"Tidal evolution of close-in planets using a Maxwell visco-elastic rheology"

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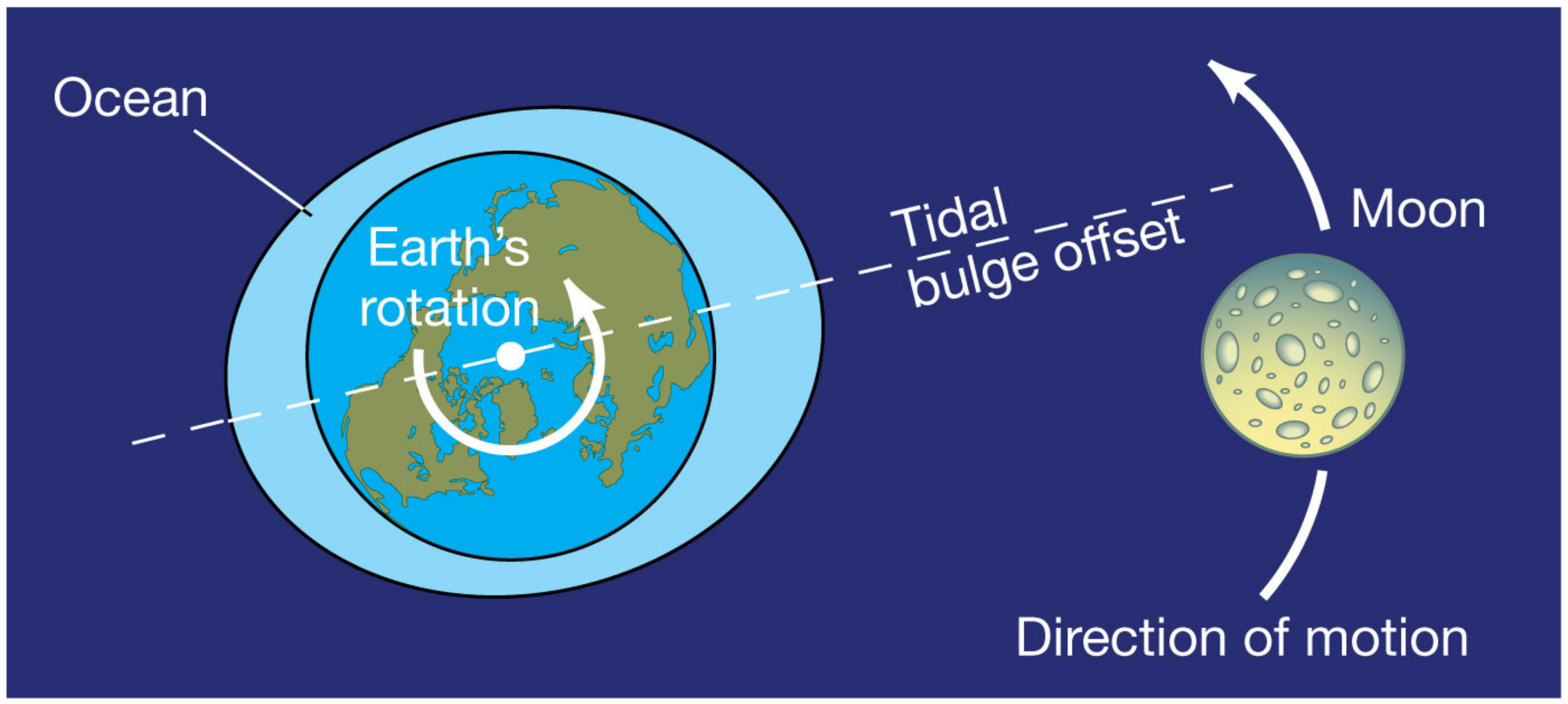
Tidal effects



Global Picture:

Poincaré (1898)

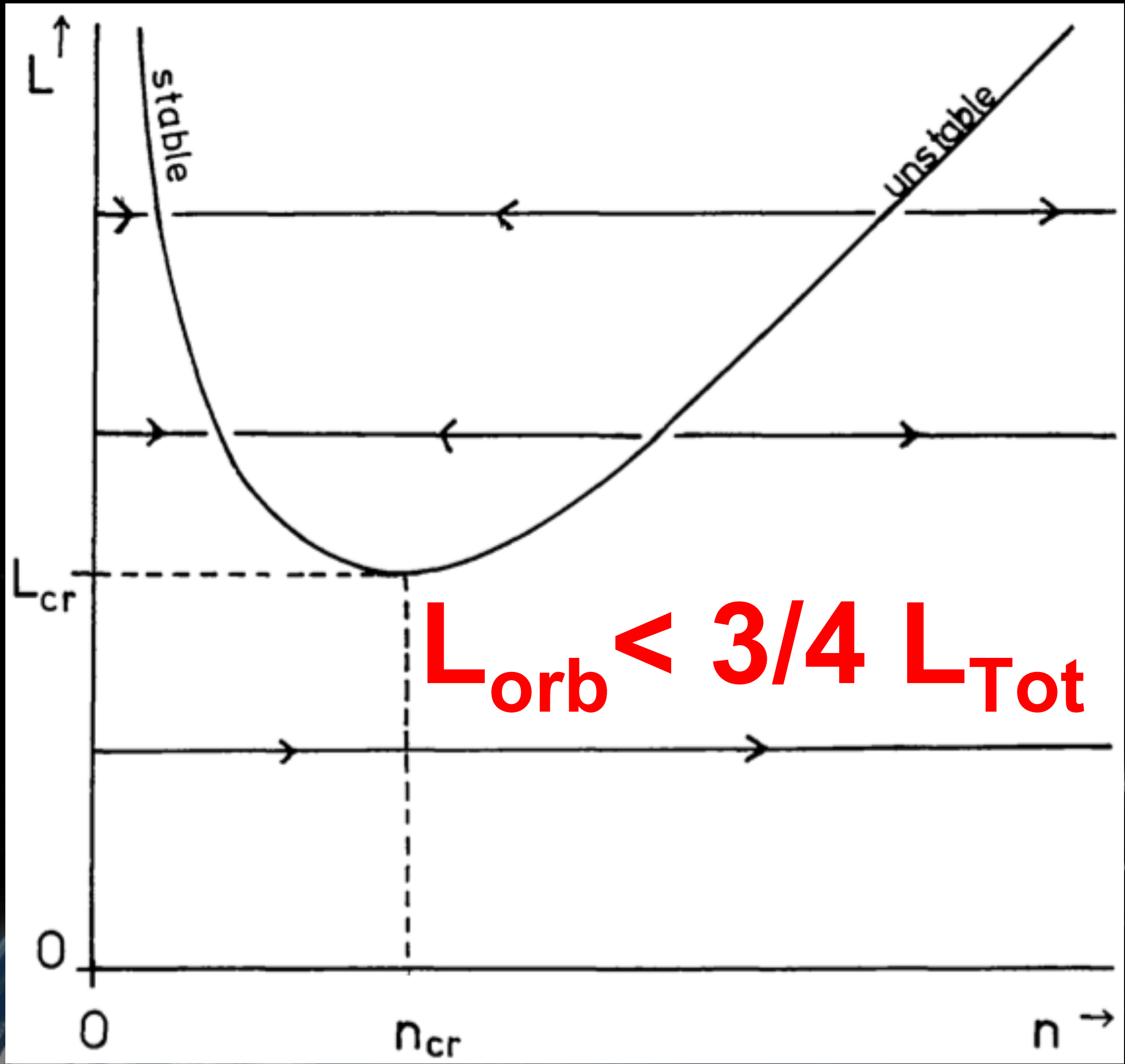
Landau & Lifshitz (1960)

Hut (1980)

$P_{orb} = P_{rot}$

pependicular axis (ε=0)

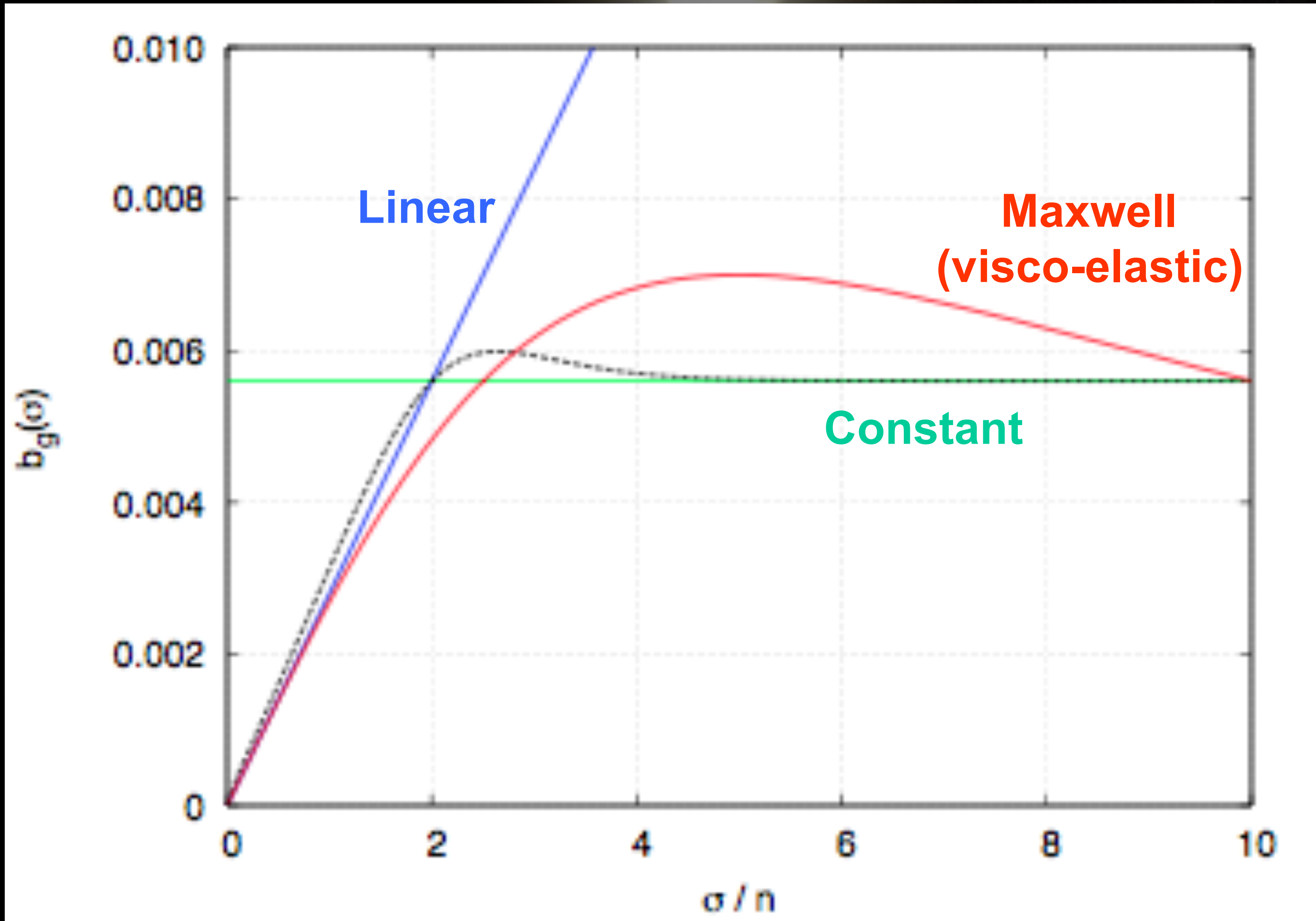
circular orbits (e=0)



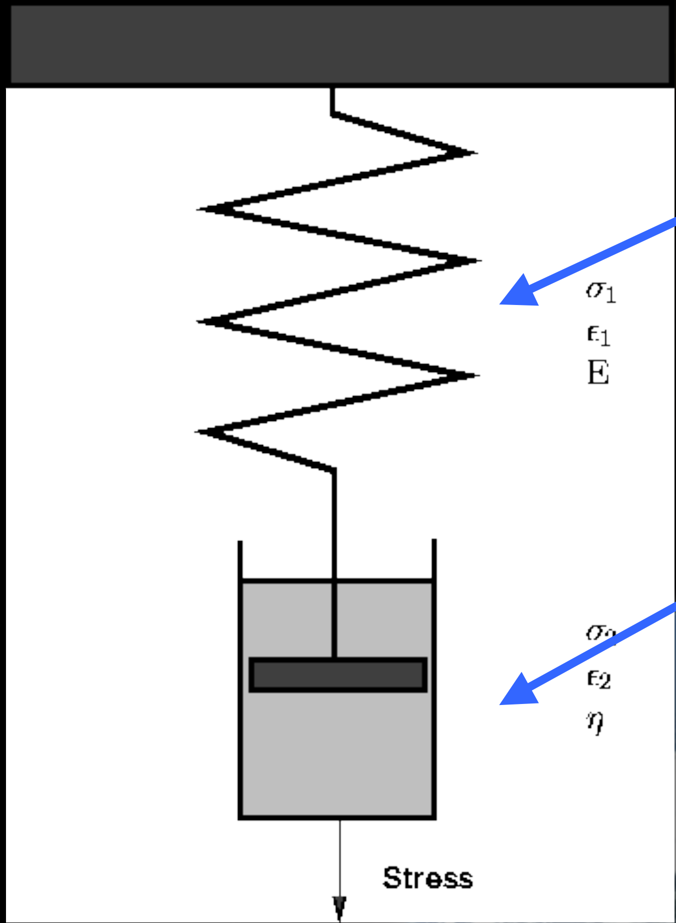
$L_{orb} < 3/4\ L_{Tot}$

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

Tidal models



Maxwell model (1867)



elastic

stress $$\sigma = E\,\epsilon$$ strain

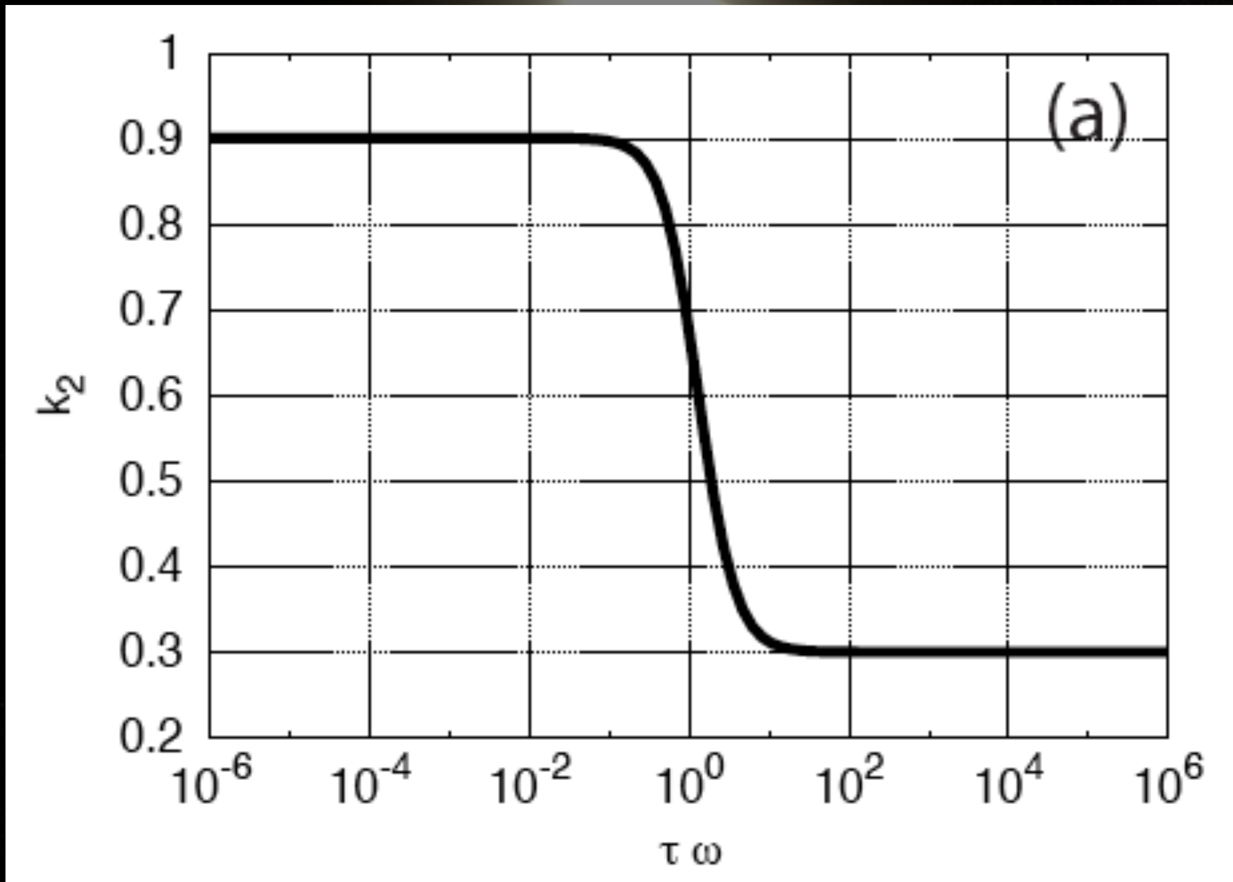
viscous

$$\sigma = \eta\, d\epsilon / dt$$

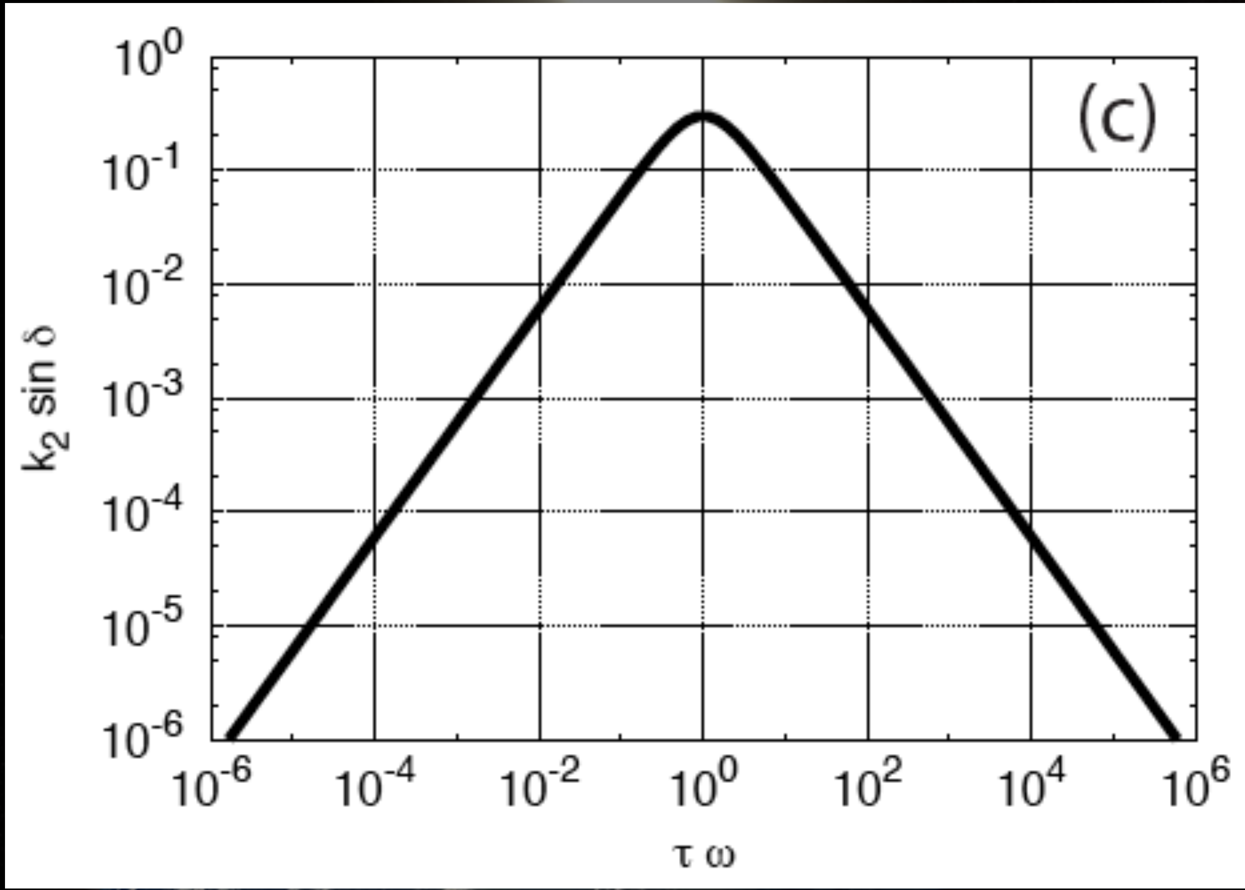
$$\frac{d\epsilon_{\text{Total}}}{dt} = \frac{d\epsilon_D}{dt} + \frac{d\epsilon_S}{dt} = \frac{\sigma}{\eta} + \frac{1}{E}\frac{d\sigma}{dt}$$

$$\frac{1}{E}\frac{d\sigma}{dt} + \frac{\sigma}{\eta} = \frac{d\epsilon}{dt}$$

Deformation



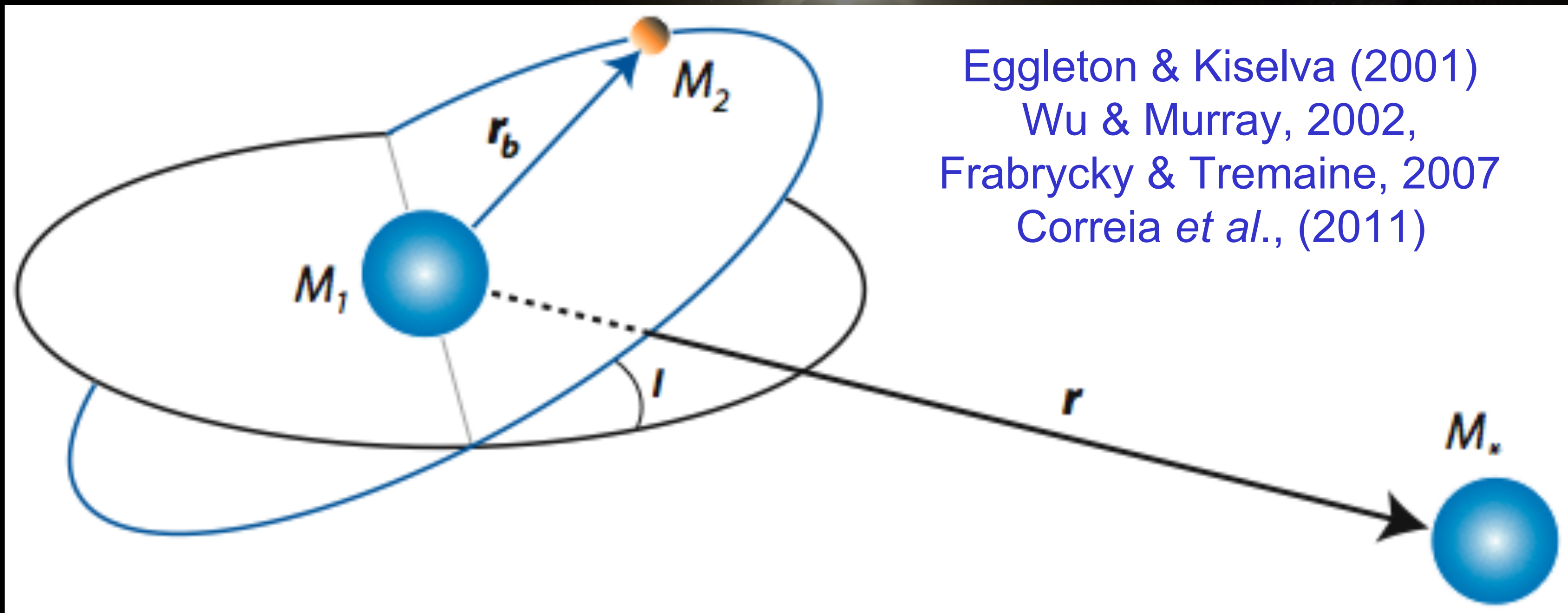
Dissipation



HD 80606

Naef et al, 2001

(a_p = 0.45 AU, e_p = 0.92)

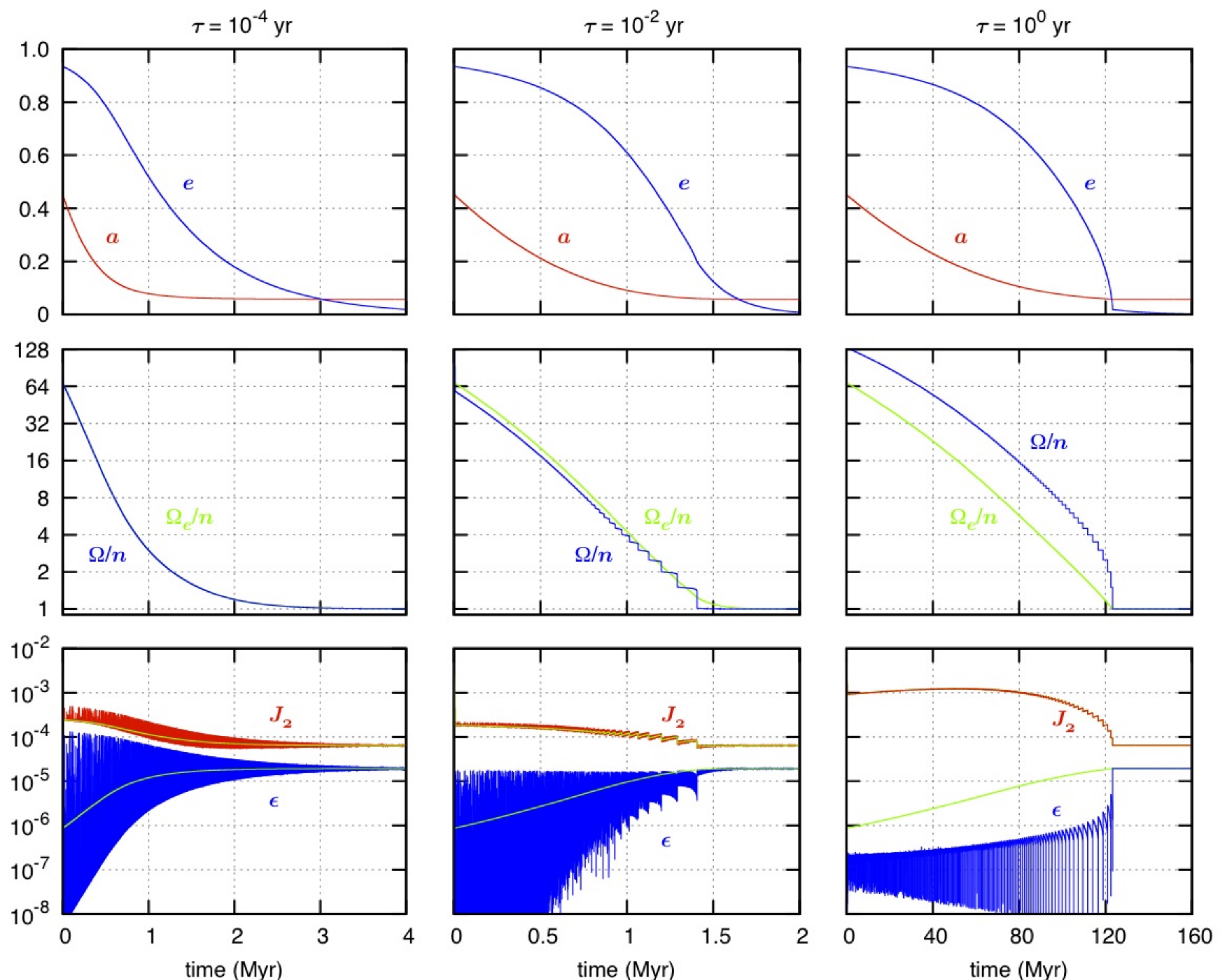


Kozai effect:

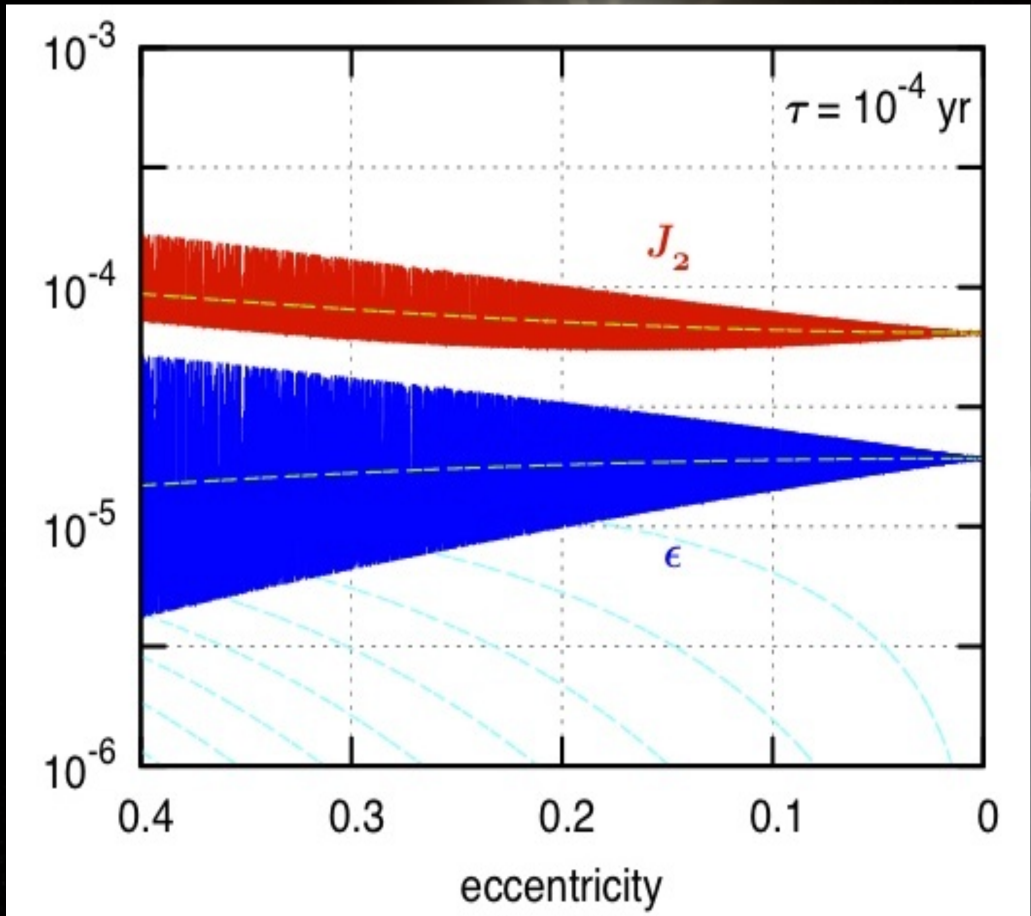
(*I* > 39º)

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

HD 80606 (n ~ 10-2 yr)



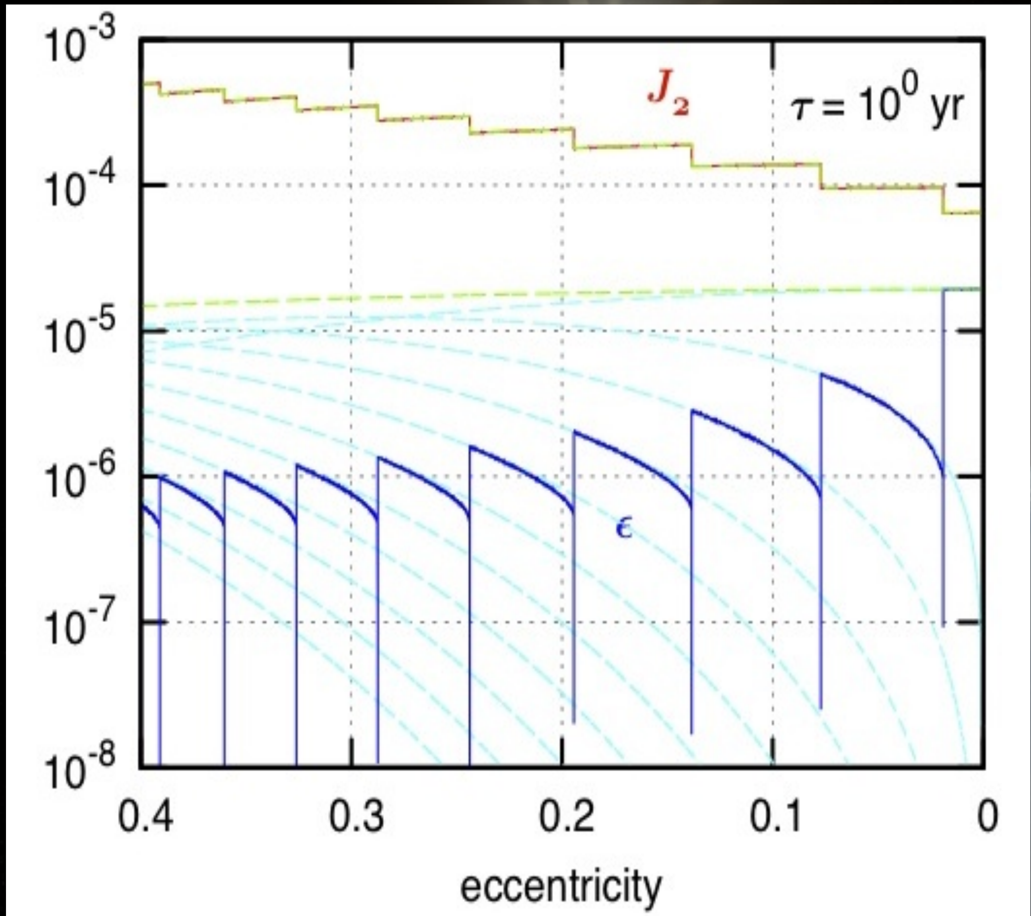
HD 80606 - deformation (τ << 1/n)



$$\langle \epsilon \rangle_M = \frac{k_f}{4} \frac{m_0}{m} \left(\frac{R}{a} \right)^3 (1 - e^2)^{-3/2}$$

$$\left\langle \epsilon_p \right\rangle_M = \beta_{2p} = \frac{k_f}{4} \frac{m_0}{m} \left(\frac{R}{a} \right)^3 X_{2p}^{-3,2}(e)$$

HD 80606 - deformation ($\tau \gg 1/n$)



$$\langle \epsilon \rangle_M = \frac{k_f}{4} \frac{m_0}{m} \left(\frac{R}{a} \right)^3 (1 - e^2)^{-3/2}$$

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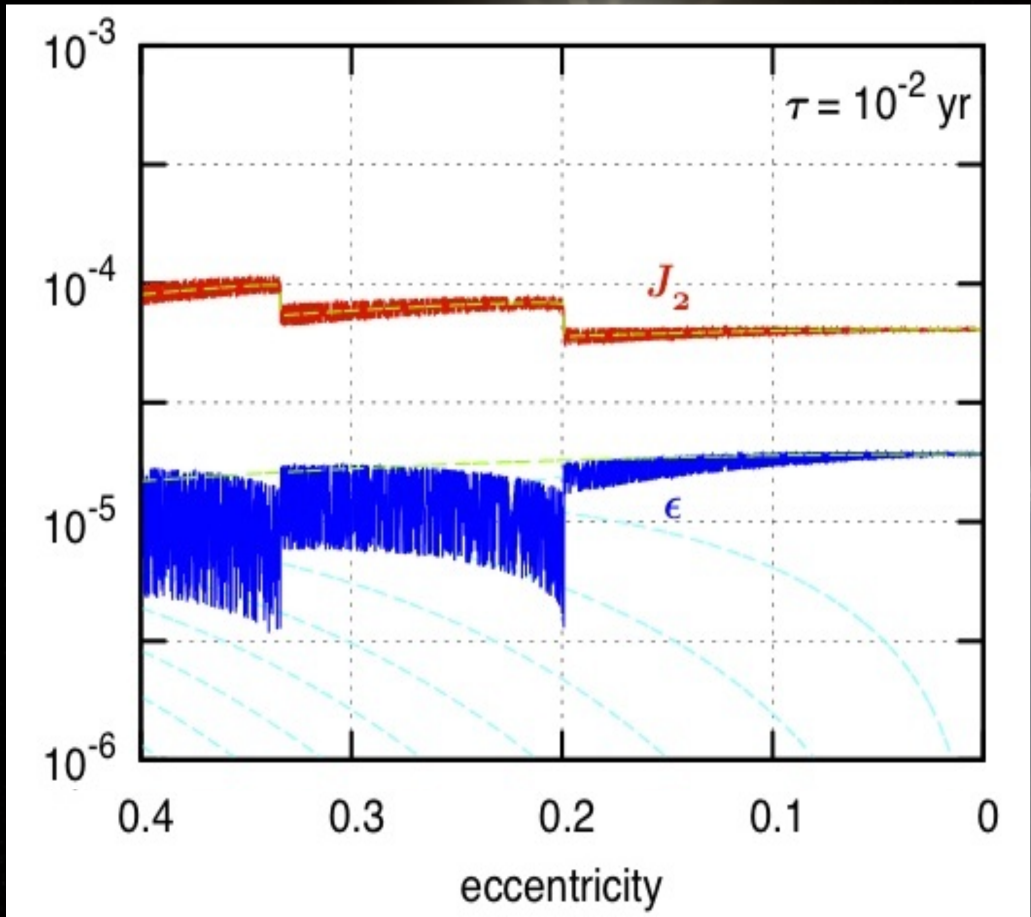
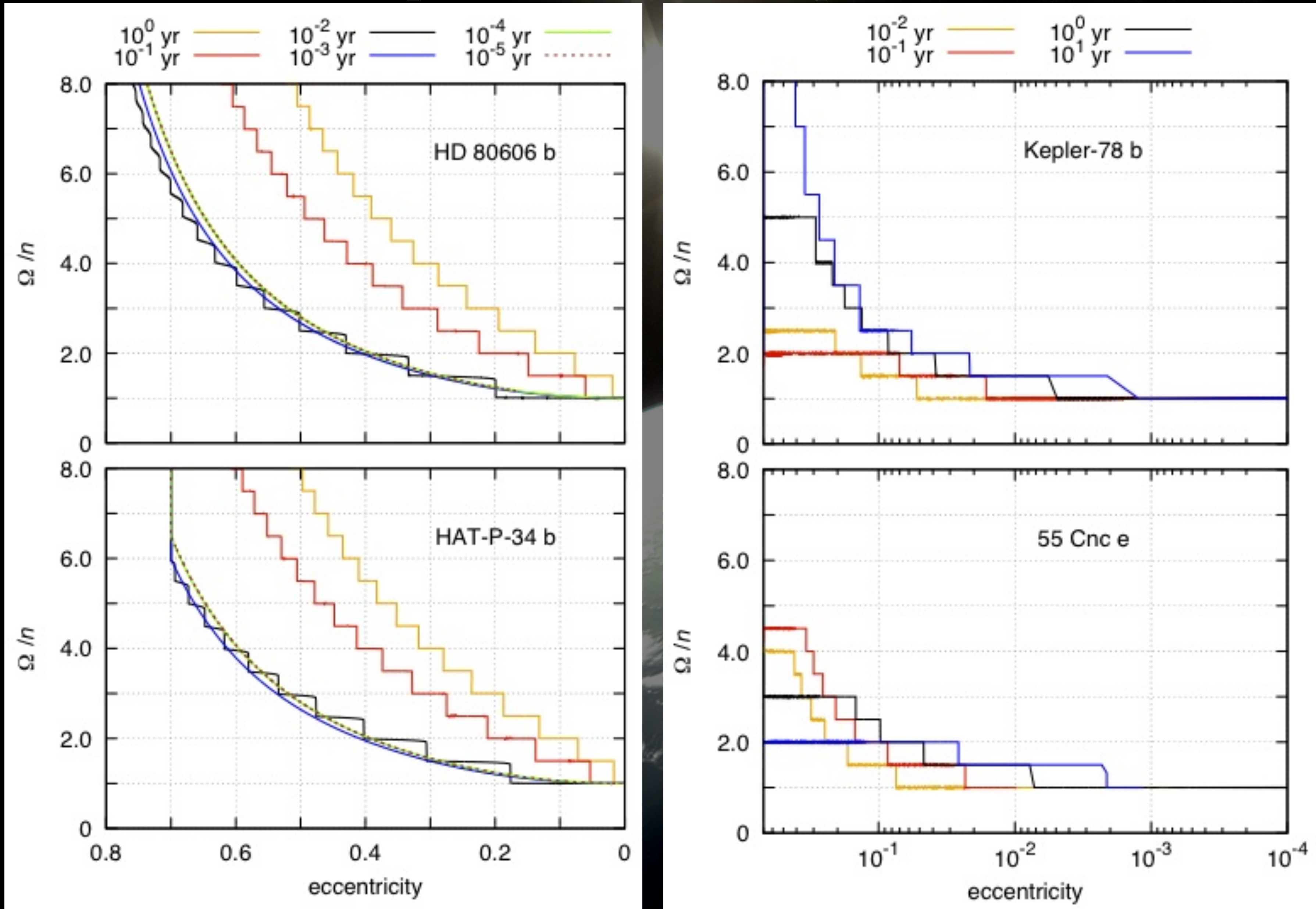
HD 80606 - deformation (τ ~ 1/n)



$$\langle \epsilon \rangle_M = \frac{k_{\rm f}}{4} \frac{m_0}{m} \left(\frac{R}{a} \right)^3 (1 - e^2)^{-3/2}$$

$$\left\langle \epsilon_p \right\rangle_M = \beta_{2p} = \frac{k_{\rm f}}{4} \frac{m_0}{m} \left(\frac{R}{a} \right)^3 X_{2p}^{-3,2}(e)$$

Hot-Jupiters / super-Earths



Conclusions

- We replaced a Fourier series by a rheological law of deformation of the potential. This allow us to simultaneously take into account deformation and dissipation.
- We no longer need to truncate the series for high eccentricities and we avoid a large number of terms. The deformation is also valid for all tidal regimes.
- Spin-orbit resonances arise naturally when the deformation time-scale is longer than the orbital period. The stability increases with the deformation time-scale.
- For rocky planets, the spin-orbit resonances are possible for very low values of the eccentricity, so we expect that some of these planets are not synchronous with the star.