Institute for Advanced Study

# Multi-planetary systems

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# Projects that I will not talk about today

Symplectic integrators

Viscous overstability

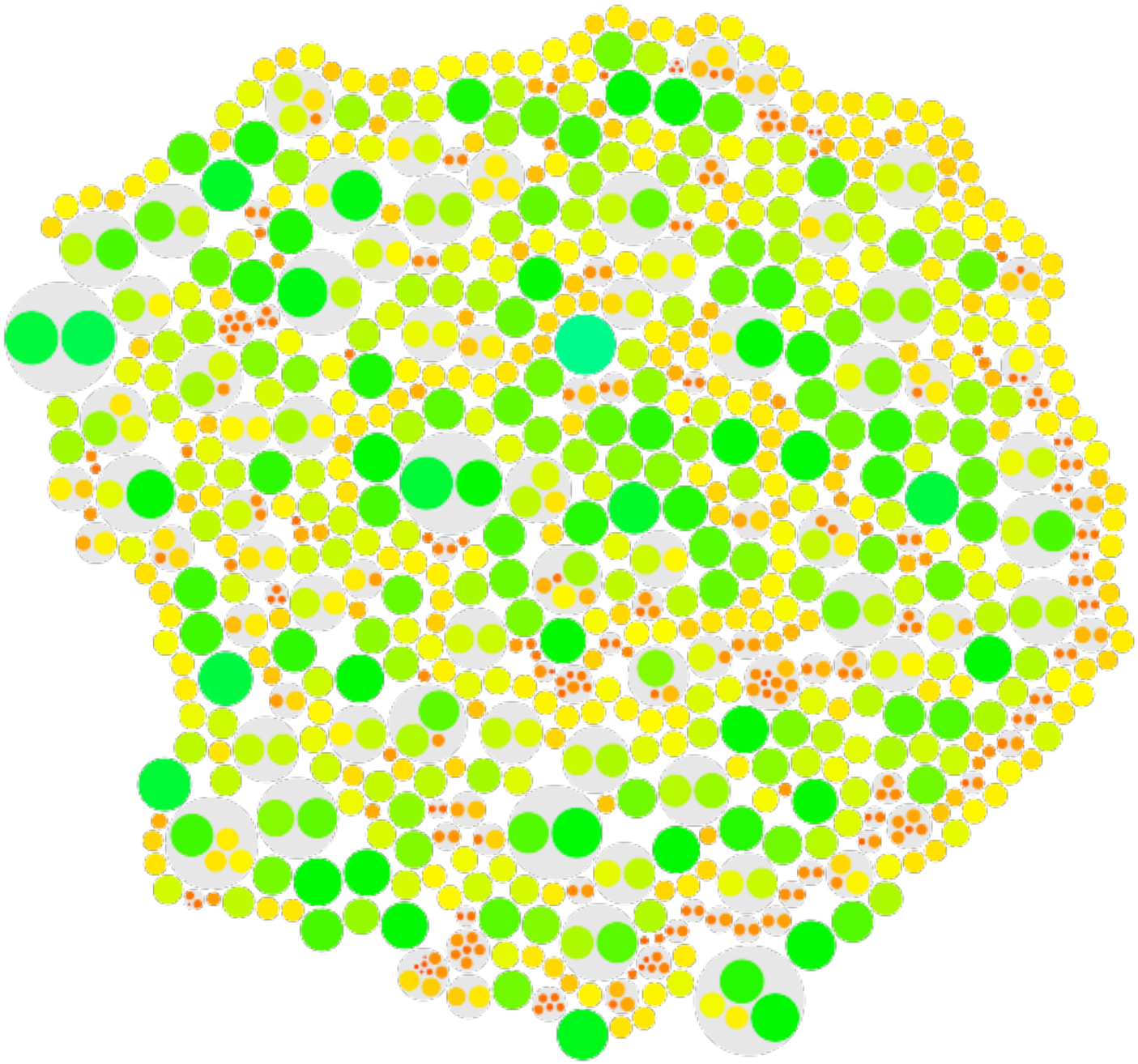
Parallel tree codes

Stability of exo-moons

Open Exoplanet Catalogue

Simulations of dense rings

# All discovered extra-solar planets

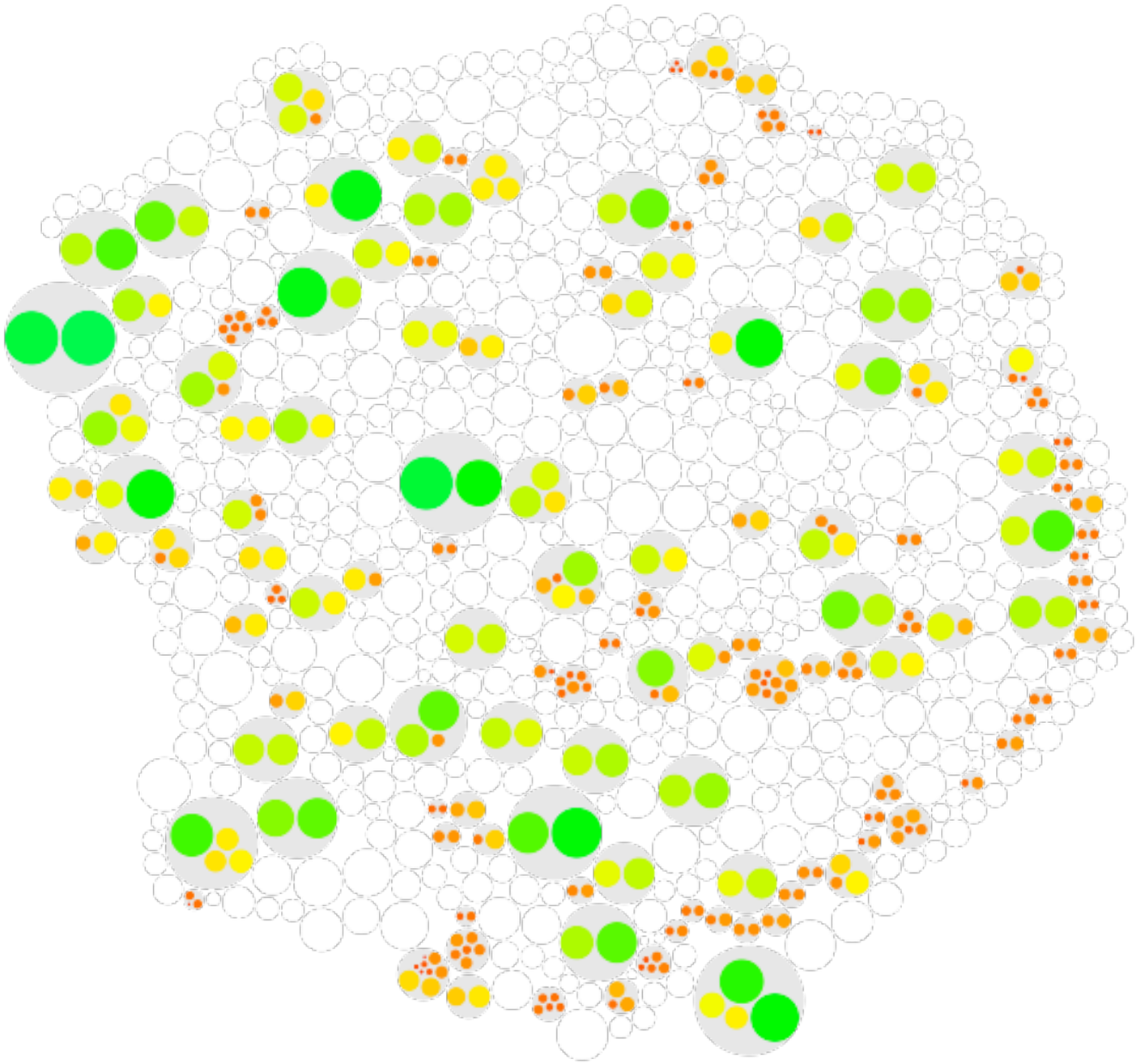


**869 confirmed extra-solar planets**

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

Open Exoplanet Catalogue (Rein 2012b)

# All multi-planetary systems



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Open Exoplanet Catalogue (Rein 2012b)

# Take home message I

There are a lot of planets.


Exoplanet App by Hanno Rein
Available on the Apple AppStore

# Take home message II

The variety of planets and planetary systems is enormous.

# Recipe:
# 1. Planet migration
# 2. Resonances

# I. Planet migration

# Planet formation

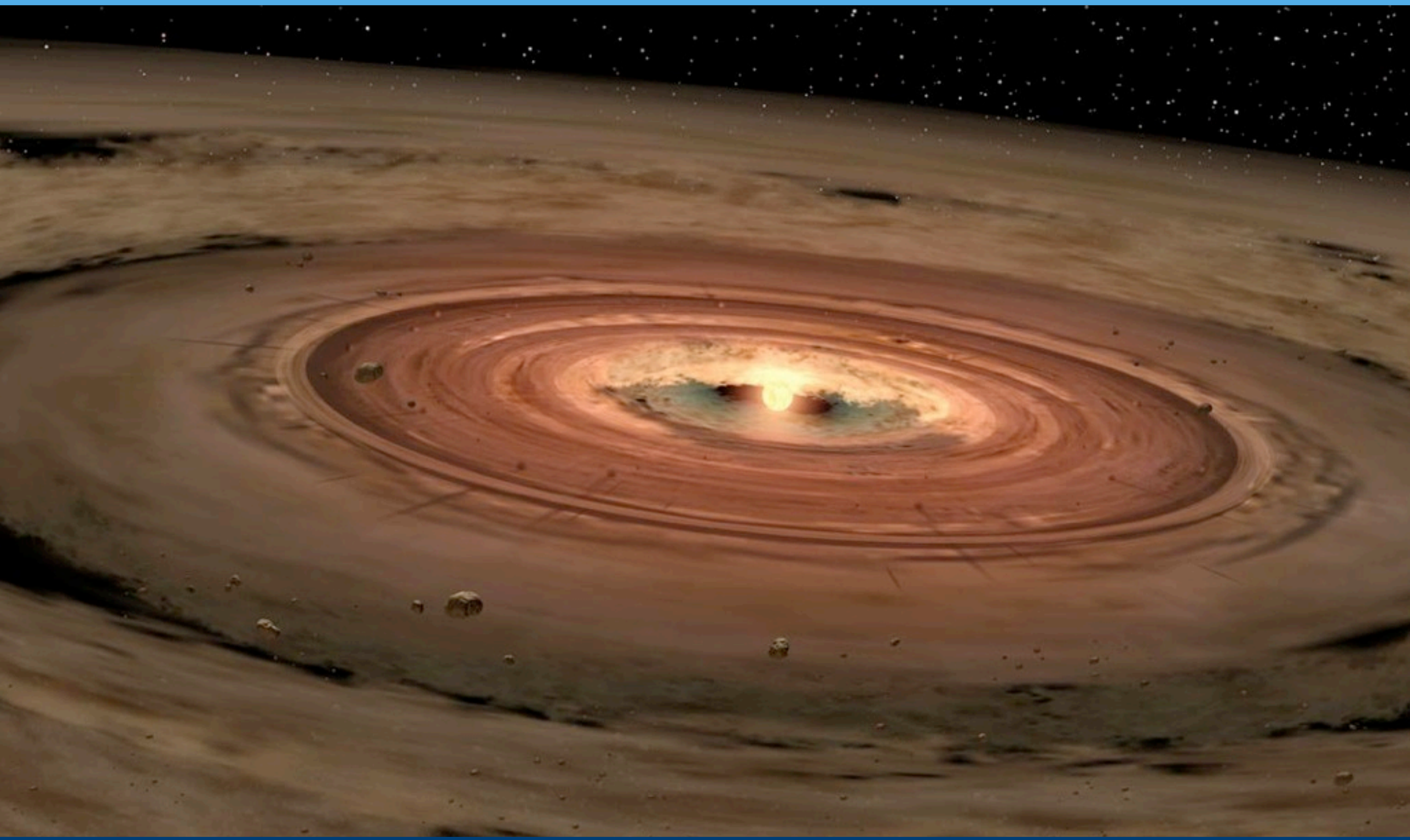
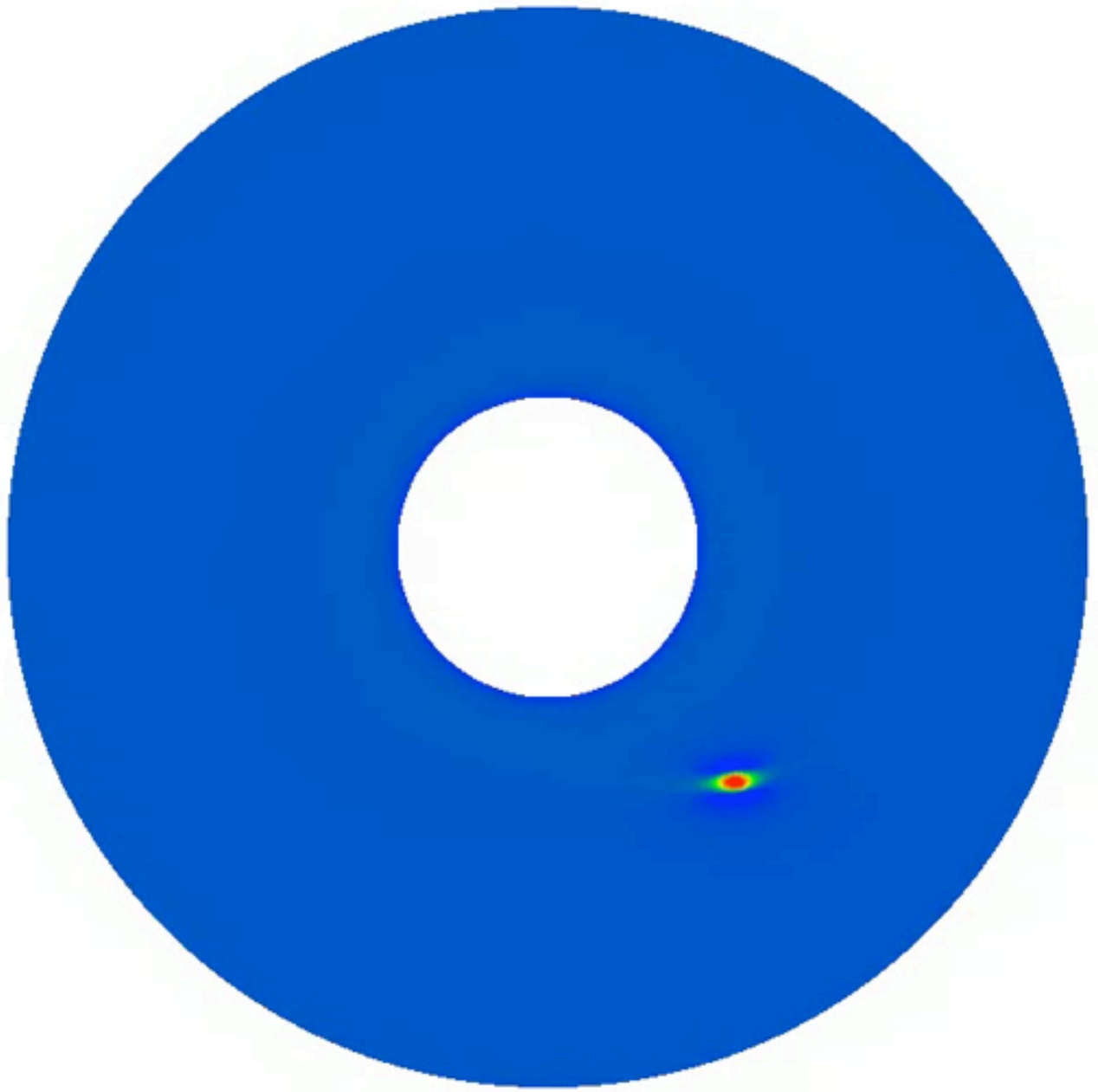


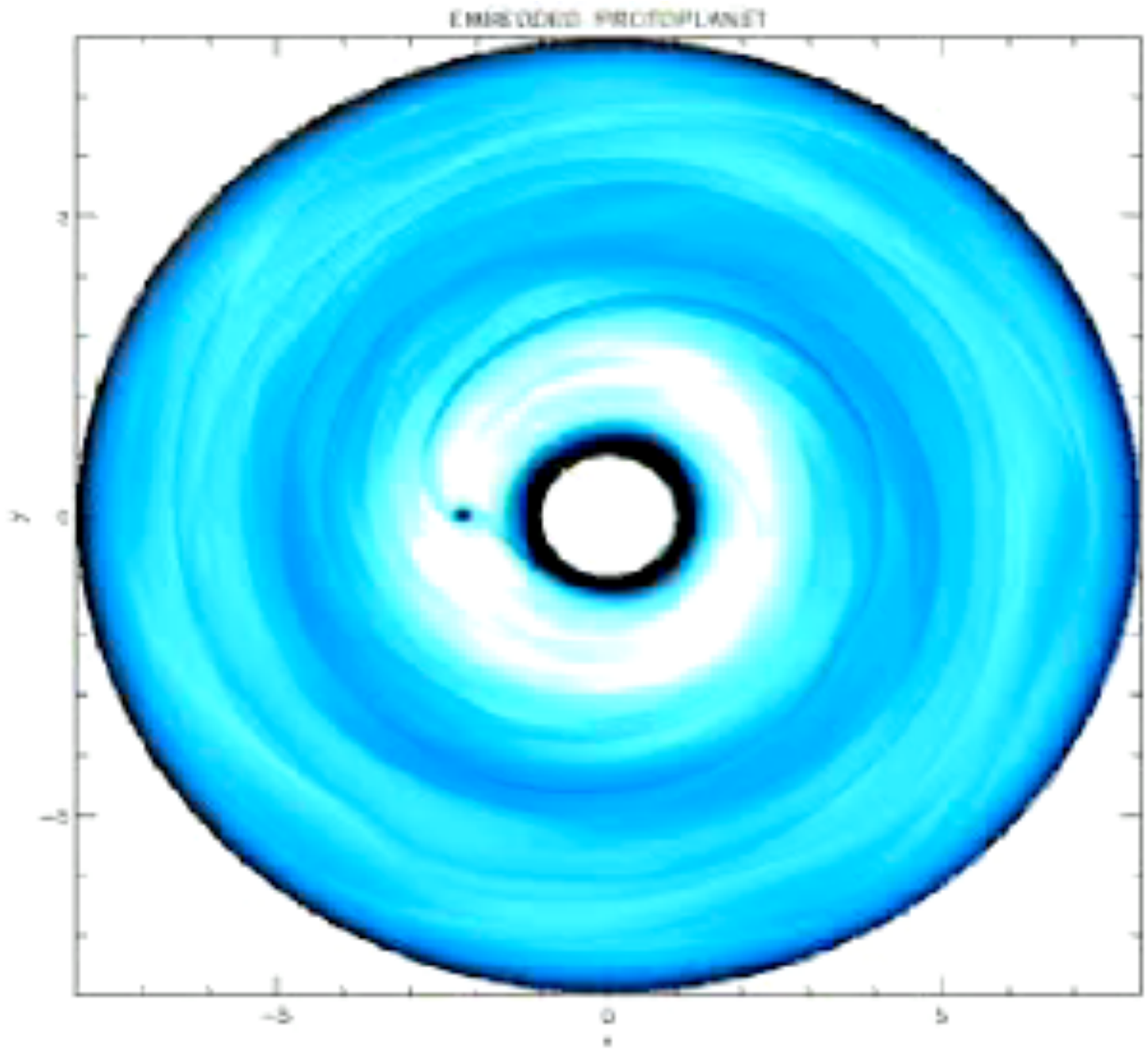
Image credit: NASA/JPL-Caltech

# Smooth migration



2D hydro code Prometheus (Rein 2010)

# Stochastic migration



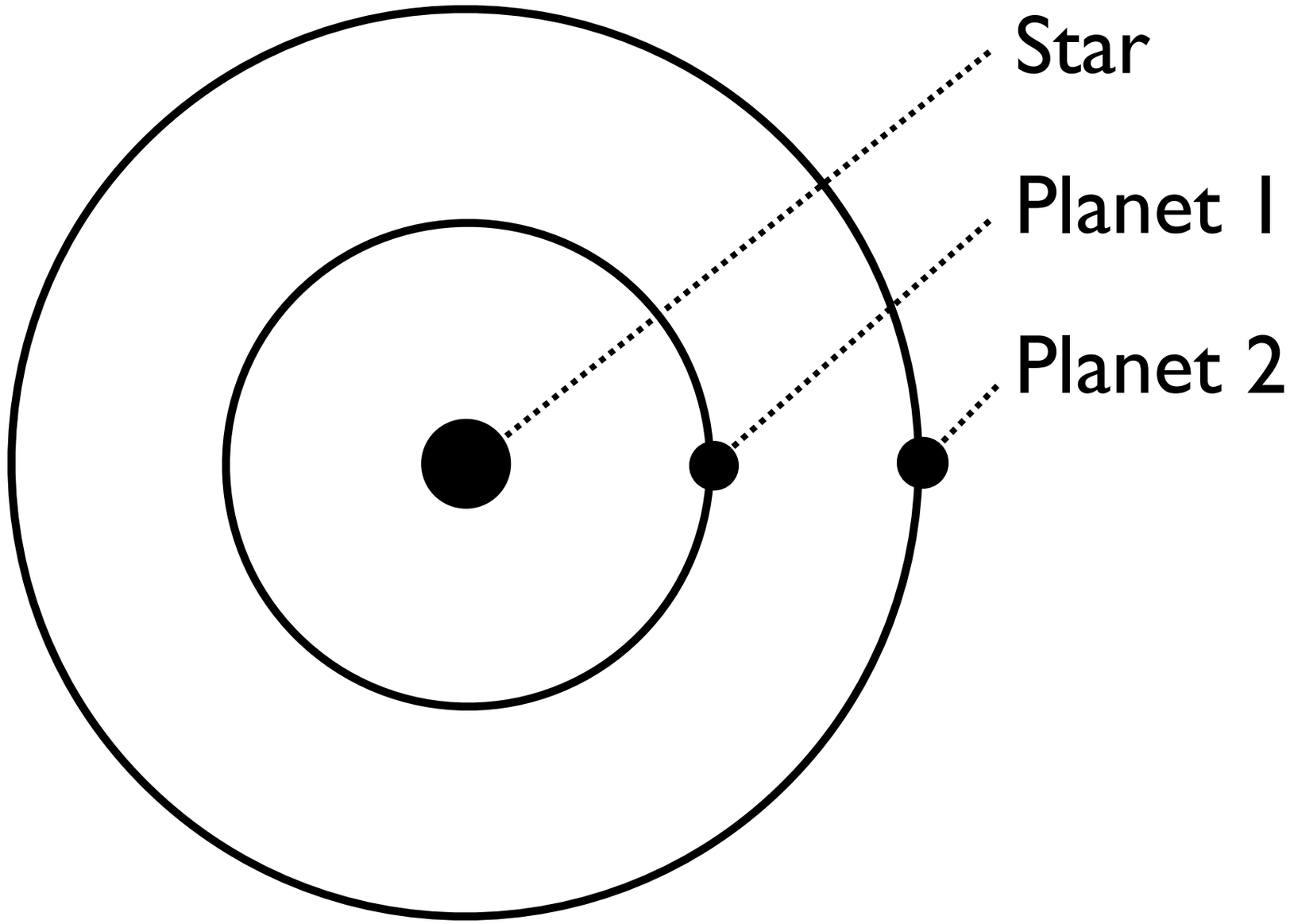
Animation from Nelson & Papaloizou 2004
Random forces measured by Laughlin et al. 2004, Nelson 2005, Oischi et al. 2007

# Take home message III

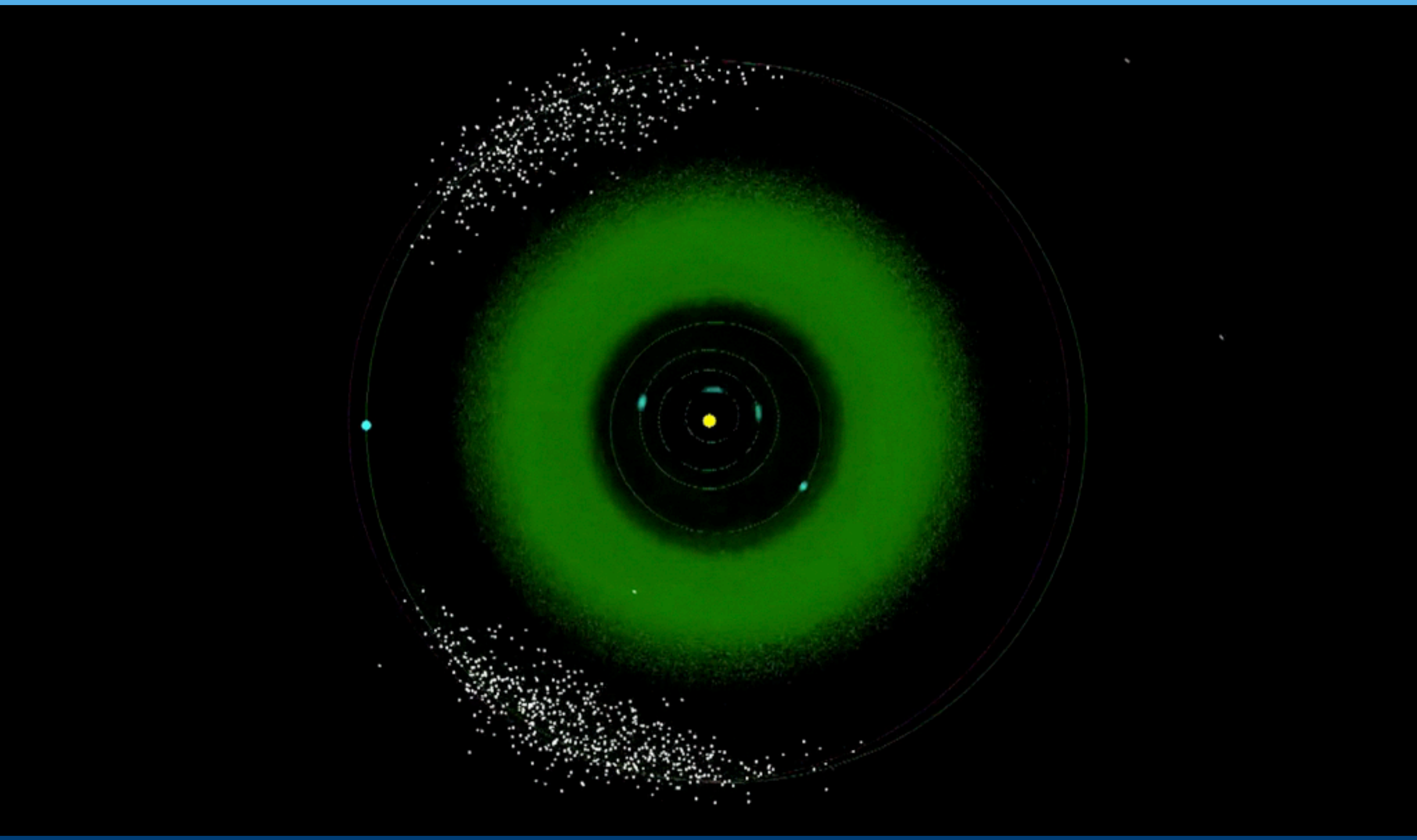
planet + disc = migration

# 2. Resonances

# 2:1 Mean Motion Resonance

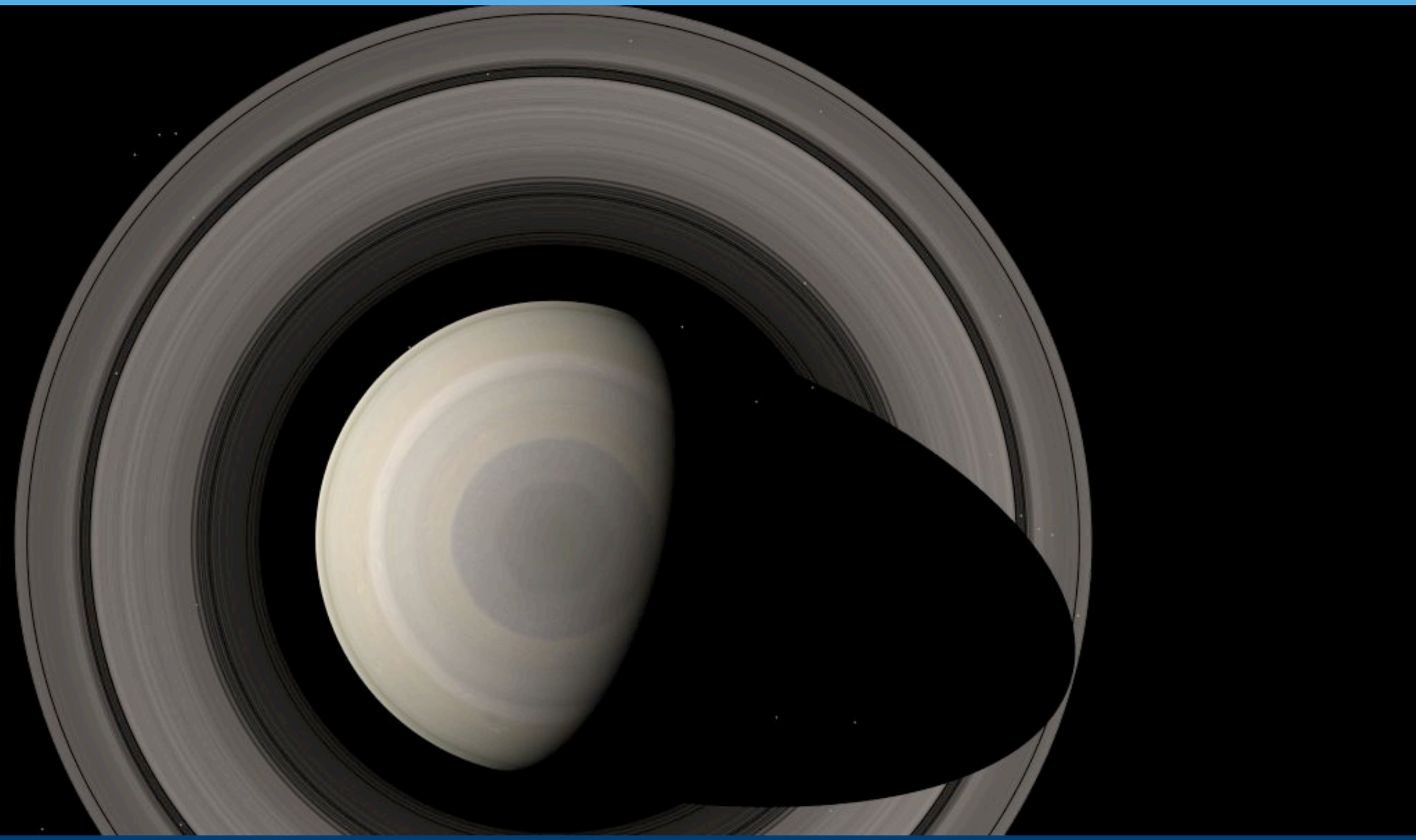


# Asteroids in resonance with Jupiter

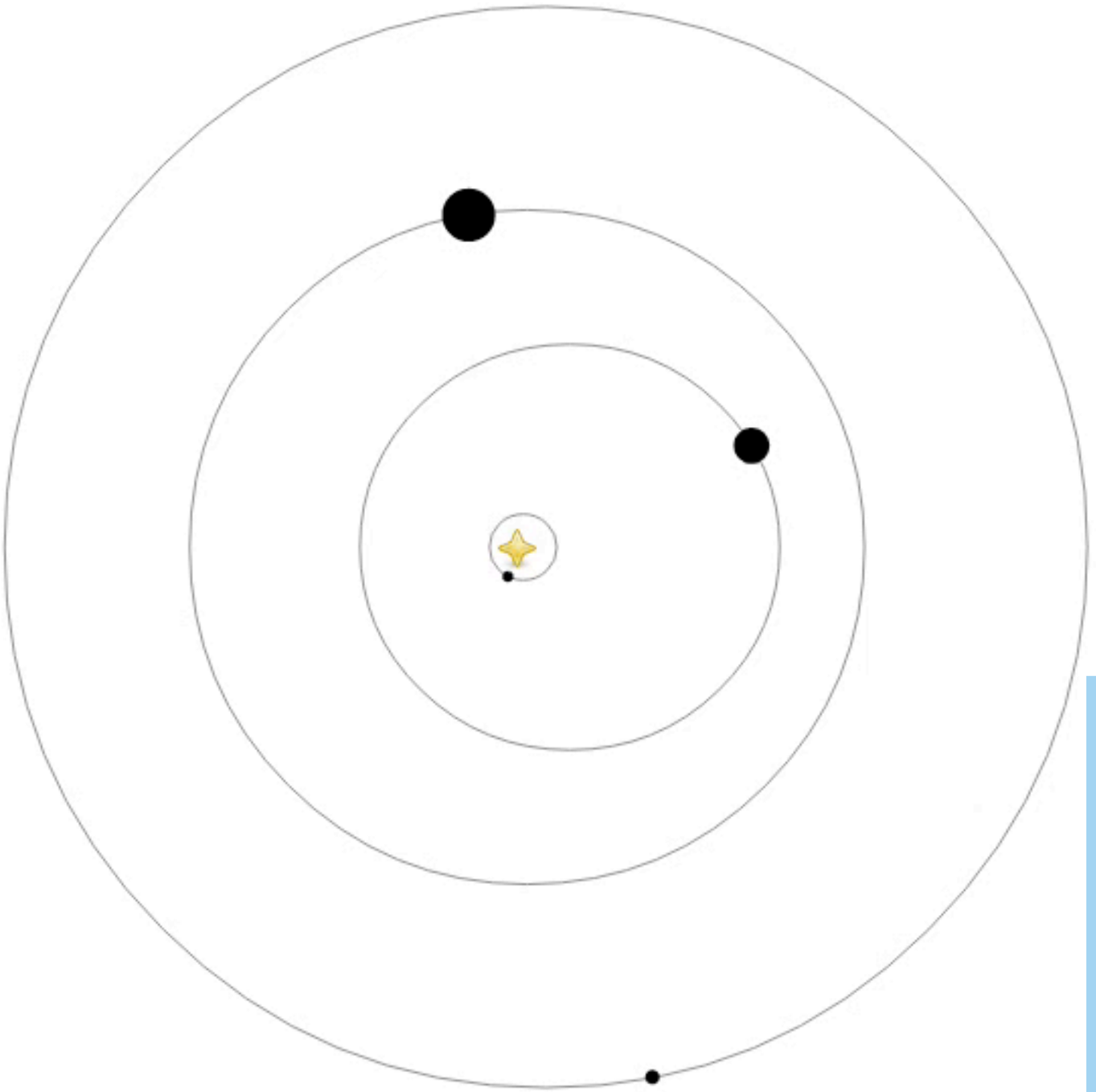


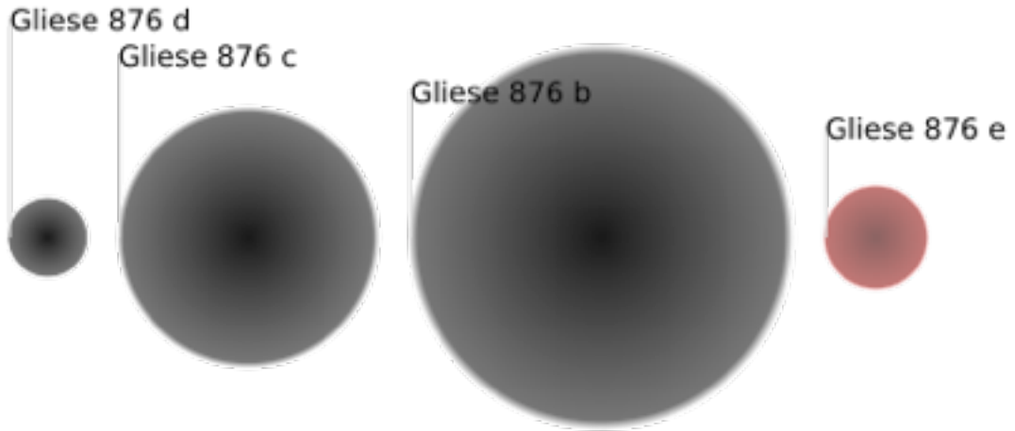
Scott Manley

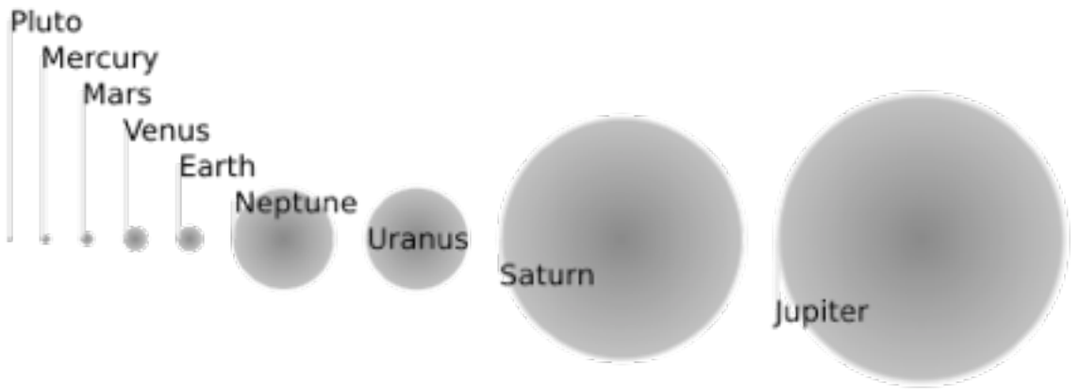
# Saturn's rings are sculpted by resonances



# The system Gliese 876





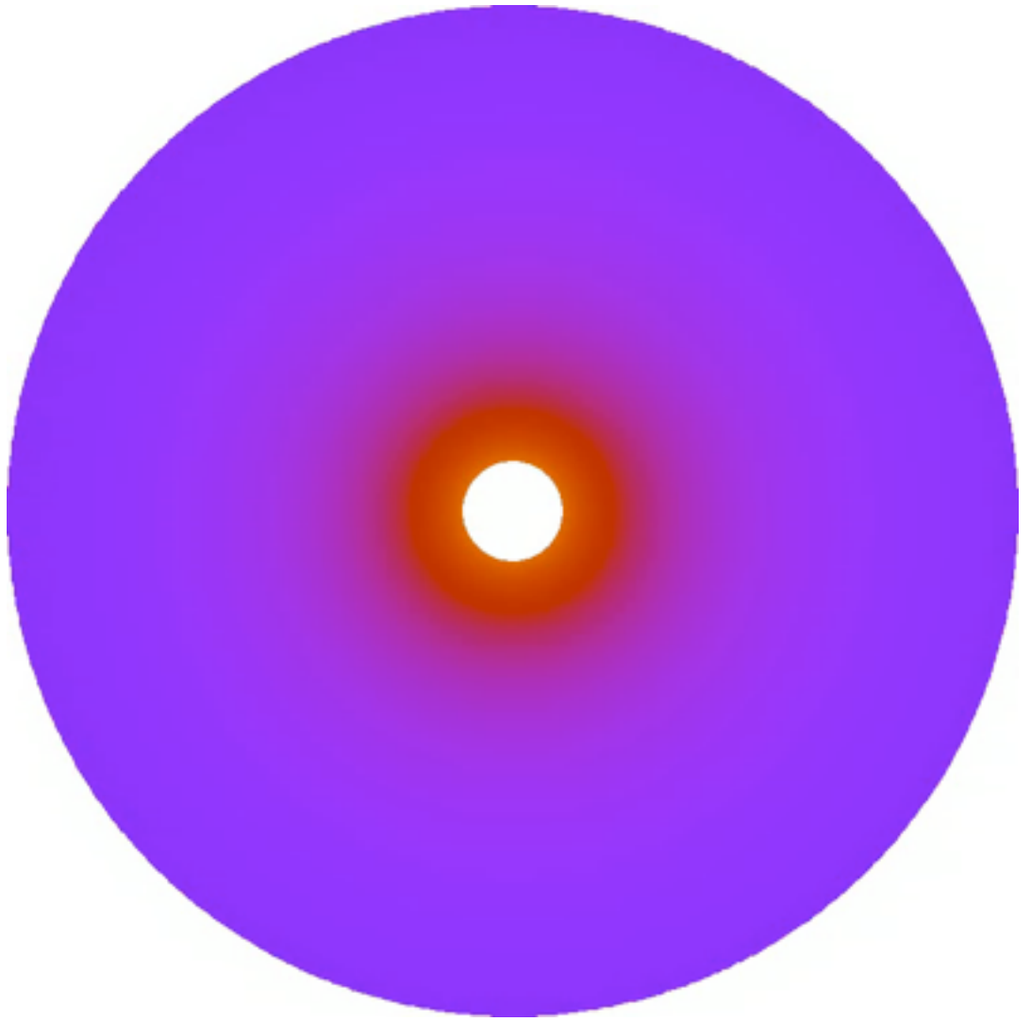

- Massive planets.
- Locked in a resonance.
- Observed with high accuracy.

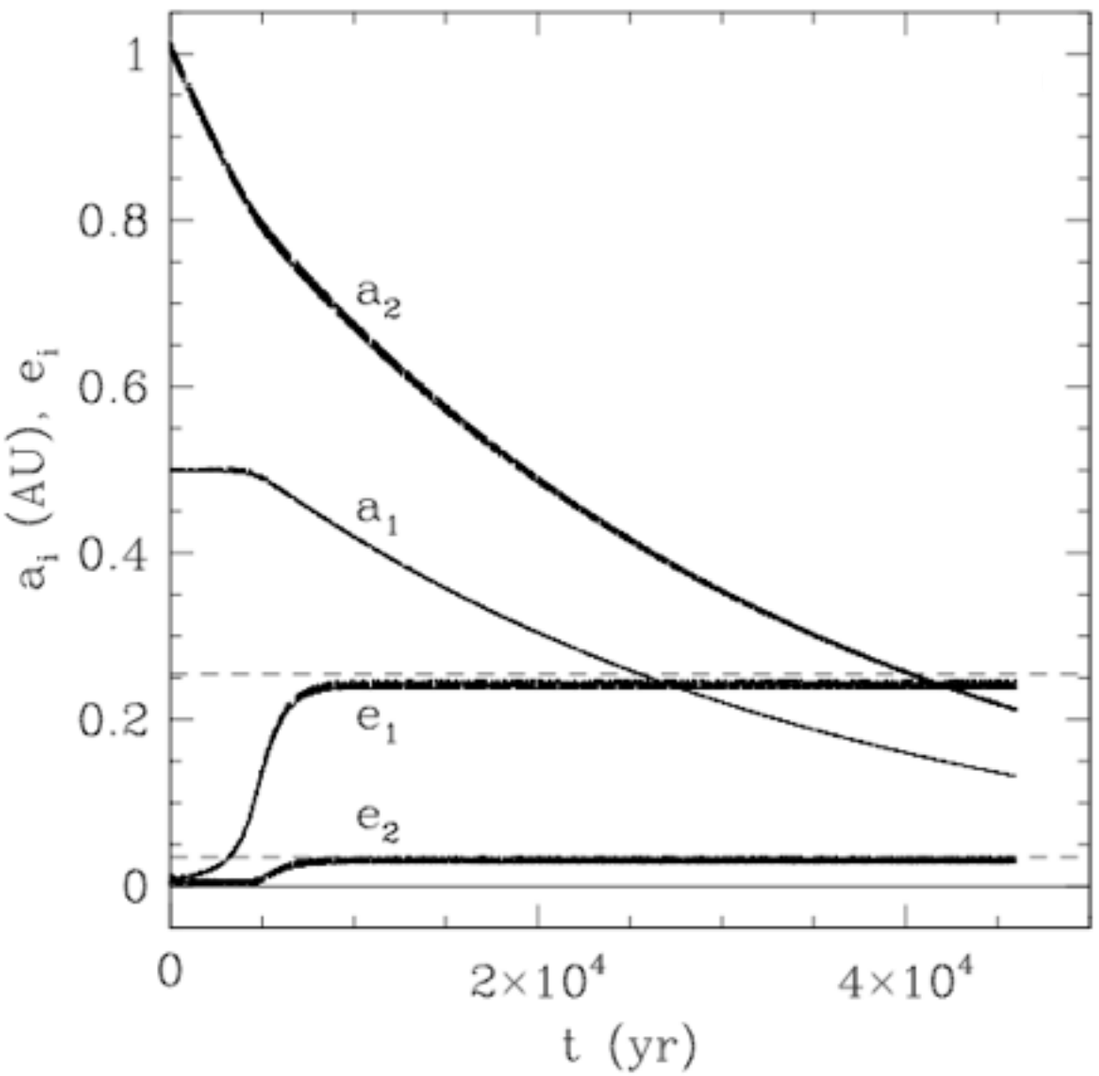
Open Exoplanet Catalogue (Rein 2012b)

# Take home message IV

Resonances are special dynamical configurations.

# Formation of GJ 876: Resonance capture






- Migration can explain this special resonant configuration
- Both the period ratio and the eccentricities are reproduced

Lee & Peale 2002, Rein et al 2012

# Take home message V

2 planets + migration = resonance

# The case 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

Carter et al (2012), Frank Melchior, Eric Agol

# Snow line

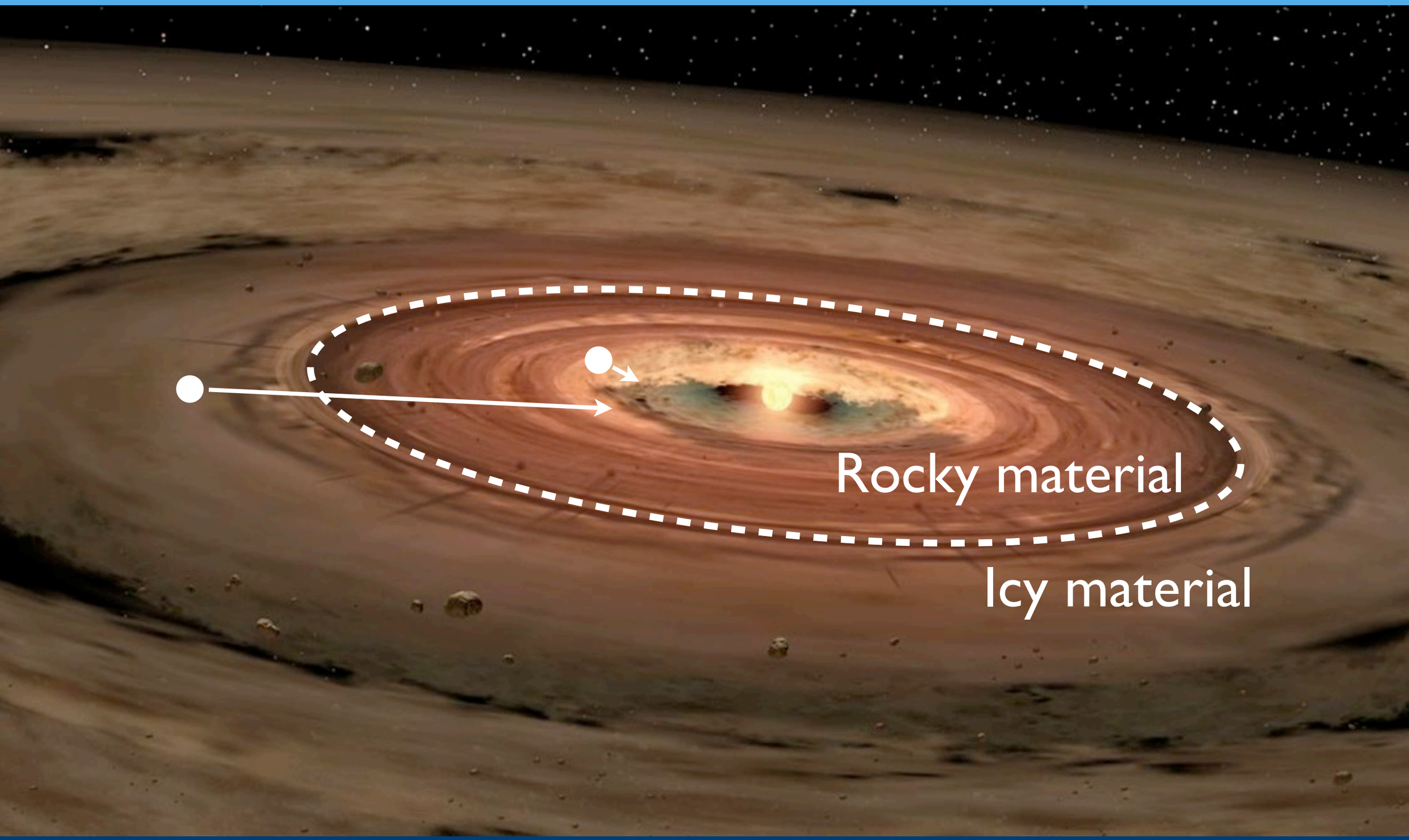
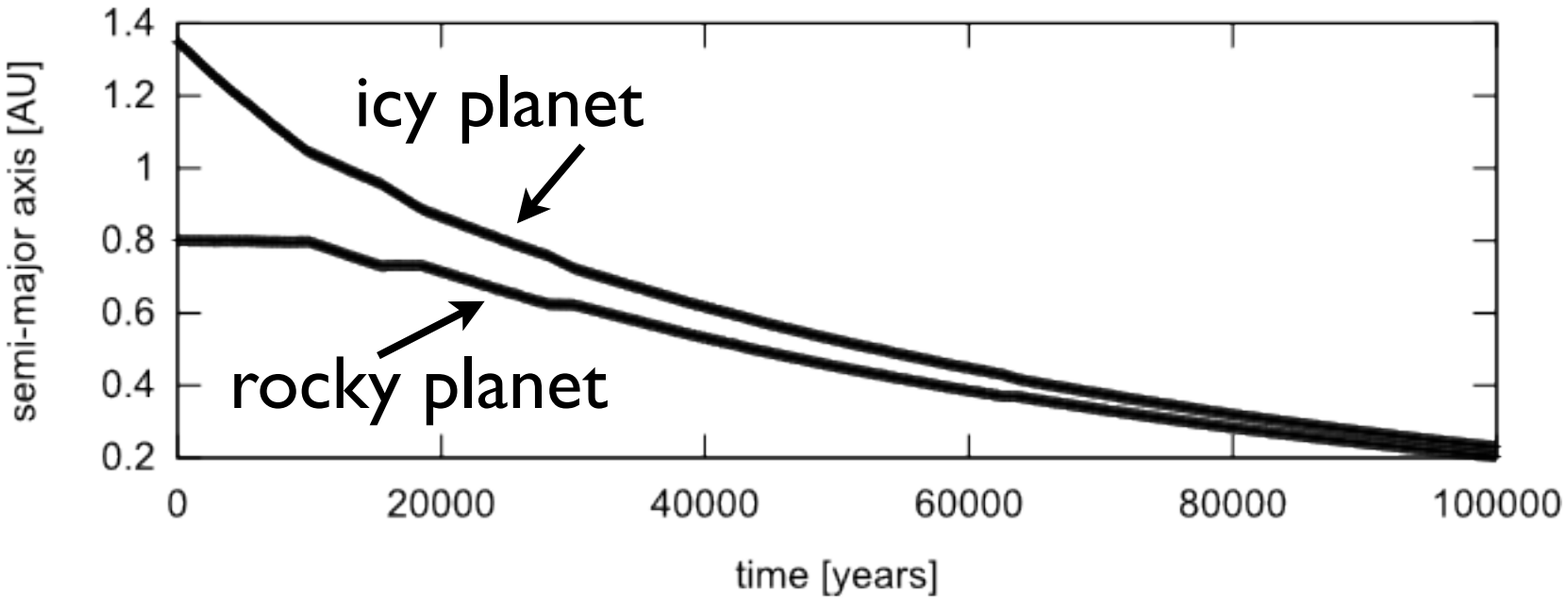
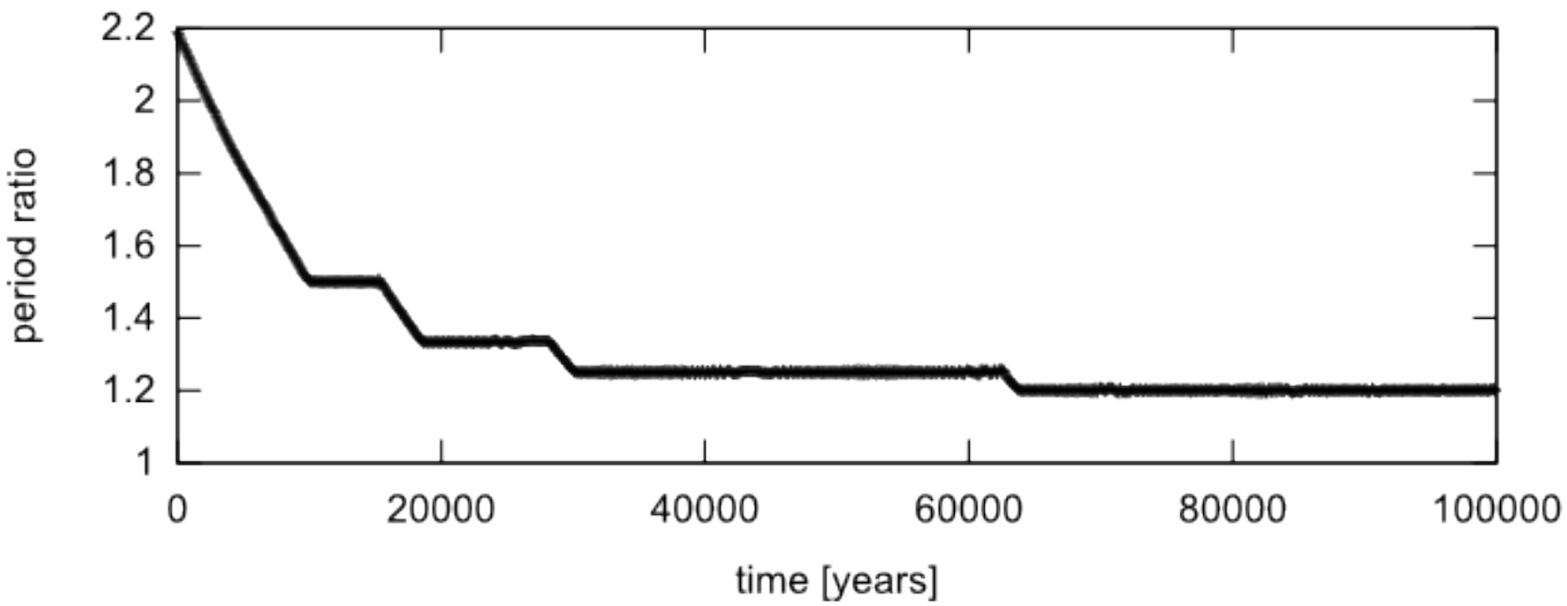



Image credit: NASA/JPL-Caltech

# 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

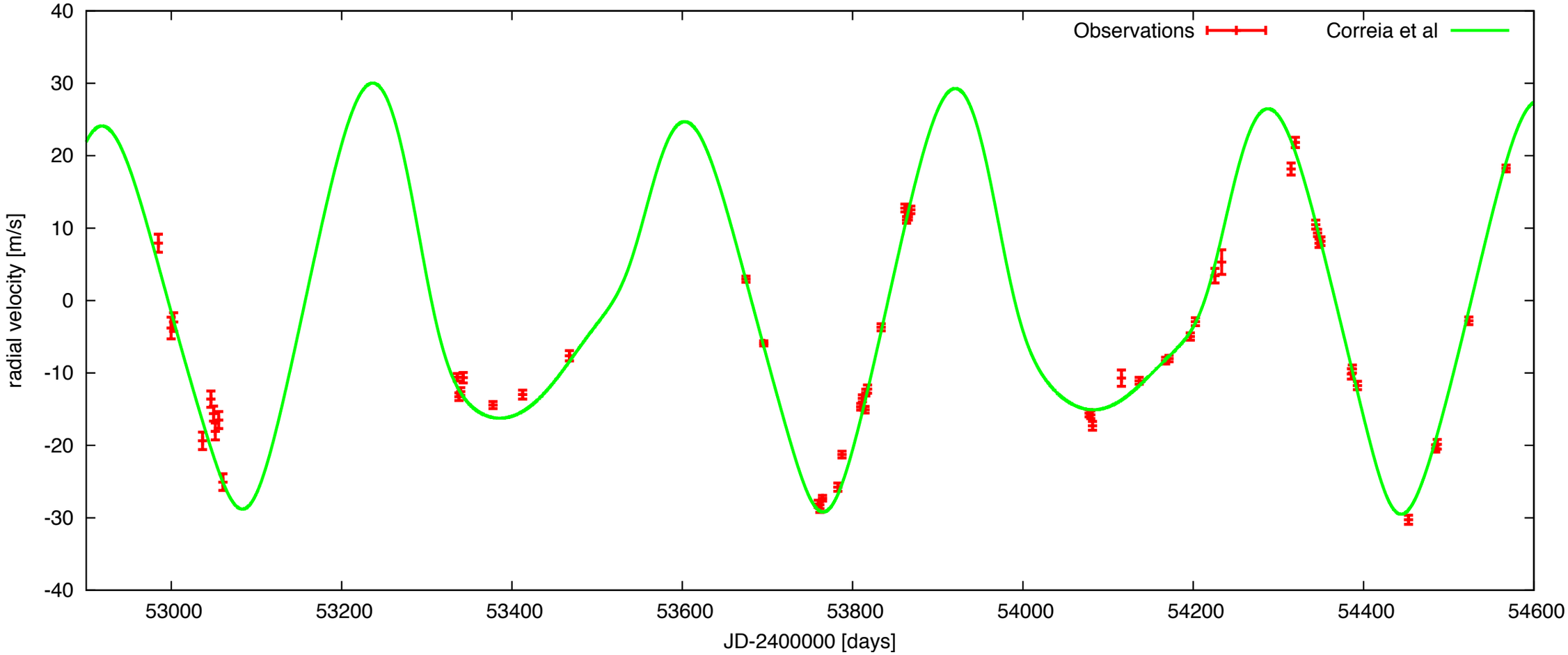
Paardekooper, Rein & Kley (in prep)

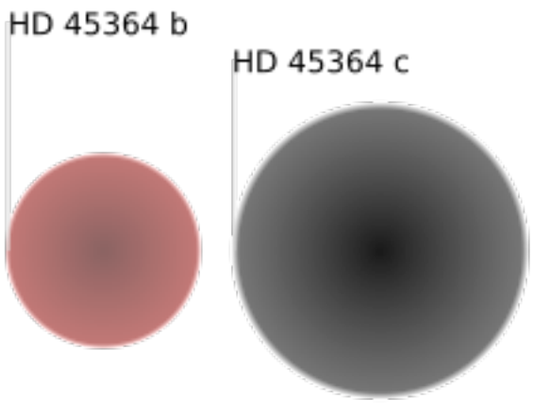
# Take home message VI

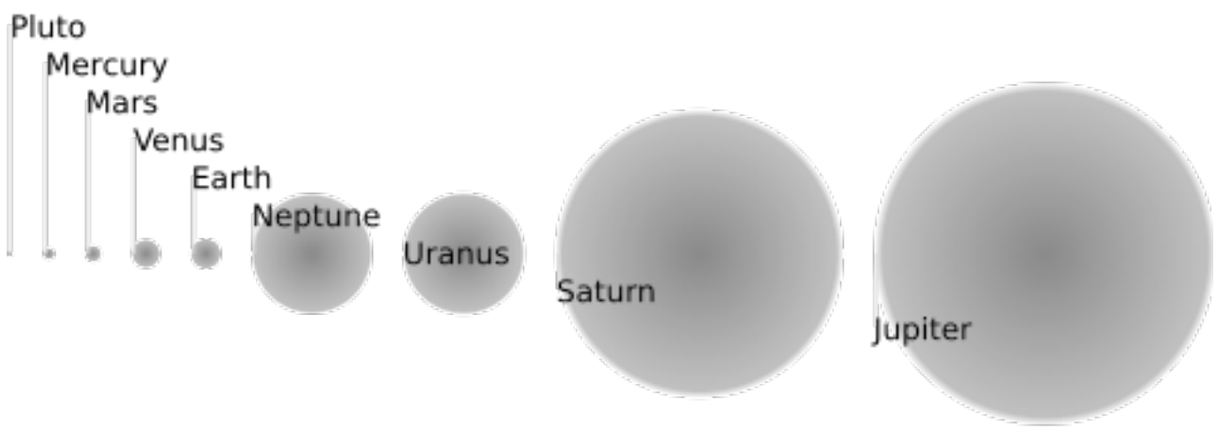
We find planets where they didn't form. This is a result of migration.

# The formation of HD45364

# HD45364

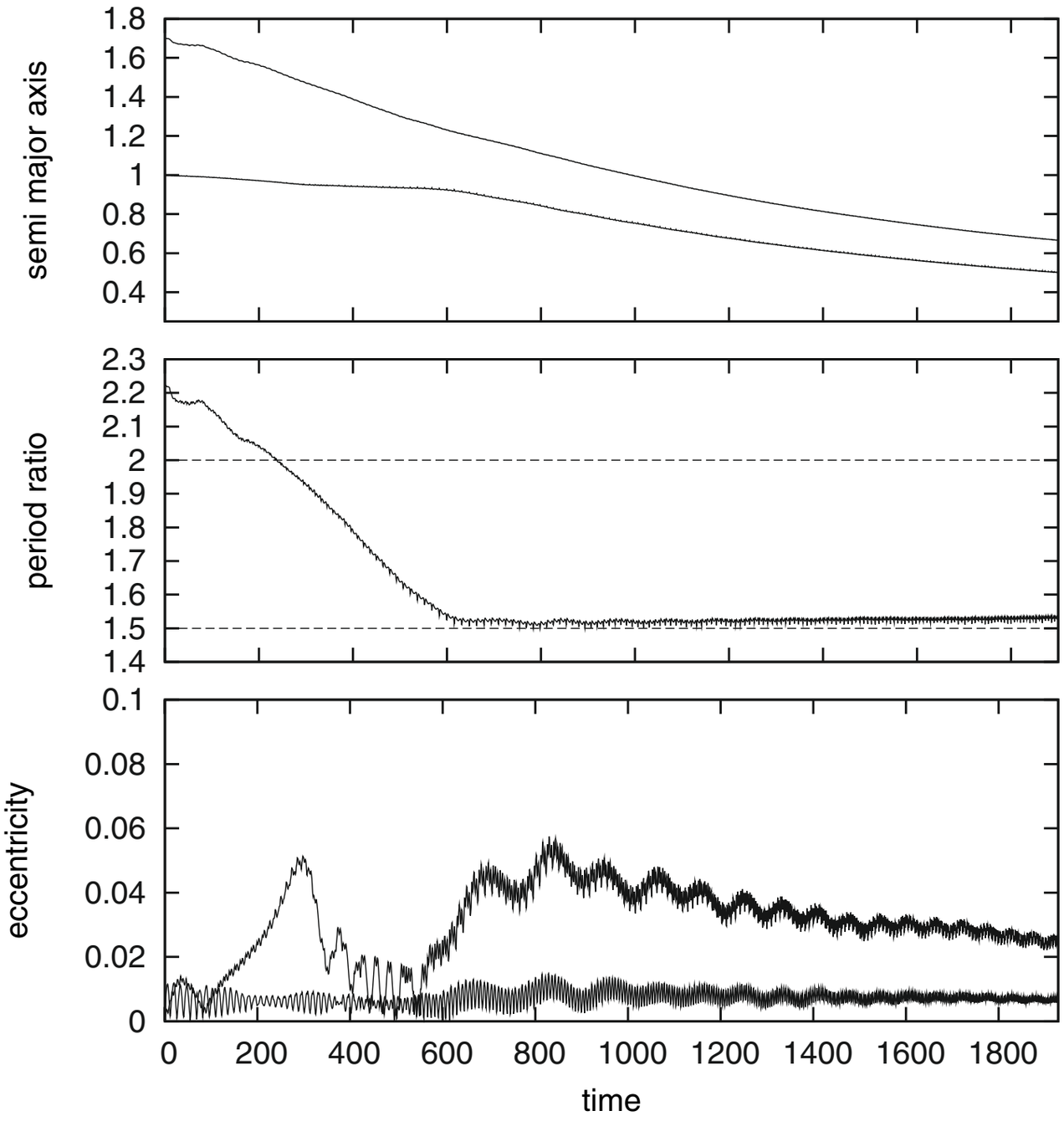


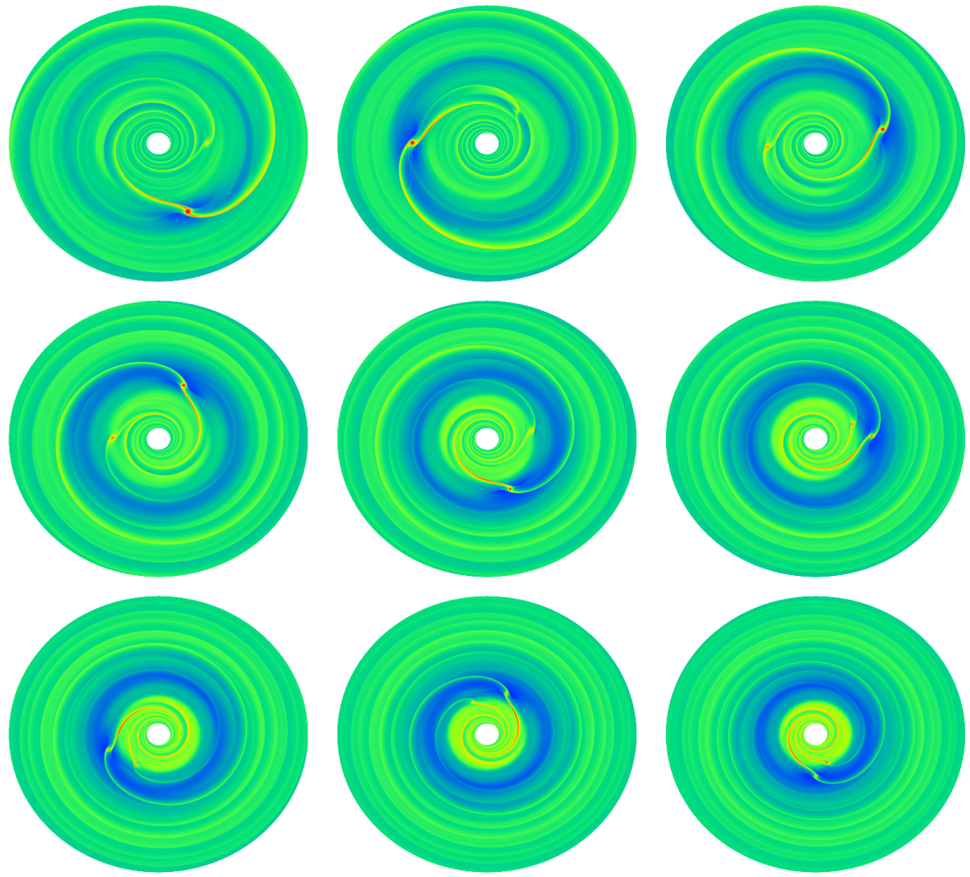




Correia et al 2009, Visual Exoplanet Catalogue

# Formation scenario for HD45364



Rein, Papaloizou & Kley 2010

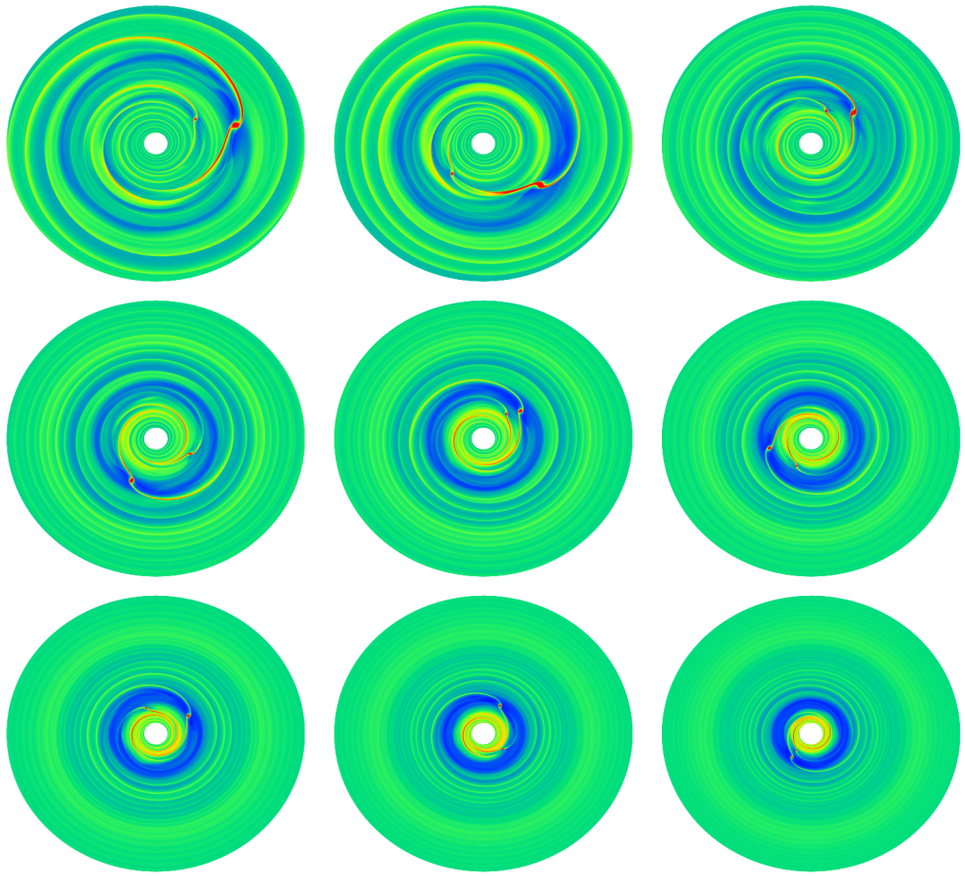
# Lessons learned from HD45364

## Massive disc (5 times MMSN)

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

## Large scale-height (0.07)

- Slow migration once in resonance
- Resonance is stable

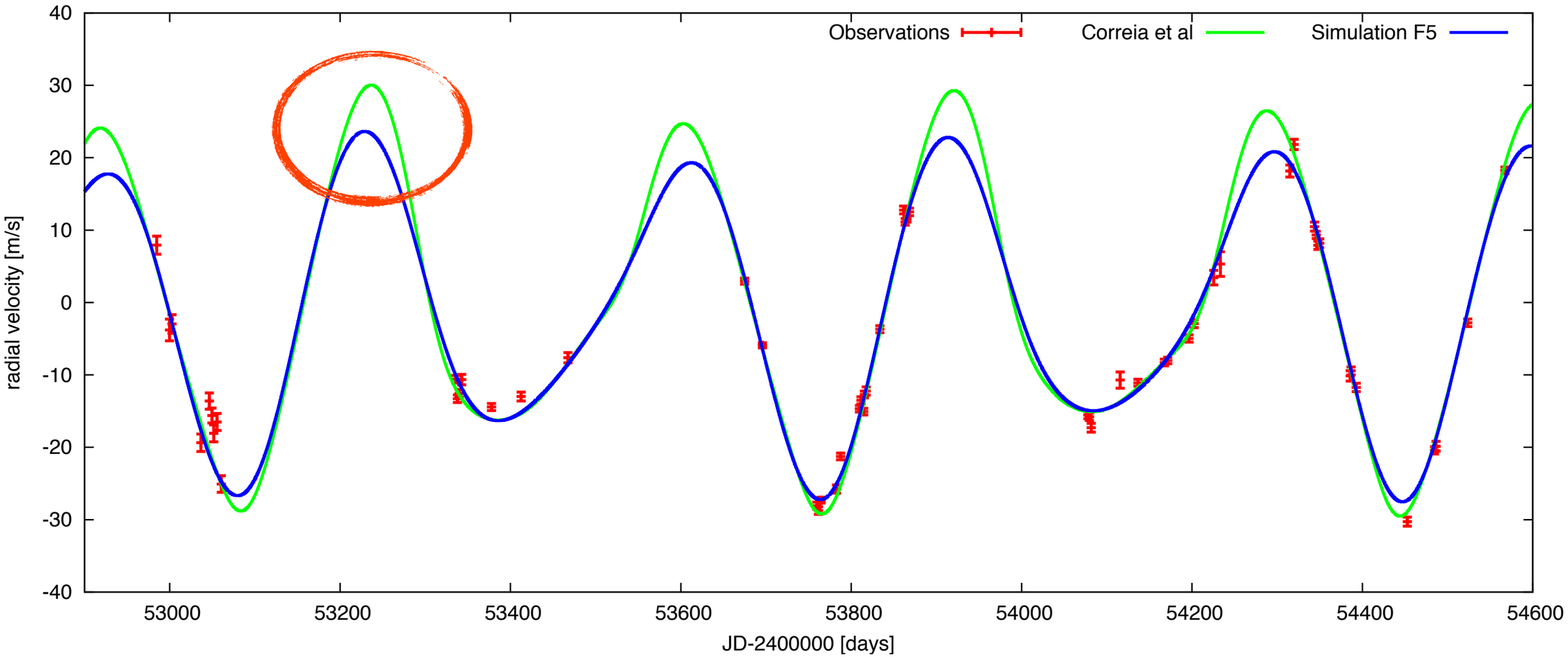


Rein, Papaloizou & Kley 2010

# Take home message VII

Migration scenarios provide us with valuable information about the environment of planet formation.

# Testable predictions!




## Our formation model predicts a specific set of orbital parameters

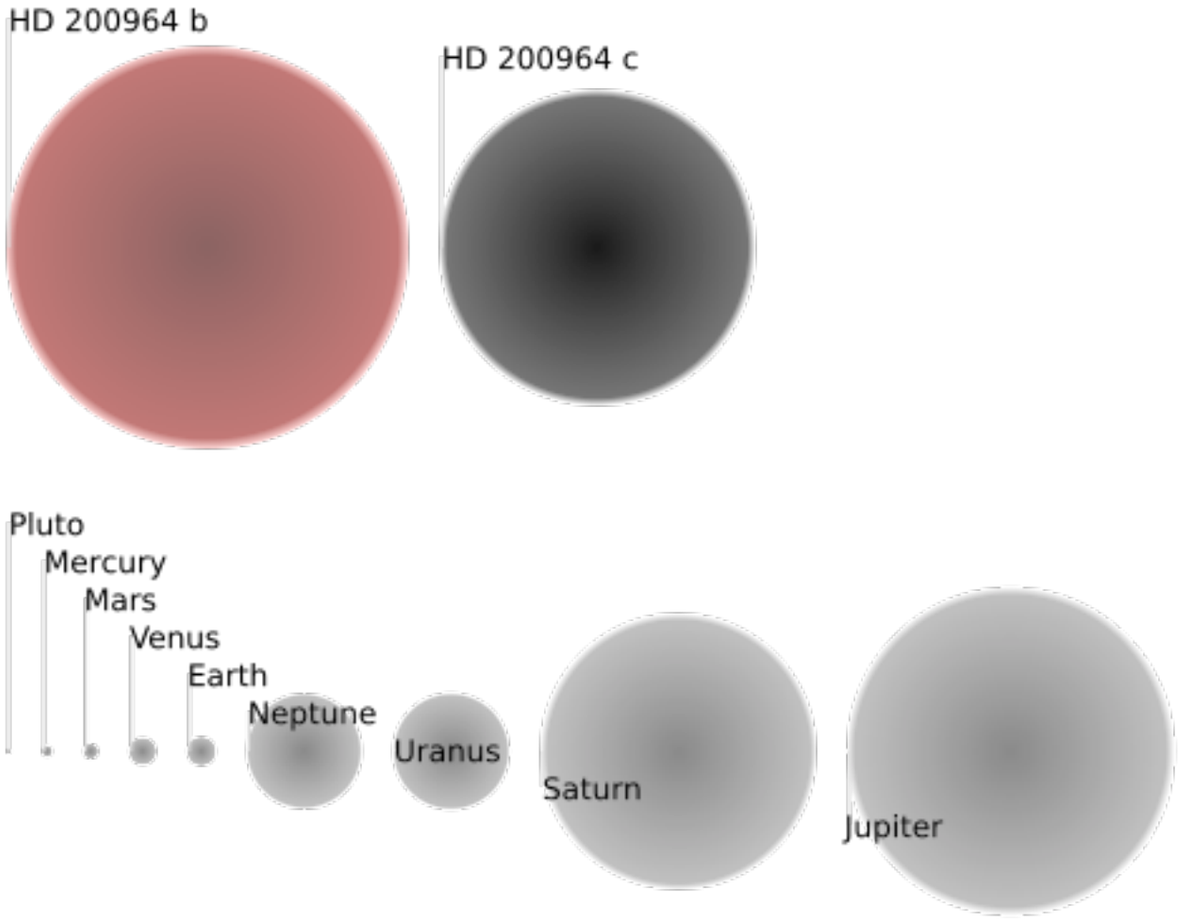
- Consistent with current observations
- Testable with just a few well-timed radial velocity data points.

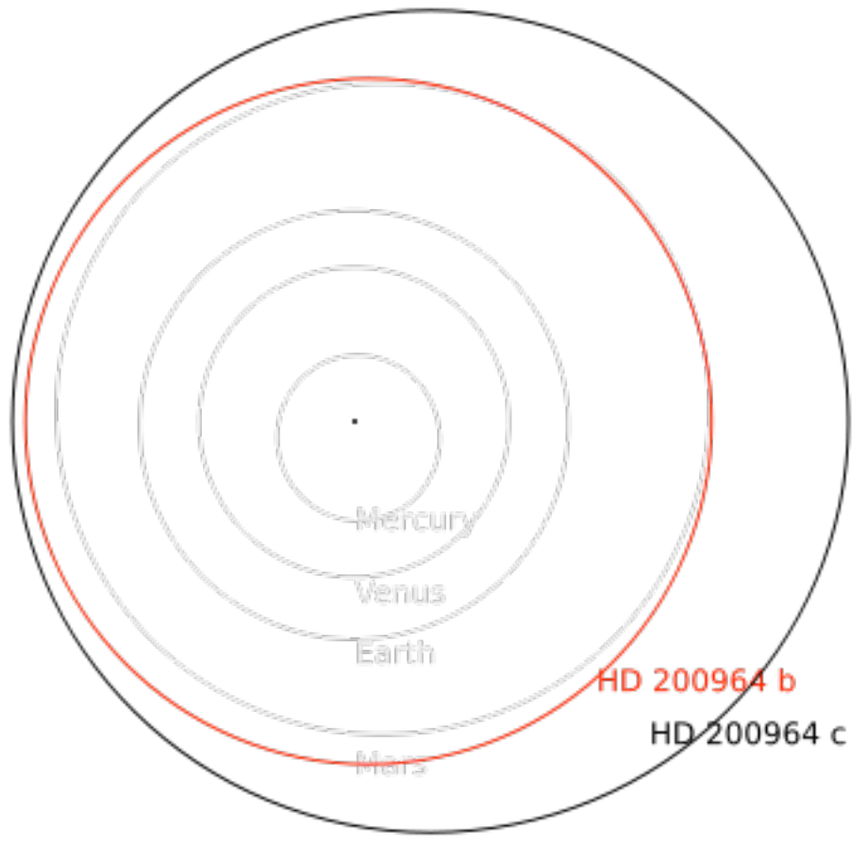
Rein, Papaloizou & Kley 2010

# HD200964
# The impossible system?

# HD200964

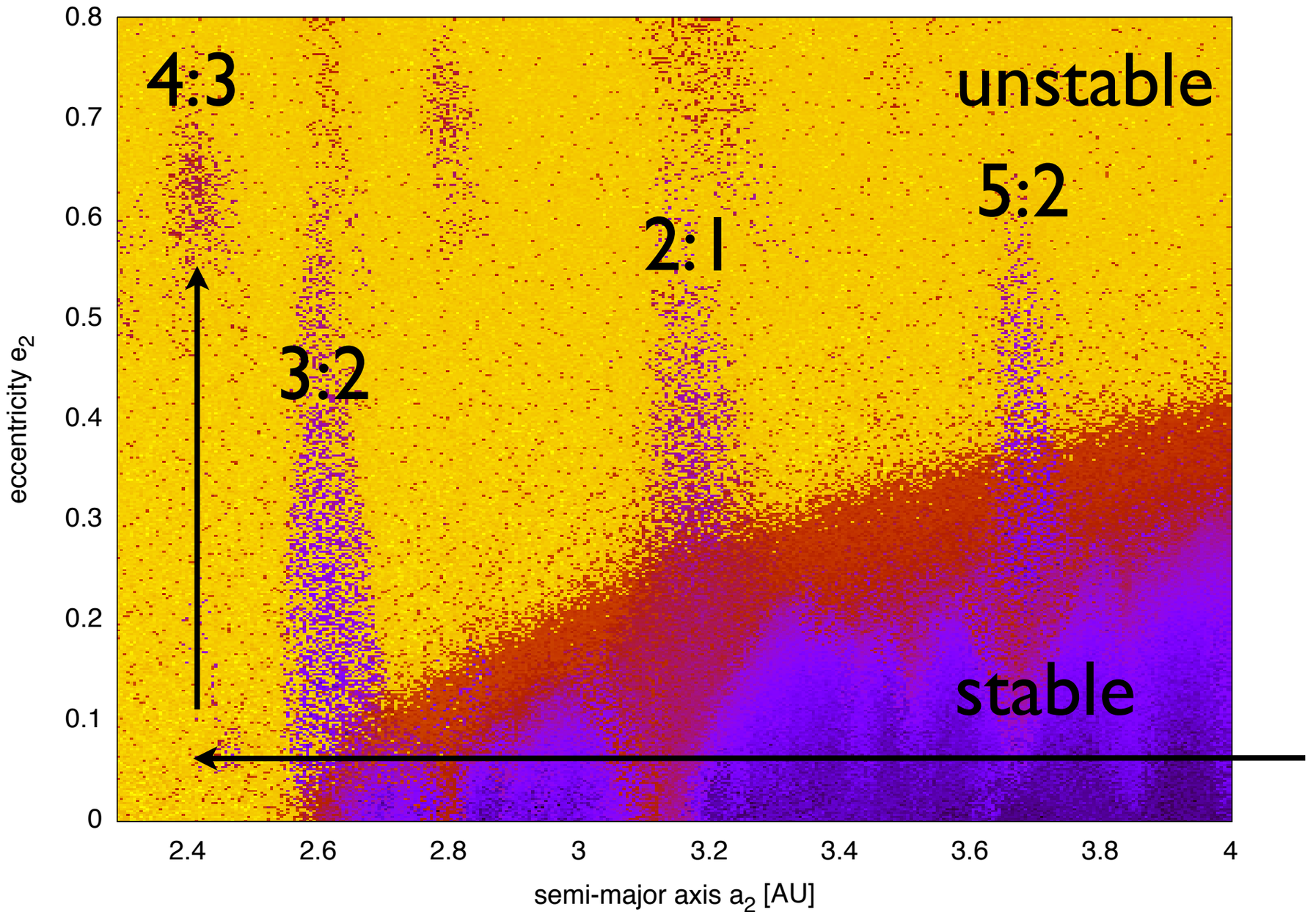
- Two massive planets 1.8 $M_{Jup}$ and 0.9 $M_{Jup}$
- Period ratio close to 4:3
- Another similar system, to be announced soon.




Rein, Payne, Veras & Ford (2012)

# Stability of HD200964




Rein, Payne, Veras & Ford (2012)

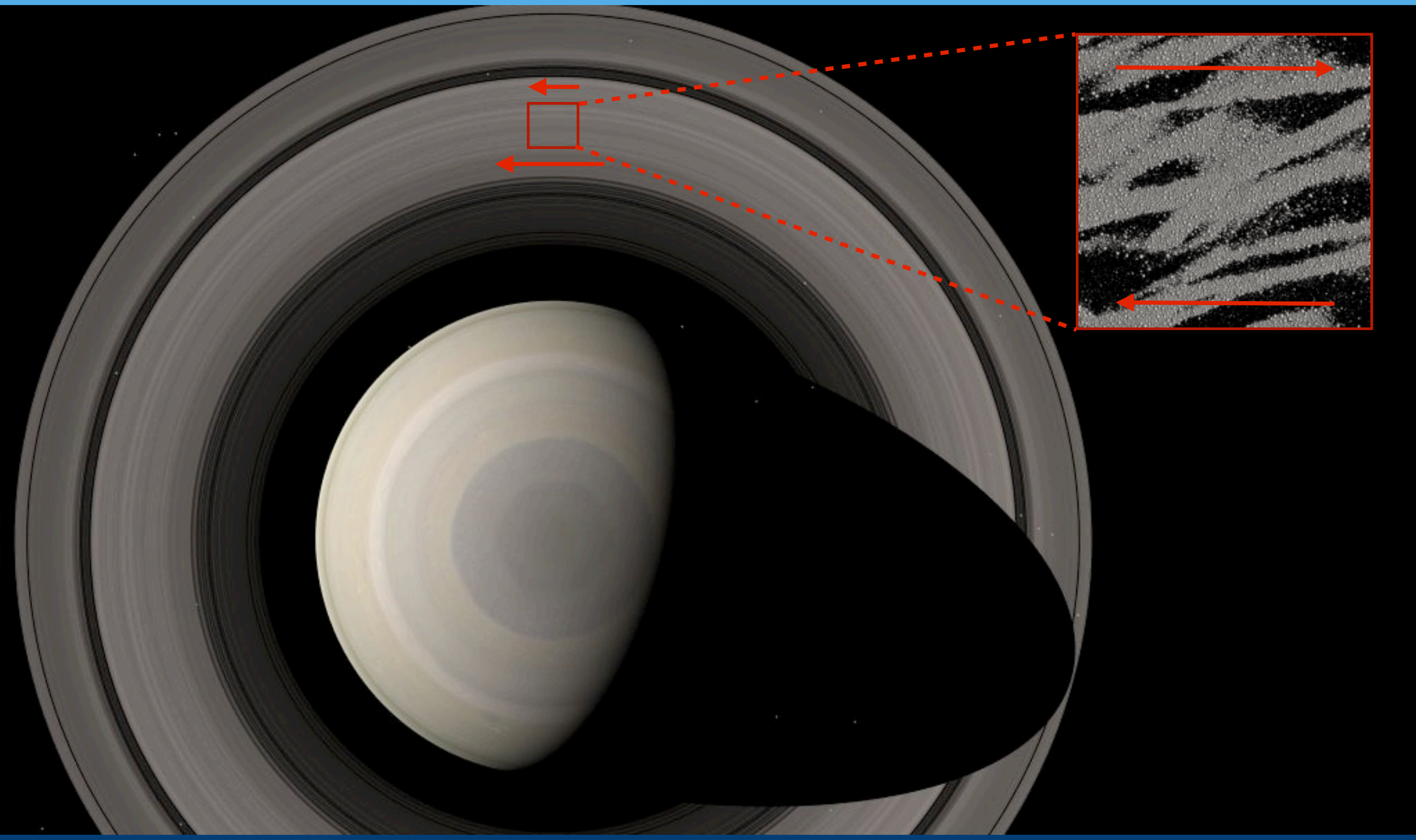
# Take home message VIII

We don't understand everything*.

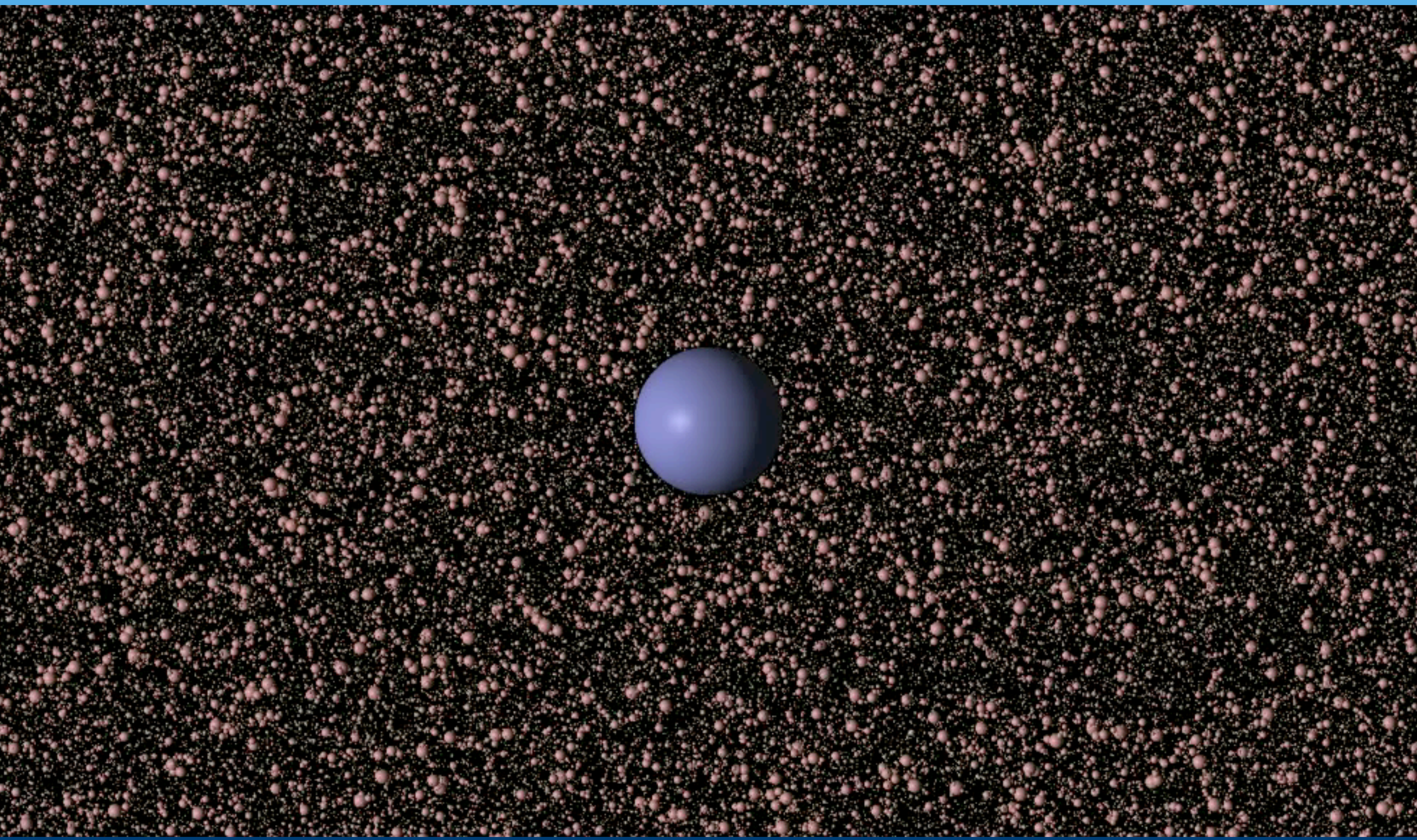
*just yet

# Saturn's Rings

# Saturn is a smaller version of the Solar System



# Stochastic Migration



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

# Summary

## The formation of multi-planetary systems

Many planets are in systems where multiple planets orbit the same star.

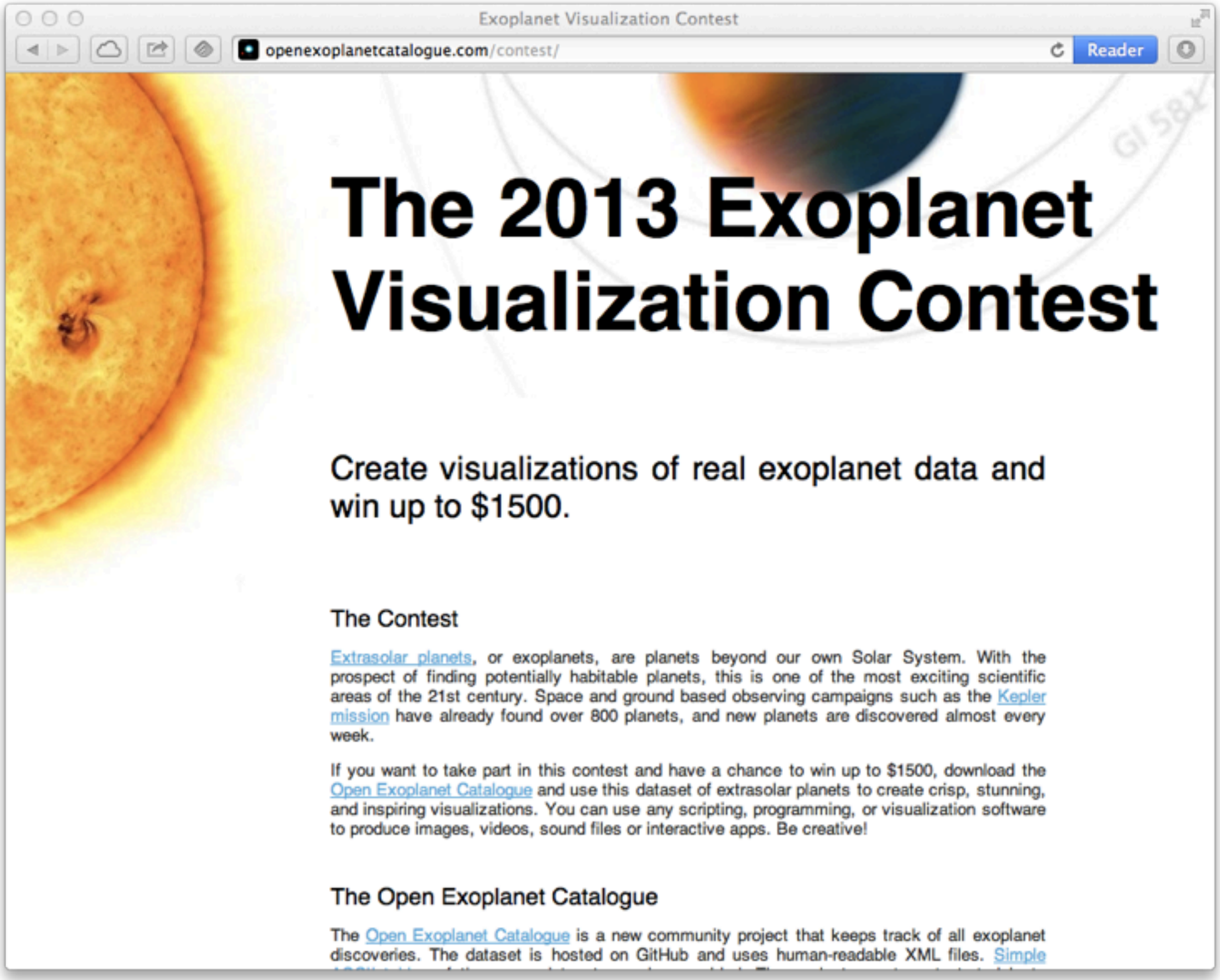
By studying the current dynamical configuration we can learn a lot about the physical environment at the time when the planets formed.

| | |
|---|---|
| Gliese 876 | Best example for the effects of dissipative planet migration. |
| Kepler-36 | Very different composition, brought onto close orbits by migration. |
| HD45364 | Had to form in a massive disc. |
| HD 200964 | We have no clue (yet). |

## The big picture

Understanding the formation of multi-planetary systems is essential if we want to know if the Solar System is special, if life is special.

# Exoplanet Visualization Contest




openexoplanetcatalogue.com/contest/