Institute for Advanced Study

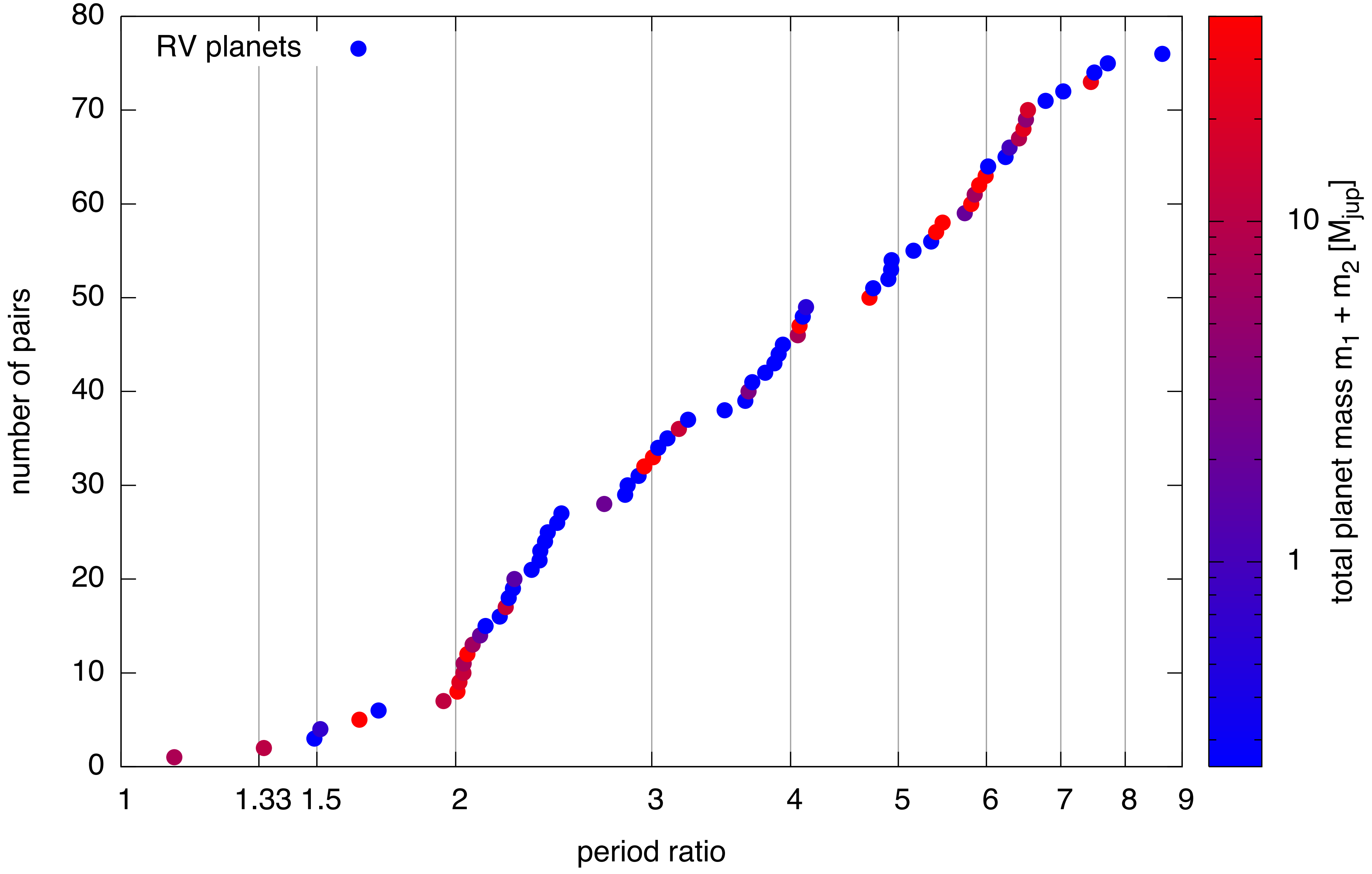
Formation of resonant multi-planetary systems

Hanno Rein @ NAOJ, Tokyo, March 2012

Statistics of multiple planets (using iPhone App)

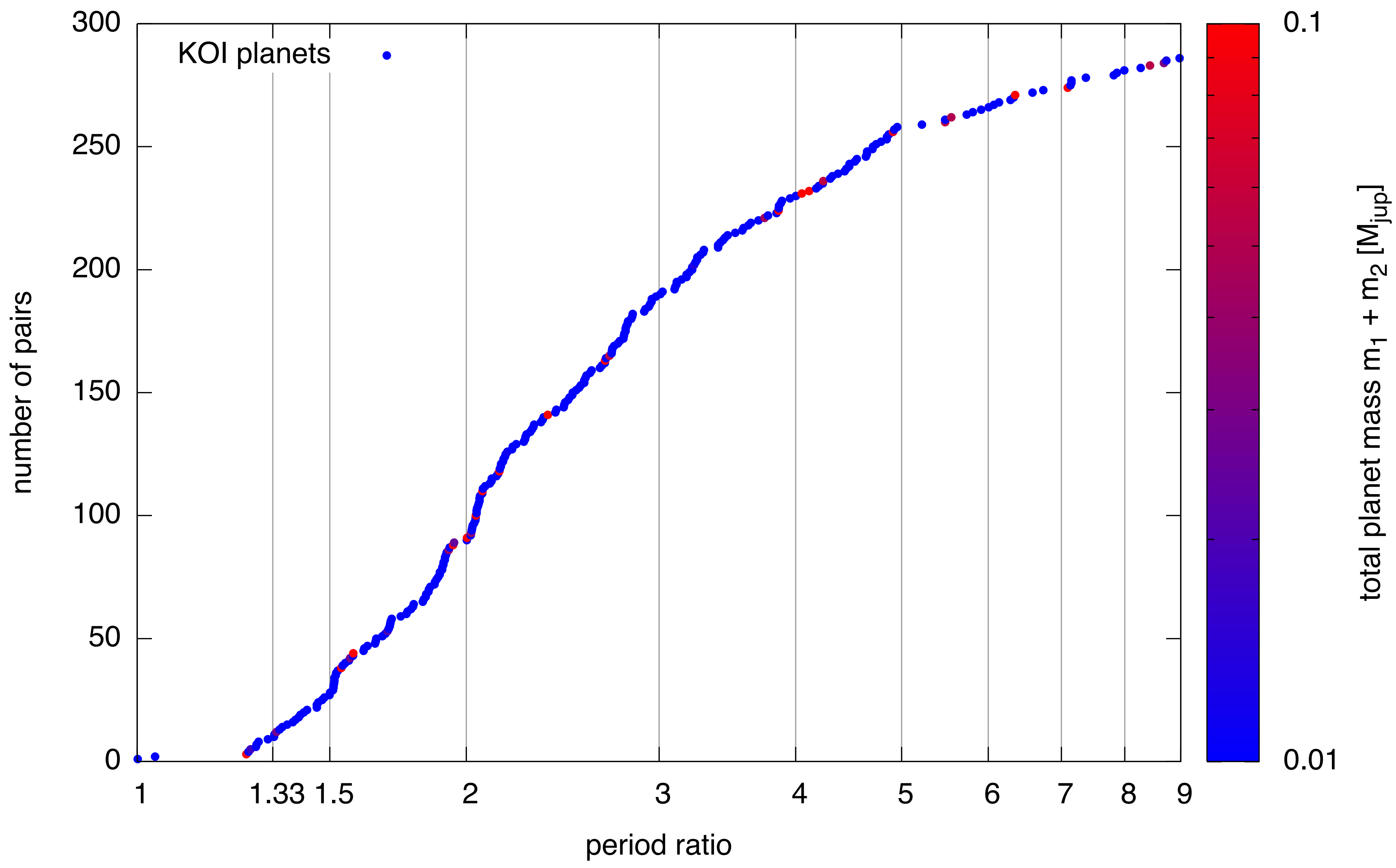
Available for free on the Apple AppStore.

Radial velocity planets



Rein, Payne, Veras & Ford (2012 in prep)

Kepler's transiting planet candidates



Rein, Payne, Veras & Ford (2012 in prep)

Recipe

Migration

Resonances

Migration in a non-turbulent disc

Planet formation

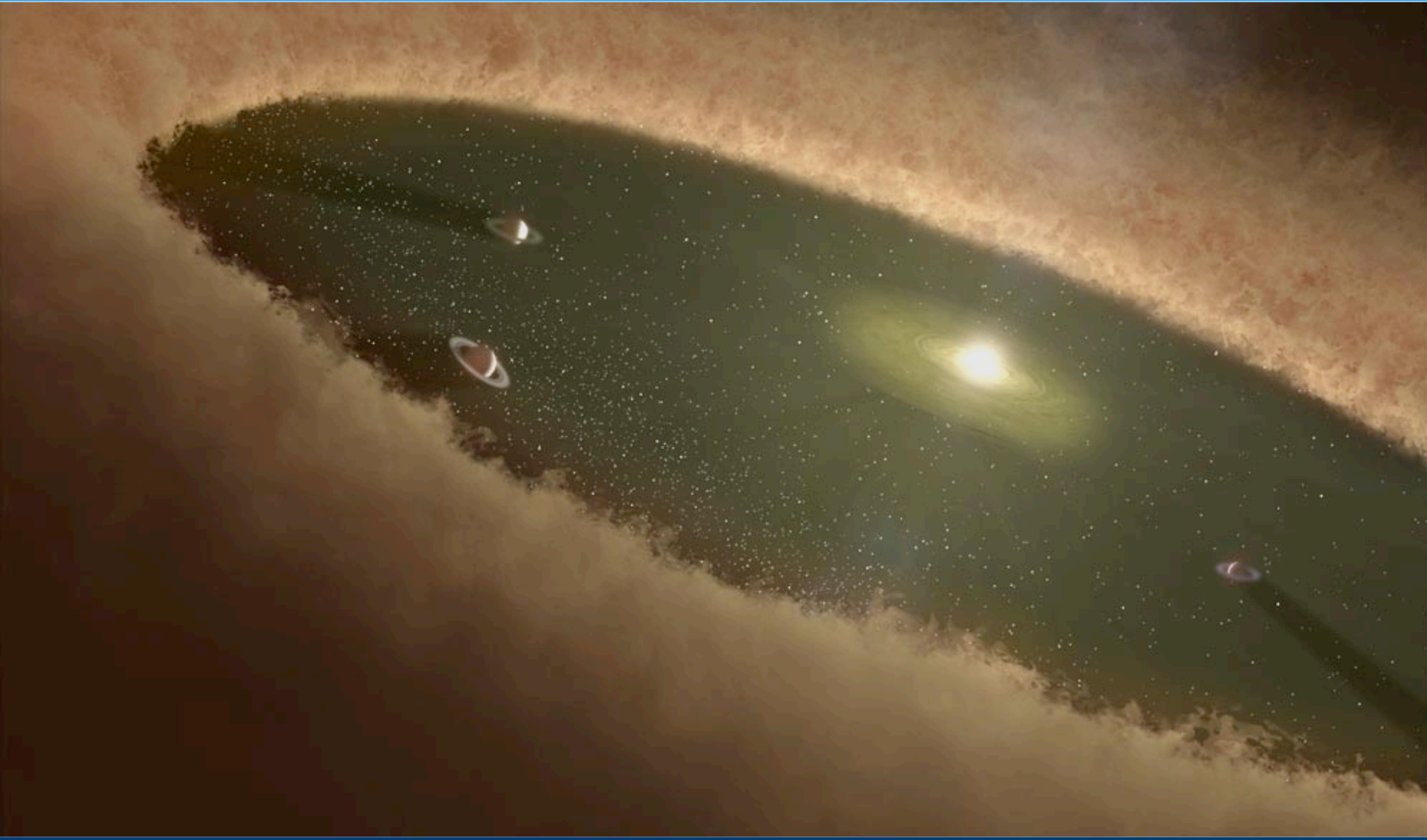
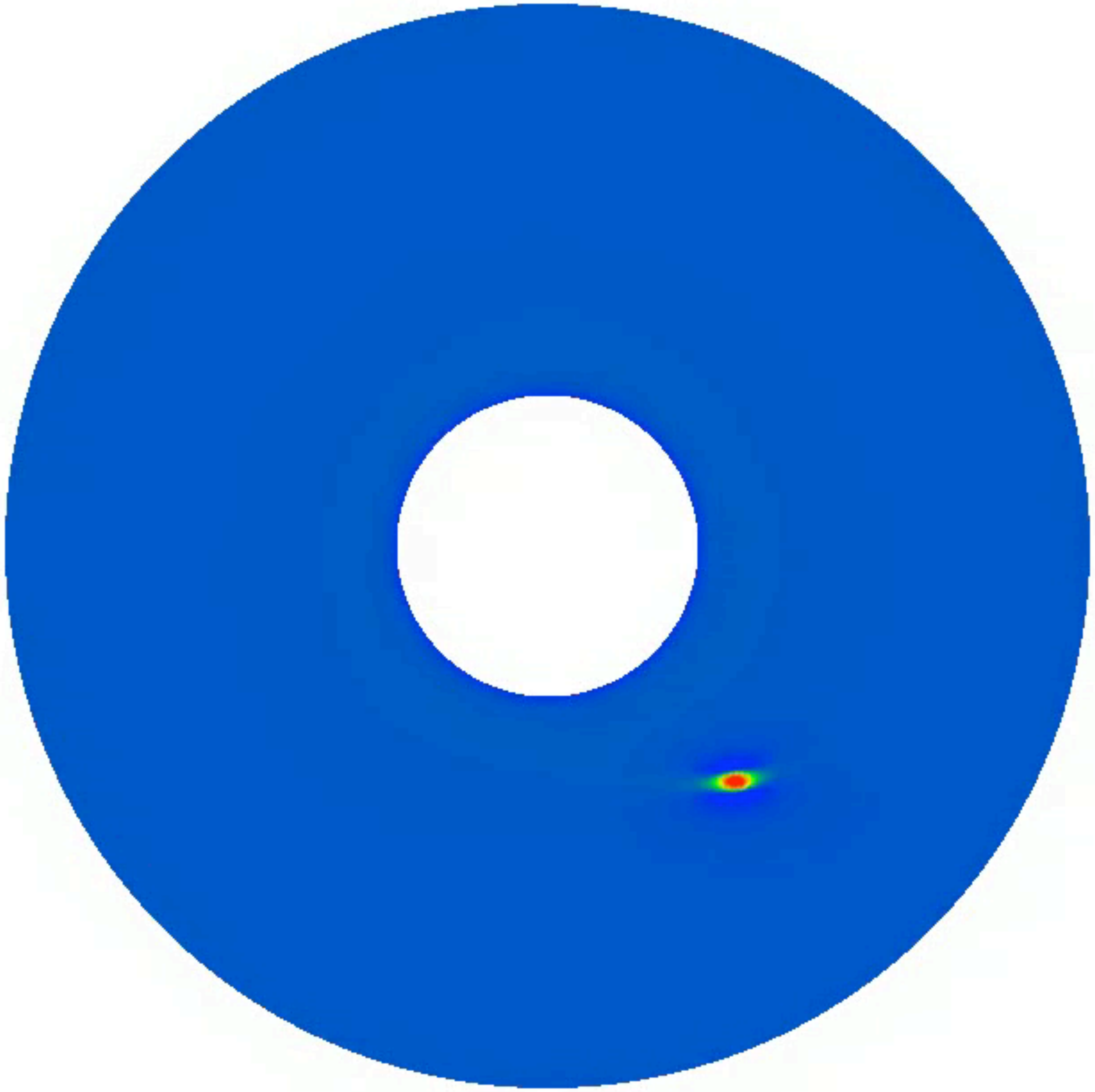


Image credit: NASA/JPL-Caltech

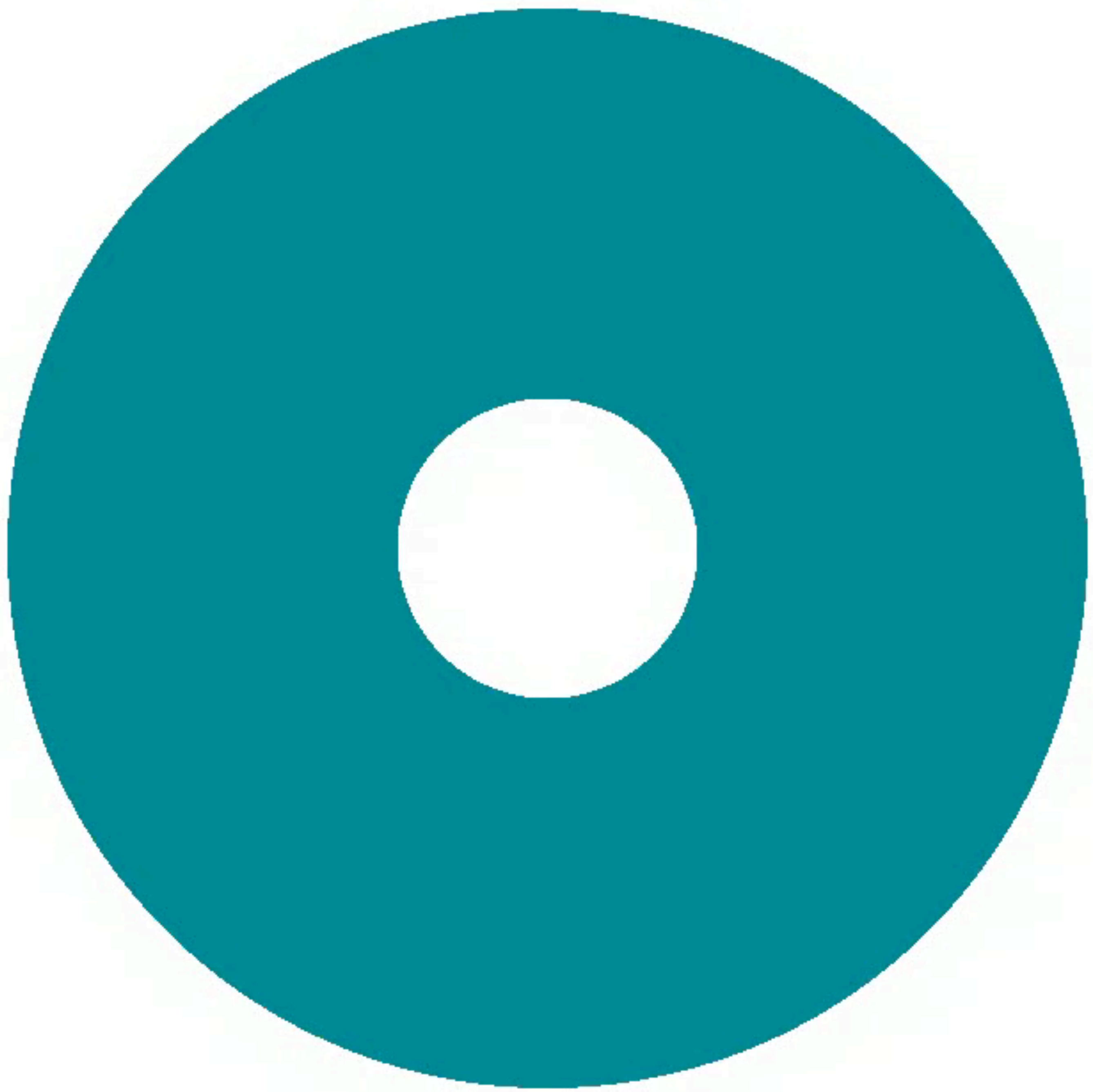
Migration - Type I

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



Migration - Type II

- Massive planets (typically bigger than Saturn)
- Opens a (clear) gap
- Migration rate is slow
- Follows viscous evolution of the disc



Gap opening criteria

Disc scale height

Stellar mass

$$\frac{3}{4}\frac{H}{R_{\rm Hill}} + \frac{50M_*}{M_p\mathcal{R}} \leq 1$$

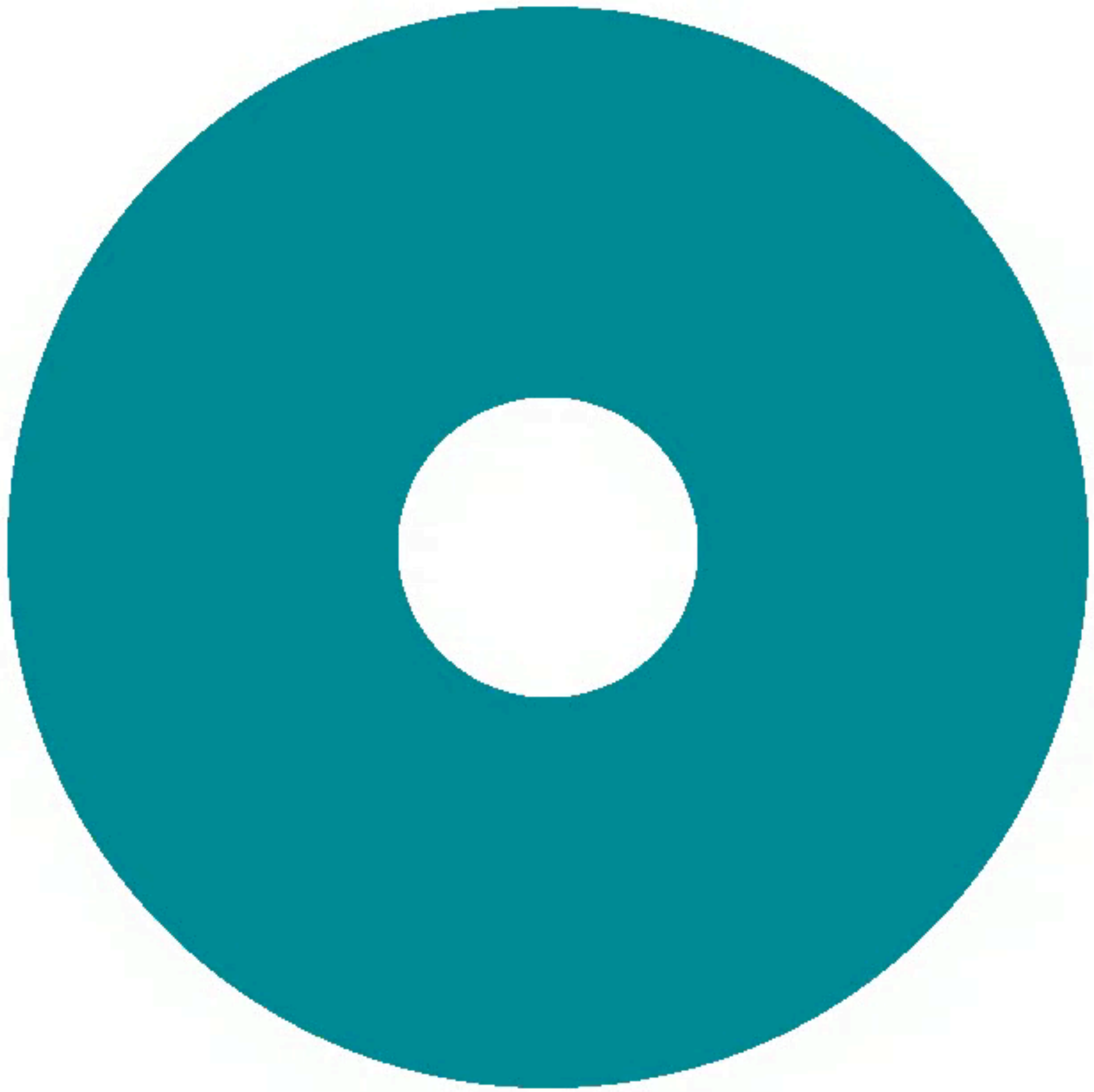
Planet mass

Viscosity $^{-1}$

Crida et al 2006

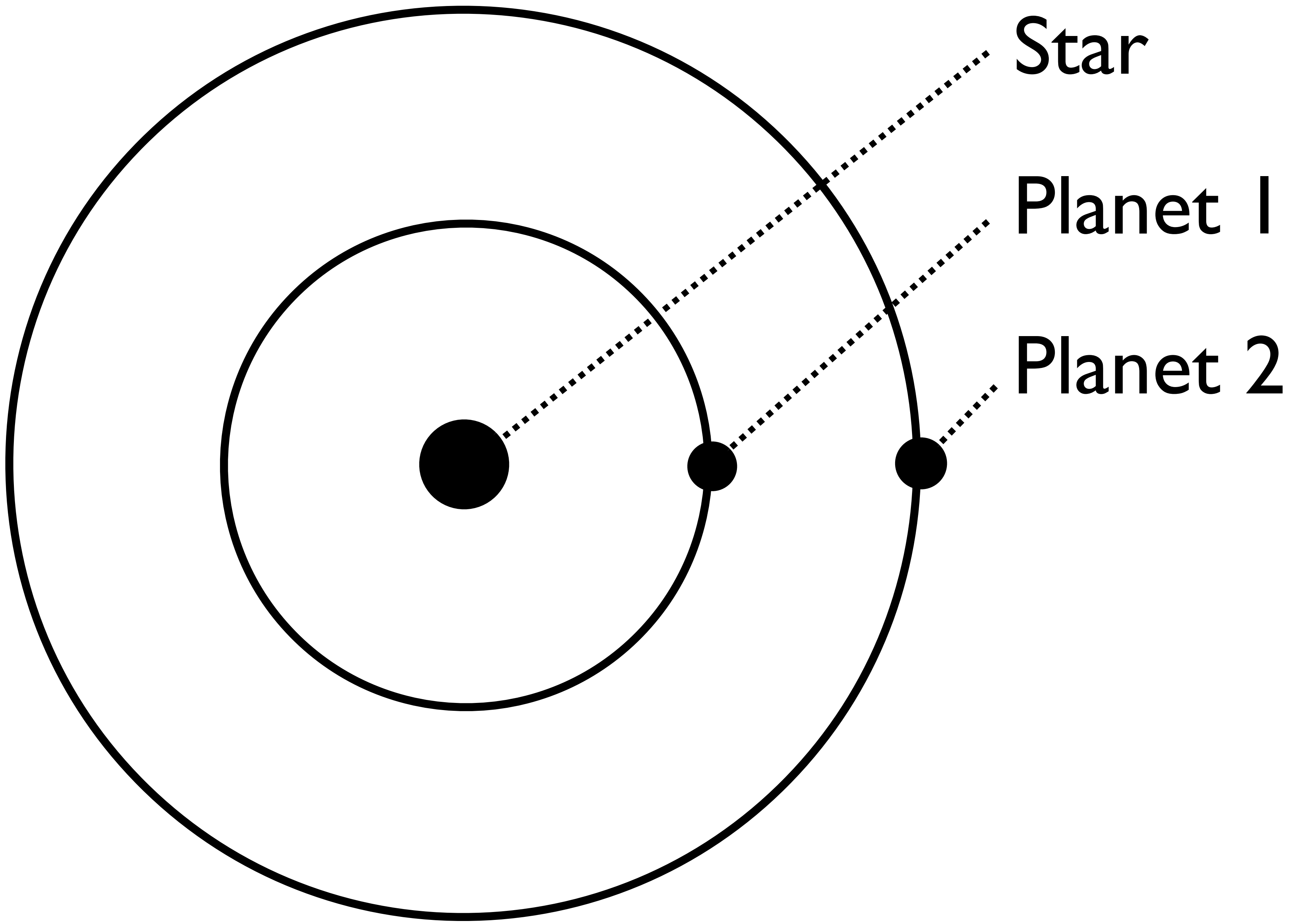
Migration - Type III

- Massive disc
- Intermediate planet mass
- Tries to open gap
- Very fast, few orbital timescales

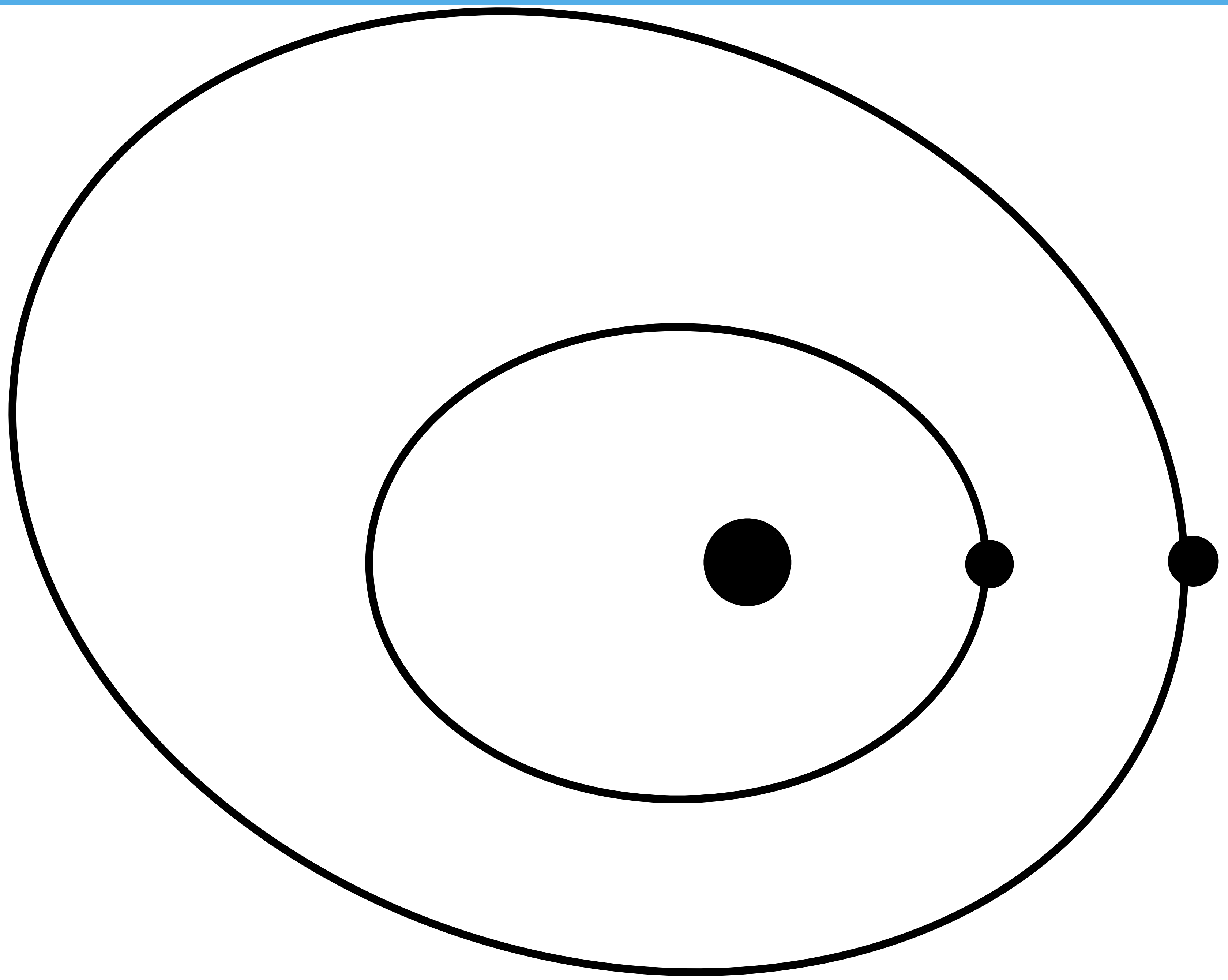


Resonance capture

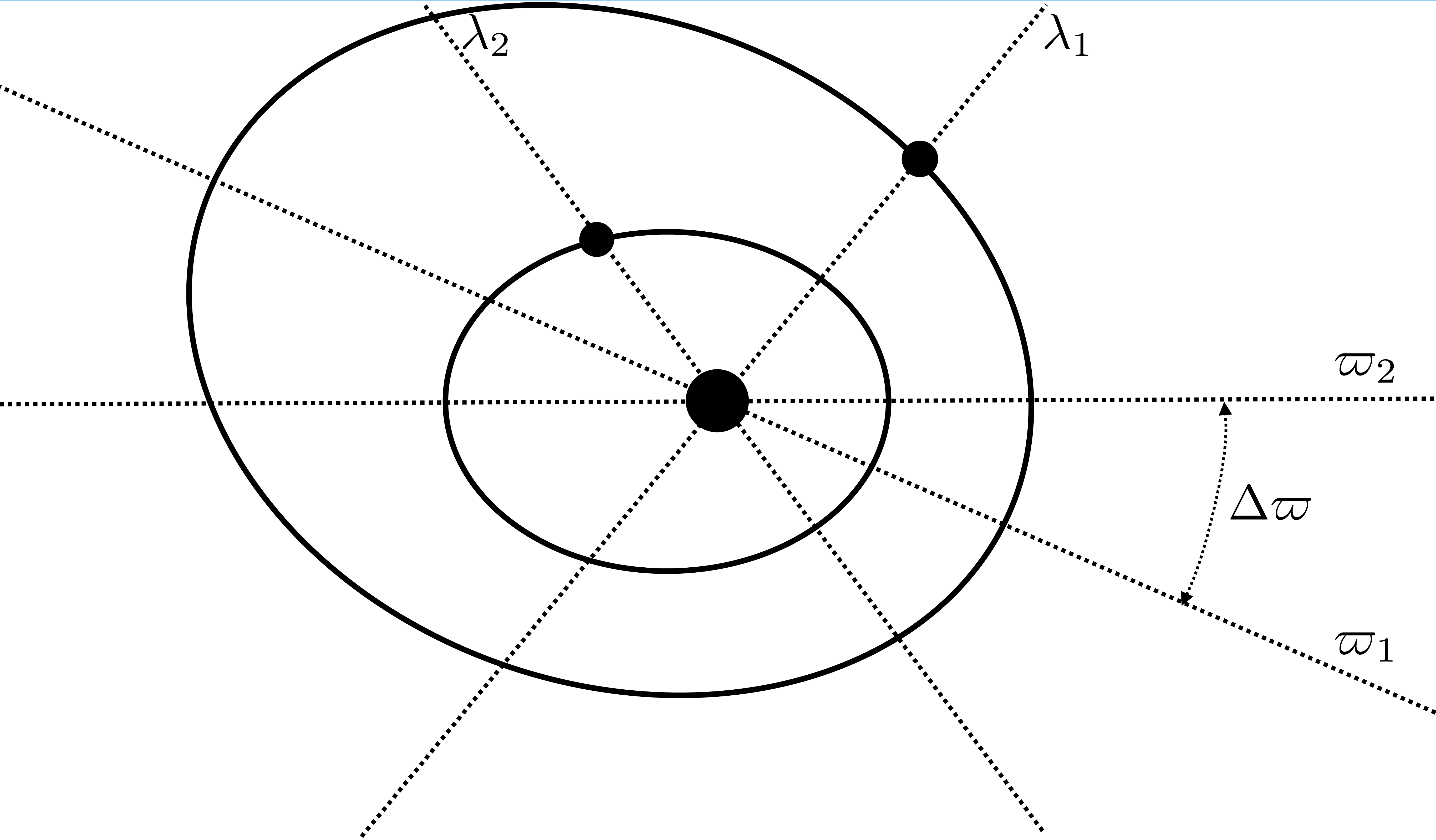
2:1 Mean Motion Resonance



2:1 Mean Motion Resonance



2:1 Mean Motion Resonance



Resonant angles

- Fast varying angles

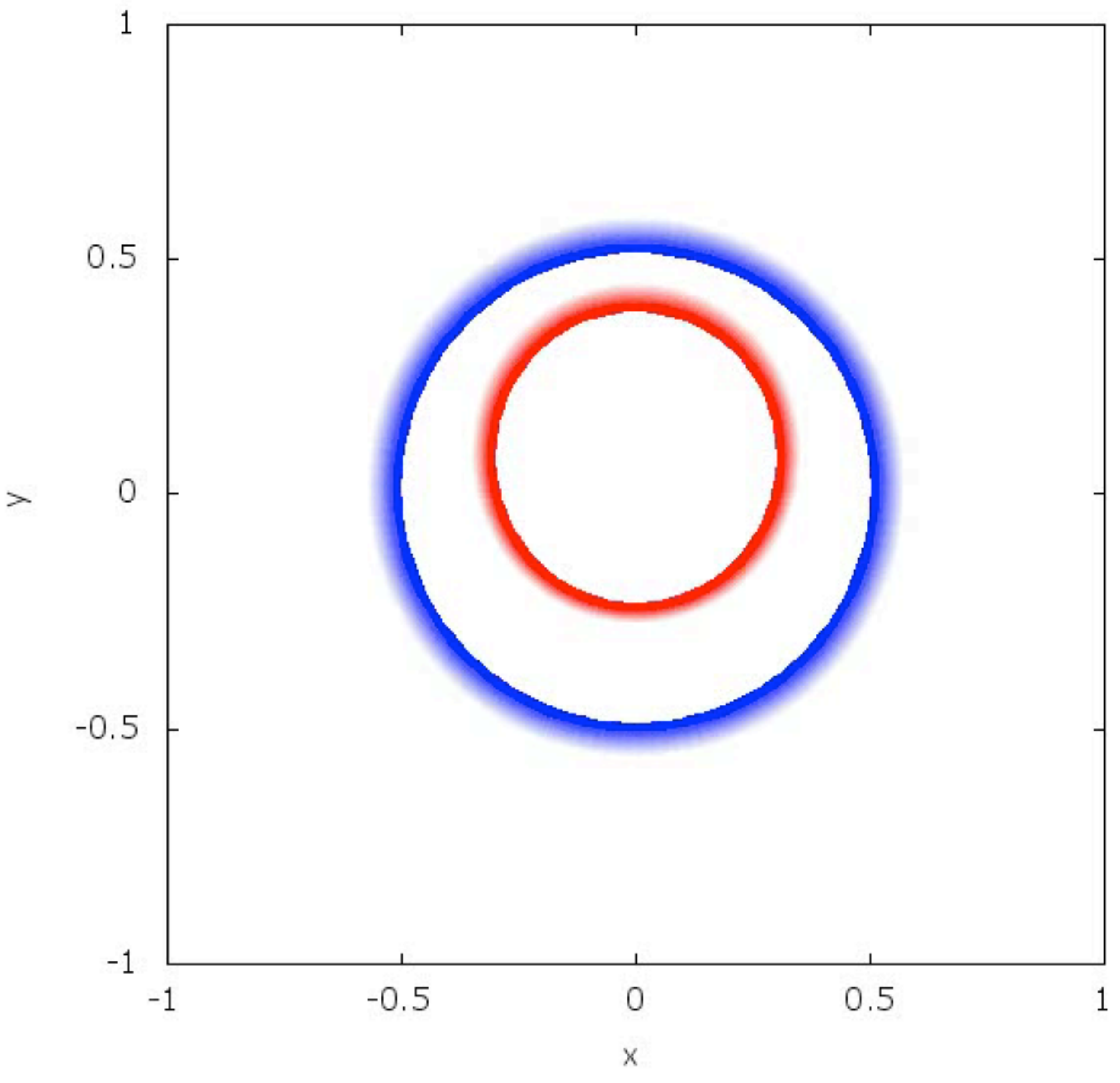
$$\lambda_1 - \varpi_1 \qquad\qquad \lambda_2 - \varpi_2$$

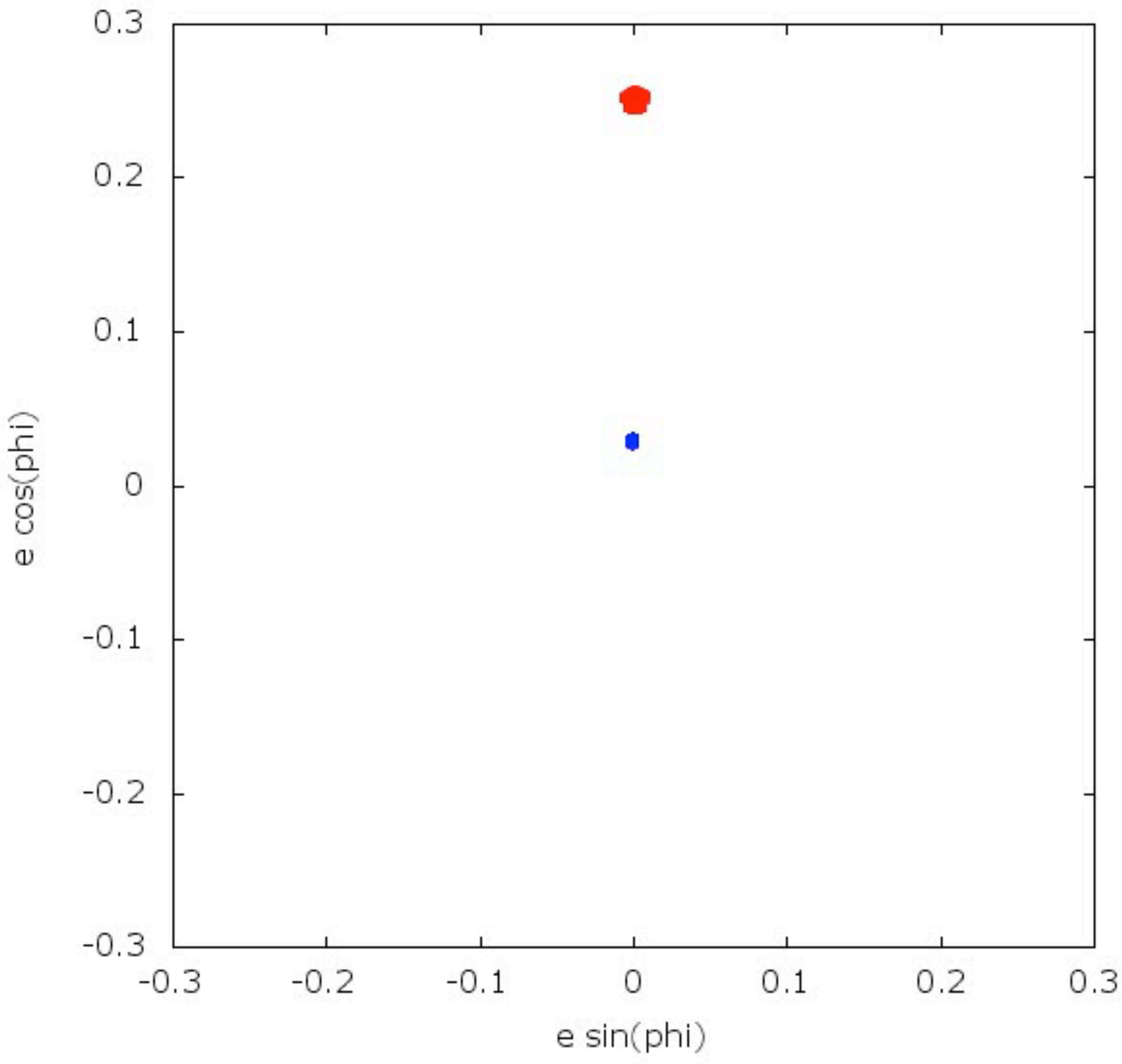
- Slowly varying combinations

$$\begin{aligned}\phi_1 &= \lambda_2 - 2\lambda_1 + \varpi_2 \\ \phi_2 &= \lambda_2 - 2\lambda_1 + \varpi_1 \\ \Delta\varpi &= \varpi_1 - \varpi_2\end{aligned}$$

- Two are linear independent

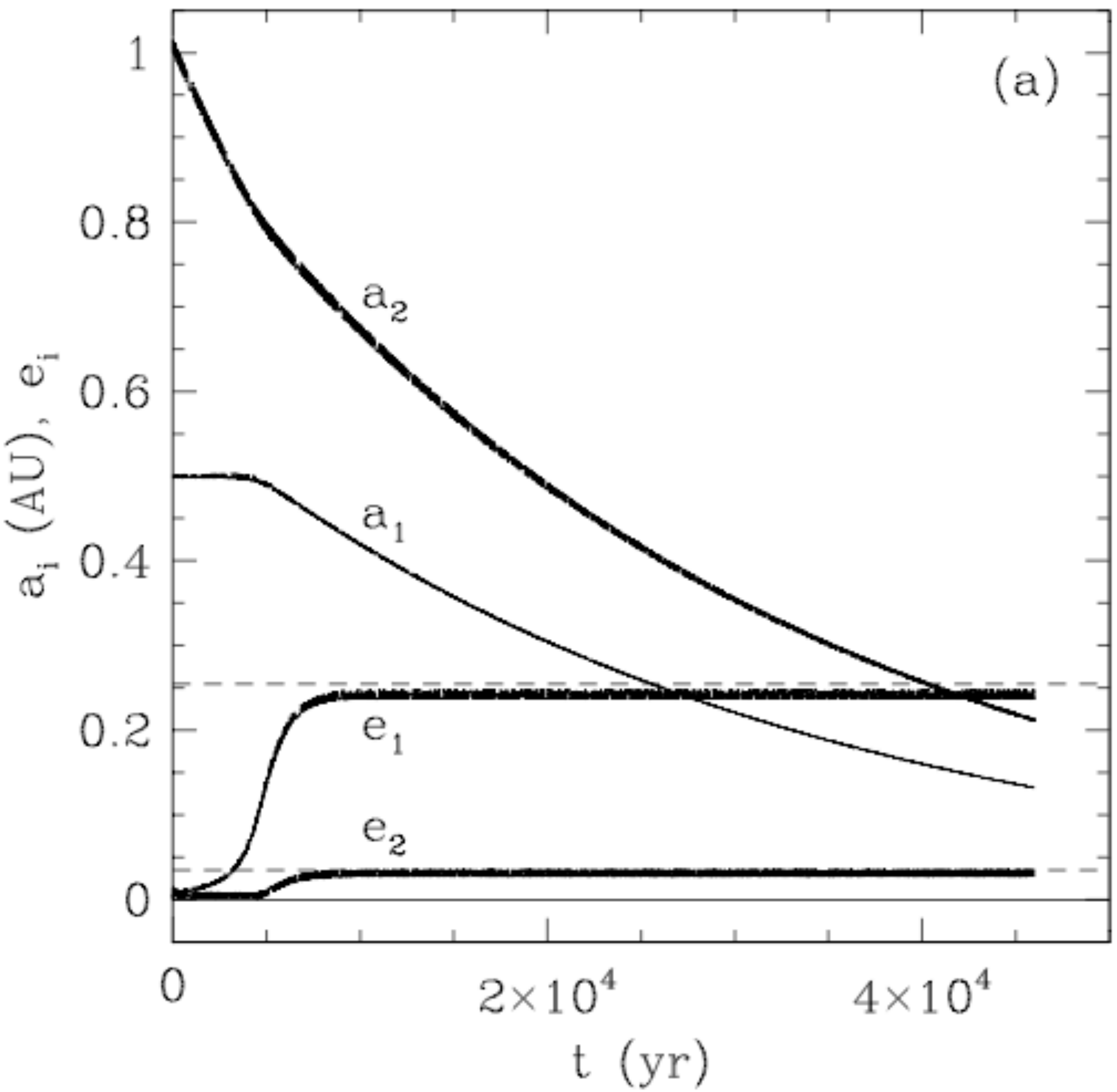
Non-turbulent resonance capture: two planets





$$\phi_1 \quad = \quad \lambda_2 - 2\lambda_1 + \varpi_2$$

GJ 876



Lee & Peale 2002

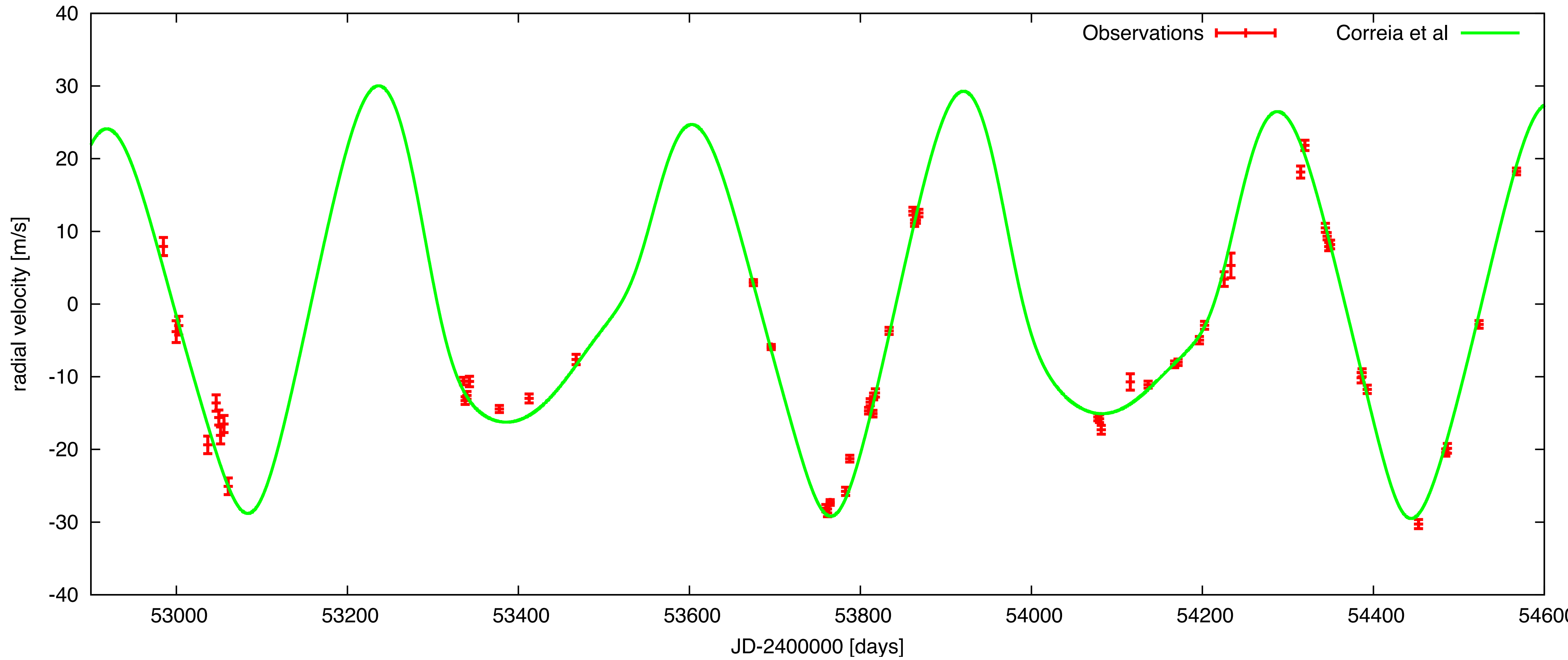
Take home message I

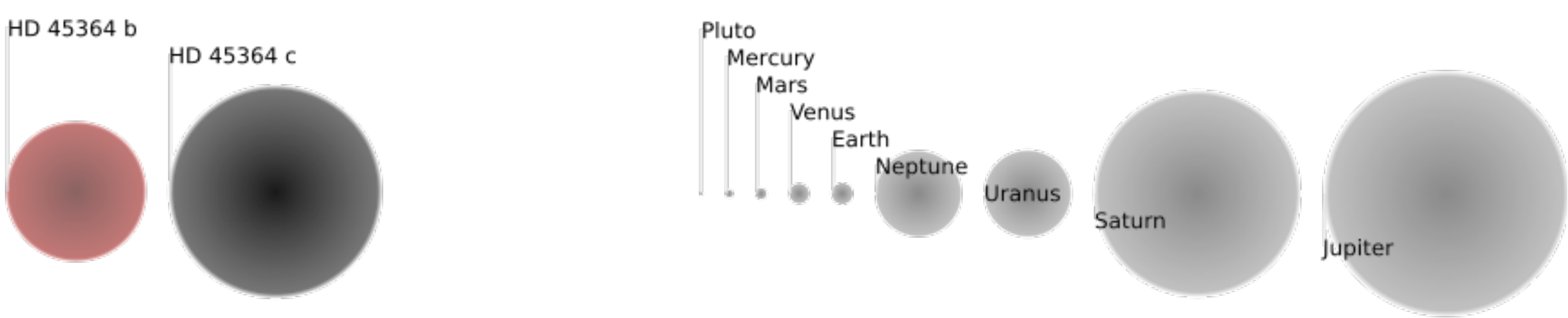
planet + disc = migration

2 planets + migration = resonance

HD 45364

HD45364



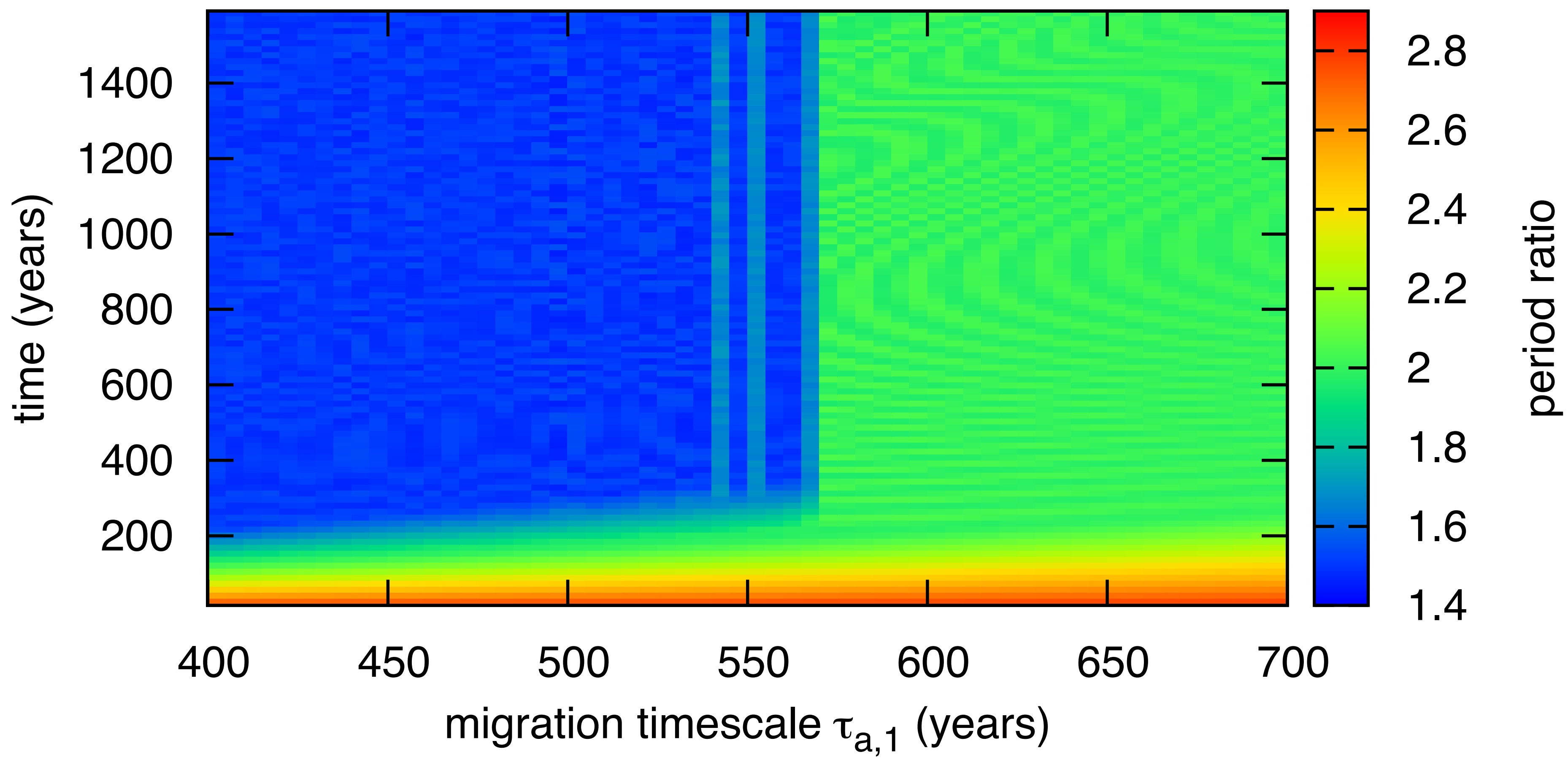


Correia et al 2009, Visual Exoplanet Catalogue

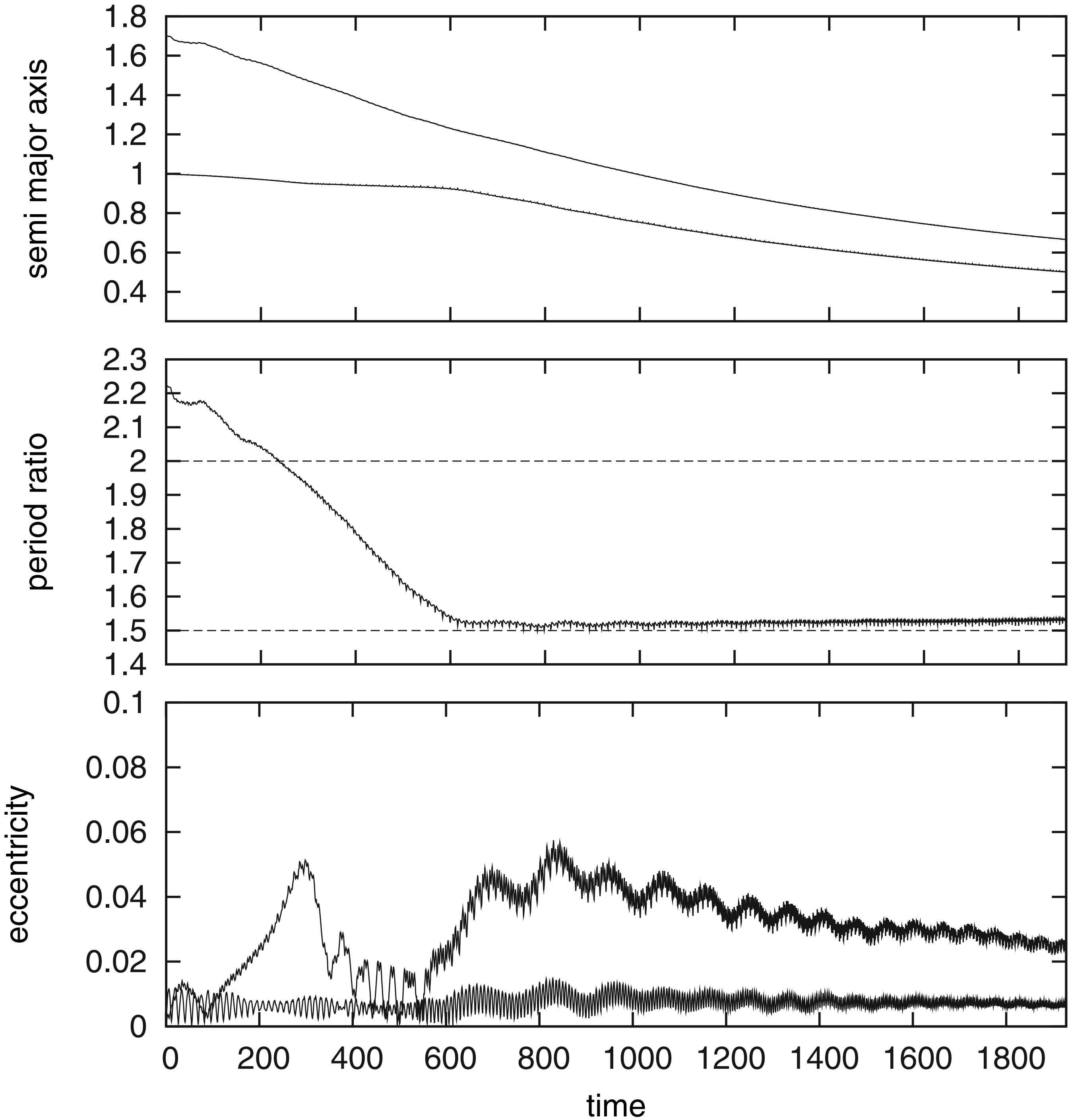
Formation scenario for HD45364

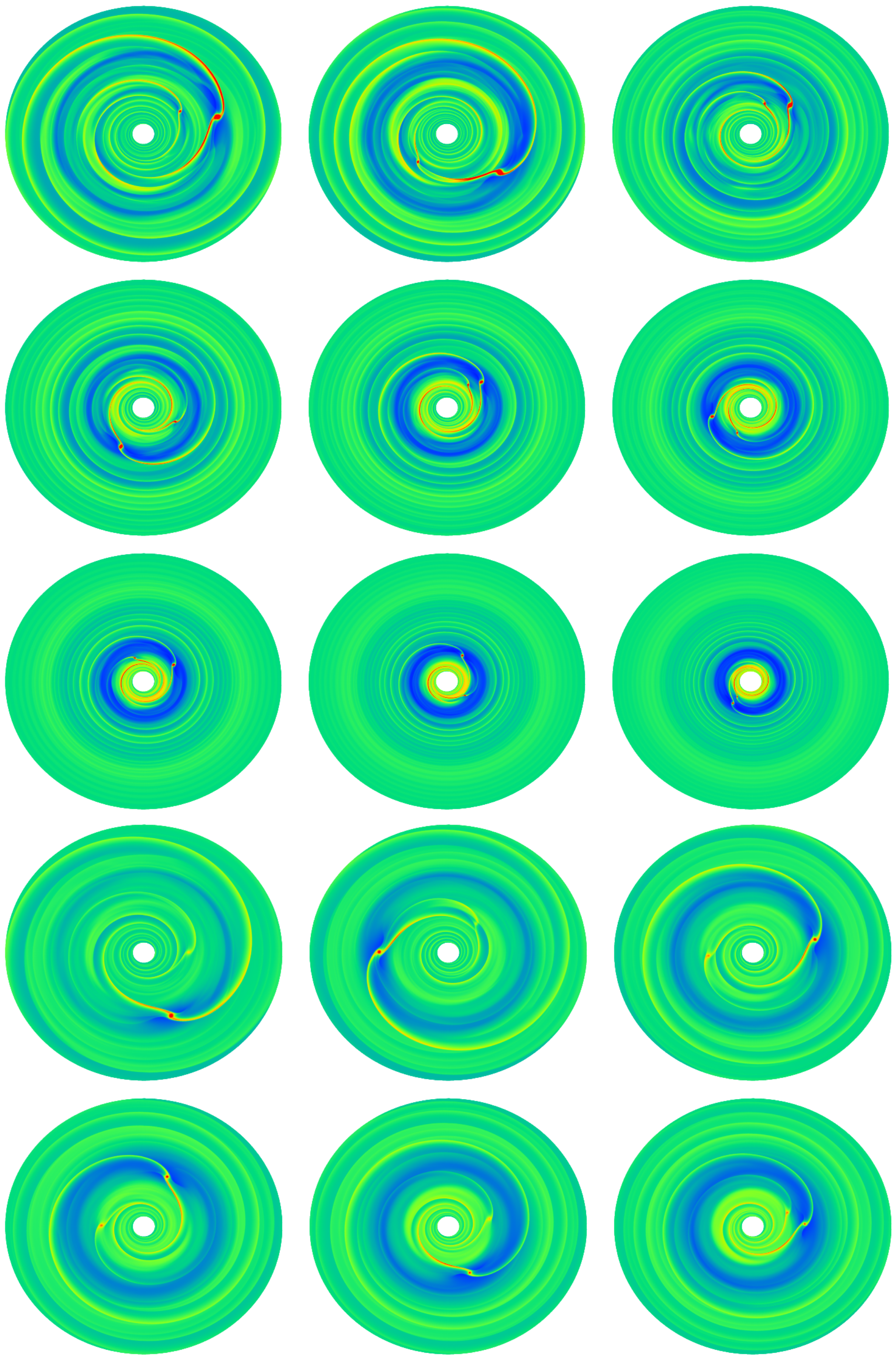
- Two migrating planets
- Infinite number of resonances

- Migration speed is crucial
- Resonance width and libration period define critical migration rate



Formation scenario for HD45364





Rein, Papaloizou & Kley 2010

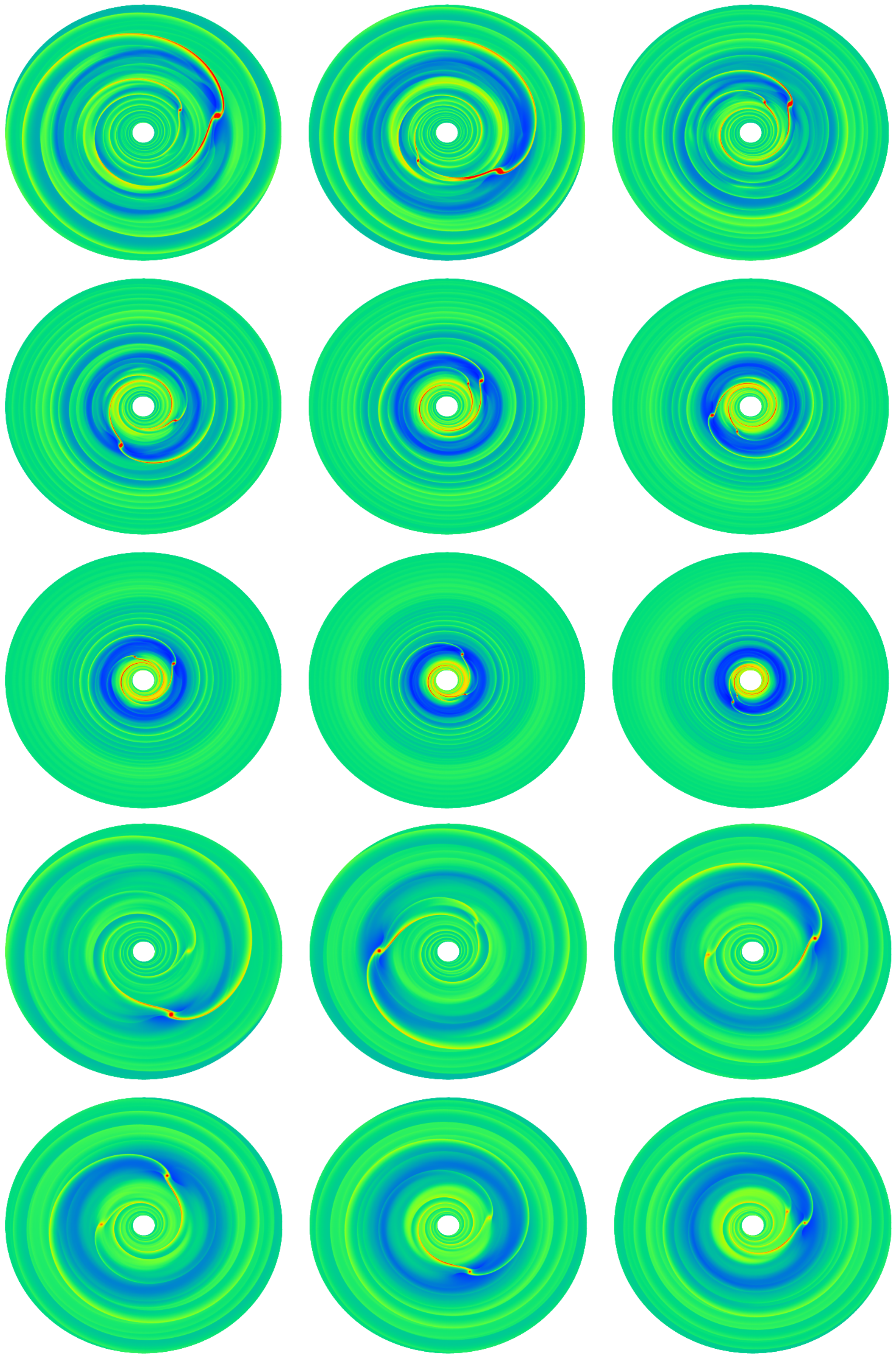
Formation scenario for HD45364

Massive disc (5 times MMSN)

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

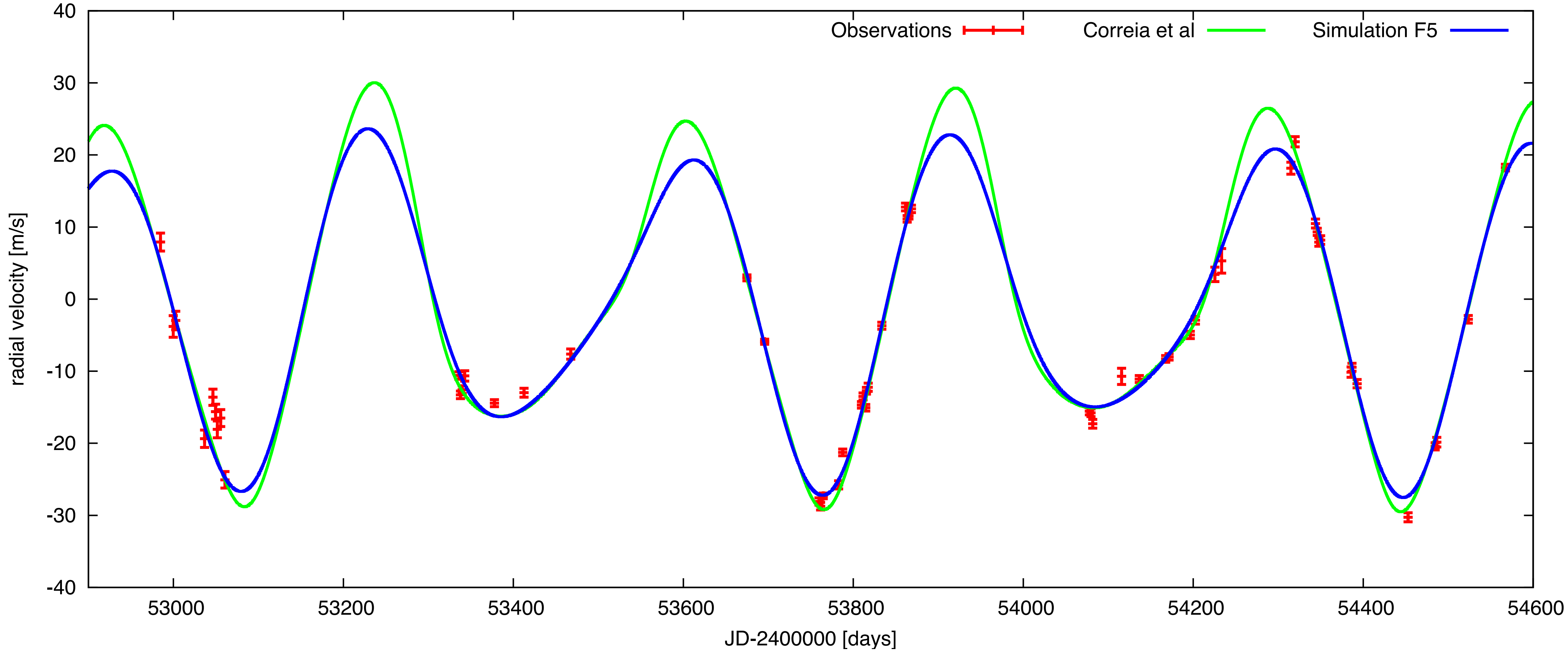
Large scale-height (0.07)

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



Rein, Papaloizou & Kley 2010

Formation scenario leads to a better ‘fit’



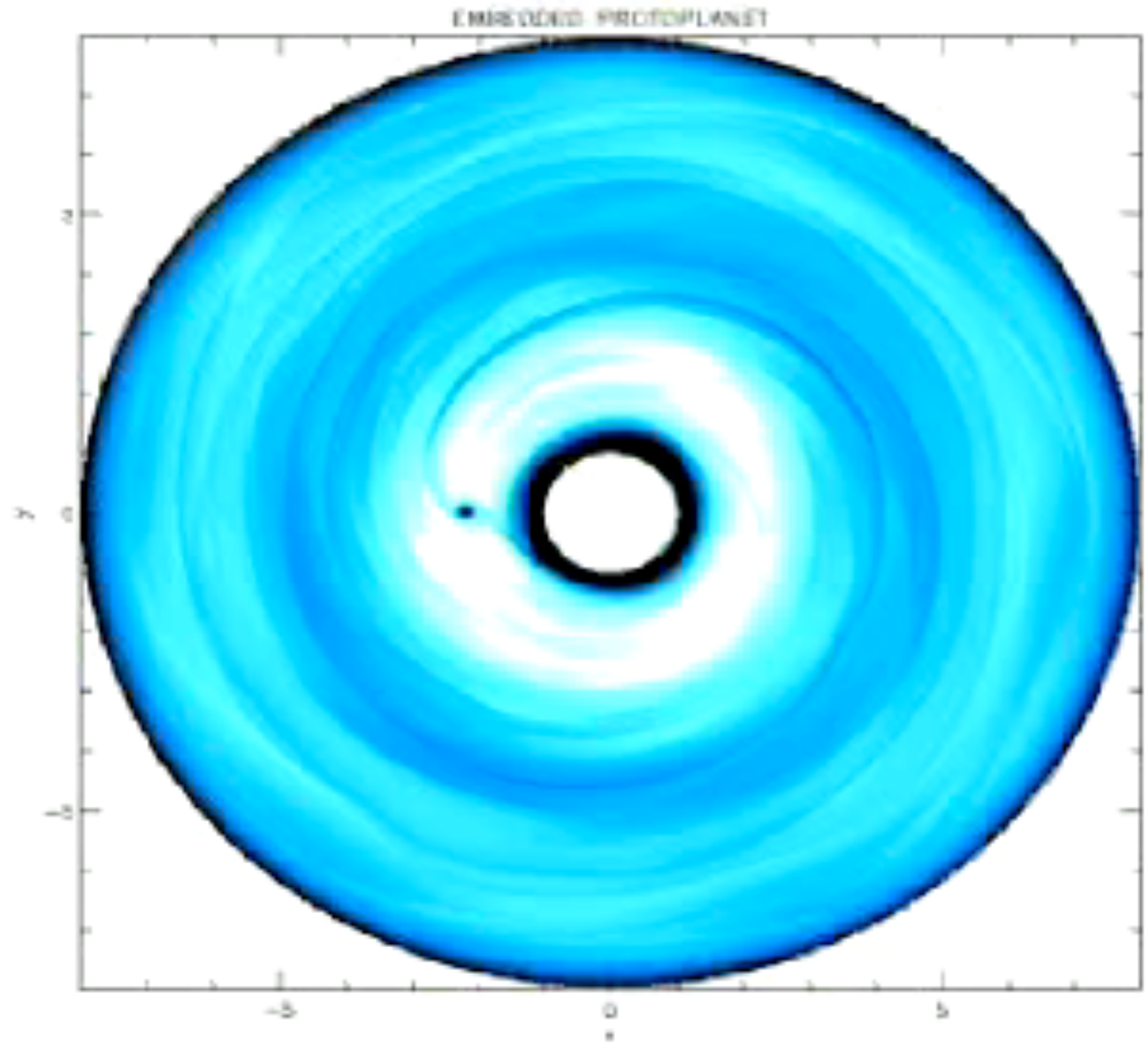
Parameter	Unit	Correia et al. (2009) b	Correia et al. (2009) c	Simulation **F5** b	Simulation **F5** c
$M \sin i$	$[\mathrm{M_{Jup}}]$	0.1872	0.6579	0.1872	0.6579
M_*	$[M_\odot]$	0.82		0.82	
a	[AU]	0.6813	0.8972	0.6804	0.8994
e		0.17 ± 0.02	0.097 ± 0.012	0.036	0.017
λ	[deg]	105.8 ± 1.4	269.5 ± 0.6	352.5	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

Migration in a turbulent disc

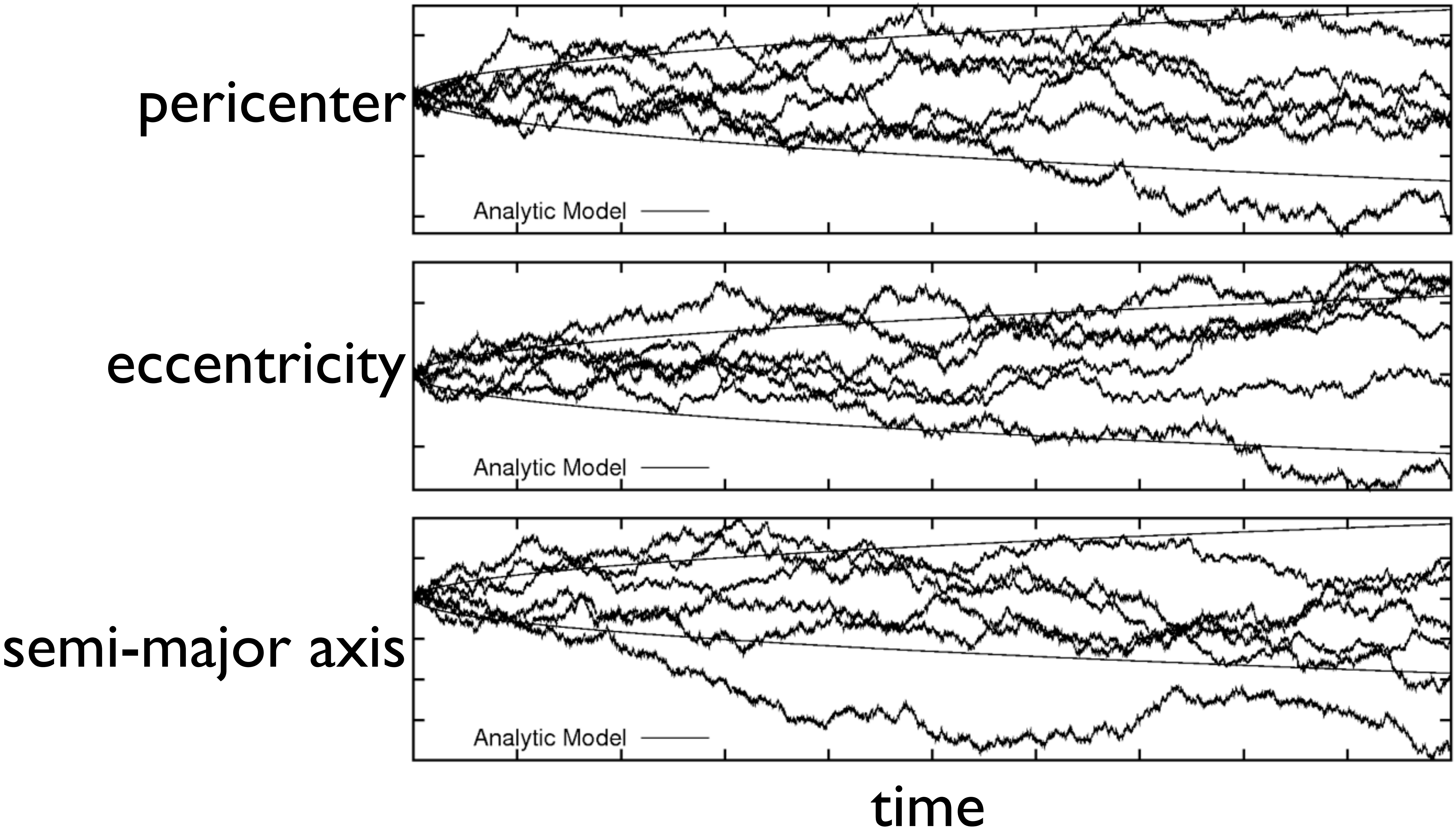
Turbulent disc

- 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



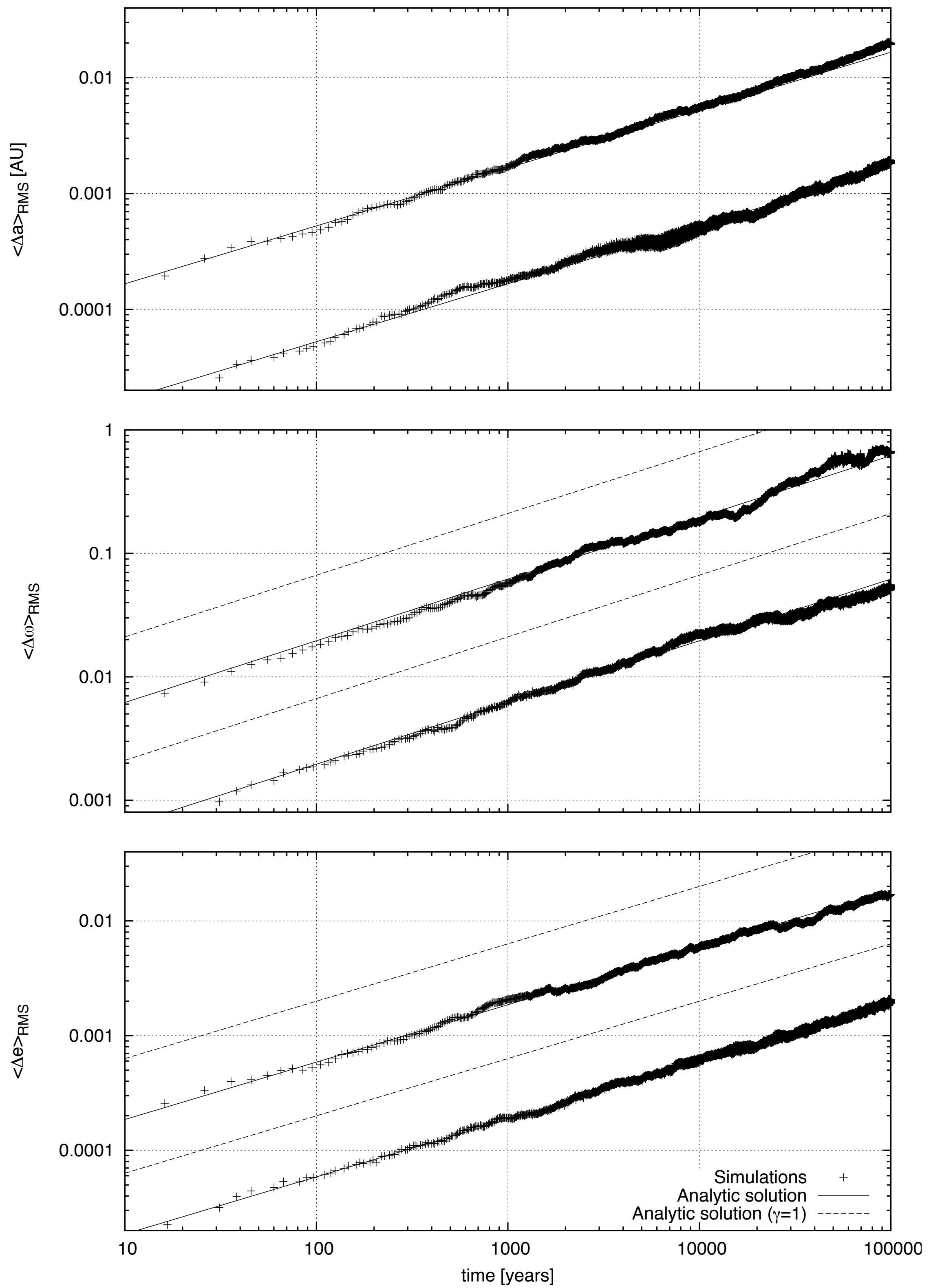
Rein & Papaloizou 2009

Analytic growth rates for 1 planet

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

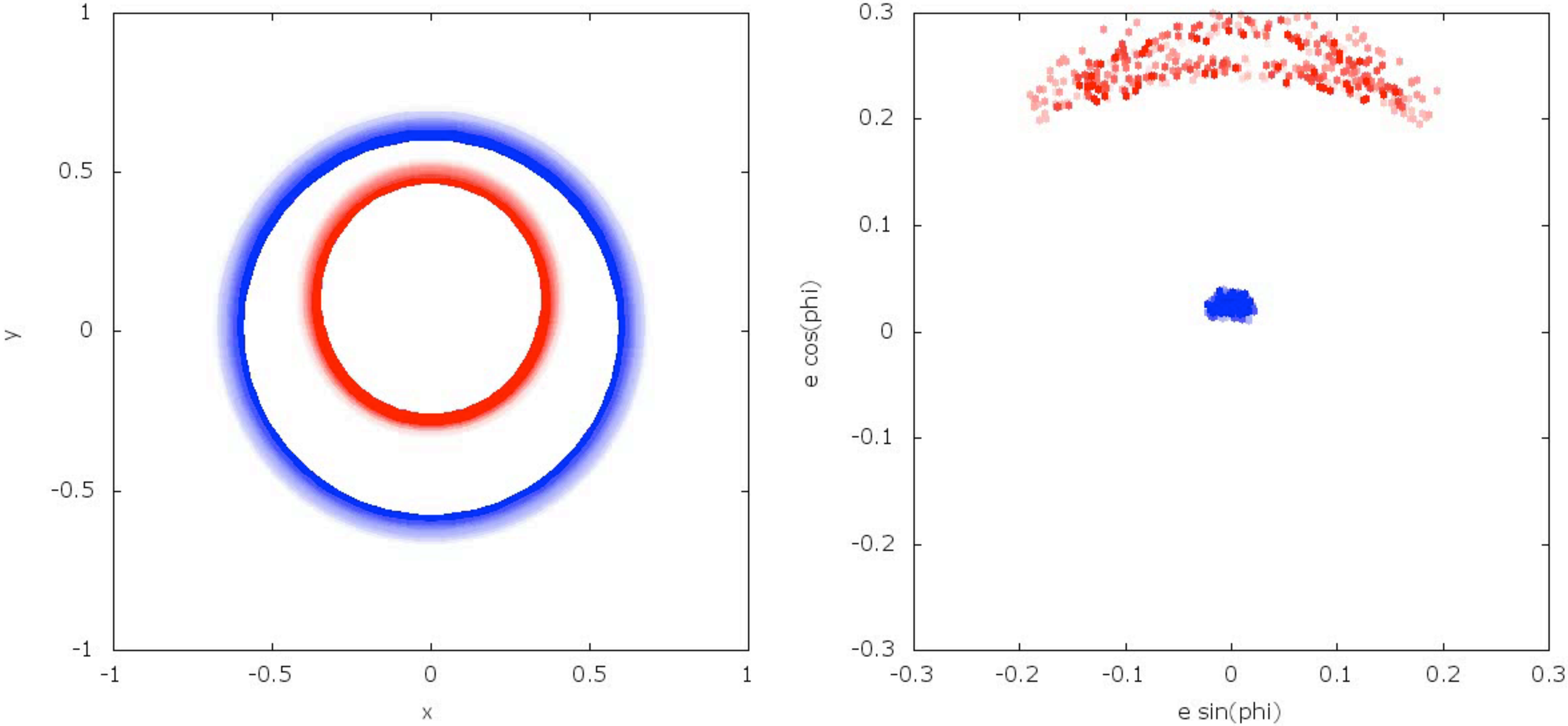
$$(\Delta \varpi)^2 = \frac{2.5}{e^2}\frac{\gamma D t}{n^2 a^2}$$

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



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

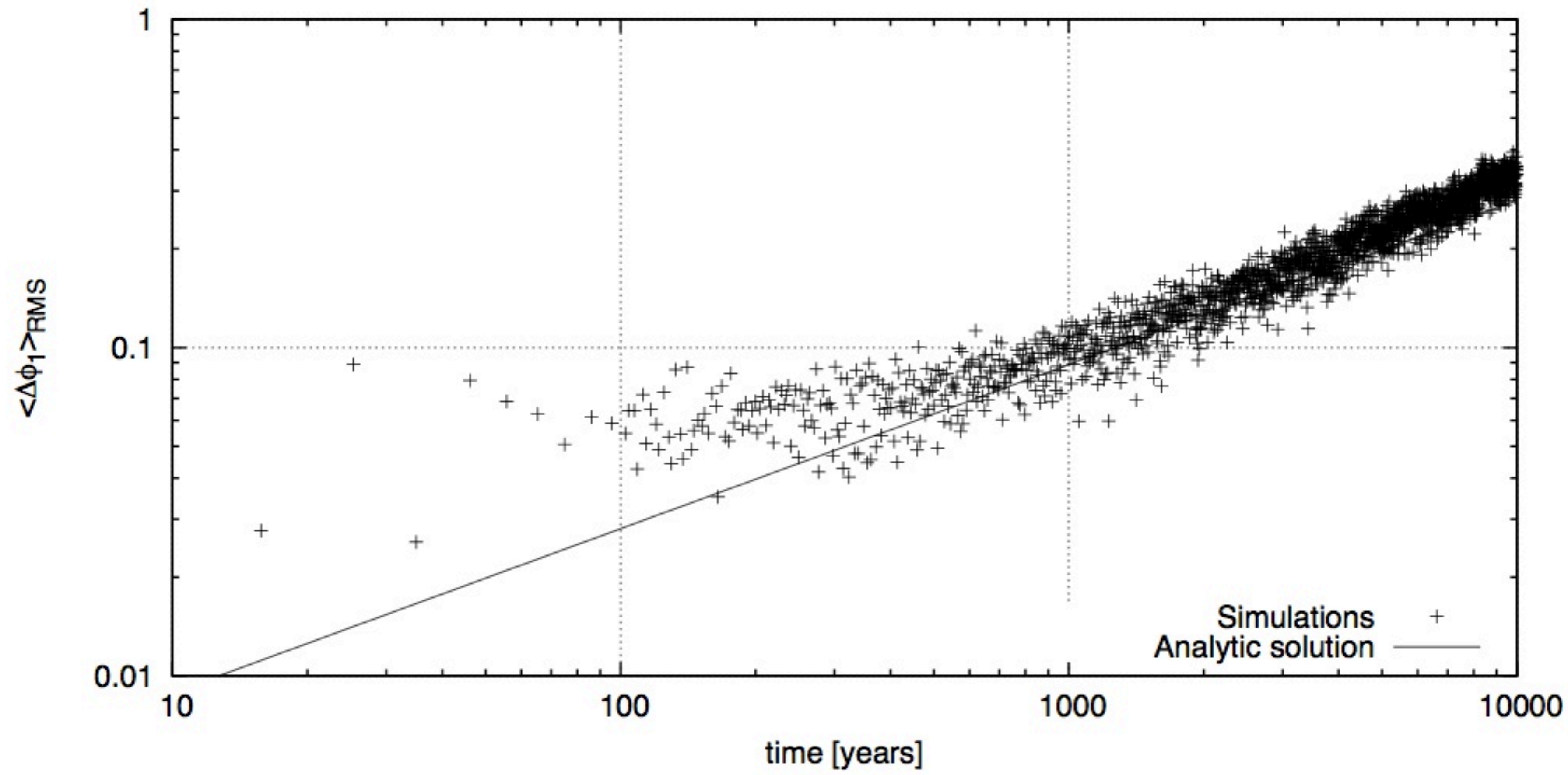
Two planets: turbulent resonance capture



Analytic growth rates for 2 planets

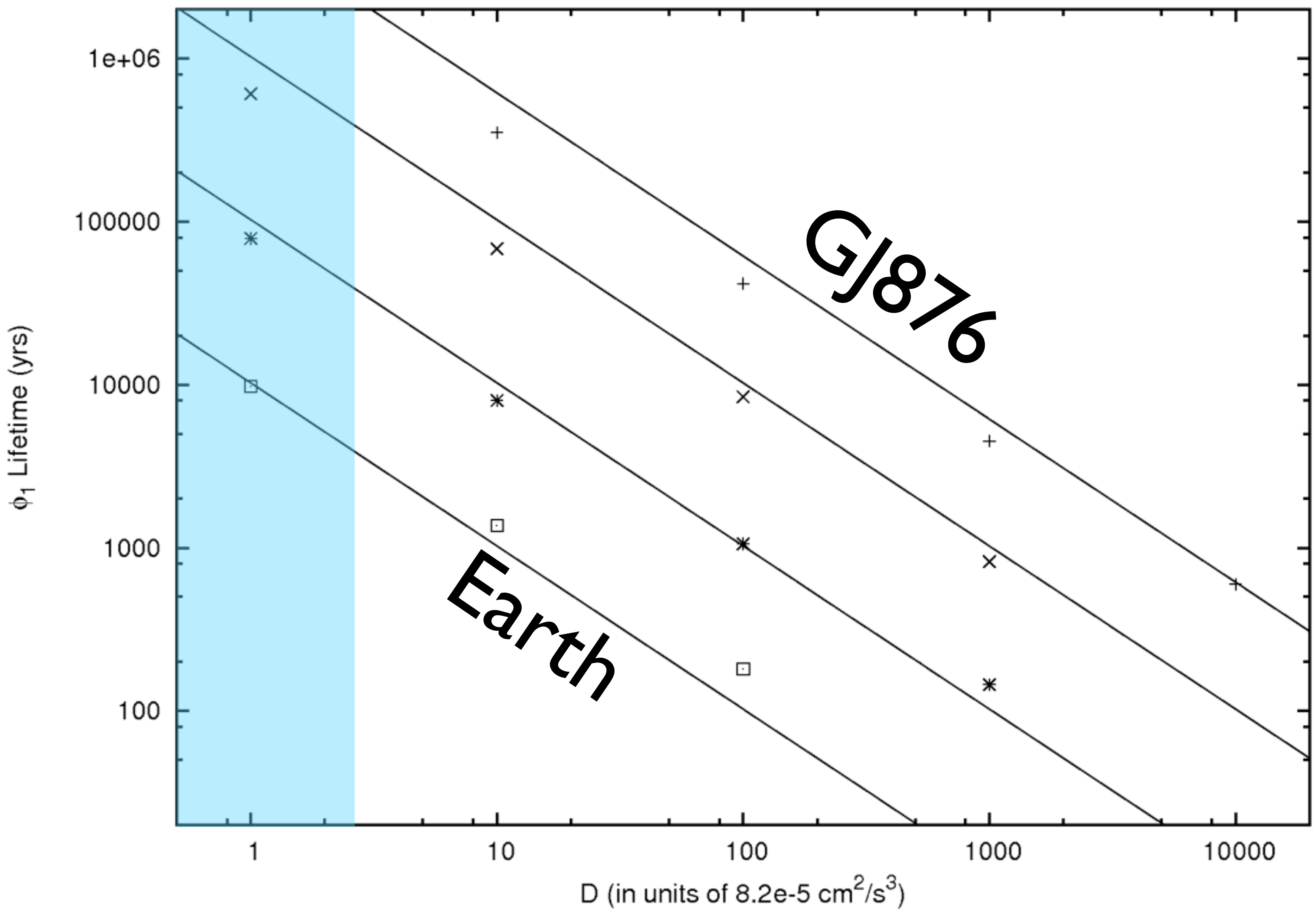
$$\frac{(\Delta\phi_1)^2}{(p+1)^2} = \frac{9\gamma_f}{a_1^2\omega_{lf}^2}\,D\,t$$

$$(\Delta(\Delta\varpi))^2 = \frac{5\gamma_s}{4a_1^2n_1^2e_1^2}\,D\,t$$



Rein & Papaloizou 2009

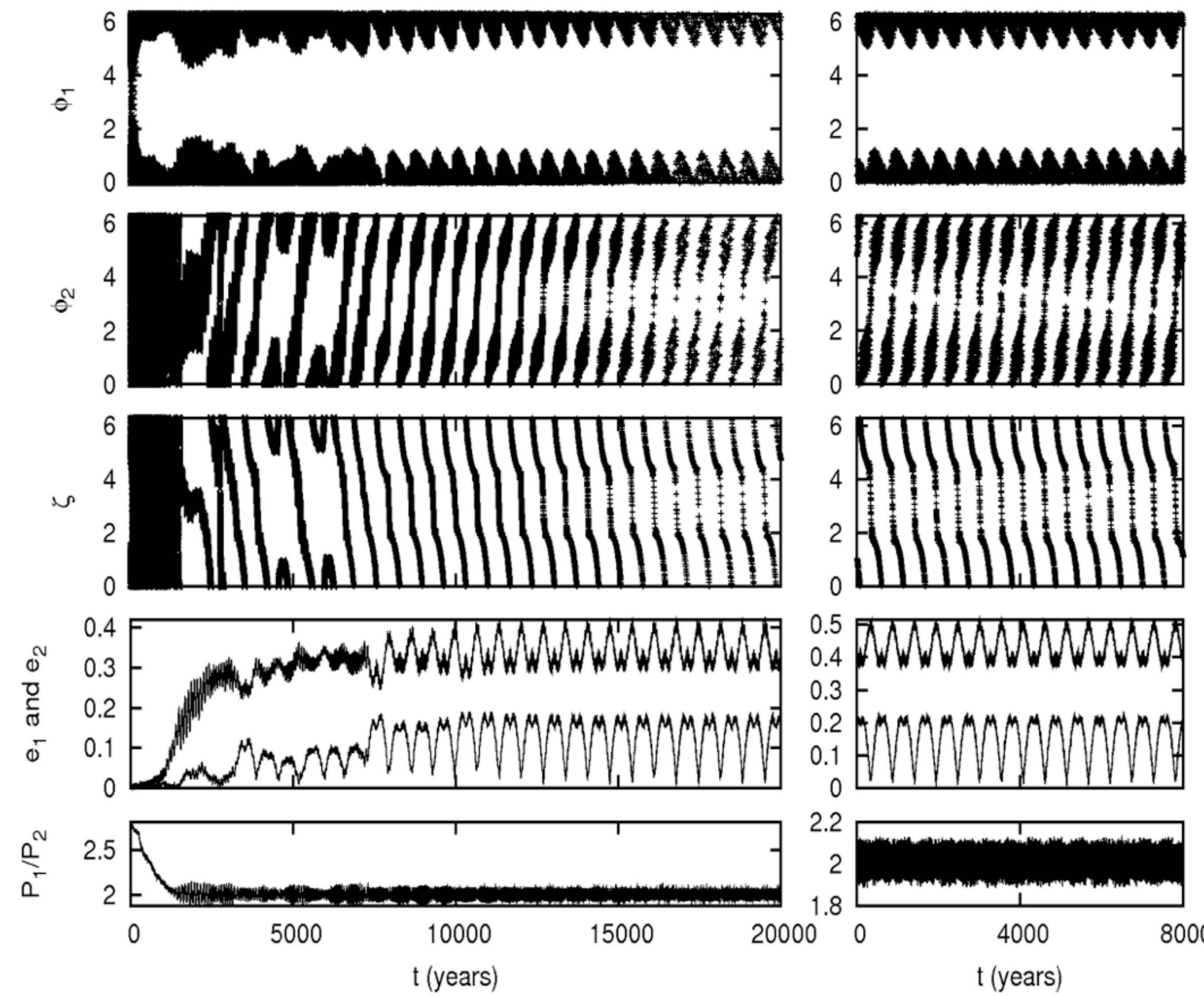
Multi-planetary systems in mean motion resonance



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

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

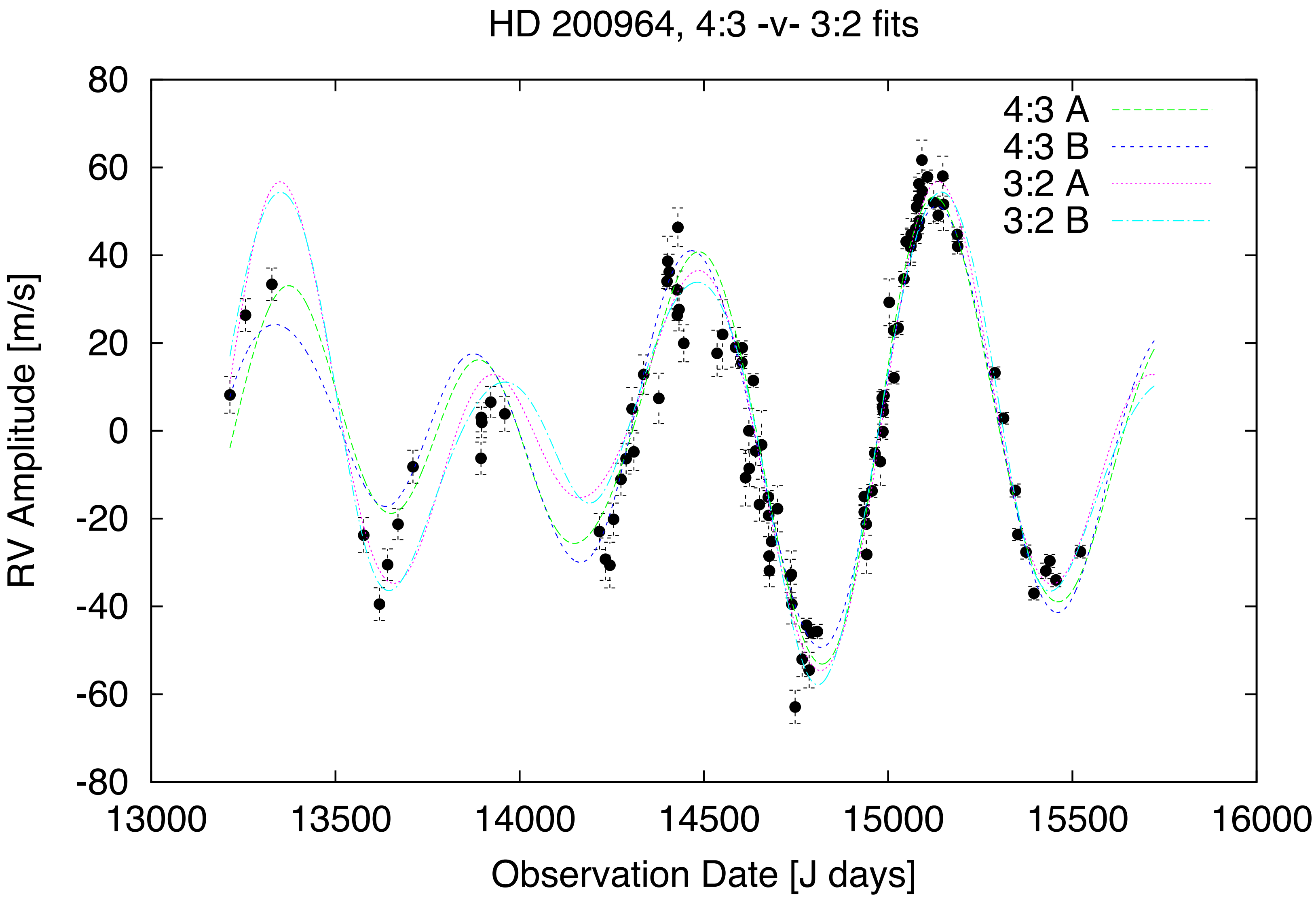


Take home message II

Migration scenarios can explain the dynamical configuration of many systems in amazing detail

HD200964
The impossible system?

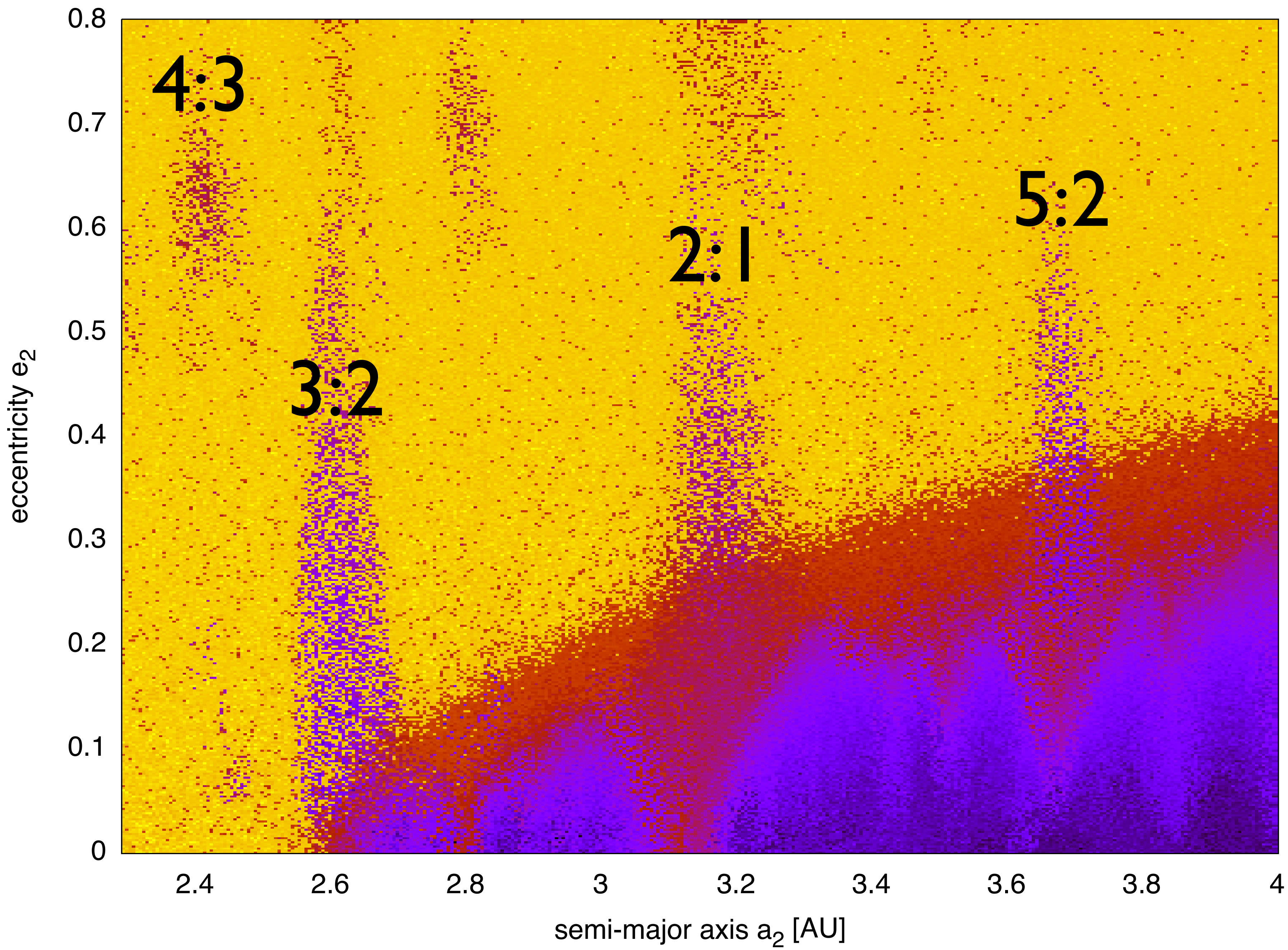
Radial velocity curve of HD200964



- Two massive planets 1.8 M_{Jup} and 0.9 M_{Jup}
- Period ratio either 3:2 or 4:3
- Another similar system, to be announced soon
- How common is 4:3?
- Formation?

Plot by Matthew Payne

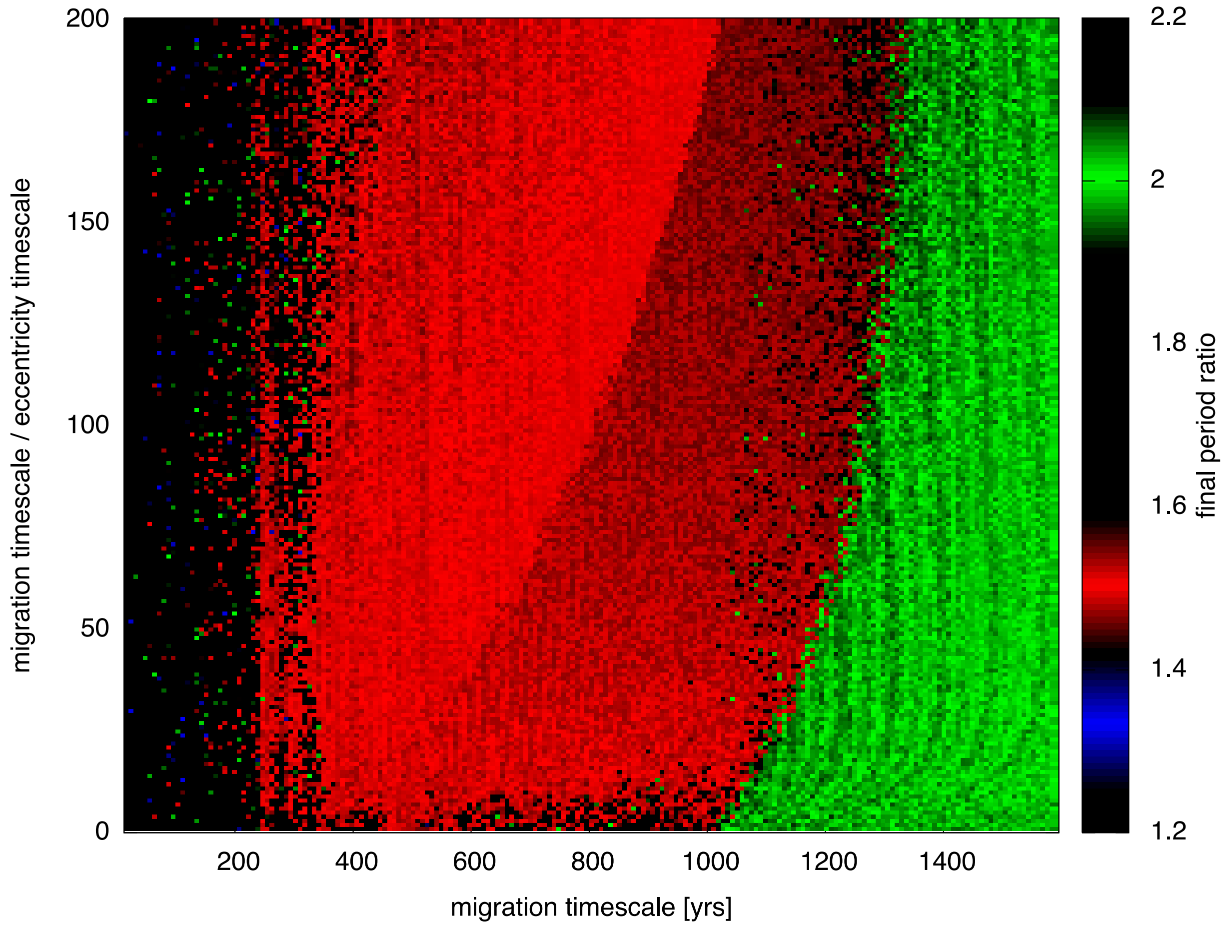
Stability of HD200964



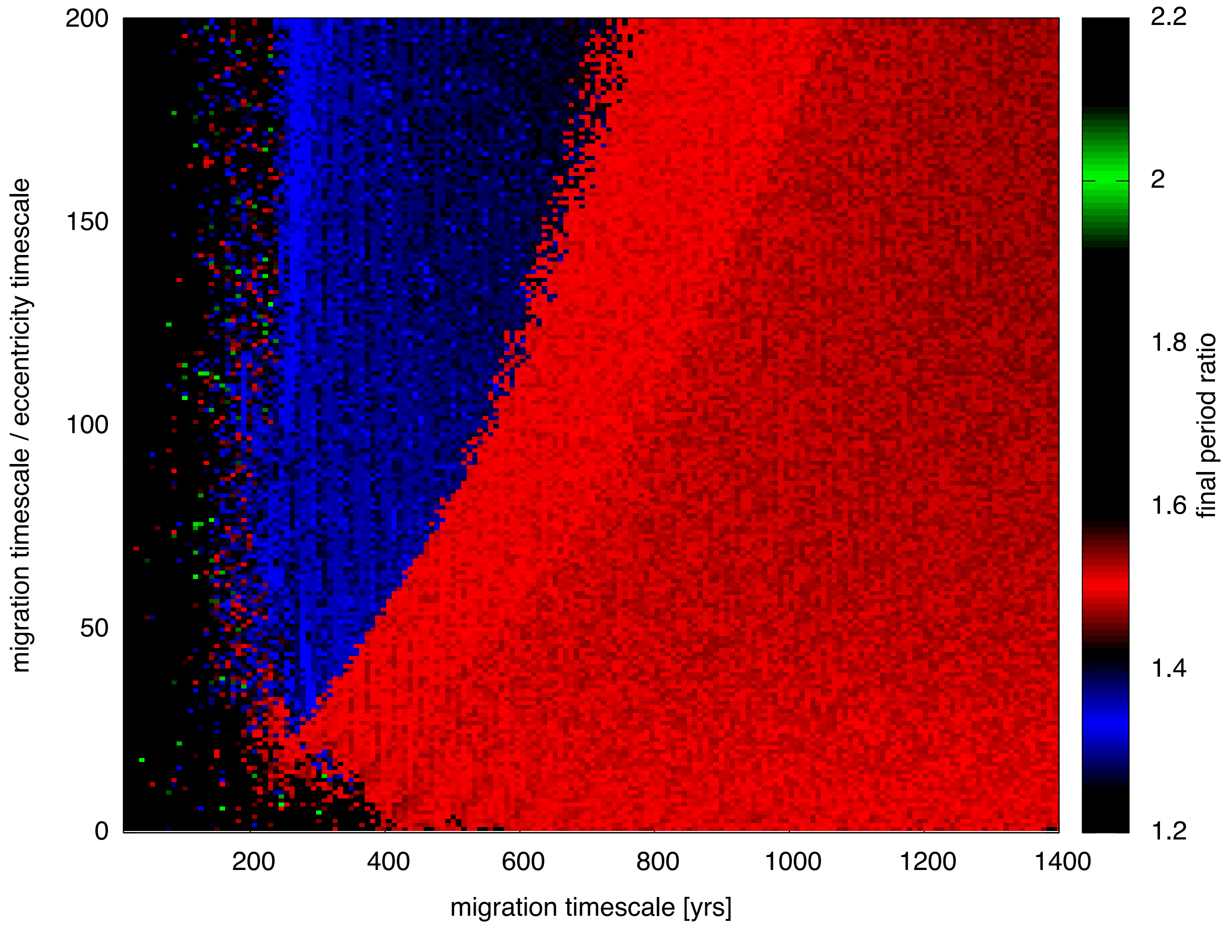
Rein, Payne, Veras & Ford (2012 in prep)

Standard disc migration doesn't work

observed masses

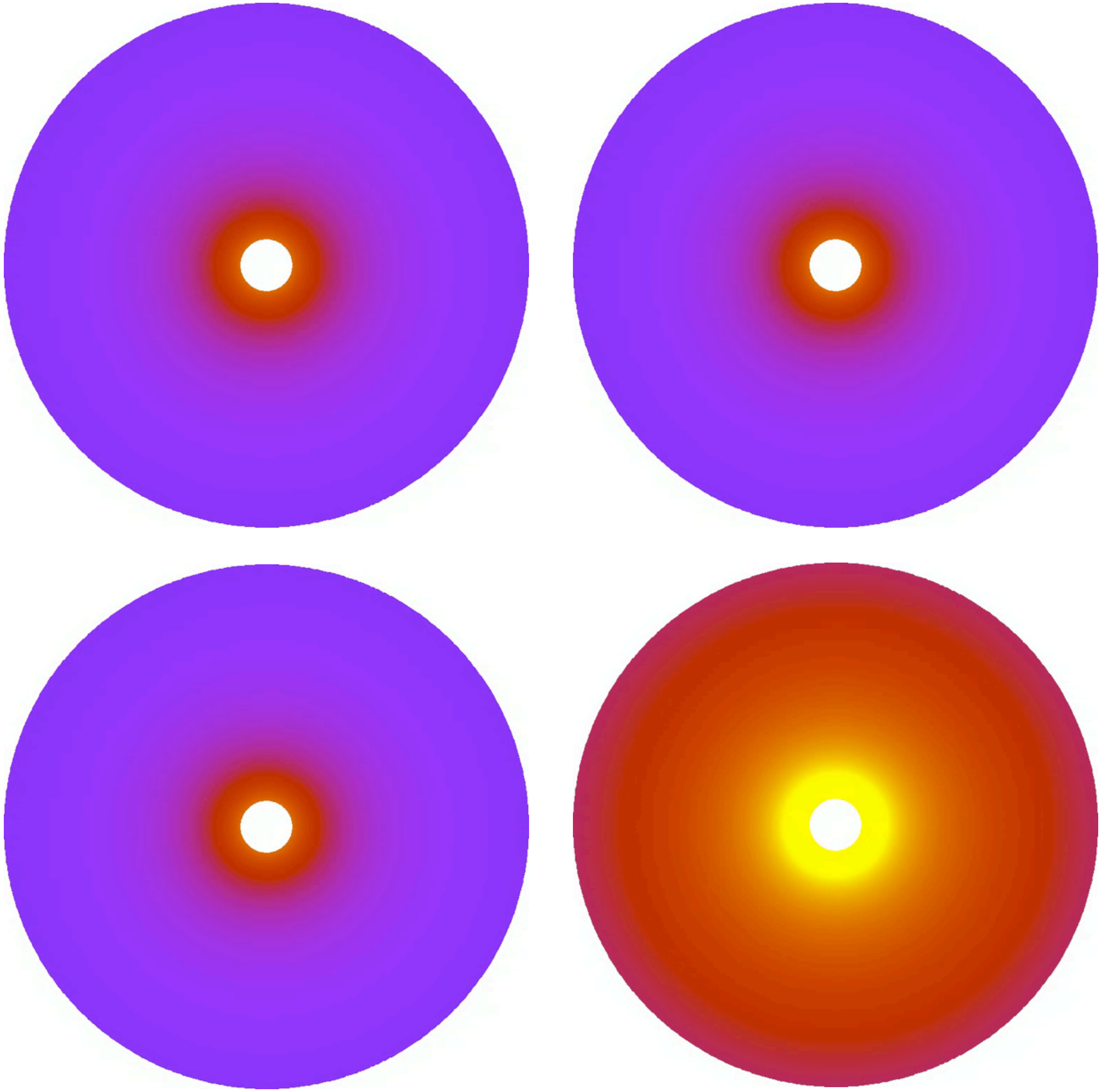


reduced masses



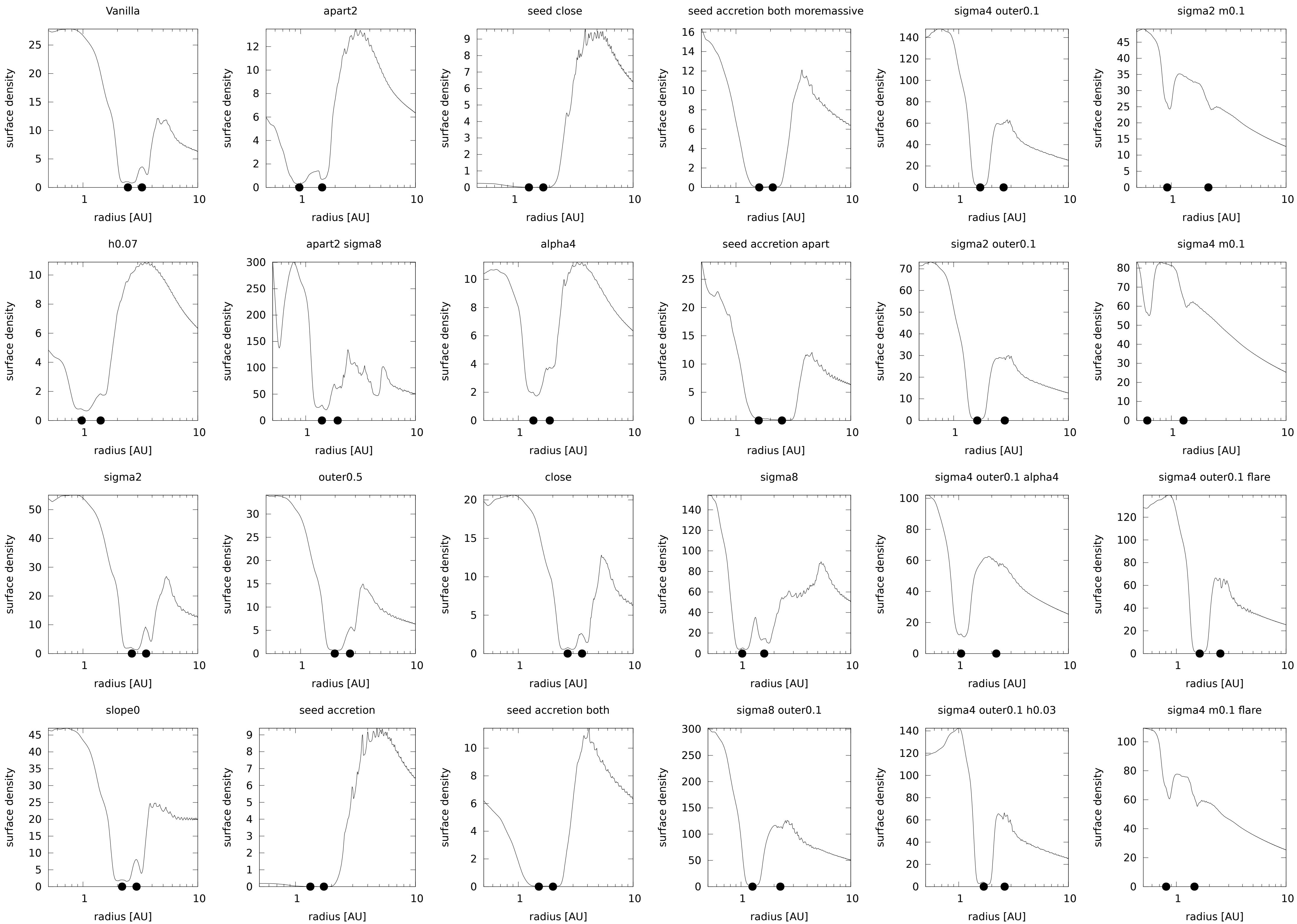
Rein, Payne, Veras & Ford (2012 in prep)

Hydrodynamical simulations I



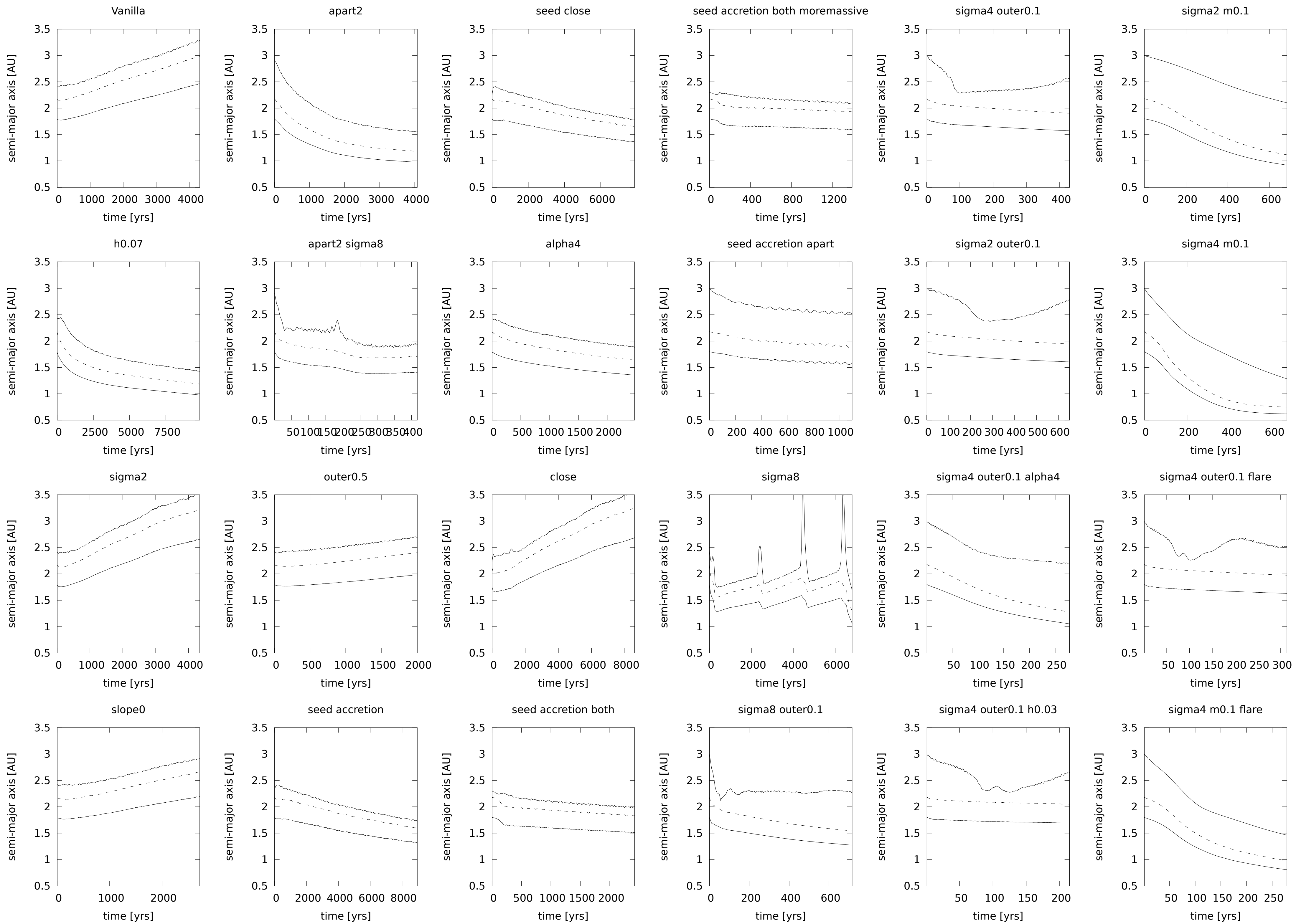
Rein, Payne, Veras & Ford (2012 in prep)

Hydrodynamical simulations II



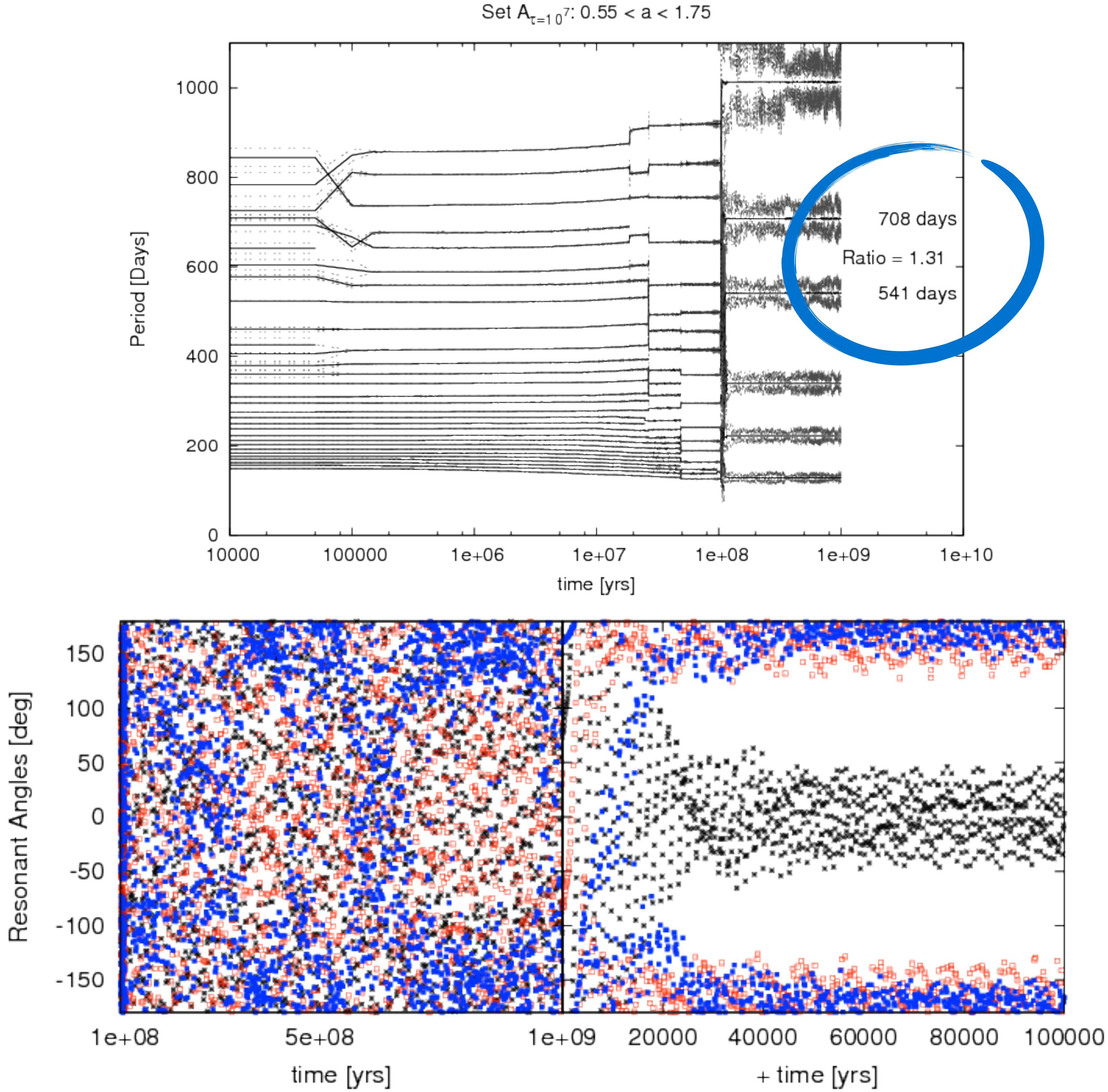
Rein, Payne, Veras & Ford (2012 in prep)

Hydrodynamical simulations III



Rein, Payne, Veras & Ford (2012 in prep)

Scattering of embryos



Rein, Payne, Veras & Ford (2012 in prep)

HD200964

- In situ formation?
- Main accretion while in 4:3 resonance?
- Planet planet scattering?
- A third planet?
- Observers screwed up?

Take home message III

We don't understand everything (yet).

Conclusions

Conclusions

Formation of multi-planetary systems

Number of system increases almost every week.
Kepler has large number of planets, but not very suitable for detailed analysis

Multi-planetary system provide insight in otherwise unobservable formation phase
Dynamical configuration keeps a record of history

GJ876	formed in the presence of a disc and dissipative forces
HD128311	formed in a turbulent disc
HD45364	formed in a massive disc
HD200964	did not form at all