Institute for Advanced Study

Formation of Multi-Planetary Systems

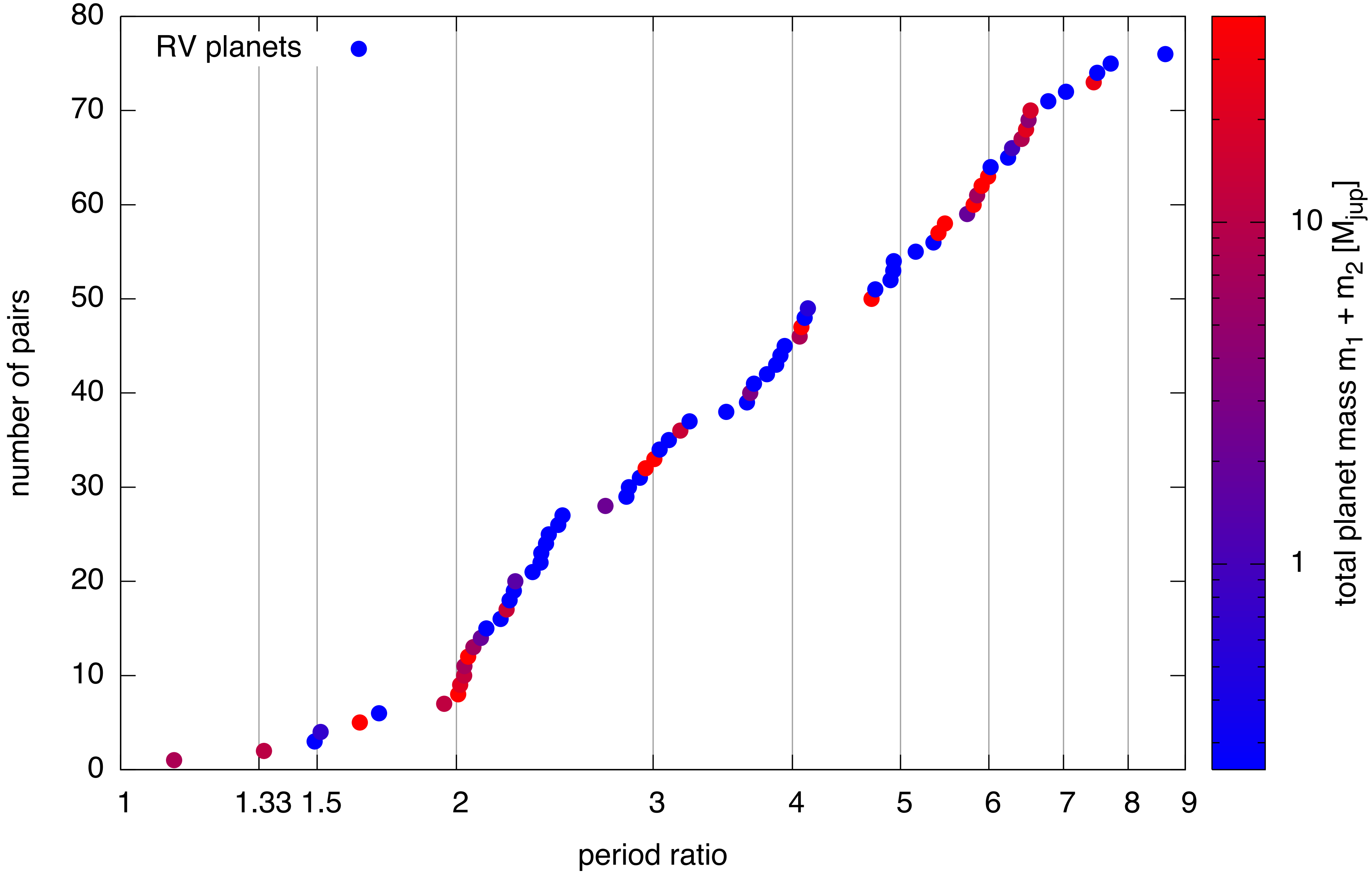
Success and Failure of Planetary Migration Theory

Hanno Rein @ JPL Pasadena, July 2012

Statistics of multiple planets (using iPhone App)

Available for free on the AppStore.

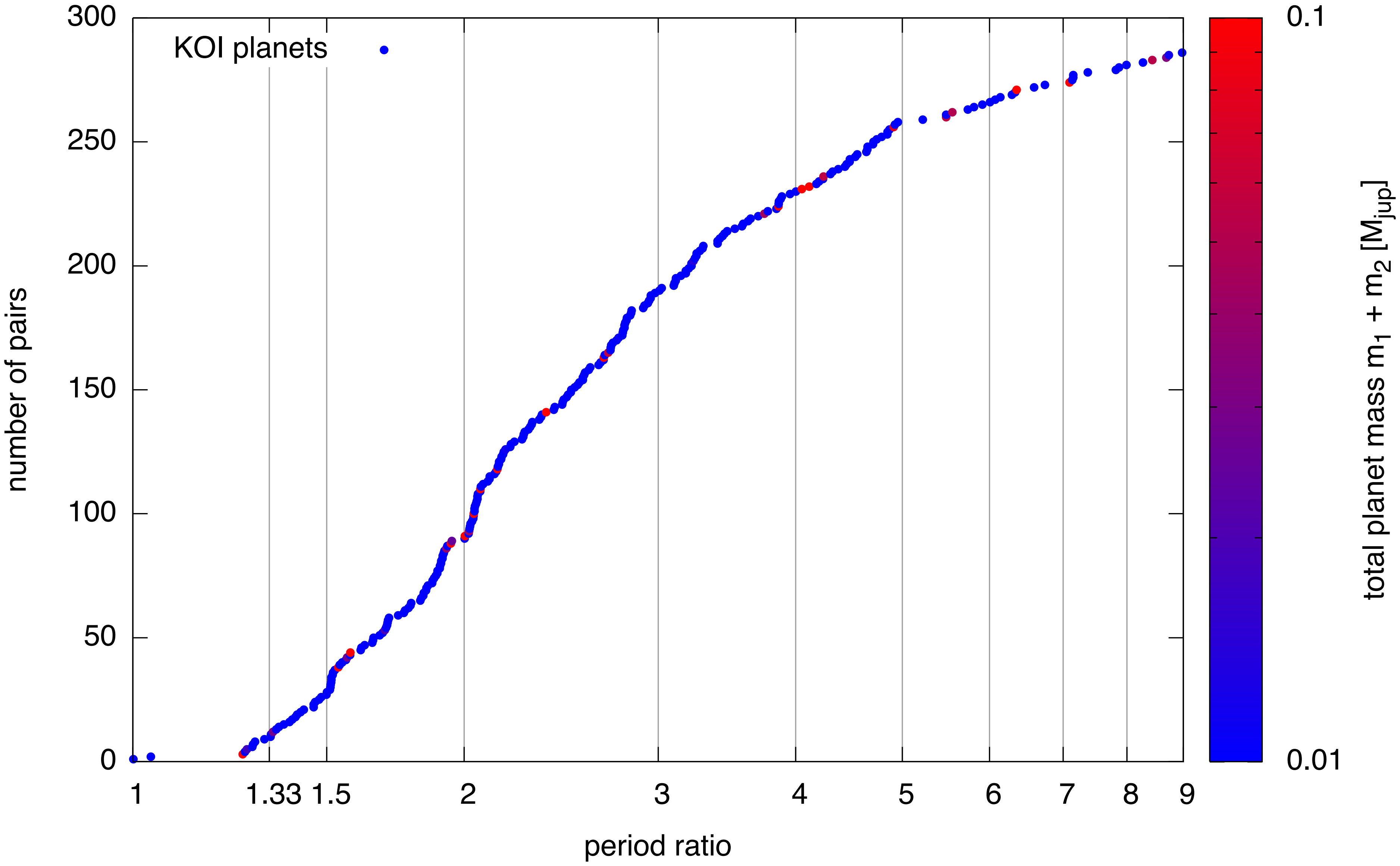
Radial velocity planets



- Periods of systems with massive planets tend to pile up near integer ratios
- Most prominent features at 4:1, 3:1, 2:1, 3:2

Rein, Payne, Veras & Ford (in press)

Kepler's transiting planet candidates



- Period ratio distribution much smoother for small mass planets
- Deficiencies near 4:3, 3:2, 2:1
- Excess slightly outside of the exact commensurability

Rein, Payne, Veras & Ford (in press)

Recipe

Disk-Migration

Resonances

Migration in a non-turbulent disc

Planet formation

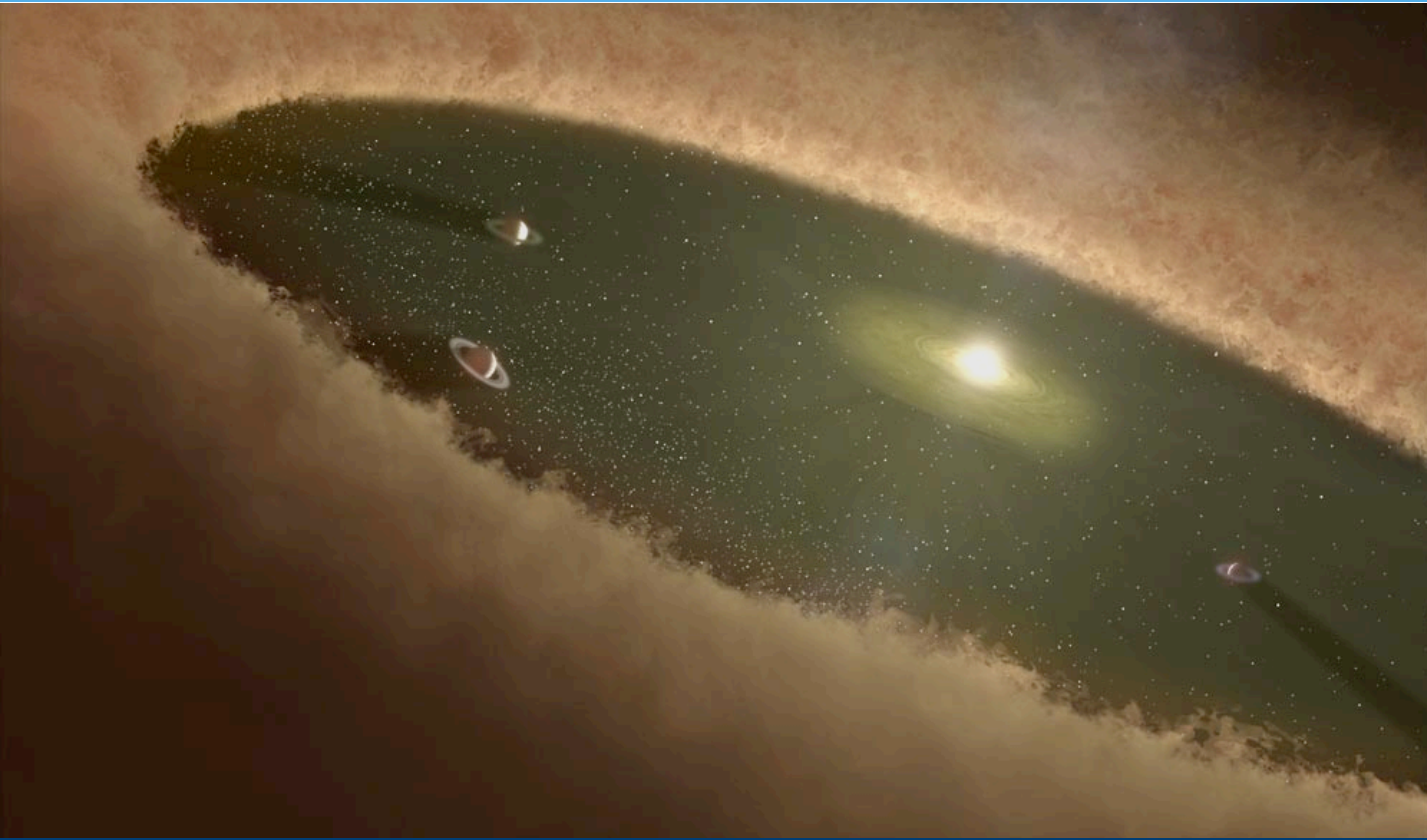


Image credit: NASA/JPL-Caltech

Gap opening criteria

Disc scale height

Stellar mass

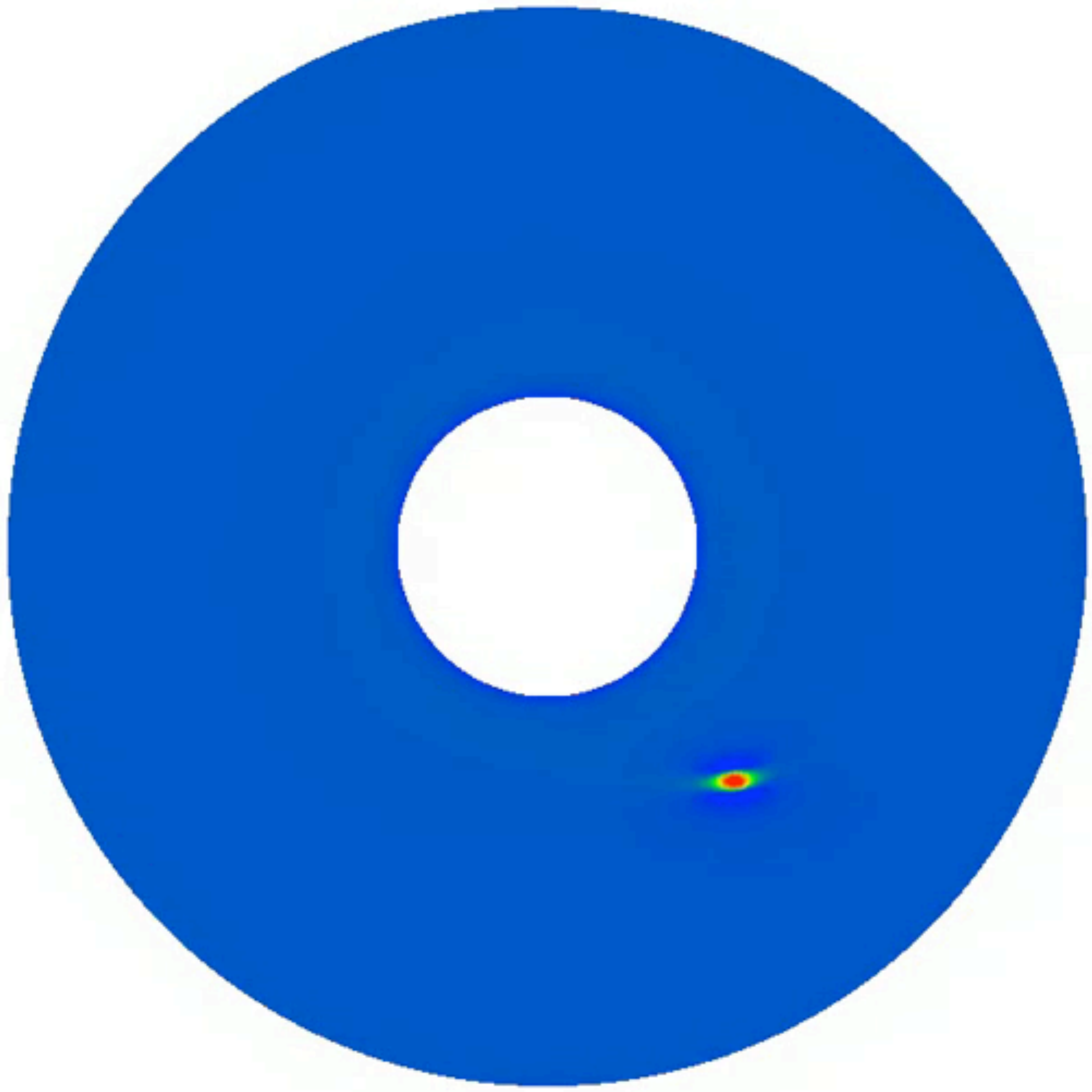
$$\frac{3}{4}\frac{H}{R_{\mathrm{Hill}}} + \frac{50M_*}{M_p\mathcal{R}} \leq 1$$

Planet mass

Viscosity $^{-1}$

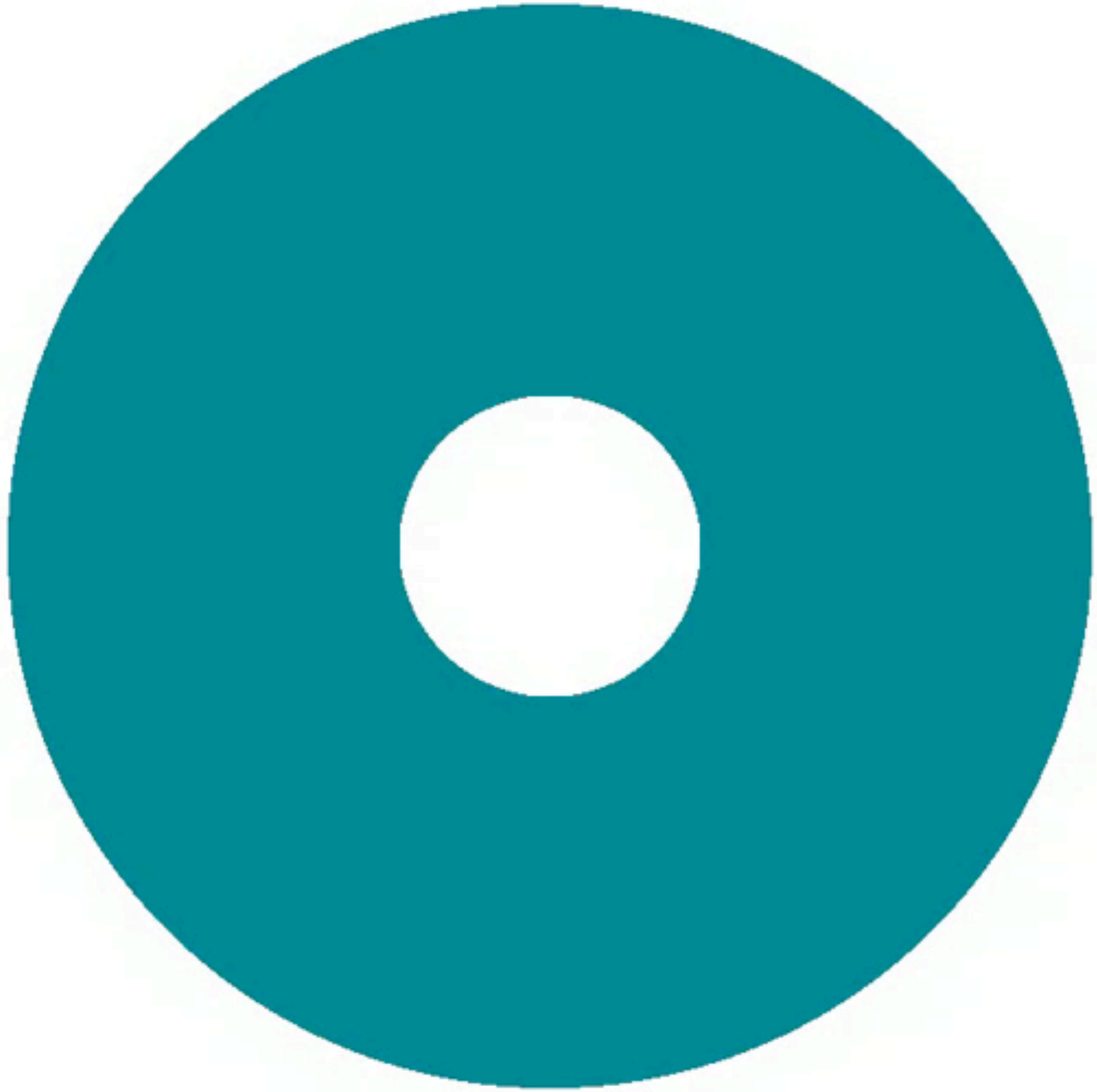
Migration - Type I

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



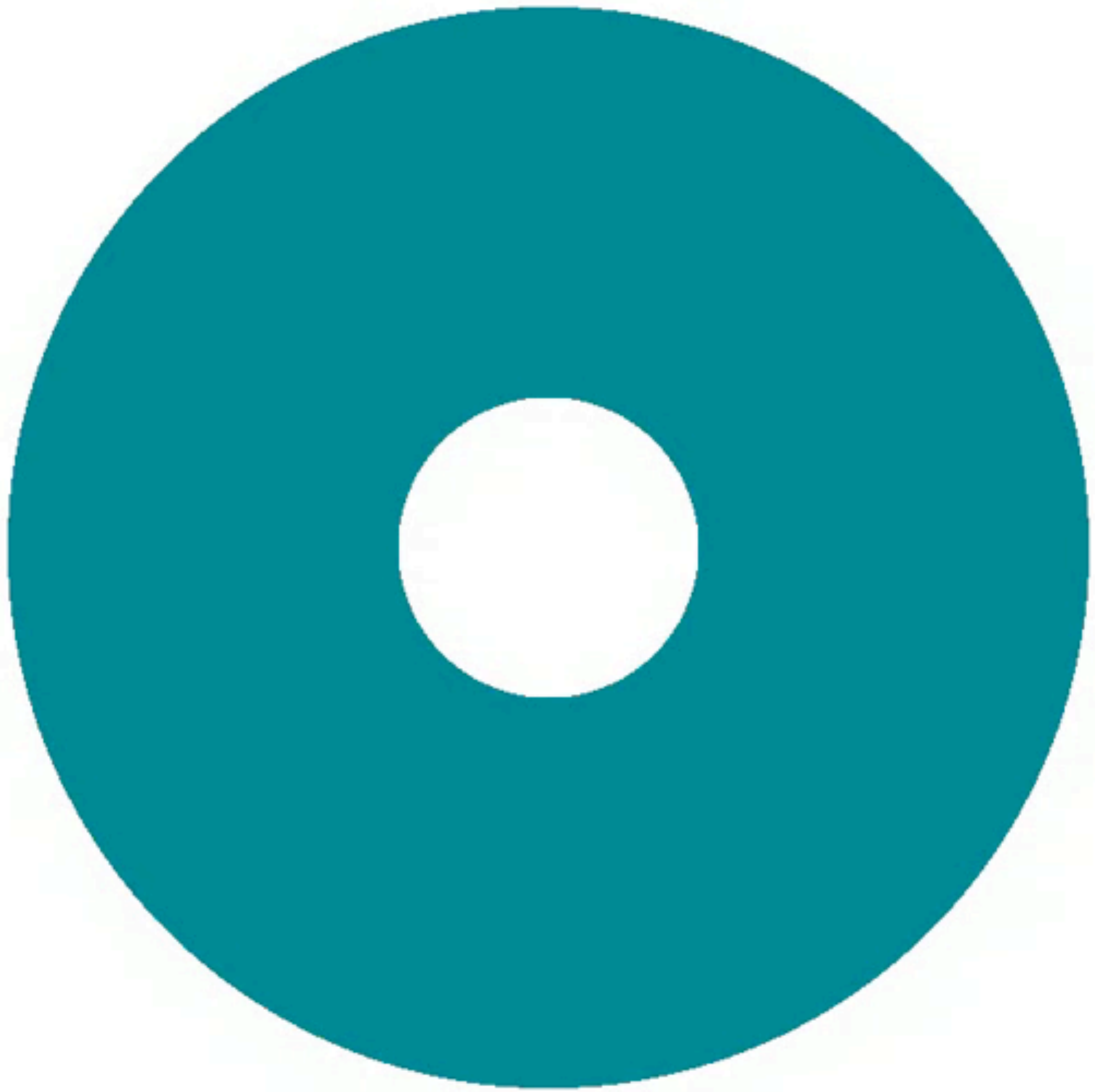
Migration - Type II

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



Migration - Type III

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

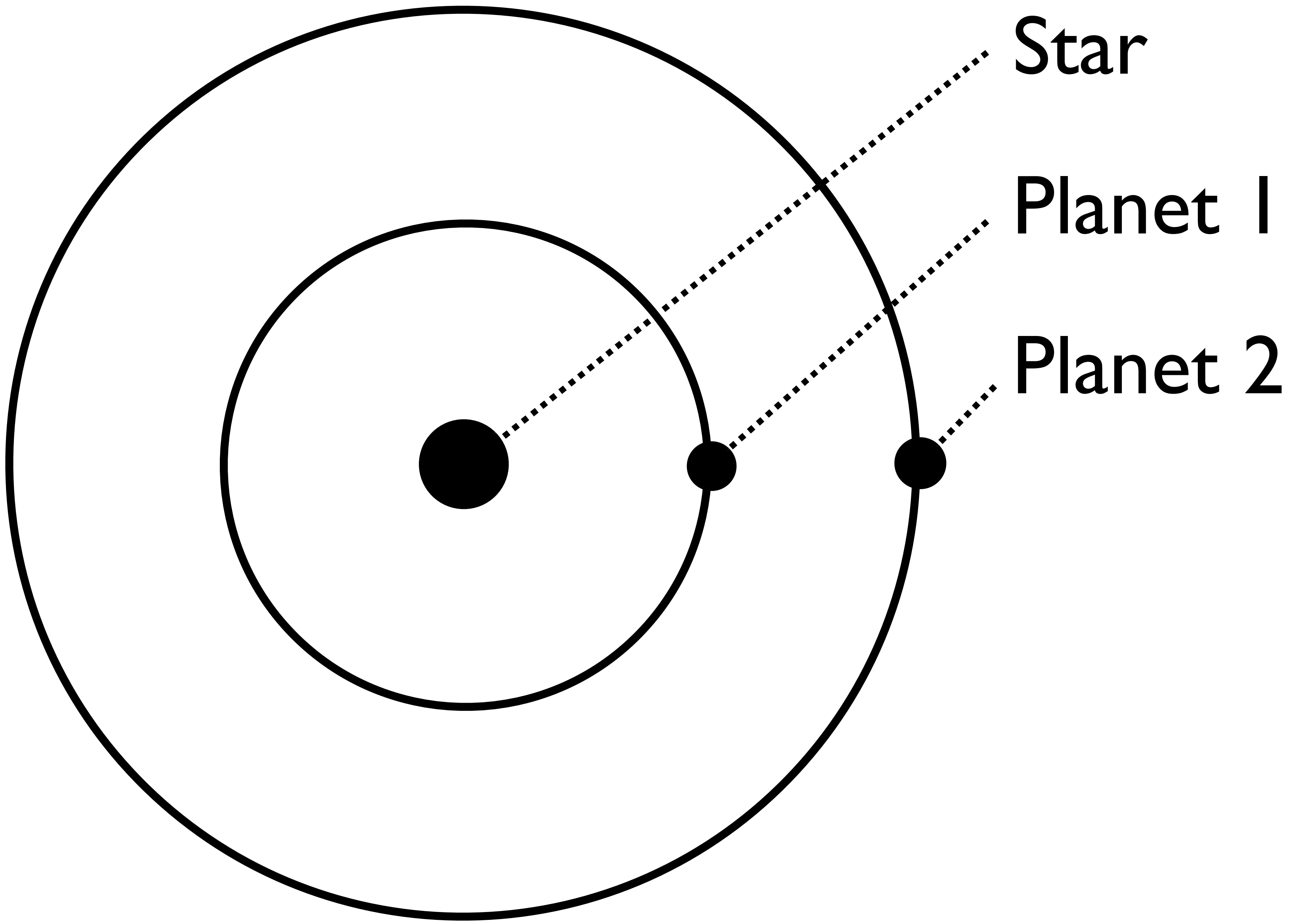


Take home message I

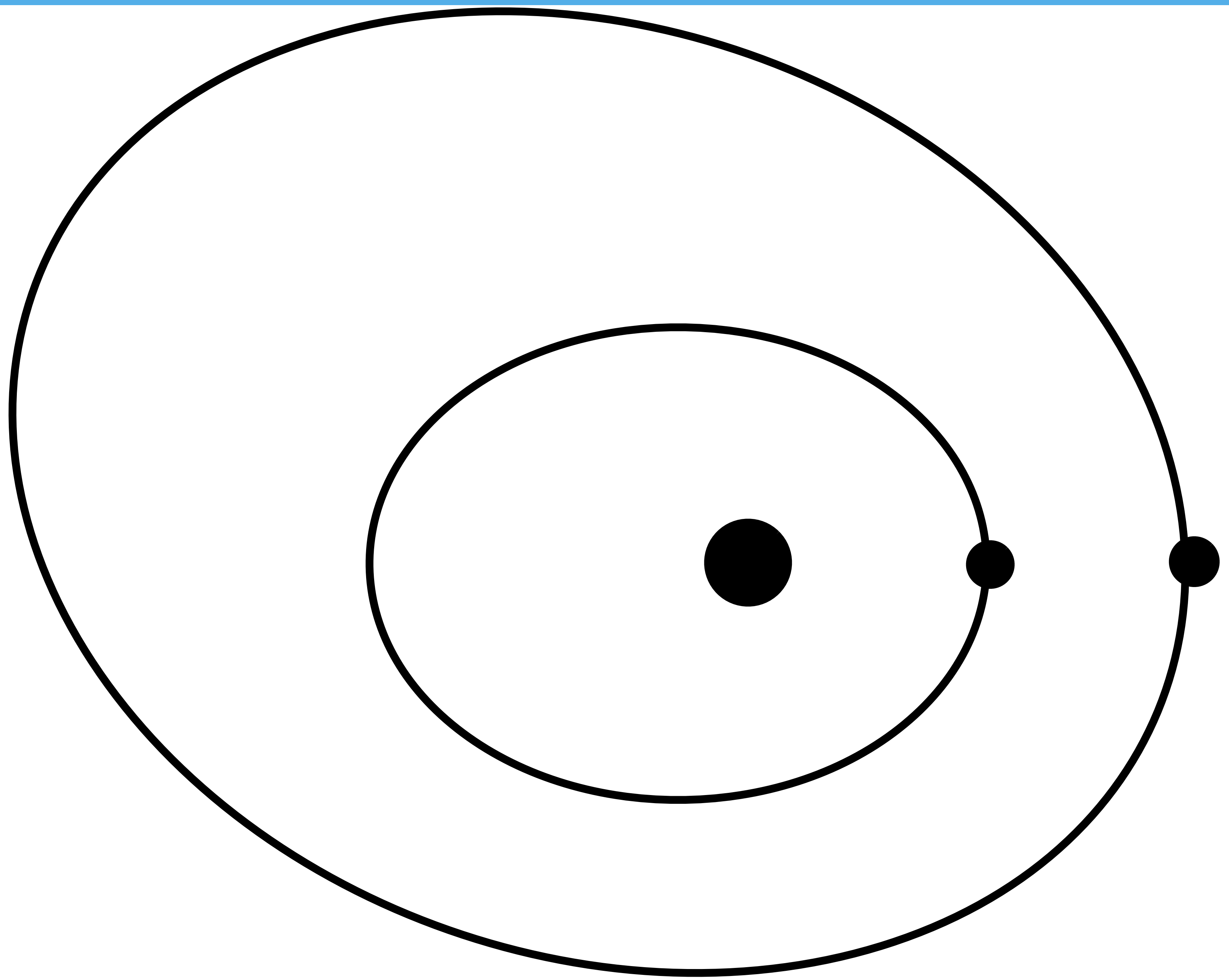
planet + disc = migration

Resonance capture

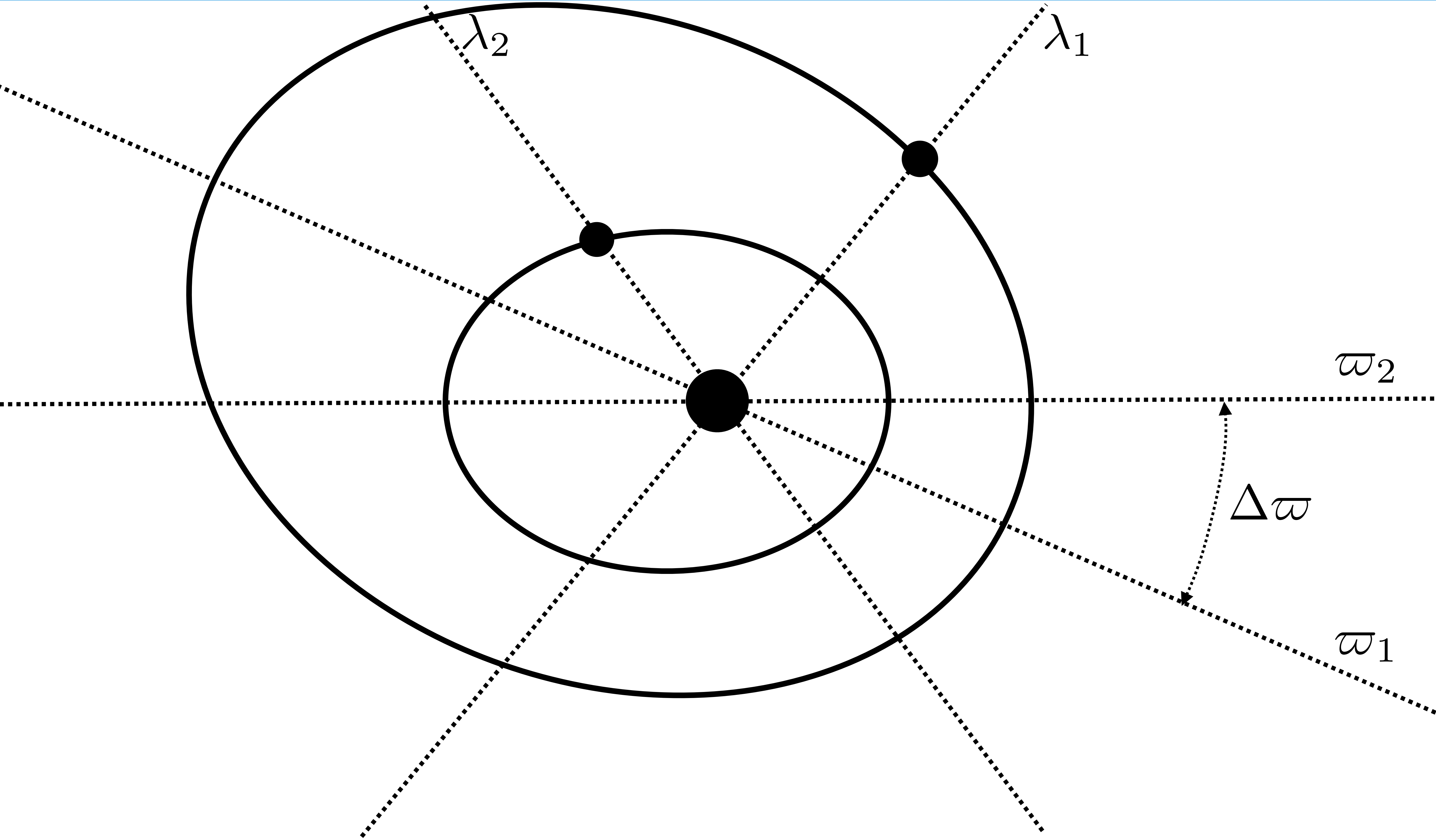
2:1 Mean Motion Resonance



2:1 Mean Motion Resonance



2:1 Mean Motion Resonance



Resonant angles

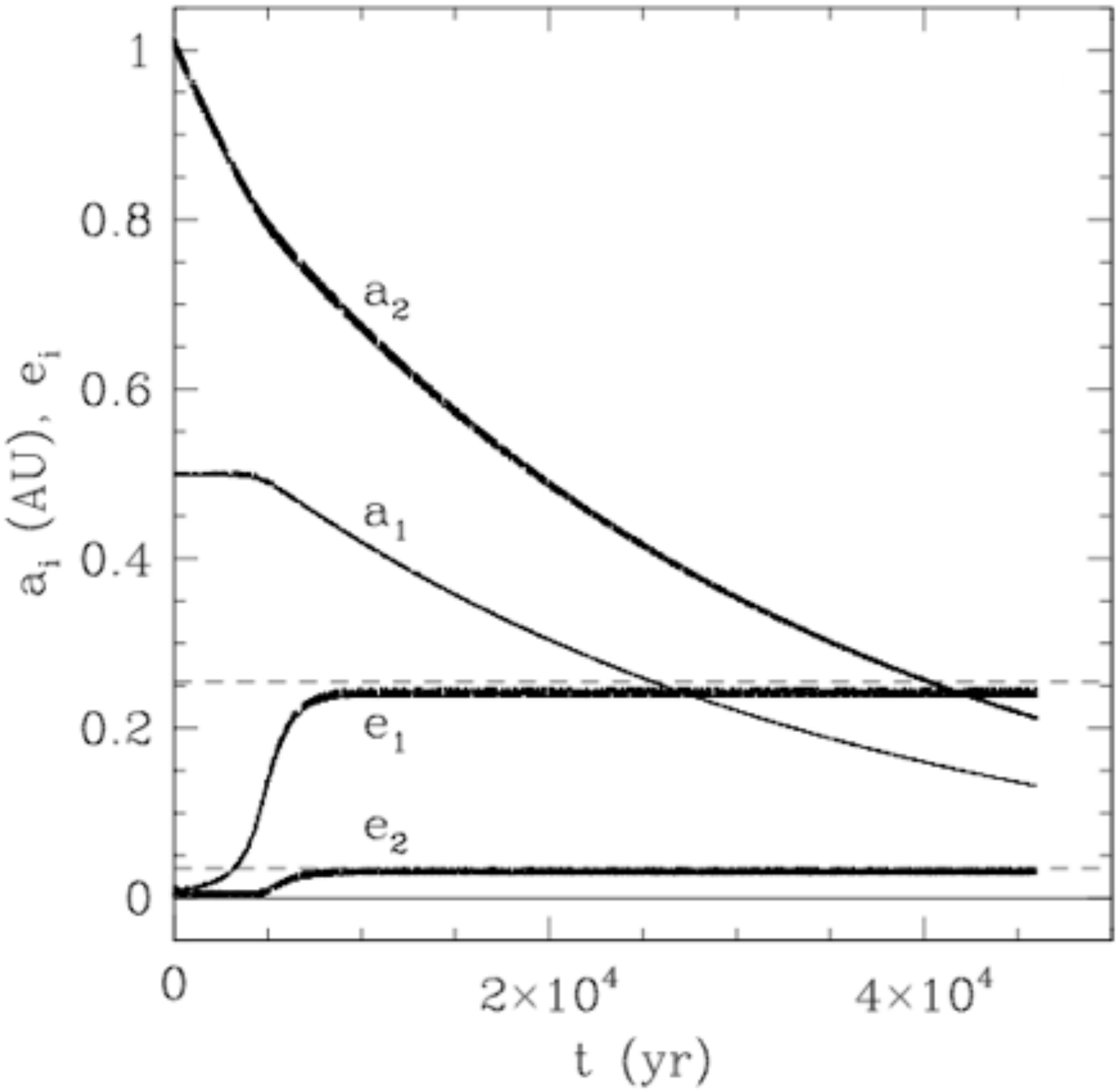
Fast varying angles

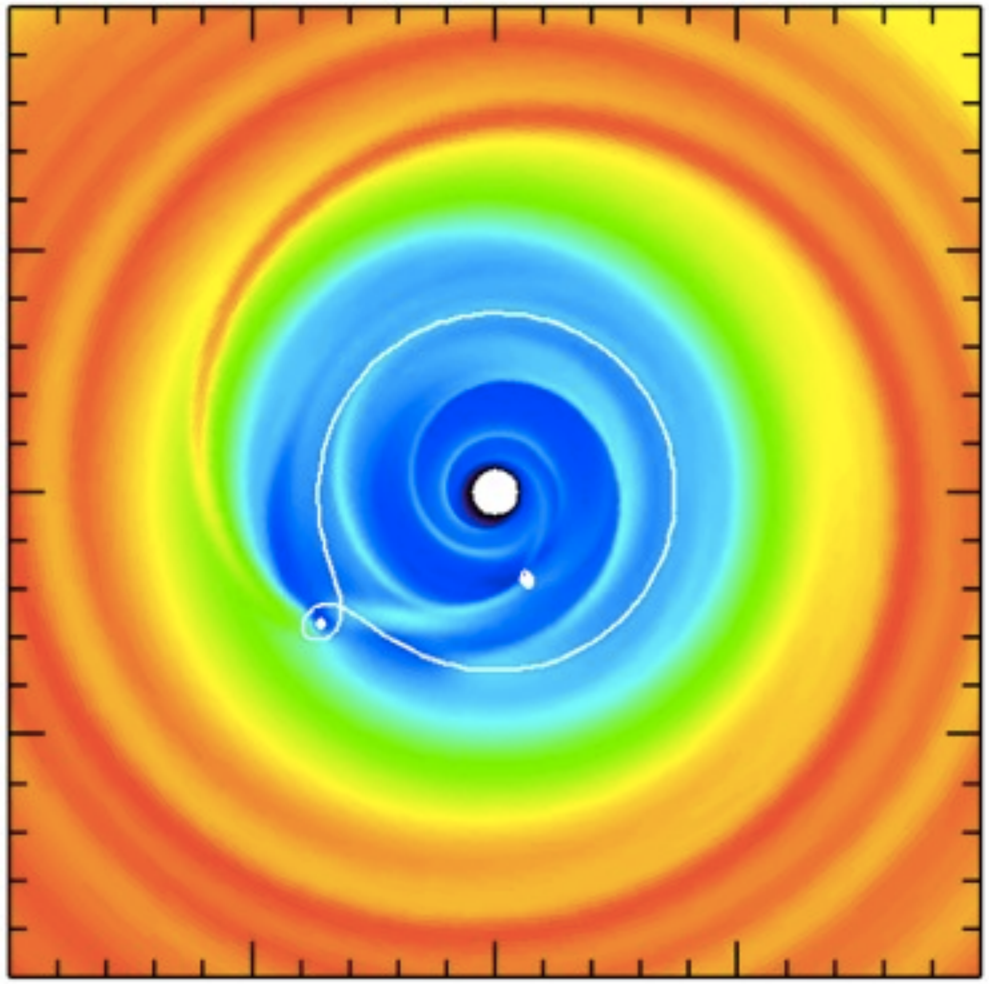
$$\lambda_1 - \varpi_1 \qquad\qquad \lambda_2 - \varpi_2$$

Slowly varying angles

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

Formation of GJ 876





N-body simulations

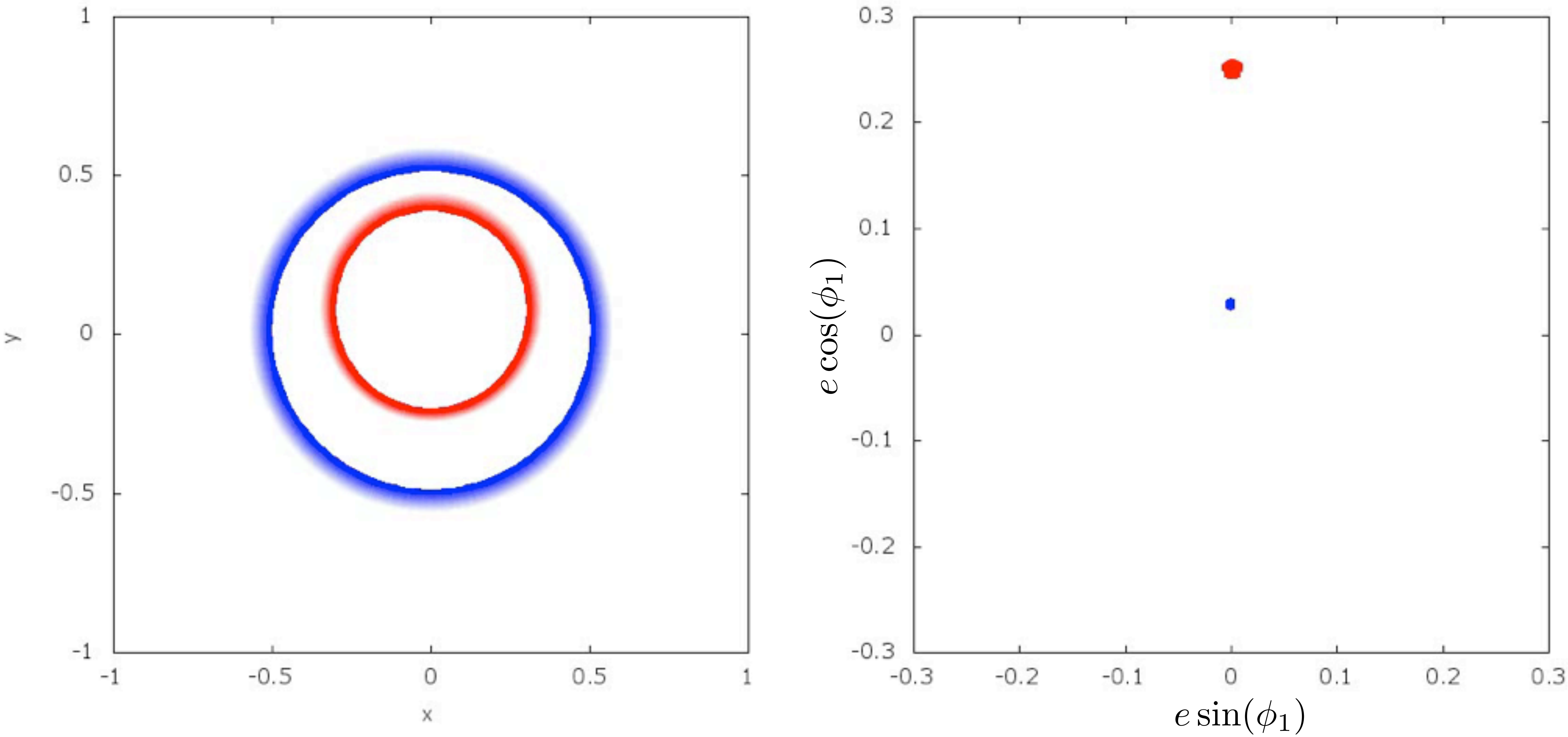
- Correct period ratio
- Correct equilibrium eccentricity
- Correct libration pattern
- Does not depend on details

Hydro simulations

- Consistent with N-body simulations
- More free parameters

Lee & Peale 2002, Kley et al. 2004

Non-turbulent resonance capture: two planets



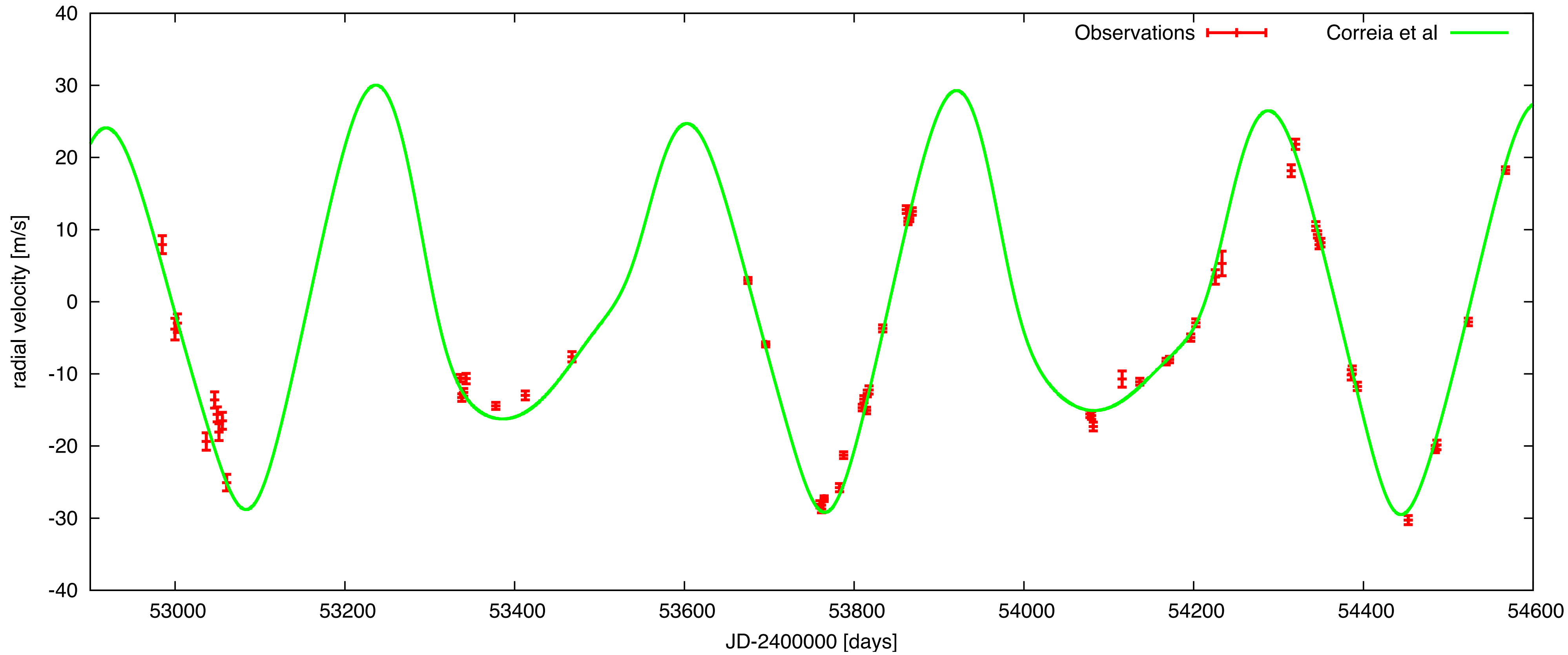
parameters of GJ 876

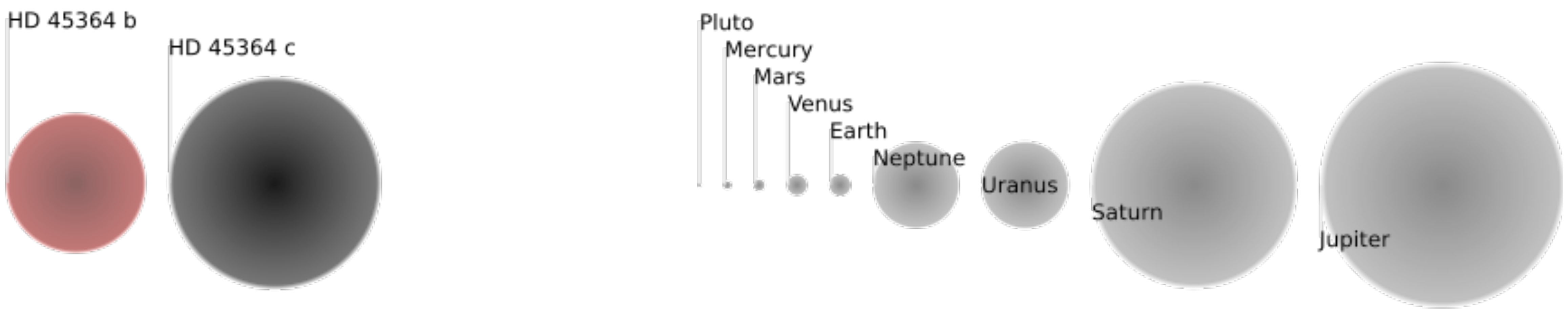
Take home message II

2 planets + migration = resonance

HD 45364

HD45364





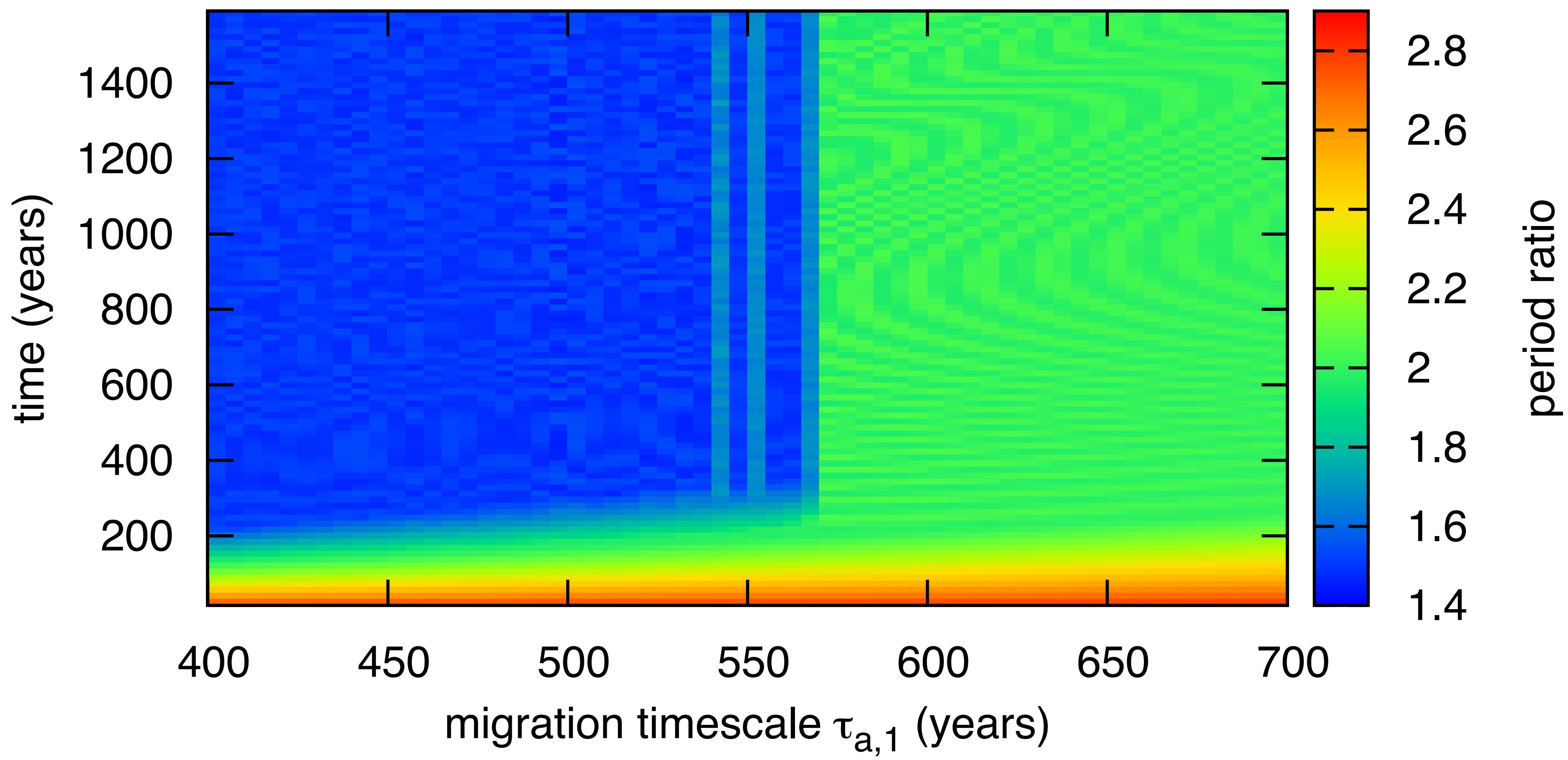
Correia et al 2009, Visual Exoplanet Catalogue

Formation scenario for HD45364

- Two migrating planets
- Infinite number of resonances

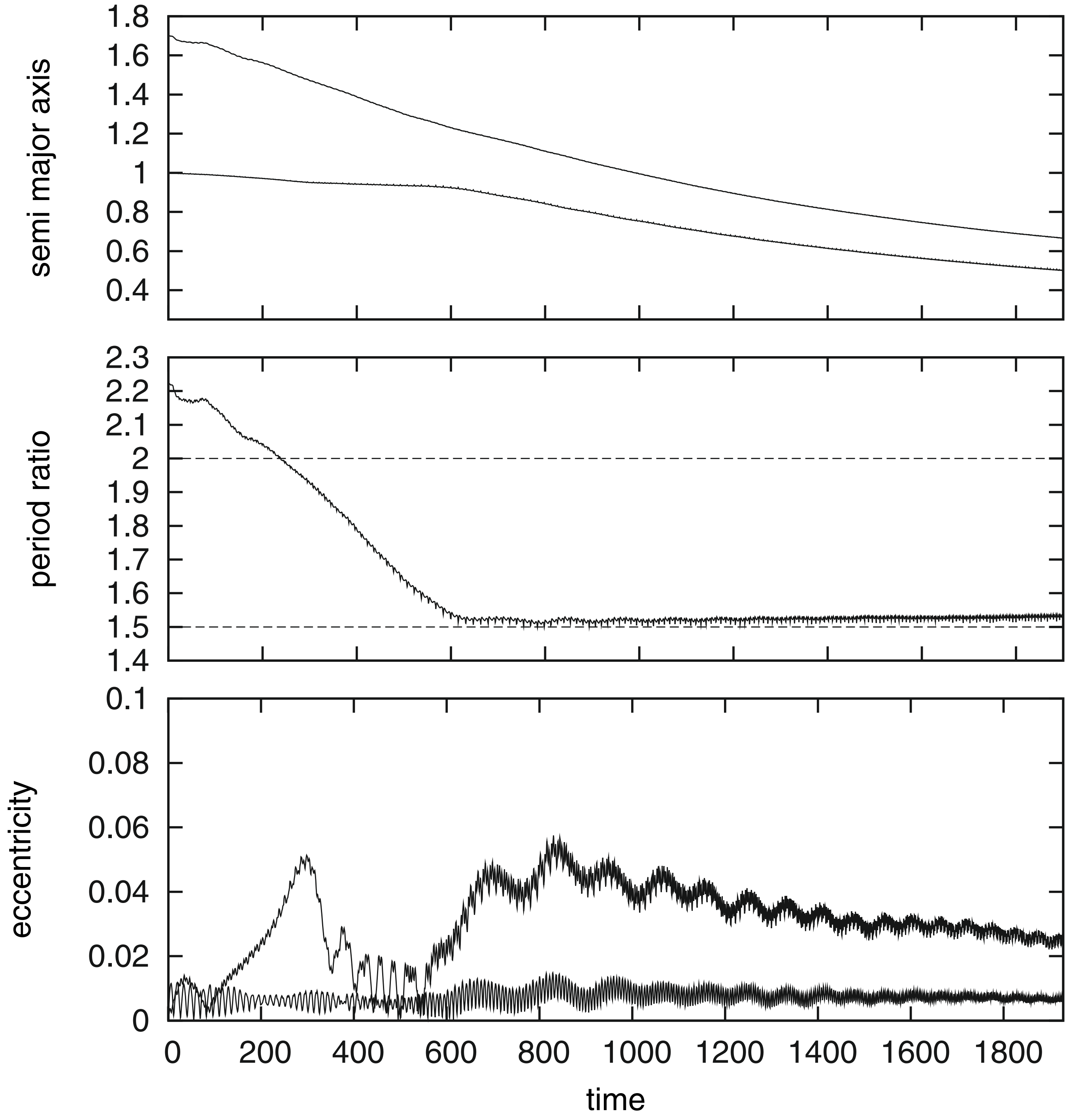
1:2 7:8 3:2 1:3 3:4

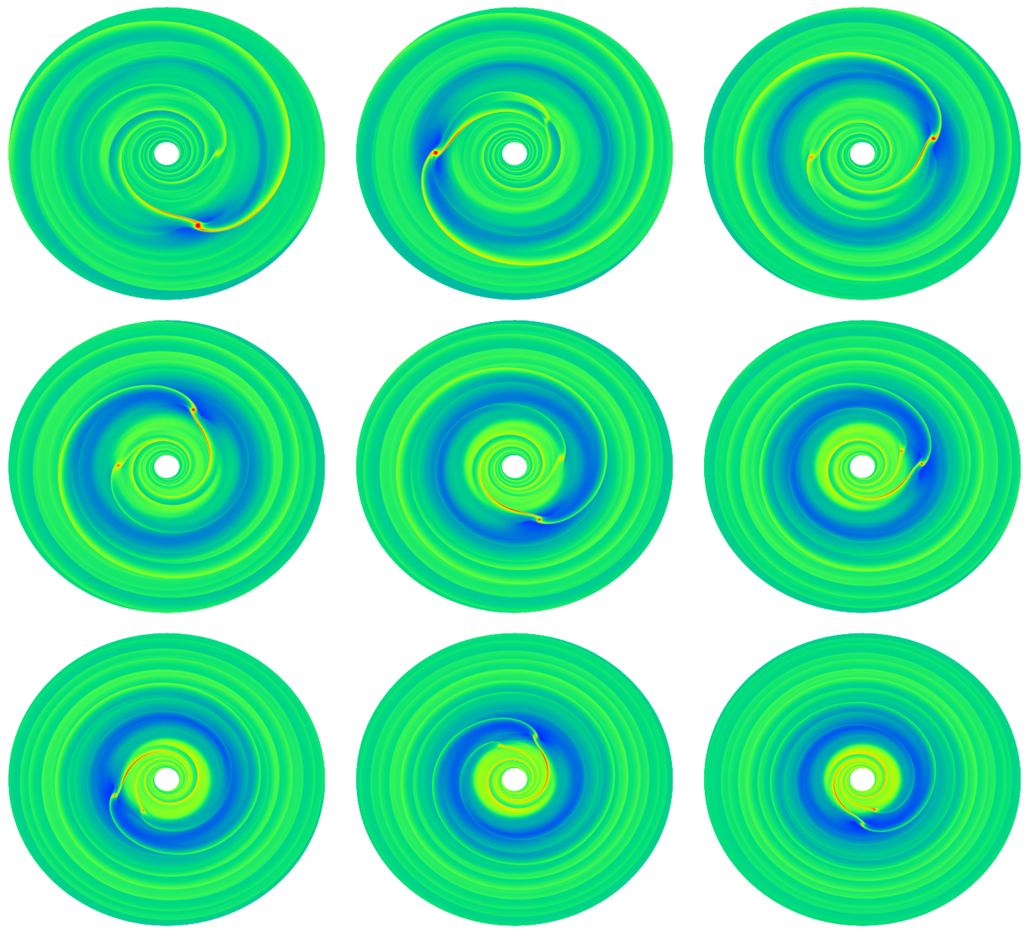
- Migration speed is crucial
- Resonance width and libration period define critical migration rate



Rein, Papaloizou & Kley 2010

Formation scenario for HD45364





Rein, Papaloizou & Kley 2010

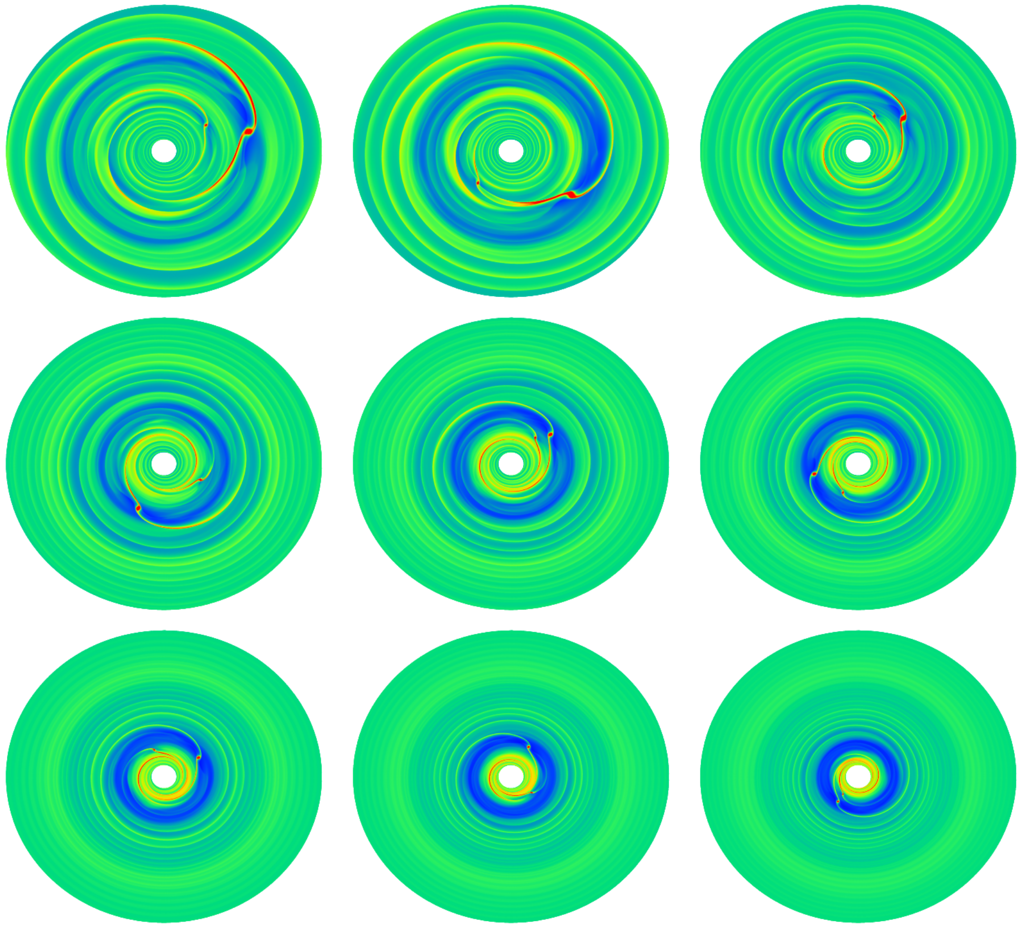
Formation scenario for HD45364

Massive disc (5 times MMSN)

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

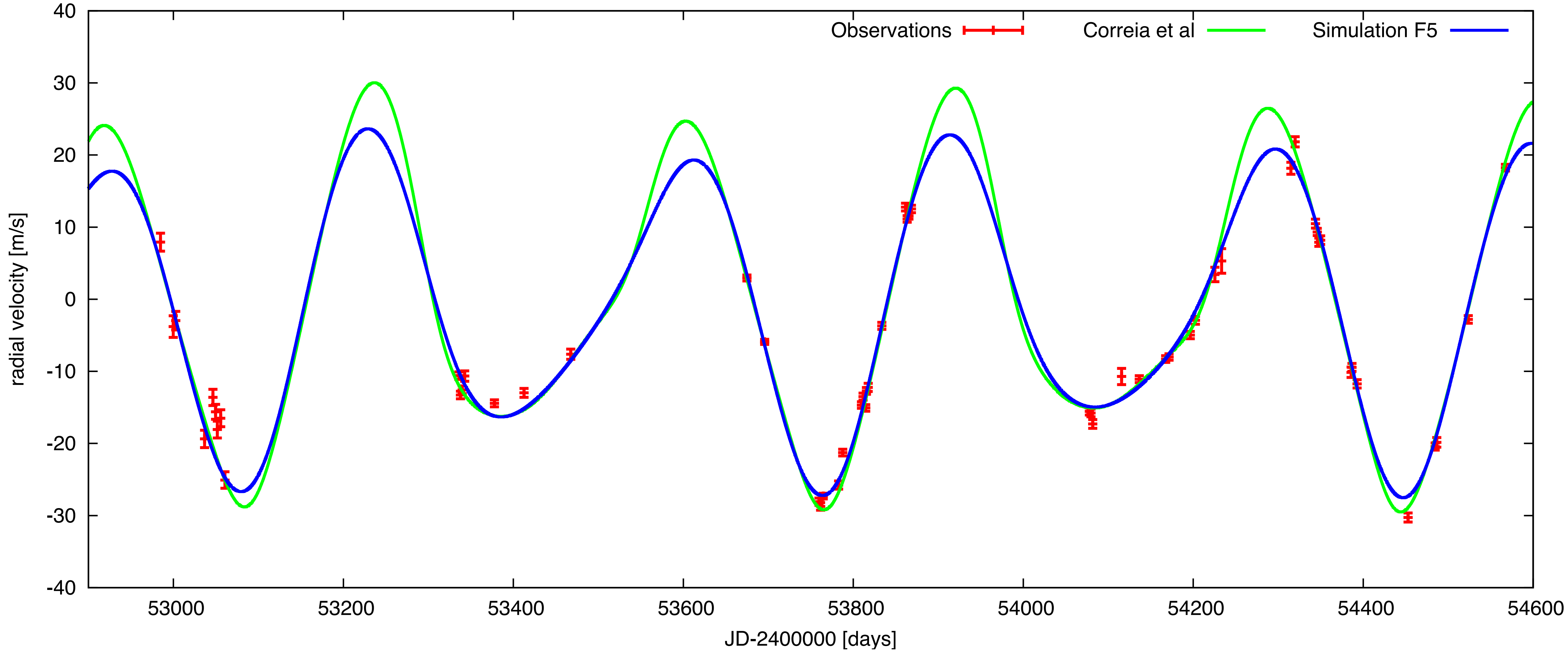
Large scale-height (0.07)

- 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'



		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

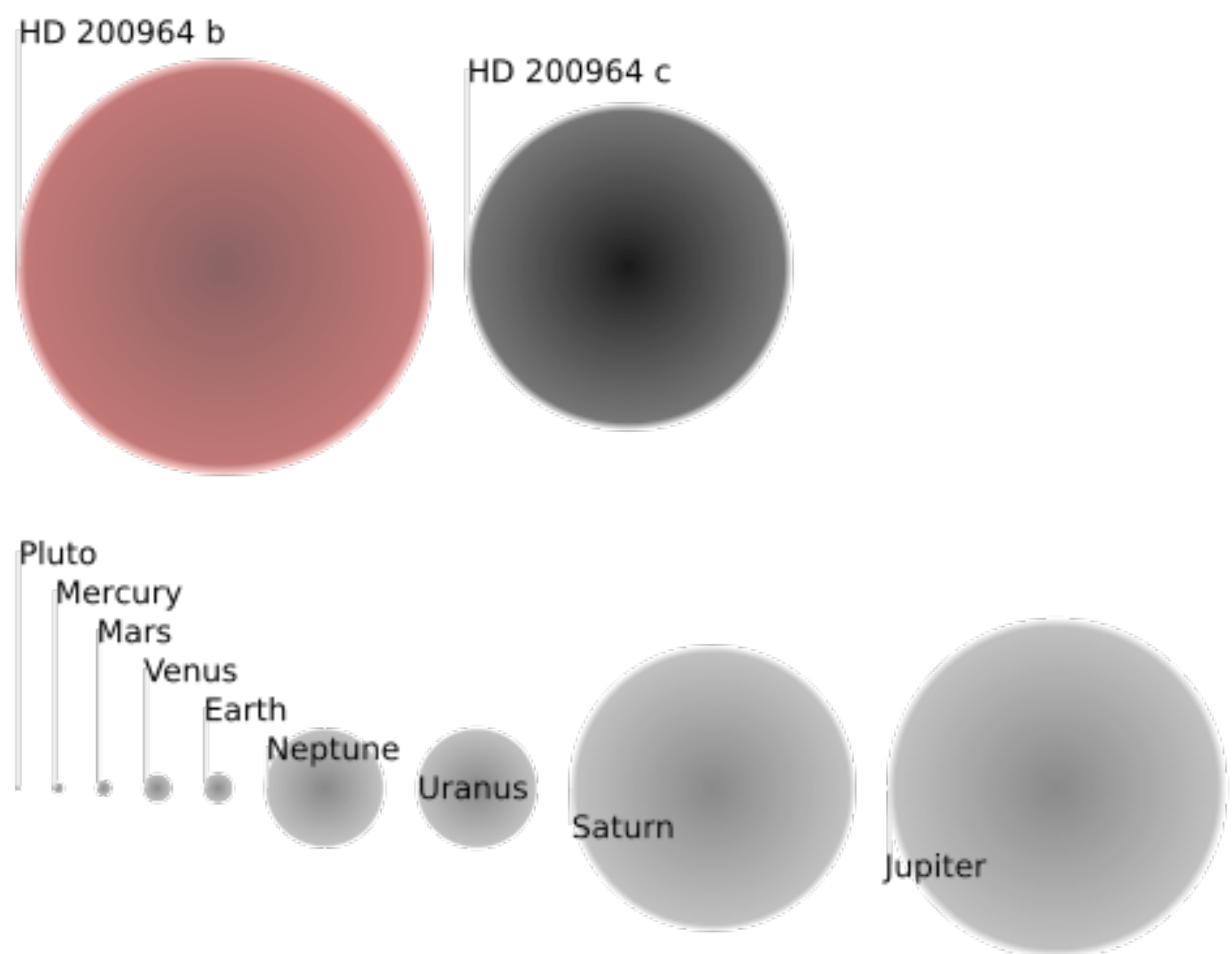
Take home message III

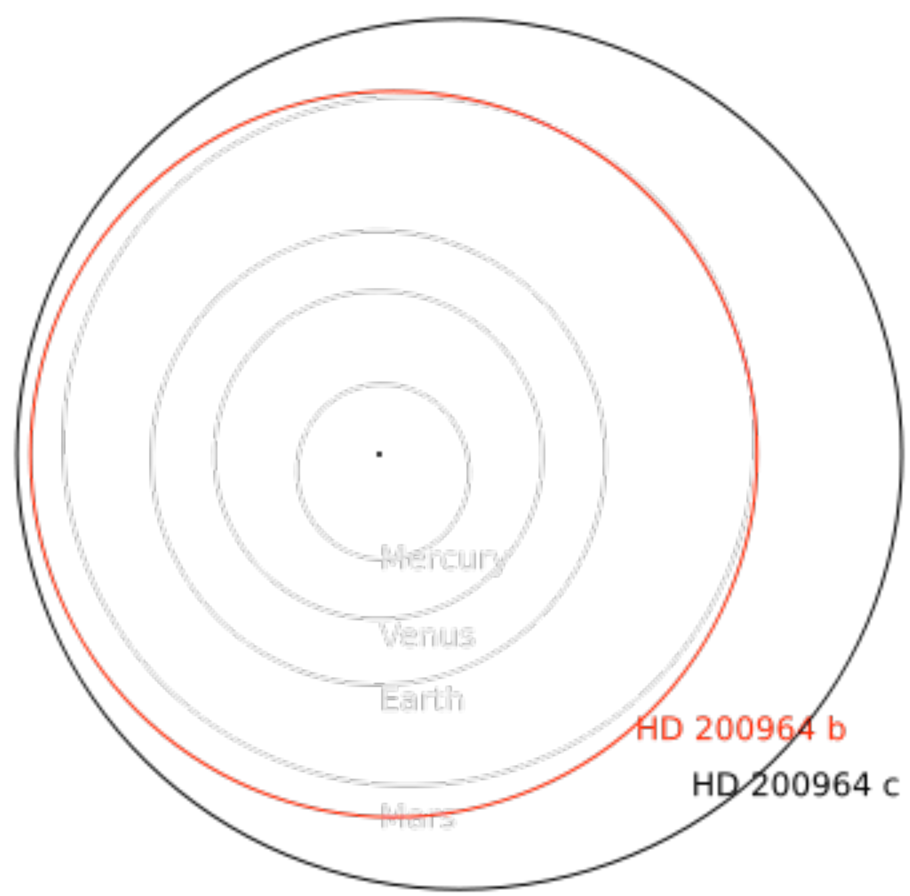
Resonant systems tell us something about the (currently) unobservable formation phase.

HD200964
The impossible system?

Radial velocity curve of HD200964

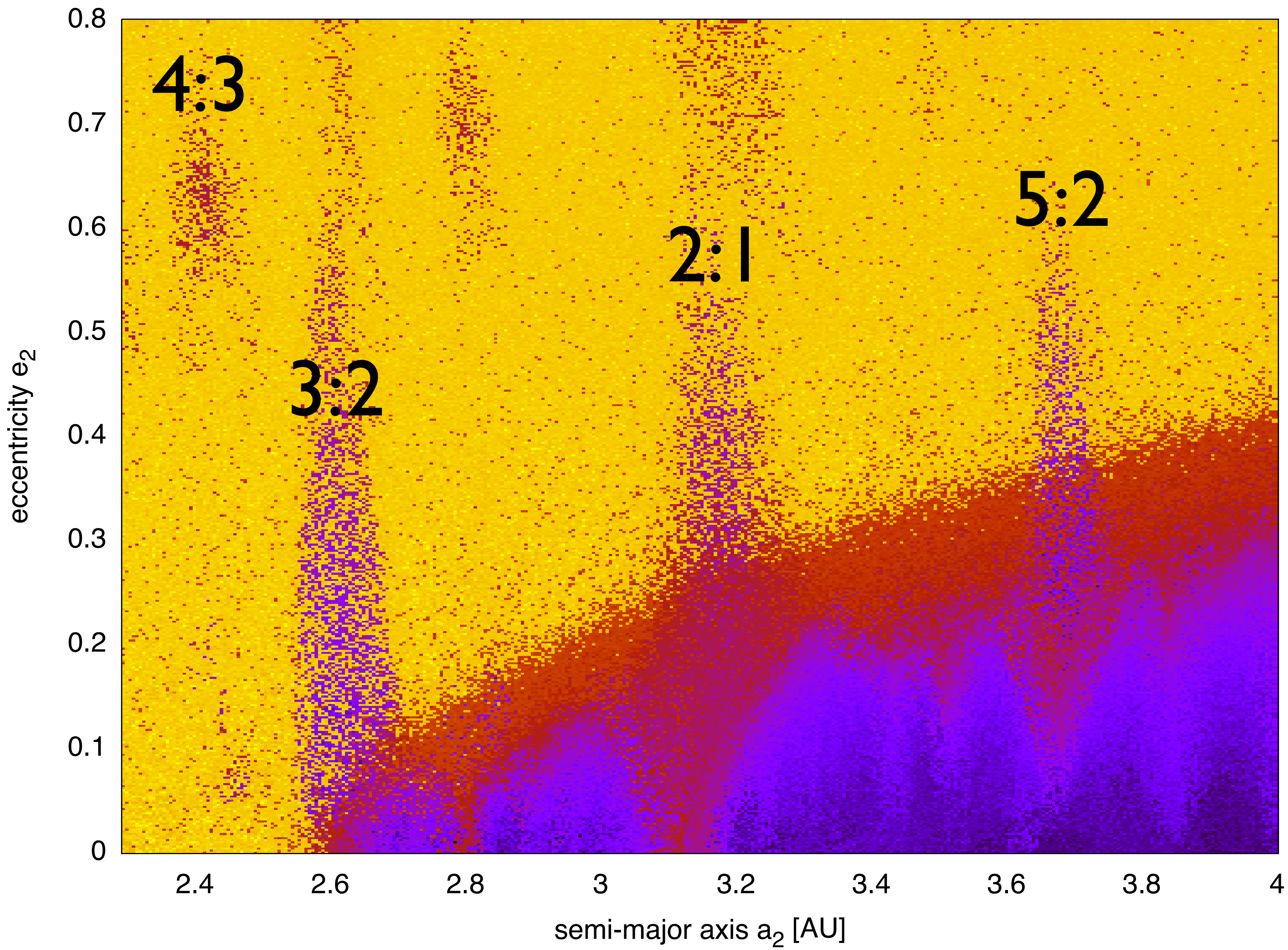
- Two massive planets 1.8 M_{Jup} and 0.9 M_{Jup}
- Period ratio close to 4:3
- Another similar system, to be announced soon.





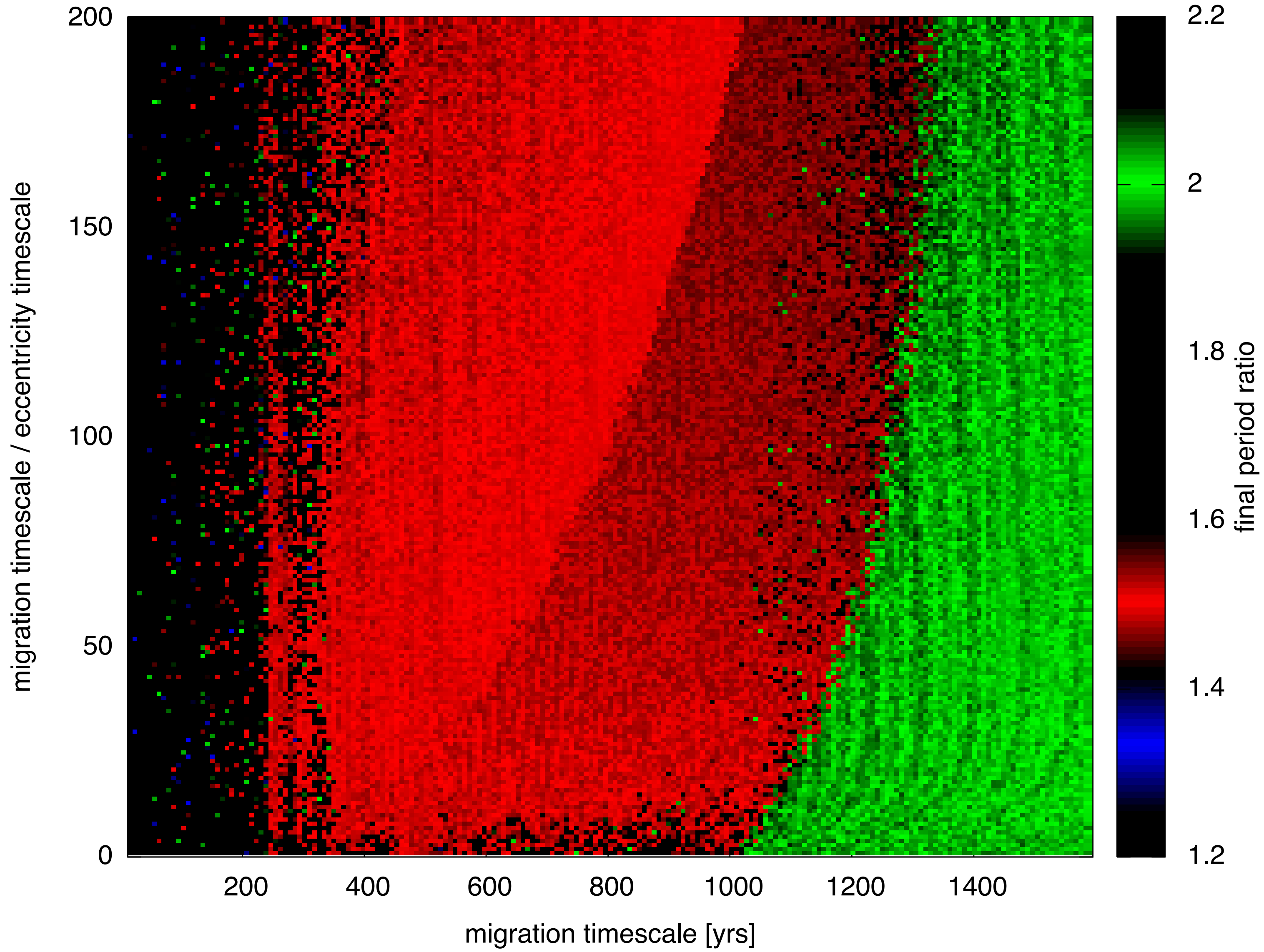
Plot by Matthew Payne

Stability of HD200964



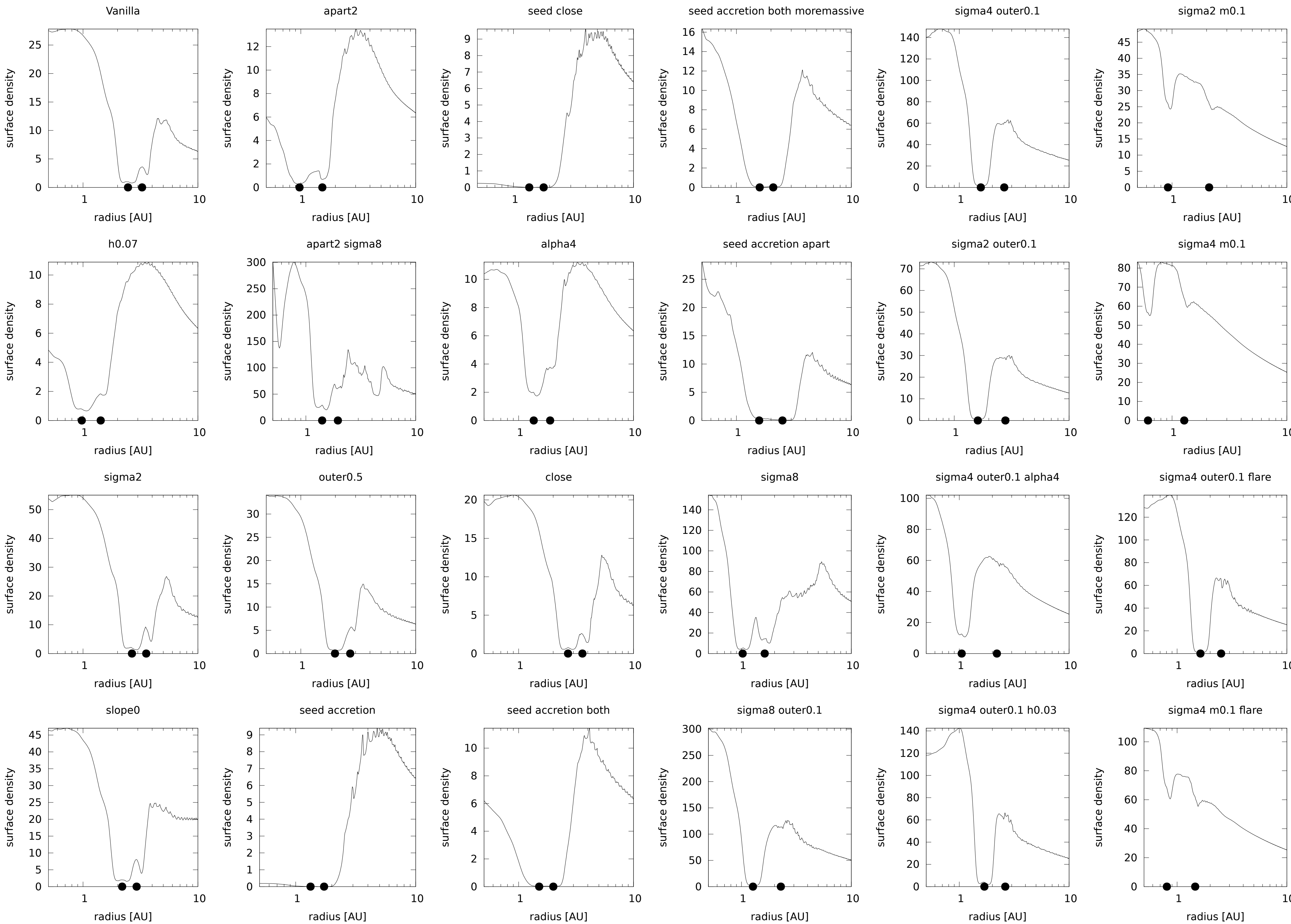
Rein, Payne, Veras & Ford (in press)

Standard disc migration doesn't work



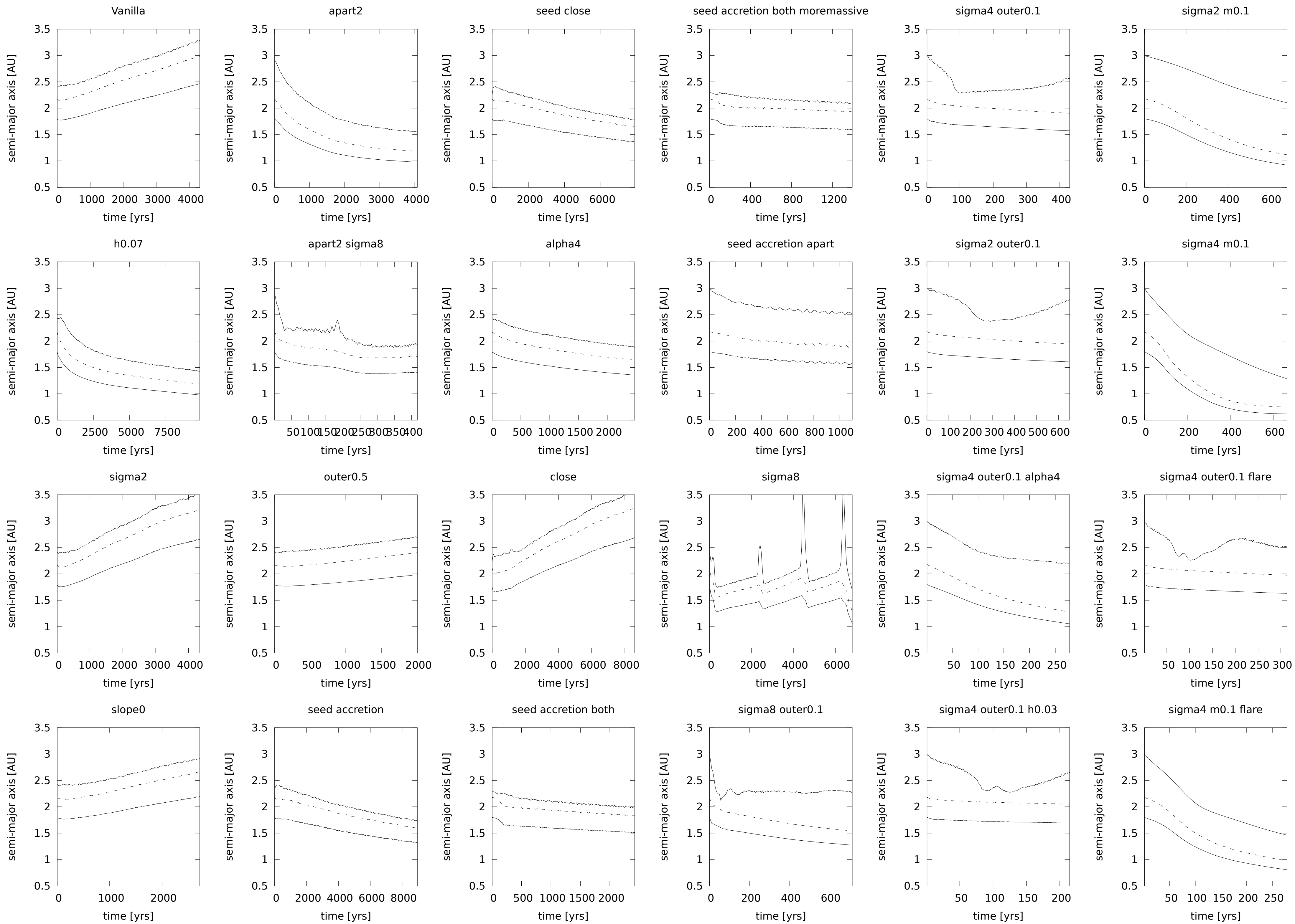
- N-body simulations
- Smooth migration scenario with variable damping rates
- Not a single simulation ends up in 4:3 resonance
- 2:1 and 3:2 resonances are possible

Hydrodynamical simulations



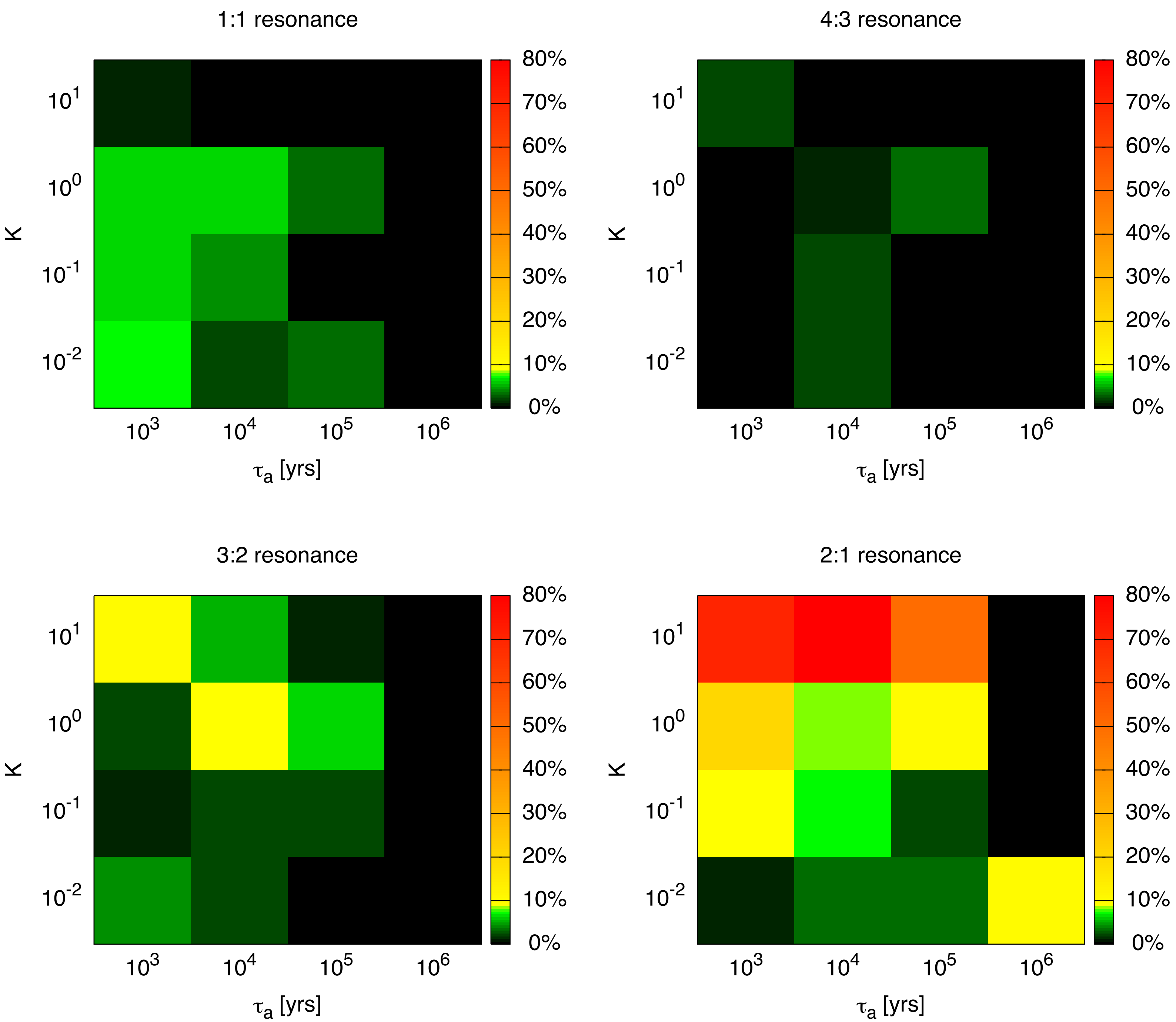
Rein, Payne, Veras & Ford (in press)

Hydrodynamical simulations II



Rein, Payne, Veras & Ford (in press)

Scattering of embryos



- Fine tuned initial conditions
- Small number of systems in 4:3 resonance form
- More systems end up in 1:1 resonances

Rein, Payne, Veras & Ford (in press)

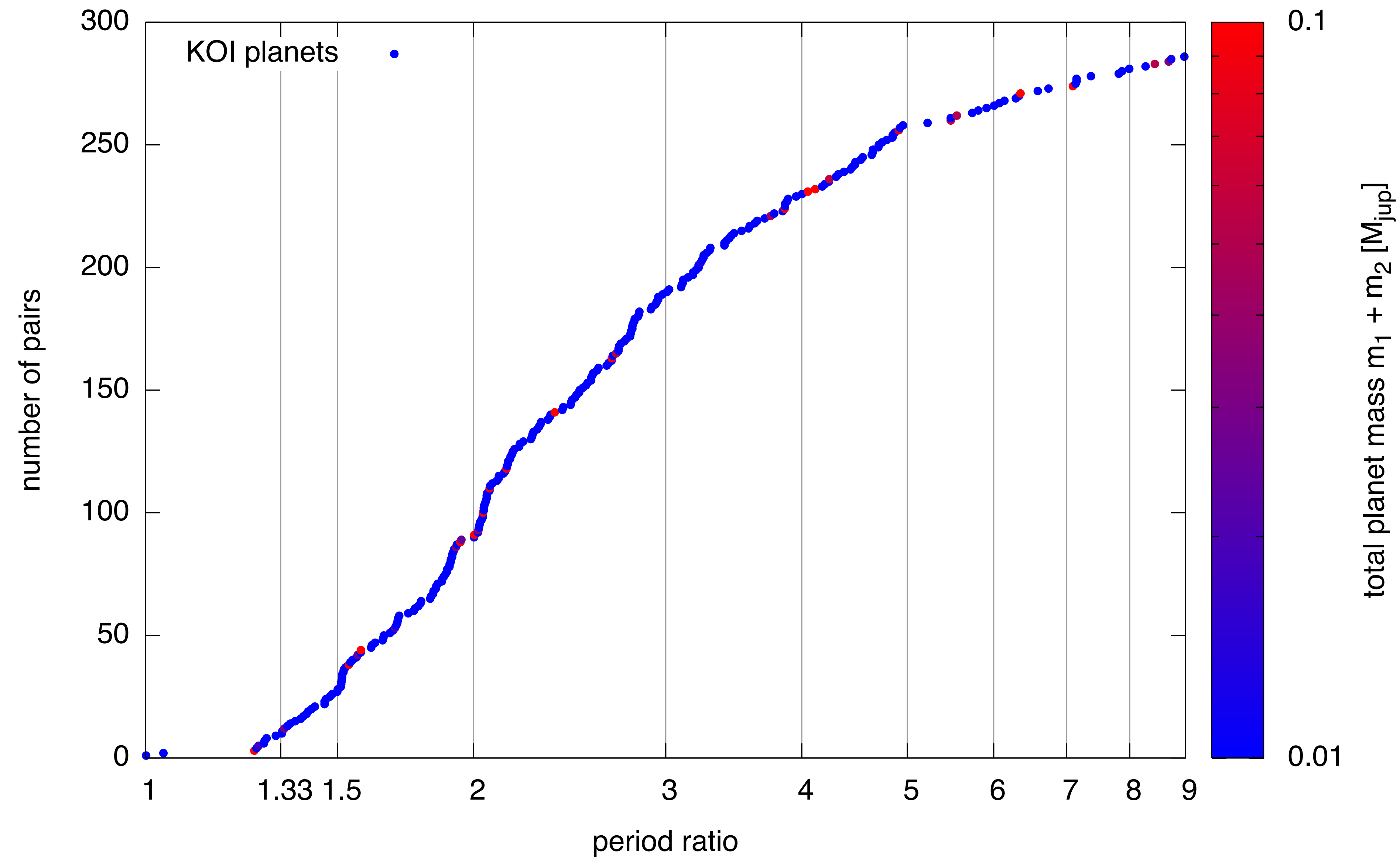
Take home message IV

We don't understand everything*.

*just yet

Migration in a turbulent disc

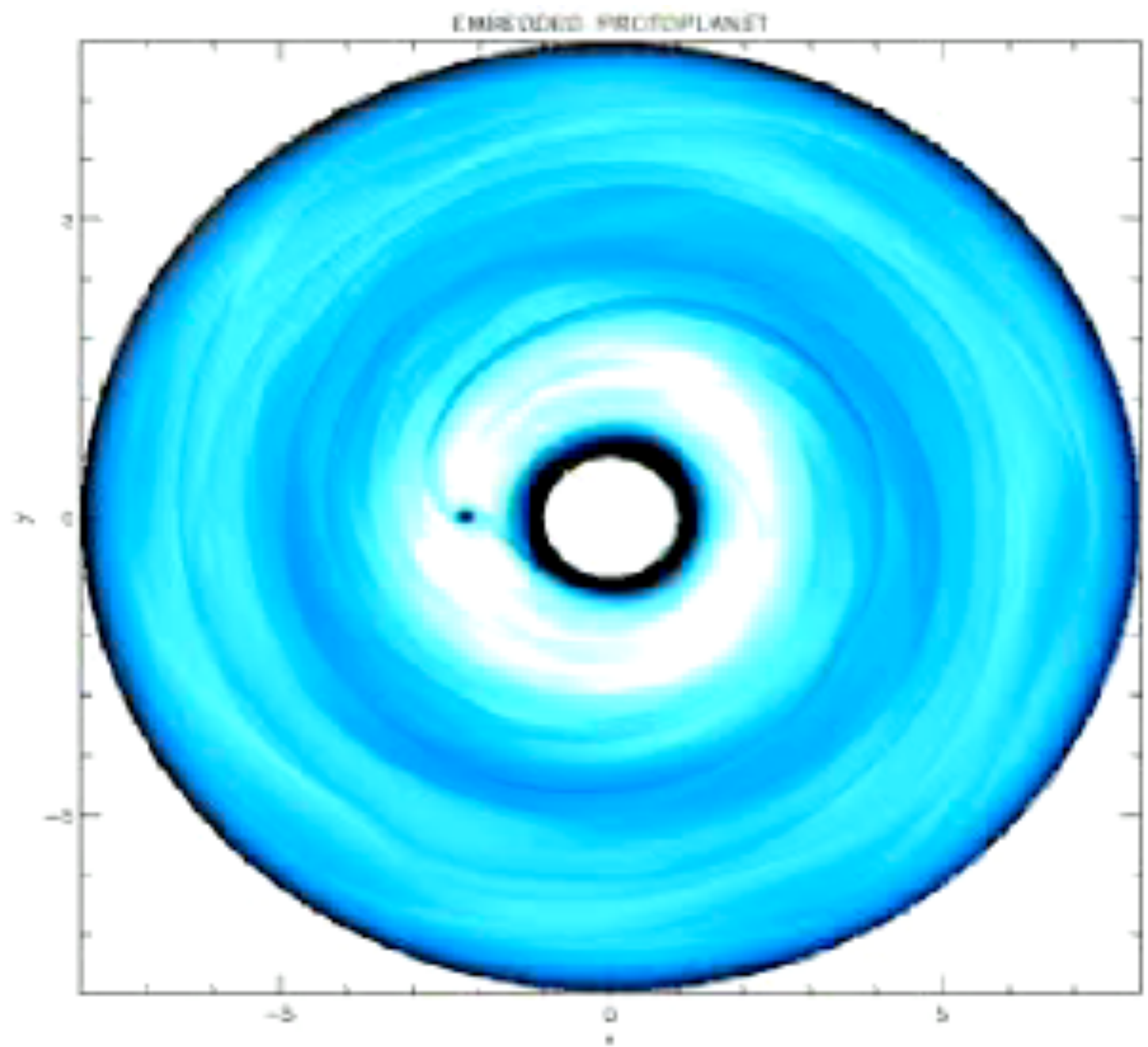
Kepler's transiting planet candidates



Rein, Payne, Veras & Ford (in press)

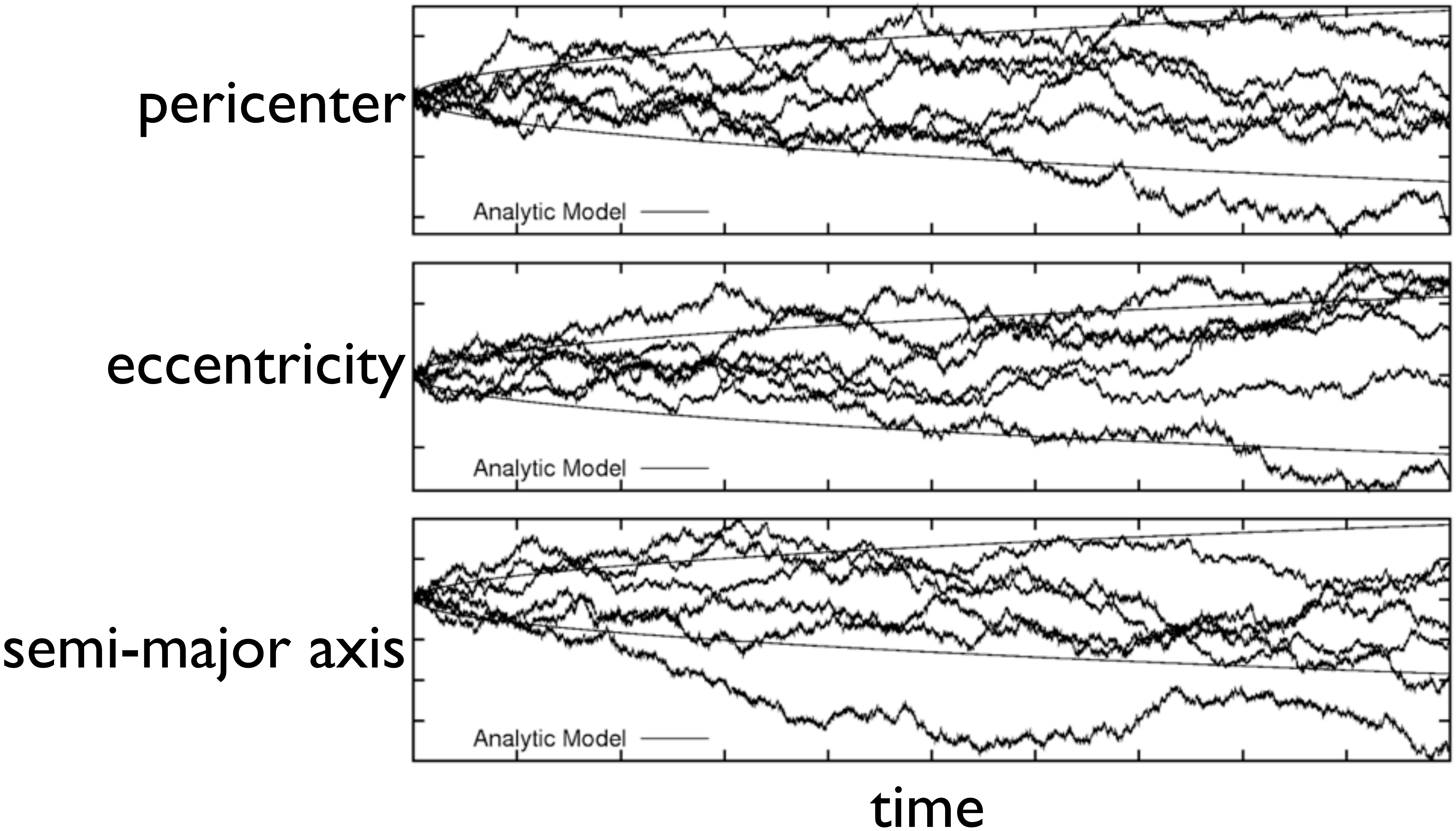
Turbulent disc

- 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

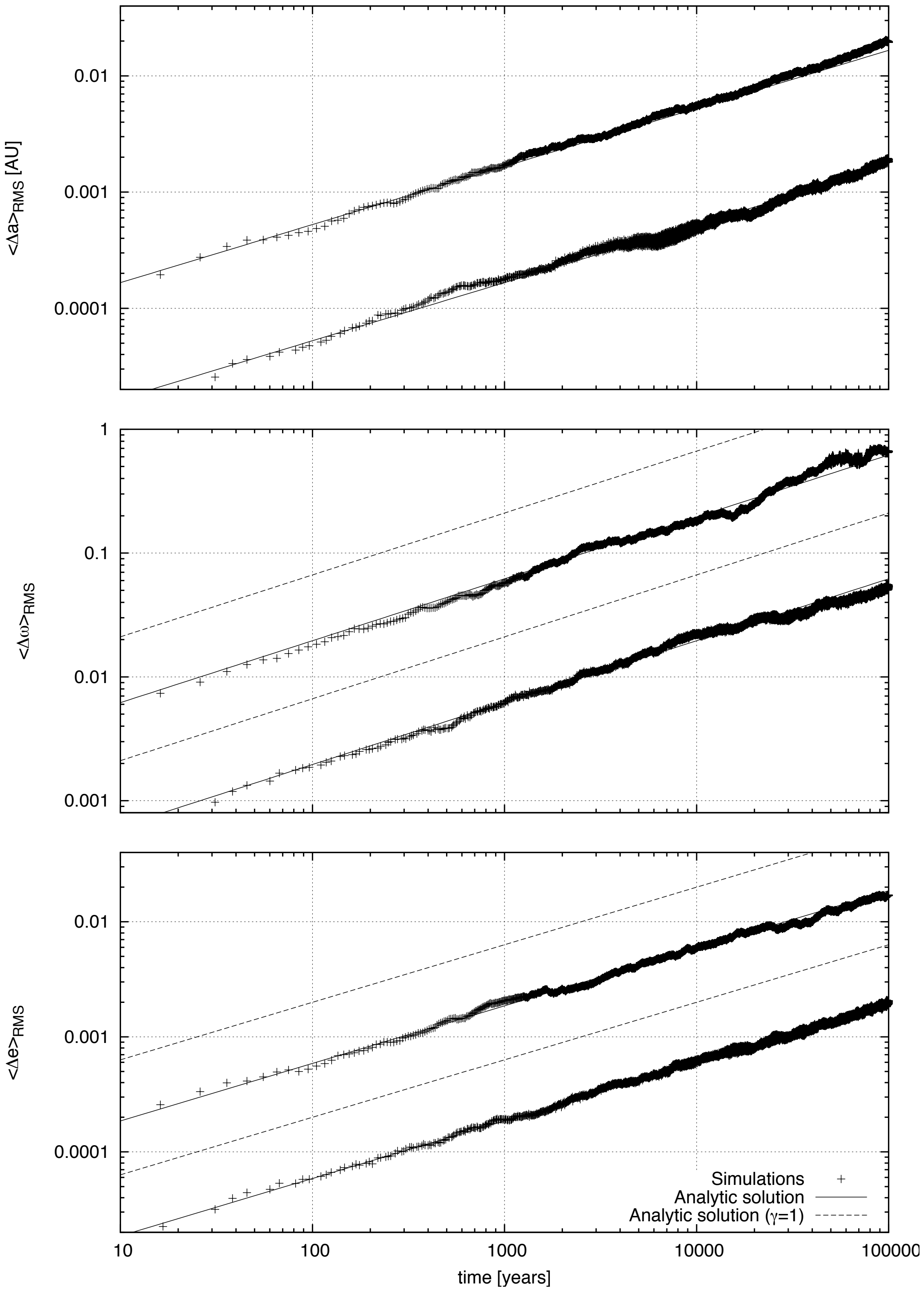

pericenter
Analytic Model
eccentricity
Analytic Model
semi-major axis
Analytic Model
time

Analytic growth rates for 1 planet

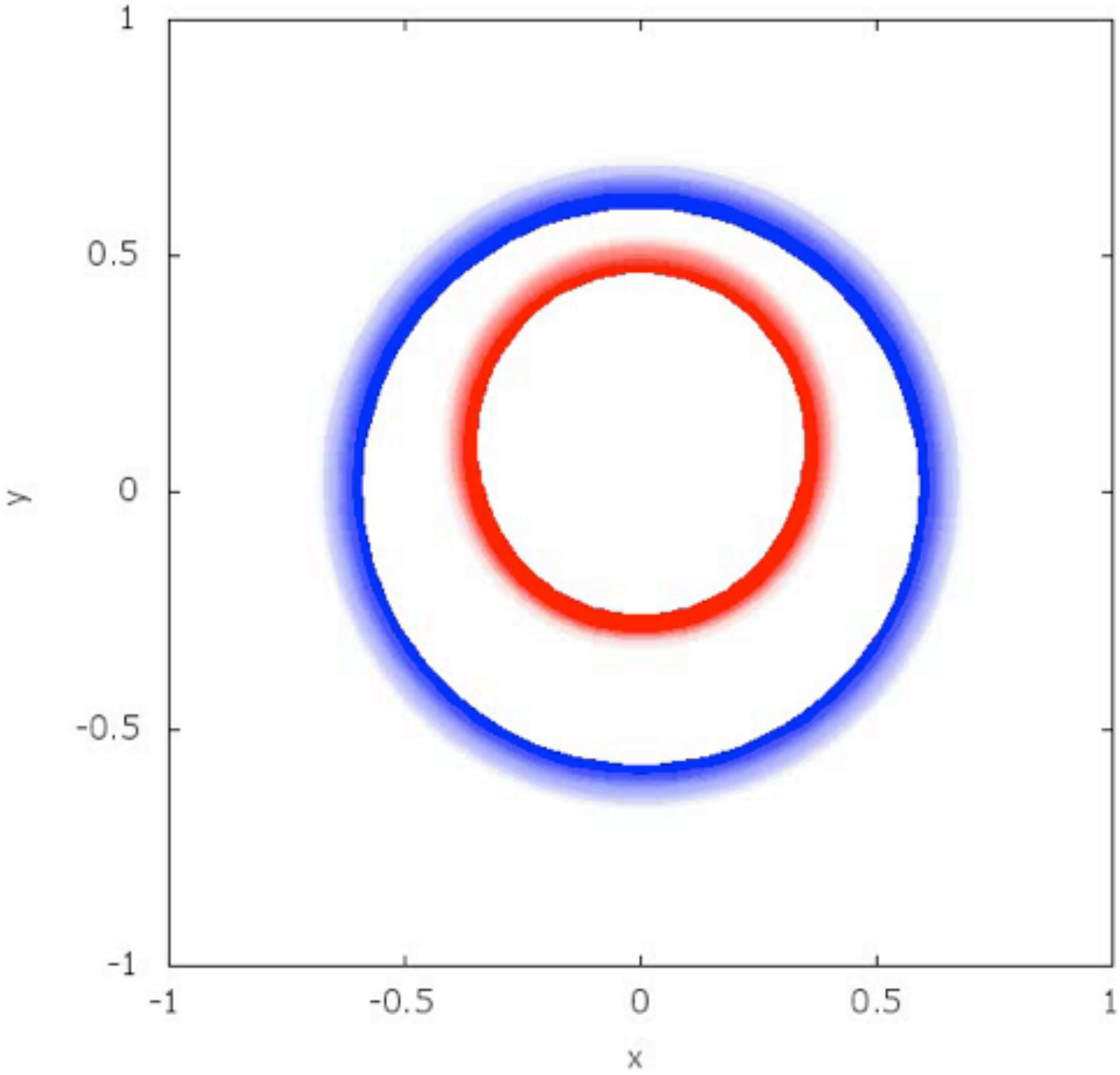
$$(\Delta a)^2 = 4\frac{Dt}{n^2}$$

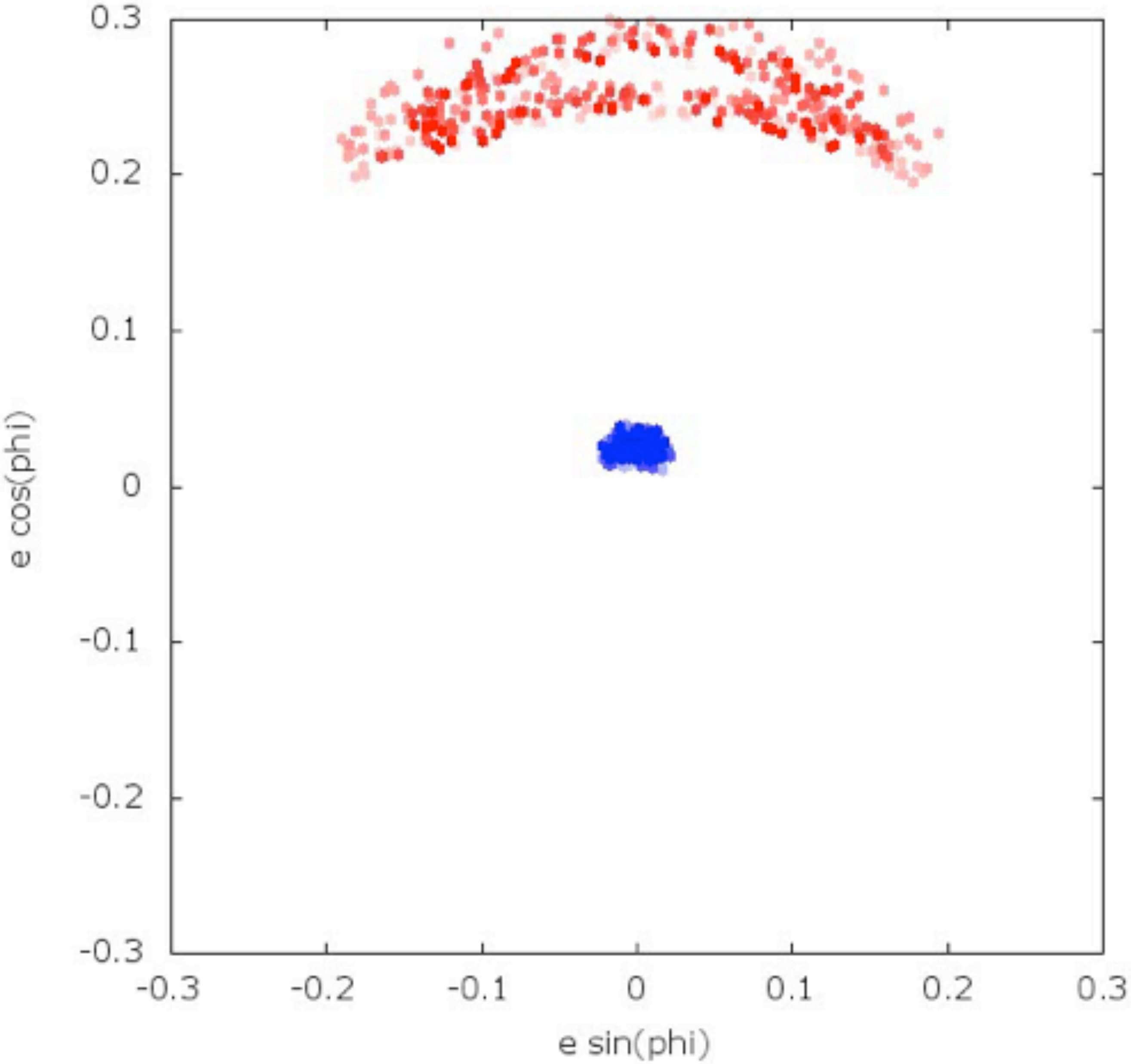
$$(\Delta \varpi)^2 = \frac{2.5}{e^2}\frac{\gamma D t}{n^2 a^2}$$

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



Two planets: turbulent resonance capture

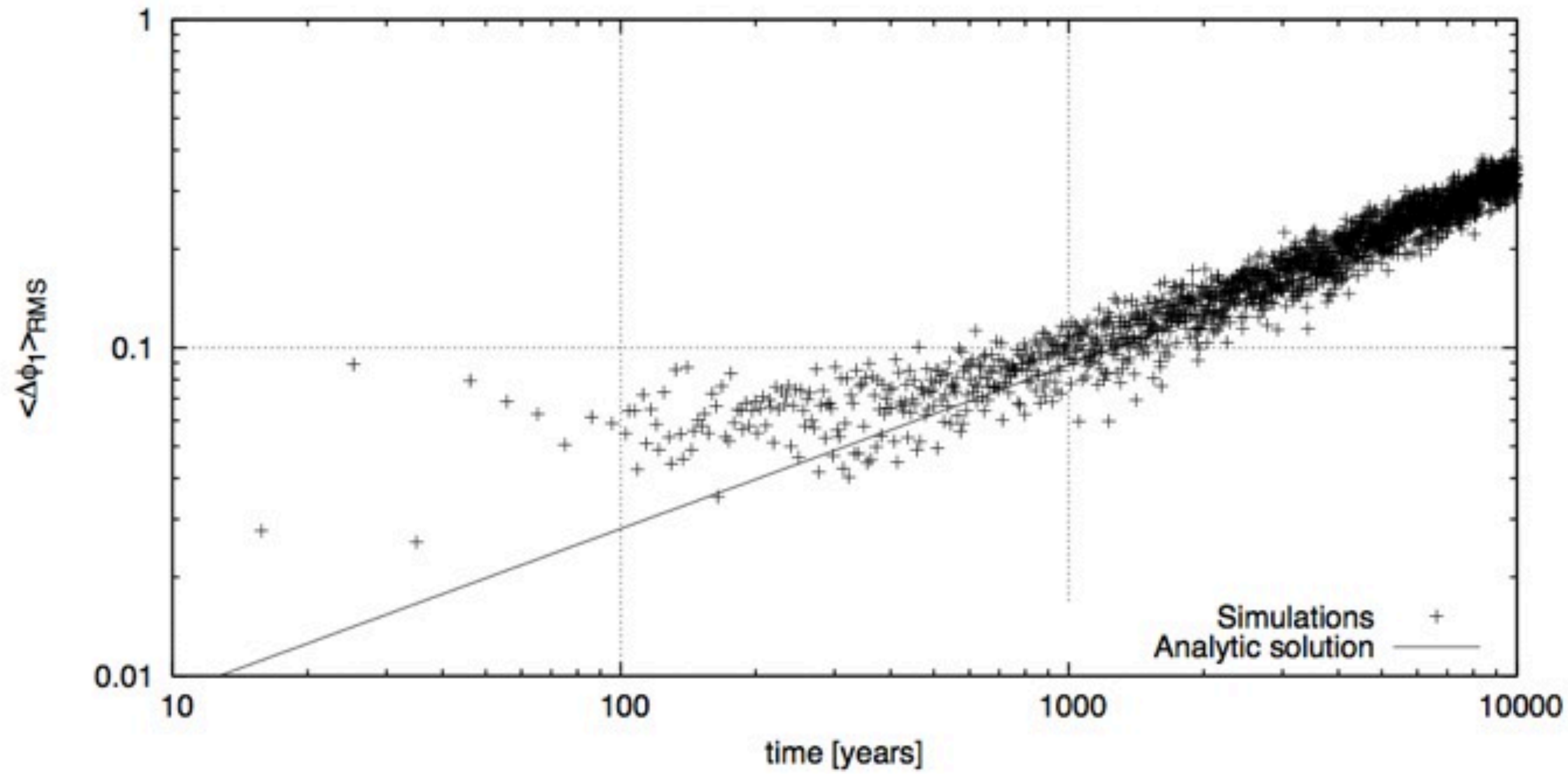




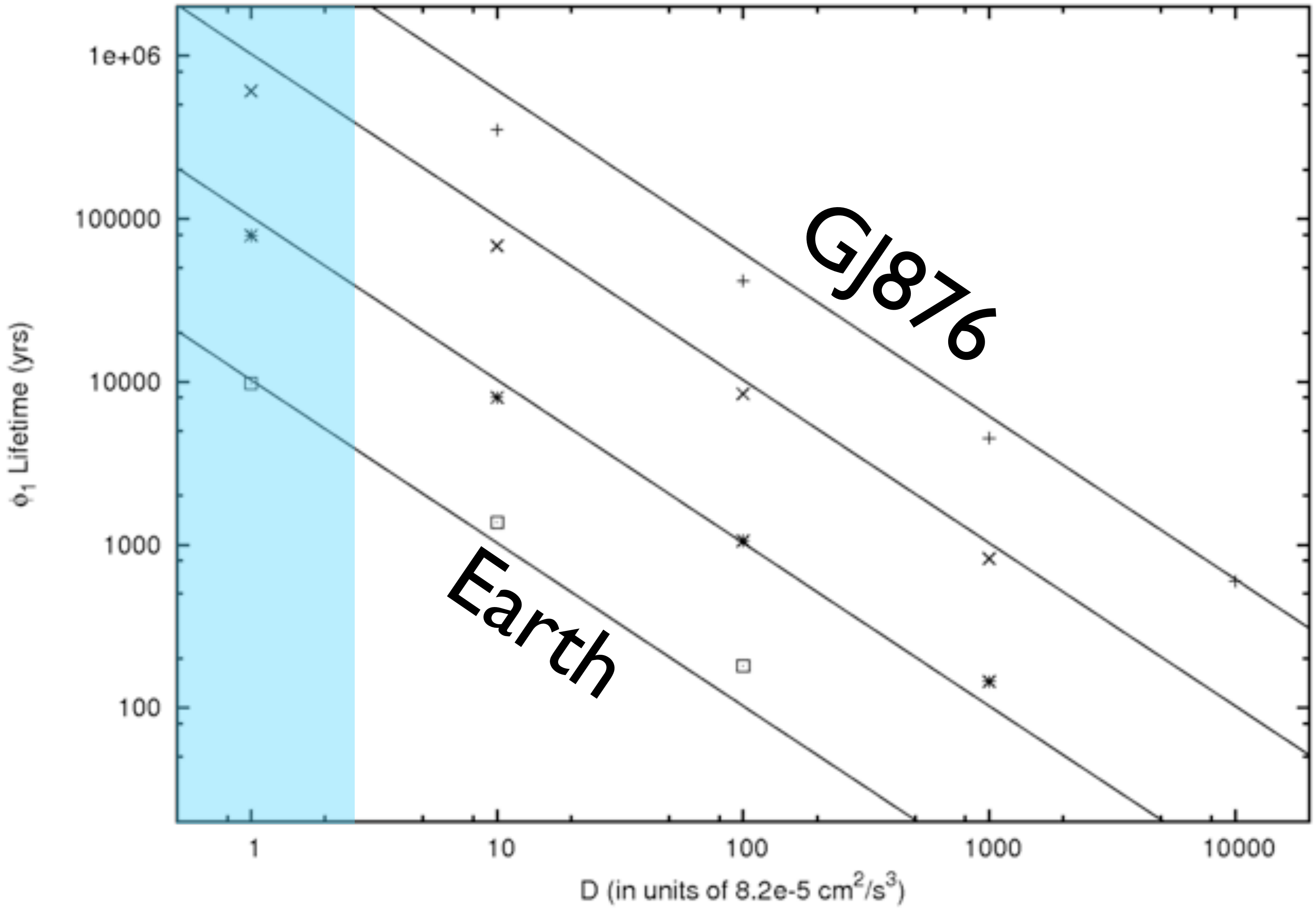
Analytic growth rates for 2 planets

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

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



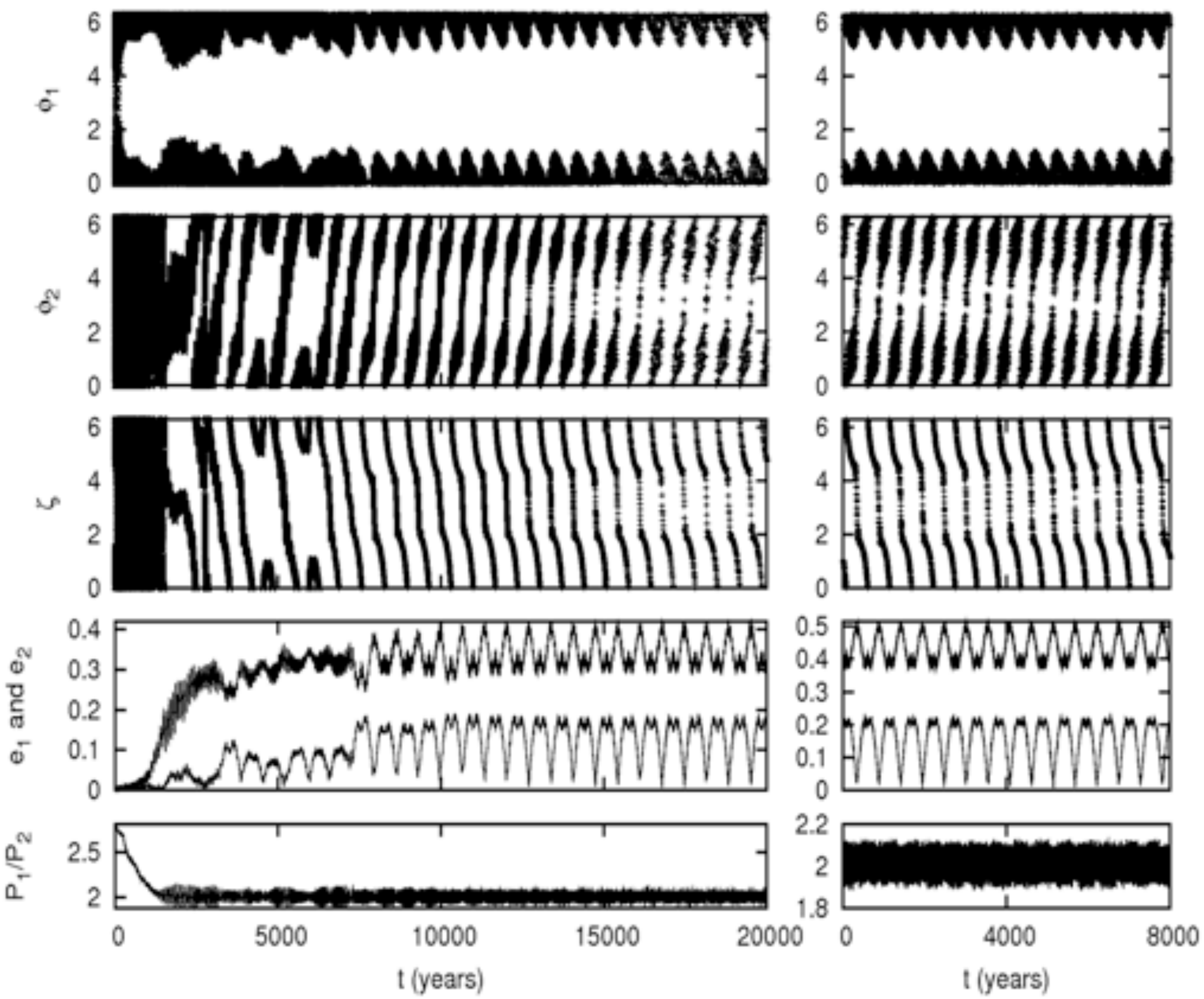
Multi-planetary systems in mean motion resonance



- 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

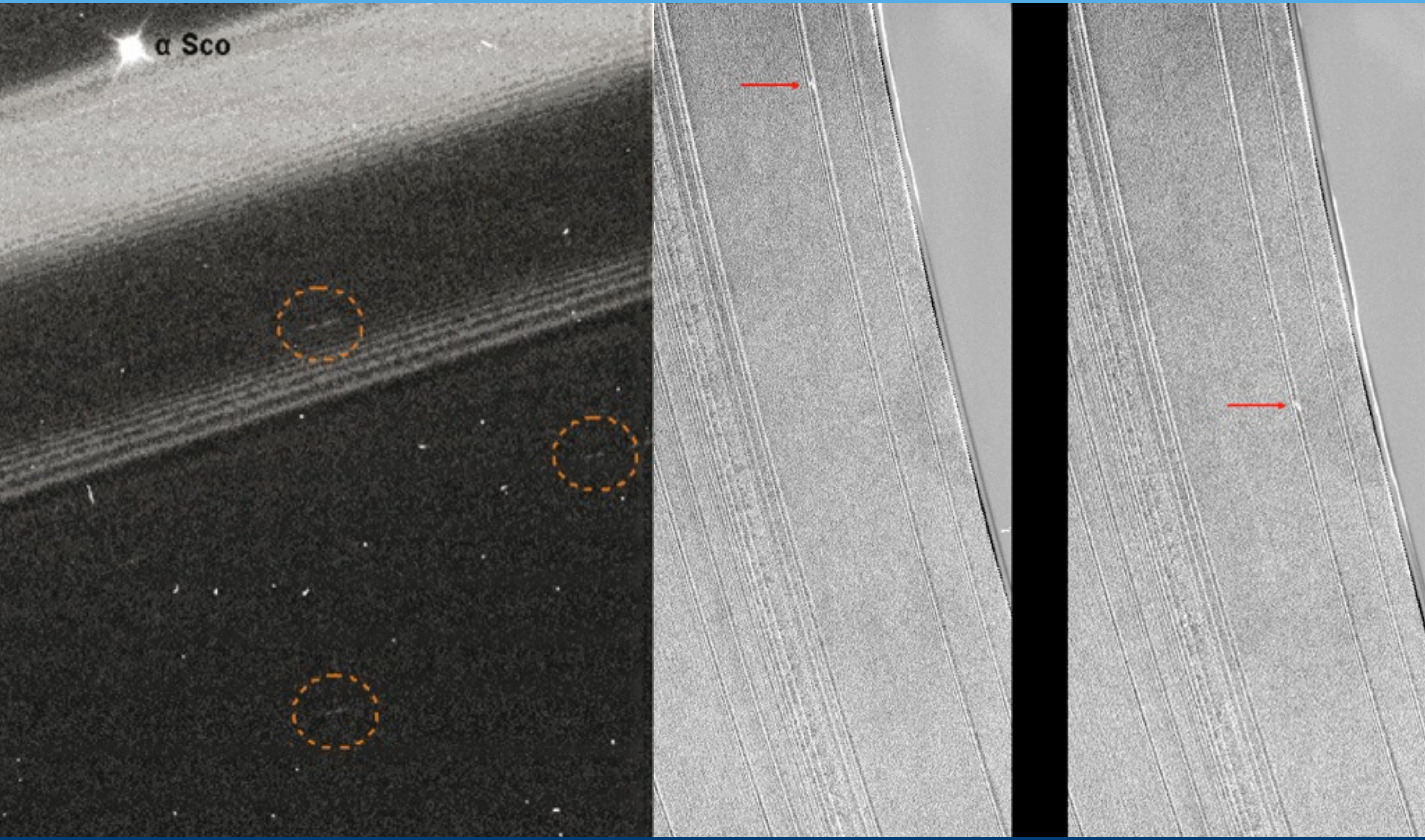


Rein & Papaloizou 2009

Take home message V

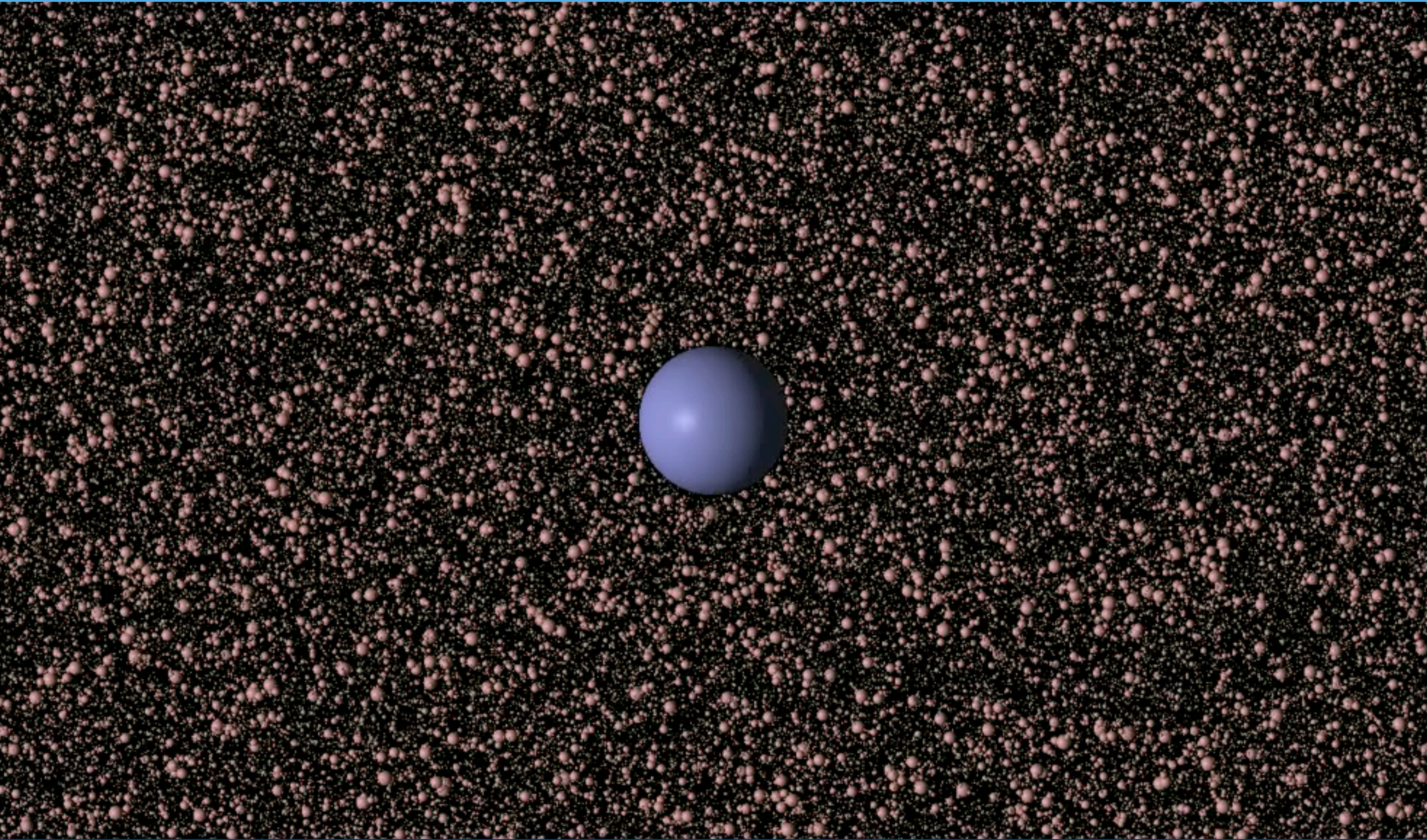
Small mass planets might show signs of stochastic migration.

Propeller structures in A-ring



Porco et al. 2007, Sremcevic et al. 2007, Tiscareno et al. 2006, NASA/JPL-Caltech/Space Science Institute

Random walk



REBOUND code, Rein & Papaloizou 2010, Crida et al 2010

Conclusions

Conclusions

Formation of multi-planetary systems

The number of multi-planetary systems increases almost every week.

Kepler discovered a large number of planets but most are not suitable for a detailed individual analysis.

Multi-planetary system provide insight in otherwise unobservable formation phase.
We already understand many details of the migration history of exoplanets.

GJ876	formed in the presence of a disc with dissipative forces
HD45364	formed in a massive disc
HD128311	formed in a turbulent disc
HD200964	did not form at all
Kepler planets	formed in a disk, pushed out of resonance by a variety of mechanisms

.... not the end of the story ....