Astronomy 101

Our Planetary System

"We succeeded in taking that picture, and, if you look at it, you see a dot. Look again at that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives…on a mote of dust suspended in a sunbeam."

Carl Sagan

The Goal: Comparative Planetology

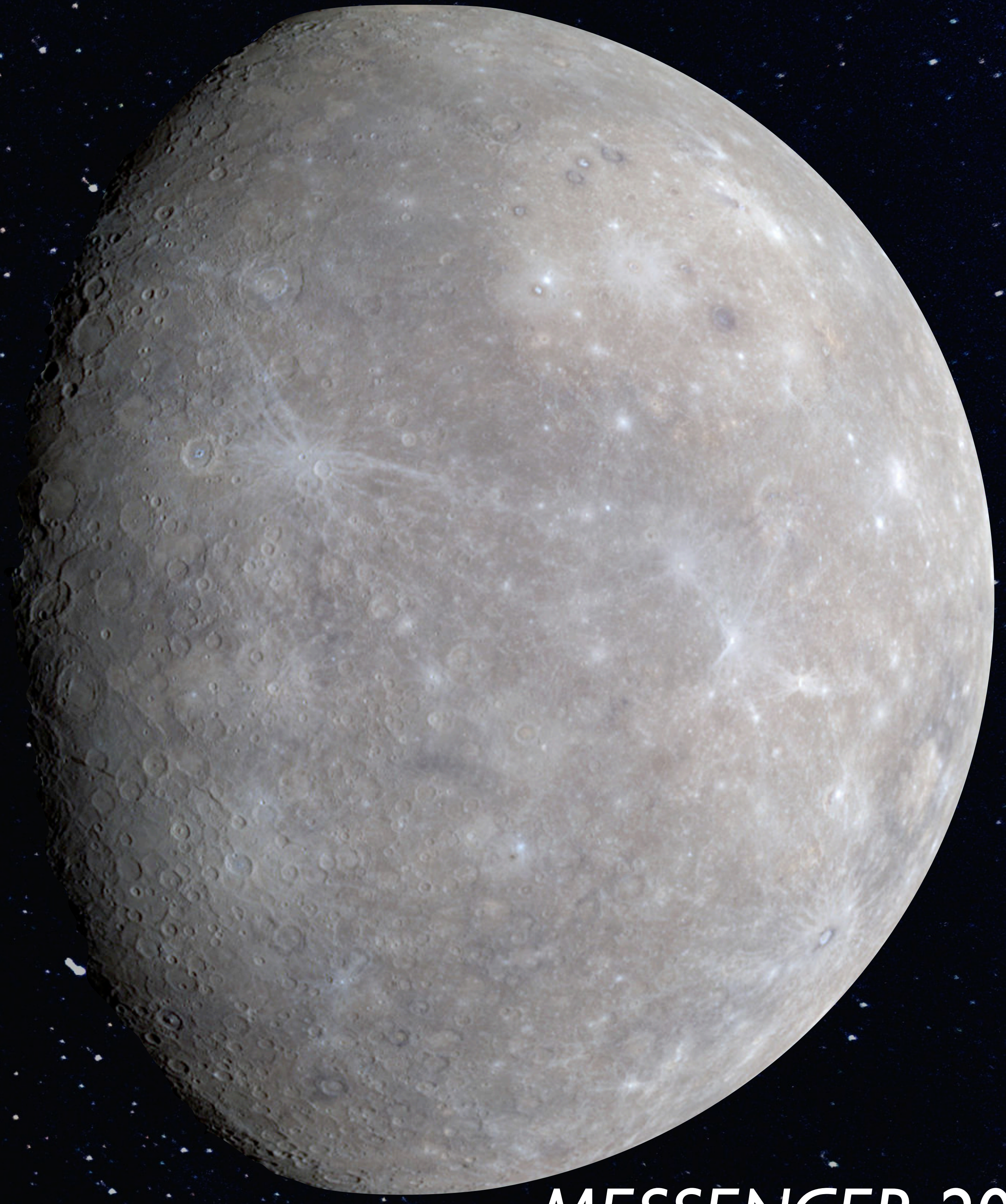
Sometimes we study the worlds of the Solar System individually, but other times we compare each world to one another, seeking to understand their similarities and differences; this is called comparative planetology

Before we can compare the planets, we must have a general idea of the nature of our Solar System and of the characteristics of individual worlds

We begin with Mercury…

Mercury

- Average distance: 0.39 AU
- Radius: 2440 km = $0.38R_{Earth}$
- Mass: $0.055M_{Earth}$
- Average density: 5.43 g/cm^3
- Composition: rocks, metals
- Average surface temp: 700 K (day), 100 K (night)
- Moons: 0


MESSENGER, 2008

The innermost and smallest planet, it has no active volcanoes, no wind, rain, or life

Tidal forces from the Sun have forced it into a 3:2 rotation/orbit scenario: it has 58.6-day rotation period and a 87.9-day orbit, giving it days and nights that last about 3 Earth months each

Mercury is heavily cratered, but also shows evidence of past geological activity and its high density indicates that it has a very large iron core

Venus

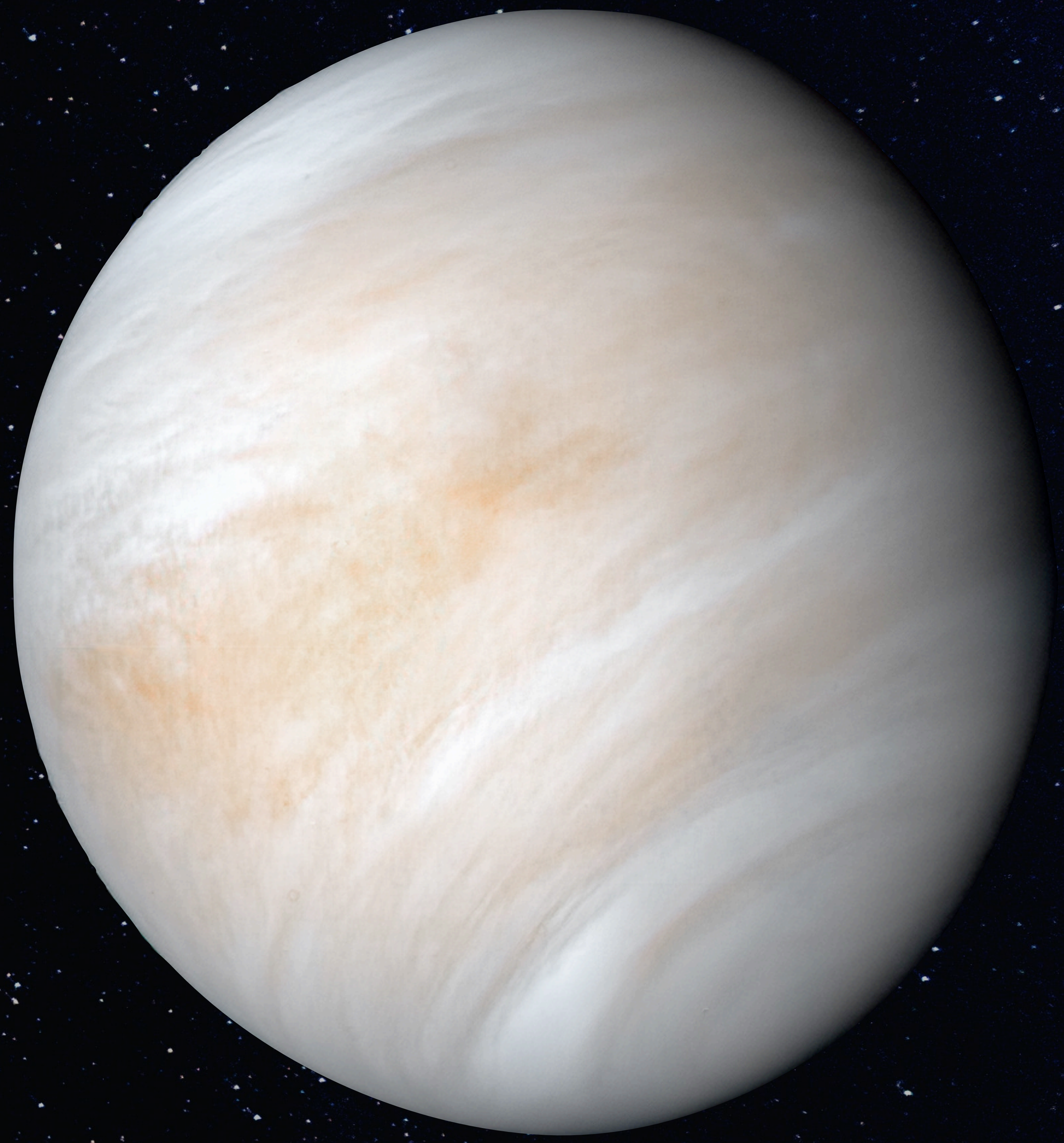
- Average distance: 0.72 AU
- Radius: 6051 km = $0.95 R_{Earth}$
- Mass: $0.82 M_{Earth}$
- Average density: 5.24 g/cm^3
- Composition: rocks, metals
- Average surface temp: 740 K
- Moons: 0

Venus is nearly identical in size to Earth, but it rotates on its axis very slowly and in the opposite direction

Its surface is hidden by dense clouds, so very little was known about its surface until a few decades ago with penetrating radar

The surface was revealed to have mountains, valleys, craters, and evidence of past volcanic activity

We know that Venus has a *greenhouse effect* which bakes its surface to a temperature of about 470℃, hotter than a pizza oven!



Mariner 10, 1974

Earth

- Average distance: 1 AU
- Radius: 6378 km = $1R_{Earth}$
- Mass: $1.00M_{Earth}$
- Average density: 5.52 g/cm^3
- Composition: rocks, metals
- Average surface temp: 290 K
- Moons: 1

Our home planet, the only known oasis of life in our Solar System, the only known planet with oxygen to breathe, ozone to shield from solar radiation, and abundant liquid water

Blue oceans cover nearly three-fourths of its surface, broken by continental land masses and scattered islands; at night, the glow of artificial light reveals the presence of an intelligent civilization

The Earth is also the first planet encountered to have a moon: the Moon is surprisingly large compared to Earth, likely having formed from a giant impact early in Earth's history

Apollo 17, 1972

Mars

- Average distance: 1.52 AU
- Radius: 3397 km = $0.53 R_{Earth}$
- Mass: $0.11 M_{Earth}$
- Average density: 3.93 g/cm^3
- Composition: rocks, metals
- Average surface temp: 220 K
- Moons: 2 (very small)

Mars is the last terrestrial planet, larger than Mercury but smaller than Earth and has two moons, Phobos and Deimos

Although Mars is barren today, it is likely that there once was liquid water on its surface

Mars's surface has volcanoes that dwarf Earth’s mountains, a canyon that covers one-fifth of its surface, and polar ice caps made of CO_2, but is not habitable: the air pressure is very low, the temperatures usually below freezing, and a CO_2 atmosphere

Viking 1, 1980

Phobos

Deimos

Mars Reconnaissance Orbiter, 2008/2009

Jupiter

- Average distance: 5.20 AU
- Radius: 71,492 km = 11.2R_{Earth}
- Mass: 318M_{Earth}
- Average density: 1.33 g/cm^3
- Composition: hydrogen, helium
- Average surface temp: 125 K
- Moons: 79

Hubble Space Telescope, 2014

Jupiter is the largest planet in the Solar System, so large that its largest storm, the Great Red Spot, is large enough to swallow Earth twice!

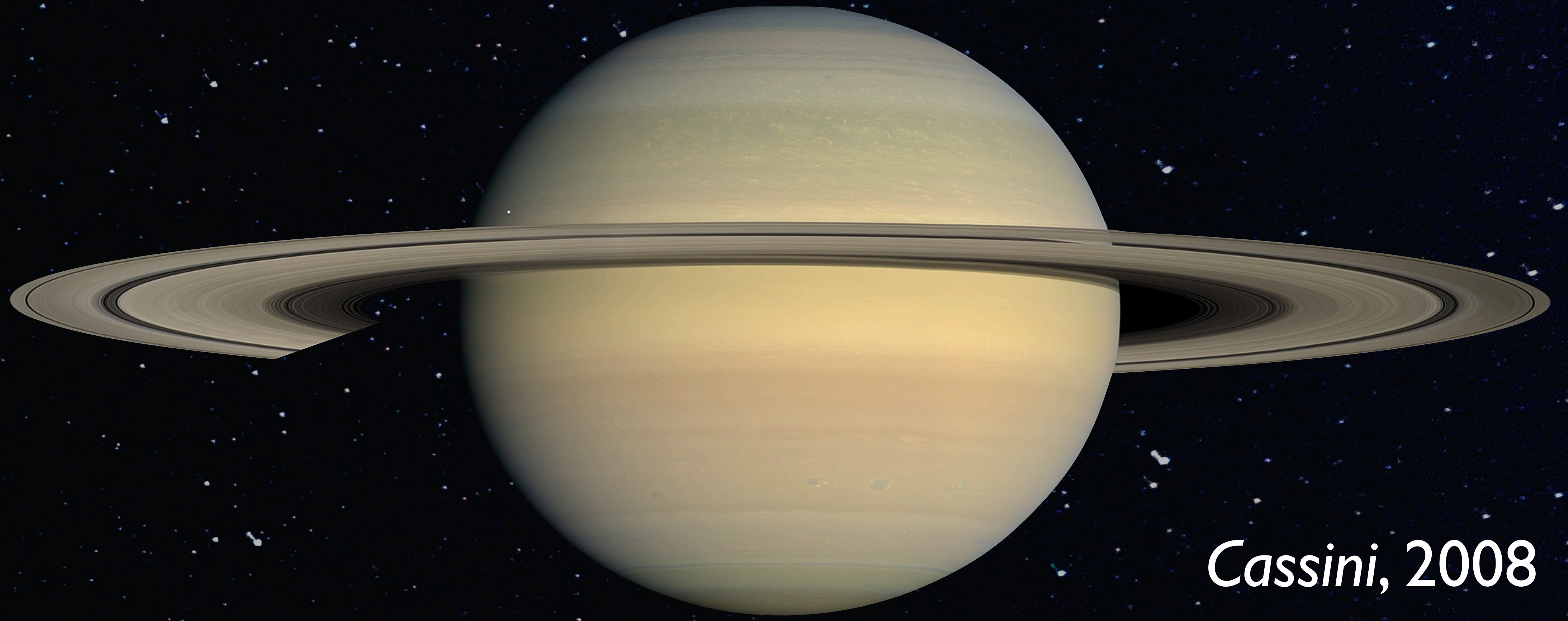
Like the Sun, Jupiter is primarily made of hydrogen and helium with no solid surface

Jupiter reigns over dozens of moons and a thin set of rings; four moons are large enough that we'd call them planets if they orbited the Sun!

Io is the most volcanically active world; Europa may have an ocean of subsurface water; Ganymede and Callisto might also have subsurface oceans

Saturn

- Average distance: 9.54 AU
- Radius: 60,268 km = $9.4R_{\text{Earth}}$
- Mass: $95.2M_{\text{Earth}}$
- Average density: 0.70 g/cm^3
- Composition: hydrogen, helium
- Average surface temp: 95 K
- Moons: 82



Cassini, 2008

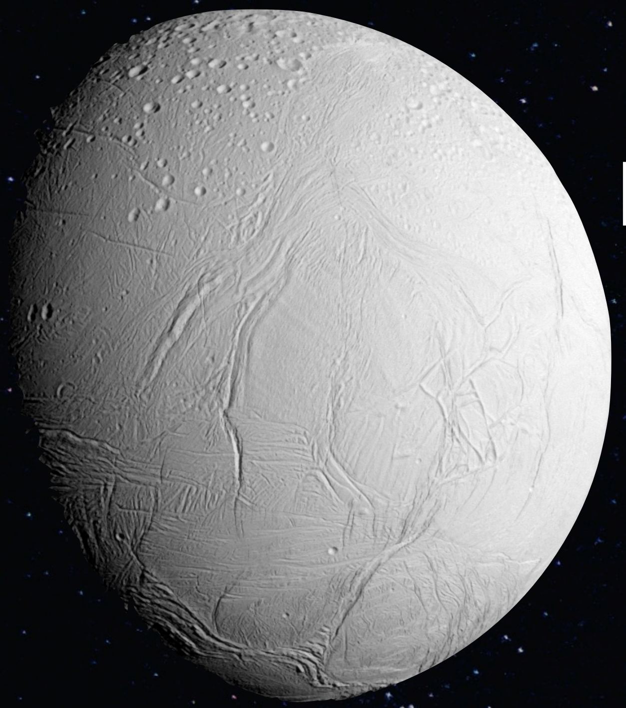
Saturn is only slightly smaller than Jupiter, but its lower density (low enough to float in water!) makes it considerably less massive

Saturn is famous for its spectacular rings, which look solid at a distance, but are made of countless small particles ranging in size from dust grains to city blocks

It also hosts dozens of moons, two of which are geologically active:

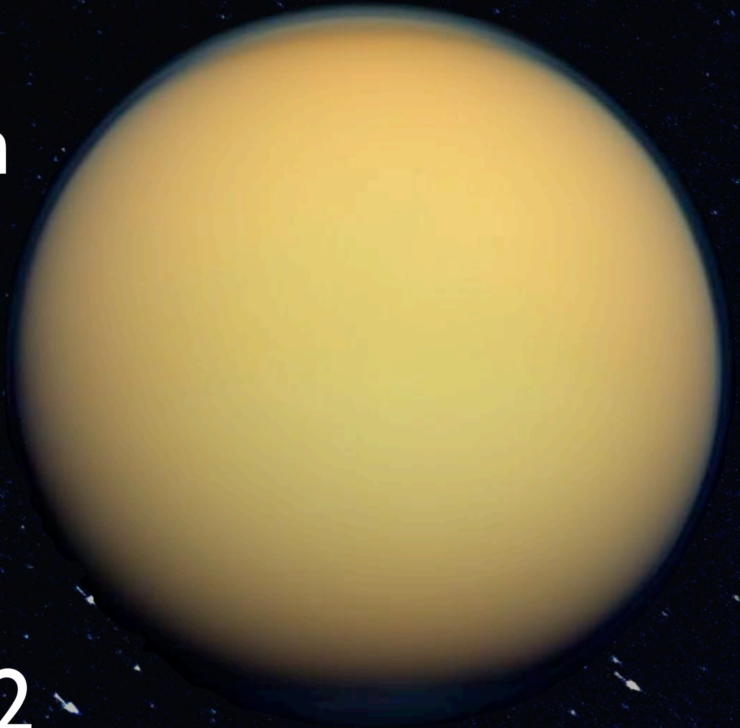
Enceladus has ice fountains, and Titan is the only moon with a thick atmosphere!

Enceladus



Cassini, 2015

Titan



Cassini, 2012

Uranus

- Average distance: 19.2 AU
- Radius: 25,559 km = $4.0R_{Earth}$
- Mass: $14.5M_{Earth}$
- Average density: 1.32 g/cm^3
- Composition: hydrogen, helium, hydrogen compounds
- Average surface temp: 60 K
- Moons: 27

Voyager 2, 1986

Twice as far as Saturn lies Uranus, made of hydrogen, helium, and hydrogen compounds such as water, ammonia, and methane; the methane gives Uranus its pale blue-green color

The entire Uranian system is tilted on its side, perhaps the result of a cataclysmic collision during its formation; this gives it extreme seasonal variations

Only one spacecraft has visited Uranus, *Voyager 2*, and much of what we know about the planet comes from that mission

Neptune

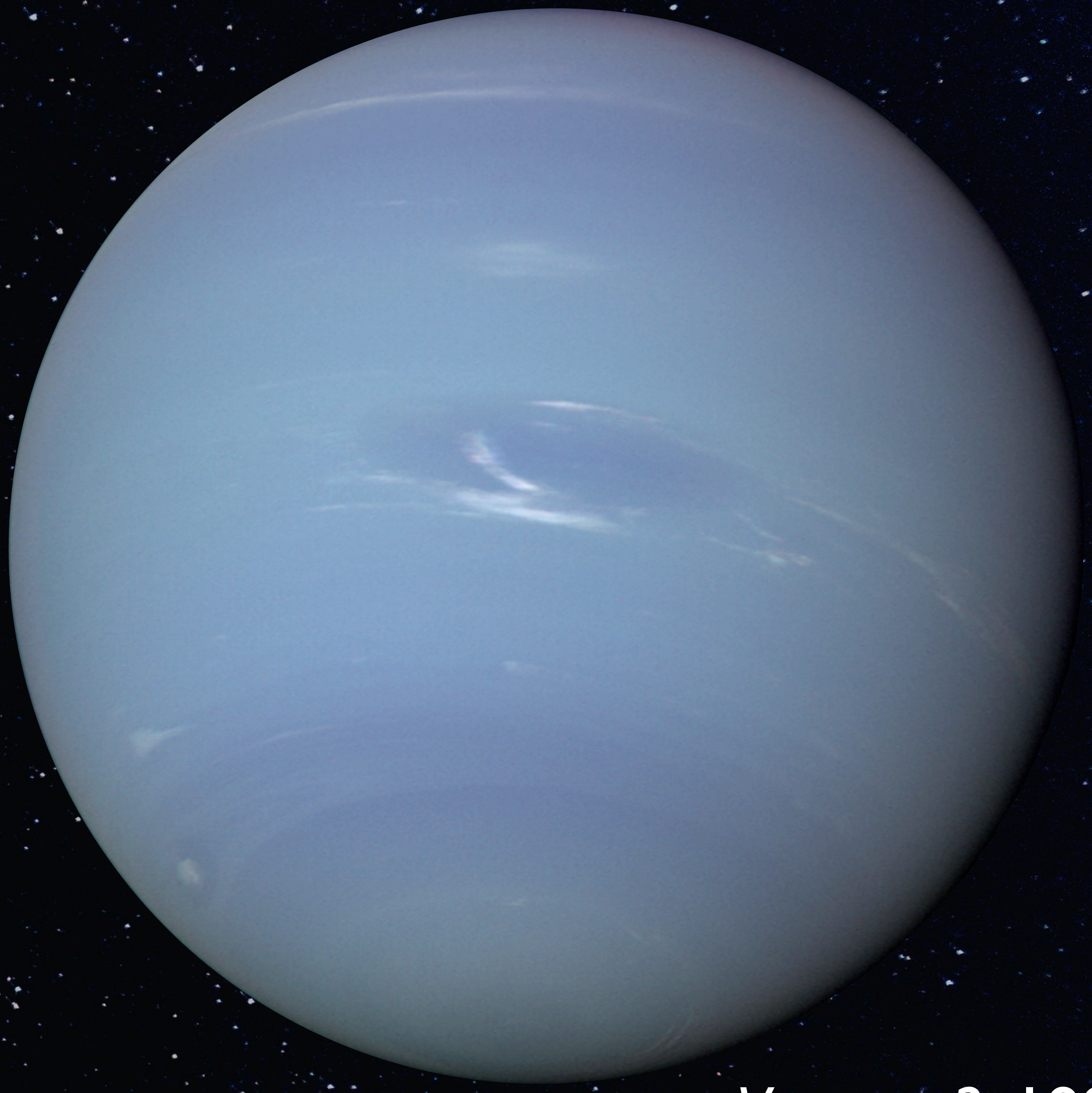
- Average distance: 30.1 AU
- Radius: 24,764 km = $3.9R_{Earth}$
- Mass: $17.1M_{Earth}$
- Average density: 1.64 g/cm^3
- Composition: hydrogen, helium, hydrogen compounds
- Average surface temp: 60 K
- Moons: 14

Slightly smaller than Uranus, it is more strikingly blue and slightly more massive than Uranus

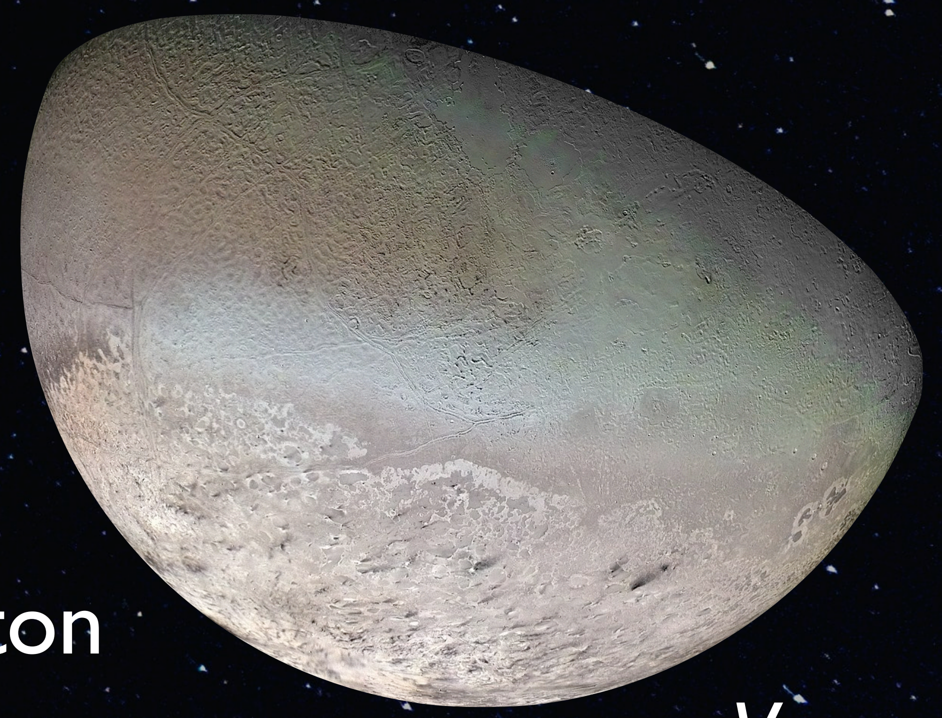
Neptune has rings and numerous moons; its largest is Triton which is larger than Pluto

> Triton's icy surface has features that appear like geysers, although they spew nitrogen gas rather than water; it also is the only large moon to orbit its planet backwards

Like Uranus, Neptune has been visited only by *Voyager 2*



Voyager 2, 1989



Triton

Voyager 2, 1989

Dwarf Planets: Pluto, Eris, and More!

- Average distance: 39.5 AU
- Radius: 1187 km = $0.19R_{\text{Earth}}$
- Mass: $0.0022M_{\text{Earth}}$
- Average density: 1.86 g/cm^3
- Composition: ices, rock
- Average surface temp: 40 K
- Moons: 5

After the 2005 discovery of Eris, Pluto was "demoted" to *dwarf planet* status: too small to qualify as official planets, but large enough to round in shape

Pluto and Eris belong to thousands of icy objects beyond Neptune making up the *Kuiper belt*

Located far away from the Sun, the dwarf planets out here are perpetually dark; Pluto is tidally locked with its largest moon, Charon, in synchronous rotation

New Horizons is the only satellite to have visited these worlds

New Horizons, 2015

Charon

New Horizons, 2015

Four Major Patterns in the Solar System

Patterns of motion among large bodies

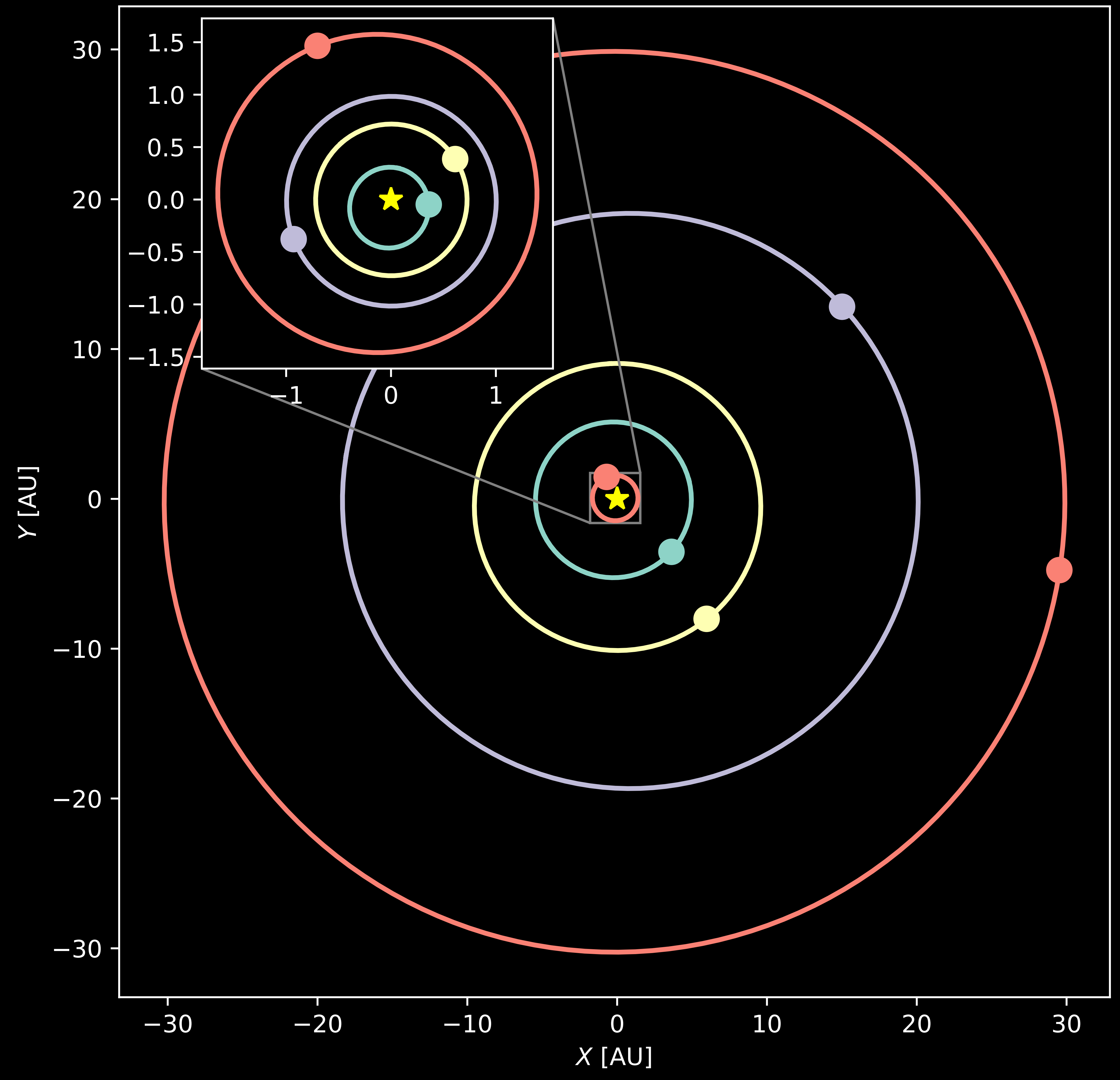
Two major types of planets

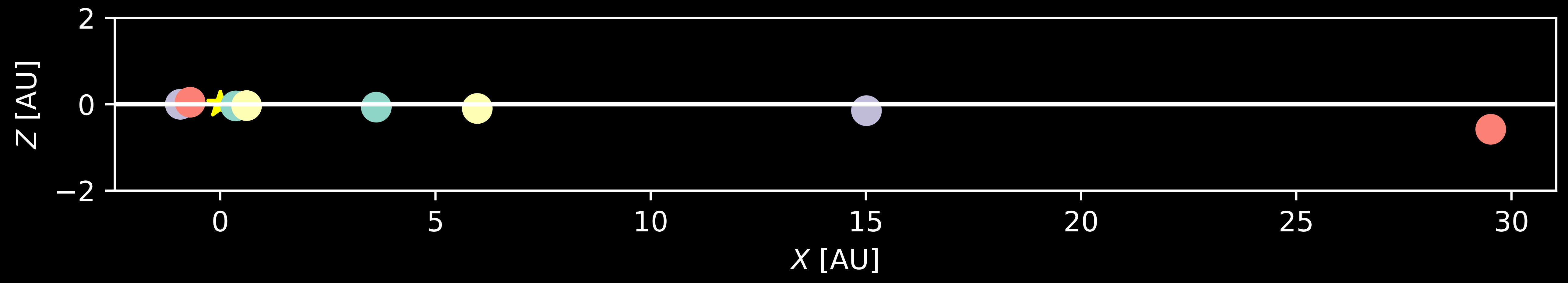
Asteroids and comets

Exceptions to the rules

Patterns of Motion Among Large Bodies

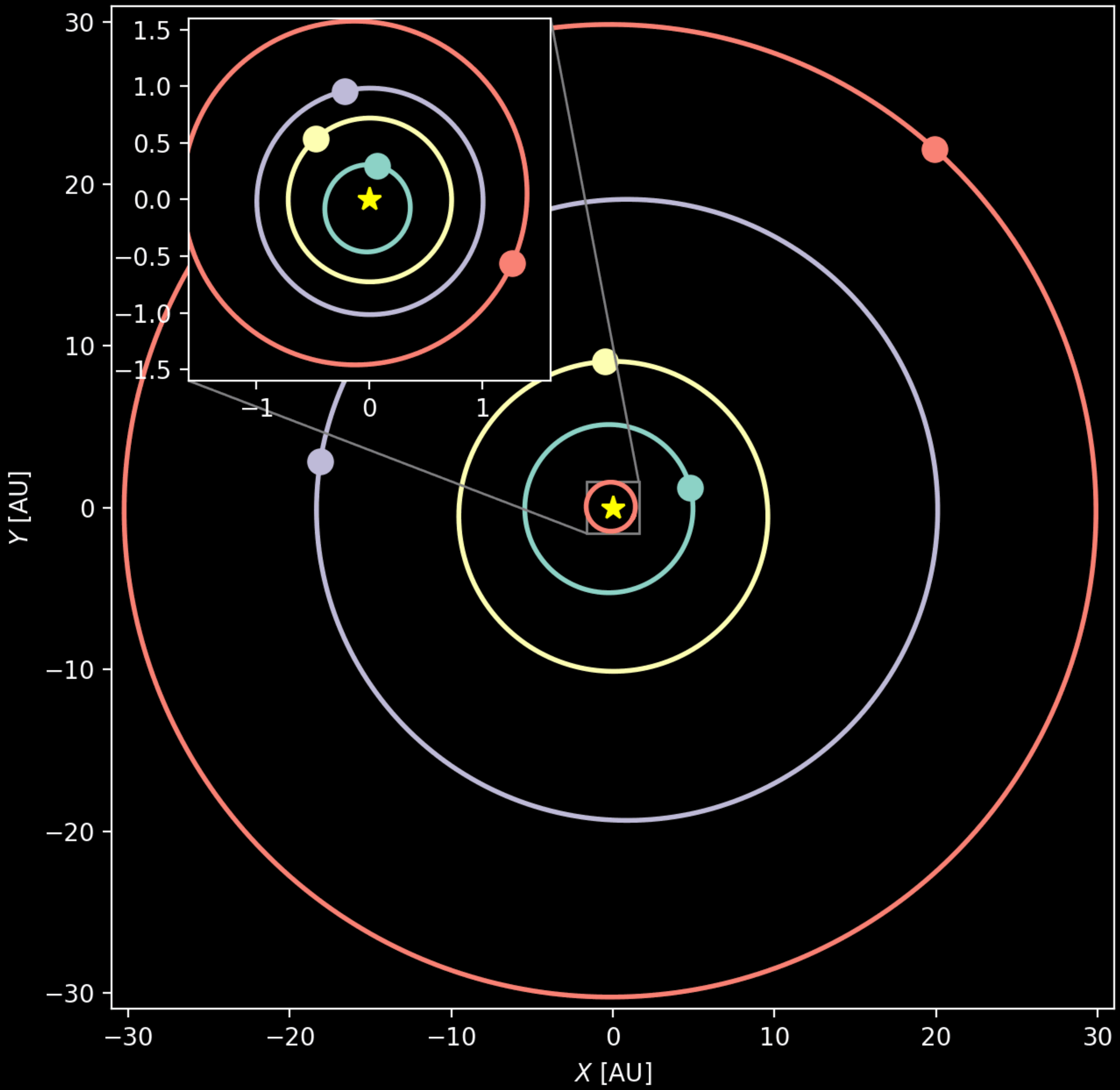
All planetary orbits are nearly circular and lie nearly in the same plane





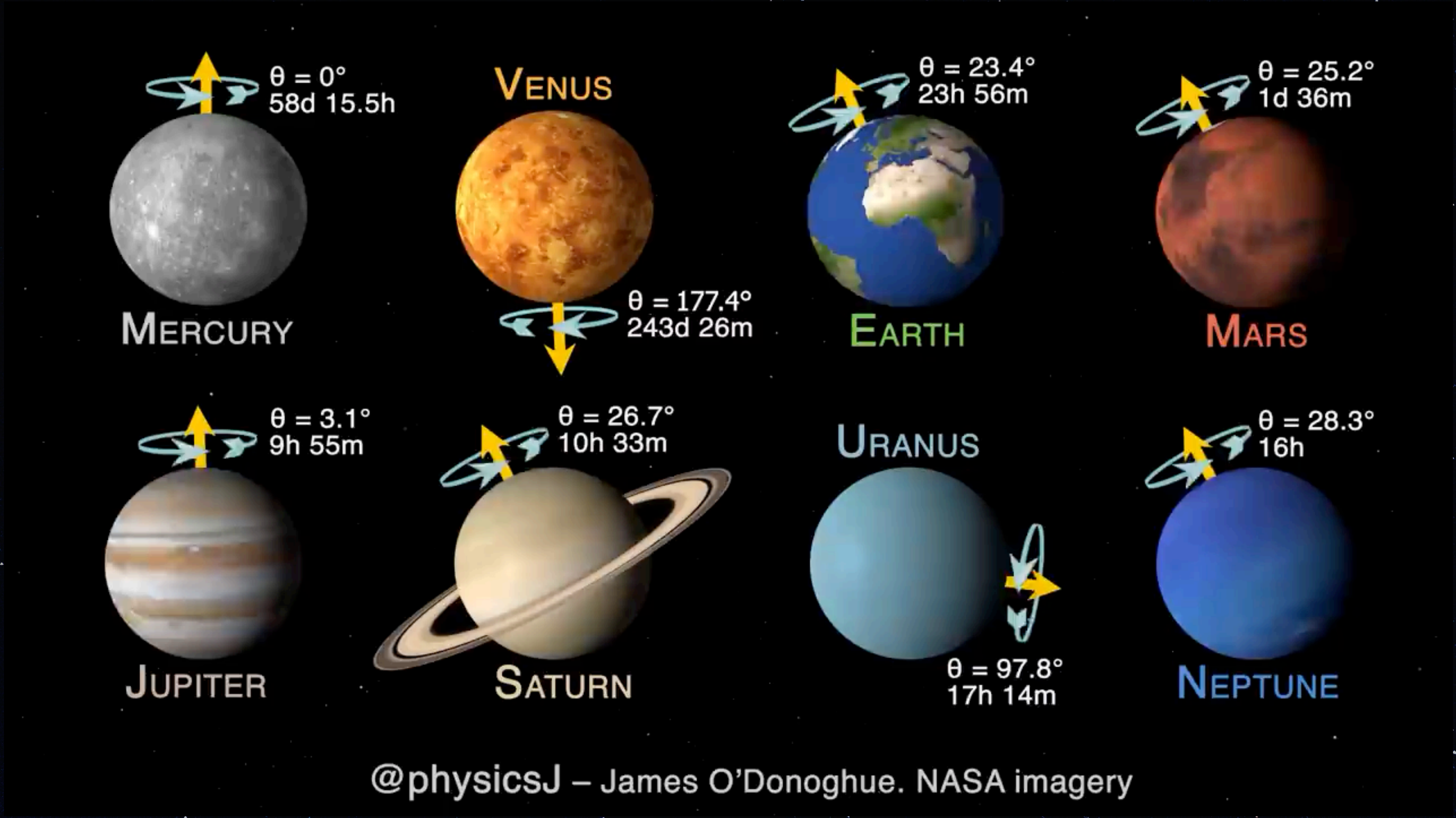
Patterns of Motion Among Large Bodies

All planets orbit the Sun in the same direction: counterclockwise as viewed from above Earth's North Pole



Patterns of Motion Among Large Bodies

Most planets rotate in the same direction in which they orbit, with fairly small axis tilts; the Sun also rotates in this direction



Patterns of Motion Among Large Bodies

Most of the Solar System's large moons exhibit similar properties in their orbits around their planets

Two Types of Planets

Terrestrial Planets   Gas Giants / Jovians

Planet	Average Distance [AU]	Average Radius [km]	Mass [Earth = 1]	Average Density [g/cm³]	Orbital Period	Rotation Period	Axis Tilt	Average Temperature [K]	Composition	Known Moons	Rings?
Mercury	0.387	2440	0.055	5.43	87.9 d	58.6 d	0.0°	700/100	Rocks, metals	0	No
Venus	0.723	6051	0.82	5.24	225 d	243 d	177.3°	740	Rocks, metals	0	No
Earth	1.00	6378	1.00	5.52	1 yr	23.93 h	23.5°	290	Rocks, metals	1	No
Mars	1.52	3397	0.11	3.93	1.88 yr	24.6 h	25.2°	220	Rocks, metals	2	No
Jupiter	5.20	71,492	318	1.33	11.9 yr	9.93 h	3.1°	125	H, He, H compounds	79	Yes
Saturn	9.54	60,268	95.2	0.70	29.5 yr	10.6 h	26.7°	95	H, He, H compounds	82	Yes
Uranus	19.2	25,559	14.5	1.32	83.8 yr	17.2 h	97.9°	60	H, He, H compounds	27	Yes
Neptune	30.1	24,764	17.1	1.64	165 yr	16.1 h	29.6°	60	H, He, H compounds	14	Yes
Pluto	39.5	1187	0.0022	1.86	248 yr	6.39 d	112.5°	44	Ices, rock	5	No
Eris	67.7	1168	0.0028	2.3	557 yr	1.08 d	78°	43	Ices, rock	1	No

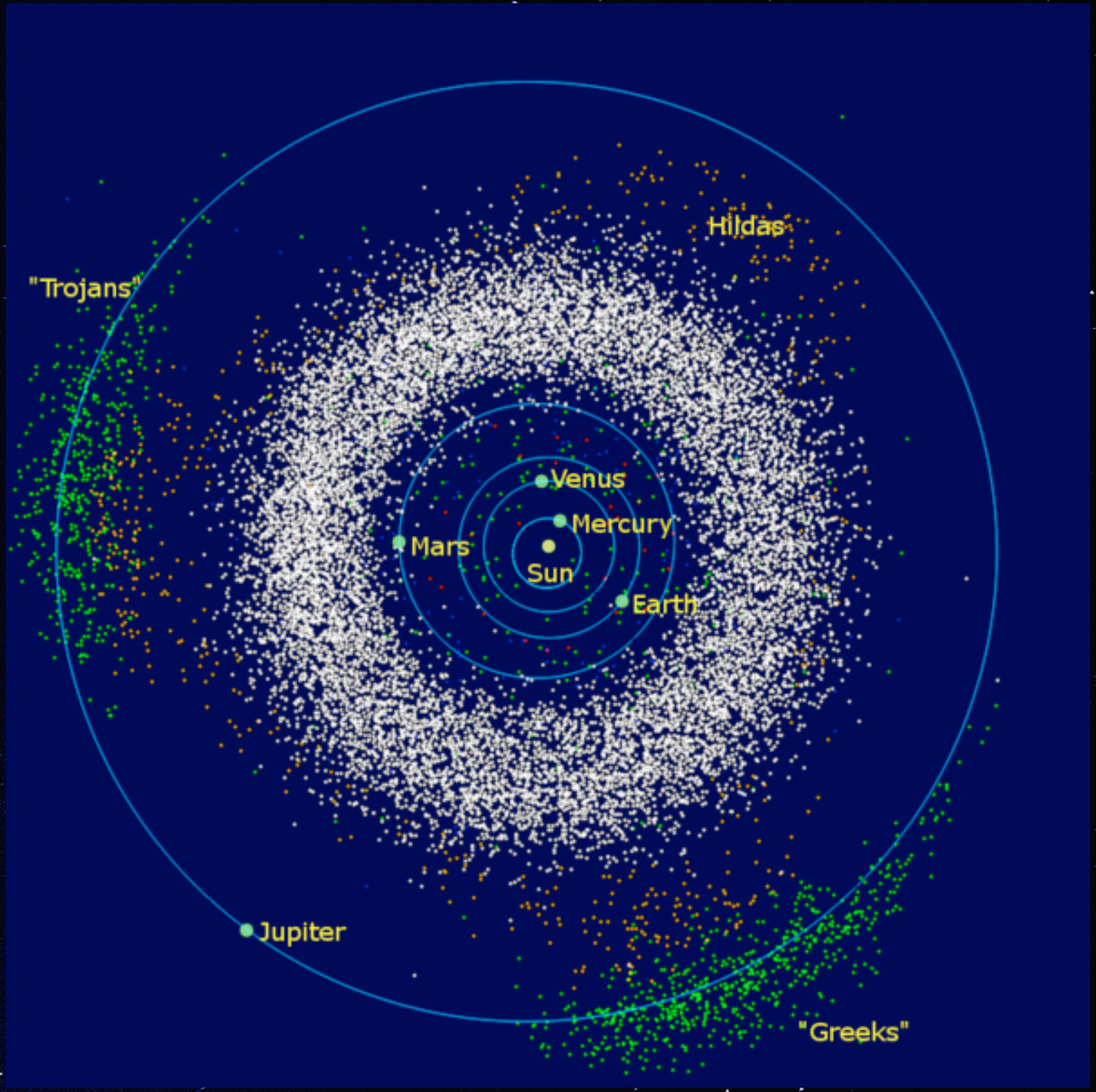
Close Small Dense Rock & Metal

Far Huge Less Dense Gases

Asteroids and Comets

There are a vast number of small objects orbiting the Sun

Asteroids are rocky objects found in the inner solar system



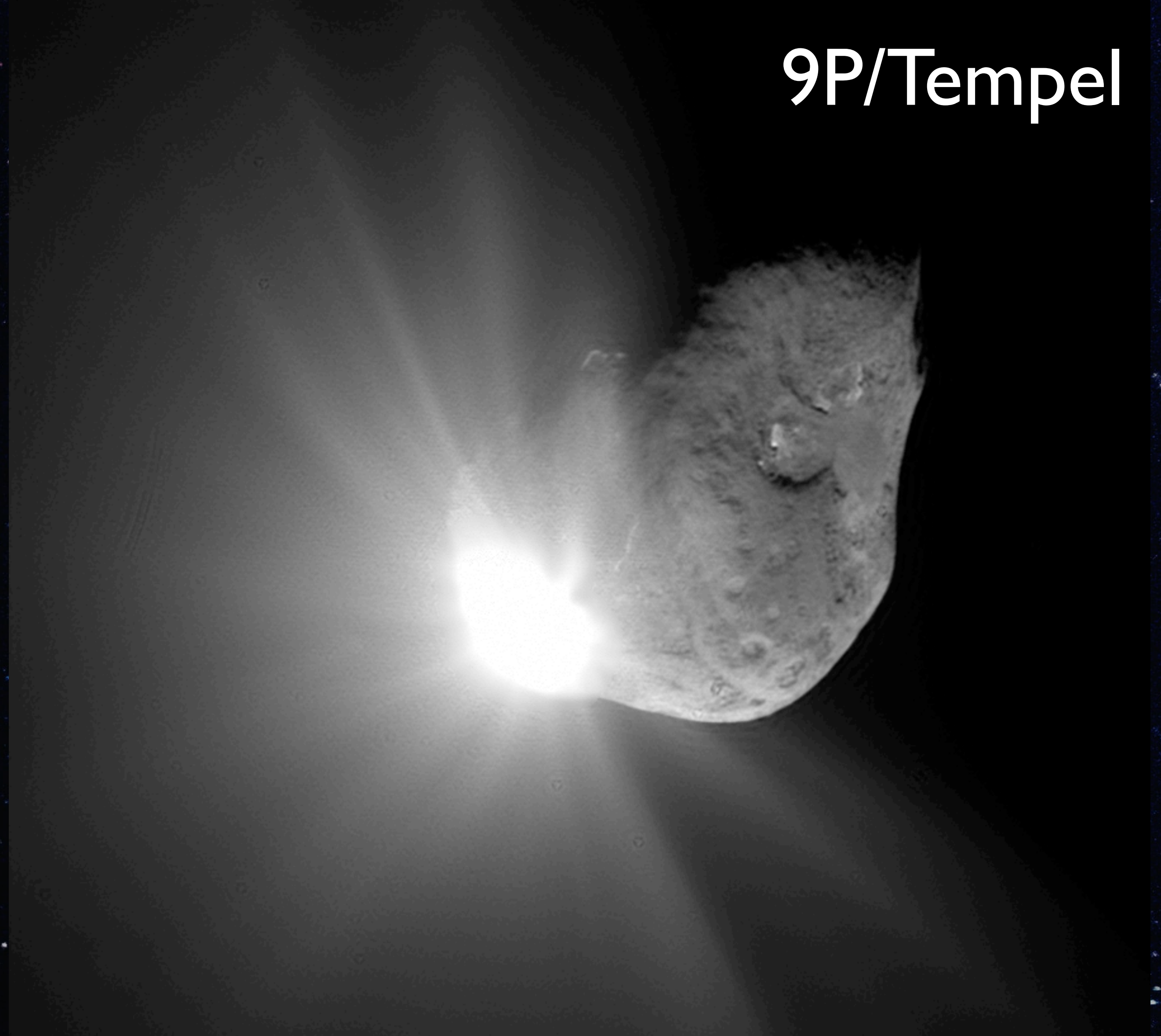
Galileo, 1993

Most asteroids are very small, less than 1000 km across

Most asteroids are located within the Asteroid Belt, between Mars and Jupiter

Space is big! The asteroids aren't actually that close to each other, *so the odds aren't "3,720 to 1" C-3PO*

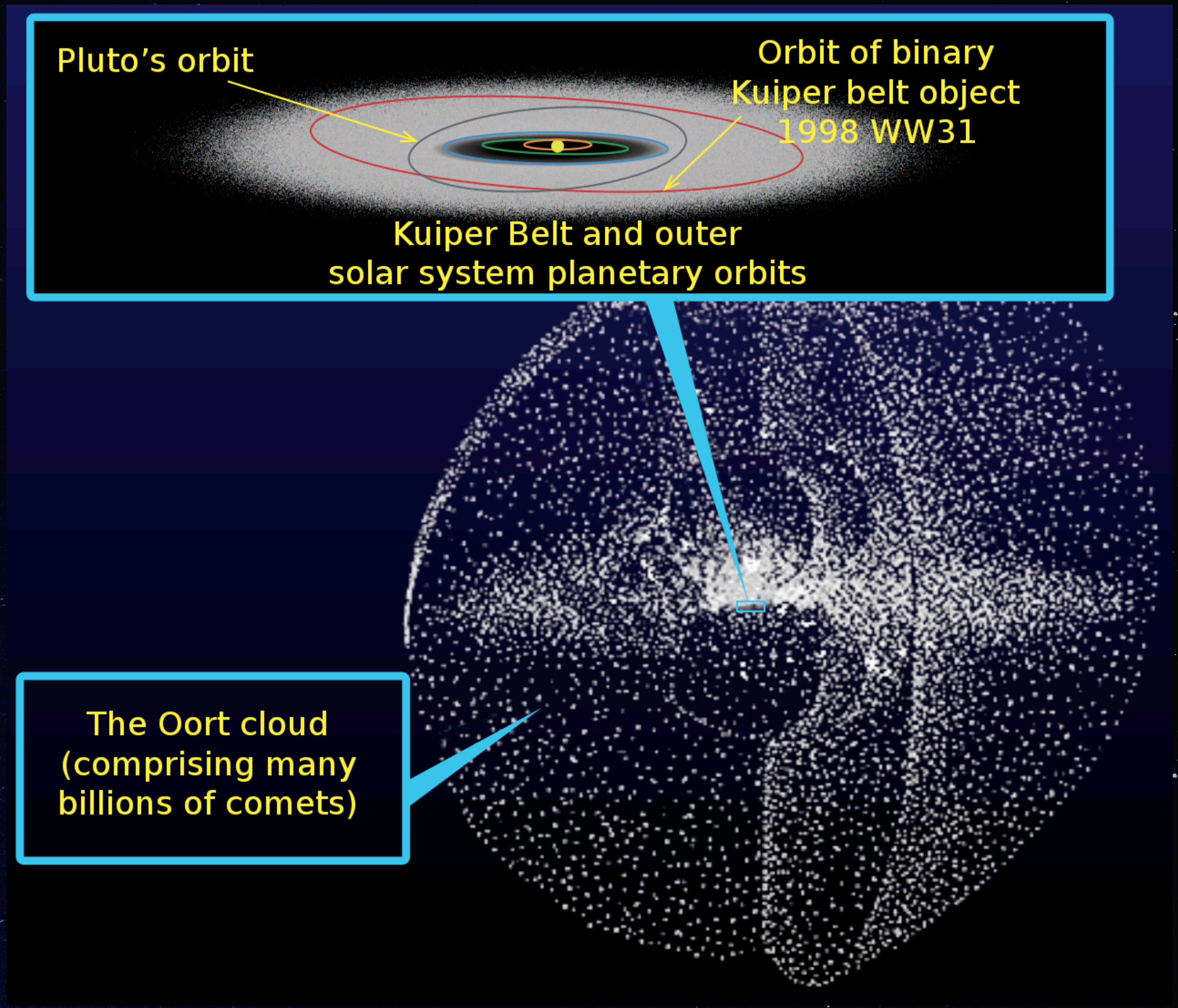
Asteroids and Comets



Deep Impact, 2005

Comets are icy objects found in the outer solar system

Most comets are thought to be no bigger than 16 km (10 mi)



Two spots where comets can come from:

- Kuiper Belt: donut-shaped region beyond Neptune containing 100,000 icy objects including Pluto and Eris
- Oort Cloud: much more distance spherical swarm of trillions of comets

Exceptions to the Rules

While most of the planets rotate in the same direction they orbit, Venus and Uranus are the notable exceptions

Venus spins backwards and Uranus spins on its side!

While most planets fall into two categories, terrestrial or gas giant, dwarf planets like Pluto don't fit into those categories

Planetary moons are also much smaller than their planets, except for the Earth/Moon system

Even if a theory explains the "big picture" patterns we see, there needs to be room in it to explain the exceptions too

Spacecraft Exploration

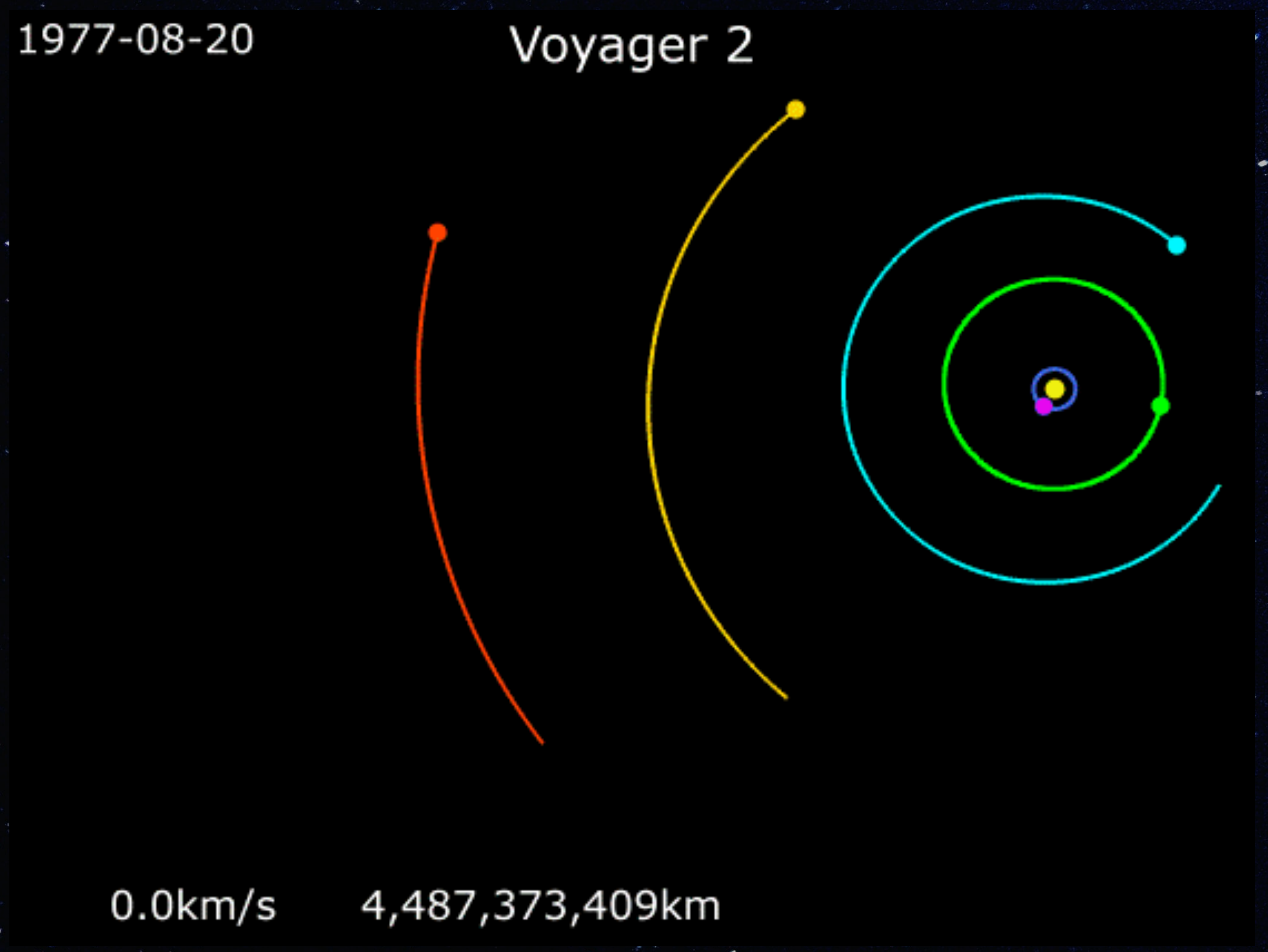
Spacecraft exploration comes in four major categories:

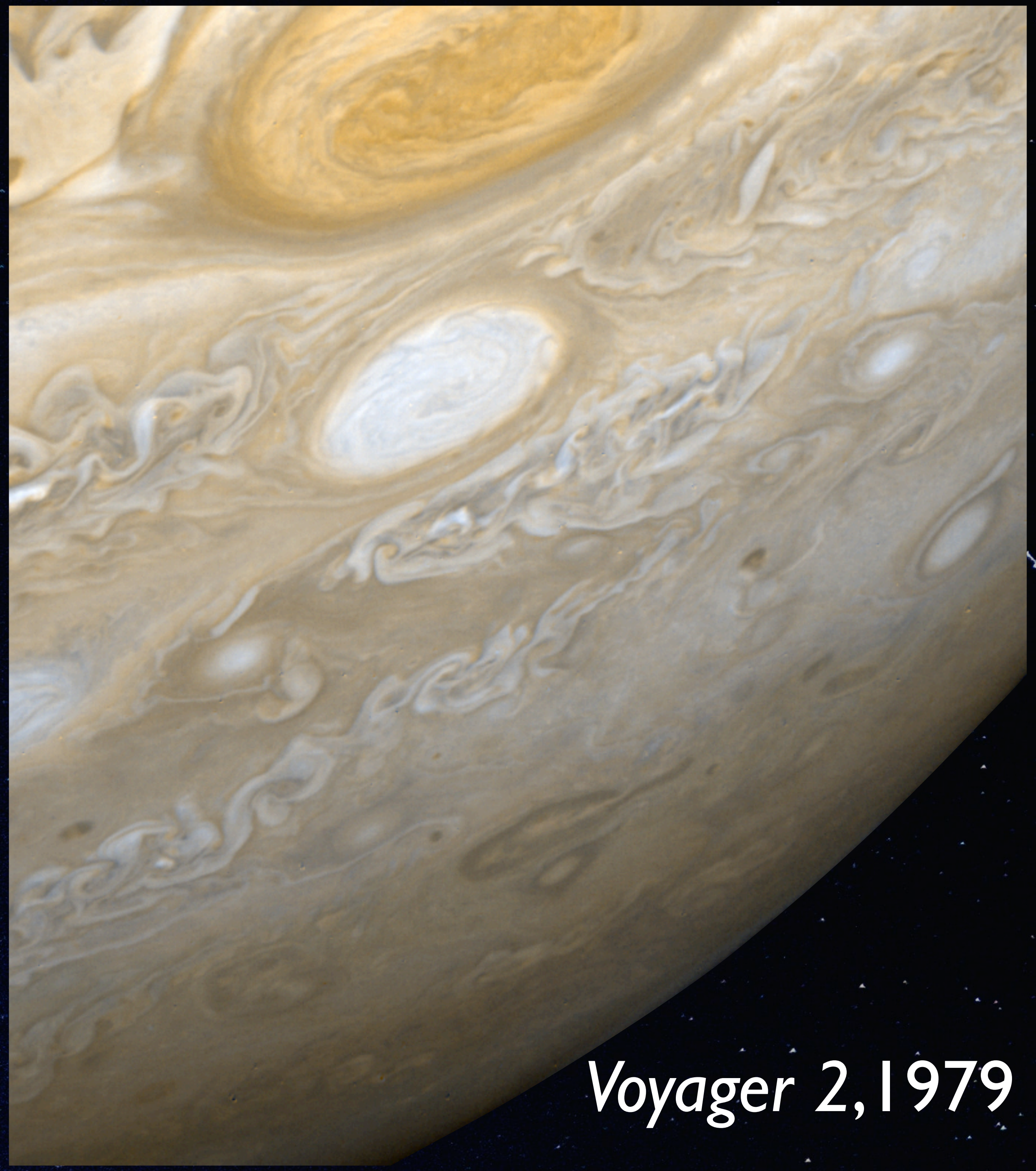
- Flybys
- Orbiters
- Landers or probes
- Sample return missions

Spacecraft Exploration - Flybys

Flybys are generally the cheapest option: send them towards a planet and they don't need fuel to insert themselves into orbit

Furthermore, they can visit multiple planets!




Voyager 2,1979

Jupiter


Voyager 2, 1981

Saturn


Voyager 2, 1986

Uranus


Voyager 2, 1989

Neptune

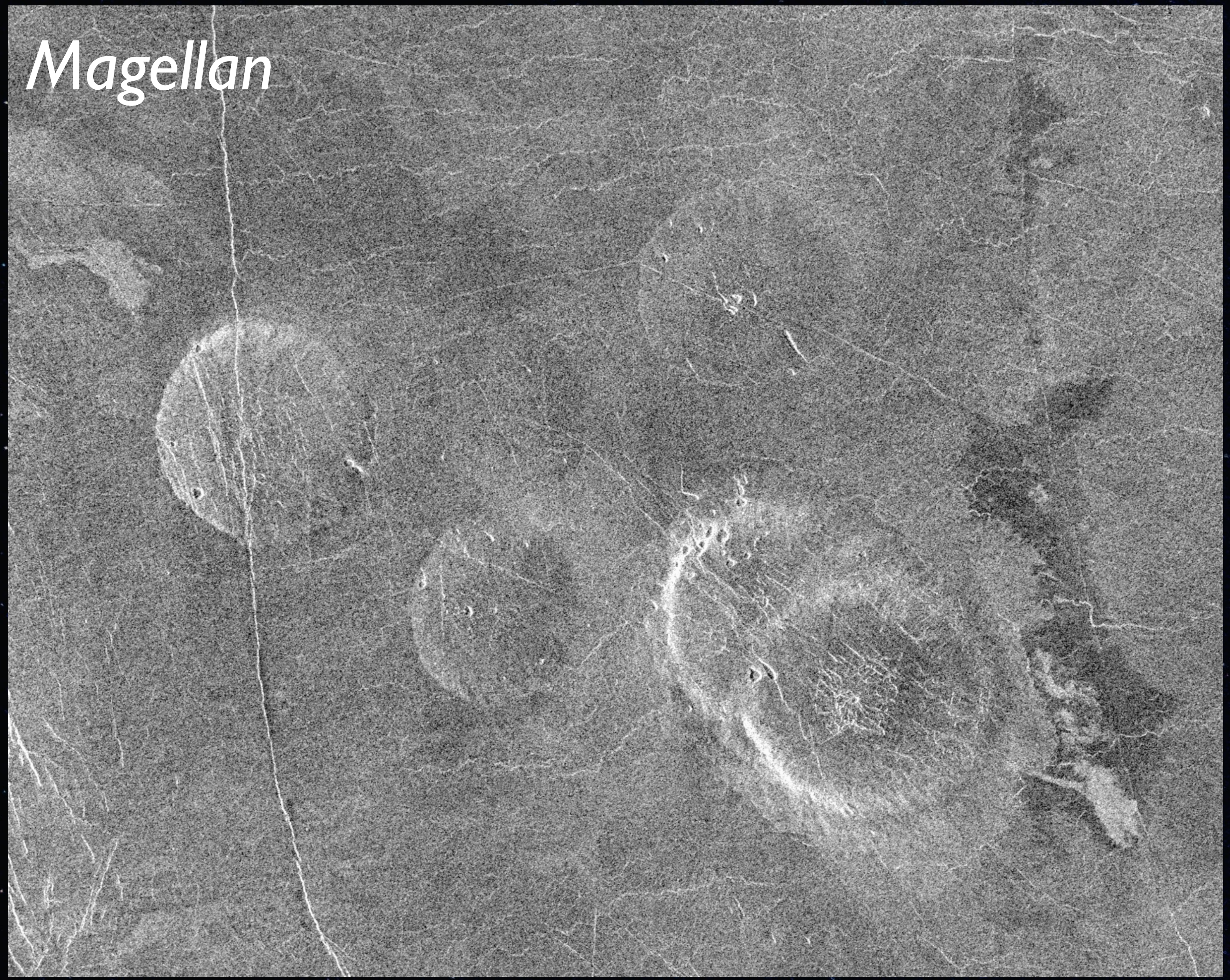
Spacecraft Exploration - Orbiters

Orbiters are able to study a planet for a much longer period of time than flybys

However, orbiters are generally more expensive since they must also carry enough fuel to insert themselves into planetary orbits

Magellan, May 5, 1989

Dickinson Crater

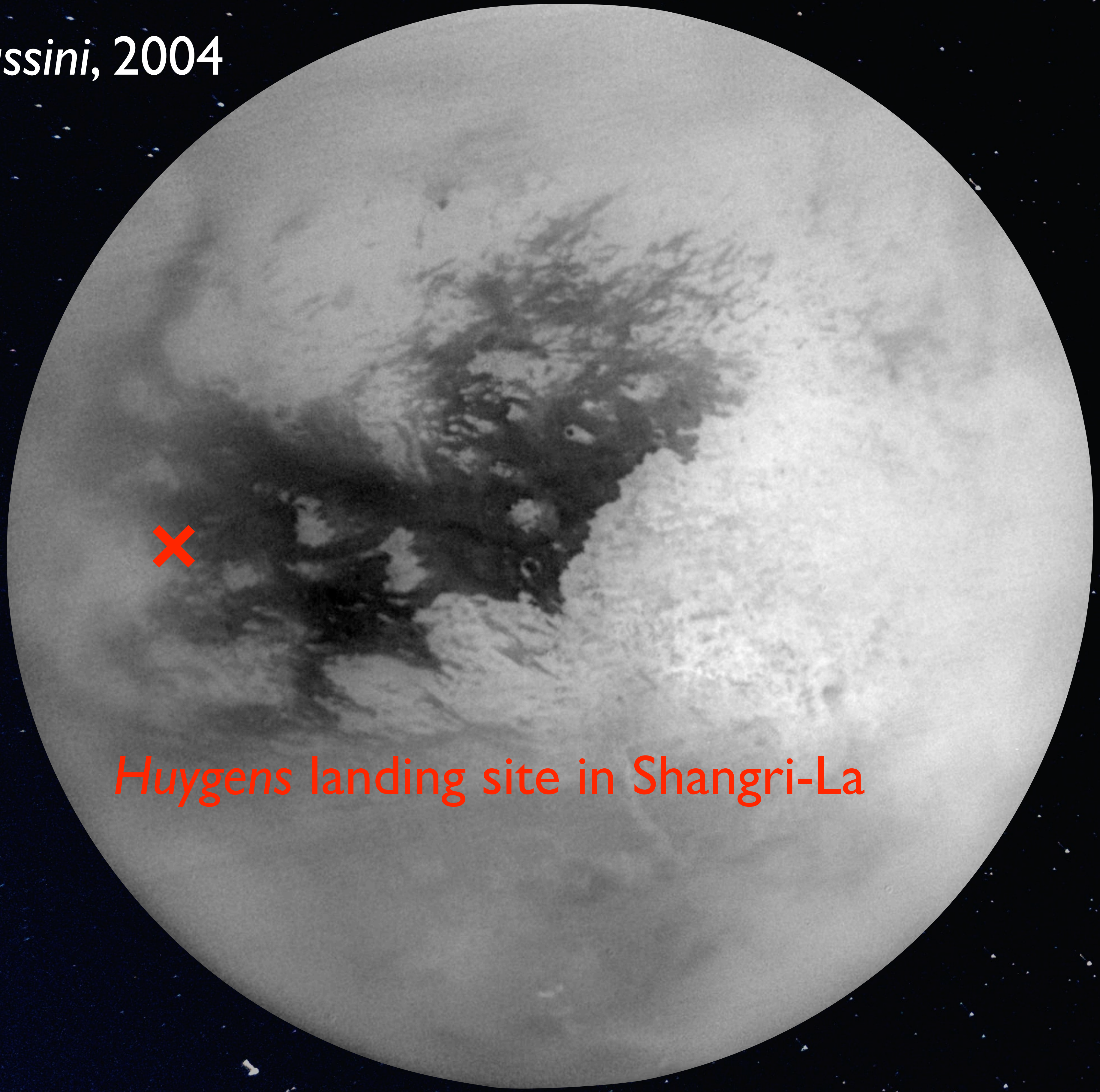


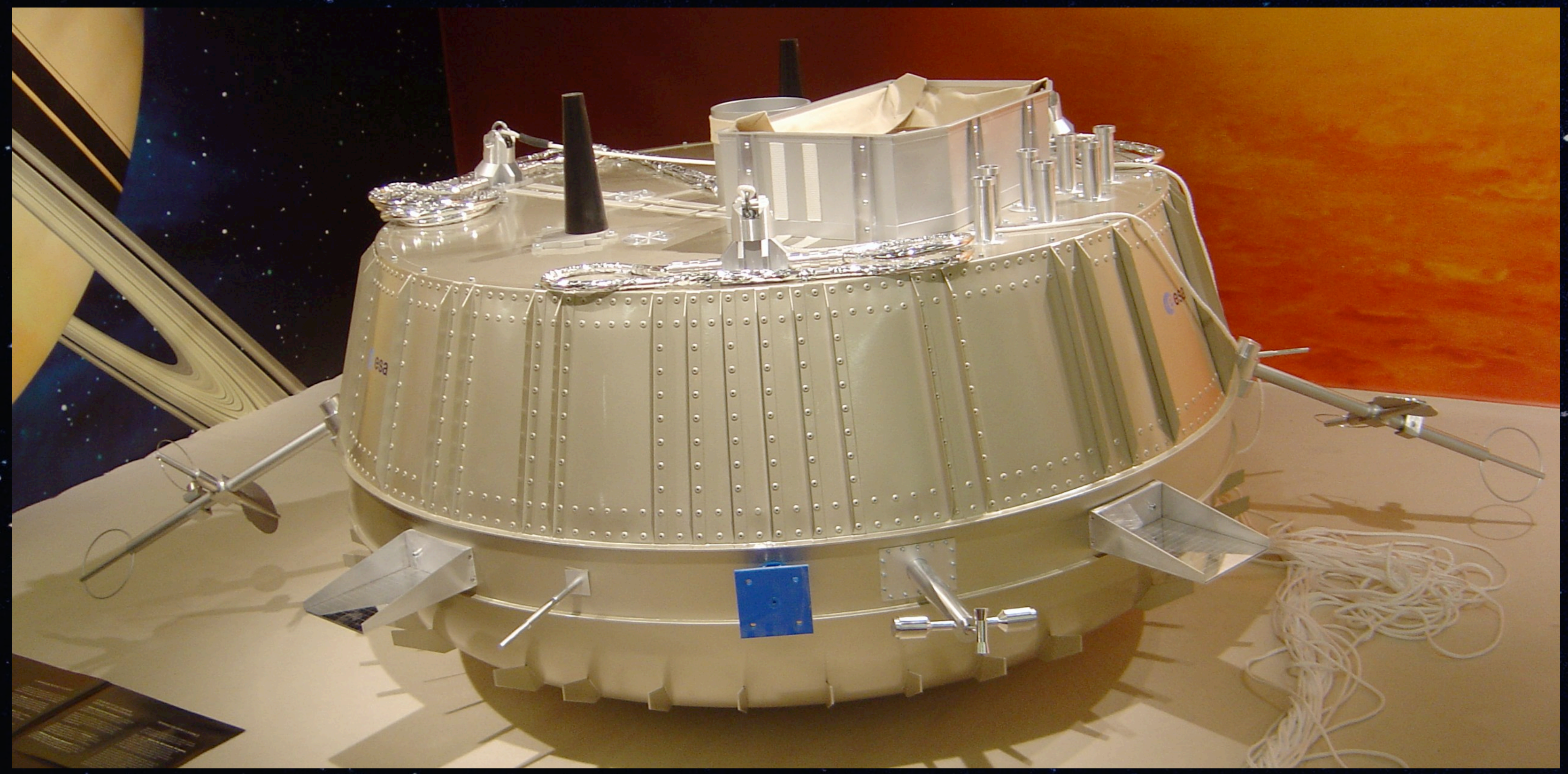
Liban Farra

Spacecraft Exploration - Landers and Probes

Landers and probes offer us the most "up close and personal" views of the worlds of the solar system

Cassini, 2004





Huygens

The Surface of Titan

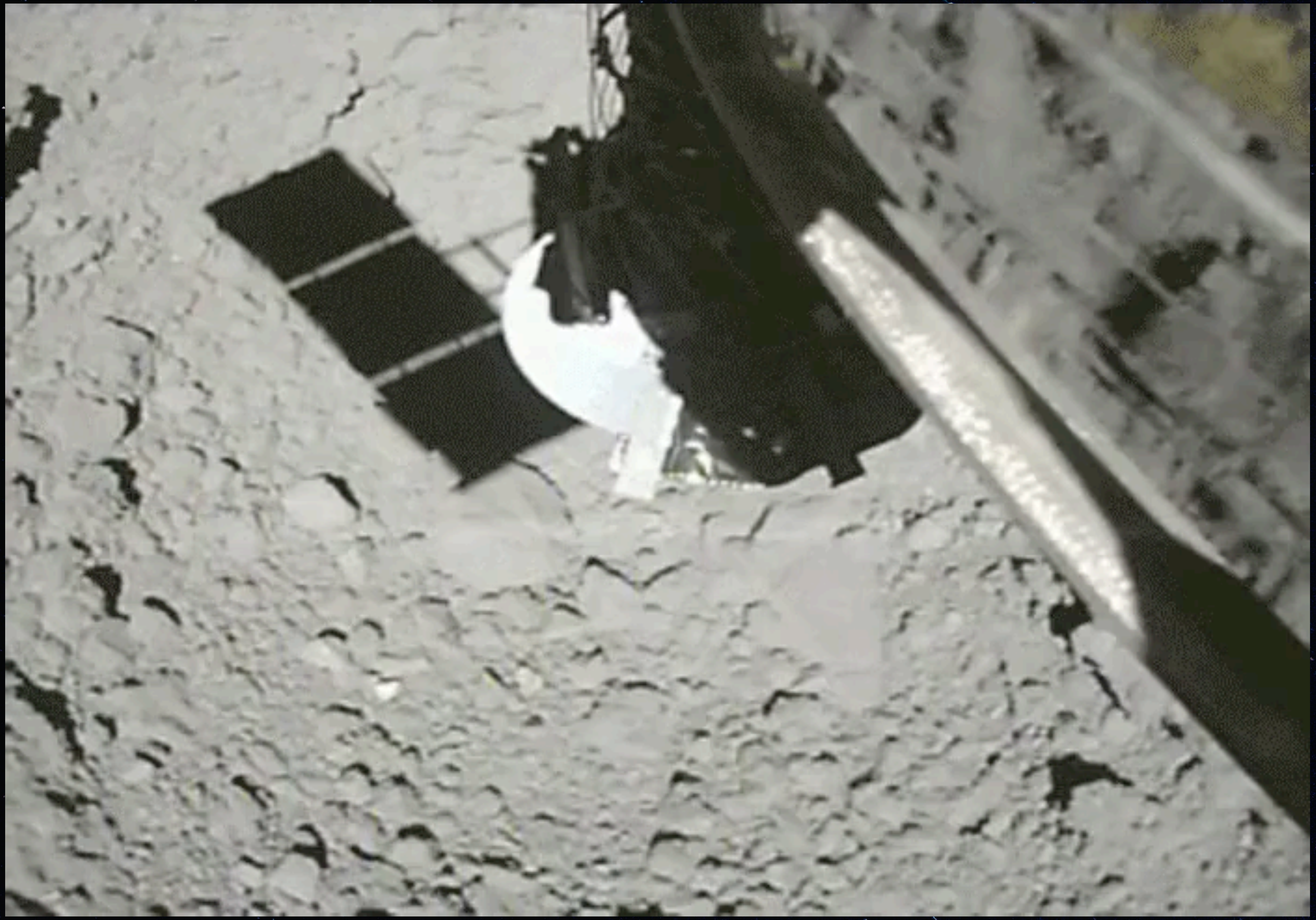
Spacecraft Exploration - Sample Return Missions

Although probes and landers can carry out experiments, those experiments must be designed in advance and fit on the spacecraft

162173 Ryugu, *Hayabusa2*

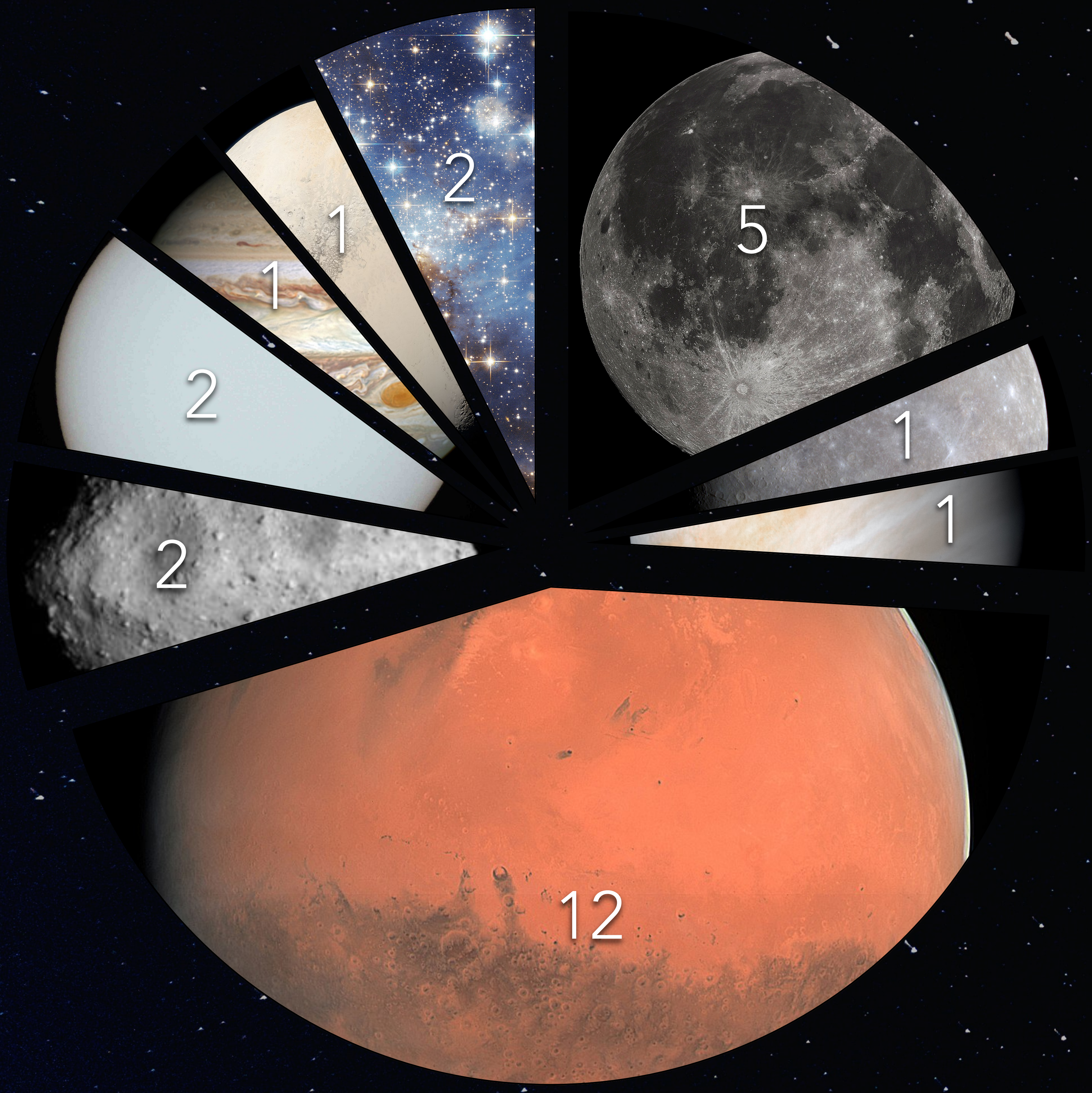
One way around these limitations is to take samples from other worlds and bring them back to Earth for study

Hayabusa2, JAXA



Hayabusa2 touching down on 162173 Ryugu on July 11, 2019

There are currently 27 *active* spacecraft in the solar system investigating other worlds!



Body	Mission	Mission Time	Spacecraft Type	Agency
Moon	ARTEMIS P1/P2	April 2011 - present	Orbiter	NASA
	Lunar Reconnaissance Orbiter	September 2009 - present	Orbiter	NASA
	Queqiao	June 2018 - present	Orbiter	CNSA
	Chang'e 4 & Yutu-2	January 2019 - present	Lander & Rover	CNSA
	Chandrayaan-2	August 2019 - present	Orbiter	ISRO
Mercury	*BepiColumbo*	*December 2025 (en route)*	*Orbiter*	*ESA & JAXA*
Venus	Akatsuki	December 2017 - present	Orbiter	JAXA
Mars	2001 Mars Odyssey	October 2001 - present	Orbiter	NASA
	Mars Express	December 2003 - present	Orbiter	ESA
	Mars Reconnaissance Orbiter	March 2006 - present	Orbiter	NASA
	Curiosity	August 2012 - present	Rover	NASA
	Mangalyaan	September 2014 - present	Orbiter	ISRO
	MAVEN	September 2014 - present	Orbiter	NASA
	Trace Gas Orbiter	October 2016 - present	Orbiter	ESA
	InSight	November 2018 - present	Lander	NASA
	Emirates Mars Mission	February 2021 - present	Orbiter	UAESA
	Tianwen-1	February 2021 - present	Orbiter & Rover	CNSA
	Perseverance	February 2021 - preset	Rover	NASA
	Ingenuity	April 2021 - present	Helicopter	NASA
Asteroids	Hayabusa2	June 2018 - present	Sample Return	JAXA
	OSIRIS-REx	December 2018 - present	Sample Return	NASA
Sun	Parker Solar Probe	January 2019 - present	Orbiter	NASA
	Solar Orbiter	*2023 (en route)*	*Orbiter*	*ESA*
Jupiter	Juno	July 2016 - present	Orbiter	NASA
Kuiper Belt	New Horizons	July 2015 - present	Flyby	NASA
Beyond the Solar System	Voyager 1	January 1979 - present	Flyby	NASA
	Voyager 2	July 1979 - present	Flyby	NASA

Formation of the Solar System

"The evolution of the world may be compared to a display of fireworks that has just ended: some few red wisps, ashes and smoke. Standing on a cooled cinder, we see the slow fading of the suns, and we try to recall the vanished brilliance of the origin of the worlds."

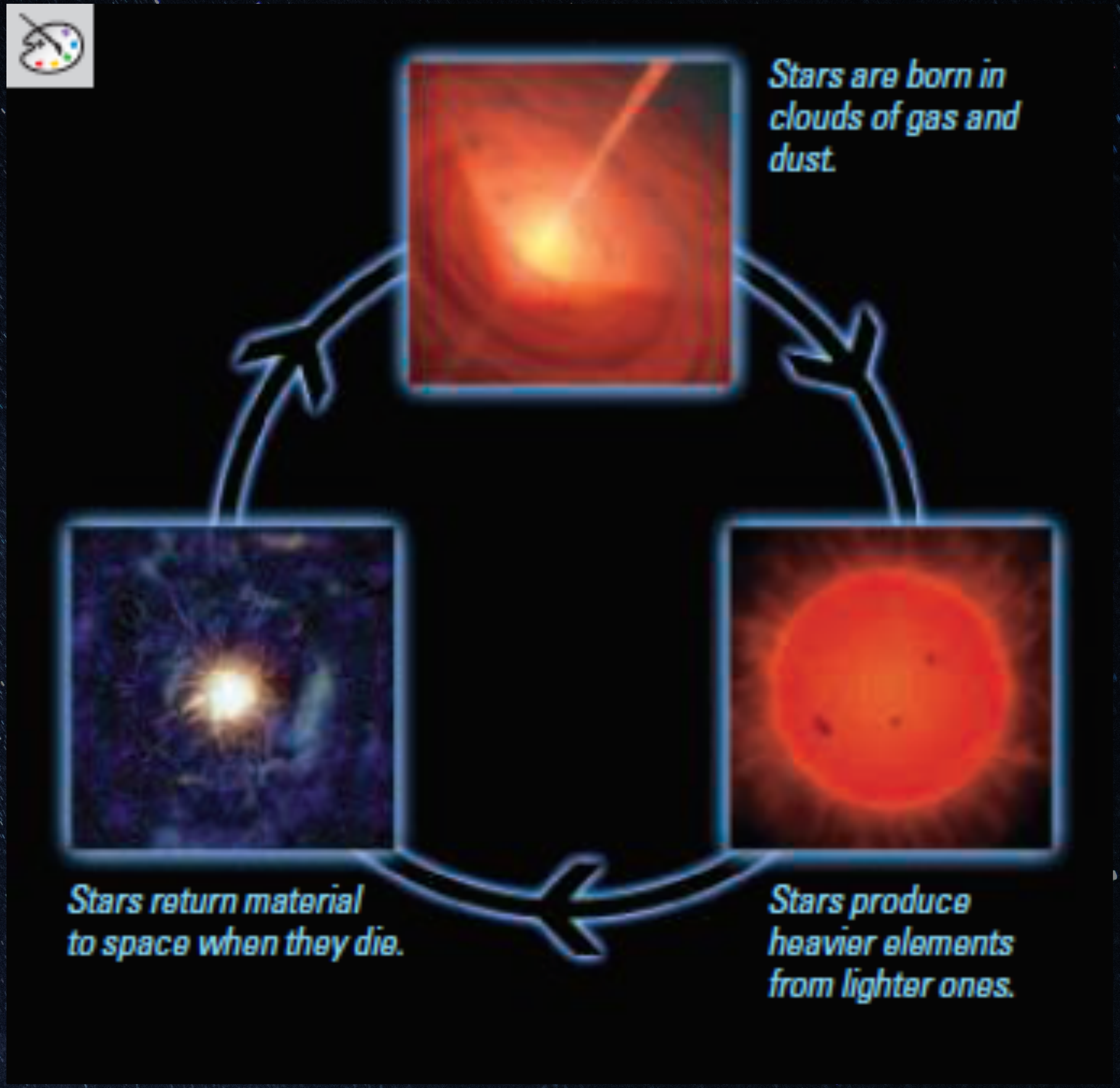
Georges Lemaître

The Origins of the Solar System

The nebular theory begins with the idea that our Solar System was born from the gravitational collapse of an interstellar cloud of gas, called the solar nebula, giving birth to the Sun and the planets

The gas that formed that original interstellar cloud was the product of billions of years of galactic recycling from previous generations of stars

The gas cloud consisted of 98% hydrogen and helium and 2% everything else, and strong observational evidence supports this scenario



Explaining the Patterns of Motion

Initially, the solar nebula probably began as a large and roughly spherical cloud of very cold, low-density gas that was so spread out that gravity probably could not have pulled it together to collapse

Likely, the collapse was triggered by a nearby event, such as a shockwave from a nearby supernova

Once the collapse started, gravity enabled it to continue, increasing with strength as the cloud grew smaller, but other physical laws are also in play to explain the patterns of motion

Explaining the Patterns of Motion

As the solar nebula shrank in size, three important processes altered its density, temperature, and shape:

Heating: the temperature of the solar nebula increased as it collapsed as gravitational potential energy was converted into the kinetic energy of individual particles and then into thermal energy as they crashed into each other

Spinning: due to conservation of angular momentum, the imperceptible rotation of the cloud increased as the cloud shrank, ensuring that not all of the material fell into the center

Flattening: as particles collided with each other, the resulting particles had the average velocity of the original particles, so a chaotic system became more ordered

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Because of conservation of energy, the cloud heats up as it collapses. Because of conservation of angular momentum, the cloud spins faster as it contracts.

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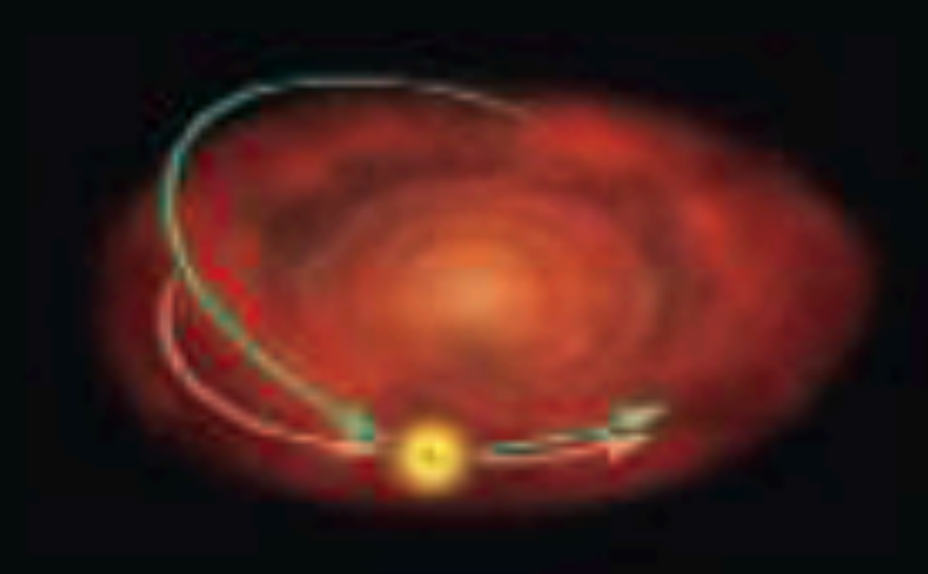

Collisions between particles flatten the cloud into a disk.

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Explaining the Patterns of Motion

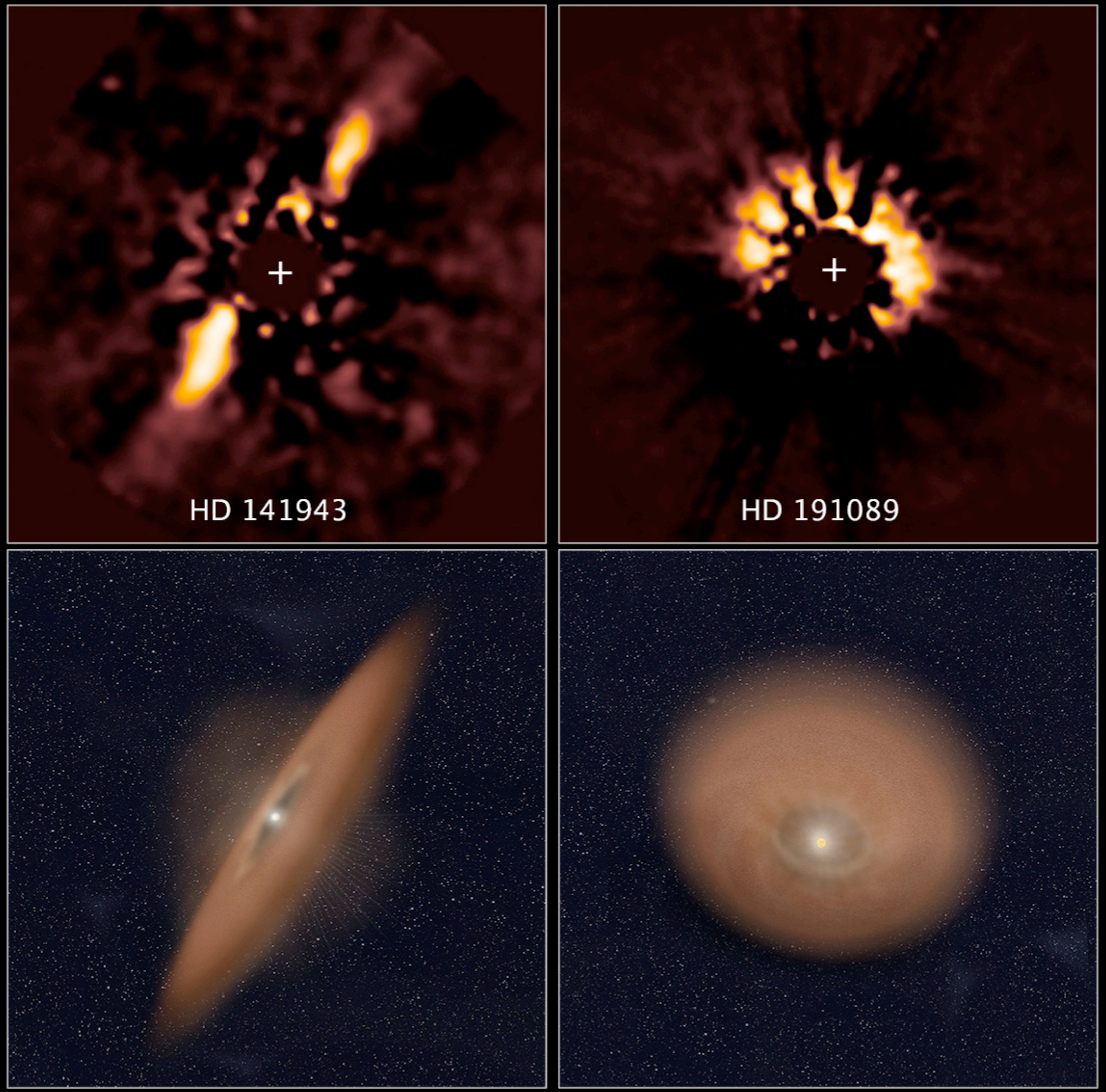
The formation of the spinning disk explains the orderly motions of the Solar System today!

- The planets all orbit the Sun in nearly the same plane because they all formed in a flat disk
- The direction in which the disk was spinning became the direction of the Sun's rotation and the orbit of the planets
- The fact that collisions made orbits more circular on average explains why the planets have nearly circular orbits
- Computer simulations have shown that planets would also tend to rotate in the same direction that they formed

Testing This Model

These same processes should affect other collapsing gas clouds, so if we find other disks around other stars, then our model is confirmed!

The heating of the collapsing cloud of gas should emit thermal radiation in the infrared



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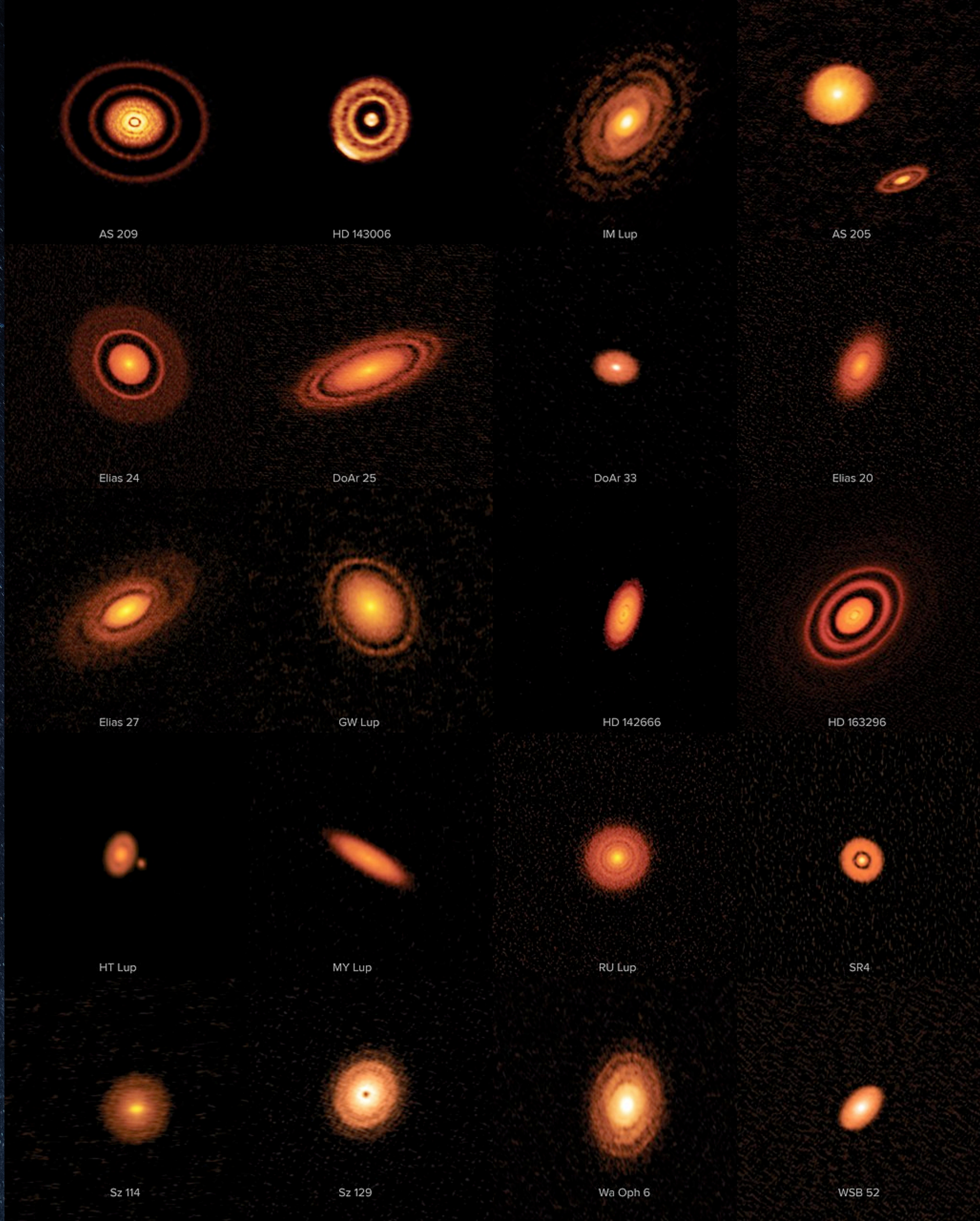


Why do we have two types of planets—terrestrial and Jovian?

Explaining the Two Types of Planets

In the center of the disk, gravity drew together enough material to form the Sun, but further out the material was too sparse for gravity to clump it together

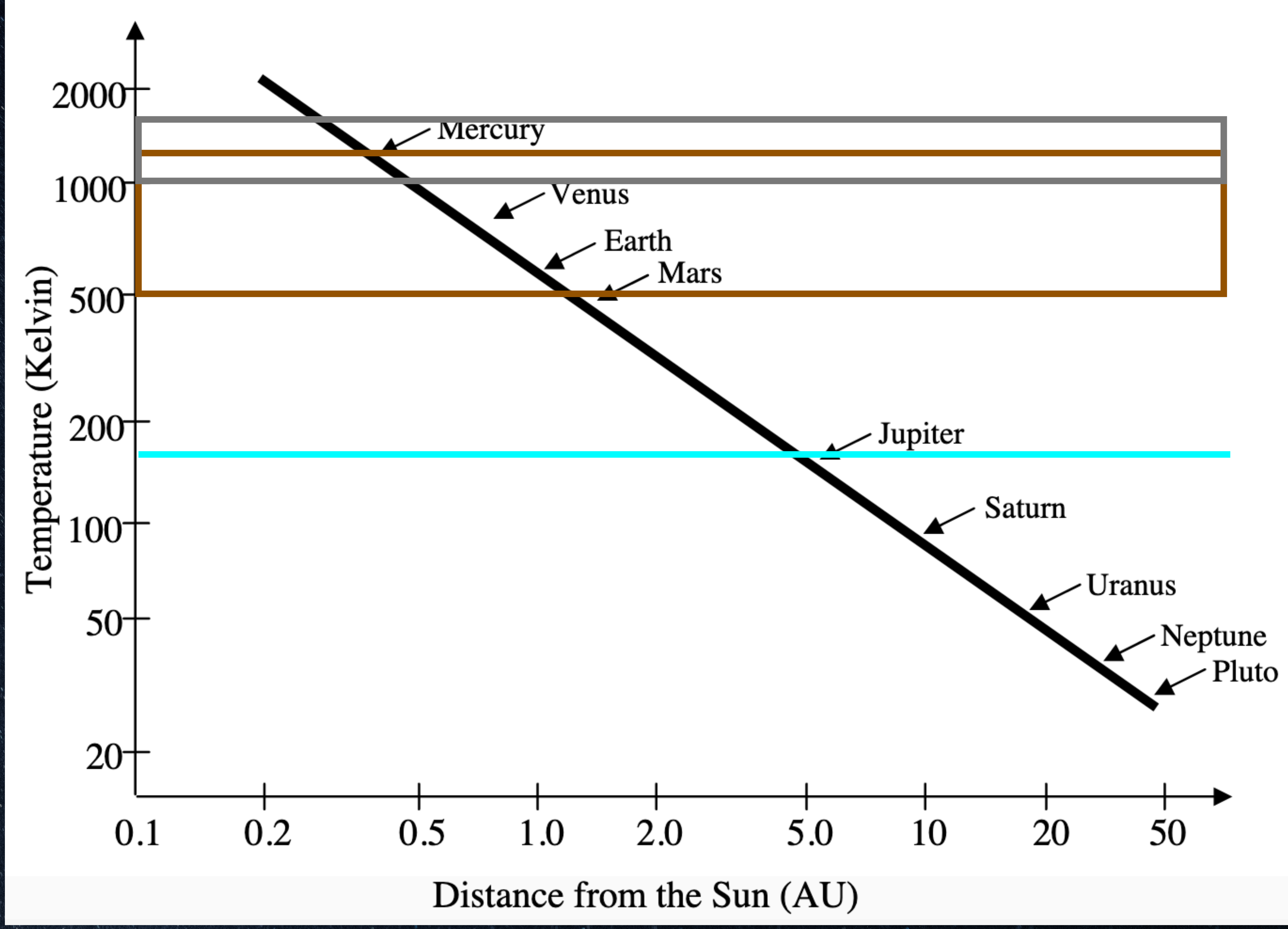
The planets had to form out of the gas: at low enough temperatures, some atoms or molecules in a gas may bond and solidify in a process known as condensation

Hydrogen & Helium gas (98%) does not condense at any temperature

Hydrogen compounds (1.4%) condense into ices below about 150 K

Rock (0.4%) condenses into solid form between 500 K and 1300 K

Metal (0.2%) condenses at temperatures below 1000 K to 1600 K



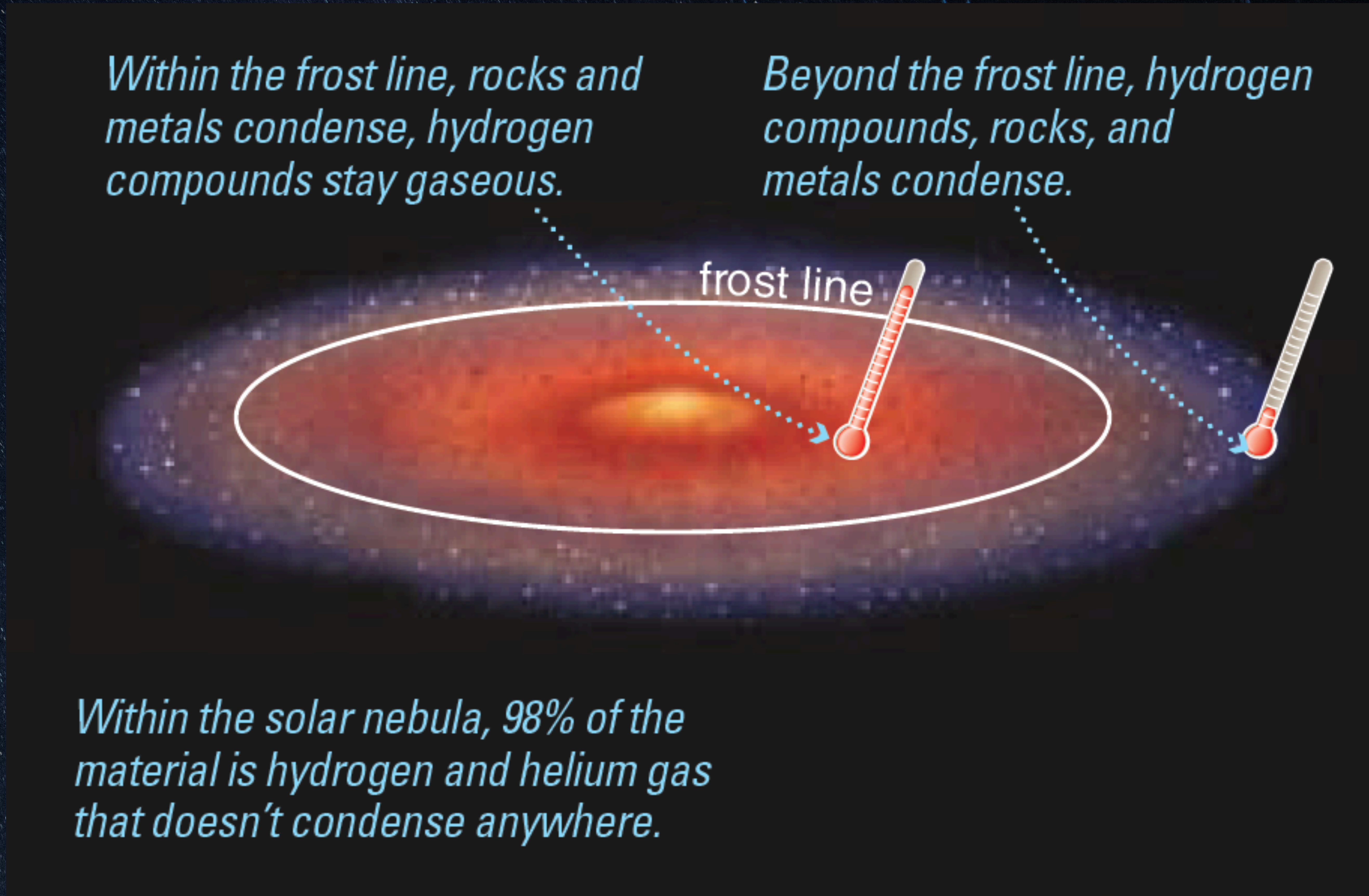
Explaining the Two Types of Planets

Since most of the solar nebula was made up of hydrogen and helium which don't condense, most of the nebula was gaseous; other materials would condense out of the gas when the temperature allowed

Around Mercury's orbit, it was cool enough for metals and some types of rock to condense into solid particles

More types of rock condensed out of the nebula around where Venus, Earth, and Mars would form

It was cold enough for hydrogen compounds to condense beyond the frost line, which was between the current orbits of Mars and Jupiter



Building the Terrestrial Planets

The process by which these small "seeds" grew into planets is called <u>accretion</u>

- Small particles had the same orderly circular paths as the gas, so "collisions" were more like gentle touches
- These particles were too small for gravity to pull them together, but electrostatic forces caused particles to stick to each other, eventually growing large enough for gravity to take over and accelerate the growth becoming <u>planetesimals</u>

Planetesimal growth happened rapidly at first in just a few million years, but once they reached ~100 km in size, growth became more difficult

Gravity altered the planetesimals' orbits, making them cross each other and their large sizes made the collisions more destructive than constructive; only the large ones survived to become planets

Making the Jovian Planets

Accretion should have happened in a similar way in the outer solar system, and there was way more material since ice could condense out there

These icy planetesimals were able to grow so large and massive that their gravity captured some of the hydrogen and helium of the nebula, making their gravity stronger, pulling in more gas, etc

This also explains the large moons of the Jovian planets: the same process of heating, spinning, and flattening that the solar nebula went through also happened to the gas drawn in by the Jovian planets

Where did all the gas and dust go?
How do we get rid of it?

Clearing Out the Nebula

Most of the hydrogen and helium never went into forming the planets, so it must have been cleared away by a combination of high-energy X-rays and UV light from the Sun and the solar wind

The clearing of the gas sealed the compositional fates of the planets:

- If the gas stayed around longer, it might've cooled enough for ices to condense in the inner solar system, changing the nature of the terrestrial planets
- If the gas was cleared earlier, the raw materials to form planets might've been swept away before planets could form

In turn, this allowed the Sun to transfer some of its angular momentum to the gas, allowing the Sun to be spinning as slowly as it does today

The Origins of the Asteroids and Comets

Asteroids and comets are "leftovers" from the process of planet formation

They are likely only a small fraction of the planetesimals that once roamed the Solar System: the rest were either thrown into space by gravitational encounters or collided with the planets

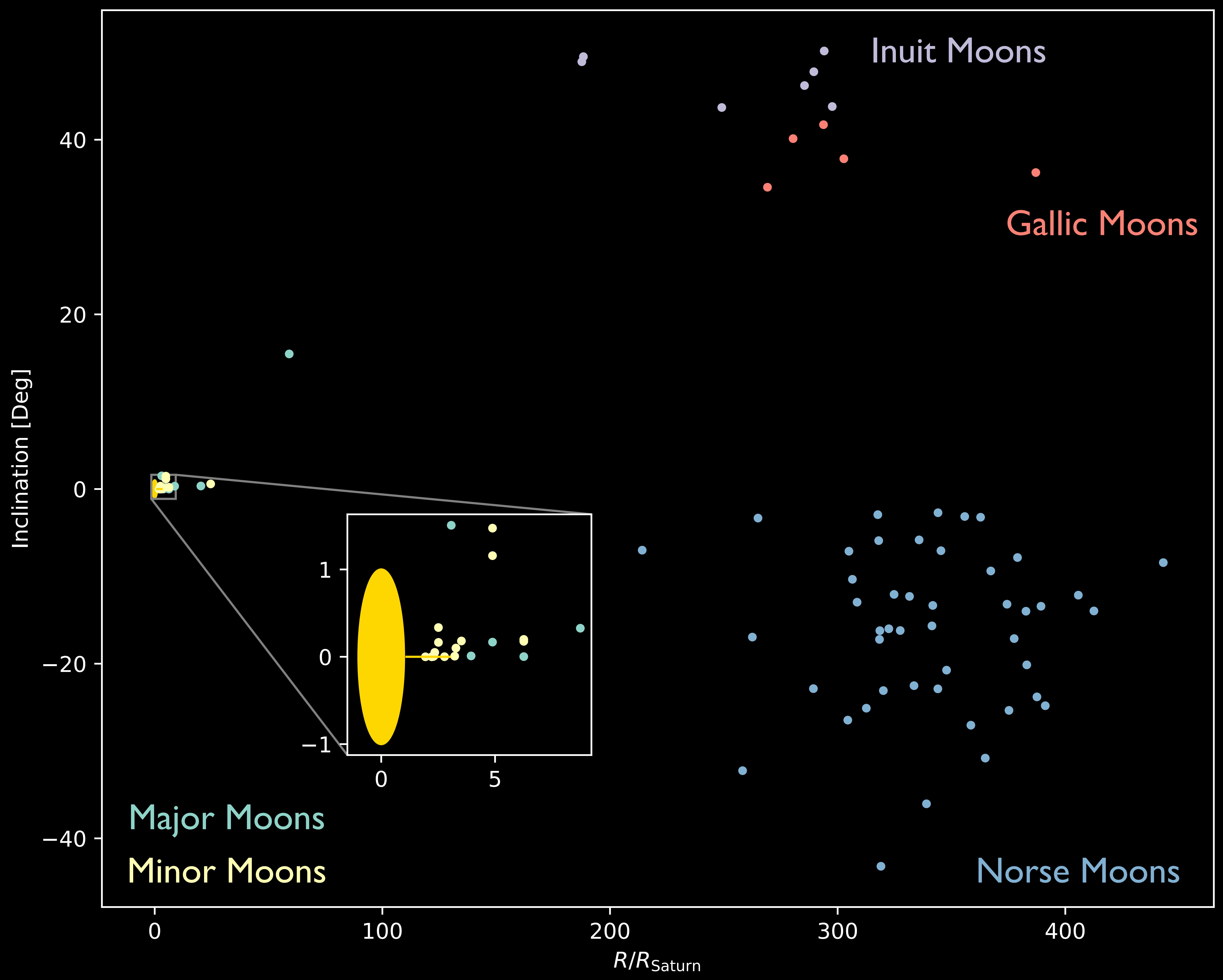
The vast majority of these impacts occurred during the period of Heavy Bombardment during the first few hundred million years of our Solar System

Since water could not condense in the inner solar system, it likely that these impacts brought water and other hydrogen compounds from the outer solar system inward

The Exceptions — Captured Moons

Moons that go in the "wrong" direction or have large inclinations relative to their planet's equator are likely captured planetesimals

They were likely captured while the Jovian planets had a disk of gas surrounding them, causing nearby planetesimals to lose orbital energy due to friction

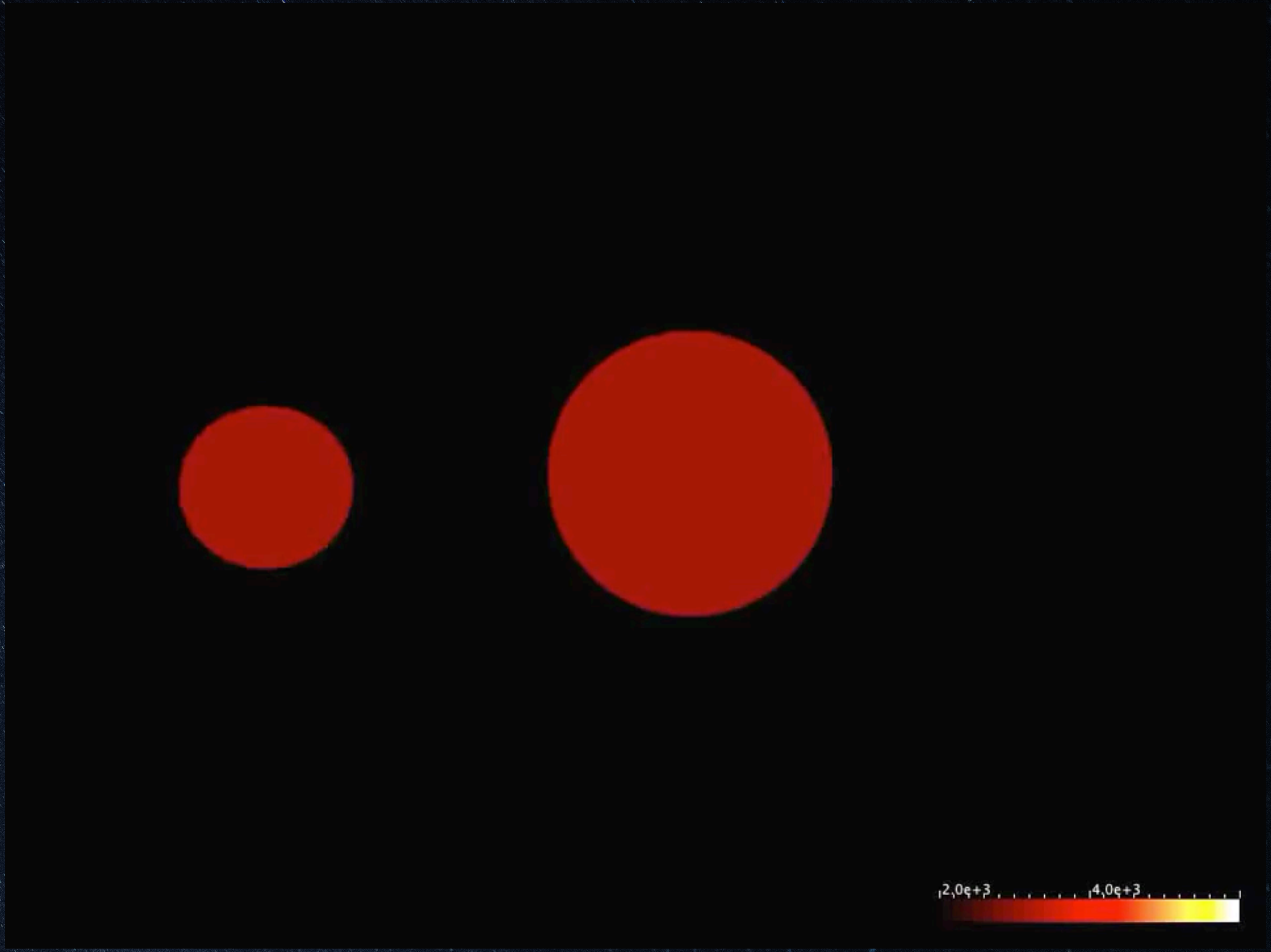


The Exceptions — The Moon

Capture processes can't explain our Moon, because it is too large to have been captured by a small planet like Earth

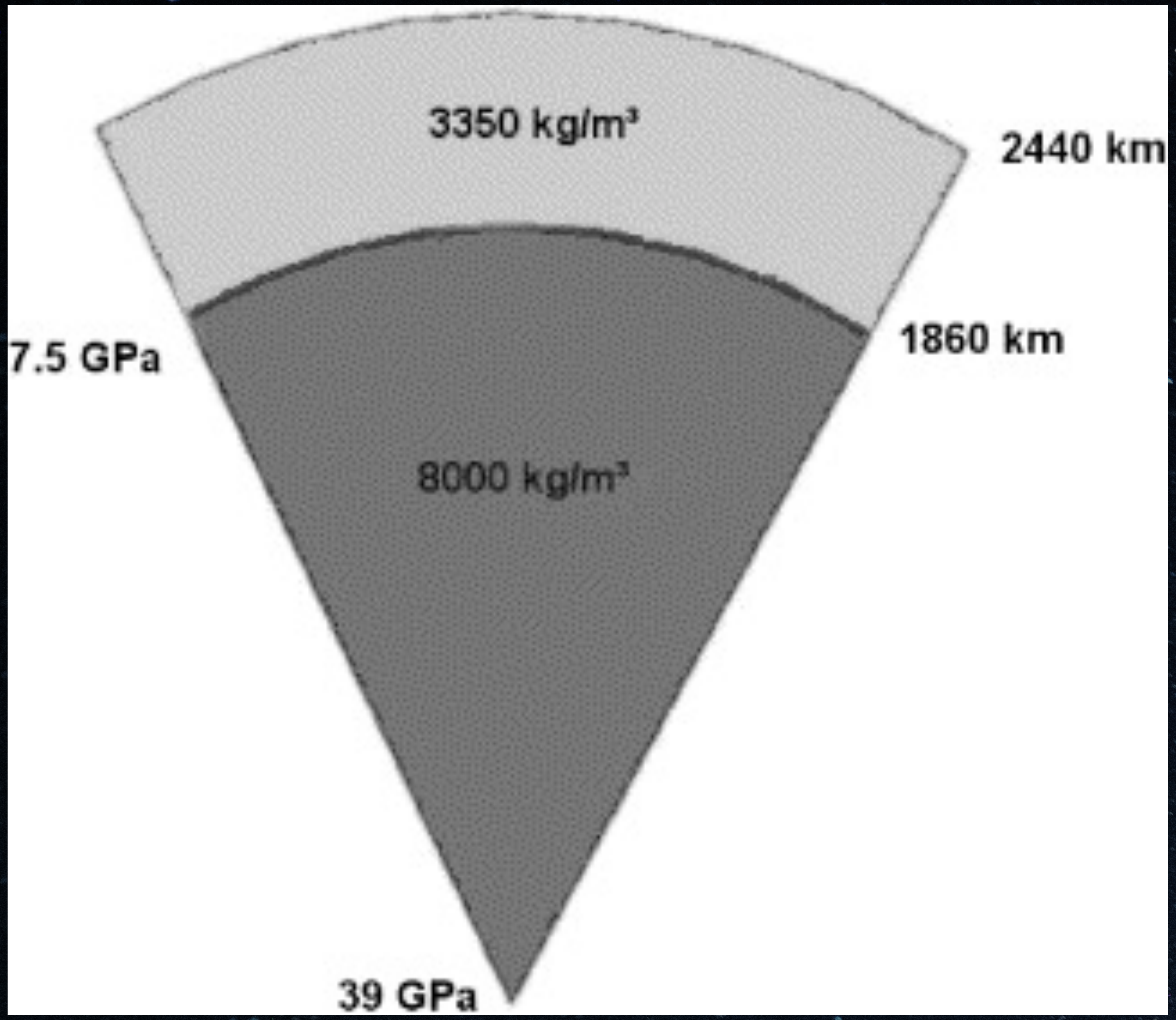
It also couldn't have formed simultaneously with the Earth because then the two would be made of the same material at the same density; the Moon's density is about 60% of Earth's

The leading hypothesis is the giant impact theory: a Mars-sized object hit Earth, blasting Earth's outer layers into space which collected in an orbit around Earth and formed the Moon

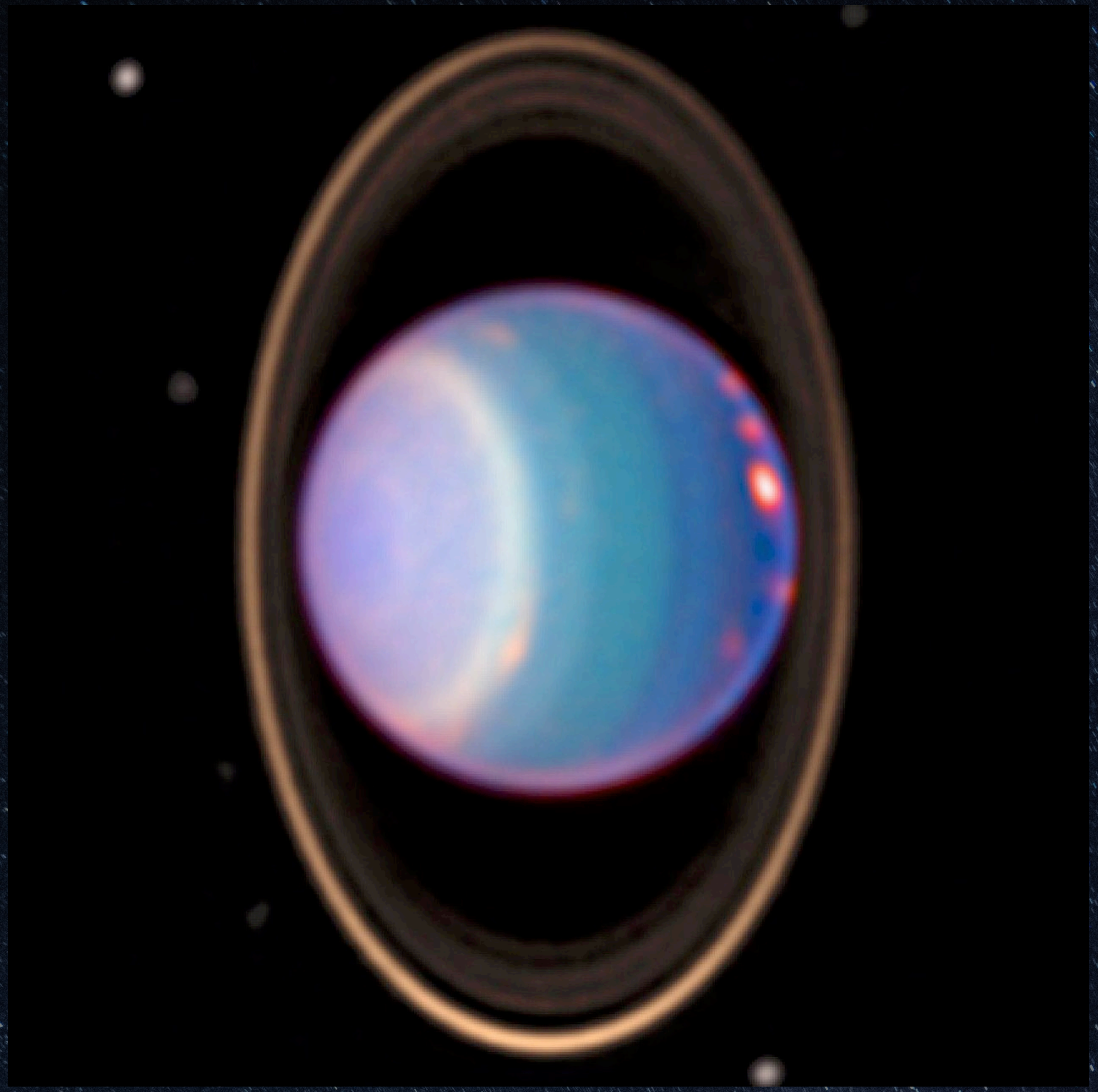


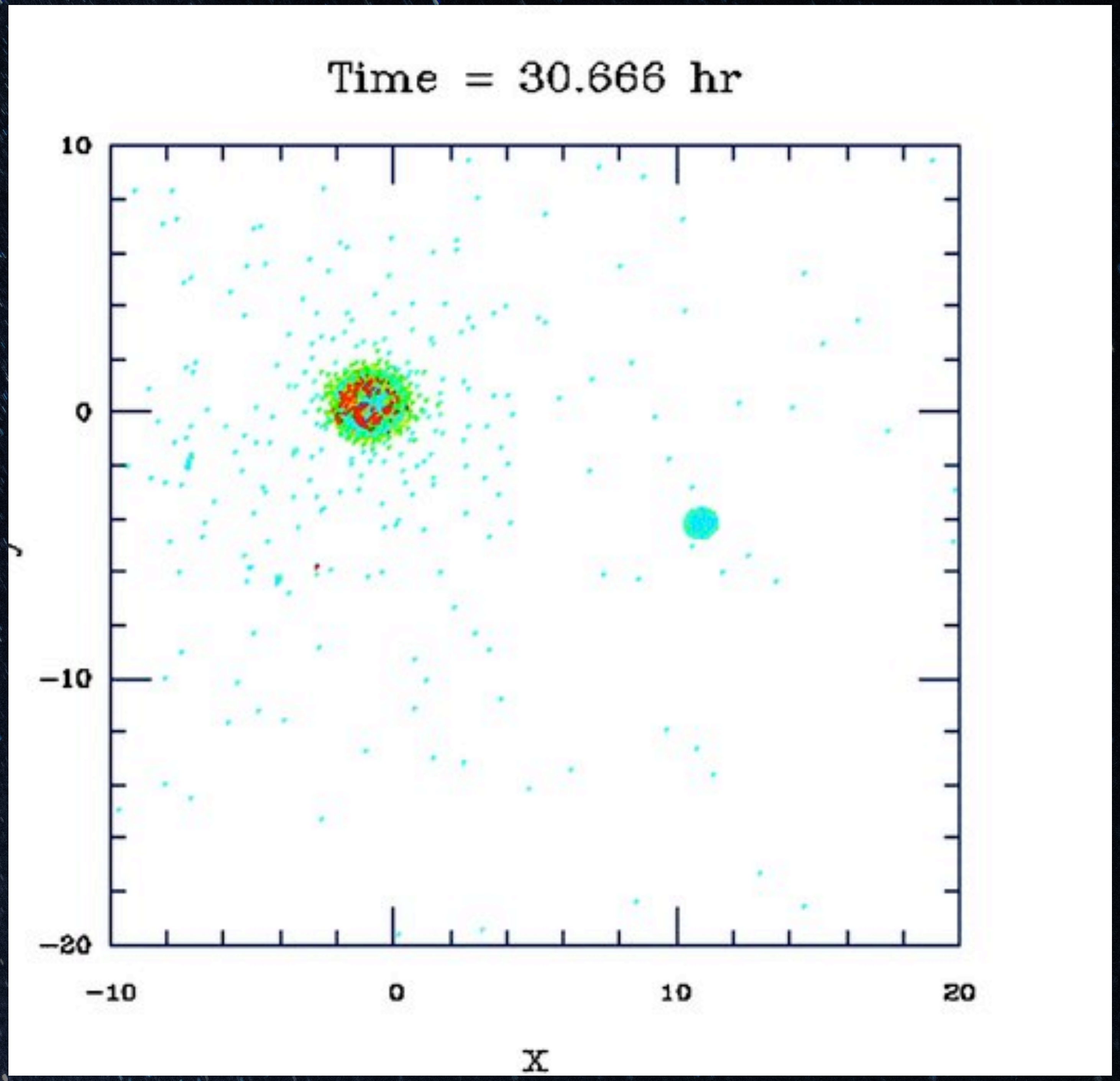
Nakajima & Stevenson (2014)

The Exceptions — Other Impacts



Spohn et al. (2001)


HST near-infrared (1998)



Canup (2010)

Mercury has a large core, perhaps left behind after a giant impact?

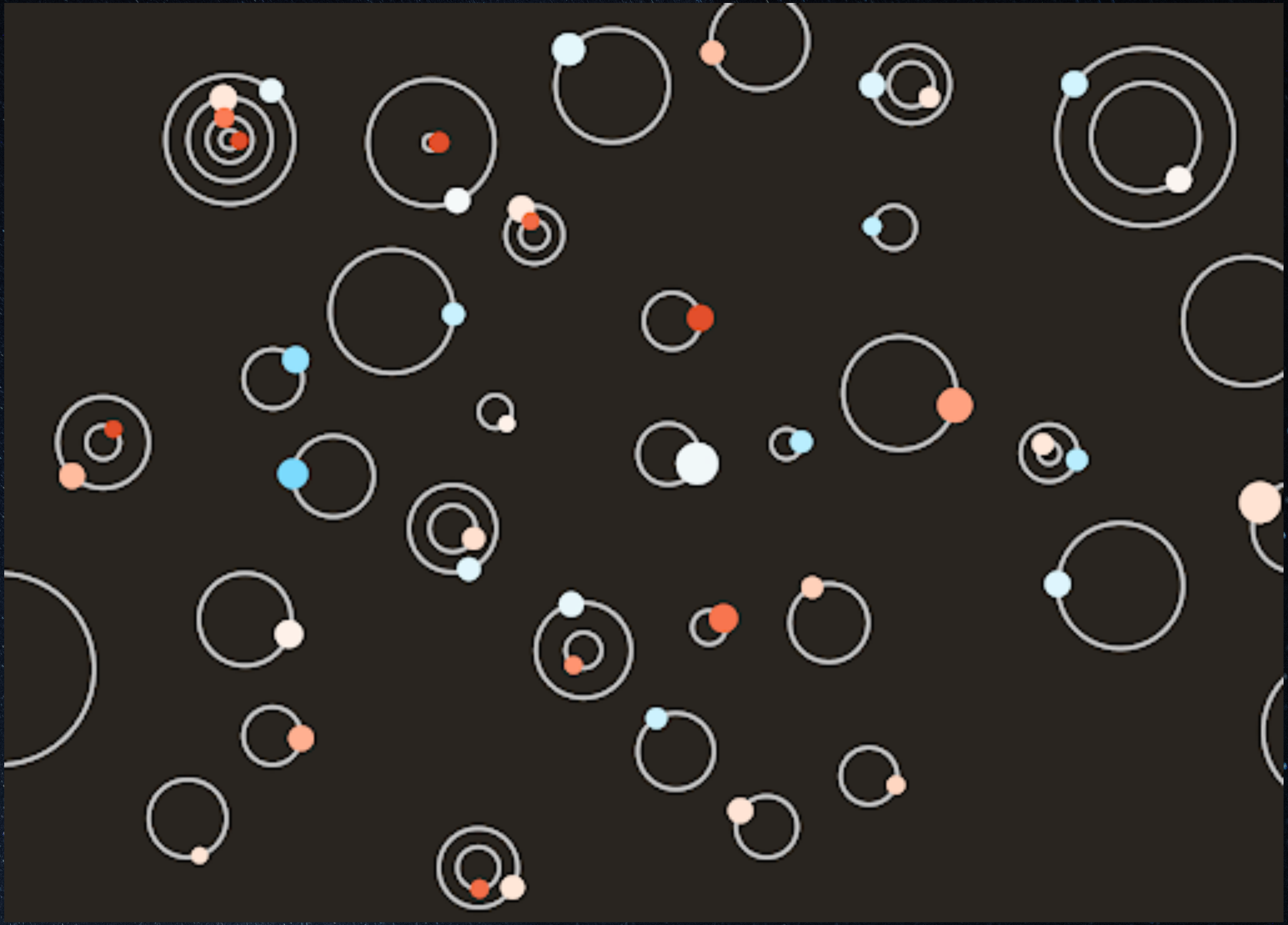
Uranus is tilted on its side; another giant impact?

Could an impact have created the Pluto-Charon system?

Was all of this simply a matter of *planetary destiny?*

Although the nebular theory can tell us a lot about the formation of our solar system and explain a lot of the features we see today, it does not mean that it was all destined to be this way

Other solar systems can be radically different from our own, so the same processes that formed our orderly system of planets can lead to a completely different organization around a different star



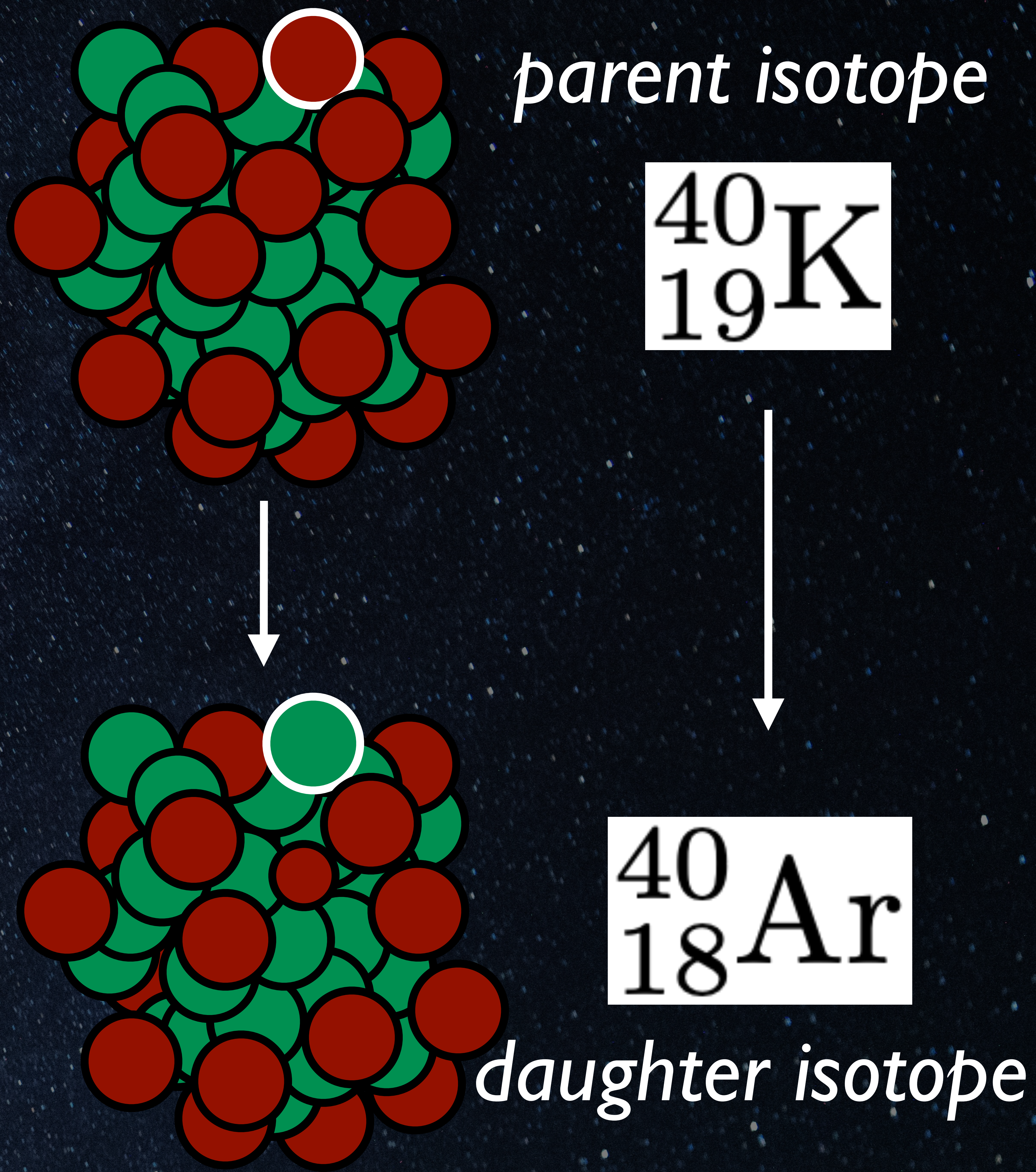
When was the Solar System born?

How do we know the age of a rock?

<u>Radiometric dating!</u>

By measuring the proportion of various atoms and isotopes in a rock, we can calculate how long ago that rock was last solidified

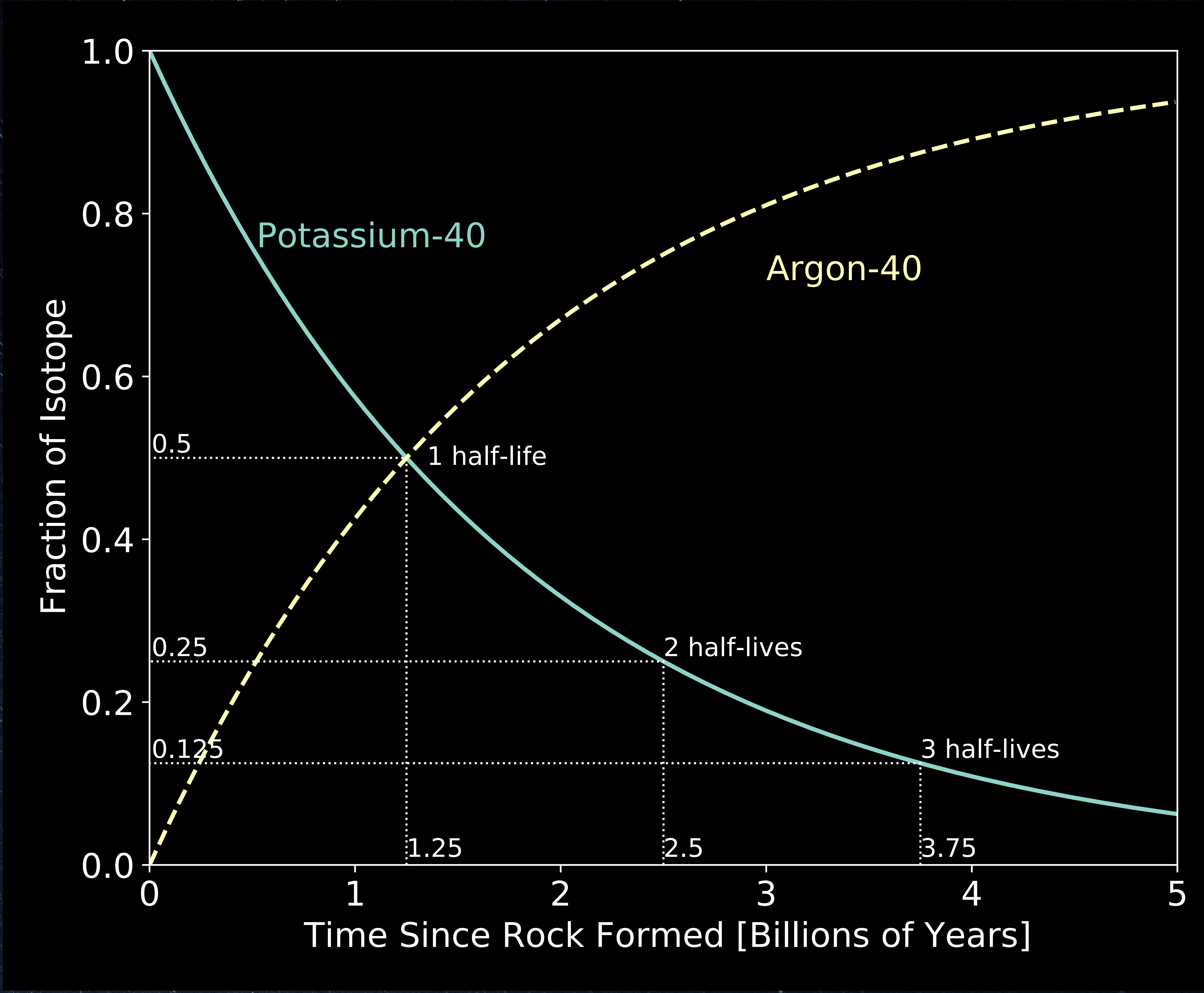
Some isotopes are <u>radioactive</u>: their nuclei undergo spontaneous decay, such as breaking into two pieces or having a neutron turn into a proton



Half-Lives

By studying a collection of a specific isotope, scientists are able to determine their <u>half-life</u>: the time it would take for half of the parent nuclei to decay

Every radioactive isotope has its own unique half-life, ranging from a fraction of a second to billions of years; the half-life for potassium-40 to argon-40 is 1.25 billion years



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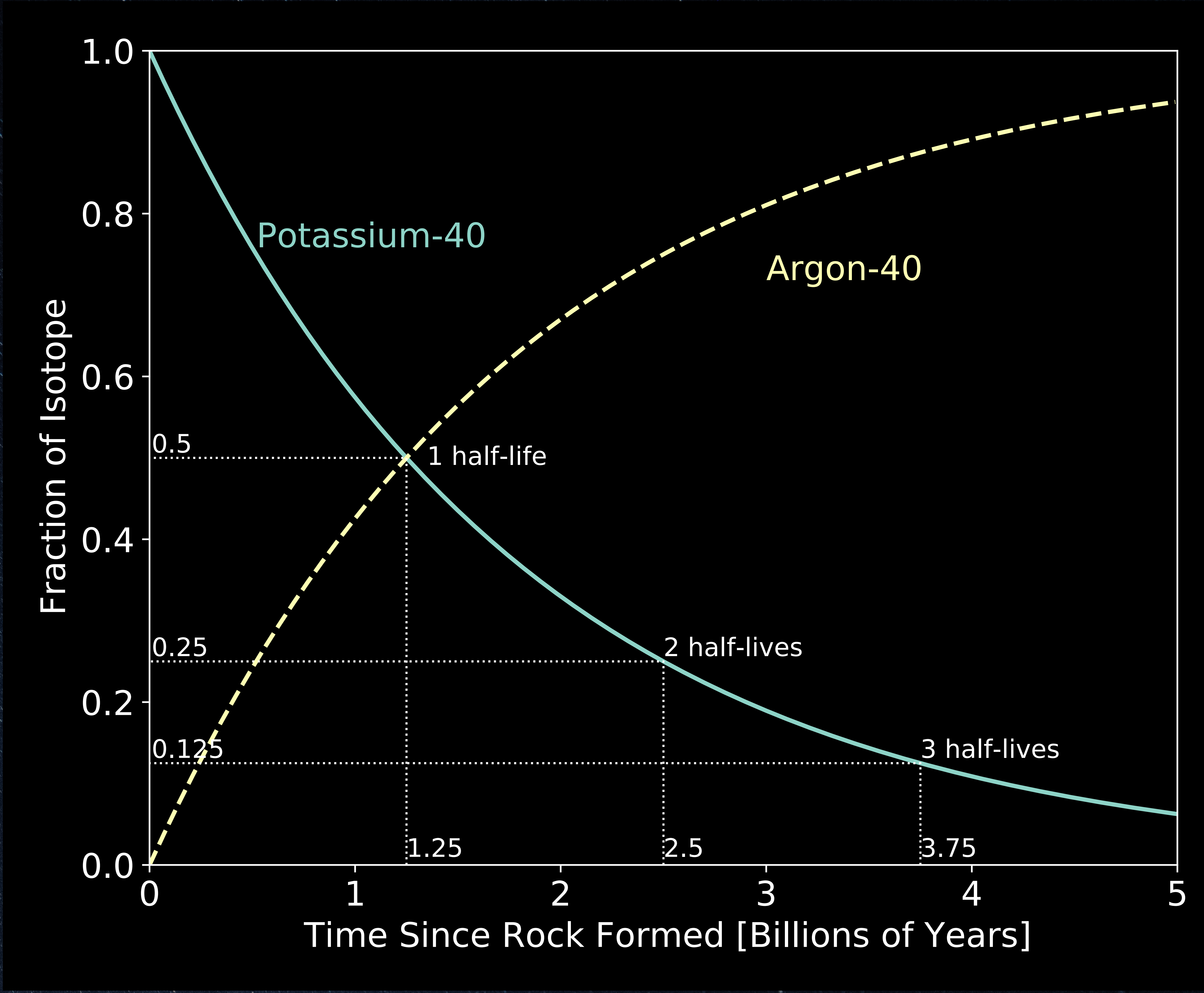
Suppose you find a rock with equal amounts of potassium-40 and argon-40: if all the argon-40 came from this decay chain, then the rock must be 1.25 billion years old



How do we radiometrically date the Earth?

We find many rocks of different ages on the Earth: the youngest were just formed from molten lava, while the oldest are about 4 billion years old

But the Earth's surface has changed over time, so even those rocks are not as old as the Earth

The *Apollo* astronauts brought back Moon rocks that have been dated to be about 4.4 billion years old from the half-life of uranium-238

This is still not the age of the solar system, since the impact that formed the Moon happened after the solar system was mostly put together

A *gneiss* rock!
(4.03 Gya)

(4 Gya)
"Big Bertha," Moon

Dating Meteorites

To go all the way back to the origins of the Solar System, we must find rocks that have not melted or vaporized since they first condensed out of the solar nebula: meteors

Meteorites that have fallen to Earth are the most pristine rocks to radiometrically date: the oldest ones formed about 4.56 billion years ago!

In other words, the age of our Solar System is just one-third the 14 billion year age of the Universe!