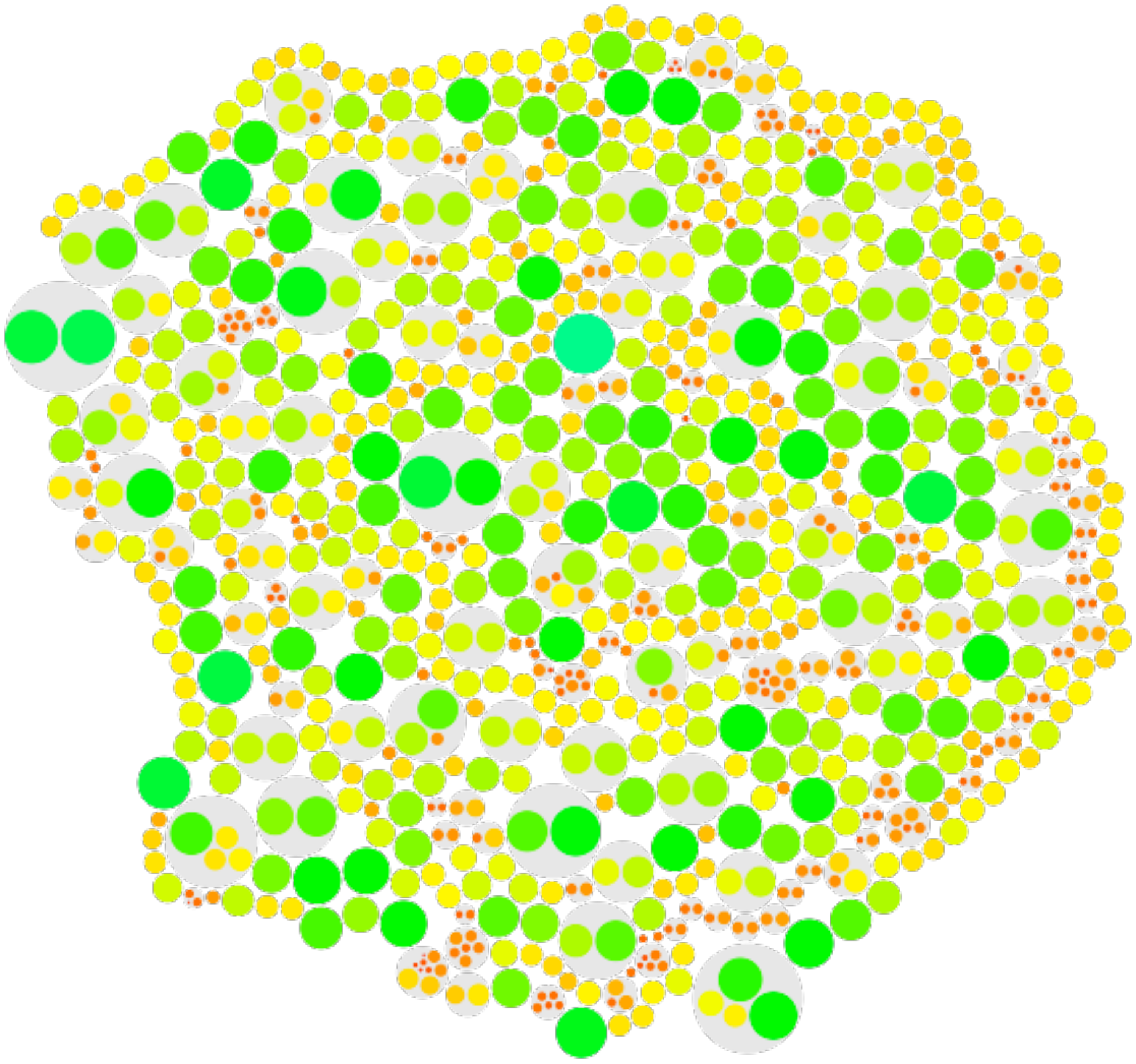
Institute for Advanced Study

1) The case for stochastic orbital migration
2) Open Exoplanet Catalogue

Hanno Rein @ CITA, March 2013

Extra-solar planet census

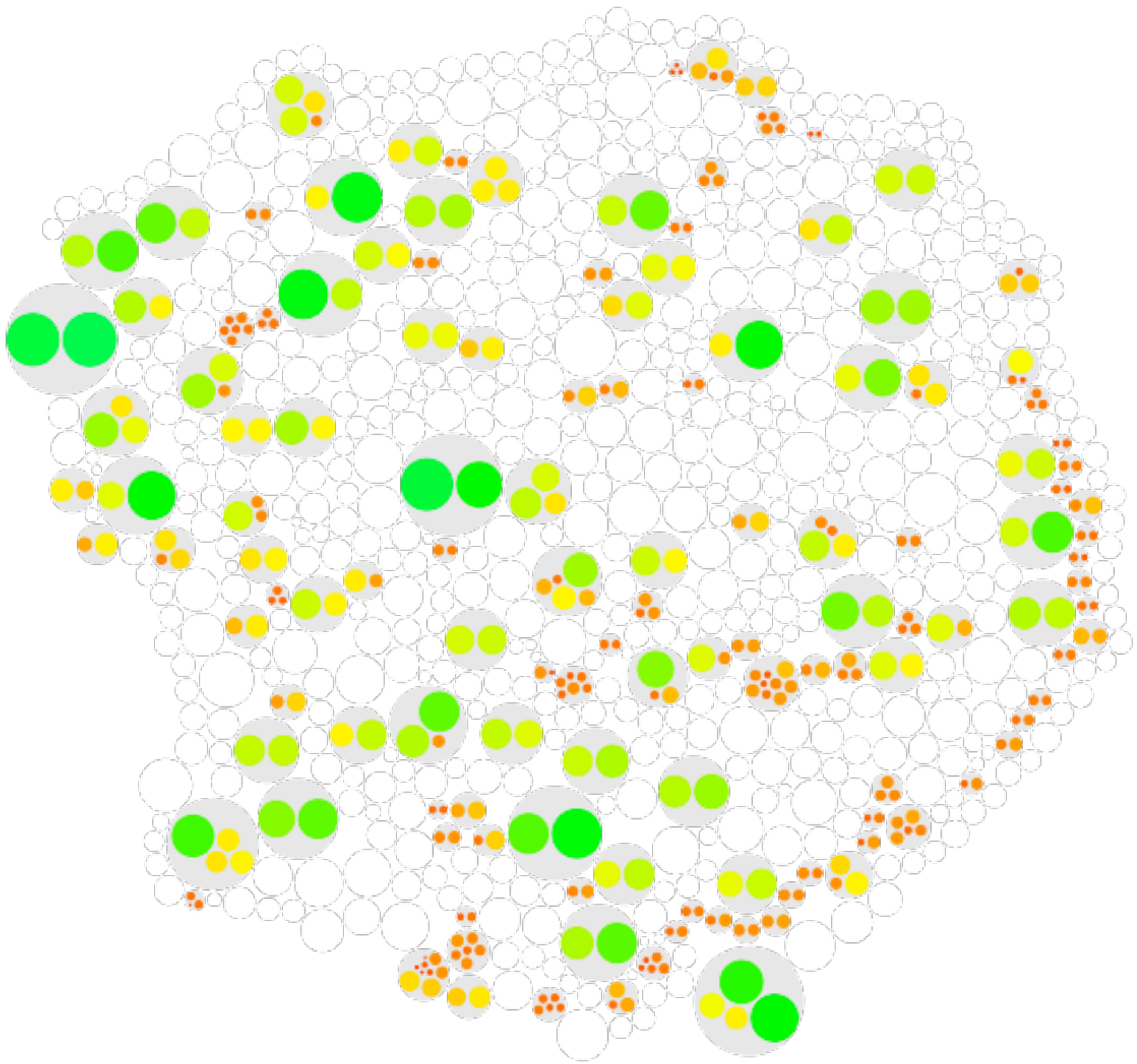
All discovered extra-solar planets



869 confirmed extra-solar planets

- Super-Jupiters
- (Hot) Jupiters
- Neptunes
- Super-Earths
- Earth-like planets

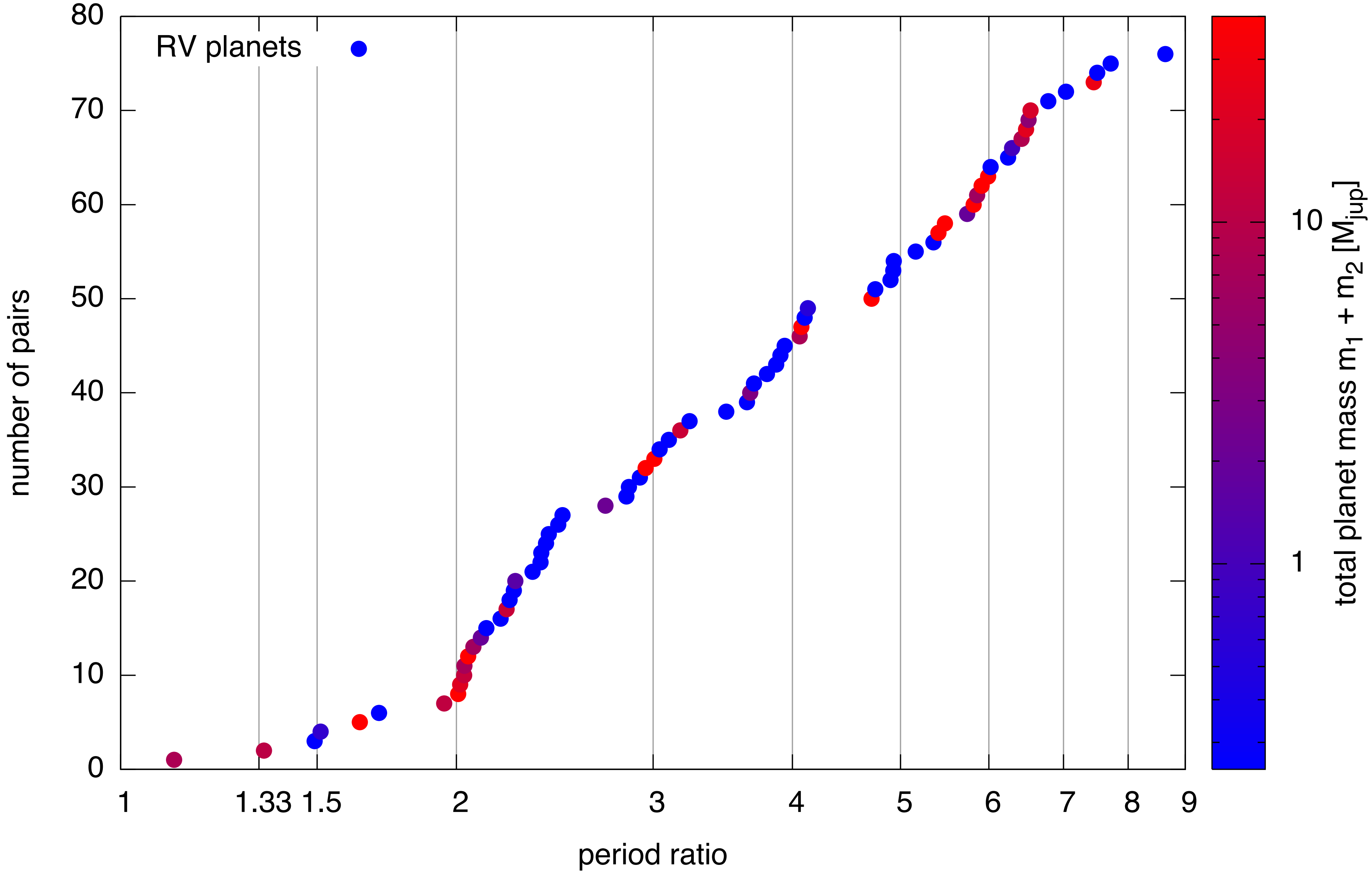
All multi-planetary systems



327 confirmed planets in multi-planetary systems

- Multiple Jupiters
- Densely packed systems of Neptunes and (Super)-Earths
- 1 Solar System
- Some systems are deep in resonance

Radial velocity planets

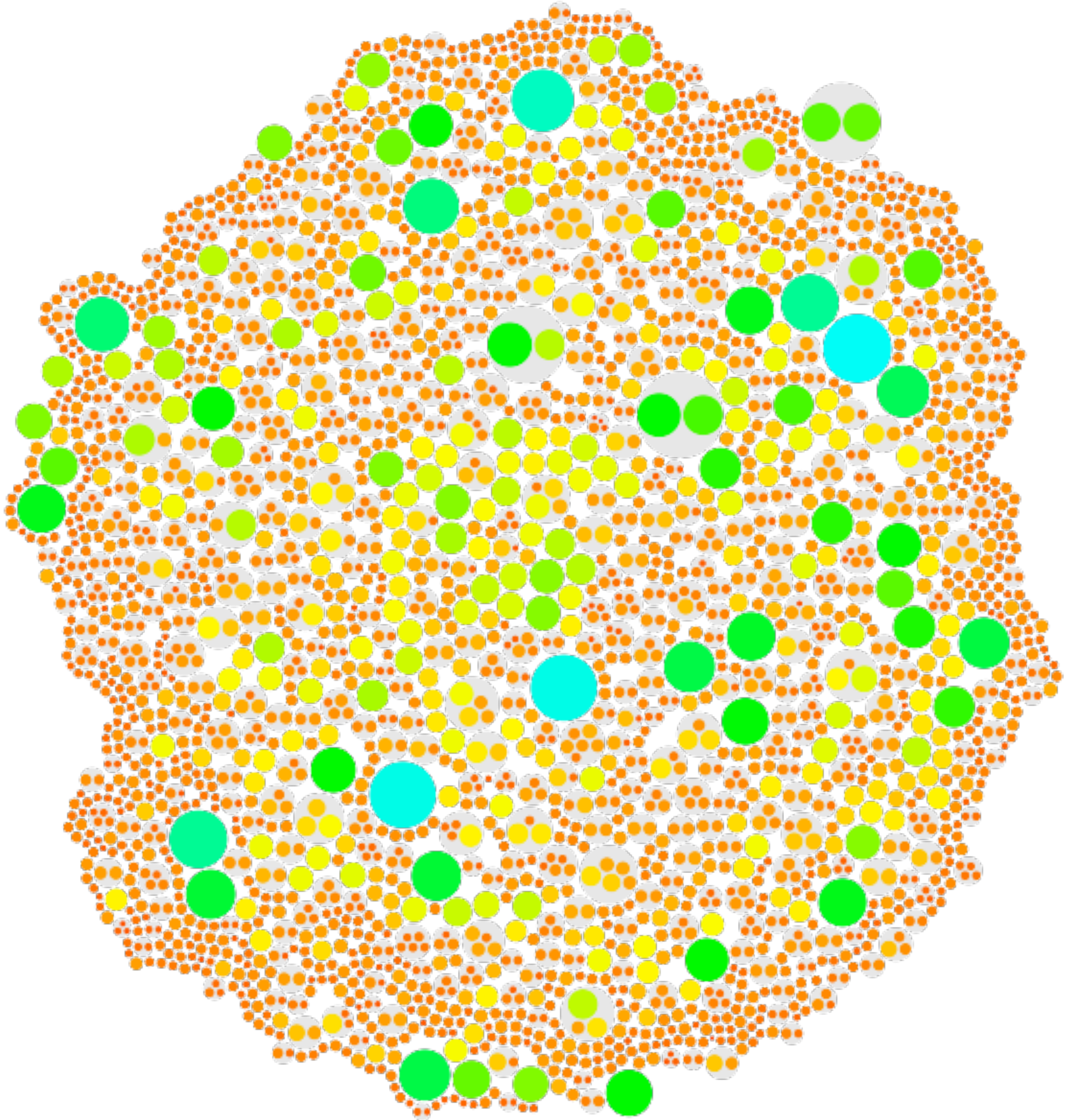


Cumulative period ratio in multi-planetary systems

- 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 (2012)

Kepler candidates

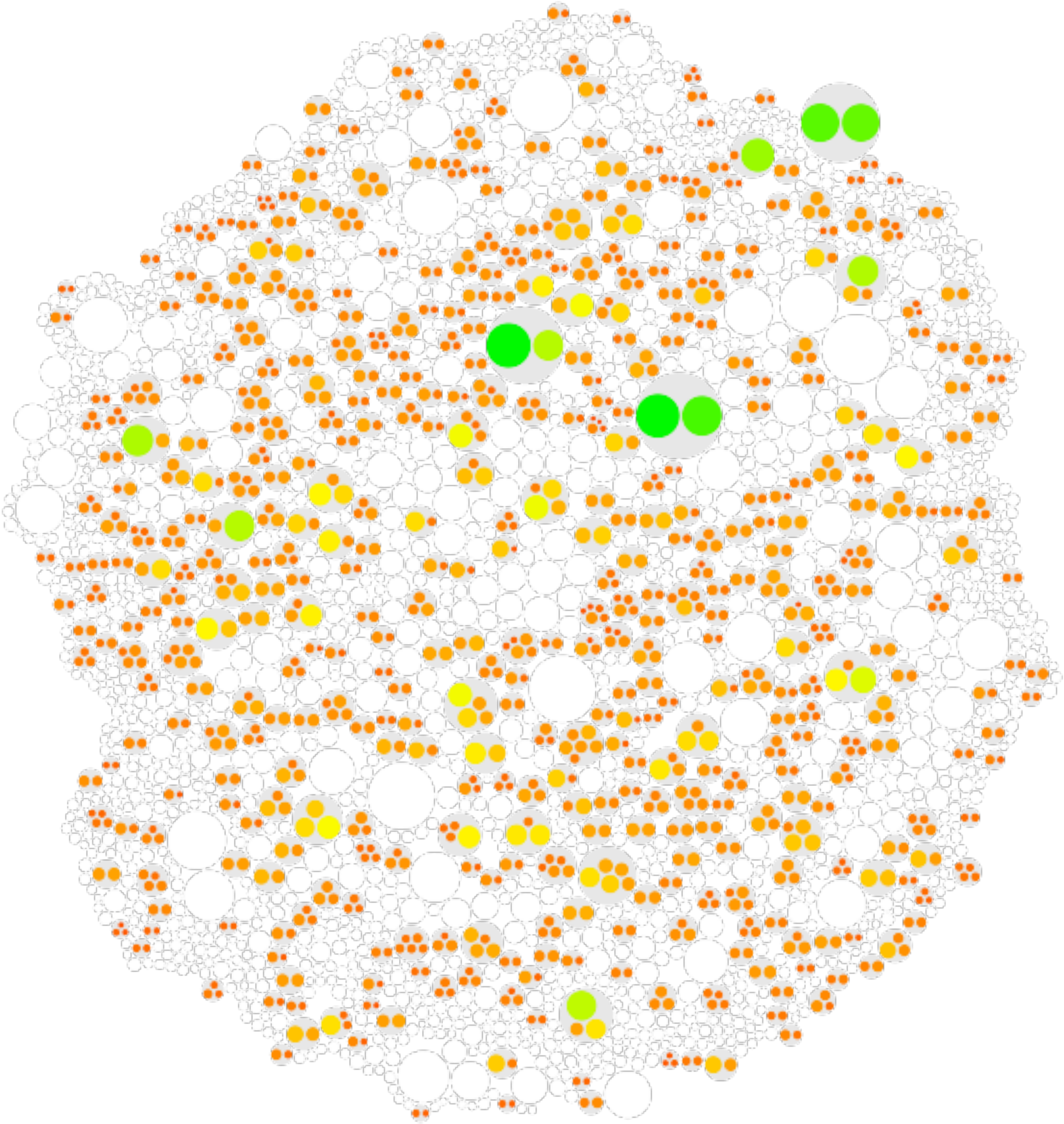


2740 planet candidates

- Probing a different regime
- Small mass planets
- A lot of planets

Open Exoplanet Catalogue (Rein 2012b)

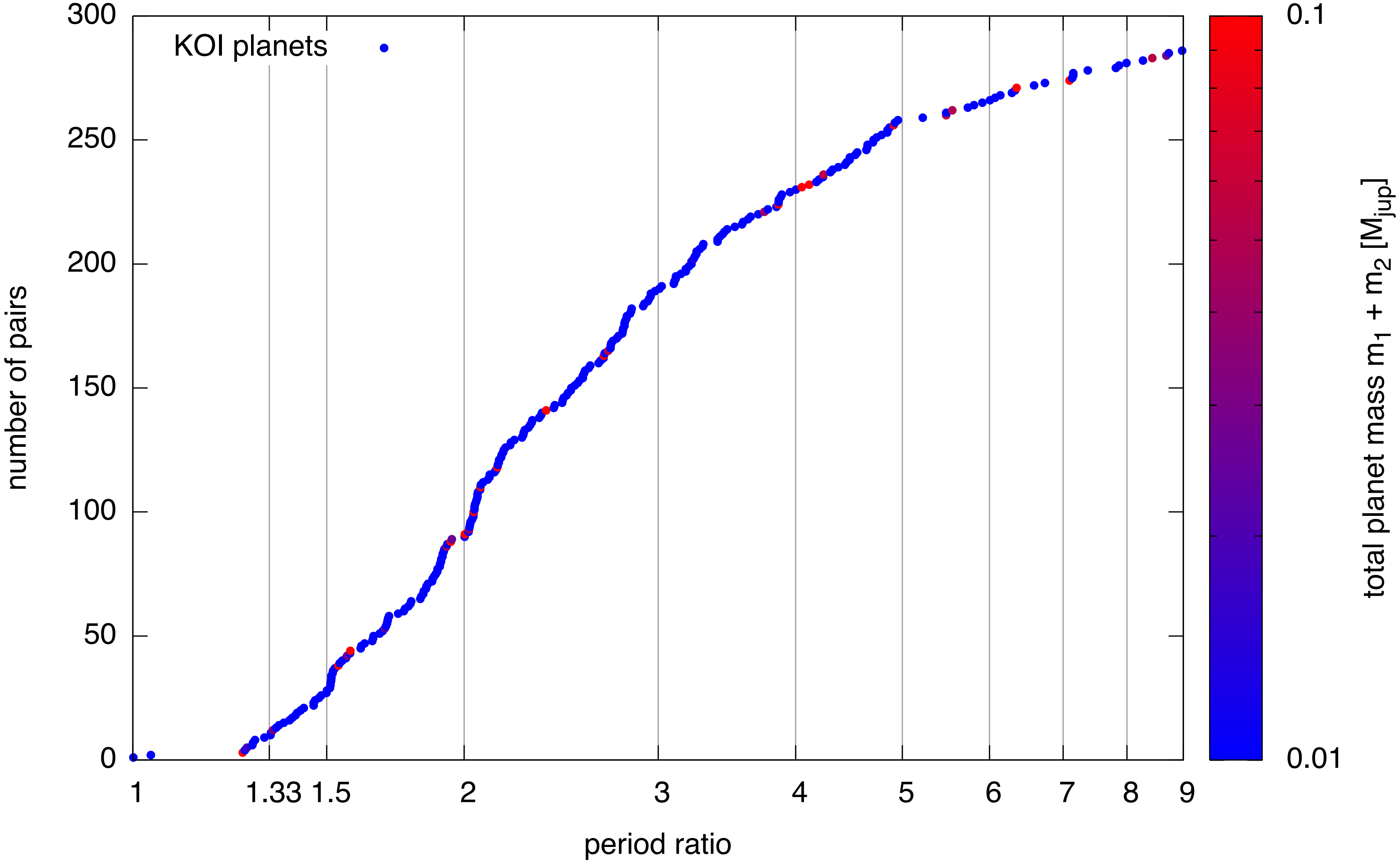
Kepler candidates with multiple planets



Kepler multi-planetary systems

- Small mass planets
- Hierarchical systems
- Densely packed
- Not many are in resonance

Kepler's transiting planet candidates

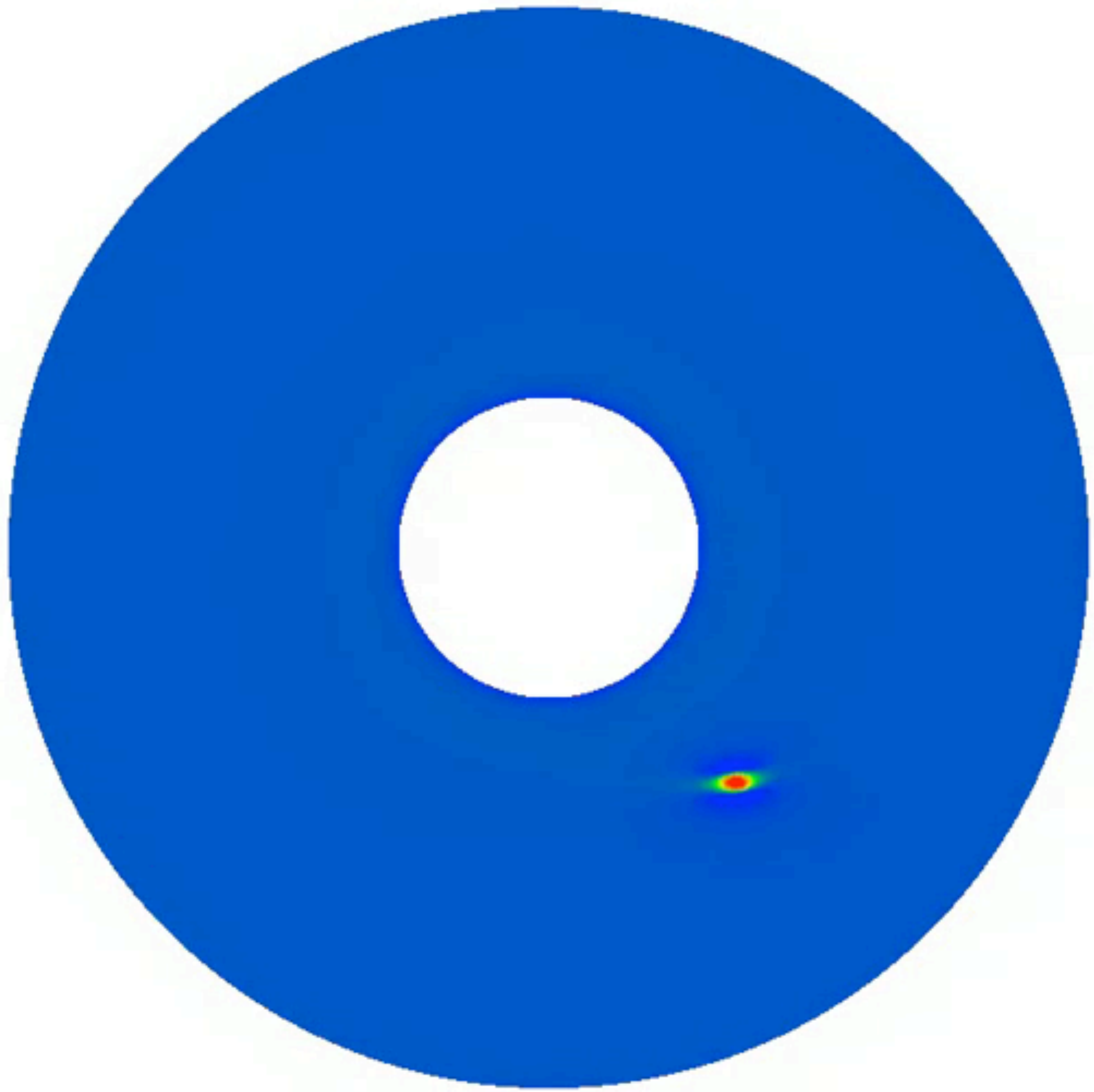


- Period ratio distribution much smoother for small mass planets
- Deficiencies near 4:3, 3:2, 2:1
- Excess slightly outside of the exact commensurability

Stochastic orbital migration

Migration - Type I

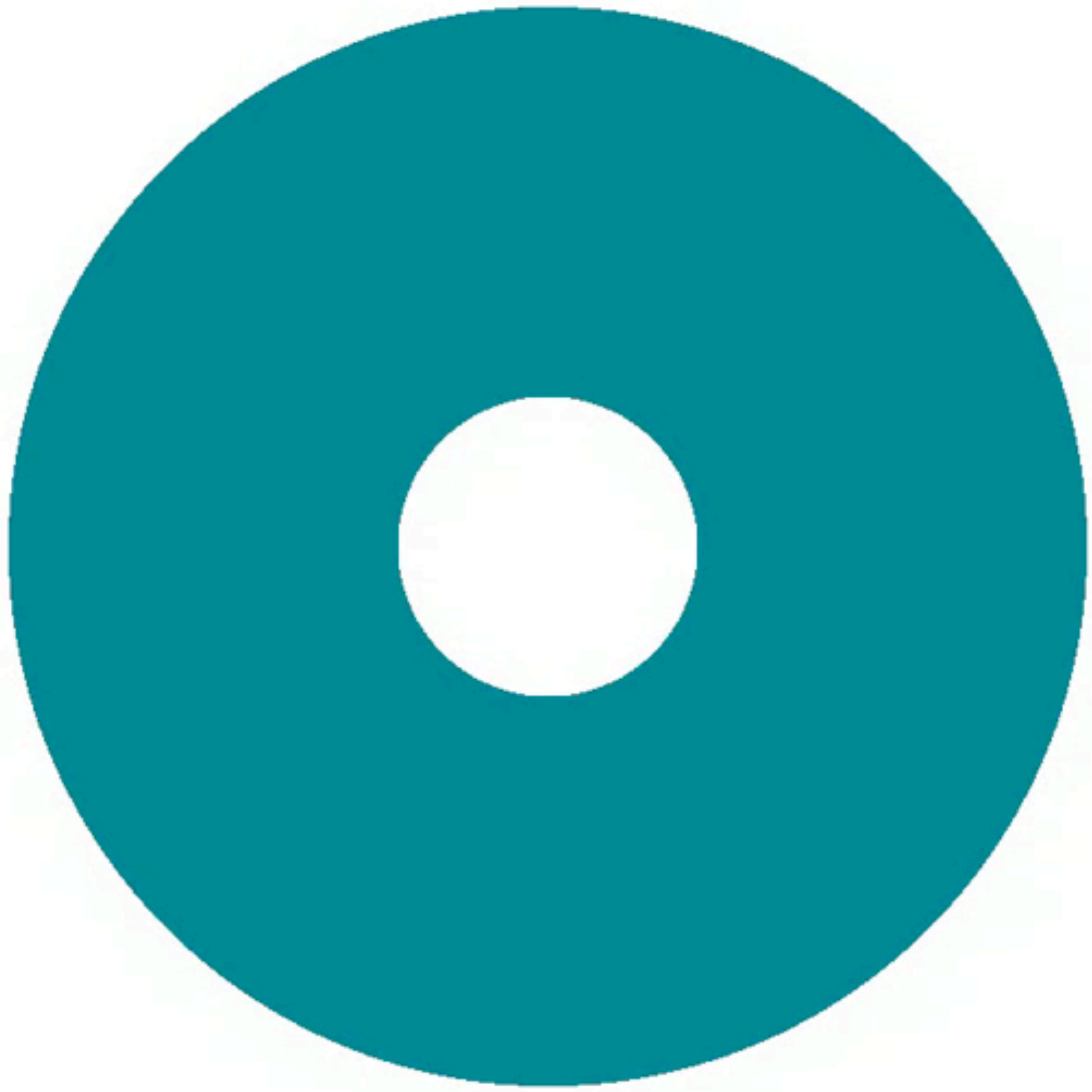
- Low mass planets
- No gap opening in disc
- Migration rate is fast
- Depends strongly on thermodynamics of the disc



2D hydro code Prometheus (Rein 2010)

Migration - Type II

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



2D hydro code Prometheus (Rein 2010)

How does a real protoplanetary disk look like?

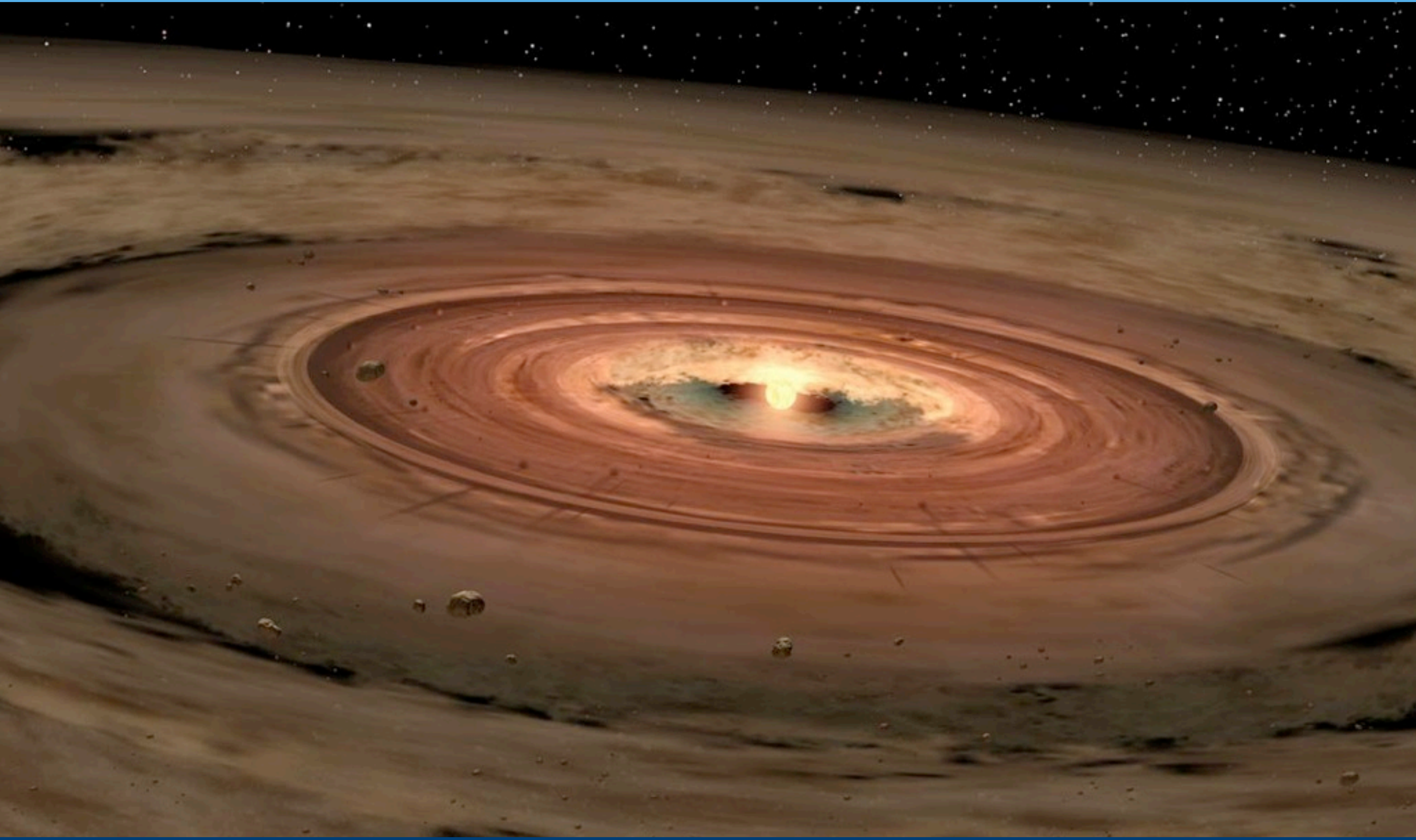
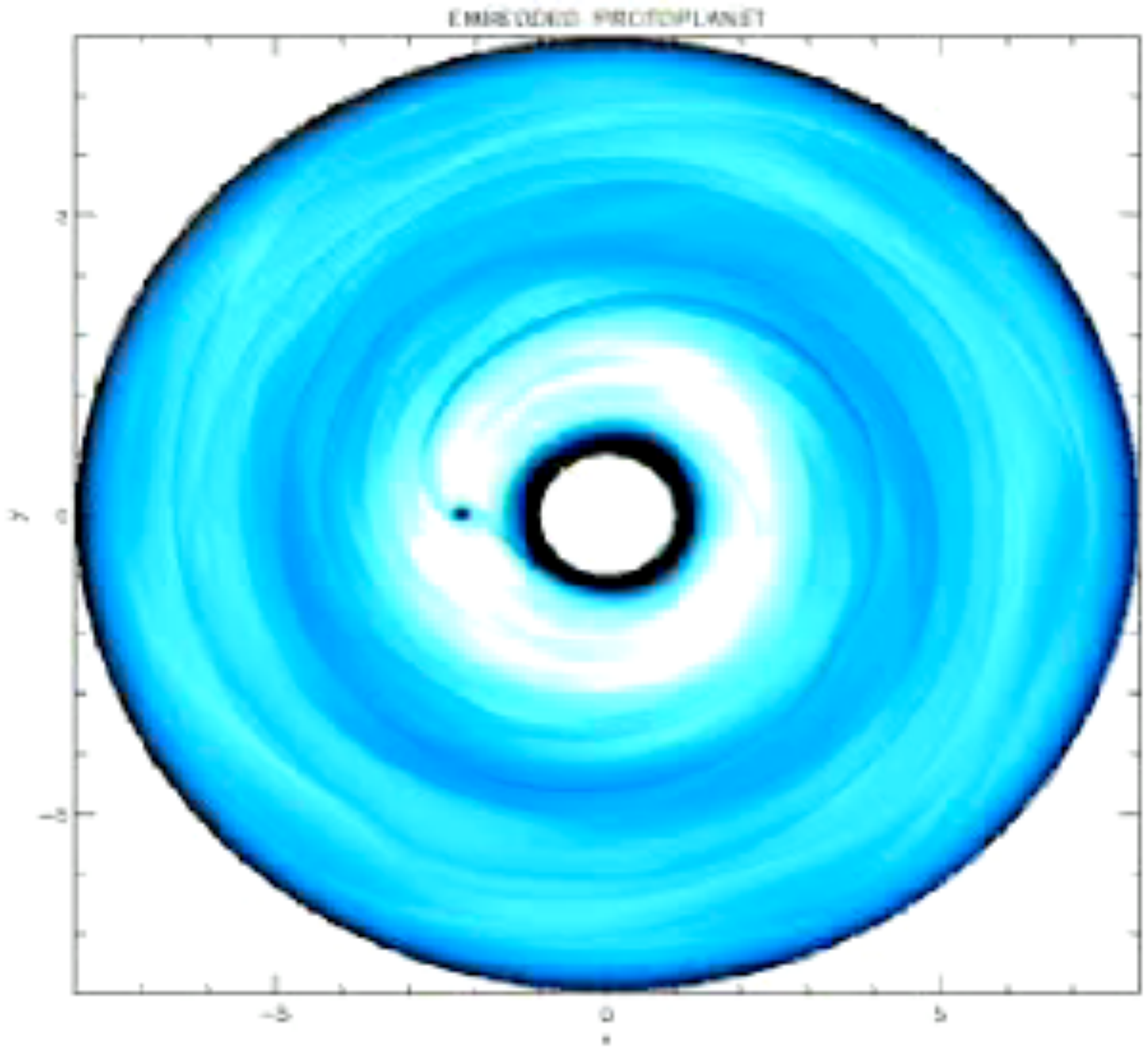


Image credit: NASA/JPL-Caltech

Why think about stochastic migration?

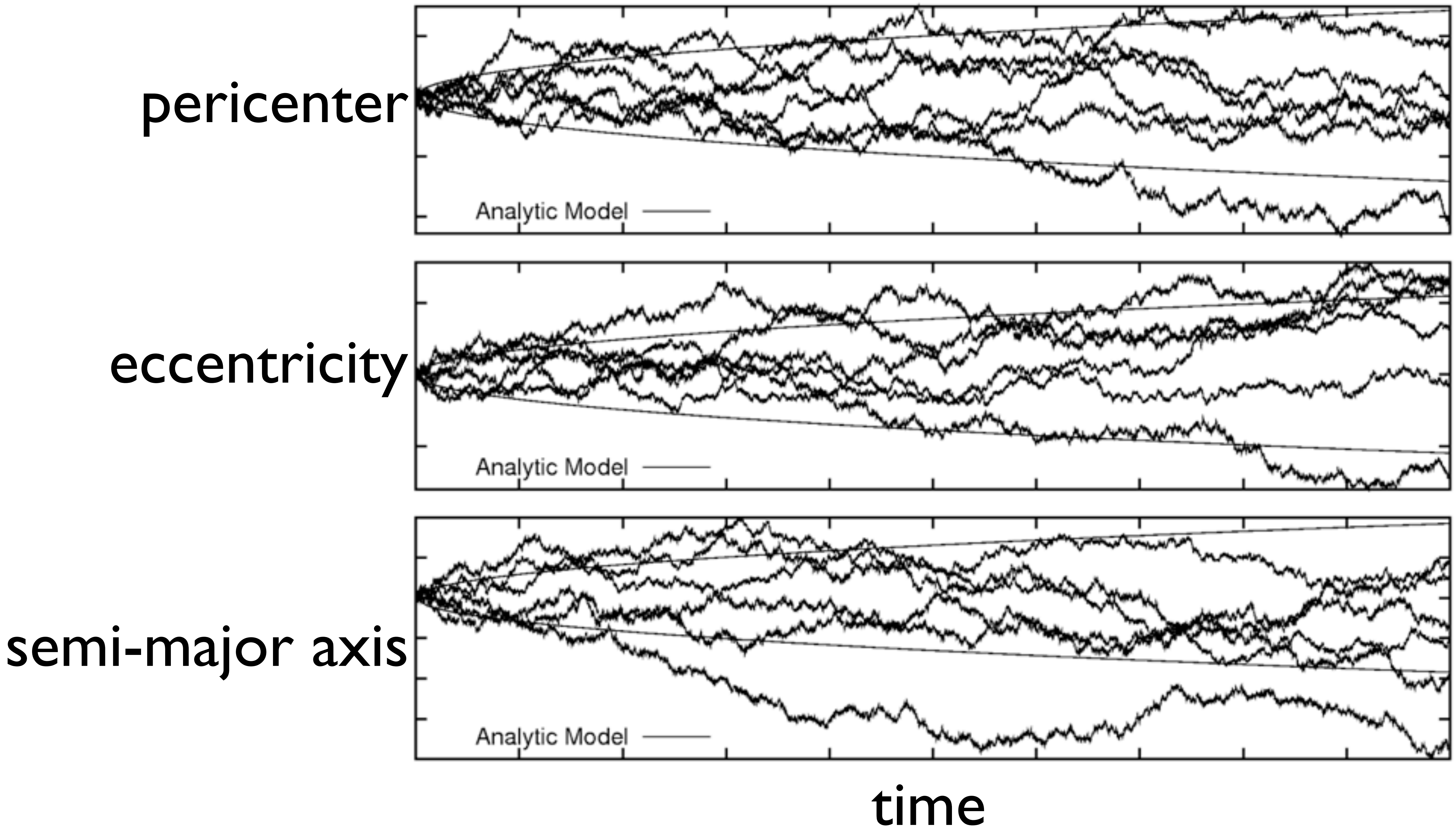
- Angular momentum transport
- Magnetorotational instability (MRI)
- Density perturbations interact gravitationally with planets
- Stochastic forces lead to random walk
- Large uncertainties in strength of forces



Animation from Nelson & Papaloizou 2004

Random forces measured by Laughlin et al. 2004, Nelson 2005, Oischi et al. 2007

Random walk in all orbital parameters



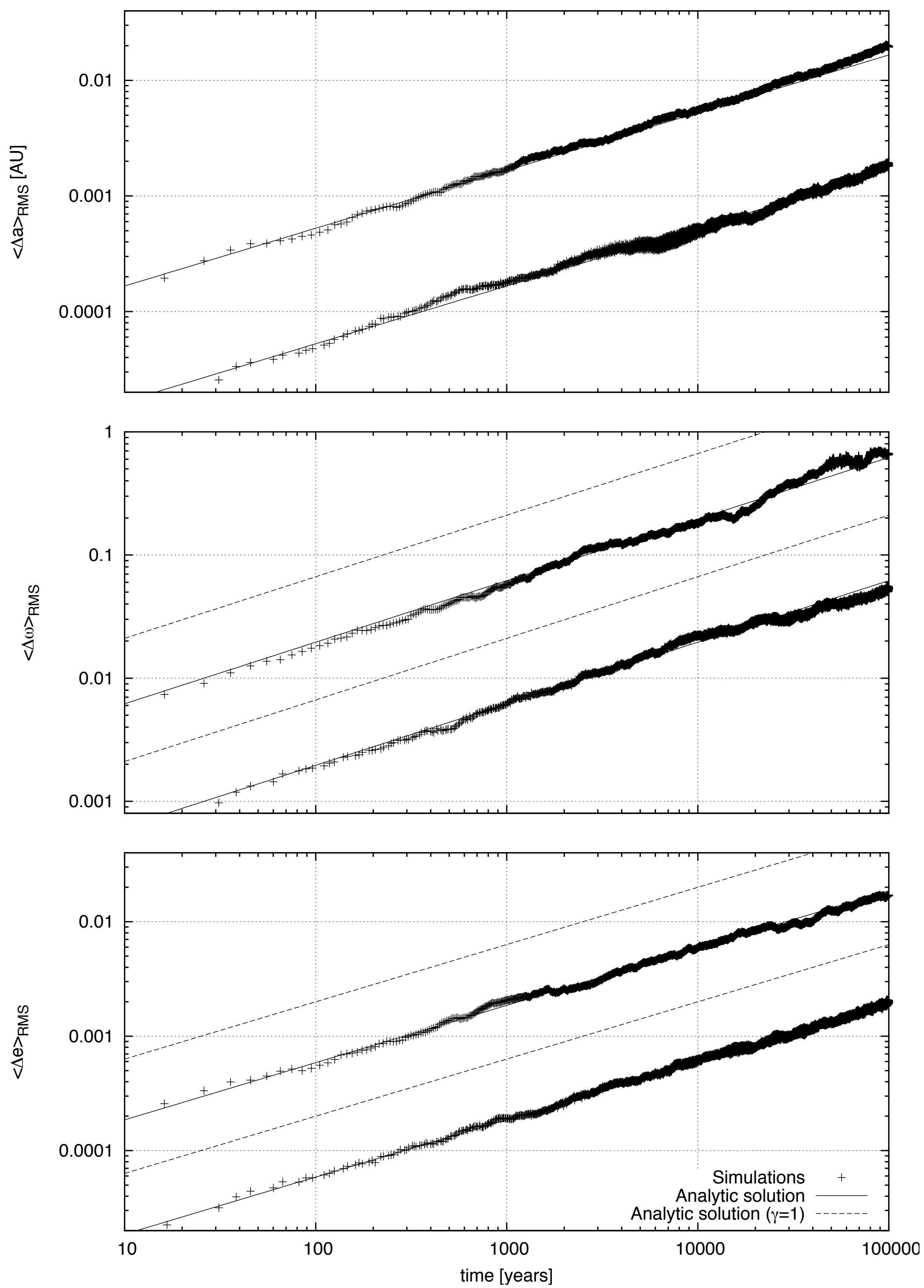
Rein & Papaloizou 2009

Analytic growth rates for 1 planet

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

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

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

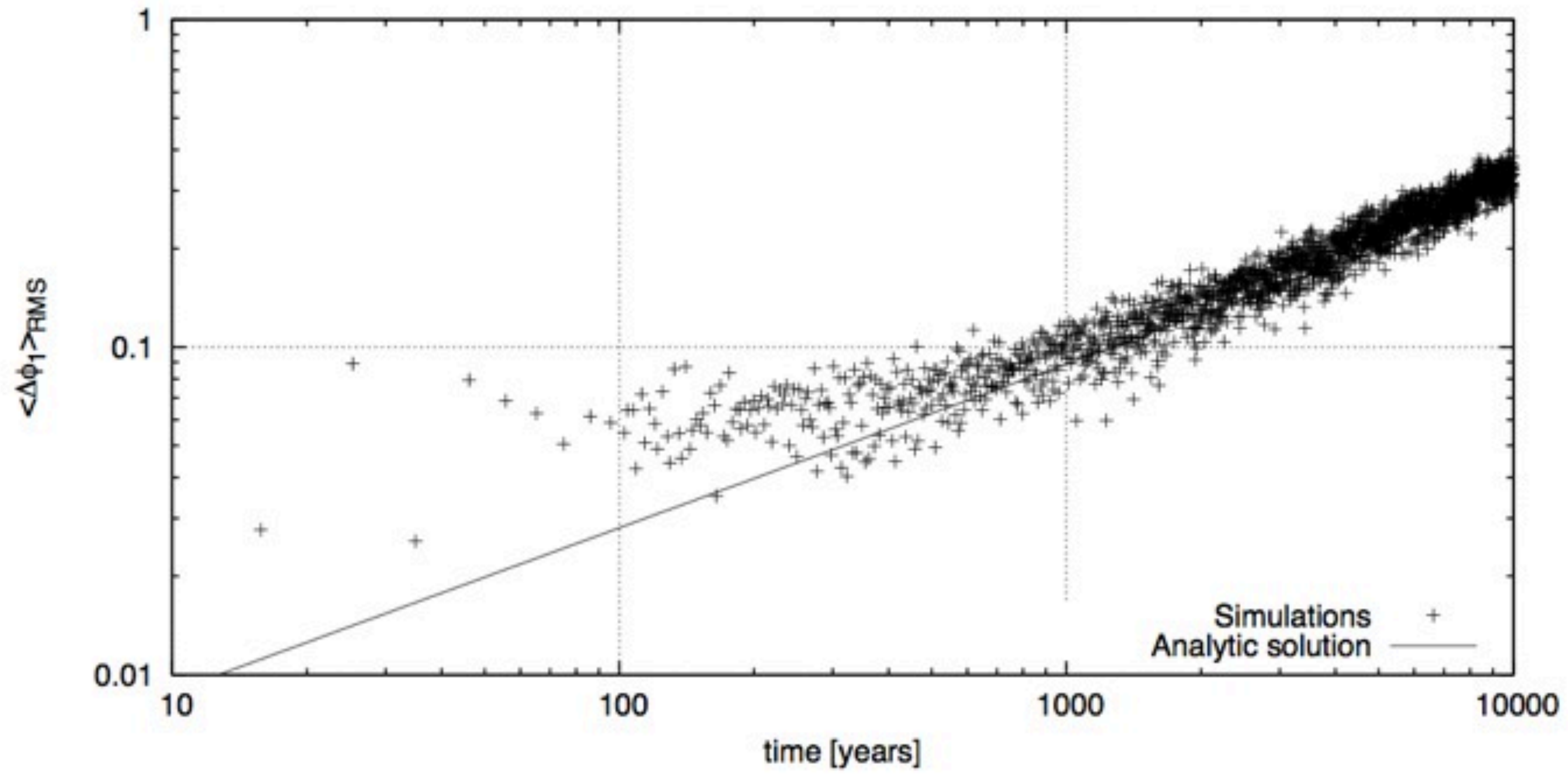


Rein & Papaloizou 2009, Adams et al 2009, Rein 2010

Analytic growth rates for 2 planets

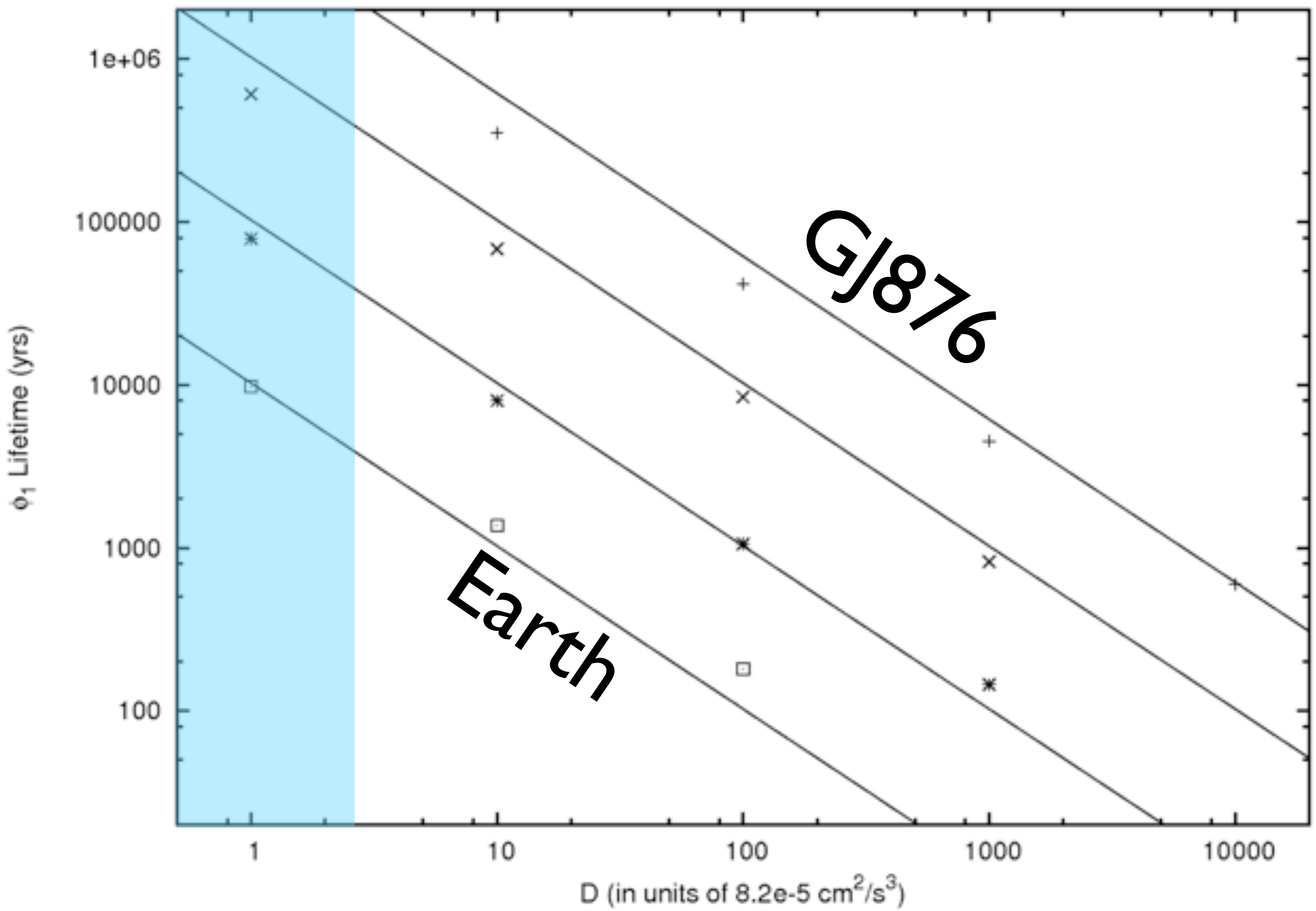
$$\frac{(\Delta\phi_1)^2}{(p+1)^2} = \frac{9\gamma_f}{a_1^2\omega_{lf}^2}\, D\, t$$

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



Rein & Papaloizou 2009

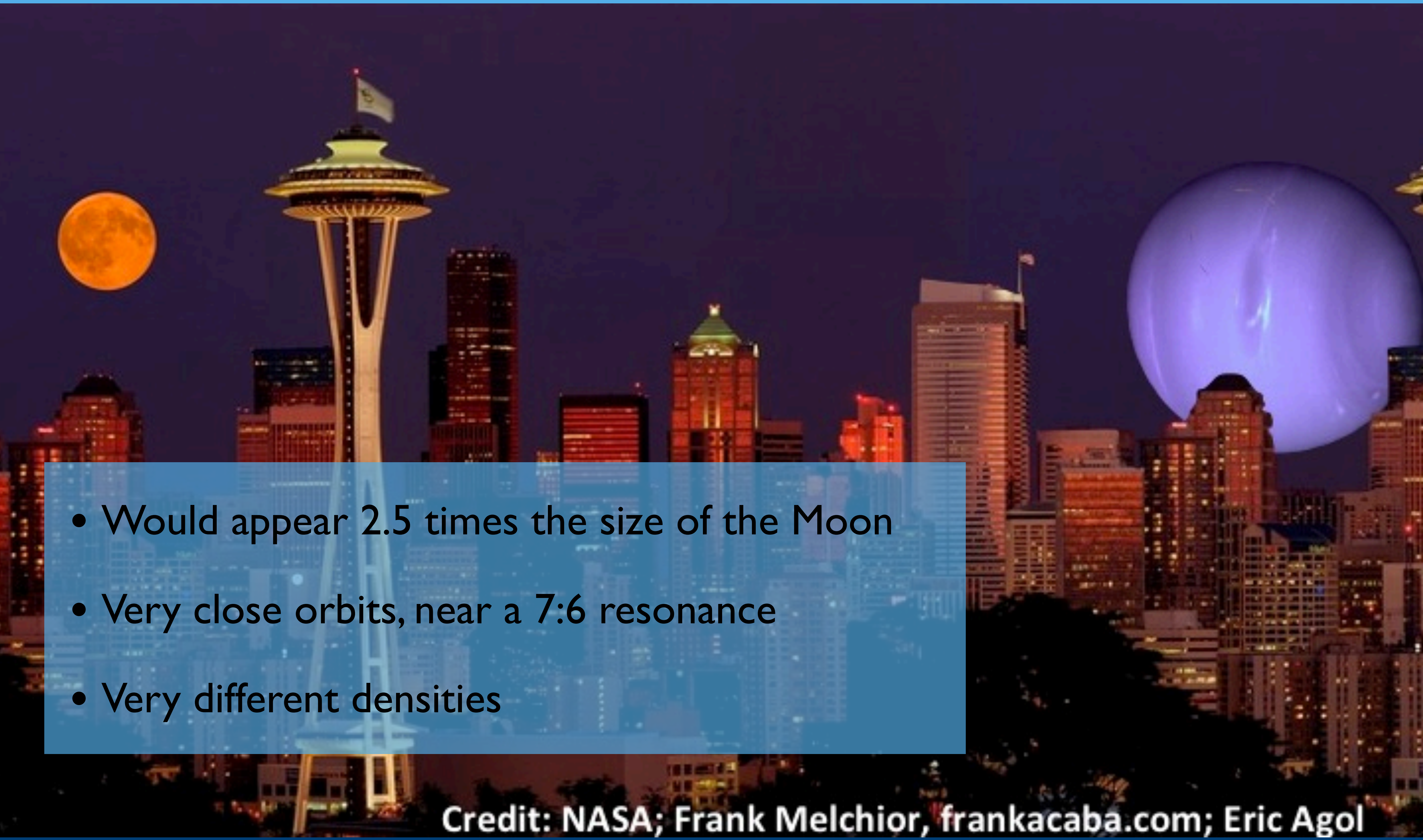
Multi-planetary systems in mean motion resonance



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

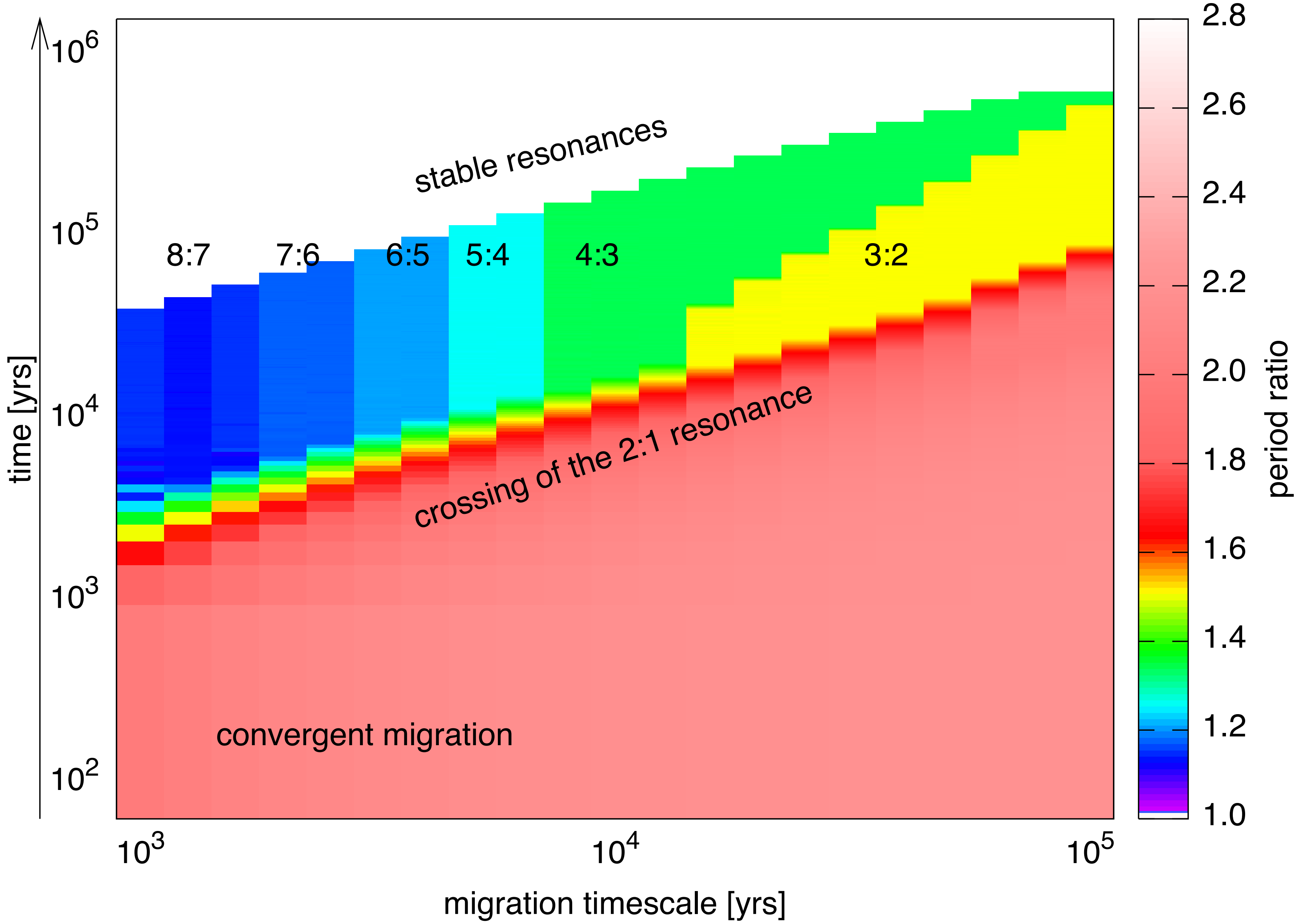
The formation of Kepler-36

Kepler-36 c as seen from Kepler-36 b



- Would appear 2.5 times the size of the Moon
- Very close orbits, near a 7:6 resonance
- Very different densities

Formation of Kepler-36



- Migration rate and mass ratio determine the final resonance
- Higher order resonances require faster migration rates
- Higher mass planets end up in lower order resonances
- Once in resonance, planets often stay there for the rest of the disc lifetime

Pardekooper, Rein & Kley (in prep)

Problem with Kepler-36

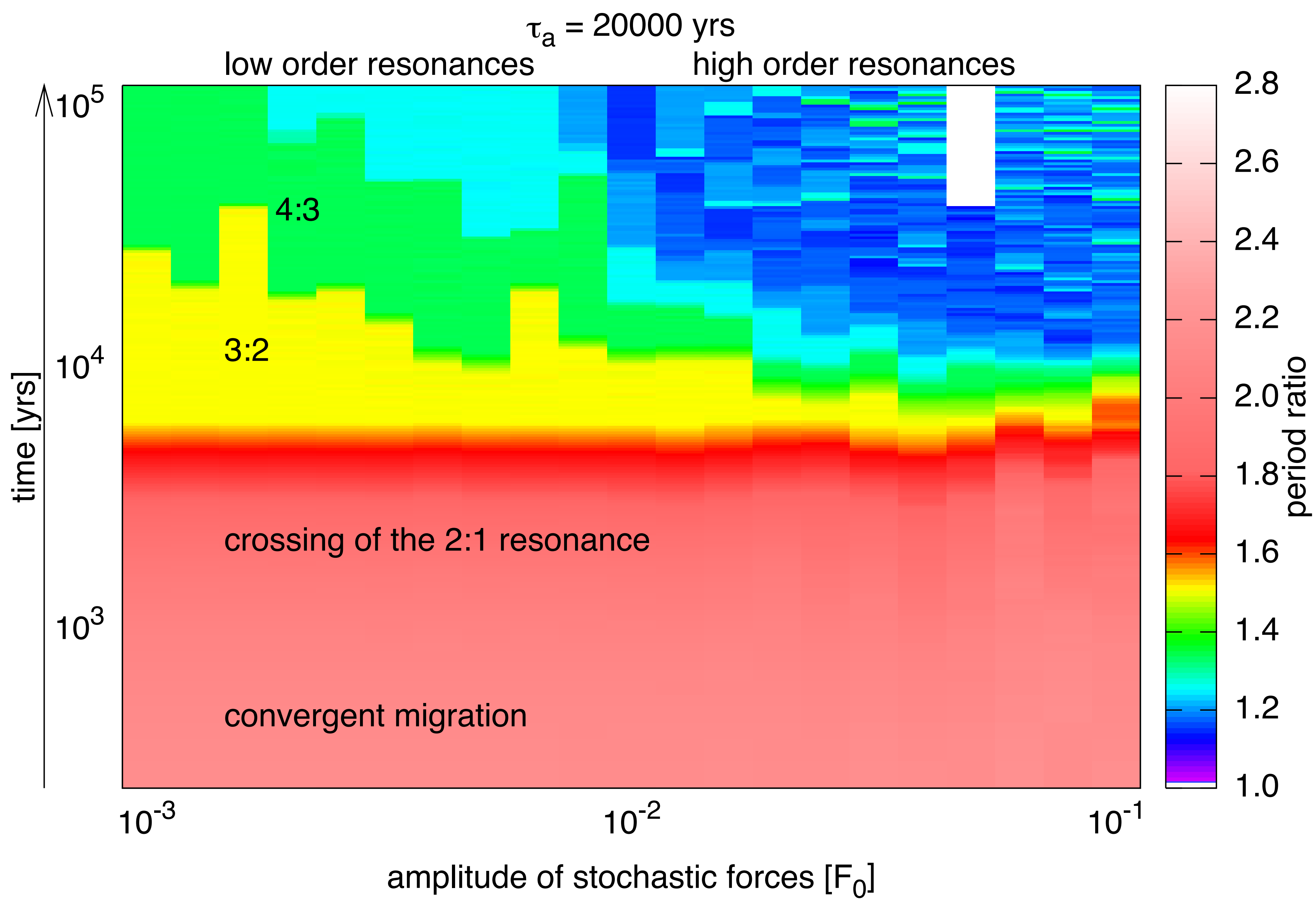
<1000 years

Need extremely fast migration rate to capture into a high order resonance.

Unrealistically fast.

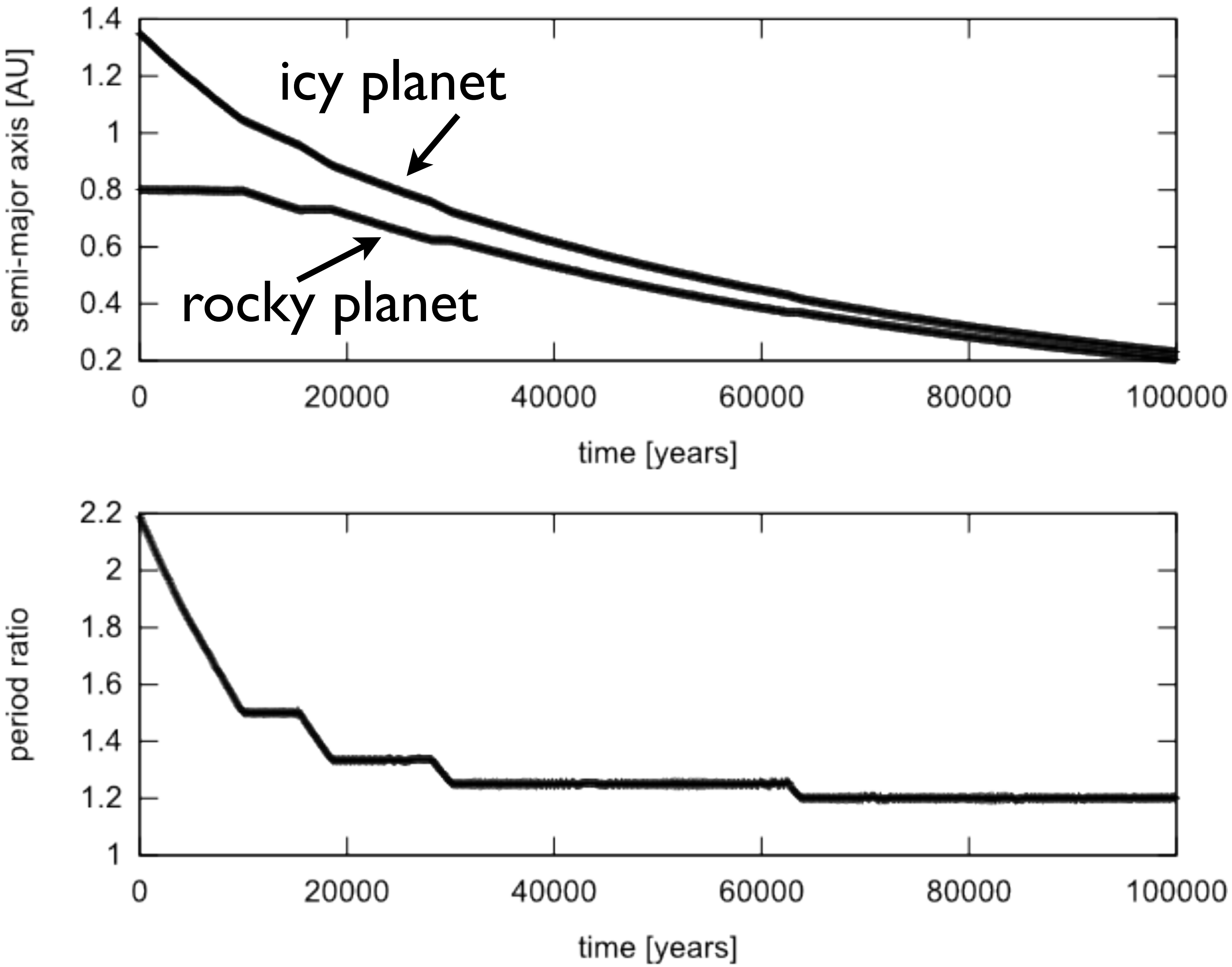
Planets are not large enough to migrate in Type III regime.

Solution: Stochastic migration



Pardekooper, Rein & Kley (in prep)

Convergent migration in Kepler-36



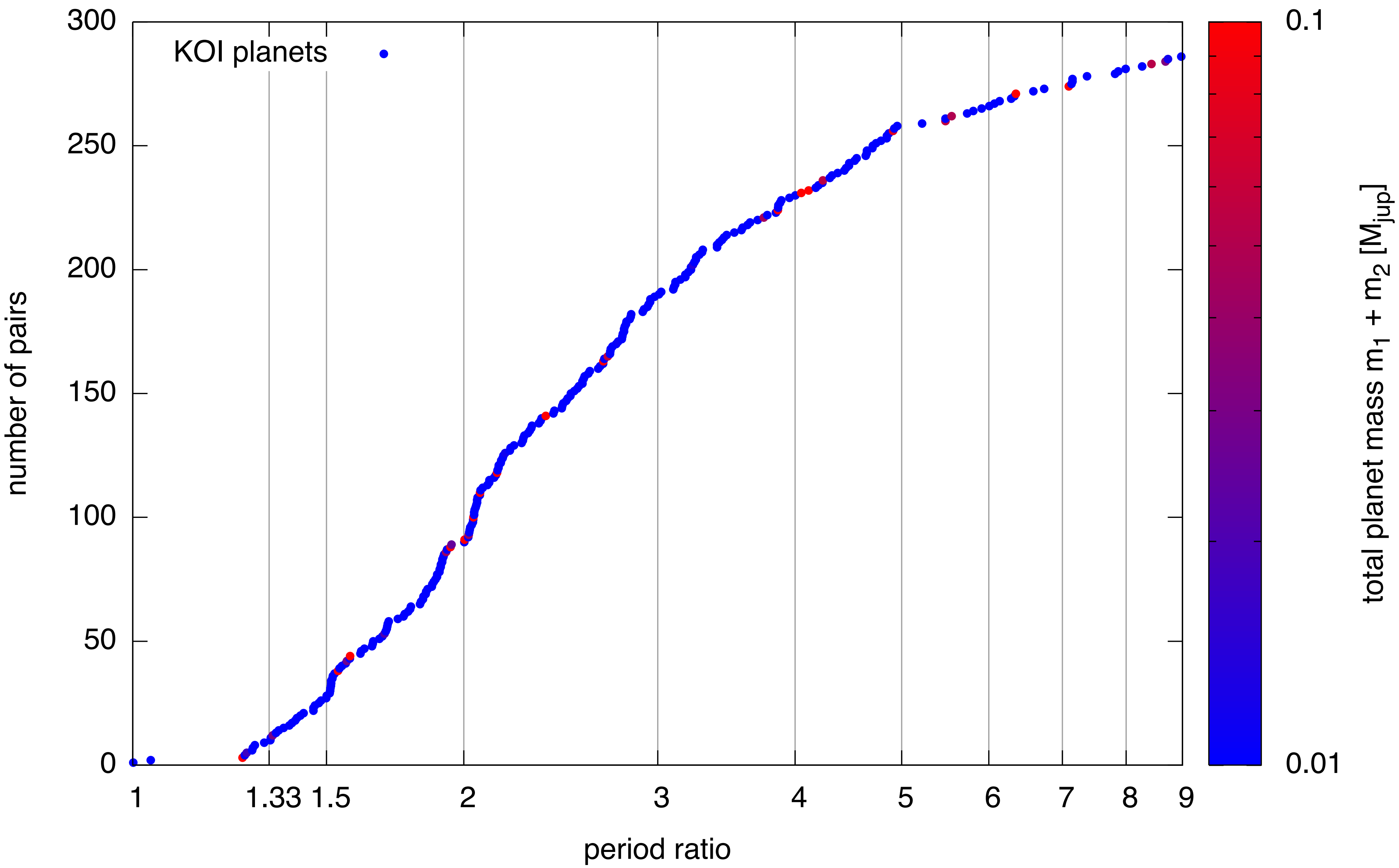
Successful formation scenario for Kepler-36

- Getting planets of different origin (composition) close together
- Forming stable high order resonances
- Capture probability greatly enhanced by adding a small amount of stochastic migration

Pardekooper, Rein & Kley (in prep)

A statistical analysis

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

Testing stochastic migration: Method

Architecture and masses from observed KOIs

Placing planets in a MMSN, further out, further apart, randomizing all angles

N-body simulation with migration forces

Testing stochastic migration: Advantages

Comparison of statistical quantities

- Period ratio distribution
- Eccentricity distribution
- TTVs

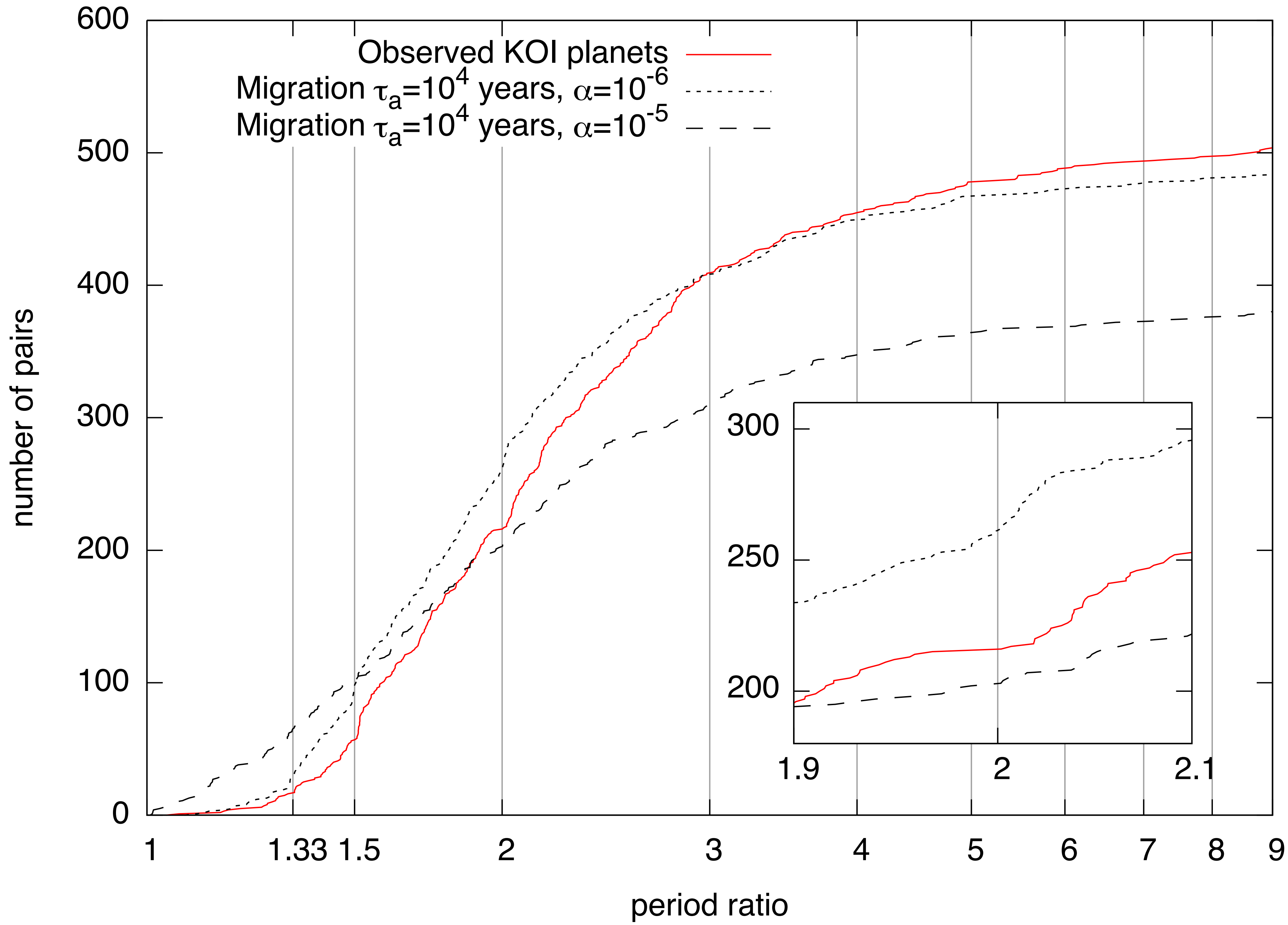
Comparison of individual systems

- Especially interesting for multi-planetary systems
- Can create multiple realizations of each system

No synthesis of a planet population required

- Observed masses, architectures
- Model independent

Preliminary results



Wish list

Physical disk model

- 1D hydrodynamic simulation
- Coupled to N-body simulations

Completeness

- Include planets missed by Kepler

Other physical effects

- Tidal damping

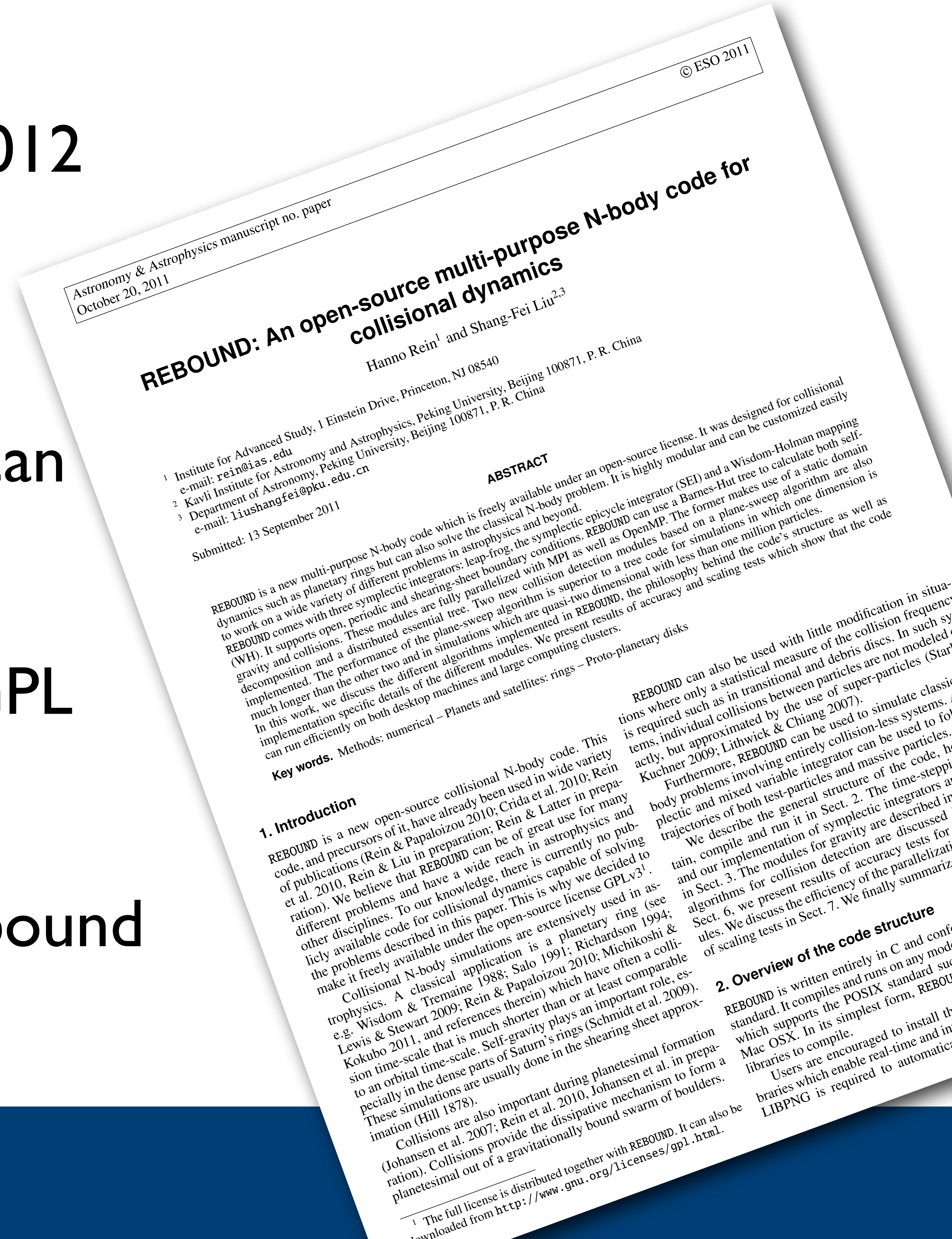
GPU based integrators

- Allows for much bigger samples
- Wider parameter space exploration

Saturn’s Rings

REBOUND

- Code description paper published by A&A, Rein & Liu 2012
- Multi-purpose N-body code
- Only public N-body code that can be used for granular dynamics
- Written in C99, open source, GPL
- 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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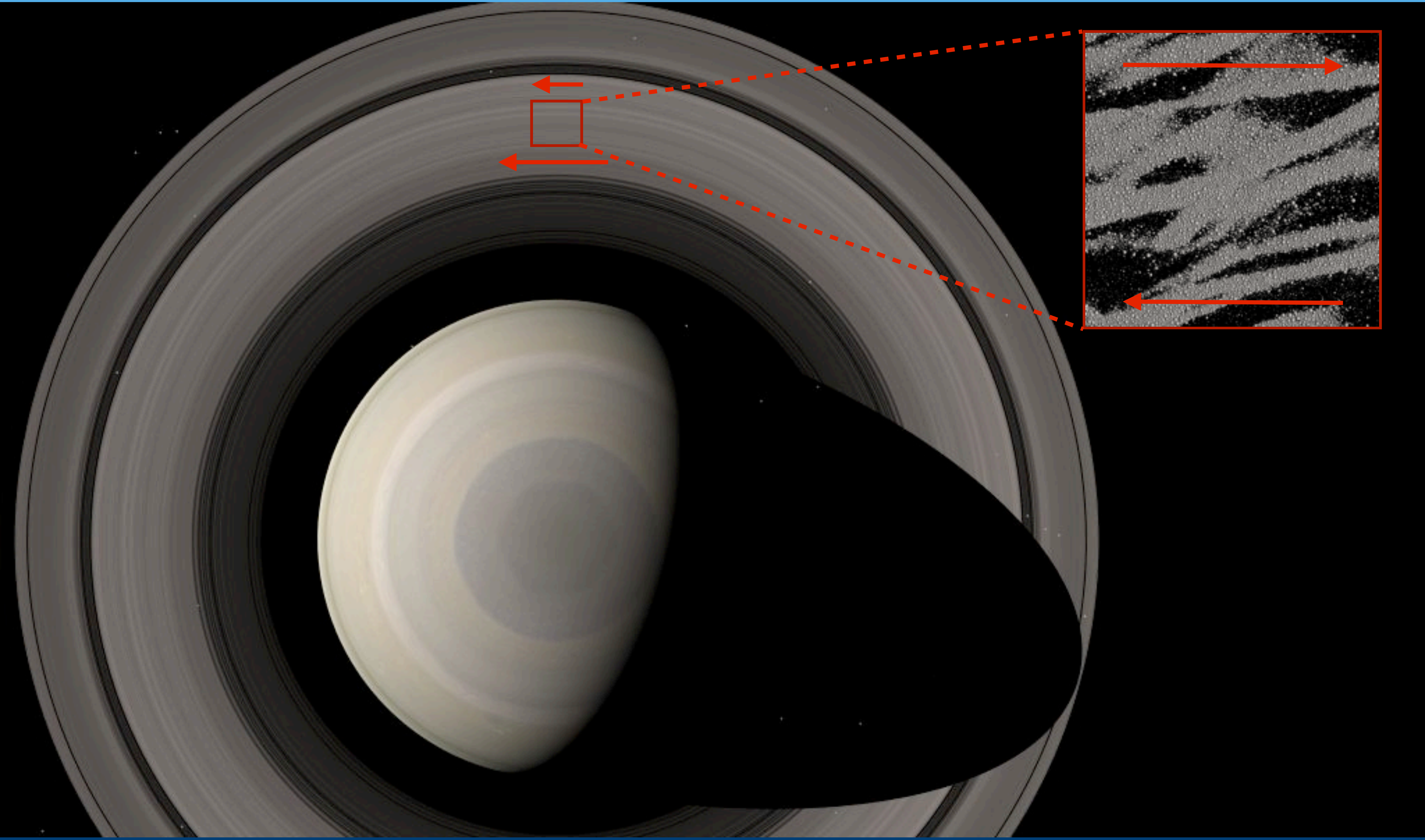
Submitted: 13 September 2011

ABSTRACT

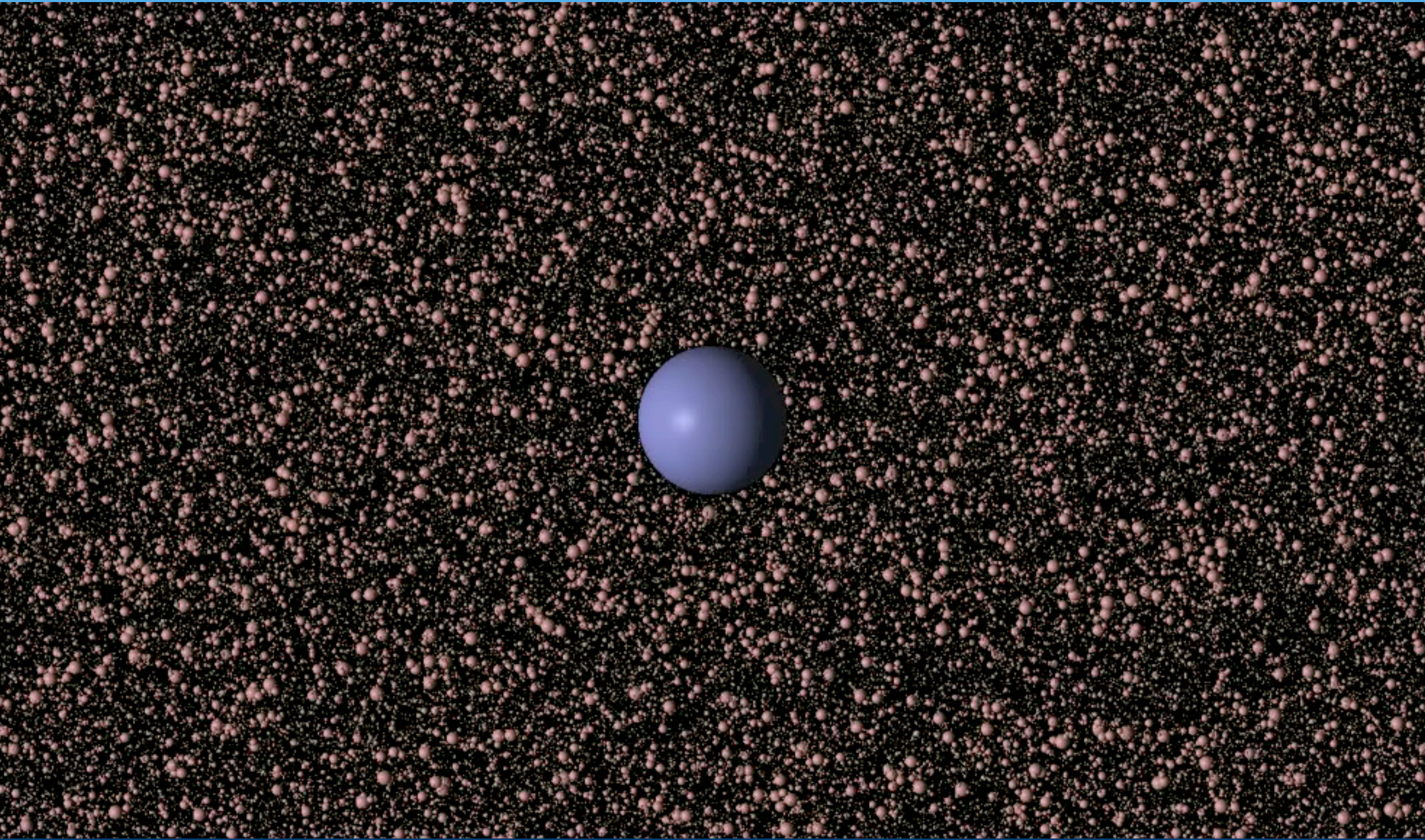
REBOUND is a new multi-purpose N-body code which is freely available under an open-source license. It was designed for collisional dynamics such as planetary rings but can also solve the classical N-body problem. It is highly modular and can be customized easily to work on a wide variety of different 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

Saturn is a smaller version of the Solar System

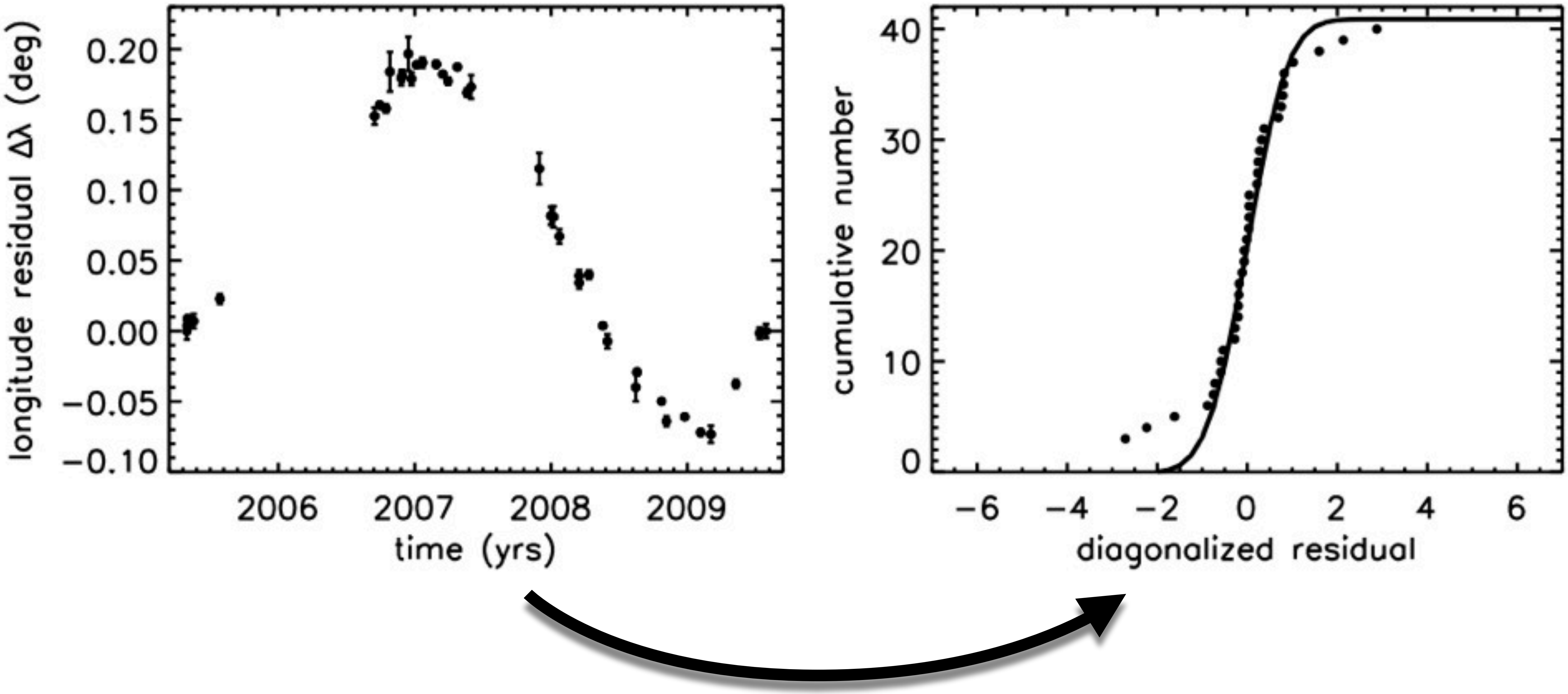


Stochastic Migration



REBOUND code, Rein & Papaloizou 2010, Crida et al 2010, Pan, Rein, Chiang & Evans 2012

Random walk?

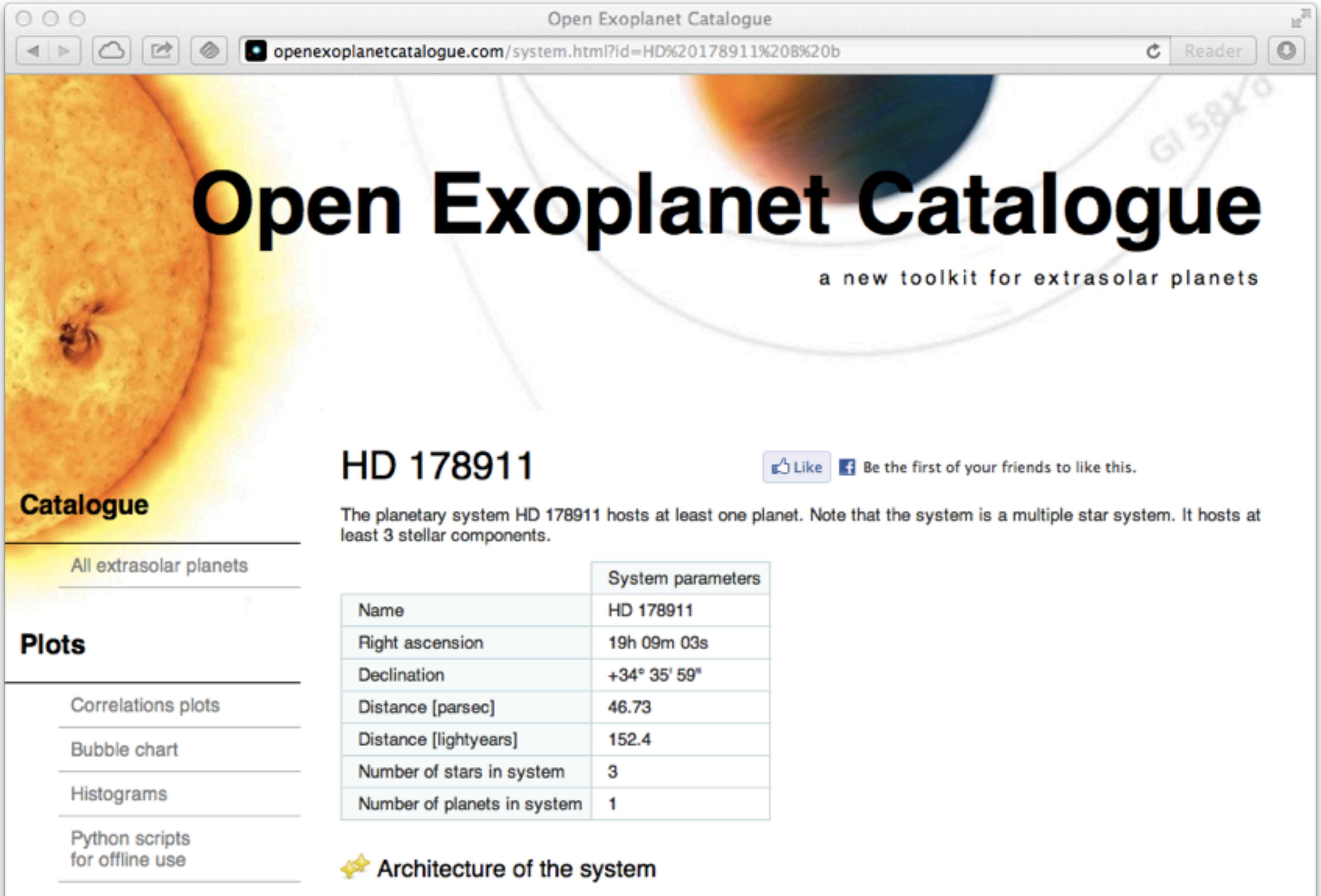


Diagonalization

Institute for Advanced Study

Open Exoplanet Catalogue

Why do we need another exoplanet catalogue?



openexoplanetcatalogue.com

Common drawbacks of astronomical catalogues

Centralized

- Impossible to correct typos, add data without sending an e-mail to the person in charge
- Closed ecosystem

Slow and outdated

- It can take days/weeks/months for new planets to be added
- Maintainer can be holiday or abandon the project

Web-based

- Website are badly written
- Requires flash or java plugin
- Need a constant internet connection
- Restricted to a very limited, predefined set of possible queries

Old-fashioned formats

- Static tables are not adequate to represent diverse dataset
- Almost impossible to include binary/triple/quadruple systems
- Not flexible when adding new data
- Unintuitive to parse

Open Exoplanet Catalogue

Open source philosophy

- Unrestrictive MIT license
- Community project
- Everyone can contribute and modify data
- Everyone can expand it
- Distributed, no need for a server/website
- Private clones with confidential data

Based on git

- Distributed version control system
- Used by Linux kernel and most other open source projects
- Every single value, every change ever made is logged, verifiable

Ready to go

- 674 systems, 51 binary system, 870 exoplanets, 9 solar system objects, 2740 KOI objects
- ~10 million users

Hierarchical data structure

- Uses plain XML
- Can represent arbitrary configurations in systems with stellar multiplicity >1
- Extremely easy and intuitive to parse in almost any language
- Compresses extremely well
- size ~ 100KB

Example of a system file: 42 Dra b


```
<system>
    <name>42 Dra</name>
    <rightascension>18 25 59</rightascension>
    <declination>+65 33 49</declination>
    <distance>97.3</distance>
    <star>
        <mass>0.98</mass>
        <radius>22.03</radius>
        <magV>4.83</magV>
        <metallicity>-0.46</metallicity>
        <spectraltype>K1.5III</spectraltype>
        <planet>
            <name>42 Dra b</name>
            <list>Confirmed planets</list>
            <mass>3.88</mass>
            <period>479.1</period>
            <semimajoraxis>1.19</semimajoraxis>
            <eccentricity>0.38</eccentricity>
            <description>42 Draconis is a metal poor star.</description>
            <discoverymethod>RV</discoverymethod>
            <lastupdate>09/03/23</lastupdate>
            <discoveryyear>2009</discoveryyear>
            <new>0</new>
        </planet>
        <name>42 Dra</name>
    </star>
</system>
```

Example of a python script parsing all systems

```
import xml.etree.ElementTree as ET, glob
for filename in glob.glob("*.xml"):
  tree = ET.parse(open(filename, ’r’))
  planets = tree.findall(".//planet")
  for planet in planets:
    print planet.findtext("./name")
    print planet.findtext("./mass")
```

OpenExoplanetCatalogue.com

arXiv:1211.7121

Summary

The case for stochastic orbital migration

- Stochastic migration is directly observable in Saturn's rings.
- Protoplanetary disks are turbulent due to the MRI.
- Stochastic migration plays an important role for small mass planets.
- Resonances can easily get destroyed.
- Tendency to form high order resonance.
- Very soon, we will understand how most planets in the Kepler sample formed.

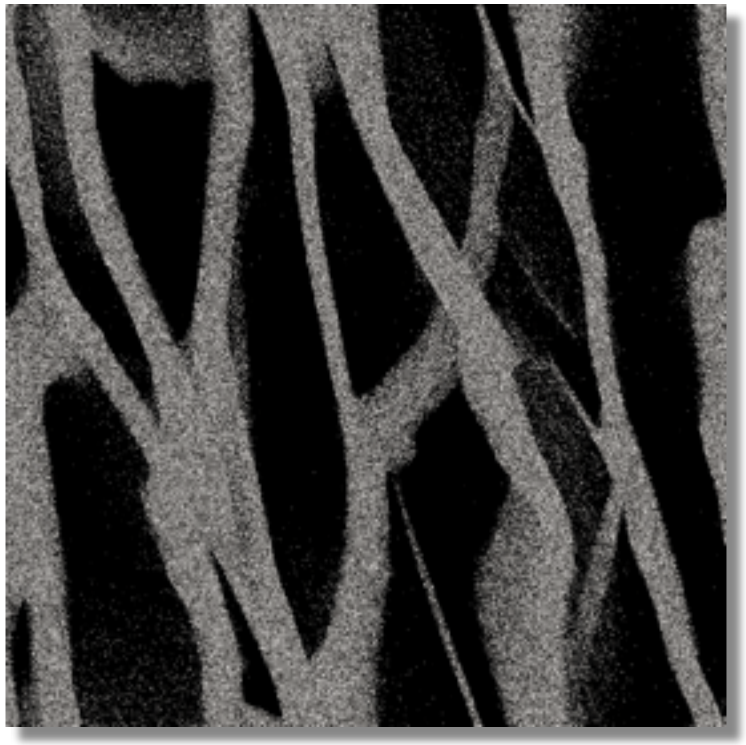
Open Exoplanet Catalogue

Use it!
Contribute to it!

Paardekooper, Rein & Kley (in prep), Rein, Payne, Veras & Ford (2012), Rein (2012a), Rein & Papaloizou (2009)

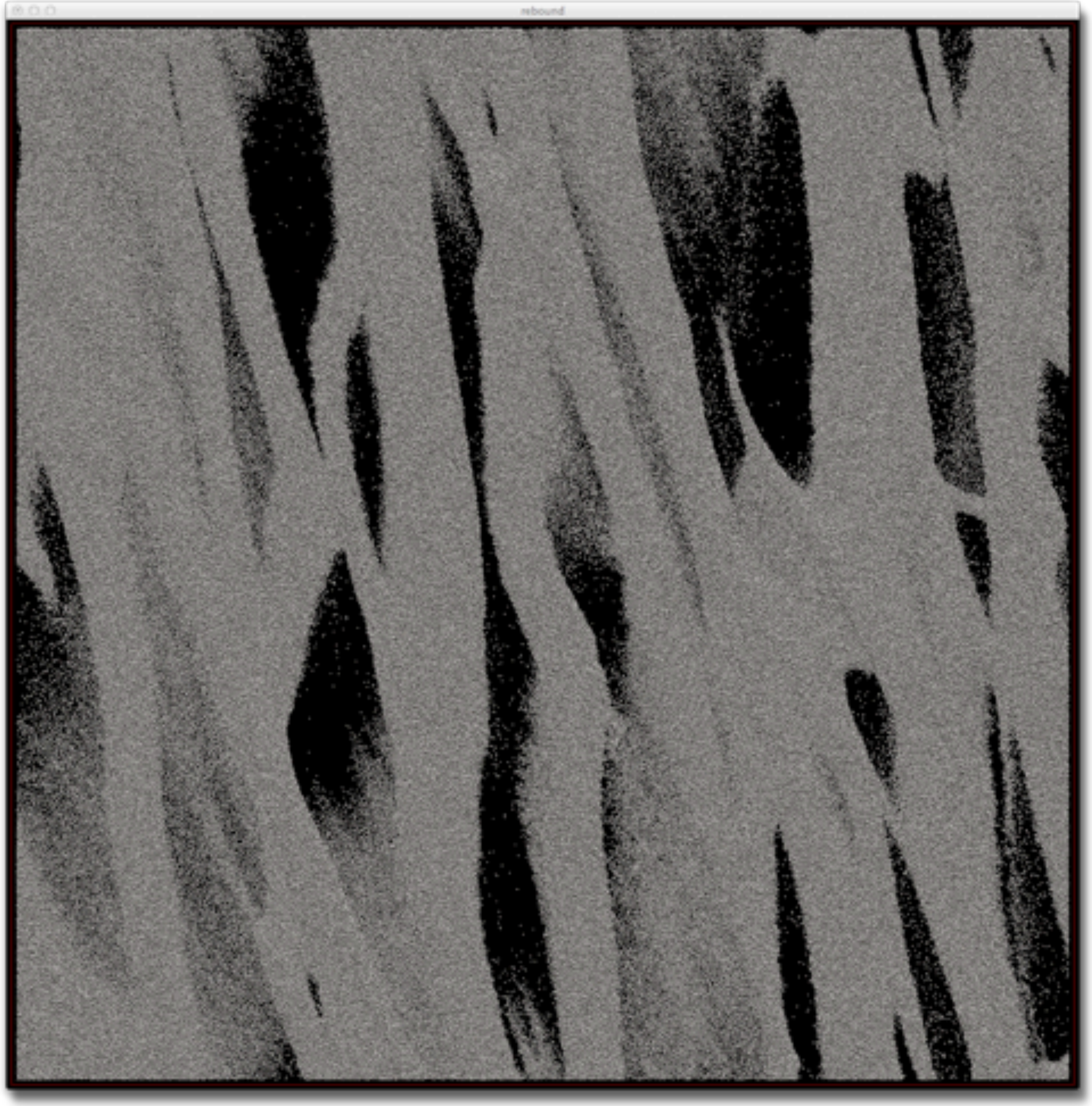
Comparison to previous work

- Robbins et al. (2010)
- Largest simulation
  N = 524.000
- Runtime ~17 days

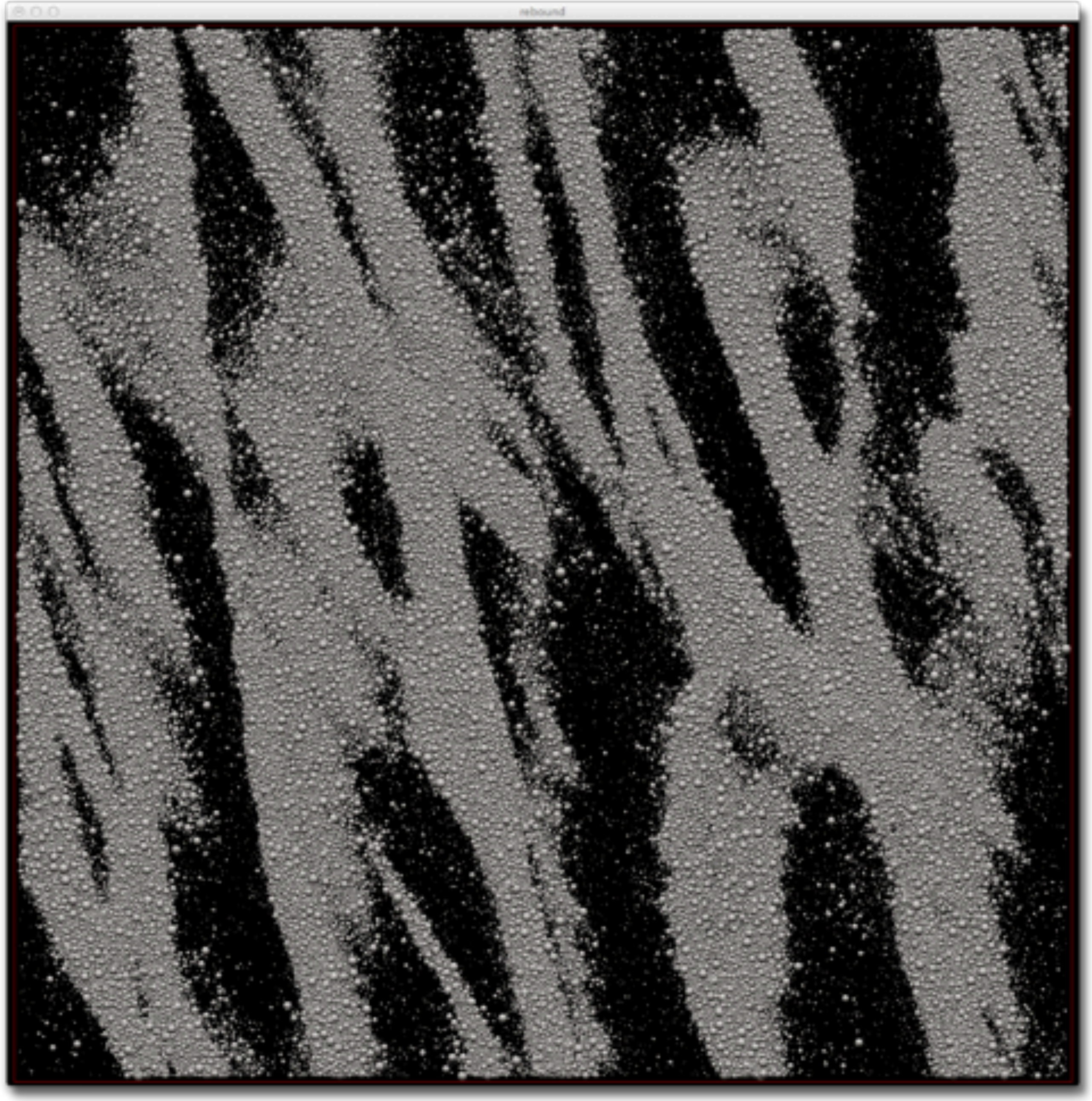


- Rein & Kokubo (in prep)
- Largest simulation (so far)
  N = 10.185.912
- Runtime ~2 days

Dense Rings



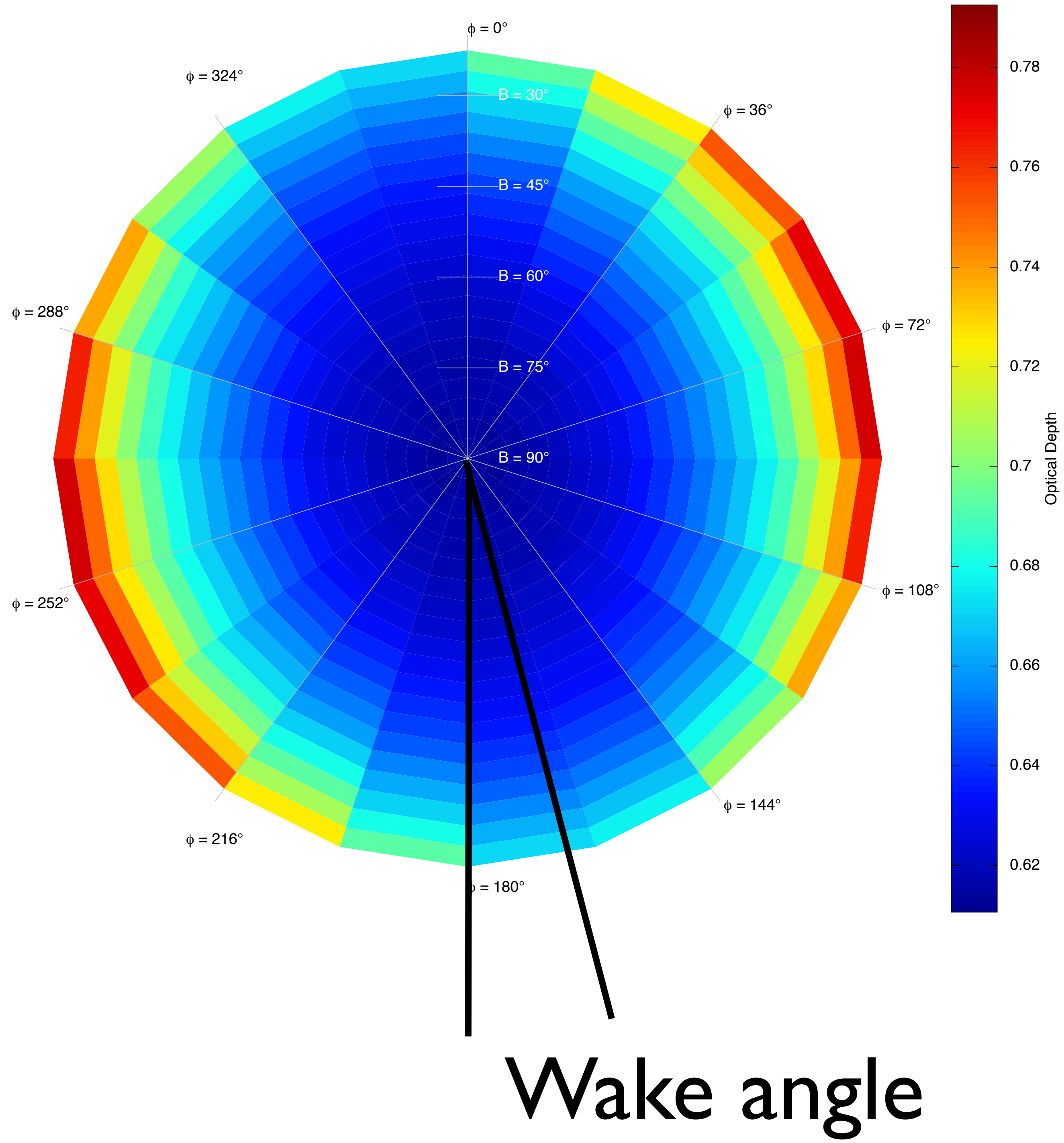
- Geometric optical depth ~ 8



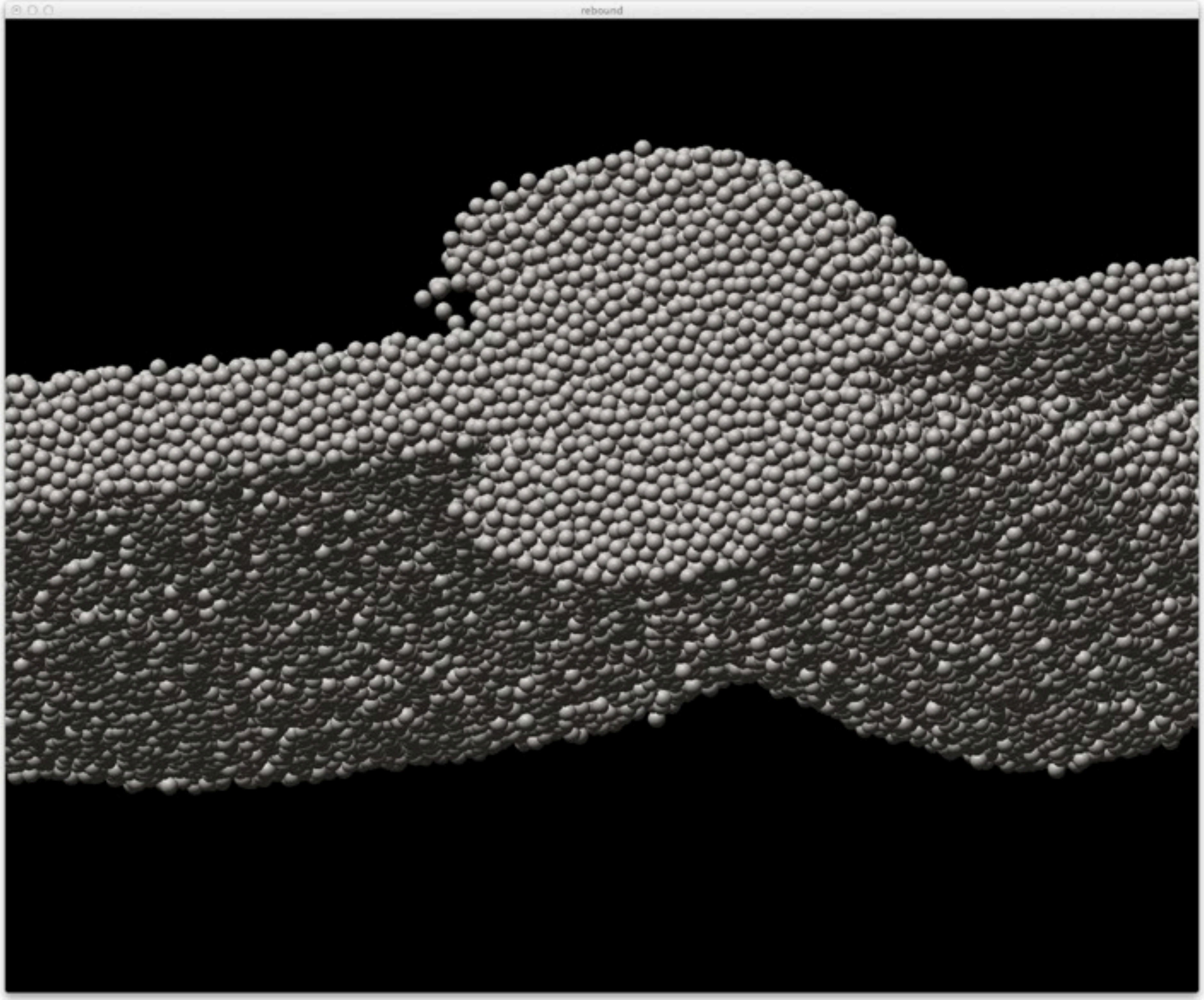
- Geometric optical depth ~ 2
- Realistic size distribution

Rein & Kokubo (in prep)

Actual Optical Depth

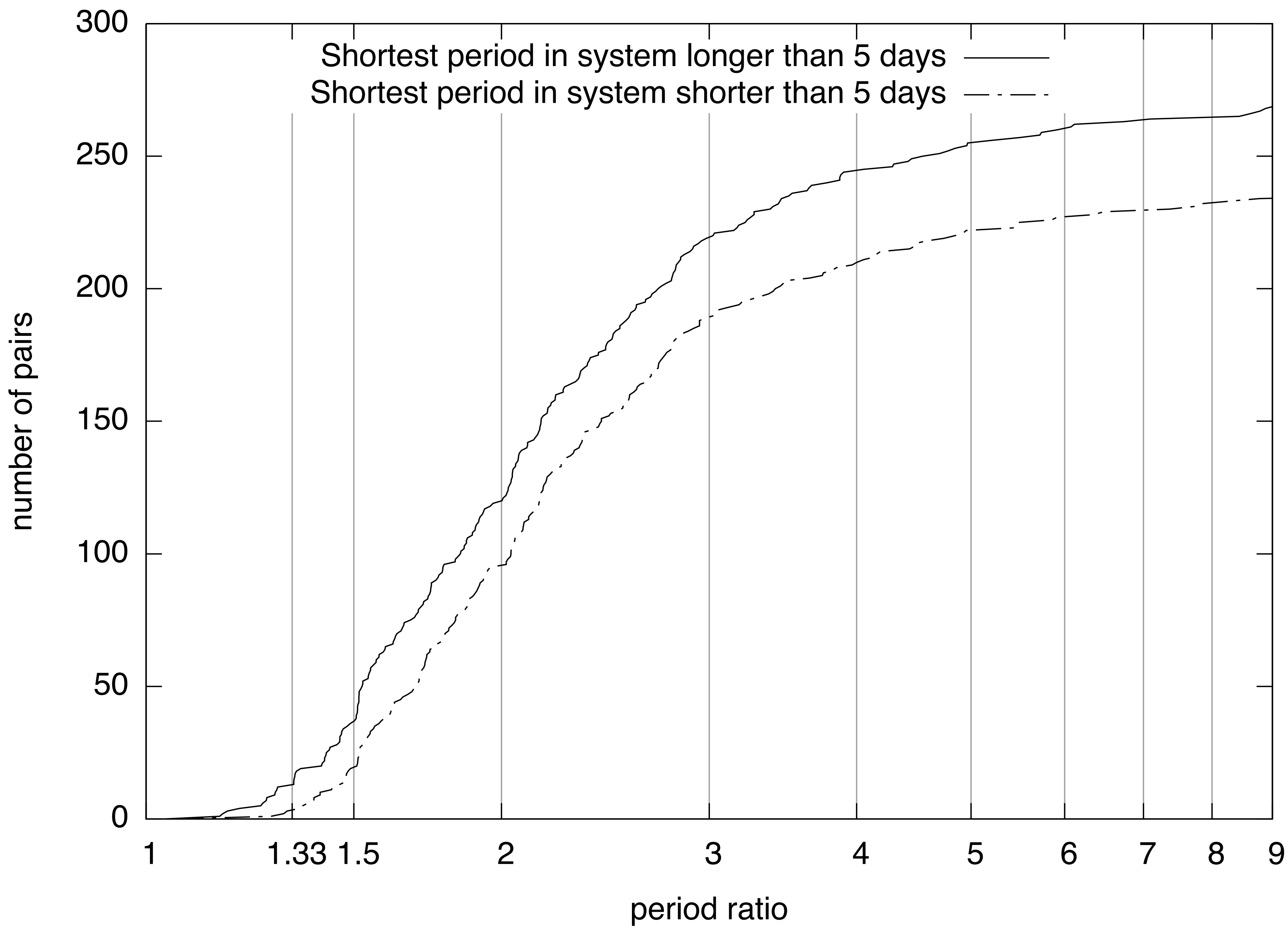


Dense rings



Rein & Kokubo (in prep)

No different for close-in/far-out planets



Rein 2012

Random walk?

$$\Delta\lambda(n\delta t) = -\sum_{i=1}^{n} \frac{3\Omega}{2a} \Delta a(i\delta t)\delta t$$
$$= -\frac{3\Omega\delta t}{2a} \sum_{i=1}^{n} \sum_{j=0}^{i-1} \xi_j$$
$$= -\frac{3\Omega\delta t}{2a} \sum_{j=0}^{n-1} (n-j)\xi_j$$

- The observed longitude residual is a double integral
- Linear combination of individual kicks