Formation of higher order resonant exoplanetary systems

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Resonant systems

2:1 MMR systems:

Very well studied

GJ 876 – Lee & Peale (2002), Crida et al (2008)
HD 128311, HD 73524 – Sandor & Kley (2006), Sandor et al (2007)

3:2 MMR

HD 45364 – Correia et al (2009), Rein et al (2010)

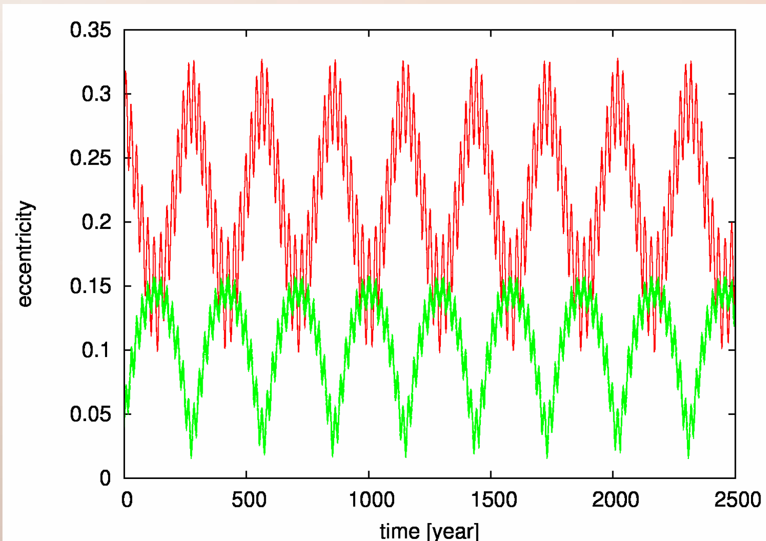
3:1 MMR

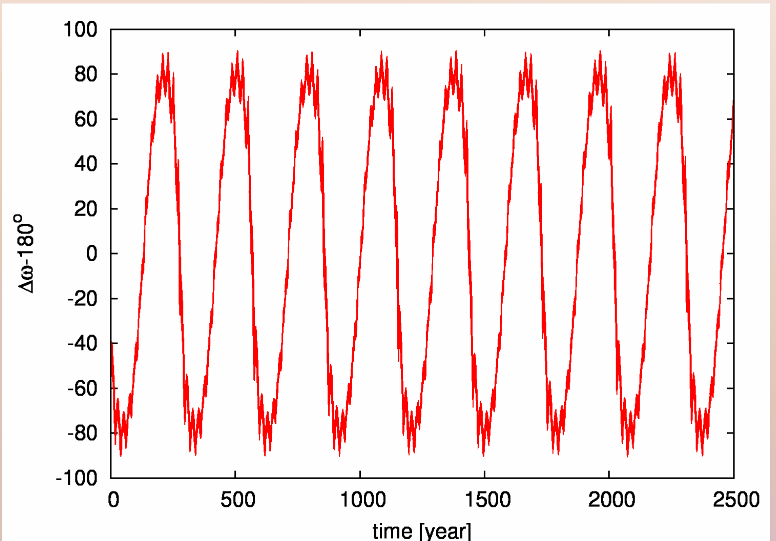
Two planets around 55 Cancri – questioned by Naef et al (2004)
Fischer et al (2008) no resonance at all

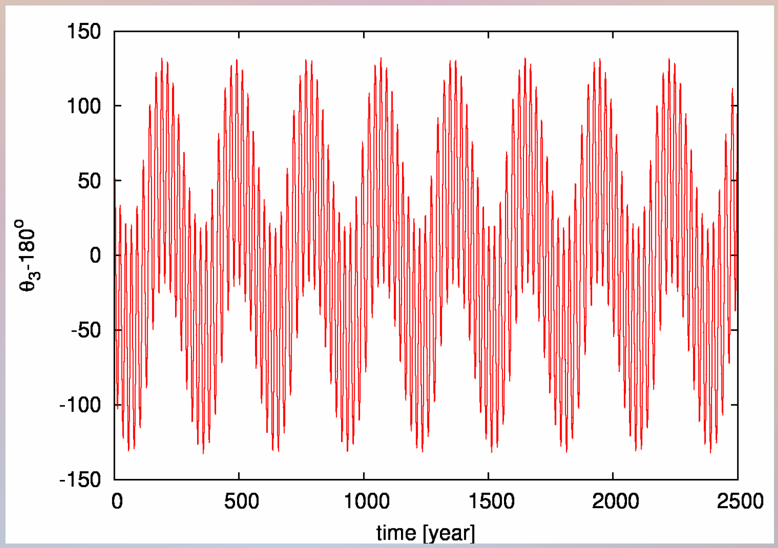
HD 60532 – Desort et al (2008), Laskar & Correia (2009)
This is the first confirmed 3:1 MMR system!

4:1 MMR
HD 108874 – Gozdziewski et al (2006) stability analysis

Orbital solution of Laskar & Correia for HD 60532







The corresponding orbital elements used as initial conditions are in the paper of Laskar & Correia (2009)

Apparent contradiction to the THEORY!!!
(Beaugé et al 2003)

When $e_1 > 0.13$, ***asymmetric libration***
(i.e. around a value different to 0° or 180°)
But here this is not the case!

Modeling formation: hydrodynamical simulations

Full hydrodynamical simulations of two embedded planets in a protoplanetary disk through ***migration*** (Sándor & Kley, 2010 A&A)

Three different sets of the planetary masses were studied:

1. $i = 90^{\circ}$: *m1*= 1.048 m*J*, *m2* = 2.487 m*J*

2. $i = 30^{\circ}$: *m1*= 2 x 1.048 m*J*, *m2* = 2 x 2.487 m*J*

3. $i = 20^{\circ}$: *m1*= 3.15 m*J*, *m2* = 7.46 m*J*

A factor of ≈ 3 comparing to the first case!

Mass of the central star: $M_* = 1.44\ M_{sun}$

Aim: investigate which set of planetary masses is favored by the hydrodynamical simulations?

And why the observed behavior of the planets differs from the theoretical expectations?

Setup of the hydro simulations

Additional hydro setup – celestial mechanicians may jump this part :-)

Flat accretion disk with constant aspect ratio: $H(r)/r = h = 0.05$
$H(r)$: vertical extension of the disk

Computation domain: 0.2 – 5.0 units

Initial surface density profile: $\Sigma(r) = \Sigma_o \, r^{-1/2}$

where $\Sigma_o = 3.1 \times 10^{-4}$ at 1 distance unit

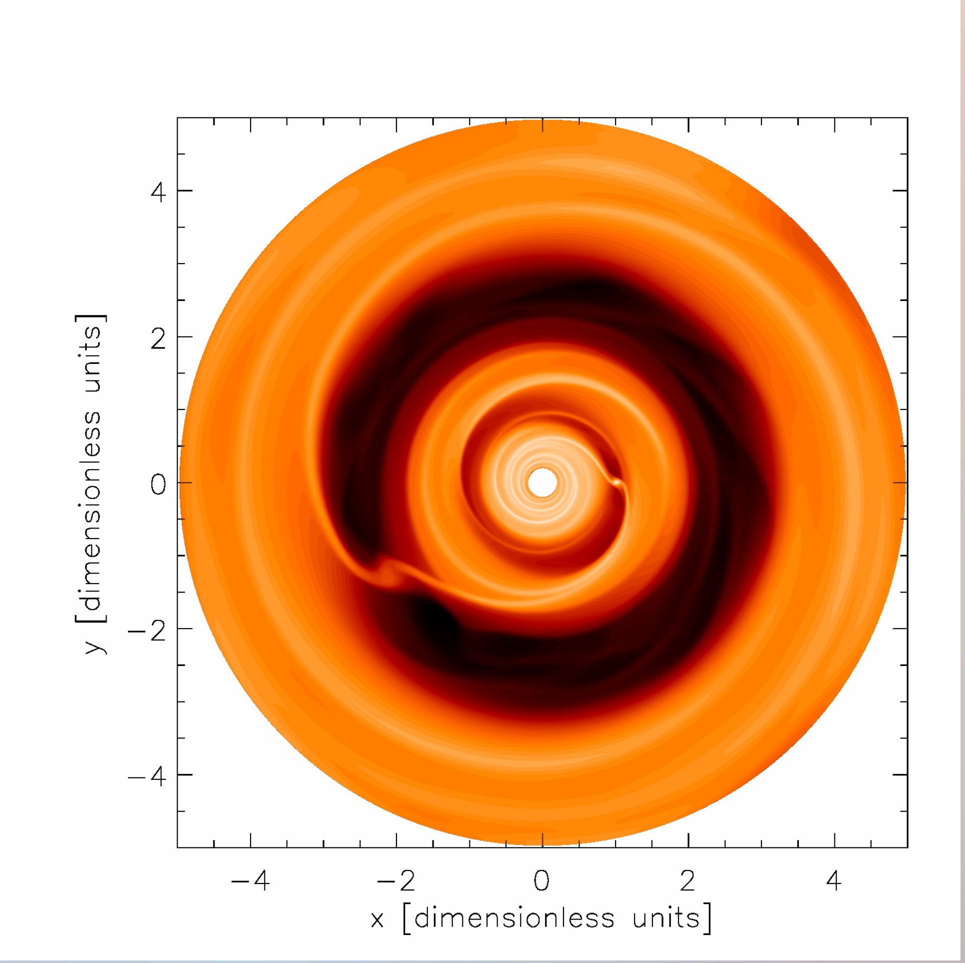
Gas accretion toward the star is driven by an α-type viscosity: $\alpha = 0.01$

Logarithmic grid in radial direction: 256 x 500 gridcells

Planets are placed initially at r1 = 1 and r2 = 2.5 distance units

A nice picture to wake up the audience

The quasi steady state of the surface density distribution of the disk material after 500 orbital periods of the inner planet on fixed orbits.



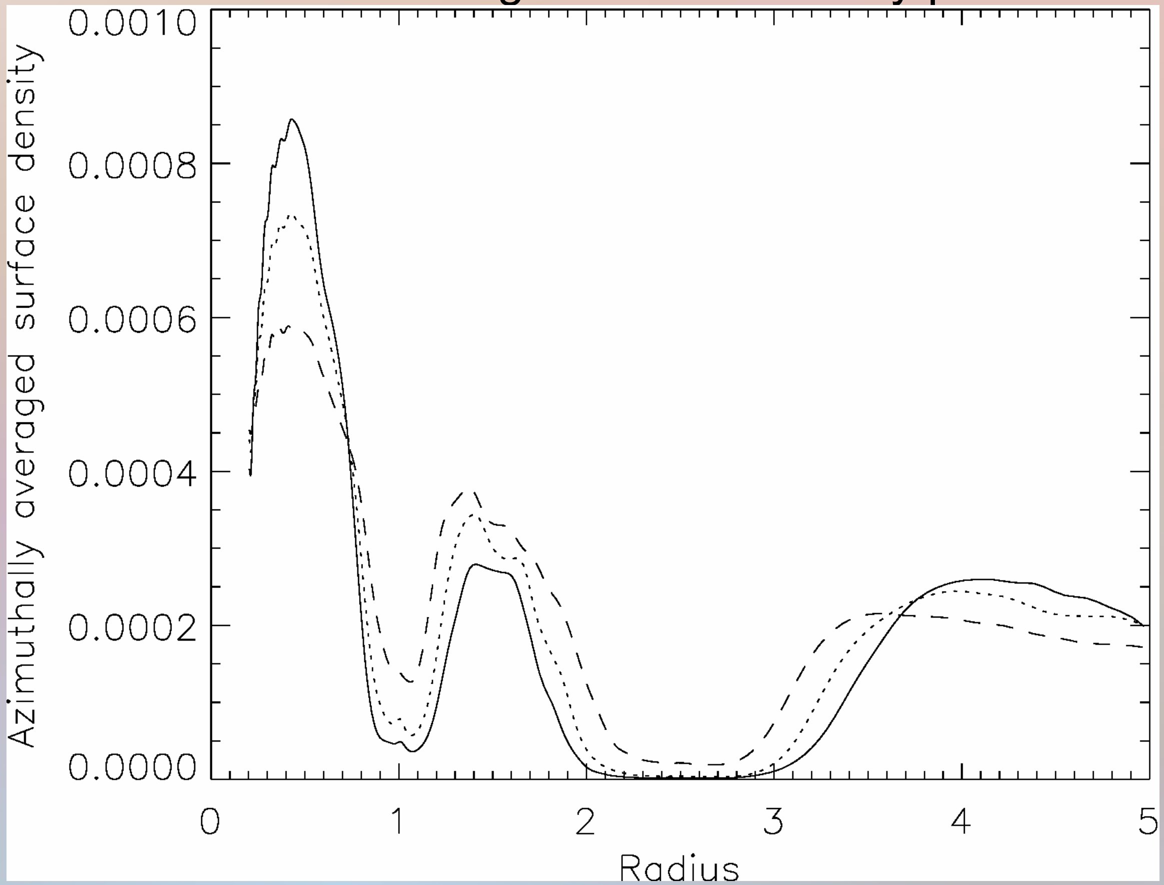
Reaching this state, the planets are released and migrate toward the star.

Reason: the non-homogeneous density distributions (see the spiral wave structure) exert torques Into the planets – they begin to migrate (type II migration).

Resonant capture – only for the large masses

Small masses: inner planet migrated faster than the outer one
Intermediate masses: migration speed of the planets were almost equal
Large masses: outer planet migrated faster than the inner one → resonant capture

WHY? See the averaged surface density profile:



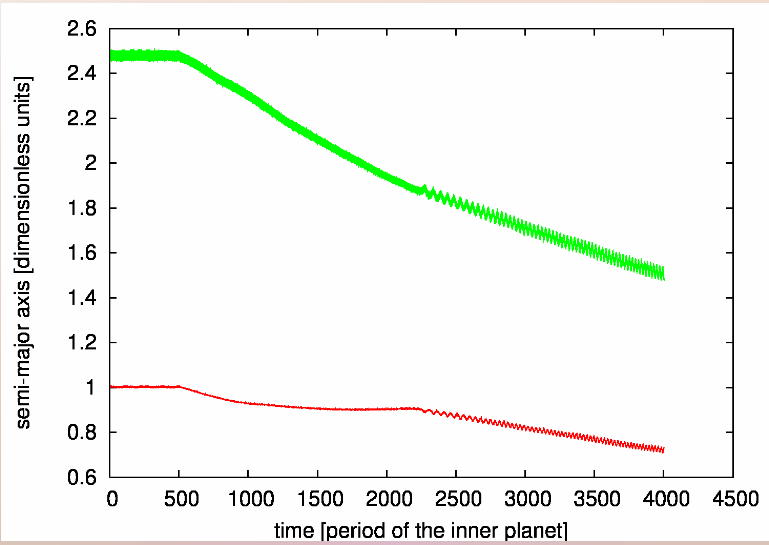
Dashed line: small masses
Dotted line: interm. masses
Solid line: large masses

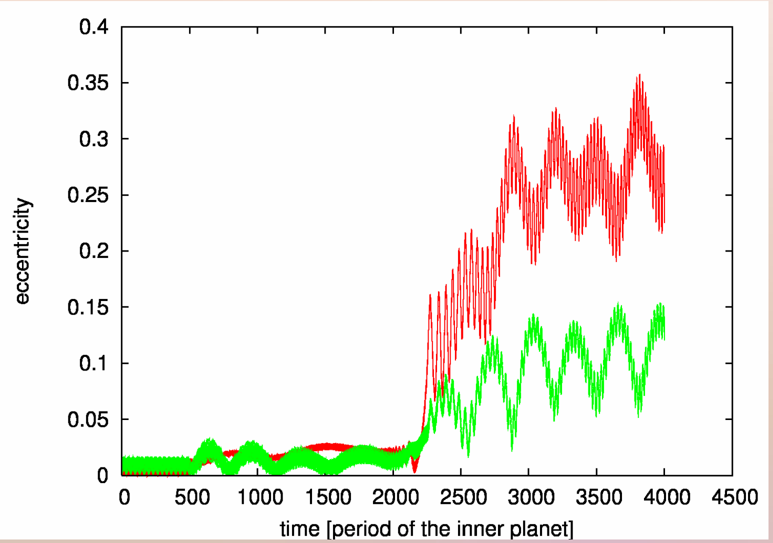
Inner planet's migration is governed by the middle part of the disk and the inner disk:

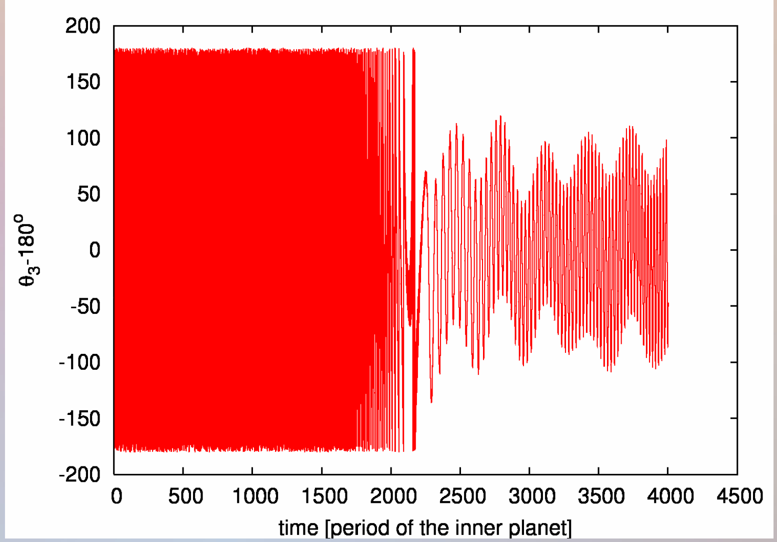
Massive middle disk: slows down the planet, inward migration

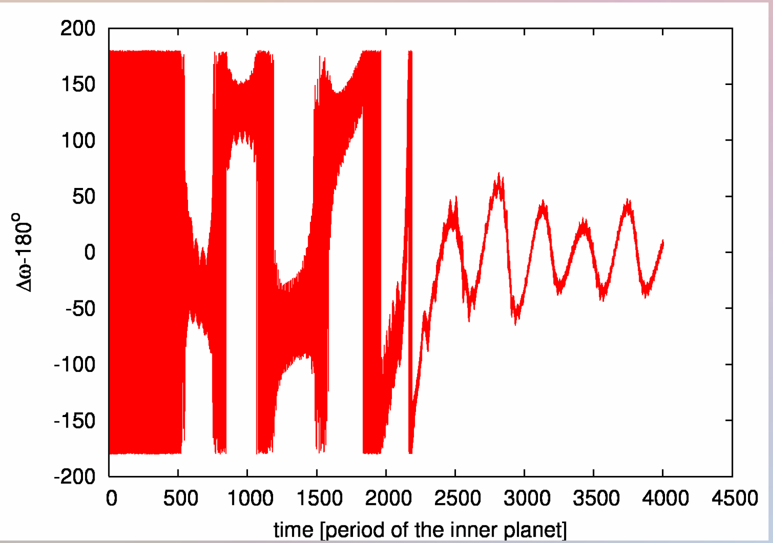
Massive inner disk: accelerates the planet, outward migration

The resulted system in the 3:1 MMR









Laskar&Correia's orbital behavior reproduced, the contradiction to the theory survived !!!

New stationary solutions for HD 60532

Inner disk – a small note

Conjecture: the inner disk may play a special role as “pumping” energy into the system

1. Kley et al. (2004) found that if there is no inner disk in the system, the planets enter either a 2:1 or a 3:1 MMR depending on the speed of migration

2. In their simulations they found the asymmetric libration predicted by Beaugé et al.

3. We performed dissipative three-body simulations without and with an inner disk, and our results show that indeed, the inner disk is responsible for the symmetric stationary solution.

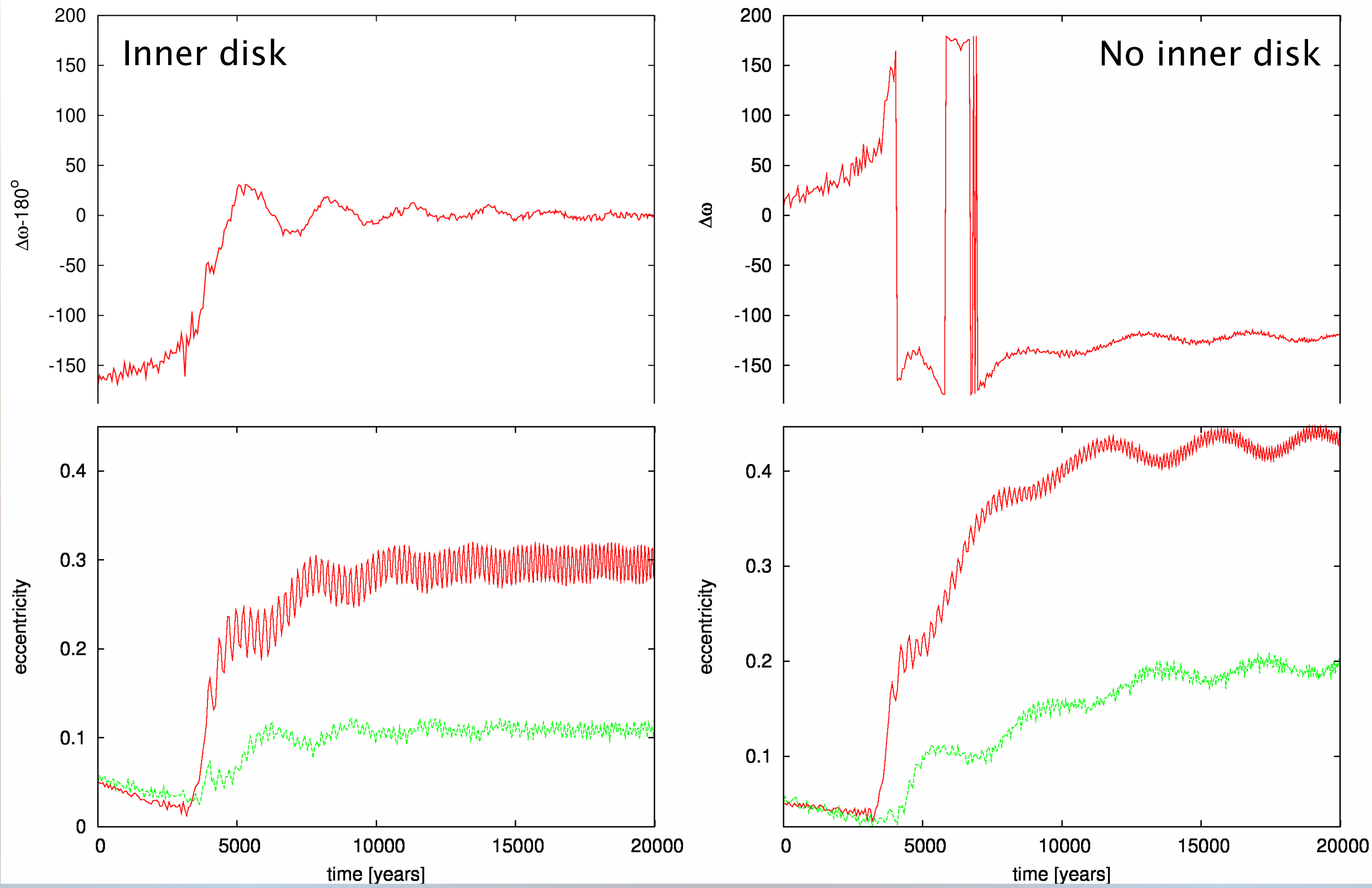
For mimicking the effect of an inner disk through three-body integrations consult Sándor et al, 2007; Crida et al, 2008.

Conclusion:

1. The inner disk does not enable the system to reach the stationary solution predicted by the theory, and found by hydro simulations.

2. Formation of 3:1 MMR systems may be possible, however not so easy to form them as the 2:1 MMR systems.

New stationary solutions for HD 60534



A real higher order resonant system: HD 108874 ?

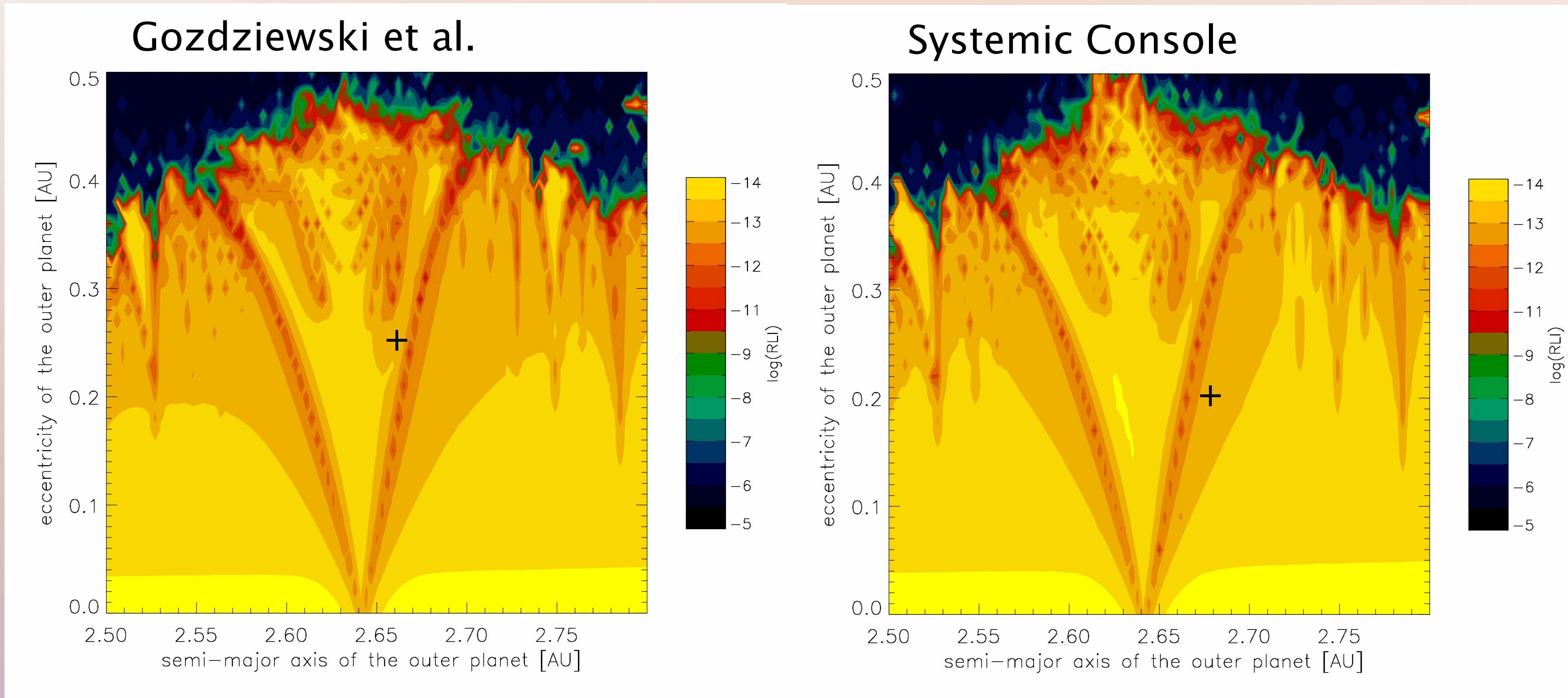
HD 108874 a system which might be in a 4:1 MMR.

Gozdziewski et al, 2006: orbital solution in which one of the resonant angles librates, however, no apsidal corotation – not easy to form by a convergent migration scenario.

Another stable solution can be found by using the Systemic Console (www.oklo.org), in which the planets are only close to the 4:1 MMR.

Question: *Do we really need the planets to be engaged into the 4:1 MMR?*

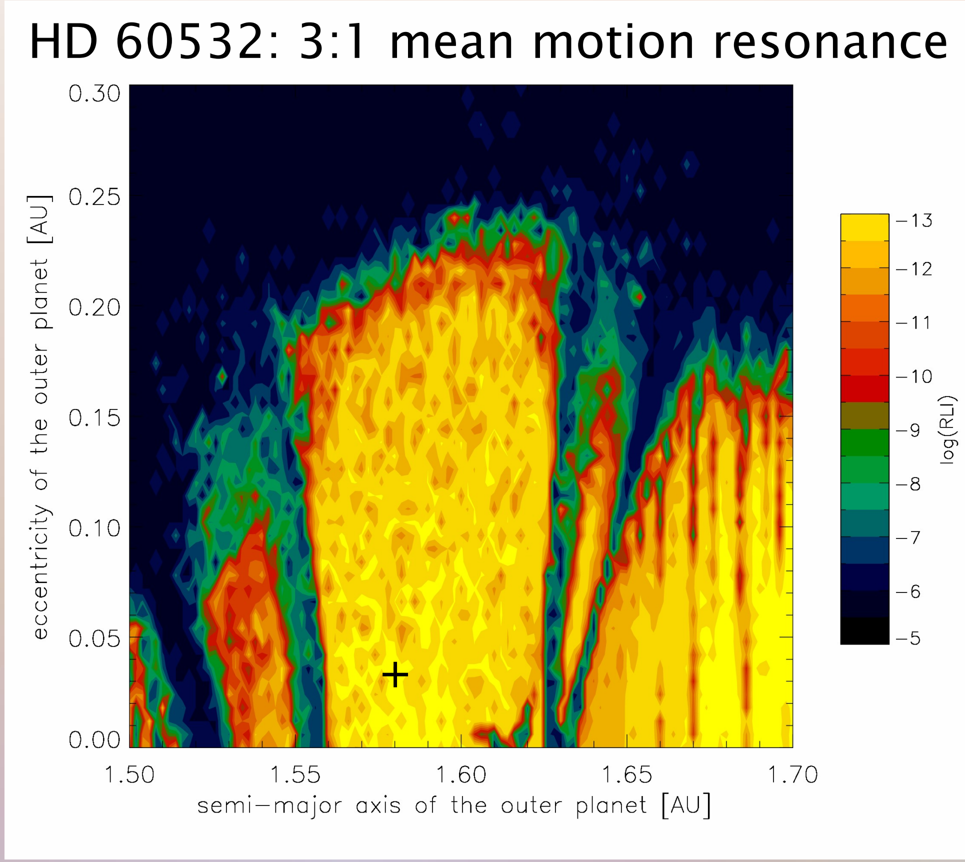
Structure of the 4:1 MMR around the two solutions

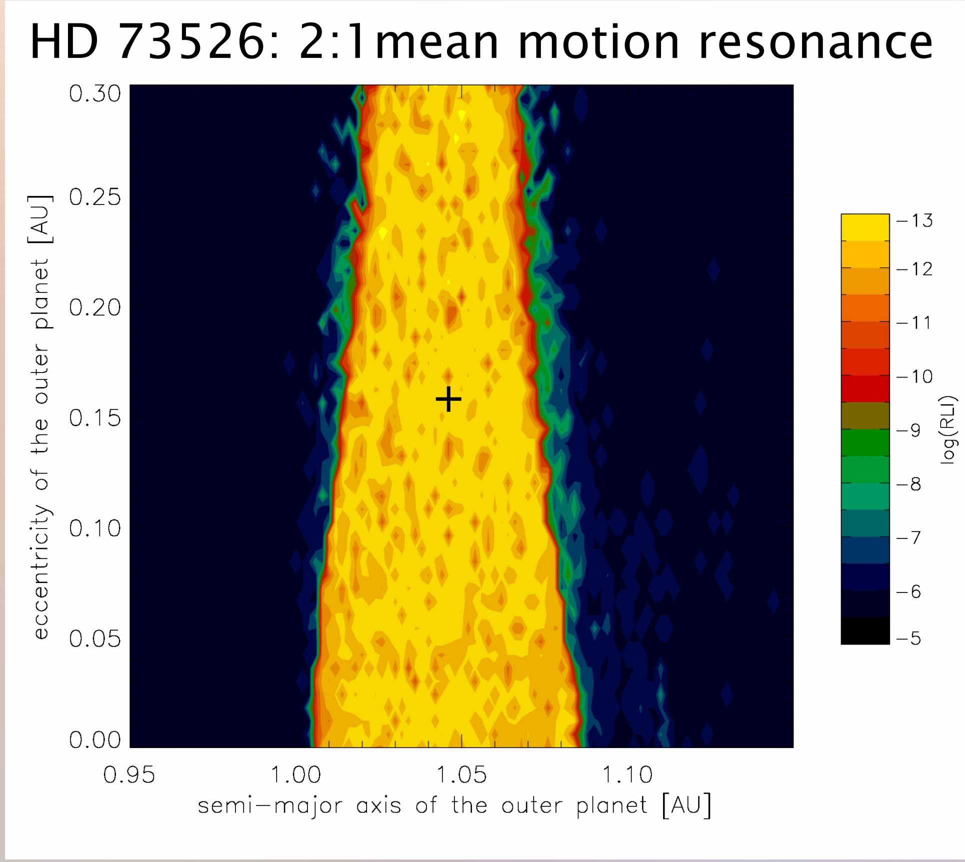


Only a slight difference between the pictures, the majority of the *a-e* plane hosts ordered motion. The 4:1 MMR has not a really protective character, at least in the case of HD 108874.

Contrary to these pictures, the lower order resonances are REALLY protective!

Structure of the lower order resonances





In the cases of lower order resonances the protective character of the resonances is clearly seen !!!

Another problem to reach the 4:1 MMR

For two planets to be captured into the 4:1 resonance one of them should have relatively large eccentricity – 0.1 … 0.15.

This can be achieved, if there are 3 planets migrating in the protoplanetary disk, the outer one captures the middle one into a 2:1 MMR, the eccentricity of the middle planet is increased, and approaching the inner planet, a capture into the 4:1 MMR can happen – idea by Rein & Papaloizou.

Complicate scenario, but it can be realized using four body integrations with dissipative forces for migration.

Unfortunatelly, no hydrodynamical runs can support this idea so far...

Final conclusion regarding the 4:1 MMR:

Contrary to the 2:1 and 3:1 MMRs, the 4:1 resonance has no protective character anymore. The resonance is not needed to “stabilize” the orbital solution.