

The Long-Term Dynamical Evolution of Planetary Systems

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How do planetary systems evolve?

Planetary systems evolve due to the exchange of angular momentum and/or energy:

- 1) among multiple planets
- 2) between planets and planetesimal disks
- 3) between planets and other stars
- 4) via tides with stellar host

Two-body problem (Brahe, Kepler, Newton)

Planets orbit in ellipses around the host star.

$$E = -\frac{GM_1M_2}{2a}$$

$$e^2 = 1 + \frac{2EJ^2}{G^2\mu^3M^2}$$

What happens to planetary systems?

For well-separated two-planet systems, get periodic oscillations in eccentricity and inclination.

Can get collisions or ejections if planets get close enough - planets do the work on each other.

Thus qualitative changes in the architecture of planetary system can occur.

Can get changes due to encounters in clusters or stellar companions or planet-disk interactions.

The Plan

- 1) Begin with our Solar System.
- 2) Then tightly-packed systems.
- 3) Interactions between planetary systems and other stars (*crowded places*).
- 4) Hot jupiters.

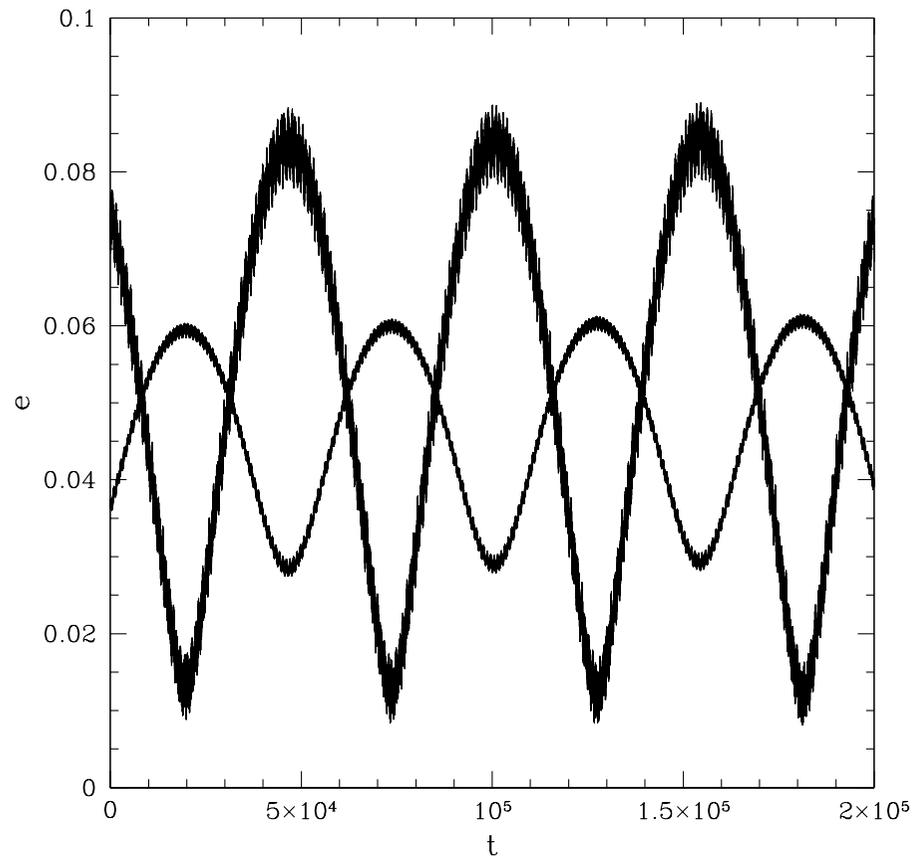
Key Points contained in boxes.

Our Solar System

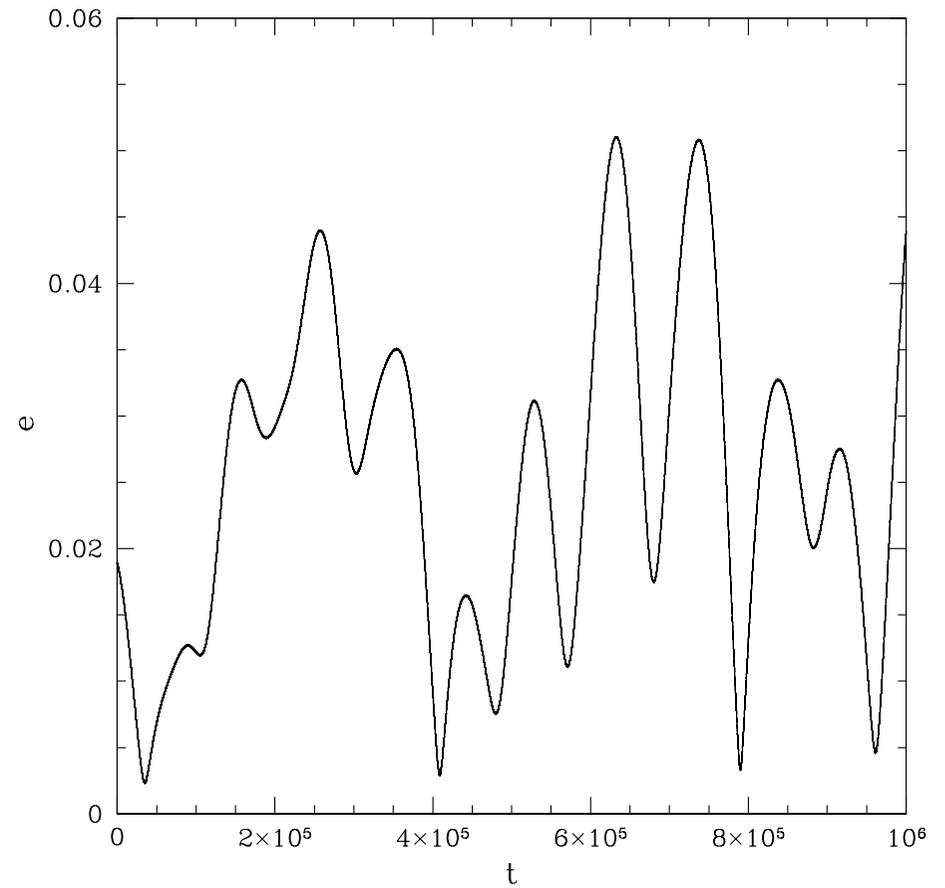
The giant-planet sub-system of the Solar System is stable although the terrestrial-planet sub-system is marginally unstable with a small chance of planet-planet encounters during the lifetime of the Sun.

e.g. Sussman & Wisdom 1992; Laskar 1994, 2008;
Murray & Dermott 1999; Guzzo 2005; Hayes 2008;
Batygin & Laughlin 2008; Laskar & Gastineau 2009

Eccentricity of Jupiter and Saturn



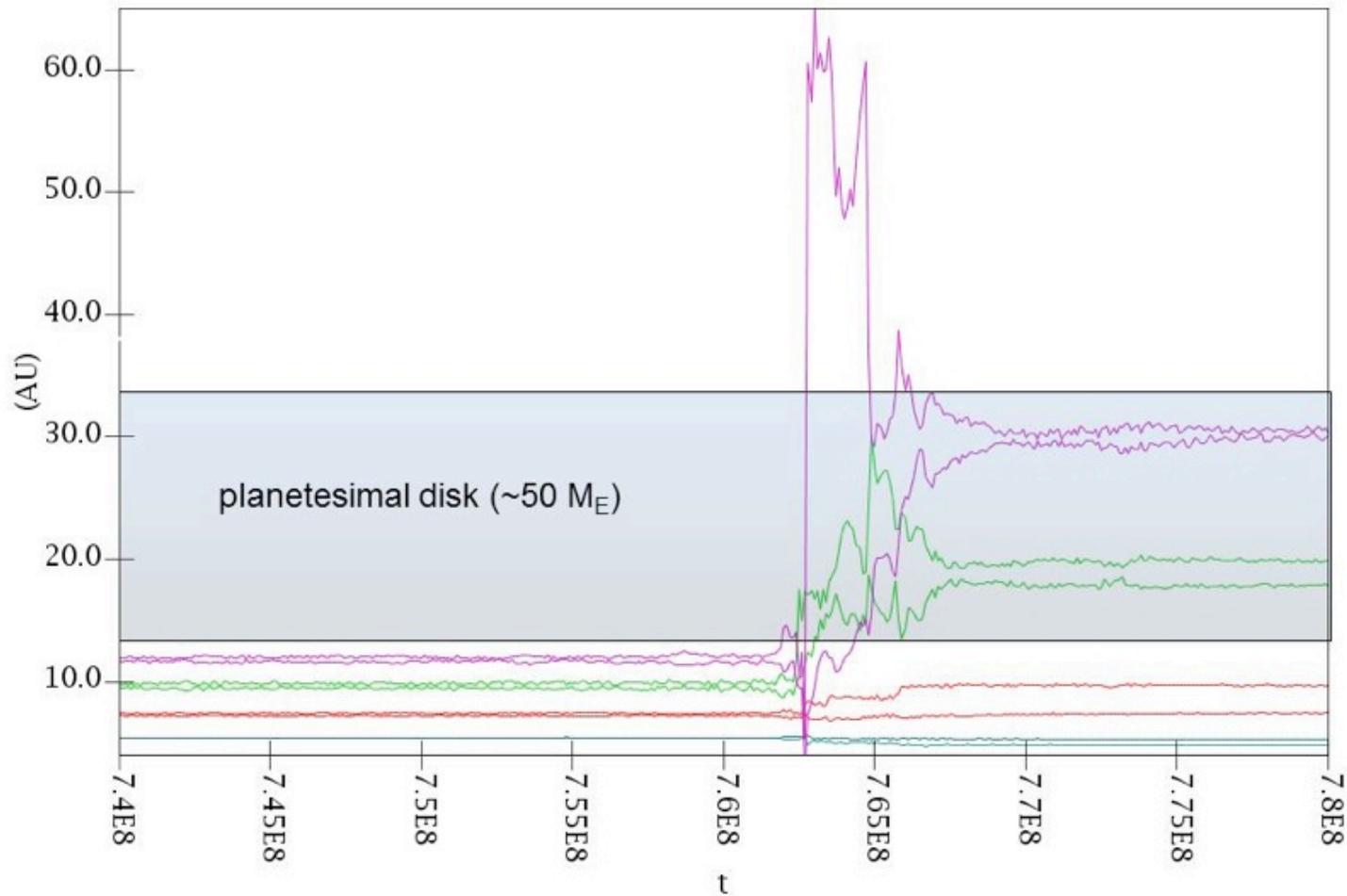
Eccentricity of Earth



Interactions with planetesimal disks will cause planets to migrate which in turn can lead to instabilities within a planetary system. This process probably played an important role in the early history of our own Solar System.

e.g. Fernandez & Ip 1984; Hahn & Malhotra 1999; Gomes et al 2004; Tsiganis et al 2005; Gomes et al 2005; Levison et al 2011

Planet-disk interactions in our Solar System



(Data from Levison et al, 2011, AJ, 142, 152)

Aging systems may become unstable when the host star evolves to become a white dwarf, and loses mass, as the relative strength of the planet-planet interactions increase compared to the interactions between the planets and host star.

e.g. Duncan & Lissauer 1998; Debes & Sigurdsson 2002; Veras et al 2013; Voyatzis et al 2013

Kepler systems are also flat

By considering the ratio of three, two and single-planet transits, one gets a limit on mutual inclinations.

Lissauer et al 2011; Tremaine & Dong 2012;
Johansen et al 2012; Fang & Margot 2012

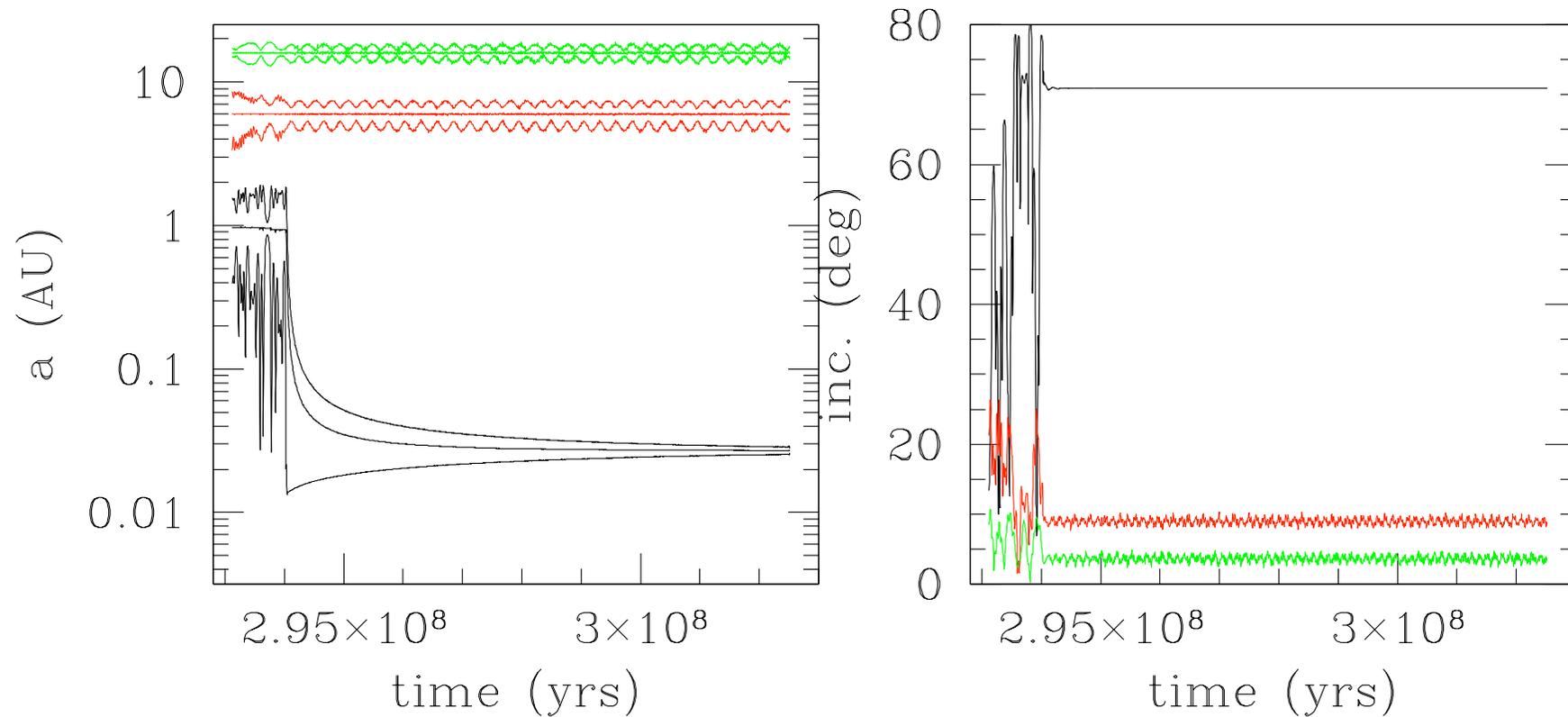
Tightly-packed systems

Secular interactions cause the redistribution of angular momentum amongst planets in a system. In systems with a sufficiently large angular momentum deficit (AMD), such redistribution can lead to close planetary encounters.

$$\text{AMD} \equiv \sum_k \Lambda_k \left(1 - \cos i_k \sqrt{1 - e_k^2} \right)$$

$$\Lambda_k = \frac{M_k M_*}{M_k + M_*} \sqrt{G(M_* + M_k) a_k}$$

Secular chaos could produce hot Jupiters



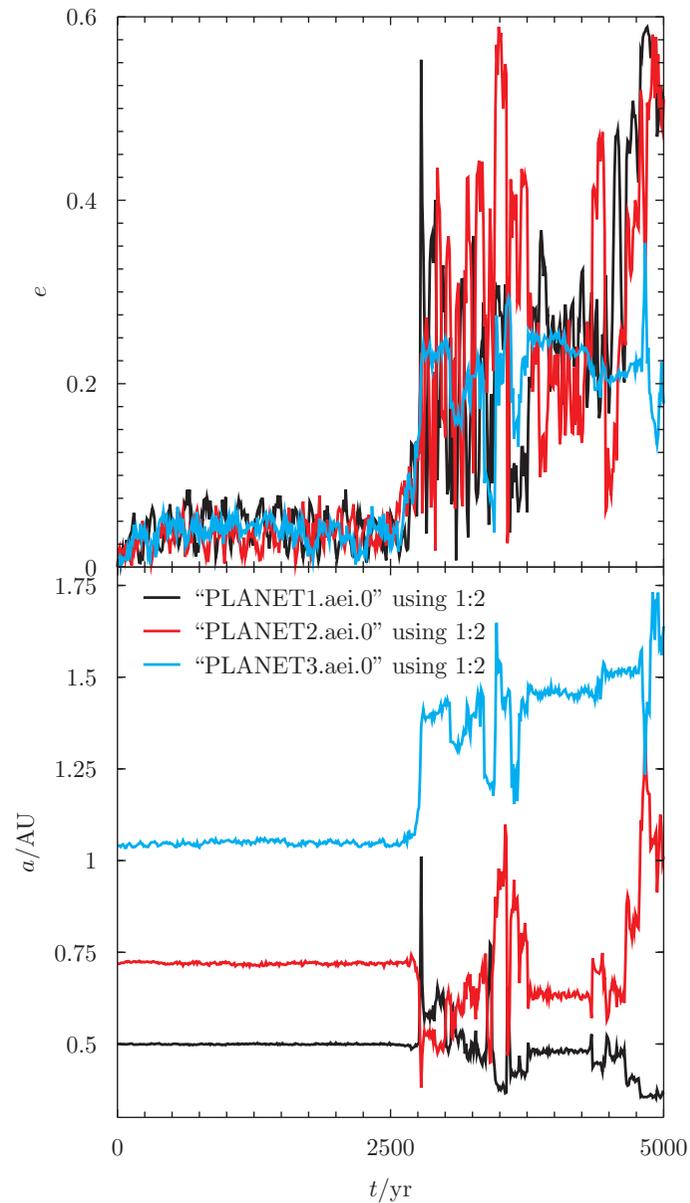
(Wu & Lithwick, 2011, ApJ, 735, 109)

Planet-planet scattering in tighter planetary systems can lead to close encounters between planets. The timescale before a system undergoes such encounters is a strong function of the separation of planets.

e.g. Chambers et al 1996;
Marzari & Weidenschilling 2002

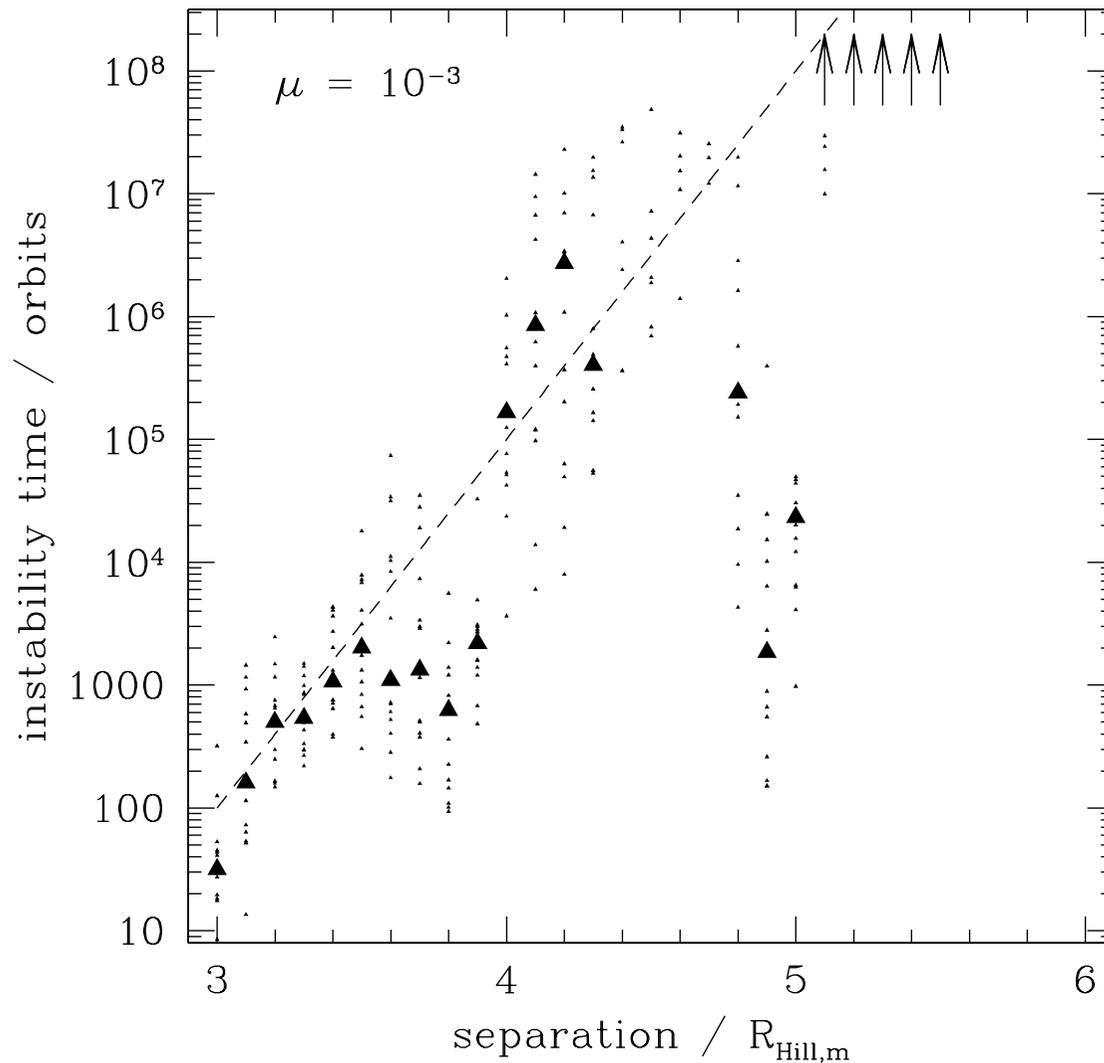
An unstable system containing three Jupiters

(Ross Church,
private comm.)



see also:
Quillen (2011)

Instability time as a function of separation



$$R_{\text{Hill},m} \equiv \left(\frac{M_k + M_{k+1}}{3M_*} \right)^{1/3} \times \frac{a_k + a_{k+1}}{2}$$

(after Chambers et al 1996, *Icarus*, 119, 261; Marzari & Weidenschilling 2002, *Icarus*, 156, 570)

The outcome of planetary close encounters is a function of the Safronov number.

$$\Theta^2 = \left(\frac{M_p}{M_*} \right) \left(\frac{R_p}{a_p} \right)^{-1}$$

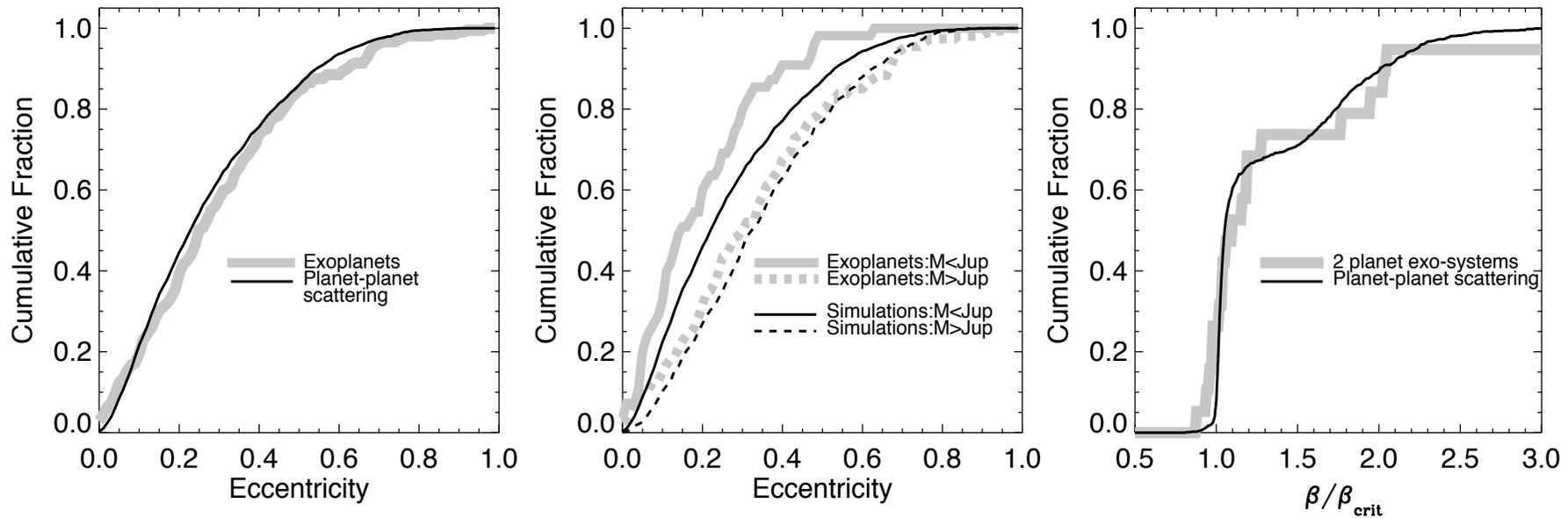
Collisions dominate when the planetary surface escape speeds are smaller than orbital speeds.

Planetary scattering will be more common when the surface escape speeds are larger than the planetary orbital speeds in a system.

11 < 30 < 64

The observed eccentricity distribution can be explained as an outcome of planet-planet scattering in unstable systems. Massive planets have to be formed in systems with other massive planets in order to reproduce the observed correlation between planetary mass and orbital eccentricity.

e.g. Adams & Laughlin 2003; Moorhead & Adams 2005; Juric & Tremaine 2008; Chatterjee et al 2008; Ford & Rasio 2008; Raymond et al 2010; Beaugé & Nesvorný 2012

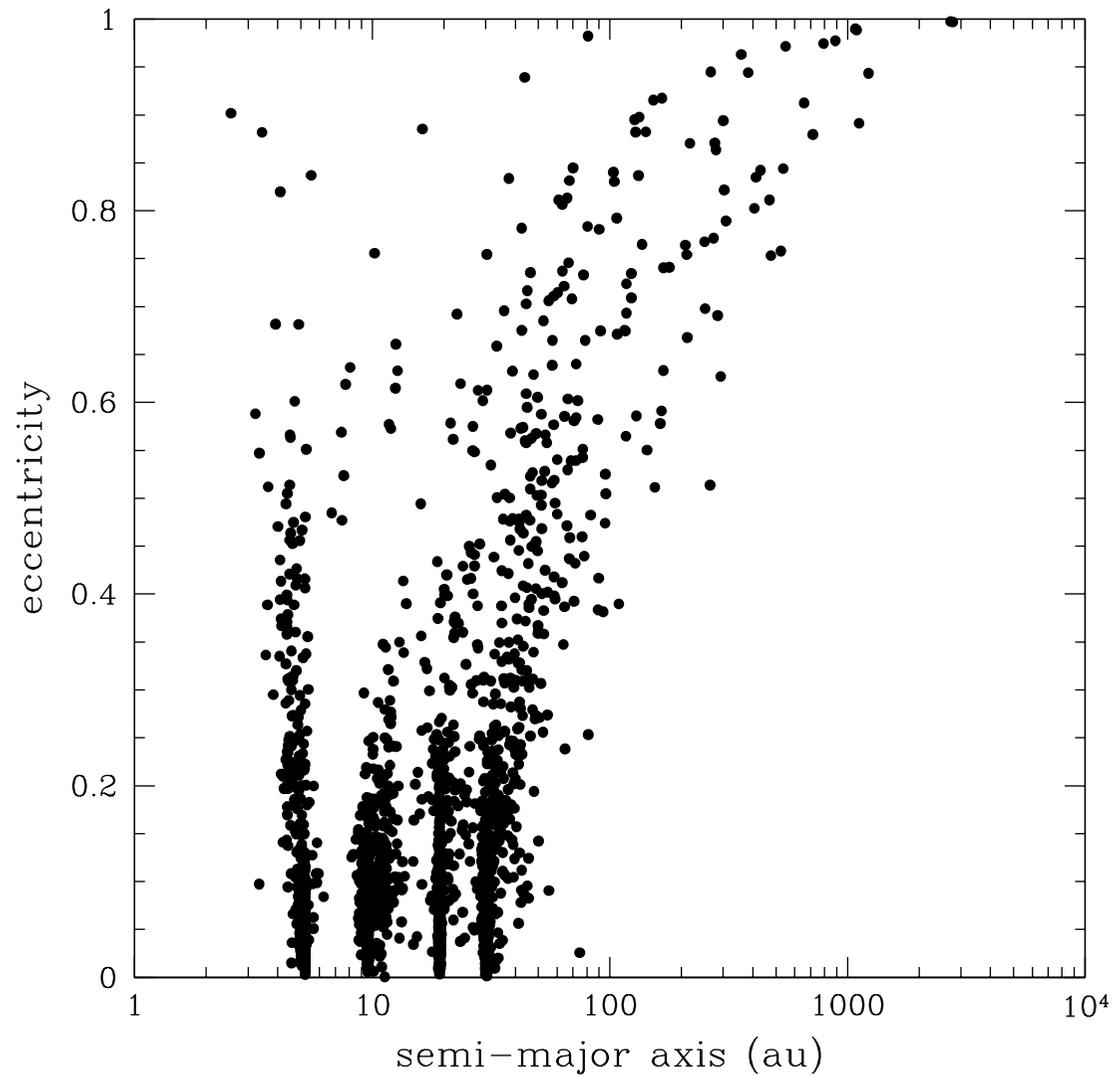


(after Barnes & Greenberg 2006, *ApJ*, 647, L163; Raymond et al 2009, *ApJ*, 696, L98; Raymond et al 2010, *ApJ*, 711, 772)

Planets are predicted to pass through a phase of wide orbits within unstable planetary systems as ejections occur only after several scatterings. Imaging surveys will therefore inform us about the frequency of unstable systems.

Scharf & Menou 2009;
Veras, Crepp & Ford 2009;
Malmberg, Davies & Hogg 2011

The four gas giants 10^8 years after fly-by ($r_{\min} < 100$ AU)



(Malmberg, Davies & Heggie, 2011, MNRAS, 411, 859)

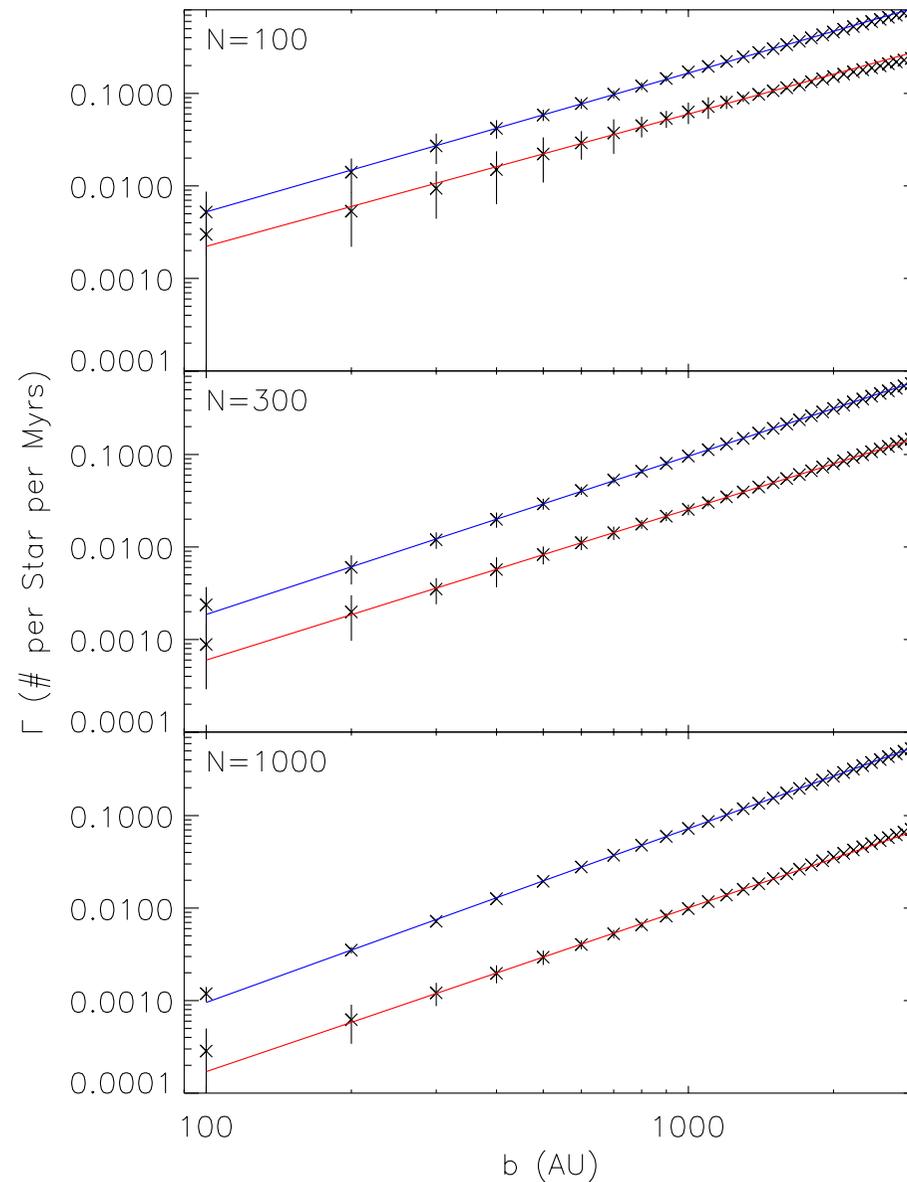
Crowded Places

Fly-by encounters in stellar clusters will occur in dense birth environments. Such encounters may lead to the direct ejection of planets in some cases. In other encounters, perturbations to the planetary orbits lead to instabilities on longer timescales. The intruding star may also pick-up a planet from the system.

e.g. Adams et al 2006; Malmberg et al 2007;
Proszkow & Adams 2009; Allison et al 2009;
Parker & Quanz 2012.

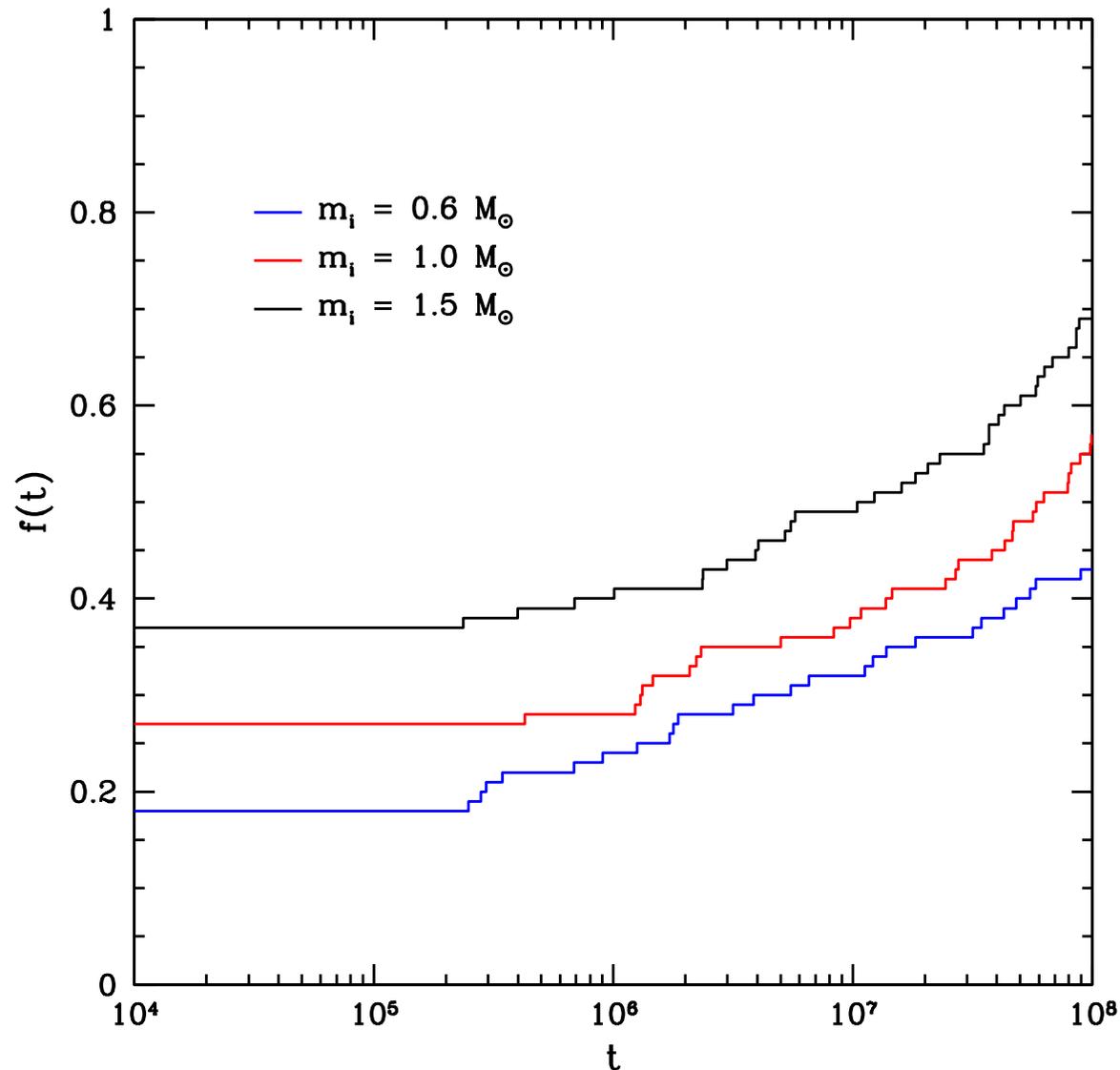
$$\tau_{enc} \simeq 3.3 \times 10^7 \text{ yr} \left(\frac{100 \text{ pc}^{-3}}{n} \right) \left(\frac{v_{\infty}}{1 \text{ km/s}} \right) \left(\frac{10^3 \text{ AU}}{r_{min}} \right) \left(\frac{M_{\odot}}{M} \right)$$

How common are fly-by encounters?



(Adams et al., 2006, ApJ, 641, 504)

The long term effect of fly-bys (within 100 AU)



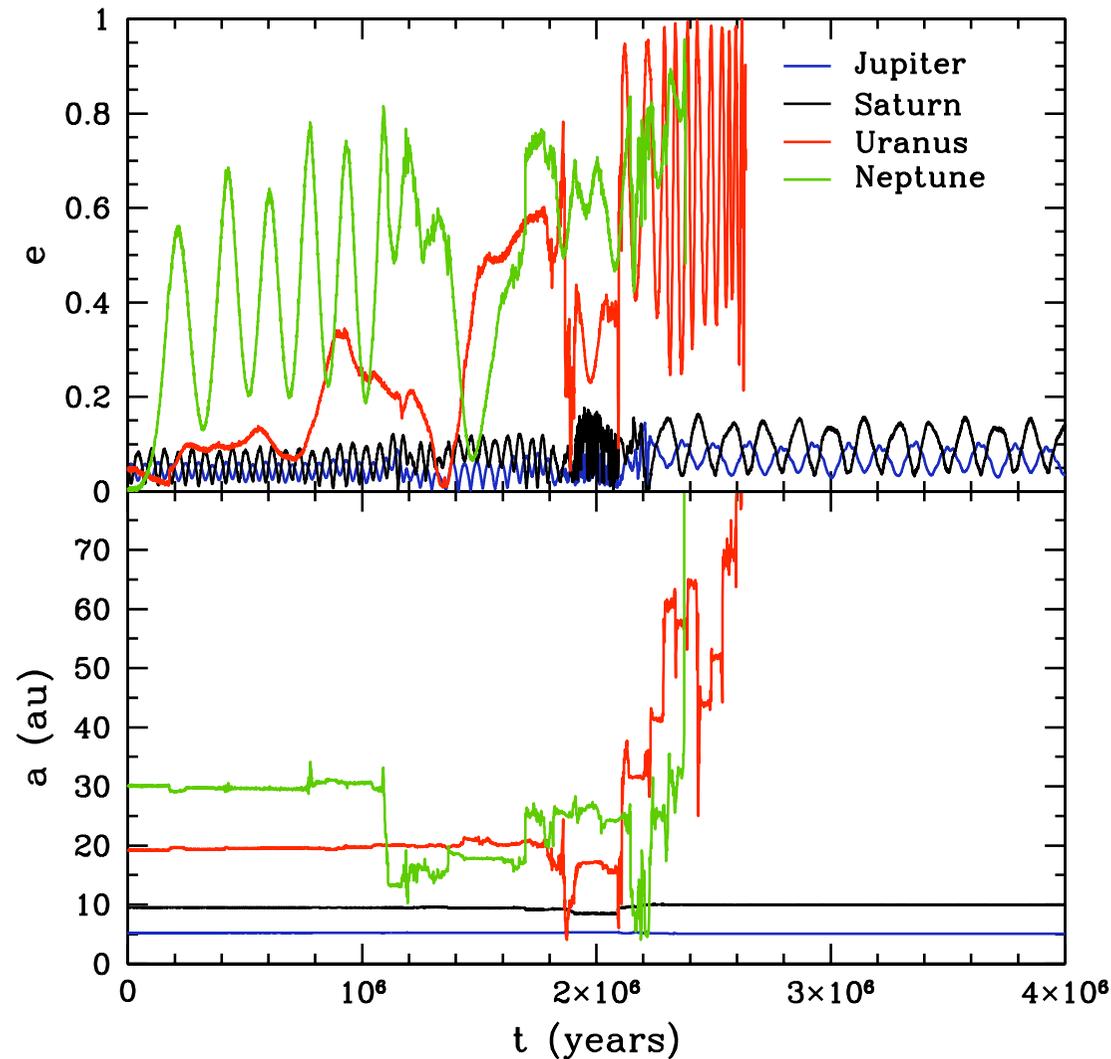
The fraction of solar-mass stars with four gas giants in a cluster of 700 stars that lose at least one planet within 100 million years of a close fly-by: **0.15**

(Malmberg, Davies & Heggie, 2011, MNRAS, 411, 859)

Exchange into binaries can occur in stellar clusters. Planetary systems may be de-stabilised by the perturbing effect of the companion star through the Lidov-Kozai mechanism where the outer planet suffers periods of higher eccentricity leading it to have strong encounters with other planets.

e.g. Lidov 1962; Kozai 1962; Innanen et al 1997; Malmberg et al 2007; Malmberg & Davies 2009

The four gas giants in a binary



(Malmberg, Davies & Chambers, 2007, MNRAS, 377, L1;
Malmberg & Davies, 2009, MNRAS, 394, L26)

Hot Jupiters

The formation of hot jupiters is an interesting question. Observations using the Rossiter-McLaughlin effect show that a number of hot jupiters are highly-inclined compared to what would be expected given the stellar rotation.

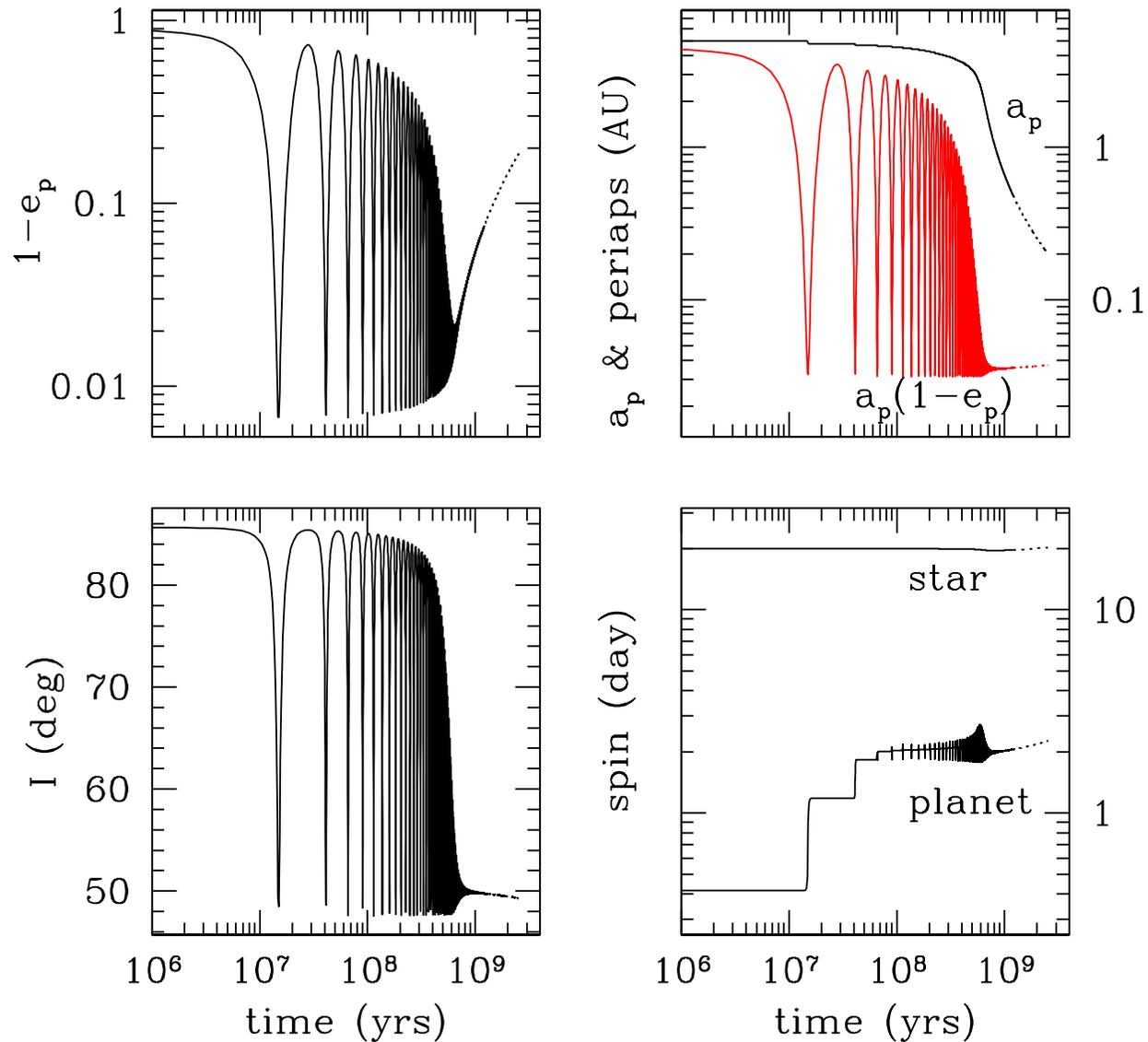
e.g. Triaud et al 2010

The origin of hot Jupiters through dynamical interactions may involve one of five possible routes:

- 1) Lidov-Kozai evolution of a one-planet system perturbed by a binary stellar companion;
- 2) Lidov-Kozai evolution in a multiple-planet system;
- 3) scattering of multiple planets;
- 4) secular evolution unrelated to the Kozai resonance;
- 5) the re-orientation of circumstellar disks before planets form via interaction

e.g. Innanen et al 1997; Wu & Murray 2003; Takeda & Rasio 2005; Fabrycky & Tremaine 2007; Malmberg & Davies 2009; Bate et al 2010; Naoz et al 2011; Nagasawa & Ida 2011; Beaugé & Nesvorný 2012; Batygin 2012; Dawson et al 2012

Making a hot Jupiter via the Lidov-Kozai mechanism



(Wu & Murray, 2003, ApJ, 589, 605)

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Summary

- 1) Secular interactions and AMD.
- 2) Instability timescales vary enormously.
- 3) Multiplicity matters.
- 4) Scattering can match observed eccentricities.
- 5) Flybys and binary companions can mess up a planetary system.
- 6) Hot jupiters may form through one of several dynamical processes.