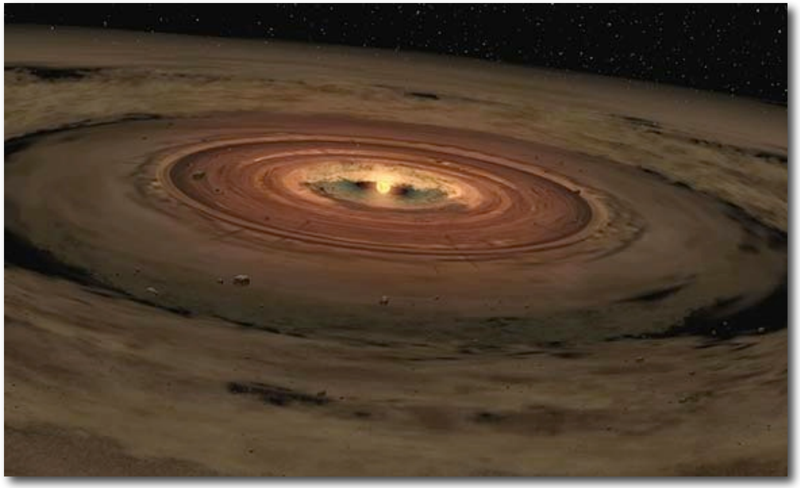
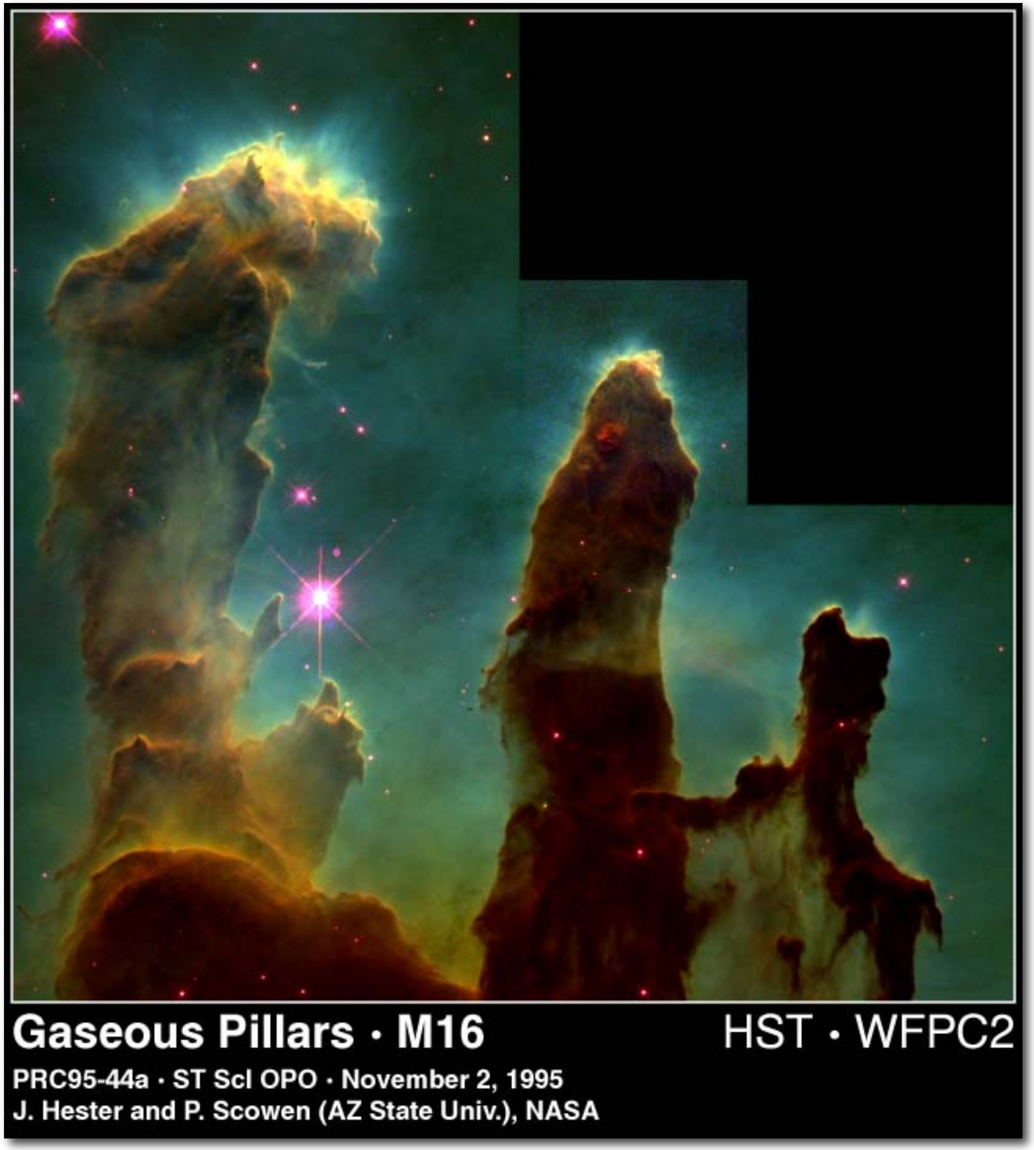
Solar System/Planet Formation

Read chapter 13!!





Solar System Formation: Constraints

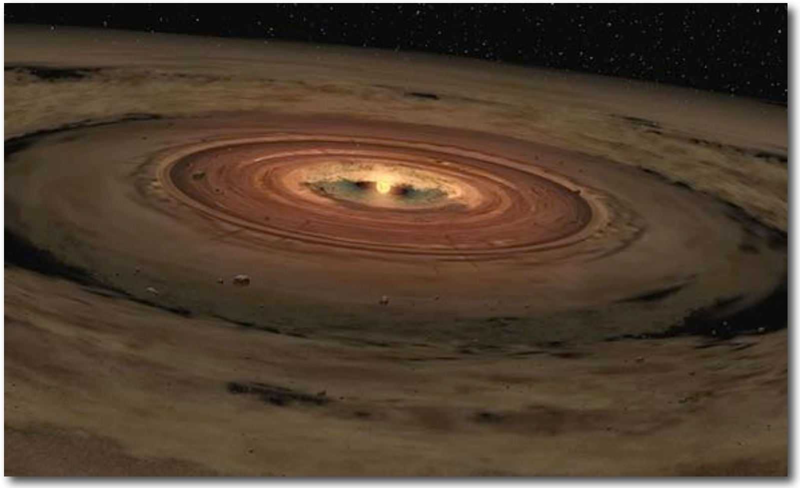
- Sun has 99.8% of mass, <2% of angular momentum
- Low inclination & eccentricity of planet orbits
- Most planets have low obliquity
- Large outer planets have ~solar composition
- Small inner planets enriched in heavy elements
- Impact craters on virtually every planetary body
- “Debris” in asteroid belt, Kuiper belt
- Meteorites have common age: ~4.6 Ga
- Oldest Moon rocks ~4.36 – 4.5 Ga

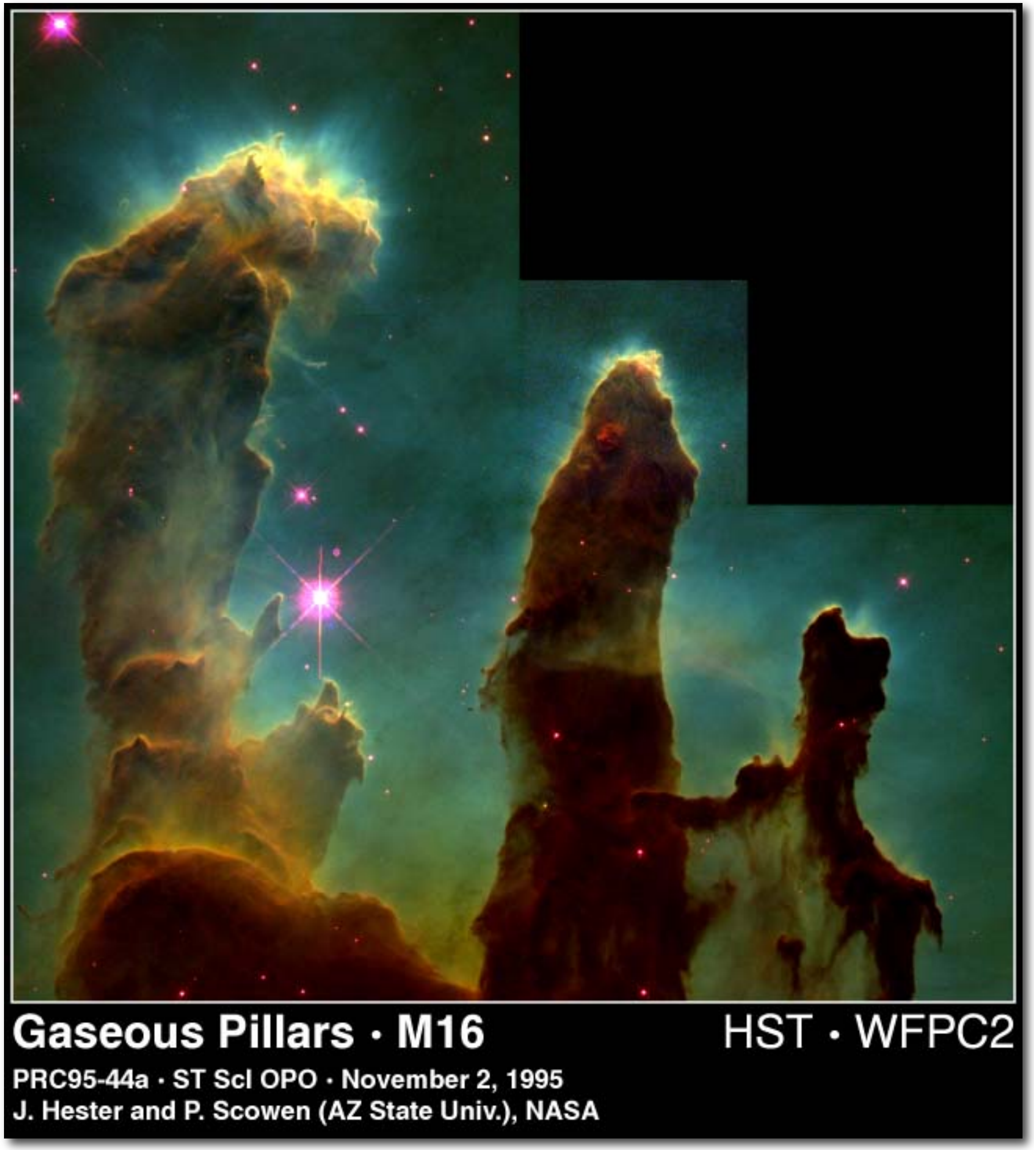
Solar System/Planet Formation

Gas Clouds to Stars/Planets

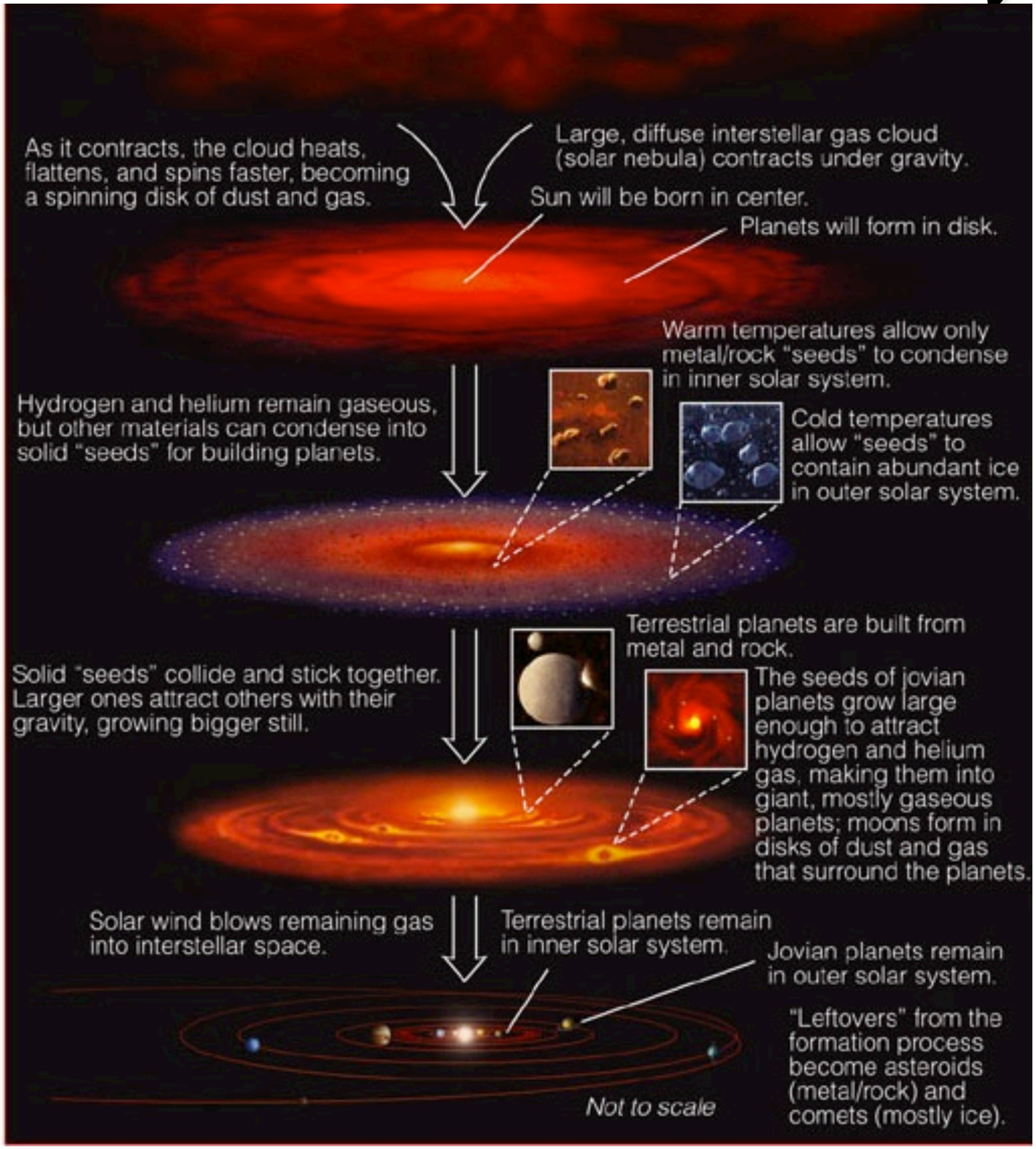
Planet Migration

Satellite Formation

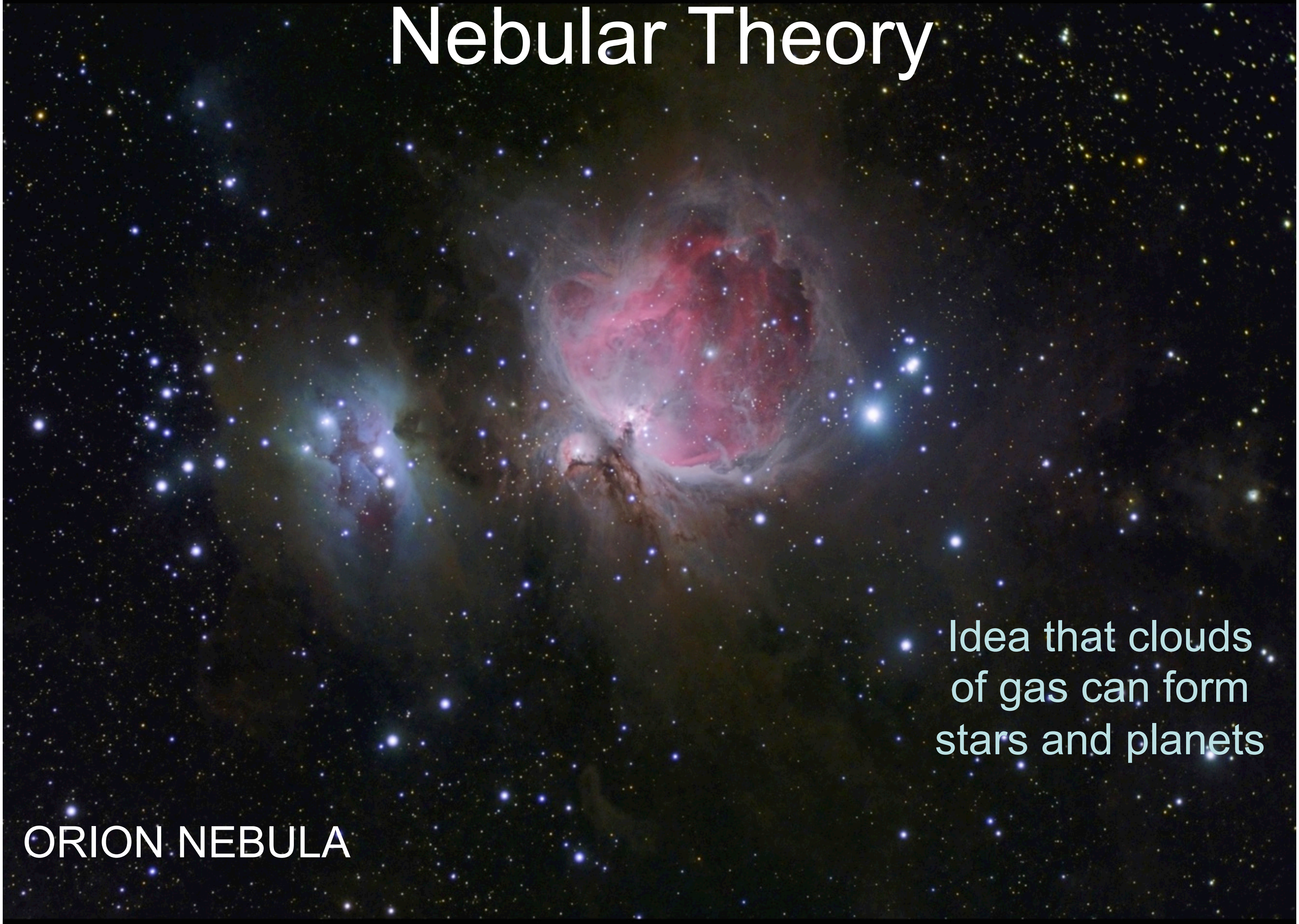




The Formation of the Solar System



Nebular Theory



Starting Conditions

Giant Molecular Clouds:

- COLD (10-30 K)
- LARGE (10^2s of light-years across, 10^6 M_{Sun})
- CHEMISTRY:

  98% H and He

  1.4% "ices"

  0.4% "rock"

  0.2% metal

*Cloud probably needs to be "nudged" to start forming stars

ORION NEBULA

Formation of the Solar System

STEPS:	EVIDENCE:
CLOUD COLLAPSE	•young stars seen in collapsing gas clouds
ROTATING DISK	•planets orbit in same direction and same plane •Sun and planets rotate in same direction •disks seen around other stars
CONDENSATION	•terrestrial planets and asteroids found near Sun •jovian planets, icy moons, comets found farther away
ACCRETION	•many meteorites are made of smaller bits •heavy cratering on oldest planet surfaces •asteroids, comets are “leftovers”
GAS CAPTURE?	•Jupiter, Saturn are mostly hydrogen and helium

Formation of the Solar System

STEPS:

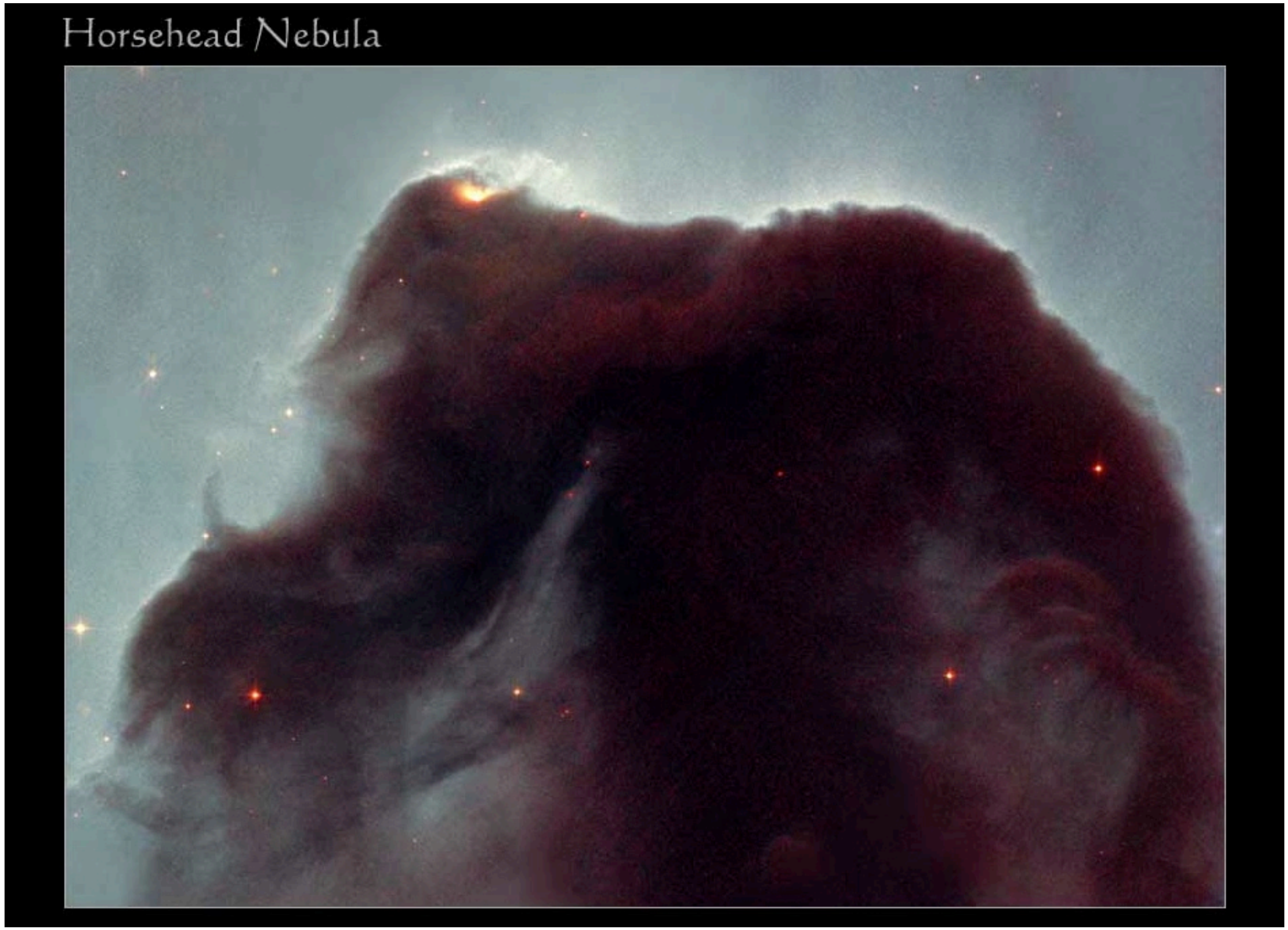
CLOUD COLLAPSE

Considering only gravity:

$$t_{\rm ff}^{1} = \sqrt{\frac{3\pi}{32 G \rho_{\rm cl}}}$$

EVIDENCE:

- young stars seen in collapsing gas clouds



Formation of the Solar System

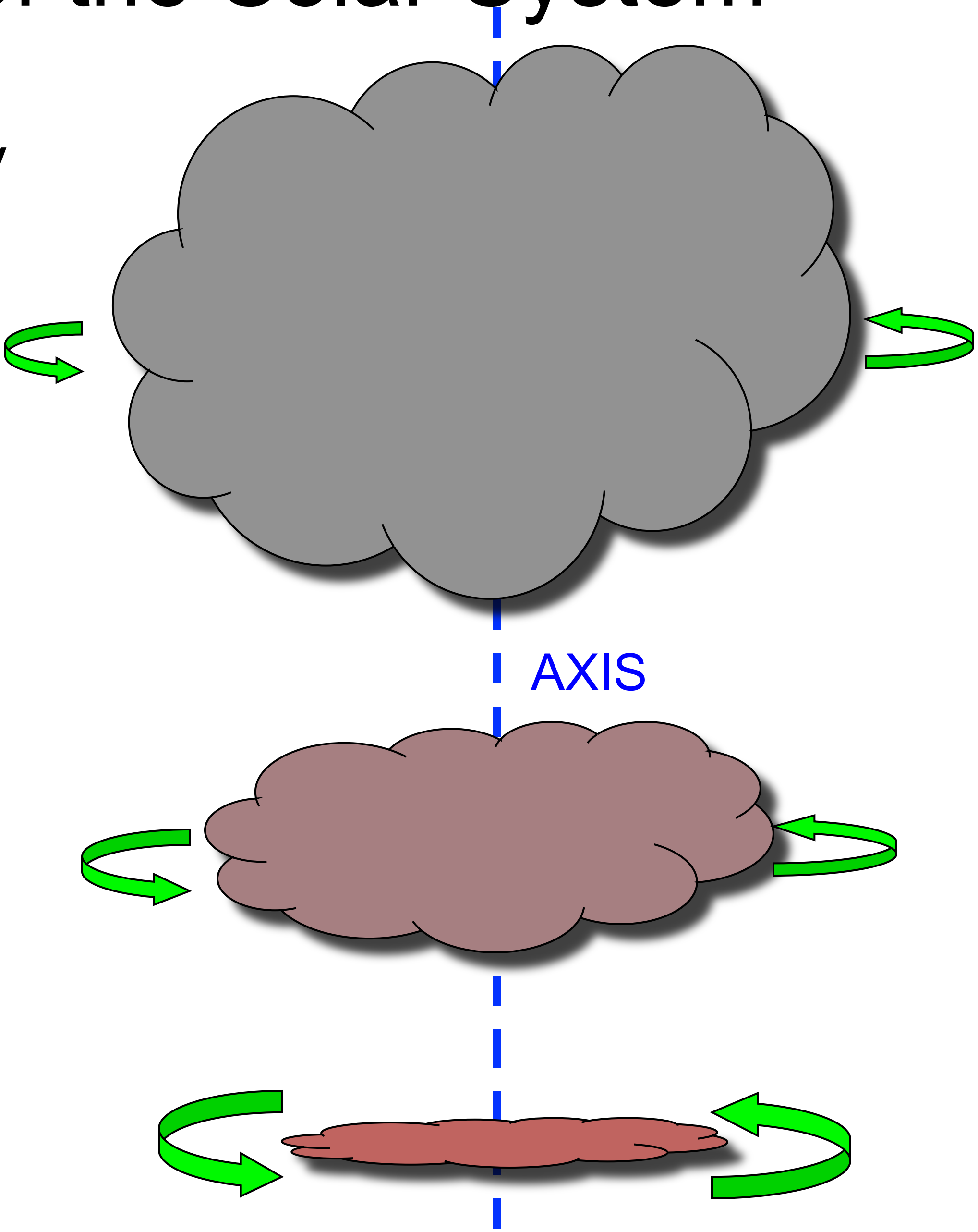
Cloud starts out with a tiny rotation…

CONSERVATION OF ANGULAR MOMENTUM:

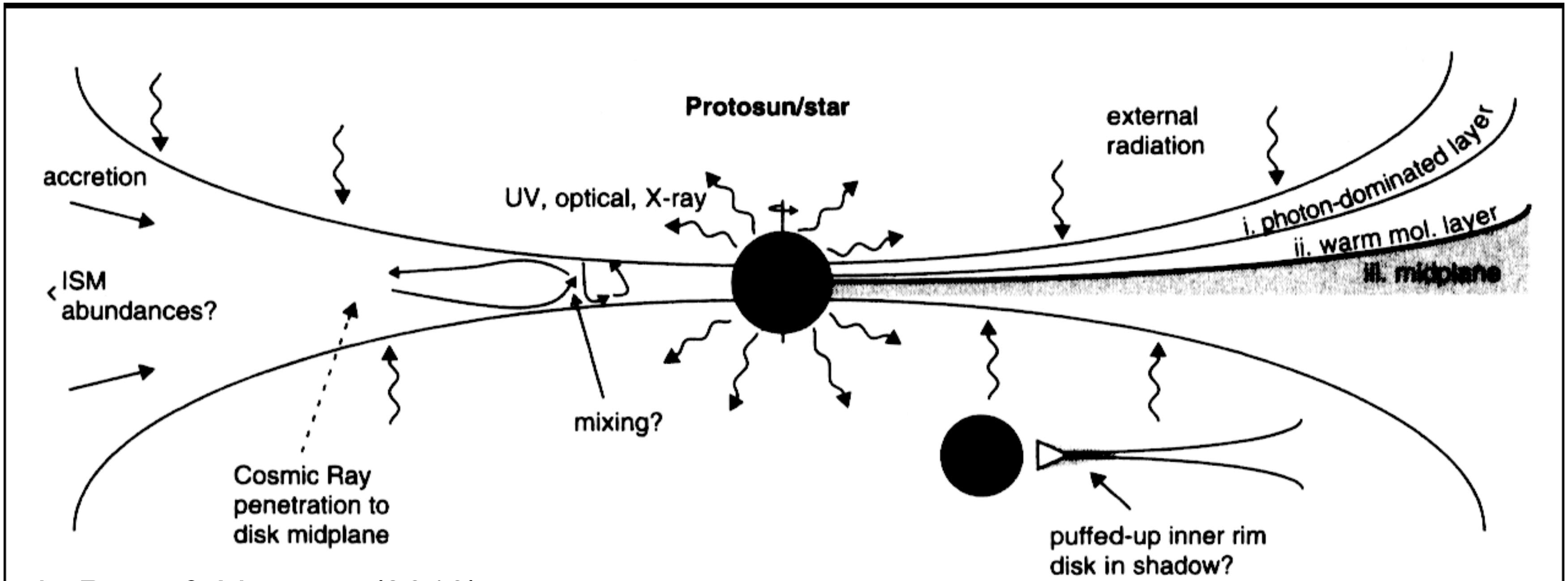
Gas falling toward axis starts rotating faster

Gas falling parallel to axis doesn't rotate faster

Fast rotation helps some gas orbit around center



Formation of the Solar System: Flared Disk



de Pater & Lissauer (2010)

$$\rho_{g_z} = \rho_{g_{z_0}} e^{-z^2/H_z^2}, \tag{13.10a}$$

$$P_z = P_{z_0} e^{-z^2/H_z^2}, \tag{13.10b}$$

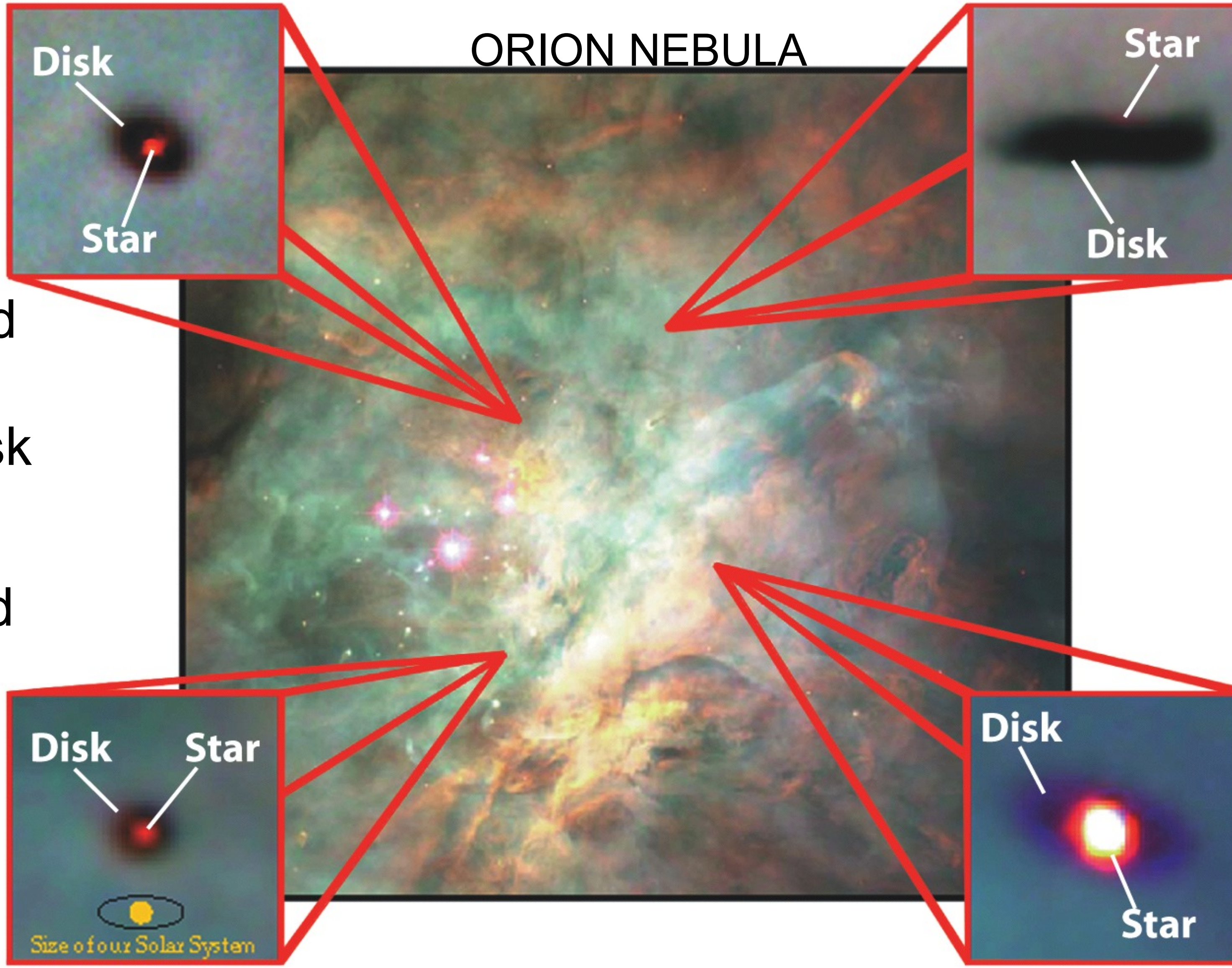
where the Gaussian scale height, H_z, is given by:

$$H_z = \sqrt{\frac{2kTr_\odot^3}{\mu_a m_{amu} G M_\odot}}. \tag{13.11}$$

The Rotating Disk

Part of cloud becomes flattened disk

Examples seen around other stars



Bipolar Outflows: An HST Film

http://n.pr/oimi5j

Formation of the Solar System

STEPS:

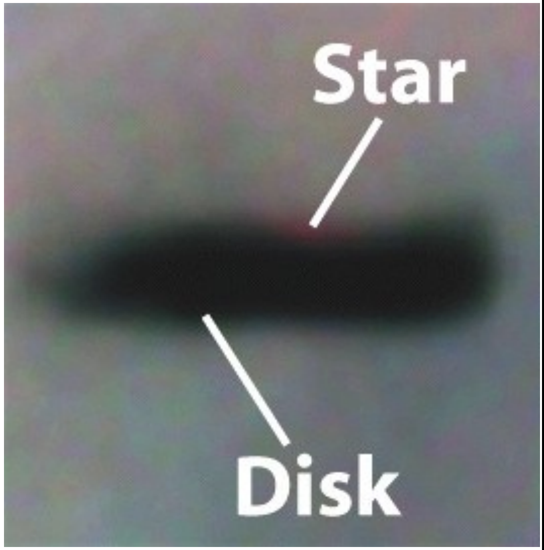
CLOUD COLLAPSE

↓

ROTATING DISK

EVIDENCE:

- young stars seen in collapsing gas clouds
- planets orbit in same direction and same plane
- Sun and planets rotate in same direction
- disks seen around other stars

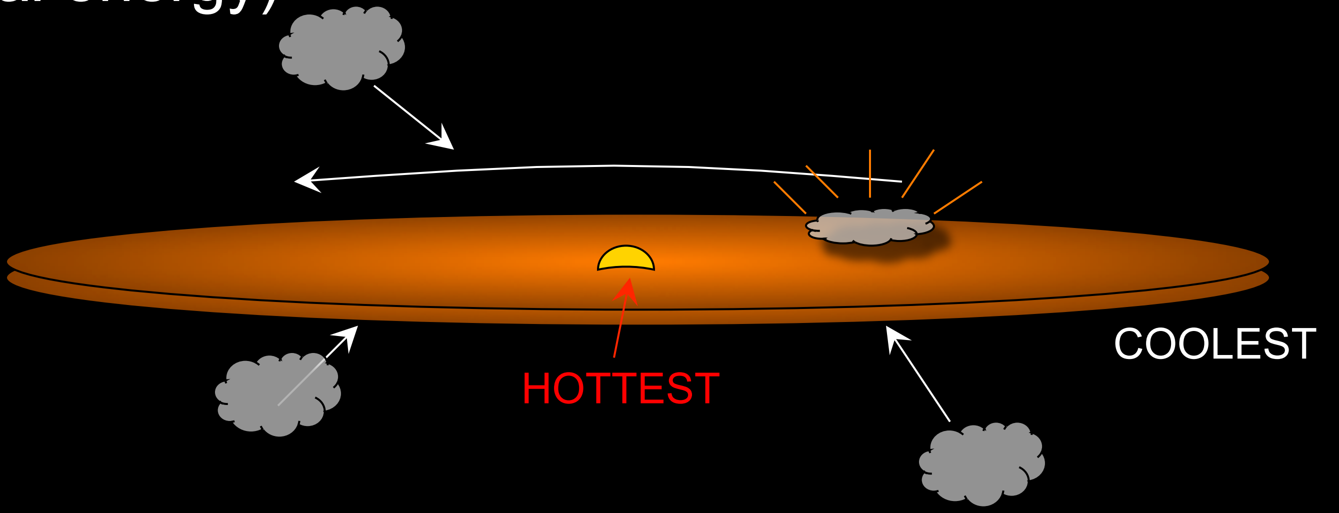


Heating

CONSERVATION OF ENERGY:

As gas undergoes collisions, it heats up…

(kinetic --> thermal energy)



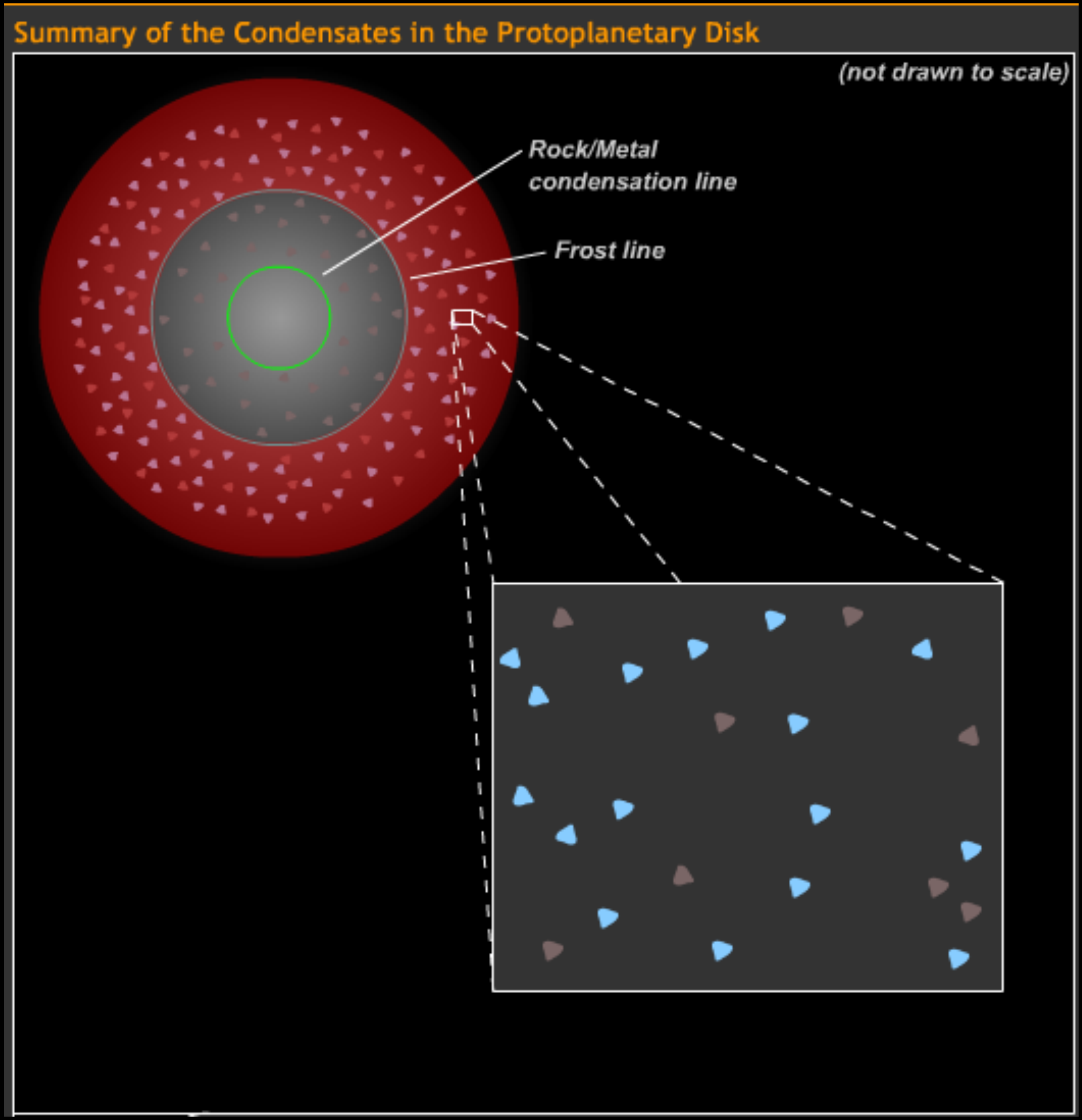
The center of disk gets hottest

Raw Materials for 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%

The most abundant raw materials:

1. H, He gases
2. “ices” (hydrogen compounds)
3. rock and metal



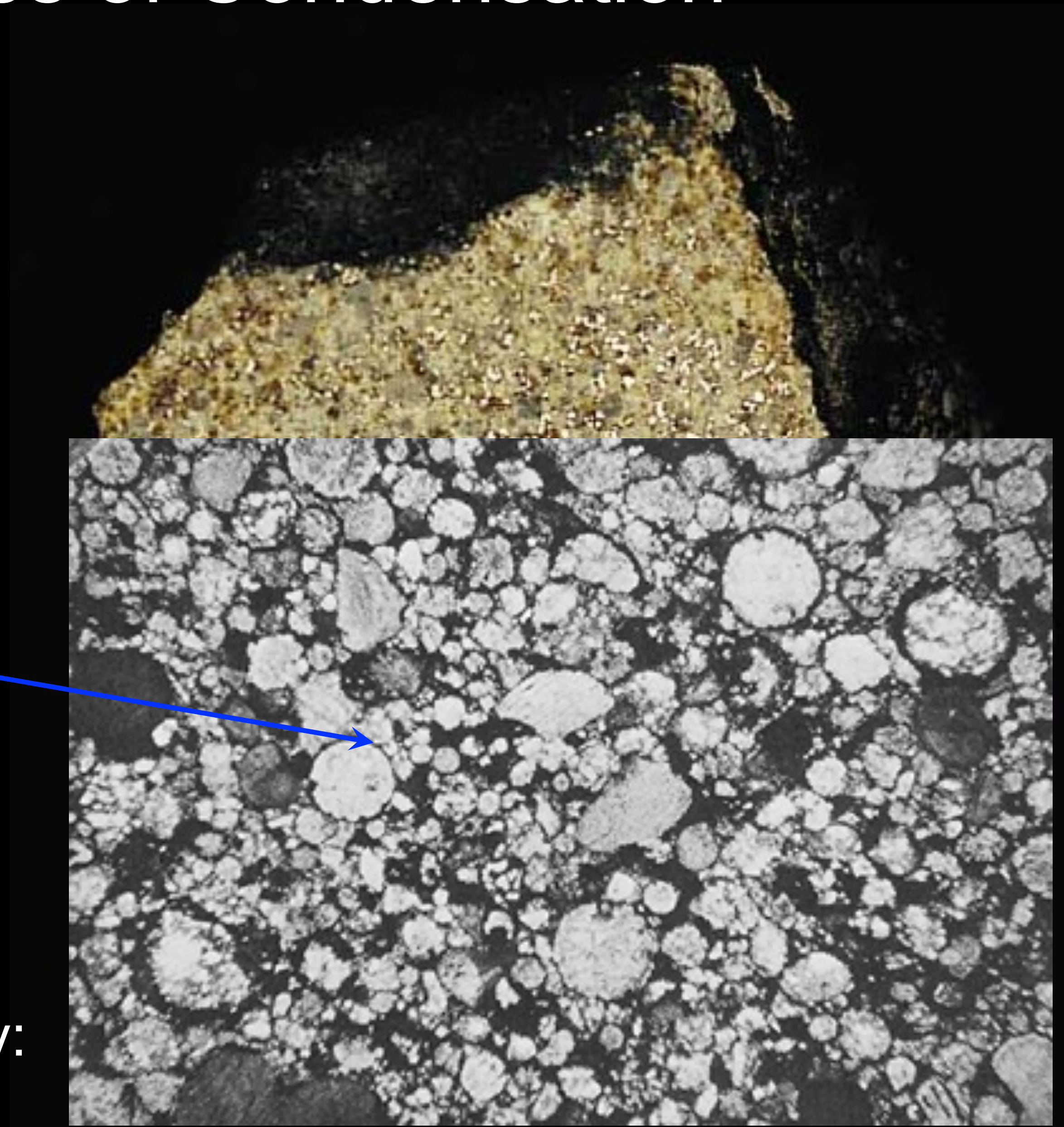
- Tiny ‘dirt’ particles formed from condensed rock/metal
- Tiny <u>ice crystals</u> condensed from hydrogen compounds like water… but ONLY far from Sun due to thermal gradient

Examples of Condensation

Inner solar system:

↔ rocky, metallic dust condensed together into small objects

meteorite cut-away:



Formation of the Solar System

STEPS:

CLOUD COLLAPSE

ROTATING DISK

CONDENSATION

EVIDENCE:

Cloud collapse:

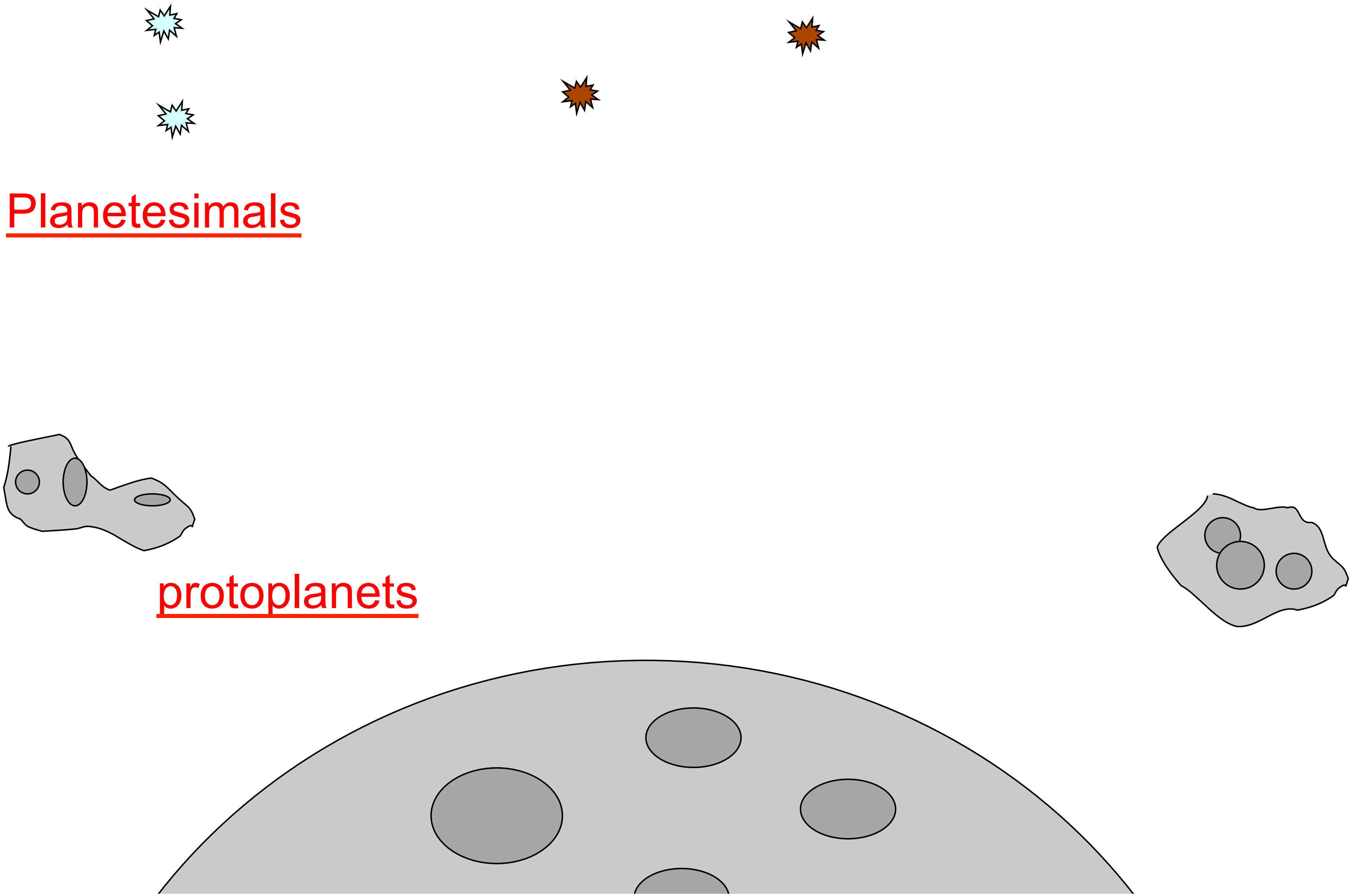
- young stars seen in collapsing gas clouds

Rotating disk:

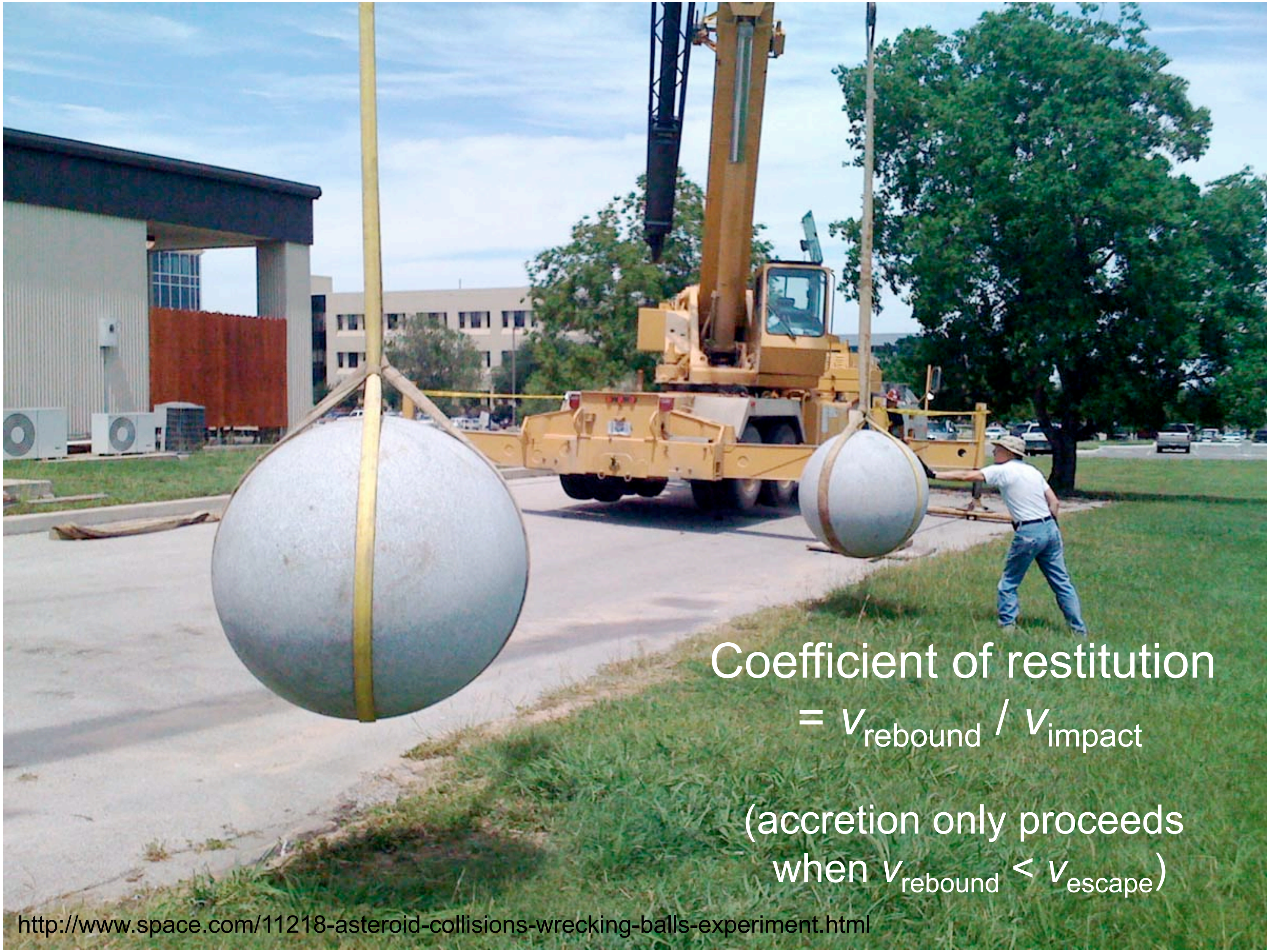
- planets orbit in same direction and same plane
- Sun and planets rotate in same direction
- disks seen around other stars

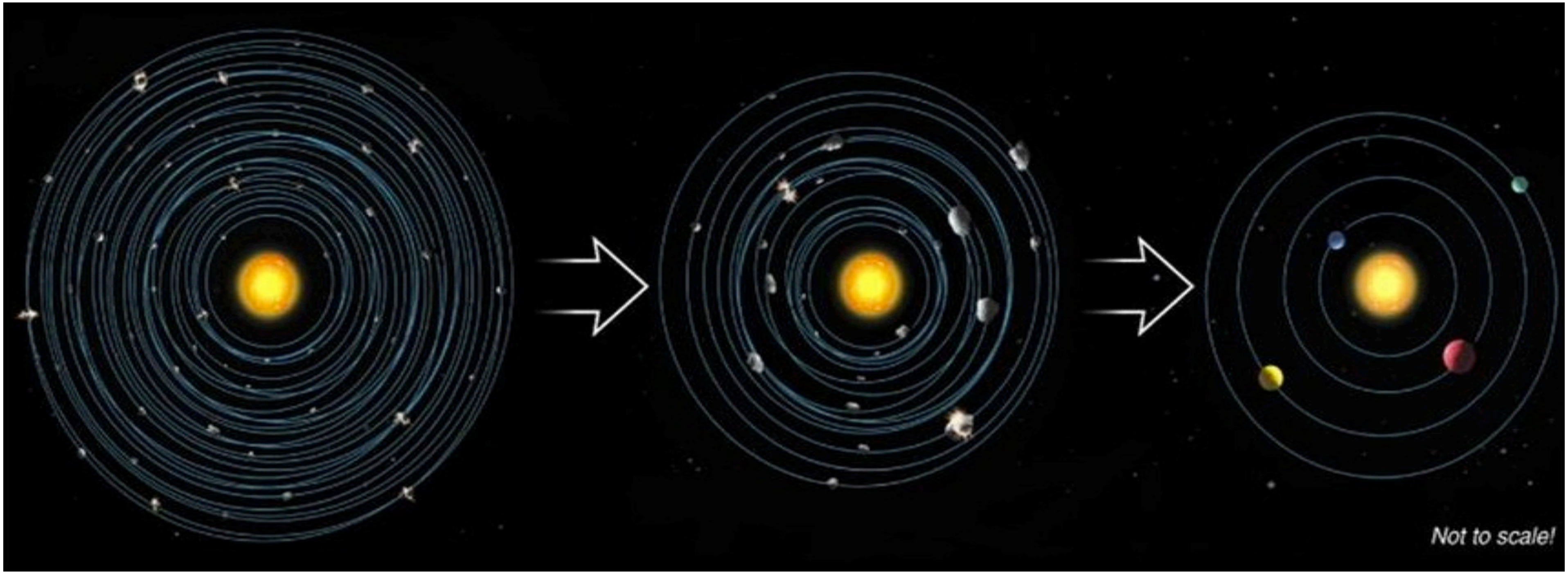
Condensation:

- terrestrial planets and asteroids found near Sun
- jovian planets, icy moons, comets found farther away


Planetesimals
protoplanets

Elastic or inelastic collisions?




Not to scale!

Formation of the Solar System

STEPS:

1. CLOUD COLLAPSE
   - •young stars seen in collapsing gas clouds
2. ROTATING DISK
   - •planets orbit in same direction and same plane
   - •Sun and planets rotate in same direction
   - •disks seen around other stars
3. CONDENSATION
   - •terrestrial planets and asteroids found near Sun
   - •jovian planets, icy moons, comets found farther away
4. **ACCRETION**
   - •many meteorites are made of smaller bits
   - •heavy cratering on oldest planet surfaces
   - •asteroids, comets are "leftovers"

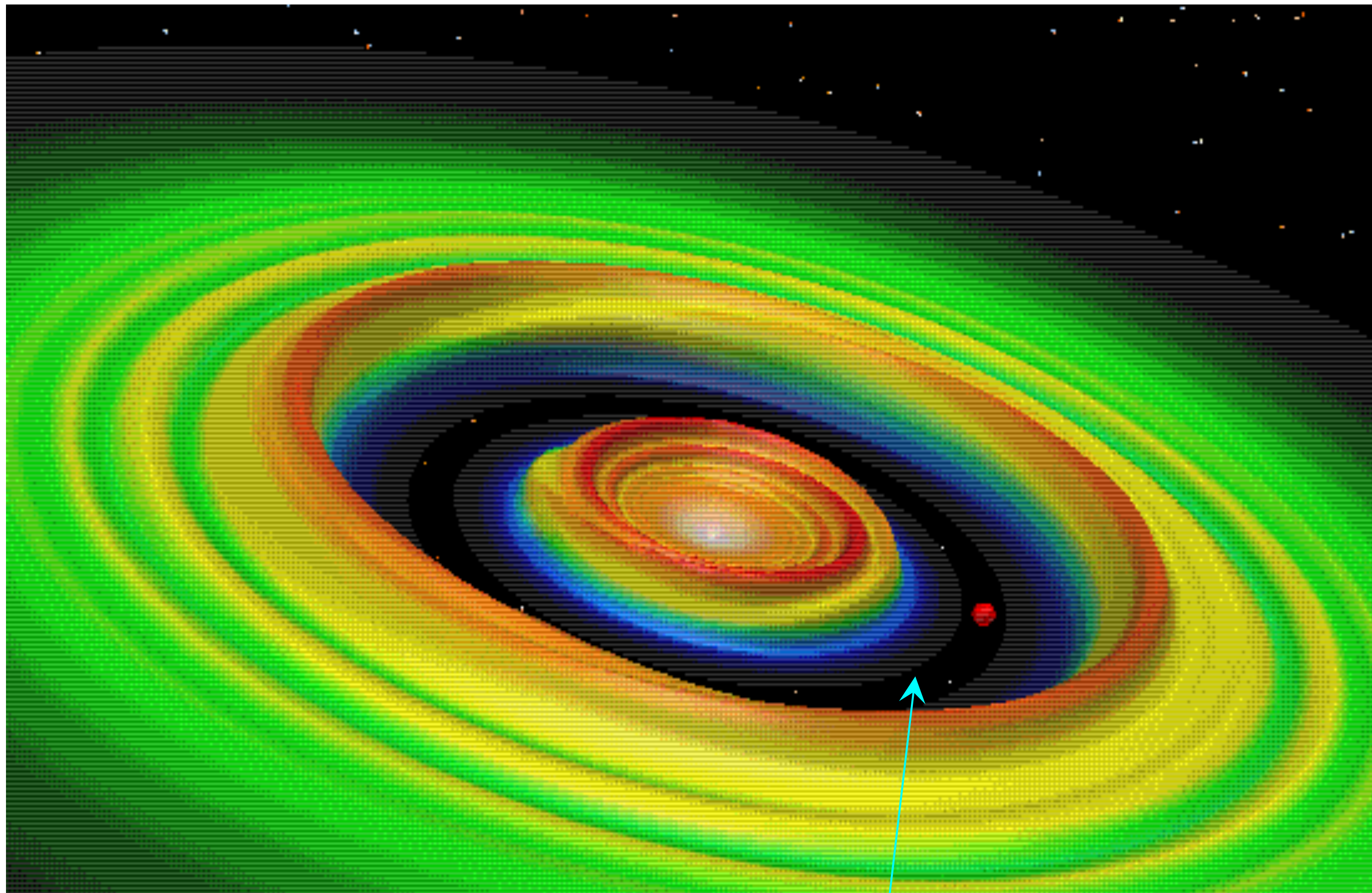
EVIDENCE: (listed beside each step above)

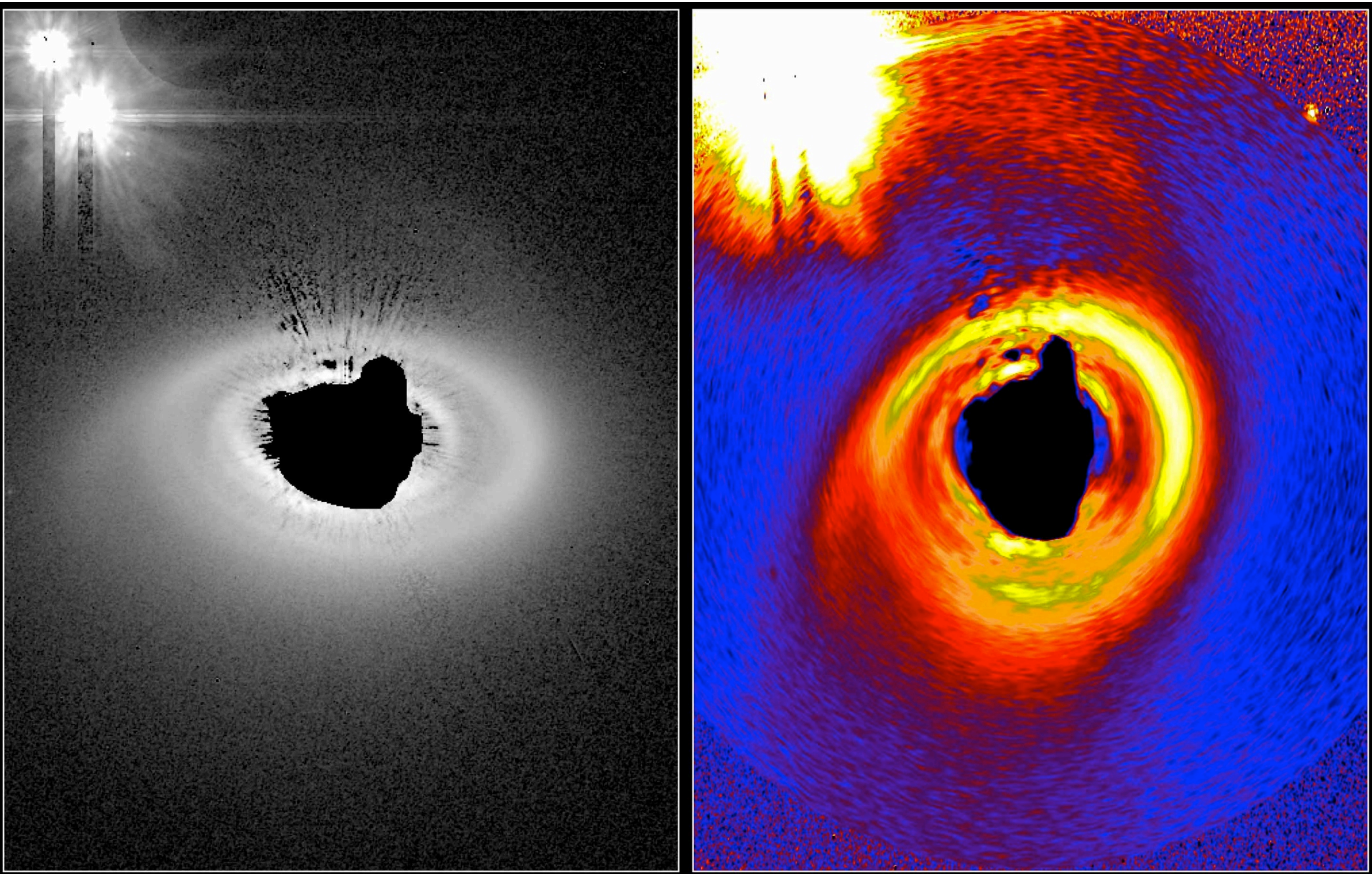
Gas Capture

Cores of jovian planets are large enough (≥ ~10 M_{Earth}) that <u>their gravity captures and holds gas</u> (hydrogen and helium)

→ Uranus and Neptune may have reached this core size too late to capture substantial gas before it was blown out of the solar system

<u>Computer simulation:</u>





HD 141569 Circumstellar Disk

Hubble Space Telescope ▪ ACS HRC Coronagraph

Formation of the Solar System

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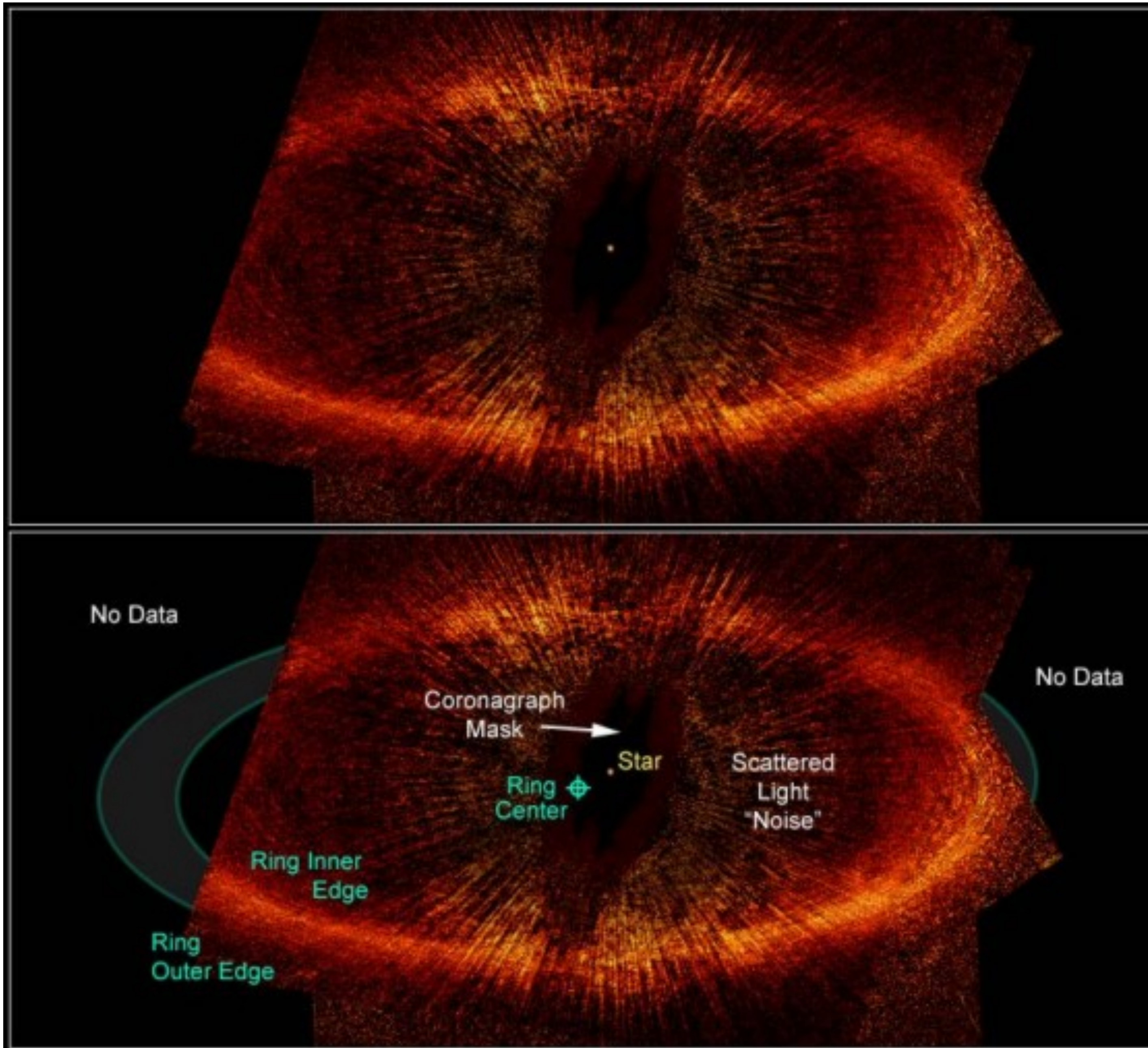
GAS CAPTURE?	•Jupiter, Saturn are mostly hydrogen and helium

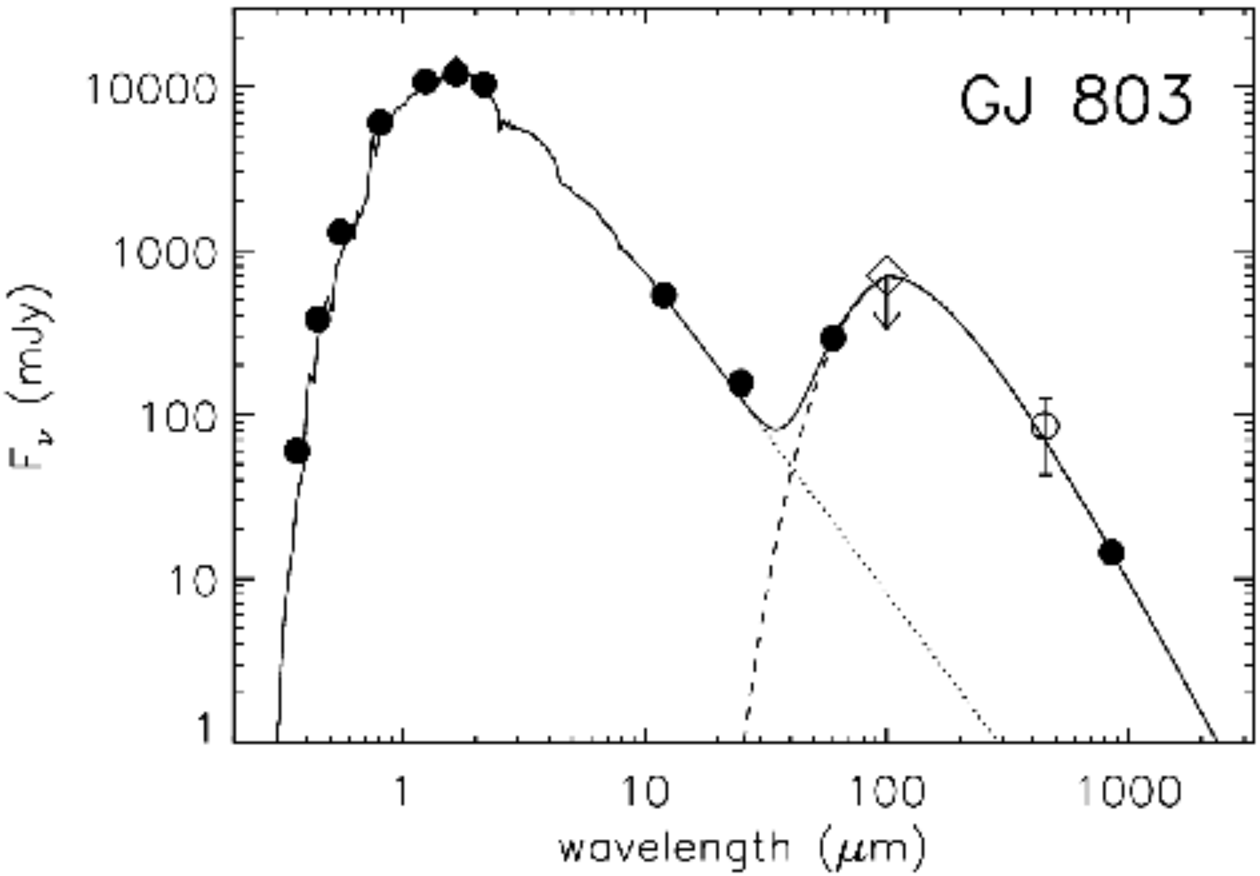
Leftovers

Gas is eventually captured or pushed out by wind from the star, but dust and planetesimals remain

→ Late collisions form "debris disks"

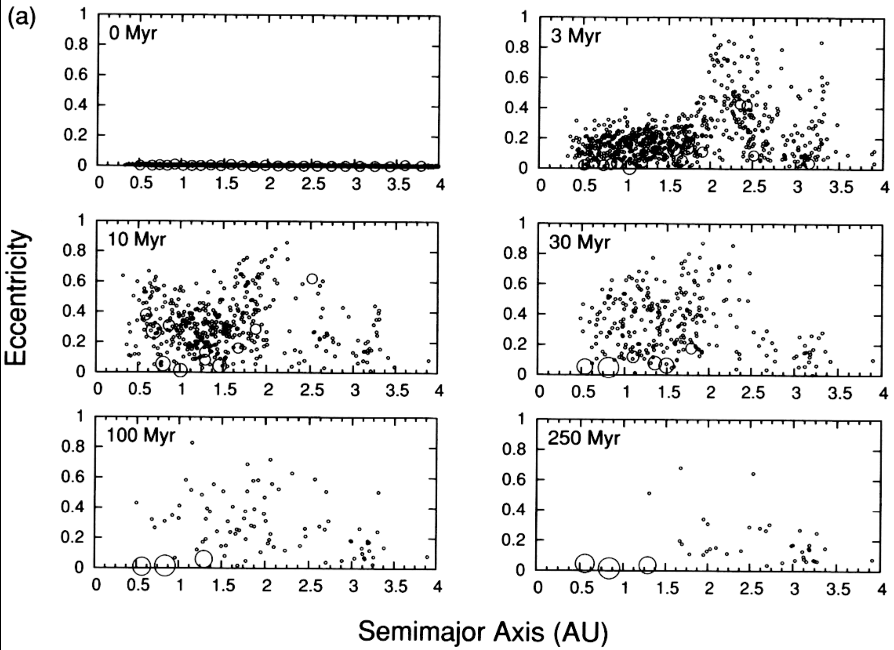


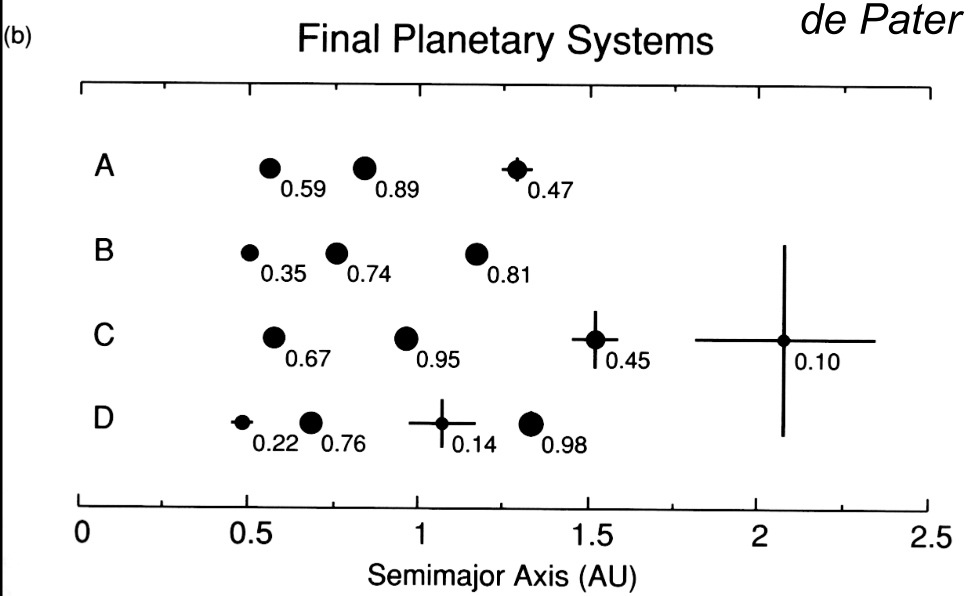
Debris disks → infrared excesses



Studying debris disks

The randomness of it all…





de Pater & Lissauer (2010)

Physical properties also affected by randomness of late accretion

- *Rotation rates/obliquities*
- *Bulk composition (Mercury)*
- *Surface topography (Mars)*

Giant planet sizes/orbits also influenced by random chance…