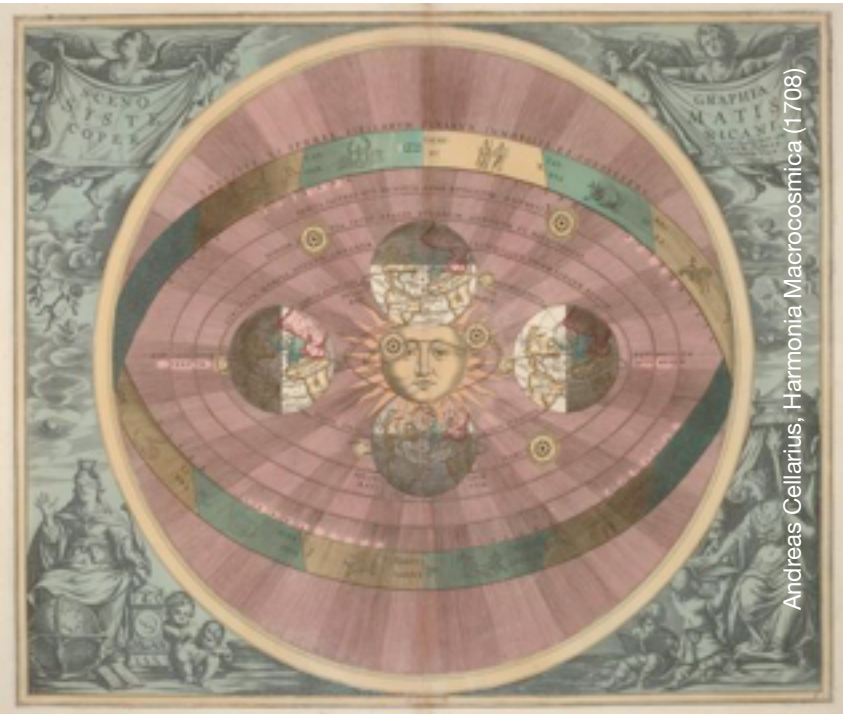
Today

- Solar System Formation

Events

- Homework Due Thu Feb 26 (today)
- Dr. Marcel Pawlowski substitutes
- (Prof. McGaugh visiting Yale)

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


Andreas Cellarius, Harmonia Macrocosmica (1708)

RECHERCHES
PHYSIQUES
ET ASTRONOMIQUES,
SUR LE PROBLEME PROPOSE'
POUR LA SECONDE FOIS
Par l'Académie Royale des Sciences de Paris.

Quelle eſt la cauſe phyſique de l'inclinaiſon des Plans des Orbites des Planetes par rapport au plan de l'Equateur de la révolution du Soleil autour de ſon axe ; Et d'où vient que les inclinaiſons de ces Orbites ſont différentes entre elles.

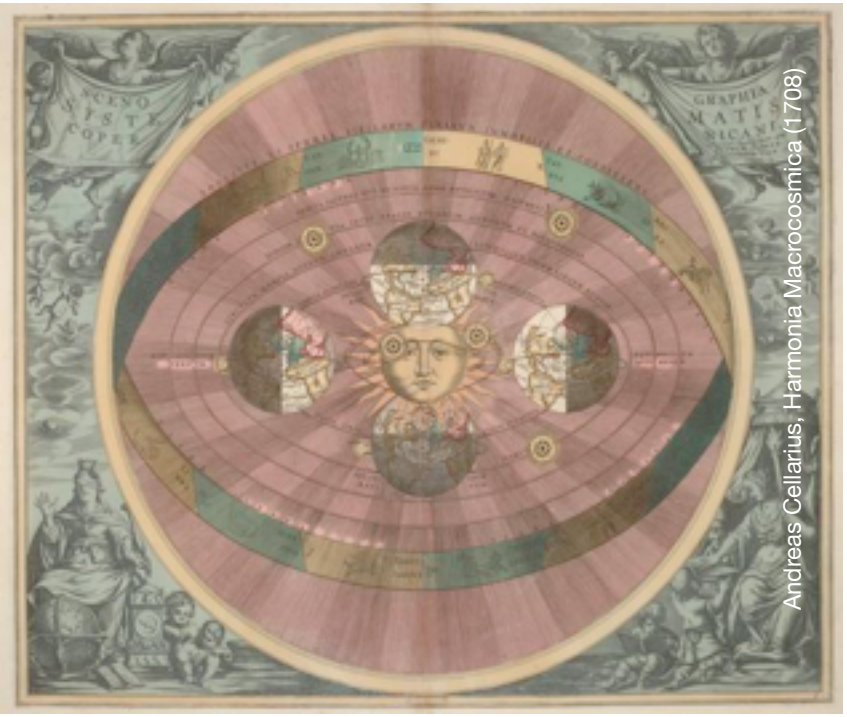
PIECE DE M. DANIEL BERNOULLI,
DES ACADÉMIES DE PETERSBOURG, DE BOLOGNE, &c.
& Profeſſeur d'ANATOMIE & de BOTANIQUE
en l'Univerſité de Bâle.

Qui a partagé le Prix double de l'année 1734.

Traduite en François par ſon Auteur.

M iij

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

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

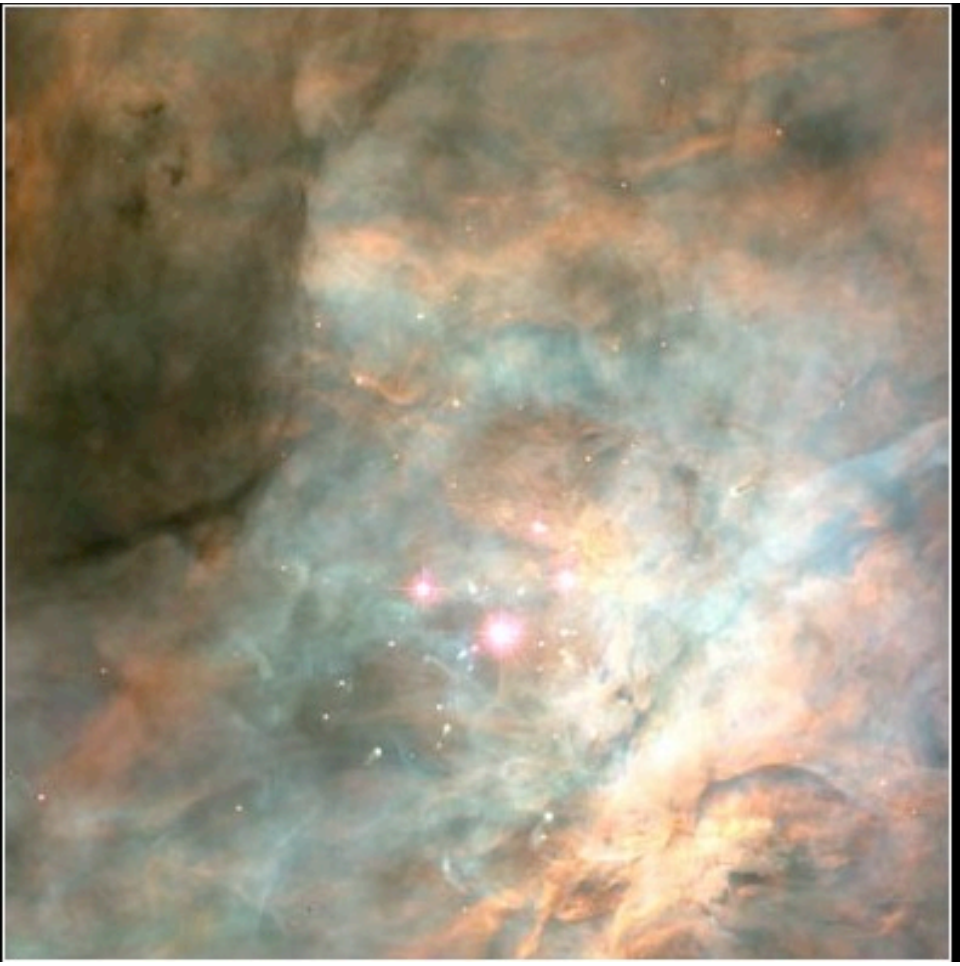
Proposed early:
- Immanuel Kant (1755)
- Pierre-Simon Laplace (1796)

SS formation movie

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


Star Forming Clouds
(The Eagle Nebula)

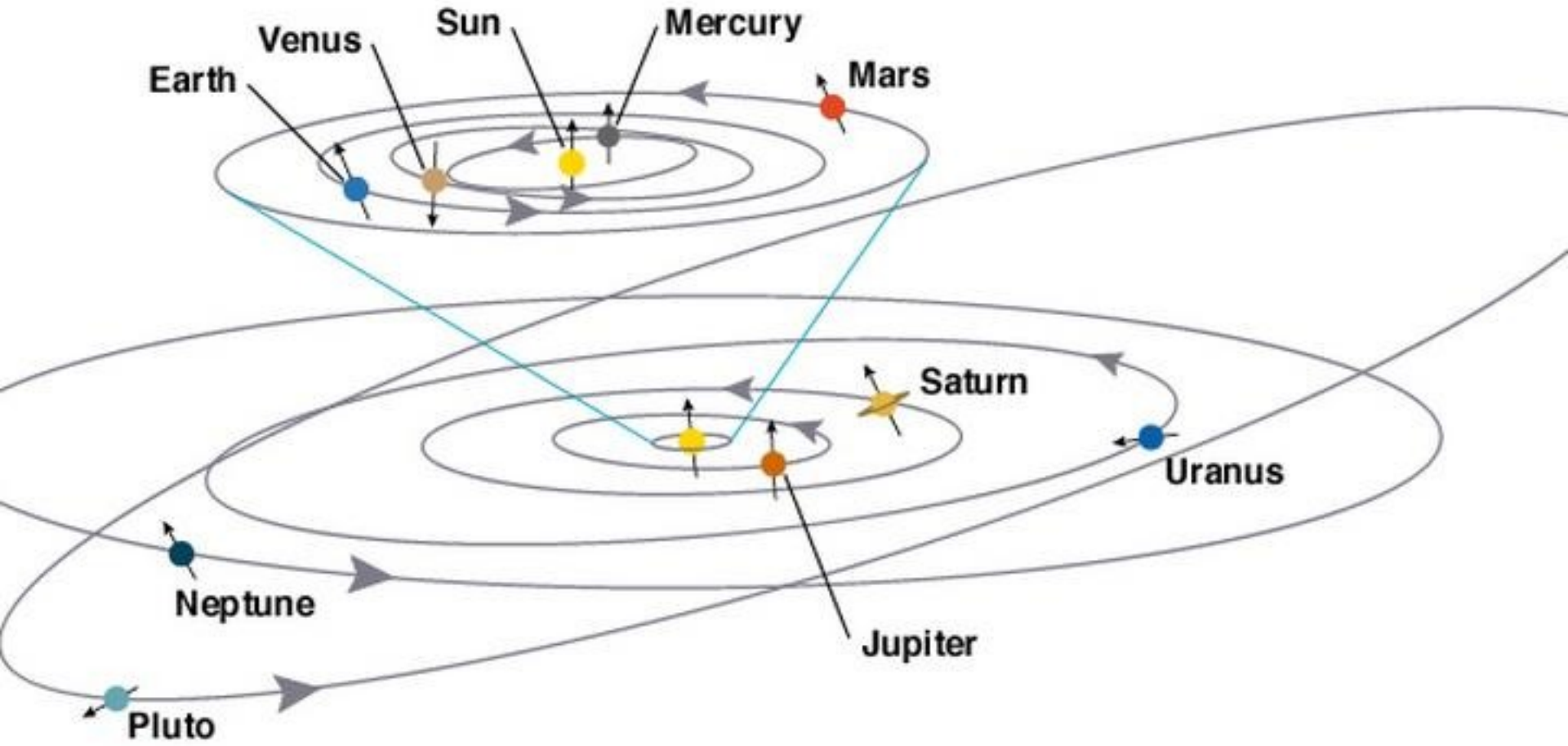
Young stars in the Orion Nebula

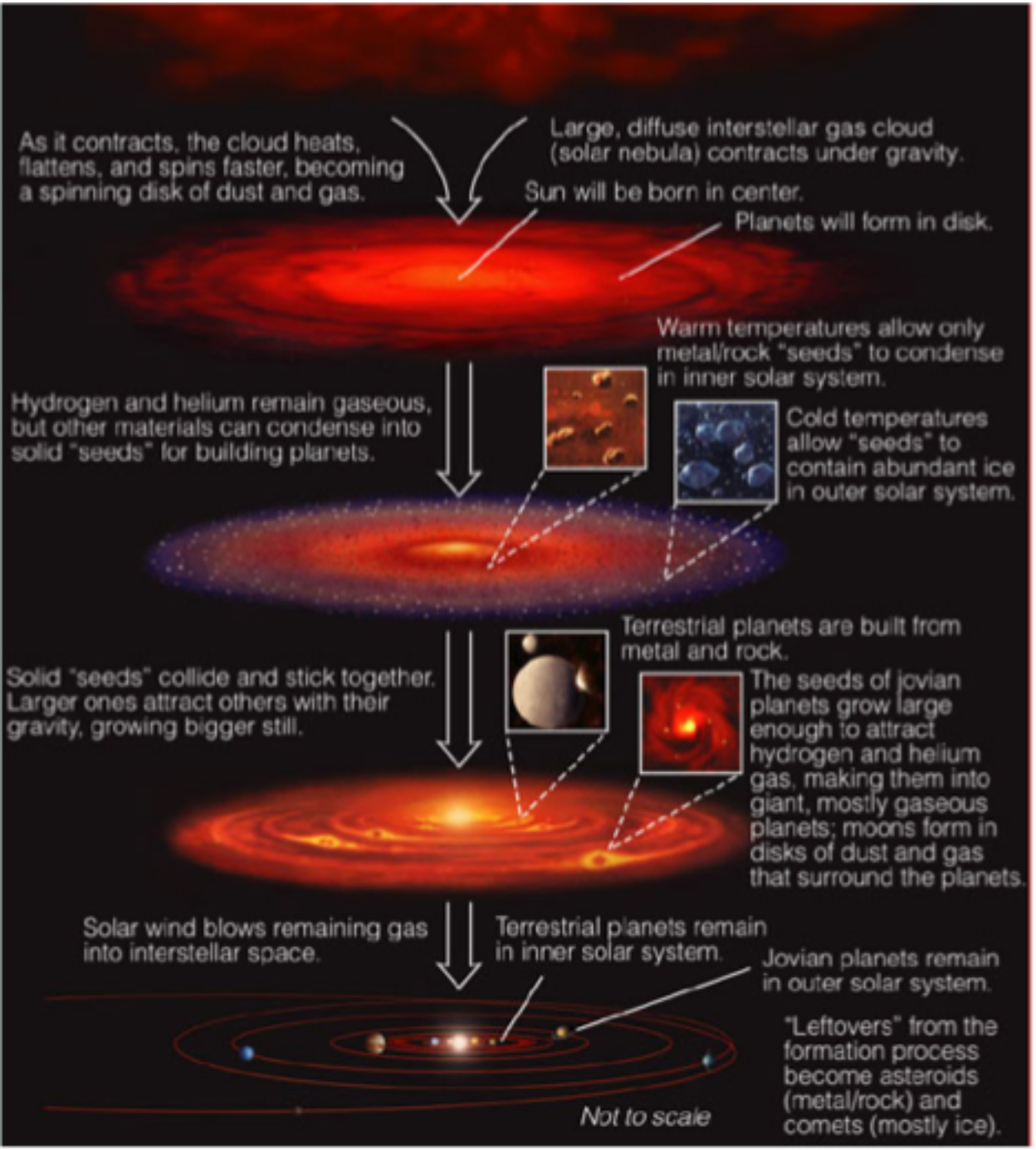


Optical Light

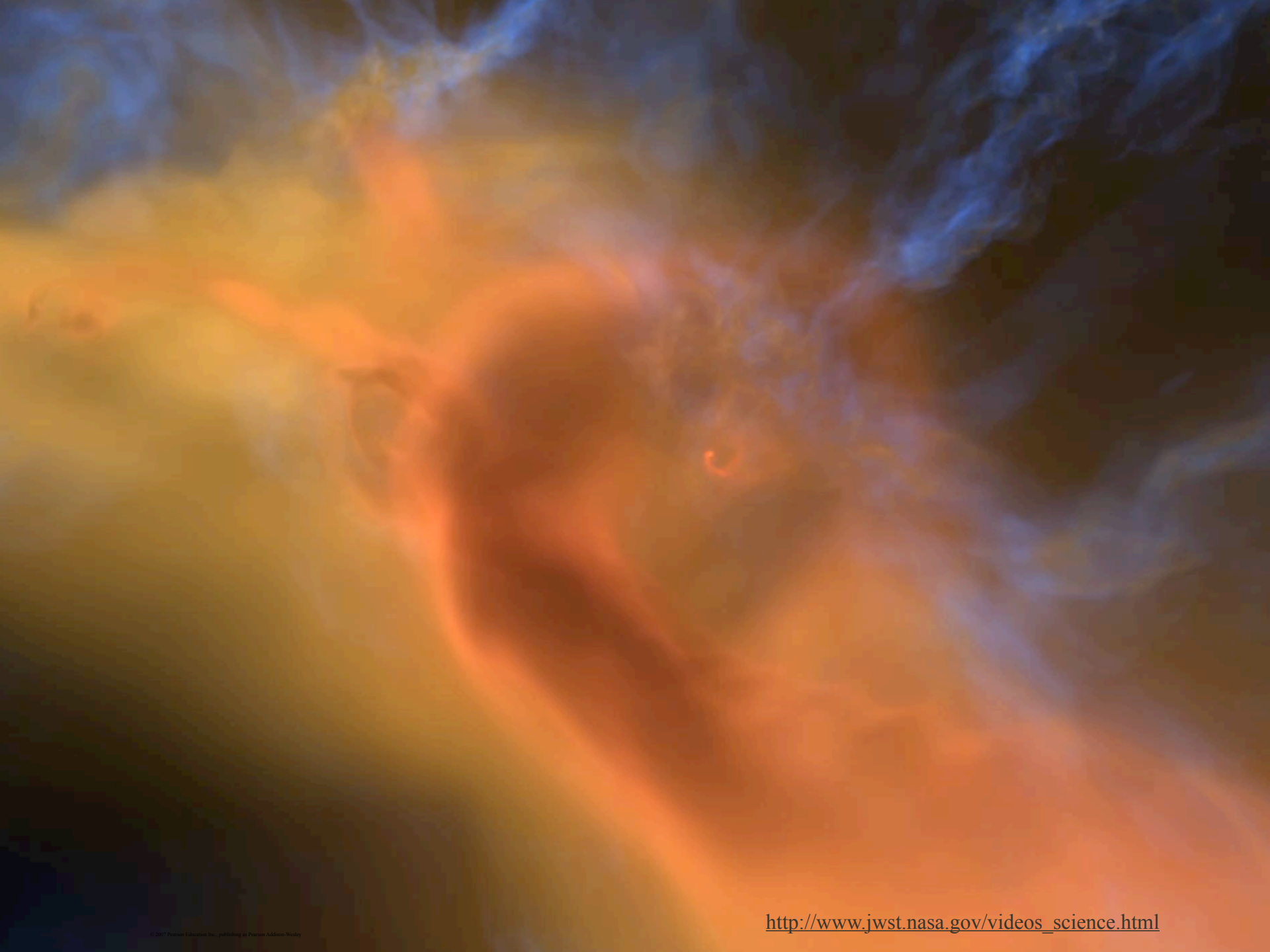
Infrared Light

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

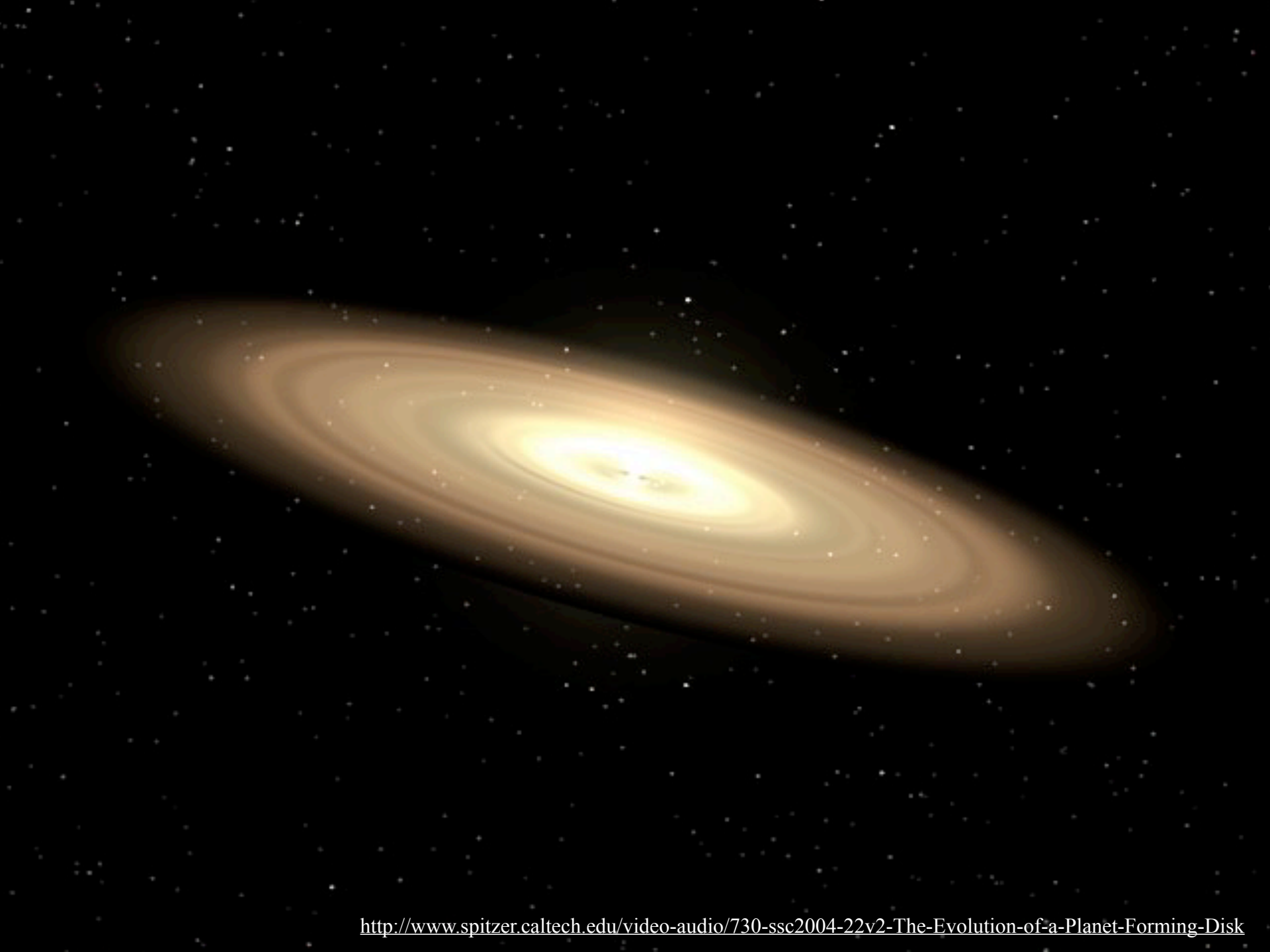




- Nebula spins up as it collapses (angular momentum conserved)
- Solid particles condense out of gas
- Particles collide; form ever larger objects
- Most mass eventually swept up into planets

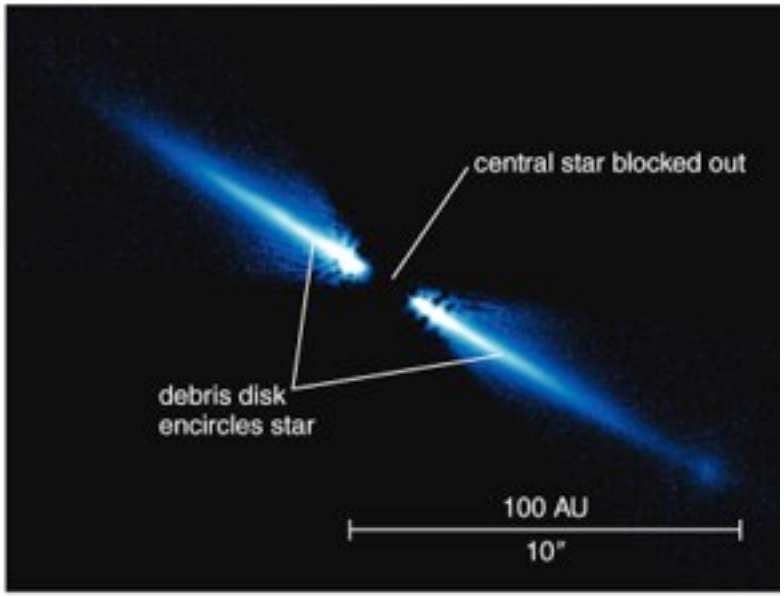


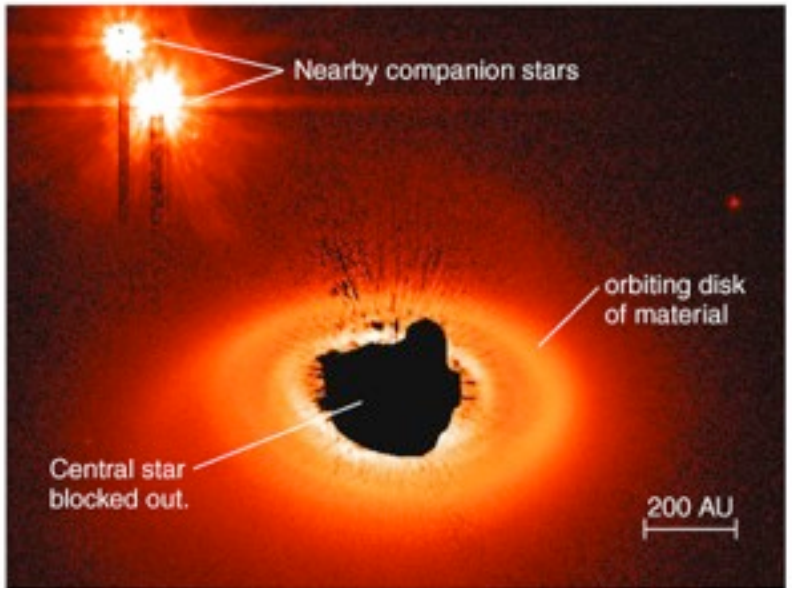
http://www.jwst.nasa.gov/videos_science.html



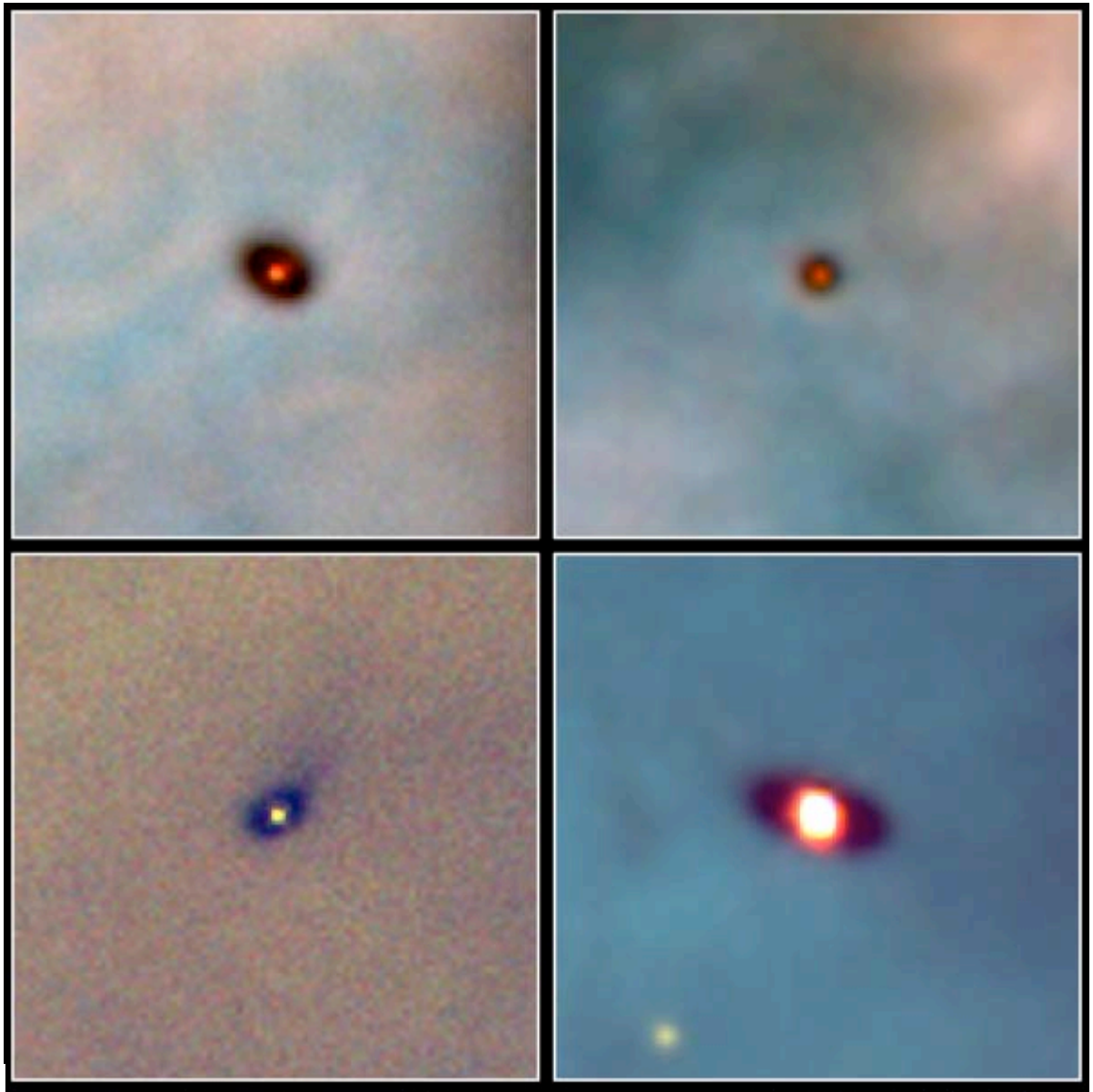
http://www.spitzer.caltech.edu/video-audio/730-ssc2004-22v2-The-Evolution-of-a-Planet-Forming-Disk

Disks Around Other Stars





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

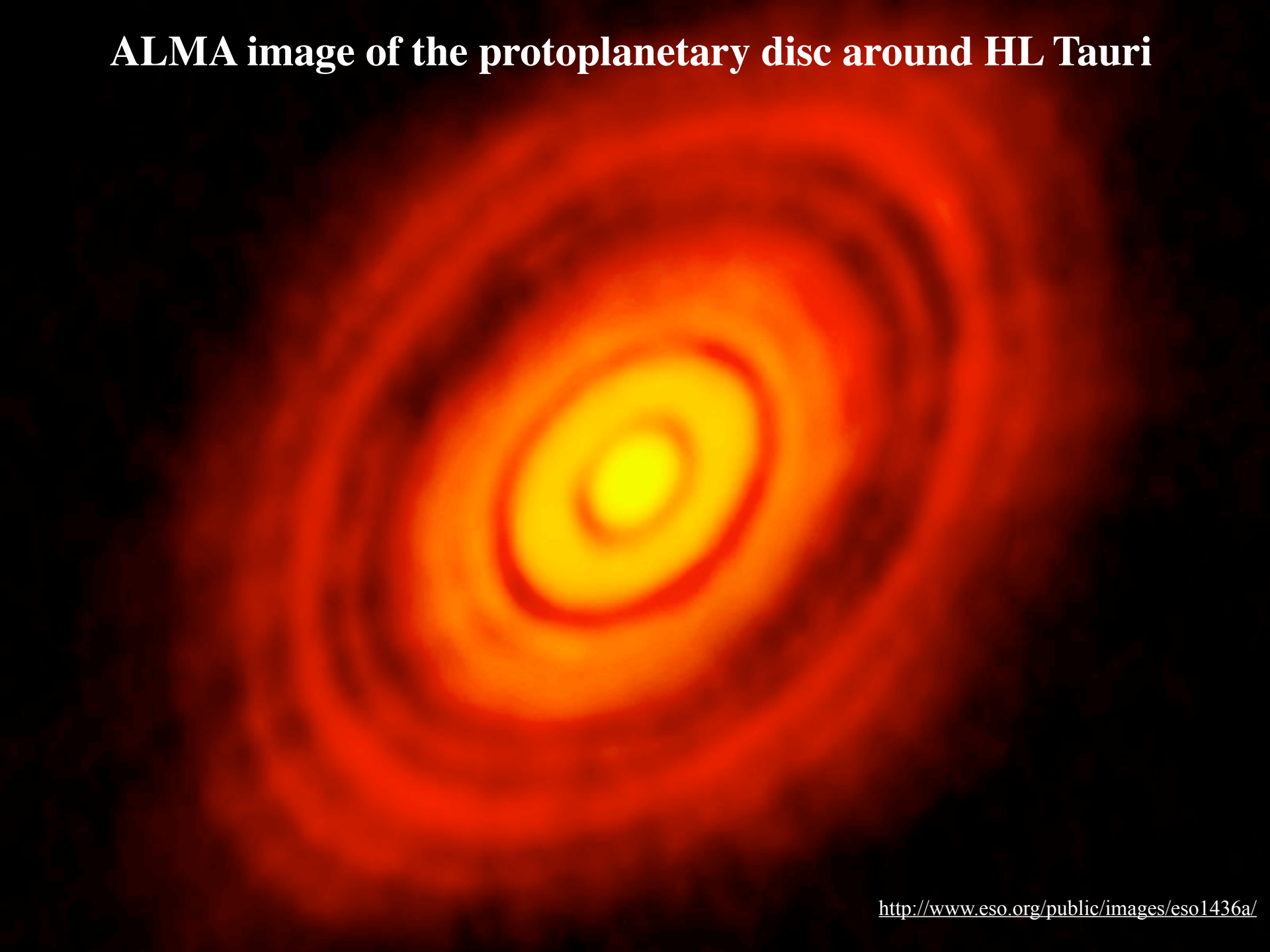


Protoplanetary Disks
Orion Nebula

HST • WFPC2

PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

ALMA image of the protoplanetary disc around HL Tauri



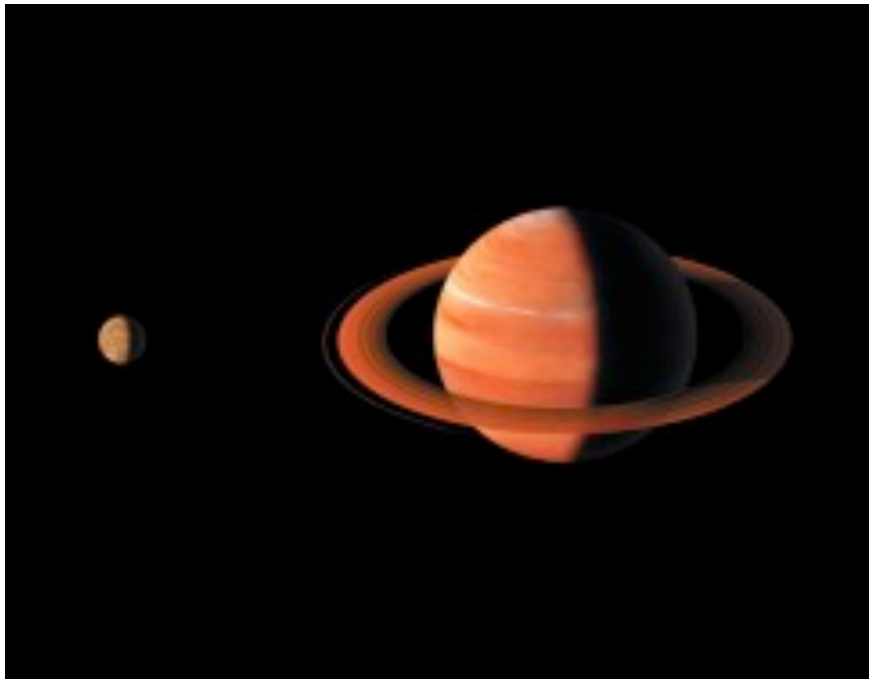
http://www.eso.org/public/images/eso1436a/

The Formation of Planets

Our goals for learning:

- Why are there two major types of planets?
- Where did asteroids and planets come from?
- Do we explain the existence of the Moon and other exceptions to the rules?
- When did the planets form?

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%

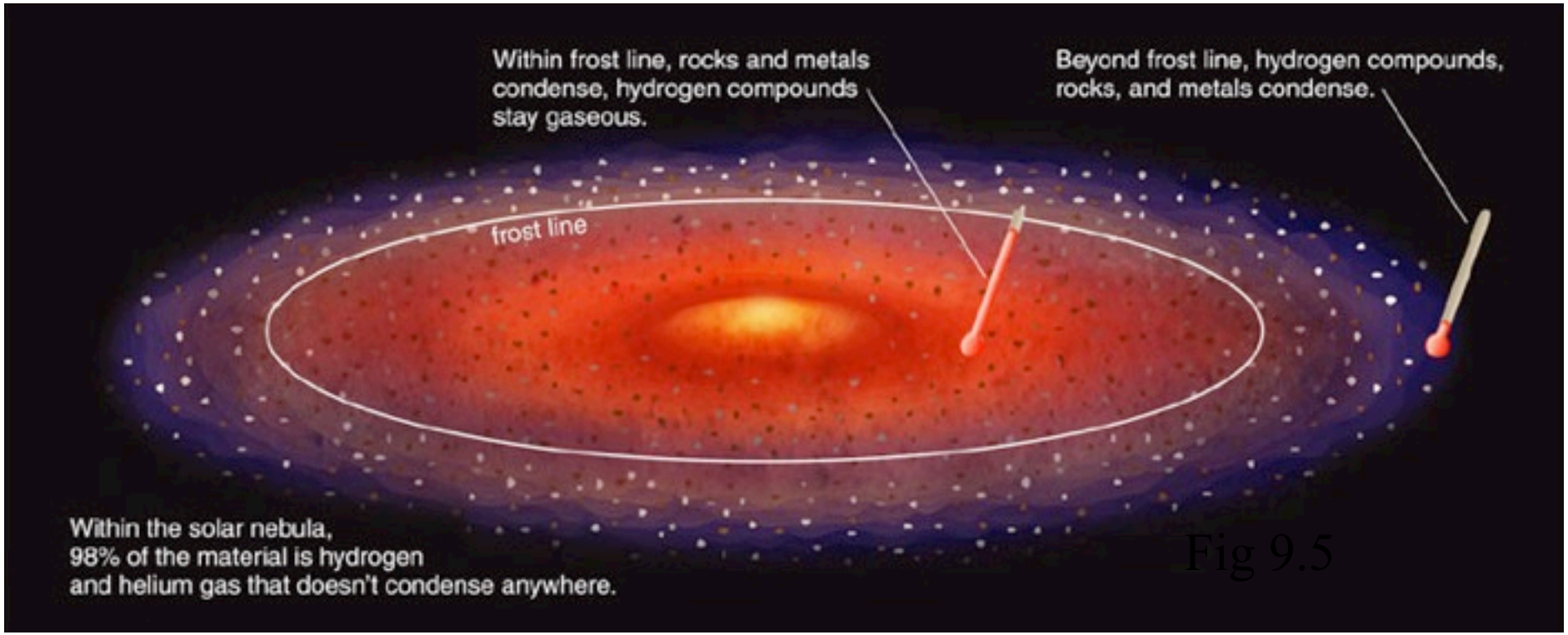


Fig 9.5

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.

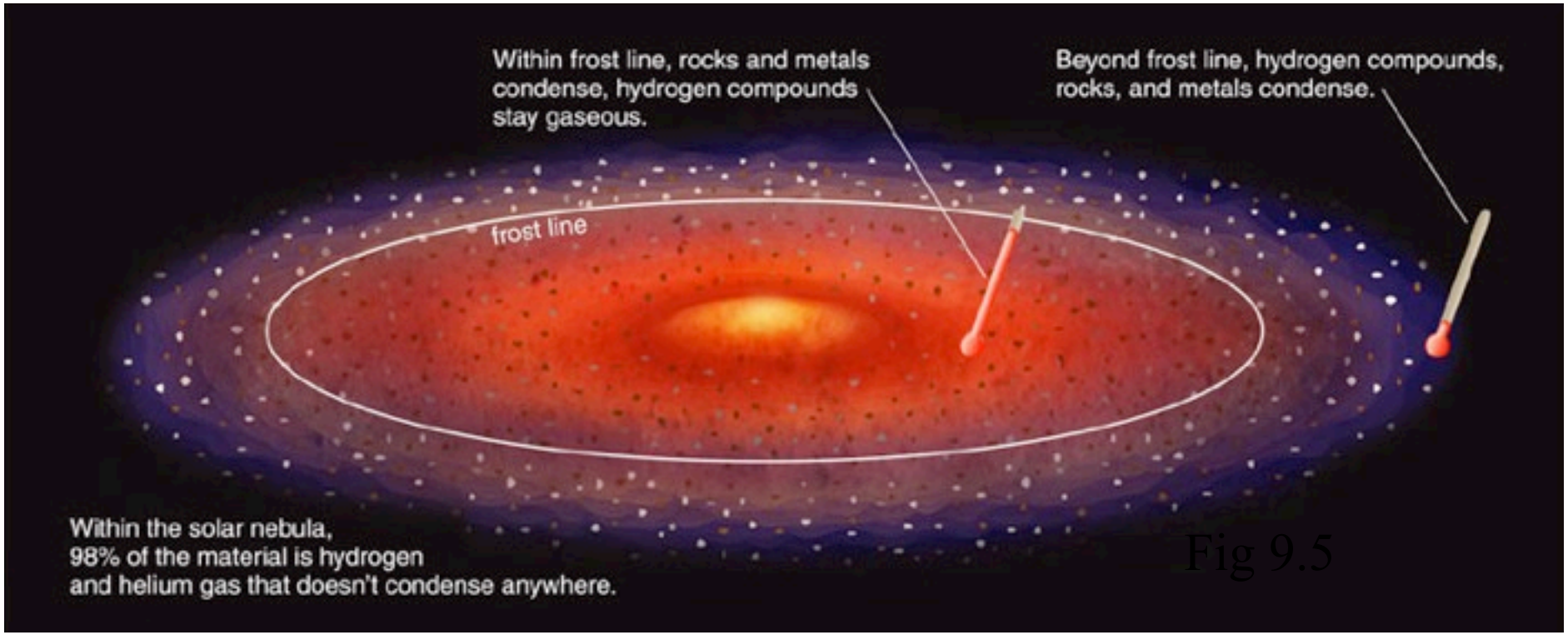


Fig 9.5

<u>FROST LINE</u> <u>at about 3.5 AU</u>

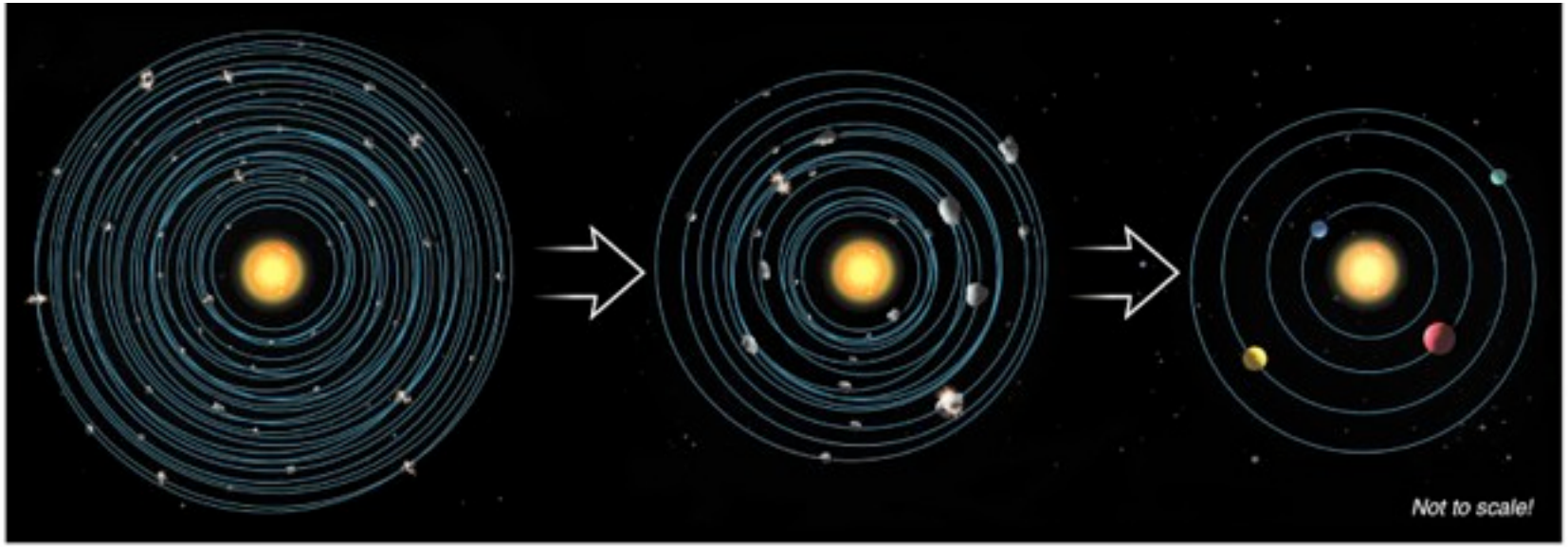
Inside the ***frost line***: Too hot for hydrogen compounds to form ices
- only get rocky asteroids and planets

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.

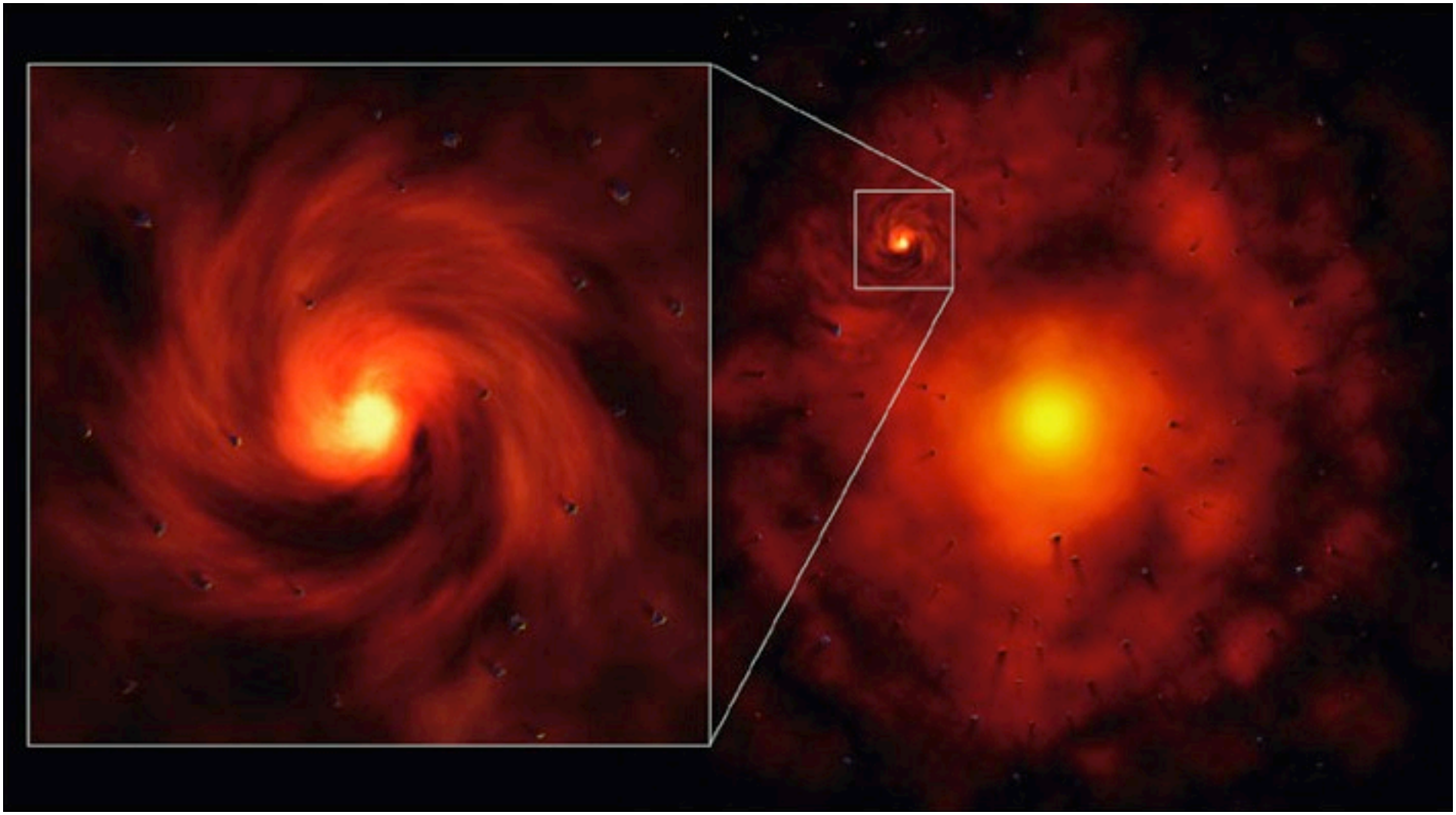
Accretion of Planetesimals



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

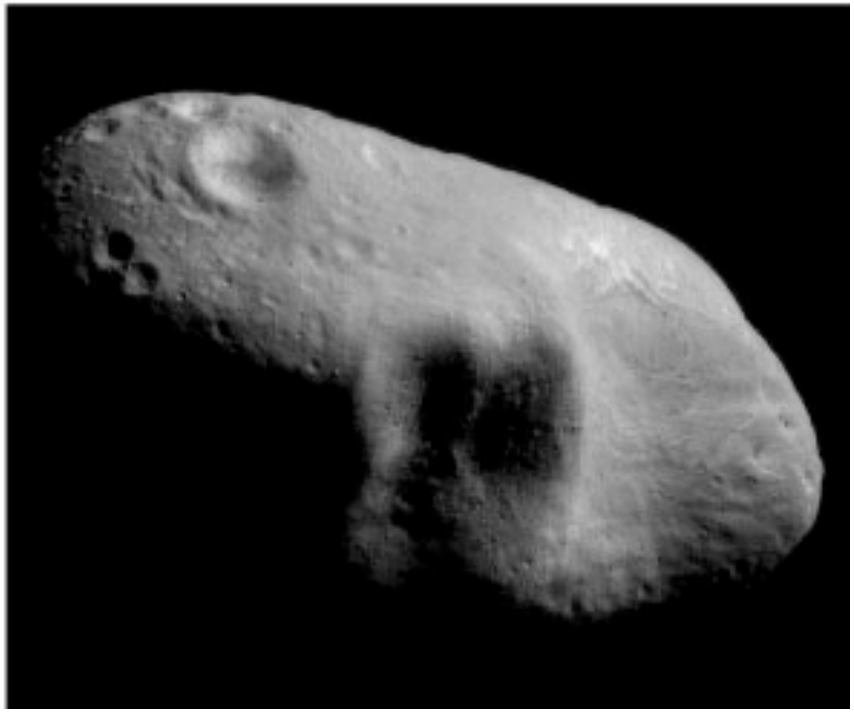
Formation of Jovian Planets

- 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.

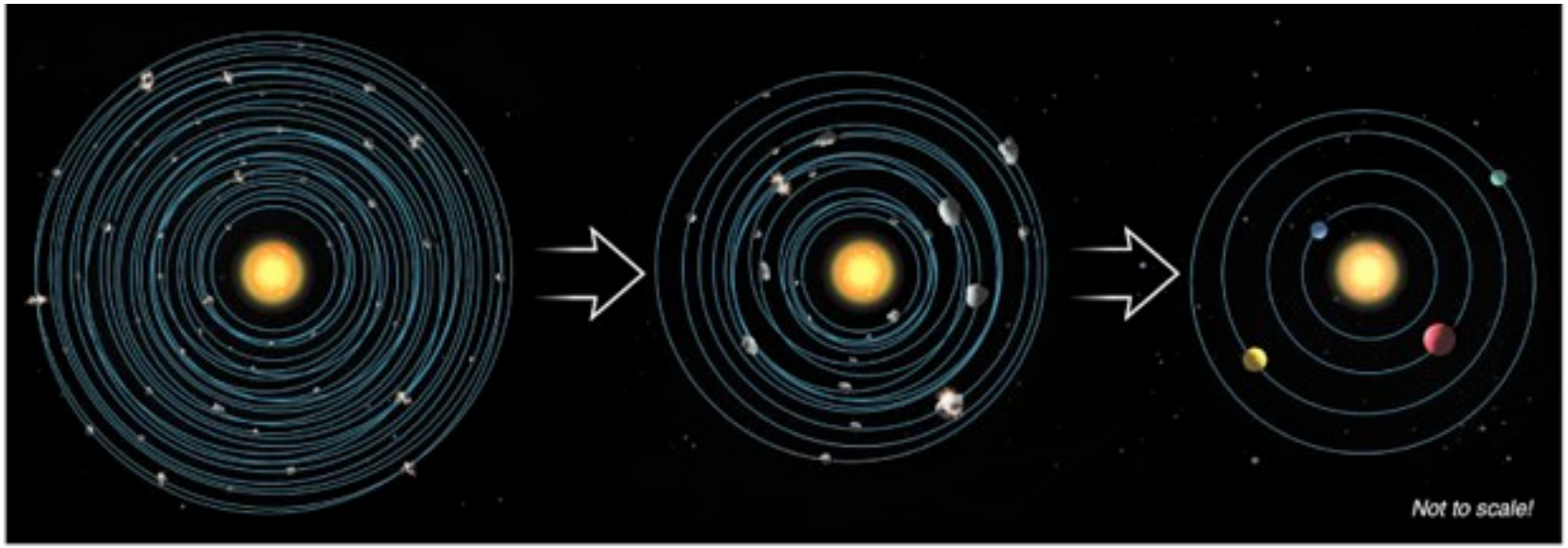


Moons of jovian planets form in miniature disks - like microcosms of the solar nebula.

Where did asteroids and comets come from?

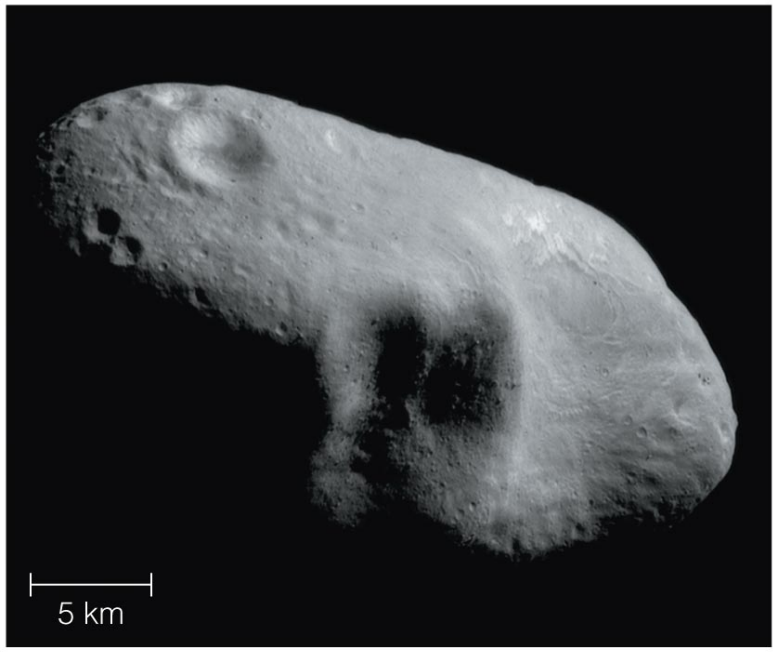


Asteroids and Comets



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

Asteroids



Inside the “frost line”, small rocky planetesimals exist as asteroids.

Jupiter’s gravitational tugs kept them from accreting into a bigger planet, so they remain in the asteroid belt.

Comets

Beyond the “frost line”, lots of icy planetesimals remain. These are the comet nuclei.

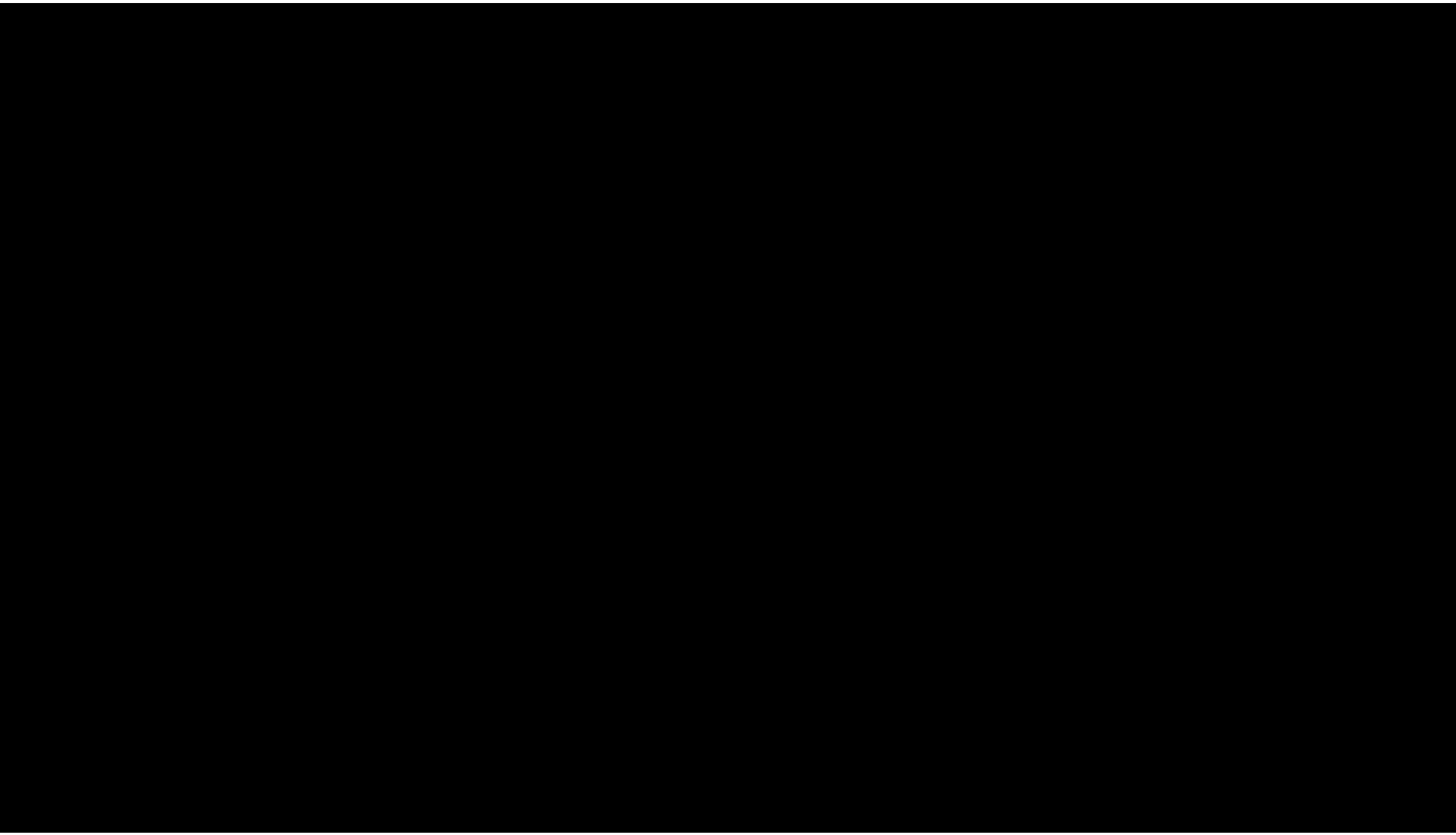
Comet nuclei beyond Neptune’s orbit remain in the flattened Kuiper Belt.

Comet nuclei originally near the orbits of the big planets (Jupiter, Saturn, Uranus, and Neptune) got kicked out into the far distant Oort Cloud by those planets’ gravity.

Heavy Bombardment

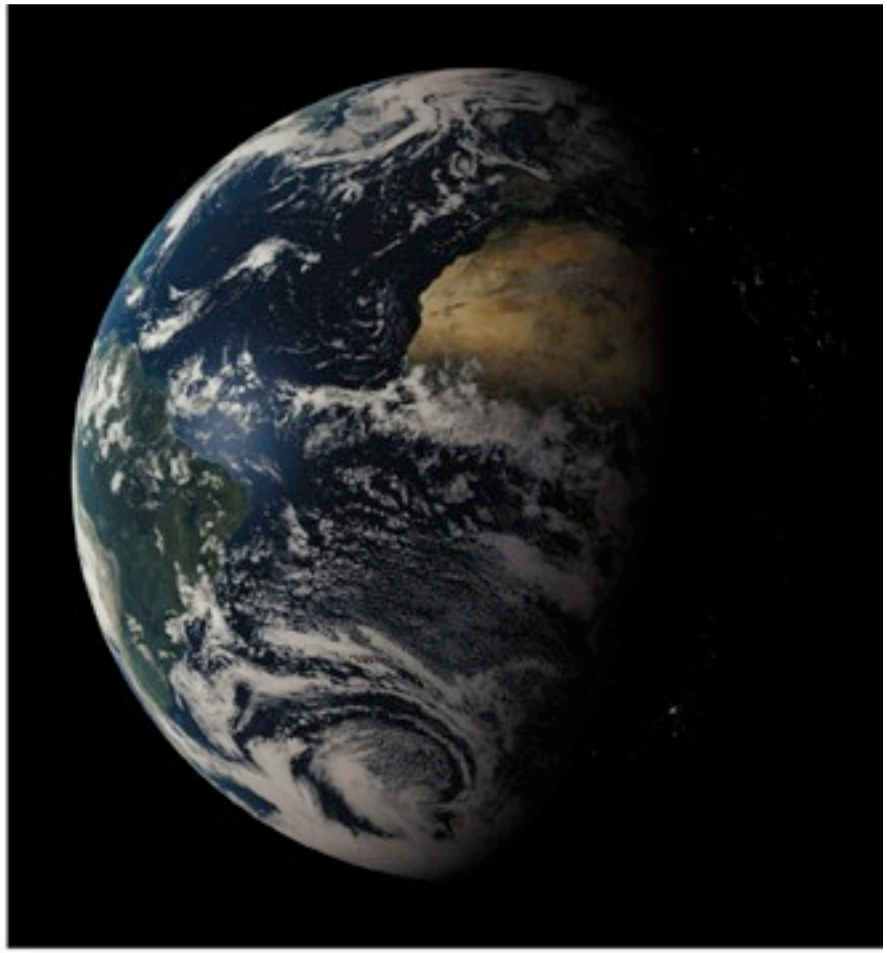
- Leftover planetesimals bombarded other objects in the late stages of solar system formation.

Cratering movie



http://svs.gsfc.nasa.gov/cgi-bin/details.cgi?aid=10930#

Origin of Earth's Water

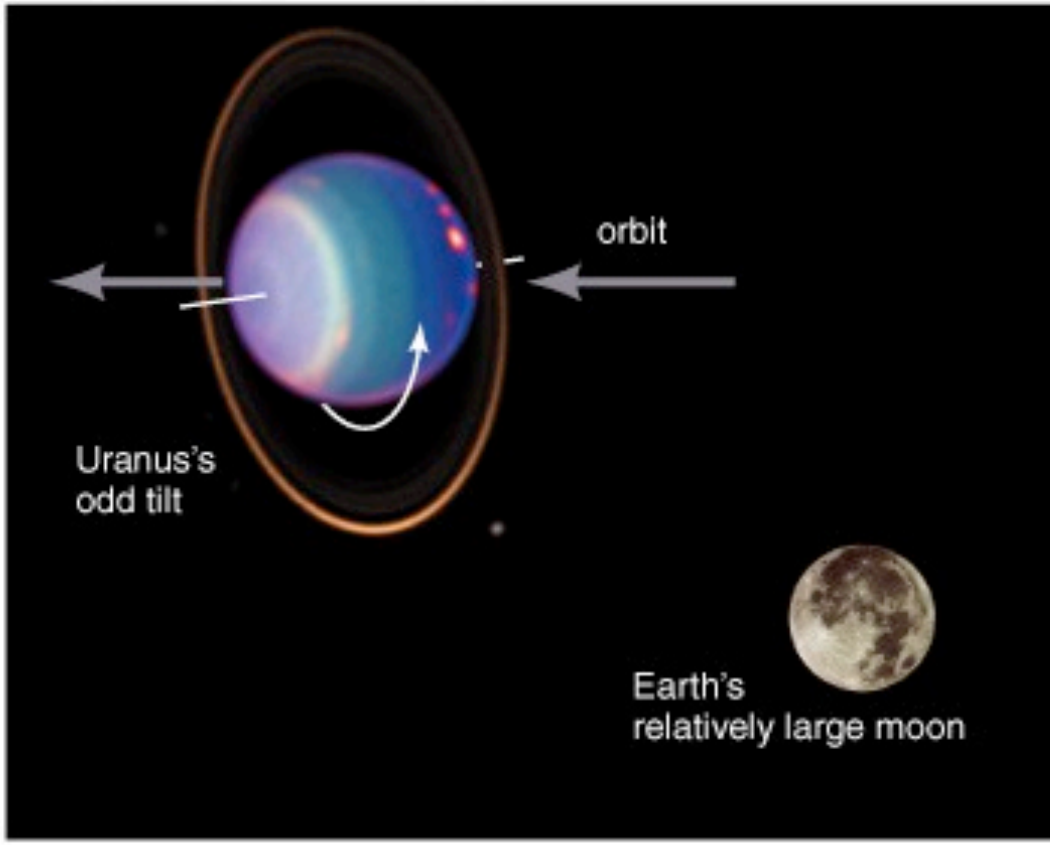


- Water may have come to Earth by way of icy planetesimals from the outer solar system.

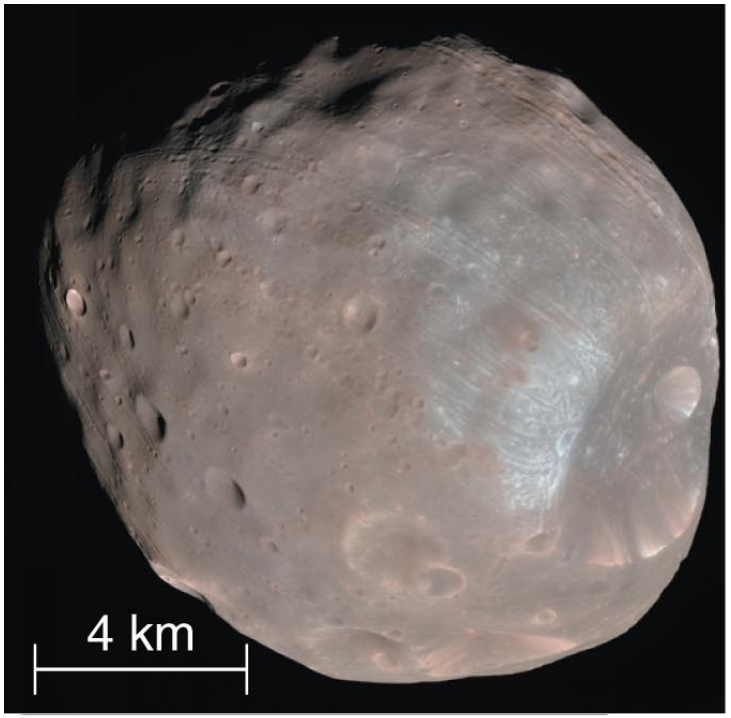
What about the exceptions?

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

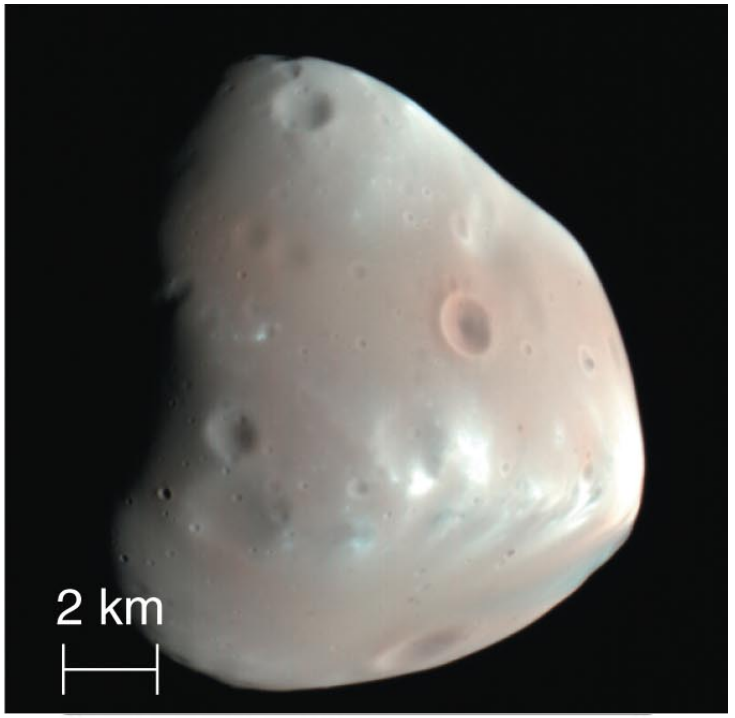
Thought to be due to the last big collision.



Captured Moons



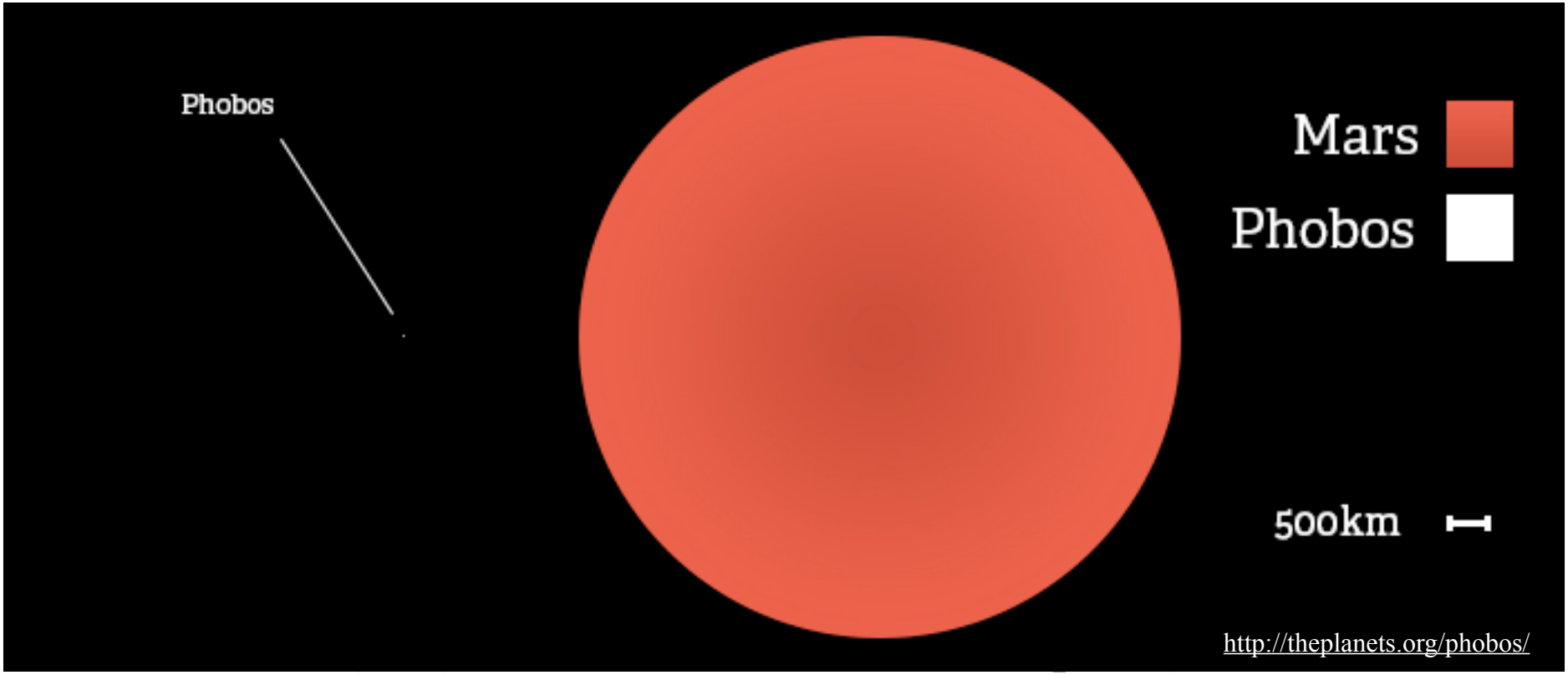
Phobos (fear)



Deimos (panic)

- The unusual moons of Mars and some other planets may be captured asteroids.
- left over planetesimals?

Captured Moons



- The unusual moons of Mars and some other planets may be captured asteroids.
- left over planetesimals?

Formation of our Moon

Earth's moon: Giant Impact?

Earth’s moon: Giant Impact?

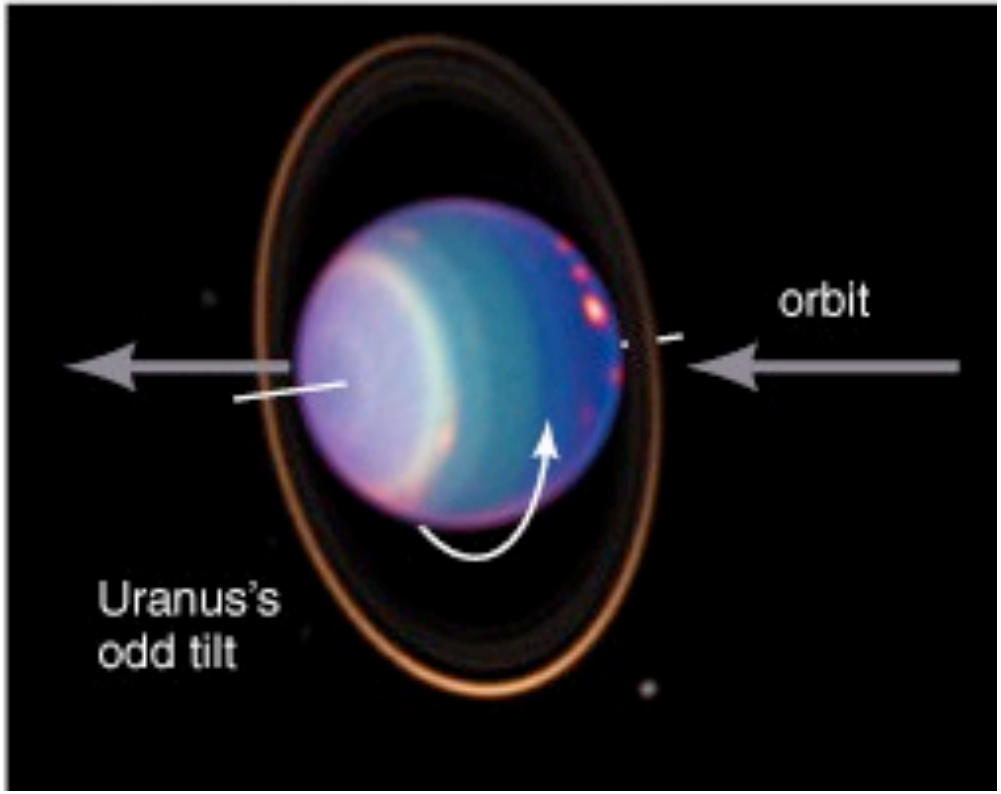
Robin M. Canup
http://www.boulder.swri.edu/~robin/

Evidence for Giant Impact

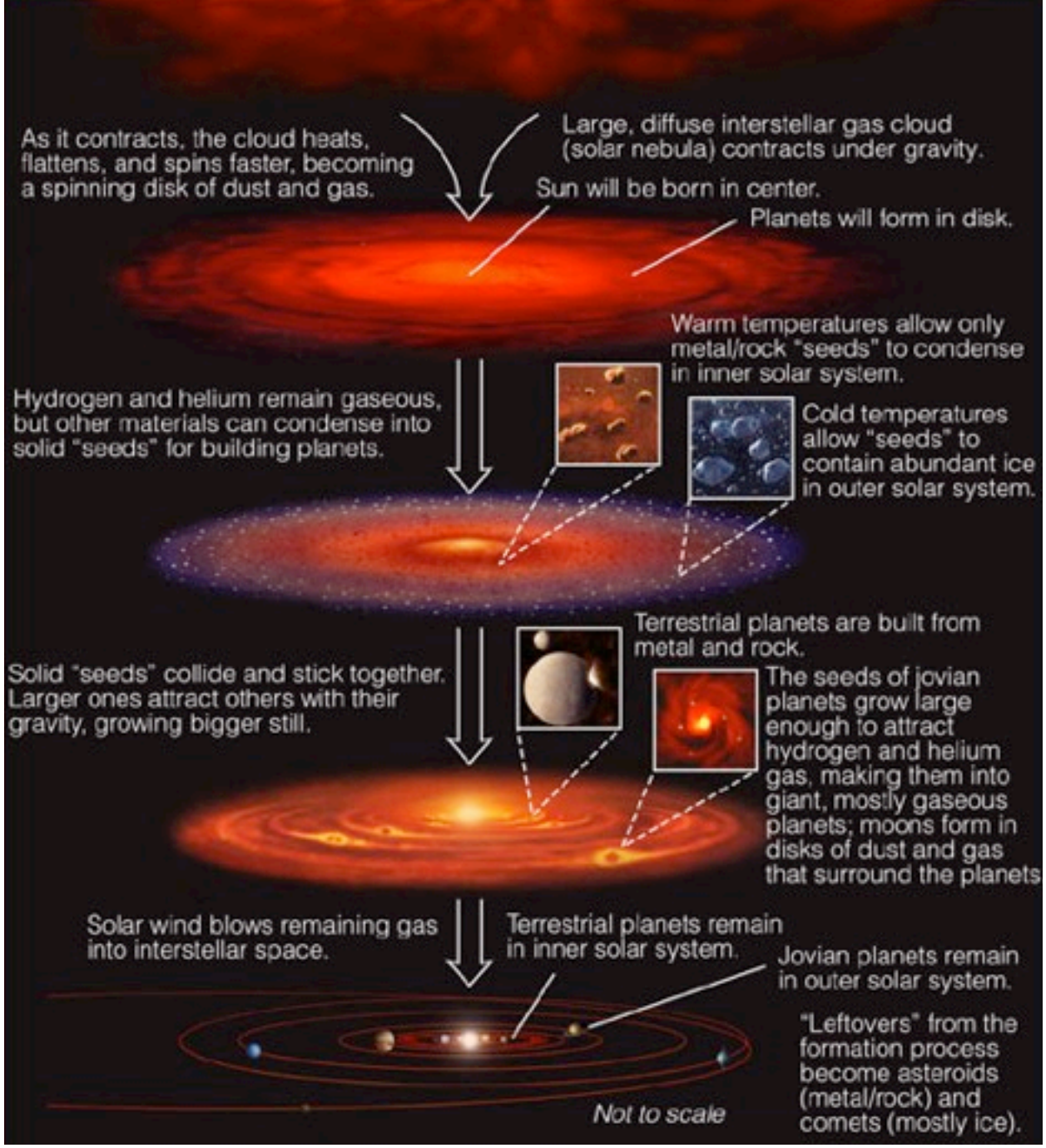
Sounds kind of crazy – why couldn't the Moon just have formed the same way the Earth did?

1. Composition of the Moon is similar to that of the Earth's mantle (its outer layers) but unlike the Earth, it lacks a massive iron core.
2. There is scarcity of volatiles in the Moon – compounds like water, which are easily vaporized at high temperatures.

Odd Rotation



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

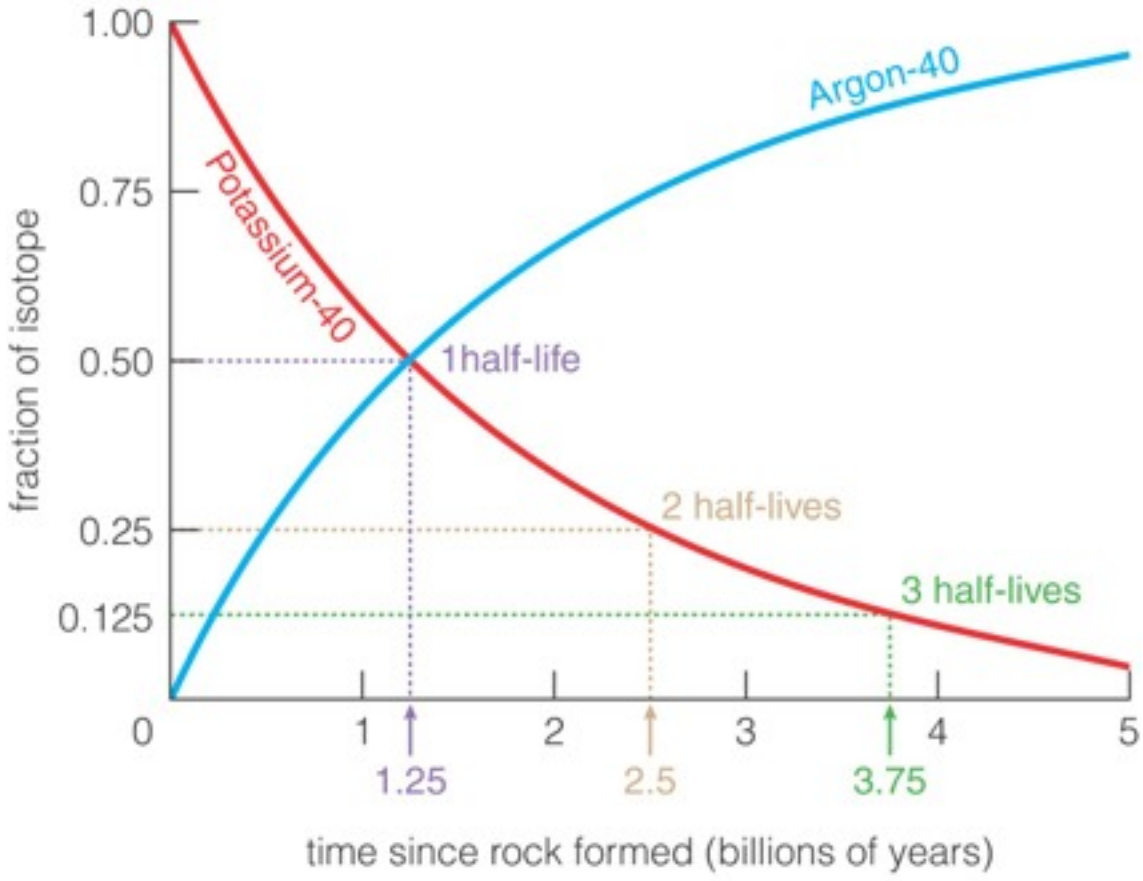


- Nebula spins up as it collapses (angular momentum conserved)
- Solid particles condense out of gas
- Particles collide; form ever larger objects
- Most mass eventually swept up into planets

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.

Dating the Solar System

- Radiometric dating tells us that the oldest moon rocks are 4.4 billion years old.
- The oldest meteorites are 4.5 billion years old.
- This dates the age of the solar system to about 4.5 billion years.

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.