Institute for Advanced Study

The formation of multi-planetary systems

Hanno Rein
@ Gloucester County College
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Outline

A short history of finding planetary systems beyond our own solar system

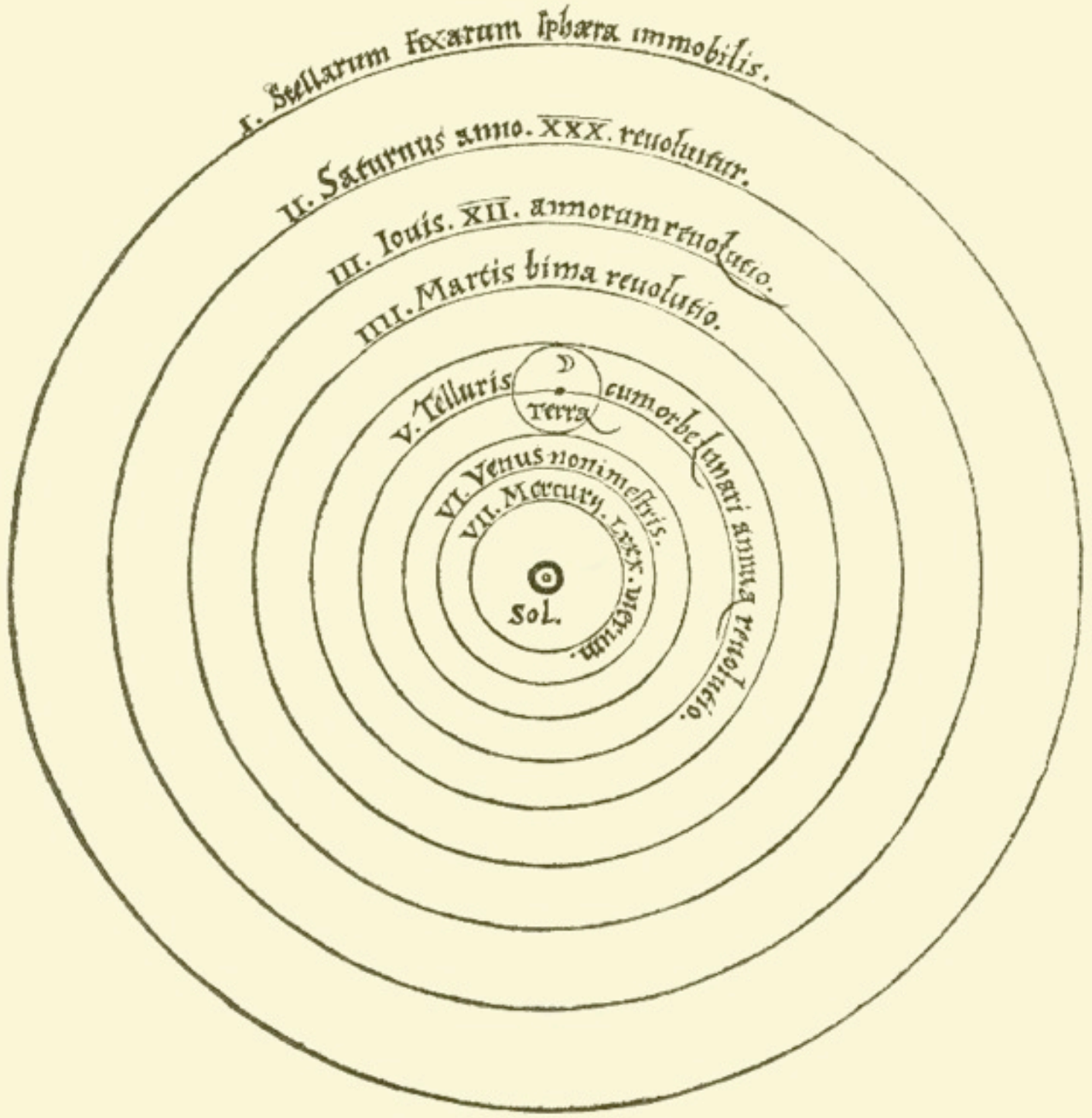
Resonances

Formation of resonant systems

Is our solar system special?

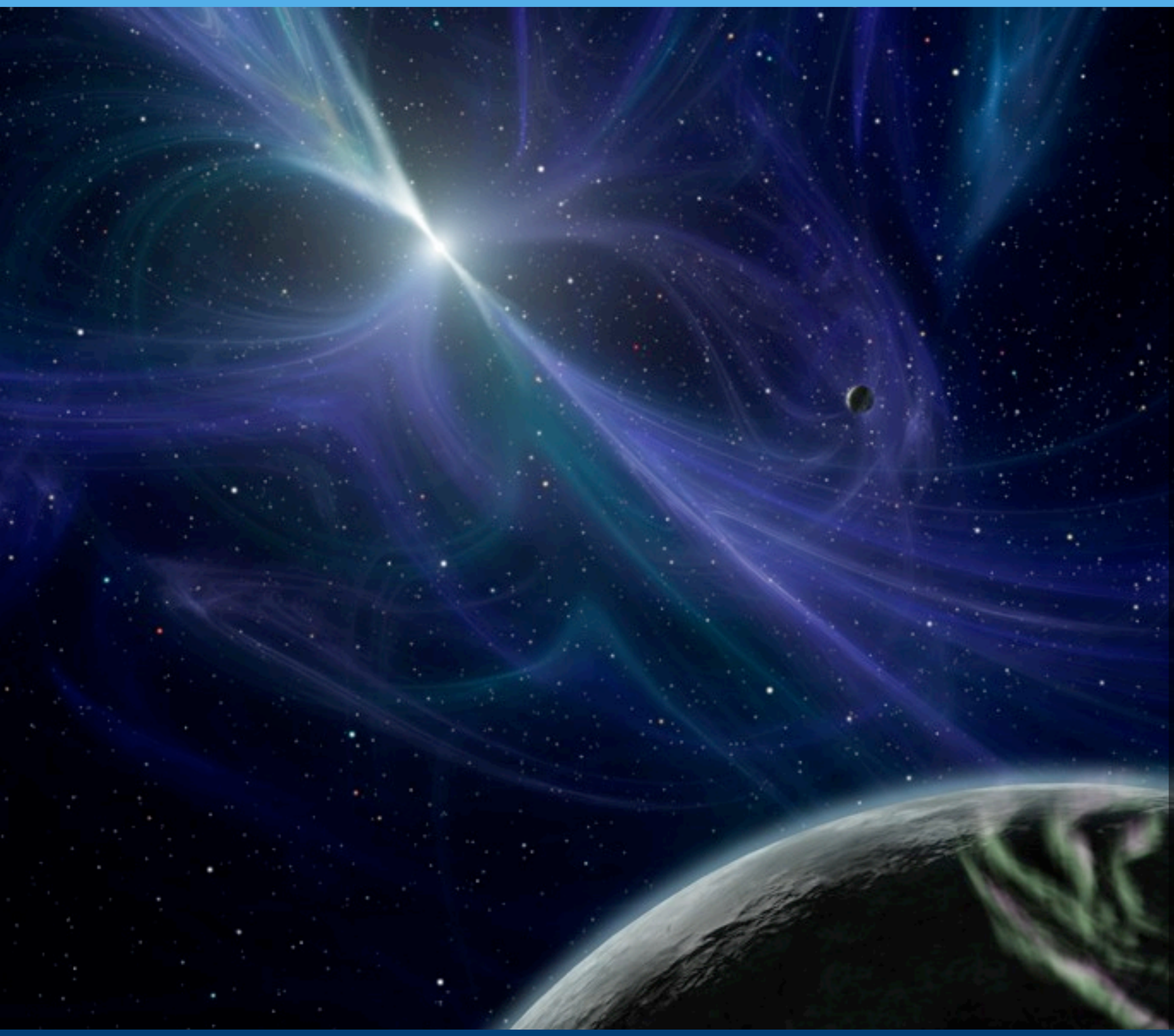
A short history of finding planetary systems beyond our own solar system

Nicolaus Copernicus



Nicolaus Copernicus, De revolutionibus orbium coelestium, 1543.

The first planet: PSR 1257+12



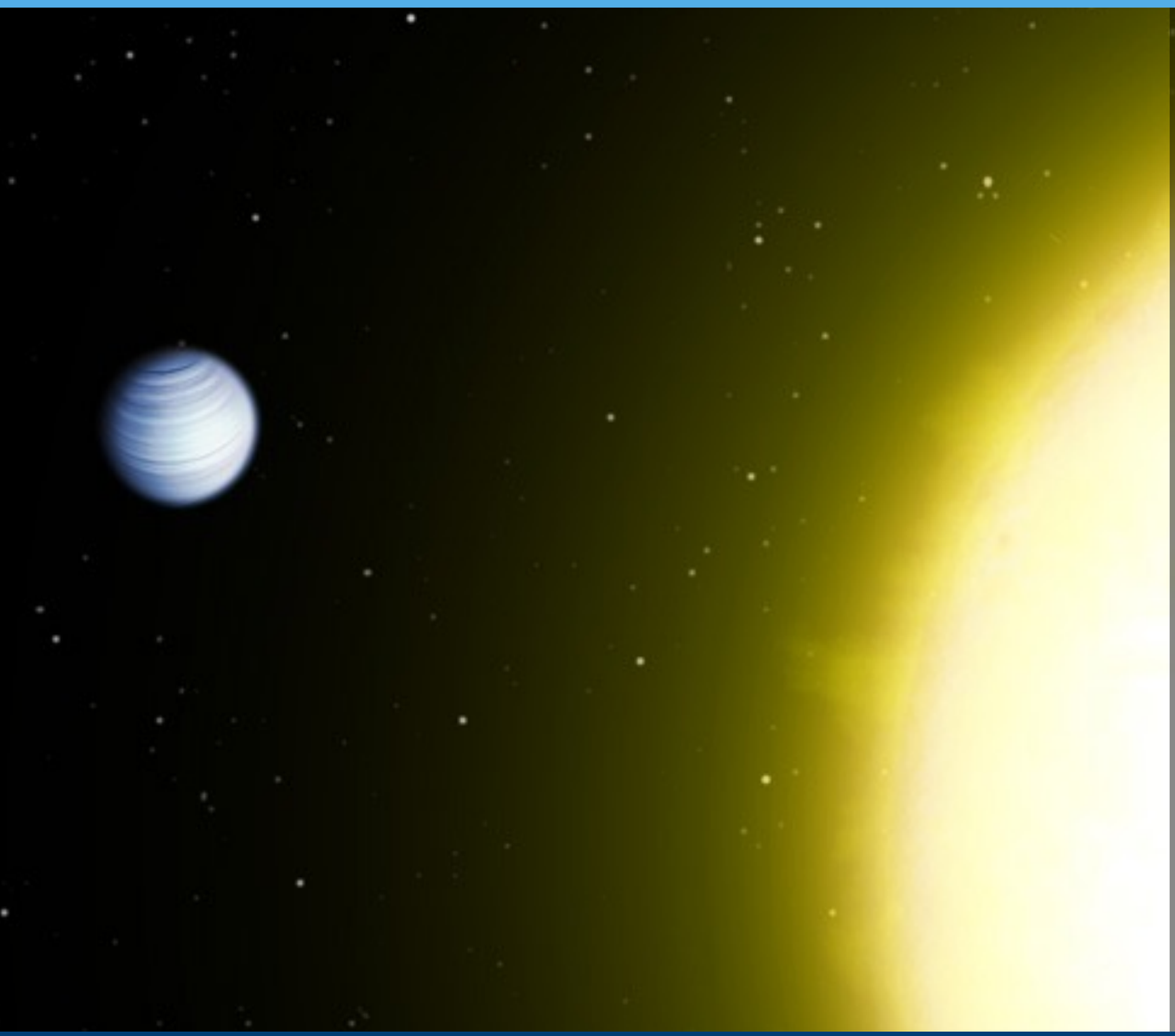
First confirmed planet sized object outside our solar system.

Detected by pulsar timing variations.

Nothing like any anything that we knew before.

Illustration by NASA/JPL-Caltech/R. Hurt (SSC), 1990.

First planet around a Sun-like star: 51 Pegasi b

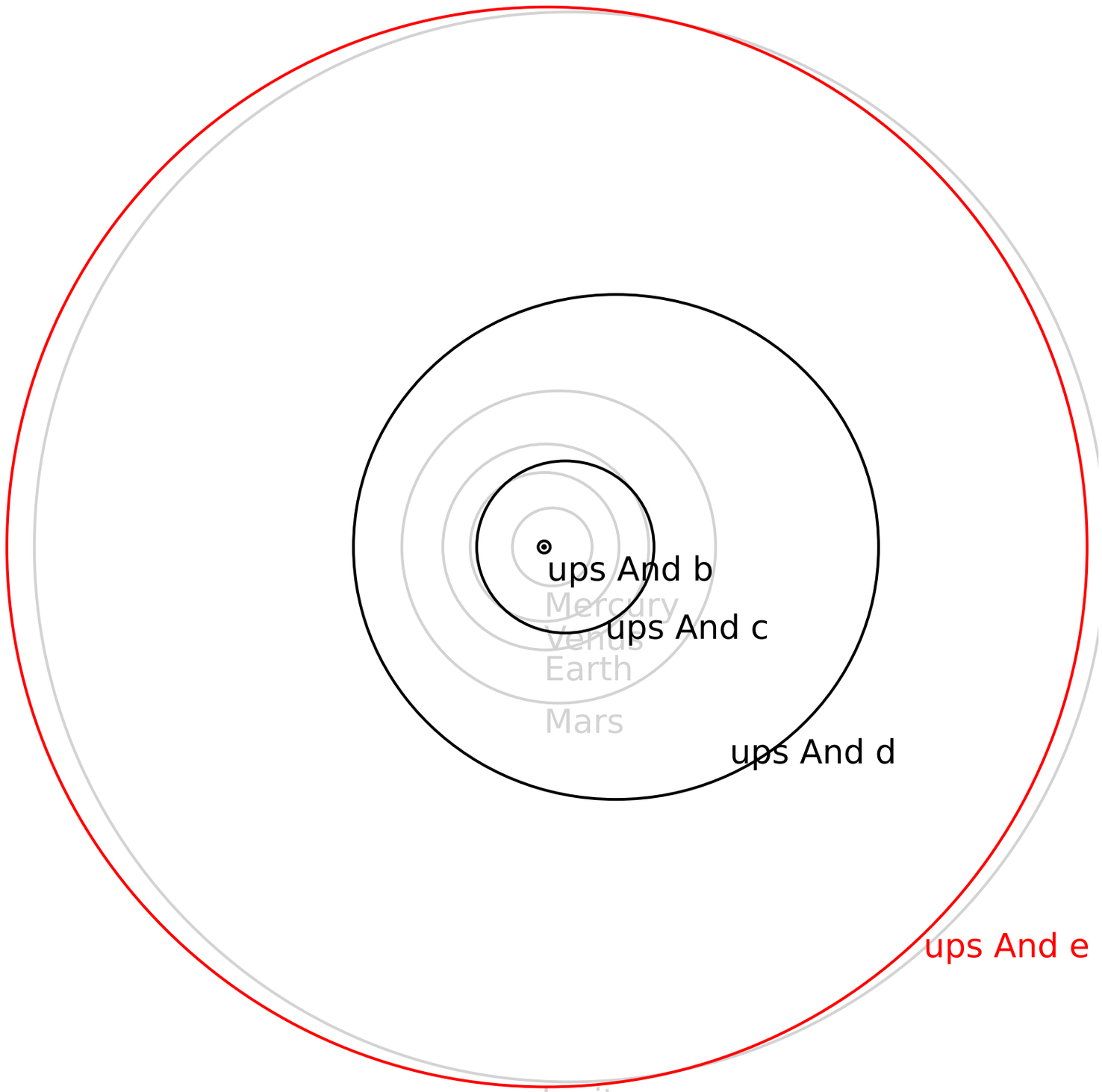


Detected by radial velocity variations by Michel Mayor (Geneva).

Again, nothing like any anything we knew before: Hot Jupiter.

4 day orbit.

The first multi-planetary system: Ups Andromedae

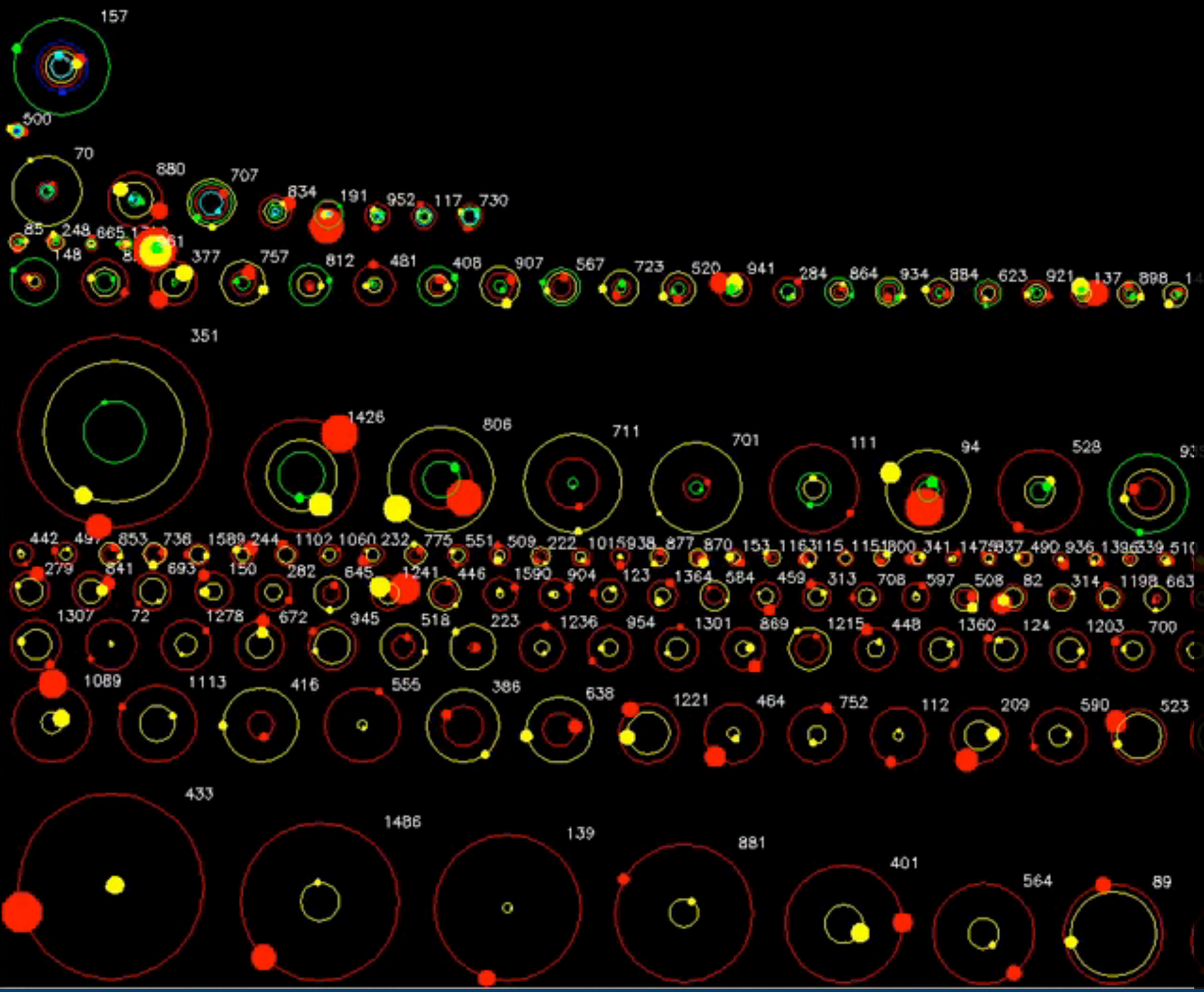


Detected by radial velocity.

Four very massive planets including one Hot Jupiter on a 5 day orbit.

The planets' mutual inclination is more than 30°.

Candidates detected by the Kepler spacecraft



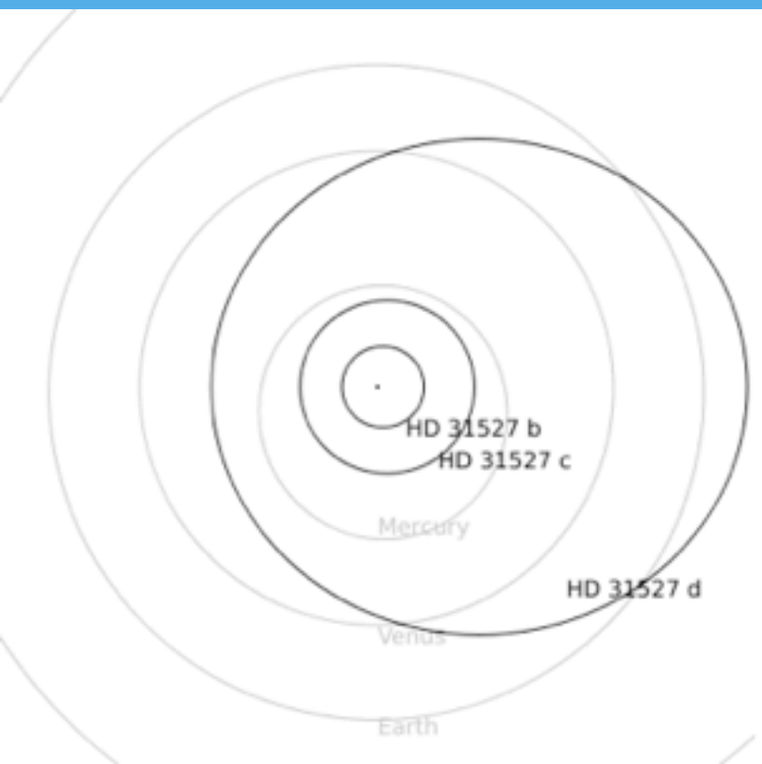
Detected by the transits method.

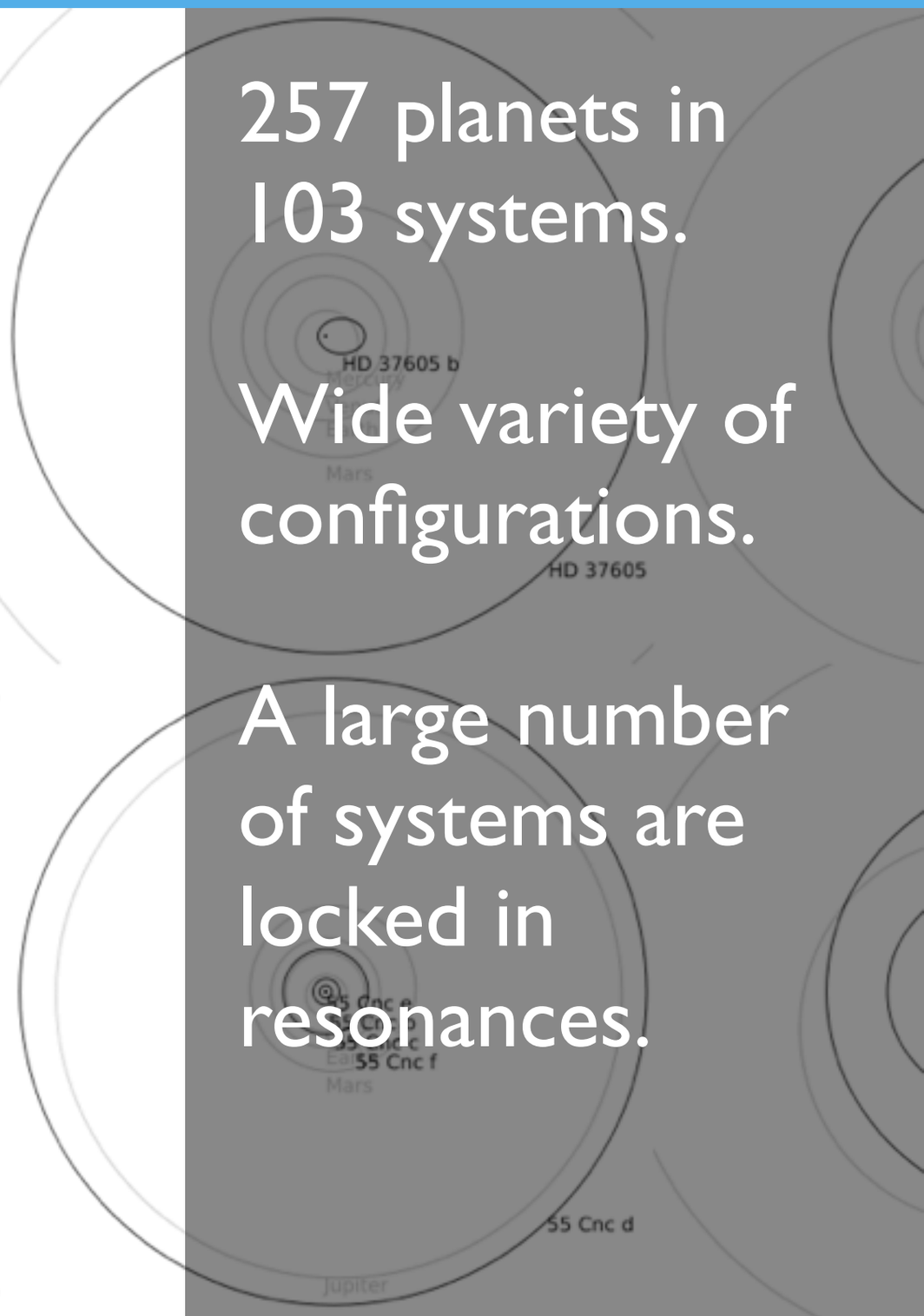
More than 170 multi-planetary systems.

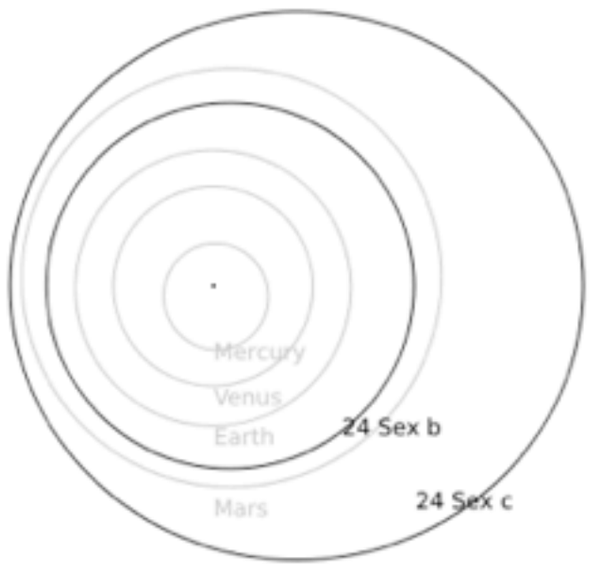
Mostly small mass planets made of ice and rock.

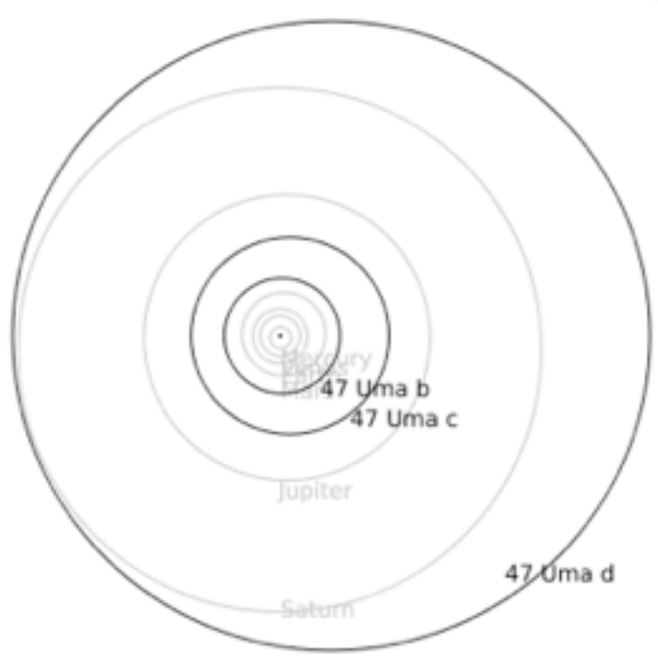
Illustration by Dan Fabrycky.

Today's census of multi-planetary systems









257 planets in 103 systems.

Wide variety of configurations.

A large number of systems are locked in resonances.

Visual Exoplanet Catalogue, http://exoplanet.hanno-rein.de.

Resonances

Resonance catastrophe at Tacoma Narrows

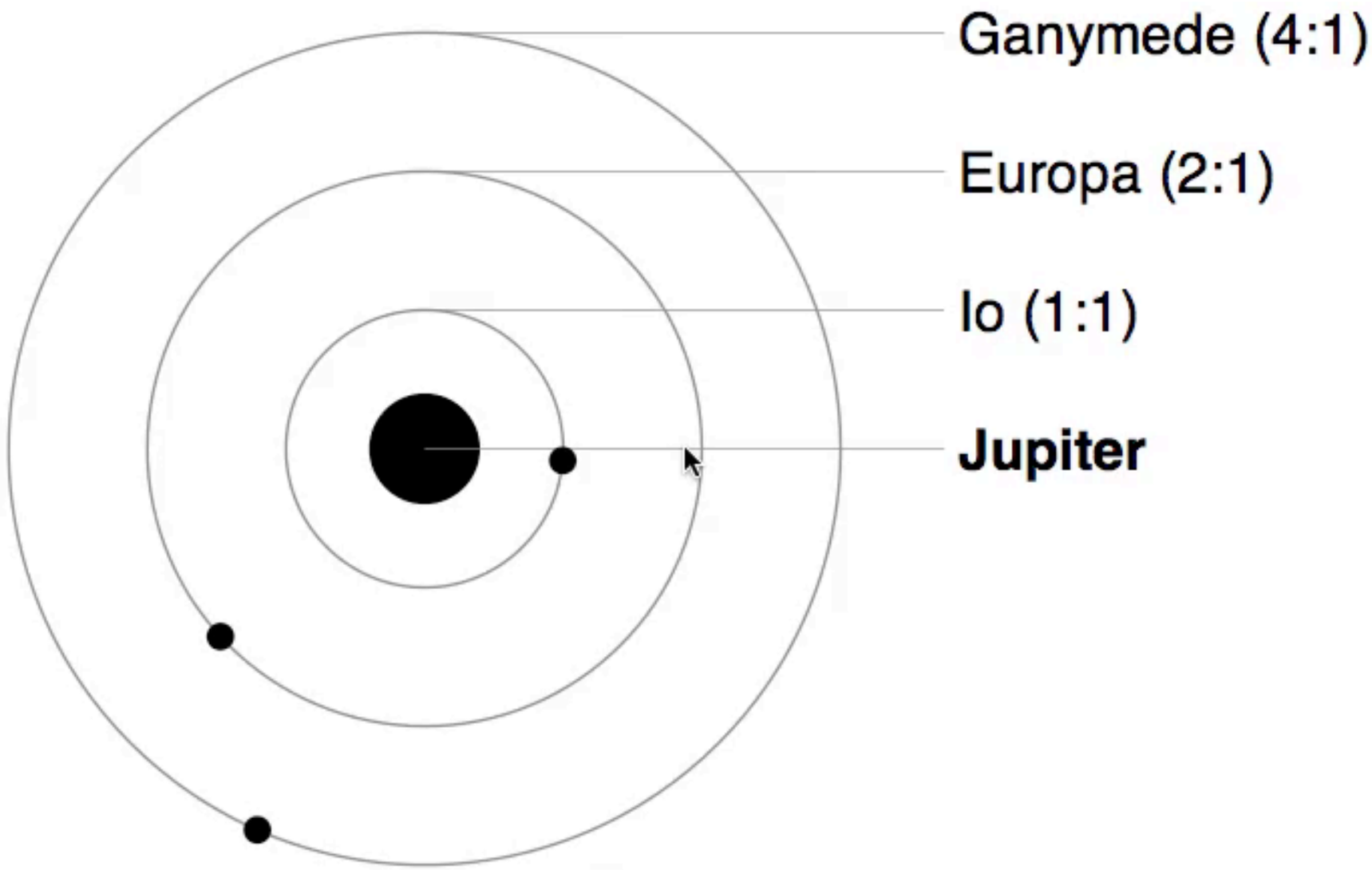
Forced resonance.

Wind is creating periodic force.

This period is similar to the bridge's own period.

http://www.youtube.com/watch?v=P0Fi1VcbpAI

Resonances in the solar system



The Laplace resonance is a 4:2:1 resonance.

Orbital periods are integer ratios of each other.

This is a very stable configuration.

Moon Earth Spin coupling.

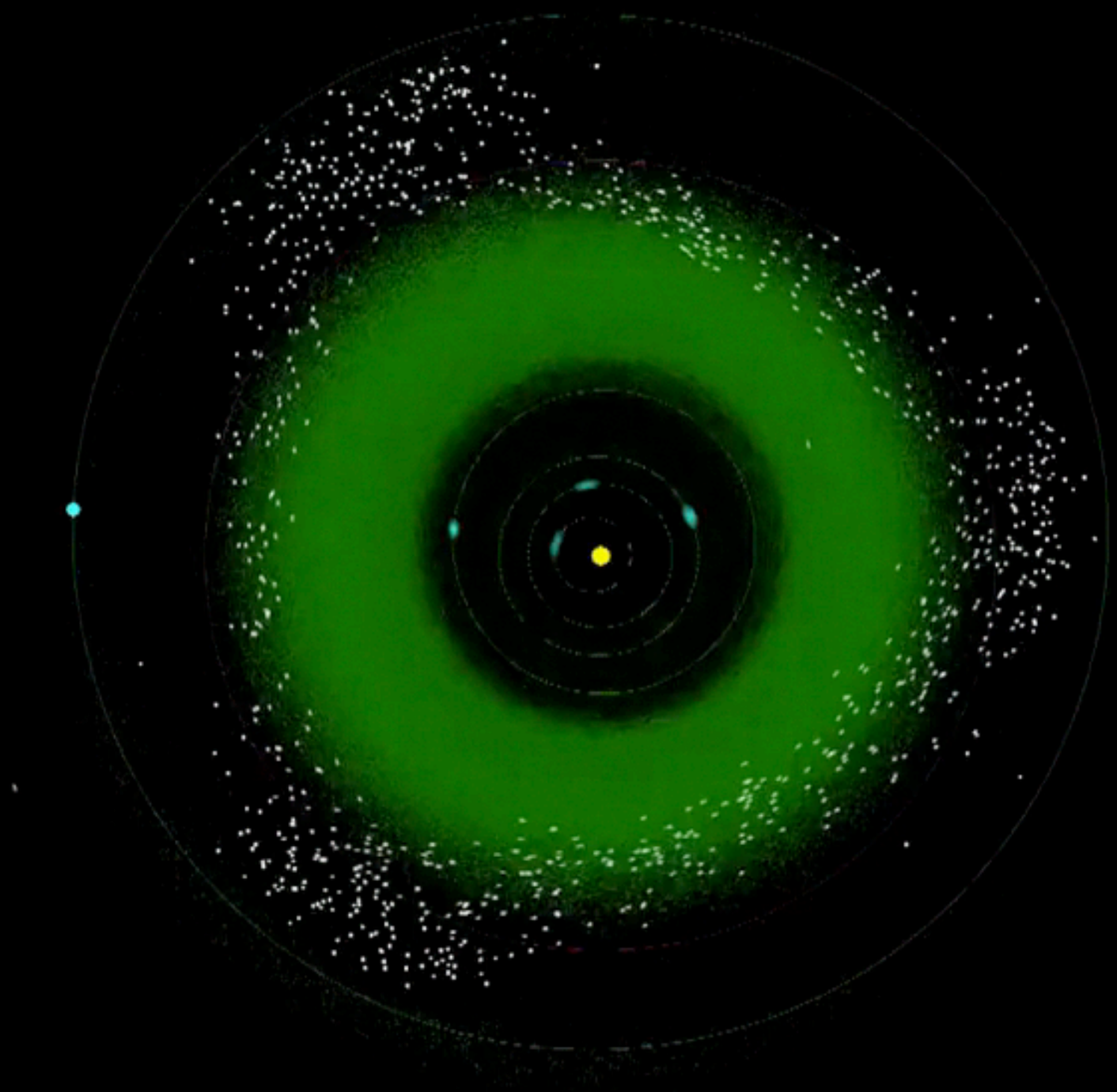
The Moon is tidally locked to the Earth.

Nobody saw the far side of the Moon until 1959.

This is a 1:1 spin orbit resonance.

In a few billion years the Earth will be locked too.

Asteroid in resonance with Jupiter



Scott Manley

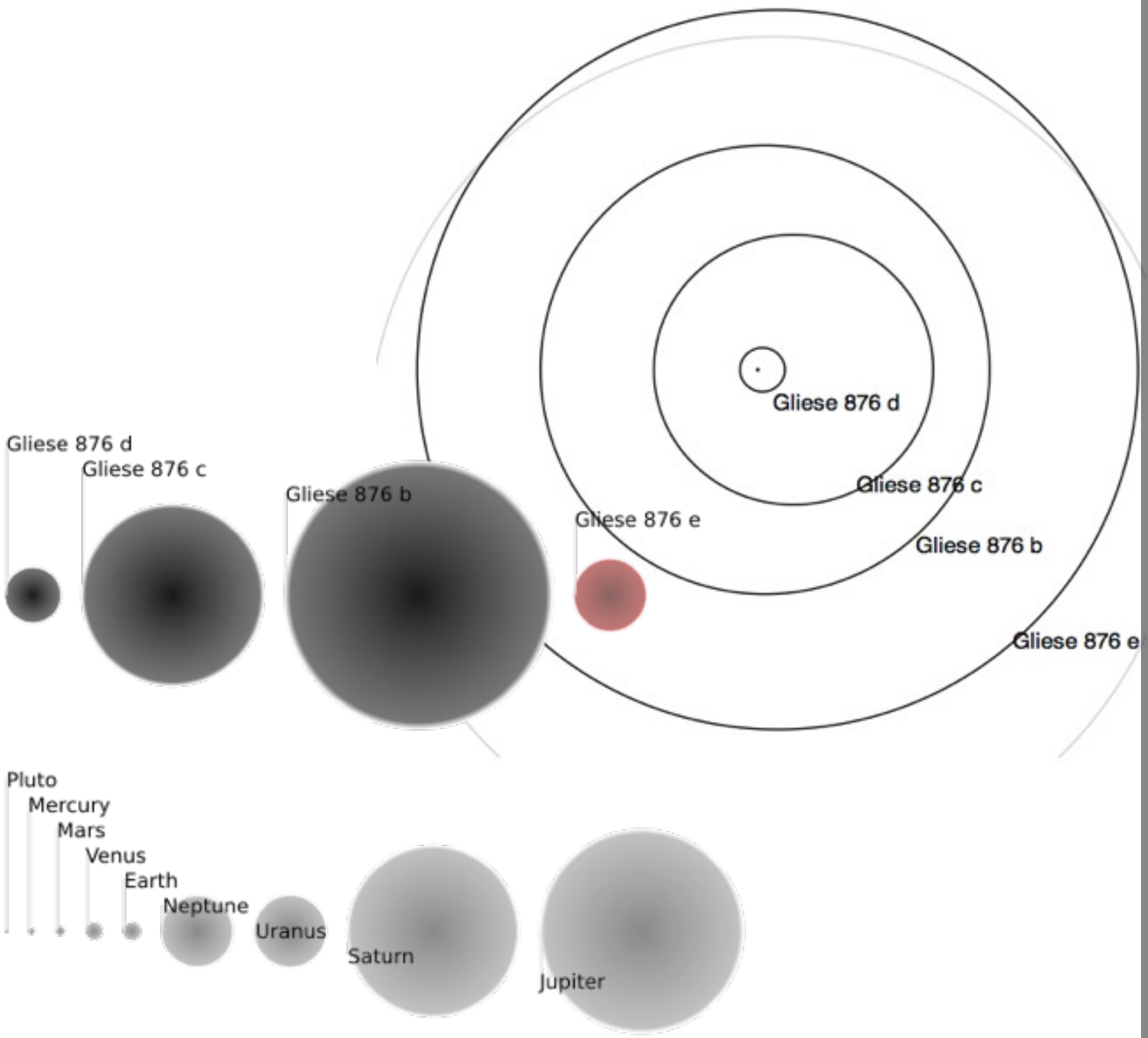
Resonances...

... can be good.

... can be bad.

Formation of resonant systems

A system in 2:1 resonance: Gliese 876



Massive planets.

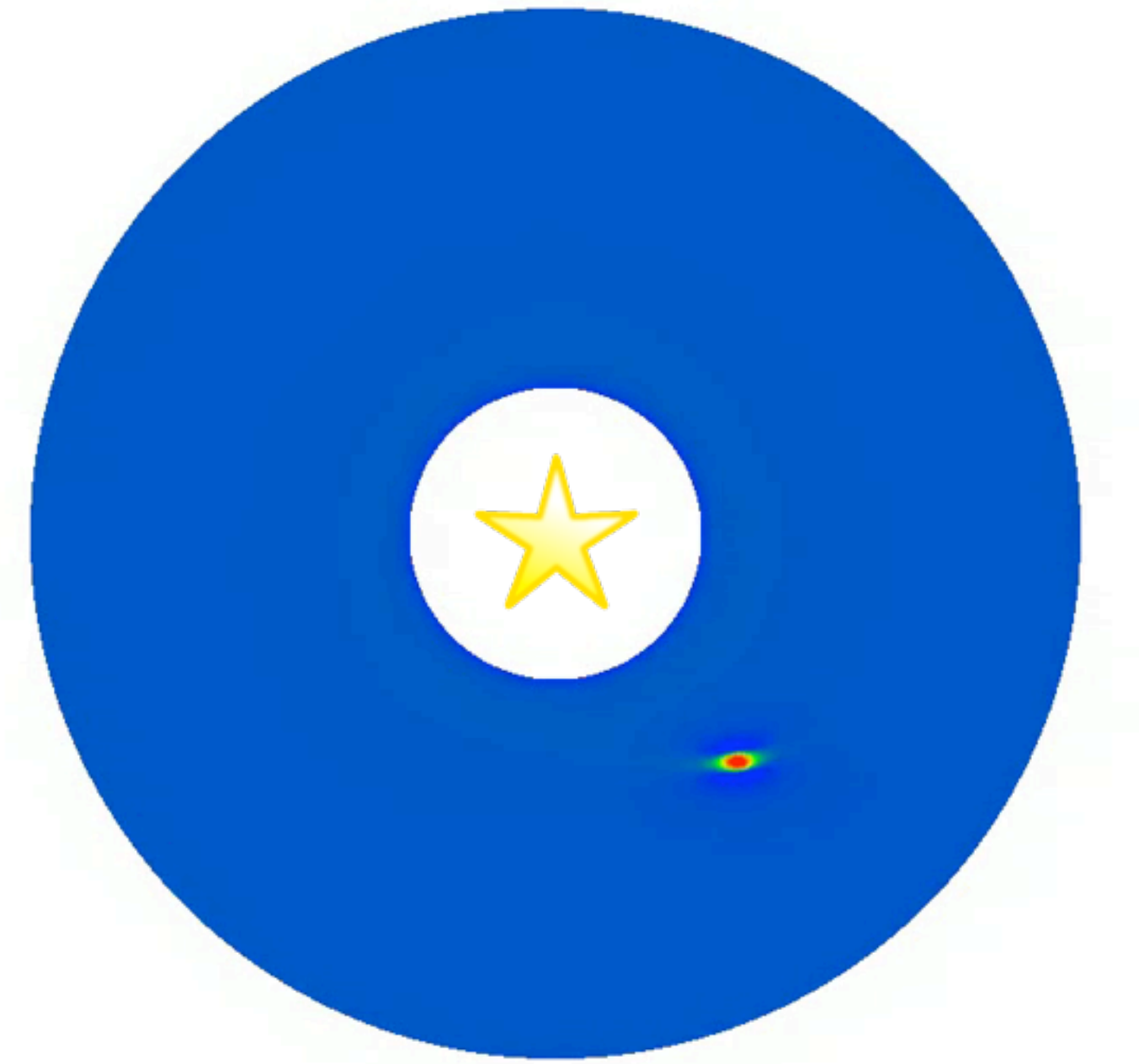
Close in orbits.

Locked in a 2:1 resonance.

Close to Earth: 15 light years.

Observed with high accuracy.

Moving planets around: Migration

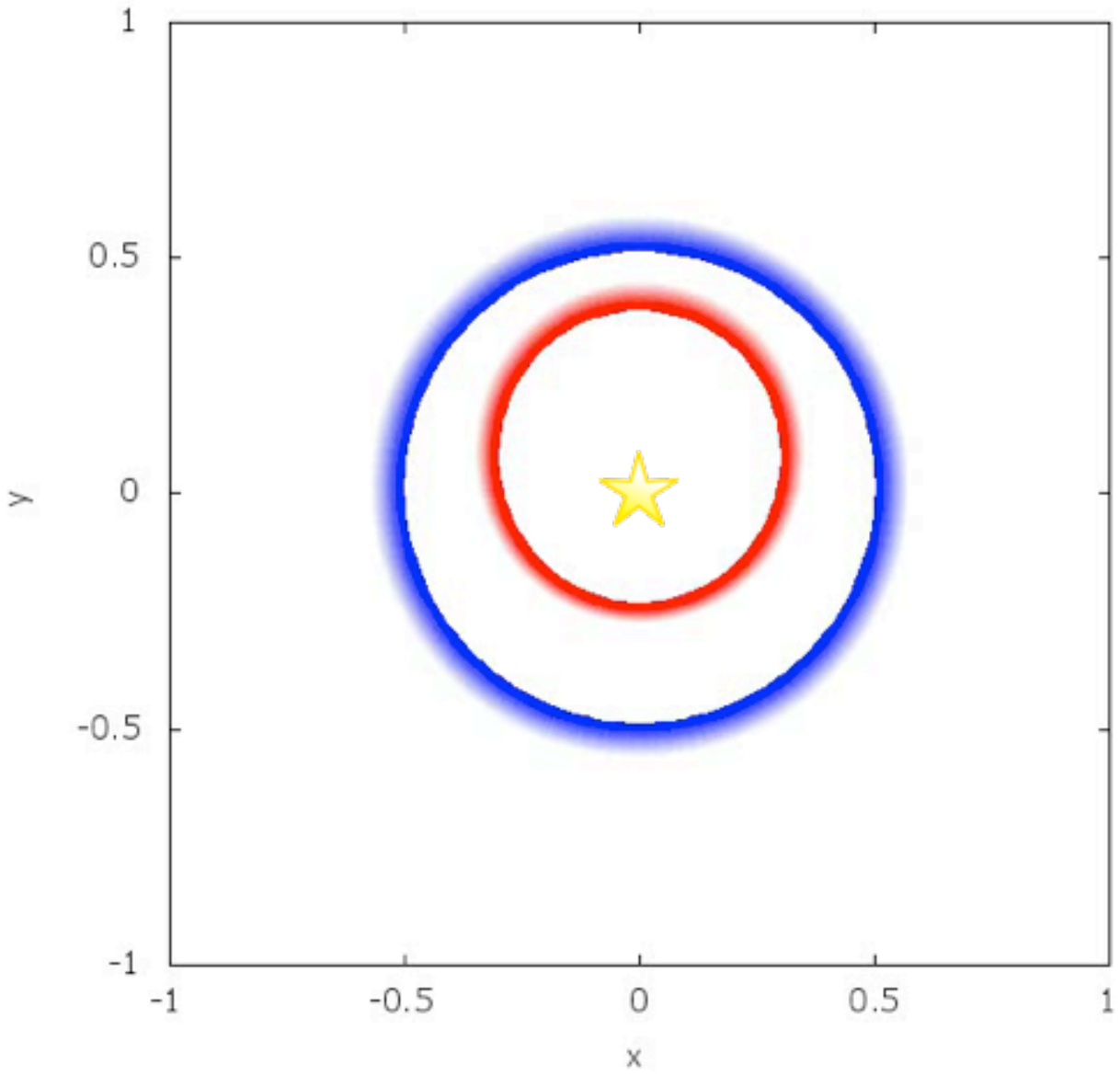


Planets form in proto-planetary disks.

They can interact with these disks. This can change the their orbits.

Different planets move at different speeds.

Resonance capture

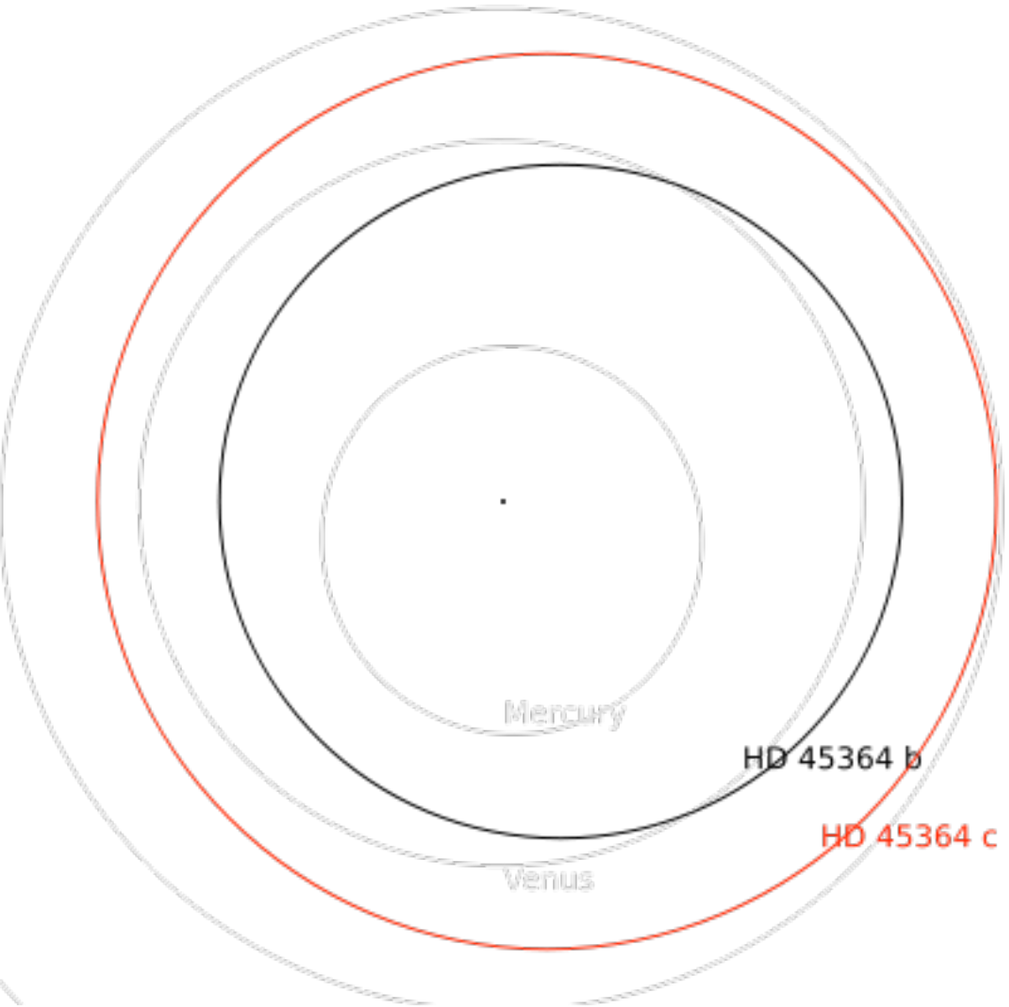


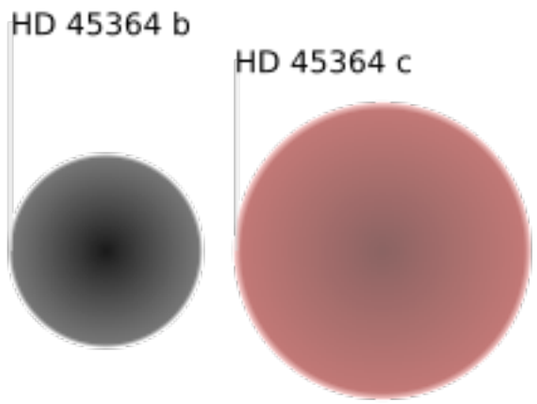
If two planets migrate, they can capture in resonance.

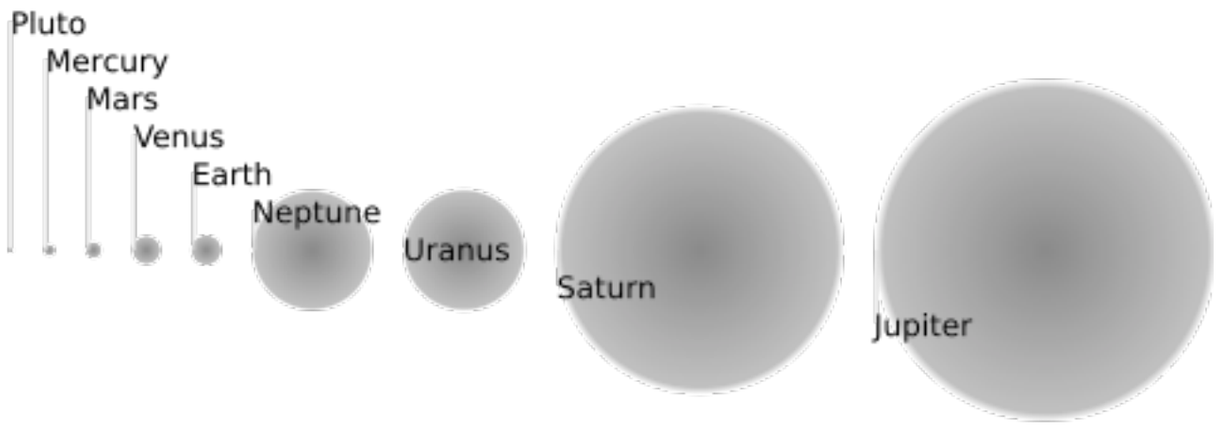
After the resonance capture, they move together.

This is a 'good resonance'. The setup is very stable.

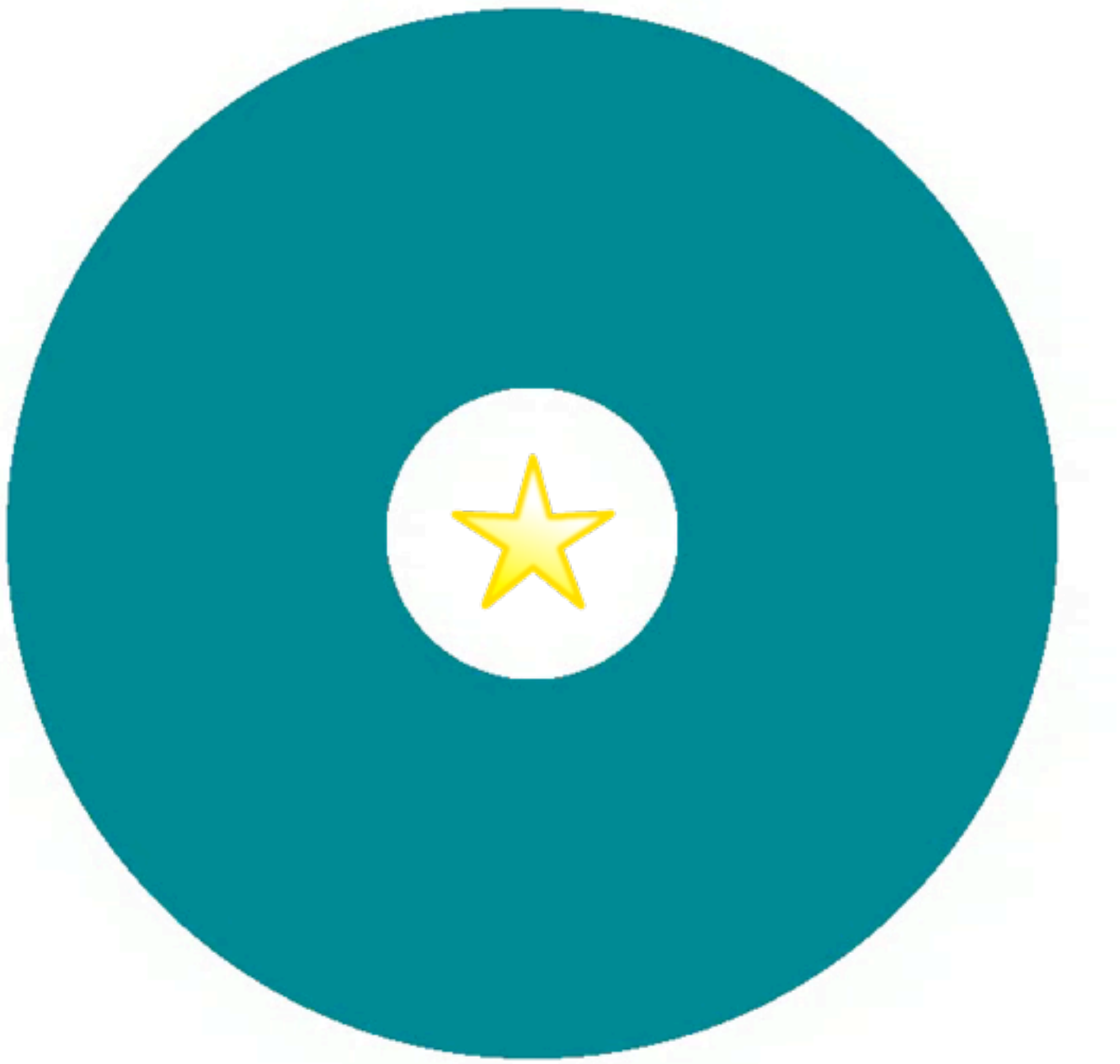
A system in a 3:2 resonance: HD 45364







Moving planets around quickly: Type III migration



This is the fasted way to move planets around.

The entire process takes place in a few years.

Occurs in very massive disks.

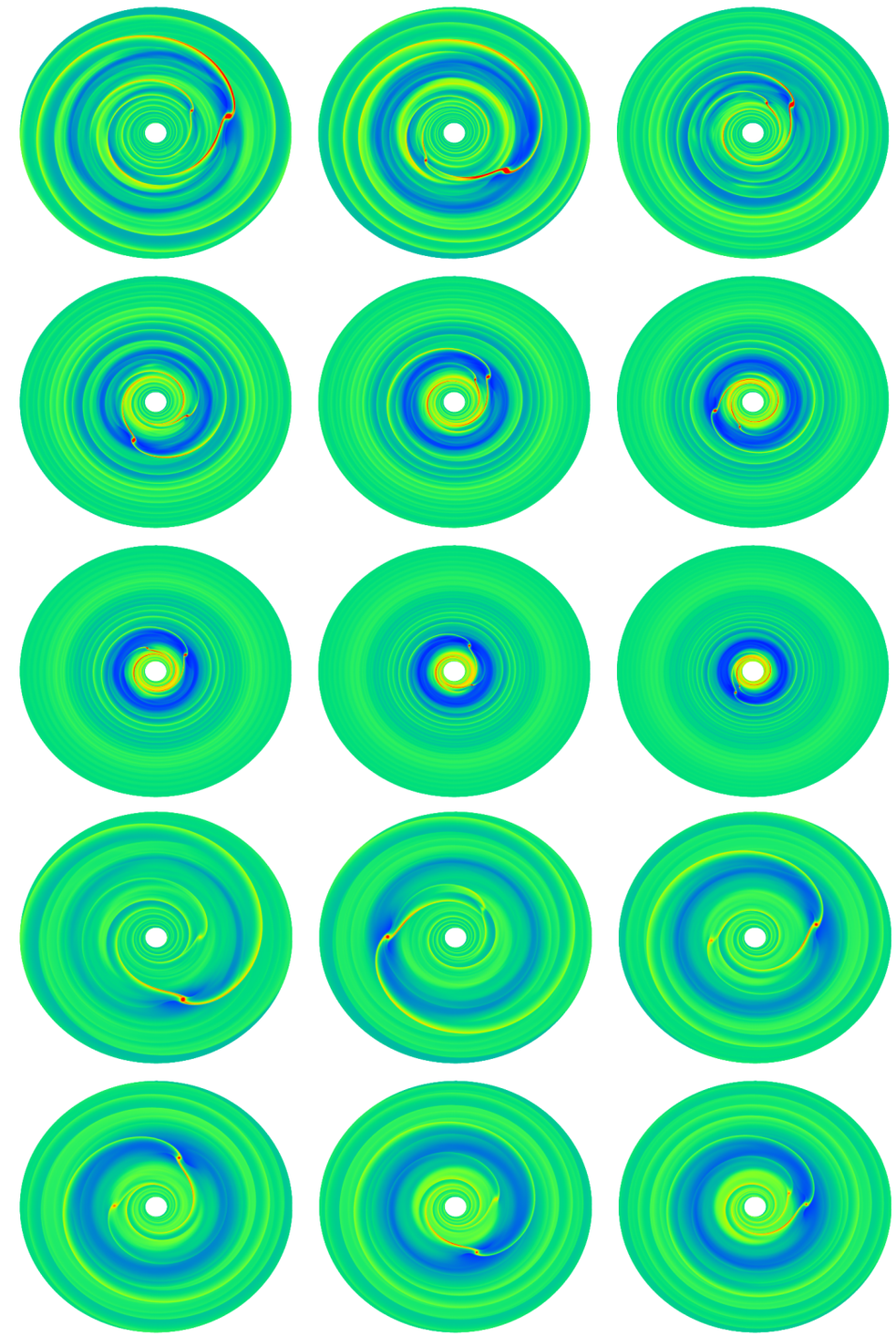
Formation scenario for HD45364

The planets need to move very quickly.

Otherwise they get captured in the 2:1 resonance like Gliese 876.

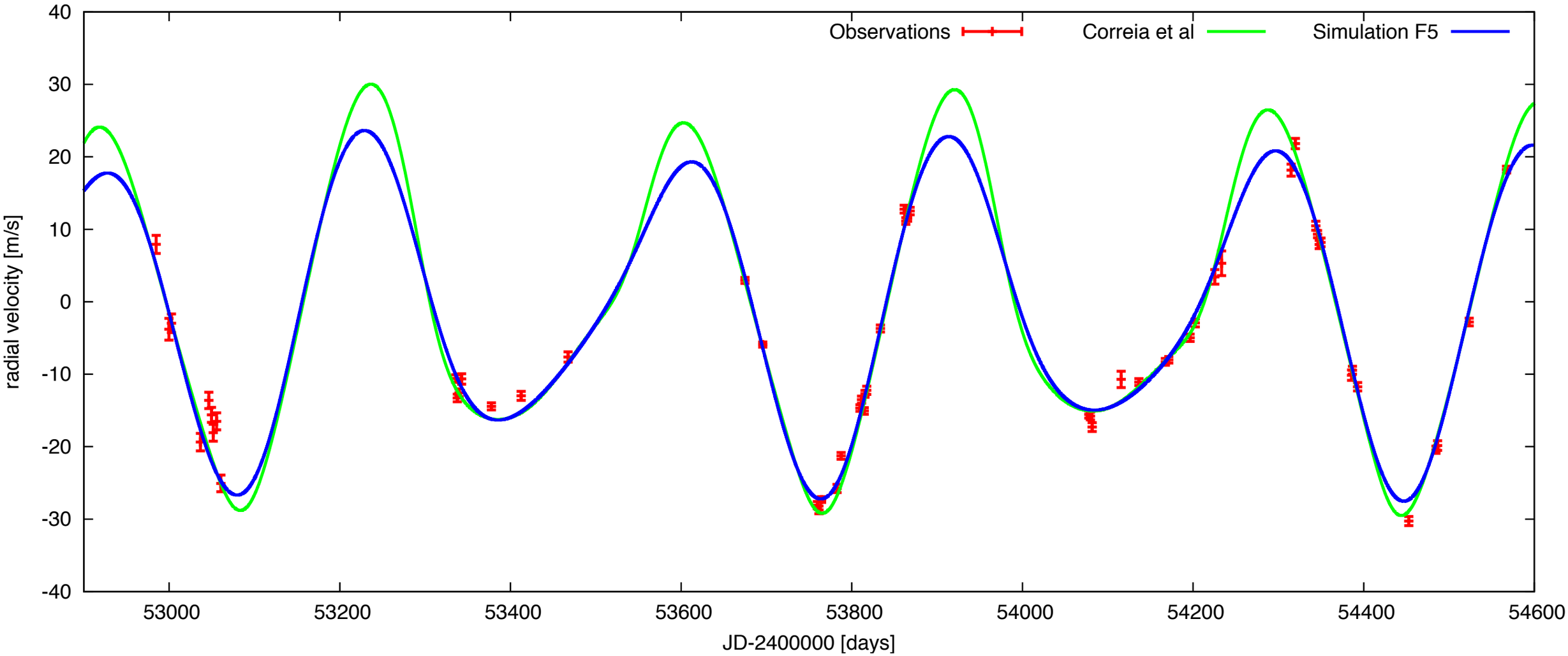
To solve the puzzle, we need Type III migration.

This allows us to reproduce the observed systems AND make predictions.



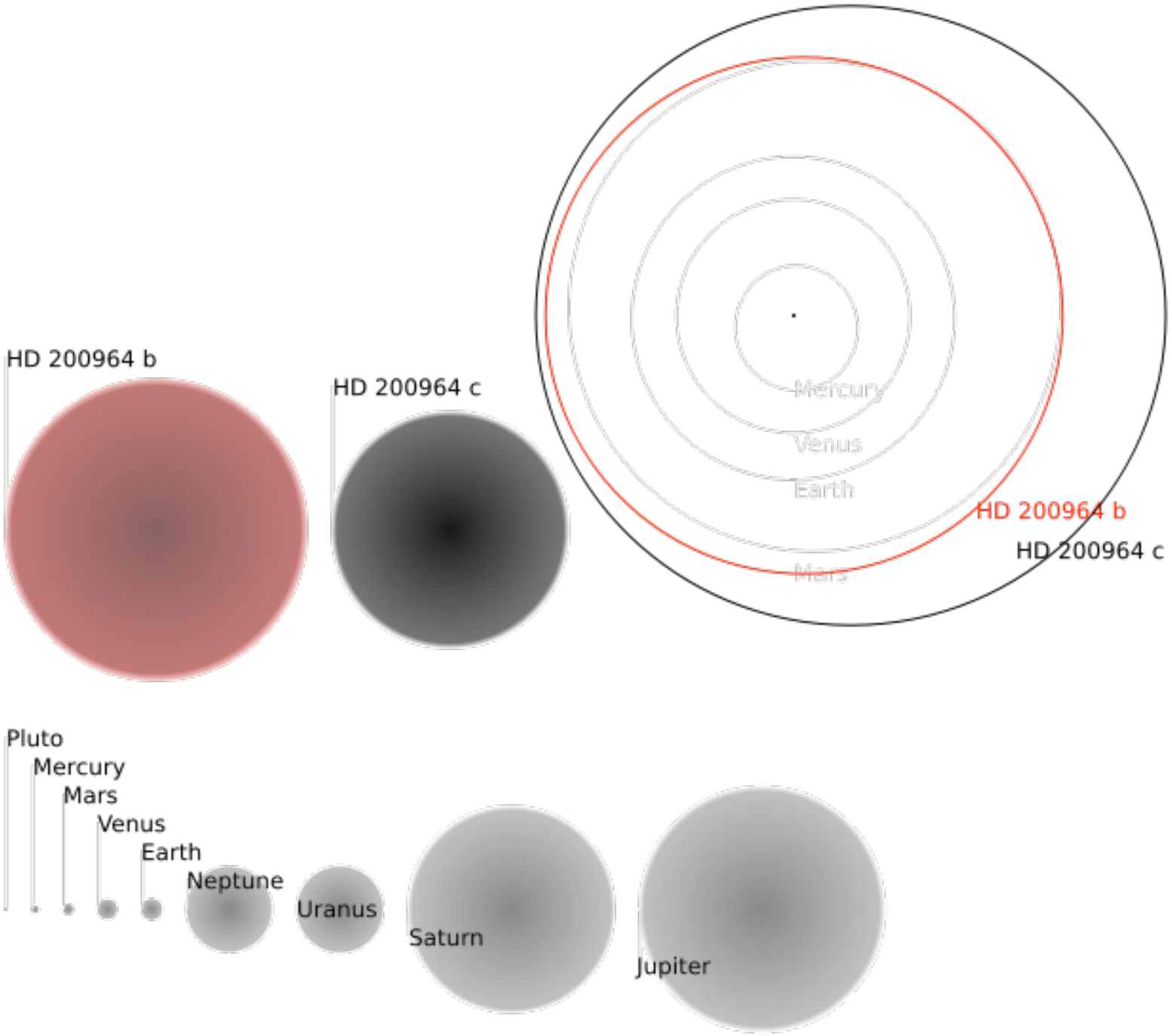
Rein, Papaloizou & Kley 2010

Testing a theory with predictions



Rein, Papaloizou & Kley 2010

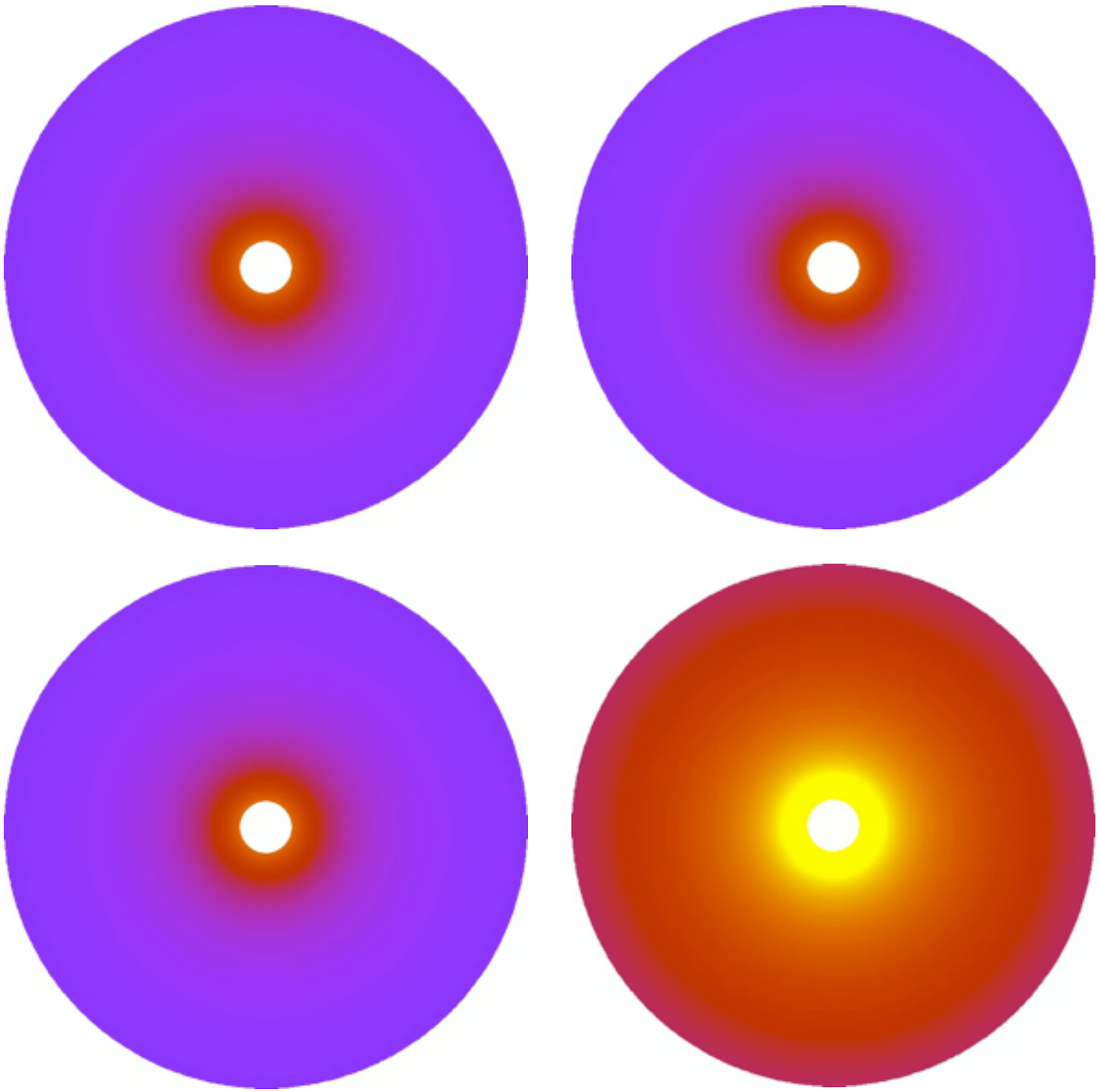
Getting closer: HD 200964



The planets in this system are only stable when protected by a 4:3 resonance.

How can we form this system?

How to form HD 200964?



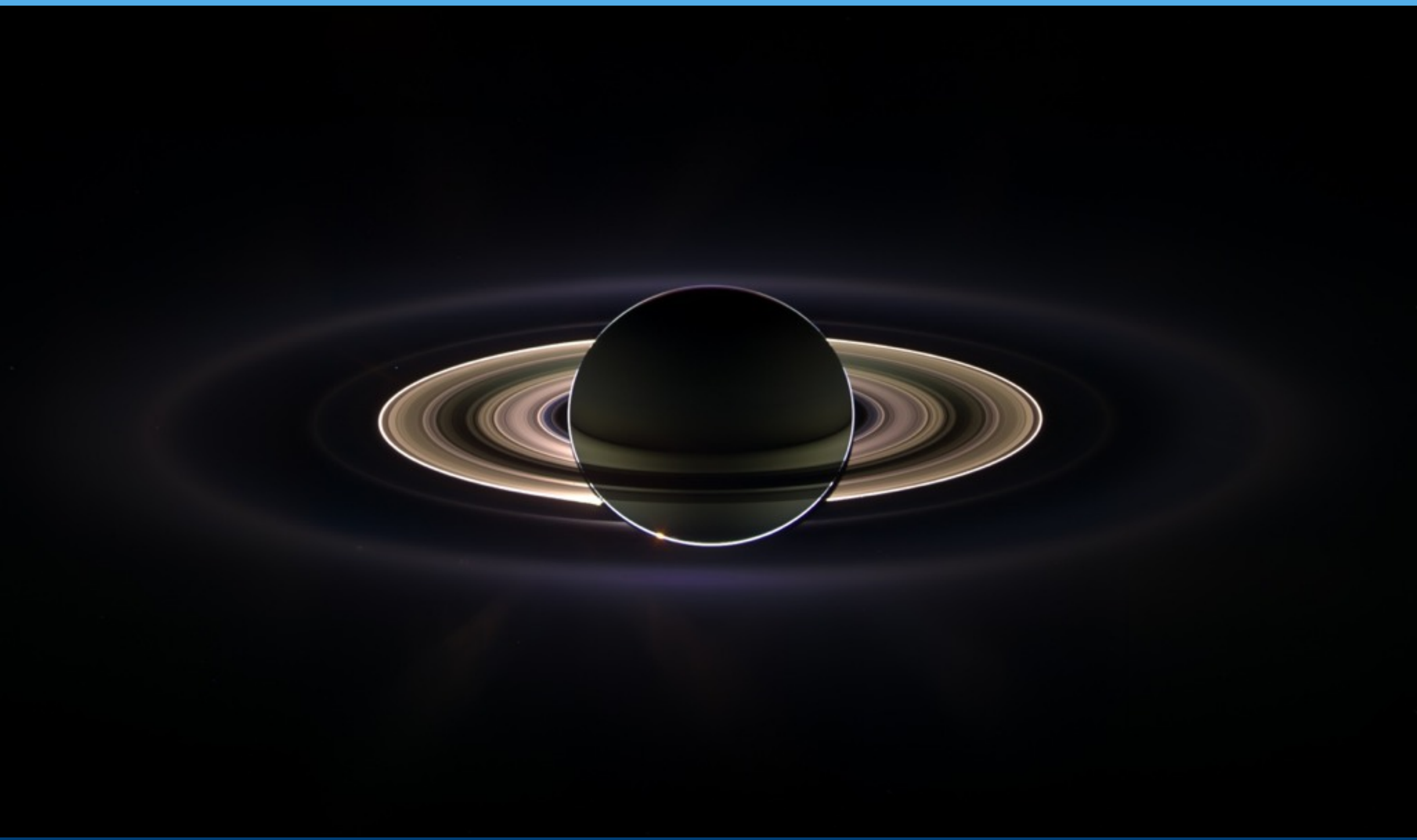
Migration leads to resonance, but the wrong one.

Alternatives such as planet-planet scattering also doesn't work.

We have no idea...

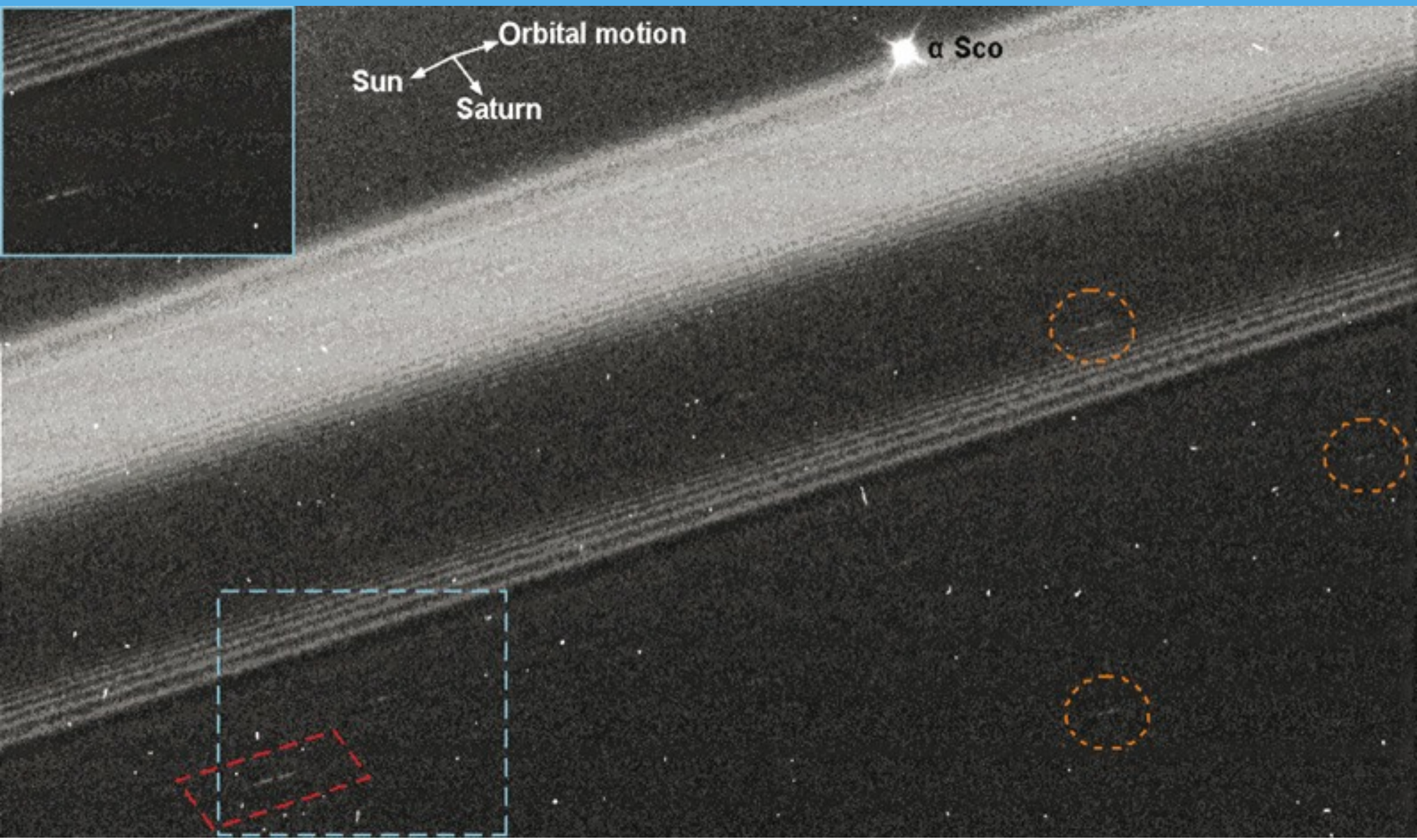
Moonlets in Saturn's Rings

Cassini spacecraft



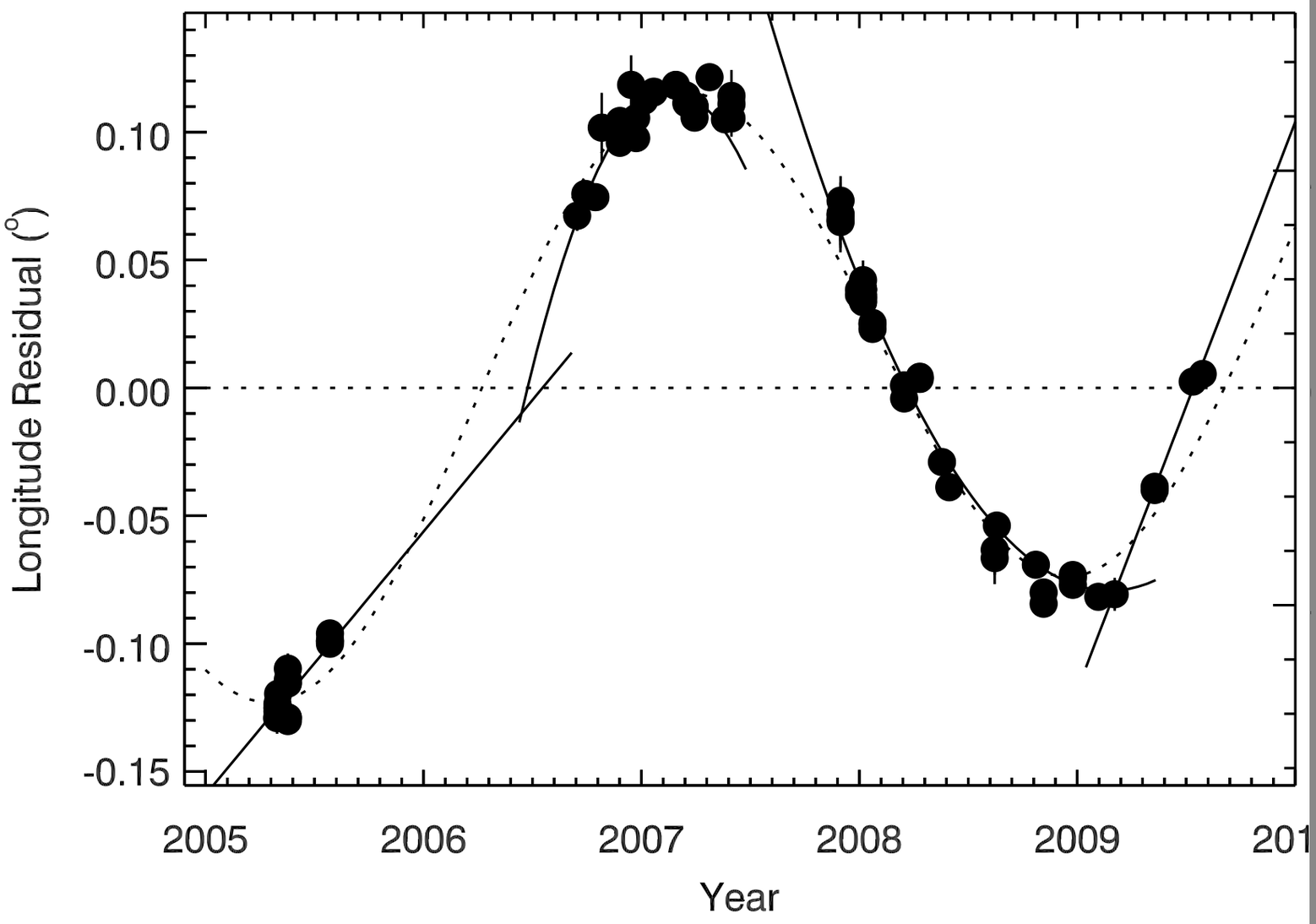
NASA/JPL/Space Science Institute

Close-up of Saturn's rings: propeller structures



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

Migration in Saturn's rings



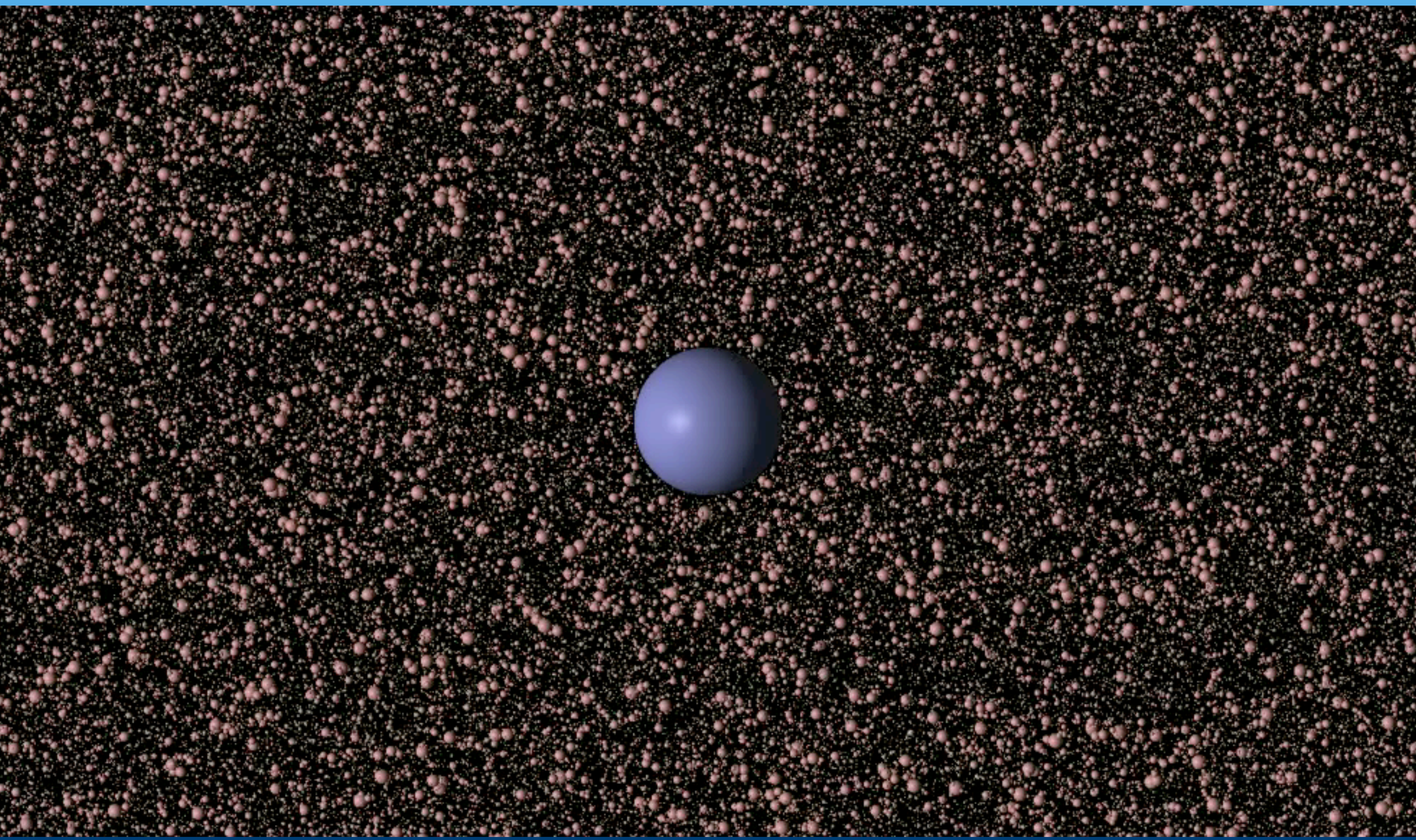
The moonlet is like a small planet.

It also migrates. But now we can observe it directly!

It might now migrate smoothly because Saturn's rings are very turbulent.

Tiscareno et al. 2010

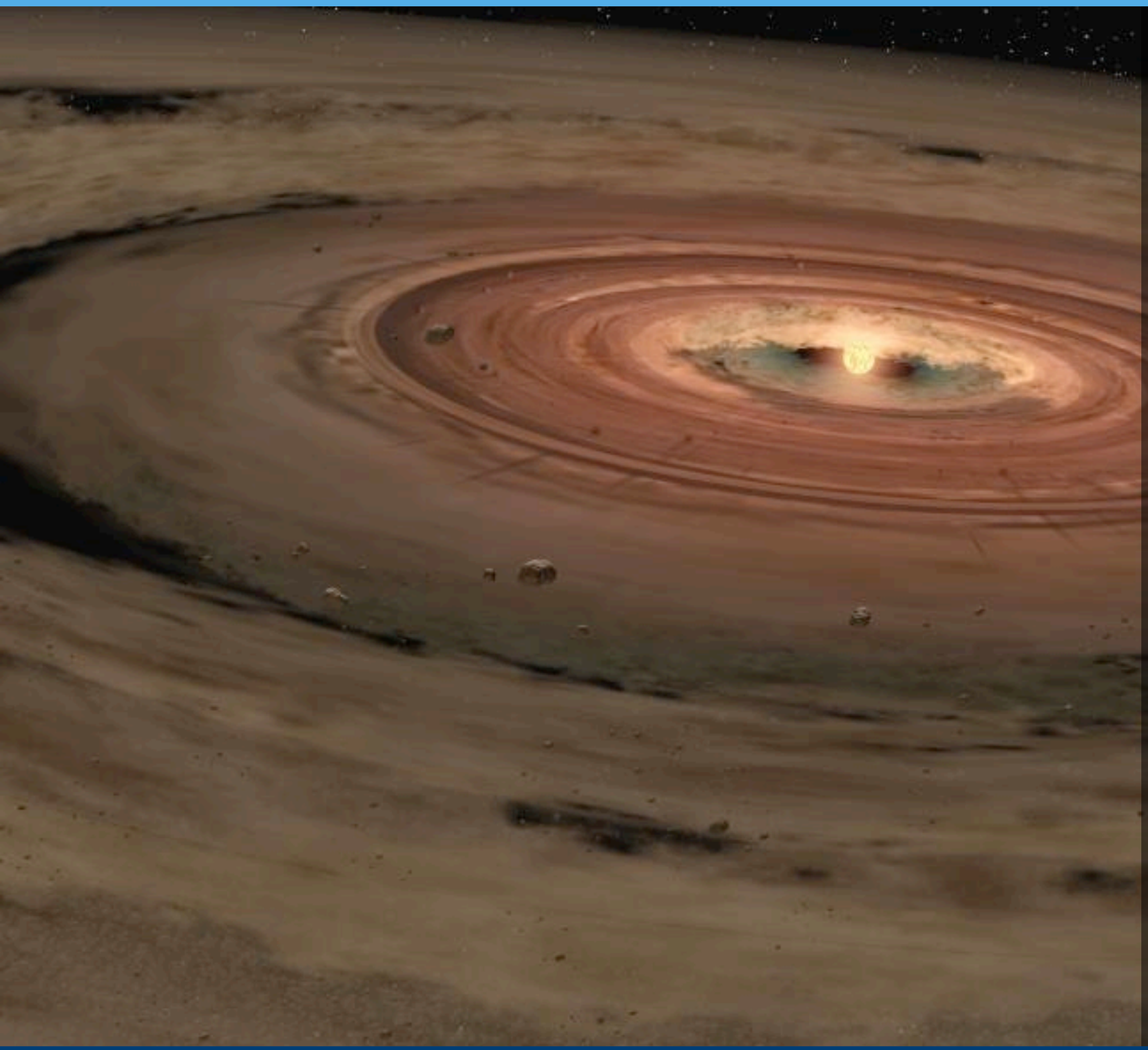
Random walk



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

Is our solar system special?

Planet migration in the solar system



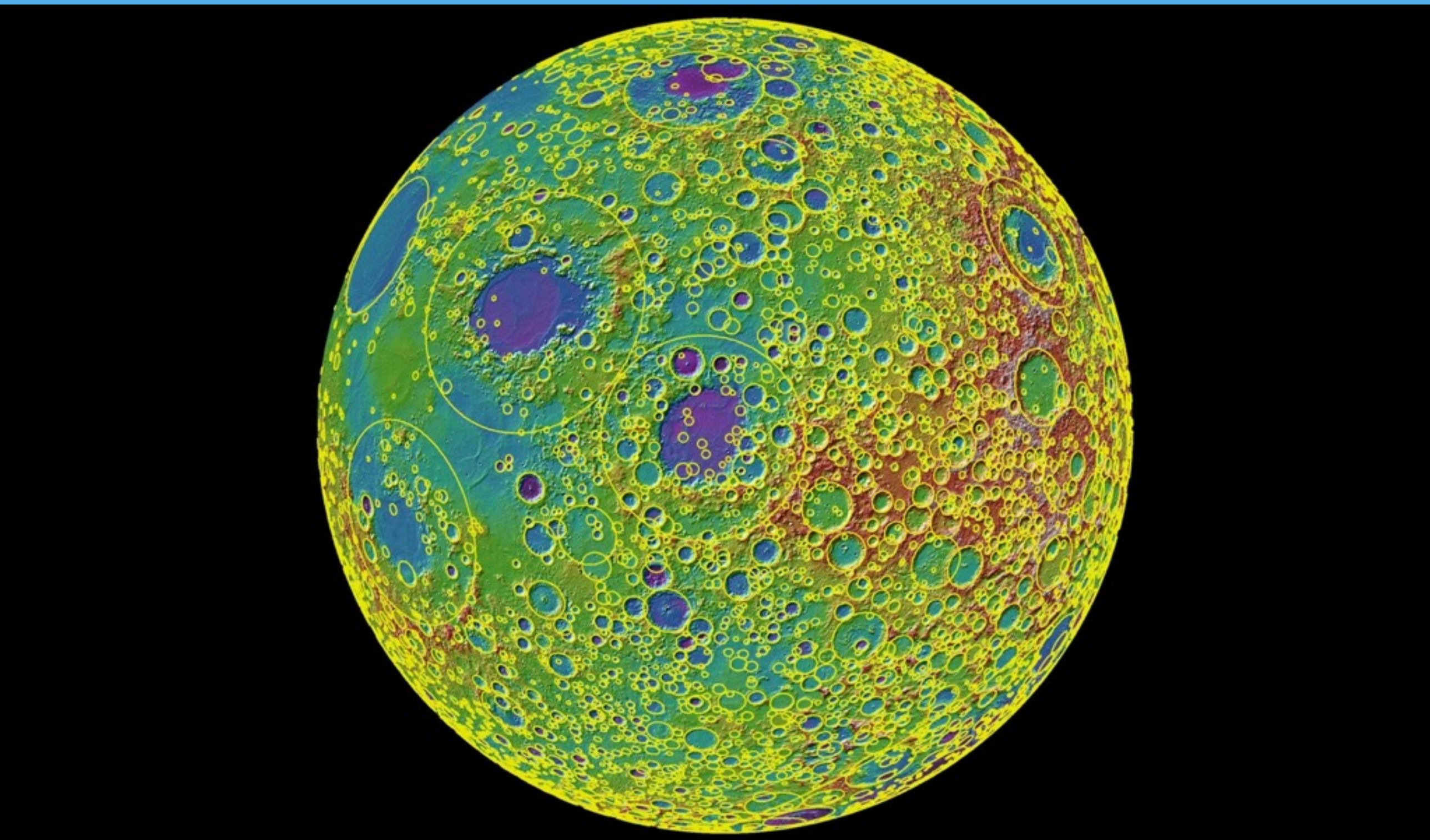
Planet migration in the proto-planetary disk piles up the giant planets in a resonant chain.

Planetesimal disk is left over as well.

This is the starting configuration of the nice model.

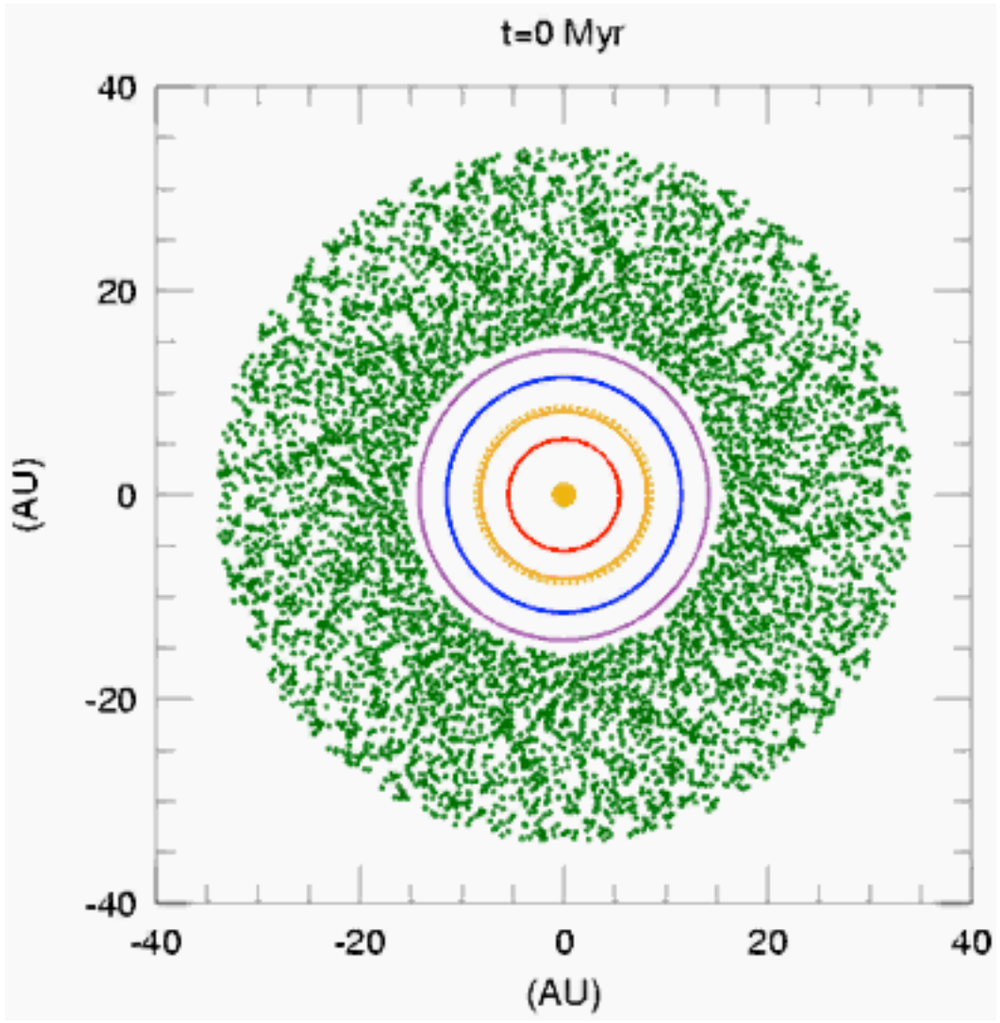
NASA/JPL-Caltech/T. Pyle (SSC)

Moon crater count



NASA/LRO/LOLA/GSFC/MIT/Brown

Our best guess how the solar system formed.



Migration results in compact, resonant system.

Planetesimal disk allows planets to migrate just a little bit outside of the resonance.

Triggers the late heavy bombardment.

Are we special?

Yes.

No.

Are we alone?

Are we alone?

$$N = R^* \cdot f_p \cdot n_e \cdot f_\ell \cdot f_i \cdot f_c \cdot L$$

The Drake Equation.

R^*

Rate of star formation in galaxy

f_p

Fraction of planets with life that develop intelligent life

n_e

Fraction of planets that can support life

f_ℓ

Fraction of planets that actually go on to develop life at some point

f_i

Fraction of civilizations that develop a technology that releases detectable signs of their existence into space

L

Length of time for which such civilizations release detectable signals into space

10

NO

Thank you!