Planets in Resonances
- Capture through Migration -

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Exoplanets: Statistics

- Total: 120 (March, 2004)
- Systems with 2 or more planets: 12
- 1 Transiting Planet (HD 209458)
- OGLE Candidates: 3 (TR-3, TR-10, TR-56)
- Planetary Systems in Binaries: 15
- Planetary Systems in Mean Motion Resonance: 3

Resonant Systems

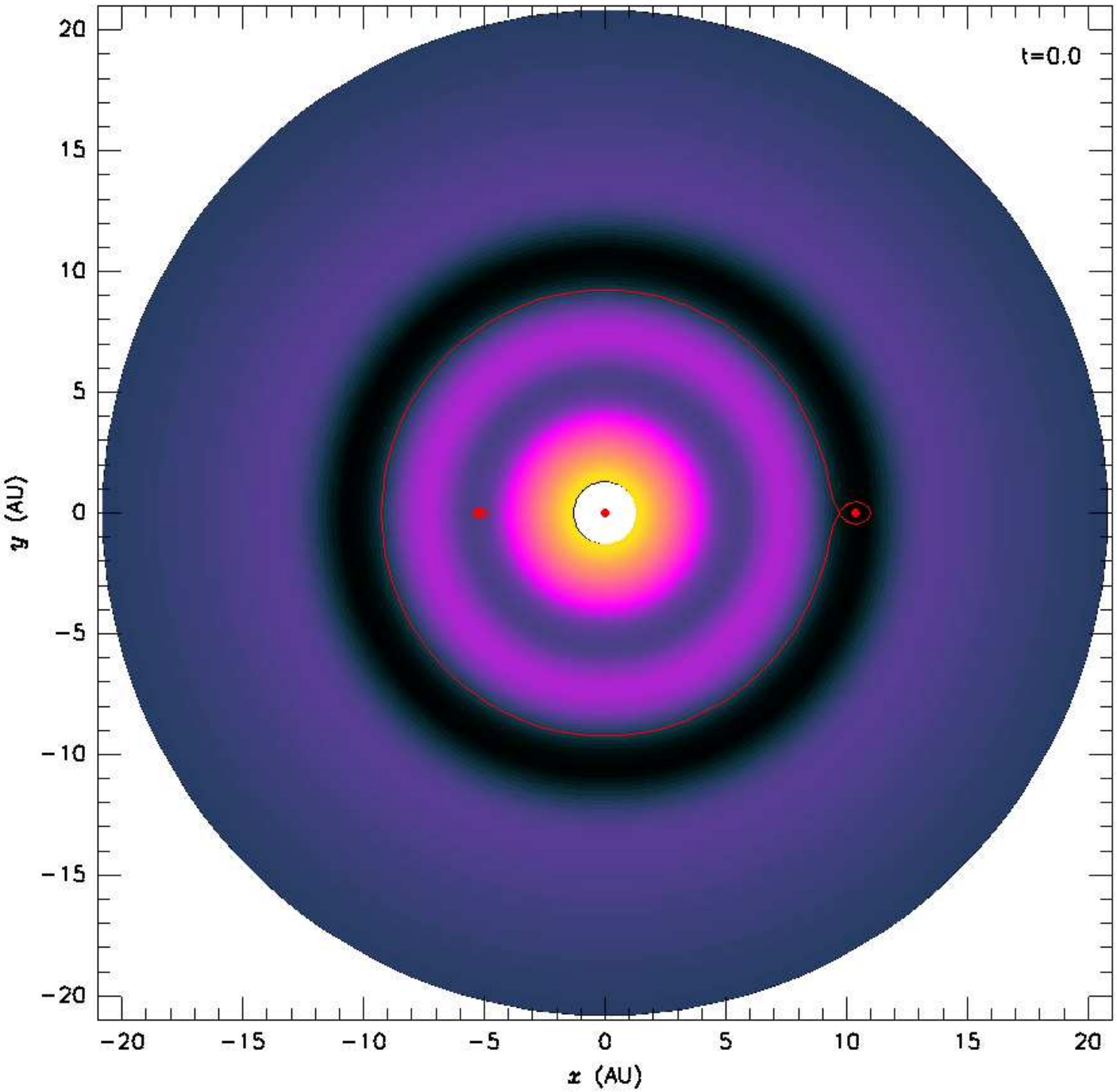
Total: 120 Planets Systems: 12 Resonant: 3

System	No	P [d]	$M \sin i$ [M_{Jup}]	a [AU]	e	ϖ [deg]	M_* [$M_\odot$]
GJ 876	c	30.57	0.56	0.13	0.24	159	0.32
(2:1)	b	60.13	1.89	0.21	0.04	163	
HD 82943	b	221.6	0.88	0.73	0.54	138	1.05
Oct. 2003		219.4	1.85	0.75	0.38	124	
(2:1)	c	444.6	1.63	1.16	0.41	96	
		435.1	1.84	1.18	0.18	237	
55 Cnc	b	14.65	0.84	0.11	0.02	99	0.95
(3:1)	c	44.26	0.21	0.24	0.34	61	
	d	5360	4.05	5.9	0.16	201	

Theoretical Modeling I

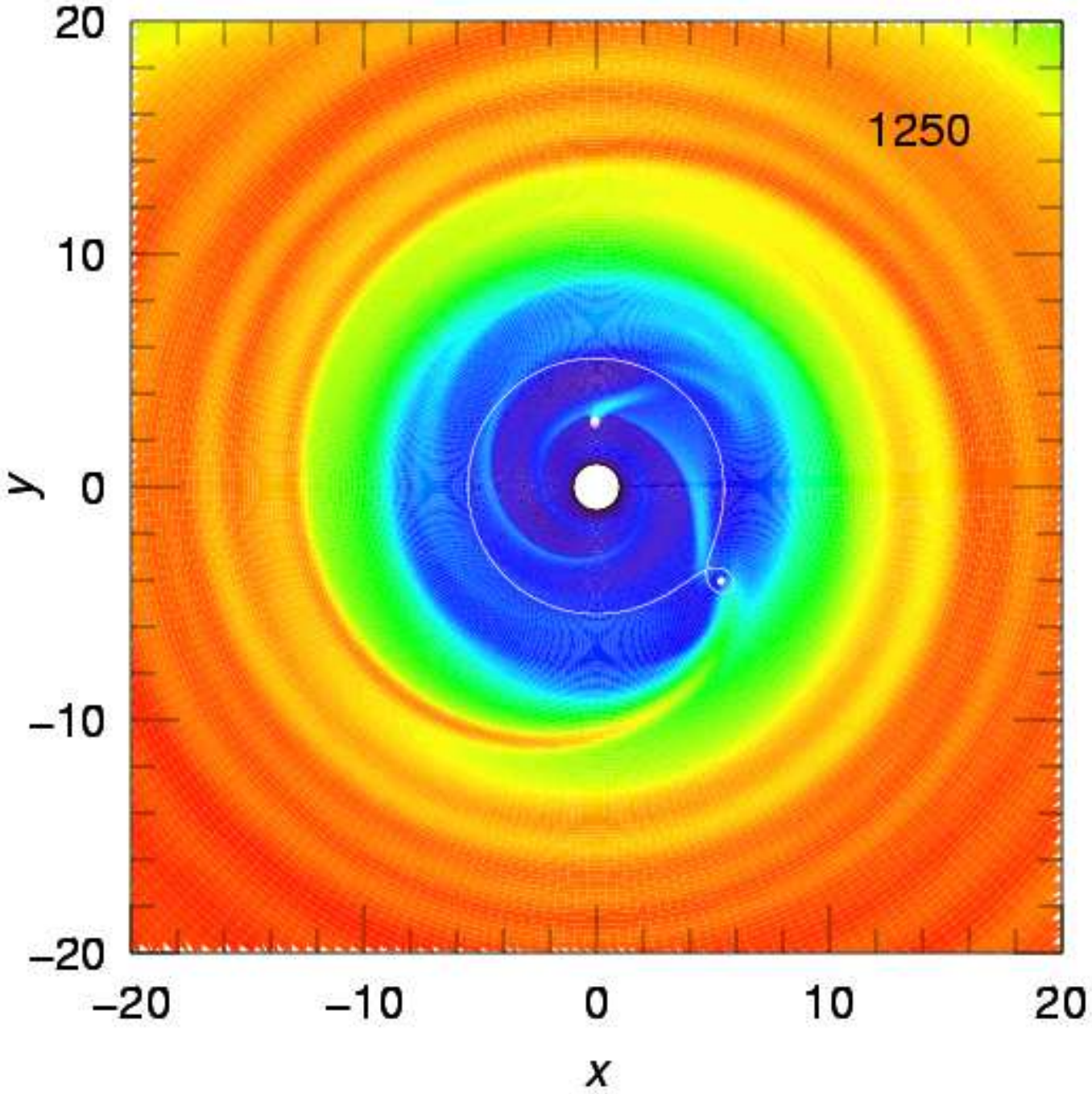
- Hydrodynamic evolution of 2 embedded planet in a disk
- Flat disk (in r-φ-plane): 2D-Hydro, and 3-body problem
- Include full gravitational effect of disk onto all objects
- No disk self-gravity
- Disk: $\Sigma(r) \propto r^{-1/2}$, $\alpha = 10^{-3} - 10^{-2}$, H/r = 0.05 - 0.10
- Planets: eg. $1 M_{Jup}$ at 4 and 10 AU, around $1 M_{\odot}$ star
  – can grow in mass
- Integration time: $\approx 10^4$ planetary orbits

Initial Model



Axisymmetric
Initial Gaps

Global Evolution of the System



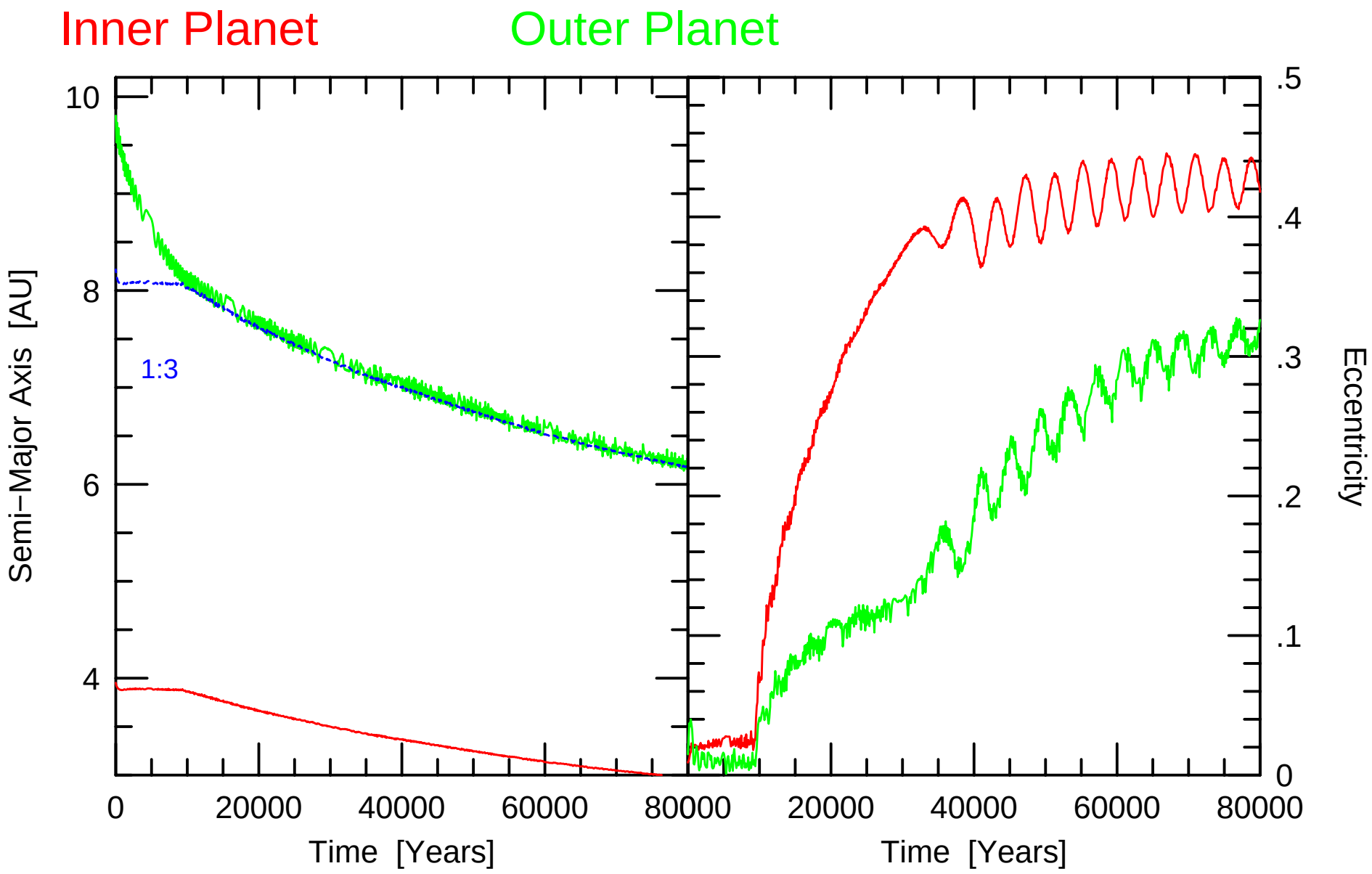
Inner Cavity:
$M_{out} > M_{in}$

Outer Planet:
Inward Migration

Inner Planet:
Stalled

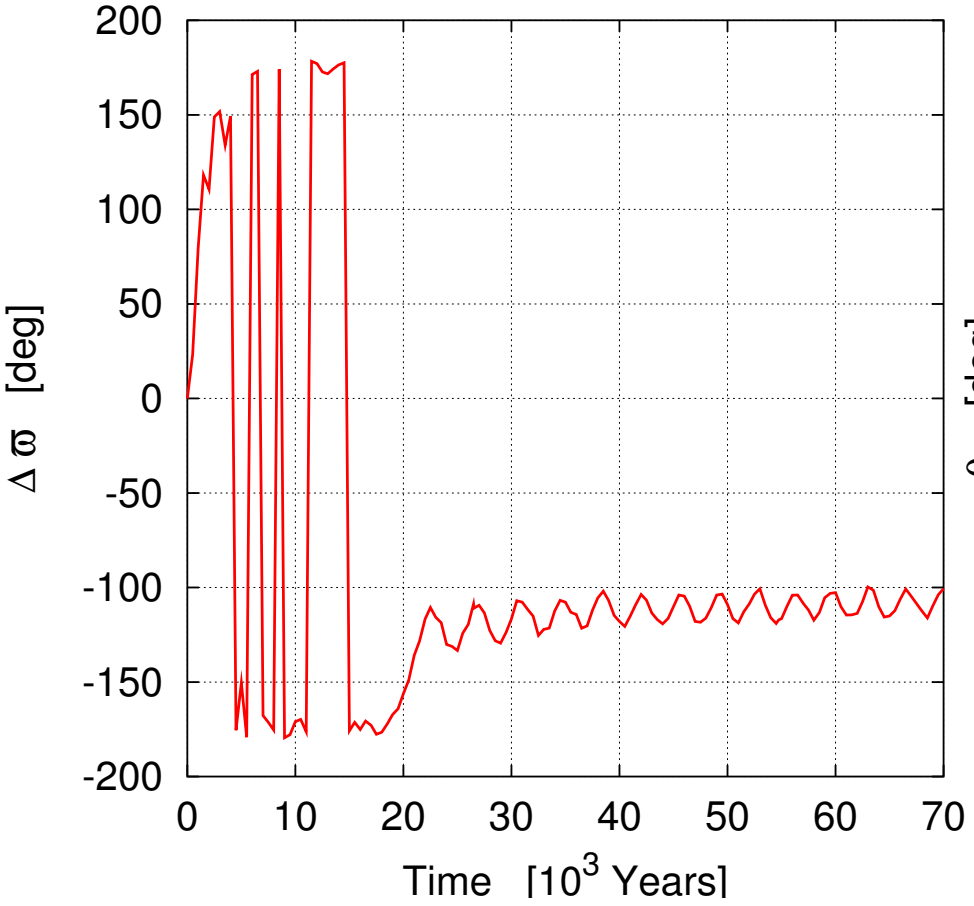
Resonant capture

Sample: Capture in 3:1

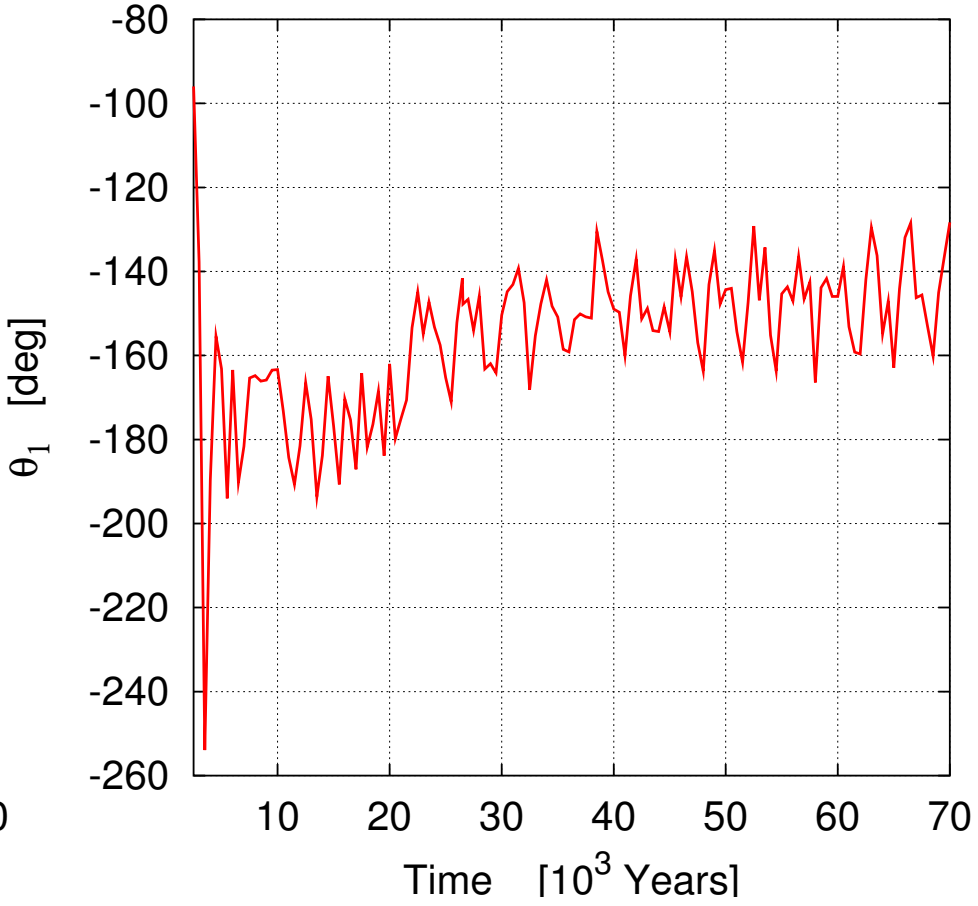


Resonant Angles

$\Delta\varpi = \varpi_2 - \varpi_1$ vs. Time



$\Theta_1 = 3\,\lambda_2 - \lambda_1 - \varpi_1$



Non-symmetric configuration (3:1 resonance)

Theoretical Modeling II

Damped N-Body Simulations

NO hydrodynamics

Only gravitational interaction between star and planets

Disk backreaction as damping force

Specify: $\frac{\dot{a}}{a}$ and $\frac{\dot{e}}{e} \longrightarrow$ correction forces (cf. Lee & Peale, 2002)

drive typically outer planet

much faster execution time

$\longrightarrow$ statistics for many models (cf. Nelson & Papaloizou, 2002)

Disadvantage: Parameter not known a priori

Here: Adjust parameter to full hydro-models

Damping Specification

Choose:

$$\frac{\dot{a}}{a} = -\frac{1}{\tau(t)} \quad \text{with} \quad \tau(t) = \tau_0 + \beta t$$

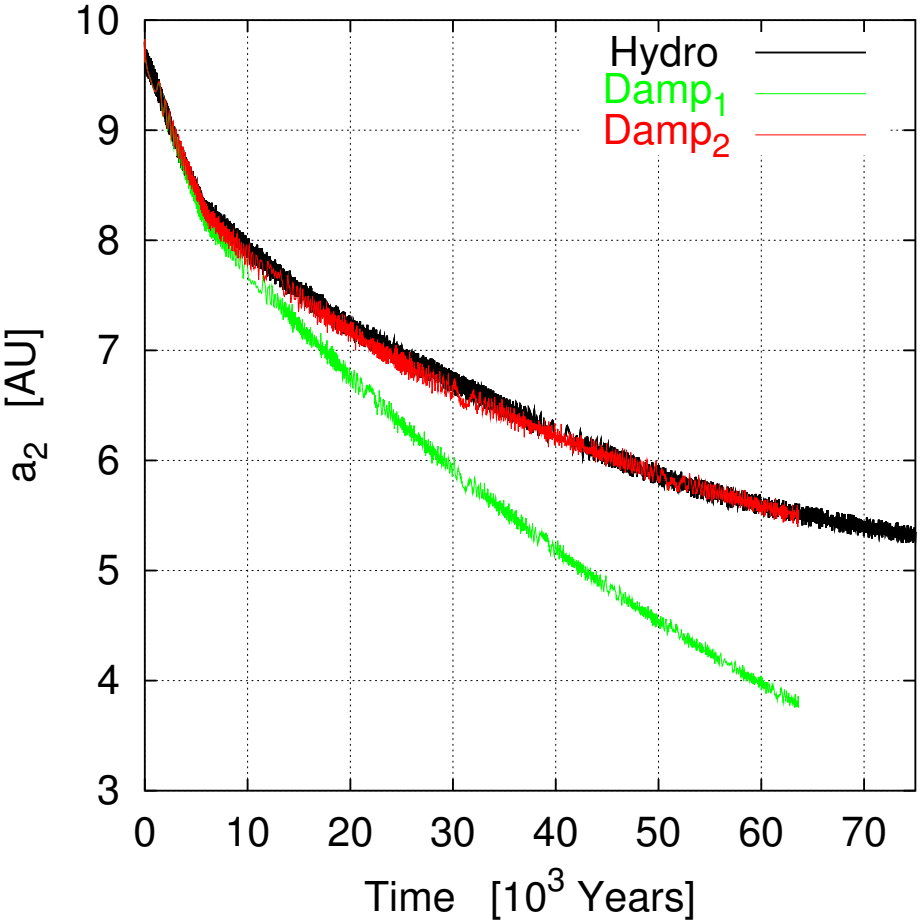
and

$$\frac{\dot{e}}{e} = K\,\frac{\dot{a}}{a} \quad \text{with} \quad K > 0$$

Hydro vs. Damped N-body

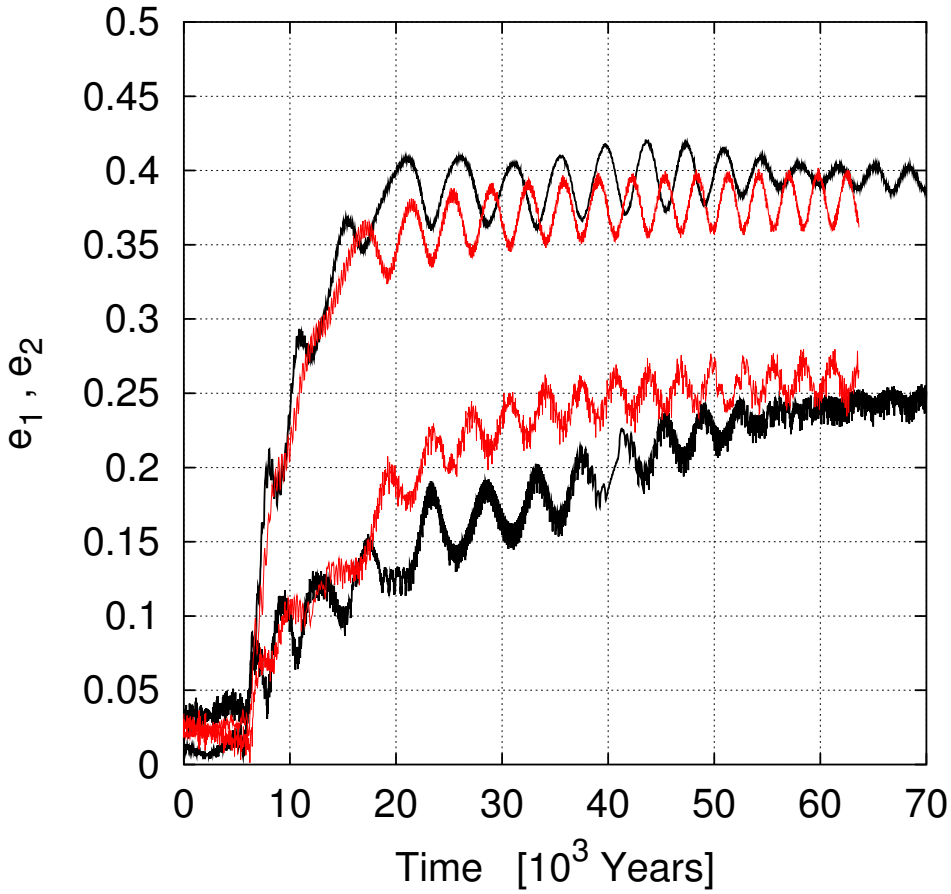
Semi-major Axis vs. Time

β=0, β=1



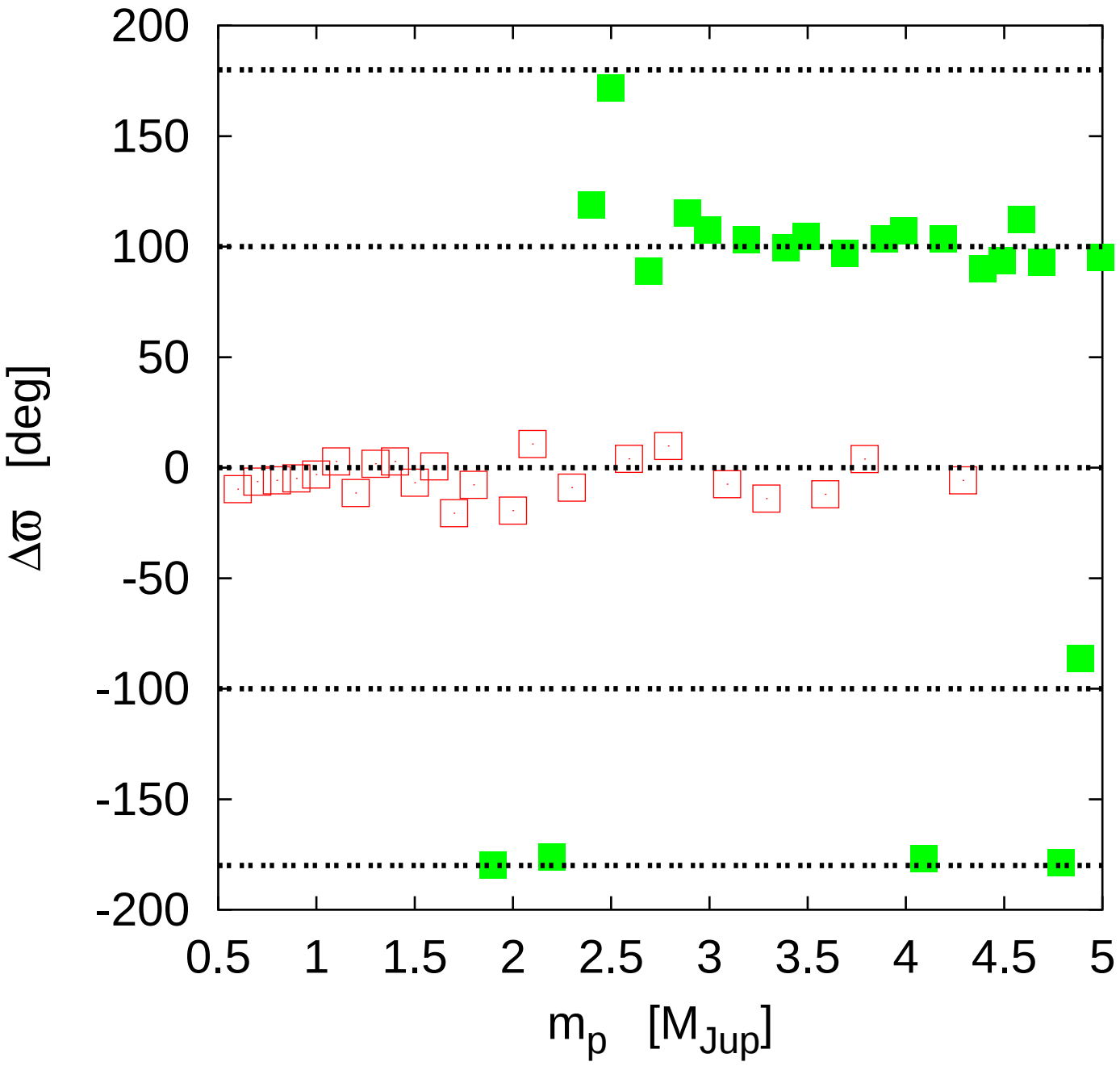
Eccentricity vs. Time

Hydro, K = 3.0



From comparison with hydro: K $\approx \mathcal{O}(1)$ and $\beta \approx \mathcal{O}(1)$

Capture Probabilities



$m_1 = m_2 = m_p$

$\Delta\varpi = \varpi_2 - \varpi_1$

⊡ 2:1 Resonance

$|\Delta\varpi| = 0^o$

Aligned

■ 3:1 Resonance

$|\Delta\varpi| = 180, 100^o$

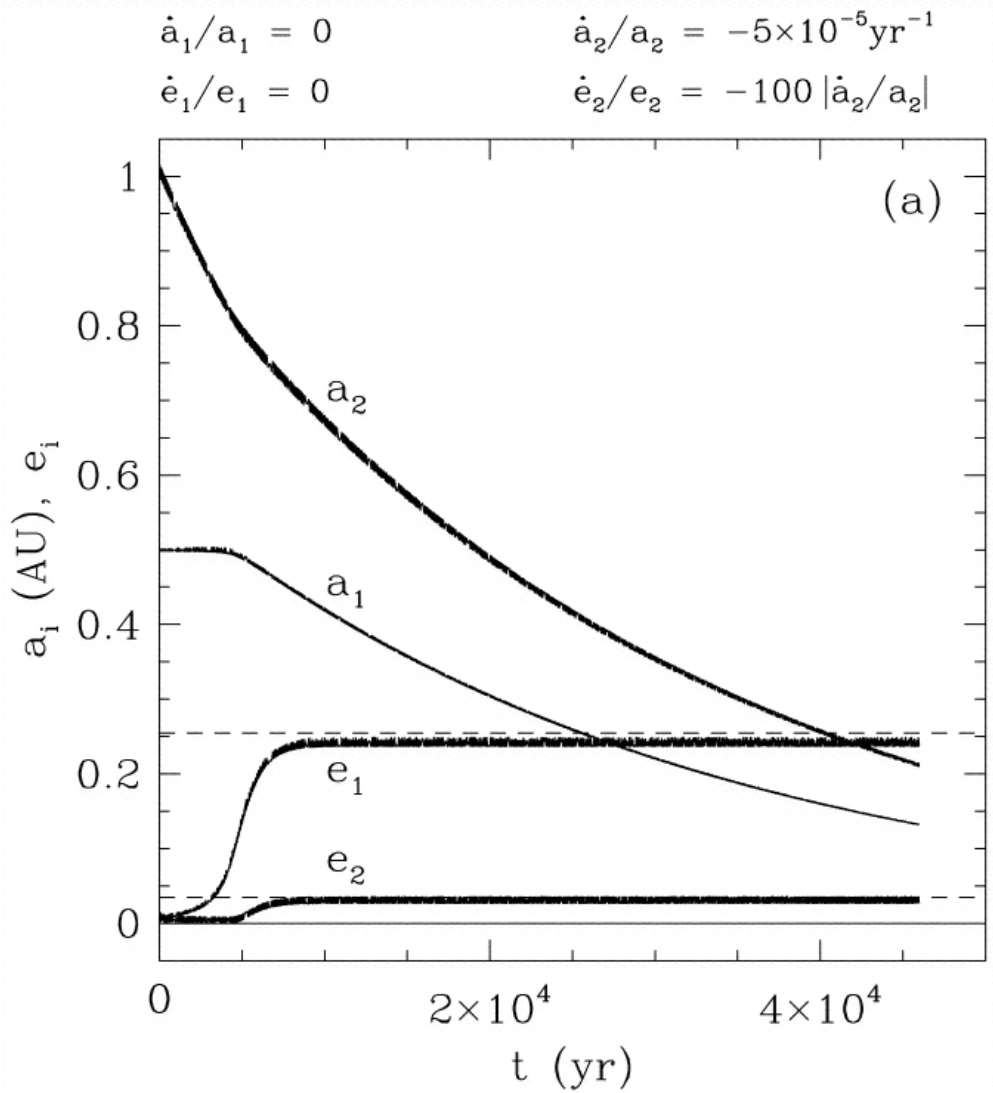
Anti-aligned

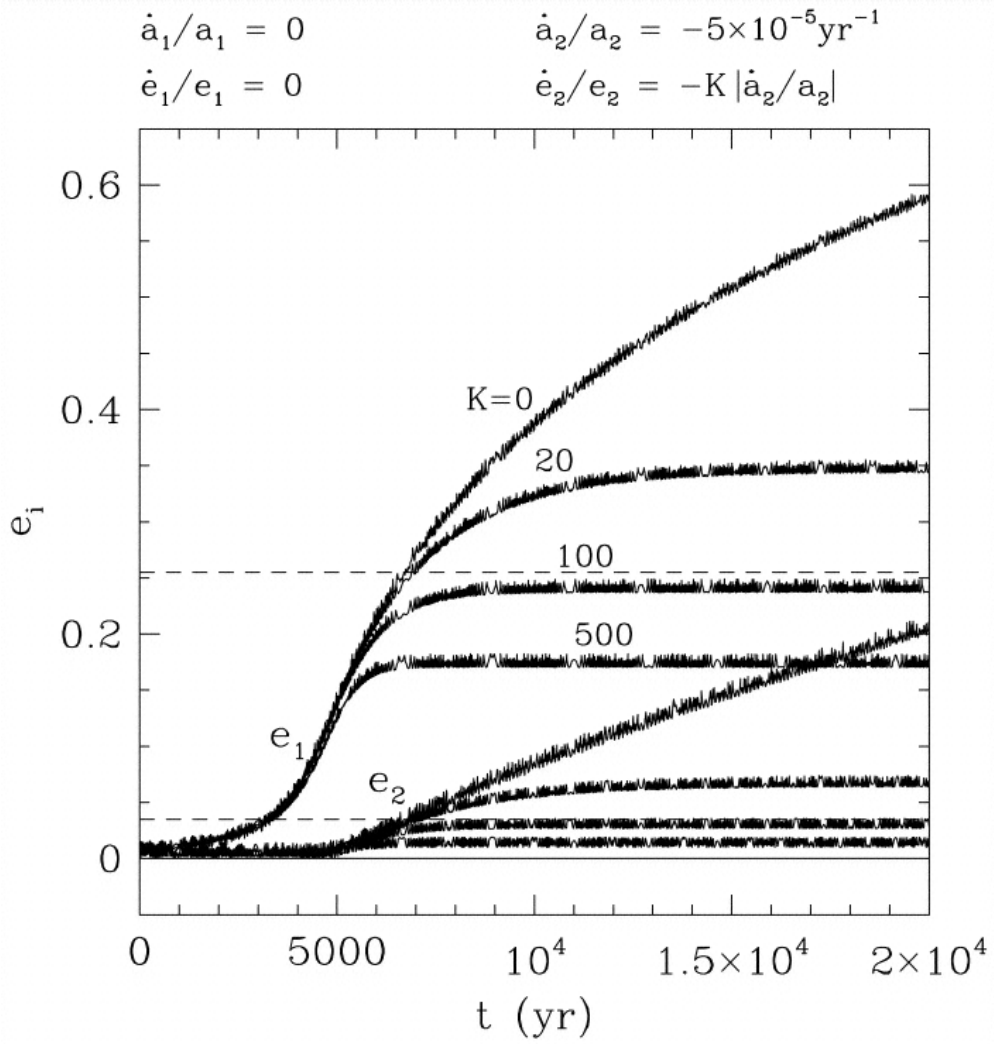
Non-aligned

(Kley, Peitz & Bryden 2004)

Matching GJ 876: I

Using damped N-Body (Lee & Peale, 2002)

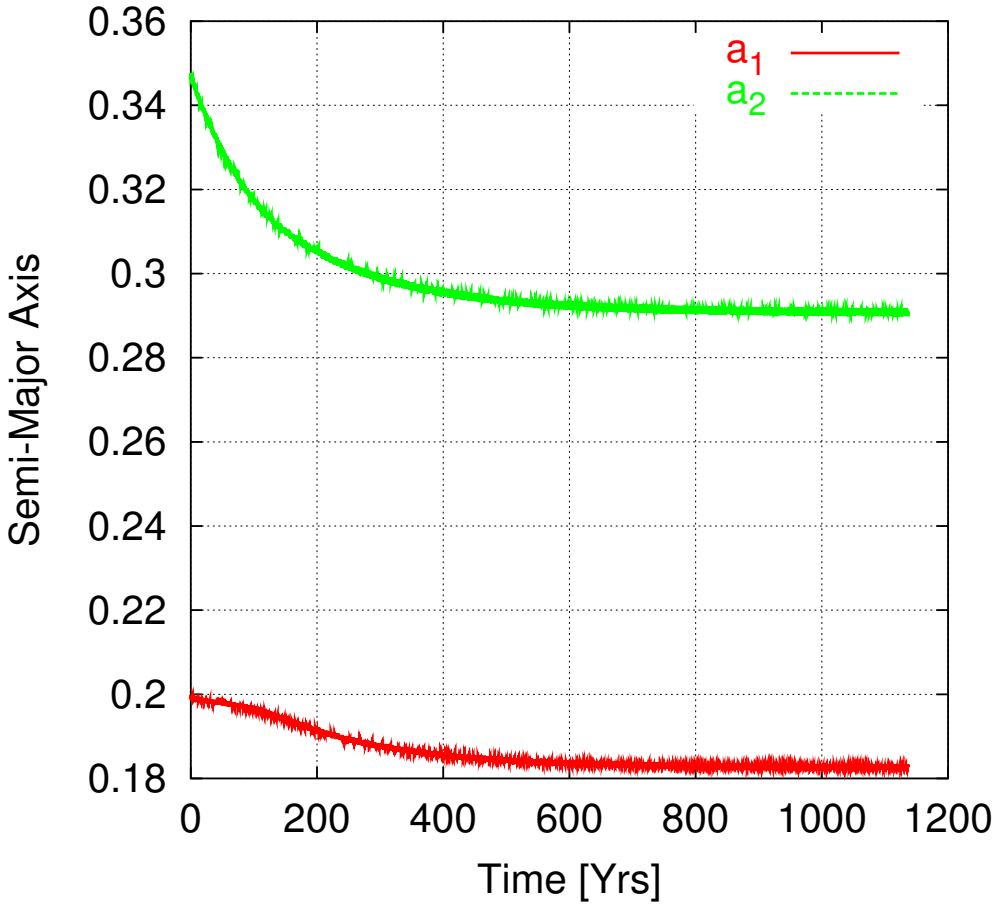


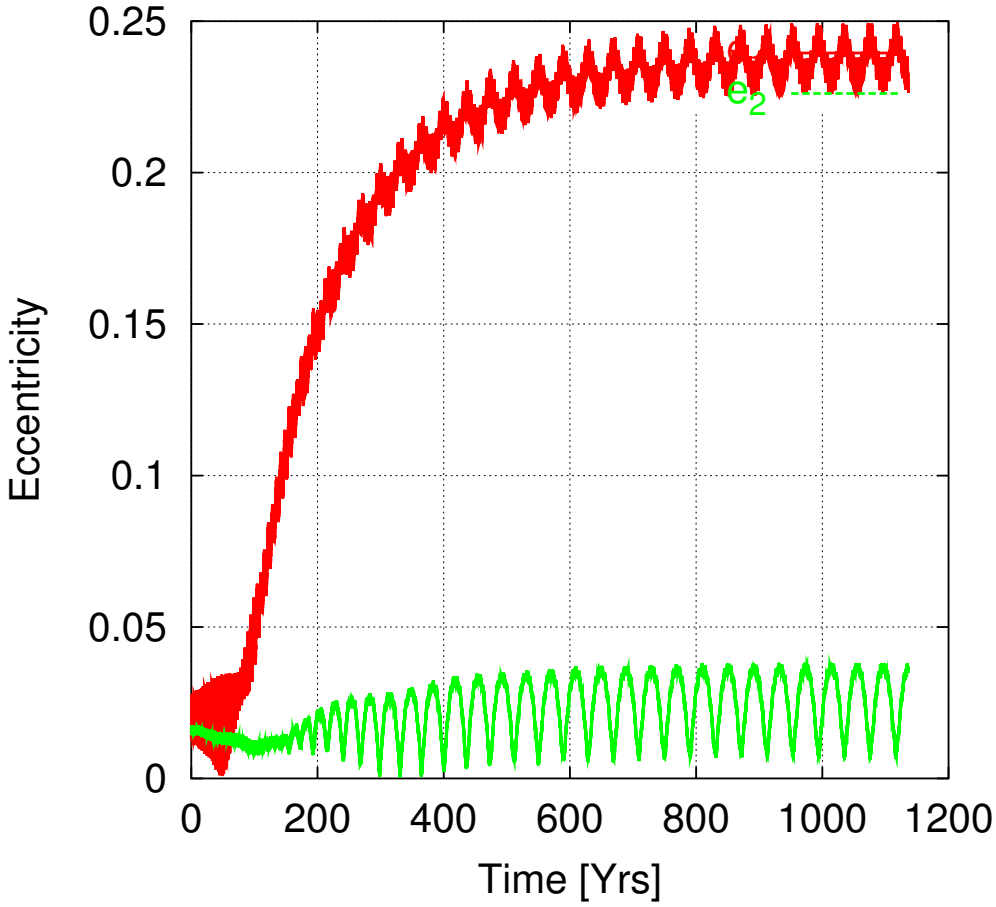


Need: High Damping, K ≈ 100, for match

Matching GJ 876: II

Using full hydro-models



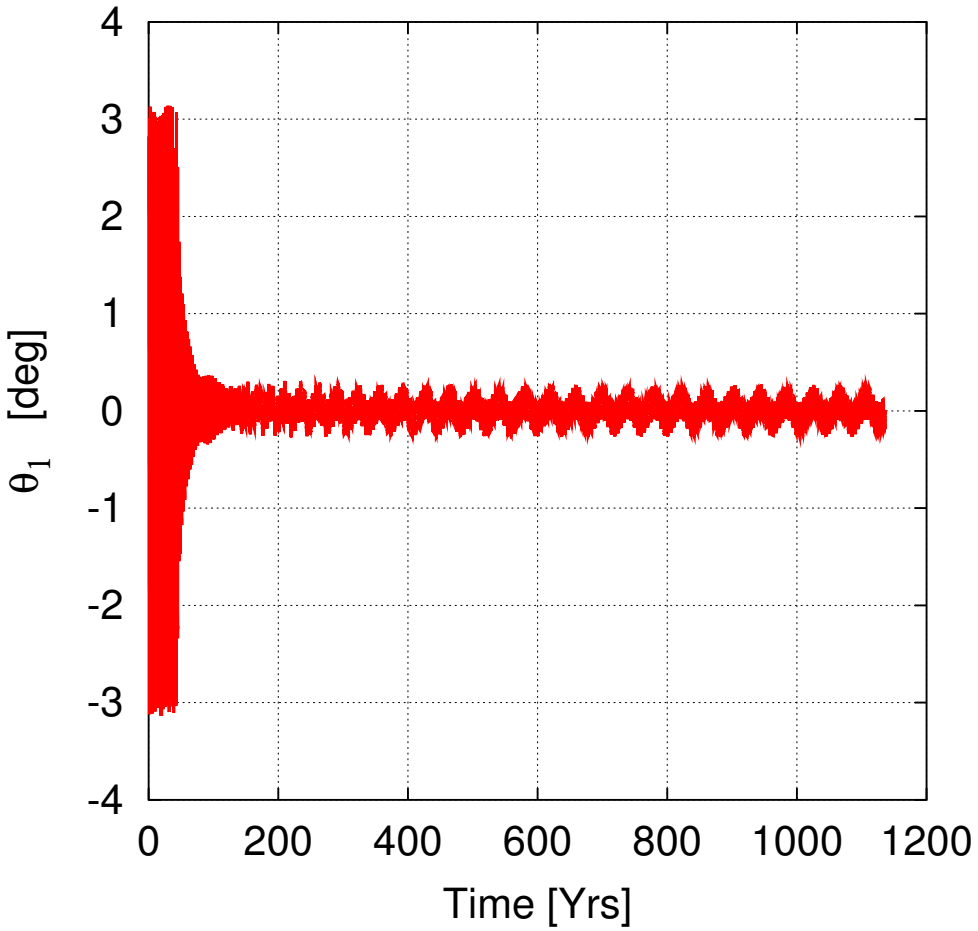


Note: Disk dissipates during evolution

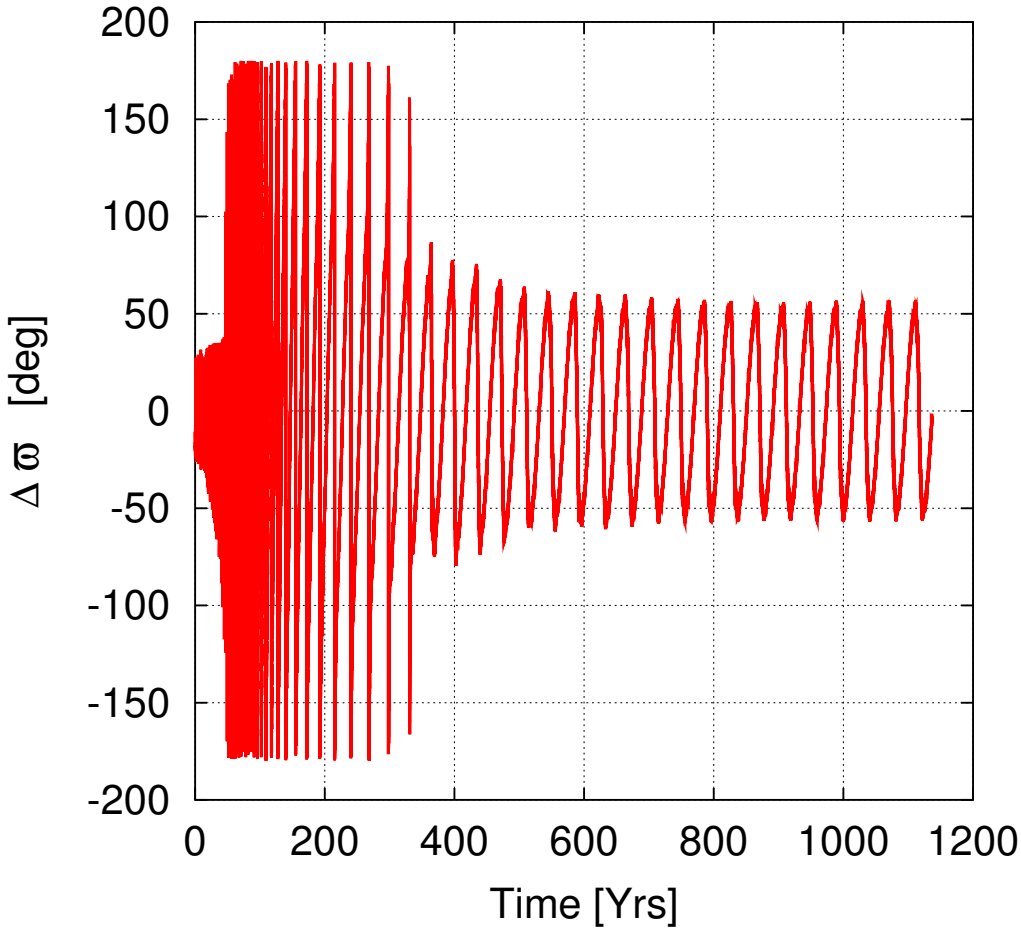
Matching GJ 876: III

Using full hydro-models

$\Theta_1 = 2\,\lambda_2 - \lambda_1 - \varpi_1$



$\Delta\varpi = \varpi_2 - \varpi_1$ vs. Time



Note: Large libration of periapse

Discussion

- Different migration speeds $\rightarrow$ Resonant Capture
- Eccentricity rises
- Locking of apsidal lines
- Outer planet has higher mass, inner higher eccentricity

- Type (eg. 2:1, 3:1) of resonance ??
- Influence of: Migration Speed (Disk Mass), Initial Conditions (e), Planet Masses, ... ??
- GJ 876: High e_2 damping, fine tuning of parameter, ... ??
- HD 82943: Parameter, high eccentricities, ... ??

End

The End