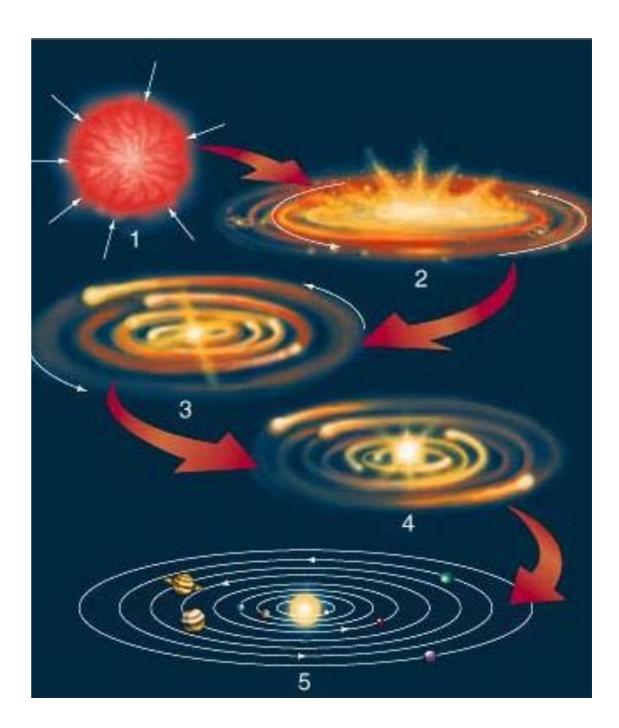
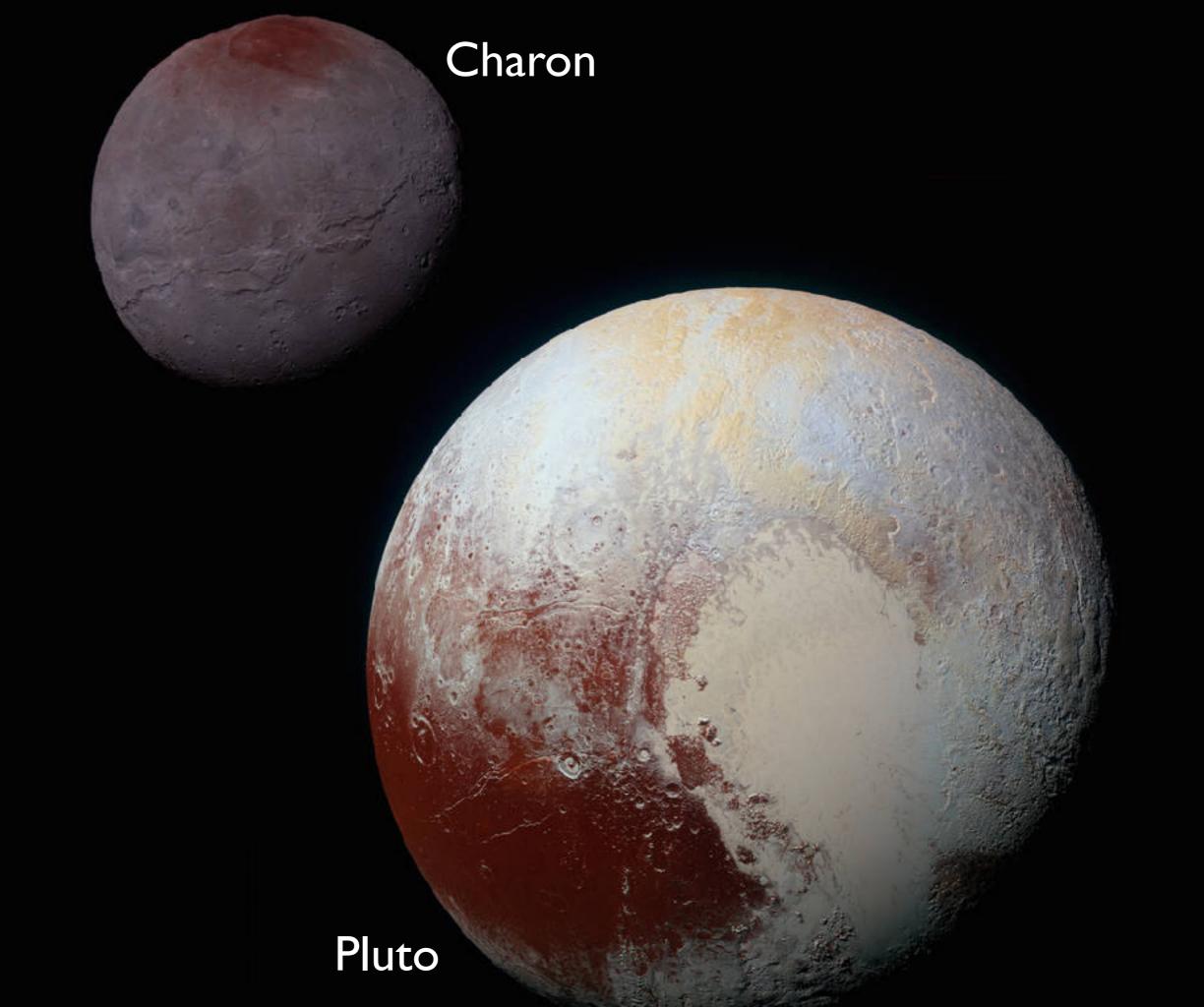
# Today

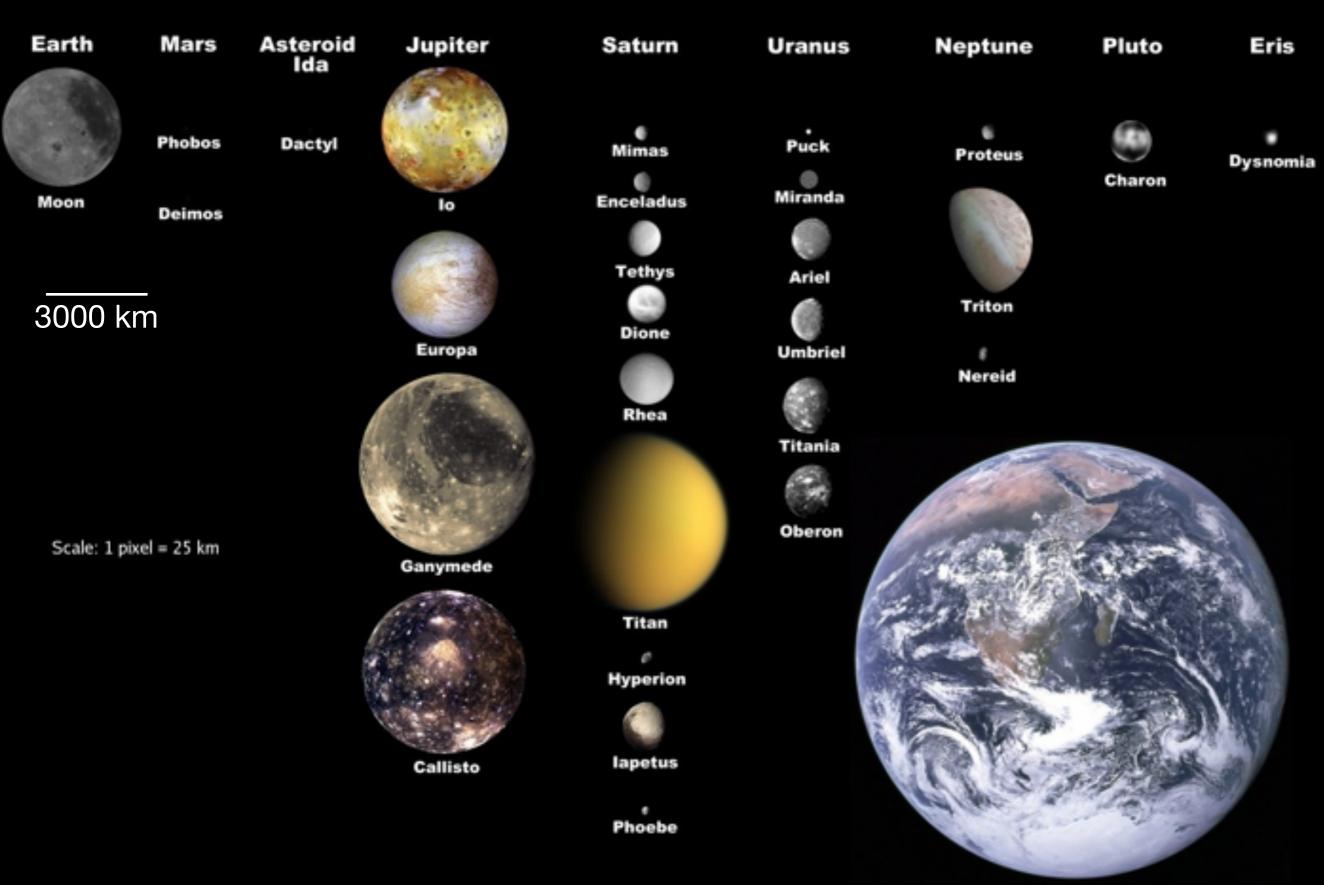
- Solar System Formation
  - a few more bits and pieces

• Homework due





#### Selected Moons of the Solar System, with Earth for Scale



Earth

#### Asteroids



433 Eros - 33 × 13 km NEAR, 2000





5535 Annefrank 2867 6.6 × 5.0 × 3.4 km 5.9 × Stardust, 2002 Roset

2867 Steins 5.9 × 4.0 km Rosetta, 2008

-

9969 Braille 2.1 × 1 × 1 km Deep Space 1, 1999

25143 Itokawa 0.5 × 0.3 × 0.2 km Hayabusa, 2005

awa 9969 .2 km 2.1 × <sup>005</sup> Deep Sp

9P/Tempel 1 7.6 × 4.9 km Deep Impact, 2005



81P/Wild 2 5.5 × 4.0 × 3.3 km Stardust, 2004

951 Gaspra 18.2 × 10.5 × 8.9 km <sub>Galileo, 1991</sub>

253 Mathilde - 66 × 48 × 44 km NEAR, 1997

Dactyl [(243) Ida I] 1.6 × 1.2 km Galileo, 1993

-



19P/Borrelly

 $8 \times 4 \text{ km}$ 

Deep Space 1, 2001

small 1P/Halley - 16 × 8 × 8 km Vega 2, 1986 irregular

#### rocky bodies

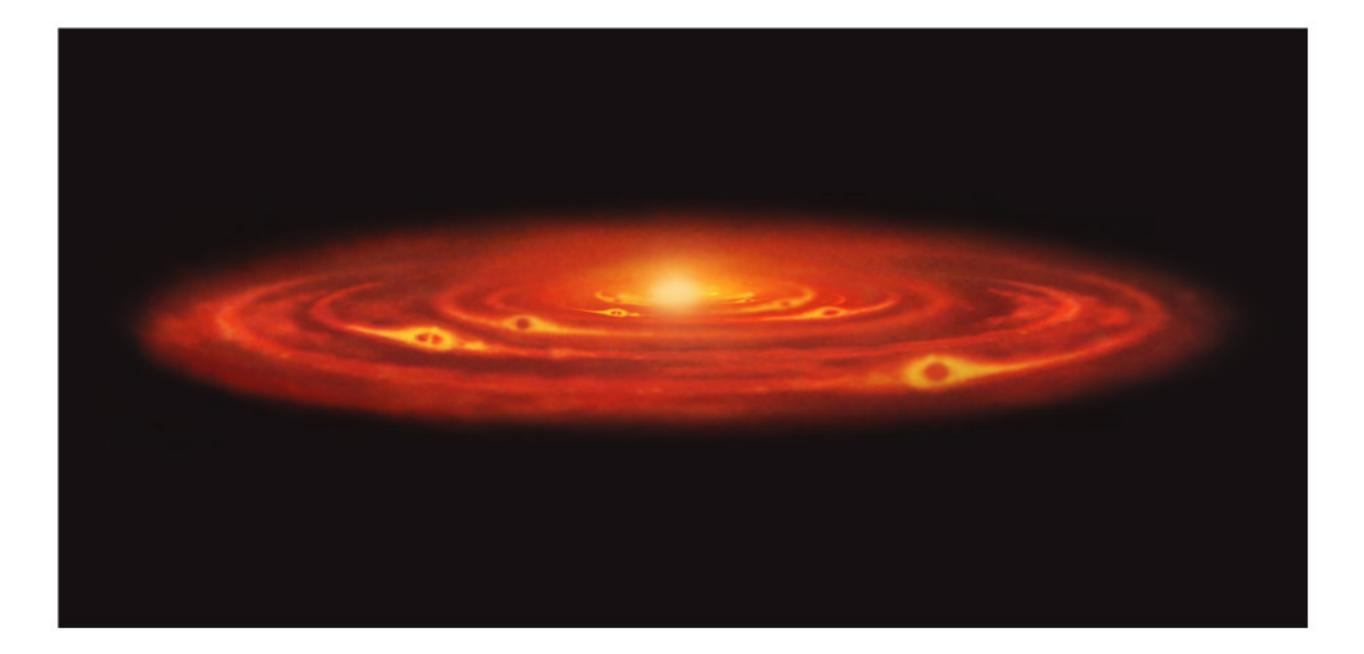
243 Ida - 58.8 × 25.4 × 18.6 km Galileo, 1993



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



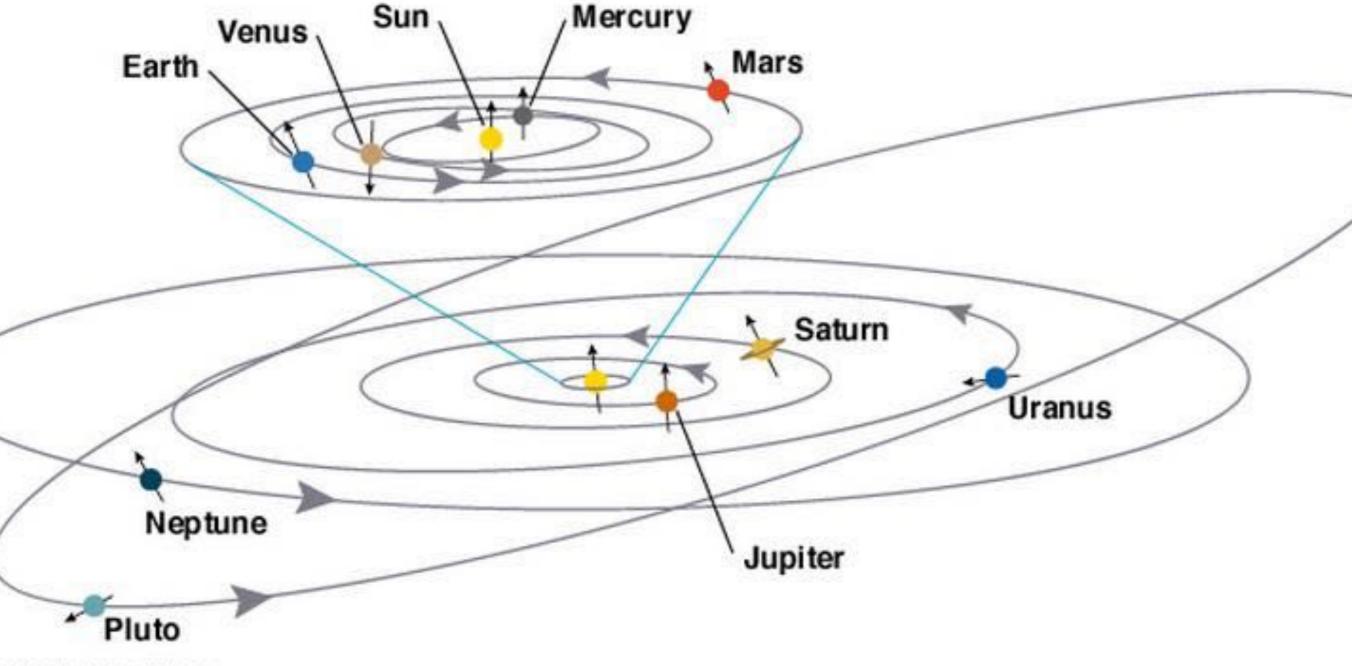
What are the odds that the orbital planes of the planets are so well aligned by chance?

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<sup>-6</sup>)

Need to explain why the solar system is so structured

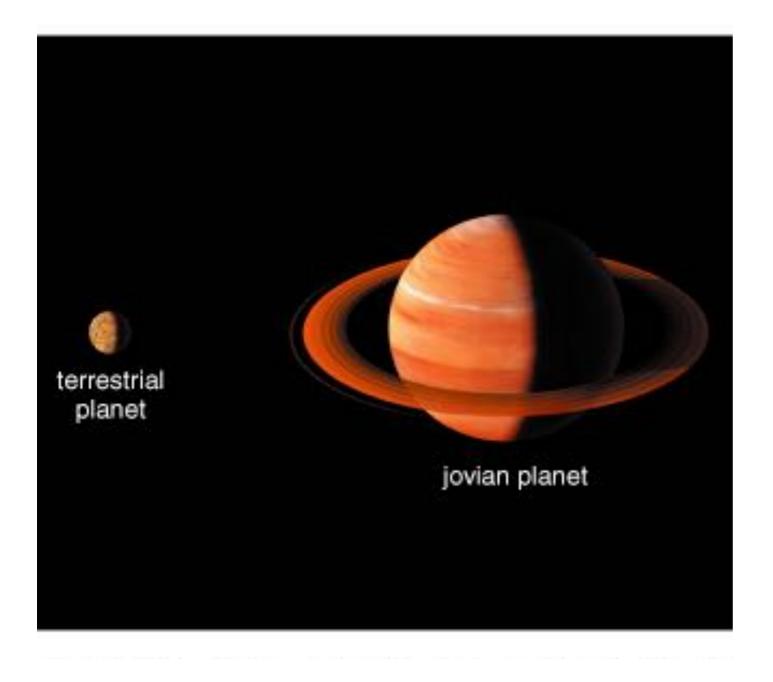
#### Clues to Solar System Formation



right © Addison Wesley

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

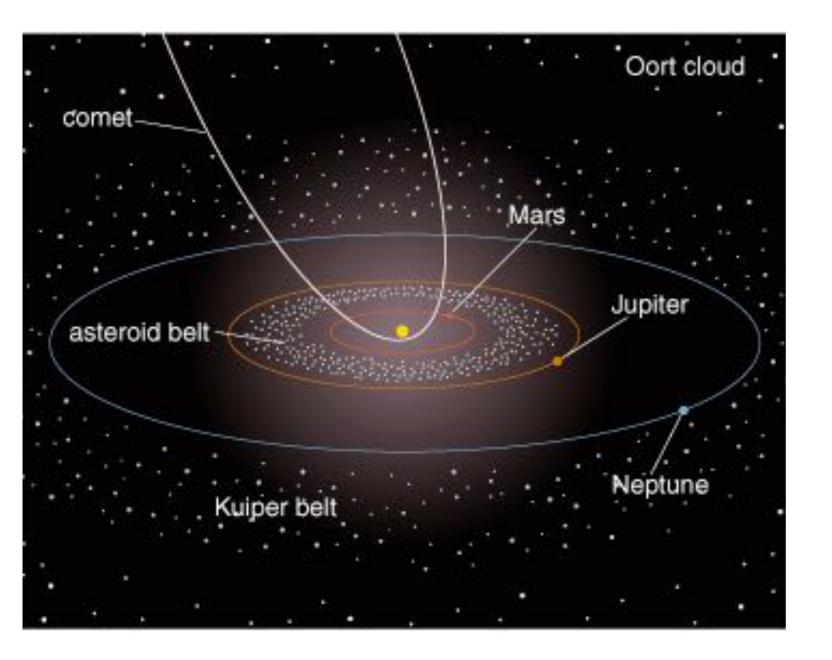
Expect more distinctions with new discoveries



Earth to scale

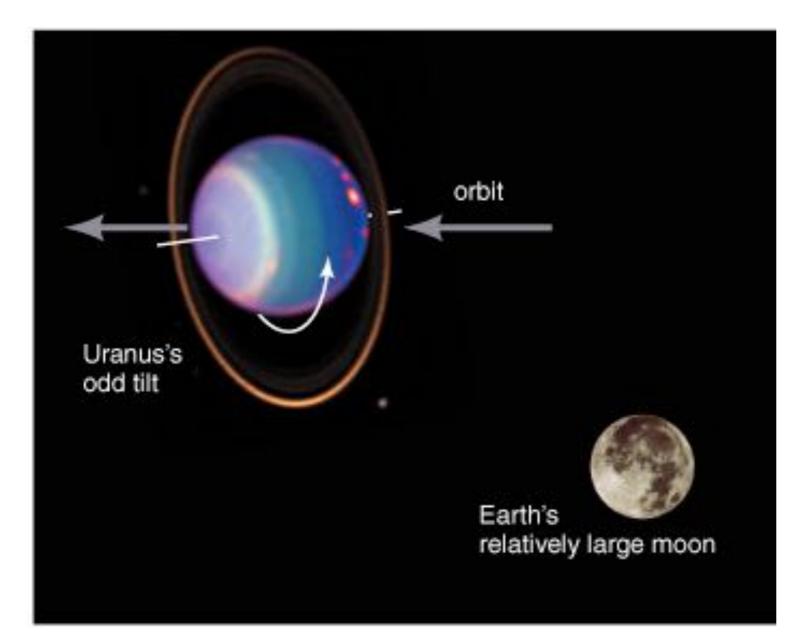
#### Neptune to scale

## 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.

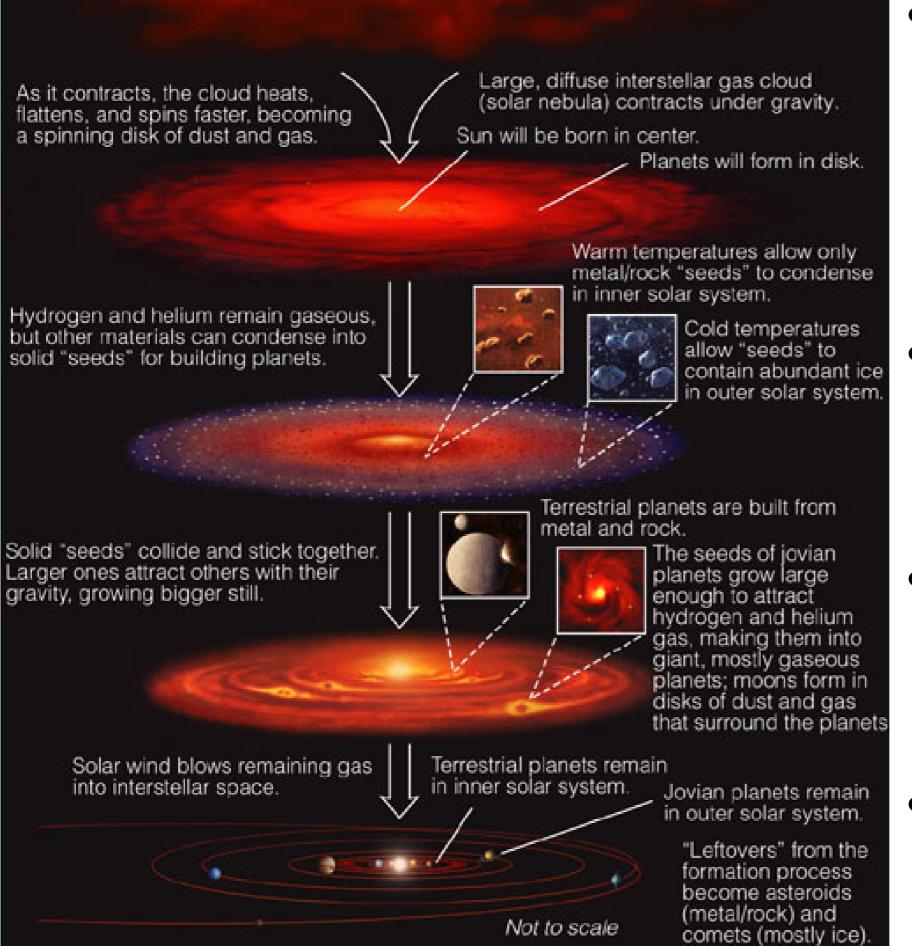


According to the *nebular theory,* our solar system formed from a giant cloud of interstellar gas.

(*nebula* = cloud)

Also known as the *solar nebula* hypothesis

SS formation movie <u>http://www.spitzer.caltech.edu/video-audio/730-ssc2004-22v2-The-Evolution-of-a-Planet-Forming-Disk</u>



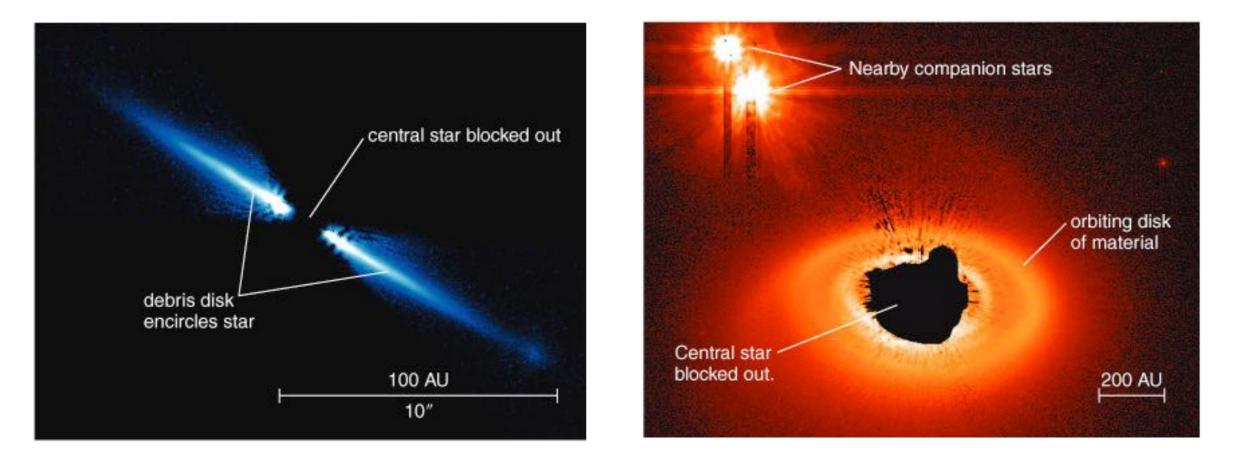
 Nebula spins up as it collapses (angular momentum conserved)

Solid particles
 condense out of
 gas

• Particles collide; form ever larger objects

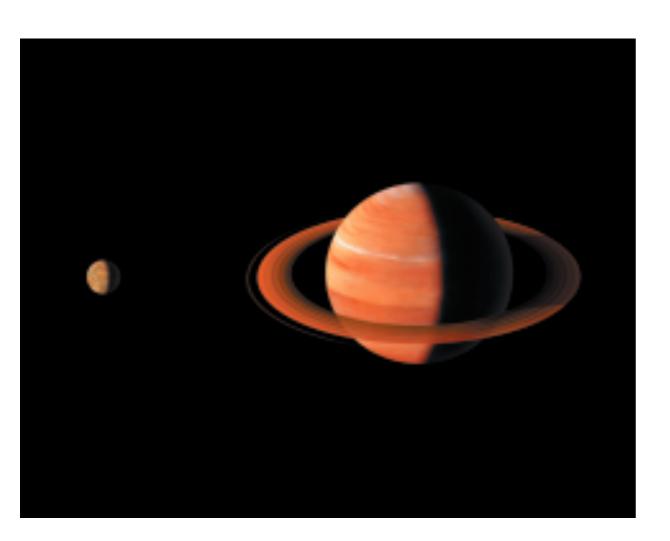
 Most mass eventually swept up into planets

## Disks Around Other Stars

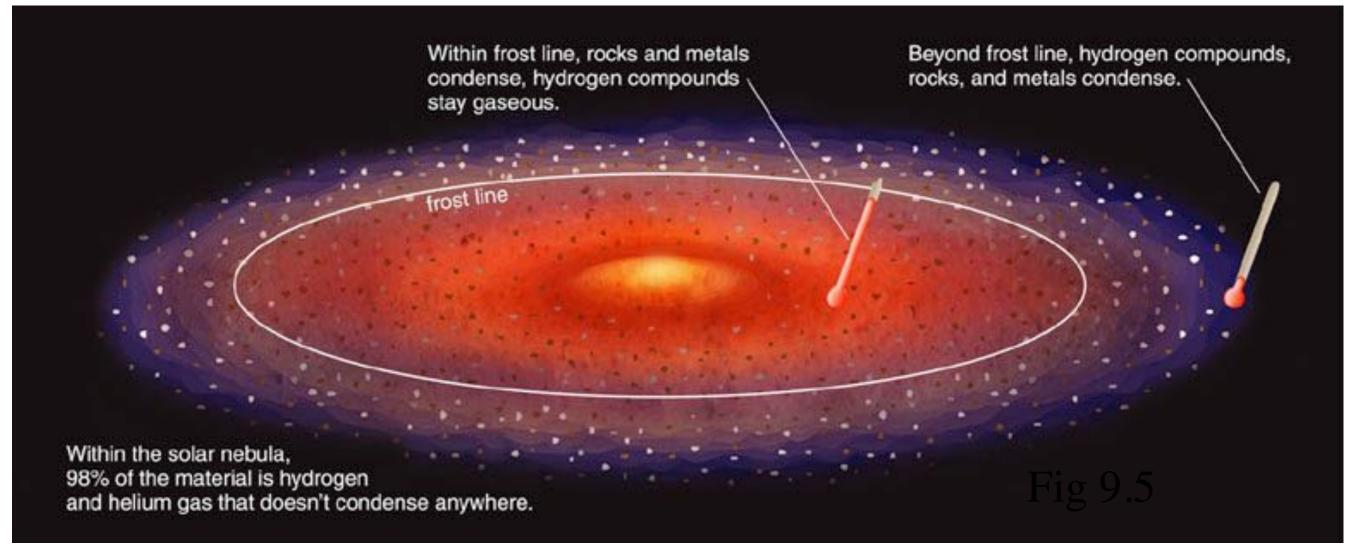


• Observations of disks around other stars broadly support the nebular hypothesis.

# Why are there two major types of planets?



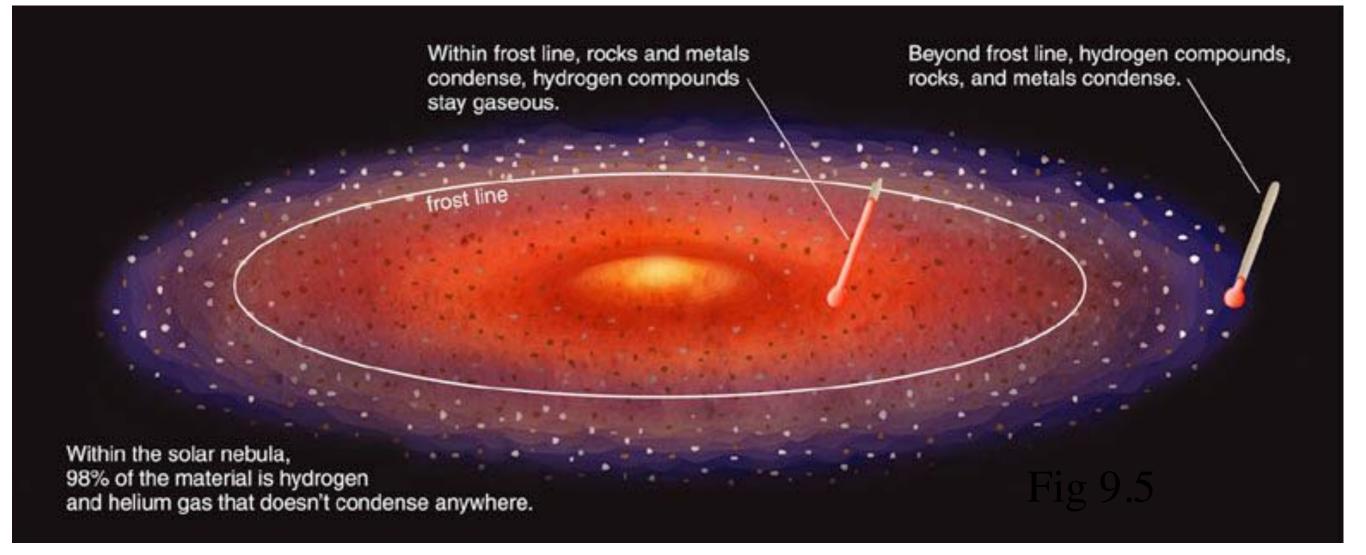
	Examples	Typical Condensation Temperature	Relative Abundance (by mass)
Hydrogen and Helium Gas	hydrogen, helium	do not condense in nebula	98%
Hydrogen Compounds	water (H <sub>2</sub> O) methane (CH <sub>4</sub> ) ammonia (NH <sub>3</sub> )	<150 K	1.4%
Rock	various minerals	500– 1,300 K	0.4%
Metals	iron, 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

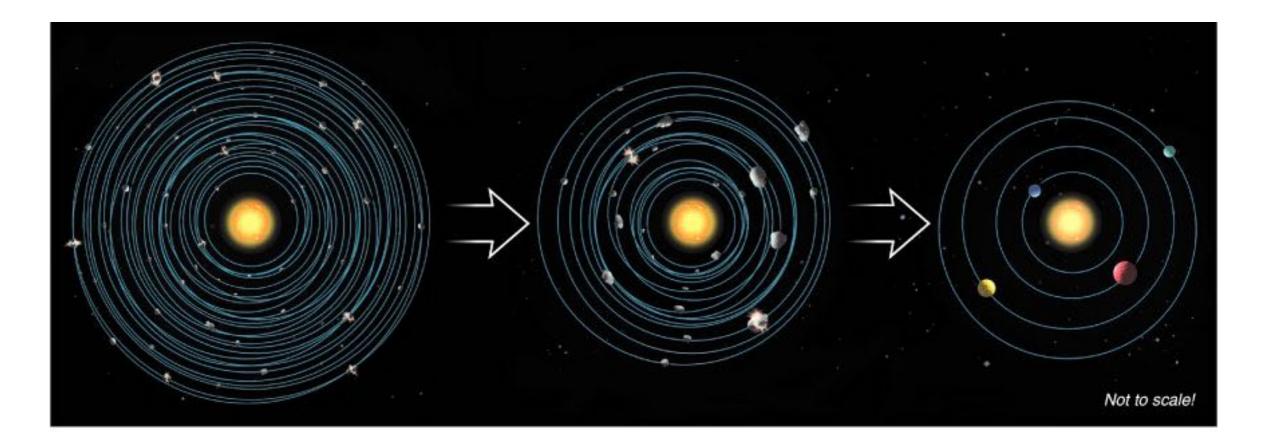
#### Outside the *frost line*: Cold enough for ices to form

- 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.

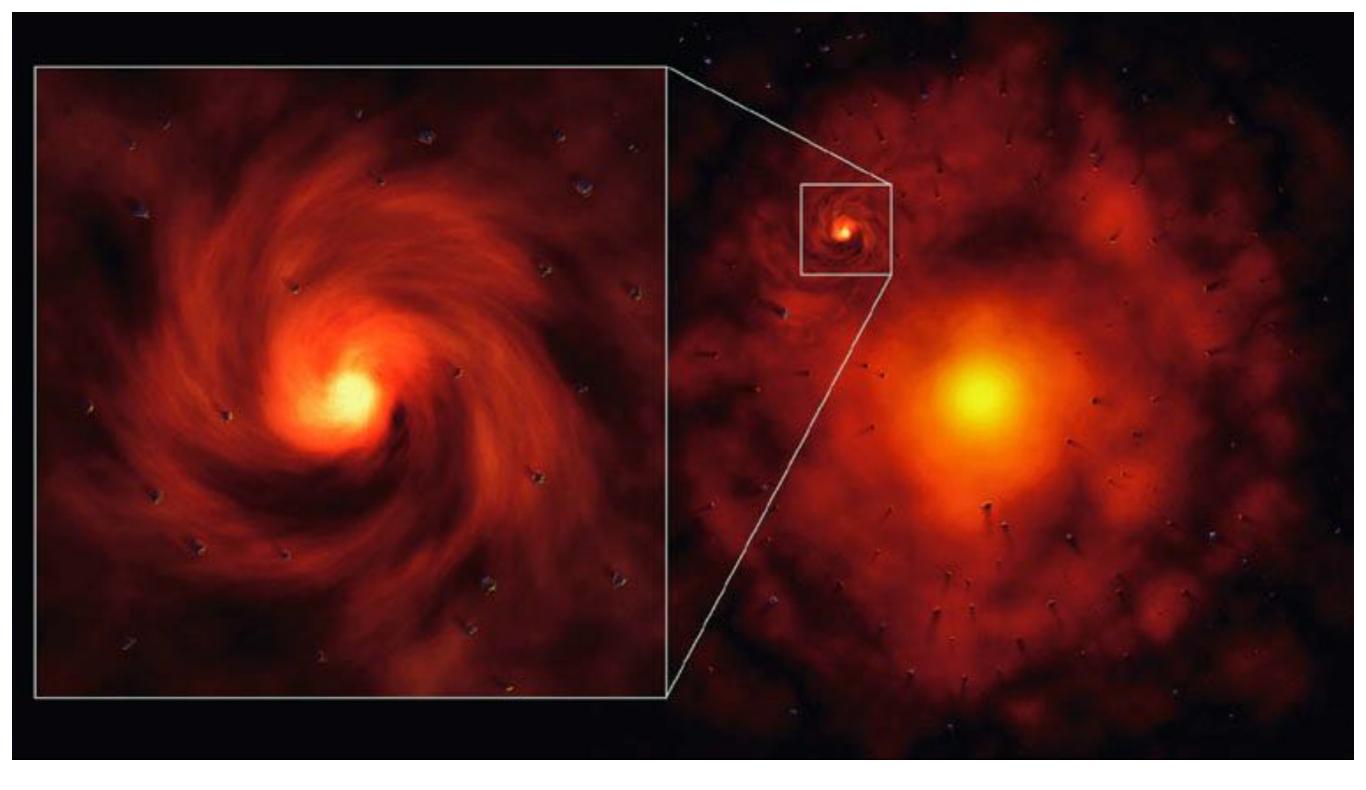
### Accretion of Planetesimals



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

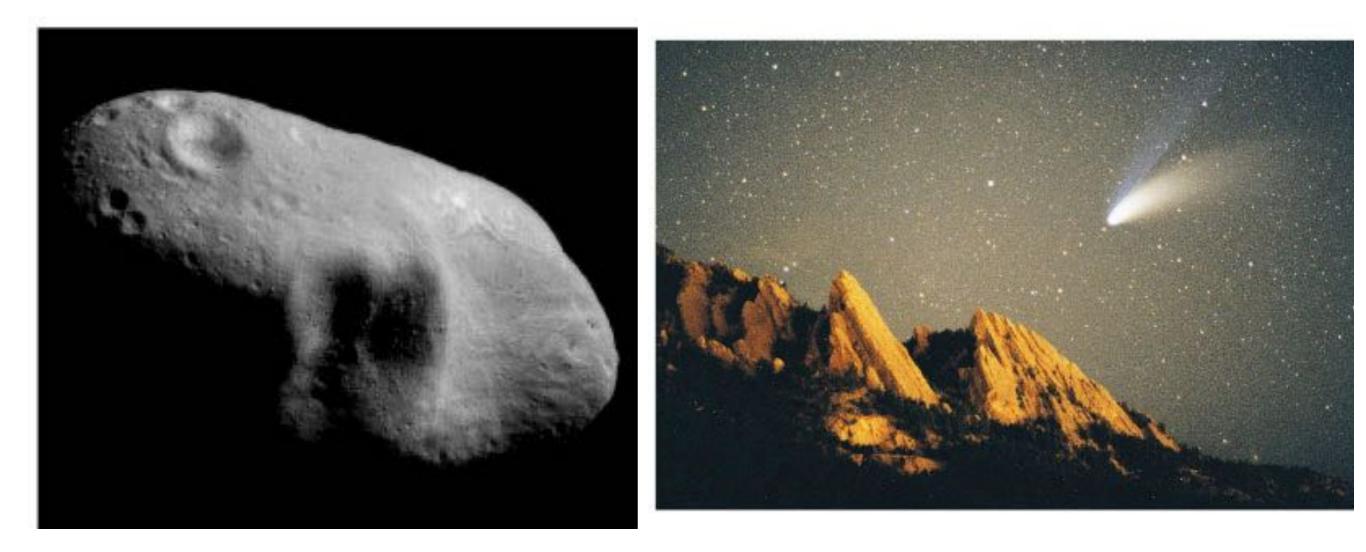
## Formation of Jovian Planets

- 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.

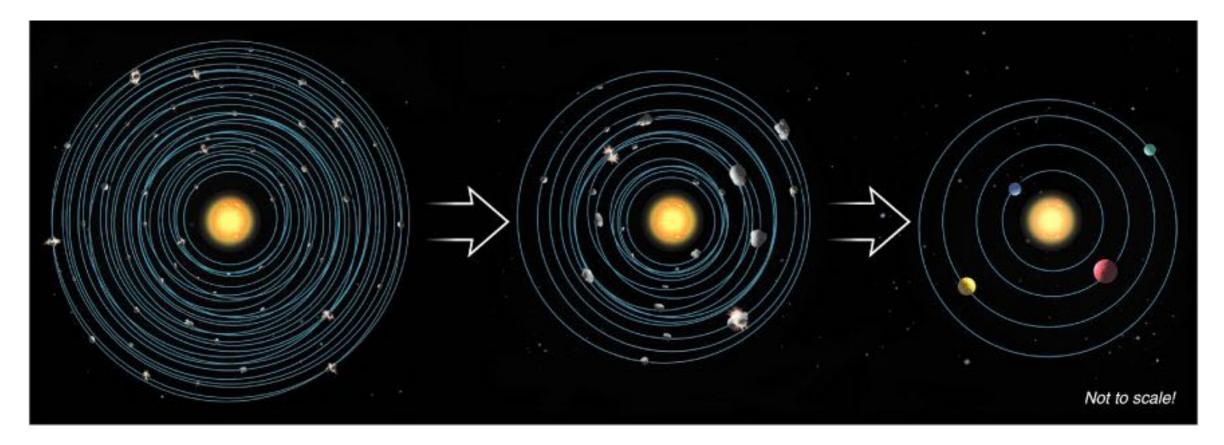


Moons of jovian planets form in miniature disks - like microcosms of the solar nebula.

# Where did asteroids and comets come from?

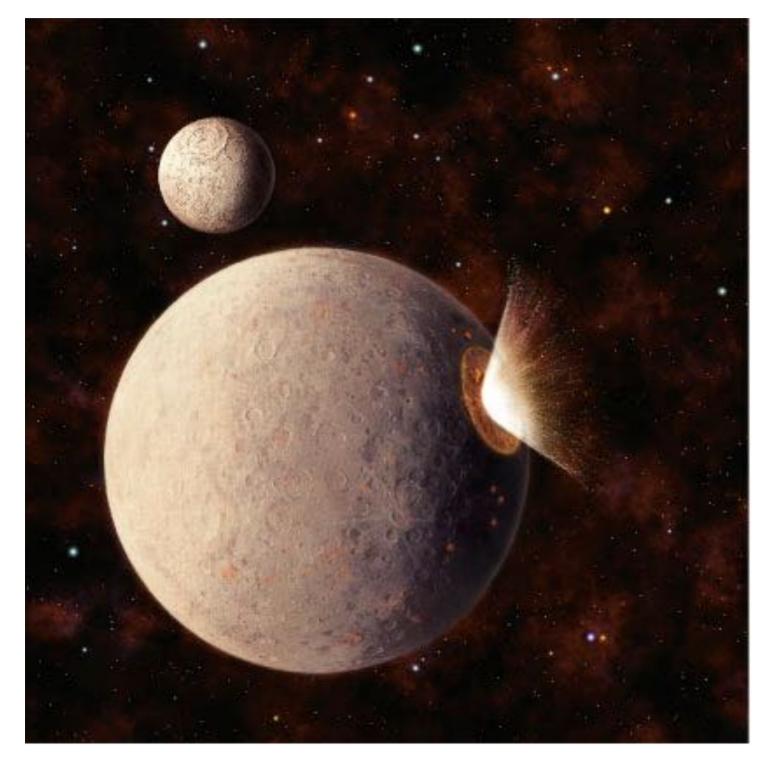


### Asteroids and Comets



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

# Heavy Bombardment



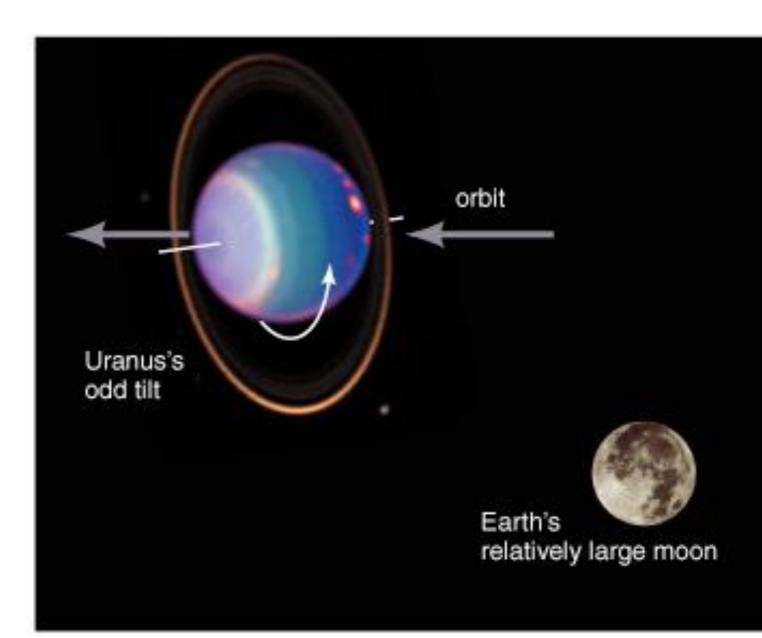
• Leftover planetesimals bombarded other objects in the late stages of solar system formation.

"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?

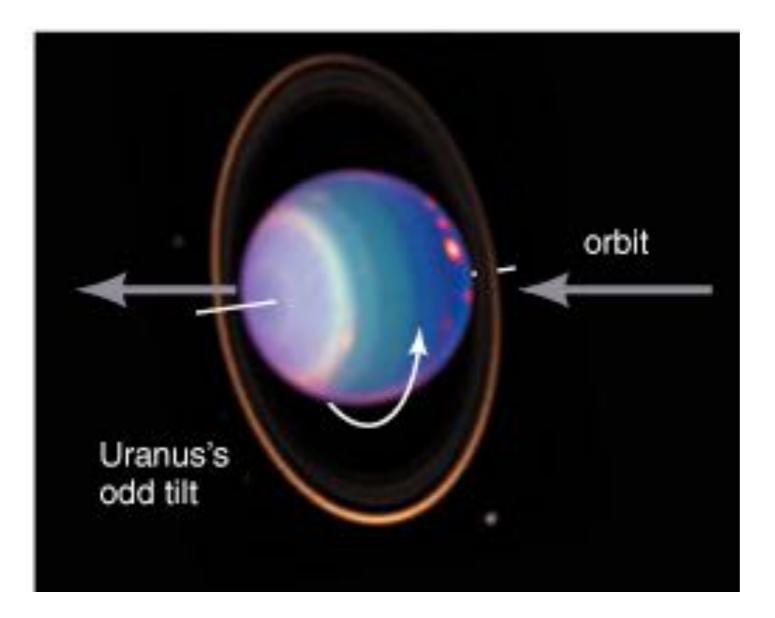
Giant impact stripped matter from Earth's crust

#### Stripped matter began to orbit

#### Then accreted into Moon

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

## Odd Rotation



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

As it contracts, the cloud heats, flattens, and spins faster, becoming a spinning disk of dust and gas.

Large, diffuse interstellar gas cloud (solar nebula) contracts under gravity. Sun will be born in center. Planets will form in disk.

Warm temperatures allow only

metal/rock "seeds" to condense

Cold temperatures

contain abundant ice in outer solar system.

allow "seeds" to

The seeds of jovian planets grow large

hydrogen and helium gas, making them into

giant, mostly gaseous planets; moons form in disks of dust and gas

enough to attract

Hydrogen and helium remain gaseous, but other materials can condense into solid "seeds" for building planets.

in inner solar system.

Solid "seeds" collide and stick together. Larger ones attract others with their gravity, growing bigger still.



Solar wind blows remaining gas into interstellar space.

Terrestrial planets remain in inner solar system.

Not to scale

Jovian planets remain in outer solar system.

that surround the planets

"Leftovers" from the formation process become asteroids (metal/rock) and comets (mostly ice). • Nebula spins up as it collapses (angular momentum conserved)

Solid particles condense out of gas

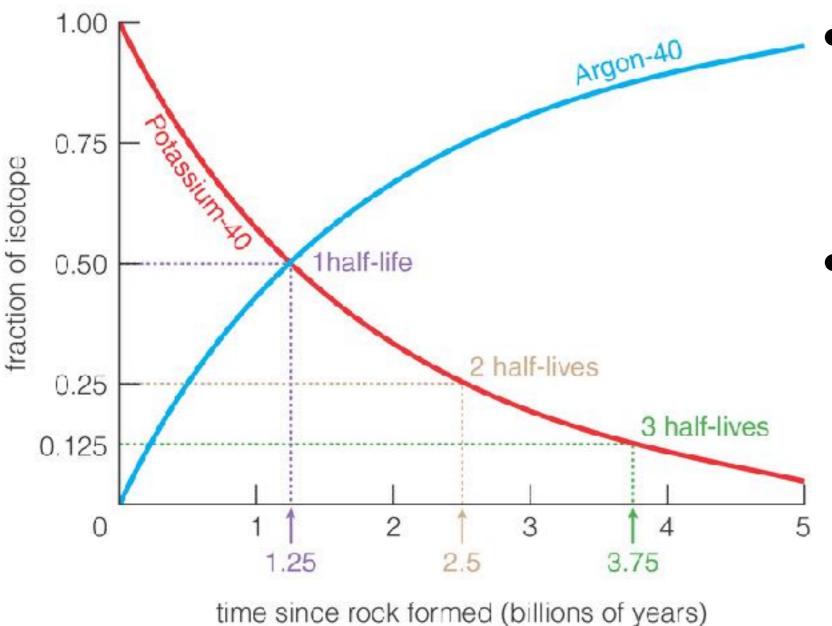
Particles collide; form ever larger objects

Most mass eventually swept up into planets

## 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



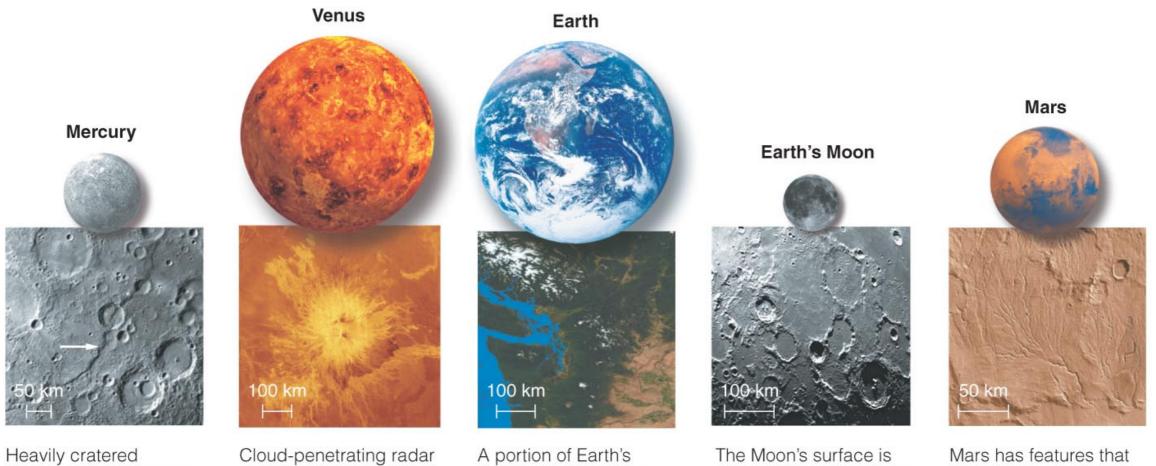
Age dating of meteorites via radio-isotopes tells us that the solar system is about 4.5 billion years old.

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).

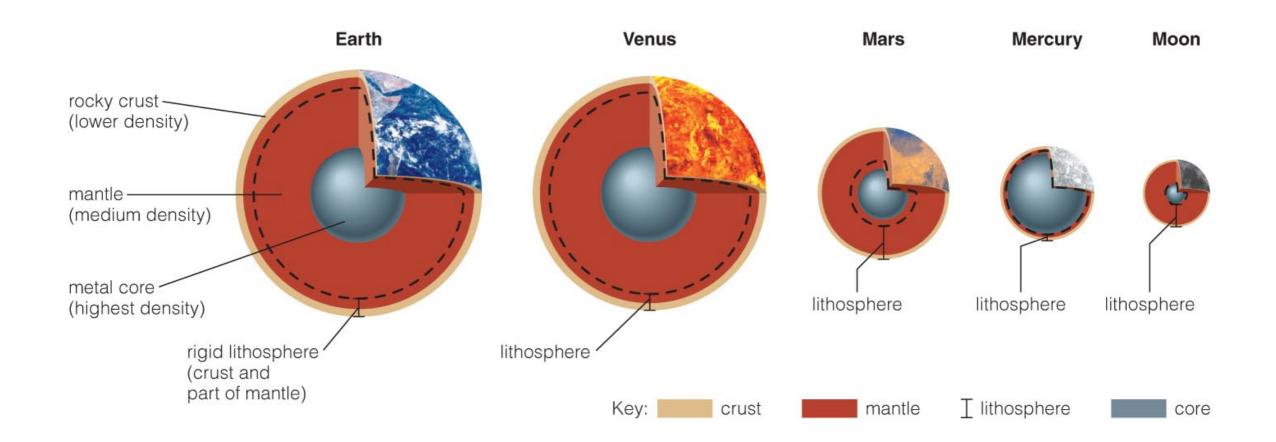
Cloud-penetrating rada revealed this twinpeaked volcano on Venus.

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

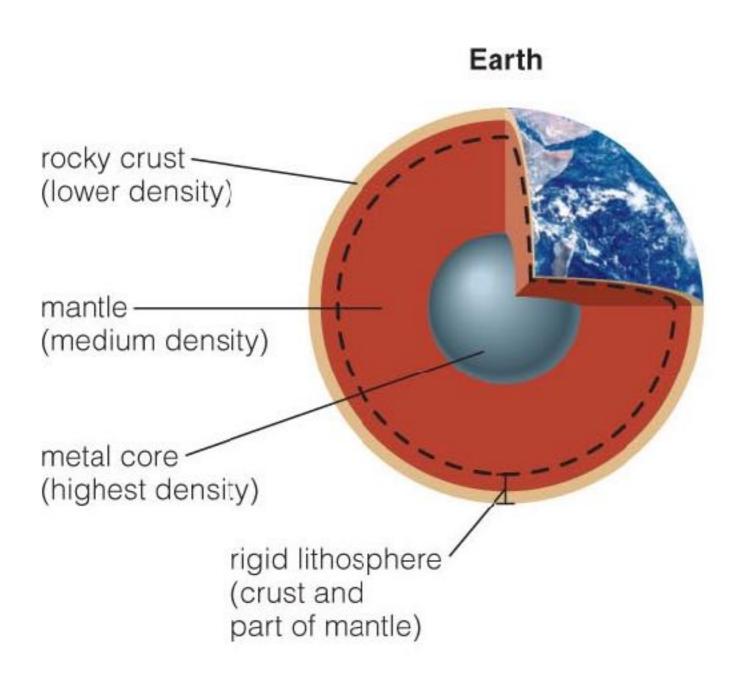
The Moon's surface is heavily cratered in most places.

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

#### Planetary surfaces & interiors



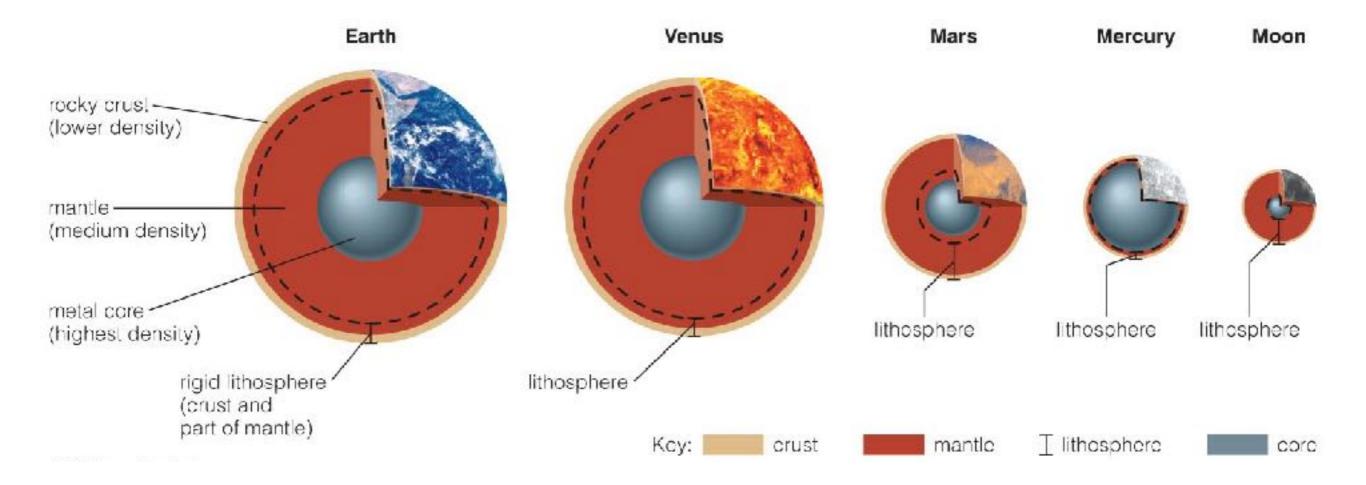
#### **Earth's Interior**



 Core: highest density; nickel and iron

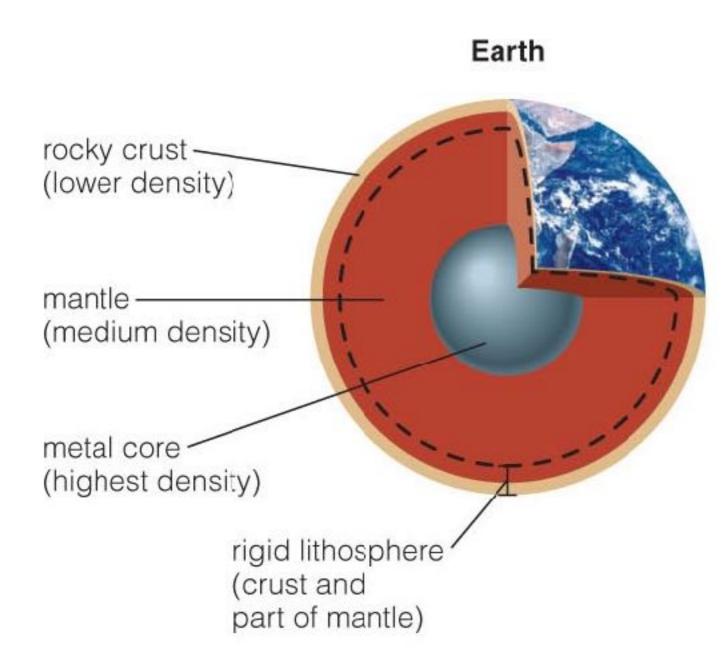
- Mantle: moderate density; silicon, oxygen, etc.
- Crust: lowest density; granite, basalt, etc.

#### **Terrestrial Planet Interiors**



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

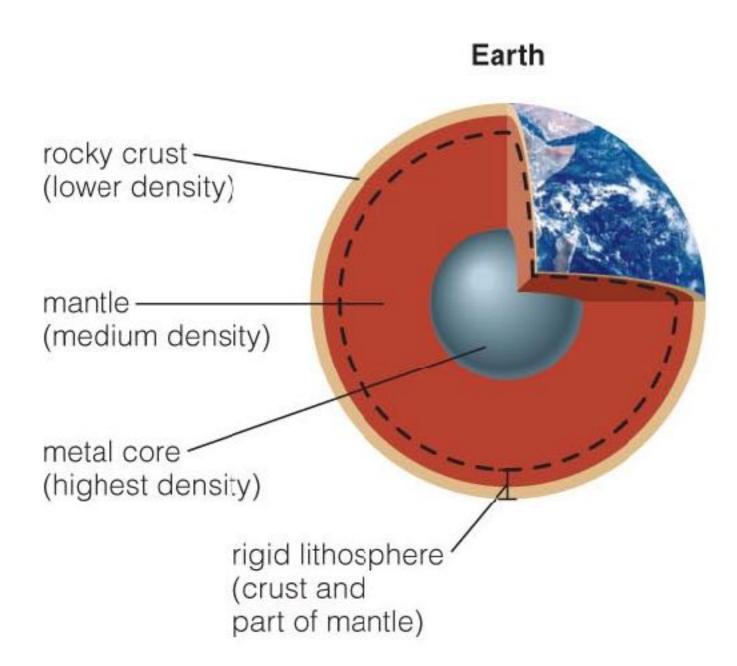
#### Differentiation



 Gravity pulls highdensity 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.