Forming Short-Period Planets:
High-e and Low-e Migration and Tidal Dissipation

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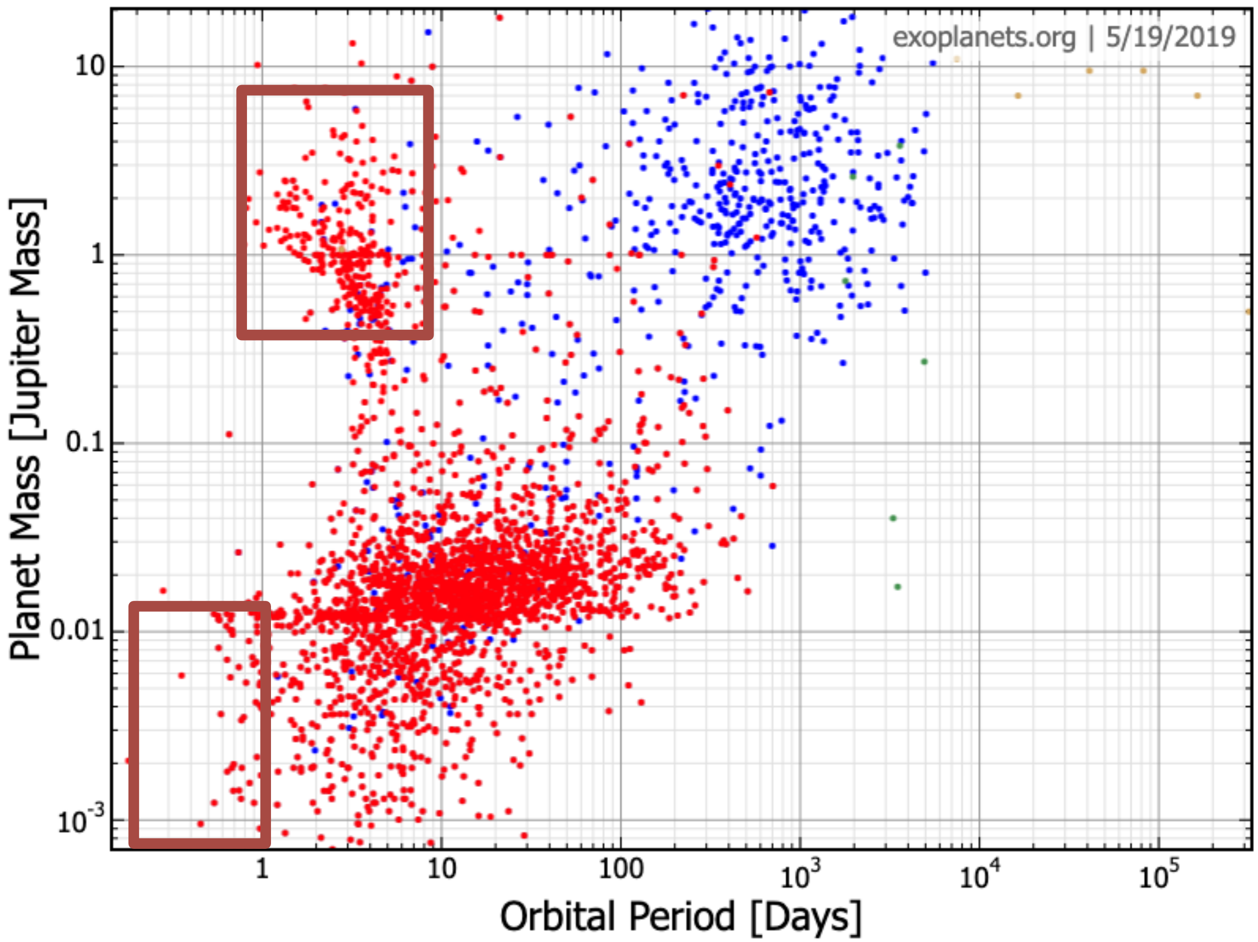


Hot Jupiters:
Giant planets with
P<10d

Ultra-Short Planets:
Small planets with
P<1d

Hot Jupiter Formation

(see Dawson & Johnson 2018 for HJ review)

Formation in Protoplanetary Disks (Migration vs In-Situ)

– Young proto-HJ candidates observed (e.g. CI Tau)

-- WASP-47b (HJ with small neighbors)

– Can misalignment (stellar spin vs orbit) be produced?

(e.g. Bate+10; Lai+11; Batygin 12; Batygin & Adams 12; Lai 14; Spalding & Batygin 14; Zanazzi & Lai 18)

HIGH-ECCENTRICITY MIGRATION

(e.g. Eggleton+01; Wu & Murray 03; Fabrycky & Tremaine 07; Nagasawa+08; Wu & Lithwick 11; Beauge & Nesvorny 12; Naoz+12; Storch et et al.14; Petrovich 15a,b; Anderson+16; Munoz & Lai+16; Wu 18; Vick & Lai+19; Teyssandier, Lai+19)

High-eccentricity Migration

1. Planet (formed at ~AU) is excited to a high-e orbit (small pericenter) by interactions with other planet(s) or companion star(s)

2. Tidal dissipation in the planet circularizes and shrinks the orbit

Pros:

-- Accounts for HJ pile-up at a few Roche radii

-- Explains the lack of nearby low-mass neighbors for most HJs (Huang+16)

-- Can naturally account for large stellar obliquities (spin-orbit coupling dynamics important; Storch+2014; Anderson+16)

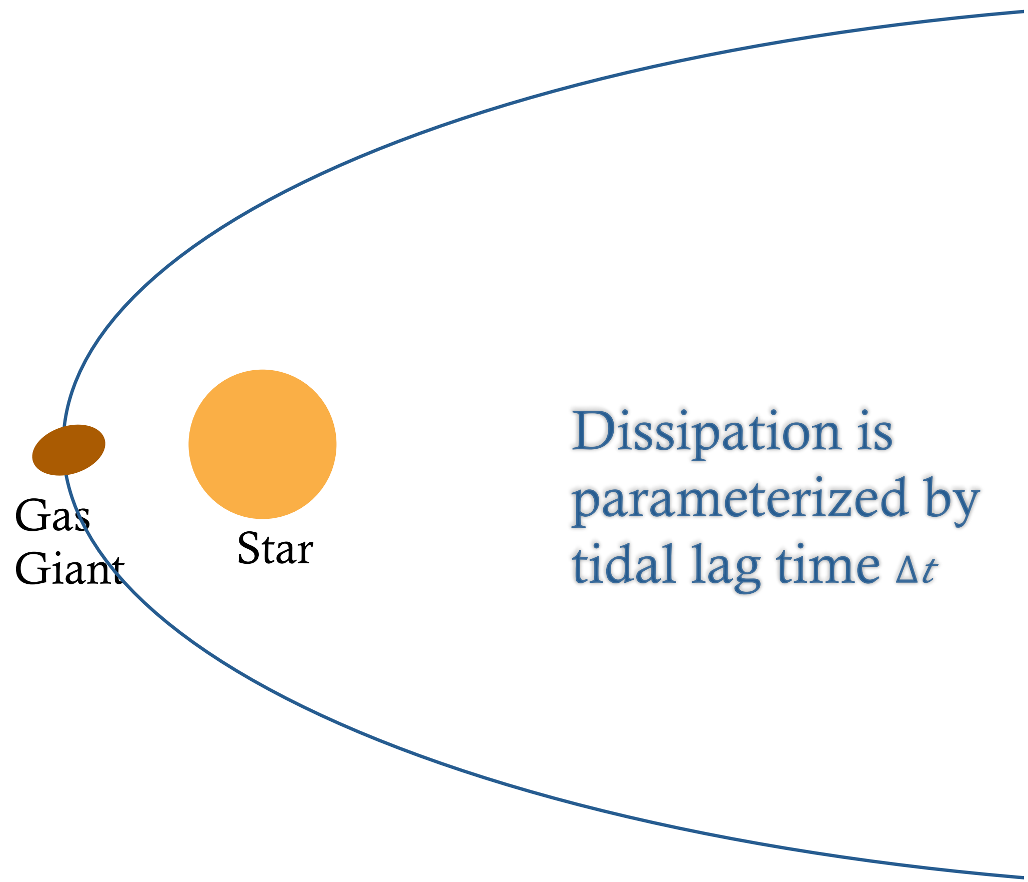
Tidal dissipation in giant planet

Previous works

-- Based on weak friction tidal model (parameterized); must assume that the planet is 10+ more dissipative than Jupiter for efficient migration

-- Hard to produce HJs with P>5d

-- HJ formation fraction is significantly reduced by tidal disruption



Dissipation is parameterized by tidal lag time Δt

Recent work: Dynamical (chaotic) tides in migrating giant planets

significantly resolves these issues and “improves” high-e migration theories

Vick & Lai 2018
Wu 2018
Vick, Lai & Anderson 2019

Michelle Vick (Cornell Ph.D. 2020)

Dynamical tides of planet on eccentric orbit

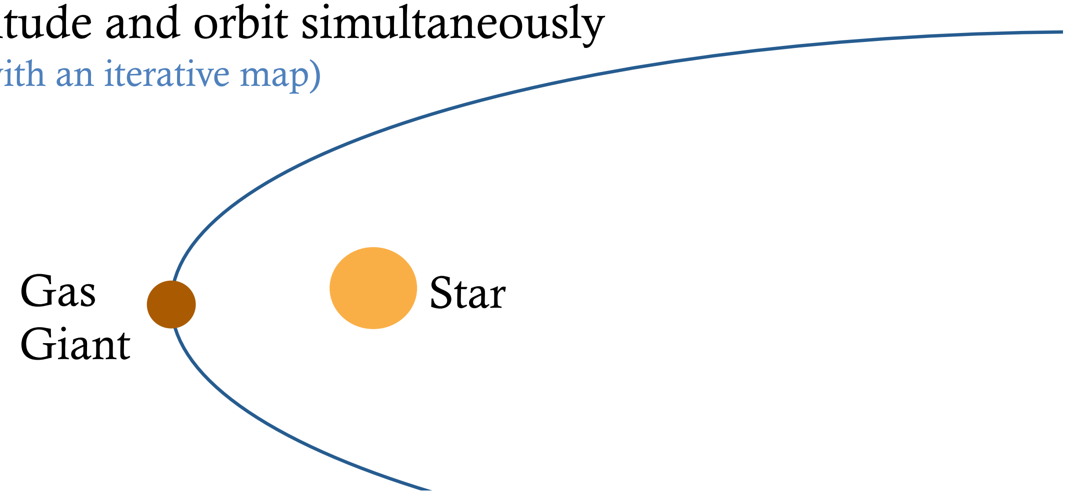
-- Near pericenter, the tidal potential of the star excites oscillation modes of the planet (f-modes, inertial modes, etc)

-- The energy transfer in each pericenter passage depends on the oscillation phase of the mode

Typical scale of energy transfer in each passage $\pm\Delta E_\alpha(r_{\rm peri})$

-- Need to evolve complex mode amplitude and orbit simultaneously

(for high-e system, evolution can be modeled with an iterative map)

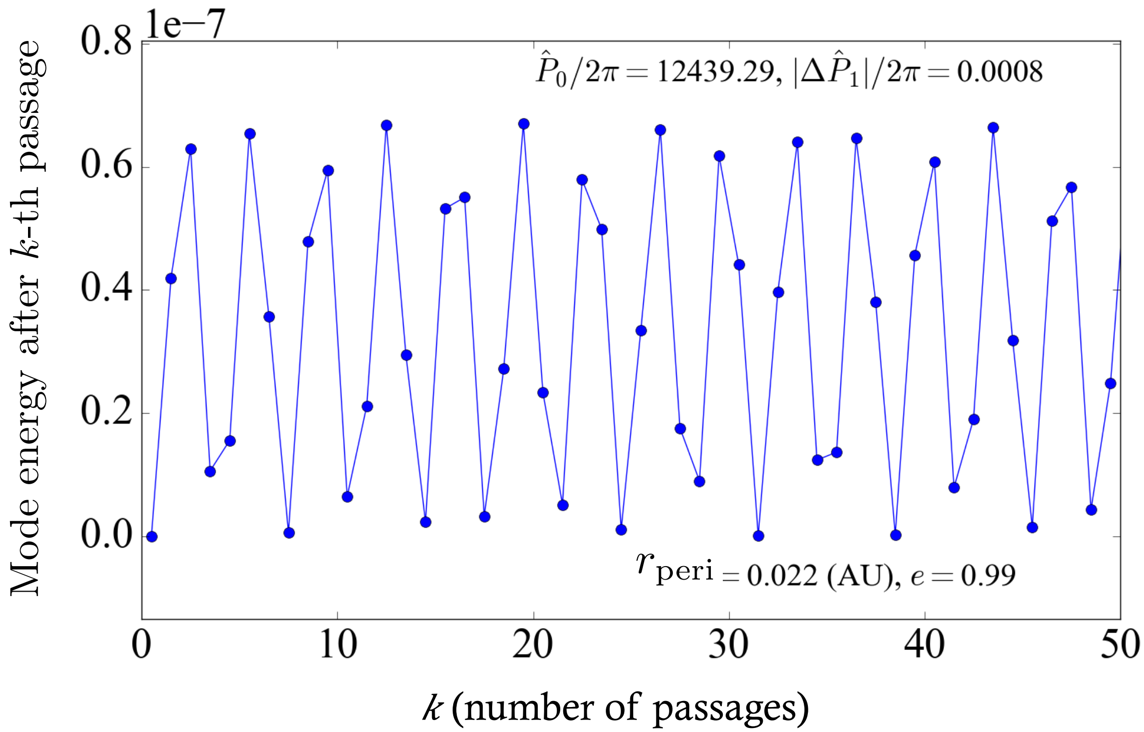


How does the mode energy evolve over many orbits?

Two different behaviors:

How does the mode energy evolve over many orbits?

Behavior 1: Low-amplitude oscillations

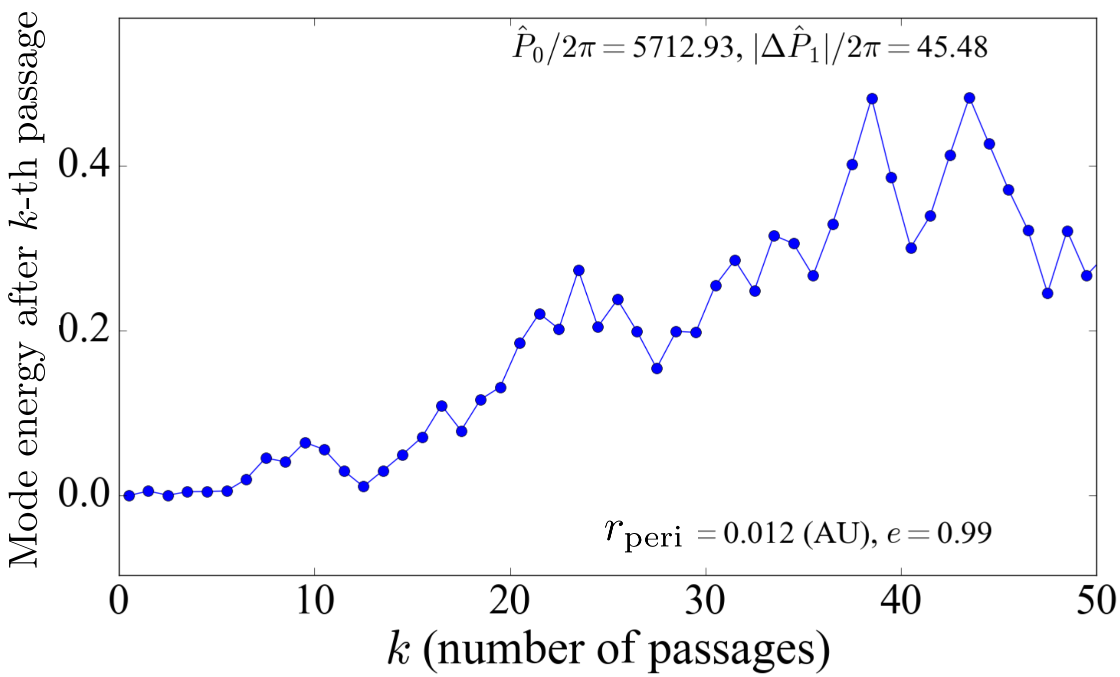


Occurs for relatively large $r_{\rm peri}$

Mode energy stays around small values

How does the mode energy evolve over many orbits?

Behavior 2: Chaotic mode growth (quasi-diffusive)

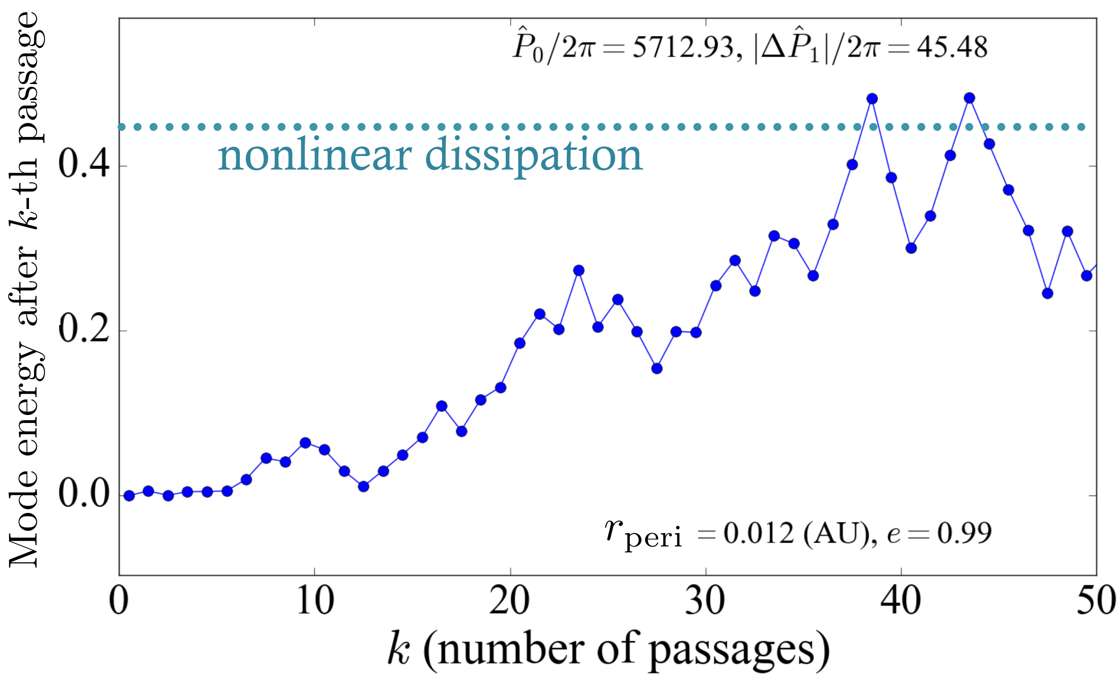


Occurs for sufficiently small $r_{\rm peri}$ and large e

Mode energy grows chaotically to large values – of order the initial orbital binding energy

How does the mode energy evolve over many orbits?

Behavior 2: Chaotic mode growth (quasi-diffusive)

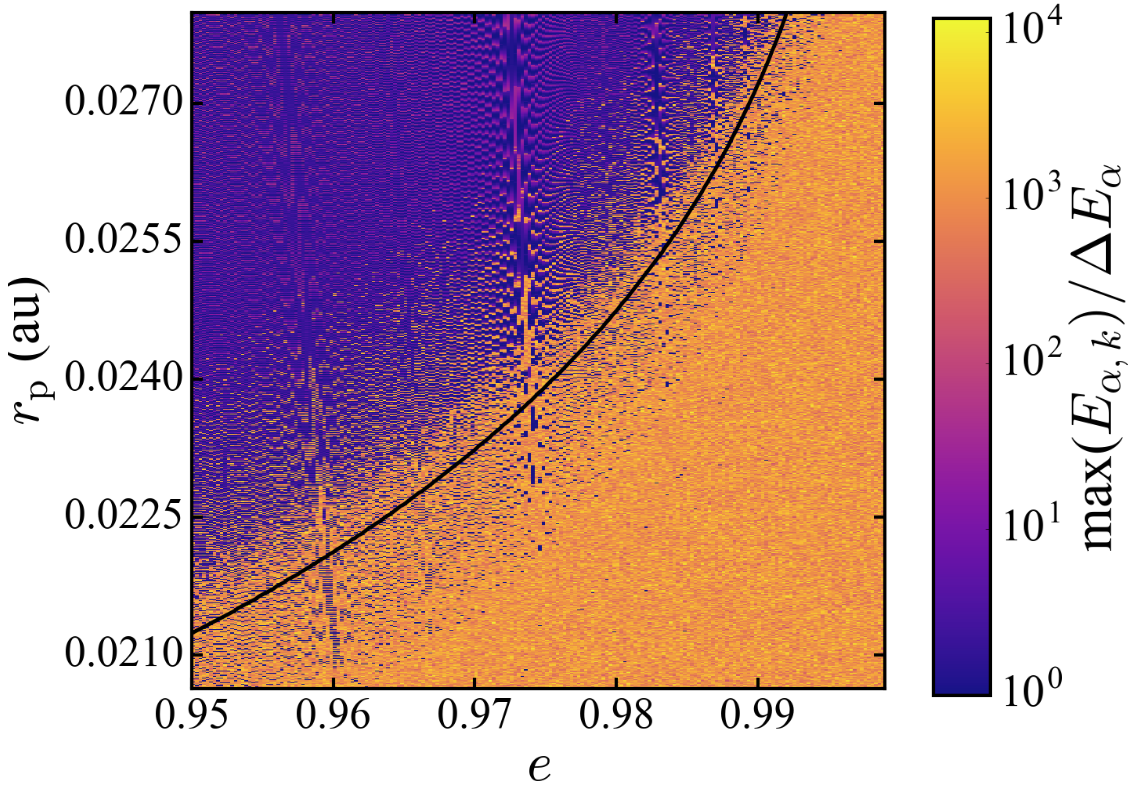


Occurs for sufficiently small $r_{\rm peri}$ and large e

Mode energy grows chaotically to large values – of order the initial orbital binding energy

When the mode energy reaches some fraction of the planet binding energy ➔ rapid nonlinear dissipation.

Maximum mode energy reached in 10,000 orbits (in units of the initial orbital energy)



Small r_p, large e
➔ Chaotic mode growth

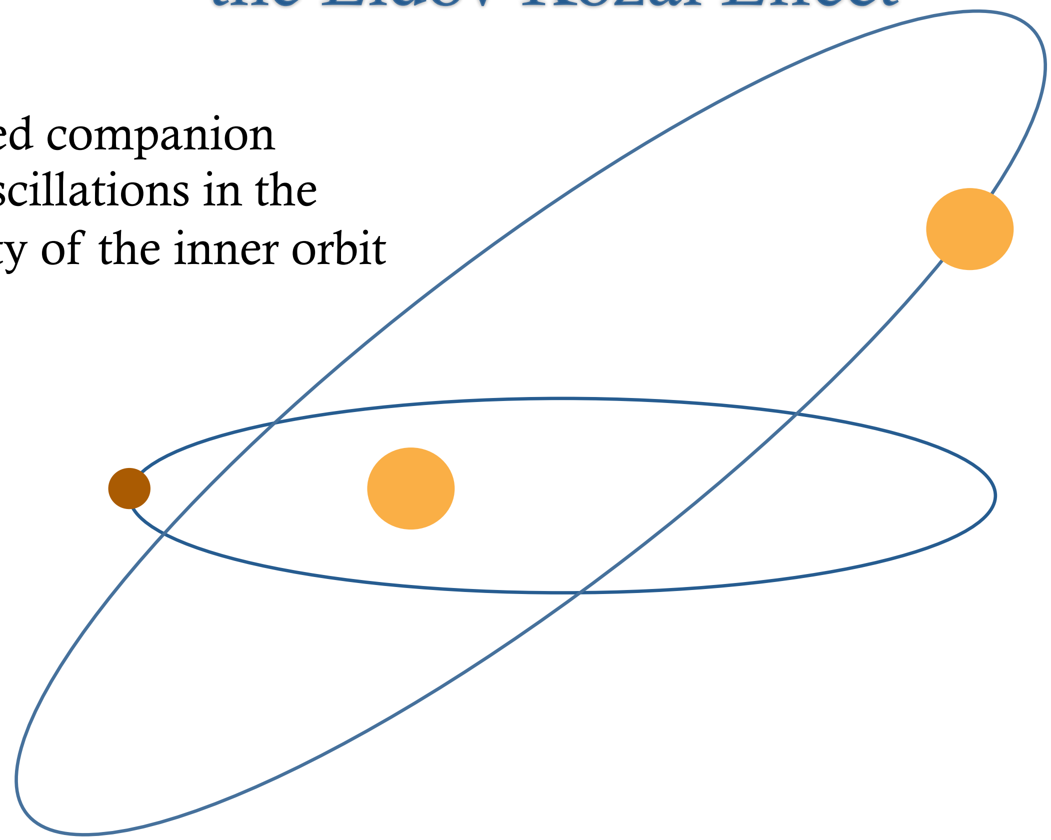
Regular → Chaotic transition:

$$\omega_\alpha \Delta P_{\rm orb} = \frac{3}{2}\omega_\alpha P_{\rm orb}\frac{\Delta E_\alpha}{|E_{\rm orb}|} \sim 1$$

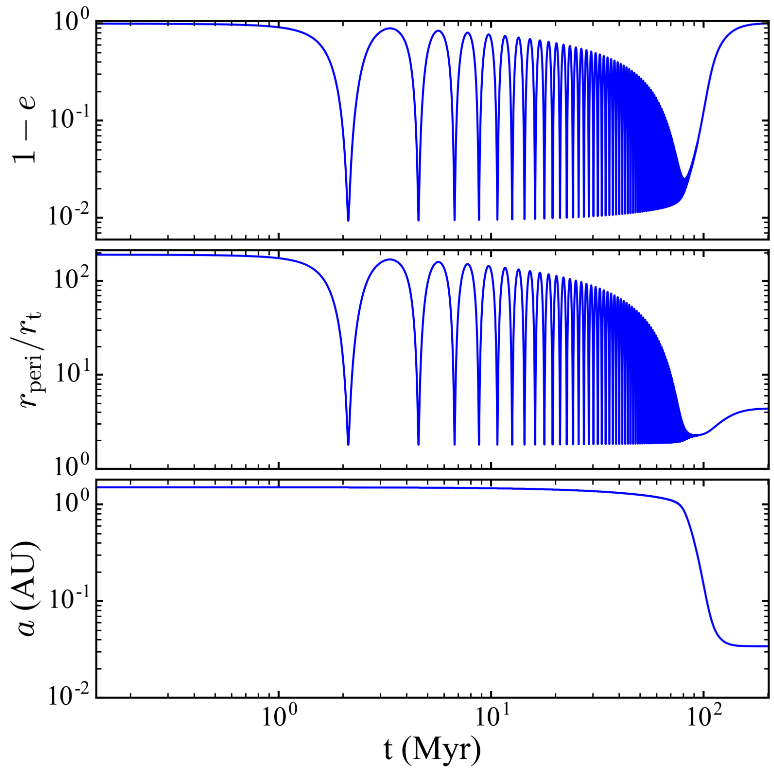
(phase shift due to energy transfer)

Example of High-eccentricity Migration: the Lidov-Kozai Effect

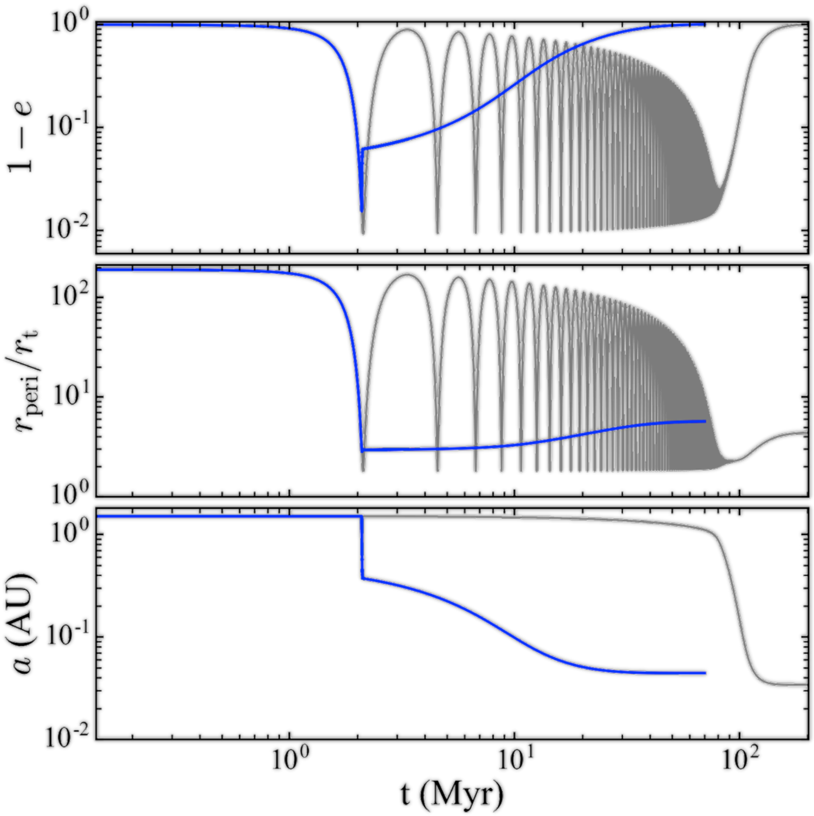
An inclined companion induces oscillations in the eccentricity of the inner orbit



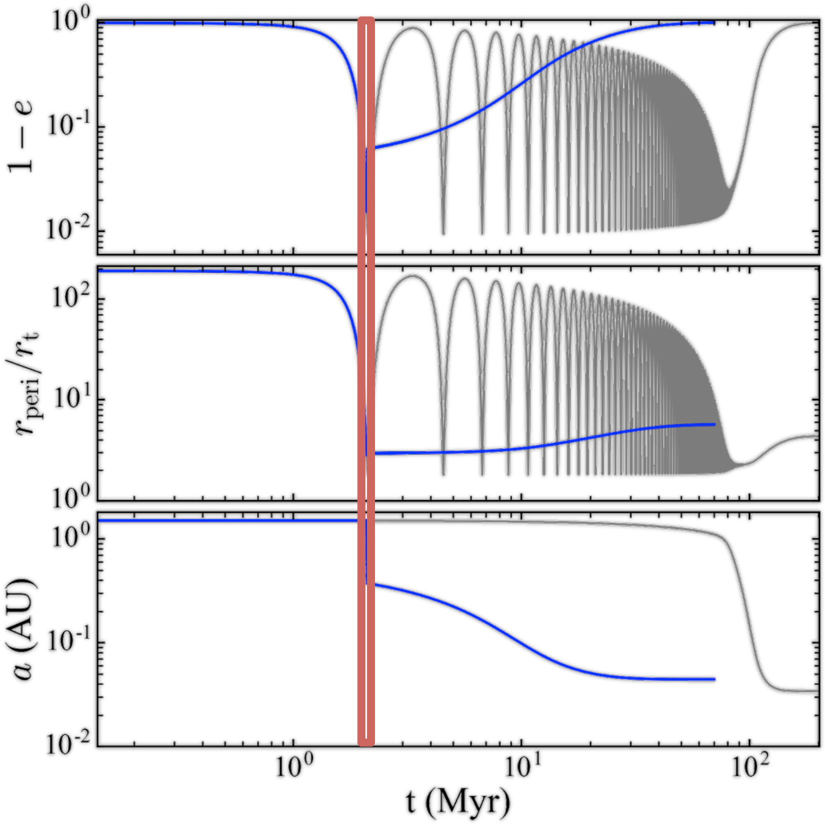
Lidov-Kozai Migration with Weak Tidal Friction

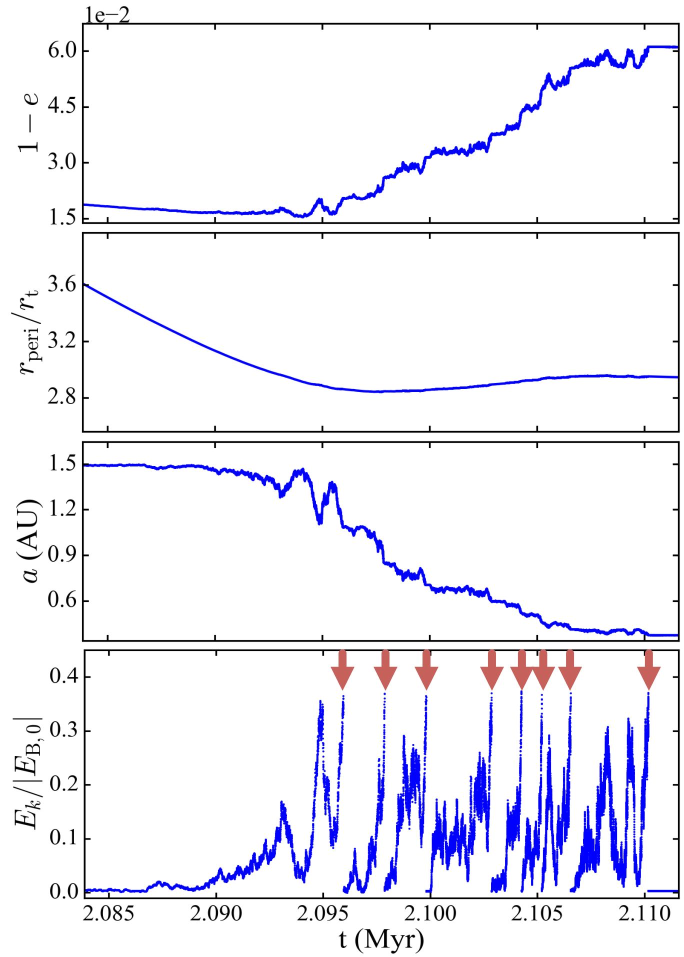


Lidov-Kozai Migration with Dynamical Tides

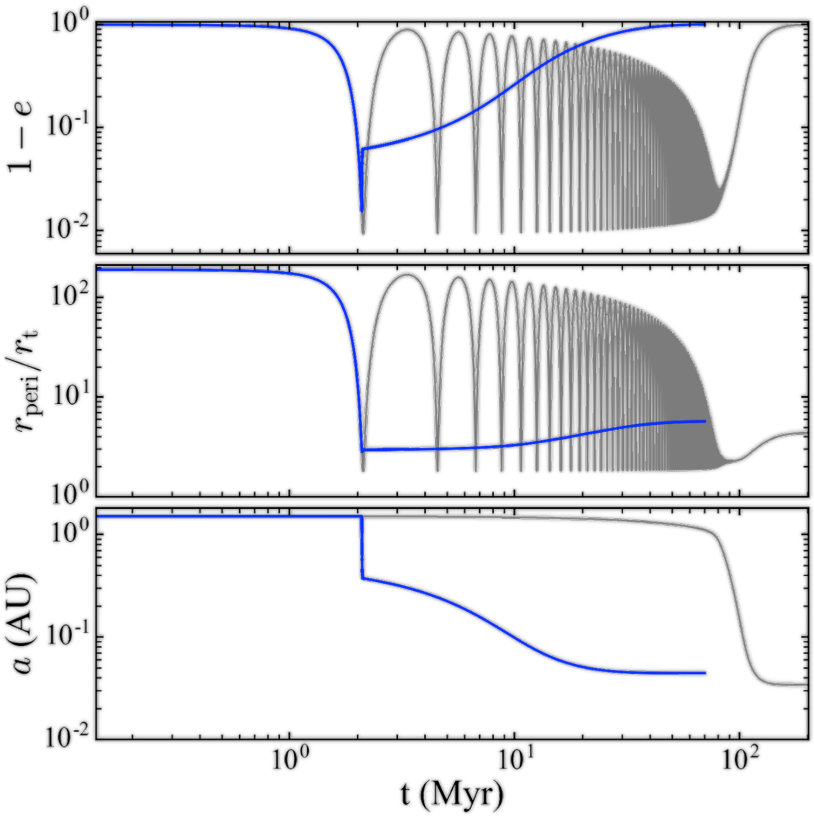


Lidov-Kozai Migration with Dynamical Tides





Lidov-Kozai Migration with Dynamical Tides



Migration occurs in two stages:

1.Chaotic dynamical tides rapidly shrink the orbit
➔ eccentric warm Jupiter (decoupled from the perturber).

2. Weak tidal friction efficiently circularizes the orbit
➔ hot Jupiter.

Lidov-Kozai Migration with Dynamical Tides

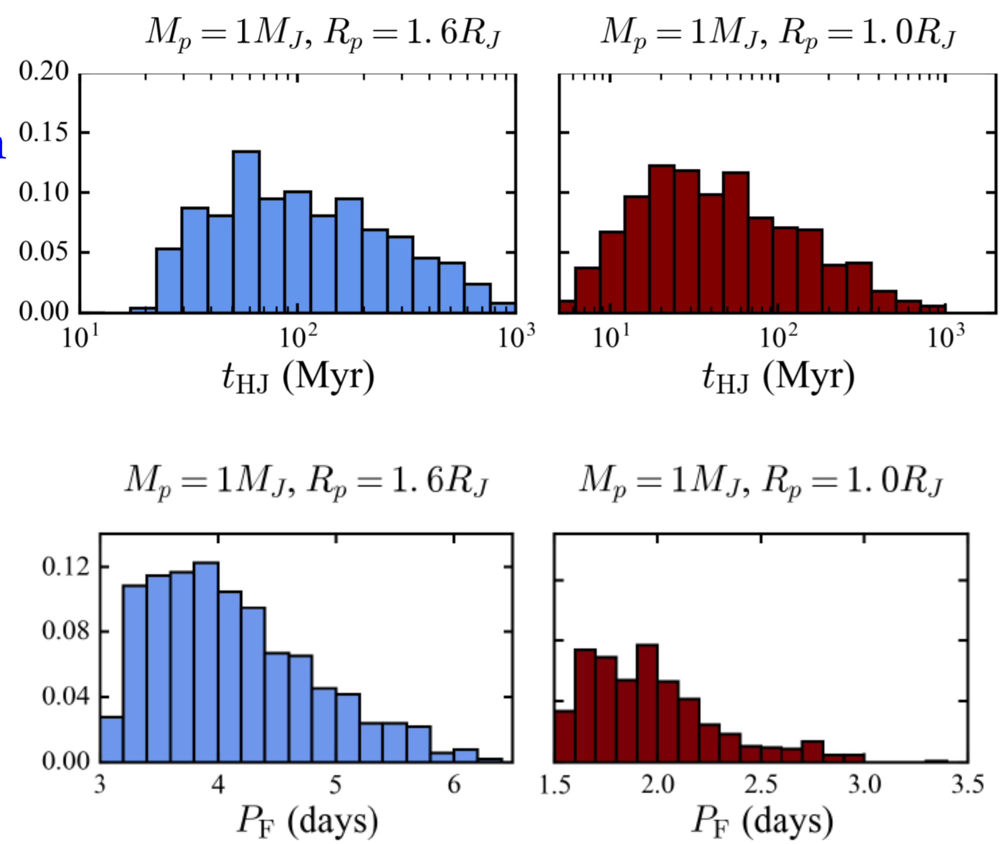
"Nice" Features of Dynamical (Chaotic) Tides :

1. Reduce migration time (by >10)

2. Save some planets from tidal disruption
   (strong dissipation truncates high-e excursion)

➔Higher HJ formation efficiency

3. Can produce HJs at ~5 days "easily"
   (strong dissipation, younger/bigger planets)

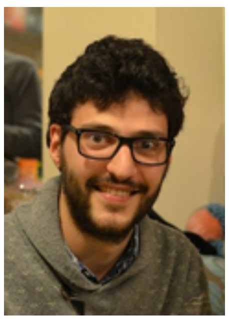


Another flavor of high-e migration: Secular Chaos

Secular interactions between three giant planets can chaotically push the inner planet to high e when
(1) Sufficient "Eccentricity reservoir" (Angular Momentum Deficit, AMD) is present in the system;
(2) Secular resonances exist and overlap

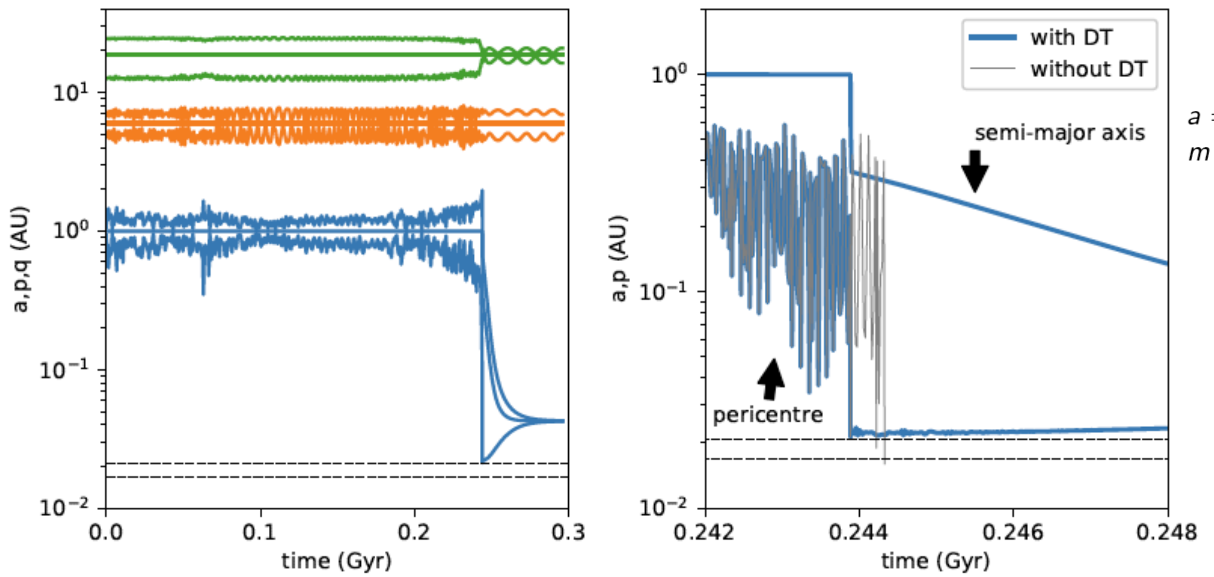
Suggested by Wu & Lithwick (2011) for HJ formation (see Laskar 2008)

Teyssandier, Lai & Vick (2019): First systematic study including proper physical ingredients: Tidal disruption, tidal dissipation (weak friction & dynamical tides), spin-orbit couplings



J. Teyssandier

High-e migration via secular chaos: An example



$a = (1, 6, 18.6)$ au, $e = (0.06, 0.18, 0.33)$, $i = (4, 16, 8)$, $m = (1, 1.9, 2.8) M_J$.

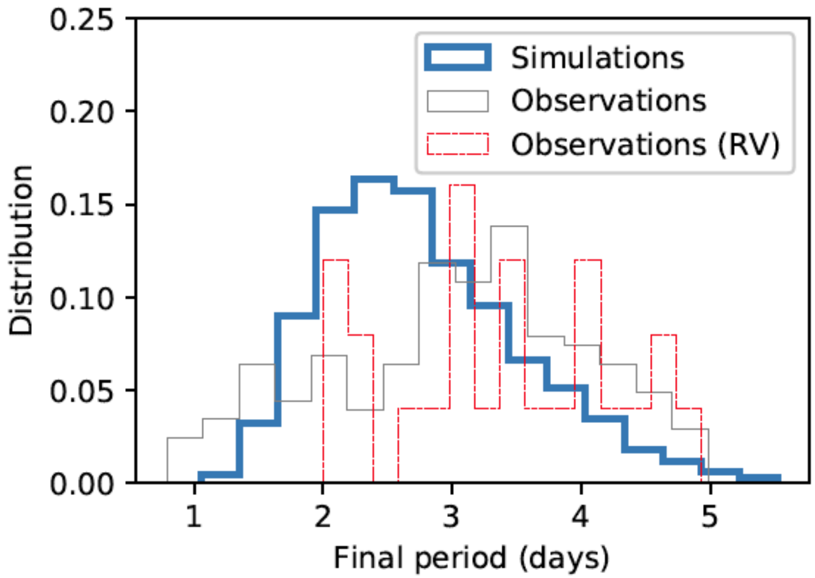
Key messages:

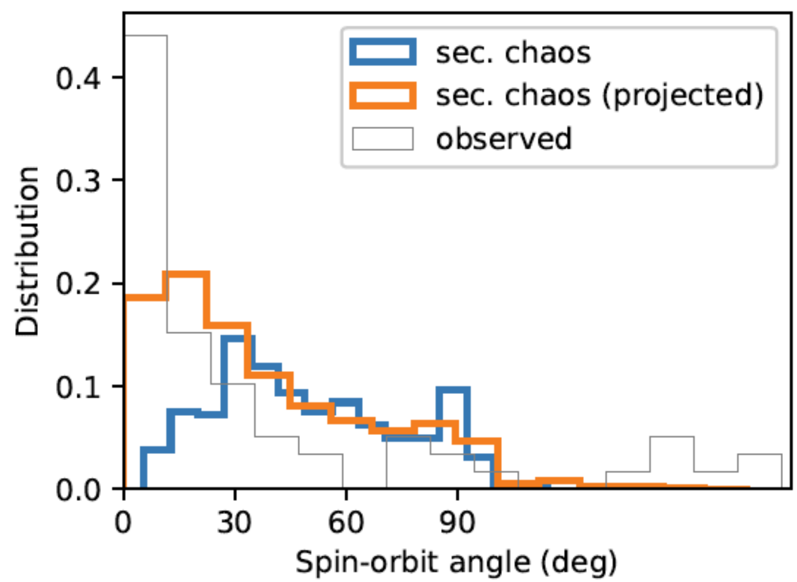
-- With only weak friction, (almost) all planets that migrate inward are tidally disrupted.

--- Dynamical tides help !

High-e migration via secular chaos & dynamical tides

Even with dynamical tides…





Hard to produce P>5d planets

Cannot produce retrograde planets

Summary on HJ Formation

Disk migration contributes some fraction?

young HJs, WASP-47b

High-e migration is alive and well

-- Sudden e-excitation is not favored: Planets are tidally disrupted

e.g. strong scatterings, octupole (eccentric) Kozai, secular chaos

Gentle/slow e-excitation (e.g., simple Lidov-Kozai) works better

-- Dynamical tides (chaotic behavior) on giant planets (physics-based theory) resolve many problems of high-e migration

Increase the HJ formation efficiency

Save some planets from tidal disruption

Produce planets with longer P (peak at 3-5 days)

-- Unsolved issues: What happens to the planet with tidal heating?

Ultra-Short-Period Planets (USPs)

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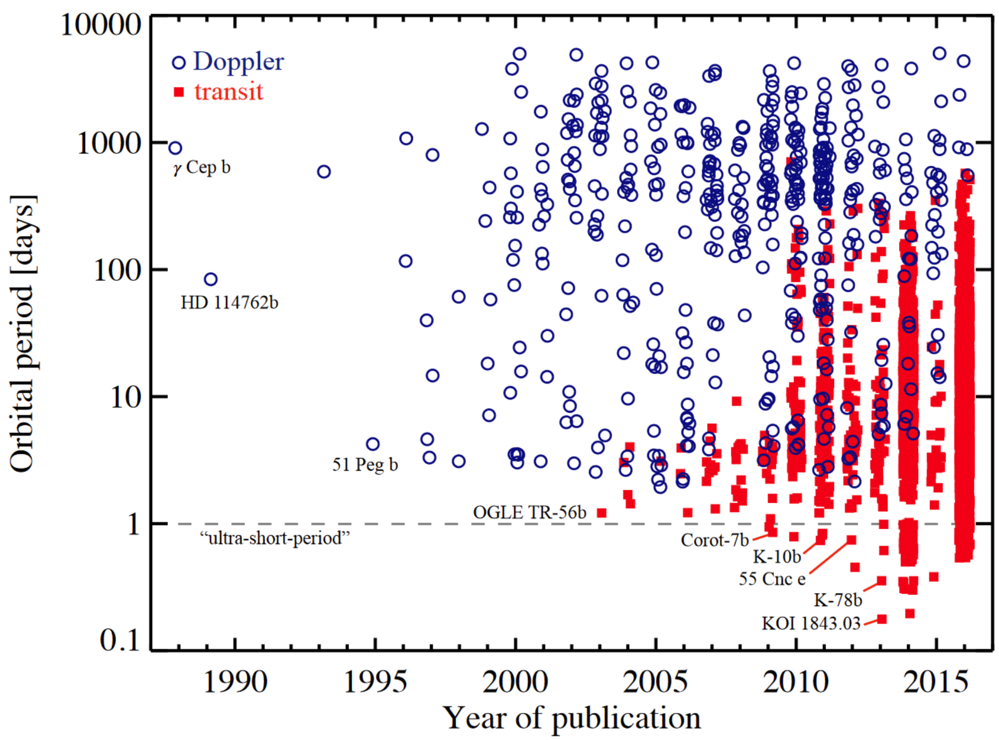


Winn et al 2019 (review)

Small planets ($R<2R_E$) with $P<1$ day

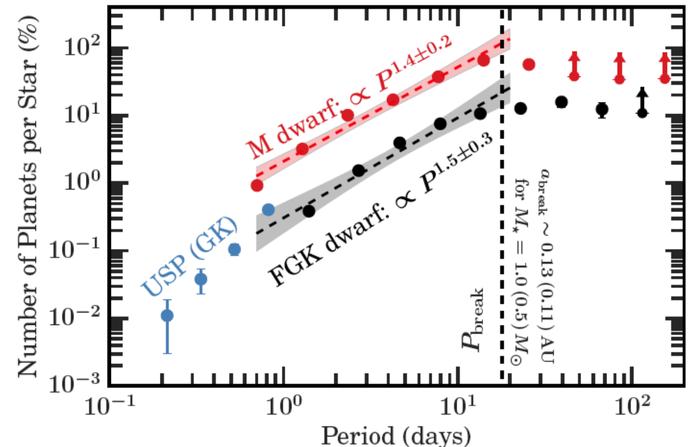
~70 so far found by transits

~0.5% of Sun-like stars have USPs

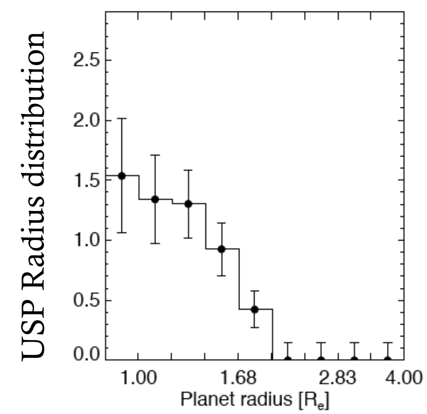
USPs are likely a distinct population

-- Period distribution differs from “normal” short-period super-Earths

-- Different size distribution ($R<2R_E$; no Fulton valley)



Lee & Chiang 2017



Winn+2019

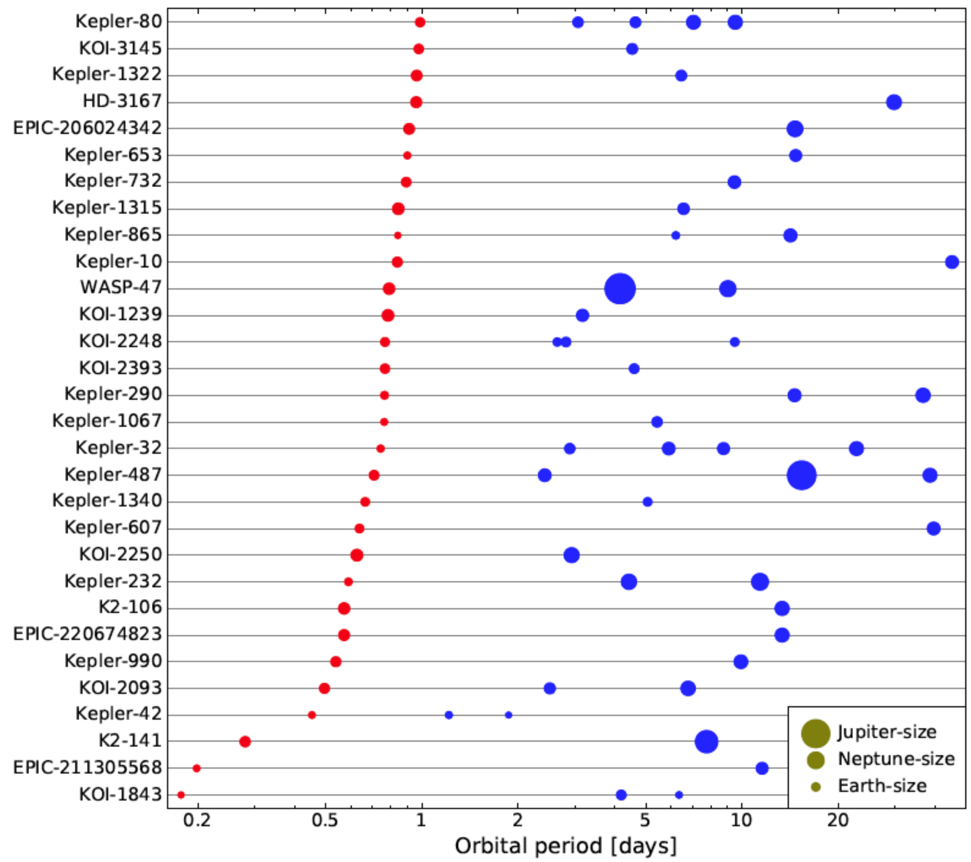
USPs are likely a distinct population

-- Period distribution differs from "normal" short-period super-Earths

-- Different size distribution ($R<2R_E$; no Fulton valley)

-- Systems with USPs have larger mutual inclinations ($\sim 7^0$ vs 2^0 for normal Kepler multis; Dai+2018)

-- Fewer co-transiting companions;
Companion of USP has $P_2/P_1 > 15$ (vs ~1.3-4)



Winn+2019

USP Formation Mechanisms

- In-Situ formation: unlikely
  T~2000K at P=1d

- **Migration**

-- Disk migration
Could play a role, but P<1d is well inside magnetospheric truncation of PPD (Lee & Chiang 17)

-- Tidal dissipation in host star (Lee & Chiang 2017)
Could play a role, but require P<1d to migrate within 10 Gyr;
inconsistent with HJs with P<1 day

-- Tidal dissipation in planet
Require a way to excite/maintain the planet's eccentricity

➔ Low-eccentricity migration (Pu & Lai 2019)

Alternative: high-e migration via secular chaos (Petrovich+18)

Low-e migration/formation of USPs

Pu & Lai (2019)

Bonan (Michael) Pu

Start with

-- Kepler multi's with at least 3 planets, with inner P_1= a few days

-- Innermost one (m_1) has low mass (a few Earth), outer ones somewhat more massive

-- Initial e_i ~ 0.05-0.1, mutual inclination ~ a few degrees

What happens?

-- Eccentricity vectors of planets "communicate" with each other through gravity
each planet undergoes apsidal precession and "shares" eccentricities
"sharing" can be strong due to apsidal precession resonances

-- Tidal dissipation on inner planet damps its eccentricity,
balanced by "receiving" eccentricity from the outer planets

-- With non-zero eccentricity maintained, the inner planet undergoes tidal decay in orbit ➔ USP

Equations

Complex eccentricity of each planet $\mathcal{E}_i \equiv e_i \exp(i\varpi_i)$

Eccentricity N-planet system $\vec{\mathcal{E}} = \begin{pmatrix} \mathcal{E}_1 \\ \mathcal{E}_2 \\ \vdots \end{pmatrix}$

Evolution of eccentricities: $\frac{d}{dt}\vec{\mathcal{E}}(t) = i\mathbf{H}(t)\vec{\mathcal{E}}(t),$

$$H(t) = \begin{pmatrix} \tilde{\omega}_1 & -\nu_{12} & \cdots & -\nu_{1N} \\ -\nu_{21} & \tilde{\omega}_2 & \cdots & -\nu_{2N} \\ \vdots & \vdots & \ddots & \vdots \\ -\nu_{N1} & -\nu_{N2} & \cdots & \tilde{\omega}_N \end{pmatrix}$$

$$\tilde{\omega}_i \equiv \omega_i + i\gamma_i = \sum_{j\neq i} \omega_{ij} + \omega_{i,\mathrm{gr}} + \omega_{i,\mathrm{tide}} + i\gamma_i$$ (apsidal precession and tidal e-damping)

ν_{ij} (eccentricity sharing between planets)

Orbital decay: $\dot{a}_1 = -2\gamma_1 |\mathcal{E}_1|^2 a_1 - \gamma_\star a_1$

Planetary tide:

$$\left(\frac{\dot{a}_1}{a_1}\right)_{\mathrm{tide}} = -2\gamma_1 e_1^2 = -1.9\times 10^{-9} k_{2,1} \left(\frac{\Delta t_{L,1}}{100\mathrm{s}}\right)\left(\frac{e_1}{0.02}\right)^2 \times \left(\frac{M_\star}{M_\odot}\right)^2 \left(\frac{m_1}{M_\oplus}\right)^{-1} \left(\frac{R_1}{R_\oplus}\right)^5 \left(\frac{a_1}{0.02\ \mathrm{au}}\right)^{-8} \mathrm{yr}^{-1}$$

Stellar tide:

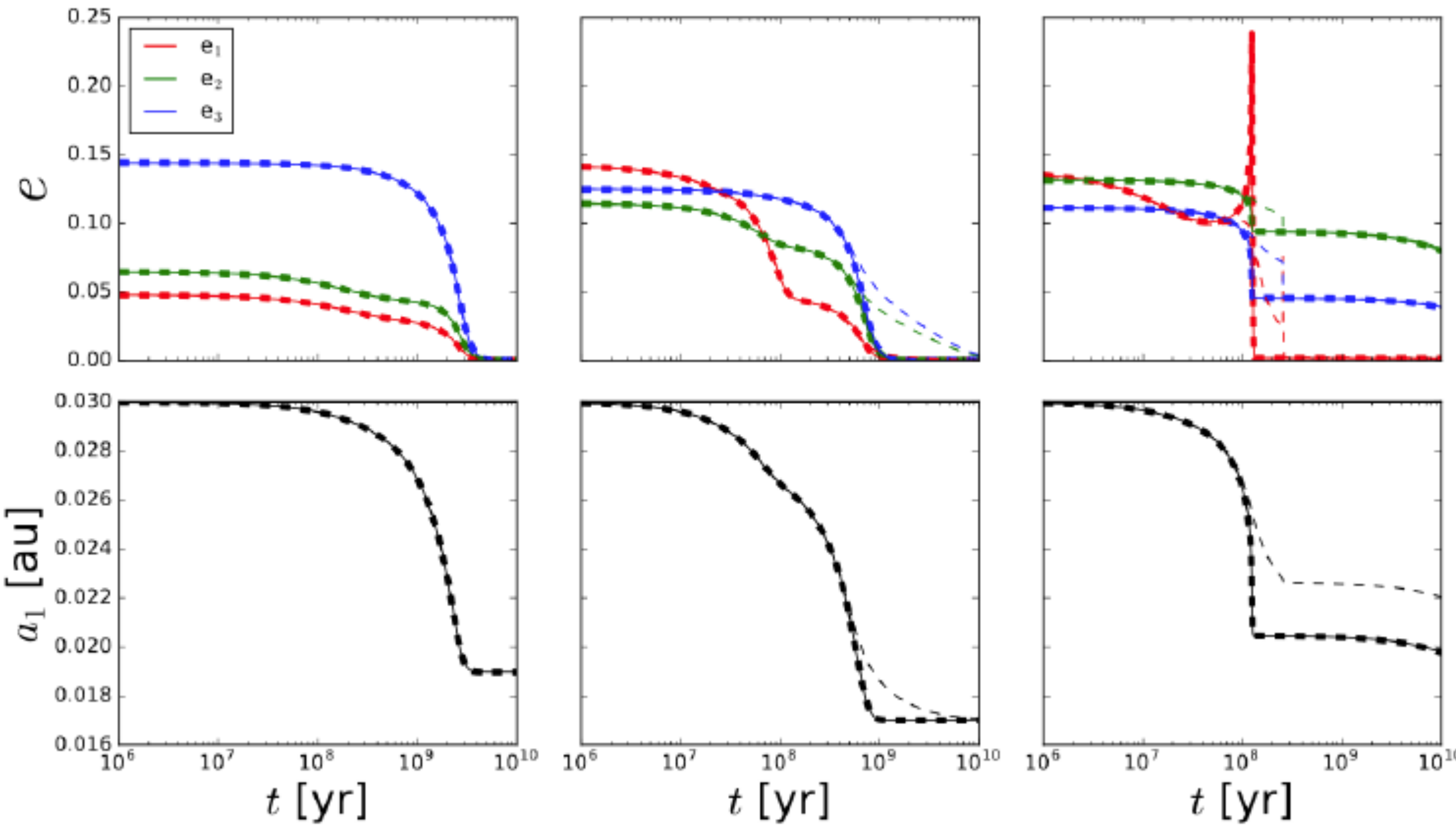
$$\left(\frac{\dot{a}_1}{a_1}\right)_{\mathrm{tide}\star} \equiv -\gamma_\star = -\frac{9}{2}\left(\frac{m_1}{M_\star}\right)\left(\frac{R_\star}{a_1}\right)^5 \frac{n_1}{Q'_\star} = -1.85\times 10^{-9} \left(\frac{M_\star}{M_\odot}\right)^{-1/2} \left(\frac{R_\star}{R_\odot}\right)^5 \left(\frac{Q'_\star}{10^6}\right)^{-1} \times \left(\frac{m_1}{M_\oplus}\right)\left(\frac{a_1}{0.01\ \mathrm{au}}\right)^{-13/2} \mathrm{yr}^{-1},$$

Technical challenges of solving equations:

Orbital decay occurs over ~10 Gyrs, but apsidal precession can be as short as ~10 years
➔ Direct integration requires ~10^9 cycles

Trick:
Eccentricity eigenmodes, proper phase averaging (need to capture apsidal resonances)

Three sample evolutions:



m = [1, 7, 15] M_{earth}

Initial a = [0.03, a_2, 0.15] au

Initial e = [0, 0, 0.15]

From left to right: a_2 = [0.05, 0.07, 0.1] au.

Criteria for USP formation

(Why need N>2 planets?)

1. The system must have adequate Angular Momentum Deficit (AMD)

$$\mathrm{AMD}_i = m_i\sqrt{GM_\star a_i}\left(1-\sqrt{1-e_i^2}\right)$$

"eccentricity reservoir"

Require eccentric, massive companion(s) at large distances to supply enough AMD; otherwise all planets maybe circularized before the inner planet decays to short period

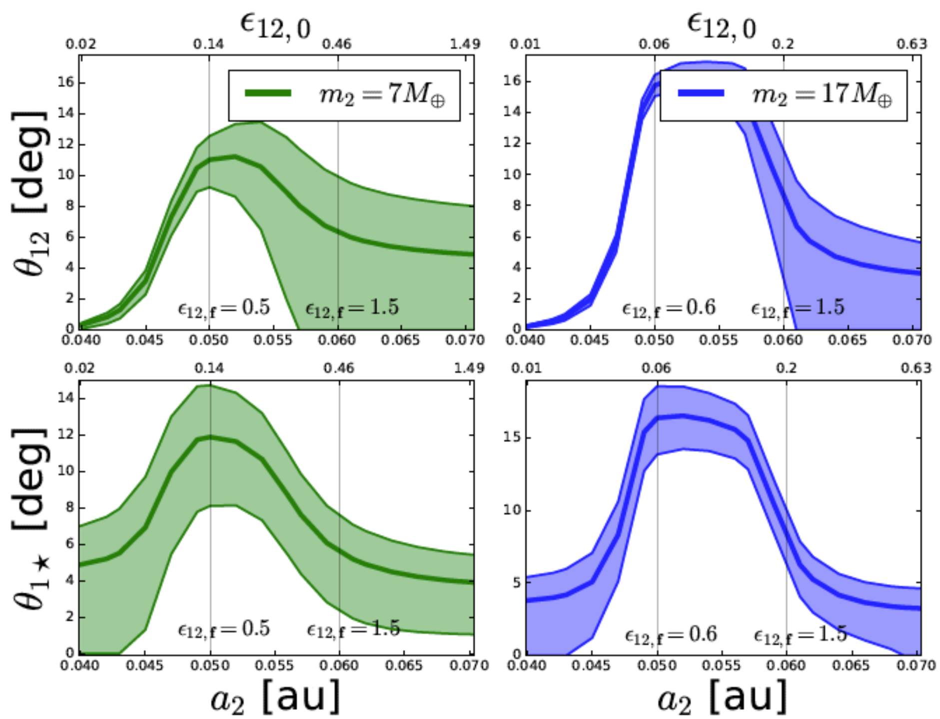
2. The forced ("shared") eccentricity e_1 must be > a few % in order to have appreciable orbital decay within 10 Gyrs

Require eccentric, massive companions at small distances

Bonus: Excitation of mutual inclination

During low-e migration, the mutual inclination of planets is excited

Inclination resonance roughly coincide with eccentricity/apsidal resonance

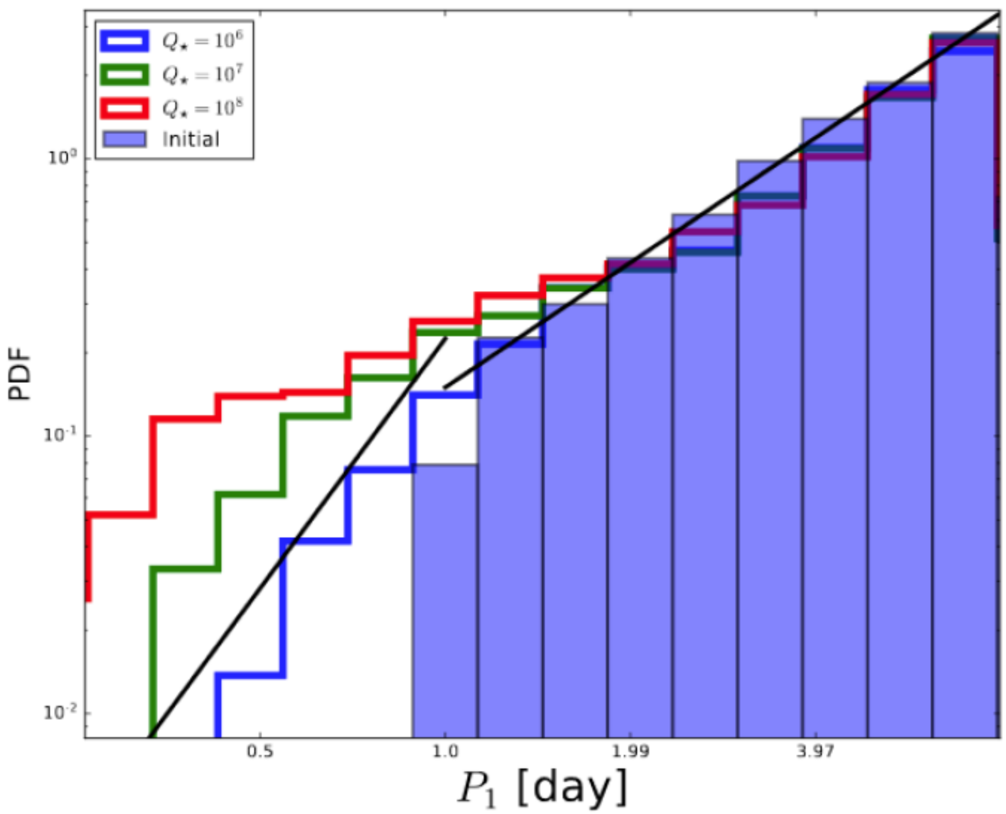


Simple Population Model

Generate one million 3-planet proto-USP systems

- m_1 ~ log-uniform in [1, 3] M_{Earth}
- m_2, m_3 ~ log-uniform in [3, 20] M_{earth}
- Initial P_1 ~ power-law distribution $dN/d \ln P = P^{1.5}$ on [0.5, 8] days
- P_2/P_1 and P_3/P_2 ~ log-uniform on [2, 4]
- Q_* chosen randomly from [10^6, 10^7, 10^8]
- Q_1 chosen randomly from [1/70, 1/200, 1/700]
- Evolve for 10 billion years
- Star has initial spin-period 5 days and spin downs to 35 days

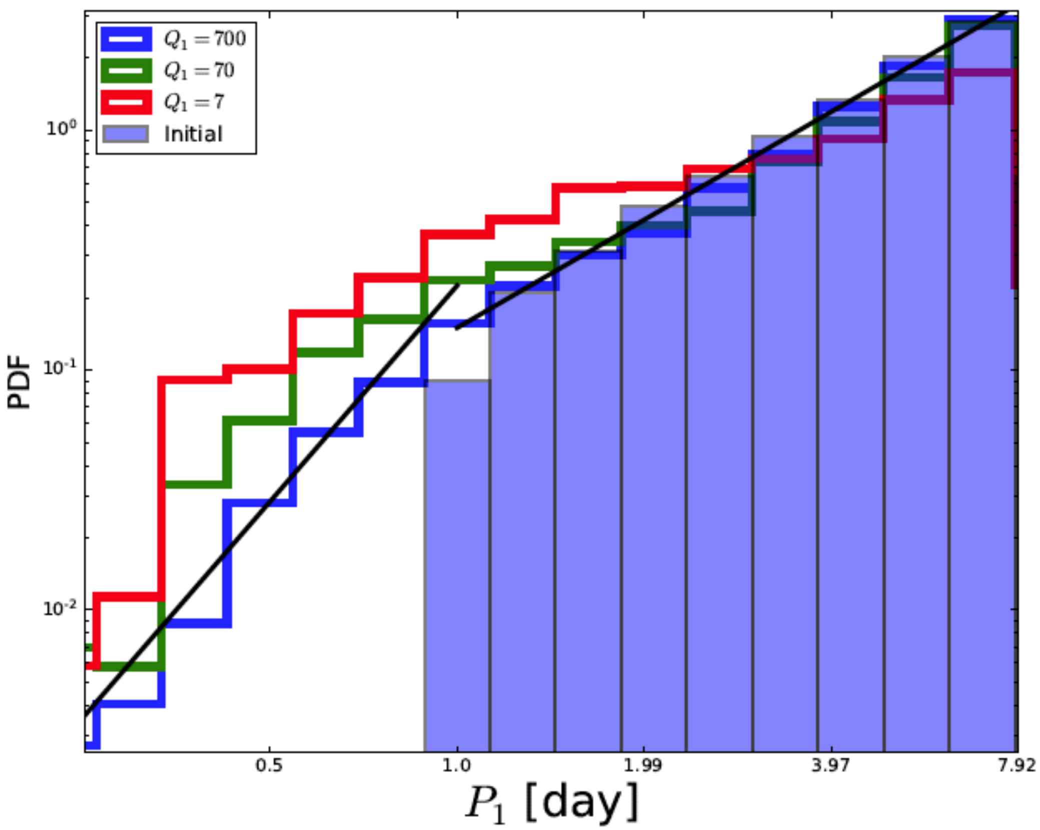
Simulated final period distribution



Planet $\Delta t_{\rm L} = 100$ s ($Q = 70$ at P=1 day)

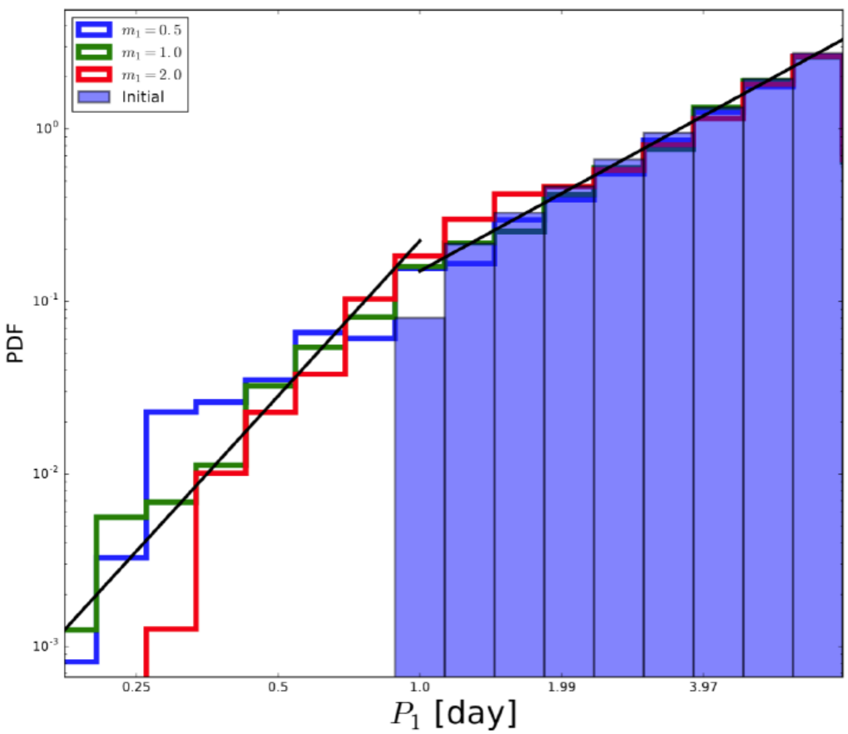
- Black lines: Power-law distribution suggested by Lee & Chiang (2017)
- Solid blue bins: Initial P_1
- **Red, green, blue: Final P_1 for different values of Q_***

Dependence on Q_1

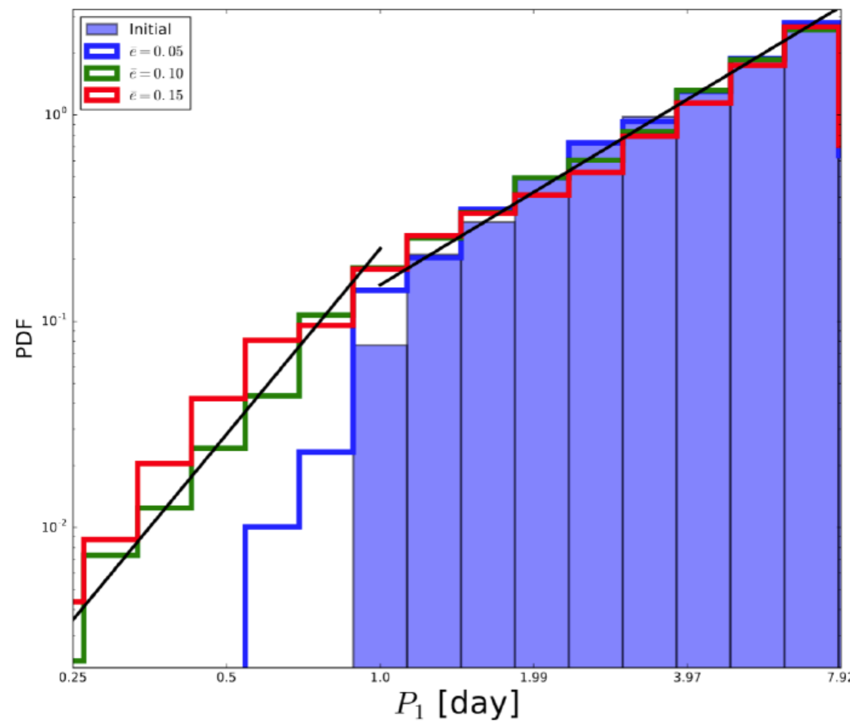


$Q'_\star = 10^7$

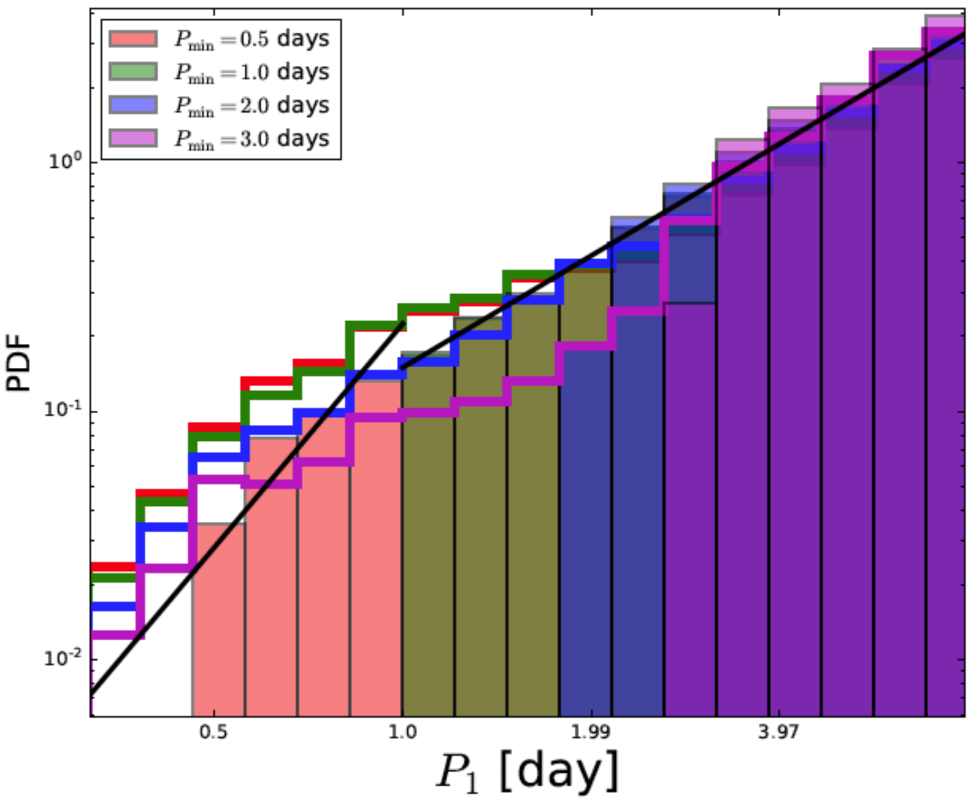
Dependence on m_1



Dependence on initial $e_{2,3}$

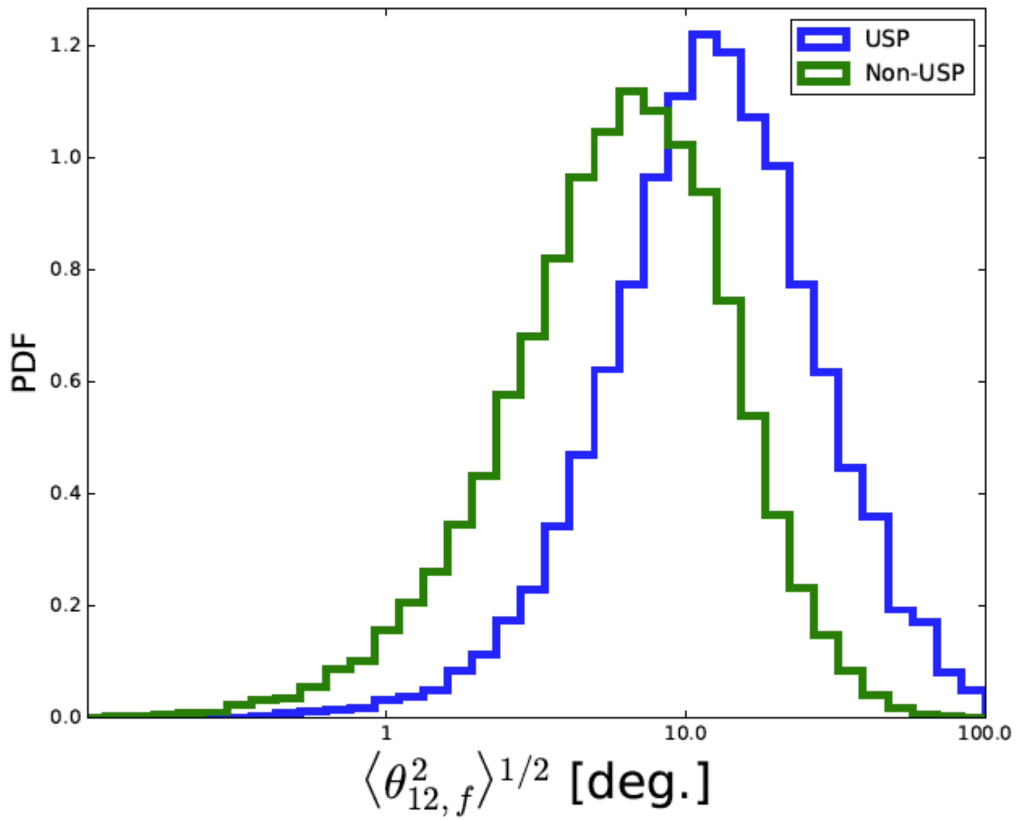


Dependence on initial P_{min}

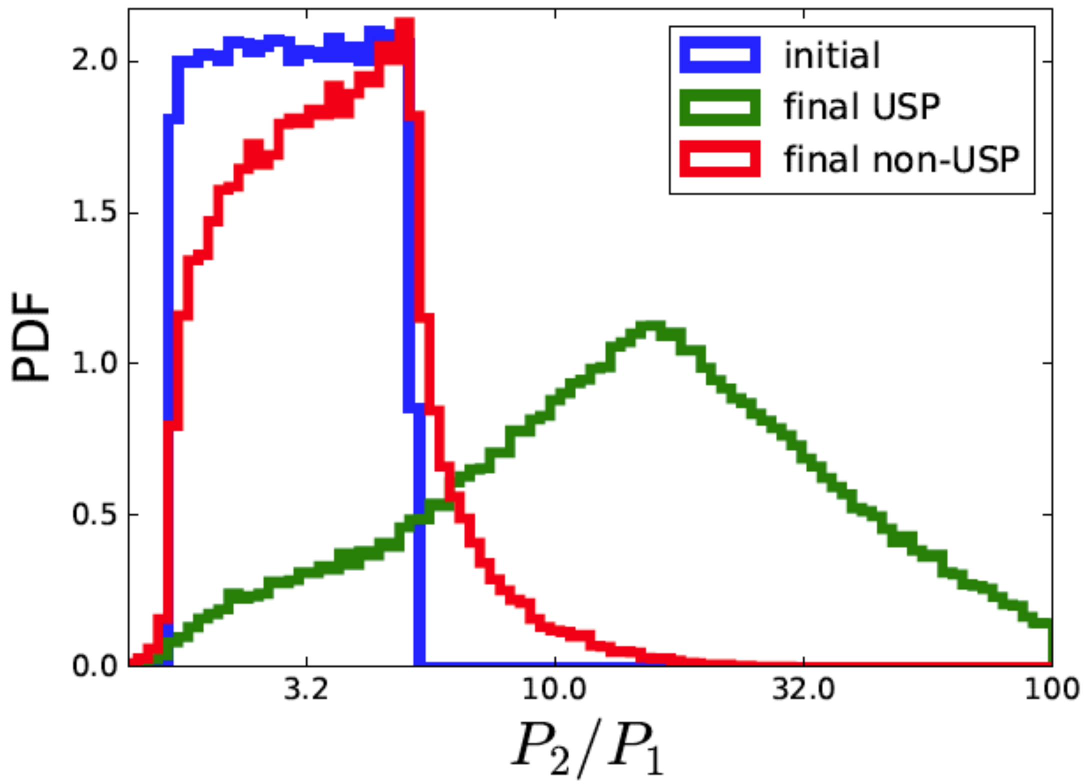


Our model is agnostic about any planets at P < 1d -- they all decayed away

Our model produces large mutual inclinations for USP systems



Our model produces large period ratios for USP systems



Summary on USPs

Low-e tidal migration can robustly make USPs out of normal Kepler multis

Requires small inner planet at 1 < P < 3 days, with 2 or more external super-Earth or mini-Neptune companions that are mildly eccentric (>0.05-0.1); they can have wide range of masses and periods

Key physics

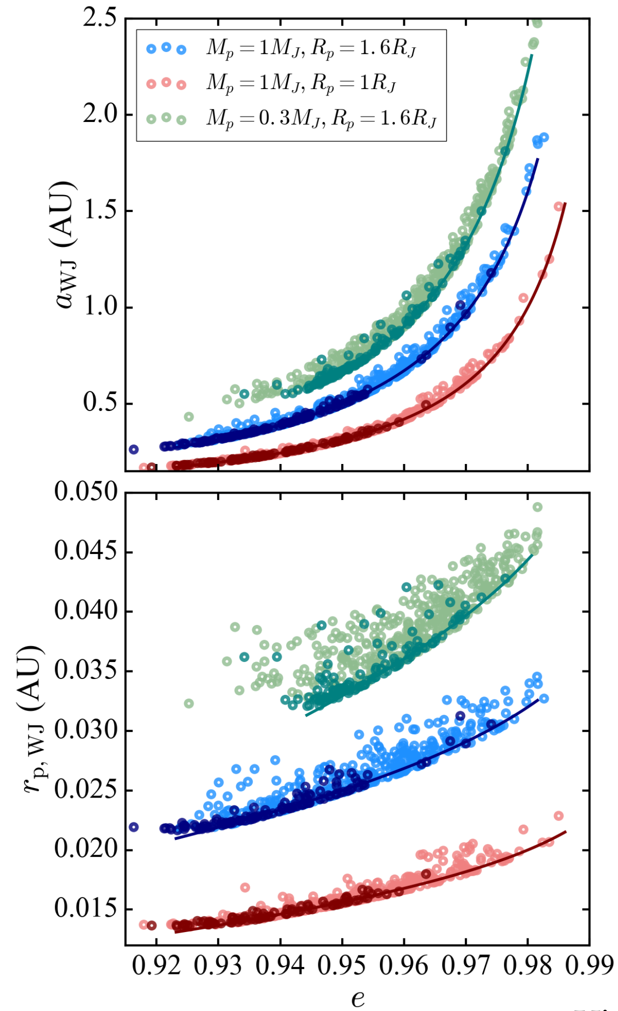
-- "Sharing" of eccentricities between different planets by gravitational interactions
-- Apsidal resonance enhances the sharing
-- Orbital decay due to planetary tide (and stellar tides at P < 1d)
-- Excitation of mutual inclinations

Adding more planets make it easier --- More AMD and more resonances

The final distribution of USPs produced agrees with observations under wide conditions

e.g., $Q'_\star = 10^7$, and is robust against factor of a few changes in Q_1, m_1 etc.

Eccentric Warm Jupiter Properties



Vick et al. (2019)

Hot Jupiter Properties

Vick et al. (2019)