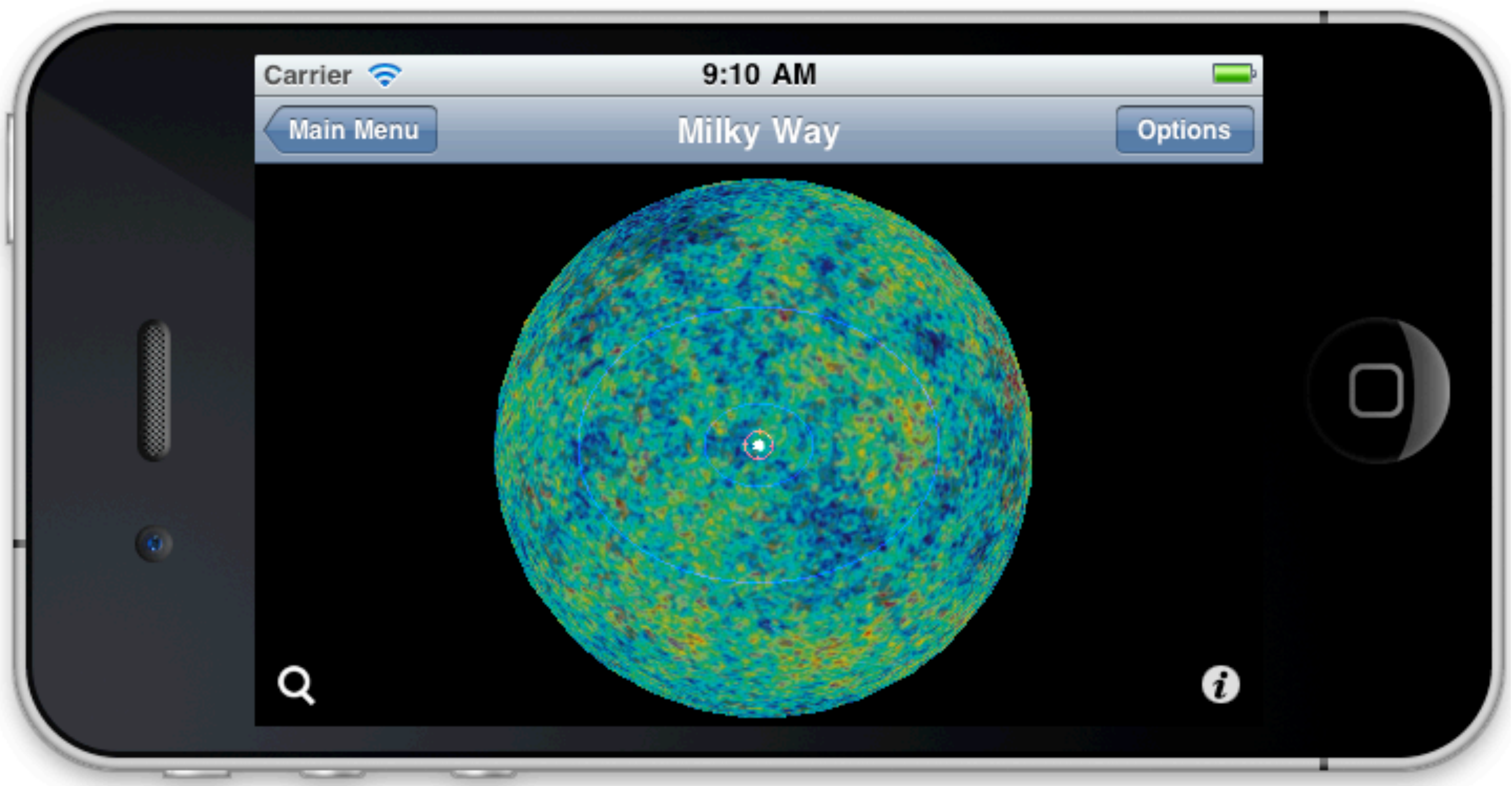
Exoplanets in perspective



'Exoplanet' available as a free download for iOS on the iTunes AppStore

Institute for Advanced Study

Exoplanets, migration, turbulence, resonances and inclined orbits

~~Saturn's rings~~

Hanno Rein @ ISIMA 2011 KIAA Beijing

Migration in a non-turbulent disk

Multi-planetary systems

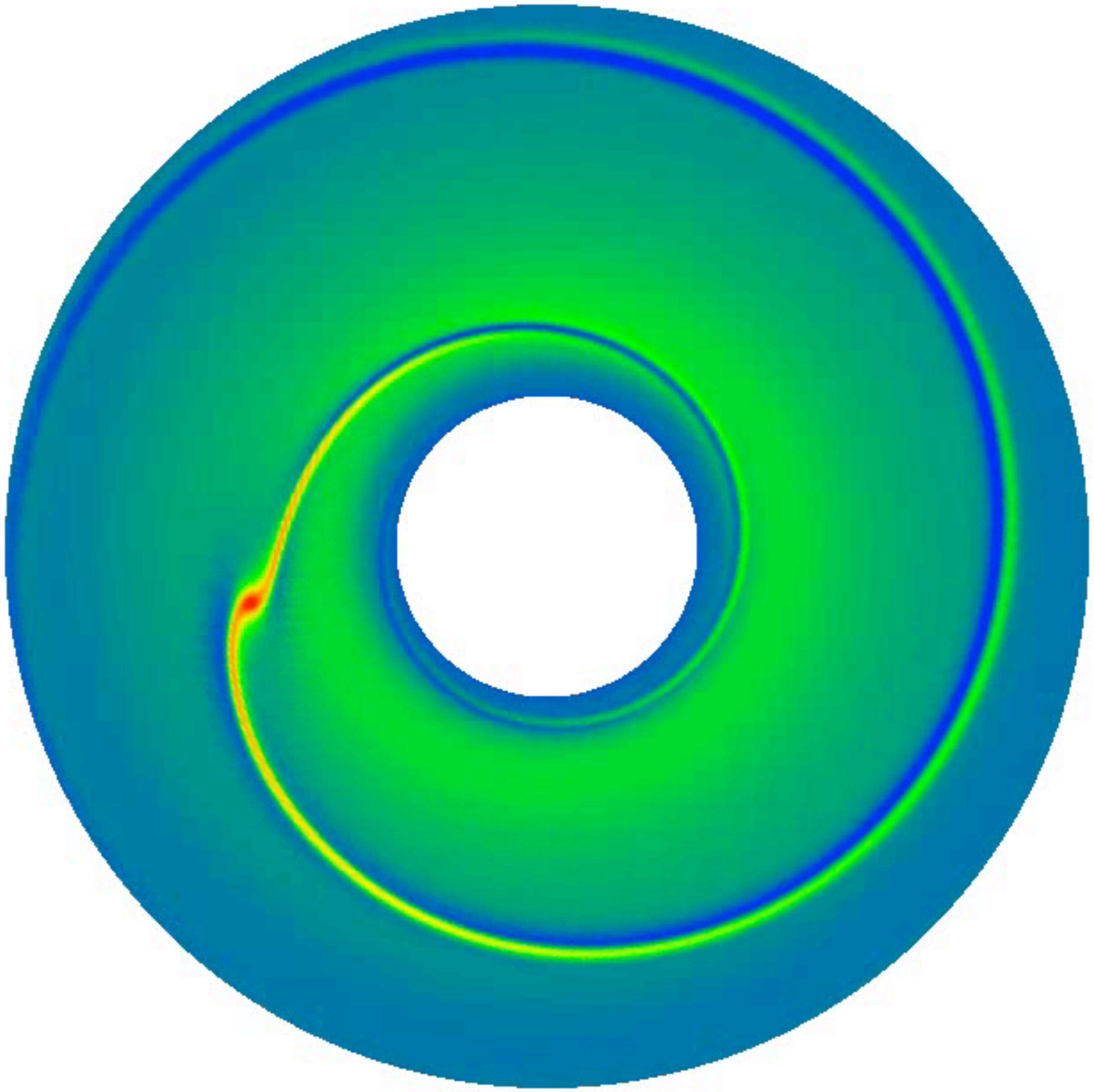
planet + disk = migration

2 planets + migration = resonance

Lee & Peale 2002, Kley & Nelson 2008, Sandor et al 2007, Rein et al 2010

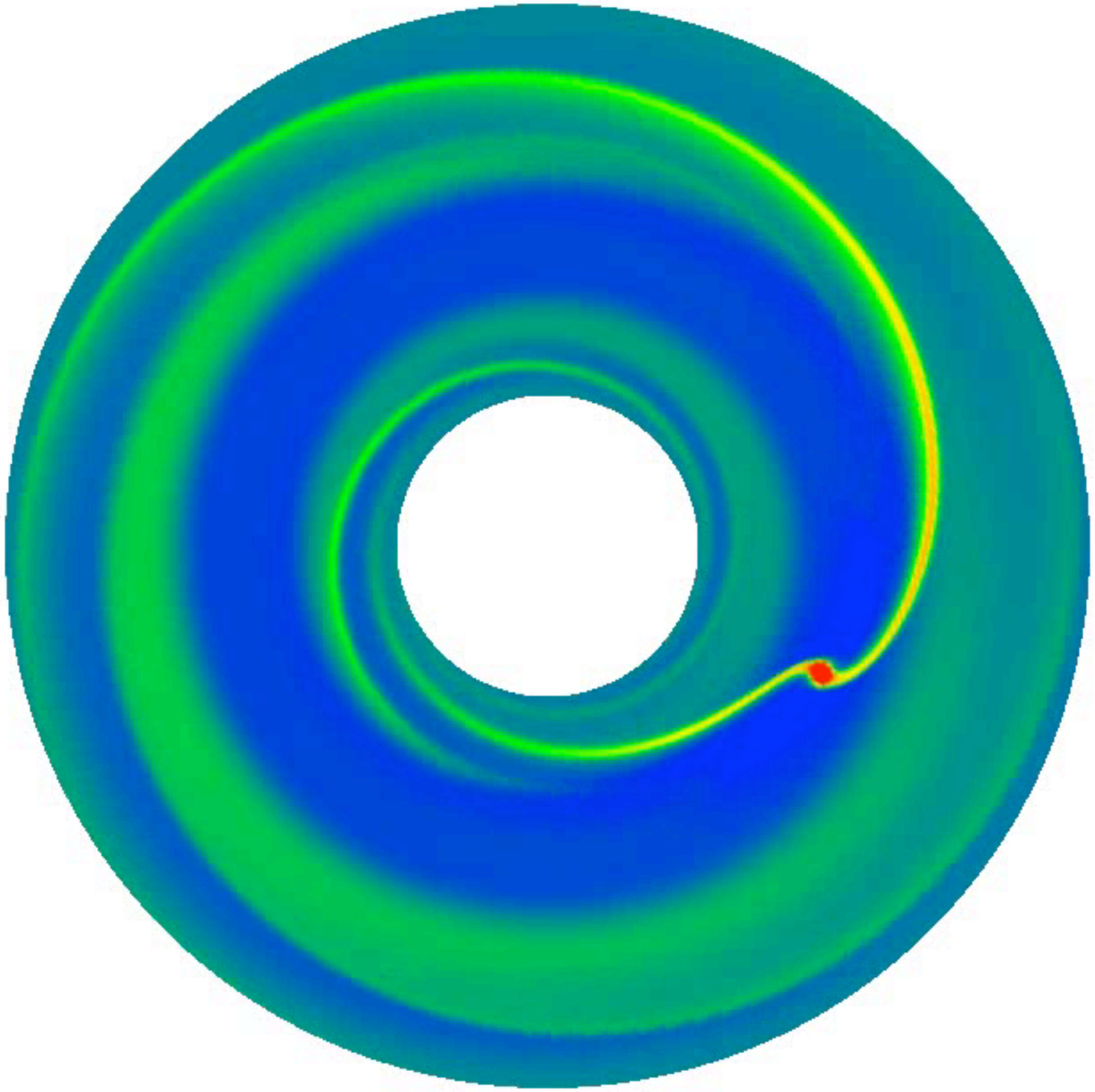
Migration - Type I

- Low mass planets
- No gap opening in disk
- Migration rate is fast
- Depends strongly on thermodynamics of the disk



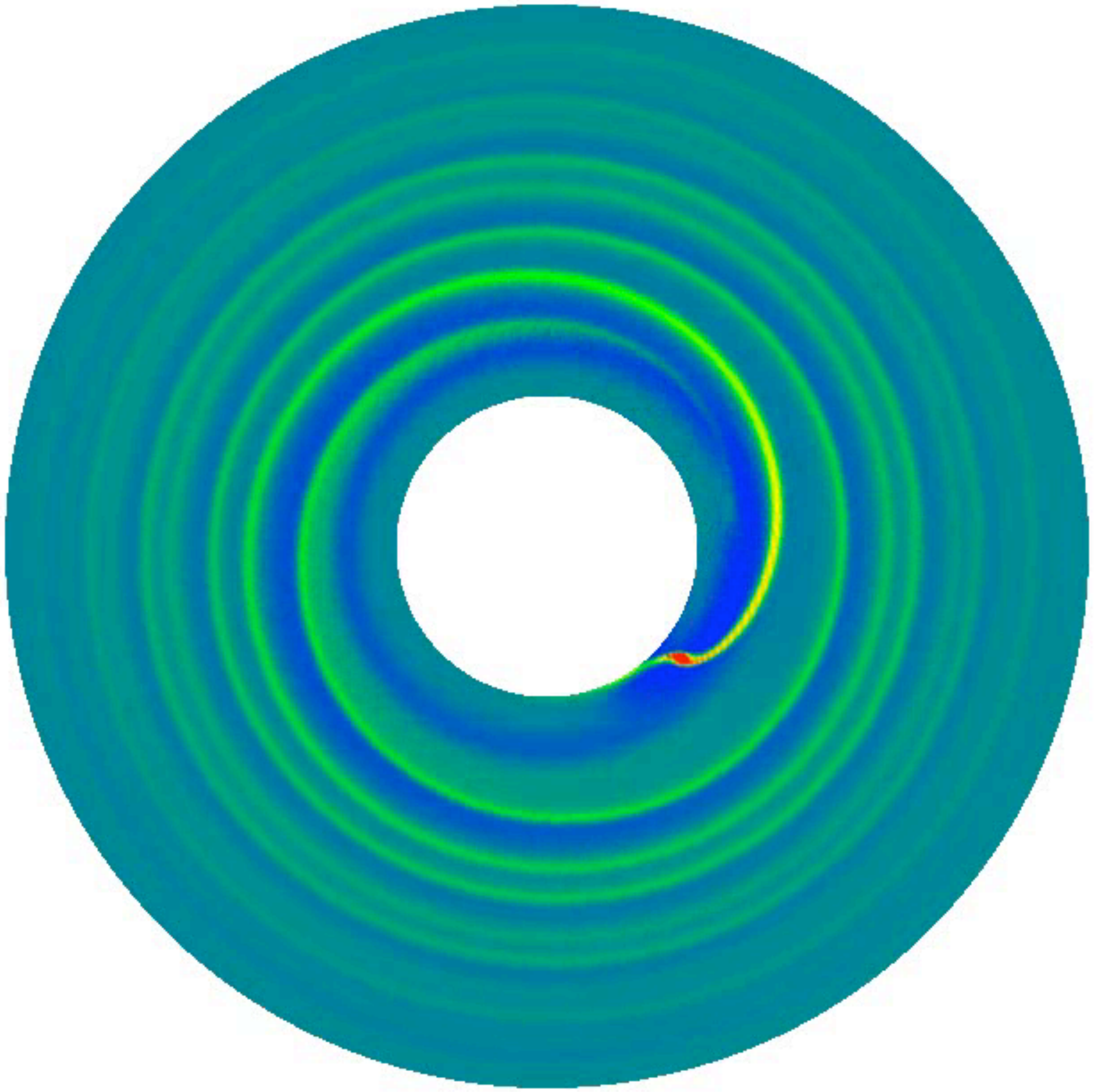
Migration - Type II

- High mass planets
- Opens gap
- Follows viscous evolution of the disk

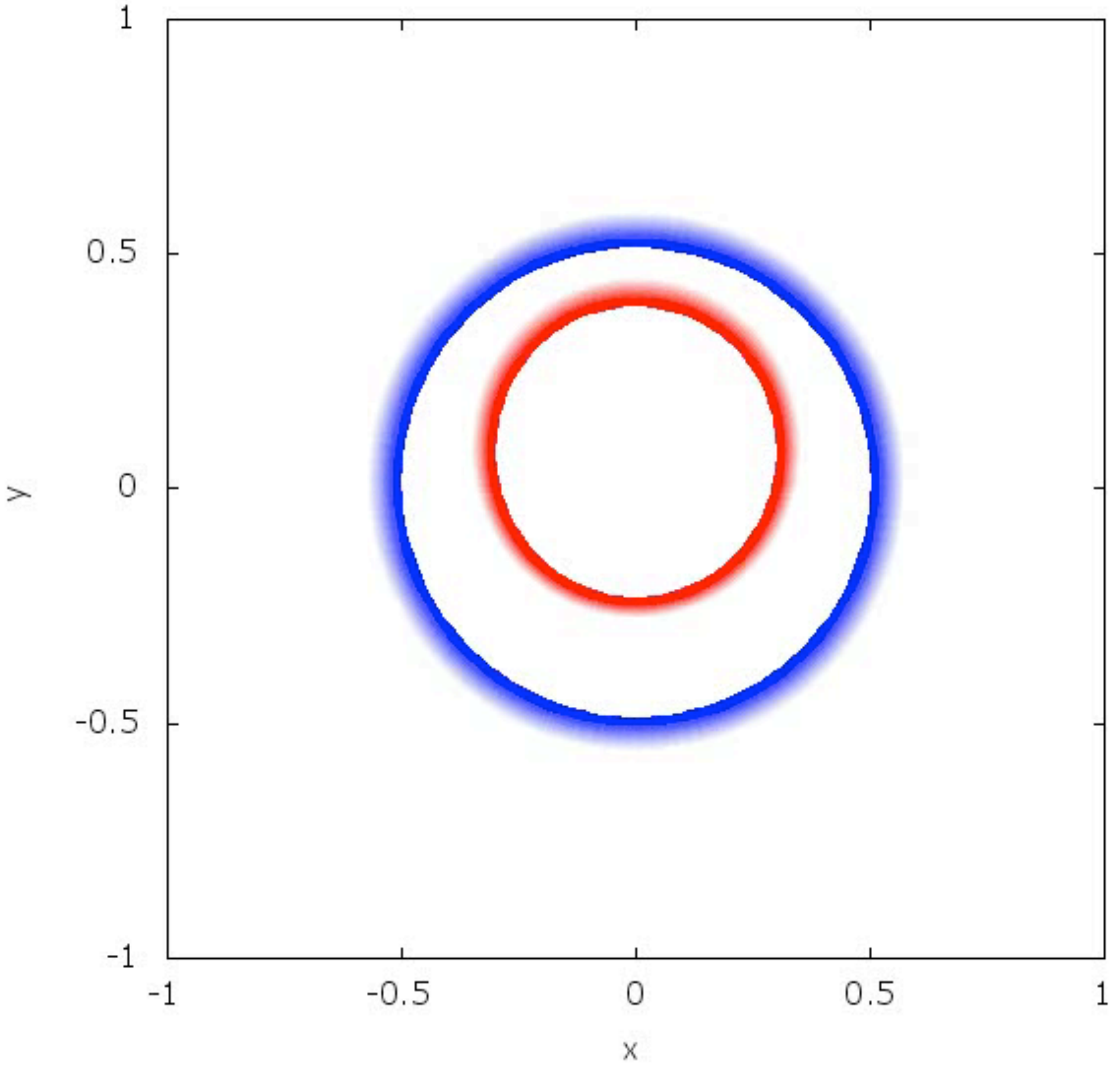


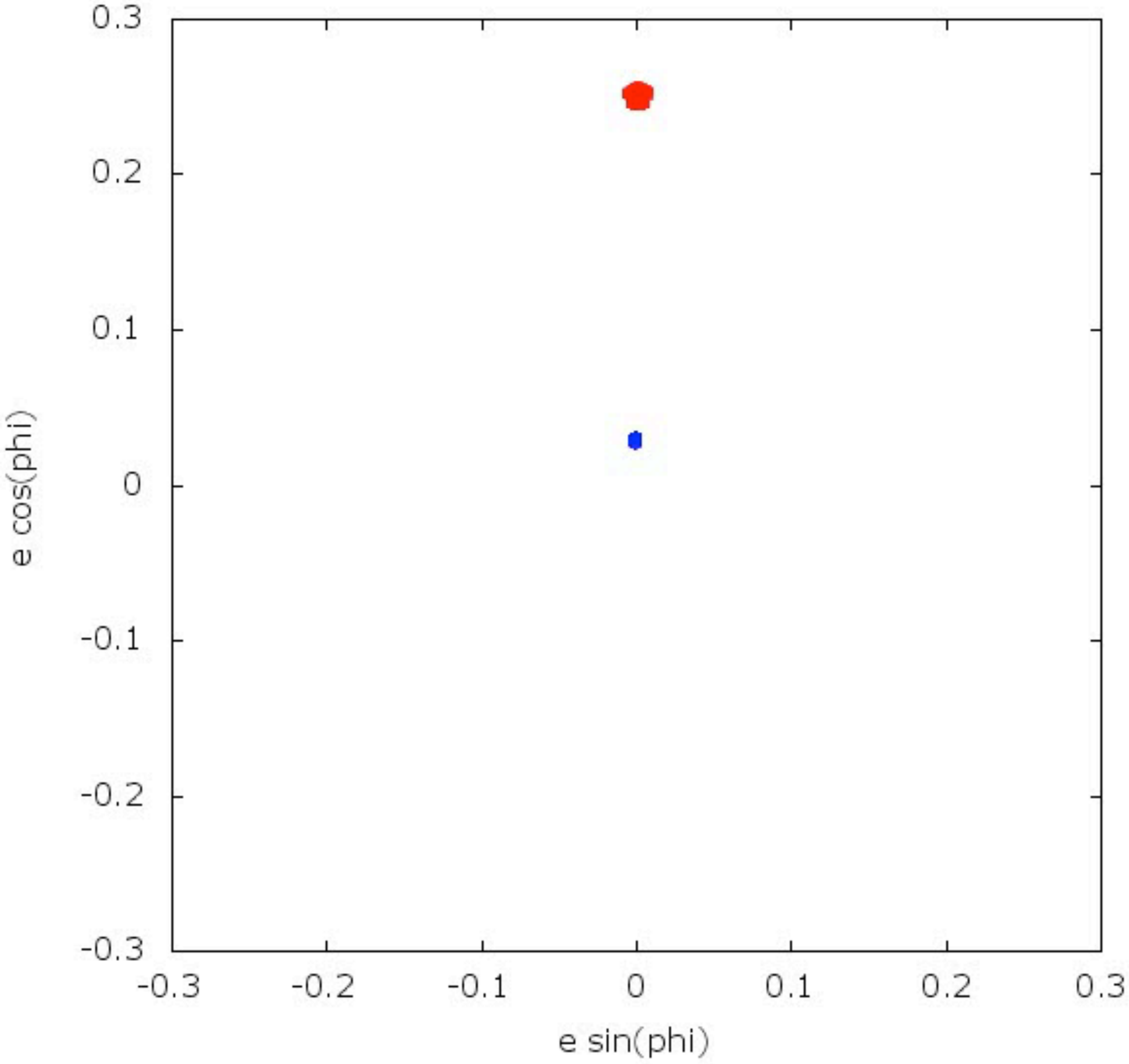
Migration - Type III

- High mass disk
- Intermediate planet mass
- Very fast



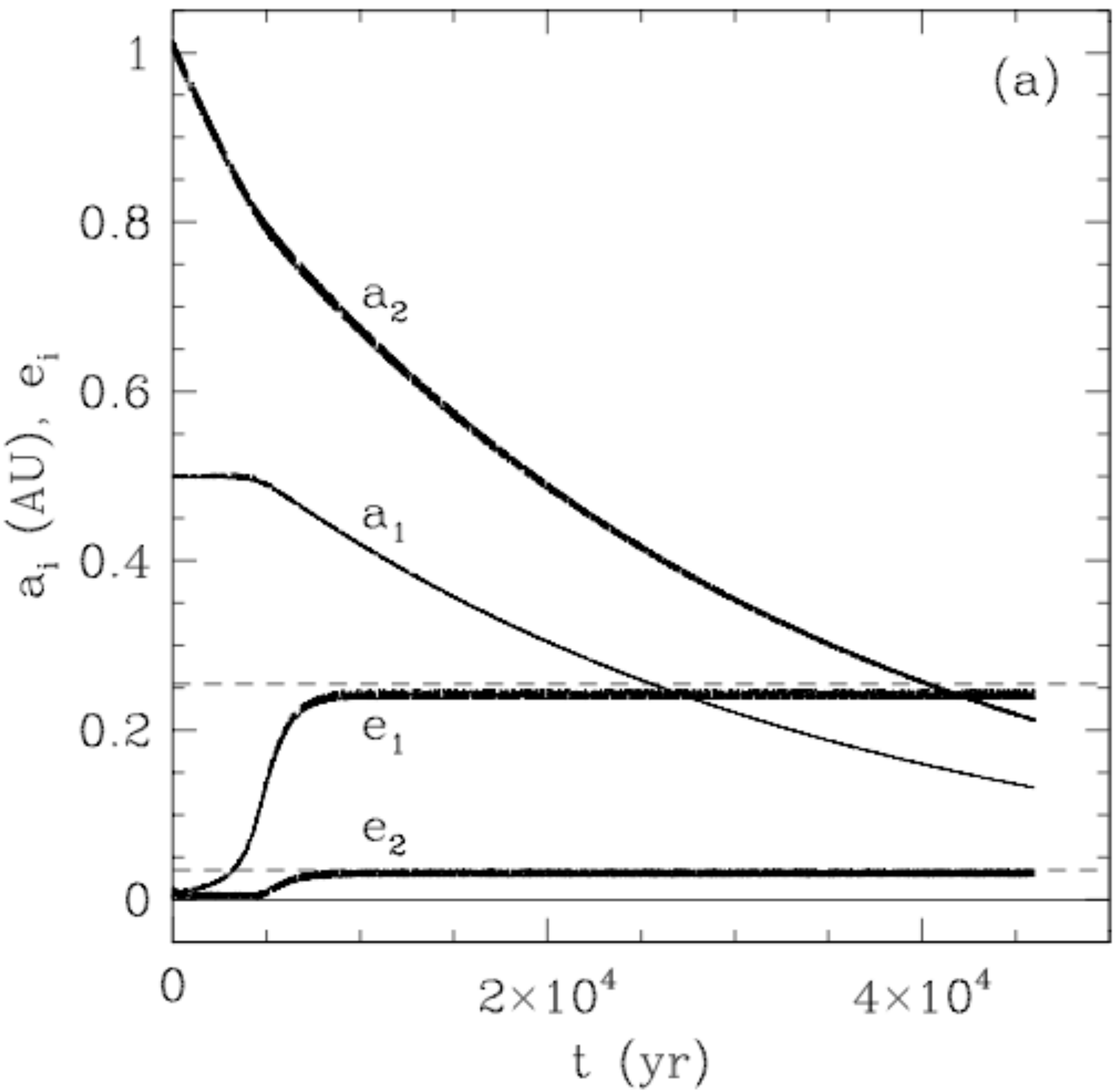
Two planets: non-turbulent resonance capture





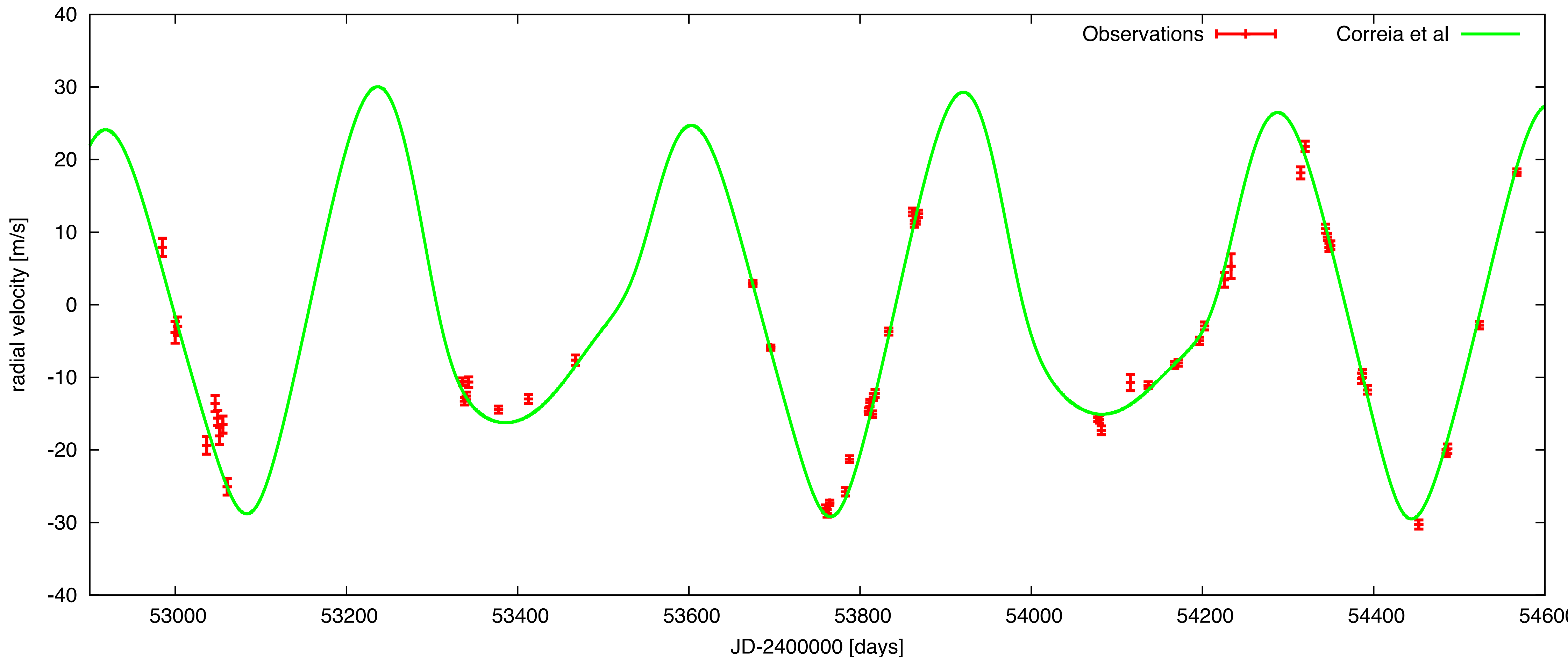
parameters of GJ 876

GJ 876



Lee & Peale 2002

HD45364



- Planets are in a 3:2 resonance
- Two planets around a low mass star

$$m_1 = 0.1872\ M_{jup} \qquad m_2 = 0.6579\ M_{jup}$$

- Planets' masses swapped compared to solar system

Correia et al 2009

Formation scenario

- Two migrating planets
- Infinite number of resonances
- How to choose?
- Initial positions
- Migration speed is crucial
- Resonance width and libration period define critical migration rate

1:2

1:3

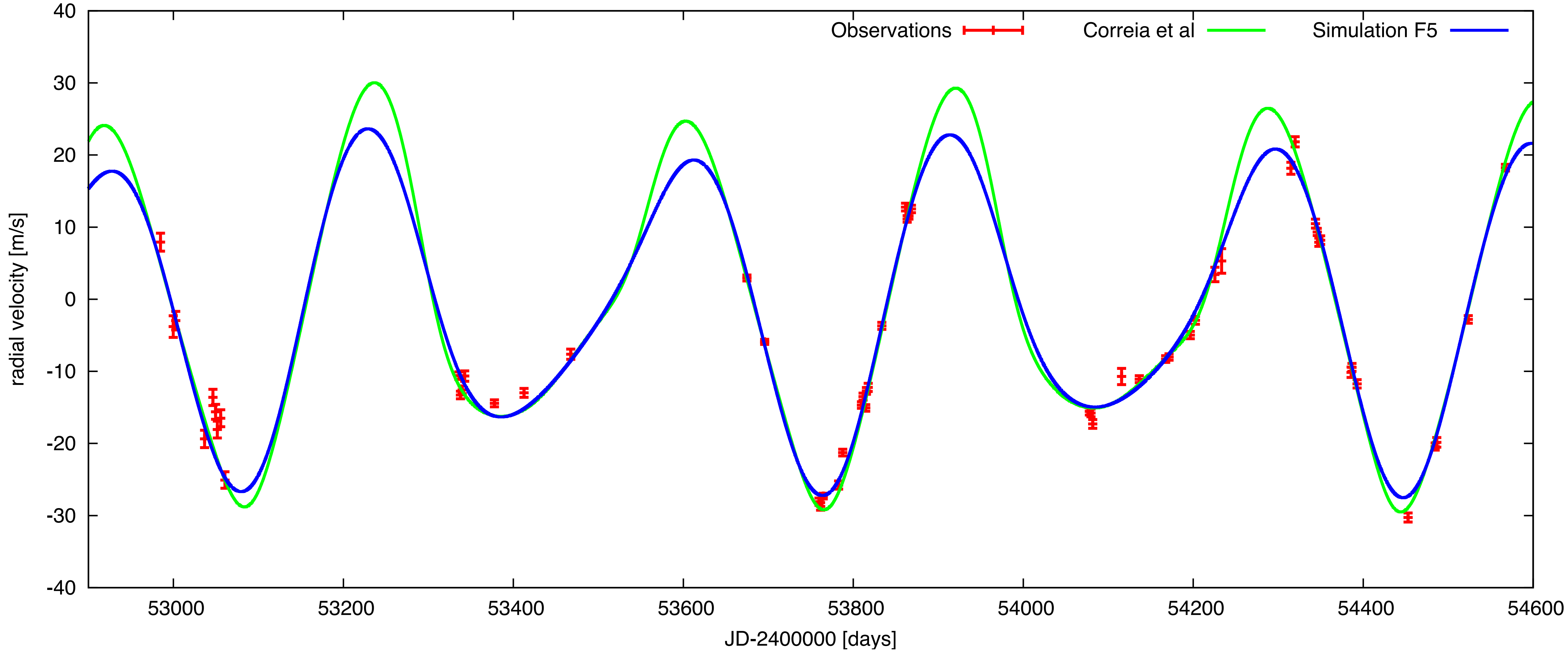
3:2

7:8

1:4

Rein, Papaloizou & Kley 2010

Formation scenario leads to a better 'fit'



		Correia et al. (2009)		Simulation **F5**	
Parameter	Unit	b	c	b	c
$M \sin i$	$[\mathrm{M_{Jup}}]$	0.1872	0.6579	0.1872	0.6579
M_*	$[M_\odot]$	0.82		0.82	
a	[AU]	0.6813	0.8972	0.6804	0.8994
e		0.17 ± 0.02	0.097 ± 0.012	0.036	0.017
λ	[deg]	105.8 ± 1.4	269.5 ± 0.6	352.5	153.9
ϖ^a	[deg]	162.6 ± 6.3	7.4 ± 4.3	87.9	292.2
$\sqrt{\chi^2}$		2.79		2.76^b (3.51)	
Date	[JD]	2453500		2453500	

Rein, Papaloizou & Kley 2010

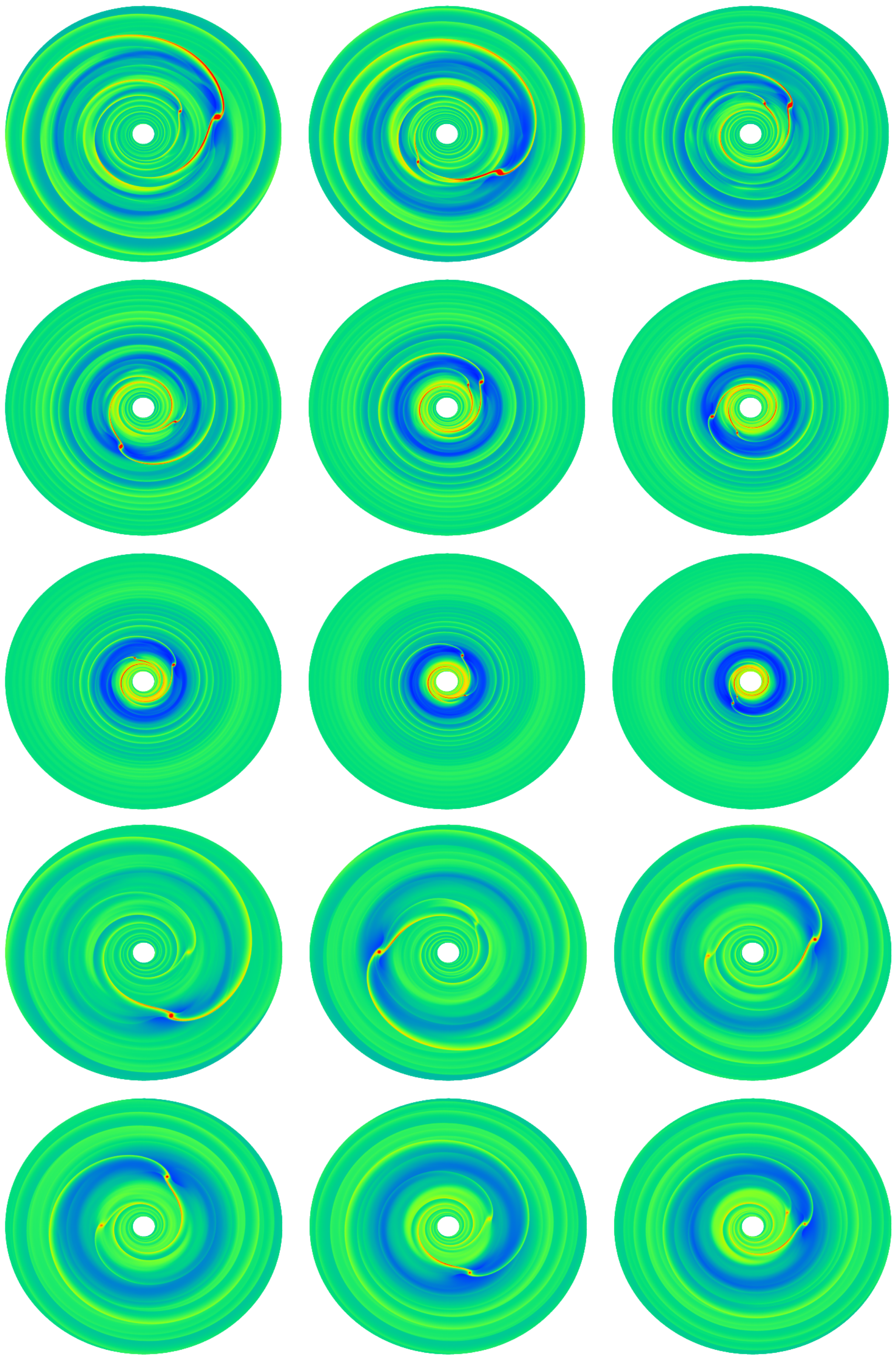
Formation scenario for HD45364

Massive disc (5 times MMSN)

- Short, rapid Type III migration
- Passage of 2:1 resonance
- Capture into 3:2 resonance

Large scale-height (0.07)

- Slow Type I migration once in resonance
- Resonance is stable
- Consistent with radiation hydrodynamics

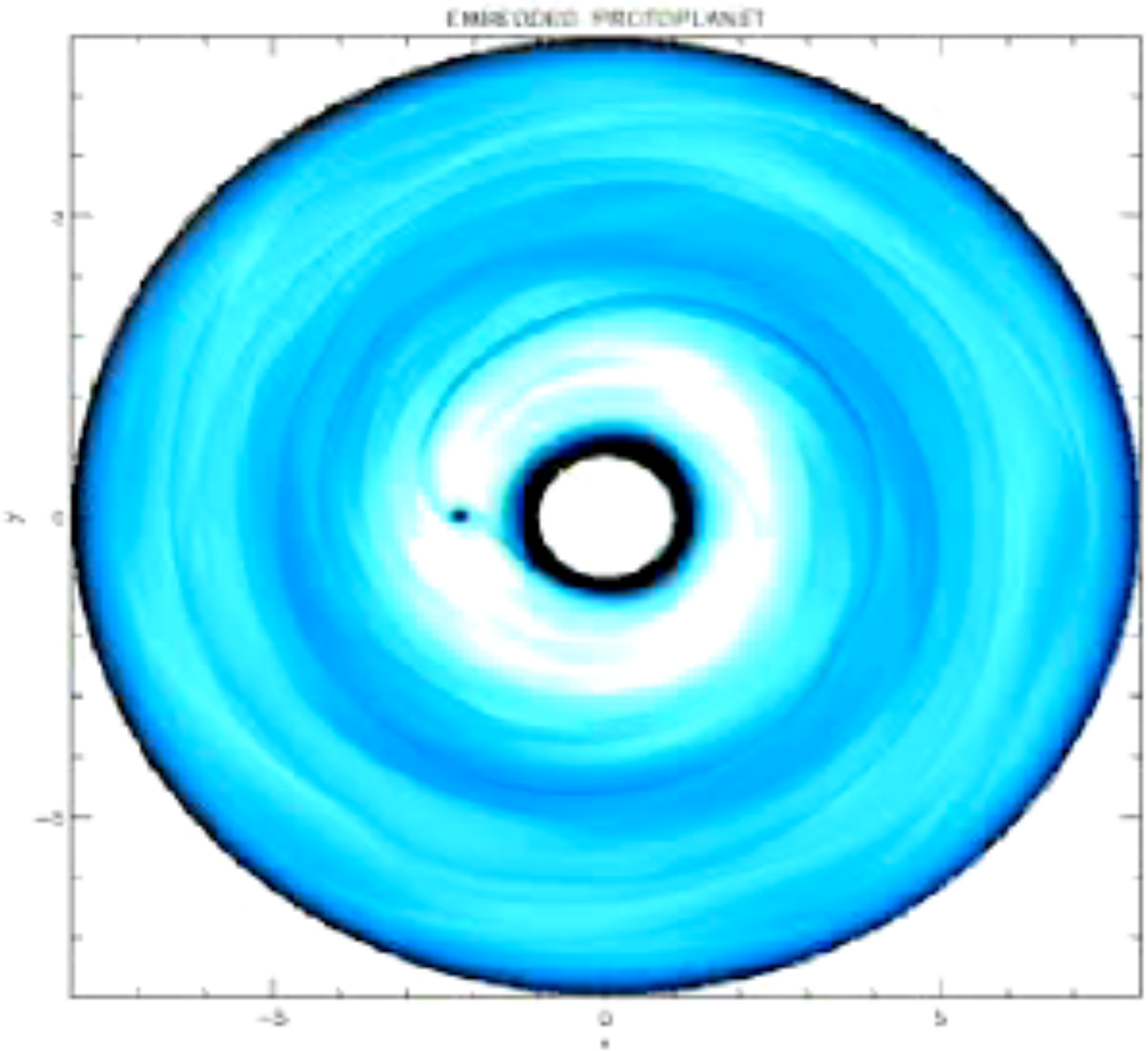


Rein, Papaloizou & Kley 2010

Migration in a turbulent disc

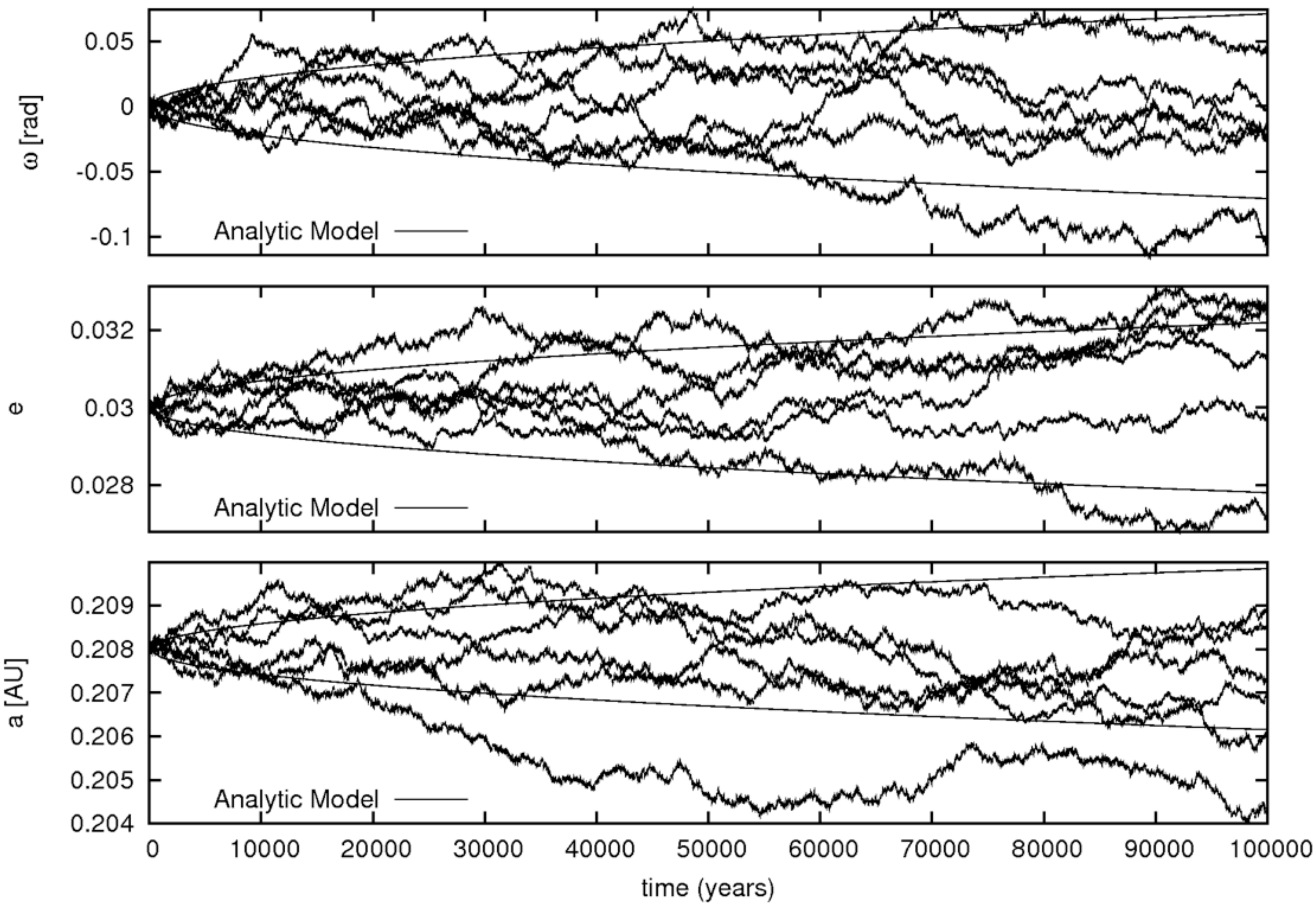
Turbulent disc

- Angular momentum transport
- Magnetorotational instability (MRI)
- Density perturbations interact gravitationally with planets
- Stochastic forces lead to random walk
- Large uncertainties in strength of forces



Animation from Nelson & Papaloizou 2004
Random forces measured by Laughlin et al. 2004, Nelson 2005, Oischi et al. 2007

Random walk



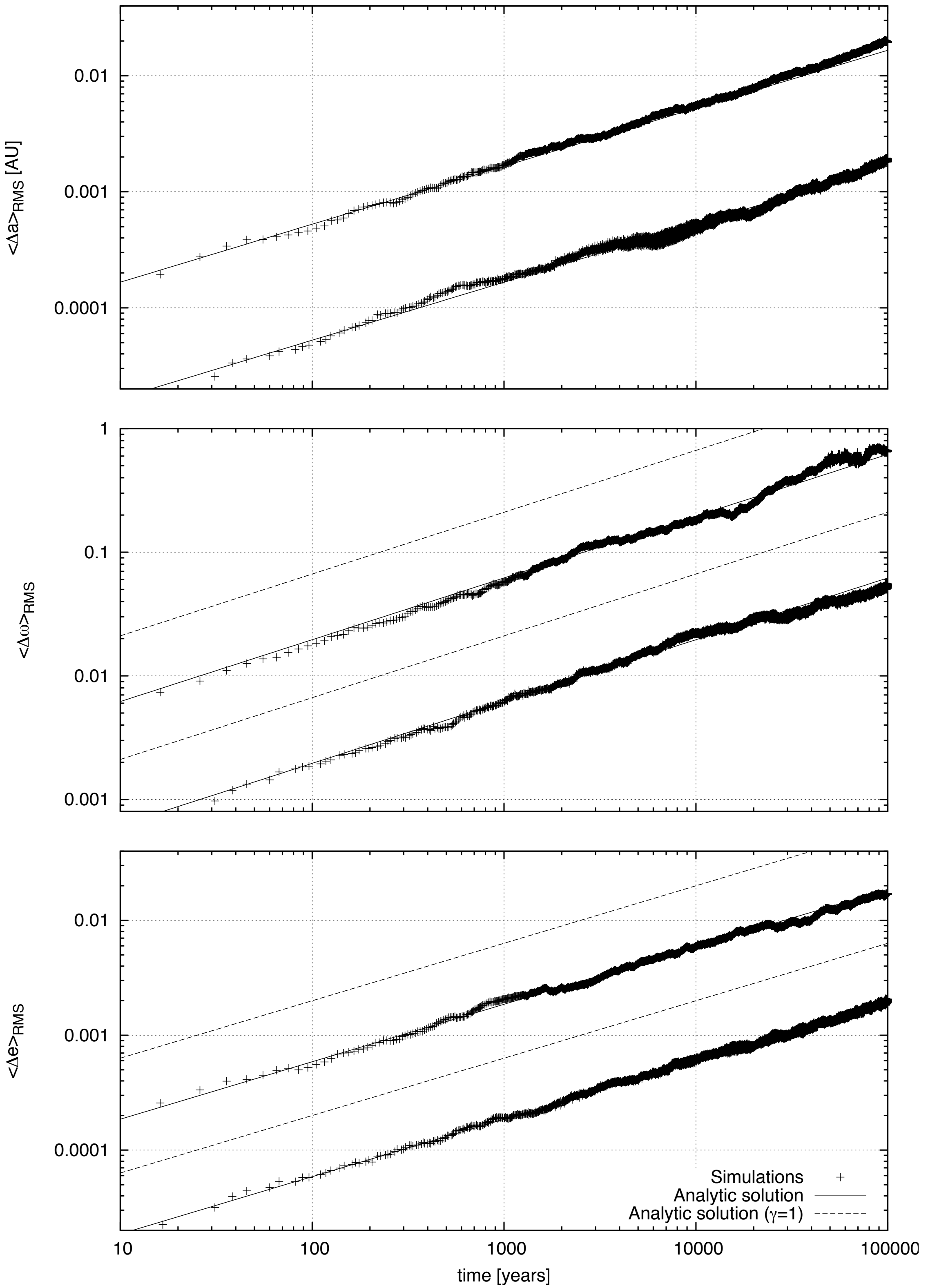
Rein & Papaloizou 2009

Correction factors are important

$$(\Delta a)^2 = 4\frac{Dt}{n^2}$$

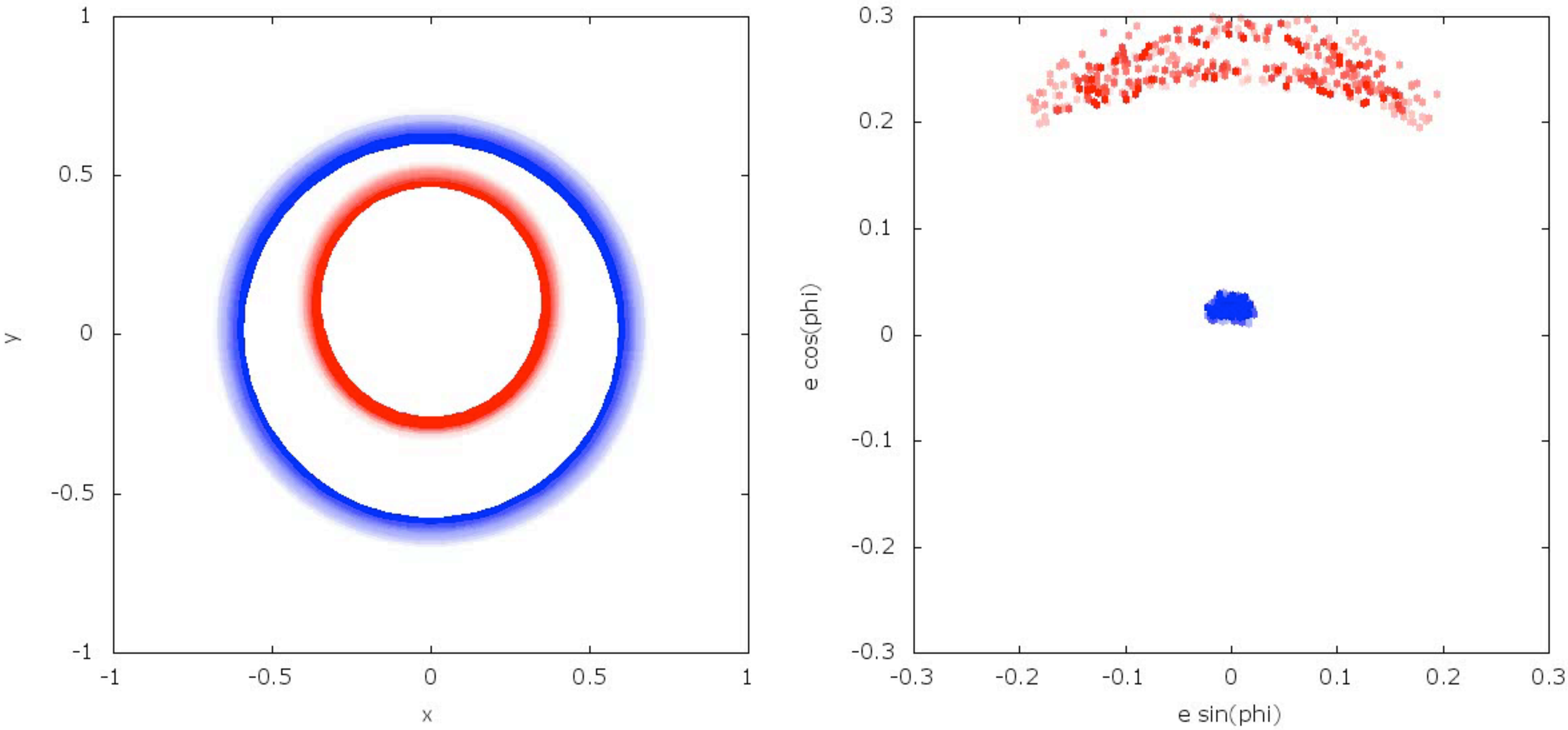
$$(\Delta \varpi)^2 = \frac{2.5}{e^2}\frac{\gamma Dt}{n^2a^2}$$

$$(\Delta e)^2 = 2.5\frac{\gamma Dt}{n^2a^2}$$



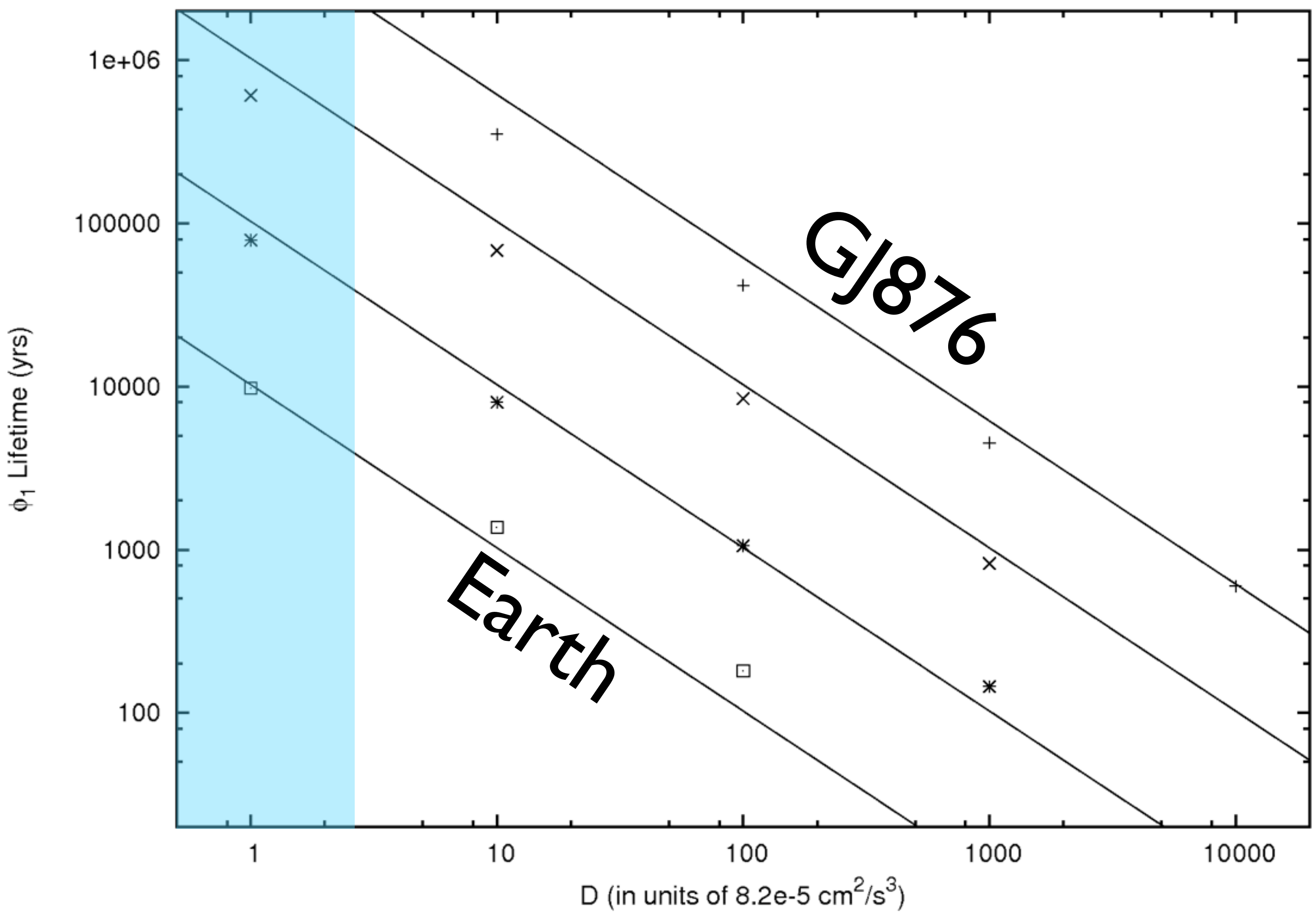
Rein & Papaloizou 2009, Adams et al 2009, Rein 2010

Turbulent resonance capture



Rein & Papaloizou 2009

Multi-planetary systems in mean motion resonance

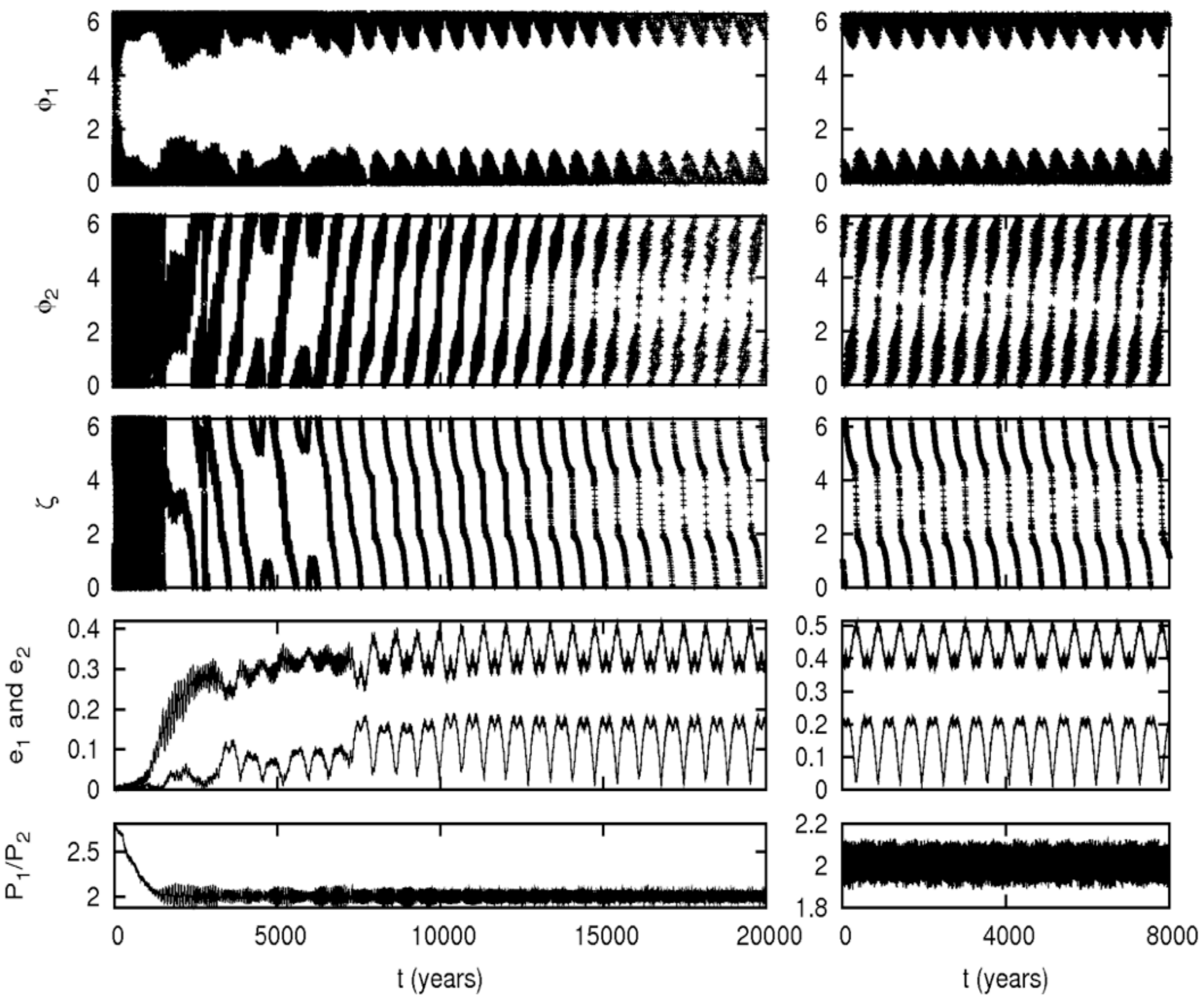


- Stability of multi-planetary systems depends strongly on diffusion coefficient
- Most planetary systems are stable for entire disc lifetime

but

Modification of libration patterns

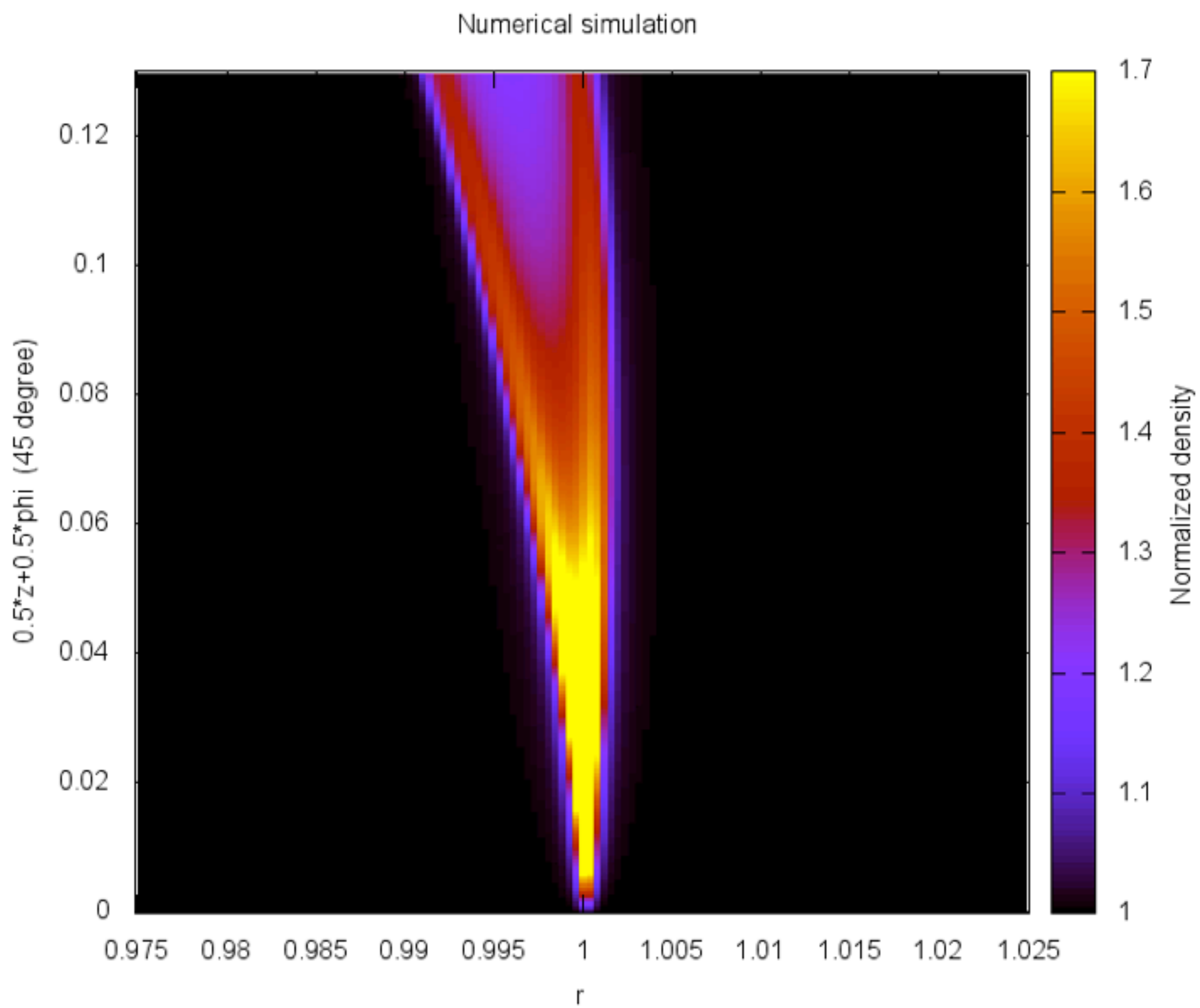
- HD128311 has a very peculiar libration pattern
- Can not be reproduced by convergent migration alone
- Turbulence can explain it
- More multi-planetary systems needed for statistical argument



Rein & Papaloizou 2009

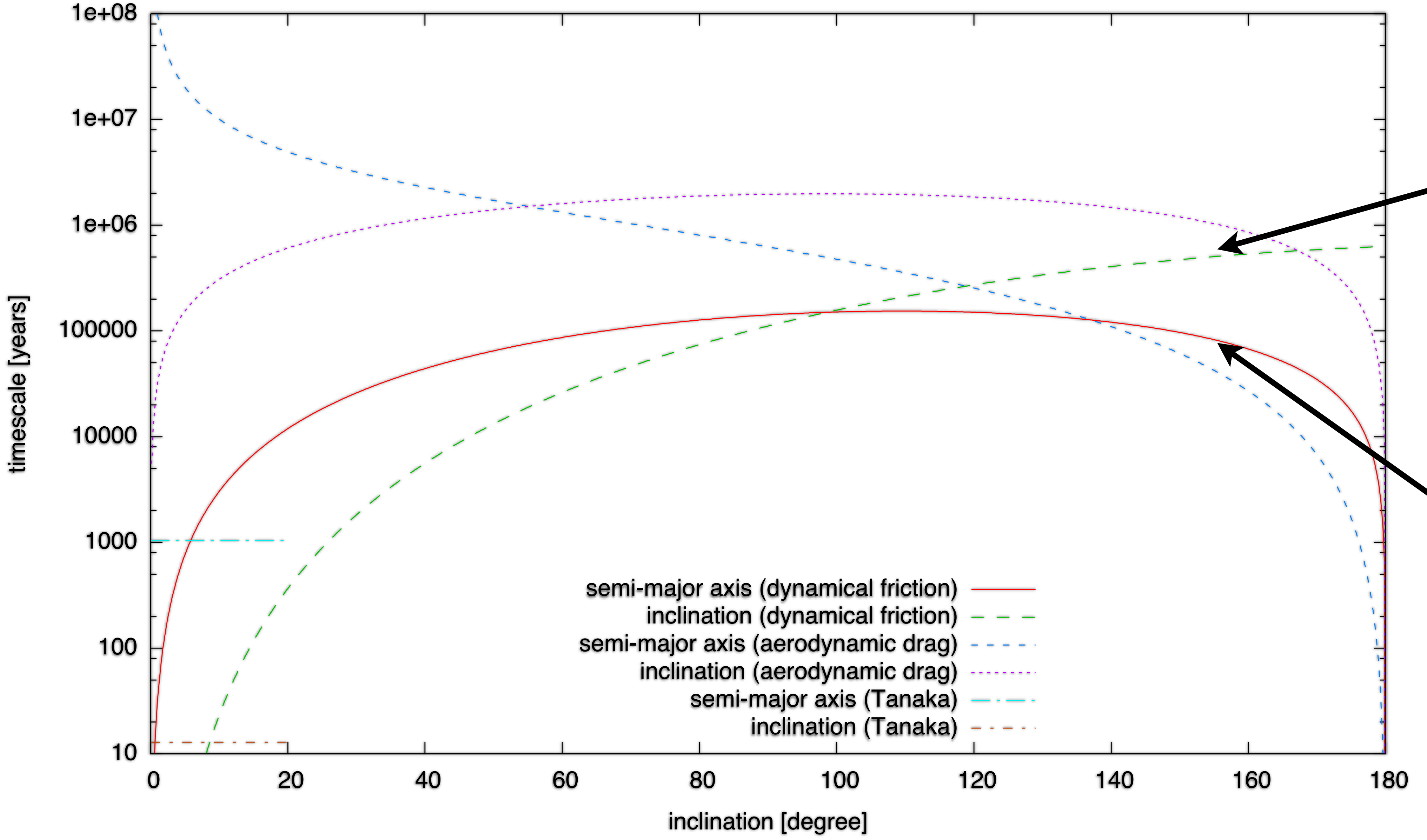
Highly inclined systems

Highly inclined planets and disks



Rein 2011

Highly inclined planets and disks



$$\tau_i = \frac{i}{\dot{i}}$$

$$\tau_a = \frac{a}{\dot{a}}$$

Conclusions

Conclusions

Resonances and multi-planetary systems

Multi-planetary system provide insight in otherwise unobservable formation phase
Overwhelming evidence that dissipative effects (disk) shaped many systems
Turbulence can be traced by observing multi-planetary systems
Distinctive from non-turbulent migration scenarios
Highly inclined systems might not re-align even if the disk is still present

Moonlets in Saturn's rings

Small scale version of the proto-planetary disc
Dynamical evolution can be directly observed
Evolution is dominated by random-walk
Caused by collisions and gravitational wakes
Might lead to independent age estimate of the ring system

see talk in 2 weeks