Origin of Hot Jupiters: Secular Chaos

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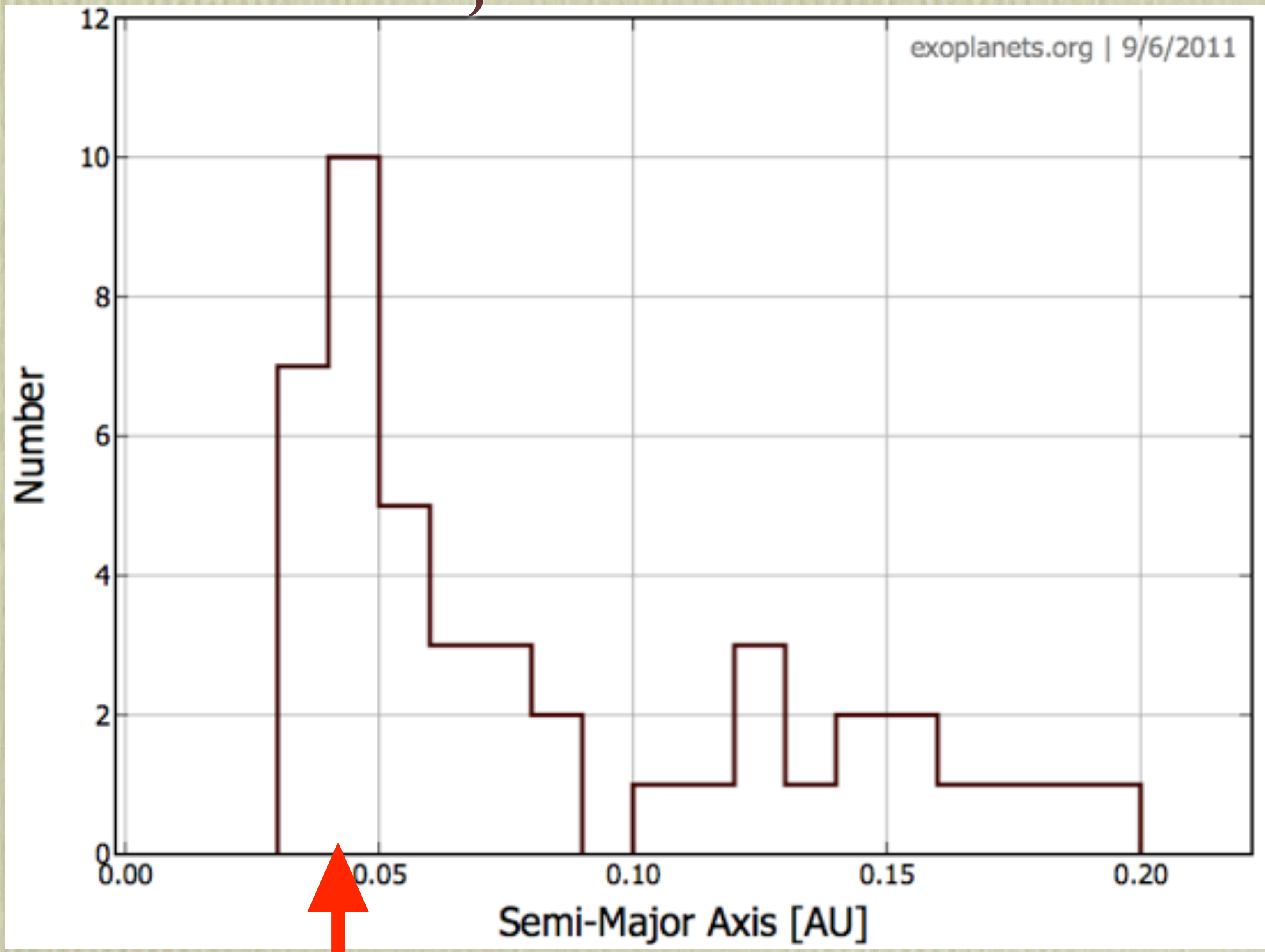
Hot Jupiters

Semimajor Axis Distribution



(RV-discovered planets with $0.1\ M_{Jup} < M \sin i < 3\ M_{Jup}$)

hot Jupiters (~3 day orbits)

- ~ 1% of FGK stars have hot Jupiters
- How did Jupiters migrate from >1 AU to < 0.1AU?

A New Migration Mechanism: Secular Chaos

(Wu & Lithwick 2011)

- Start with a few Jupiters beyond an AU, on widely-spaced, mildly eccentric & inclined orbits

- focus on secular (i.e. orbit-averaged) interactions. Okay if no close encounters or strong resonances.

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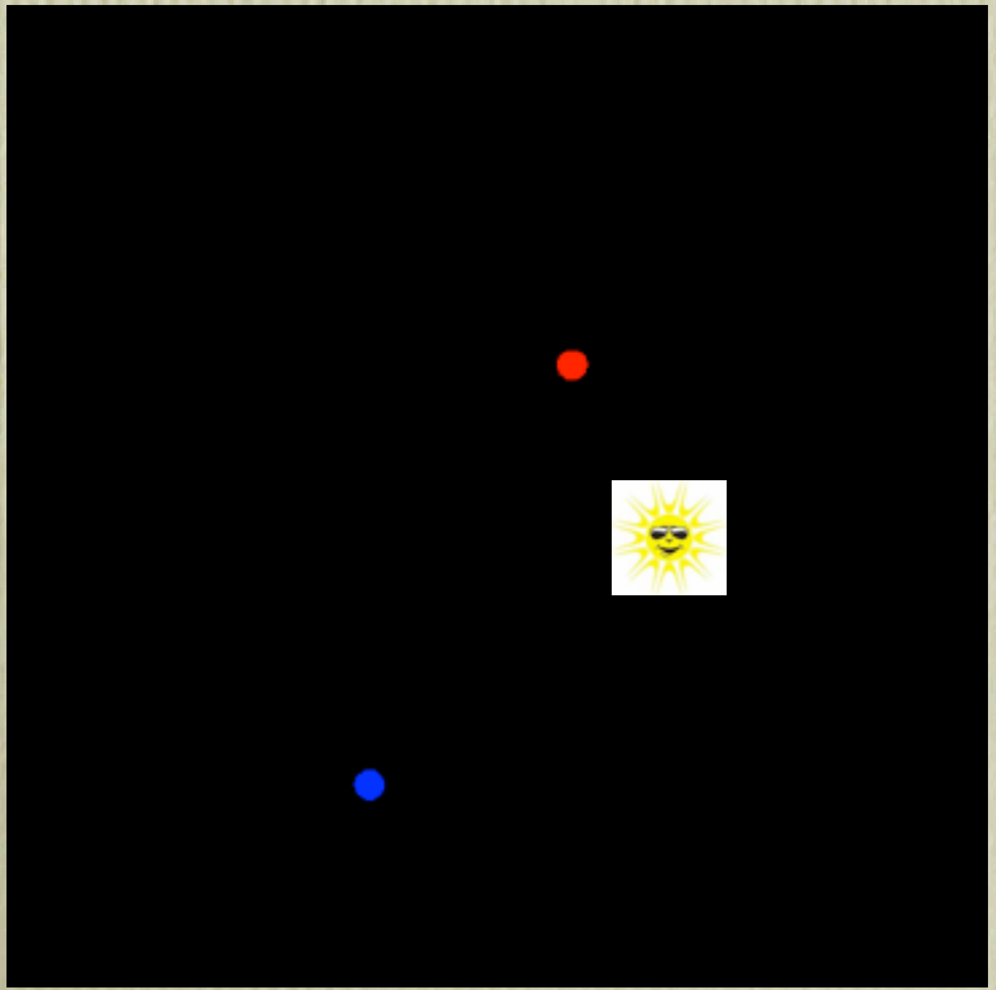

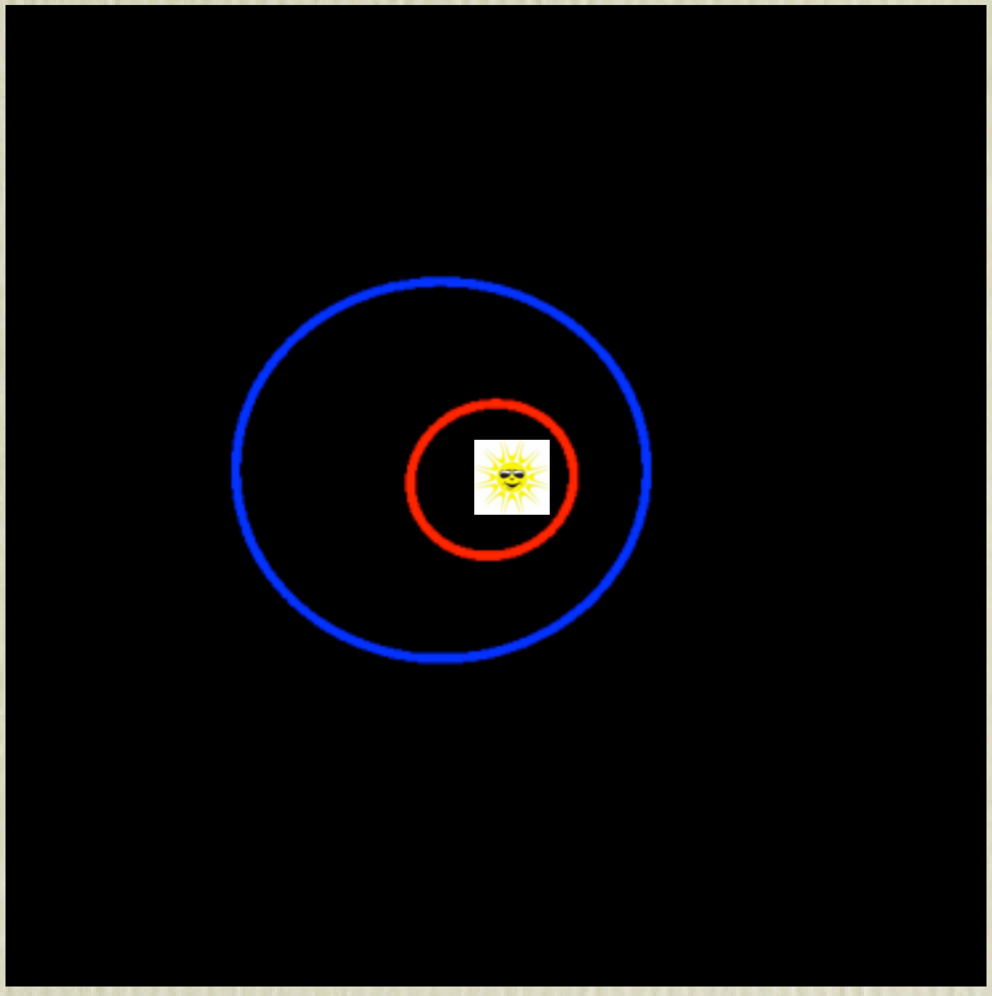

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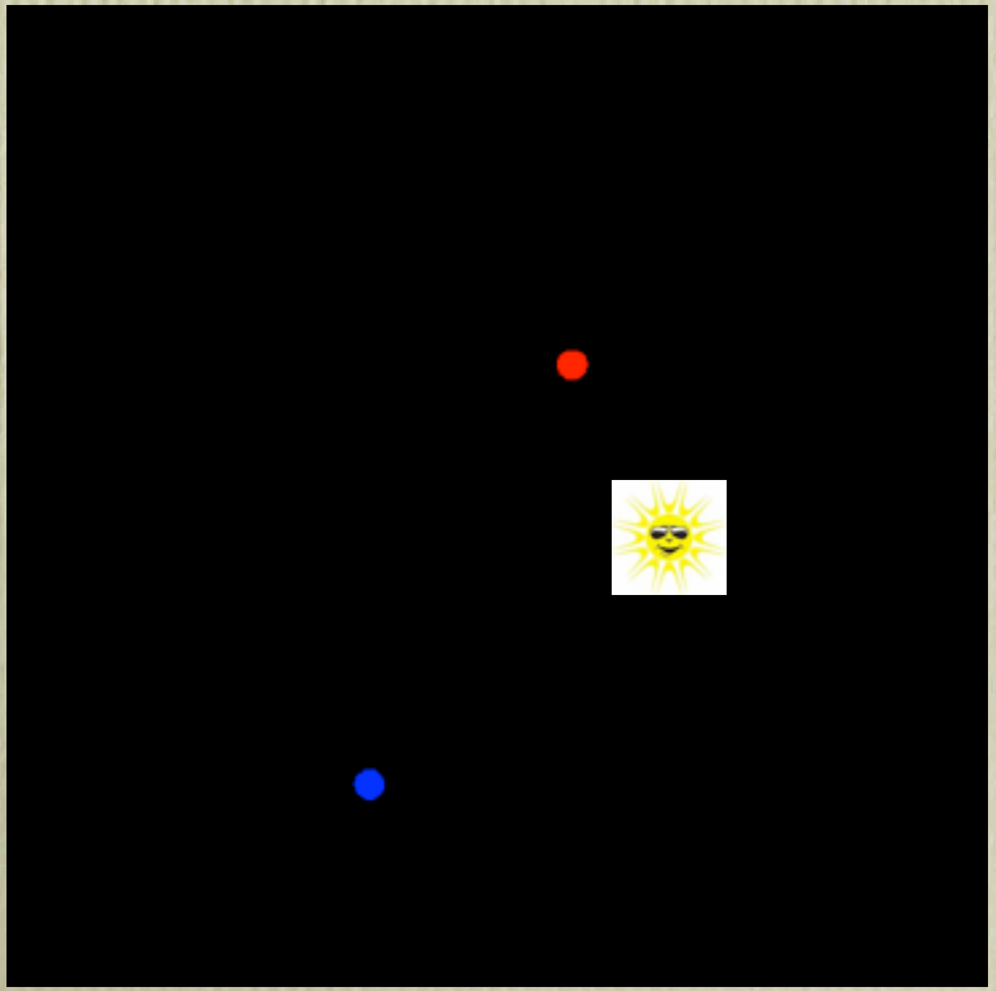
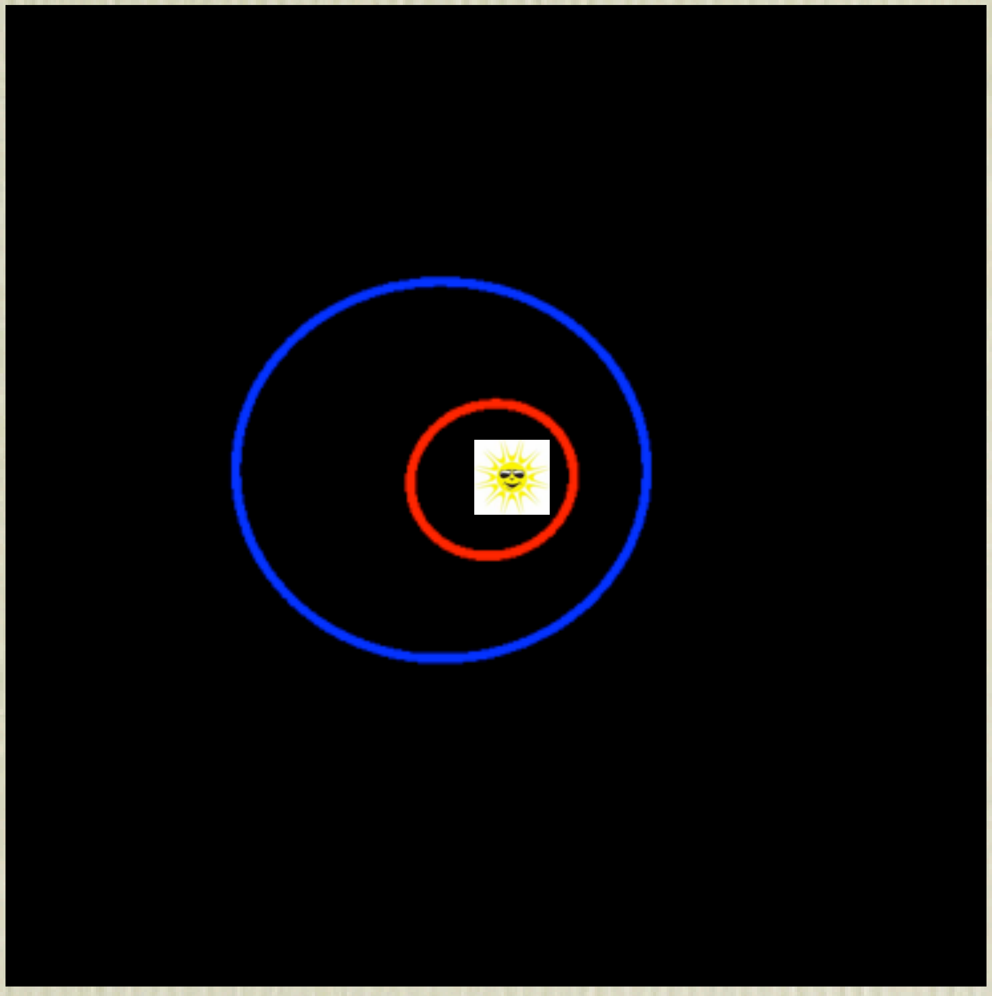
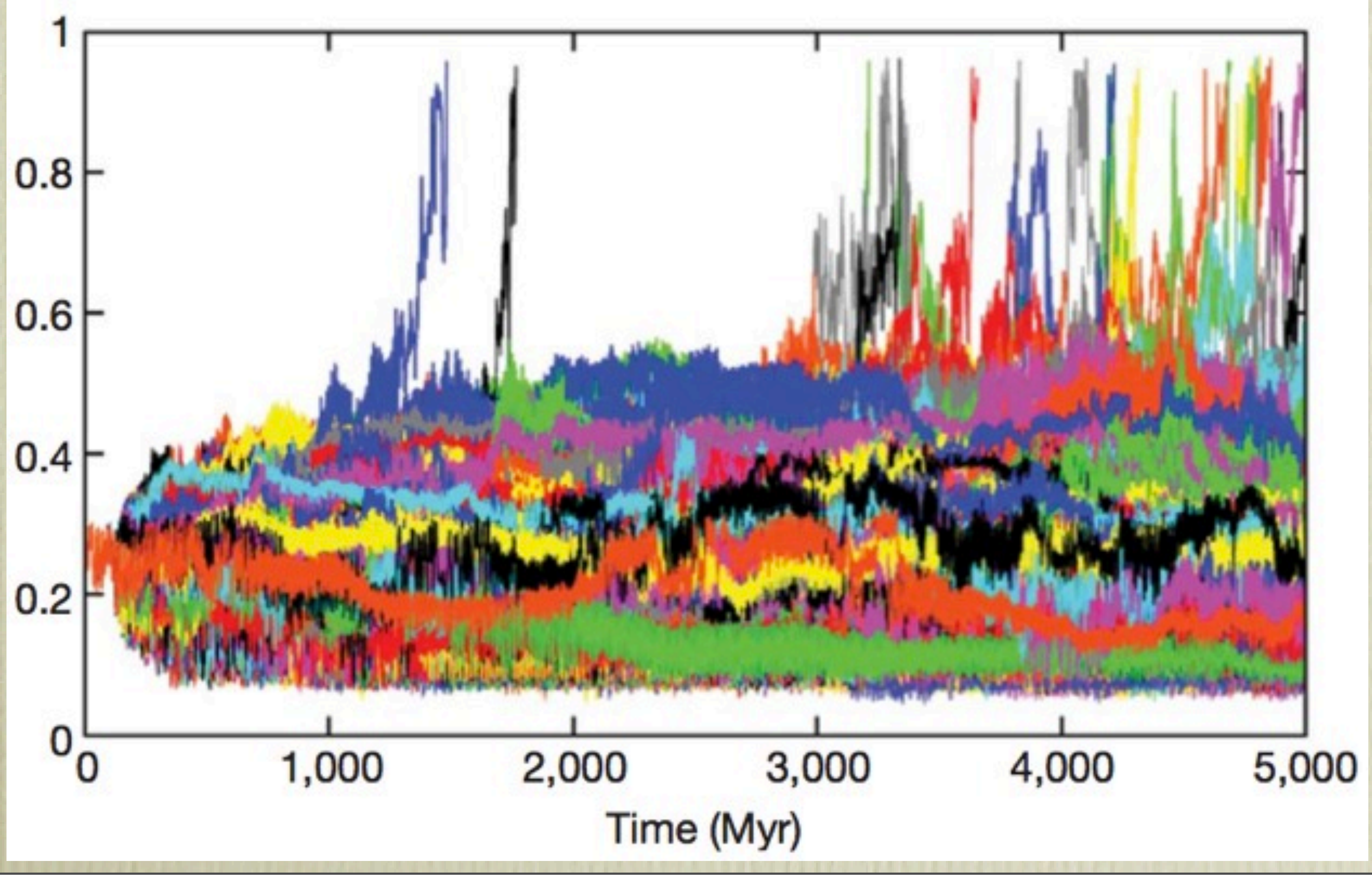




Secular Chaos in the Solar System

- secular interactions can lead to chaos
- e.g., terrestrial planets' orbits driven by secular chaos

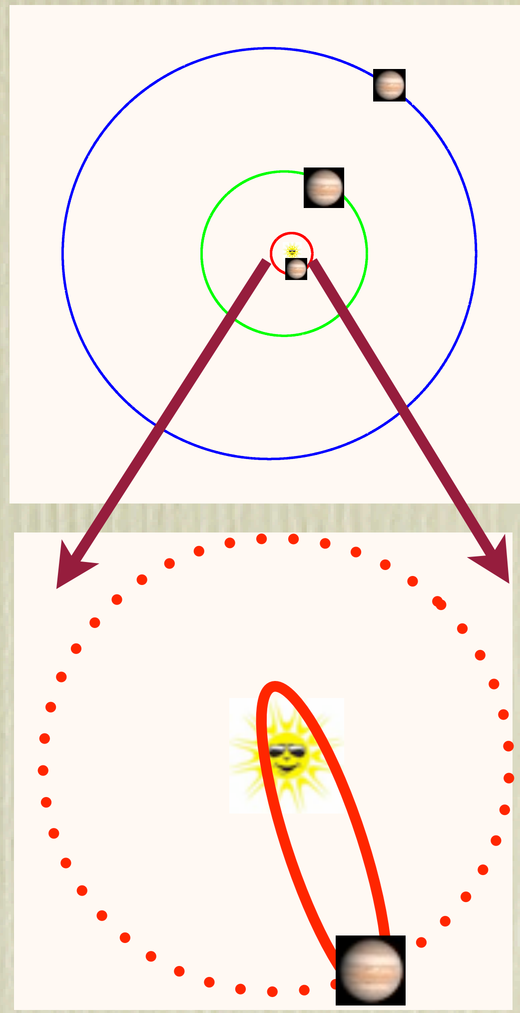
Mercury's eccentricity (2501 realizations)



(Laskar & Gastineau `09)

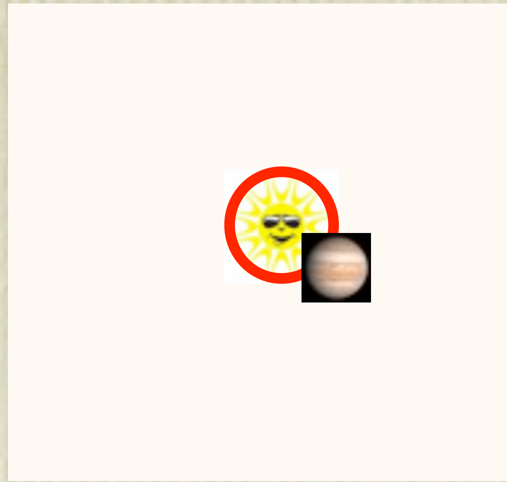
Migration by Secular Chaos

- Start with 3 jupiters on widely-spaced, mildly eccentric & inclined orbits



- If secular chaos can increase planet 1's eccentricity sufficiently ($e_1 \gtrsim 0.99$) ...

- Then tides raised by star can circularize planet 1 onto a tight orbit
  $\Rightarrow$ hot jupiter



Angular Momentum Deficit (AMD)

(e.g. Laskar '97)

- AMD ≡ deficit of angular momentum of system due to e,i > 0

$$\approx \sum_{\text{planets}} \frac{1}{2} m \sqrt{a} (e^2 + i^2)$$

- AMD constant under secular interactions

- To form hot jupiter by secular chaos, need

$$\text{AMD} \quad > \quad m_1 \sqrt{a_1}$$

initial

An N-body simulation with GR and tides

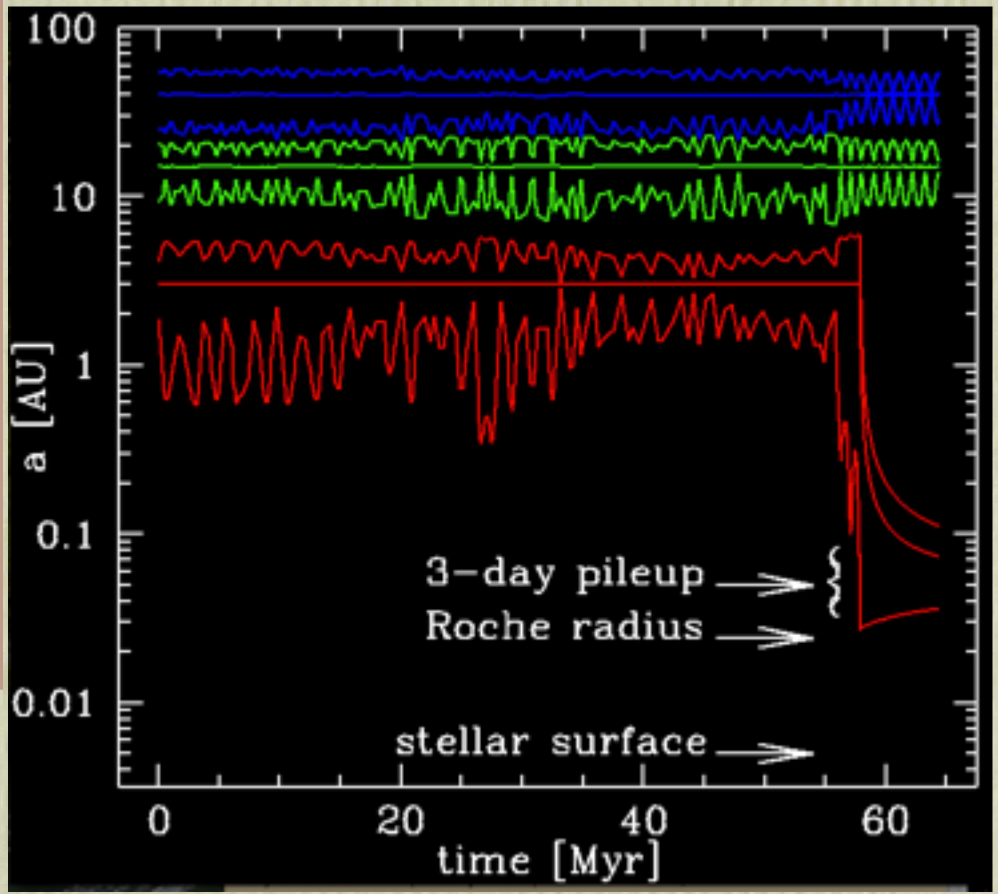
(tides include precession and dissipation)

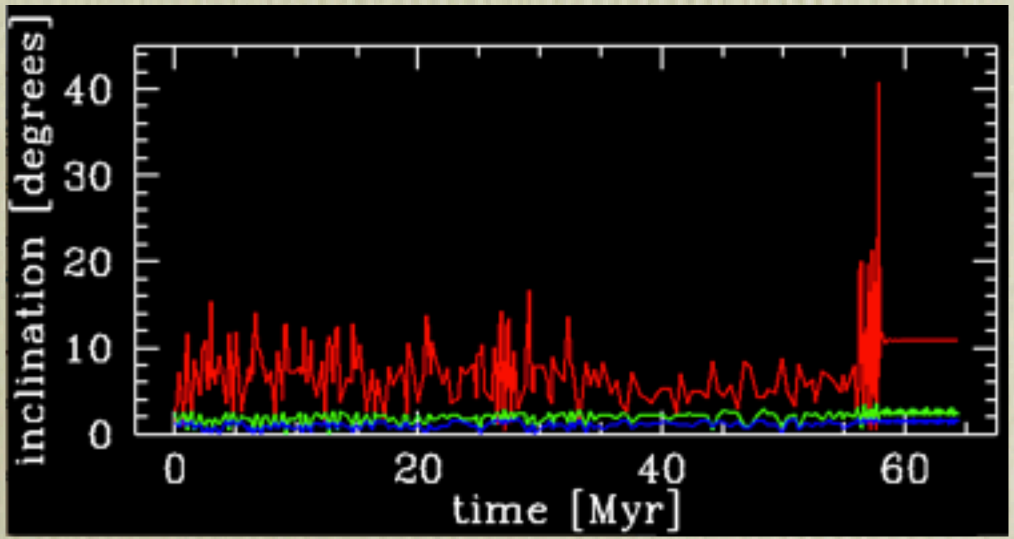
initial values:

m[m$_{jup}$]	a[AU]
1	40
1	15
0.3	3

e=0.38
i=e/10

AMD = $1.5\, m_1 \sqrt{a_1}$

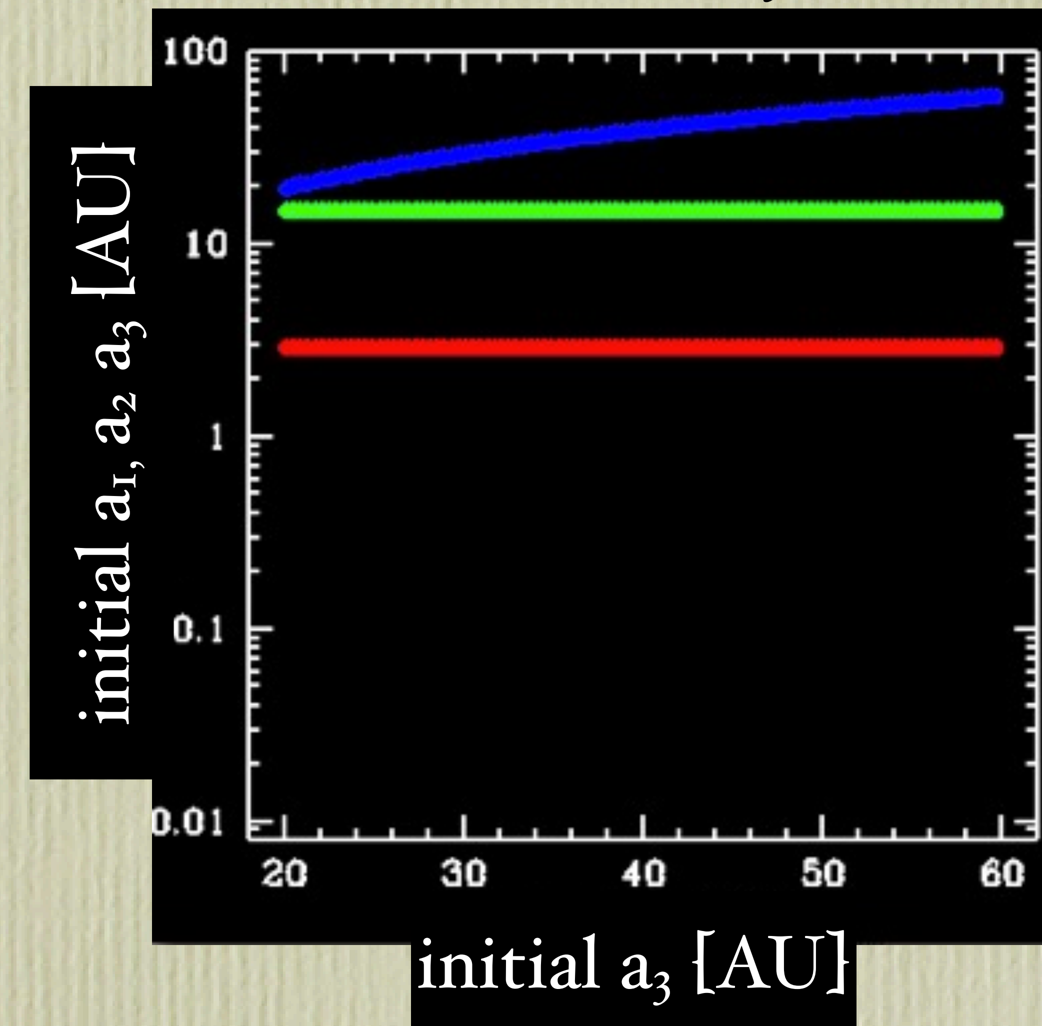




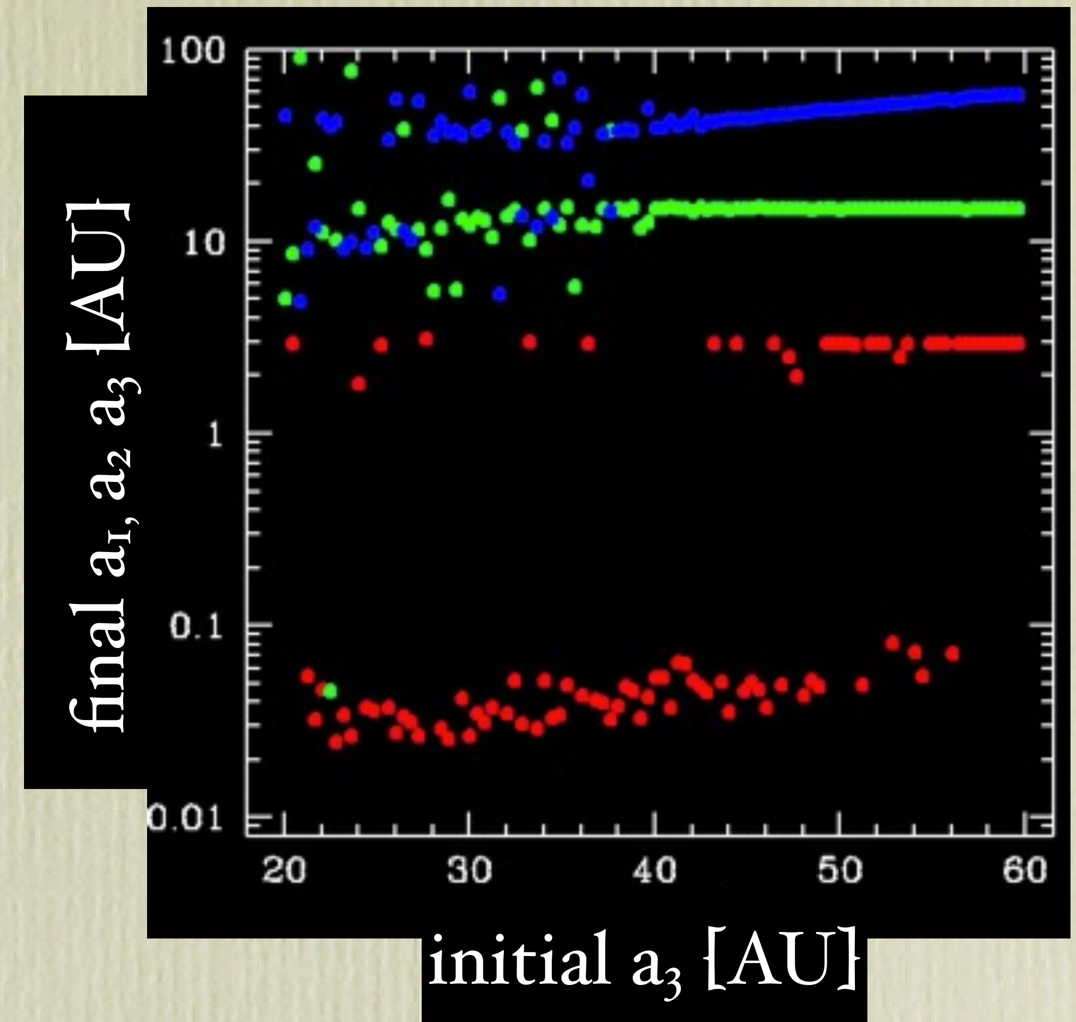
- secular dominates (a's constant)
- e_1 chaotically diffuses until periapse near Roche radius
- planet tidally circularized at ~ 2×Roche radius (Ford & Rasio '06)
- need gradual e_1 growth ⇒ planet scattering alone can't work (Nagasawa's talk Tues.)

100 Simulations with AMD = 1.5 $m_1\sqrt{a_1}$

initial: 20 AU≤ a_3 ≤ 60 AU

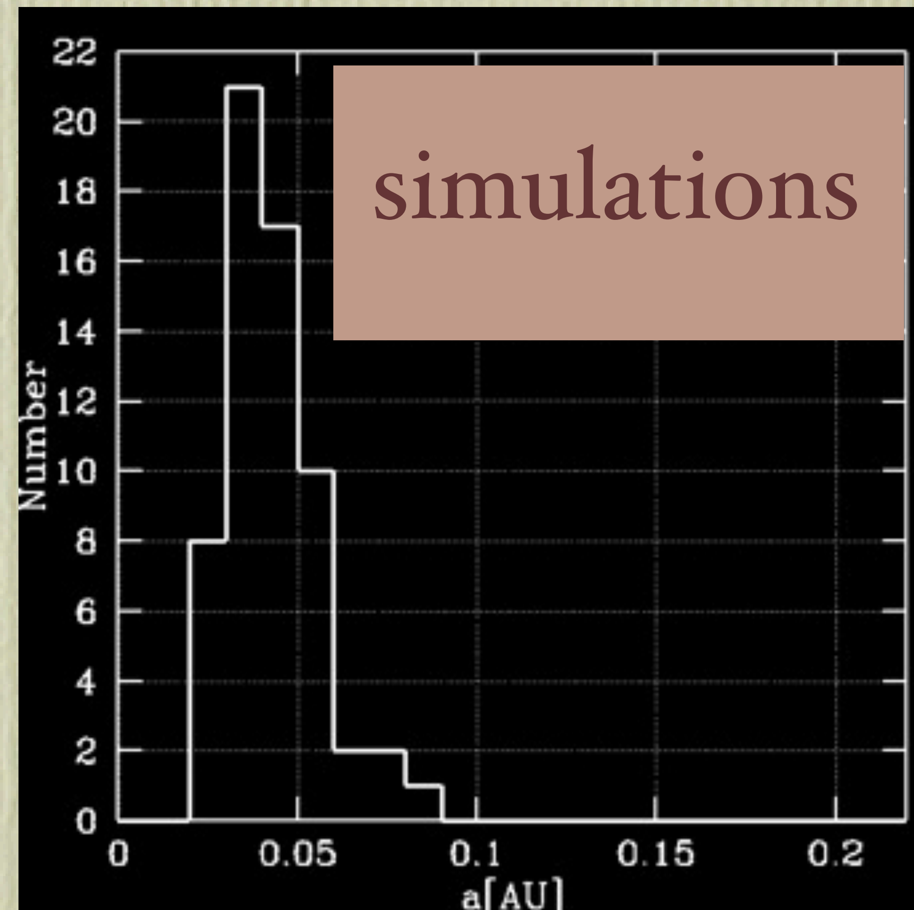


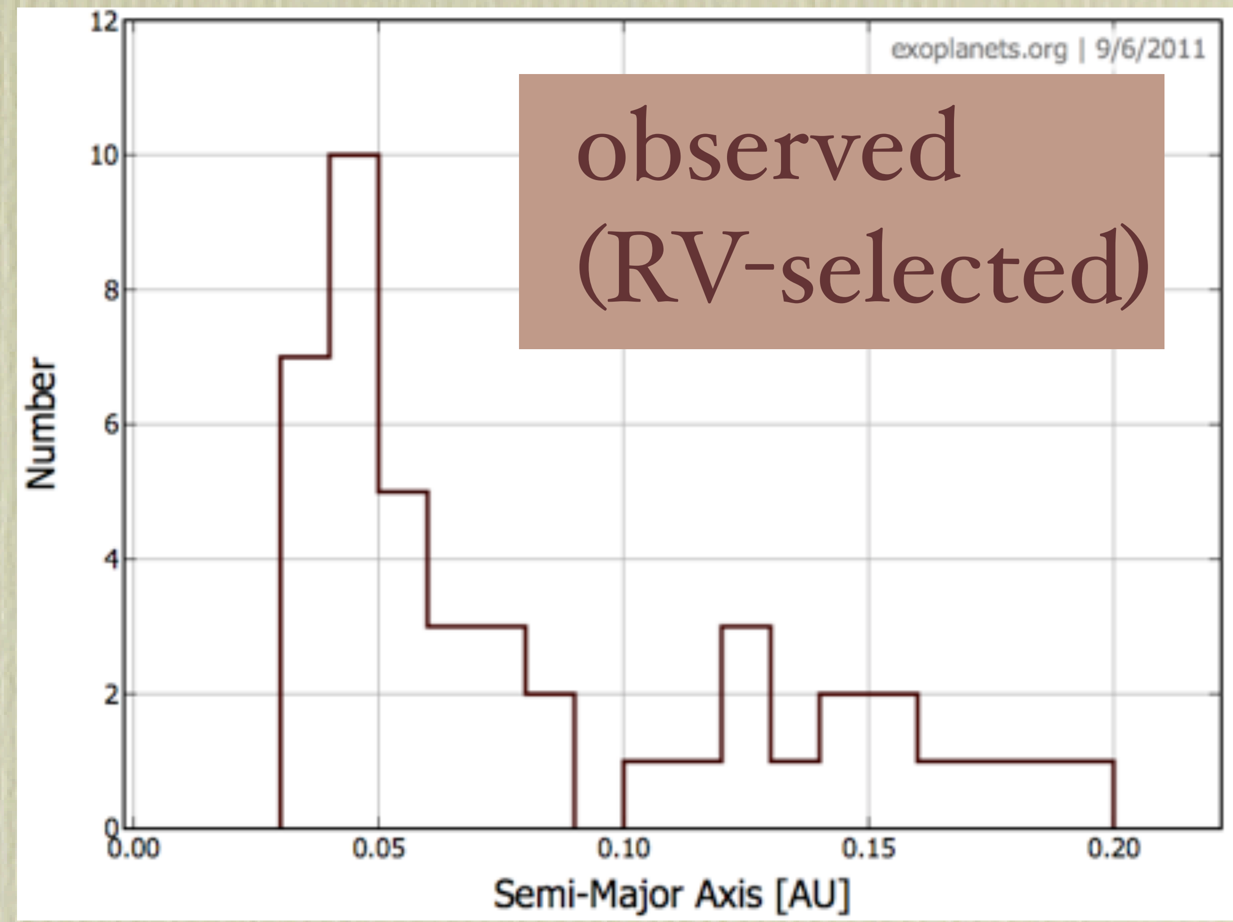
final



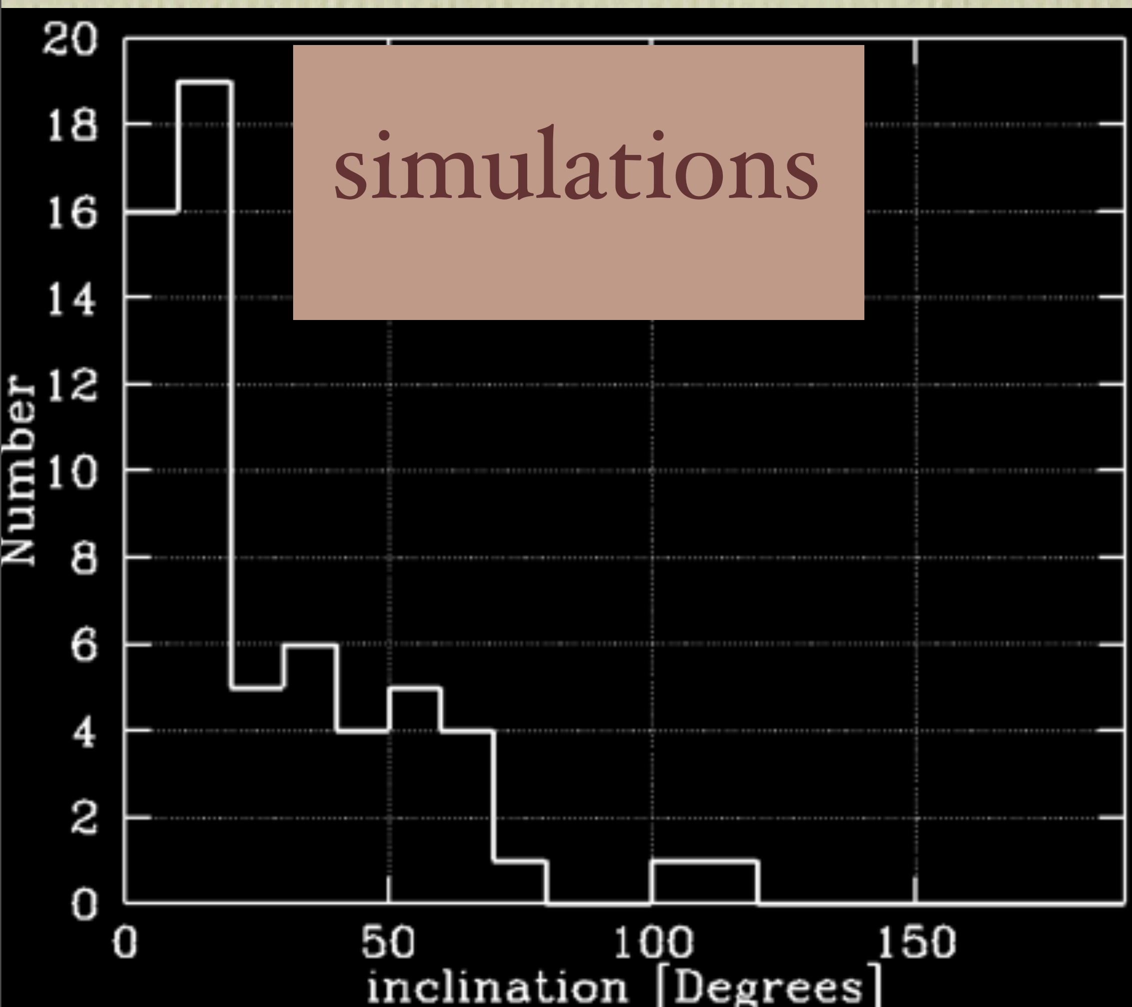
- robust: 62 hot jupiters!
  - (17 ejection/collision & 21 no dramatic change)

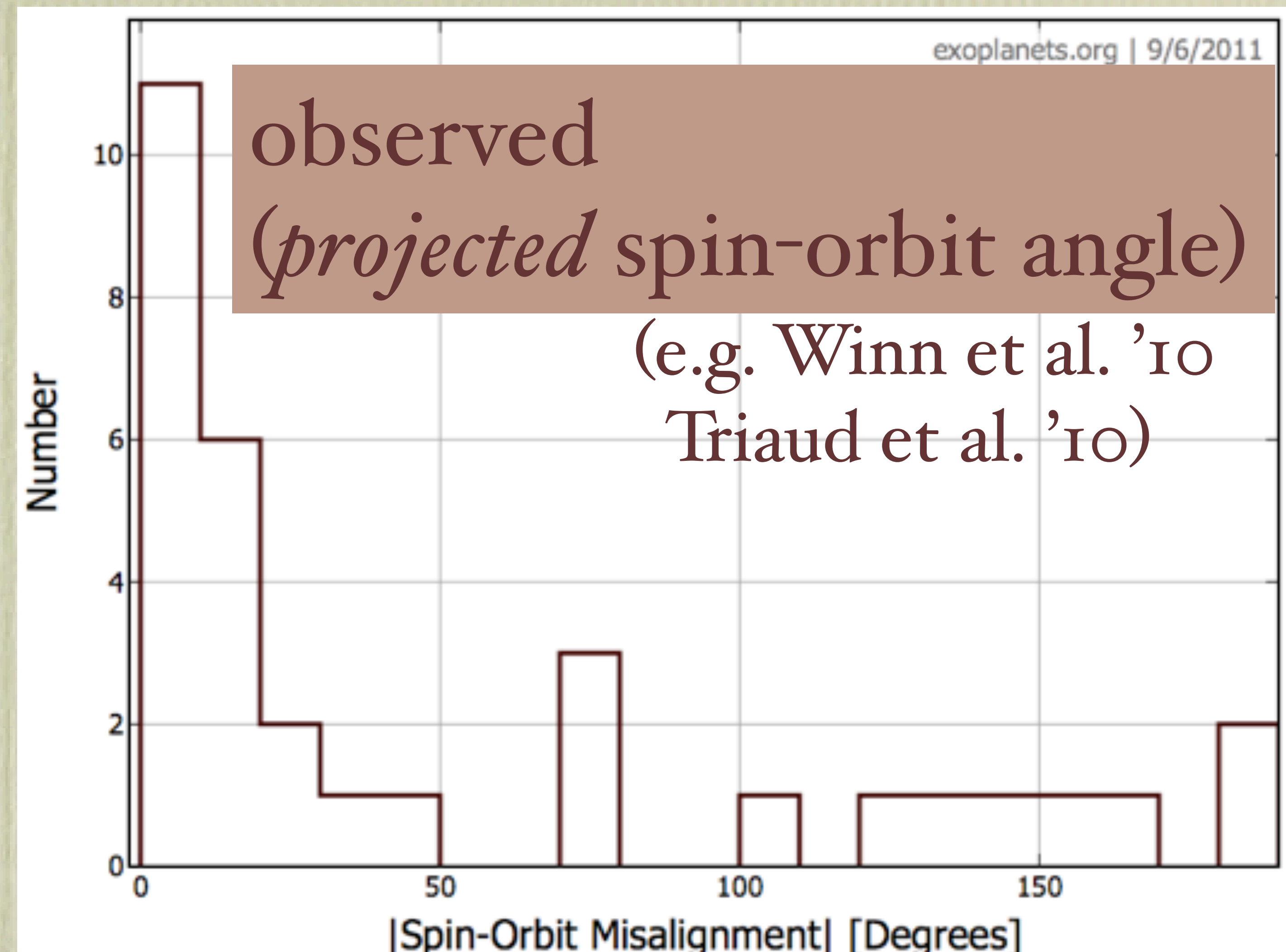
Semi-major axis distribution





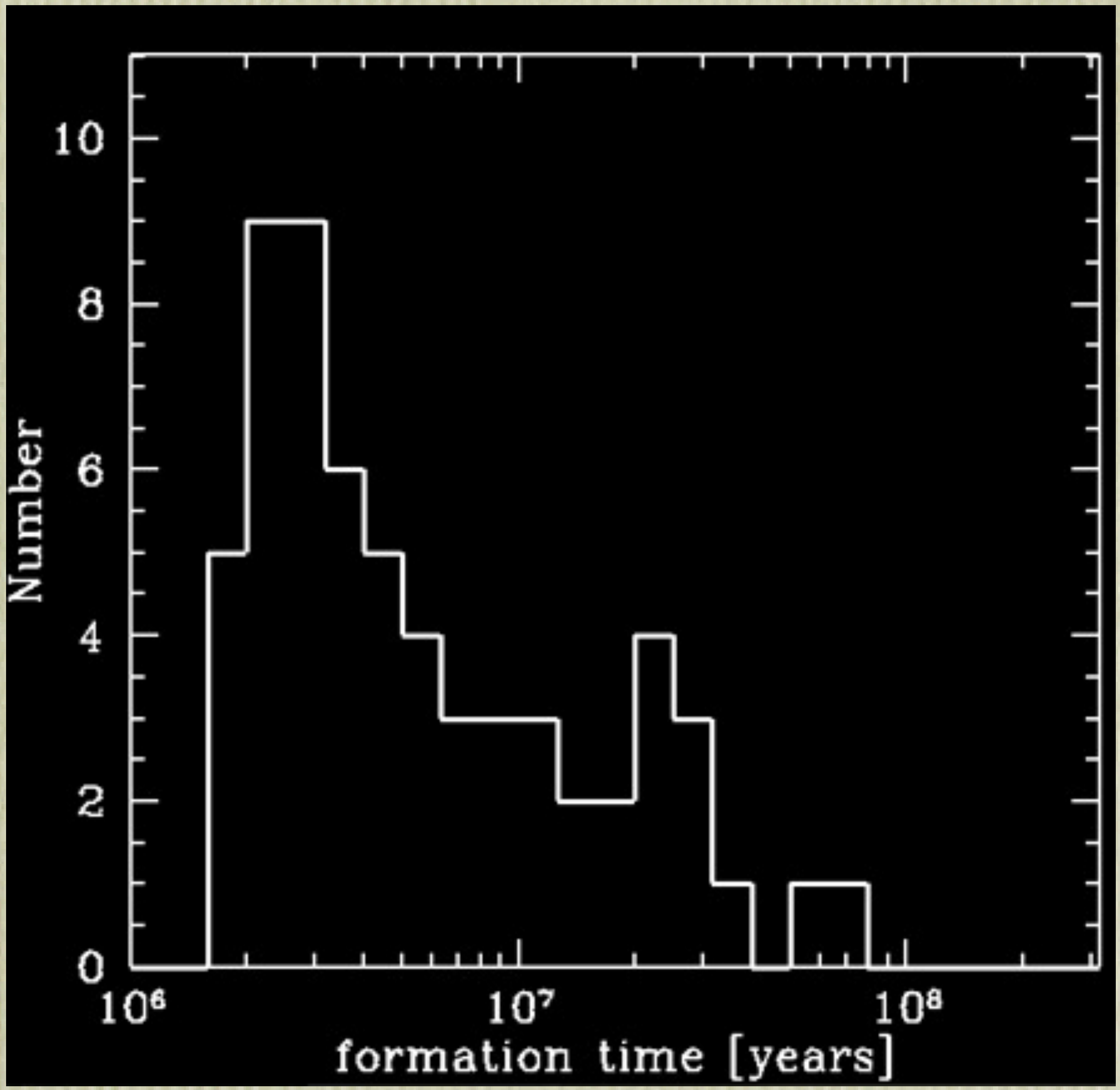
Hot Jupiter Inclination Distribution

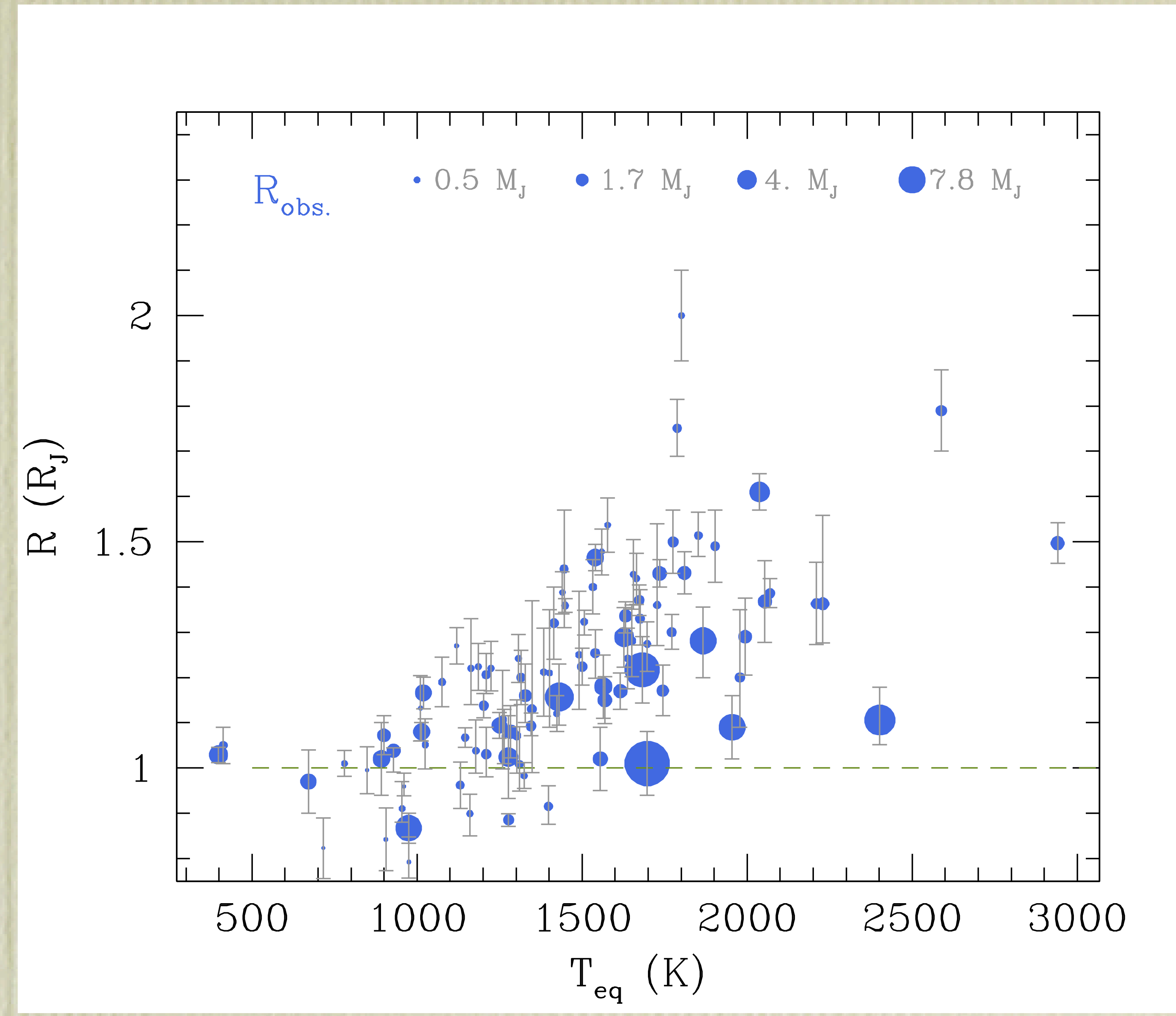




- two populations: aligned and misaligned
  (cf. Fabrycky & Winn 2009)
- can be retrograde (Naoz et al. 2011)

Formation time distribution

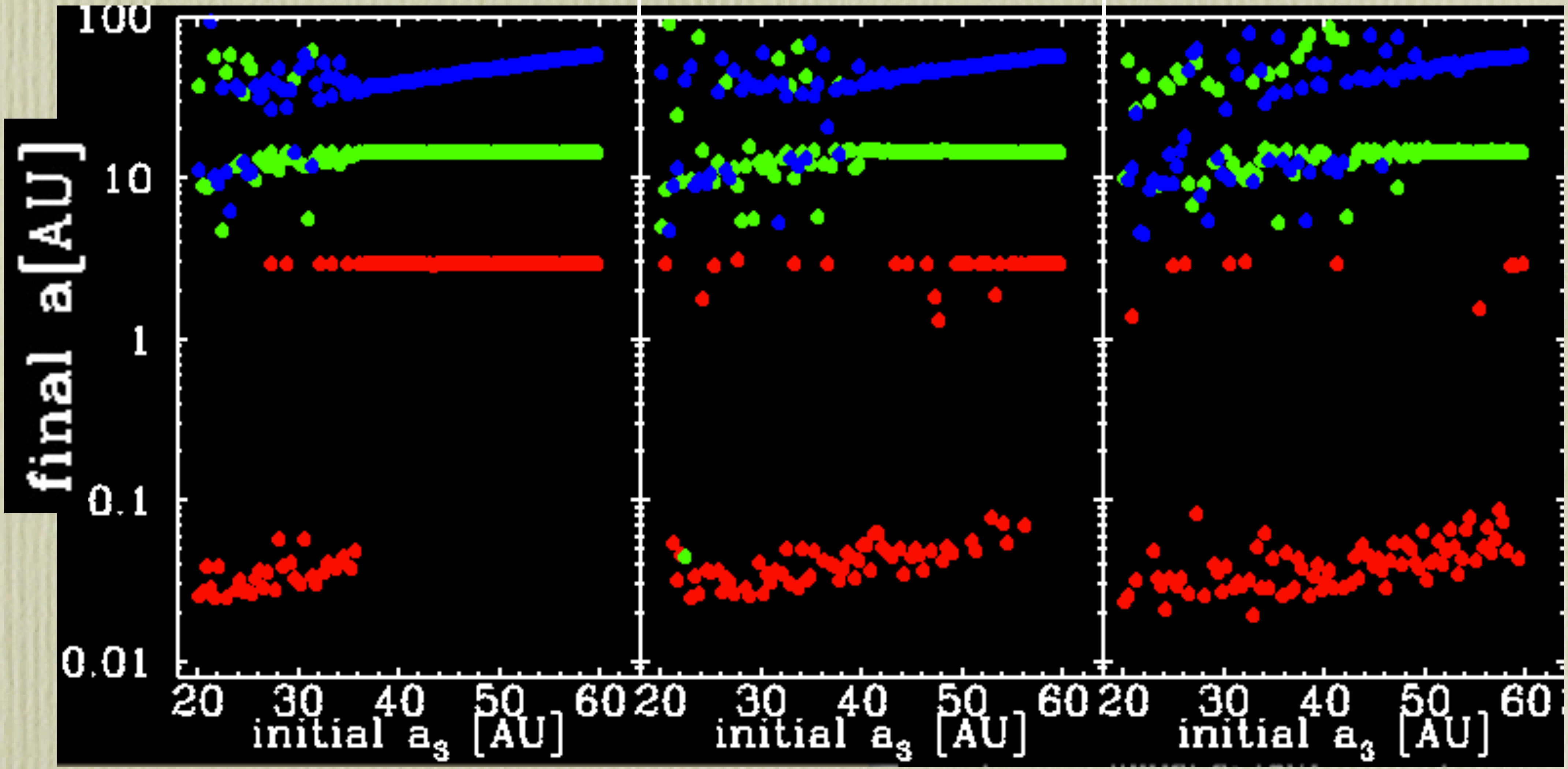




- can explain range of radii

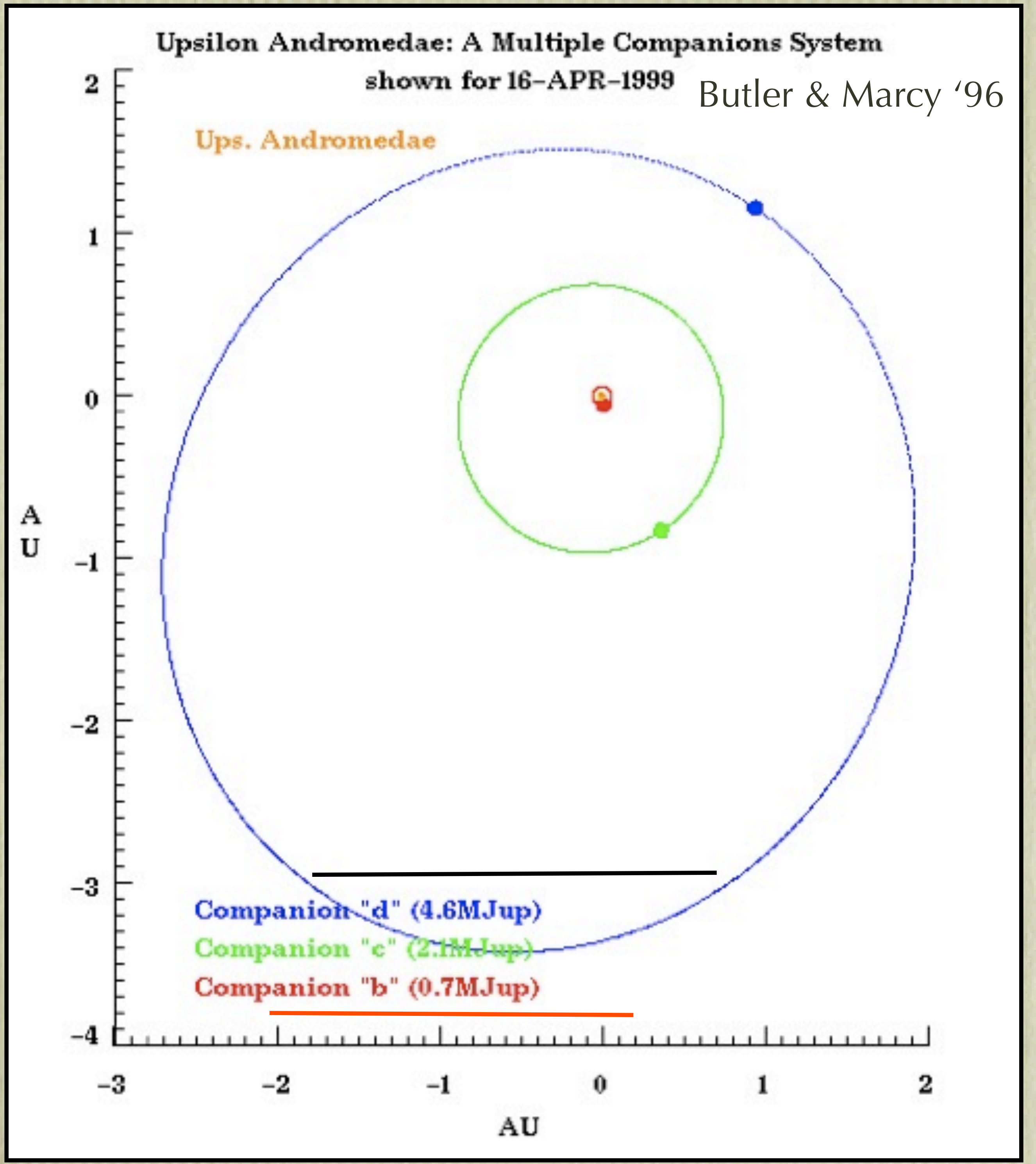
(cf. talk by Yanqin Wu)

AMD = 0.77 $m_1\sqrt{a_1}$ | AMD = 1.5 $m_1\sqrt{a_1}$ | AMD = 2.3 $m_1\sqrt{a_1}$



33 hot jupiters | 62 hj's | 80 hj's

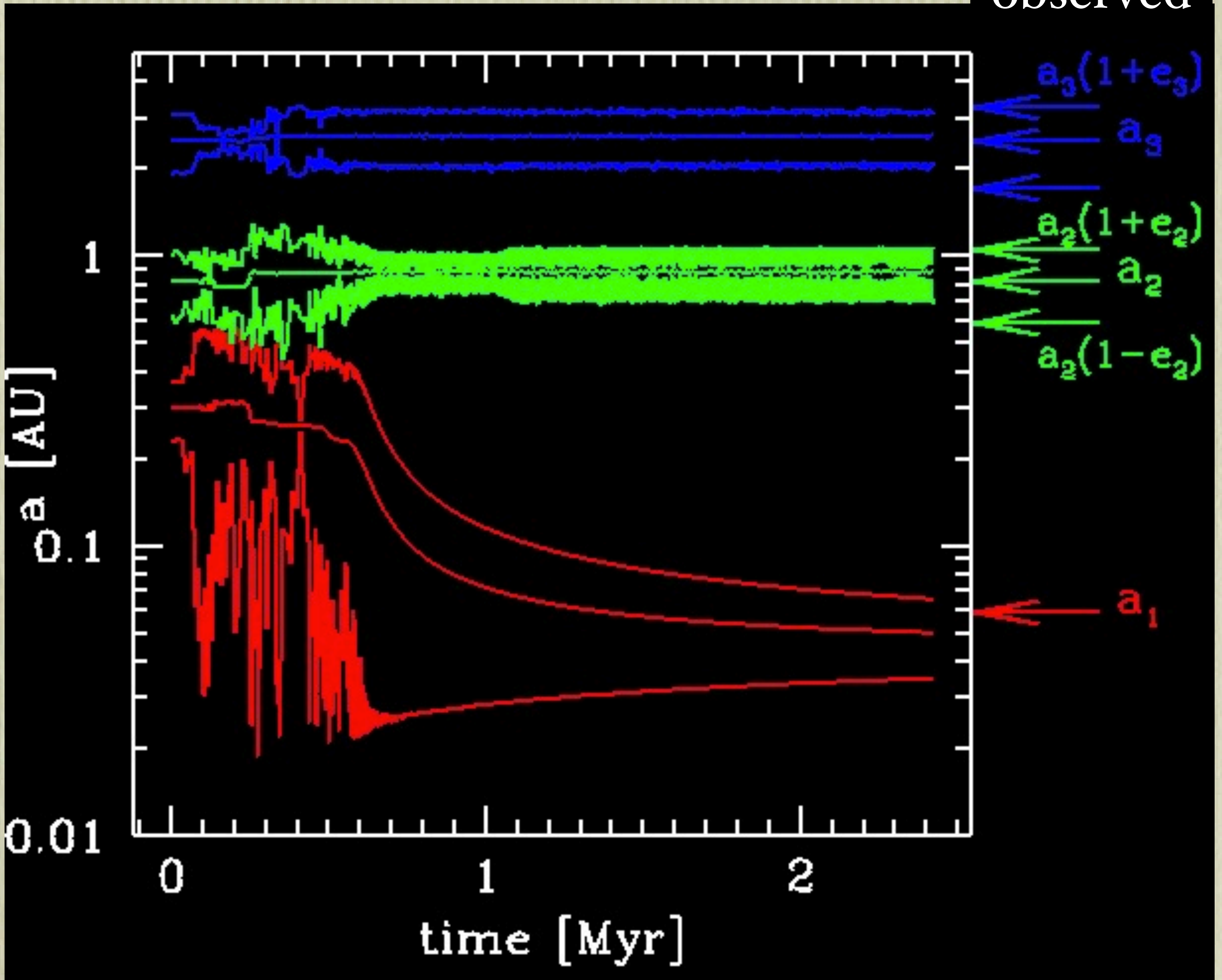
A Worked Out Example: Upsilon Andromedae



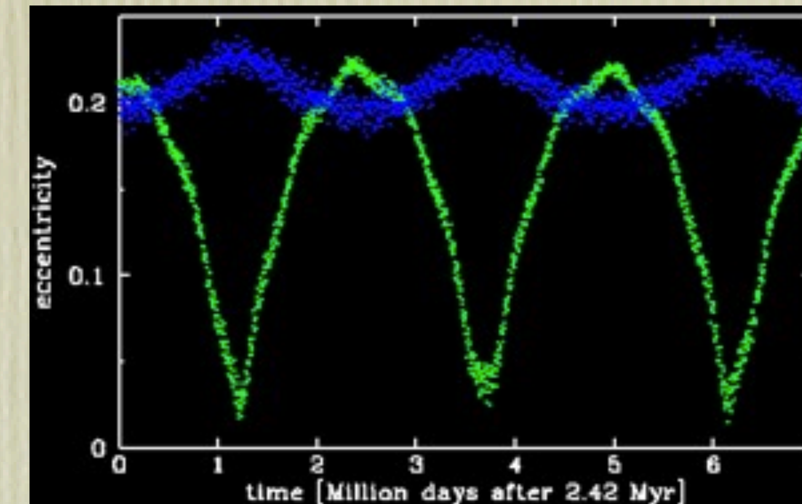
- Hot jupiters usually alone, *but* Ups And. an exception

Simulation of Ups. And. Formation:

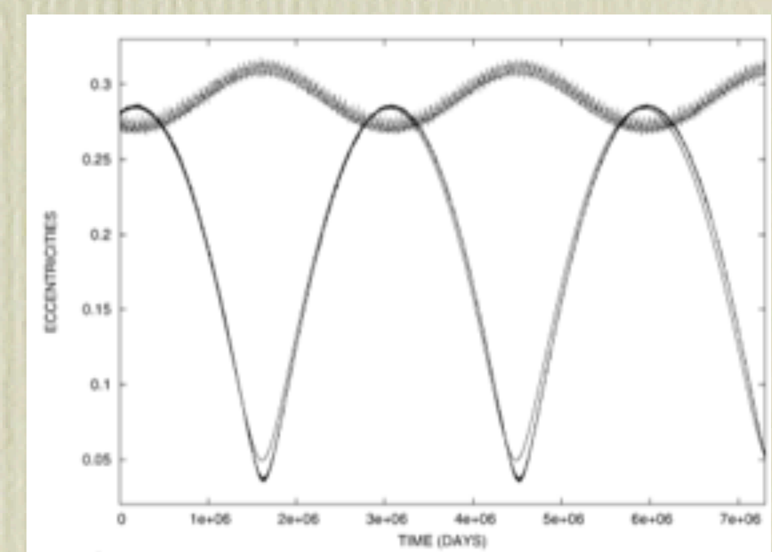
observed



simulation



“real” Ups. And.



(Libert & Henrard ’06)

Comparison with Observations

observation	explanation
3-day pile-up	gradual e-growth (timescale $\gtrsim 10^5$ yrs) + tidal dissipation
range of stellar obliquities (R-M)	can produce both high and low i's
lack of close companions	none up to a few AU, but predict more jupiters beyond a few AU
Masses lower than average	easier to excite low mass planets

Other Hot Jupiter Formation Mechanisms

- Stellar Kozai: - Produces too few hot jupiters (Wu et al. '07)
  (Wu & Murray '03, Fabrycky & Tremaine '07)
  - Does not explain low masses
  - But: planetary Kozai (Nagasawa et al. '08, Naoz et al. '11)

- Planet scattering: - Cannot directly form hot jupiter
  (Rasio & Ford '96)
  - Can increase AMD, helping secular chaos.

- Disk Migration: - Hard to explain why alone, or high inclinations, or 3-day pile-up, or low masses
  (Lin & Papaloizou '86)