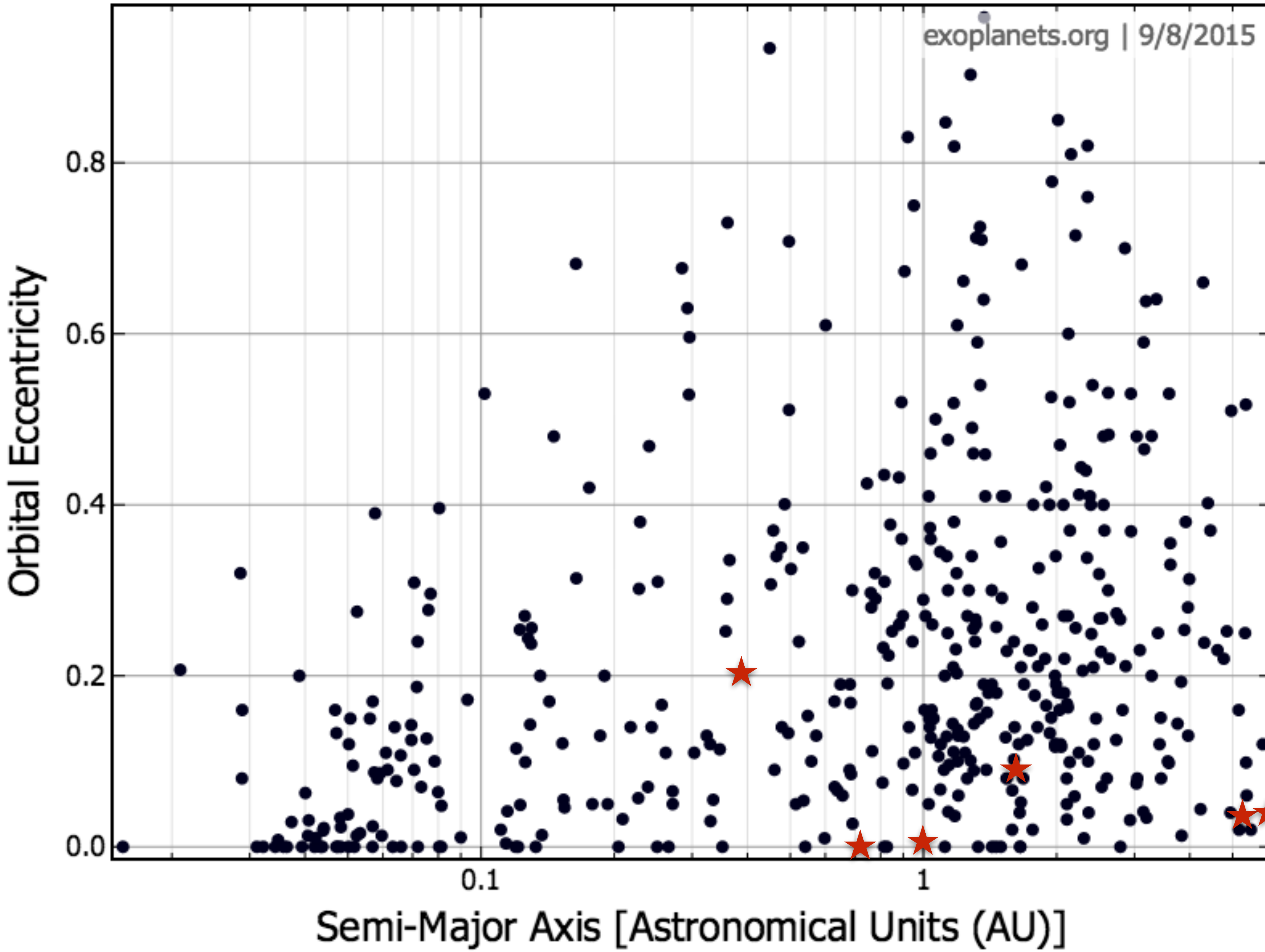
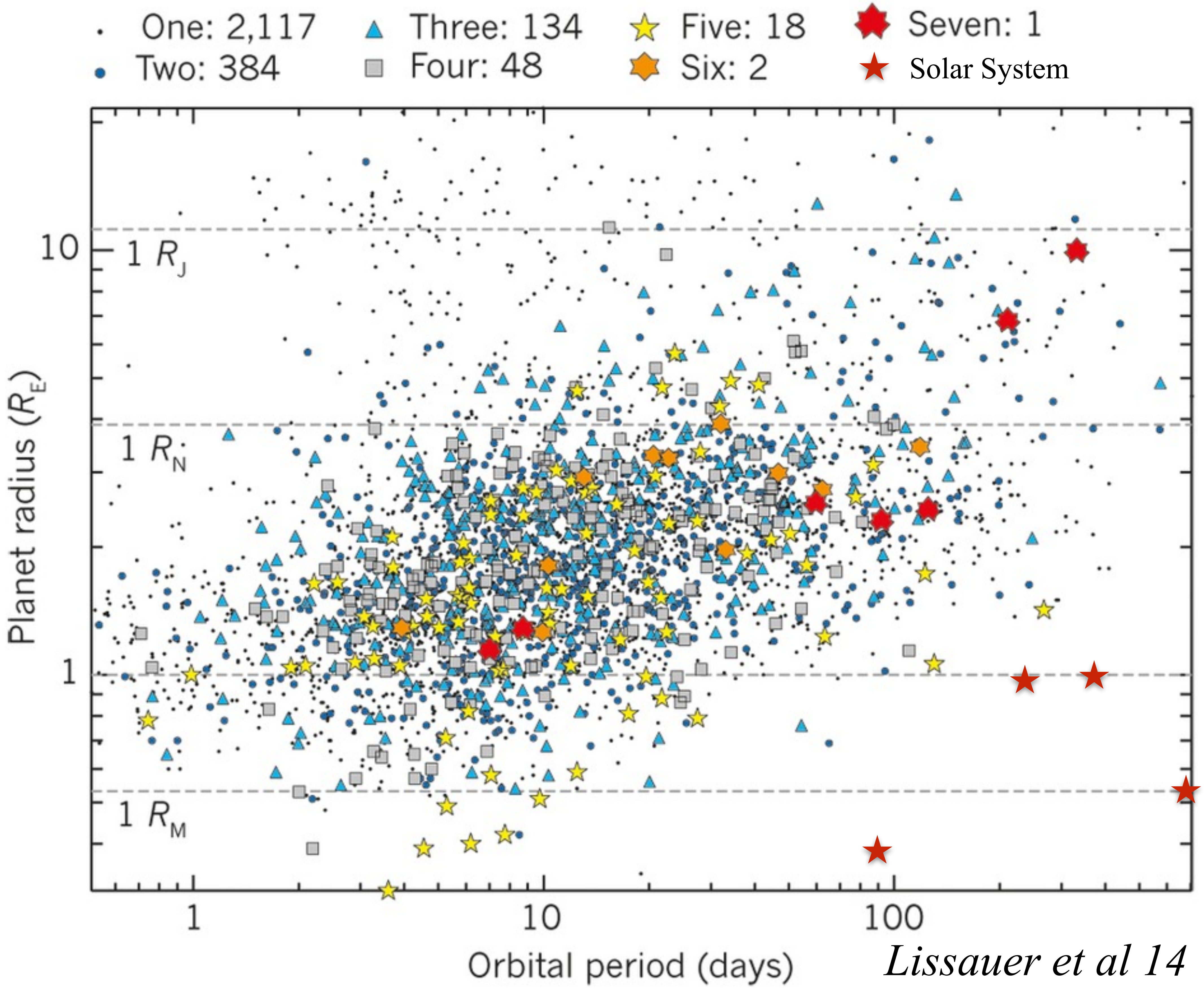
Dynamic Exoplanets

Alexander James Mustill

Exoplanets: not (all) like the Solar System



Exoplanets: not (all) like the Solar System

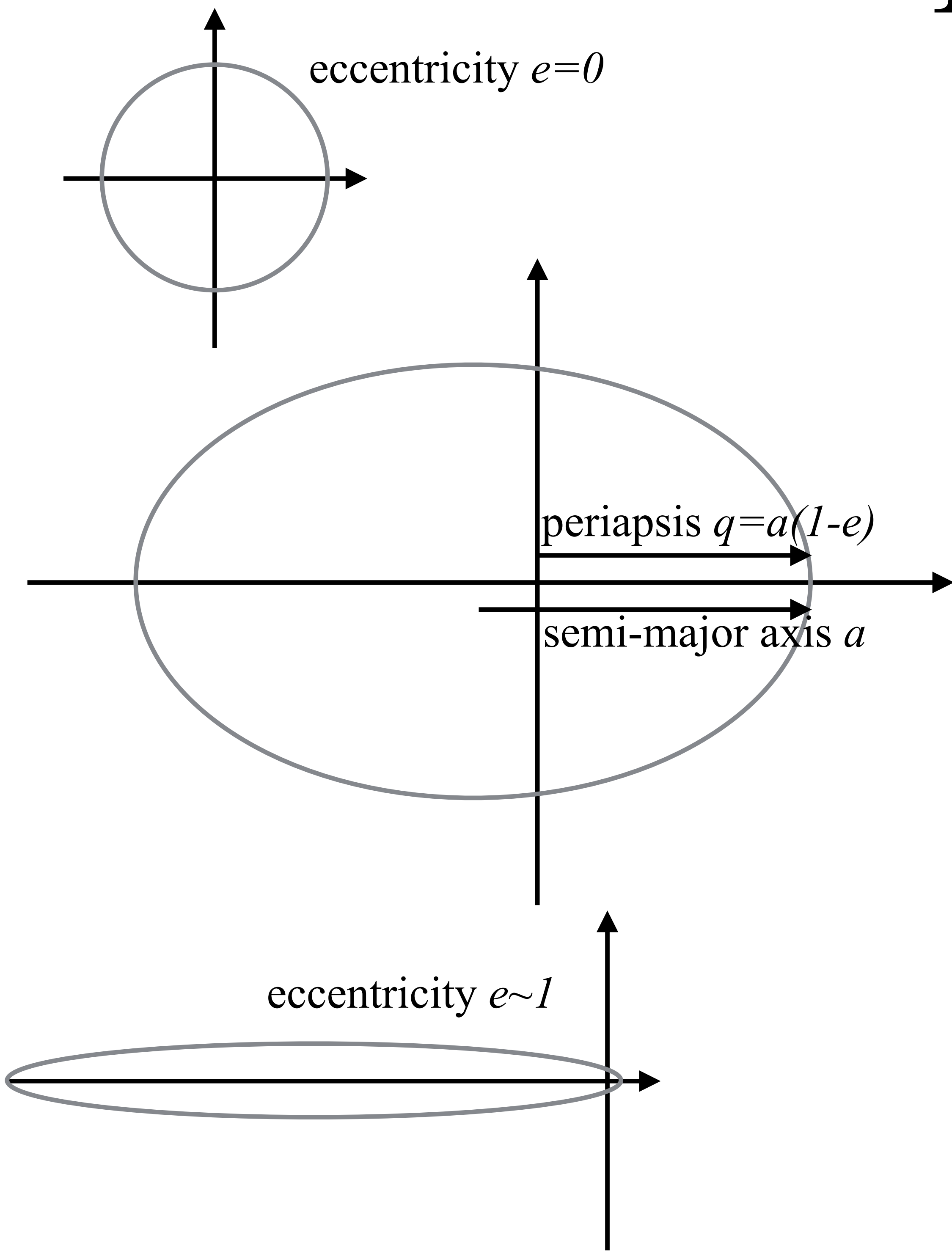


Lissauer et al 14

Key questions to bear in mind

- What is role of formation versus role of later evolution?
- How prevalent is instability, and what triggers it?
- How are outer systems and inner systems linked?

The Keplerian orbit



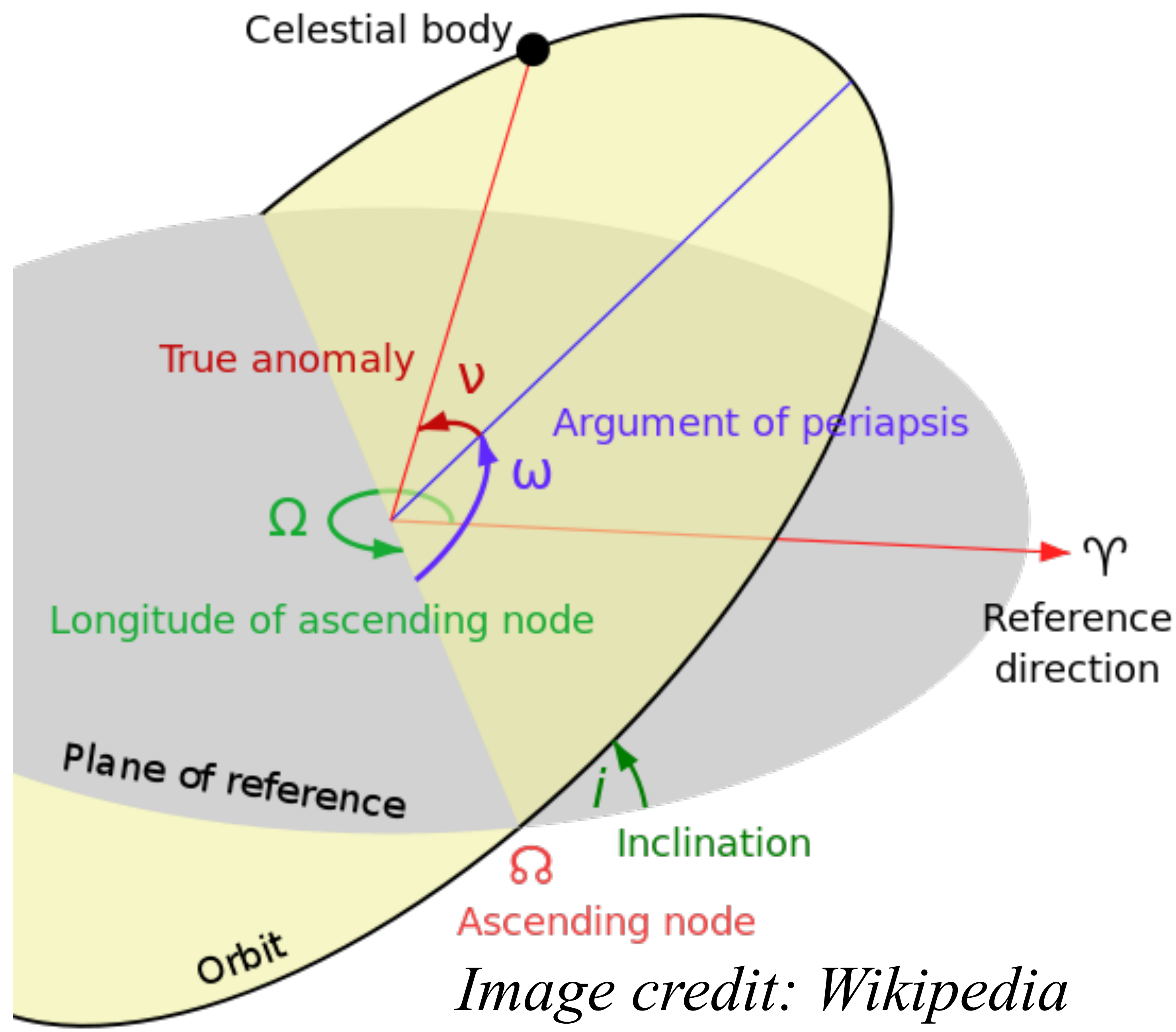


Image credit: Wikipedia

The Keplerian orbit

- Given bodies' masses, orbit uniquely determined by 6 orbital elements:
  - semi-major axis a
  - eccentricity e
  - inclination i
  - true anomaly v, f, or mean anomaly M
  - argument of periapsis ω
  - longitude of ascending node Ω

The Keplerian orbit

- In the 2-body problem, all the orbital elements are constant except for the mean anomaly (or equivalent)

- In a Hamiltonian framework, can use M, ω, Ω as canonical positions; conjugate momenta are then

  - $L = \mu^*\sqrt{(\mu a)}$

  - $G = \mu^*\sqrt{(\mu a(1-e^2))}$

  - $H = \mu^*\sqrt{(\mu a(1-e^2))}\cos i$

- Hamiltonian itself is

  - $\mathscr{H} = -\mu^2\mu^{*3}/(2L^2)$

The Keplerian orbit

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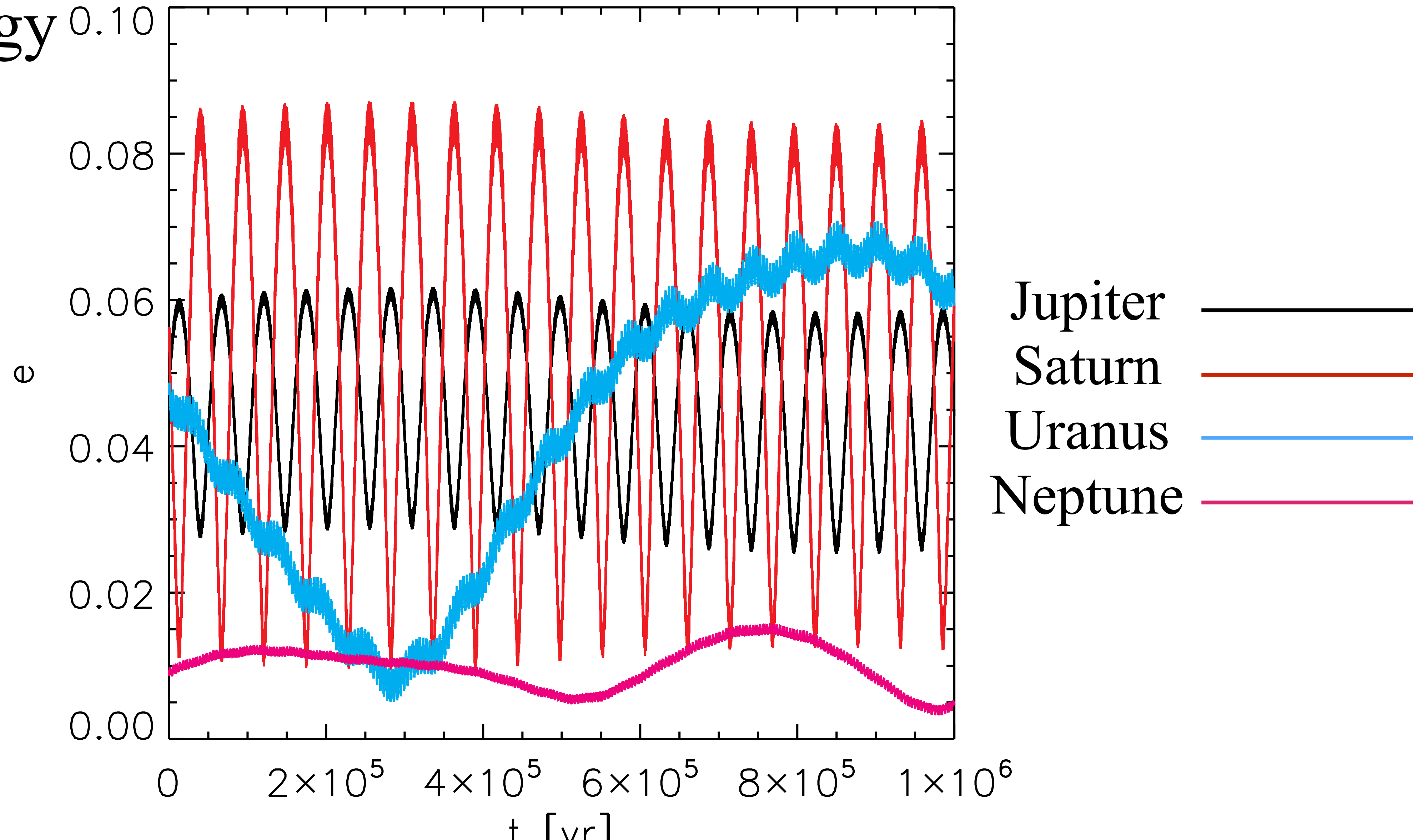
- In a Hamiltonian framework, can use M, ω, Ω as canonical positions; conjugate momenta are then
  - $L = \mu^*\sqrt{(\mu a)}$
  - $G = \mu^*\sqrt{(\mu a(1\text{-}e^2))}$ *Angular momentum*
  - $H = \mu^*\sqrt{(\mu a(1\text{-}e^2))}\cos i$
- Hamiltonian itself is
  - $\mathcal{H} = -\,\mu^2\mu^{*3}/(2L^2)$ *Energy*

The N>2-body problem

- In general intractable
- 2 approaches: numerical, or analytical with simplifying assumptions
- For planetary dynamics, can usually treat the planets as on perturbed Keplerian orbits
  - $\mathscr{H} = -\mu^2\mu*^3/(2L^2) + \mathscr{R}(M_i,\omega_i,\Omega_i,L_i,G_i,H_i)$
- *Hill sphere* where planet's gravity dominates over star's is of radius
  - $r_{\mathrm{H}} = a \sqrt[3]{(m_{\mathrm{pl}}/(3m_{\bigstar}))} \sim 0.01a$ for Earth
- lots of orbits with small perturbations can mean big effects
- Textbook by Murray & Dermott (1999, CUP) "Solar System Dynamics"

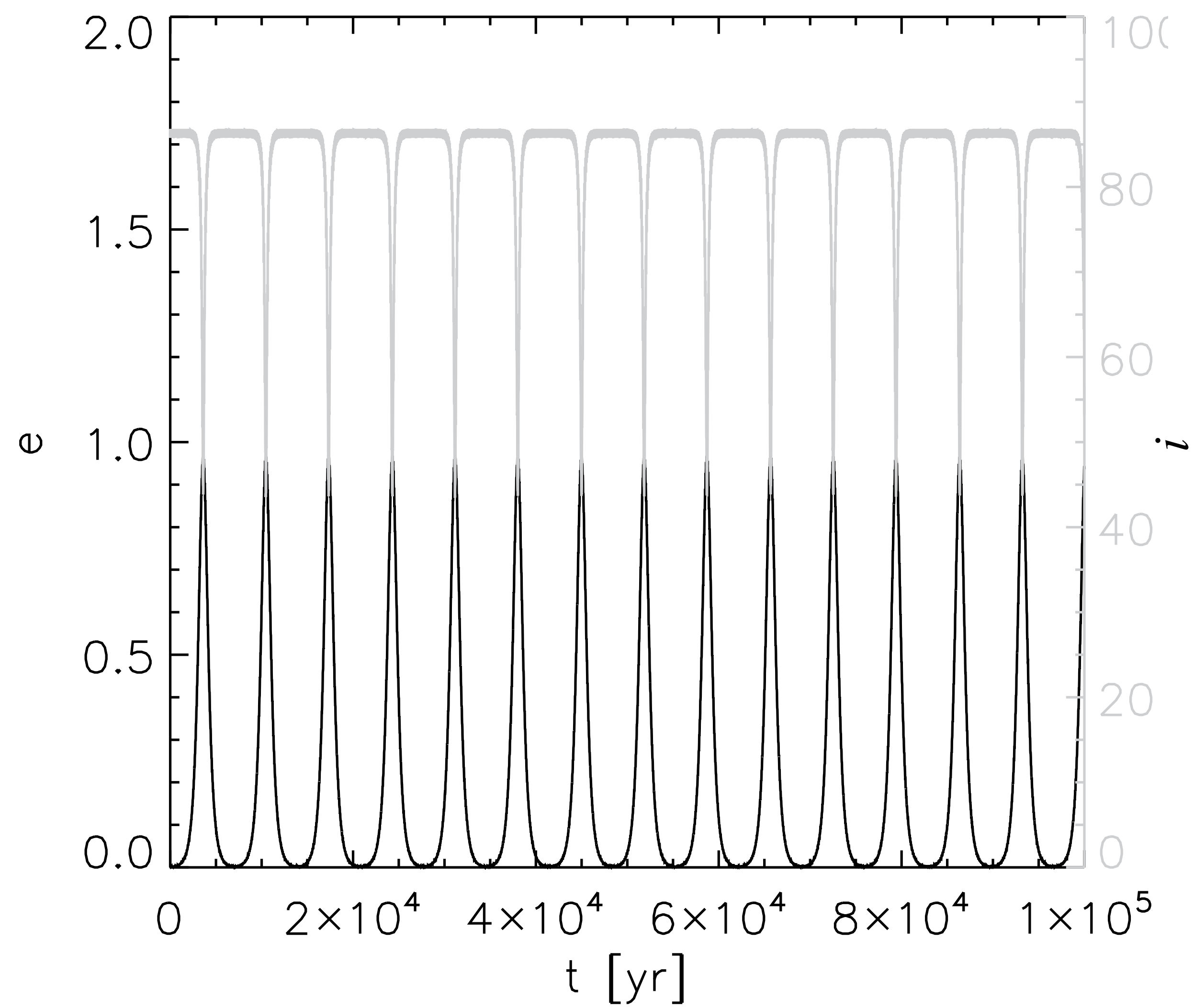
Secular evolution

- Mutual perturbations averaged over orbital time-scales
- Exchange of angular momentum with no change in energy



Kozai perturbations

- Achieve very high *e* starting from high *i*
- Particularly important in systems with wide binary companion



Resonances

- Occur when two important frequencies are commensurate (*e.g.* 2:1)
- Mean motion (*e.g.* Neptune–Pluto, asteroid belt)
- Secular (*e.g.* asteroid belt)
- Drivers of instability… but can be stabilising

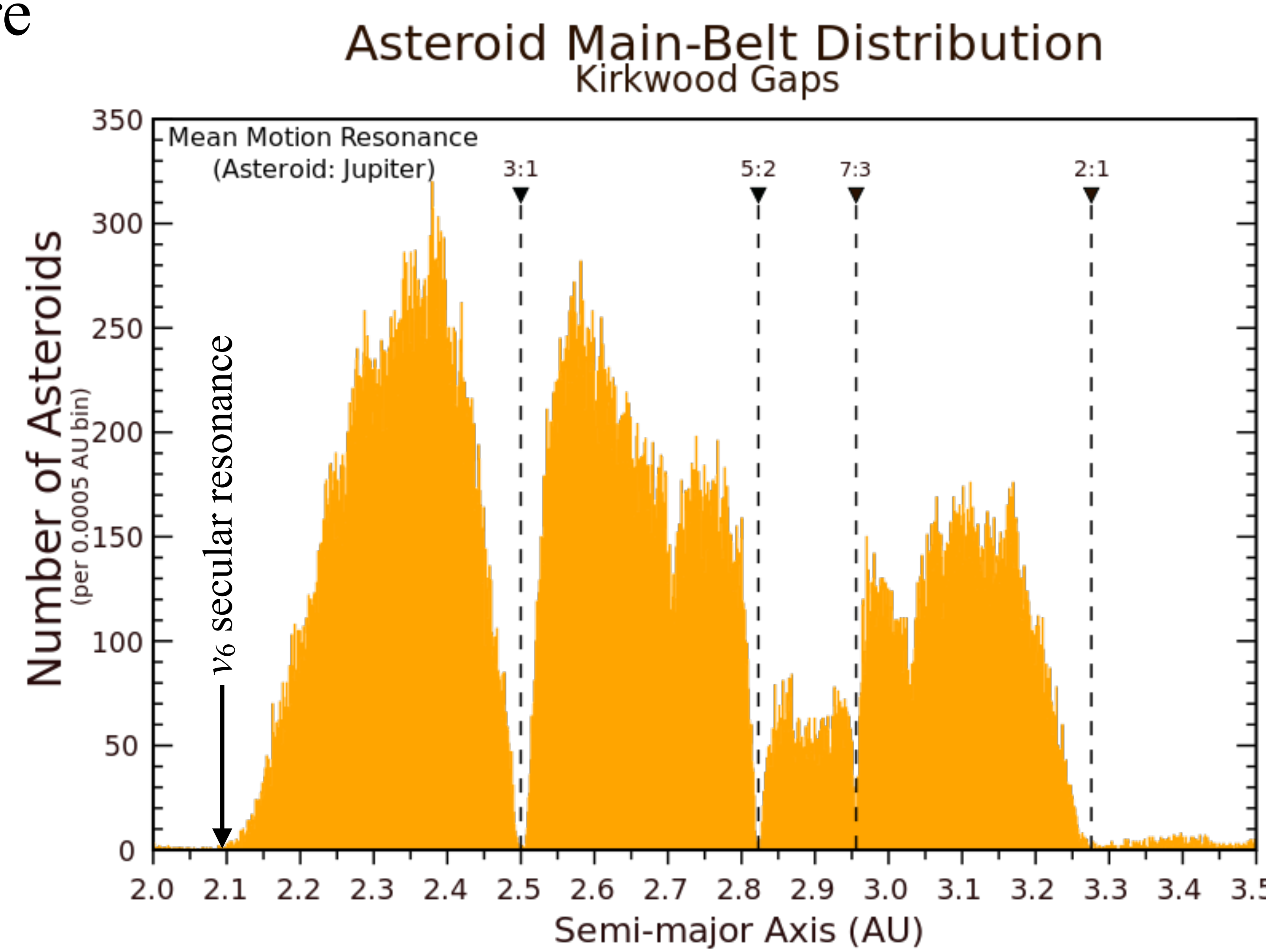
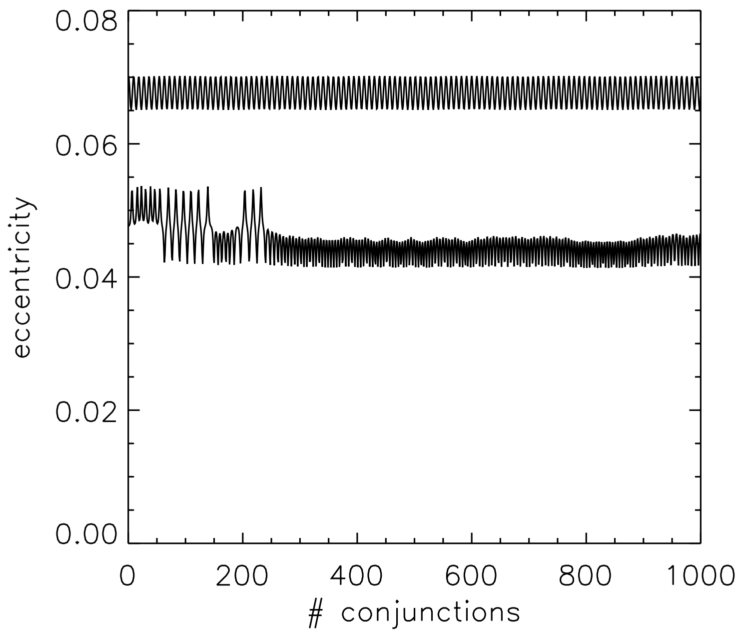
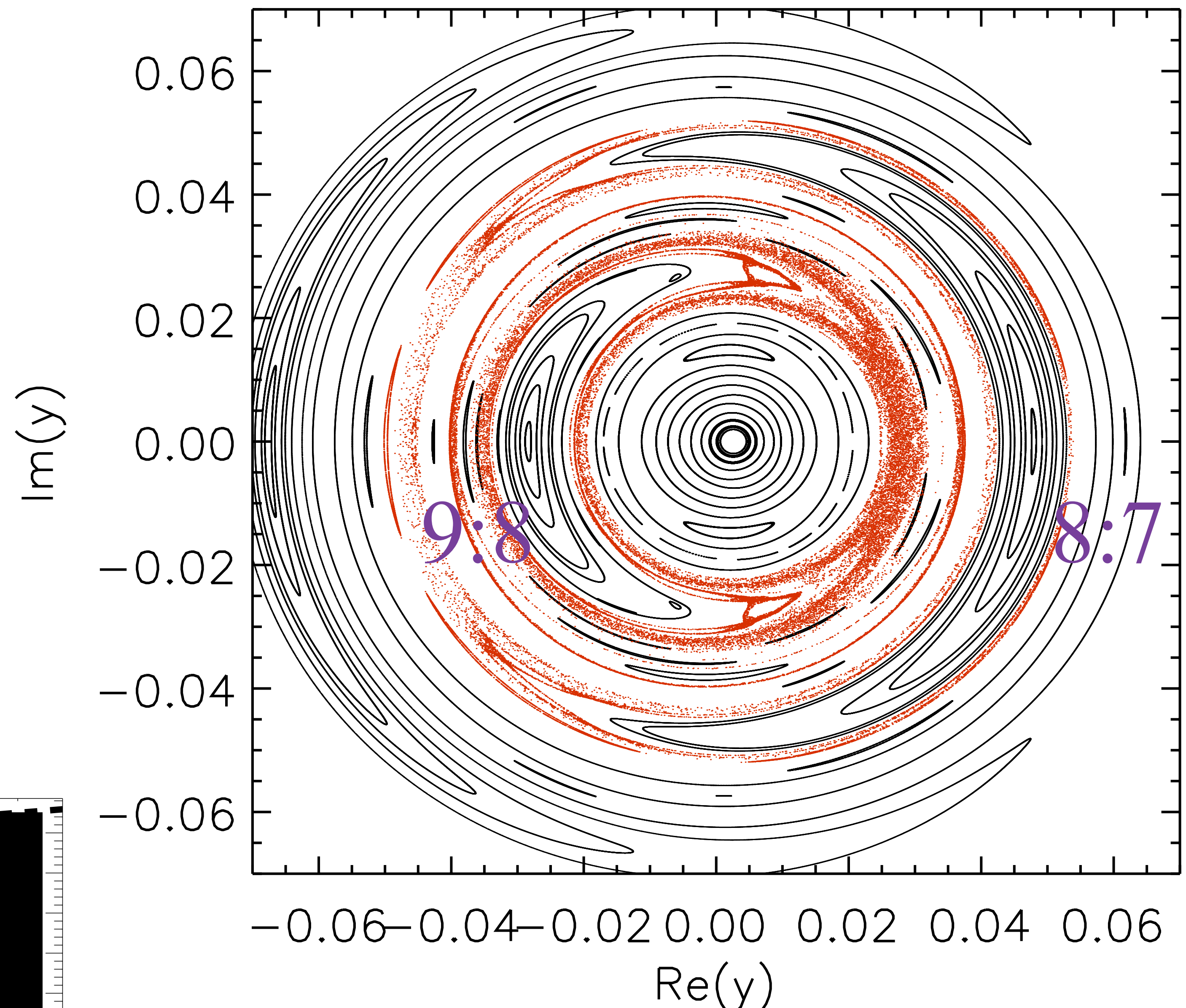
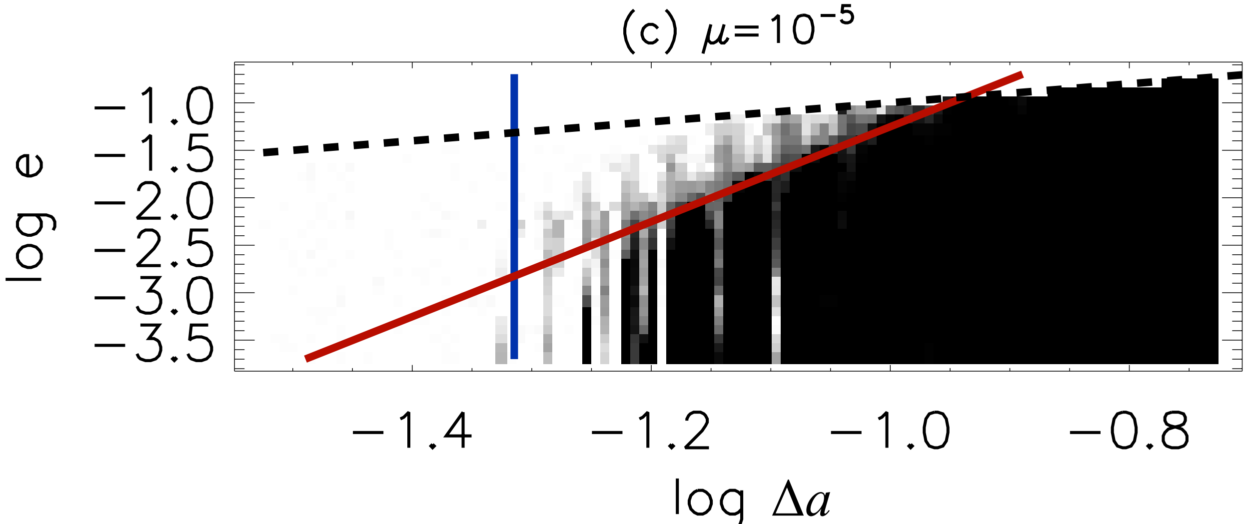


Image credit: Wikipedia

Resonances







Mustill & Wyatt 12

Scattering

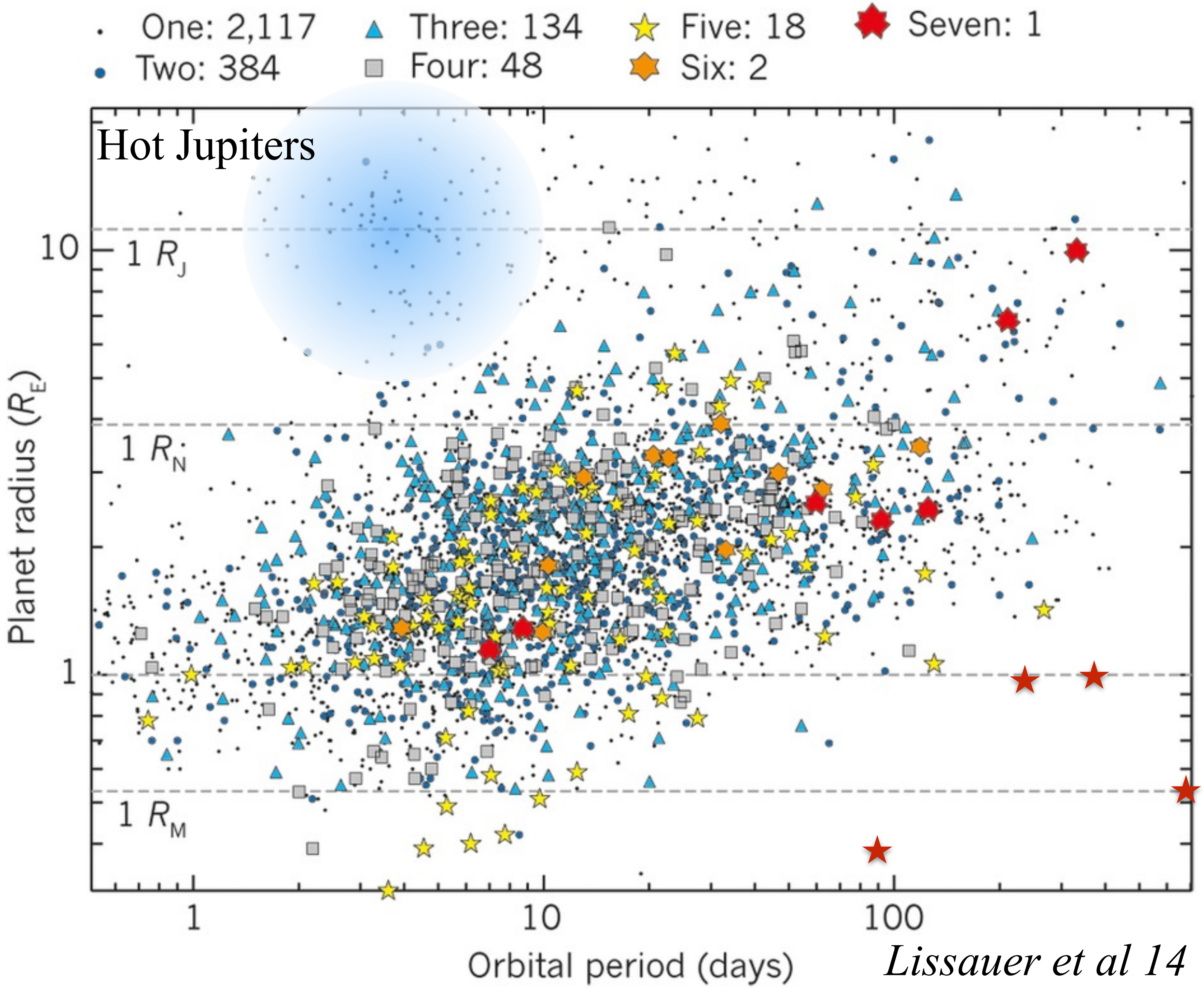
- When the perturbed Keplerian approximation breaks down: impulsive changes to orbits

- May occur after long period of gentler evolution

- Outcome governed by Safronov number: ratio of escape to orbital velocity $\Theta^2 = (m_{\mathrm{pl}}/m_\star)(a/R_{\mathrm{pl}})$

- Leads to collision between planets or large change to orbit (leading to ejection or collision with star)

Hot Jupiters and planetary multiplicity



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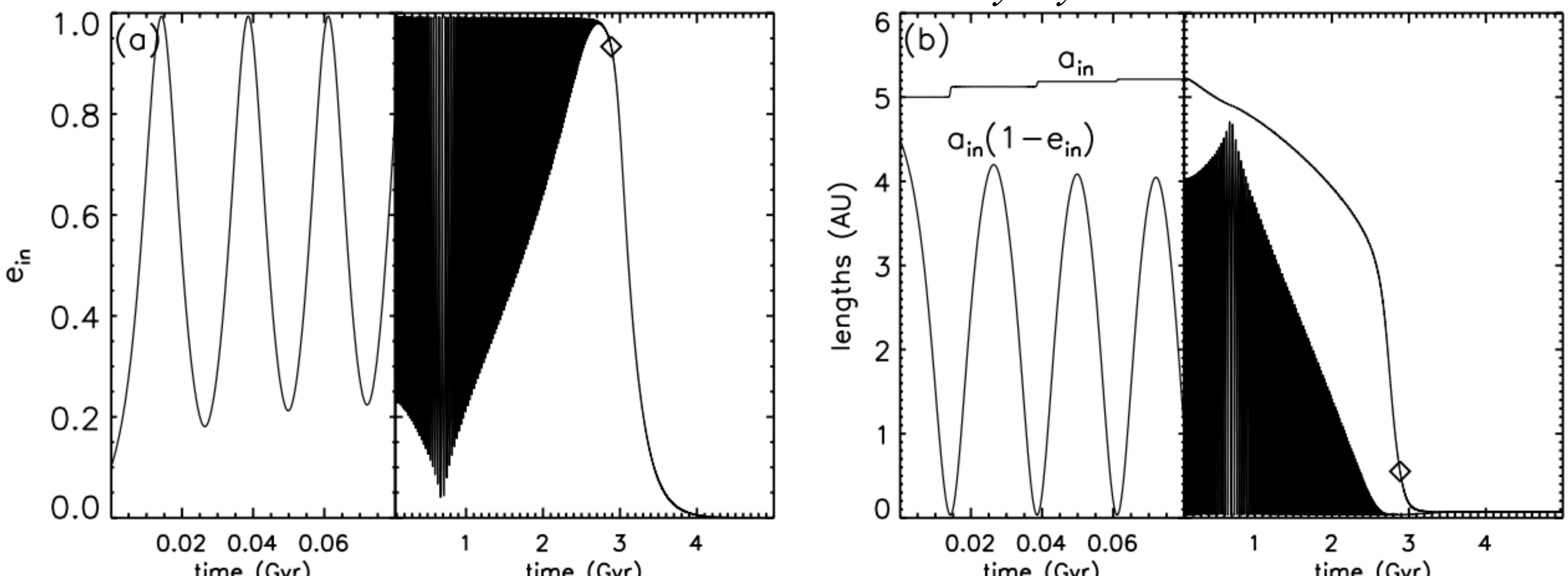
Dynamical delivery

- Kozai, secular, scattering in outer system
- Followed by tidal damping

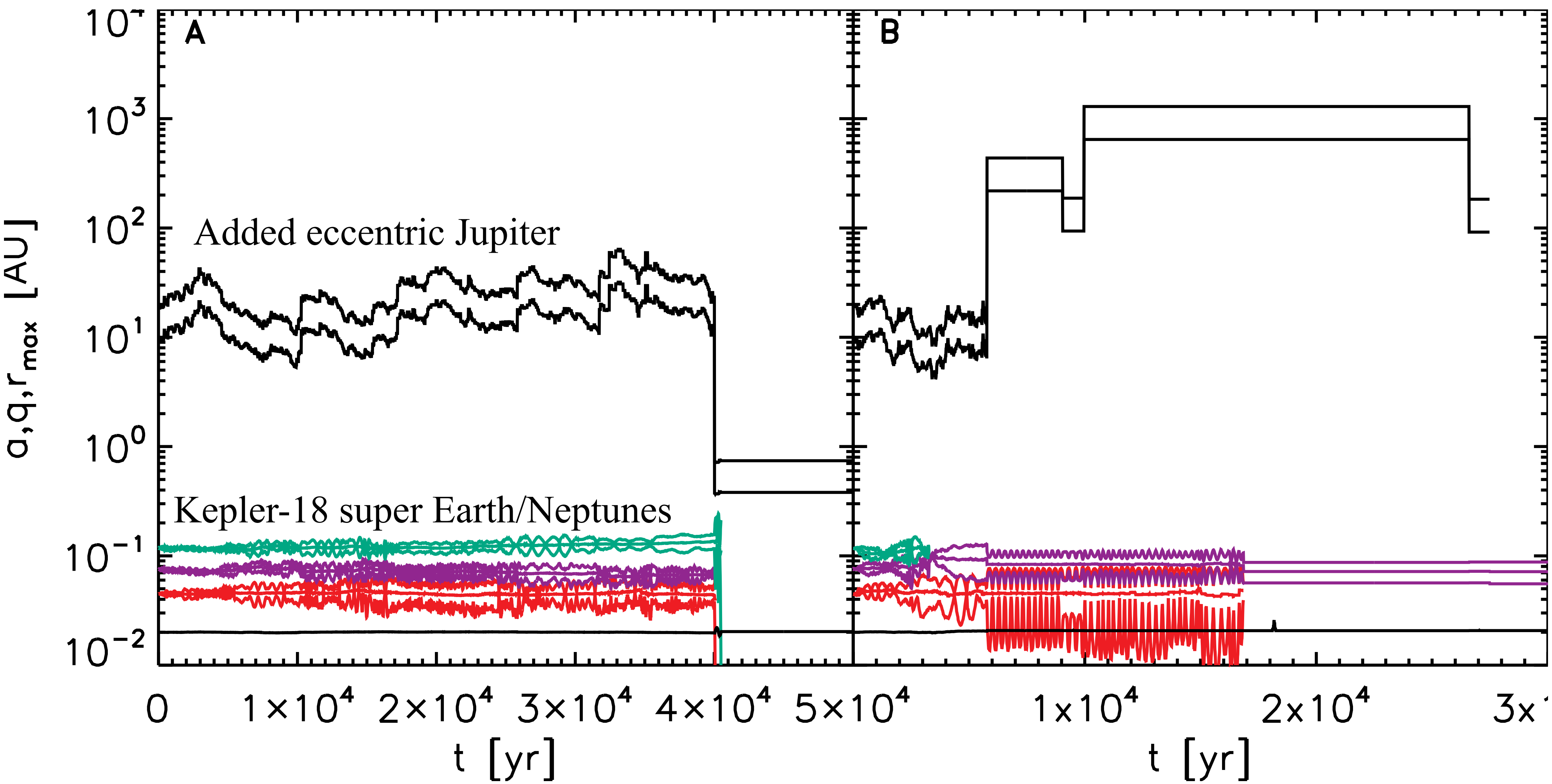
Fabrycky & Tremaine 07



What happens to inner system?

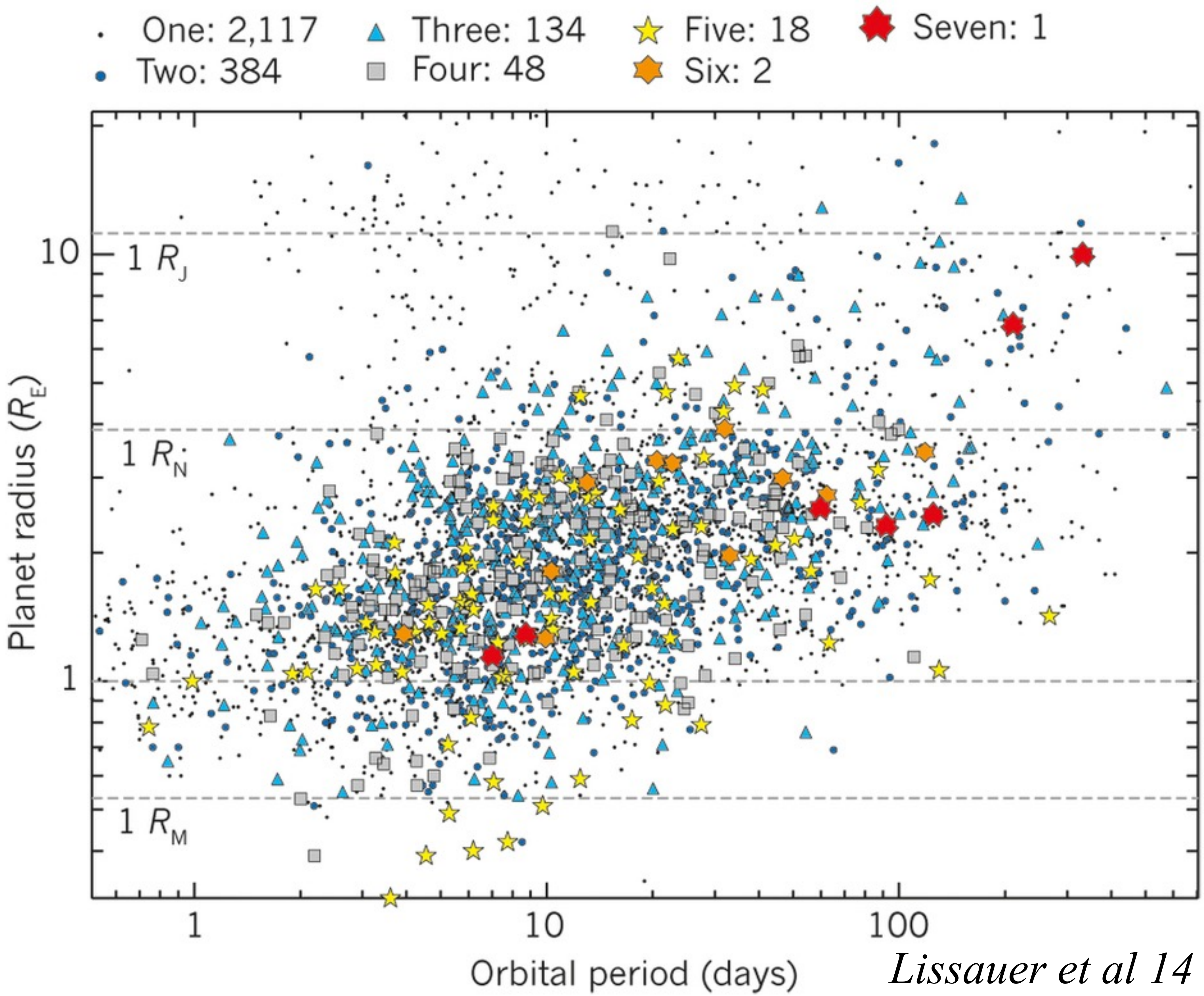
- Take a 3-planet Kepler system as an example
- Throw in Jupiter without worrying about outer system (Mustill, Davies & Johansen 2015)
- Inner system totally cleared
- or Jupiter ejected

What happens to inner system?



Mustill, Davies & Johansen 15

Singles in general



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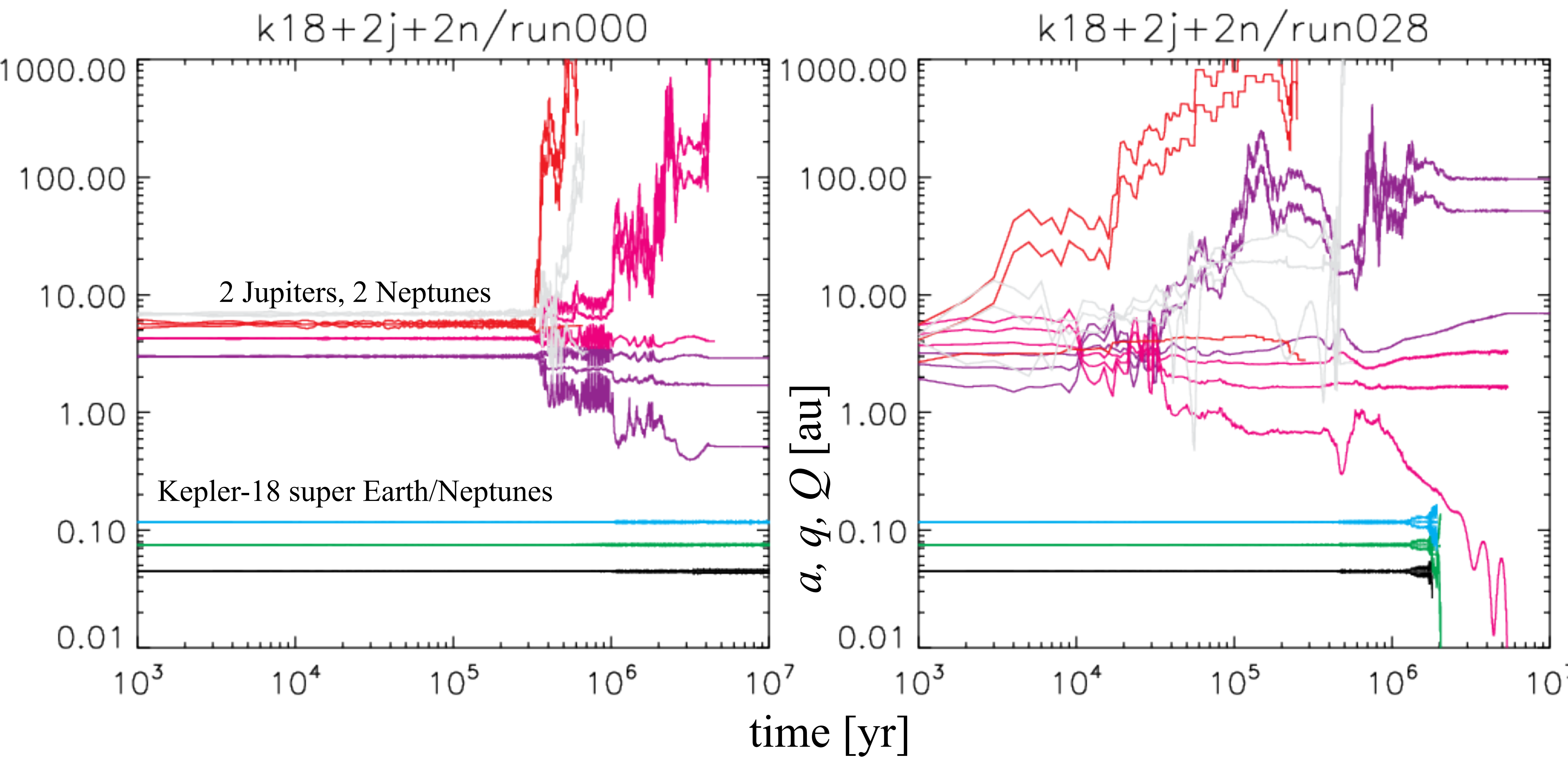
Singles in general

- Singles in general: too many to have arisen from higher-multiplicity population (Johansen et al 2012)
- Is this primordial (lots of systems form only singles) or a result of later evolution?
- Kepler triples are not unstable (Johansen et al et al 2012)
- Can we disrupt triples externally?
- What about higher multiples (Pu & Wu 2015, Gladman & Volk 2015, Mustill et al in prep)

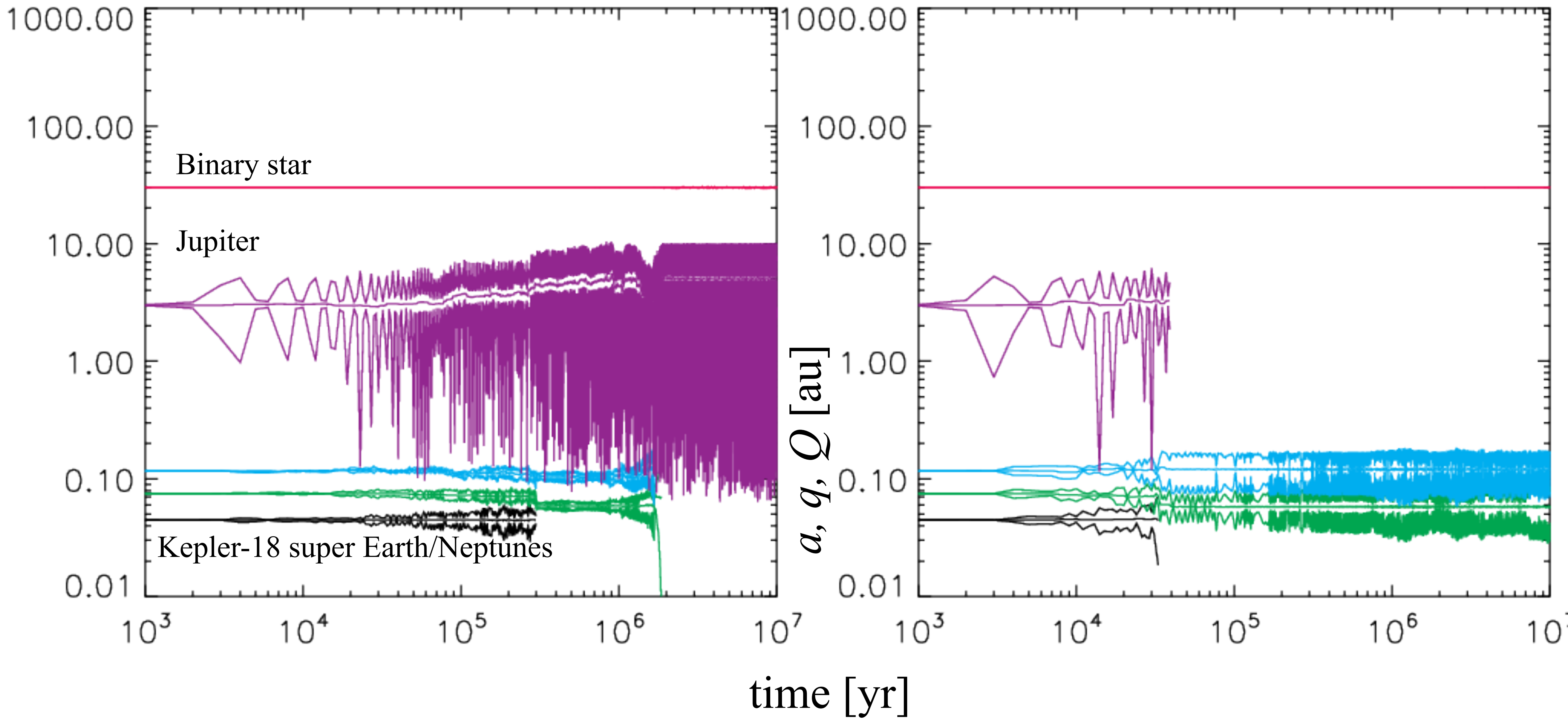
Realistic Jupiter delivery

- Now treat some realistic delivery scenarios (Mustill, Davies & Johansen in prep):
- Kozai by binary
- Scattering in multi-giant system
  - (see also Daniel Carrera in prep: effects of scattering on Earth-like planets)

Example of scattering



Example of Kozai



Some example stats

system	0 planets	1 planet	2 planets	3 planets
K18 + Kozaied Jupiter	44 *69%*	1 *2%*	10 *16%*	9 *14%*
K18 + Kozaied Jupiter + GR	27 *42%*	23 *36%*	8 *13%*	6 *9%*
K18 + scattering giants at 3au	14 *11%*	8 *6%*	4 *3%*	102 *80%*
K18 + scattering giants at 1au	9 *28%*	4 *13%*	3 *9%*	15 *47%*

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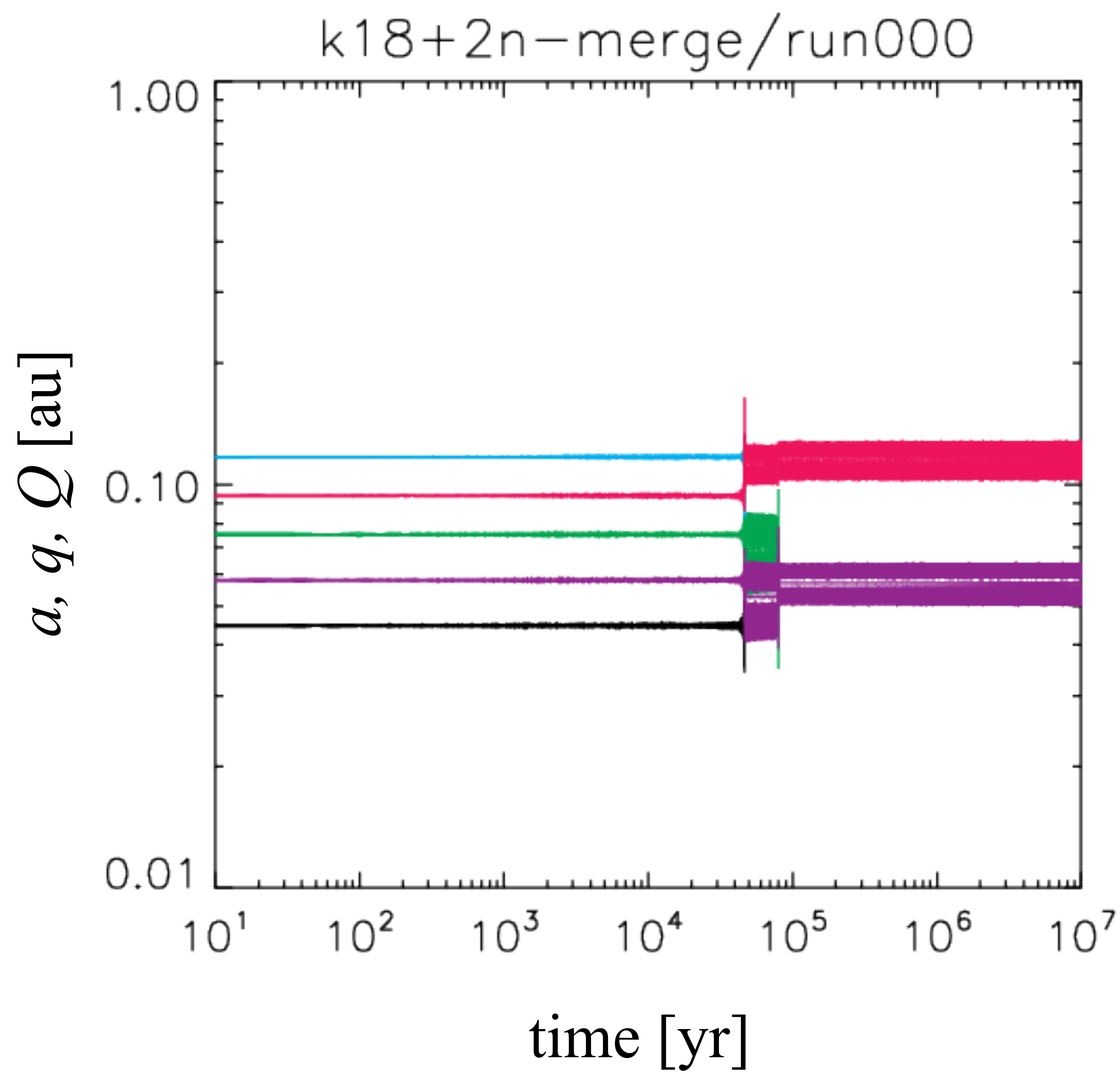
Best at making singles

Example Quintuple



Quintuple stats

- Starting from an unstable quintuple, we end up with doubles or triples
- But we assume perfect merging in collisions—not necessarily realistic
- Collision velocities $\sim e\, v_{\mathrm{kep}}$ can be significantly higher than escape velocity $\Rightarrow$ collisions erosive or destructive

Ongoing work

- “Population synthesis” studies of Kozai and scattering in outer systems, with Kepler systems on the inside
- Use higher-multiplicity Kepler systems as the templates: what happens to the multiplicities of unstable quintuples?
- Investigate role of non-merging collisions

Key points

- The *N*-body problem is considerably harder, and richer, than the 2-body problem
- Instability often preceded by long periods of more quiescent evolution
- Many extra-Solar systems unlike our own
  - eccentric giants
  - close-in Super-Earths
- Multiplicities shaped by dynamical evolution