Protoplanet Migration in 3D Disks with Low Viscosity

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Critical Questions:

1) If planets (or their cores) are formed in regions where disk viscosity is low (such as in the "dead zone"), how will their migration change?
2) Vortices generation by planets and their roles in low viscosity disks.

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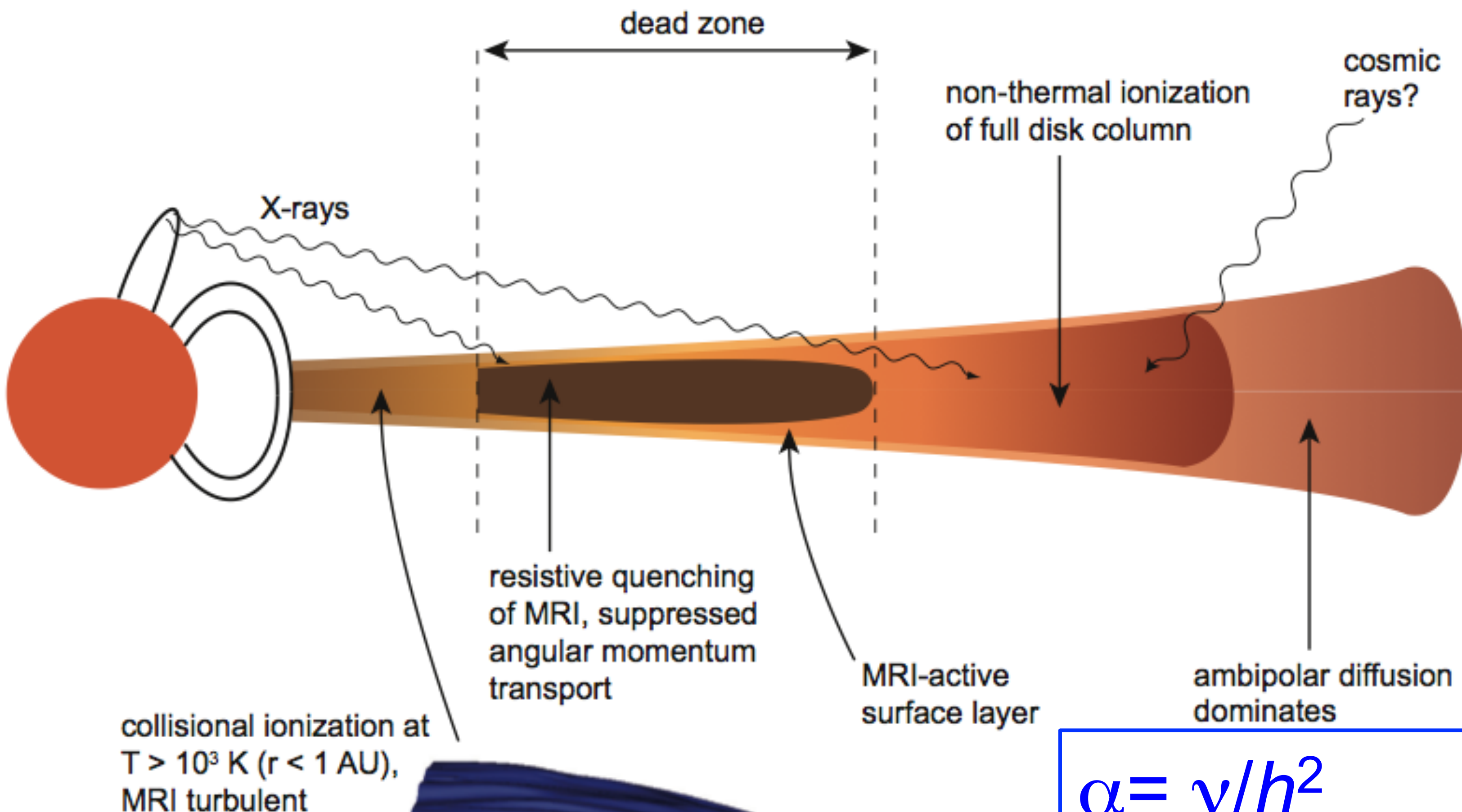
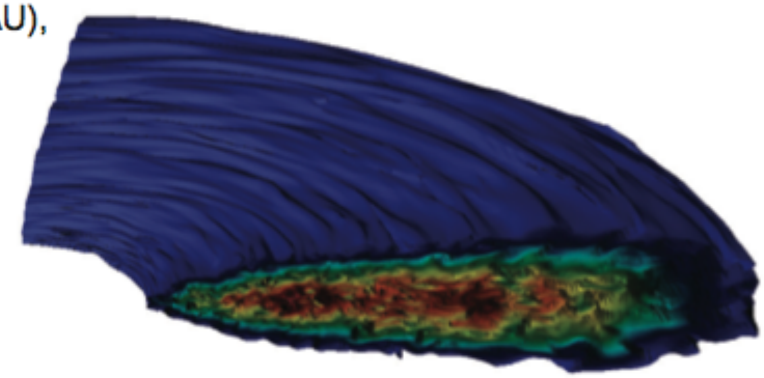
Many solutions have been proposed to address the Type I migration problem (e.g., Paardekooper’s work and many others)

Our focus: low viscosity disks

1) 2D studies
2) 3D studies

1) Structure of Protoplanetary Disks





Armitage'11

$\alpha = \nu / h^2$

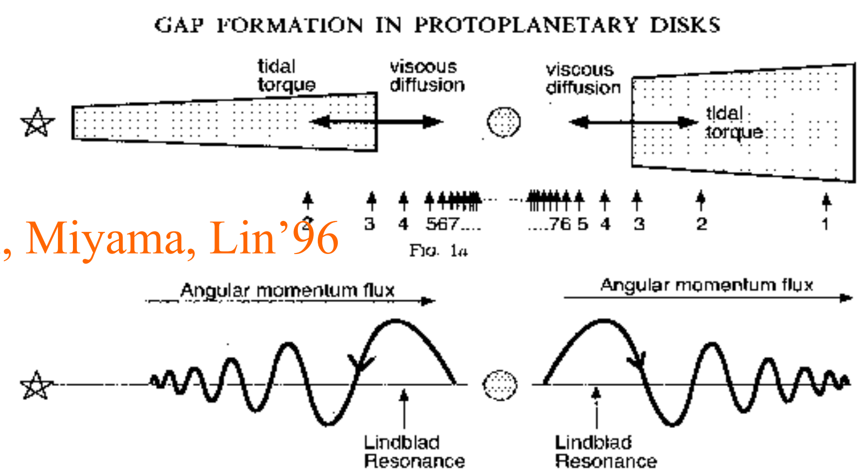
1) For h =0.035,

$\alpha = 10^{-3}$ gives ν = 1.2e−6

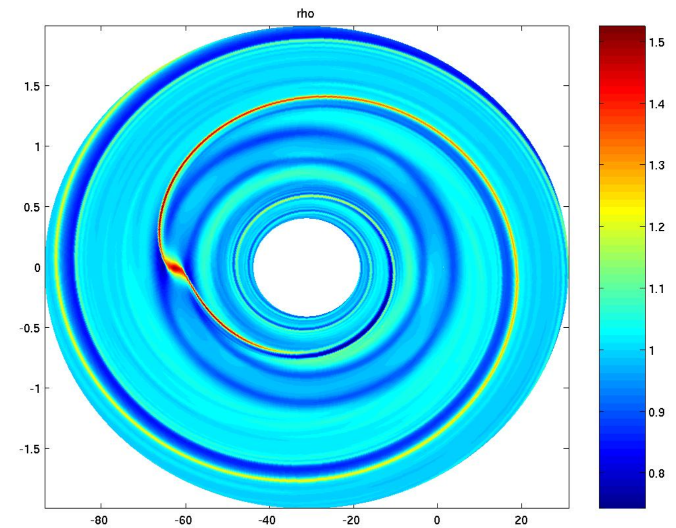
2) For h =0.05,

$\alpha = 10^{-3}$ gives ν = 2.5e−6

2) Damping of Angular Momentum Flux



Takeuchi, Miyama, Lin'96



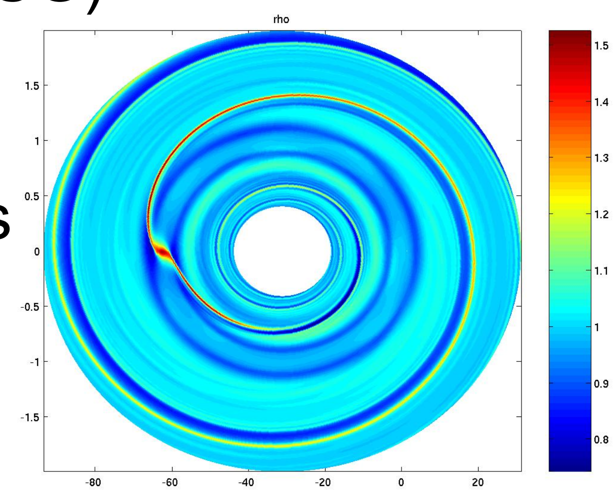
•Planet excites density waves in the disk at the Lindblad resonances.

•Ingoing (outgoing) waves carry a negative (positive) angular momentum flux as they move away from planet into the disk interior (exterior).

•Waves can dissipate by **either disk viscosity and/or by shocks**.

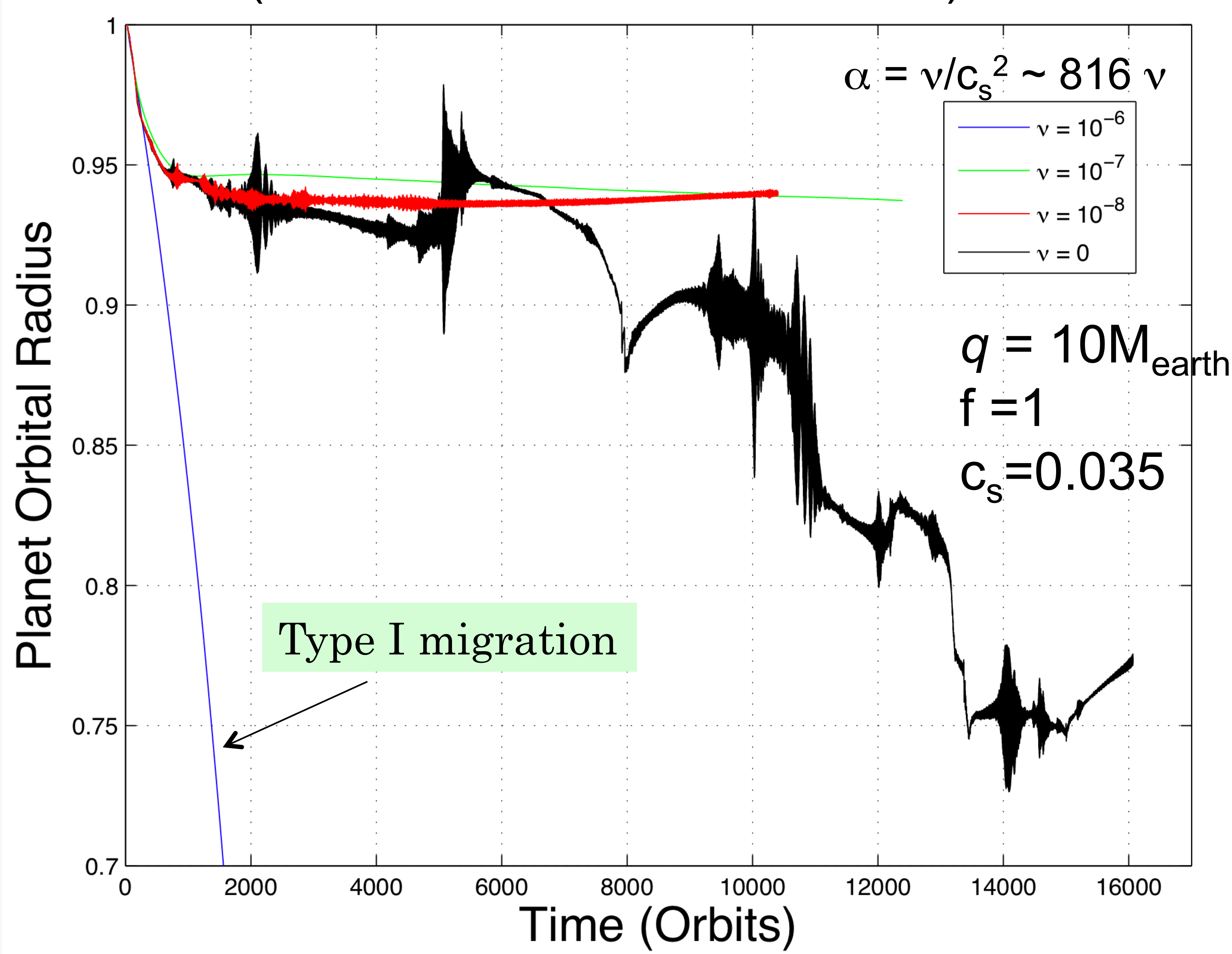
2D Problem Setup

- 2D disk size: $0.4 < r / r_p < 2.0$
- Isothermal: $c_s / v_{\phi 0} = 0.035 – 0.05$ (const c_s or const h/r)
- Initial surface density: $\Sigma(r) = 152\ f\ (r/5\ \text{AU})^{-3/2}\ \text{g cm}^{-2}$,
- Planet mass: $\mu = 3\text{x}10^{-6}$ and up
- Pseudo-3D softening for the planet potential (Li et al. 2005)
- Resolution: typically (n_r,n_φ)=(800,3200) up to (1200x4800)
- Disk (constant) viscosity: $\nu = 10^{-6}, 10^{-7}, 10^{-8}, 0 \rightarrow$ inviscid limit
- Disk self-gravity is included (Li, Buoni, Li 2009)
- Initially in radial force equilibrium (with DSG)
- Disk mass: 0.5 – 50 MMSN
- Run time: > 10,000 orbits
- Both non-accreting and accreting planets
- Code: LA-COMPASS (Li & Li)



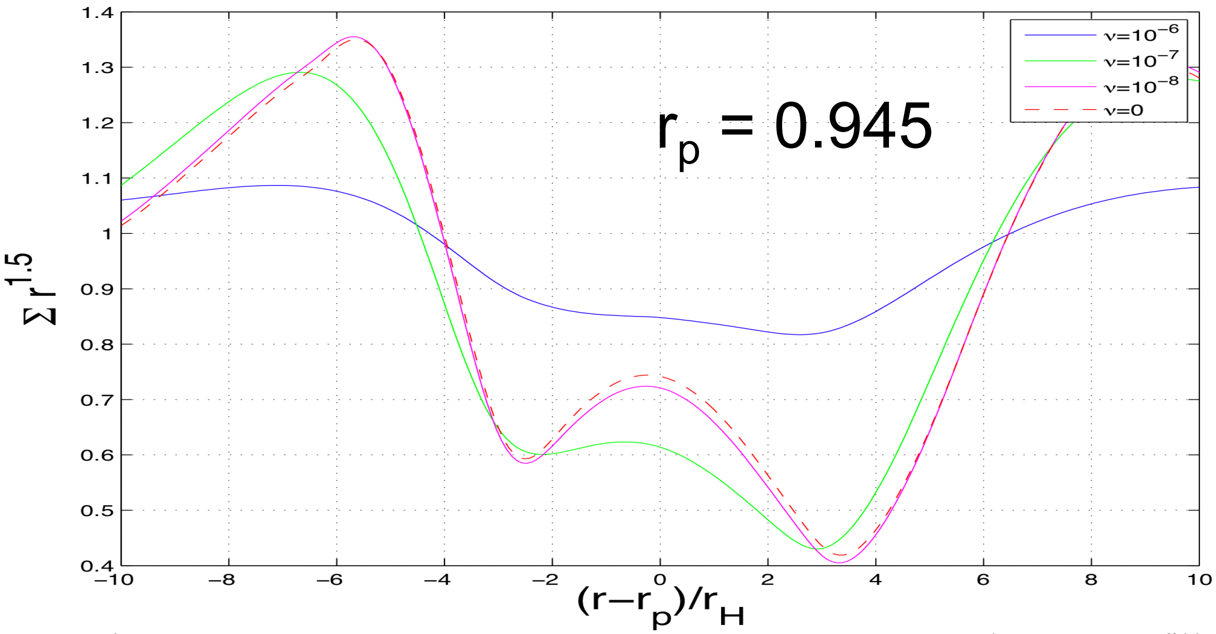
Migration in Disks with Different Viscosity

(Li et al. 2009, Yu et al. 2010)



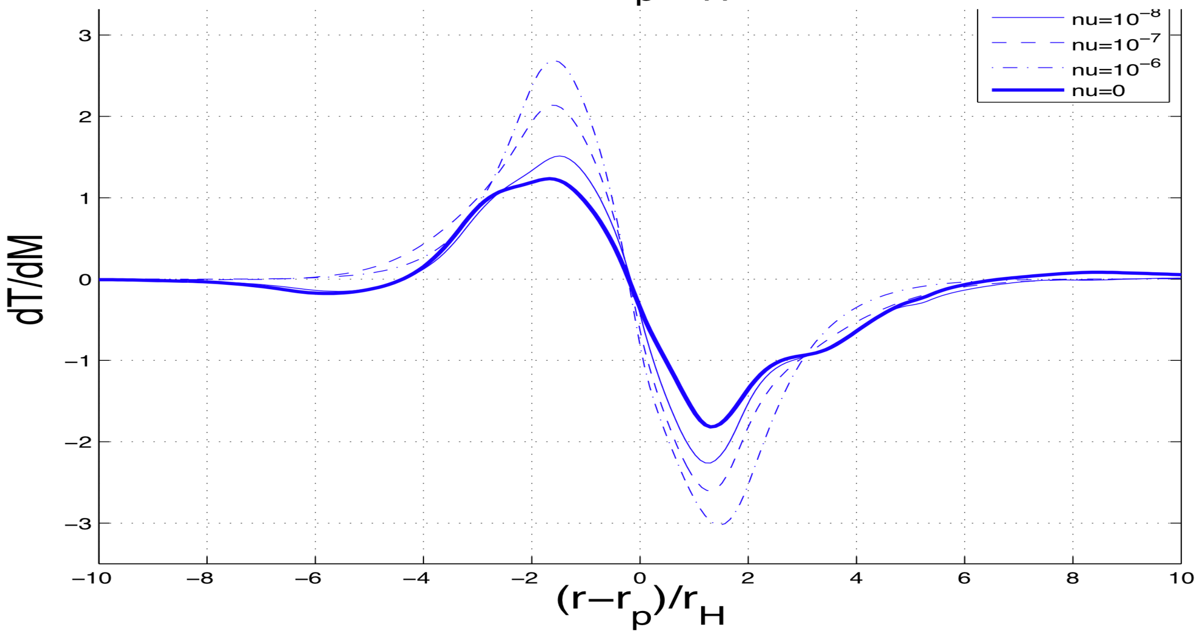
Density Feedback Effect

Surface density



Theory:
Lin & Papaloizou'86
Rafikov'02
Ward'97

torque density

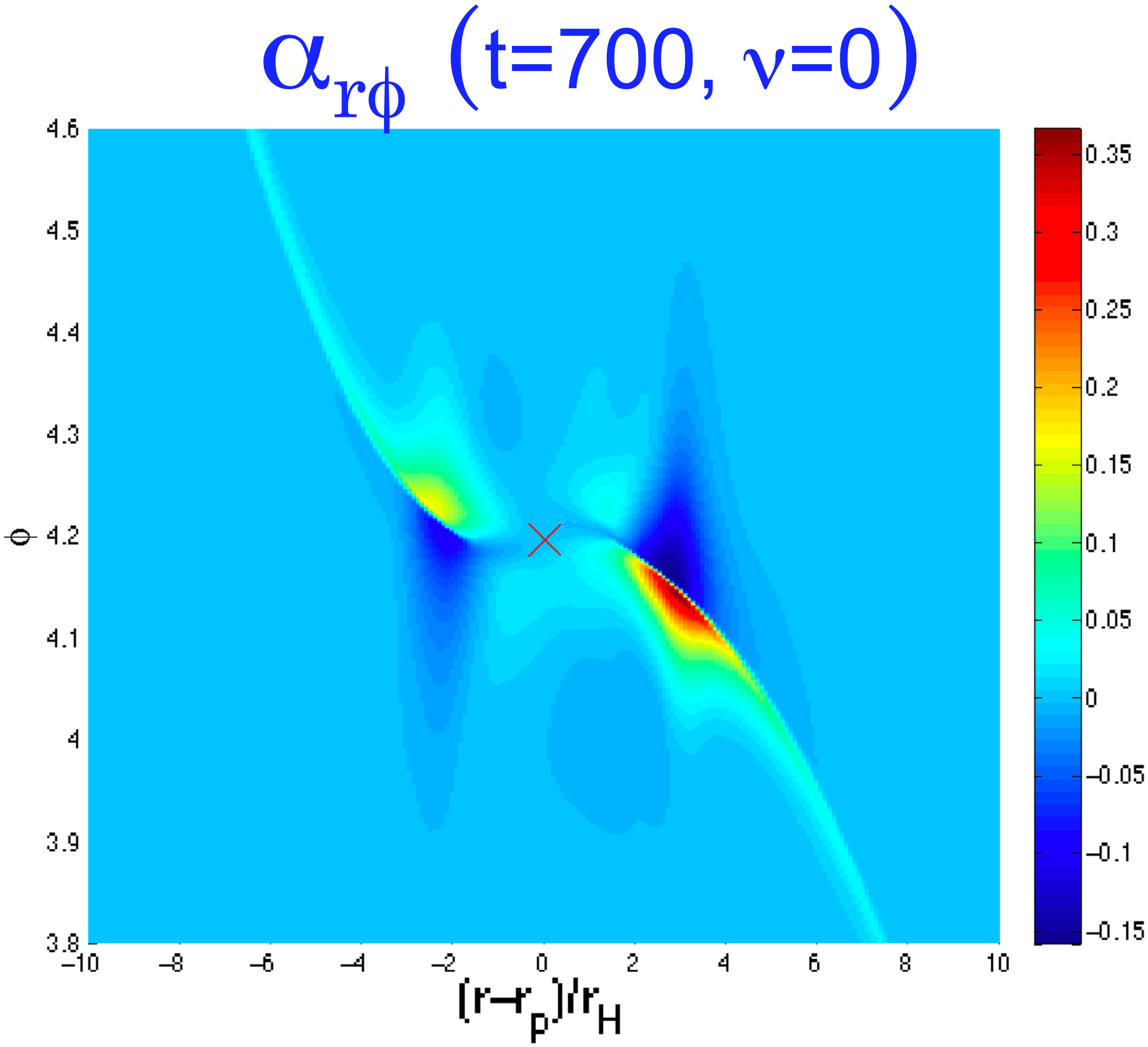


Simulations:
Li et al.'09
Yu et al.'10

Transport by Reynolds Stress $\alpha_{r\phi}$ from shocks

$$\alpha_{r\phi}(\text{Reynolds}) = \frac{\langle u_r u_\phi \rangle_\phi}{c_s^{\ 2}}$$

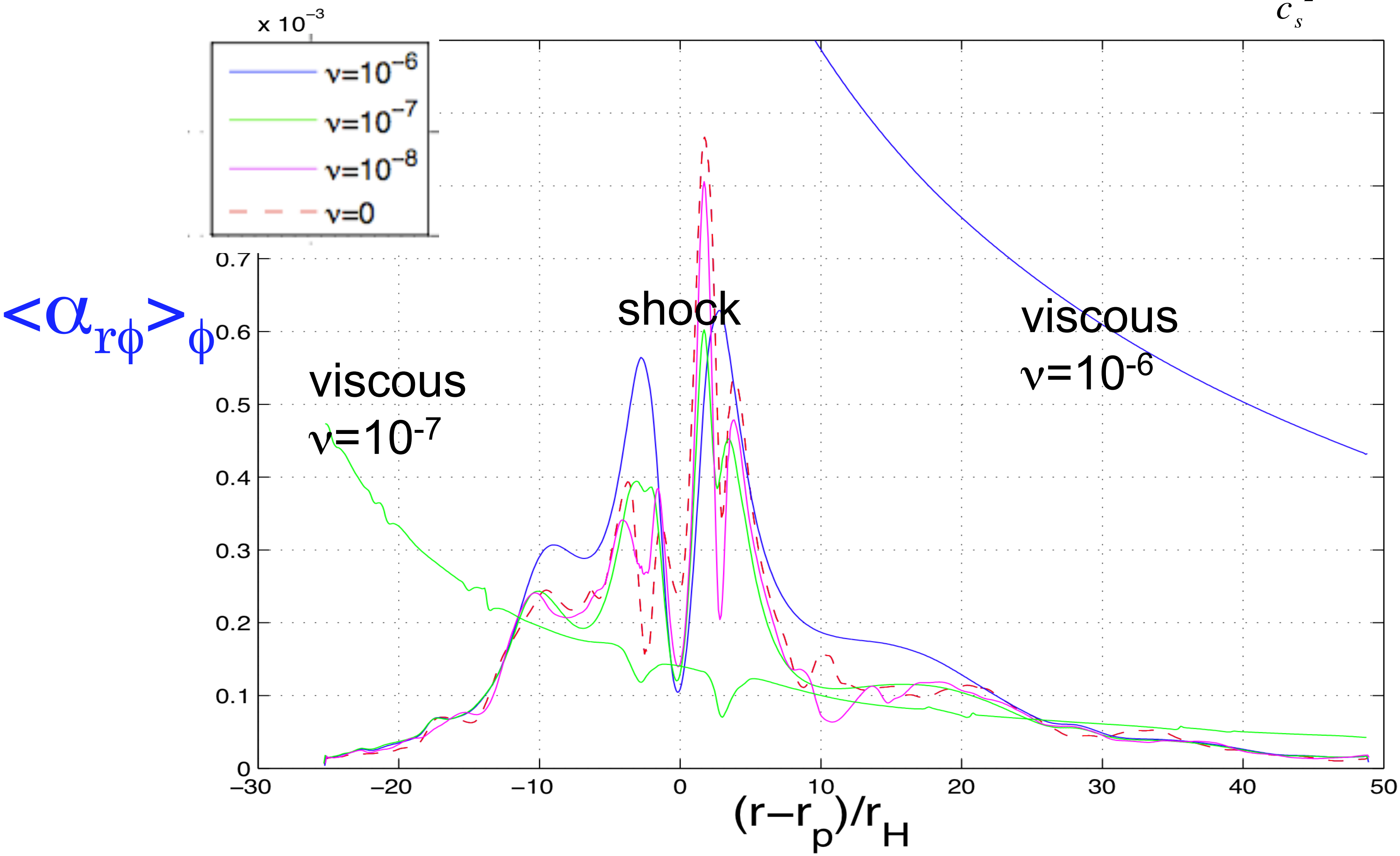
$$\alpha(\text{viscous}) = \frac{\langle \nu R (d\Omega / dR) \rangle_\phi}{c_s^{\ 2}}$$



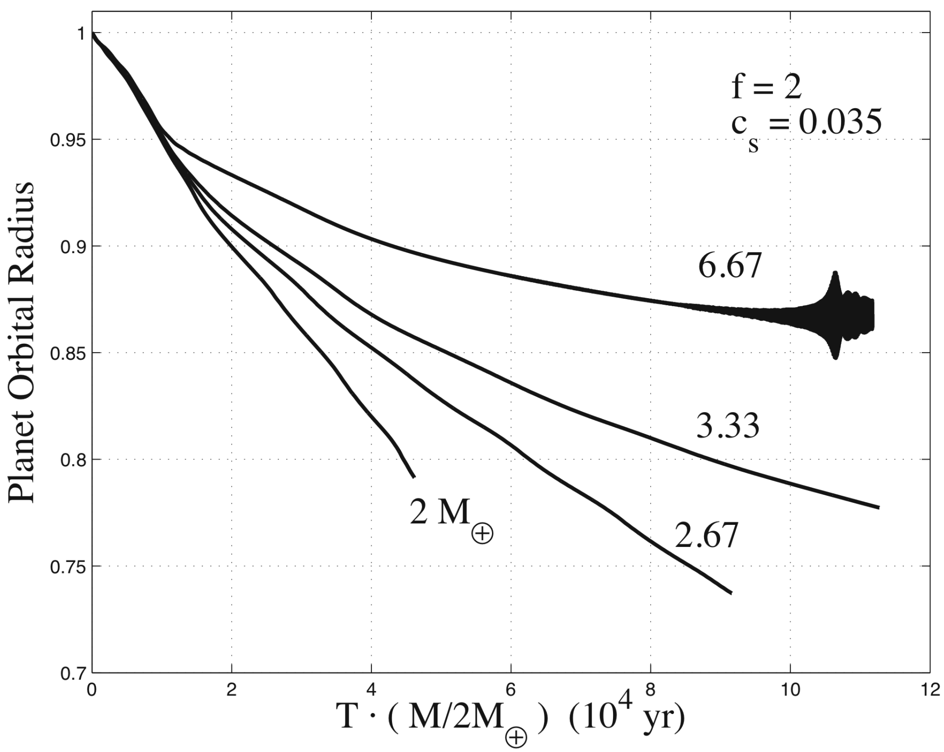
Shock Damping Dominates when ν < 1e-7

$$\alpha_{r\phi}\,(\text{Reynolds}) = \frac{\langle u_r u_\phi \rangle_\phi}{c_s^{\,2}}$$

$$\alpha(\text{viscous}) = \frac{\langle \nu R (d\Omega / dR) \rangle_\phi}{c_s^{\,2}}$$



Critical Planet Mass for Halting Type I Migration ($\nu = 0$)



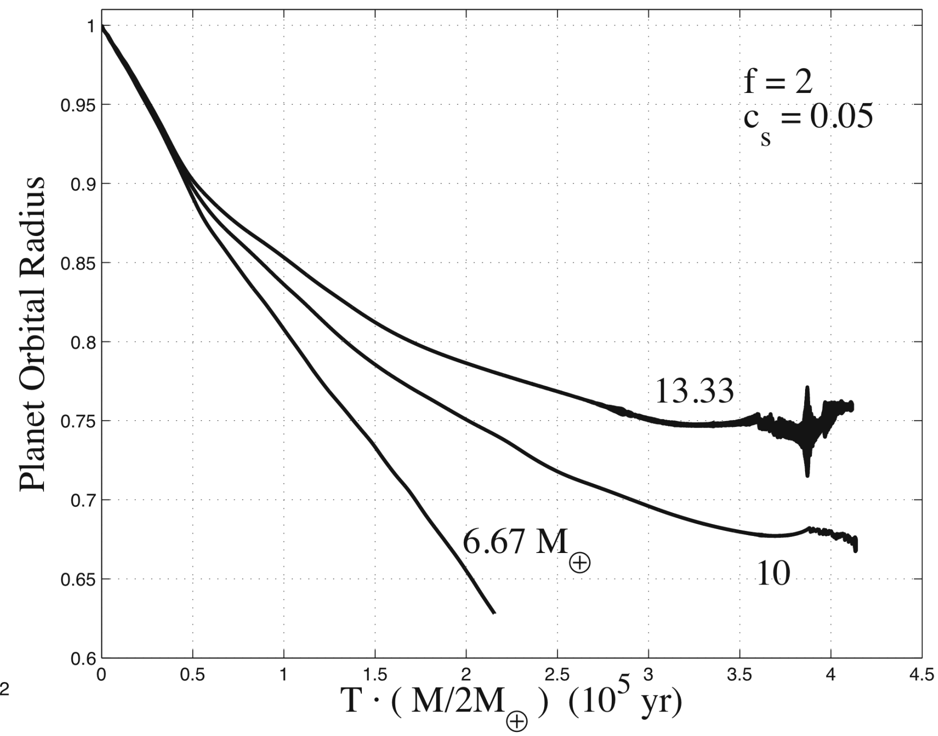
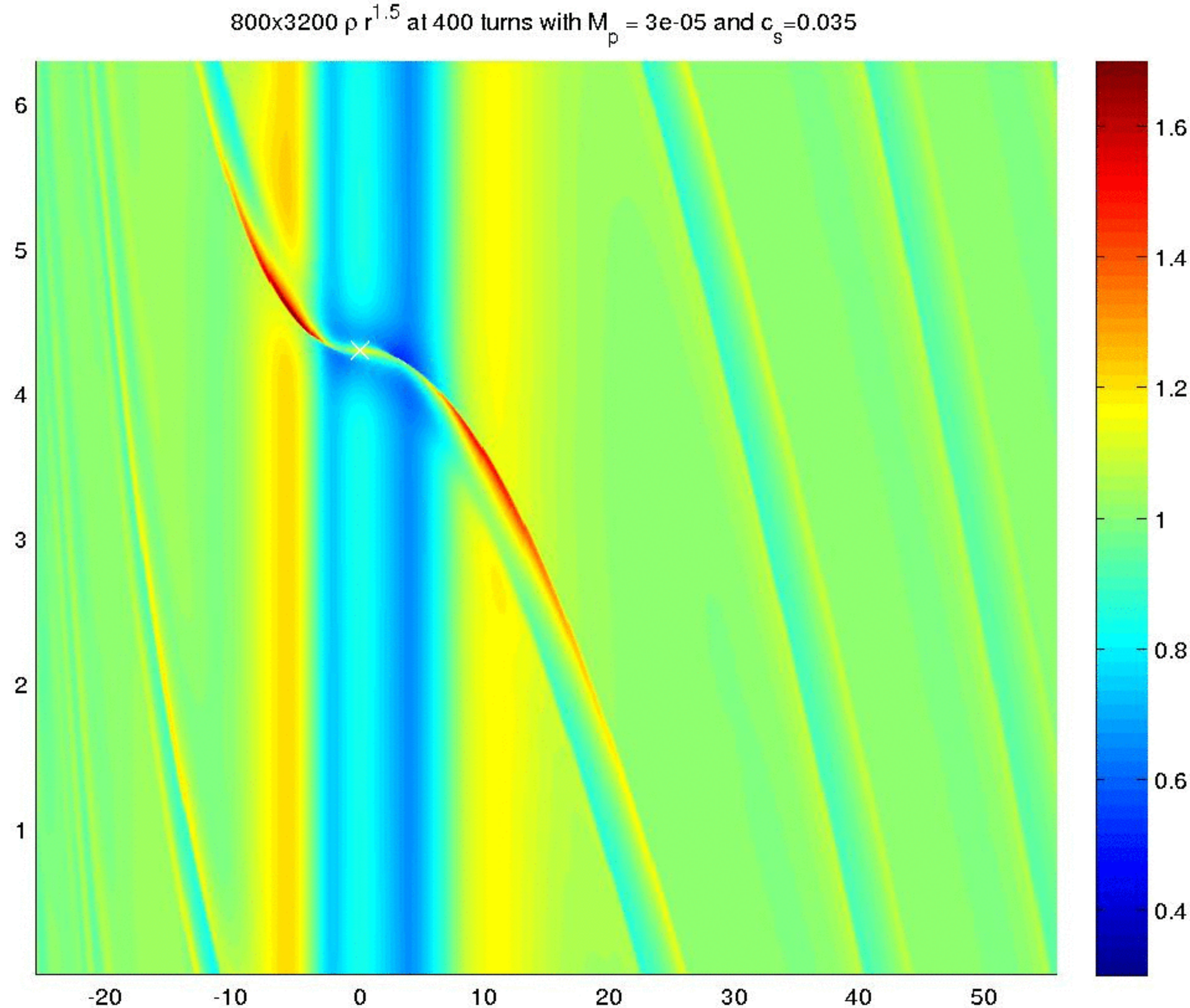


Table 1: Critical Planet Mass $M_{cr}(M_\oplus)$ from Simulations and Theory (Rafikov 2002)

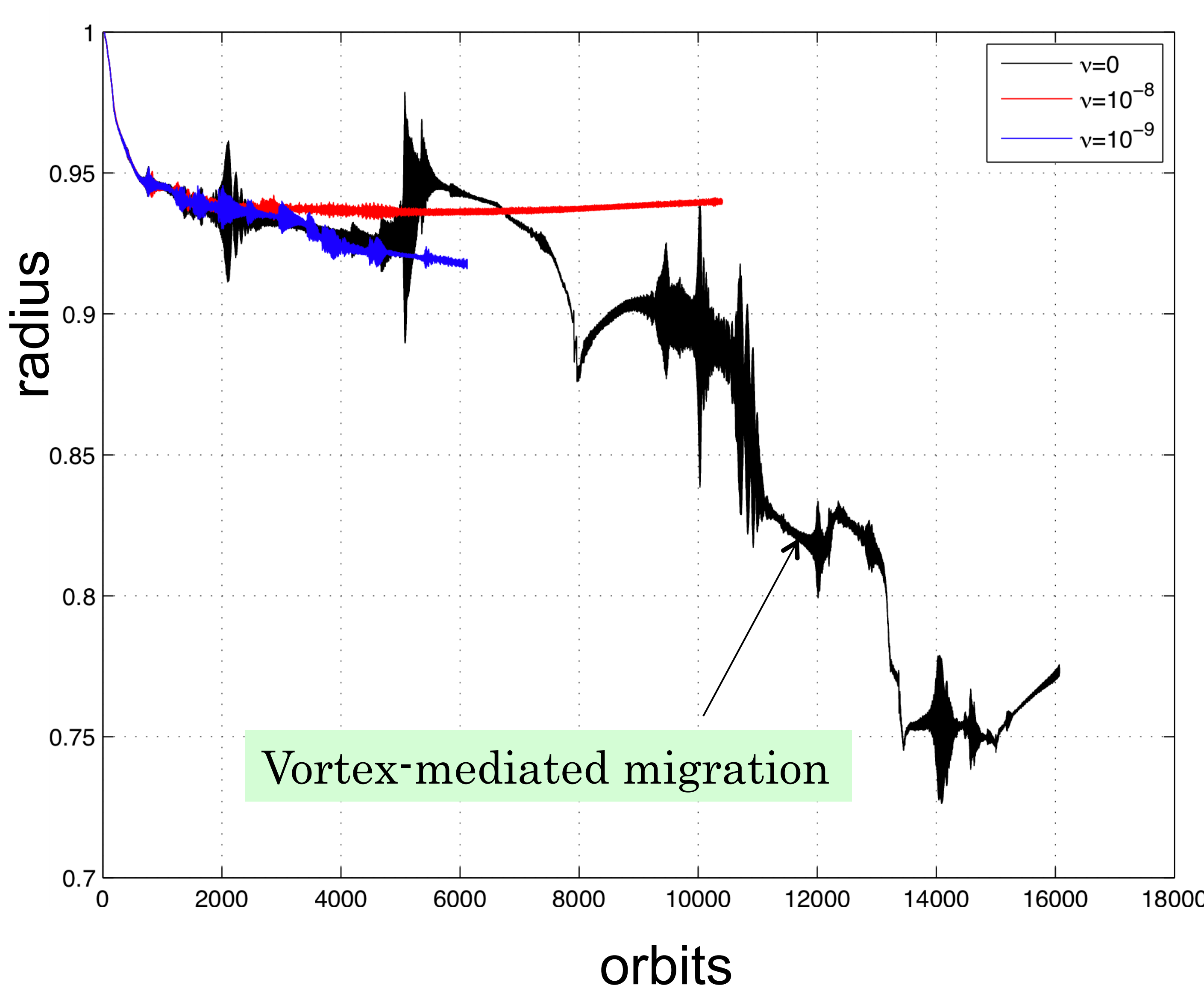
	$f=1$		$f=2$		$f=5$	
h	simulation	theory	simulation	theory	simulation	theory
0.05	~ 9	8.4	~ 9	10.9	~ 15	15.5
0.035	~ 3	2.9	~ 3	3.7	~ 6	5.3

Li et al.'09

Very
Low
Viscosity



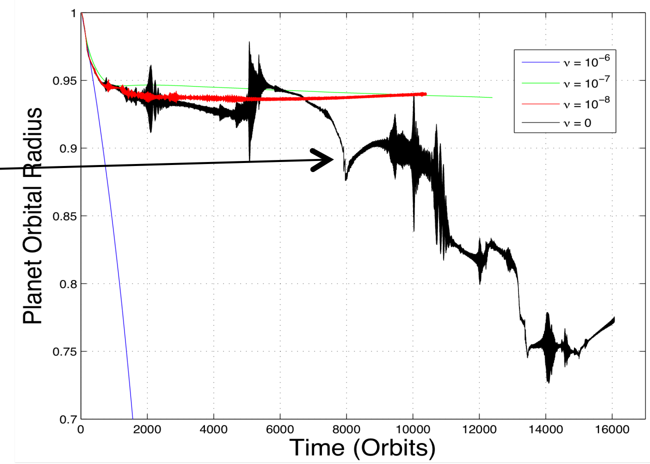
Low viscosity: Rossby Vortex Instability



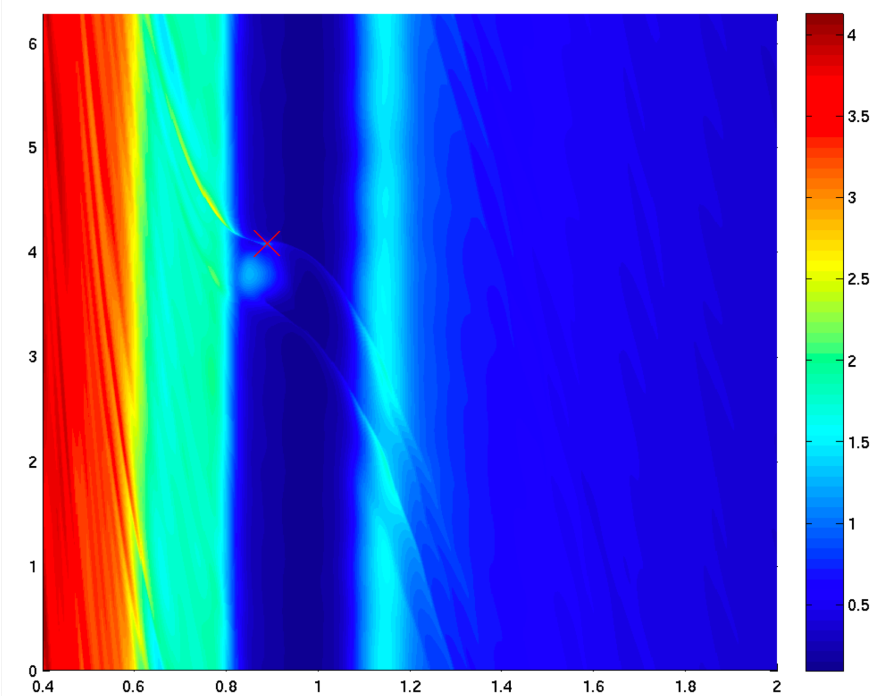
Koller et al.'03
Li et al.'05
Li et al.'09
Yu et al.'10

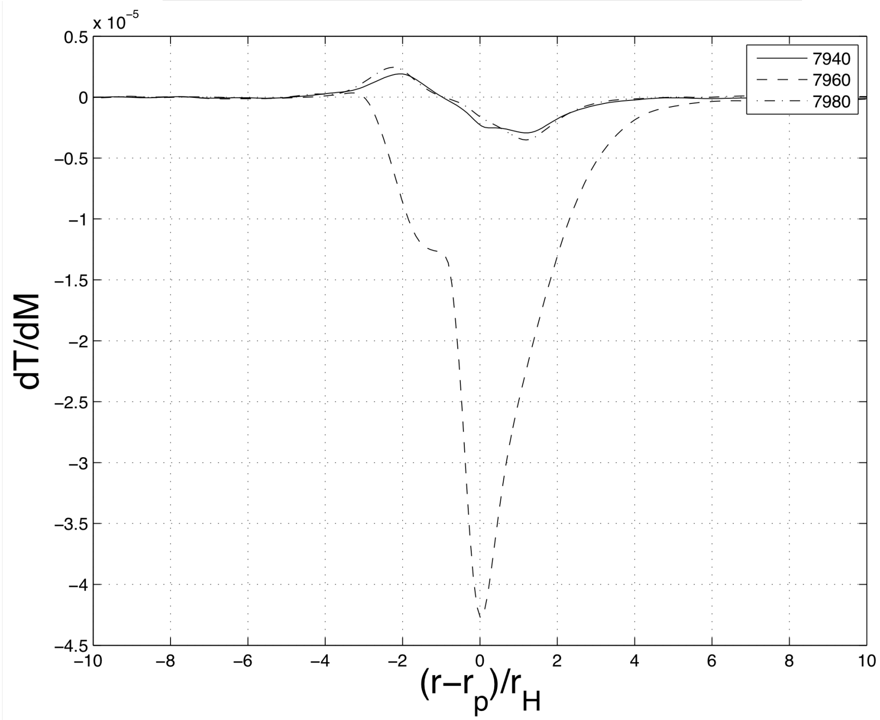
Vortex-mediated Migration

t =6400 – 8000 orbits



$\Sigma\, r^{1.5}$ at t =7960





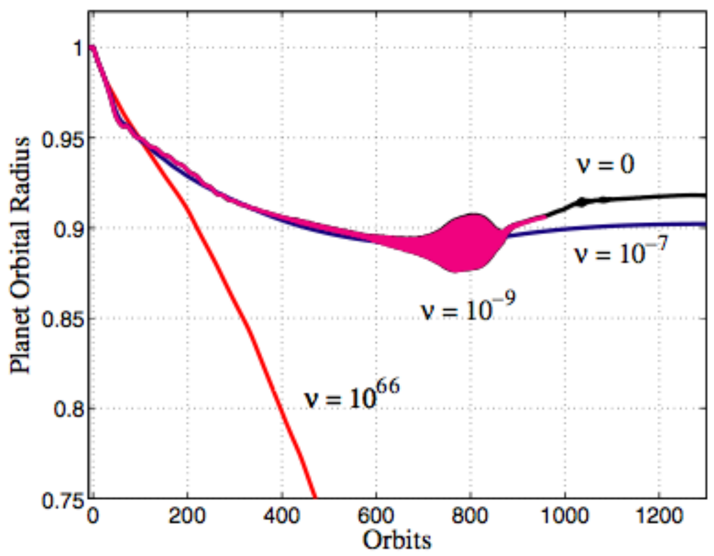
What happens in 3D?

3D Problem Setup

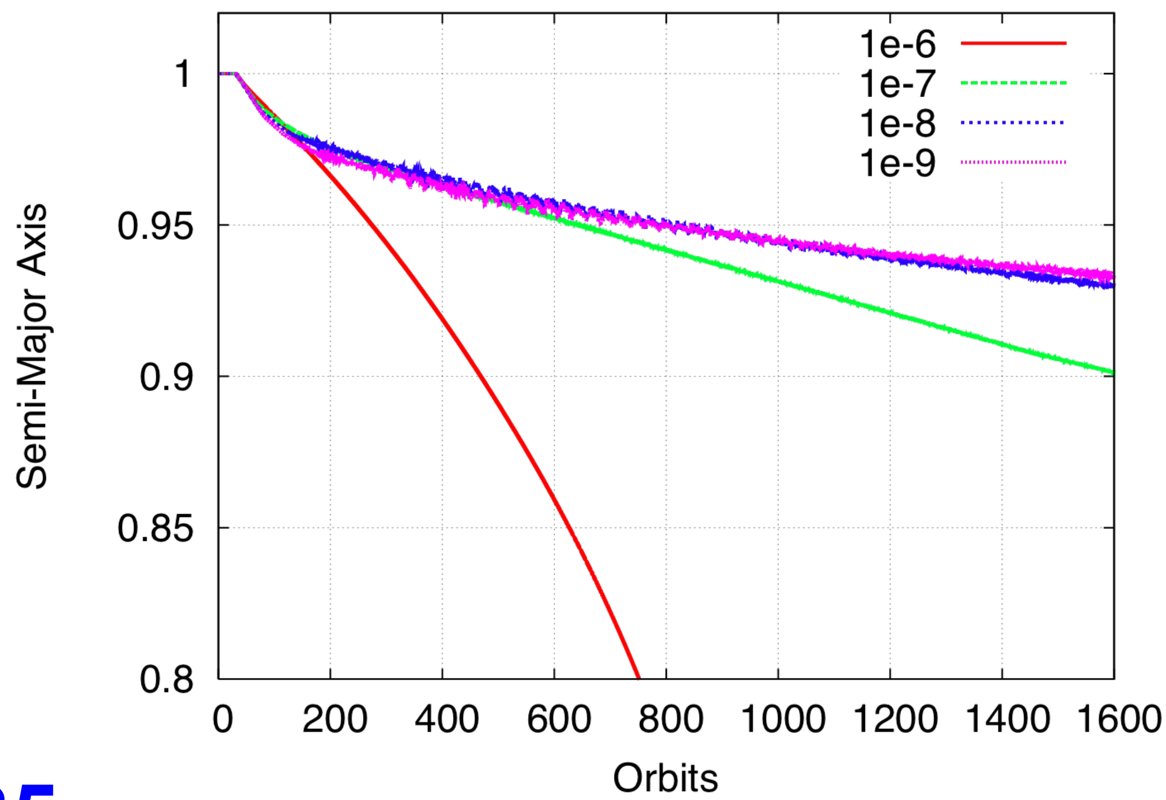
- spherical coordinates
- radial disk size: $0.4 < r / r_p < 2.0$
- locally Isothermal: c_s= 0.035 – 0.05 (const c_s and/or const h/r)
- Initial density: $\rho(r,z) = r\_cy^{-3} * \exp(-z^2)$,
- Planet mass: $\mu = 3\text{x}10^{-6}$ and up
- Resolution: (n_r,n_θ,n_φ)=(384,42,1536) up to (768x84x3072)
- Disk (constant) viscosity: $\nu = 10^{-6}, 10^{-7}, 10^{-8}, 0 \rightarrow$ inviscid limit
- Disk self-gravity is included
- Initially in force equilibrium (with DSG)
- Disk mass: 0.5 – 50 MMSN
- Run time: > 3,000 orbits
- Both non-accreting and accreting planets
- Code: LA-COMPASS (Li & Li)

Migration in Disks with Different Viscosity

2D



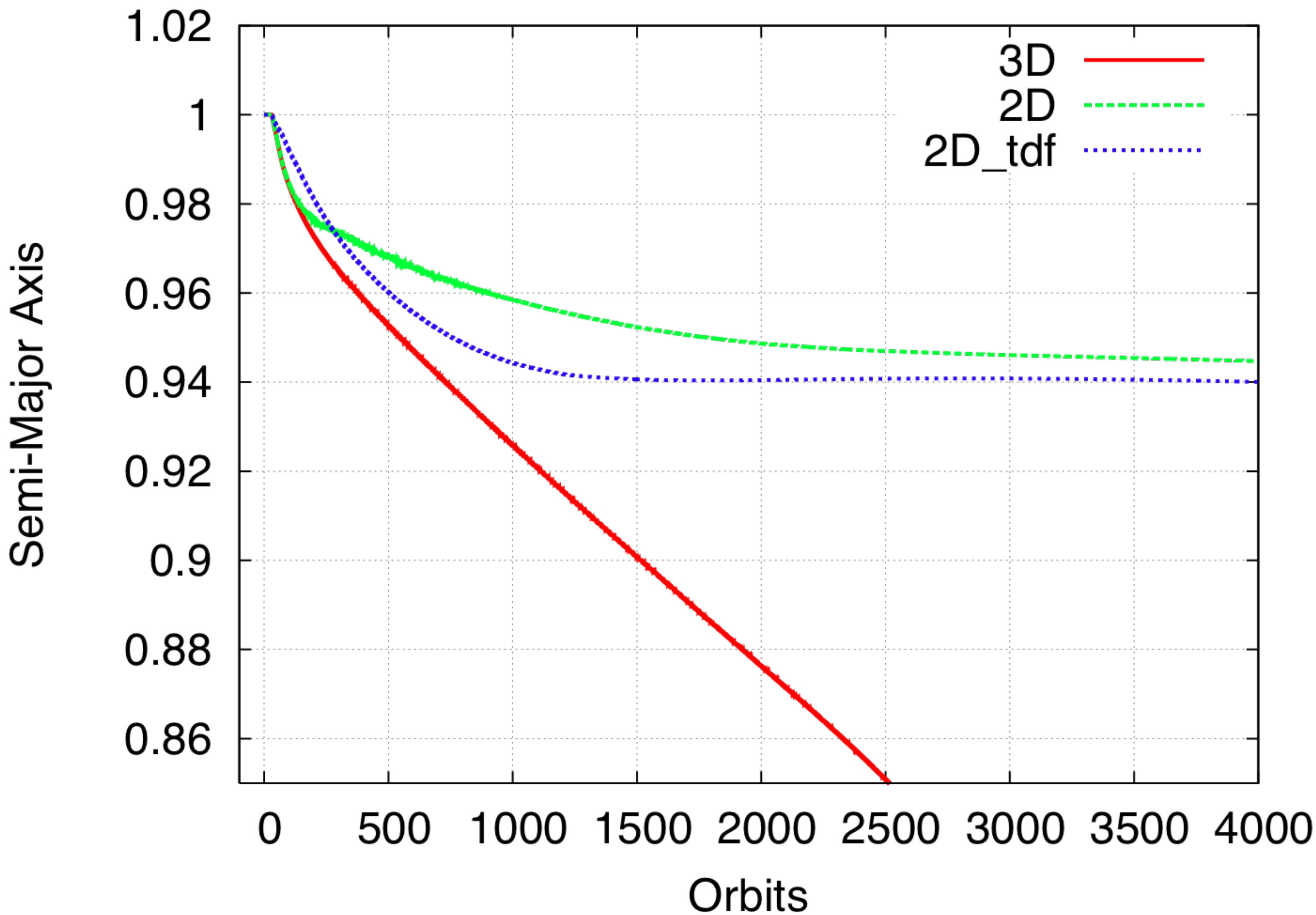
3D



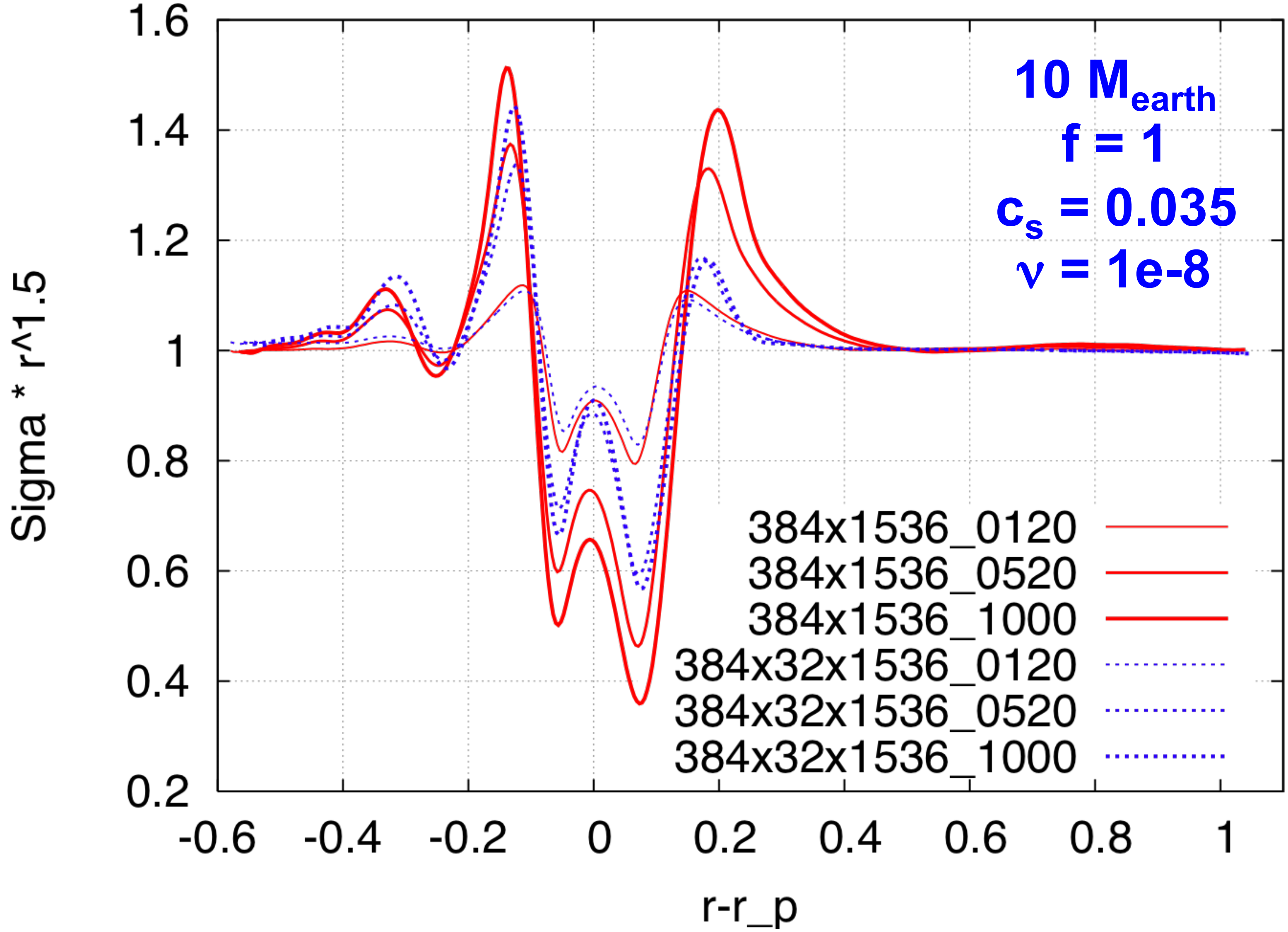
10 M_{earth}, c_s=0.035

Comparing 2D vs. 3D

(10 M_{earth}, c_s=0.035, ν=1e-7)

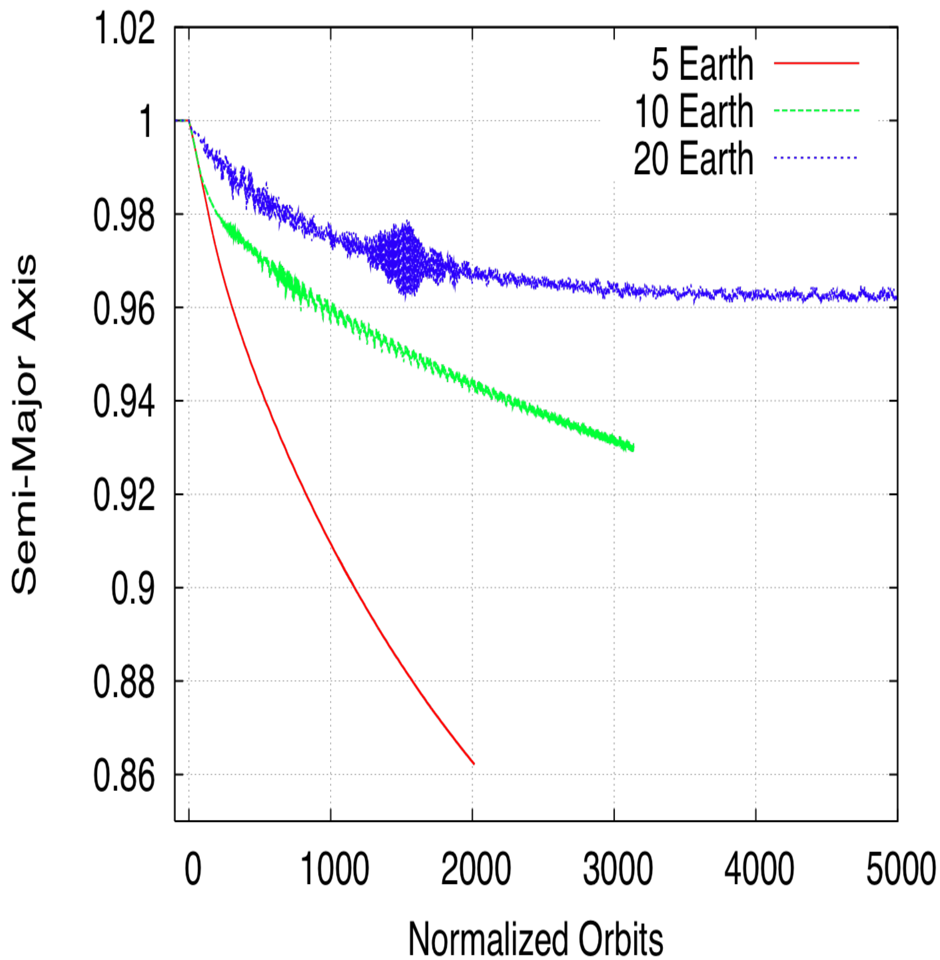


Comparing 2D vs. 3D – density evolution

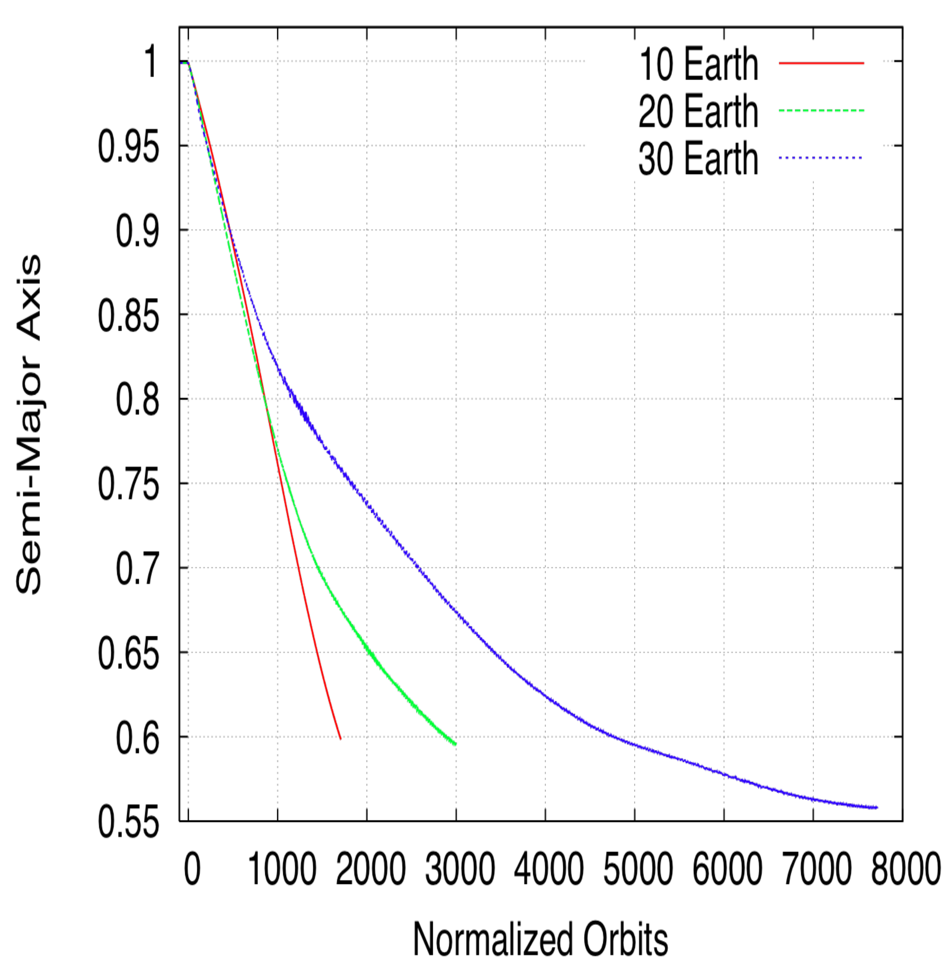


Critical Mass is larger in 3D than 2D

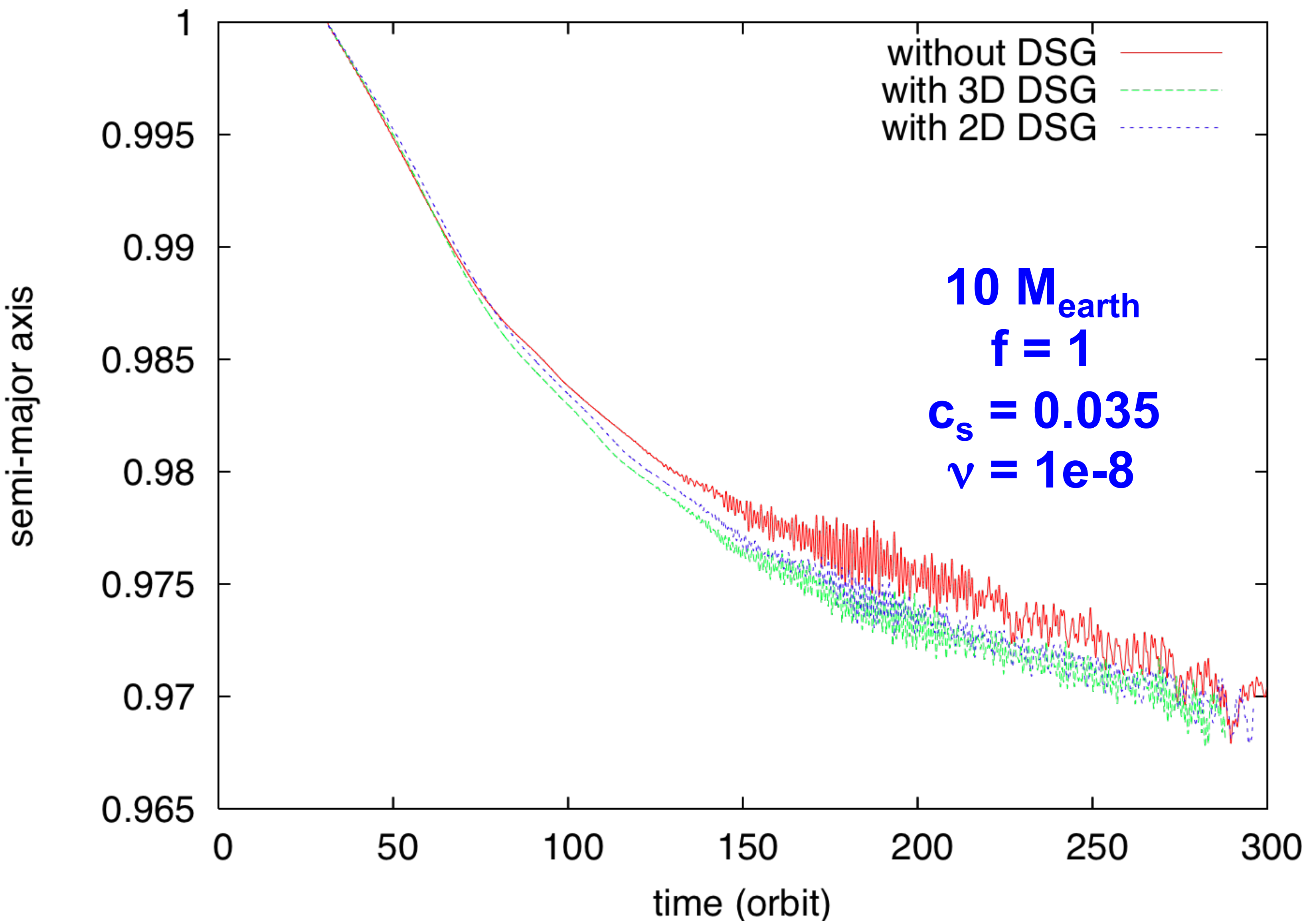
$c_s = 0.035$



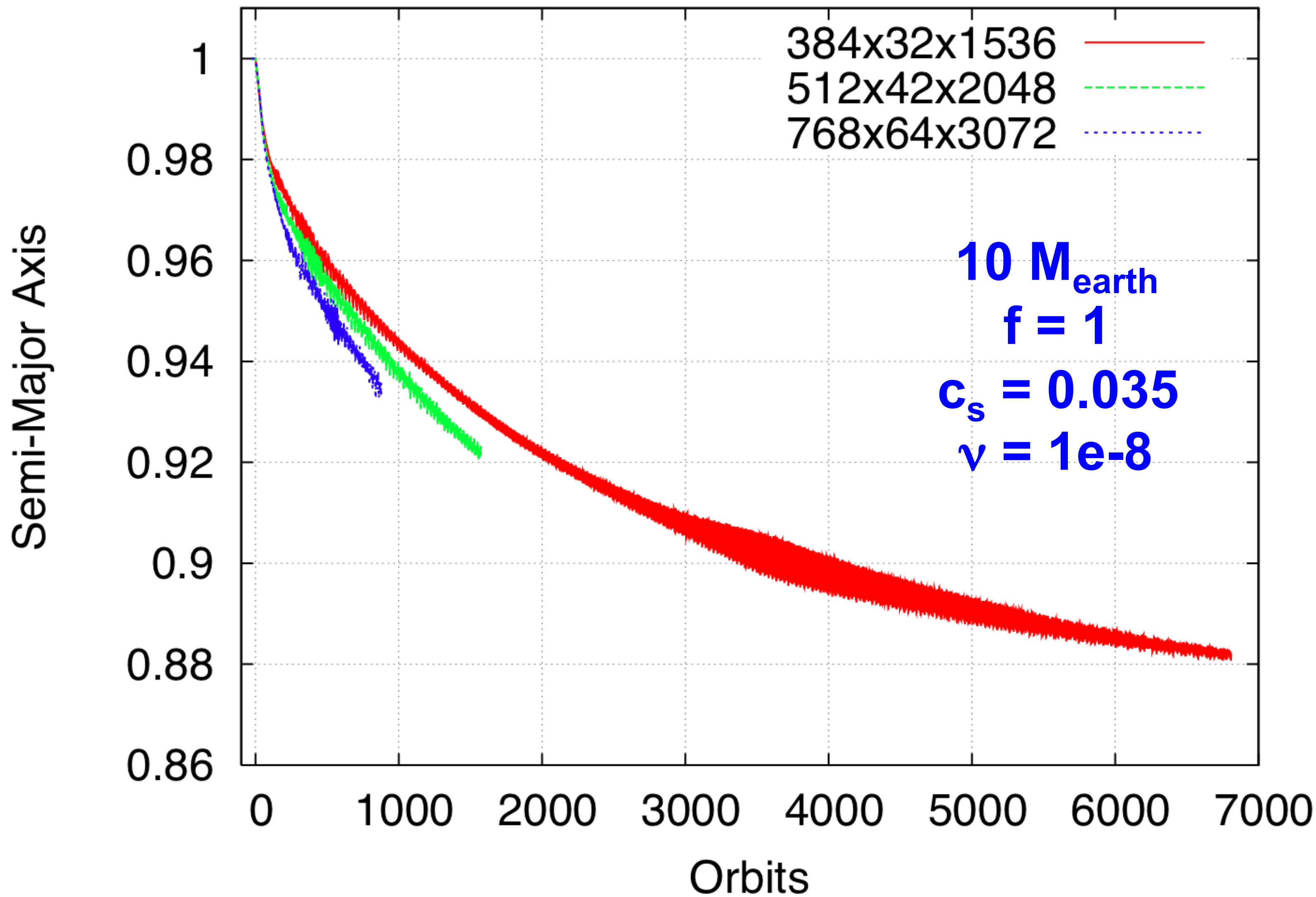
$c_s = 0.05$



Effects of DSG in 3D



Effects of Resolution – 3D

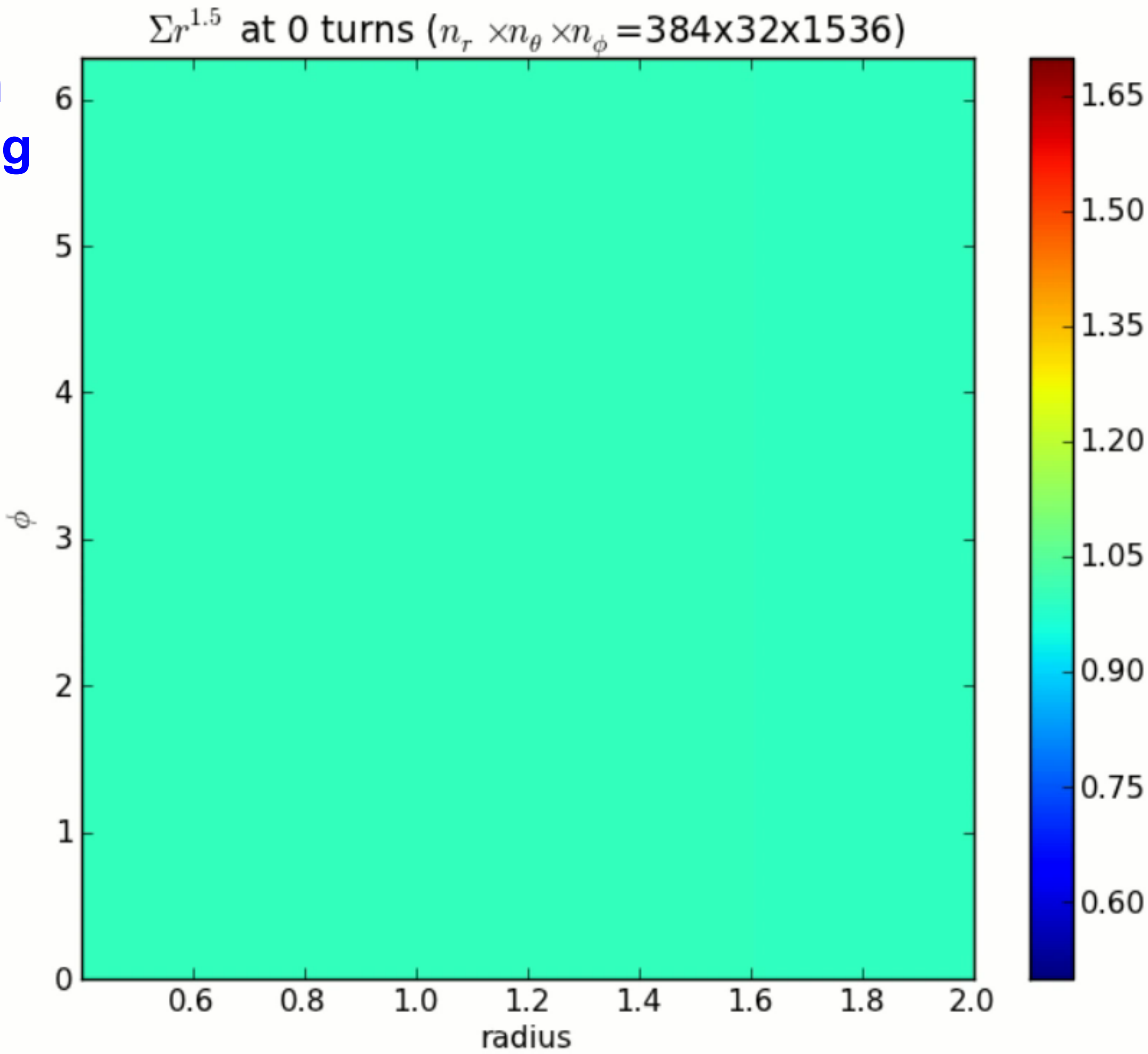


3D Vortices

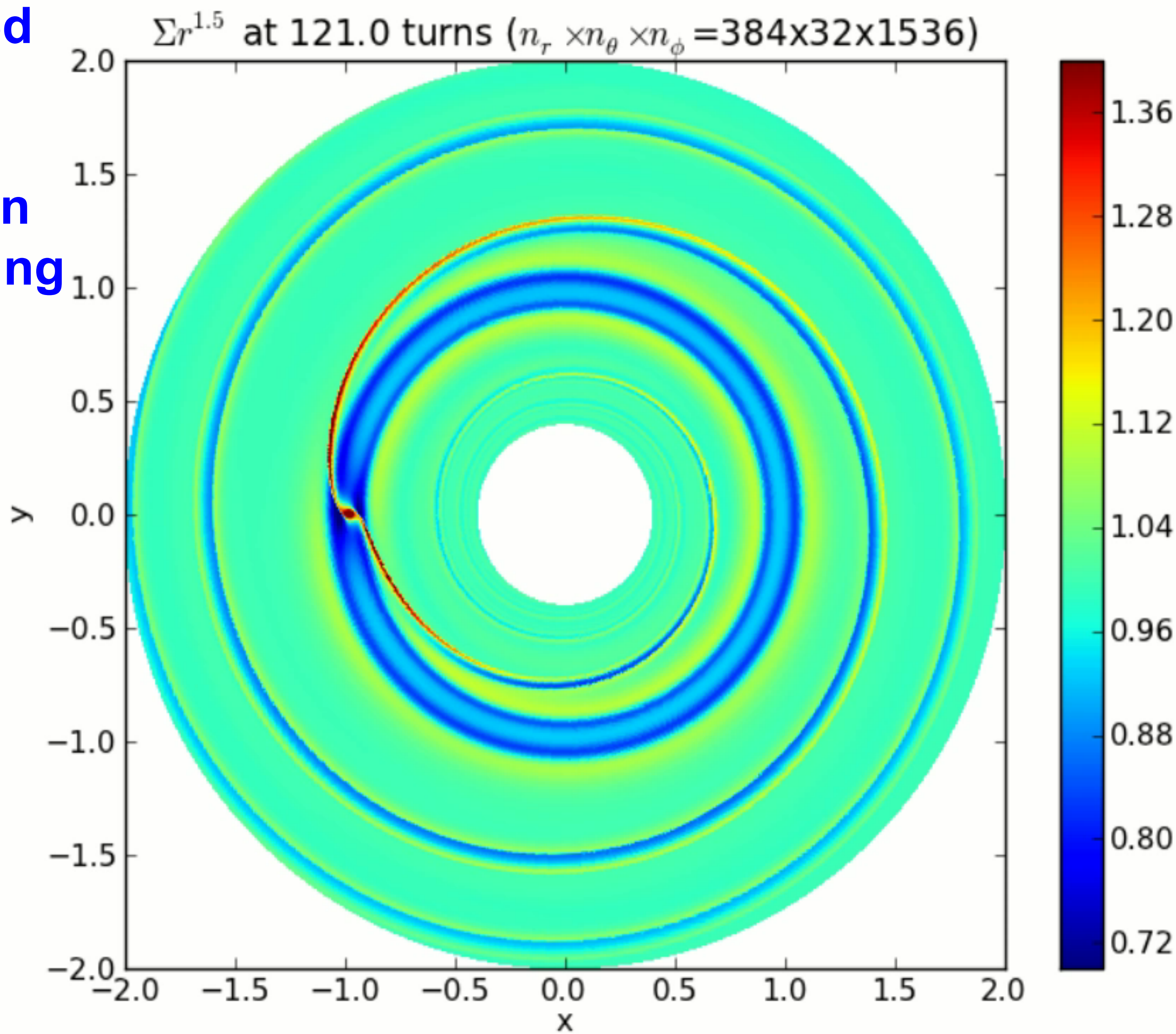
- Excited by (even) low mass planets when disk viscosity is low
- Robust and long-lived (driven and "regulated" by the planet)

Vortex Formation and Merging

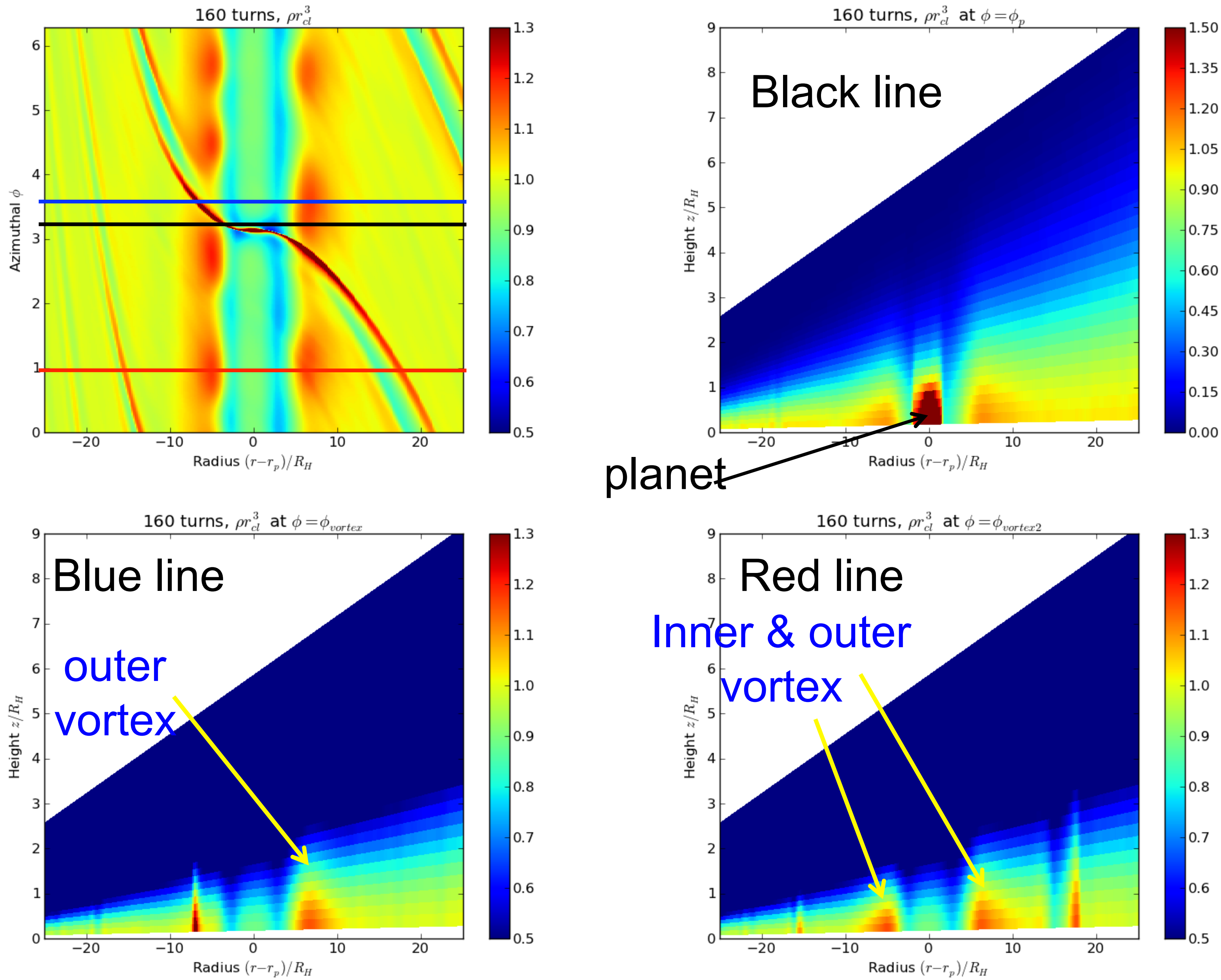
10 M_{earth}
f = 1
c_s = 0.035
ν = 1e-8



A detailed look at vortex formation and merging



10 M_{earth}
f = 1
c_s = 0.035
ν = 1e-8



160 turns, ρr_{cl}^3
Azimuthal ϕ
Radius $(r-r_p)/R_H$
160 turns, ρr_{cl}^3 at $\phi=\phi_p$
Black line
Height z/R_H
planet
160 turns, ρr_{cl}^3 at $\phi=\phi_{vortex}$
Blue line
outer vortex
160 turns, ρr_{cl}^3 at $\phi=\phi_{vortex2}$
Red line
Inner & outer vortex

Summary:
Migration in Low Viscosity Isothermal Disks

1. High viscosity: the usual Type I
2. Intermediate viscosity: similar to viscous case, ~10^6 orbits
3. Low viscosity: vortex-mediated migration

A) When viscosity is low, **the shock damping of the density waves is dominant. This produces a strong density feedback effect**. This significantly slows down/halt the Type I migration.

B) Feedback effect in 3D is weaker than in 2D.

C) Vortices generated at edges of density troughs will merge after several hundred orbits, forming “banana” and seemingly stable and long-lived (> 7000 orbits).

D) Would be interesting to investigate the dust dynamics in such situations.

Thank you!