



Multi-planetary systems

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Projects that I will not talk about today

Symplectic integrators

Viscous overstability

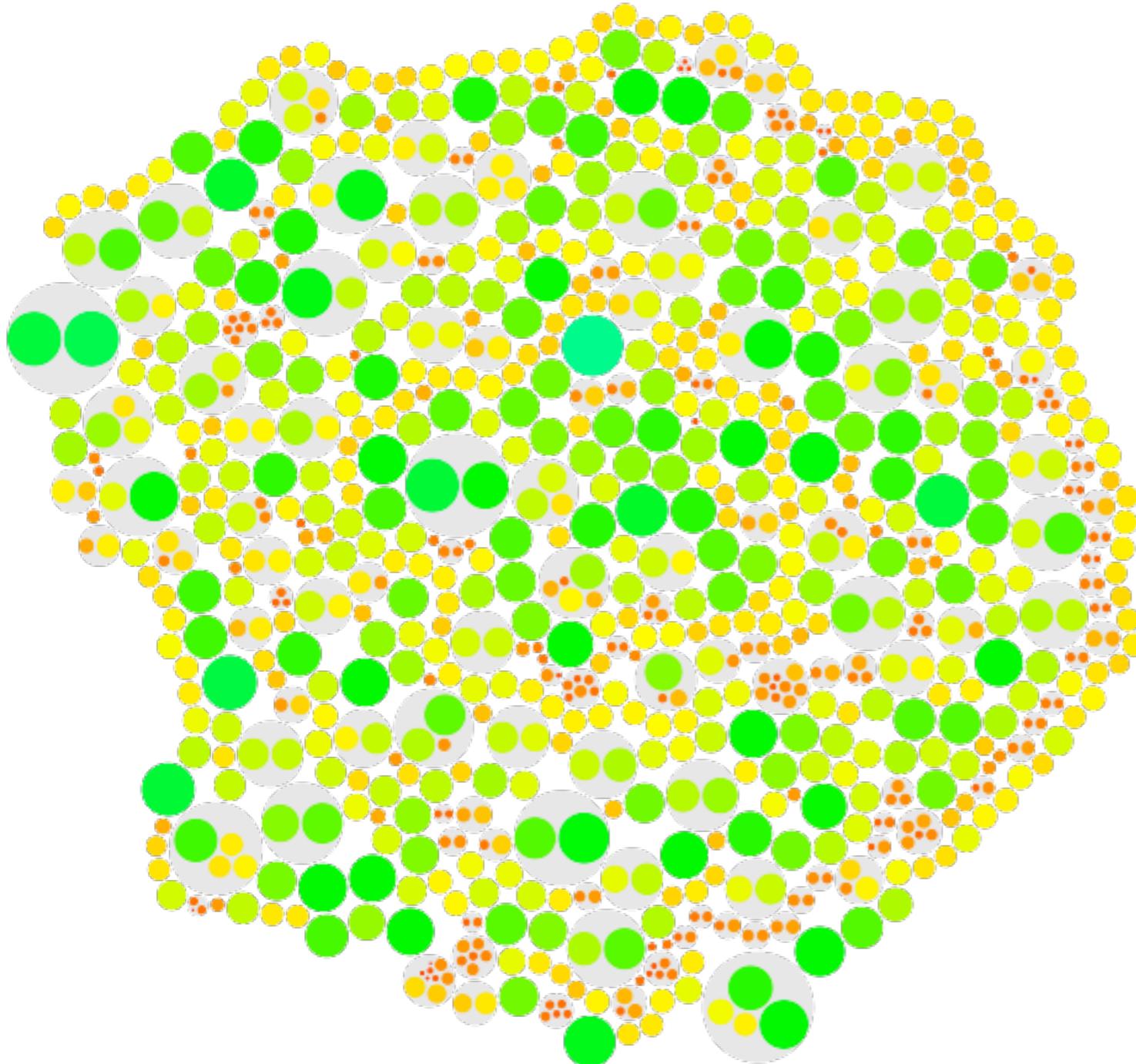
Parallel tree codes

Stability of exo-moons

Open Exoplanet Catalogue

Simulations of dense rings

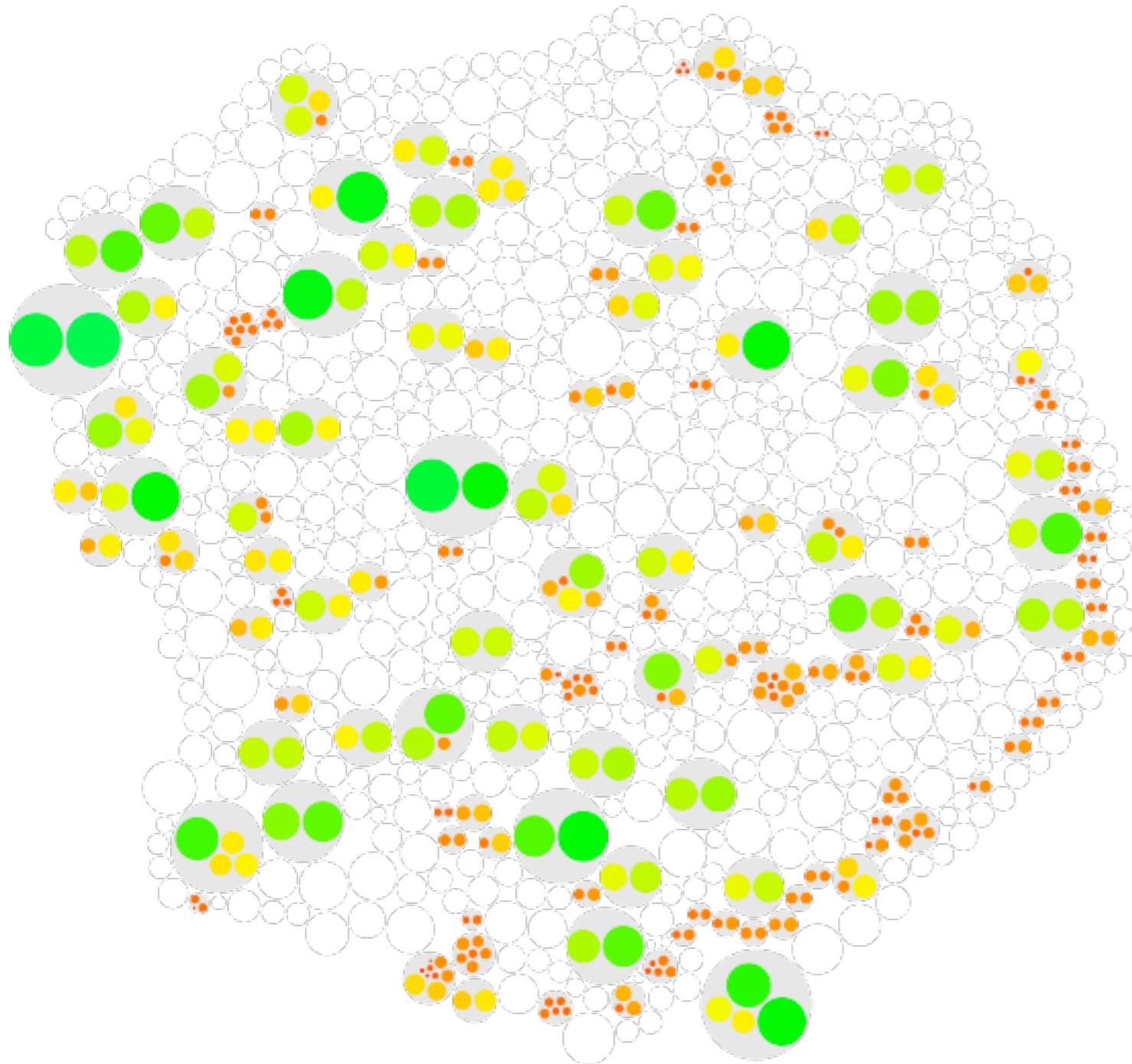
All discovered extra-solar planets



869 confirmed extra-solar planets

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

All multi-planetary systems



869 confirmed extra-solar planets

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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:

- I. Planet migration
2. Resonances

I. Planet migration

Planet formation

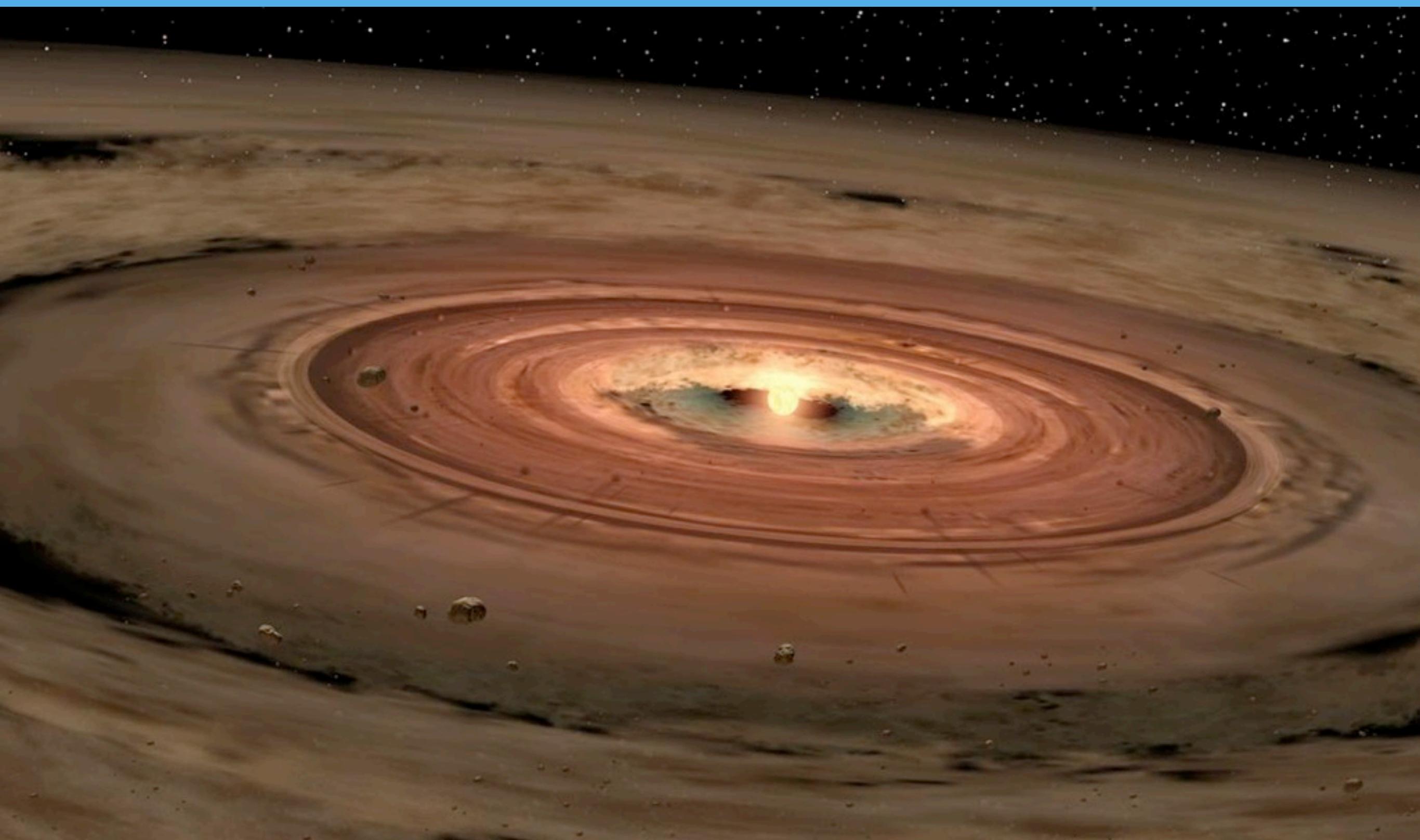
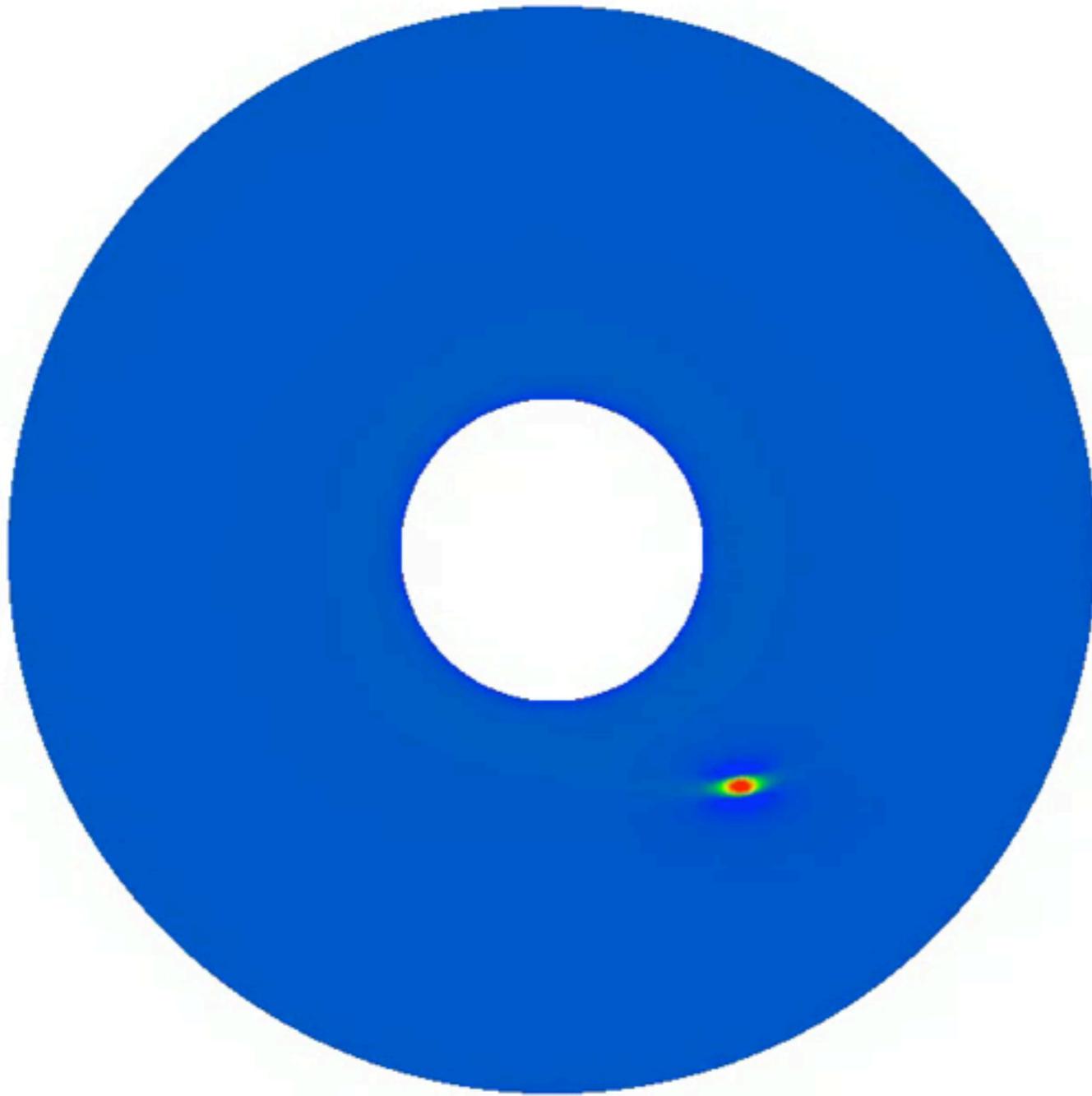


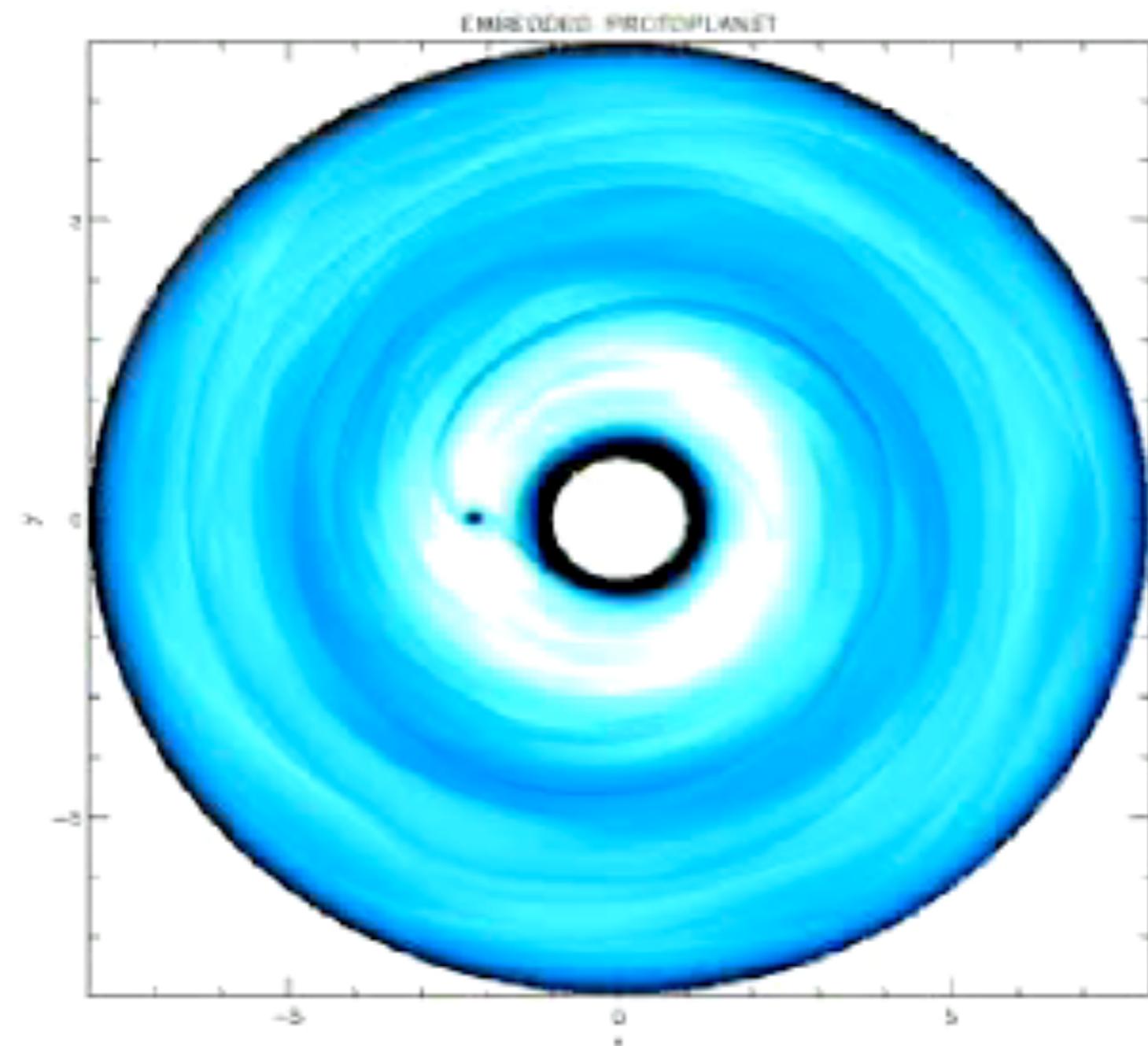
Image credit: NASA/JPL-Caltech

Smooth migration



2D hydro code Prometheus (Rein 2010)

Stochastic migration



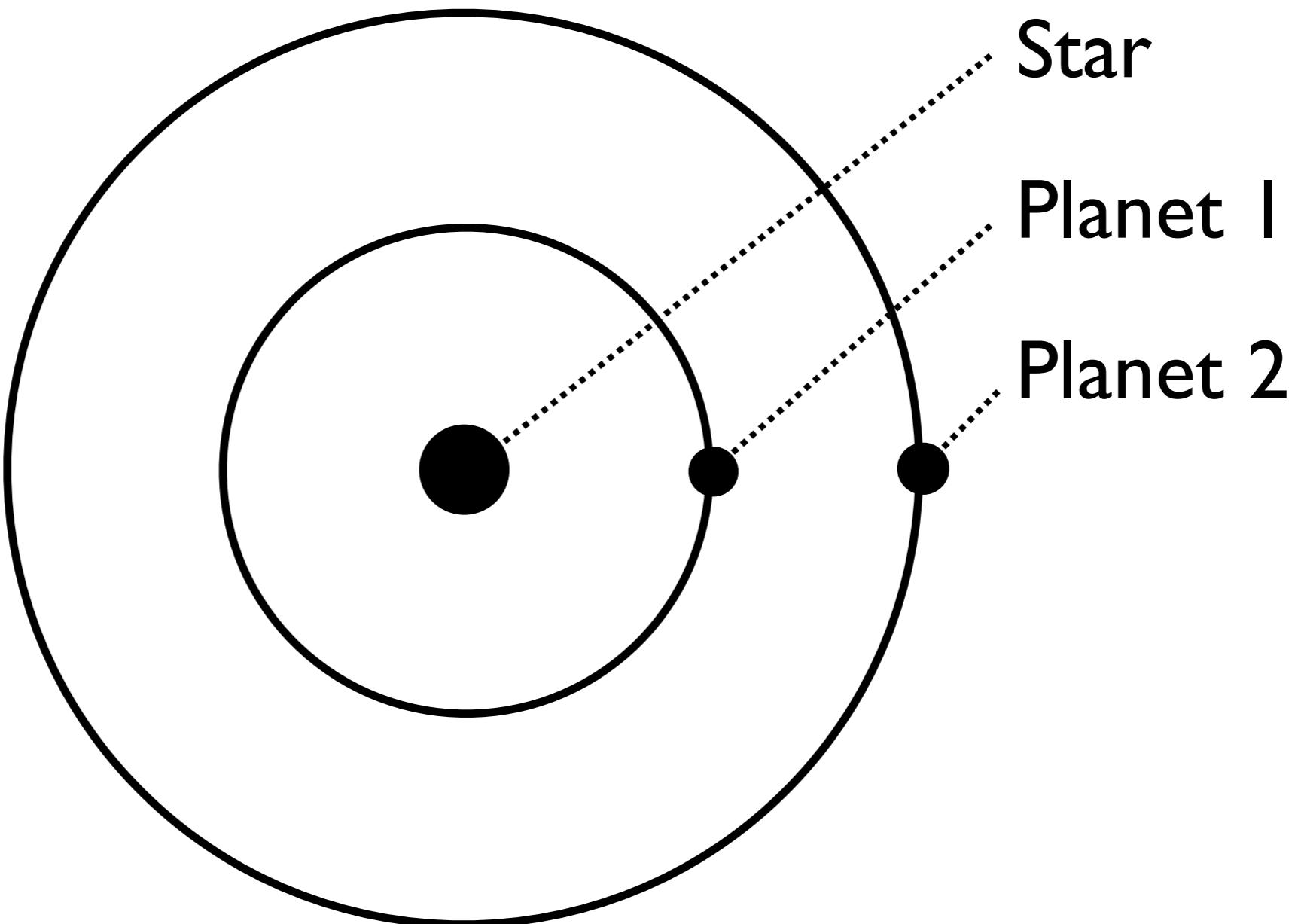
Animation from Nelson & Papaloizou 2004
Random forces measured by Laughlin et al. 2004, Nelson 2005, Oischi et al. 2007

Take home message III

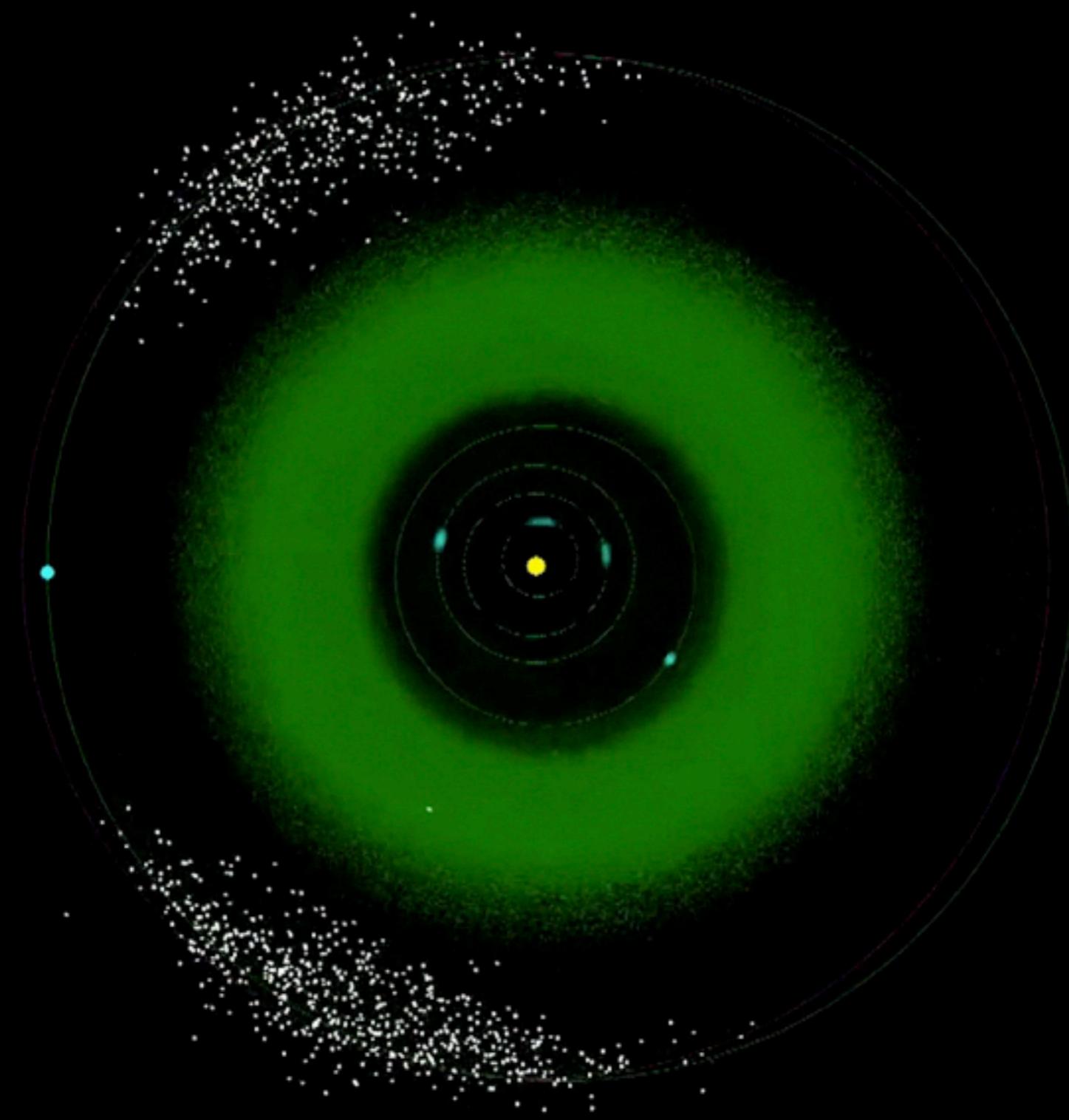
planet + disc = migration

2. Resonances

2:1 Mean Motion Resonance

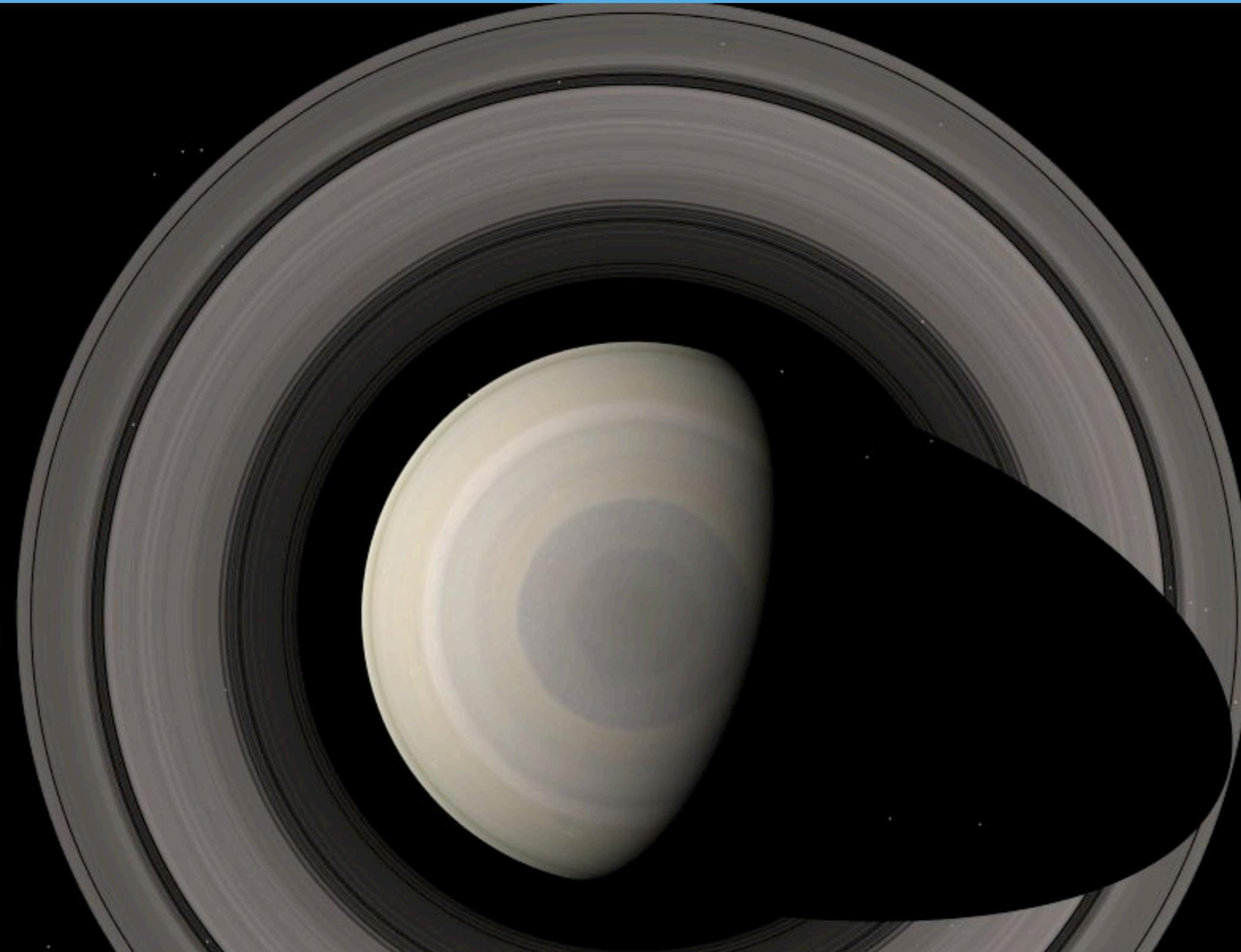


Asteroids in resonance with Jupiter

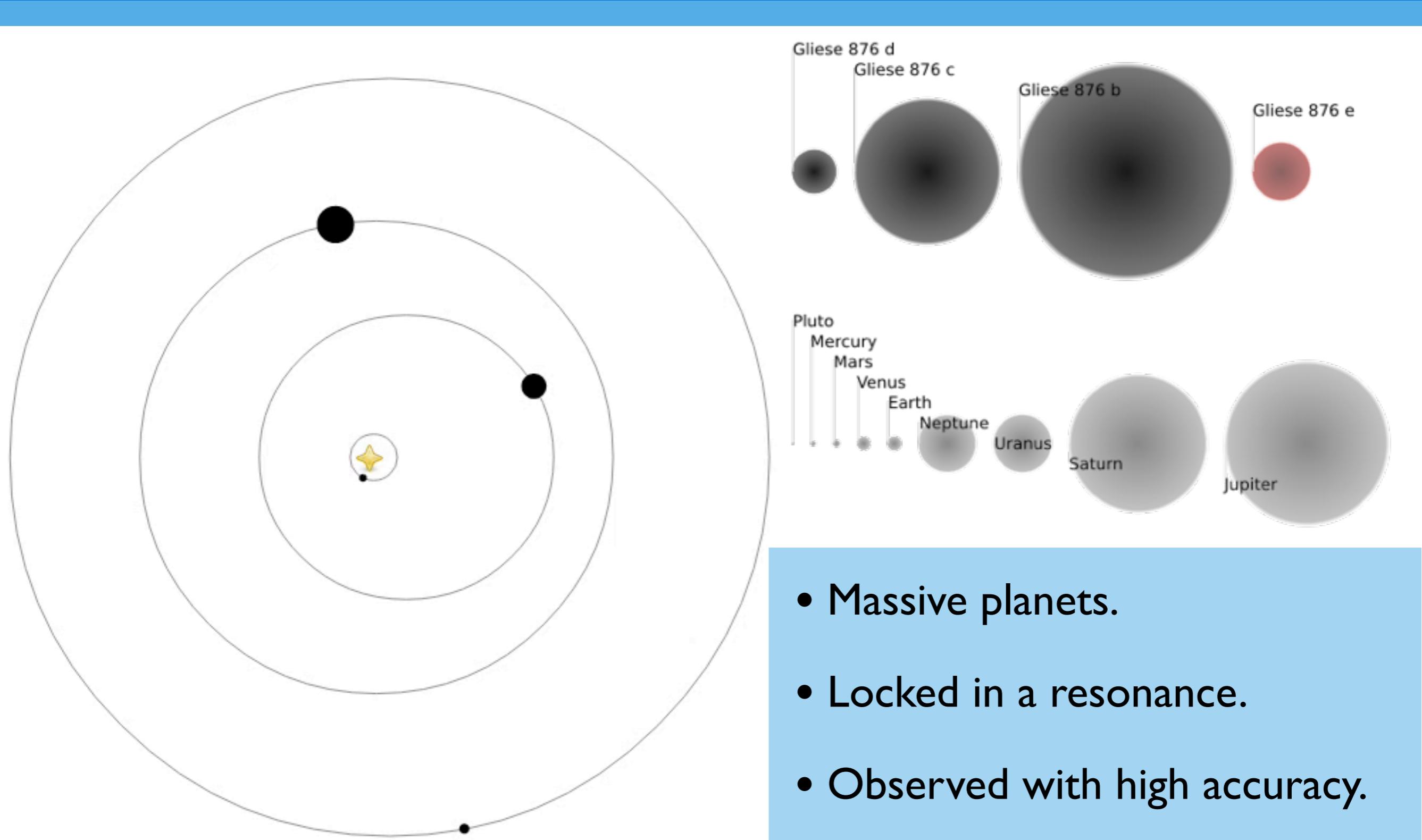


Scott Manley

Saturn's rings are sculpted by resonances



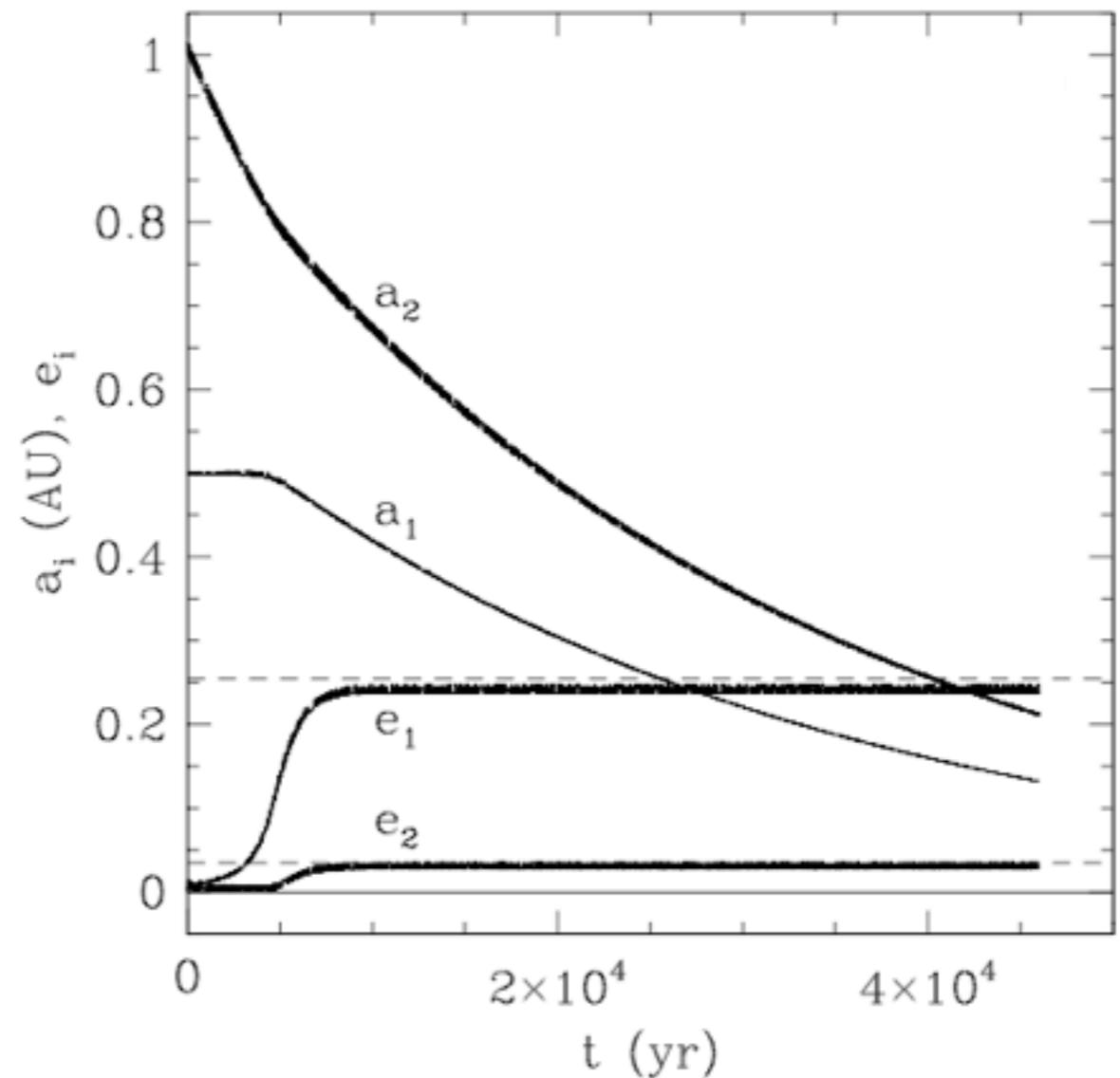
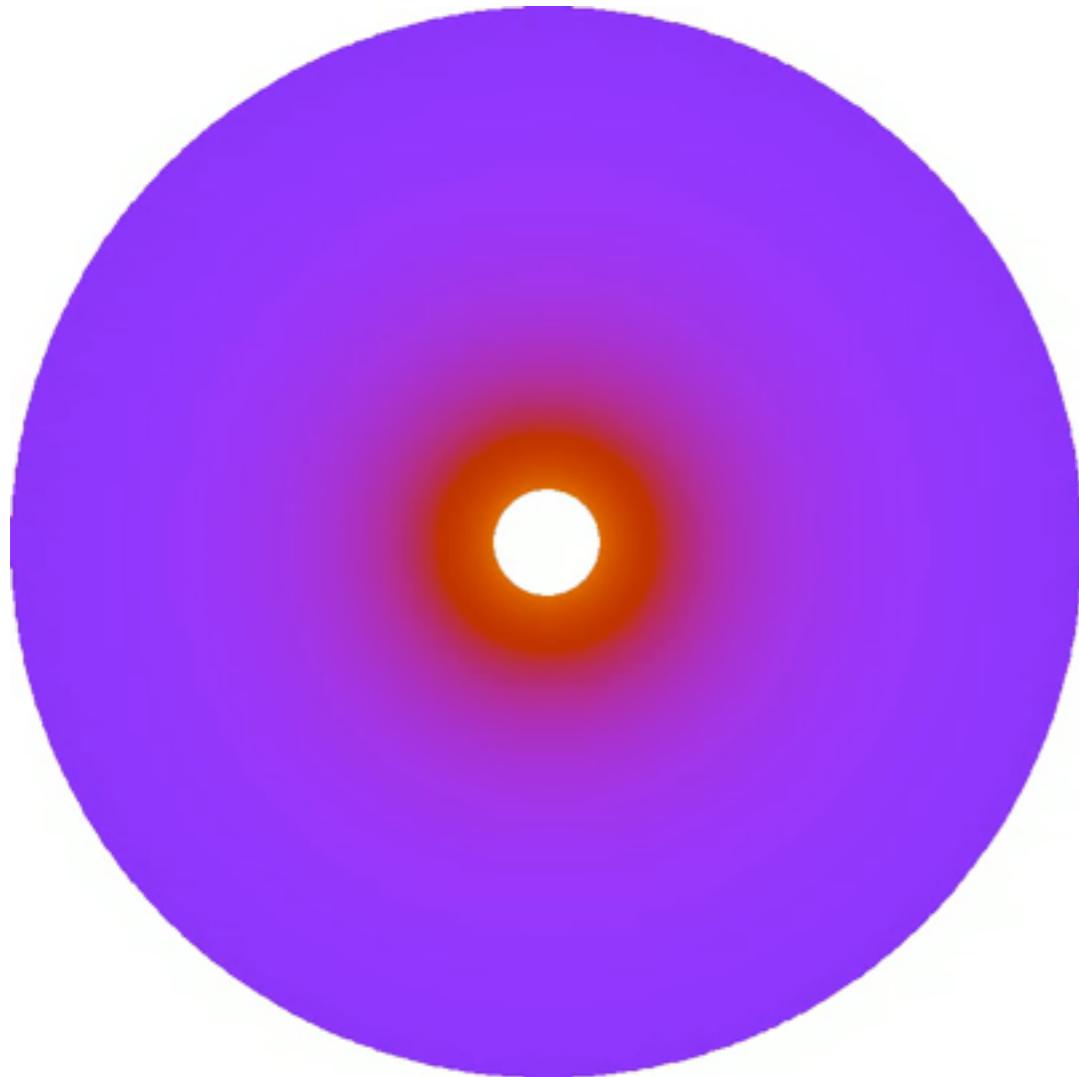
The system Gliese 876



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

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



Snow line

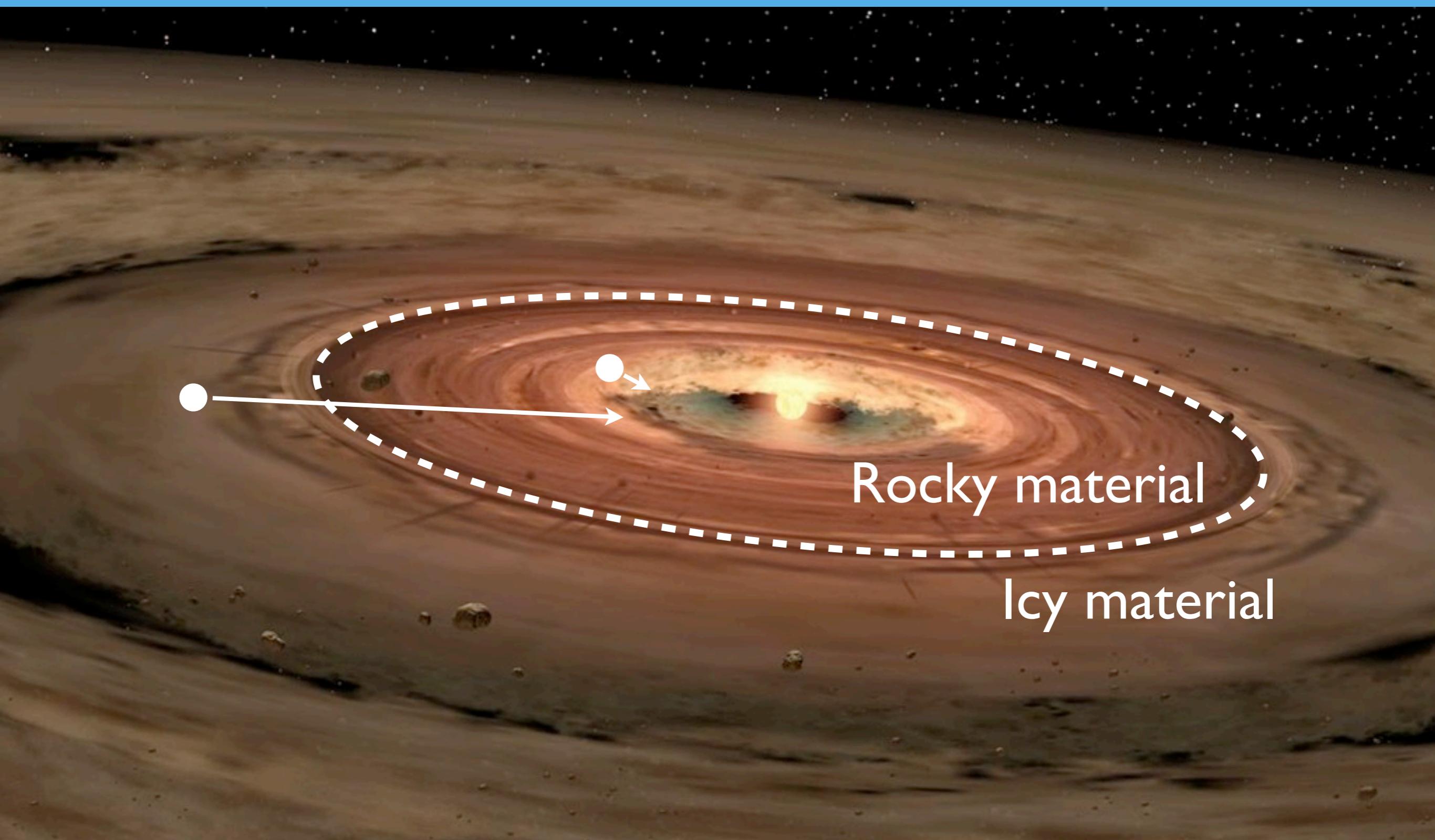
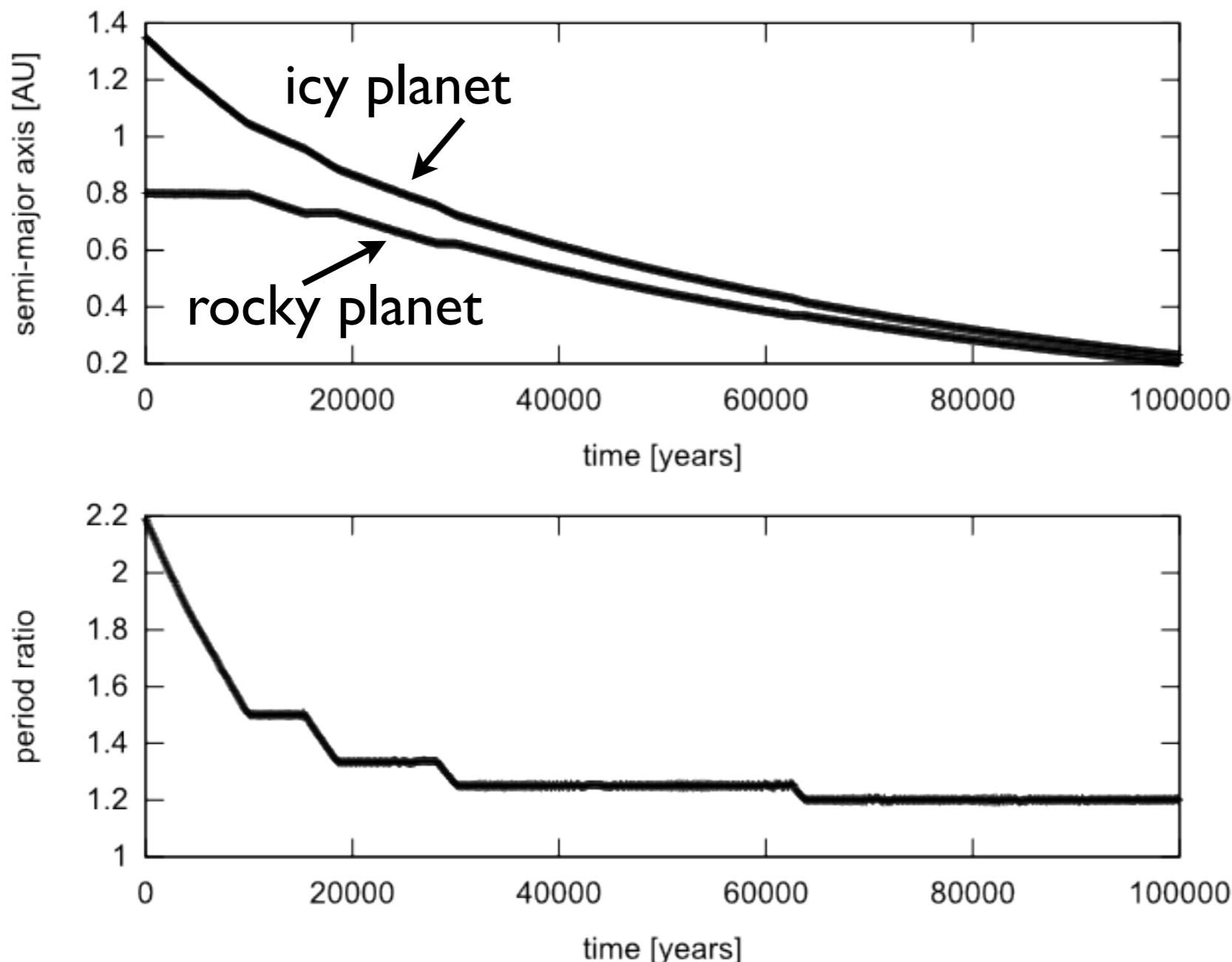


Image credit: NASA/JPL-Caltech

Convergent migration in Kepler-36



Successful formation scenario for Kepler-36

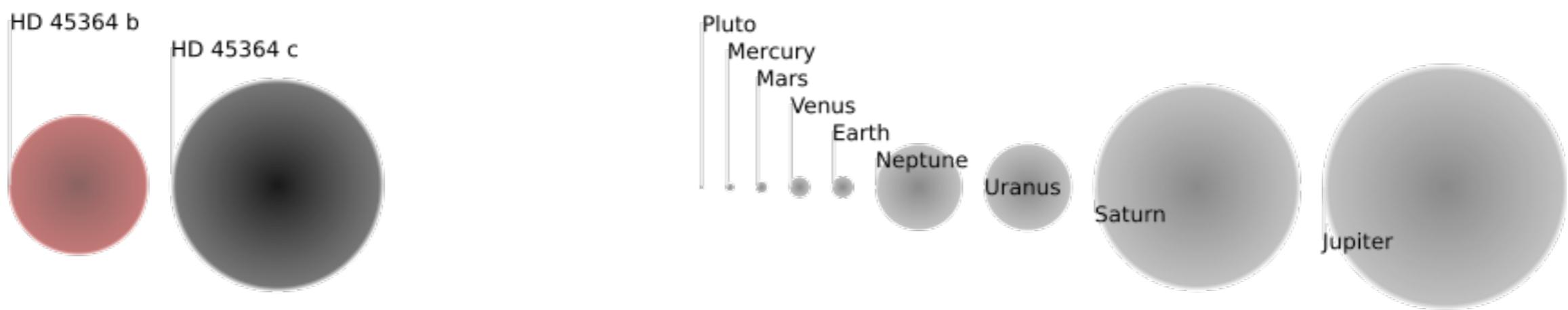
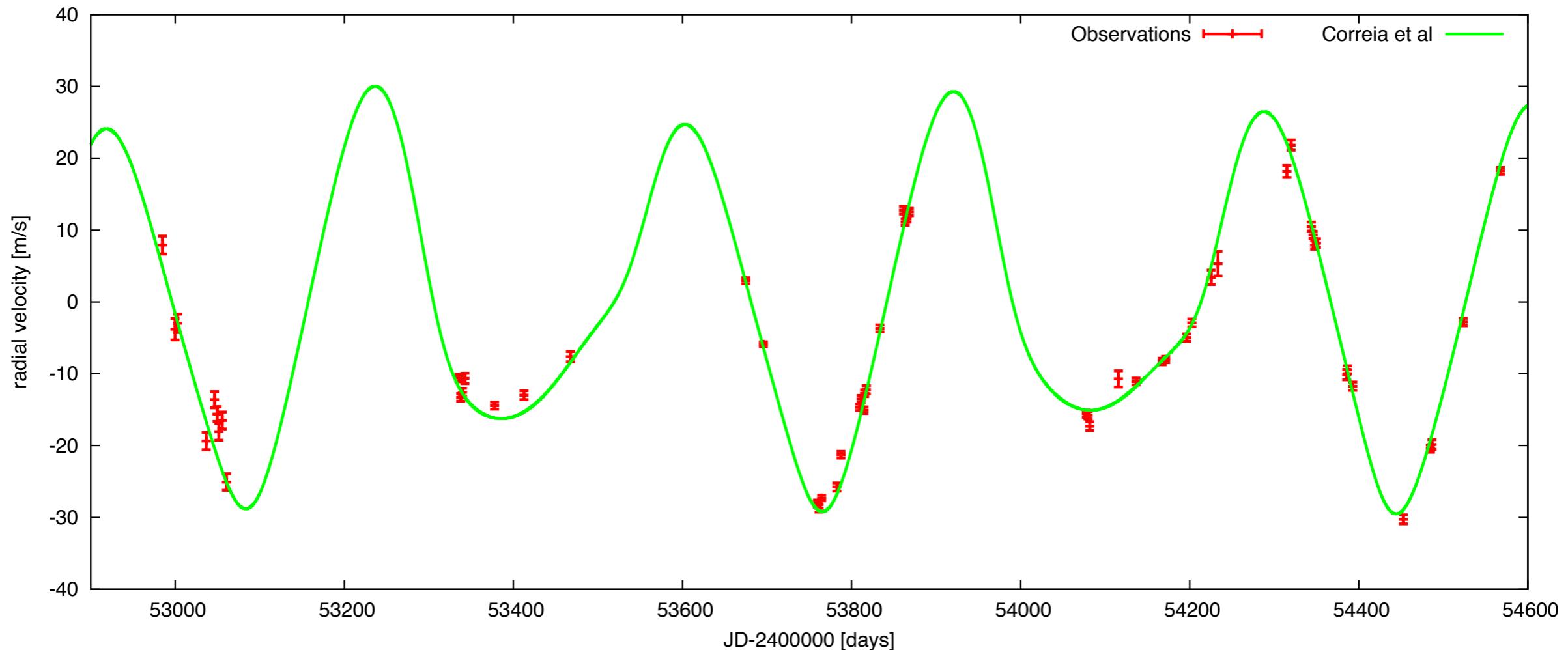
- Getting planets of different origin (composition) close together
- Forming stable high order resonances
- Capture probability greatly enhanced by adding a small amount of stochastic migration

Take home message VI

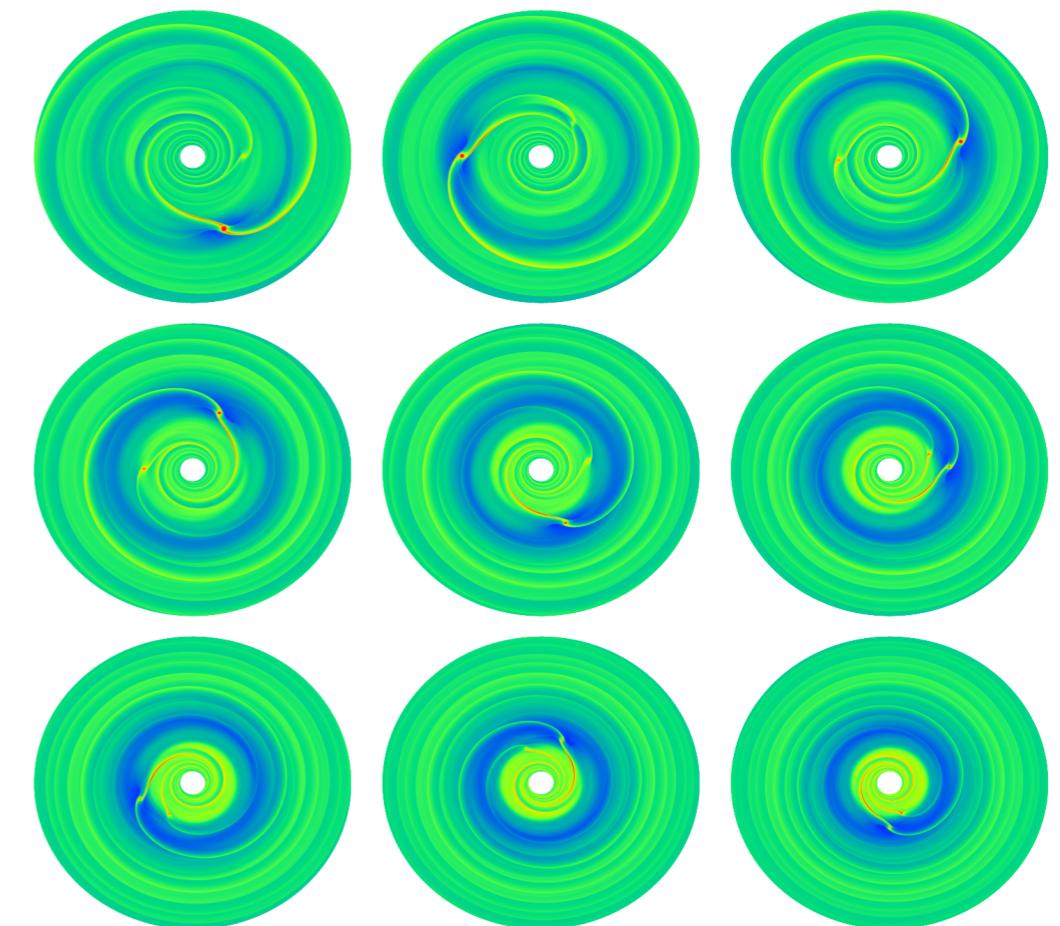
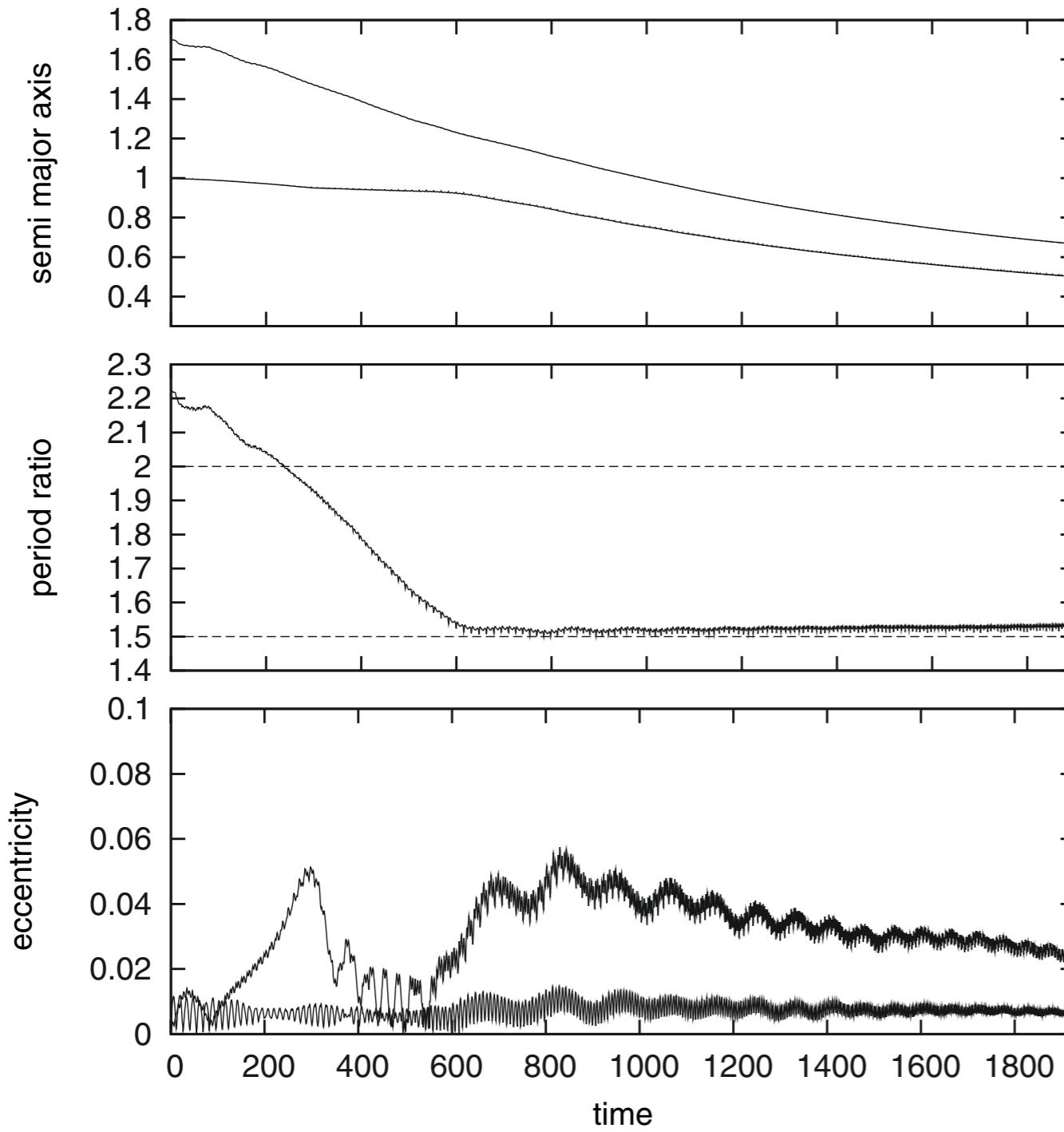
We find planets where they didn't form. This is a result of migration.

The formation of HD45364

HD45364



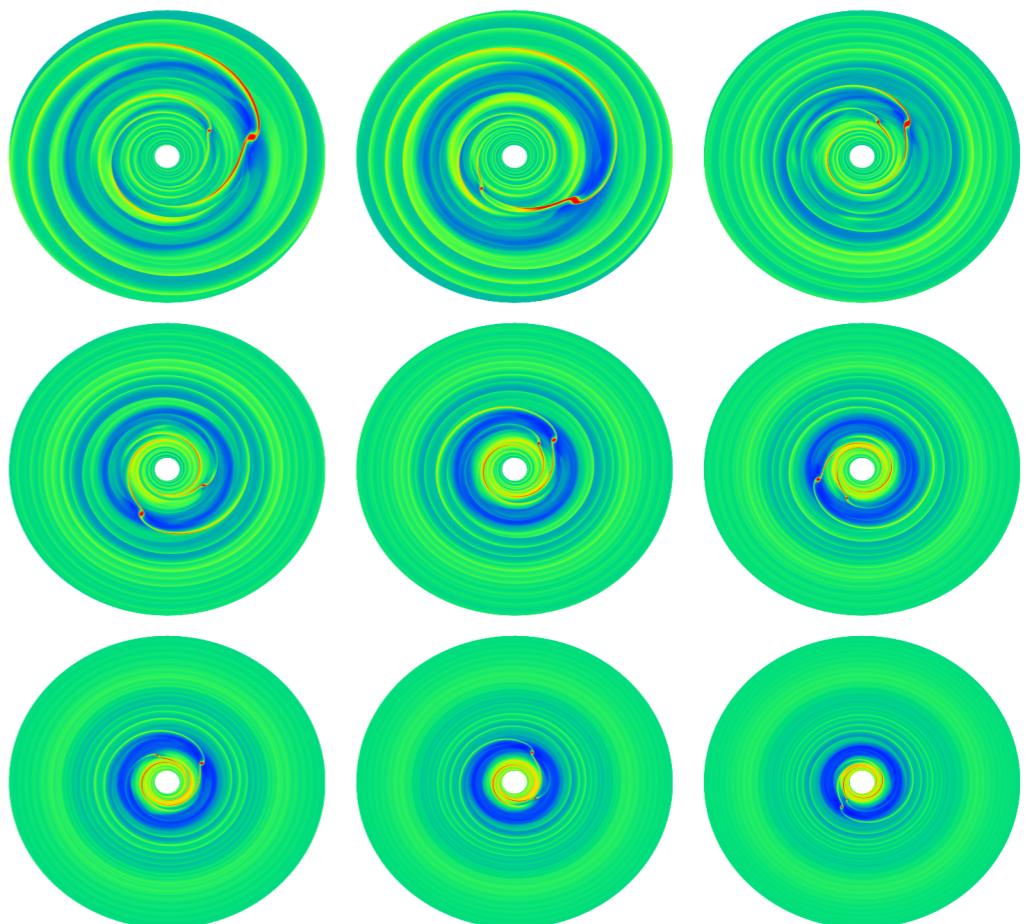
Formation scenario for HD45364



Lessons learned from HD45364

Massive disc (5 times MMSN)

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



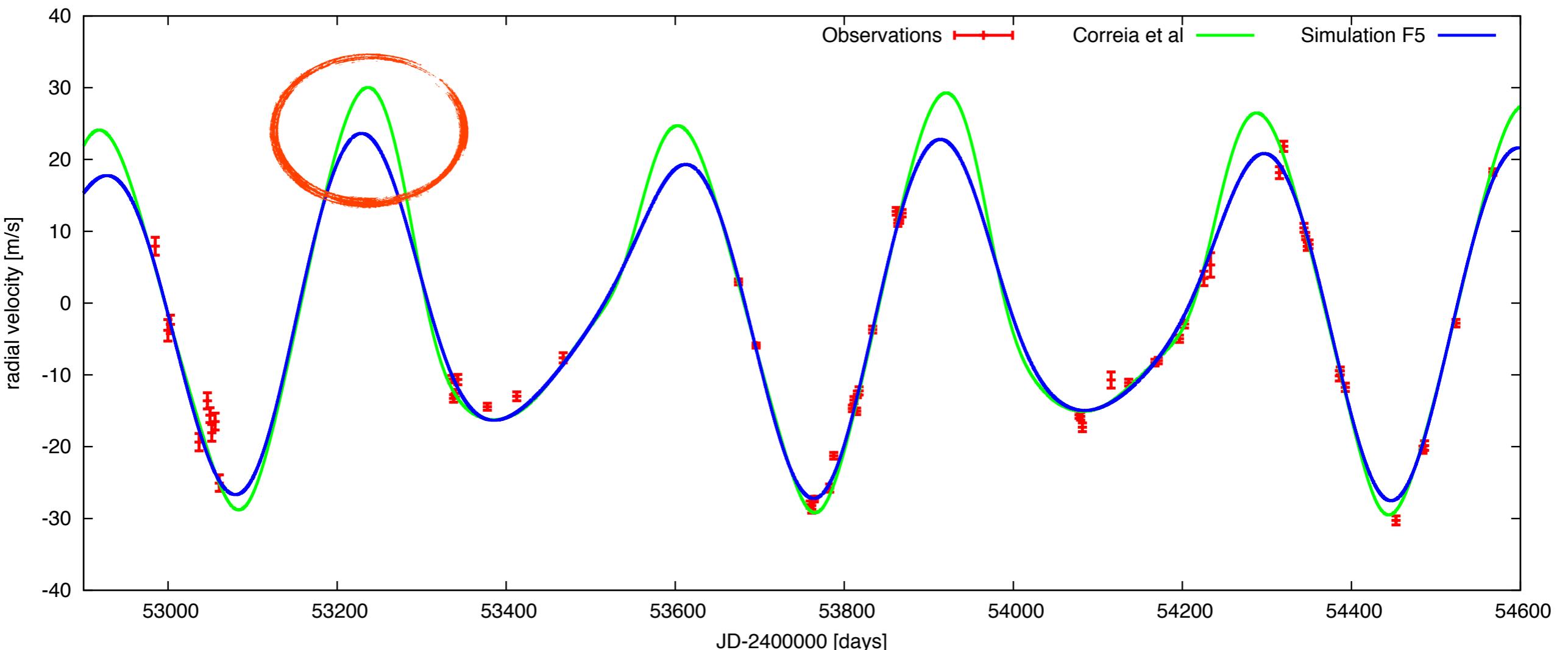
Large scale-height (0.07)

- Slow migration once in resonance
- Resonance is stable

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

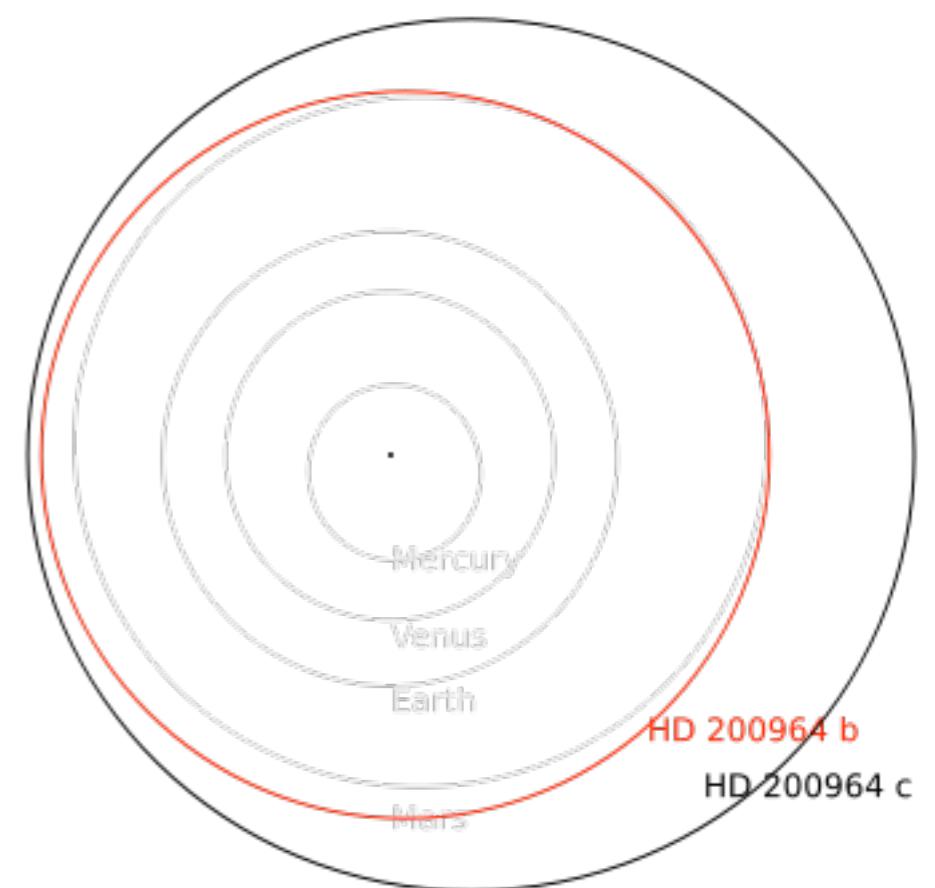
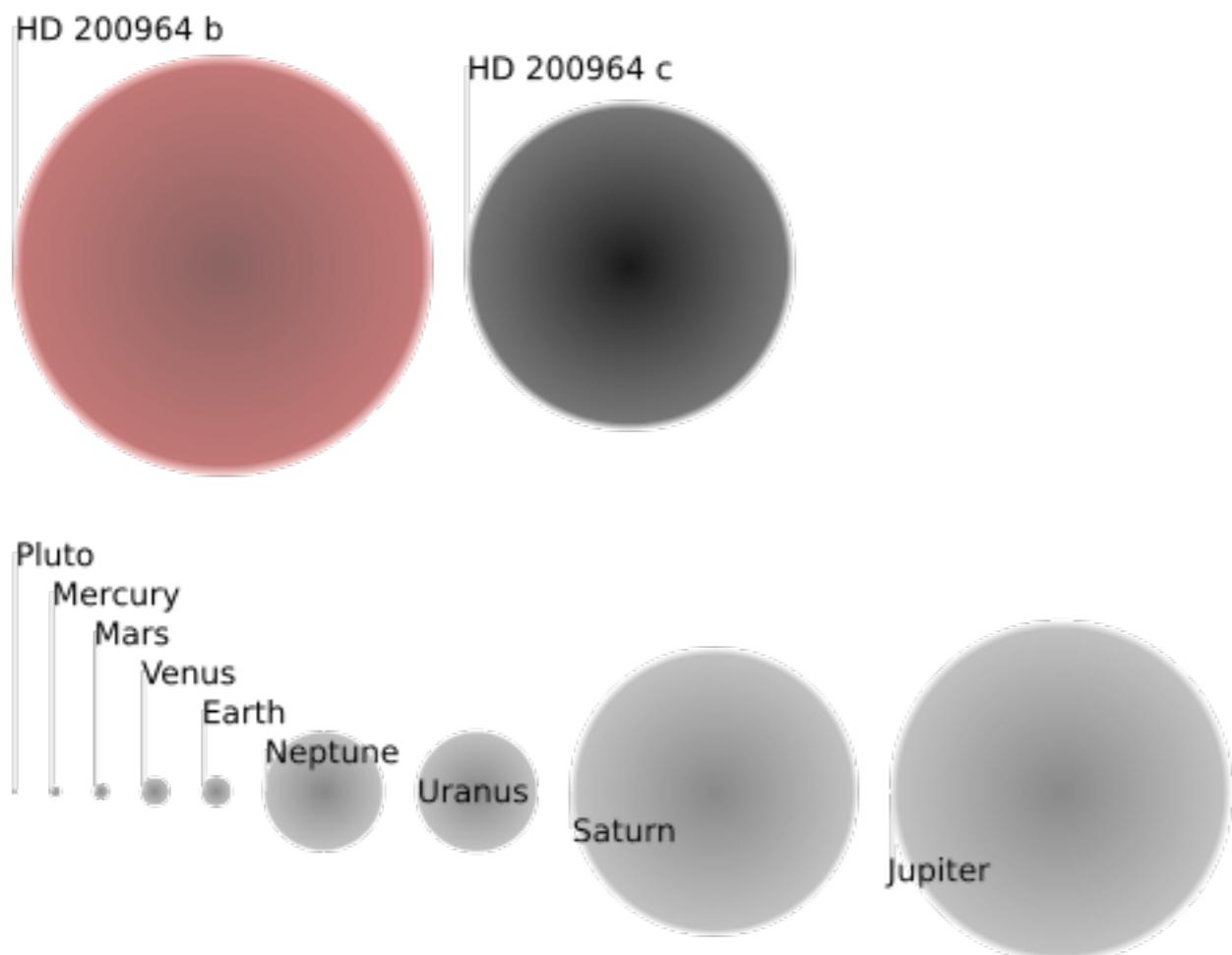
- Consistent with current observations
- Testable with just a few well-timed radial velocity data points.

HD200964

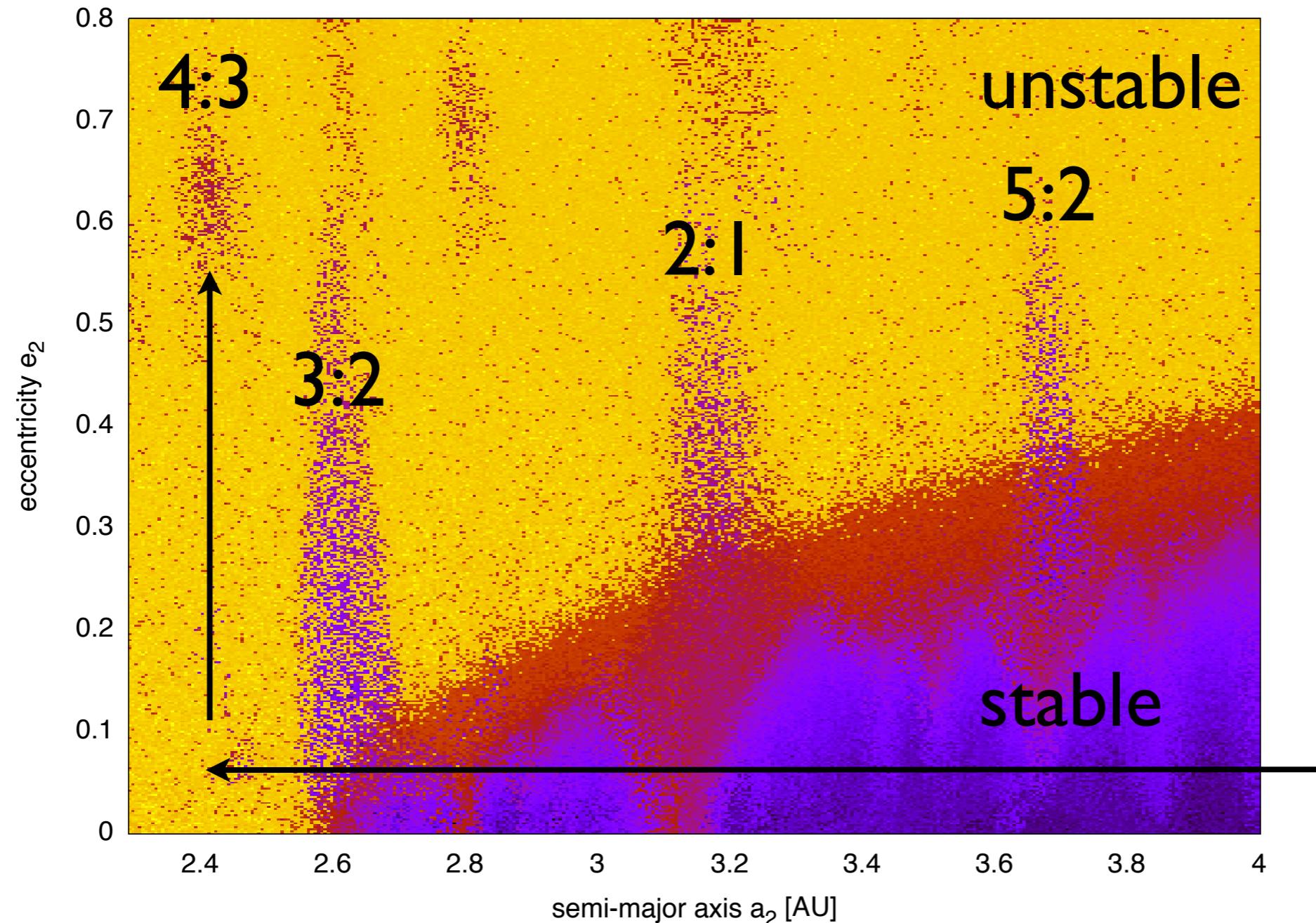
The impossible system?

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.



Stability of HD200964



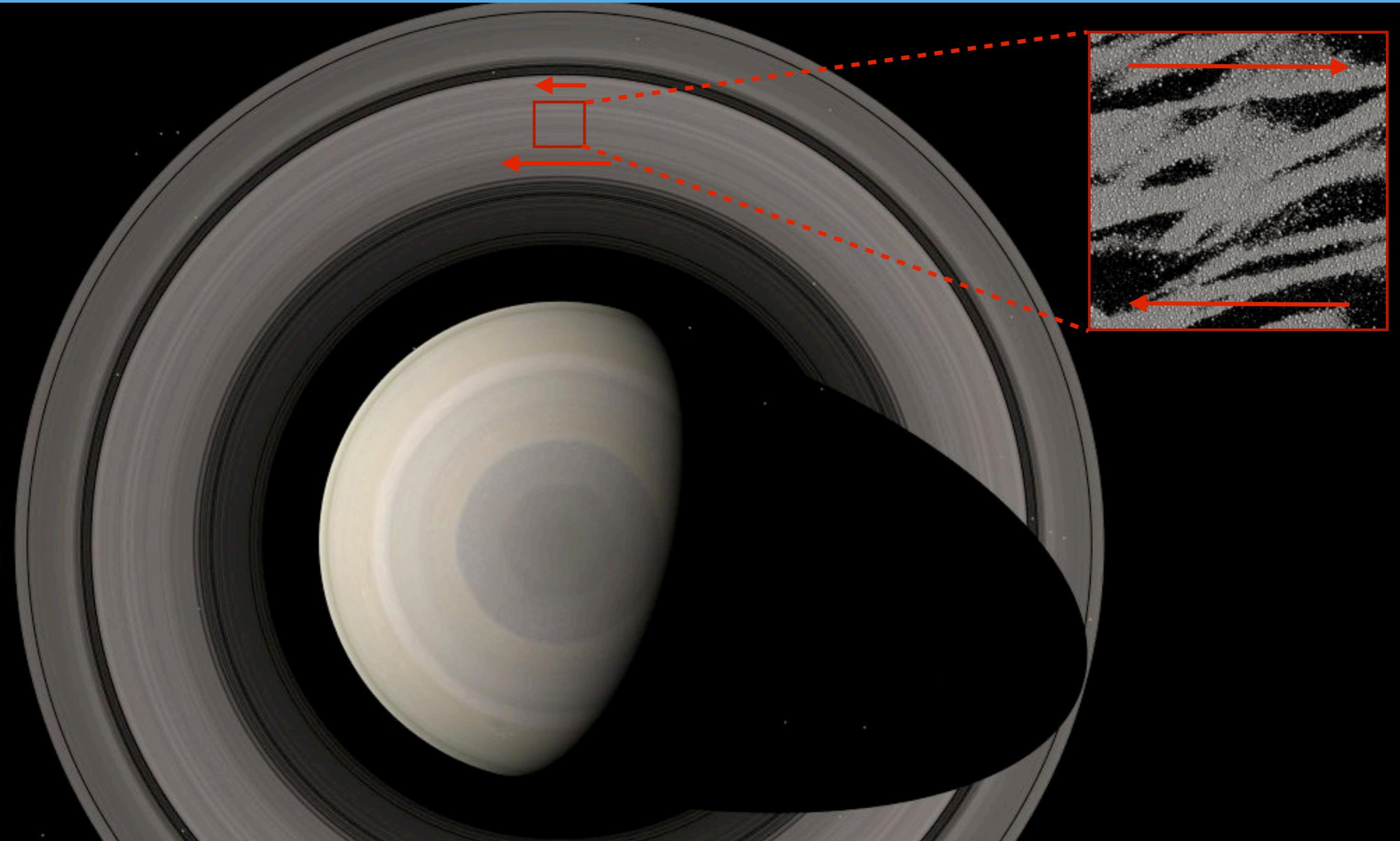
Take home message VIII

We don't understand
everything*.

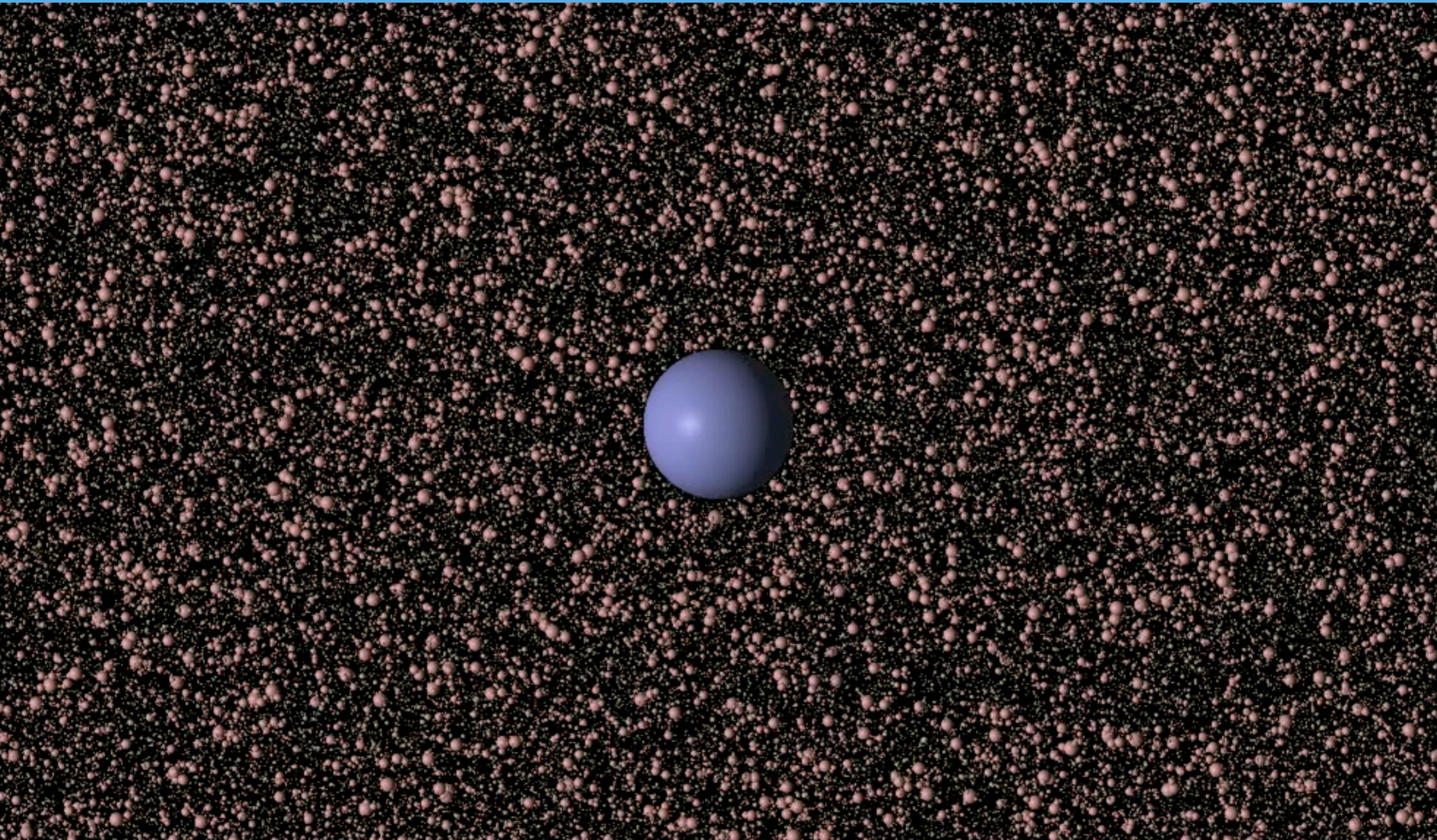
*just yet

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.

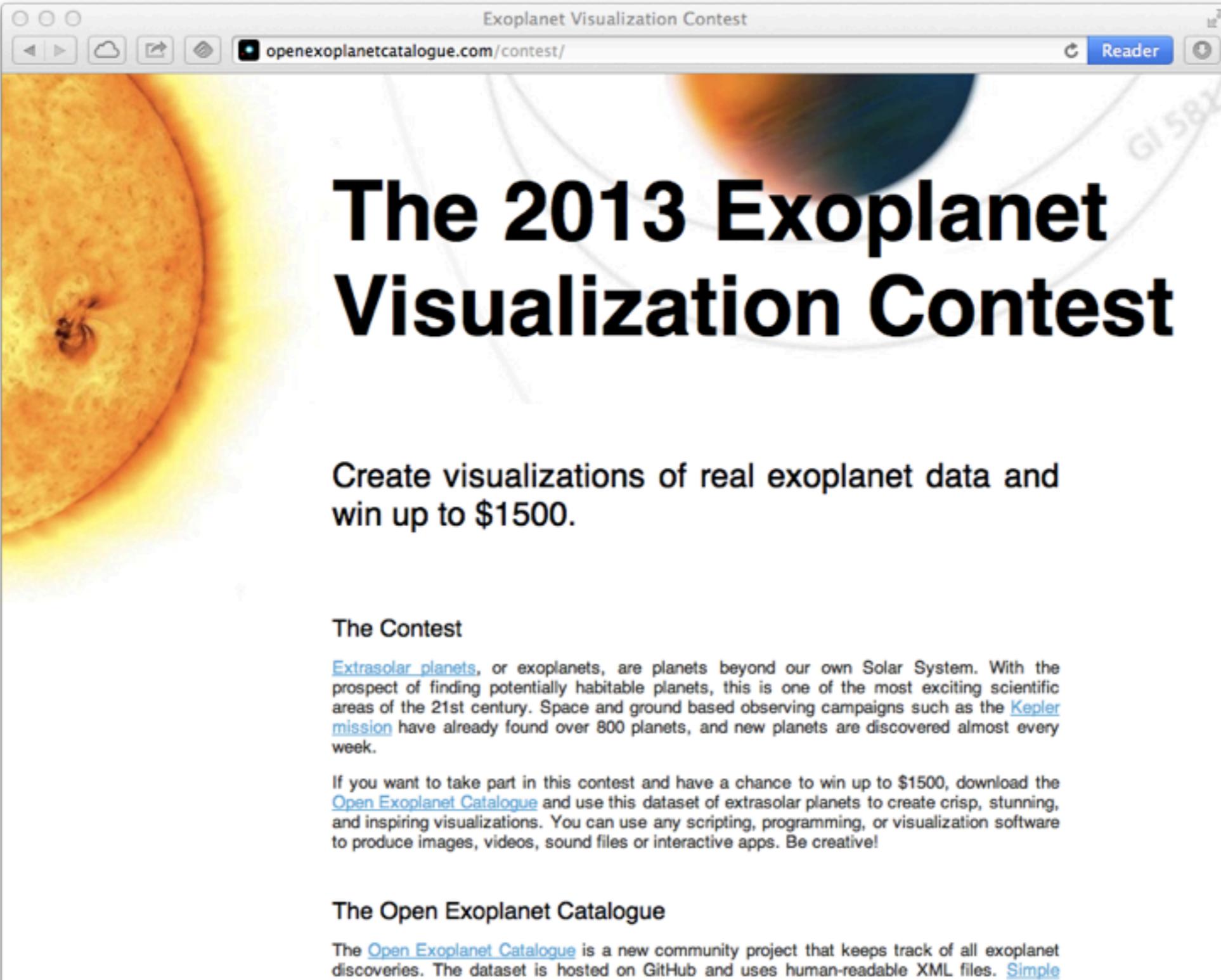
HD45364 Had to form in a massive disc.

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



The screenshot shows a web browser window with the title "Exoplanet Visualization Contest" at the top. The URL "openexoplanetcatalogue.com/contest/" is visible in the address bar. The page features a large image of the Sun on the left and a planet on the right. The main text reads: "The 2013 Exoplanet Visualization Contest". Below this, it says: "Create visualizations of real exoplanet data and win up to \$1500." A section titled "The Contest" provides information about extrasolar planets and the Kepler mission. Another section, "The Open Exoplanet Catalogue", describes the project's purpose and GitHub hosting.

The 2013 Exoplanet Visualization Contest

Create visualizations of real exoplanet data and win up to \$1500.

The Contest

Extrasolar planets, or exoplanets, are planets beyond our own Solar System. With the prospect of finding potentially habitable planets, this is one of the most exciting scientific areas of the 21st century. Space and ground based observing campaigns such as the [Kepler mission](#) have already found over 800 planets, and new planets are discovered almost every week.

If you want to take part in this contest and have a chance to win up to \$1500, download the [Open Exoplanet Catalogue](#) and use this dataset of extrasolar planets to create crisp, stunning, and inspiring visualizations. You can use any scripting, programming, or visualization software to produce images, videos, sound files or interactive apps. Be creative!

The Open Exoplanet Catalogue

The [Open Exoplanet Catalogue](#) is a new community project that keeps track of all exoplanet discoveries. The dataset is hosted on GitHub and uses human-readable XML files. [Simple](#)