Kirkwood gaps".
- Differentiate between classical, resonant, and scattered objects beyond Neptune.
- Understand the three main criteria that defines a planet.
- Compare short-period and long-period comets in terms of their origin and orbital timescales.
- Explain how the Poynting-Robertson effect clears large particles form the Solar System.
- Calculate the Poynting–Robertson timescale for a particle spiraling into the Sun.
- Describe the origins of Zodiacal Light.
- Differentiate between meteors, meteorites, and meteoroids.

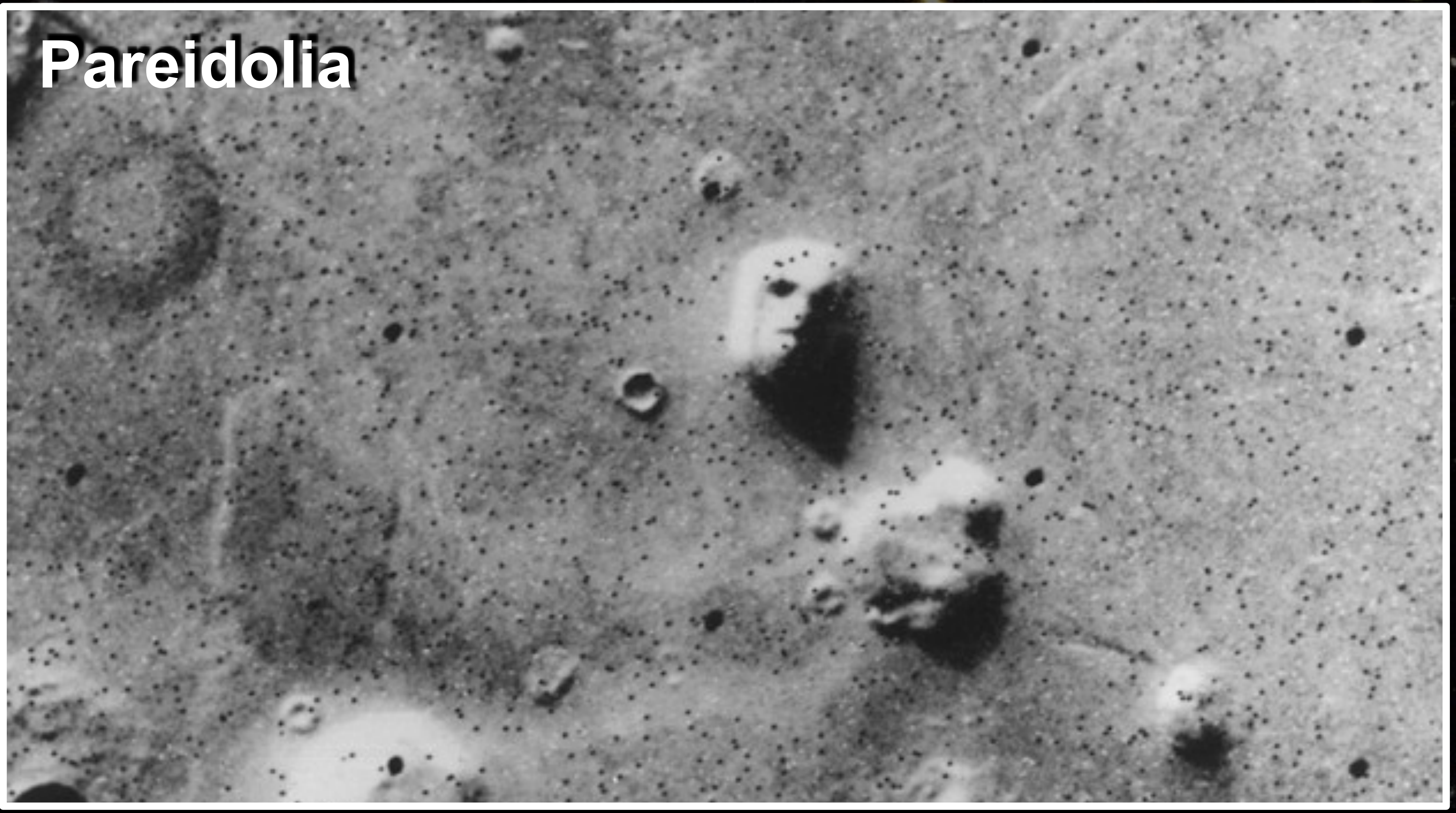
Humans are excellent at pattern recognition.


Faces



Languages


Mathematical sequences


Pareidolia

Titius-Bode Rule

In 1776, the astronomer Johann Titius noticed a *numerical pattern* in the spacing between planets that could be described by the formula:

$$a[\mathrm{AU}] = 0.4 + 0.3 \times (2^n),$$

where $n = \infty,\ 1,\ 2,\ 3, \ldots$ is assigned to each planet in order of increasing distance from the Sun.

This formula suggests each planet is roughly twice as far from the Sun as the planet before it.

Johann Titius (1729-1796)

Johann Bode (1747-1826)

Titius-Bode Rule

The Titius-Bode Rule predicted the existence of two missing planets!

Titius-Bode Rule (AU)	Actual (AU)	Planet
$0.4 + 0.0 = 0.4$	0.39	Mercury
$0.4 + 0.3 = 0.7$	0.72	Venus
$0.4 + 0.6 = 1.0$	1.00	Earth
$0.4 + 1.2 = 1.6$	1.52	Mars
$0.4 + 2.4 = 2.8$	??	??
$0.4 + 4.8 = 5.2$	5.20	Jupiter
$0.4 + 9.6 = 10.0$	9.58	Saturn
$0.4 + 19.2 = 19.6$	??	??

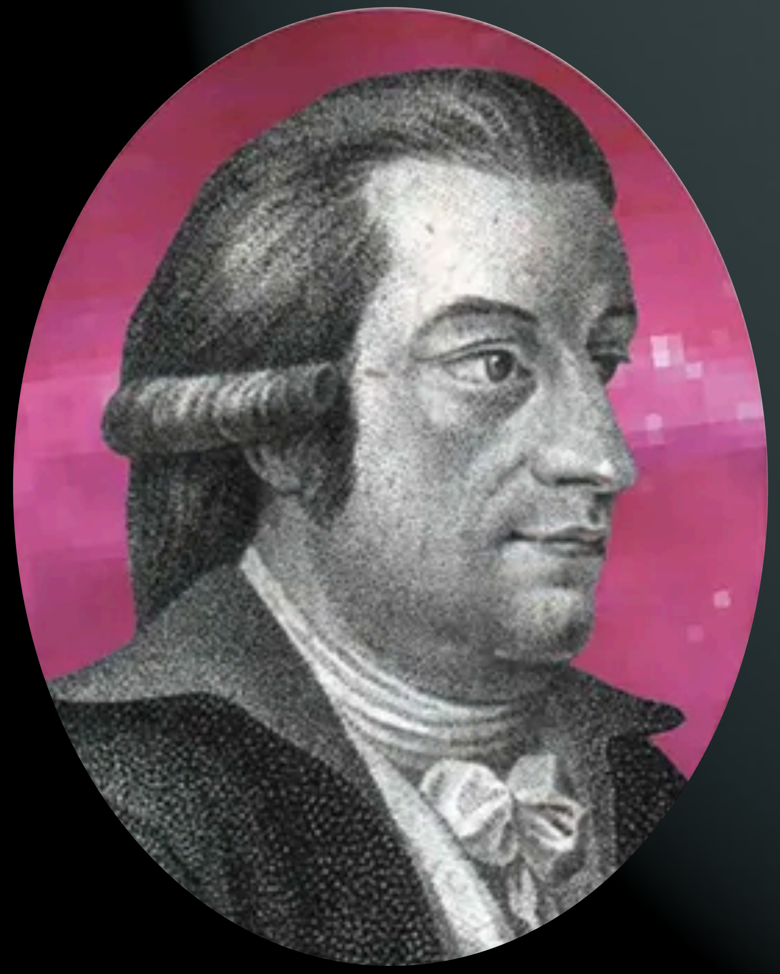
- This first planet was **predicted to orbit between Mars and Jupiter** with major axis of $a = 2.8\ \mathrm{AU}$.
- The second planet was **predicted to be located at about twice the distance to Saturn,** with a semi-major axis of $a = 19.8\ \mathrm{AU}$.

The Discovery of Uranus

The Titius-Bode rule was merely a mathematical curiosity until the year 1781 when Sir William Herchel discovered the planet Uranus at $19.18\ \text{AU}$ — which differed from the predicted value of $19.6\ \text{AU}$ by only 2%!

Herschel's discovery prompted the formation of the **"Celestial Police"**, a few dozen astronomers tasked with patrolling the space between Mars and Jupiter to find the missing planet.

Johann Schröter



Baron Franz Xaver von Zach

Karl Harding

Heinrich Olbers

Sir William Herschel (1738-1822)

The Discovery of Ceres

In 1801, the Italian astronomer *Giuseppe Piazzi*, serendipitously discovered an object with an object a 2.77 AU.

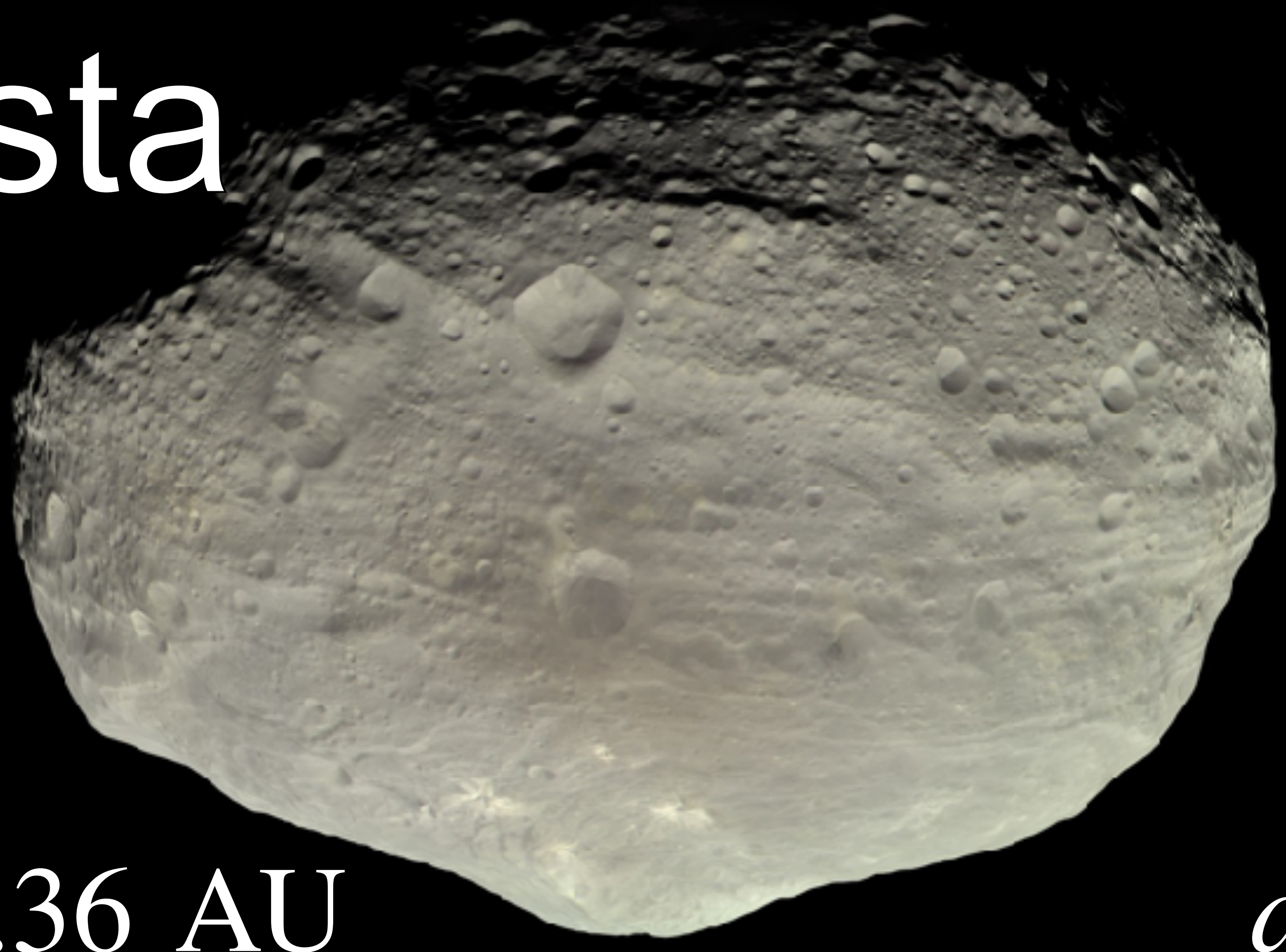
- This object was located was within 1% of the value predicted by the Titius-Bode rule!
- Piazzi called this object "Ceres" after the Roman goddess of agriculture.
- Today, we know that Ceres is a roughly spherical body with a radius of 480 km, about 25% the size of the Moon.

Giuseppe Piazzi (1746-1826)

The Discovery of Vesta, Pallas, and Juno.

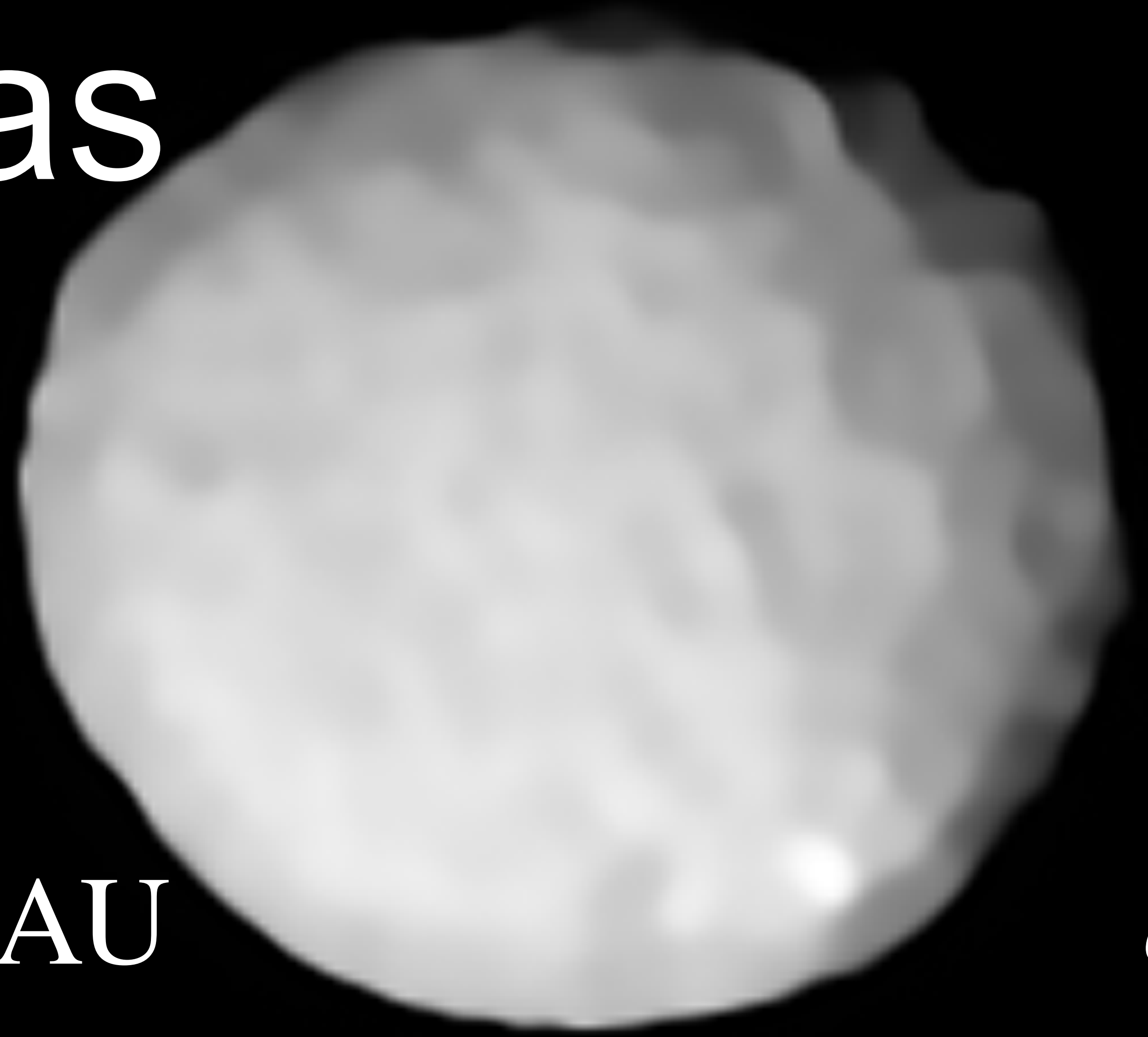
Following the discovery of Ceres, the celestial police went on to identify three additional objects around 2.5 AU with mean radii between 115-260 km.

Vesta



$a = 2.36$ AU

Pallas



$a = 2.77$ AU

Juno

$a = 2.67$ AU

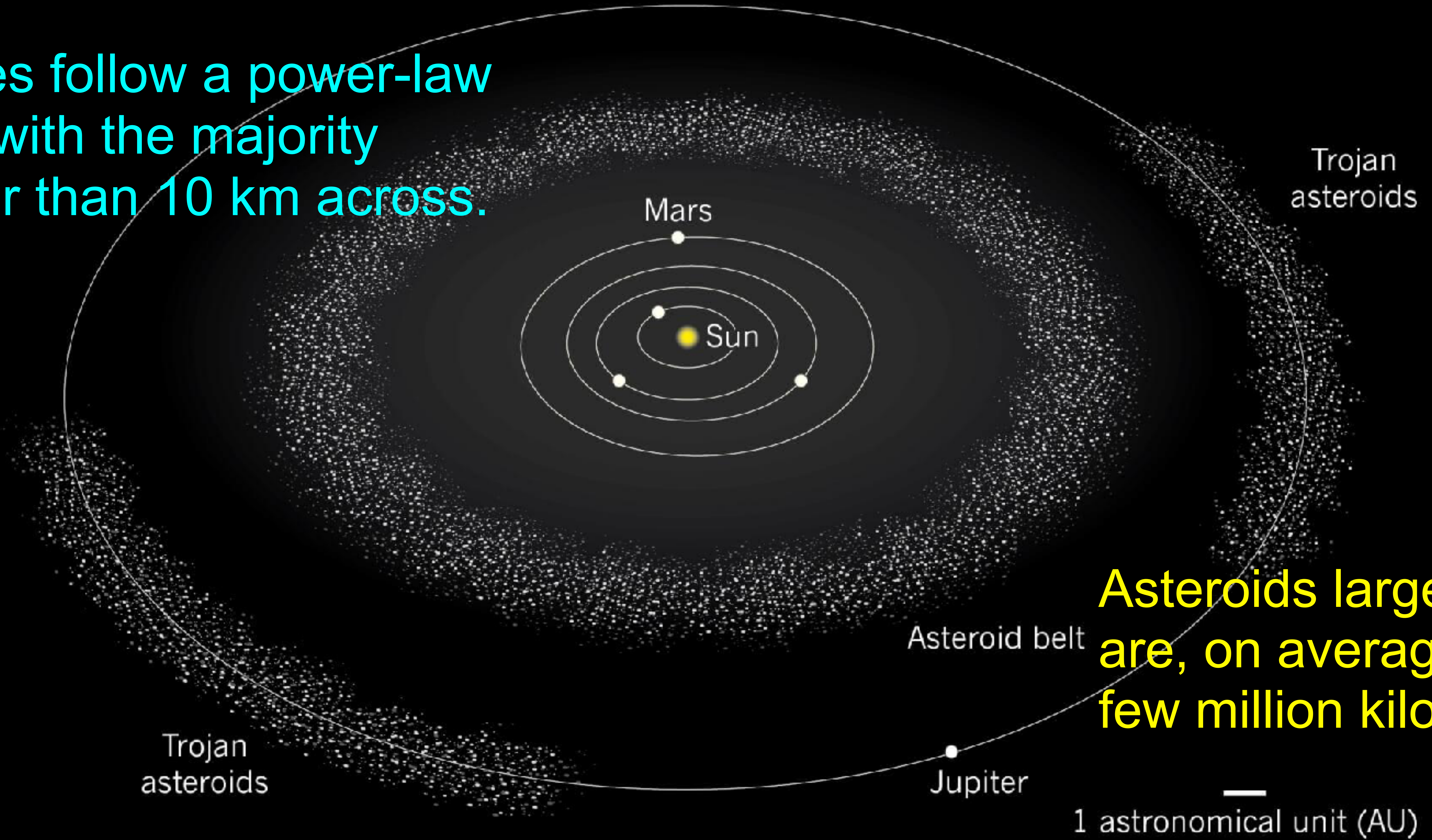
William Herschel dubbed these objects *asteroids* — meaning “starlike”, as he could hardly resolve them even with his largest telescopes.

They have also been referred as “minor planets” given their small size relative to the terresetial and jovian planets.

The Asteroid Belt

There are currently over 1.3 million asteroids known today!

Asteroid sizes follow a power-law distribution, with the majority being smaller than 10 km across.



Asteroids larger than 1 km are, on average, spaced a few million kilometers apart!

Earlier this year, **over 2100 new asteroids were discovered (4000 detected)** after 10.5 hours of exposing with the LSST camera on the Vera Rubin Observatory.

Near-Earth Asteroids (NAEs)

Most asteroids orbits between 1.8 - 3.3 AU, with eccentricities ranging from 0.05 - 0.3, and inclination between 0 - 30°. However, some asteroids orbit relatively close to the Earth.

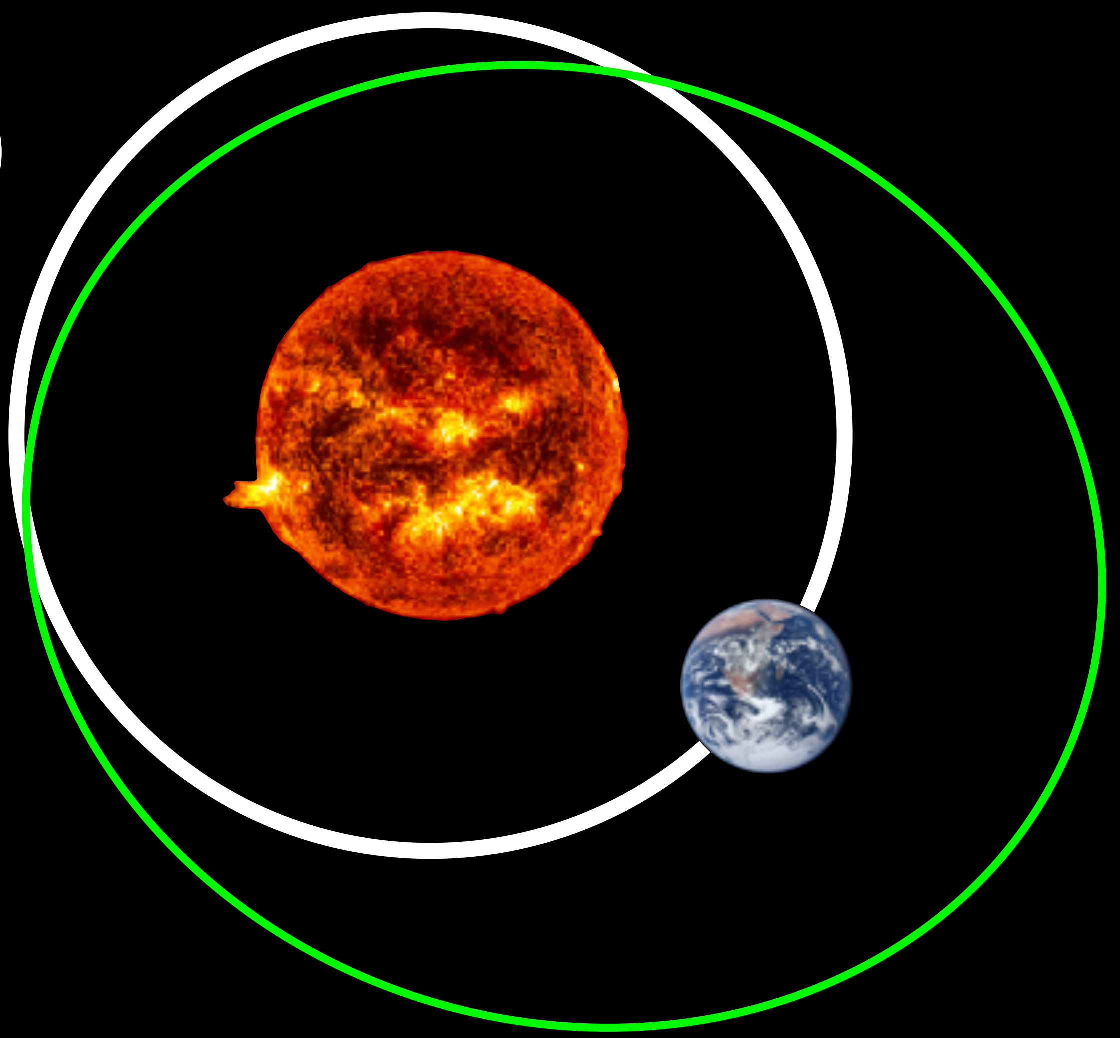
1) **Apollos:** Earth-crossing asteroids with $a > 1$ AU and a perihelion inside Earth's orbit.

2) **Atens:** Earth-crossing asteroids with $a < 1$ AU and an aphelion outside Earth's orbit.

3) **Amors:** NAEs with orbits that lie outside Earth's orbit but inside Mars's orbit.

4) **Atiras:** NAEs with orbits *entirely contained within Earth's orbit.*

1)



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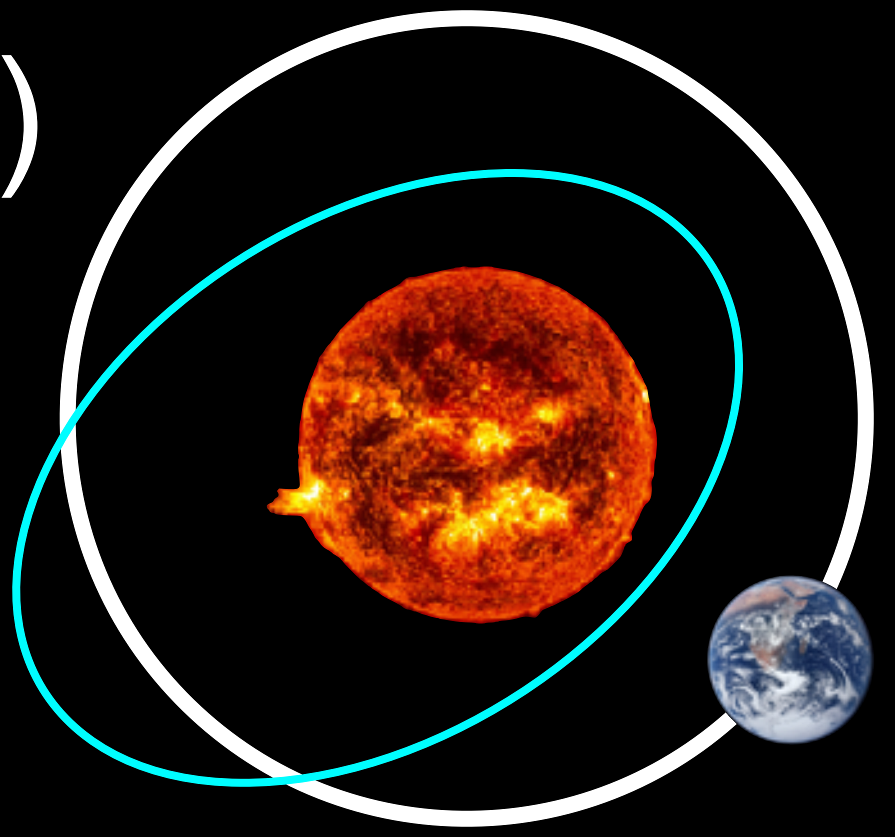

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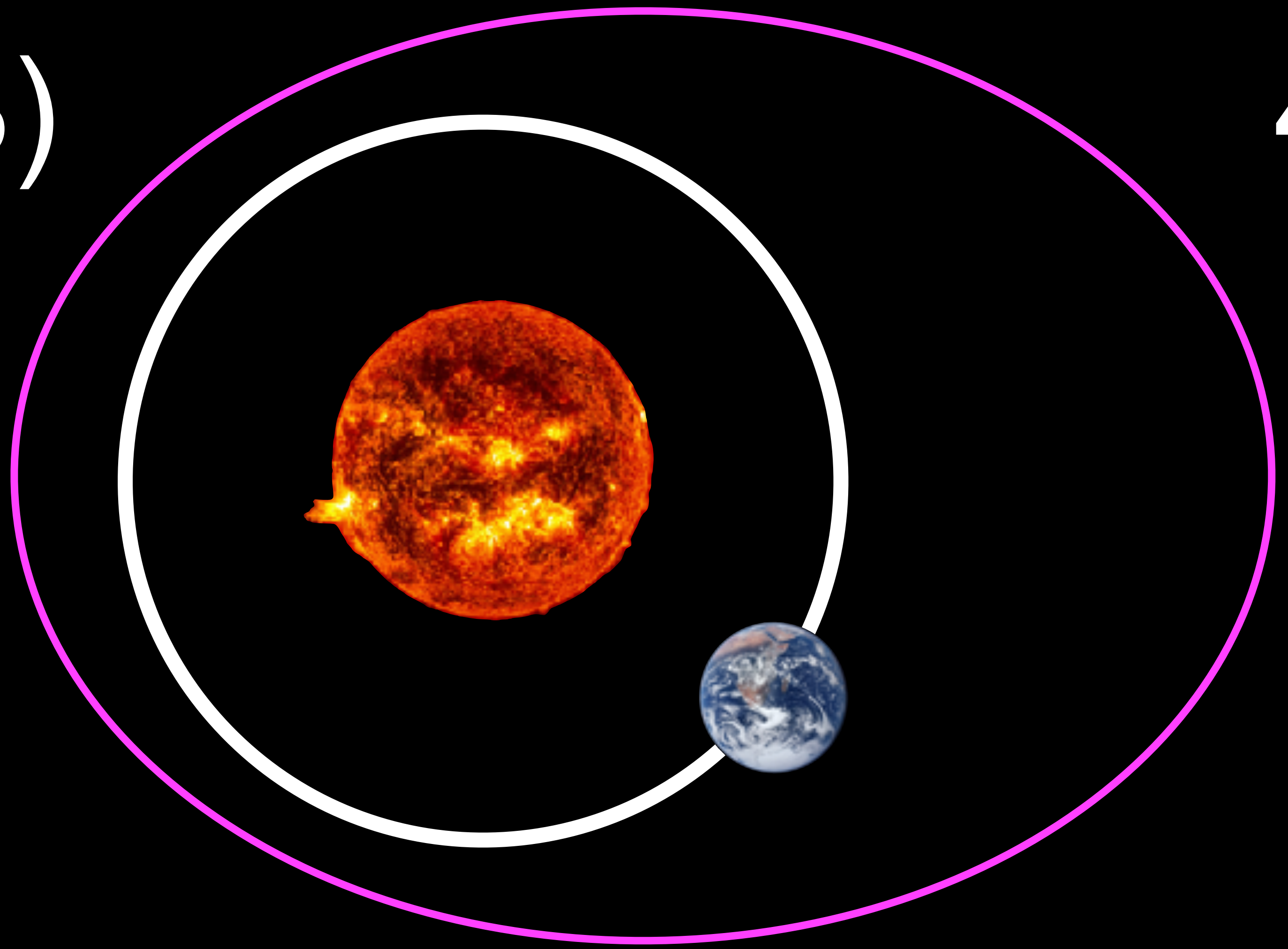

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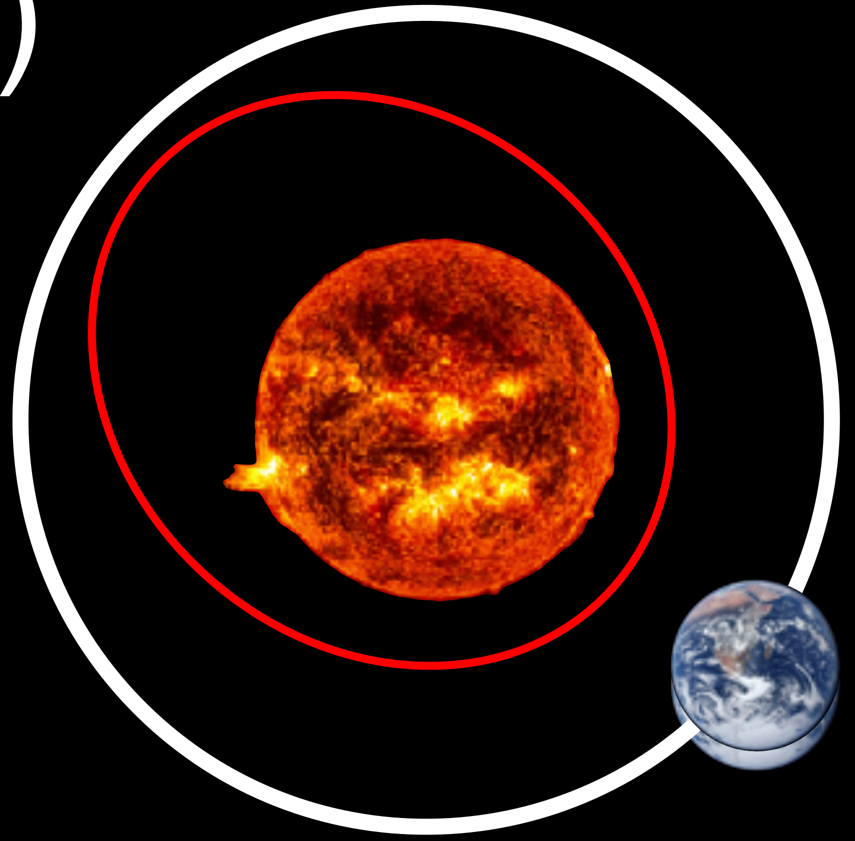
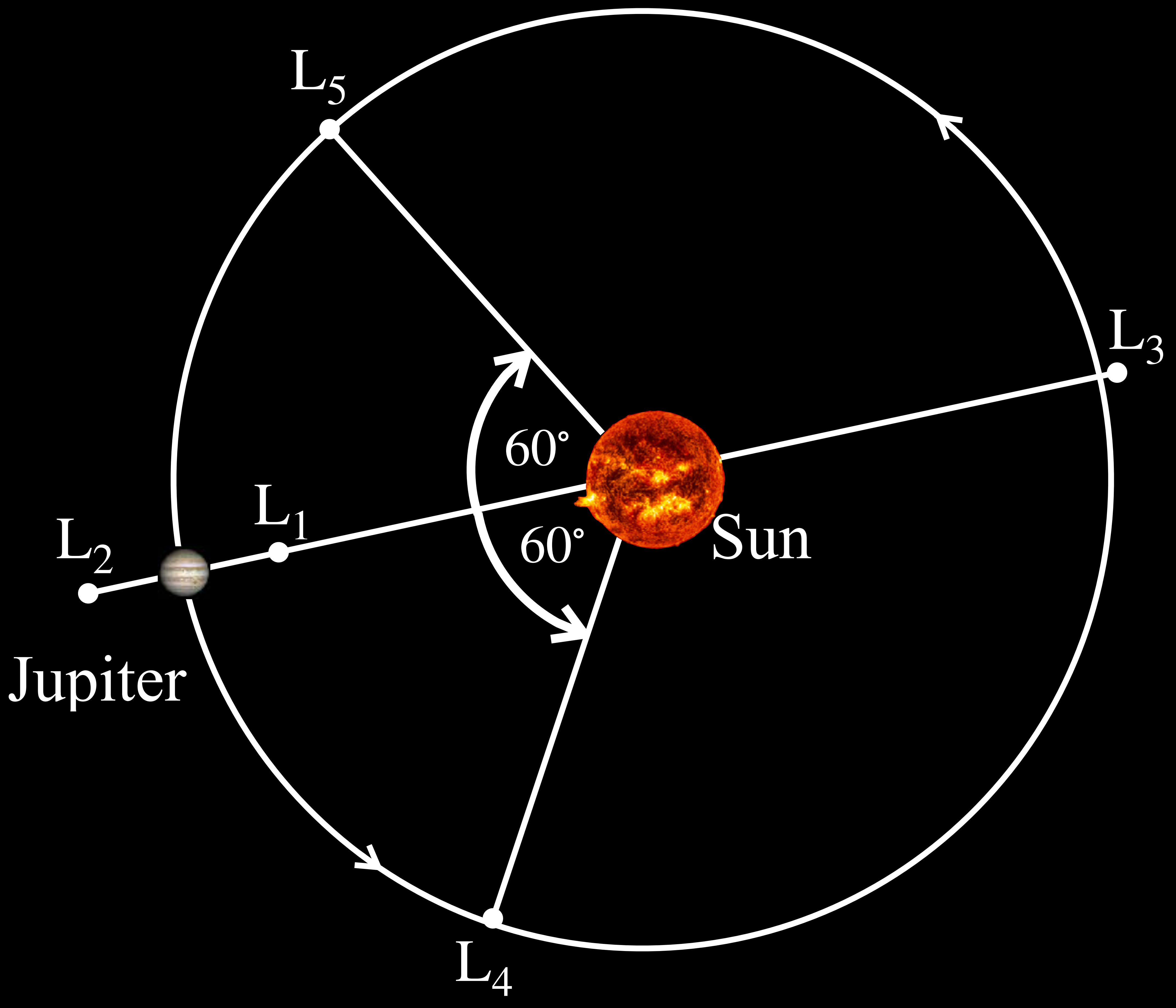
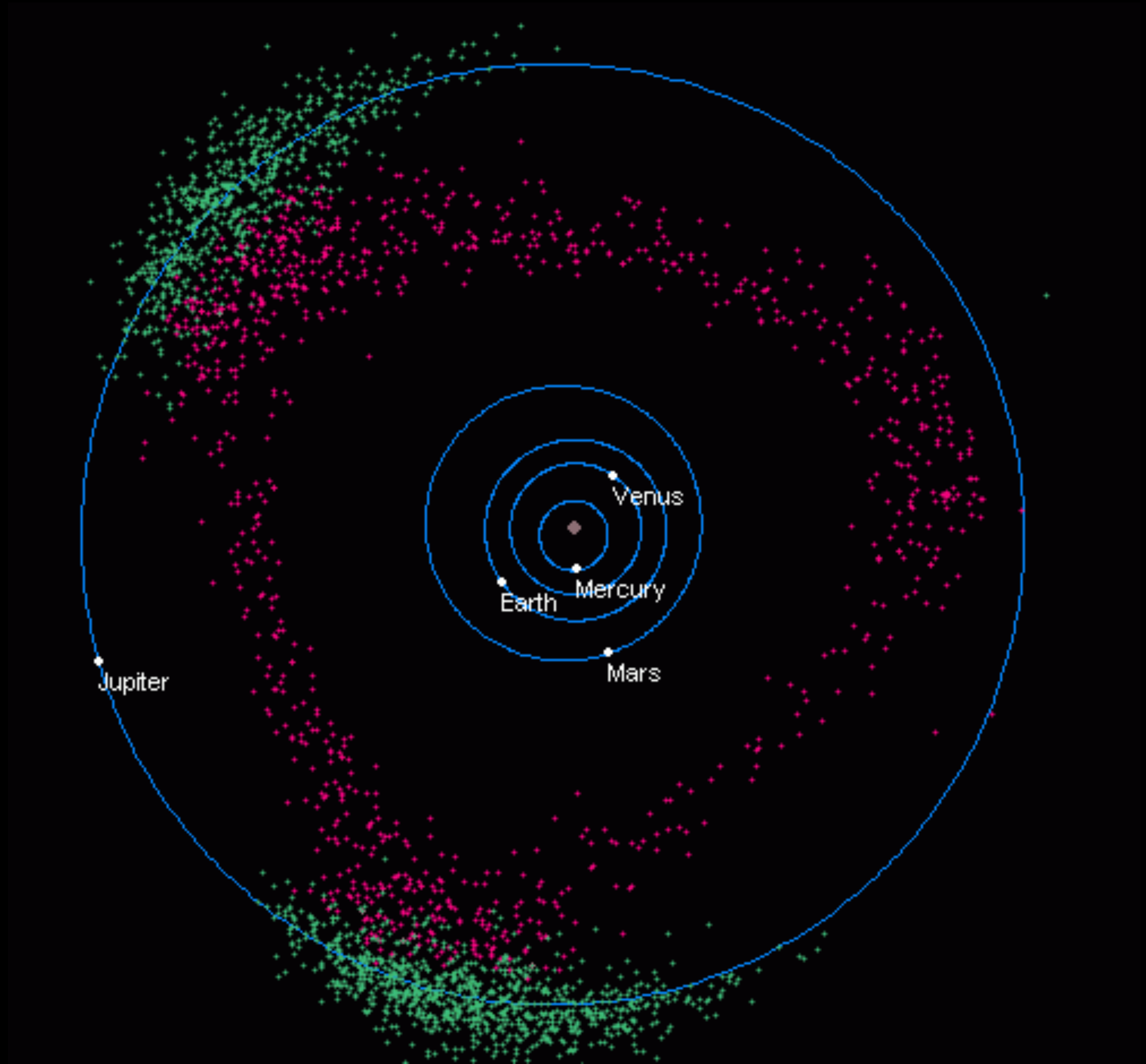


Trojans and Hildas

The Trojan asteroids are at the same orbital distance as Jupiter at *Lagrange points* L4 (Greek camp) and L5 (Trojan camp).

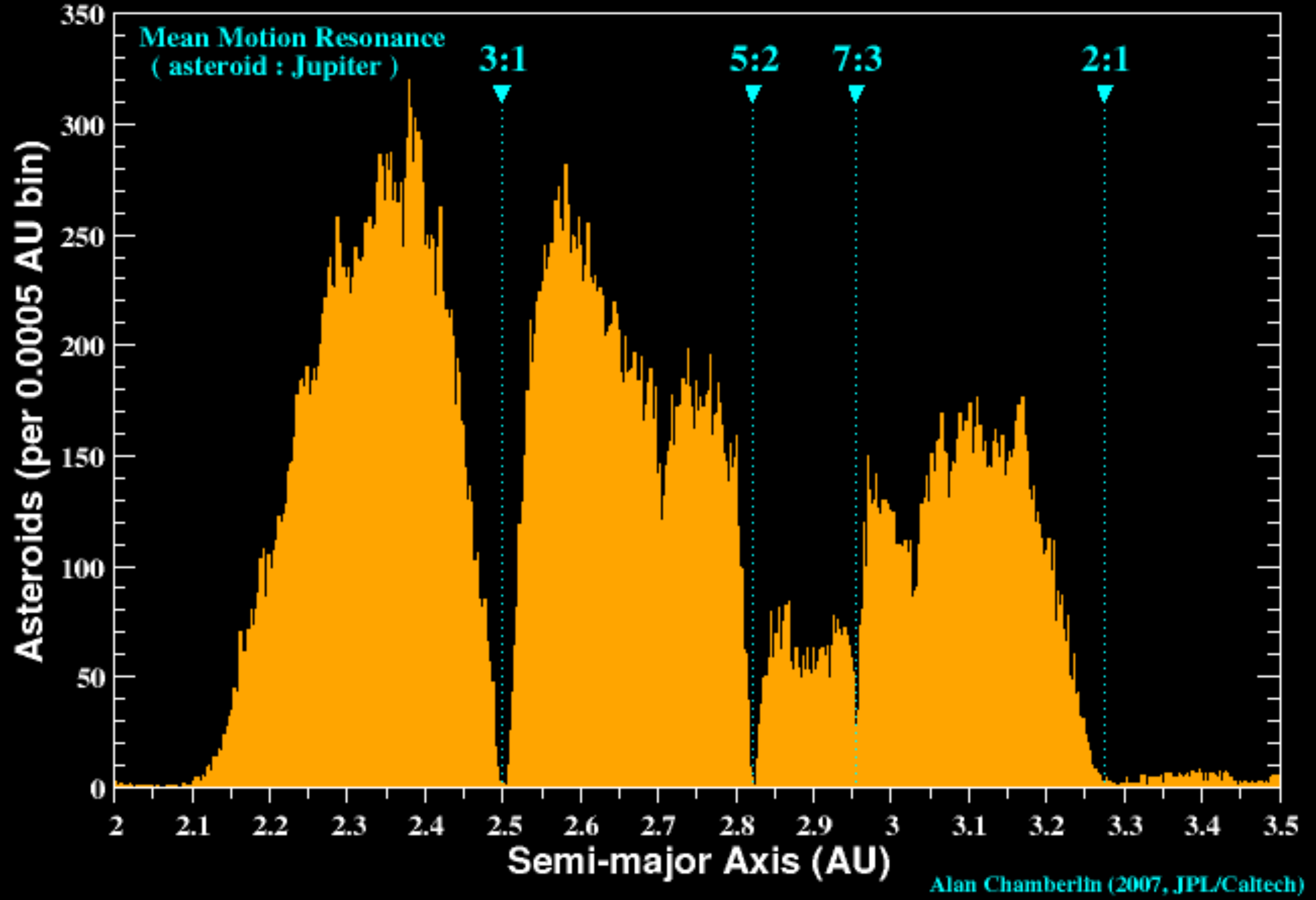
The Hilda asteroids are in a **3:2 mean-motion resonance with Jupiter** and their orbits that trace a nearly equilateral triangle, with vertices near the Lagrange points L3, L4, and L5.





Kirkwood Gaps

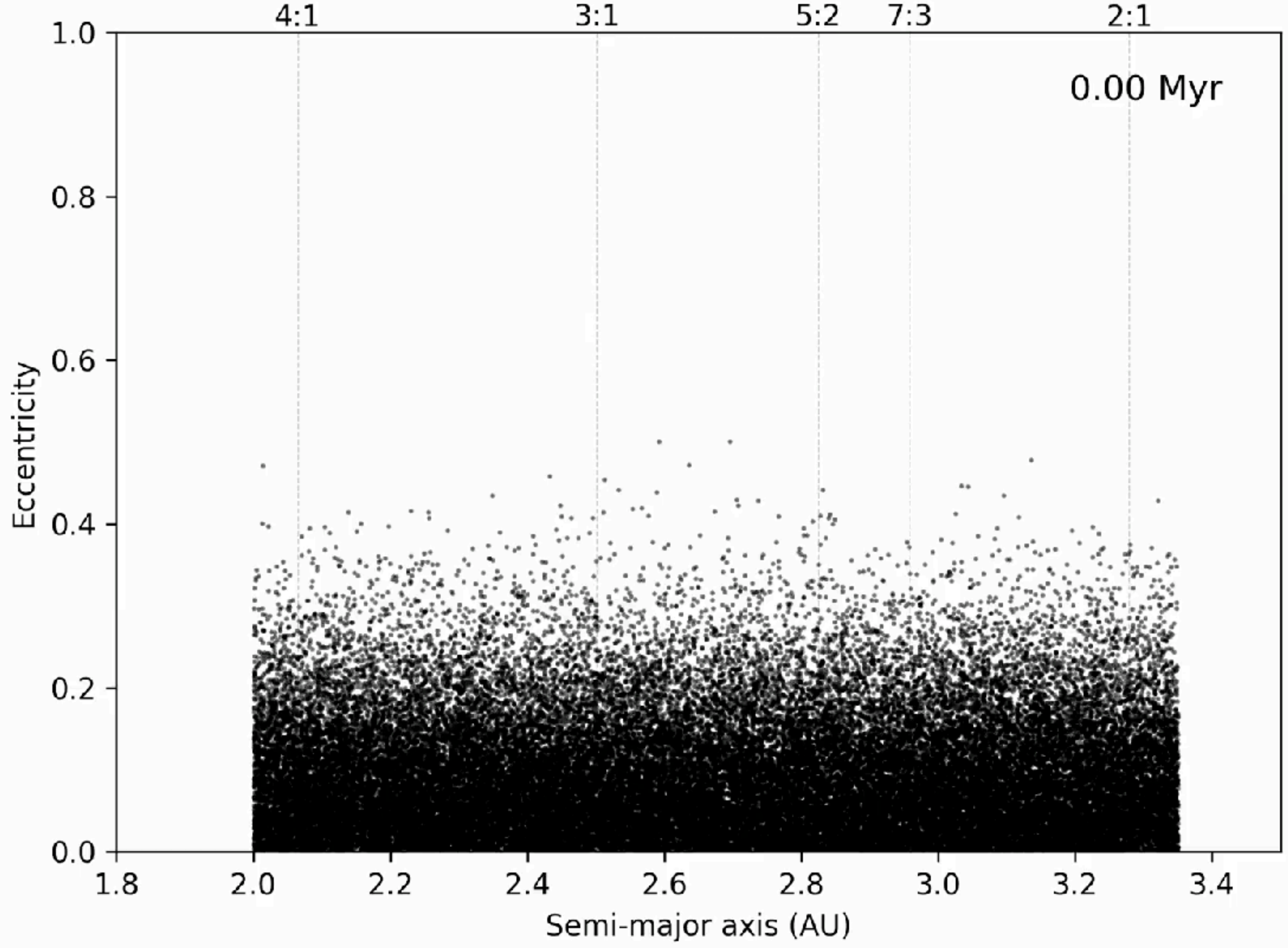
The distribution of asteroids has gaps called *Kirkwood gaps*, caused by mean-motion resonances where Jupiter's repeated gravitational tugs destabilize asteroid orbits.



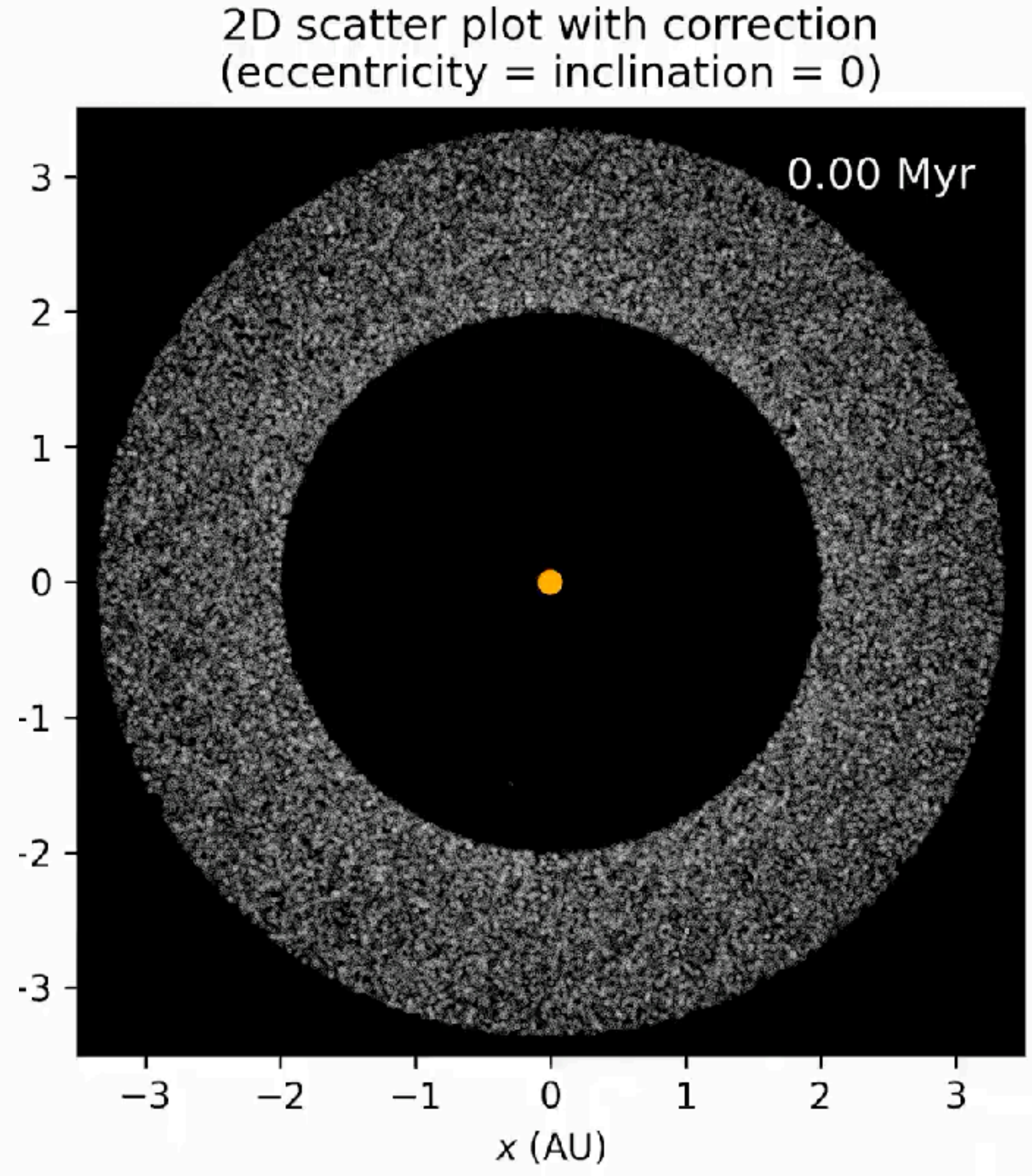
Asteroids near these resonances are gradually pulled into more eccentric orbits by the gravitational force exerted by Jupiter, clearing out those regions and creating the Kirkwood gaps.

Simulation of the formation of Kirkwood gaps

1D distribution



2D distribution



Pause

Assessment of Learning Objectives

Q1: Which of the following classes of asteroids cross Earth's orbit?

Hildas = 1️⃣

Apollos = 2️⃣

Amors = 3️⃣

Trojan = 4️⃣

Assessment of Learning Objectives

Q2: The Kirkwood gaps in the asteroid belt are created by mean-motion resonances with Neptune.

True = 1️⃣ False = 2️⃣

Objects beyond Neptune (Trans-Neptunian Objects)

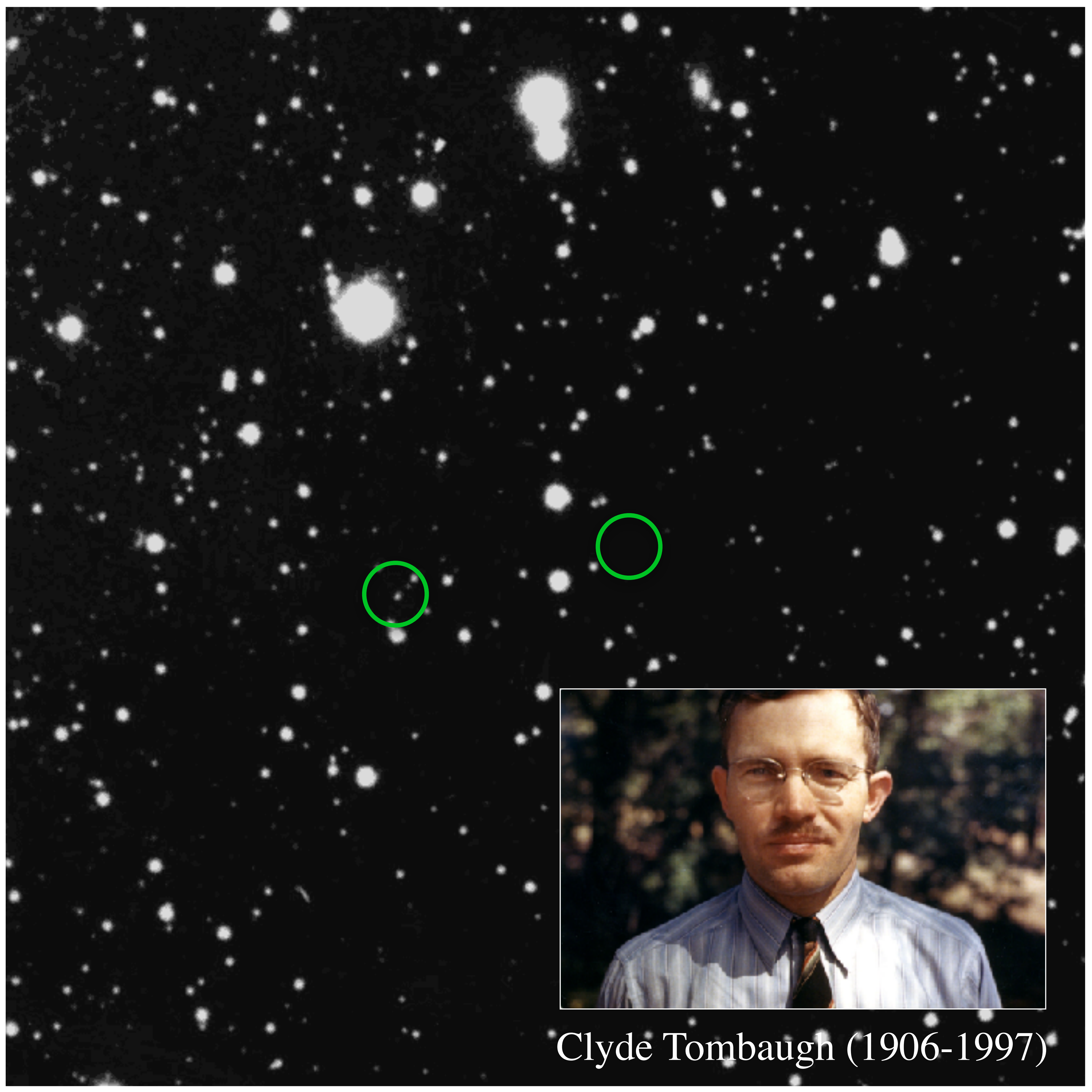
Finding faint objects *smaller than Neptune* at distances farther than Neptune ($a > 30.1\ \mathrm{AU}$) requires imaging the same patch of sky on consecutive nights and looking for moving objects.

An object on a nearly circular orbit beyond Neptune will have an apparent angular speed $\omega \leq 1.6\ \mathrm{arcmin\ day}^{-1}$ at *opposition*.

As a result, distant TNOs can be easily distinguished from asteroids at $a \approx 3\ \mathrm{AU}$, which move much faster along the celestial sphere (e.g., $\omega \approx 12\ \mathrm{arcmin\ day}^{-1}$).

Discovery of Pluto

By comparing images of the same part of the sky on different nights, astronomers can “blink” them to spot moving objects, a technique Clyde Tombaugh used to discover Pluto in 1930.


Clyde Tombaugh (1906-1997)

Pictured with **Charon**

Pluto: Beloved Planet (1930-2006)

Pluto and the Planet Debate

After hundreds of **trans-Neptunian objects** were discovered, including some **larger than Pluto,** astronomers began to ask: *Is Pluto really a planet?* and more broadly, *what exactly is a planet?*

In 2006, the **International Astronomical Union (IAU)** adopted an official definition: a **planet** is a solar system object that meets all of the following criteria:

1. It is in orbit around the Sun, and is **not a satellite of another planet.**
2. It has sufficient mass for its self-gravity to overcome its compressional strength, and thus **assume a spherical, or spheroidal, shape in hydrostatic equilibrium.**
3. It has **cleared its orbital neighborhood** (this criterion is often referred to as "orbital dominance").

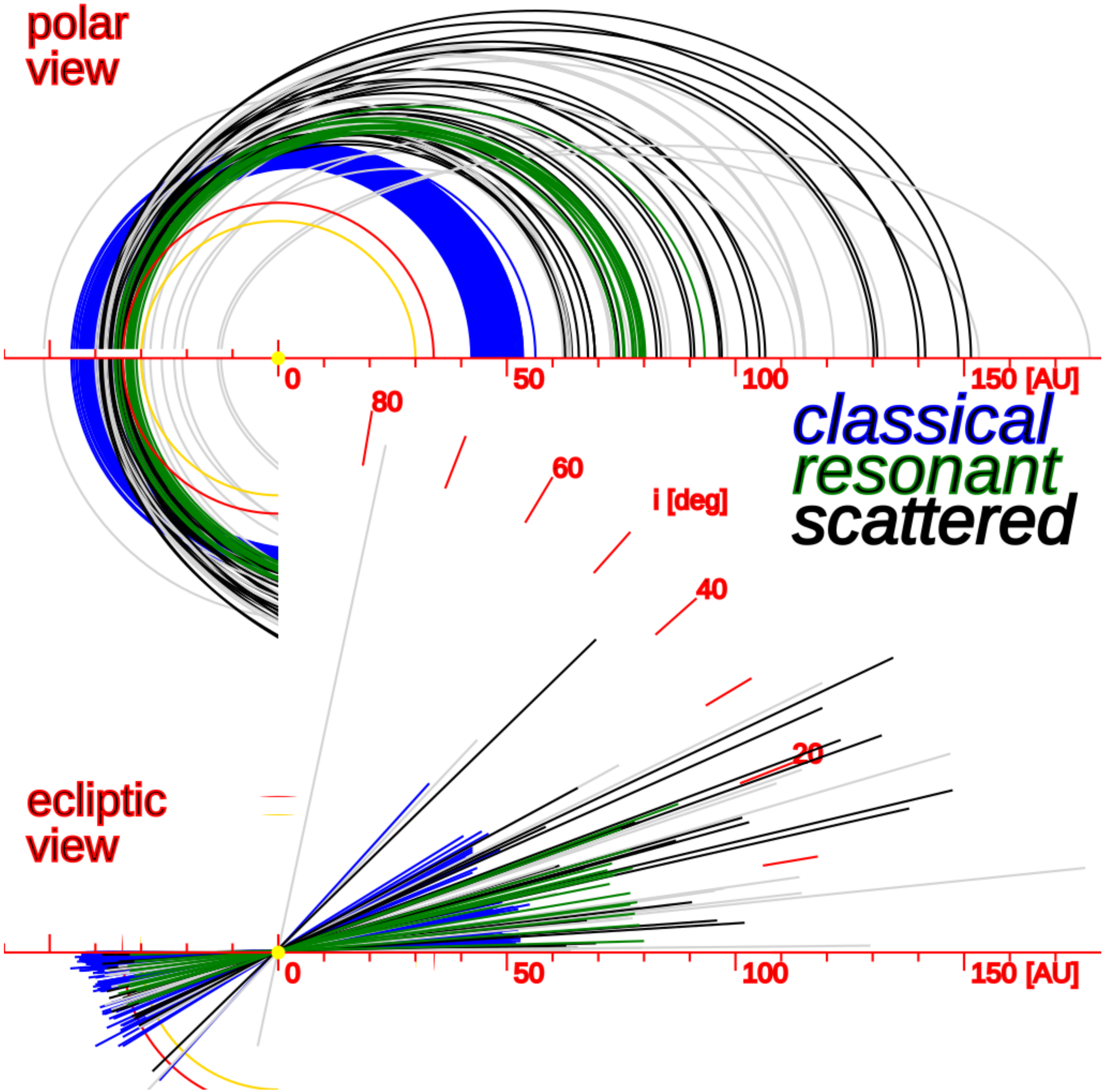
The Kuiper Belt is a torus of small icy bodies beyond Neptune, extending from 30 - 50 AU. Kuiper Belt Objects (KBOs) are primarily classified into two main groups: **classical and resonant.**

Scattered Disk Objects are bodies between 50 - 1000 AU that were gravitationally scattered by Neptune, giving them highly eccentric and elongated orbits.

Classical KBOs: Orbits like those originally expected for the Kuiper Belt, before astronomers began discovering objects there (i.e., low eccentricity and low inclination).

Resonant KBOs: Orbits in a stable, repeating resonance with Neptune (e.g., 2:3 for Pluto, meaning 2 orbits of Pluto for every 3 of Neptune).

Scattered Disk Objects: Highly elliptical and inclined orbits caused by Neptune's scattering; some reach hundreds of AU from the Sun and far above the ecliptic.




Pause

Assessment of Learning Objectives

Q3: Pluto is classified as a scattered Kuiper Belt Object.

True = 1️⃣ False = 2️⃣

Assessment of Learning Objectives

Q4: Eris is classified as a resonant Kuiper Belt Object.

True = 1️⃣   False = 2️⃣

Have we found all the planets?

Six distant objects beyond Neptune have been discovered with orbits aligned in the same direction and tilted similarly relative to the plane of the Solar System. that all line up in a single direction, and tilt nearly identically away from the plane of the Solar System. Researchers using N-body simulations have found that this configuration could be explained by an undiscovered ninth planet.

Brain Break – Think-pair-share

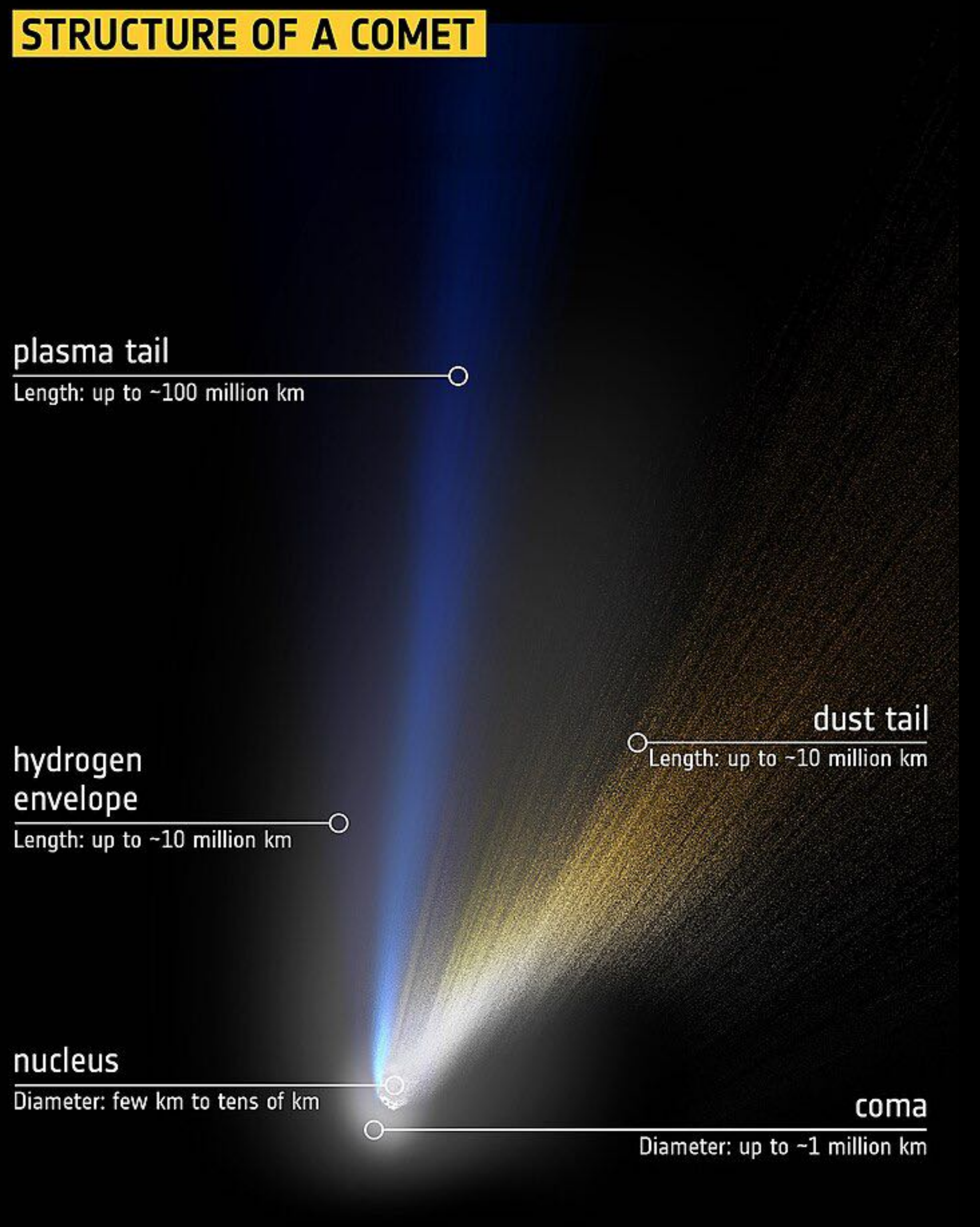
Even today, we are still searching for the hypothesized Planet 9, estimated to have a mass **10 times that of Earth**, and an elongated orbit between **400-800 AU.**

Imagine that you have been tasked with designing a survey to detect this faint, cold, distant, and slow-moving object.

- **What type of telescope and instruments would you use?**
- **What wavelengths would you observe?**
- **What observing cadence and survey strategy would you adopt?**
- **Assuming it exists, are there any upcoming surveys capable of detecting it?**

Comets

- Too small to be directly detected, but we can see their evolution over their orbit.
- Made up of loosely packed ices mixed with rocky material
- Sublimation produces the **coma**, which can be much bigger than the **nucleus**.
- Ionized gas is swept away by the solar wind creating the **ion (plasma) tail**.
- Dust particles are pushed on by *radiation pressure* from the Sun in a curved **dust tail**.



Two Classes of Comets | Short Period

Short-period comets have orbital periods less than 200 years — i.e., located at < 34 AU.

- Most have moderate inclinations ($i < 30°$), though a few are retrograde ($i > 90°$), and typical eccentricities are large ($e \sim 0.8$).
- The most famous short-period comet is Comet Halley with a period of 76 years.
- Thought to originate from the Kuiper Belt.

Two Classes of Comets | Long Period

Long-period comets have orbital periods greater than 200 years — i.e., located at > 34 AU.

- Their inclinations are nearly random, with as many retrograde and prograde orbits.
- They have extremely high eccentricities ($e \approx 1$).
- Some long-period comets have incredibly long orbits, with periods up to 30 million years, implying a distance of a ~ 100,000 AU!
- Thought to originate from the “Oort Cloud”.


Solar System Distances
Sun
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Termination Shock
Heliopause
Oort Cloud
α-Centauri
AC +79 3888
1
10
100
1,000
10,000
100,000
1,000,000
Voyager 1
Heliosphere
Interstellar Space

HW Prep Problem

The Comet Halley has a perihelion distance $q = 0.586\ \mathrm{AU}$ and orbital eccentricity $e = 0.967$.

a.) What is the semimajor axis of its orbit in AU (to 2 decimal places)?

b.) What is its orbital speed at perihelion in km/s (to 2 decimal places)?


Pause

Meteoroids and Dust

The standard model of planetary formation proposes that tiny solid particles condensed from the pre-solar nebula and gradually stuck together to form larger bodies called *planetesimals*. These planetesimals then collided and merged over time, eventually building the planets.

We know that the **formation planets from planetesimals was not completely efficient** as we see leftover planetesimals today in the form of comets and asteroids.

Similarly, **the formation of planetesimals from smaller particles was likely not fully efficient**, leaving behind residual dust grains throughout the Solar System.

However, as we'll see, non-gravitational processes can remove small solid particles from the Solar System over time.

Scattering of Light Review

The scattering cross-section σ depends on the ratio L/λ, where L is particle size and λ is the wavelength of light

- **Rayleigh Scattering ($L \ll \lambda$):** When particles are much smaller than the wavelength the scattering cross-section scales as $\sigma \propto \lambda^{-4}$, meaning smaller wavelengths of light are preferentially scattered. This is the reason why the day sky is blue and sunsets are red.

- ***Mie Scattering*** **($L \sim \lambda$):** When particles are similar size to the wavelength, the scattering cross-section scales as $\sigma \propto \lambda^{-1}$. Common for dust with $L \sim 1\ \mu m$ and has the effect of scattering red and near-IR light. This is the reason why dusty galaxies look red.

- ***Geometric scattering ($L \gg \lambda$):*** When particles are much larger than the wavelength, the scattering cross-section becomes wavelength independent. Common for large particles such as water droplets $L \sim 10\ \mu m$. Since all light is evenly scattered, the objects appear white — reason why clouds are white.

Radiation Pressure

The smallest solid particles can be removed by ***radiation pressure***, which is defined as.

$$F_{\rm rad} = P_{\rm rad}\sigma_{\rm pr},$$

where $P_{\rm rad}$ is the pressures exerted by photons and $\sigma_{\rm pr}$ is the effective cross-section of the particle for interactions with photons.

For a spherical dust grain of radius R, the cross-section can be written as

$$\sigma_{\rm pr} = Q_{\rm pr}\pi R^2,$$

where πR^2 is the *geometrical cross-section*, and $Q_{\rm pr} \leq 1$ is the *radiation pressure coefficient*.

Radiation Pressure

The value of $Q_{\rm pr}$ depends primarily on the size of the dust grain relative to the wavelength of the light acting on it.

We've seen that the peak wavelength of the Sun is $\lambda_{\rm peak} \approx 5000\ \text{Å}$.

If a dust grain has $R \gg \lambda_{\rm peak} \rightarrow Q_{\rm pr} = 1 \rightarrow \sigma_{\rm pr} = \pi R^2$

If a dust grain has $R \ll \lambda_{\rm peak} \rightarrow Q_{\rm pr} \ll 1 \rightarrow \sigma_{\rm pr} \sim (R/\lambda_{\rm peak})^4$

However, since dust grains can absorb AND scatter light, the dependence of $Q_{\rm pr}$ deviates from the pure Rayleigh scattering.

Empirically, it is found that dust grains made of rock or ice have $Q_{\rm pr} \propto R^2$ in the limit $R \ll \lambda_{\rm peak}$.

Radiation Pressure

Pressure, defined as force per unit area, is equivalent to "momentum flux".

The momentum of a photon is given by,

$$p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda} \quad \text{(de Broglie equation)}$$

We can use this expression to relate the pressure of solar radiation to the solar energy flux:

$$\mathrm{P_{rad}} = \frac{\text{force}}{\text{area}} = \frac{\text{momentum}}{\text{time} \times \text{area}} = \frac{\text{energy}}{\text{speed of light} \times \text{time} \times \text{area}} = \frac{\text{energy flux}}{\text{speed of light}}$$

Radiation Pressure

The energy flux of the Sun is the ratio of the total energy output of the Sun ($L_\odot$) to the surface area of a sphere of radius r.

$$\text{energy flux of the Sun} = \mathrm{F(d)} = \frac{\mathrm{L}_\odot}{4\pi \mathrm{r}^2}$$

Therefore, the pressure of solar radiation can be written as

$$P_{\mathrm{rad}} = \frac{\text{energy flux}}{\text{speed of light}} = \frac{1}{c}\frac{L_\odot}{4\pi r^2}.$$

Radiation Pressure

Radiation pressure will push a *spherical* particle away from the Sun, with a force

$$F_{\rm rad} = P_{\rm rad}\sigma_{\rm pr} = \frac{L_\odot}{4\pi r^2 c} Q_{\rm pr}\,\pi R^2 = \frac{L_\odot}{4c}\left(\frac{R^2}{r^2}\right) Q_{\rm pr}$$

At the same time, the Sun will exert a gravitational force on the particle

$$F_{\rm grav} = -\frac{GM_\odot m}{r^2} = -\frac{GM_\odot}{r^2}\frac{4\pi\rho R^3}{3}$$

Radiation Pressure

If we take the ratio of these forces we get,

$$\frac{F_{\rm rad}}{|F_{\rm grav}|} = \frac{3}{16\pi}\frac{L_\odot}{GM_\odot c}\frac{Q_{\rm pr}}{\rho R} = 5800\ \text{Å}\left(\frac{1000\ \mathrm{kg\,m^{-3}}}{\rho}\right)\left(\frac{1}{R}\right)Q_{\rm pr}$$

Limiting cases of small vs. large grains:

- When $R \ll \lambda_{\rm peak}$ the radiation pressure coefficient scales a $Q_{\rm pr} \propto R^2$, meaning that for **small grains** the ratio of the radiative force to gravitational force increases linearly with R.

- When $R \gg \lambda_{\rm peak}$ the radiation pressure coefficient scales a $Q_{\rm pr} = 1$, meaning that for **large grains** the ratio of the radiative force to gravitational force decreases as $1/R$.

Radiation Pressure

Escape condition: Dust grains will be ejected from the Solar System if the outward radiative force exceeds the inward gravitational force.

This occurs when the grain radius (R) satisfies:

$$R < 5800\ \text{Å} \left(\frac{1000\ \text{kg}\,\text{m}^{-3}}{\rho} \right) Q_{\text{pr}}$$

This tells use that,

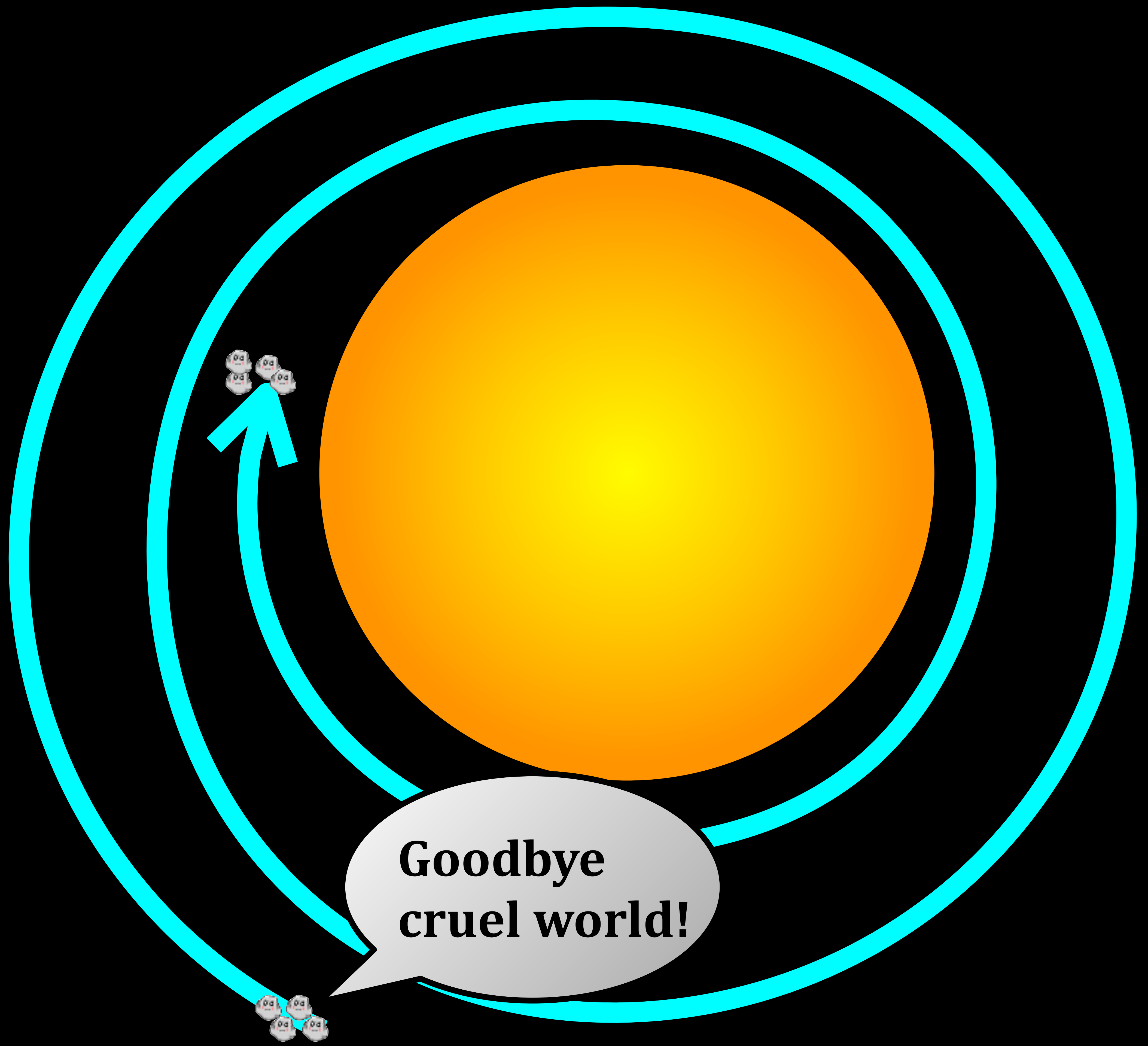
- Large grain ($R \gg \lambda_{\text{peak}}$) will **not** be blown away because gravity dominates.
- Tiny grains ($R \ll \lambda_{\text{peak}}$) **will only** be expelled if their **density is very low**.
  - This is because the values of Q_{pr} fall off too rapidly as R decreases.
- Intermediate grains ($R \sim \lambda_{\text{peak}} \sim 5000\ \text{Å}$) are efficiently accelerated and can be **blown out of the solar system** by radiation pressure.


Pause

Poynting-Robertson Effect

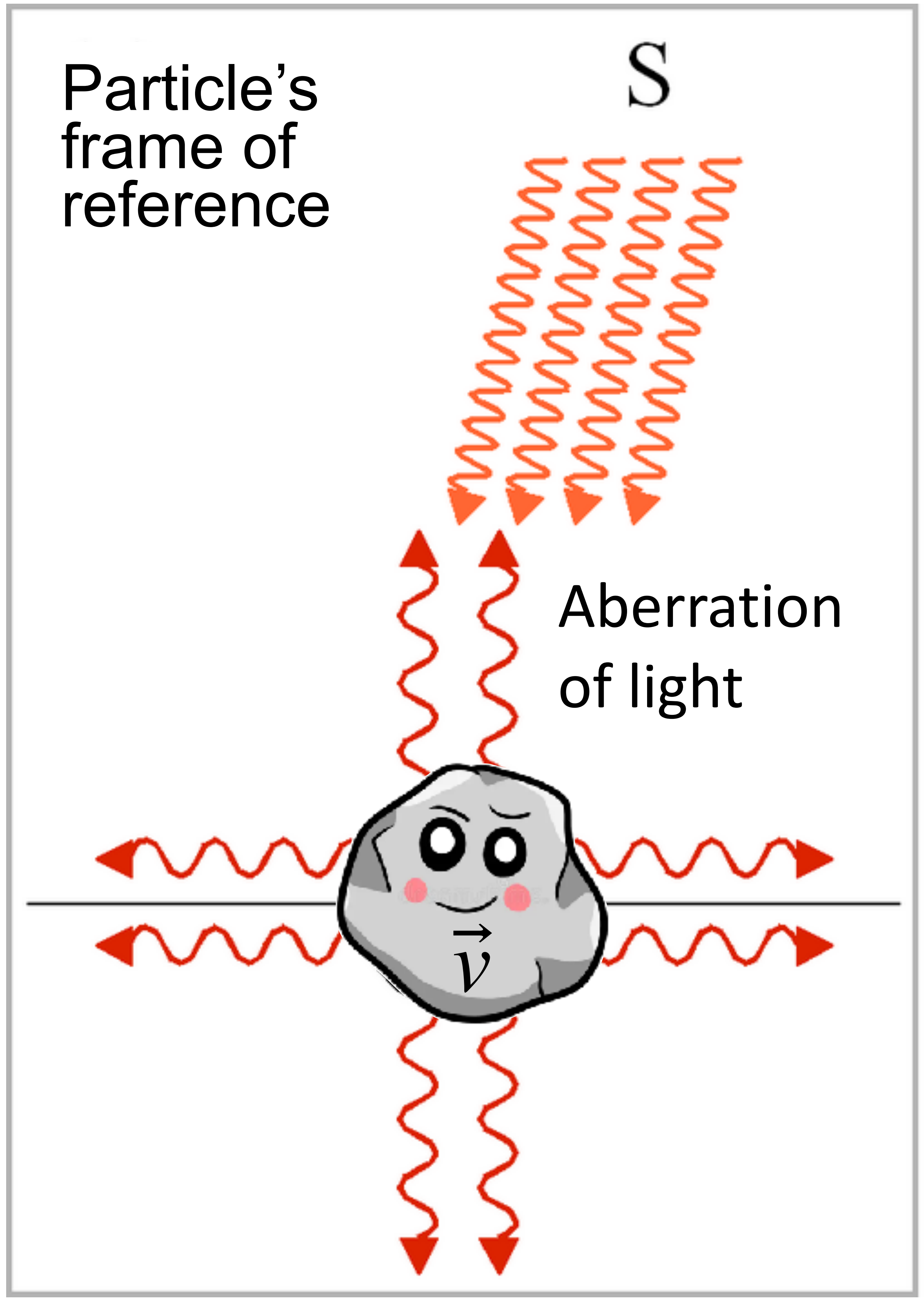
For large dust grains with $R \gg 5000\ \text{Å}$, where the Sun's gravity dominates over radiation pressure, a mechanism known as the **Poynting–Robertson effect.**

The Poynting-Robertson effect acts like a brake, **reducing the angular momentum of the particles and causing them to slowly spiral toward the Sun.**



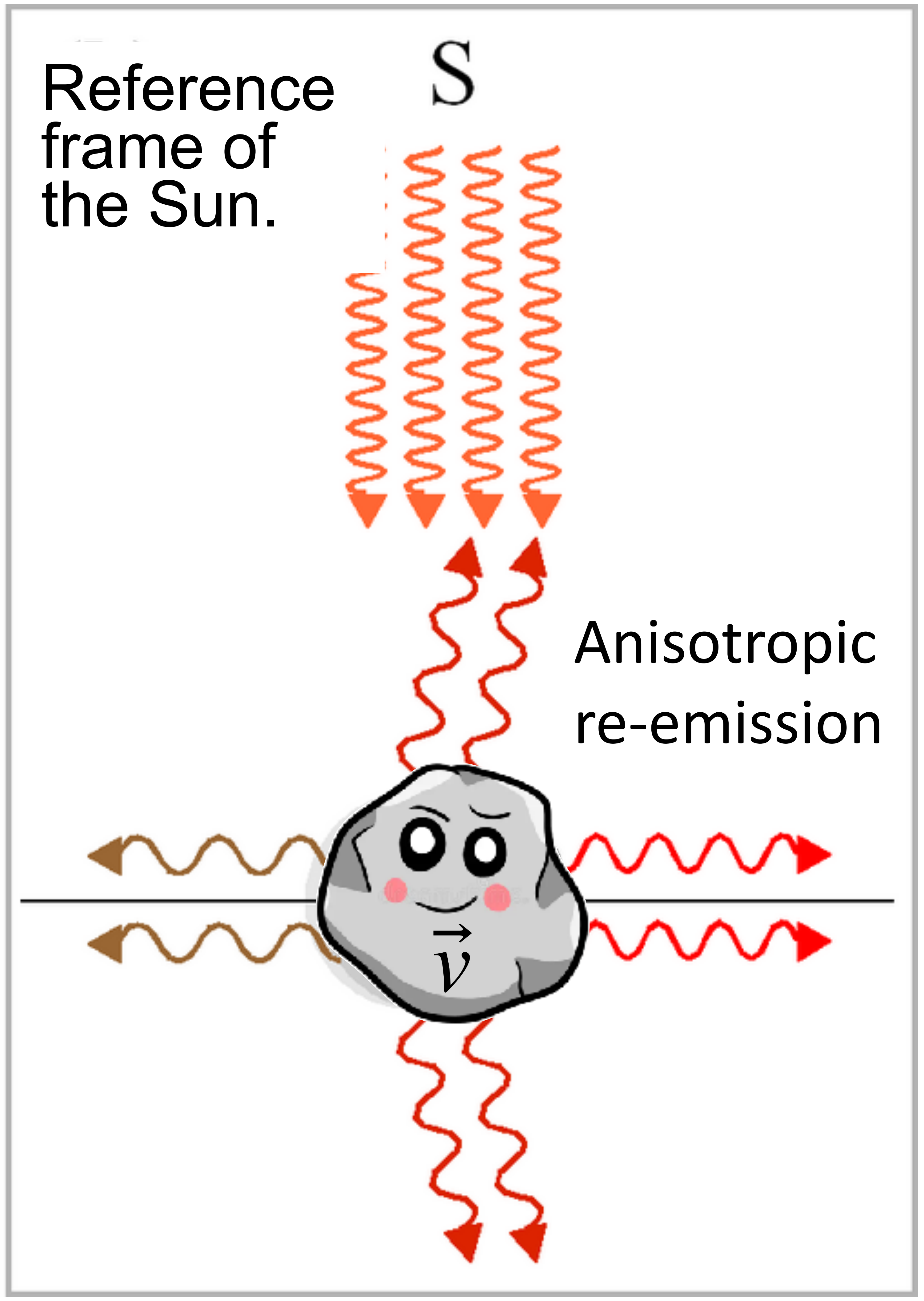
Poynting–Robertson Drag: Particle's reference frame

- Due to the **aberration of light**, the grain "sees" sunlight coming slightly **forward along its orbit.**
- As a consequence, the radiation force is **not perfectly parallel,** producing a **torque that removes angular momentum.**
- This causes the particle to **spiral inward toward the Sun**.



Poynting–Robertson Drag: Sun's reference frame

- The particle absorbs sunlight and re-emits it in an anisotropic manner (i.e., with a preferred direction).
- This anisotropic re-emission is slightly **forward along the grain's motion** due to its velocity.
- This causes a **net drag force opposite the orbital motion**, reducing angular momentum and causing the grain to **spiral inward toward the Sun**.



Poynting-Robertson Timescale

Assuming roughly spherical particles on circular orbits with $R \gg \lambda_{\text{peak}} \sim 5000\ \text{Å}$ (hence $Q_{\text{pr}} = 1$), we can derive how long it'll take to spiral into the Sun. This is known as the **Poynting-Roberston Timescale.**

$$t_{\text{PR}} \approx 0.7\ \text{Gyr} \left(\frac{a}{1\ \text{AU}}\right)^2 \left(\frac{\rho}{1000\ \text{kg m}^{-3}}\right) \left(\frac{R}{1\ \text{m}}\right),$$

where, a is the orbital distance, ρ is the density of the particle, and R is the radius of the particle.

Therefore, over the Solar System's lifetime (~4.6 Gyr) we should expect:

- Sub-meter rocky particle ($\rho \approx 3000\ \text{kg m}^{-3}$) to have been cleared out to ~1.5 AU.
- Sub-centimeter rocky particles ($\rho \approx 3000\ \text{kg m}^{-3}$) to have been cleared out to ~15 AU.

Zodiacal Light

Despite the presence of radiation pressure and the Poynting–Robertson effect, we find that tiny particles still exist in the inner solar system, and we see them along the ecliptic in reflected sunlight.

This is known a “zodiacal light” and is seen as a triangular glow in night skies free of moonlight and light pollution as seen in this photo was taken at La Silla Observatory in Chile.

Meteoroids & Meteors

The particles that scatter light to create zodiacal light are called **meteoroids**. These small particles (diameters < 10 cm) originate from comets and asteroids and are **constantly replenished through collisions.**

Once they enter the Earth's atmosphere, they are heated by friction with air molecules, light up, and the outer layer vaporizes.

We call the long glowing streaks of ionized gas **meteors**. Most are very small, and only bigger ones make it to the surface (> size of basketball).

Meteorites

Estimated 25 million observable meteors enter the atmosphere every day — most vaporize in the atmosphere.

They are found as either

1) Stony: Silicate rocks, 95% of all meteorites

2) Iron: made of an iron-nickel alloy (85%/15%)

The majority of meteorites are found in deserts (Antarctica and Africa), where they are preserved.

Meteorites

Once a meteor lands on Earth it becomes **meteorite.**

Some of them come from other planets, where large impacts accelerated material to large velocities to escape.

The gases trapped within meteorites reveal their origin, which tends to match their planets’ atmospheres.

“Black Beauty” Martian meteorite


Questions?

Reminders

- **HW #6 is due Tuesday, 11/18 by 11:59 pm.**

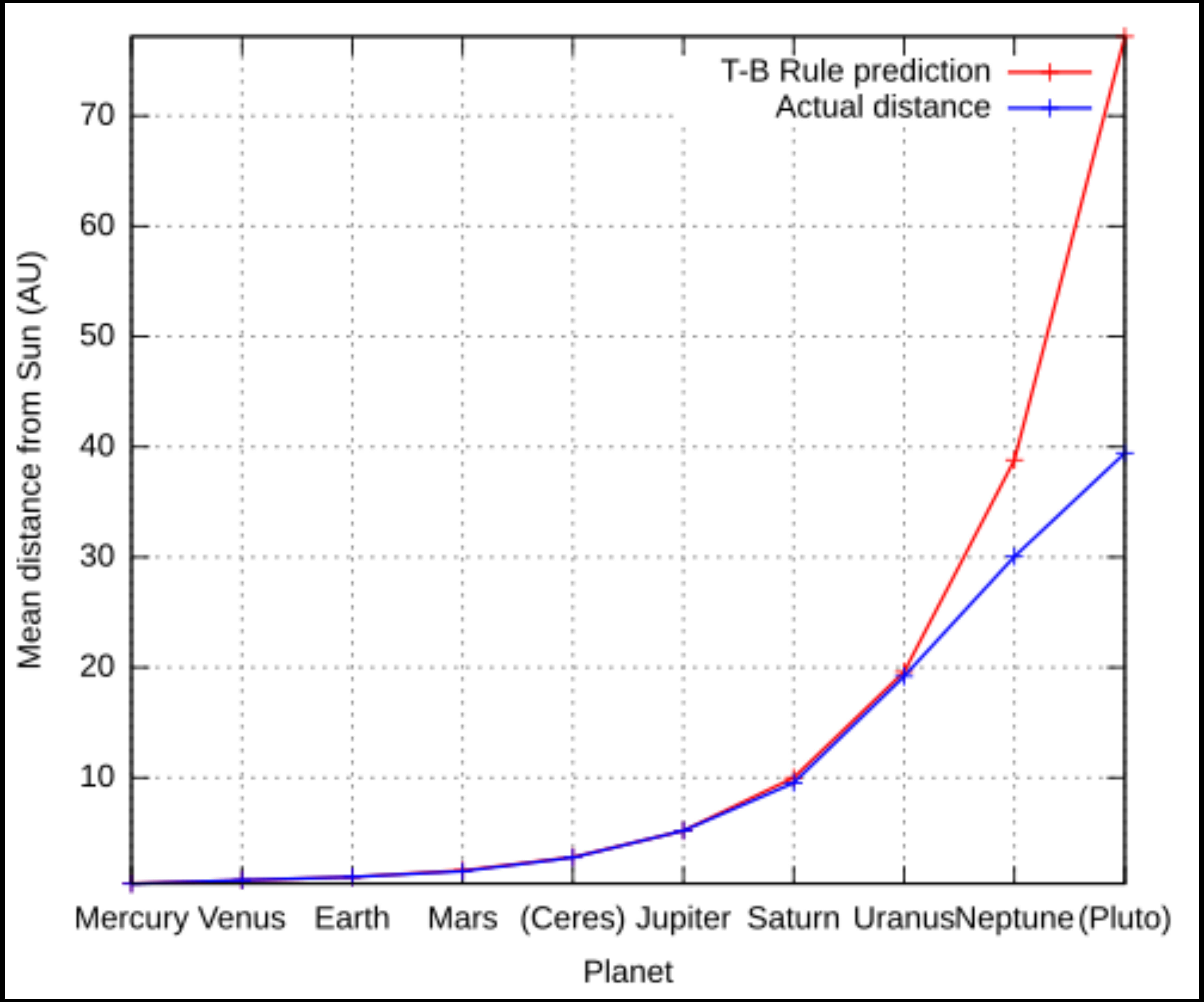
- **HW #7 is due Tuesday, 11/25, by 11:59 pm.**

- **Coding project is due Sunday, 11/30 by 11:59 pm.**

- Log into canvas and submit your answer to the discussion question by the end of the day to receive participation credit.

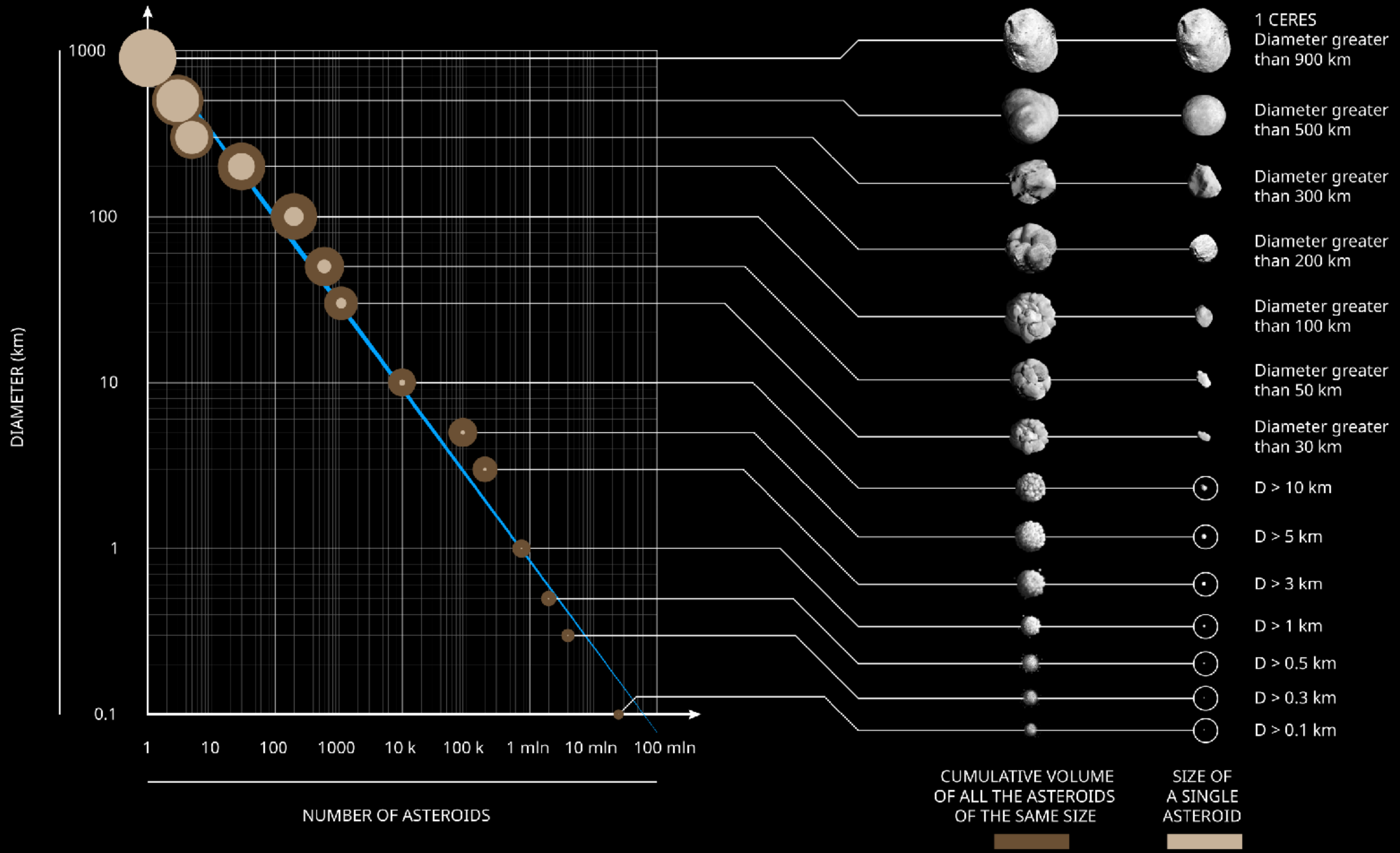
Additional Slides

The Titius-Bode Rule Fails at Large Heliocentric Distances



Testing the Titius-Bode law on exoplanets (Astrobites article)

Size vs. number of asteroids



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