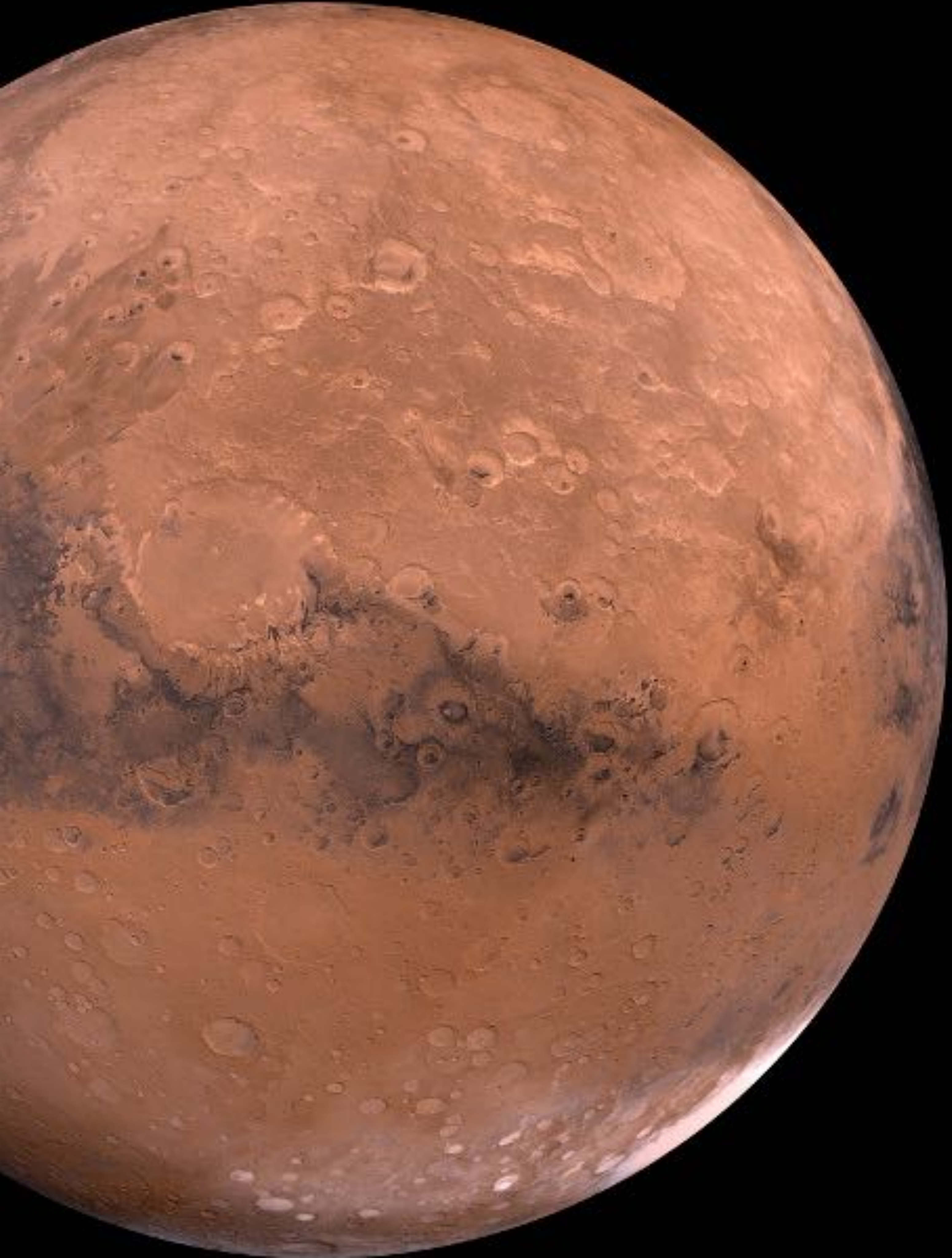
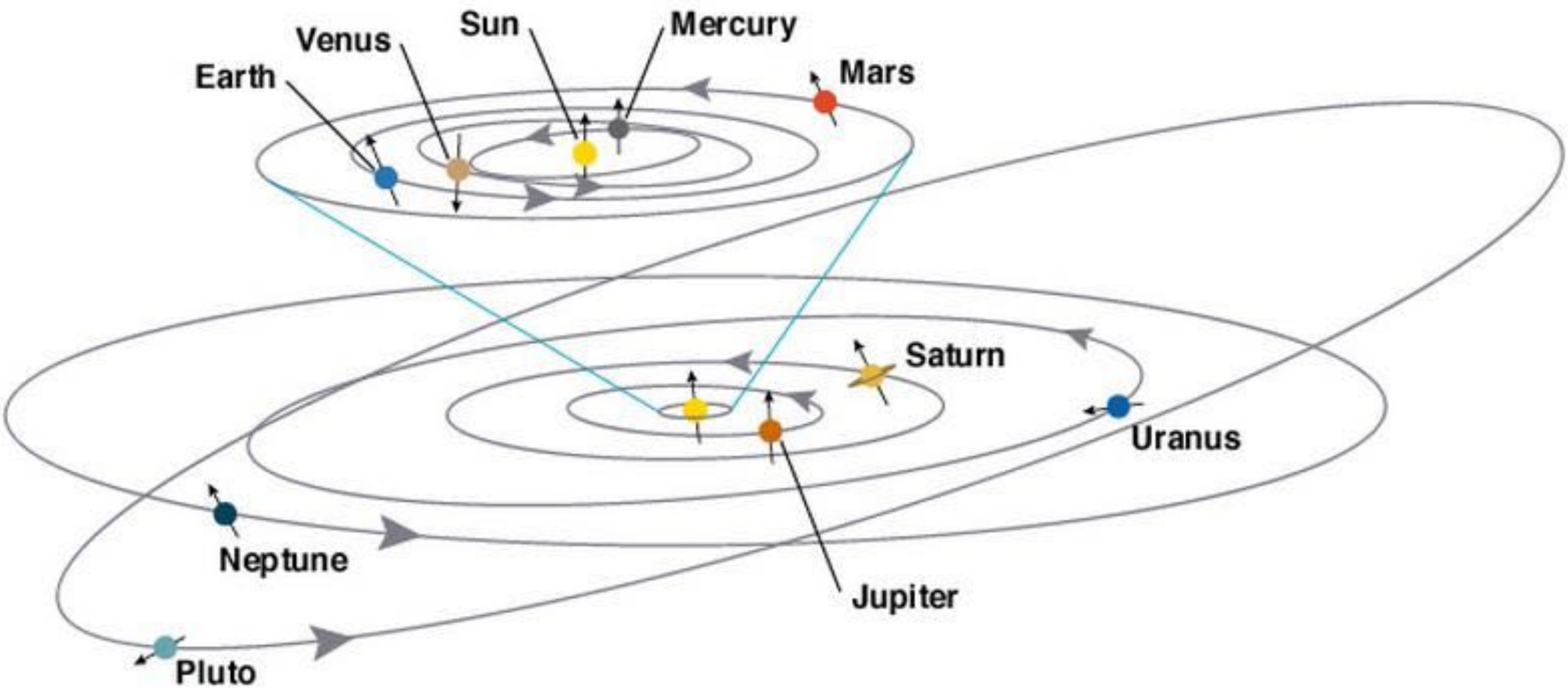


Today

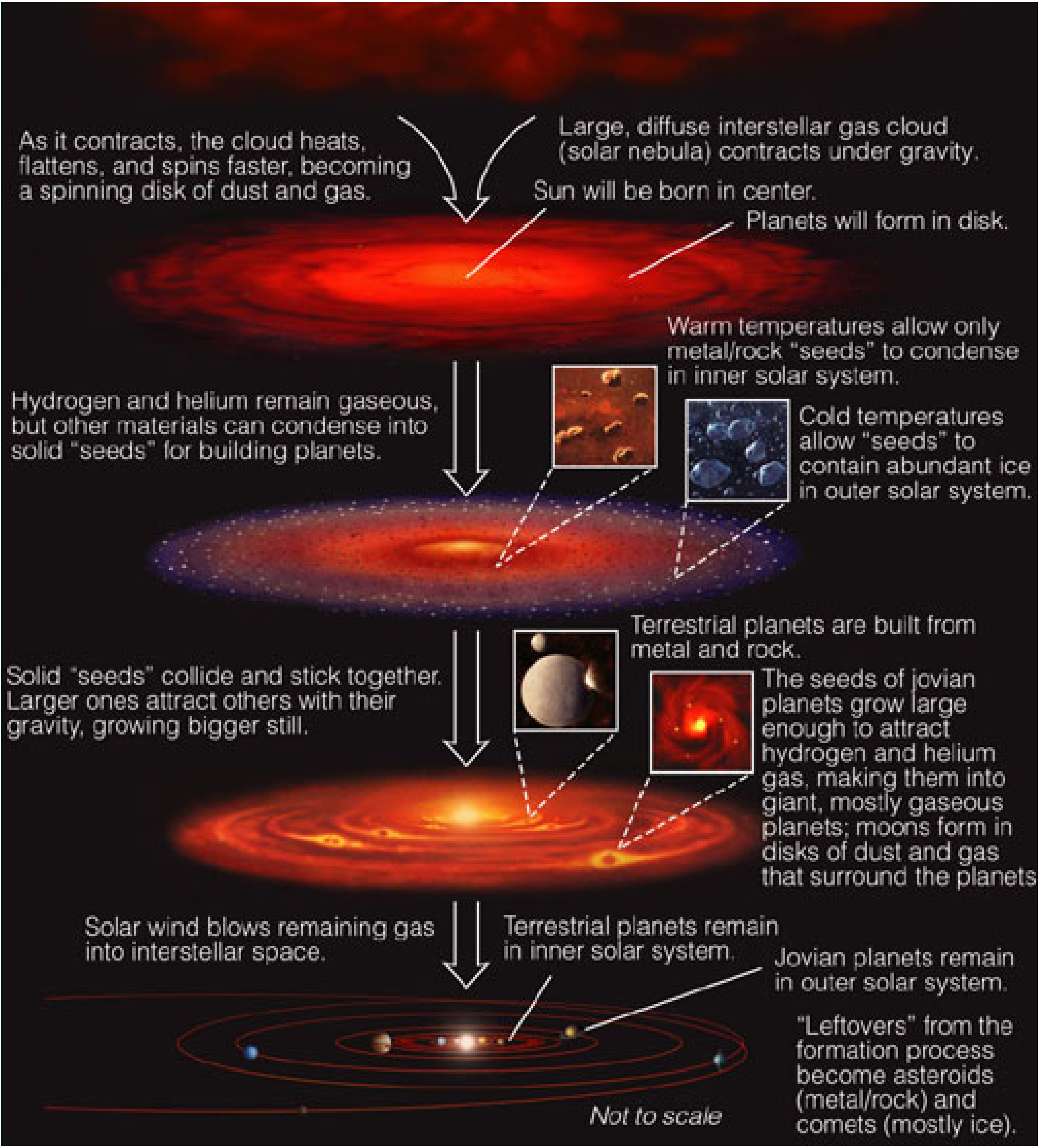
- Planet formation
- Terrestrial Planets

What caused the orderly patterns of motion in our solar system?



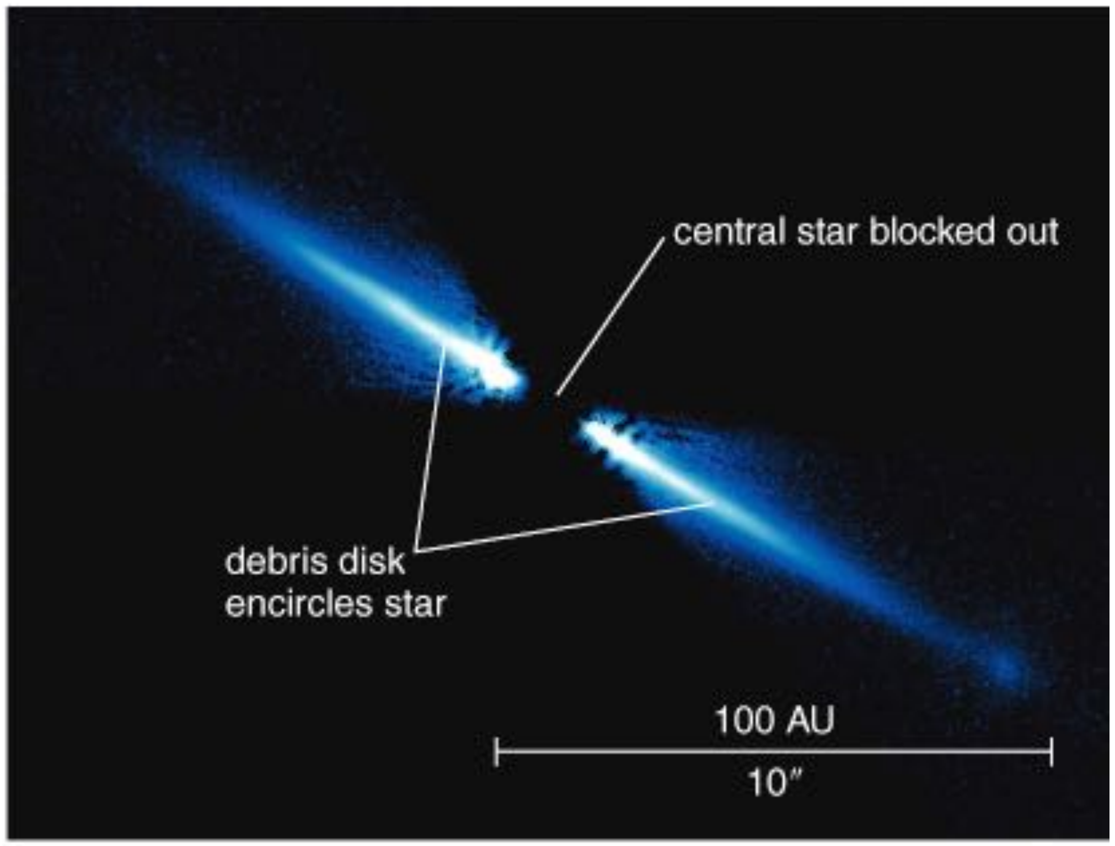
solar nebula hypothesis

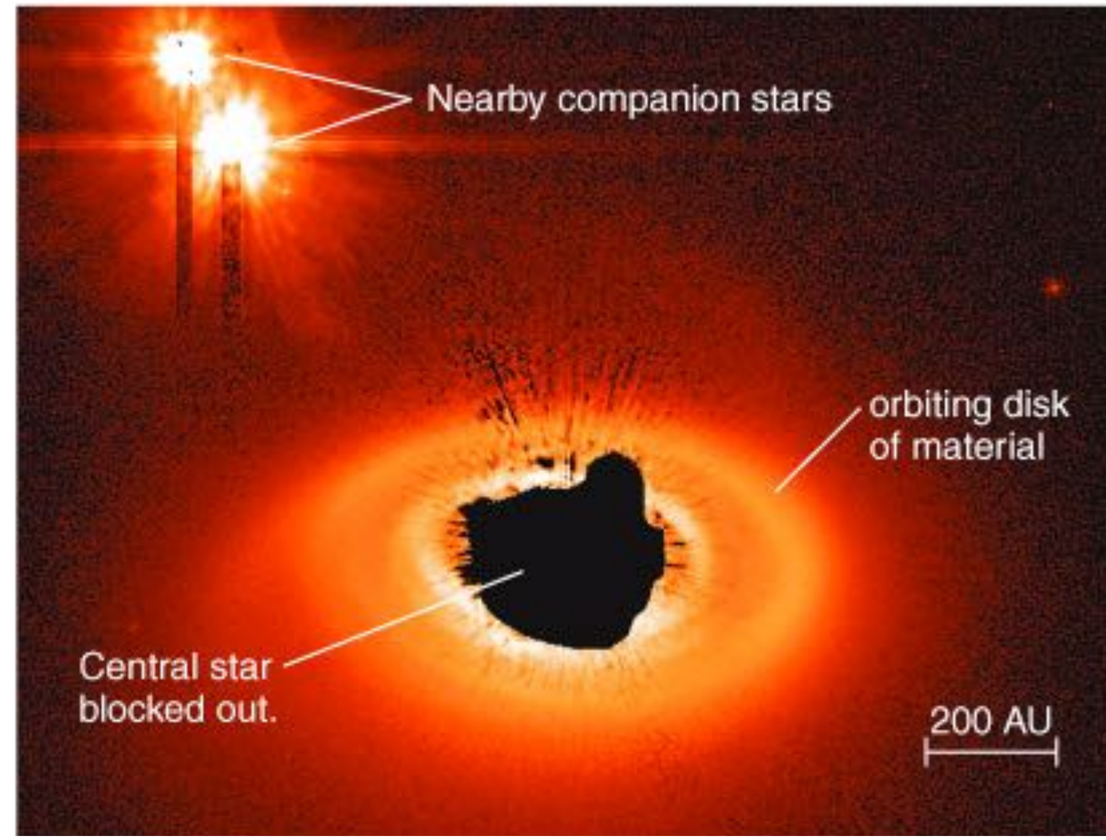
The dissipation of gas causes it to settle into a single plane where angular momentum is conserved



- 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

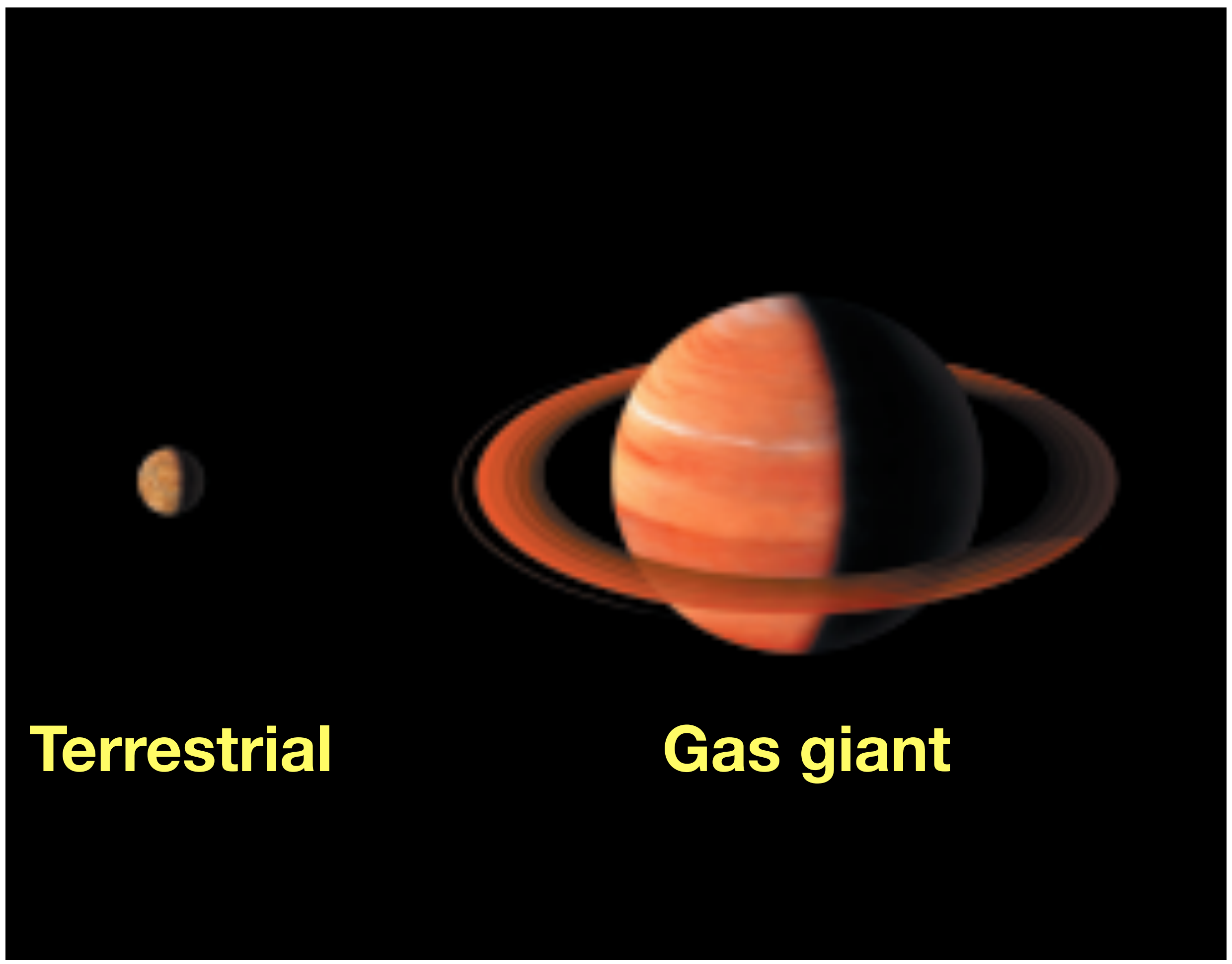
Disks Around Other Stars

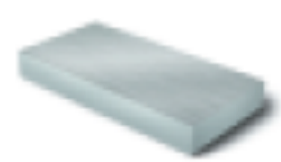




- We observe proto-planetary disks directly around some young stars.

Why are there different 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%

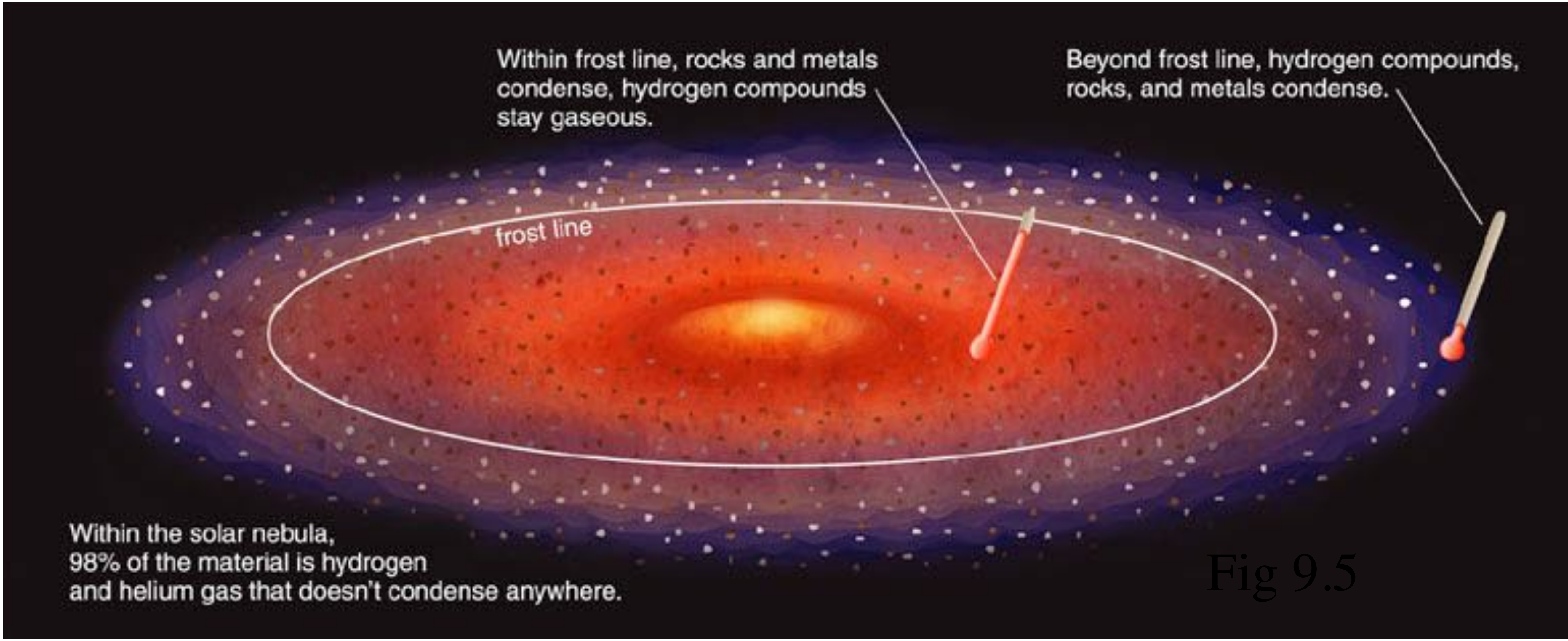
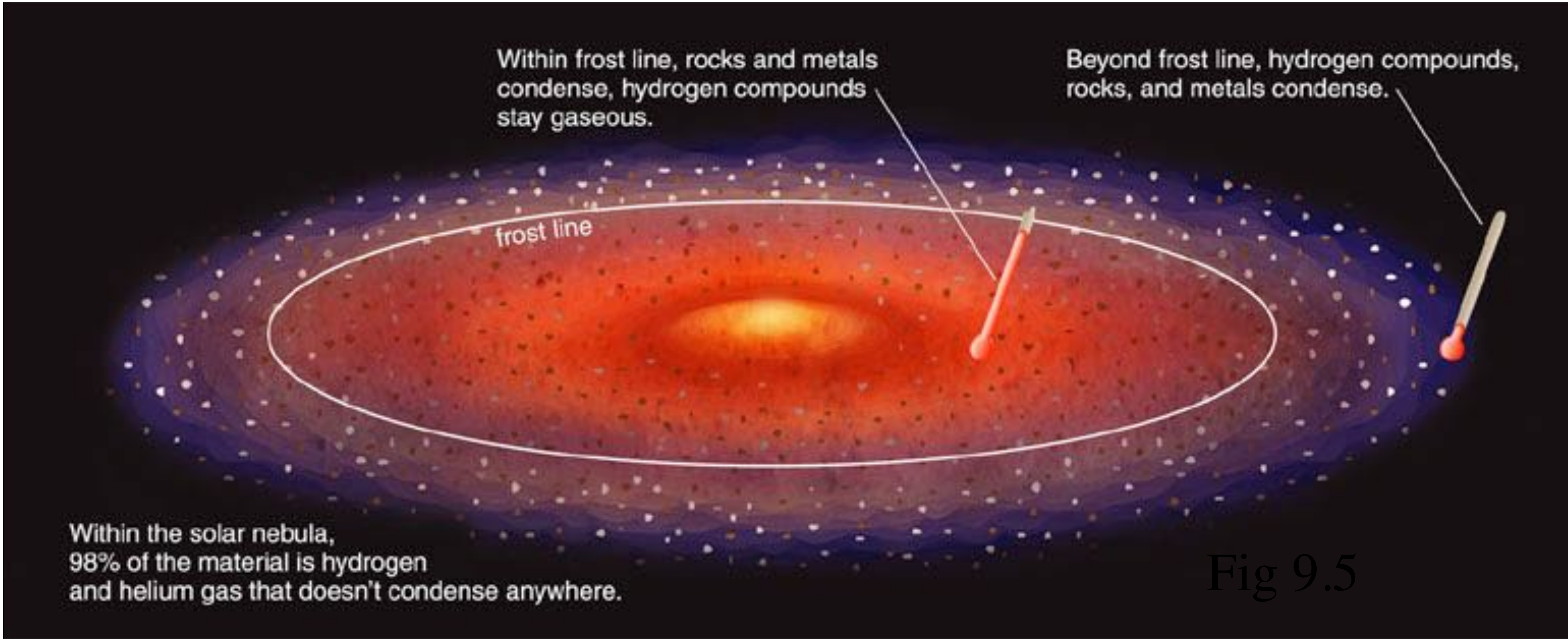


Fig 9.5

As gravity causes the cloud to contract, it heats up.

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

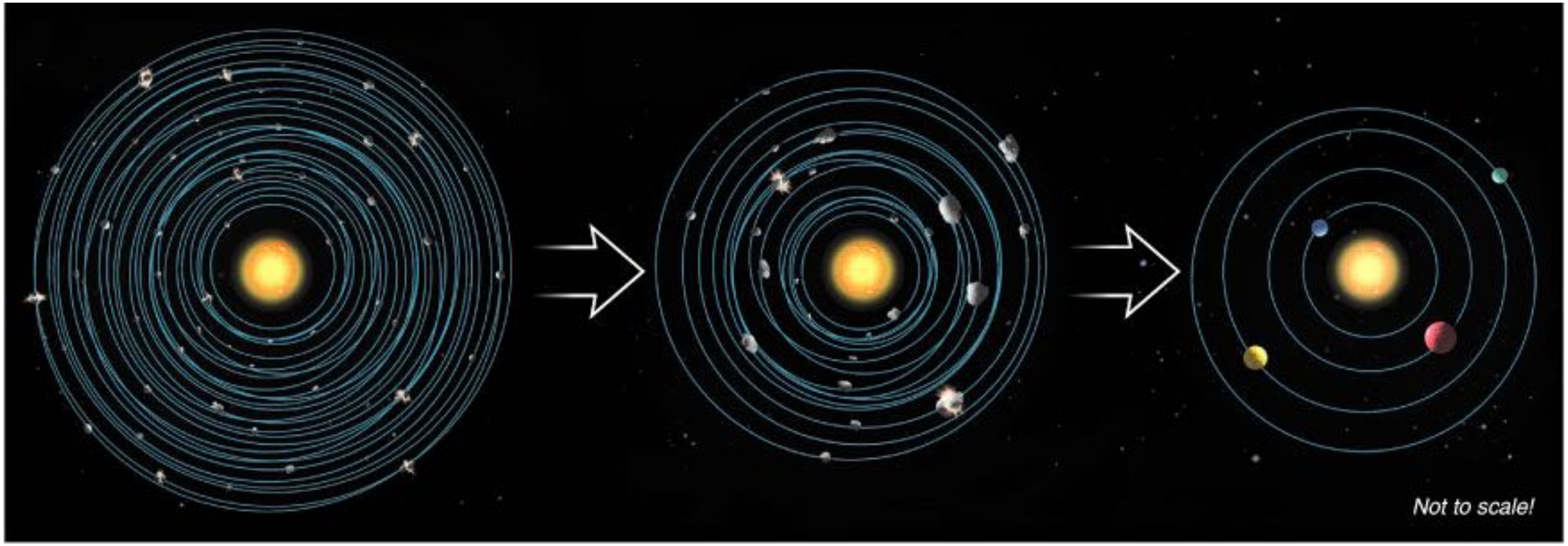
Outside the ***frost line***: Cold enough for ices to form

- 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.

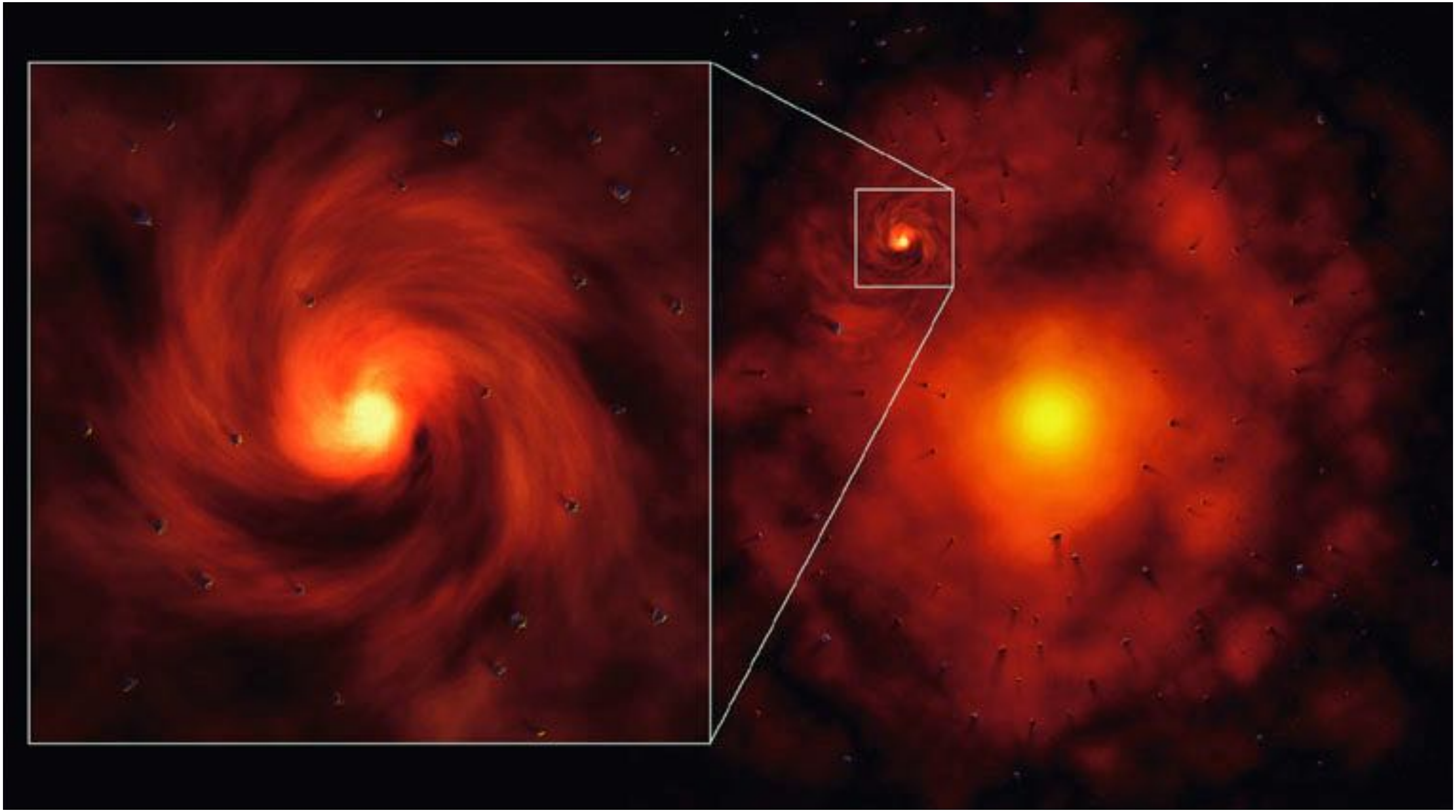
Accretion of Planetesimals



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

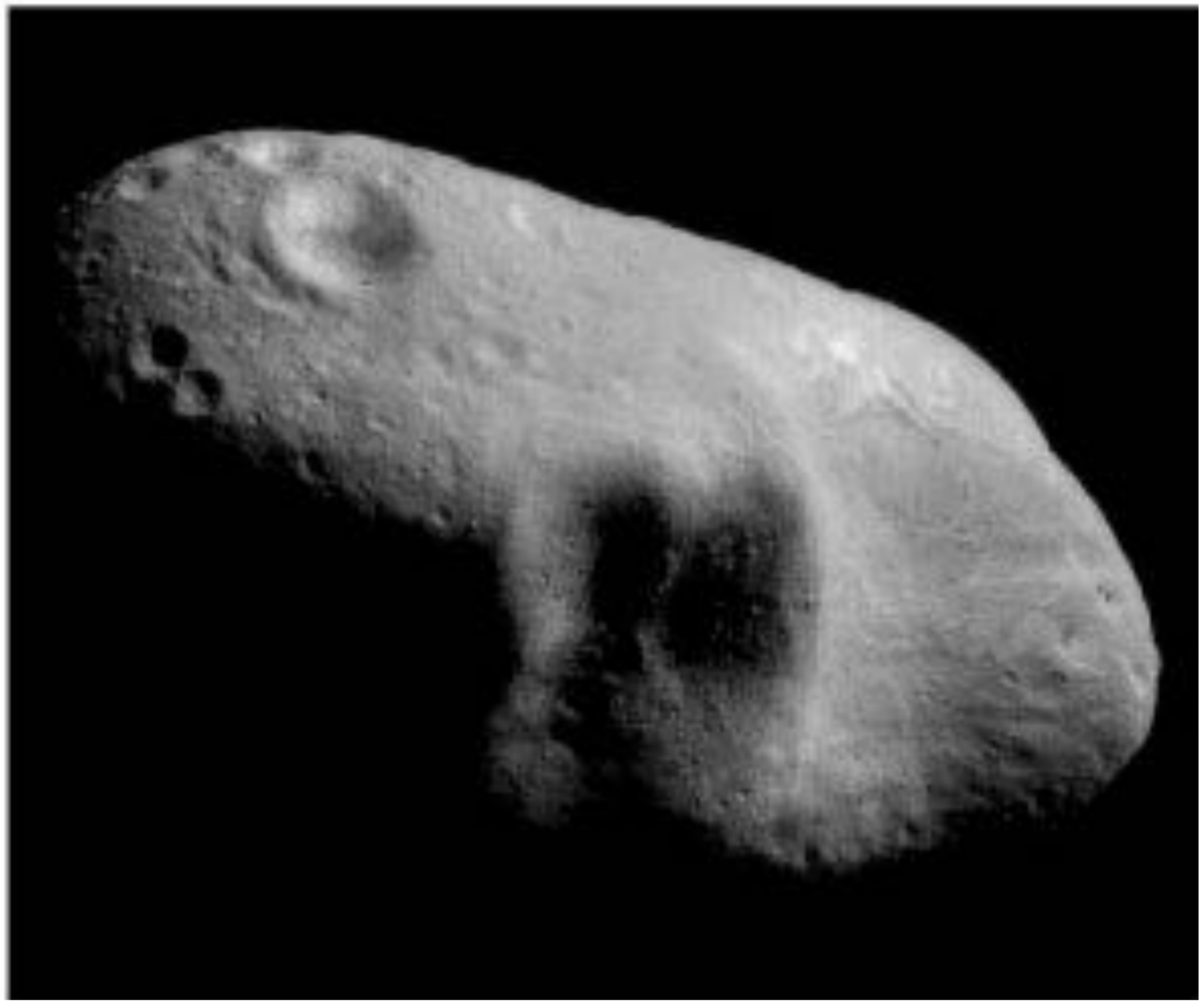
Formation of Jovian Planets

- Ice could also form small particles outside the frost line.
- Larger planetesimals and planets were able to form.
- The gravity of these larger planets acted as seeds to draw in the surrounding H and He gases.
    - there's a lot more mass available in H & He, so once a seed was large enough to capture these lightweight gases, it could grow rapidly.

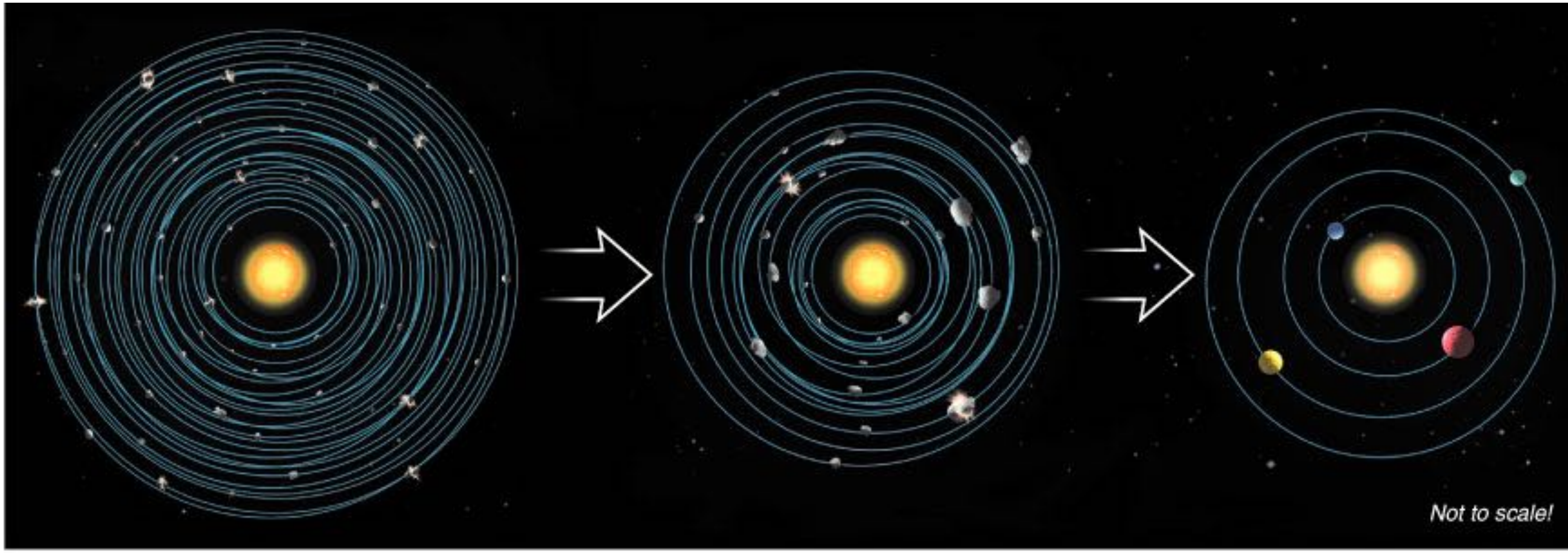


Moons of jovian planets form in miniature disks.
They form a system of orbiting moons like the sun has orbiting planets,
a microcosms of the solar nebula.

Where did asteroids and comets come from?

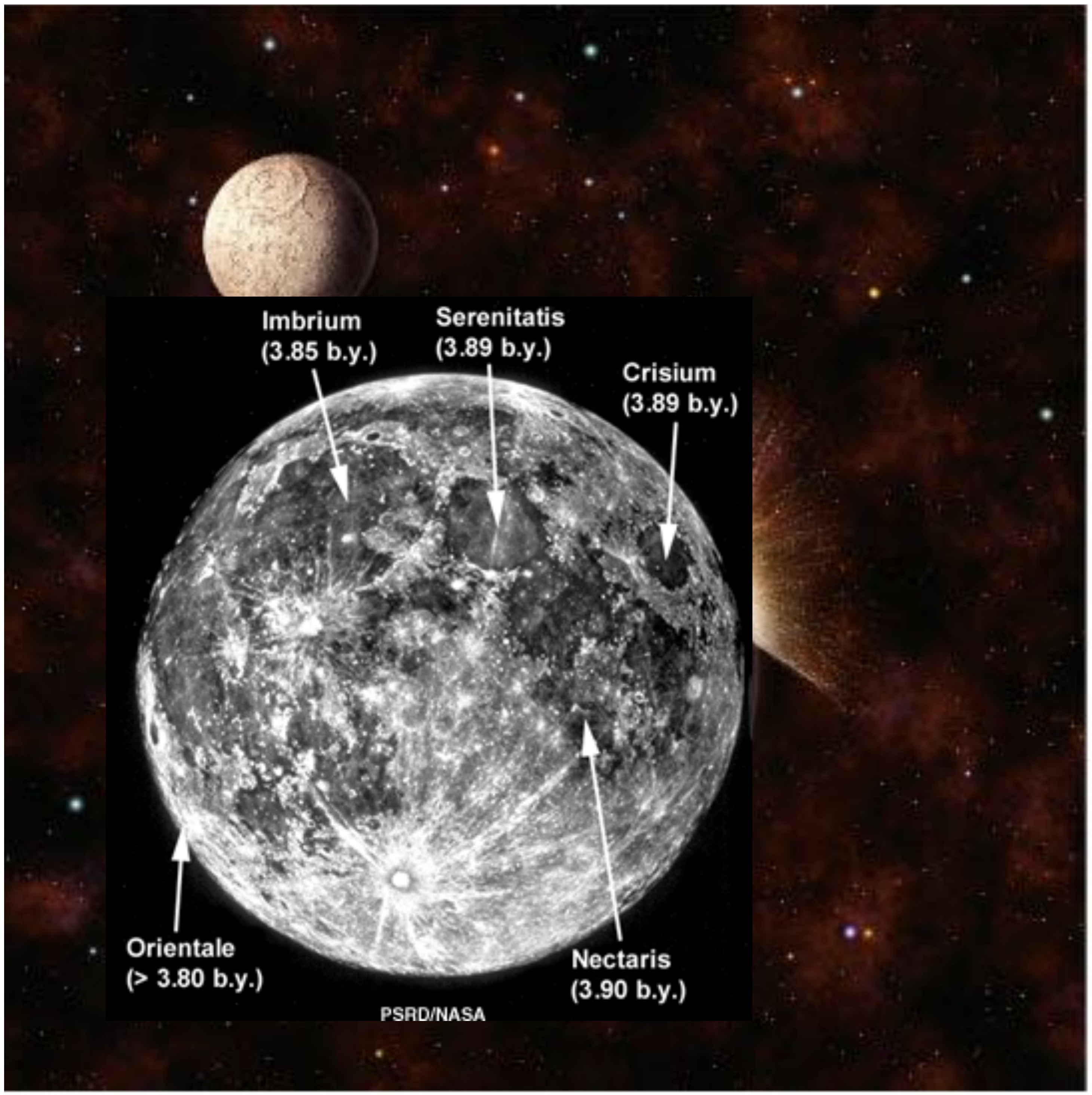


Asteroids and Comets



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

Heavy Bombardment



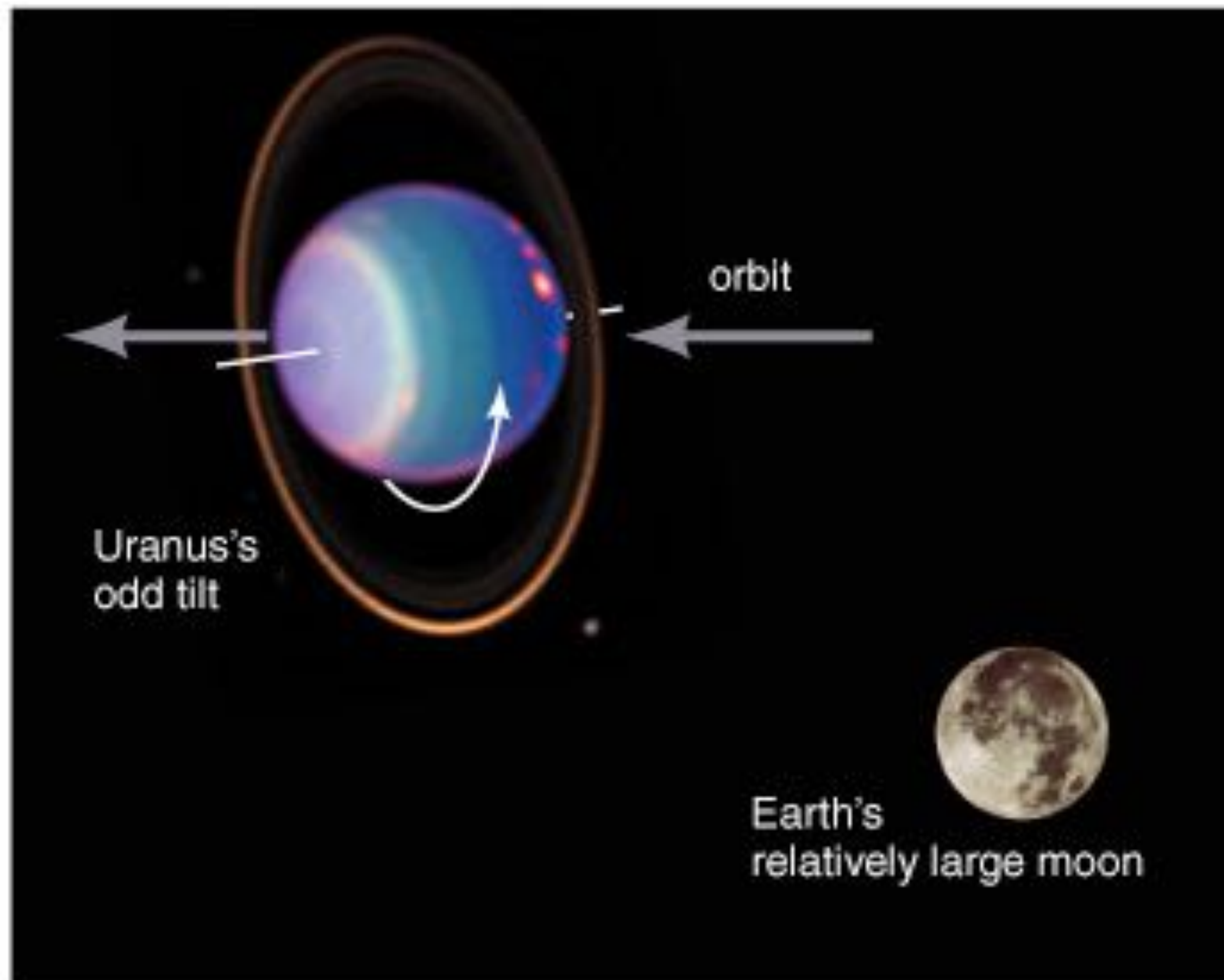
- Leftover planetesimals bombarded other objects in the late stages of solar system formation.

"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?

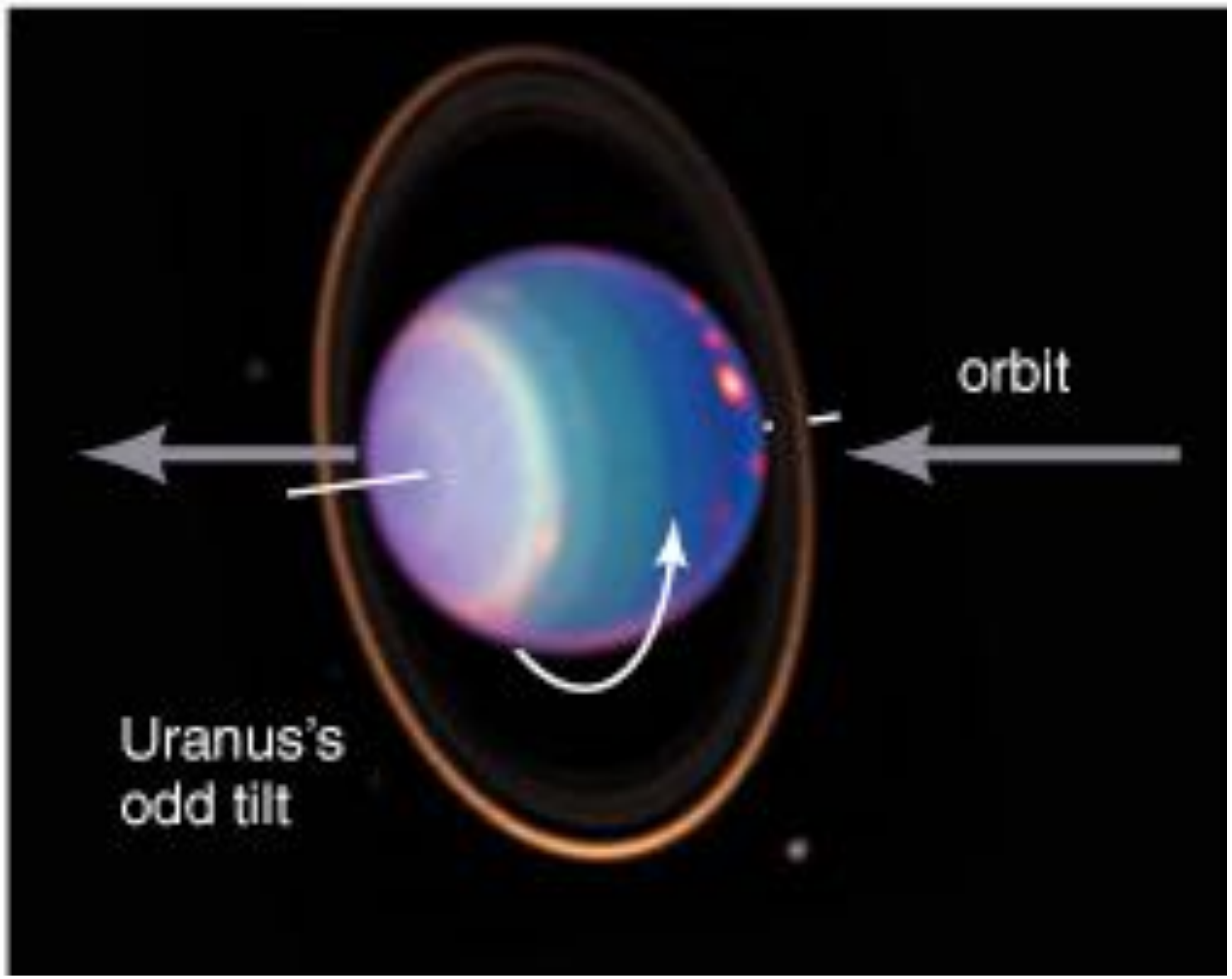
Thought to be due to the last big collision.



Earth's moon: Giant Impact?

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

Odd Rotation

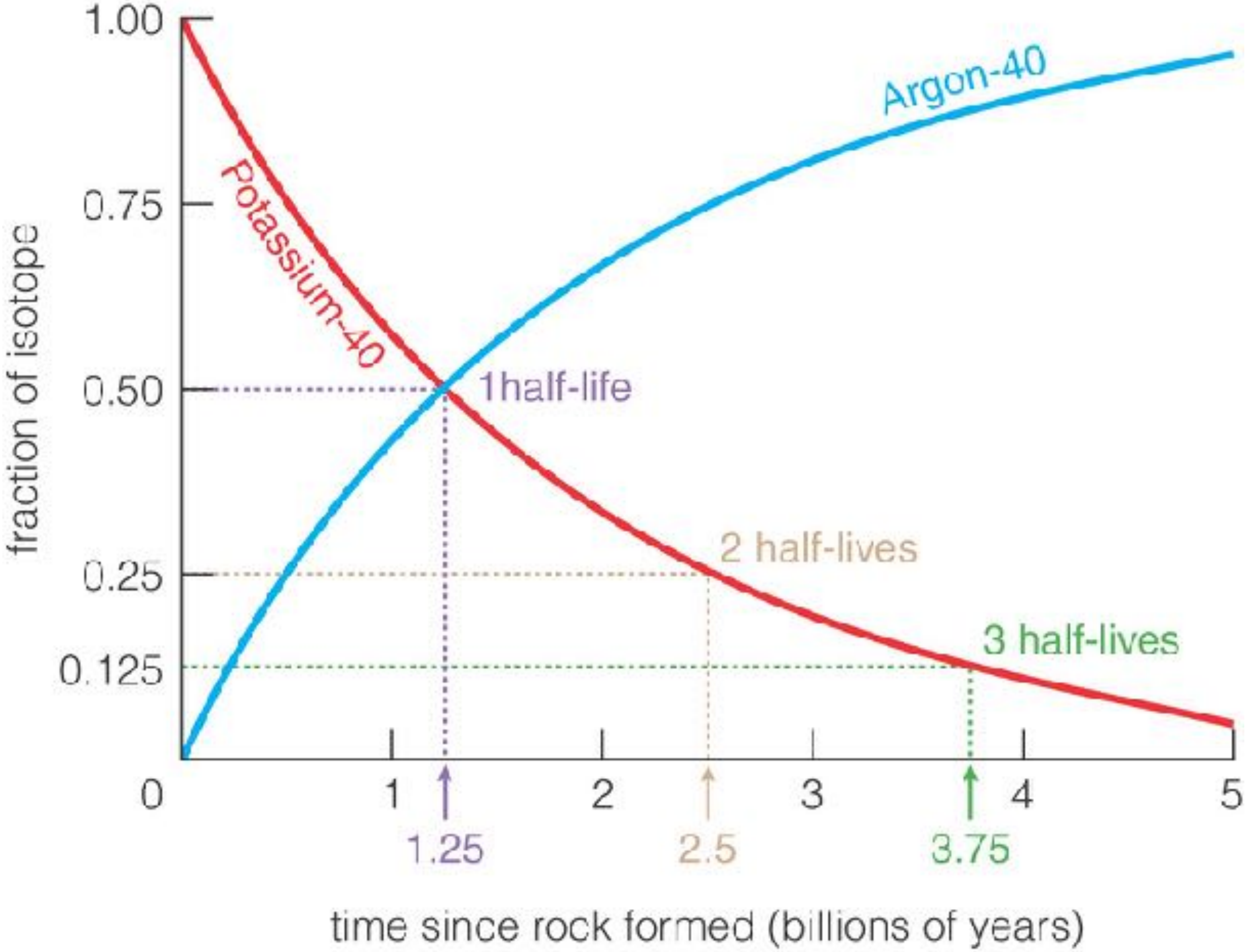


- Giant impacts might also explain the different rotation axes of some planets.

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

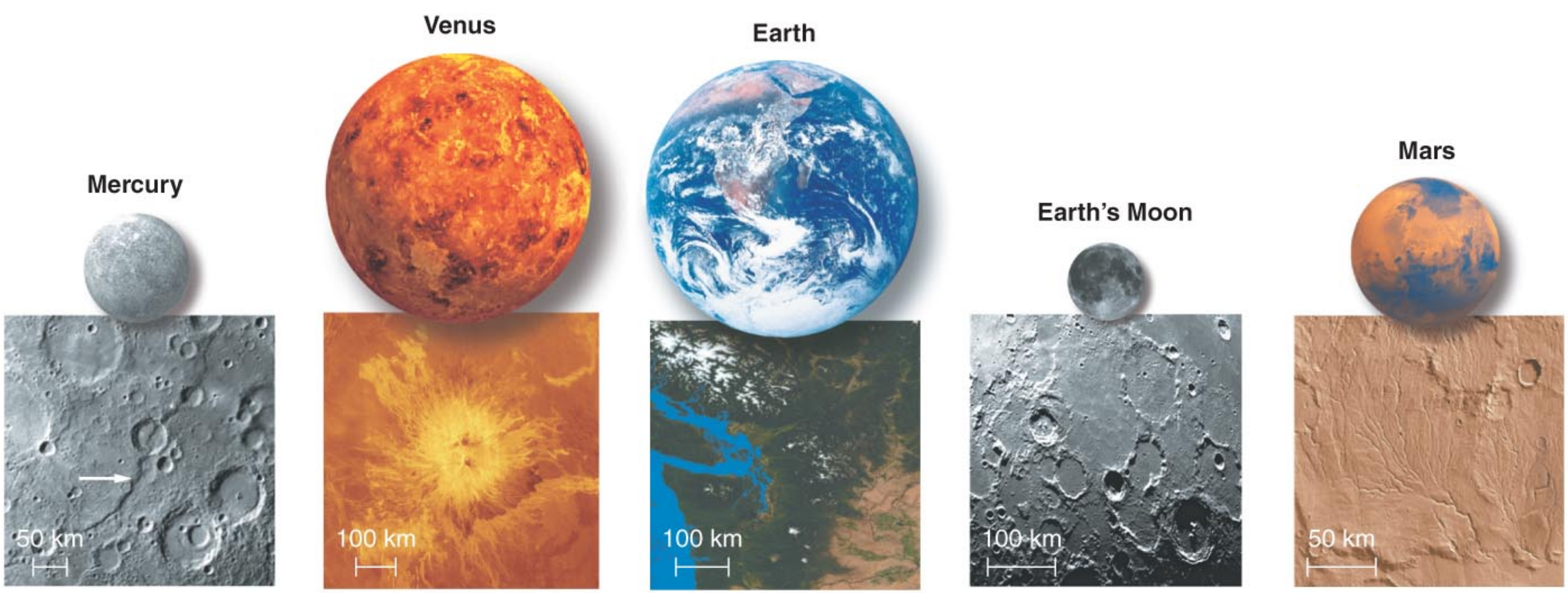
Age dating of meteorites via radio-isotopes tells us that the solar system is about 4.5 billion years old.

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.

Terrestrial planet surfaces & interiors



Heavily cratered Mercury has long steep cliffs (arrow).

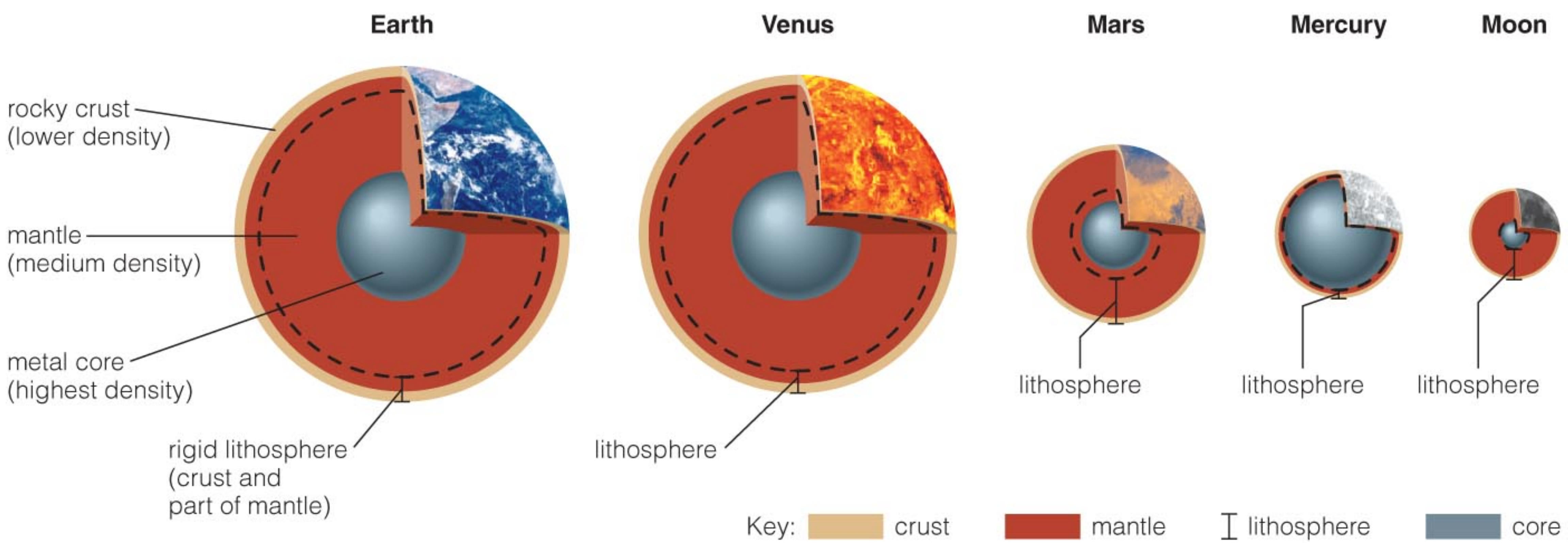
Cloud-penetrating radar revealed this twin-peaked volcano on Venus.

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

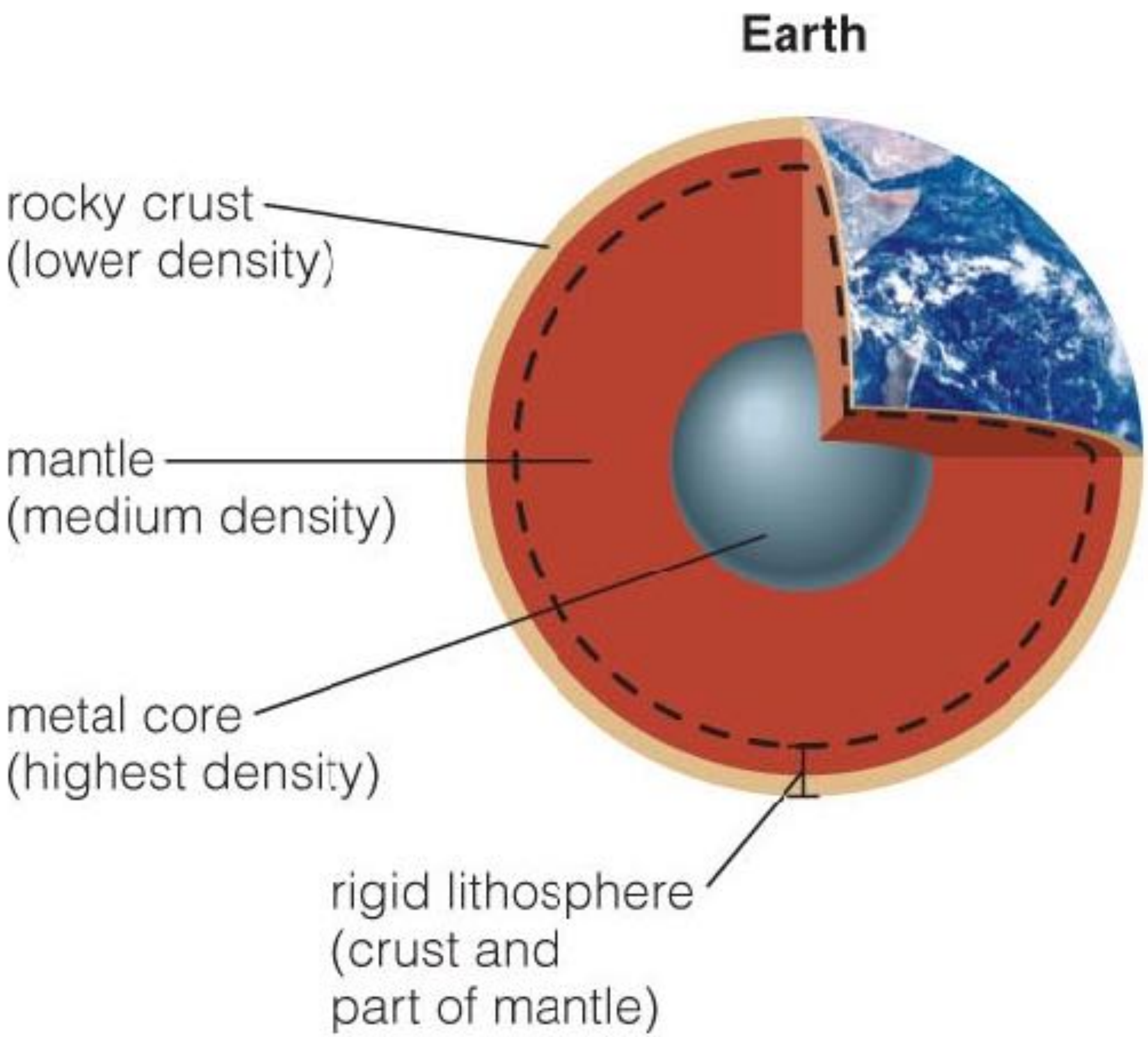
The Moon's surface is heavily cratered in most places.

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

Terrestrial planet surfaces & interiors

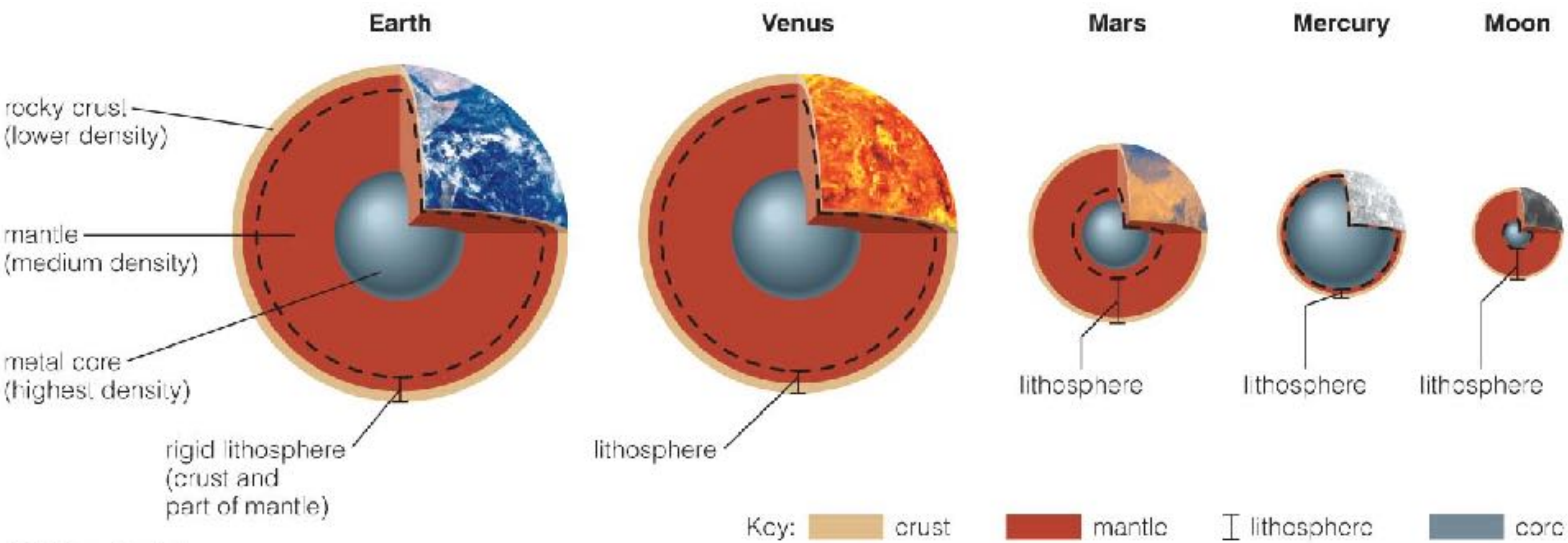


Earth's Interior



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

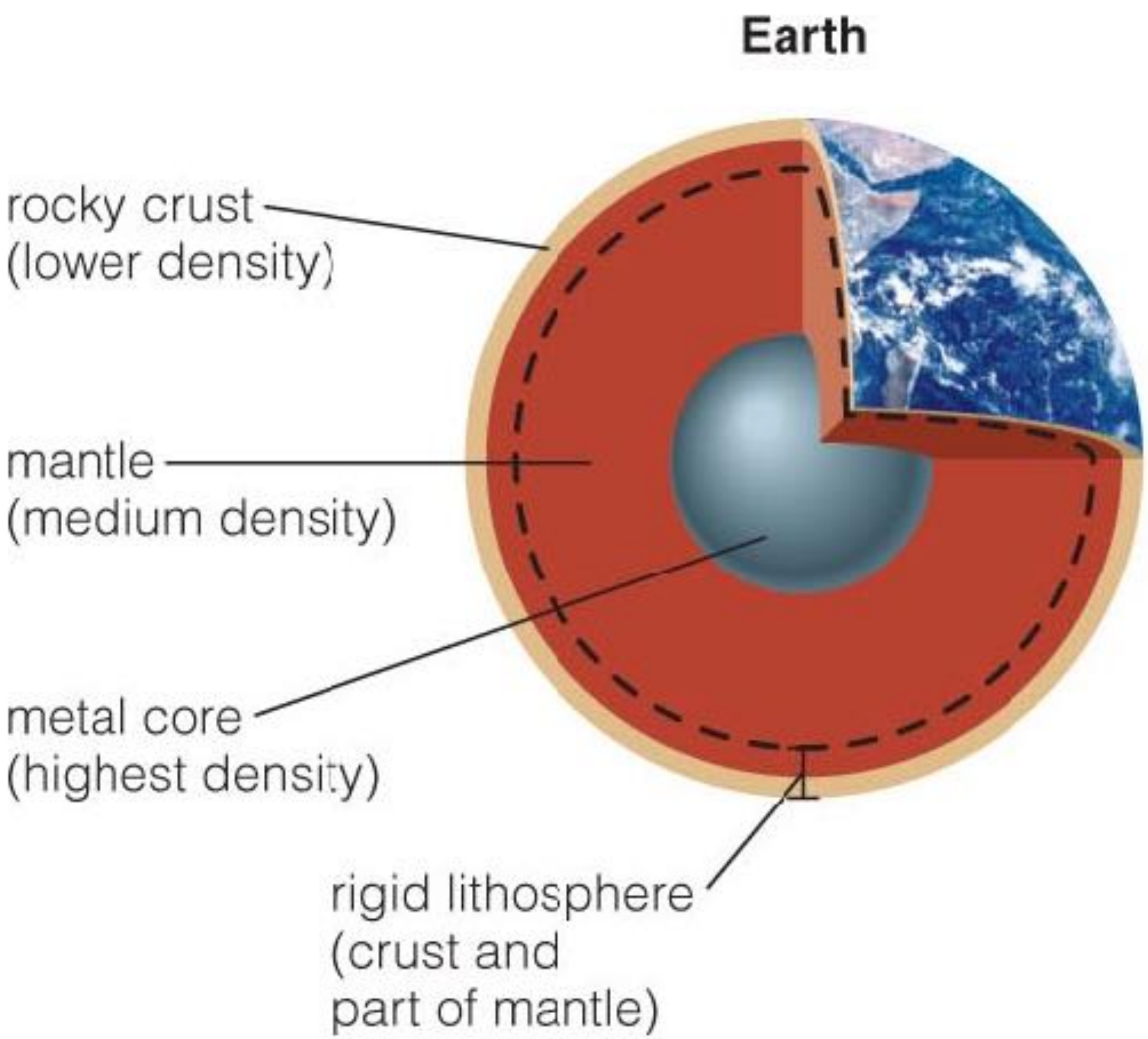
Terrestrial Planet Interiors



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

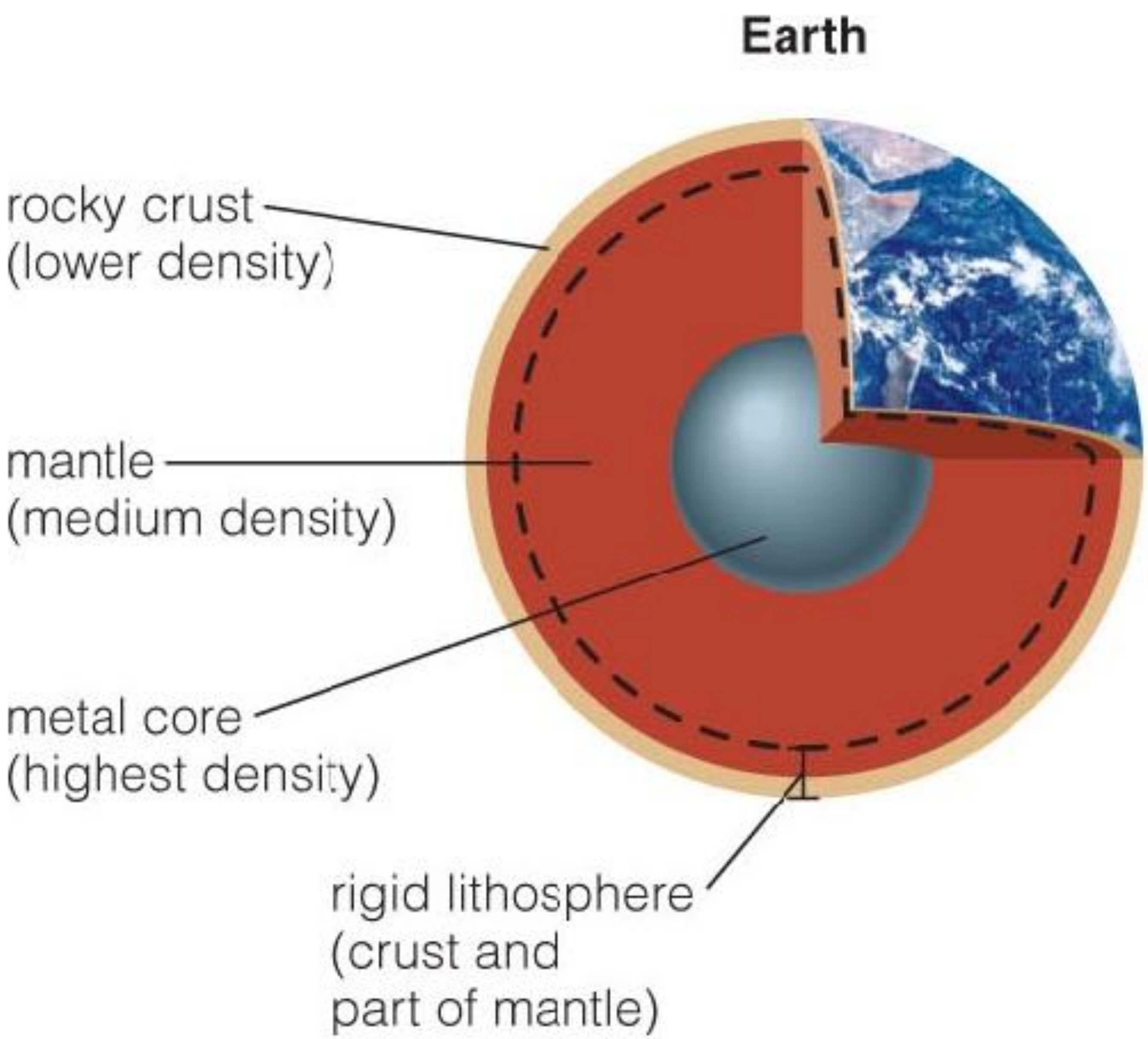
Differentiation

Planets initially molten from the heat of formation



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

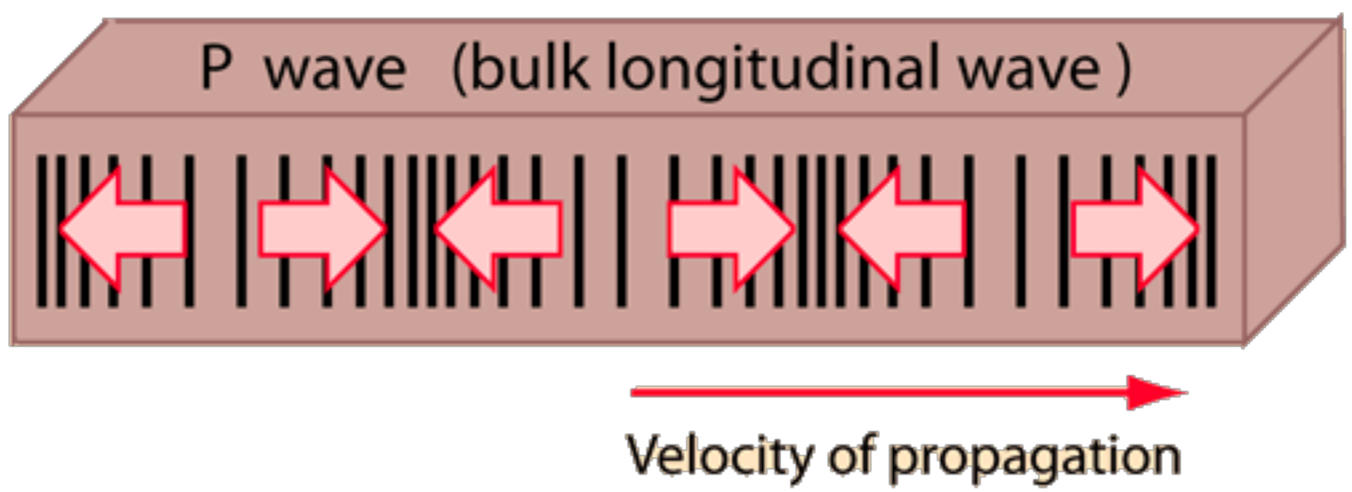
Lithosphere

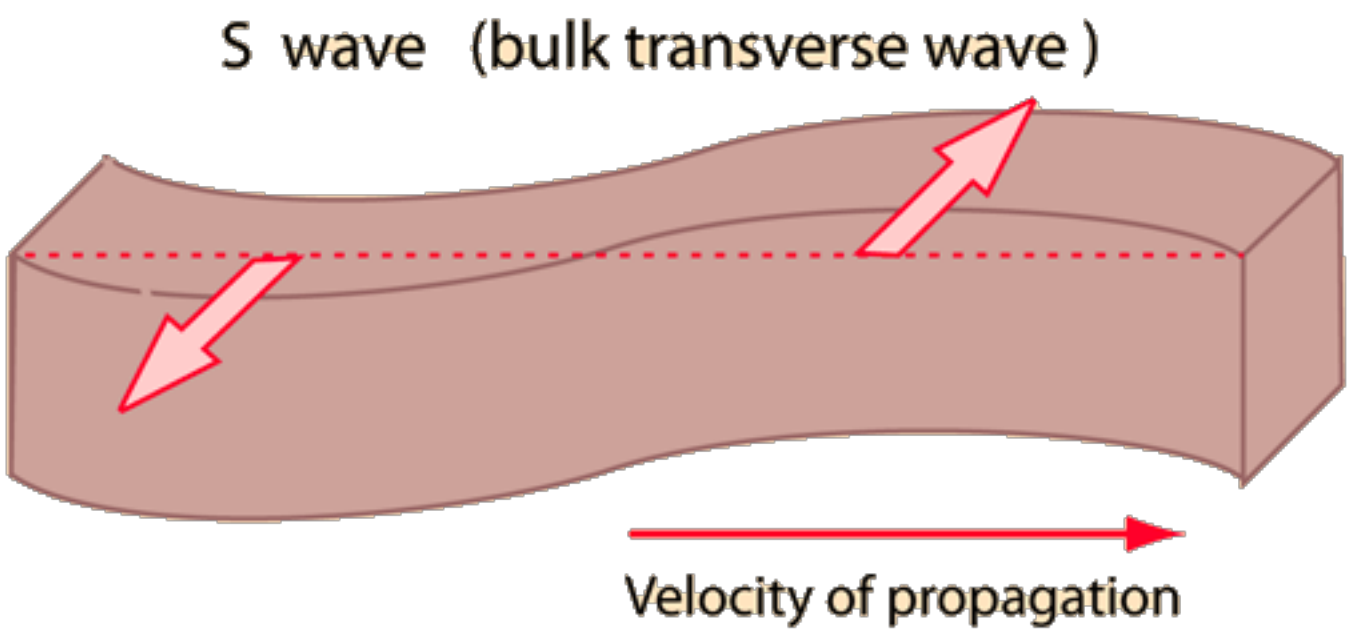


- A planet's outer layer of cool, rigid rock is called the lithosphere.
- It "floats" on the warmer, softer rock that lies beneath.
  - softer in the sense that it is not brittle like the lithosphere, deforming like plastic under stress

Seismic waves

How do we know what's inside Earth?



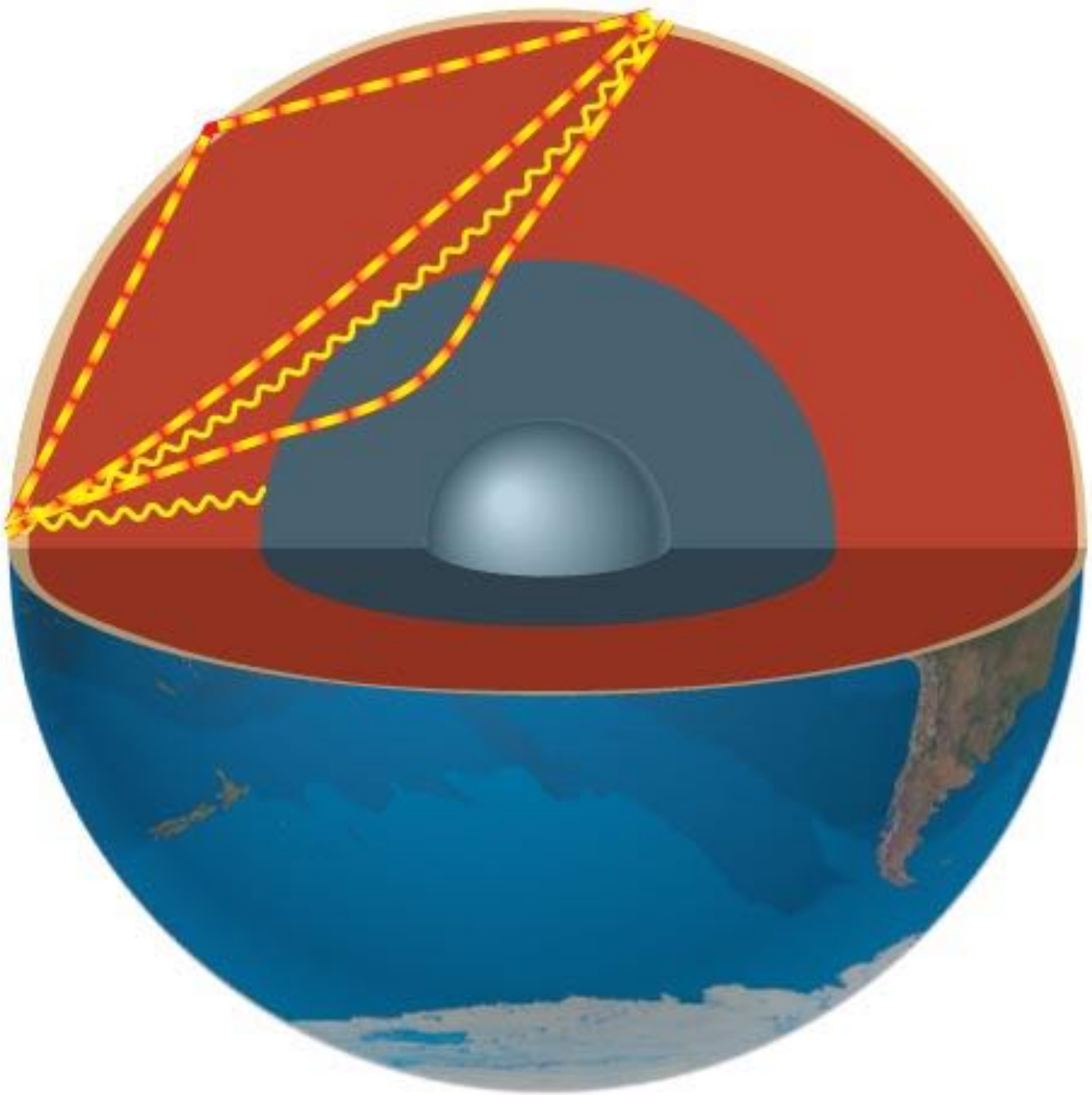


- **P waves** (primary) compressional.
  - fast propagation
  - traverse all material
- **S waves** (secondary) transverse shear.
  - slower propagation
  - do not travel through liquid or gas

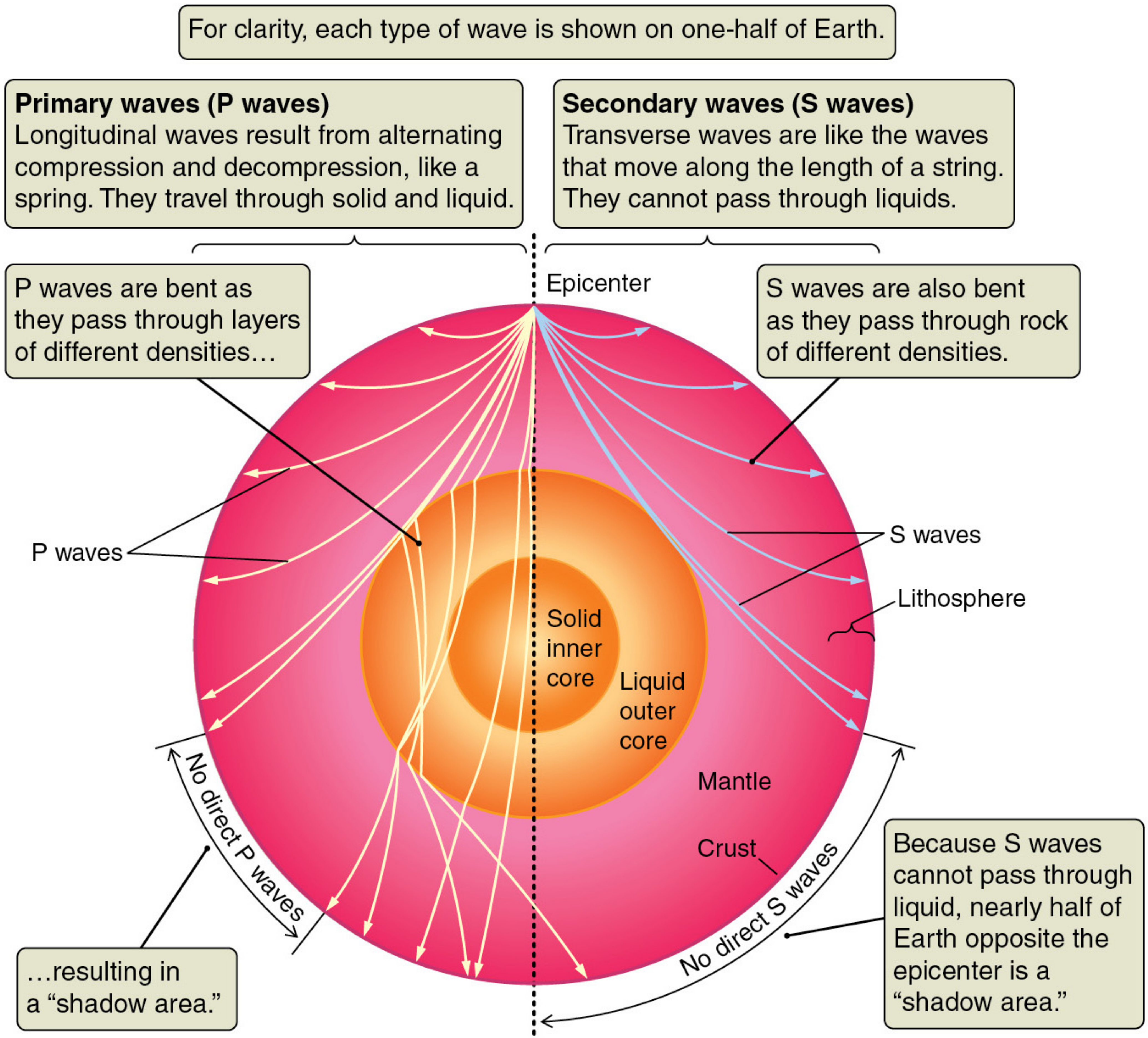
4 September 2010 mag. 7.1 Canterbury earthquake in New Zealand.

Seismic waves

How do we know what's inside Earth?

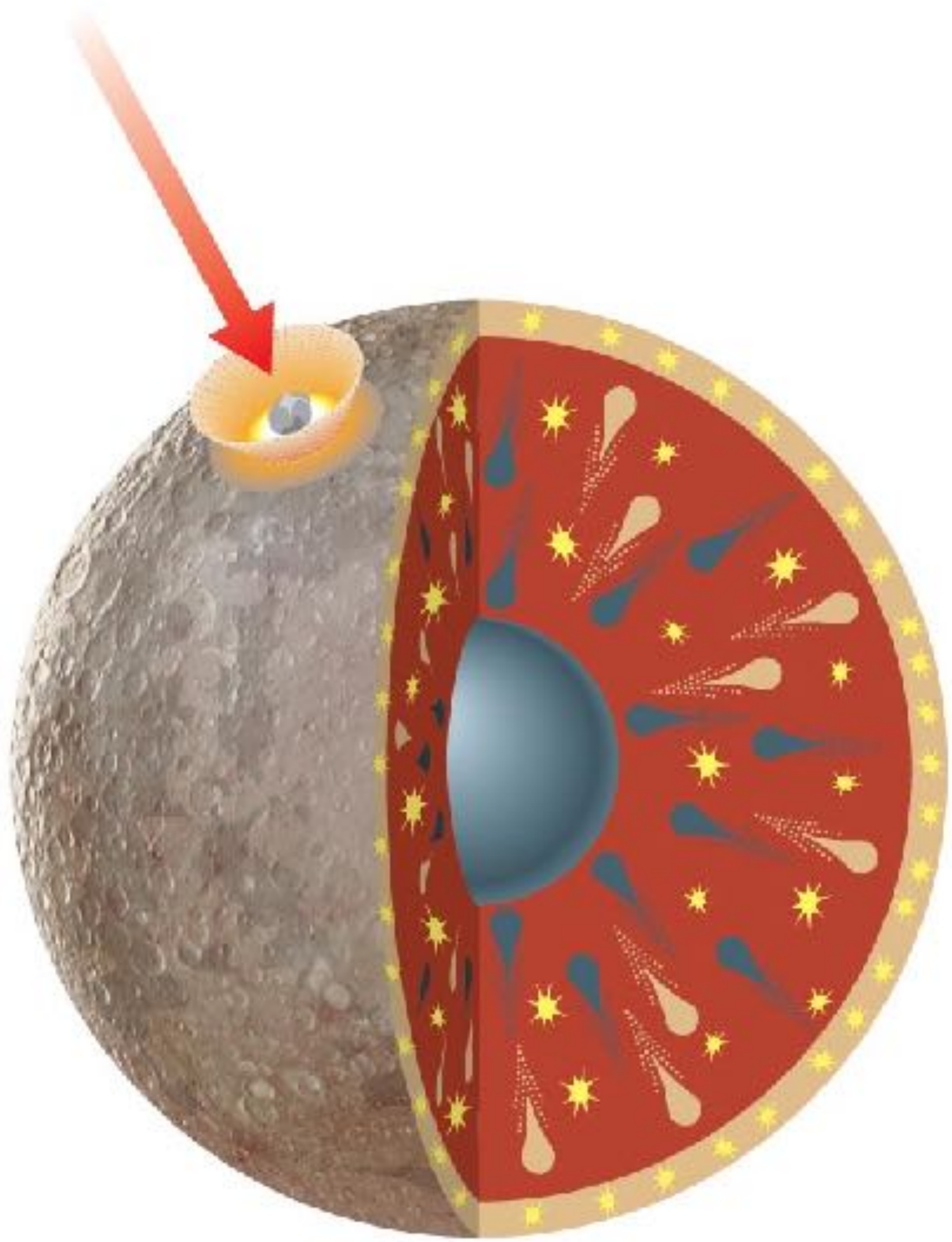


- P waves go through Earth's core, but S waves do not.
- Earth's core has a liquid outer layer that reflects S waves & refracts P waves.



For clarity, each type of wave is shown on one-half of Earth.
Primary waves (P waves)
Longitudinal waves result from alternating compression and decompression, like a spring. They travel through solid and liquid.
Secondary waves (S waves)
Transverse waves are like the waves that move along the length of a string. They cannot pass through liquids.
P waves are bent as they pass through layers of different densities…
Epicenter
S waves are also bent as they pass through rock of different densities.
P waves
S waves
Lithosphere
Solid inner core
Liquid outer core
Mantle
Crust
No direct P waves
No direct S waves
…resulting in a "shadow area."
Because S waves cannot pass through liquid, nearly half of Earth opposite the epicenter is a "shadow area."

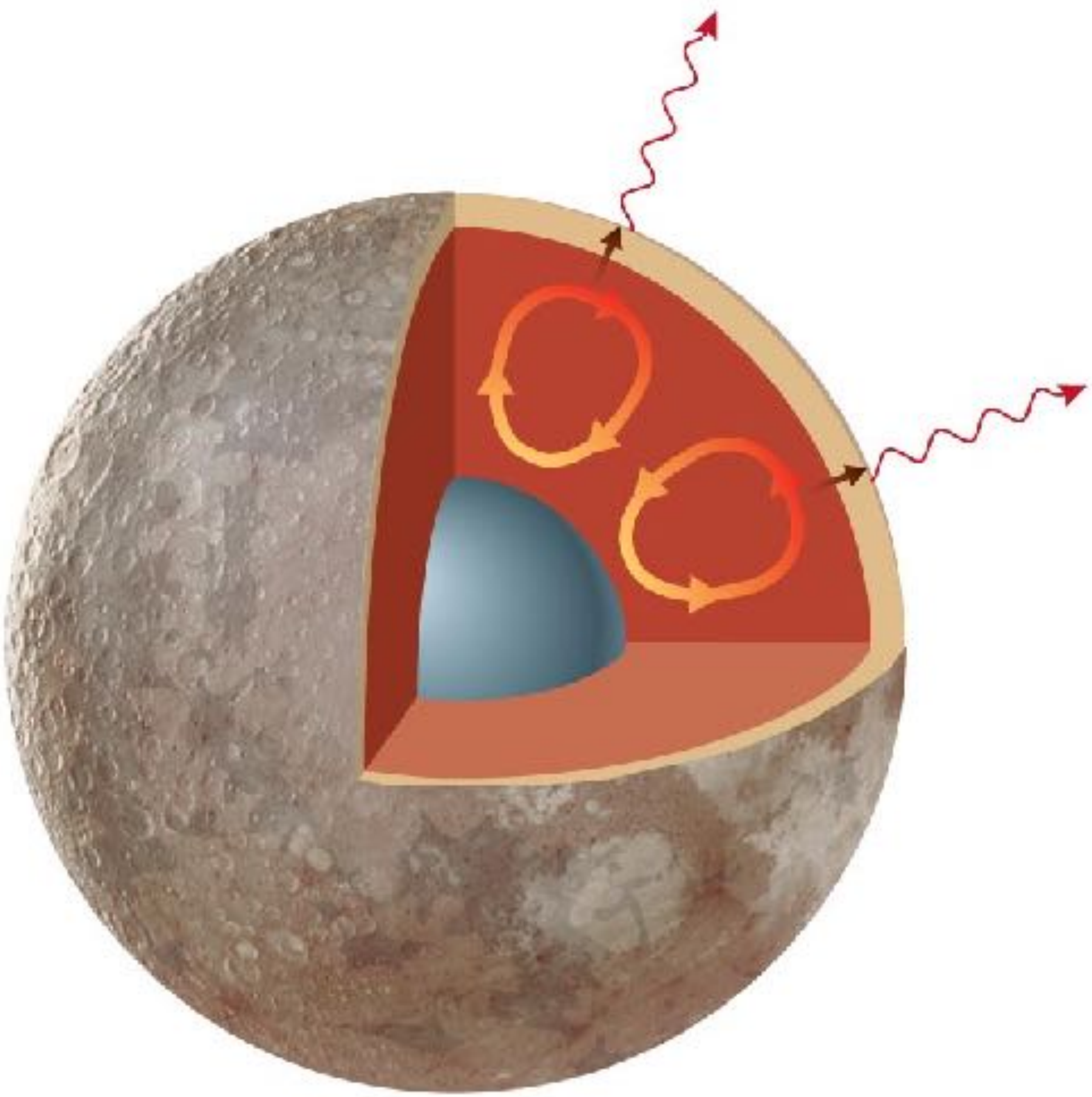
Heating of Planetary Interiors



Heat drives geological activity

- Accretion and differentiation when planets were young
  - Heat of formation
  - Differentiation releases gravitational energy as dense material sinks
- Radioactive decay is most important heat source today.
  - Long lasting energy source from trapped radioactive material

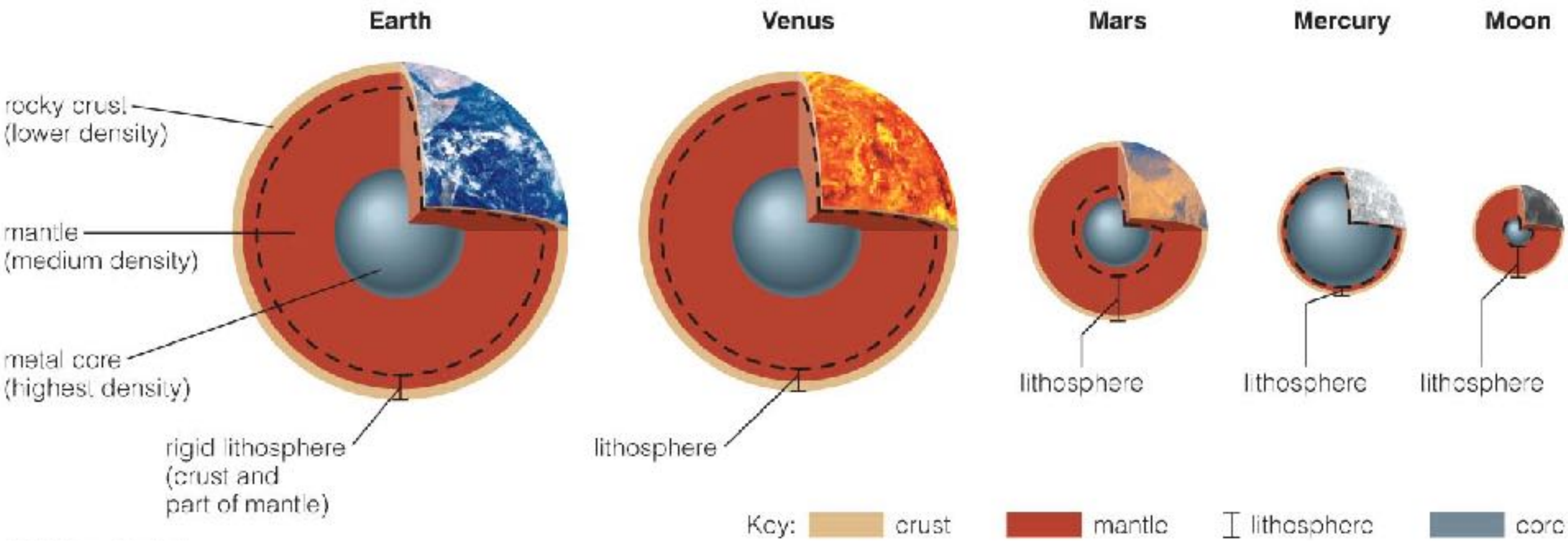
Cooling of Planetary Interiors



Heat drives geological activity

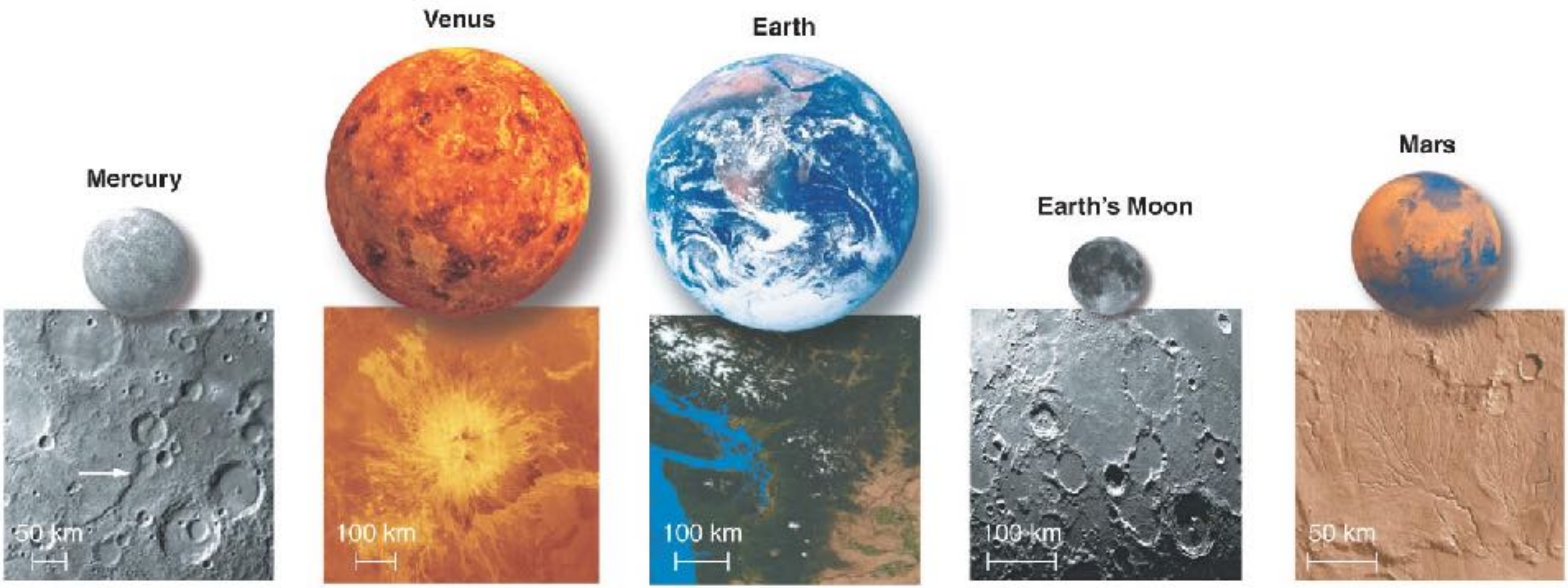
- Convection transports heat as hot material rises and cool material falls.
- Conduction transfers heat from hot material to cool material.
- Radiation sends energy into space.
  - thermal emission

Role of Size



- Smaller worlds cool off faster and harden earlier.
  – cooling time depends on surface area/volume ratio
- The Moon and Mercury are now geologically "dead."

What processes shape planetary surfaces?



Heavily cratered Mercury has long steep cliffs (arrow).

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

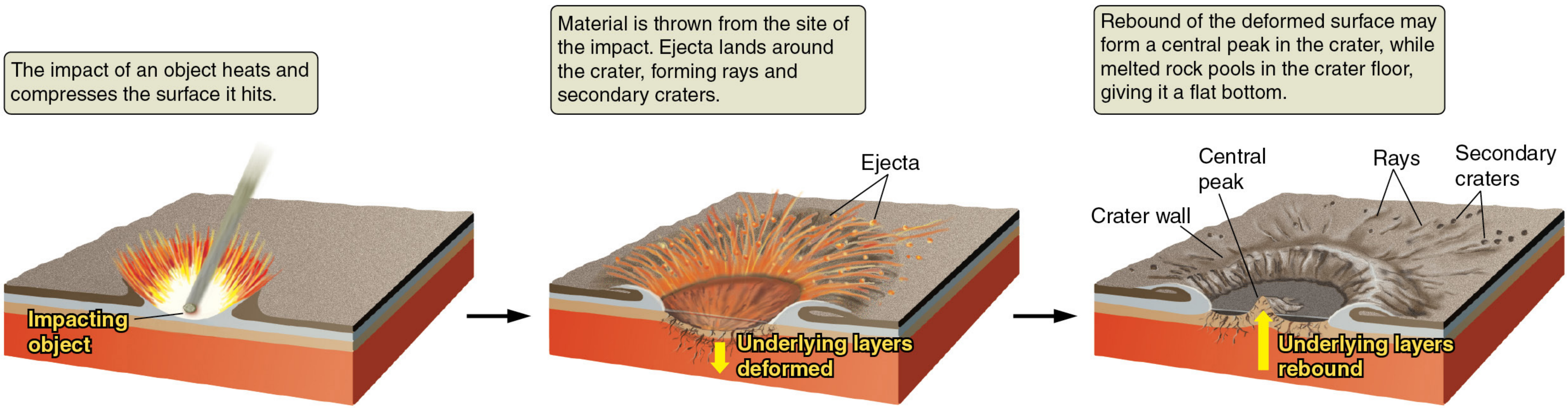
A portion of Earth's surface as it appears without clouds.

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

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

Processes That Shape Surfaces

- Impact cratering
  – Impacts by asteroids or comets
- Volcanism
  – Eruption of molten rock onto surface
- Tectonics
  – Disruption of a planet's surface by internal stresses
- Erosion
  – Surface changes made by wind, water, or ice



- Most cratering happened soon after the solar system formed.
  - Late heavy bombardment 3.8 billion years ago
- Heavily cratered surfaces are old.
  - need active geology to erase craters
- Small craters greatly outnumber large ones.
  - small impactors more common than large ones

Impact Craters

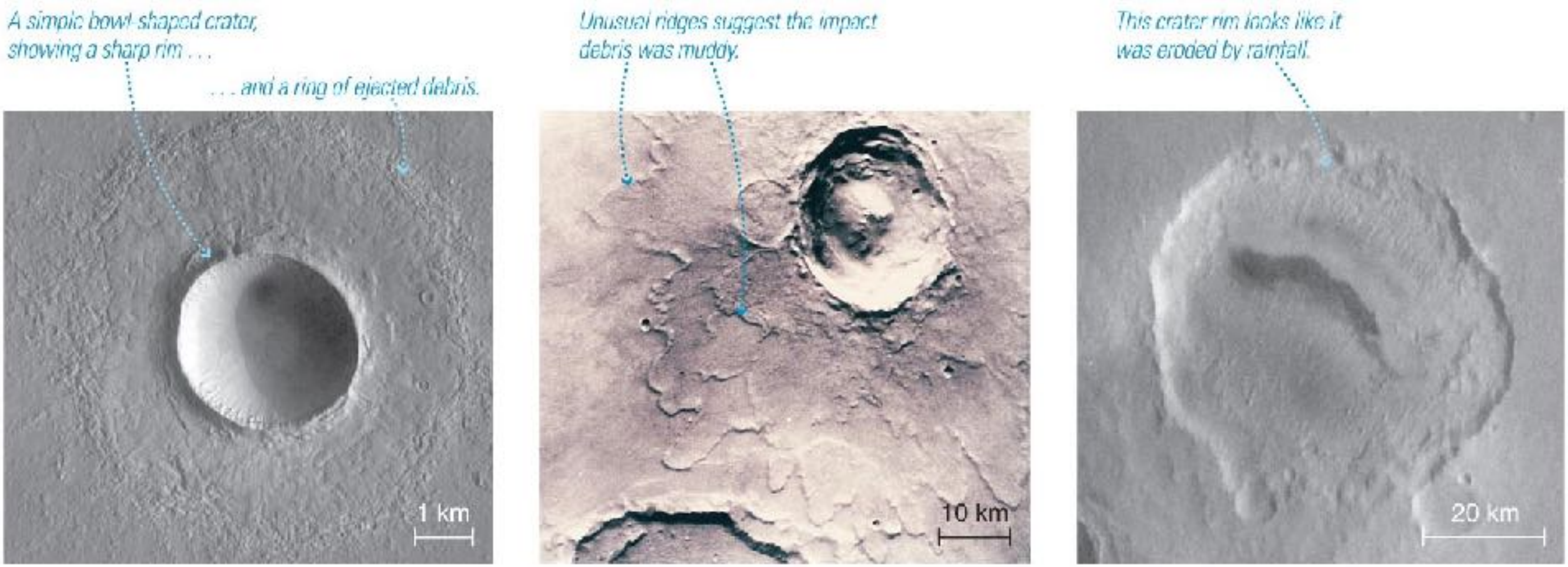
a Meteor Crater in Arizona is more than a kilometer across and almost 200 meters deep. It was created around 50,000 years ago by the impact of a metallic asteroid about 50 meters across.

b This photo shows a crater, named Tycho, on the Moon. Note the classic shape and central peak.

Meteor Crater (Arizona)

Tycho Crater (Moon)

Impact Craters on Mars



a A crater with a typical bowl shape.

b This crater was probably made by an impact into icy ground.

c This crater shows evidence of erosion.

"Standard" crater

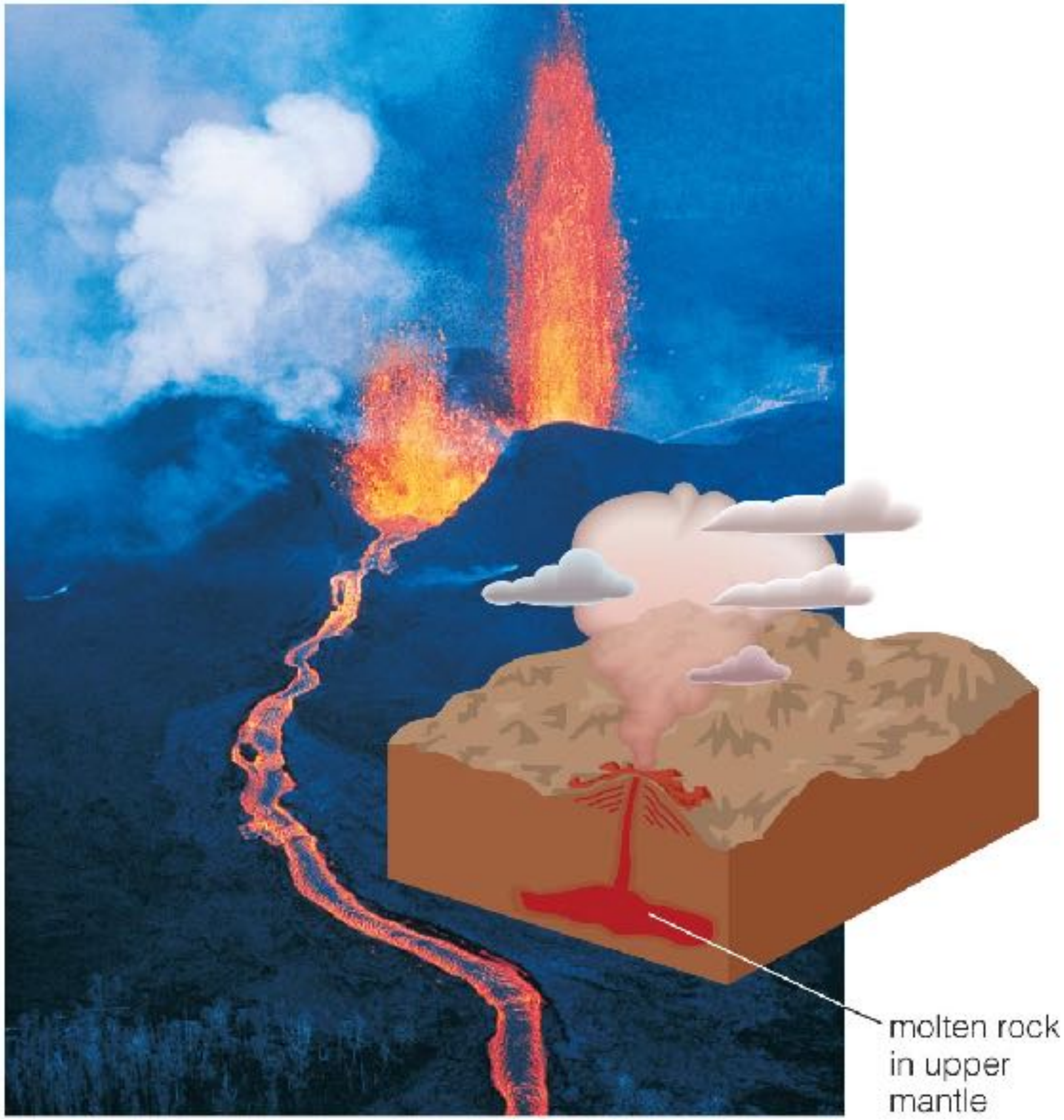
Impact into icy ground

Eroded crater

https://www.youtube.com/watch?v=8xv0ik3ugRg

water droplet video

Volcanism

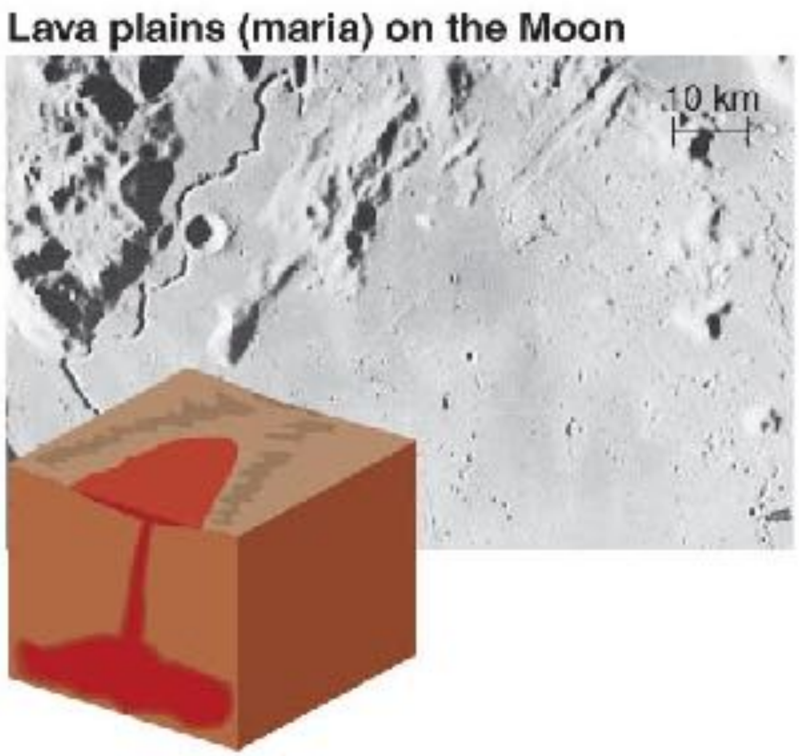


- Volcanism happens when molten rock (magma) finds a path through lithosphere to the surface.
- Molten rock is called lava after it reaches the surface.

Iceland's Bardarbunga eruption 2014/15

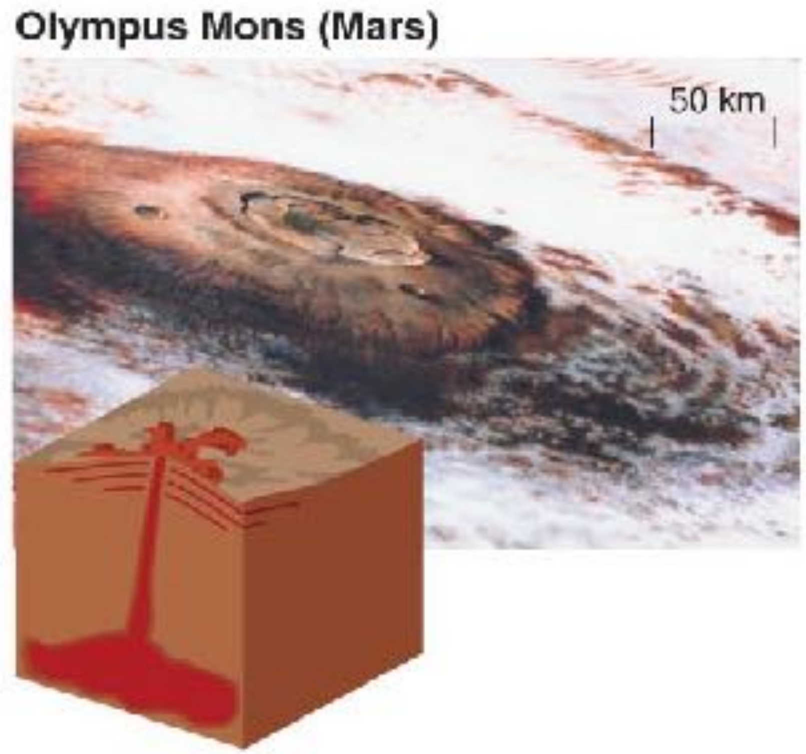
https://www.theguardian.com/world/video/2015/jan/17/icelands-bardarbunga-erupting-five-months-later

Lava and Volcanoes



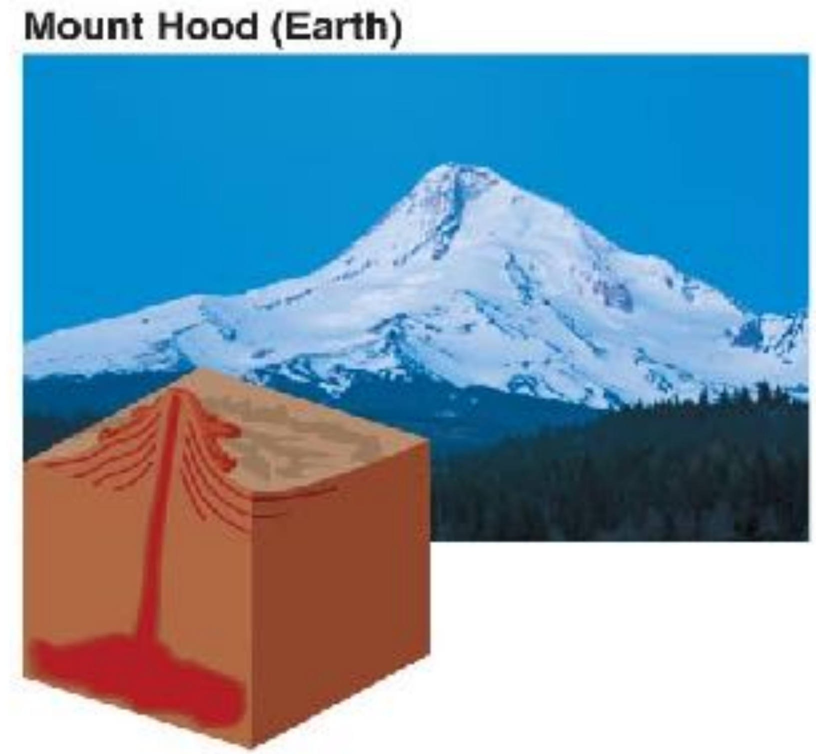
a Very runny lava makes flat lava plains like these on the Moon. The long, winding channel near the upper left was made by a river of molten lava.

Runny lava makes flat lava plains.



b Slightly thicker lava makes shallow-sloped shield volcanoes, such as Olympus Mons on Mars.

Slightly thicker lava makes broad shield volcanoes.



c The thickest lavas make steep-sloped stratovolcanoes like Oregon's Mount Hood.

Thickest lava makes steep stratovolcanoes.

Outgassing

a The eruption of Mount St. Helens, May 18, 1980.

b More gradual outgassing from a volcanic vent in Volcanoes National Park, Hawaii.

- Volcanism releases gases from Earth's interior into the atmosphere.
- How planets get an atmosphere in the first place!