Planet Migration

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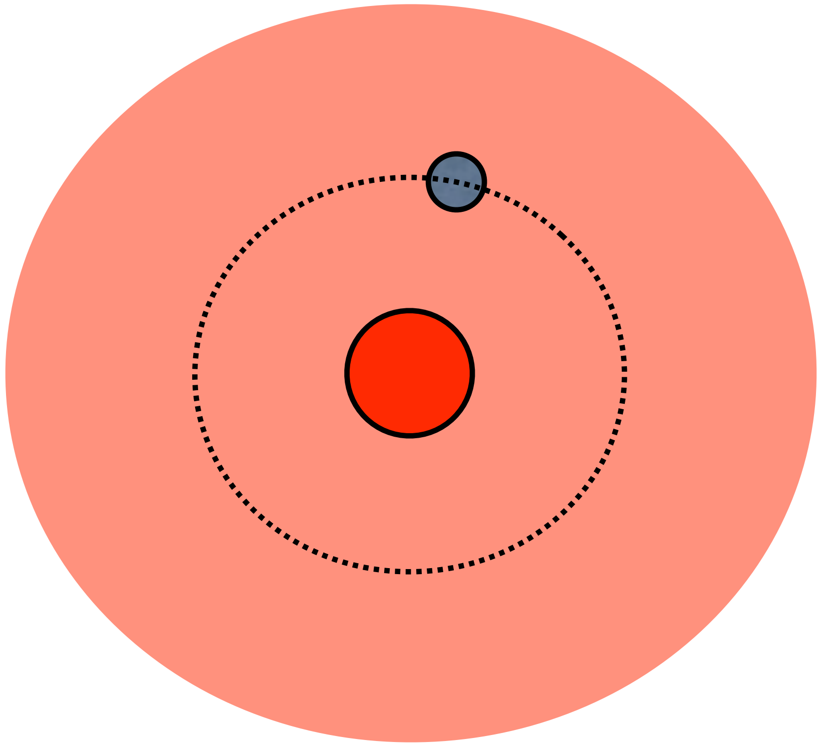
Outline

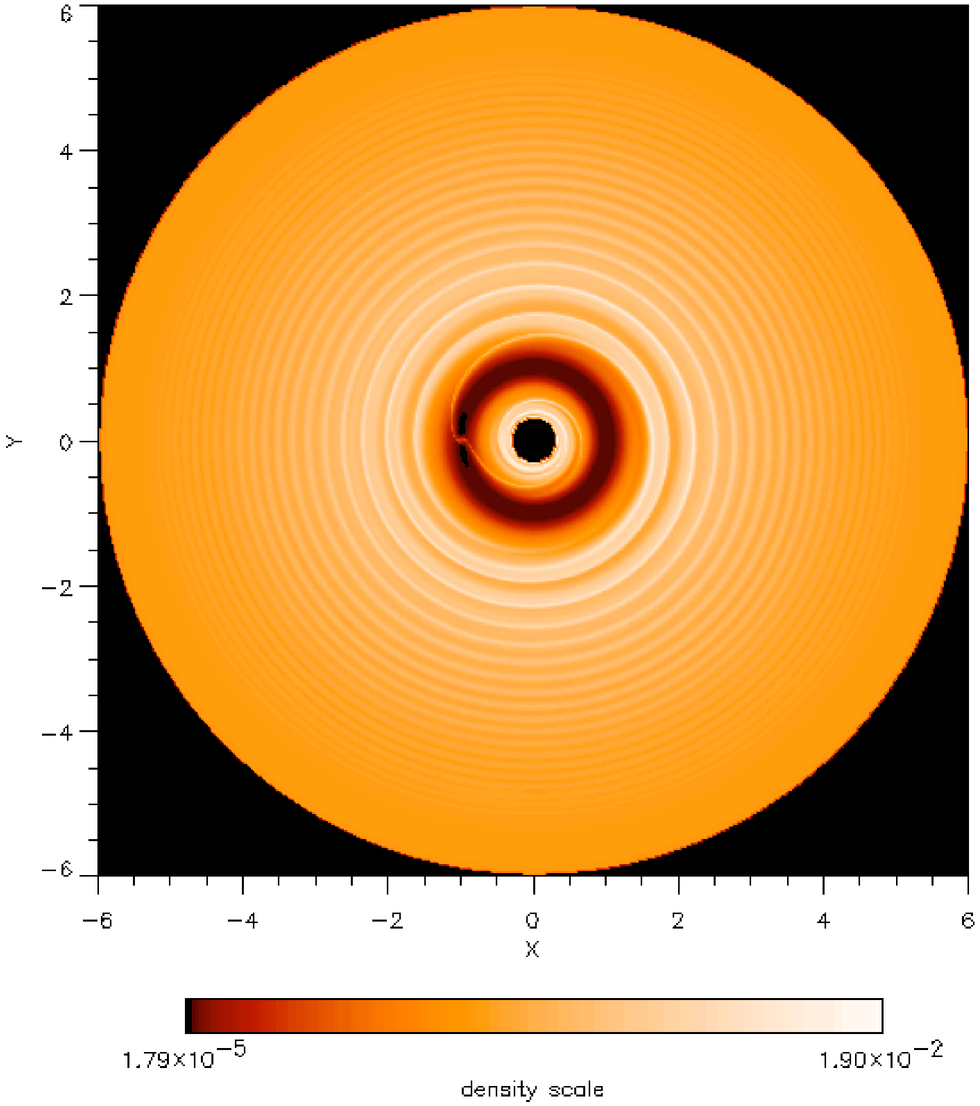
- Type 1 migration problem - too fast
- Some models for slower Type 1
  - Low turbulent viscosity (dead zone)
  - Random torques by turbulent fluctuations
  - Nonisothermal effects of coorbital torques

Forms of Migration

- Type I: Planet mass too small to open gap. Disk density largely undisturbed by planet
- Type 2: Planet mass large enough to open gap in disk.



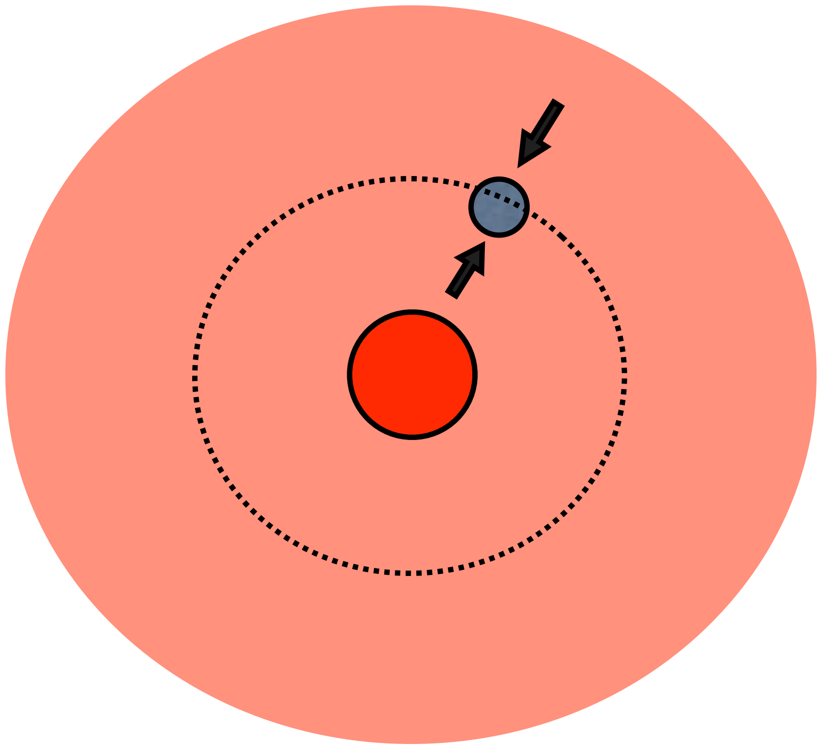
Type I



Type 2

Type 1 (nongap) Migration

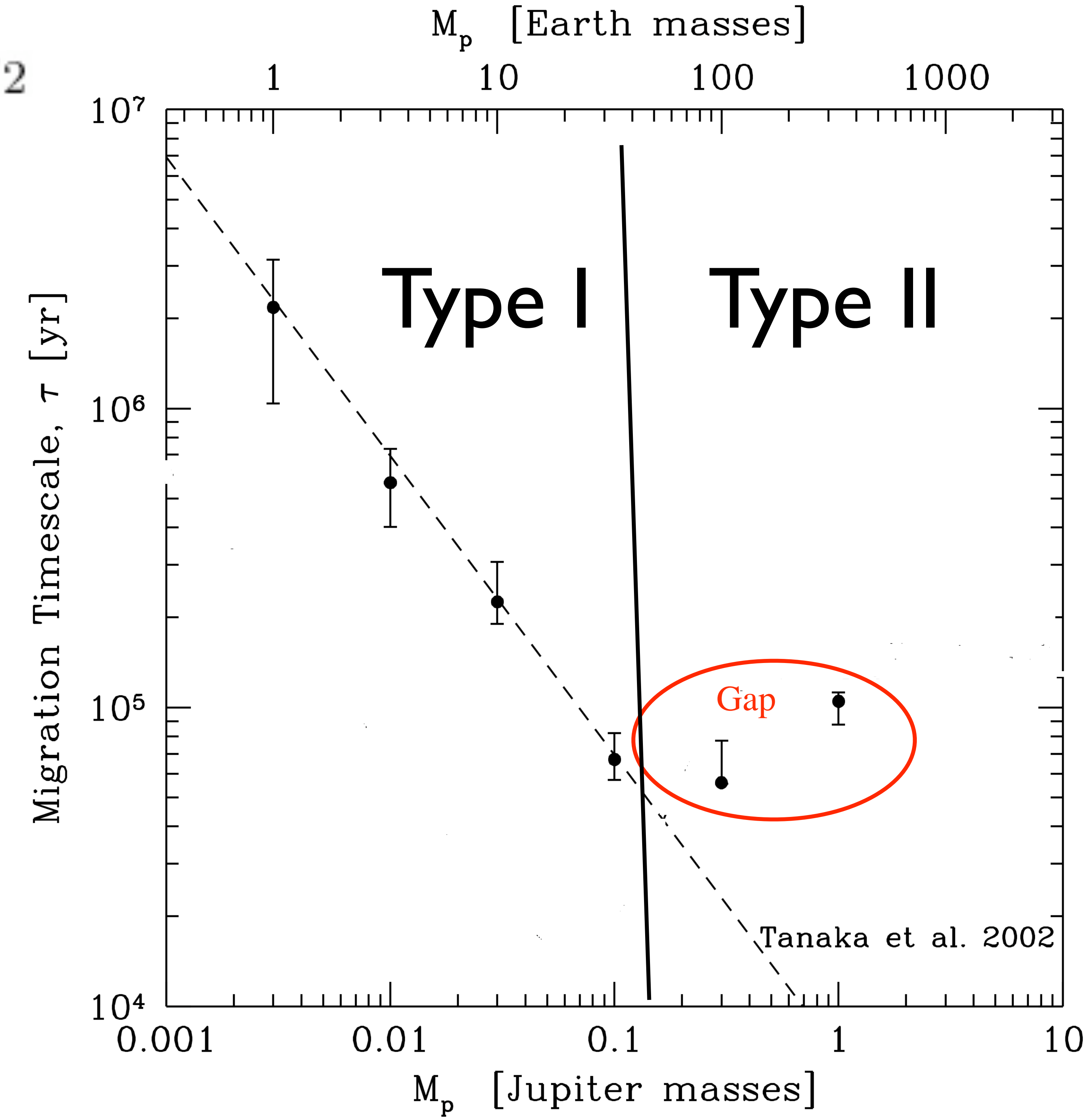
- Gravitational torques move planet radially
- Inner disk pushes planet out; outer disk pushed planet in
- Torques comparable and opposite, but inward torques win for simple disk models (Ward 1986). Even if no temperature or density gradients. Simple models: power law, moderate alpha, locally isothermal.
- Planet migration too fast for planet formation. Reduce by 10x. (Alibert et 2005, Rice & Armitage 2005, Ida & Lin 2008).



Migration Rate: 3D locally isothermal, moderate alpha, power-law disk

$$\Sigma \propto r^{-1/2}$$

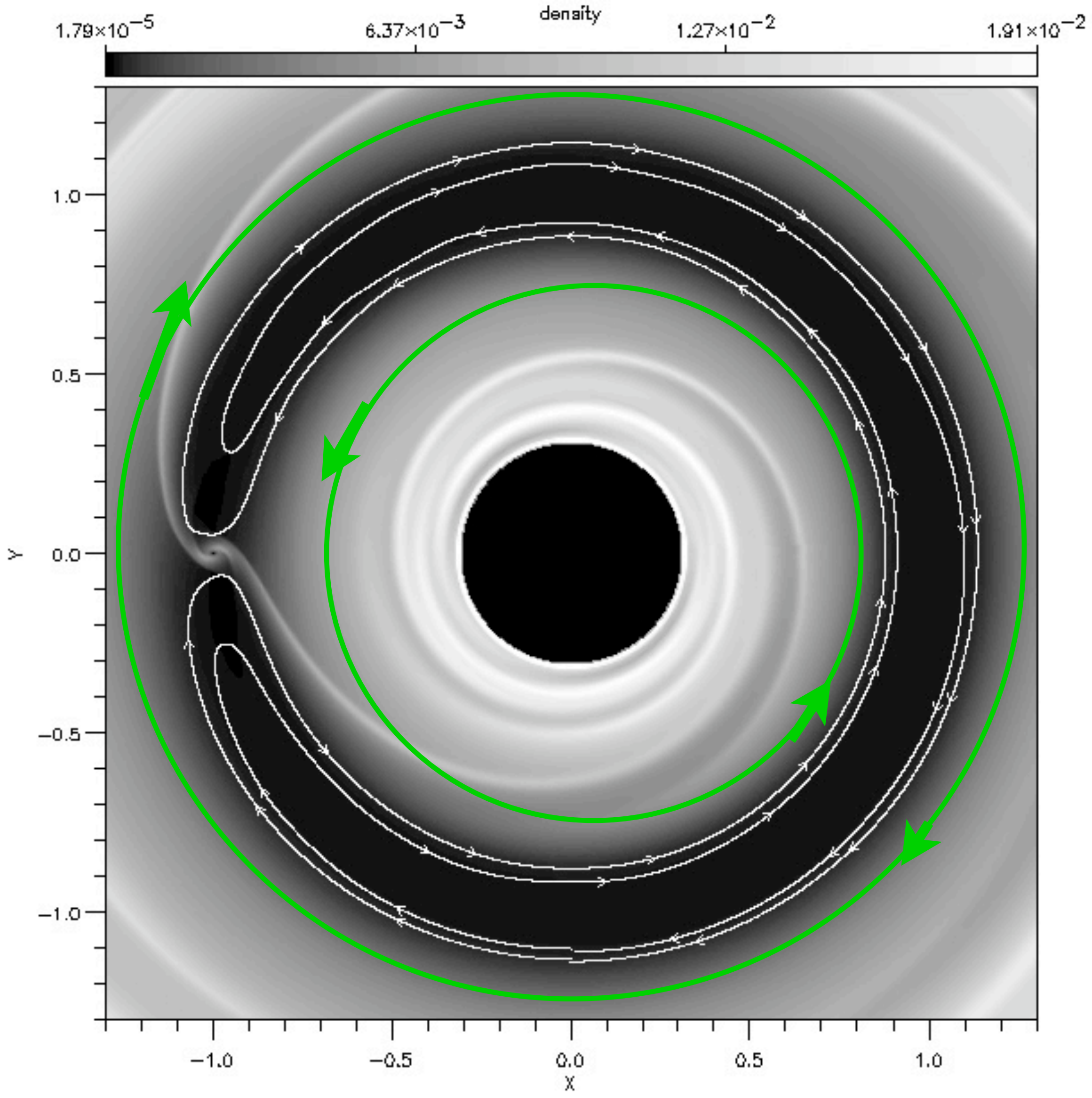
$$T \propto r^{-1}$$



Bate et al 2003

Minimum mass solar nebula

Regions of Space



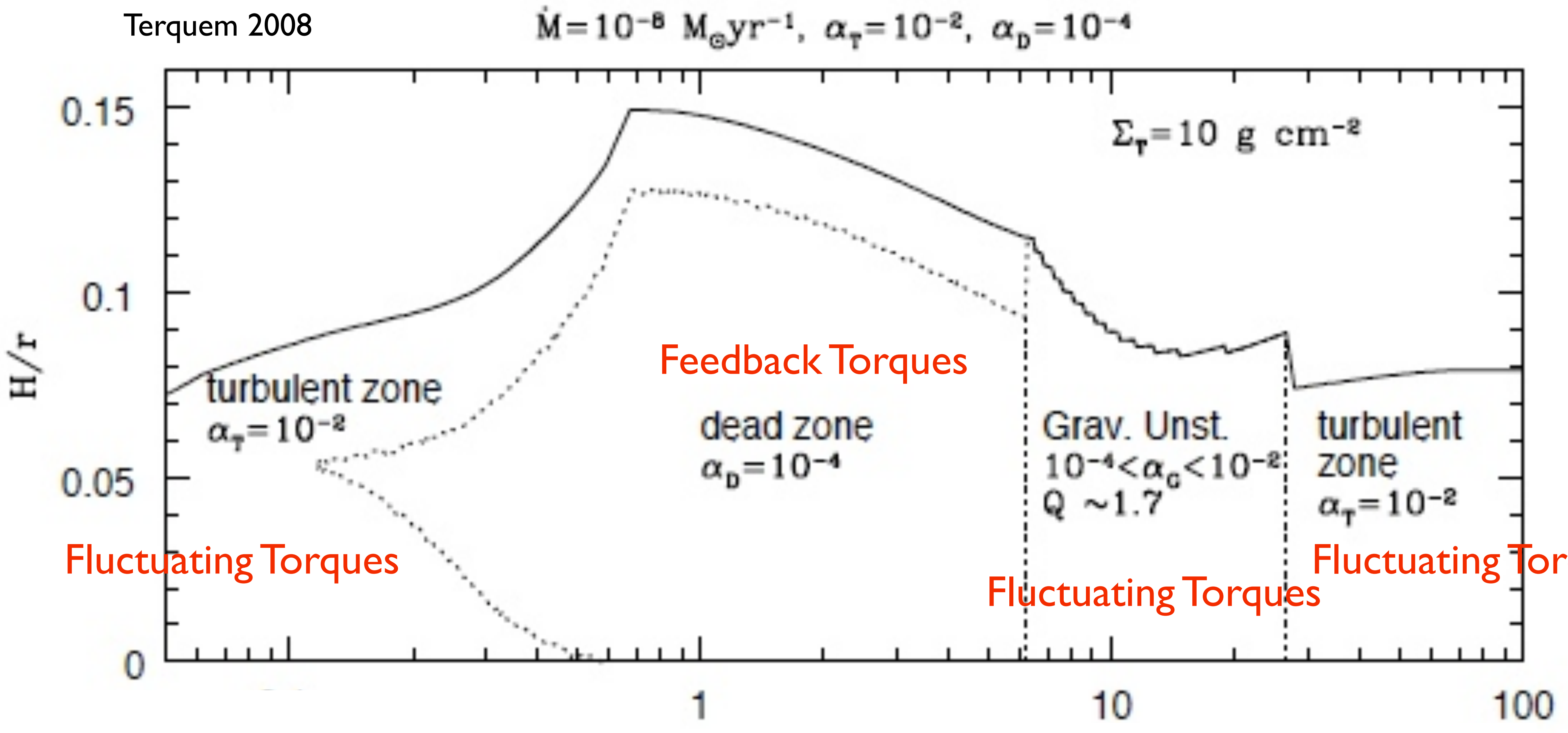
- Fully circulating (Lindblad resonances)
- Horseshoe orbits (Corotation resonance)

Challenges in computing migration rates

- Simple model (power law, moderate alpha, locally isothermal) does not work. What could be wrong?
- Lower than moderate alpha (less that 0.001)
- Description of disk turbulence by alpha model
- Disks not locally isothermal
- Disk structure: non power-law behavior can affect migration rates.

Disk Structure and Migration

Terquem 2008

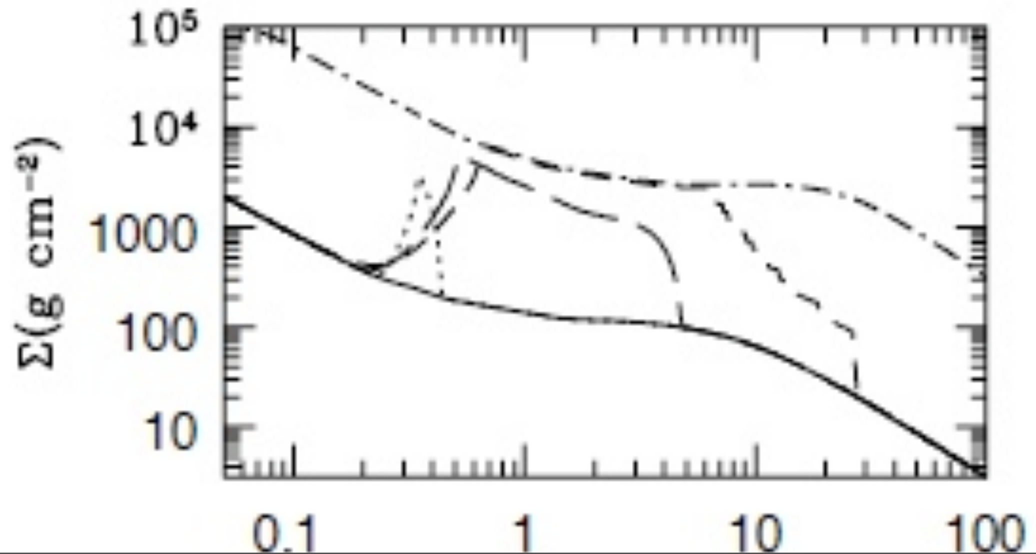


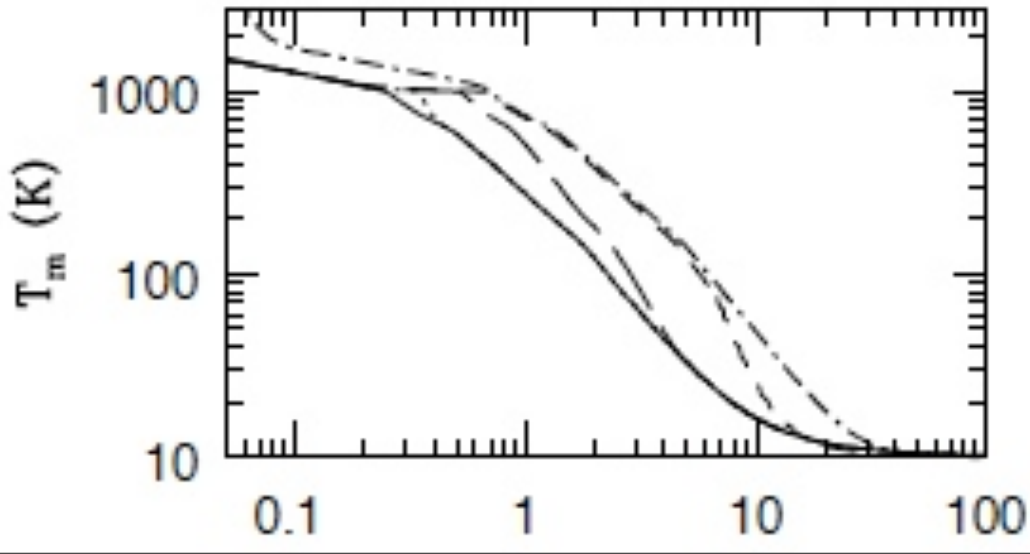
Feedback Torques

Fluctuating Torques

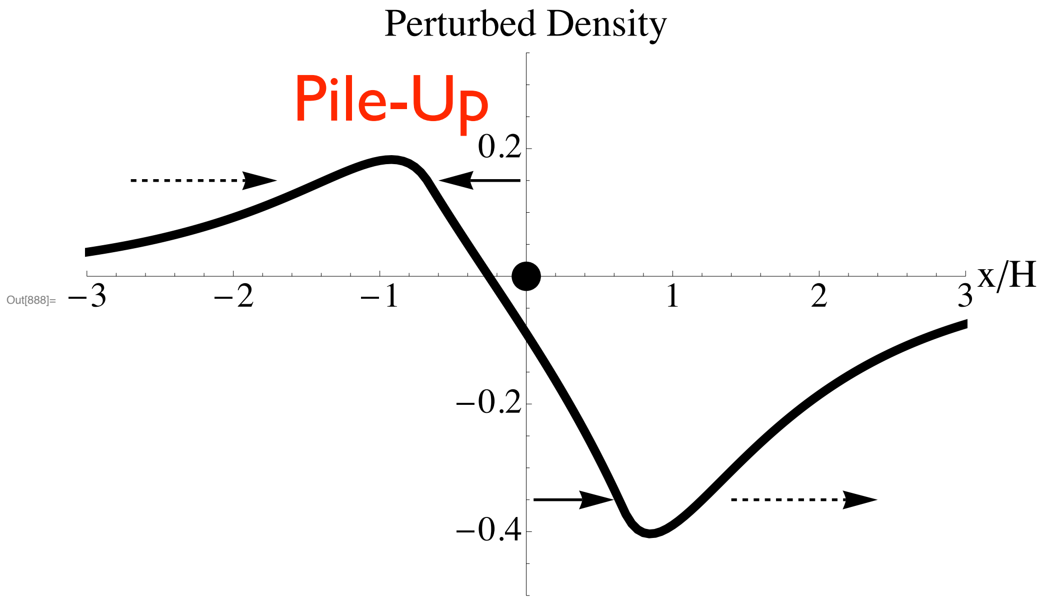
Fluctuating Torques

Fluctuating Torques



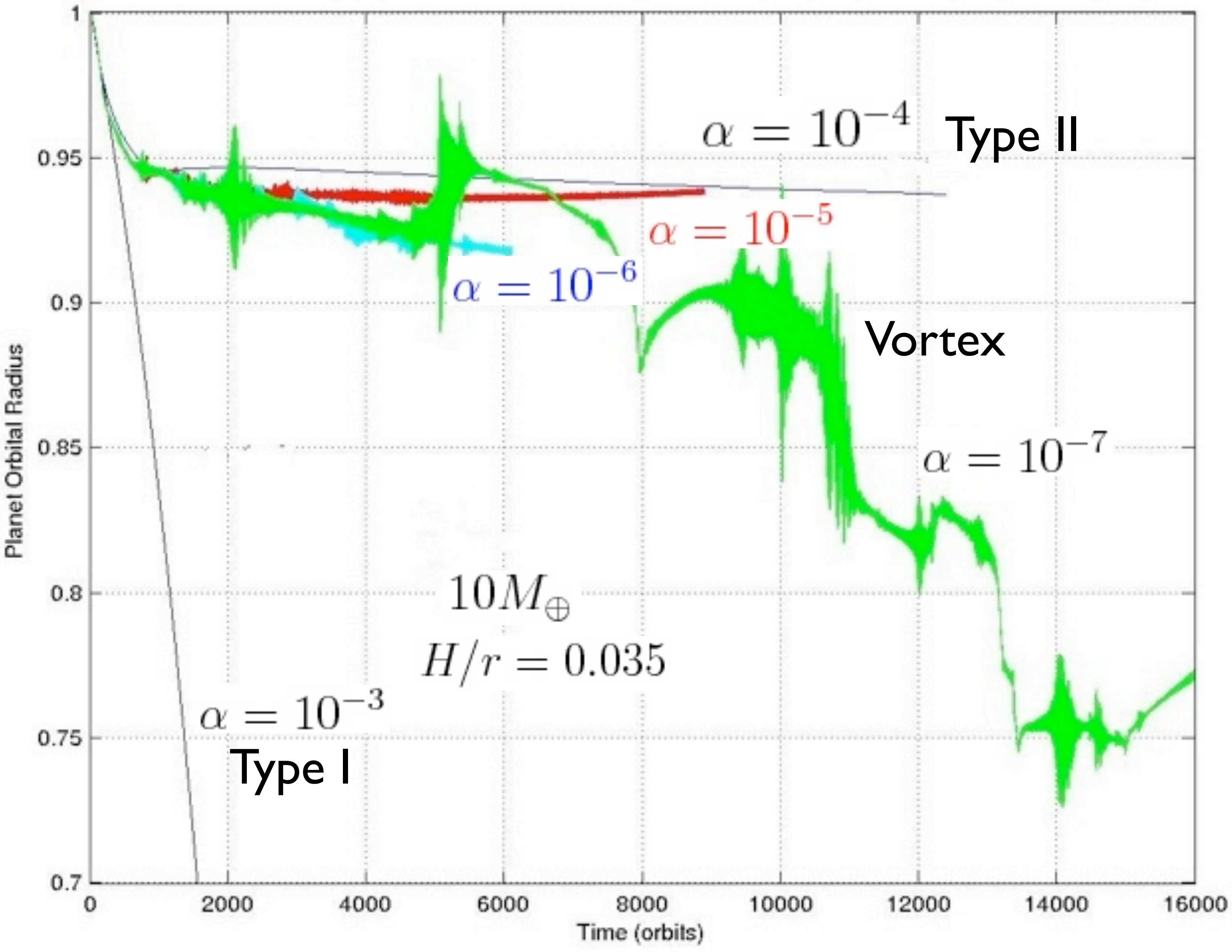


Migration in a Dead Zone (low alpha)



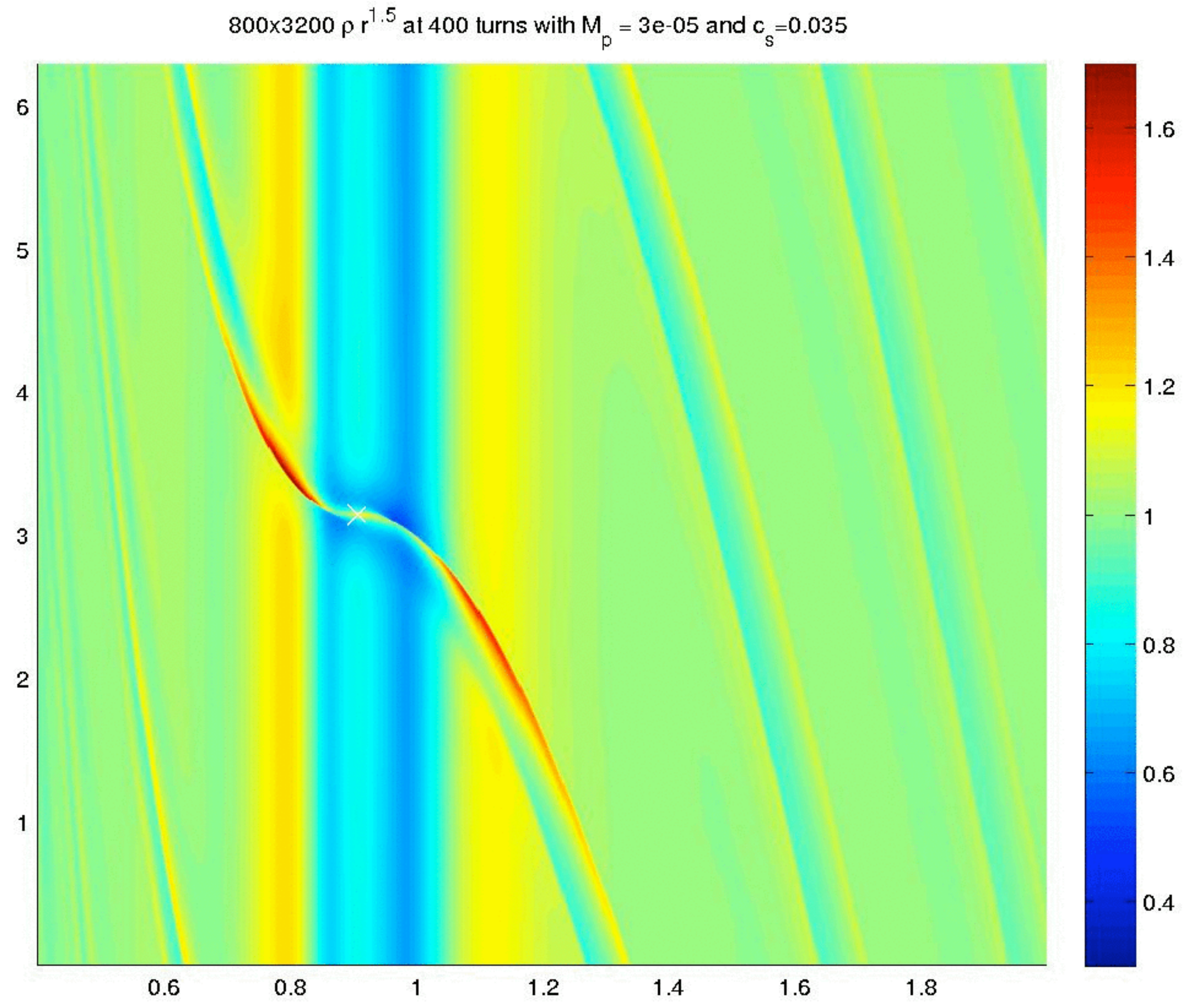
- Migrating low mass planet (10 Earth masses) causes pile-up of gas ahead of it motion in frame of planet - not erased by turbulence (Hourigan & Ward 1984; Rafikov 2002).
- Critical planet mass for stopping
- Stopping occurs before gap cleared - due to asymmetry.

Low Viscosity Feedback Simulations (Li et al 2009)

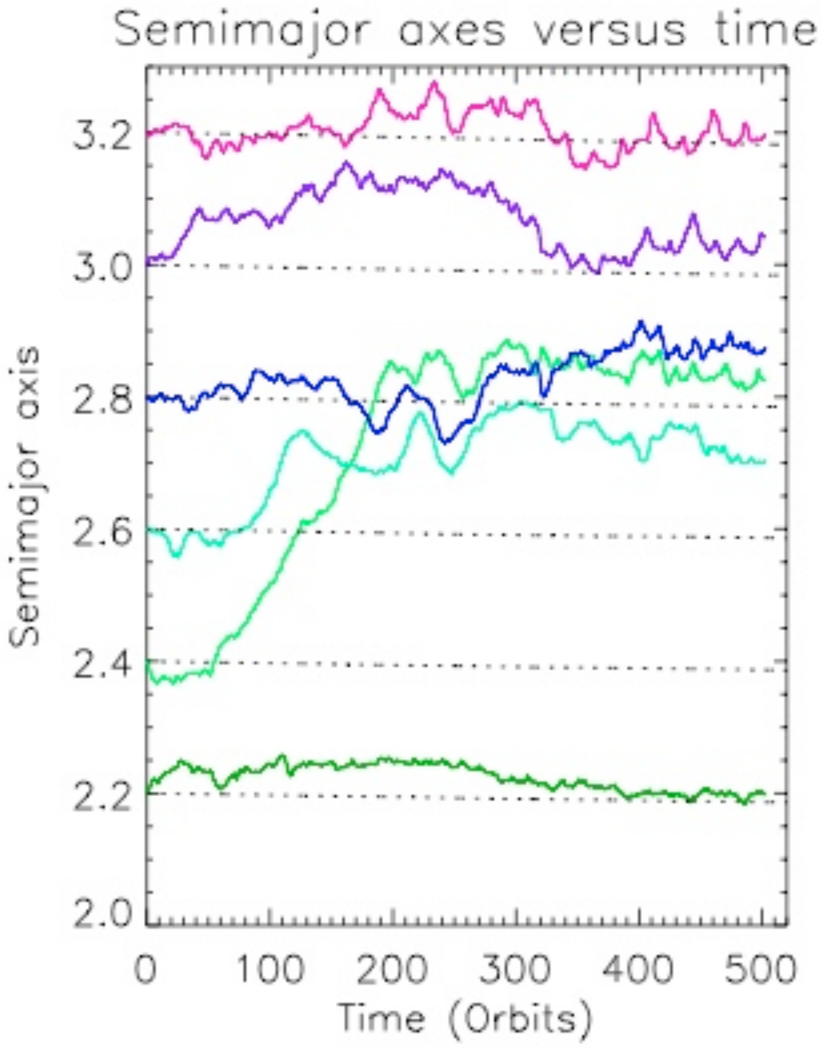


3 possible outcomes: Type I, II, and vortex dominated (jumpy)

Evolution of 10 Me planet in laminar disk



Turbulent Torques

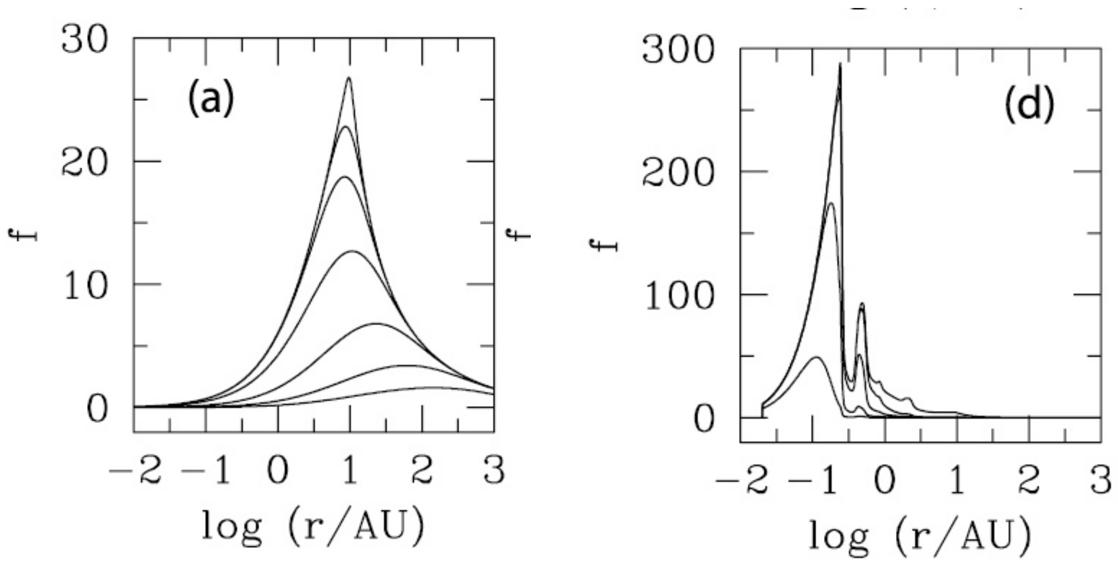


Nelson 2005

- Density fluctuations due to MRI turbulence cause random torques that complete with Type I torques
- Random walk causes radial shift as t^0.5, while for Type I varies as t.
- Migration rate depends on details of turbulence: amplitudes and timescales.

Turbulent Torques

Johnson et al
2009



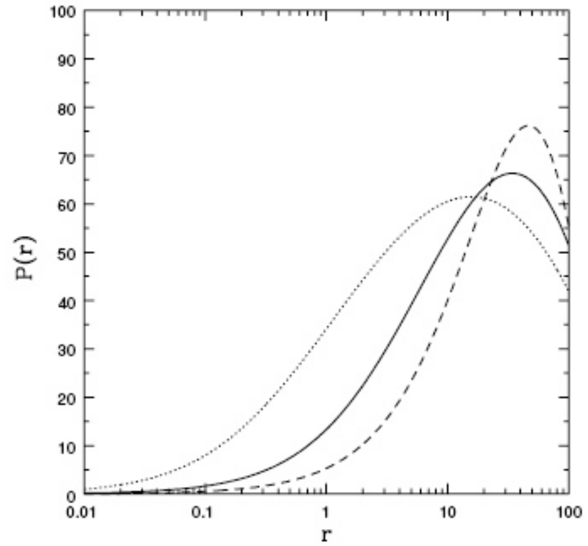


Figure 9. Eigenfunctions for the lowest-order mode solution to the Fokker–Planck equation. In the long time limit, these functions provide the distribution of angular momentum, and hence radial position, for surviving planetary cores. The three curves shown here correspond to a fixed Type I migration parameter γ and varying values of the diffusion parameter given by $\beta/\gamma = 0.01$ (dashed curve), 0.1 (solid curve), and 1 (dotted curve). As shown, the three eigenfunctions are normalized to the same (arbitrary) value.

Adams & Bloch 2009

- Current simulations only go ~ 100s of orbits. Too short to following evolution. So apply semi-analytic models.
- Semianalytic models - Fokker-Planck eq. (e.g., Johnson et al 2005, Adams & Bloch 2009) suggest that typical planet lifetimes can even be reduced by turbulence, but some declining fraction of time survives. Survival easier in outer parts of disk.
- Results depend on turbulence properties - effective diffusion coefficient. What is it?

Importance of turbulent migration

Yang et al 2009

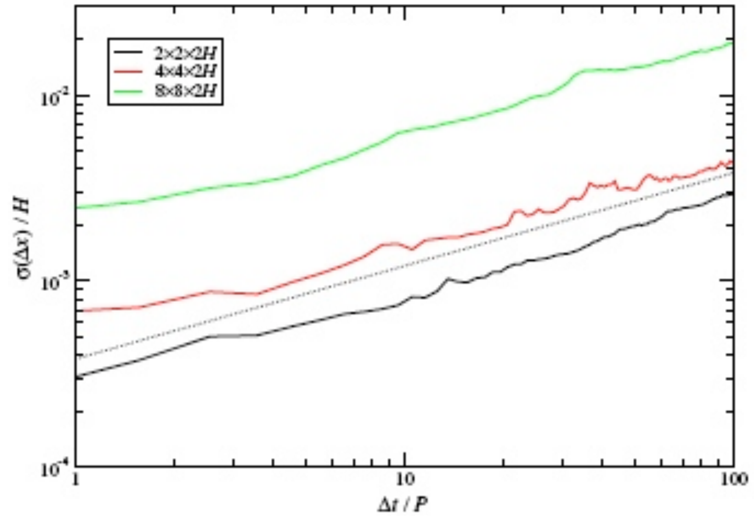


Figure 8. Standard deviation of radial drift $\sigma(\Delta x)$ as a function of elapsed time Δt for three different box sizes at a resolution of 32 points per scale height H (solid lines), where only the low-mass disk model ($\xi = 1$) and particles with zero initial eccentricity are considered. For comparison, the straight dotted line gives the best fit to the high-resolution model shown in Figure 7 (Equation (15)).

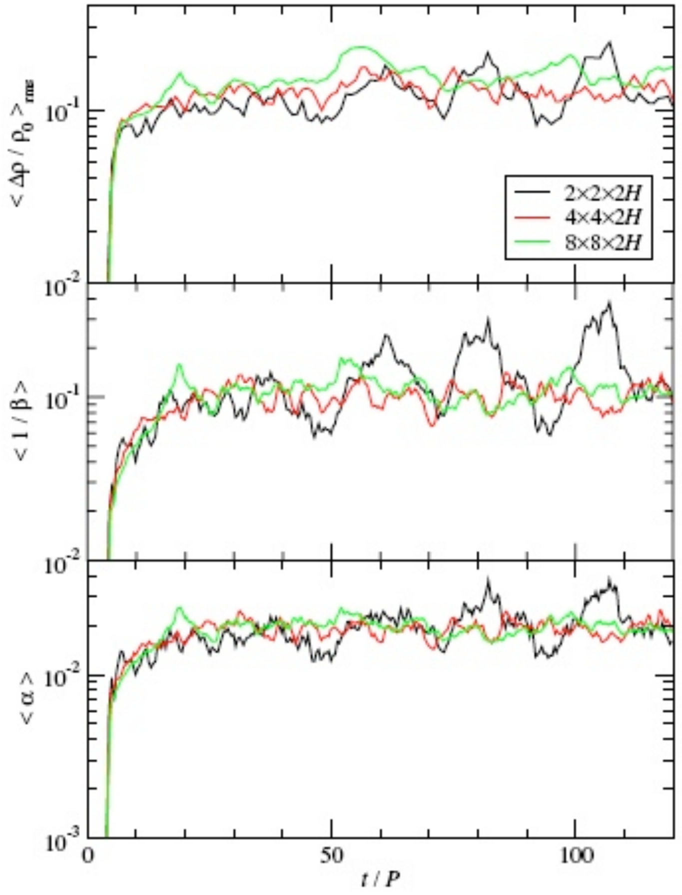


Figure 2. Density perturbation $\Delta\rho/\rho_0$, inverse plasma β, and α parameter as a function of time t for three different box sizes at a resolution of 32 points per scale height H. An external vertical magnetic field of $B_{\rm ext} = 0.08$ ($\beta_{\rm ext} = 6.2 \times 10^3$) is imposed. Properties are volume averaged over the whole computational domain and the rms value for $\Delta\rho/\rho_0$ is shown.

- If turbulence is strong enough to alter migration, then potential problem with survival of planetesimals against collisions (Ida et al 2008). May be a problem for planet formation.

- Recent, box simulations for massless particles suggest weaker effects of turbulence migration (Yang et al 2009).
  - Demonstrates validity of F-P approach

  $$\sigma(t) \propto \sqrt{t/P}$$

  - High resolution, cover smaller region of space.
  - Not yet converged with box size.
  - Type I dominates for Me or larger planets.
  - No problem for survival of planetesimals.

Thermal Effects at Corotation

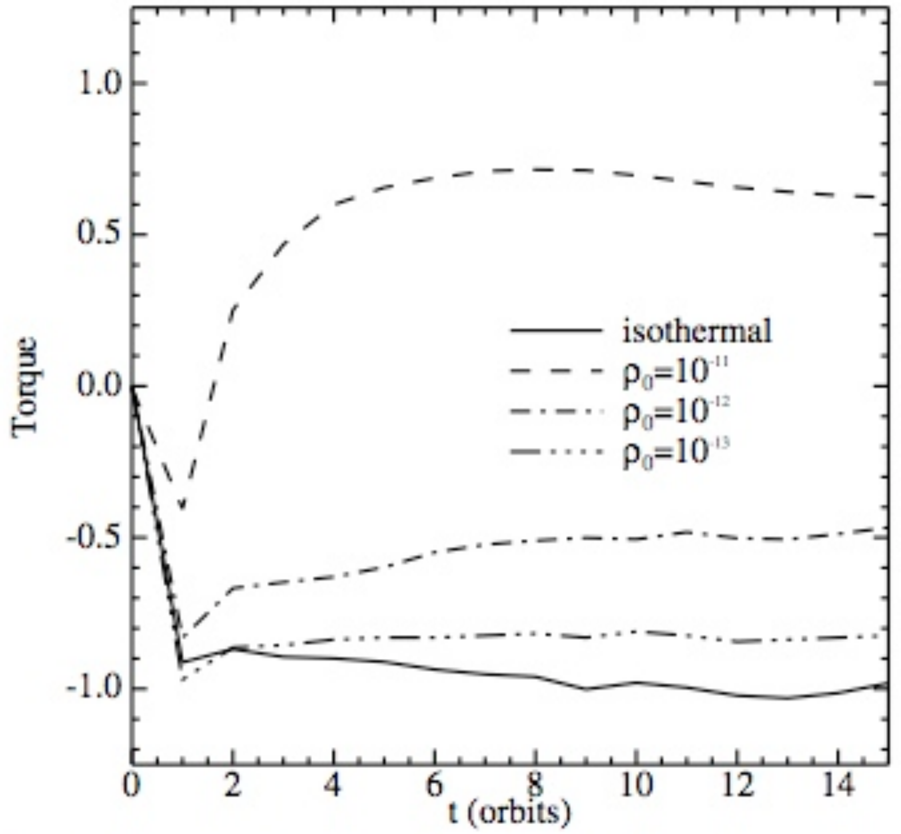


Fig. 1. Total torque on a 5 $M_\oplus$ planet as a function of time for three different midplane densities, together with the isothermal result. The torques are normalized to the analytical value found by Tanaka et al. (2002), which is reproduced by the isothermal simulation. For high densities (and thereby for high opacities) the torque becomes positive, indicating outward migration.

Paardekooper & Mellema 2006

- Most models involve locally isothermal disks.
- Nonisothermal effects can be important in migration (Paardekooper & Mellema 2006).
- Corotation torques are affected.
- Outward migration sometimes found in simulations with radiative transfer. But cannot be run very long.

Origin of Outward Torque

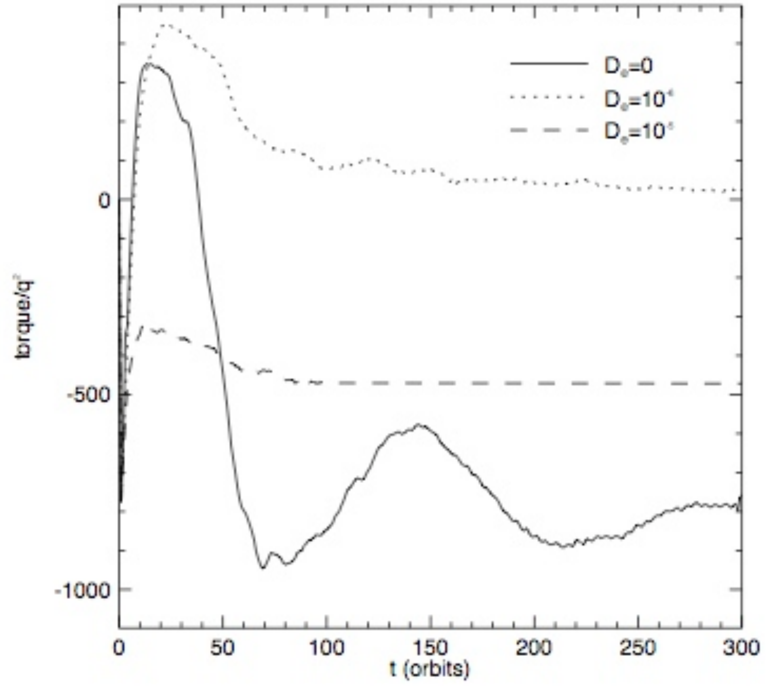
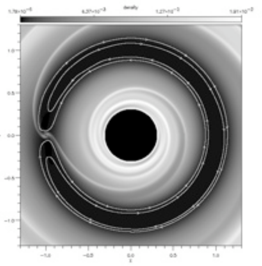


Fig. 23. Long-term evolution of the total torque, in units of $q^2\Sigma(r_\mathrm{p})\Omega_\mathrm{K}^2 r_\mathrm{p}^4$, on a $q = 1.26 \cdot 10^{-5}$ planet in a disc with $\rho_0 \propto r^{-3/2}$, $T \propto r^{-1}$ and $\gamma = 1.1$, for three different thermal diffusivities. All models have a small kinematic viscosity of $\nu = 10^{-6}\, r_\mathrm{p}^2\Omega_\mathrm{p}$. Paardekooper & Papaloizou 2008

- For adiabatic case, linear theory shows that the corotation torque has an extra contribution involving the gas entropy gradient, dS/dr (Baruteau & Masset 2008, Paardekooper & Papaloizou 2008).

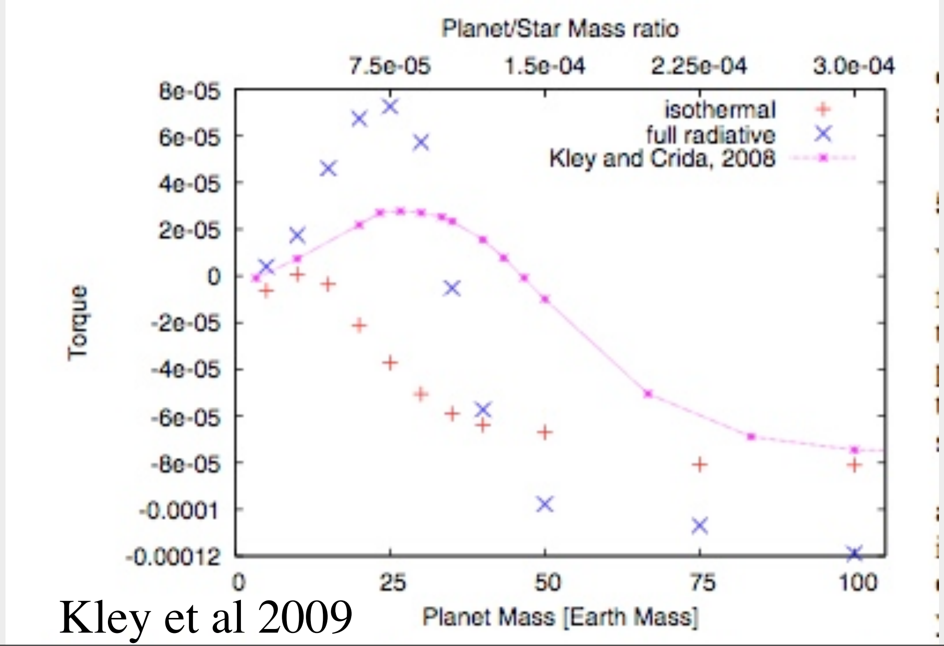
- Corotation torque is delicate requires some irreversibility to act on less than a libration timescale. Turbulent viscosity and radiation losses.



- Outward torque:
  - Sufficiently negative disk entropy gradient (nearly zero for T~ 1/r^0.5, Sigma ~ 1/r^1.5)
  - Adiabatic behavior of gas at U turn (< 10 AU for MMSN)
  - Some level of turbulent viscosity and radiative diffusivity (alpha > 10^(-3))

Possible Consequences of Outward Migration

- Outward or inward migration rates are comparable. No natural tuning to halt migration.
- But can stop where entropy gradient is less negative or disk behaves isothermally. Maybe grow planet there.
- Higher mass planet => weaker coorbital torques.
- May migrate inward at later times as disk density drops, planet mass increases, or gradients change.



Kley et al 2009

Summary

- Planet migration still a major issue for planet formation. Simplest models do not work (power law, alpha disk, locally isothermal).
- New models depend on disk structure.
- Theory questions:
  - Role of dead zones: feedback torques, edge effects
  - Role of turbulence: how effective are random torques?
  - Role of coorbital torques: effectiveness of outward torque
- Key observational issue
  What is the structure of protoplanetary disks on AU scales:
  - What are the temperature and density distributions?
  - How turbulent are the disks?
  - Are there dead zones?

See migration chapter in forthcoming textbook “Exoplanets,”
Univ. Arizona Press, ed. S. Seager