Dynamics of planetary systems

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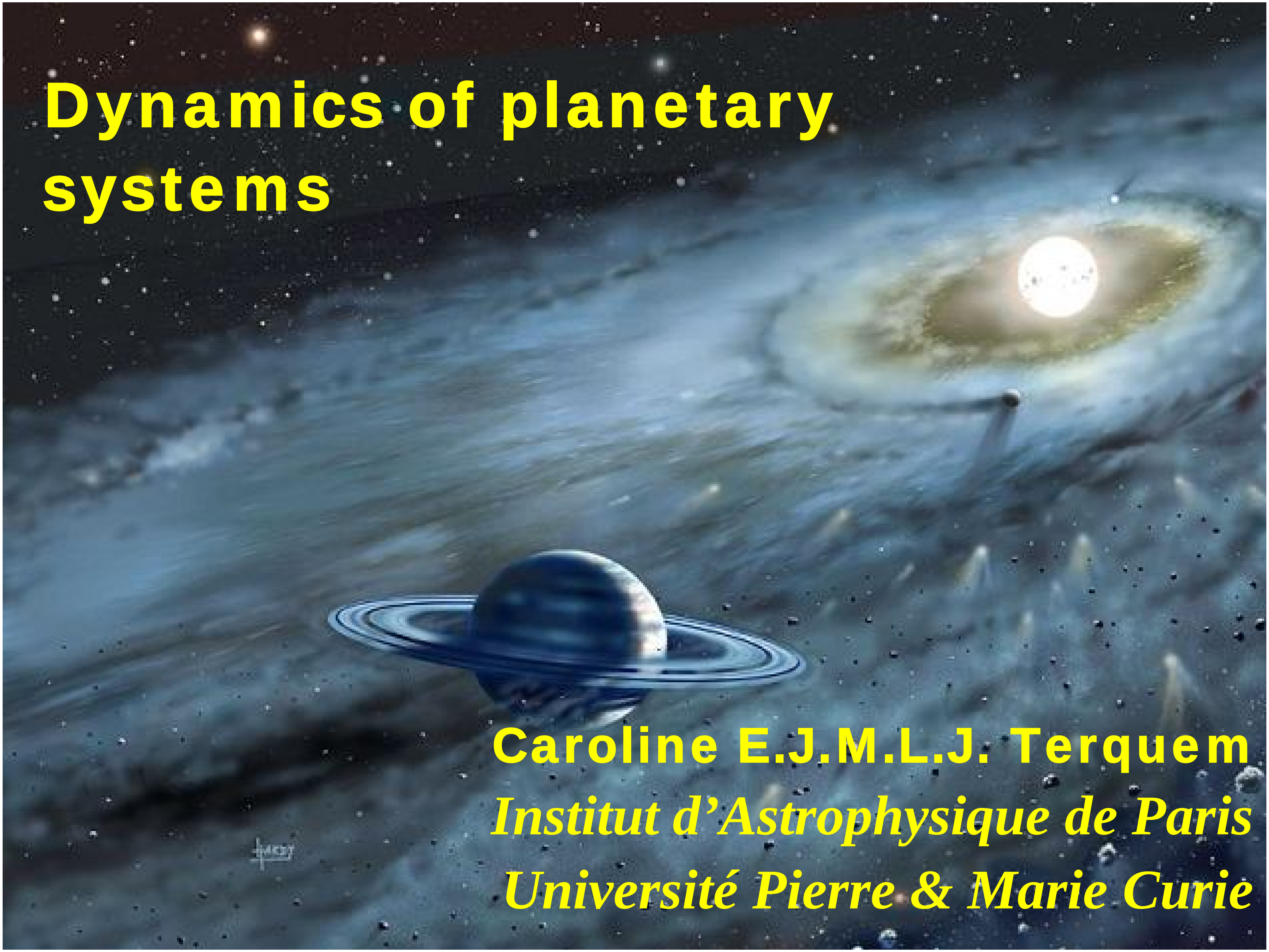


Overview

- **Migration and resonances**

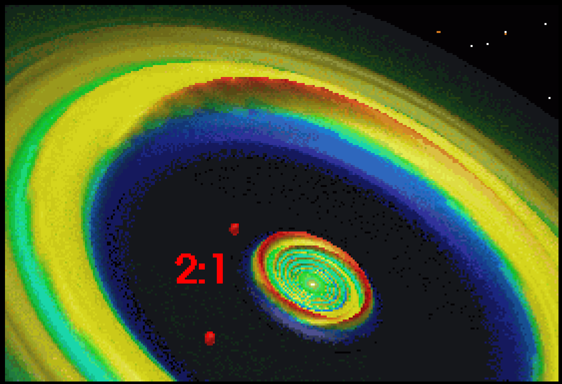
A scenario for the formation of low-mass planets

- **Inclined orbits**

A scenario for the formation of massive planets

Planet migration

(L. Cook)

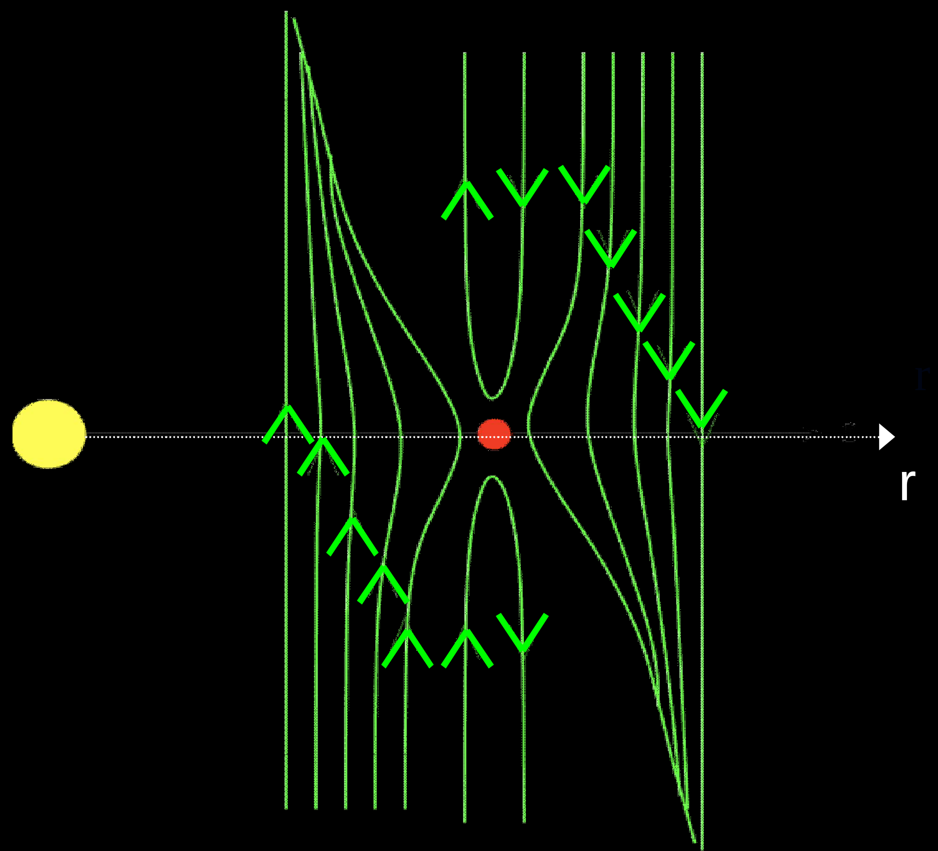


(G. Bryden)

Hot planets:
in situ formation:
too hot

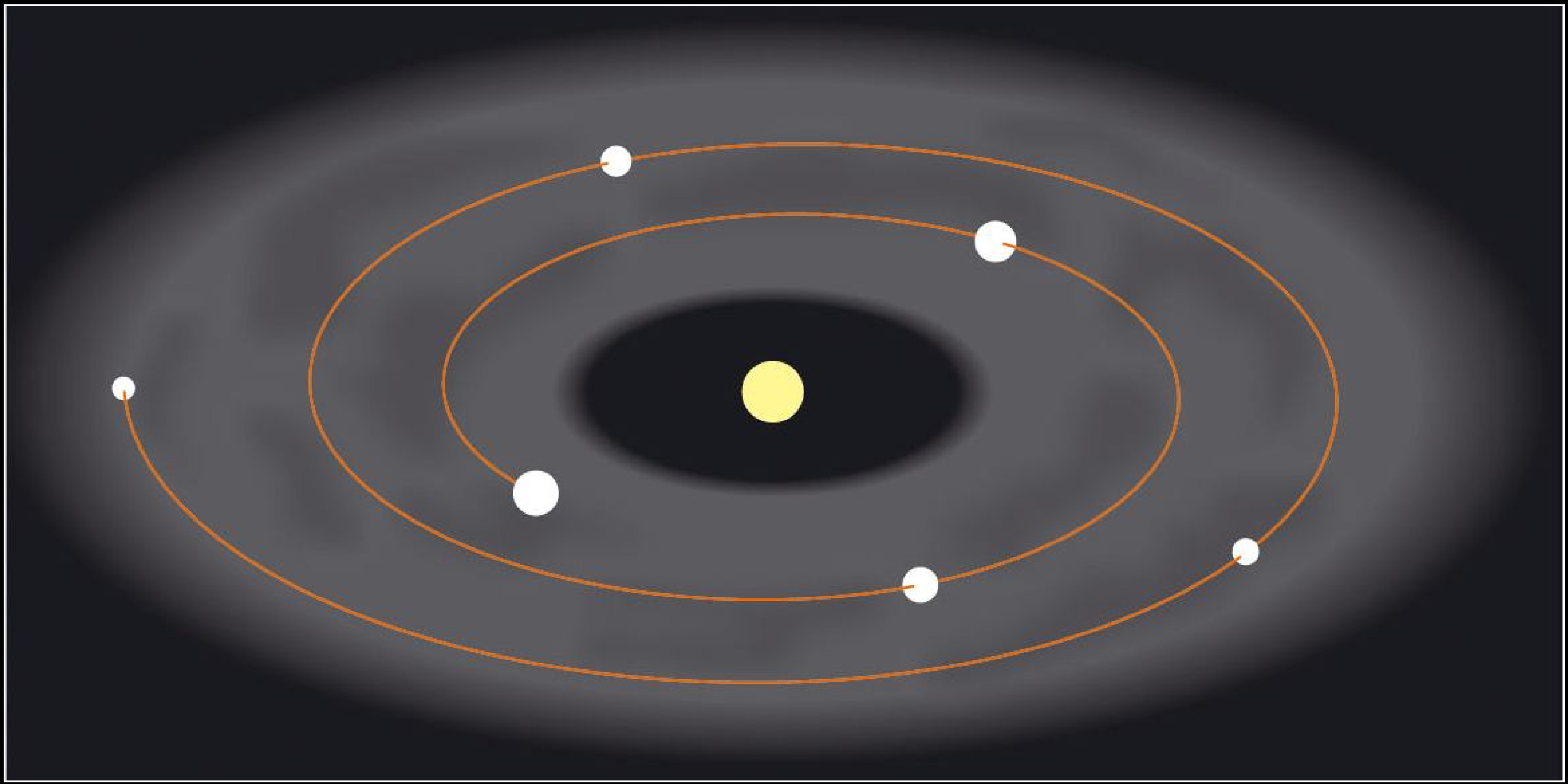
Resonant planets:
capture

Migration



(Goldreich & Tremaine 1980, Papaloizou & Lin 1984)

Type I migration (M_{pl}<10 $M_\oplus$)



$$t(yr) = 10^8 \left(\frac{M_{planet}}{M_{Earth}} \frac{\Sigma}{g/cm^2} \right)^{-1} \left(\frac{r}{au} \right)^{-1/2} 10^2 \left(\frac{H}{r} \right)^2$$

(Goldreich & Tremaine 1979, Ward 1986)

Formation of hot Super-Earths and Neptunes: Scenario

- Formation of cores at ~1 au

Interaction with the central star, mutual interactions, tidal interaction with the disk and the star

- Scatterings → collisions and mergers → growth
- Orbital migration → capture into mean motion resonances
- Tidal circularization → departure from exact commensurability but near-commensurability and apsidal locking

(Terquem & Papaloizou 2007)

Simulations

N-body integration + dissipative forces to model tidal interaction with the disk and the star.

For instance, migration $\rightarrow$ extra force:

$$\mathbf{\Gamma} = -\frac{1}{t_m}\frac{d\mathbf{r}}{dt}$$

Interaction with the disk:

For M_{planet} = 1 $M_{\oplus}$ and a = 1 au, $t_{migration} \sim 10^5$ yr

$t_{ecc} \sim 500$ yr

Interaction with the star:

For M_{planet} =1 $M_{\oplus}$, a=0.05 au, Q'=100, $t_{ecc} \sim 10^6$ yr

a=0.1 au, Q'=1000, $t_{ecc} \sim 10^9$ yr

Simulations: results

Set up:

10-12 planets with $M_{planet}=0.1$ or 1 $M_{\oplus}$ within 1 au

Inner cavity at 0.05 au

Results:

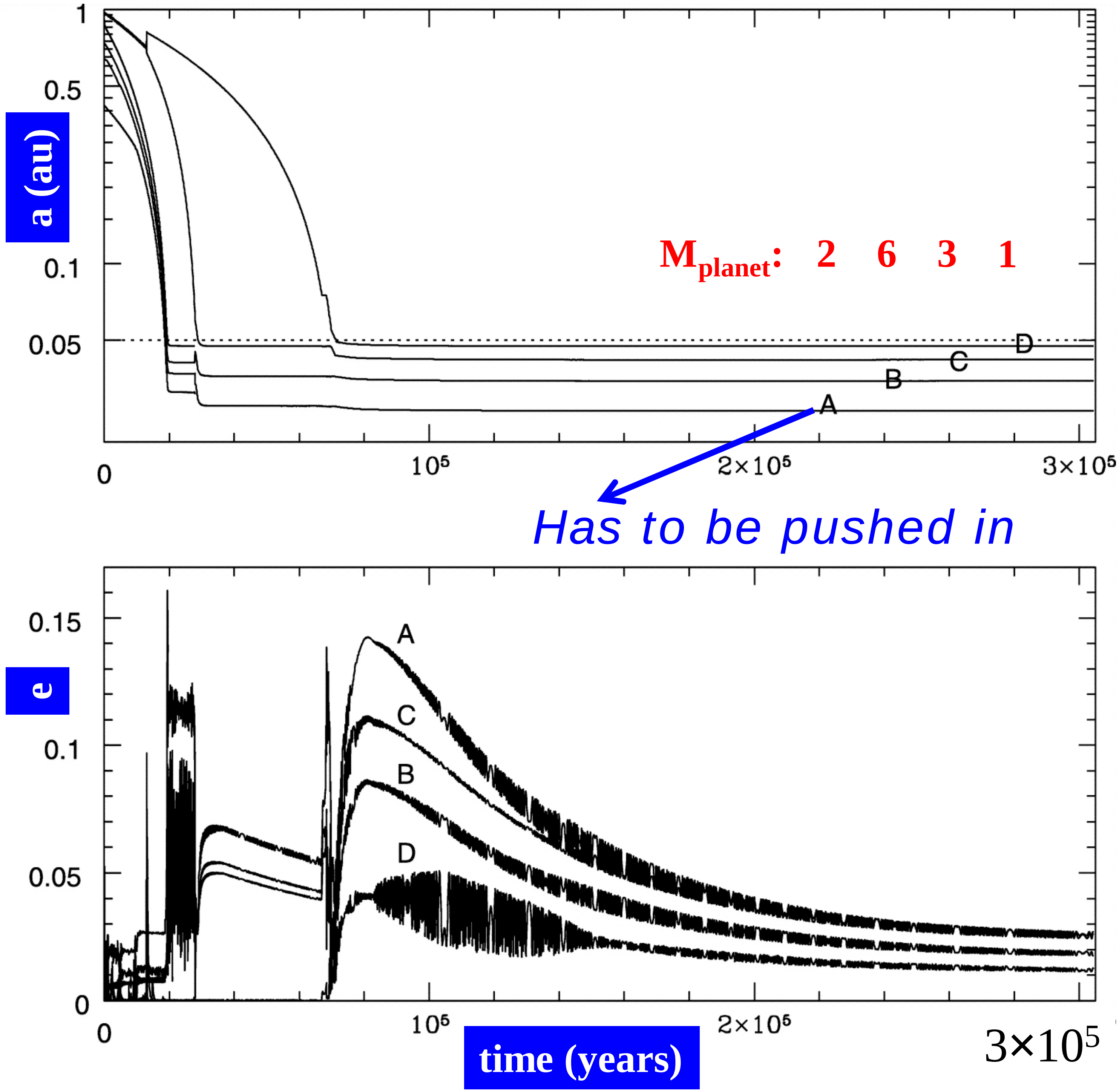
Between 2 and 5 planets inside the cavity on near-commensurate orbits with apsidal locking

12 planets

1 $M_\oplus$

Resonances:

AB: 3:2
AC: 2:1
AD: 12:5
BC: 4:3
BD: 8:5
CD: 6:5



Simulations: results

« if hot super-Earths or Neptunes form by mergers of inwardly migrating cores, then such planets are most likely **not isolated**. We would expect to always find at least one, more likely a few, companions on close and often **near-commensurable orbits**. To test this hypothesis, it would be of interest to **look for planets of a few to about 10 $M_{\oplus}$** in systems where hot super-Earths or Neptunes have already been found. »

(Terquem & Papaloizou 2007)

Systems of Hot Neptunes or Super Earths as in 2010

2 systems:

Gl 581: M_{planet} = 1.9 – 15.6 – 5.4 – 7.1 $M_{\oplus}$
P = 3.15 – 5.37 – 12.93 – 66.8 days

HD 40307: M_{planet} = 4.2 – 6.9 – 9.1 $M_{\oplus}$
P = 4.31 – 9.62 – 20.46 days

Systems of Hot Neptunes or Super Earths as in 2010

Ratio=1.70=**5/3+2%**

2.41=**5/2+4%**

Gl 581: M_{planet} = 1.9 – 15.6 – 5.4 – 7.1 $M_{\oplus}$

P = 3.15 – 5.37 – 12.93 – 66.8 days

HD 40307: M_{planet} = 4.2 – 6.9 – 9.1 $M_{\oplus}$

P = 4.31 – 9.62 – 20.46 days

2.13=**2/1+6.5%**

Ratio=2.23=**2/1+11.5%**

HD 40307: Resonant or not?

« The ratios of periods $P_2/P_1=2.23$ and $P_3/P_2=2.13$ are probably sufficiently distant to a rational value to exclude resonances. »

Mayor et al. 2009

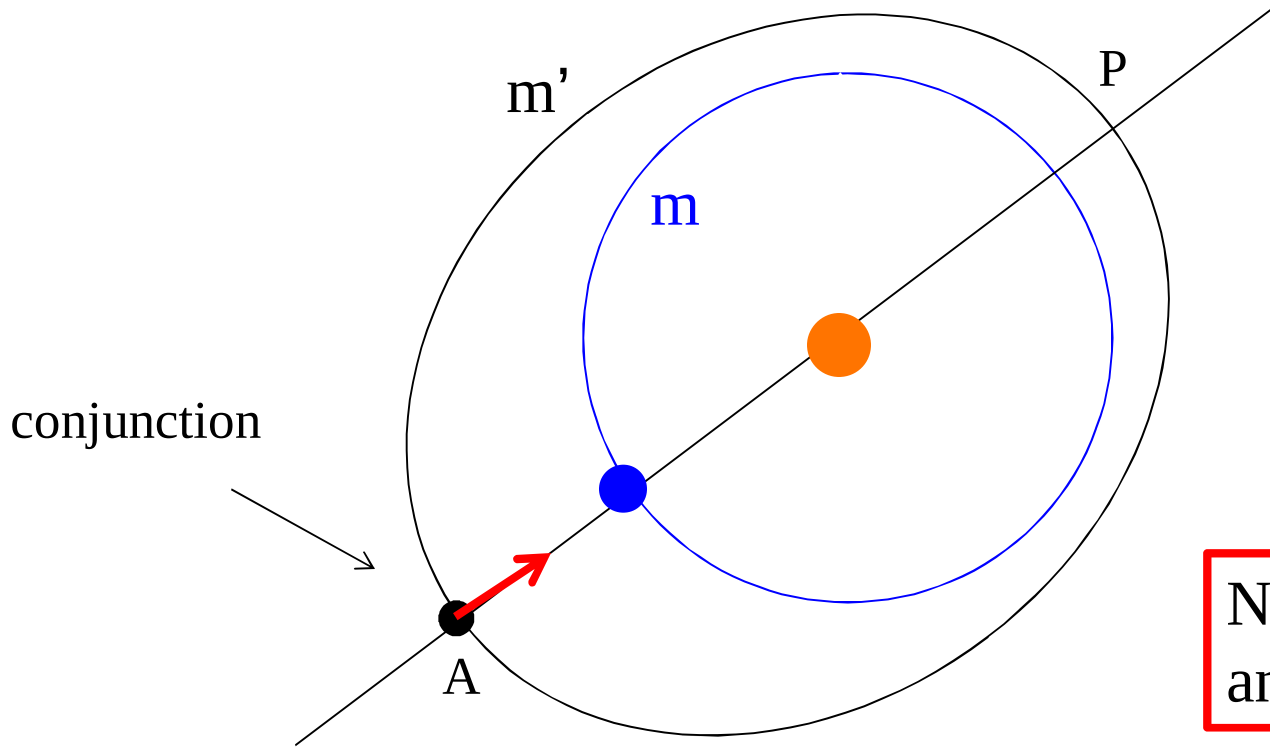
« In addition to relatively low masses, the system is striking in that the planets appear to lie close to a Laplace-like resonance: very small eccentricities (0.01) and period ratios near 4:2:1. However, as noted by Mayor et al. (2009), the observations rule out such a resonance chain with high confidence (greater than 10σ). »

Barnes et al. 2009

The Physics of resonance

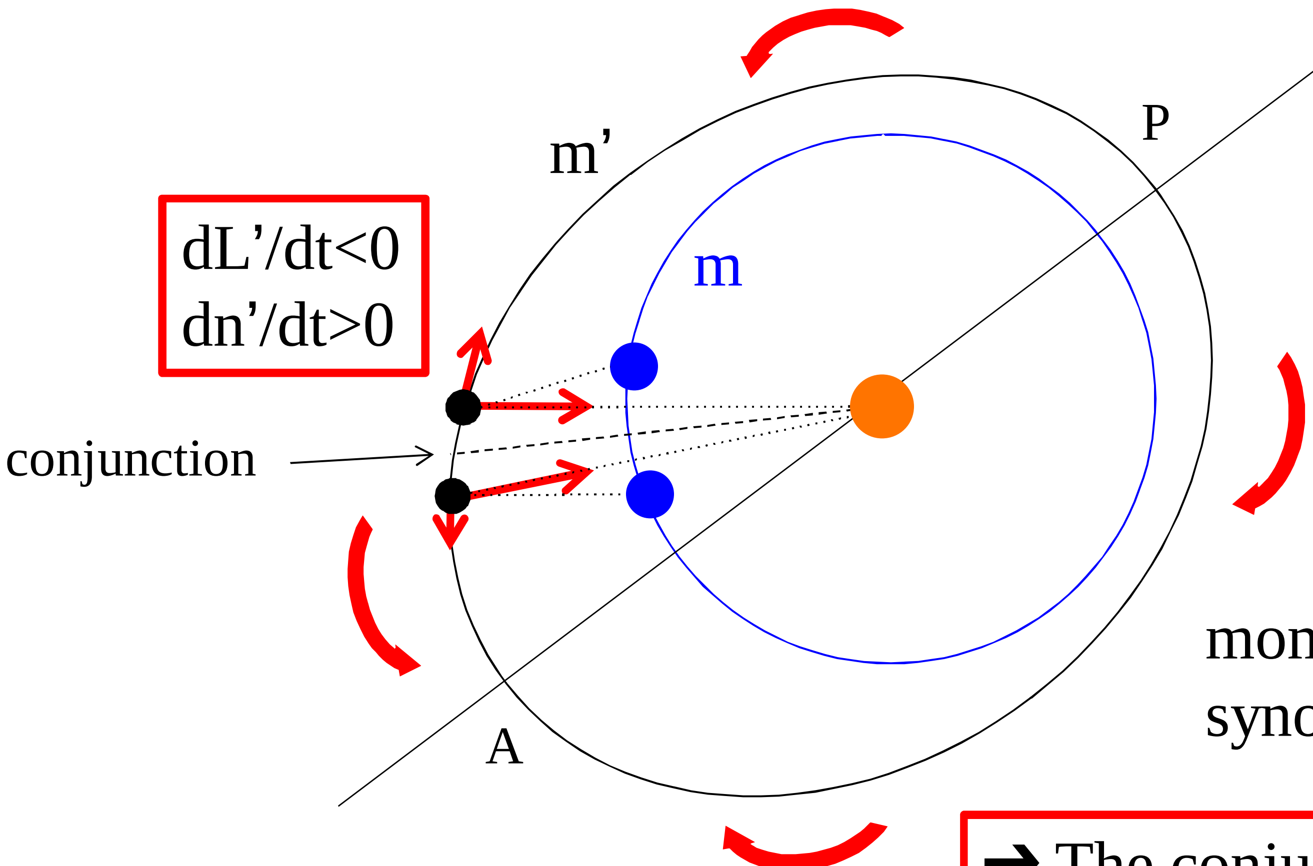
(Goldreich 1965, Peale 1976, Murray & Dermott 1999)

Commensurate mean motions:



No net transfer of angular momentum

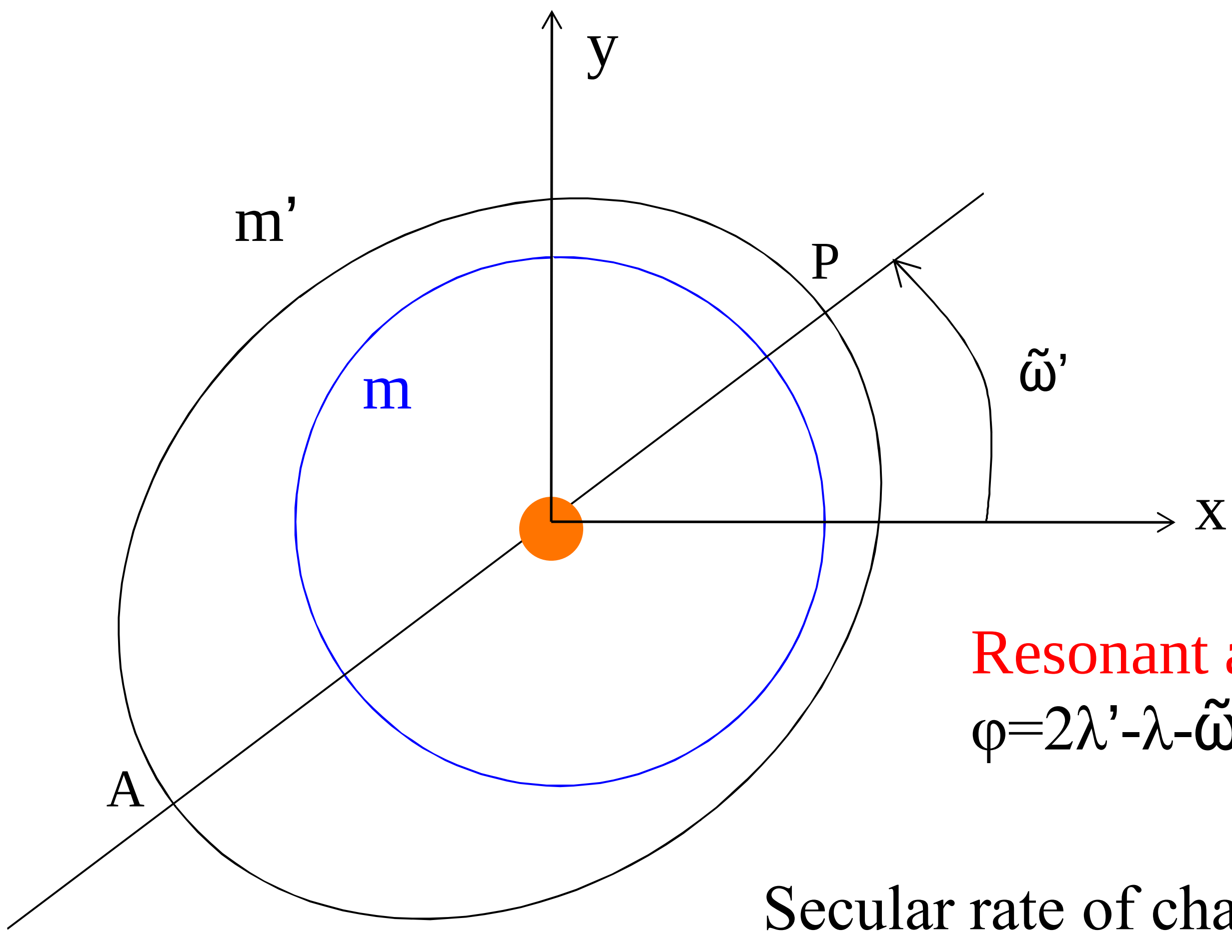
The Physics of resonance



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

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

The Physics of resonance

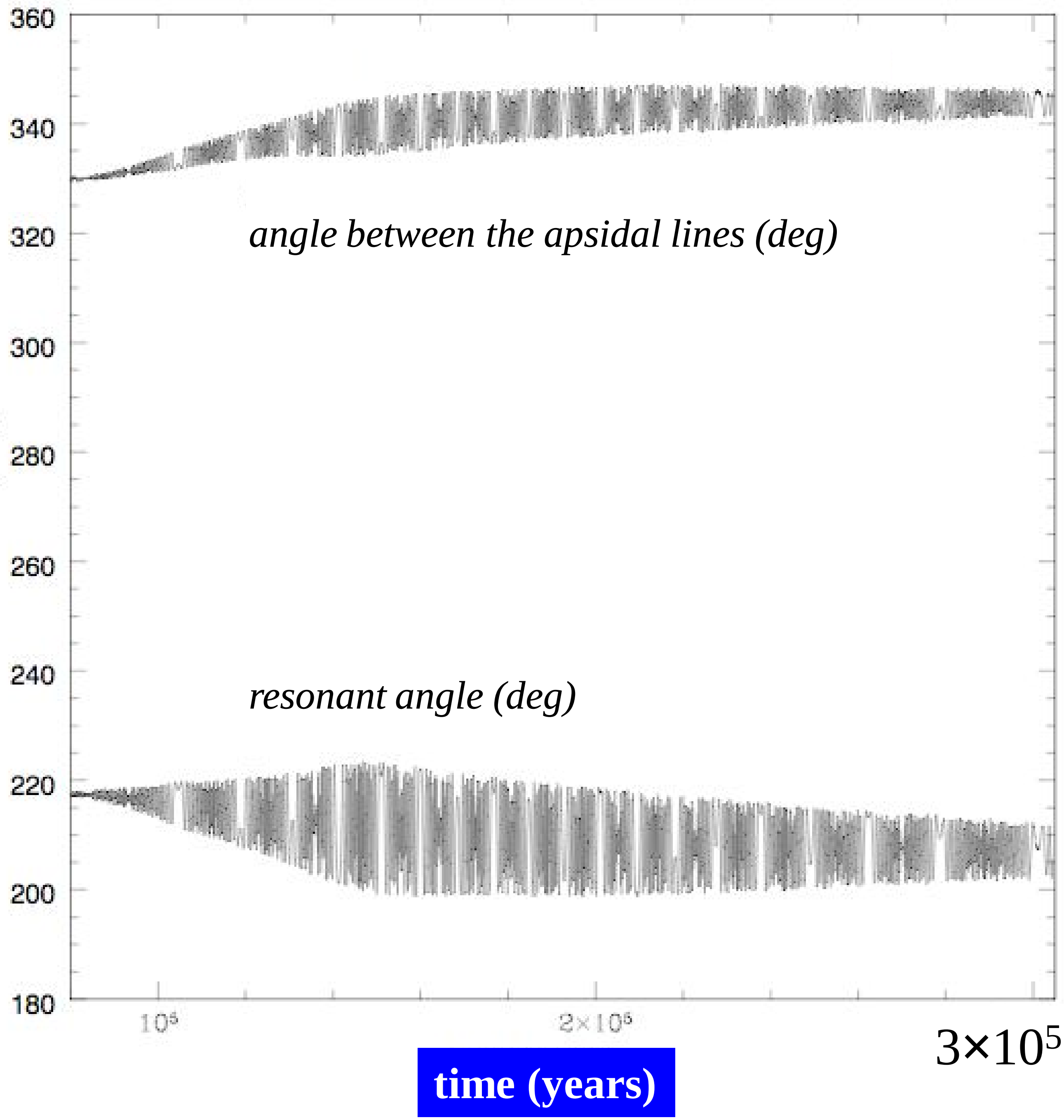


Resonant angle:
φ=2λ'-λ-ω̃': librates about π

Secular rate of change of φ = 0
➔ Terms containing cosφ and sinφ in the perturbation equations produce secular changes in the orbital elements.

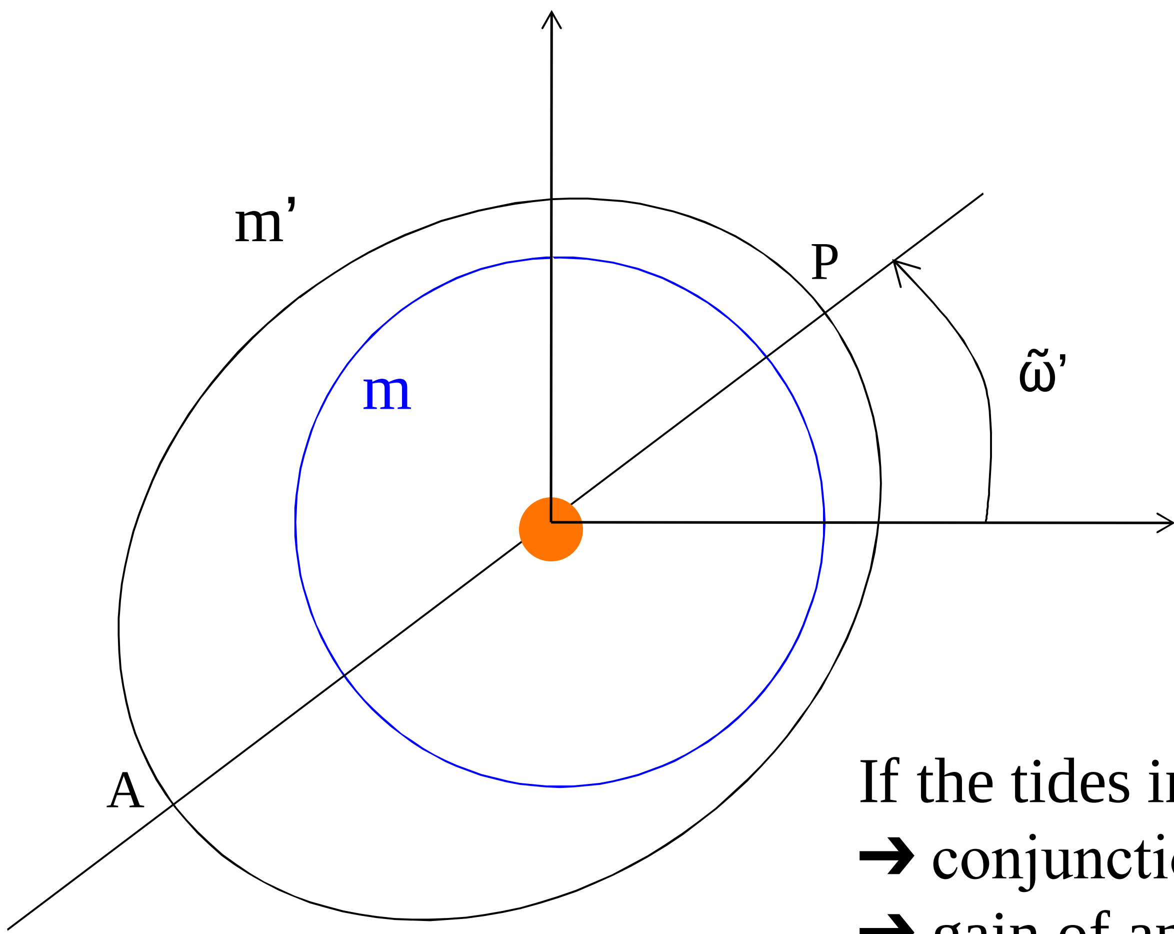
Planets A and B

3:2 resonance



The effect of tides

(Goldreich 1965)



If the tides increase the period of m:
➔ conjunction after π
➔ gain of angular momentum for m' which moves outward to preserve commensurability

The effect of tides

A commensurability is stable if the direct gravitational forces between the planets are strong enough to be able to redistribute the angular momentum.

(Goldreich 1965)

HD 40307:
Tidal interaction with the star: constant angular momentum
➔ The system spreads, departure from commensurability
But the resonant angles still librate to enable the required transfer of angular momentum

(Papaloizou & Terquem 2010)

The effect of tides

Tidal interaction with the star: preserves angular momentum

Energy loss ➔ the inner orbit shrinks

Constant angular momentum ➔ the outer orbit spreads

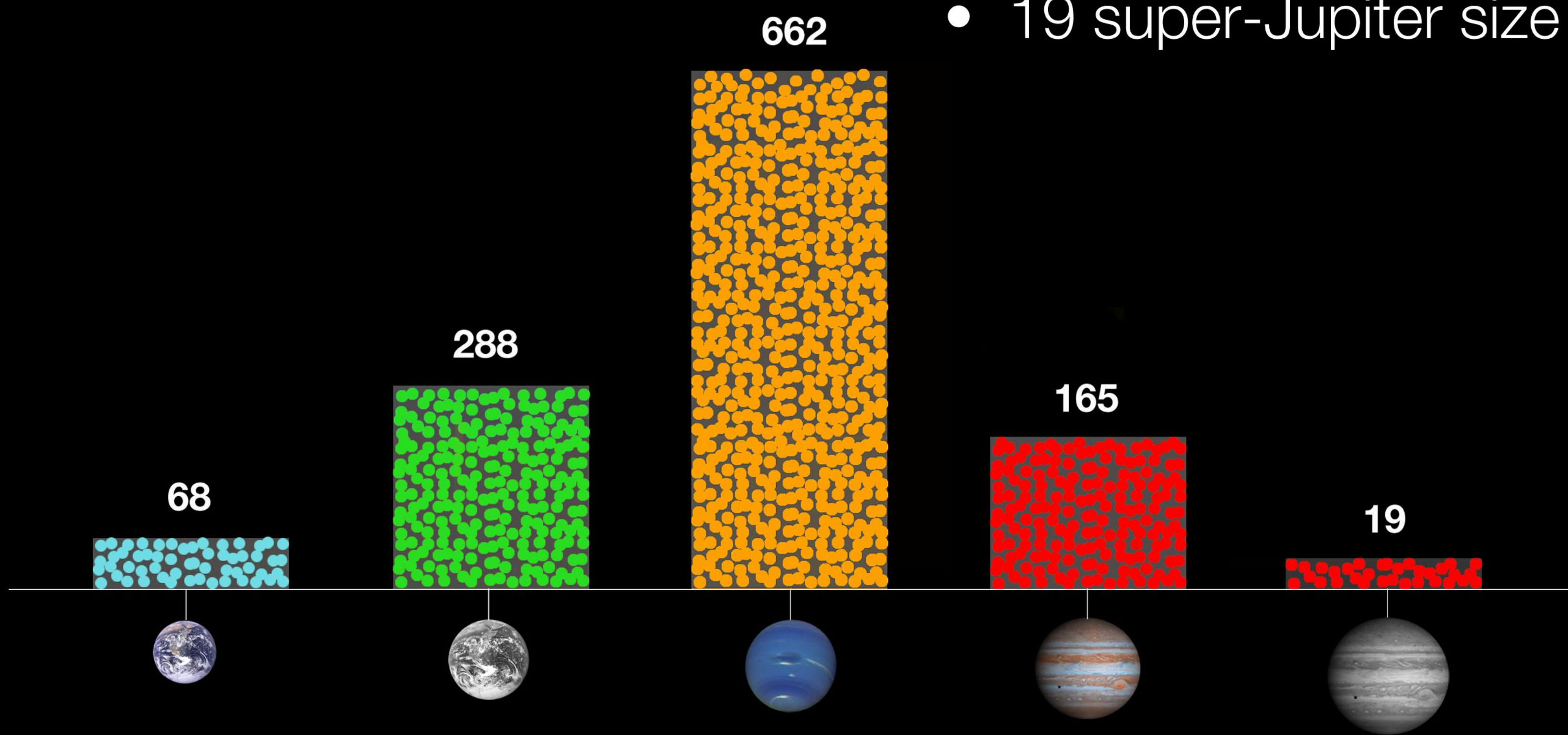
➔ departure from commensurability (P_{out}/P_{in} increases)

But the resonant angles still librate to enable the required transfer of angular momentum

(Papaloizou & Terquem 2010, HD40307)

Kepler candidates

- 68 Earth-size
- 288 super-Earth size
- 662 Neptune size
- 165 Jupiter size
- 19 super-Jupiter size



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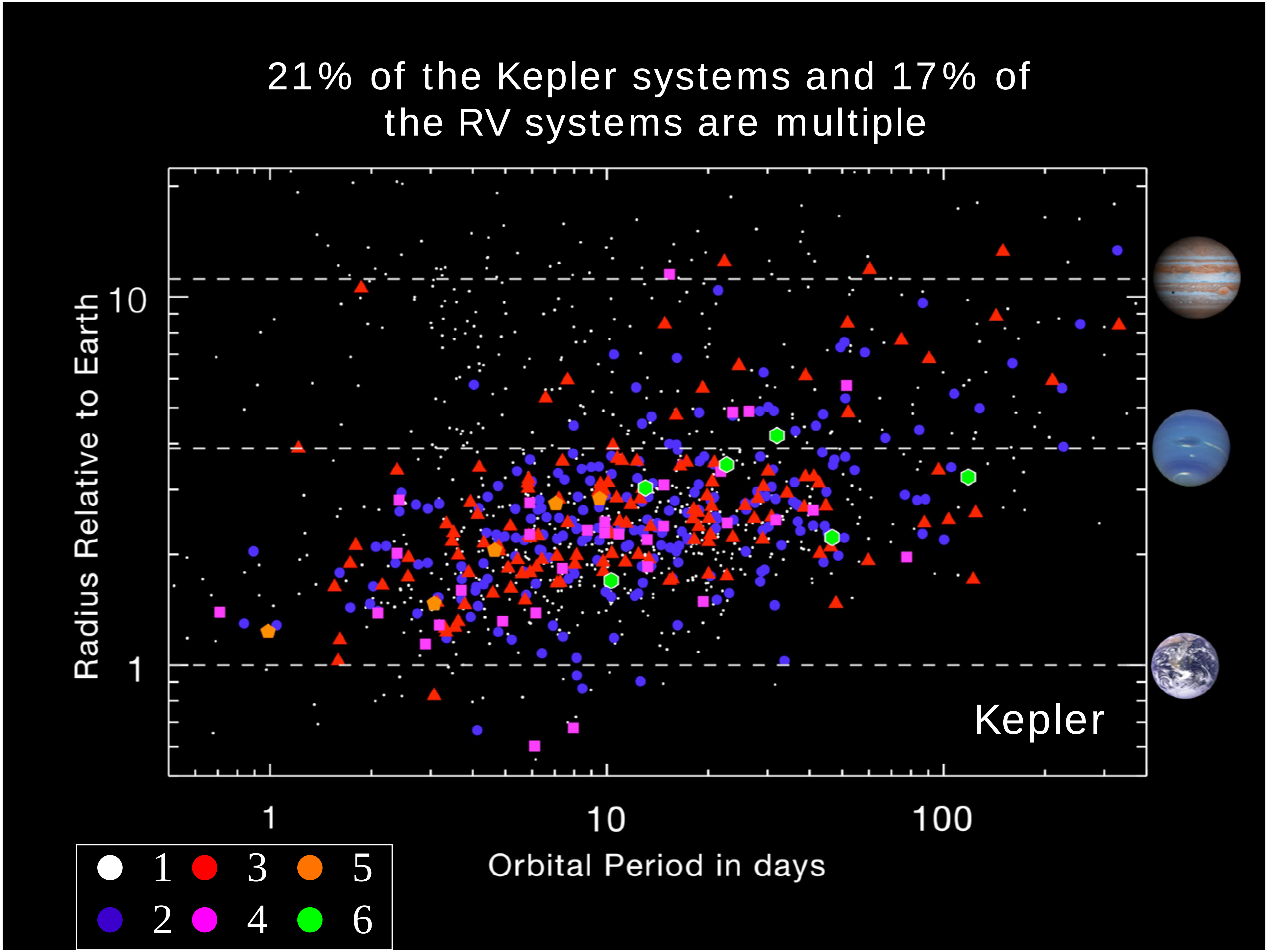
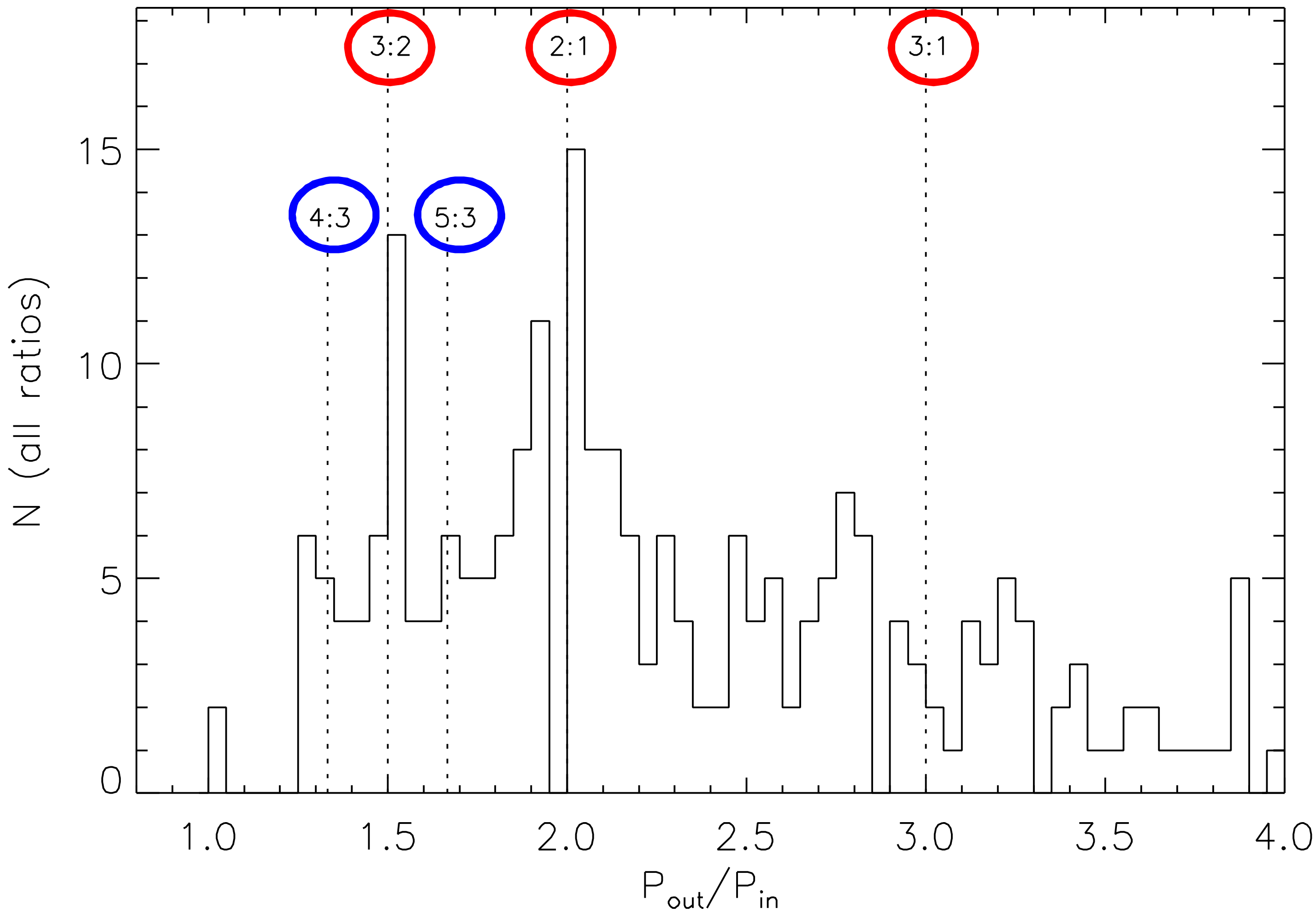

21% of the Kepler systems and 17% of
the RV systems are multiple
Radius Relative to Earth
10
1
Kepler
1
10
100
Orbital Period in days
1
3
5
2
4
6

Resonance Preference



(D. Fabrycky)

Formation of massive planets

Fragmentation of a disk or protostellar envelope on a scale of ~ 100 AU
➔ Population of massive planets (a few Jupiter masses)

Dynamical relaxation:

$$t_R = \frac{0.044\, M_*^2 P}{M_{pl}^2 N \ln(M_* / M_{pl})}$$

For M_{pl}=5 M_J and N=5, t_R~100P
i.e. t_R~10^5-10^6 yrs for scales~10^2-10^3 AU

(Papaloizou & Terquem 2001)

Formation of massive planets

Fragmentation of a disk or protostellar envelope on a scale of ~ 100 AU

➔ Population of massive planets (a few Jupiter masses)

Dynamical relaxation ends with:

(i)1 hot Jupiter and 0, 1 or 2 external companions

(ii)1 or 2 external planets

(iii)1 rather close planet and 1 external companion

10% of the planets collide with the star

All the other objects are ejected (free floating planets)

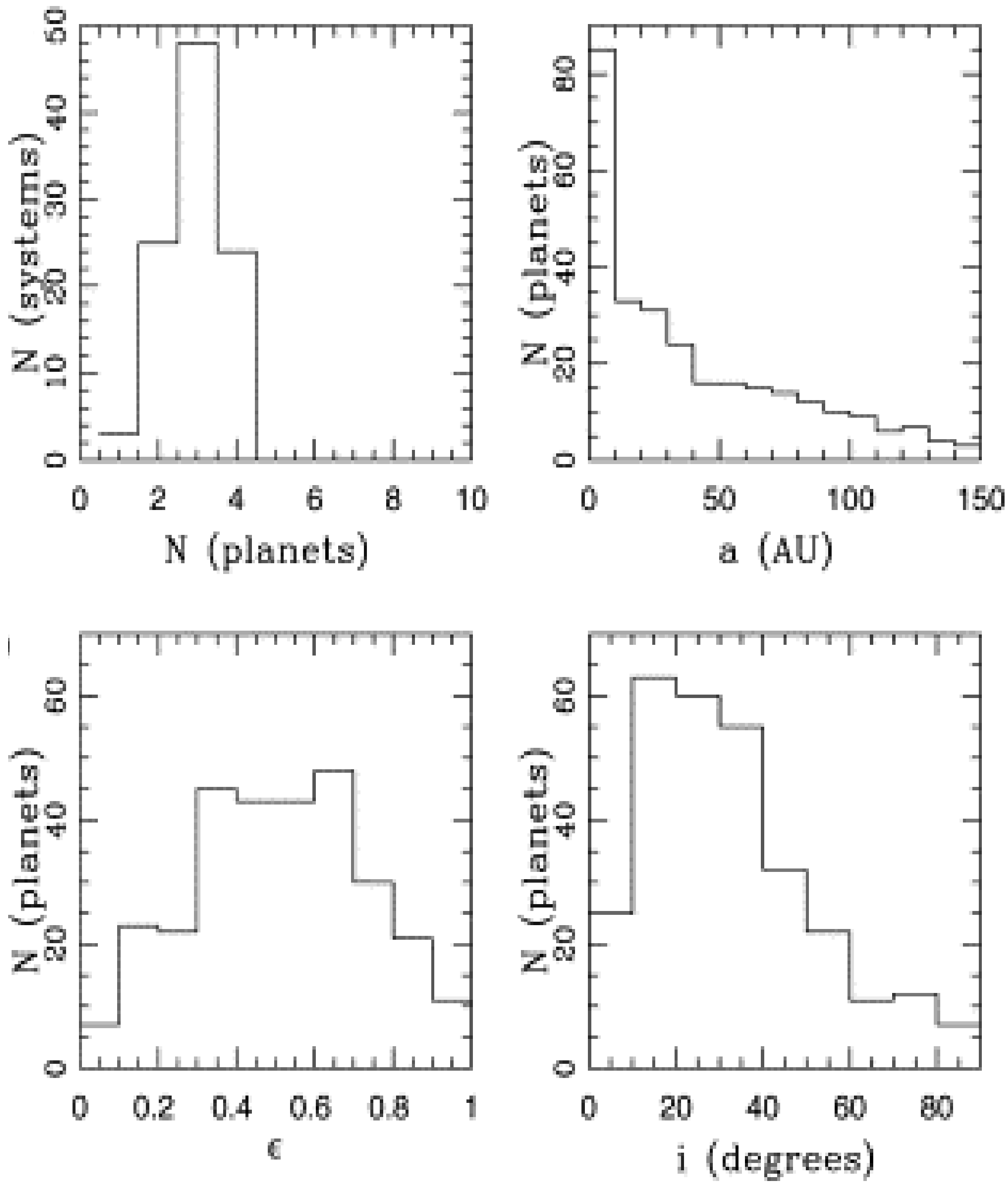
(Papaloizou & Terquem 2001)

100 simulations of 10 planet systems: statitics

(Adams & Laughlin 2003)

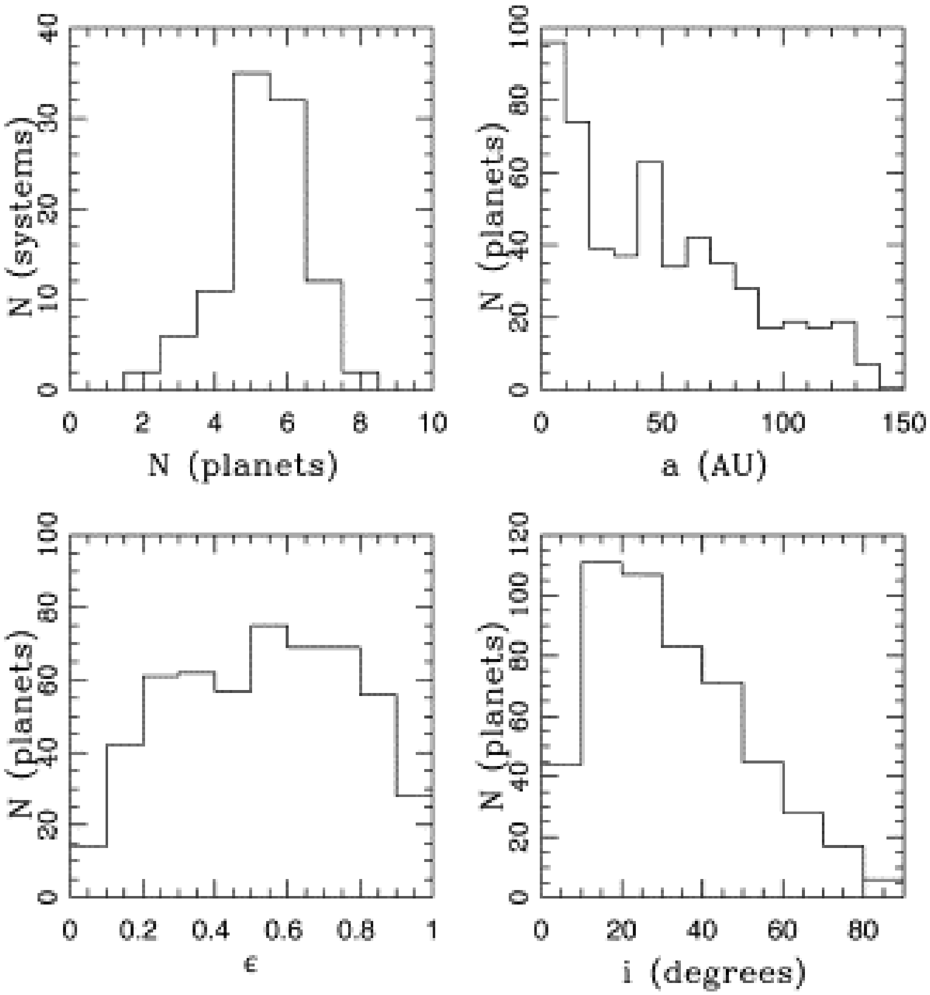
$M_{pl}=2\ M_J$

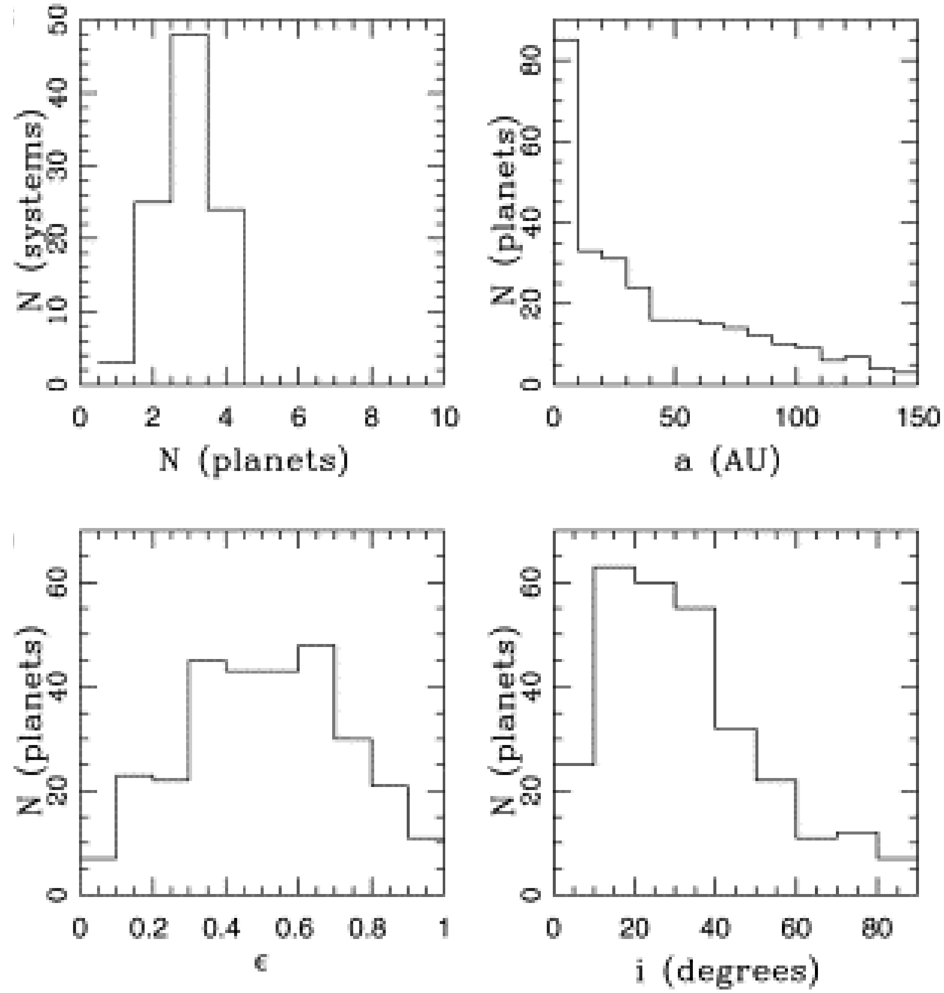
$t=10^6$ years



100 simulations of 10 planet systems: statitics

M_{pl}=1 M_J





M_{pl}=2 M_J

(Adams & Laughlin 2003)

Planets around more massive stars

« Increasing the mass of the host star by a mere factor of 1.5-2 results in an entirely new planet population which is characterized by:

• a high frequency (~26%)

• of high-mass planets ($M_P \sin i > 1.5\ M_{Jup}$)

• at large semimajor axes (a > 1 AU) »

(Bowler et al. 2010)

Also Arthur Vigan, Raphael Galicher and Eric Nielsen's talks

Two populations of planets

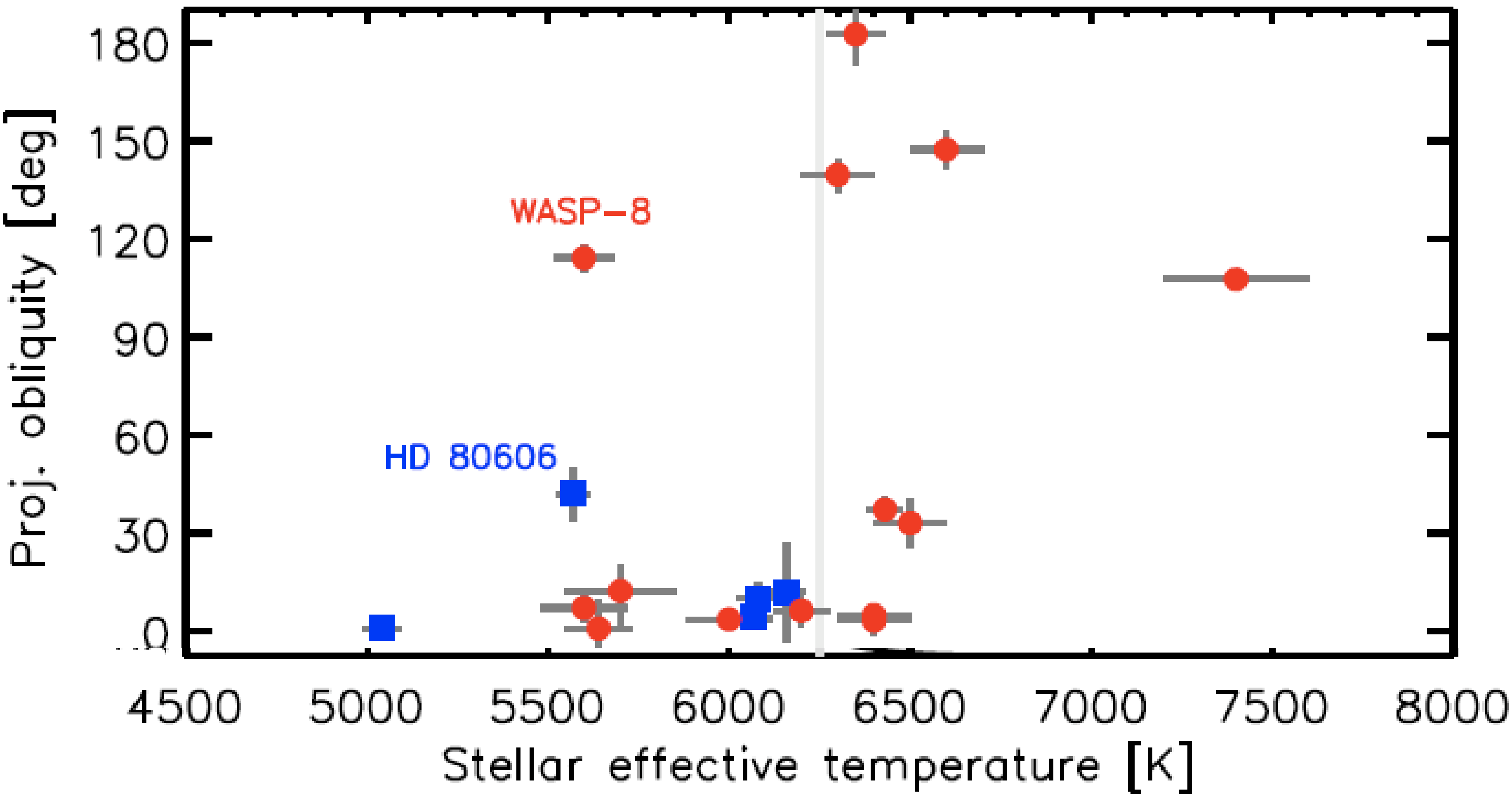
Massive planets forming through fragmentation

Lower mass planets forming through the core accretion scenario in a disk

May co-exist ➔ Interactions between the two populations (*Terquem & Papaloizou 2002*)

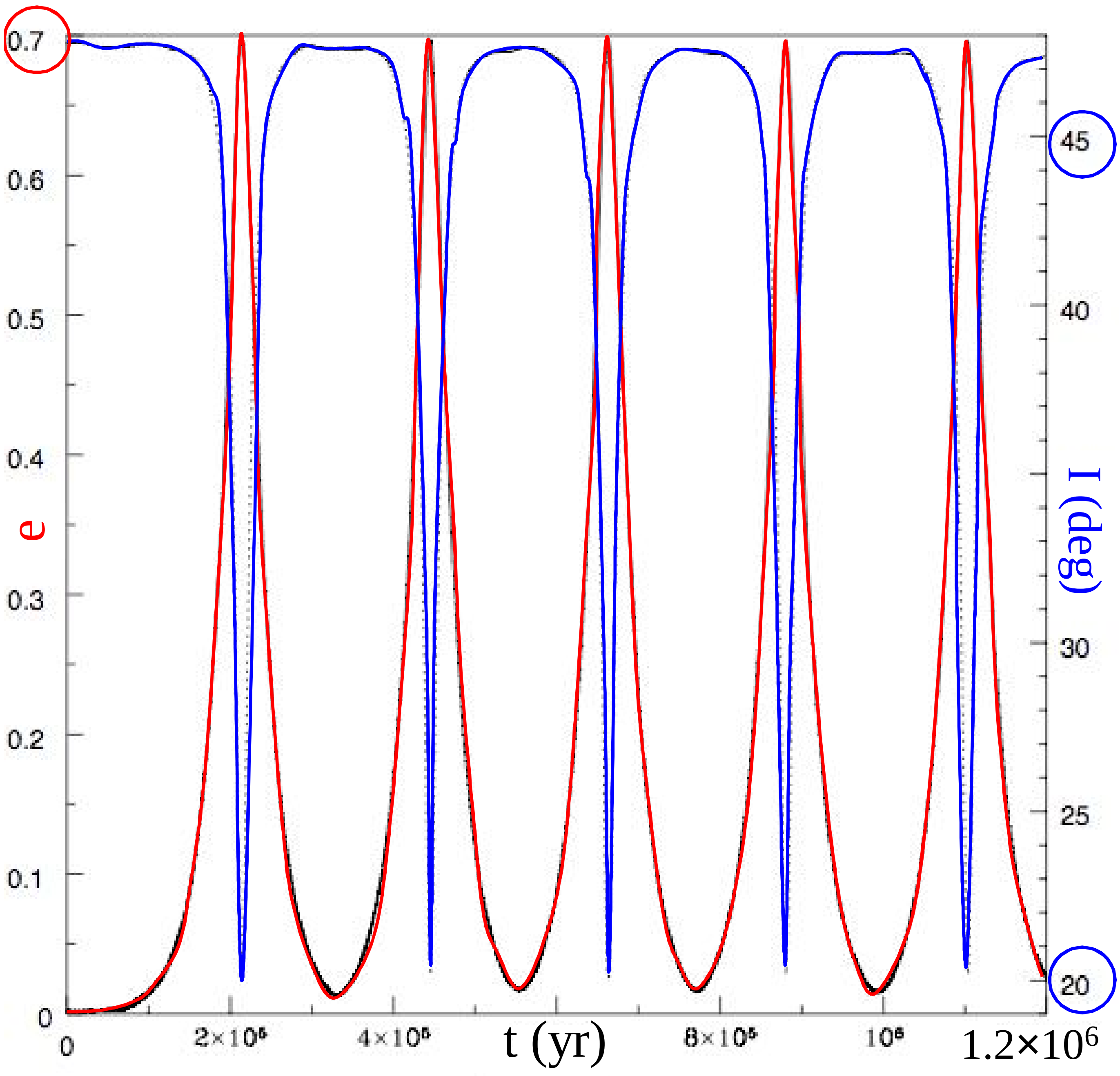
Planets on inclined orbits

Misaligned systems have hotter stars



(Winn et al. 2010, also *Schlaufman 2010)*

Interaction of an inclined planet with a disk



(Terquem & Ajmia 2010)

Set up:

Planet:

$M_{pl} = 1 M_J$

$a = 20$ AU

$e = 0$

$I_0 = 48^o$

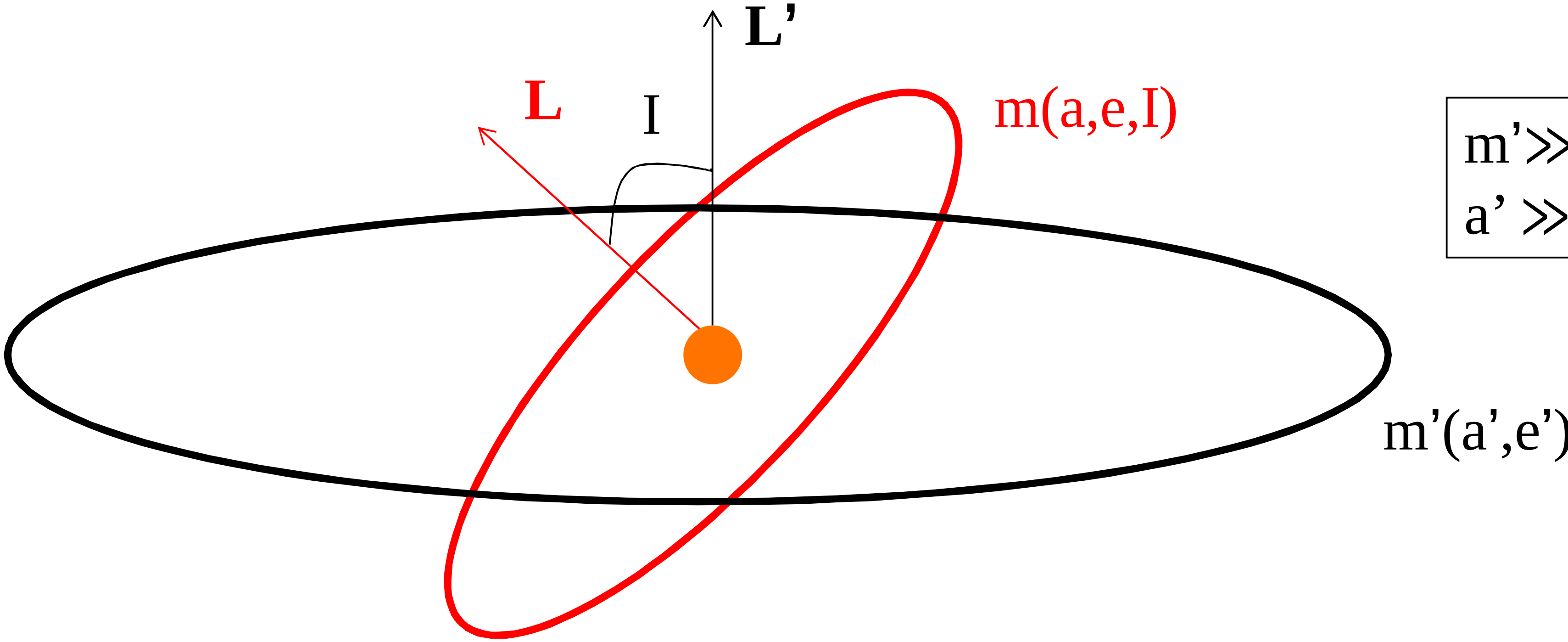
Disk:

$M_{disk} = 10^{-2} M_\odot$

$R_i = 1$ AU

$R_o = 100$ AU

Kozai mechanism



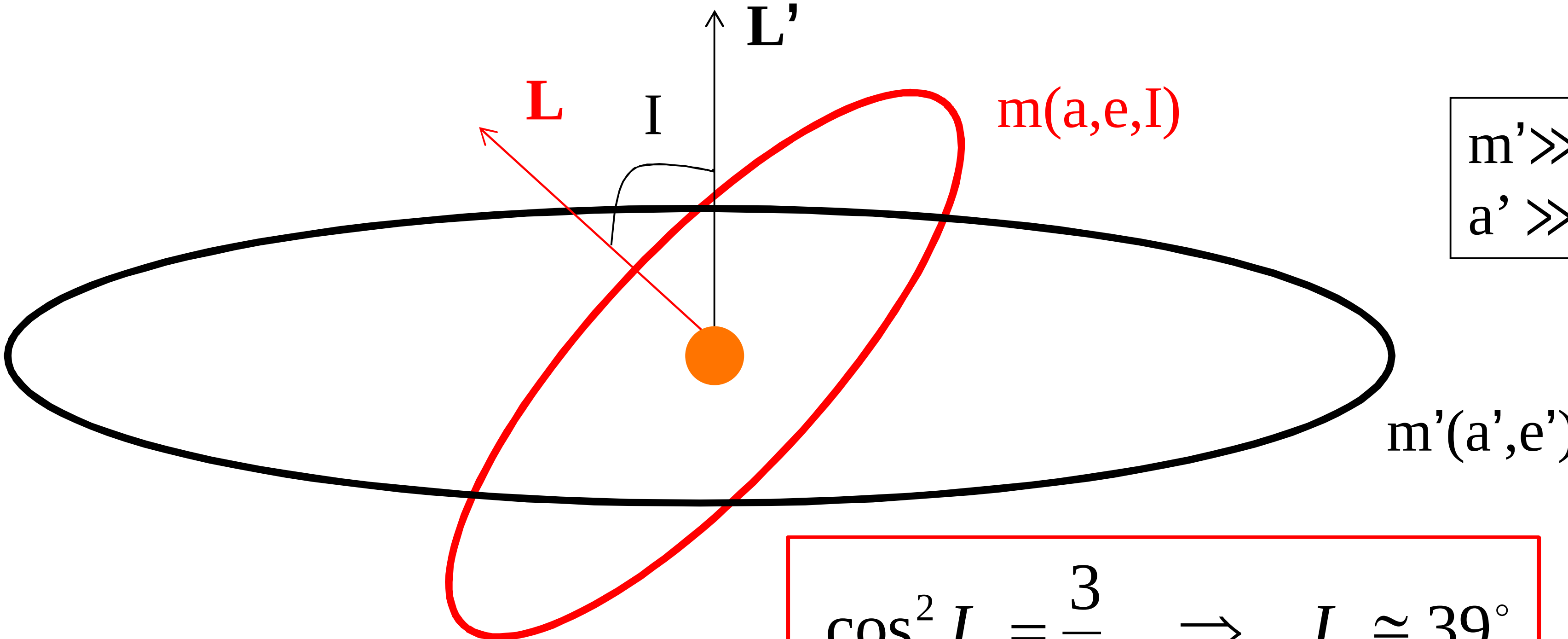
m' ≫ m
a' ≫ a

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

But if $I > I_c \cong 39^o$, then e and I oscillate ($a(1-e^2)\cos^2 I = cst$)

(Kozai 1962)

Kozai mechanism



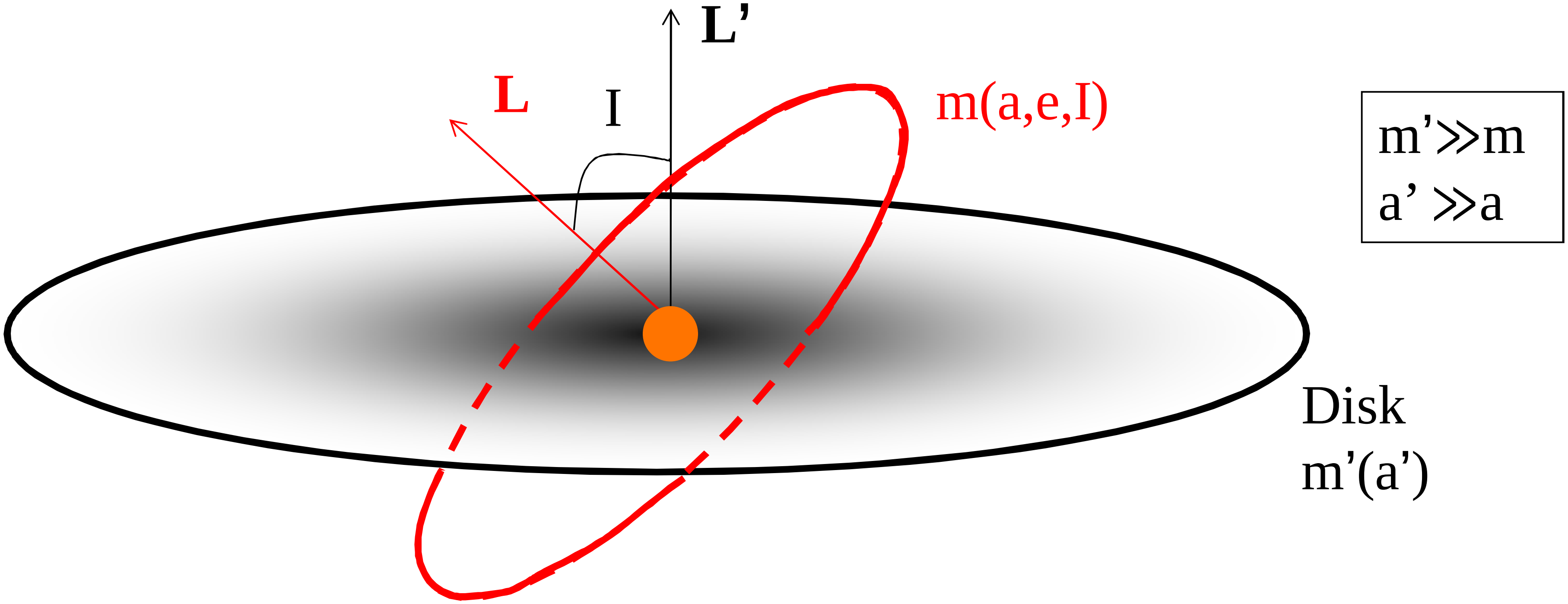
m'≫m
a' ≫a

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

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

$$t_{evol} = \frac{a'^3 M_*}{a^3 m'} T$$

Kozai cycles with a disk



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

I_c may be much smaller than 39°

Interaction of an inclined planet with a disk: The effect of friction

When the planet crosses the disk:

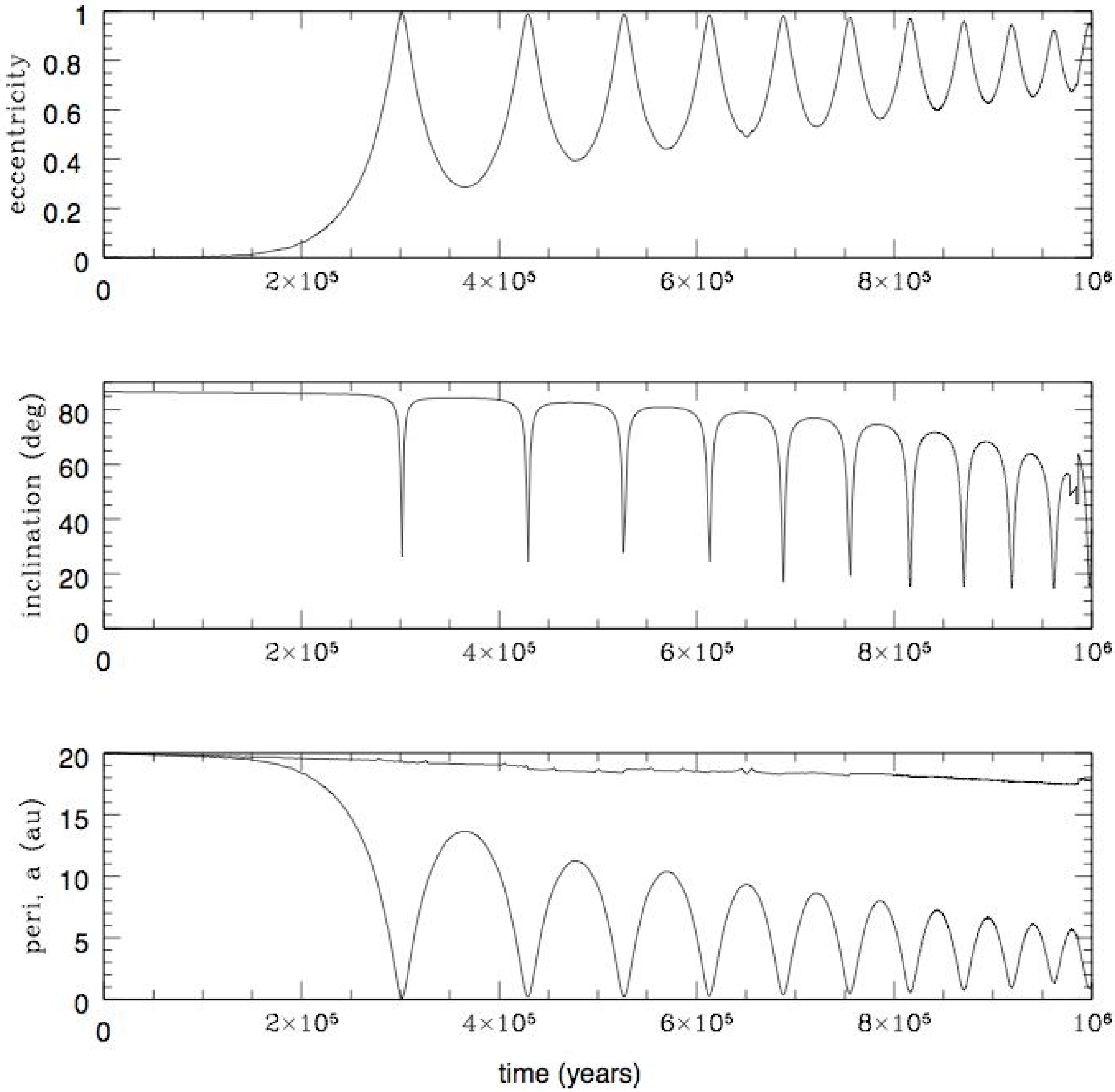
$$\Delta E = \frac{4\pi G^2 M_{pl}^2 \Sigma}{\cos I \left|\vec{v}_{pl} - \vec{v}_{disk}\right|^2} \ln\left(\frac{H}{R_{pl}}\right) + \frac{1}{2}\pi R_{pl}^2 \Sigma \left|\vec{v}_{pl} - \vec{v}_{disk}\right|^2$$

ΔE_1: dynamical friction (gravity)

ΔE_2: drag (finite size)

For a 1 M_J planet:

$$\frac{\Delta E_2}{\Delta E_1} \approx 0.2 \frac{\left|\vec{v}_{pl} - \vec{v}_{disk}\right|^4}{(GM_*/a)^2} \ll 1$$



Planet:

$M_{pl} = 0.1\ M_J$

$a = 20$ AU

$e = 0$

$I = 86^o$

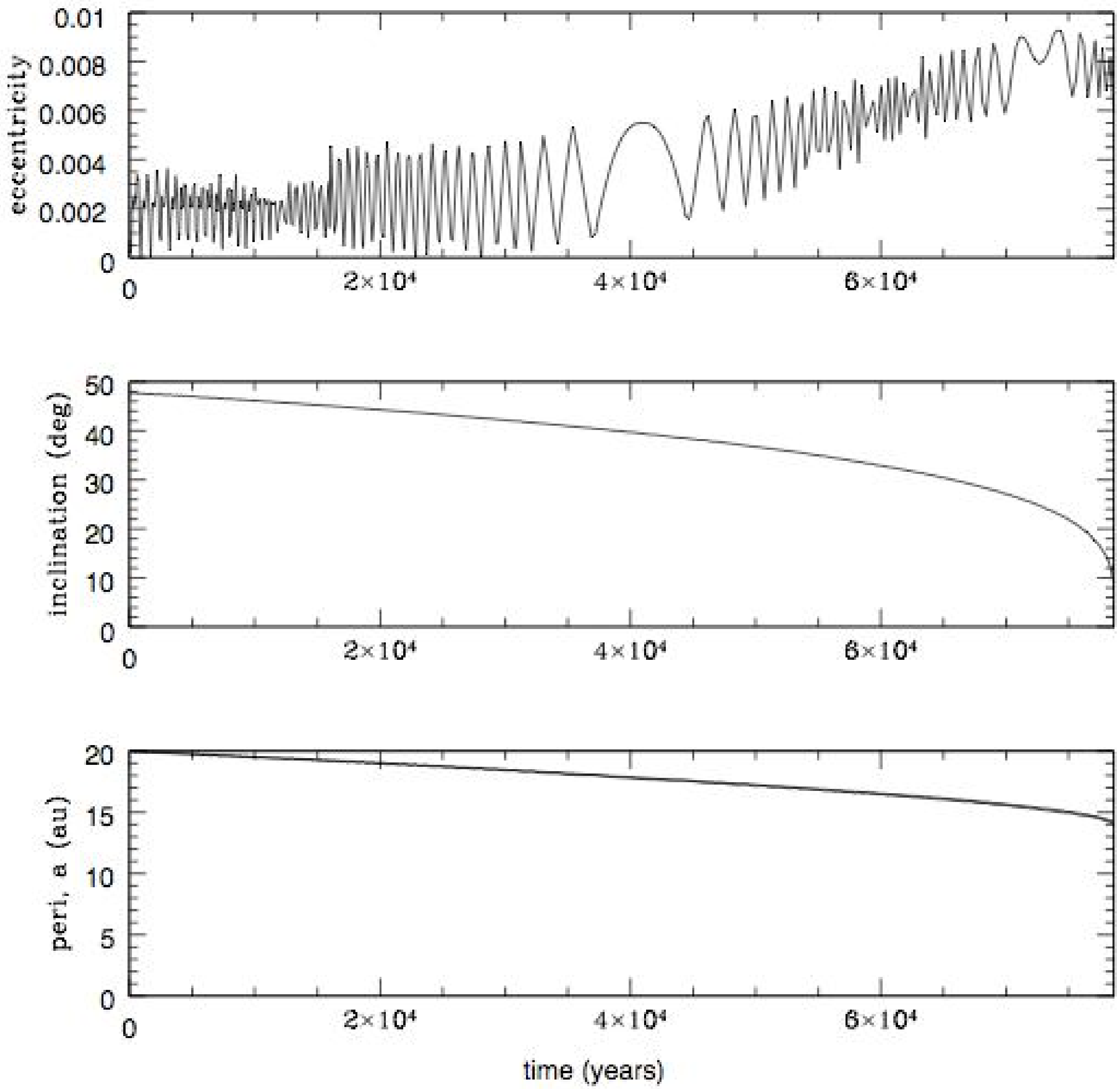
Disk:

$M_{disk} = 10^{-2}\ M_\odot$

$R_{in} = 1$ AU

$R_{out} = 100$ AU

similar to tidal dissipation *(Fabrycky & Tremaine 2007)*



Planet:

$M_{pl} = 1\ M_J$

$a = 20$ AU

$e = 0$

$I = 48^o$

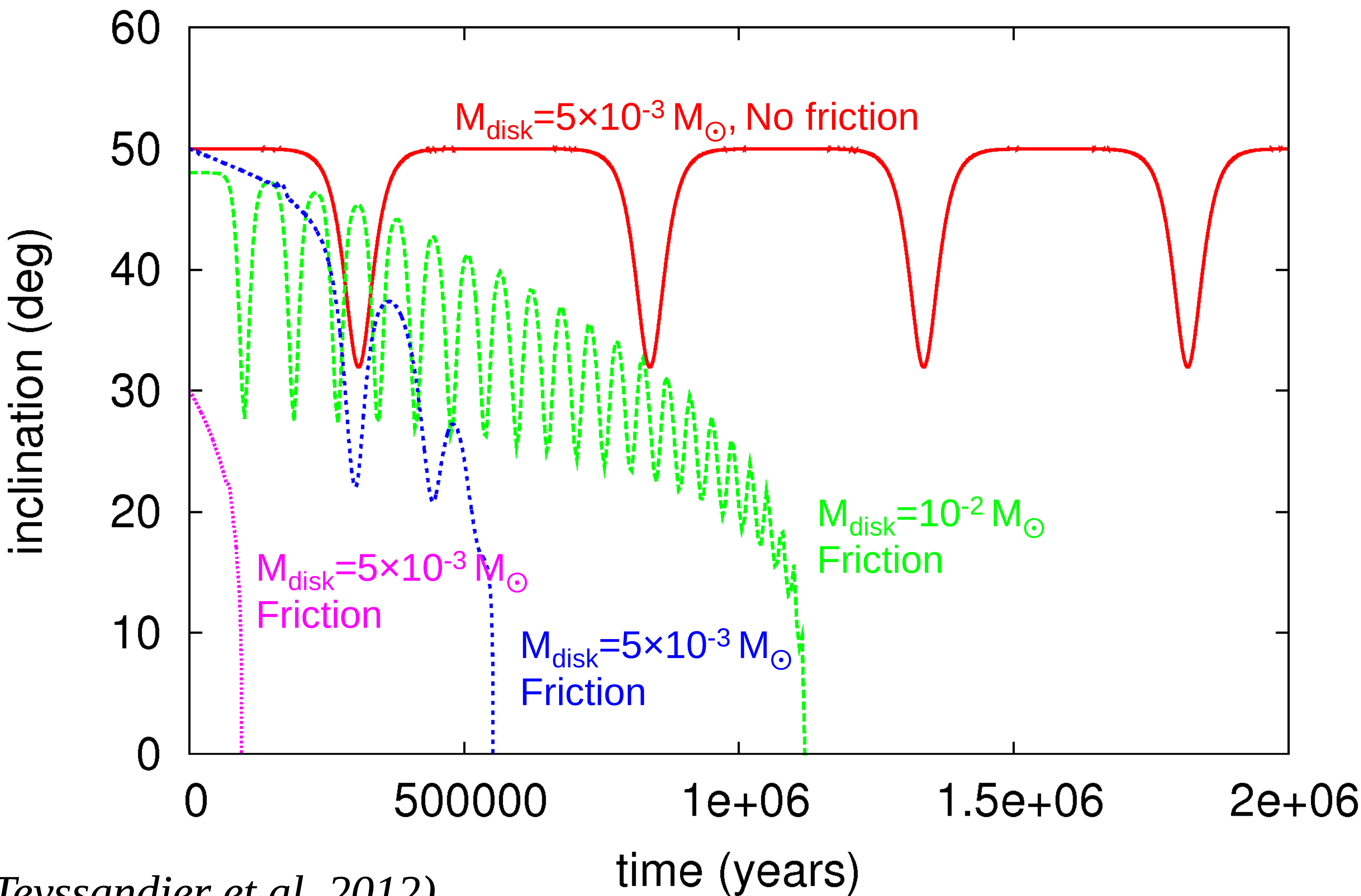
Disk:

$M_{disk} = 10^{-2}\ M_\odot$

$R_{in} = 1$ AU

$R_{out} = 100$ AU

Planet: M_{pl}=1 M_J, e=0, a=7-10 AU Disk: R_{out}=100 AU



(Teyssandier et al. 2012)

Conclusions

• *Low mass planets with near commensurate orbits:*

Even when the departure from exact commensurability is significant, the system may be resonant: libration of the resonant angles ➔ effect on the long term changes of the orbital elements

• *Massive planets interacting with a disk:*

Kozai cycles
➔ enable high inclinations to be maintained
Friction ➔ capture of the more massive planets