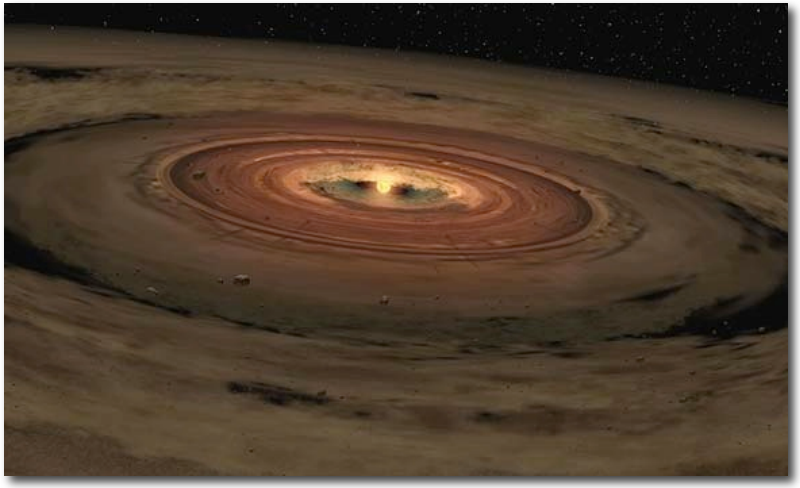
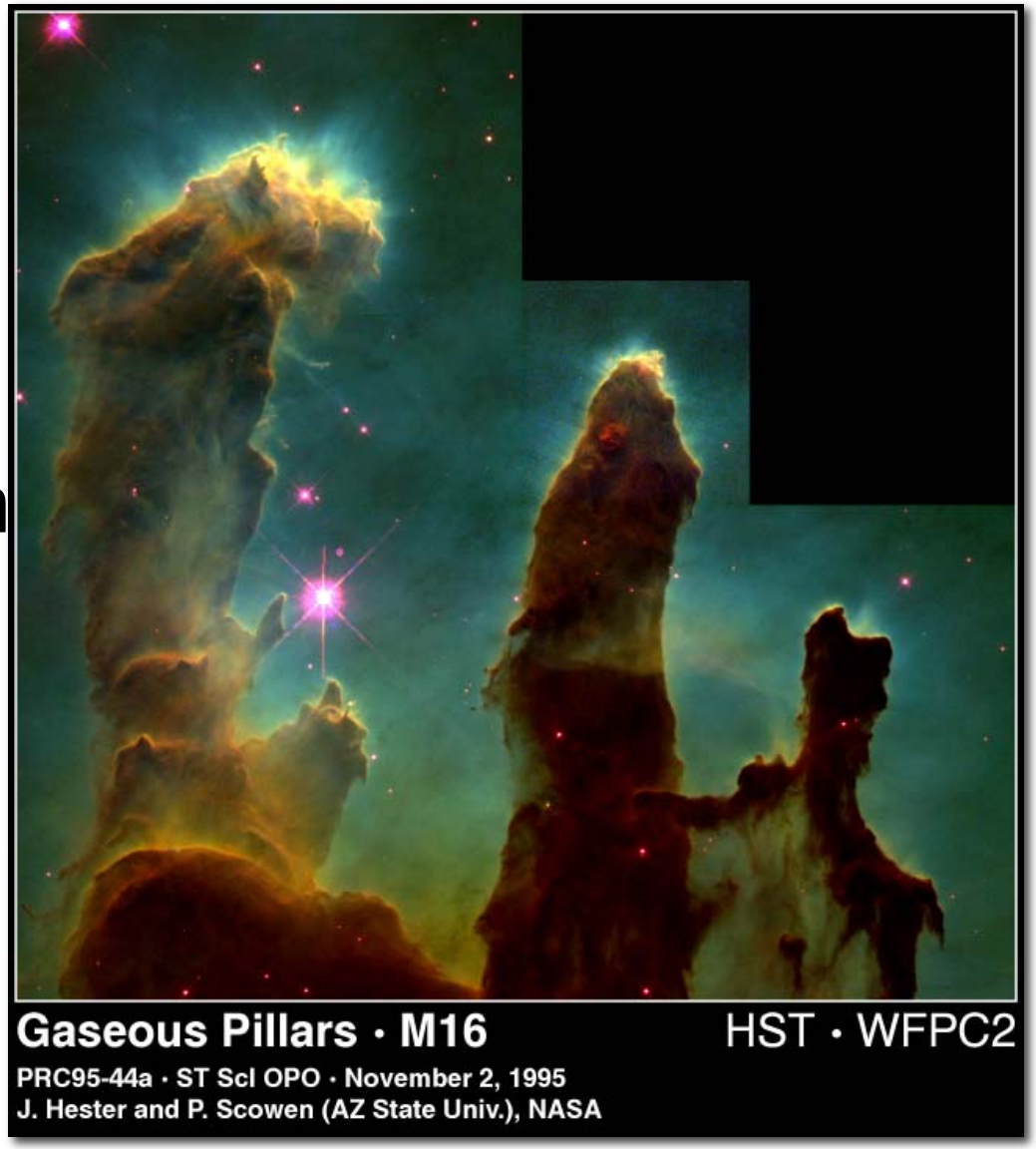
Solar System/Planet Formation

Gas Clouds to Stars/Planets

Planet Migration

Satellite Formation





Formation of the Solar System

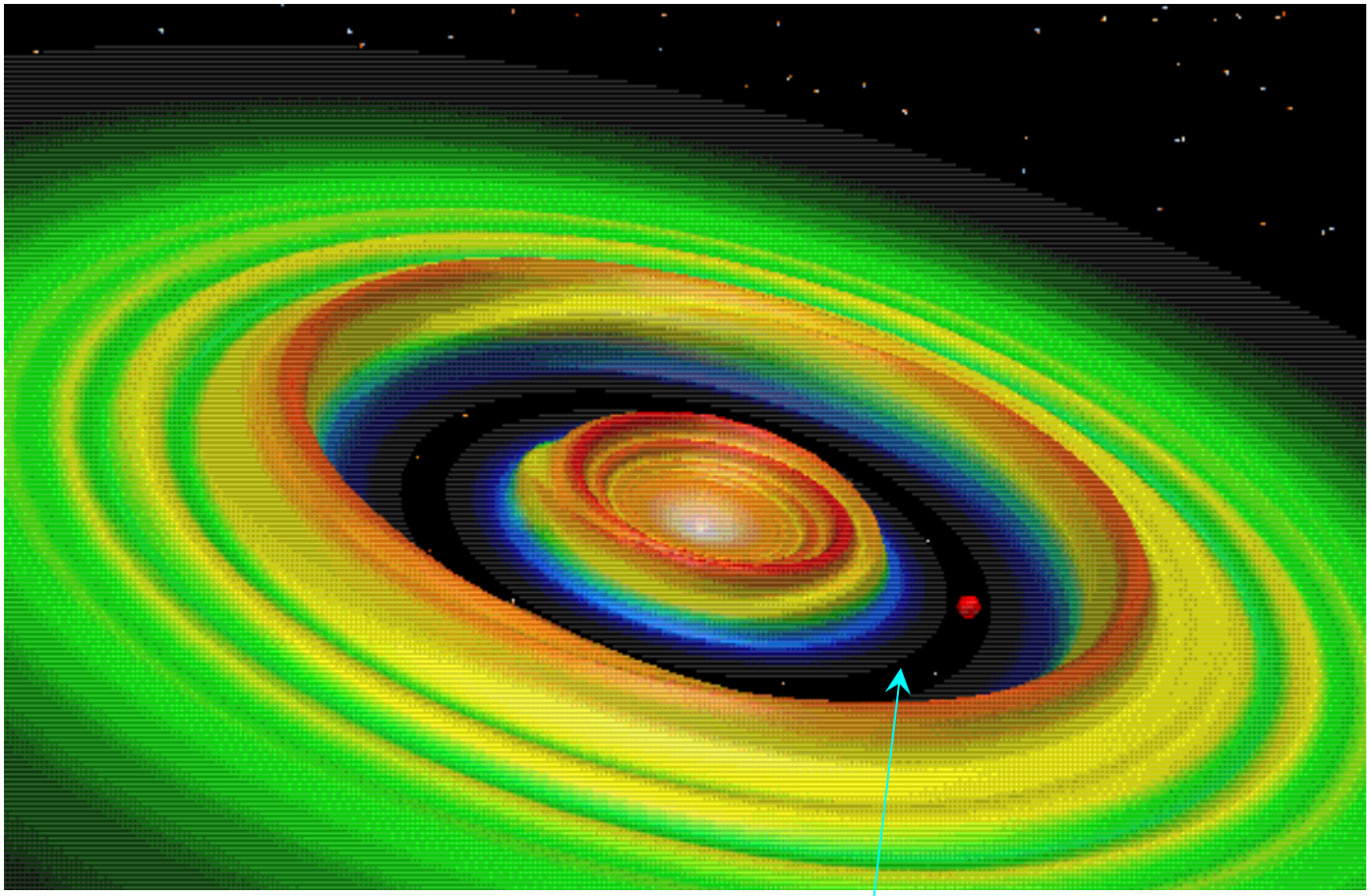
STEPS:	EVIDENCE:
CLOUD COLLAPSE	•young stars seen in collapsing gas clouds
ROTATING DISK	•planets orbit in same direction and same plane •Sun and planets rotate in same direction •disks seen around other stars
CONDENSATION	•terrestrial planets and asteroids found near Sun •jovian planets, icy moons, 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

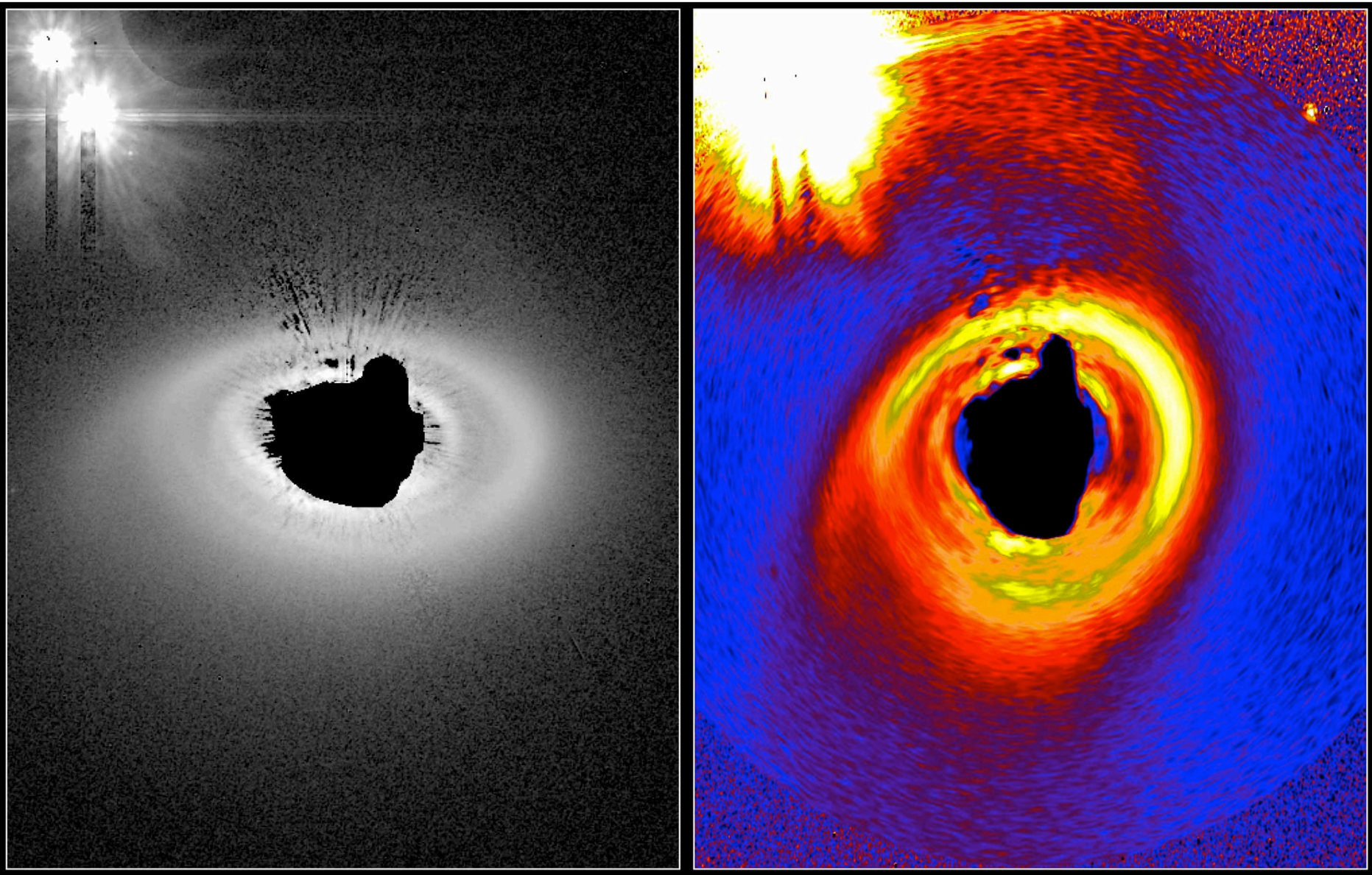
Gas Capture

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>





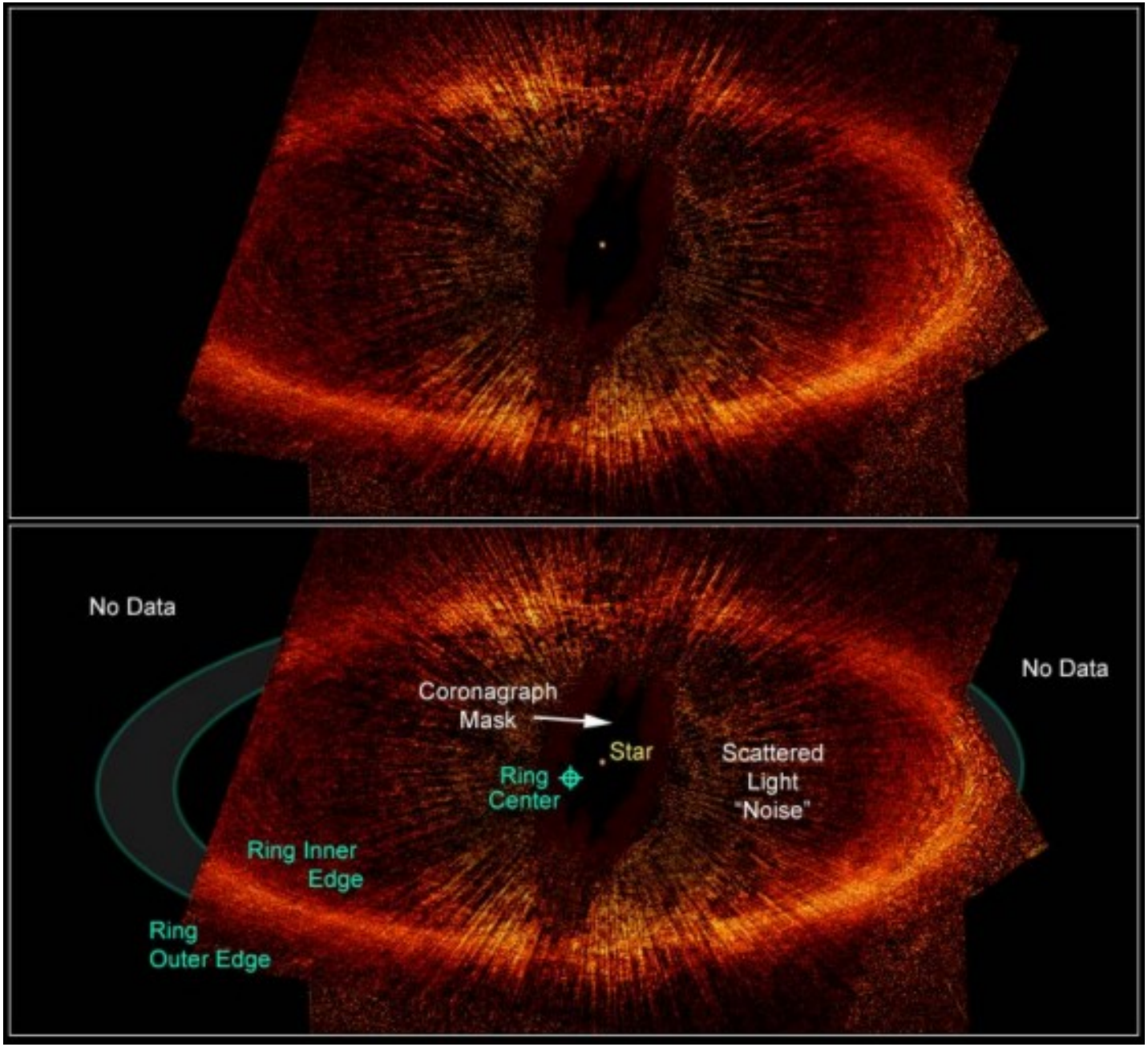
HD 141569 Circumstellar Disk

Hubble Space Telescope ▪ ACS HRC Coronagraph

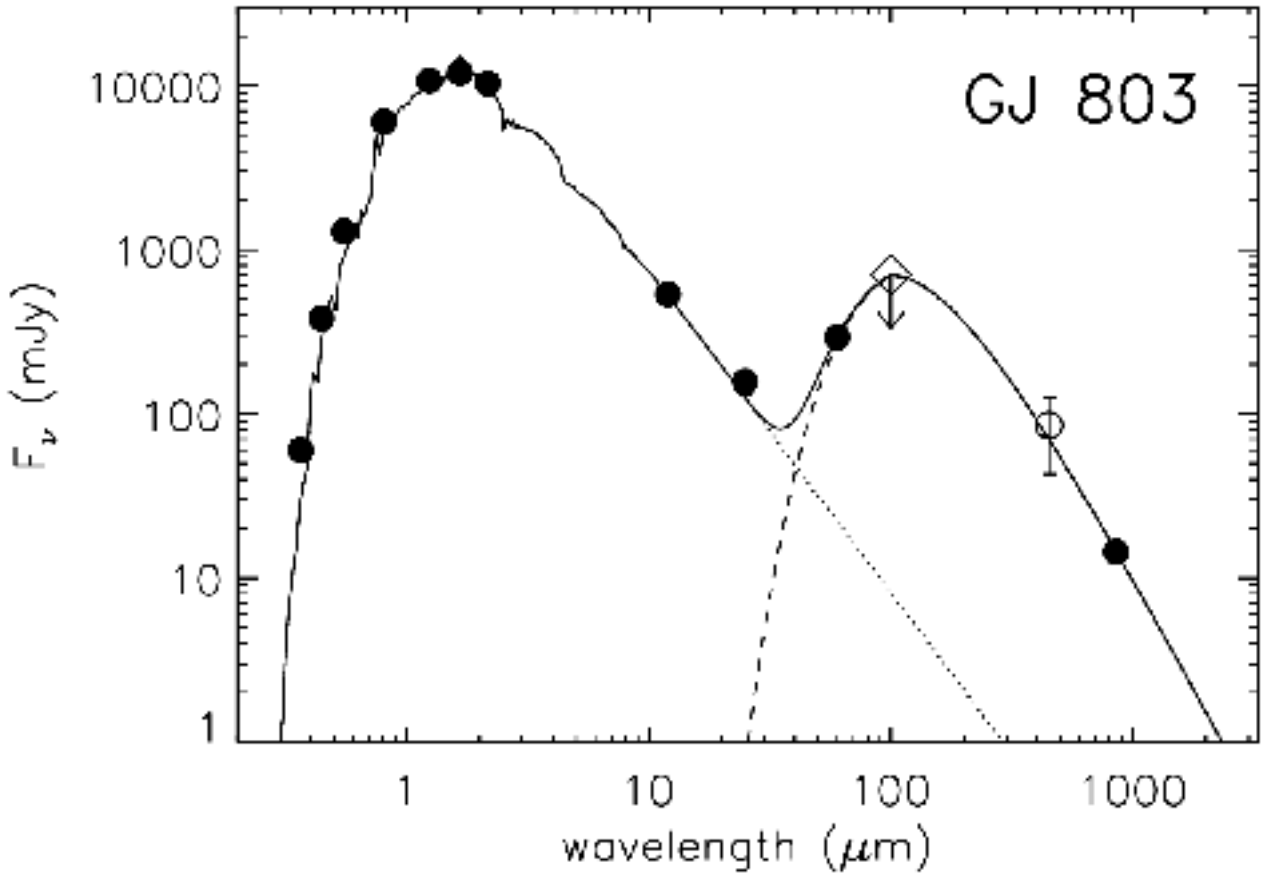
Leftovers

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

→ Late collisions form "debris disks"

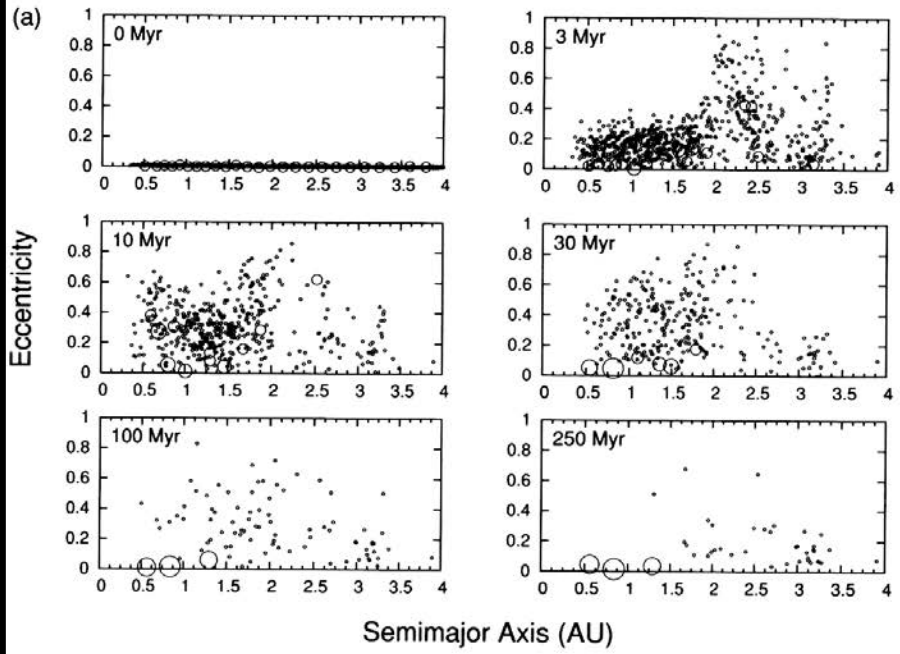


Debris disks → infrared excesses



Wray et al. (AAS, 2005)

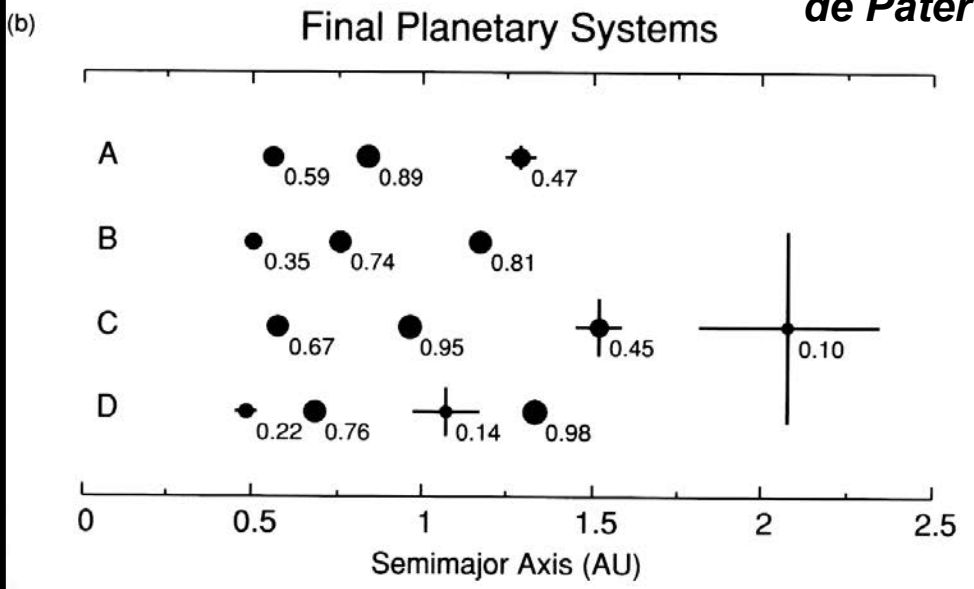
The randomness of it all…



Physical properties also affected by randomness of late accretion

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

de Pater & Lissauer (2010)



Giant planet sizes/orbits also influenced by random chance…

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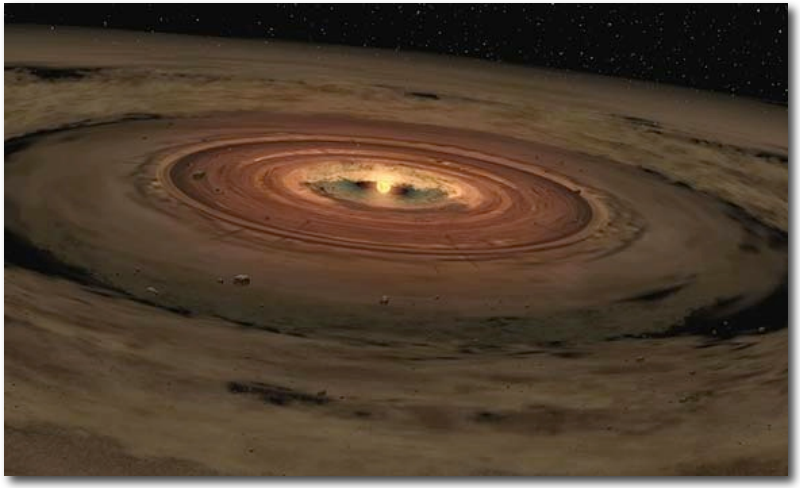
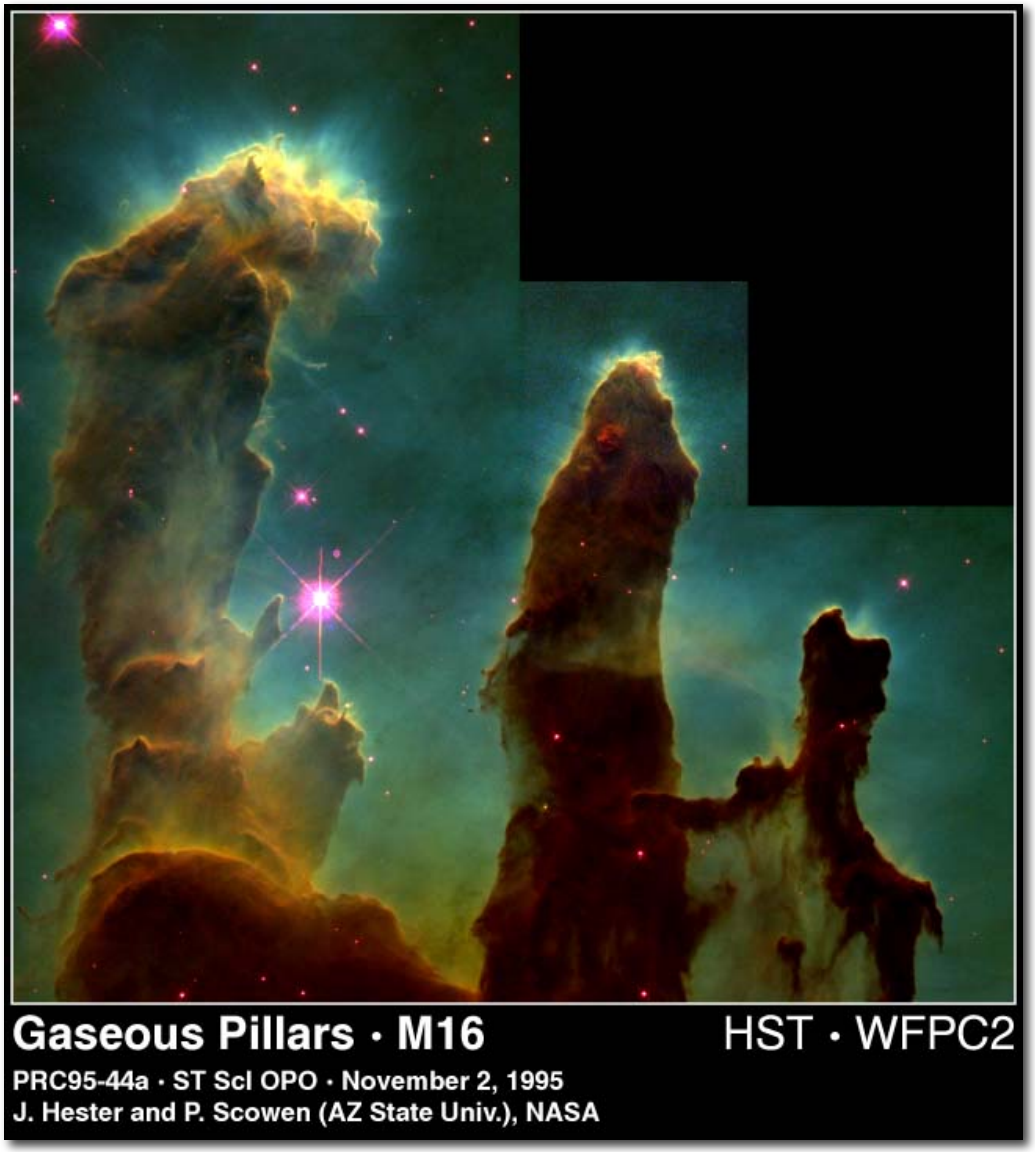
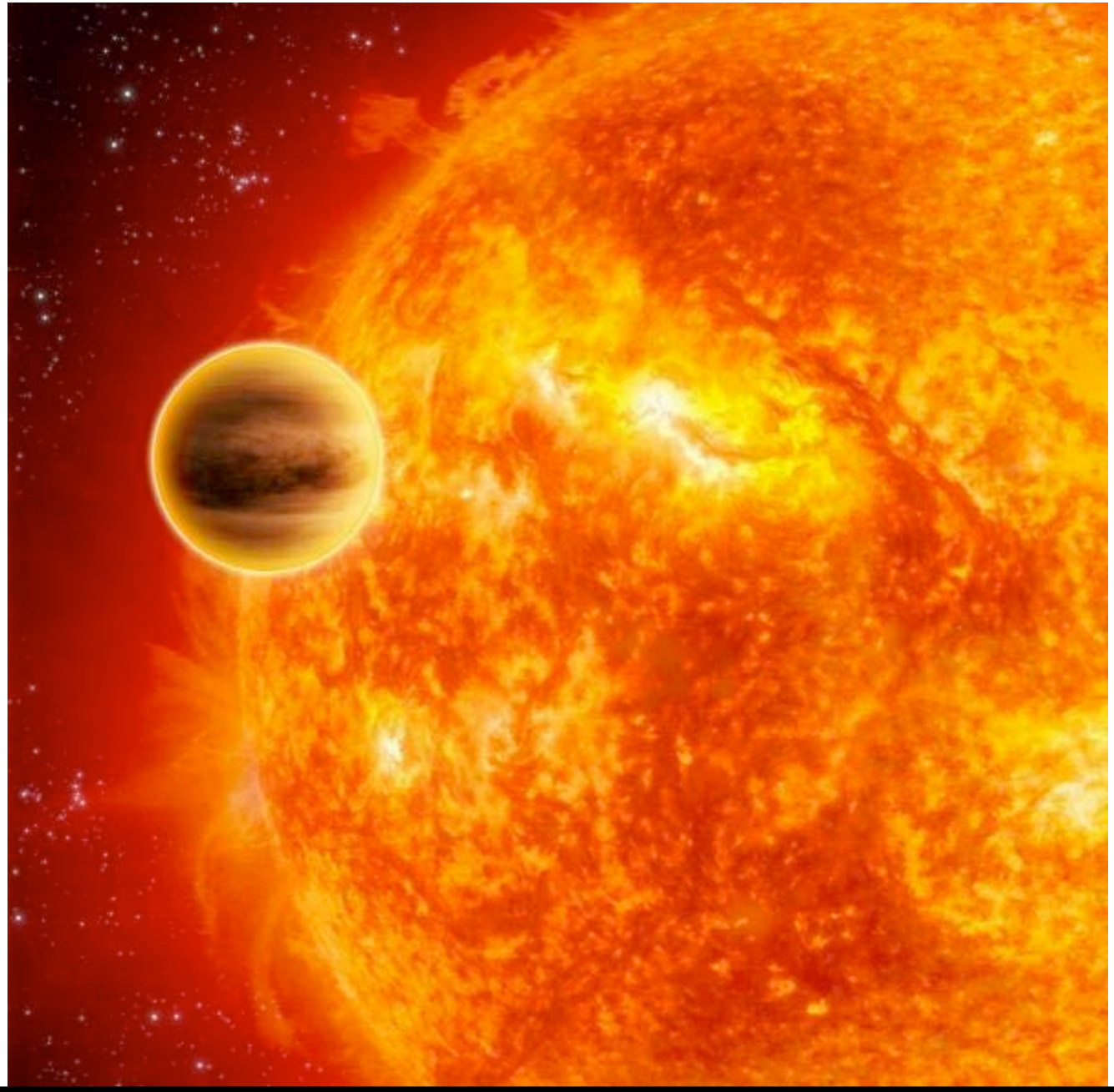
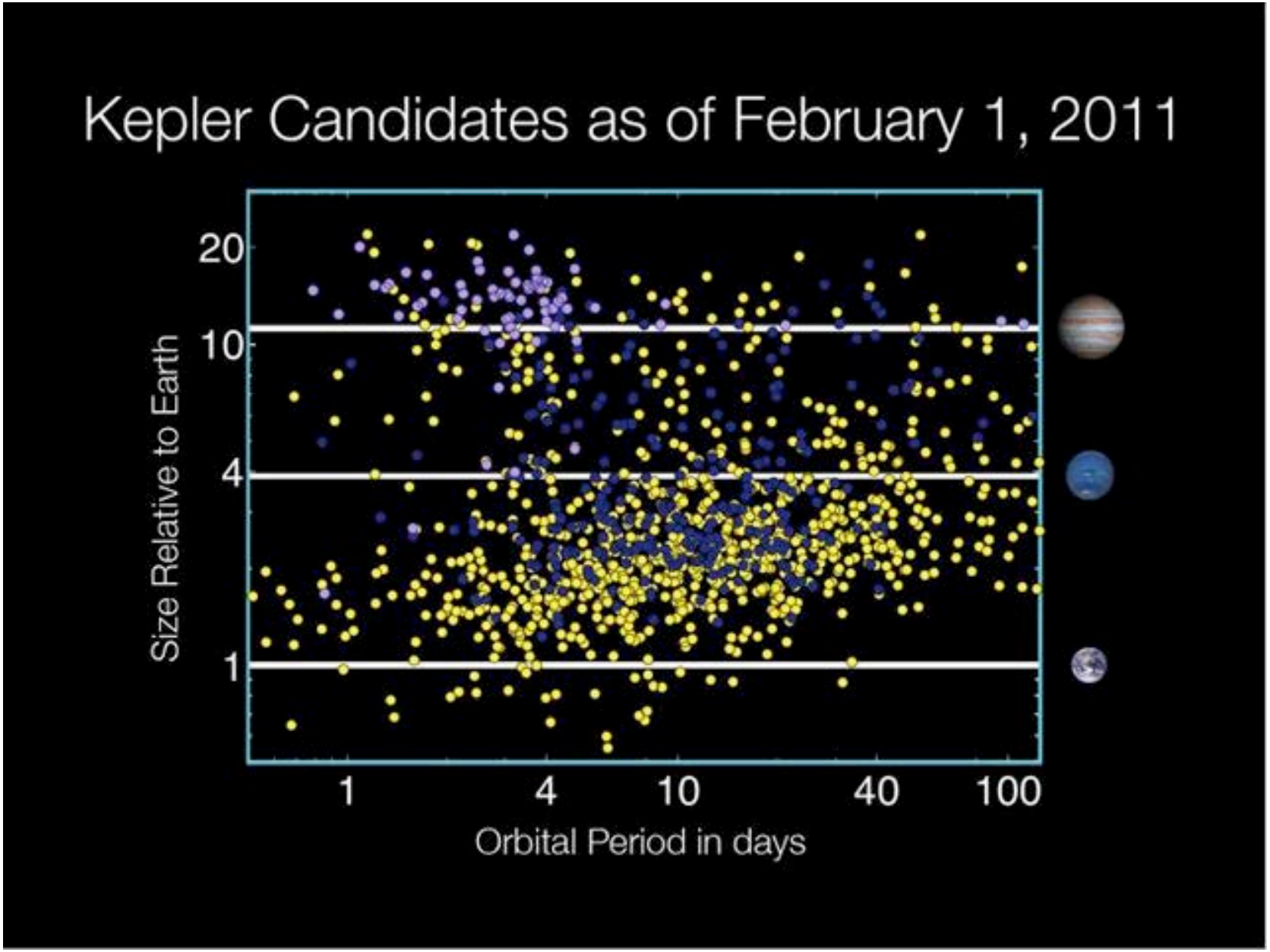




Close-in Giant Exoplanets → Migration



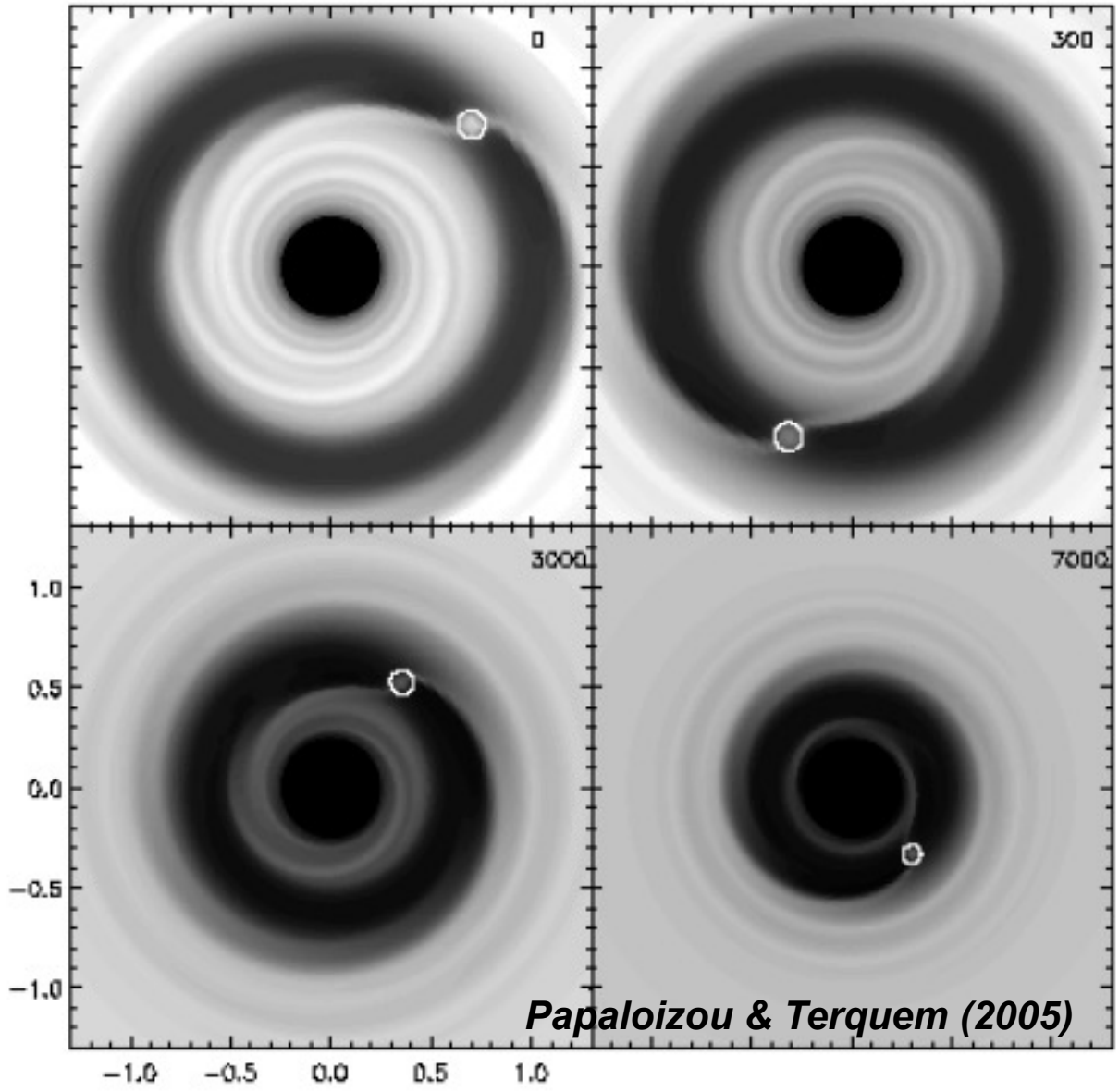
Close-in Giant Exoplanets → Migration



Inward Planet Migration

- Probably through angular momentum exchange with disk gas
  - Type II: planet orbits in disk gap
  - Type I: no gap

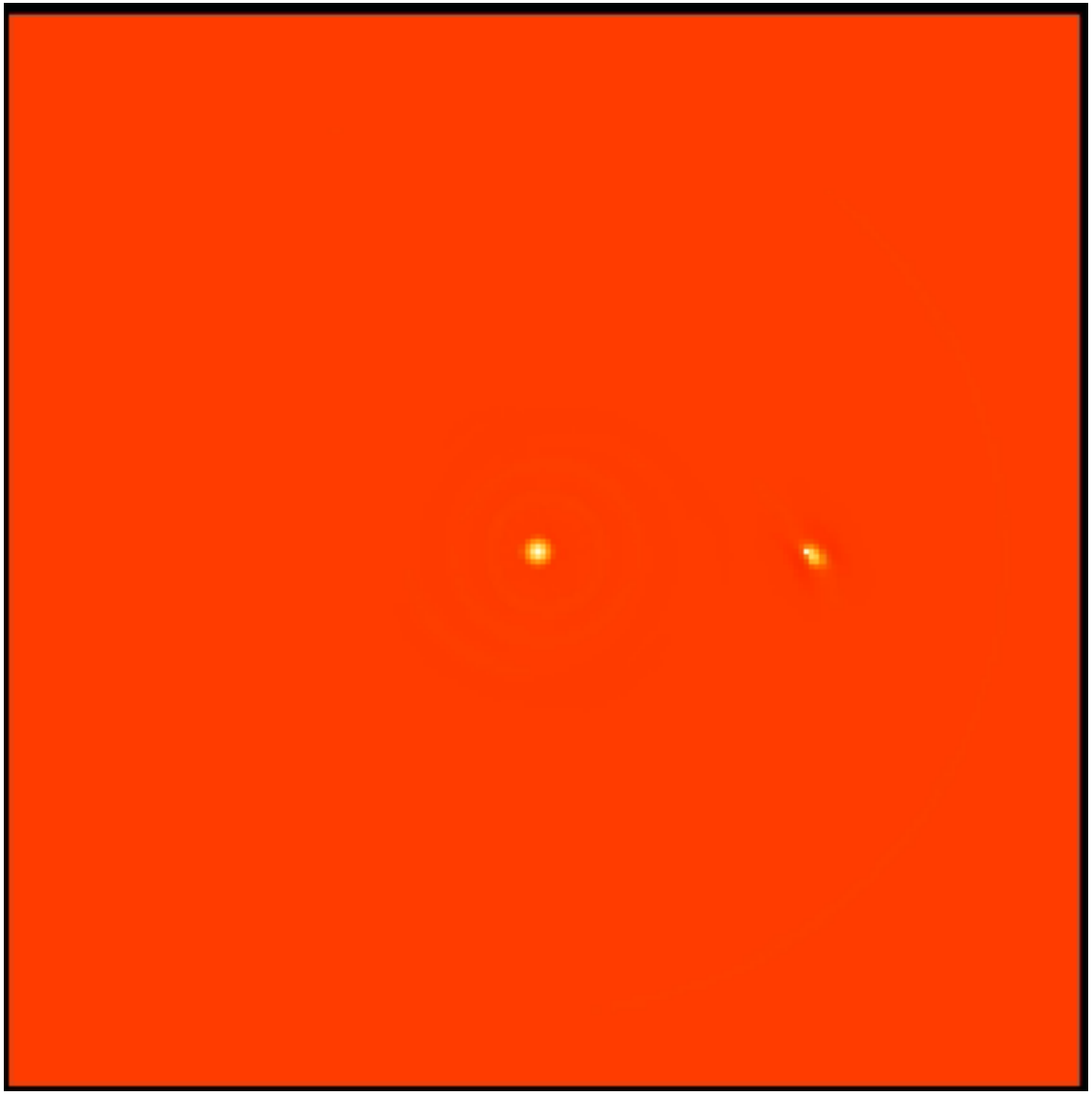
- Stopping migration before planets merge with the star may require concurrent nebula dissipation



Papaloizou & Terquem (2005)

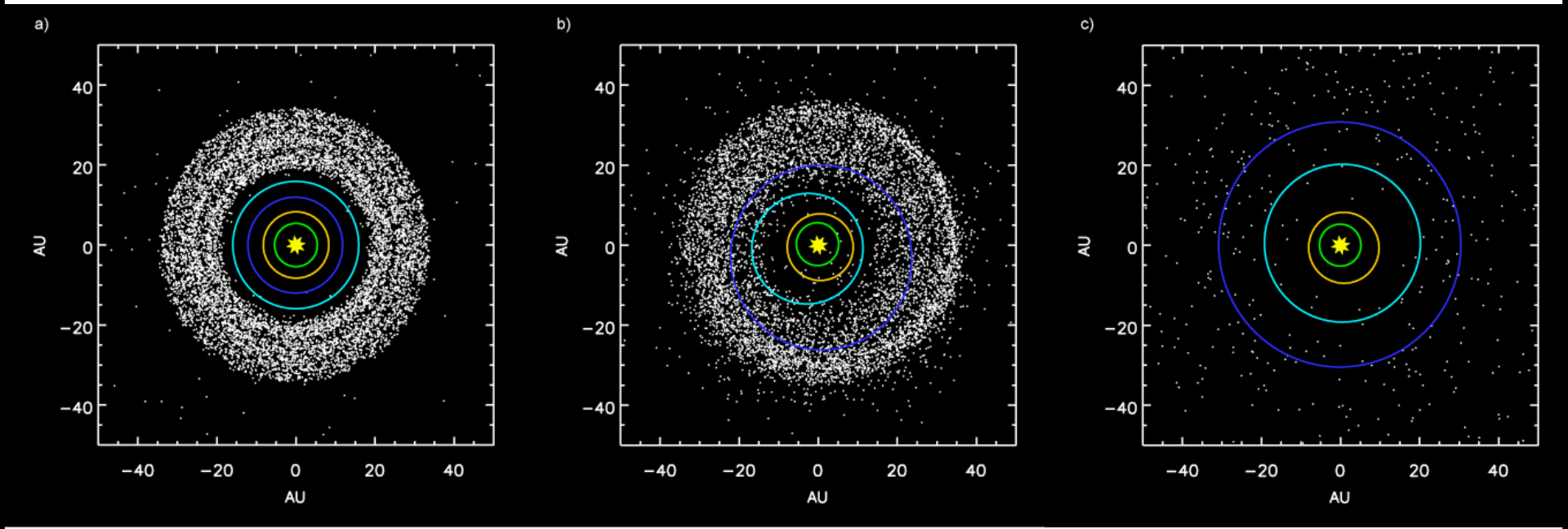
Inward Planet Migration

1.5M_{Jup} planet in 0.02$M_{\odot}$ disk (MMSN): ~100 orbits ending with simulated gas dispersal



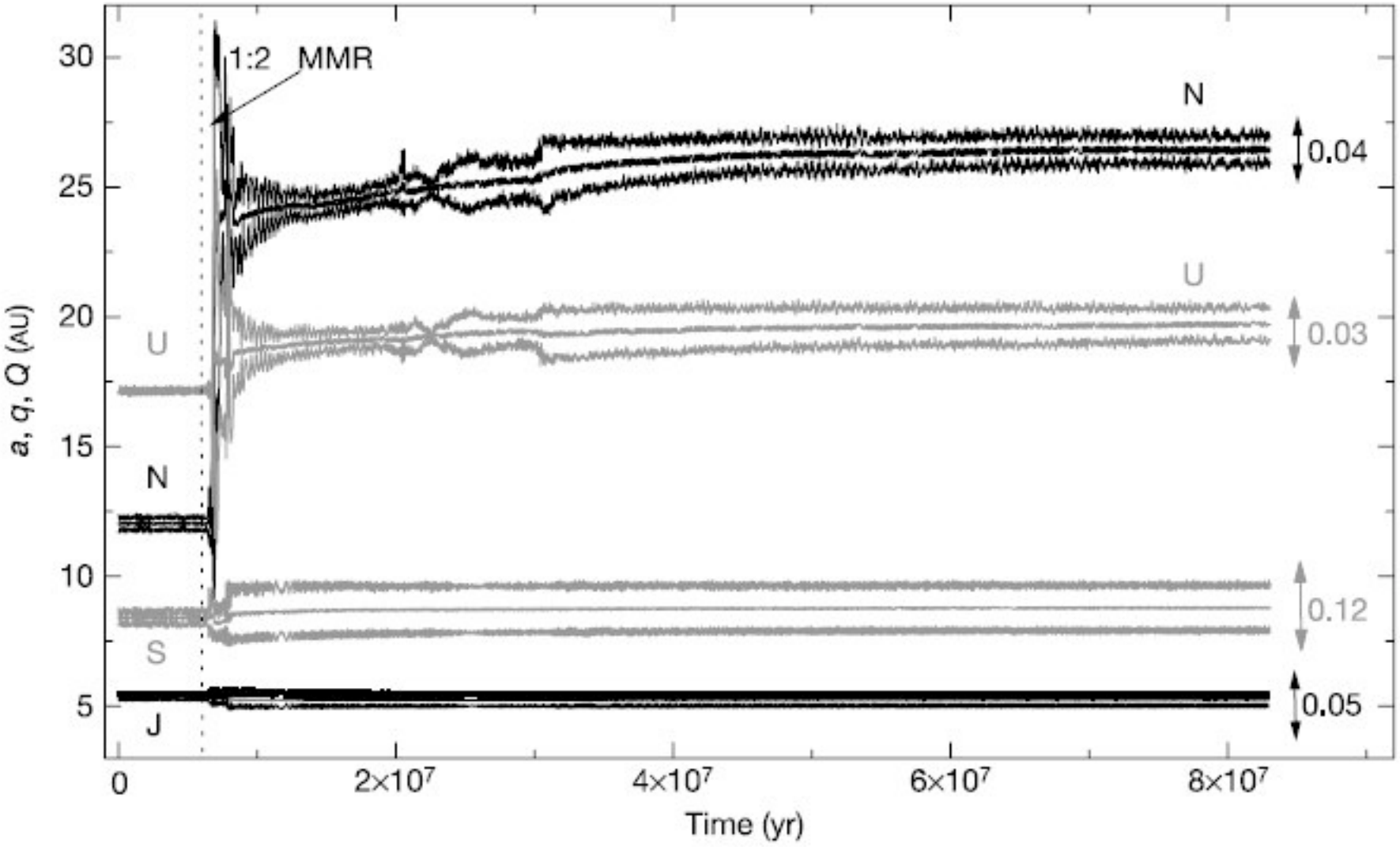
http://planets.utsc.utoronto.ca/~pawel/planets/movies.html

Outward Planet Migration: Nice Model



- All planets formed at <20 AU (high density, short orbital periods)
- Outermost planet (Uranus?!) interacted with KB planetesimals, typically "passing" them inwards to interact with other planets
- Interactions with Jupiter cause ejection to Oort cloud or beyond
- Reflex planet migrations cause Jupiter and Saturn to cross 2:1 resonance → mayhem!
  - *Uranus and Neptune move way out, switch places?!*
  - *Planetesimals scattered into inner solar system (LHB)*

Outward Planet Migration: Nice Model



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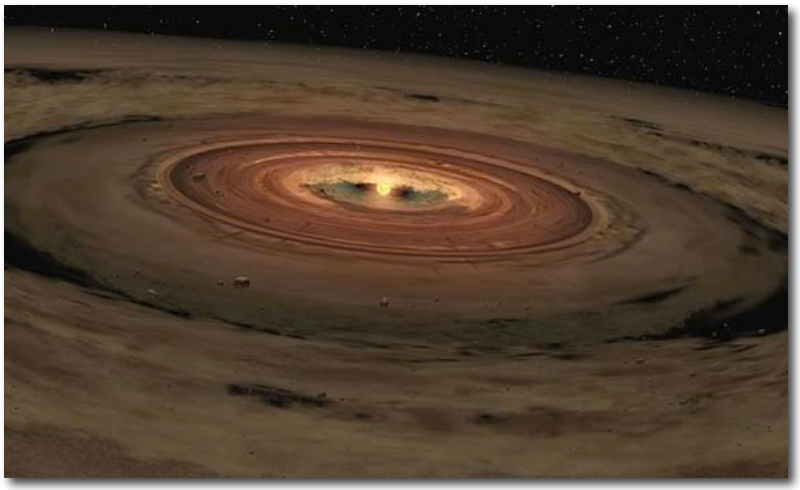
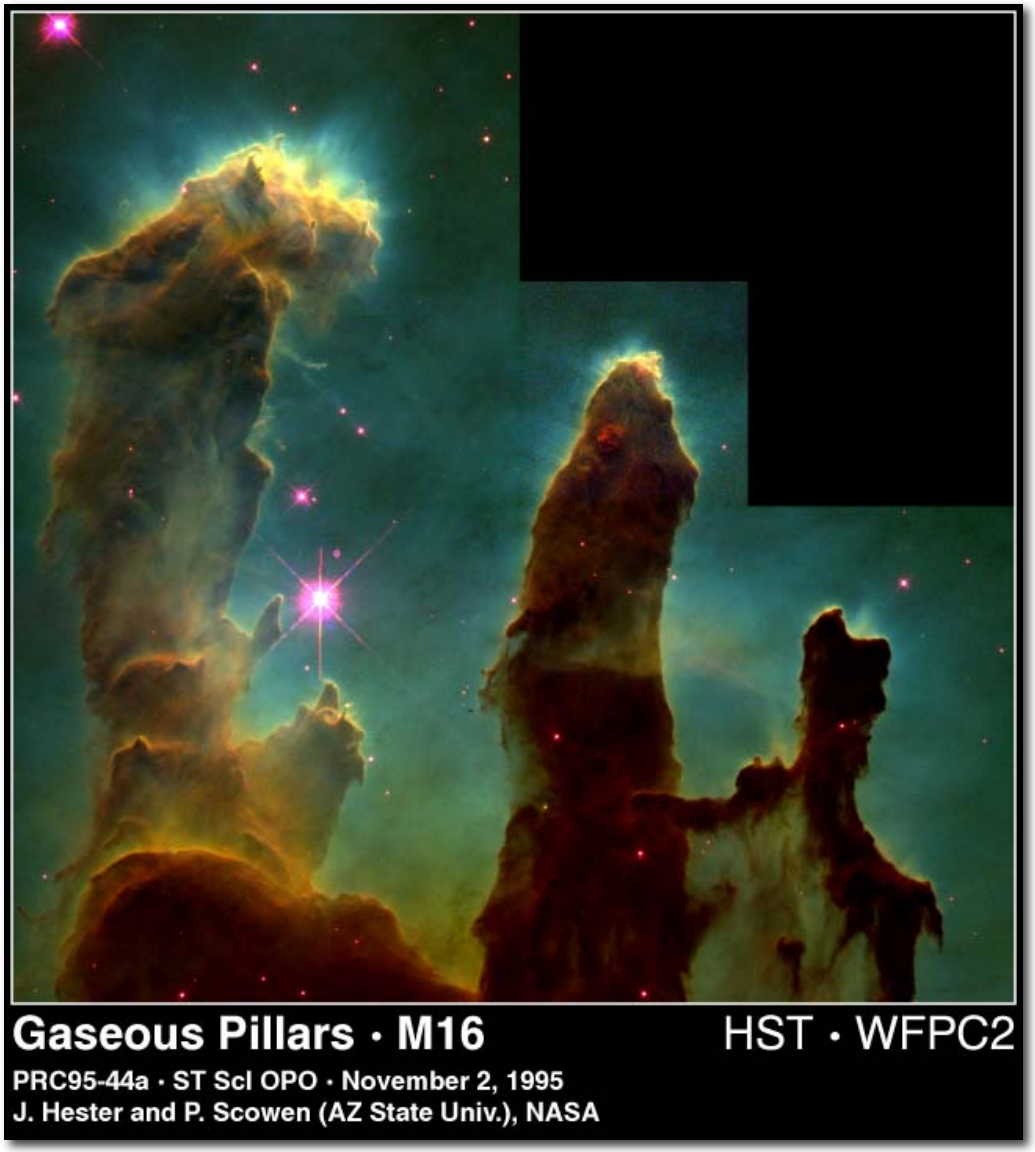
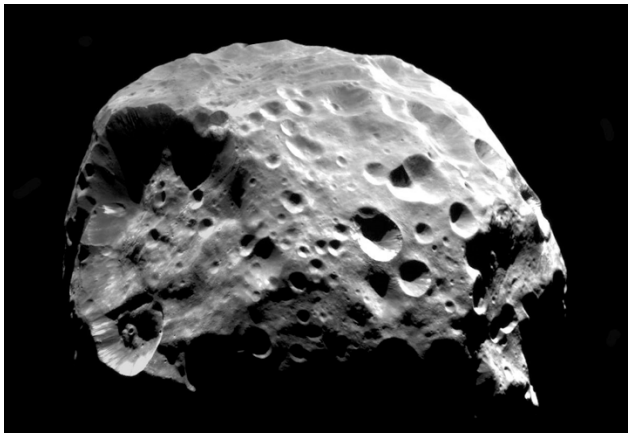




Satellite Formation Mechanisms

- Circumplanetary accretion disks (“regular satellites”)

- Capture (“irregular satellites”)

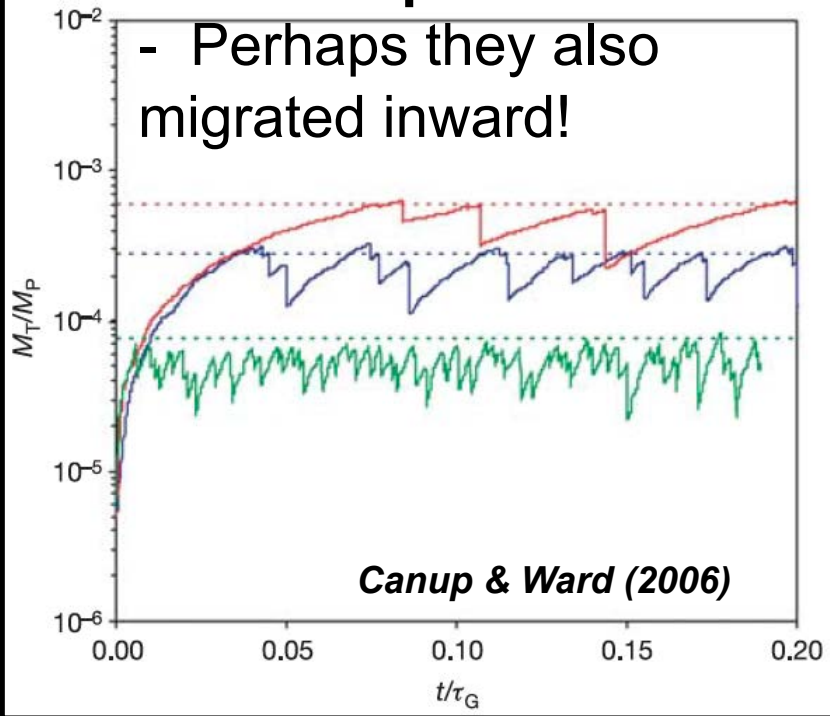


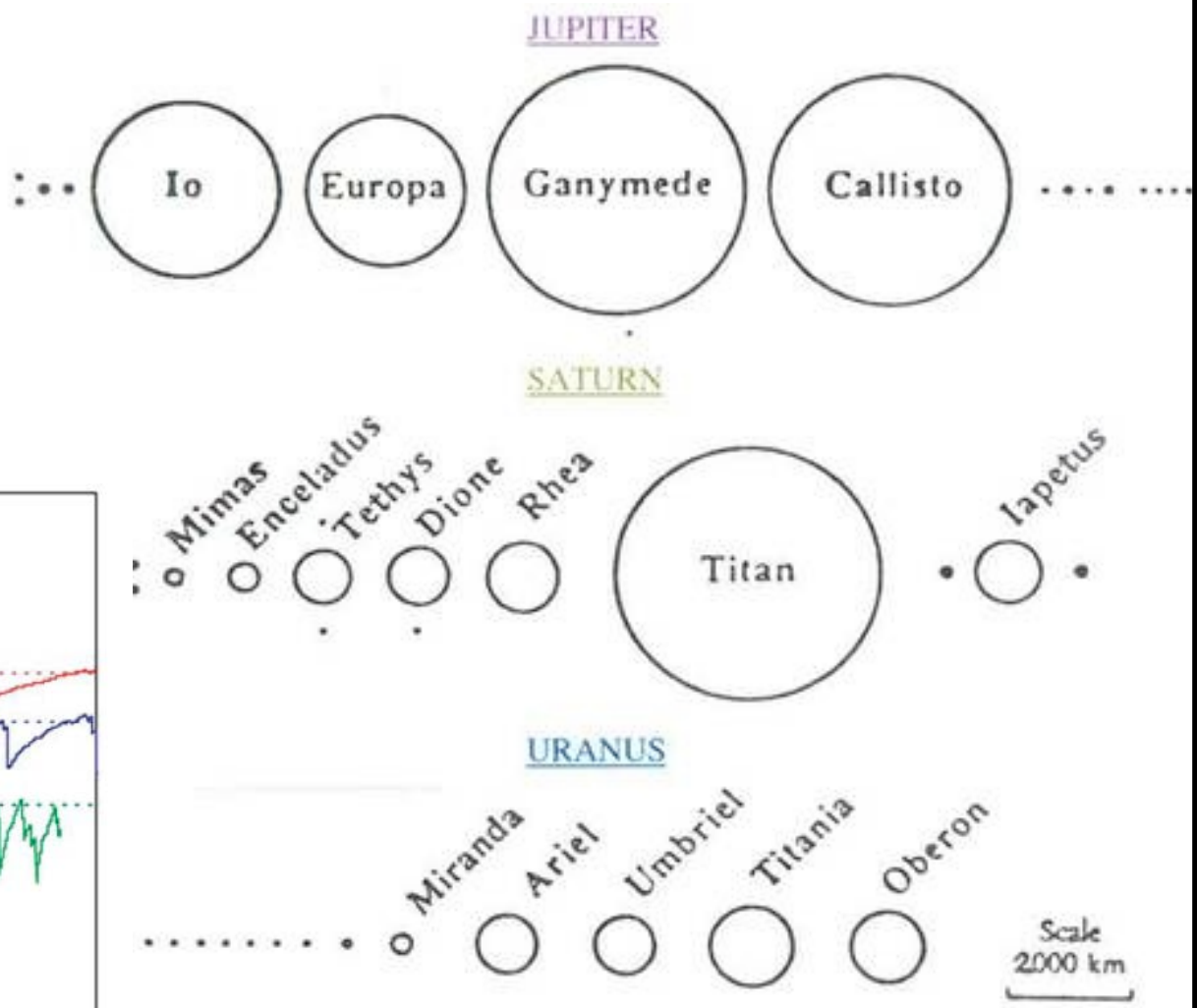
- Giant impacts

Formation of Regular Satellites

- **Regular Satellites:**
  - $M_s \sim 10^{-4} M_p$
  - $a_s < \sim 20\text{-}30 R_p$
  - $e, I \approx 0$

- **Form in "subnebula" of ~solar composition**
  - Perhaps they also migrated inward!





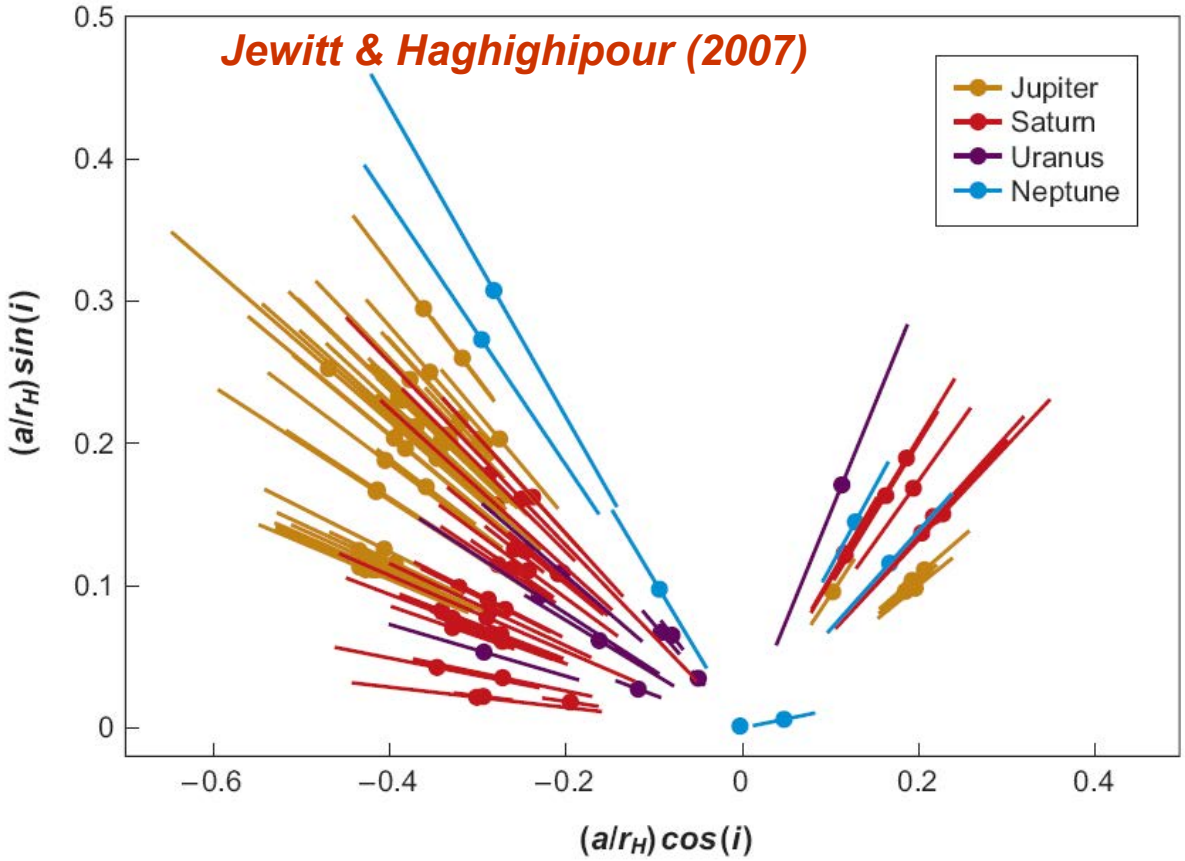
Is Pandora possible?

For the most massive planets, $10^{-4}M_p \approx$ only $0.4M_{Earth}$
… but Mars-mass worlds can retain atmospheres

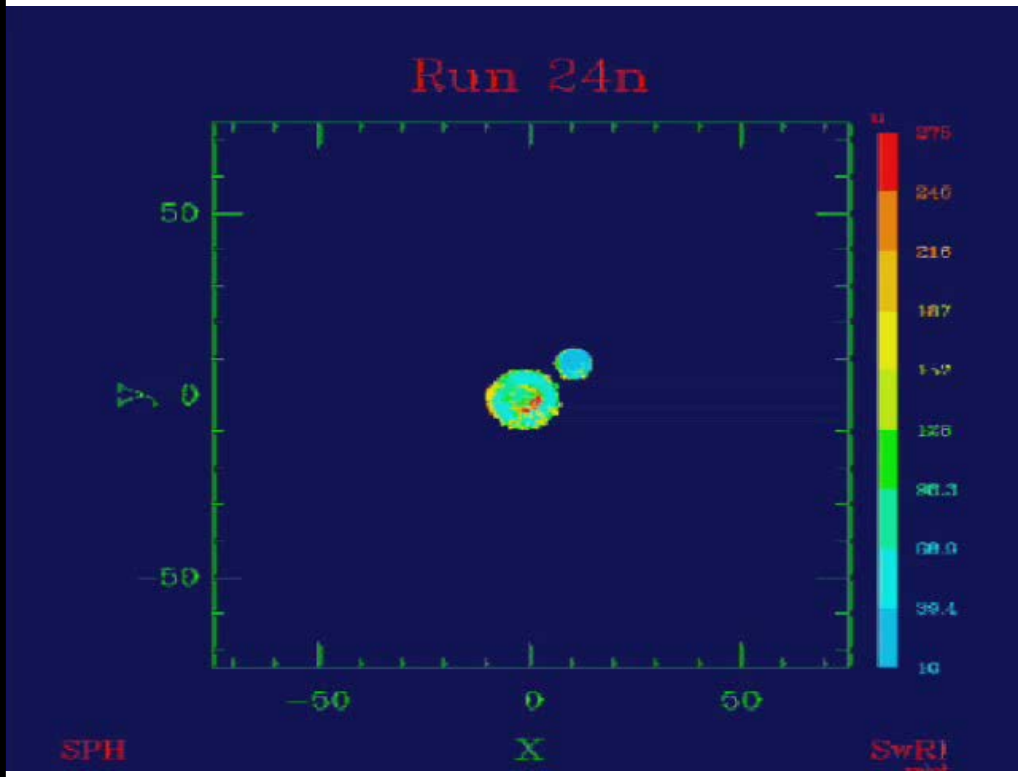
Capture of Irregular Satellites

- **Irregular Satellites: small, distant, eccentric and/or inclined (often retrograde)**

- **Capture due to 3-body interactions (collisions or scattering) most likely, probably early**



The Oddballs: Formed by Impact?



- Earth's Moon (~$10^{-2} M_{Earth}$) (Canup, 2004)
- Charon (~$10^{-1} M_{Pluto}$) (Canup, 2005)

For our Moon, this explains:

- Age (~4.4 – 4.53 Ga)
- Low volatile content
- Low bulk density (minimal iron core)
- Similar oxygen isotope ratios to Earth
- Early proximity and fast rotation of Earth