Disk-Planet Interaction

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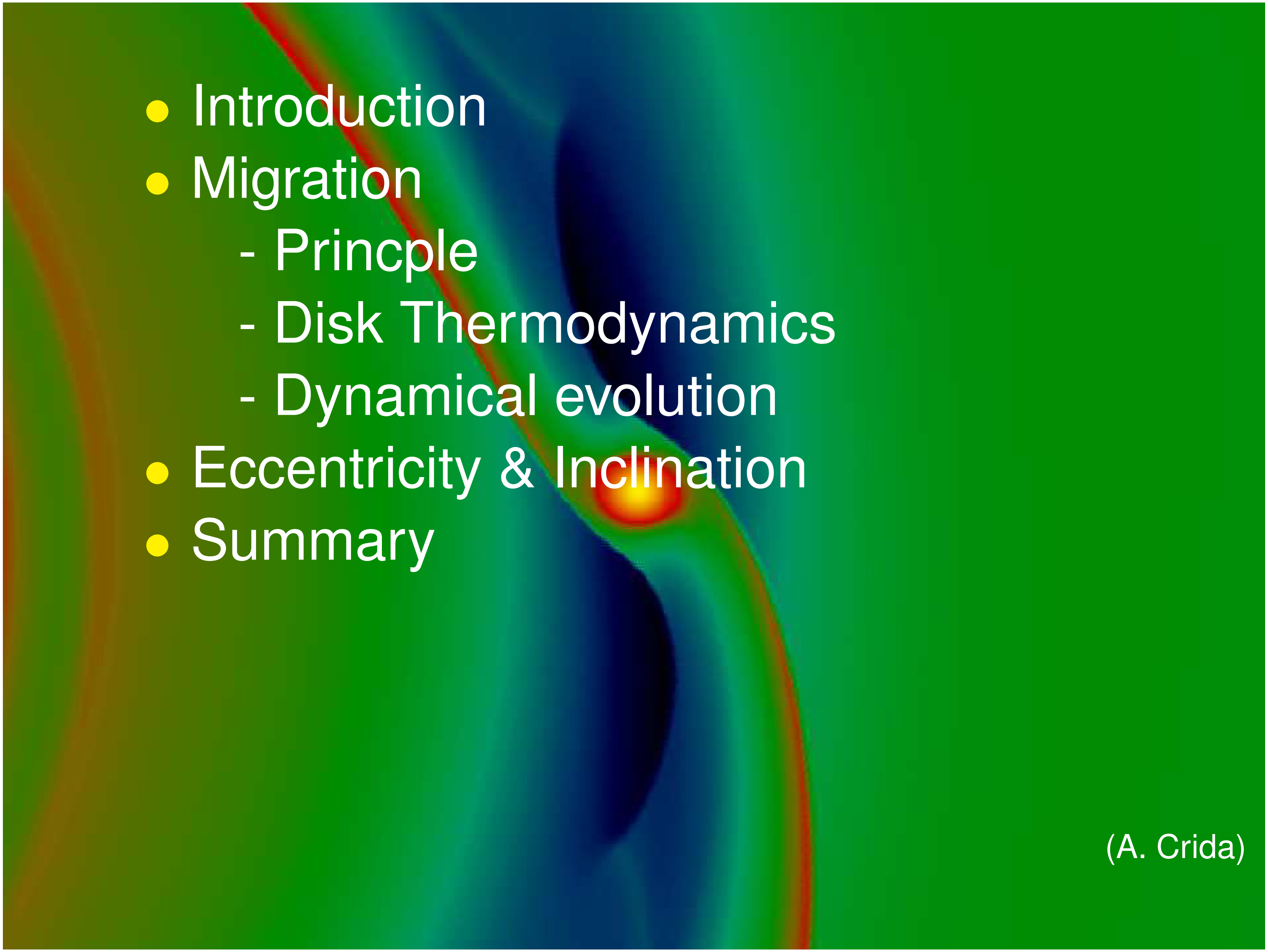
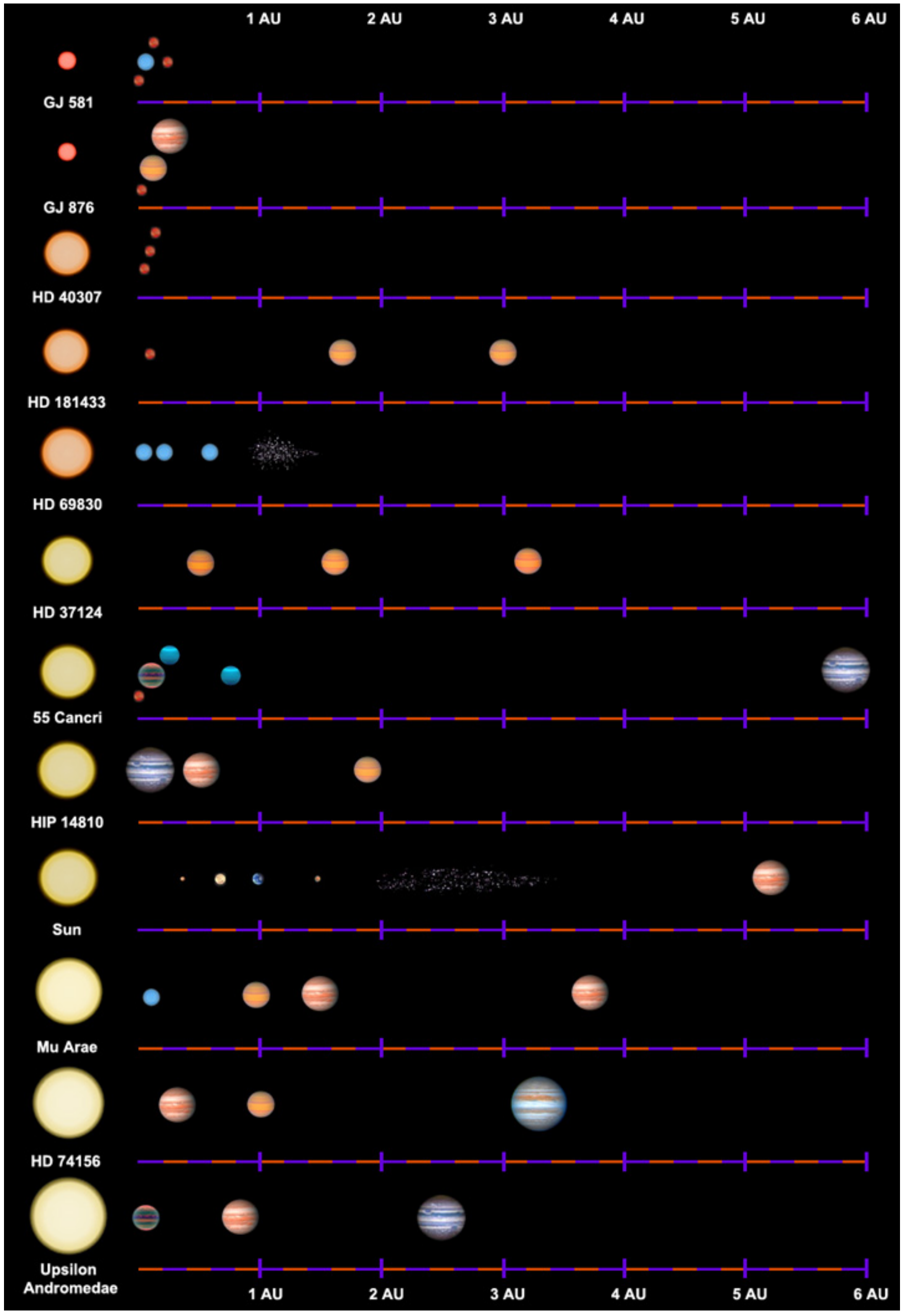
Organisation



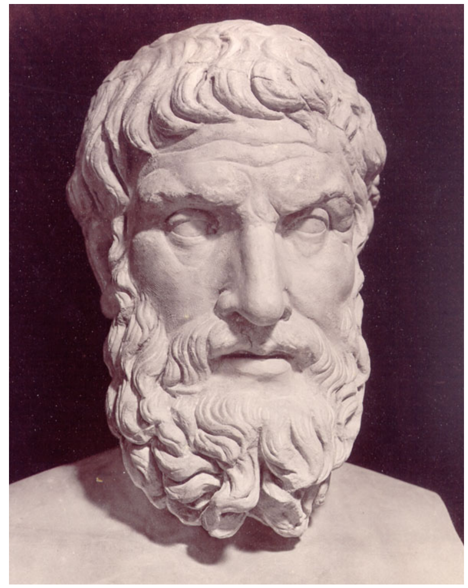
- Introduction
- Migration
    - Princple
    - Disk Thermodynamics
    - Dynamical evolution
- Eccentricity & Inclination
- Summary

(A. Crida)

Planetary Systems



Epikur (ca. 341-270 BC)
"There is an infinite number of worlds, some similar to ours some very different."

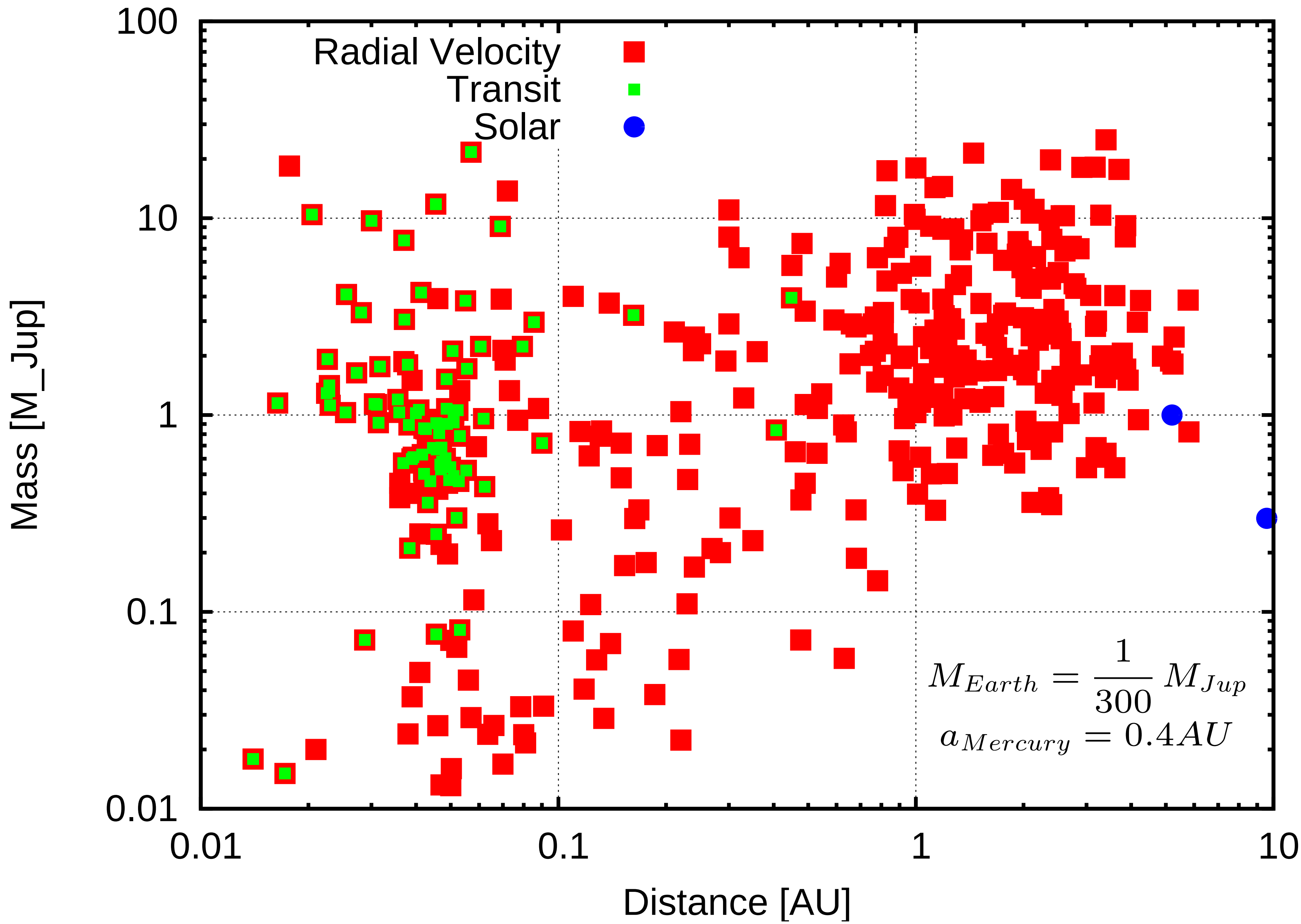


Architecture shaping by

Disk-Planet interaction!

Mass and Distance

Small distances (hot Jupiters) & large masses (Data: exoplanet.eu)



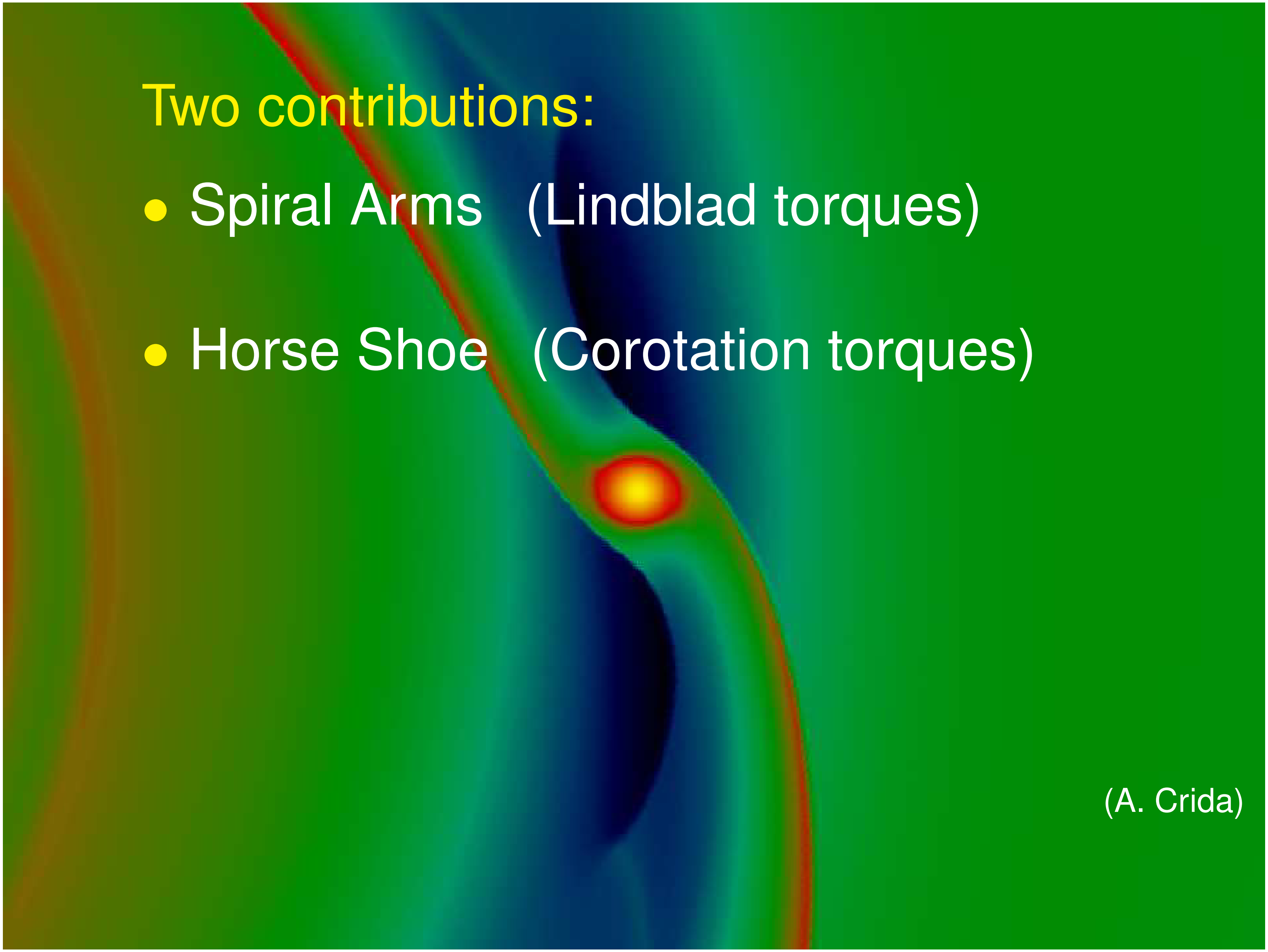
Formation Problems

- 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

But planets grow in disks:

$\Rightarrow$ Have a closer look at planet-disk interaction

Gravitational interaction



Two contributions:

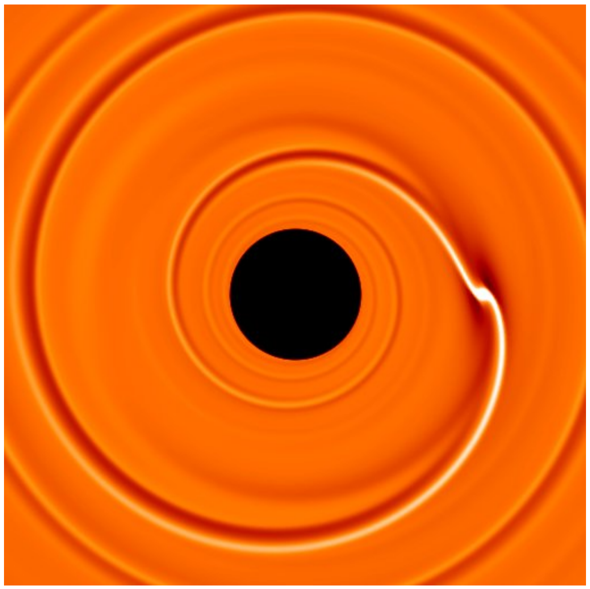
- Spiral Arms (Lindblad torques)
- Horse Shoe (Corotation torques)

(A. Crida)

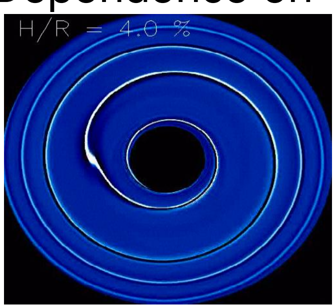
Lindblad Torques

Planet with 20 M_{Earth}
in protoplanetary Disk
Hydrodynamical Simulation
Disk with constant density

(Masset, 2002)



Dependence on Temperature, c_s



(Masset, 2002)

Planet generates spiral waves
in the density of the disk

Spirals are maxima of density

Gravitational interaction with planet

Inner Spiral
- pulls planet forward:
- positive torque

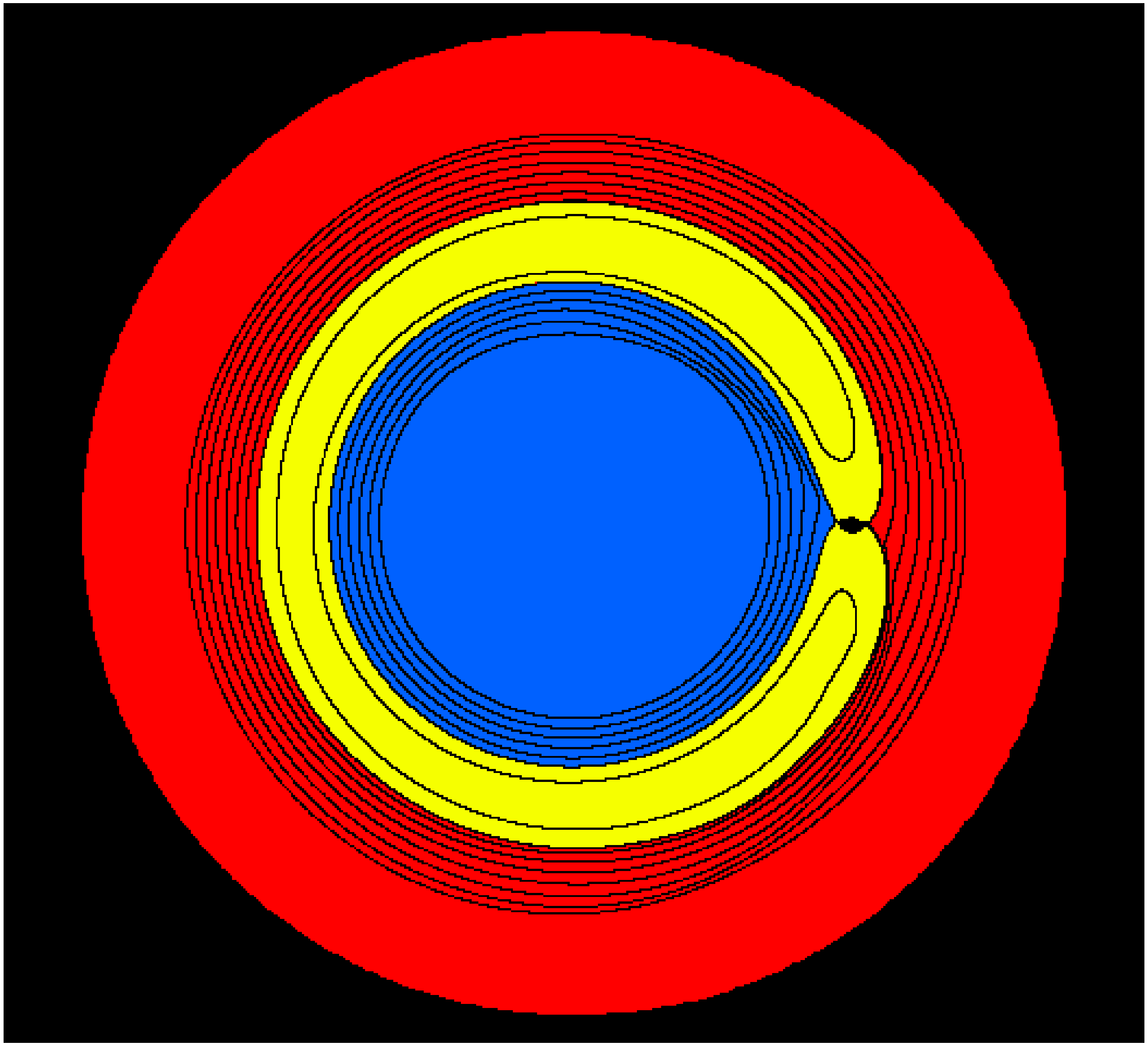
Outer Spiral
- pulls planet backward:
- negative torque

$\longrightarrow$ Net Torque

$\Longrightarrow$ Migration

Most important:
Strength & Direction ?

Corotation Torques



(F. Masset)

3 Regions

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

Horseshoe (coorbital)
$\Longrightarrow$ Corotation Torques

Efficiency:
- Difference: inward-outward kick

Scaling with:
- Vortensity gradient
- Entropy gradient

Linear Theory: Modal analysis

Axisymmetric, constant density disk, differential rotation with $\Omega(r)$

Decompose the planet potential

$$\psi_p(r,\varphi,t) = \sum_{m=0}^{\infty} \psi_m(r) \cos\{m[\varphi - \varphi_p(t)]\}$$

$\varphi_p = \Omega_p t$ Azimuth angle of the planet
$\psi_m(r)$: m-folded potential, rotating with pattern-speed Ω_p

Frequency of potential in matter frame $\omega = m(\Omega(r) - \Omega_p)$

Response when ω matches either 0 or $\pm\kappa$

(κ epicyclic frequency)

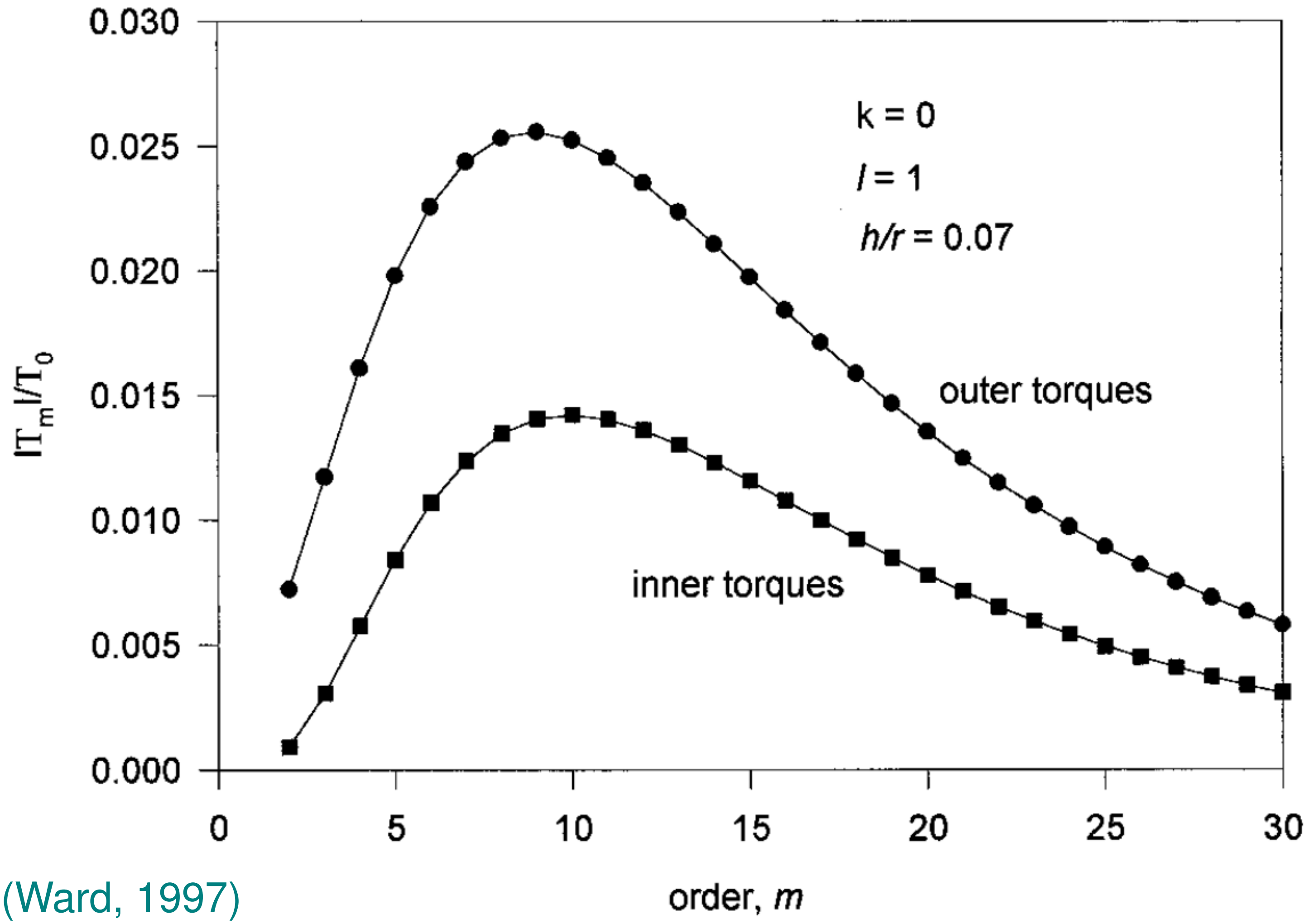
$\omega = \pm\kappa$: Outer or Inner Lindblad Resonance (Spirals)
$\omega = 0$: Corotation Resonance (Horseshoe)

Linearize hydrodynamic equations (Goldreich & Tremaine; Lin & Papaloizou)

Lindblad torques

$$\Gamma_{tot} = \int_{disk} \Sigma(\vec{r} \times \nabla\psi_p)\, df = \int_{disk} \sum_m \Sigma \frac{\partial \psi_m}{\partial \varphi} df = \sum_m \Gamma_m$$

Absolute value of Torque $|\Gamma_m|$ due to spirals for each mode m



(Ward, 1997)

Outer spiral wins

Inward migration

Migration rate (Lindblad Torques)

Migration Timescale $\tau_{\rm M}$ from $\dot{L} = \Gamma$ with $L_{\rm P} = m_{\rm P}\sqrt{G M_* a_{\rm P}}$

$$\frac{1}{a_{\rm P}} \frac{d a_{\rm P}}{dt} = \frac{1}{\tau_{\rm M}} = 2 \frac{\Gamma}{L_{\rm P}} \tag{1}$$

Lindblad torques: 3D results from spirals (Tanaka et al. 2002)

$$\Gamma_{\rm L} = -(2.34 - 0.1 \alpha_\Sigma)\,\Gamma_0 \quad \text{with} \quad \Gamma_0 = \left(\frac{m_{\rm P}}{M_*}\right)^2 \left(\frac{H}{r}\right)^{-2} \Sigma_{\rm p}\, a_{\rm p}^4\, \Omega_{\rm P}^2 \tag{2}$$

with density slope $\Sigma \propto r^{-\alpha_\Sigma}$ (3)

Time scale: 1 $\rm M_{Earth}$ at 1 AU: 10^5 Years (shorter than growth time)

Corotation Torque

$$\Gamma_{\rm CR} \propto \frac{d}{dr}\left(\frac{\Sigma}{B}\right) \tag{4}$$

Where B is the 2nd Oort constant. Note: B/Σ is specific vorticity

Corotation torques: from horseshoe region (Tanaka et al. 2002)

$$\Gamma_{\rm CR} = 1.36\left(\frac{3}{2} - \alpha_\Sigma\right)\Gamma_0 \tag{5}$$

Total torque (spirals and corotation)

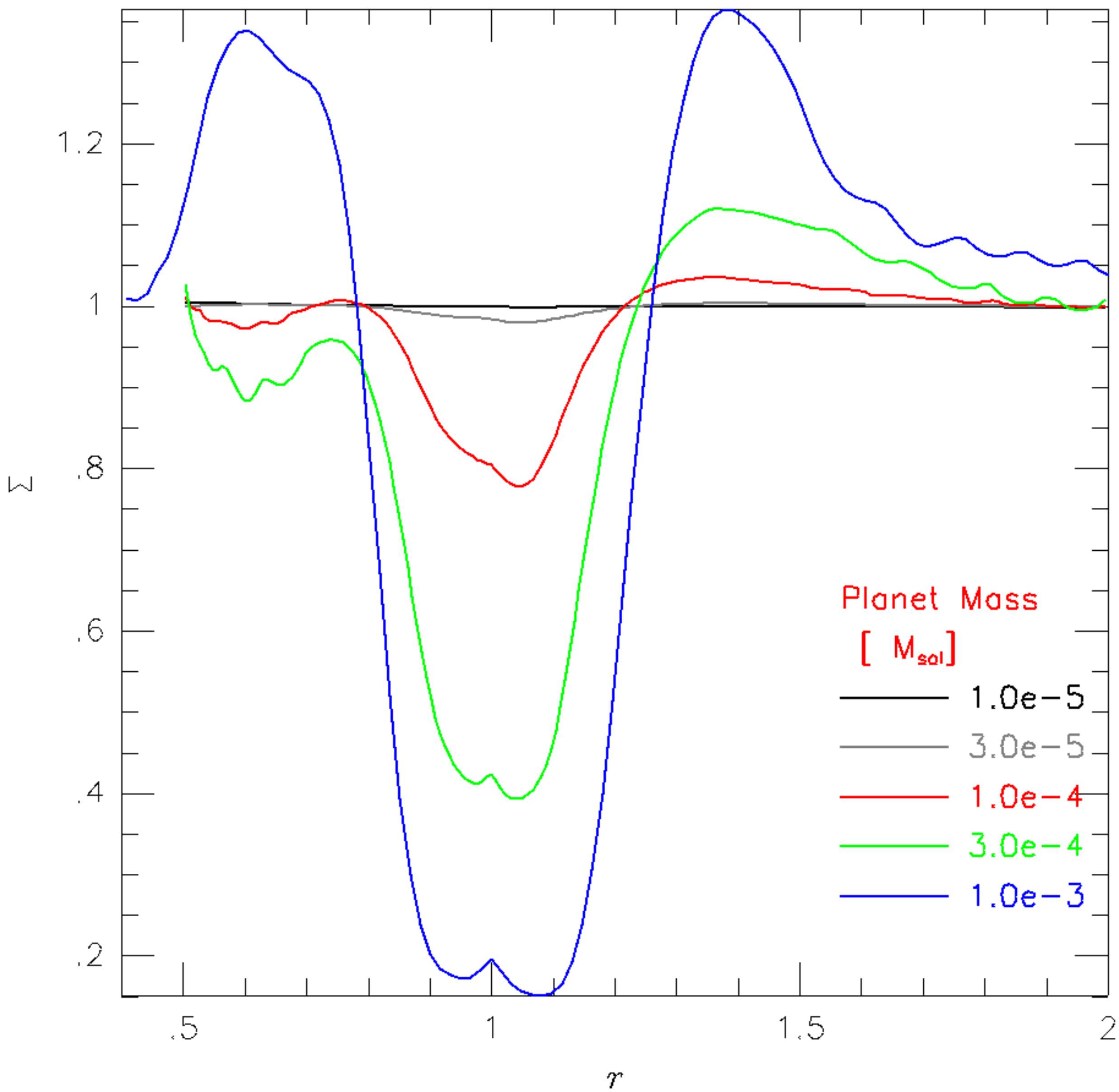
$$\Gamma = \Gamma_{\rm L} + \Gamma_{\rm CR} \tag{6}$$

Typically: $|\Gamma_{\rm CR}| < |\Gamma_{\rm L}|$ Inward migration

NOTE: In MMSN $\Sigma \propto r^{-3/2}$, i.e. $\alpha_\Sigma = 1.5 \Longrightarrow \Gamma_{\rm CR} = 0$

In linear theory: Migration inward and rapid !

Type I ⇒ Type II Gap Formation



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 Planet Mass

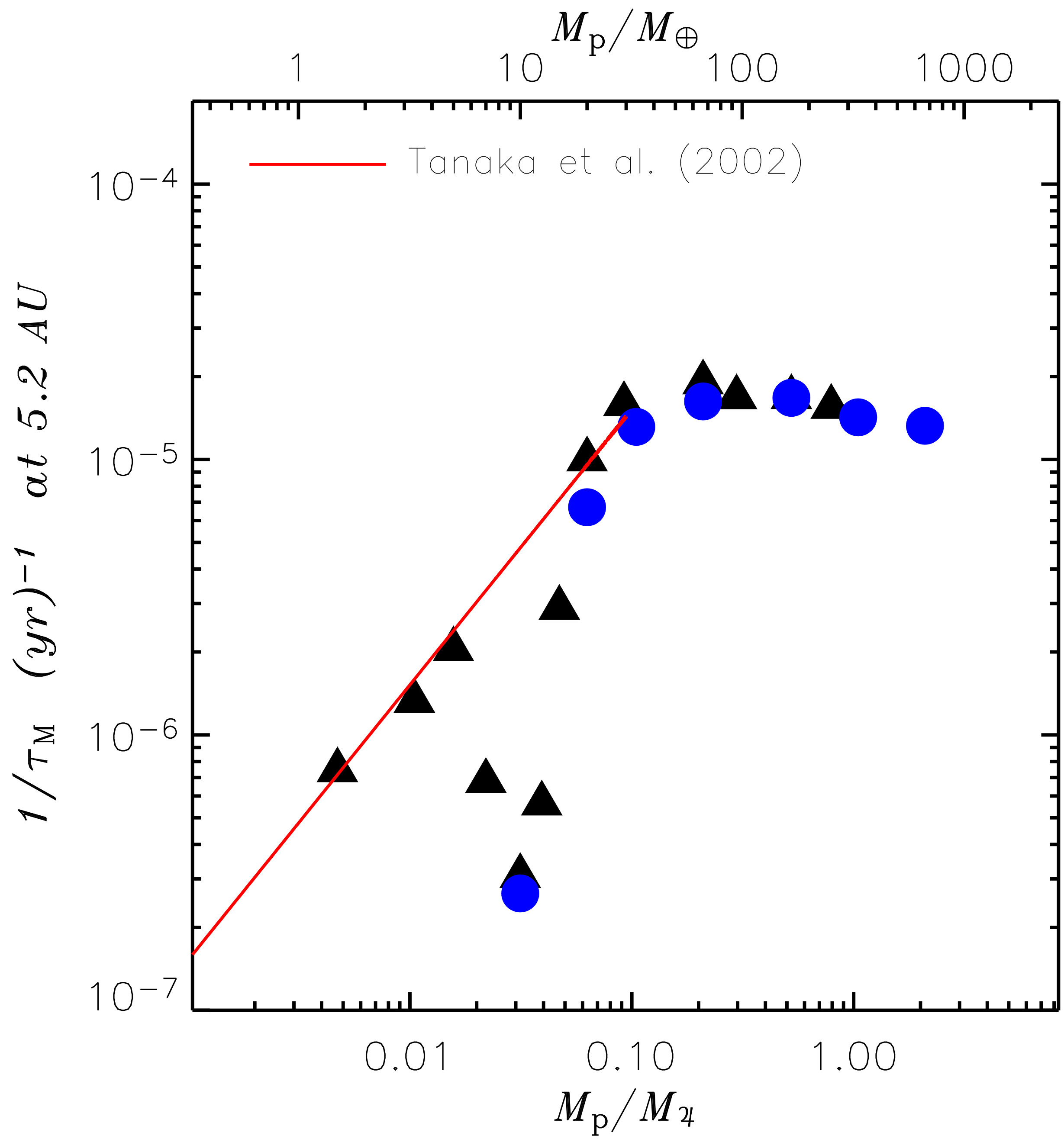
Torques reduced:

Migration slows

Type I ⇒ Type II

linear ⇒ non-linear

Migration Rate: Isothermal disk



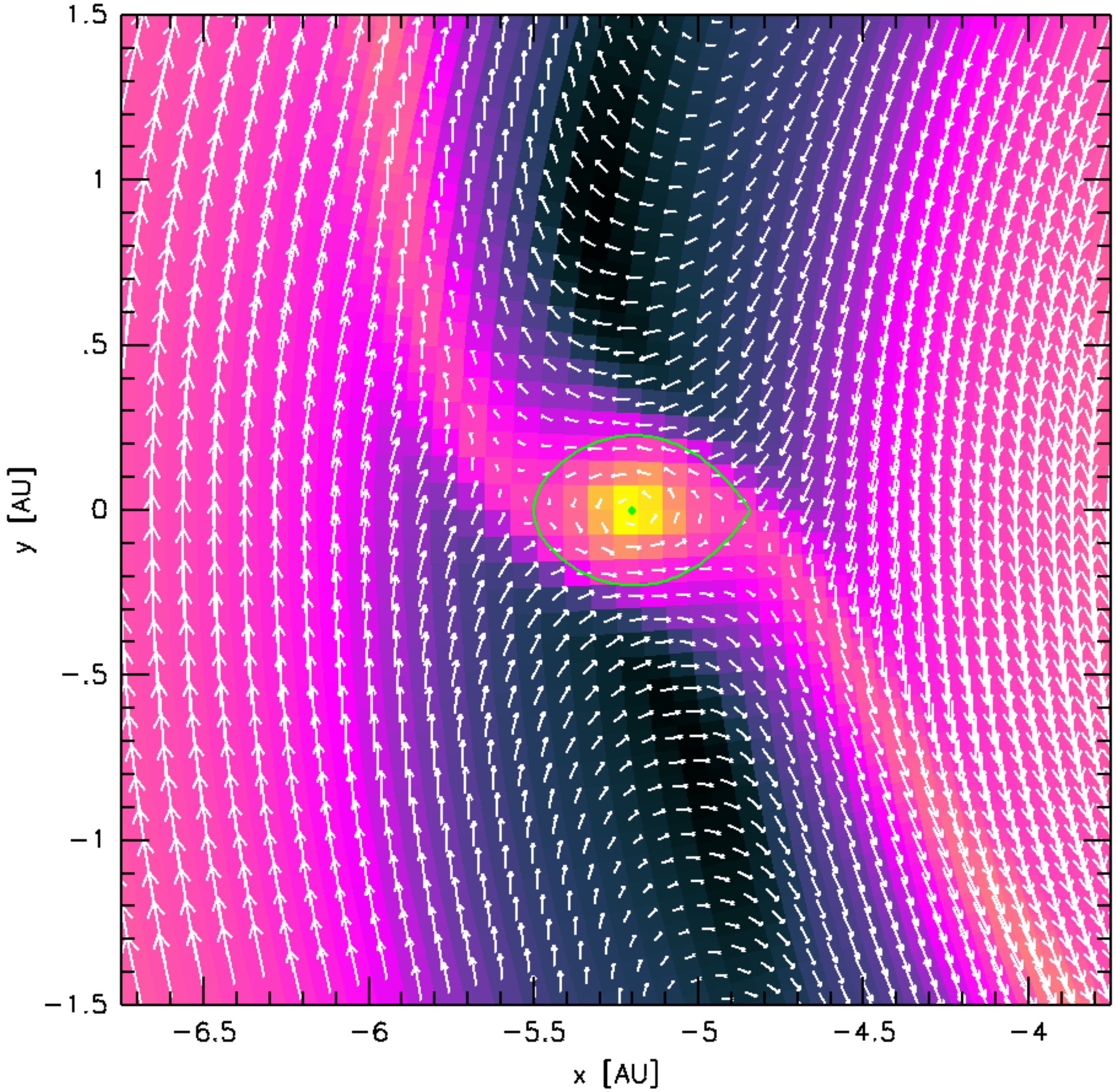
$\tau_{\rm M} = \frac{a}{\dot a}$ **vs** $M_{\rm P}$

Symbols:
Full Hydro
3D-Nested Grid
Σ(r) $\propto$ r$^{-1/2}$
D'Angelo et al. (2003)

Red Line:
Linear Theory
Tanaka et al. (2002)

Dip:
Corotation Effects
Non-linear for
$M_p \approx 10 M_{Earth}$
Depend on $\Sigma(r), H/r$
Analyzed by
(Masset et al. 2006)

Flow field & Mass grow



Surface Density
at 200 Orbits

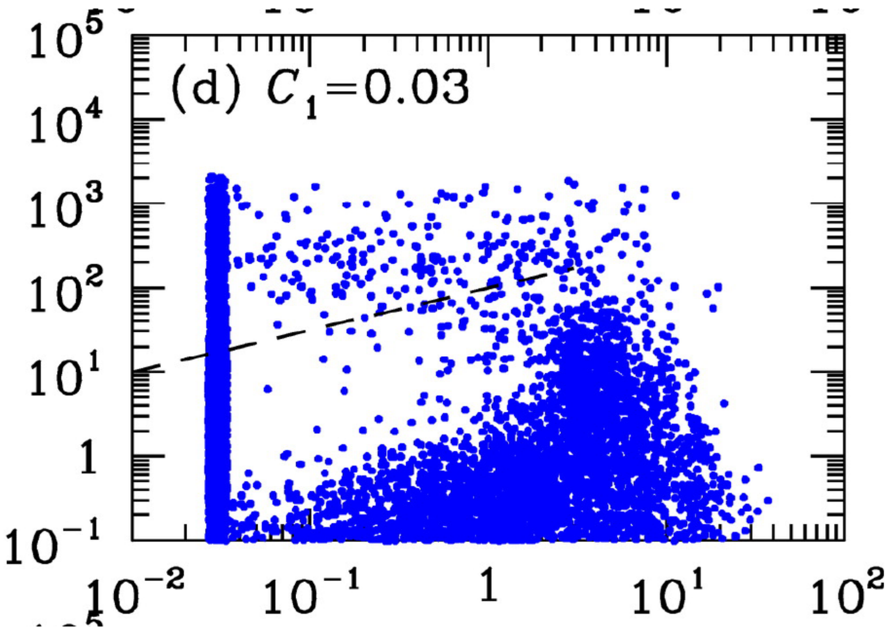
Green Dot: Planet
Green Line:
Roche-Lobe

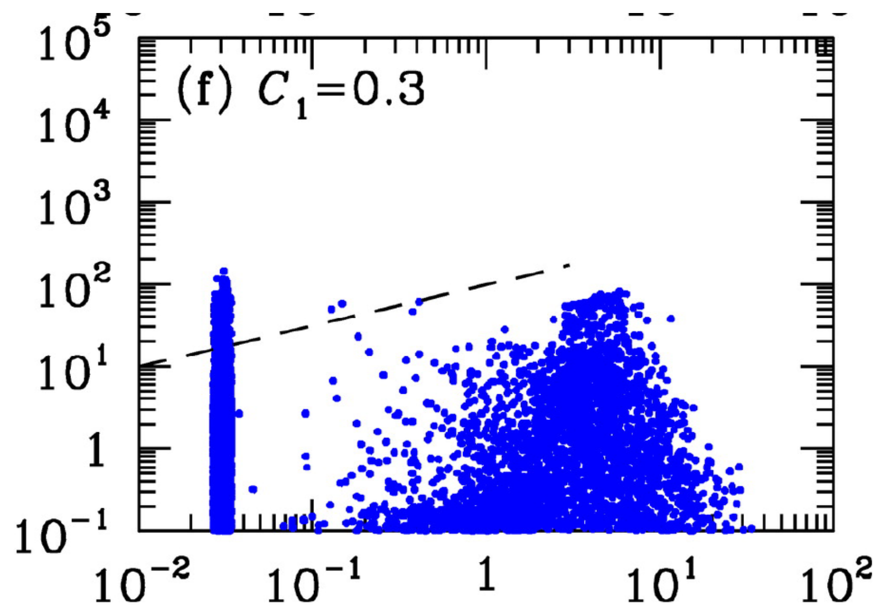
m_p = 1 M_{Jup}
a_p = 5.2 AE

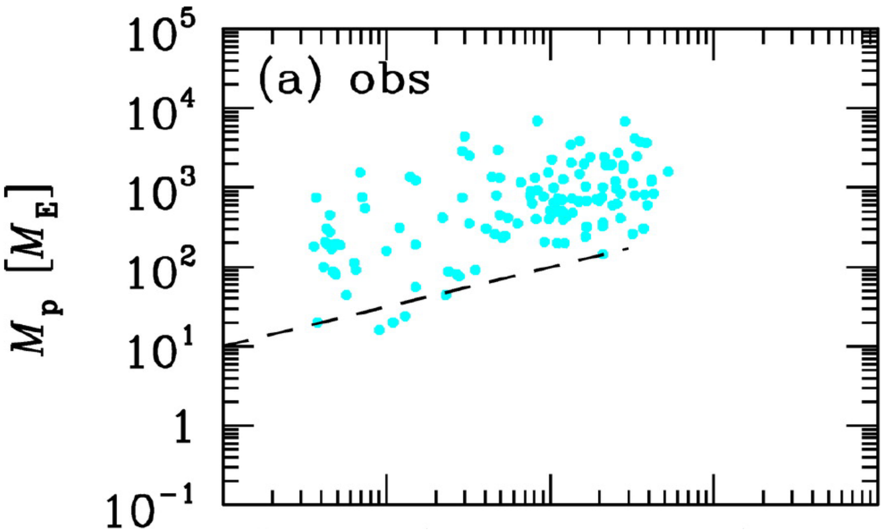
Flow-Field
⟶ Mass growth
up to a few M_{Jup}
⟶ prograde rotation

(WK, 2000)

Check with Population synthesis







Migration too efficient!

Only strong reduction of Type I (C_1) gives reasonable results

(Ida & Lin; Mordasini, Alibert & Benz)

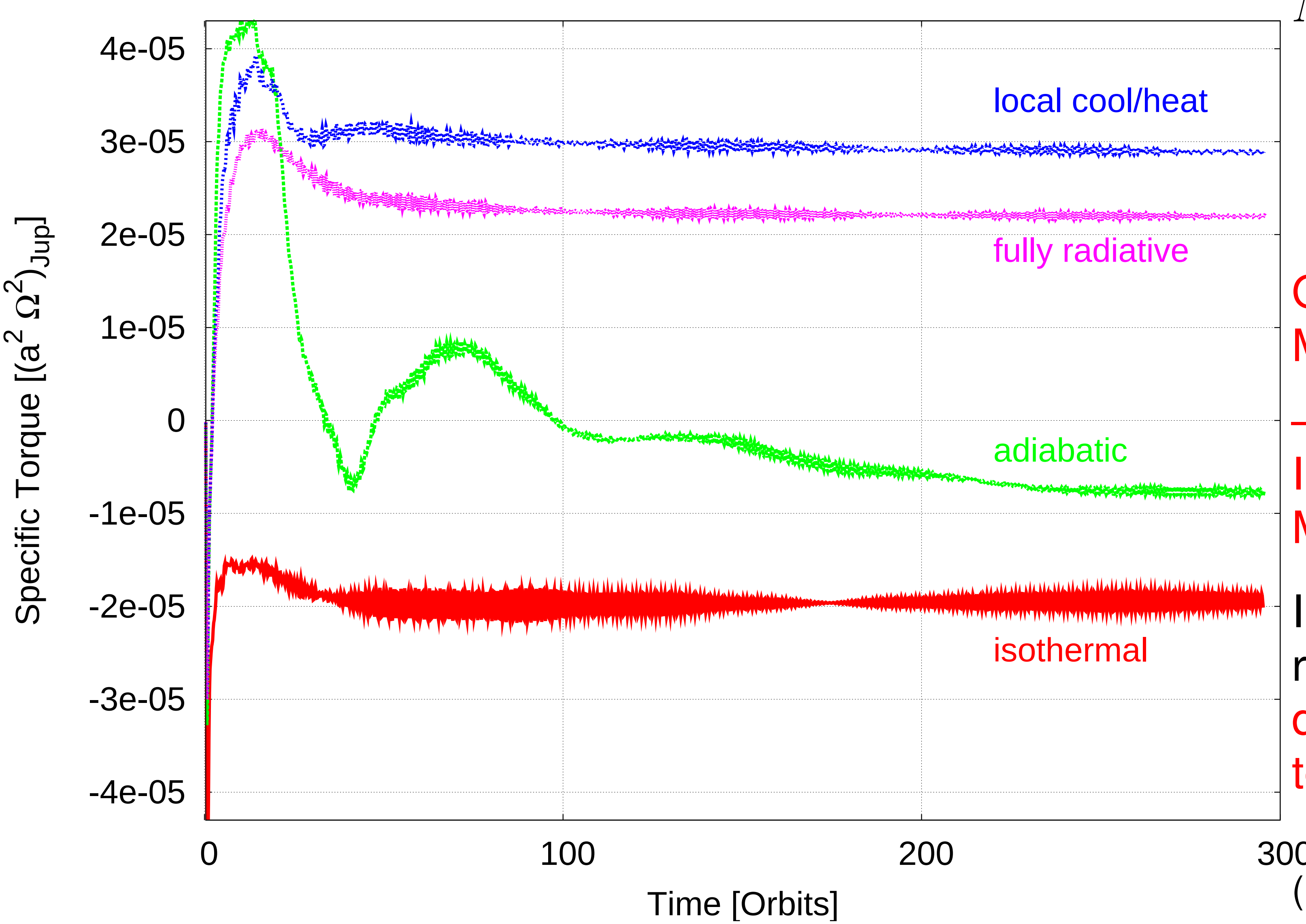
$\Rightarrow$ Need improvements:

- stochastic migration
- inviscid, self-grav. discs
- here: radiative disks

Add disk physics (2D)

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

$M_p = 20 M_{Earth}$



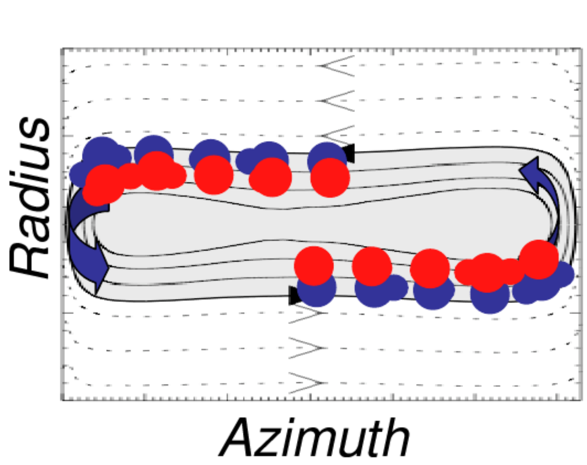
Outward Migration

Inward Migration

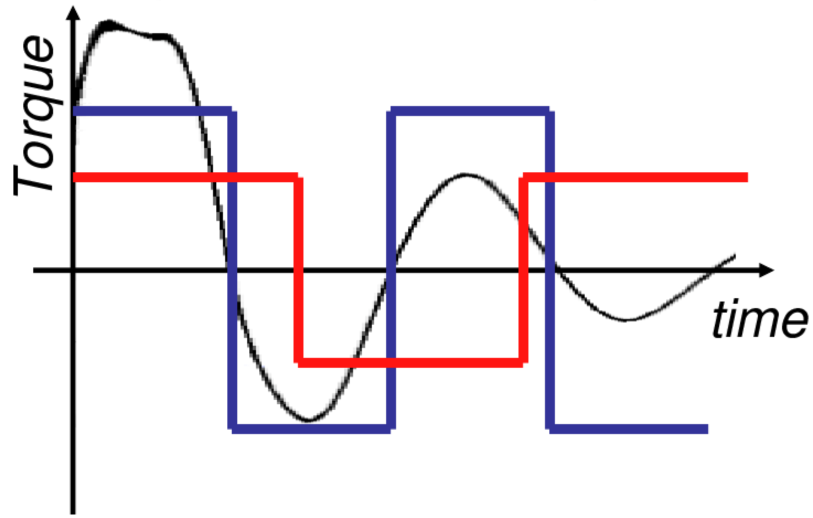
Inclusion of radiation desaturates torques

(Kley&Crida '08)

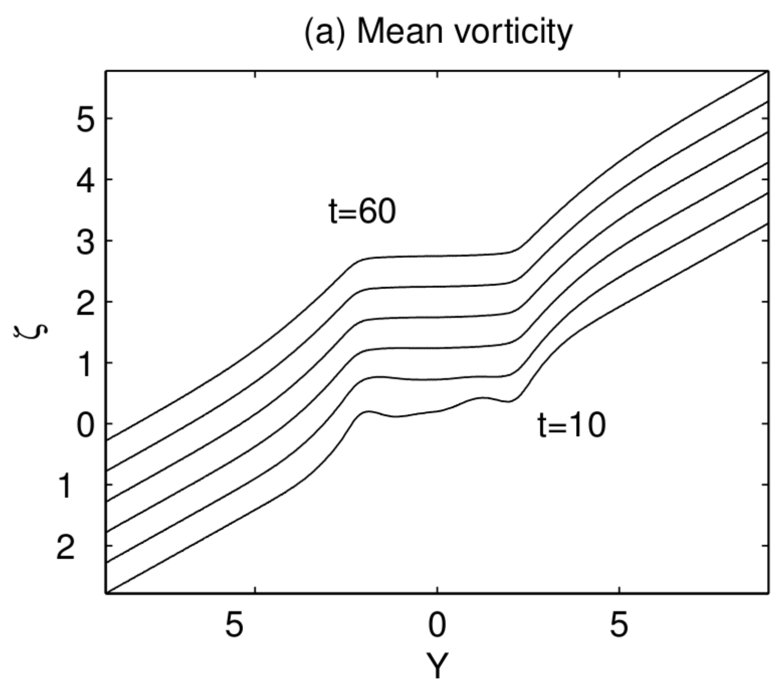
Torque Saturation



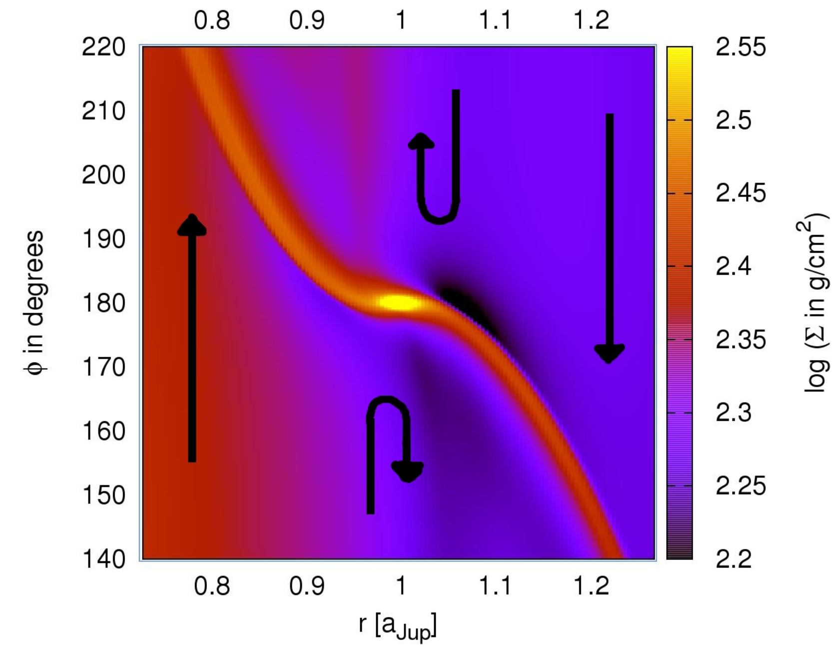
(F. Masset)



Red and Blue Orbits have different periods
⇒ Phase mixing



(Balmforth & Korycanski)

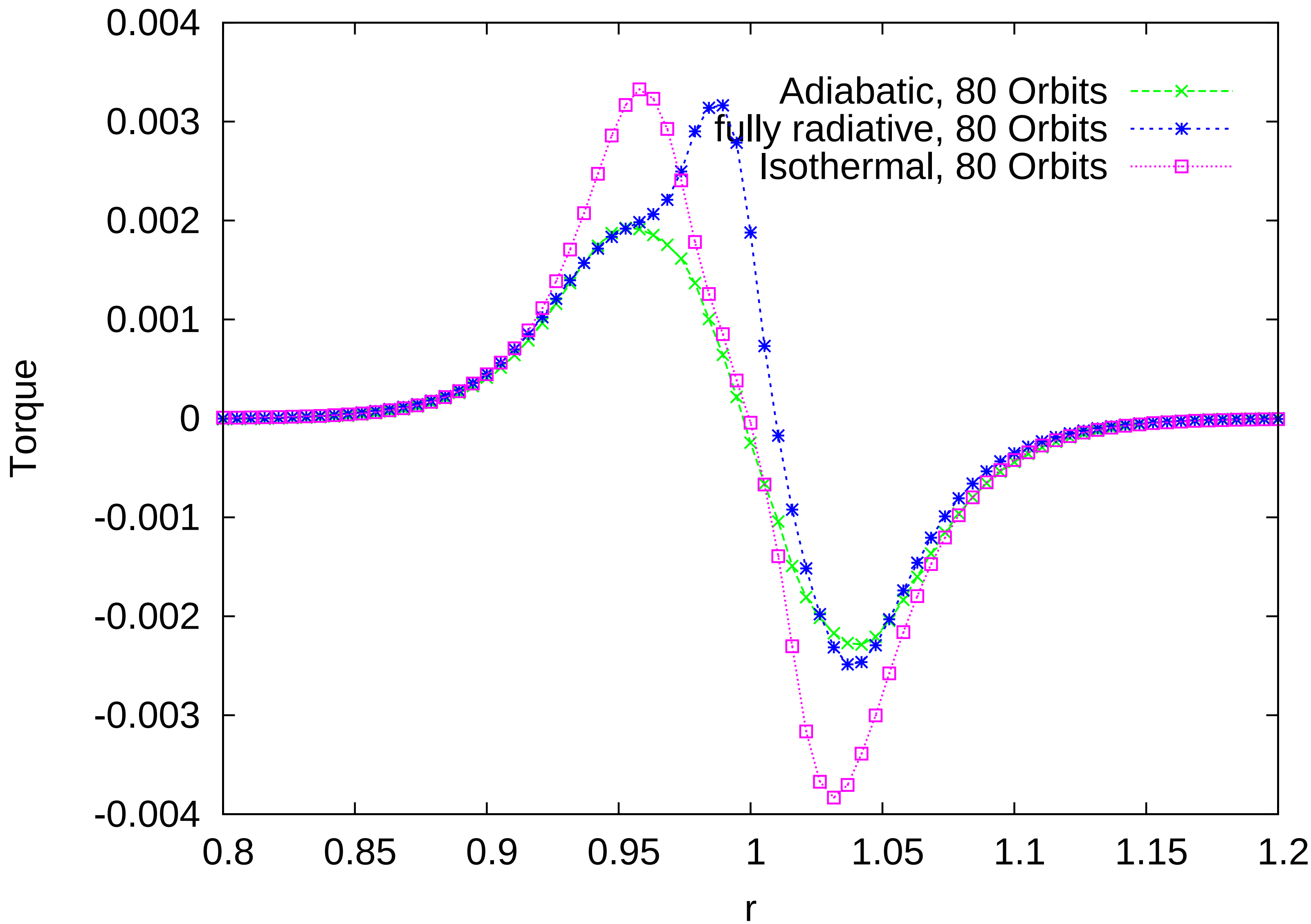


3D radiative disk (B. Bitsch)

Radial Torques density

3D-simulations, radiative diffusion, 20 M_{Earth} planet (Kley,Bitsch&Klahr '09)

$\Gamma(r)$, with $\Gamma_{tot} = \int \Gamma(r) dr$ Radiative: $\Rightarrow$ additional positive contrib.



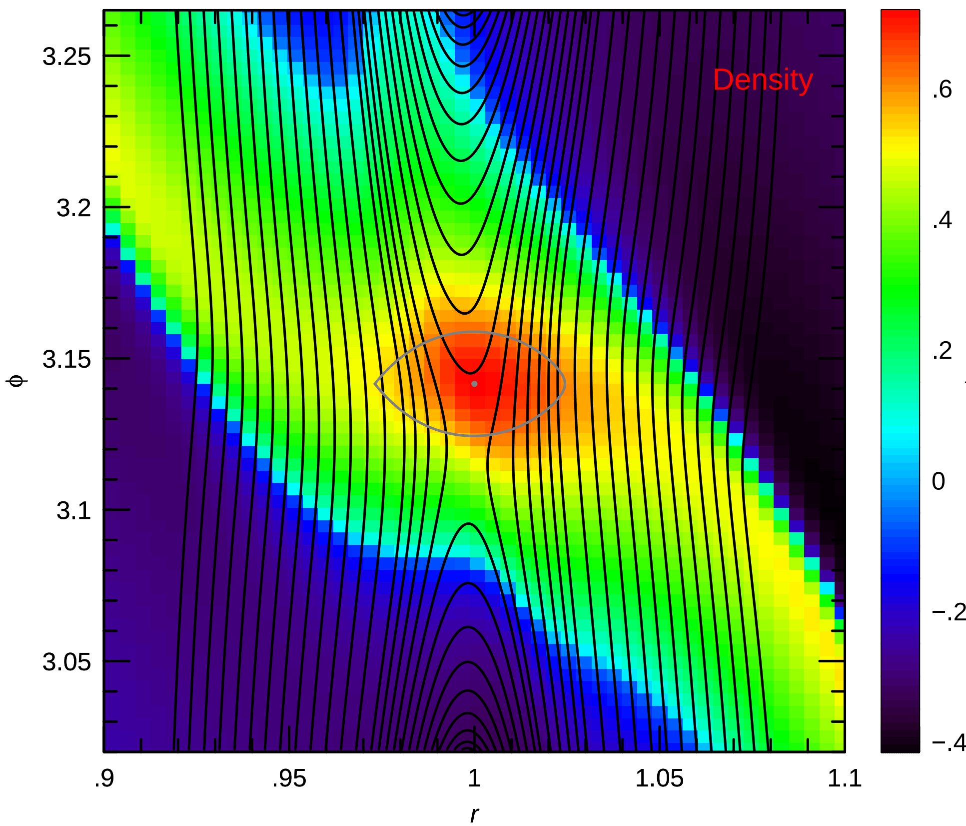
Spatial origin of torques ($r - \varphi$ plot)

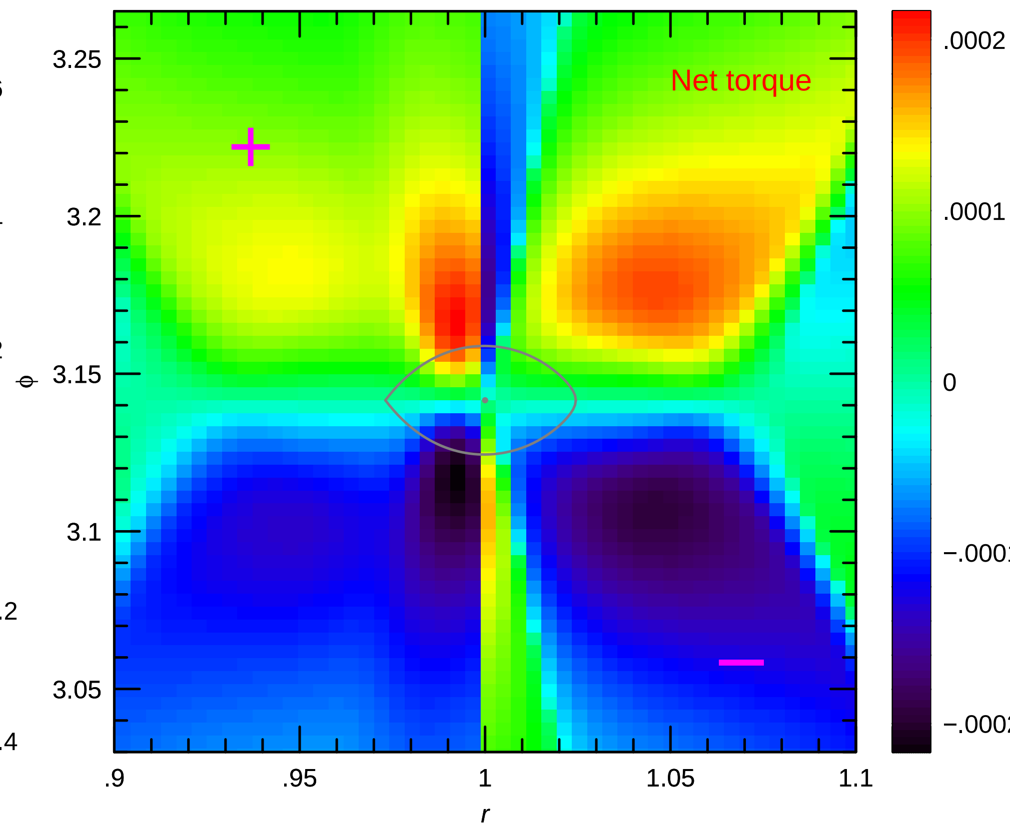
Perturbed Density

$(\Sigma - \Sigma_0)/\Sigma_0$

Net Torque contributions

$\pm\,(\Gamma(r,\varphi_p+\varphi) - \Gamma(r,\varphi_p-\varphi))$



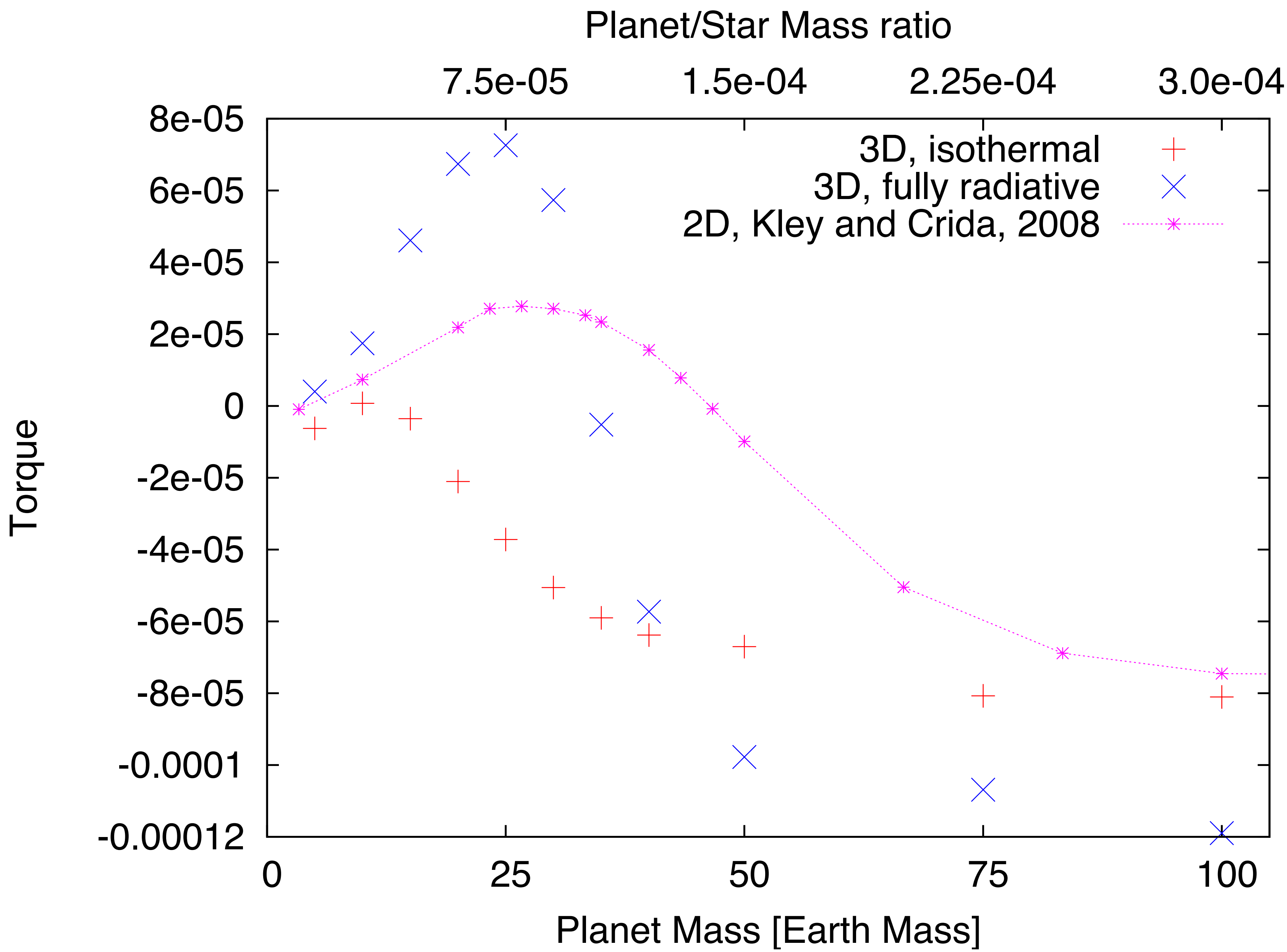


- asymmetric density and torques: − Trailing + Leading

$\Longrightarrow$ positive torques (Horseshoe drag: Ward, 1991)

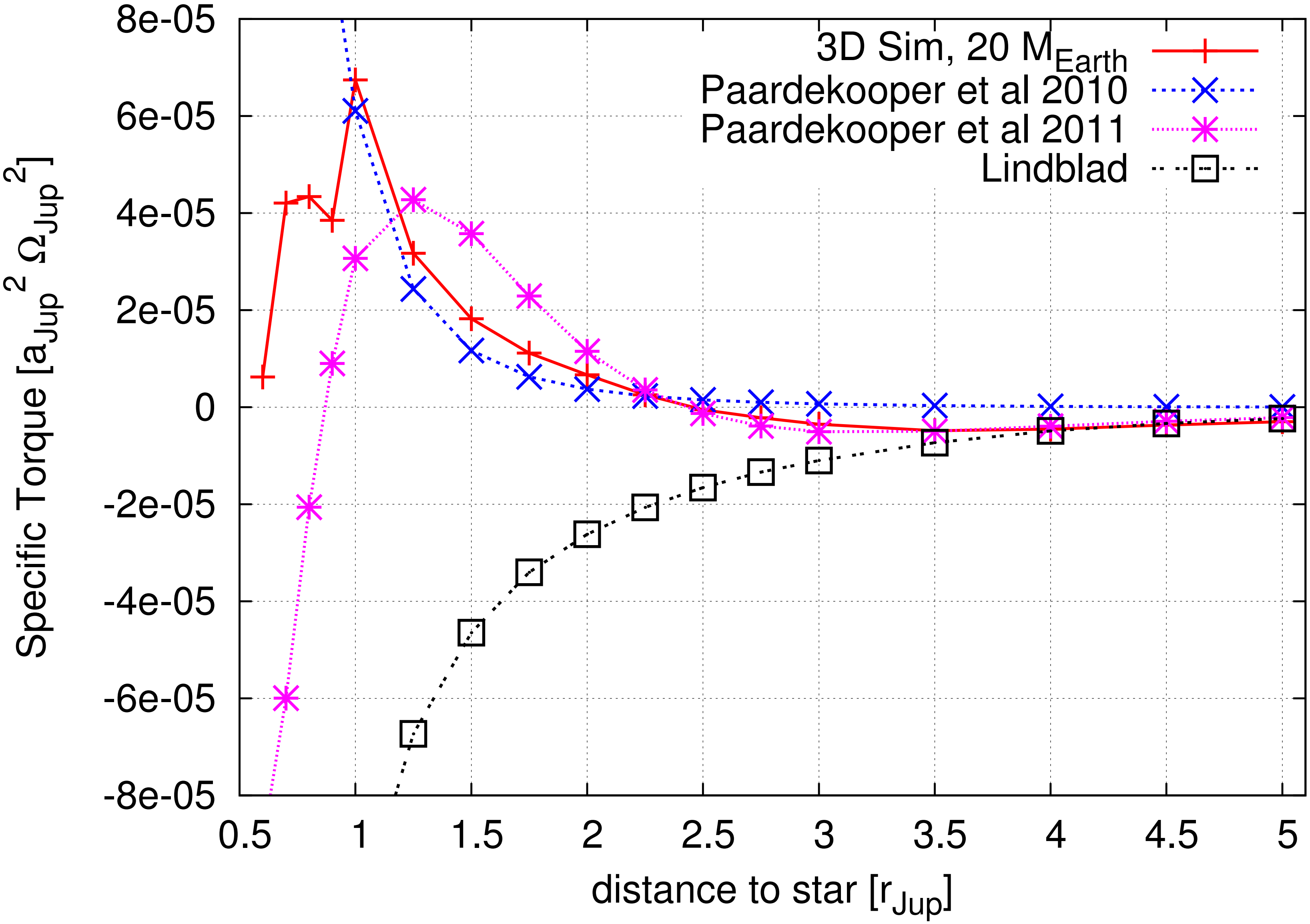
Mass dependence

Isothermal and radiative models   Outward migration for $M_p \leq 35 M_{Earth}$

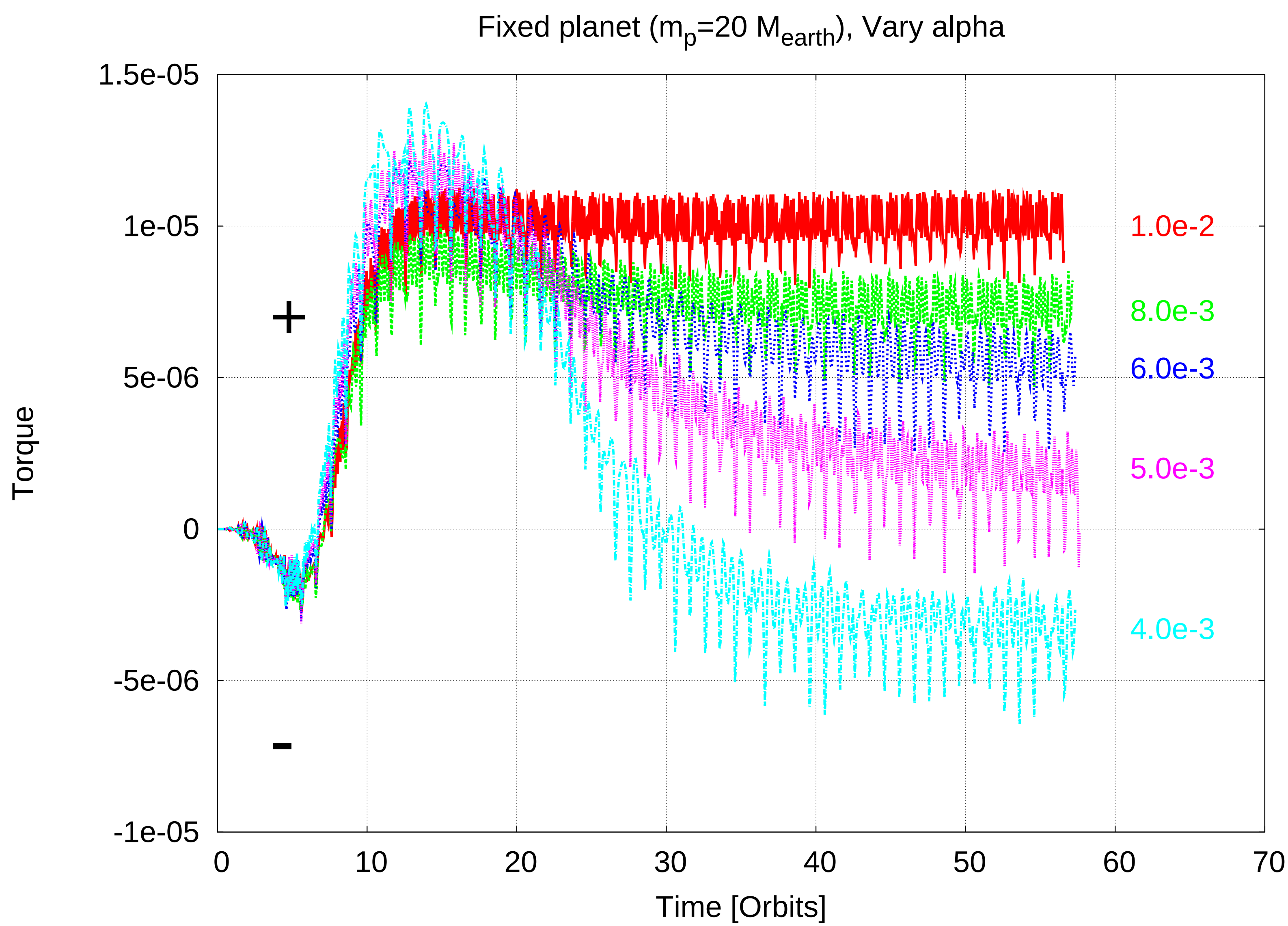


Range of outward migration

Place planets at various distances (Bitsch & Kley, 2011)



Influence of viscosity



Need viscosity (Turbulence) to maintain desaturation

Summary Migration (Type I,II)

Planet-disk interaction: Torques on Planet

Isothermal Migration is inward & rapid (lose planets)

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

Outward in radiative disks

Mass limit due to gap opening

Driven by:

Vortensity gradient

Entropy gradient

maintained by:

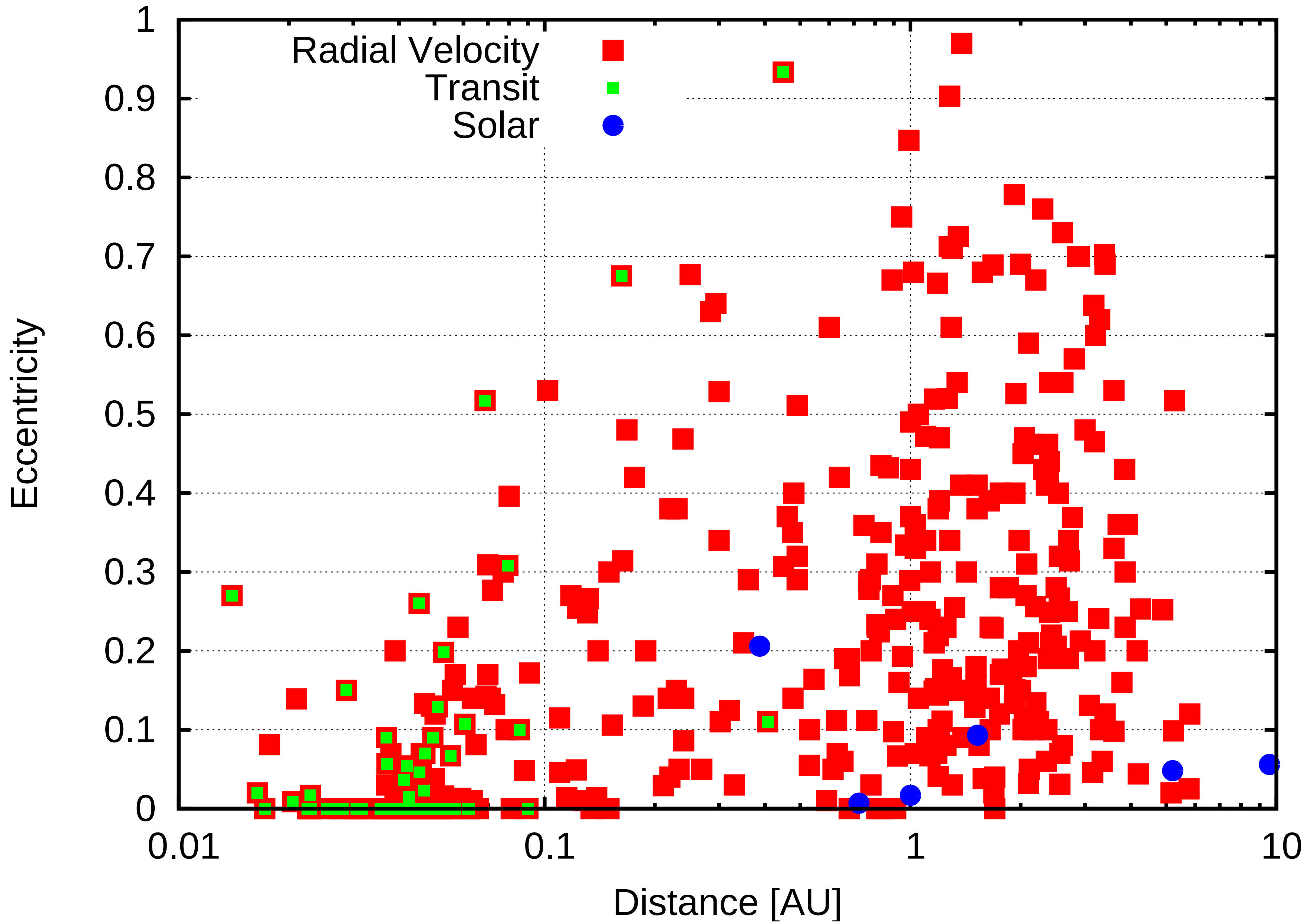
- rad. diffusion (or cooling)
- cooling time $\approx$ libration time

Need viscosity

Approximate torque formula: Masset, Casoli & Paardekooper ea 2010

Helps to prevent loss of planets see Talk: Y. Alibert

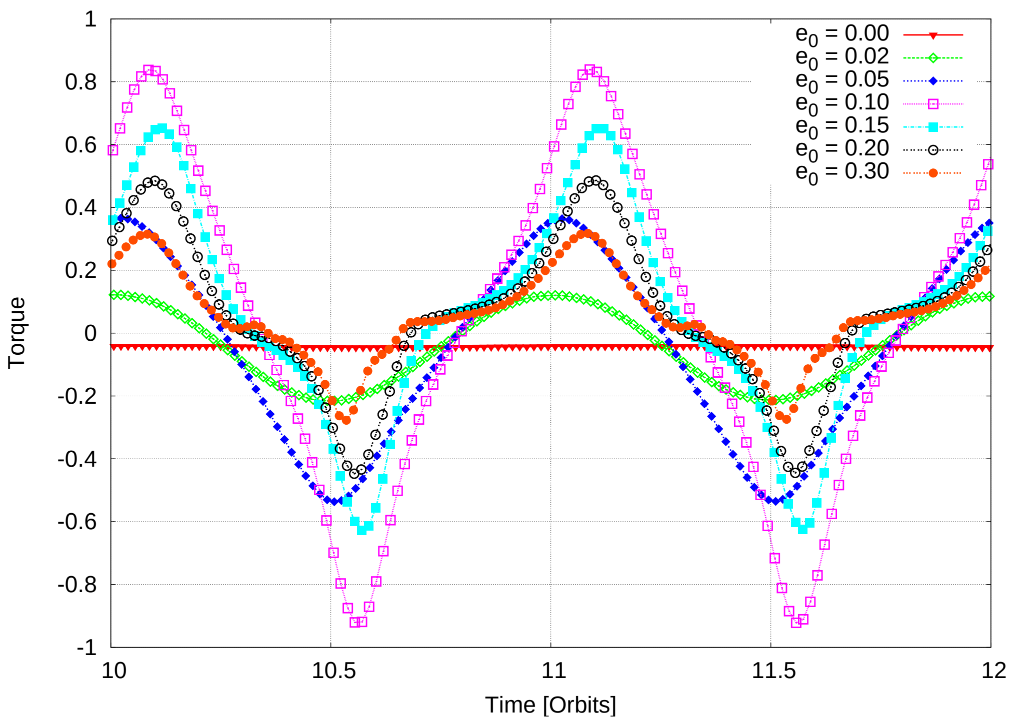
Large eccentricities (similar to binary stars) (Data: exoplanet.eu)



Low mass Planets on eccentric Orbits

Torque on planet due to disk

$$\Gamma_{\rm disk} = \int_{\rm disk} (\vec{r}_{\rm P} \times \vec{F})\Big|_z \, df$$

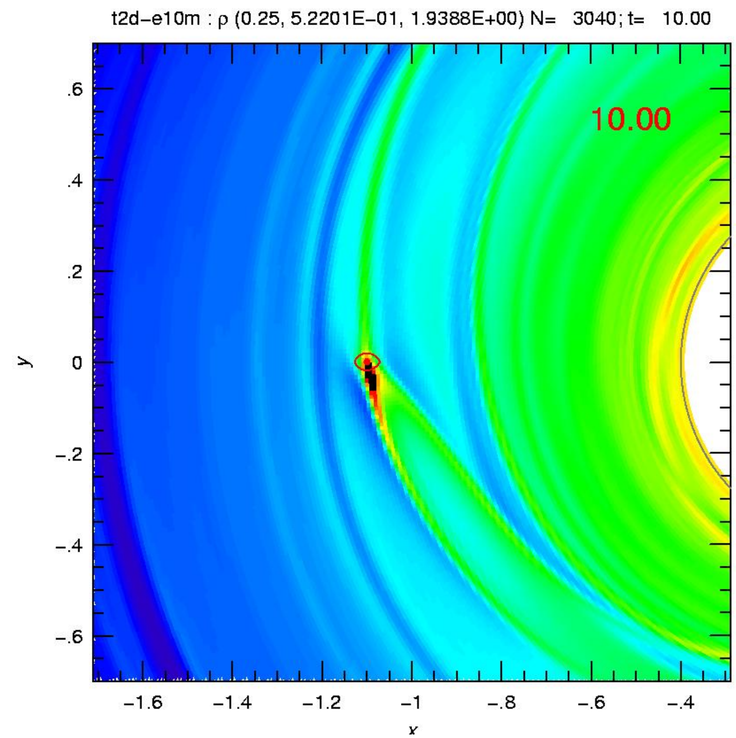


$$L_{\rm p} = m_{\rm p} \sqrt{G M_* a} \sqrt{1 - e^2}$$

$$\frac{\dot{L}_{\rm p}}{L_{\rm p}} = \frac{1}{2}\frac{\dot{a}}{a} - \frac{e^2}{1-e^2}\frac{\dot{e}}{e} = \frac{\Gamma_{\rm disk}}{L_{\rm p}}$$

Power: Energy loss of planet

$$P_{\rm disk} = \int_{\rm disk} \dot{\vec{r}}_{\rm p} \cdot \vec{F} \, df$$

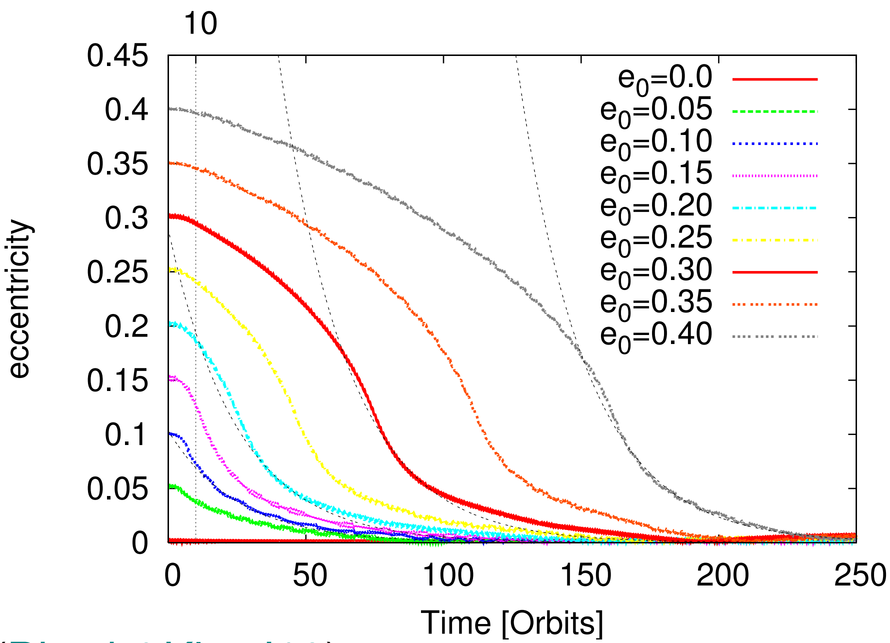


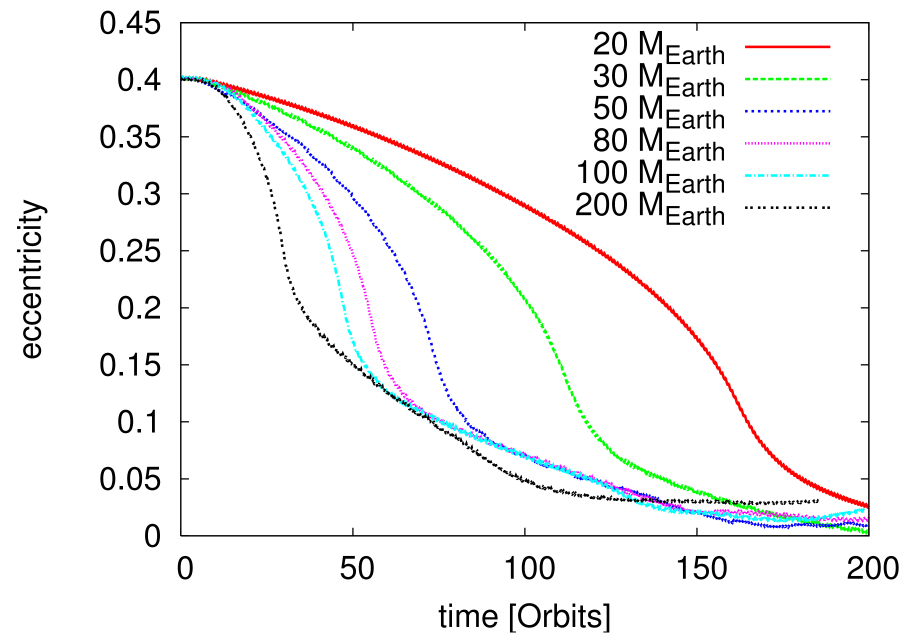
$$E_{\rm p} = -\frac{1}{2}\frac{G M_* m_{\rm p}}{a}$$

$$\frac{\dot{E}_{\rm p}}{E_{\rm p}} = \frac{\dot{a}}{a} = \frac{P_{\rm disk}}{E_{\rm p}}$$

Fix planet mass $M_p = 20 M_{Earth}$
- Vary initial Eccentricity

Vary Planet Mass $10 - 200 M_{Earth}$
- Same $e_0 = 0.40$





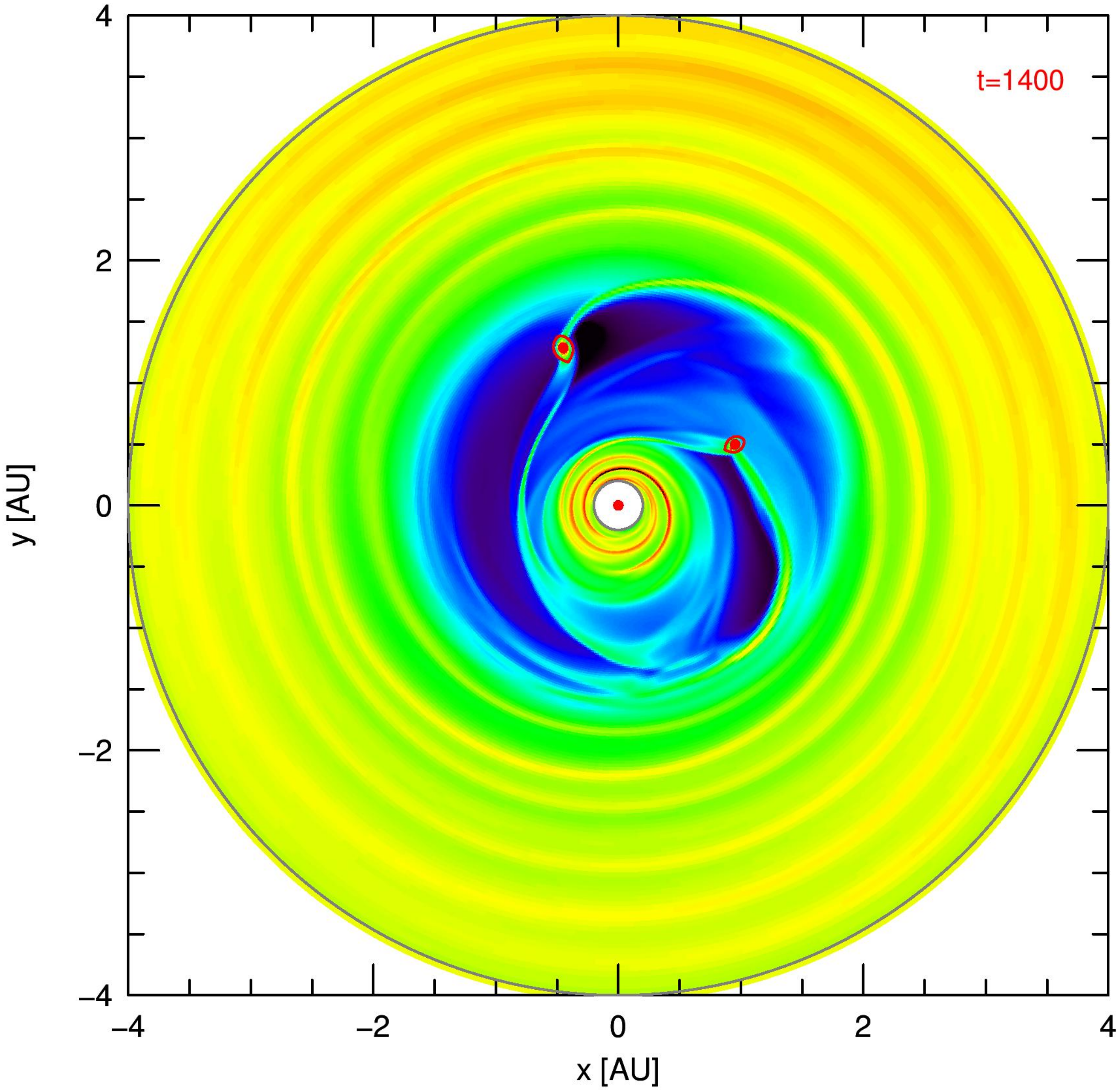
(Bitsch&Kley '10)

- e-damping for all planet masses. ($\Longrightarrow$ Poster Bertram Bitsch)
  Small e: exponential damping, large e: $\dot{e} \propto e^{-2}$
- Need $e < 0.01 - 0.02$ for outward migration to work (radiative disks)

$\Longrightarrow$ Need multiple objects ! (and Scattering)

Resonant capture

2 massive Planets in disk



Two planets:
joint, large gap

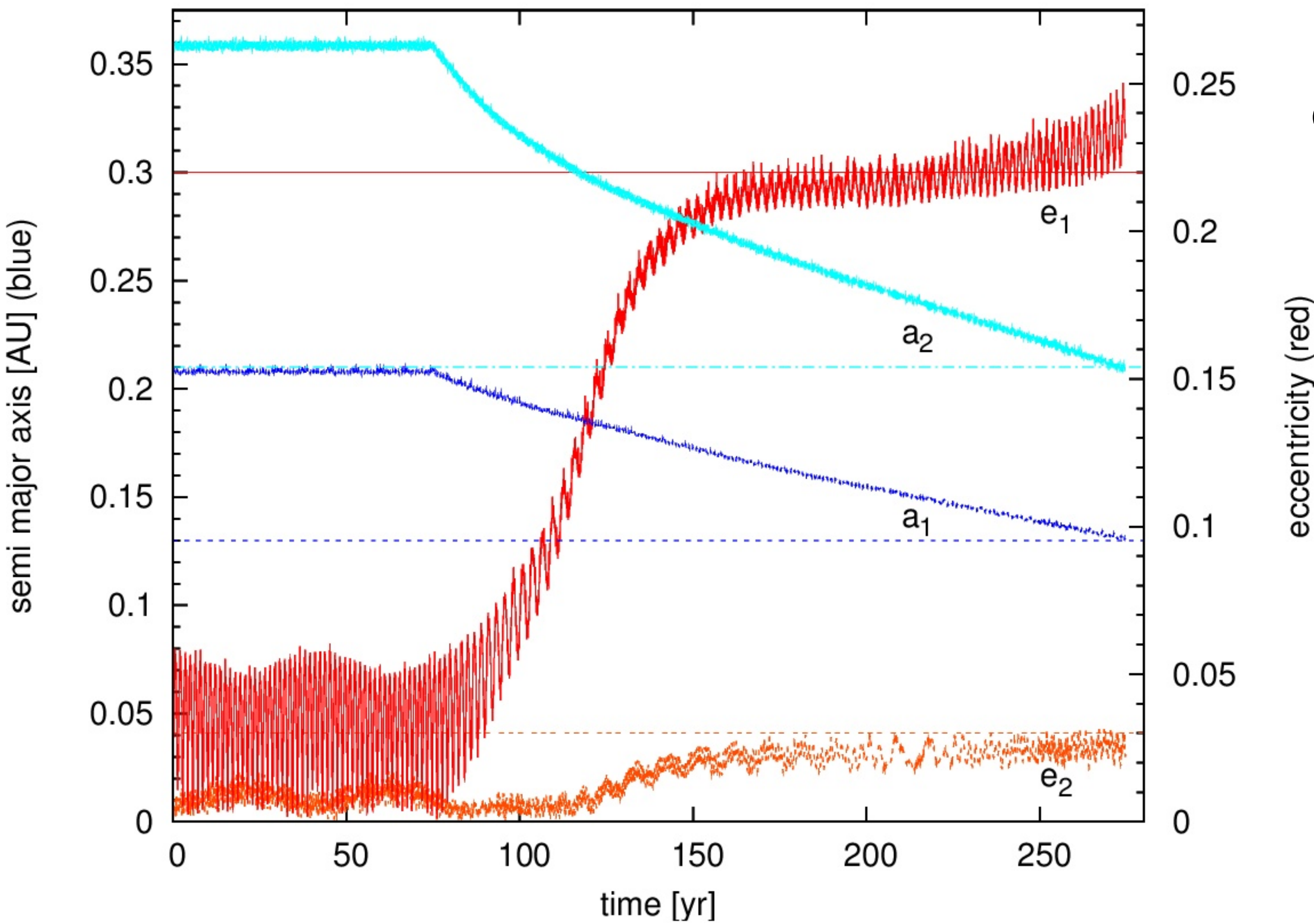
Outer planet :
Pushed inward

Inner planet :
Pushed outward

Seperation reduction:
Resonant capture

Pumping through Resonances

Here: System-parameter of GJ 876 (2 planets in 2:1 resonance, 60:30 days)



Compactification

Excitation

(Crida ea., 2007)

System ends in: apsidal corotation, with correct eccentricities

Less disk damping: $\Rightarrow$ much higher e $\Rightarrow$ Instability

Recent additions

- Radial Velocity technique

  HD 45364: system in 3:2 resonance

  HD 60532: system in 3:1 resonance

  GJ 876: additional outer planet, 4:2:1 Laplacian resonance ?

  (System with clearest sign of 2:1 resonance)

- Transit timing

  Kepler: 5 new multiple planet systems (tbc)

  (3 near resonance, 2 $\times$ 2:1, 1 $\times$ 5:2)

  WASP-3b: need outer perturber; near 2:1 or 5:2

  NN Ser: eclipsing post-common-envelope binary, $P_{orb} = 3.12$hrs

  WD & M4 dwarf, 2 planets in 2:1 resonance

- Direct Imaging

  HR 8799: 3 planet system at large distances)

  (massive planets: 7, 10, 10 M_{Jup})

  (at 24, 38, 68 AU; (stable only if in: 4:2:1 resonance)

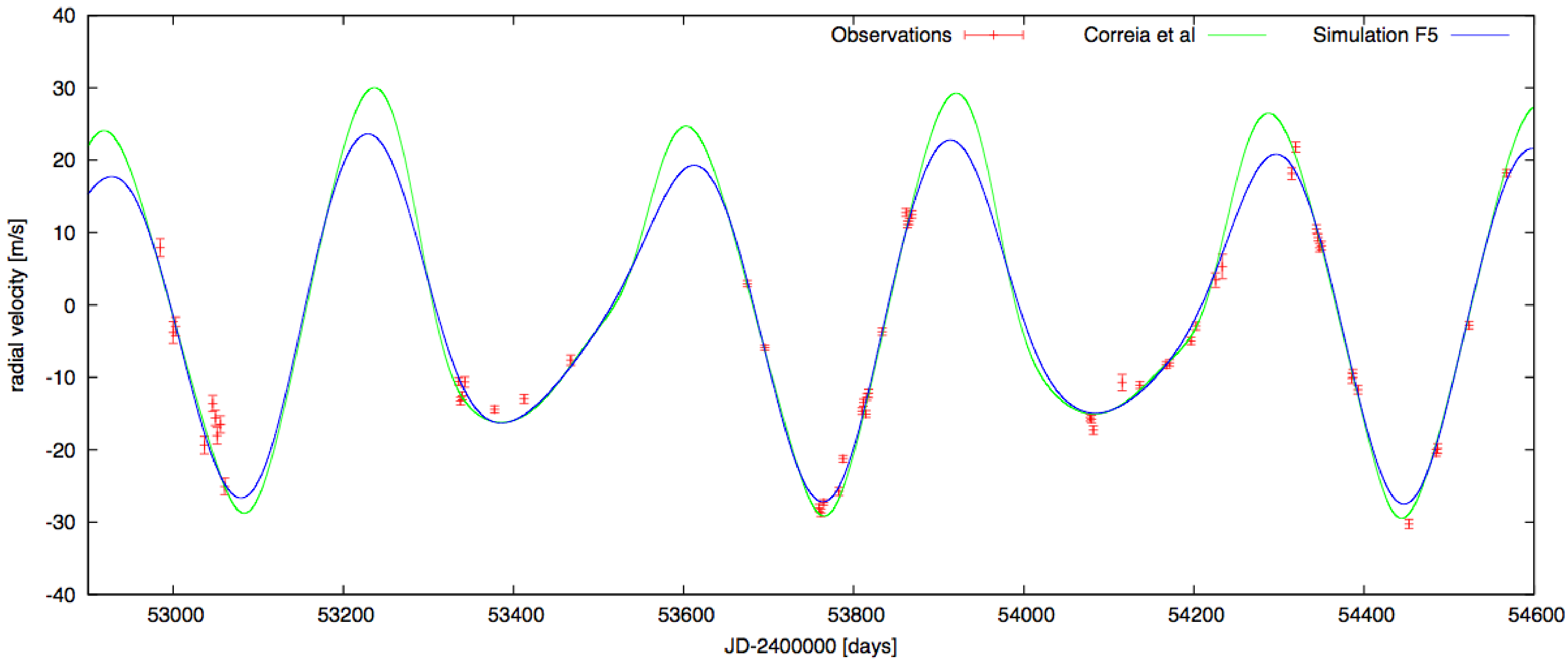
About 30% of multi-planet system close to MMR (Wright ea. 2011)

The system HD 45364

Announced by: Correia ea. 2009

3:2 Resonance, $m_1 = 0.19, m_2 = 0.69 M_J$, at 0.68, 0.89 AU

System formation through full 2D hydrodyn. simulations!



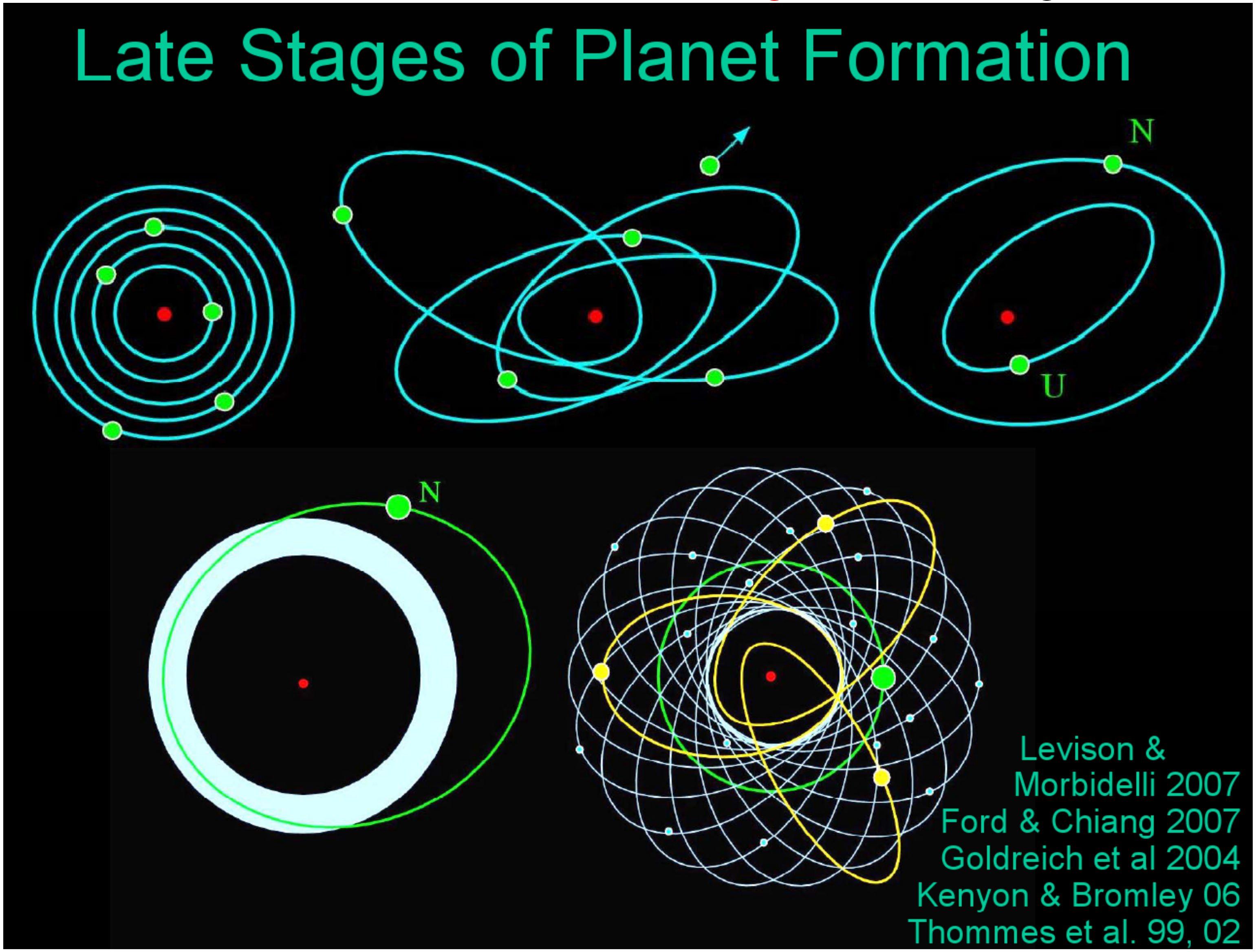
Observed e: 0.17, 0.097, Simulation: 0.036, 0.017, same χ^2

(Rein, Papaloizou, Kley, 2010)

For clarification: More observations !

Scattering Processes

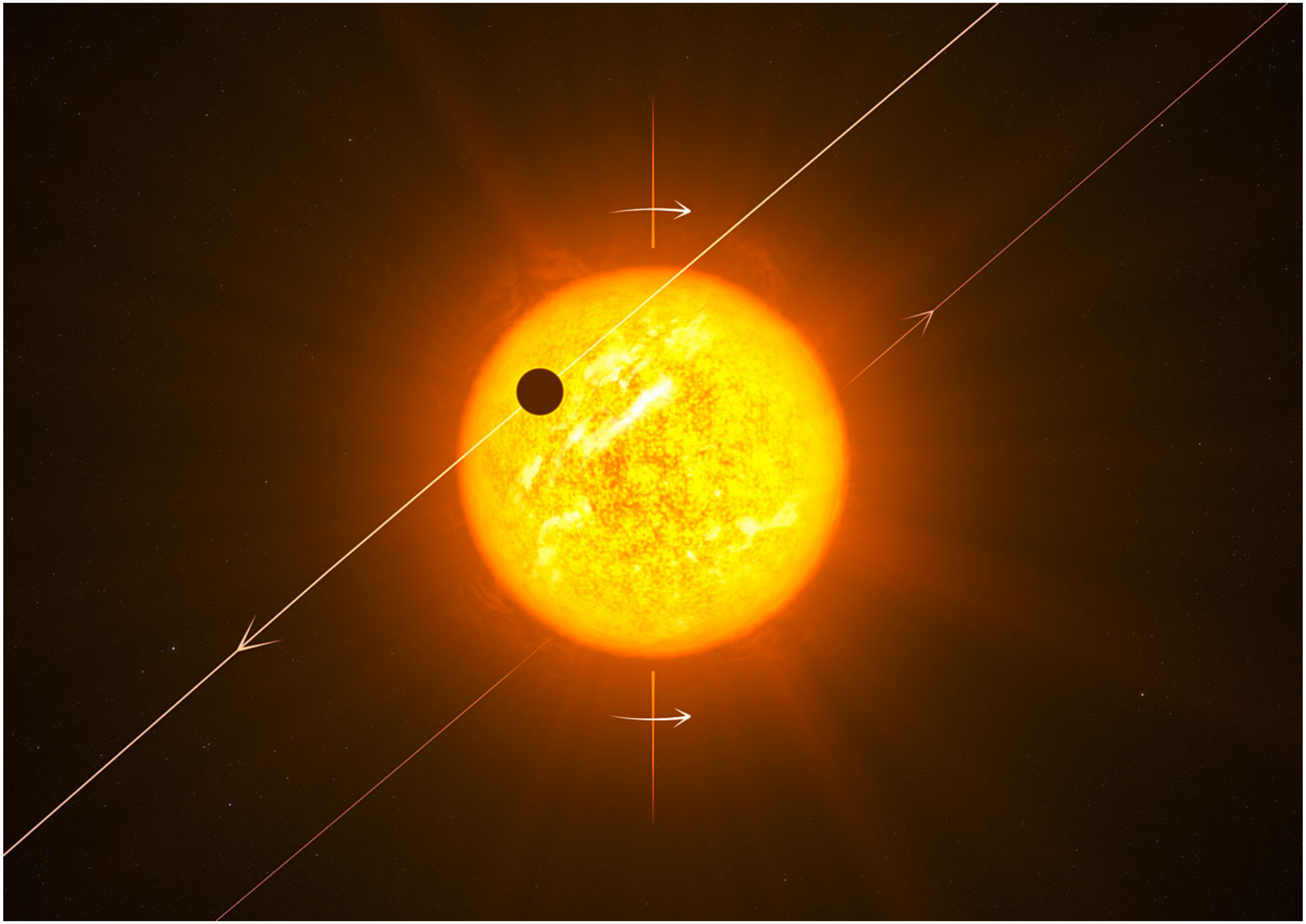
Gravitational interaction after disk has gone! $\Rightarrow$ High eccentricities



(Slide from Eric Ford)

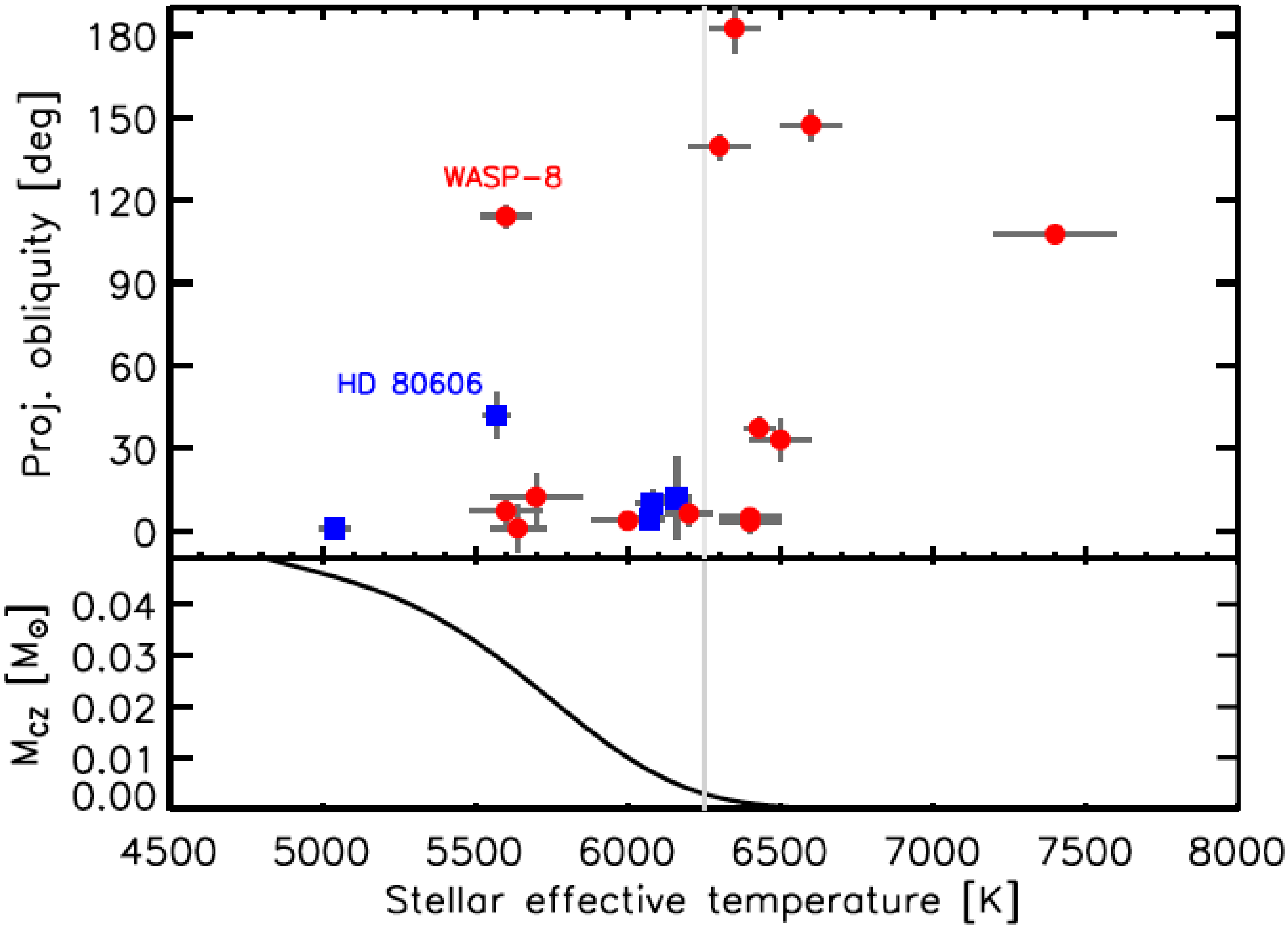
"Turning Planetary Theory Upside Down"

ESO press release 13. April, 2010
"Misalignment of planetary orbit and stellar rotation" (Triaud et al. 2010)



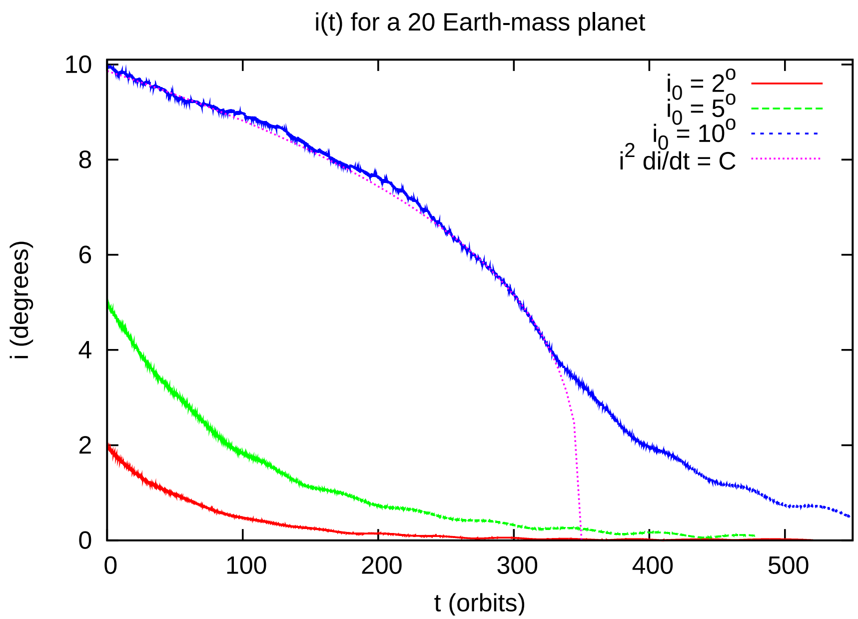
Obliquity vs. stellar Mass

Sky projected angle (Winn et al., 2010)



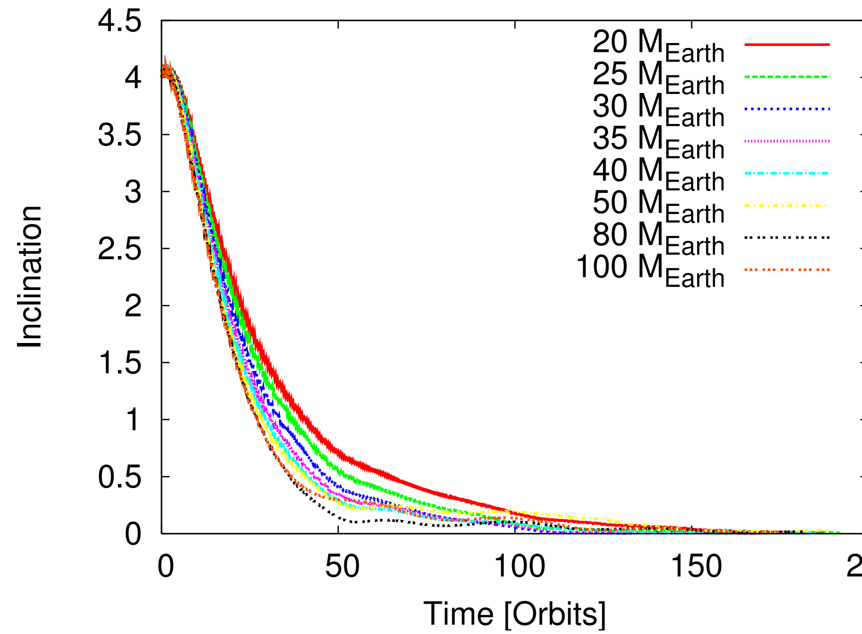
Planets in 3D radiative disks

Fix planet mass $M_p = 20 M_{Earth}$
- Vary inital Inclination



(Cresswell ea 2007; Bitsch&Kley 2011)

Vary Planet Mass $20 - 100 M_{Earth}$
- Same $i_0 = 4$deg



- i-damping for all planet masses. ($\Longrightarrow$ Poster Bertram Bitsch)
  Small i: exponential damping, large i: $\dot{i} \propto i^{-2}$
- Migration still outward upto $i \approx 4^o$

$\Longrightarrow$ Need multiple objects ! (Scattering)

Summary

- Planet-disk interaction moves planets
  - Inward for isothermal disks
  + possibly outward/slowed in radiative disks
  - for small planets, small eccentricities, opacities
  + helps to avoid too rapid type I (see Pop.synthesis)
- Eccentricity & Inclination damped by disk
- Resonant migration
  + explain resonant planets
  + supplies initial conditions for scattering
- Eccentric & inclined planets through scattering
  - Obliquity vs. stellar mass

The End