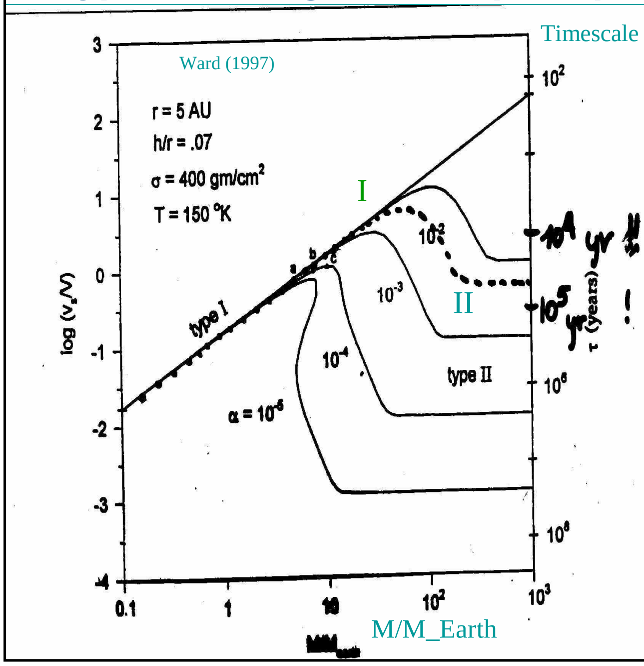
Migration Type I :
embedded

Migration Type II :
more in the open

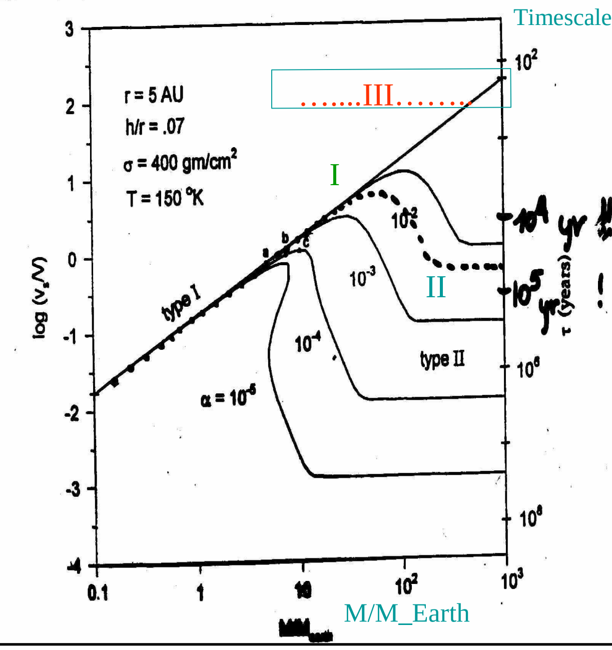
Type I-III Migration of protoplanets/exoplanets



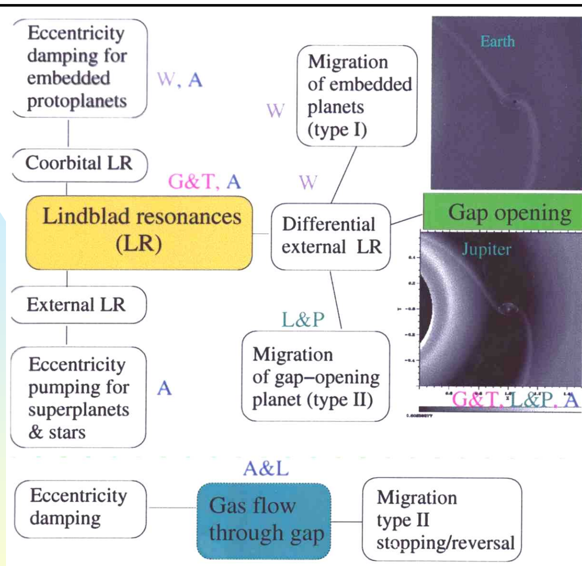
- Disks repel planets:
- Type I (no gap)
- Type II (in a gap)
- Currently THE problem is: how not to lose planetary embryos (cores) ?

Migration:	Interaction:	Timescale of migration:
type 0	Gas drag + Radiation press.	from ~1e2 yr to disk lifetime (up to 1e7 yr)
type I	Resonant excitation of waves (LR)	> 1e4 yr
type II & IIb	Tidal excitation of waves (LR)	> 1e5 yr
type III	Corotational flows (CR)	> 1e2 - 1e3 yr
N-body	Gravity	> 1e5 yr (?)

Type I-III Migration of protoplanets/exoplanets



- If disks repel planets:
- Type **I** *(no gap)*
- Type **II** *(in a gap)*
- If disks attract planets: Type **III**
- Q's:
- Which way do they migrate?
- How fast?
- Can the protoplanets survive?



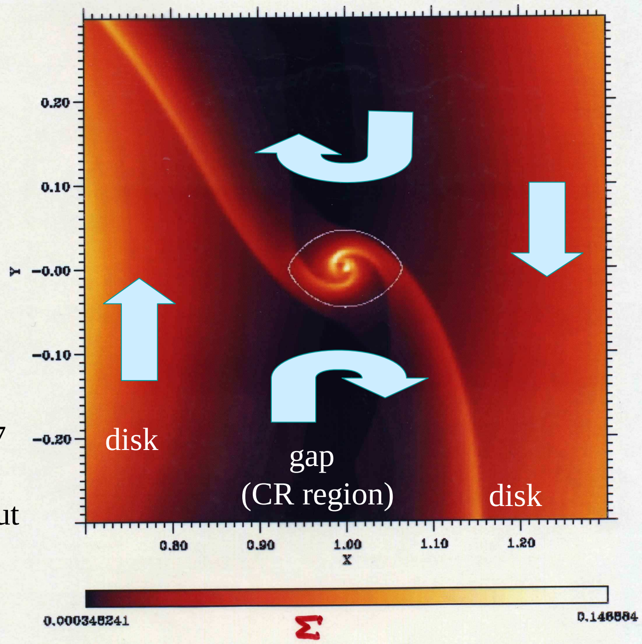
A = Artymowicz (1992, 1993)
A&L = Artymowicz & Lubow (1991, 1996)
G&T = Goldreich & Tremaine (1979, 1980)
L&P = Lin & Papaloizou (1979, 1986)
W = Ward (1986, 1997)

Variable-resolution PPM (Piecewise Parabolic Method) [Artymowicz 1999]

Jupiter-mass planet, fixed orbit a=1, e=0.

White oval = Roche lobe, radius r_L= 0.07

Corotational region out to x_CR = 0.17 from the planet



Outward migration type III of a Jupiter

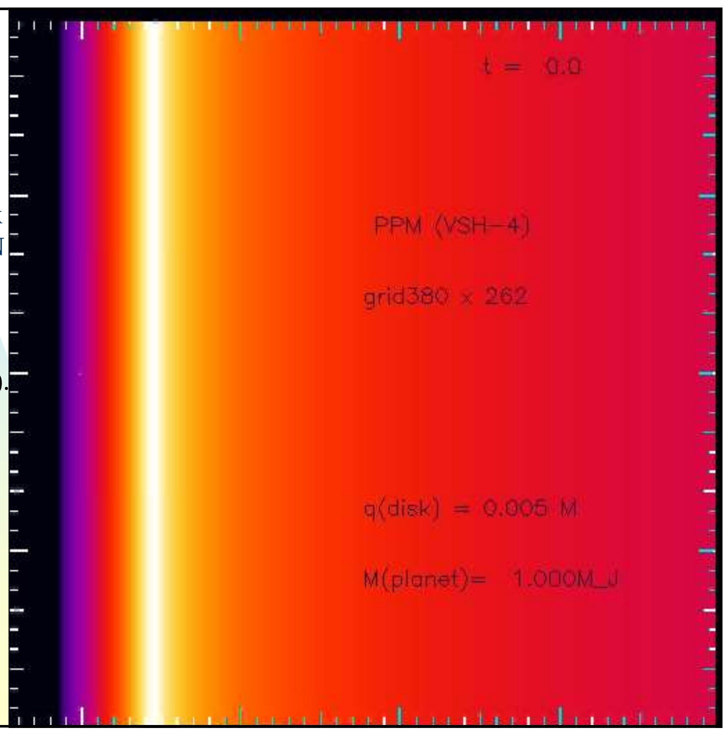
Inviscid disk with an inner clearing & peak density of 3 x MMSN

Variable-resolution, adaptive grid (following the planet). Lagrangian PPM.

Horizontal axis shows radius in the range (0.5-5) a

Full range of azimuths on the vertical axis.

Time in units of initial orbital period.



What is more important: **L**indblad **R**esonances & waves or **C**orotation?

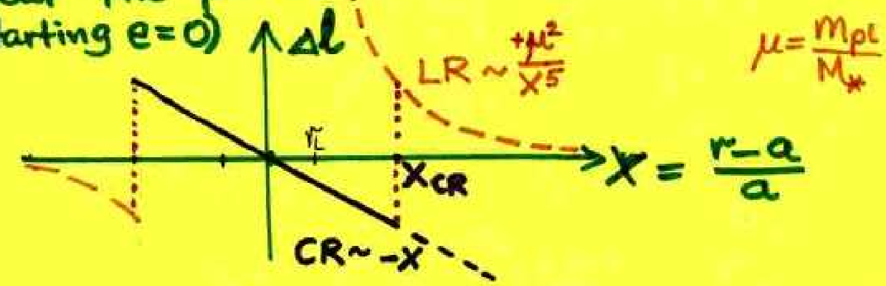
$x_{CR} =: \zeta \, r_L$ $\qquad \frac{x_{CR}}{\zeta} = r_L = \left(\frac{\mu}{3}\right)^{\frac{1}{3}}$

Why is ζ important?

Competition between CR & LRs.

Angular momentum gain in one passage near the planet

(starting $e=0$)



Shearing sheet (disk) provides flux of incoming matter $\sim \Sigma \left|\frac{3}{2}\Omega x\right|$, therefore a one-sided torque estimation gives

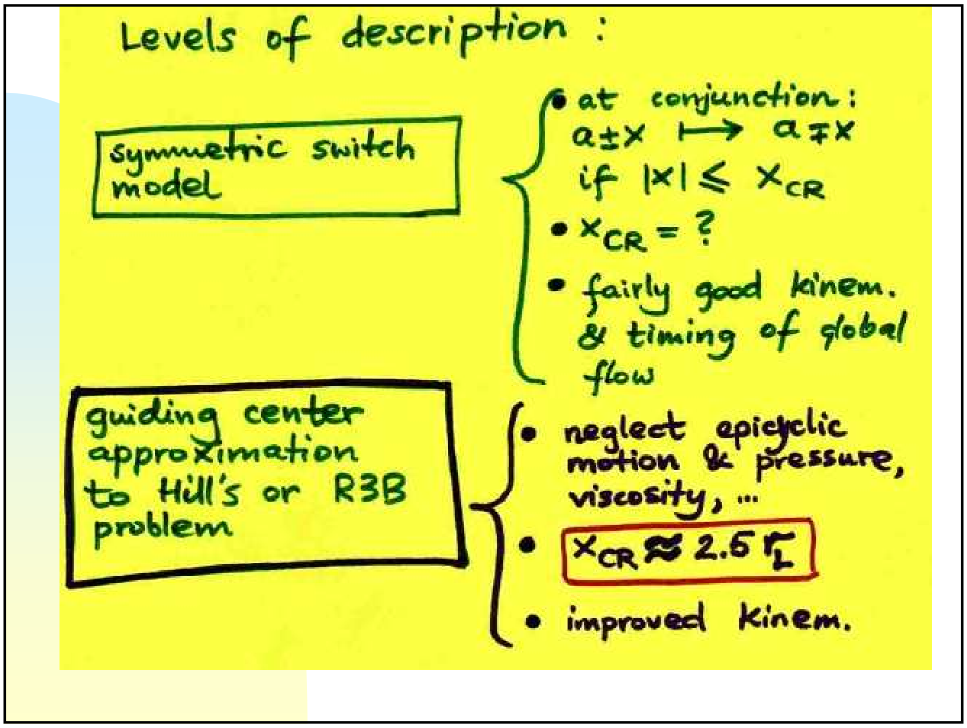
$$T_{CR}^{(1)} \sim \int_0^{x_{CR}} (-x)\,|x|\,\Sigma \, dx \sim -\Sigma \, x_{CR}^3$$

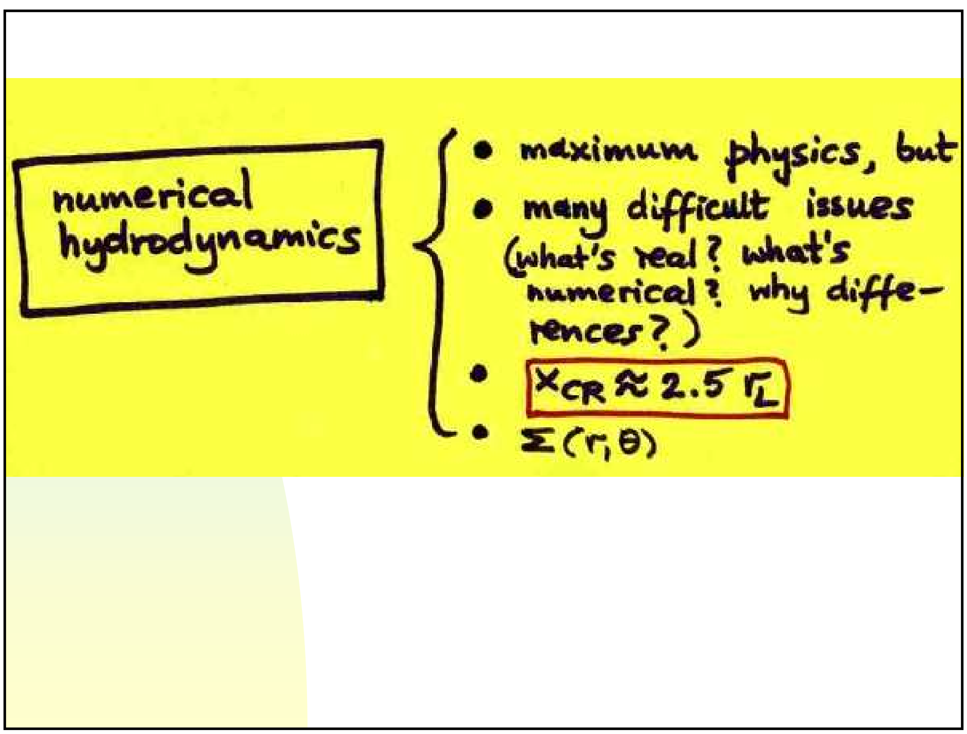
$$T_{LR}^{(1)} \sim \int_{x_{CR}}^{+\infty} \frac{\mu^2}{x^5}\,|x|\,\Sigma \, dx \sim \mu^2 \Sigma \, x_{CR}^{-3} \sim$$

$$\sim \Sigma \, x_{CR}^3 \, \zeta^{-6}$$

$T_{CR}^{(1)} : T_{LR}^{(1)} \sim 10:1$

(cf. R3B results of Ida & Lin 2001)


Levels of description :
symmetric switch model
• at conjunction : a±x ⟼ a∓x if |x| ≤ x_CR
• x_CR = ?
• fairly good kinem. & timing of global flow
guiding center approximation to Hill's or R3B problem
• neglect epicyclic motion & pressure, viscosity, ...
• x_CR ≈ 2.5 r_L
• improved kinem.


numerical hydrodynamics
• maximum physics, but
• many difficult issues (what's real? what's numerical? why differences?)
• x_CR ≈ 2.5 r_L
• Σ(r, θ)

Toy models, regularized theories

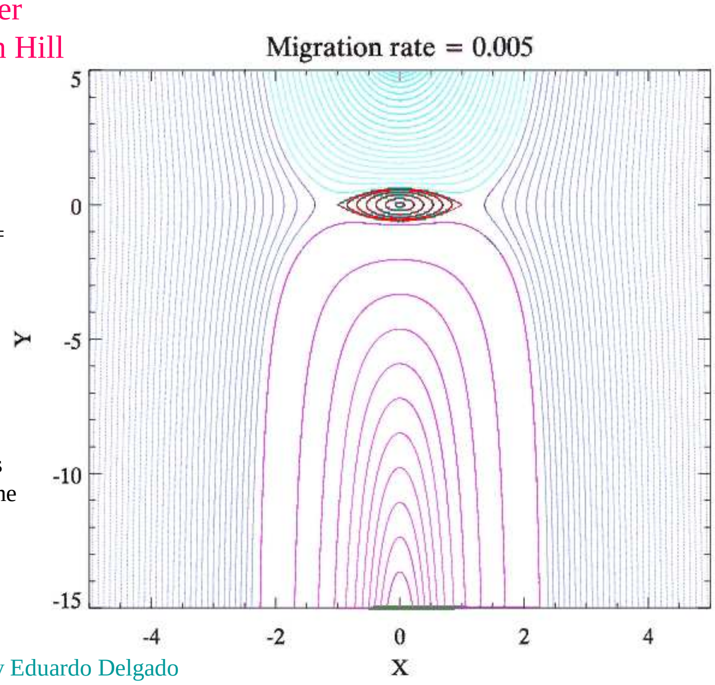
looking at orbits and separatrices
rather than doing a questionable Fourier decomposition
+ inifinitesimal perturbations theory

- Capture essentials!
- Give results resembling full 2-d hydrodynamics

Guiding center trajectories in Hill problem

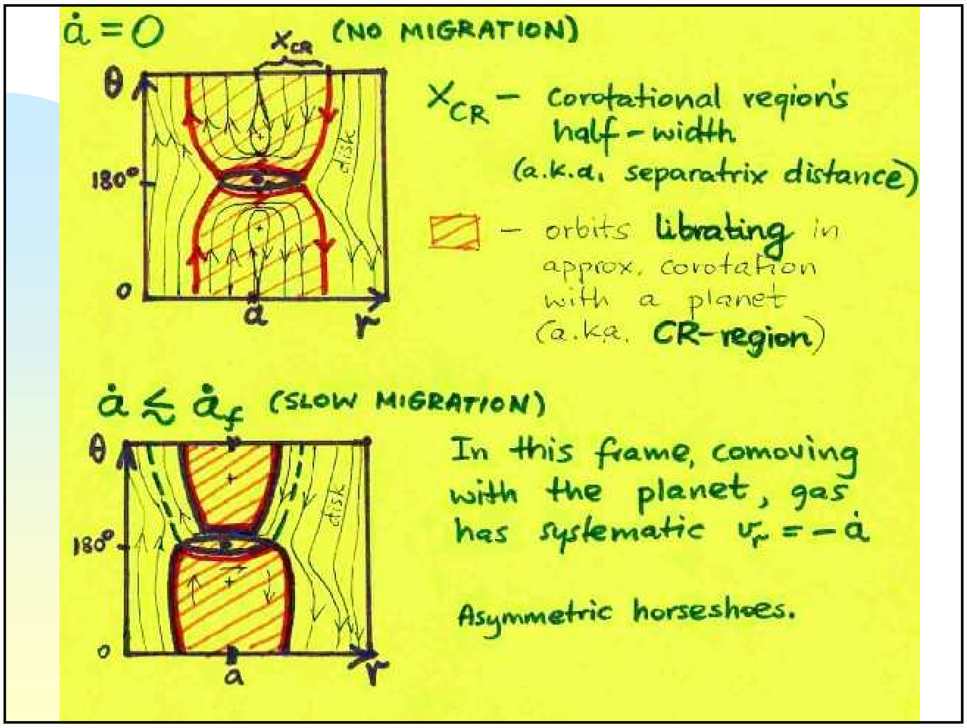
Unit of distance = Hill sphere

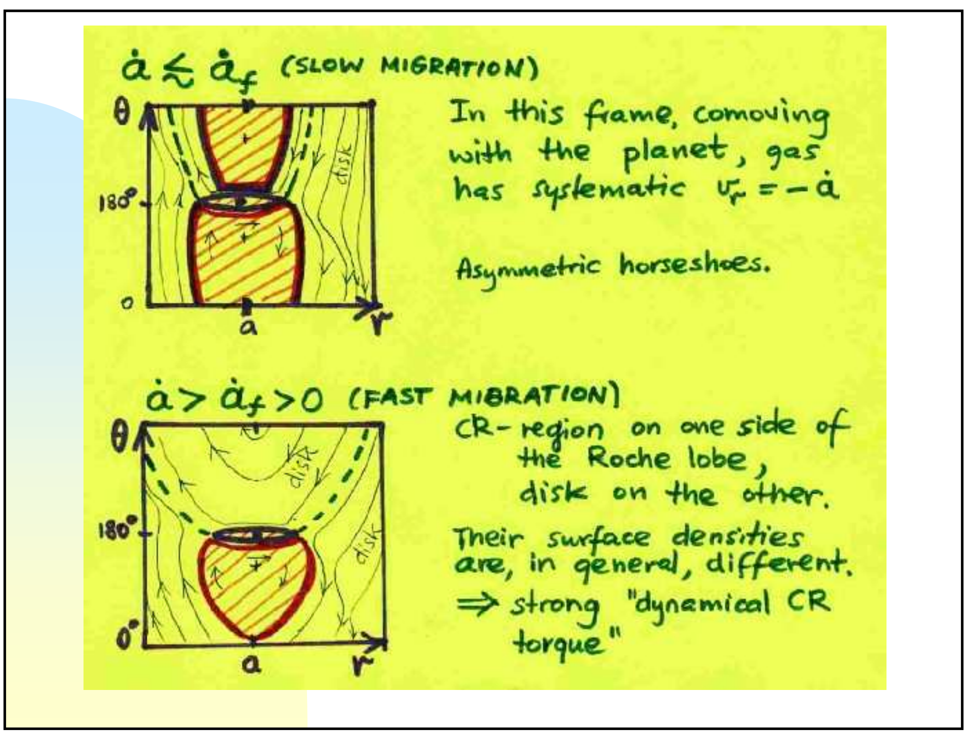
Unit of da/dt = Hill sphere radius per dynamical time



Animation by Eduardo Delgado

Migration type III

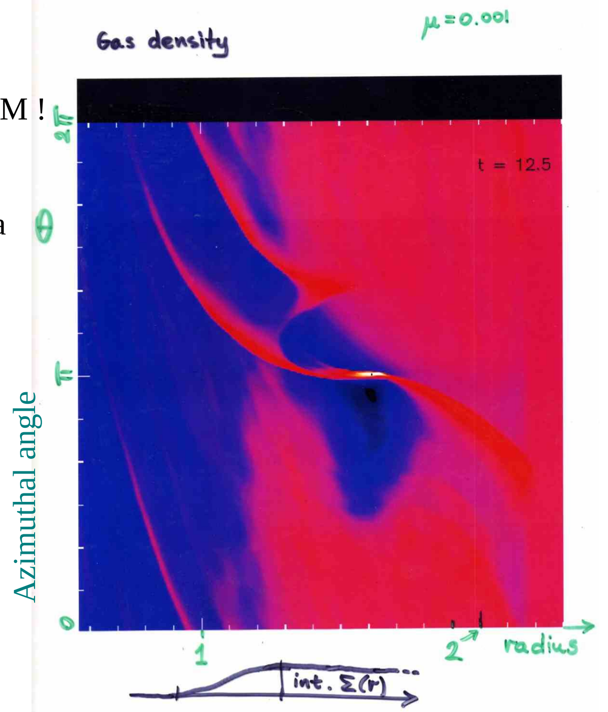




Migration type III

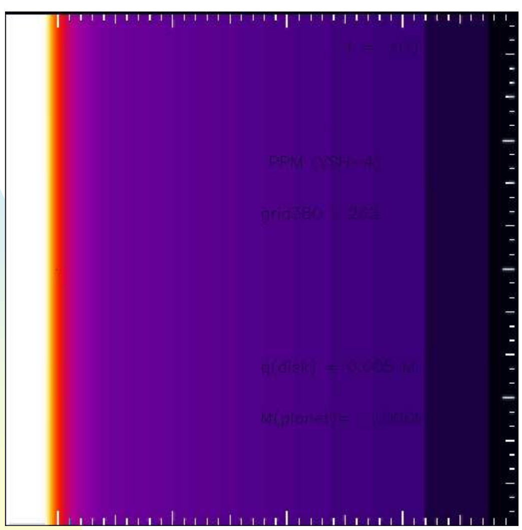
The migration type III engine runs on VACUUM !

Do you see the dark area below the planet?



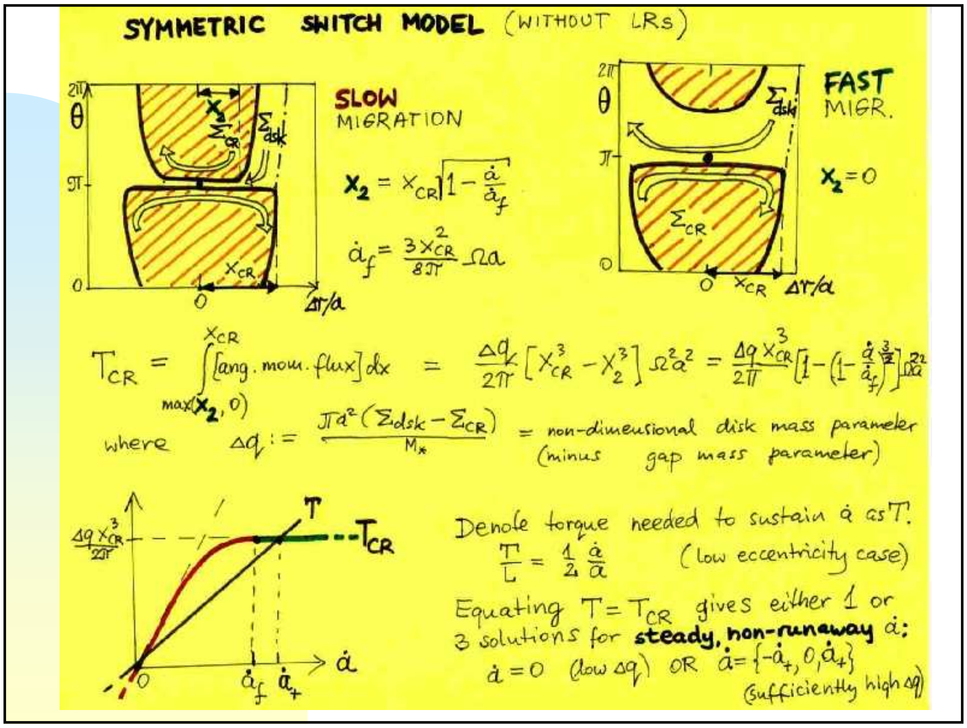
Potential vorticity, Jupiter simulation

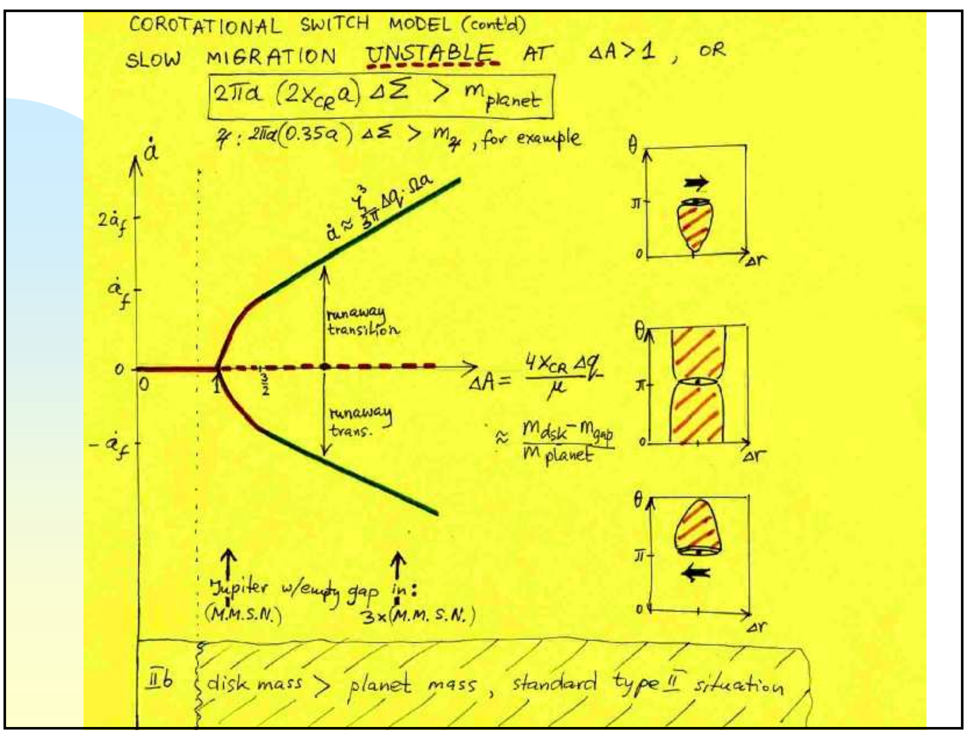
Azimuth (full range)



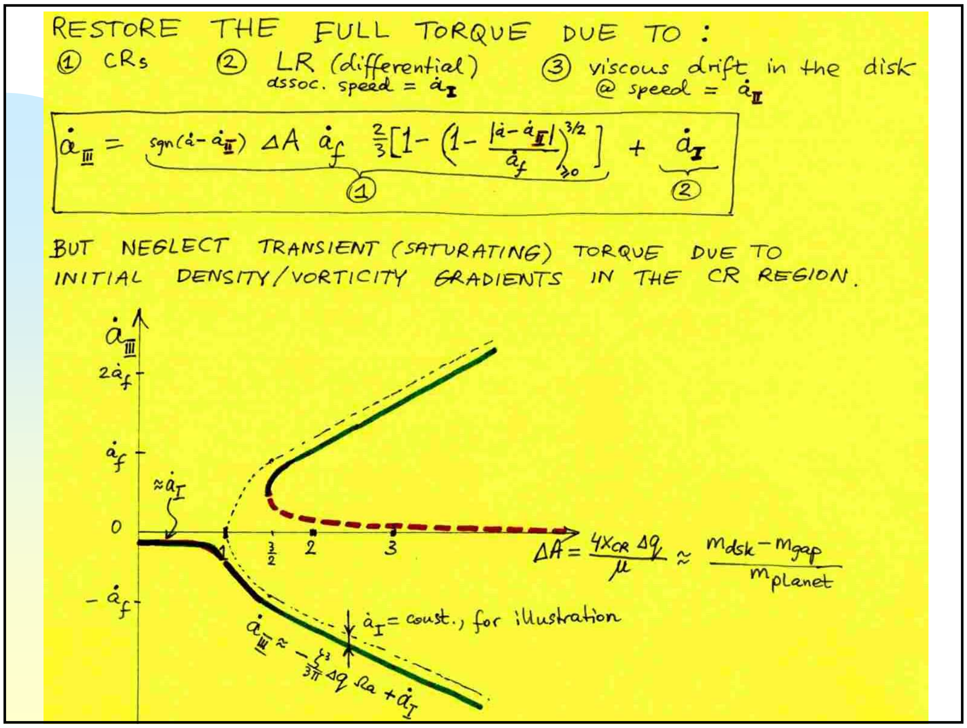
Radius from 0.5a to 5a

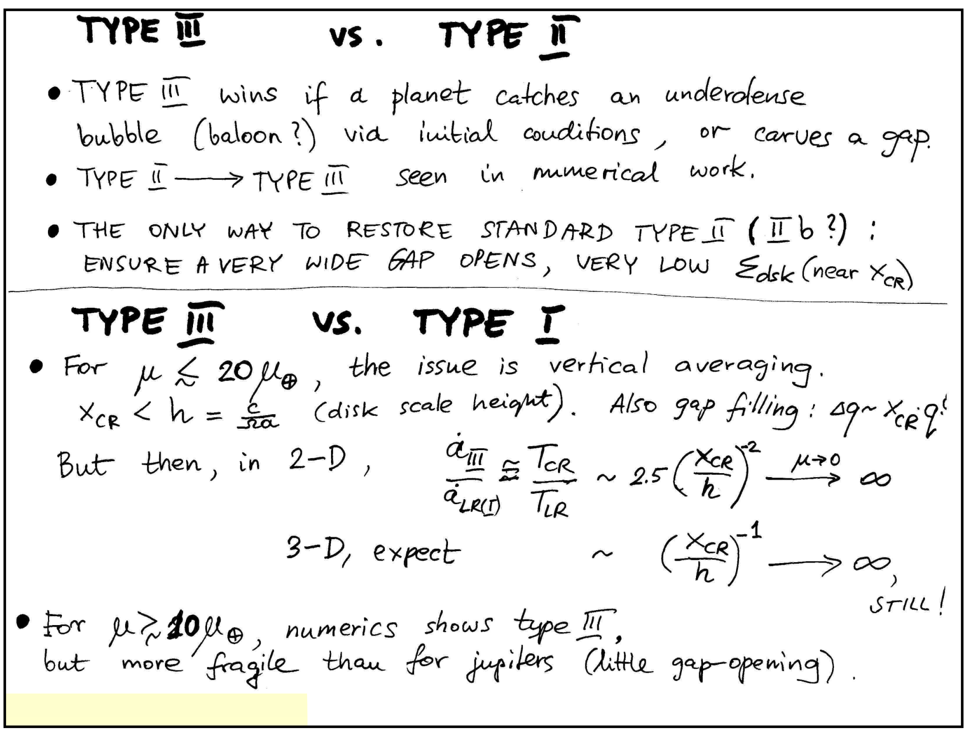
Migration type III





Migration type III





Next Steps: Toward a better LR/CR perturbation theory

- Previous perturbation theories started from circular unperturbed orbits [do not exist]
- and assumed infinitesimal perturbations (Fourier decomposition allowed) [not always!]

- Alternative way: unperturbed state adjusted for perturbation. Trajectories of all essential types (disk orbits, corotational hairpin/horeseshoes, closed orbits around planet)
- On that set of unperturbed flow lines, 1st order perturbation should give a better approximation
- Migration and additional effects can be incorporated

Are there ANY SURVIVORS of type III migration?!

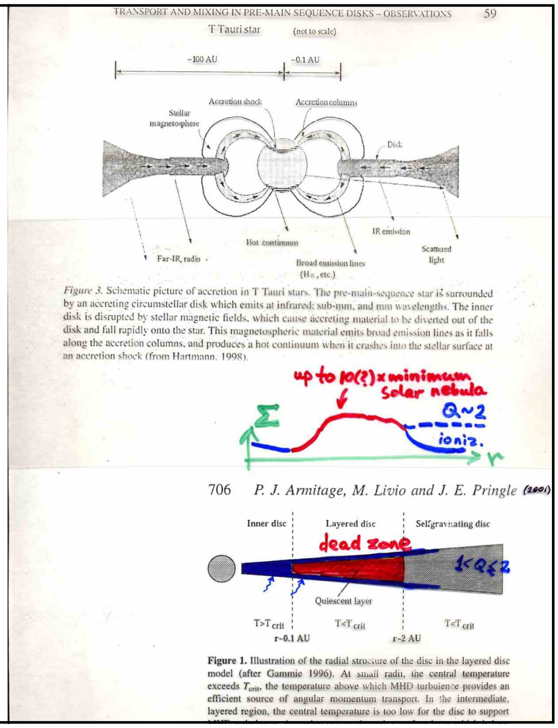
Of course...

Migration type III

Why edges or gradients?

Magnetic cavity

Dead zones

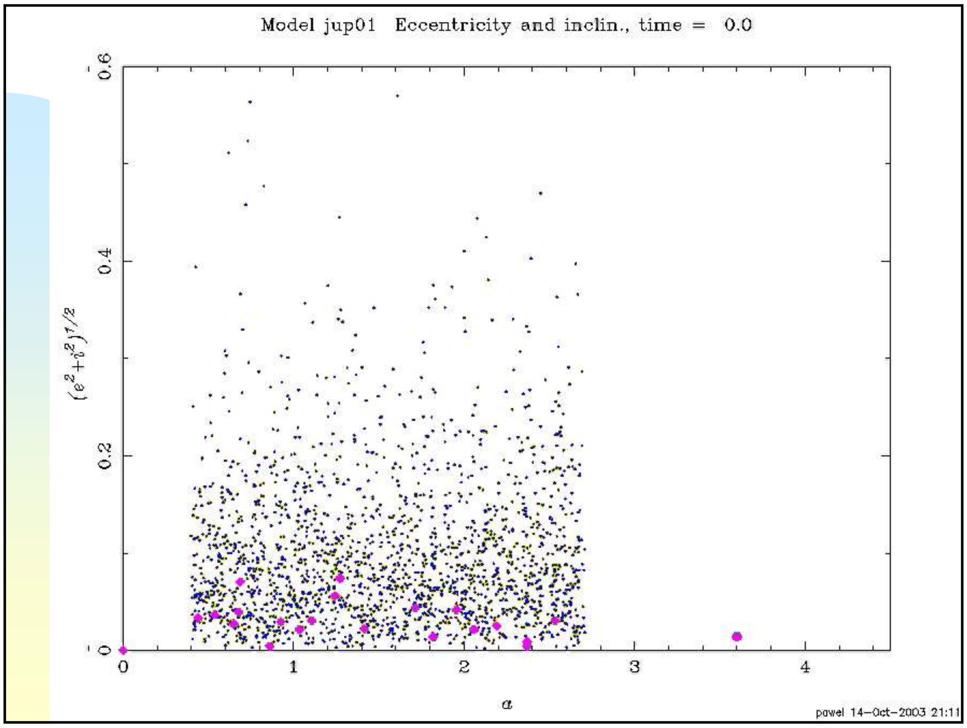


Unsolved problem of the Last Mohican scenario of planet survival in the solar system:

Can the terrestial zone survive a passage of a giant planet?

- N-body simulations, N~1000 (Edgar & Artymowicz 2004)
- A quiet disk of sub-Earth mass bodies reacts to the rapid passage of a much larger protoplanet (migration speed = input parameter).
- Results show increase of velocity dispersion/inclinations and limited reshuffling of material in the terrestrial zone.
- Migration type III too fast to trap bodies in mean-motion resonances and push them toward the star
- Evidence of the passage can be obliterated by gas drag on the time scale << Myr ---> passage of a pre-jupiter planet(s) not exluded dynamically.

Migration type III

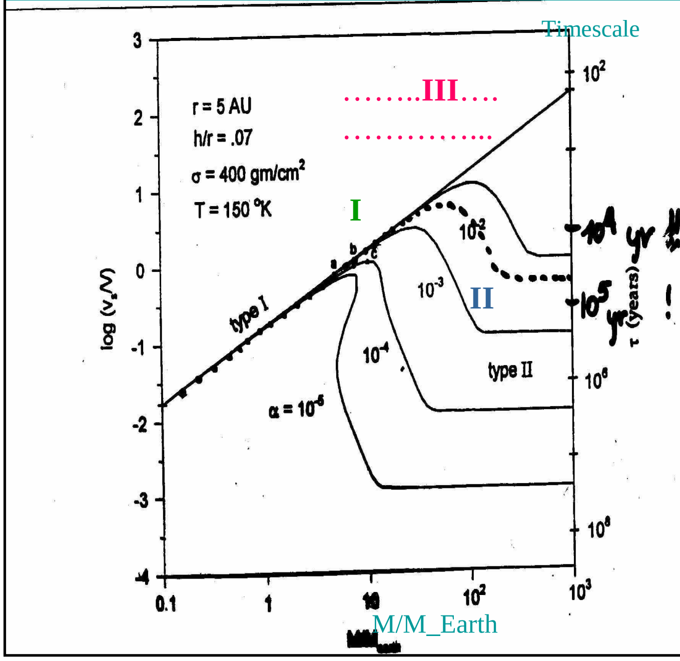


Summary of type-III migration

- New type, sometimes extremely rapid (timescale < 1000 years). CRs >> LRs
- Direction depends on prior history, not just on disk properties.
- Supersedes a much slower, standard type-II migration in disks more massive than planets
- Preliminary results: modifies or replaces type-I migration
- Very sensitive to disk density (or vortensity) gradients.
- Migration stops on disk features (rings, edges and/or substantial density gradients.) Such edges seem natural (dead zone boundaries, magnetospheric inner disk cavities, formation-caused radial disk structure)
- Offers possibility of survival of giant planets at intermediate distances (0.1 - 1 AU),
- ...and of terrestrial planets during the passage of a giant planet on its way to the star.
- If type I superseded by type III then these conclusions apply to cores as well, not only giant protoplanets.

Migration type III

Migration of protoplanets/exoplanets



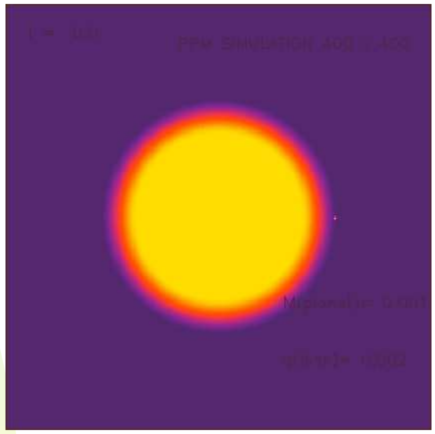
If disks repel planets:

Type **I** *(no gap)*

Type **II** *(in a gap)*

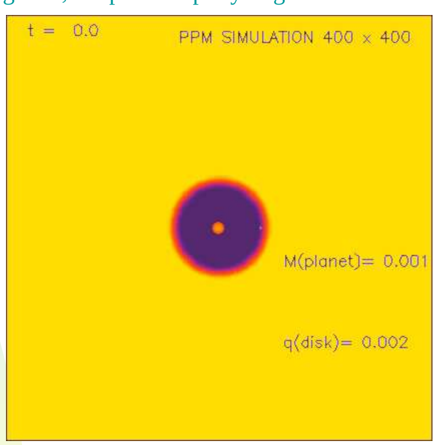
Disks attract planets: Type **III**

Consider a one-sided disk (**inner disk only**). The rapid inward migration is OPPOSITE to the expectation based on shepherding (Lindblad resonances).



Like in the well-known problem of "sinking satellites" (small satellite galaxies merging with the target disk galaxies),
Corotational torques cause rapid inward sinking.
(Gas is trasferred from orbits inside the perturber to the outside.
To conserve angular momentum, satellite moves in.)

Now consider the opposite case of an **inner hole** in the disk.
Unlike in the shepherding case, the planet rapidly migrates outwards.



Here, the situation is an inward-outward reflection of the sinking satellite problem.
Disk gas traveling on hairpin (half-horeseshoe) orbits fills the inner void and moves the planet out rapidly (type III outward migration). Lindblad resonances produce spiral waves and try to move the planet in, but lose with CR torques.

Migration type III

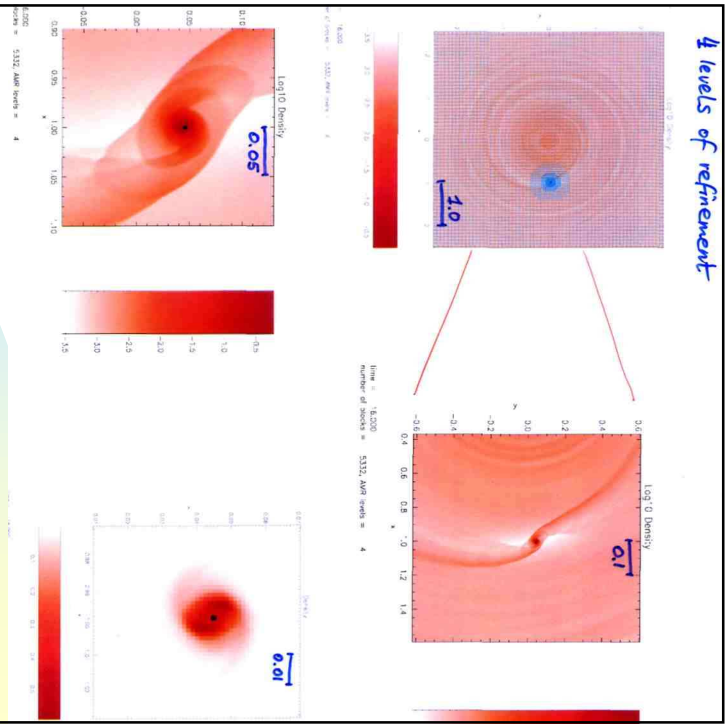
AMR = Adaptive Mesh Refinement

code FLASH (square inertial grid, 5 levels)

parallel (MPI)

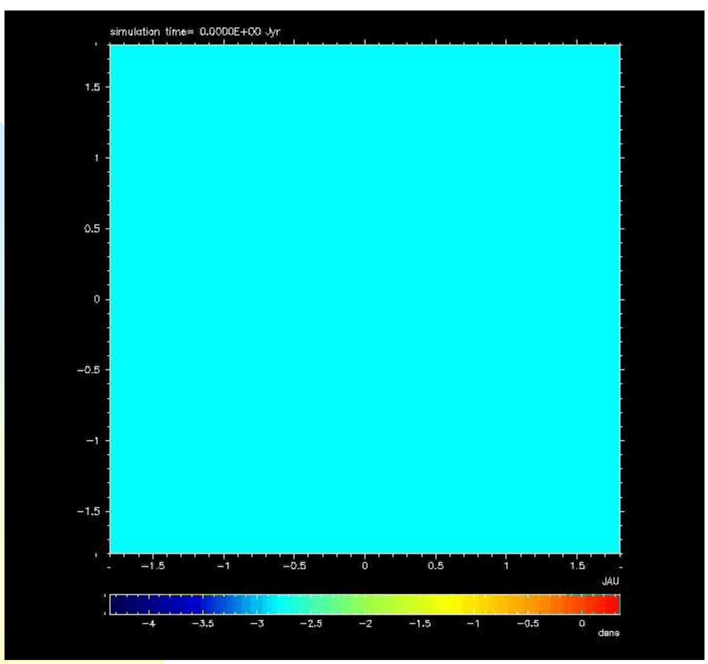
individual dt by Peplinski (2003)

Resolution ~physical size of the planet

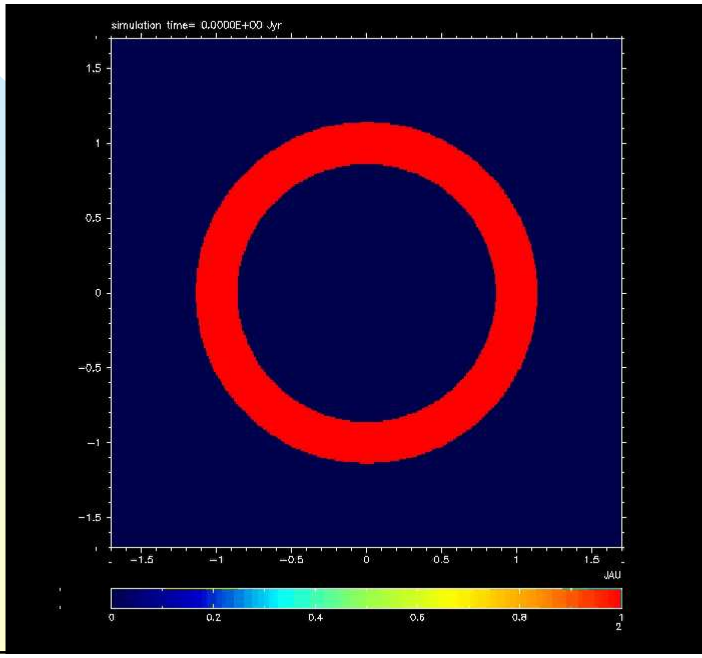


AMR PPM (Flash) simulation of a Jupiter in a standard solar nebula. 5 levels/subgrids.

(Peplinski and Artymowicz 2004)



AMR PPM (FLASH). Jupiter simulation by Peplinski and Artymowicz (in prep.).
Red color marks the fluid initially surrounding the planet's orbit.



Numerical Troubles:

resolution

grav. Softening and zones where torques are ignored

self-gravity of gas (missing)

gas heating (and other effects)

the usual troubles: boundary conditions, instabilities, unexplained crashes,

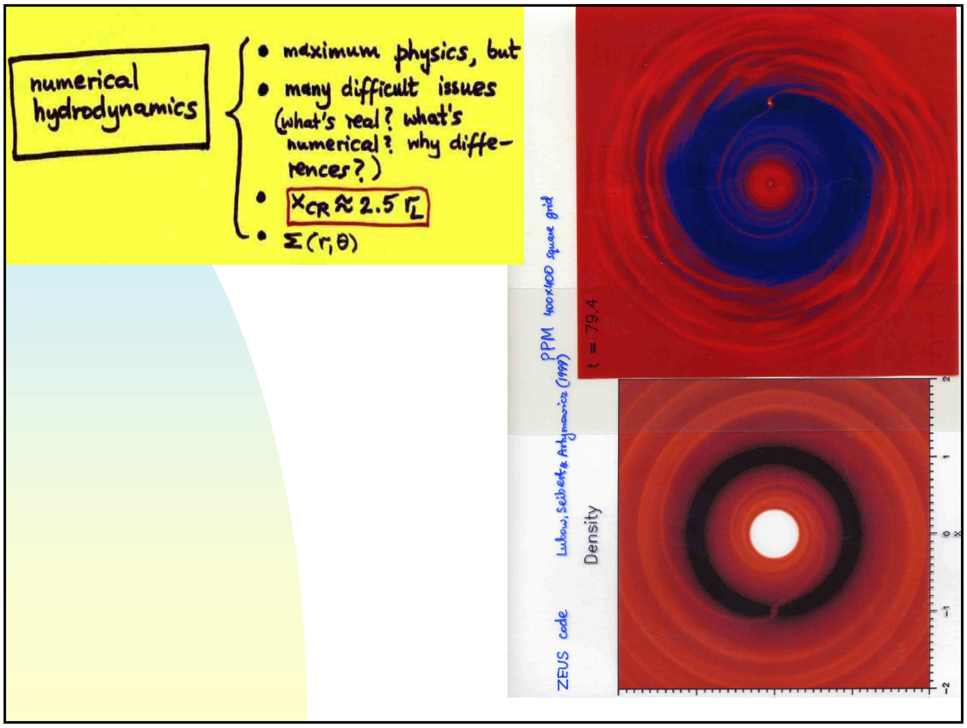
the unusual troubles: extreme vortex production and/or variability of flow in some codes

---> Comparison or Test Problem

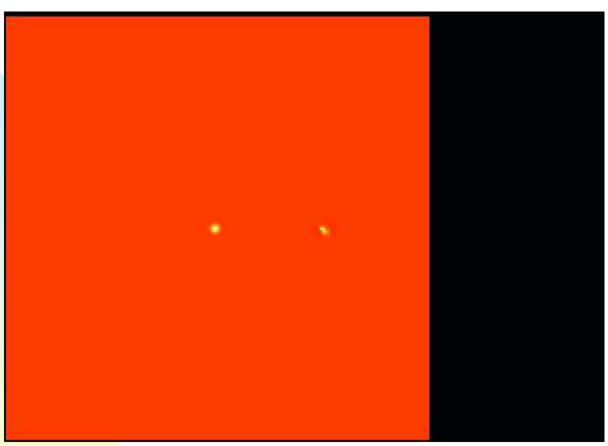
mini-workshop scheduled for May 2004 in Stockholm (EU Network on Planets)

(www.astro.su.se/~pawel/planets/test.hydro.html)

Migration type III



Simulation of a Jupiter-class planet in a constant surface density disk with soundspeed = 0.05 times Keplerian speed.
PPM by Artymowicz (2000), in medium resolution (300 x 300 grid)

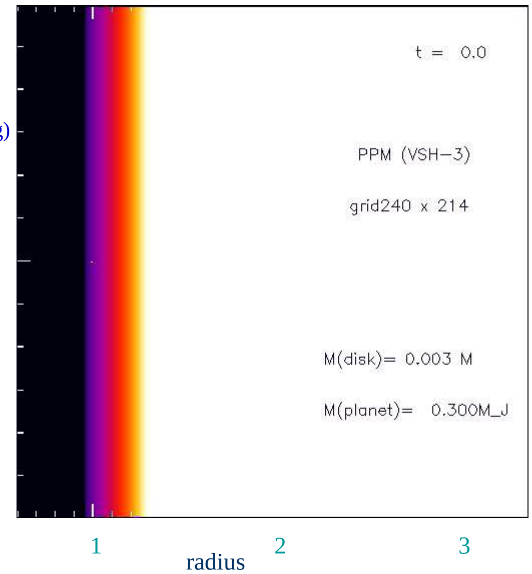


Although this is clearly a type-II situation (gap opens), the migration rate is NOT that of the standard type-II, which is the viscous accretion speed of the nebula.

Saturn-mass protoplanet in a solar nebula disk

(1.5 times the Minimum Nebula, PPM, Artymowicz 2003)

Azimuthal angle (0-360 deg)

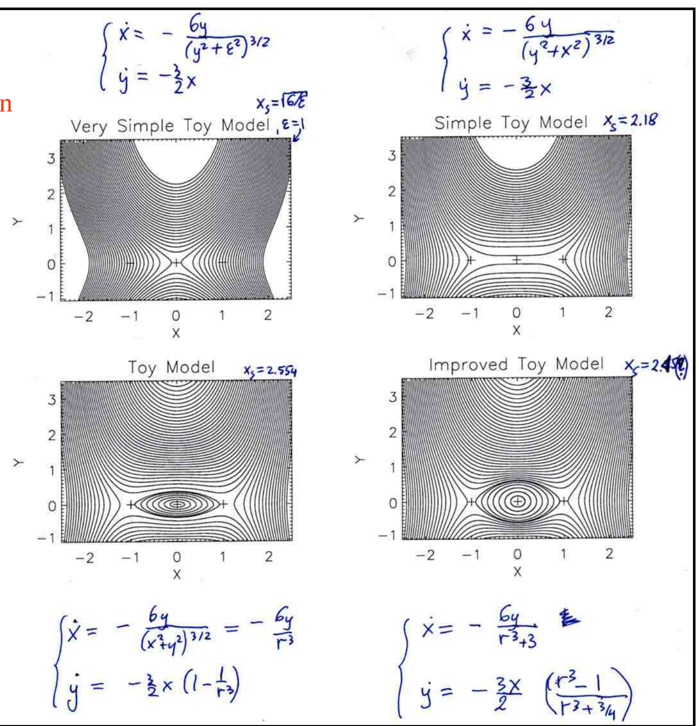


Type III outward migration

Condition for FAST migration: disk mass (in CR region) similar to planet mass.

Notice a carrot-shaped bubble of "vacuum" behind the planet. Consisting of material trapped in librating orbits, it produces CR torques smaller than the matrial in front of the planet. The net CR torque powers fast migration.

Examples of simple orbital sets obtained from the simplification of Hill's equations of motion.



Toy models of CR-directed migration type III