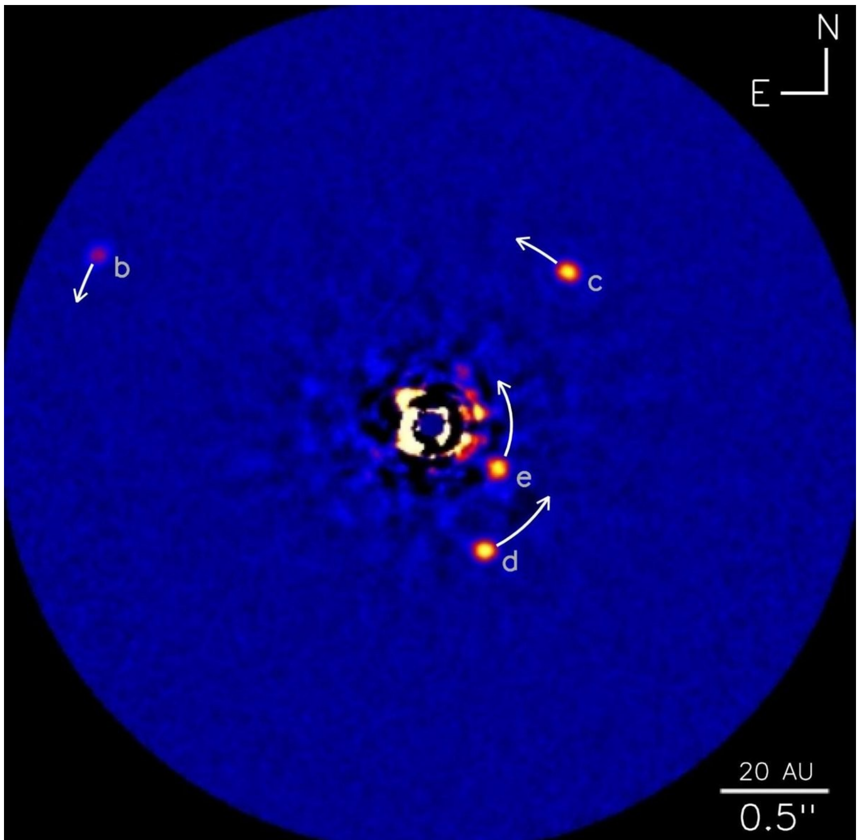
EXOPLANETS: Resonant chains & Apsidal Corotations



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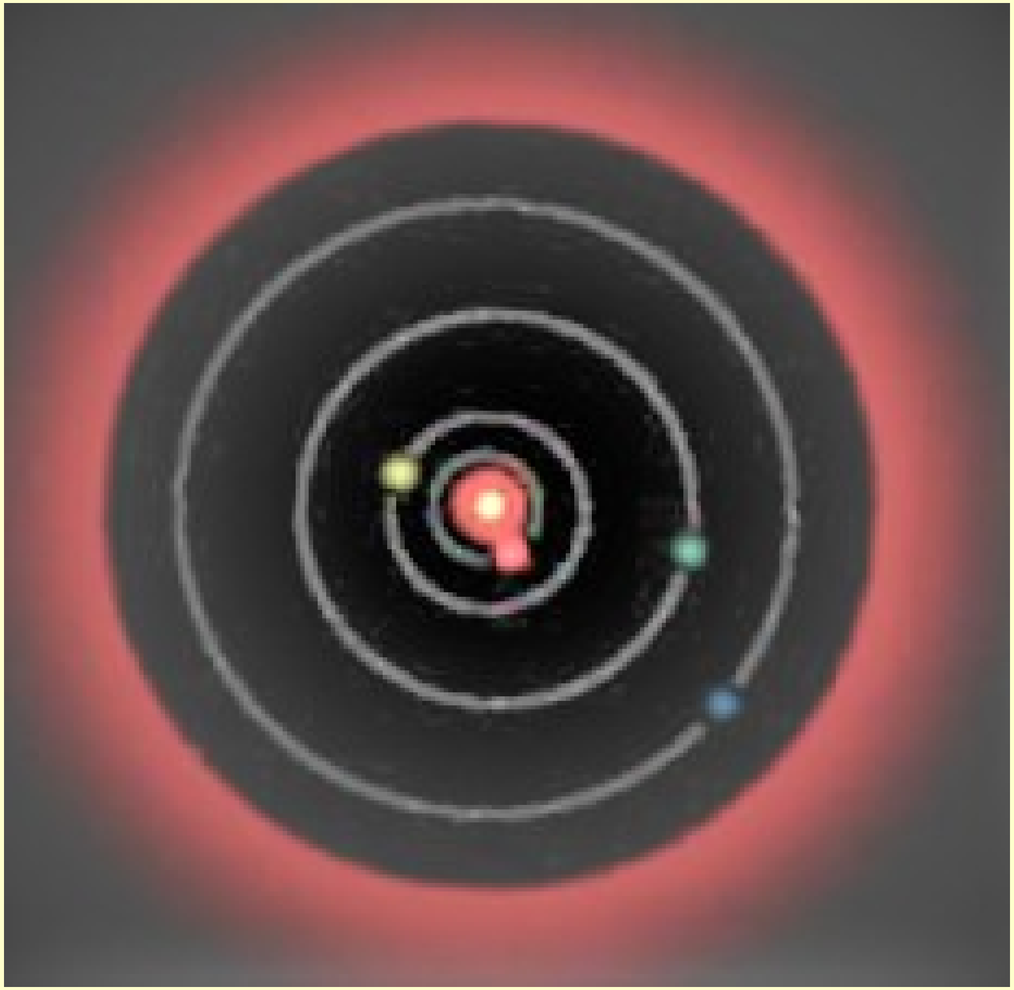
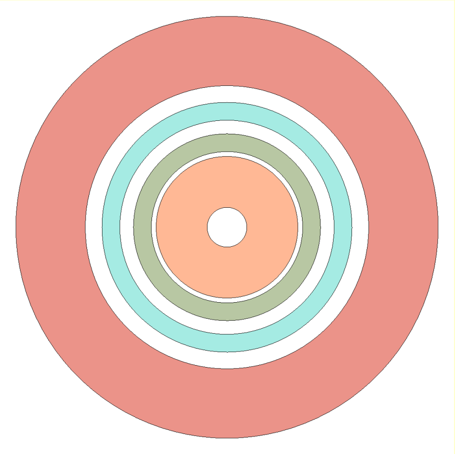
SOLAR SYSTEM ARCHITECTURE AND STABILITY



AGE
5 BILLION
YEARS

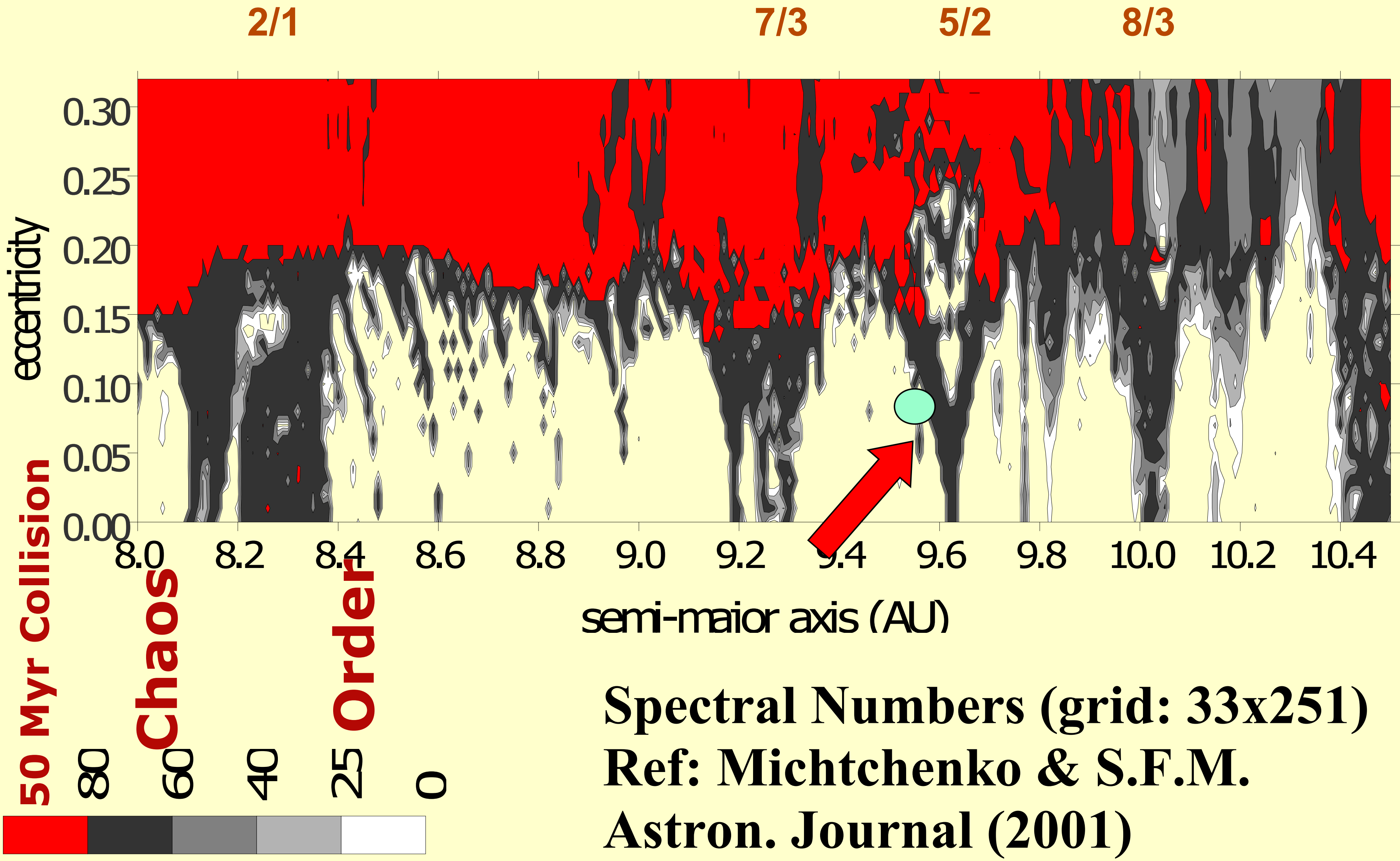


OUTER PLANETS PERIODS

		(k/k')
JUPITER	P=5.20 yr	
		} 2/5
SATURN	P=9.58	
		} 1/2
URANUS	P=19.20	
		} 2/3
NEPTUNE	P=30.05	

$$kn-k'n' \begin{cases} 0.41 \text{ deg/yr} \\ 0.63 \\ 0.08 \quad \text{resp.} \end{cases}$$

Solar System with Saturn initialized on a grid of different initial conditions



Spectral Numbers (grid: 33x251)
Ref: Michtchenko & S.F.M.
Astron. Journal (2001)

EXOPLANETS

K2-138

		(k/k')	2n-3n'
I	P=2.3531 days		
		} 2/3	2.613 deg/d
II	P=3.5600		
		} 2/3	2.482
III	P=5.4048		
		} 2/3	2.487
IV	P=8.2616		
		} 2/3	2.496
V	P=12.7576		

This system is very close to a periodic solution

Resonant chains with 3 or more exoplanets

GJ 876 ([illegible])	4 (1+3)	[2:1],[2:1]	(*)
HD 158259	5	[3:2],[3:2],[3:2],[3:2]	
HR 8799 ([illegible])	4 (1+3)	[2:1],[2:1]	(*)
Kepler-60	3	[4:3],[5:4]	(*)
Kepler-80	5 (1+4)	[3:2],[3:2],[4:3]	(*)
Kepler-90 (duas cadeias)	8 (3+5)	[5:4],[5:3]	
		[3:2],[4:3],[3:2],[11:7]	
Kepler-223	4	[4:3],[3:2],[4:3]	
K2-138	6 (5+1)	[3:2],[3:2],[3:2],[3:2]	(*)
TOI-178 ([illegible])	6 (1+5)	[2:1],[3:2],[3:2],[4:3]	(*)
Trappist-1	7 (6+1)	[8:5],[5:3],[3:2],[3:2],[4:3]	(*)
V 1298 Tauri	4 (1+3)	[3:2],[2:1]	

(*) with known masses

EXOPLANETS

GJ-876

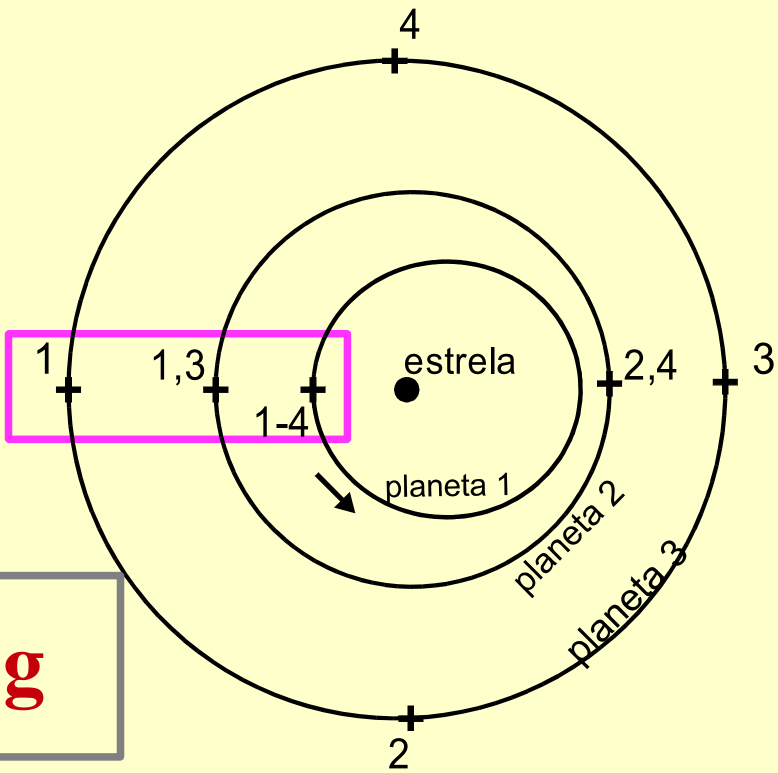
(k/k')

I	P=1.94 days		m=0.02 Mjupiter
II	P=30.097	} 1/2	m=0.83
III	P=61.106	} 1/2	m=2.66
IV	P=123.83		m=0.05

Laplacian Resonance $n_1 - 3n_2 + 2n_3 = 0$

PERIODIC SOLUTION named after DE SITTER (Kaptein Lab Groningen, 1907)

???



$$\lambda_1 - 3\lambda_2 + 2\lambda_3 = -7\text{deg}$$

different from Laplace's solution

Ref:

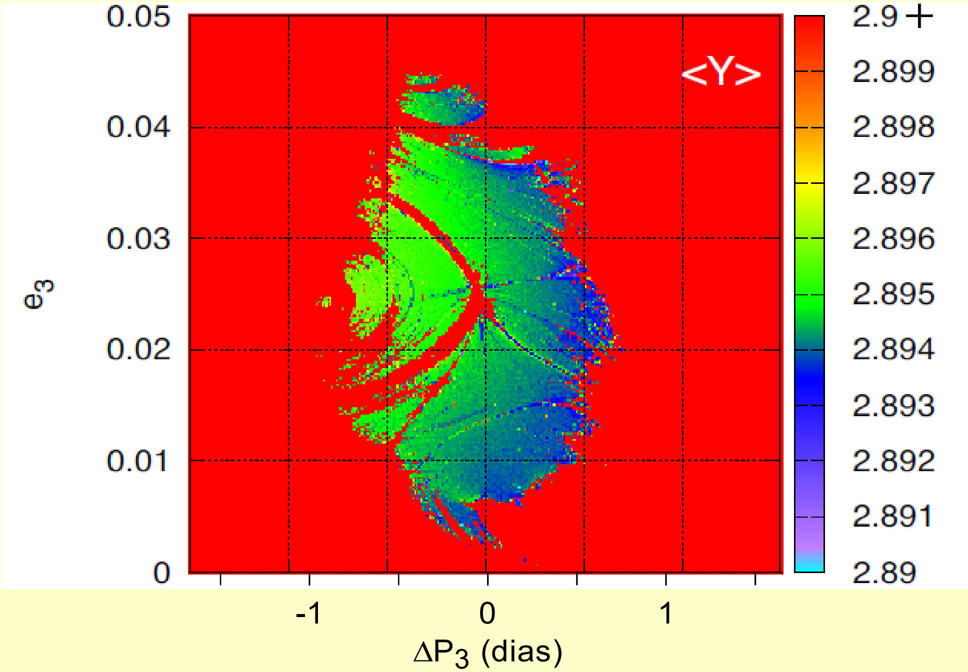
Broer, H., Hanssmann, H., Discr.Cont.Dyn.Syst. (2020)

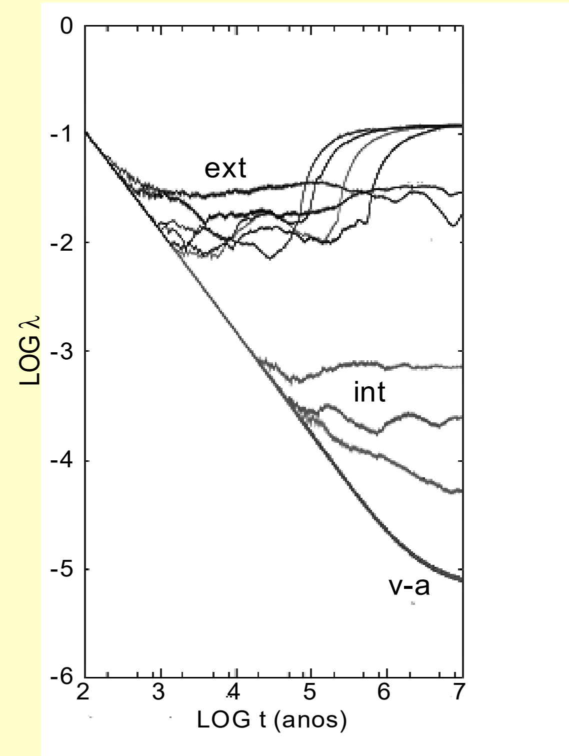
A. Celletti et al. Celest. Mech. Dyn. Astron. (2018) 130:15

G.Pucacco, Cel. Mech, Dyn, Astron, (2021) 133:11

Lyapunov

Dynamical Map with MEGNO



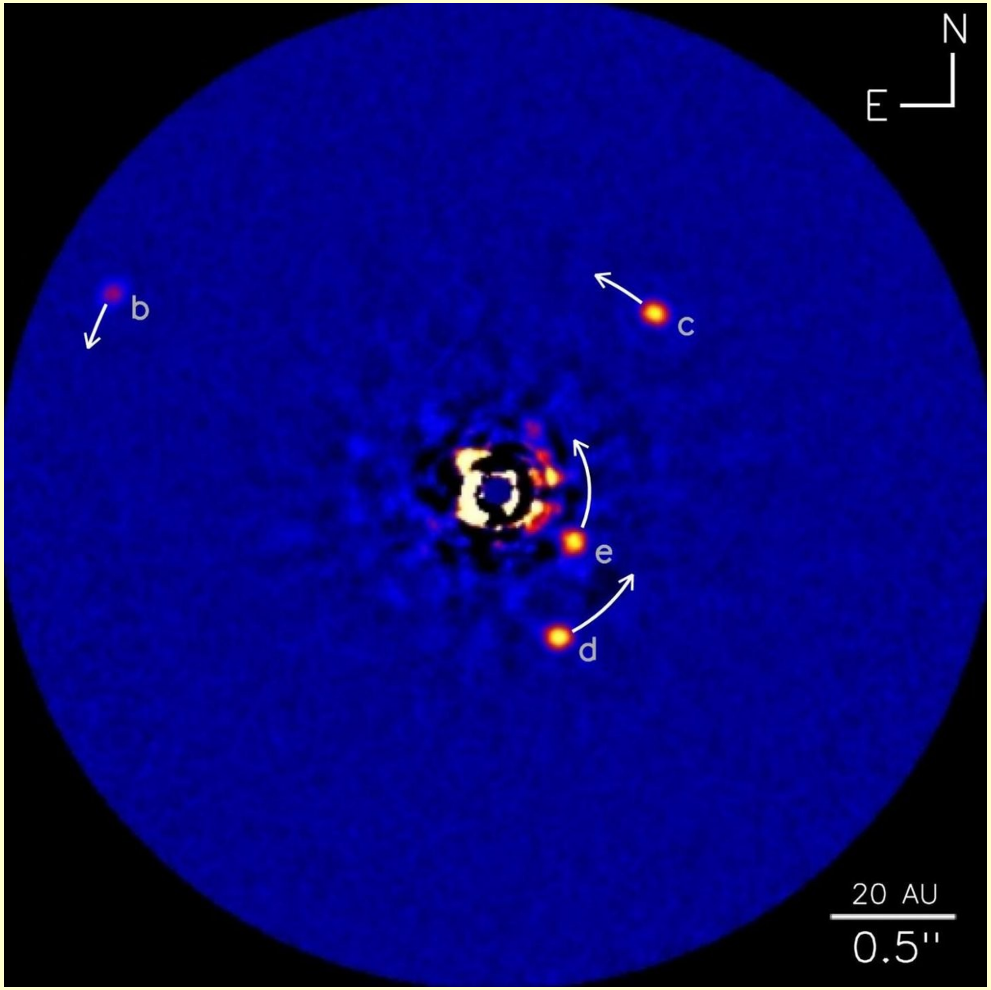


Ref: Martí, J.G., Cincotta, P.M., Beaugé, C.: Chaotic diffusion in the Gliese-876 planetary system. Mon. Not. R. Astron. Soc. 460, 1094–1105 (2016)

N.B. DP_3~2 days

HR 8799

Age 30 Myrs



EXOPLANETS

HR 8799

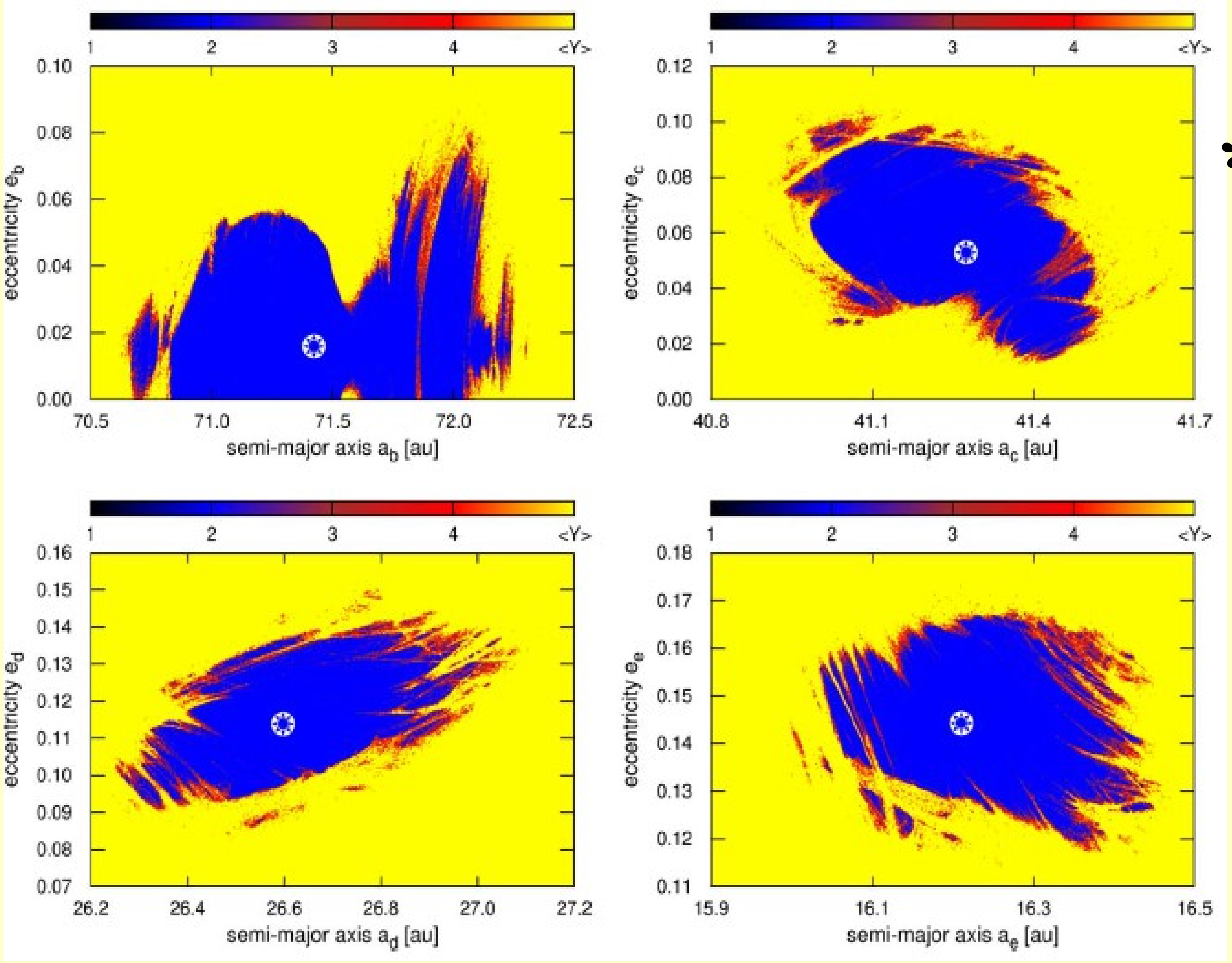
(k/k')

I	P=42 years		m ~ 7 Mjup
		}~½	
II	P=101		m ~ 9.2
		}~½	
III	P=205		m ~ 8.3
		}~½	
IV	P=431		m ~ 8.3

(Fabricky et al. coplanar model)

(Gozdziewski & Migaszewski

Dynamical maps with near-periodic solution of the 1+4-body problem (Gozdziewski and Migaszewski Astrophys.J.Lett. 902:L40)



* constrained best-fit

(MEGNO)

EXOPLANETS

TOI-178 (Tess)

(A compact system of super-Earths)

Planet	Period	(k/k')	kn-k'n'
I	P=1.91456 days		
		3/5	
II	P=3.23845		
		1/2	1.473
III	P=6.5577		
		2/3	1.381
IV	P=9.9619		
		2/3	1.372
V	P=15.2319		
		3/4	1.370
VI	P=20.7095		

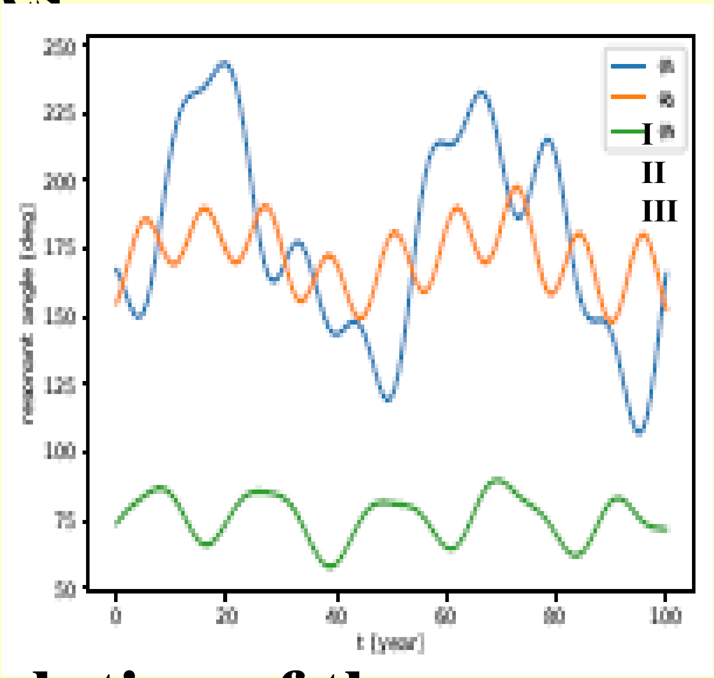
Masses: 4 to 8 earth

Planets II to VI - Chain of 3 Laplacian Resonances

I) $n_2 - 3n_3 + 2n_4 = 0$

II) $2n_3 - 5n_4 + 3n_5 = 0$

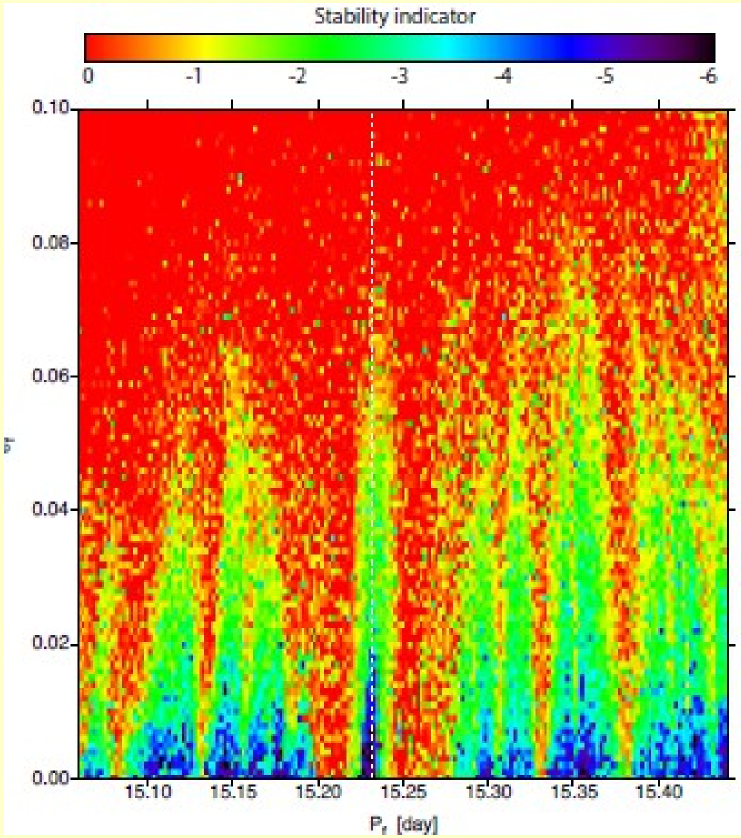
III) (2x) $(n_1 - 3n_2 + 2n_3) = 0$

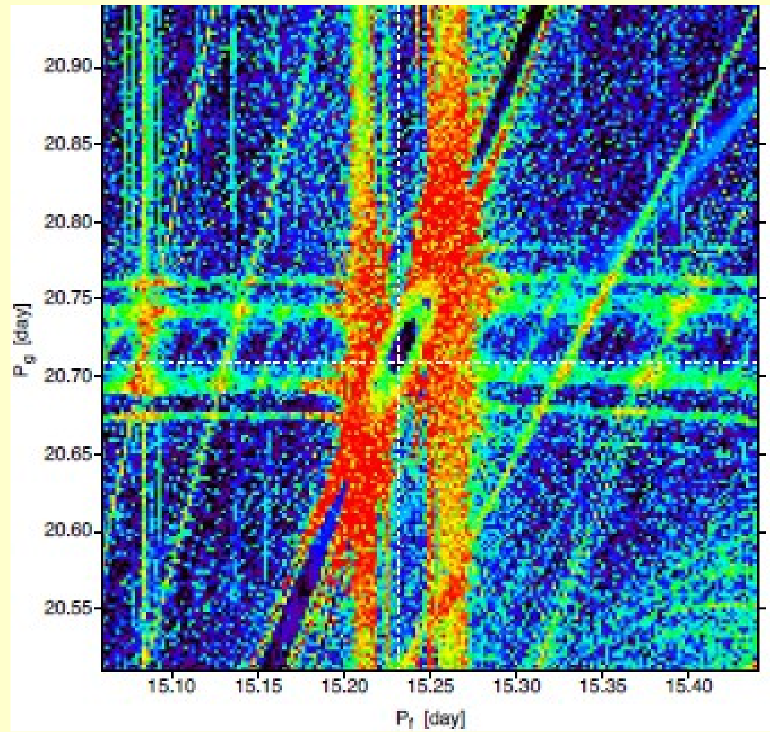


Evolution of the corresponding angles in simulations using initial conditions & masses as determined from the observations

Ref: Leleu, A., et al.
Six transiting planets and a chain of Laplace resonances in TOI-178. Astron. Astrophys, (2021).

FREQUENCY MAP analyses of the TOI-178 resonances





P_5 vs. e_5 **P_5 vs P_6**

Leleu et al. 2021 (+IMCCE)

APSIDAL COROTATION RESONANCES
Periodic solutions of the planetary 3-body problem with e > 0

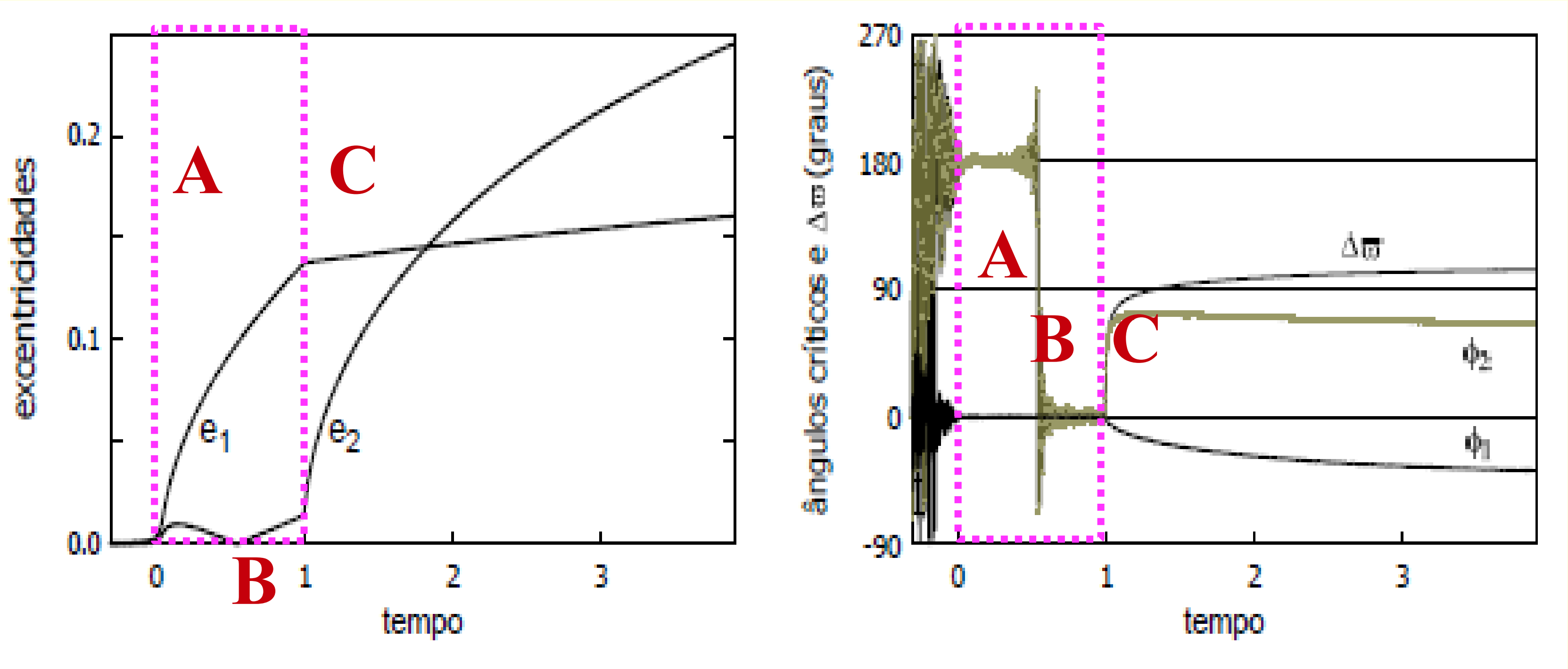
APPROACHES

1) **Periodic Orbits of the 1+2 problem –**
   John Hadjidemetriou and Thessaloniki school

2) **Numerical constructions with an ad-hoc dissipation**
   S. Ferraz-Mello @ São Paulo

3) **Equilibrum solutions of the averaged Hamiltonian**
   Cristian Beaugé (Cordoba, Argentina) and
   Tatiana A.Michtchenko (São Paulo)

Resonance 2:1 - Numerical constructions with an ad-hoc dissipation pushing the inner orbit outwards (convergent migration)



Events: A... it reaches the PO close neighborhhod.

B... the pericenter of P_2 changes of side.

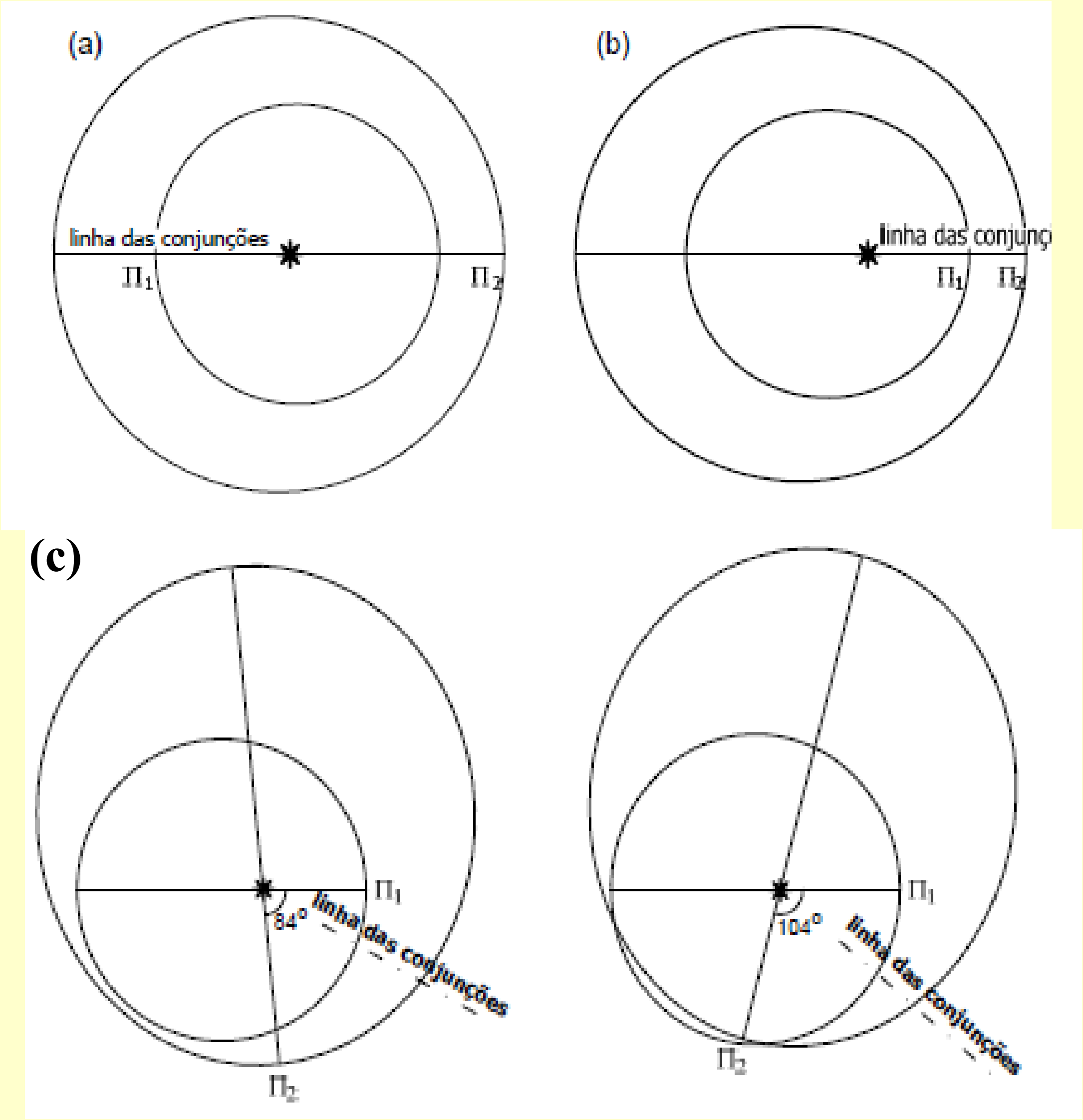
C... the PO becomes asymmetric

Critical angles: $\phi_j = \lambda_1 - 2\lambda_2 + \varpi_j$

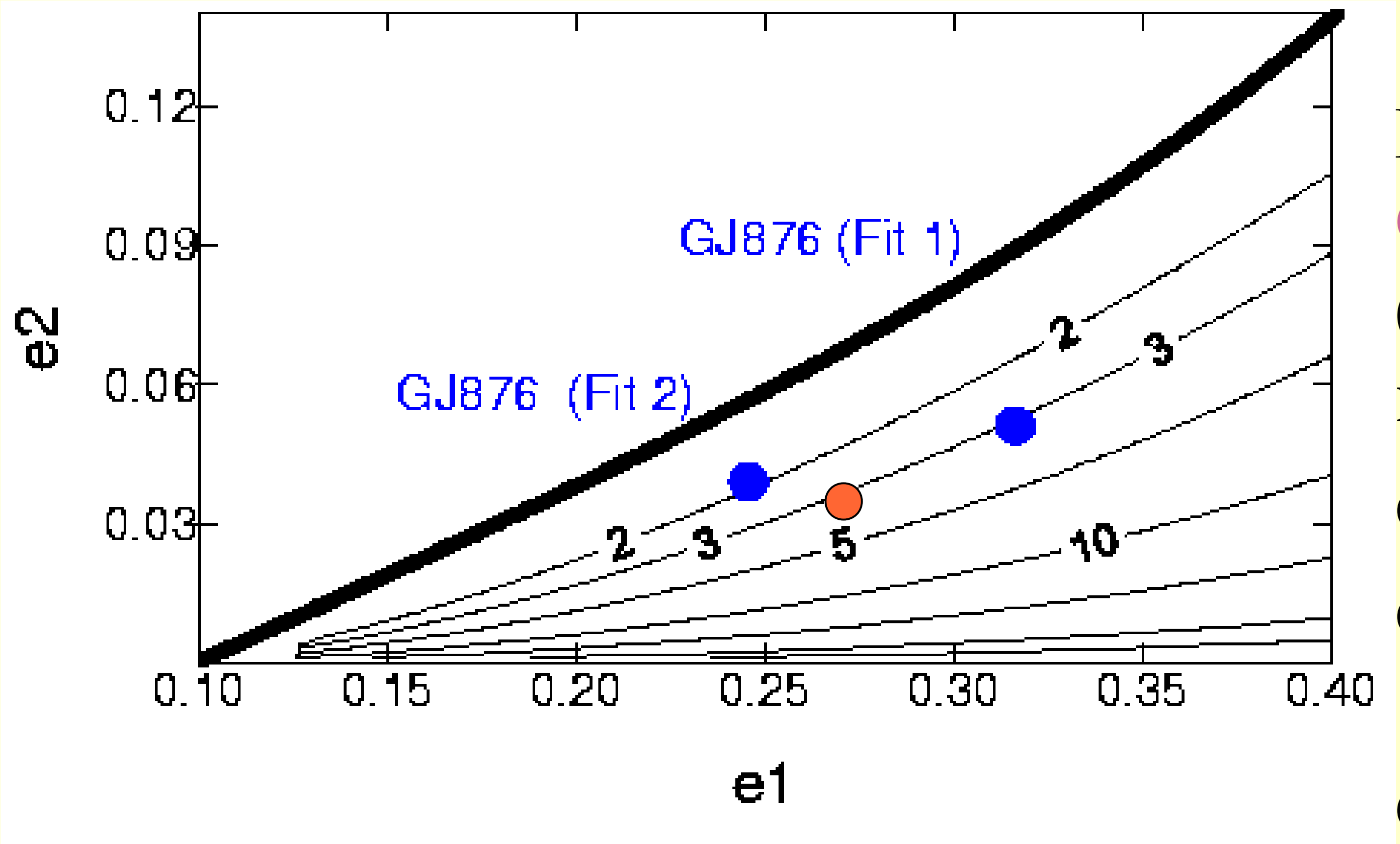
Ref: Ferraz-Mello, Beaugé and Michtchenko, CeMDA 87, 99 (2003)

Symetric 2/1ACR

Assymetric 2/1 ACR



Locus of Stable stationary solutions with aligned periastra for different mass ratios



Ex: ● GJ 876 (II,III)

$m_2/m_1=3.02$

$e_1=0.03$

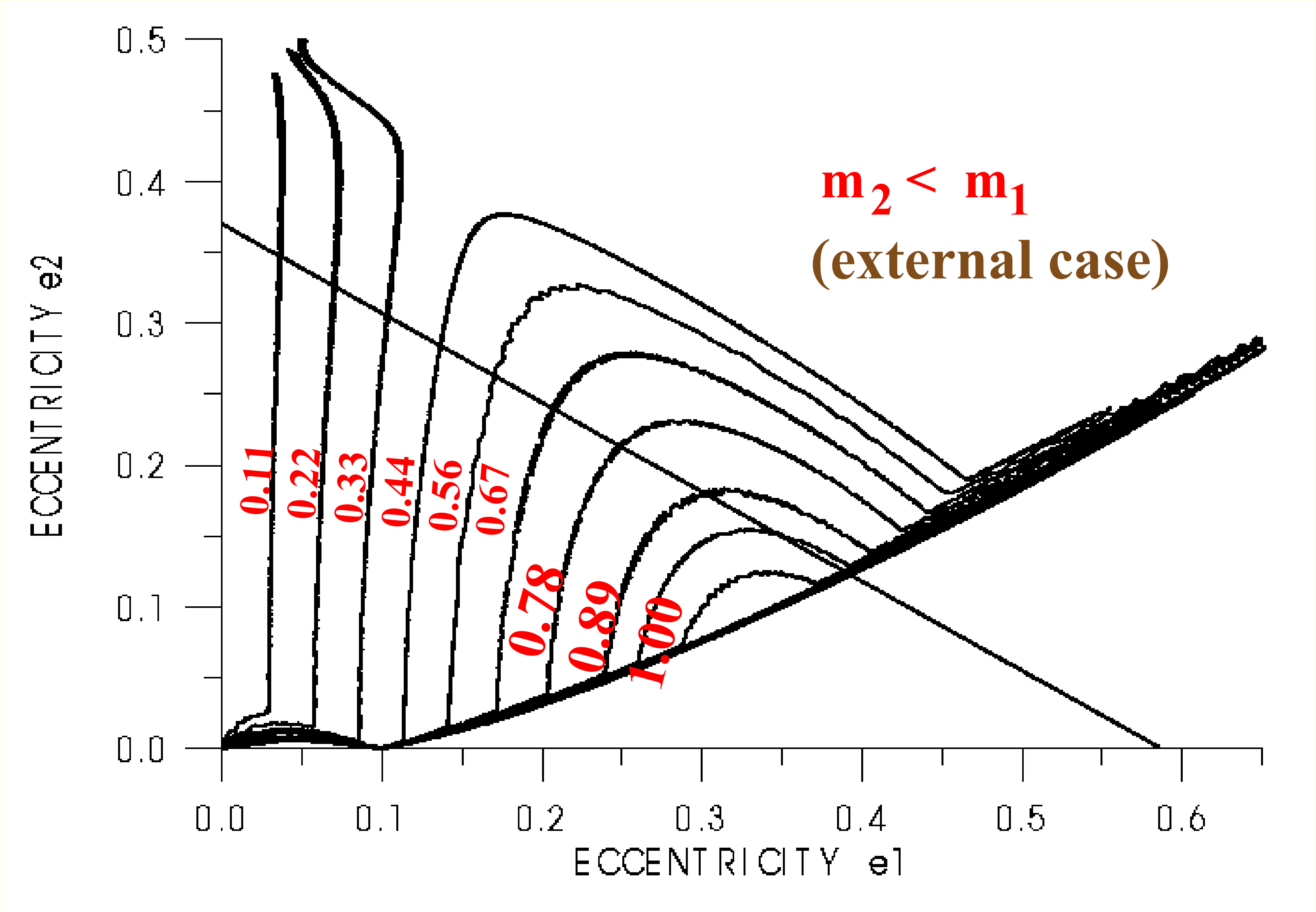
$e_2=0.27$

● old determ.

Mass ratios $m_2/m_1 > 1$ (so-called "internal case")

Ref: Beaugé et al. (2003) Astrophys. J.

Stable asymmetric solutions. 2/1 resonance



Ref: SFM, Beaugé & Michtchenko, Cel. Mech. Dyn. Astron. (2003)

3/1 ACR

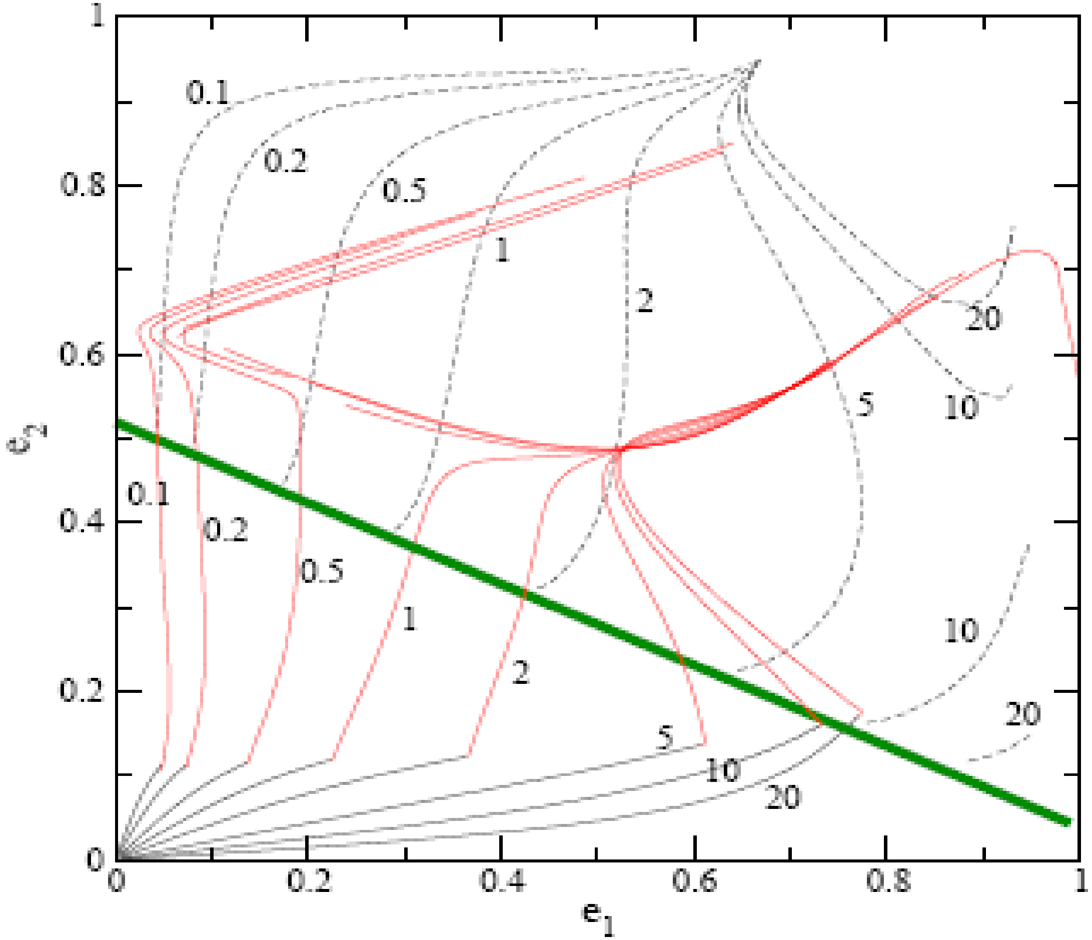
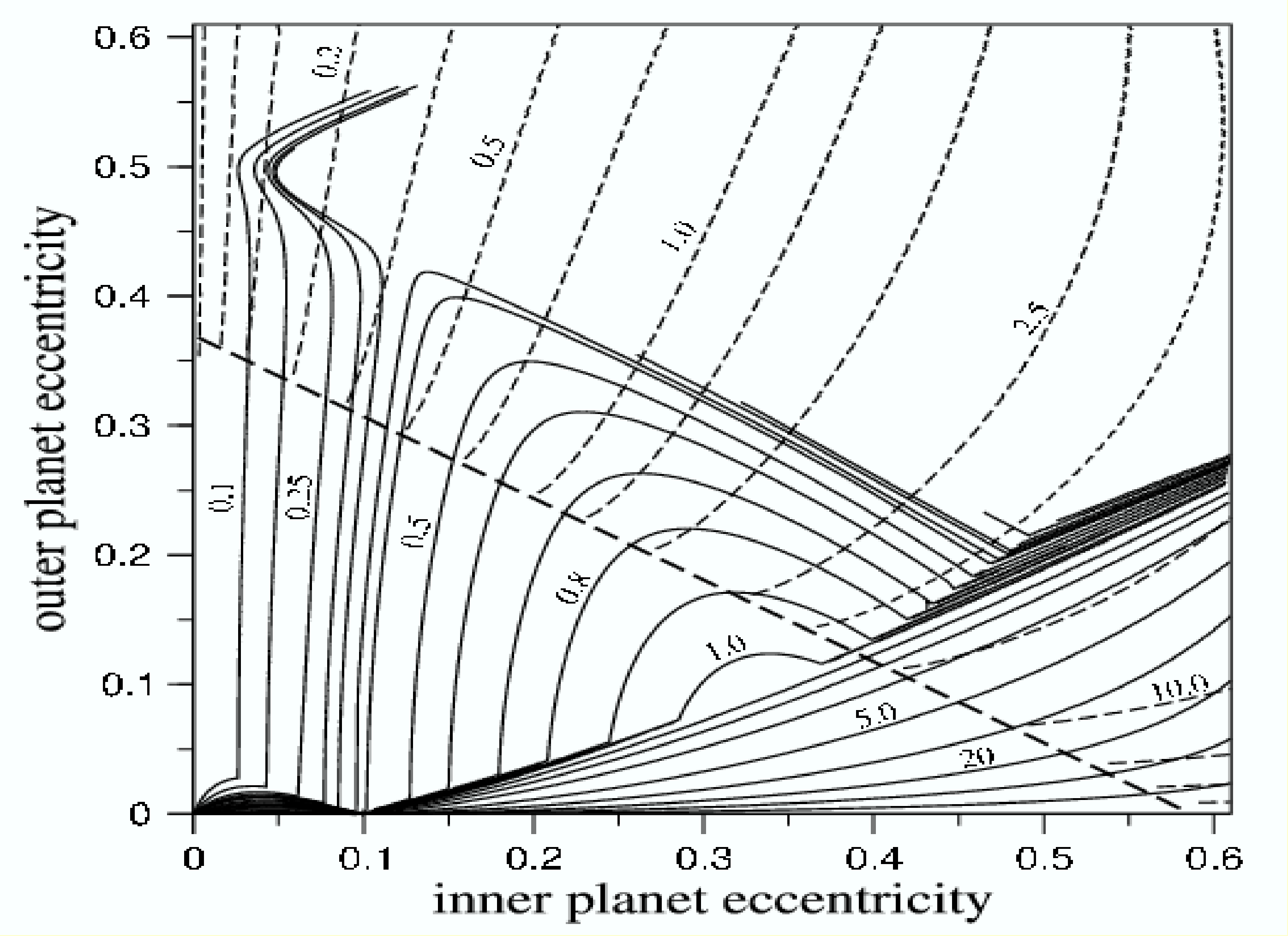


Figure 10. Families of symmetric and asymmetric apsidal corotations for the 3/1 MMR in the plane (e_1, e_2). Black continuous lines correspond to $(0, \pi)$ solutions, red to asymmetric corotations, and broken black to (π, π). The broad green dotted curve are points of possible collisions between the planets.

Ref. T.A.Michtchenko et al. (2006) CeMDA

end

THANKS EVERYBODY!



Ref. T.A.Michtchenko et al. (2006) CeMDA
2/1 planetary ACR

JUPITER'S GIANT SATELLITES
(GALILEAN SATELLITES)

		(k/k')	n−2n'
I	P= 1.77 days		
		} 1/2	0.740^0/d
II	P= 3.55		
		} 1/2	0.739^0/d
III	P= 7.15		
IV	P=16.7		

$$n_1 - 3n_2 + 2n_3 = 0$$

Laplacian Resonance

$$n_1 - 3n_2 + 2n_3 = 0$$

$$\lambda_1 - 3\lambda_2 + 2\lambda_3 \sim \pi$$