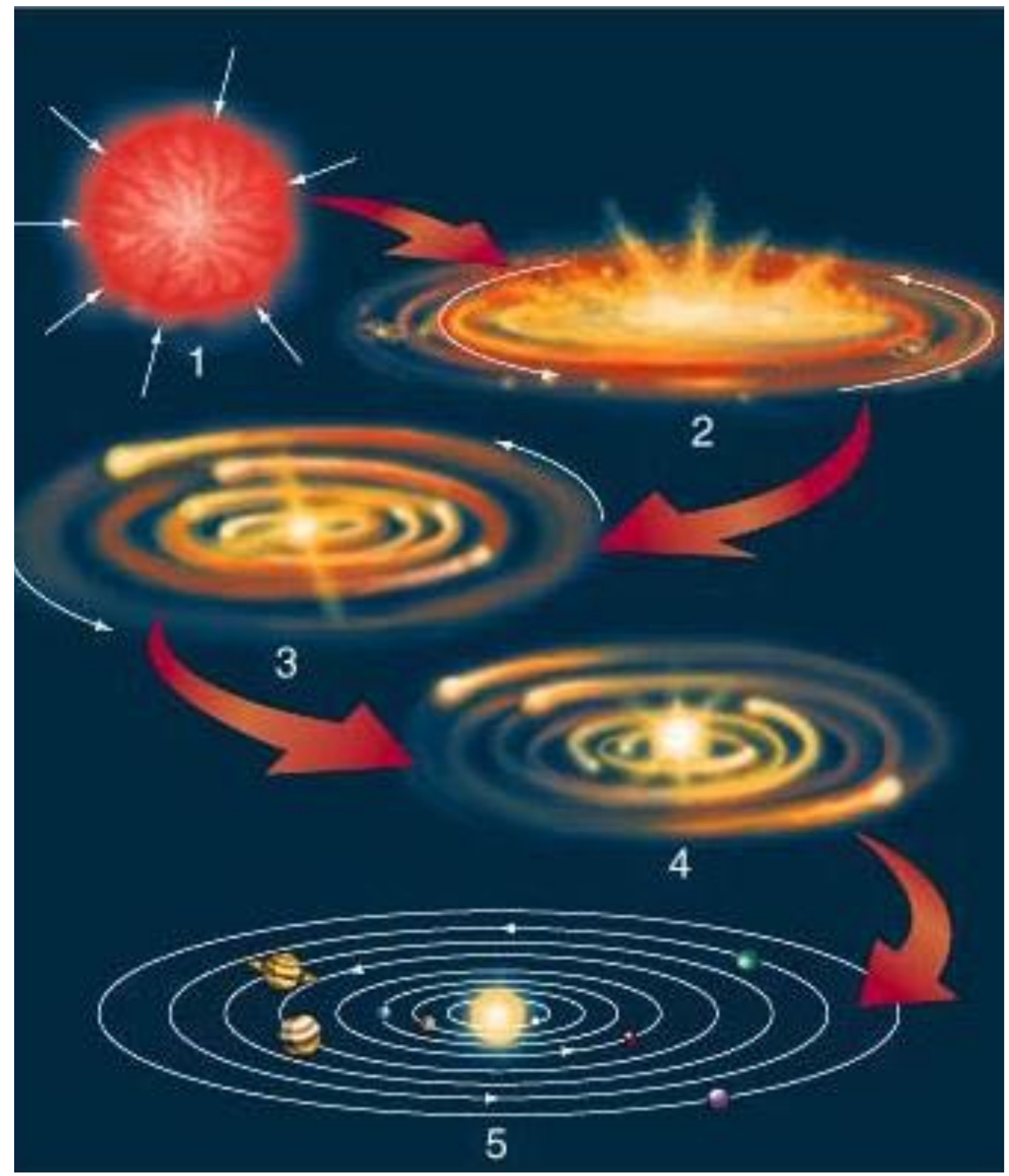
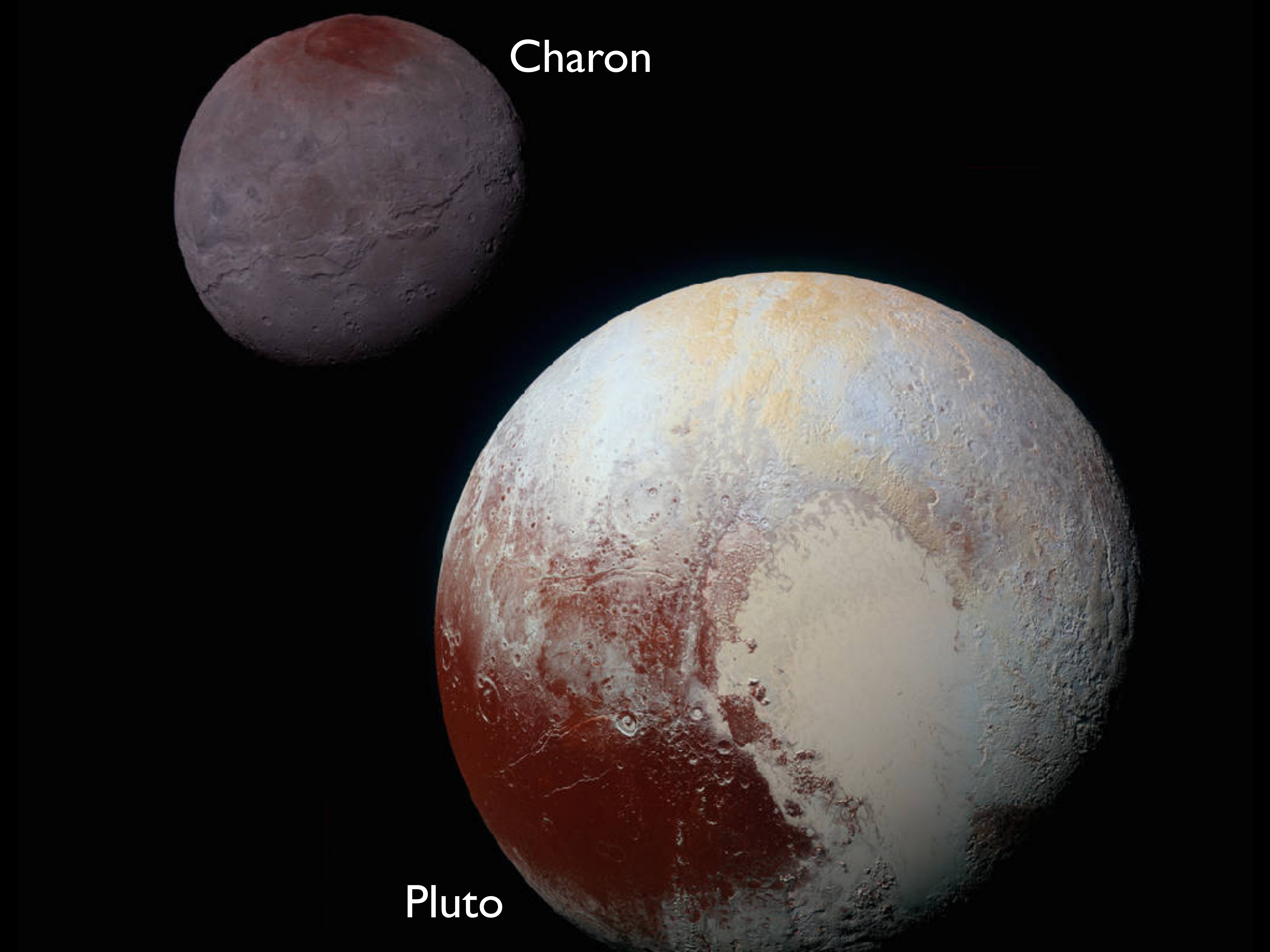
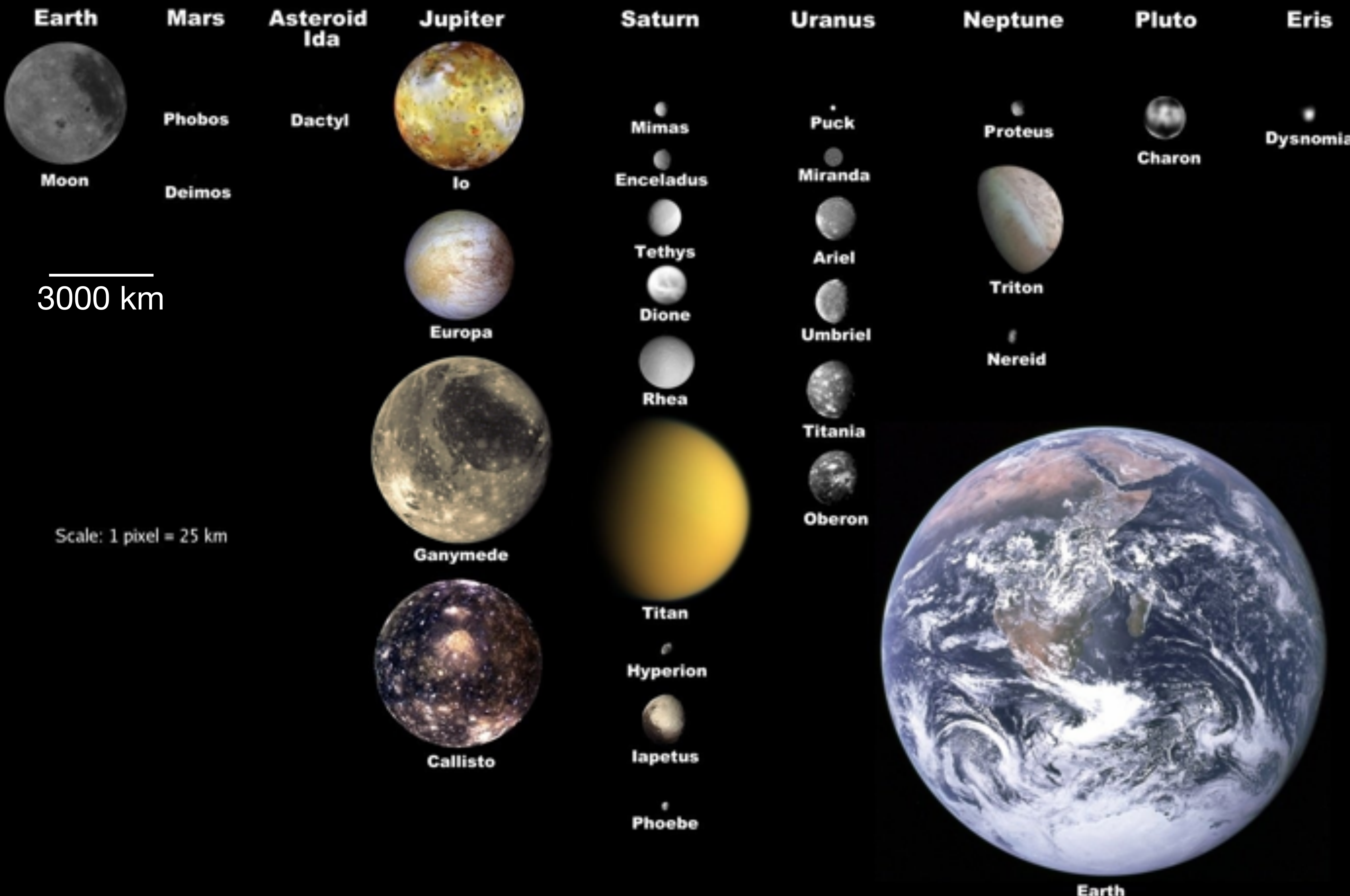
Today

- Solar System Formation
  - a few more bits and pieces
- Homework due

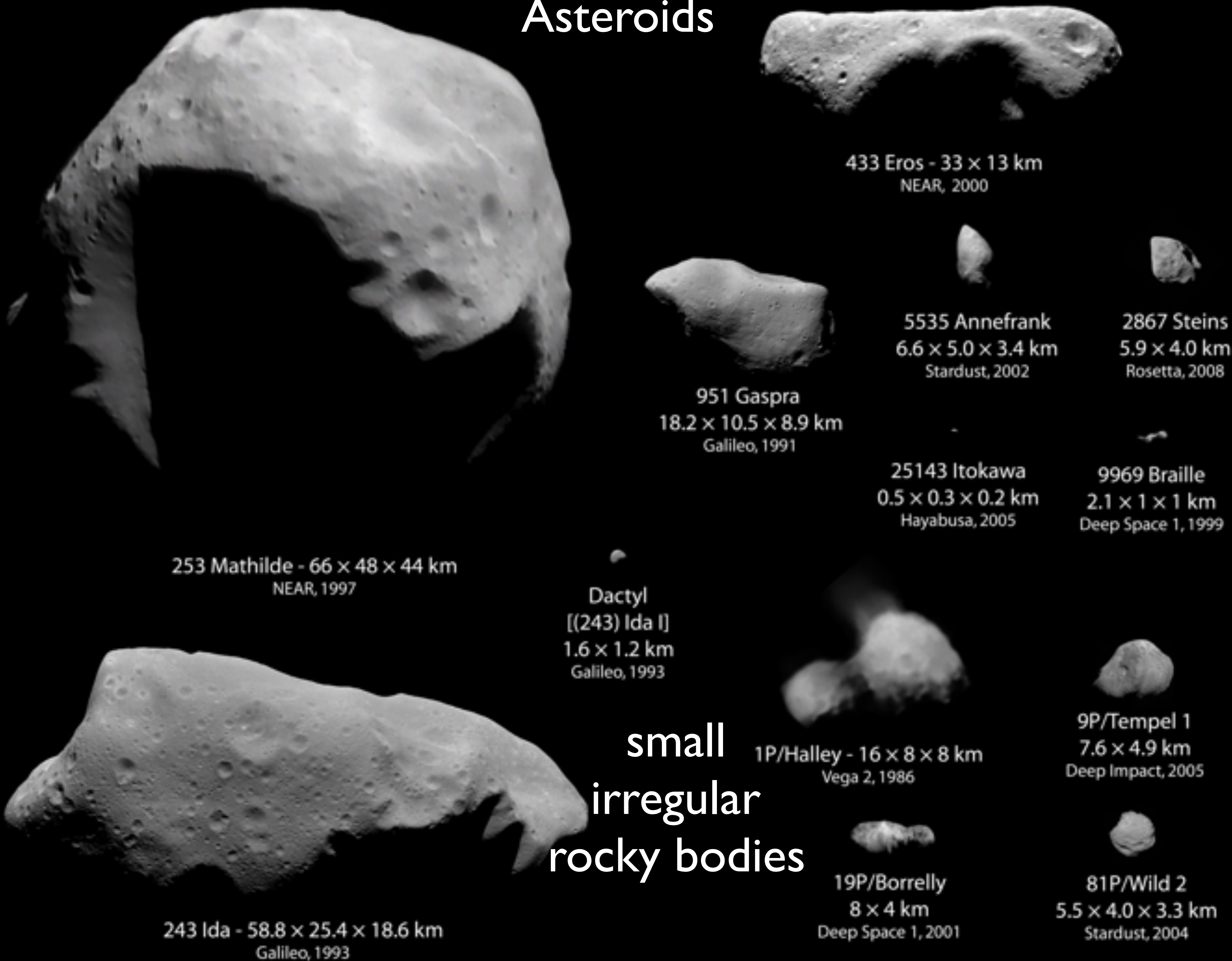



Charon
Pluto

Selected Moons of the Solar System, with Earth for Scale



Asteroids



small
irregular
rocky bodies

Comets icy bodies

Formation of the Solar System

How did these things come to be?

Why are the orbits of the planet so well aligned? Daniel Bernoulli, 1734

What are the odds that the orbital planes of the planets are so well aligned by chance?

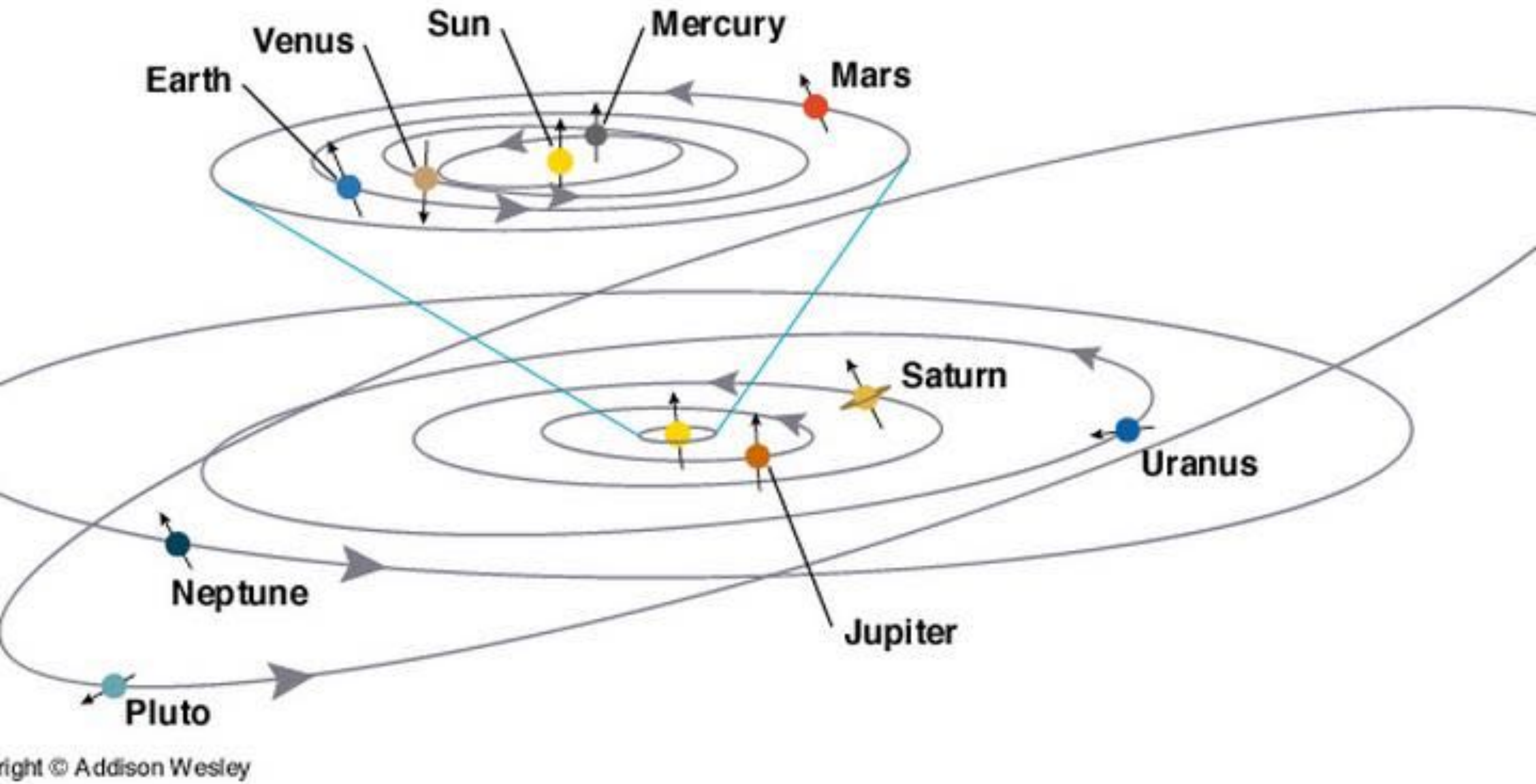
tes de ces deux Orbites. On verra par-là que cette probabilité eſt ſi petite, qu'elle doit paſſer pour une impoſſibilité morale.

"We will see thence that this probability is so small, that it must to be received as a moral impossibility."

About 1 in 1 Million (10^{-6})

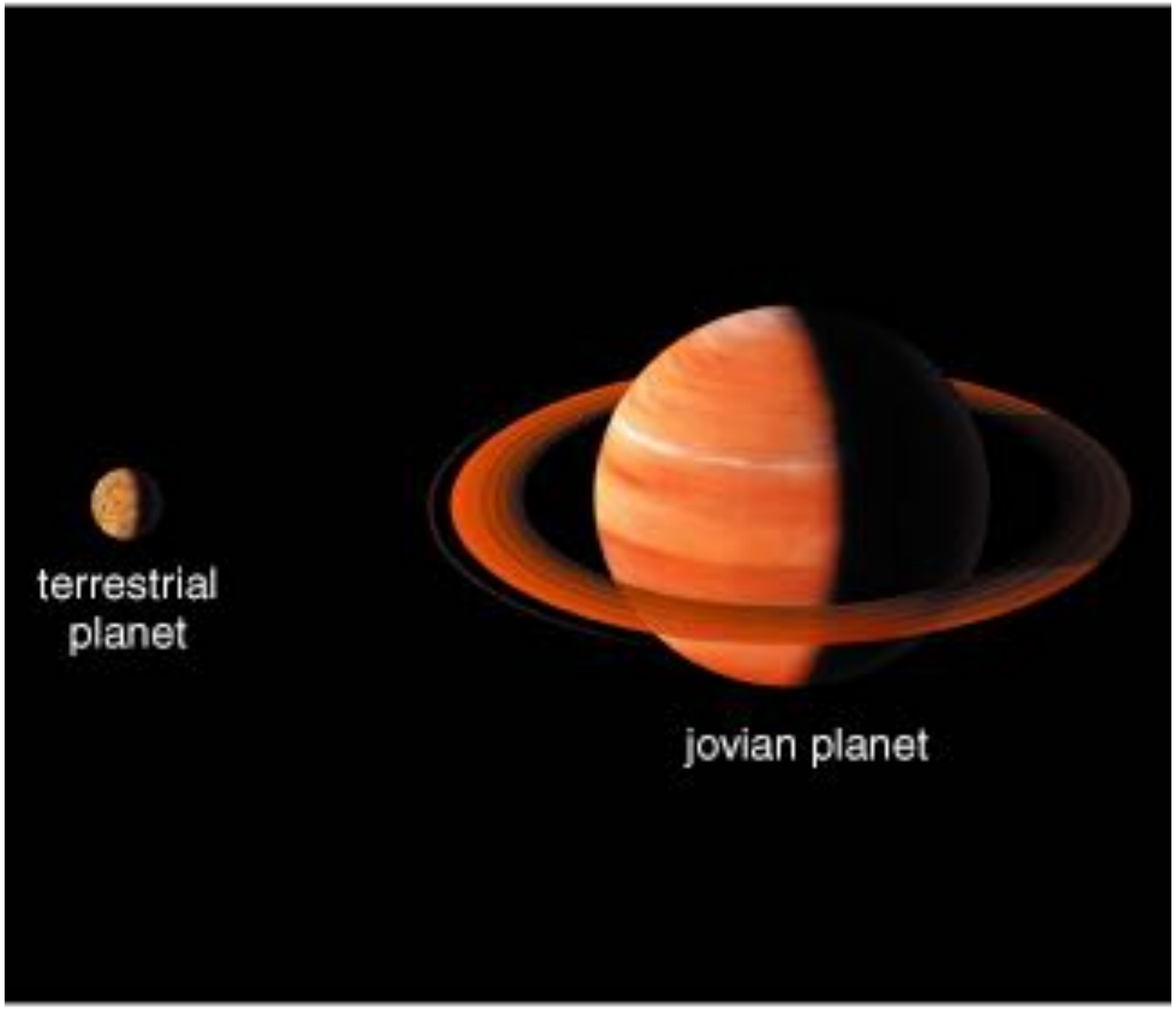
Need to explain why the solar system is so structured

Clues to Solar System Formation



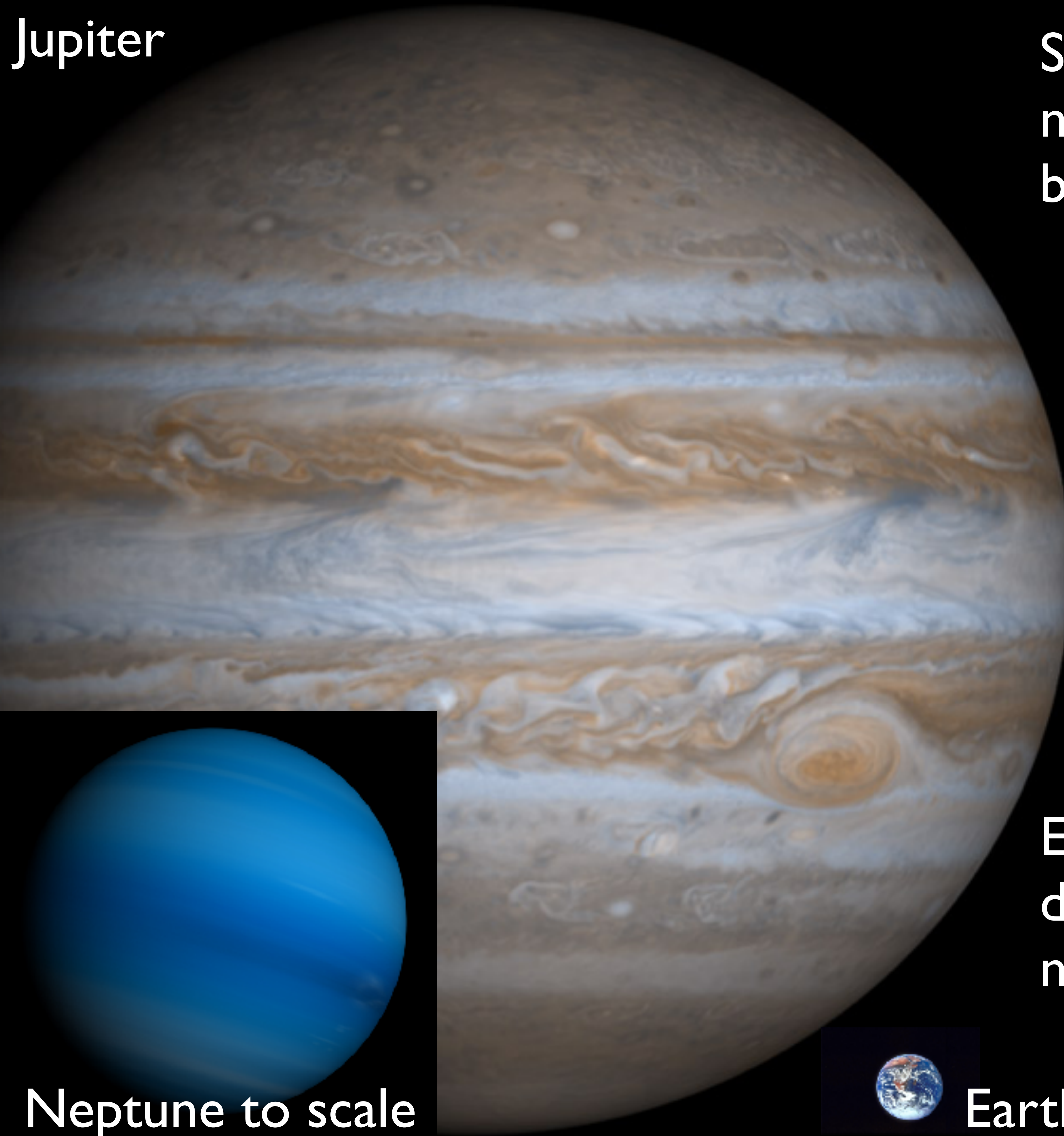
Planar, prograde motion: everything spinning in the same sense

Two Major Planet Types



- Terrestrial planets are rocky, relatively small, and close to the Sun.
- Jovian planets are gaseous, larger, and farther from the Sun.

Jupiter



Some astronomers now distinguish between

Gas Giants
Jupiter, Saturn

and

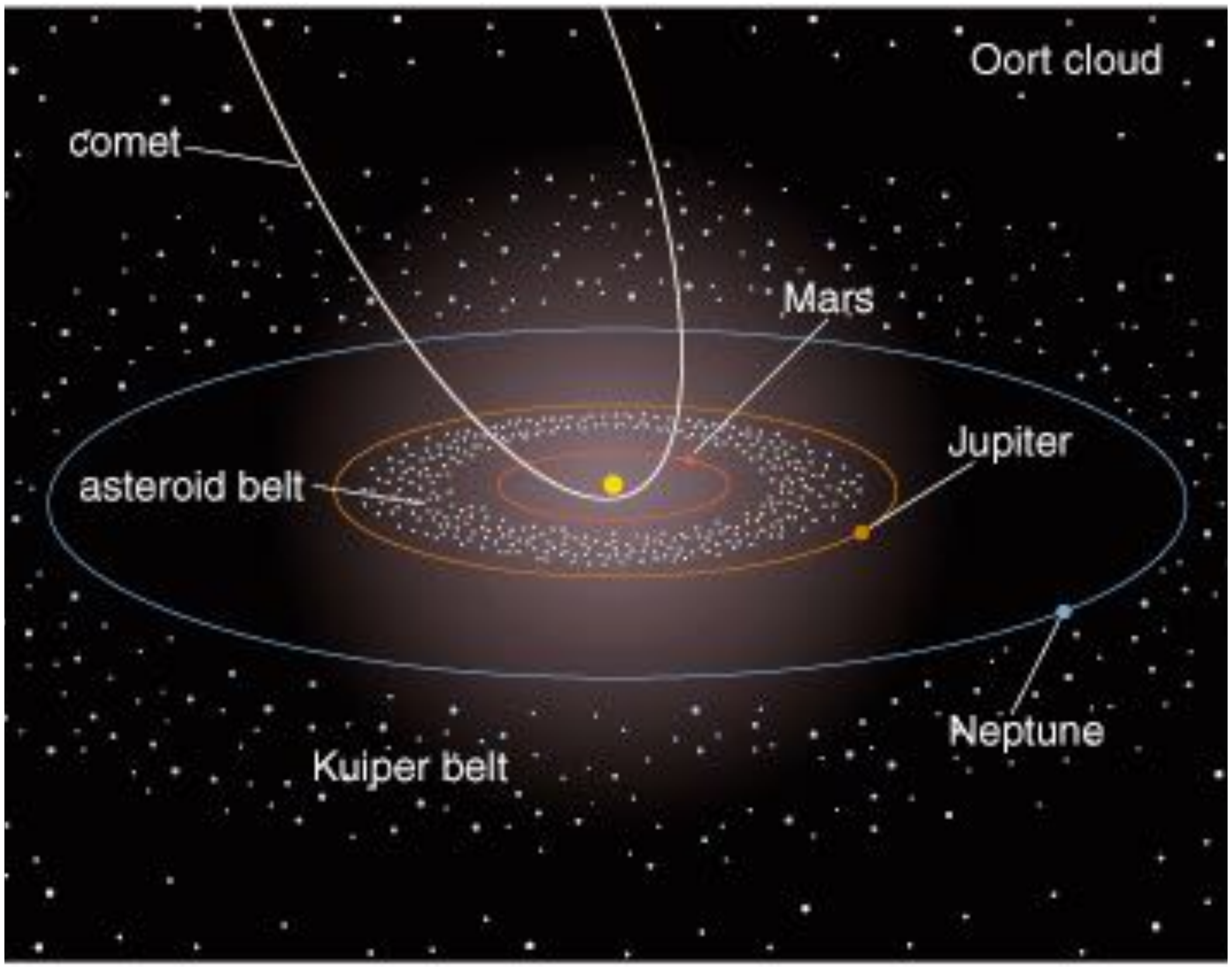
Ice Giants
Uranus, Neptune

Expect more distinctions with new discoveries

Neptune to scale

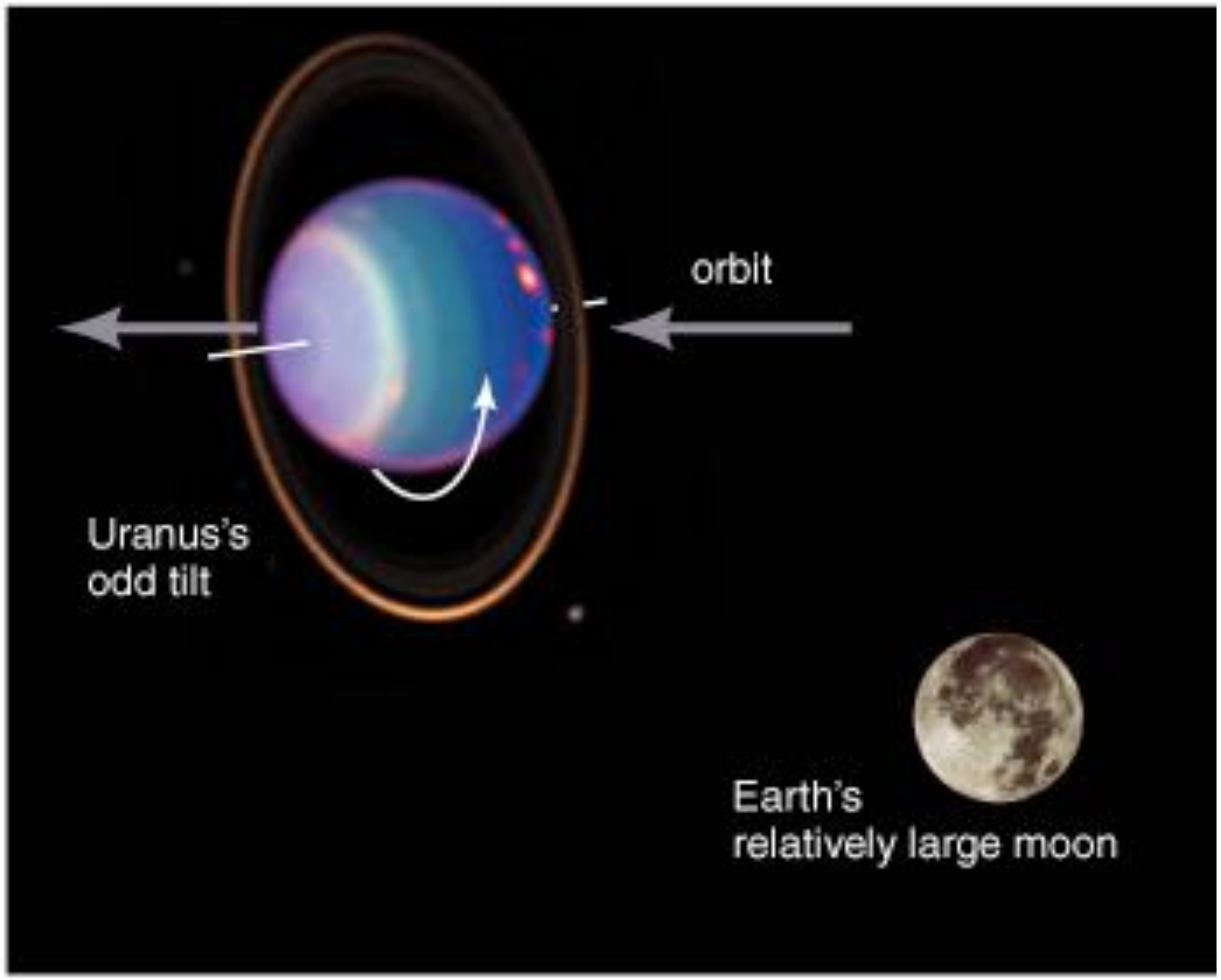
Earth to scale

Swarms of Smaller Bodies



- Many rocky asteroids and icy comets populate the solar system.
- Rocky things close to the sun
- Icy things farther out

Notable Exceptions



- Several exceptions to normal patterns need to be explained.

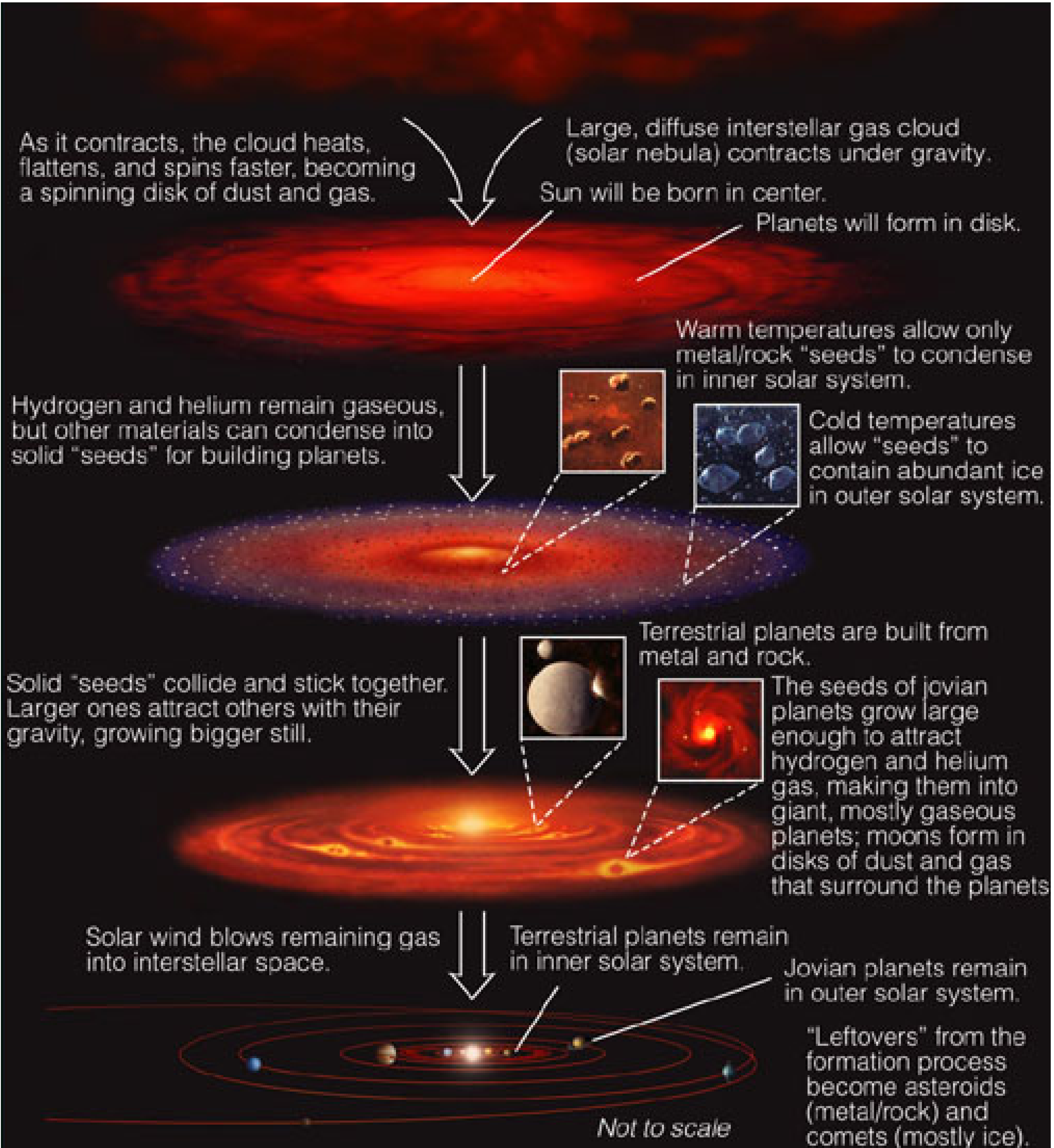
According to the ***nebular theory,*** our solar system formed from a giant cloud of interstellar gas.

(***nebula*** = cloud)

Also known as the ***solar nebula*** hypothesis

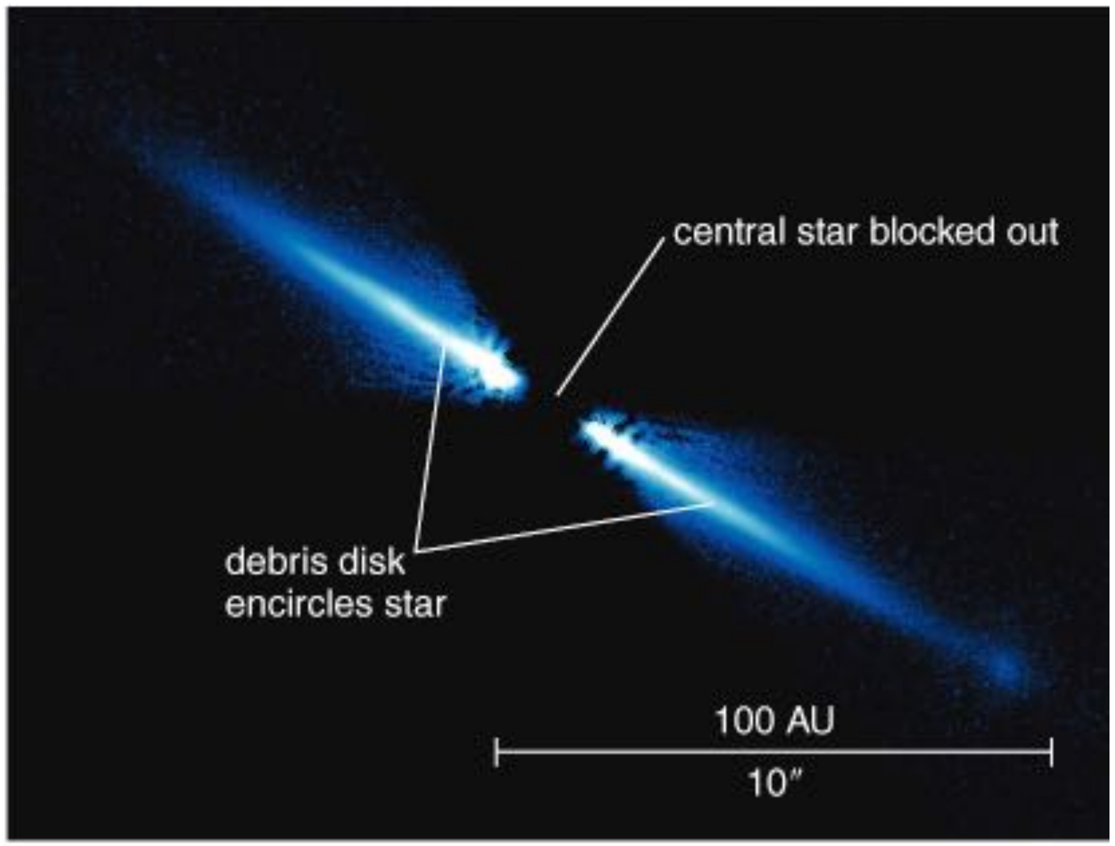
SS formation movie

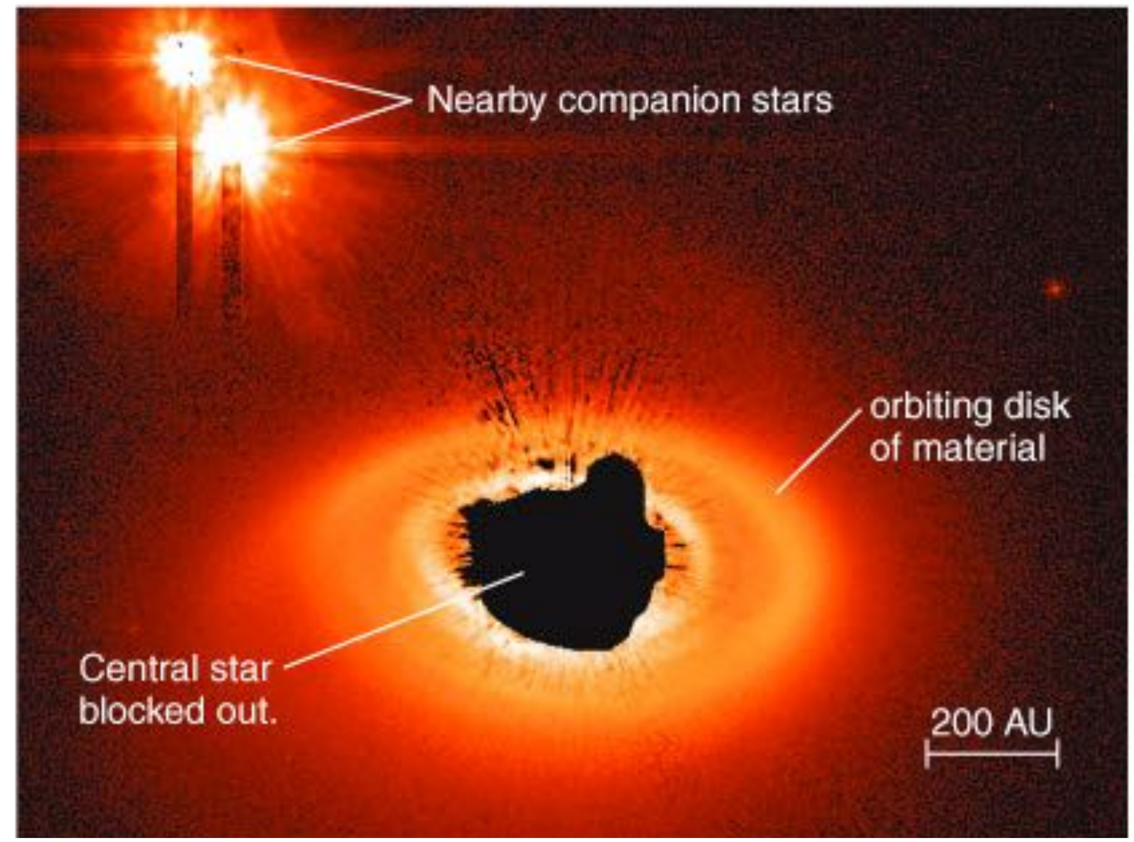
http://www.spitzer.caltech.edu/video-audio/730-ssc2004-22v2-The-Evolution-of-a-Planet-Forming-Disk



- Nebula spins up as it collapses (angular momentum conserved)
- Solid particles condense out of gas
- Particles collide; form ever larger objects
- Most mass eventually swept up into planets

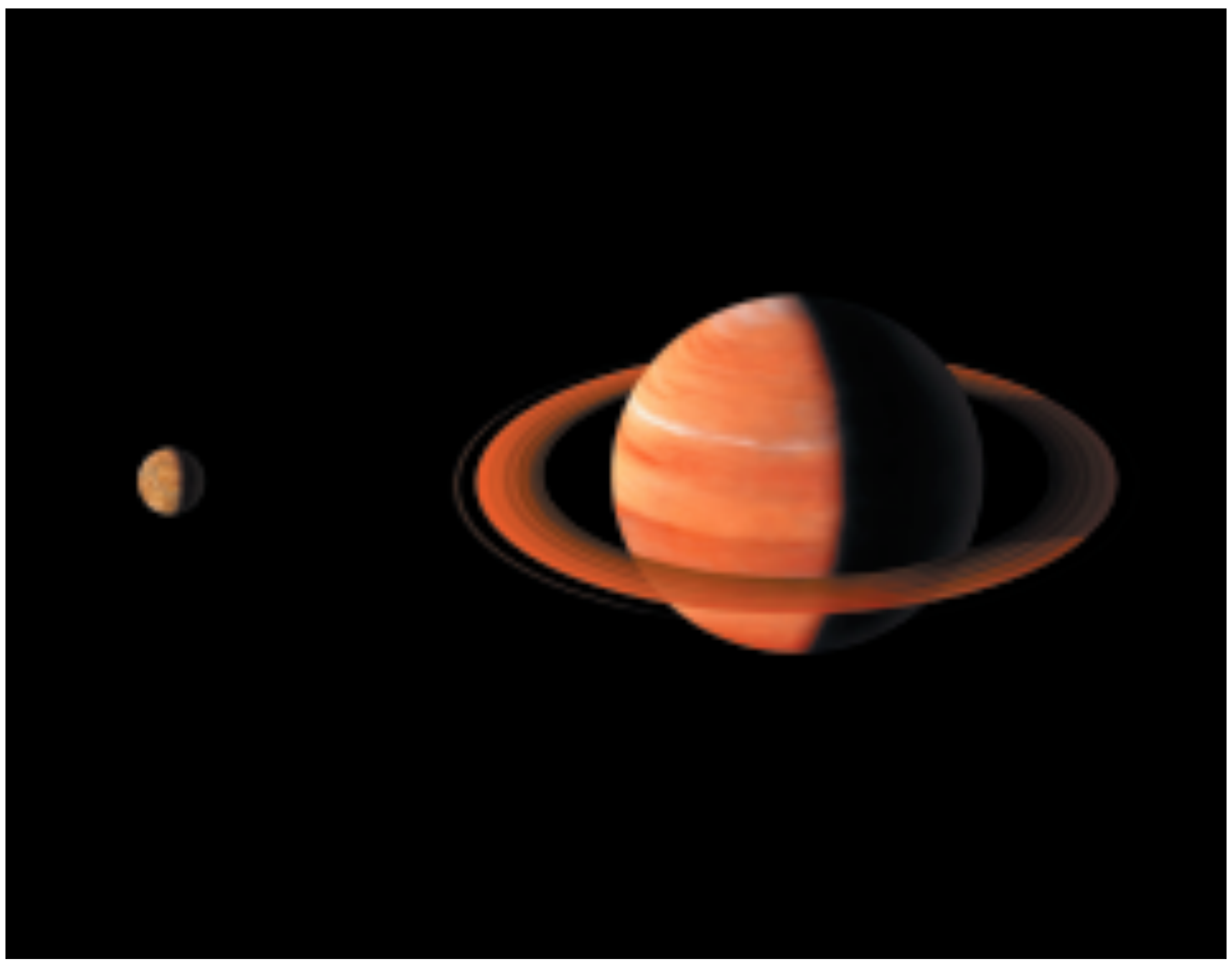
Disks Around Other Stars

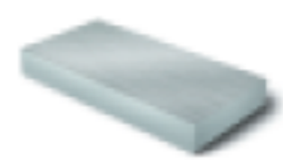


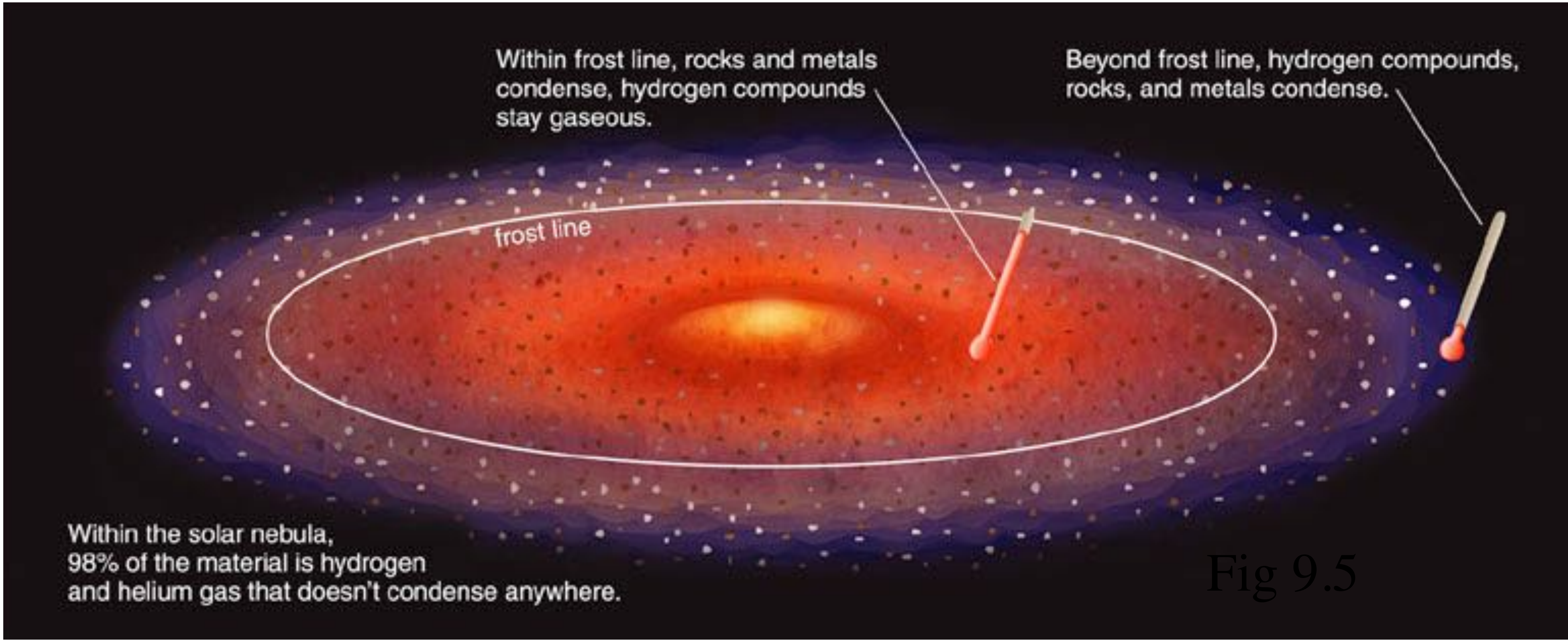


- Observations of disks around other stars broadly support the nebular hypothesis.

Why are there two major types of planets?



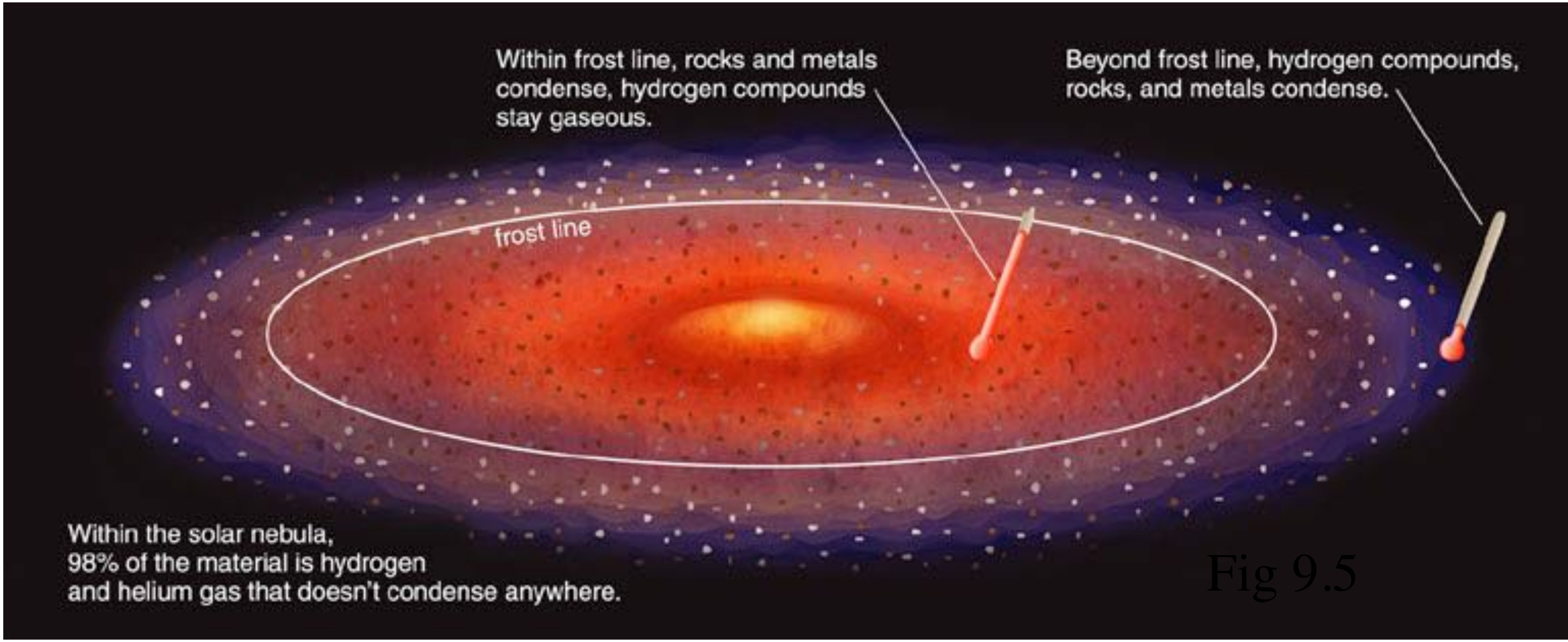
	Examples	*Typical Condensation Temperature*	*Relative Abundance (by mass)*
Hydrogen and Helium Gas 	hydrogen, helium	do not condense in nebula	98%
Hydrogen Compounds 	water (H_2O) methane (CH_4) ammonia (NH_3)	<150 K	1.4%
Rock 	various minerals	500–1,300 K	0.4%
Metals 	iron, nickel, aluminum	1,000–1,600 K	0.2%



As gravity causes the cloud to contract, it heats up.
(The same process continues to heat Jupiter, a tiny bit.)

Inner parts of the disk are hotter than outer parts.

Rock can be solid at much higher temperatures than ice.



FROST LINE at about 3.5 AU

Inside the ***frost line***: Too hot for hydrogen compounds to form ices

- only get rocky asteroids and planets

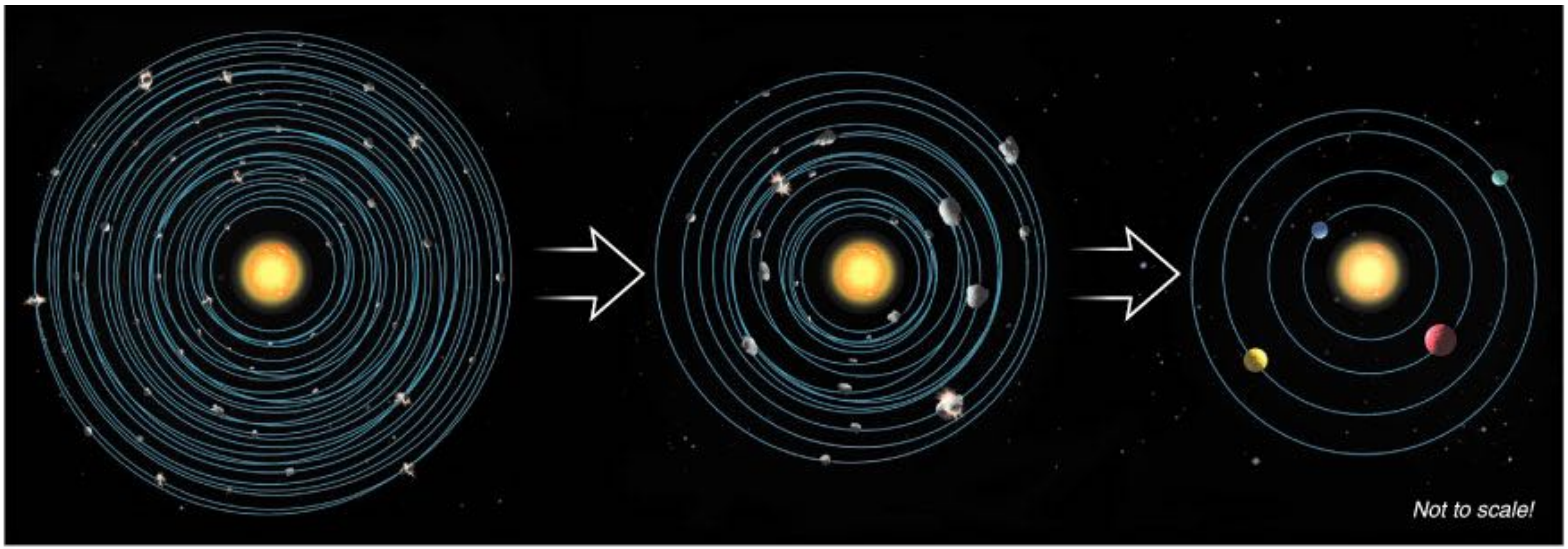
Outside the ***frost line***: Cold enough for ices to form

- get icy moons and comets
- ice is a major component of their total mass

Formation of Terrestrial Planets

- Small particles of rock and metal were present inside the frost line.
- Planetesimals of rock and metal built up as these particles collided.
- Gravity eventually assembled these planetesimals into terrestrial planets.

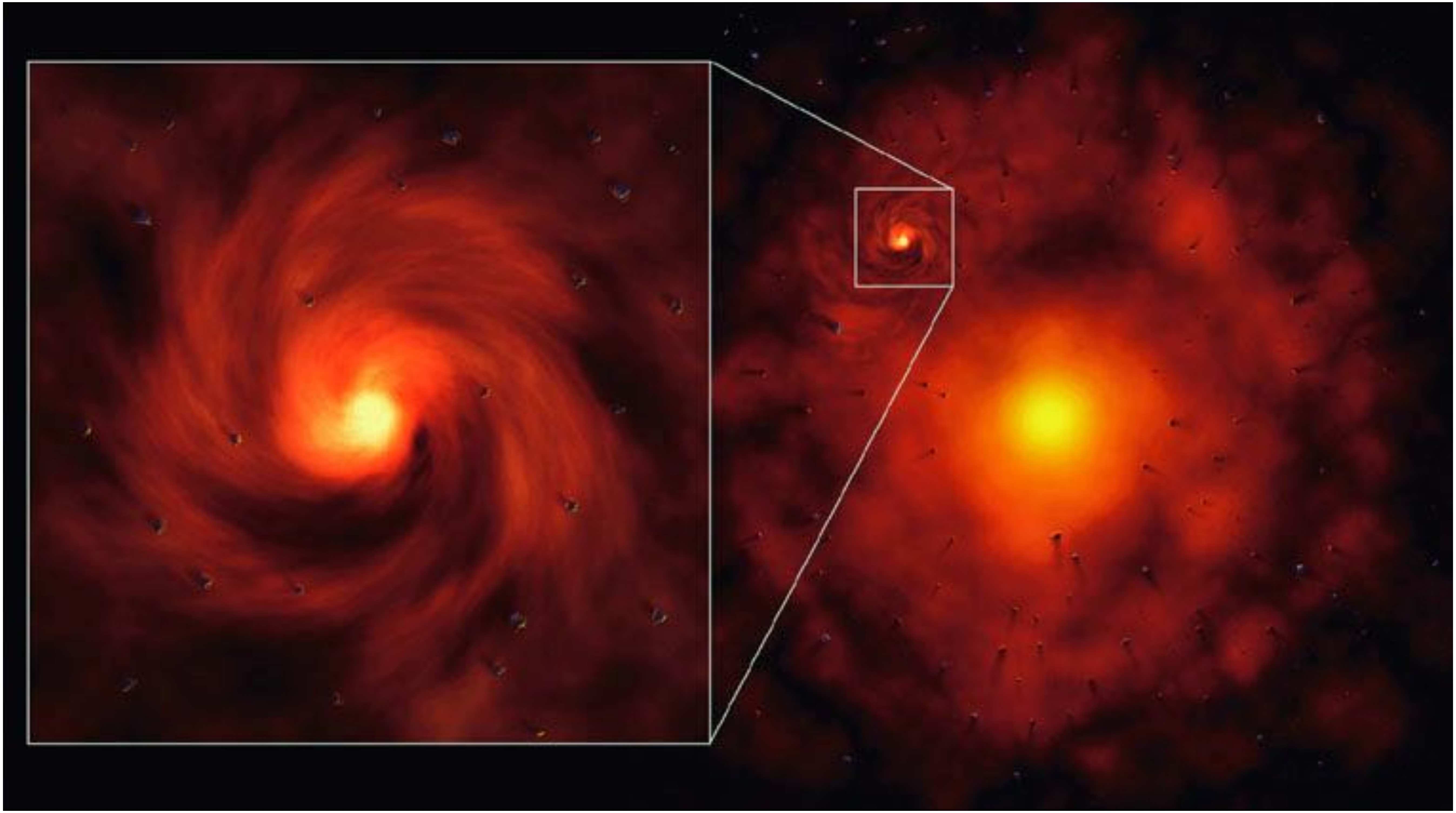
Accretion of Planetesimals



- Many smaller objects collected into just a few large ones.

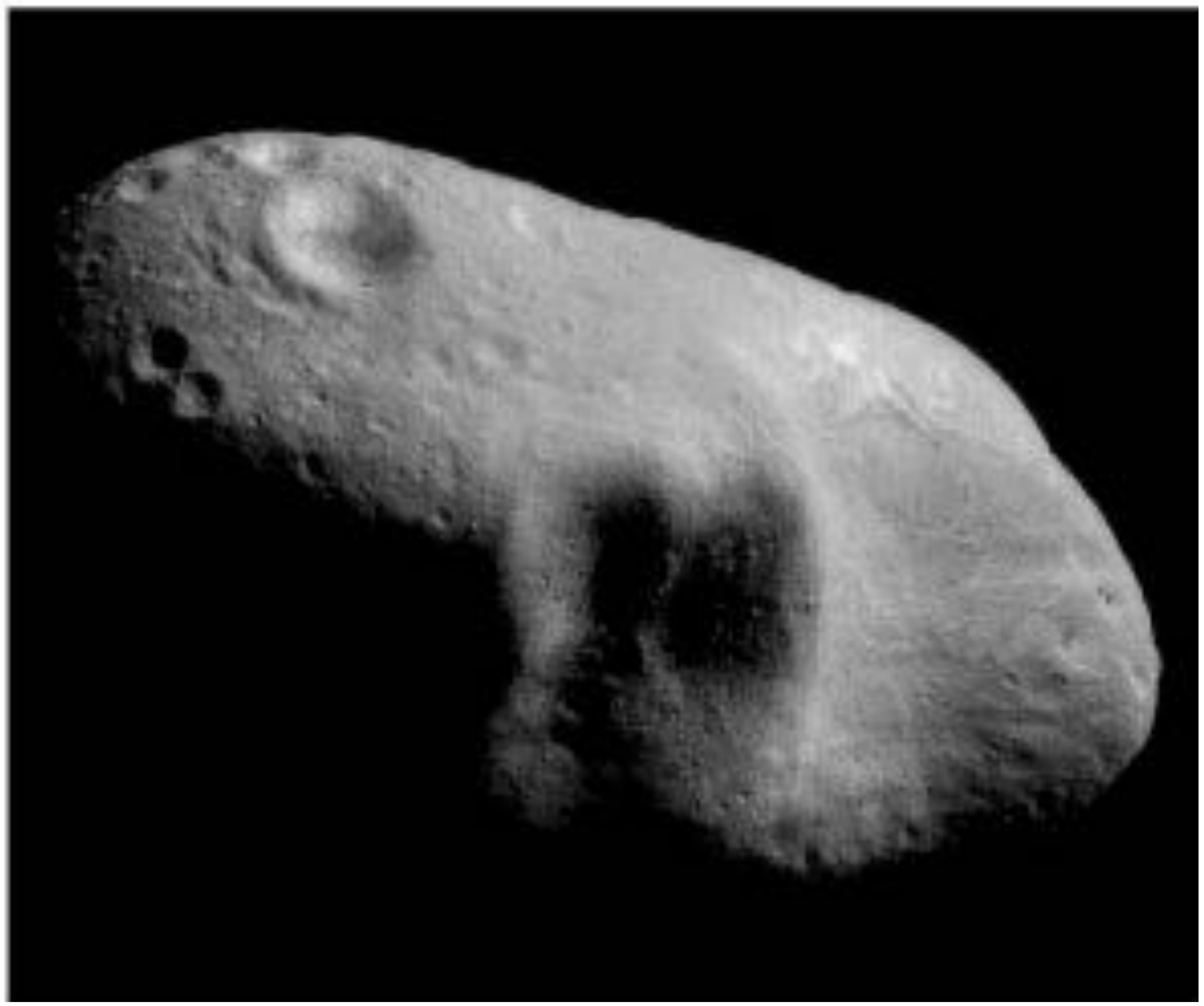
Formation of Jovian Planets

- Ice could also form small particles outside the frost line.
- Larger planetesimals and planets were able to form.
- The gravity of these larger planets was able to draw in surrounding H and He gases.

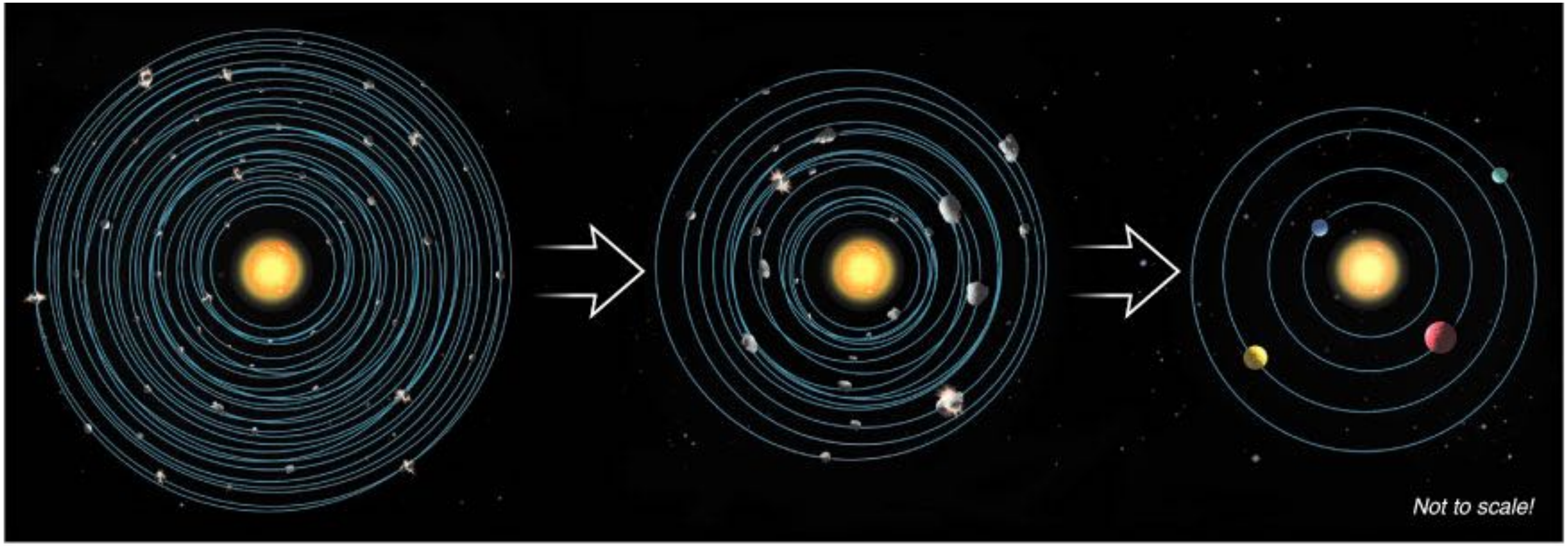


Moons of jovian planets form in miniature disks - like microcosms of the solar nebula.

Where did asteroids and comets come from?



Asteroids and Comets



- Leftovers from the accretion process
- Rocky asteroids inside frost line
- Icy comets outside frost line

Heavy Bombardment

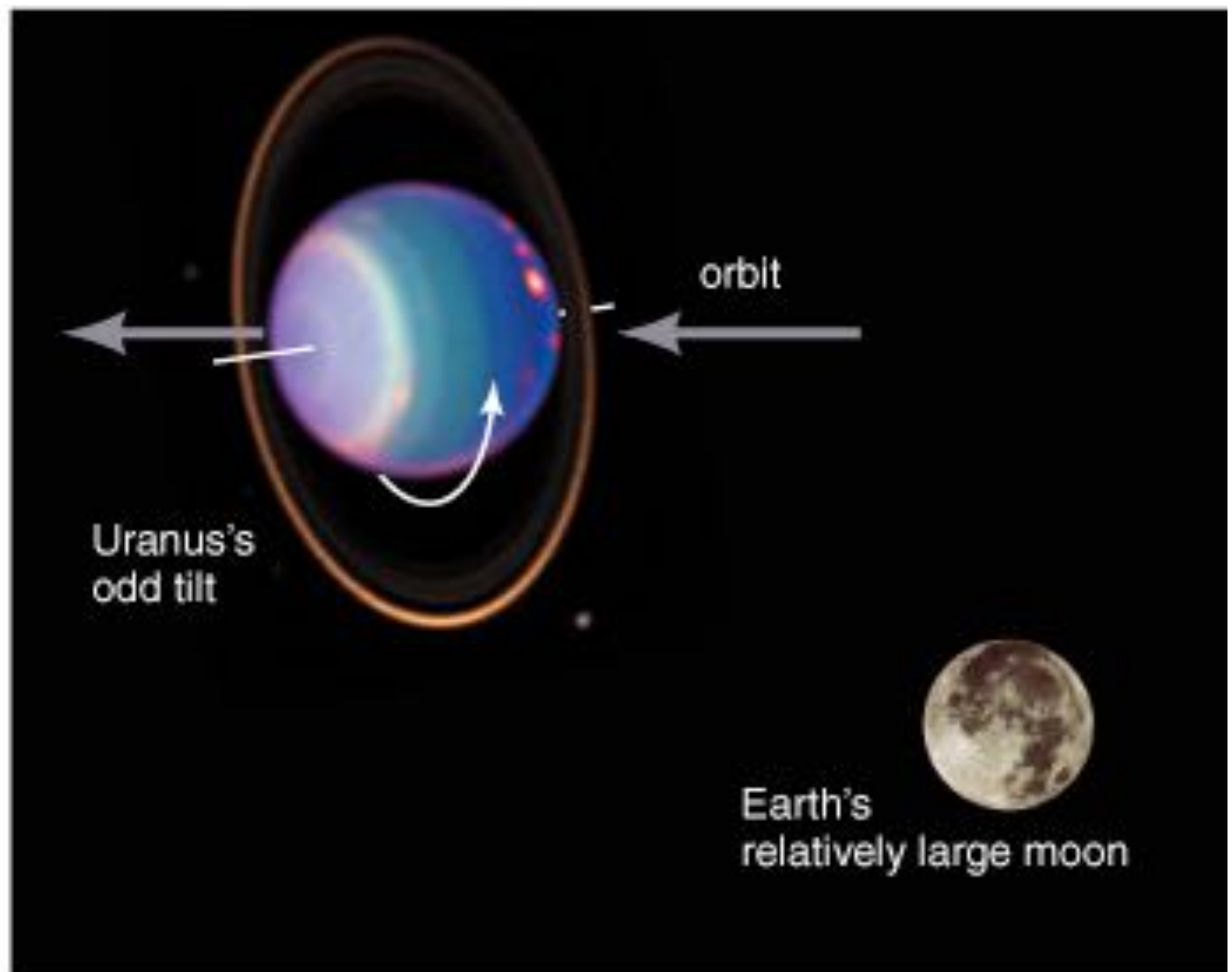
- Leftover planetesimals bombarded other objects in the late stages of solar system formation.

"Late heavy bombardment"
3.8 Billion years ago

What about the exceptions?

- Venus spins retrograde
- Uranus tipped almost perpendicular
- Why do we have a moon?

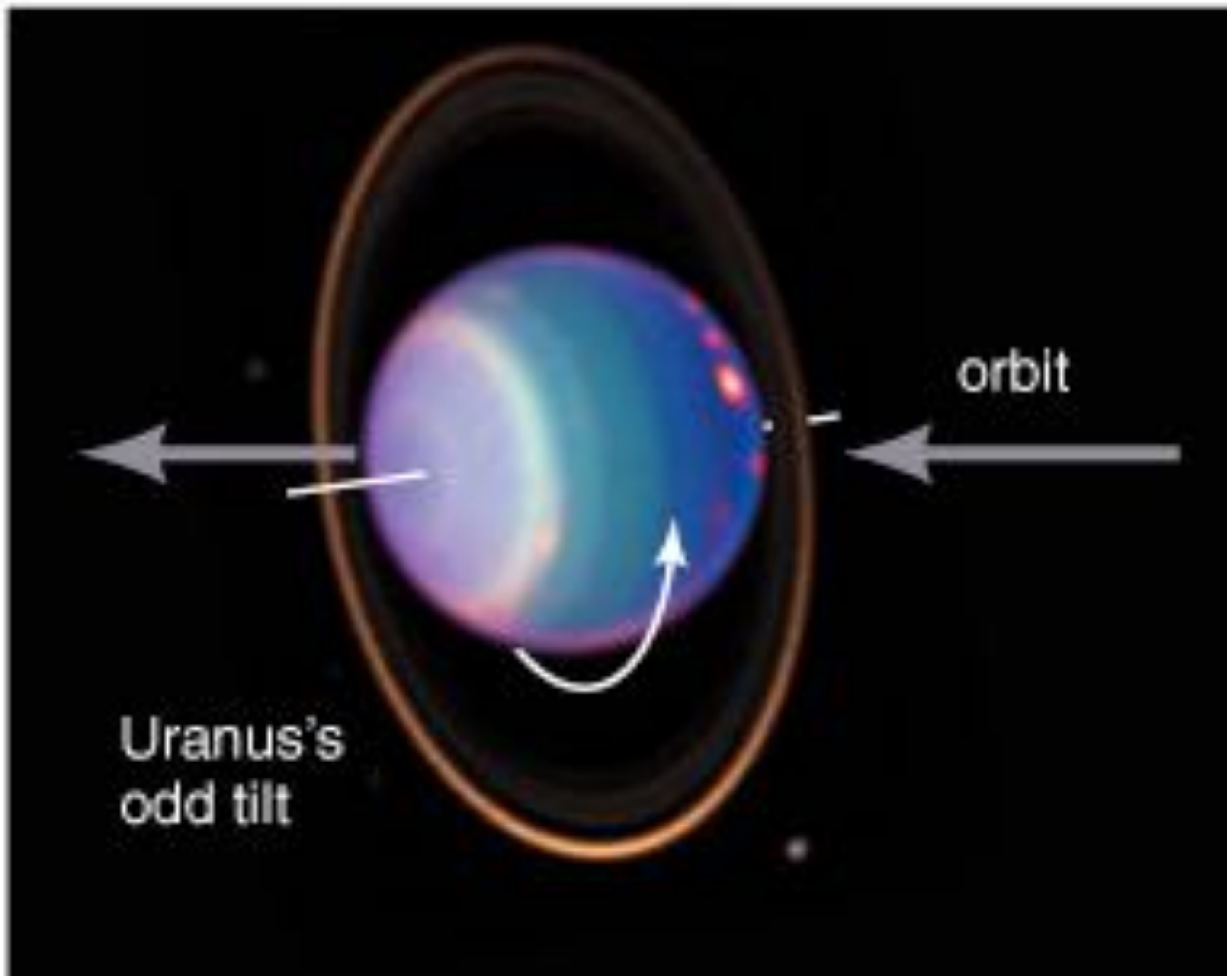
Thought to be due to the last big collision.



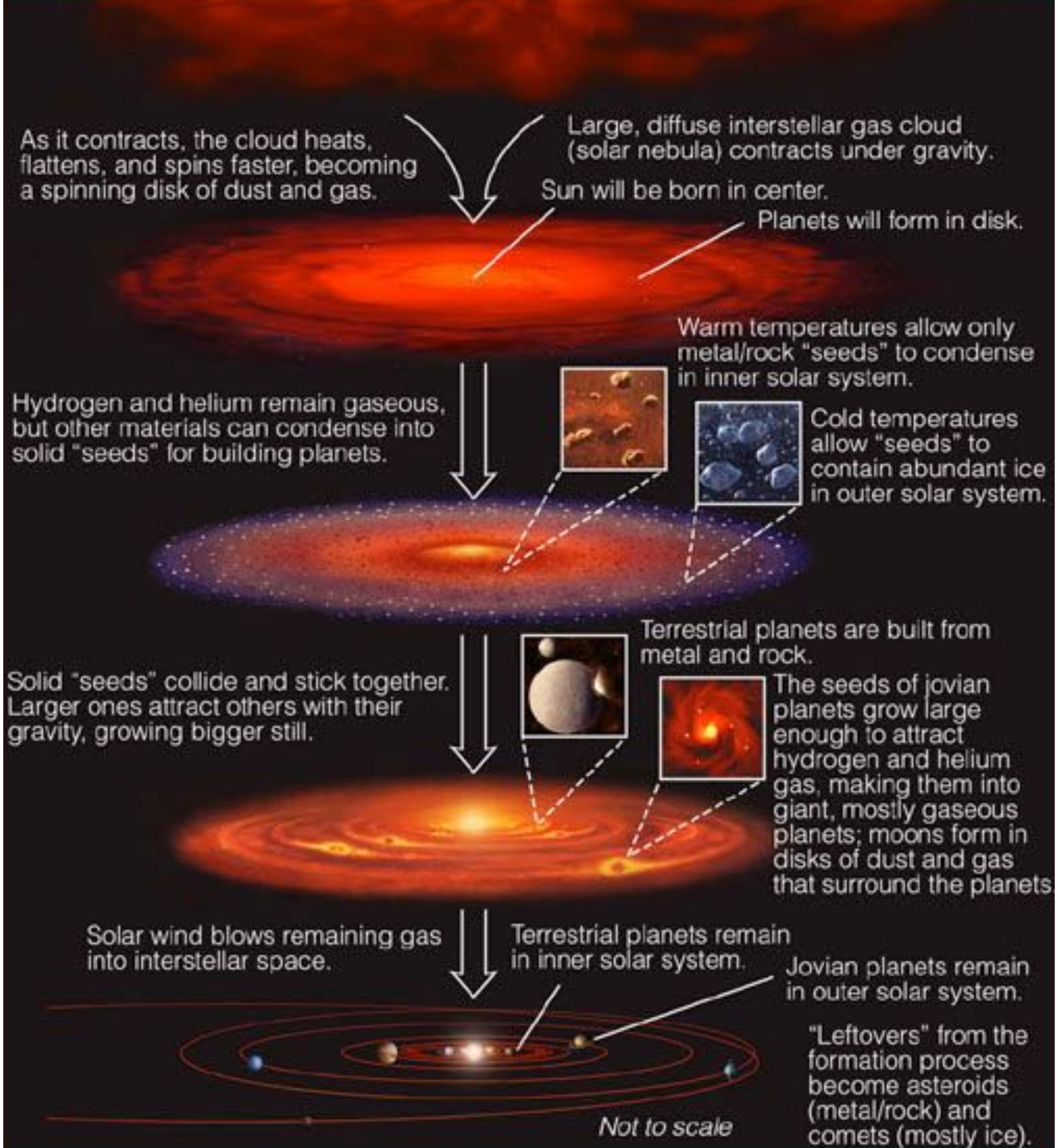
Earth's moon: Giant Impact?

https://www.youtube.com/watch?v=mQAdYWcA7ig

Odd Rotation



- Giant impacts might also explain the different rotation axes of some planets.



- Nebula spins up as it collapses (angular momentum conserved)
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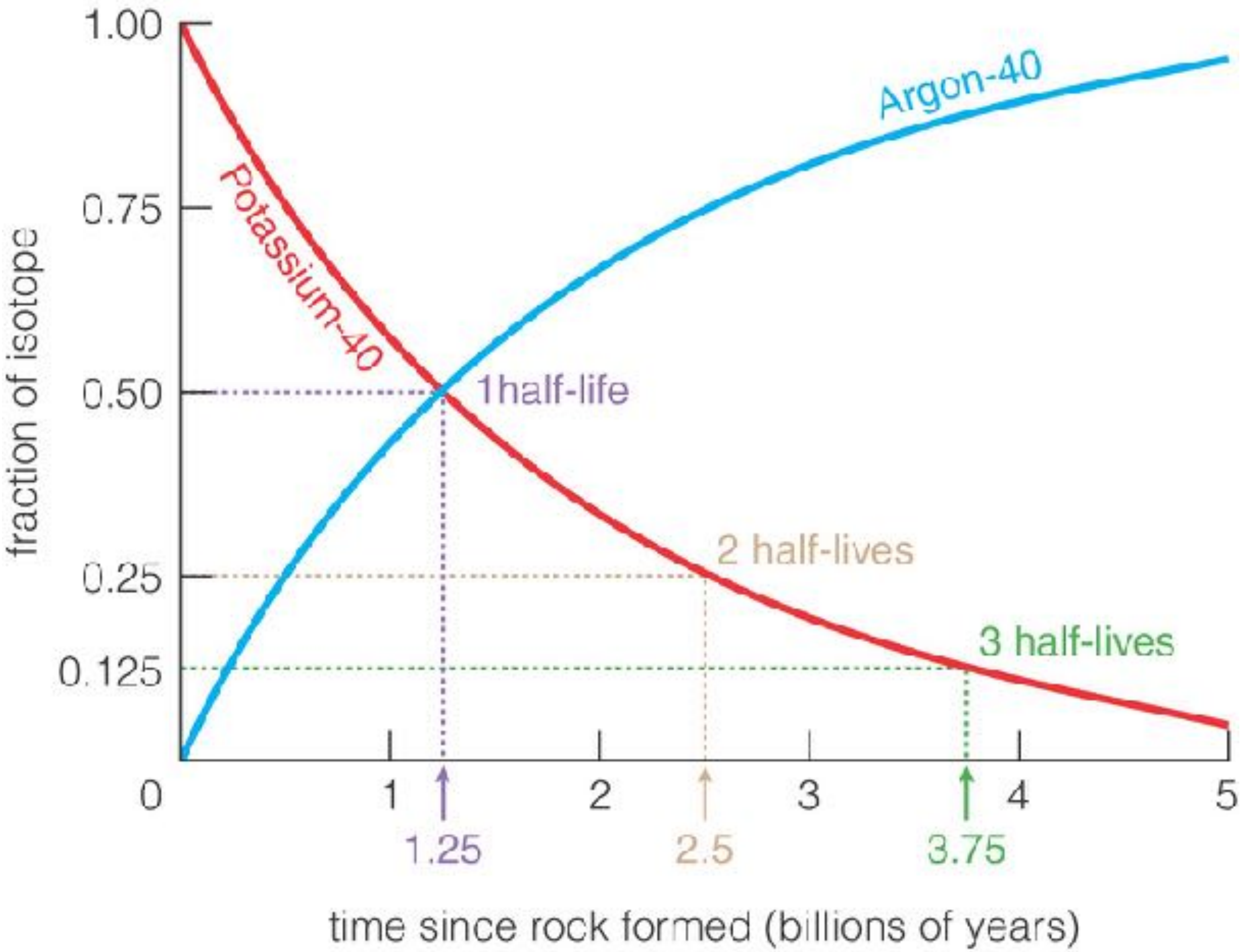
When did the planets form?

- We cannot find the age of a planet, but we can find the ages of the rocks that make it up.
- We can determine the age of a rock through careful analysis of the proportions of various atoms and isotopes within it.

Radioactive Decay



- Some isotopes decay into other nuclei.
- A **half-life** is the time for half the nuclei in a substance to decay.

Dating the Solar System

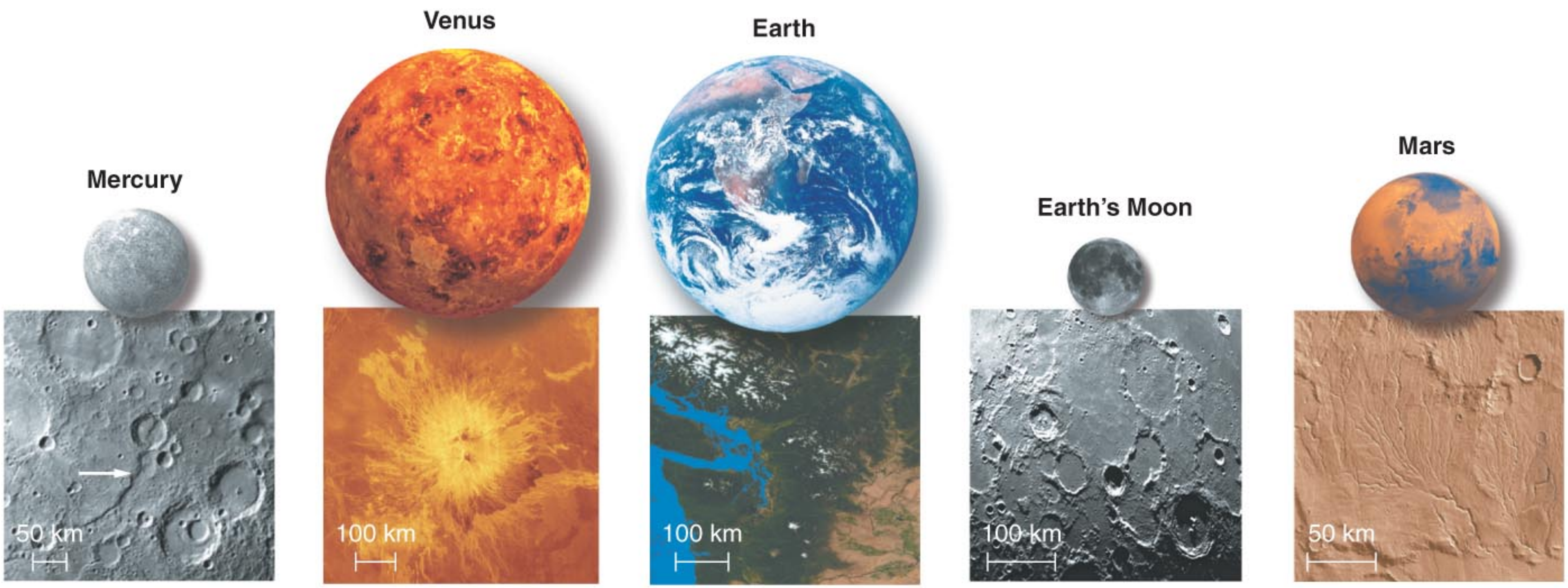
Age dating of meteorites via radio-isotopes tells us that the solar system is about 4.5 billion years old.

A similar age is found for the oldest moon rocks returned by Apollo.

Solar System Formation

- The solar system formed about 4.5 billion years ago from the collapse of an interstellar gas cloud (the ***solar nebula***).
- The planets formed by coagulation of smaller particles (planetesimals).
- Planets all line in the same orbital plane, all orbit in the same direction, and mostly spin in the same direction because the angular momentum of the solar nebula was conserved.
- The exceptions may record the lasting effects of the last enormous collisions.

Planetary surfaces & interiors



Heavily cratered Mercury has long steep cliffs (arrow).

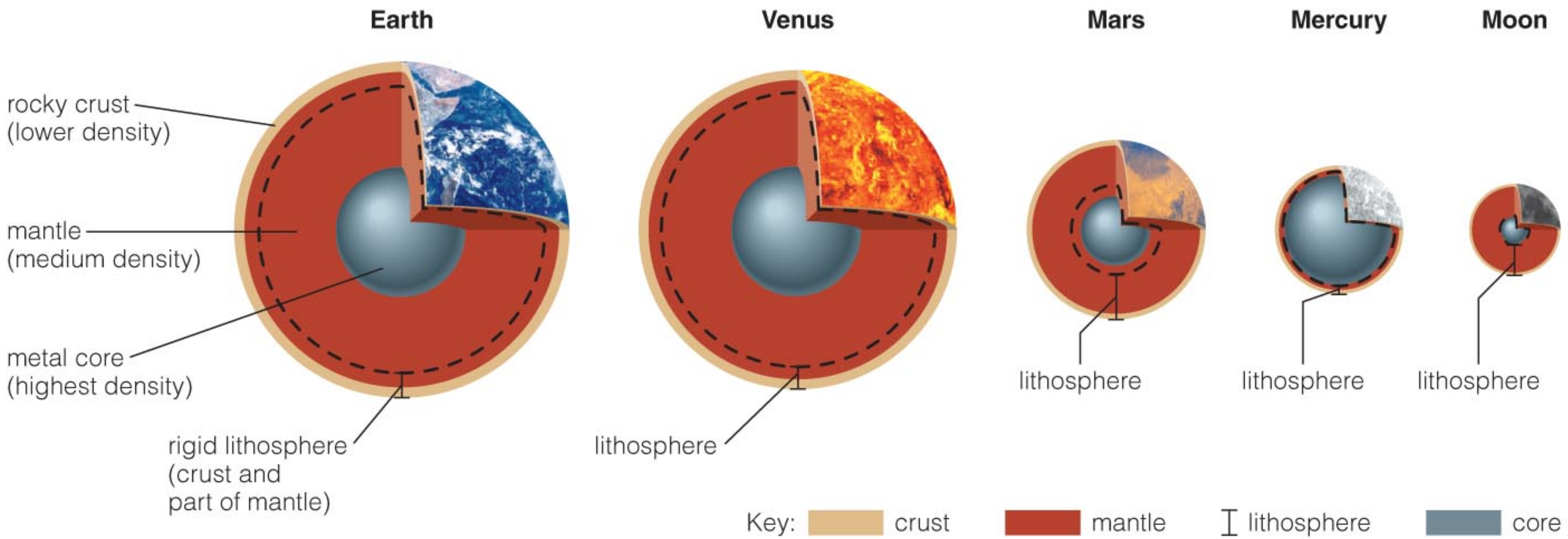
Cloud-penetrating radar revealed this twin-peaked volcano on Venus.

A portion of Earth's surface as it appears without clouds.

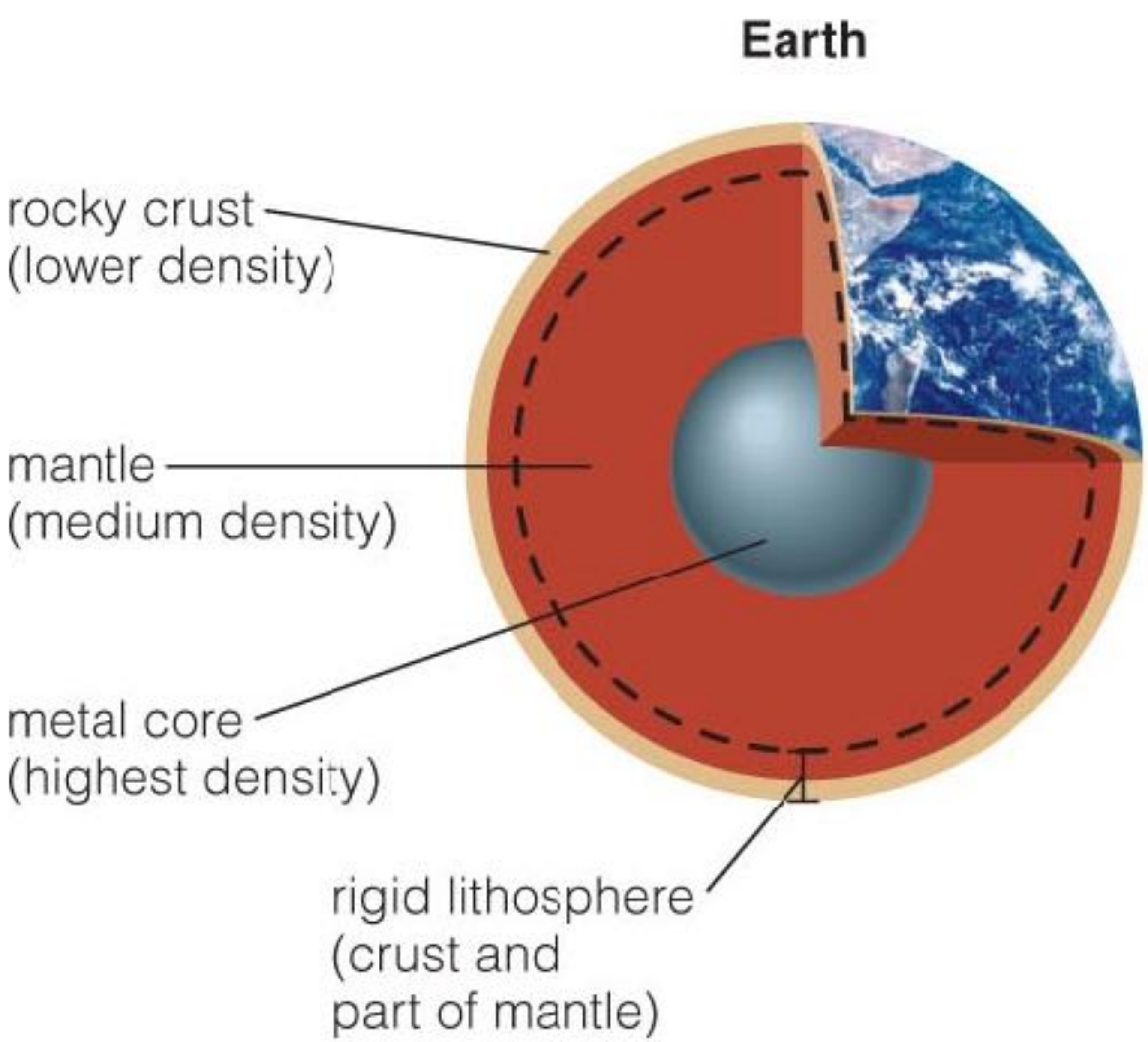
The Moon's surface is heavily cratered in most places.

Mars has features that look like dry riverbeds; note the impact craters.

Planetary surfaces & interiors

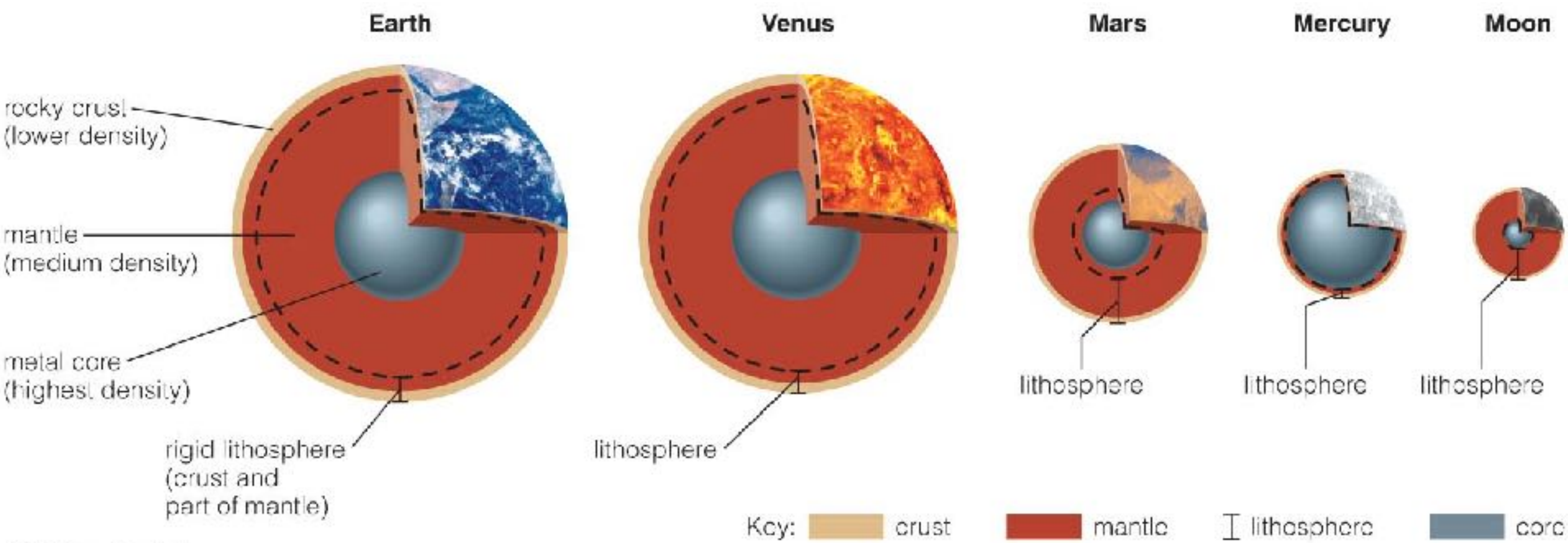


Earth's Interior



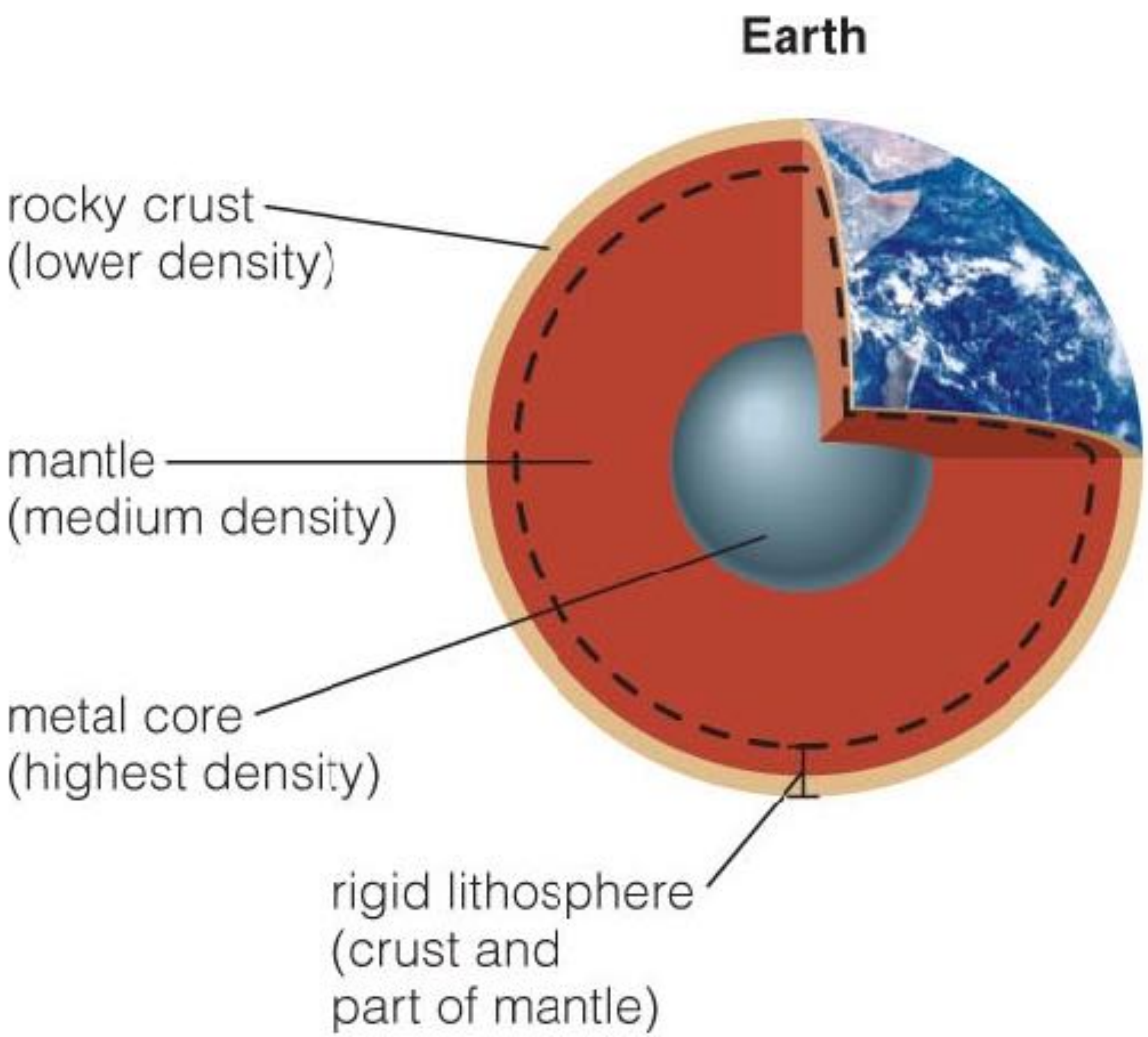
- Core: highest density; nickel and iron
- Mantle: moderate density; silicon, oxygen, etc.
- Crust: lowest density; granite, basalt, etc.

Terrestrial Planet Interiors



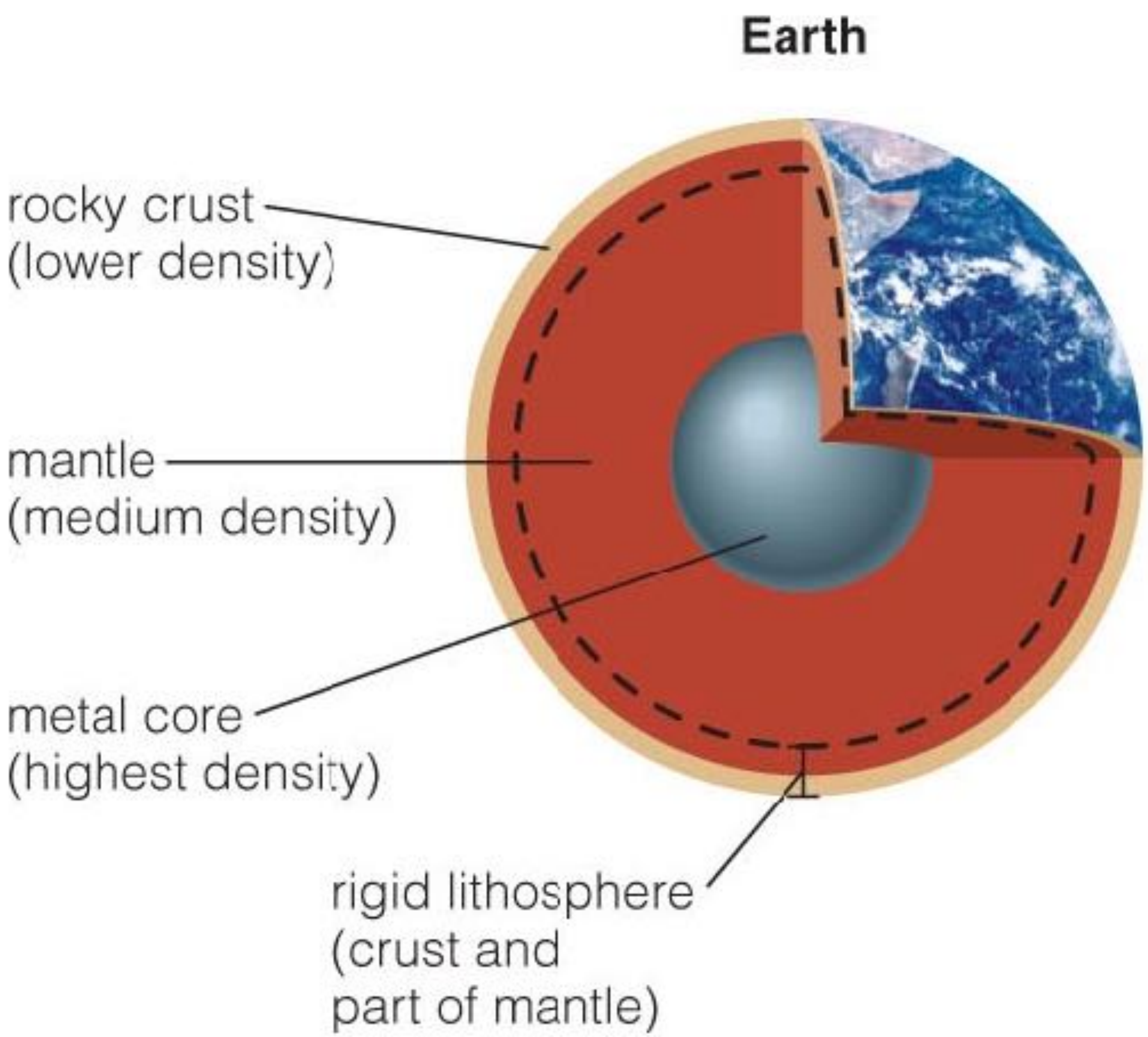
- Applying what we have learned about Earth's interior to other planets tells us what their interiors are probably like.

Differentiation



- Gravity pulls high-density material to center.
- Lower-density material rises to surface.
- Material ends up separated by density.

Lithosphere



- A planet's outer layer of cool, rigid rock is called the lithosphere.
- It "floats" on the warmer, softer rock that lies beneath.