News and Reminders

Homework 4 due now

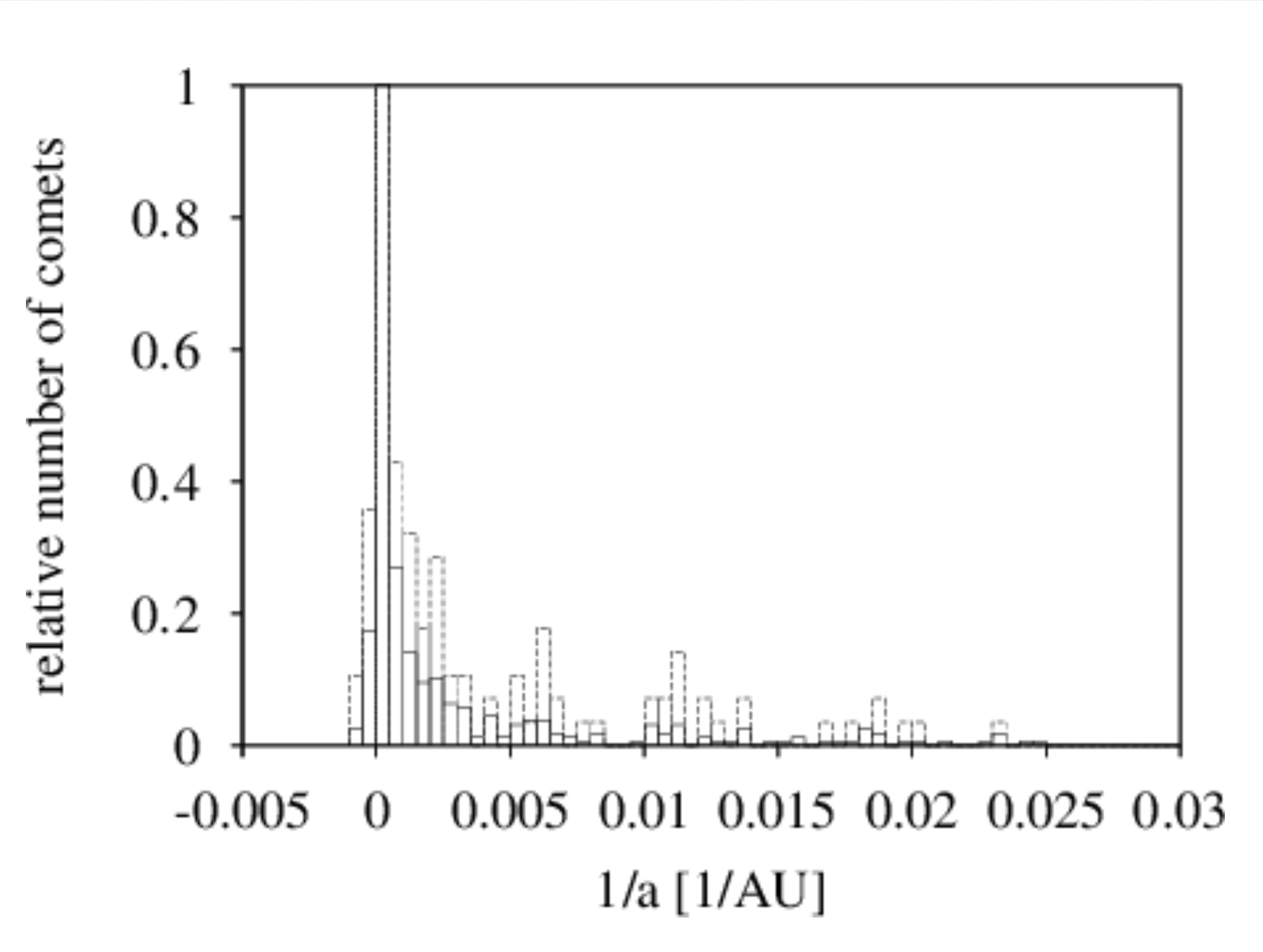
Homework 5 posted today or tomorrow

Next reading quiz on Wednesday, Nov. 6: ch. 13.1 - 13.4

End of semester proposal due dates:

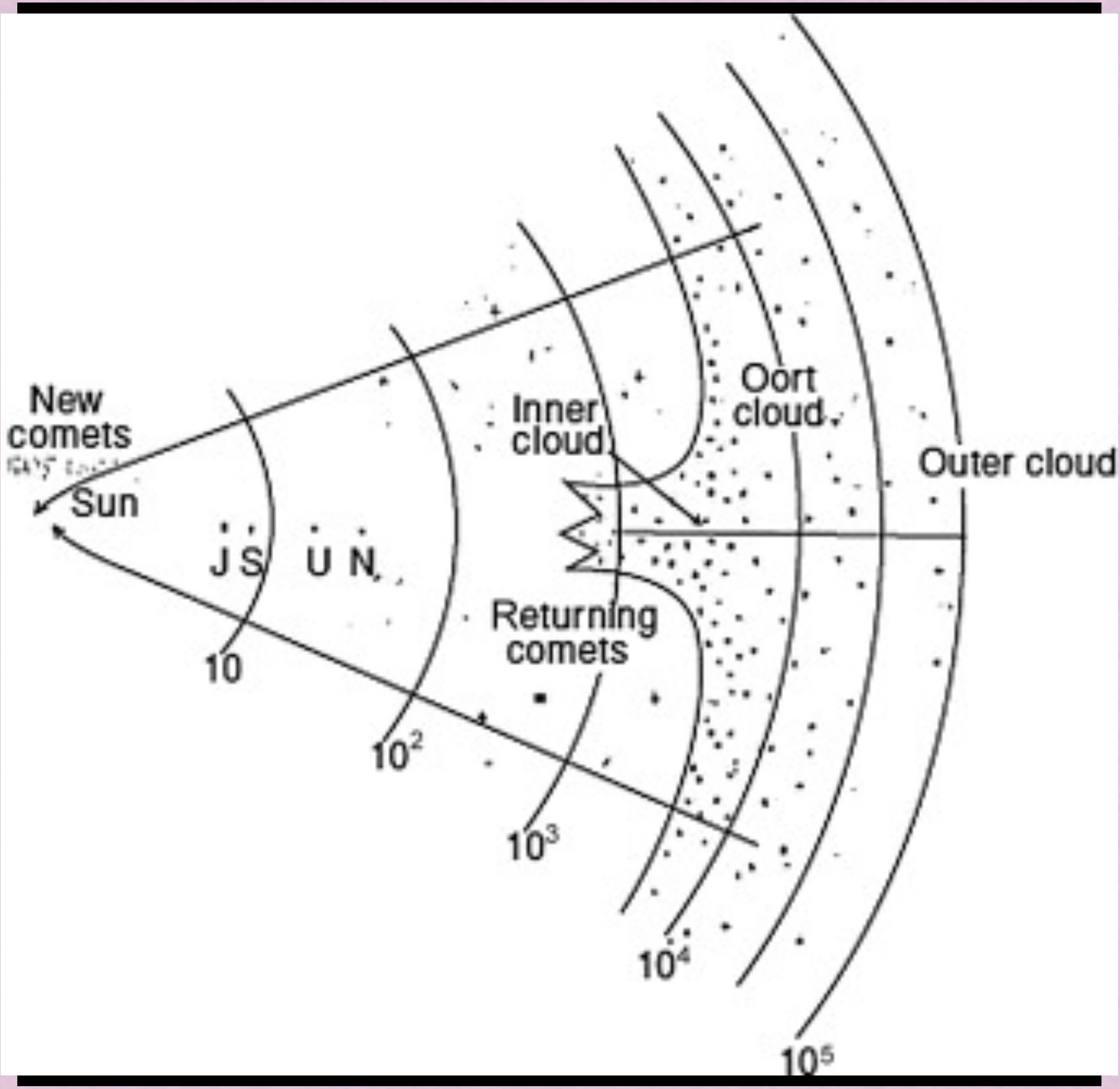
- To submit or not to submit: today!
- Abstract due: Monday, Nov. 11
- Proposal due: Monday, Dec. 2

Comets



10^{11} - 10^{12} “unseen” comets in the Oort cloud

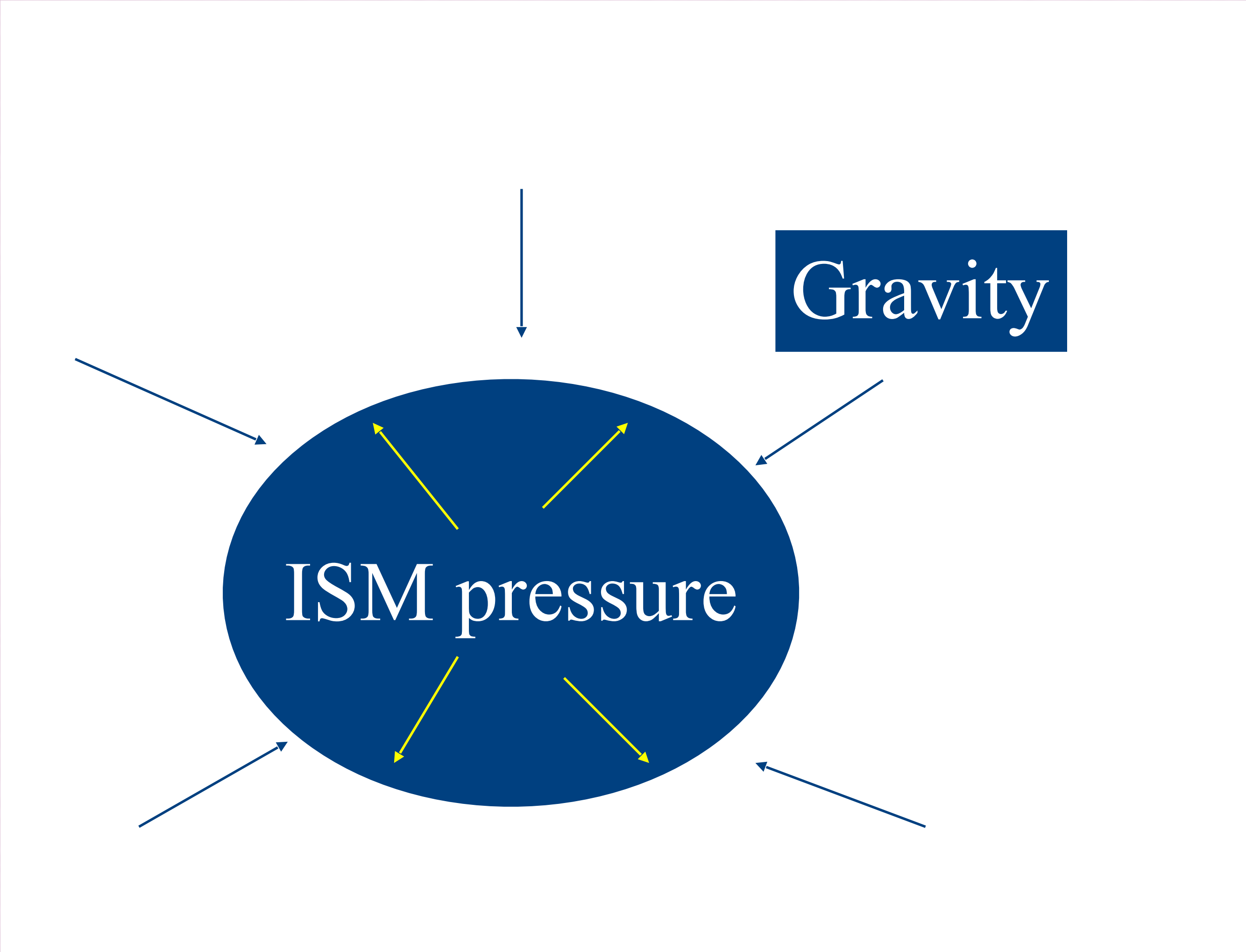
Oort Cloud



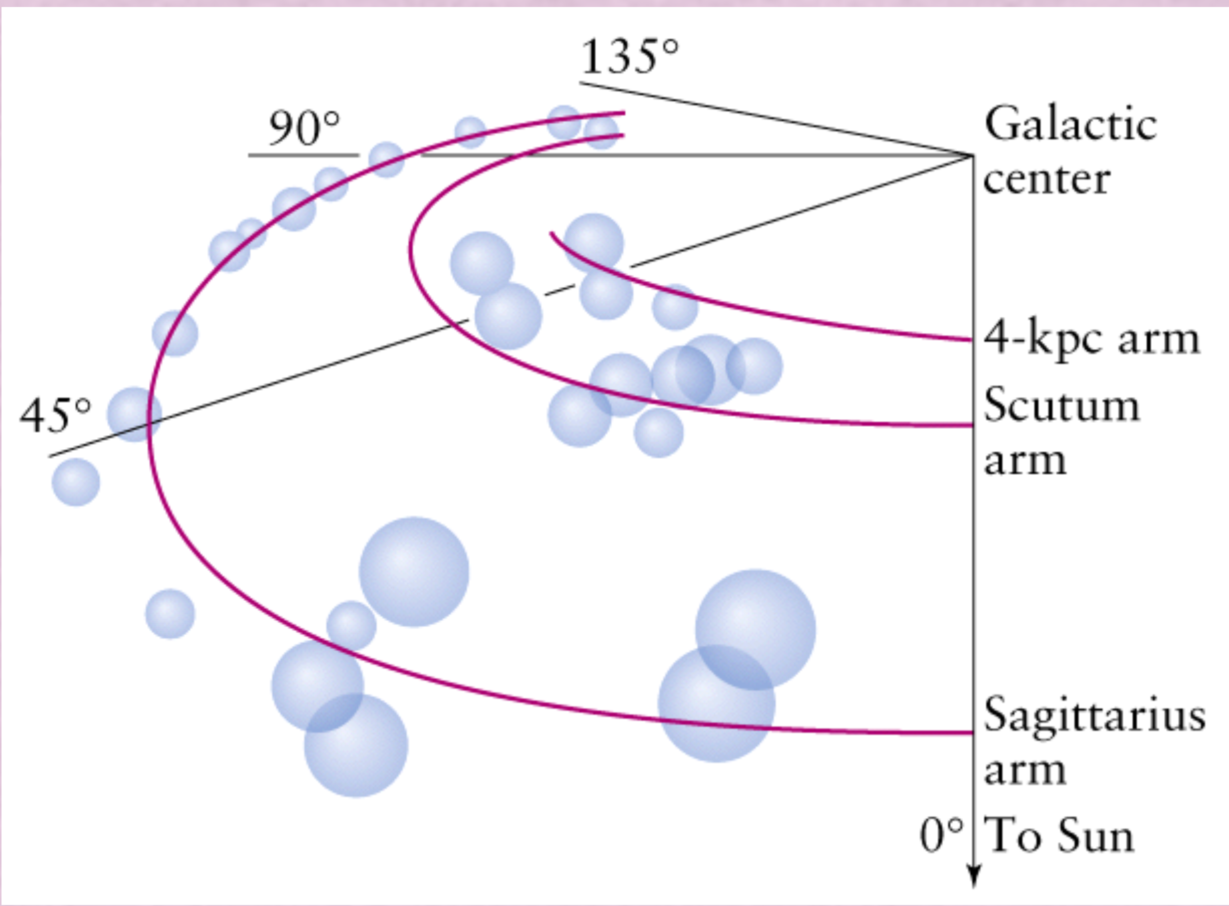
New comets
Sun
J S U N
10
10^2
Inner cloud
Returning comets
10^3
Oort cloud
10^4
Outer cloud
10^5

Star formation
Cloud collapse

- A cloud withstands gravitation by its internal pressure
- At $n \sim 10^{24}$ cm^{-3}, we get a star

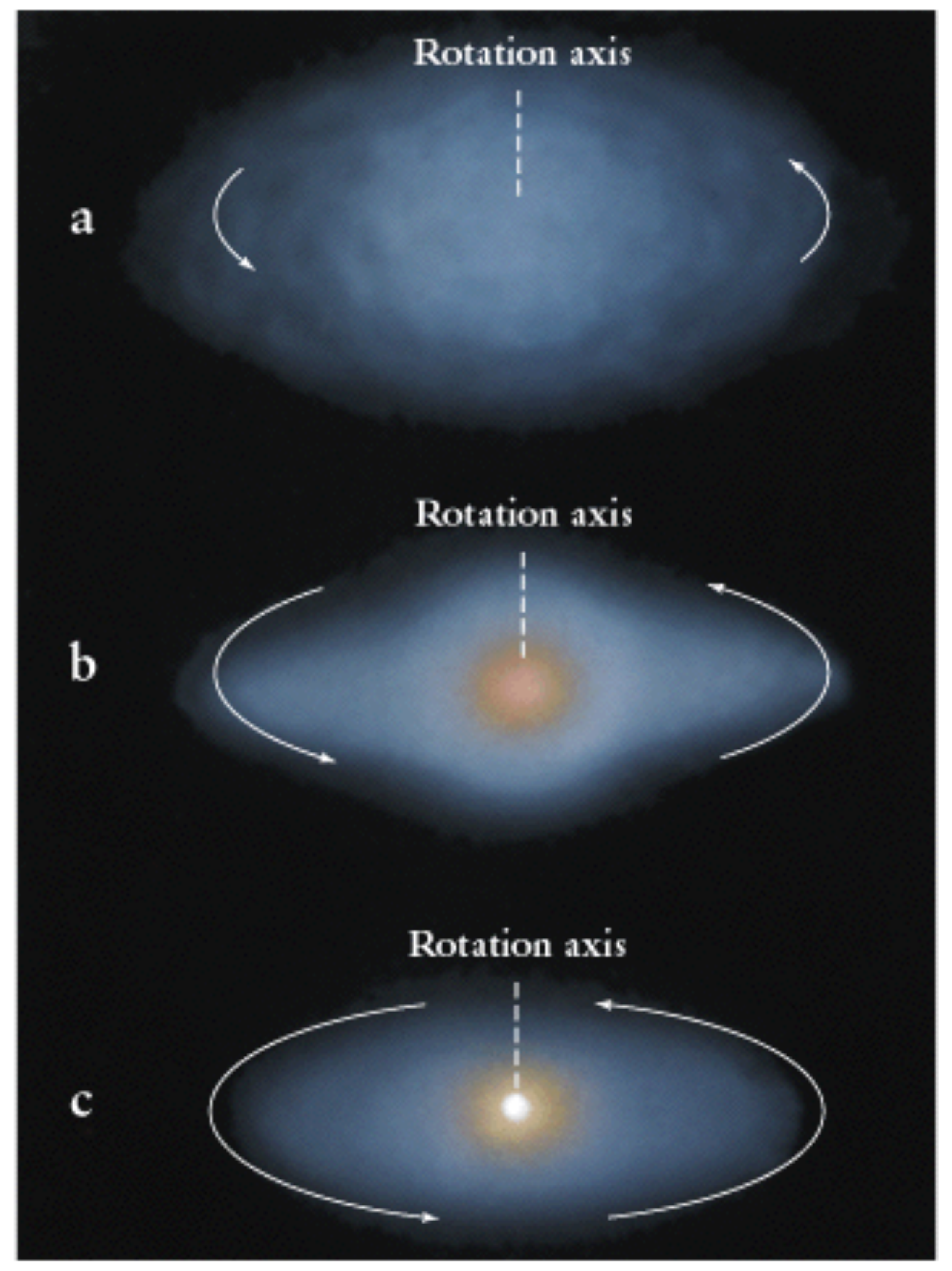


- Internal pressure sources: gas pressure from internal heat, radiation pressure
- A collapse (gravity>internal pressure) can be triggered by
  - Collisions with other clouds (cloud-cloud collisions)
  - Shocks from supernovas
  - Passage through a spiral arm in the Galaxy (density enhancement)



Star formation
"Clump" to protostar

- Gravity causes cloud to shrink
- Conservation of angular momentum will cause cloud to spin faster as it shrinks shrink
- rotation slows the collapse in the direction perpendicular to the spin axis, leading to **a flattened disk**
    - Outer parts spin-up, and form a protostellar disk through gas friction
    - this slows the collapse since protostar can only get new material through inner parts of disk (which has lost angular momentum from gas friction and magnetic diffusion).



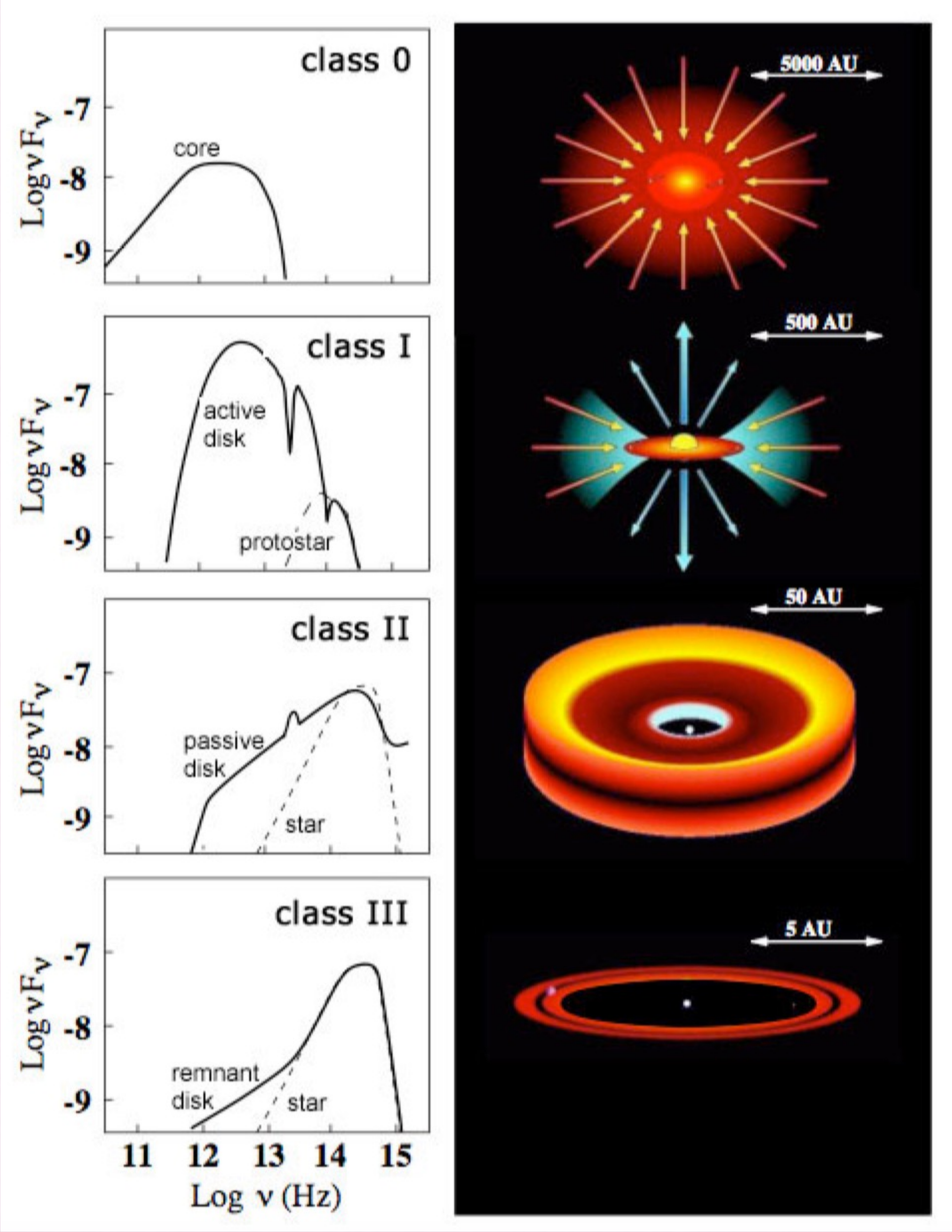
Star formation
Core ignition

- Eventually, the contracting protostar will become hot and dense enough in core for nuclear reactions to start (~a few million K).
- Enormous energy released, stopping gravitational contraction.
- The star enters the main sequence burning hydrogen to helium.

10^4 years

10^5 - 10^6 years

10^6 - 10^7 years



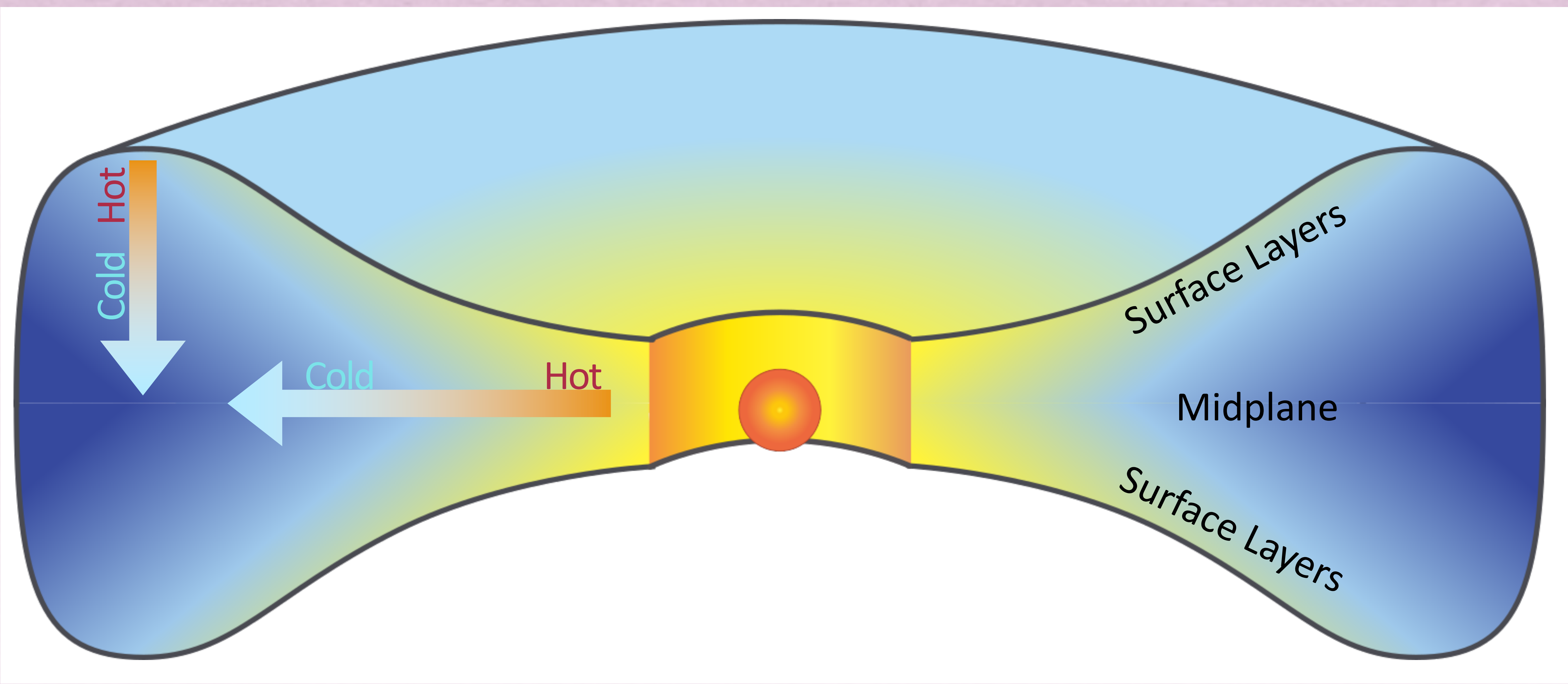
Dependence on Stellar Mass

The protoplanetary disk is responsible for planet formation around the star. Is this possible that a disk erodes away and never builds planets? If yes, what can be the possible causes?

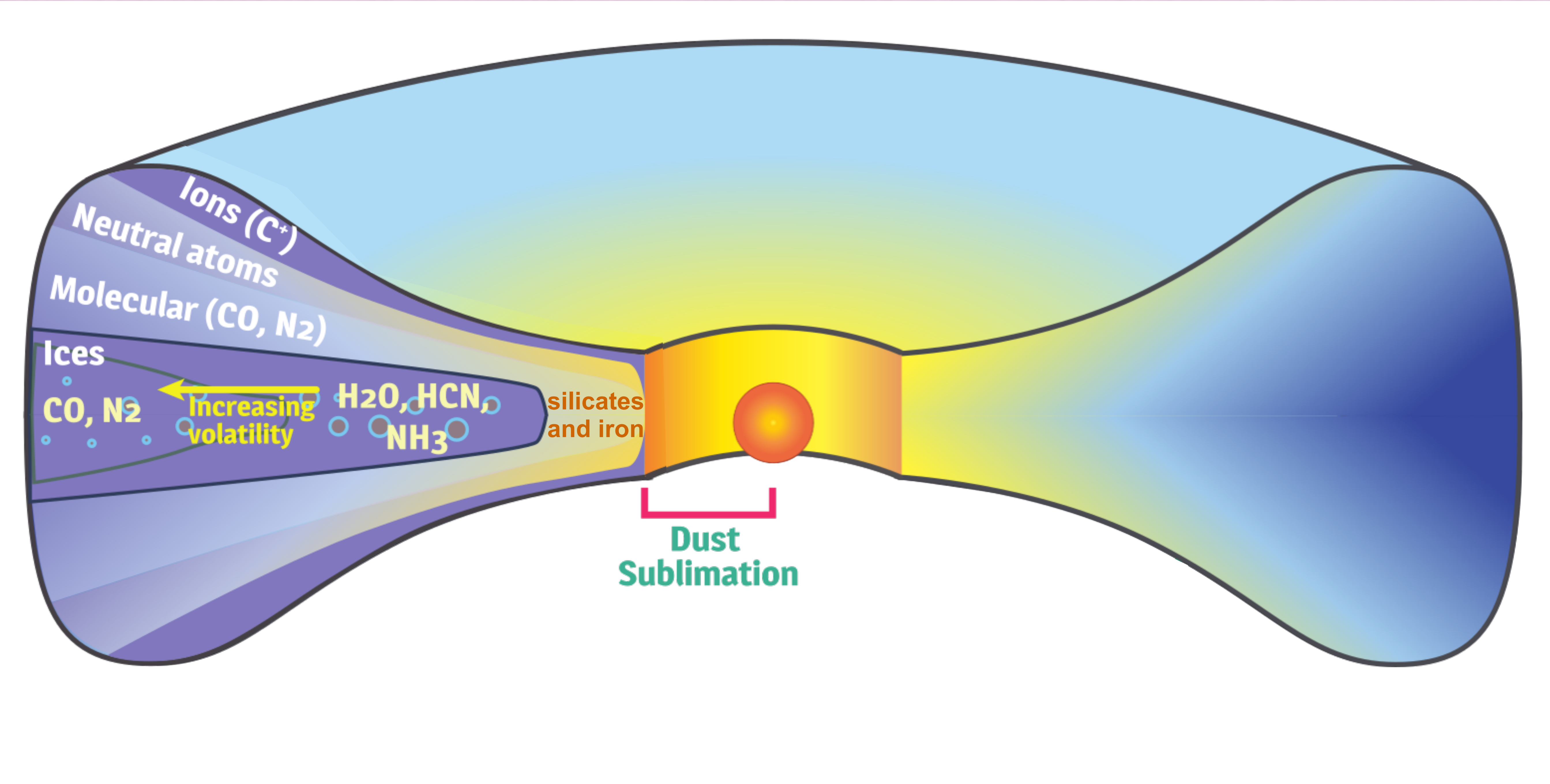
Mass (solar masses)	Time (years)	Spectral type
60	3 million	O3
30	11 million	O7
10	32 million	B4
3	370 million	A5
1.5	3 billion	F5
1	10 billion	G2 (Sun)
0.1	1000s billions	M7

Images of Disks (Optical-NIR)

Disk Structure



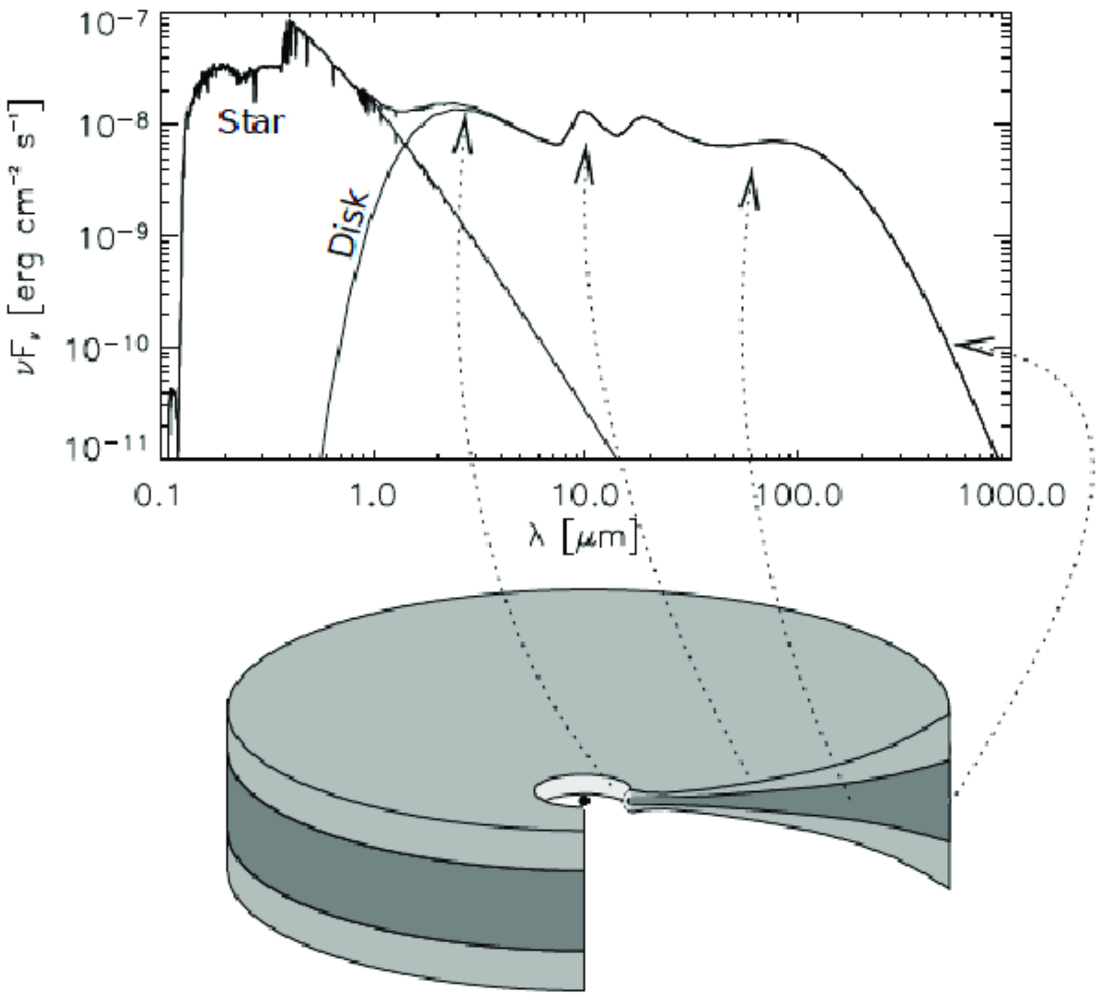
Disk Structure



Disk Structure

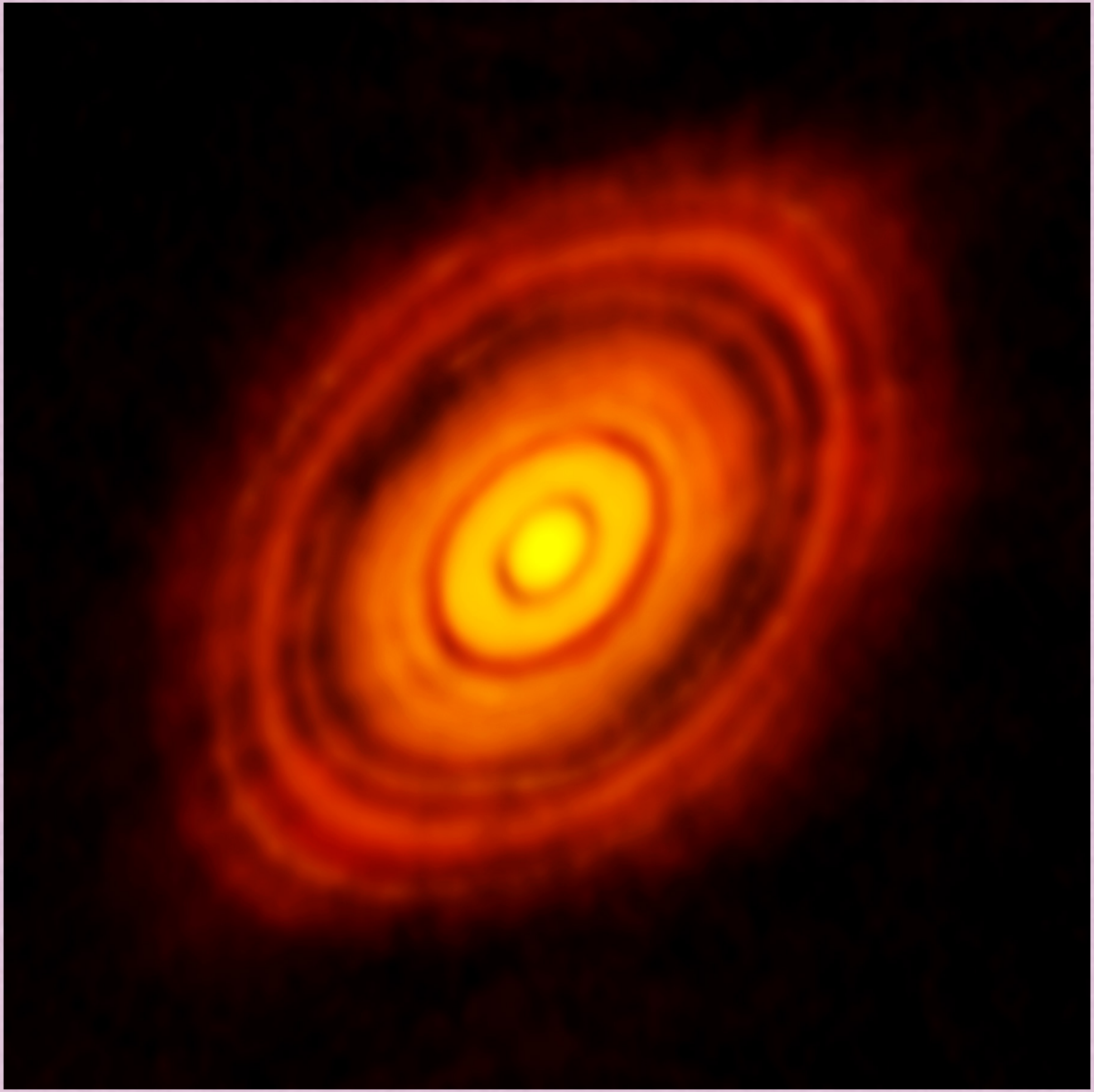
- IR = disk surface closer to the star (0.1 - 10s of AU)
- sub-mm = larger distances and deeper into the disk

Disks are optically thick in infrared and optically thin in millimeter

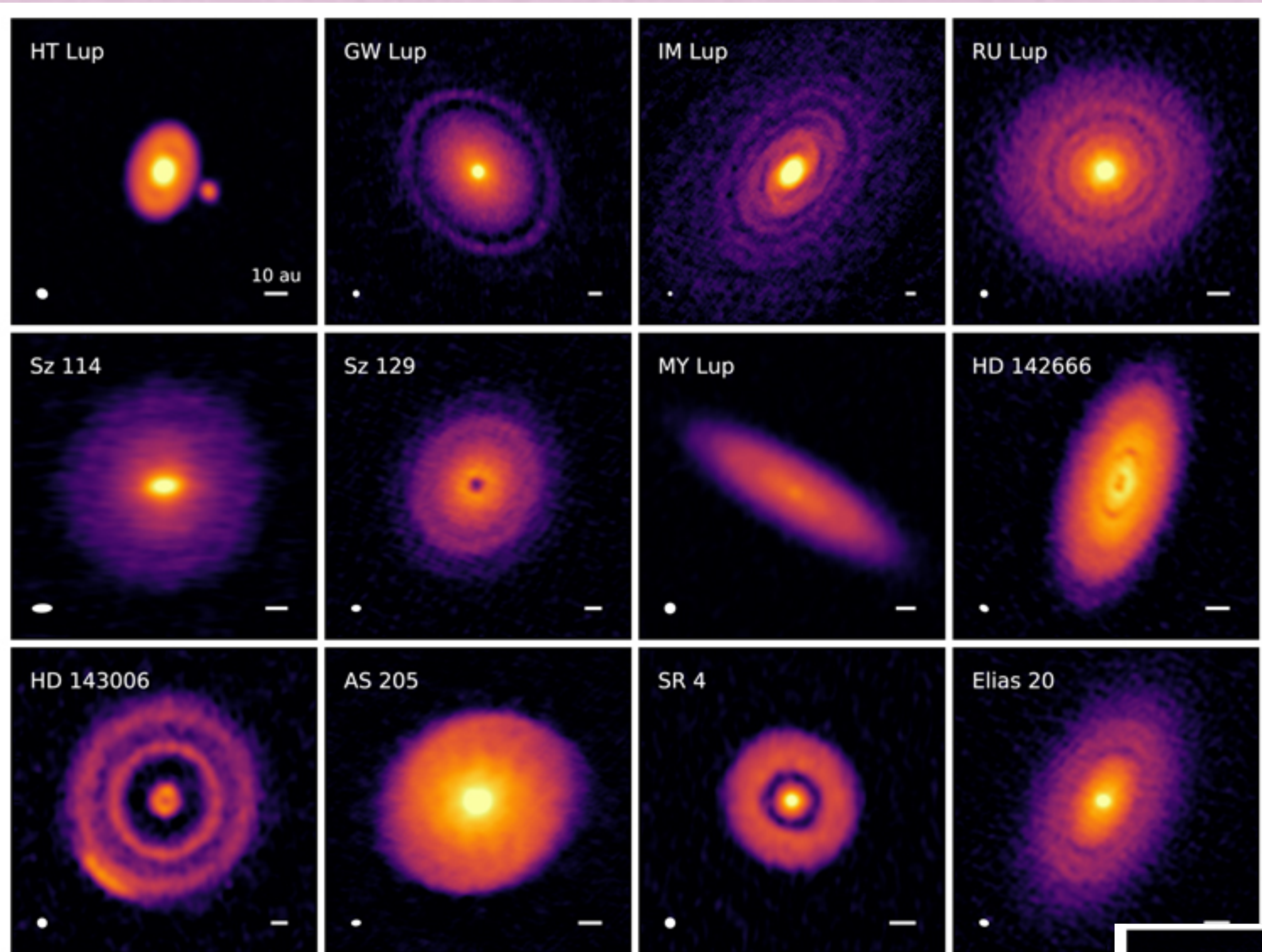


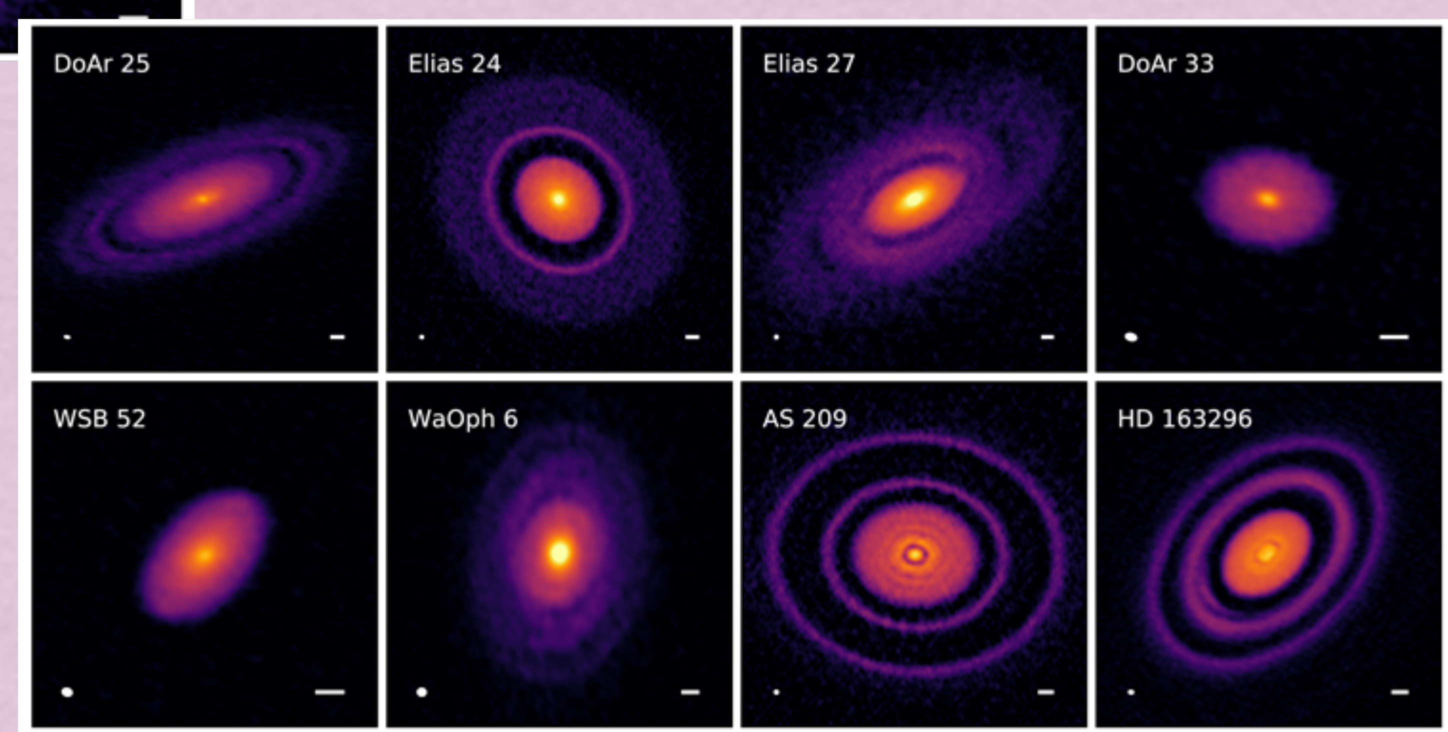
Atacama Large Millimeter Array

HL Tau (ALMA image)



Images of Disks (mm)





Andrews et al. (2018)

A Solar System Planet Formation Model Must Explain Its Properties

- **Orbits + angular momentum distribution:** circular vs. eccentric; is SS packed?
- **Sizes and densities of planets:** density ~decreases with distance
- **Shapes and densities of small bodies:** porous! esp. R < 100 km
- **Asteroid and Kuiper belts + Comets**
- **Moons**
- **Rings:** interior to largest moons
- **Age:** chondritic meteorites -> 4.568 Gyr -> formed very early; Earth+Moon rocks are younger.
- **Meteorites:** cool grains + heated inclusions -> mixing of solids in the disk; similar ages -> fast accretion period
- **Isotopic composition:** isotopic ratios mostly uniform, some variation from radioactive decay/incomplete mixing; also: where did the short-lived initial isotopes come from?
- **Differentiation:** needs melting -> implies high T at some point in past
- **Composition of atmospheres:** H abundance lower than Sun, metal abundances higher than Sun.
- **Surface structure:** some surfaces are too cratered to explain with today's impact rates