Evolution of multiplanet systems: an overview

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WP: Exoplanetary formation and orbital evolution

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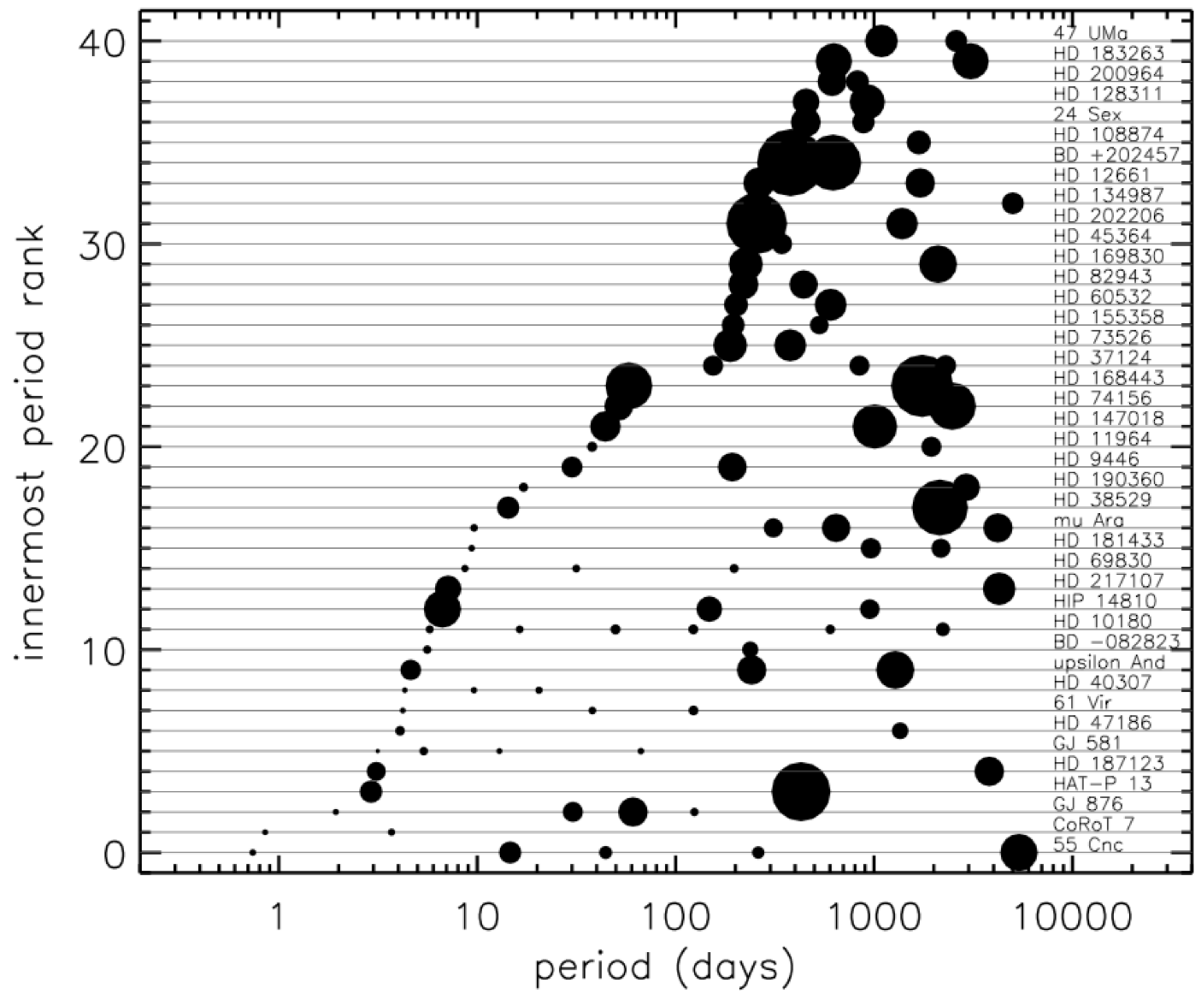
Radial velocity multiple planets



Kepler multiplanet systems

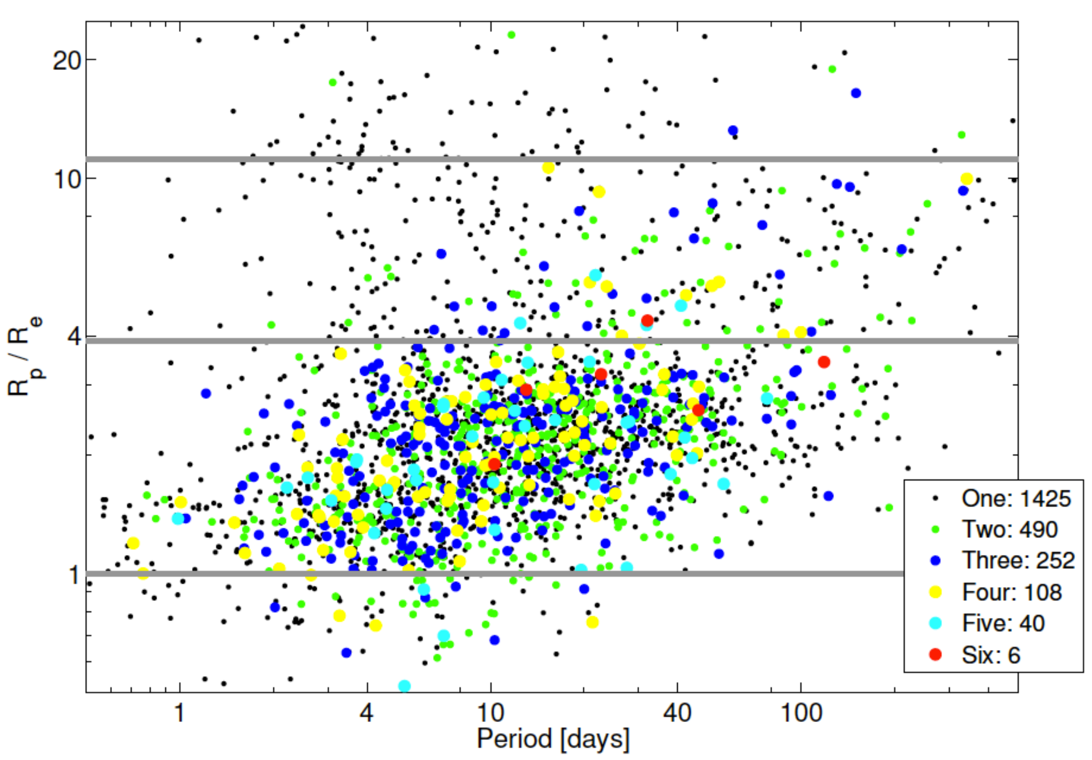
3277 planet candidates: 20% of KOI host stars show evidence for transiting multiplanet systems (Batalha et al 2012)

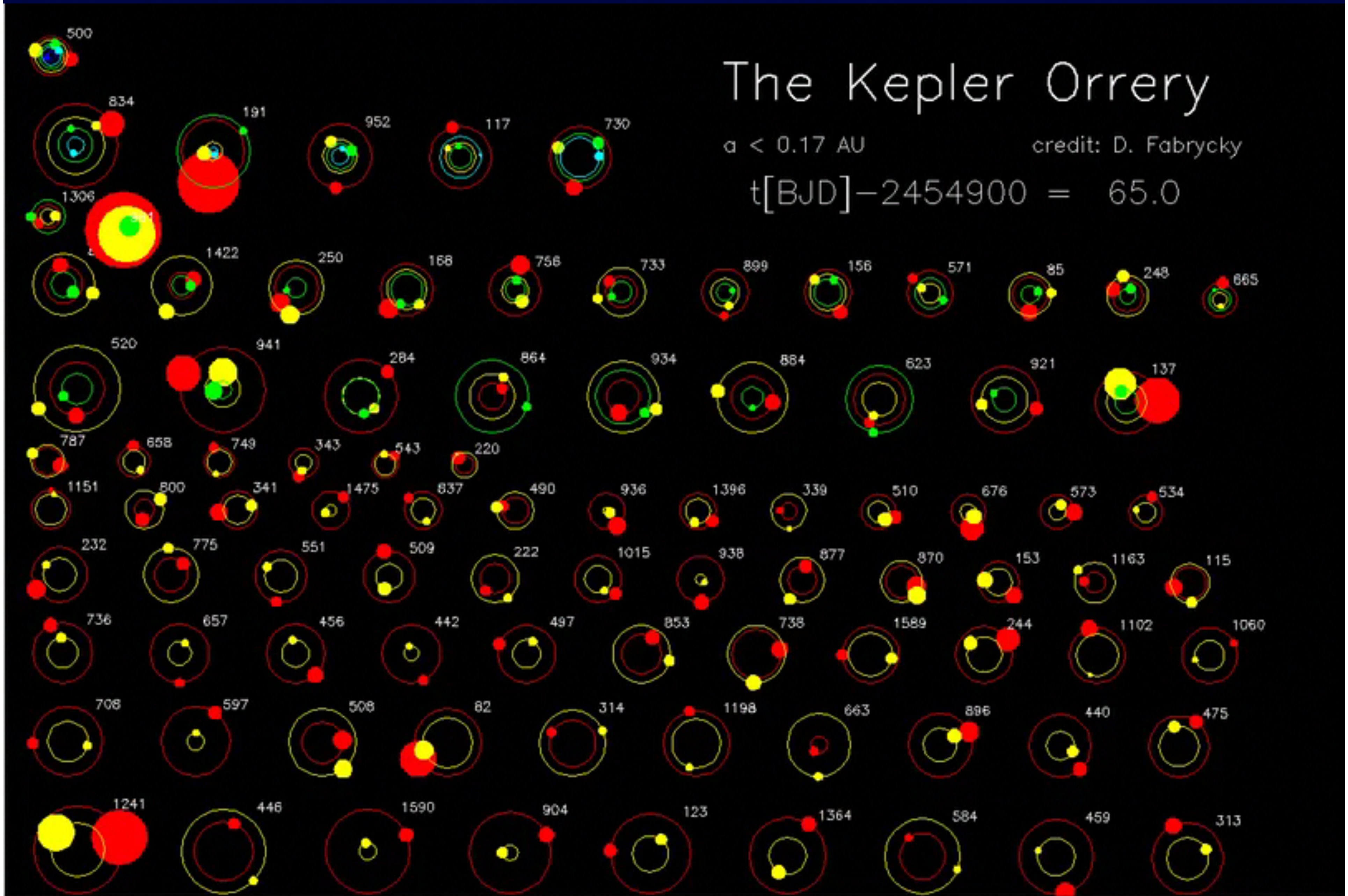
Candidate multi-systems: 885 planet candidates within 361 systems. (Fabrycky et al 2012)

Confirmed planets: ~ 78 confirmed planet host stars: 40 multiplanet systems (www.kepler.nasa.gov)

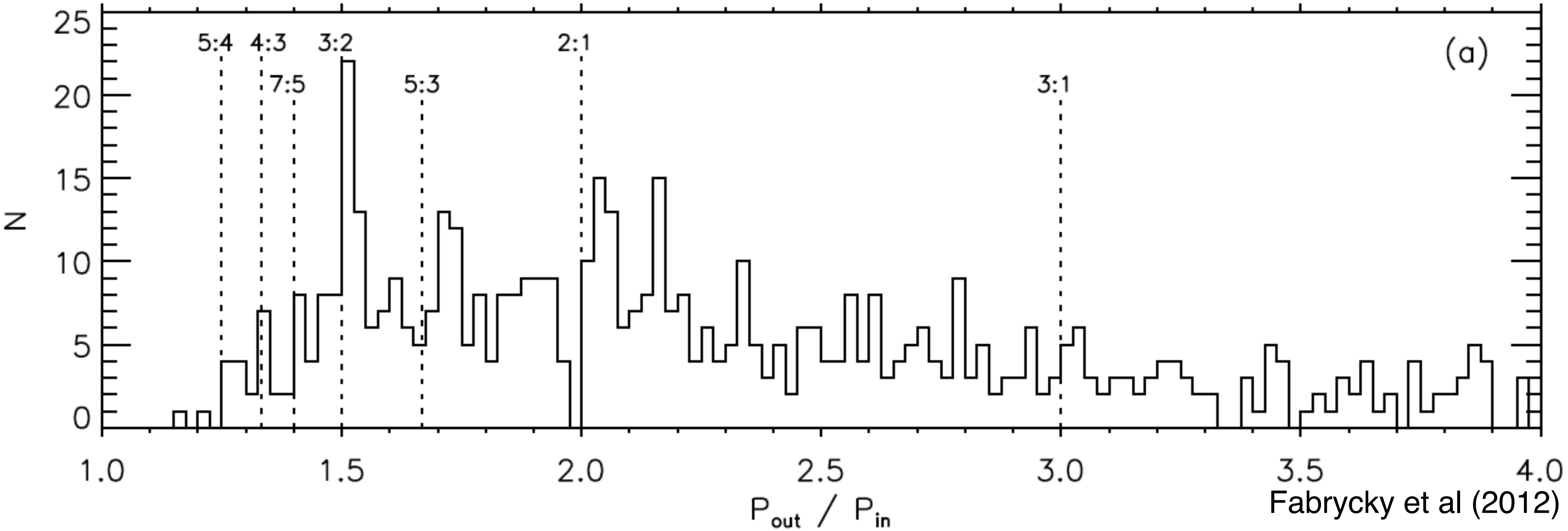
Almost by definition these systems are coplanar and compact

Precision transit timing
➔ planet-planet dynamics




The Kepler Orrery
a < 0.17 AU
credit: D. Fabrycky
t[BJD]−2454900 = 65.0
500
834 191 952 117 730
1306
1422 250 168 756 733 899 156 571 85 248 665
520 941 284 864 934 884 623 921 137
787 658 749 343 543 220
1151 800 341 1475 837 490 936 1396 339 510 676 573 534
232 775 551 509 222 1015 938 877 870 153 1163 115
736 657 456 442 497 853 738 1589 244 1102 1060
708 597 508 82 314 1198 663 896 440 475
1241 446 1590 904 123 1364 584 459 313

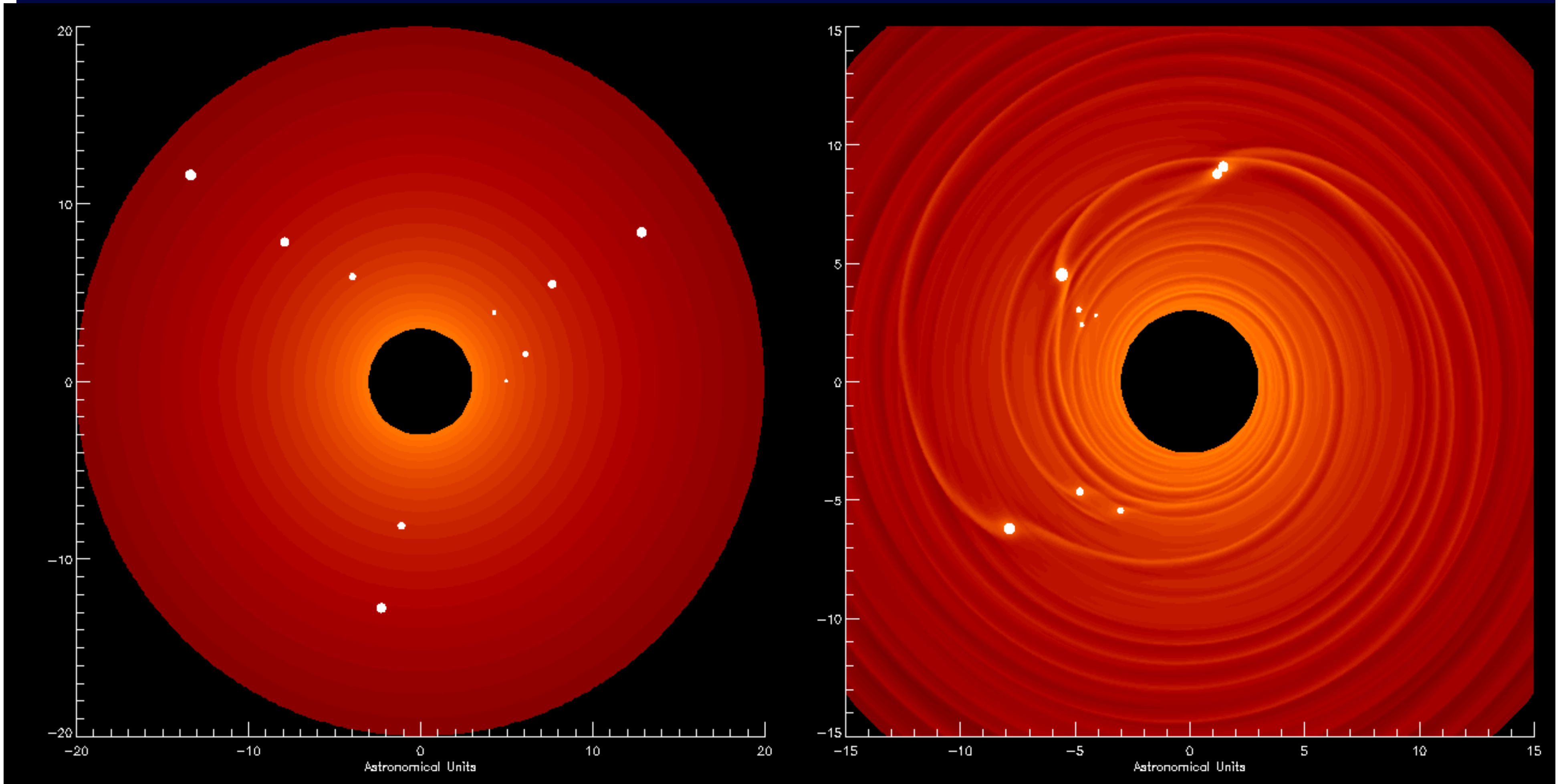
Period ratios between planet pairs



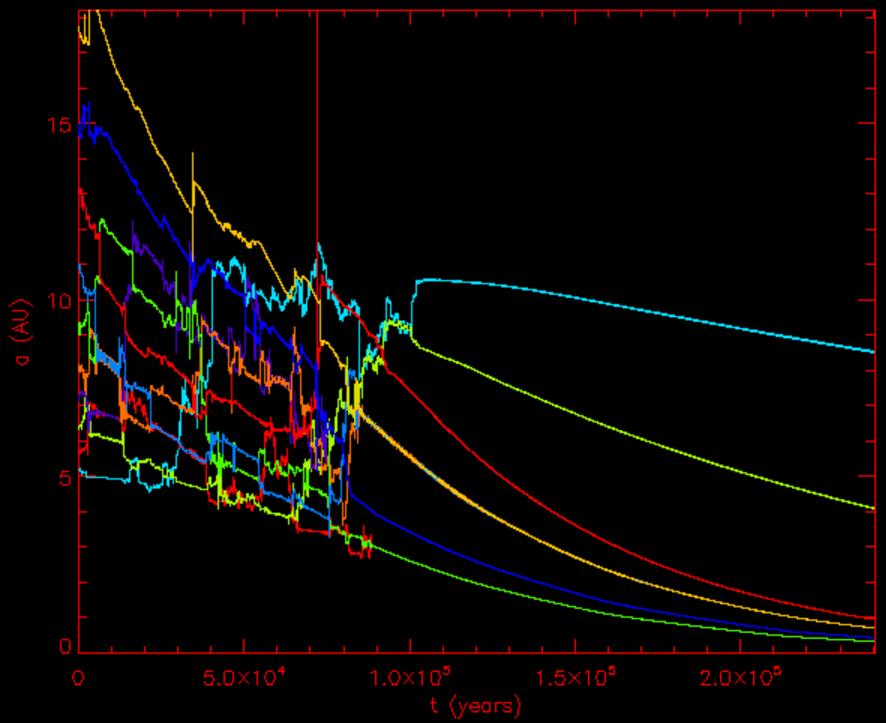
Fabrycky et al (2012)

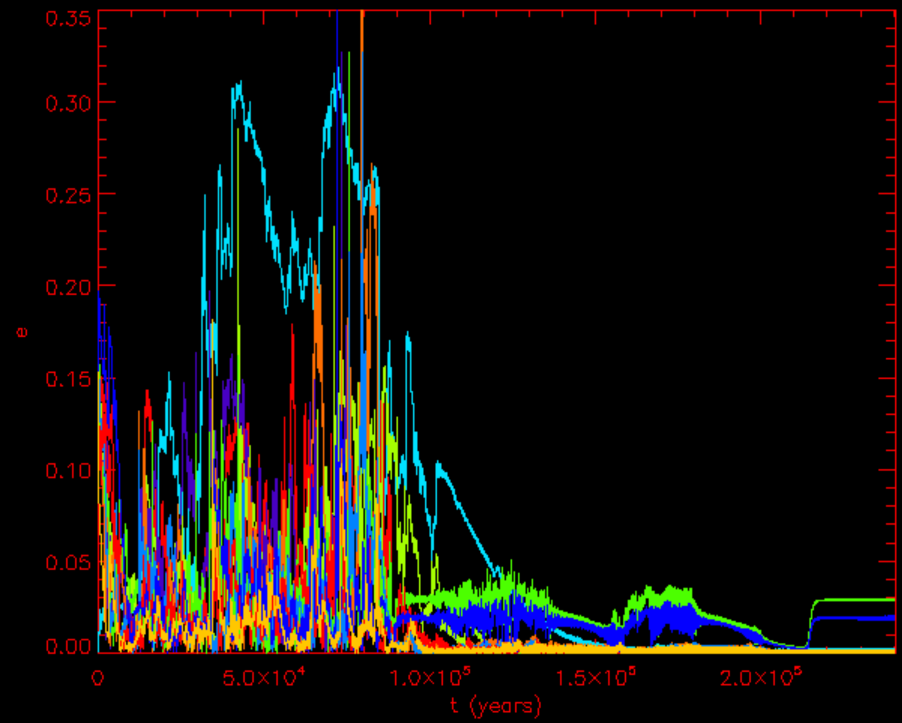
- Broad distribution – most pairs are non-resonant
- Factor-of-2 enhancements near 2:1 and 3:2 resonance
- Enhancement is on the *wide* side of the resonance

Theoretical expectations for systems of low mass planets



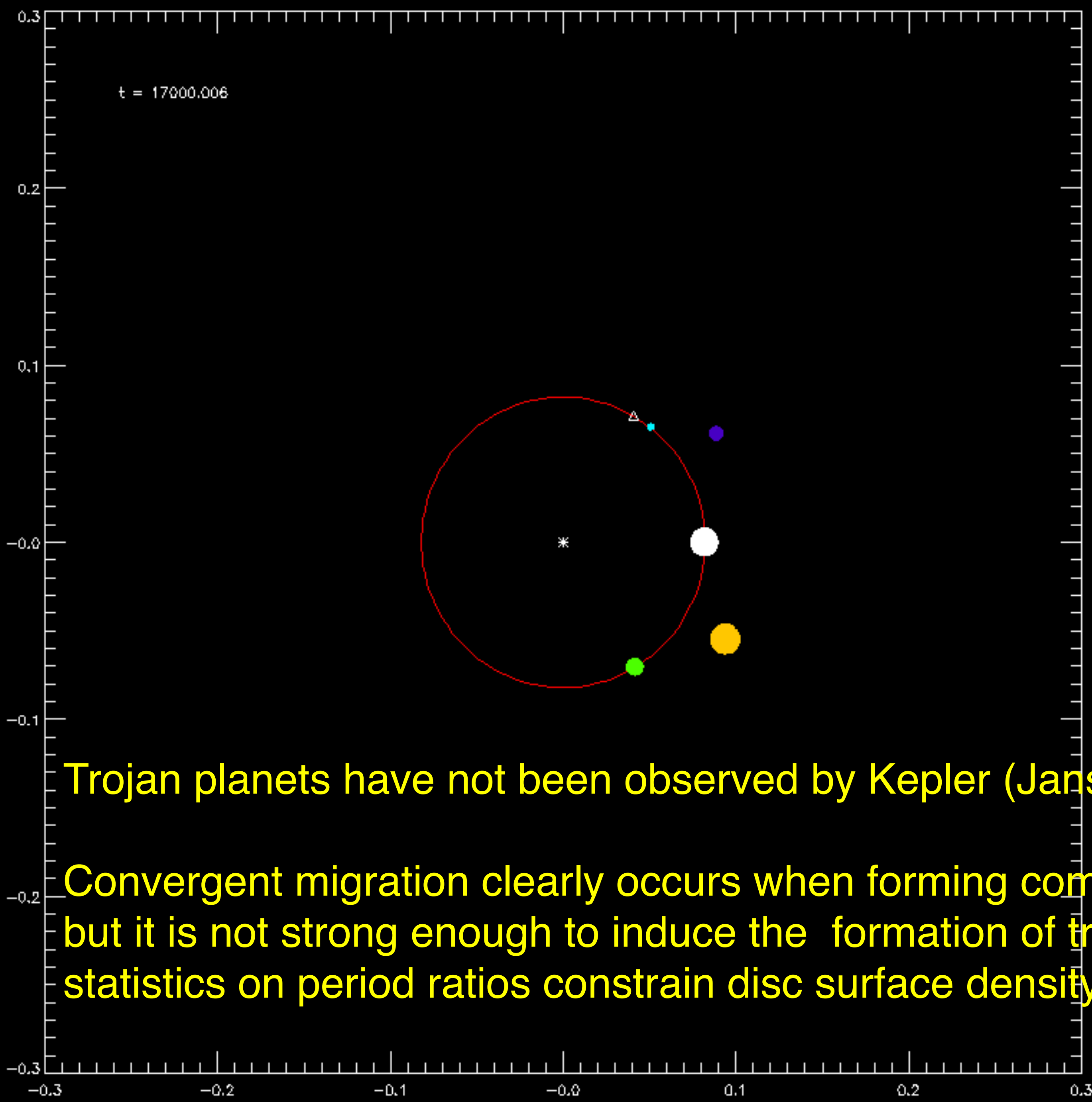
Systems of multiple low mass planets migrate inward via type I migration.





Although there are collisions, scattering and reordering of semimajor axes, the general trend is for the planetary swarm to move inward.

Convergent migration leads to the formation of resonant convoys.
Trojan planets in 1:1 resonance are formed frequently
– including exotic systems containing trojan planet systems in mean motion resonance with adjacent trojan systems.



Inner trojan system containing 3 planet in 5:4 MMR with exterior trojan system containing 2 planets

Trojan planets have not been observed by Kepler (Janson 2013) !

Convergent migration clearly occurs when forming compact systems, but it is not strong enough to induce the formation of trojans ➔ statistics on period ratios constrain disc surface density profiles etc…

The theoretically predicted preference for low mass planets to occupy mean motion resonances is not generally observed in the Kepler data

Exceptions are found: Kepler 18 (2:1, 2:1 resonance chain)
KOI-262 (6:5 resonance)
KOI-730 (4:3, 3:2, 4:3 resonance chain)

How to explain pile-up for period ratios just outside 2:1 and 3:2 ?

Data suggests that systems were originally in resonance but evolved to non-resonant configuration

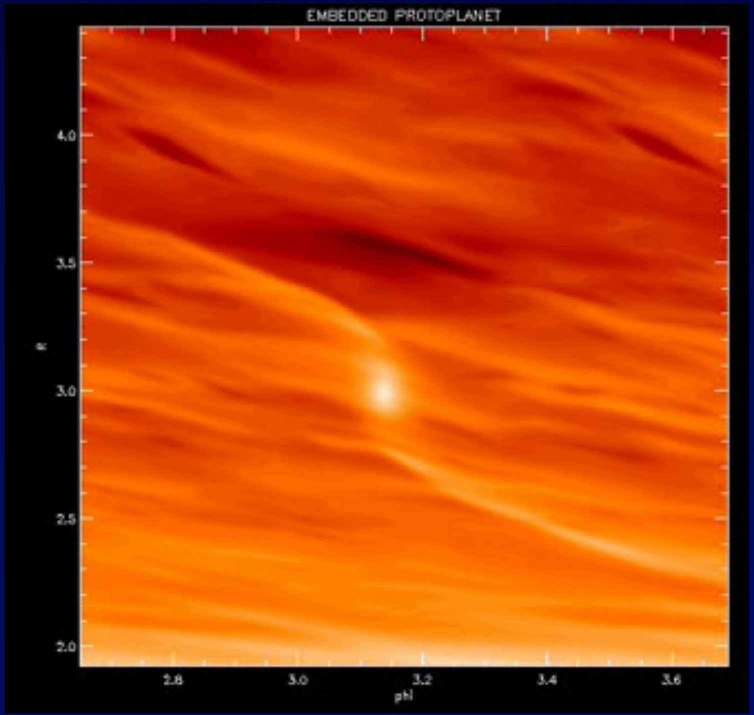
Preference for systems to be just wide of resonance indicates that after resonance capture, innermost planets migrate inward and/or outer planets migrate outward

Stochastic migration due to turbulence

Planets migrate toward resonance

Turbulent density fluctuations induce stochastic planet migration that breaks the resonance
(e.g. Rein & Papaloizou 2010)

This can explain why planets are not exactly in resonance, but predicts equal probability for planets to be either just inside or outside of resonance



Nelson & Papaloizou (2004)

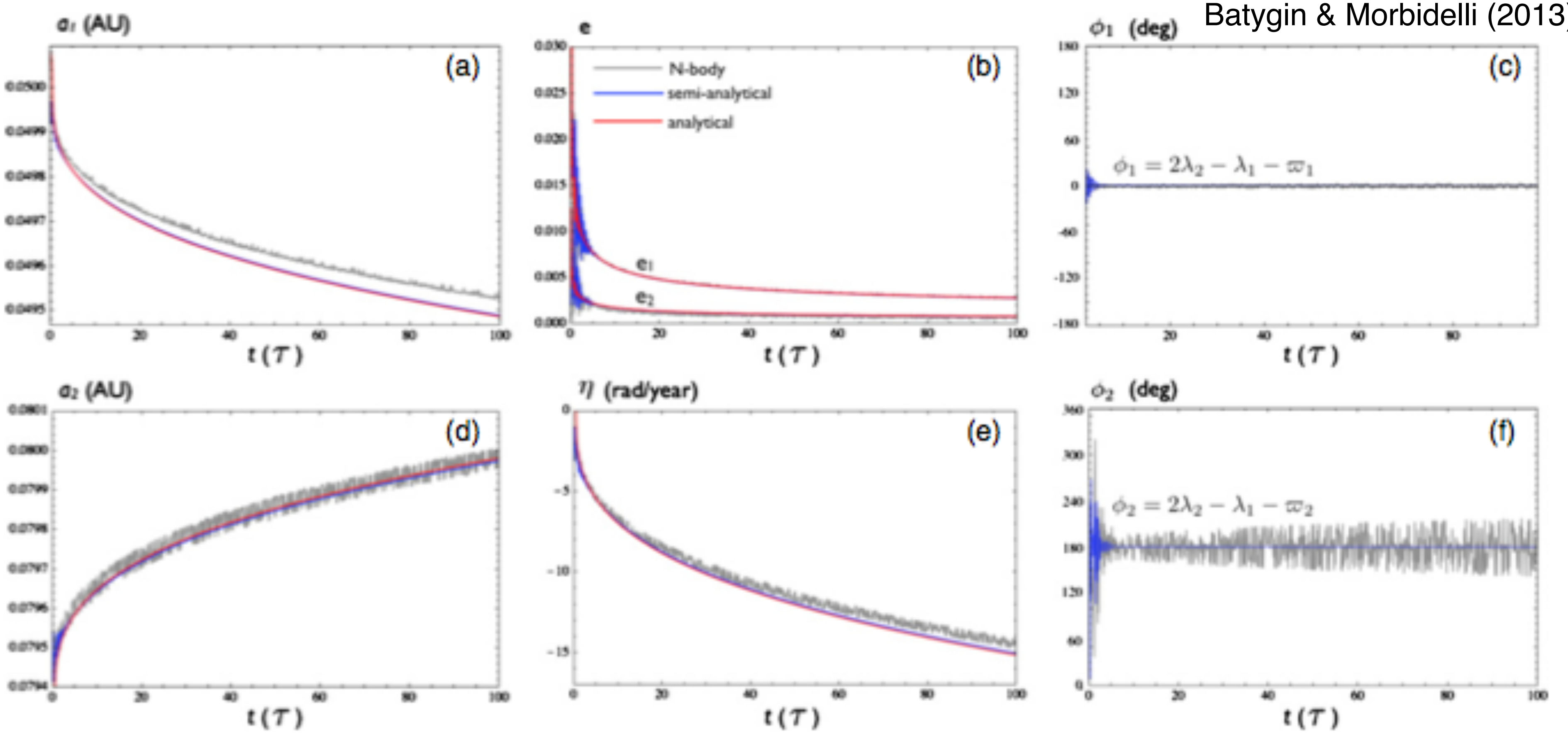
Kepler-36 b&c very close to 7:6 resonance (but just interior to it).

Stochastic migration model has been applied successfully to explain this system (Paardekooper, Rein & Kley 2013)

Tidal interaction with central star

Short-period multiplanet systems in resonance – eccentricity of inner planets damped on secular timescales through tidal interaction with the star (Terquem & Papaloizou 2007; Papaloizou 2011; Batygin & Morbidelli 2013).
Energy dissipation causes the planetary orbits to diverge from commensurability

Batygin & Morbidelli (2013)

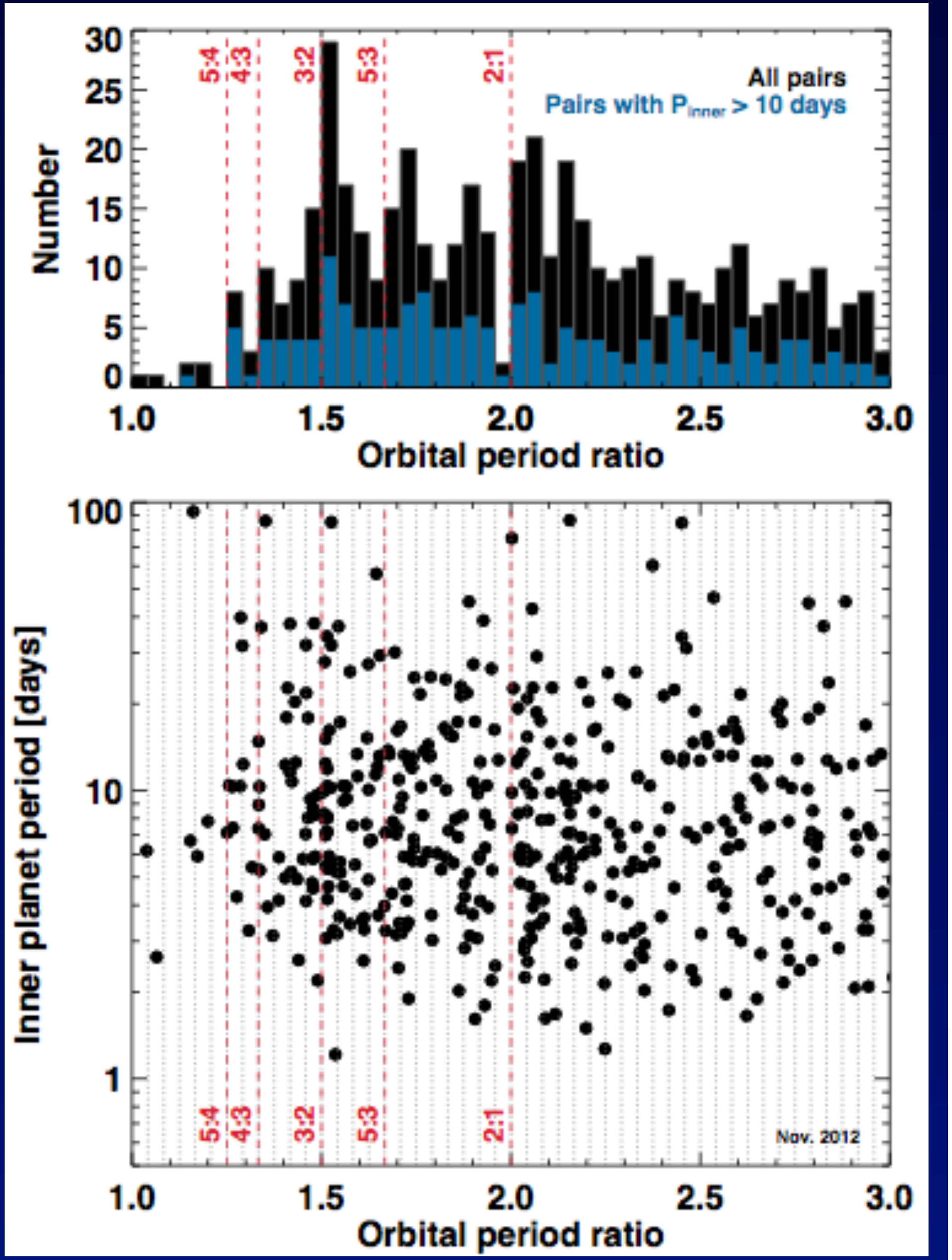


Spiral wake-planet interactions

Tidal dissipation through interaction with central star not effective for orbital periods > 10 days.

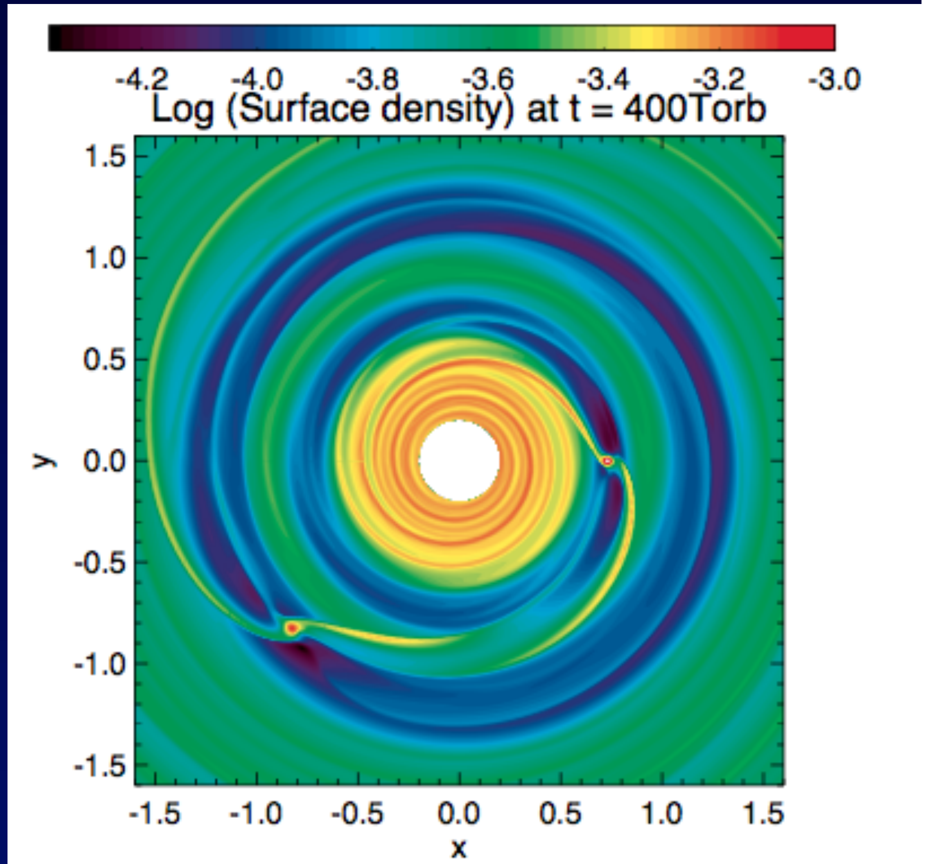
Systems with inner planet orbit period > 10 days still display excess of pairs just exterior to 2:1 and 3:2

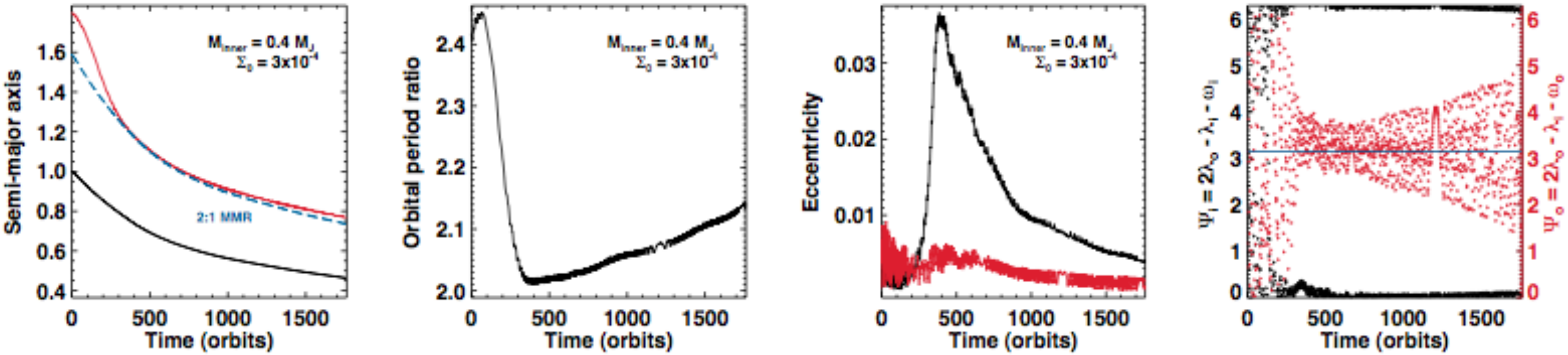
Convergent migration involving an inner gap-forming planet and an exterior lower mass body can be halted and reversed by wake-planet interactions (Podlewska-Gaca et al 2012)



Recent simulations suggest that near commensurability of Kepler-46 can be explained by wake-planet interactions driving divergent migration after initial phase of locking in 2:1 (Baruteau & Papaloizou 2013).

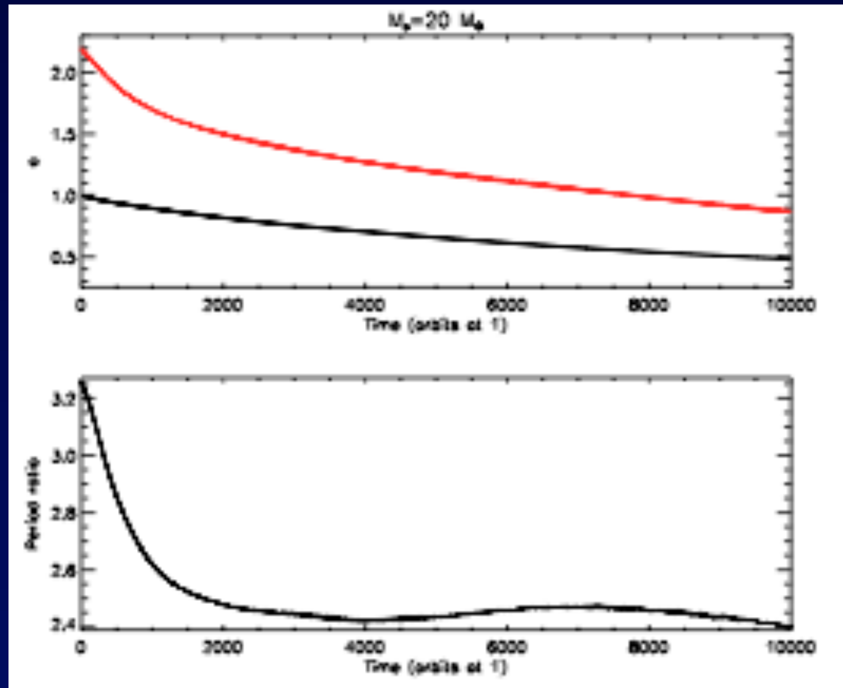
Require inner planet to be ~ gap forming so spiral wakes dissipate in corotation region of companion body



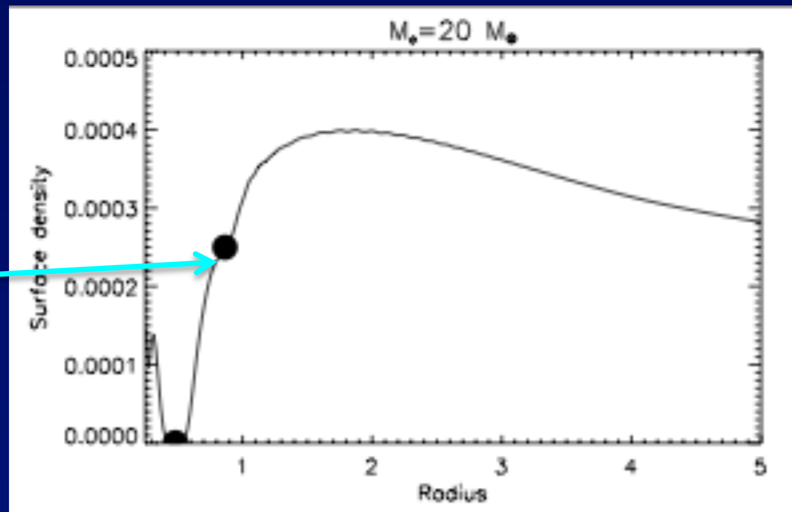


Trapping at the edges of gaps

Near-resonances can be created when gap forming planets trap lower mass planets at the edge of their gaps due to corotation torques
(Pierens & Nelson 2008)



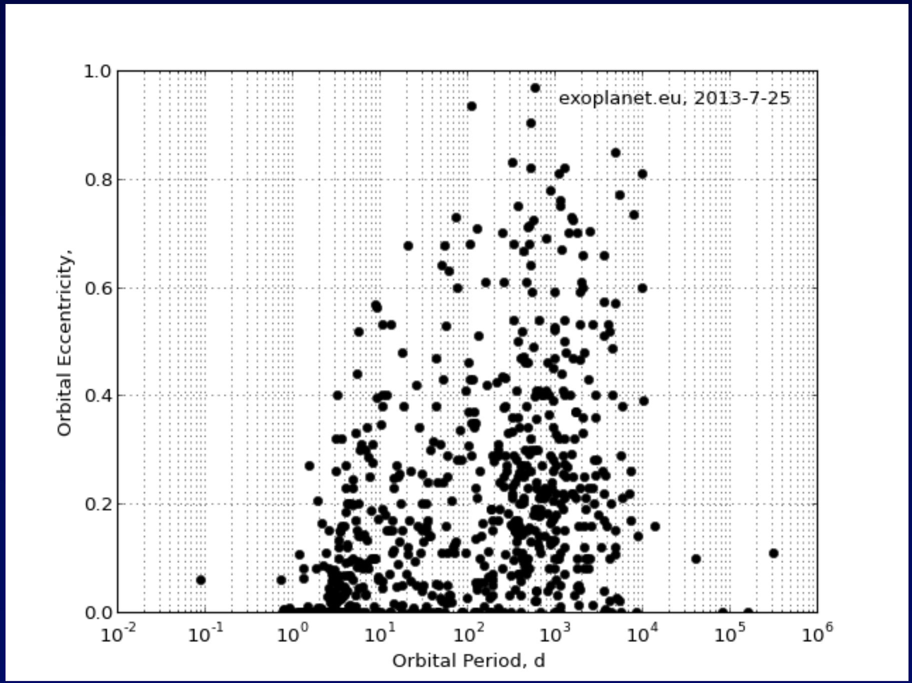
Corotation and Lindblad torques cancel



Planet-planet scattering

Disc-planet interactions tend to damp the eccentricities of planetary mass bodies (Papaloizou, Nelson & Masset 2001)

Planetary eccentricities probably due to planet-planet scattering (the "Jumping Jupiter" model Marzari & Weidenschilling 1996, Rasio & Ford 1996)



2-planet systems on circular orbits are stable if $\Delta \geq 2\sqrt{3}R_{H(1,2)}$

where $R_{H(1,2)} = \left[\frac{m_1+m_2}{3M_*}\right]^{1/3}\frac{(a_1+a_2)}{2}$

No criterion exists for defining stability of systems with > 2 planets

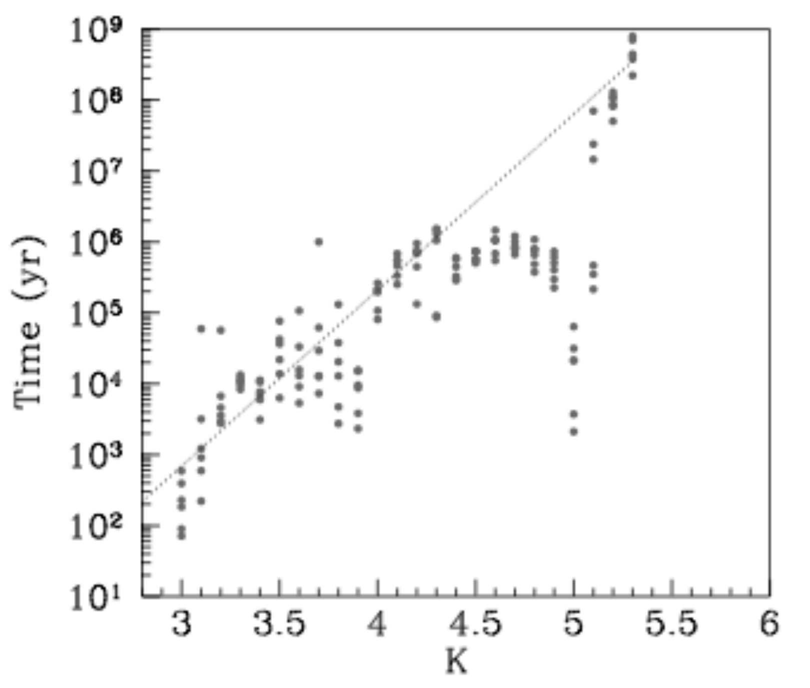
For systems with ≥ 3 planets the instability time scale is strong function of separation
(Chambers et al 1996; Marzari & Weidenschilling 2002)

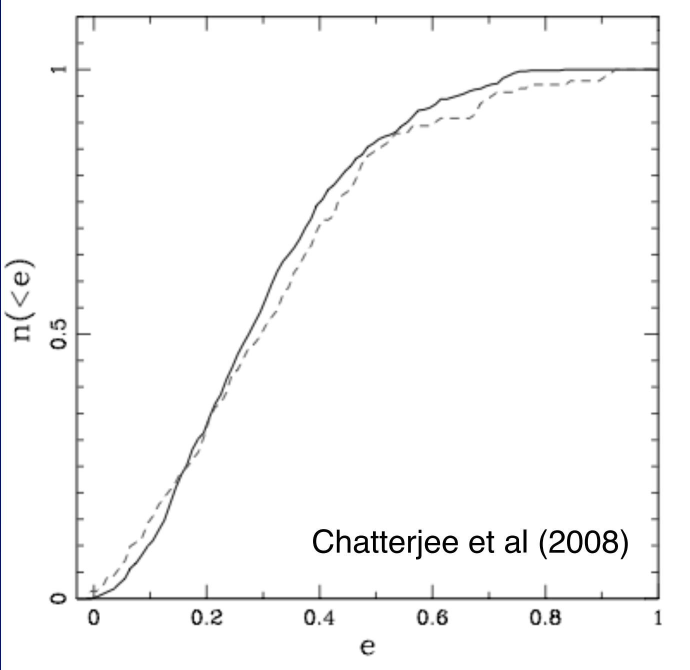
$a_2 = a_1 + KR_{H(1,2)}$ $a_3 = a_2 + KR_{H(2,3)}$

Require convergent migration to bring giant planets into close promity ?

Simulations with 3 unstable planets with realistic masses predict eccentricities in good agreement with data

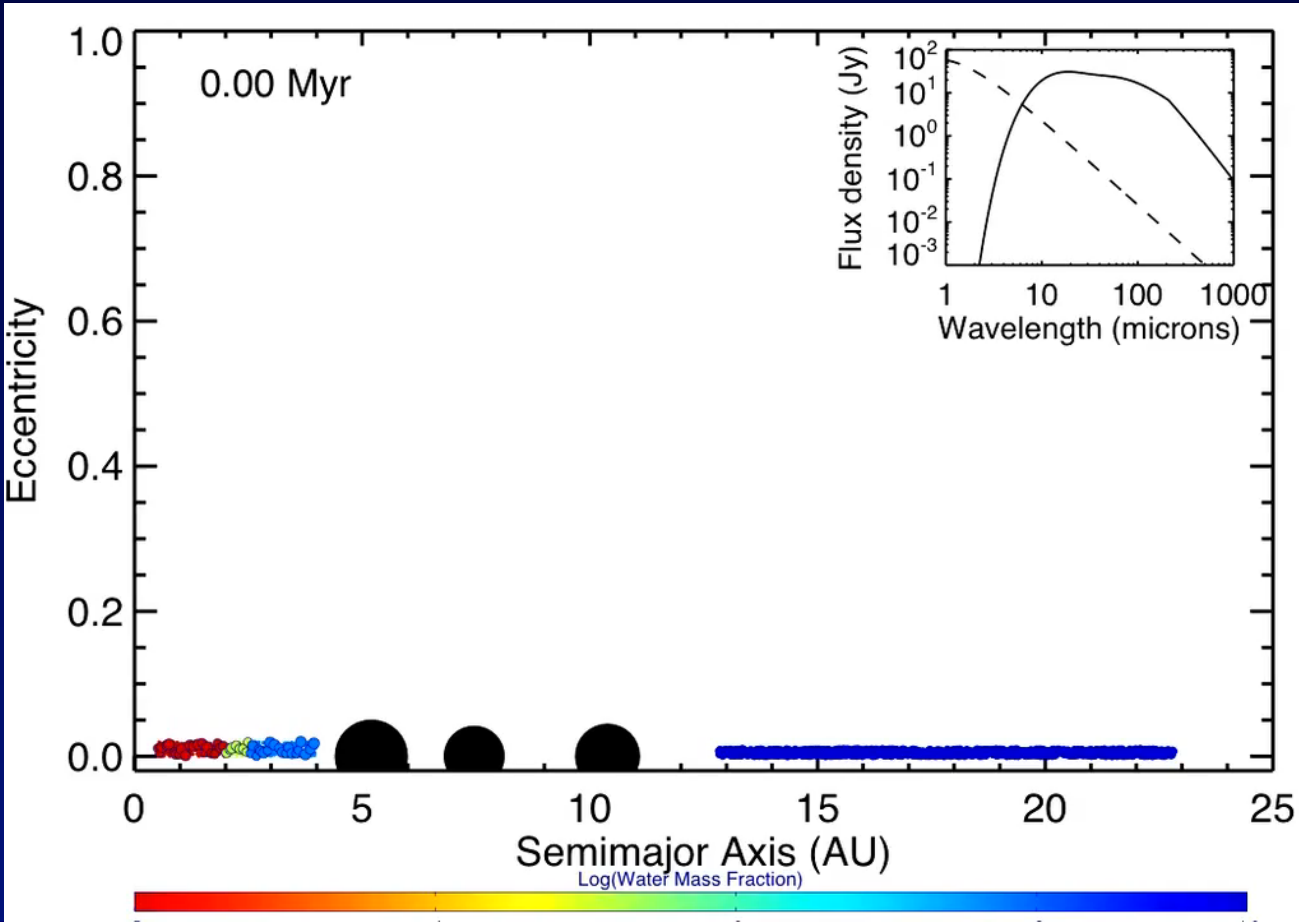
➔ eccentric giants born in compact unstable multisystems ?





Influence of Jumping Jupiters on terrestrial planet formation

Raymond et al (2011, 2012)

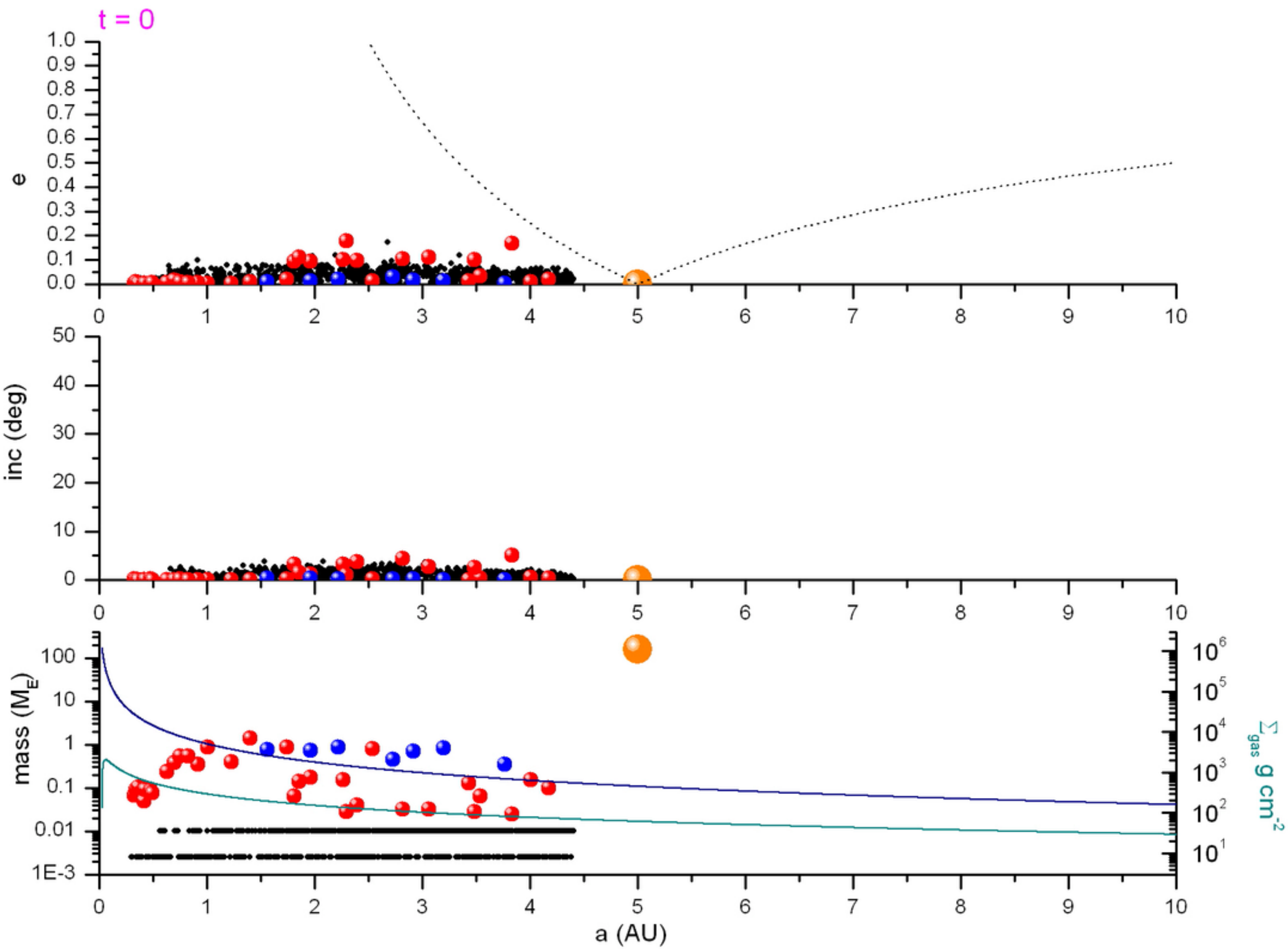


Hot Jupiters and exterior low mass planets

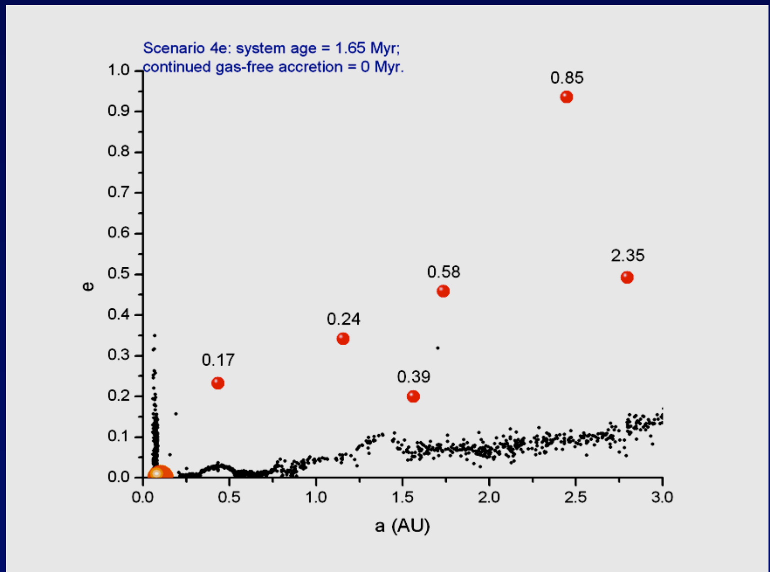
Planet-planet scattering combined with tidal interaction with central star can form hot Jupiters (e.g. Nagasawa et al 2008; Beauge & Nesvorny 2013)

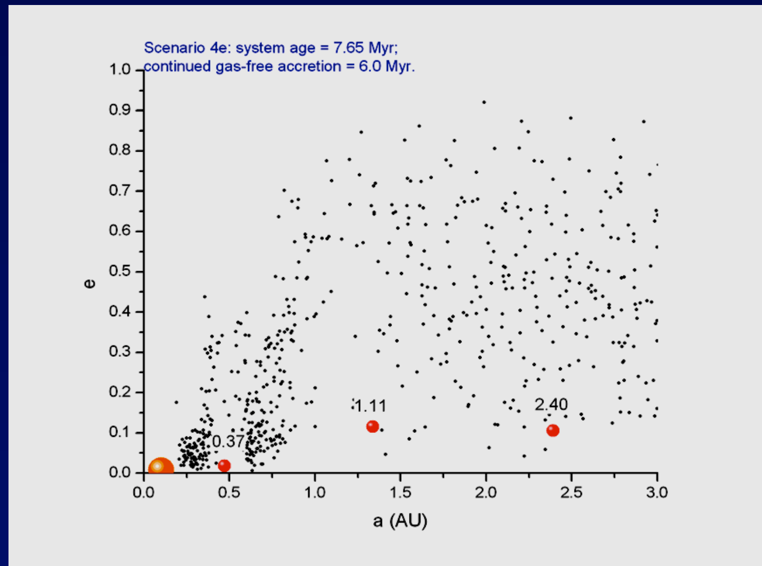
Gradual circularisation of a long-period Jovian planet through tides is likely to destroy any interior system

Type II migration of a giant during terrestrial planet formation and its effect on the formation of habitable planets
(Fogg & Nelson 2005, 2007, 2009; Raymond et al 2006)


t = 0
e
inc (deg)
mass (M_E)
Σ_{gas} g cm^{-2}
a (AU)
1E-3
0.01
0.1
1
10
100
10^1
10^2
10^3
10^4
10^5
10^6

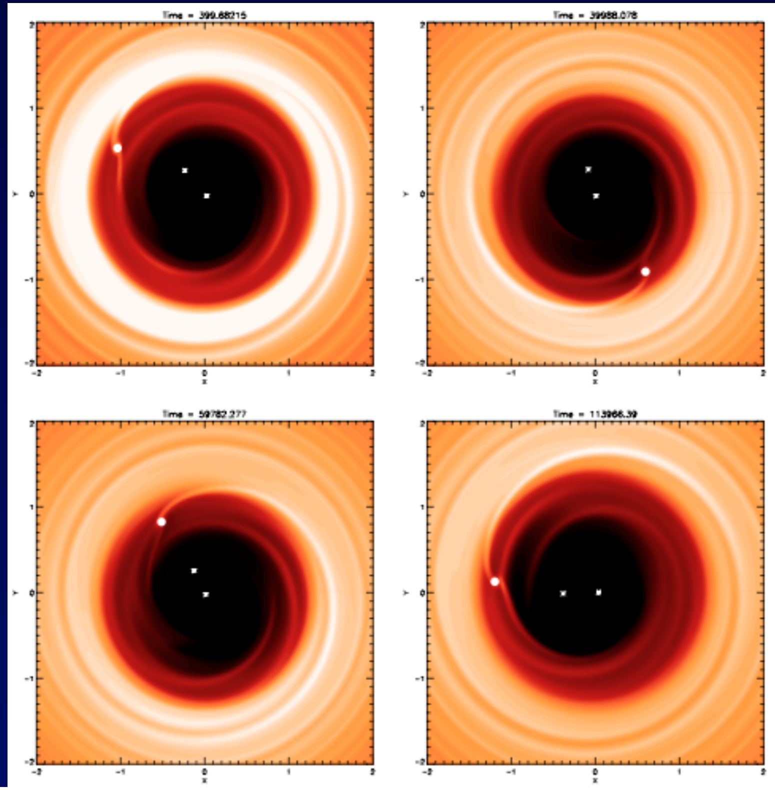
Long-term evolution:
"Ocean-planets" predicted in the habitable zone





The existence of terrestrial planets in hot Jupiter systems depends on the migration mechanism for the giant planet

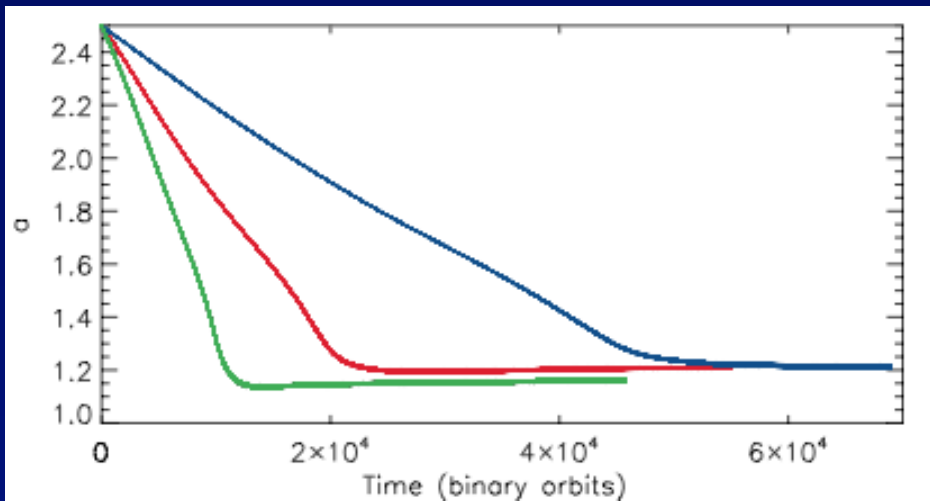
Circumbinary planets

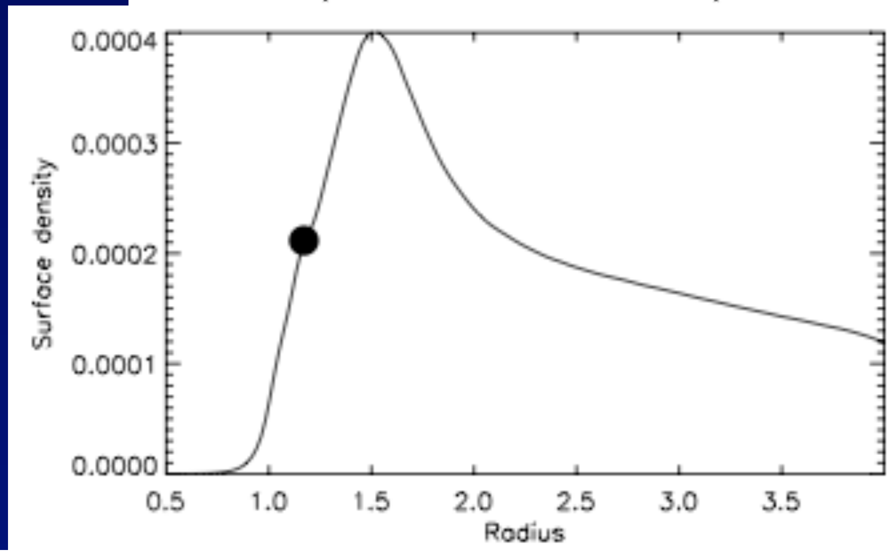


Central binary creates tidally truncated cavity. Circumbinary planets may migrate toward binary and halt at cavity edge (Nelson 2003, Pierens & Nelson 2007, 2008a,b, 2013)

Planets with masses up to ~ Saturn halt at cavity

Jovian planets tend to migrate closer to binary
- resonances can cause scattering
(Nelson 2003, Pierens & Nelson 2008)

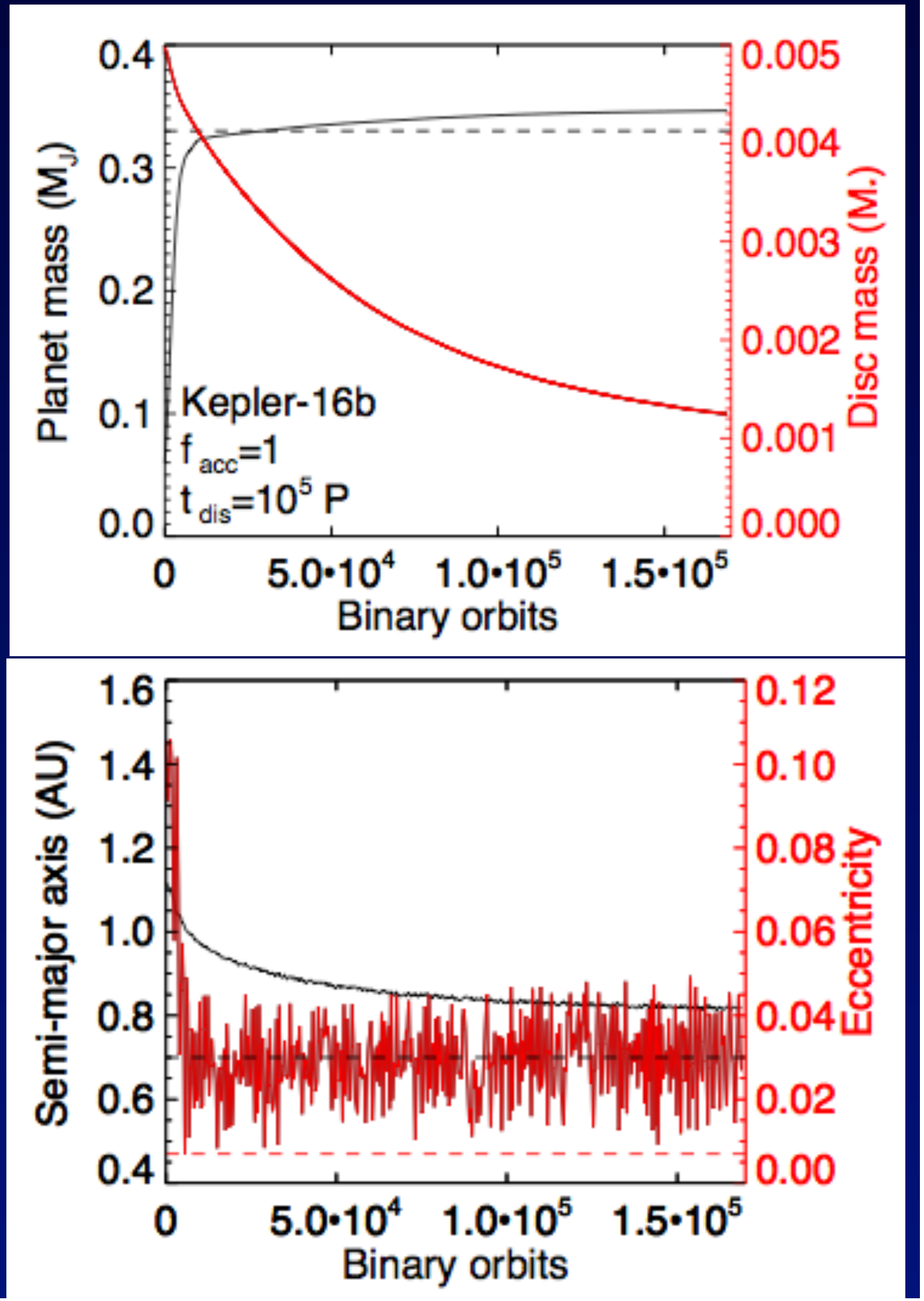


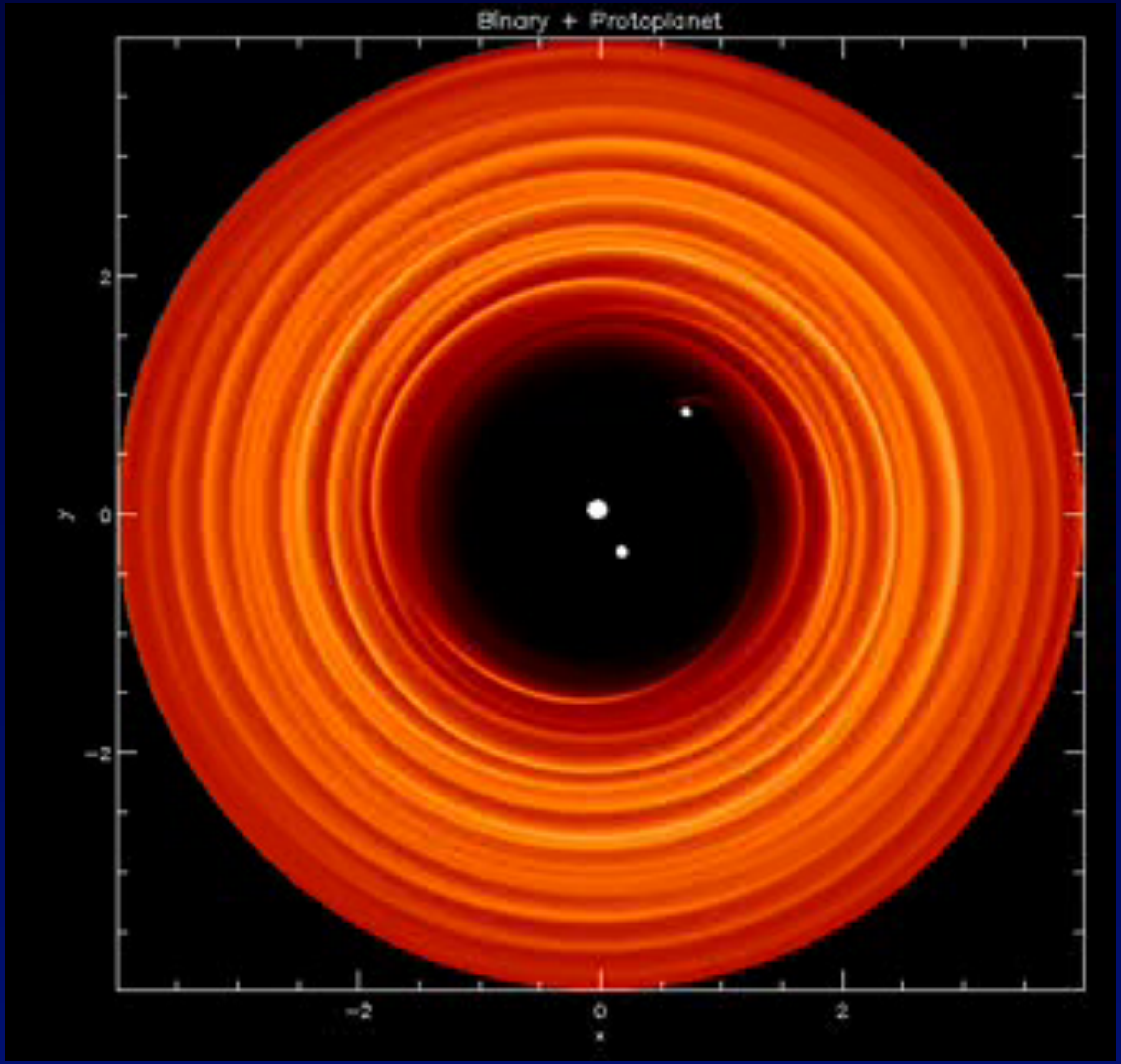


Models can be quite successful in reproducing Kepler 16, 34 and 35 systems (Pierens & Nelson 2013)

Basic paradigm of core formation at large distance from binary followed by migration and gas accretion is ~ consistent with Kepler data

Planet eccentricity tends to be a bit too large – disc eccentricity ??





The fate of a circumbinary Jovian planet…