Planetary migration: basics, recent results and new challenges

Clément Baruteau

University of California at Santa Cruz

ISIMA, UCSC, Aug. 05th 2010

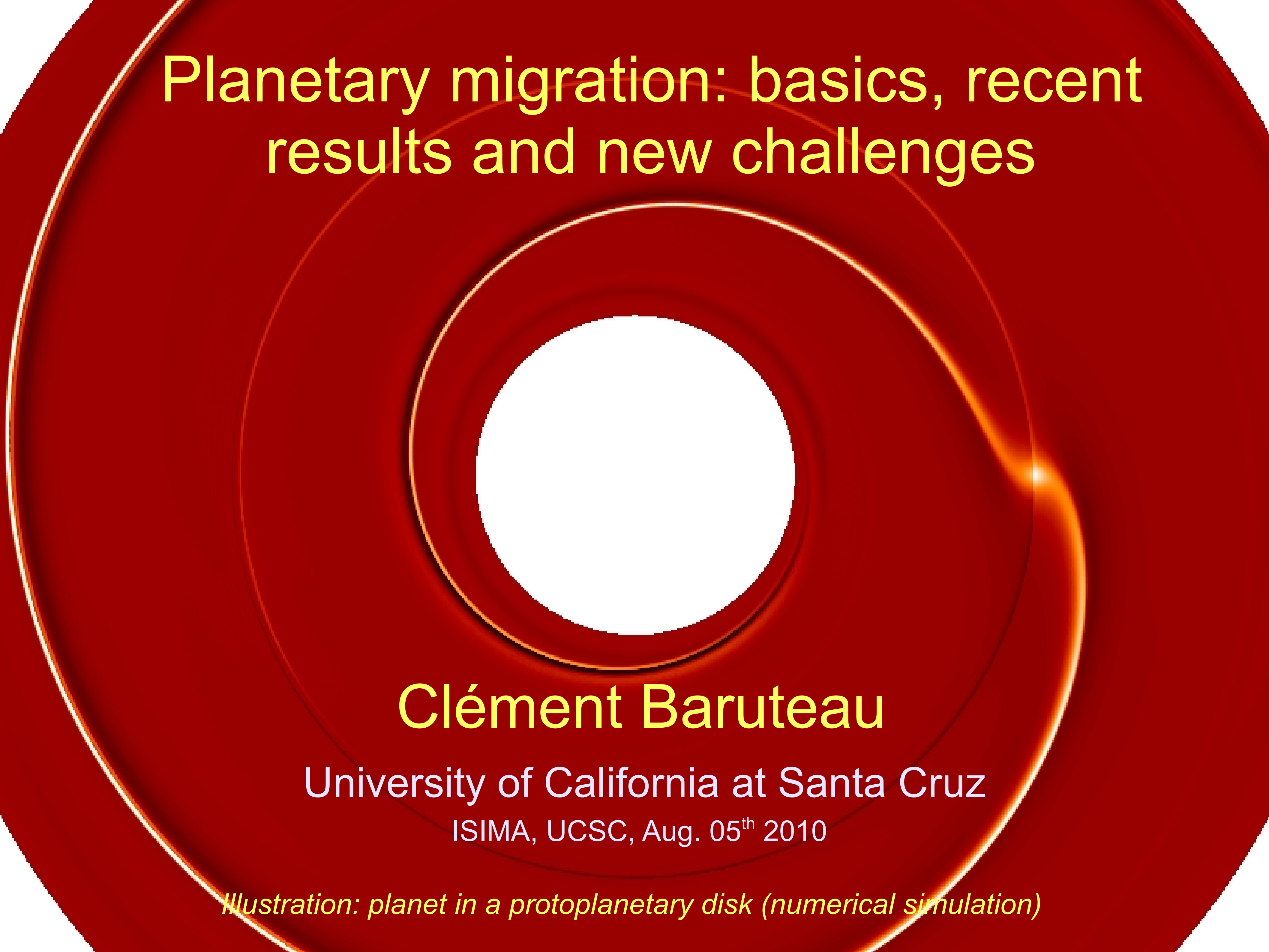
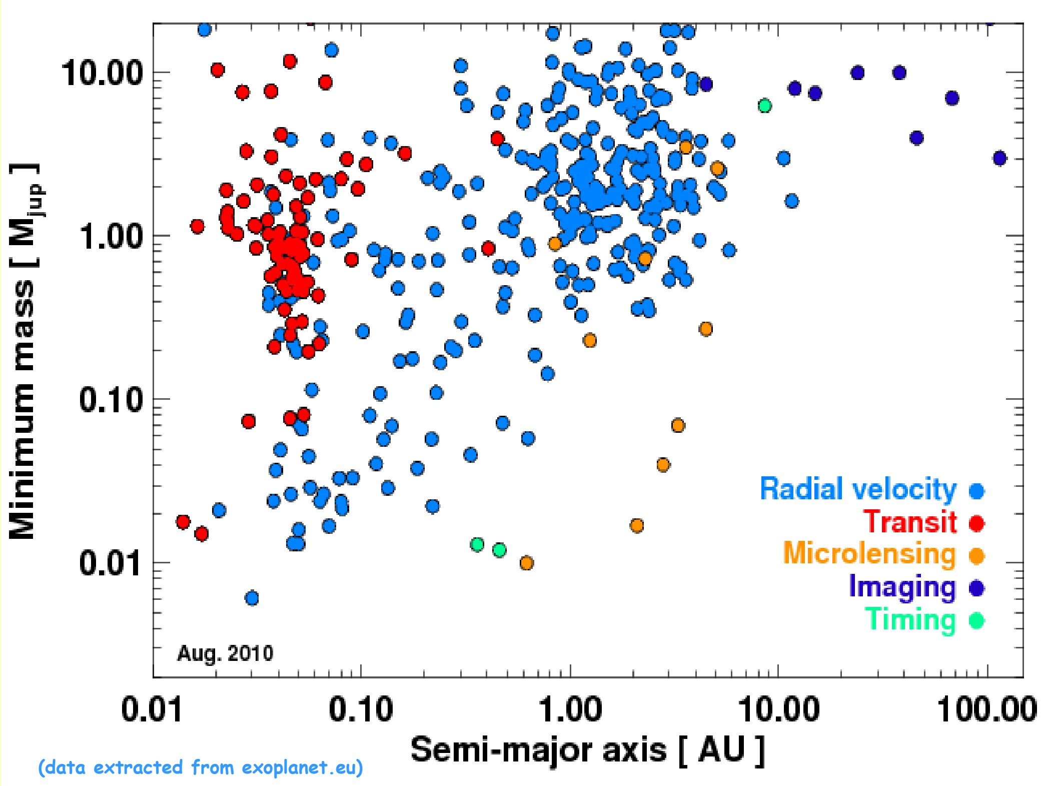
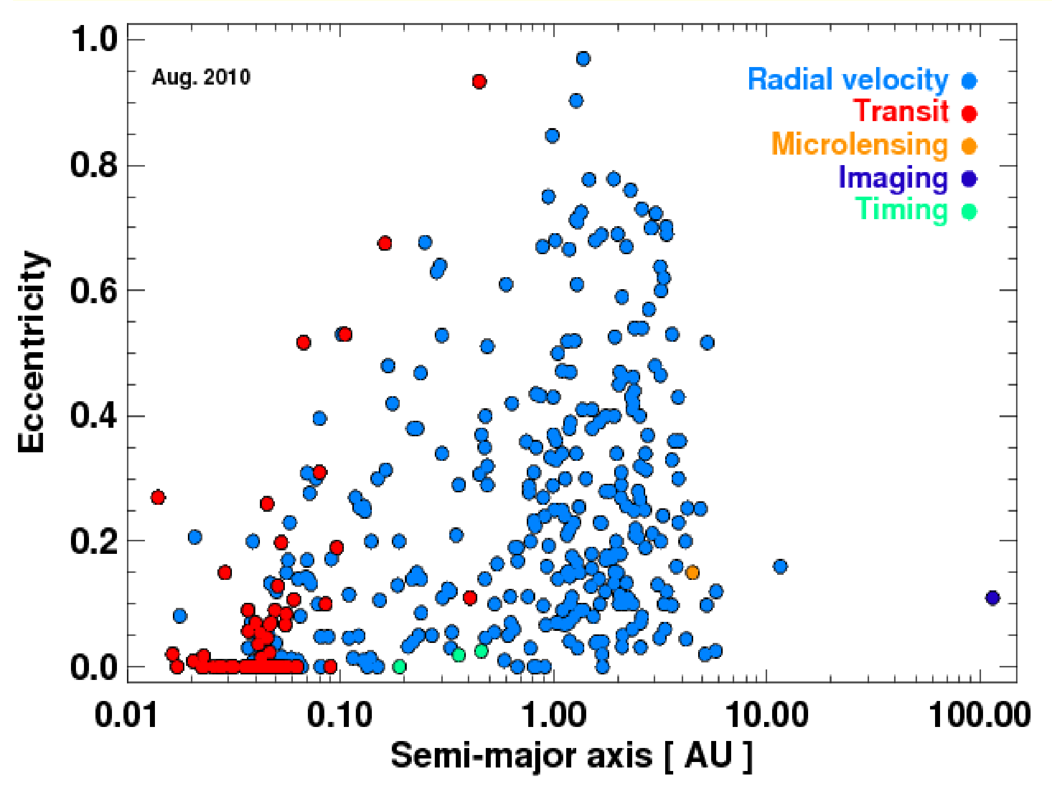


Illustration: planet in a protoplanetary disk (numerical simulation)

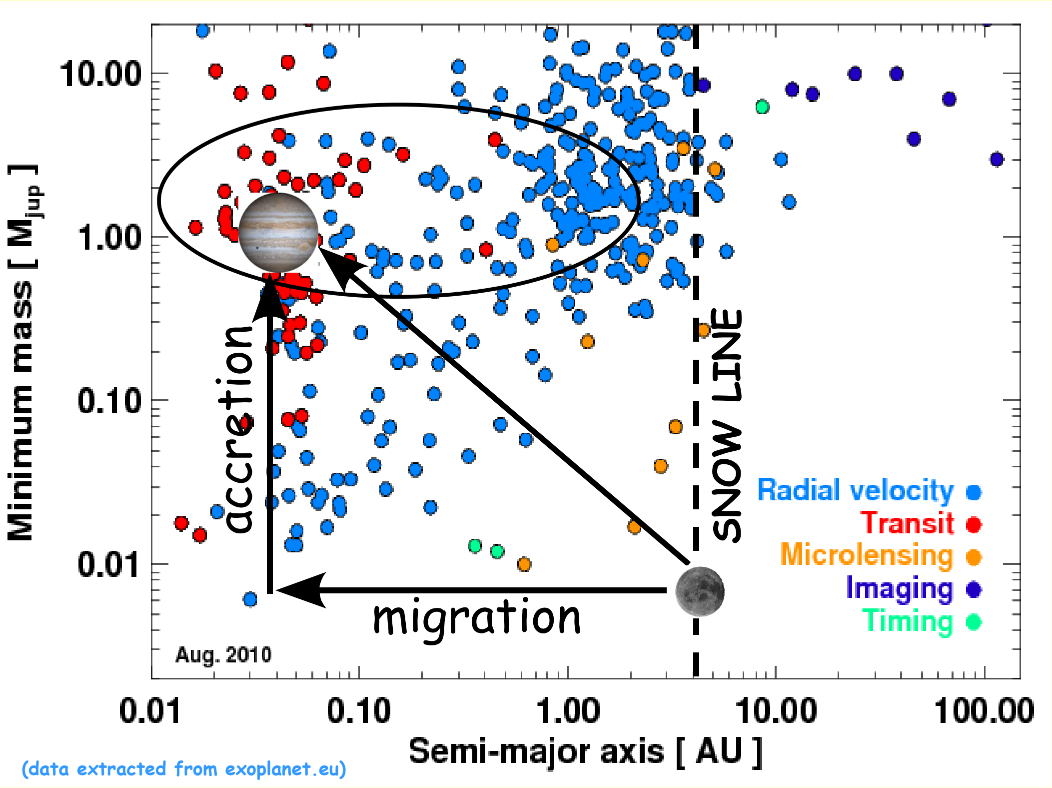
Exoplanets statistical properties

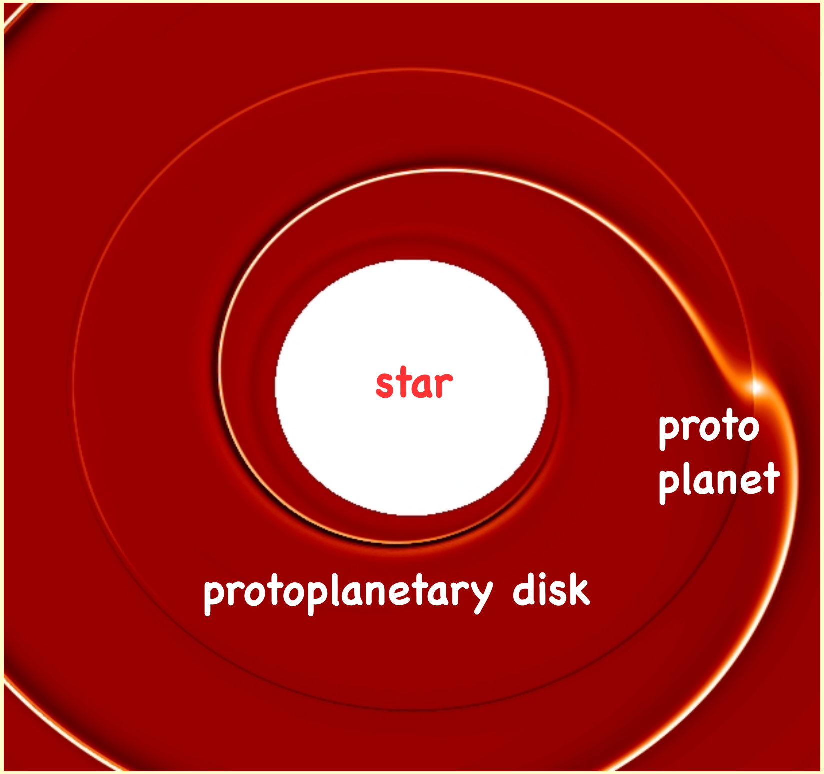
473 exoplanets to date





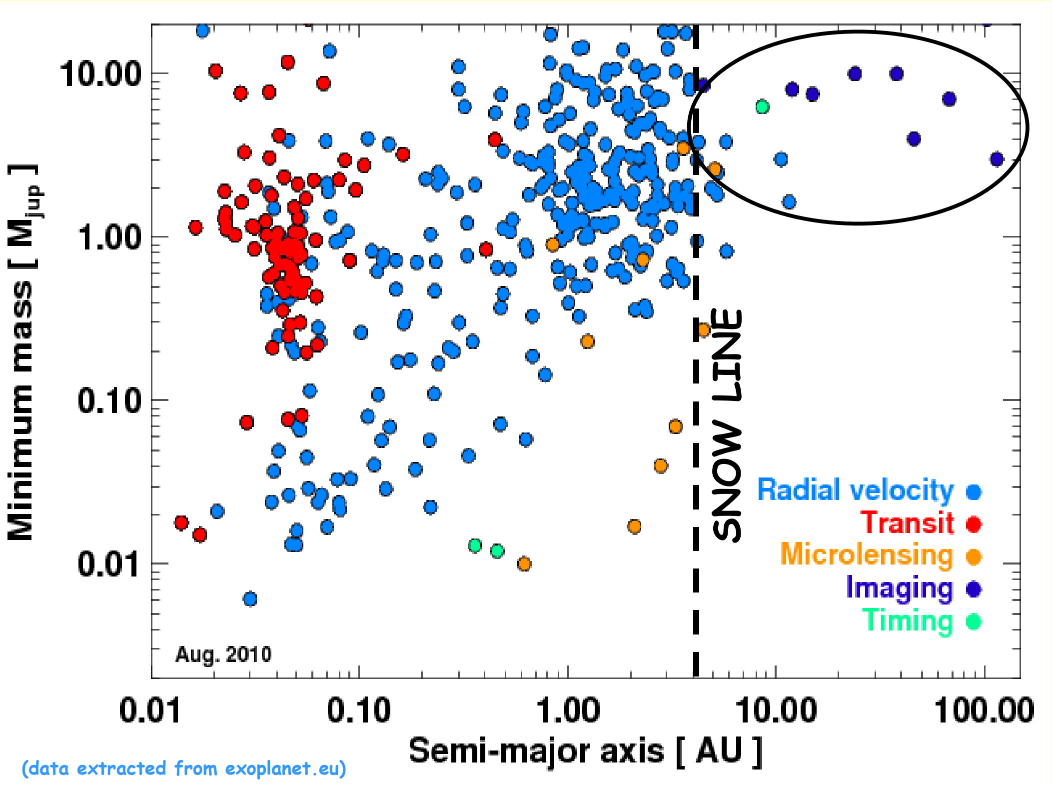
Connection with planetary formation

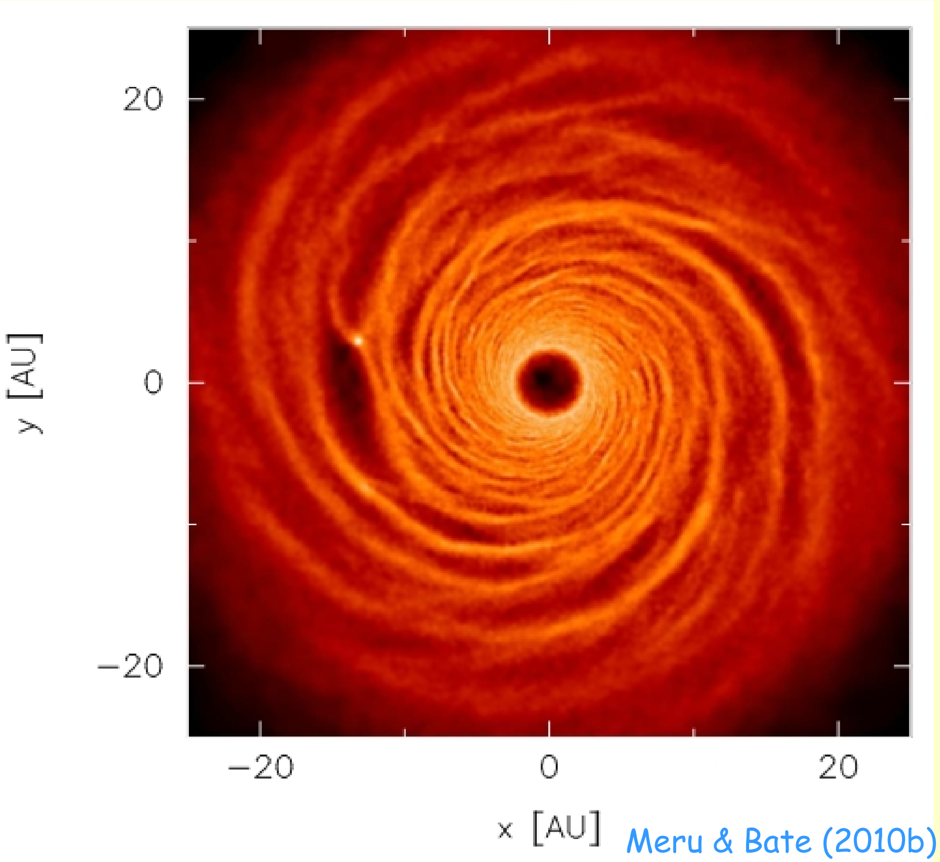




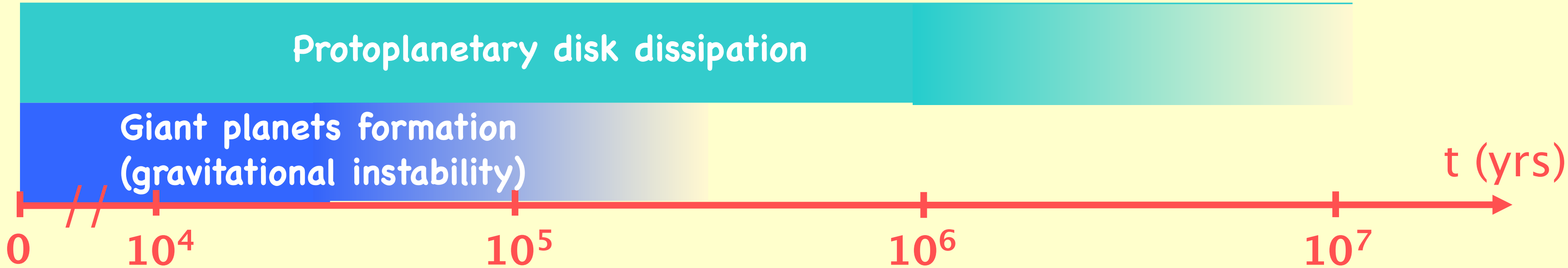
Hot Jupiters should have formed further out and migrated inward

Connection with planetary formation

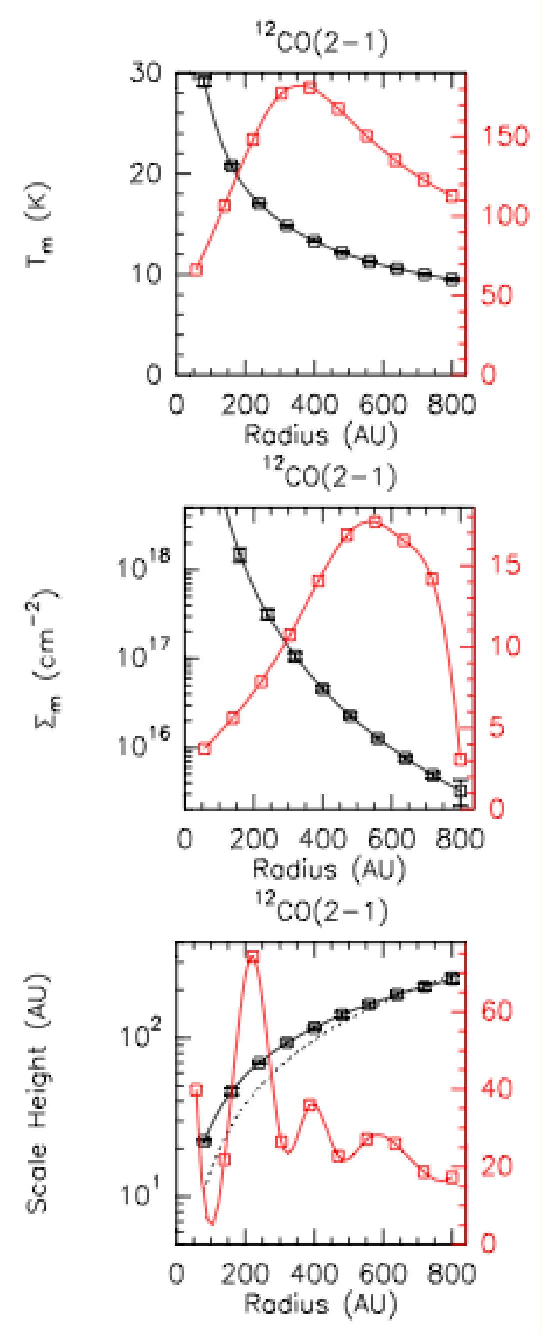




Possible fast formation far through gravitational instability, but what about migration?



What do we know about protoplanetary disks?



Piétu et al. (2007)

Millimeter interferometry (e.g. CO emission lines) gives insight into disk properties beyond ~ 50 AU, *a priori* far from regions of planet formation (1-10AU)

Surface density and **temperature** are modelled as power-law functions of radius, $\Sigma \sim r^{-1.5}$, $T \sim r^{-0.5}$

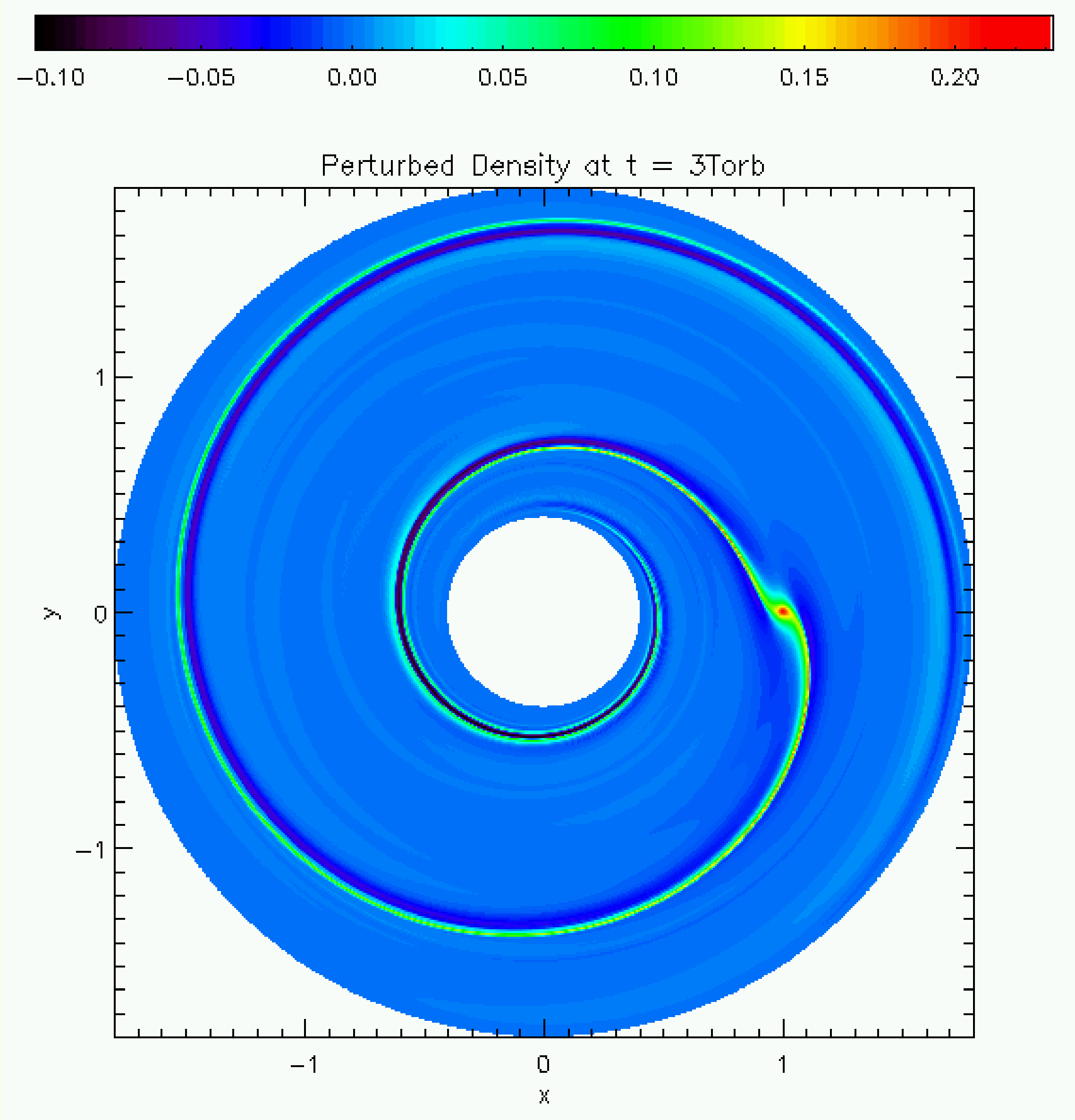
In (the inner) regions of planet formation, disks should be **optically thick**, and their self-gravity should be negligible

Disk turbulence in these regions? generally modelled by viscous diffusion.

Disk response to an embedded protoplanet

(see animation)

Disk response to an embedded protoplanet



The planet excites a one-armed spiral wake propagating both inwards and outwards.

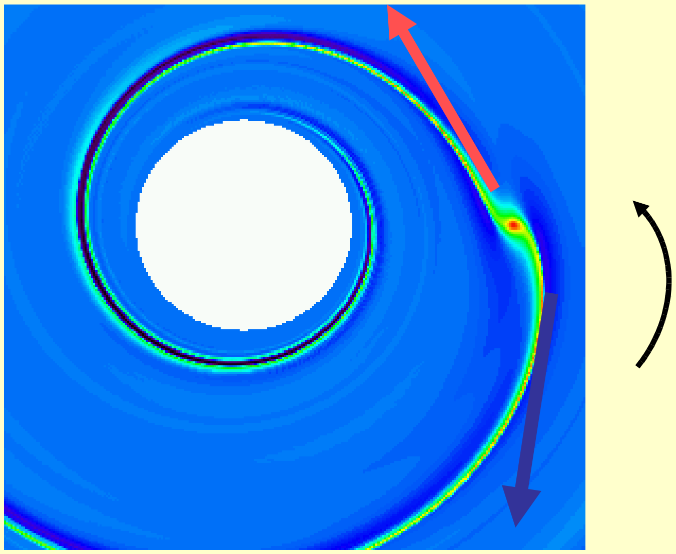
The gravitational force that the wake exerts onto the planet modifies the planet's semi-major axis, eccentricity and inclination.

Planetary migration

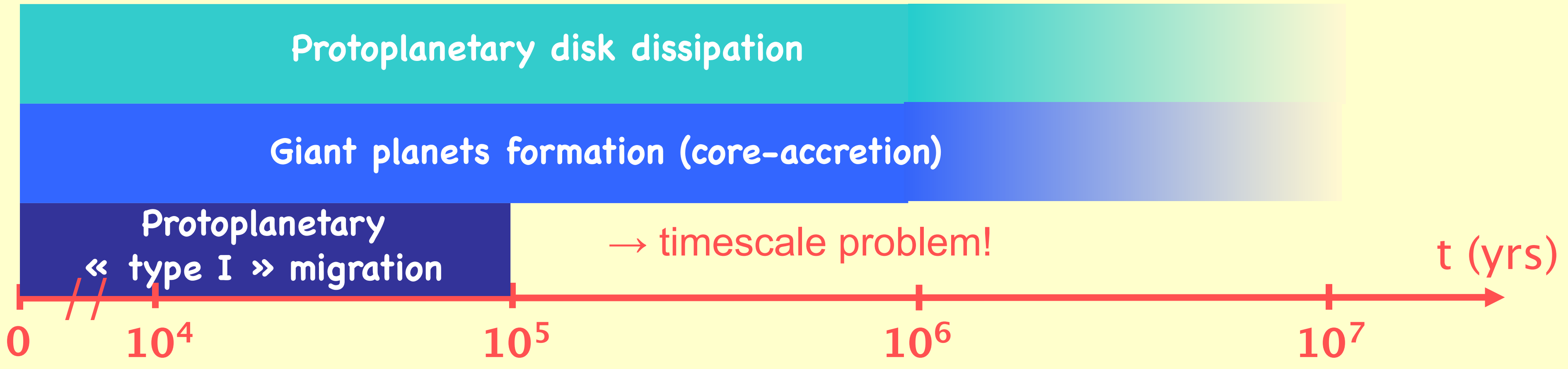
Disk response to an embedded protoplanet

The inner wake exerts a **positive torque** on the planet, and tends to impose an **outward migration**

The outer wake exerts a negative torque on the planet, and tends to impose an inward migration

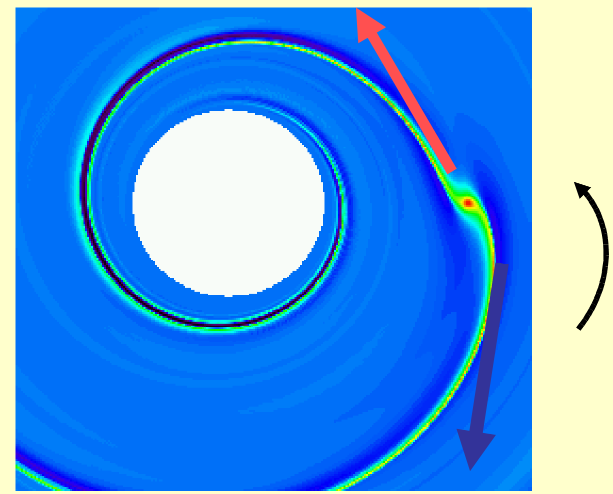


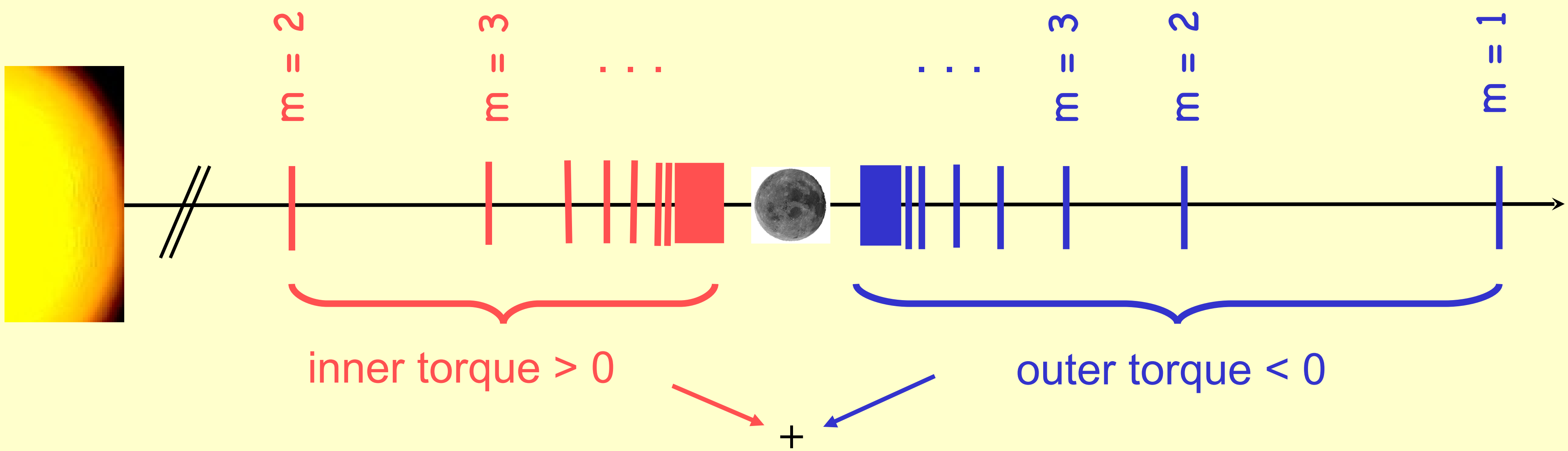
The sum of these two torques, called the differential Lindblad torque, is negative $\rightarrow$ inward migration (Ward 1986)



Differential Lindblad torque: resonances

Formalism of the **Lindblad Resonances**



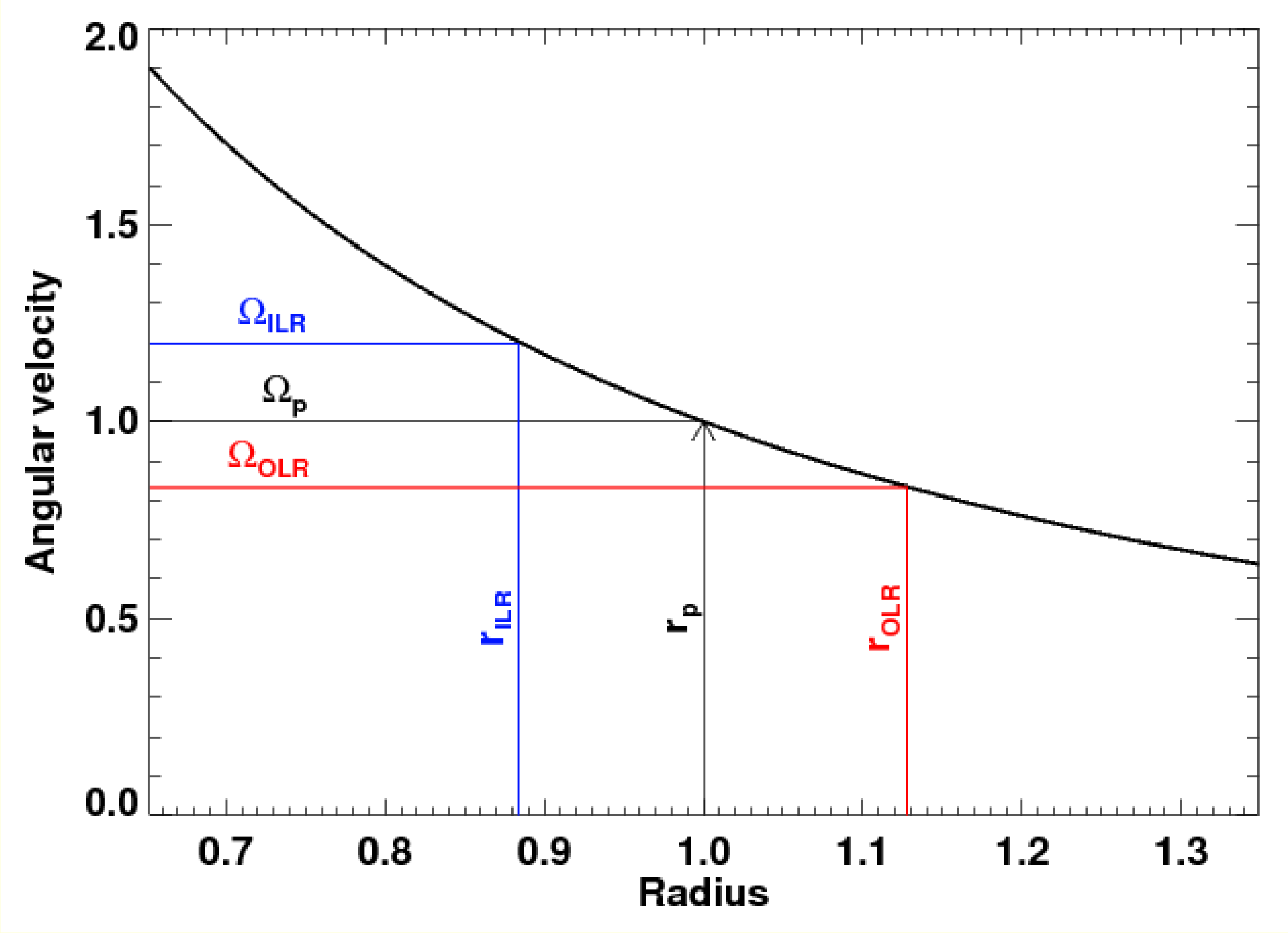


differential Lindblad torque < 0

(Ward 1986, Artymowicz 1993)

Differential Lindblad torque

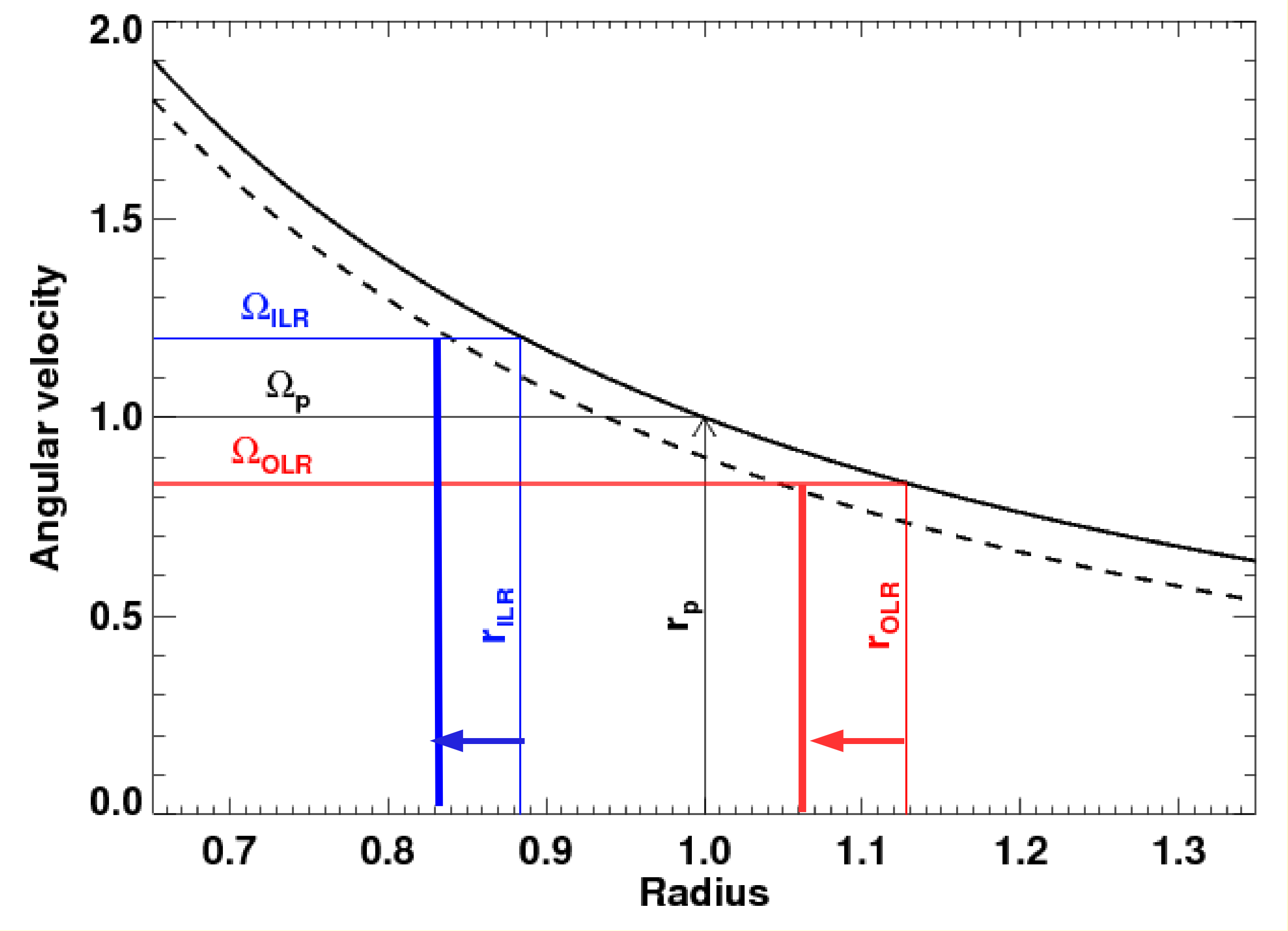
Can we reverse the sign of the Lindblad torque with a steeper surface density profile ?



Now assume a steeper surface density profile...

Differential Lindblad torque

Can we reverse the sign of the Lindblad torque
with a steeper surface density profile ?



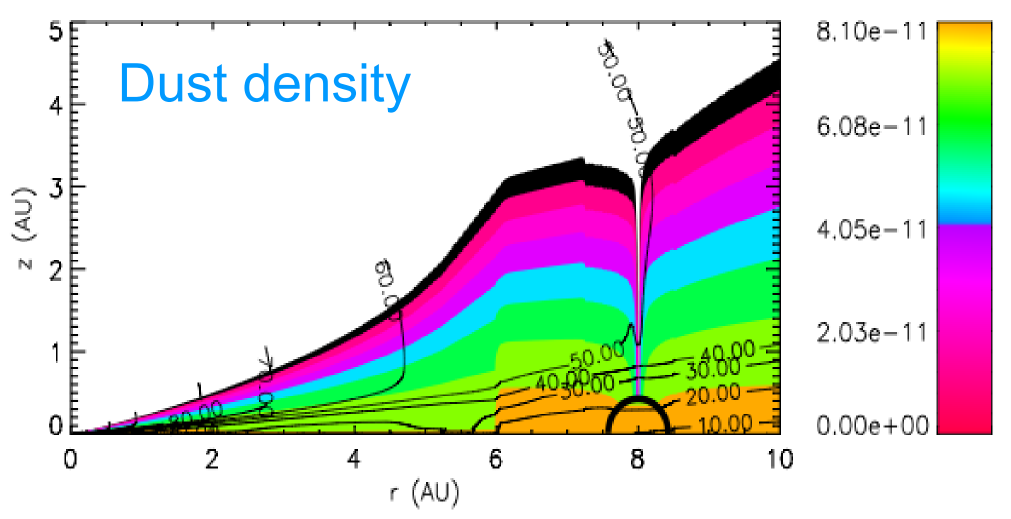
→ No, the Lindblad torque is insensitive to the density gradient

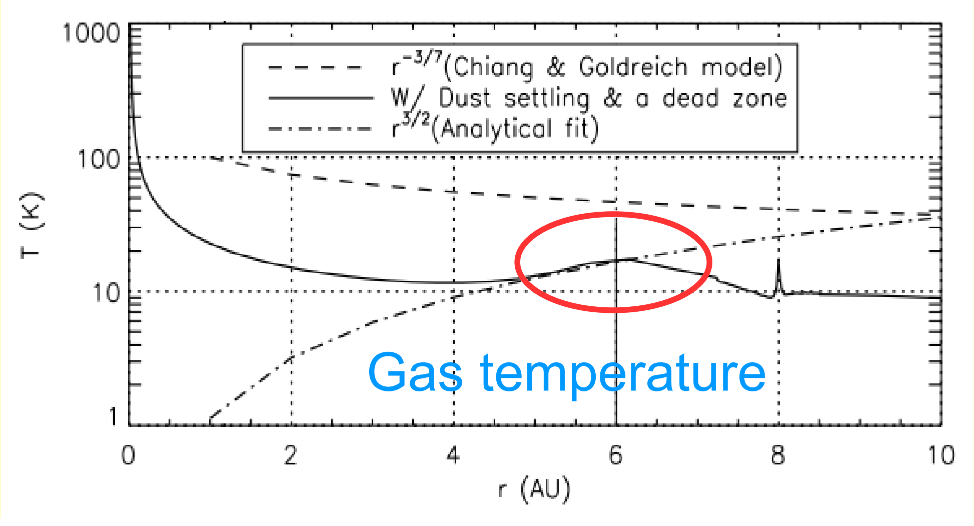
Ward 1997

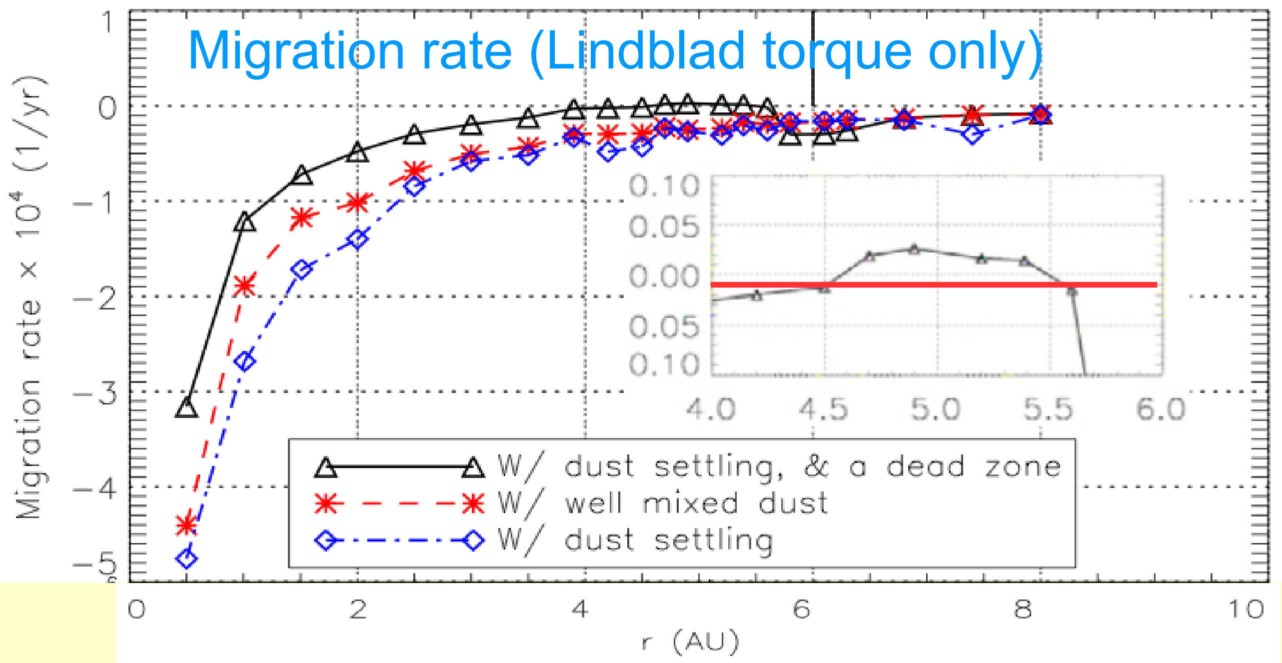
Differential Lindblad torque

But, the Lindblad torque may be reduced or even reversed in a super-Keplerian disk, e.g.:

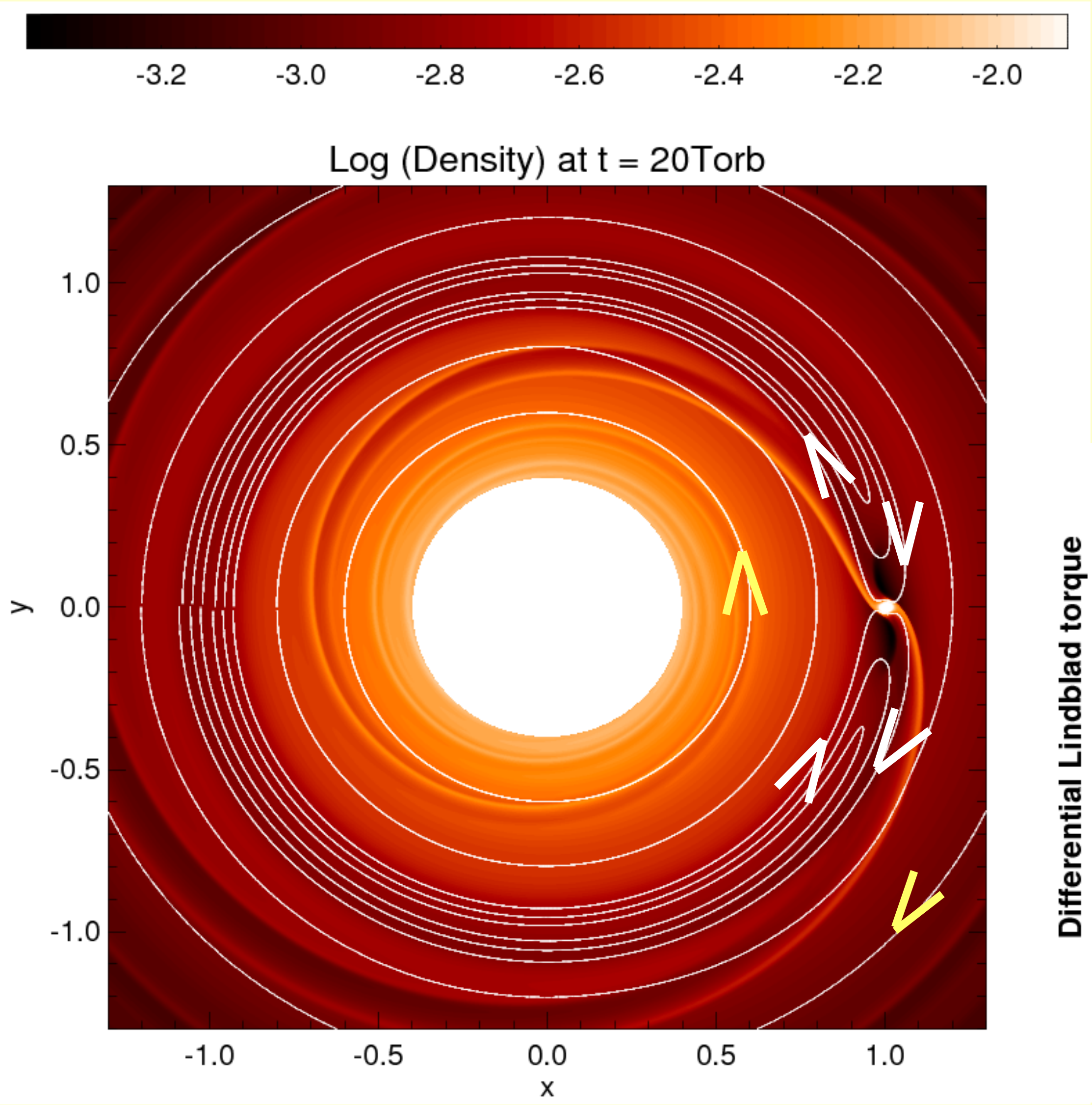
Hasegawa & Pudritz 2010







Type I migration in a nutshell

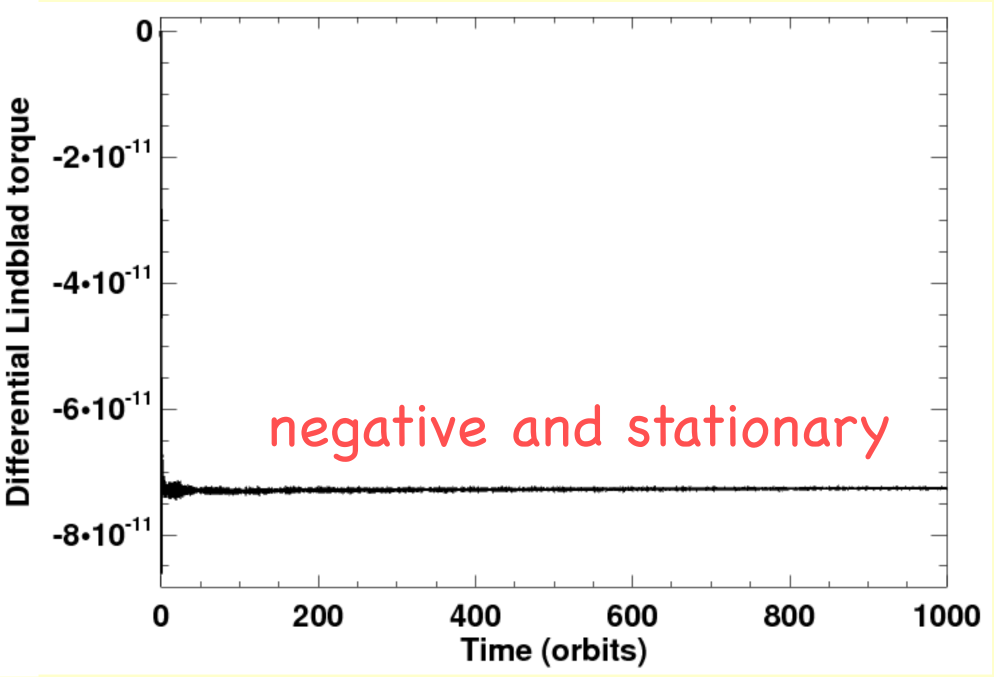


The planet exchanges angular momentum with:

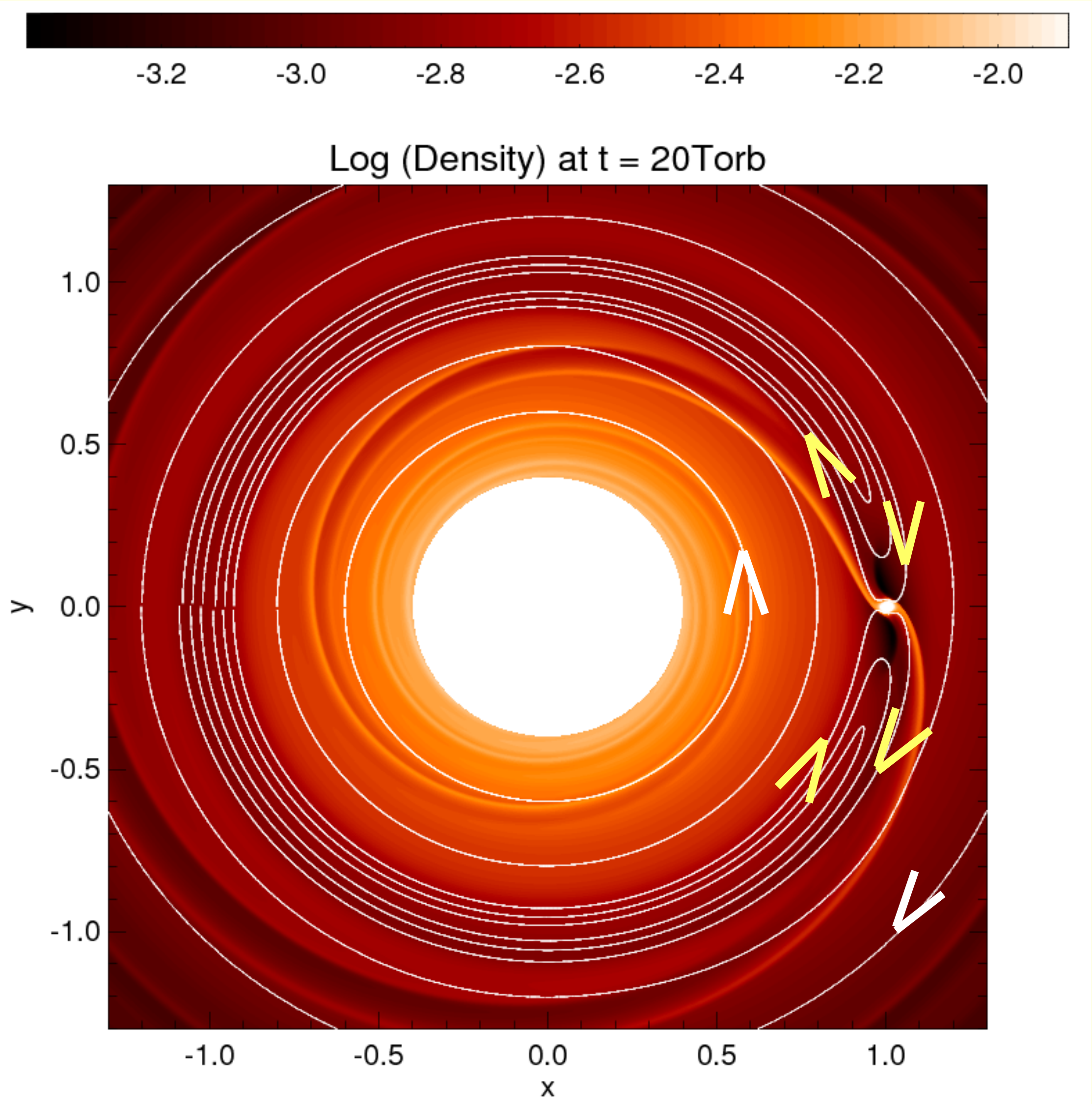
- **circulating** fluid elements:

  → differential Lindblad torque

- **librating** fluid elements:



Type I migration in a nutshell



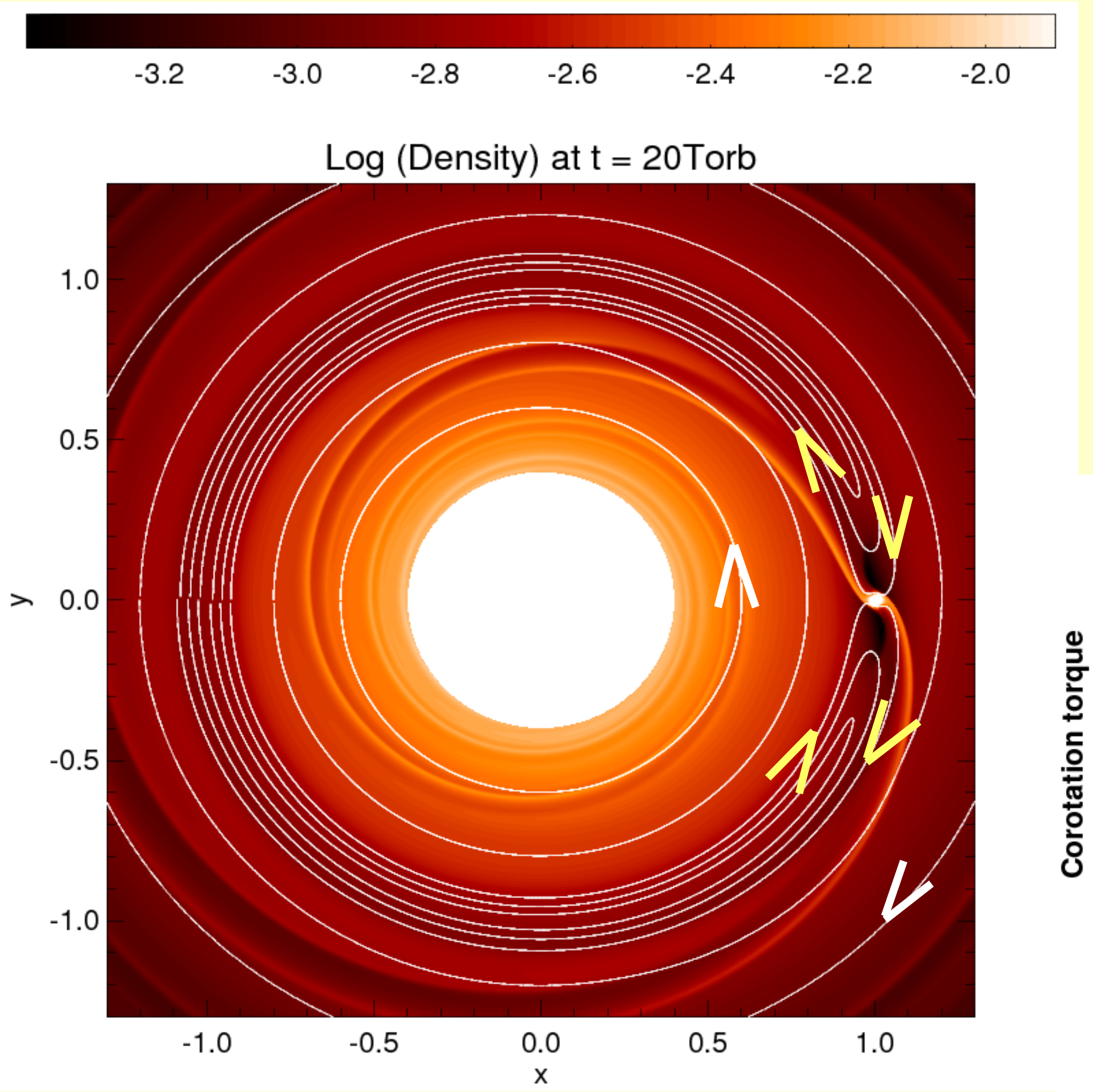
The planet exchanges angular momentum with:

- **circulating** fluid elements:

- **librating** fluid elements:

  → corotation torque (horseshoe drag)

Type I migration in a nutshell

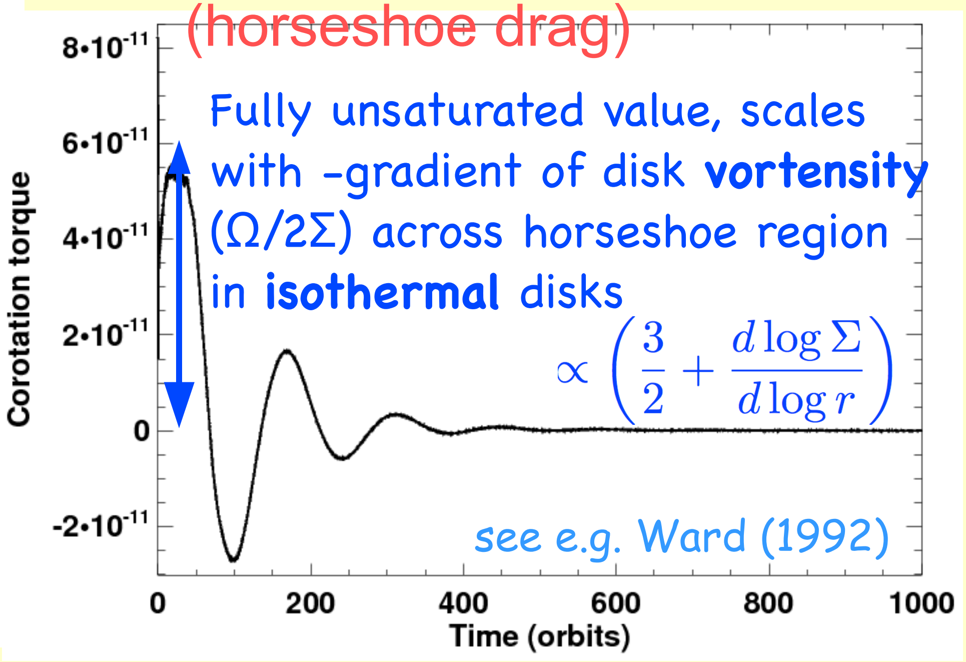


The planet exchanges angular momentum with:

- **circulating** fluid elements:

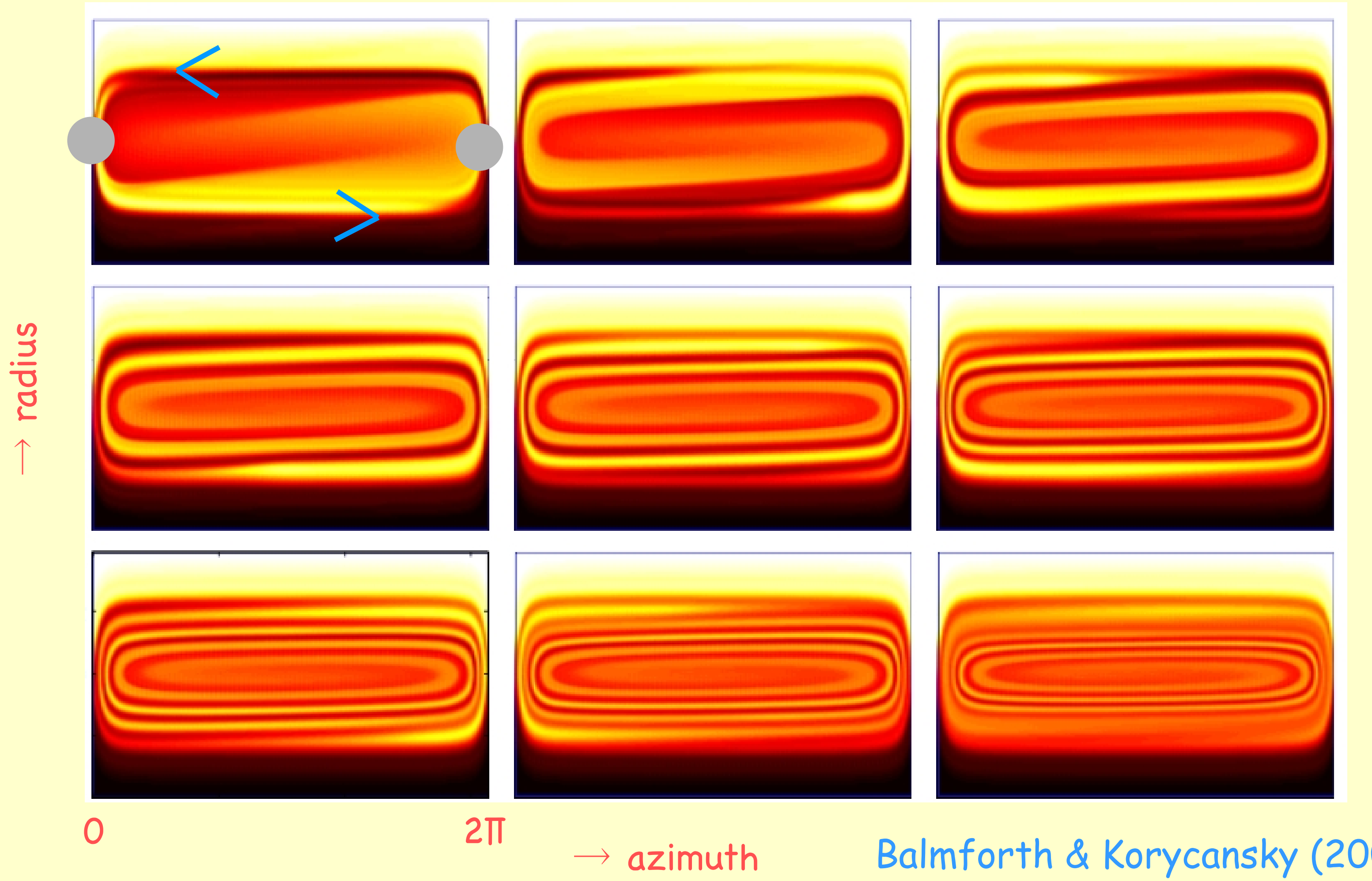
- **librating** fluid elements:

  → corotation torque (horseshoe drag)



Saturation of the corotation torque

Vortensity is advected in 2D inviscid barotropic flows



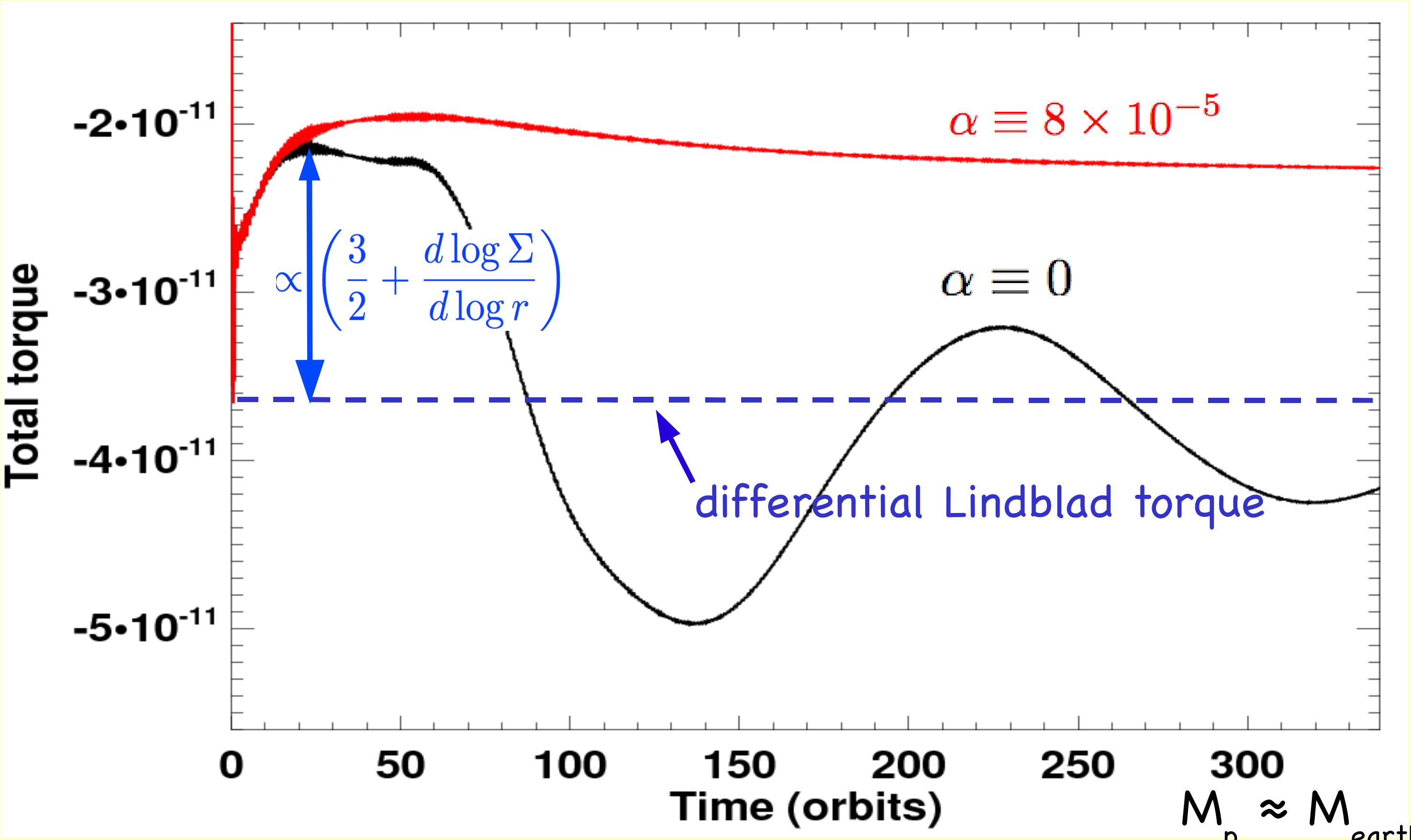
Balmforth & Korycansky (2001)

In such flows, the horseshoe drag ultimately **vanishes** (saturates) as vortensity is progressively stirred up in the horseshoe region

Desaturating the corotation torque

Viscosity (disk is **laminar, ν** = α c H) diffuses vortensity inside of the horseshoe region, and can maintain the corotation torque to its (maximum) fully unsaturated value...

Masset (2002)

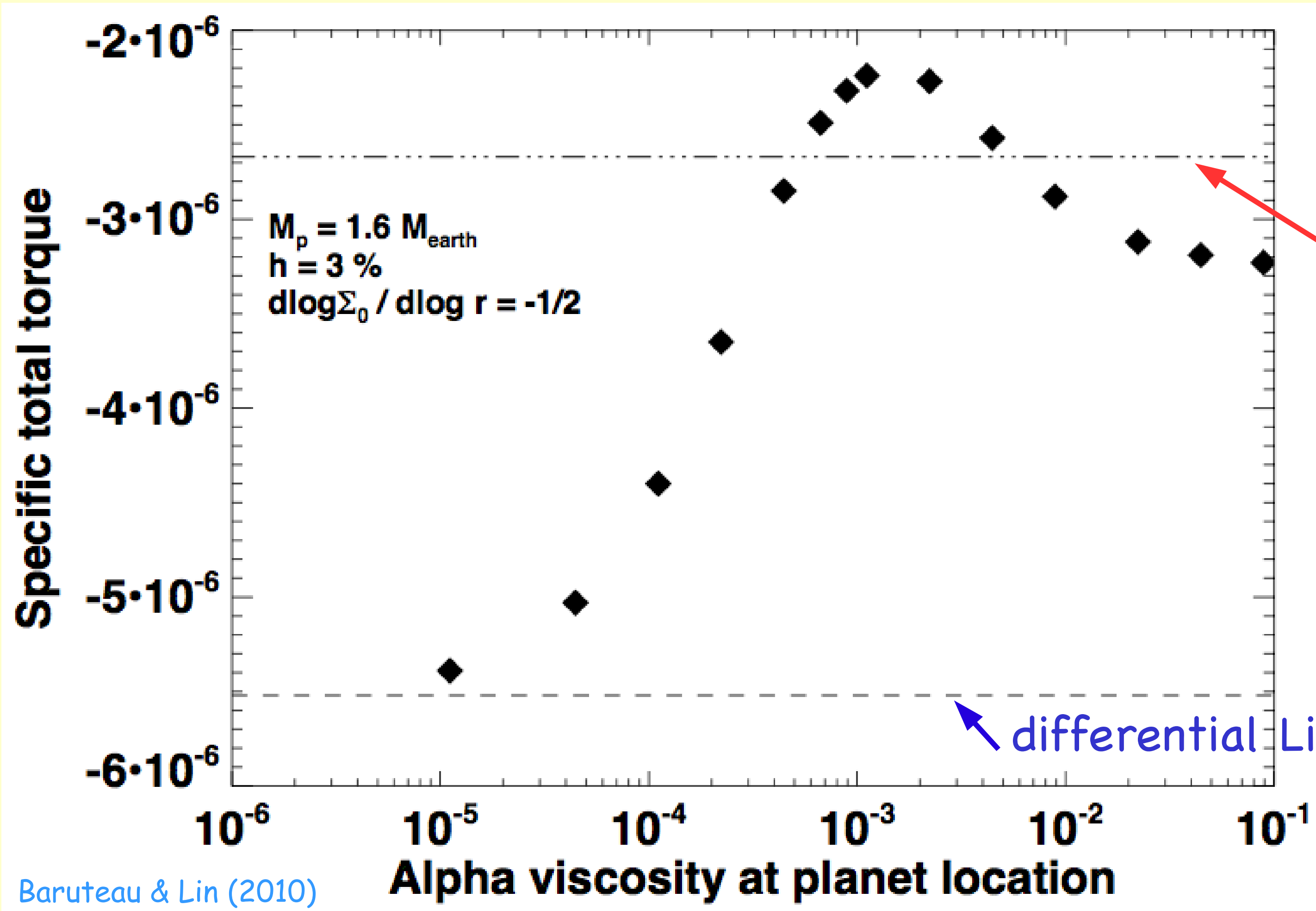


$M_p \approx M_{earth}$

Desaturating the corotation torque

… but not any viscosity does the job!

Masset (2002)



fully unsaturated torque

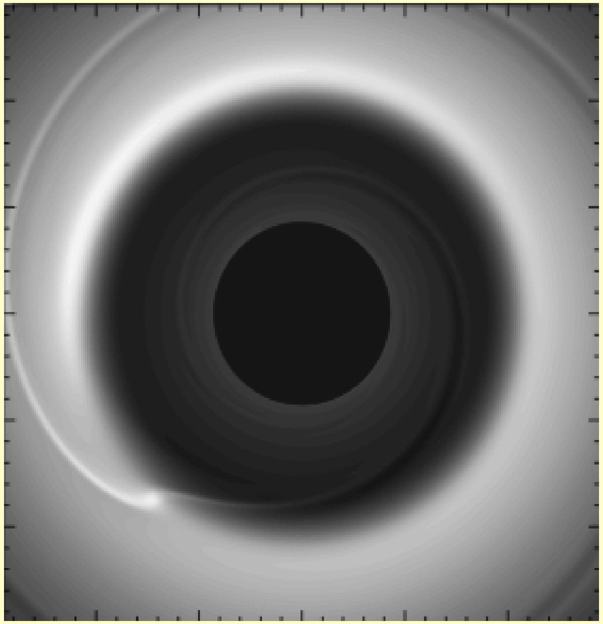
The corotation torque potentially slows down type I migration, *still* it is too fast!

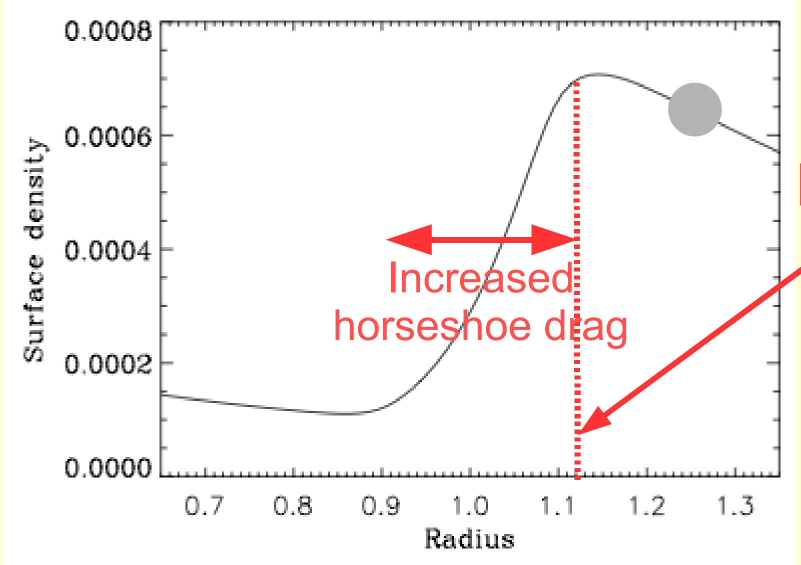
Enhancing the corotation torque: the planet trap

Migration towards an underdense cavity

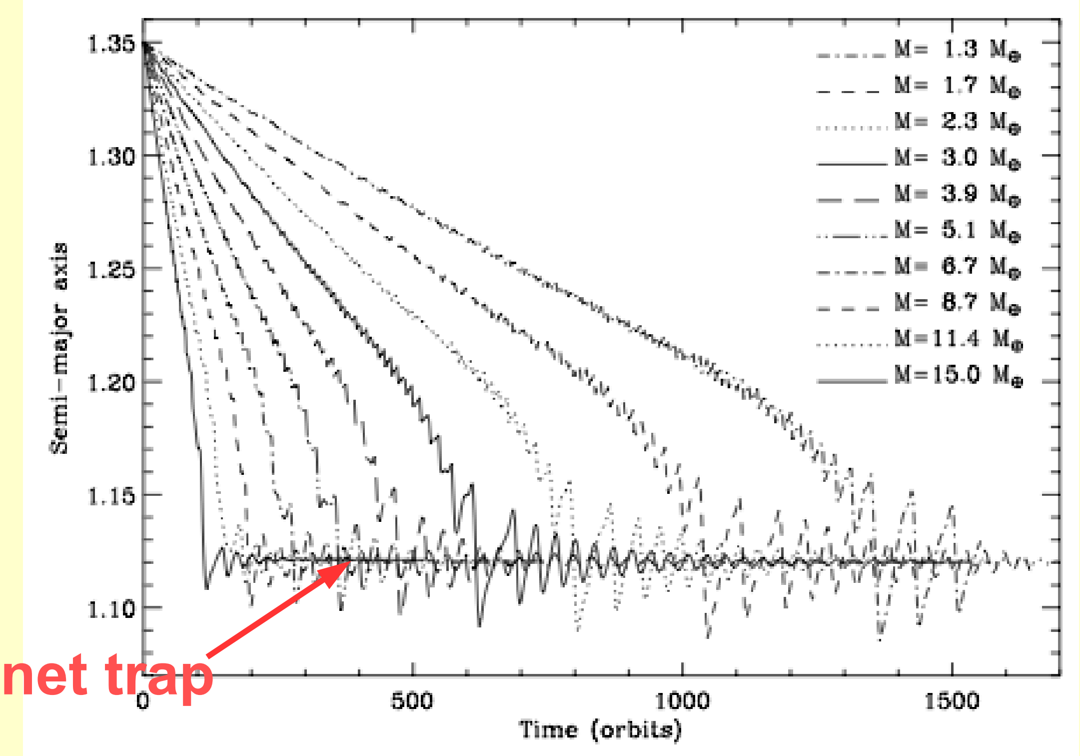
Masset et al. (2006)

e.g.: inner edge of the dead zone





planet trap

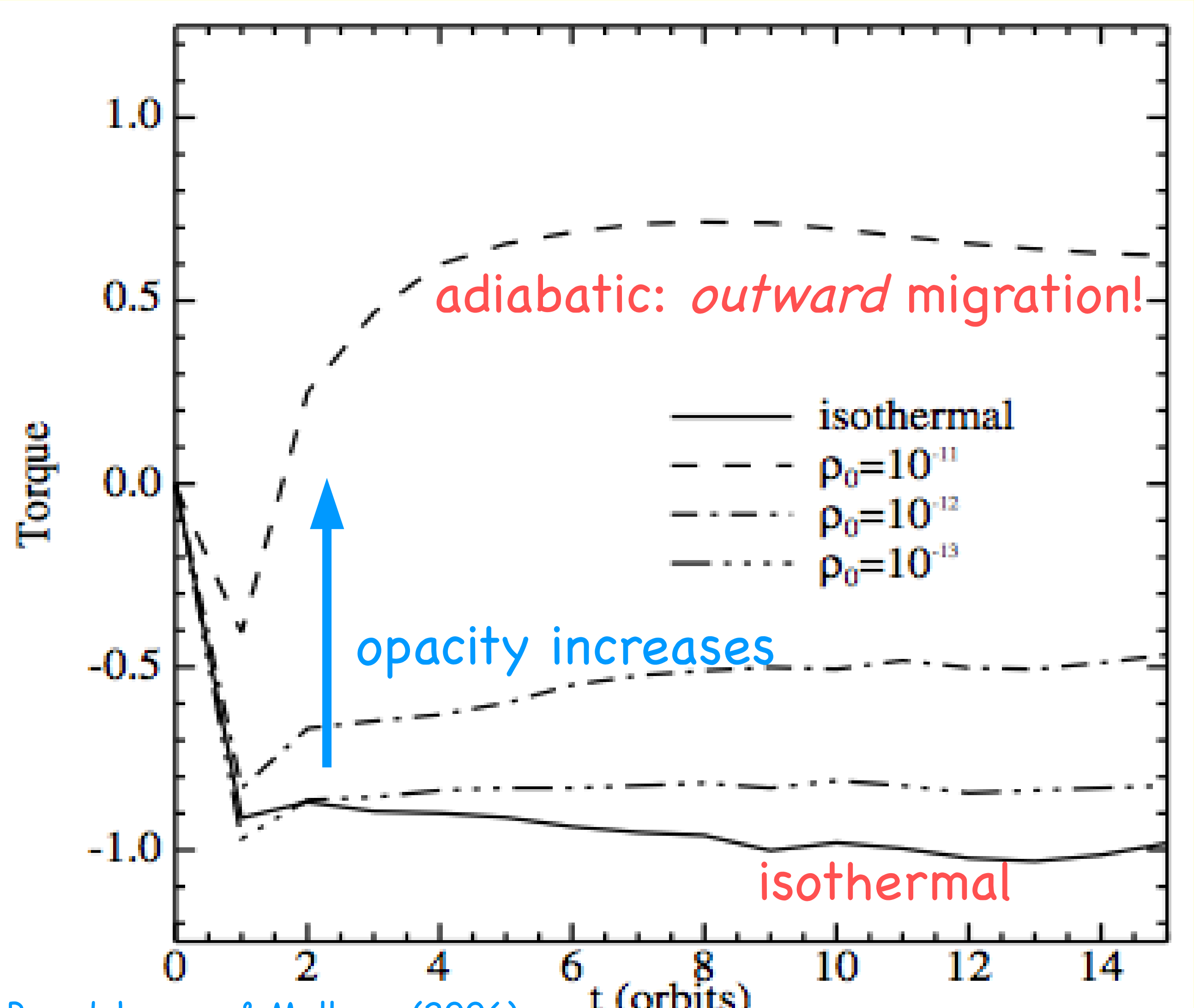


Provided it is unsaturated, the corotation torque may stall type I migration close to the location of a pressure maximum

Enhancing the corotation torque in radiatively inefficient disks

Inclusion of the **gas thermodynamics**:

Paardekooper & Mellema (2006) – 3D + radiative transfer

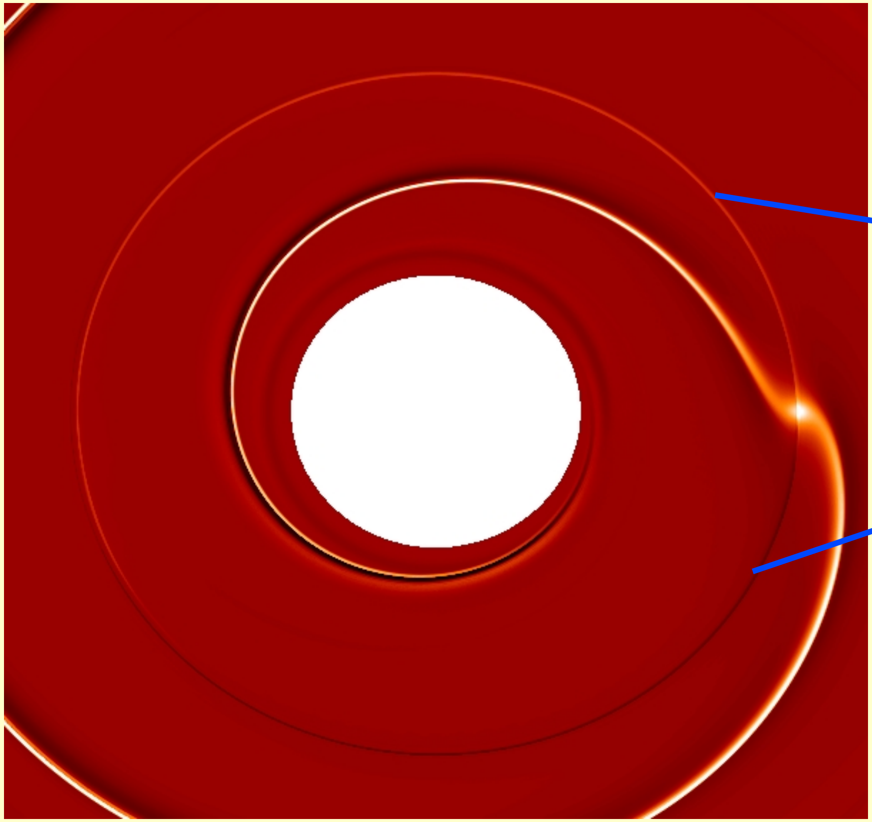


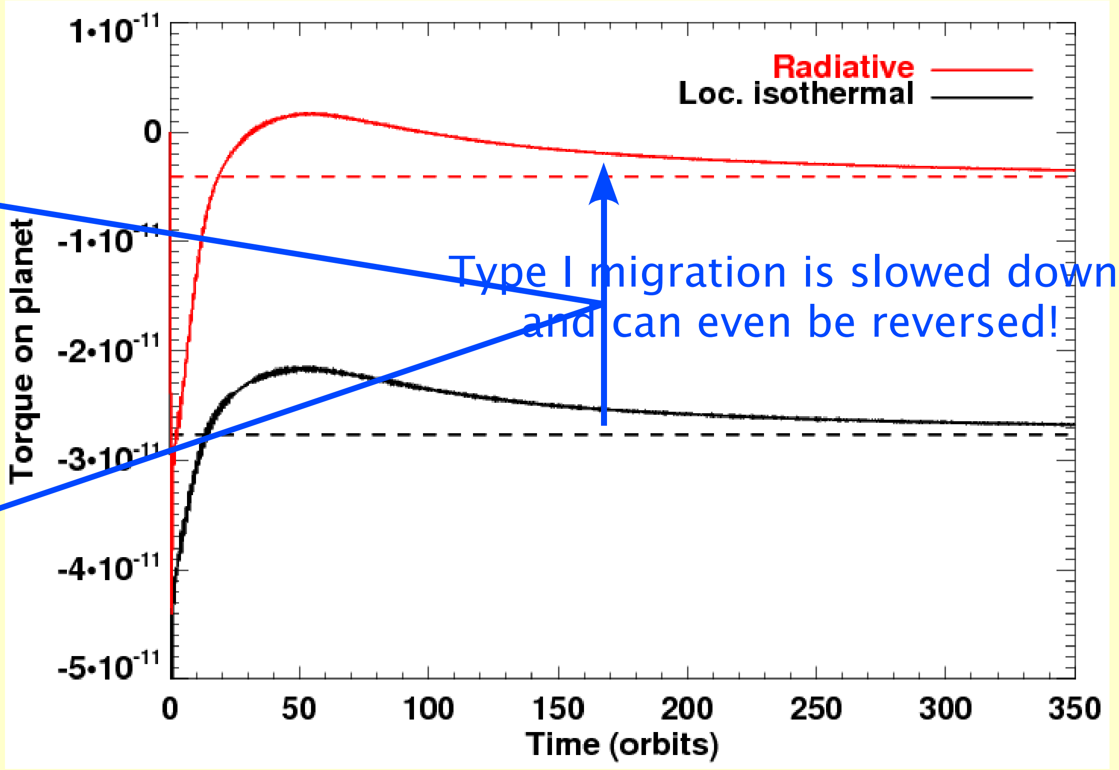
Paardekooper & Mellema (2006)

Enhancing the corotation torque in radiatively inefficient disks

Additional component of the horseshoe drag, scaling with the entropy gradient

Baruteau & Masset (2008a), Paardekooper & Papaloizou (2008), Masset & Casoli (2009), Paardekooper, Baruteau, Crida & Kley (2009)





This boost of the corotation torque may **solve** the lingering problem of a “too fast” type I planetary migration

A torque formula for population synthesis models

This boost of the corotation torque may **solve** the lingering problem of a “too fast” type I planetary migration

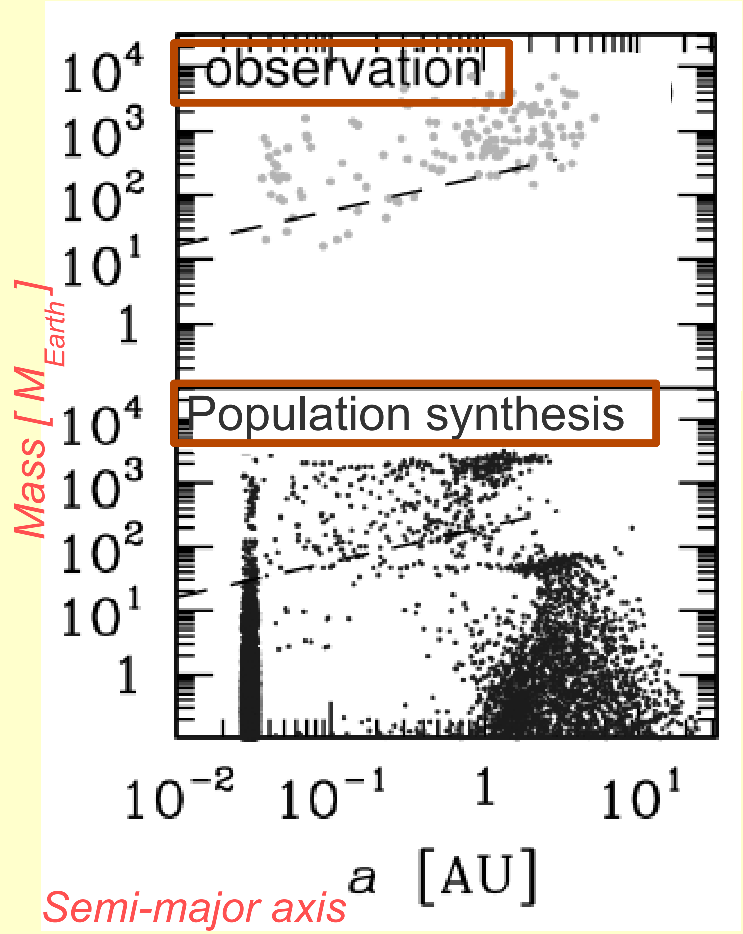
- depending on the entropy (density+temperature) gradient

- depending on the magnitude of the diffusion processes (viscosity + thermal diffusion)

A torque formula for population synthesis models

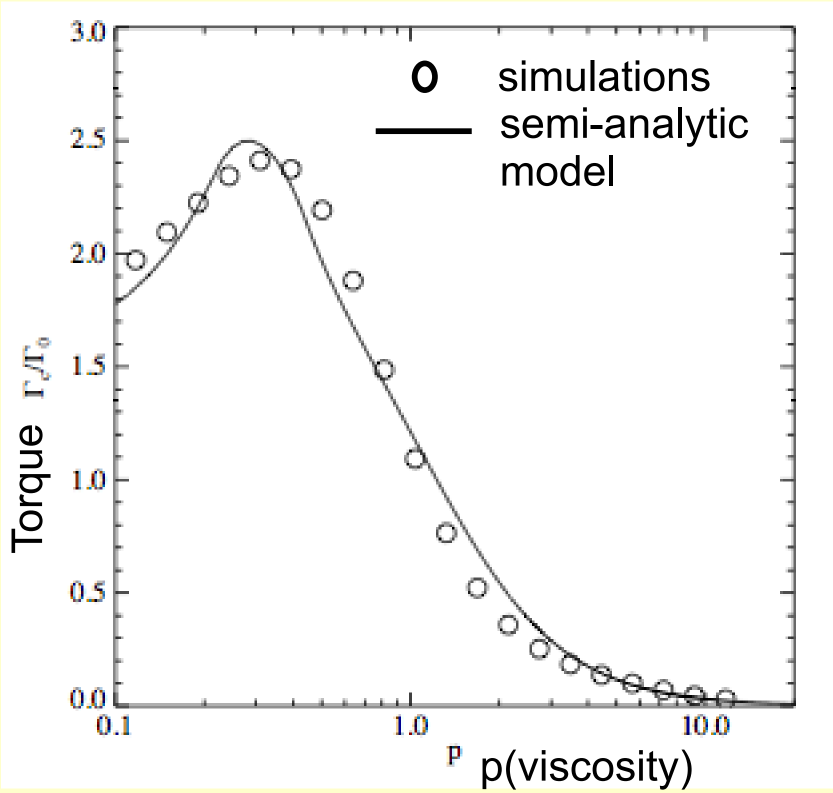
This boost of the corotation torque may **solve** the lingering problem of a "too fast" type I planetary migration

- depending on the entropy (density+temperature) gradient
- depending on the magnitude of the diffusion processes (viscosity + thermal diffusion)



Ida & Lin 08

→ need for a **torque formula** to be used by **population synthesis models**



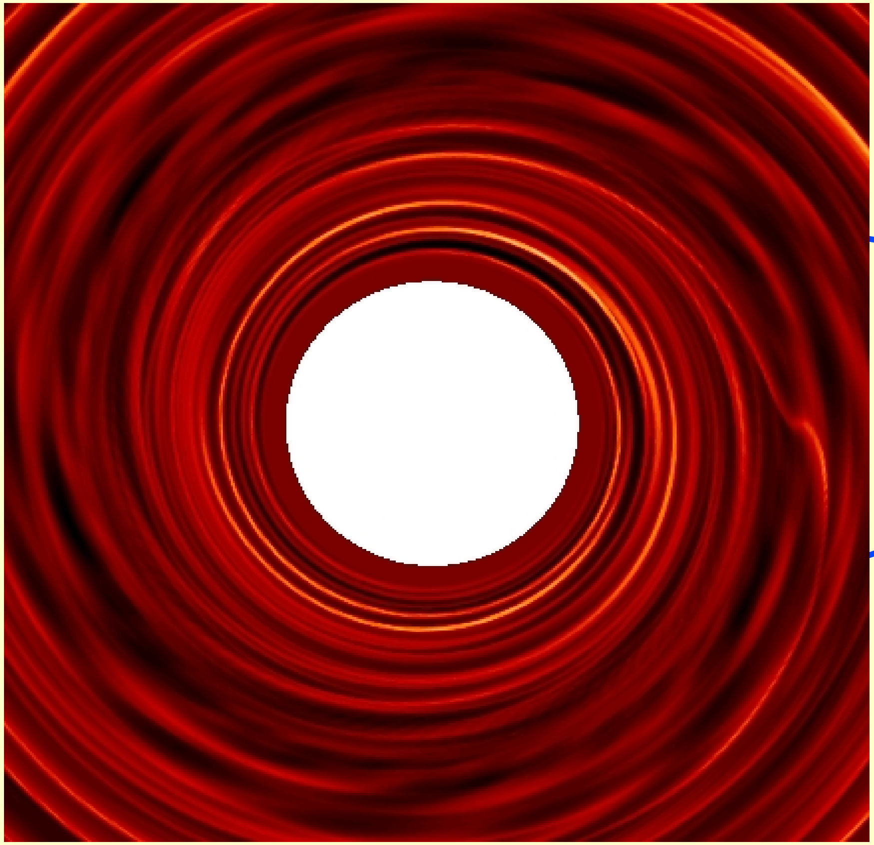
Paardekooper, Baruteau & Kley 2010

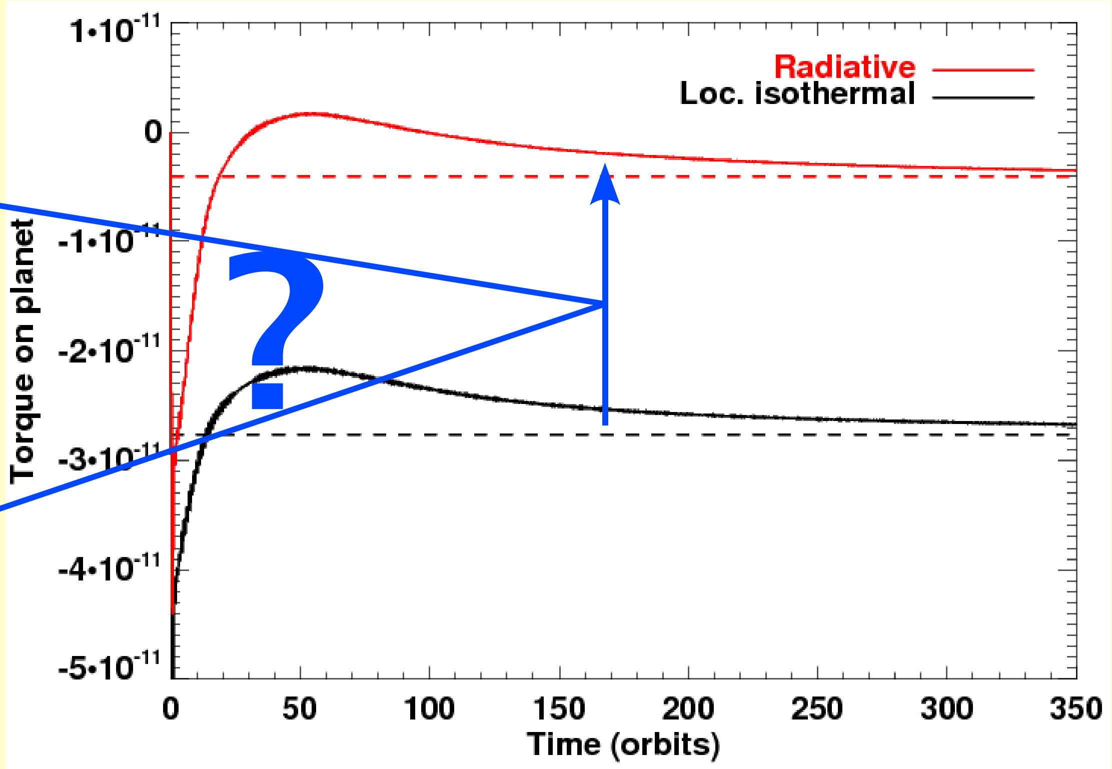
A torque formula for population synthesis models

This boost of the corotation torque may **solve** the lingering problem of a “too fast” type I planetary migration

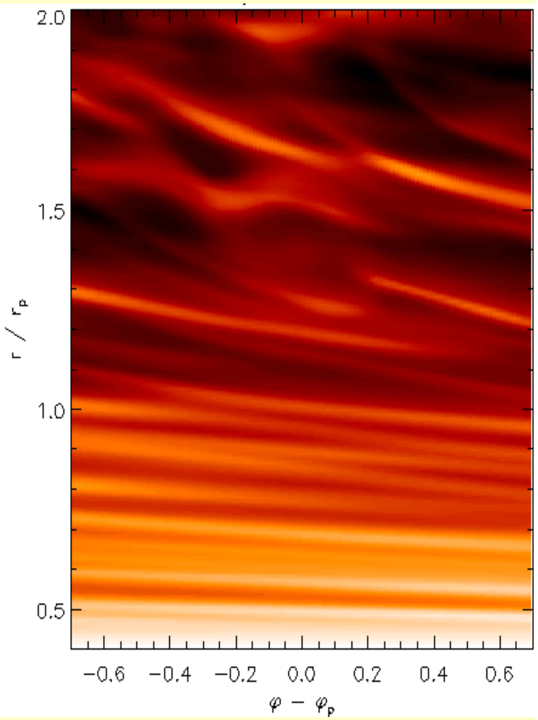
- depending on the entropy (density+temperature) gradient
- depending on the magnitude of the <u>diffusion</u> processes (viscosity + thermal diffusion)

→ what happens in a ***turbulent*** disk?

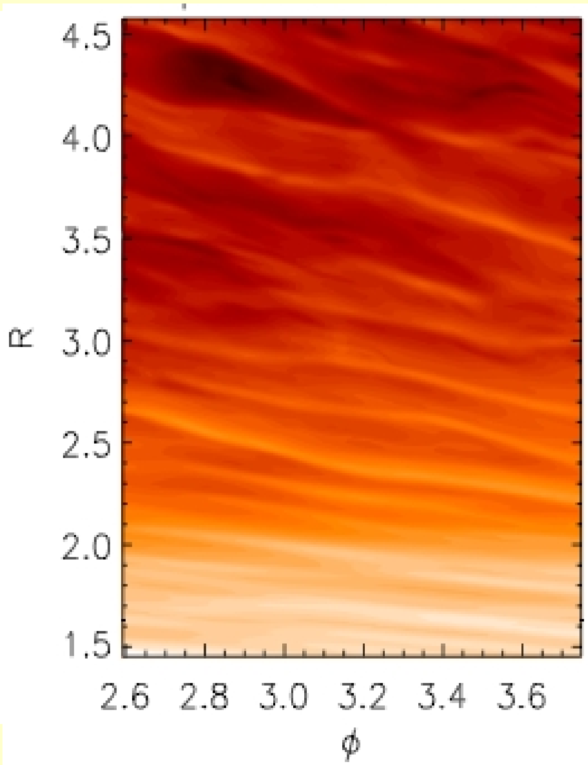




Corotation torque in turbulent disks



Baruteau & Lin 10
(stochastic forcing)



Nelson & Papaloizou 04
(MRI turbulence)

Context

3D MHD calculations... coming soon!

Aim

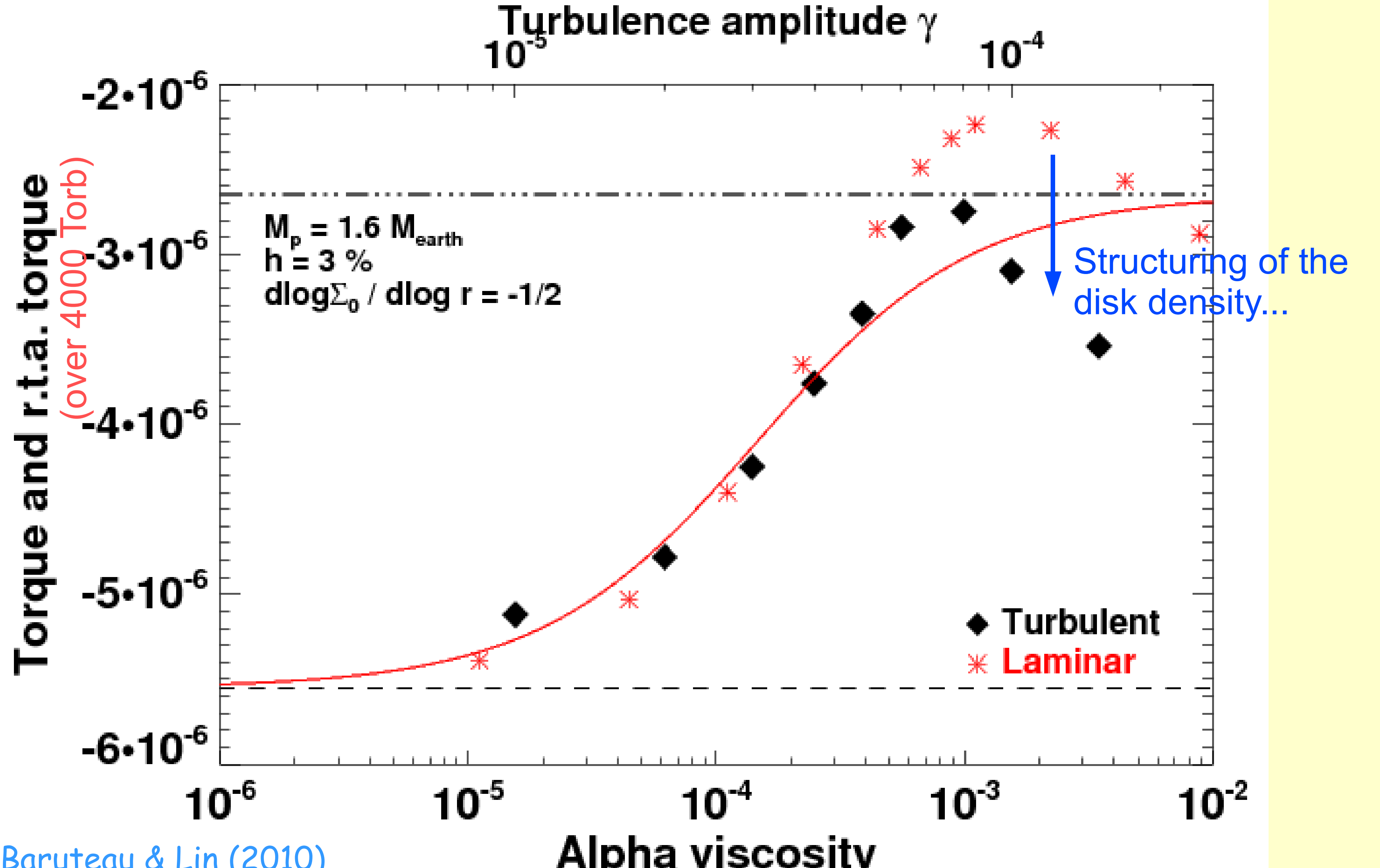
desaturation of the corotation torque with turbulence

Methods

2D Hydro + stochastic forcing (turbulent potential, Laughlin et al. 2004)

The parameters of the « turbulent potential » are **tuned** to give turbulence statistical properties as close as possible to those of 3D MHD runs

Comparison with laminar disk models

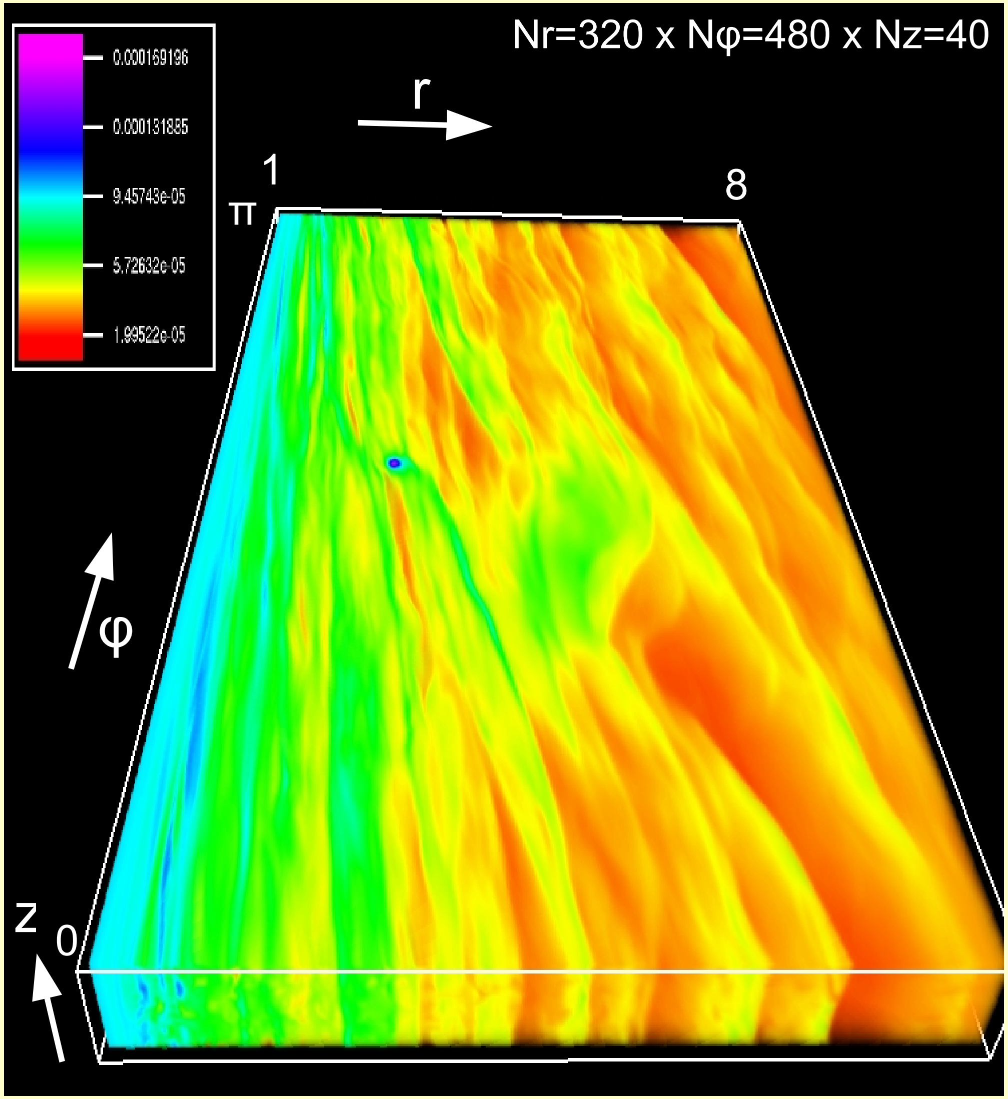


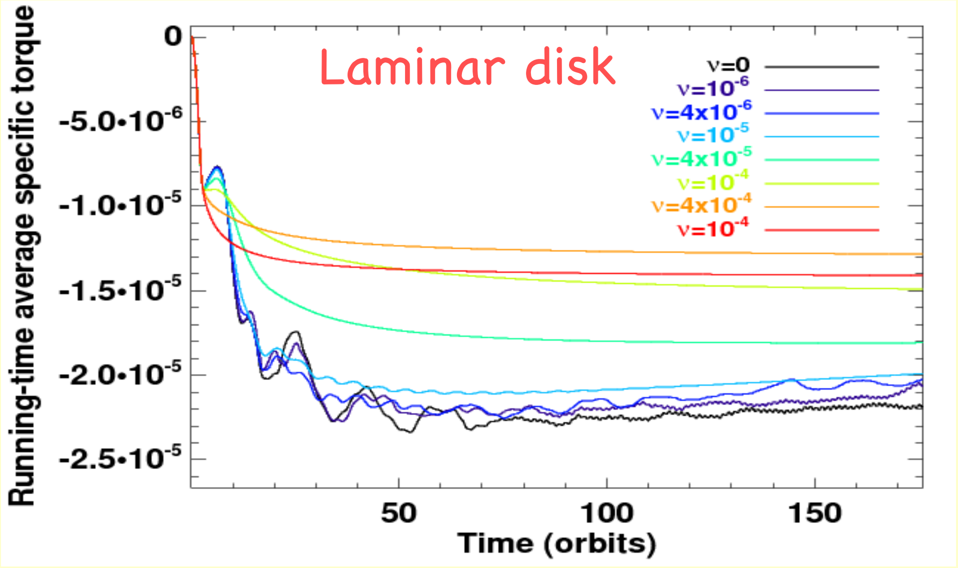
Baruteau & Lin (2010)

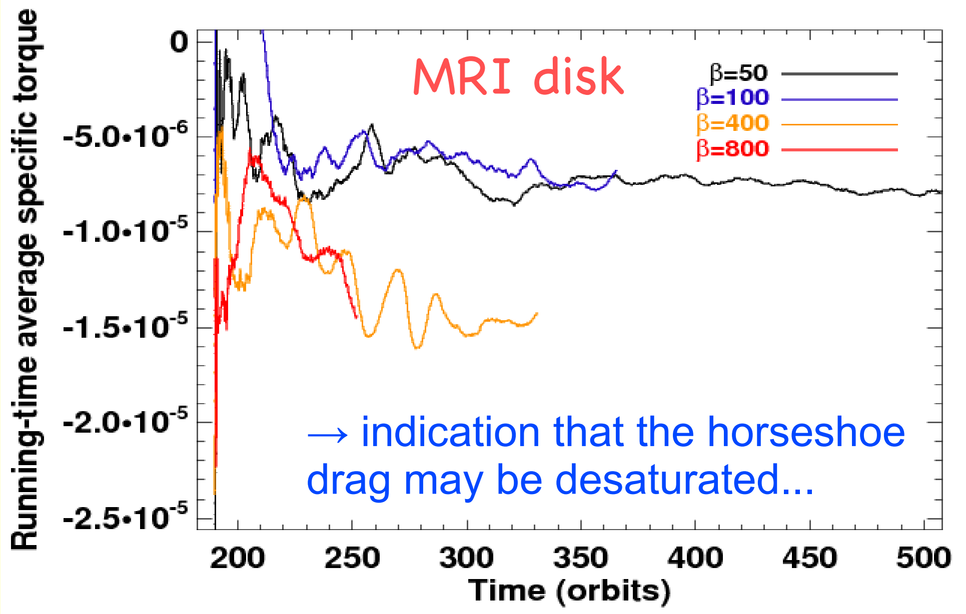
(associated with vortensity diffusion coefficient)

These results suggest that the desaturation properties of the corotation torque in turbulent disk models agree with those of laminar disk models

What about in MRI simulations?

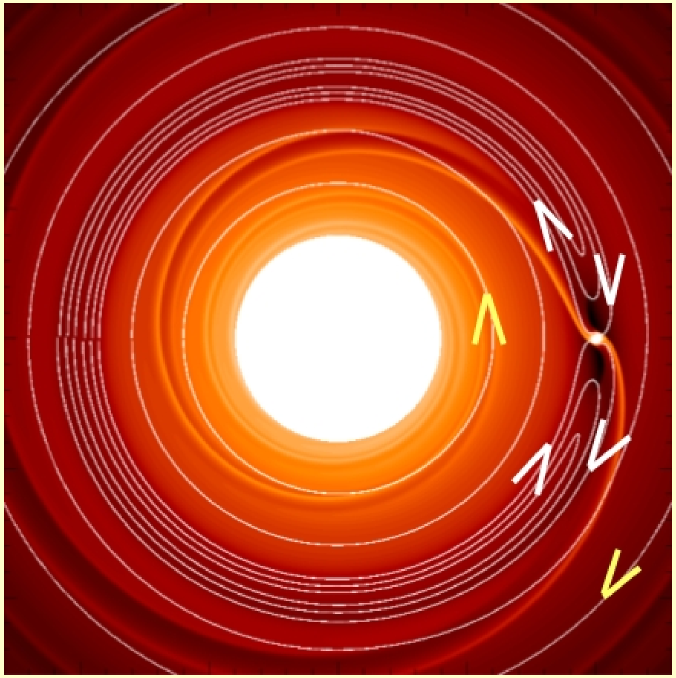




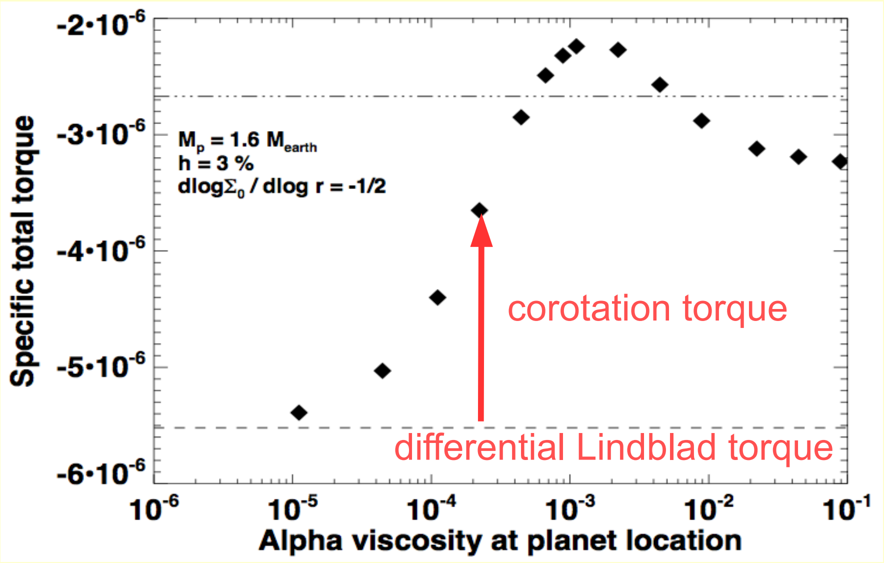


… work in progress with Fromang, Nelson & Masset ...

Summary on type I migration

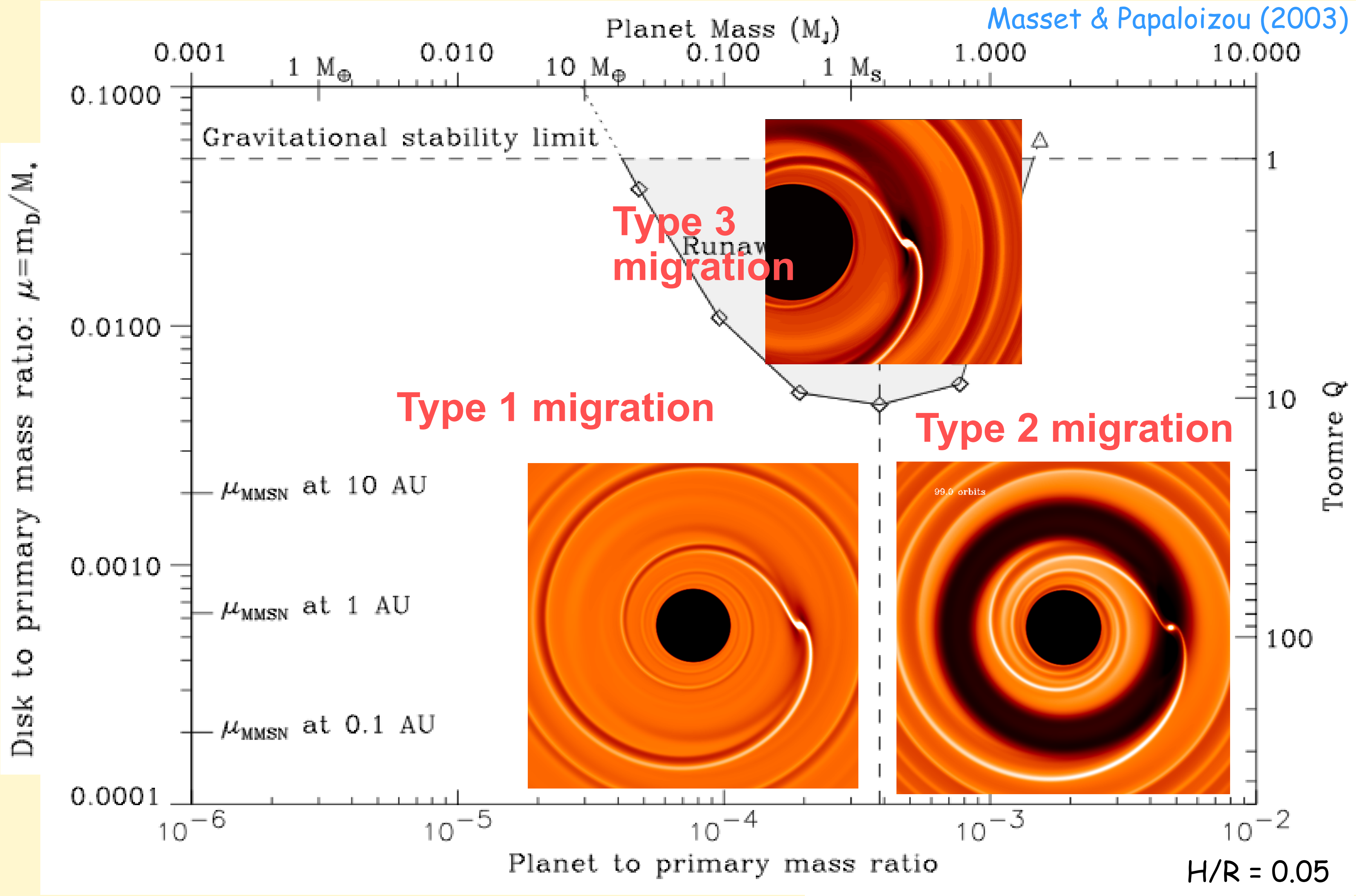


The torque driving the migration of low-mass planets is two-fold:



To do list:
- interplay with MHD turbulence (e.g. dead zone and planet trap), including several planets
- 3D torque formula for type I migration in radiative disks
- ...

Larger planet masses: the planet migration zoo



Gap-opening criterion:
Crida et al. (2006)

$$\frac{3}{4} h(a) \left(\frac{q}{3}\right)^{-1/3} + \frac{50\nu(a)}{q\, a^2\, \Omega(a)} \lesssim 1$$


Courtesy of F. Masset
Thank you for your attention!