The formation of the giant planets: early or late?

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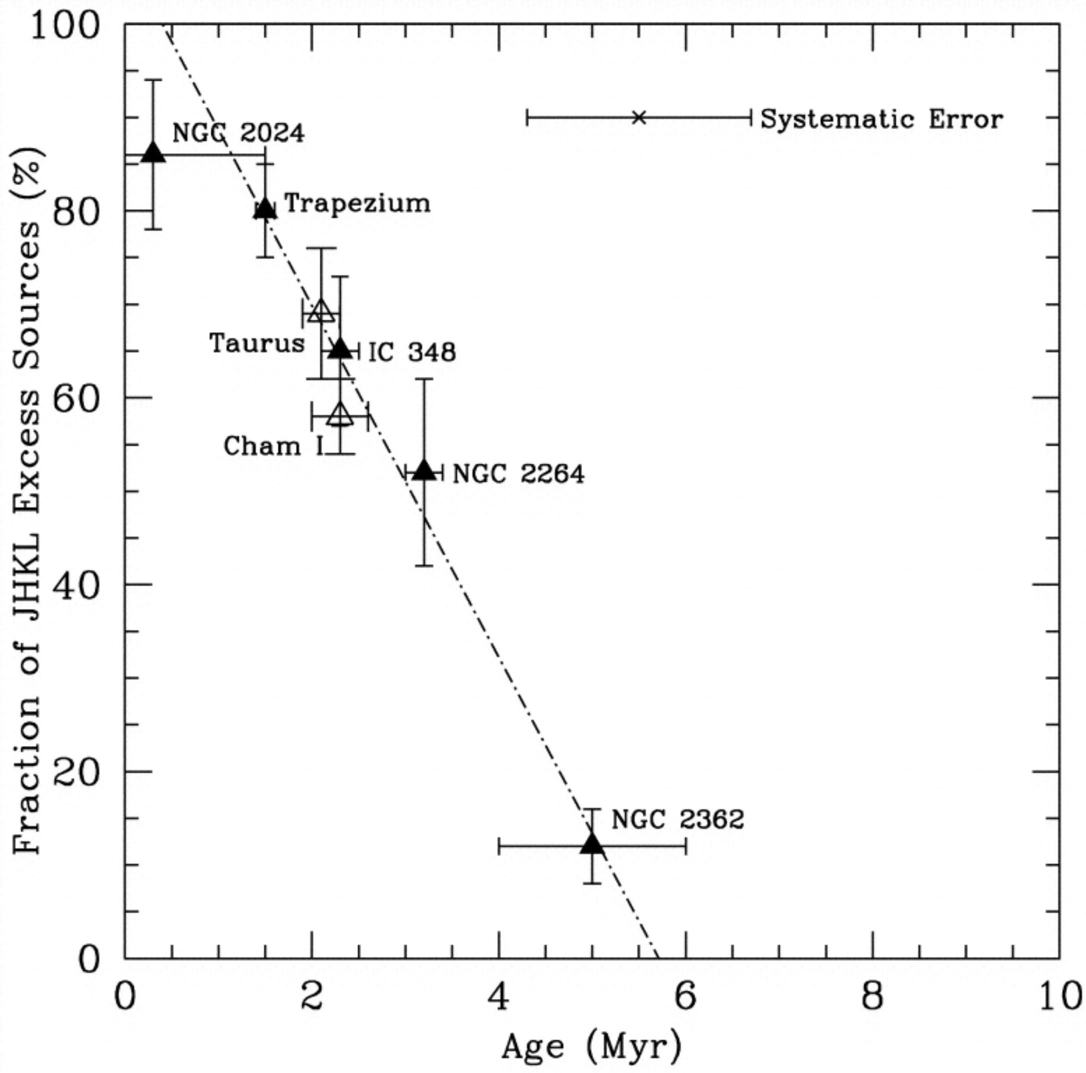
Basic facts

- Giant planets are made of hydrogen & helium
- Gaseous disks seem to disappear quickly
- ~7% of solar type stars seem to have giant planetary companions

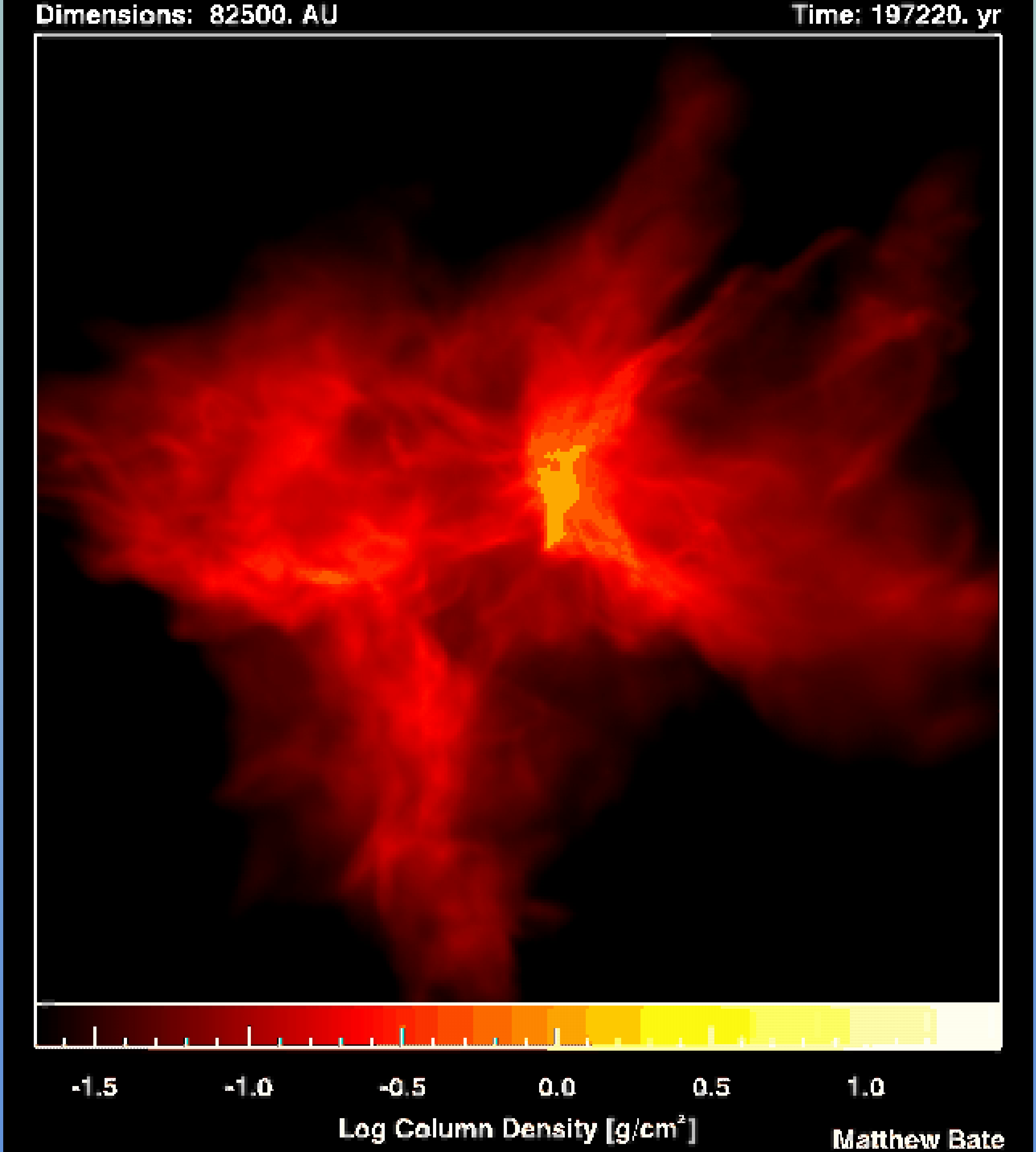


Haisch et al. 2001

The dissipation of gaseous disks...

- Viscous dissipation: rapid inside 10 AU, but very inefficient for r>100AU.
- Photoevaporation by the central star: efficient close to the star only (<10AU)
- Photoevaporation by external sources: efficient far from the central star (>20AU), but requires massive stars
- Tidal stripping: efficient at r>100AU, but requires dense stellar population

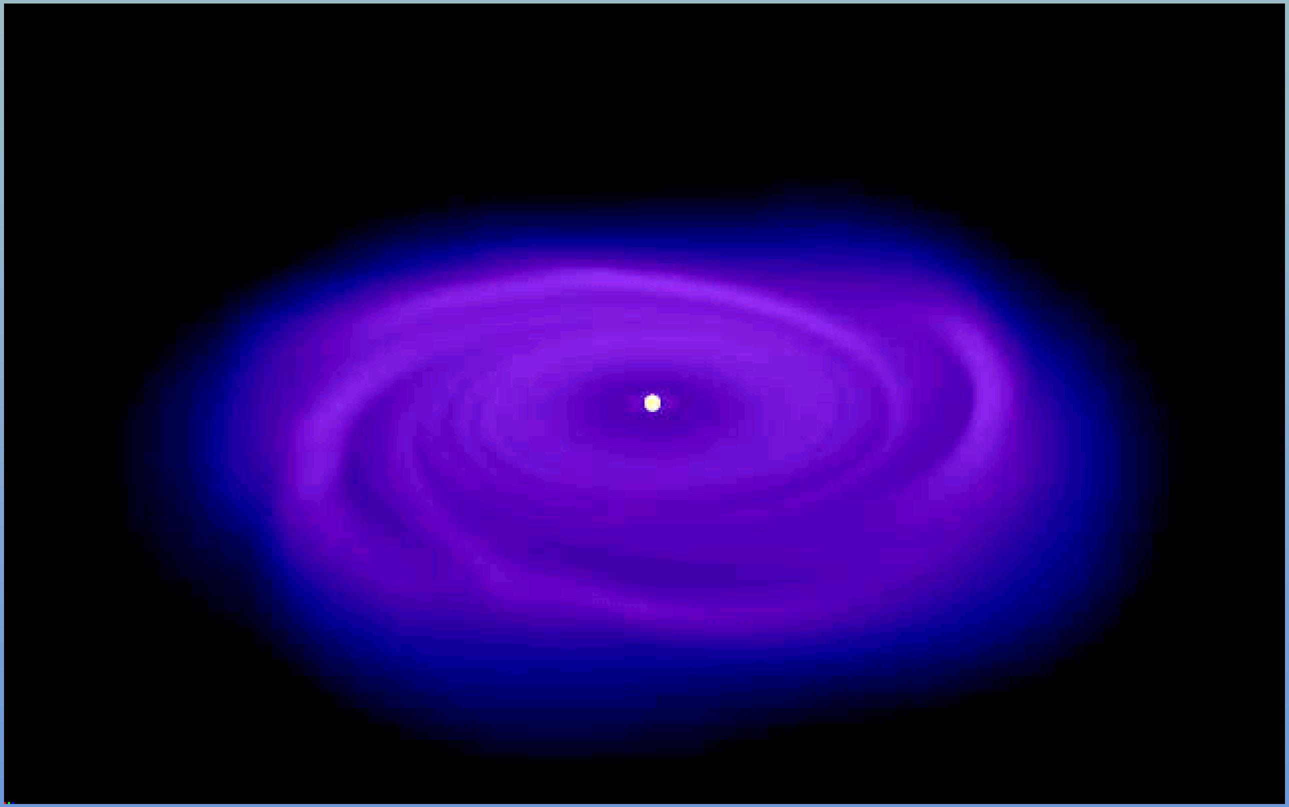
See review by Hollenbach et al., PPIV


Dimensions: 82500. AU
Time: 197220. yr
-1.5
-1.0
-0.5
0.0
0.5
1.0
Log Column Density [g/cm²]
Matthew Bate

Basic questions

- Do giant planets form rapidly ($t < 3\text{Myr}$)?
  - – NO? Implies giant planets are RARE
  - – YES? Implies sometimes they don’t form, or they disappear
- Can we grow them fast enough?
  - – With a direct gravitational instability: YES
  - – By core accretion: probably YES
- Did they form early (in a massive disk), or late (in a disk with a mass of a few M_{jup})?

A quick formation mode: direct gravitational instability

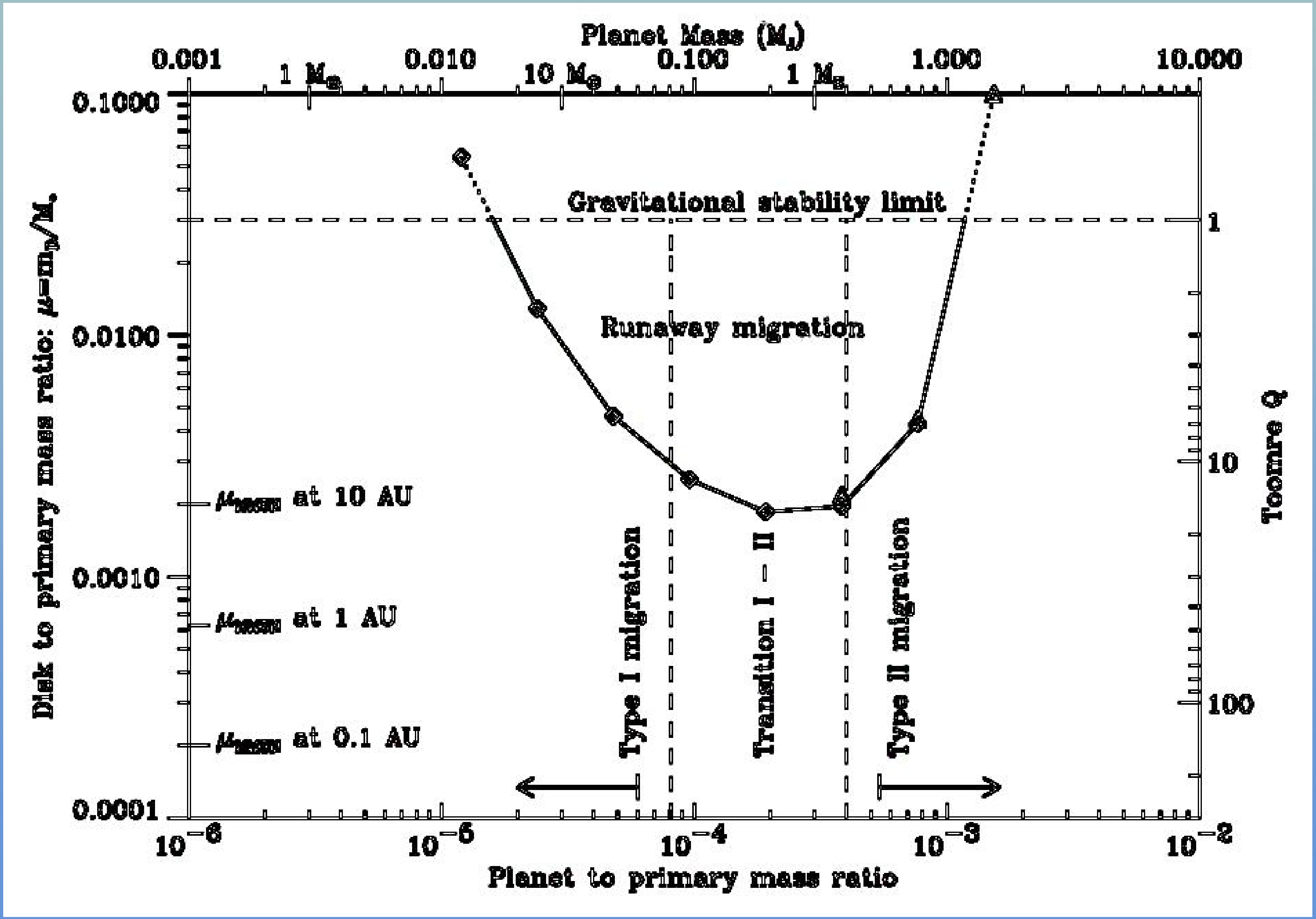


Mayer et al. 2002

A quick formation mode: direct gravitational instability

- Requires a massive & cold nebula (Q<2)
- Simulations: thermodynamics?
  - Two independent methods (SPH, Hydrodynamics)
- Formation timescale (a few 100 years!) is very short compared to the timescale over which the disk is formed by collapse (at least 10^5 years)
- Giant planets would then form early, in a still massive accretion disk

A critical problem:Type III migration



Masset & Papaloizou 2003

Another problem: halting planetary growth

- Gap opening doesn’t appear to be capable of halting planetary growth
  - particularly critical for the gas instability formation scenario
  - possible timing with nebula dissipation requires fine tuning!

Mass flow through a gap

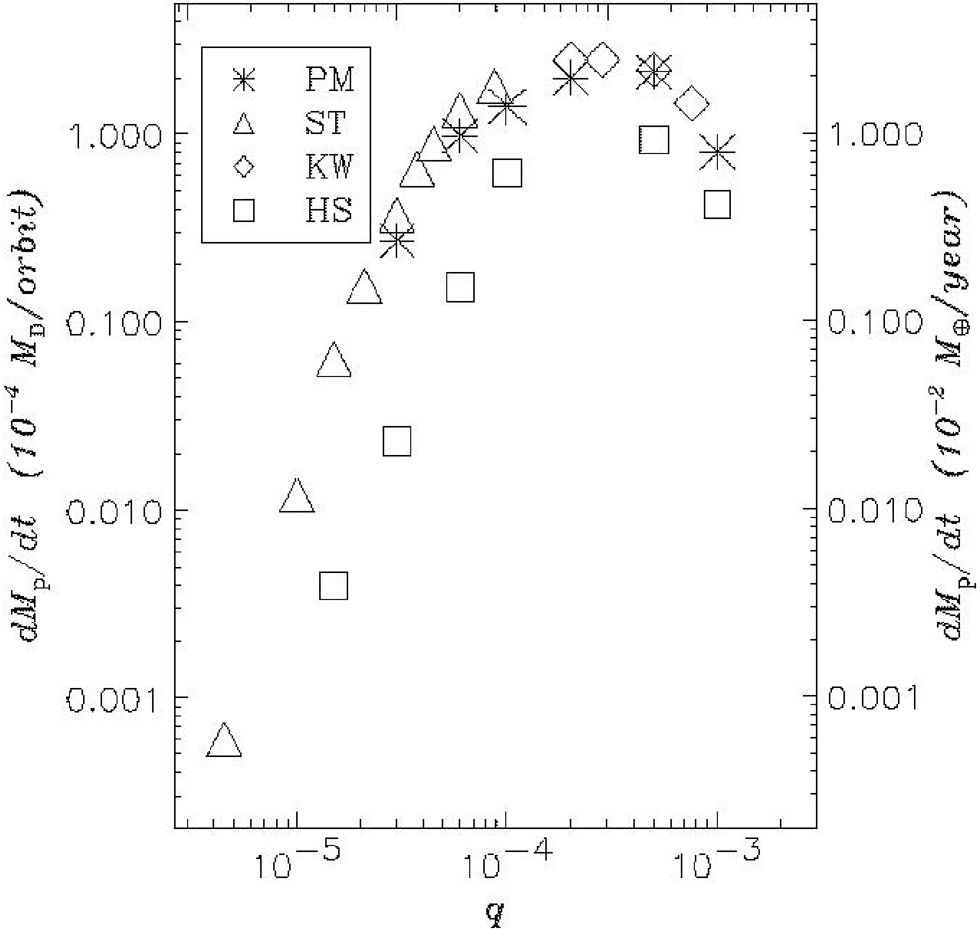


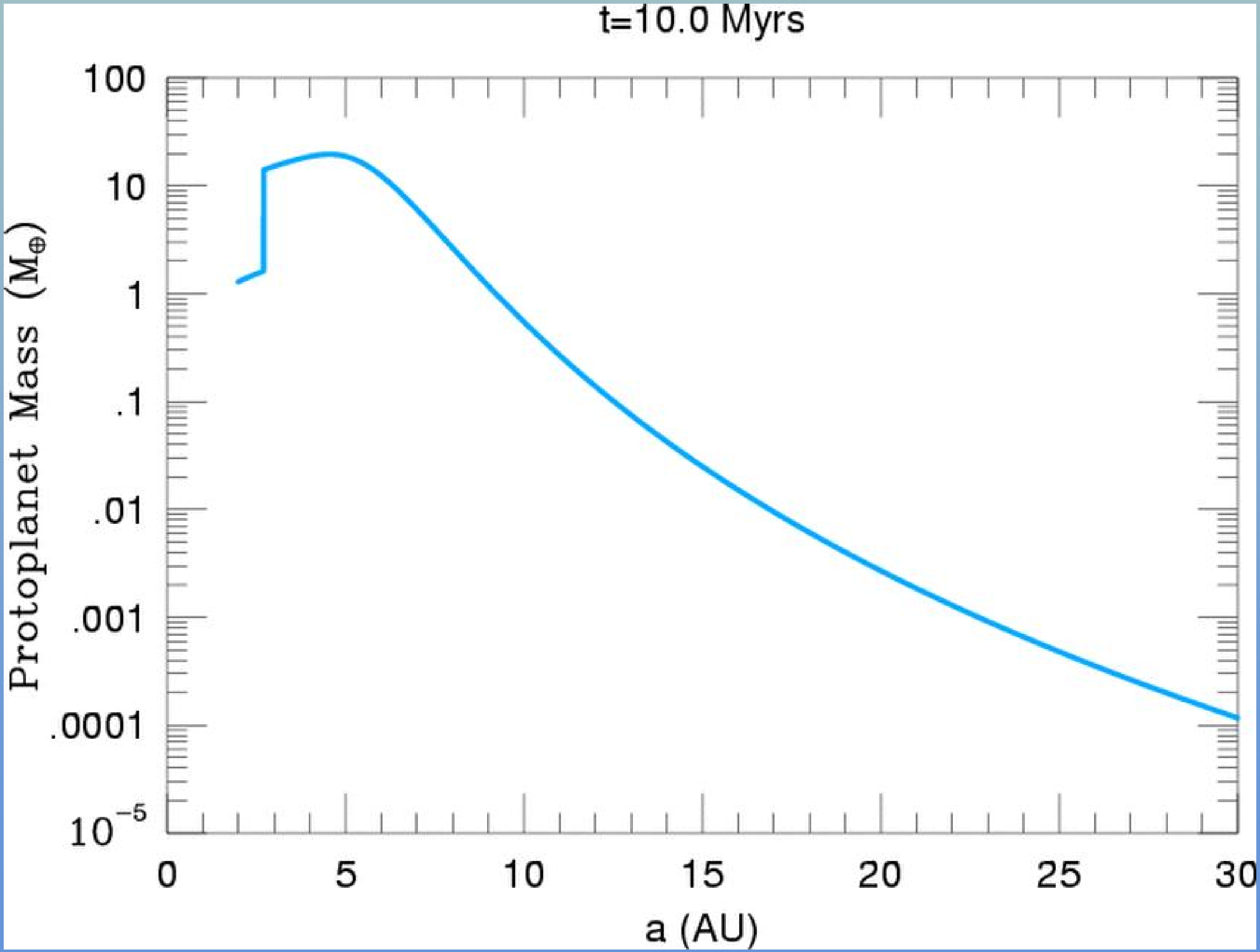
Fig. 7.— Planet's accretion rate as function of the normalized planet mass q. Different symbols stand for the different forms of gravitational potential Φ_p adopted in the computations. Apart from those models run with the homogeneous sphere potential Φ_p^{HS} (see eq. [6]), mass is removed from a volume, centered on the planet, with radius $\kappa_{ac} = 0.1\,R_H$ (see Table 3 for some details concerning the simulation with $M_p = 1.5\ M_\oplus$). Models for which $\Phi_p = \Phi_p^{HS}$ have κ_{ac} equal to $0.2\,R_H$ if $M_p > 20\ M_\oplus$ and to $0.15\,R_H$ if $M_p = 20\ M_\oplus$; otherwise κ_{ac} is set to $0.1\,R_H$.

Kley et al. 2002

A slow formation mode: concurrent accretion of solids and gas

- Accretion of solids by runaway growth
  - Not always easy: migration of solids & excitation of planetesimals can dramatically affect the growth
- Slow capture of the surrounding hydrogen and helium as soon as M_{core}>~5 M_{Earth}
- Rapid capture of the envelope as soon as M>~30M_{Earth}
- Same process for Jupiter, Saturn, Uranus, Neptune and terrestrial planets

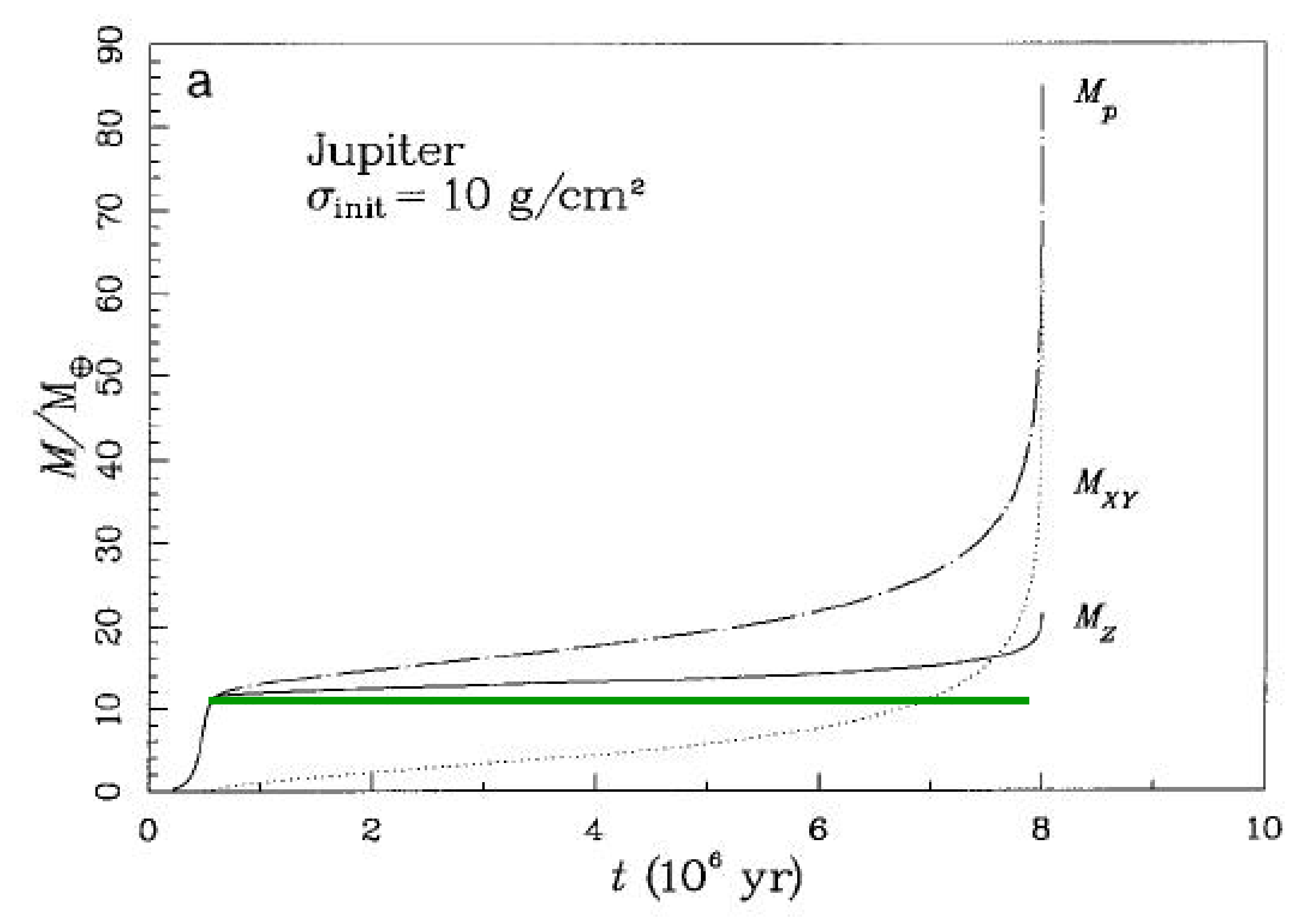
Runaway growth: the end product in a 5x minimum solar nebula

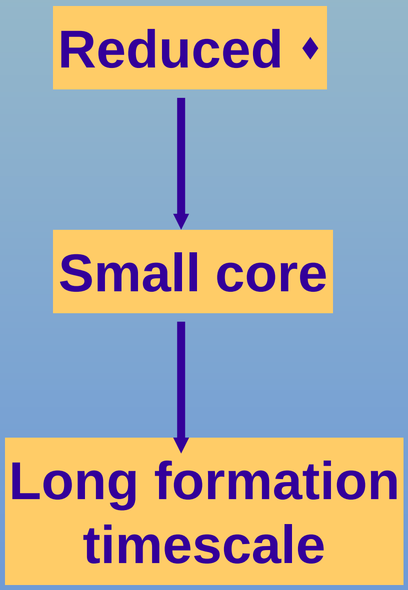


Thommes, Duncan & Levison 2002

Forming Jupiter by accretion

- Concurrent accretion of solids and gas (Pollack et al. 1996)
- Final core mass depends on surface density in the nebula





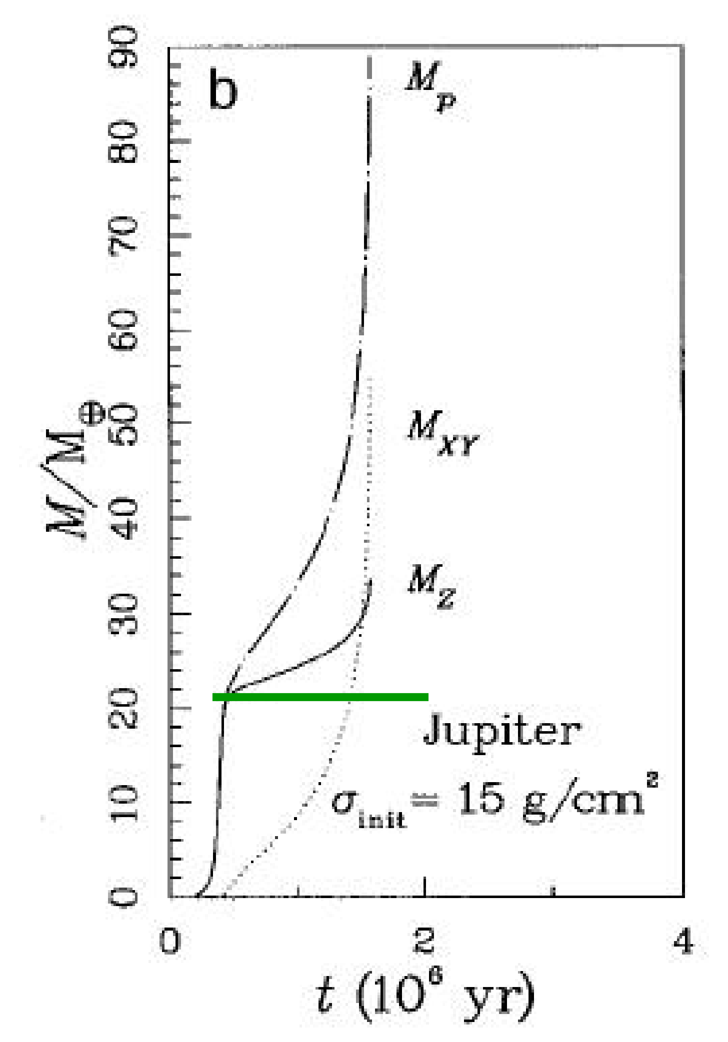
Reduced ♦

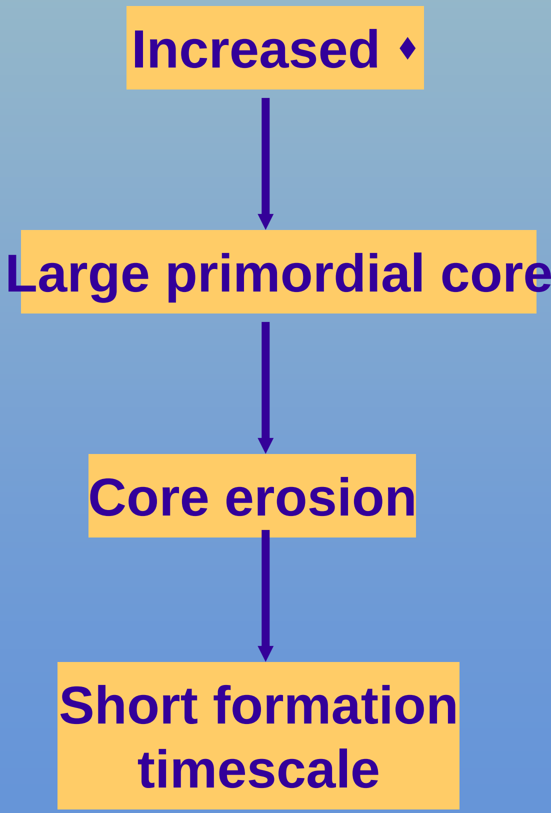
Small core

Long formation timescale

Possible rapid formation of Jupiter by accretion & core erosion

- Concurrent accretion of solids and gas (Pollack et al. 1996)



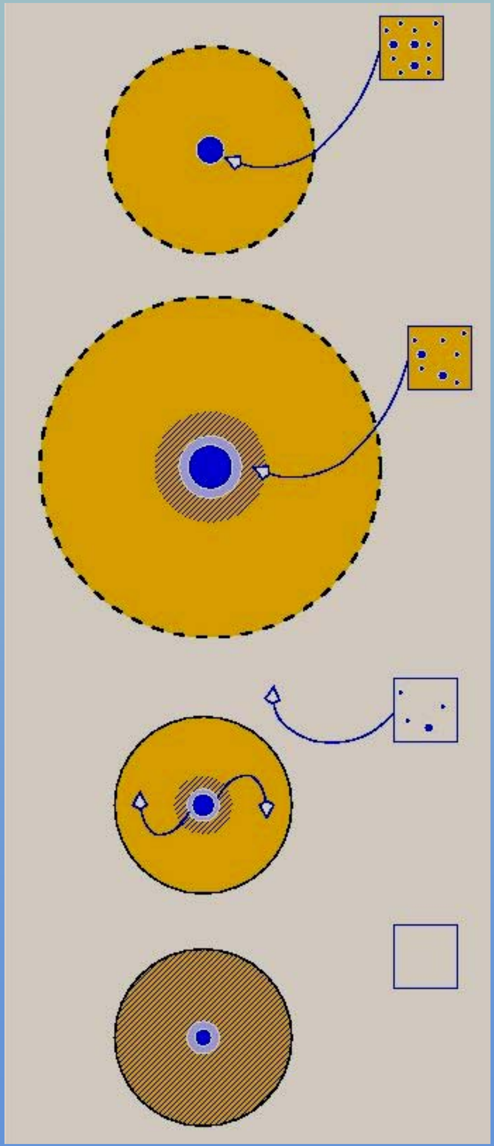

Increased ♦

Large primordial core

Core erosion

Short formation timescale

Delivering planetesimals (& water) to the giant planets



- Core accretion: planetesimals are delivered onto the central core.
- Core accretion: planetesimals cannot reach the core intact. (Podolak et al. 1988; Pollack et al. 1996)
- Envelope capture: accretion efficiency drops (Guillot & Gladman 2000): core erosion?
- Present: enriched atmospheres.

Core erosion

Energy needed to redistribute a small core of mass 👎m_{core} in a planet of total mass *M* and radius *R:*

$$\Delta E_{grav} = -\varpi \frac{GM}{R} \Delta m_{core}$$

Erosion mass flux (fraction of the convective energy in the first convective cell):

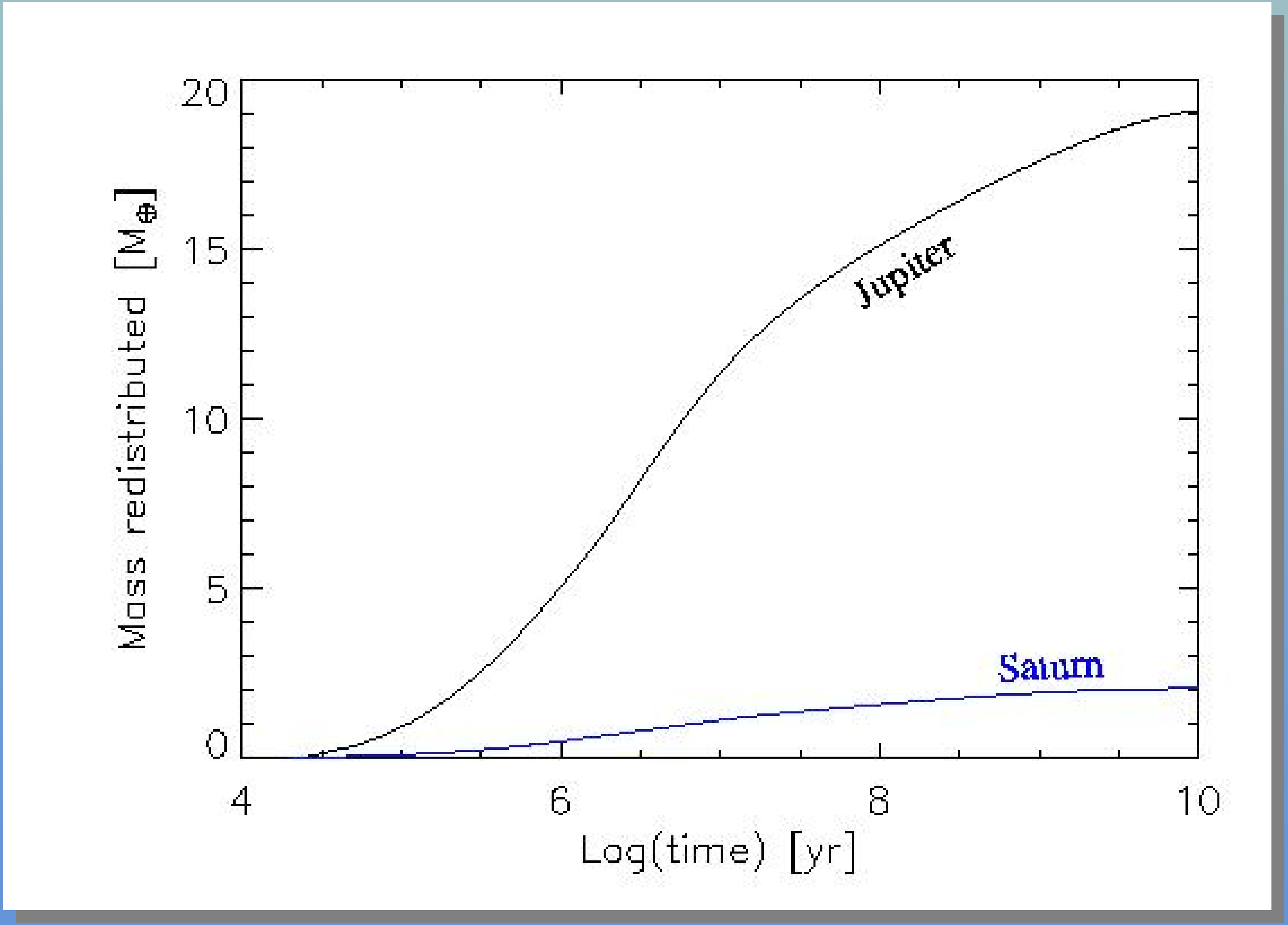
$$\dot{m}_{core} = -\frac{\chi}{\varpi} \frac{RL_1}{GM}$$

$$\varpi \approx 3/10$$

$$\chi \approx \sqrt{D/K} \approx 0.1$$

molecular diffusivity D~10^{-3}-10^{-4} cm^{2}s^{-1}
thermal diffusivity K~0.1 cm^{2}s^{-1}

Core erosion: Jupiter & Saturn

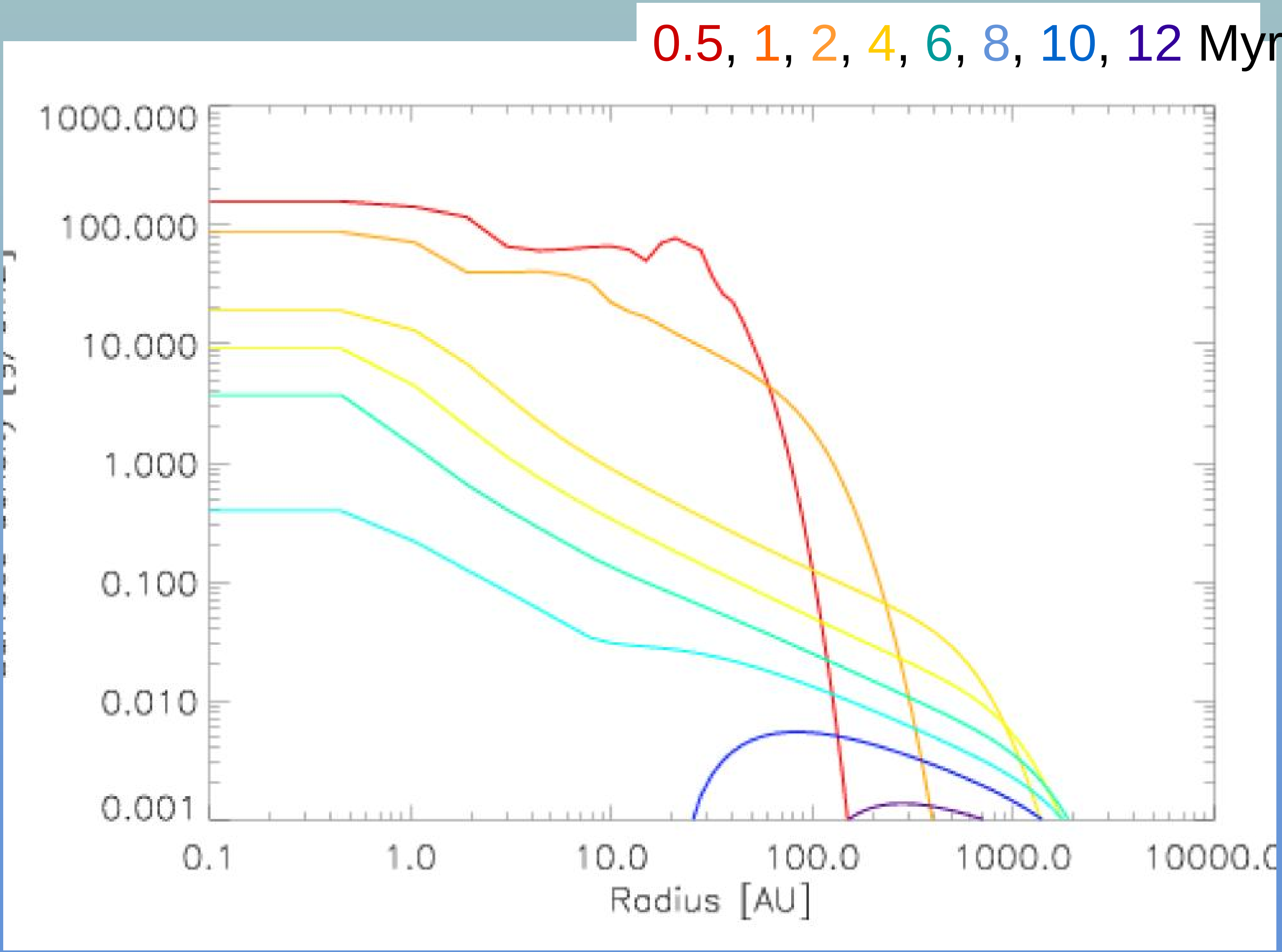


Guillot, Stevenson, Hubbard & Saumon, « Jupiter book »

A “Nice” formation scenario

- Assume collapse of molecular cloud in solid rotation
- Assume constant turbulent alpha (here α=0.03)
- Begin forming the cores late in nebula evolution when type I migration is suppressed
- Account for nebula photoevaporation
- Giant planets swallow the remains of the nebula (gas + solids)
- Don’t bother with details (accretion, planetesimal growth vertical structure etc)

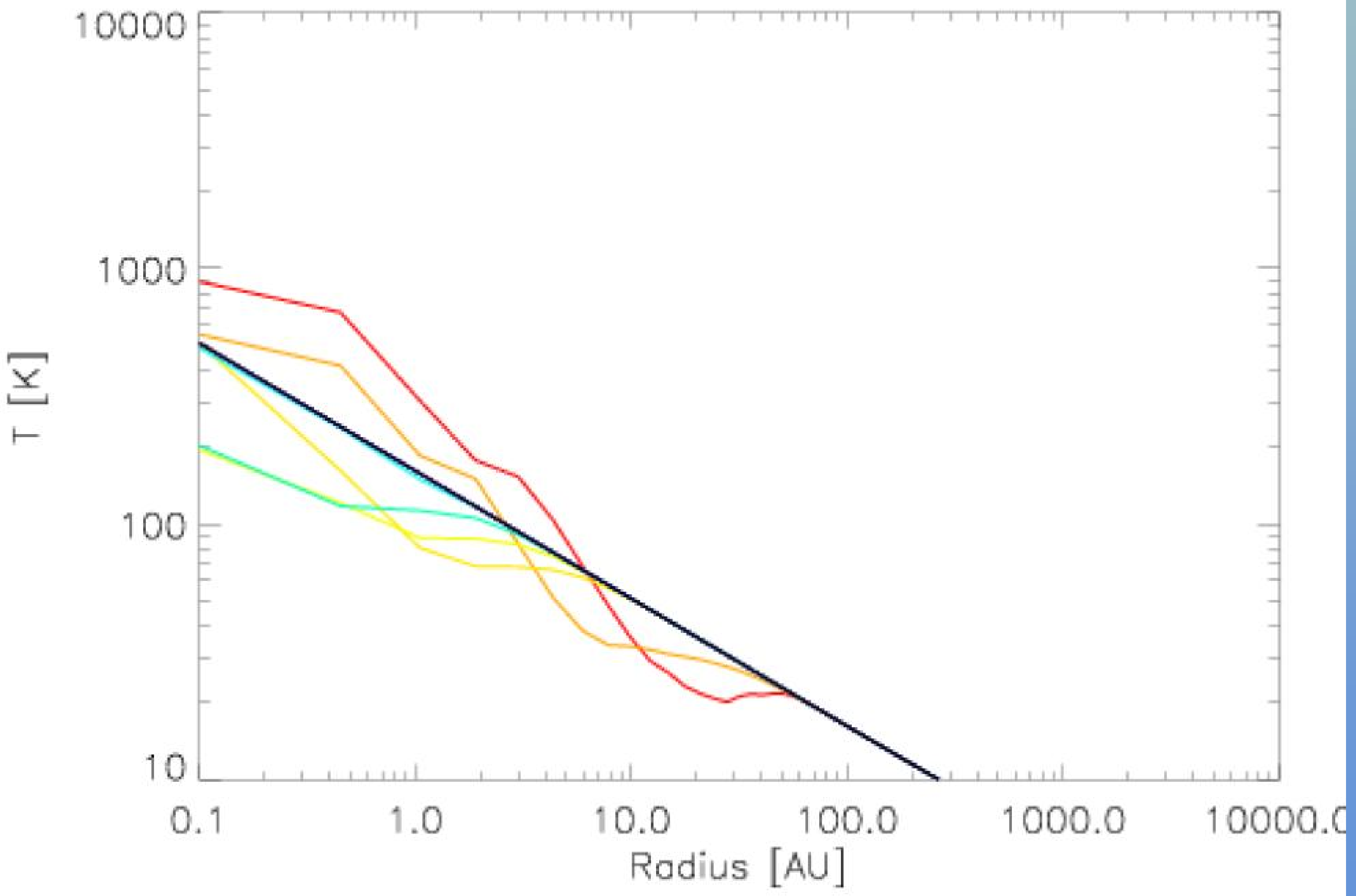
Nebula evolution: surface densities



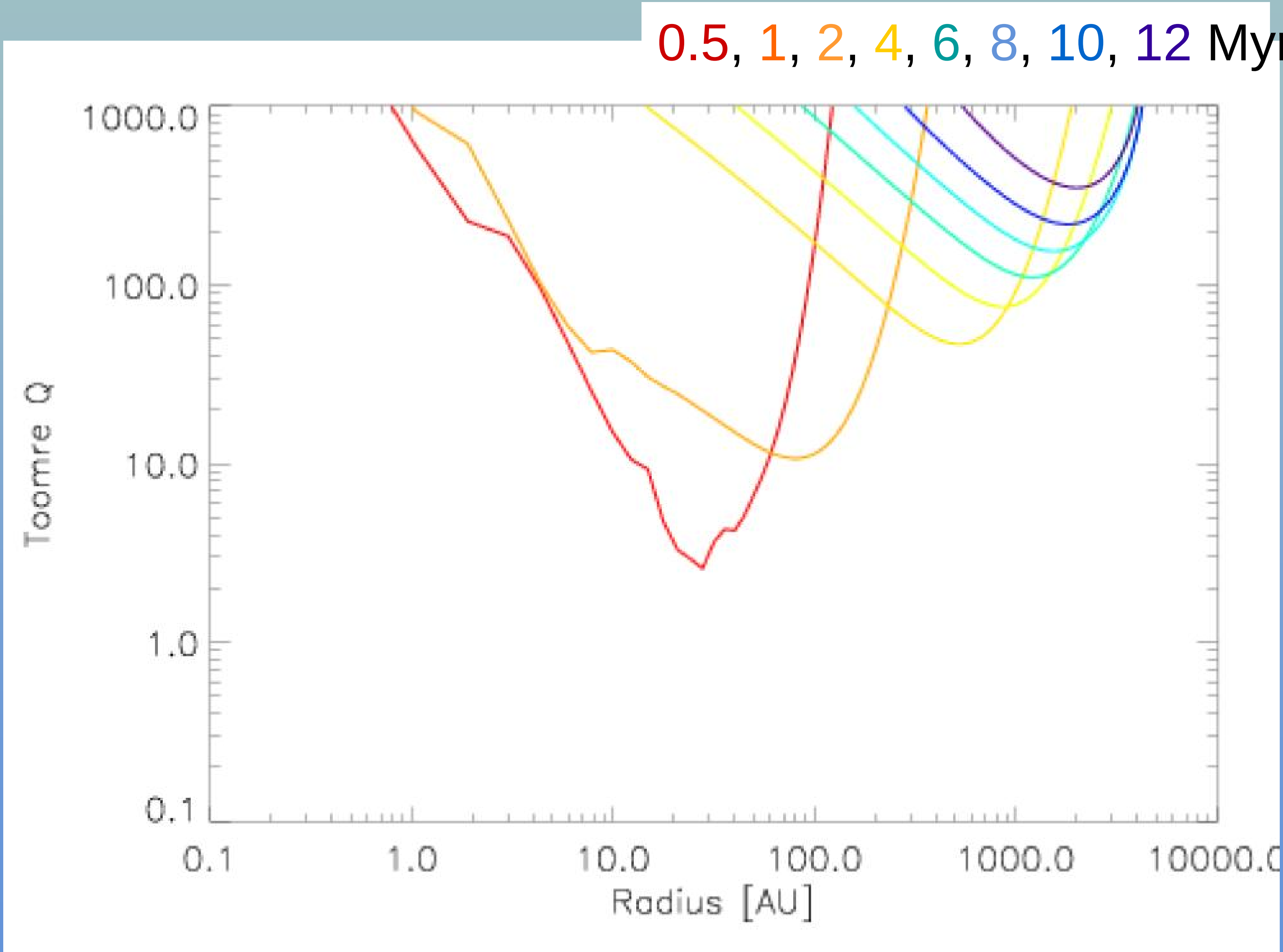
0.5, 1, 2, 4, 6, 8, 10, 12 Myr

Nebula evolution: midplane temperatures

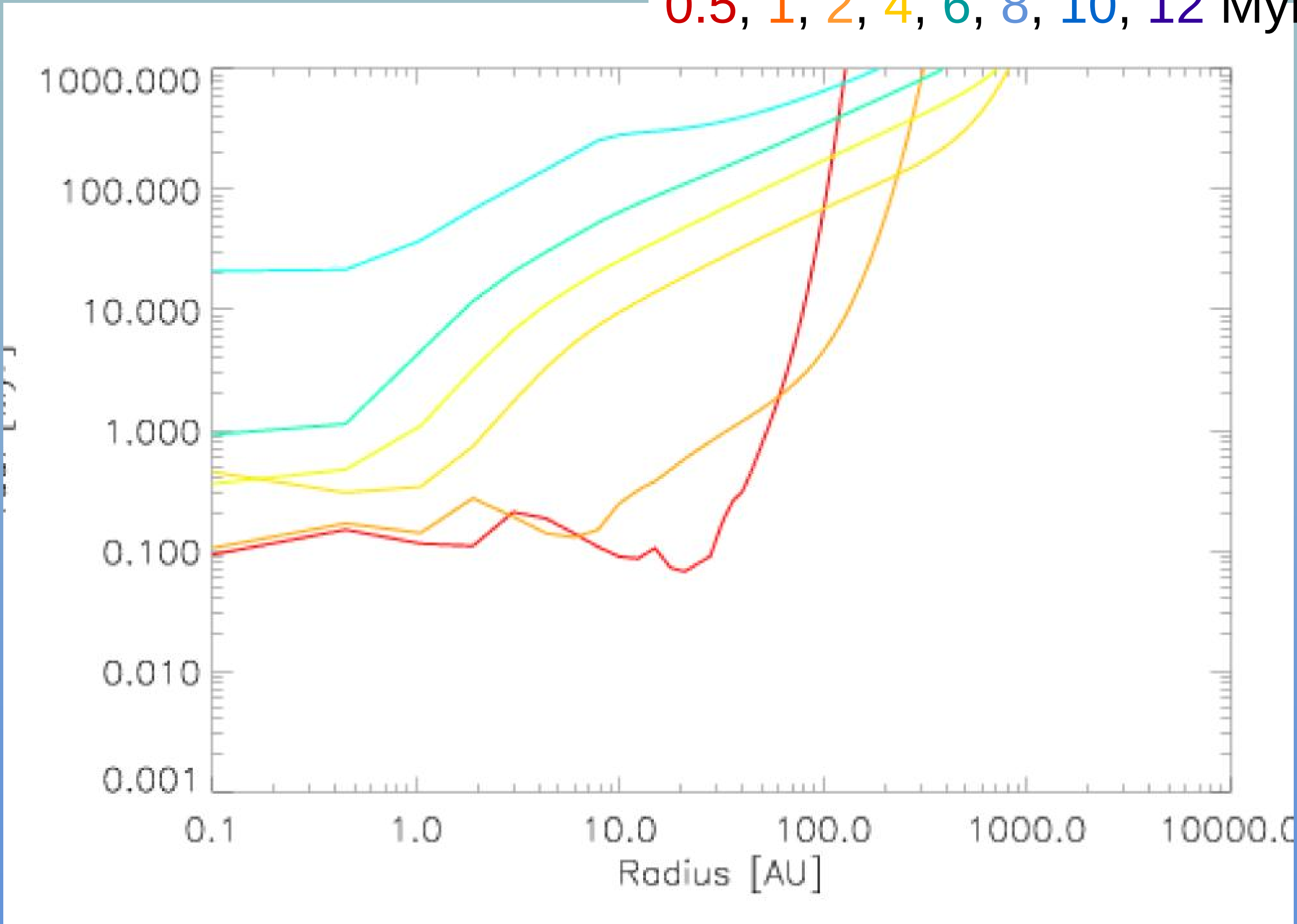
0.5, 1, 2, 4, 6, 8, 10, 12 Myr



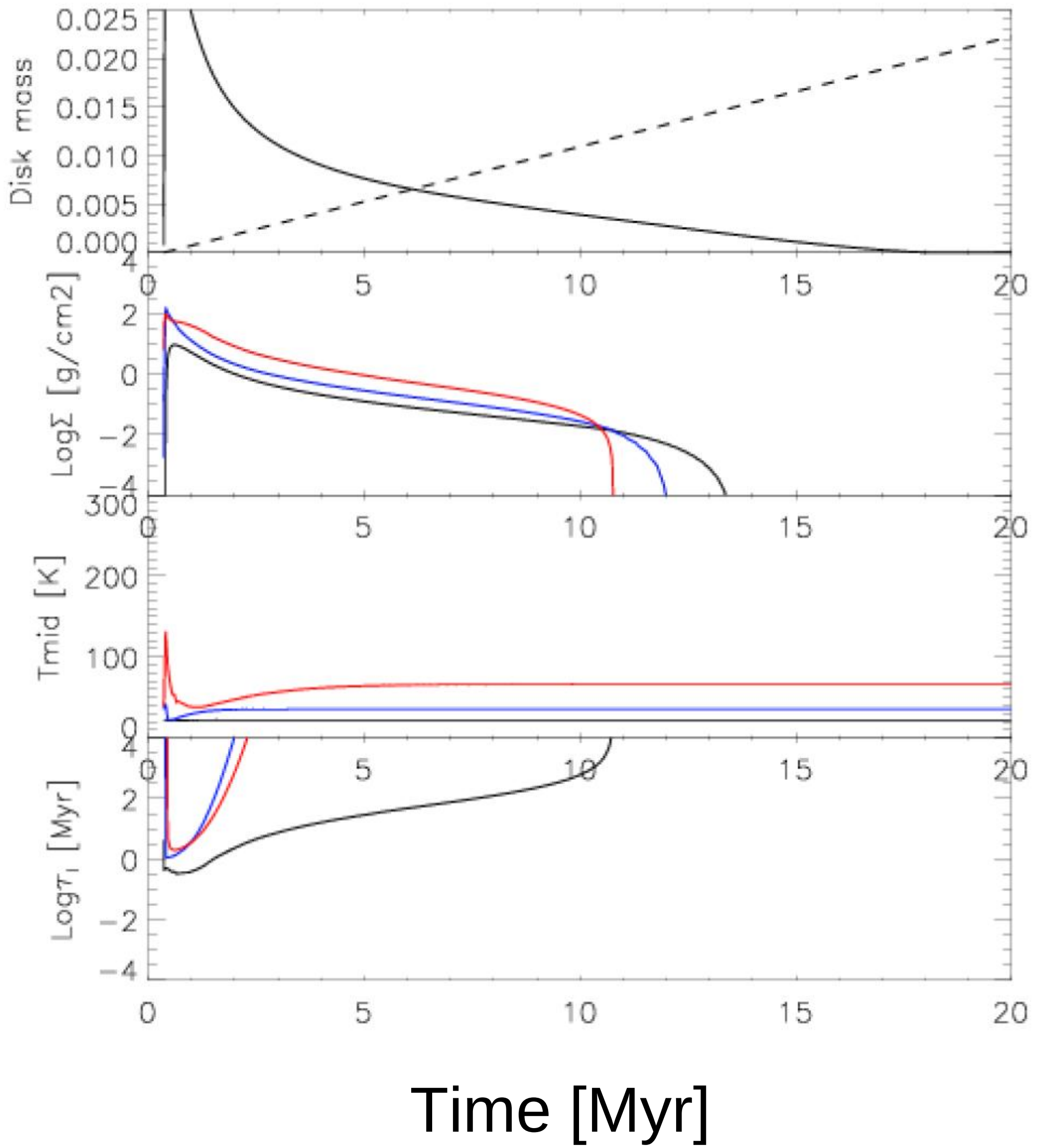
Nebula evolution: Toomre parameter


0.5, 1, 2, 4, 6, 8, 10, 12 Myr

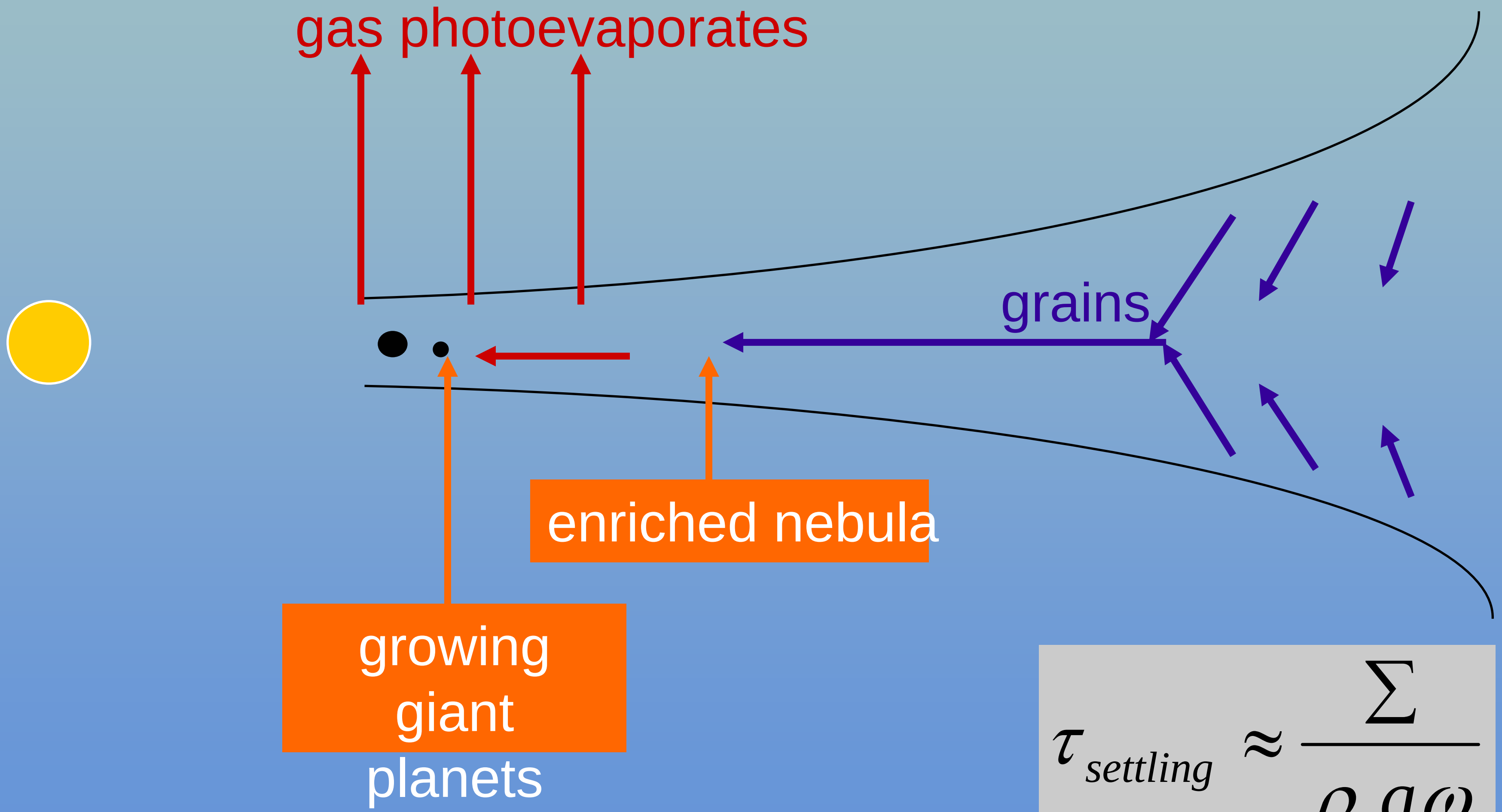
Nebula evolution: Type I migration


0.5, 1, 2, 4, 6, 8, 10, 12 Myr

Nebula evolution: time dependence



Global picture



gas photoevaporates

grains

enriched nebula

growing giant planets

$$\tau_{settling} \approx \frac{\Sigma}{\rho_s a \omega}$$

Photoevaporation

- Leads to hydrodynamic escape (mean free path << H)
- Assumed surface density loss (hydrogen):

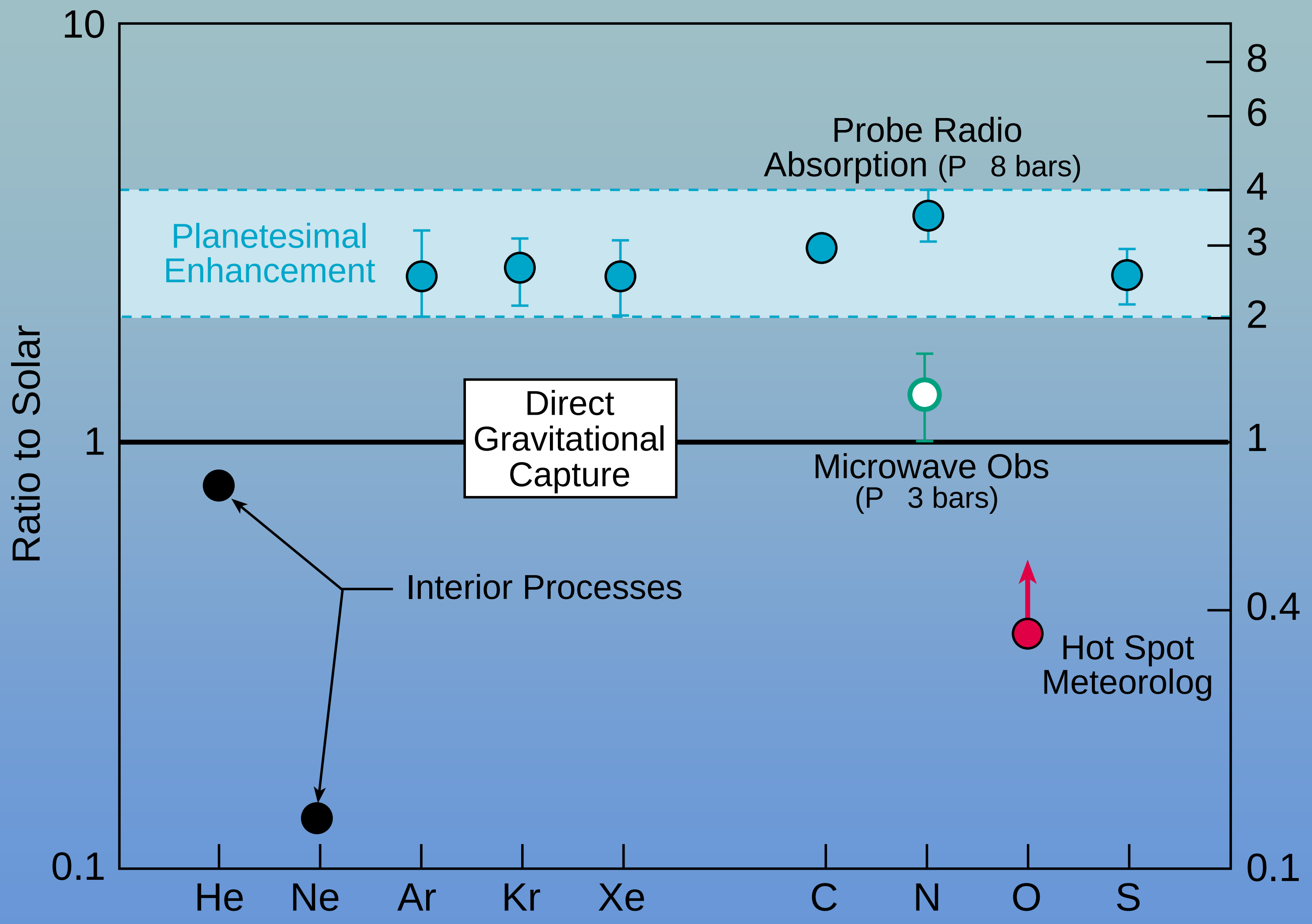
$$\dot{\Sigma}_{UV} \approx 2\times10^{-12}\sqrt{\phi_{41}}R_{g,AU}r_{AU}^{-5/2}g.cm^{-2}.s^{-1}$$

- Simple approach (Hunten et al. 1986): elements escape except above a critical mass:

$$\frac{m_c}{m_1} = 1 + \frac{kT\,\dot{\Sigma}_{UV}}{bg_0X_1m_1^2} \approx 20000@10AU$$

- Atomic argon escapes, not grains

The Galileo probe results



Ratio of Jovian to Solar Abundances

Owen et al. Nature (1999)

Delivering argon to Jupiter

- Ar condenses at very low temperatures (~30K)
- Present in 3 times solar abundance in Jupiter's atmosphere
  - requires decoupling from H,He delivery
- Possible clathration (Gautier et al. 2001, Hersant et al. 2003)
  - implies late delivery
  - requires a number of free cages ⇒high H_2O abundance
  - requires that most of the mass is in small particules
- Direct condensation?
  - requires low temperatures: TBI (work with L. Abe)

Argon: clathration

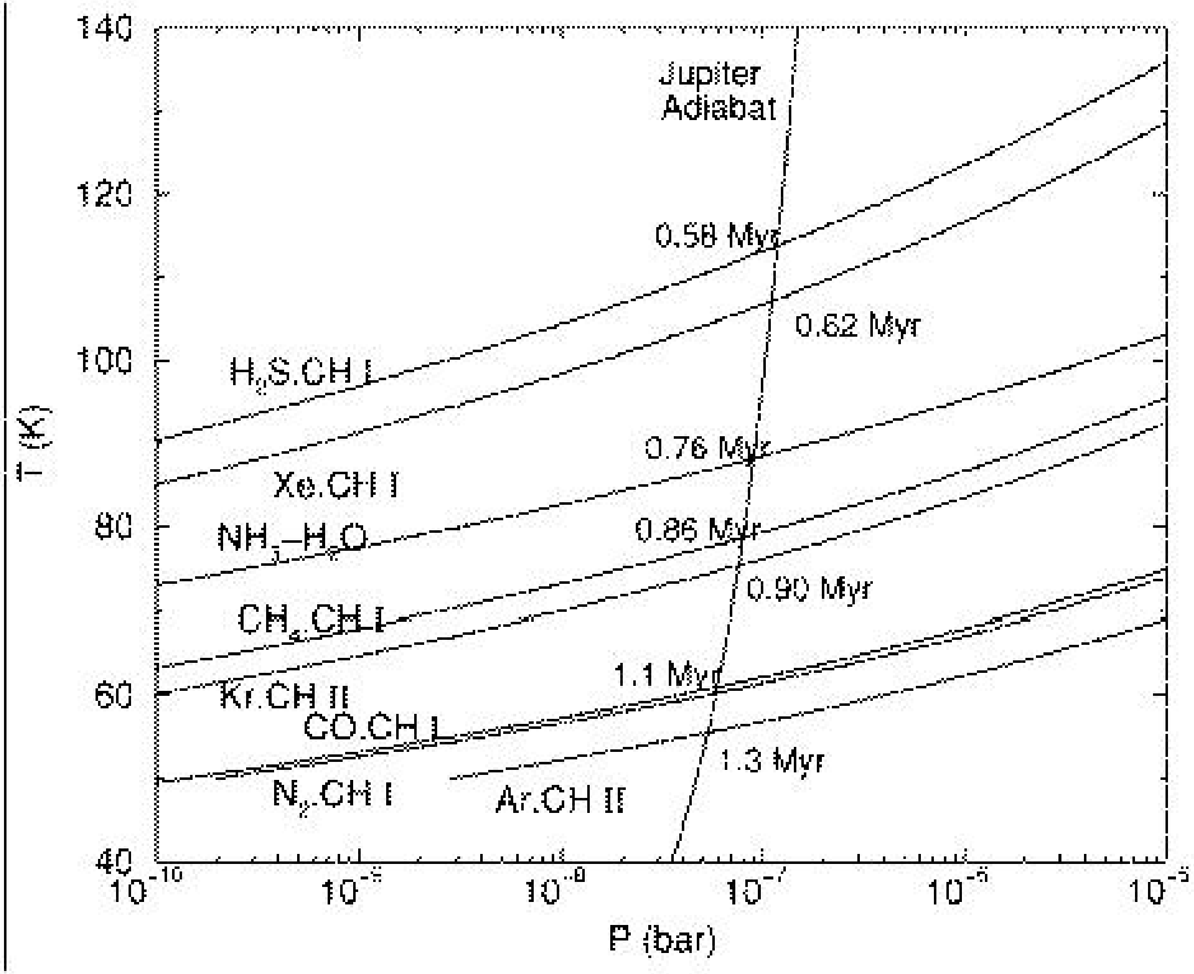


FIG. 2.—Curves of stability of clathrate hydrates of H_2S, Xe, CH_4, CO, N_2, and Ar, together with the Jupiter adiabat from the nominal nebula of the model of Hersant et al. (2001). CH I and CH II refer to clathrate hydrates of type I and type II, respectively (see text for more details). The condensation curve of the NH_3-H_2O hydrate is also shown.

In conclusion...

- A slow formation of Jupiter agrees with models of formation of the galilean moons (Stevenson, Canup & Ward)
- Qualitative explanation of the star metallicity/radial velocimetry planets correlation (eg. Gonzalez, Santos et al.)
- Possibility of gravitational instability of the dust disk (gas depletion)

buts

- Terrestrial planets (X-wind?)
- Growth of planetesimals?
  - Runaway growth in a low surface density nebula yields small cores
  - requires migration to grow
- Timing of growth?
  - Jupiter, Saturn, Neptune, Uranus…and the nebula dissipates
- Gas accretion onto the planets?
  - Requires slow accretion (isotropic) for 10 Me cores
- Gravitational interactions?