

## Formation of Stars (and planetary systems)

Star Formation sites: "Giant molecular clouds"

$$M = 10 - 10^6 M_{\odot}$$

$$R = \text{10s of pc} \quad (1 \text{ pc} = 2 \times 10^5 \text{ au})$$

$$T = 10 - 100 \text{ K (cold!)}$$

Condition for grav. collapse to be allowed:  
must be unable to maintain HSE

$$E_{\text{grav}} \approx \frac{GM^2}{R}$$

$$E_{\text{therm}} \approx n_{\text{H}} kT \cdot \frac{4}{3} \pi R^3$$

$$= \frac{M N_{\text{Avo}} kT}{\mu}$$

Collapse if  $E_{\text{therm}} < E_{\text{grav}}$

$$\frac{M N_{\text{Avo}} kT}{\mu} < \frac{GM^2}{R}; R < R_{\text{crit}} = \frac{GM\mu}{N_{\text{Avo}} kT}$$

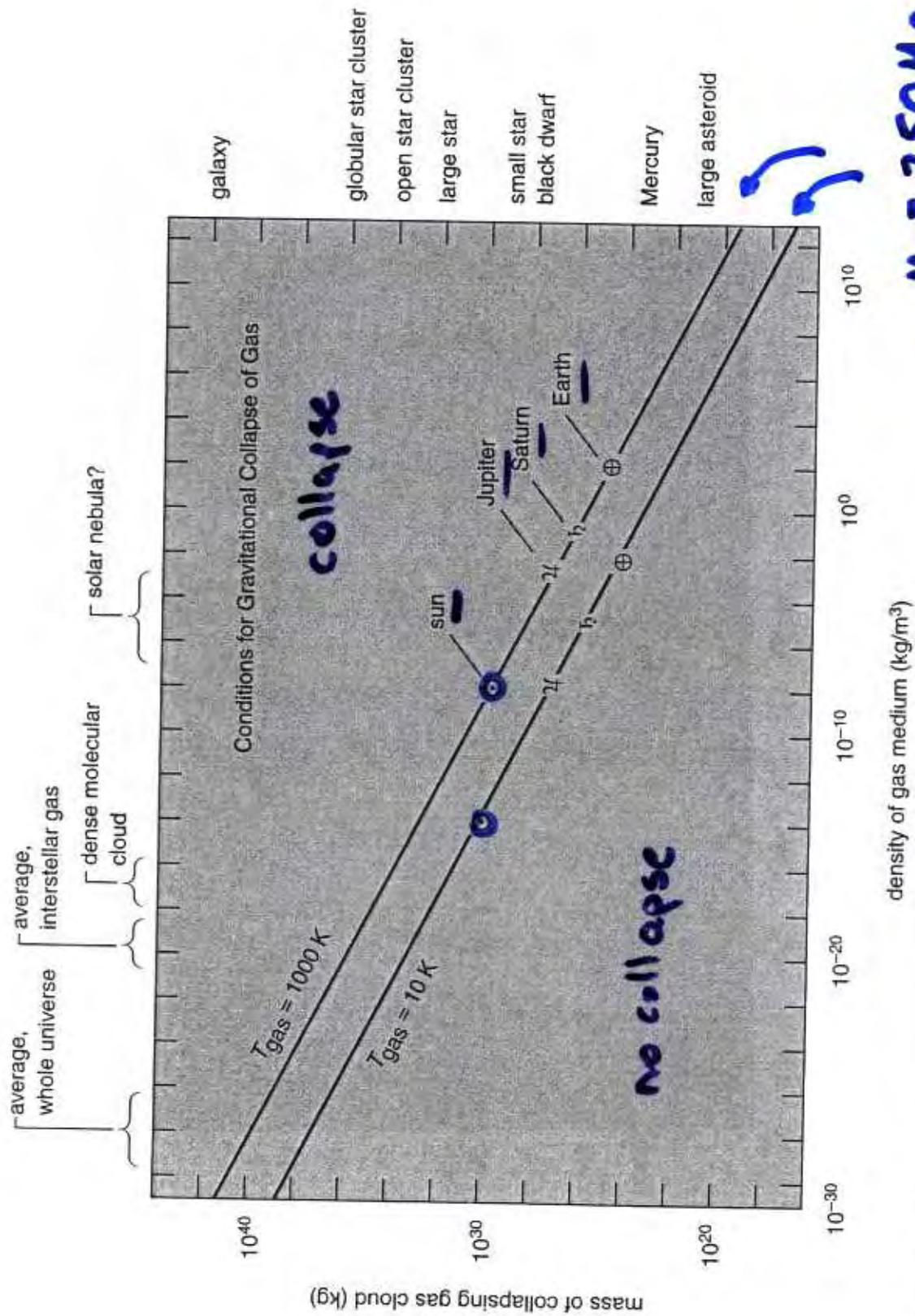
plugging in numbers:  $R_{\text{crit}} = 0.05 \text{ pc} \left(\frac{M}{M_{\odot}}\right) \mu \left(\frac{T}{10 \text{ K}}\right)^{-1}$

Jupiter  
Mass scale

-or- since  $M = \frac{4}{3} \pi R^3 \frac{n \mu}{N_{\text{A}}}$

$$R_{\text{crit}} = 4.03 \text{ pc} \cdot 13.7 \text{ pc} \left(\frac{T}{10 \text{ K}}\right)^{+1/2} \left(\frac{n}{1 \text{ cm}^{-3}}\right)^{-1/2}$$

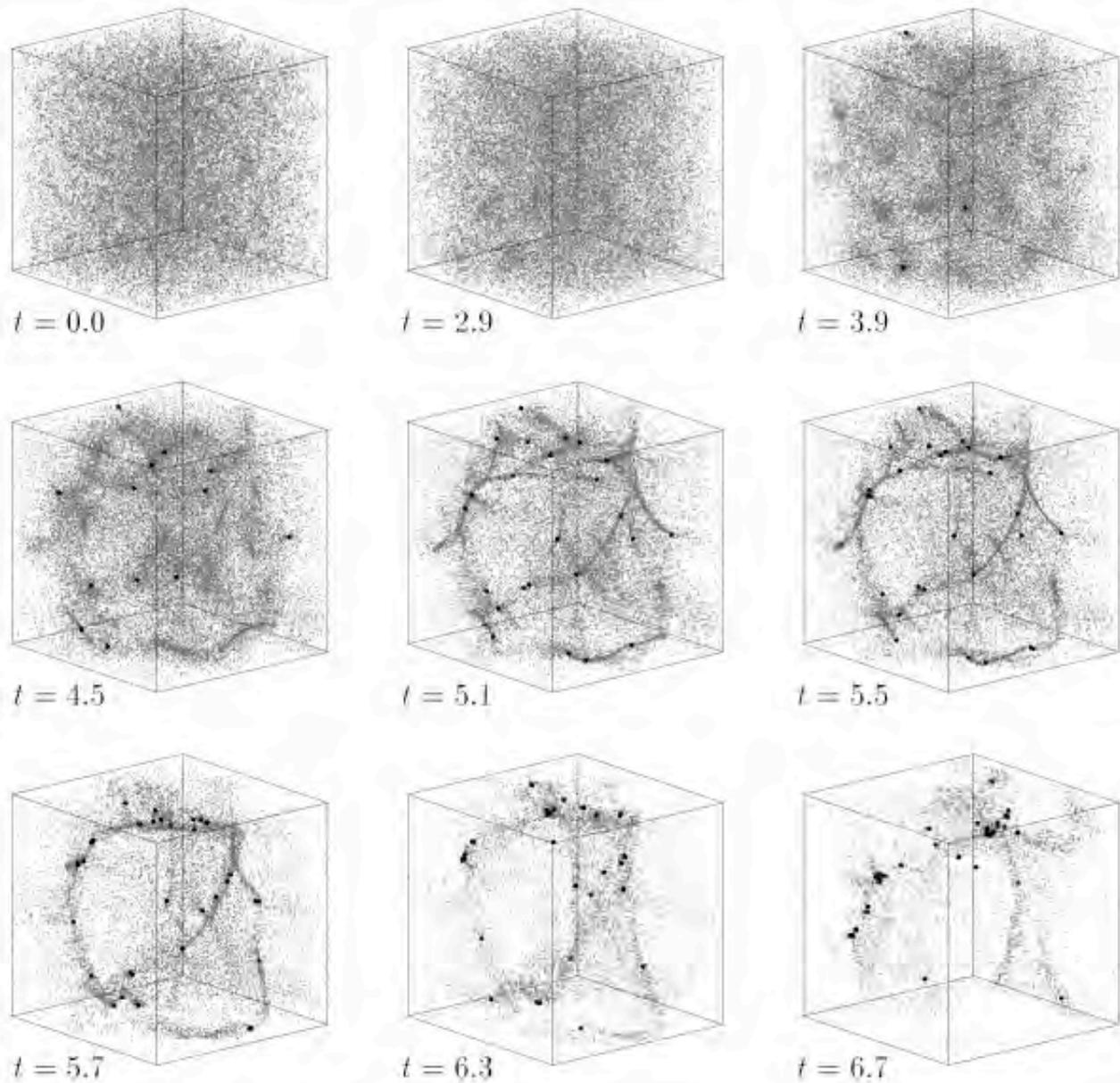
-or-  $M_{\text{crit}} > 790 M_{\odot} \left(\frac{T}{10}\right)^{3/2} \left(\frac{n}{10}\right)^{-1/2} \mu^{-2}$



**Figure 4-3.** A guide to formation of astronomical objects by means of gravitational collapse. A diagonal line for each specified temperature shows the minimum density of gas (bottom scale) at that temperature required to initiate collapse in a gas cloud of specified mass (left scale). Clouds to the right of their appropriate temperature line would tend to collapse; clouds to the left would not.

**Fig. 3**
[CITED IN TEXT](#) | [HI-RES IMAGE](#) (814kb) | [←](#) [→](#)

Time evolution of model **A1b**. It contains  $5 \times 10^5$  SPH particles, and the initial density distribution is generated from a fluctuation spectrum with  $\nu = 1$  that is truncated for modes  $k < 4$ . The snapshots correspond to the following stages of the dynamical evolution:  $t = 0.0$ , initial particle distribution;  $t = 2.9$ , the maximum density contrast has reached half the value required to identify compact objects as protostellar cores;  $t = 3.9$ , the first protostellar cores have formed and contain, altogether,  $M_* = 2\%$  of the total gas mass;  $t = 4.5$ ,  $M_* = 10\%$ ;  $t = 5.1$ ,  $M_* = 30\%$ ;  $t = 5.5$ ,  $M_* = 50\%$ ;  $t = 5.7$ ,  $M_* = 60\%$ ;  $t = 6.3$ ,  $M_* = 75\%$ ; and  $t = 6.7$ ,  $M_* = 85\%$ . For legibility, only every tenth nonaccreted gas particle is displayed (*small gray dots*). Protostellar cores are denoted by large dark dots.



Some things to note:

At typical ~~mass~~ densities & temperatures,  
Mass scale for collapse is of order  
Star cluster scale

But we've got issues

- stars are smaller  
as  $\rho \uparrow$ ,  $M_{crit} \downarrow \rightarrow$  fragmentation
- rotation neglected

$\Omega \sim \Omega_{galaxy}$  is  $1/2 \times 10^8 \text{ yr}^{-1} \sim 1.6 \times 10^{-16}$

~~But~~

$$\frac{E_{rot}}{E_{grav}} = \frac{MR^2\Omega^2}{GM^2/R} = \frac{\Omega^2 R^3}{GM} \approx \frac{\Omega^2}{\rho G}$$

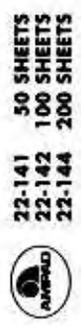
$$= \frac{\Omega^2 N_A}{\mu \rho} = 0.23 \left( \frac{\Omega}{1.6 \times 10^{-16}} \right)^2 n^{-1} \mu^{-1}$$

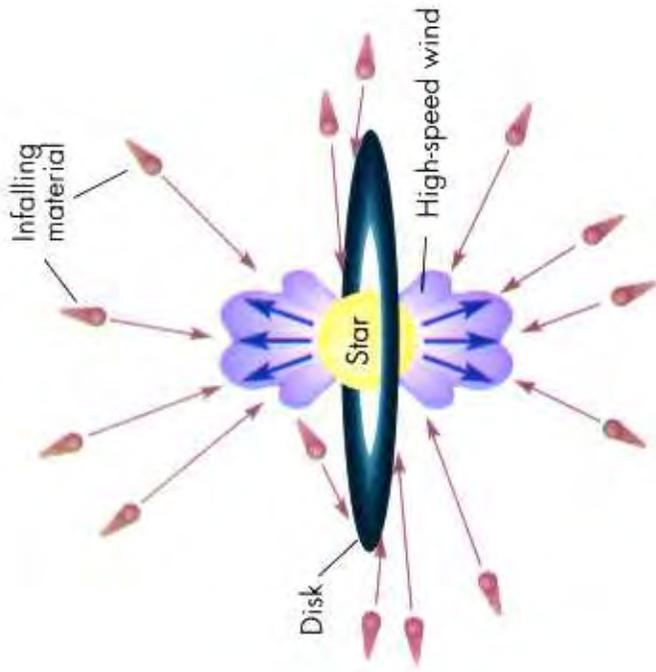
$J = MR^2\Omega$

for critical  $M, R$ ;  $J = \frac{9 \times 10^{68}}{7.65 \times 10^{52}} \left( \frac{T}{10K} \right)^{5/2} \left( \frac{n}{10} \right)^{-3/2} \mu^{-4} \left( \frac{\Omega}{1.6 \times 10^{-16}} \right)$

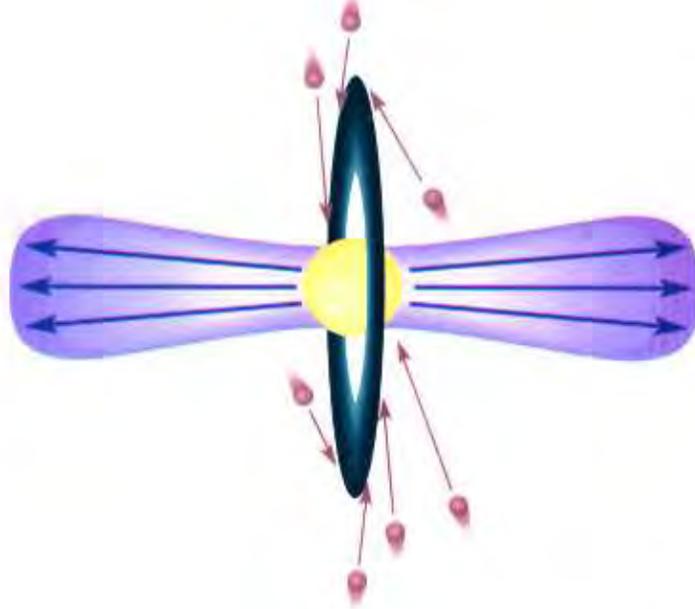
But  ~~$\Omega_{breakup}$~~   $R \Omega_{breakup} = \sqrt{\frac{GM}{R}}$ ;  $\Omega_{breakup} = \sqrt{\frac{GM}{R^3}}$

as  $R \downarrow \Omega \uparrow$  as  $R^2$   
 $\Omega_{crit.} \uparrow$  as  $R^{3/2} >$  eventually,  
 ~~$\Omega$~~   $\Omega > \Omega_{B.U.}!$





**A** Infalling material suppresses the wind.



**B** Eventually the wind becomes strong enough to break through along the polar axes.



**C** Later the wind sweeps away the disk and blows outward in all directions.

This is the angular momentum problem!

Solution remains elusive;

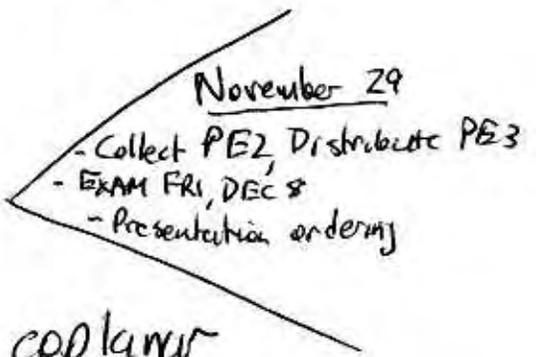
- magnetic braking?
- mass ejection (jets)
- angular momentum transport via disks?

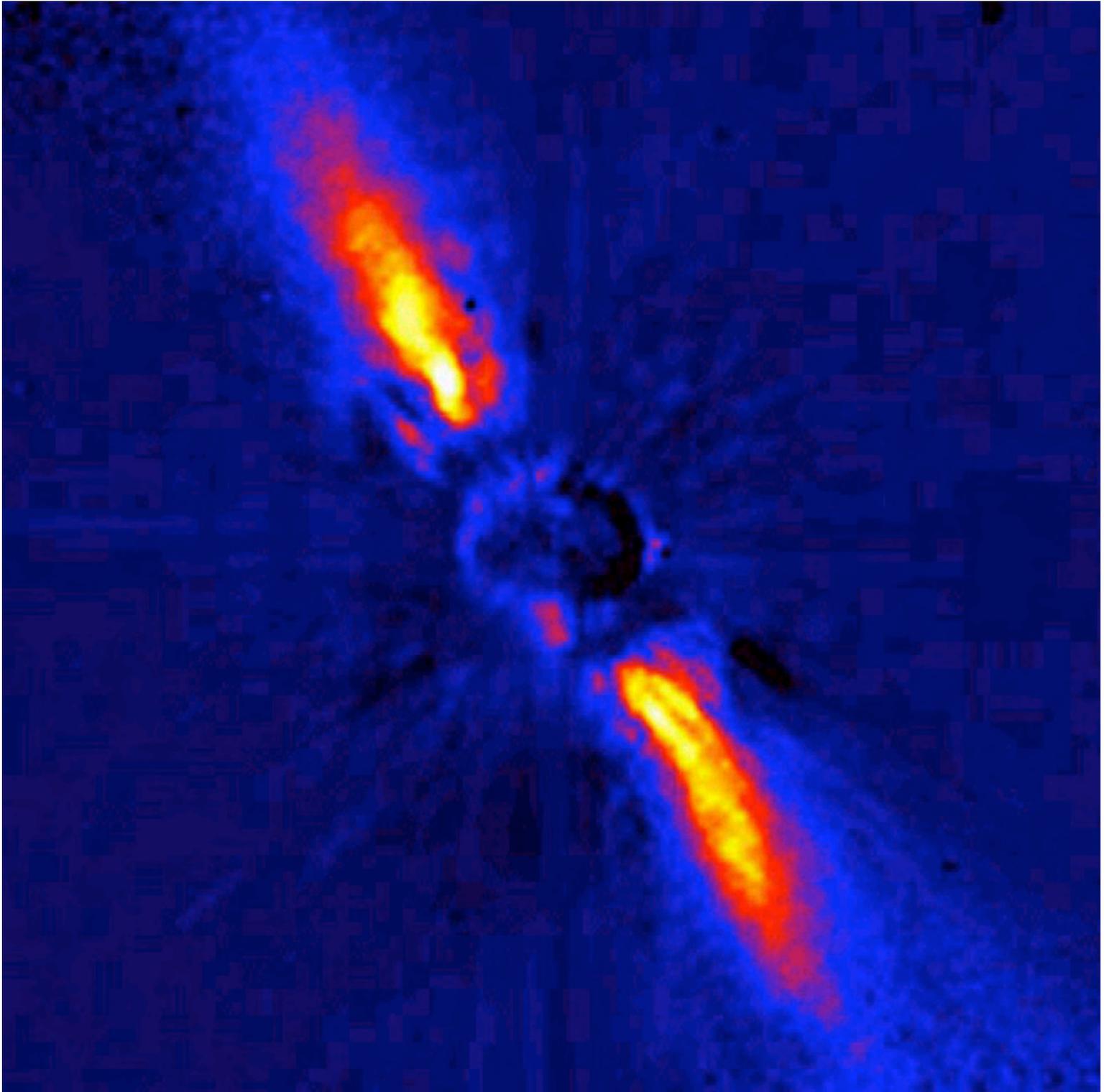
Disks must form about the equators of protostars → and it is within these disks that planets can (and do) form.

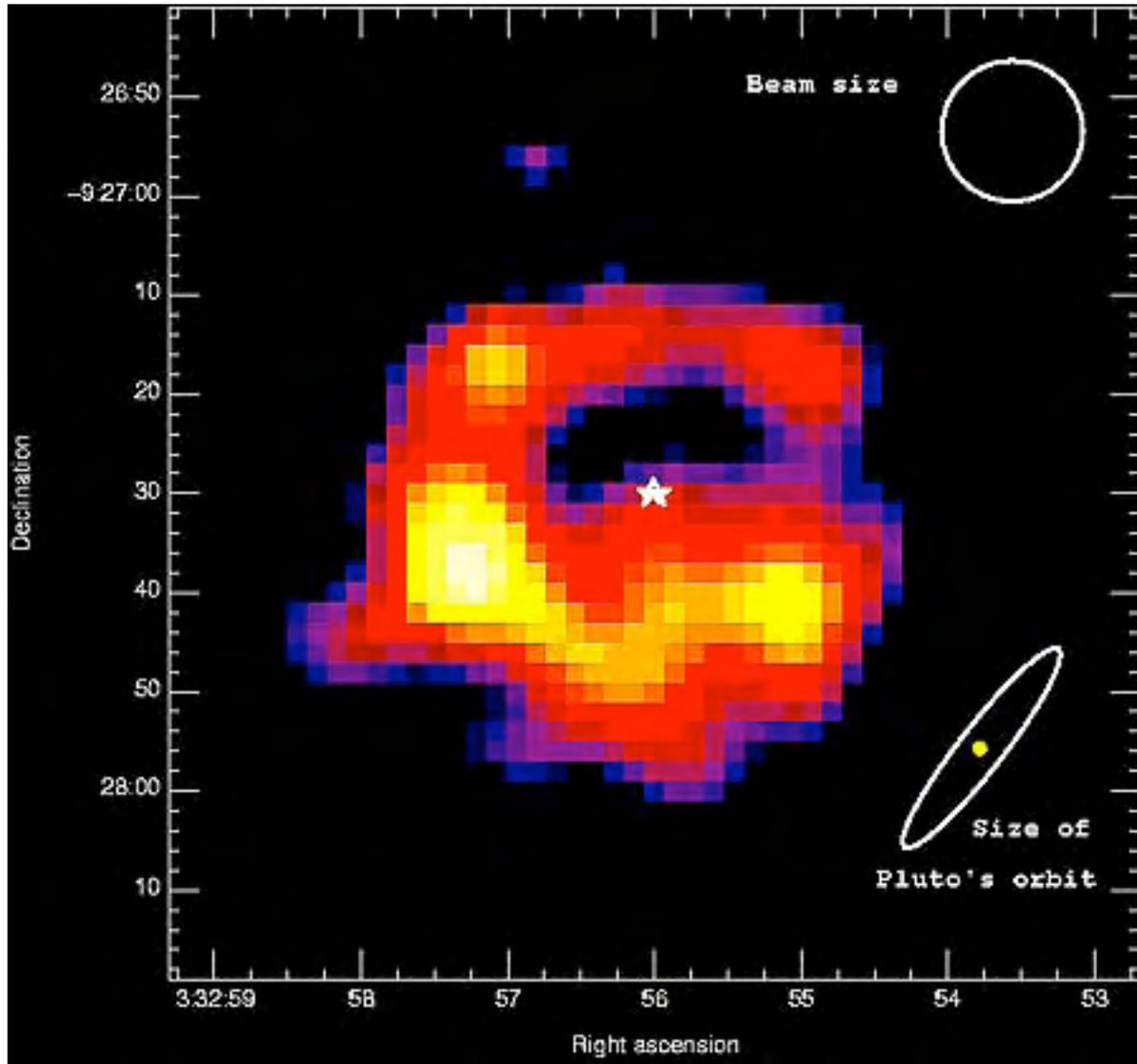
Solar System formation

Obs. "Musts":

- Planck orbits are coplanar
- ecliptic lies near solar equator
- all is prograde (orbits, solar, planet rotation)
- orbits are uncircular
- inner planets rocky, outer icy/gaseous
- meteorite composition = refractory (high-T-melt) + low T-melt
- Jovian mini-solar systems







Post-fragmentation, last stage of S.F.

Warm accretion disk surrounding new Sun

- $M_{\text{disk}} \geq 0.01 - 0.02 M_{\text{Sun}}$  ;  $R > A_{\text{photo}}$ ,  $A_{\text{h}} \approx 1 \text{ au}$

"Minimum mass solar nebula"

known solid material  $\times 50$  (for missing H, He)  
 $+ M_{\text{Jup}} + M_{\text{Sat}}$

- Warm  $\rightarrow$  primordial grains vaporized out to Asteroids

Disk/Nebula cools

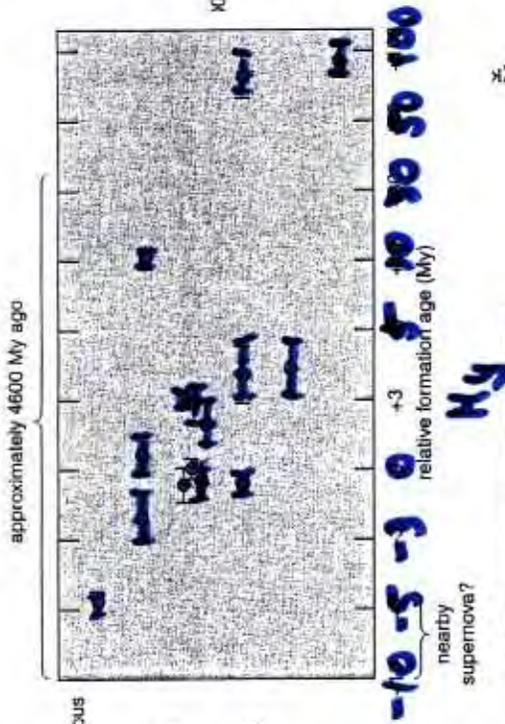
- sequential condensation of dust grains (soot, ~~graphite~~ silicates, to c-rich, graphite)
- time scale  $\approx 3 \times 10^7 \text{ y}$  (contraction time for  $1 M_{\odot}$ ) based on IR excess around young stars

Planetesimals Form:

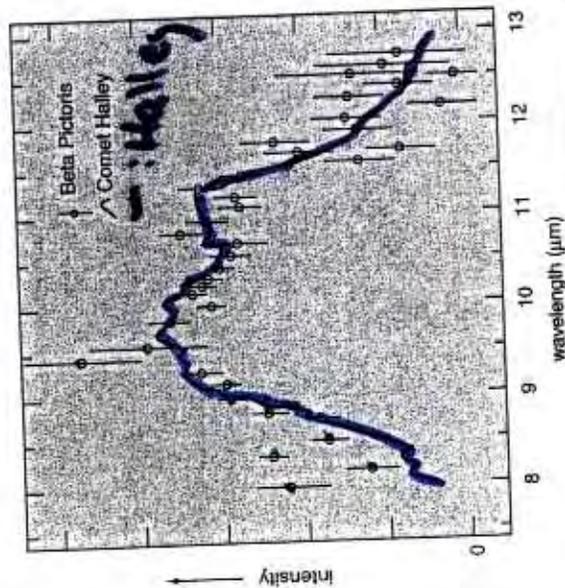
Figure 4-10  
5-2  
5-4, 5

- grains grow via sticky collisions
- settle down to disk midplane  
 $\rightarrow$  grow to macroscopic (mm scale)
- $T \approx 500 - 1000 \text{ K}$ ,  $\rho \approx 10^{-9} \text{ g/cm}^3$

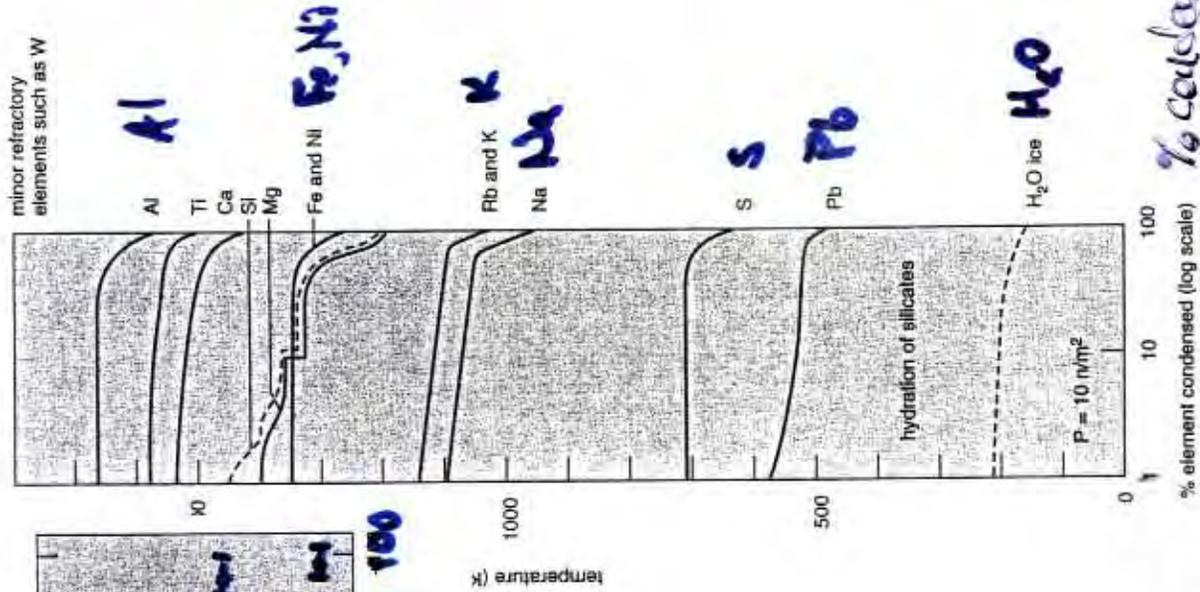




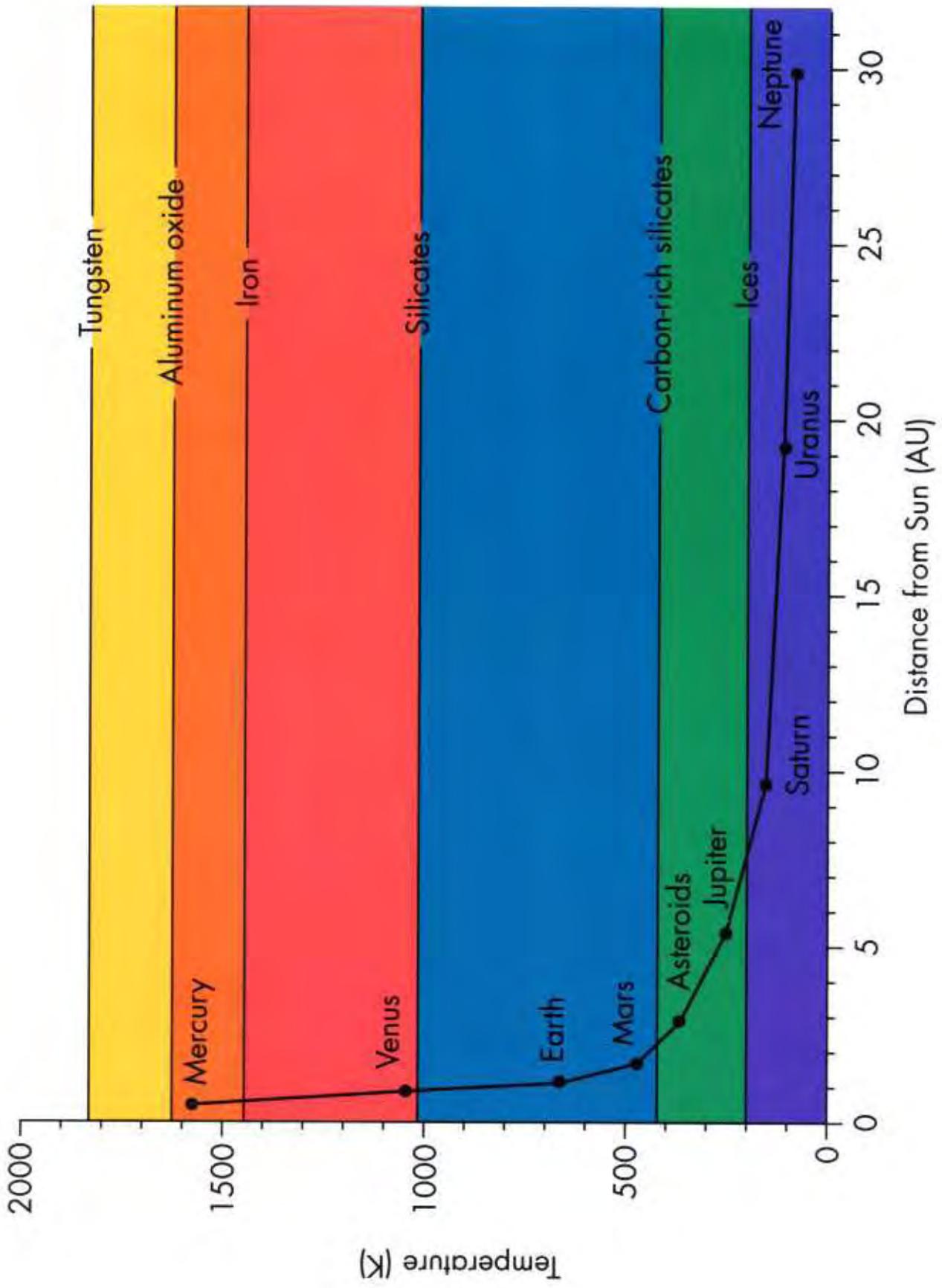
**Figure 5-1.** The first 110 My of solar system history. Formation ages of Earth and of the several meteorites (identified by type; see also Chapter 6) are not absolute but relative to the formation of a well-studied chondrite meteorite named Bjorbole, whose age is arbitrarily designated as zero. The results show that most meteorites formed during a 20-My period. Dates are interpreted from decay of radioactive iodine 129, apparently produced by a nearby supernova a few million years before the solar system formed. (Adapted from Podosek, 1970; Wasson, 1974; Pepin and Phinney, 1975)



**Figure 4-10.** The infrared spectrum of the Beta Pictoris dust disk showing a broad emission caused by overlapping 9.6 and 11.2 micron bands of silicates, strikingly similar to that of the spectrum of silicate dust blown out of Halley's Comet. (Adapted from Arty-mowicz, 1997, based on data of R. Knacke and S. Fajardo-Acosta)



**Figure 5-4.** Condensation of elements from gas in the solar nebula as temperature drops, calculated by Grossman (1975) at  $P = 0.1$  mbar. Graph does not indicate resulting mineral forms, except to note that water vapor begins to hydrate the silicate minerals below about 500 K and freezes out as ice at about 200 K (Lewis, 1972a). Curves for silicon and water, materials of special planetary relevance, are dashed.



**137** Condensation and the Chemical Compositions of the Planets  
Figure 18.18

John D. Fix, Astronomy: Journey to the Cosmic Frontier, 2e. Copyright © 1999 by The McGraw-Hill Companies, Inc. All Rights Reserved.

- Accretion of "dust bunnies" to denser clumps,  $\dot{M} \sim 1 \text{ m}$   
( $\tau \sim 10^4 - 10^5 \text{ y}$ )

- Continued growth to  $\sim 1 \text{ km}$  "particles" via further collisions, gravity taking charge - MUST HAPPEN QUICKLY

- Clearing of remaining material via "solar" wind

- Rapid growth of largest few clumps  $\rightarrow$  to planet-sized bodies (cores)  
"Oligarchic growth"

Beyond "Frost line"

- ice particles participate in growth to much larger cores

- @  $\sim 10 M_{\oplus} \rightarrow$  "runaway" accretion of  $\text{H}_2$   
 $\rightarrow$  to form giant planets

Key issues

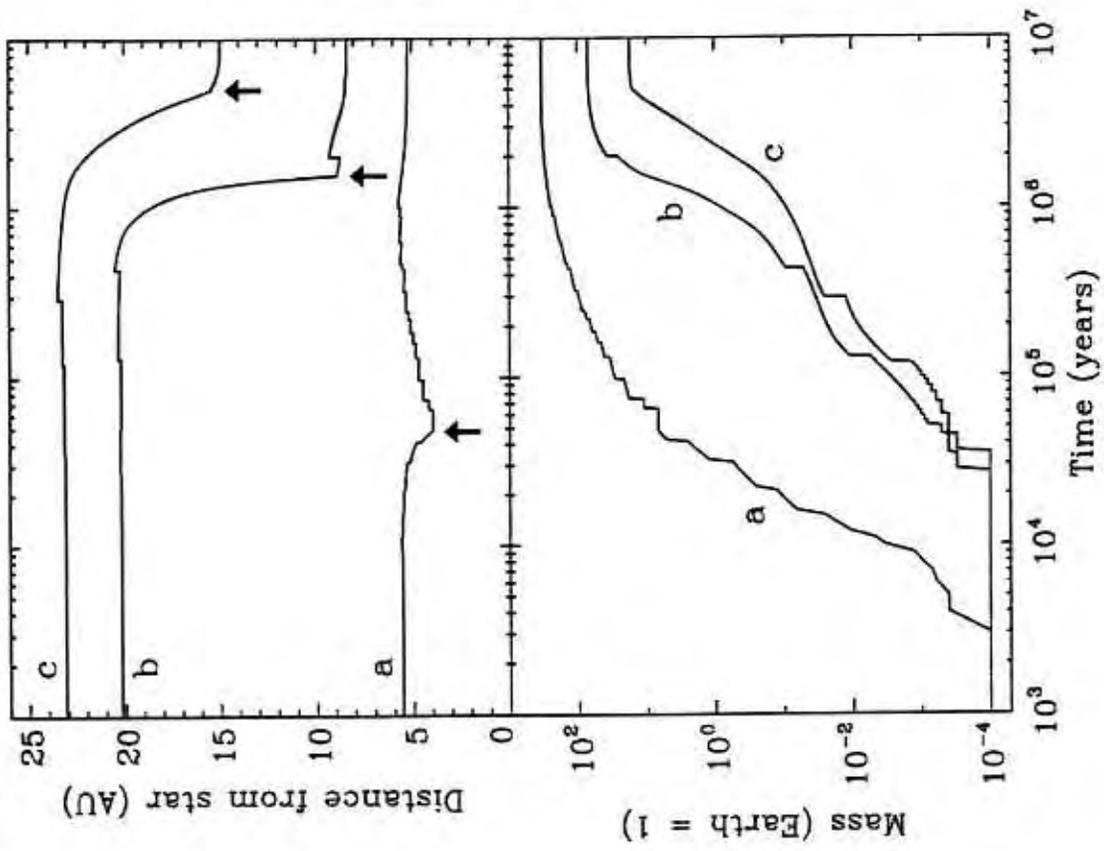
- Condensation temperature  $\neq T(r)$  in nebula
- Core accretion (above) vs grav. instability

Migrating spiral wave driven in gas  $\rightarrow J$ , planet moves  
 $\tau \sim 10^4 \text{ y} - 10^5 \text{ y}$

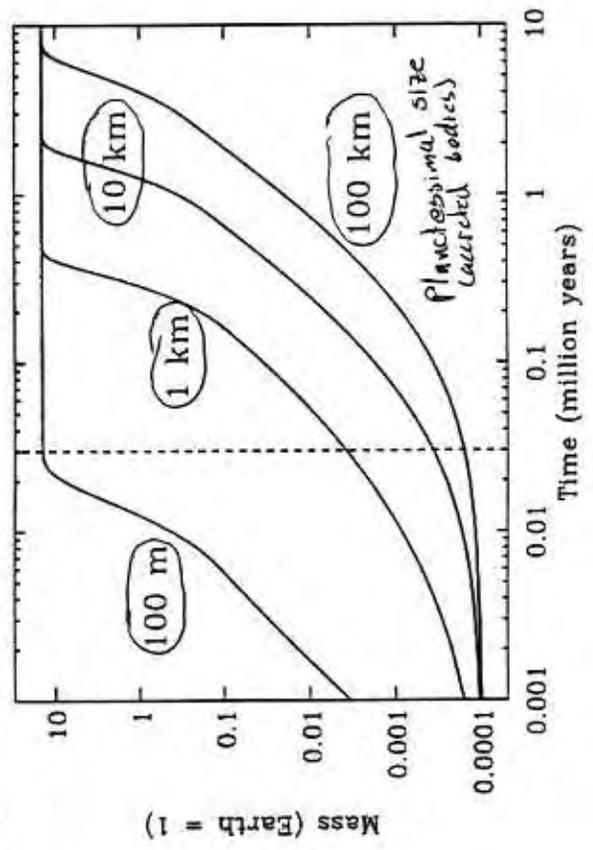
22-141 50 SHEETS  
22-142 100 SHEETS  
22-144 200 SHEETS



**Fig. 2** Evolution of three surviving cores in a protoplanetary disk with  $r = 100$  m,  $\sigma = 3 \times 10^{-5}$ , and  $\Sigma_{\text{solid}} = 6 \text{ g cm}^{-2}$  at 5 AU. Growth is calculated using the model described in § 2. *Upper panel:* Distance from the star. Arrows show when each core opens a gap in the disk. *Lower panel:* Core masses.



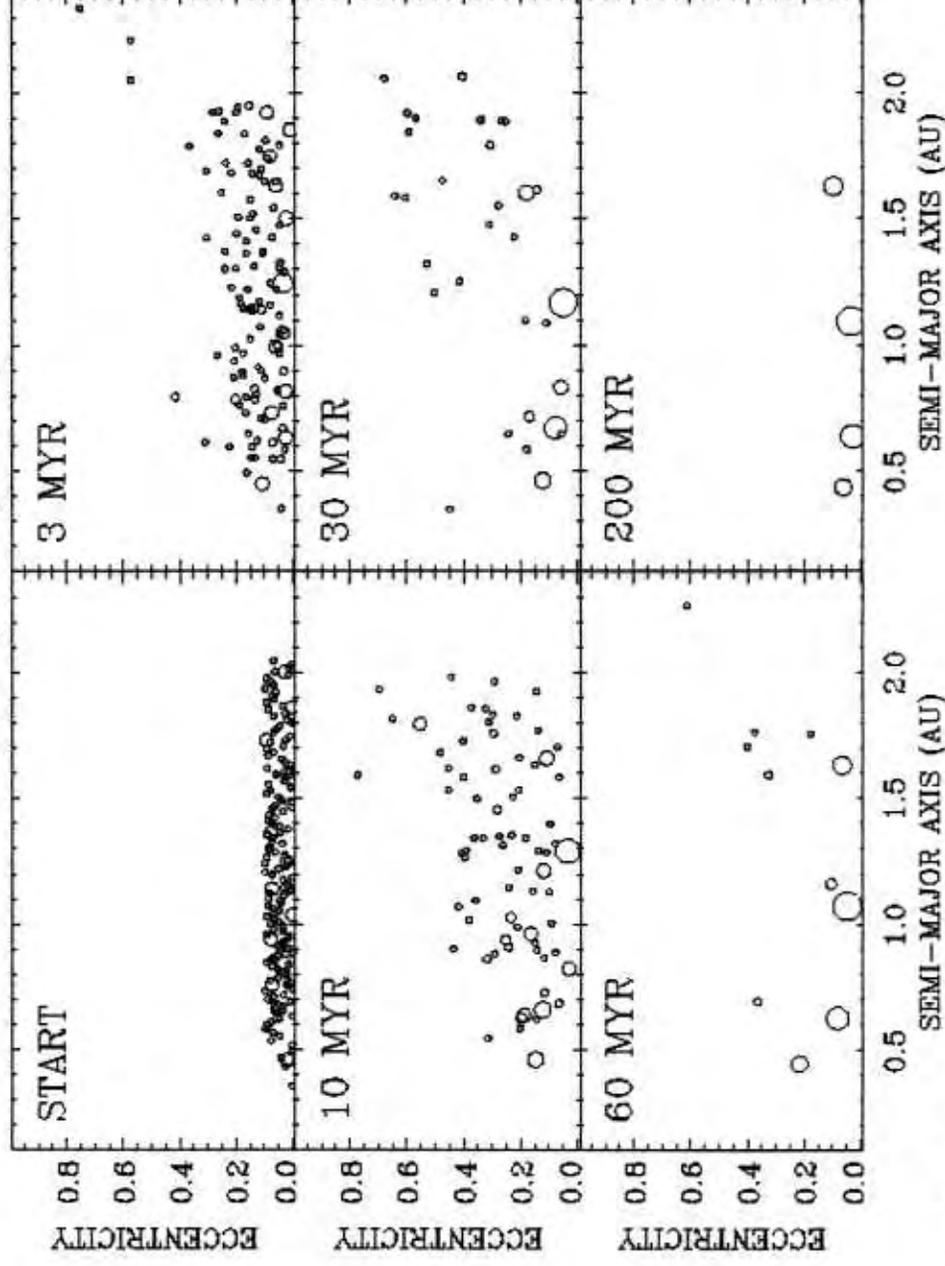
**Fig. 1** Growth of a core at 5 AU from the Sun according to eq. (1), with  $\epsilon$  and  $i$  determined by an equilibrium between perturbations from nearby cores and damping due to gas drag. Migration is neglected. Here,  $\Sigma_{\text{solid}} = 10 \text{ g cm}^{-2}$ , and  $\Sigma_{\text{gas}}/\Sigma_{\text{solid}} = 90$ . Each curve shows growth for a different  $r$ . The dotted line shows the type I migration timescale.



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1 Dec 2006

# Oligarchy - final assembly stage

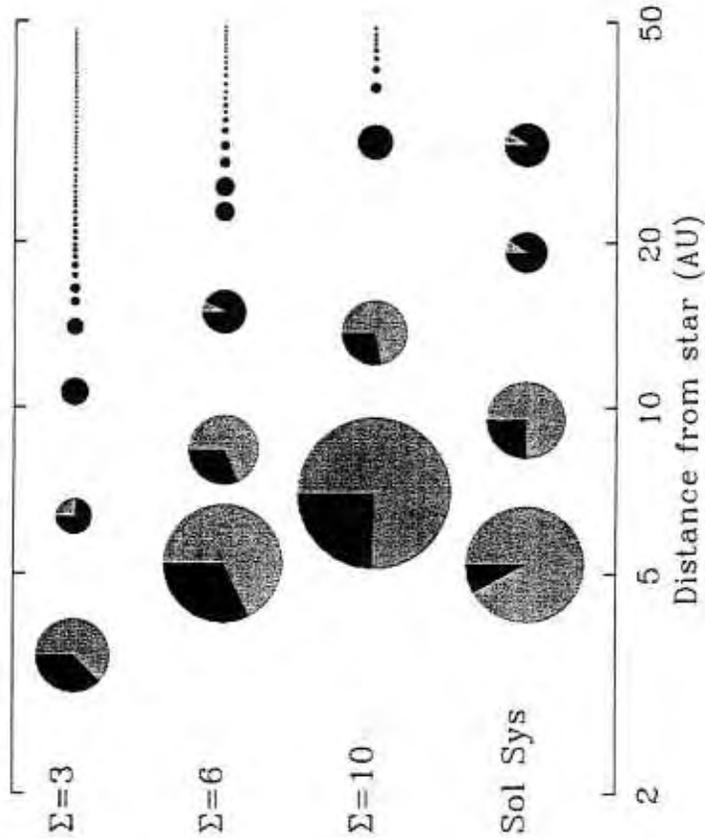
(embryos to planets)



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2001

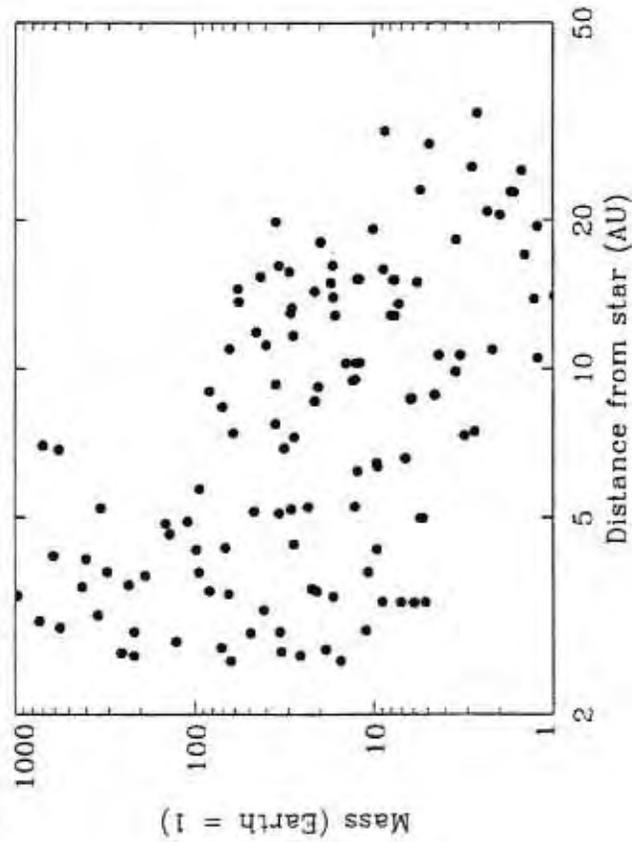
- N-body simulations
- sensitive to initial conditions - final structure a random process
- generally, (e, i) of simulated planets > Earth and Venus

Outcome of three simulations with  $r = 100 \text{ m}$  and  $\alpha = 3 \times 10^{-5}$ . The value of  $\Sigma_{\text{solid}}$  at 5 AU in each case is indicated. Surviving planets are represented by circles with radius  $\propto M^{1/3}$ . The black and gray segments of each circle give the solid and gas mass fractions, respectively. The last row of circles marked "Sol Sys" shows the giant planets of the solar system.



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Planets generated in 48 simulations with  $100 \text{ m} \leq r \leq 500 \text{ m}$  and  $3 \times 10^{-5} \leq \alpha \leq 3 \times 10^{-4}$ .



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# Extrasolar Planetary Systems

- if SS form model ok, there should be lots of SS with a variety of family variation.
- now well over 200 XSP systems; few look anything like our own:
  - relatively many have "hot Jupiter"
  - much more scatter in  $e \frac{a}{a}$  diagram
  - host star-metallicity trend

1995-1st discovery

## Detection Techniques:

bias towards short period planets built-in (Zgradad)

- Radial velocity variations (orbital reflex motion)
  - ↳ M/s sensitivity
  - ↳ easier to find massive, close planets
- astrometry (reflex orbital motion)
- transits eclipse of \* by planet is geom ok
  - ↳ bigger planets (Jupiter → ~~0.005~~ 0.005 mag)
  - ↳ shorter periods (Earth → 30 μmag)
- KEPLER MISSION (for repeats)
- grav. microlensing
  - lensing event perturbation

FIGURES: e vs a histograms of M,  
M vs a Z<sub>star</sub>  
a

ISSUES.

interconnected

- HOT JUPITERS ?!
- ↳ must form far from \* (beyond frost line) & migrate inwards
- MIGRATION
- wide range of eccentricity  
↳ more scattering in oligarchic phase
- Metallicity correlation  
↳ "self enrichment" or primordial?
- ??

Future

- longer period planets
- lower mass planets  
Kepler, COROT (occultations)  
TPF, SIM (astrometry, coronagraphs)

Stay tuned!

