F.R.S.-FNRS Contact Group "Astronomie & Astrophysique"
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Formation mechanisms of highly non-coplanar systems

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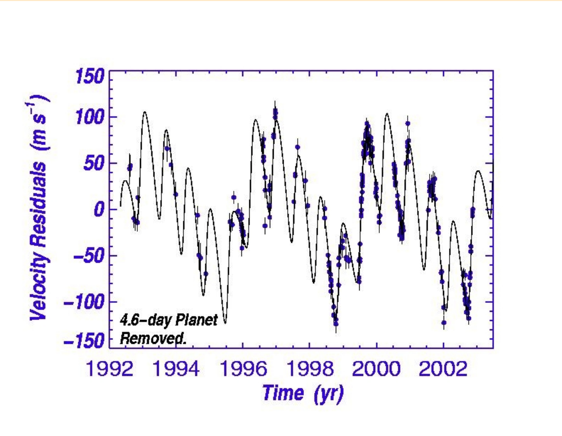
Overview

- Detections of exoplanetary systems, but no spatial resolution of the orbits



Overview

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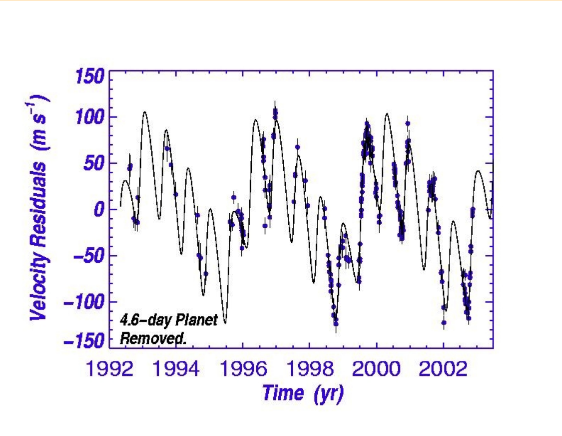
- Analytical studies: Stable highly non-coplanar planetary systems can exist
(e.g. Michtchenko et al. 2006, Libert & Henrard 2007, Libert & Tsiganis 2009a)

  either following normal secular dynamics
  or due to the action of a phase-protection mechanism (MMR, Kozai resonance)



Overview

- Ups Andro: mutual inclination of ~30° between the orbital planes of planets c and d (McArthur et al. 2010)

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NEW OBSERVATIONAL CONSTRAINTS ON THE υ ANDROMEDAE SYSTEM WITH DATA FROM THE *HUBBLE SPACE TELESCOPE* AND HOBBY-EBERLY TELESCOPE*

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ABSTRACT

We have used high-cadence radial velocity (RV) measurements from the Hobby-Eberly Telescope with existing velocities from the Lick, Elodie, Harlan J. Smith, and Whipple 60″ telescopes combined with astrometric data from the *Hubble Space Telescope* Fine Guidance Sensors to refine the orbital parameters and determine the orbital inclinations and position angles of the ascending node of components υ And A c and d. With these inclinations and using $M_* = 1.31 M_\odot$ as a primary mass, we determine the actual masses of two of the companions: υ And A c is $13.98^{+2.3}_{-5.3}$ $M_{\rm JUP}$, and υ And A d is $10.25^{+0.7}_{-3.3}$ $M_{\rm JUP}$. These measurements represent the first astrometric determination of mutual inclination between objects in an extrasolar planetary system, which we find to be $29.^\circ9 \pm 1^\circ$. The combined RV measurements also reveal a long-period trend indicating a fourth planet in the system. We investigate the dynamic stability of this system and analyze regions of stability, which suggest a probable mass of υ And A b. Finally, our parallaxes confirm that υ And B is a stellar companion of υ And A.

Key words: astrometry – planetary systems – planets and satellites: dynamical evolution and stability – planets and satellites: fundamental parameters

Online-only material: color figures, machine-readable table

Overview

- Formation of such systems ?

Planets formed close to their current location

↓ **discovery of exoplanets**

After their formation, planets may have migrated to their current location

[Nice model – Tsiganis, Gomes, Morbidelli & Levison]

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Dynamical mechanisms for the formation of two-planet systems with high mutual inclination, starting from a coplanar system that undergoes Type II migration ?

Work in collaboration with K. Tsiganis (Aristotle University of Thessaloniki)

First case:
Two-planet coplanar systems in a gas disc

[Libert & Tsiganis, MNRAS 400, 2009]

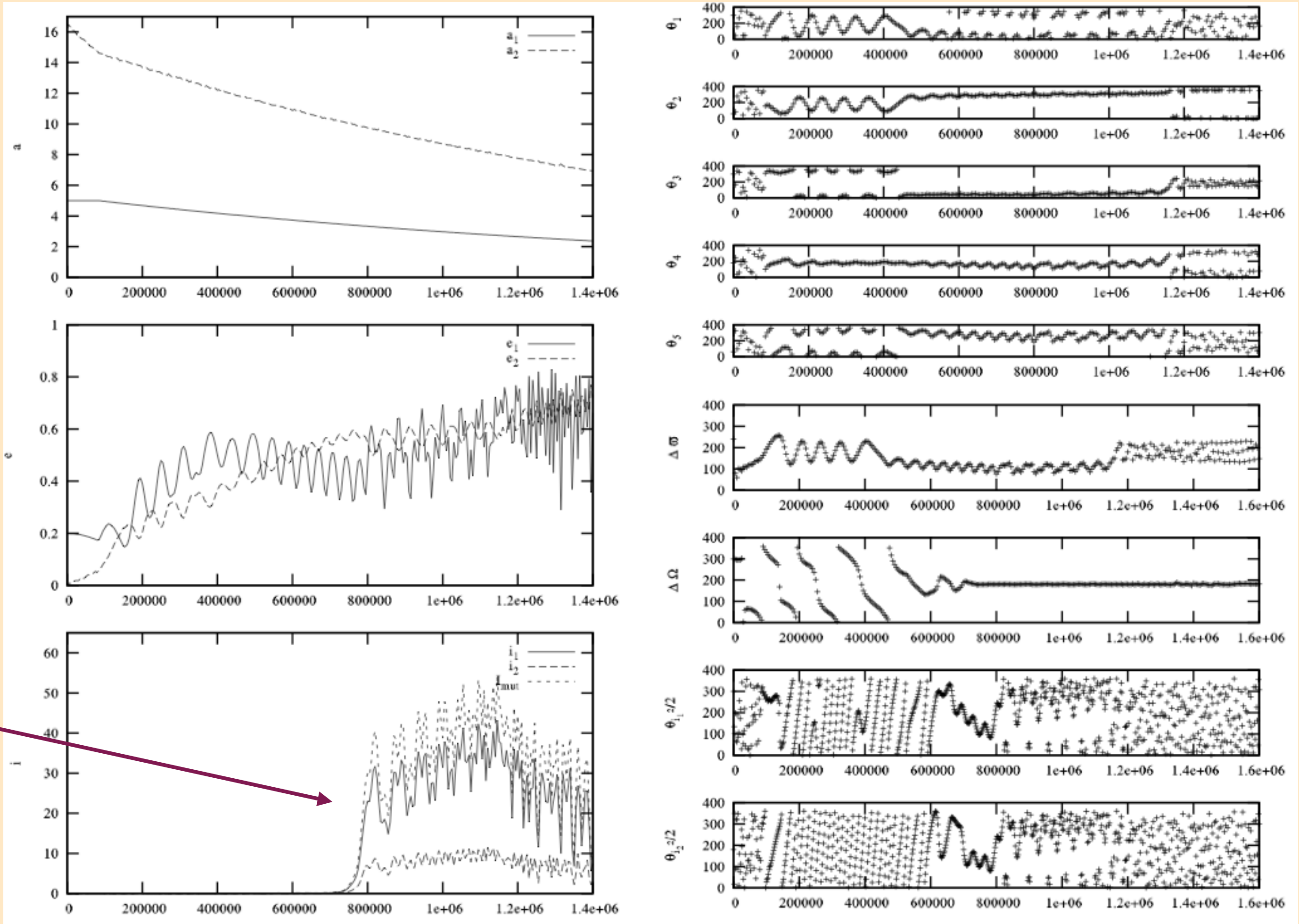
Exoplanetary systems in mean-motion resonances (MMR) are thought to have been captured as a result of gas-induced (Type II) orbital migration of the planets initially much further appart

- 2/1, 3/1, 4/1, 5/1 or 5/2 MMR capture (e.g. Nelson & Papaloizou 2002)
- Resonant eccentricity excitation (e.g. Lissauer, Peale & Cuzzi 1984; Lee & Peale 2002)
- Thommes & Lissauer (2003): starting with slightly non-coplanar orbits, **resonant inclination excitation** occurs during the migration in 2/1 MMR
- Libert & Tsiganis (MNRAS 400, 2009): resonant inclination excitation occurs **also for high-order resonance capture**

$$\lambda_1 - 5\lambda_2 + k\varpi_1 + l\varpi_2$$

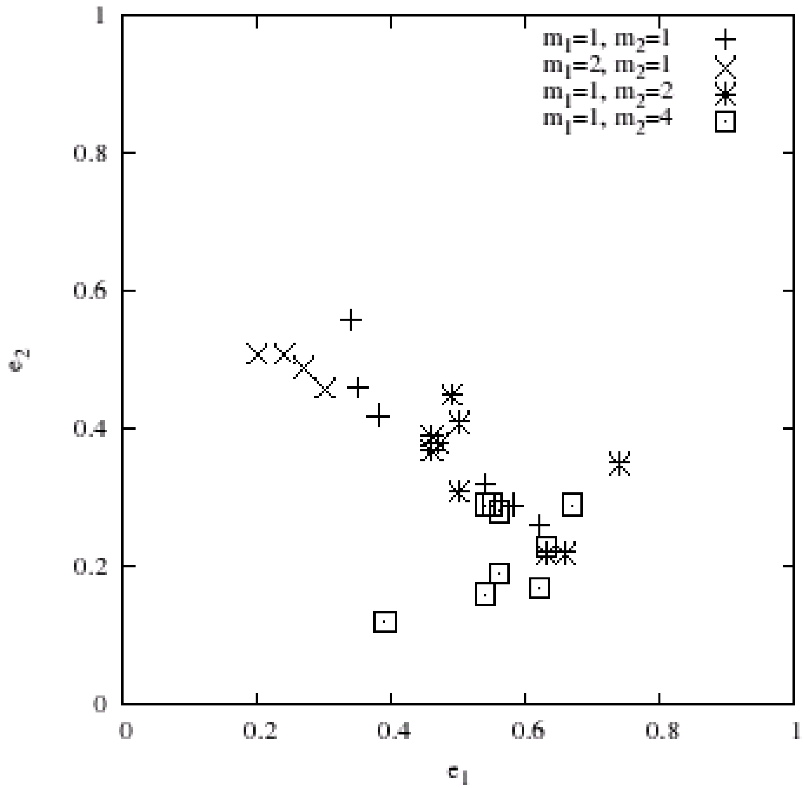
hyp: a_1=5 UA

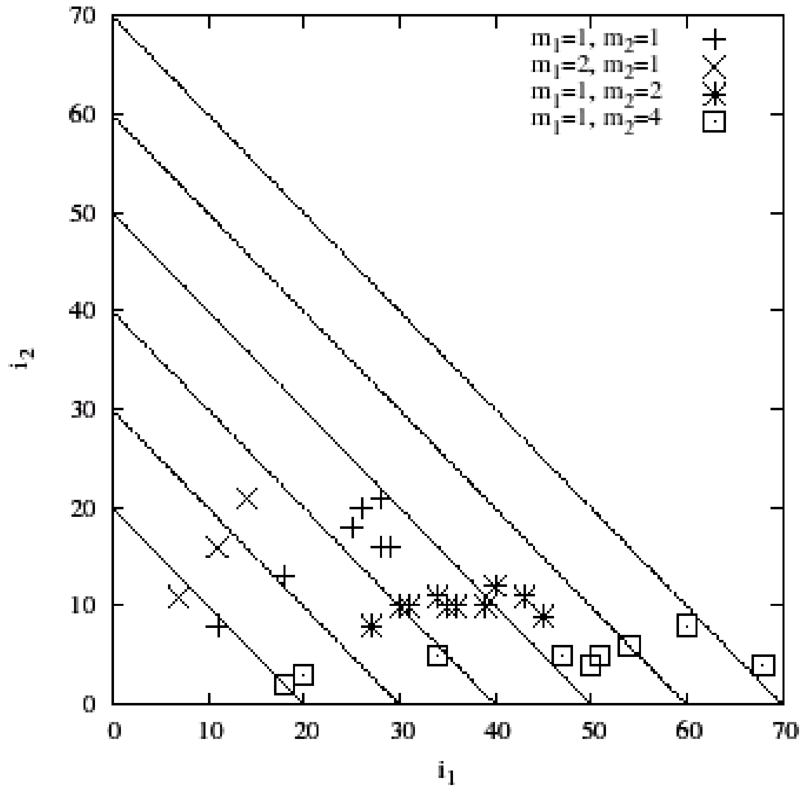
a_2=16.5 UA



$$2\lambda_1 - 10\lambda_2 + k\Omega_1 + l\Omega_2$$

Resonant inclination excitation is a usual outcome, even for a 5/1 capture !

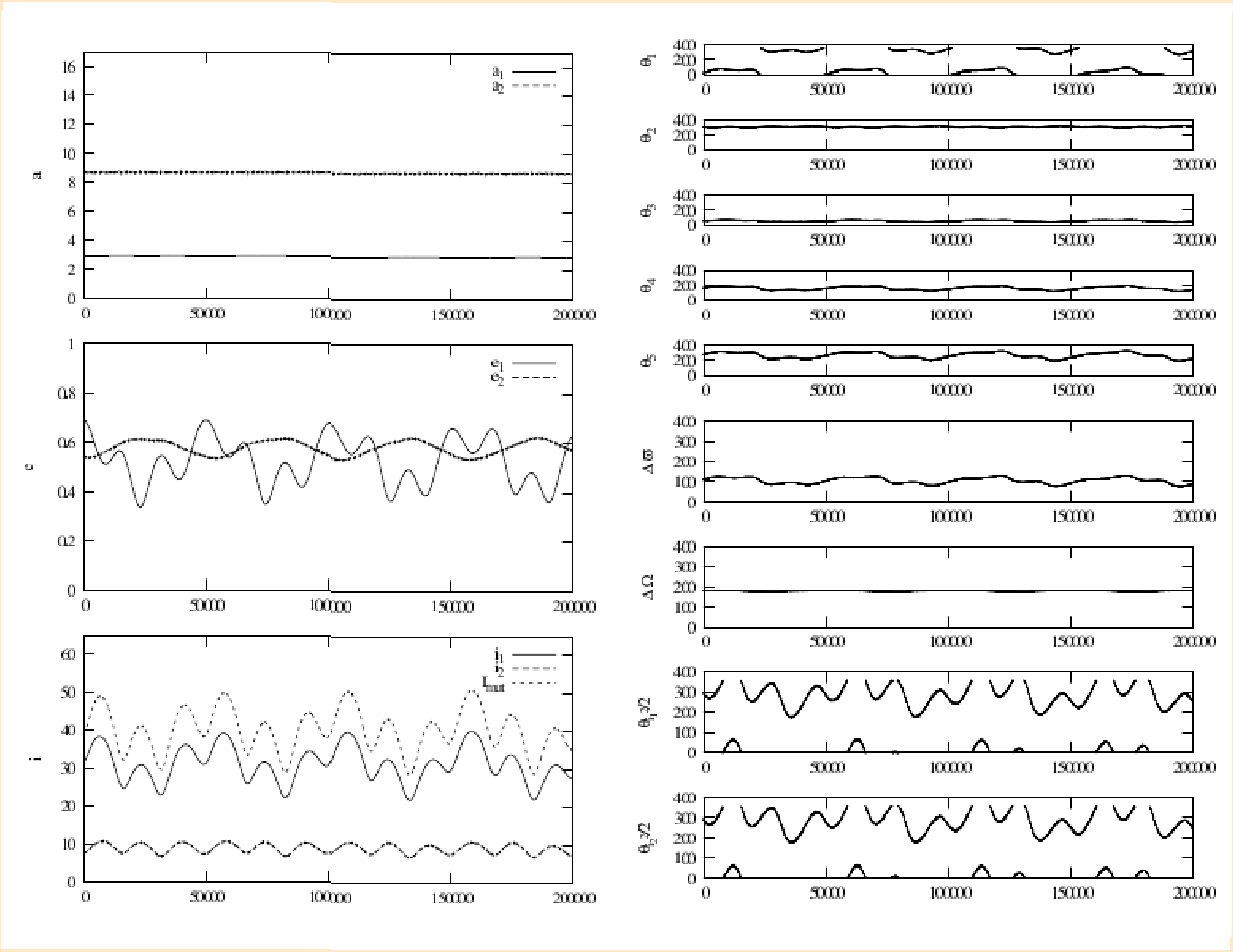




Inclination excitation requires at least one of the eccentricities to be e > 0.4

Maximal mutual inclinations between 20° and 70° during the migration

If we abruptly stop the migration: stable resonant systems with high mutual inclination



Second case:
Three-planet coplanar systems in a gas disc, as a test for a mechanism that can lead naturally to planet-planet scattering in order to form non-resonant non-coplanar systems

[Libert & Tsiganis, MNRAS 412, 2011]

The three planets can be trapped in a multiple MMR, as in Morbidelli et al. (2007) for the young solar system

Trapping in three-planet resonant configuration during gas-driven migration is common (Libert & Tsiganis, CeMDA 111, 2011):

- Main multiple-planet resonance captures are

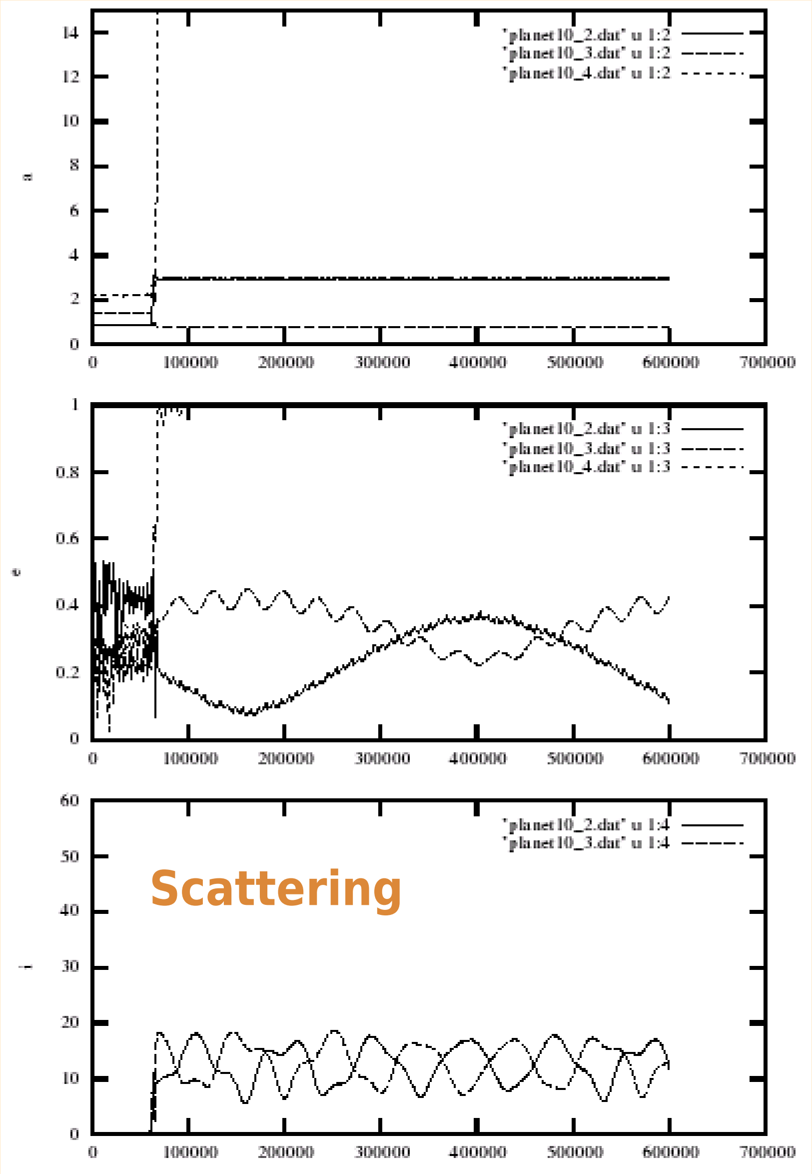
  n3:n2:n1=**1:2:4** (e.g. HR8799, Gl876)

  n3:n2:n1=**1:3:6**.

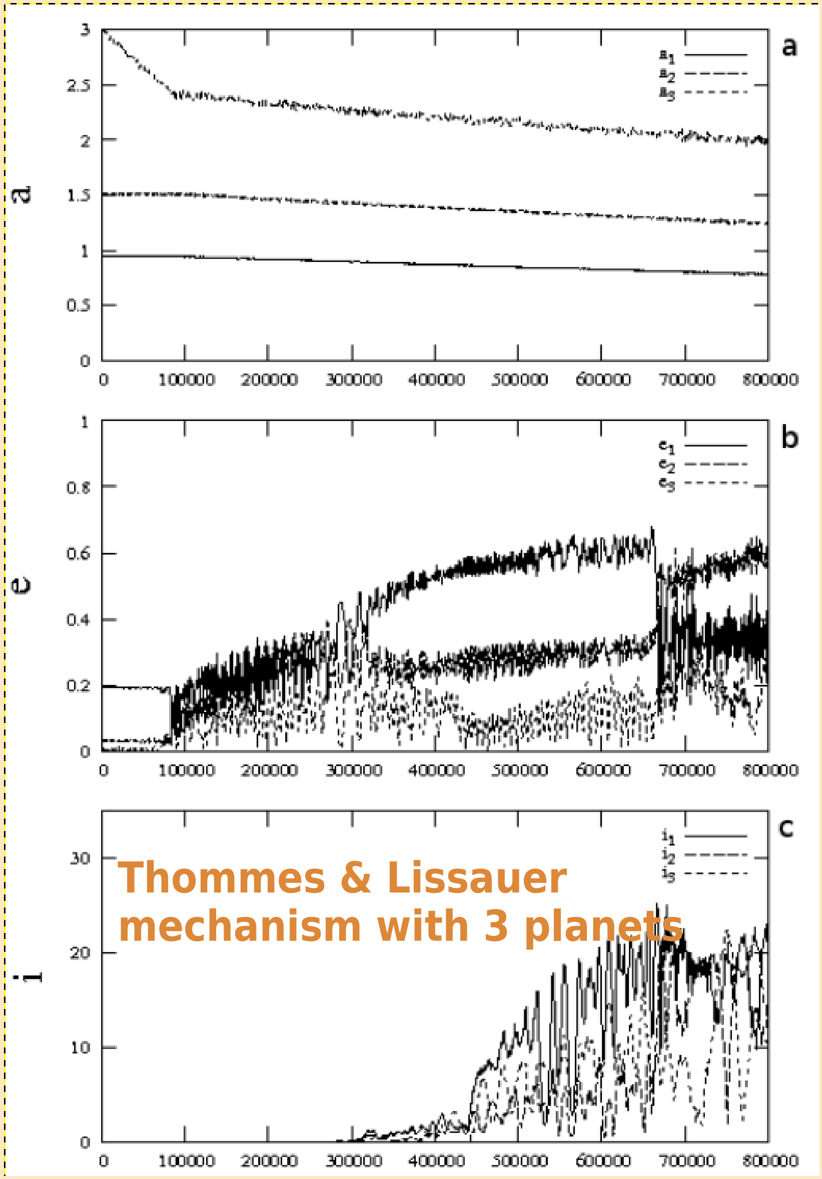
- Some other observed resonances are 1:4:8, 1:2:5, 2:3:6, 2:5:10, 3:8:12, 4:10:15

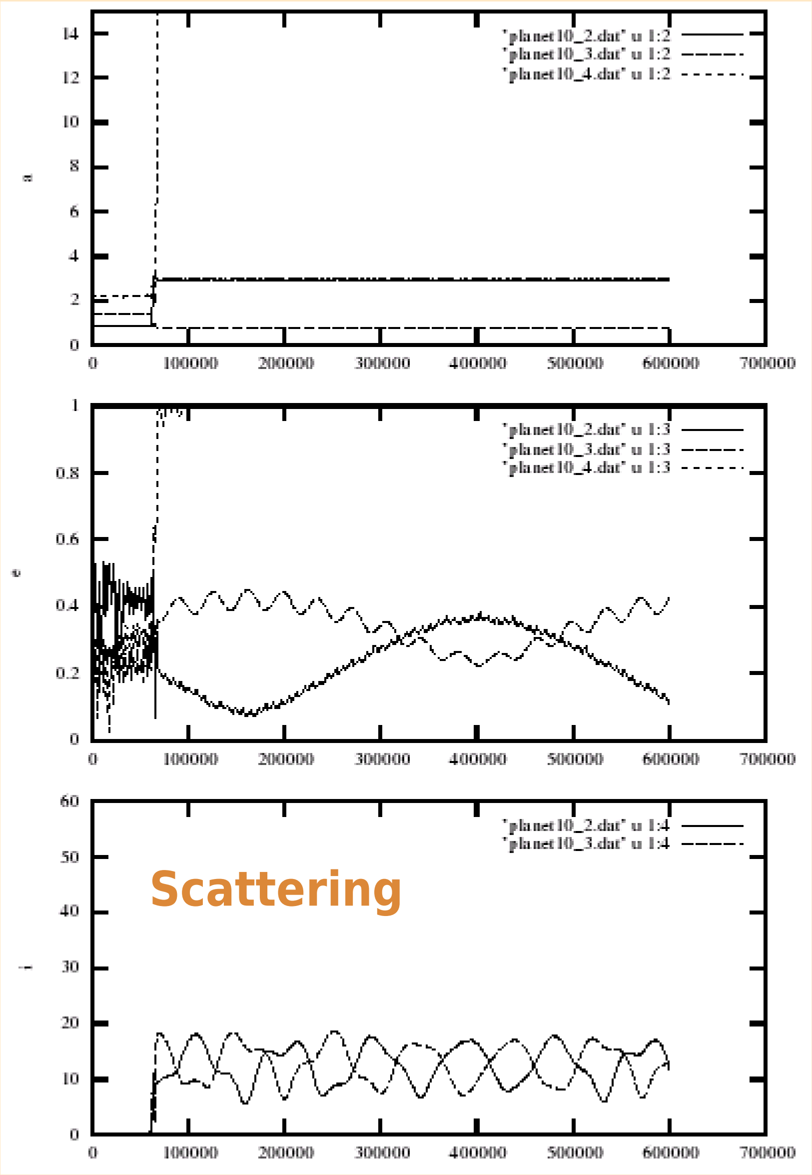
Once in a three-planet configuration

- Resonant eccentricity excitation
- Unstable configuration
- Multi-planet scattering
- Inclination excitation



Some examples of inclination excitation

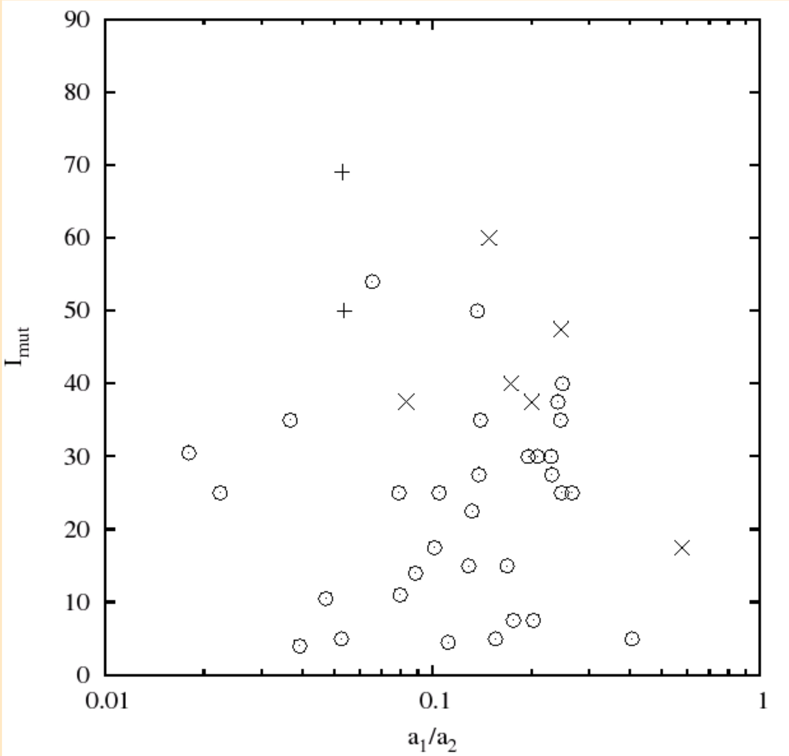




Three-planet resonant systems: 9 of 90 simulations

Two-planet systems: 40 of 90 simulations

Nearly all surviving two-planet systems are outside 8/1 MMR and even hierarchical



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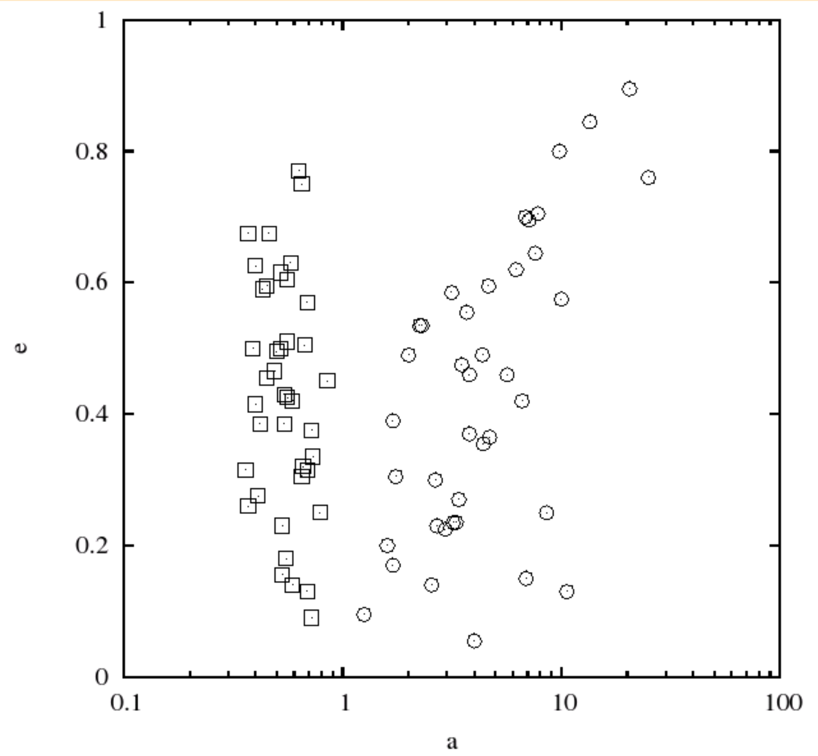
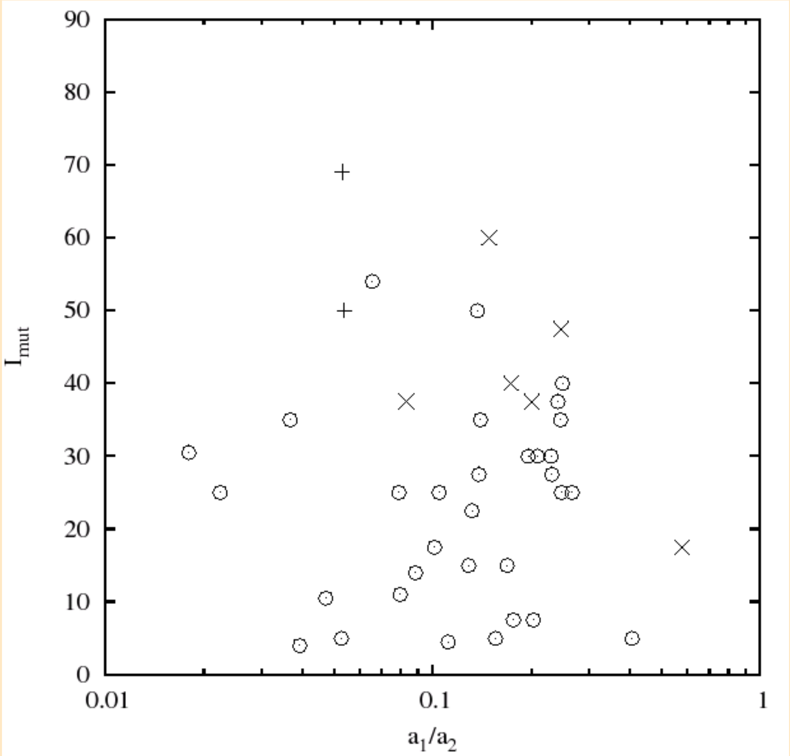


Values of the eccentricities are diversified and in agreement with those of the exosystems detected so far



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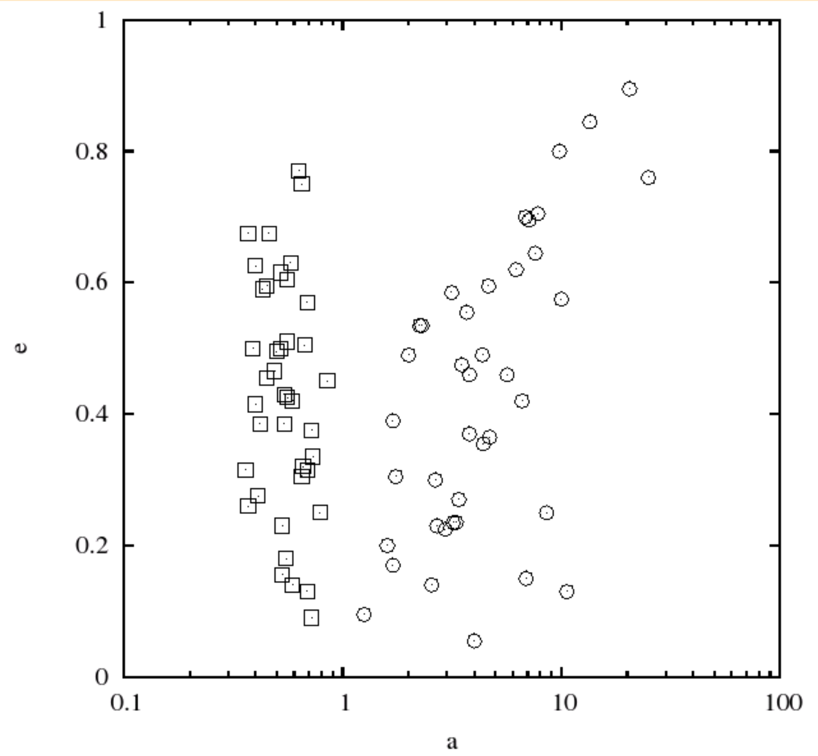

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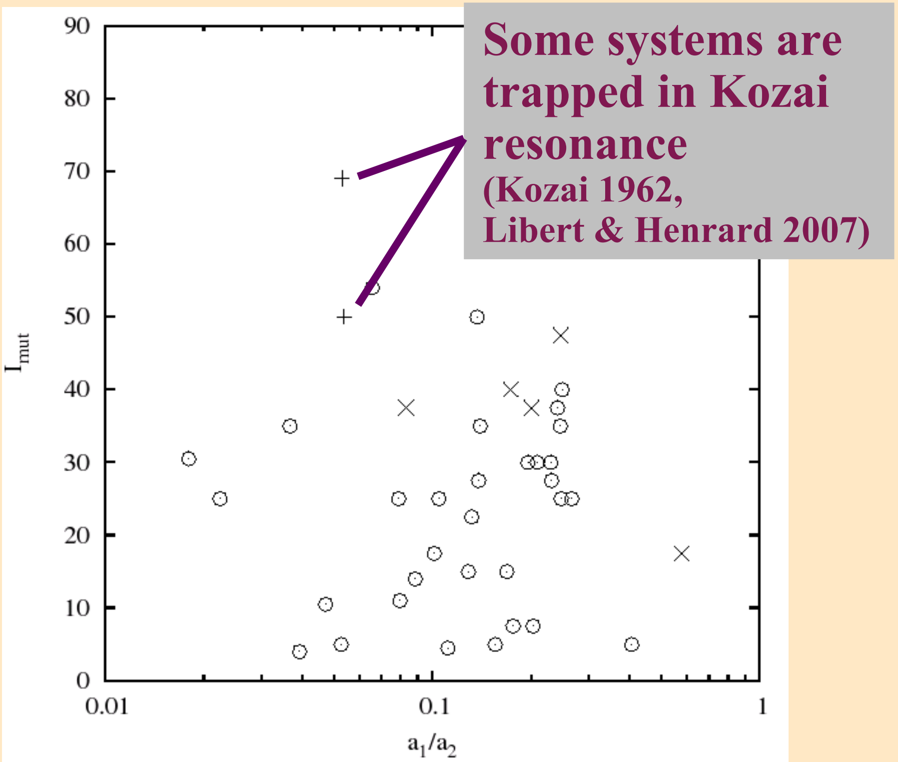

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Conclusion

Formation of highly non-coplanar systems:

- Resonant inclination excitation is a usual outcome for high order resonances observed for all configurations as long as
  (i) the inner planet is not very massive
  (ii) at least one of the planets develops an eccentricity $e > 0.4$.

- Three planets can be trapped in multiple resonance
  - Increase of the eccentricities
  - Unstable configuration
  - Planet-planet scattering, possible formation of non-coplanar systems

In order to confirm these results, hydrodynamical simulations are currently performed in collaboration with the Nice Observatory

Work in progress


Thank you for your attention