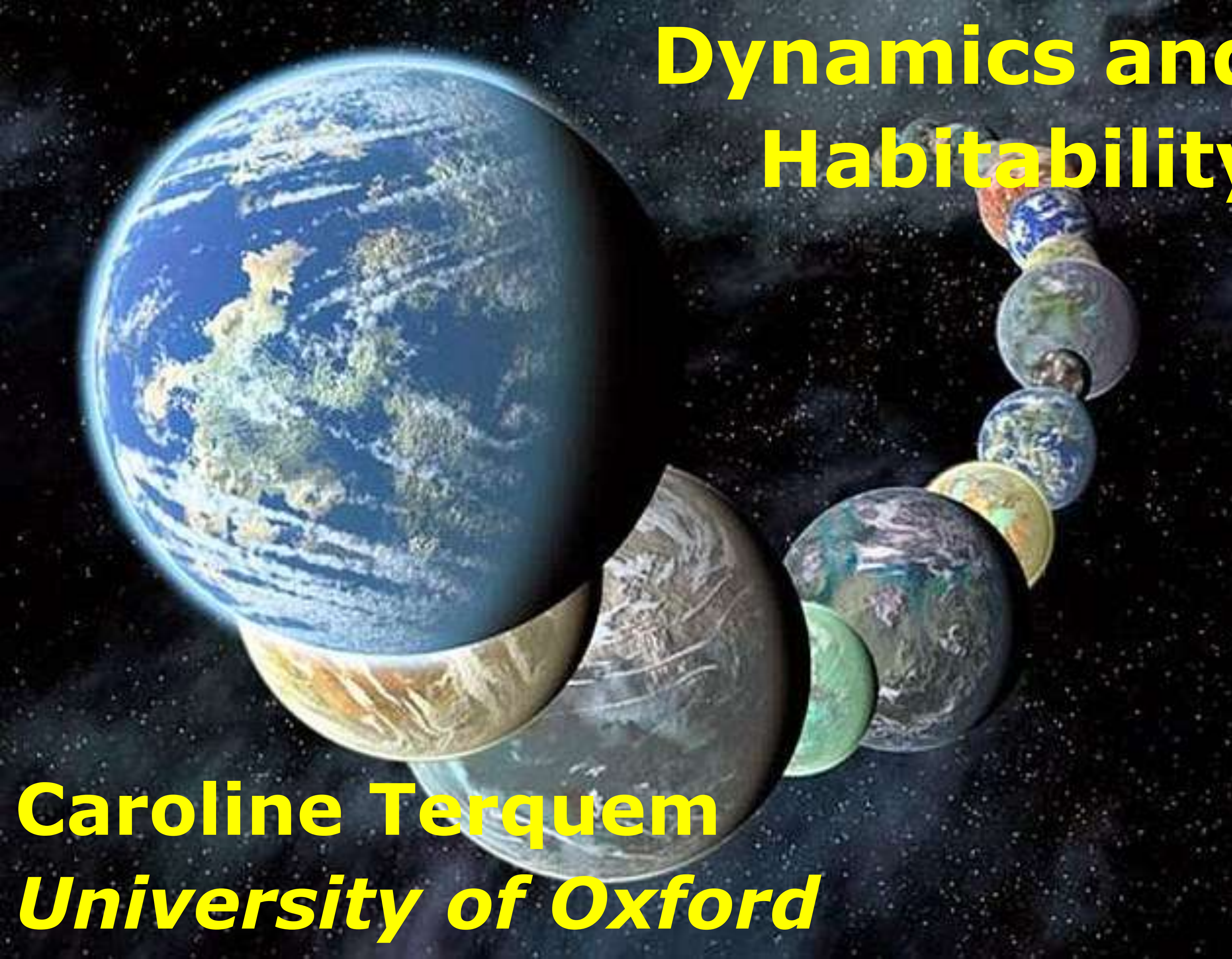

Dynamics and Habitability

Caroline Terquem
University of Oxford

Habitability

Atmospheric habitability:

Liquid water is required in the atmosphere over geological timescales for the development of carbon-based life (Kasting et al. 1993).

Dynamical habitability:

Dynamical requirement that terrestrial planets in the habitable zone are not taken out of this zone by gravitational interactions with stars or other planets.

PROCEEDINGS OF THE ROYAL SOCIETY A | MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Dynamical, biological and anthropic consequences of equal lunar and solar angular radii

Steven A. Balbus

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The nearly equal lunar and solar angular sizes as subtended at the Earth is generally regarded as a coincidence. This is, however, an incidental consequence of the tidal forces from these bodies being comparable. Comparable magnitudes implies strong temporal modulation, as the forcing frequencies are nearly but not precisely equal. We suggest that on the basis of palaeogeographic reconstructions, in the Devonian period, when the first tetrapods appeared on land, a large tidal range would accompany these modulated tides. This would have been conducive to the formation of a network of isolated tidal pools, lending support to A. S. Romer's classic idea that the evaporation of shallow pools was an evolutionary impetus for the development of chiridian limbs in aquatic tetrapodomorphs. (…)

Habitable zone

For 0.3 to 10 M_{Earth} planets around a 1 $M_{\odot}$ star, the habitable zone is between 0.7 and 1.3 AU (Kasting et al. 1993).

Eccentric planet:

Eccentric planet: $r_{min}=(1-e)a$, $r_{max}=(1+e)a$
For a=1 AU, the planet has excursions outside the habitable zone for **e>0.3** (but large variations in insolation for smaller e)

An eccentric planet may also enter the interaction zone of a giant planet, which is $3R_{Hill}=3a'(m'/3M_*)^{1/3}$.

Generating an eccentricity

Scattering

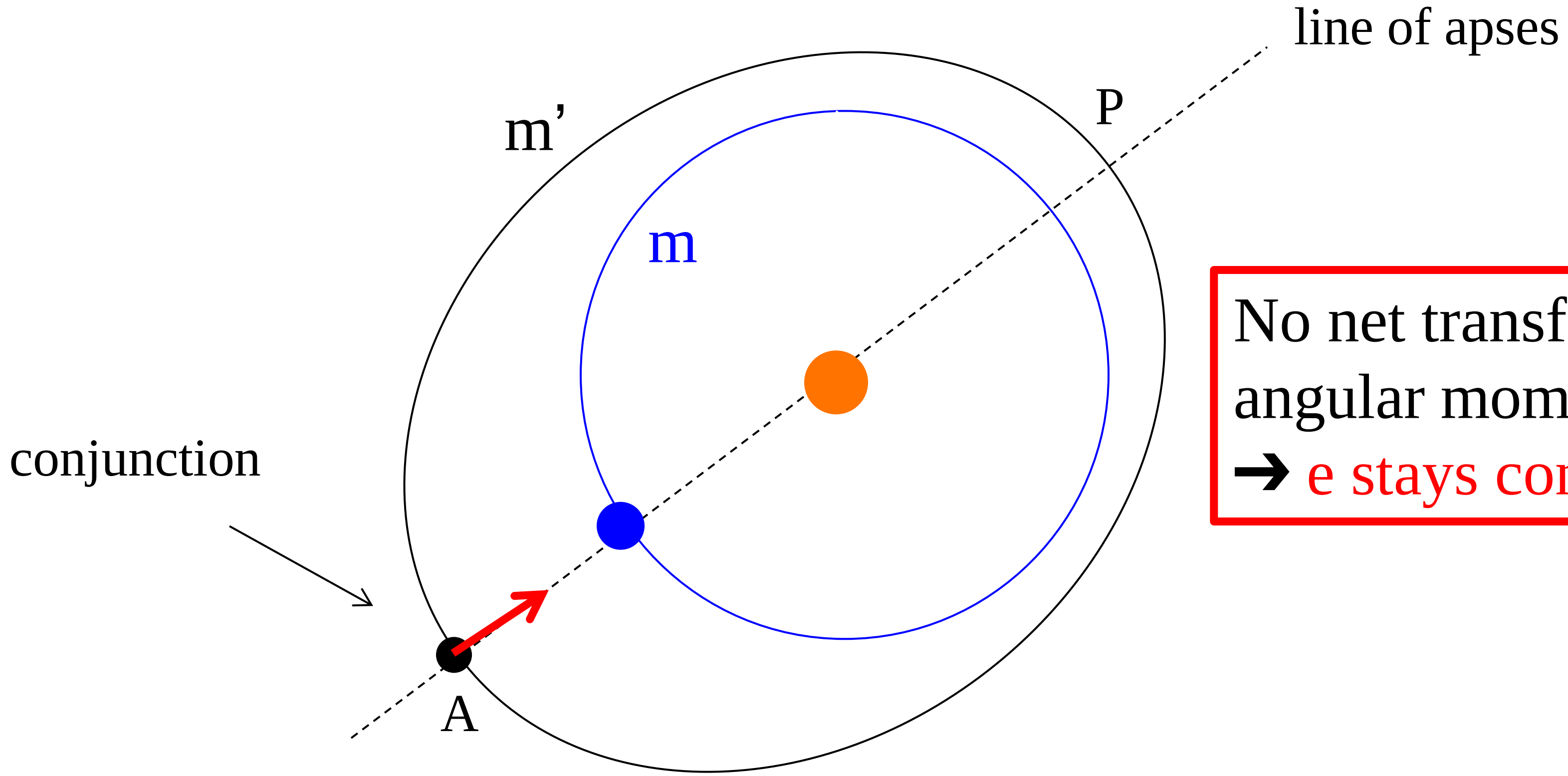
Mean motion resonances: commensurability of the frequencies of orbital revolution

Secular variations: perturbation ➔ precession of the direction of pericenter and precession of the line of nodes ➔ quasi-periodic variations of the eccentricity and inclination

Secular resonances: commensurability of the frequencies of orbital precession (e.g Kozai-Lidov)

Mean motion resonances

Commensurate mean motions:

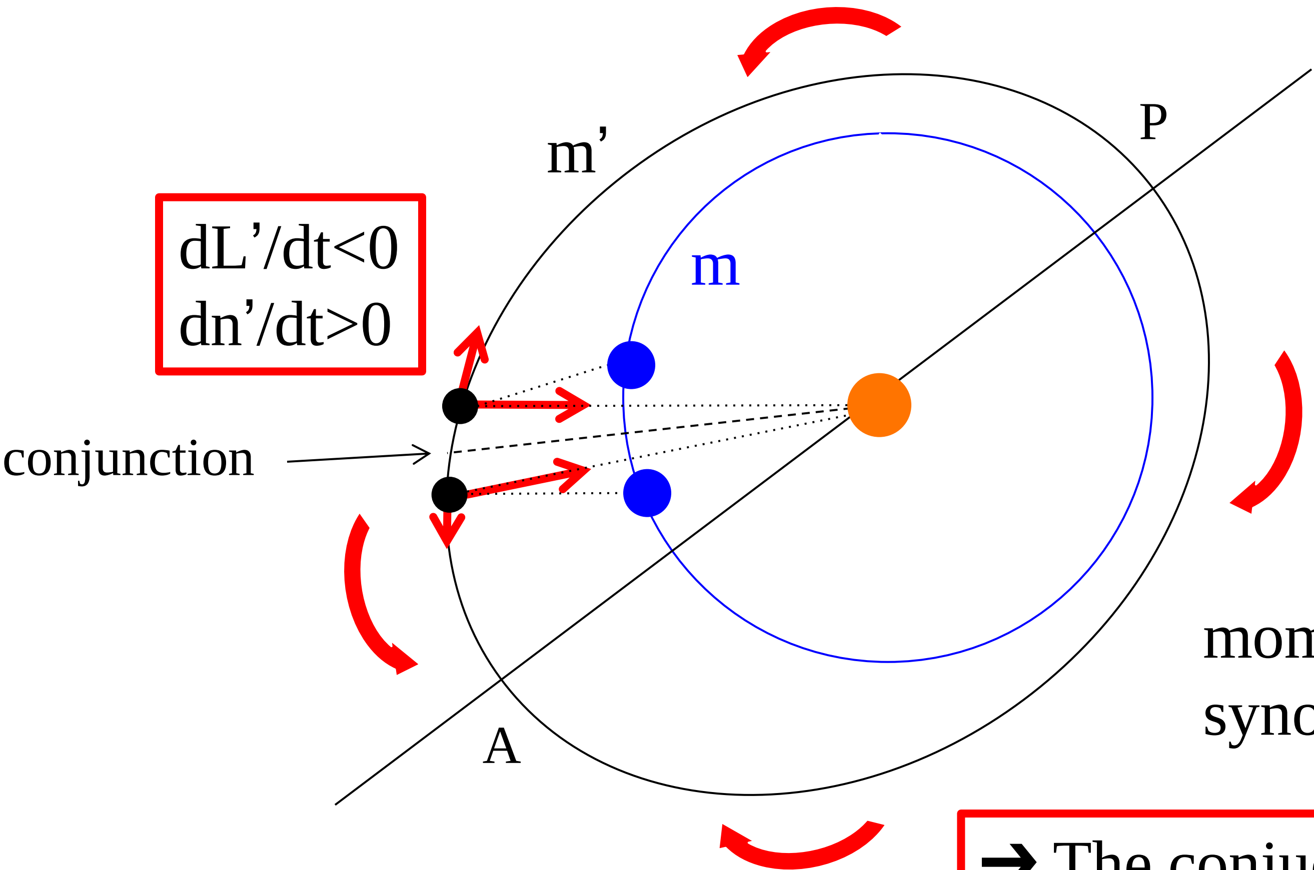


No net transfer of angular momentum
➔ e stays constant

If the line of apses precesses (interaction between planets), the position of the conjunction librates stably around it, preserving the commensurability.

(Goldreich 1965, Peale 1976, Murray & Dermott 1999)

The Physics of resonance



Net loss of angular momentum by m’ over a synodic period.

➔ The conjuctions librate stably about the apocenter, preserving the commensurability.

Mean motion resonances

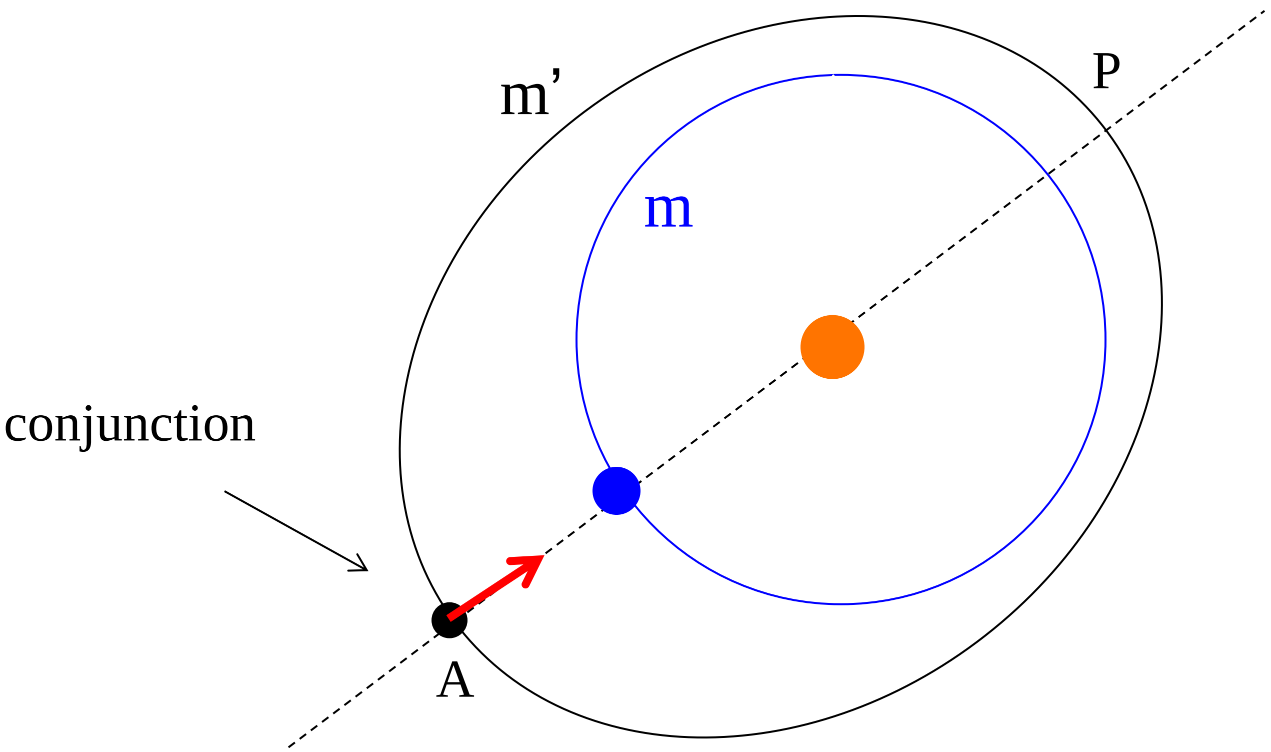
The resonance is stable only if conjunction happens when the two masses are far apart. When the eccentricities are small, this corresponds to pericenters aligned or antialigned. But sometimes the stable position is asymmetric (Beaugé et al. 2003).

Otherwise, repeated interaction at conjunction disrupts the resonance.

Migrating planets locked in resonances

If m' is pushed inwards (e.g. migration), dL'/dt<0, then Ω' increases and conjuction occurs after apocenter.

Interaction between the planets then increases Ω, i.e. dL/dt<0, such as to bring conjunction back towards apocenter.



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Since conjunction is offset from the line of apses, there is a net transfer of angular momentum that keeps the orbits locked in resonance ➔ e increases

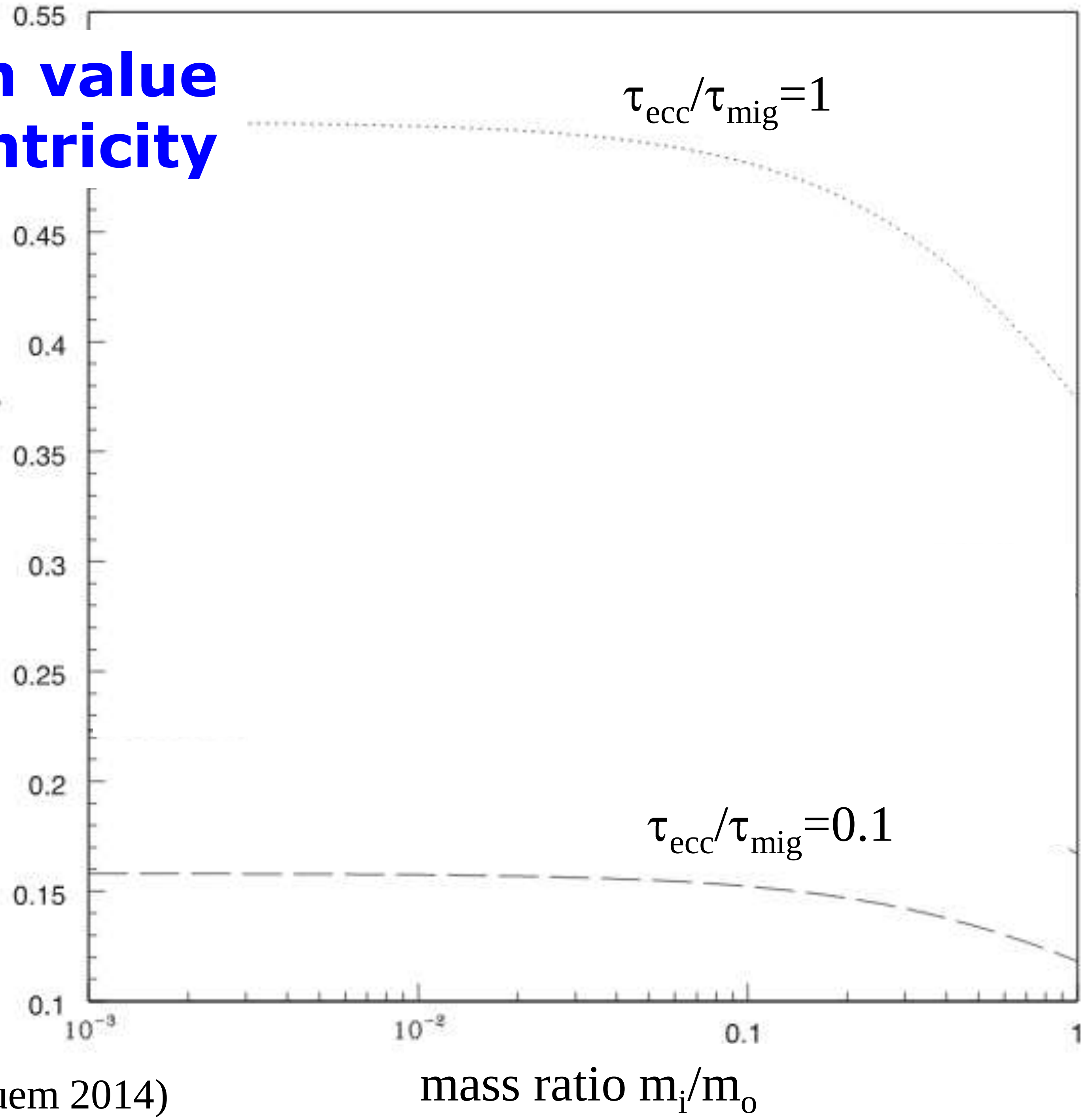
Damping due to the disc ➔ equilibrium value for e

Equilibrium value of the eccentricity

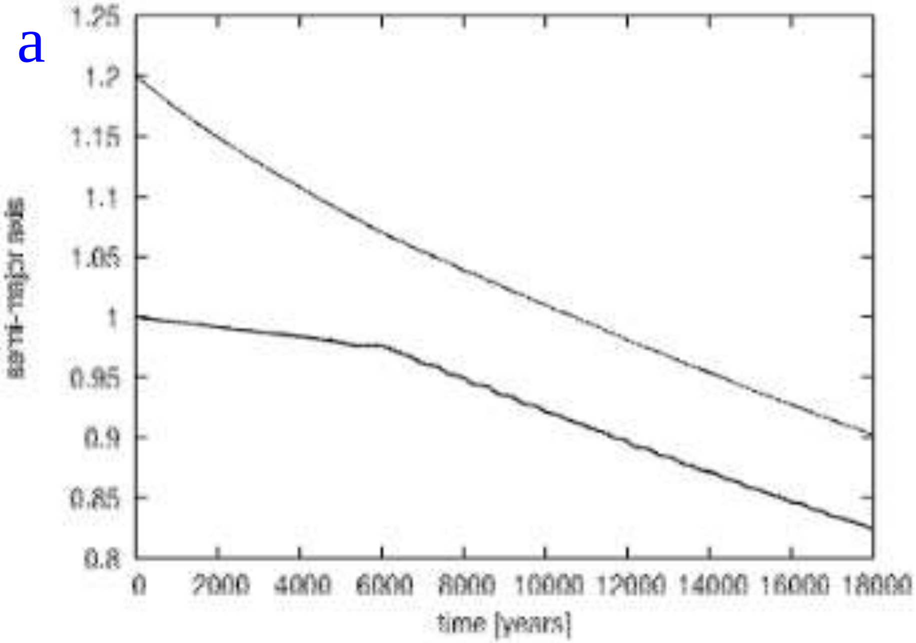
Typically,
$\tau_{ecc}/\tau_{mig} \approx 10^{-2}$

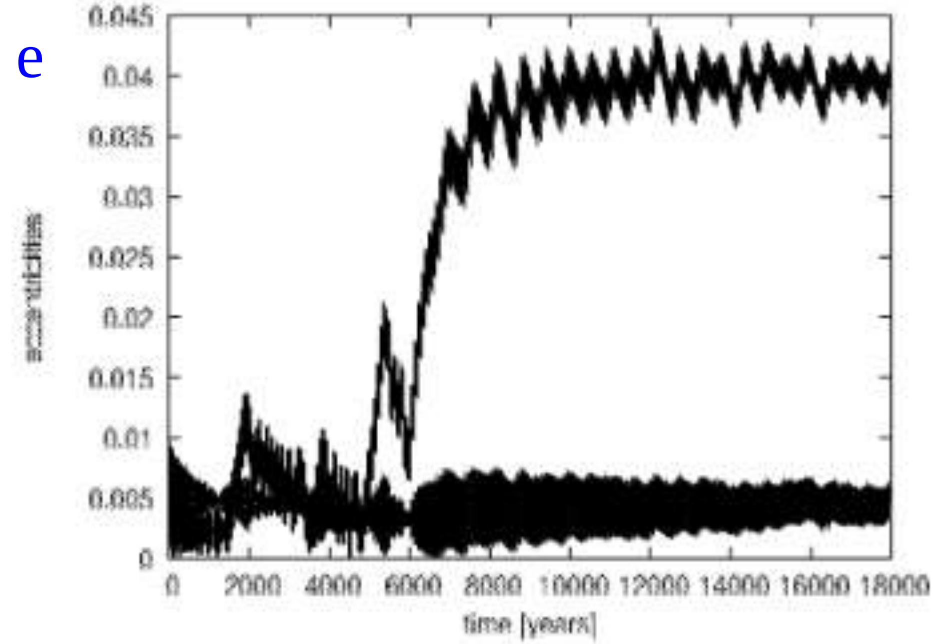
$e \propto (\tau_{ecc}/\tau_{mig})^{1/2}$

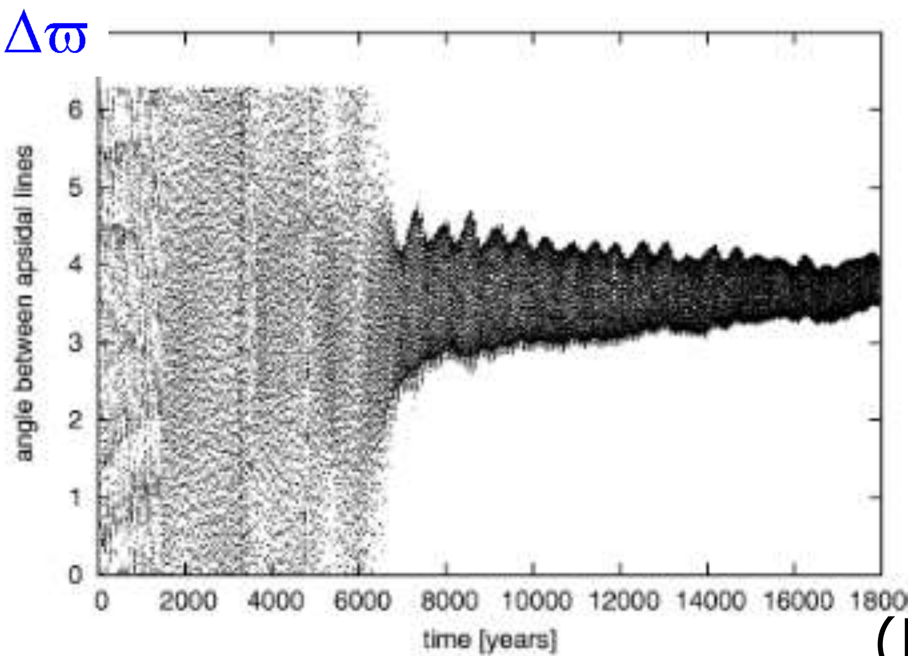
➔ $e < 0.1$



(Teyssandier & Terquem 2014)







m_0=4 M_{Earth}

m_i=1 M_{Earth}

8:7 resonance

(Papaloizou & Szuszkiewicz 2005)

Migrating planets locked in resonances

The evolution during the disc phase is important to stabilize the system, as there is damping.

Has to be taken into account in numerical simulations of systems without disc (initial conditions).

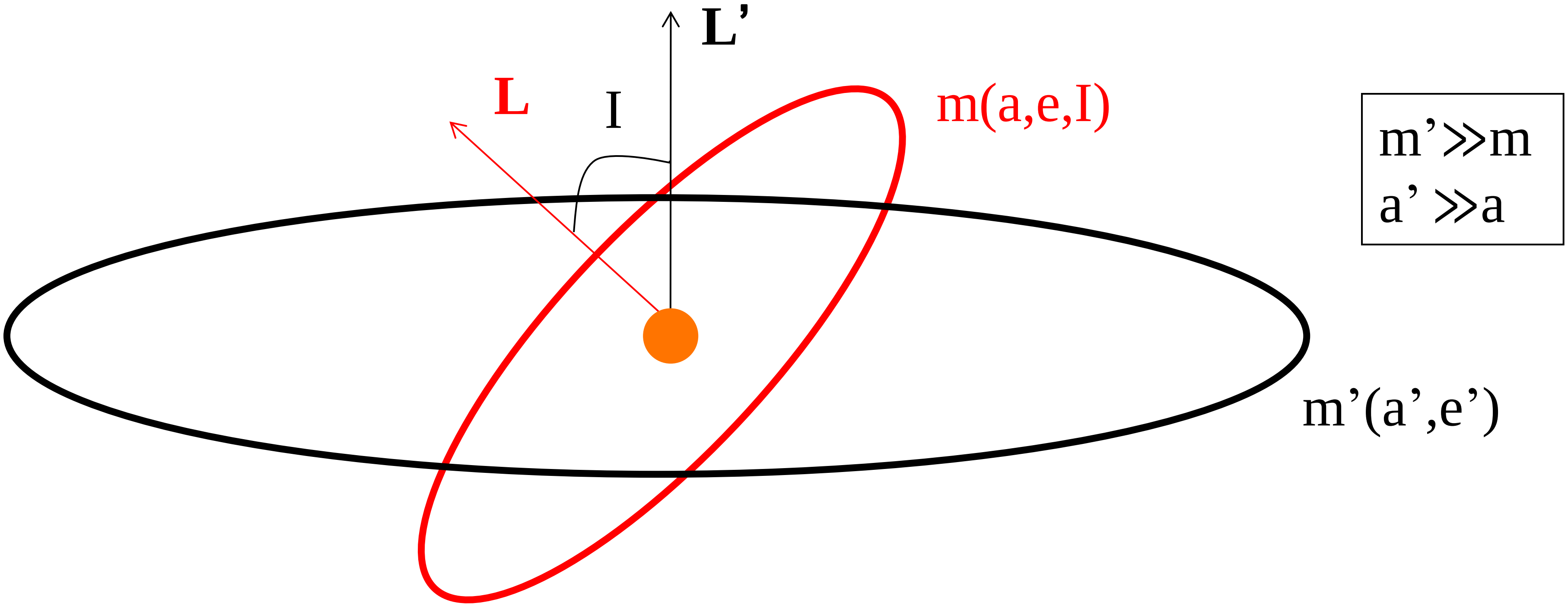
Secular eccentricity variations

Play an important role in the stability of planets in habitable zones when a giant planet is present in the system (Menou and Tabachnik 2003)

Requires numerical integration (see, e.g., Elke Pilat-Lohinger, Rudolf Dvorak, Barbara Funk…)

Kozai-Lidov mechanism

(Kozai 1962, Lidov 1962)



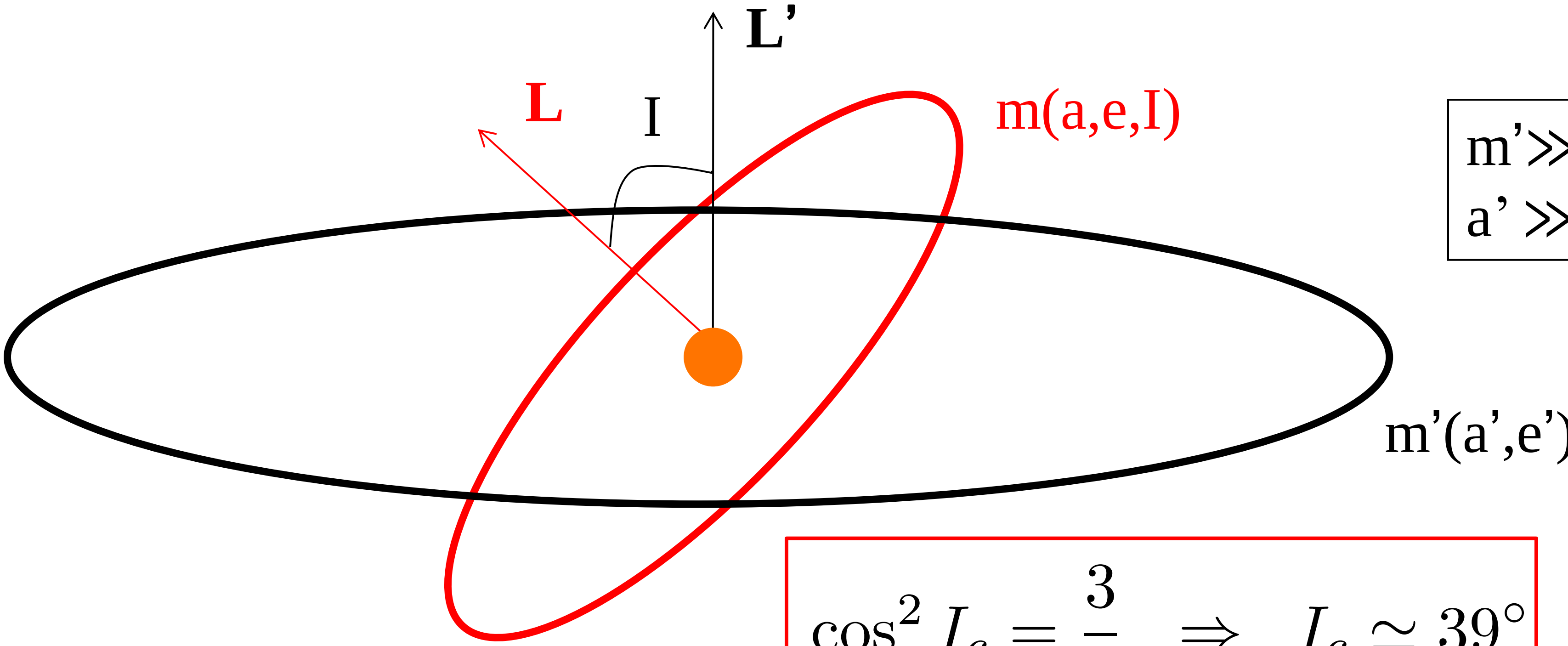
Circular orbits: **L** and **L'** precess around **L**+**L'**

But if $I > I_c$, then large oscillations of e and I

[$a(1-e^2)\cos^2 I = cst$]

Precession rate of the nodal line = - that of the pericentre

Kozai-Lidov mechanism



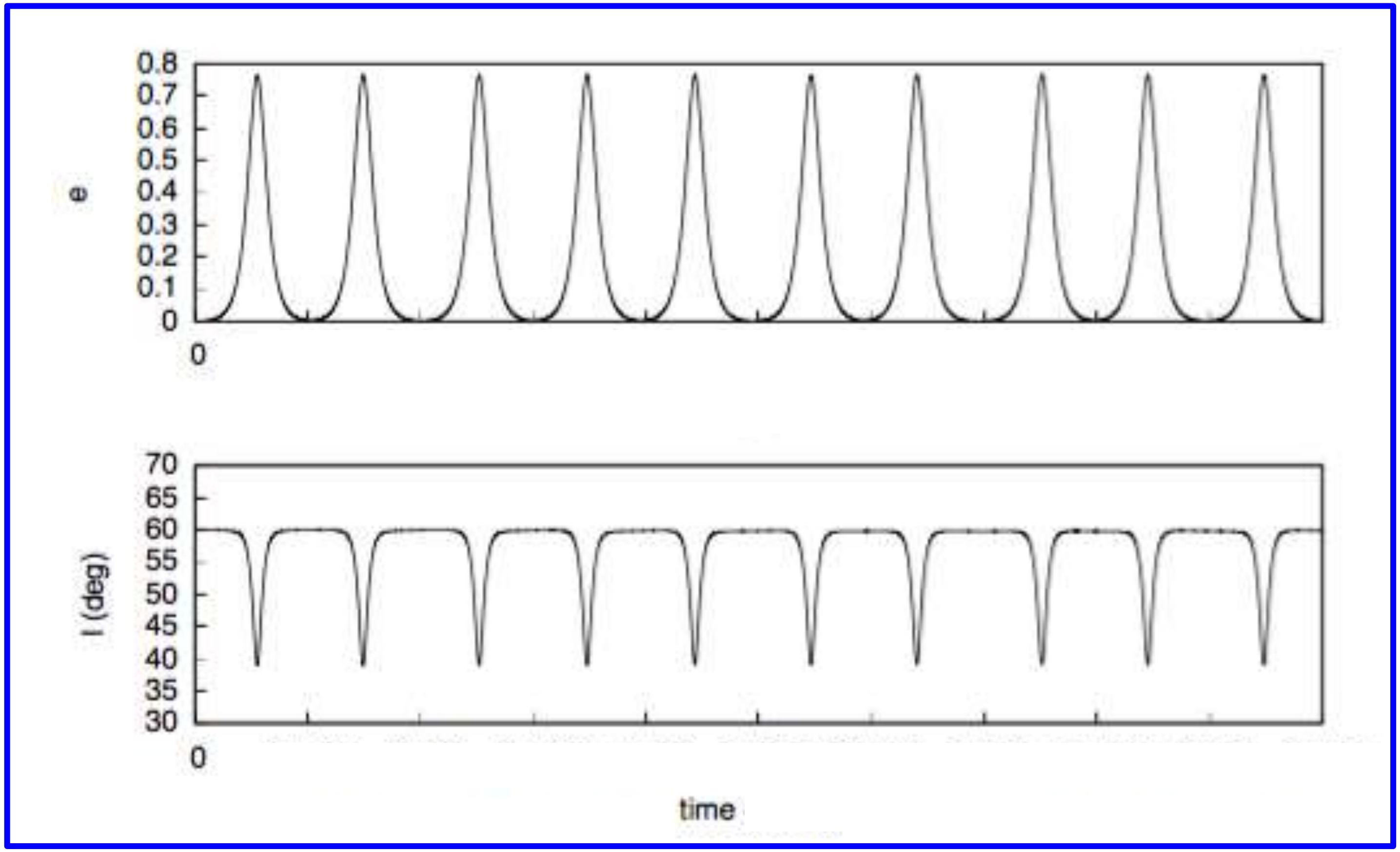
m'≫m
a' ≫a

$$\cos^2 I_c = \frac{3}{5} \quad \Rightarrow \quad I_c \simeq 39^\circ$$

$$e_{\rm max} = \sqrt{1 - \frac{5}{3}\cos^2 I_0}$$

$$t_{\rm evol} = \left(\frac{a'}{a}\right)^3 \frac{M_\star}{m'} T$$

Kozai cycles



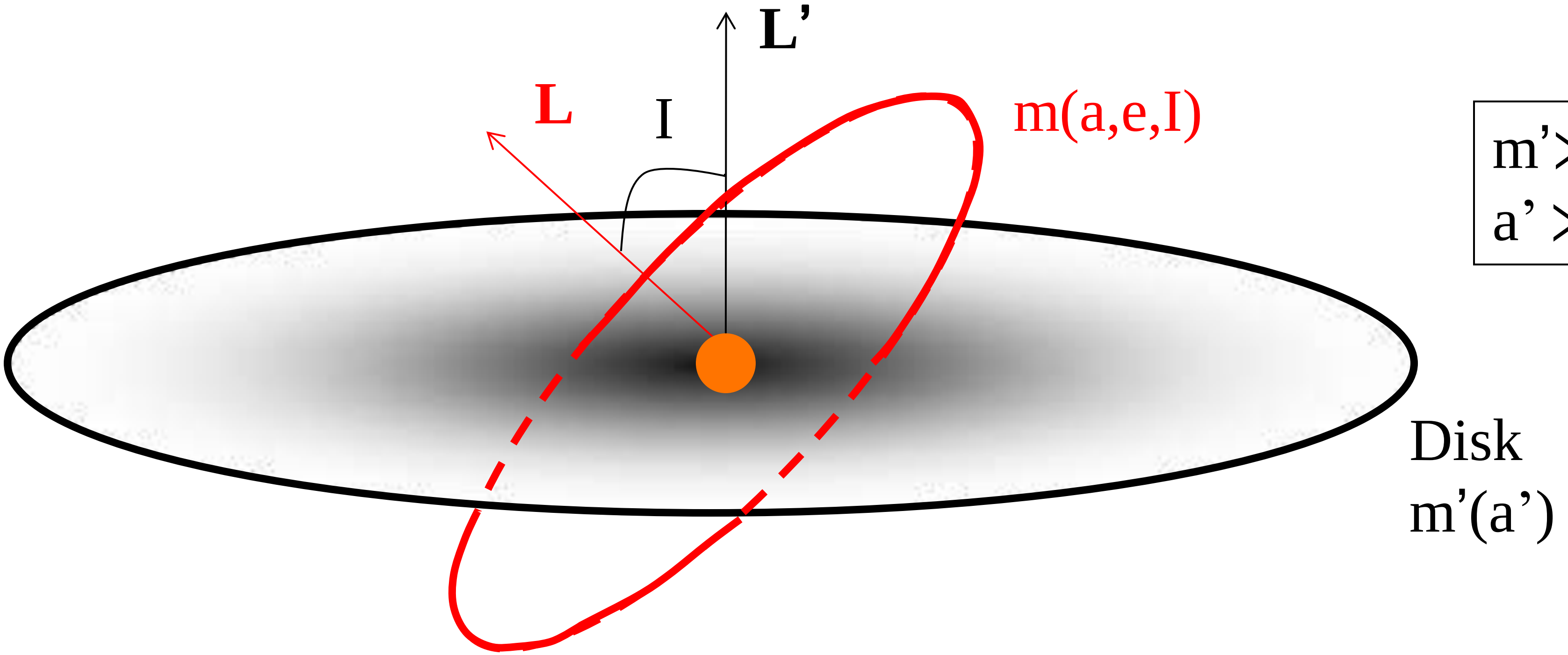
(Jean Teyssandier, PhD Thesis, 2014)

For $m=1\ M_{Earth}$ and $a=1$ AU:

- if $m'=1\ M_J$ and $a'=10$ AU, $t_{evol} \approx 10^6$ yrs
- if $m'=1\ M_\odot$ and $a'=300$ AU, $t_{evol} \approx 10^7$ yrs

(See also B. Funk, A.-S. Libert, A. Suli, and E. Pilat-Lohinger, 2011)

Kozai cycles with a disk



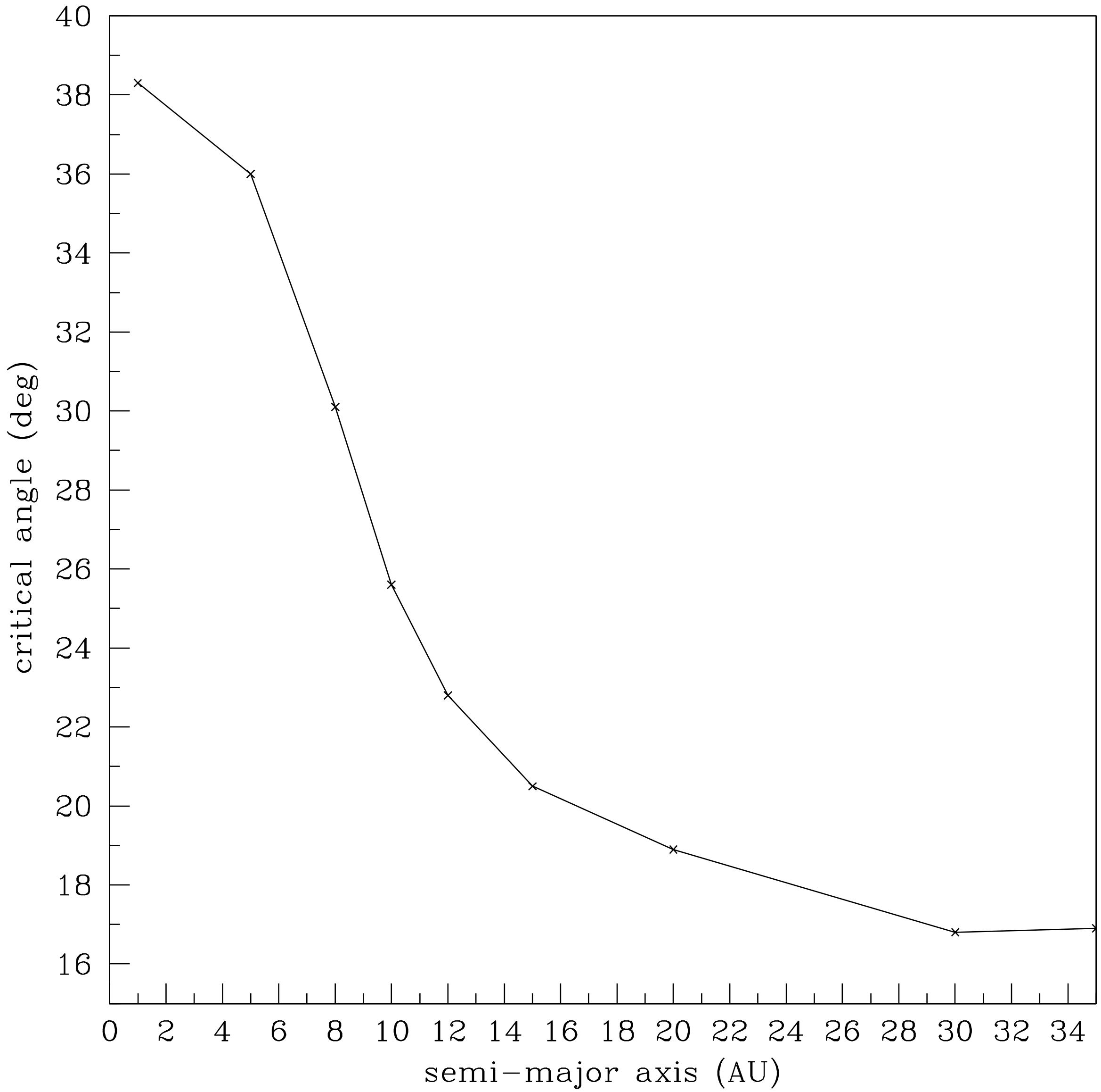
m' ≫ m
a' ≫ a

Kozai cycles if most of the disk mass is beyond the planet orbit

I_c may be much smaller than 39°

(Terquem & Ajmia 2010)

Kozai cycles with a disk



Planet:
M_{pl}=1 M_J

Disk:
M_{disk}=10^{-2} $M_\odot$
R_{in}=10 AU
R_{out}=100 AU

(Teyssandier, Terquem & Papaloizou 2013)

Conclusions

- Planets in the habitable zone of systems containing only terrestrial planets (Earths and super-Earths) are likely to be stable (see, e.g., *The stability of ultra-compact planetary systems*, B. Funk, G. Wuchterl, R. Schwarz, E. Pilat-Lohinger, and S. Eggl, 2010)

- When at least one giant planet is present, case by case study has to be done.

- Z. Sandor, A. Suli, B. Erdi, E. Pilat-Lohinger and R. Dvorak (2007) have constructed a stability catalogue of the habitable zones in extrasolar planetary systems.

- Planets in binaries ➔ Elke Pilat-Lohinger, Siegfried Eggl…