Reading: Chap. 21, Sect.21.1, 21.3-21.6
Final Exam: Wednesday, December 18; 4:30-6:30PM - **Room: *MacKay 0117***
Homework 10: Due in recitation Dec. 6 / 9

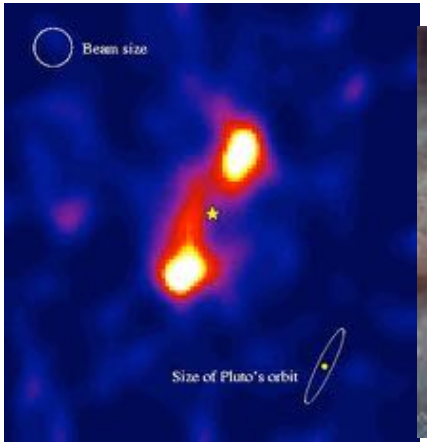
Last time: Our Sun

- The SUN:
  - statistics
  - photosphere, chromosphere, corona
  - the solar magnetic cycle
- Source of the Sun's energy:
- Hydrogen Fusion
  - energy source for 10 billion years

Today: **Formation of Planetary Systems**

- Observational Clues: from our current Solar System & the stars
- Collapse of interstellar cloud
  - collapse, fragmentation, spinup and disk formation
- The Solar Nebula (the SS 4.6 Gyr ago)
- Planet formation
  - differential condensation & the frost line
  - accretion - growth of planetessimals

The Solar Nebula Theory



http://www.jach.hawaii.edu/JCMT/publications/newsletter/n16/fom_ann.jpg

The planets formed in a dust-filled disk of gas surrounding the very young Sun

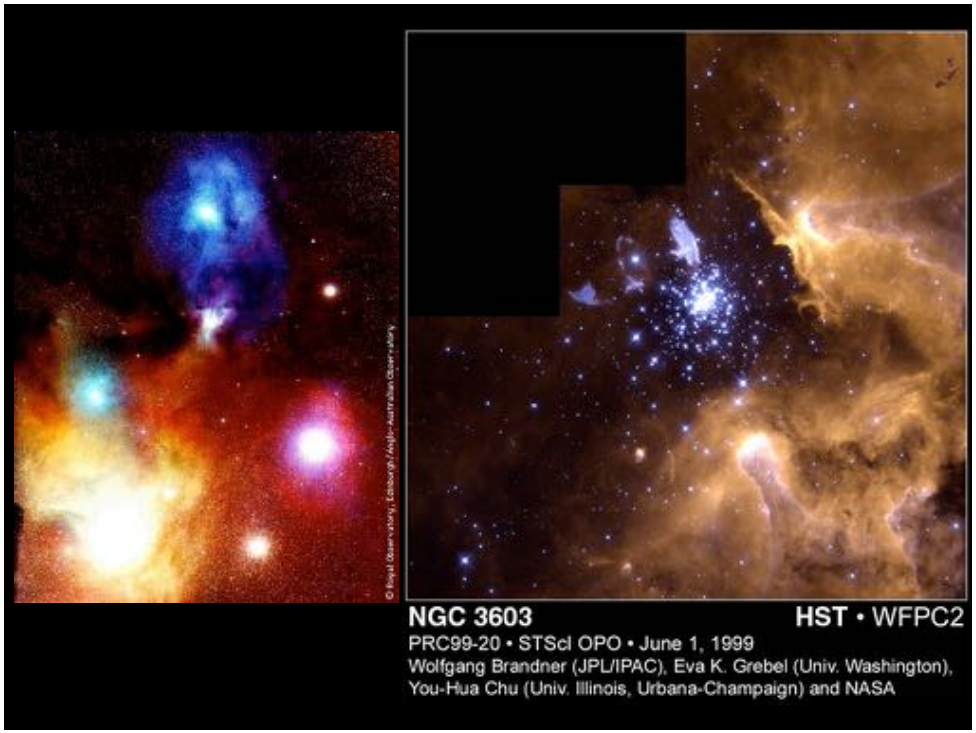
Formation of Planetary Systems

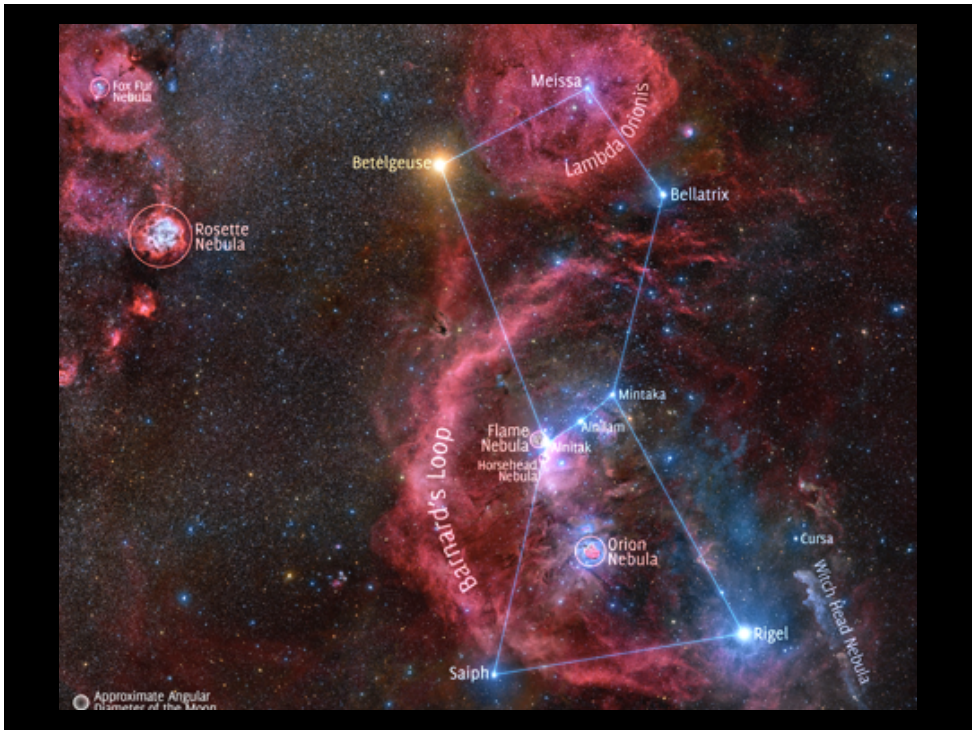
- Where to begin?
  - Evidence from our current Solar System
  - Evidence from the Stars
- First phases: collapse to star plus disk
  - interstellar cloud – gravity takes over
  - angular momentum – disk formation
- The Solar Nebula
  - mass and composition
  - temperature distribution
- Planet formation
  - condensation
  - accretion into planetessimals
  - accretion into planets and satellites

Where to begin?

- Evidence from our current Solar System
  - all planetary orbits are
    - counterclockwise
    - nearly circular
    - in the same plane

    } **Planets formed out of a disk**
  - inner planets are rocky
  - outer planets are gas balls
- Evidence from the Stars
  - there are many other solar systems
  - there are many multiple star systems
  - youngest stars are embedded in dust and gas

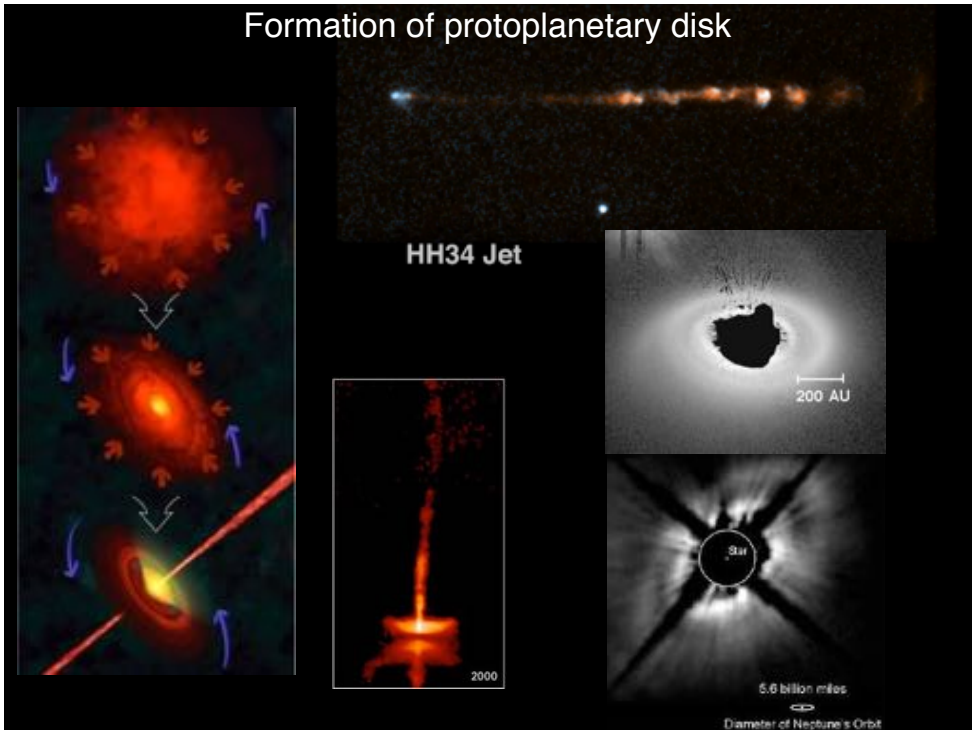


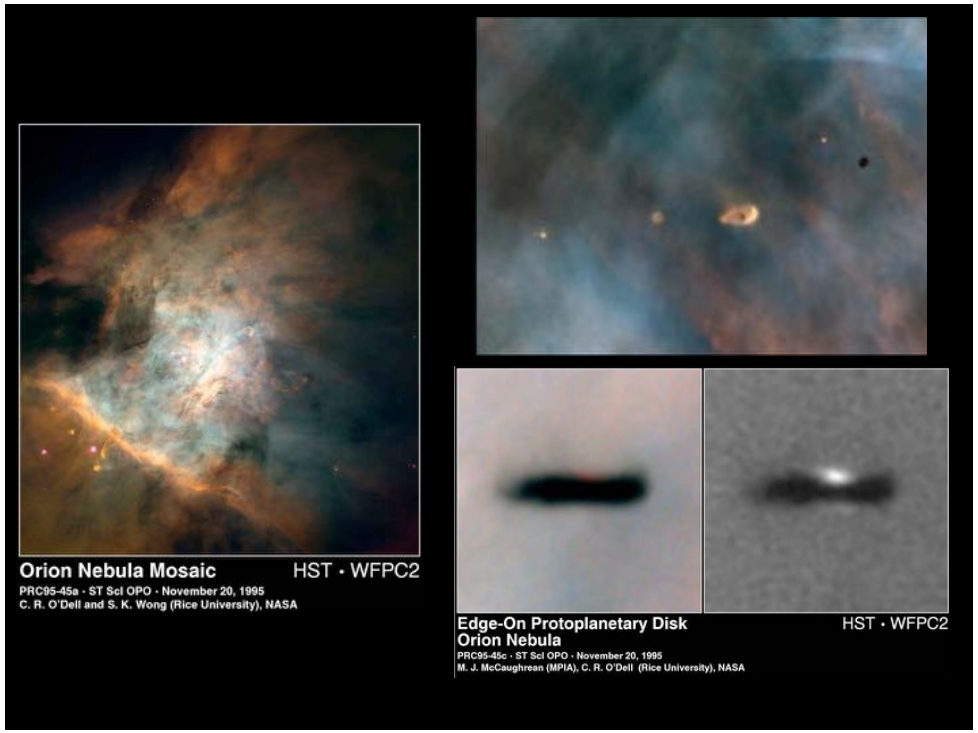


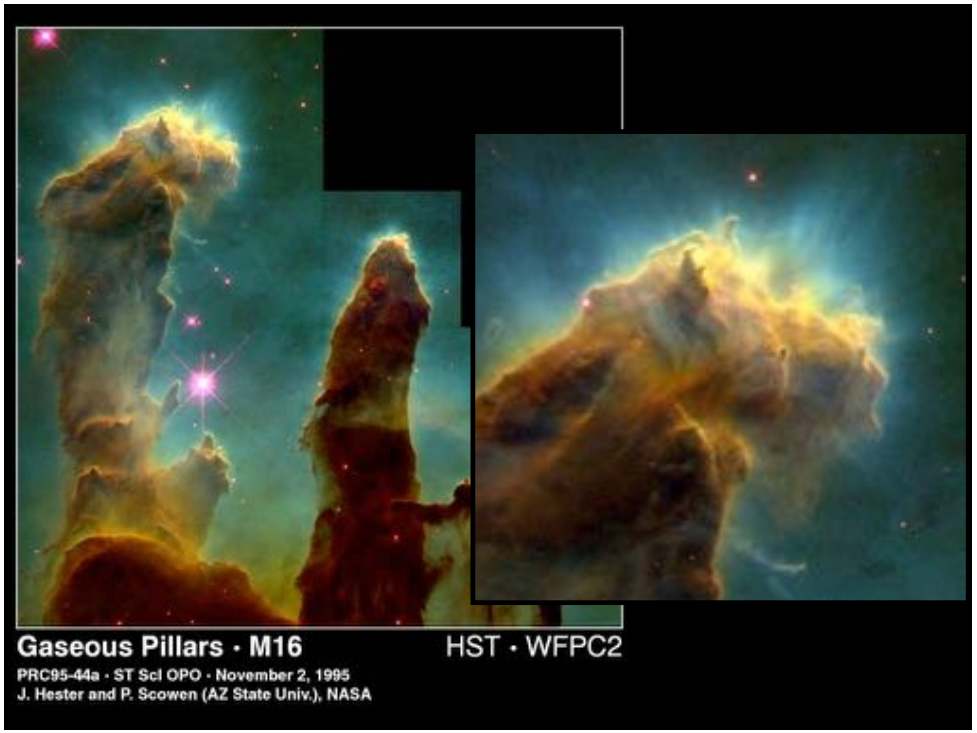
First phase: collapse of interstellar cloud

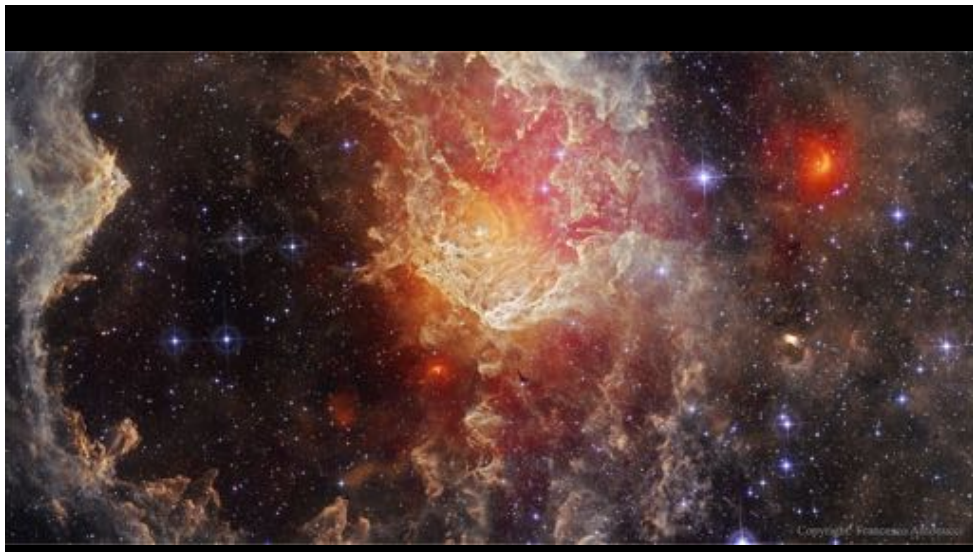
- Molecular Clouds: clumps of interstellar medium
  - mass: up to 10^6 Msun
  - radius ~ 10 - 30 pc
- To make stars, a cloud must undergo Gravitational Collapse

- Collapse –> Spin-up –> formation of **Disk**
  - HST observations of Orion disks
  - HST observations of "Eggs" in M16
  - β Pictoris









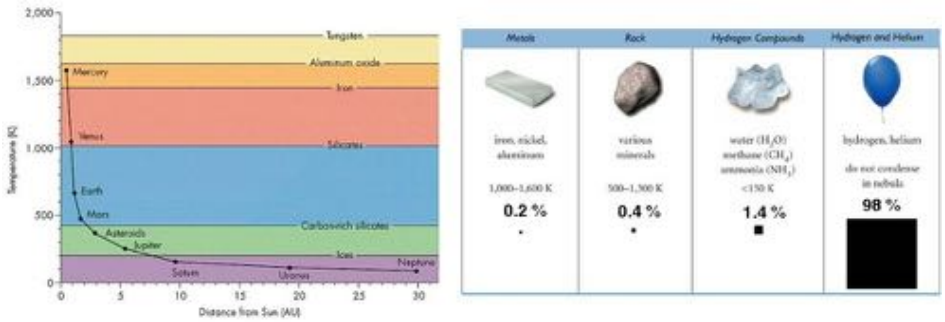
NGC7822 with WISE

The Solar Nebula (the SS 4.6 Gyr ago)

- Composition - same as the Sun
  - 74% Hydrogen
  - 24 % Helium
  - 2% "heavies" (C, O, Si, Fe)
- Mass:
  - need enough heavies for Earth, cores of Jovians
  - total mass ~ 0.1 x M_{sun}
- Temperature
  - hot in inner parts (2000K)
  - cooler with distance out (700K at Earth...)
- Size
  - 1 a.u. thick
  - extent well beyond Pluto's current orbit

Planet Formation - Condensation

- Condensation
  - 2000K is hot enough to melt all “heavies”
  - nebula cools, compounds “freeze out”
  - inner nebula
    - heavies condense into microscopic grains
    - iron, silicates (minerals and rocks)
    - **but “ices” still gaseous**
  - outer nebula - outside the **FROST LINE**
    - ices condense into grains



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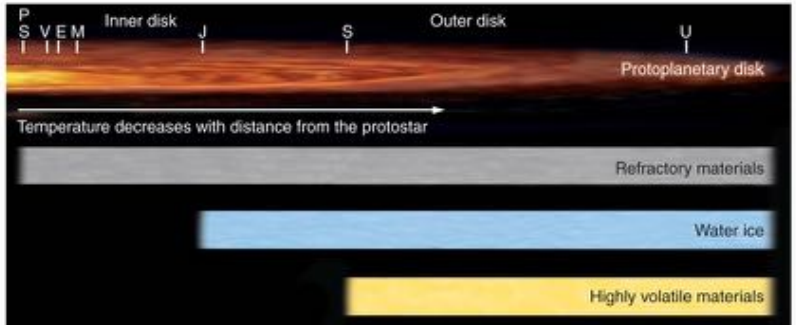

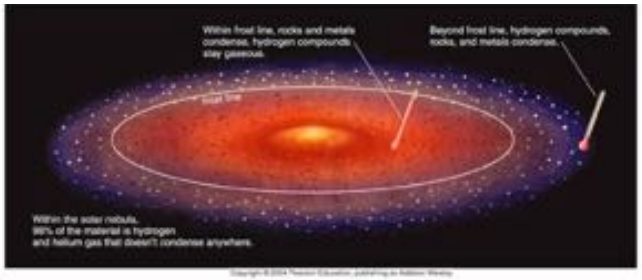

Planet Formation - Accretion

- Accretion
  - grains collide and stick —> planetessimals
  - planetesimals grow by further collisions
    - gravity holds them together when big enough
  - some planetesimals eventually become very large
  - final sweeping up into present planets

All this took a VERY SHORT time
••• less than 100 million years after initial collapse

Final Formation Stages

- Sun “Turns On”
  - solar wind blows remaining gas away
  - planet growth largely ceases

- End of Planetary Formation Phase
  - final large-scale collisions
    - Earth–Moon system
    - Mercury core formation
  - internal melting, differentiation
  - satellite formation/capture
  - large-scale sweeping/bombardment

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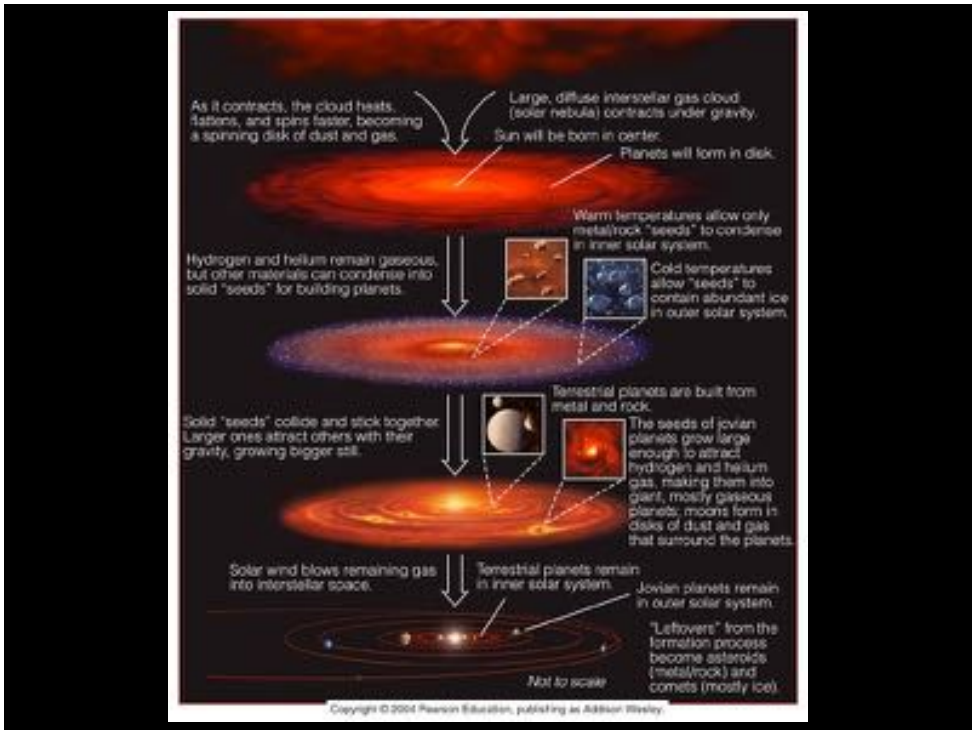
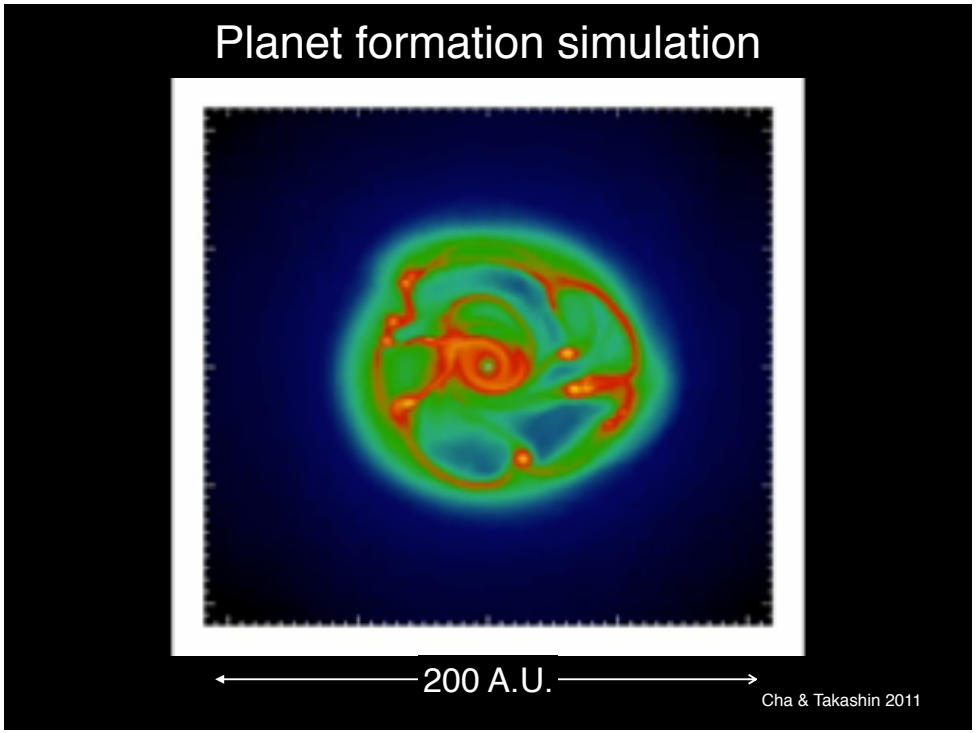
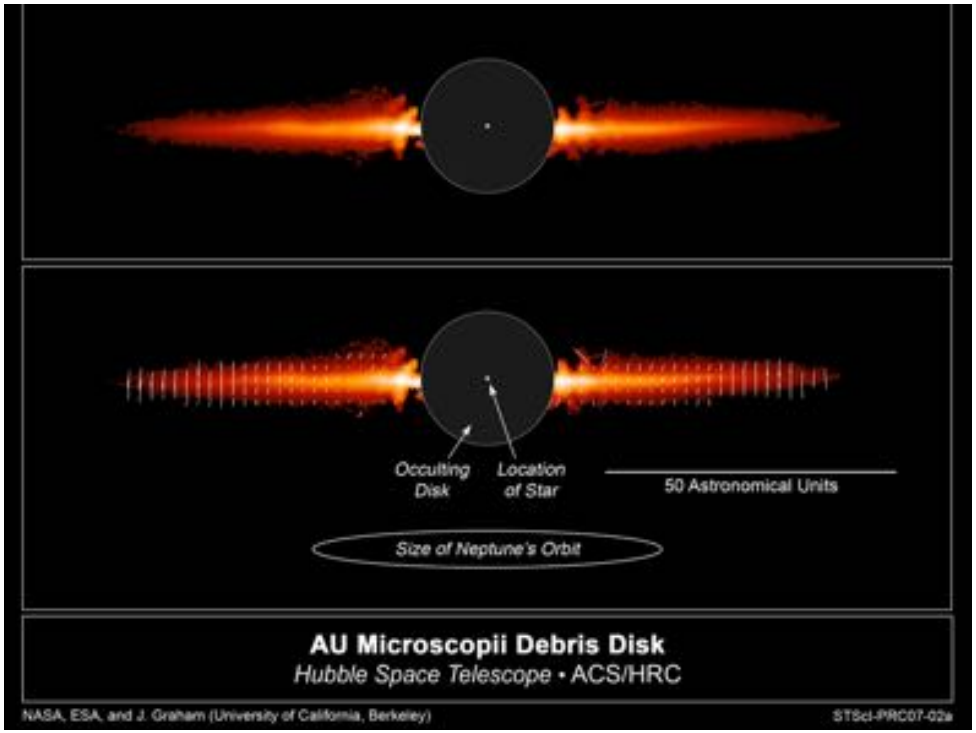
••• less than 100 million years after initial collapse

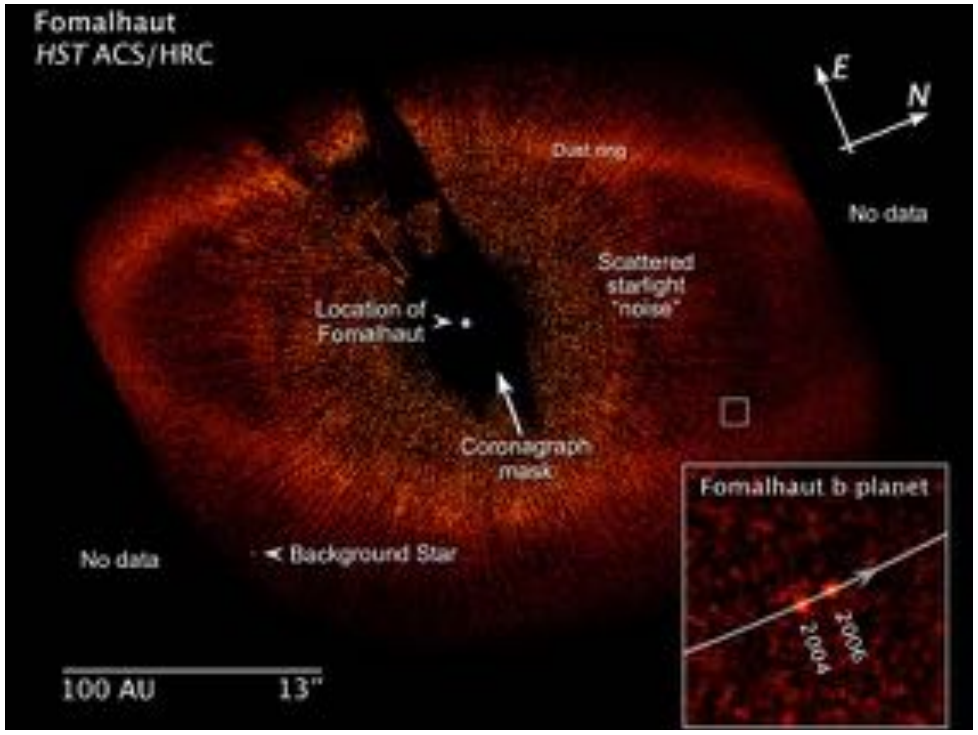


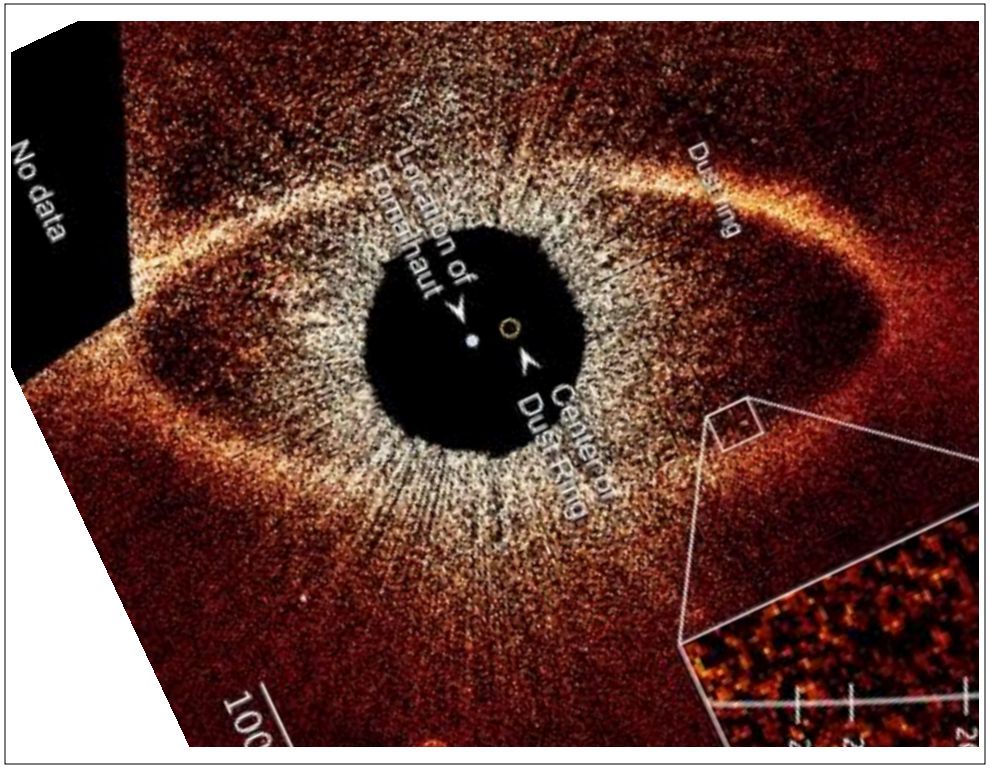


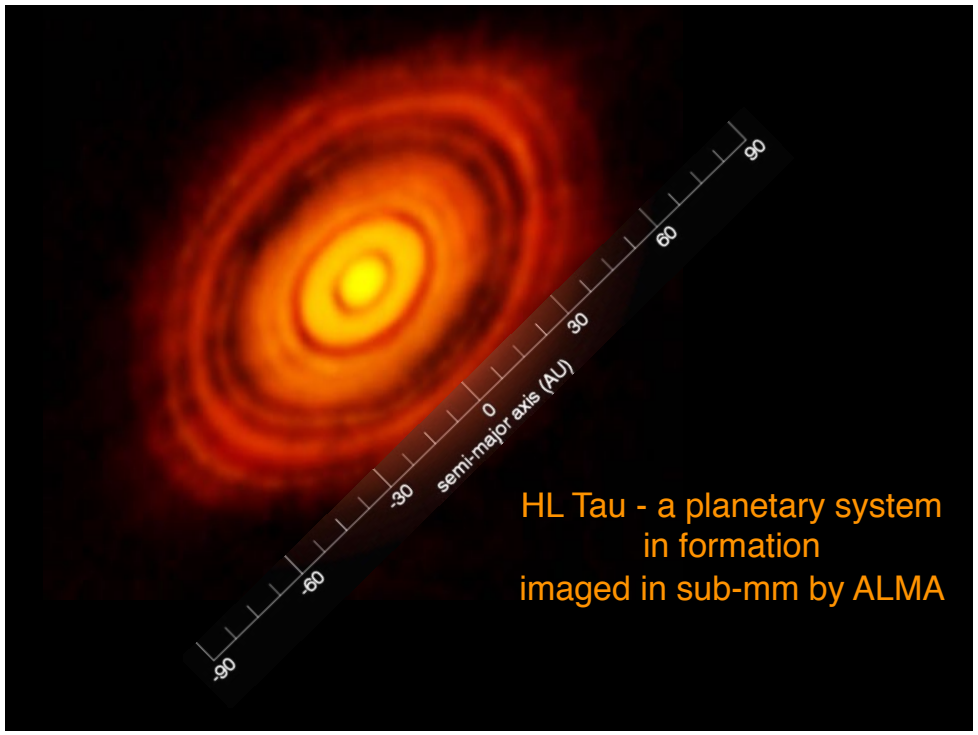
Observations - explained by the solar nebula theory

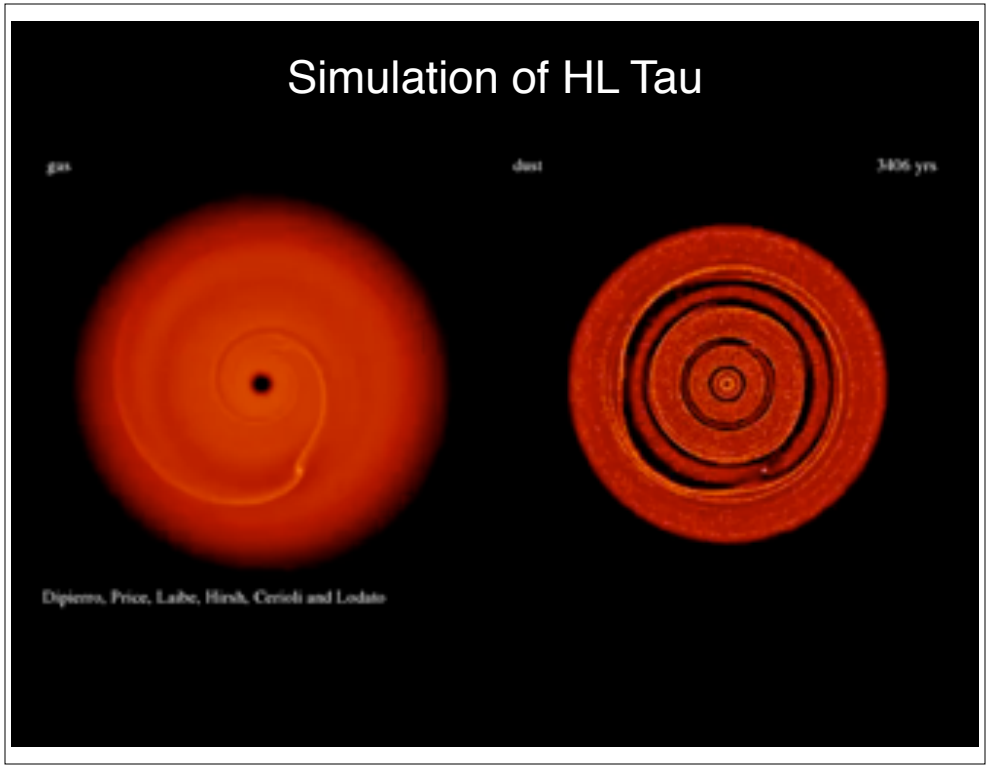
- **Orderly motions of planets**
  - arise naturally for objects formed within a spinning, flattened disk
- **Two types of planets**
  - ***within frost line*** - most abundant stuff is gaseous form only small, rocky planets
  - ***beyond frost line*** - ices more readily accrete more stuff to make big planets
- **Oddball exceptions**
  - final accretion stages - collisions, migration, and other 'accidents'




Fomalhaut
HST ACS/HRC
E
N
Dust ring
No data
Scattered
starlight
"noise"
Location of
Fomalhaut
Coronagraph
mask
Fomalhaut b planet
2006
2004
No data
Background Star
100 AU
13"


No data
Location of
Fomalhaut
Center of
Dust ring
Dust ring


90
60
30
0
-30
-60
-90
semi-major axis (AU)
HL Tau - a planetary system
in formation
imaged in sub-mm by ALMA


Simulation of HL Tau
gas
dust
3406 yrs
Dipierro, Price, Laibe, Hirsh, Cerioli and Lodato