Dynamical Evolution of Compact Multi-Planet Systems:

Effects of External Giant Planets

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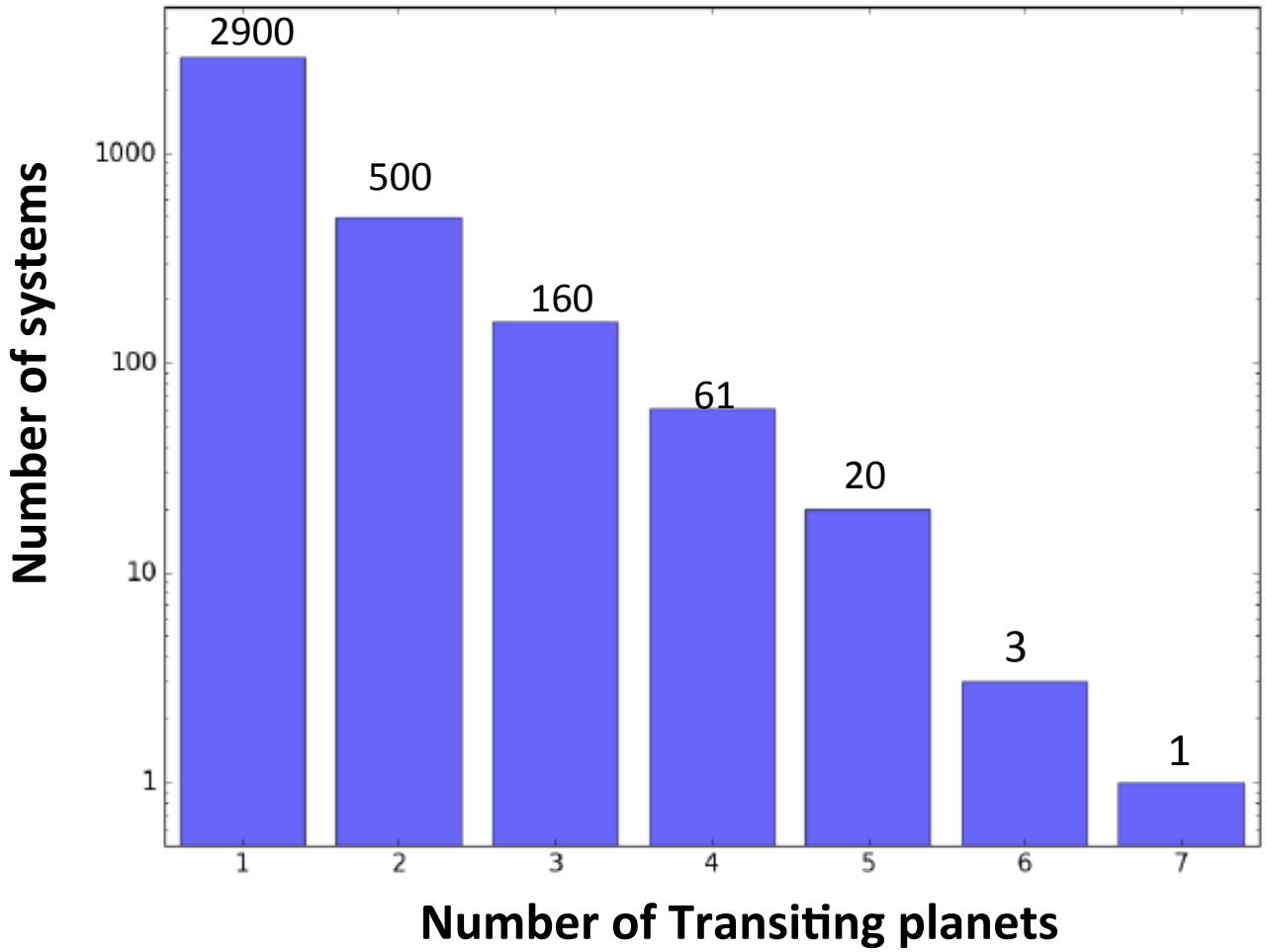
Kepler: 4700 planets in 3600 systems

(mostly super-earths or sub-neptunes, <200 days)

Observed Transit Multiplicity Distribution F (N_{tran})



An Emerging Trend:

Systems with smaller number of planets are dynamically hotter: higher eccentricities and mutual inclinations (Xie+16; Zhu+18)

Related Trends:

--- Excess of Kepler Singles – Kepler dichotomy (?)

Models with single mutual inclination dispersion fall short to explain the observed number of Kepler singles (Lissauer+11; Johansen+12; Ballard & Johnson 16)

-- **Kepler Singles have higher stellar obliquities** (Morton & Winn 14)

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Super-Earths and Cold Jupiter Connection

30-50% of inner super-Earths (P<200 d) have CJ companions (P>400 d);
These CJs are often eccentric, having undergone scatterings
(observations from many groups… see Lai & Pu 2017; Zhu & Wu 2018 for refs)

How Cold Jupiters (and scatterings) affect Inner planet system (& stellar obliquity)?

With Bonan (Michael) Pu
Kassandra Anderson

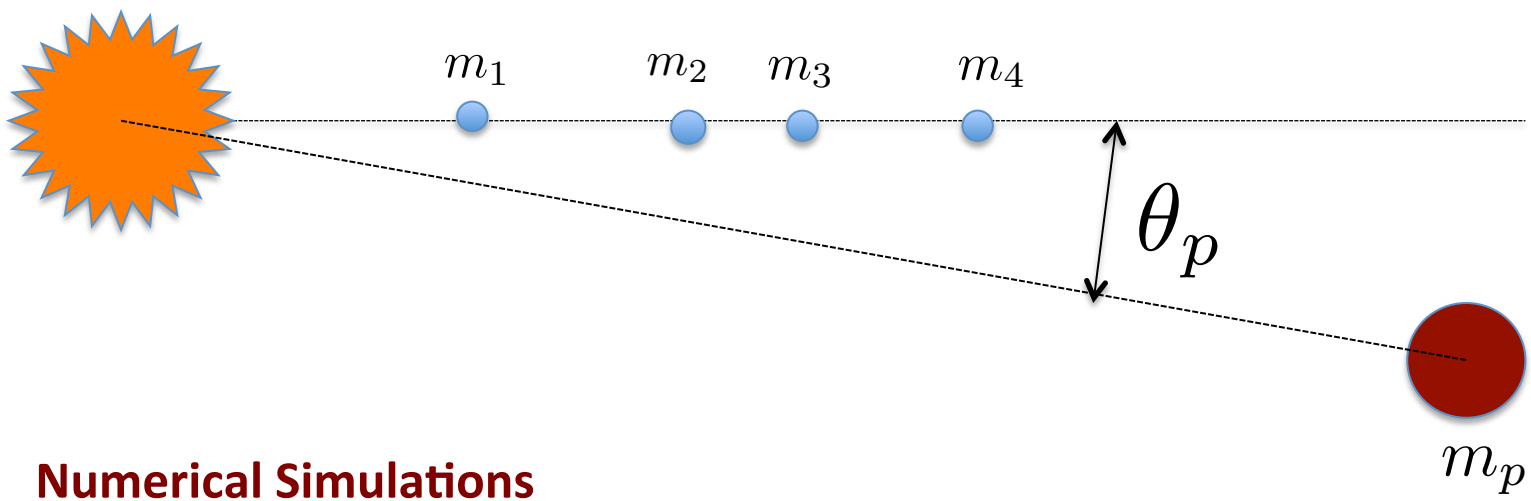
References:

Lai & Pu 2017 “Hiding Planets behind a Big Friends…”
Pu & Lai 2018 “Eccentricities and Inclinations of multiplanet systems....”
Pu & Lai 2018 “Scatterings of Cold Jupiters and its Influence on Inner Systems” (in prep)
Lai, Anderson & Pu 2018 “How do companions affect spin-orbit misalignments?”
Anderson & Lai 2018 “Teetering stars: Resonant excitation of stellar obliquities…”

N inner planets + one perturber (CJ)

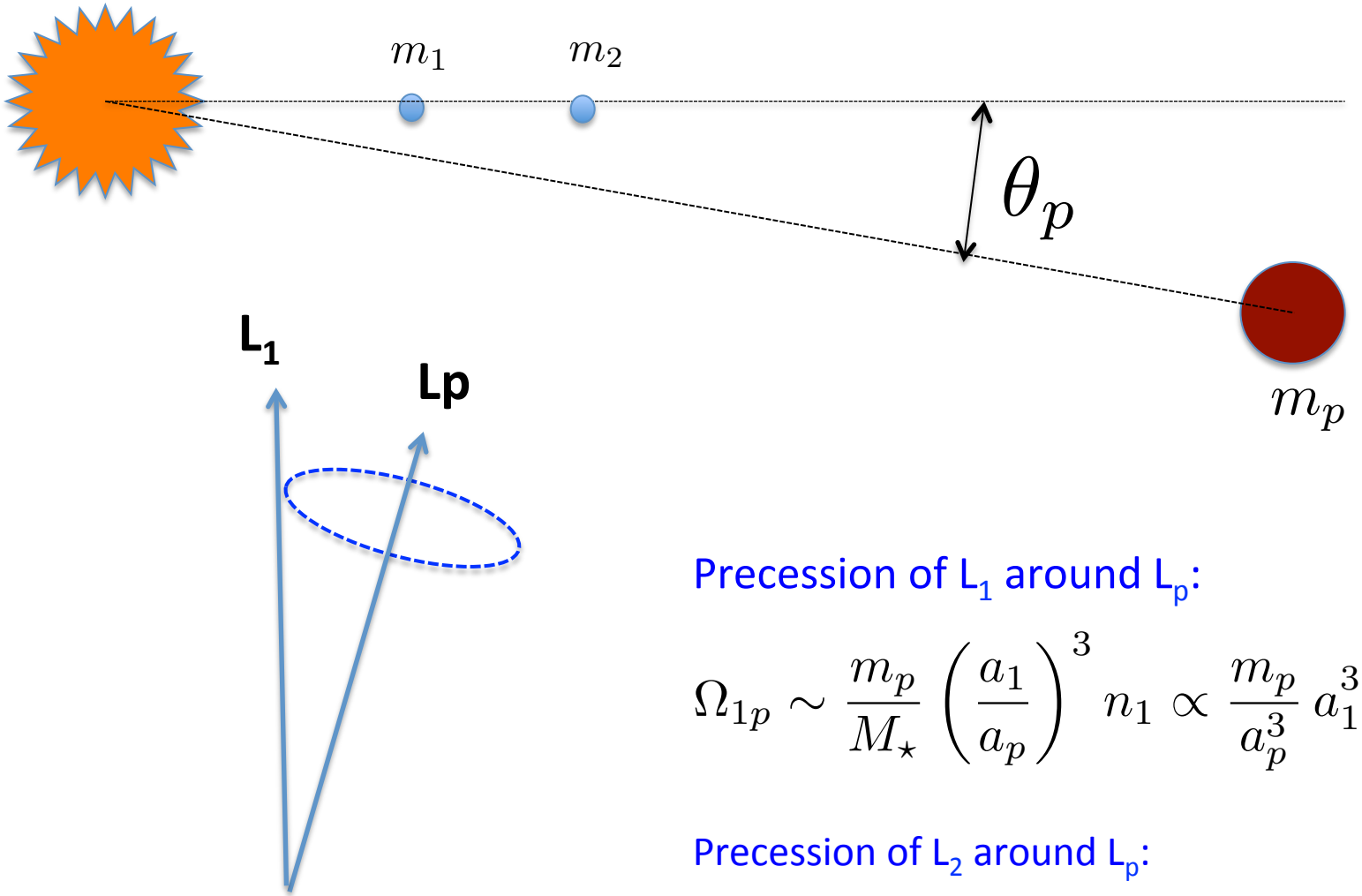
Perturber: CJ on inclined and eccentric orbit

➔ excites mutual inclinations and eccentricities in the inner system



Numerical Simulations
Analytical theory/scalings…

Lai & Pu 2017
Hansen 2017
Becker & Adams 2017
Read et al. 2017
Jontof-Hutter et al 2017
Pu & Lai 2018
Denham et al. 2018

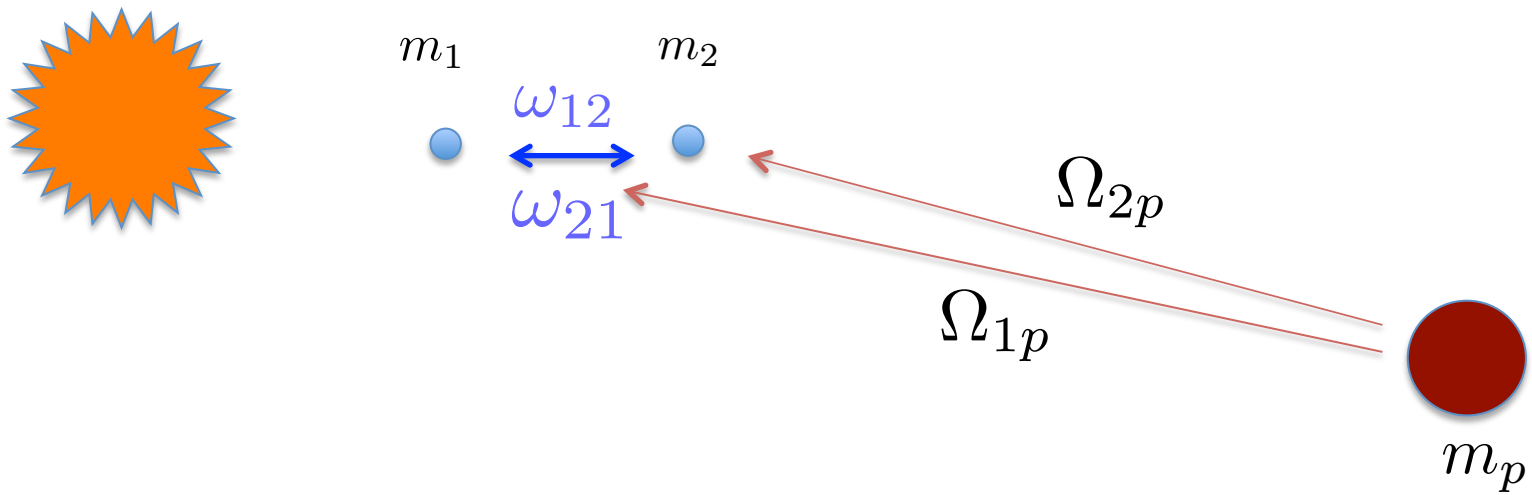


Precession of L_1 around L_p:

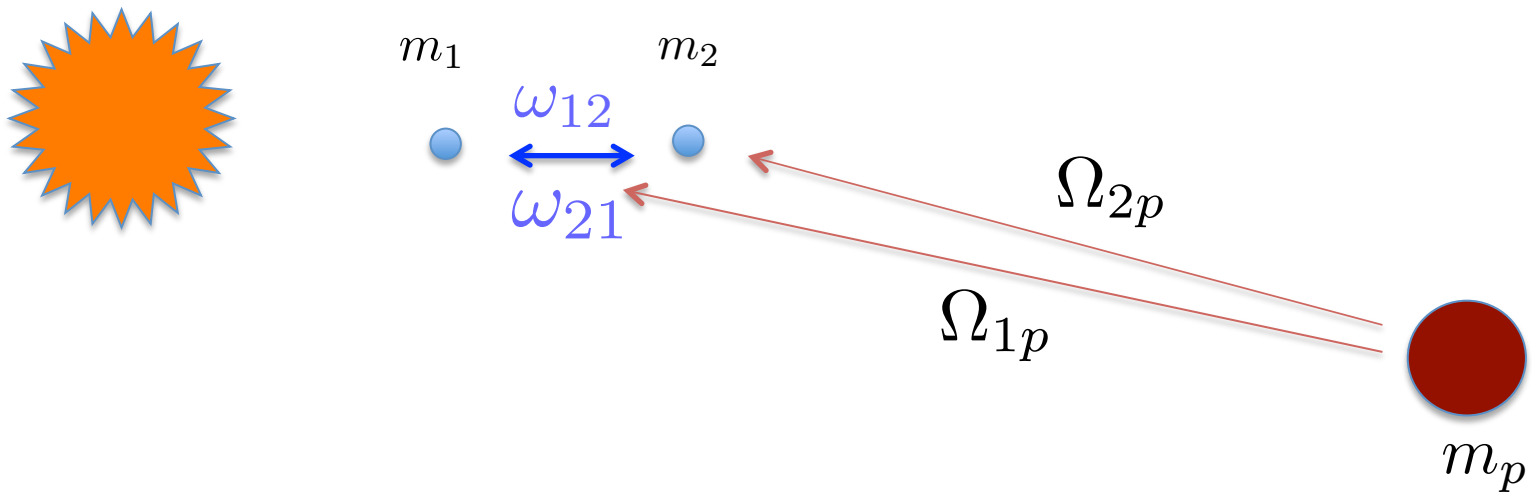
$$\Omega_{1p} \sim \frac{m_p}{M_\star}\left(\frac{a_1}{a_p}\right)^3 n_1 \propto \frac{m_p}{a_p^3}\, a_1^{3/2}$$

Precession of L_2 around L_p:

$$\Omega_{2p} \propto \frac{m_p}{a_p^3} a_2^{3/2}$$



L_1 and L_2 precess around each other at rate ω_{12}, ω_{21}



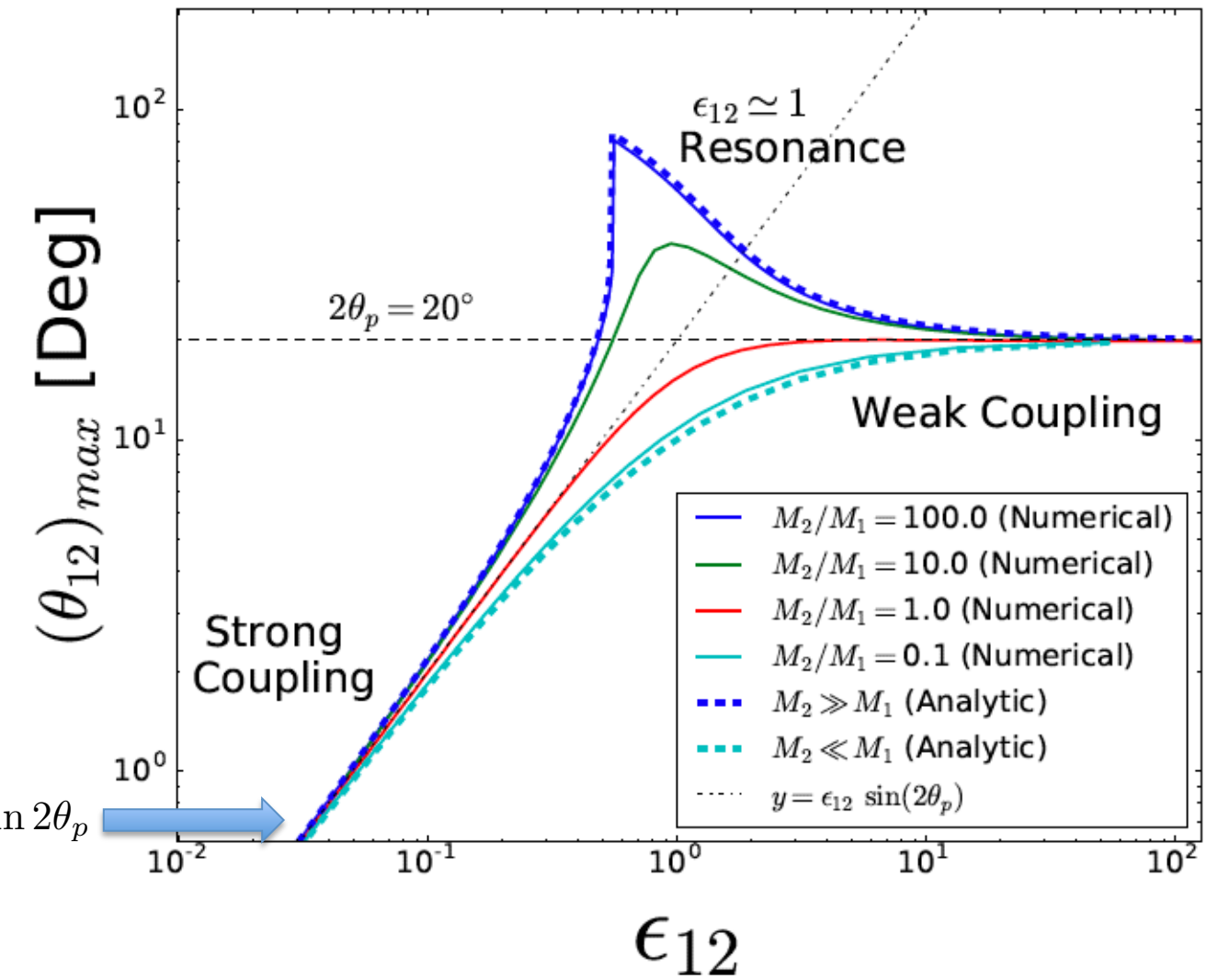
L_1 and L_2 precess around each other at rate ω_{12}, ω_{21}

Mutual inclination induced by perturber depends on **Coupling Parameter**

$$\epsilon_{12} = \frac{\Omega_{2p} - \Omega_{1p}}{\omega_{12} + \omega_{21}} \sim \frac{m_p}{m_{1,2}} \left(\frac{a_{1,2}}{a_p} \right)^3$$

Maximum Mutual Inclination Induced by external perturber

$\theta_p = 10^\circ$



$(\theta_{12})_{\max} \simeq \epsilon_{12} \sin 2\theta_p$

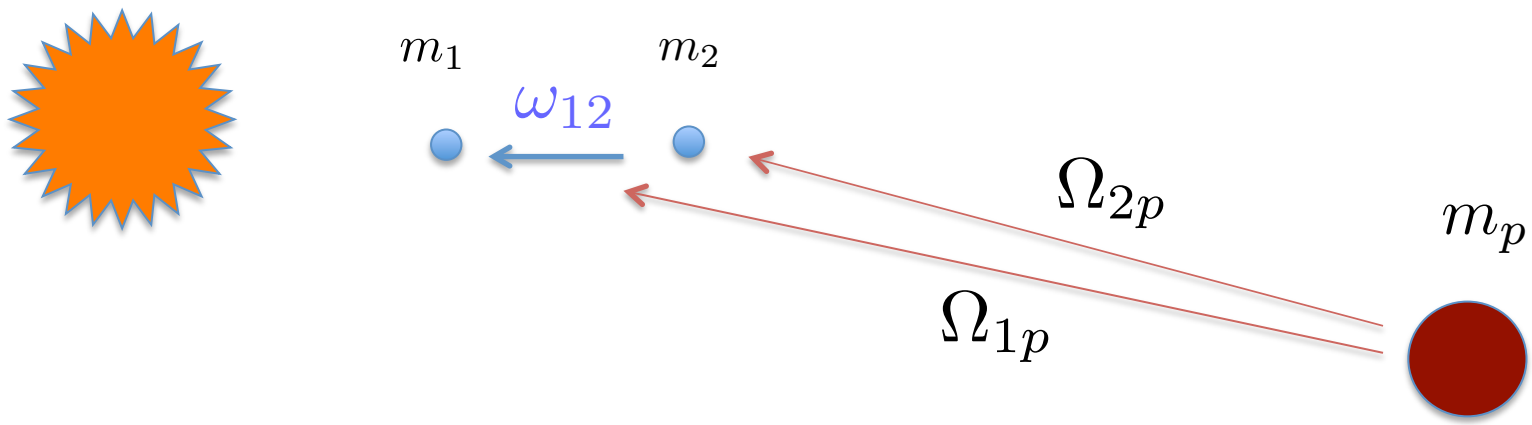
$$\epsilon_{12} = \frac{\Omega_{2p} - \Omega_{1p}}{\omega_{12} + \omega_{21}} \sim \frac{m_p}{m_{1,2}} \left(\frac{a_{1,2}}{a_p}\right)^3$$

DL & Pu 2017

Resonance Feature: $\epsilon_{12} \sim 1$

exists when $m_2 \gtrsim m_1$

Nodal Precession Resonance

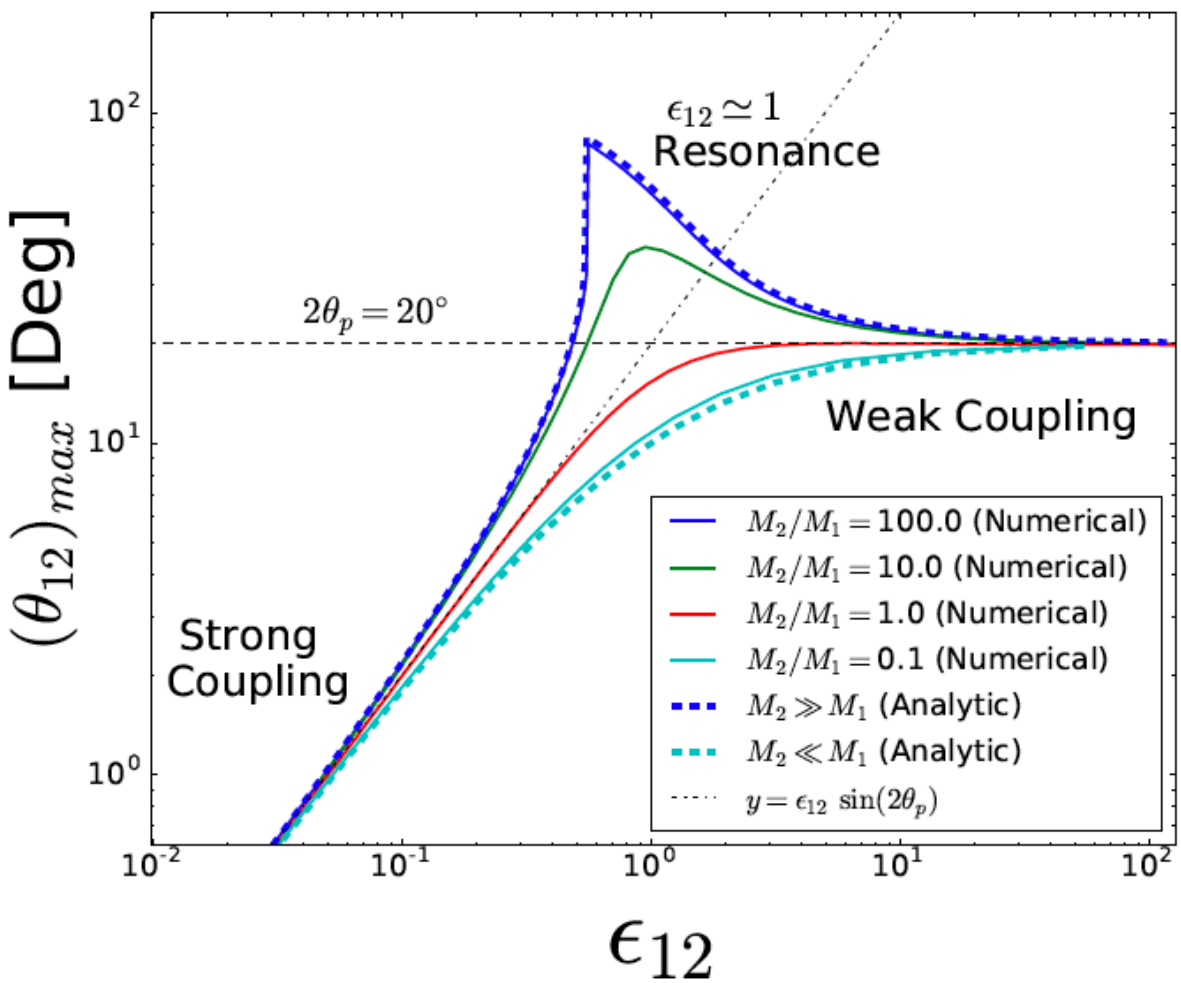


In the $m_2 \gg m_1$ limit:

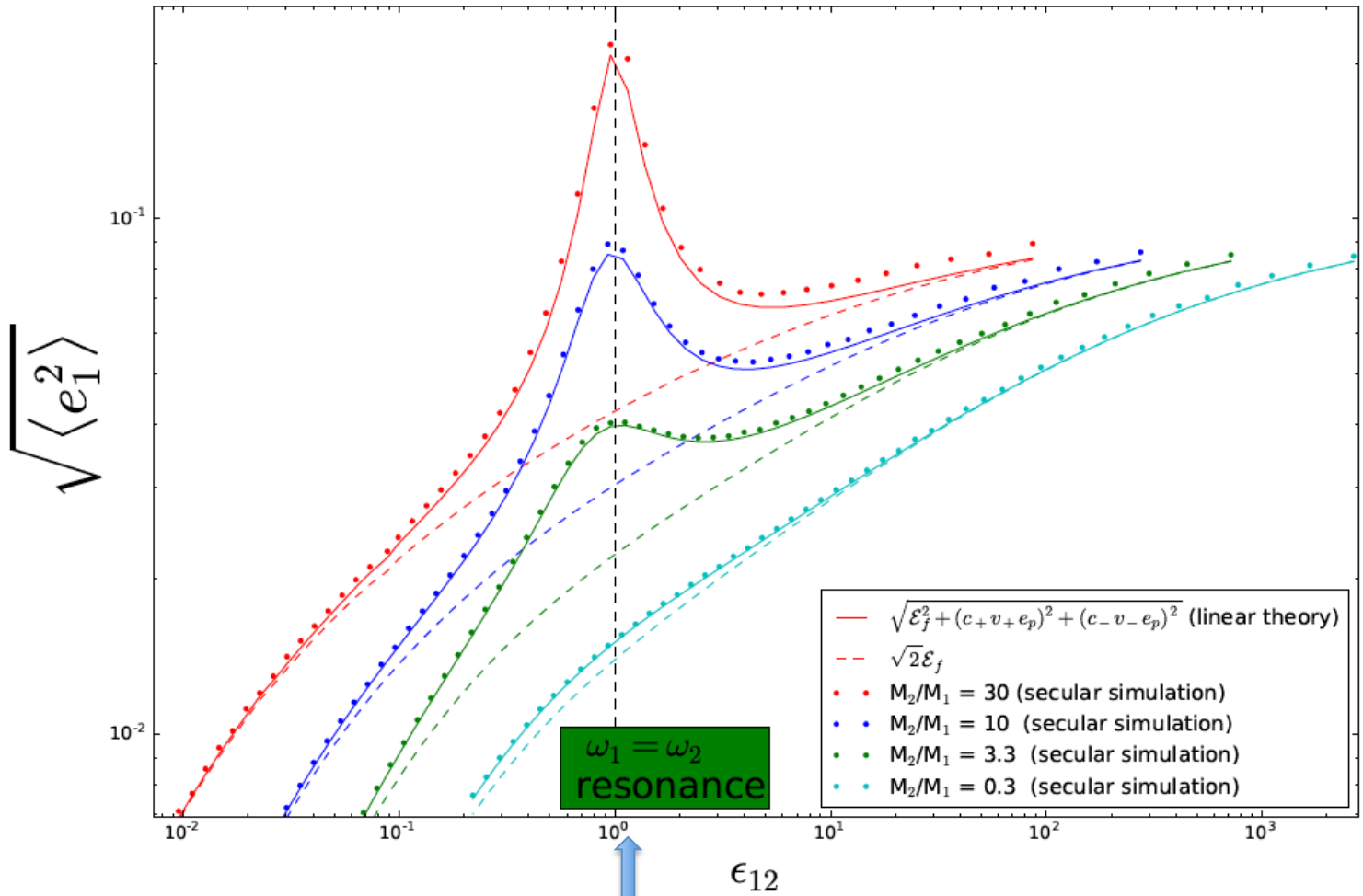
Resonance occurs at $\Omega_{2p} = \Omega_{1p} + \omega_{12}$ or $\epsilon_{12} = 1$

Resonance Feature: $\epsilon_{12} \sim 1$

Can produce much larger mutual inclination than θ_p



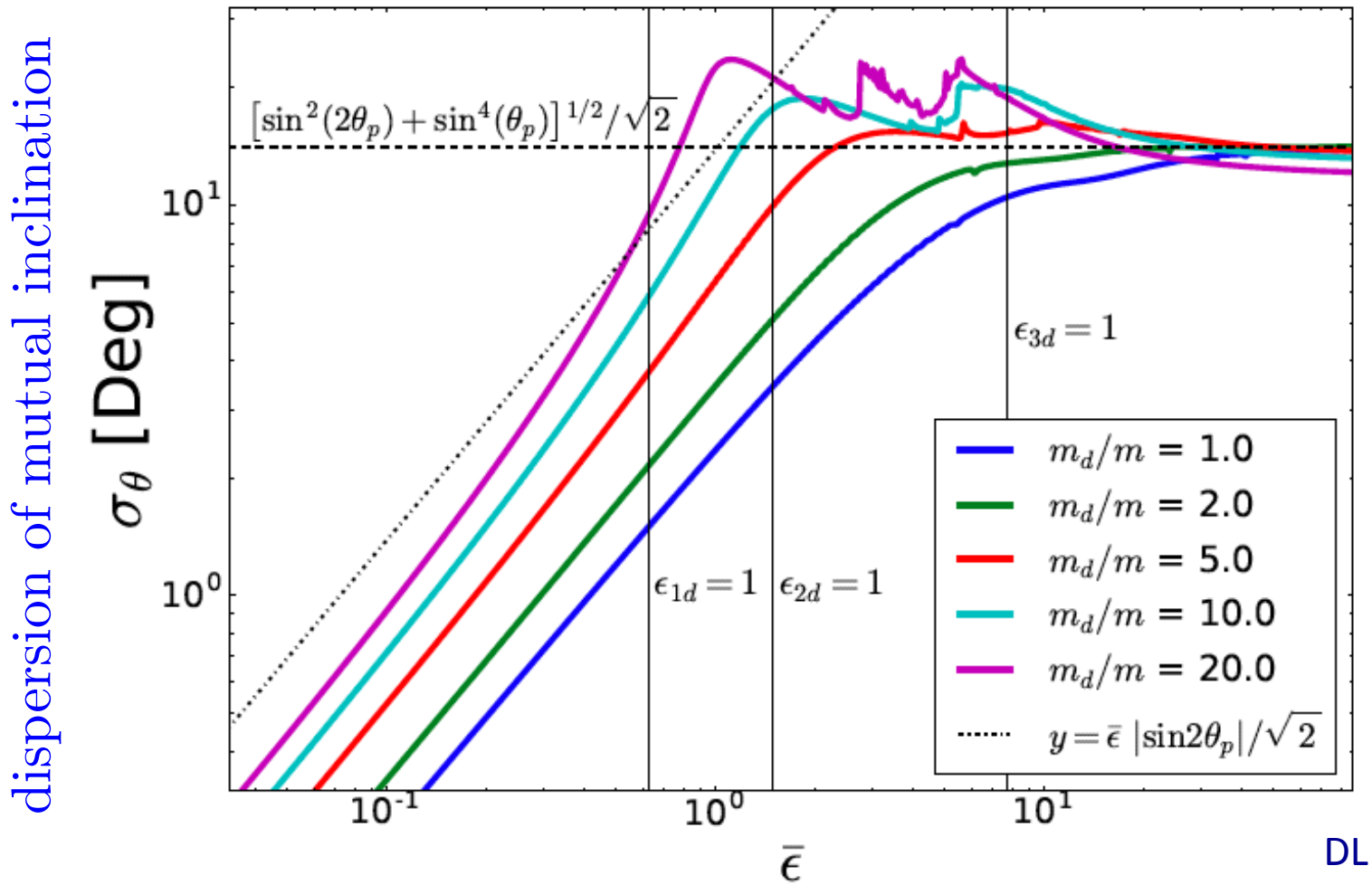
Eccentricity Excitation by External Perturber



Pu & DL 2018

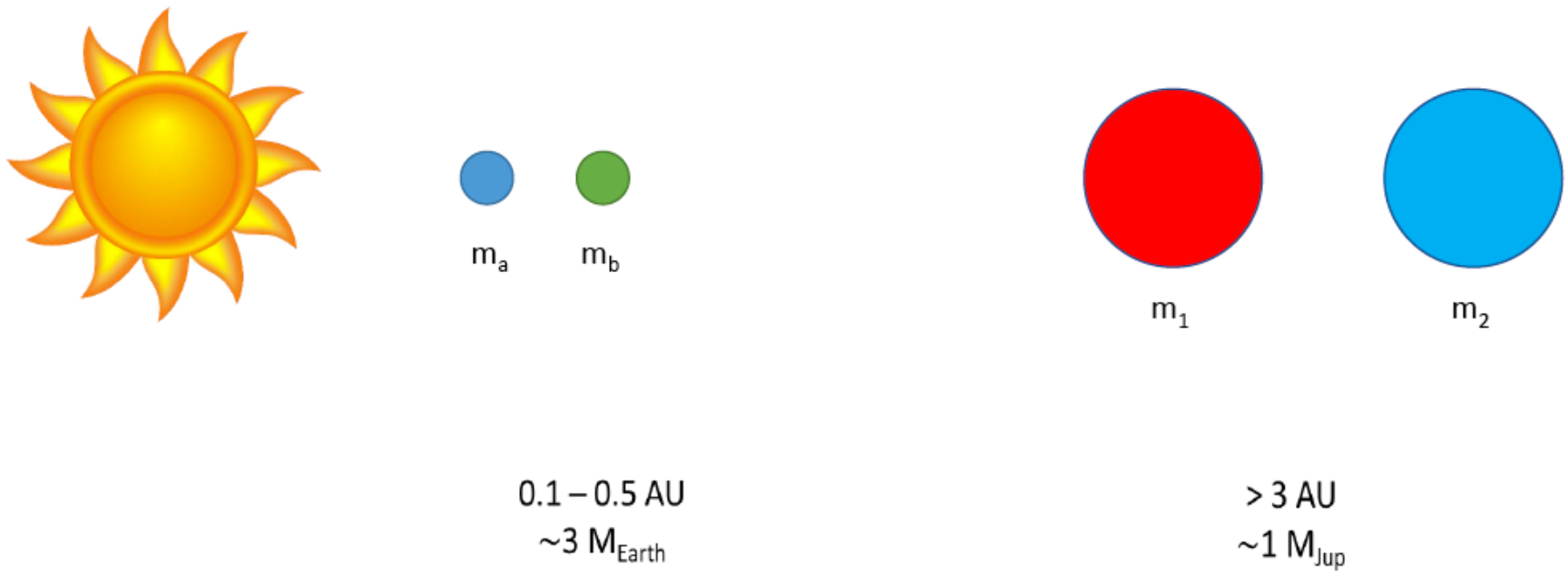
Apsidal precession resonance

4 planet system with an external perturber



DL & Pu 2017

N inner planets + 2 Cold Jupiters



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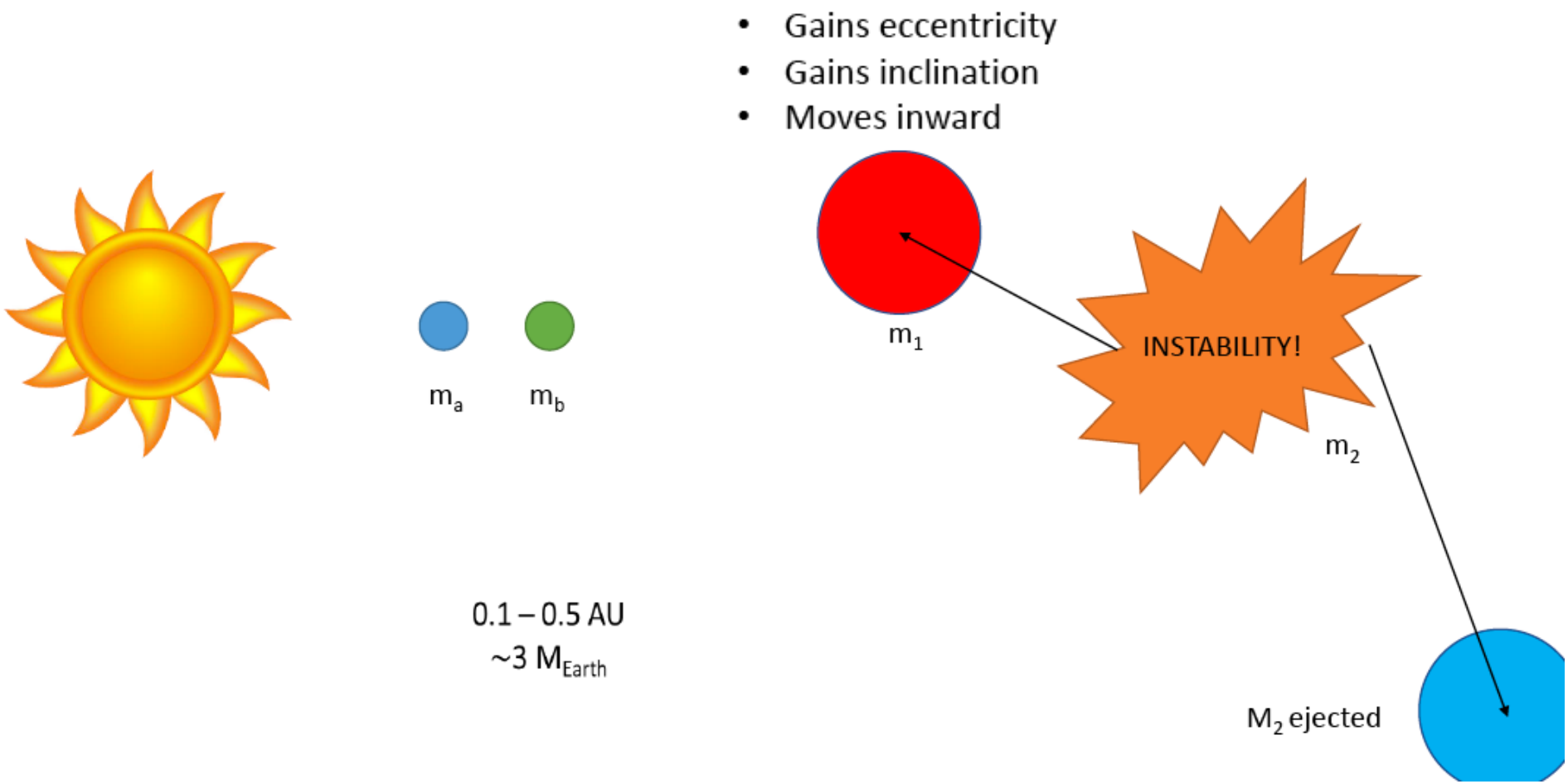


What happen to inner planets during outer "violence"?

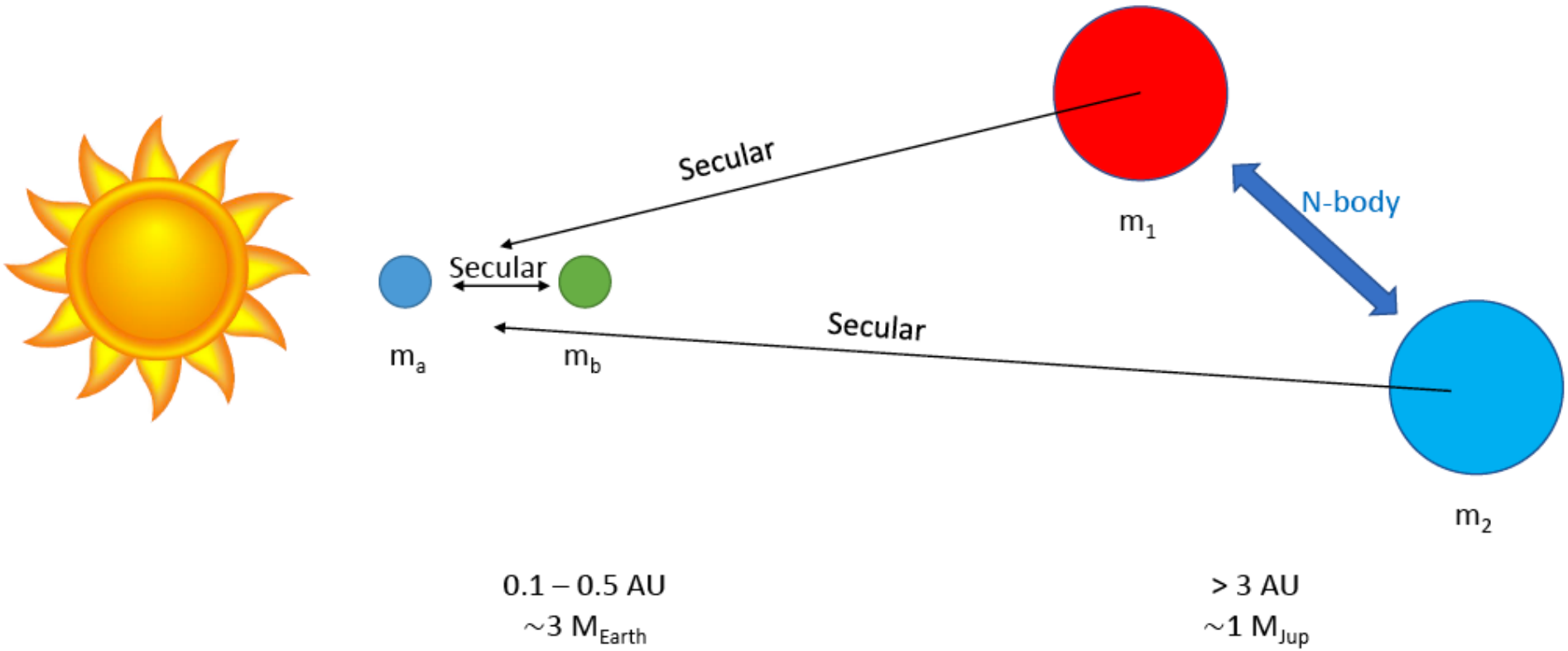
- Previous works have considered examples using N-body simulations (e.g. Carrera, Davies+16, Gratia & Fabrycky 17; Huang, Petrovich+16; Mustill, Davies+17)

- **Issues of time-scales:** Inner planets have P ~ 10 days, outer planets have P > 5 yrs; giant planet ejection timescale up to $t_{ej} \sim 10^9$ yrs , or $N_{ej} \sim 10^8$ outer orbits

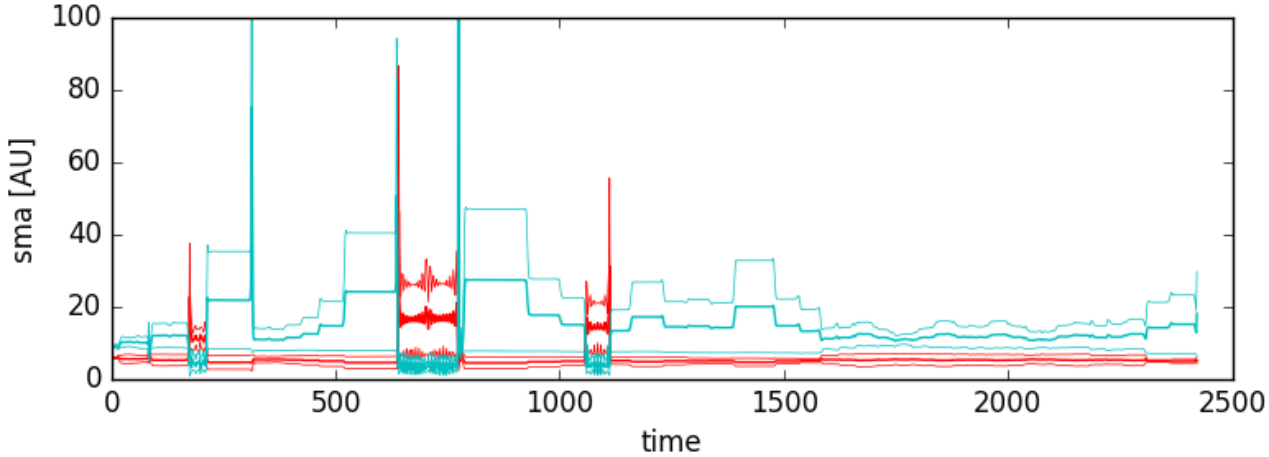
➔ Difficult to gain understanding with only a smattering of N-body simulations

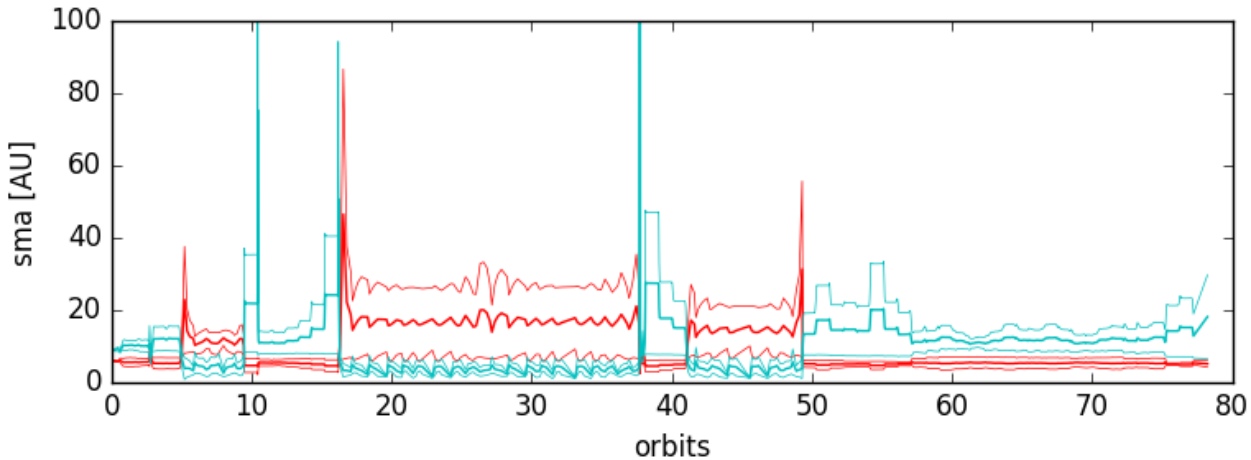
Hybrid N-Body-Secular Method

Pu & DL 2018 (in prep)



Giant planet scattering is a stochastic process…





Time evolution of *a, e, i* resemble a random walk during scattering

This drives a corresponding random walk in *e* and *i* in the inner planets over secular timescales

Giant planet scatterings:

Simulations + Statistical Theory (random walk in energy)

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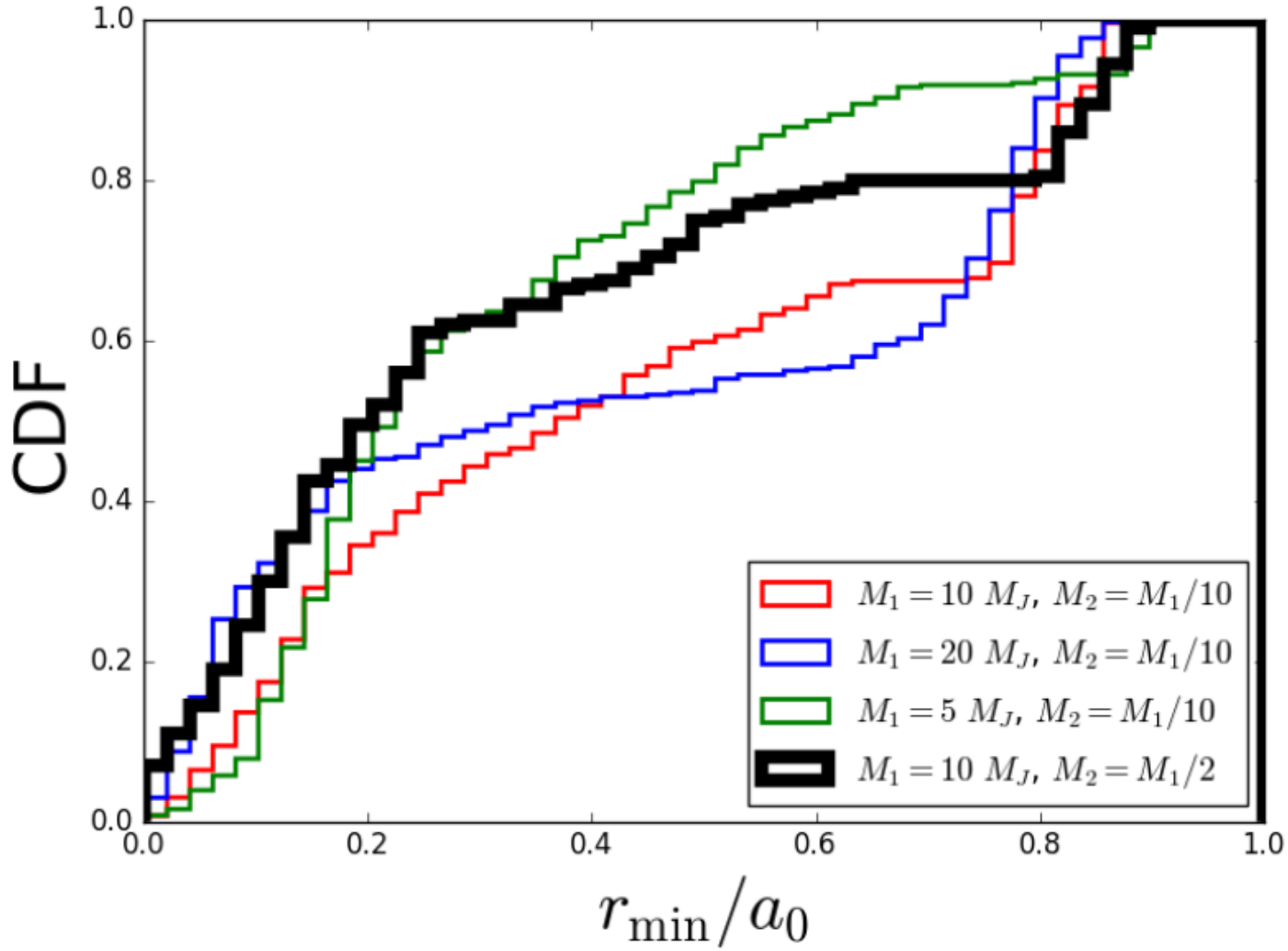
Simulations + Statistical Theory (random walk in energy)

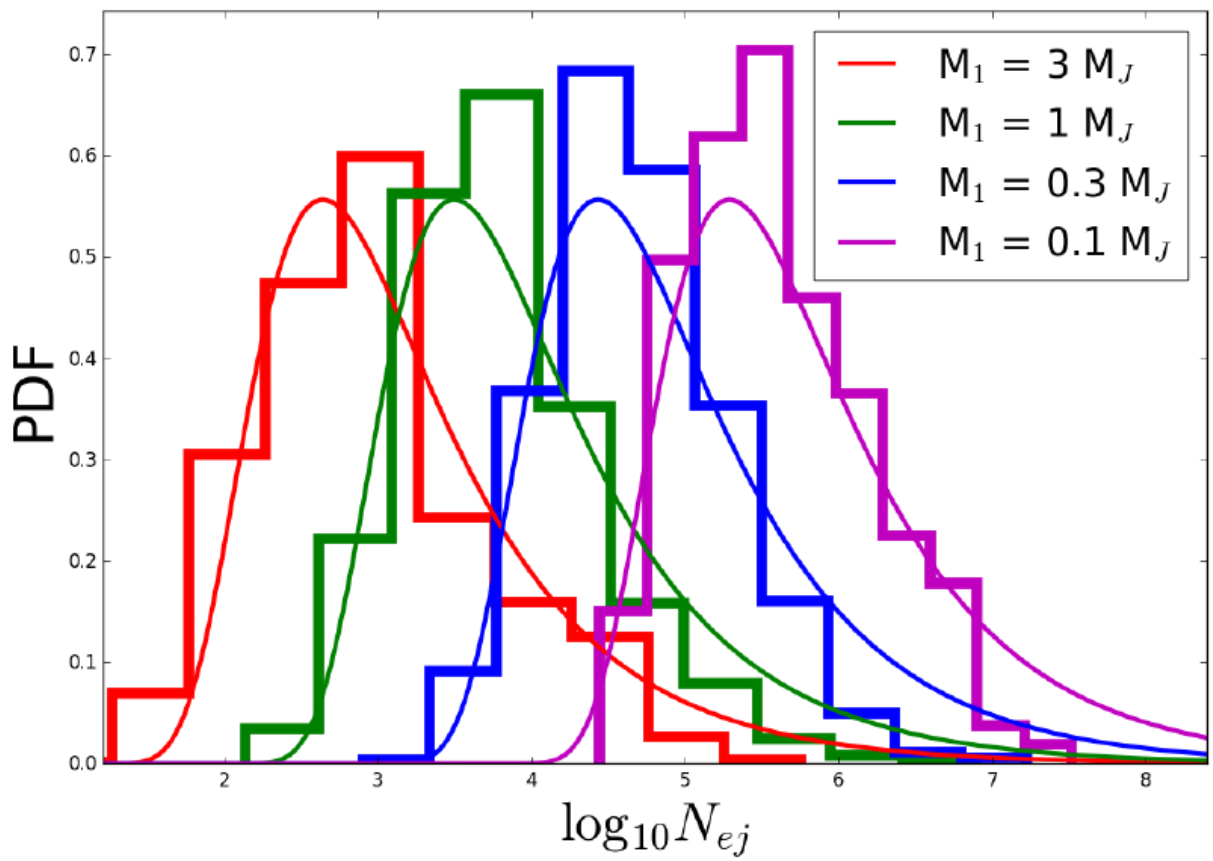
- Planets can wander inward ➔ may directly "destroy" the inner system



Pu & Lai 2018
(in prep)

Giant planet scatterings:
Simulations + Statistical Theory (random walk in energy)

- Can have a wide range of ejection times...



$$y \equiv \log N_{ej}\,, \qquad \mathrm{b} \equiv \frac{E_{2,i}}{\sqrt{\langle \delta E \rangle^2}}$$

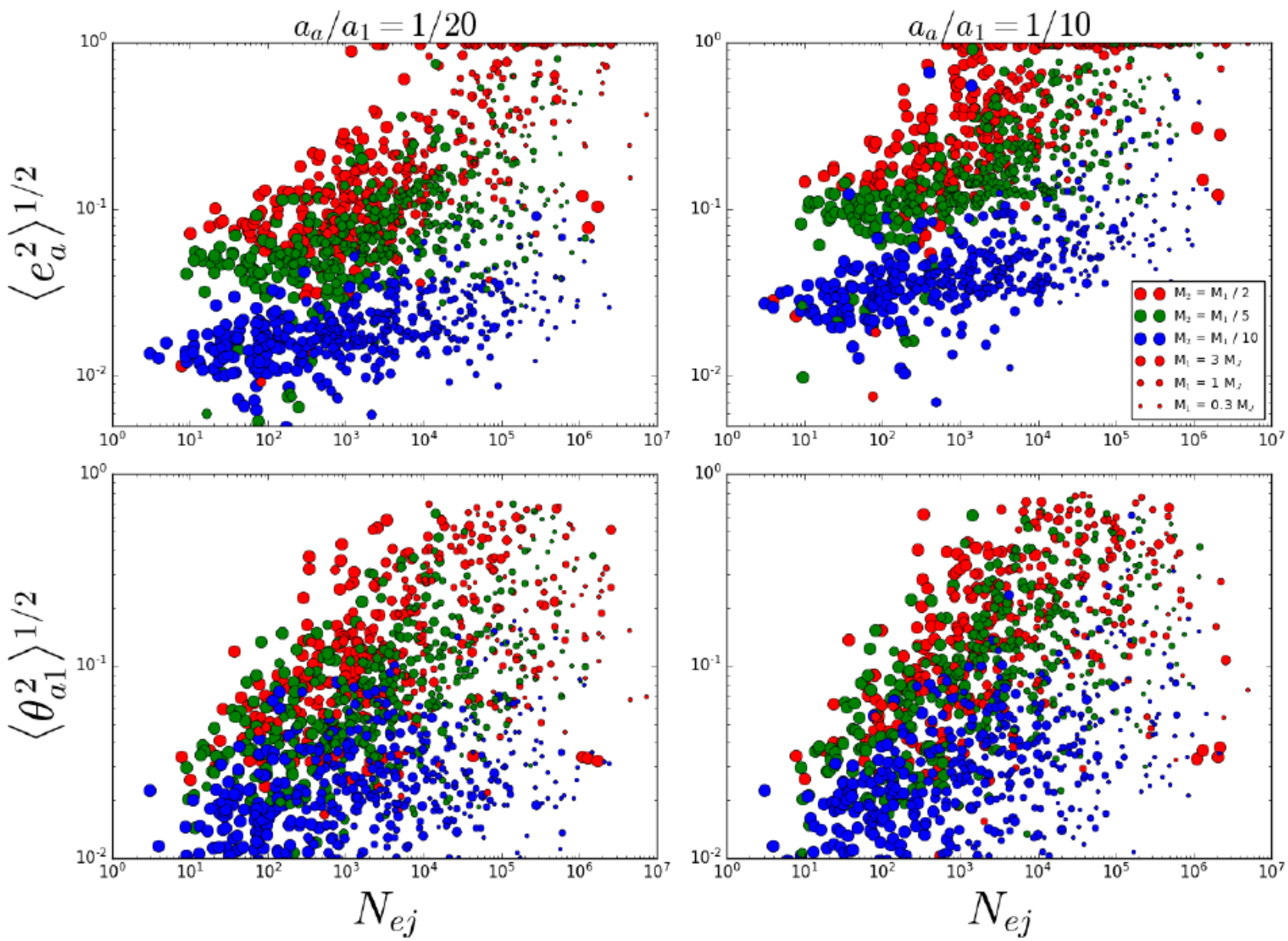
$$f(y) = \frac{b}{\sqrt{2\pi}} e^{-y/2} \exp\left(-\frac{1}{2} b^2 e^{-y}\right)$$

$$\langle N_{ej} \rangle = e^{\langle y \rangle} \simeq 3.56 b^2.$$

$$\sigma_y \equiv (\langle y^2 \rangle - \langle y \rangle^2)^{1/2} = \pi/\sqrt{2} \approx 2.22$$

Pu & Lai 2018
(in prep)

“1 + 2” Problem (one planet + two unstable giants)



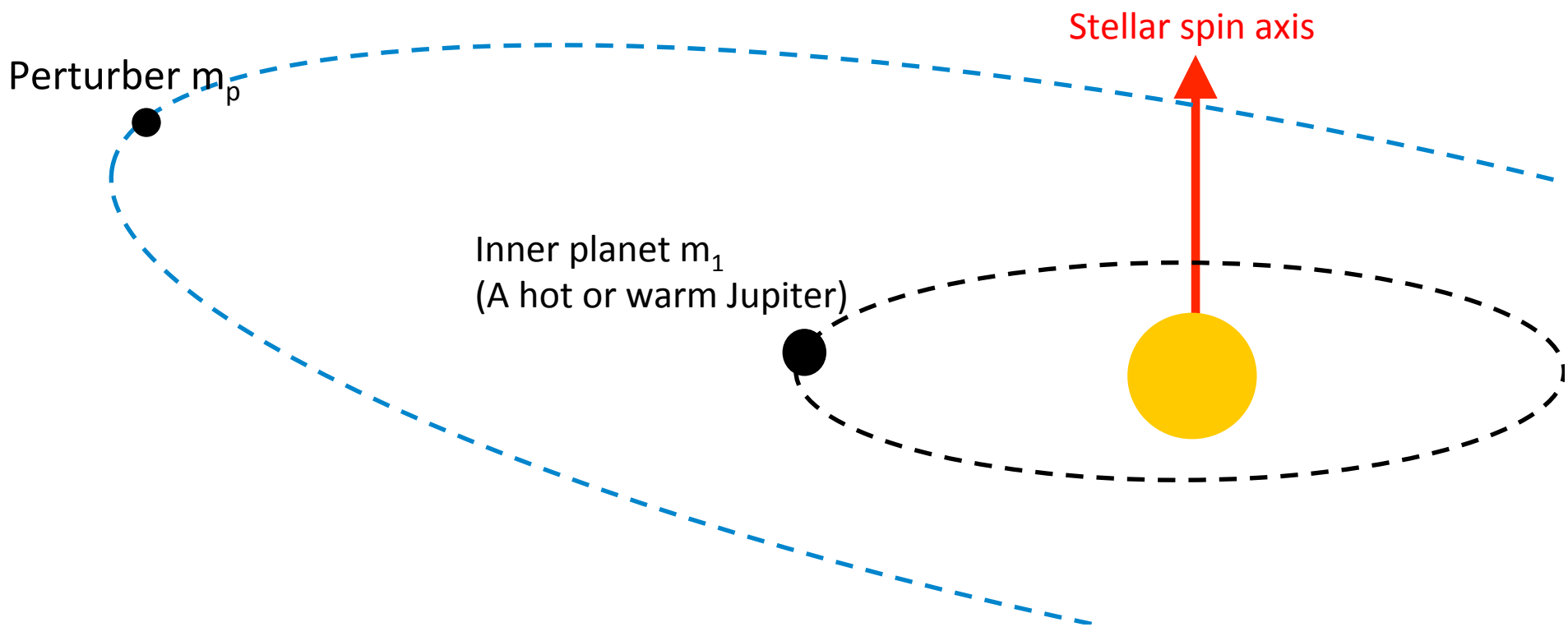
Expected Results for "N+2" Planet Systems

Depends crucially on N_{ej}

- Dynamical evolution of the inner planets determined by the ratio $N_{ej}/N_{\rm sec}$
- For $N_{ej}/N_{\rm sec} \gtrsim 1$, the eccentricity, inclination and mutual inclination scale protionally with $\sqrt{N_{ej}}$.
- Scattering of CJs is highly destructive to inner systems. Inner SEs with semi-major axis within factor of ~6 are usually destroyed.
- Inner SEs that are farther away can have their eccentricities and inclinations excited beyond their naïve secular values, but multi-planet inner systems offer protection against this excitation.

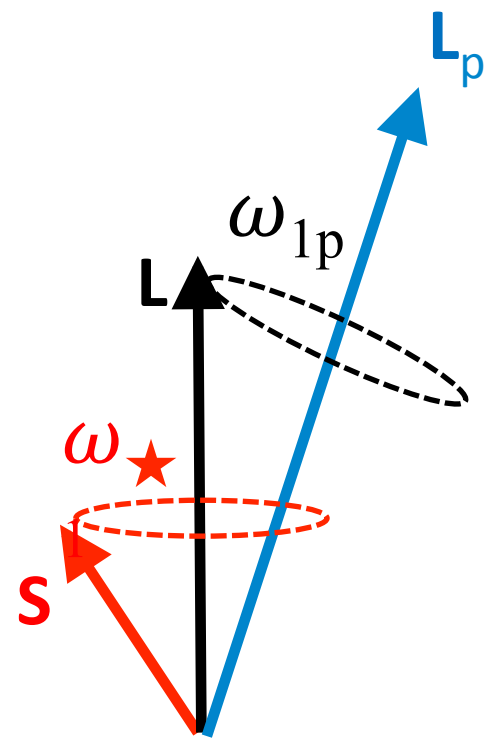
Pu & Lai 2018, 2019 (in prep)

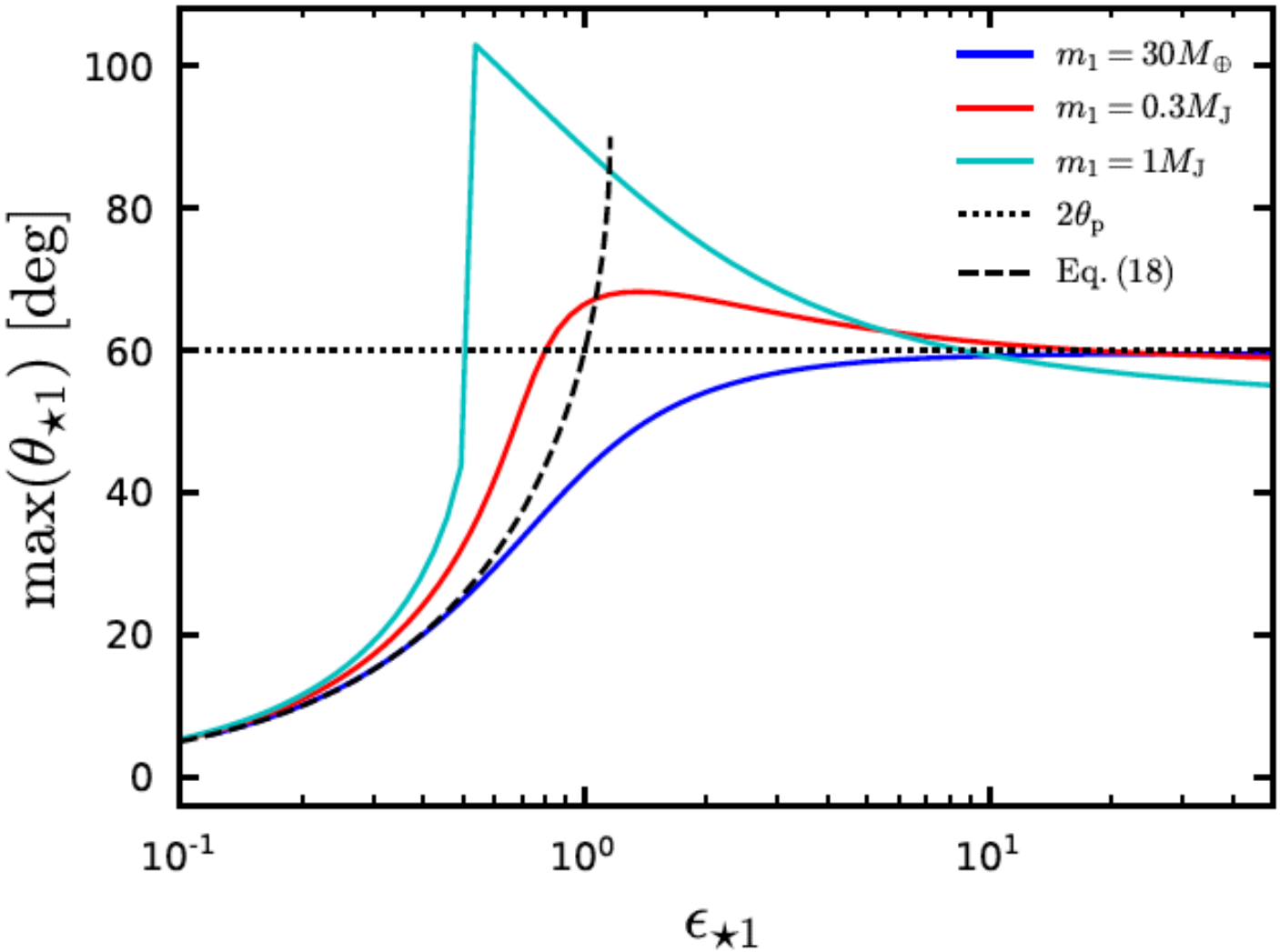
How external companion affects stellar obliquity?



Spin-orbit dynamics depend strongly on

$$\epsilon_{\star 1} \equiv \frac{\omega_{1p} - \omega_{\star p}}{\omega_{\star 1} + \omega_{1\star}}$$



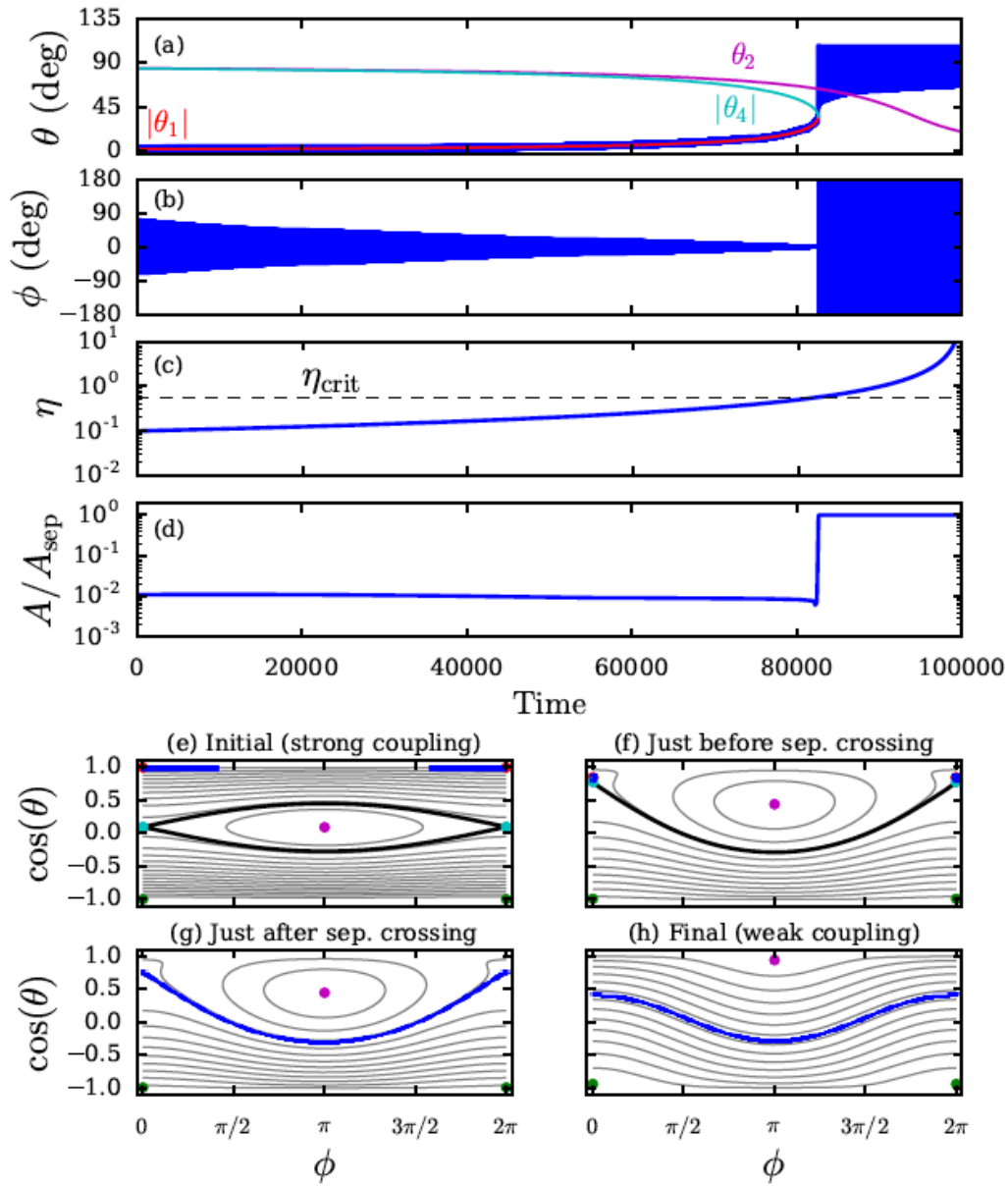


Lai, Anderson & Pu (2018)

See Boue & Fabrycky (2014) for general cases

Resonant Excitation of stellar obliquity as star spins down

Kassandra Anderson & Lai 2018



Summary

- Orbital architecture of super-Earths can be strongly affected by Cold Jupiters.
  CJs can excite eccentricities and mutual inclinations, and may destroy SEs.

- "Simple" analytical/scaling relations for "N + 1" systems

- "N + 2" systems are subtle: Result depends on ejection timescale…
  (statistical theory for 2-planet scatterings)

- Stellar obliquities are also affected...

References:

Lai & Pu 2017 "Hiding Planets behind a Big Friends…"
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Thanks