Institute for Advanced Study

1. Multi-planetary systems
2. Saturn's Rings
3. The collisional N-body code REBOUND

Hanno Rein @ NASA Goddard, January 2012

Planet formation

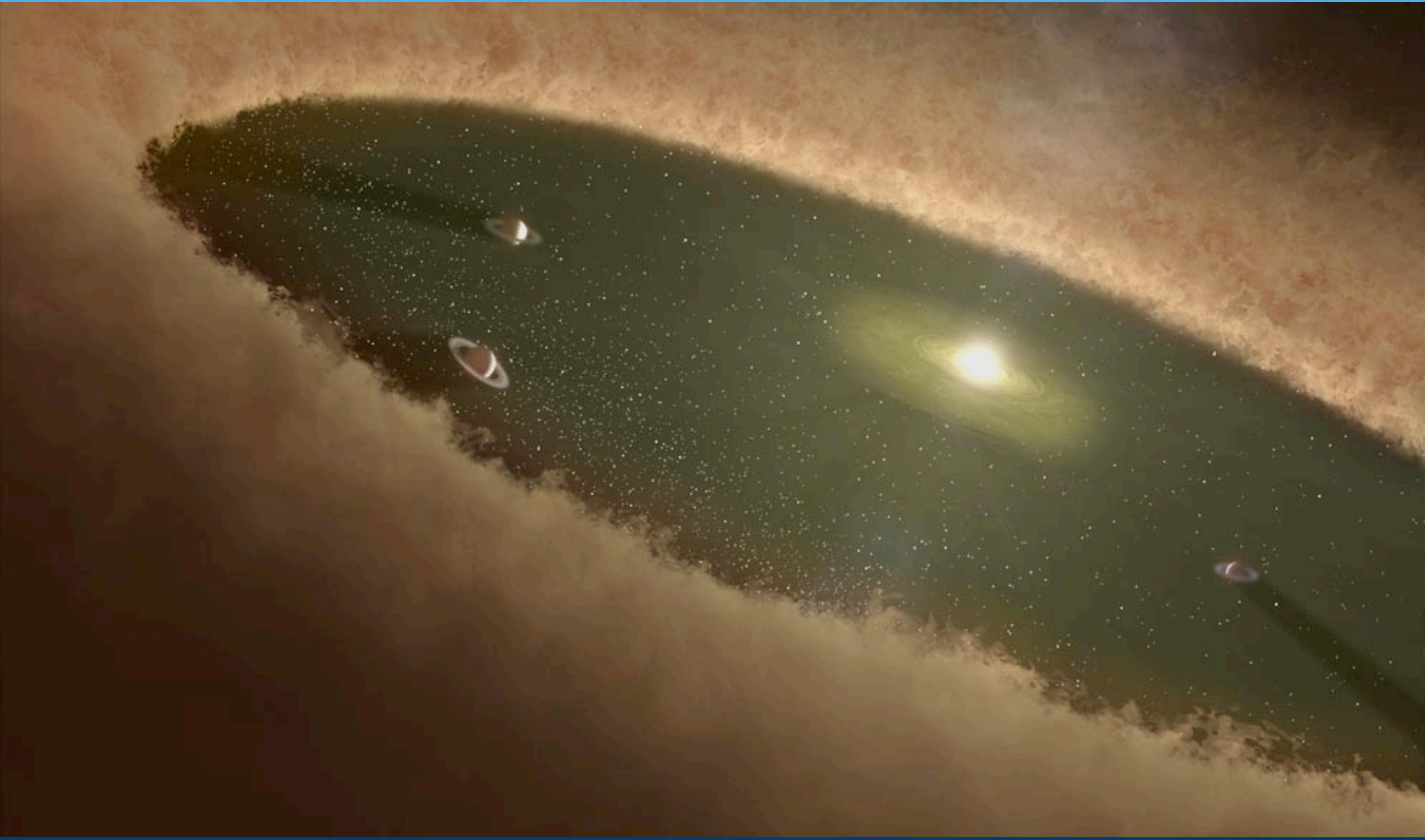
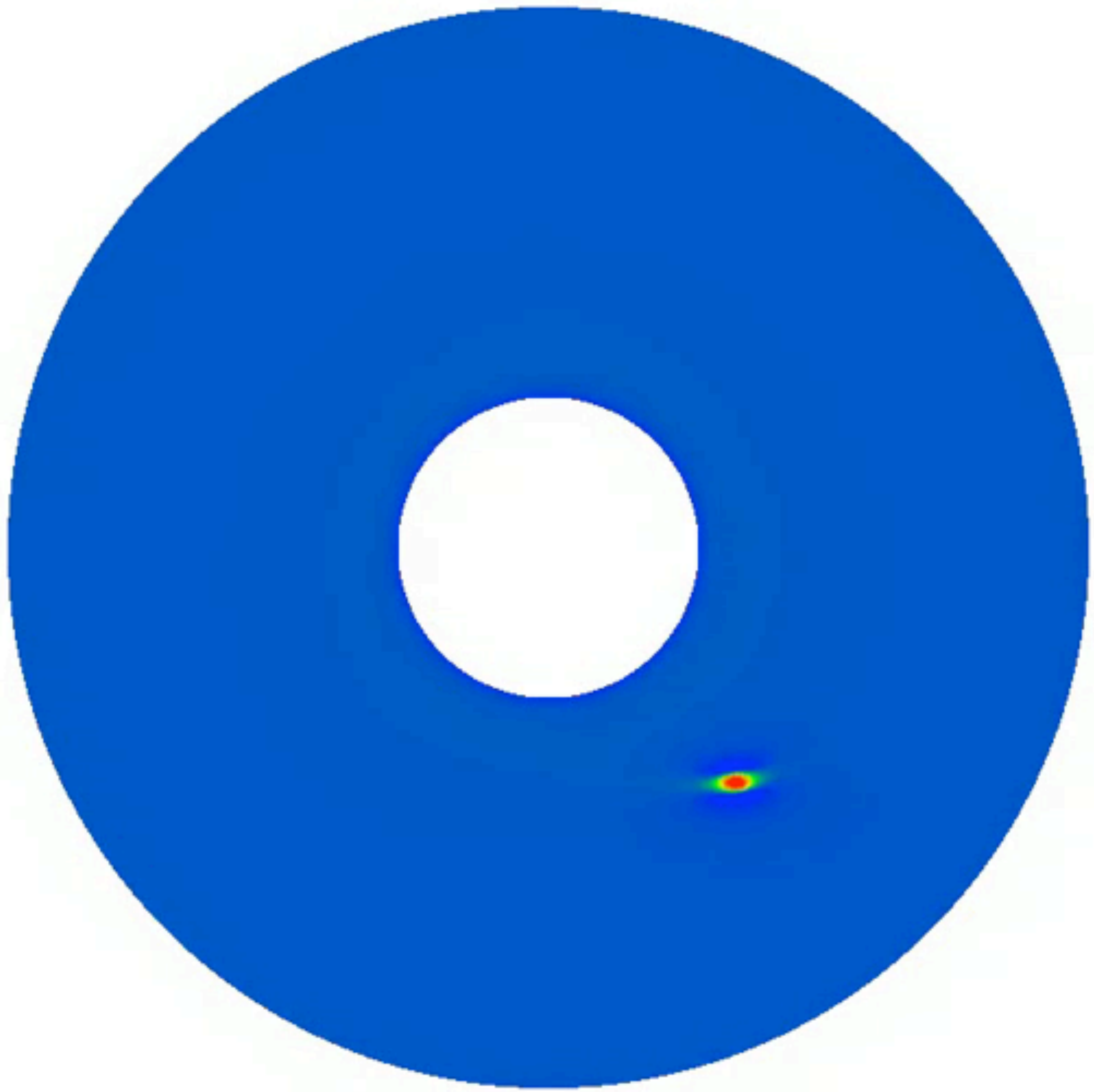


Image credit: NASA/JPL-Caltech

Migration in a non-turbulent disc

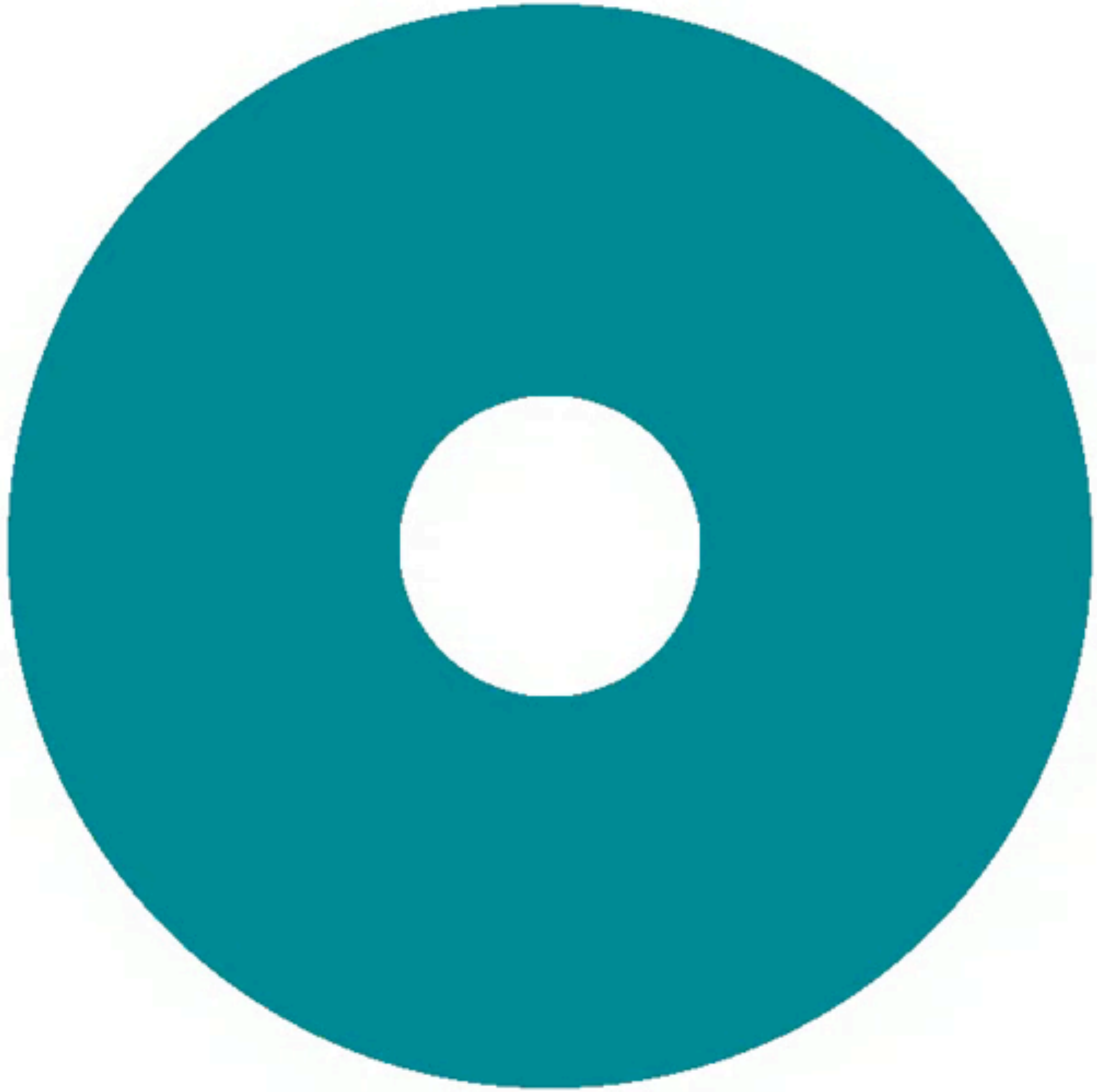
Migration - Type I

- 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

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

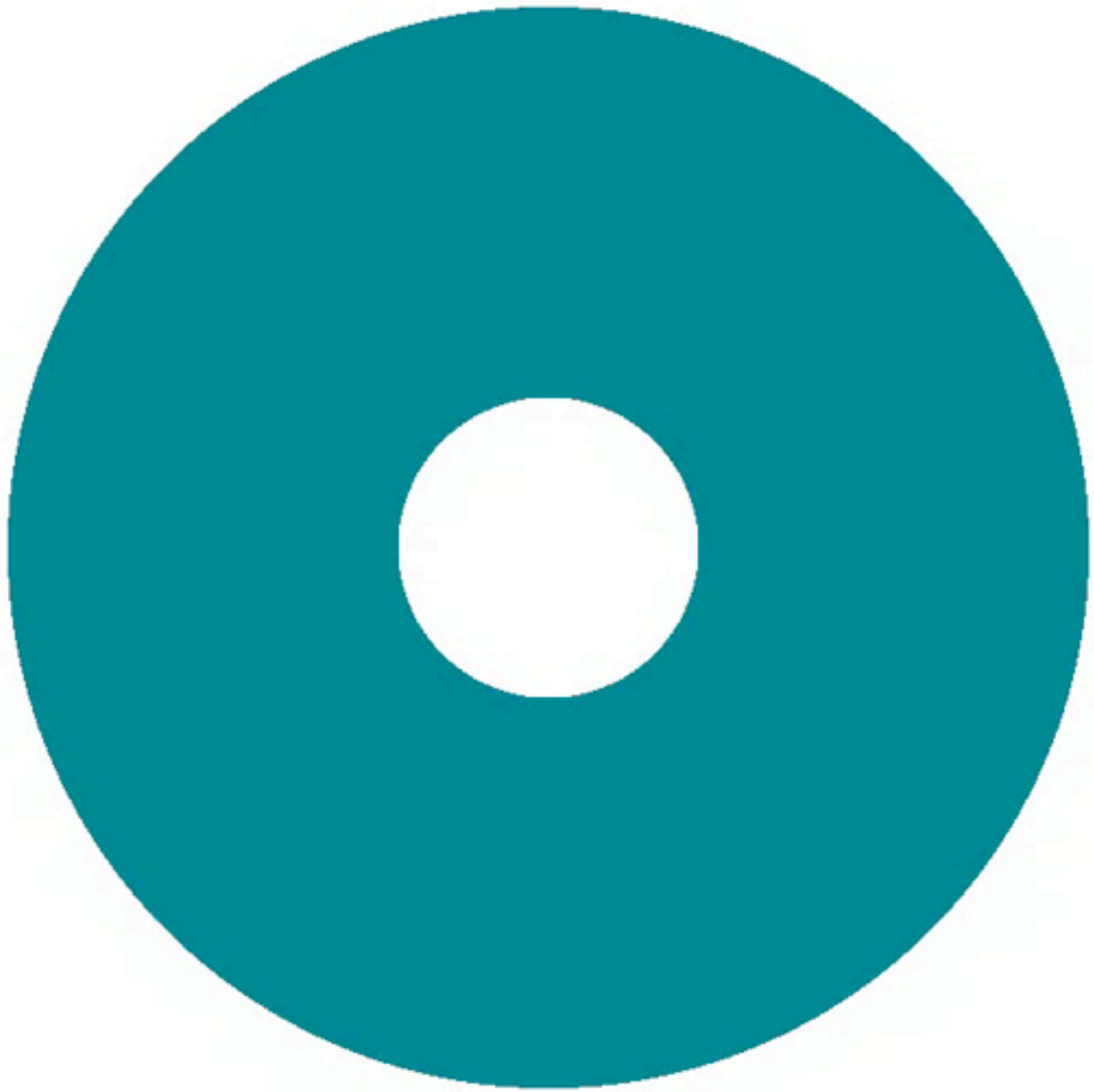
Planet mass

Viscosity $^{-1}$

Crida et al 2006

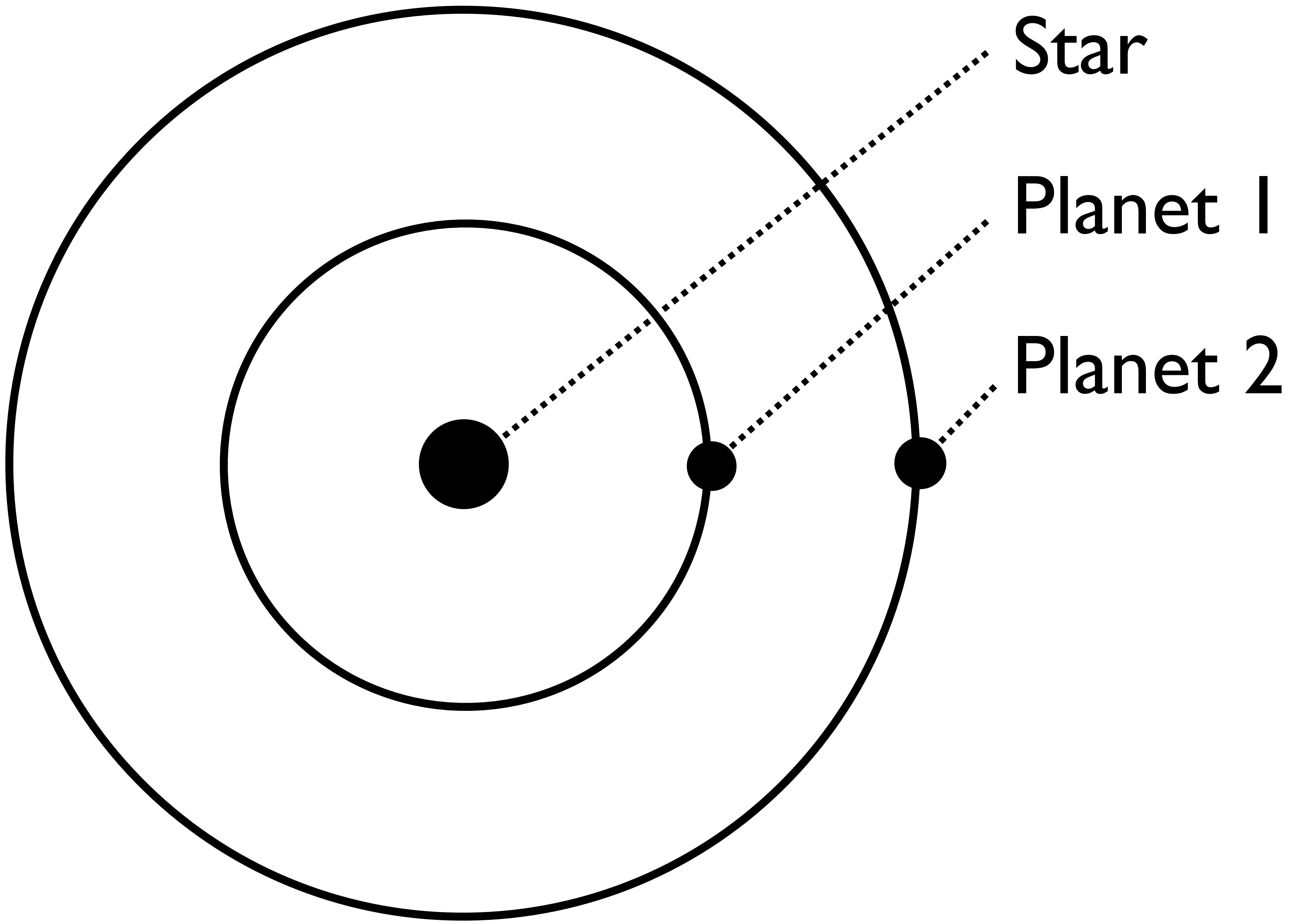
Migration - Type III

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

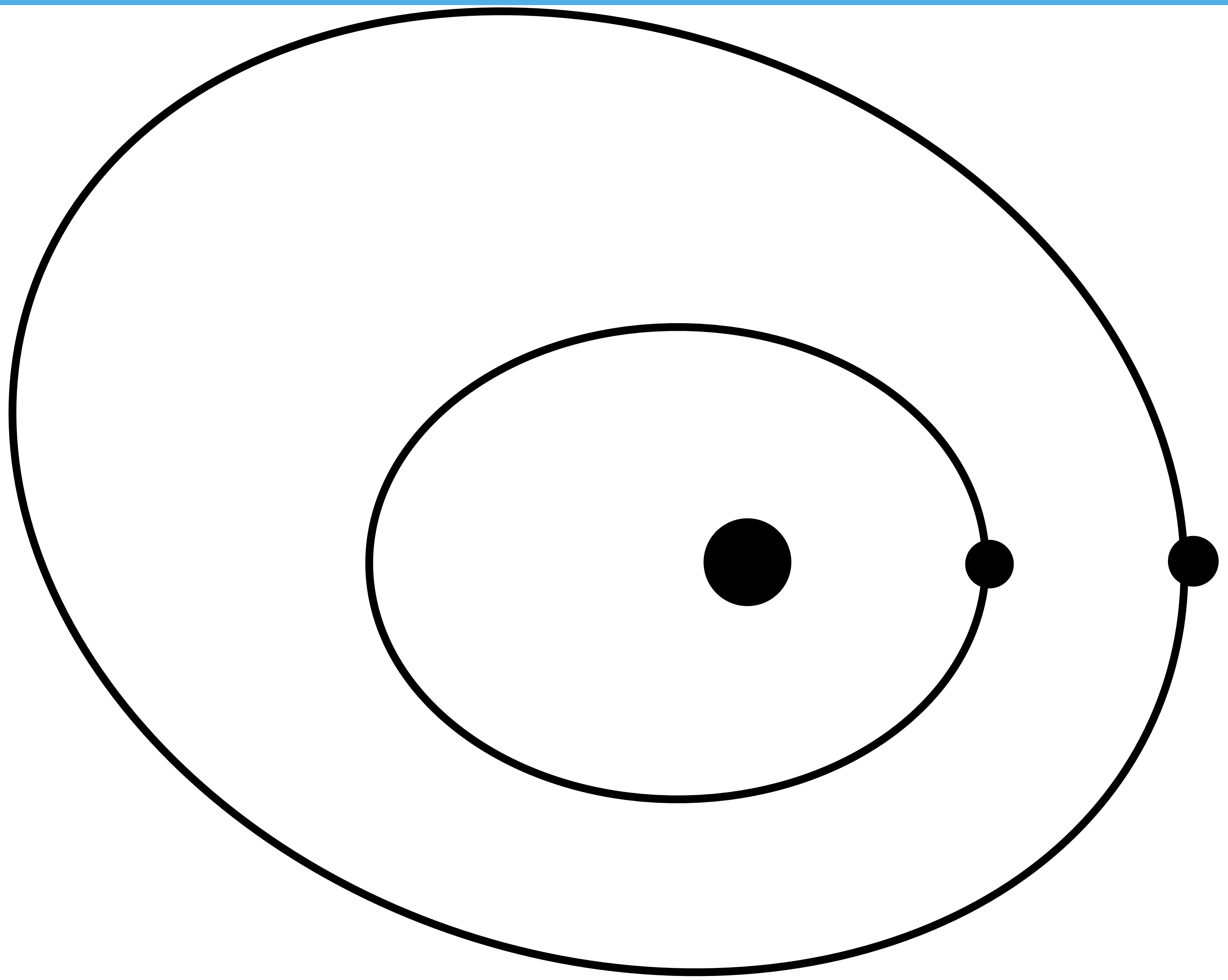


Resonance capture

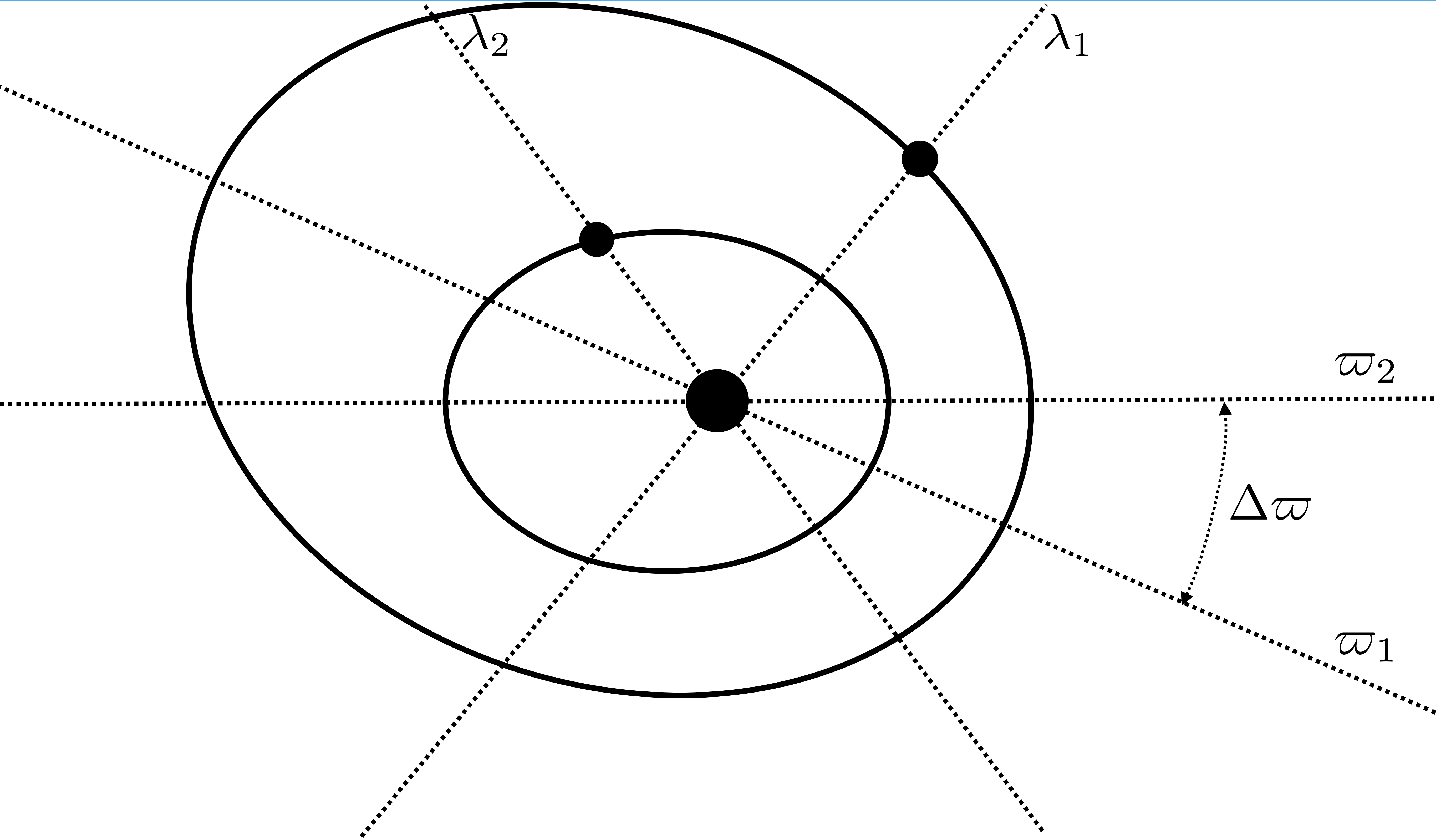
2:1 Mean Motion Resonance



2:1 Mean Motion Resonance



2:1 Mean Motion Resonance



Resonant angles

- Fast varying angles

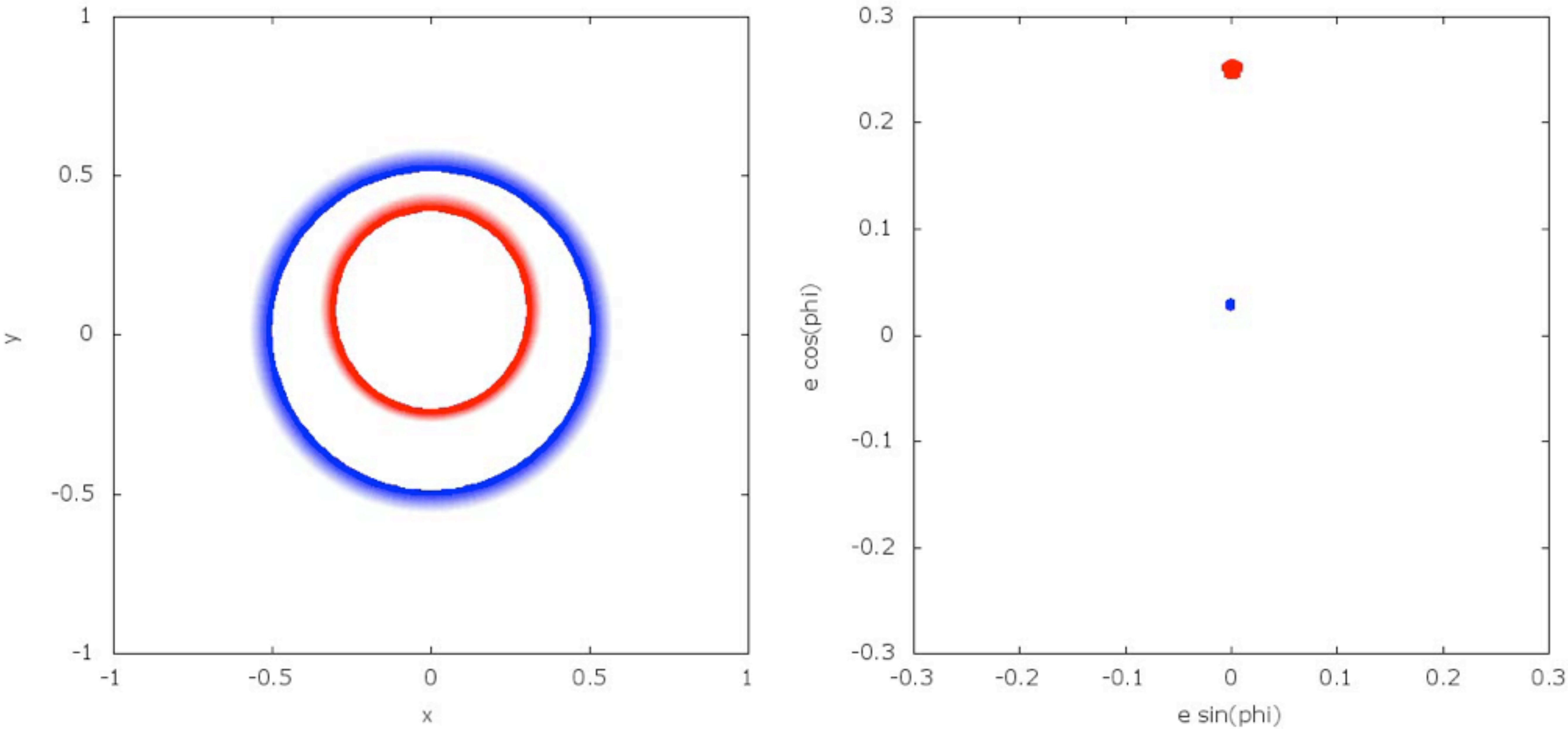
$$\lambda_1 - \varpi_1 \qquad\qquad \lambda_2 - \varpi_2$$

- 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

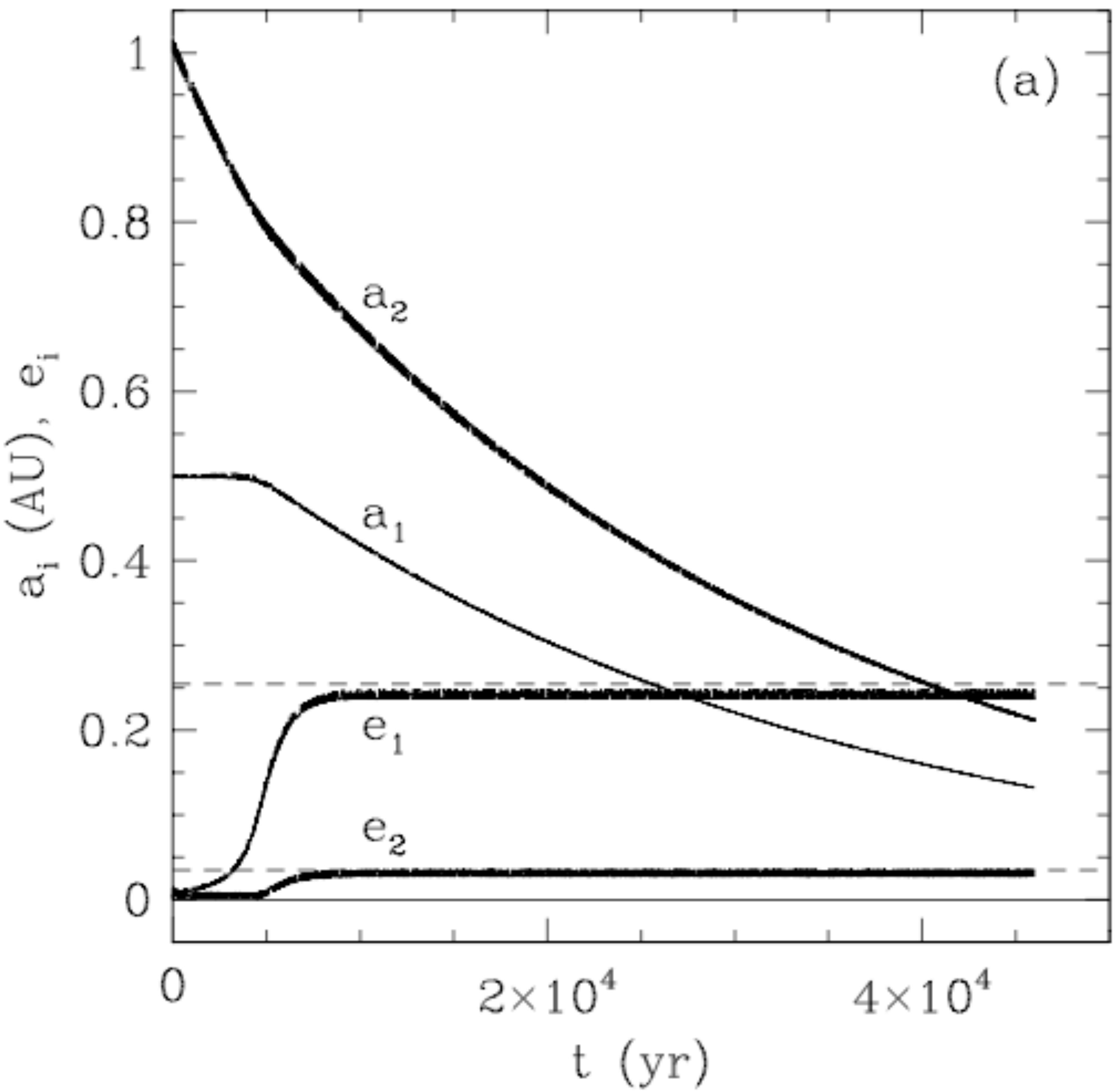
Non-turbulent resonance capture: two planets



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

parameters of GJ 876

GJ 876



Lee & Peale 2002

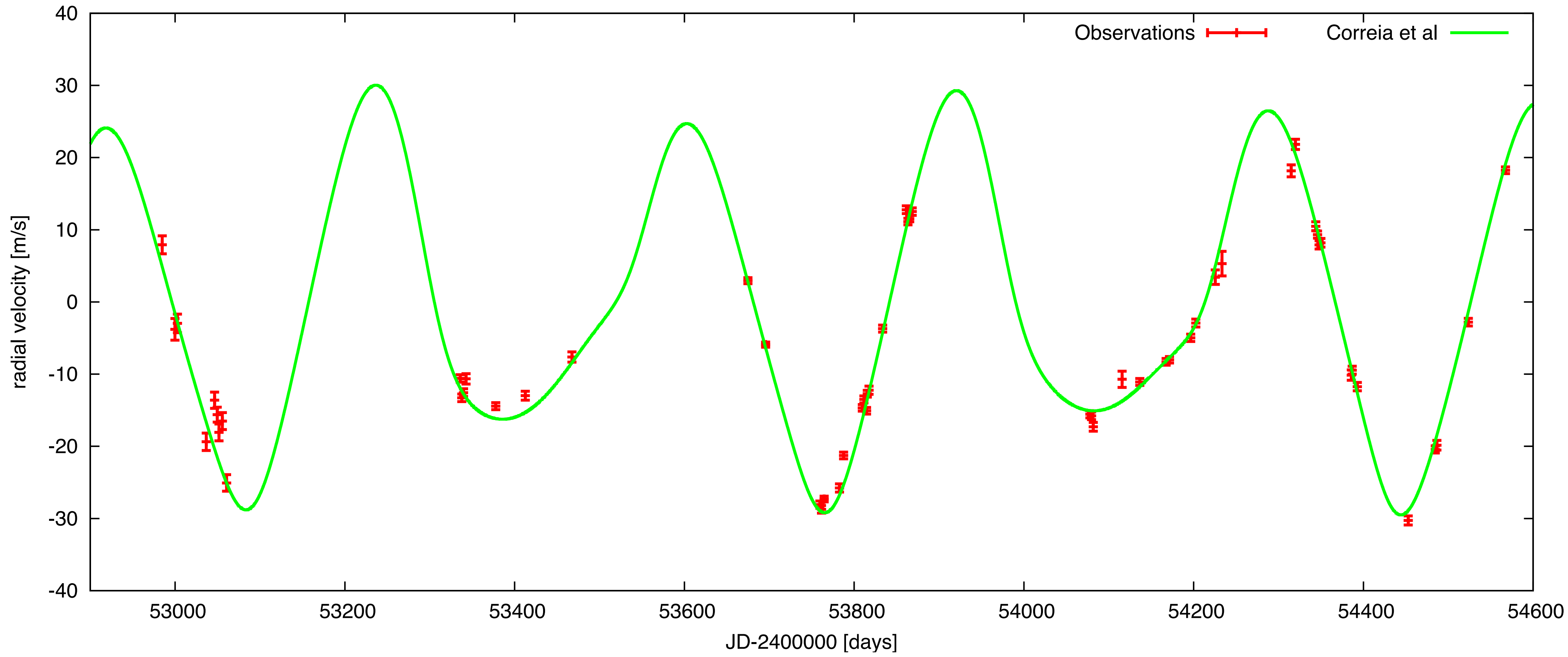
Take home message I

planet + disc = migration

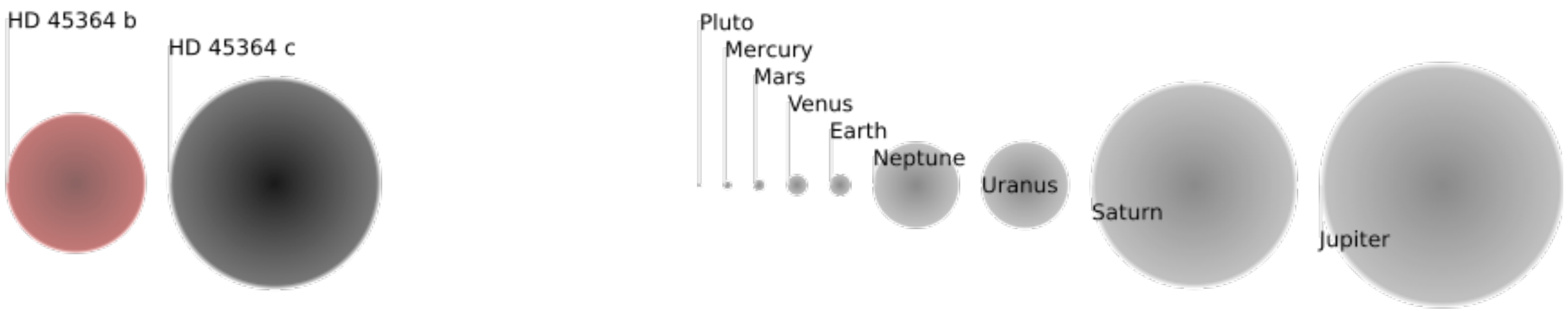
2 planets + migration = resonance

HD 45364

HD45364



Observations
Correia et al
radial velocity [m/s]
JD-2400000 [days]
40
30
20
10
0
-10
-20
-30
-40
53000
53200
53400
53600
53800
54000
54200
54400
54600



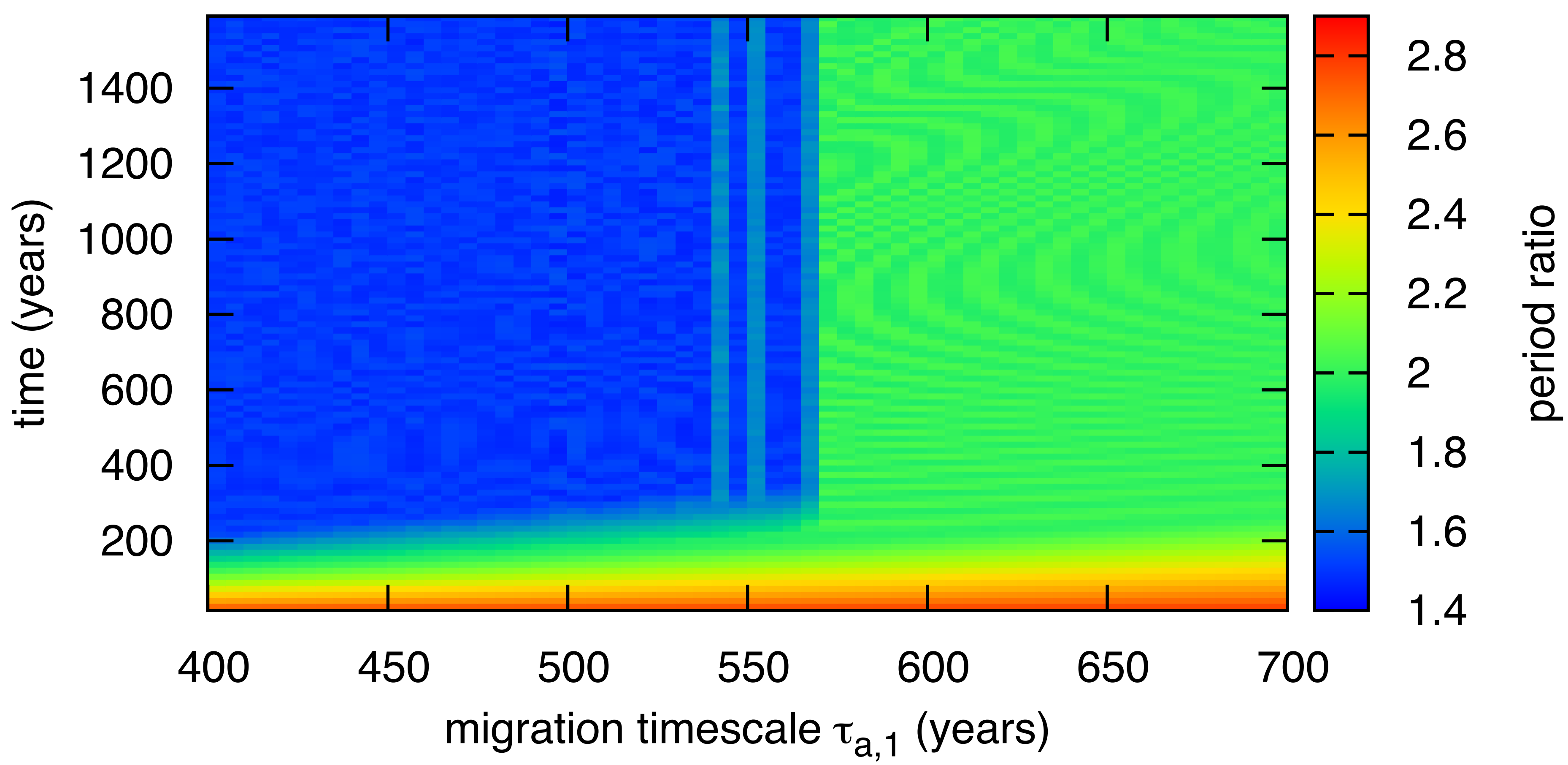
HD 45364 b
HD 45364 c
Pluto
Mercury
Mars
Venus
Earth
Neptune
Uranus
Saturn
Jupiter

Formation scenario for HD45364

- Two migrating planets
- Infinite number of resonances

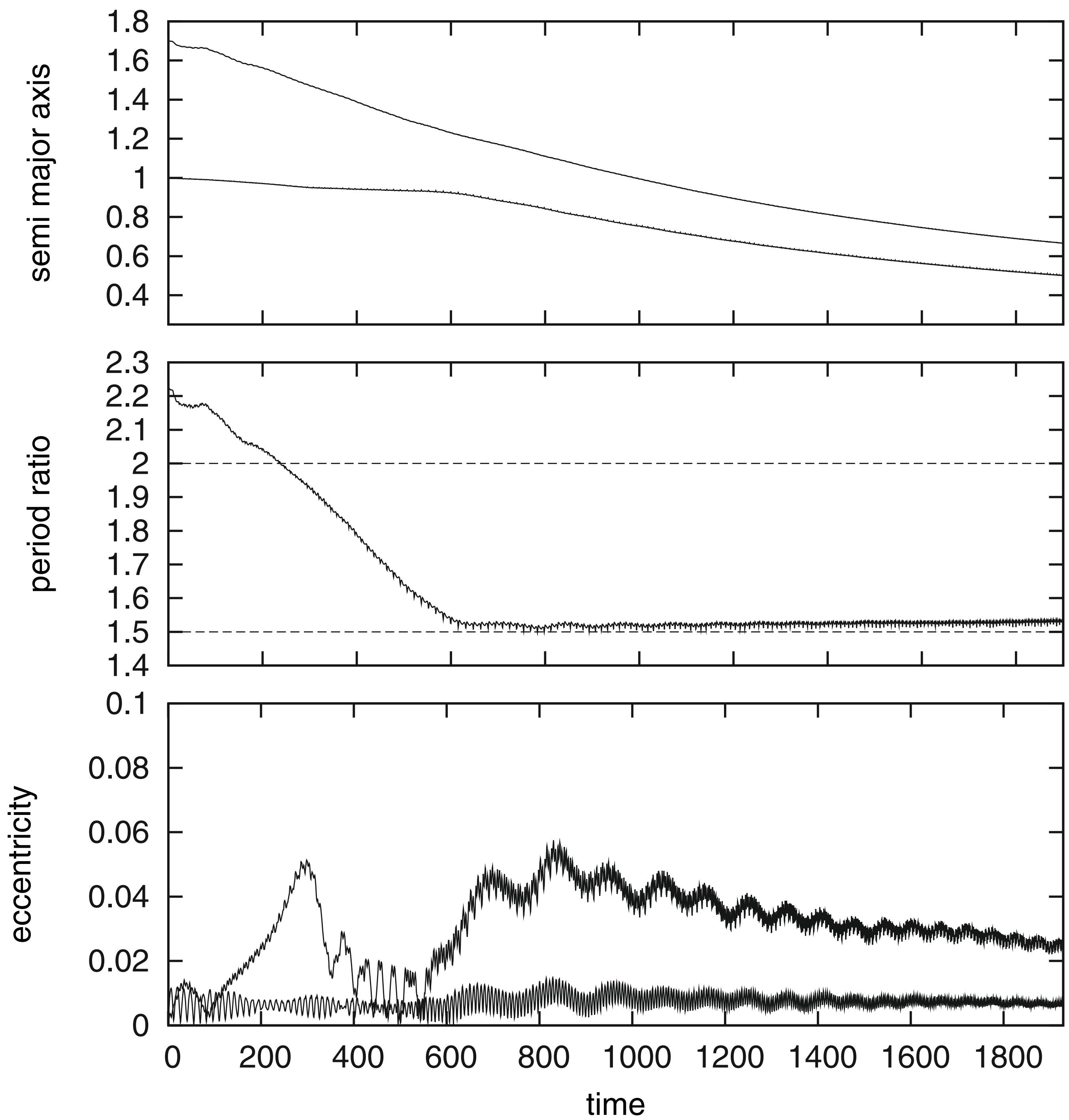
1:2 7:8 3:2 1:3 3:4

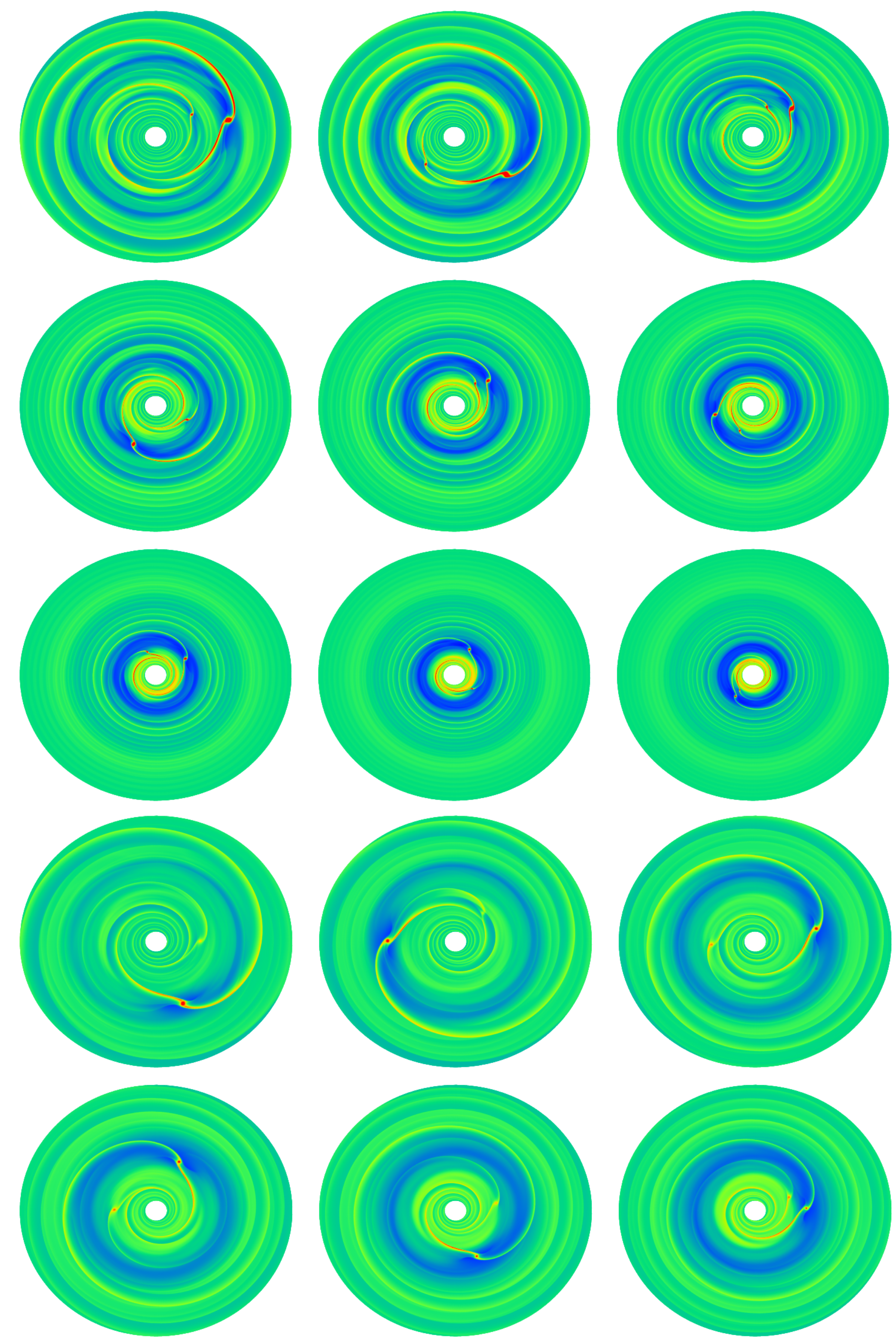
- Migration speed is crucial
- Resonance width and libration period define critical migration rate



Rein, Papaloizou & Kley 2010

Formation scenario for HD45364





Rein, Papaloizou & Kley 2010

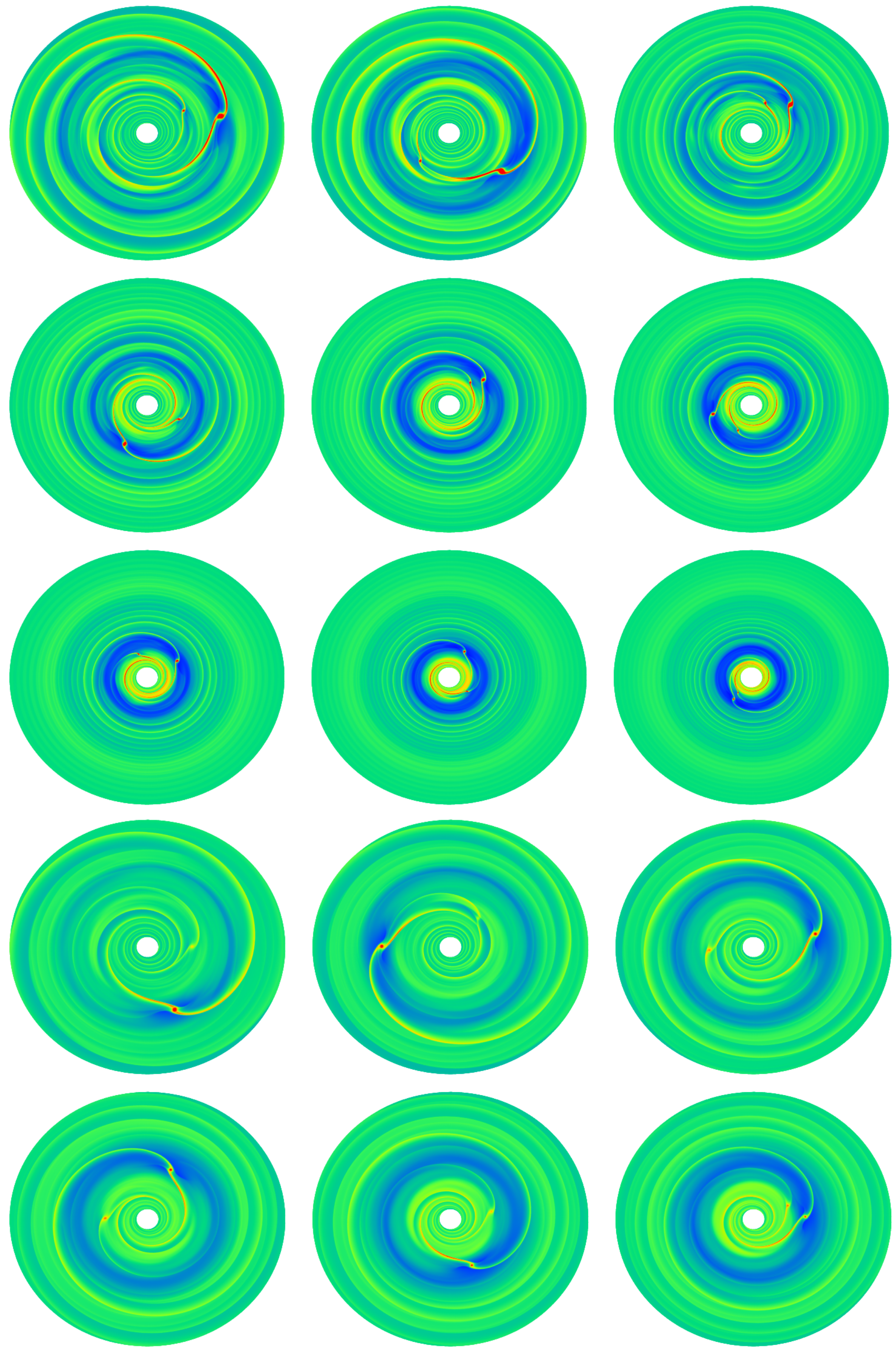
Formation scenario for HD45364

Massive disc (5 times MMSN)

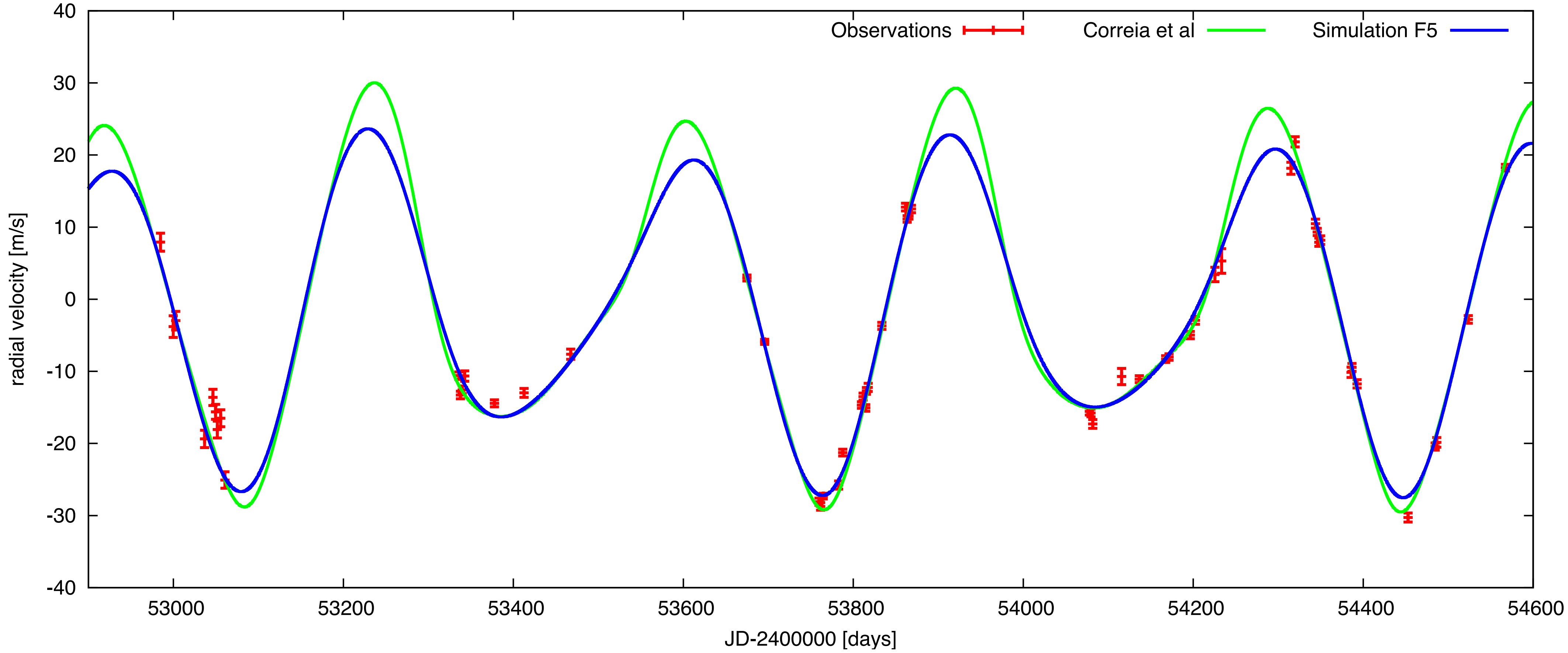
- Short, rapid Type III migration
- Passage of 2:1 resonance
- Capture into 3:2 resonance

Large scale-height (0.07)

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



Formation scenario leads to a better ‘fit’



Parameter	Unit	Correia et al. (2009) b	c	Simulation **F5** 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	

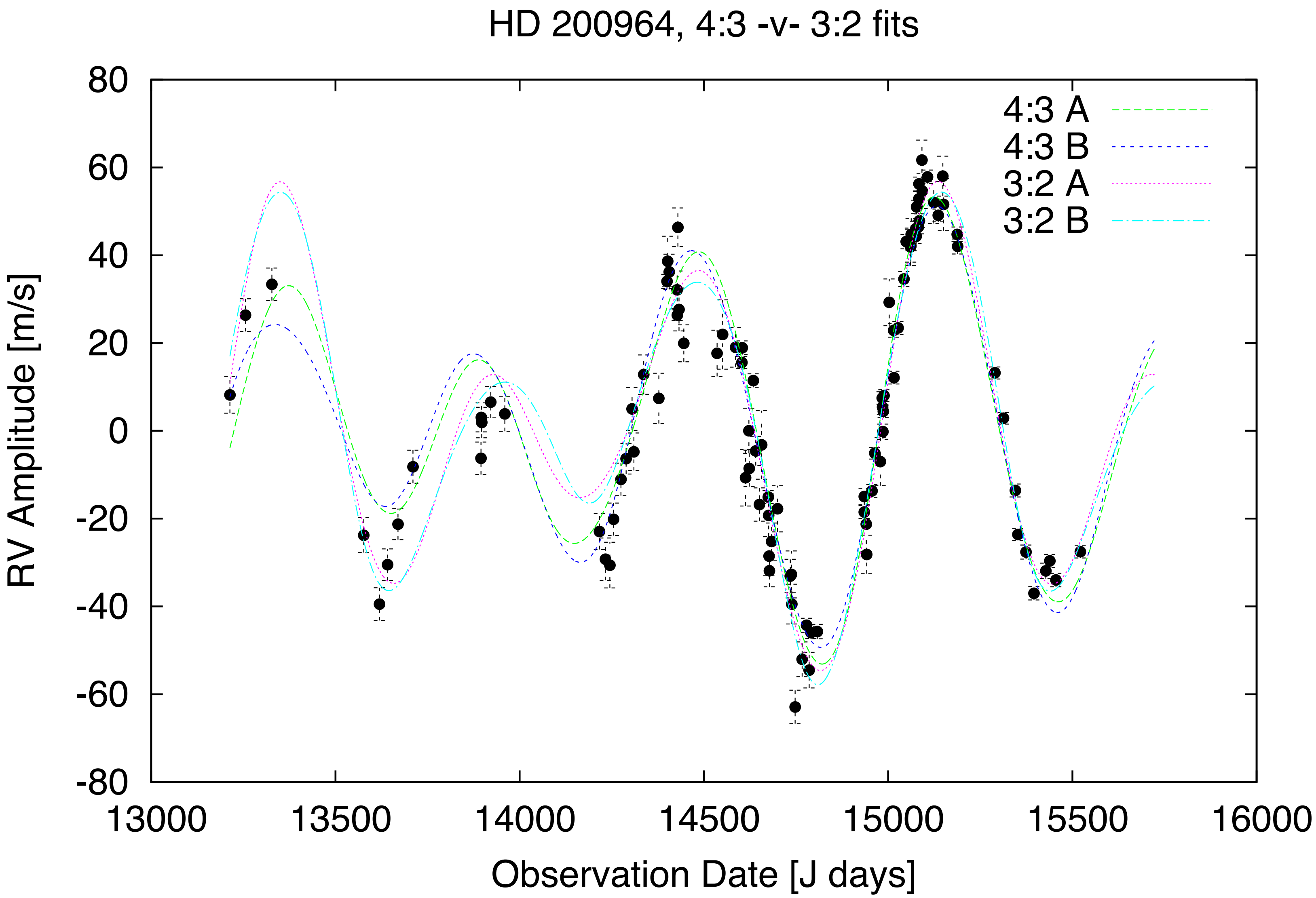
Rein, Papaloizou & Kley 2010

Take home message II

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

HD200964
The impossible system?

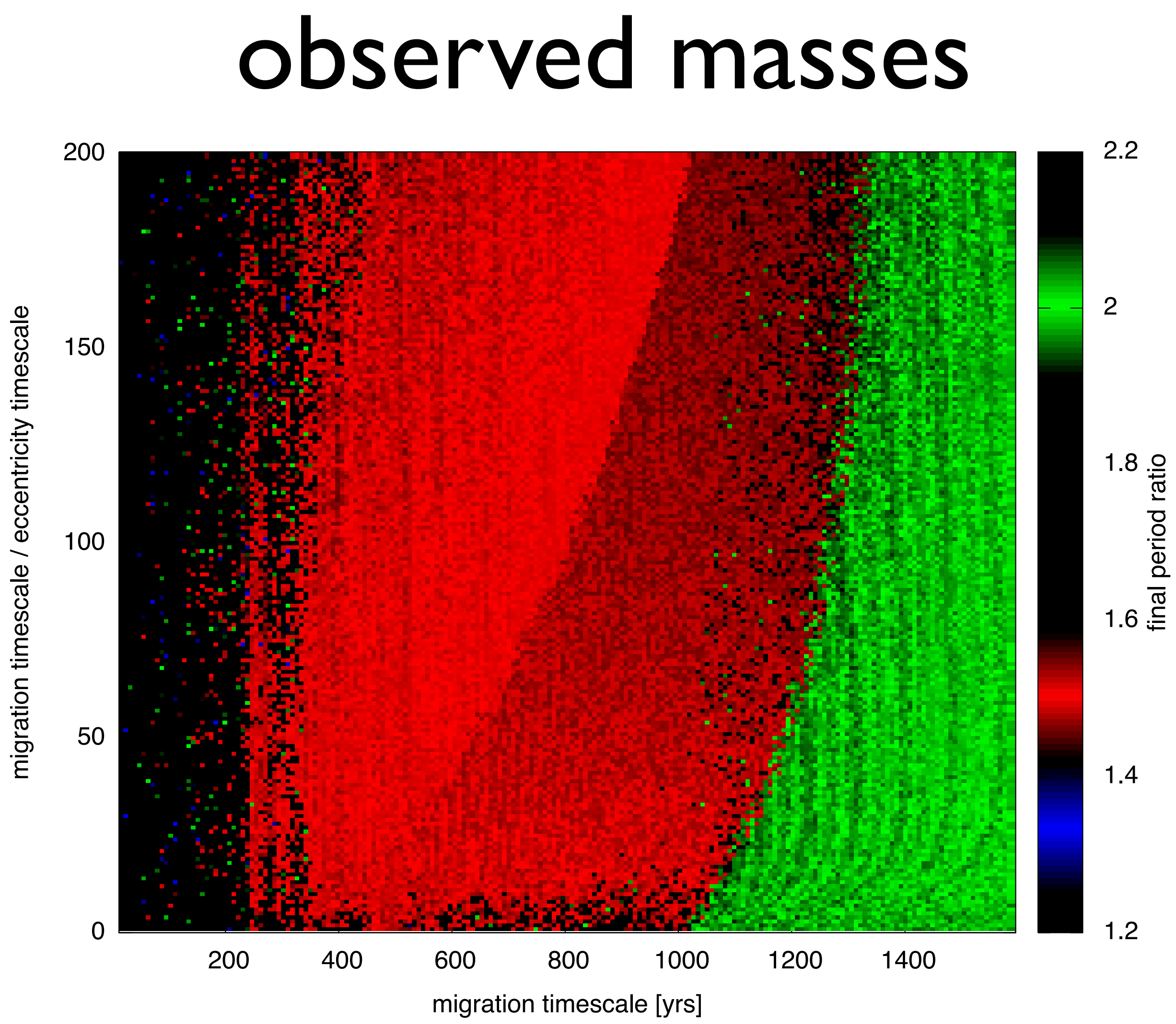
Radial velocity curve of HD200964

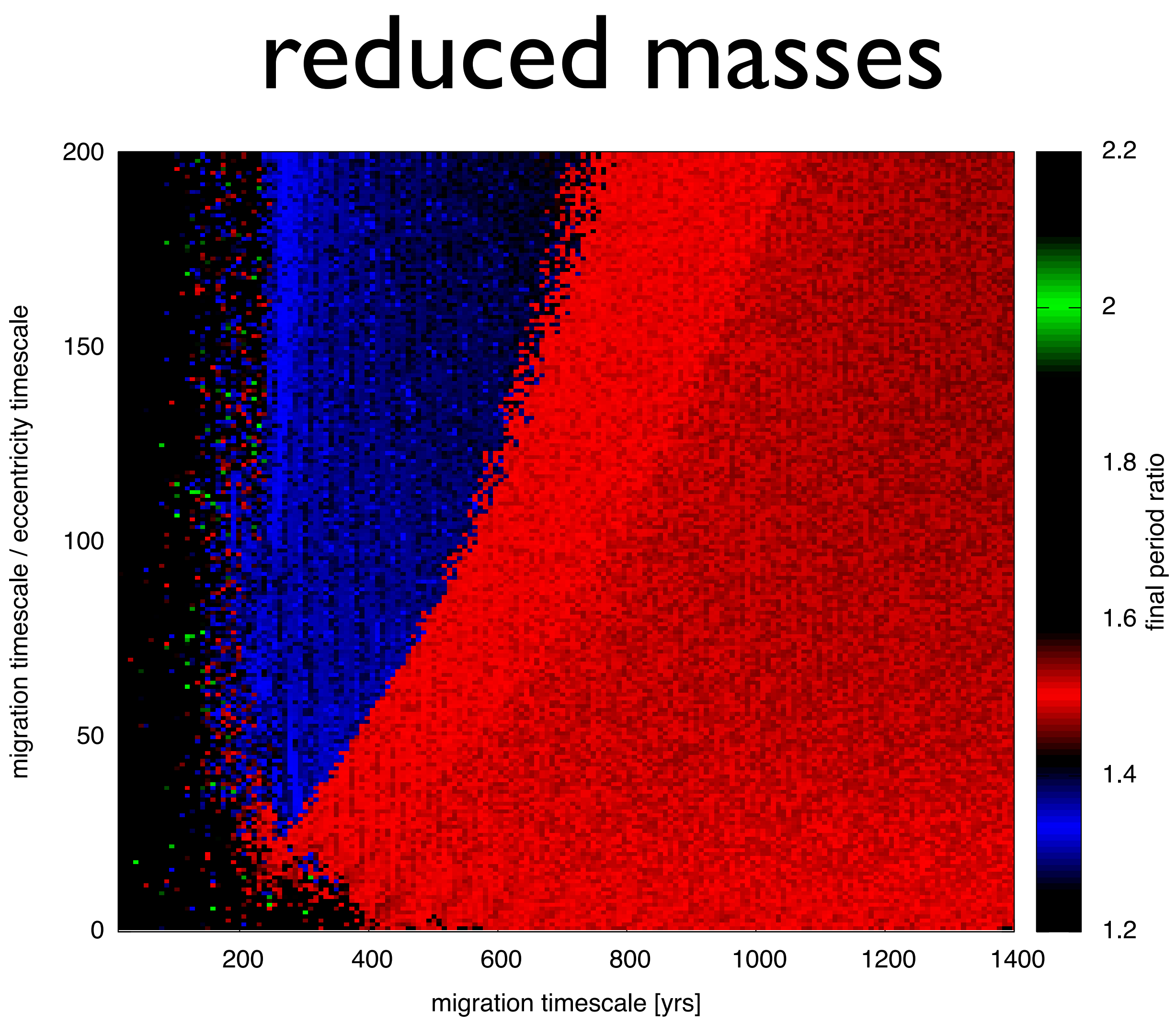


- Two massive planets 1.8 M_{Jup} and 0.9 M_{Jup}
- Period ratio either 3:2 or 4:3
- Another similar system, to be announced soon
- How common is 4:3?
- Formation?

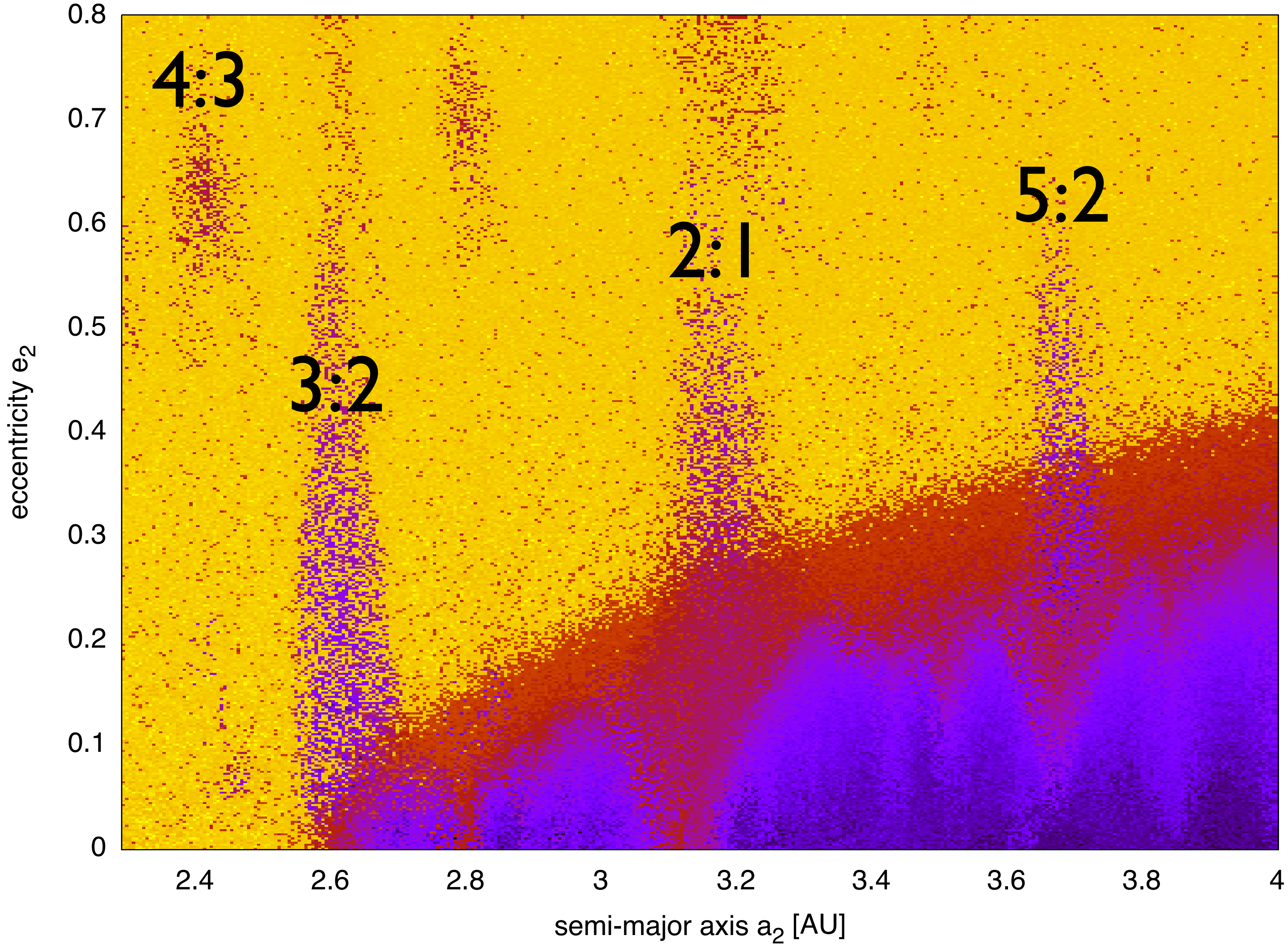
Plot by Matthew Payne

Standard disc migration doesn't work

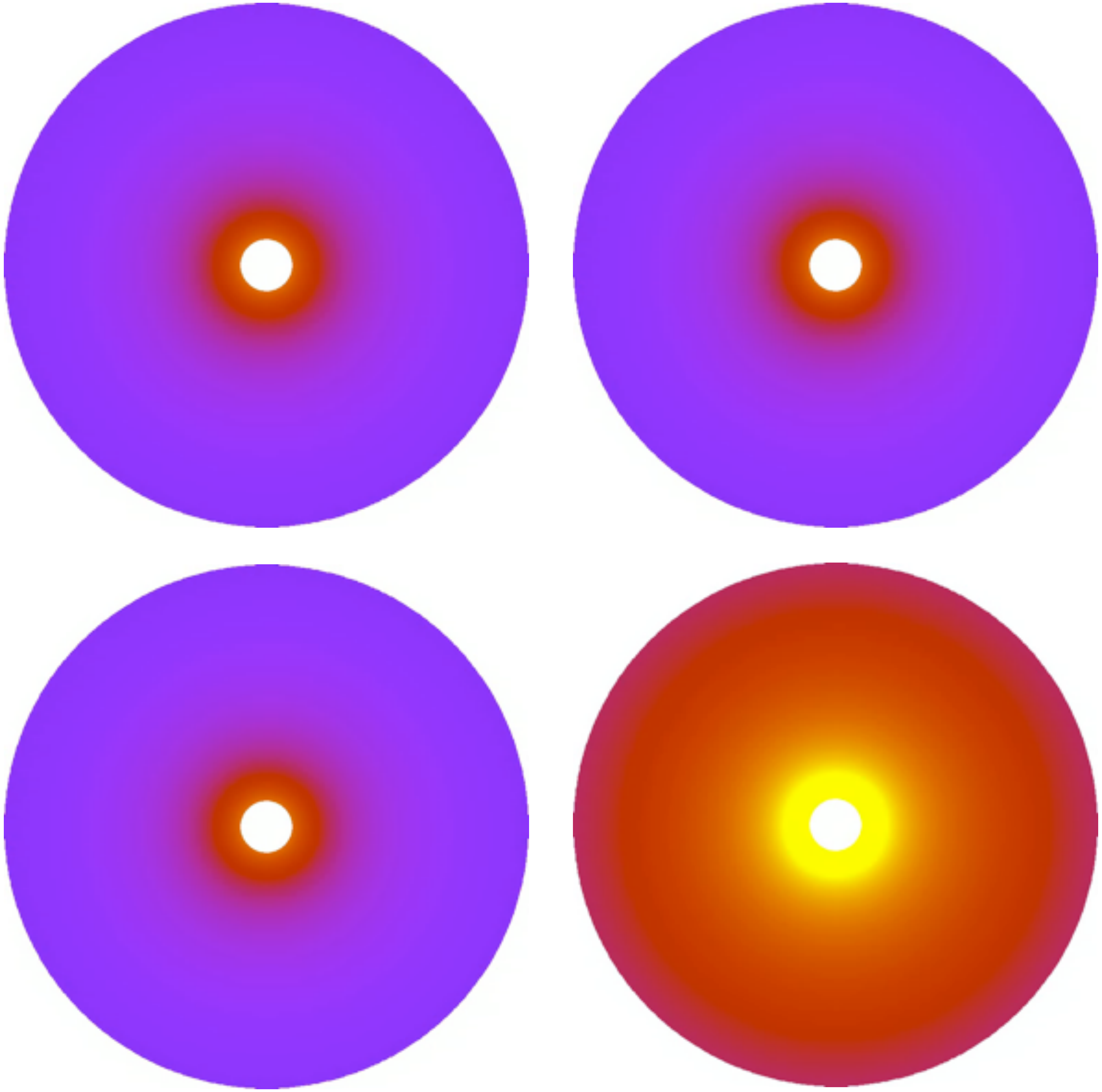




Stability of HD200964



Hydrodynamical simulations



HD200964

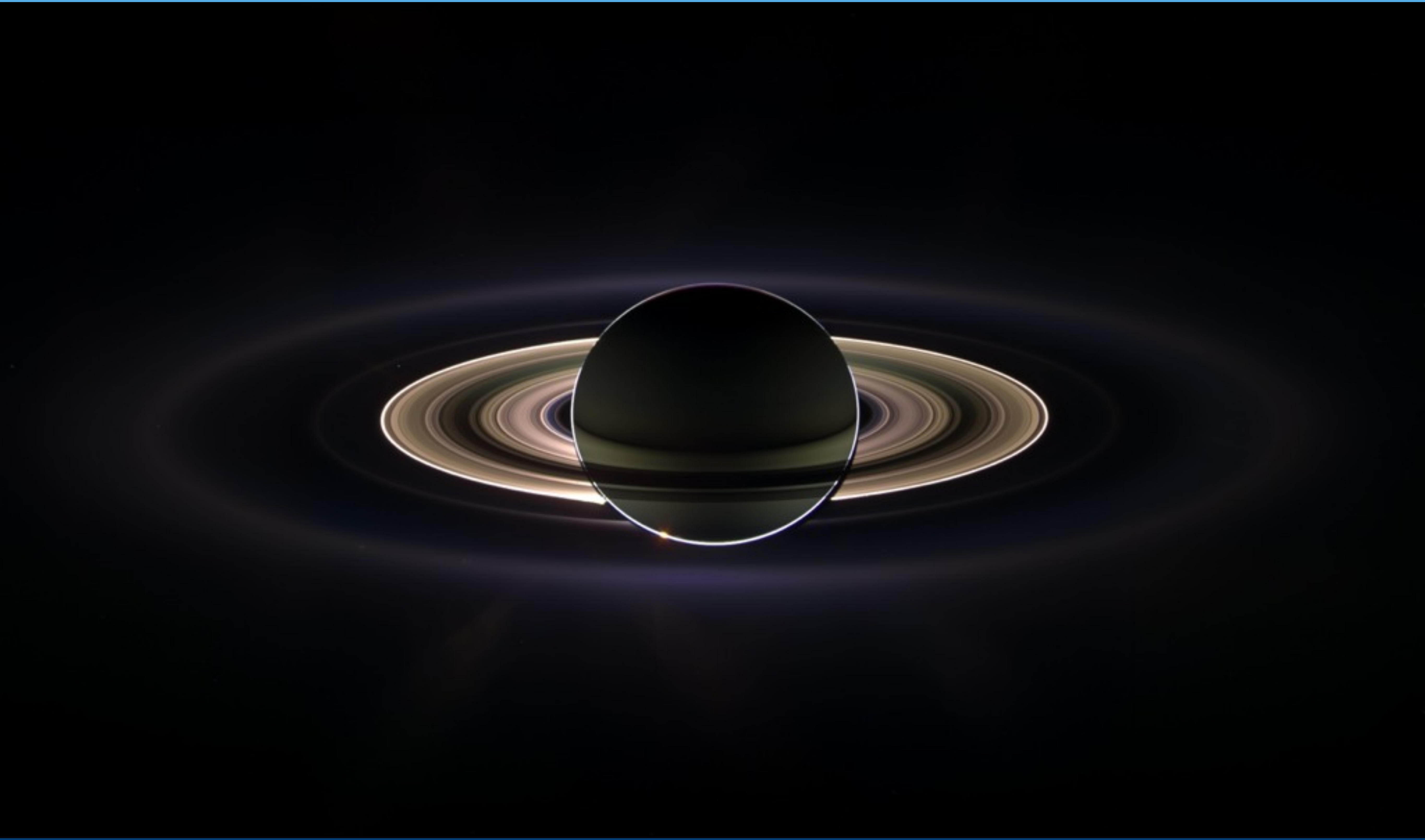
- In situ formation?
- Main accretion while in 4:3 resonance?
- Planet planet scattering?
- A third planet?
- Observers screwed up?

Take home message III

There is still a lot that we do not understand

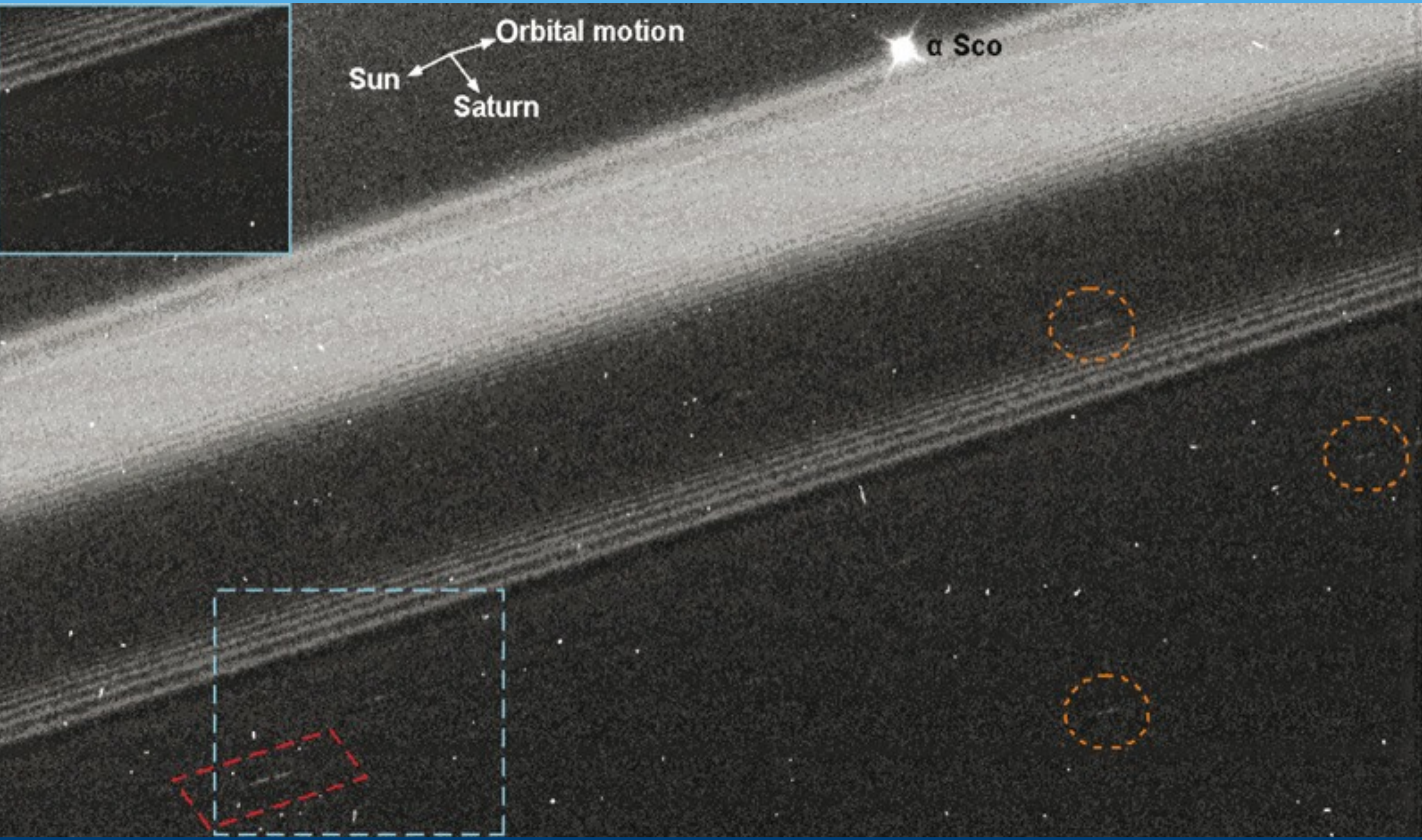
Moonlets in Saturn's Rings

Cassini spacecraft



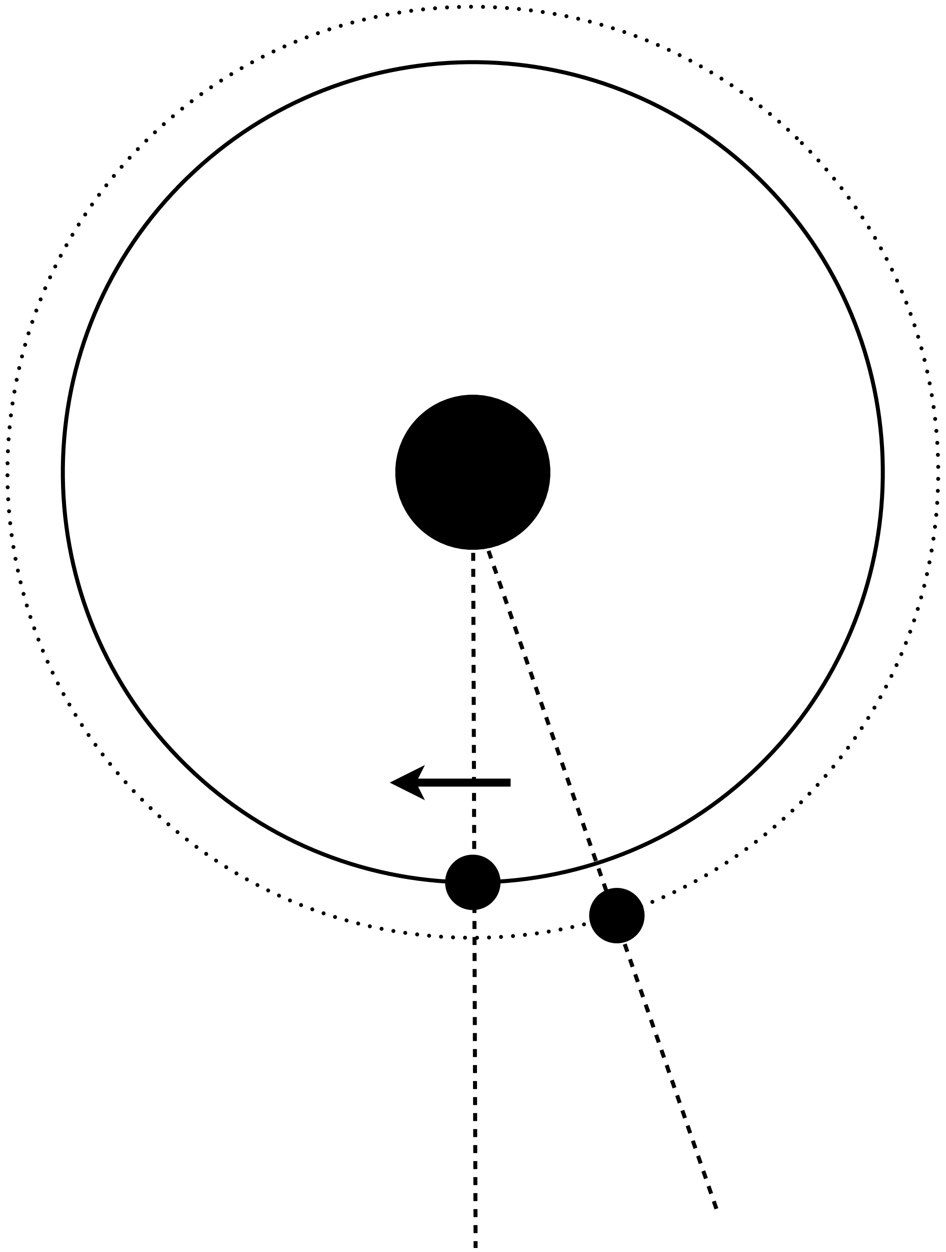
NASA/JPL/Space Science Institute

Propeller structures in A-ring



Porco et al. 2007, Sremcevic et al. 2007, Tiscareno et al. 2006

Longitude residual



Mean motion [rad/s]

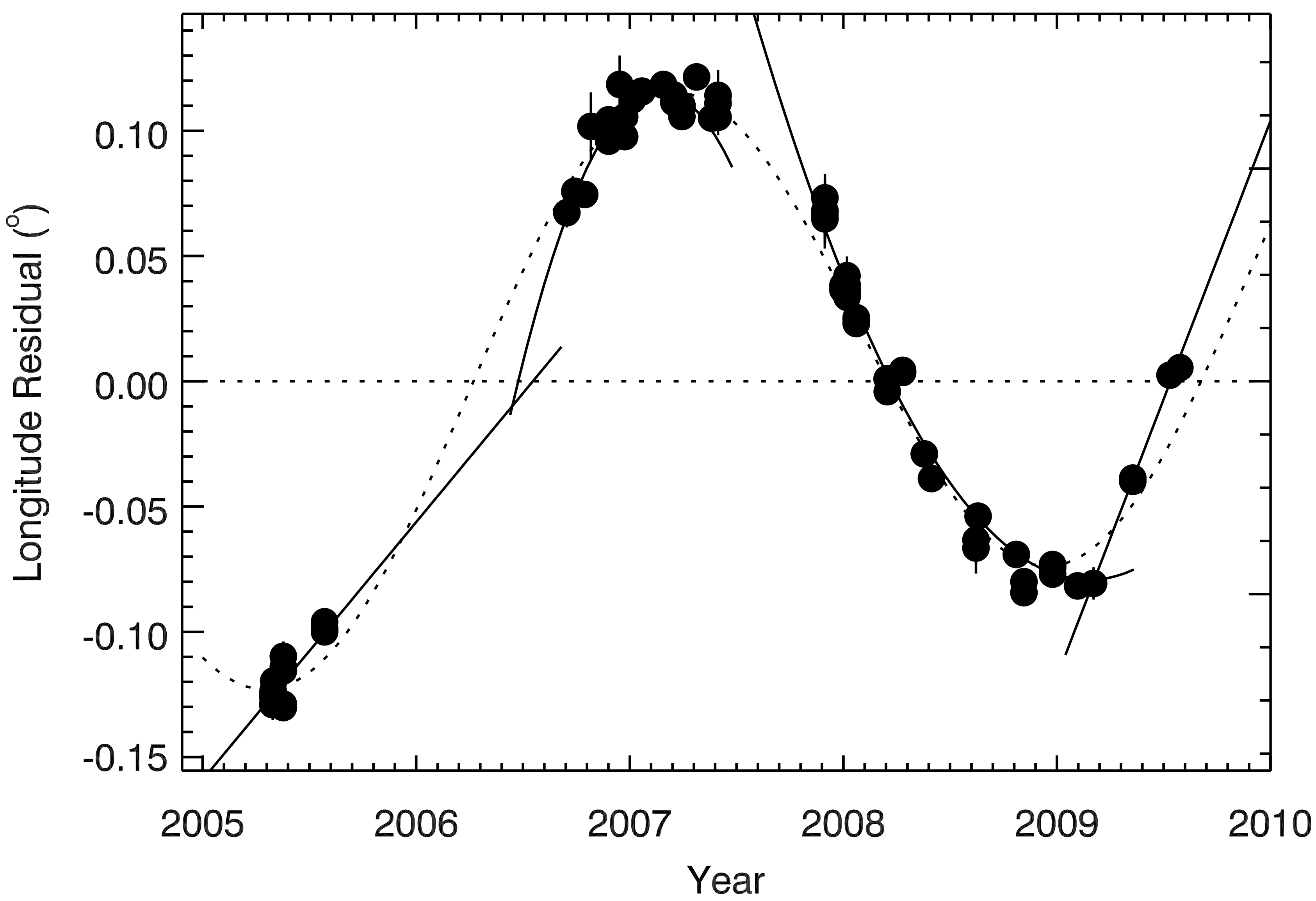
$$n = \sqrt{\frac{GM}{a^3}}$$

Mean longitude [rad]

$$\lambda = n\,t$$

$$\lambda(t) - \lambda_0(t) = \int_0^t (n_0 + n'(t'))\,dt' - \underbrace{\int_0^t n_0\,dt'}_{n_0 t}$$

Observational evidence of non-Keplerian motion



Tiscareno et al. 2010

Random walk

Analytic model

Describing evolution in a statistical manner

Partly based on Rein & Papaloizou 2009

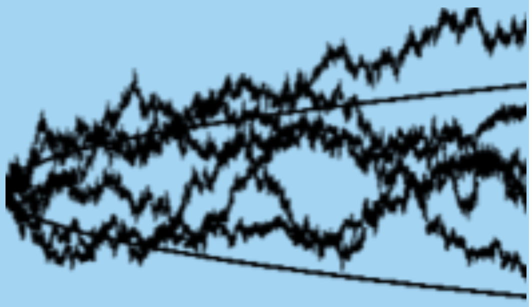
$$\Delta a = \sqrt{4\frac{Dt}{n^2}}$$

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

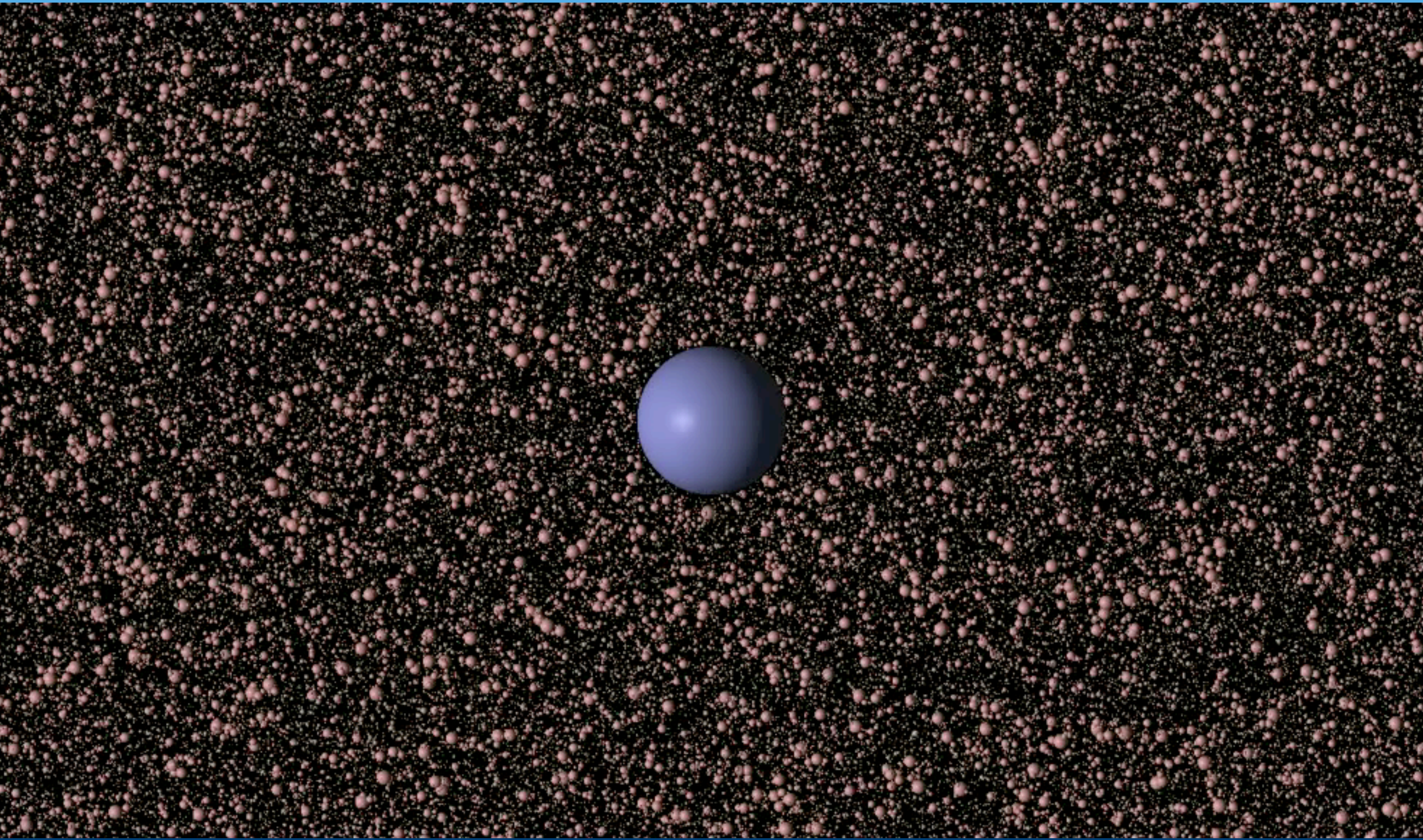
N-body simulations

Measuring random forces or integrating moonlet directly

Crida et al 2010, Rein & Papaloizou 2010

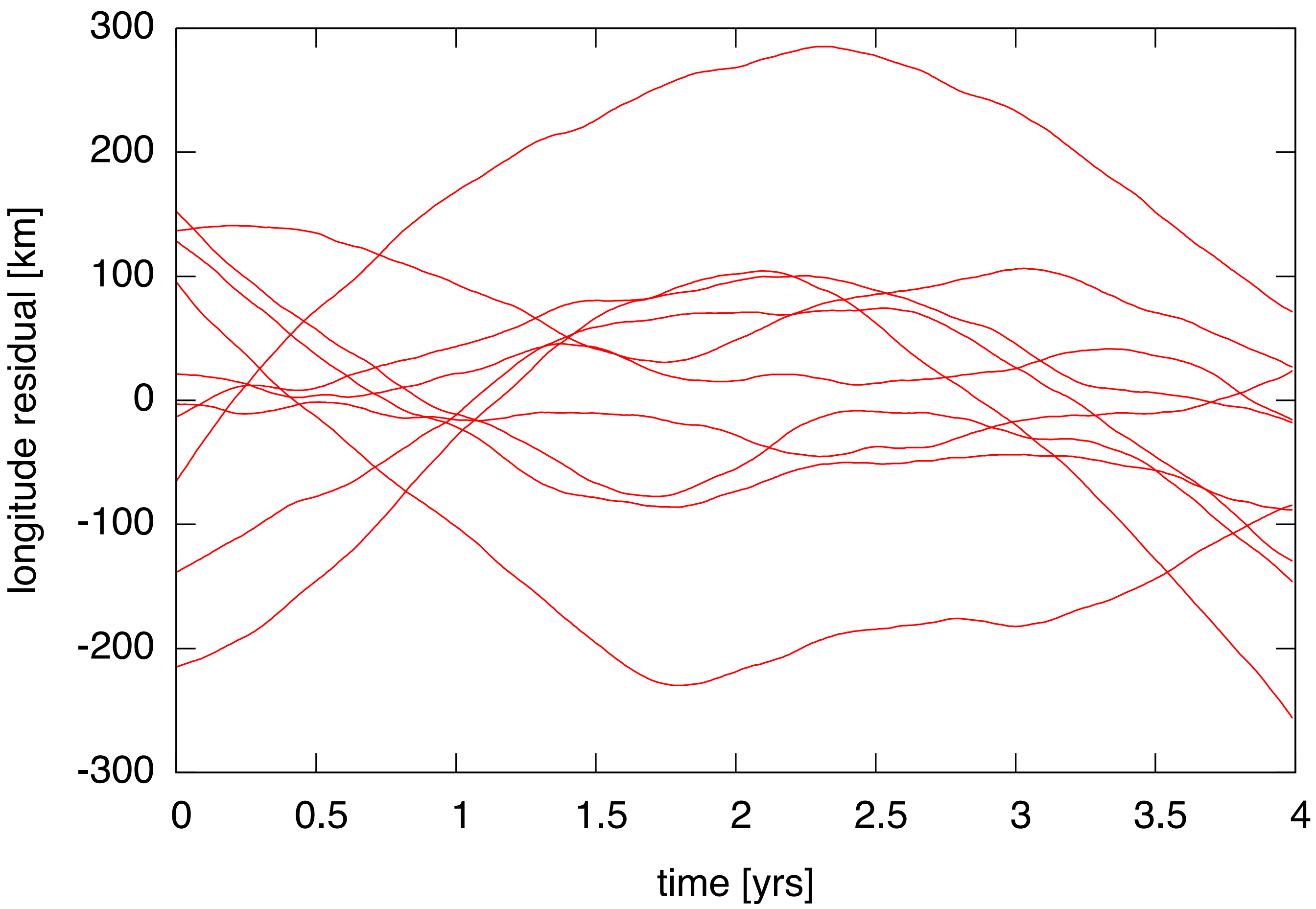


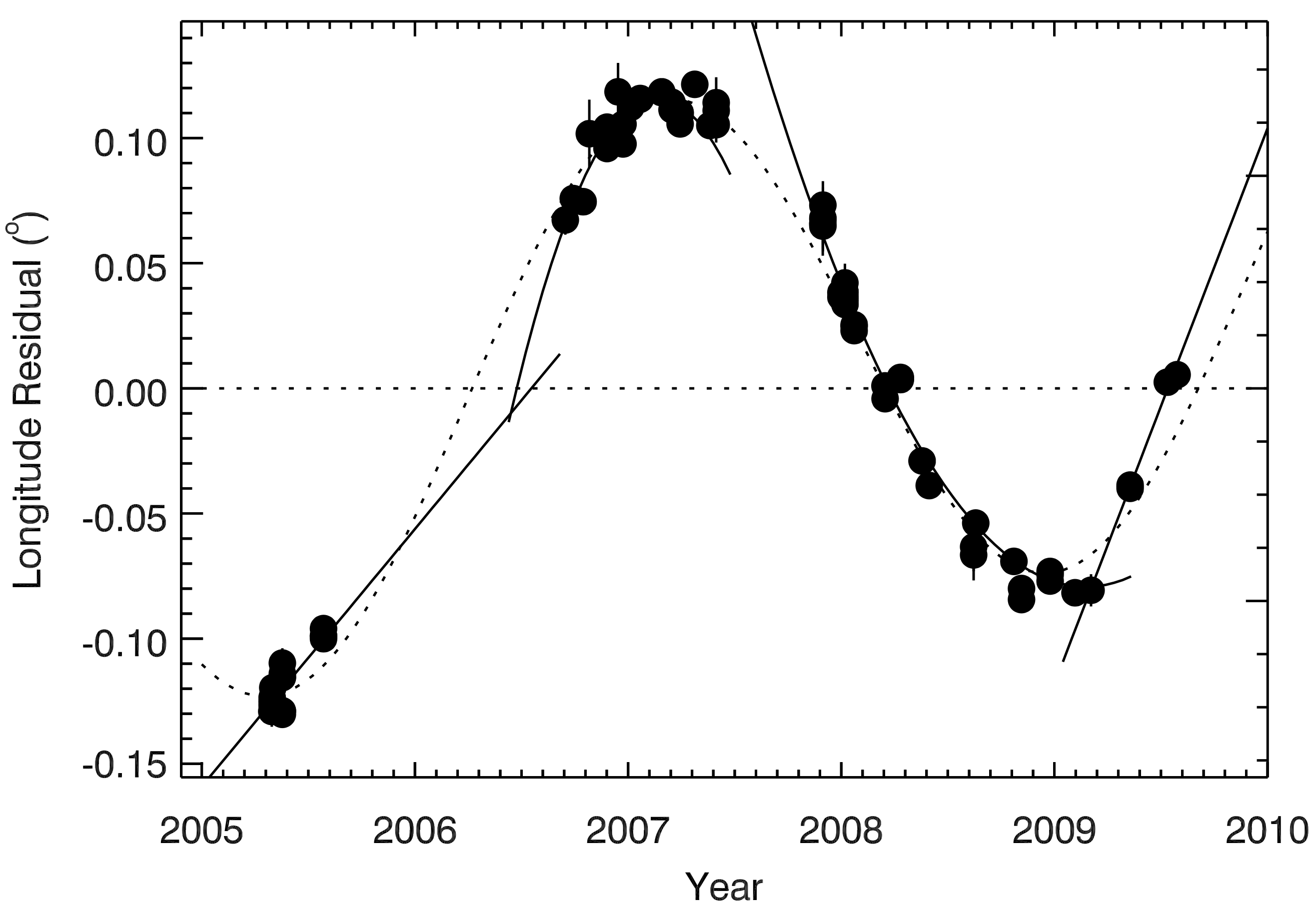
Random walk



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

Work in progress: a statistical measure





Take home message IV

Saturn's rings

=

small scale version of

a proto-planetary disc

REBOUND

A new open source collisional N-body code

Numerical Integrators

- We want to integrate the equations of motions of a particle

$$\dot{x} = v$$

$$\dot{v} = a(x, v)$$

- For example, gravitational potential

$$a(x) = -\nabla\Phi(x)$$

- In physics, these can usually be derived from a Hamiltonian

$$H = \frac{1}{2}p^2 + \Phi(x)$$

- Symmetries of the Hamiltonian correspond to conserved quantities

Numerical Integrators

- Discretization

$$\dot{x} = v \qquad \longrightarrow \qquad \Delta x = v\,\Delta t$$
$$\dot{v} = a(x, v) \qquad\qquad \Delta v = a(x, v)\,\Delta t$$

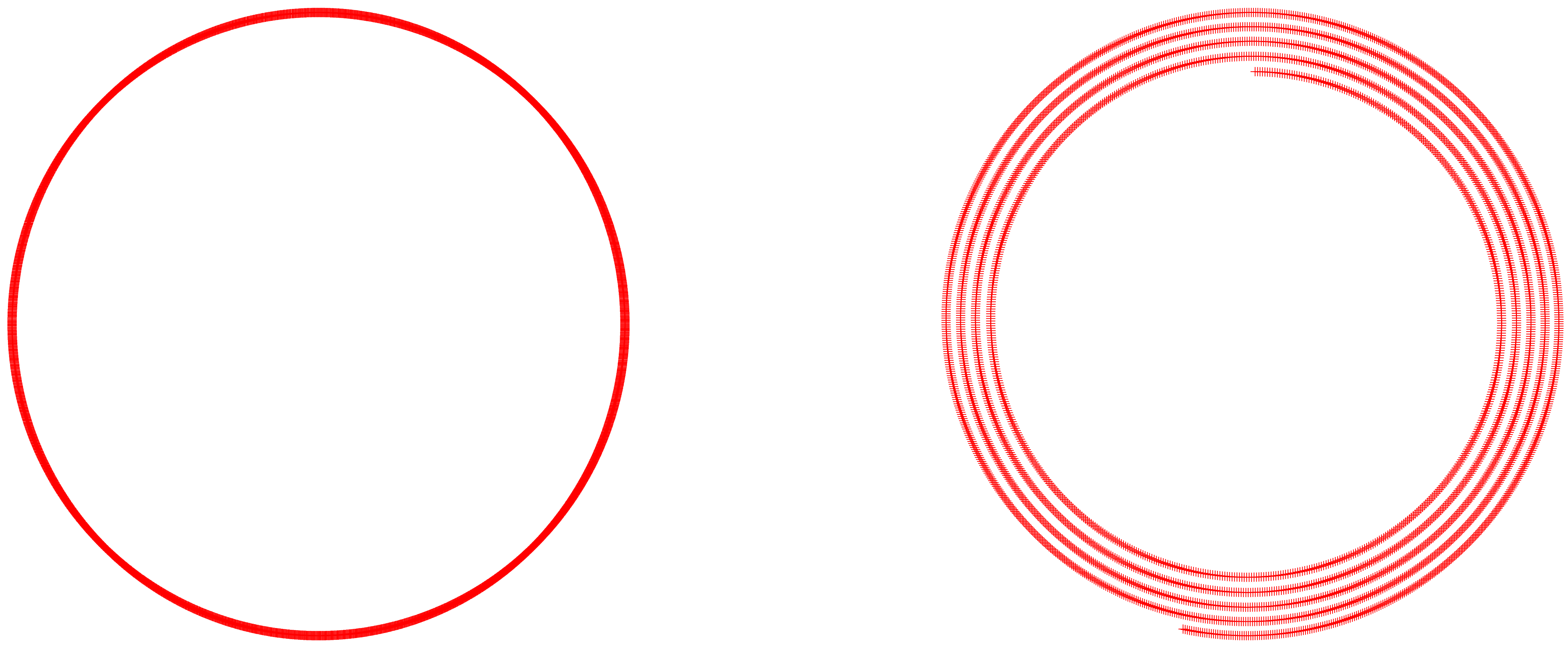
- Hamiltonian

$$H = \frac{1}{2}p^2 + \Phi(x) \qquad \longrightarrow \qquad ?$$

- The system is governed by a 'discretized Hamiltonian', if and only if the integration scheme is symplectic.

- Why does it matter?

Symplectic vs non symplectic integrators



Mixed variable integrators

- So far: symplectic integrators are great.
- How can it be even better?
- We can split the Hamiltonian:

$$H = H_0 + \epsilon \, H_{\text{pert}}$$

Integrate particle exactly with dominant Hamiltonian

Integrate particle exactly under perturbation Hamiltonian

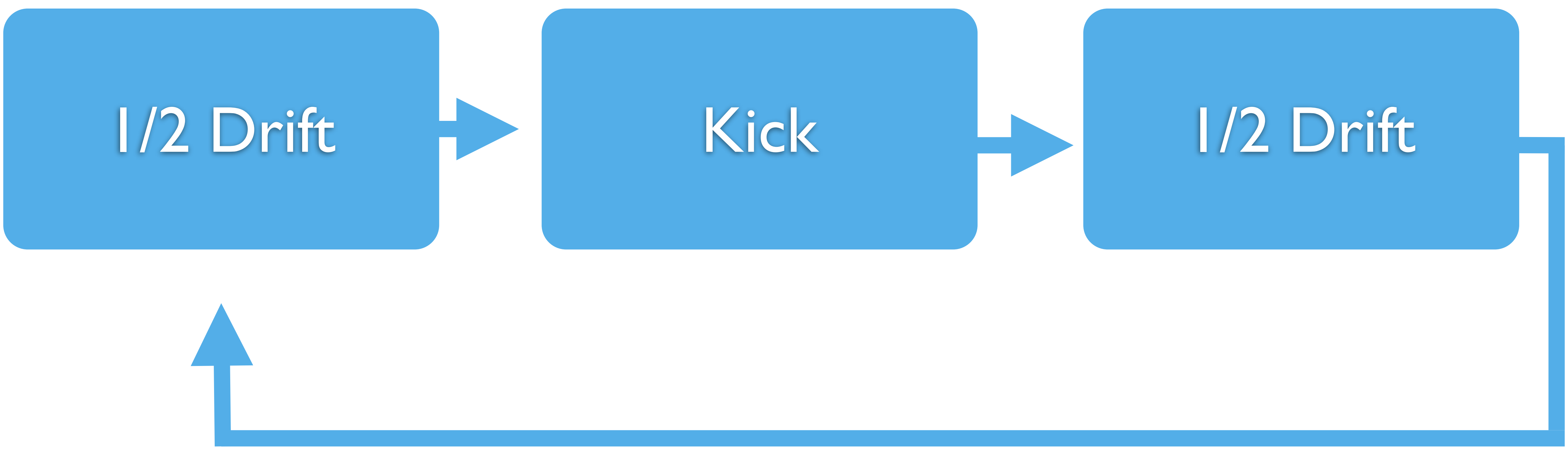
- Switch back and forth between different Hamiltonians
- Often uses different variables for different parts
- Then:

$$\text{Error} = \epsilon \, (\Delta t)^{p+1} \; [H_0, H_{\text{pert}}]$$

Example: Leap-Frog

$$H = \frac{1}{2}p^2 + \Phi(x)$$

Drift Kick



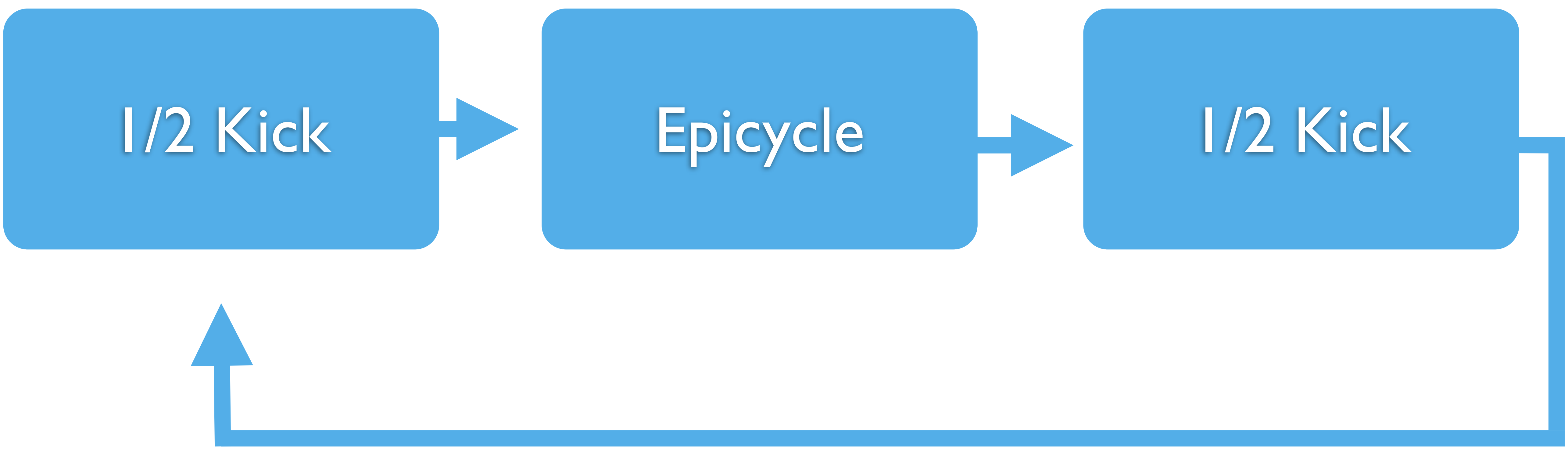
Example: SWIFT/MERCURY

$$H = \underbrace{\frac{1}{2}p^2 + \Phi_{\mathrm{Kepler}}(x)}_{\text{Kepler}} + \underbrace{\Phi_{\mathrm{Other}}(x)}_{\text{Kick}}$$

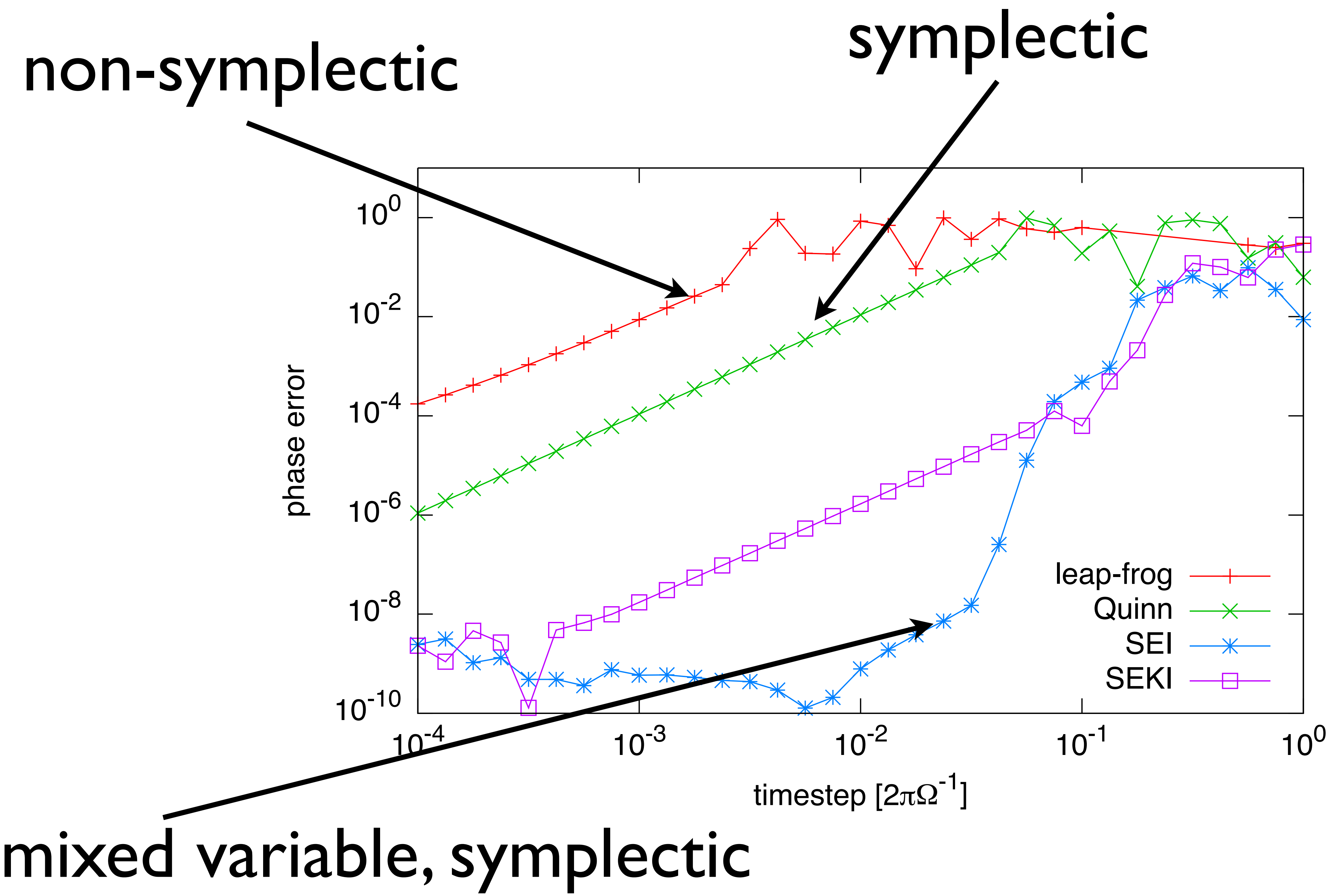
Example: Symplectic Epicycle Integrator

$$H = \frac{1}{2}p^2 + \Omega(p \times r)e_z + \frac{1}{2}\Omega^2\left[r^2 - 3(r \cdot e_x)^2\right] + \Phi(r)$$

Epicycle | Kick



10 Orders of magnitude better!



Take home message V

symplectic integrators

=

awesome

REBOUND

- Multi-purpose N-body code
- Optimized for collisional dynamics
- Code description paper recently accepted by A&A
- Written in C, open source
- Freely available at http://github.com/hannorein/rebound

Astronomy & Astrophysics manuscript no. paper
October 20, 2011

REBOUND: An open-source multi-purpose N-body code for collisional dynamics

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Submitted: 13 September 2011

ABSTRACT

REBOUND is a new multi-purpose N-body code which is freely available under an open-source license. It was designed for collisional dynamics such as planetary rings but can also solve the classical N-body problem. It is highly modular and can be customized easily to work on a wide variety of different problems in astrophysics and beyond. REBOUND comes with three symplectic integrators: leap-frog, the symplectic epicycle integrator (SEI) and a Wisdom-Holman mapping (WH). It supports open, periodic and shearing-sheet boundary conditions. REBOUND can use a Barnes-Hut tree to calculate both self-gravity and collisions. These modules are fully parallelized with MPI as well as OpenMP. The former makes use of a static domain decomposition and a distributed essential tree. Two new collision detection modules based on a plane-sweep algorithm are also implemented. The performance of the plane-sweep algorithm is superior to a tree code for simulations in which one dimension is much longer than the other two and in simulations which are quasi-two dimensional with less than one million particles. In this work, we discuss the different algorithms implemented in REBOUND, the philosophy behind the code's structure as well as implementation specific details of the different modules. We present results of accuracy and scaling tests which show that the code can run efficiently on both desktop machines and large computing clusters.

Key words. Methods: numerical – Planets and satellites: rings – Proto-planetary disks

1. Introduction

REBOUND is a new open-source collisional N-body code. This code, and precursors of it, have already been used in wide variety of publications (Rein & Papaloizou 2010; Crida et al. 2010; Rein et al. 2010, Rein & Latter in preparation; Rein & Liu in preparation). We believe that REBOUND can be of great use for many different problems and have a wide reach in astrophysics and other disciplines. To our knowledge, there is currently no publicly available code for collisional dynamics capable of solving the problems described in this paper. This is why we decided to make it freely available under the open-source license GPLv3[1].

Collisional N-body simulations are extensively used in astrophysics. A classical application is a planetary ring (see e.g. Wisdom & Tremaine 1988; Salo 1991; Richardson 1994; Lewis & Stewart 2009; Rein & Papaloizou 2010; Michikoshi & Kokubo 2011, and references therein) which have often a collision time-scale that is much shorter than or at least comparable to an orbital time-scale. Self-gravity plays an important role, especially in the dense parts of Saturn's rings (Schmidt et al. 2009). These simulations are usually done in the shearing sheet approximation (Hill 1878).

Collisions are also important during planetesimal formation (Johansen et al. 2007; Rein et al. 2010, Johansen et al. in preparation). Collisions provide the dissipative mechanism to form a planetesimal out of a gravitationally bound swarm of boulders.

[1] The full license is distributed together with REBOUND. It can also be downloaded from http://www.gnu.org/licenses/gpl.html.

REBOUND modules

Geometry

- Open boundary conditions
- Periodic boundary conditions
- Shearing sheet / Hill's approximation

Integrators

- Leap frog
- Symplectic Epicycle integrator (SEI)
- Wisdom-Holman mapping (WH)

Gravity

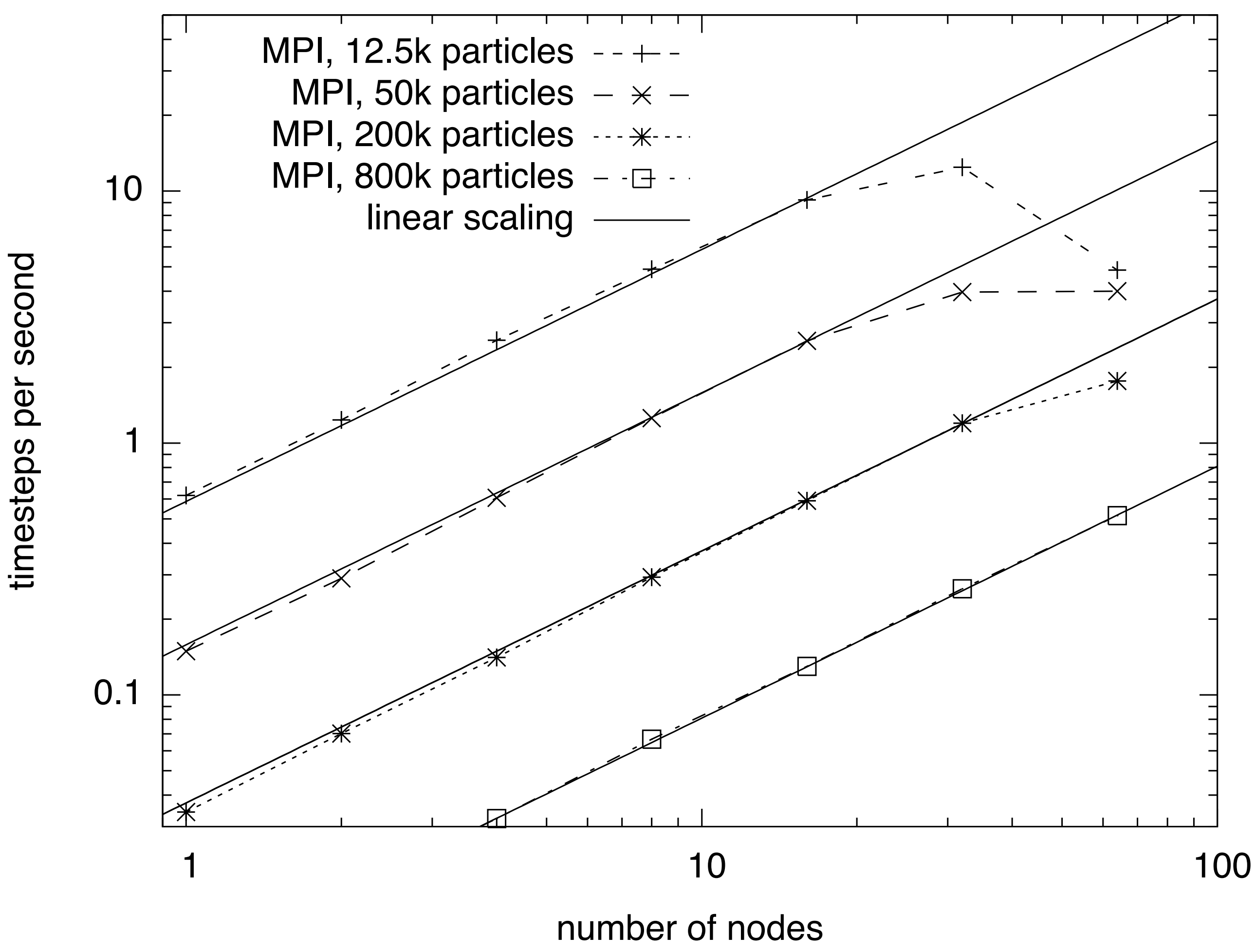
- Direct summation, $O(N^2)$
- BH-Tree code, $O(N \log(N))$
- FFT method, $O(N \log(N))$

Collision detection

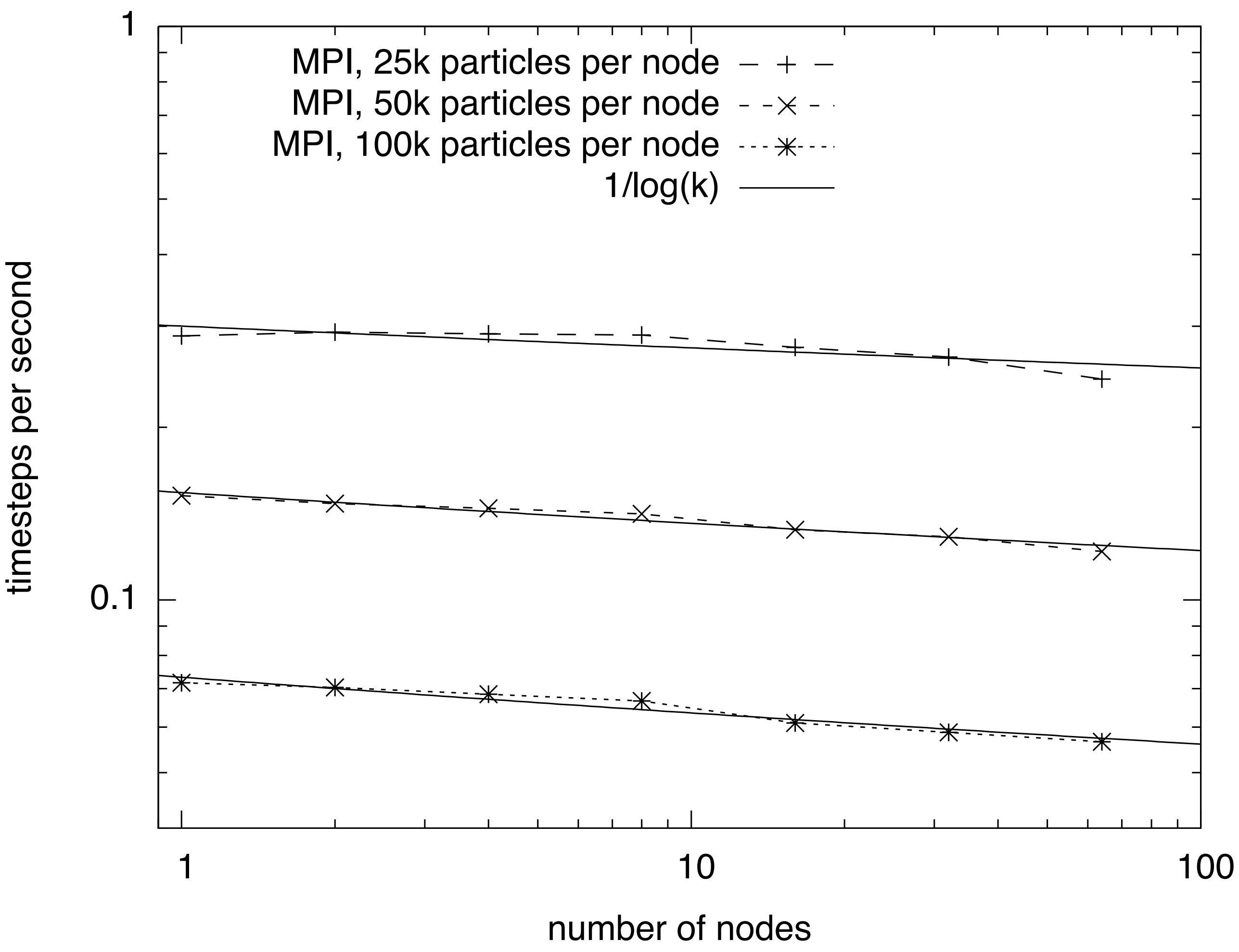
- Direct nearest neighbor search, $O(N^2)$
- BH-Tree code, $O(N \log(N))$
- Plane sweep algorithm, $O(N)$ or $O(N^2)$

REBOUND scalings using a tree

strong



weak



DEMO

Take home message VII

Download REBOUND

Conclusions

Conclusions

Resonances and multi-planetary systems

Multi-planetary system provide insight in otherwise unobservable formation phase

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

Moonlets in Saturn's rings

Small scale version of the proto-planetary disc
Random walk can be directly observed
Caused by collisions and gravitational wakes

REBOUND

N-body code, optimized for collisional dynamics, uses symplectic integrators
Open source, freely available, very modular and easy to use
http://github.com/hannorein/rebound