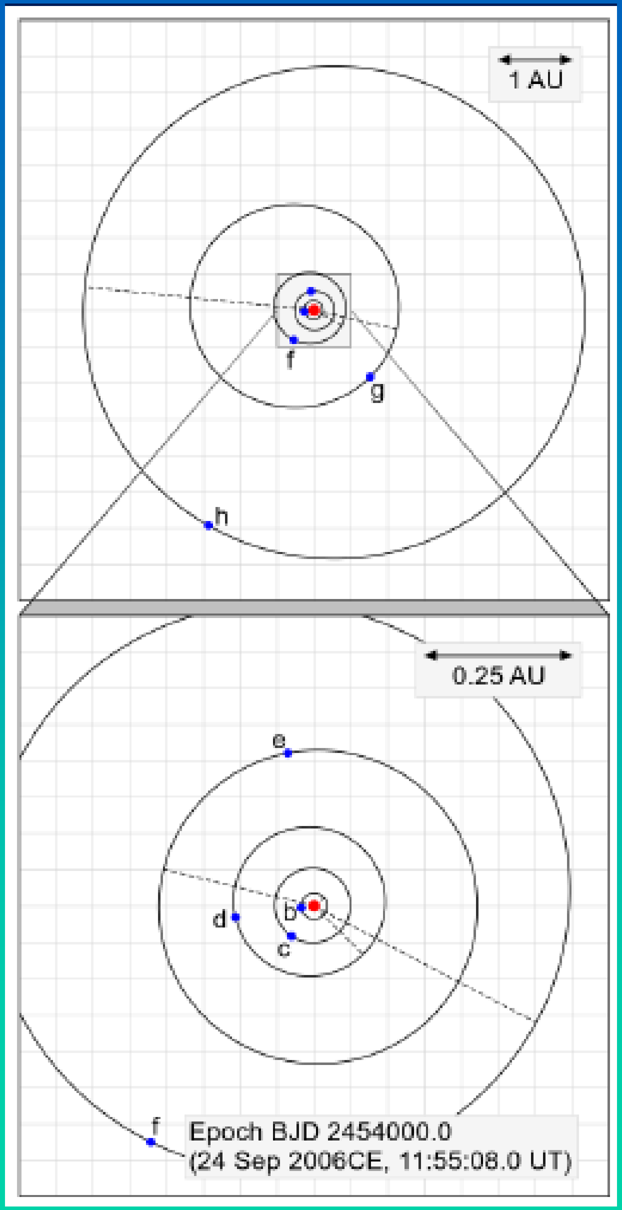

gas giant formation accelerated by disk accretion processes

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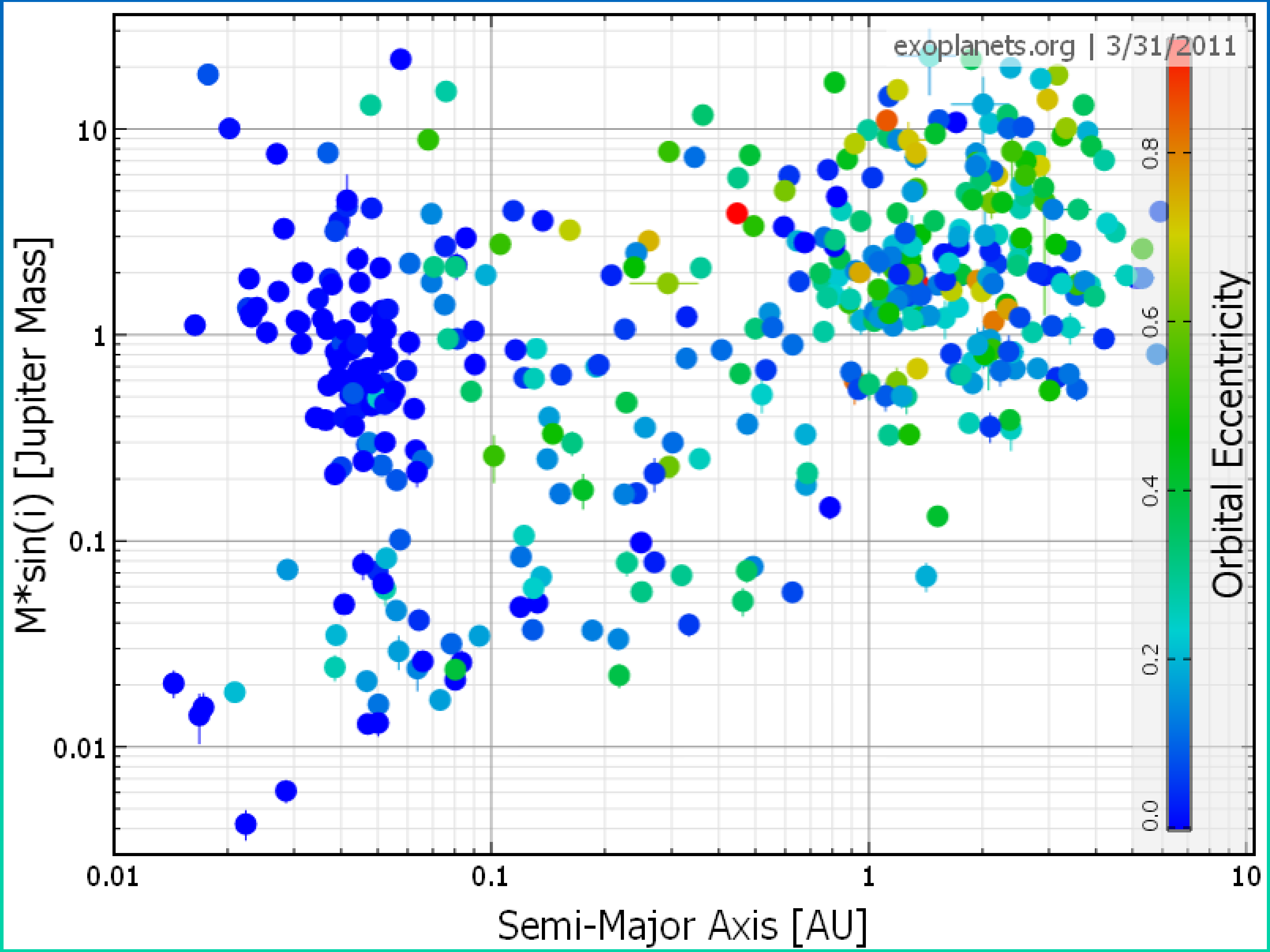
539 exoplanets observed upto Mar. 28, 2011

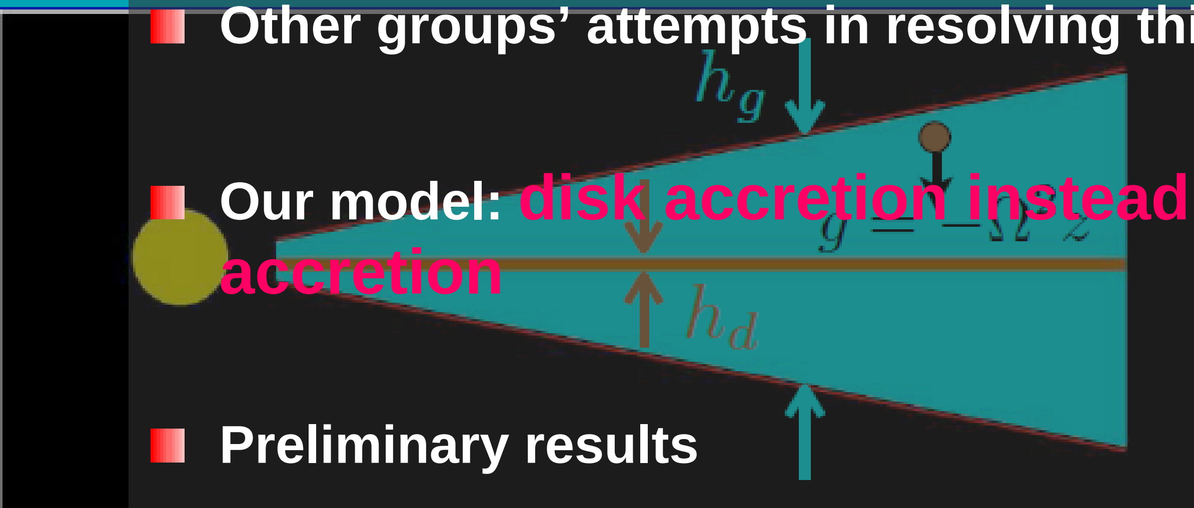
~100 transits; ~ 350 Jupiters.

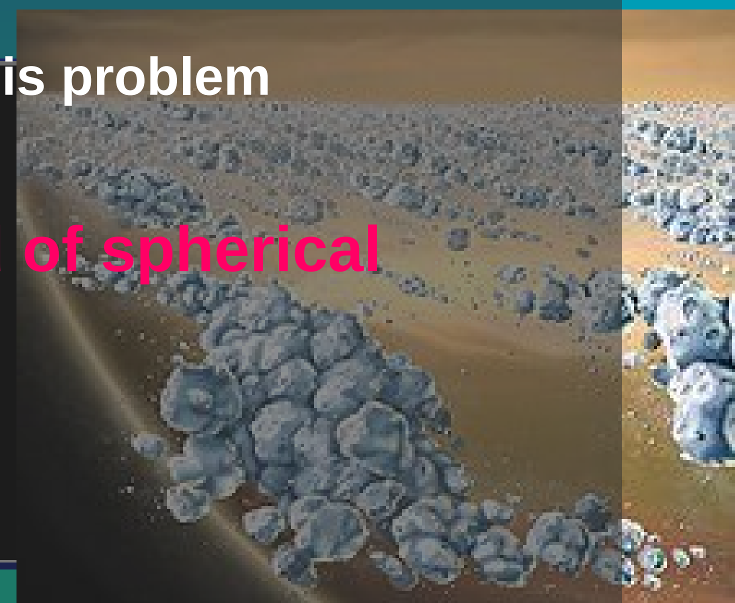


Context

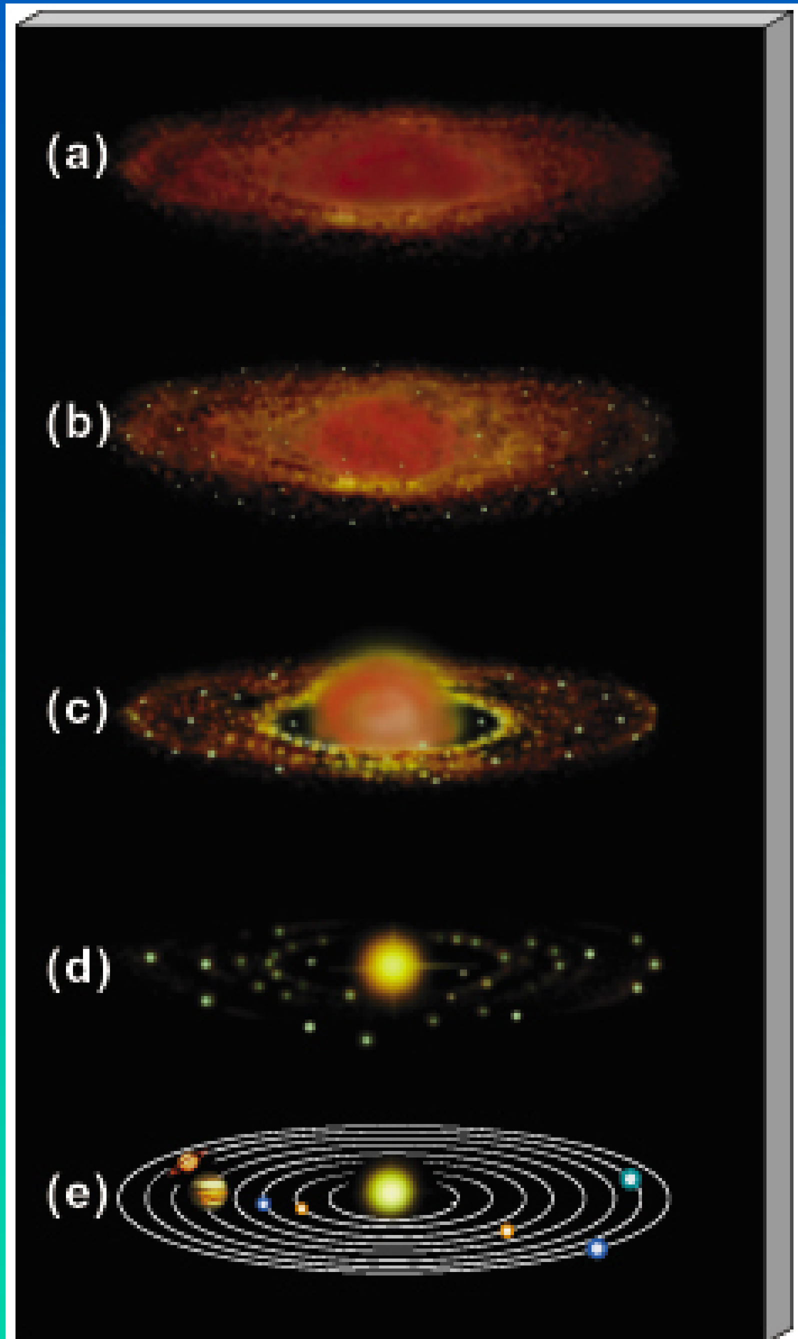
- Introduction to core-accretion model of gas giant formation:. alternative: gravitational instability
- a key problem of core-accretion model:

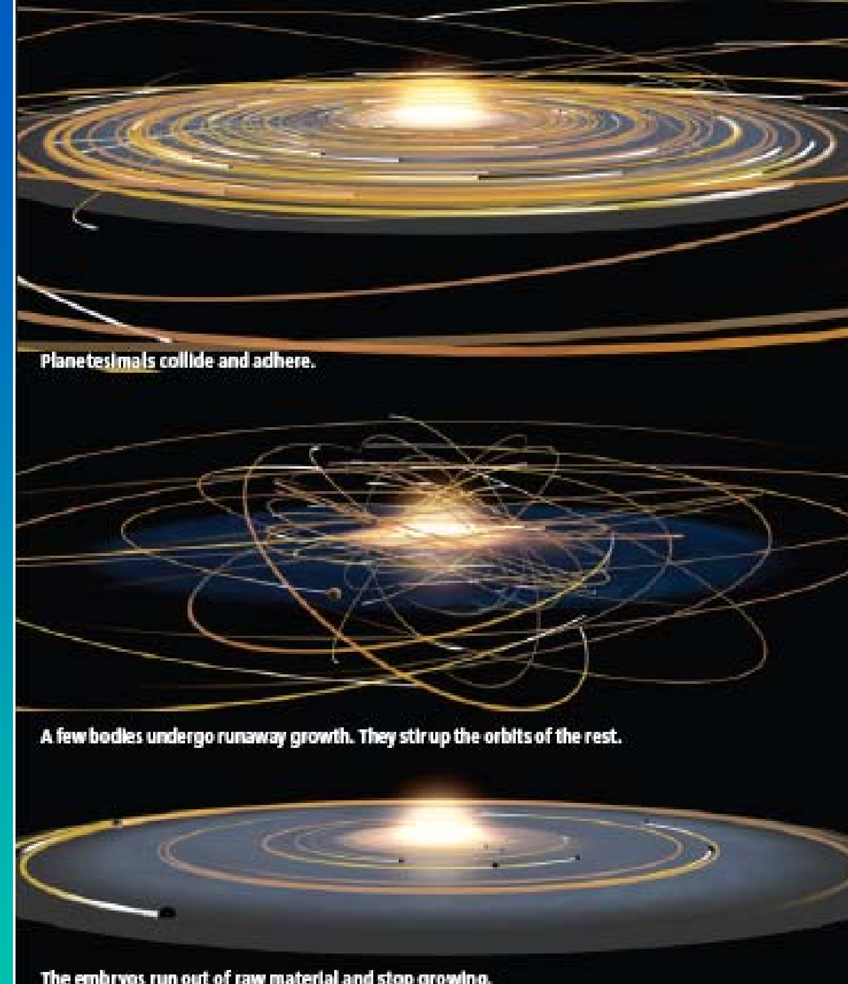
  too long formation time
- Other groups' attempts in resolving this problem





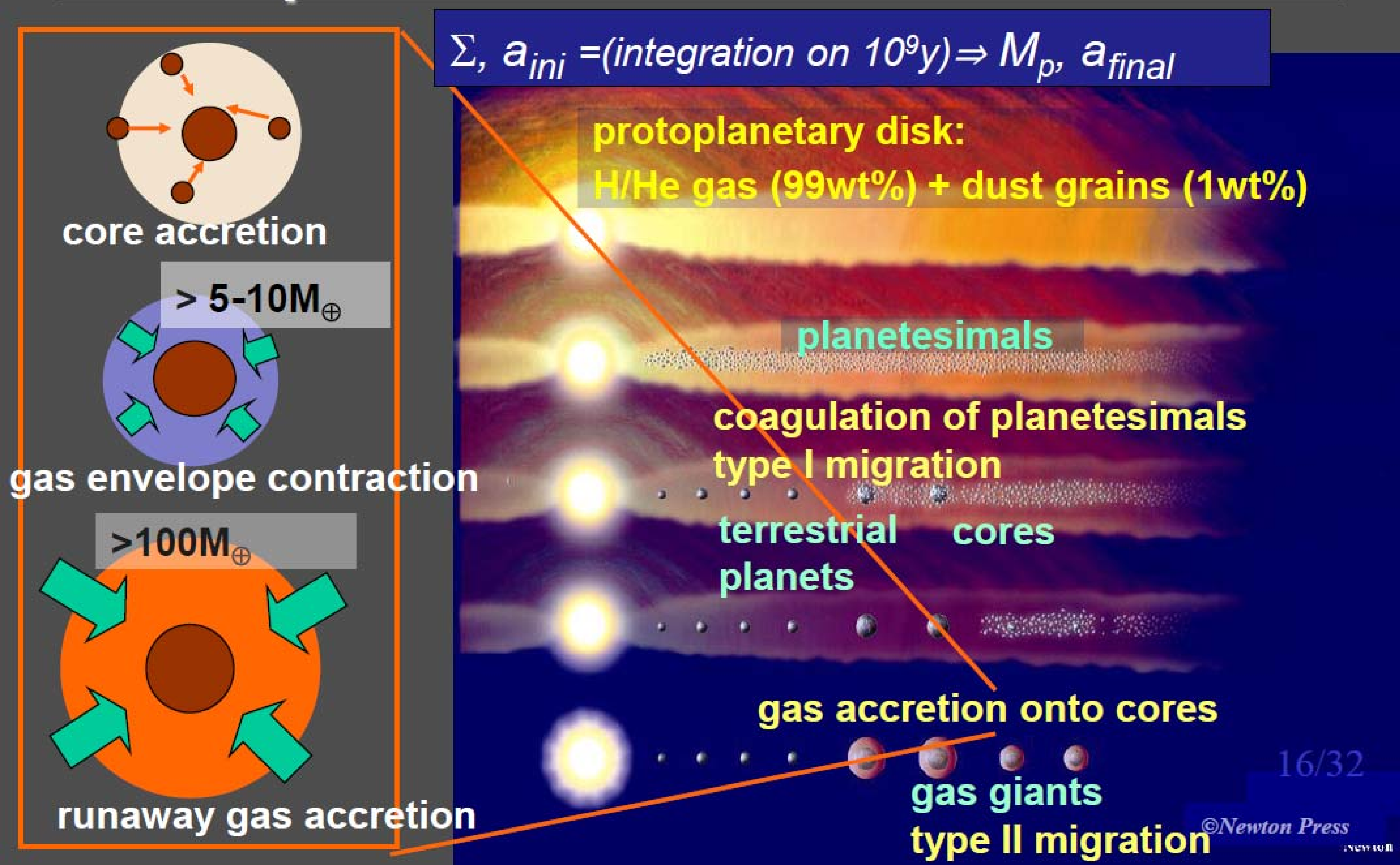
- Our model: disk accretion instead of spherical accretion
- Preliminary results
- conclusions



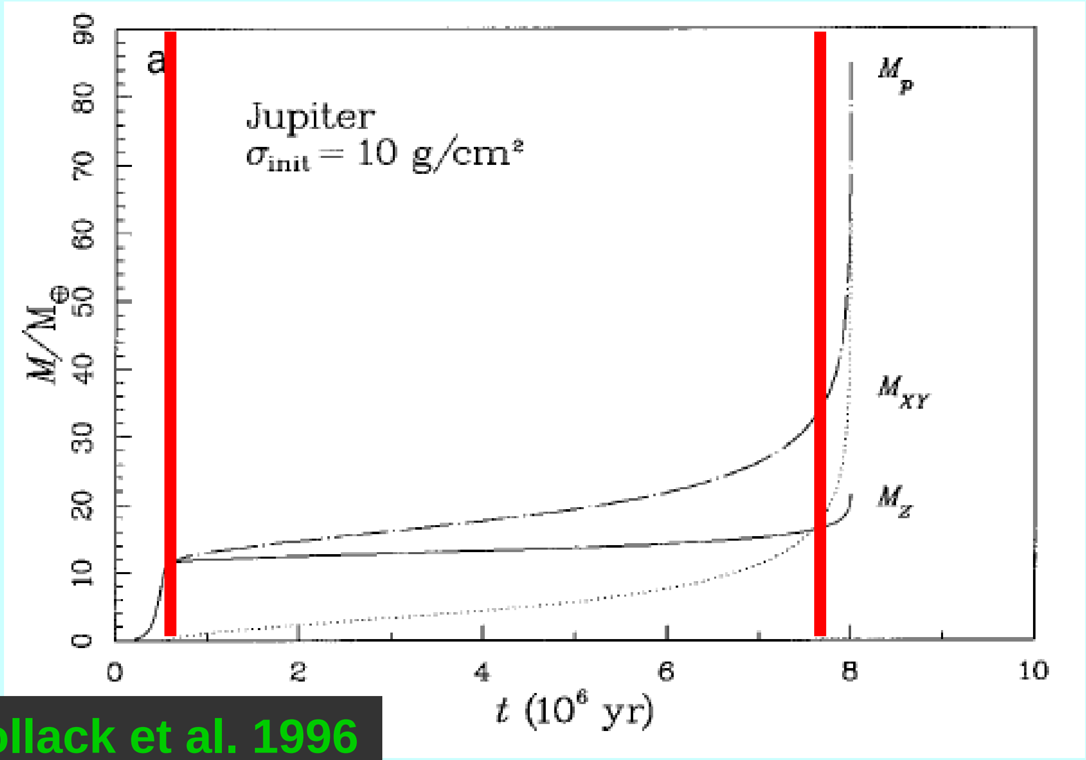


1. Dust condensation and growth
2. Planetesimal growth
3. Gas accretion
4. Orbital migration
5. Gas disk depletion
6. Long term dynamical evolution

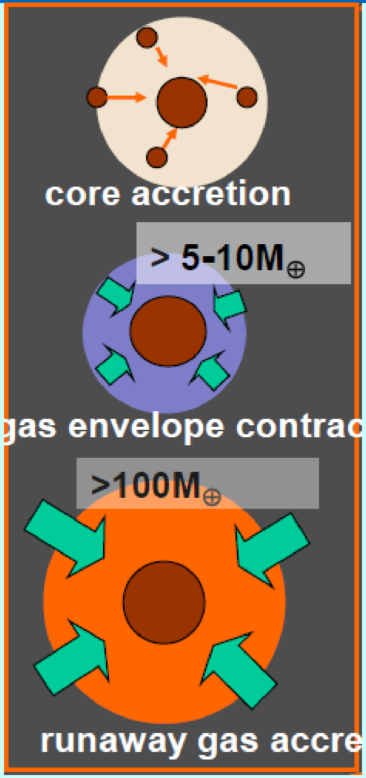
Core-accretion model of gas giant



Numerical approaches in this picture



Pollack et al. 1996



Bondi gas accretion rate: $\dot{M} \propto \frac{\rho M^2}{C_s^3}$

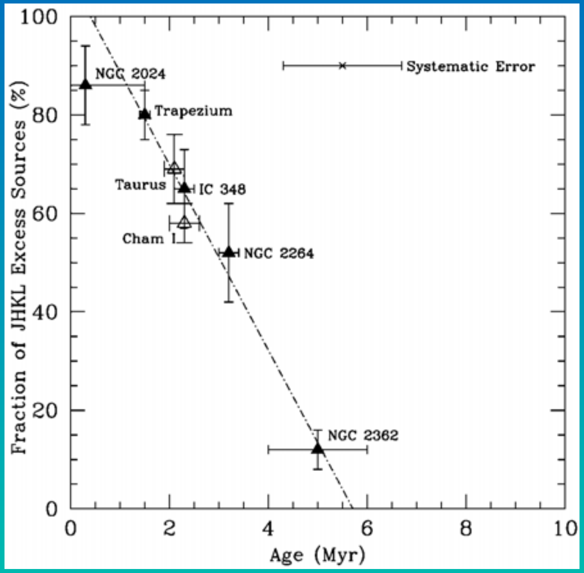
Growth timescale: $T = \frac{M}{\dot{M}} \propto \frac{C_s^3}{\rho M}$

two key conclusions:

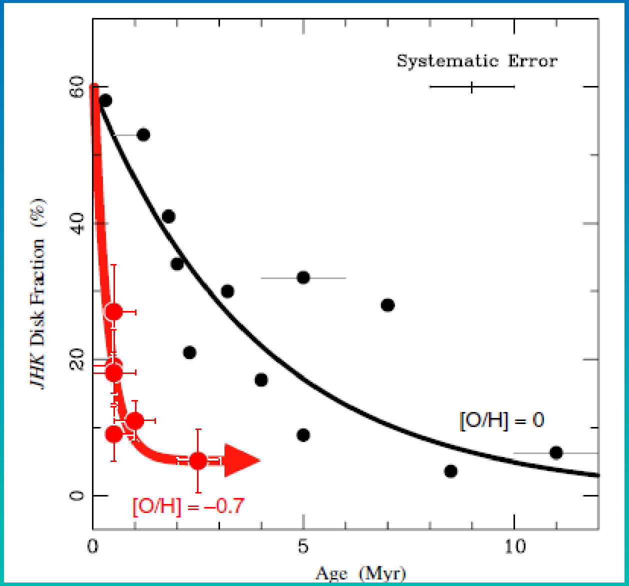
- most of the mass is accumulated during phase 3.
- most of the time is spent during phase 2.

Challenges to core-accretion model: I

- The formation time is larger than the mean lifetime (<= 3 Myr) of the protostellar disk (IR: Haisch+, 2001; Metchev+, 2004; Yasui+, 2010. sub-mm: Andrews & Williams, 2005)



Haisch+ 2001



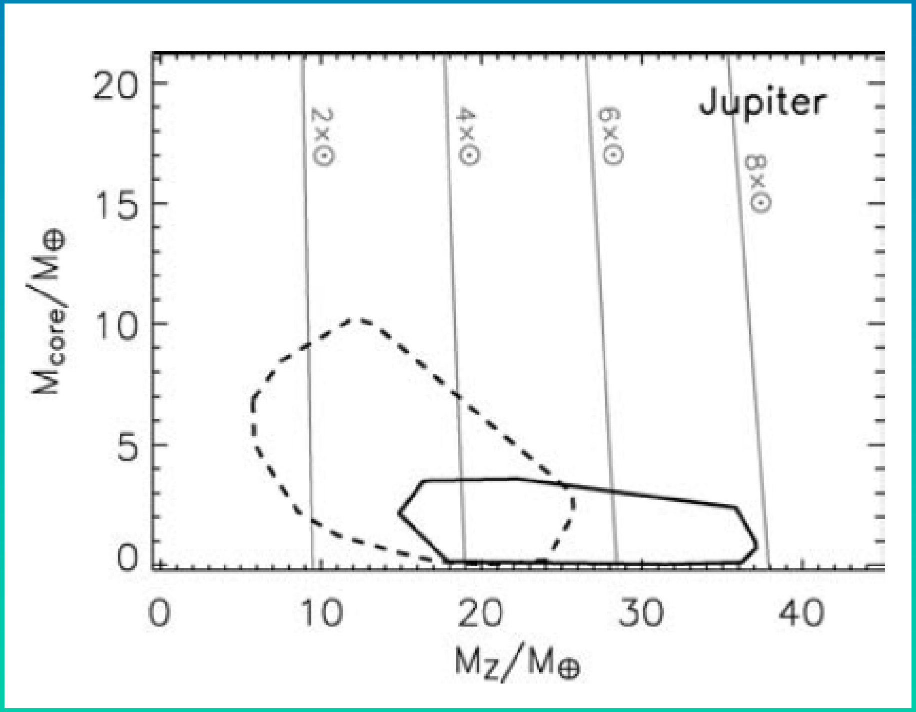
Yasui+ 2010

On the other hand, Andrews & Williams (2005): The fraction of objects detected in sub-mm (cold dust, ~10K) is nearly identical to that detected in NIR/MIR, implying that dust in inner and outer disks are removed nearly simultaneously.

Challenges to core-accretion model: II

➤ The core of Jupiter is set to 16 M_E during the modeling, while new observations indicates that it should be about 1-10 M_E (Saumon & Guillot, 2004; Guillot, 2005)

New EOS and gravitational fields obtained by *Pioneer* and *Voyager space missions.*



Guillot 2005

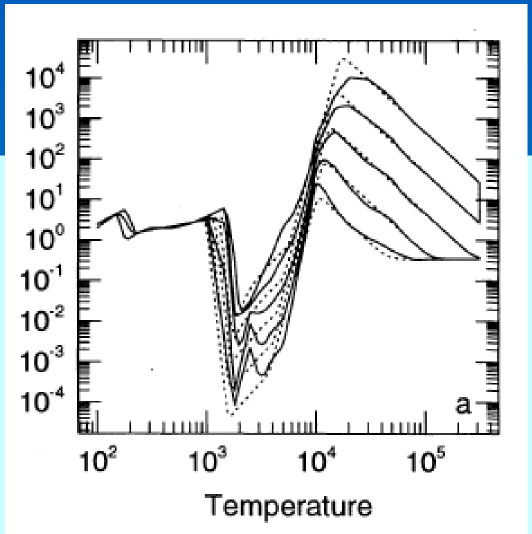
How to meet this challenge?

- **External reasons** --- During the growth of the core, consider **migration, protostellar disk evolution and gap formation**, or equivalently, modify the surrounding gas properties (Papaloizou & Terquem, 1999; Alibert et al., 2005)

→ global simulations; migration prevents depletion of the feeding zone, which is suffered by in situ formation theory.

meet this challenge - contd.

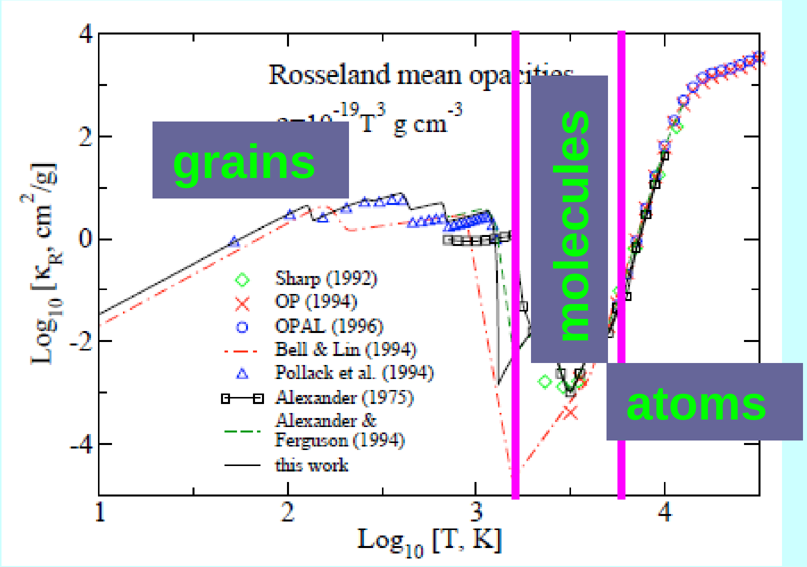
- **Internal reasons** --- **Cool efficiently through reduced dust opacity**. In order to accrete more rapidly, the thermal energy during the accretion process should be quickly lost away.



Bell & Lin 1994

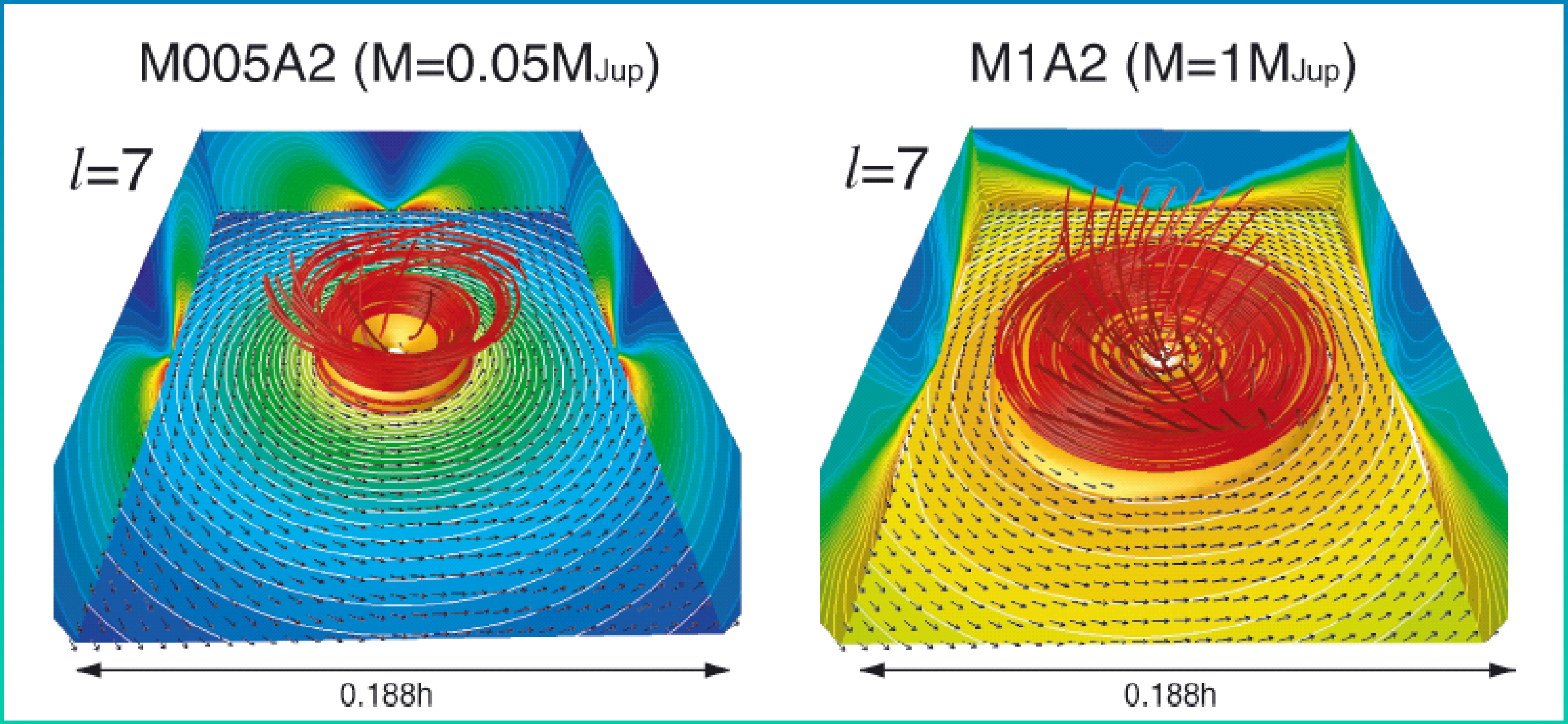
$$F(r) = \frac{L(r)}{4\pi r^2} = -\frac{ac}{3\kappa_R \rho} \frac{dT^4}{dr},$$

Opacity is dominated by small grains. → Consider grain sedimentation, coagulation, to reduce the fraction of small grains (Hubickyj et al., 2005; Lissauer et al., 2009; Movshovitz et al., 2010).



Semenov+ 2003

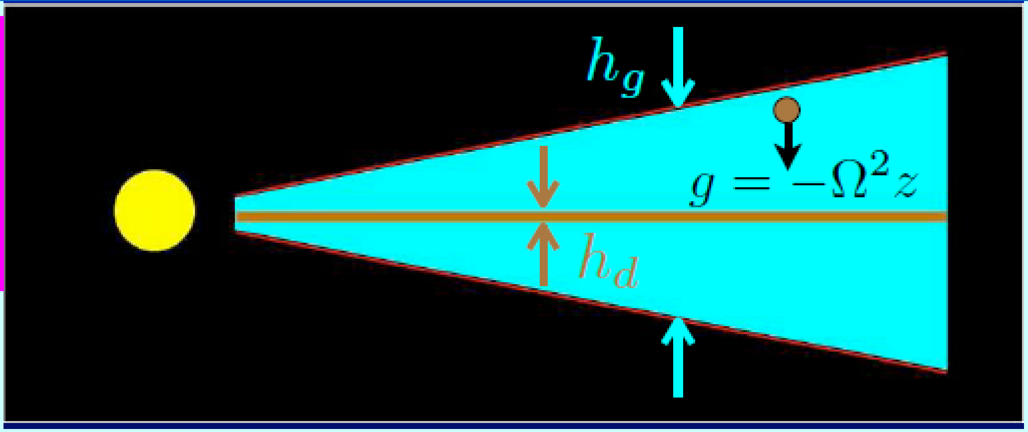
- Disk accretion at later stages, i.e., the planet mass larger than one Jupiter mass are investigated recently (Lubow, Seibert, Artymowicz 1999; Tanigawa & Watanabe 2002; Ward & Canup, 2010; etc).
- But these are for different purposes, unrelated to the topic here.



Machida 2009; Machida +, 2010

Our model: disk accretion

We believe that the key factor in the formation of gas giant is through the disk accretion instead of spherical accretion:



$$F(r) = \frac{L(r)}{4\pi r^2} = -\frac{ac}{3\kappa_R \rho}\frac{dT^4}{dr},$$

- **due to the fact of differential rotation of the protostellar disk, the feeding gas has sufficient angular momentum.**

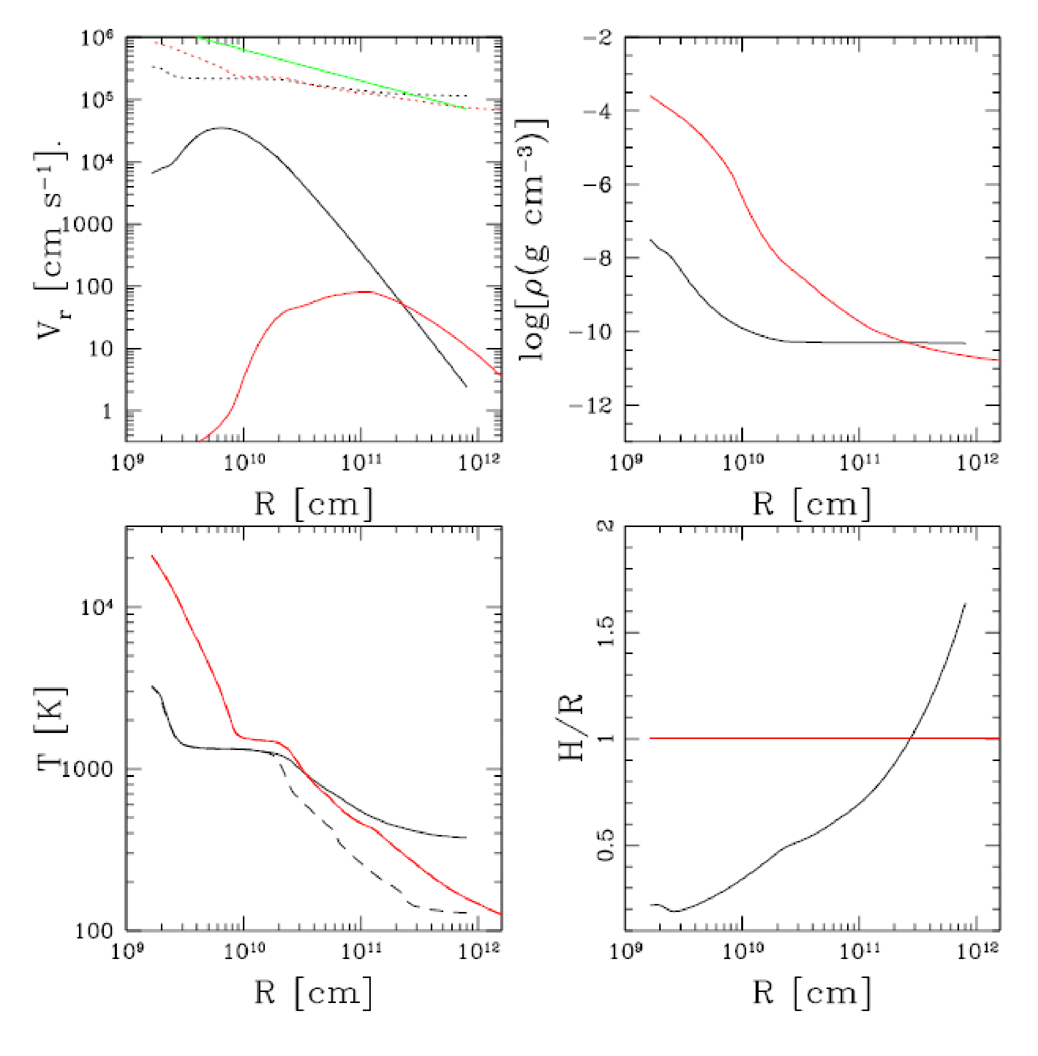
  e.g., the gas at Hill radius has a relative L(Rh) of about ~ $L_{kep}(R_h/10)$.

- **low density (and opacity) regions above the two surfaces. Small grains coupled with gas; larger grains sediment and coagulate to the mid-plane.**

- **convection within the disk, will further help to increase the radiative loss → cool more efficiently.**

!!!! This is a dynamical model, while almost all the previous work are based on hydrostatic assumptions.

Preliminary numerical results

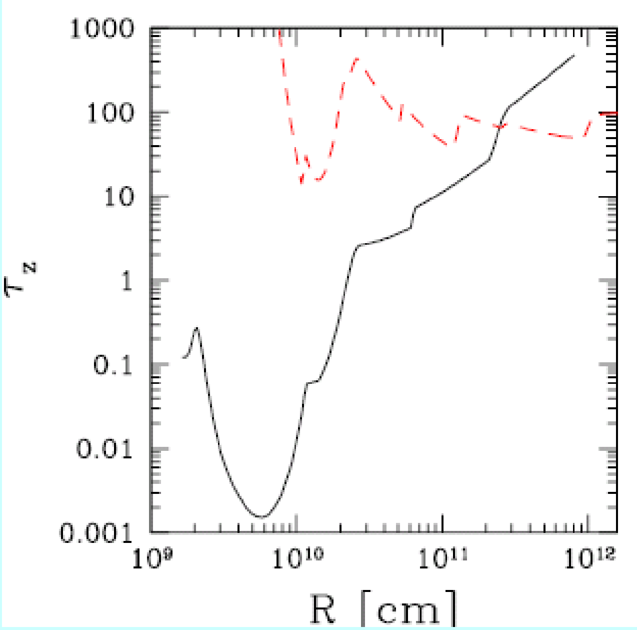


10 M_E @ 5AU of 1 M_sun

MMSN @ Hill radius

Accretion rate: 10^{-5} M_E/yr

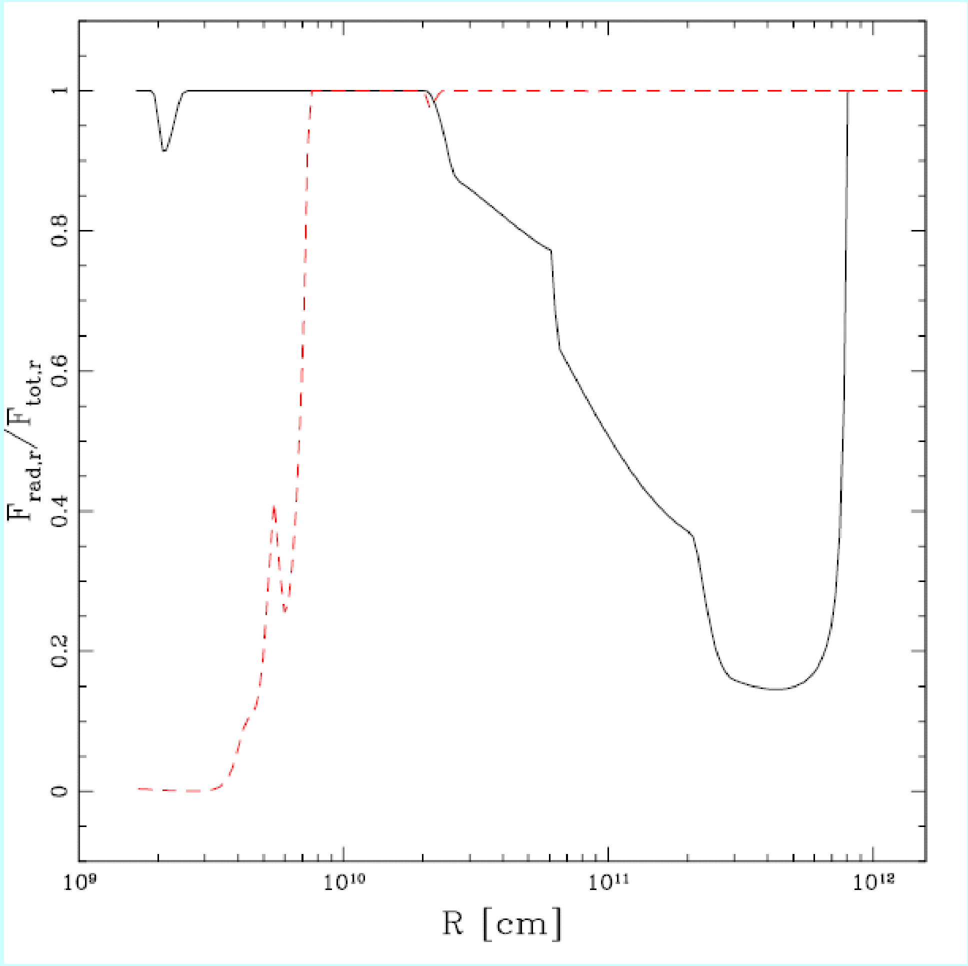
Opacity: Semenov et al. 2003



Red: spherical accretion;

black: disk accretion

Preliminary numerical results– contd.



$$F_{tot,r} = F_{rad,r} + F_{conv,r}$$

Convection plays a crucial role in both spherical and disk accretion

Discussions on grain motions

- Drag force between gas and grains (s: dust size),

$$F_d = m_p \frac{\rho}{\rho_s}\frac{C(\mathrm{Re})}{s}|\Delta v|(\dot{r} - v_g)$$

- The particle (dust) motion is governed by,

$$r'' = -\nabla\Phi - \frac{1}{m_p}F_d,$$

$(V-V_g)^2/s$ is roughly a constant for various species of dust,

Larger grains will have higher relative velocities, and will quickly settle down to the mid-plane.

Grain growth through, i.e., coagulation (Movshovitz & Podolak 2008), sedimentation (Youdin 2010), will further reduce the fraction of small grains, thus reduce the opacity of the system.

Summary

◆ The accretion process of the proto-planet is most likely to be disk-like instead of spherical.

◆ Small grains are coupled with gas, thus also in a disk configuration. Grains will coagulate and larger grains will settle down to the disk mid plane → dead zone (? Gammie 1996)

◆ Most of the thermal energy due to viscous heating in the disk are transported (through convection and radiative diffusion) to the disk surface and radiated away.