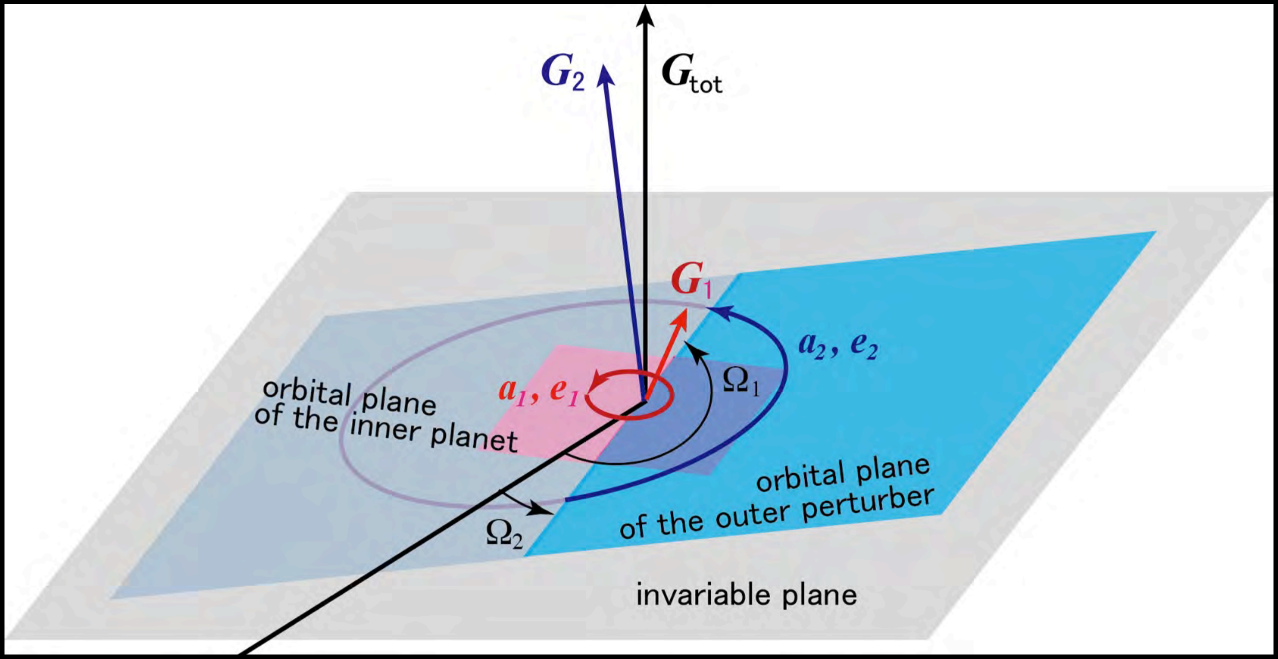
Hot Jupiters from near-coplanar hierarchical triple systems



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Ohta, Taruya & Suto: ApJ 622(2005)1118

THE ROSSITER-McLAUGHLIN EFFECT AND ANALYTIC RADIAL VELOCITY CURVES FOR TRANSITING EXTRASOLAR PLANETARY SYSTEMS

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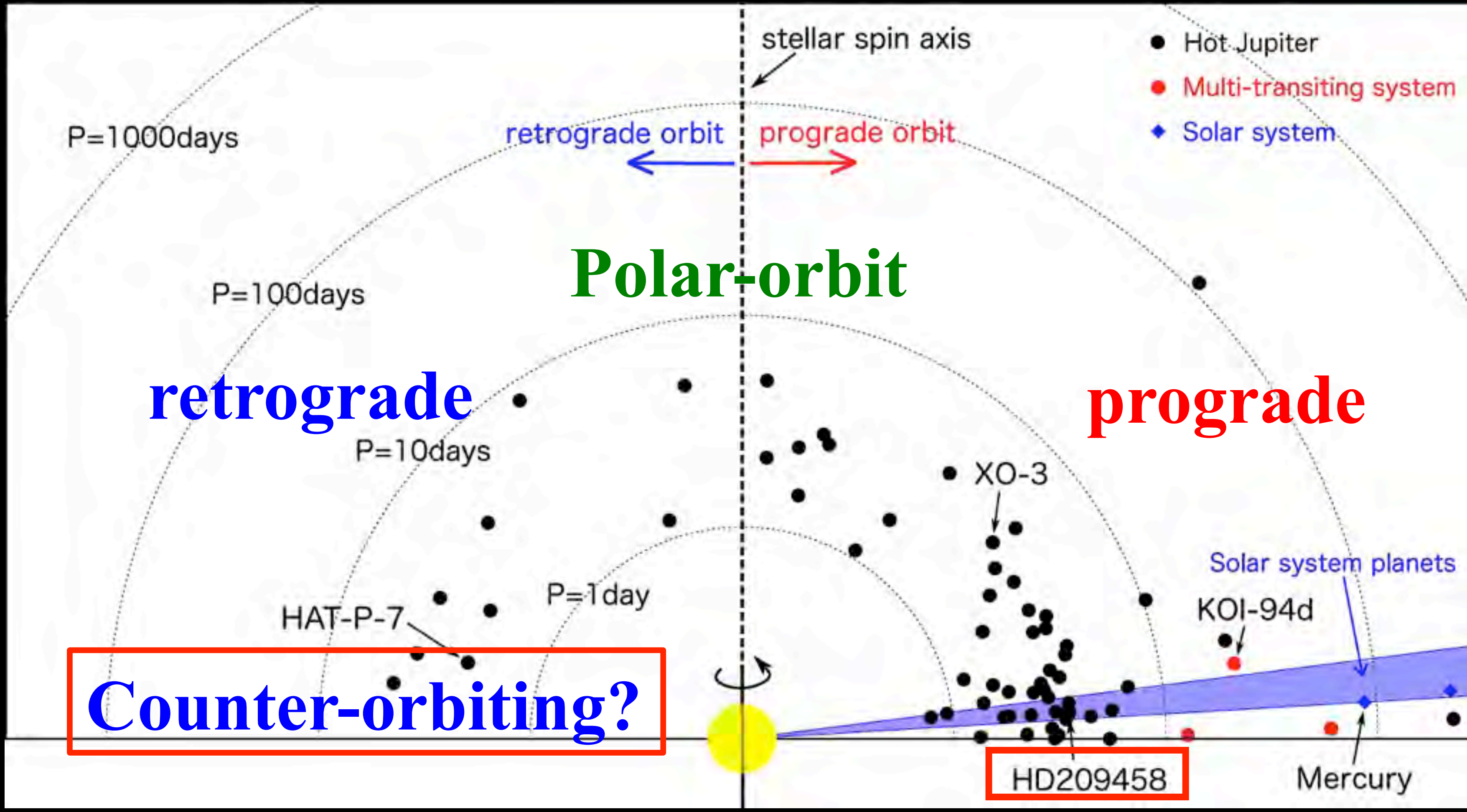
Among the recently discovered transiting extrasolar planetary systems, i.e., TrES-1 by the Trans-Atlantic Exoplanet Survey (Alonso et al. 2004) and OGLE-TR 10, 56, 111, 113, 132 by the Optically Gravitational Lens Event survey (e.g., Udalski et al. 2002c, 2002b, 2002a, 2003; Konacki et al. 2003; Bouchy et al. 2004; Pont et al. 2004), TrES-1 has similar orbital period and mass to those of HD 209458b, but its radius is smaller. Thus, it is an interesting target to determine the spin parameters via the RM effect; if its planetary orbit and the stellar rotation share the same direction as discovered for the HD 209458 system, it would be an important confirmation of the current view of planet formation out of the protoplanetary disk surrounding the protostar. If not, the result would be more exciting and even challenge the standard view, depending on the value of the misalignment angle λ.

We also note that the future satellites *COROT* and *Kepler* will detect numerous transiting planetary systems, most of which will be important targets for the RM effect in 8–10 m class ground-based telescopes. We hope that our analytic formulae presented here will be a useful template in estimating parameters for those stellar and planetary systems.

In conclusion, we have demonstrated that the radial velocity anomaly due to the RM effect provides a reliable estimation of spin parameters. Combining data with the analytic formulae for radial velocity shift Δv_s, this methodology becomes a powerful tool in extracting information on the formation and the evolution of extrasolar planetary systems, especially the origin of their angular momentum. Although it is unlikely, we may even speculate that a future RM observation may discover an extrasolar planetary system in which the stellar spin and the planetary orbital axes are antiparallel or orthogonal. This would have a great impact on the planetary formation scenario, which would have to invoke an additional effect from possible other planets in the system during the migration or the capture of a free-floating planet. While it is premature to discuss such extreme possibilities at this point, the observational exploration of transiting systems using the RM effect is one of the most important probes for a better understanding of the origin of extrasolar planets.

Projected spin-orbit angle distribution

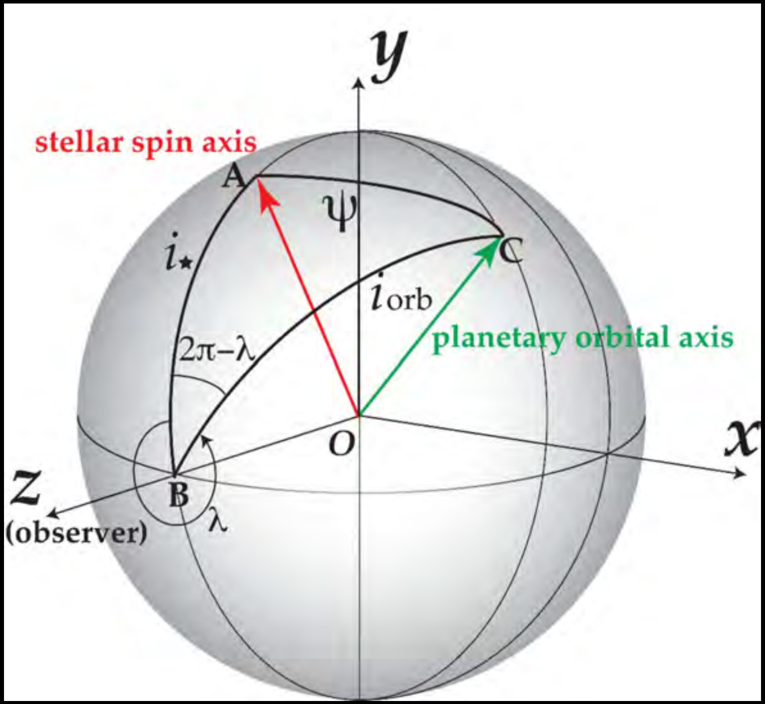


As of June 2013, 29 out of 70 planets have $\lambda > \pi/8$

Xue et al. (2014)

Spin-orbit angles of HAT-P-7b

- HAT-P-7b (a retrograde planet on the sky plane)
  - Projected: $\lambda = 186^\circ\,^{+10^\circ}_{-11^\circ}$ (Rossiter-McLaughlin effect)
  - Stellar inclination: $i_s = 27^\circ\,^{+35^\circ}_{-18^\circ}$ (asteroseismology)
  - True spin-orbit angle: $\psi = 122^\circ\,^{+30^\circ}_{-18^\circ}$



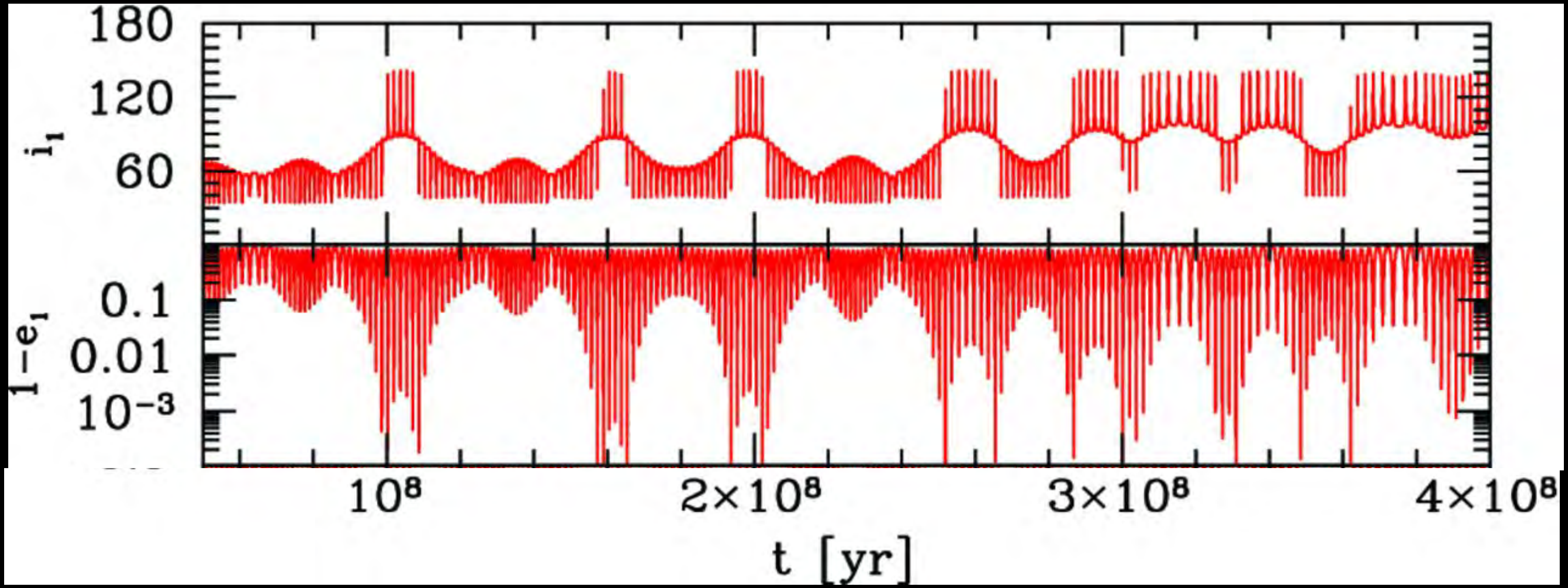
Benomar et al. 2014, PASJ 66, 94
arXiv:1407.7332

$$\cos\psi \approx \sin i_* \cos\lambda$$

- Several planets with $\lambda \fallingdotseq 180^\circ$, but none with $\psi \fallingdotseq 180^\circ$ (so far)
  - retrograde ≠ counter-orbiting

Formation of counter-orbiting planets is not easy

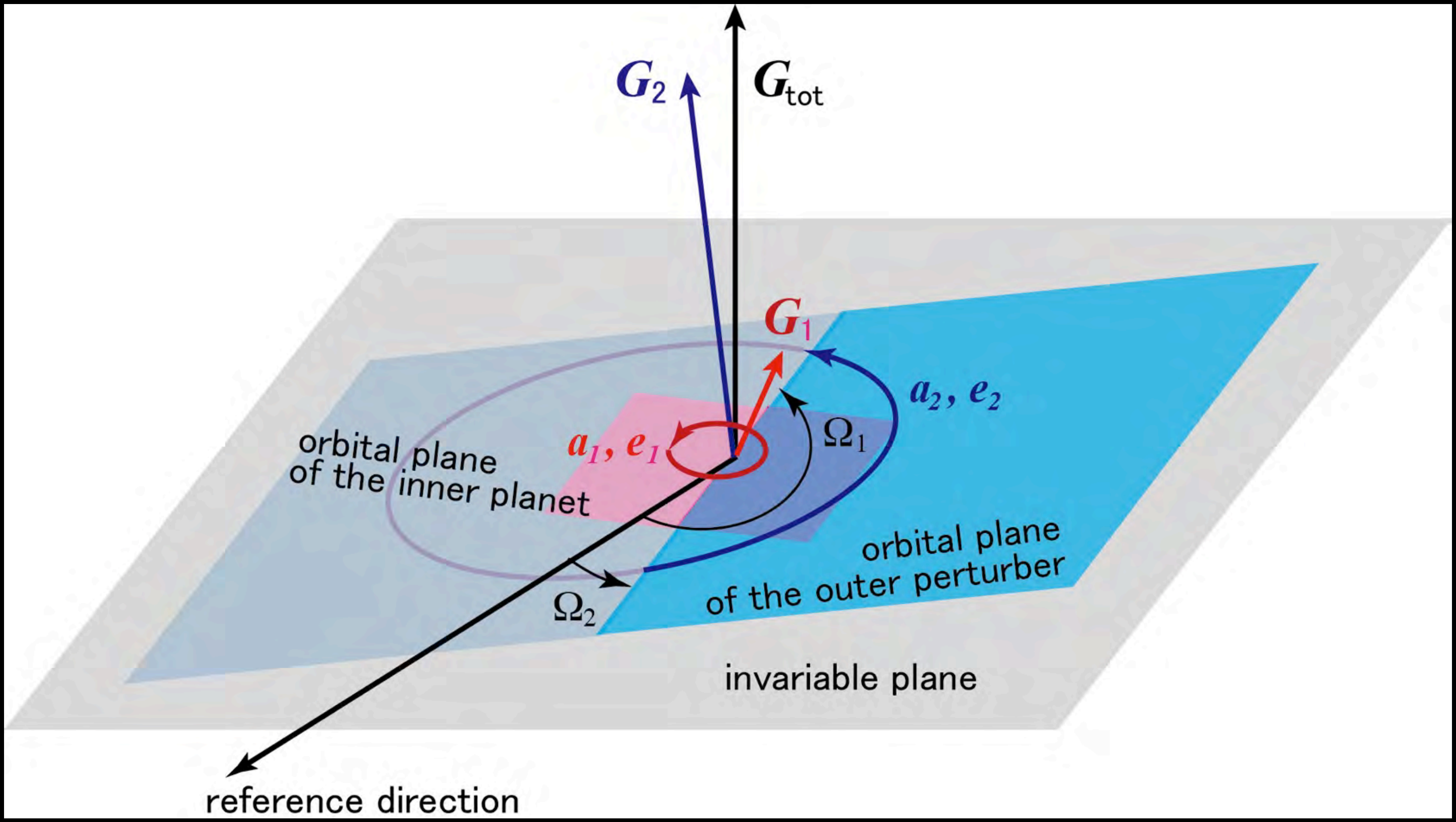
- The Lidov-Kozai mechanism
  - Large misalignment can be produced (Nagasawa et al. 2008), but not a counter-orbiting planet



An example of a three-body system with m_0 = 1 $M_\odot$, m_1 = 1 M_J, and m_2 = 2 M_J, a_1 = 4 au, and a_2 = 45 au

Naoz et al. MNRAS 431(2013)2155

A possible recipe of counter-orbiting planets → near-coplanar hierarchical triples



Li et al. (2014), Petrovich (2015), Xue & Suto (2016)

Extreme-eccentricity ~ flip condition?

- Specific angular mom. of the inner planet

$$j = \sqrt{Gm_0 a_1 (1 - e_1^2)} << 1 \Leftrightarrow e_1 \approx 1$$

  - octupole potential is important to achieve an extreme value of *e*, and thus flip *j*
  - An analytic condition for $e_{1,max} \sim 1$ is a necessary condition for the orbital flip: Li et al. (2014) and Petrovich (2015)
- But, short-range forces significantly suppress the achievable maximum *e* (Liu et al 2015)
  - Need to study numerically

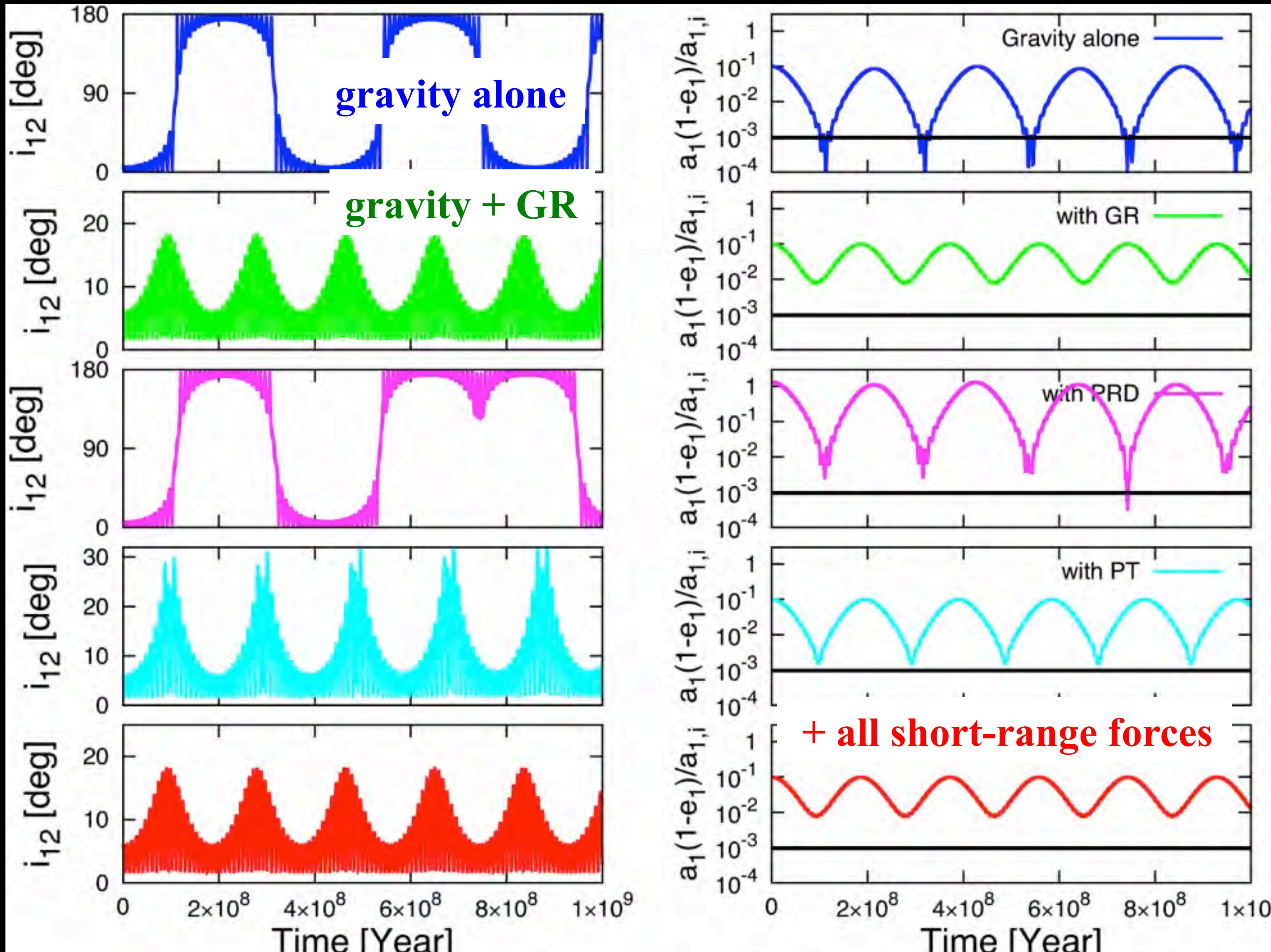
Assumptions in our numerical runs

- Near-coplanar hierarchical triples with initially aligned stellar spin and planetary orbits.
- Secular perturbation
  - Potential expanded up to the octupole order of the outer perturber $\sim (r_1/r_2)^3$
  - + short-range forces (general relativity correction, planetary rotational distortion, planetary dissipative tide, and stellar rotational distortion)
- Key parameter of the system

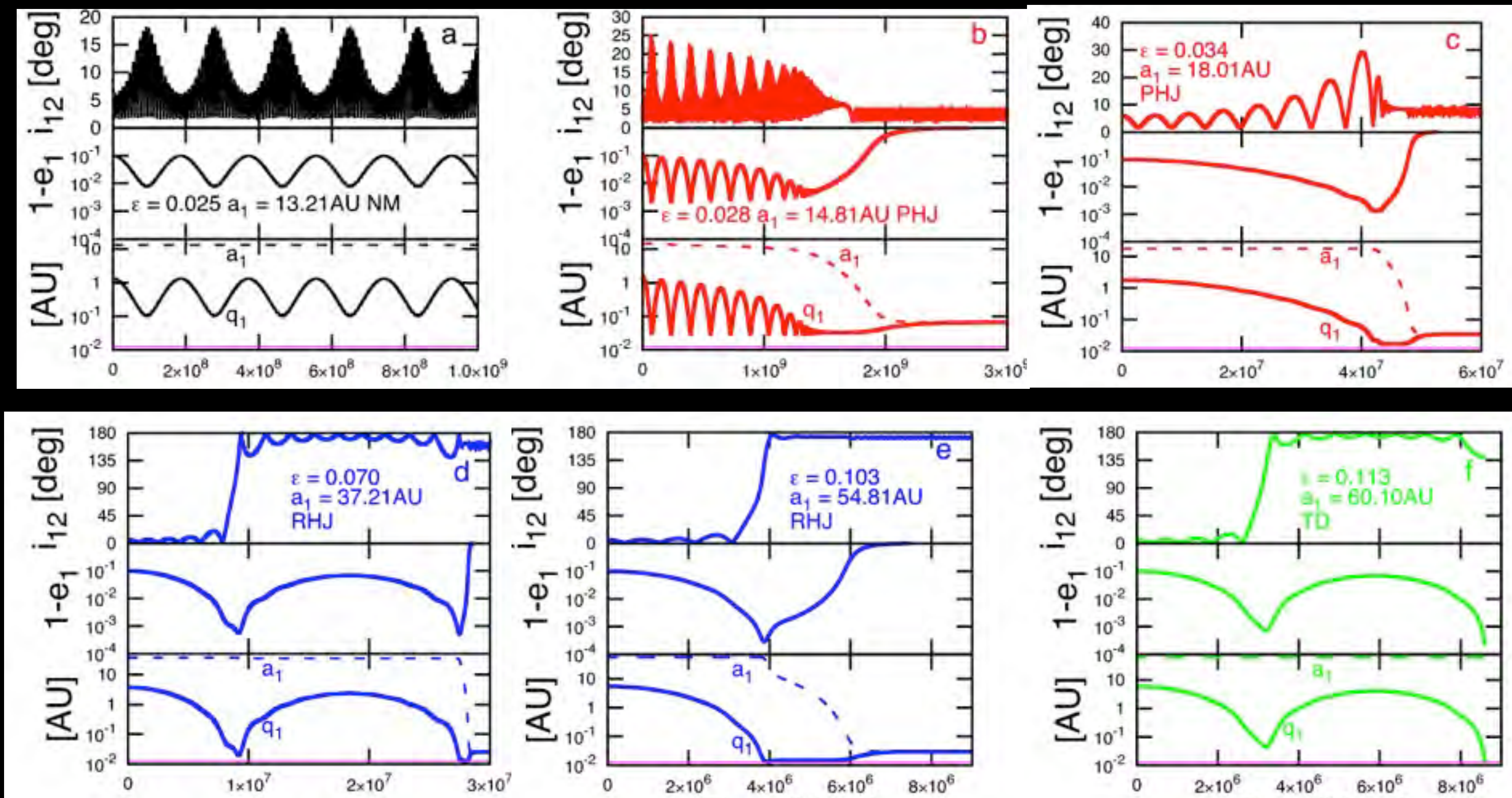
$$\varepsilon_{oct} \equiv \frac{m_0 - m_1}{m_0 + m_1} \frac{a_1}{a_2} \frac{e_2}{1 - e_2^2}$$

Effects of short-range forces

Xue & Suto (2016)

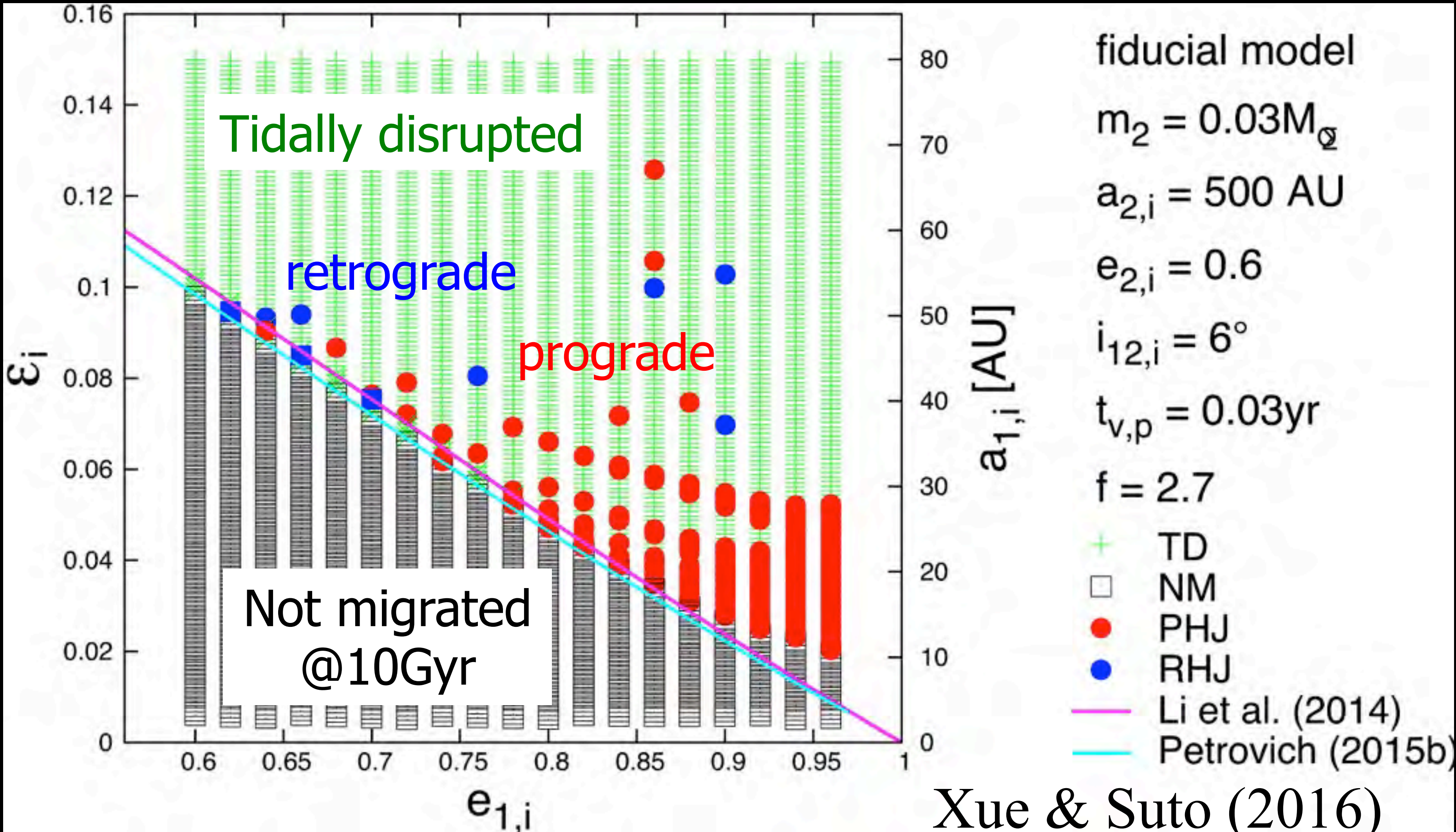


ε_{oct} changes the dynamics crucially



$e_{1,i}=0.9, e_{2,i}=0.6$, $a_{2,i}=500$au, $m_1=1M_J$, $m_2=0.03M_\odot$

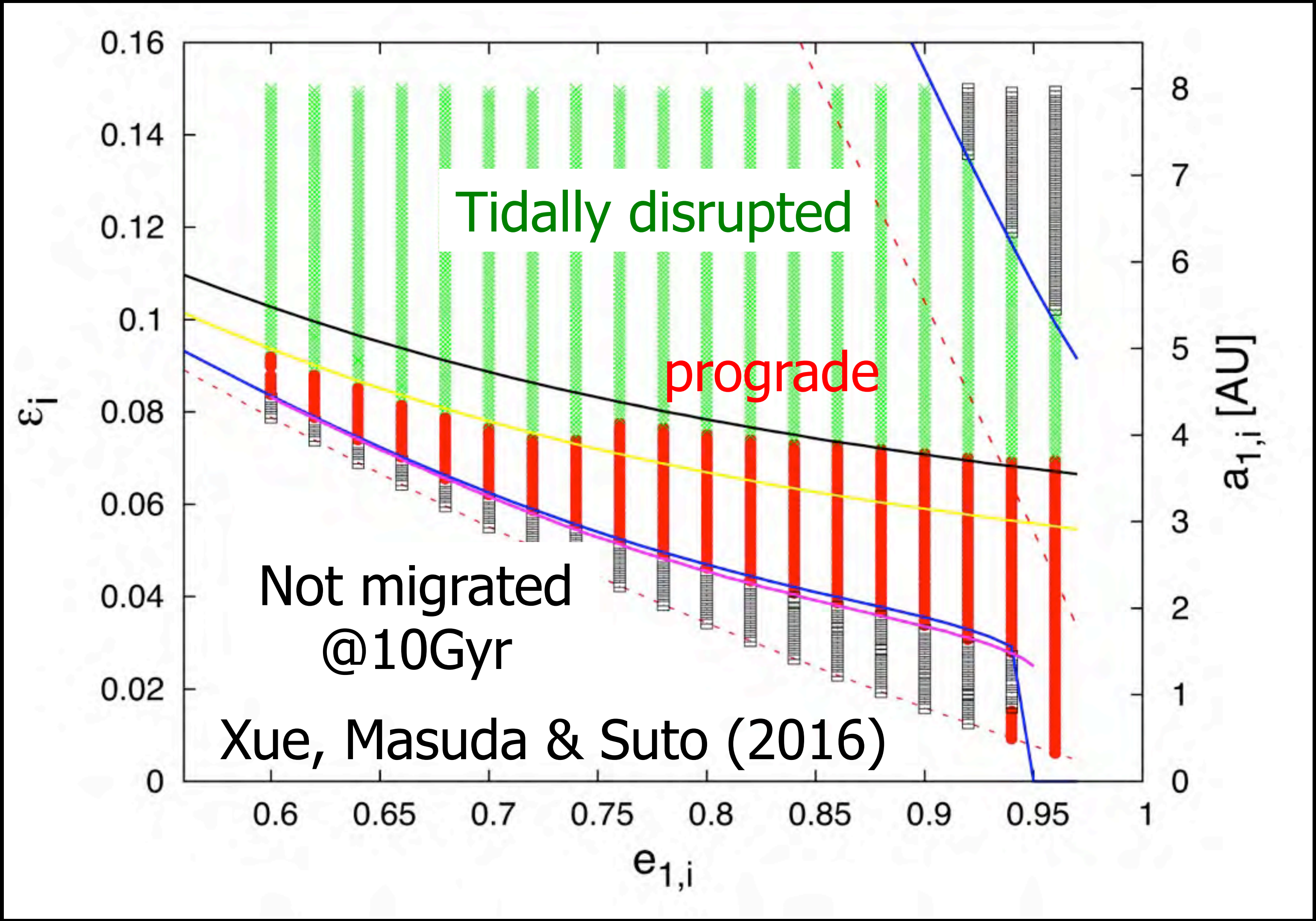
Fate of near-coplanar triples @10Gyr: a substellar perturber



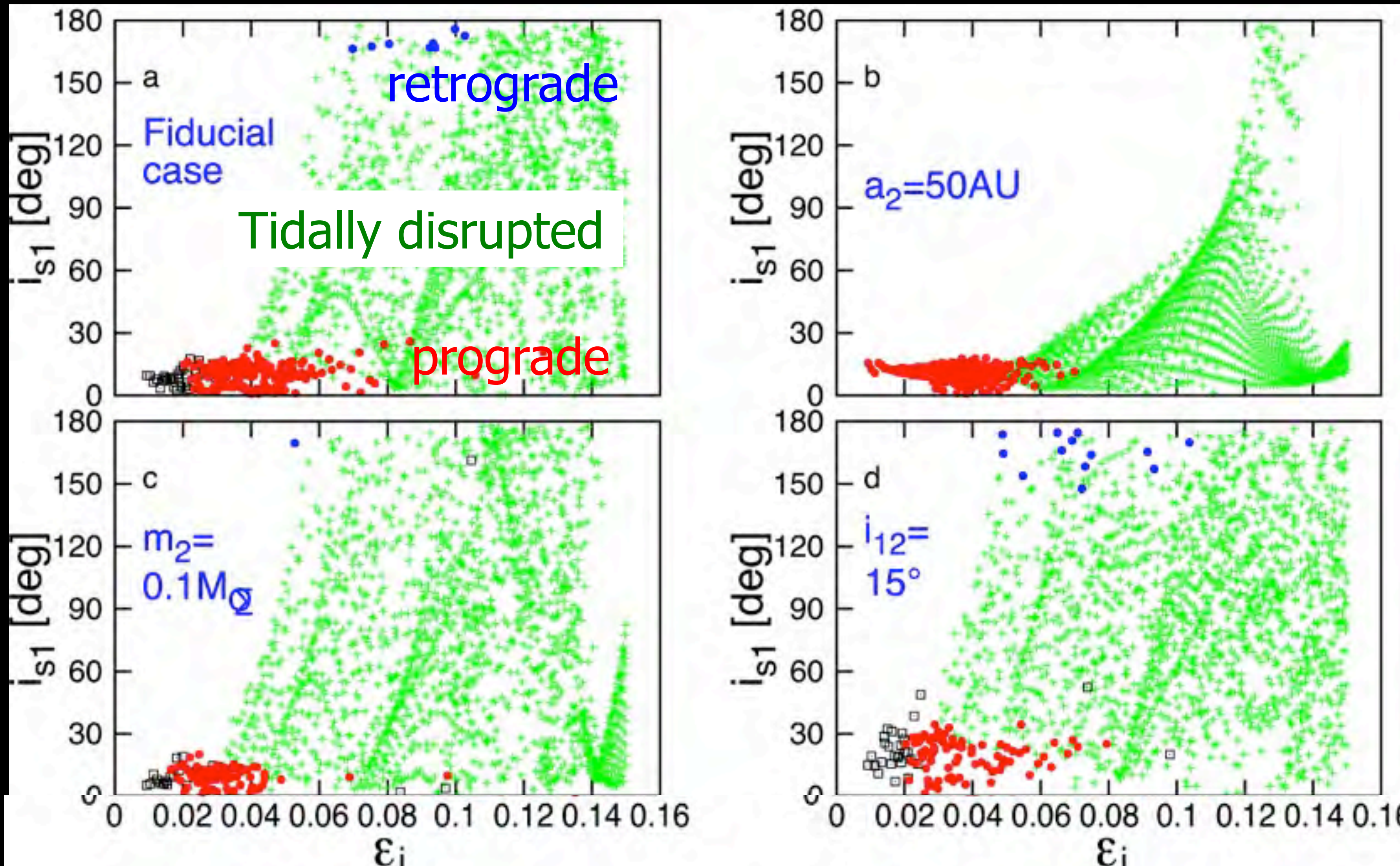
Xue & Suto (2016)

a planetary perturber case

$e_{2,i}=0.6$, $a_{2,i}=50au$, $m_2=5M_J$



Spin-orbit angle distribution for a substellar perturber



Conclusions

- Extremely difficult to account for counter-orbiting planets ($\psi \fallingdotseq 180°$)
- A large fraction of near-coplanar triples is tidally disrupted
  - 10-20 % may end up with prograde HJs
  - observational signature of tidal disruption events ?
- Counter-orbiting planets, if really exist, challenge migration/formation models
  - Not dynamical, but primordial origin ?