Planetary migration in gaseous disks: some recent results

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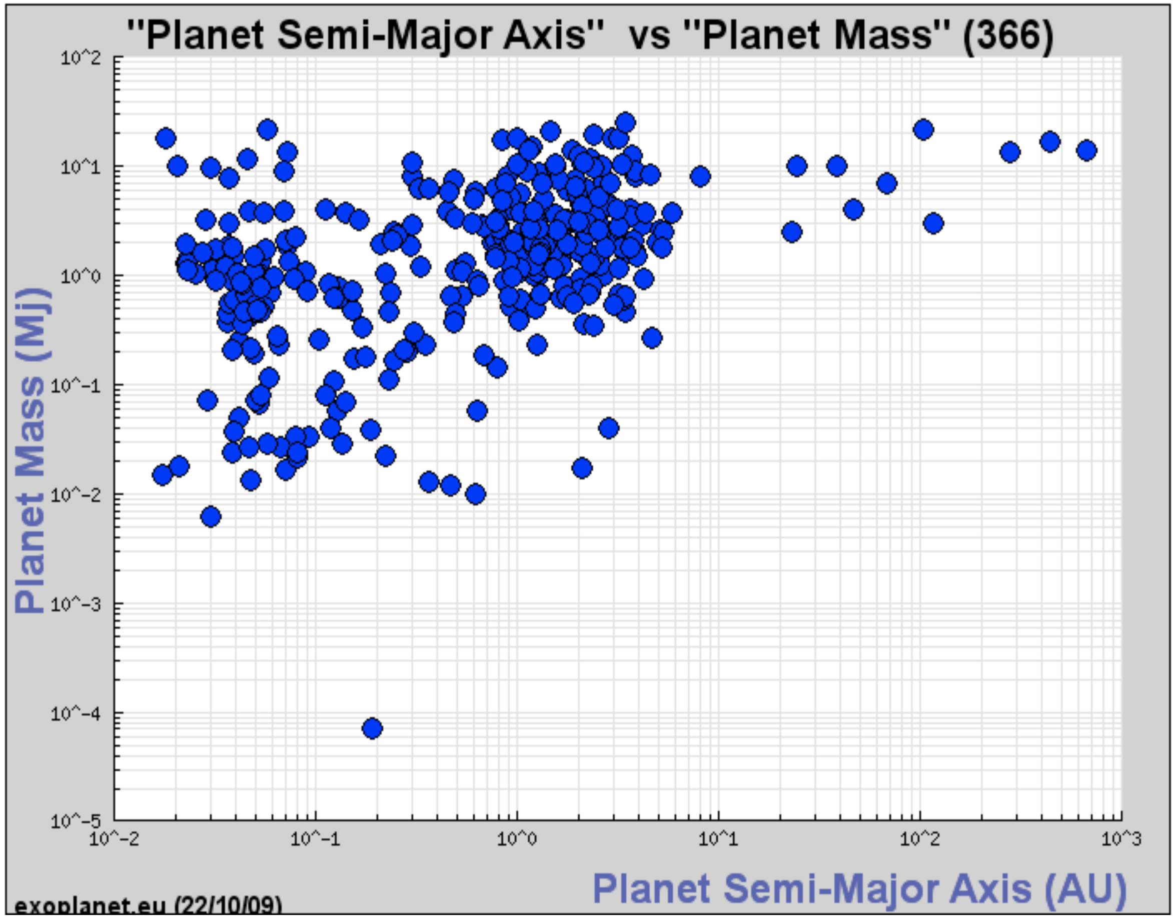
Some properties of extra-solar planets



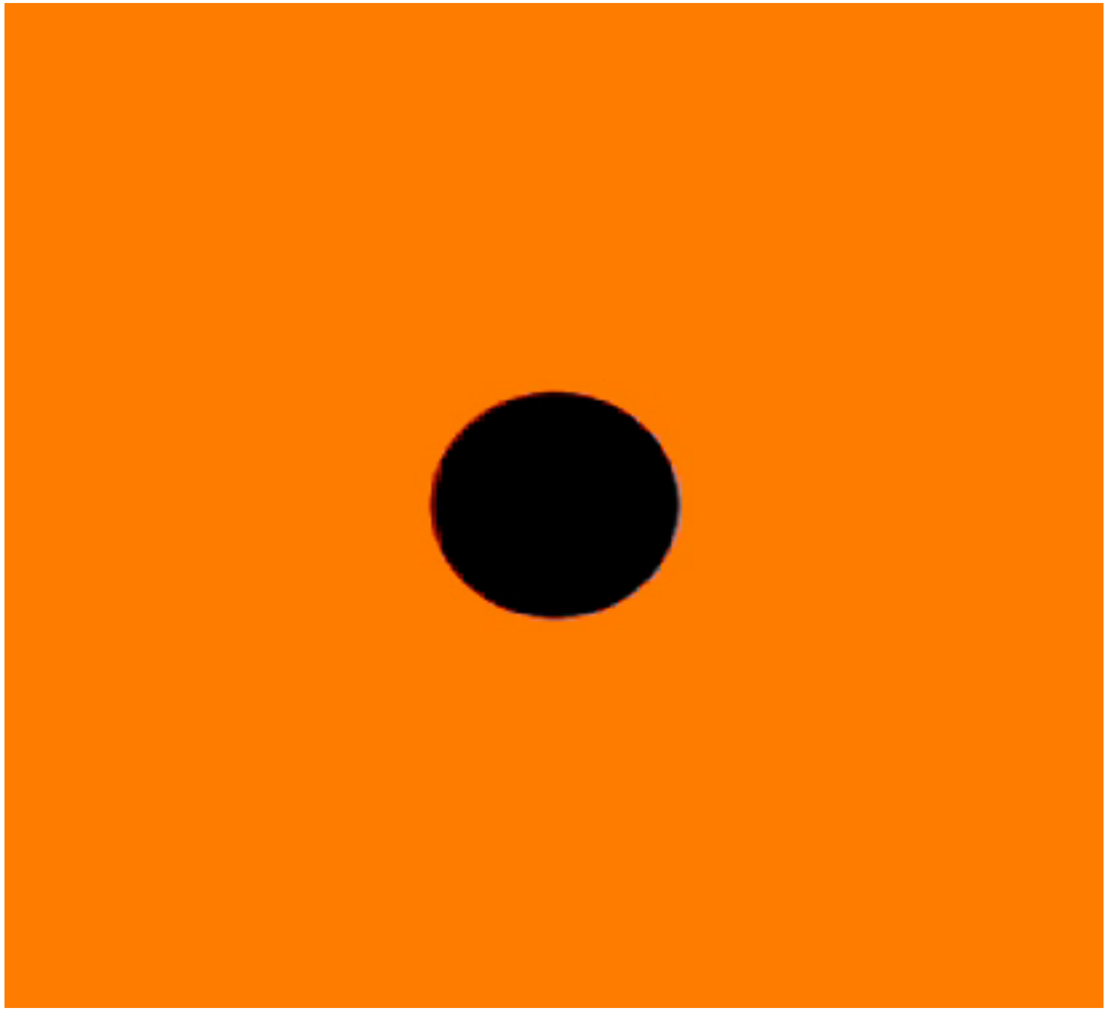
A significant fraction of extra-solar planets orbits very close to its host star (<0.2 AU)

These planets cannot have formed so close from their host star: they must have formed further out and they must have *migrated*.

How do planets migrate ? Can migration account for the statistics of orbital properties of extrasolar planets ?

Disk response to an embedded planet

Disk response to a point-like mass on a circular orbit



➔ The planet tidally excites a one-armed spiral wake that propagates both inwards and outwards.

What causes planetary migration ?

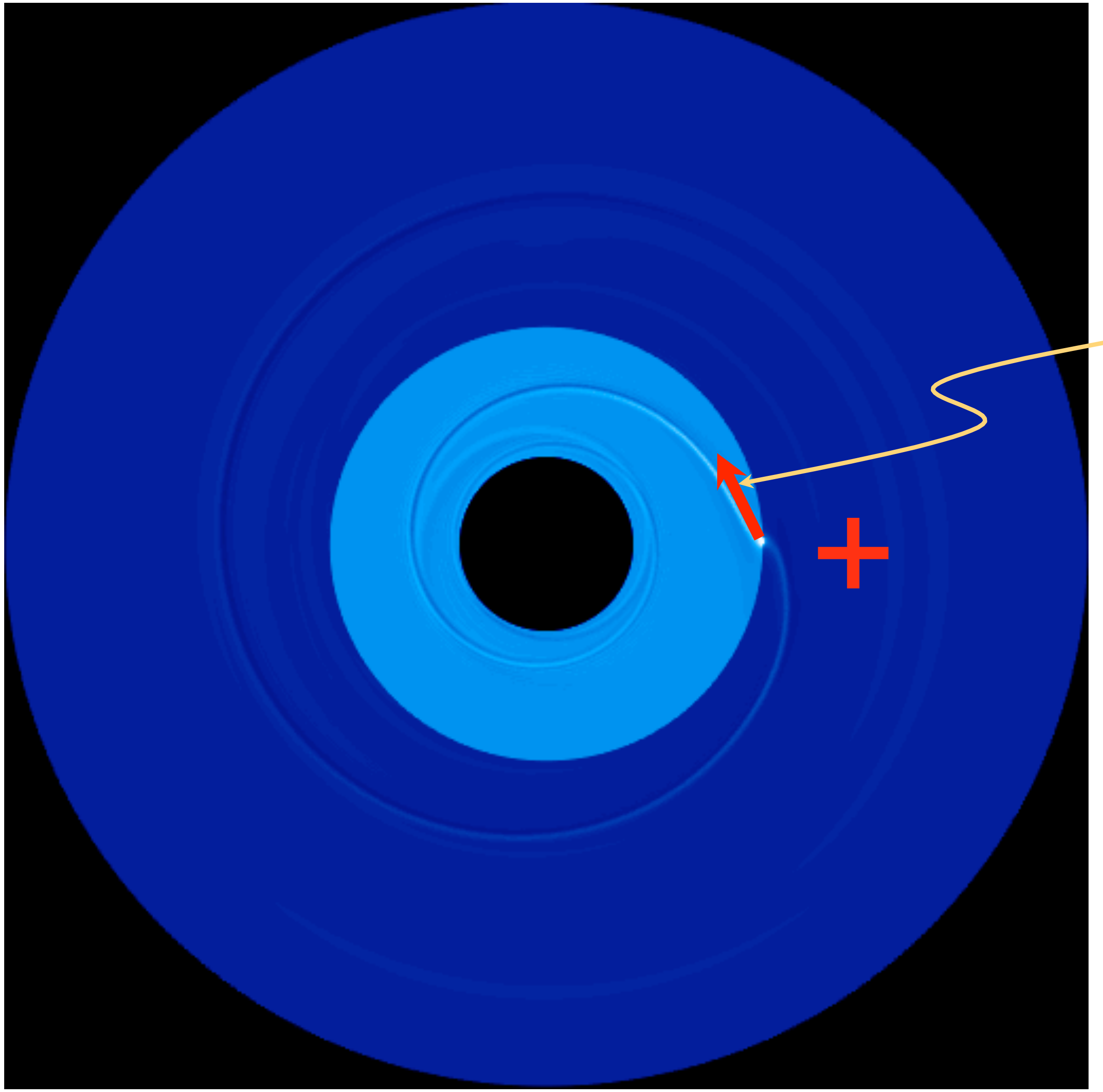
The protoplanet tidally excites a spiral wake.

This wake exerts a gravitational force on the planet

The semi-major axis, the eccentricity, the inclination vary with time.

The most spectacular effect is the variation of the semi-major axis: it is called *planetary migration.*

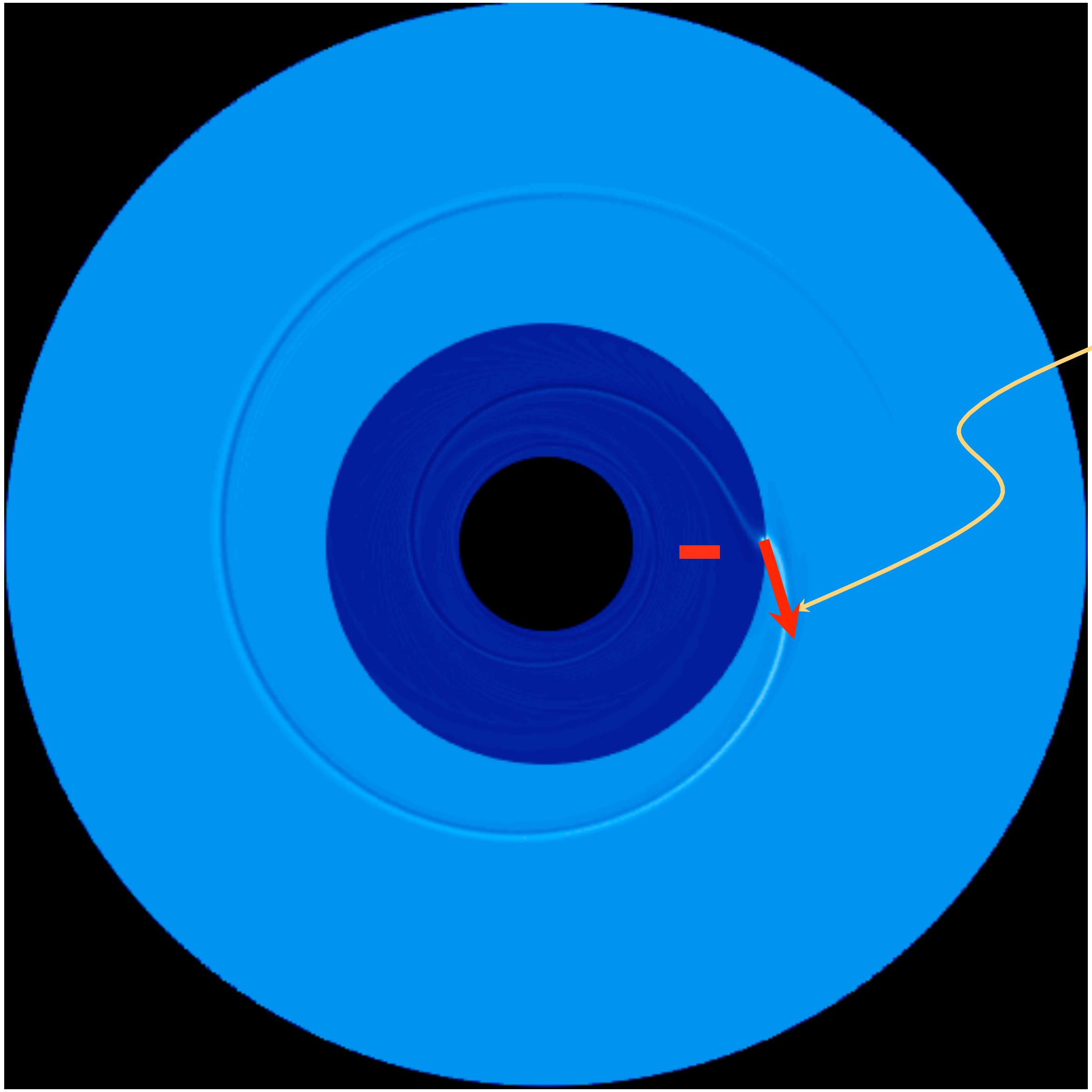
Inner disk's torque



The inner wake leads the planet.

It therefore exerts a positive torque on the latter

Outer disk’s torque



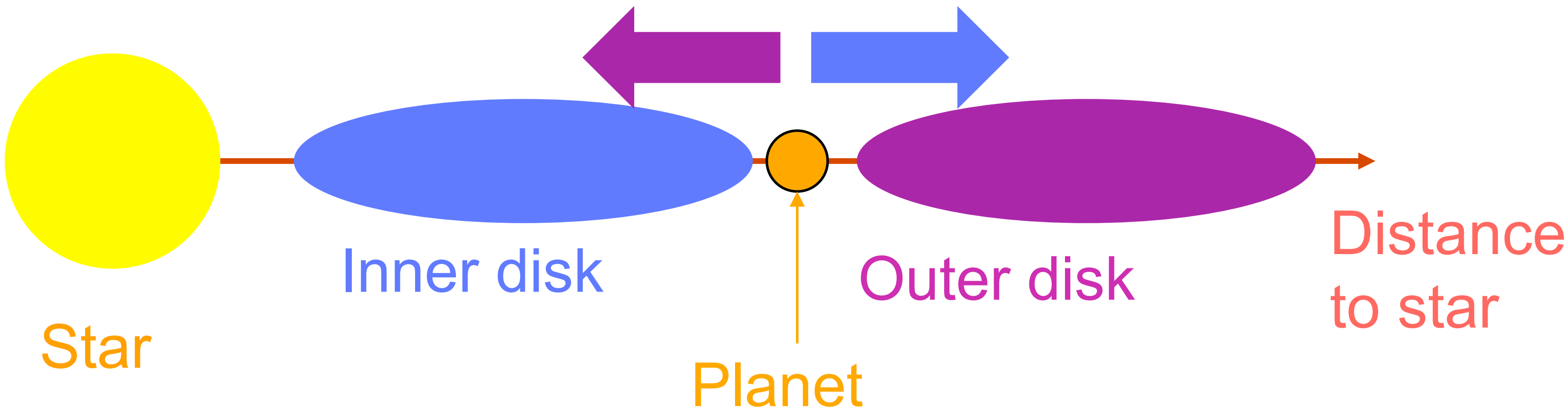
The wake in the outer disk lags the planet.

It therefore exerts a negative torque on the planet.

Imbalance between inner and outer torques

The specific angular momentum increases with the radius, therefore:

- The inner disk, which exerts a positive torque, tends to impose an outwards migration.
- The outer disk, which exerts a negative torque, tends to impose an inwards migration.

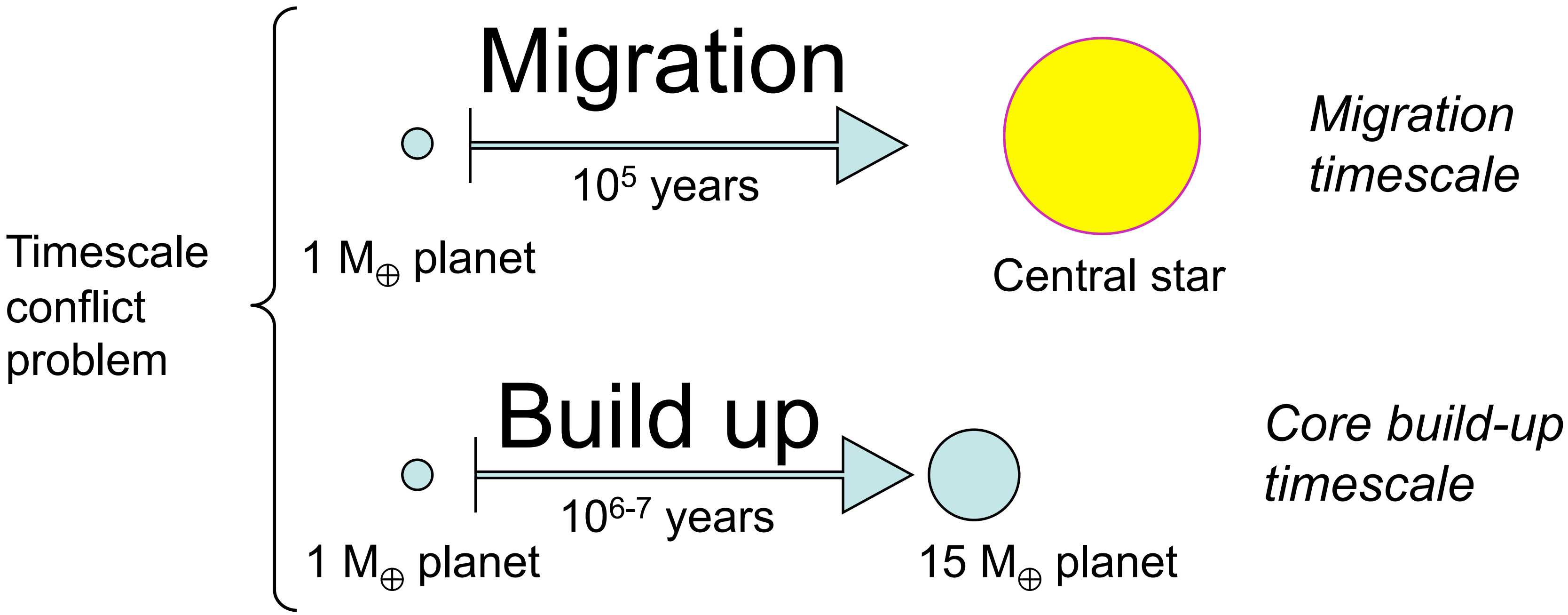


Type I migration is inwards

- A (slight) imbalance between these two torques yields a migration of the planet.
- The net torque is called the *differential Lindblad torque.*
- In the linear regime (low-mass planet), the differential Lindblad is a negative quantity (Ward 1986).
  ➔ *Type I* migration is inwards.

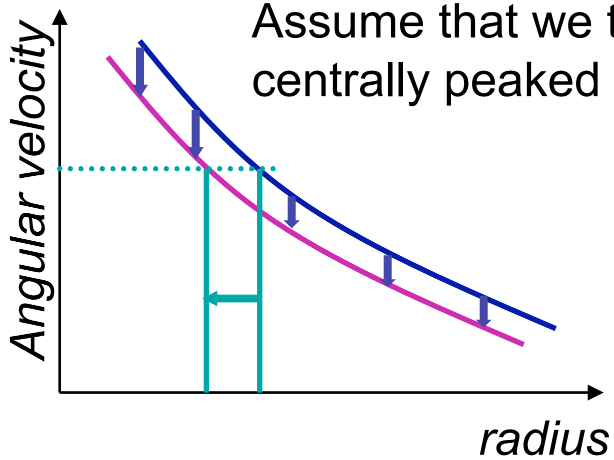
Type I migration is fast

A one-Earth mass planet, dropped in a MMSN (*Minimum Mass Solar Nebula*) at 1 AU, should be flushed onto the central object in ~ 10^5 yrs.



Type I migration is *really* inwards

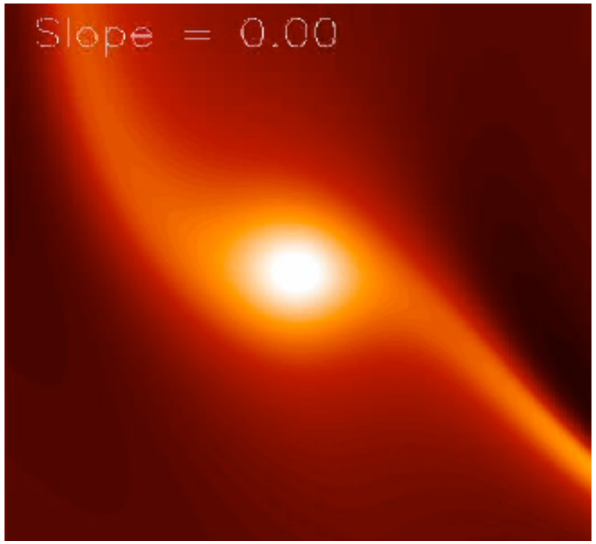
The drift rate is quite insensitive to the disk profiles (surface density and temperature).



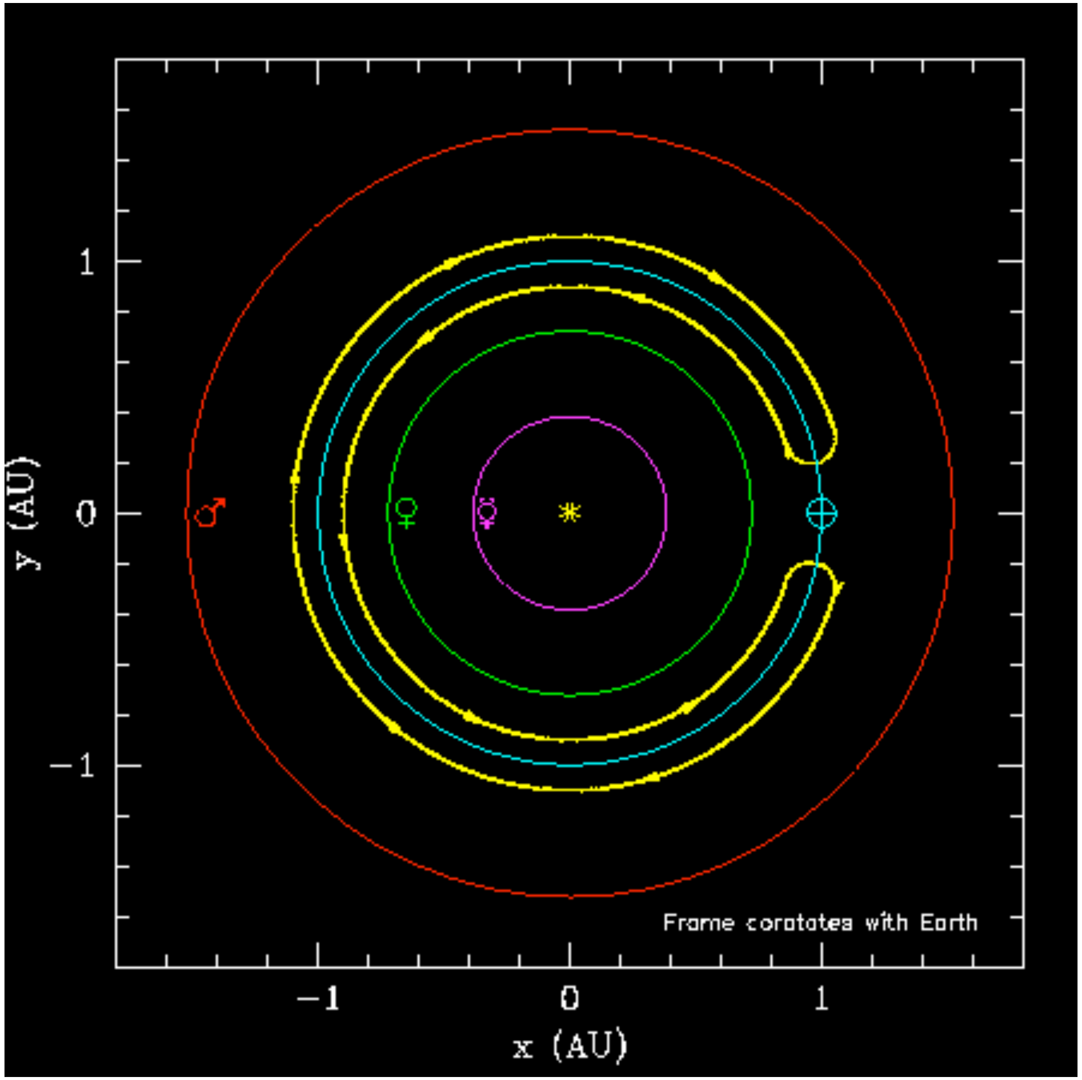
Assume that we take a centrally peaked surface density profile.

The wake is shifted inwards ➔ this frustrates the effect of the surface density variation.

Pressure buffer effect (Ward, 1997)

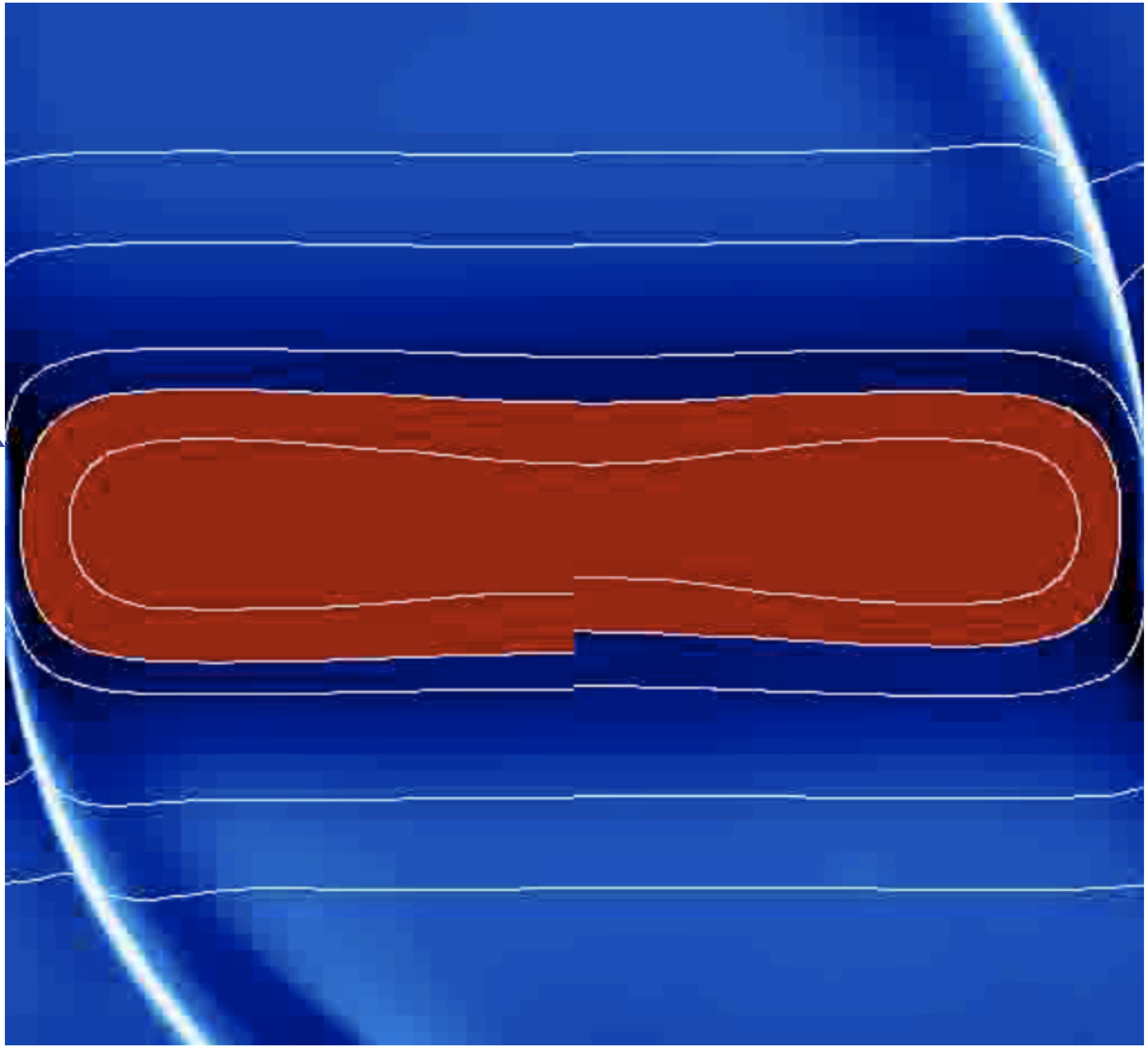


Coorbital dynamics



Horseshoe trajectories in the Earth's corotating frame.

Horseshoe drag and corotation torque

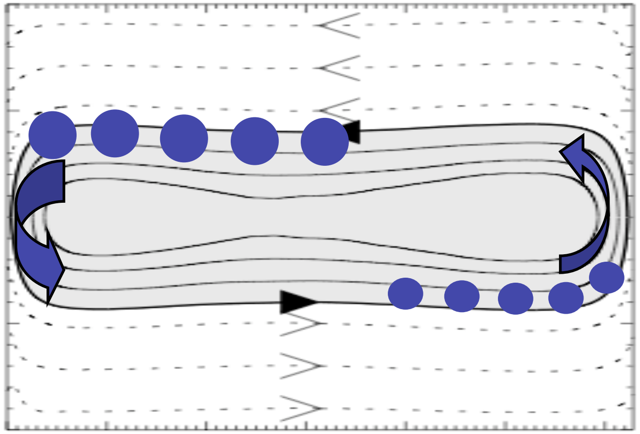


On this side a positive torque is exerted onto the planet

On this side a negative torque is exerted onto the planet.

Horseshoe drag and corotation torque

The horseshoe drag scales with the vortensity gradient (ratio of vorticity and surface density).

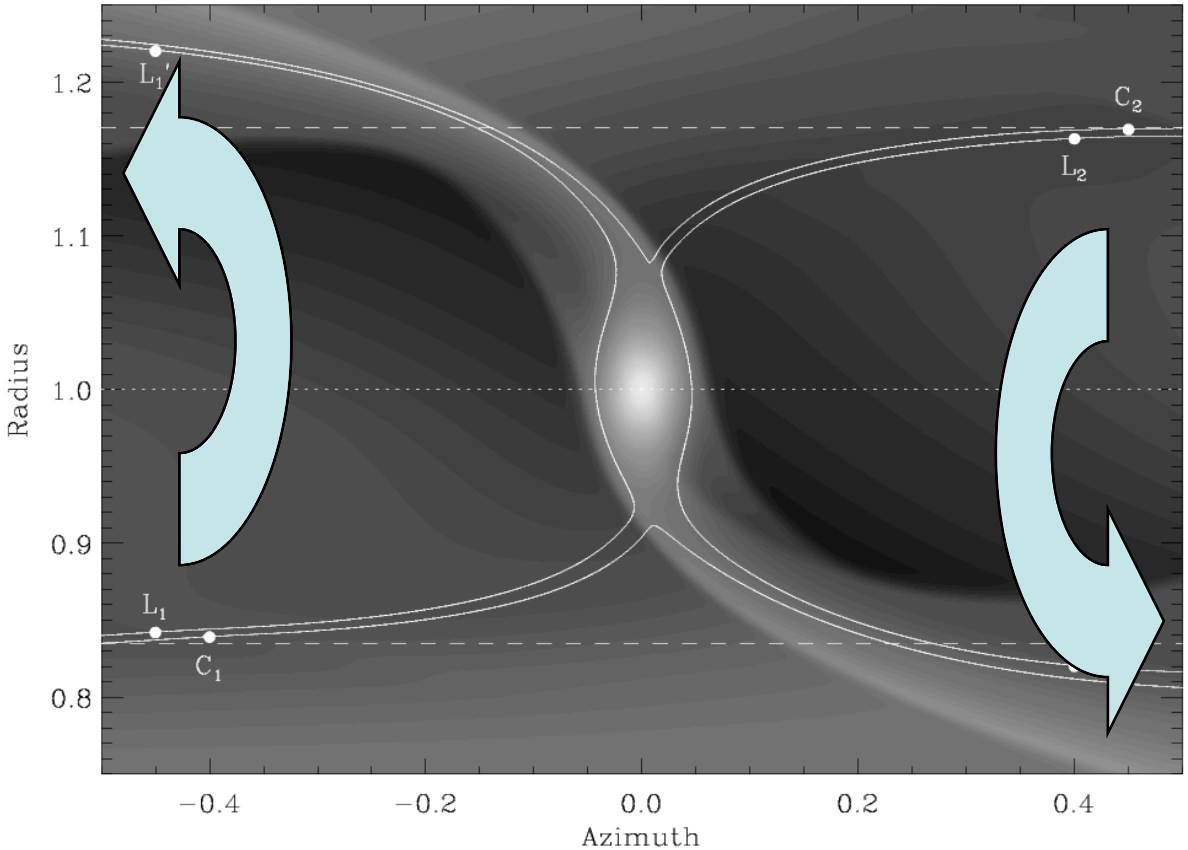


$$\Gamma_c \propto \frac{d(\Sigma/B)}{dr}$$

It is too weak to counteract the differential Lindblad torque in the linear regime.

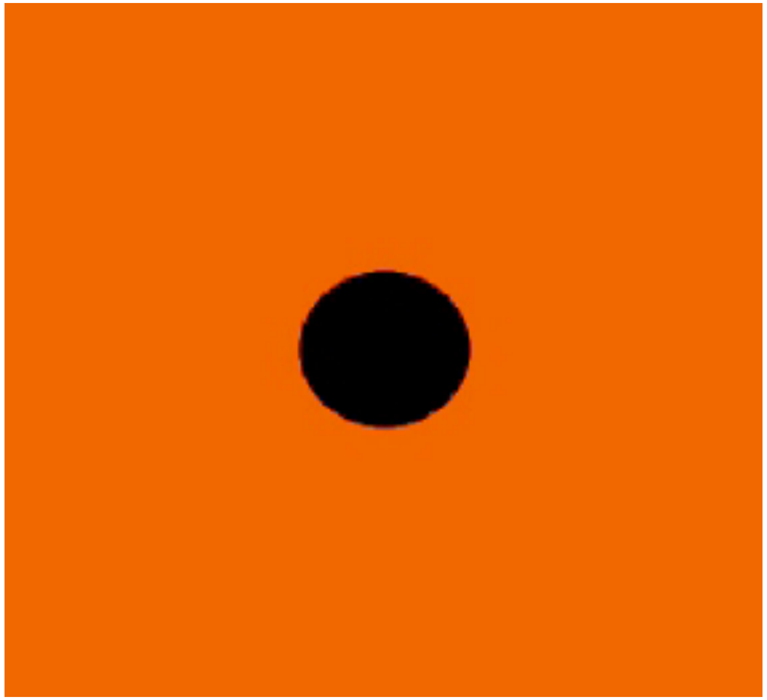
Gap clearance at large planetary mass

When the planetary mass becomes sufficiently large, the wake degenerates into a shock in the vicinity of the planet. Horseshoe U-turns then become asymmetric.



The gas leaves the horseshoe region in a few libration times and a gap is excavated around the orbit.

Gap clearance at large planetary mass

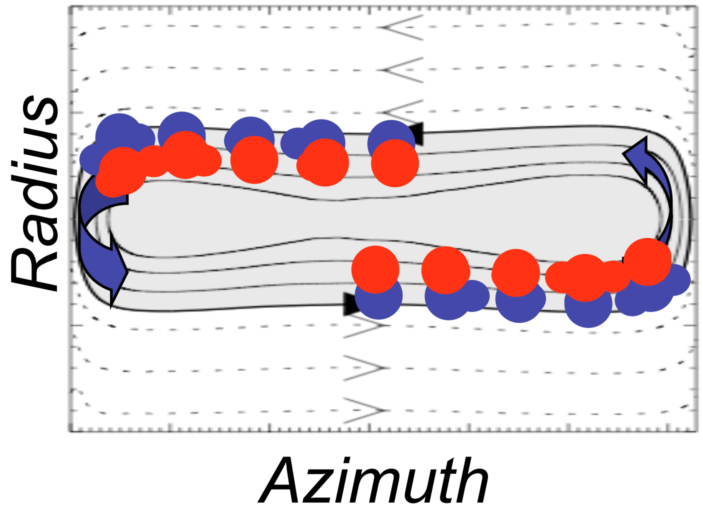


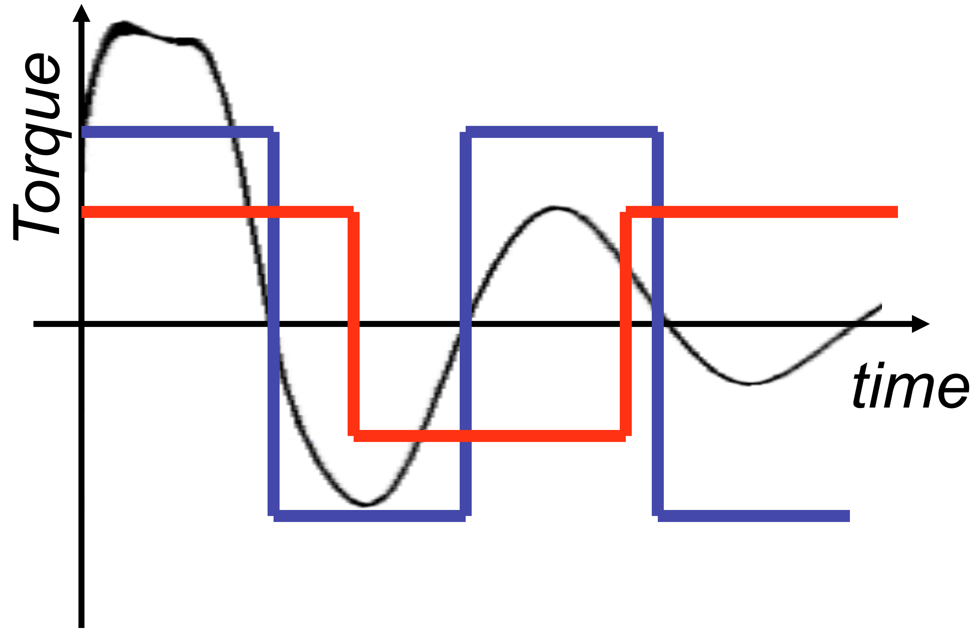
A Jovian planet clears a gap
in approximately 100 orbits.

Migration with gap = Type II migration

The planet is locked in the disk’s viscous evolution
➔ it is then much slower than type I migration.

Saturation of corotation torque





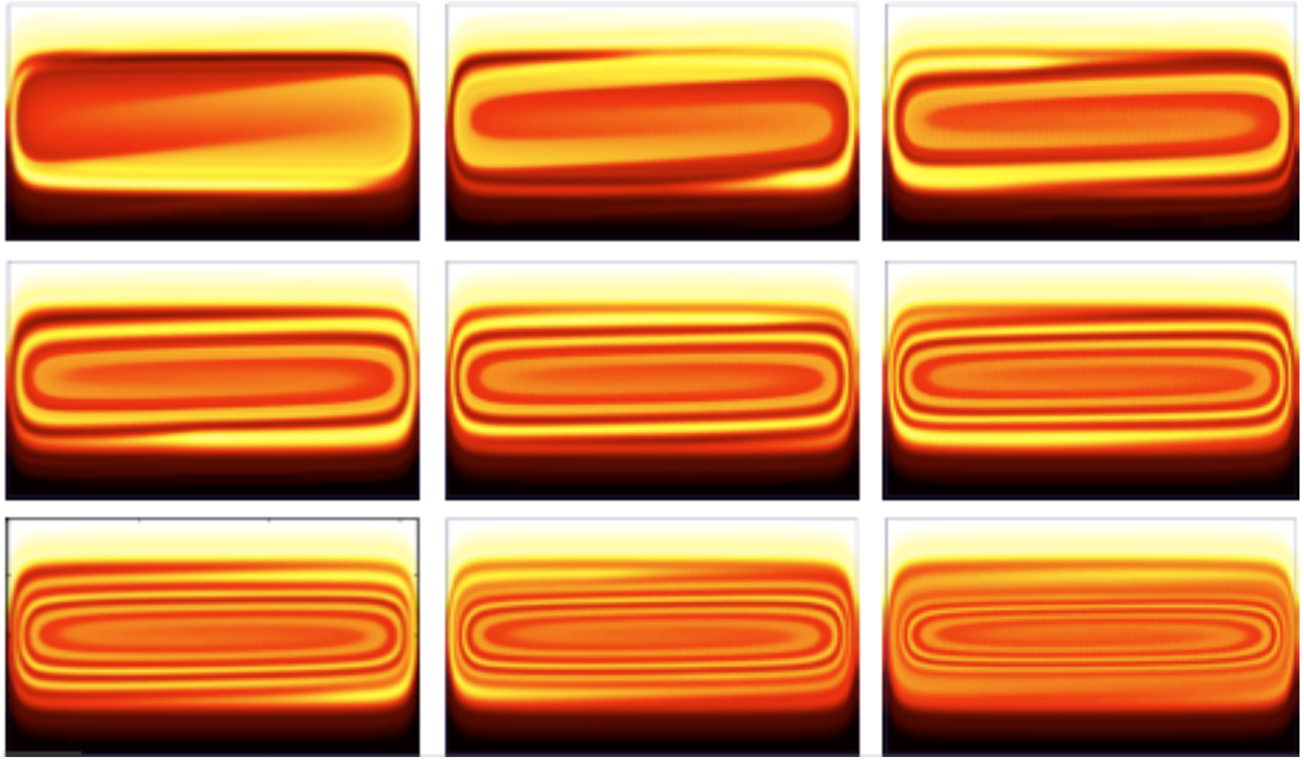
Each streamline gives a periodic contribution to the CR torque

Each streamline has a different libration time

➔ CR torque tends to 0 as a result of phase mixing

Saturation of corotation torque

The vortensity is conserved by an inviscid 2D isothermal flow



Balmforth & Korycansky, 2001

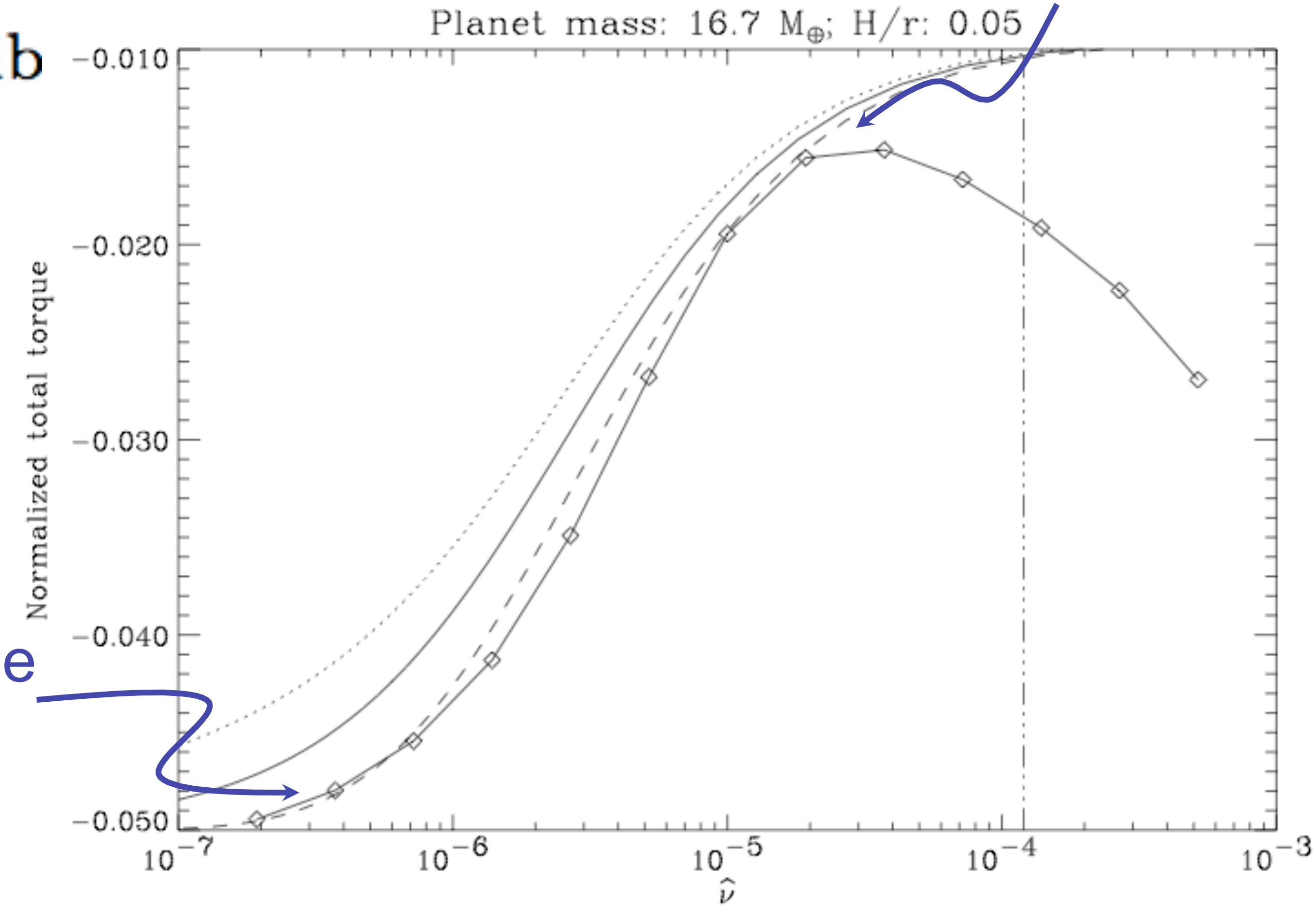
Horseshoe dynamics tends to cancel out the source of the corotation torque.

Viscous diffusion, if sufficient, can maintain an unsaturated torque.

Viscous diffusion desaturates the CR torque

Viscous diffusion is efficient if $\tau_{\mathrm{visc}} < \tau_{\mathrm{lib}}$

Unsaturated torque at large viscosity

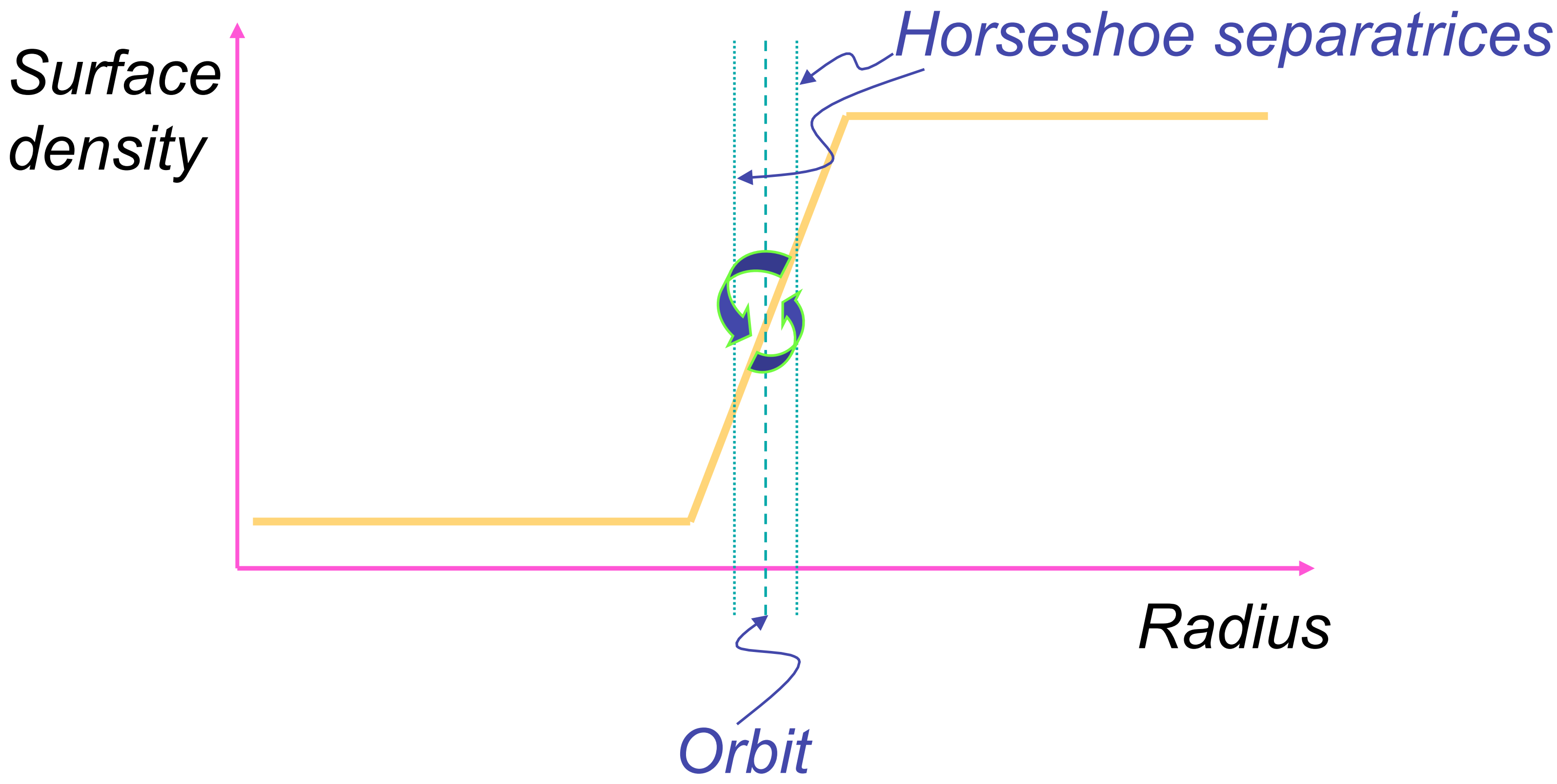


Saturated torque at low viscosity

Masset (2001, 2002)

Planetary trap at a cavity edge

The corotation torque scales with the vortensity gradient, hence is sensitive to a strong surface density gradient.



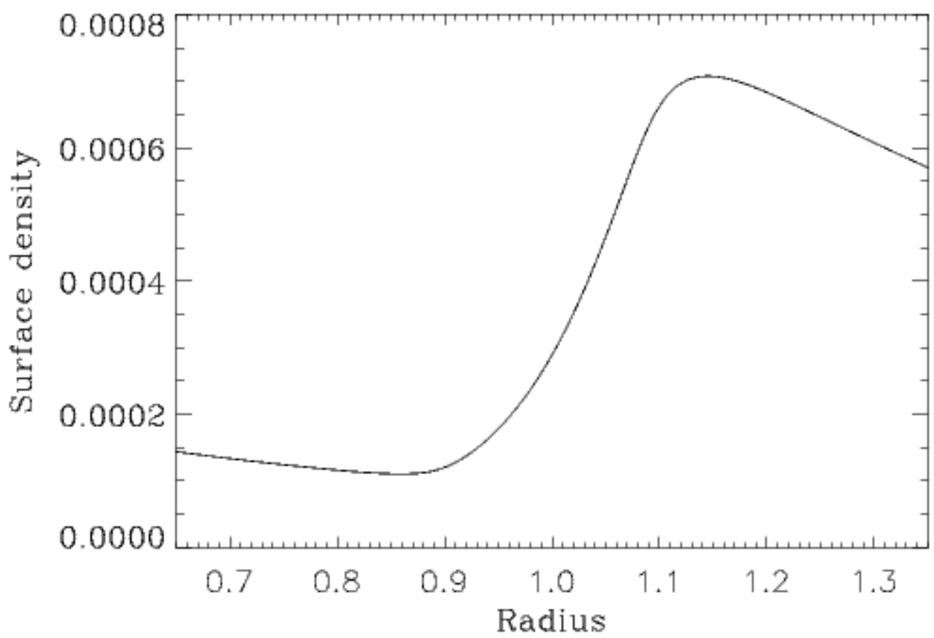
The CR torque can be arbitrarily large and positive at a cavity edge.

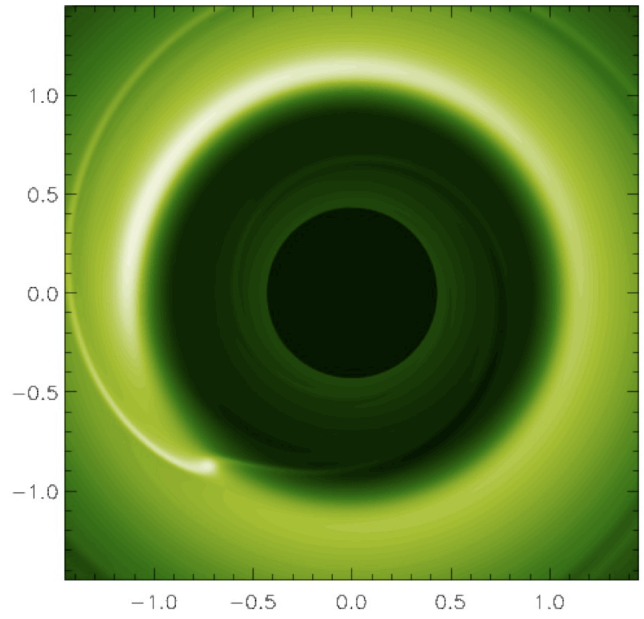
Torques on the cavity edge

	Power law disk		Cavity edge
Differential Lindblad torque	-1	x 2 - 4 →	-4
Corotation torque	+0.5	x 10 - 20 →	+5
TOTAL	< 0		> 0

Numerical simulations with a cavity

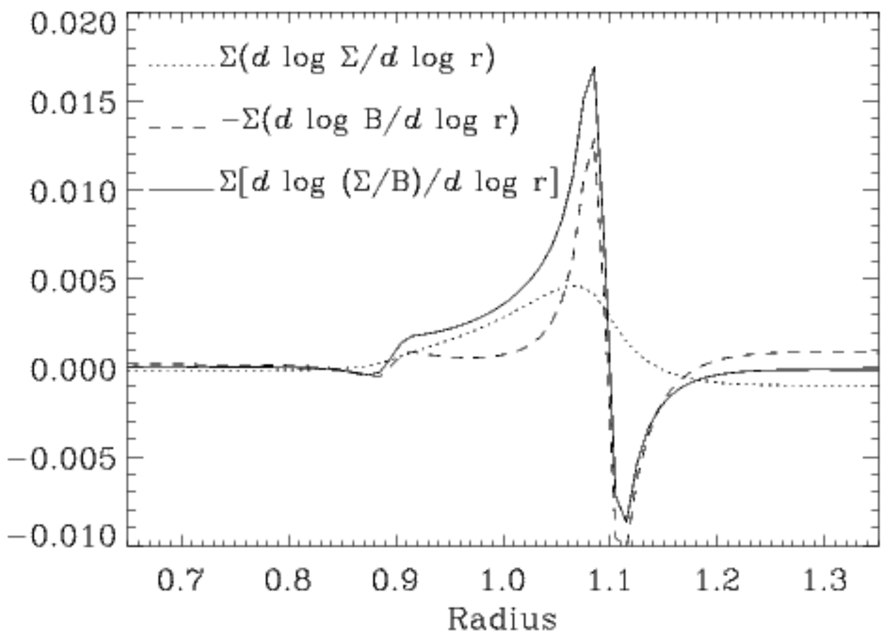
Surface density profile which includes a surface density jump.
* Realized with a jump of kinematic viscosity.
* Relaxed on 10^5 orbits





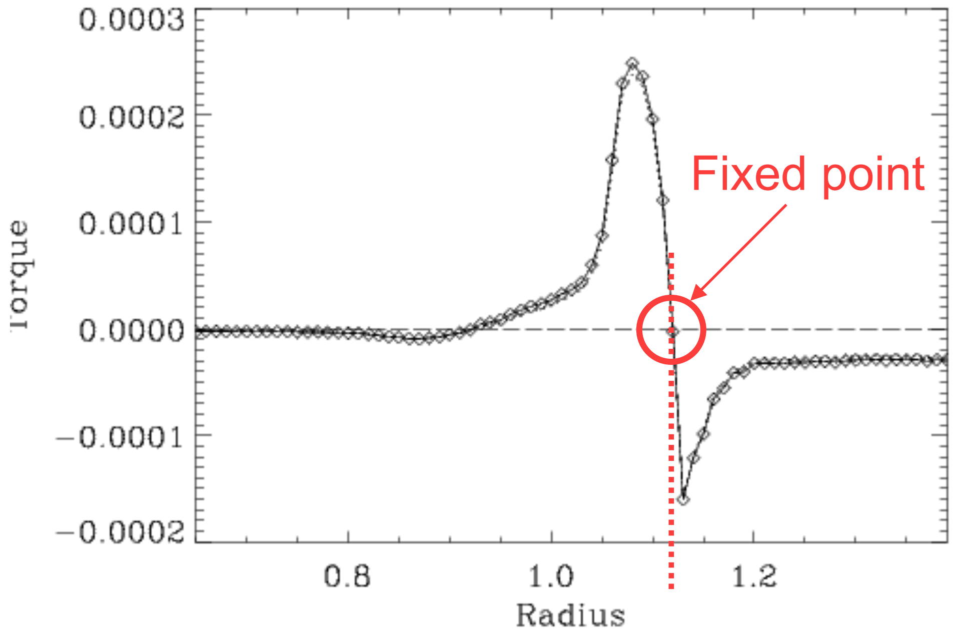
Numerical simulations with a cavity

Vortensity gradient as a function of radius.

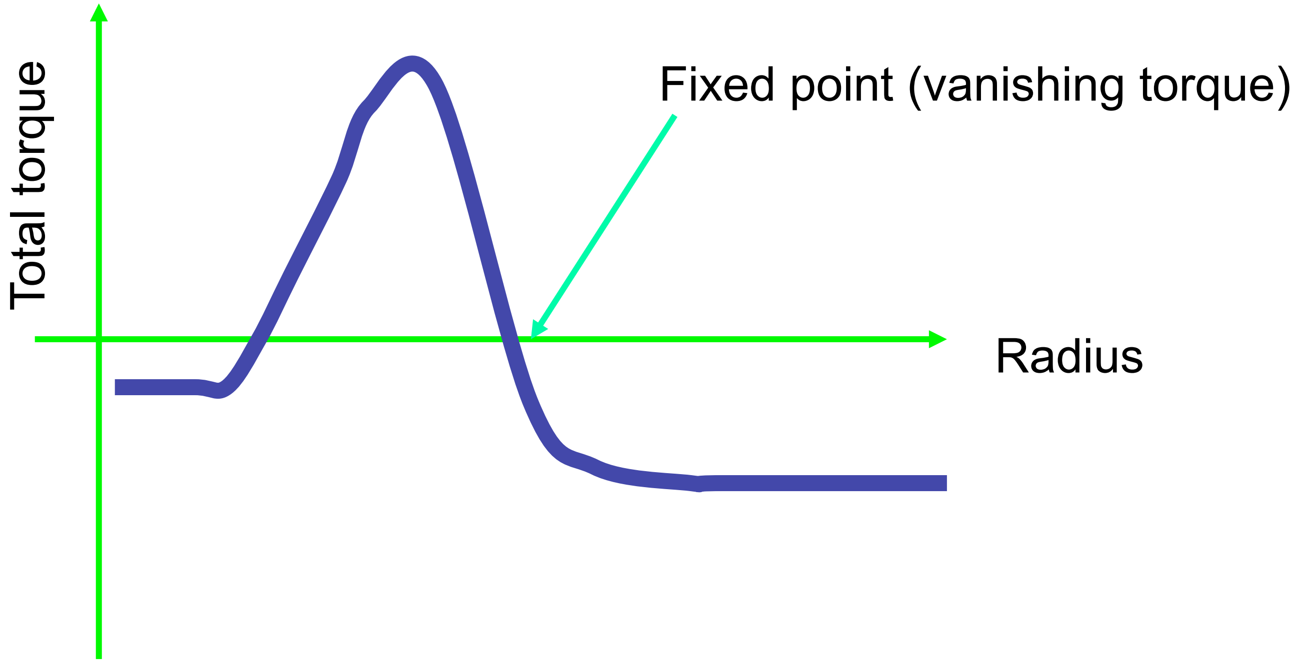


Masset, Morbidelli, Crida & Ferreira (2006)

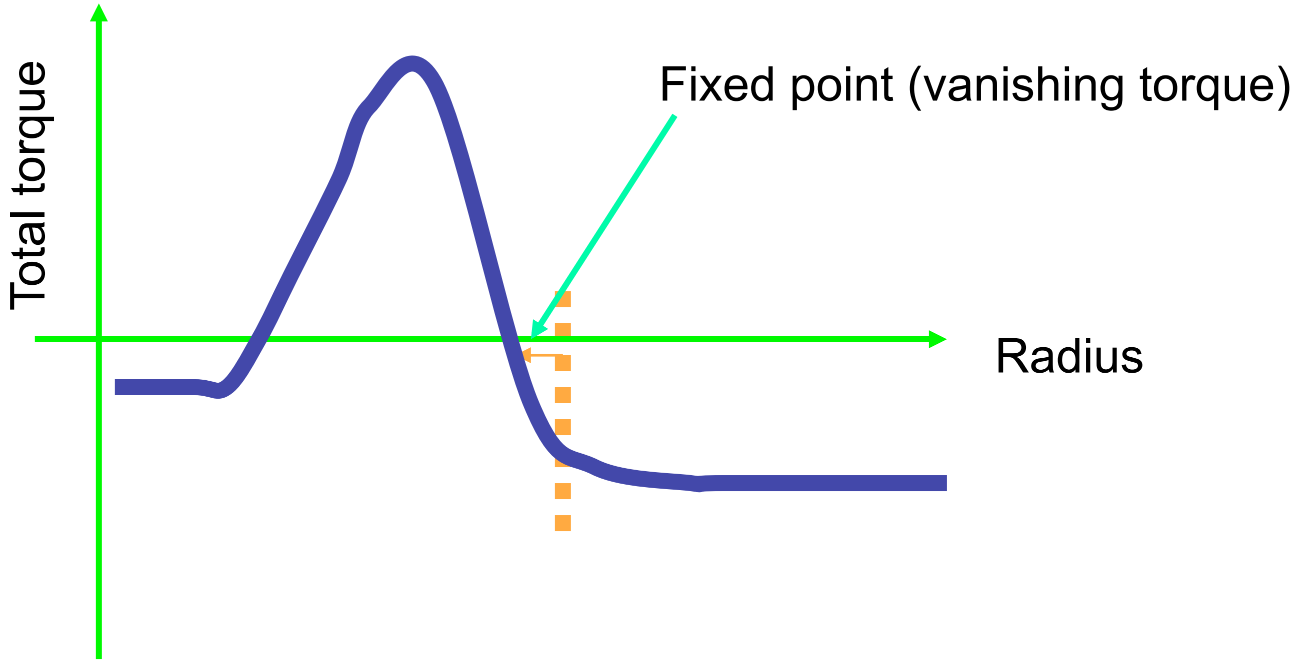
Total torque measured in 75 different calculations with 75 different semi-major axis.



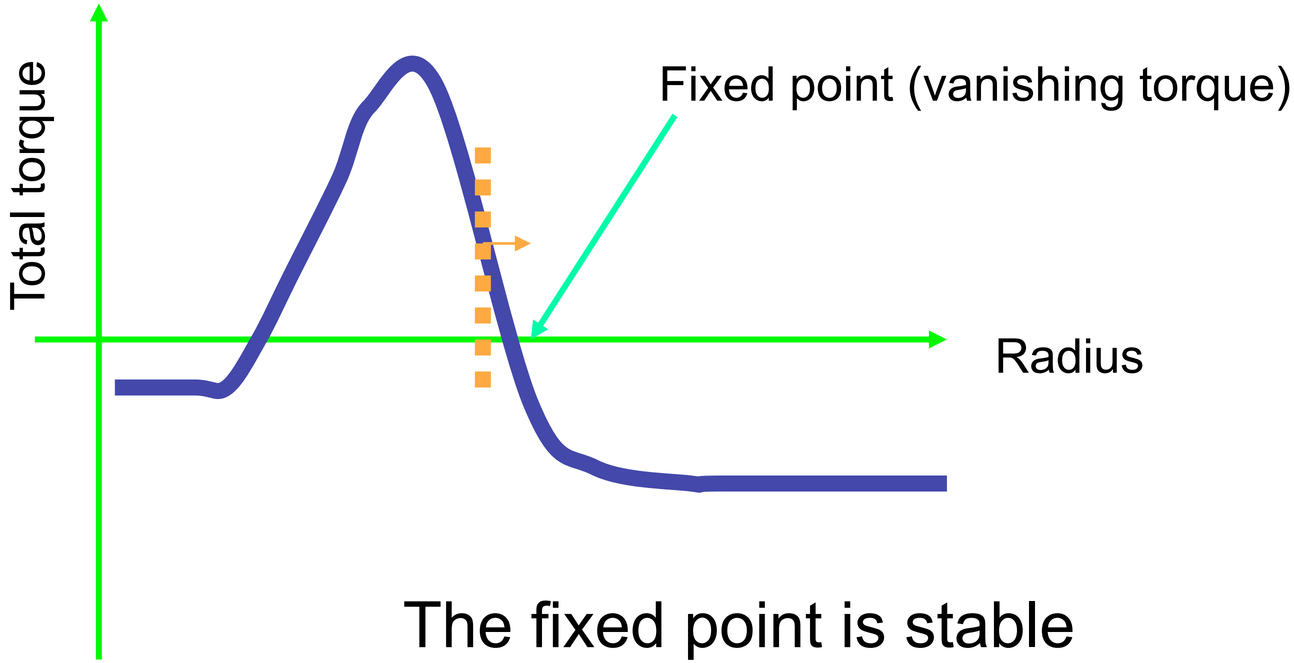
Fixed point



Fixed point

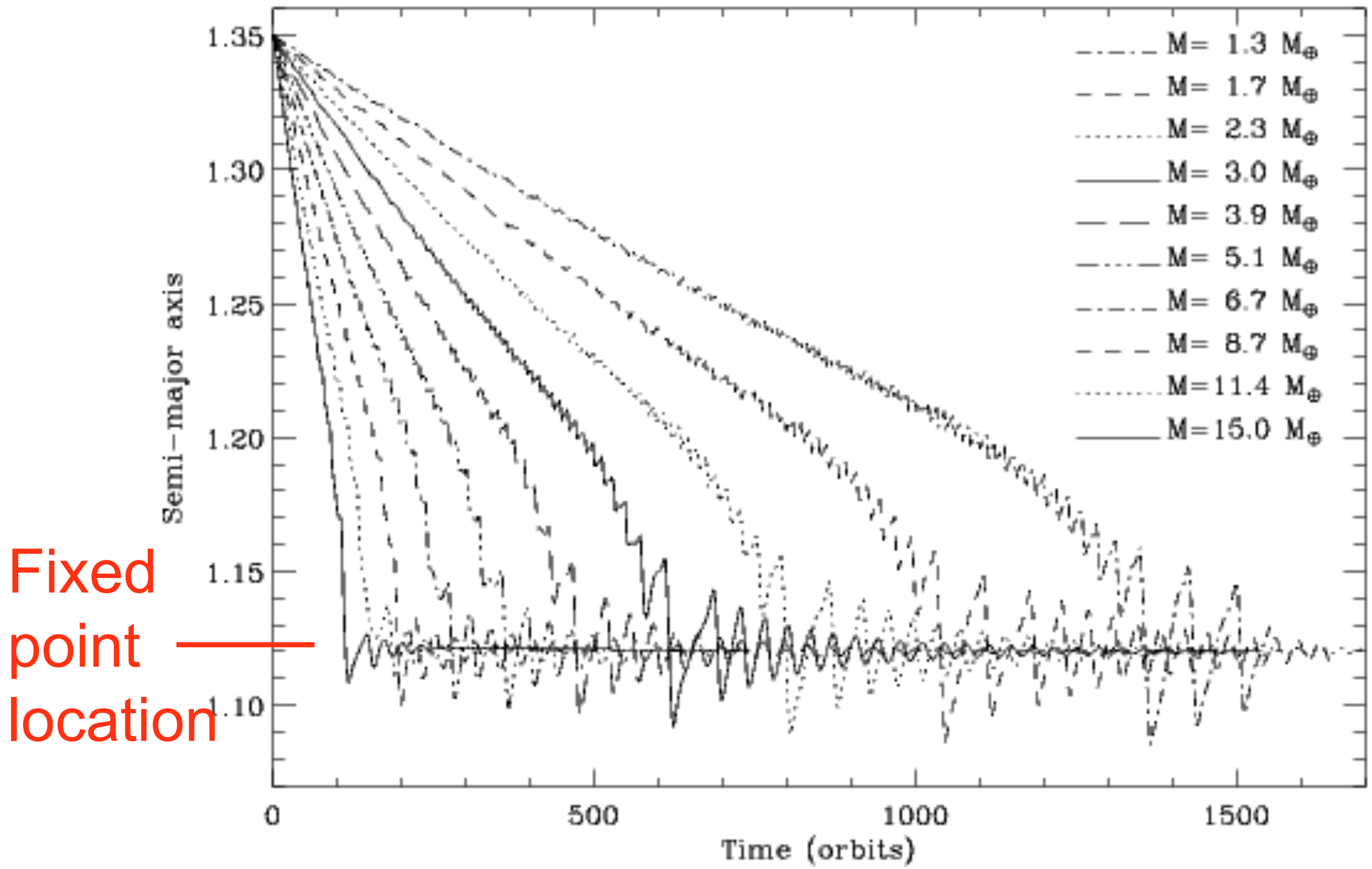


Fixed point



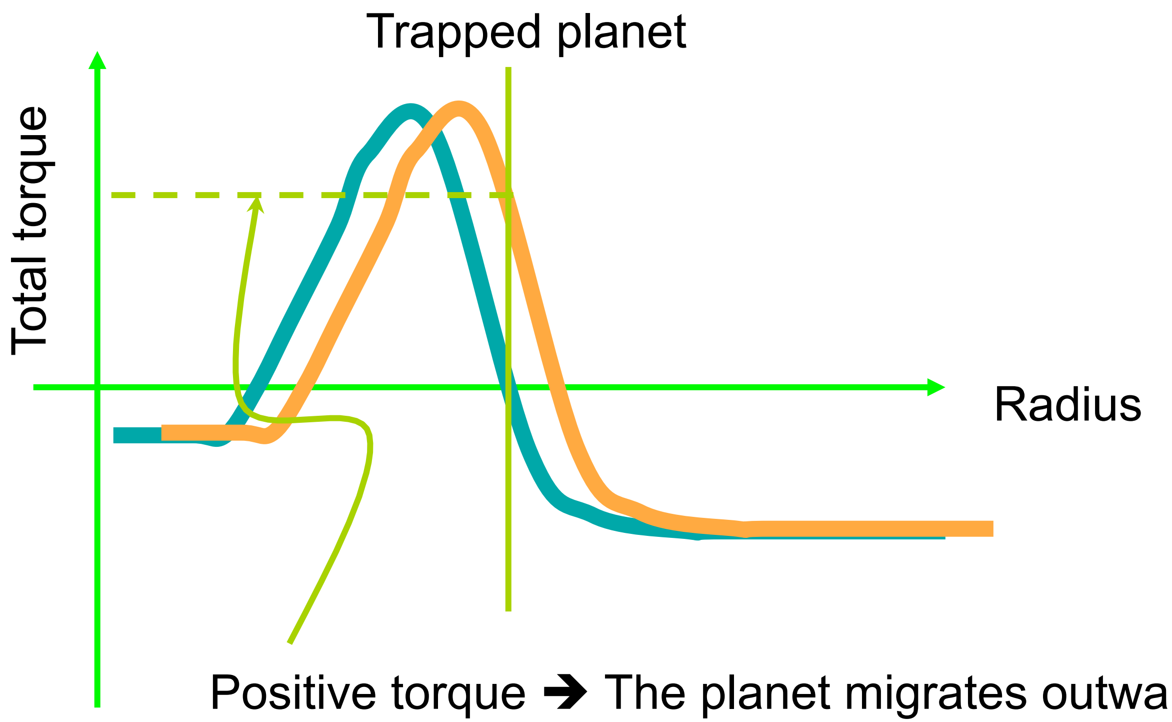
The fixed point is stable

Planetary trap at work



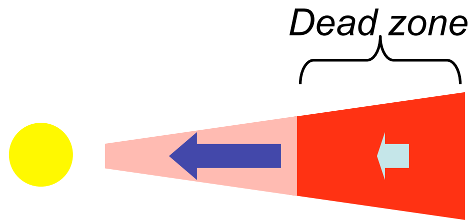
Trapping on the cavity edge

If the cavity radius varies with time,
the trapped embryos follow the cavity edge.



Positive torque ➔ The planet migrates outwards and follows the edge.

Example of cavities



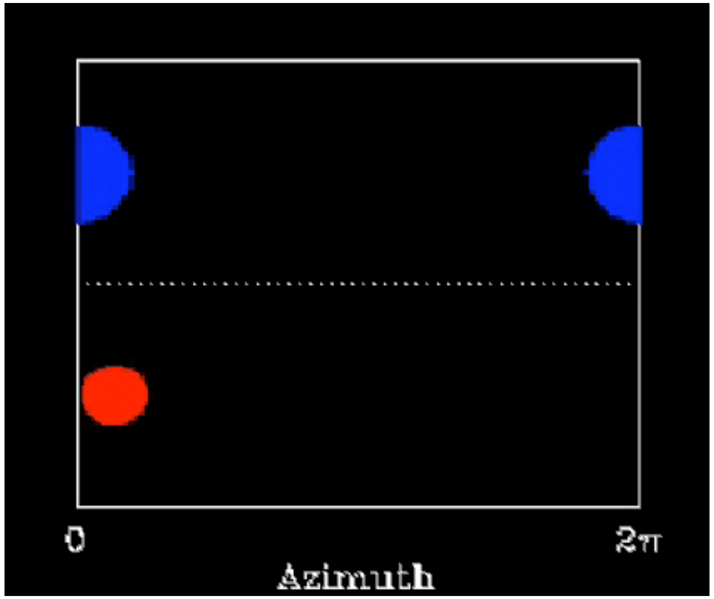
- Inner edge of the *dead zone*.

- Transition between a Standard Accretion Disk (SAD) and a jet emitting disk (SED).

- Disc truncated by tidal effects (*e.g.* at the outer edge of a gap, or disk truncated by a companion star -Pierens & Nelson, 2007-)

Note that some degree of turbulence is requested in order to avoid the CR torque's saturation.

Corotation torque on a migrating planet



Planet

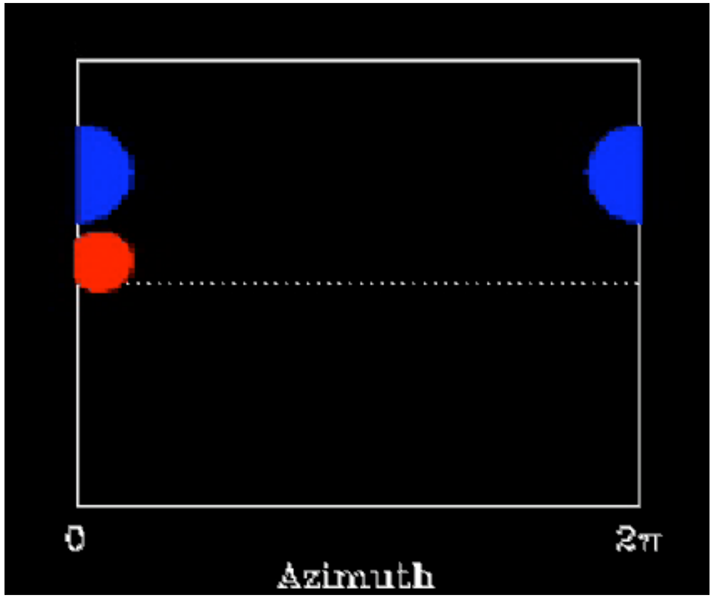
Fluid element

Dotted line : horseshoe separatrices

The planet migrates inwards → Fluid elements of the inner disk exert a negative torque

Positive feedback

Corotation torque on a migrating planet



Planet

Fluid element

Dotted line : horseshoe separatrices

The planet migrates inwards → The horseshoe region exerts a positive torque on the planet

Negative feedback

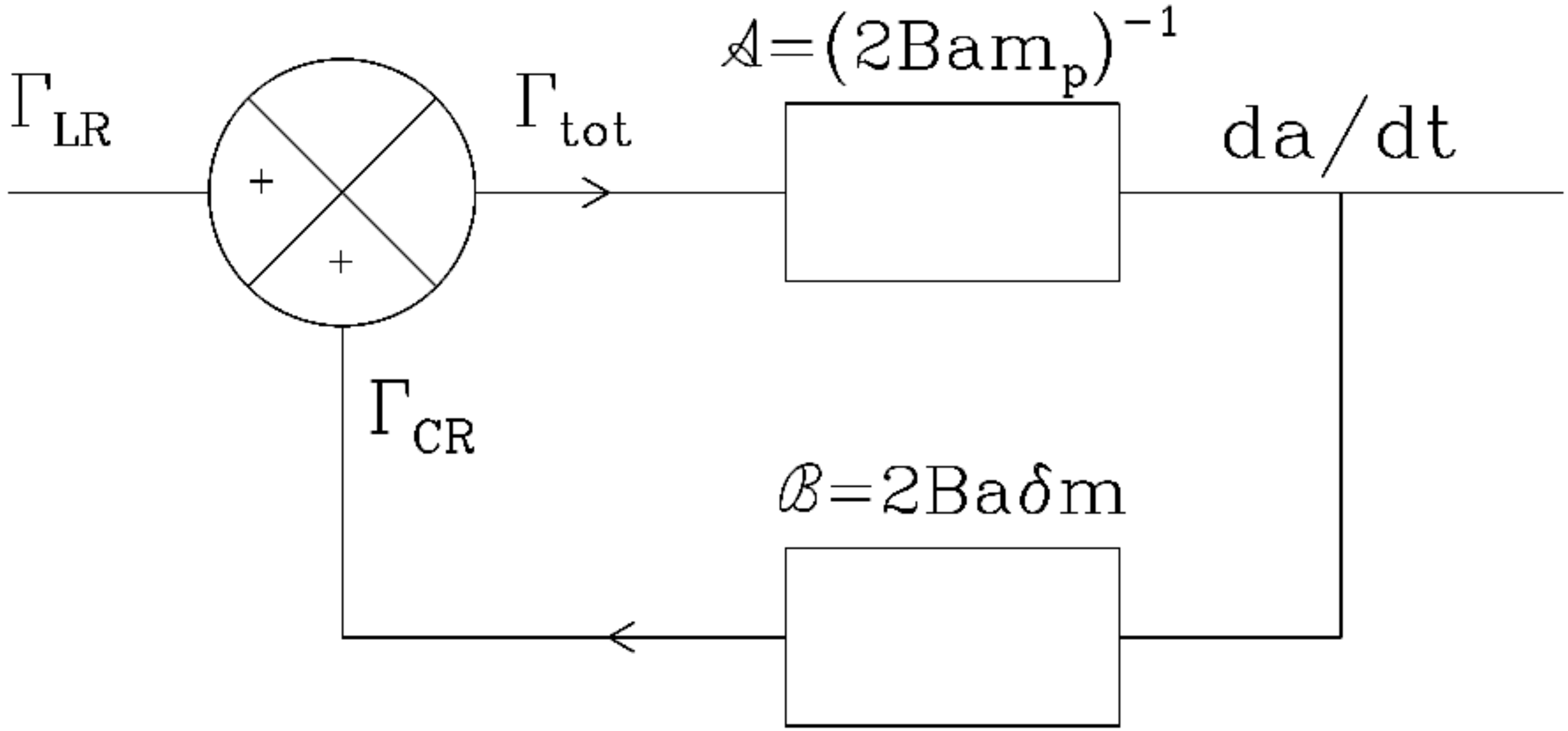
Corotation torque on a migrating planet

Both feedbacks cancel out if the disk profile is unperturbed.

If the horseshoe region is depleted, the net feed back is positive.

This can therefore happen for planets which deplete their coorbital region (giant planets).

Positive feedback loop

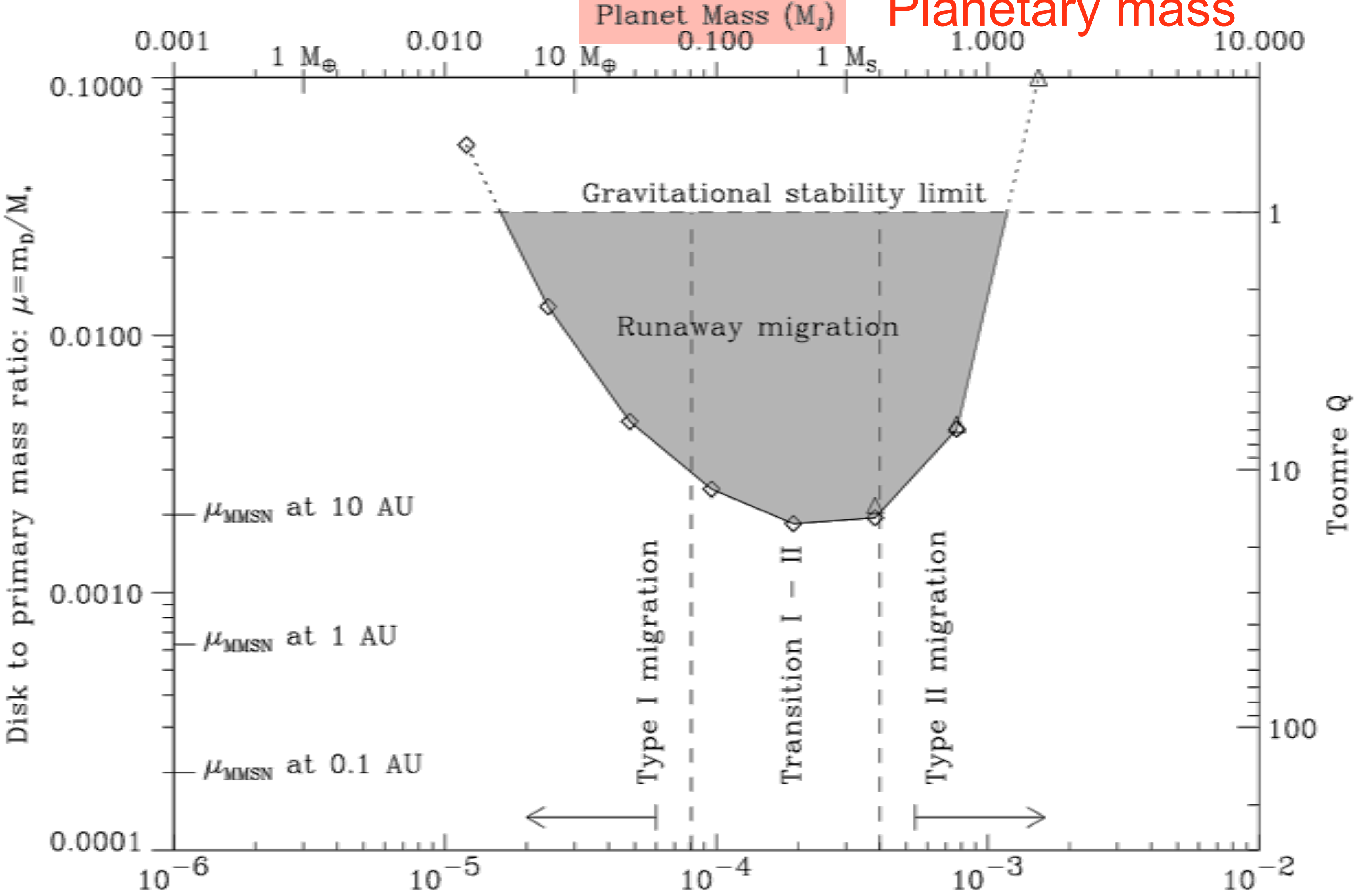


Positive feedback ➔ runaway?

Yes, if the disk is massive enough.

Type III (runaway) migration domain

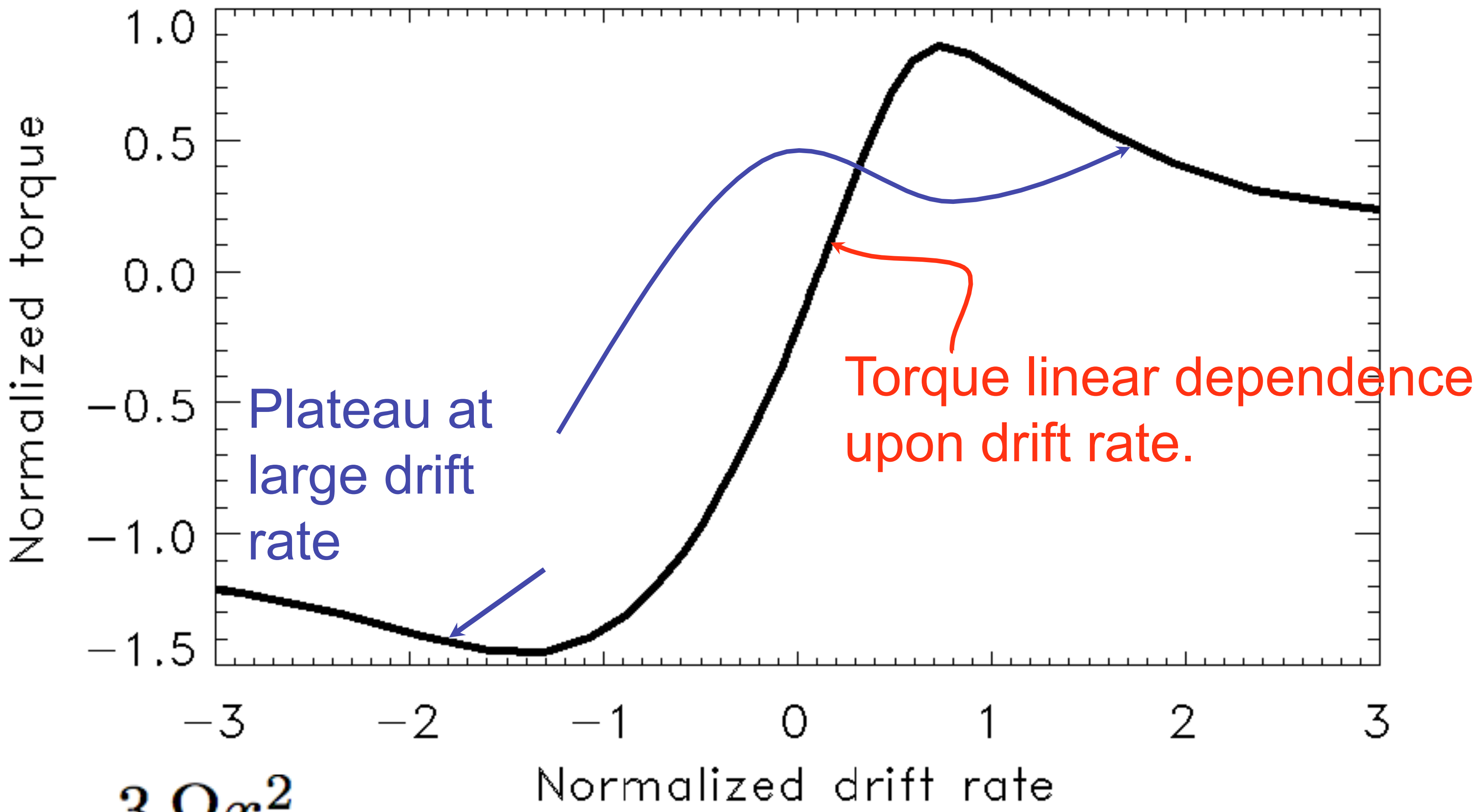
Planetary mass



Disk mass

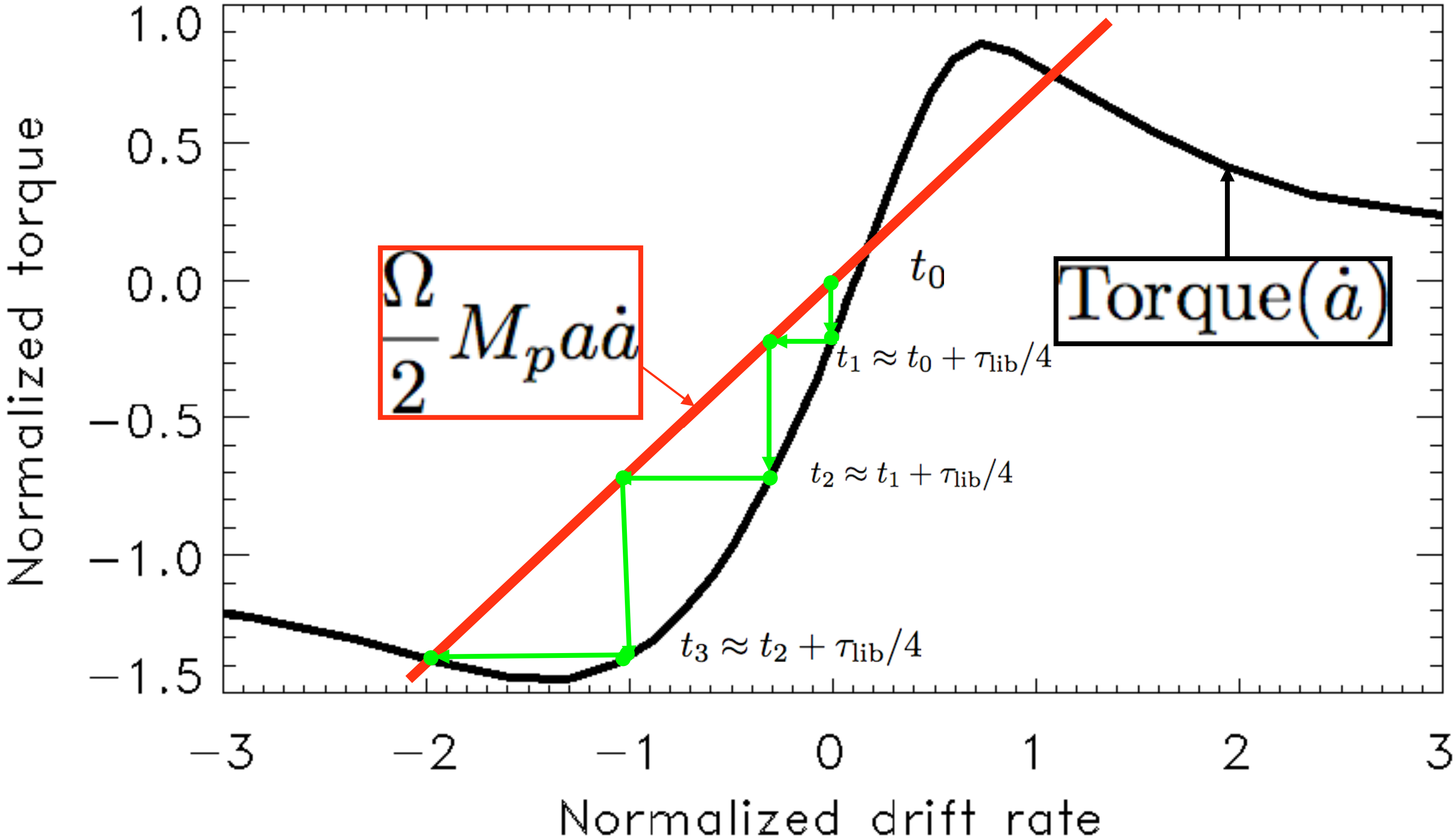
Masset & Papaloizou (2003)

Maximal type III drift rate

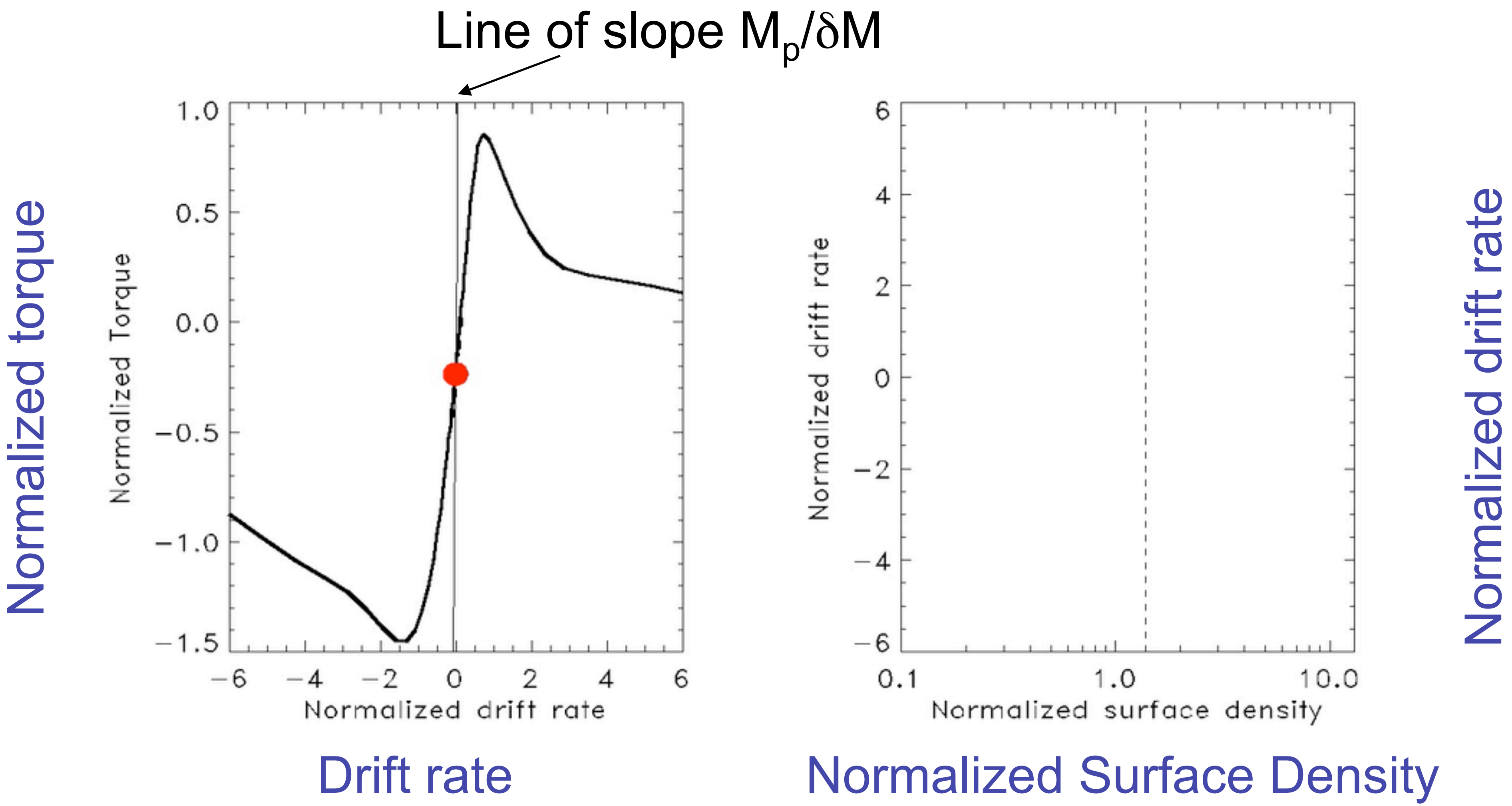


$$\dot{a}_c = \frac{3}{4}\frac{\Omega x_s^2}{\pi a}$$

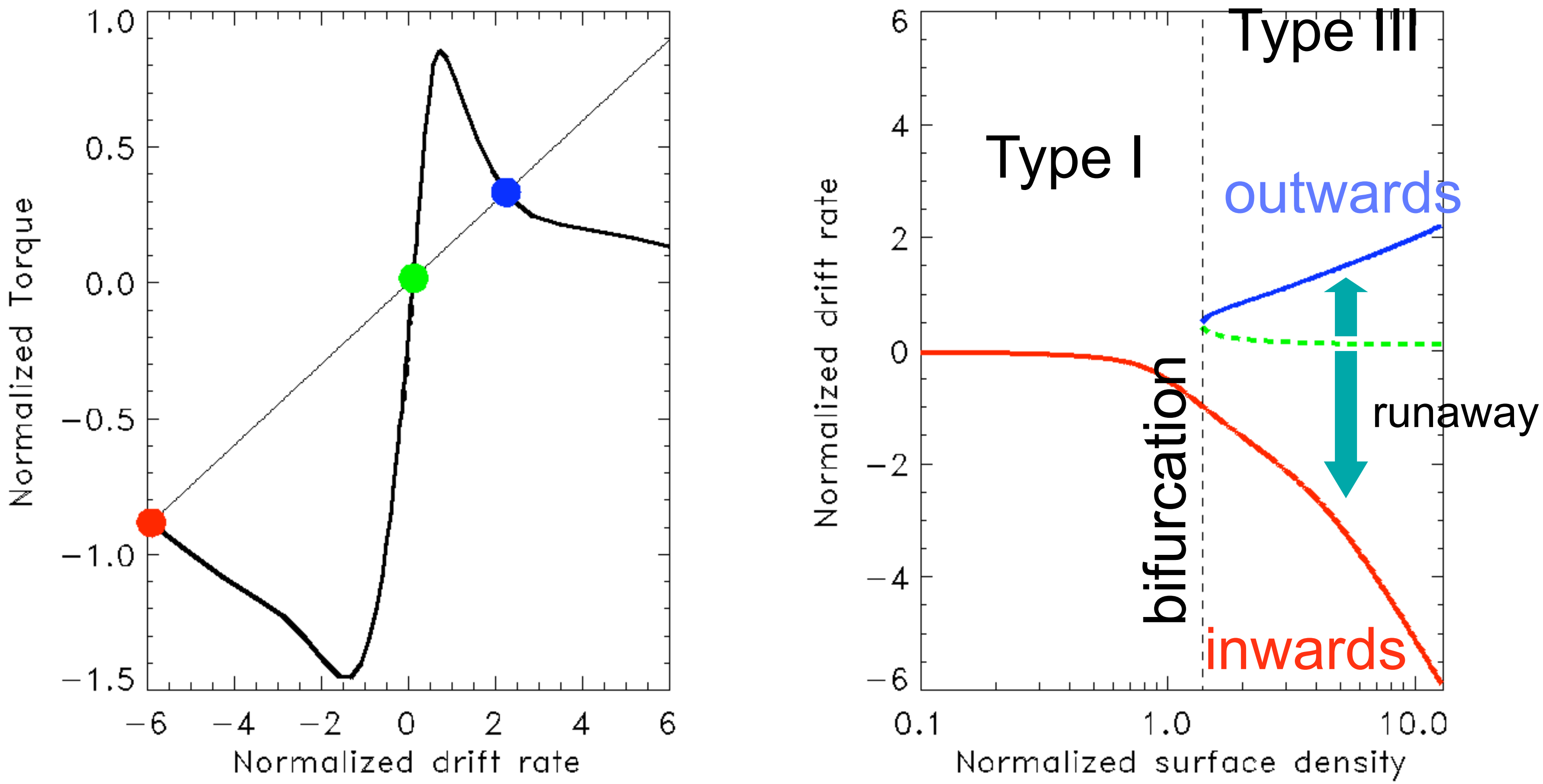
Maximal type III drift rate



Transition to type III migration

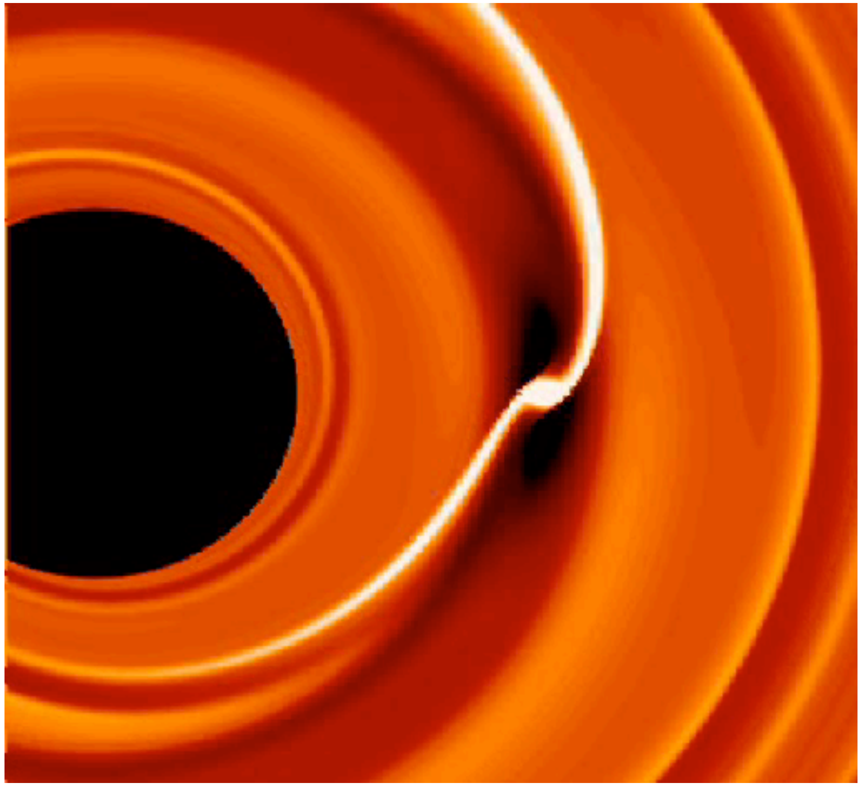


Transition to type III migration



Type III migration is inwards or outwards: potentially a rich variety of outcomes.

Type III migrating Saturn

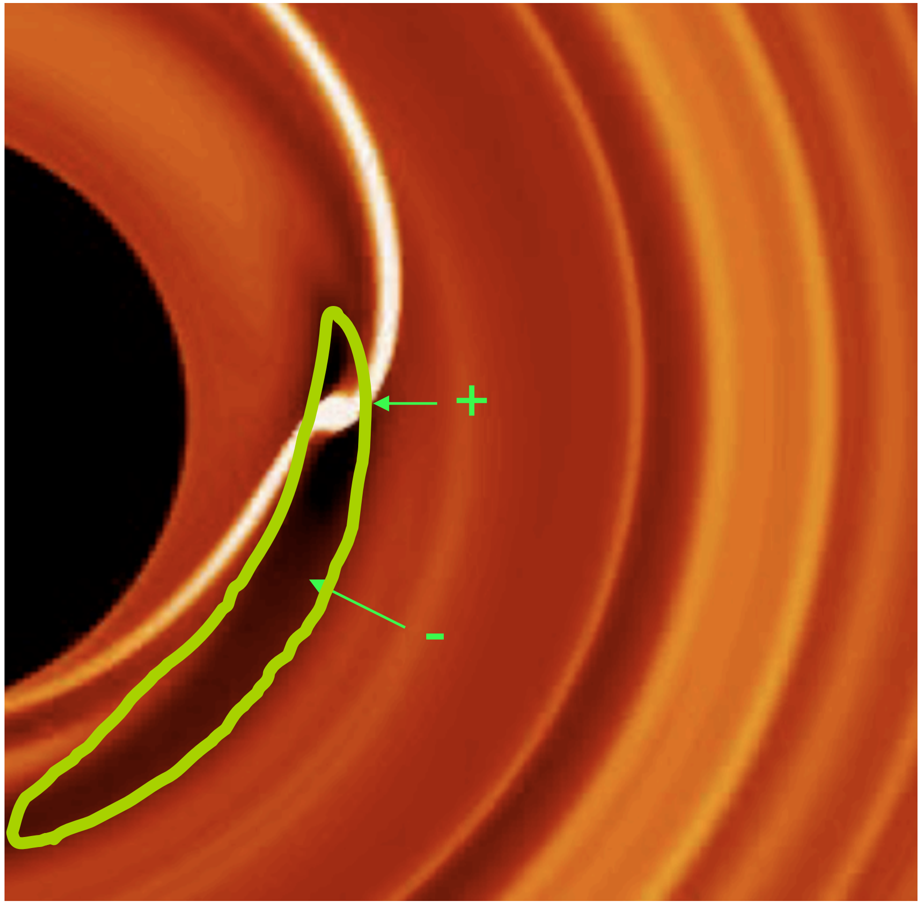


Type III migrating Saturn

What migrates has an « effective mass » M_p - CMD (*Coorbital Mass Deficit)*

Migration is type III when CMD > M_p

Masset & Papaloizou (2003)



Migration of two giant planets

Example of a « Jupiter-Saturn » system embedded in a nebula of uniform surface density.

What is the time evolution of such a system ?

Migration of two giant planets

Jupiter adopts a slow, type II migration.

Saturn migrates much faster (actually type III).

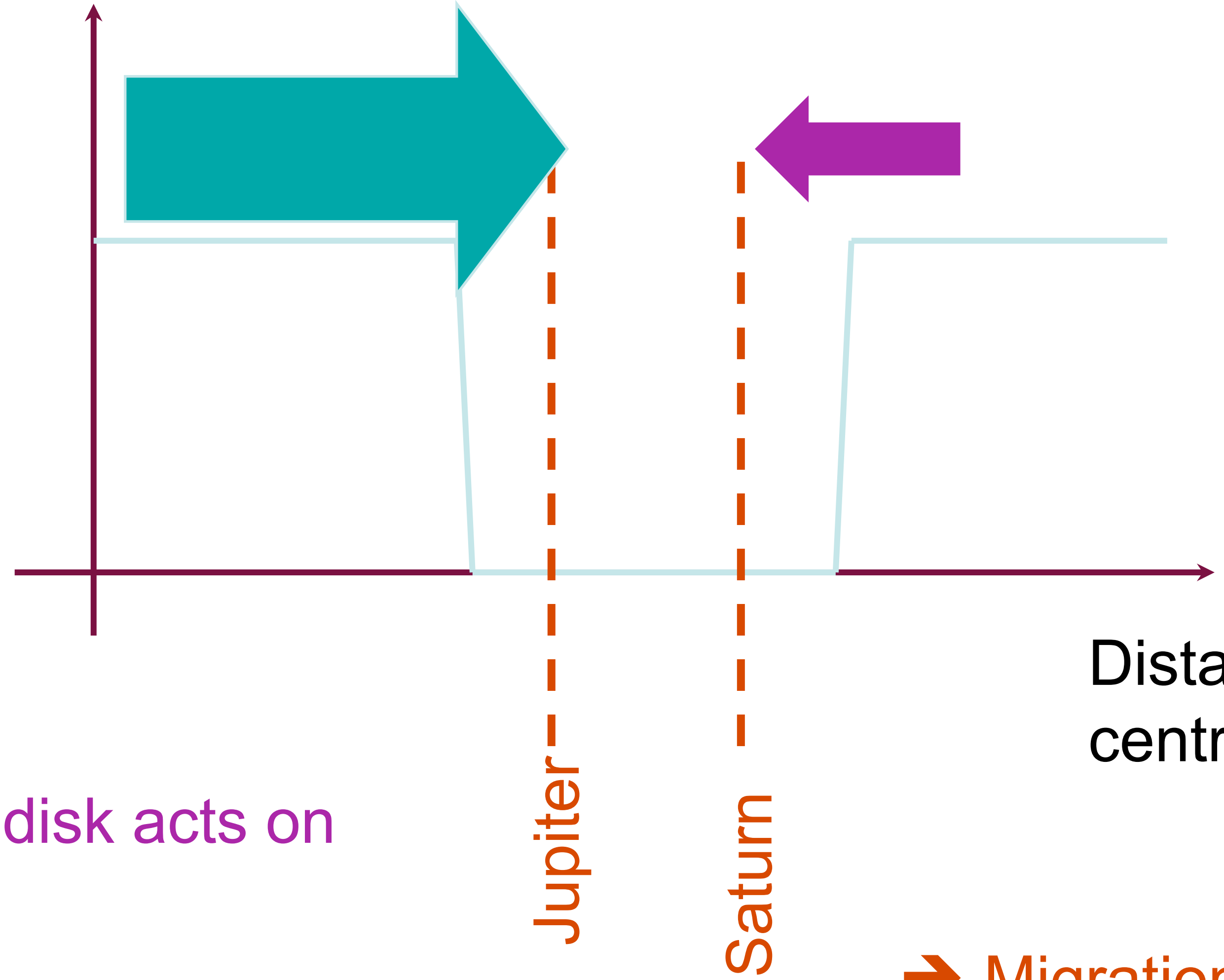
Saturn therefore catches Jupiter up.

It get locks on a mean motion resonance with Jupiter.

The gaps of both objects overlap and the two planets therefore share a wide, common gap.

What is the evolution of this system of planets locked in MMR and possessing a common gap ?

Migration of two giant planets



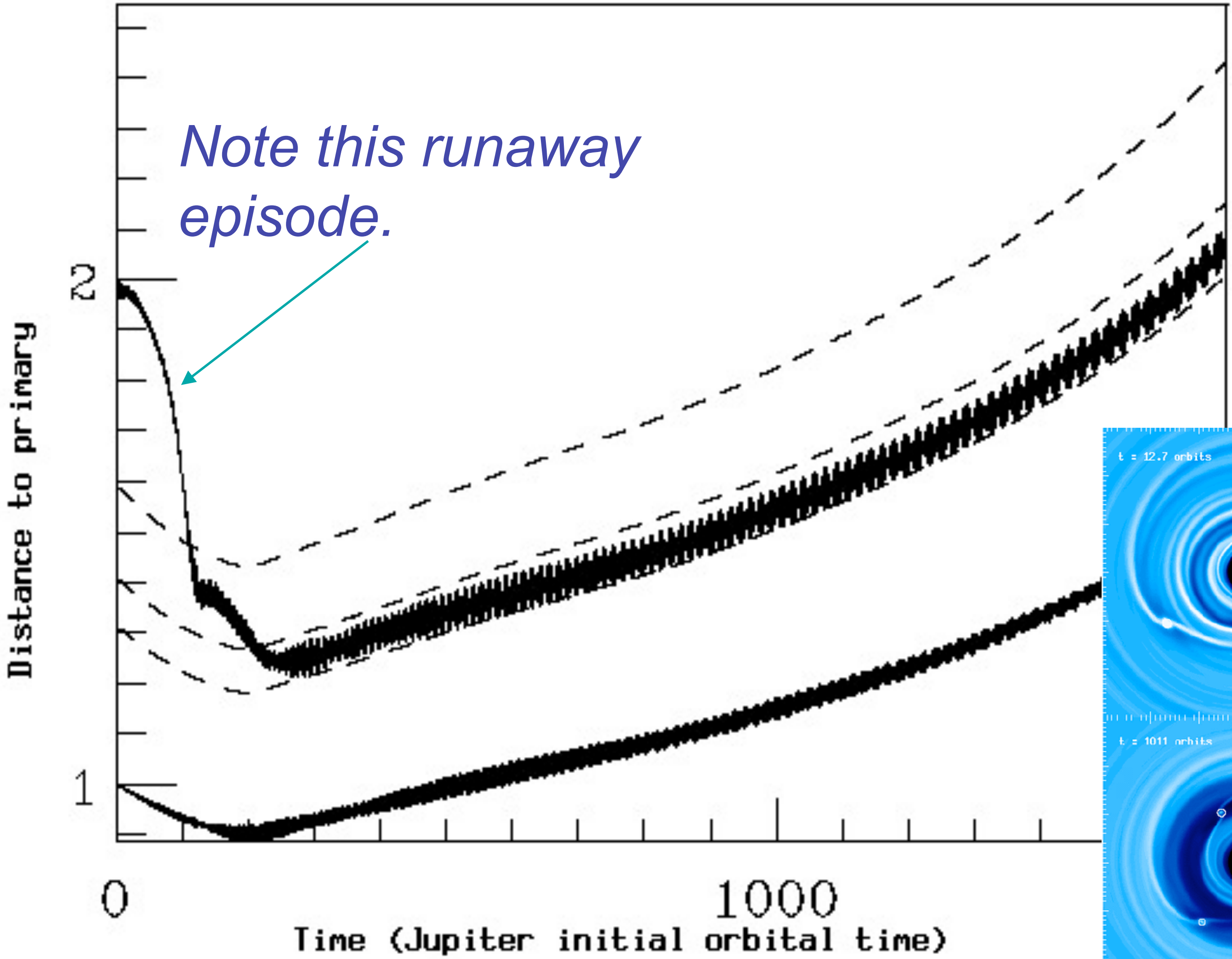
The outer disk acts on Saturn

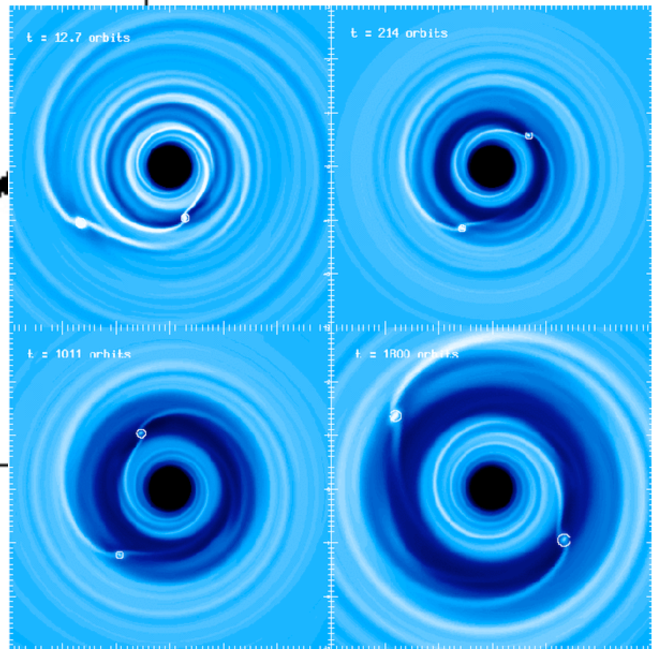
The inner disk acts on Jupiter

➔ Migration should occur outwards

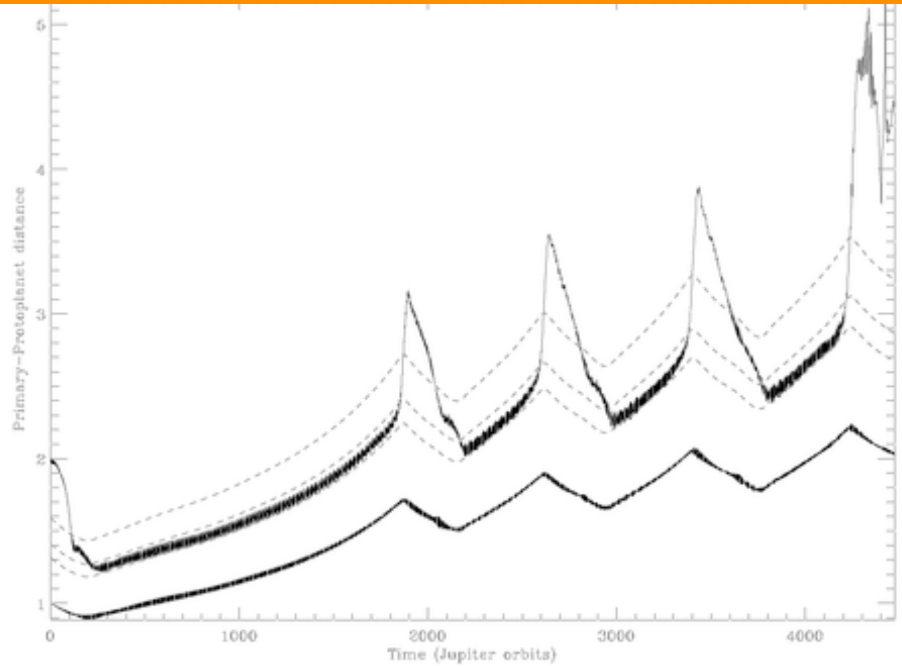
Migration of two giant planets

Masset & Snellgrove (2001)



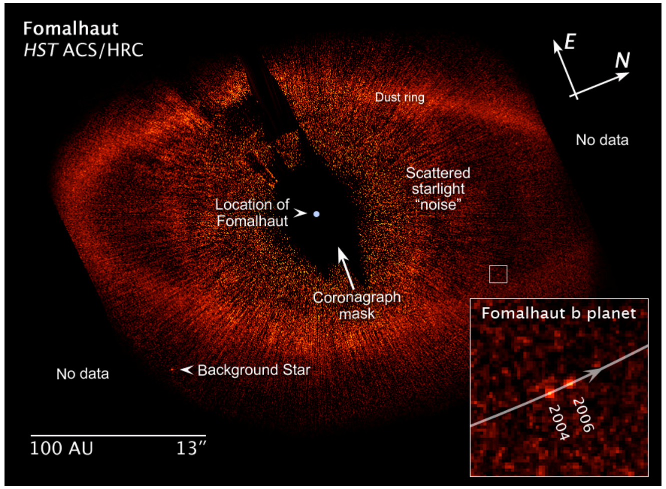


Long term behavior



Sequence of outwards and inwards type III.

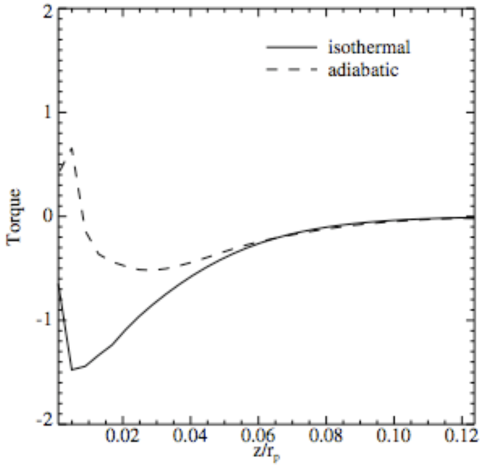
Slight outwards drift on the average.

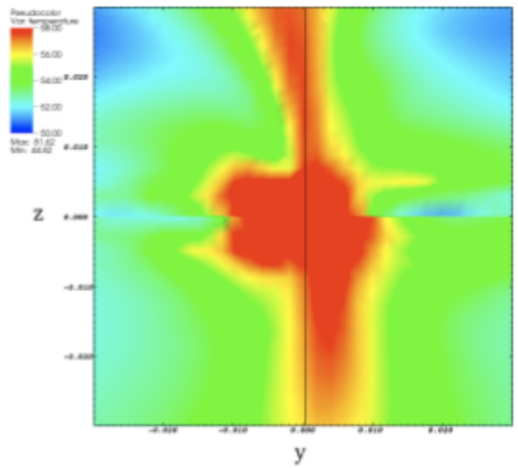


This mechanism has recently been suggested to account for the presence of Fom b, detected by Kalas et al. (2008) at 115 AU from its central star (Crida et al. 2009)

Corotation torque in non-barotropic disks

Paardekooper & Mellema (2006) find with nested grid 3D calculations and radiative transfer that a low-mass planet can actually *migrate outwards,* if the disk is sufficiently opaque, under the action of the CR torque !

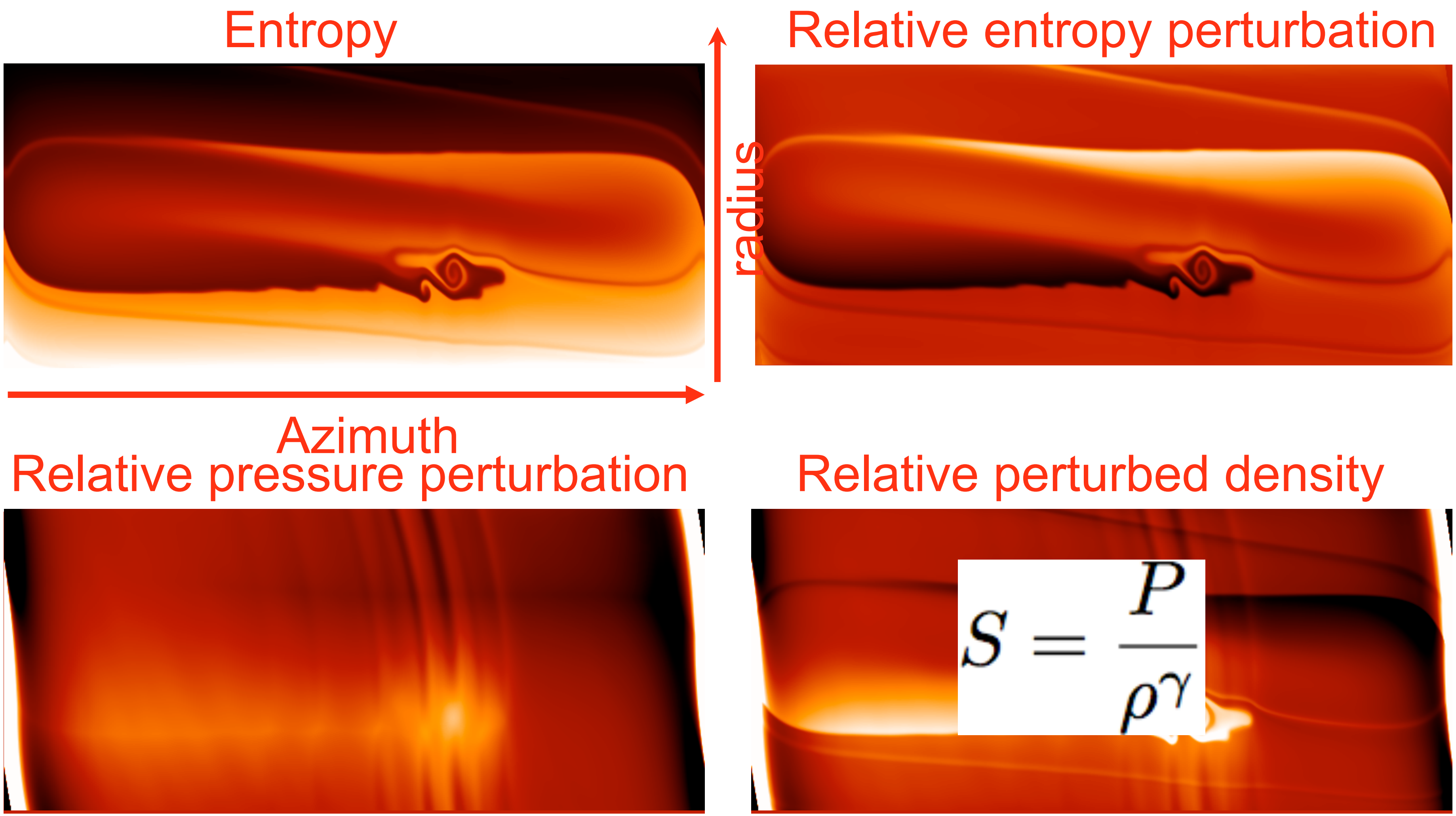




In order to understand these results ➔ 2D adiabatic simulations

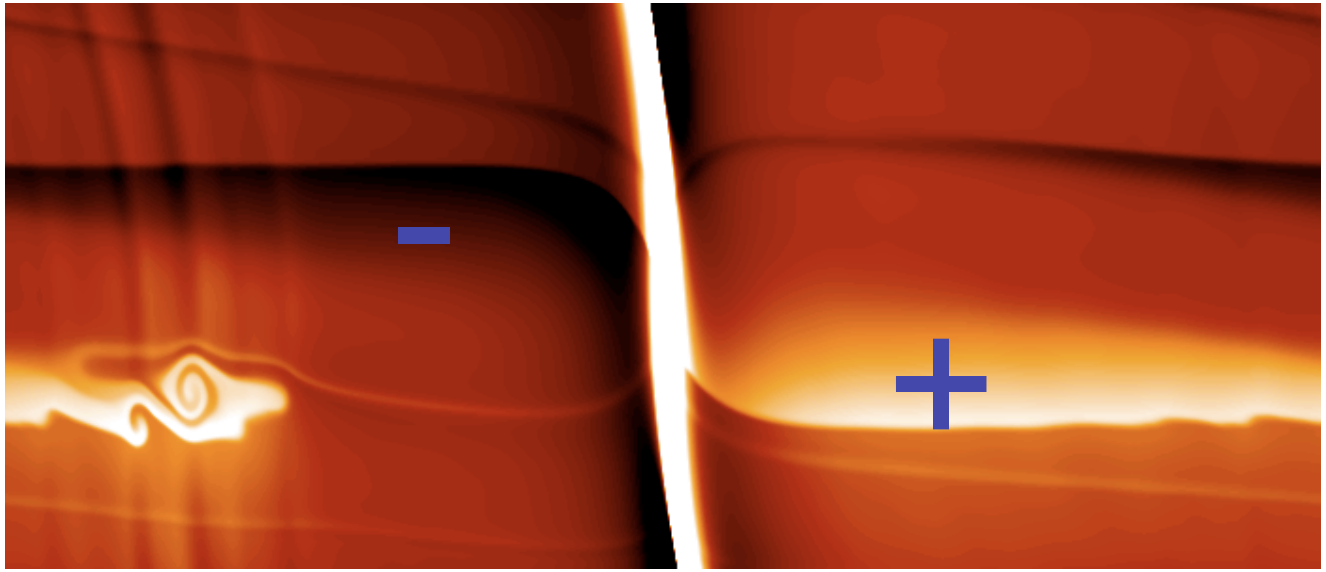
In an adiabatic flow, the entropy is conserved along a fluid element path (provided no irreversibility is introduced). This is true for the coorbital flow of a low mass planet.

Corotation torque in a 2D adiabatic disk

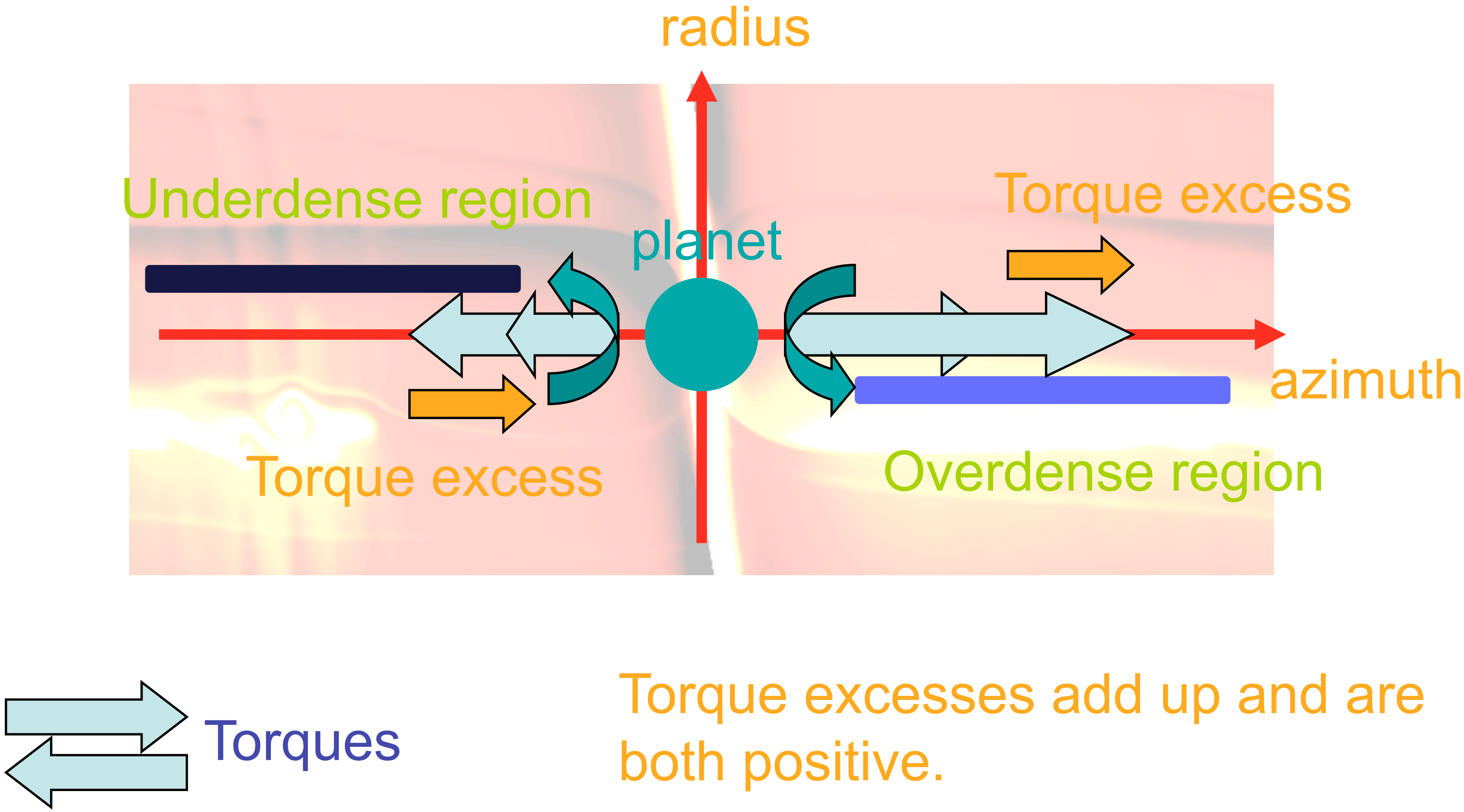


$$S = \frac{P}{\rho^\gamma}$$

Impact on corotation torque



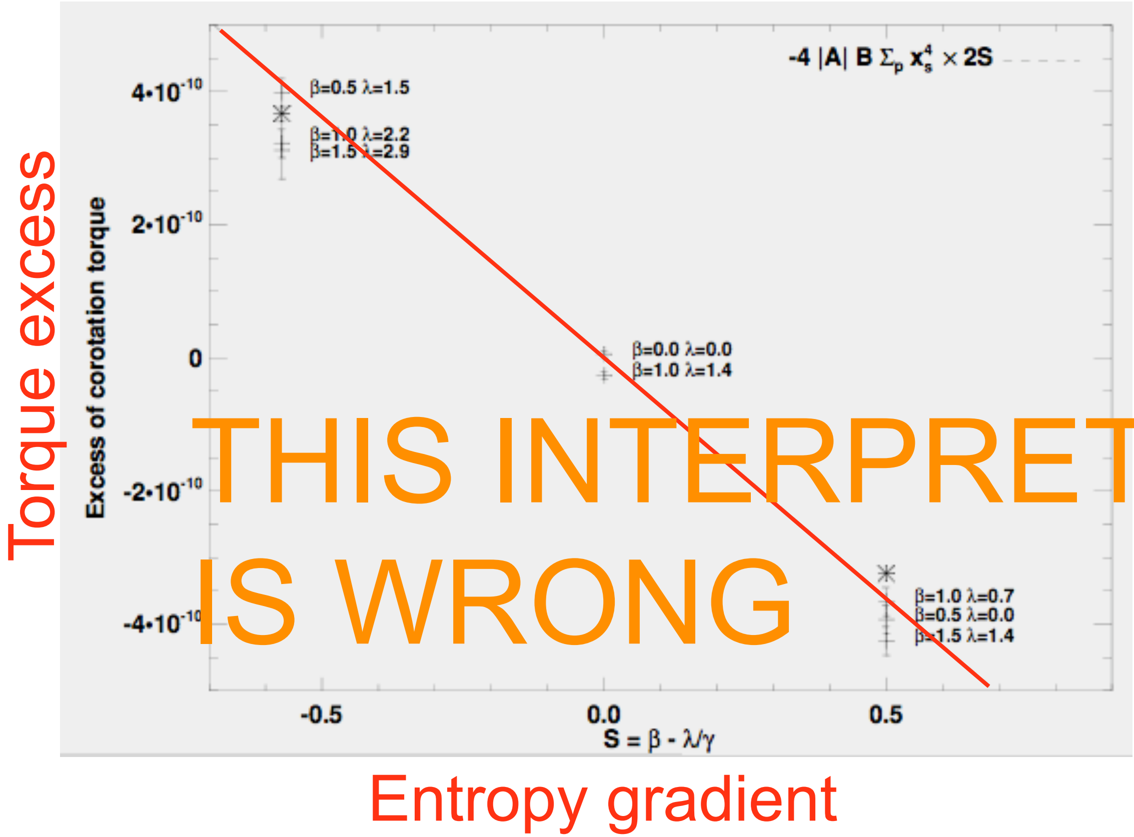
Impact on corotation torque



Torque excesses add up and are both positive.

CR torque in a radiatively inefficient disk

The torque excess therefore scales with the entropy gradient.

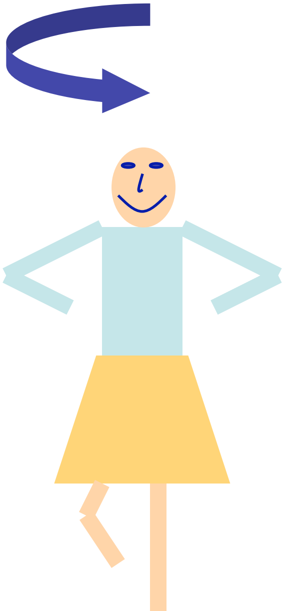


The torque excess is measured by comparing the results to a calculation with an isothermal disk.

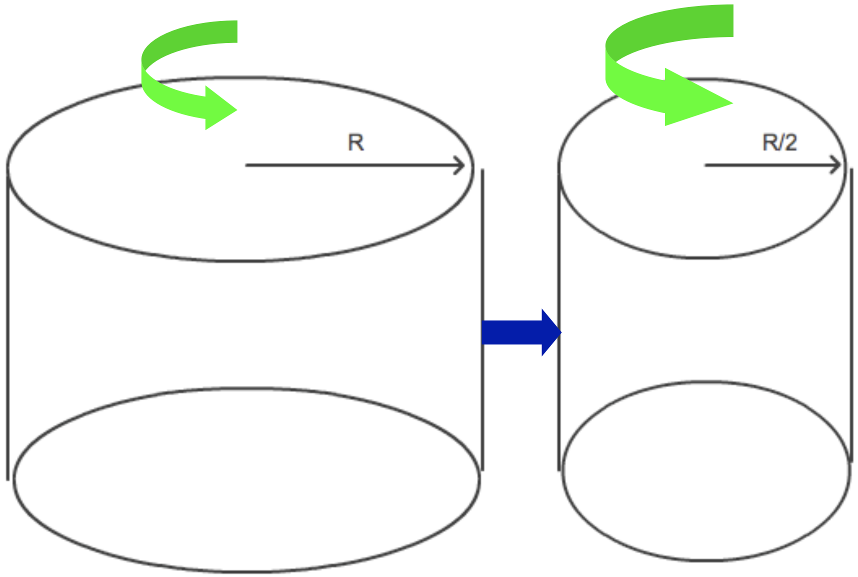
THIS INTERPRETATION IS WRONG

This excess can be sufficient to revert migration

Vortensity advection



rotation speeds up when the dancer retracts arms or legs



ω, Σ

4ω

4Σ

Vortensity is conserved

Vortensity conservation for 2D flows

The fluid elements have their vortensity conserved if the force acting on them is curl free.

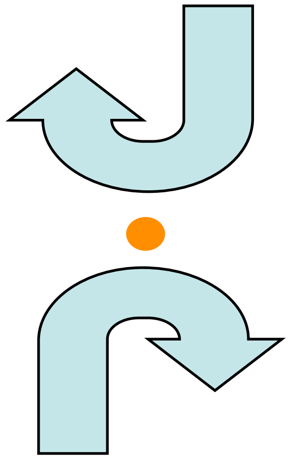
⇒ The fluid must be inviscid
⇒ The fluid must be barotropic: $P(\Sigma)$

$$\frac{D\vec{v}}{Dt} = -\frac{\vec{\nabla} P}{\Sigma} - \vec{\nabla}\Phi$$

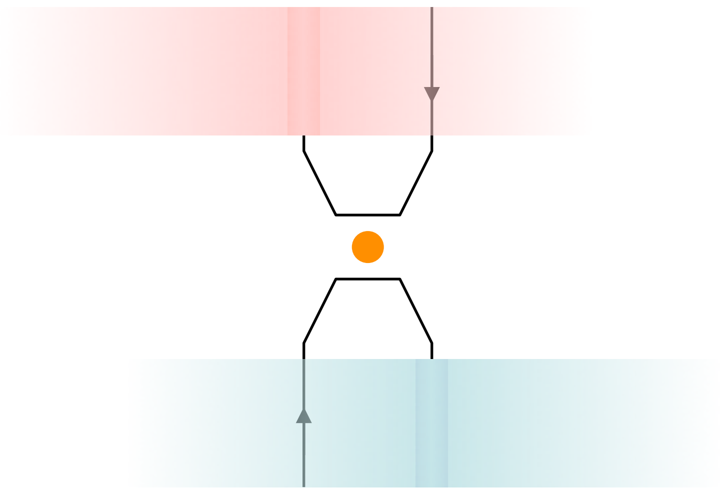
If the fluid is barotropic, then:

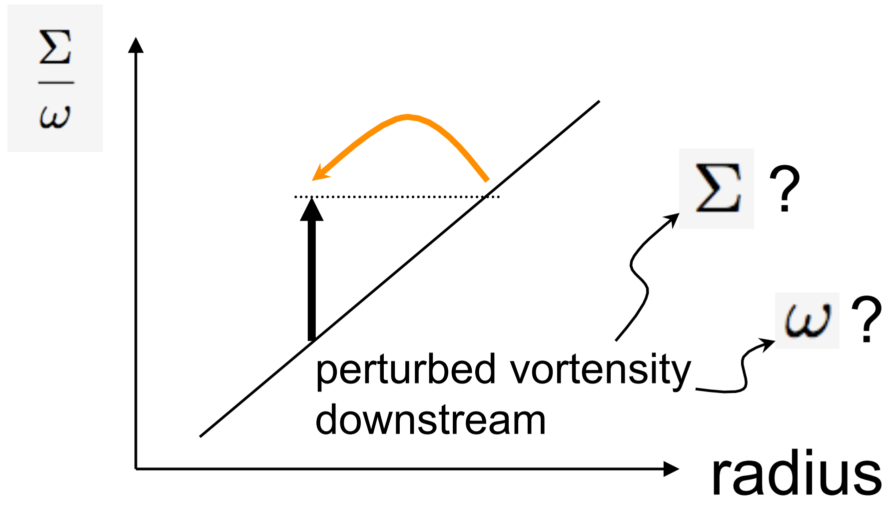
$$-\frac{\vec{\nabla} P}{\Sigma} = -\vec{\nabla} H$$ where $$H = \int \frac{dP}{\Sigma}$$ is the enthalpy

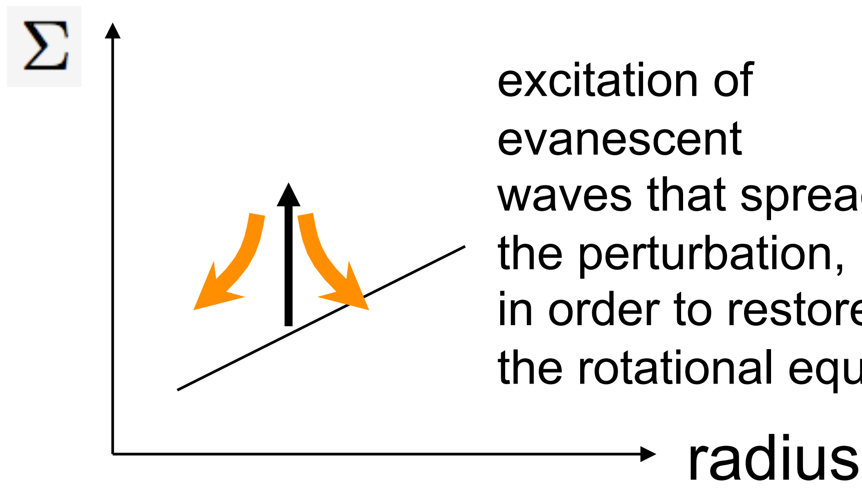
Back to isothermal (*ie* barotropic) disks



Vortensity is conserved along a U-turn

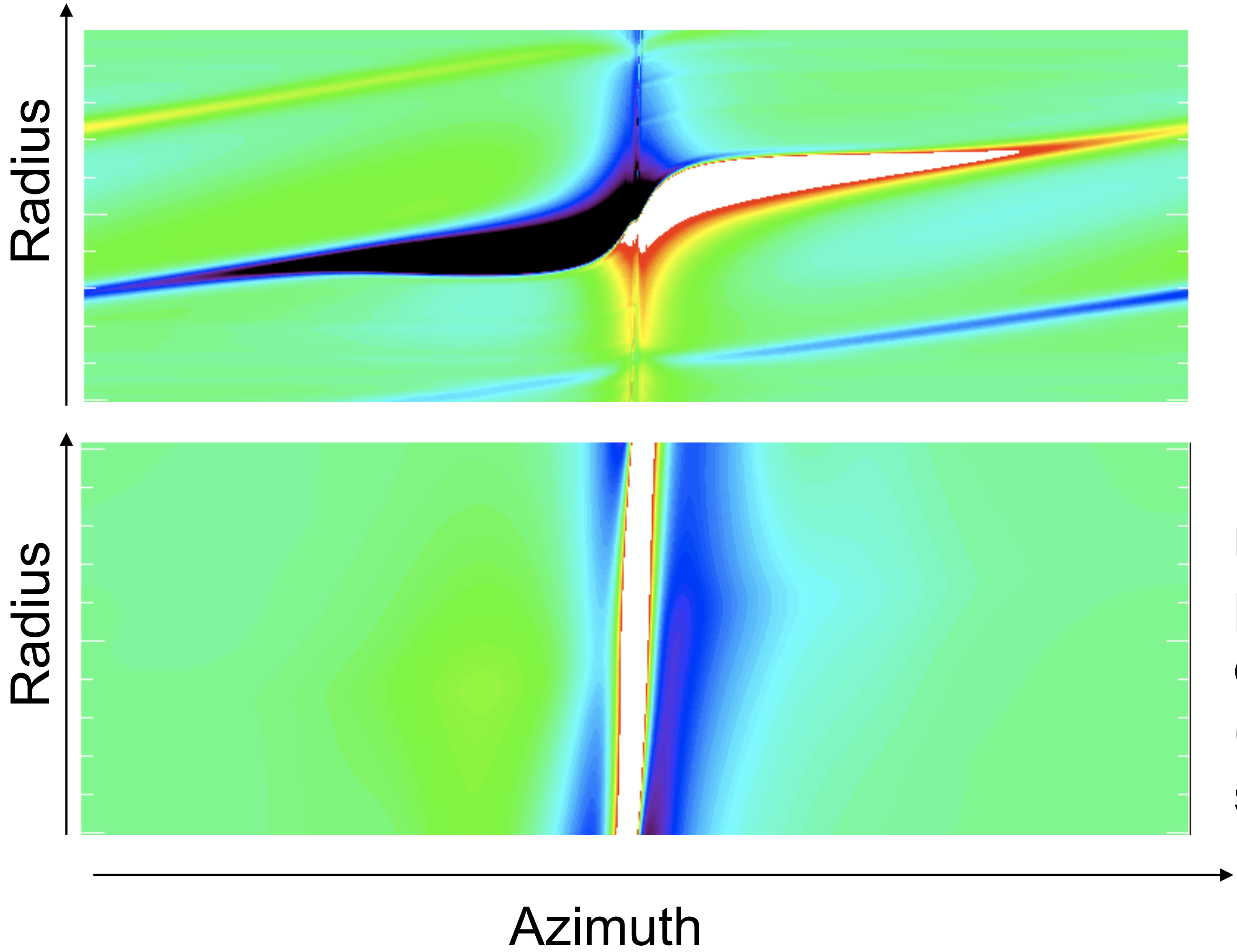






excitation of evanescent waves that spread the perturbation, in order to restore the rotational equilibrium

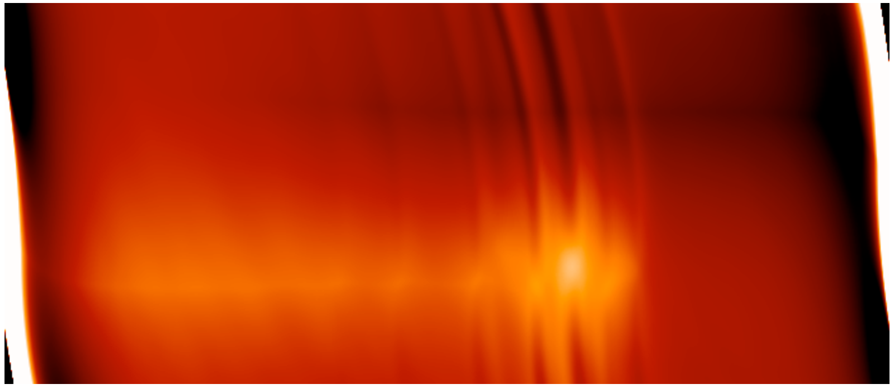
Radial spread of density disturbance



relative perturbed vortensity

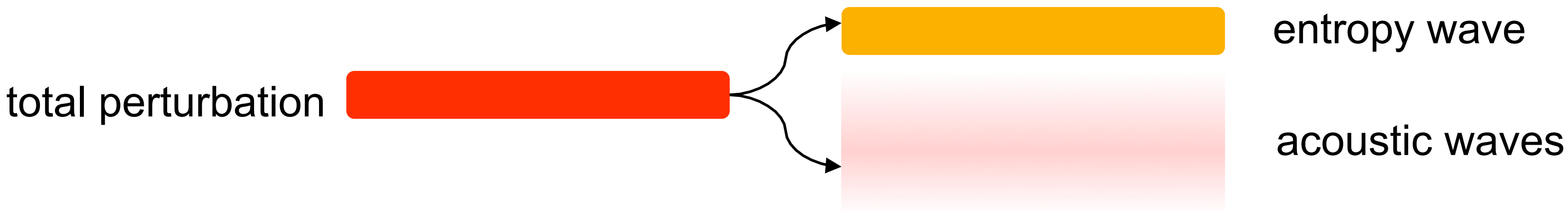
relative perturbed density (same color scale)

Baroclinic disk



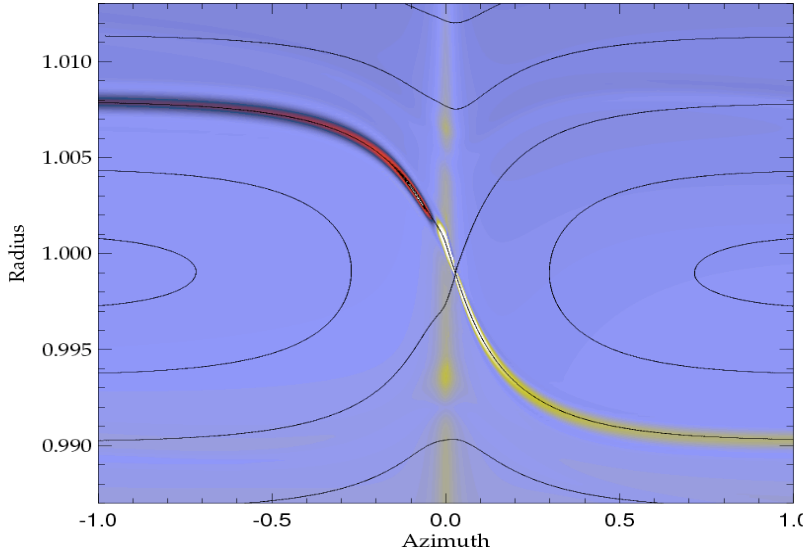
Pressure disturbance: radially spread, but plays a role like in an isothermal disk. This has been overlooked so far.

General picture: vortensity almost conserved everywhere. The perturbed vortensity downstream of the flow triggers a disturbance which projects onto acoustic waves and onto an entropy wave, but the lineic mass of the disturbance scales with the vortensity gradient, as always…

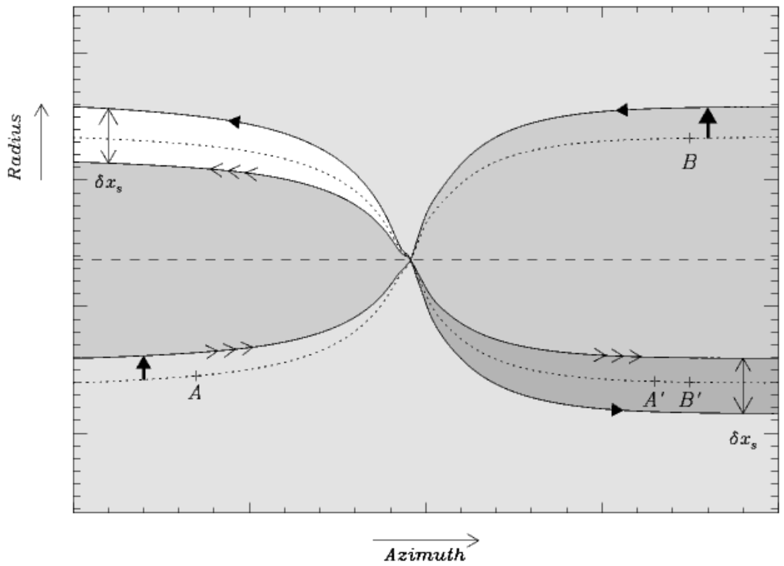


SO ?

Downstream singular vortensity



Vortensity is created at the separatrix, downstream of the flow. Scales with the entropy gradient.



In steady state, can be interpreted in terms of an asymmetry of the horseshoe region.

Very efficient. Associated perturbed density rather discreet…

Saturation of entropy related torque

The origin of the entropy related torque is now well understood.

This allows to proceed towards a study of the saturation of this torque component.

Entropy related torque function of thermal diffusion and viscosity

Expression very useful for population synthesis models

Conclusions

Theories of planetary migration have considerably evolved over the last 10 years.

The coorbital region has proven to yield a rich variety of new mechanisms.

The lingering problem of Type I migration is about to be solved.

Planetary migration is entering a more quantitative phase, and should take into account more physical processes of the disk.