The physics of planet-disk interaction

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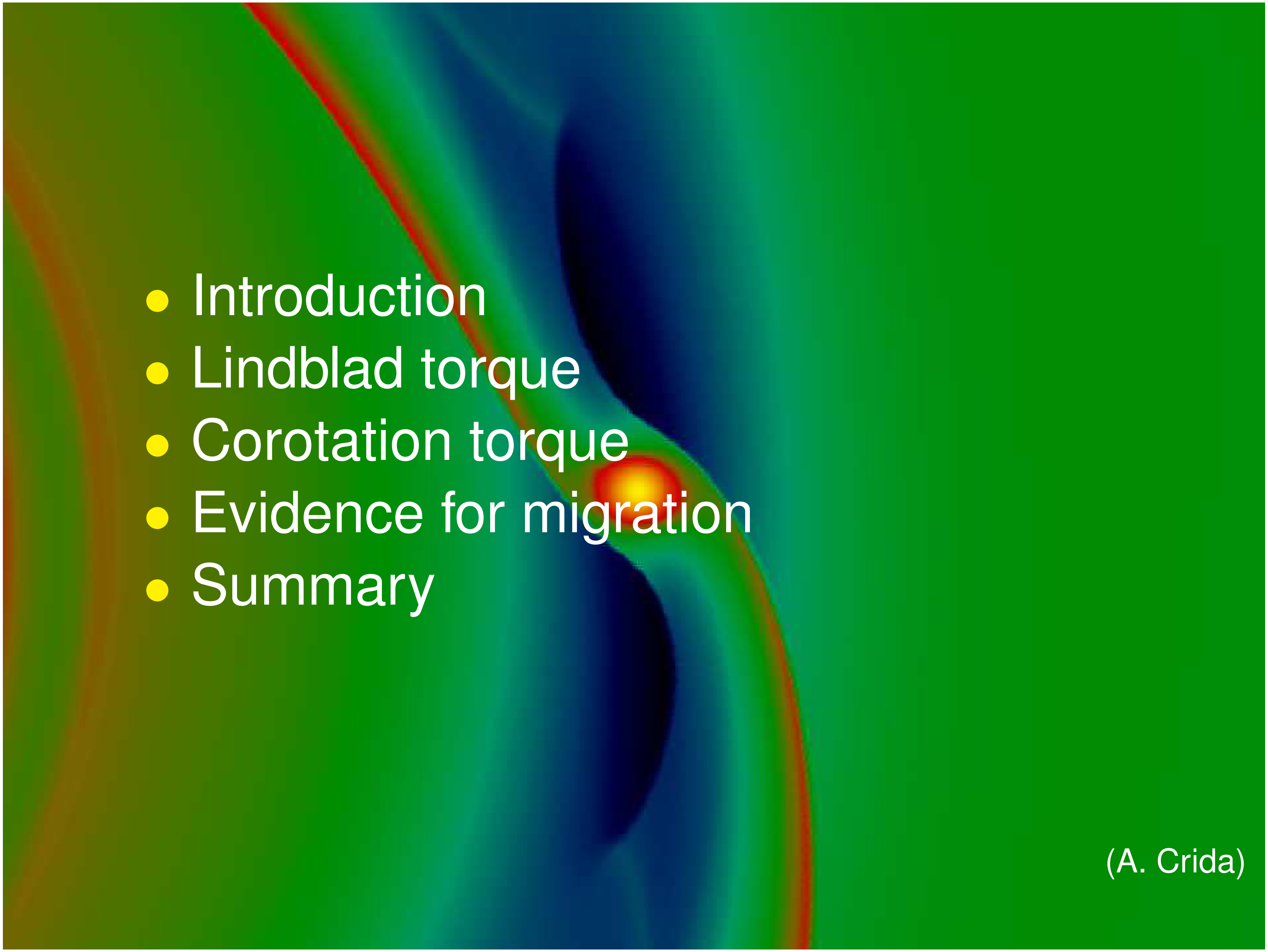
Organisation



- Introduction
- Lindblad torque
- Corotation torque
- Evidence for migration
- Summary

(A. Crida)

Planet Formation Problems

- Not possible to form hot Jupiters in situ
  - disk too hot for material to condense
  - not enough material
- Difficult to form massive planets
  - gap formation
- Eccentric and inclined orbits
  - planets form in flat disks

But planets grow in disks:
$\Rightarrow$ Have a closer look at planet-disk interaction

see Annual Review article: Kley & Nelson, ARAA, 50 (2012)

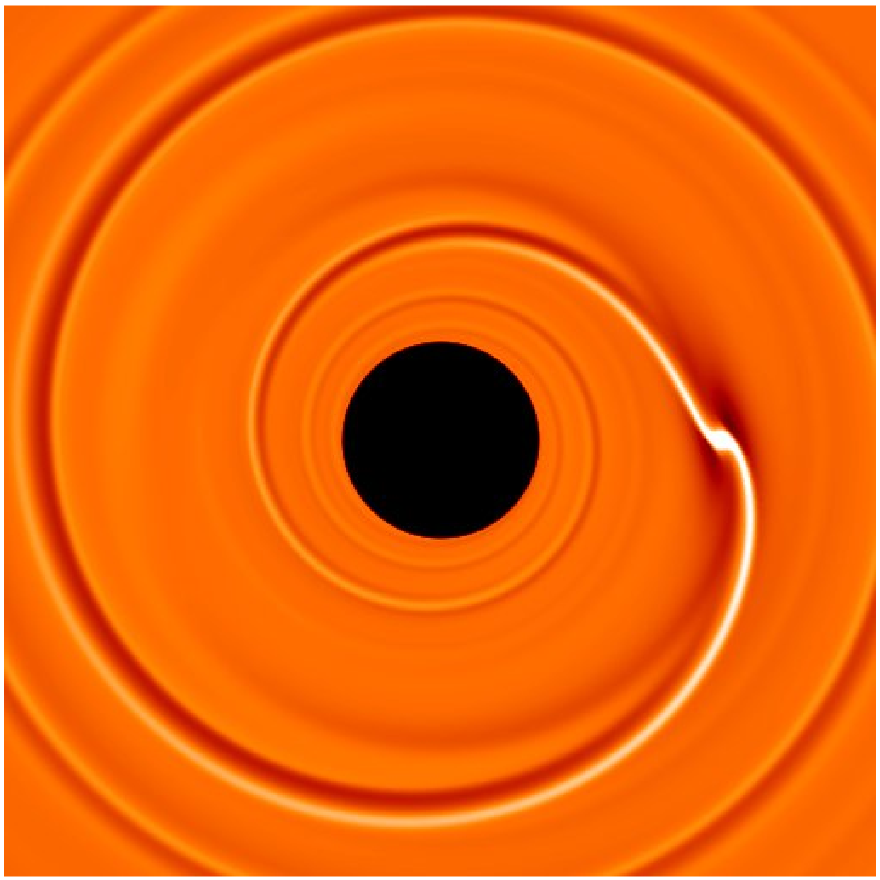
- more technical: Baruteau & Masset (2012)

Lindblad Torques (Spiral arms)

Young planets are embedded in gaseous disk

Creation of spiral arms:
- stationary in planet frame

- Linear analysis,
- 2D hydro-simulations



(Masset, 2001)

Inner Spiral
- pulls planet forward:
- positive torque

Outer Spiral
- pulls planet backward:
- negative torque

$\longrightarrow$ Net Torque

$\Longrightarrow$ Migration

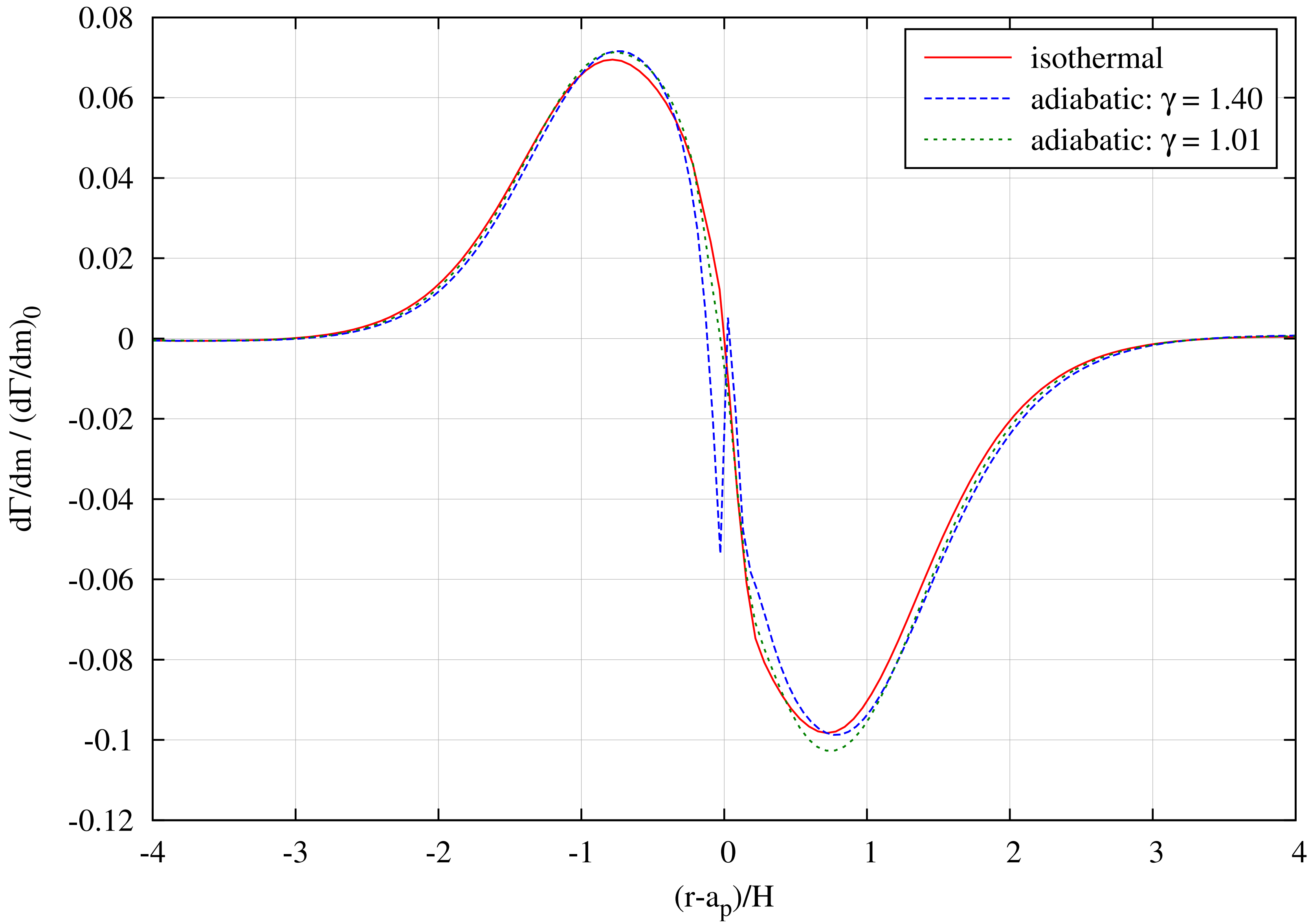
Most important:
Strength & Direction ?

Typically: Outer spiral wins
$\Longrightarrow$ Inward Migration

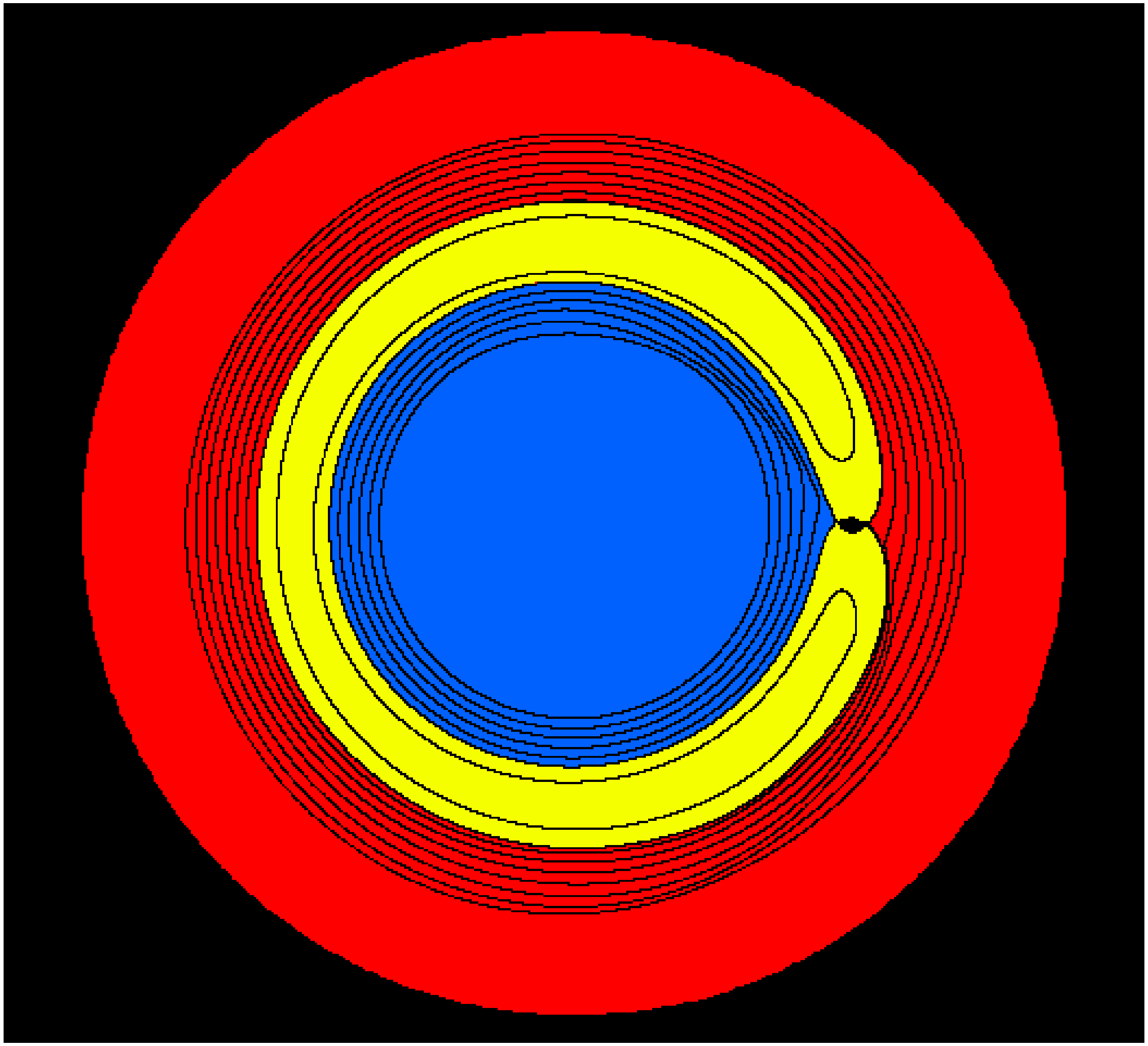
Torque scales with:
inv. Temp. $(H/r)^{-2}$, M_p^2, M_d

Lindblad torque: radial torqedensity

$$\Gamma_{\rm tot} = 2\pi \int \frac{d\Gamma}{dm}(r)\, \Sigma(r)\, r dr \quad \text{mit} \quad \left(\frac{d\Gamma}{dm}\right)_0 = \Omega_{\rm p}^2(a_{\rm p}) a_{\rm p}^2 q^2 \left(\frac{H}{a_{\rm p}}\right)^{-4}, \quad H_{\rm adi} = \sqrt{\gamma} H_{\rm iso}$$



Corotation Torque: (Horseshoe region)



(F. Masset)

3 Regions

Outer disk (spiral)
Inner disk (spiral)
$\Longrightarrow$ Lindblad torques

Horseshoe (coorbital)
$\Longrightarrow$ Corotation Torques
(Horseshoe drag)

Scaling with:
- Vortensity gradient
(Vorticity/density)

The linear Torque

Torque **on** the planet:

$$\Gamma_{\rm tot} = - \int\limits_{\rm disk} \Sigma(\vec{r}_{\rm p} \times \vec{F})\, df \;=\; \int\limits_{\rm disk} \Sigma(\vec{r}_{\rm p} \times \nabla\psi_{\rm p})\, df \;=\; \int\limits_{\rm disk} \Sigma \frac{\partial \psi_{\rm p}}{\partial \varphi} df \qquad (1)$$

From 3D analytical (Tanaka et al. 2002) and numerical (D'Angelo & Lubow, 2010) simulations, isothermal

$$\Gamma_{\rm tot} = -(1.36 + 0.62\beta_\Sigma + 0.43\beta_T)\,\Gamma_0. \qquad (2)$$

where

$$\Sigma(r) = \Sigma_0\, r^{-\beta_\Sigma} \qquad \text{and} \qquad T(r) = T_0\, r^{-\beta_T} \qquad (3)$$

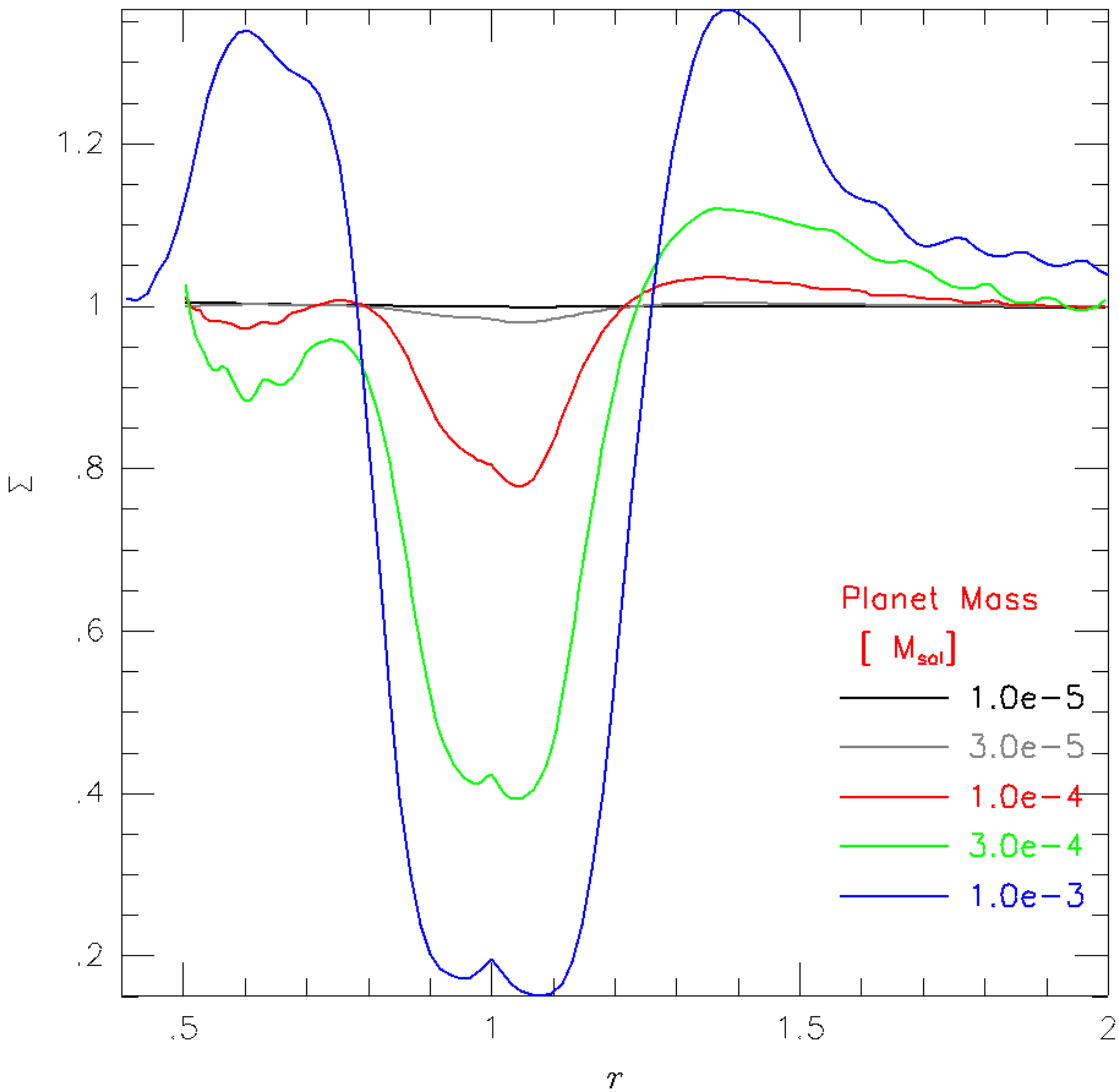
and normalisation

$$\Gamma_0 = \left(\frac{m_{\rm p}}{M_*}\right)^2 \left(\frac{H}{r_{\rm p}}\right)^{-2} \Sigma_{\rm p}\, r_{\rm p}^4\, \Omega_{\rm p}^2, \qquad (4)$$

Migration

$$\dot{J}_{\rm p} = \Gamma_{\rm tot} \quad \Rightarrow \quad \frac{\dot{a}_{\rm p}}{a_{\rm p}} = 2\frac{\Gamma_{\rm tot}}{J_{\rm p}} \qquad (5)$$

Gap formation: Type I ⇒ Type II



$M_p = 0.01\ M_{Jup}$
$M_p = 0.03\ M_{Jup}$
$M_p = 0.1\ M_{Jup}$
$M_p = 0.3\ M_{Jup}$
$M_p = 1.0\ M_{Jup}$

Depth depends on:
- M_p
- Viscosity
- Temperature

Torques reduced:

Migration slows

Type I ⇒ Type II

linear ⇒ non-linear

Saturation - Effect

2D hydro-simulations:
- small mass
- inviscid

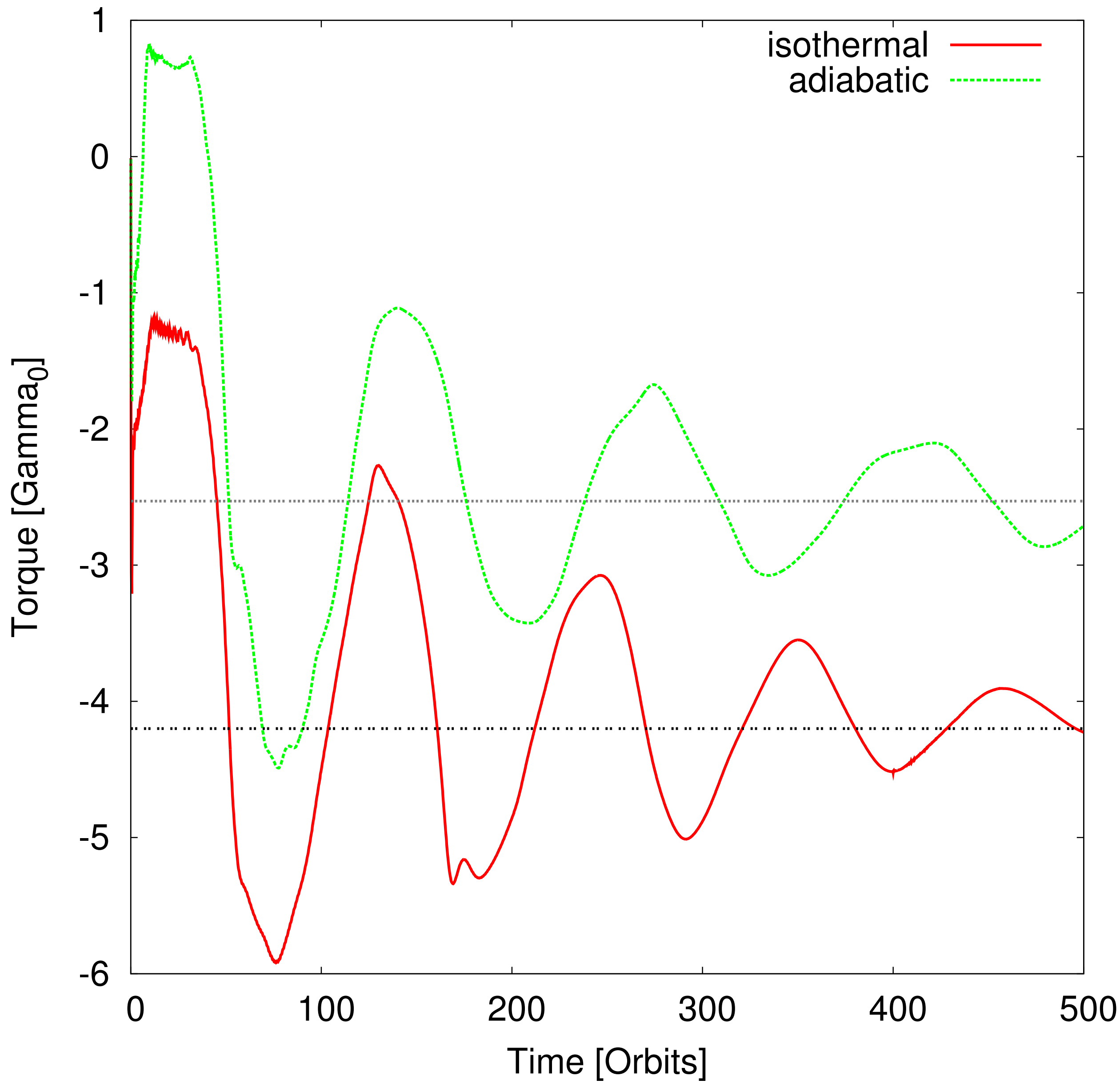
Total torque vs. time
- isothermal
- adiabatic

Note:
for barotropic and inviscid flows:

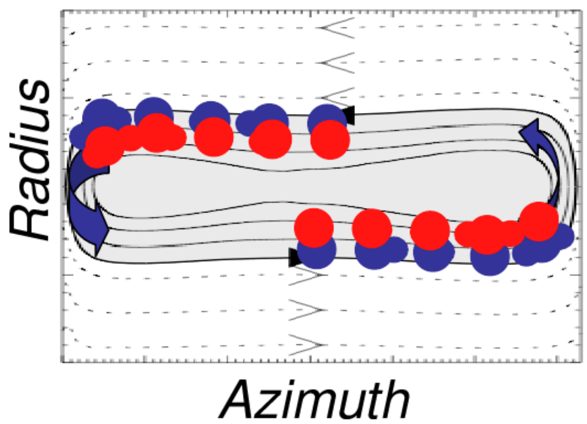
$$\frac{d}{dt}\left(\frac{\omega_z}{\Sigma}\right) = 0$$

$$\frac{dS}{dt} = 0$$

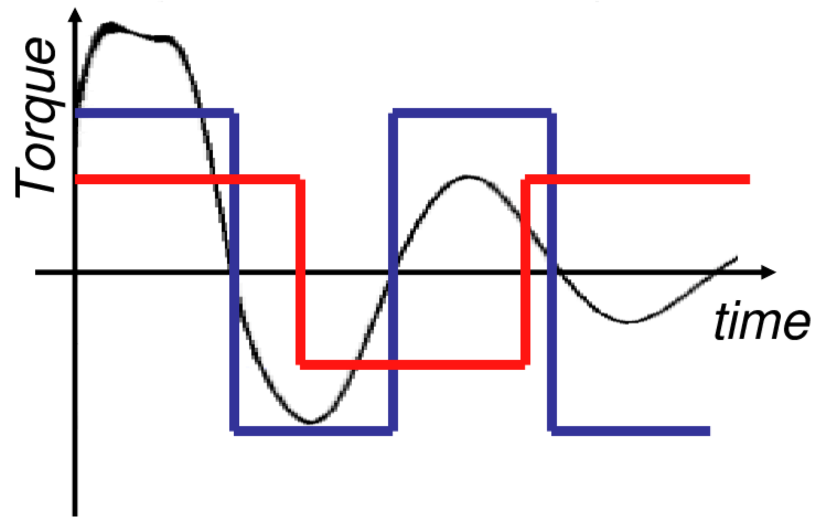
Torque depends on:
Gradients of $\omega_z/\Sigma,\ S$



Saturation - Origin

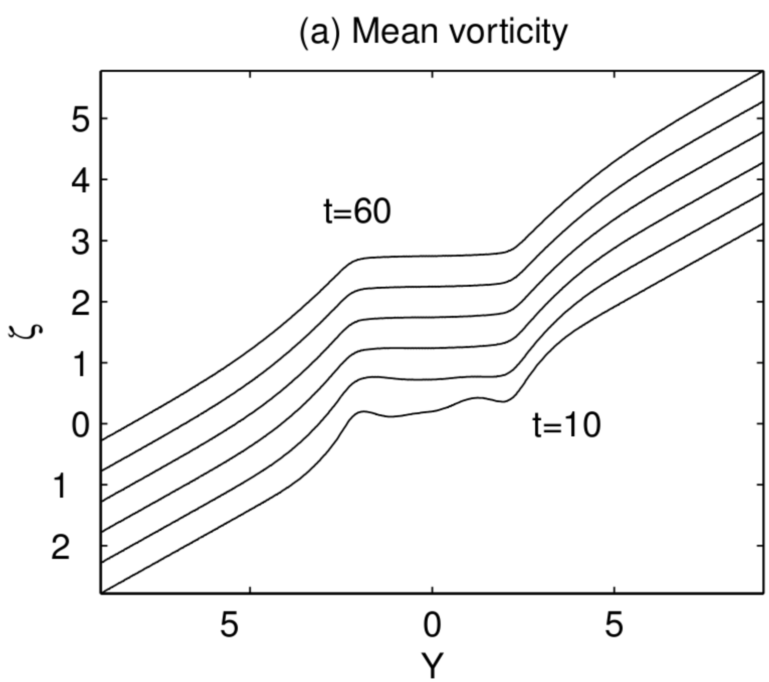


(F. Masset)

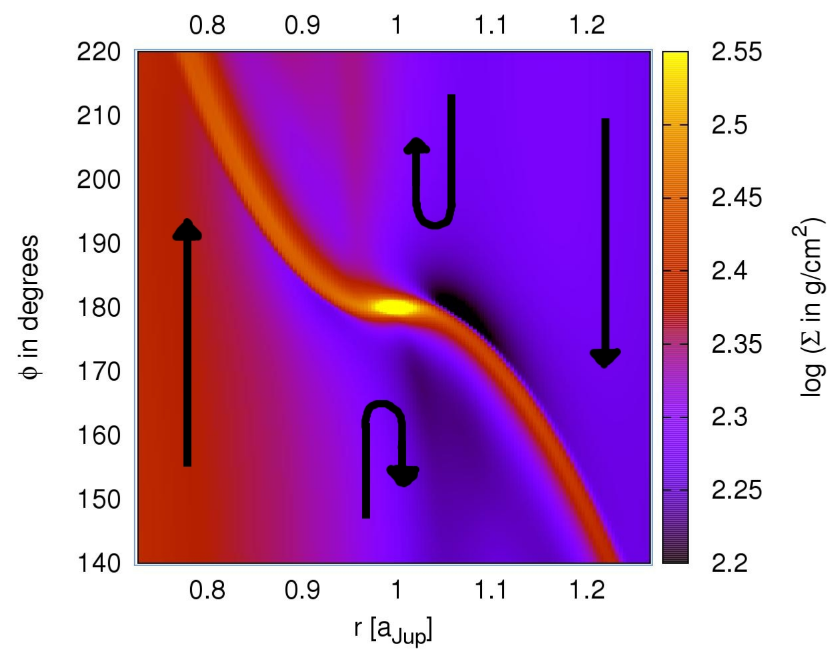


Red and Blue Orbits have different periods

$\Rightarrow$ Phase mixing



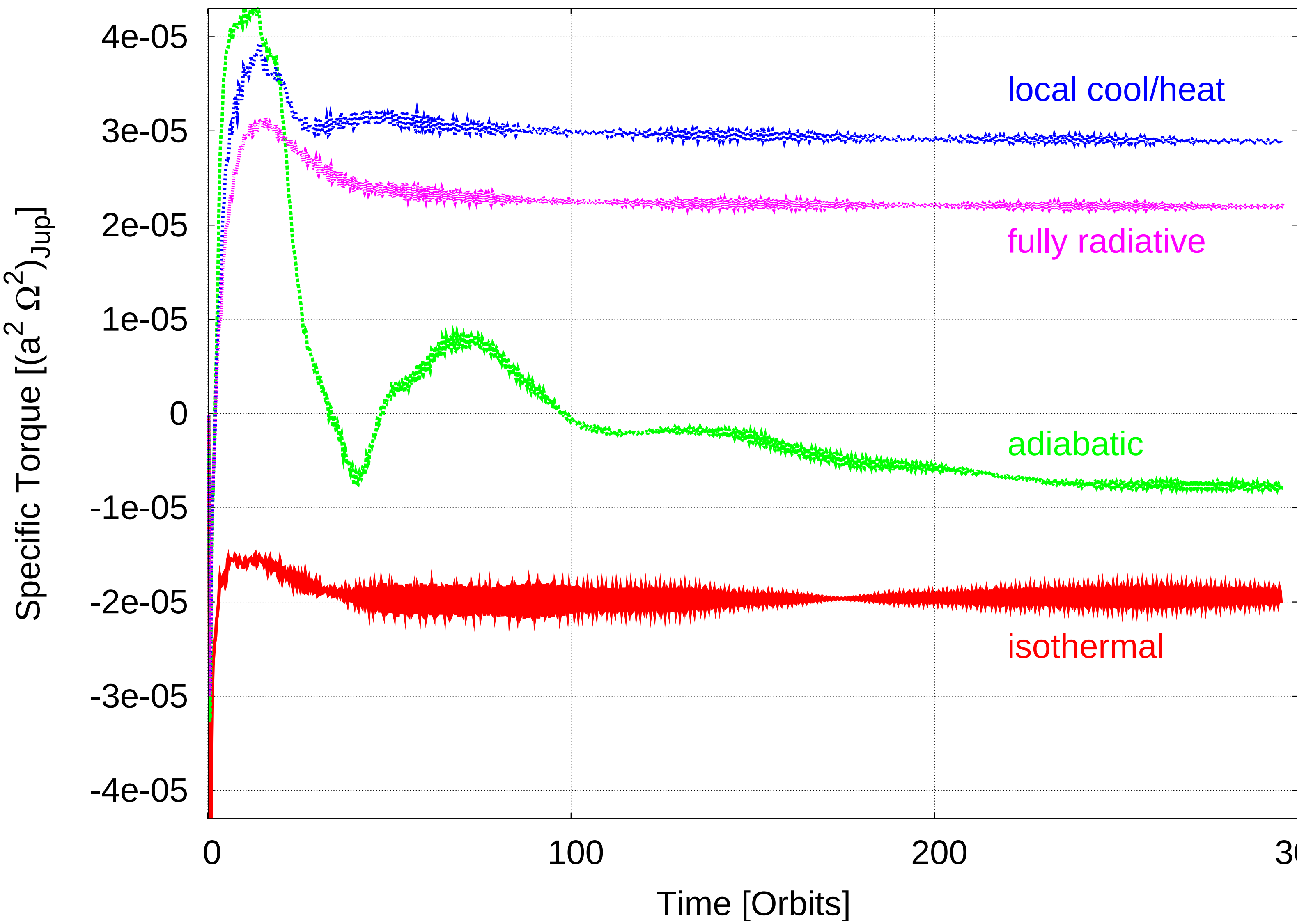
(Balmforth & Korycanski)



3D radiative disk (B. Bitsch)

Physics matters

$$\frac{\partial \Sigma c_{\rm v} T}{\partial t} + \nabla \cdot (\Sigma c_{\rm v} T \mathbf{u}) = -p\nabla \cdot \mathbf{u} + D - Q - 2H\nabla \cdot \vec{F}$$



$M_{\rm p}$ = 20 $M_{\rm Earth}$

Outward Migration

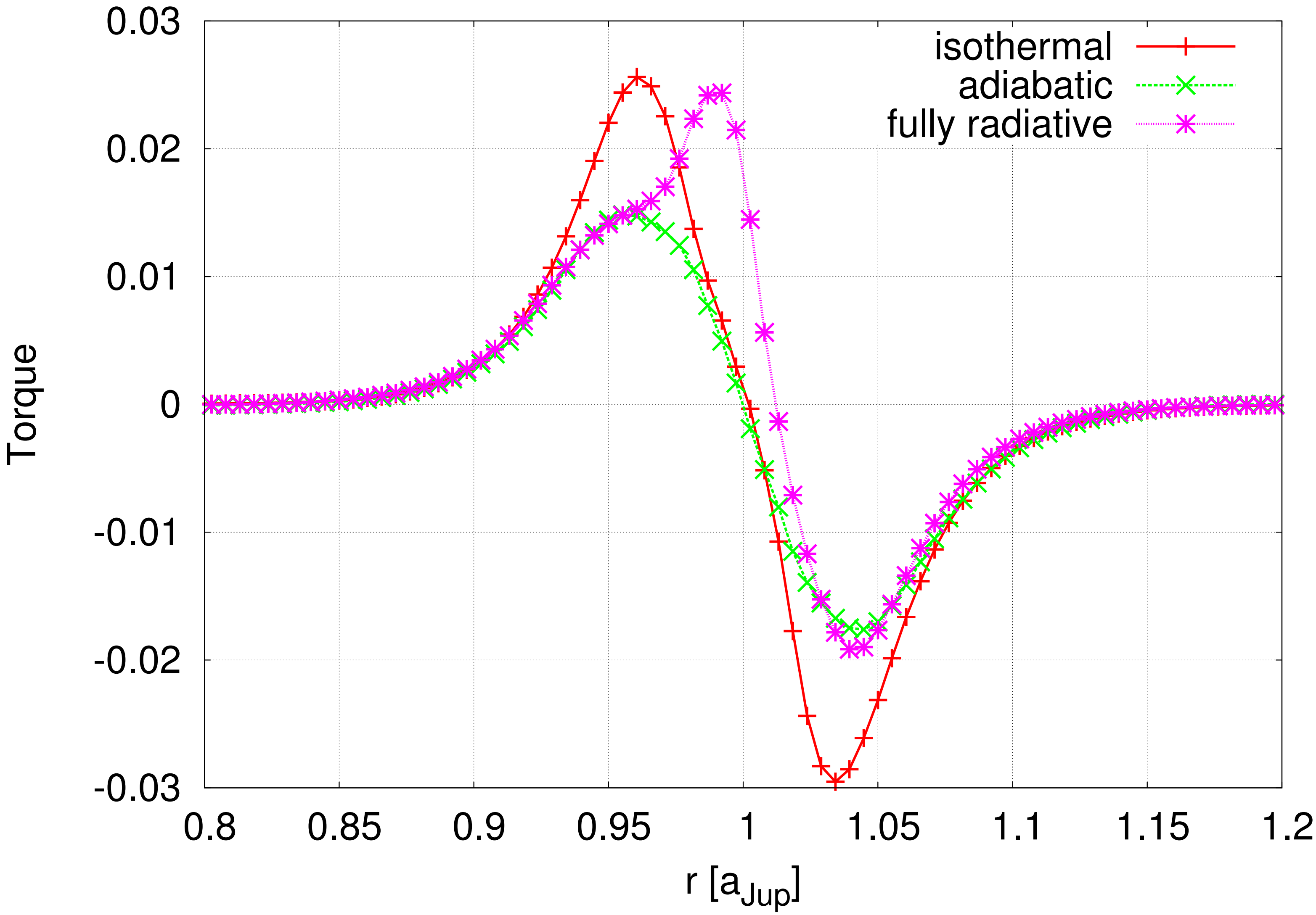
Inward Migration

(Kley&Crida '08)

Radial Torque density

3D-simulations, radiative diffusion, 20 $M_{\rm Earth}$ planet (Kley, Bitsch & Klahr 2009)

$d\Gamma/dm$, with $\Gamma_{\rm tot} = 2\pi \int (d\Gamma/dm)\Sigma dr$ Radiative: $\Rightarrow$ additional positive contrib.

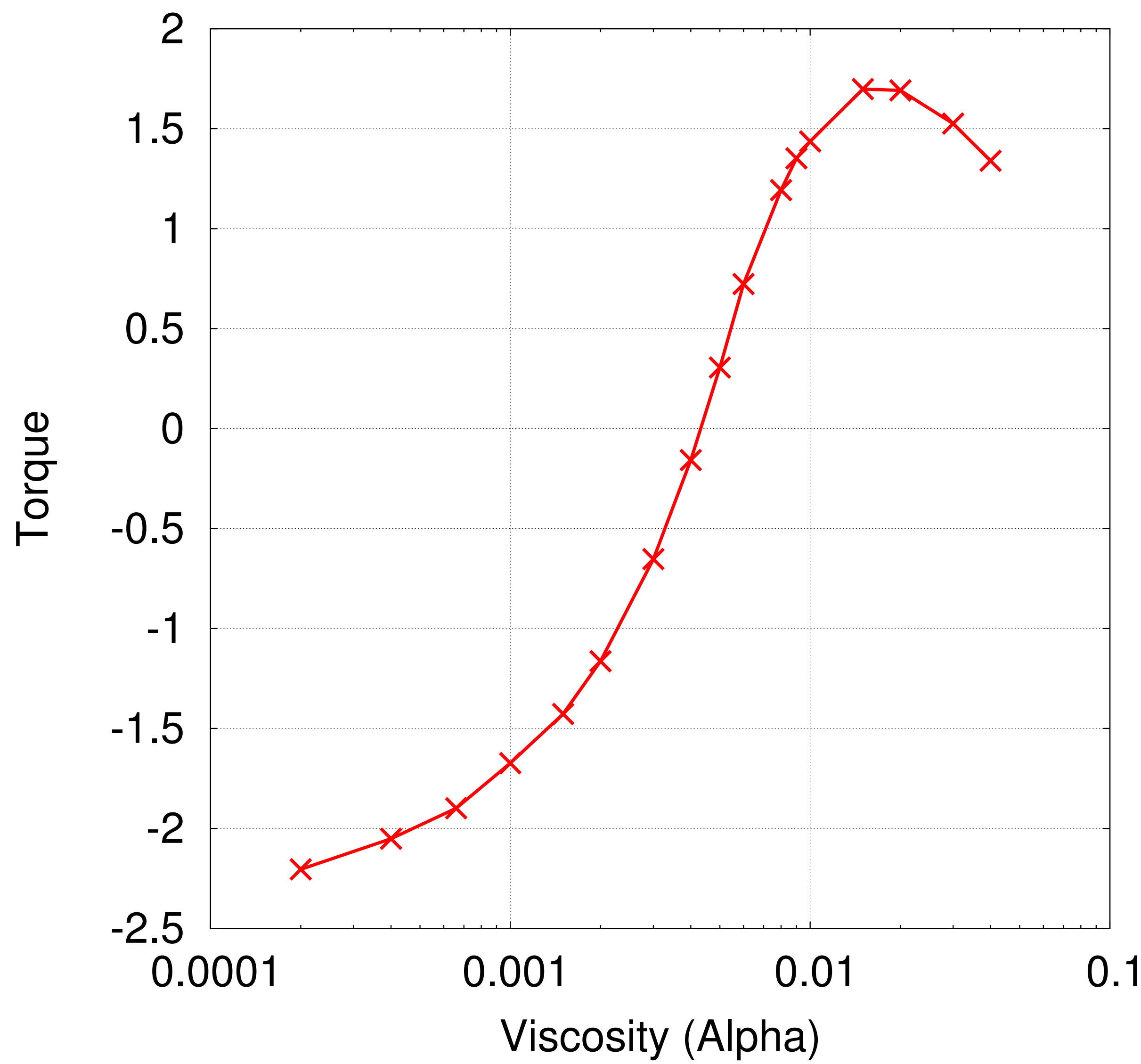


Role of viscosity

Total torque
vs. viscosity:

in viscous α-disk
2D radiative model
- in equilibrium

Efficiency depends
of ratio of timescales
$\tau_{\rm visc}/\tau_{\rm librat}$

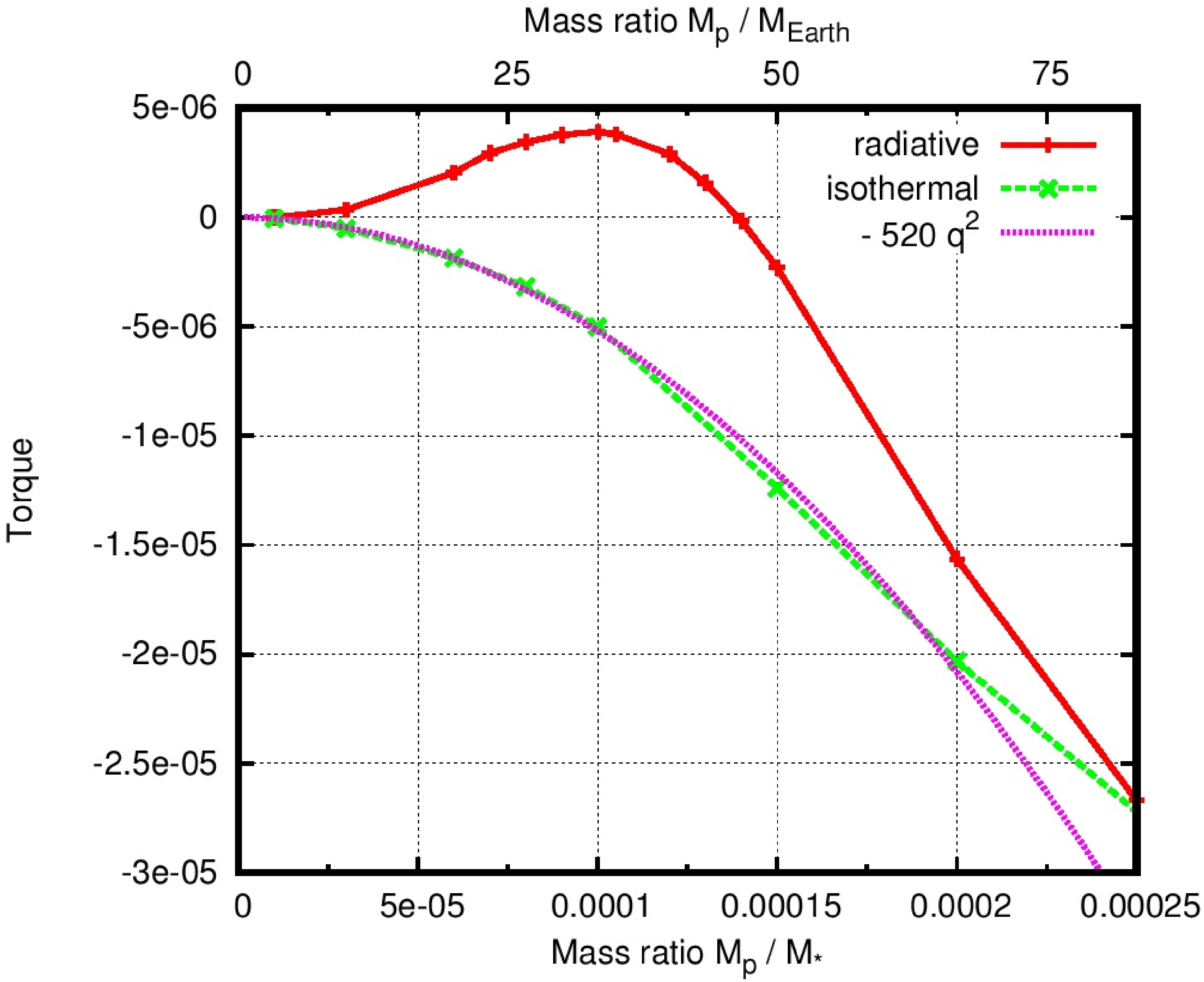


(Kley & Nelson 2012)

$\Rightarrow$ Need viscosity to prevent saturation !

Mass dependence

Isothermal and radiative models. Outward migration for $M_p \leq 40\ M_{\rm Earth}$



Vary M_p

(Kley & Crida 2008)

In full 3D

(Kley ea 2009)

With irradition:

Bitsch ea. (2012)

Evidence

- RV-Obs.: $\approx$ 50 multi-planet extrasolar planetary systems

  $\approx 1/4$ contain planets in a low-order mean-motion resonance (MMR)

  mostly in a 2:1 configuration (eg. GJ 876, HD 128311, HD 82943, ...)

  recently 3:2 (HD 45364) and 3:1 (HD 60532)

  In Solar System: 3:2 between Neptune and Pluto (plutinos)

- Resonant capture through convergent migration process

  dissipative forces due to disk-planet interaction

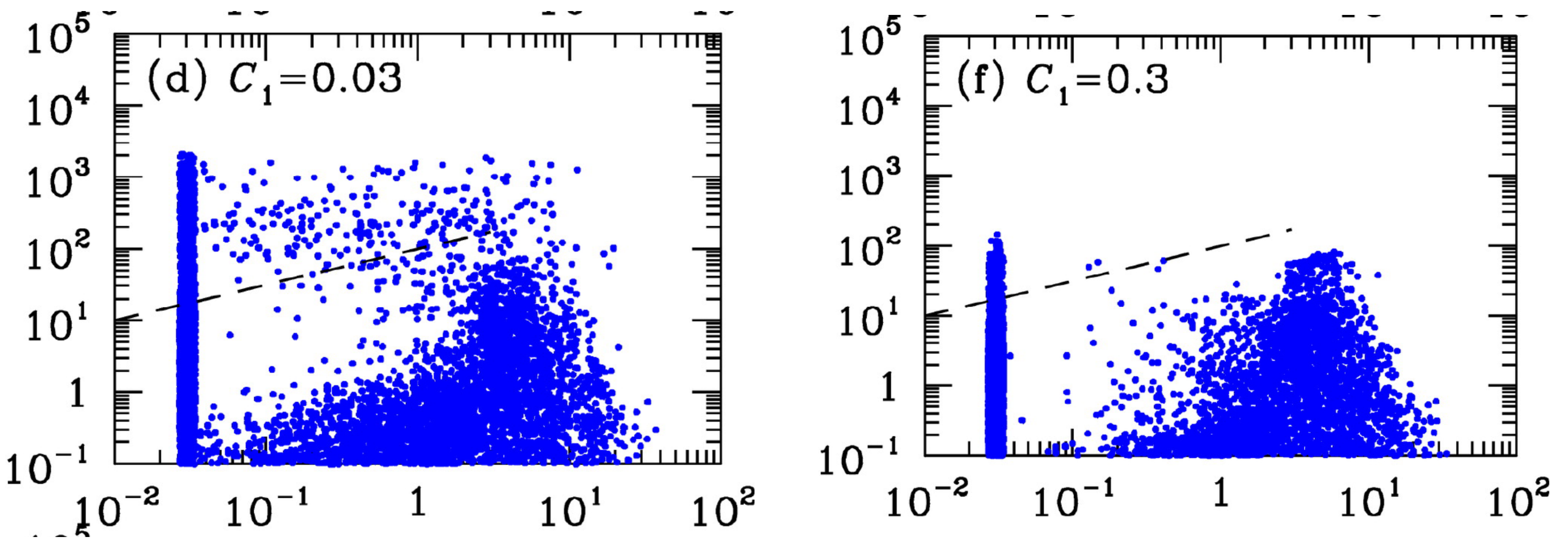
- Existence of resonant systems

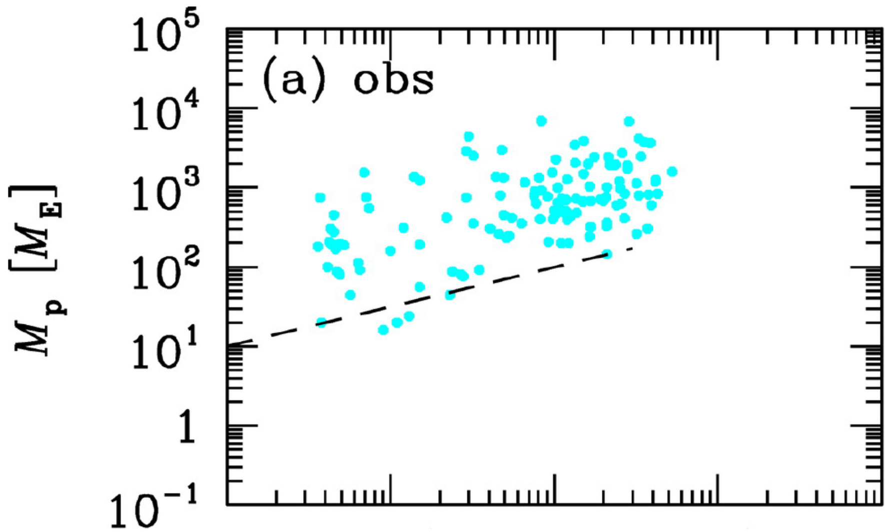
  $\Longrightarrow$ Clear evidence for planetary migration

- Hot Jupiters (Neptunes) & Kepler systems

  $\Longrightarrow$ Clear evidence for planetary migration

Check with Population synthesis





Migration too efficient!
Only strong reduction of Type I gives reasonable results
(Ida & Lin; Mordasini, Alibert & Benz)

⇒ Need improvements:
- stochastic migration
- inviscid, self-grav. disks
- radiative disks (corotation effects)

Summary

Planet-disk interaction: Torques on Planet

Isothermal Migration is inward & rapid (lose planets)

But: $\Gamma_{\rm tot} = \Gamma_{\rm L} + \Gamma_{\rm HS,ent} + \Gamma_{\rm HS,vort}$

Mass limit due to gap opening

Outward in viscous, radiative disks

Driven by:

Vortensity gradient

- maintained by: viscosity

Entropy gradient

- maintained by: rad. diffusion (or cooling)
- cooling time ≈ libration time

Need viscosity

approximate torque formulae: Paardekooper ea; Masset&Casoli

The End