“Tidal effects in multi-planetary systems”

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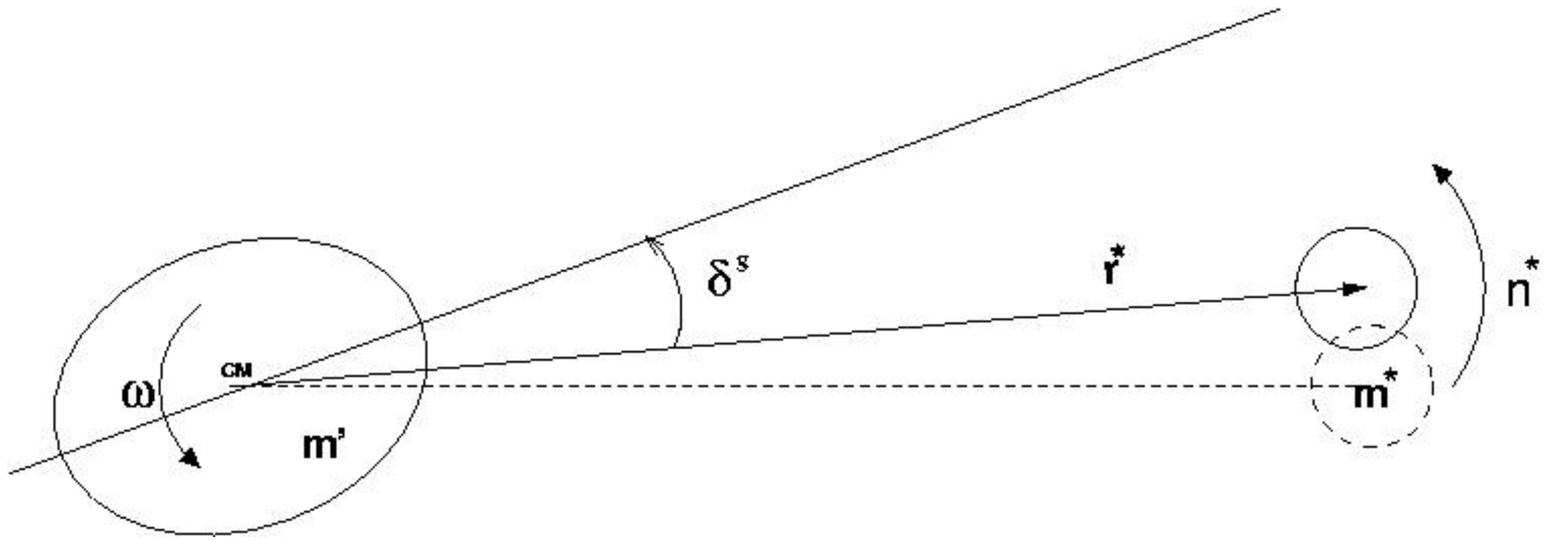
Tidal effect

Tidal effect



$P_{orb} = P_{rot}$

pependicular axis (ε=0)

circular orbits (e=0)

Case of the Moon and remaining satellites of the Solar System

Global Picture:

Poincaré (1898)

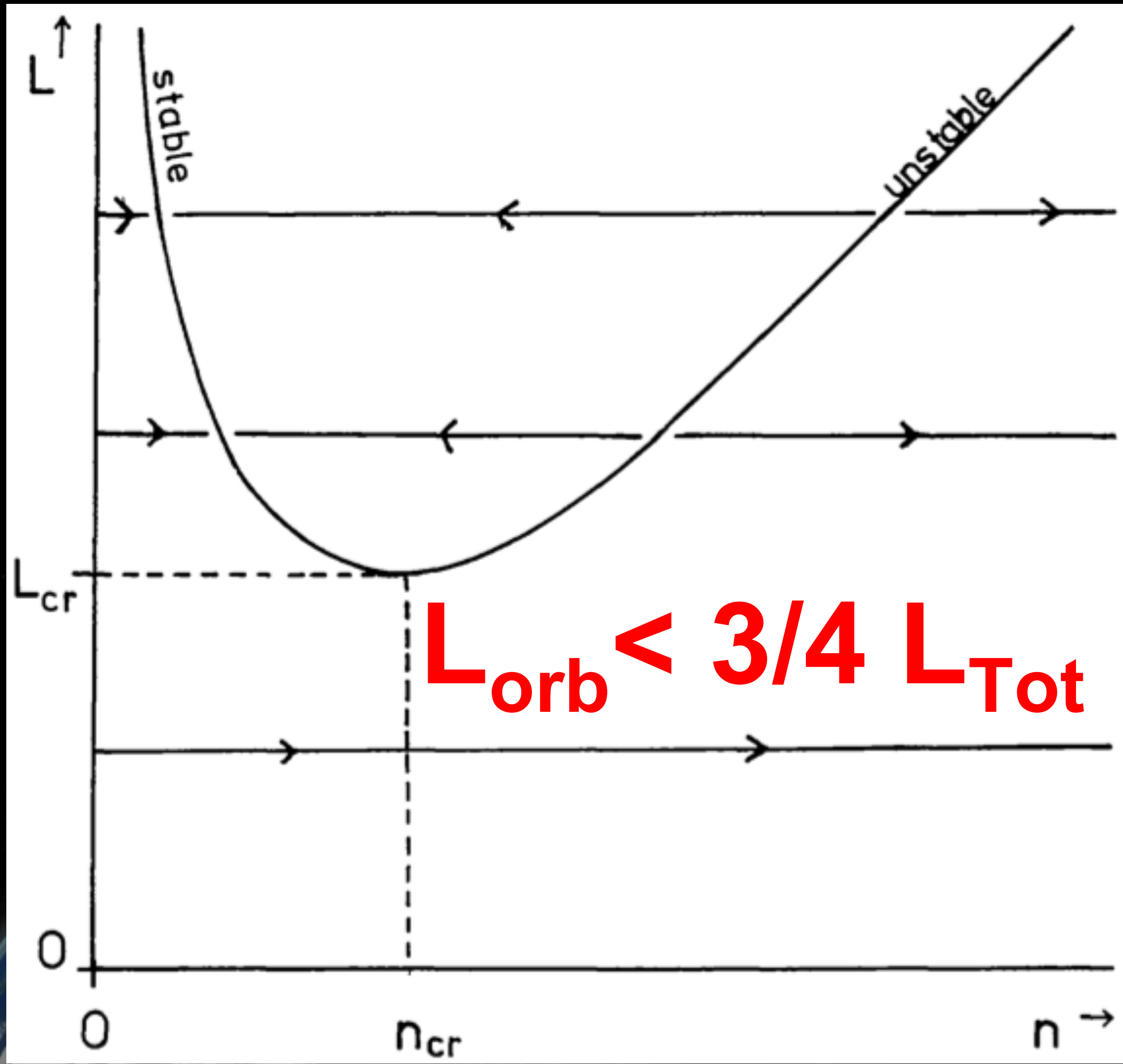
Landau & Lifshitz (1960)

Hut (1980)

$P_{orb} = P_{rot}$

pependicular axis (ε=0)

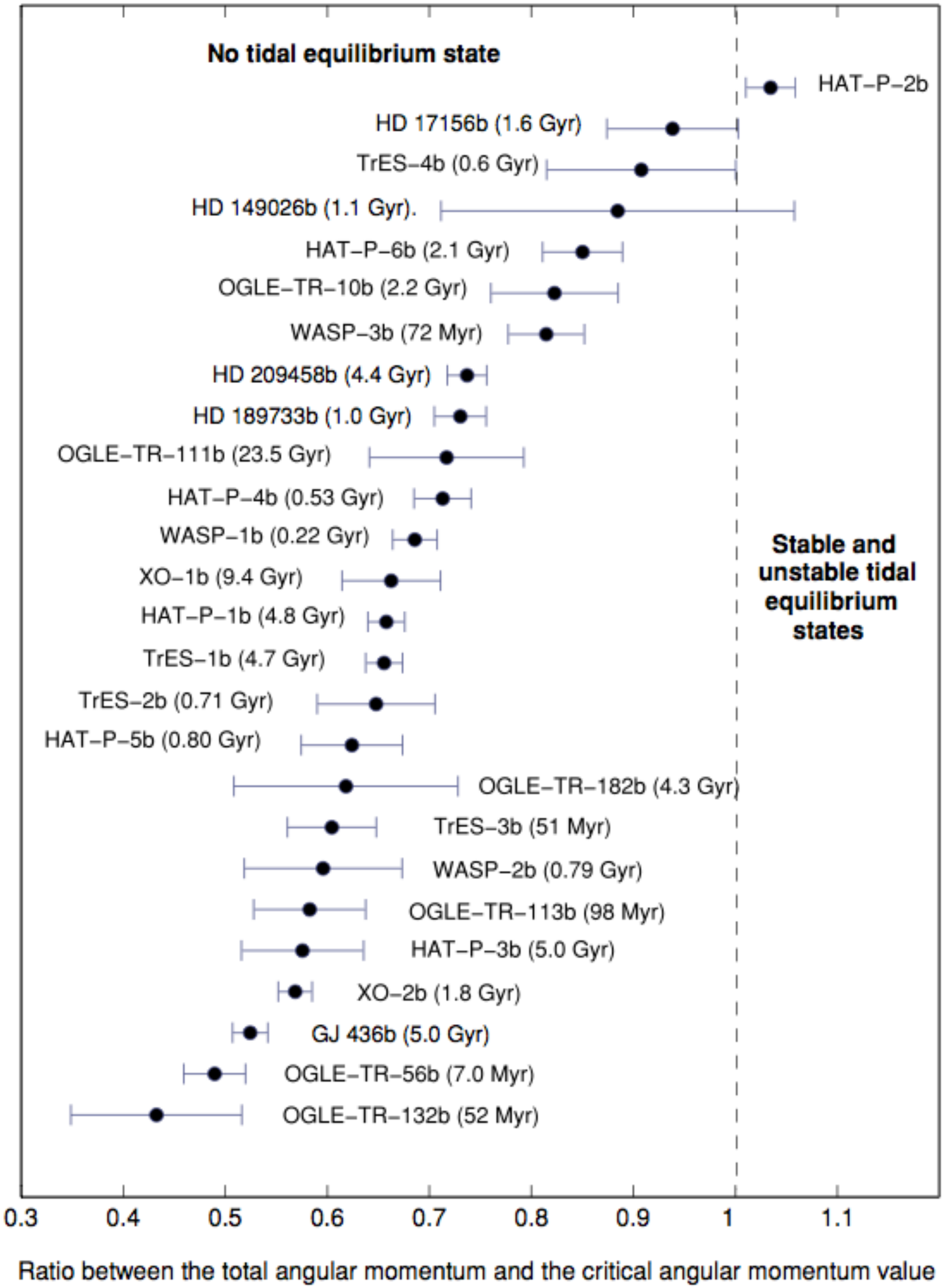
circular orbits (e=0)



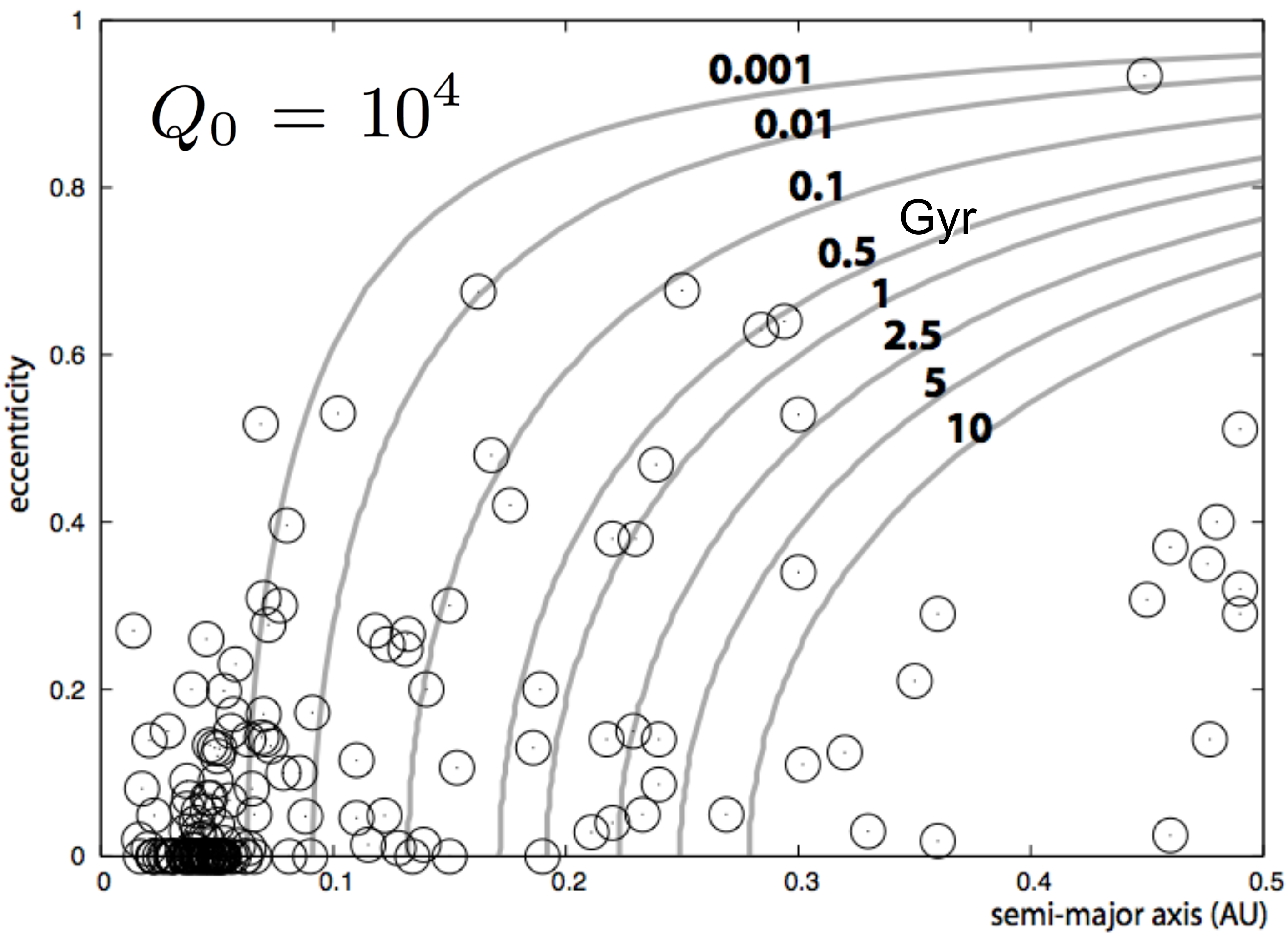
$$L_{cr} = 4\left\{\frac{1}{27}\, G\, \frac{M^3 m^3}{M+m}\,(I_1 + I_2)\right\}^{1/4}$$

Falling Hot-Jupiters

Levrard *et al.* (2009)

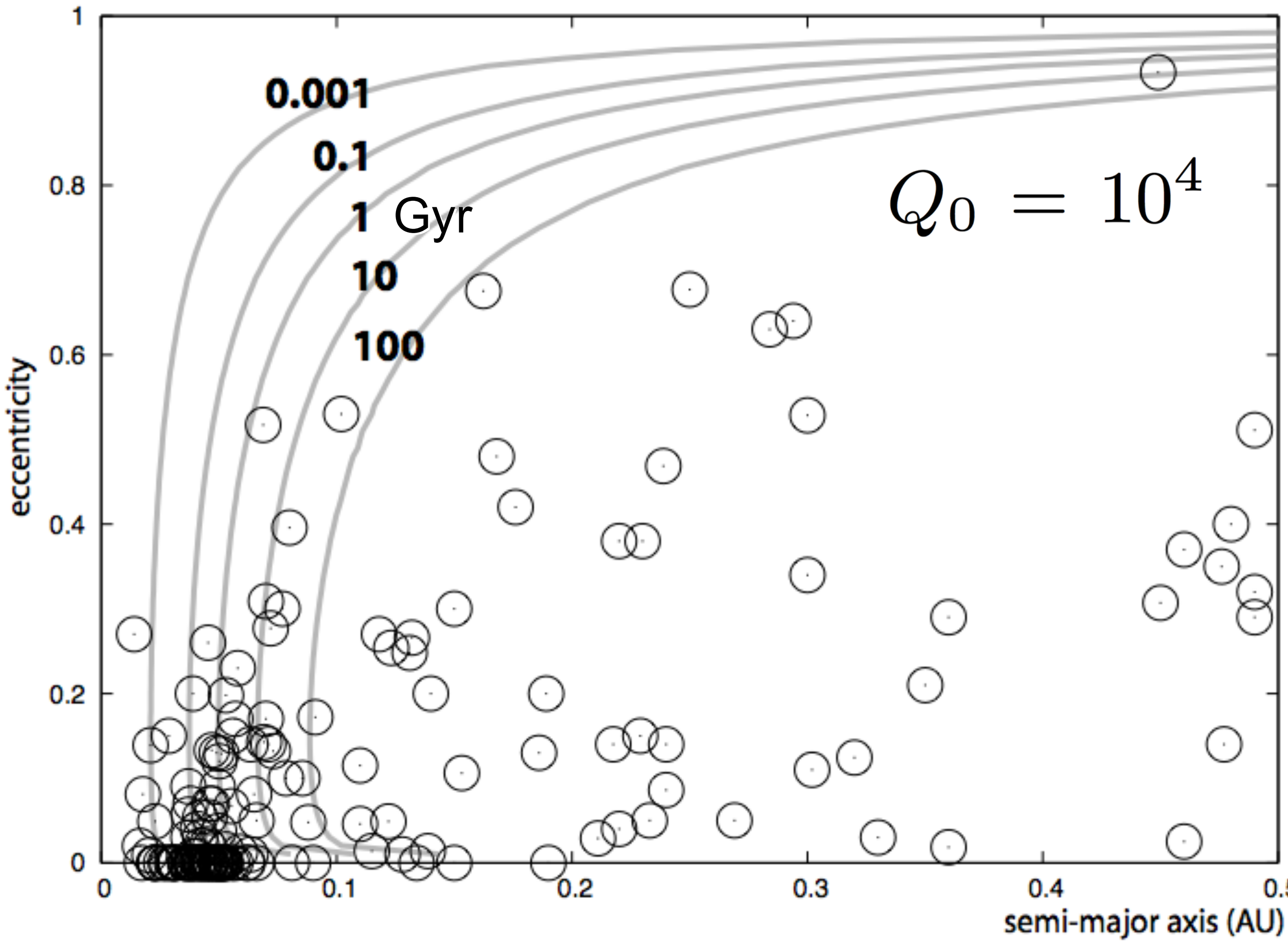


Spin evolution time-scale:



Correia & Laskar, *Exoplanets* (2010)

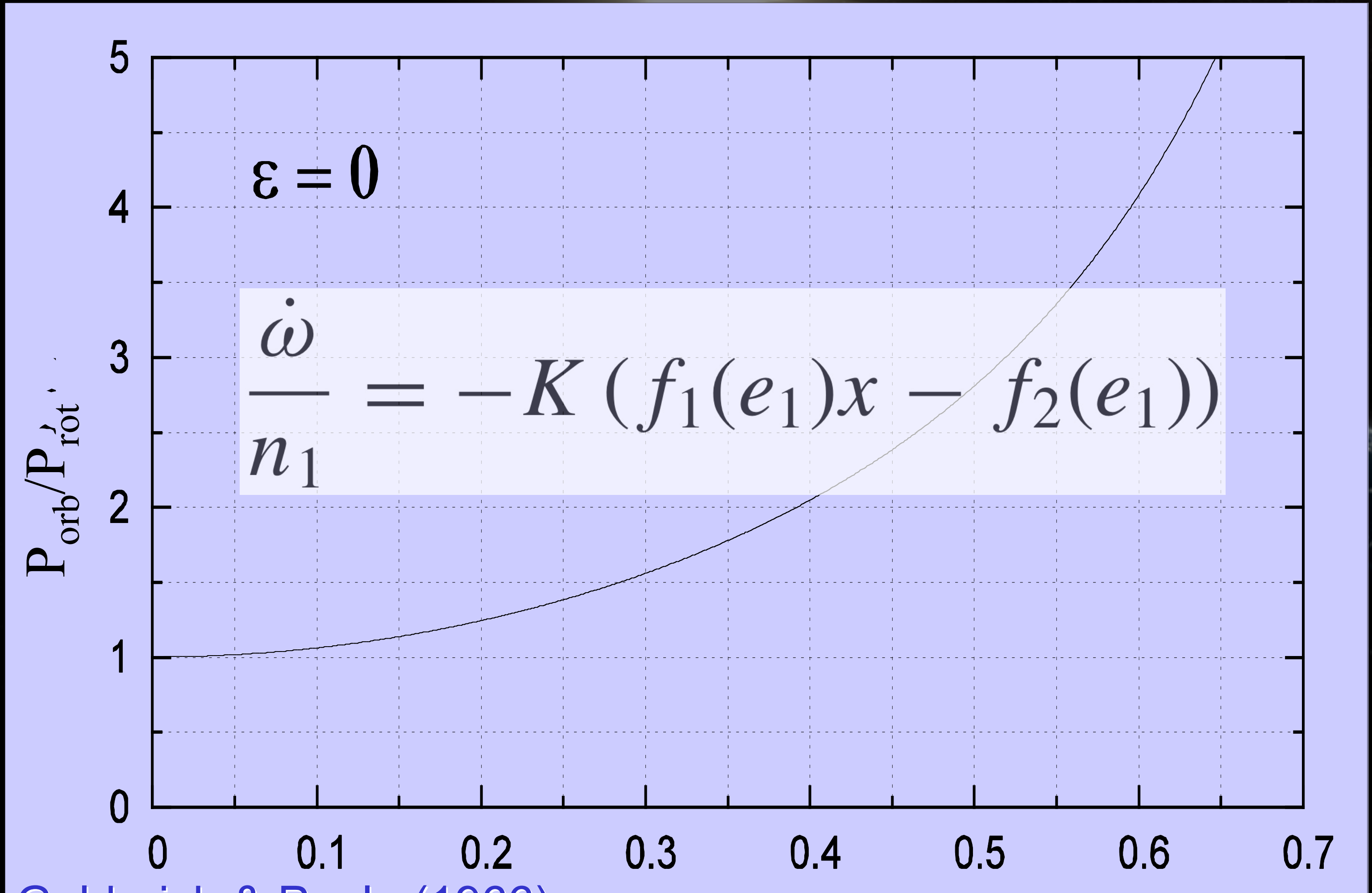
Orbital evolution time-scale:



Correia & Laskar, *Exoplanets* (2010)

Intermediate evolution:

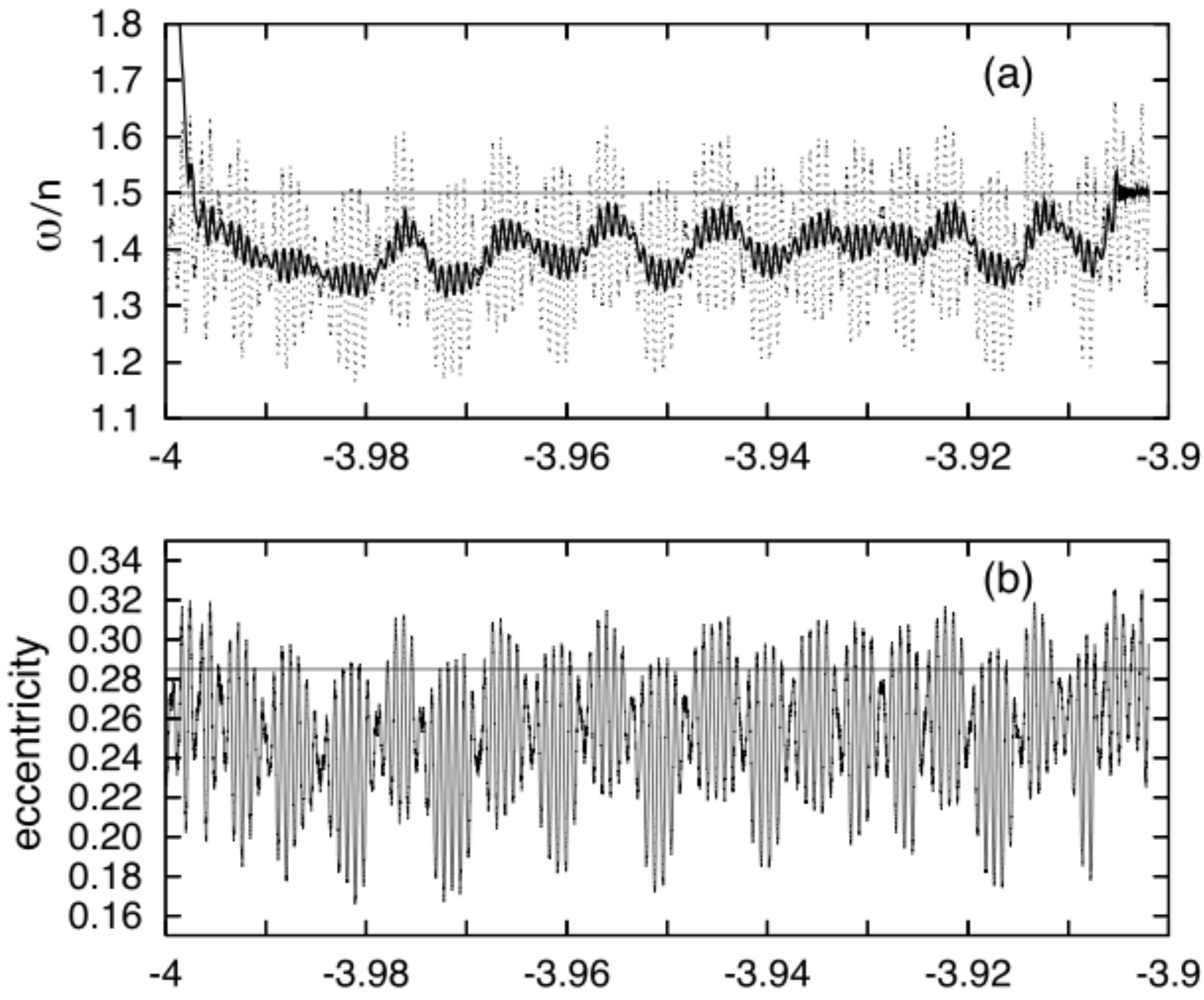
$\omega_{eq} / n = f_2/f_1(e)$



Goldreich & Peale (1966)

Rotation tidal wobble

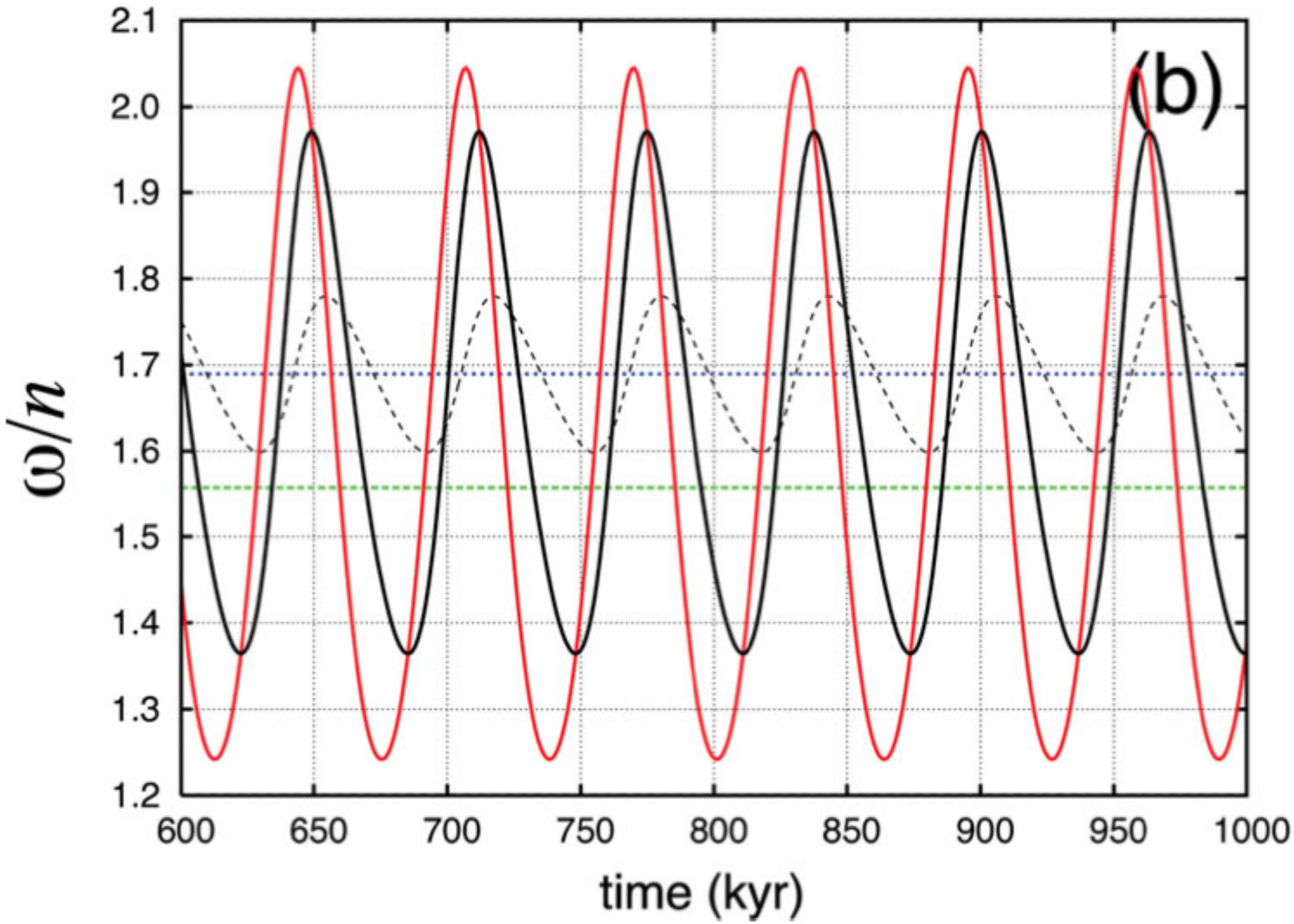
Mercury



Correia & Laskar, *Nature* (2004)

Rotation tidal wobble

Jupiter-size planets



linearized system

$$x = \omega / n$$

$$\delta \dot{e}_1 = -A \sin \varpi,$$

$$\delta e_1 = \Delta e \cos(gt + \varpi_0)$$

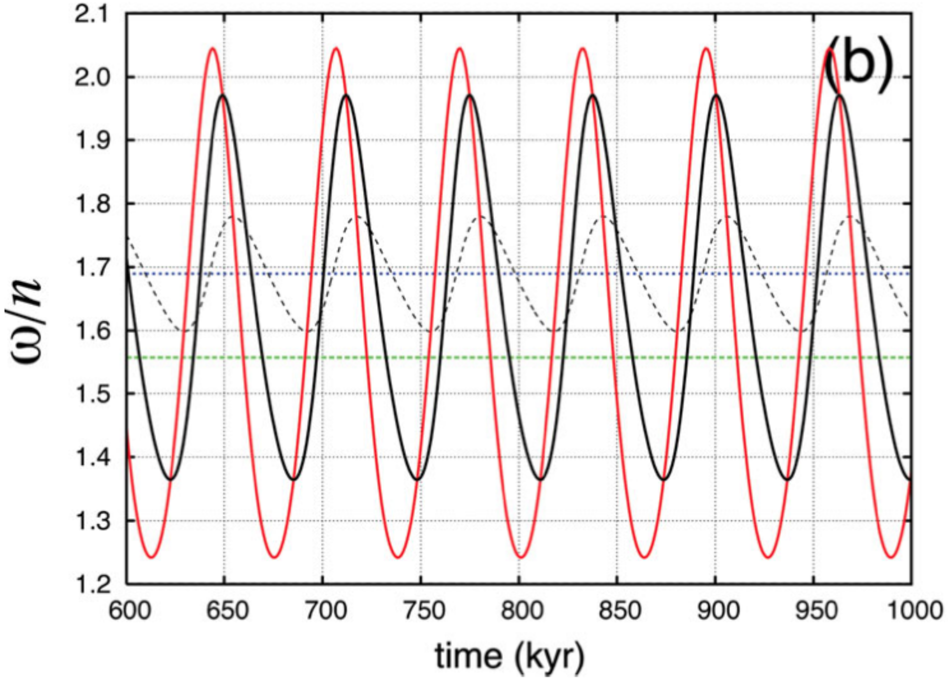
$$\dot{\varpi} = g$$

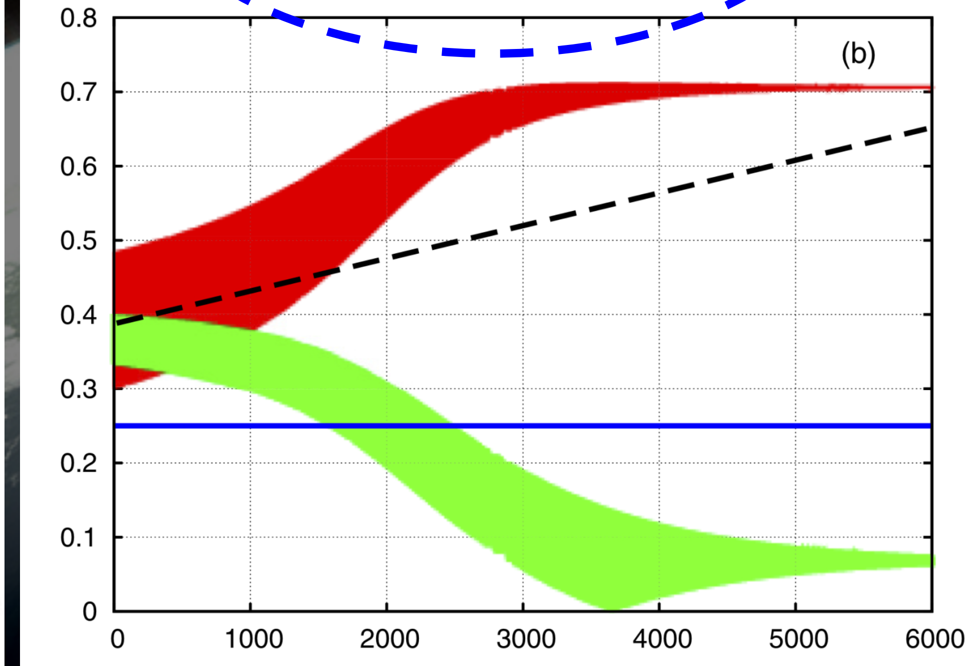
$$\delta x = \Delta x \cos(gt + \varpi_0 - \phi)$$

$$\delta \dot{x} = -\nu_x \delta x + \nu_e \delta e_1,$$

drift on the eccentricity

$$\dot{e}_1 = -A\sin(gt+\varpi_0) - \frac{g_x A}{2g}\Delta x \sin(2gt + 2\varpi_0 - \phi) - \frac{g_e A}{2g}\Delta e \sin(2gt+2\varpi_0) + \frac{g_x A}{2g}\Delta x \sin\phi .$$





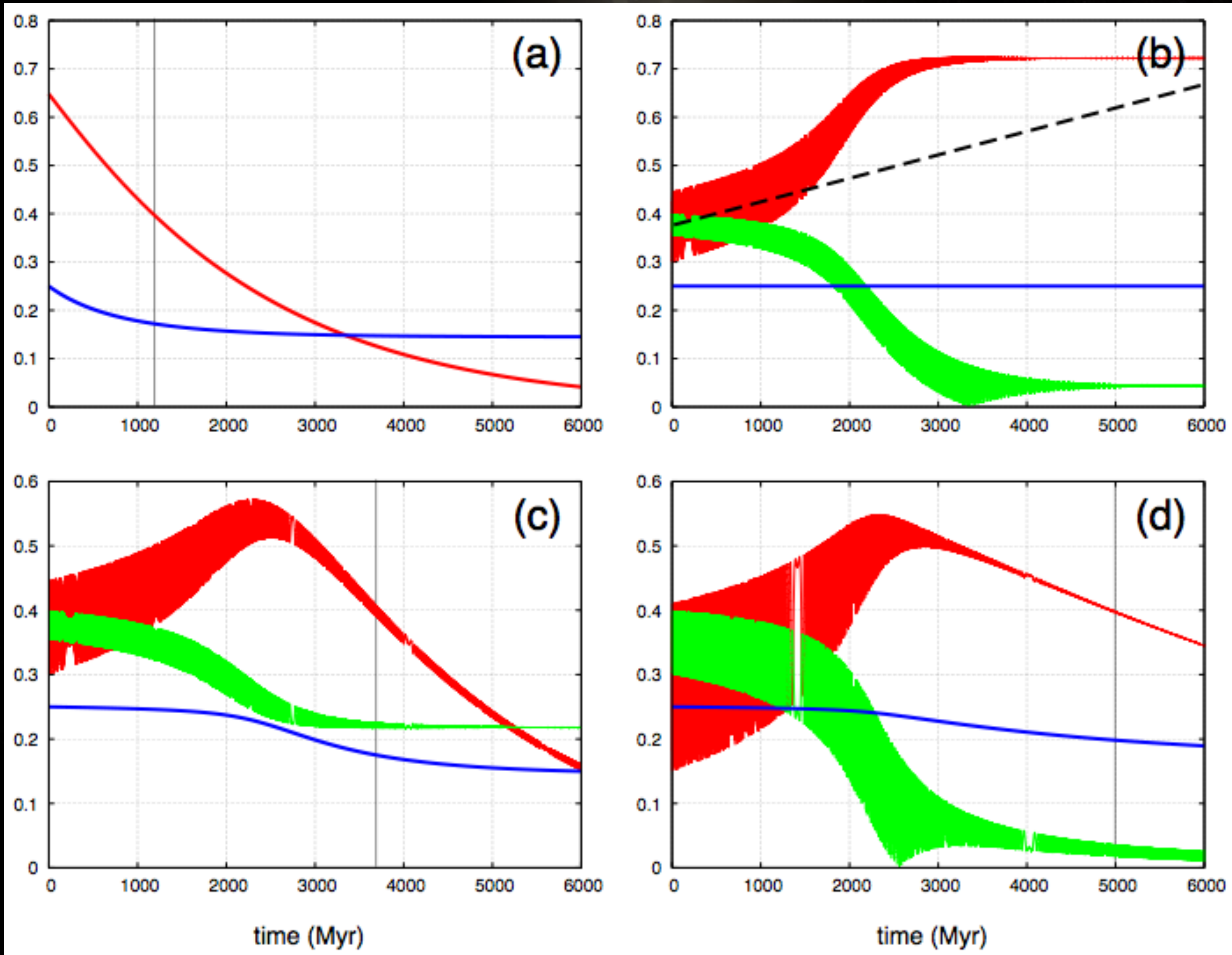
moderate close-in planets

Table 1
Single Planetary Systems with $0.1 < a_1 < 0.3$ and $e_1 > 0.3$

Star (Name)	a_1 (AU)	e_1	m_1 (M_J)	m_0 ($M_\odot$)	Age (Gyr)	τ (Gyr)
HD 108147	0.102	0.53	0.26	1.19	2.0	0.01
CoRoT-10	0.105	0.53	2.75	0.89	3.0	0.24
HD 33283	0.145	0.48	0.33	1.24	3.2	0.34
HD 17156	0.163	0.68	3.19	1.28	3.4	0.44
HIP 57050	0.164	0.31	0.30	0.34	...	39.4
HD 117618	0.176	0.42	0.18	1.05	3.9	2.06
HD 45652	0.228	0.38	0.47	0.83	...	93.3
HD 90156	0.250	0.31	0.06	0.84	4.4	35.8
HD 37605	0.260	0.74	2.84	0.80	10.7	10.6
HD 3651	0.284	0.63	0.20	0.79	5.1	15.5

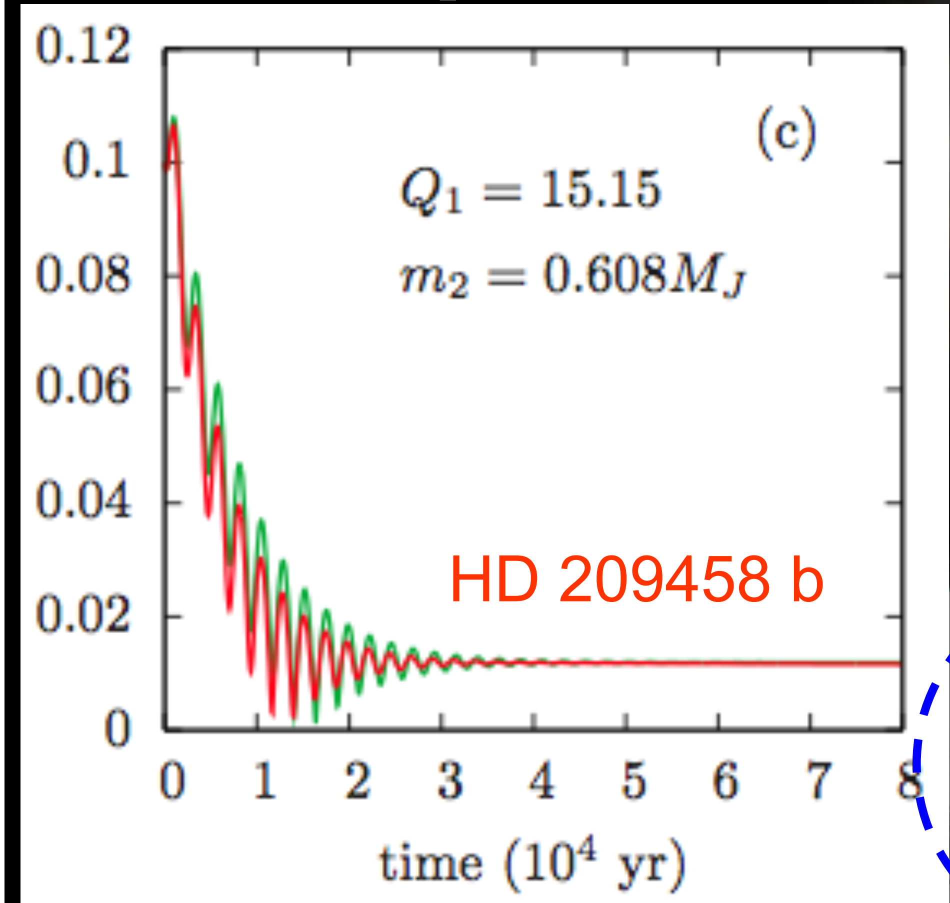
eccentricity pumping

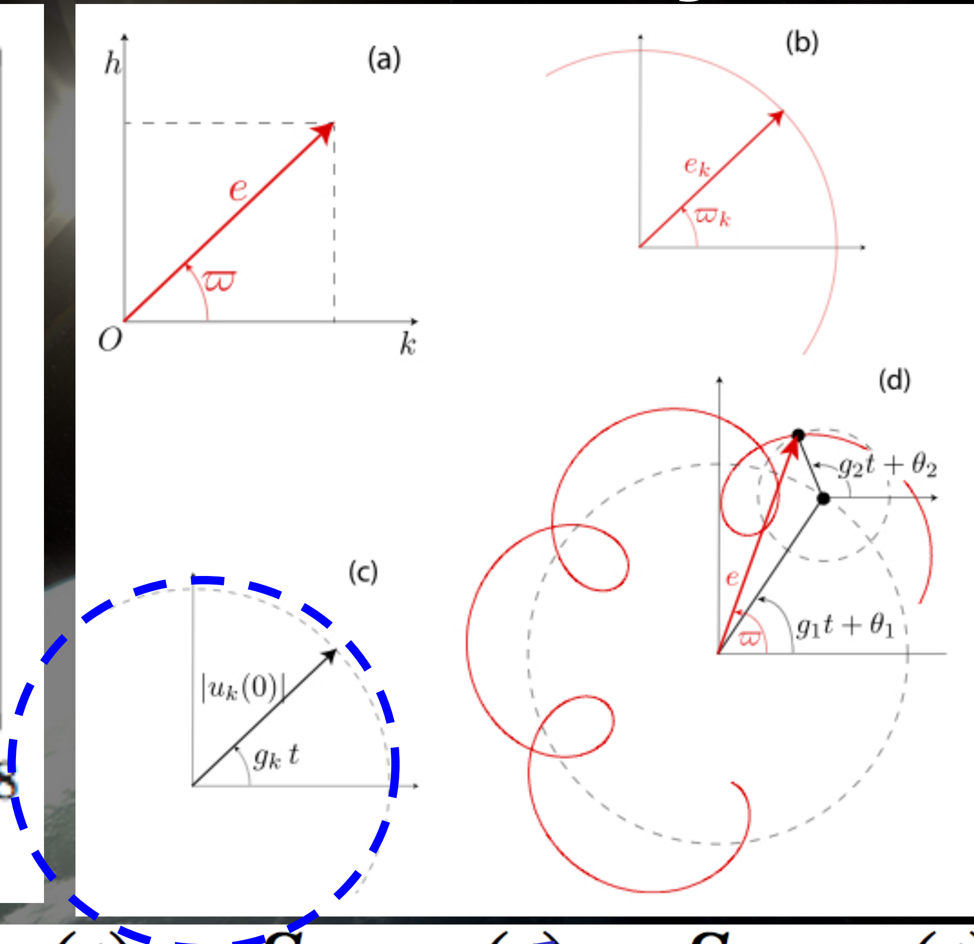
HD 117618 b



Correia, Boué & Laskar, *ApJ Lett* (2012)

equilibrium eccentricity





$$z_k = e_k e^{i\varpi_k},\ k = 1, \ldots, n$$

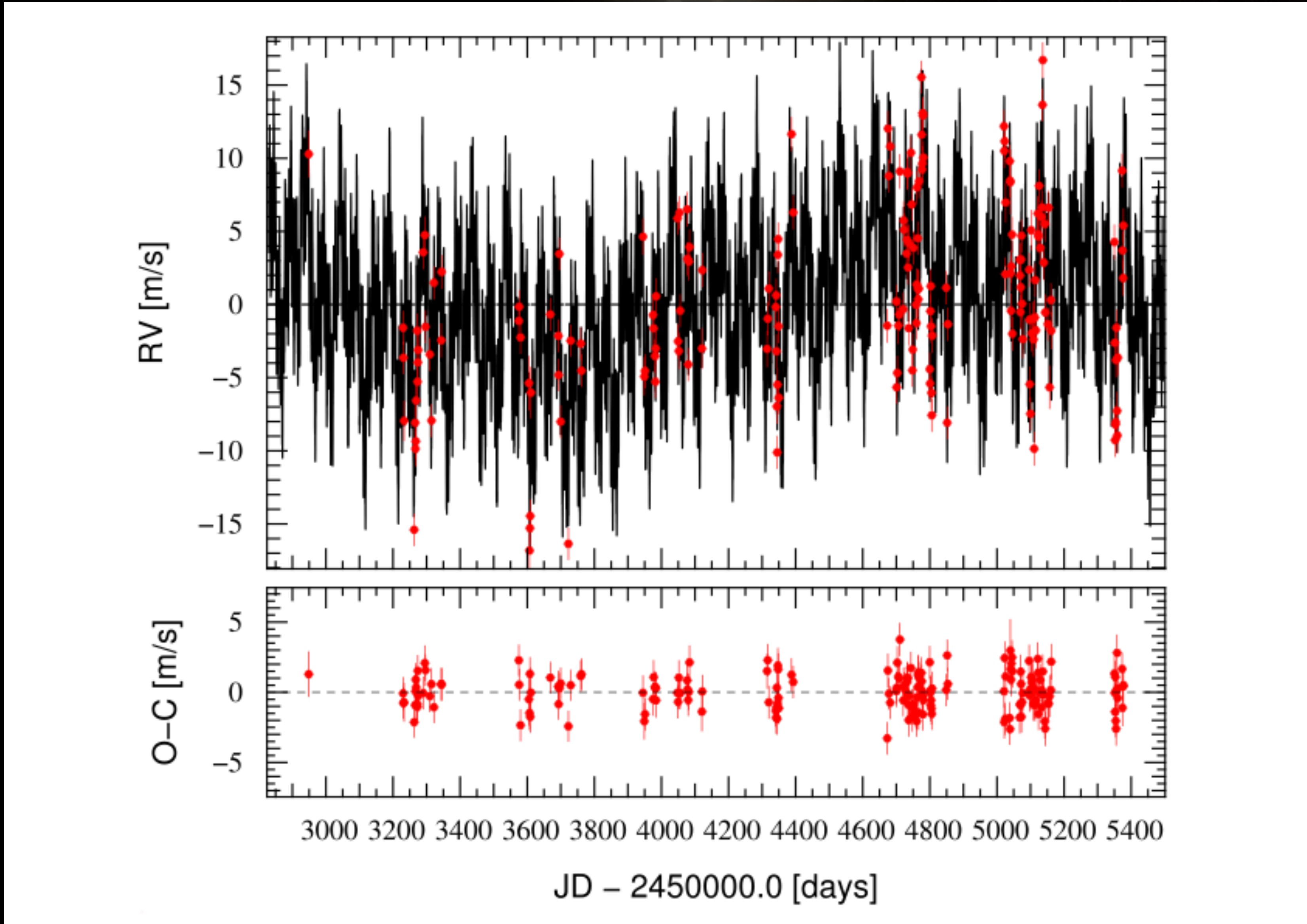
$$u_k(t) = u_k(0)e^{-\gamma_k t}e^{ig_k t}$$

$$z_1(t) = S_{11}u_1(t) + S_{12}u_2(t)$$

$$z_2(t) = S_{21}u_1(t) + S_{22}u_2(t)$$

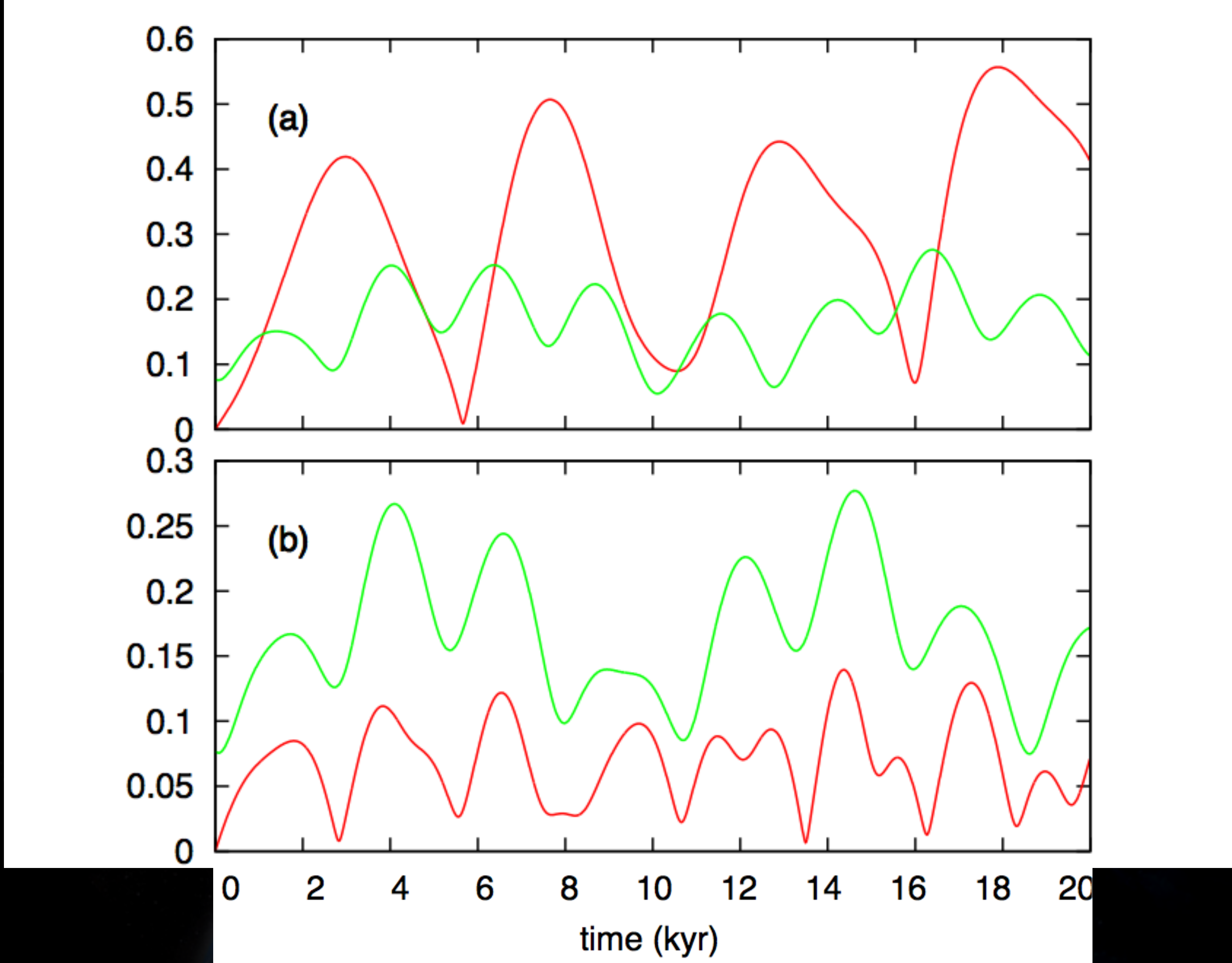
Mardling, *MNRAS* (2007); Laskar, Boué & Correia, *A&A* (2012)

HD 10180, seven planets! (or nine)



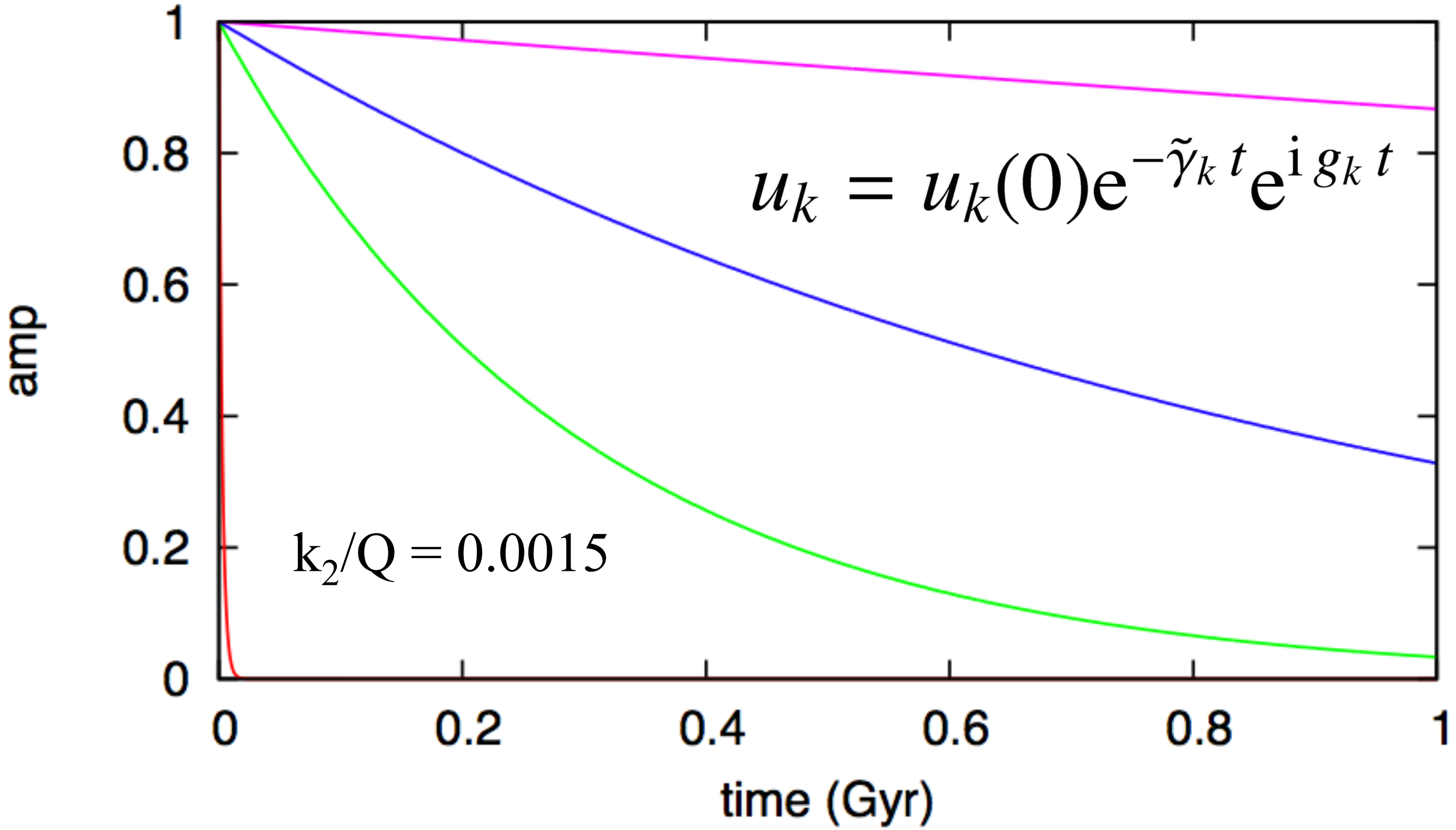
Lovis et al. (A&A 2011)

unstable system?



Lovis et al. (A&A 2011)

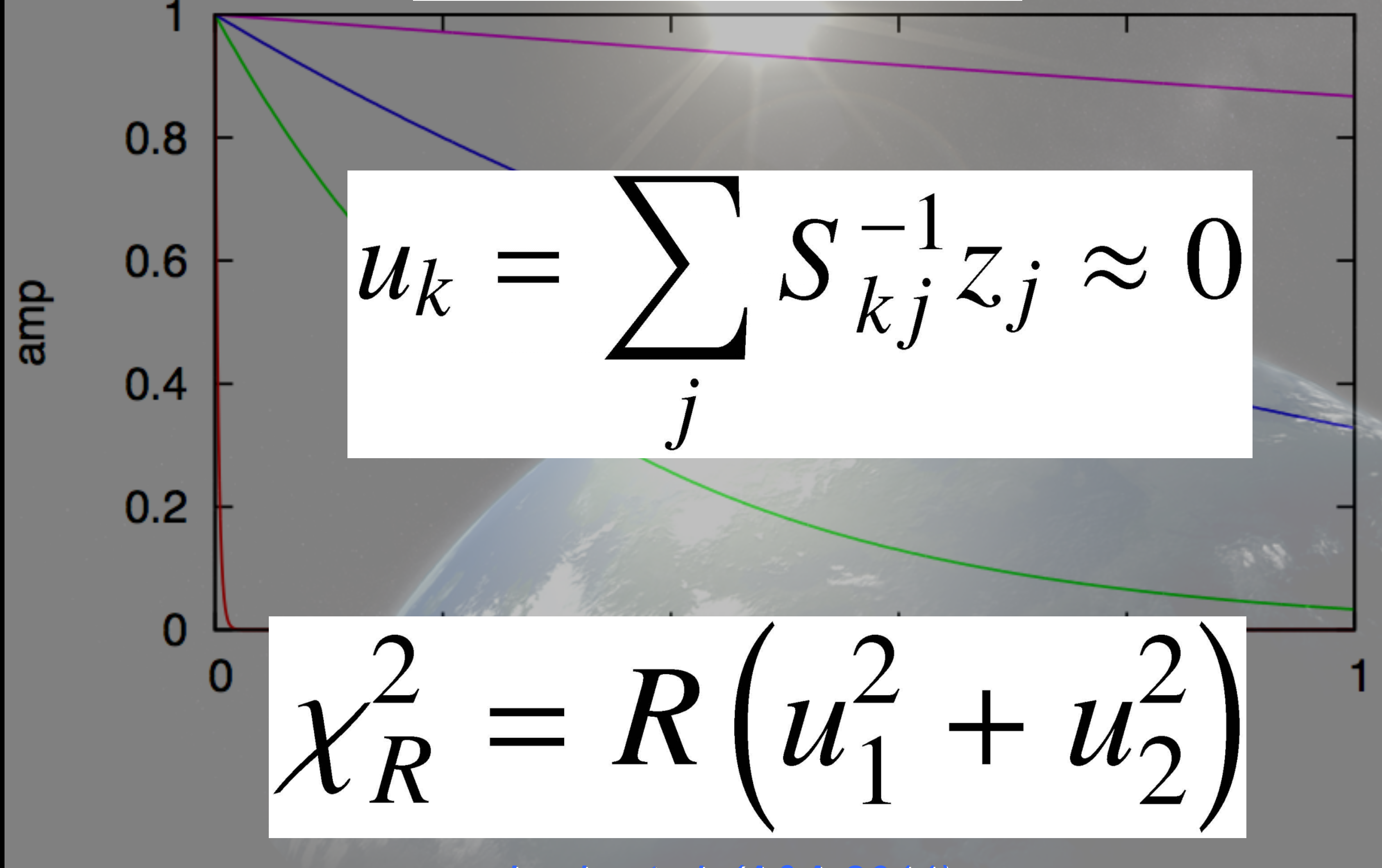
tidal dissipation



Lovis et al. (A&A 2011)

tidal constraint

$$u_k = u_k(0)\mathrm{e}^{-\tilde{\gamma}_k t}\mathrm{e}^{\mathrm{i}\, g_k t}$$

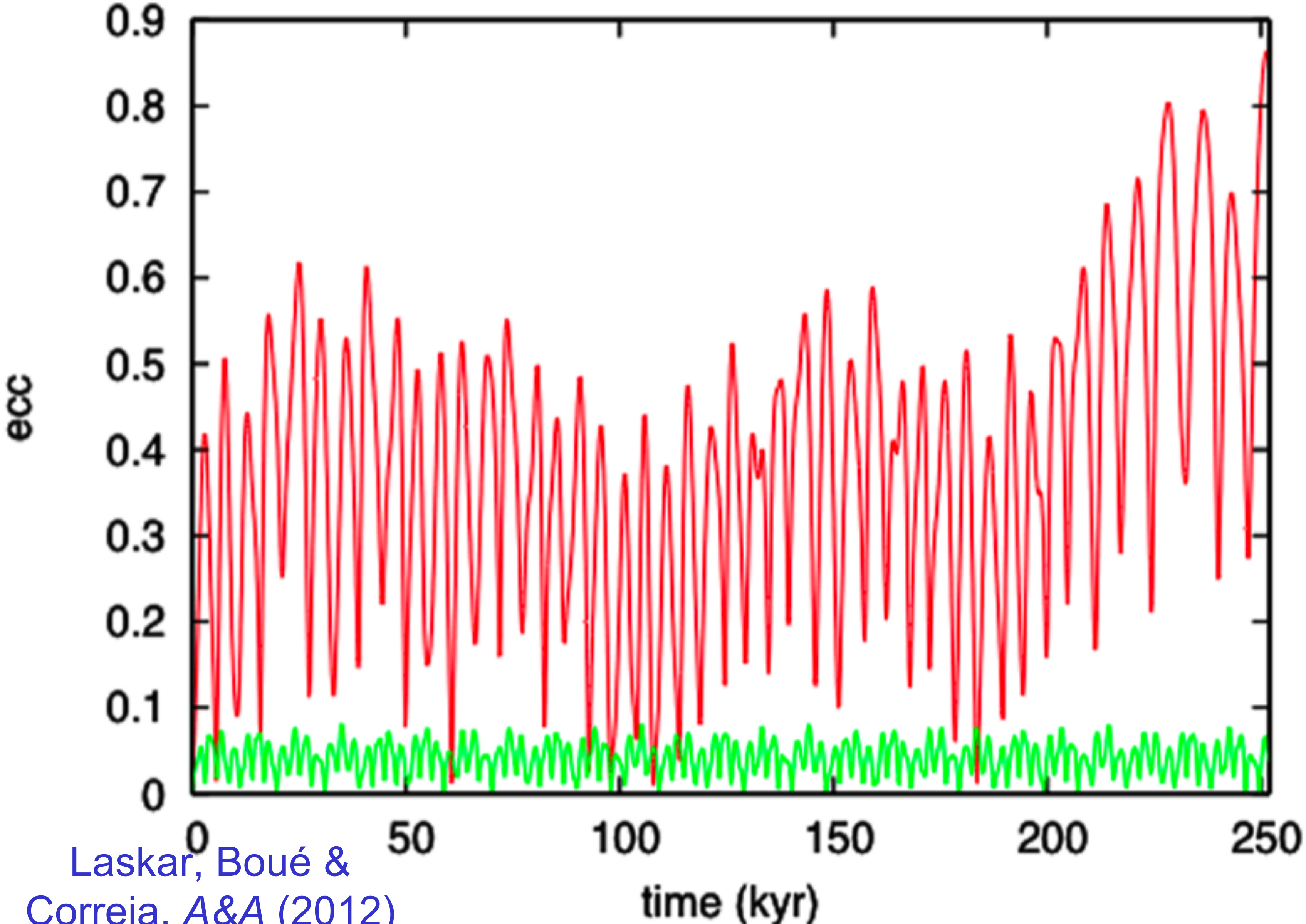


$$u_k = \sum_j S^{-1}_{kj} z_j \approx 0$$

$$\chi^2_R = R\left(u_1^2 + u_2^2\right)$$

Lovis et al. (A&A 2011)

eccentricity evolution



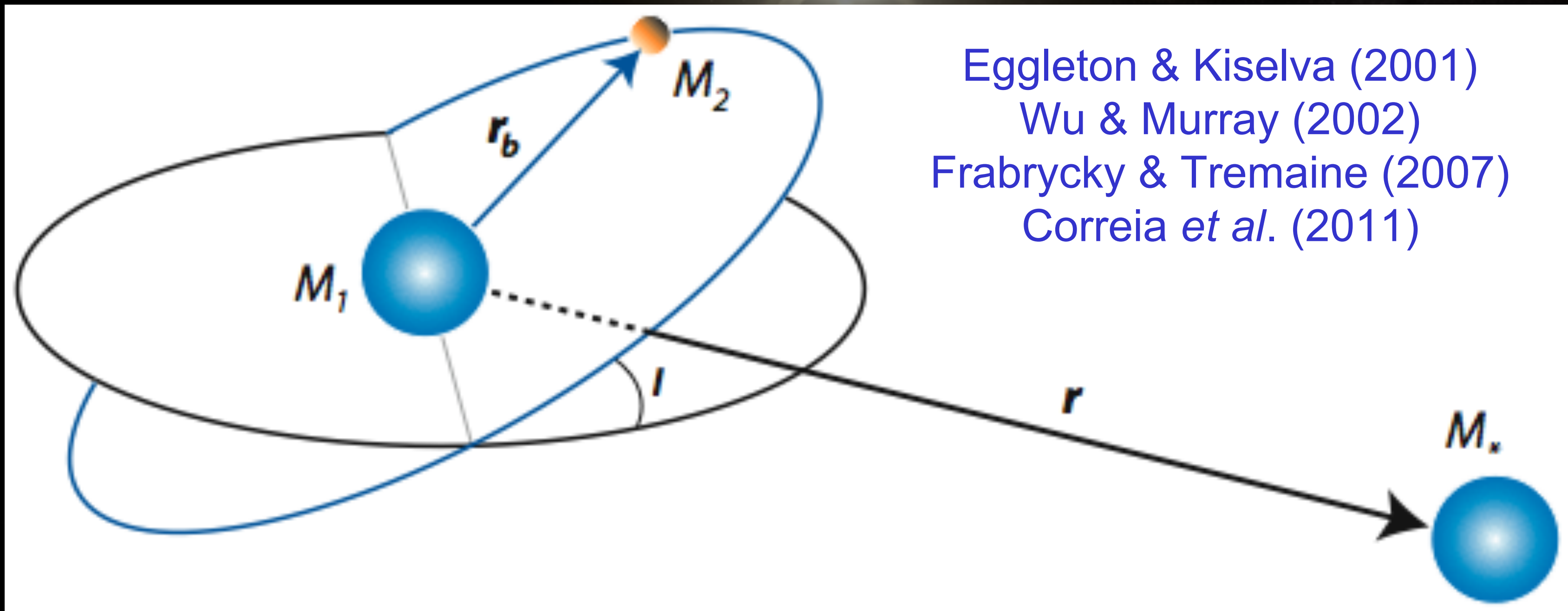
Laskar, Boué & Correia, *A&A* (2012)

HD 80606

(inner restricted problem)

Naef et al, 2001

(a_p = 0.45 AU, e_p = 0.92)

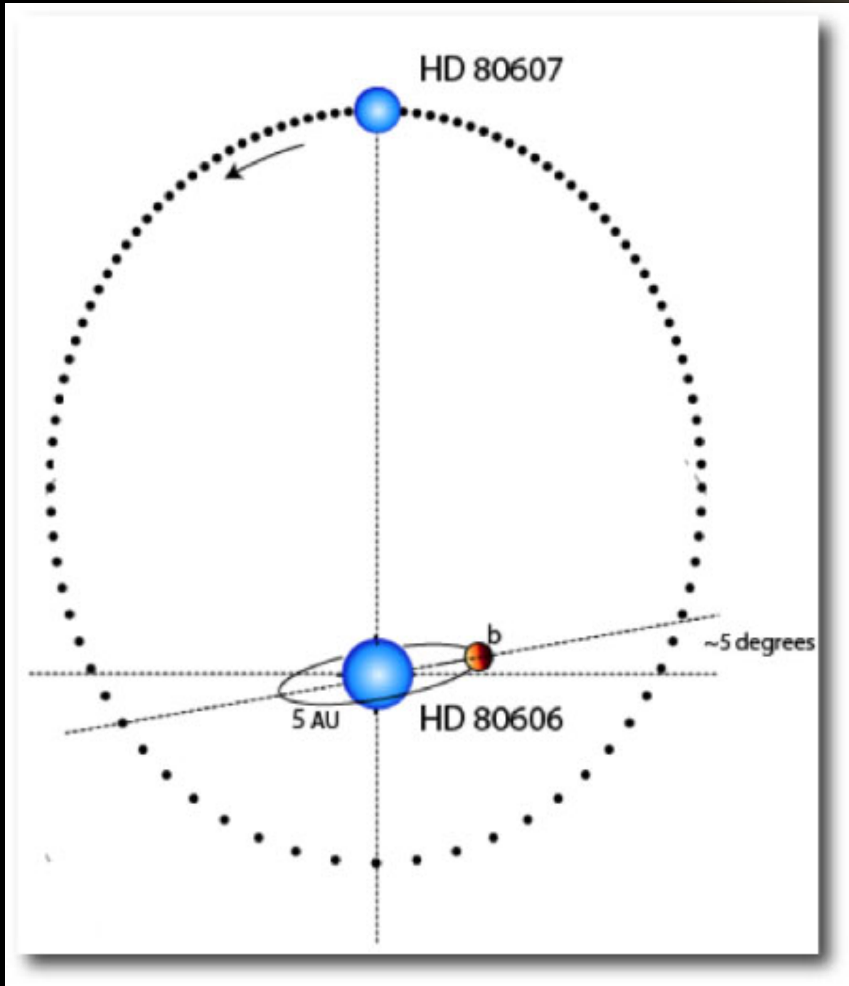


Kozai effect:
(I > 39º)

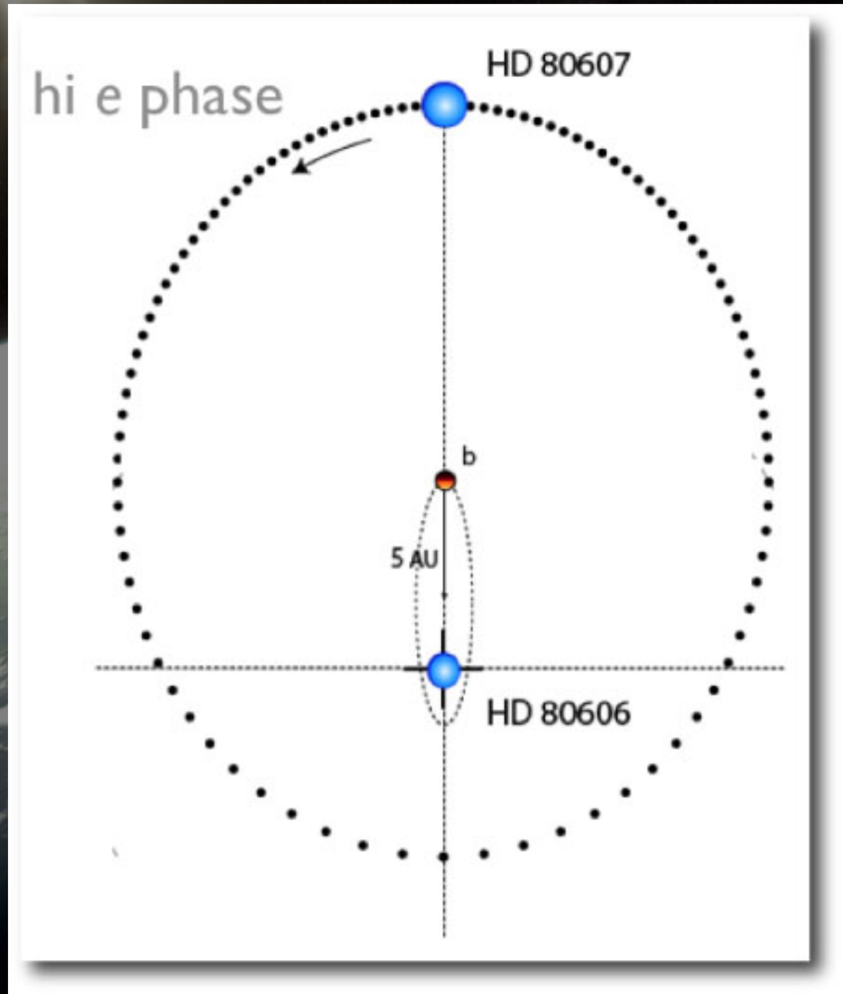
$$\sqrt{1 - e_1^2} \cos I = h_1 = Cte$$

HD 80606

I ~ 85º, e ~ 0



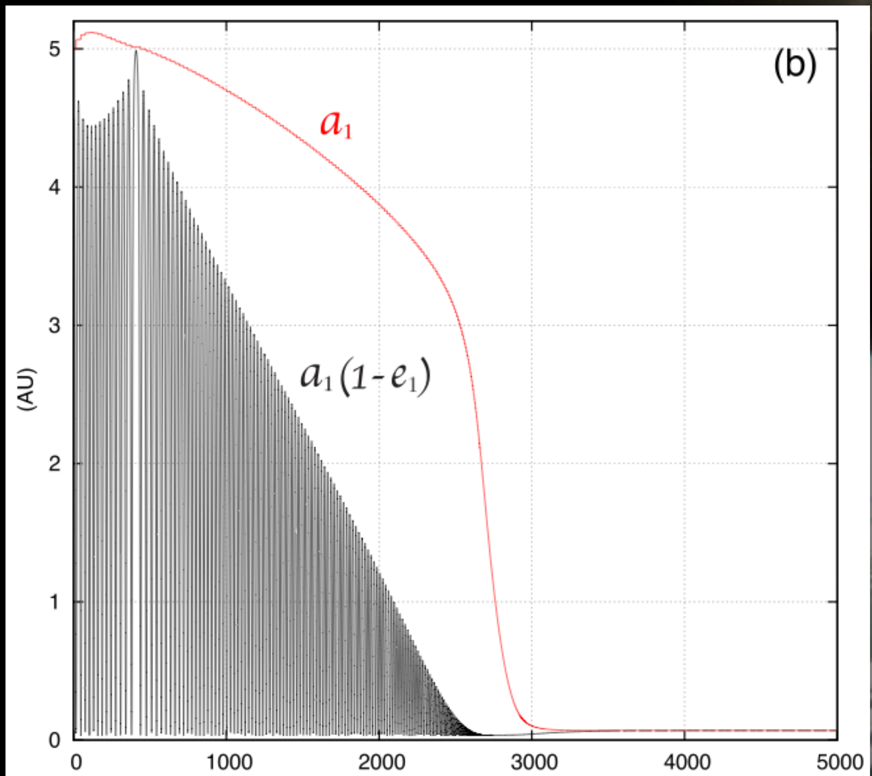
I ~ 45º, e ~ 0.99



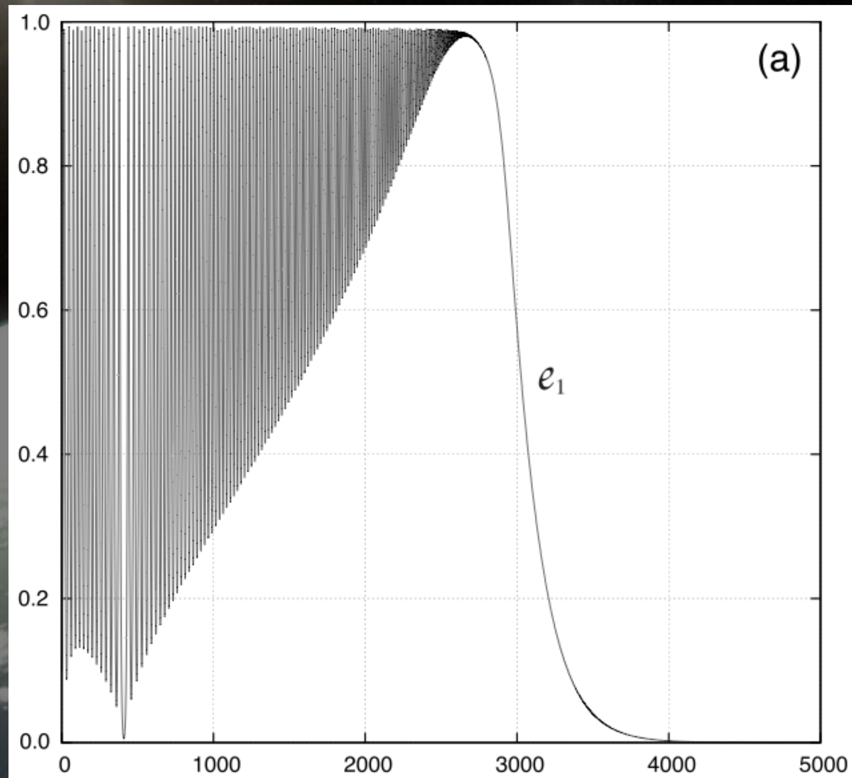
HD 80606

(a_p = 0.45 AU, e_p = 0.92)

semi-major axis



eccentricity



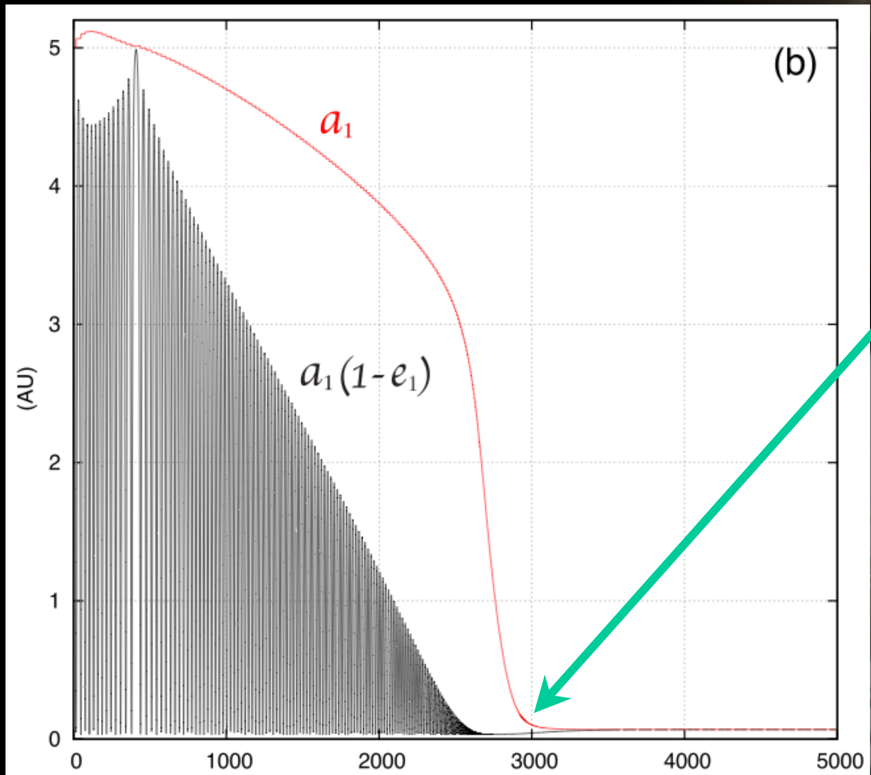
time (Myr)

Wu & Murray (2002)
Frabrycky & Tremaine (2007)
Correia *et al*. (2011)

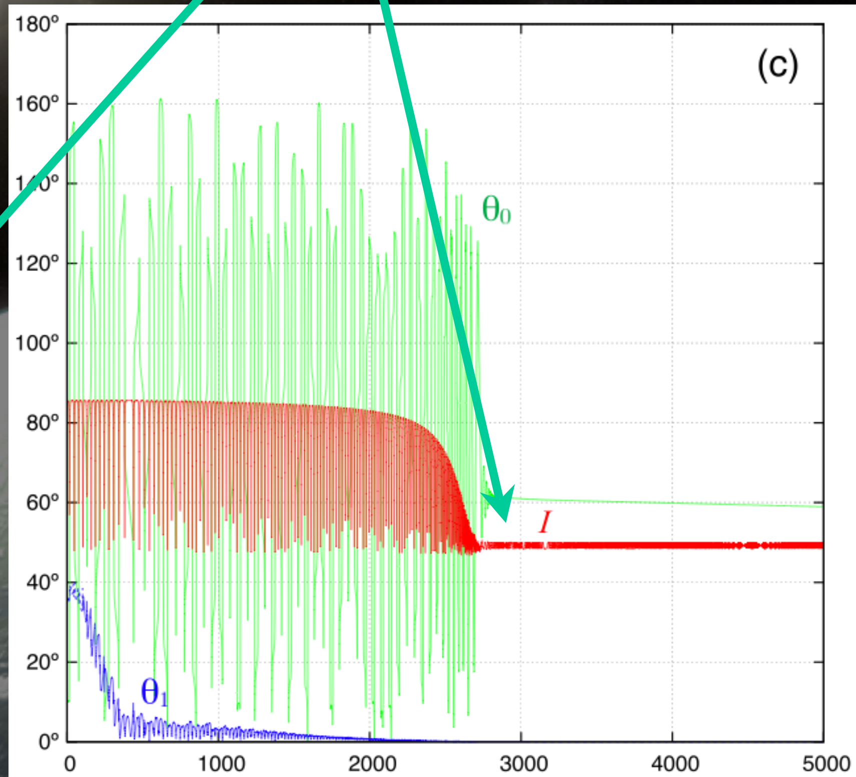
HD 80606

$(a_p = 0.45$ AU, $e_p = 0.92)$

semi-major axis



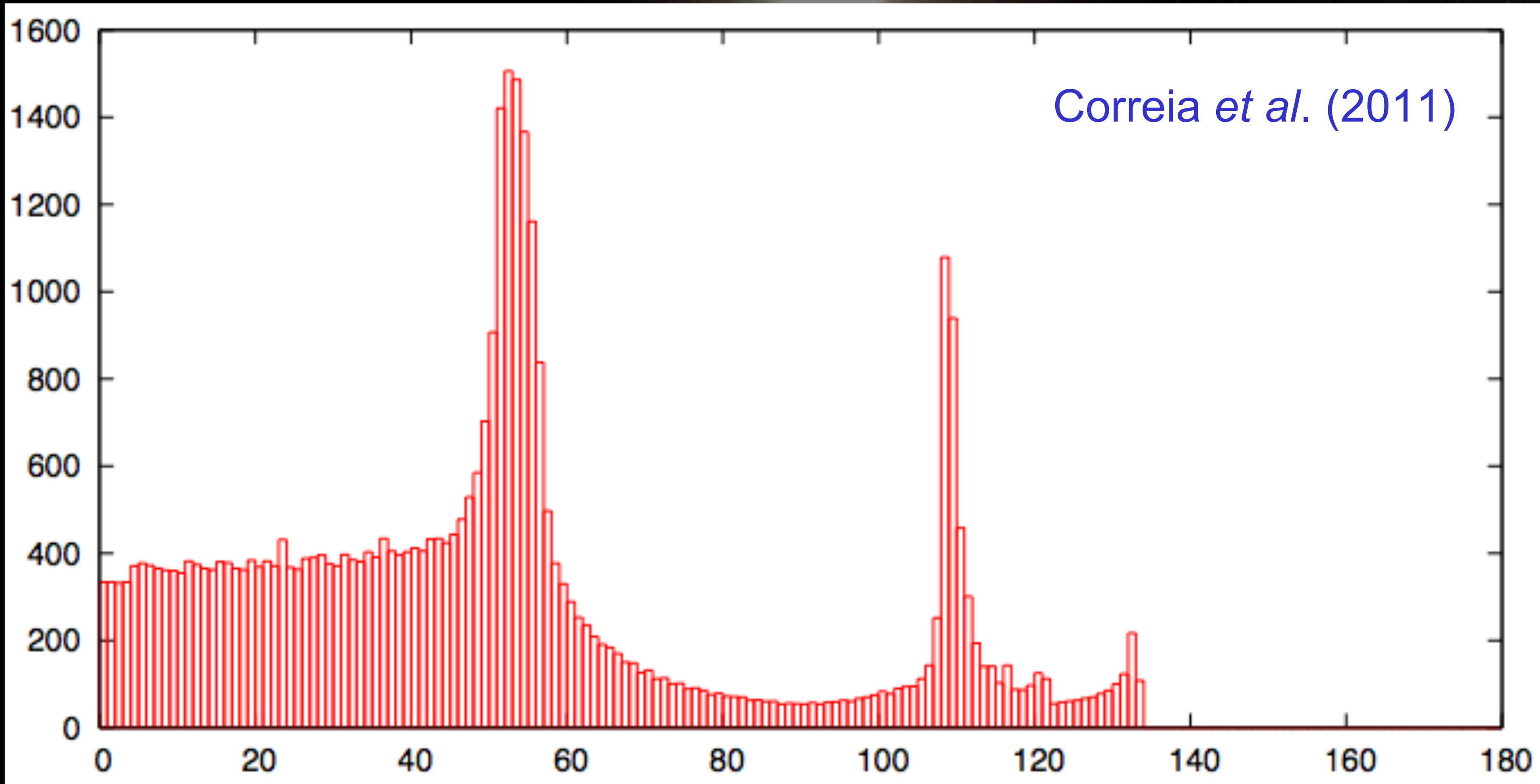
inclination / obliquity



time (Myr)

Wu & Murray (2002)
Frabrycky & Tremaine (2007)
Correia *et al.* (2011)

HD 80606 - misalignment



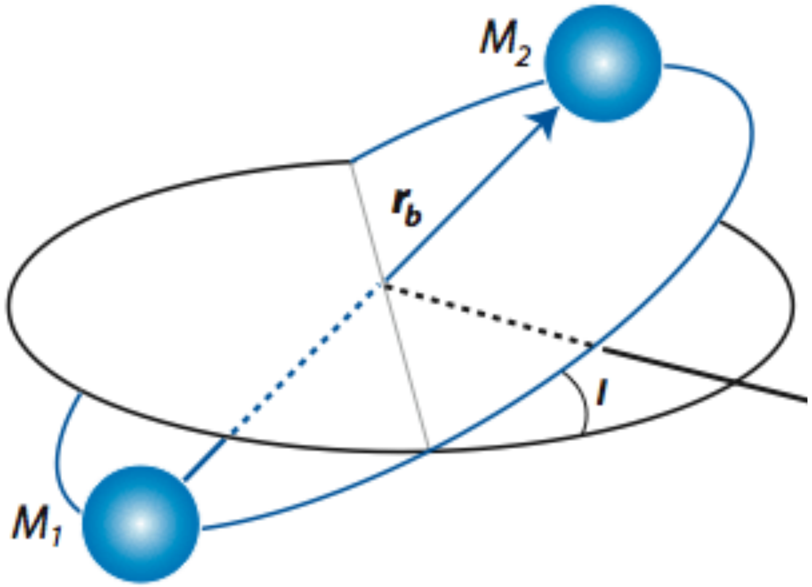
Rossiter-McLaughlin median projected angle = 50º
(Pont *et al.* 2009)

HD 98800

Torres et al. 1995

Boden et al. 2005

$a_b = 0.98$ AU, $e_b = 0.79$,
$M_1 = 0.7\ M_{sun}$, $M_2 = 0.6\ M_{Sun}$



It has a large infrared excess attributed to a circumbinary disc. Substantial extinction suggests that the pair is observed through some of this material.

Modeling indicate that this is a T Tauri transition disc that is just reaching the debris disc stage, with a collisional cascade having been recently initiated...

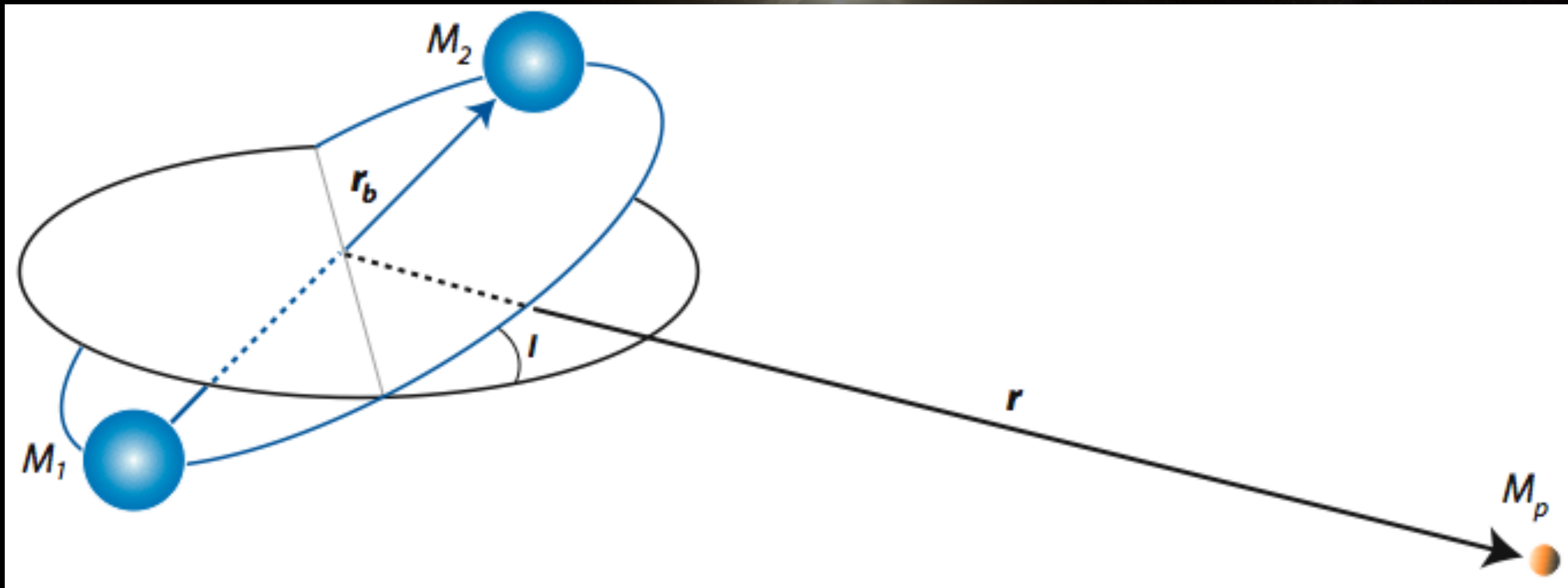
HD 98800

Torres et al. 1995

Boden et al. 2005

a_b = 0.98 AU, e_b = 0.79,

M_1 = 0.7 M_{sun}, M_2 = 0.6 M_{Sun}



I ~ 23º

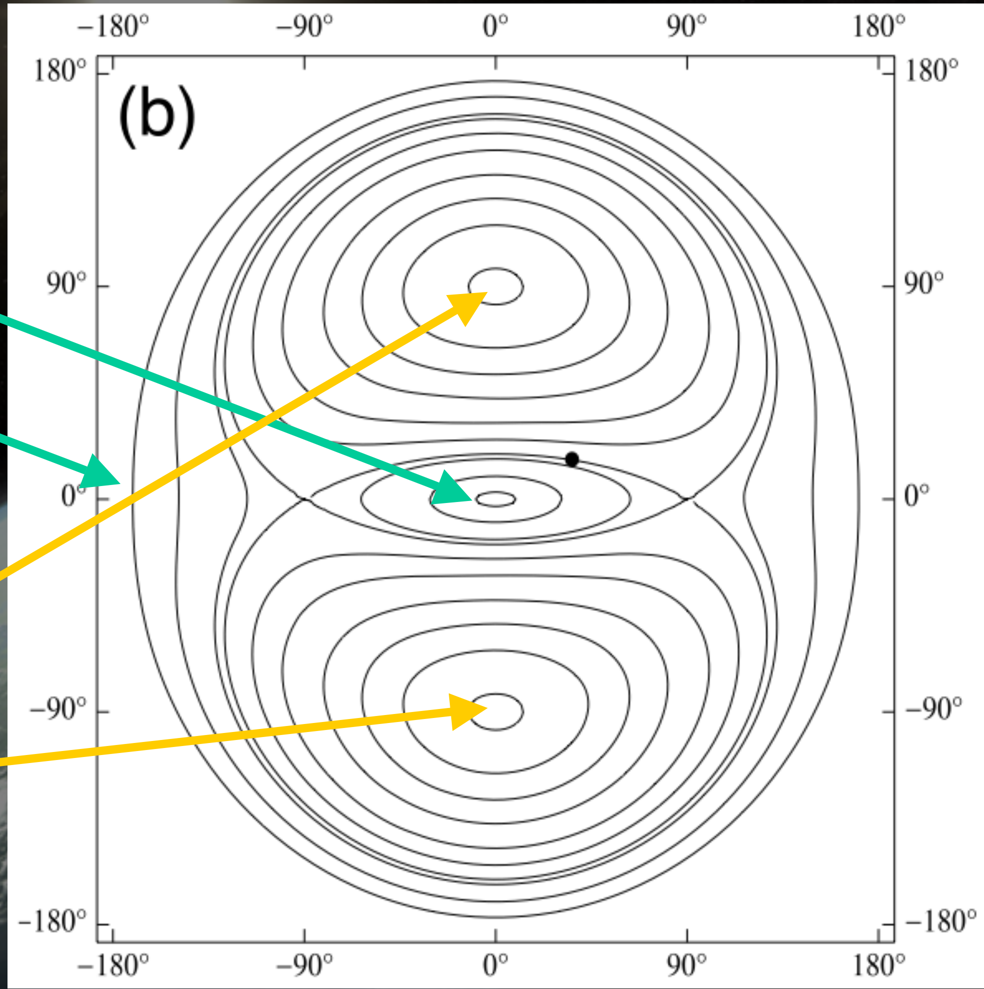
a_p = 5.2 AU, e_p = 0.5, M_p = 1 M_{Jup}

HD 98800

e = 0.79

L_2 precesses around *L_1* *(or -L_1)*

L_2 precesses around **e_1** (or -**e_1**)



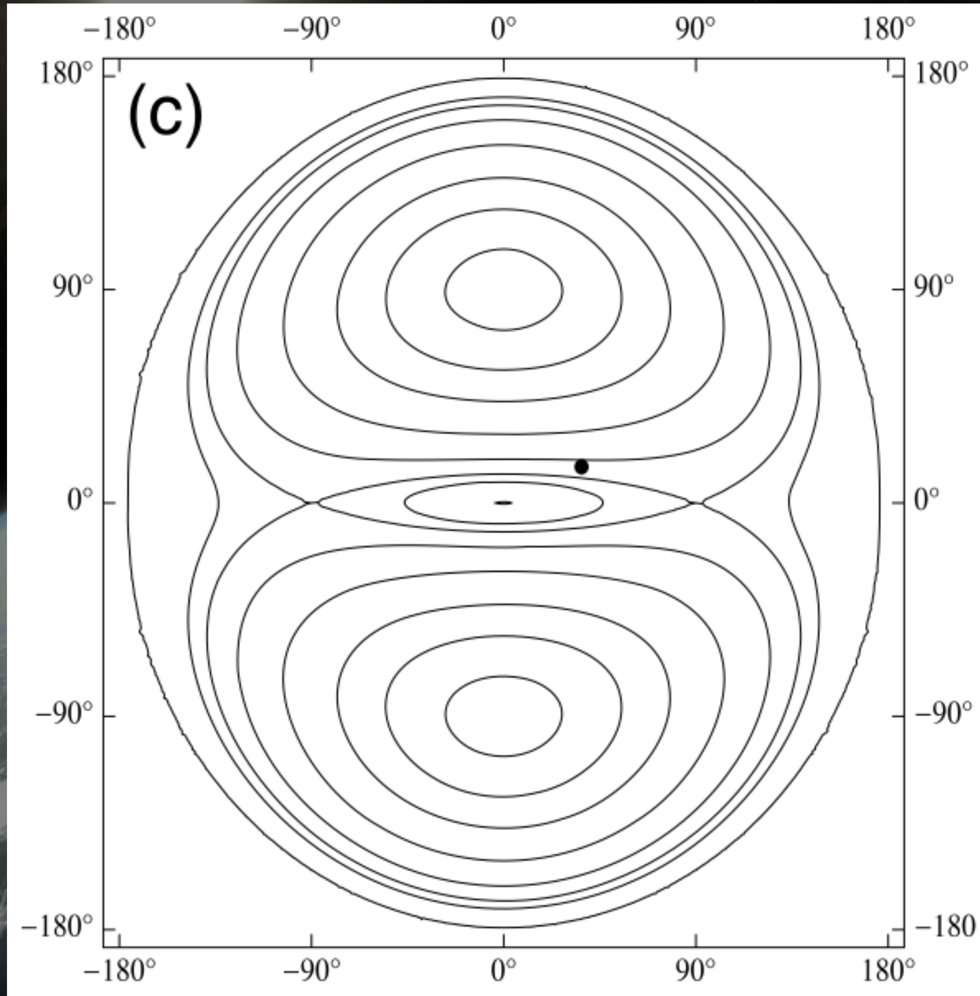
(I sin ω, I cos ω)

(Farago & Laskar, 2010)

HD 98800

e = 0.9

L_2 precesses around ***e_1***

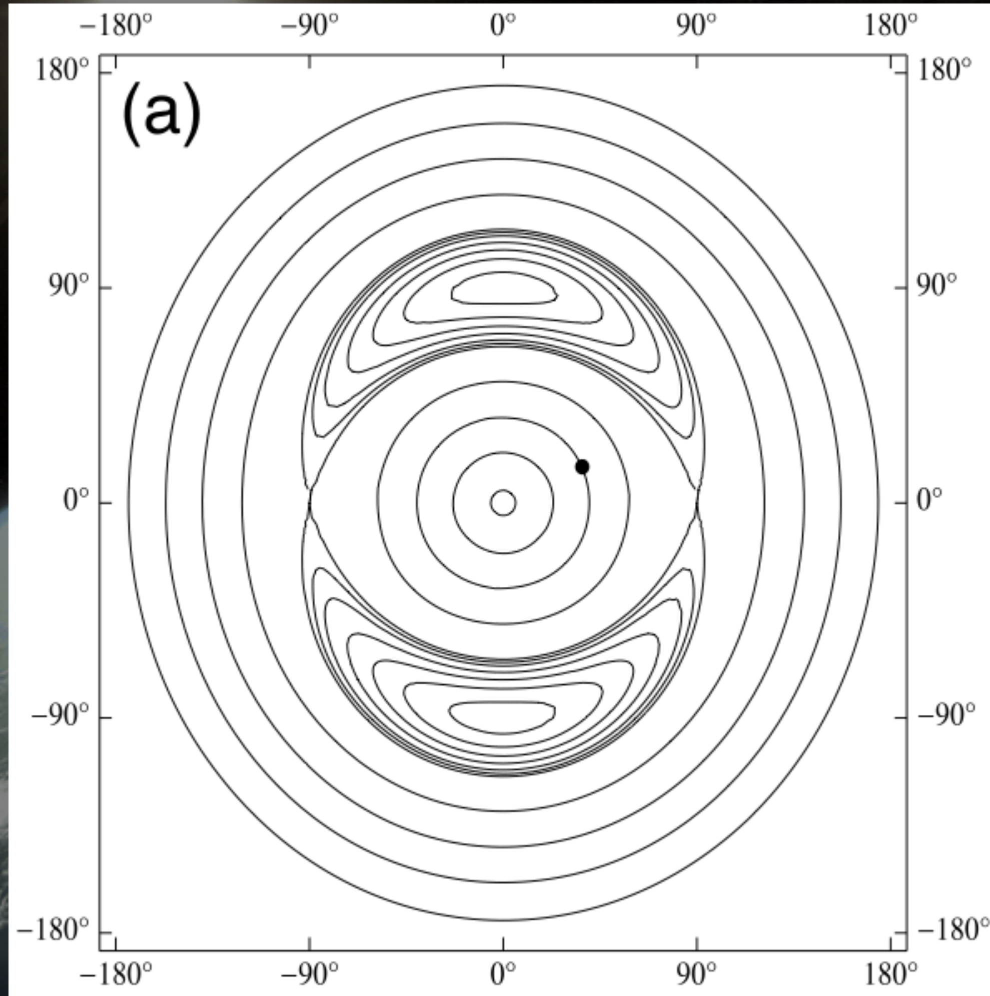


(I sin ω, I cos ω)

HD 98800

$e = 0.5$

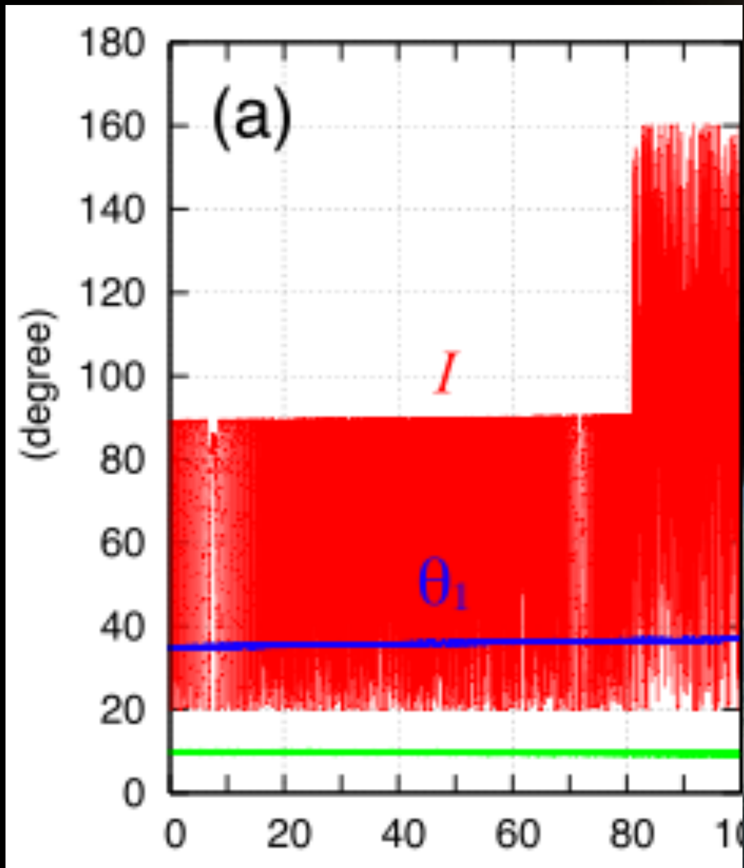
L_2 precesses around L_1



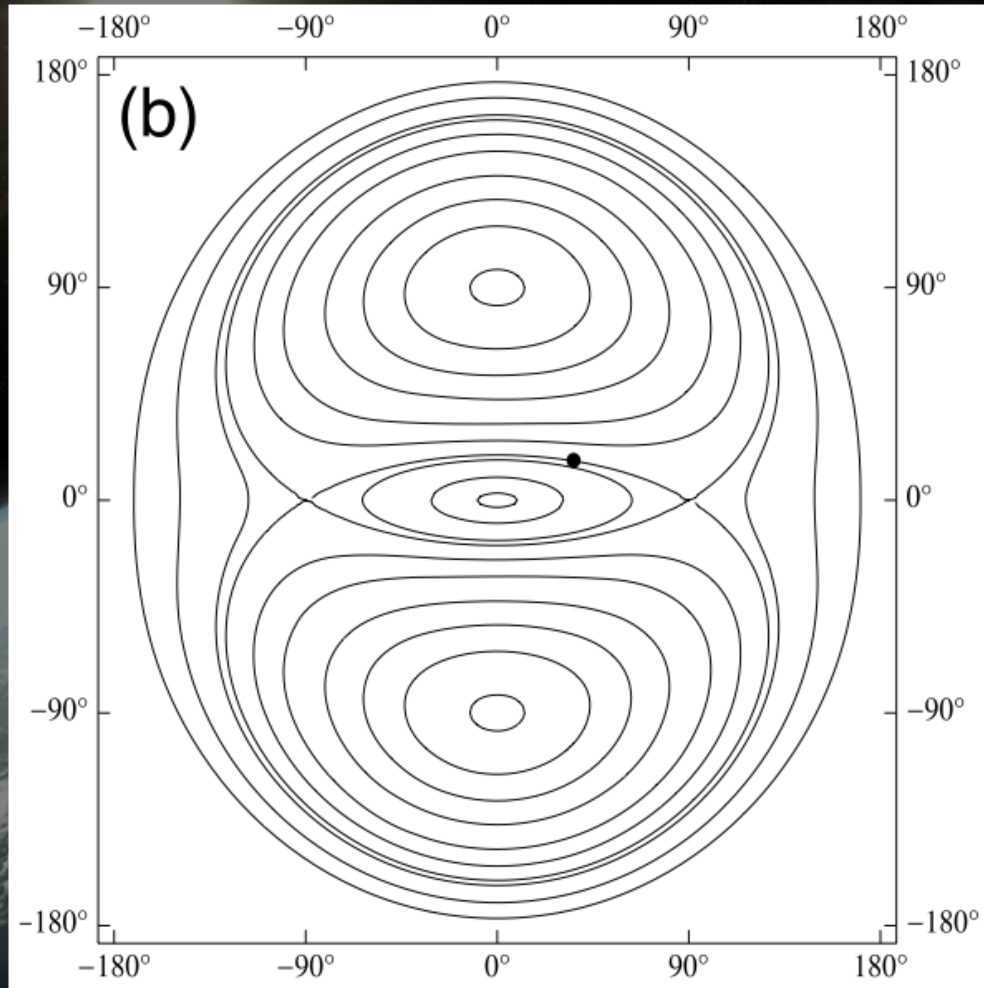
$(I \sin \omega, I \cos \omega)$

HD 98800

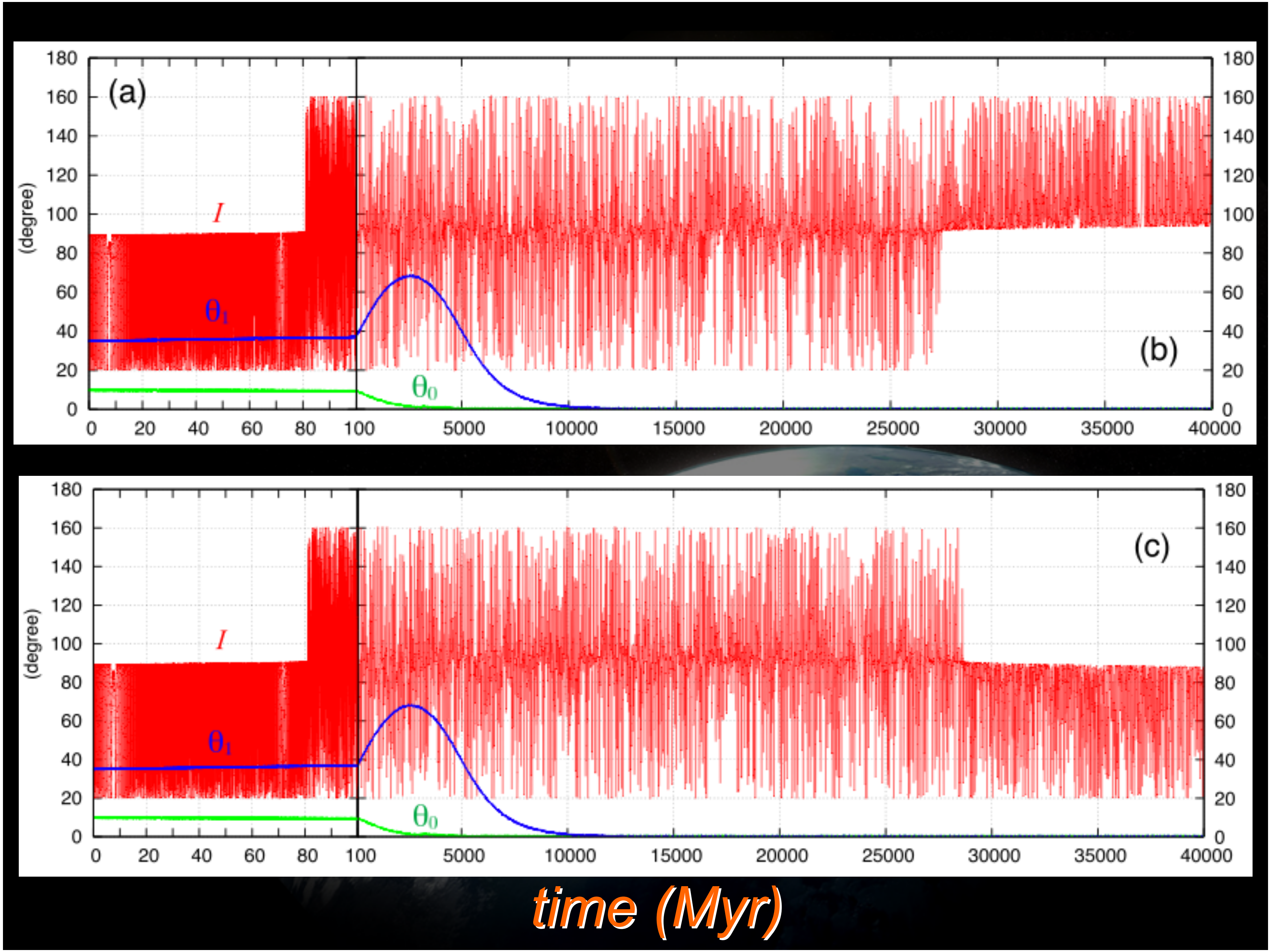
e = 0.79



time (Myr)



(I sin ω, I cos ω)



(a)
(b)
(c)
I
θ_1
θ_0
(degree)
0
20
40
60
80
100
120
140
160
180
100
5000
10000
15000
20000
25000
30000
35000
40000
time (Myr)

Conclusions

- Tidal effects are responsible for a slow secular evolution of the spins and orbits of close-in exoplanets.
- Tidal effects alone align the spin axis, synchronize the rotation and orbital periods, and damp the eccentricity of the orbit.
- Tidal effects combined with planetary perturbations may present unexpected behaviors and lead to stationary equilibriums for the spin and the orbits.
- In the restricted inner problem, a body may migrate by means of a tidal-Kozai mechanism. In the restricted outer problem, initial prograde orbits may become retrograde and vice-versa.