From planetesimals to planetary systems: a hardles race

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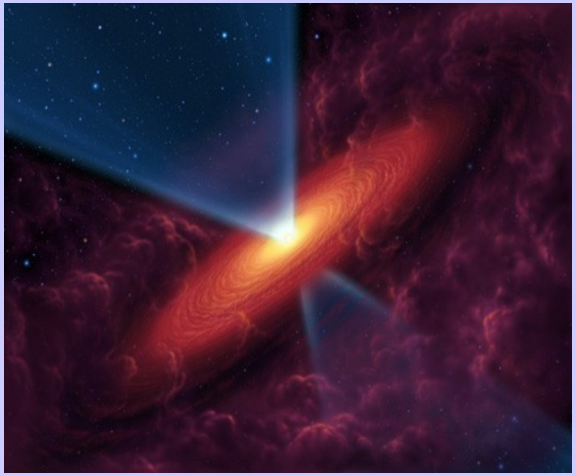
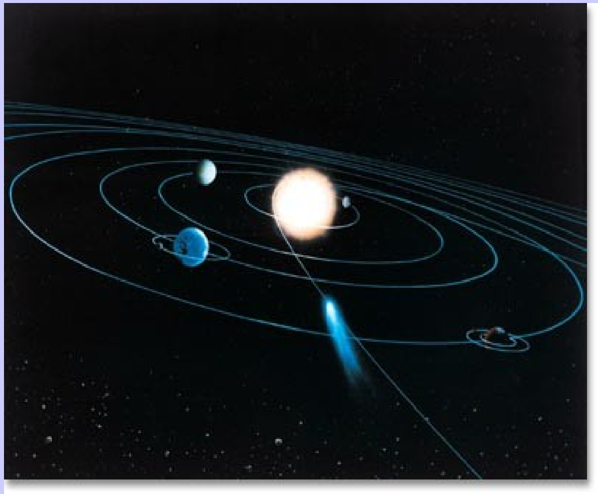
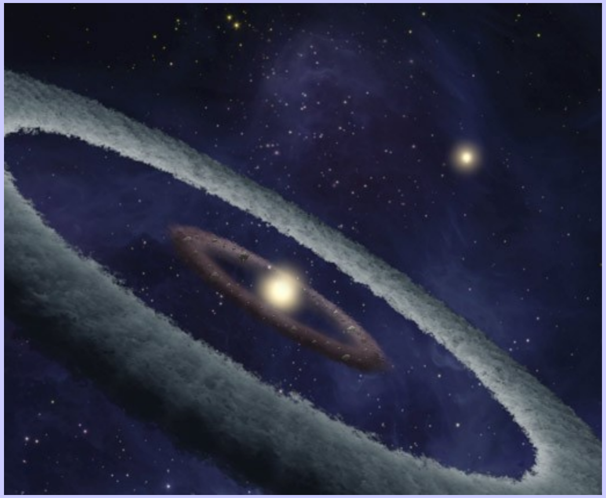
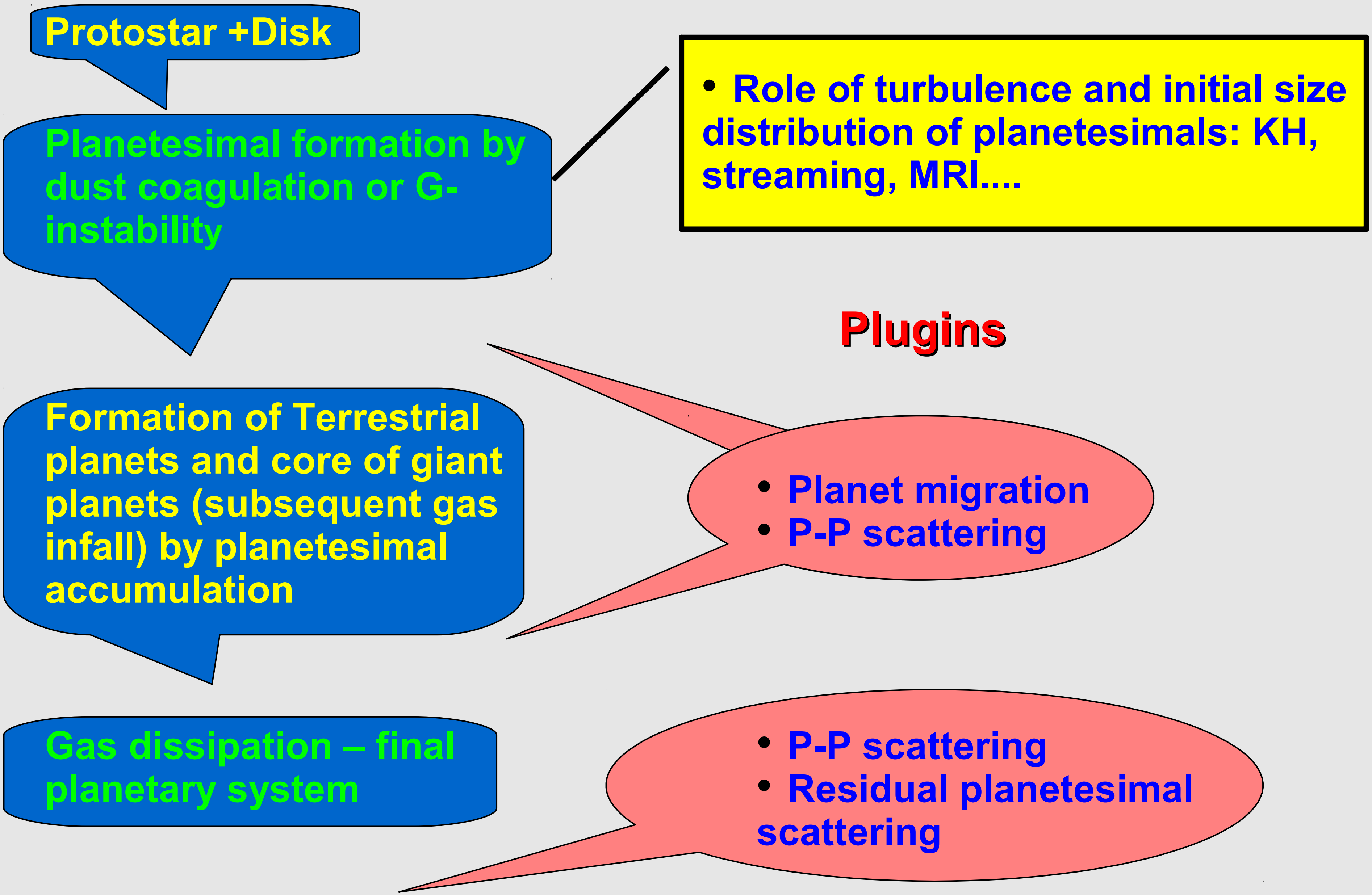






The standard model



Protostar +Disk

Planetesimal formation by dust coagulation or G-instability

- Role of turbulence and initial size distribution of planetesimals: KH, streaming, MRI....

Plugins

Formation of Terrestrial planets and core of giant planets (subsequent gas infall) by planetesimal accumulation

- Planet migration
- P-P scattering

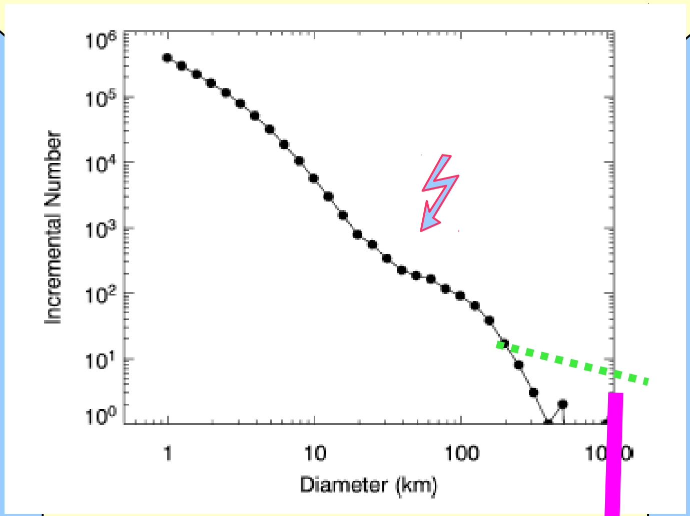
Gas dissipation – final planetary system

- P-P scattering
- Residual planetesimal scattering

Planetesimal formation and size distribution: big or small?

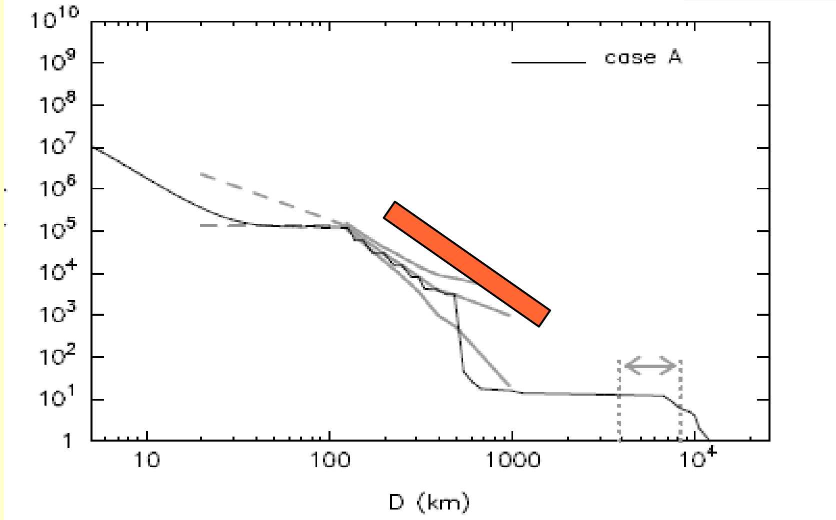
MB asteroids, Trojans and KBOs are planetesimals.

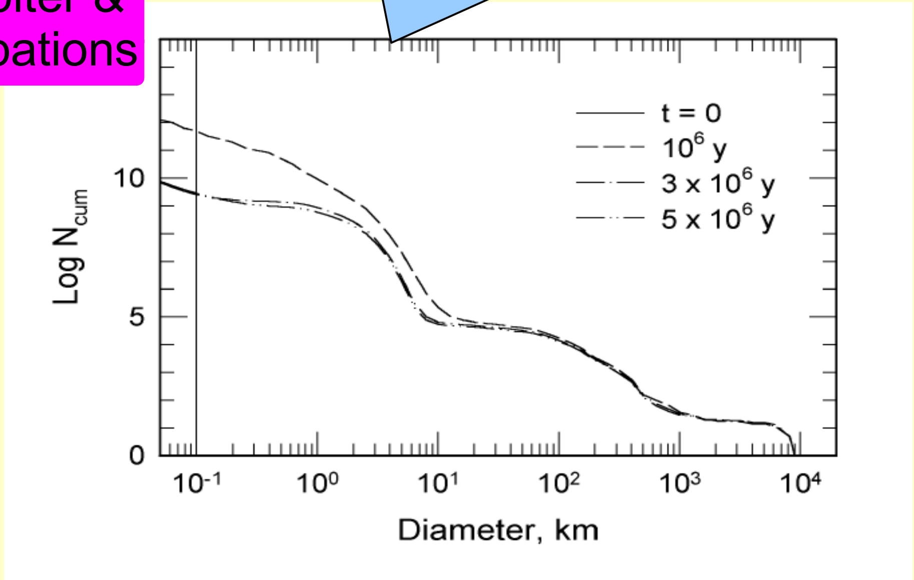
Morbidelli (Icarus 2009): streaming instability (Youdin & Johansen, 2007) or MRI lead to the formation of large planetesimals 100, 1000 km in size by turbulent motion. This explains the present asteroid size distribution (bump at 100 km)



Planetary embryos (Moon-Mars size) cleared by Jupiter & mutual perturbations

Weidenschilling (LPSC, 2009): starting from a uniform population of small planetesimals (d = 0.1 km) grown by dust coagulation, he can reproduce via planetesimal accumulation the present asteroid size distribution (bump at 100 km).

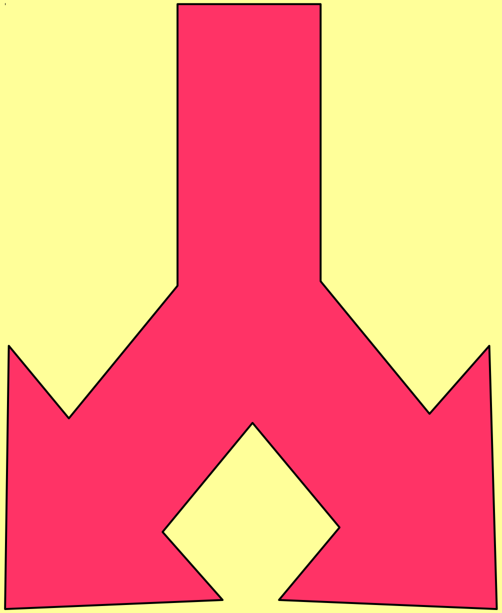




$d_0 = 0.1$ km

Planetesimal formation: possible simplified scenario

Dust collisional sticking up to 1 m size boulders

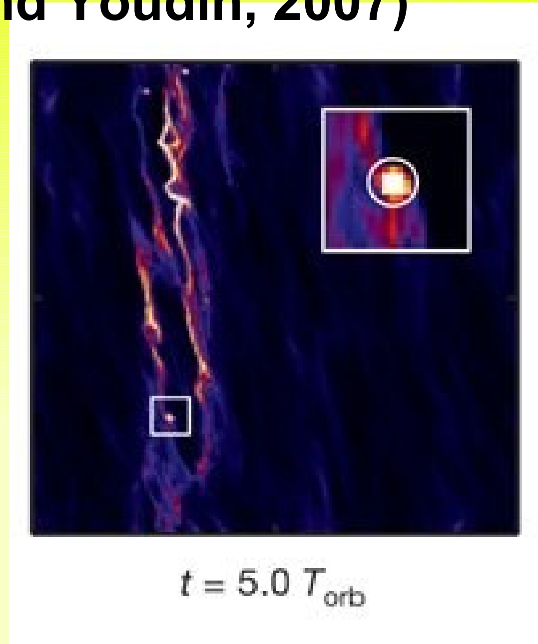


High degree of turbulence: turbulence (asymmetries in the disk density, eddies) drives formation of planetesimals and their size distribution

Low degree of turbulence: collisions continue to produce larger bodies. Uniform population of planetesimal 0.1-10 km in size form

Turbulent motion concentration:

Pencil code (Johansen and Youdin, 2007)



PROs:

- Fast accretion of large planetesimals from 1-m boulders .....
- .... which are more resistent to perturbations during subsequent accretion (giant planet, binary stars...)

CONs:

- High initial density of solids (3 times the MMSN)
- Single size particles in the simulations (small particles may contribute significantly to the the growth of larger bodies).
- Each particle is representative of many particles (pre-clumping?)
- Drag is computed from nodes around the particle and back reaction acts on the nodes. What is the effect of spreading around the back reaction of the particles?
- Poor model of the collisional physics between the particles
- Resolution issues?

Dust coagulation model

PROs:

- Smooth grow of larger bodies
- Reliable collisional model
- Initial size distribution of any kind
- Robust (it does not depend much on initial parameters)
- It can overcome the 1-m catastrophe

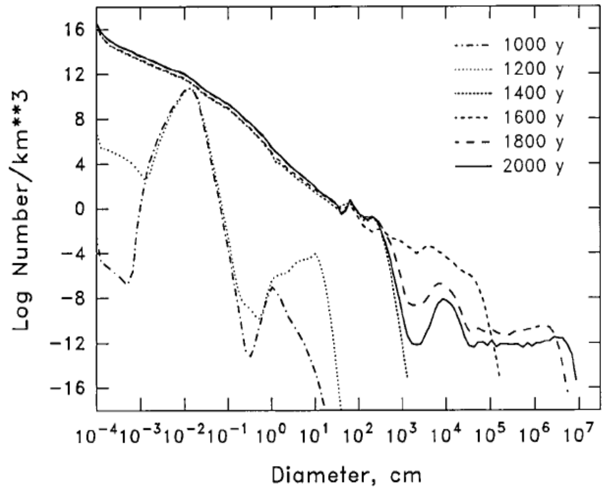


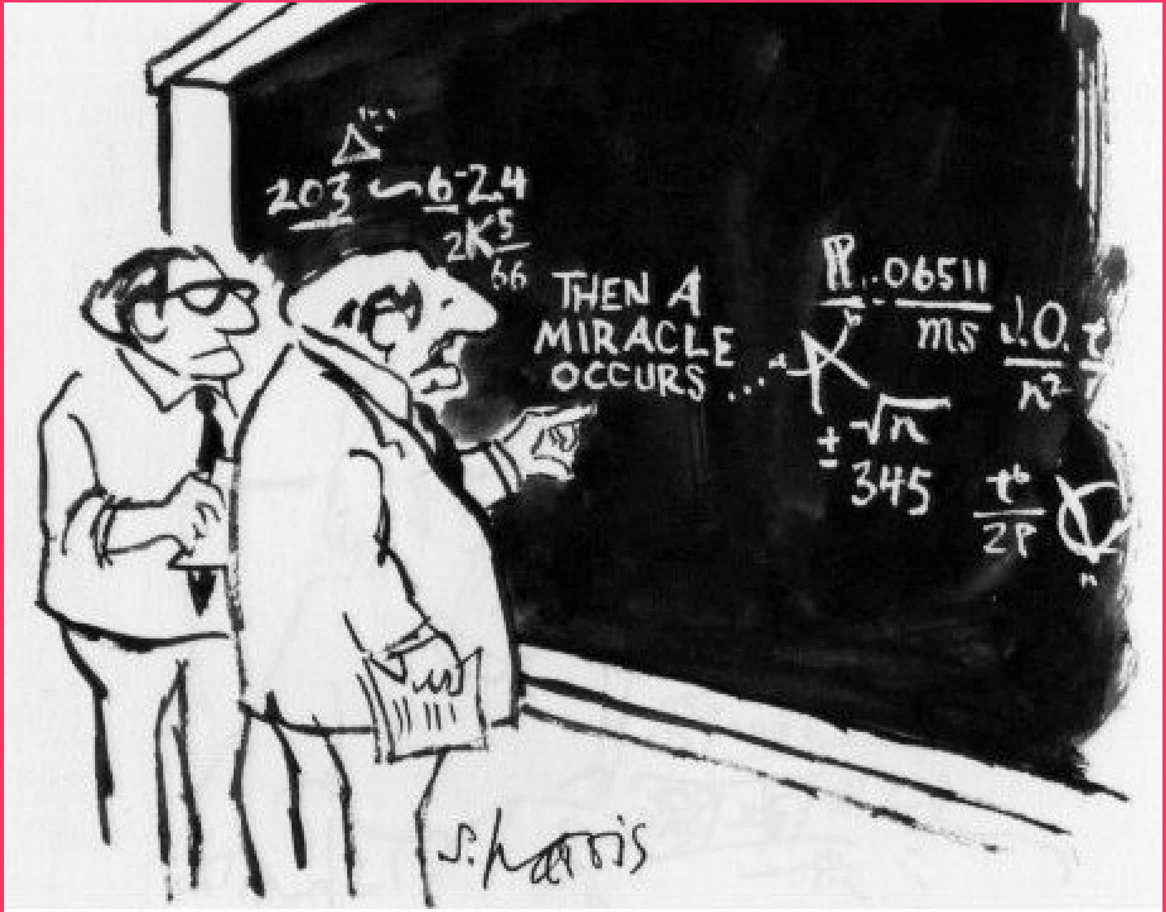
Figure 3. Size distribution of particles in the central plane of the nebula at various times. At $t = 0$, all solids consisted of grains with diameter 10^{-4} cm, uniformly mixed with the gas through the thickness of the disk. Coagulation driven by drag- induced motions results in growth, while settling concentrates mass in a dense layer in the central plane.

Weidenschilling (2000, 2009)

CONs:

- Relative impact velocity between dust particles may turn out high (Paraskov et al 2007 et al., this does not necessarely prevent coagulation)
- More sensitive to external perturbations (planetary or stellar companion)
- Degree of turbulence sets 'by hand'

We have moved from the 'miracle' stage, in particular concerning the mechanisms responsible for planetesimal formation, but still far from predicting the initial size distribution!



"I think you should be more explicit here in step two."

from *What's so Funny about Science?* by Sidney Harris (1977)

From planetesimals to planets: terrestrial planets

Planetesimals to protoplanets (10^5-10^6 yrs)

$$
\begin{aligned}
M_{\rm iso} &\simeq 2\pi a b \Sigma_{\rm solid} \\
&= 0.16 \left(\frac{\tilde{b}}{10}\right)^{3/2} \left(\frac{\Sigma_{\rm solid}}{10\ {\rm g\ cm^{-2}}}\right)^{3/2} \left(\frac{a}{1\ {\rm AU}}\right)^{3} \\
&\times \left(\frac{M_*}{M_\odot}\right)^{-1/2} M_\oplus\ ,
\end{aligned}
$$

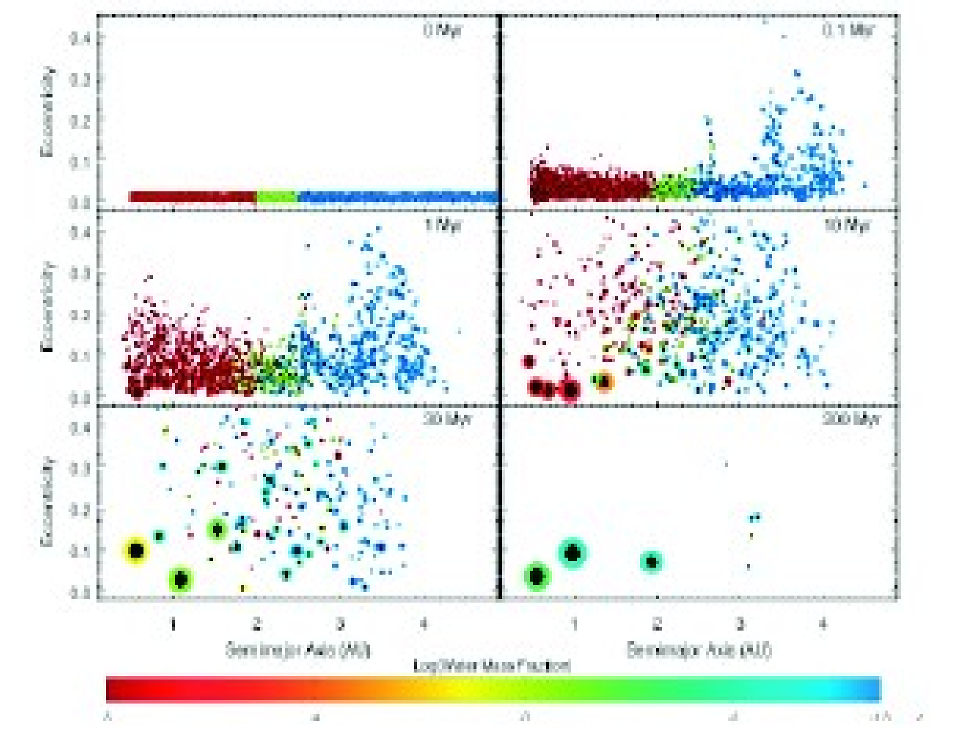
Isolation mass

At 1 AU: 0.06 M_E

At 5 AU: 1-5 M_E

Protoplanets to planets (10-100 Myr): giant impact phase.

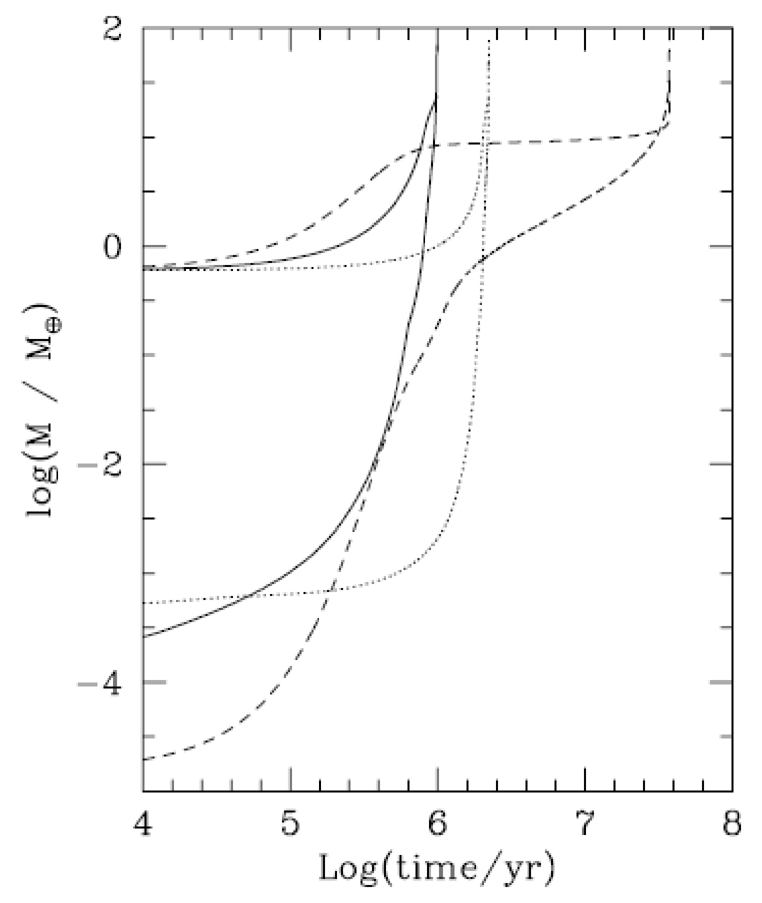
Reymond (2008)



From planetesimals to planets: giant planets

Giant impact phase much shorter due to planet migration. It prevents dynamical isolation and move the planets around filling up their feeding zone. Problems? It may be too fast and push the planet onto the star.

Alibert et al. (2005)



* Upper line: mass accreted from planetesimals
* Bottom line from gas
* Continuous line: started at 8 AU,
* Dotted: at 15 AU (all end up at 5 AU).
* Dashed line: in situ model (no migration)

Type I migration (reduced by a factor 10-100)

$$\Gamma_{\rm total}(3D) = (1.364 + 0.541\alpha)\left(\frac{M_p}{M_c}\frac{r_p\Omega_p}{c}\right)^2 \sigma_p r_p^4 \Omega_p^2$$

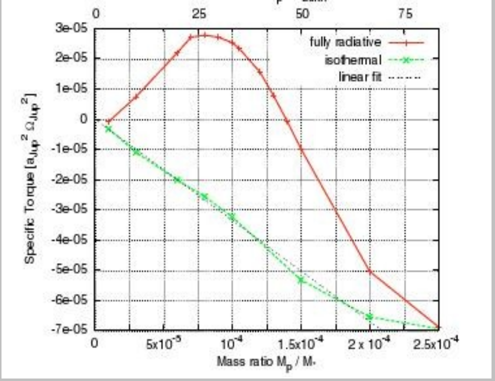
Type II migration (when gap is opened)

$$\frac{dr_p}{dt} \sim \frac{3\nu}{2r_p}$$

Planetary migration: a very complex problem

Small planets (1- 50 M_E): Type I migration

Turbulence (MRI?): stochastic migration



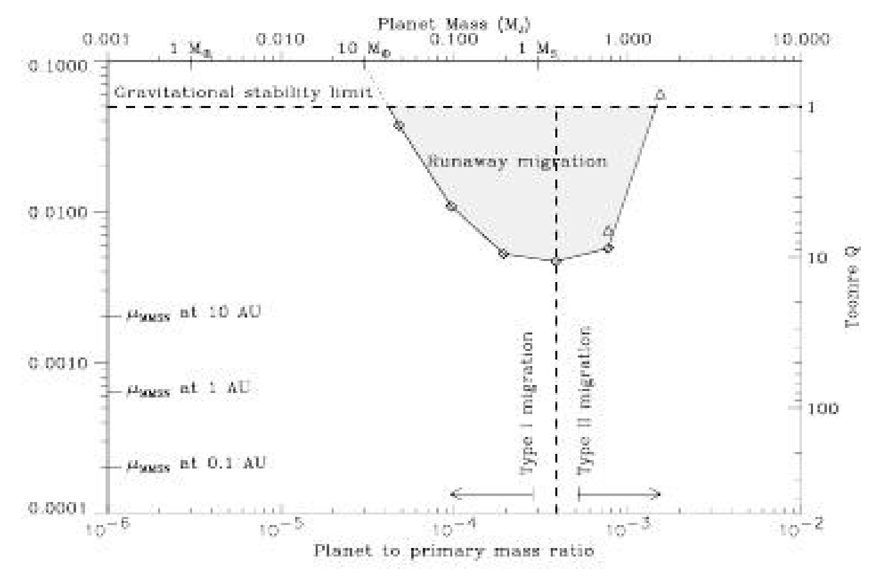
Kley & Crida (2008)

Isothermal, adiabatic, or fully radiative energy equation

2D-3D

HS drag

Masset & Papaloizou (2003)

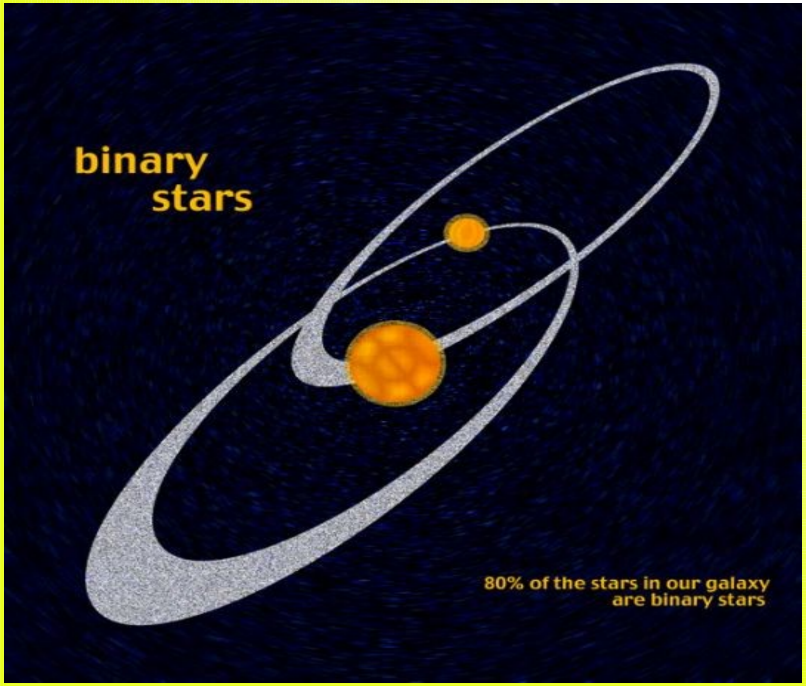


Saturn-Jupiter size planets: Type II, III migration

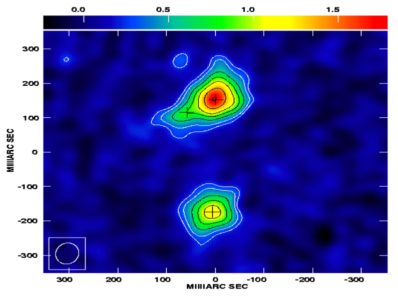
Numerical simulations: resolution close to the planet (CPD handling) and at resonances

Planet formation around single stars is a hurdles race but it works: at least 20% of stars have planetary systems (bias, metallicity....)

What about if there is a perturber (companion star or giant planet)? Secular perturbations can excite large impact velocities and halt planetesimal accumulation (and then planet formation). Jupiter halted planet formation in the asteroid region.



Planet formation in binaries:



Planets (giant ones) are less frequent in binaries (G-K stars) with a < 100 AU (Eggenberger et al. 2007) : small sample.

Influence of binarity on circumstellar disk lifetime is rather mild for a>20 AU (Monin et al., PPV): small sample.

Planetesimal accumulation may be the critical phase:

1) Eccentricity grow due to secular perturbations (Thebault et al. 2006; Marzari et al. 2007)

2) Inclination perturbations? Low inclination (< 5^o) seems to favor planet accretion (Xie & Zhou 2008). High inclination (> 10^0) is more critical.

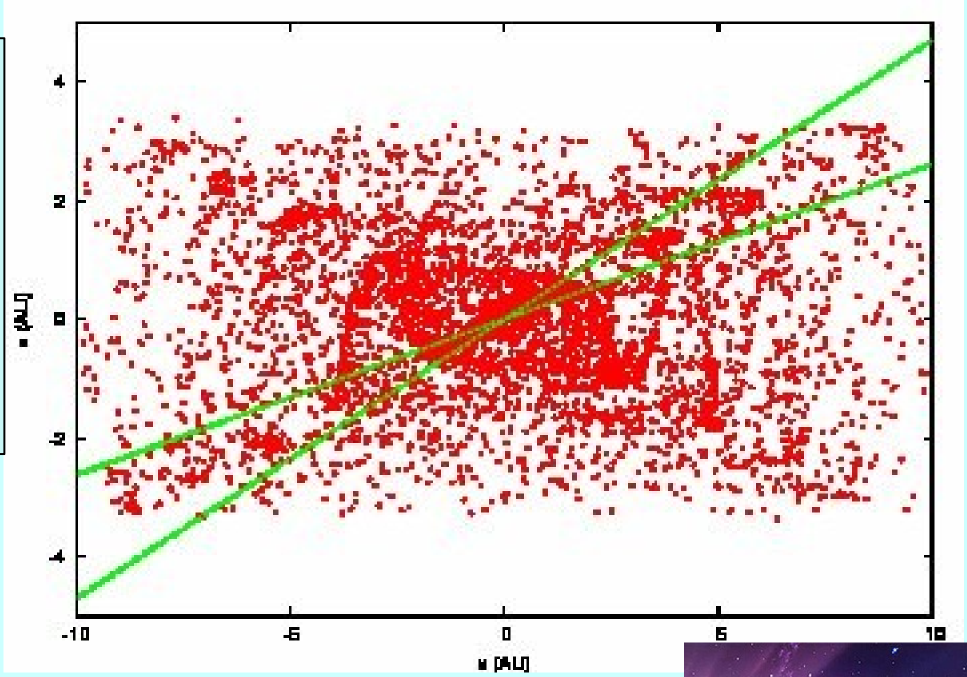
Misalignment between binary orbit and circumstellar disk plane debated:

- **Hale (1994): the primary's equator appears to be randomly inclined respect to the binary orbit for a_b>30-40 AU** (visual binaries, v sini from spectroscopic line broadening, 30 systems).

- **Jensen et al. (2004) claim that disks in binaries are aligned with each other and presumably with the binary orbit for a_b >200 AU** (i < 20^o, use of polarimetry, 9 binary systems).

What are the effects of a large inclination between the planetesimal plane and that of the companion orbit on their dynamical evolution and accumulation?

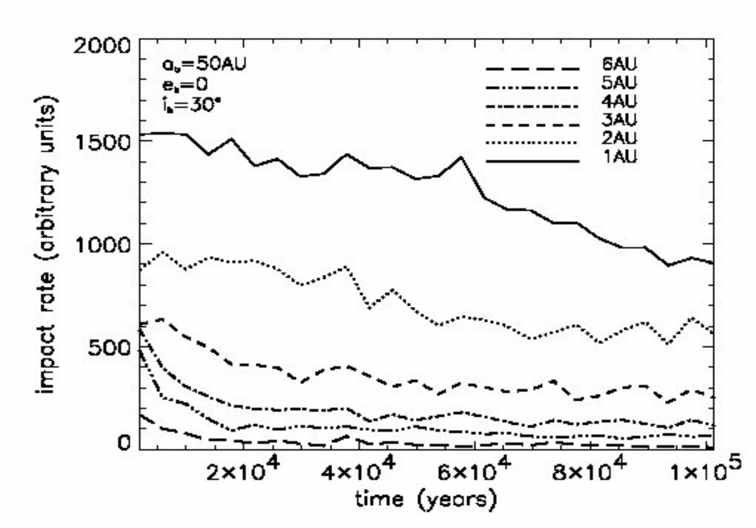
A_b=50 AU, e_b=0.2, i_m = 20°



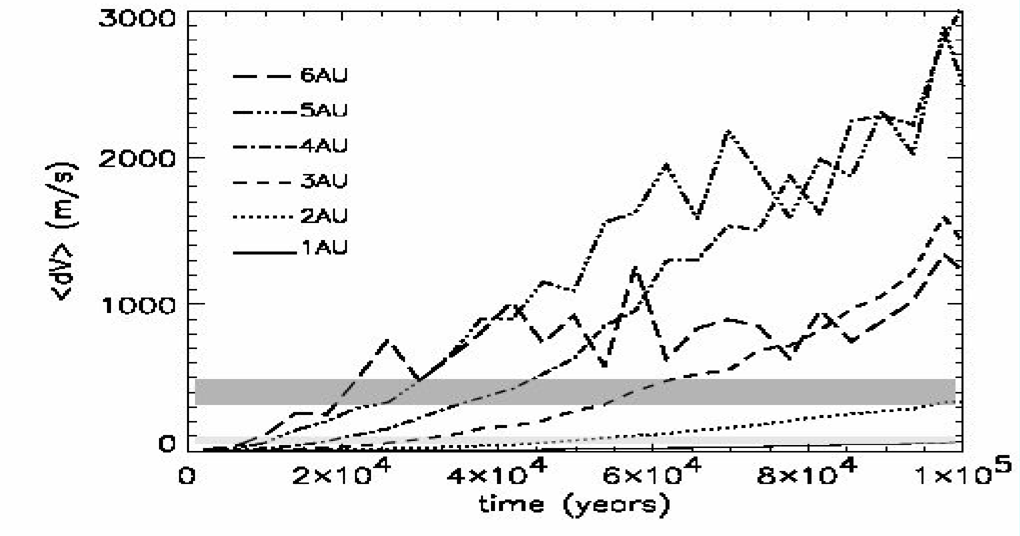
♣ **Decoupling of the planetesimals from the gaseous disk (it evolves as a rigid body precessing, Larwood 1996)**

♥ **Progressive randomization of the node longitude**

Reduction of the impact rate



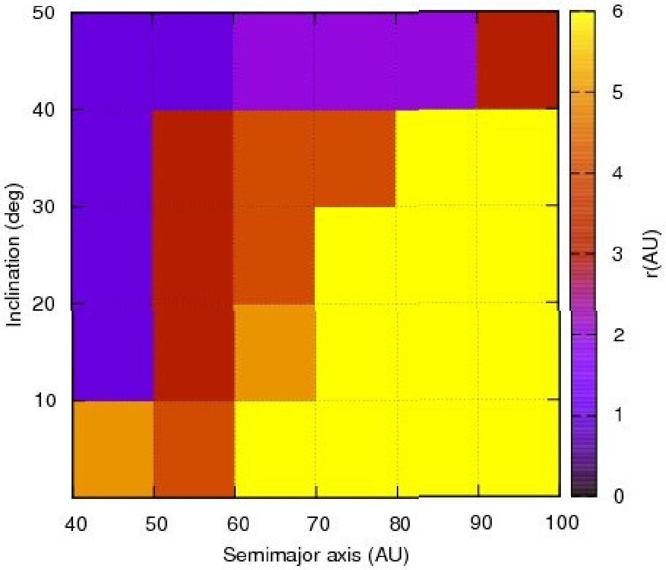
Increase of the relative velocity



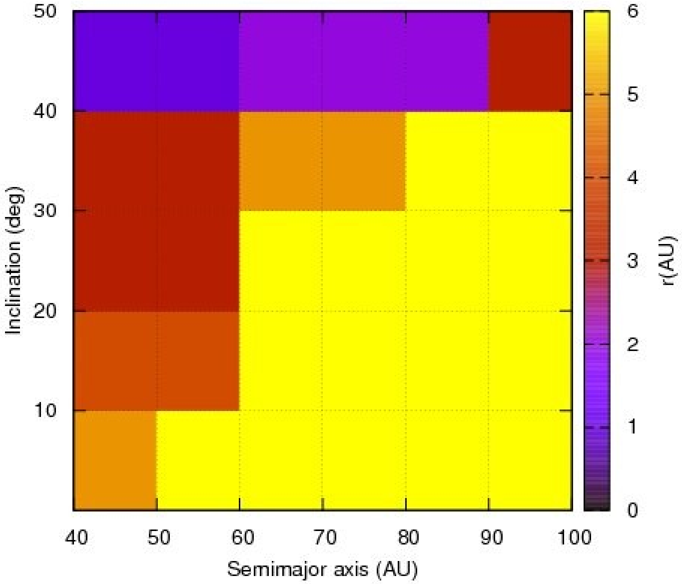
Planetesimal accretion maps

Relative planetesimal velocity is compared to erosion velocity (fragmentation threshold) and the limiting semimajor axis beyond which planetesimal accretion is possible is derived. Each square of the map refers to the lower value of the labels in the axes. The cases for $i_b = 0°$ do not include gas drag so they are only indicative.

Ecc = 0.4



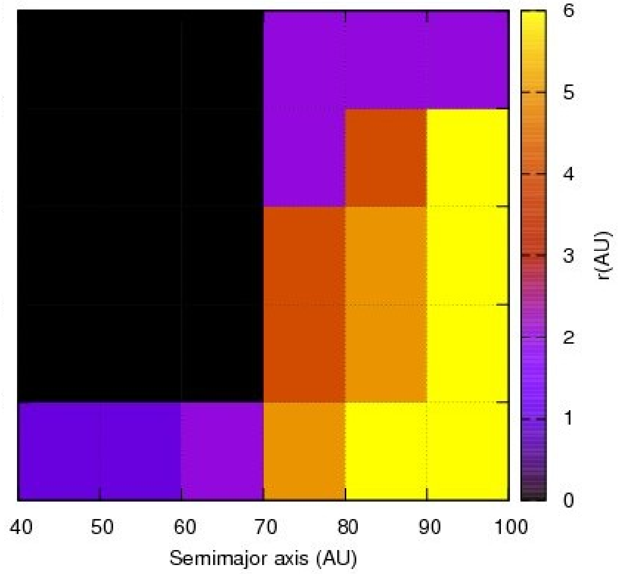
Ecc = 0.0



Effect of Kozai mechanism:

$H = (a(1-e^2))^{05} \cos i$

Ecc = 0.6

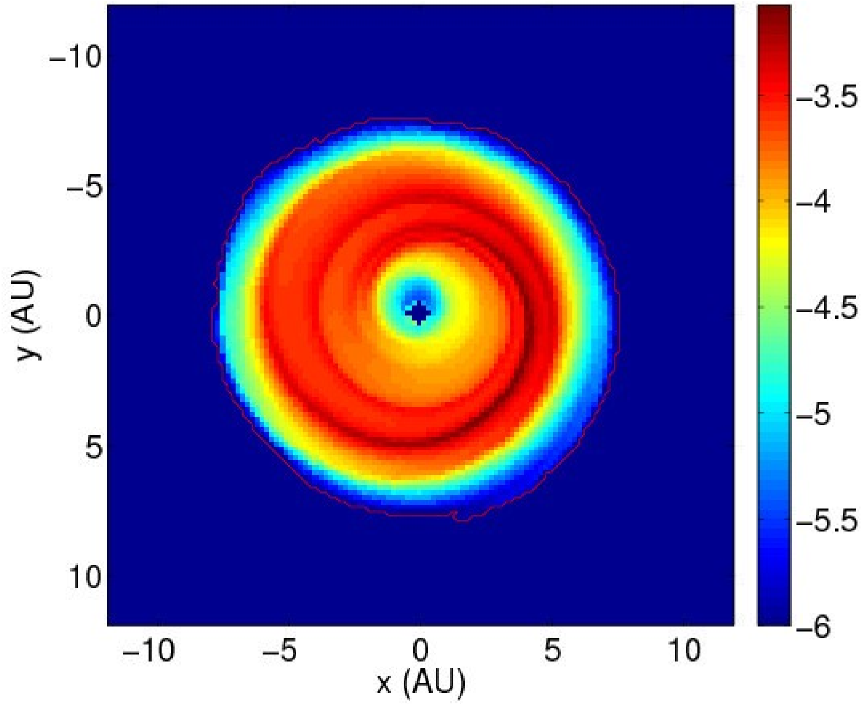


Effect of gas drag on planetesimals when they are within the disk (coplanar with the binary orbit)

- Axisymmetric approximation for the gaseous disk (N-body codes): fast and handle more than 10^6 bodies. Relative impact velocity well computed

BUT

The gaseous disk is eccentric and it has spiral waves! Drag force on planetesimals more complex. What is its effect on accretion?



Planetesimal dynamical evolution explored with hybrid codes by different studies:

- Ciecielag et al. (2007): circumstellar disk, binary in circular orbit, small planetesimals.
- Kley and Nelson (2007) Planetesimal in the Gamma Cephei system, circumstellar disk
- Paardekooper et al (2008): a = 10 AU and Gamma Cephei, circumstellar disk
- Marzari et al (2008): a = 1 AU, Circumbinary

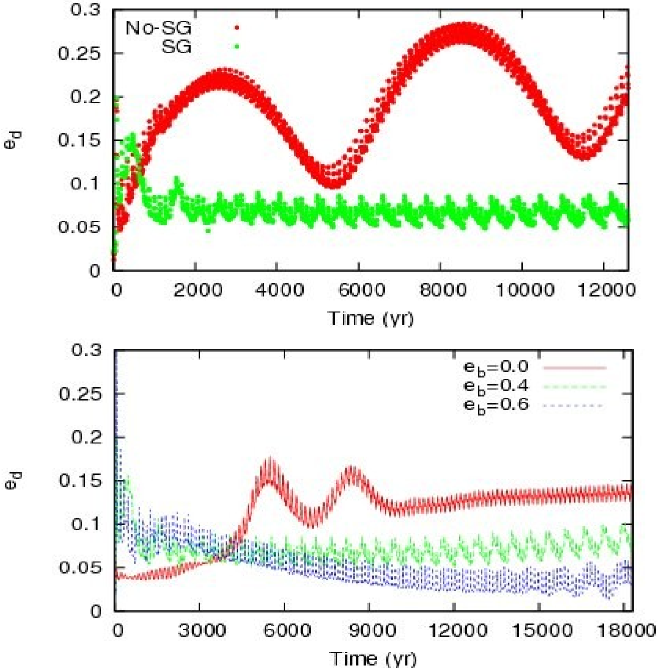
Crucial aspects from the planetesimal point of view:

- Eccentricity exciting due to the companion star, level of damping by the gas of the disk
- Alignment of the planetesimal perihelia to couterlevel the increase in eccentricity due to the companion perturbations.

Difficulties in handling the problem

- The parameter space is HUGE: orbital parameters of the binary (a,e,i), mass ratio, planetesimal sizes and initial orbits, disk properties...

Marzari et al. (2009)

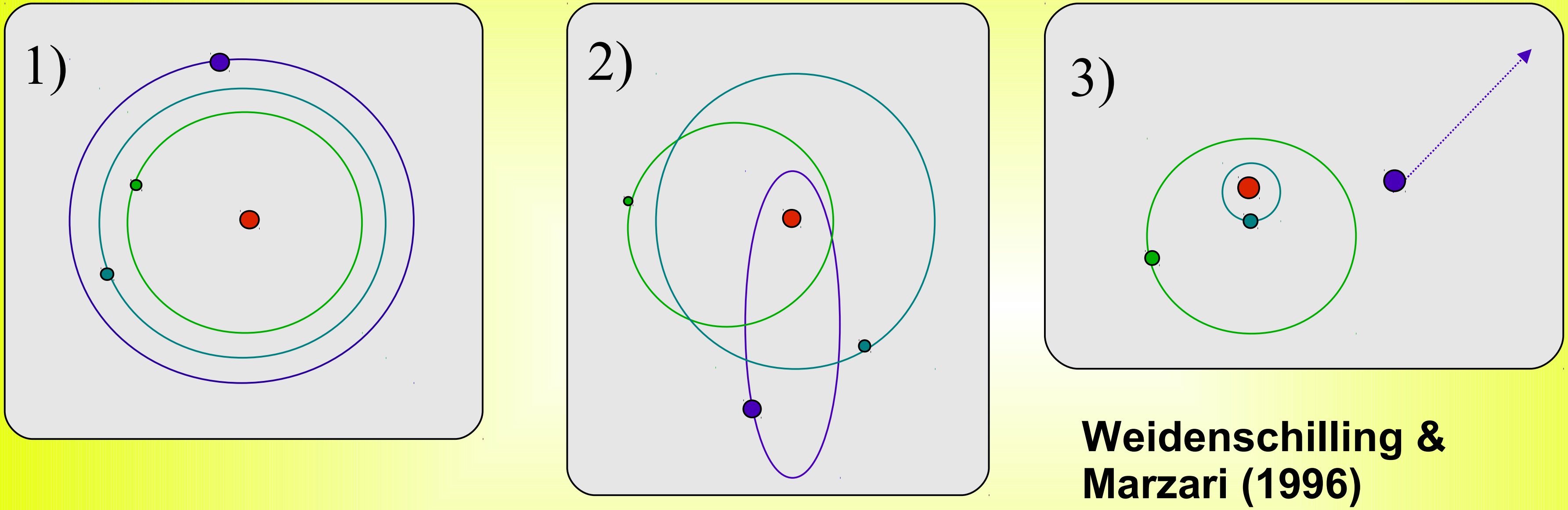


- The disk evolves with time so it is difficult to get a stationary state (self gravity seems to help). Also the binary orbits evolves. At which stage of the system shall we insert planetesimals?

- Only a few planetesiml trajectories can be computed

When planets finally form from planetesimals, the story is not ended! Migration and P-P scattering......

Planet-Planet scattering can totally change the outcome of planetesimal accumulation and increase planetary eccentricities.



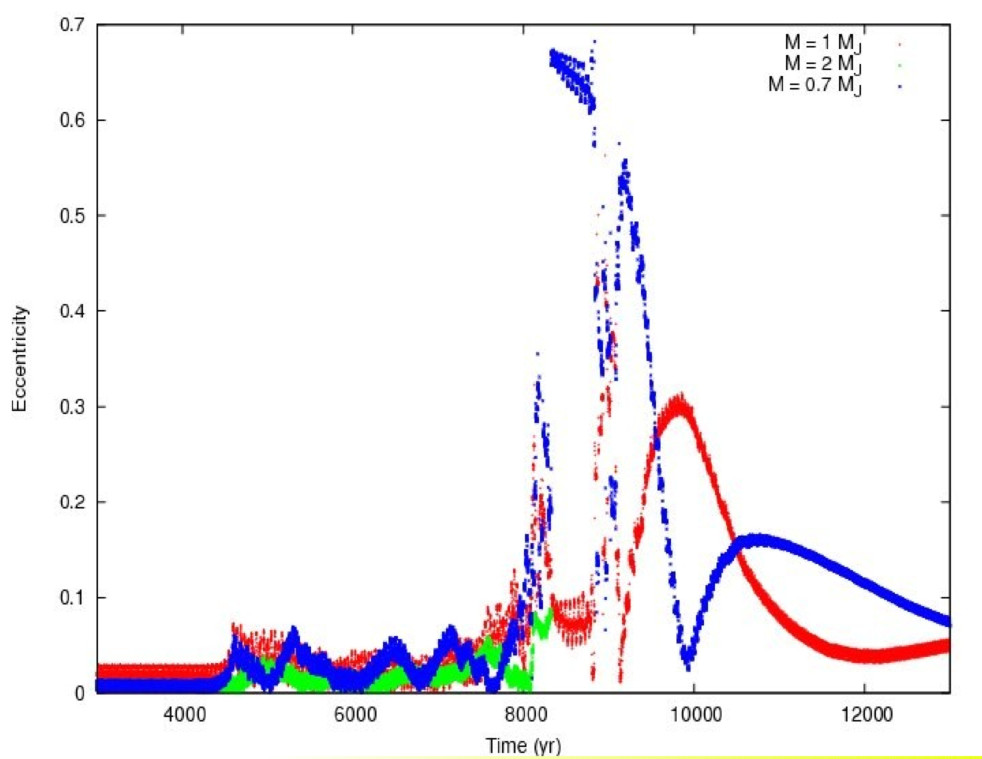
Weidenschilling &
Marzari (1996)

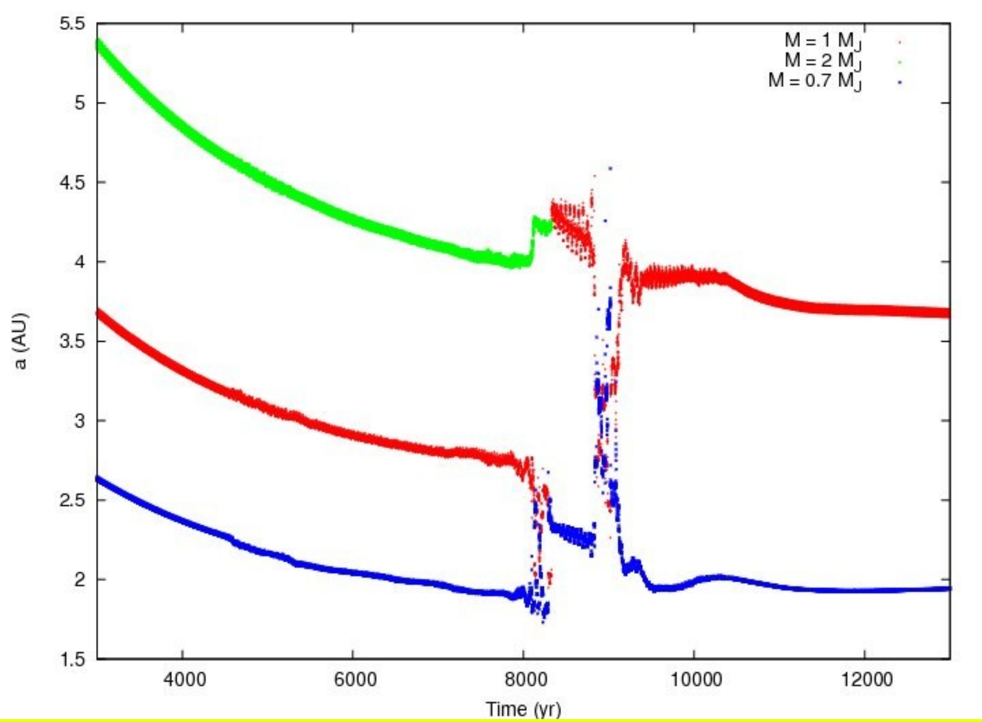
Big question:

Does it occur BEFORE or AFTER the gas dissipation?
Is resonance trapping dominant in a gaseous disk?

Example of 'Jumping Jupiters'. The density of the disk is MMSN/2. Code used is FARGO (RK5 modified to have variable stepsize). One planet (1 M_J) merges with another one (0.7 M_J) after a sequence of close encounters.

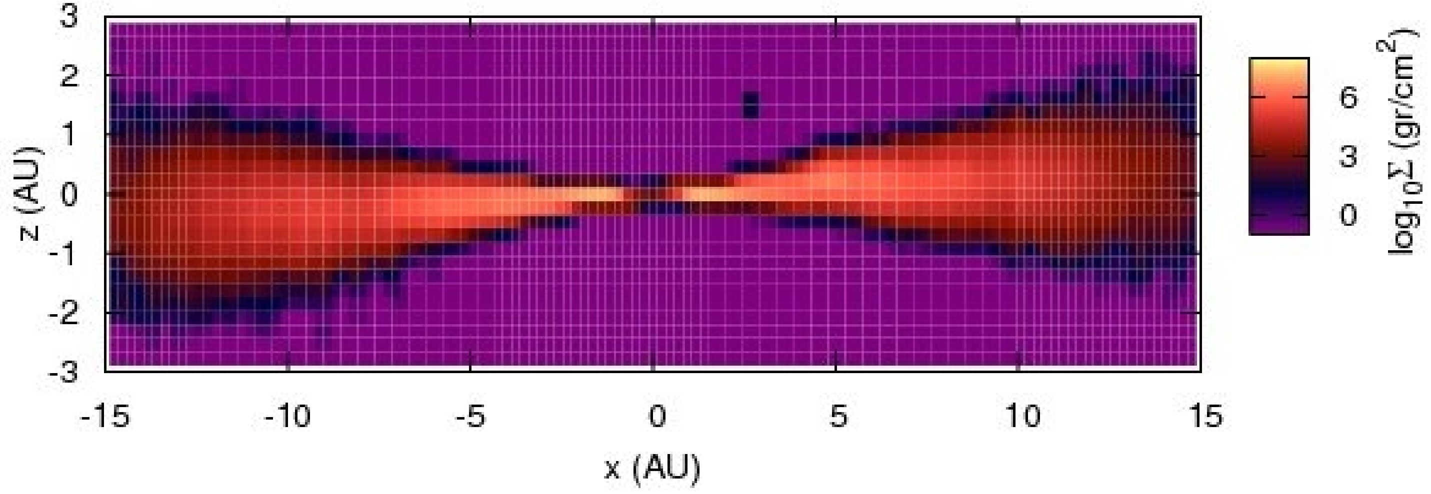
Eccentricity evolution after P-P scattering: damping or excitation because of corotation resonance saturation?

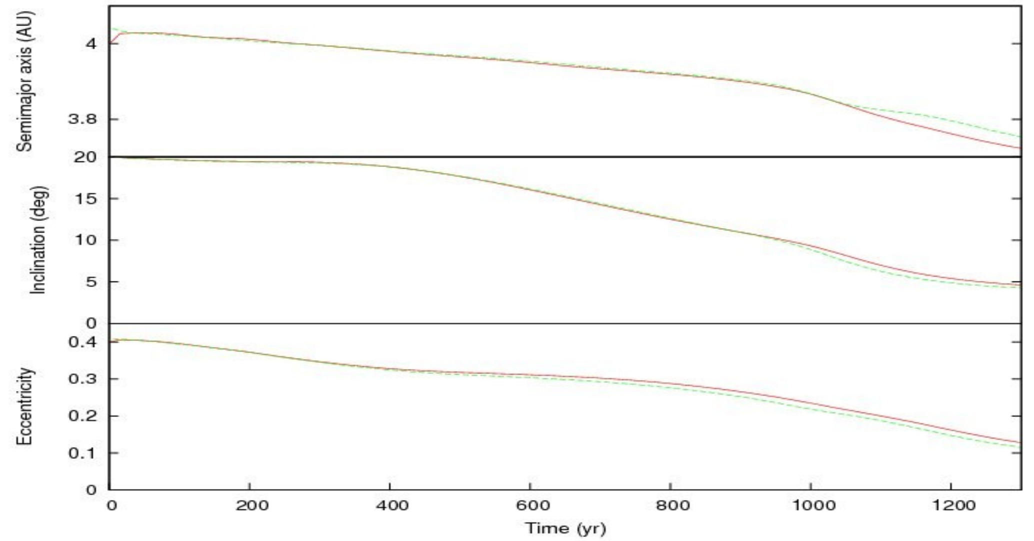




Finding planets inclined respect to the star equator (WASP-14, Johnson et al, 2009) is a strong indication that happened AFTER. Why? Jumping Jupiters can lead to inclined planetary orbits but.........

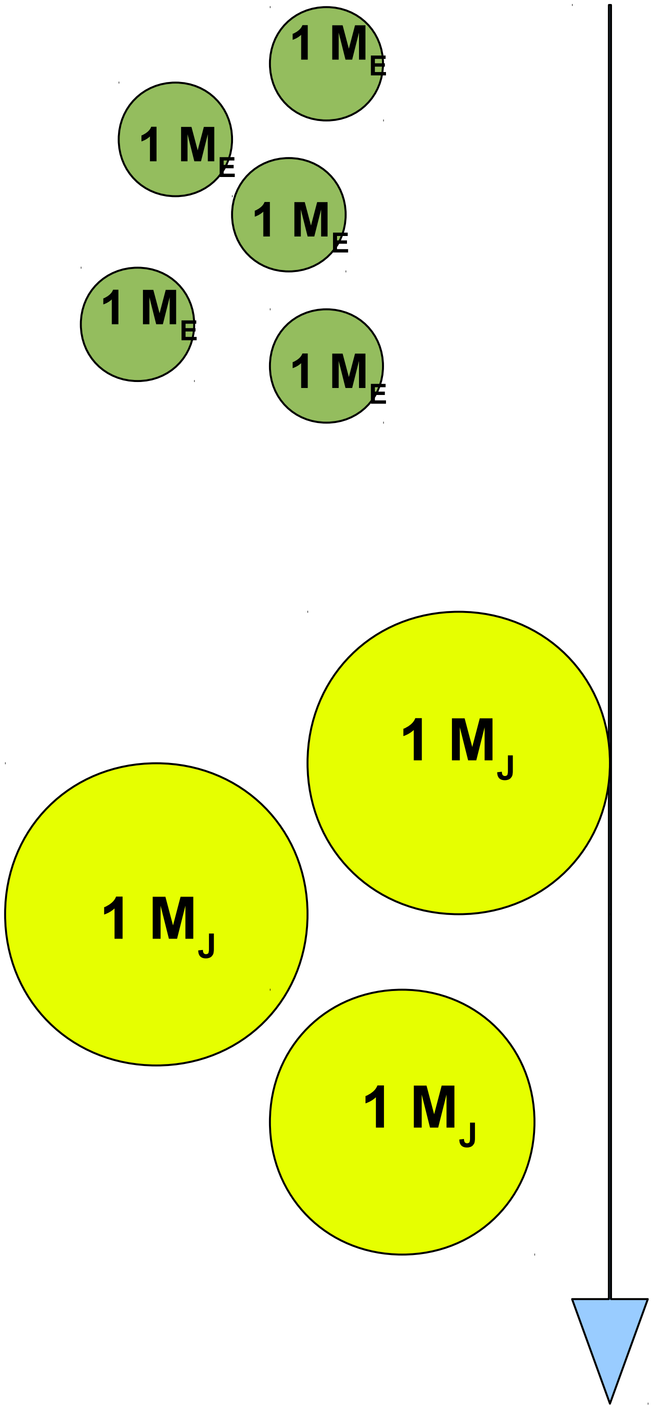
Marzari and Nelson (2009).





.....the interaction with the gaseous disk drive the planet quickly back within the disk (10^3 yrs).

Single steps of accretion well studied: it is the temporal evolution with the simultaneous mass accretion that is still out of range



- Type I migration or stochastic random walk
- P-P scattering
- Mutual impacts and accretion

- Type II, Type III migration
- Eccentricity excitation (corotation resonance saturation...)
- P-P scattering
- Resonance capture
- Residual planetesimal scattering
- Gas accretion onto the planet

OPEN PROBLEMS and FUTURE INVESTIGATIONS:

Single star:

- ► Planetesimal initial size distribution
- ► Planetary formation in presence of migration (Alibert vs. Lissauer 2009)
- ► Migration: inwards vs. outwards
- ► Interplay between P-P scattering, resonances and migration

Multiple star systems:

- ► Planetesimal formation in presence of a perturber
- ► Planetesimal accumulation process in presence of an eccentric disk
- ► Migration and P-P scattering: how is it changed by the disk perturbations of the companion?