Orbital Evolution of Exoplanets Caused by Scattering and Tides

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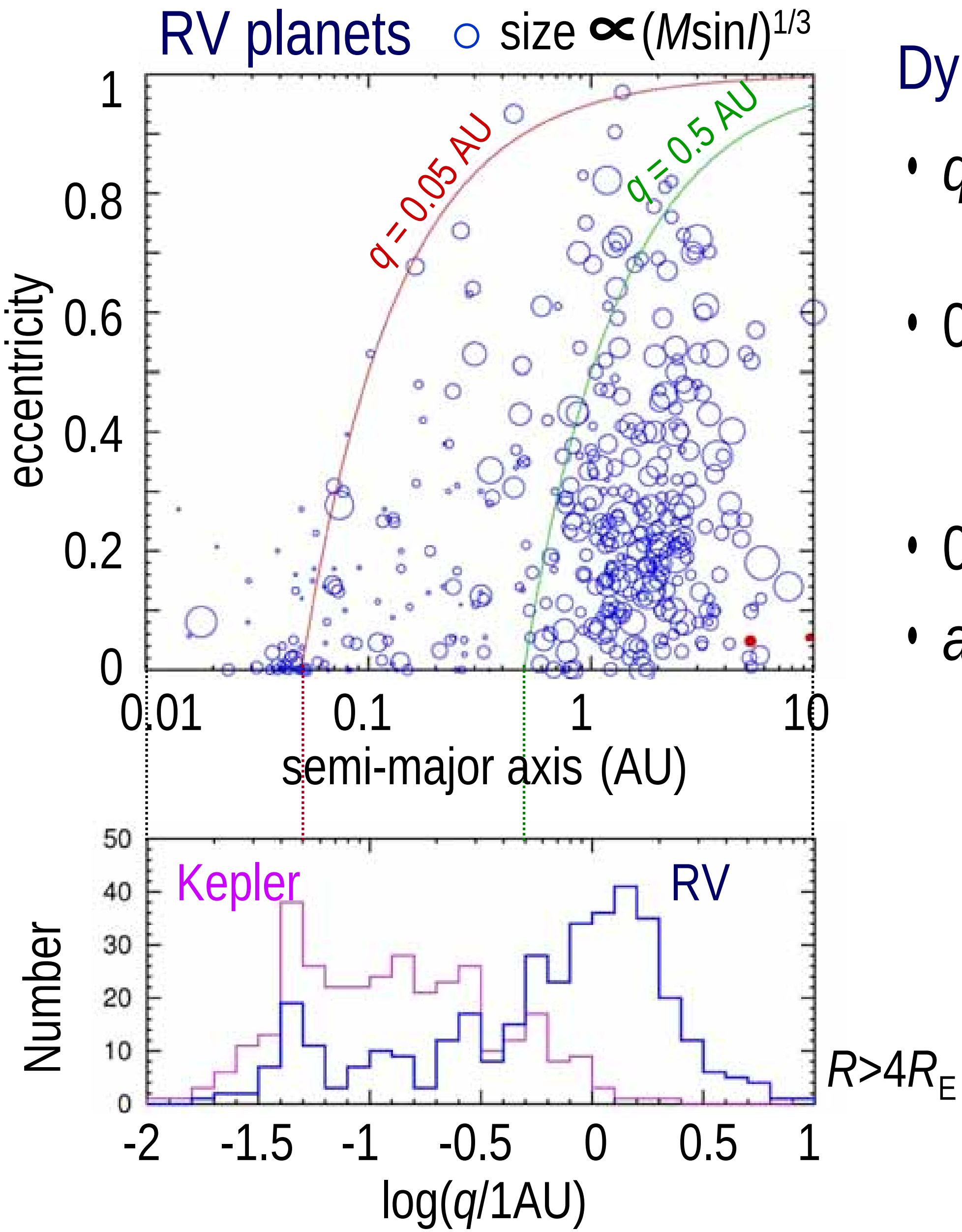
Orbits of Extrasolar Planets

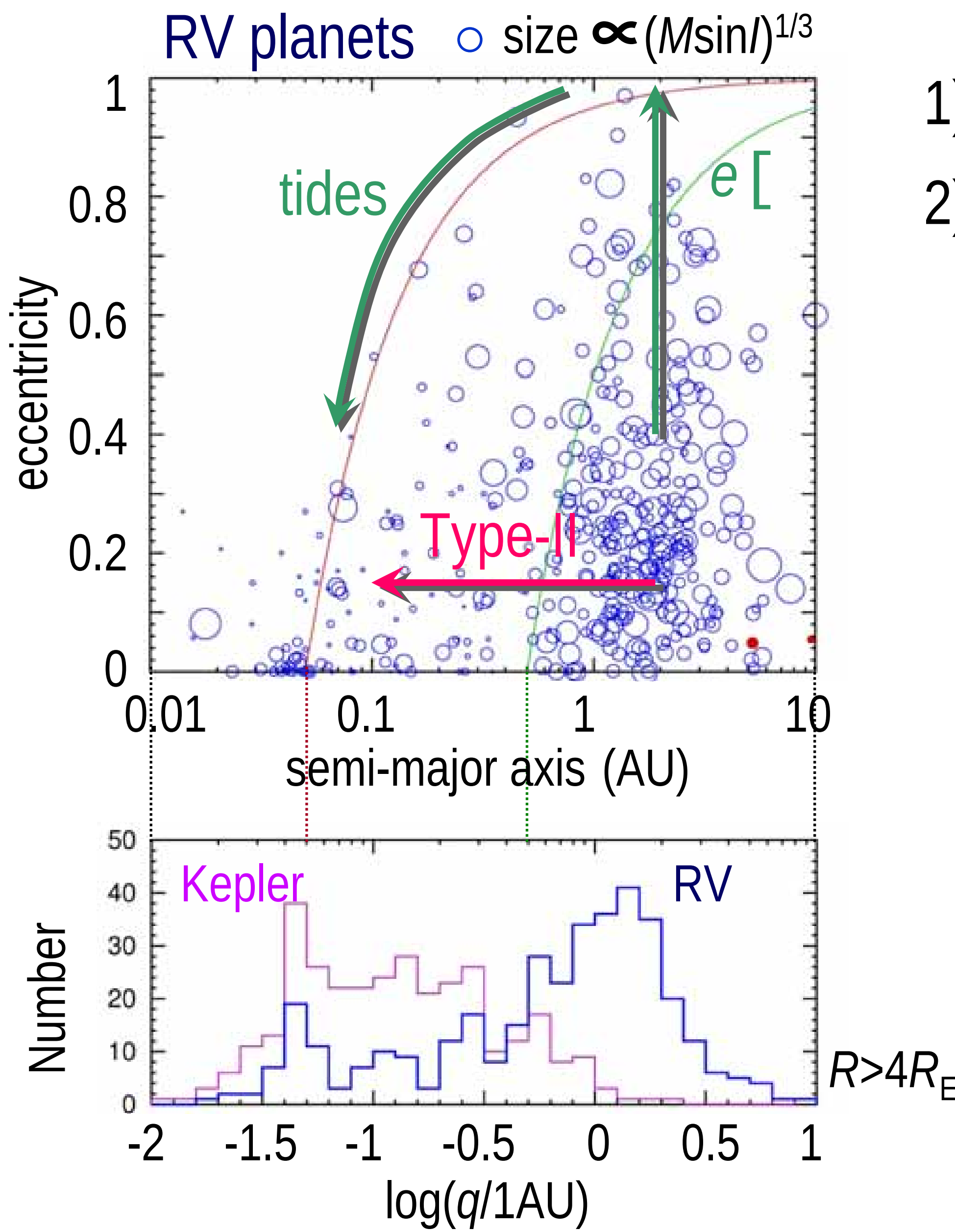


Dynamical properties

- $q=a(1-e)<0.05$AU : tidally circularized
  (Rasio & Ford '96)
- $0.5\text{AU}<q$: eccentric planets
  → scattered feature
  (e.g., Chatterjee et al. '08, Ford & Rasio '08)
- $0.1\text{AU}<q<0.5$AU: depletion of giants
- $a<0.04$AU: severely truncated
  (Borucki et al. 2011)

Origins of Close-in Planets?

→ *Previous talk by Dr. Naoz*
Wed. talk by Dr. Matsumura



1) Type-II migration (e.g., Lin et al. 1996)

2) e's excitation → *q* damping
→ tidal evolution

i) secular excitation

- Kozai migration (i_k -> e_k)
(Wu et al. '03,'07, Fabrycky & Tremaine '07)
- Secular chaos (e_j -> e_k)
(Wu & Lithwick '11, Lithwick & Wu '11)

ii) scattering

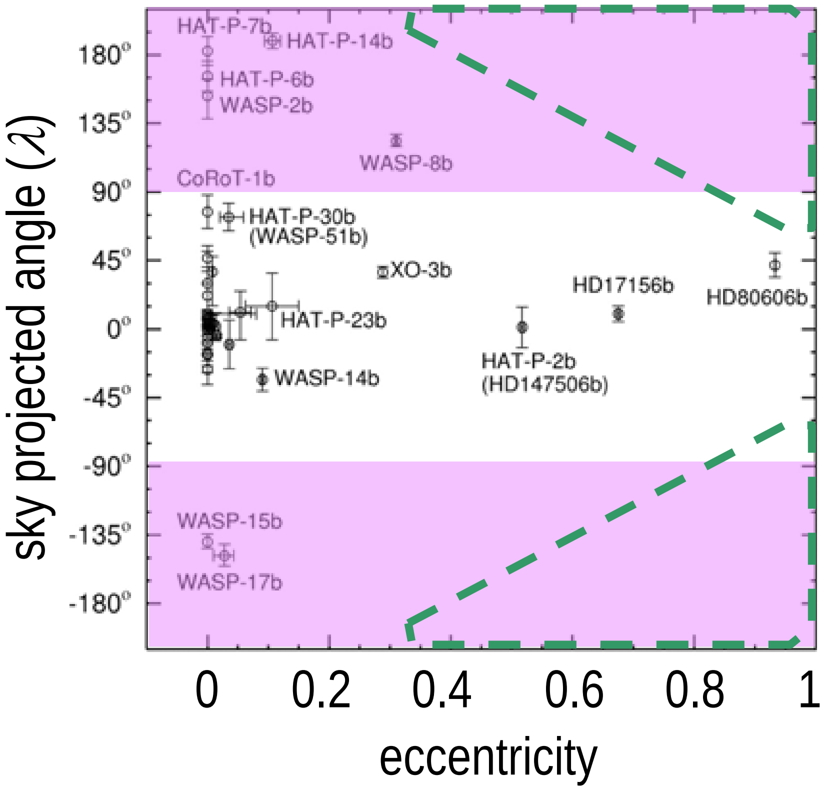
- Jumping Jupiter Model
(Rasio & Ford '96, Weidenshilling & Marzari '96, Lin & Ida '97, Marzari & Weidenshilling '02, Chatterjee et al. '08, Ford & Rasio '08,...)
- Slingshot model (Jumping Jupiter + tides)
(Rasio & Ford '96, Nagasawa et al. '08)

Inclination of Planets

→ Previous talks by Dr. Winn and Dr. Ragozzine

RM measured planets: ~40

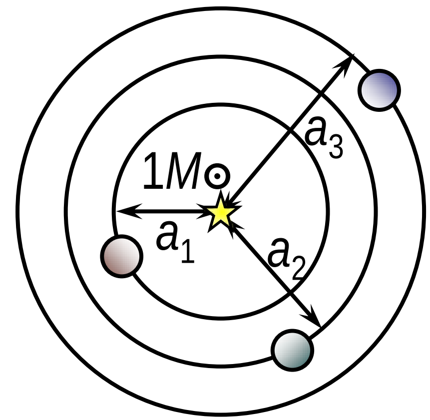
(e.g., Winn+'09, Narita+'09, Triaud+'10, Moutou+'11...)



- 7 retrogrades ($|\lambda|>90°$) & 8 highly inclined planets ($90°>|\lambda|>30°$) ($|\lambda|>30°$: 38% , $|\lambda|<20°$: 62%)
- No eccentric retrograde planet
- Aligned planets
  - type-II origins
  - Realignment (Winn+'10)

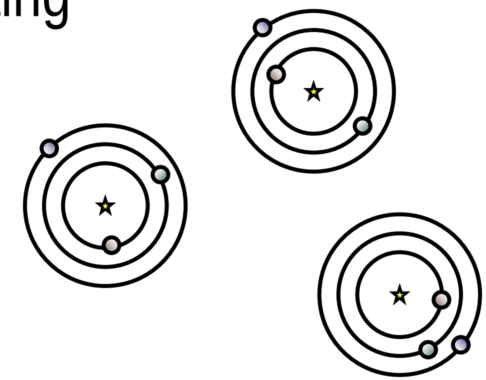
N-body Simulations (3 planets + tides)

- Three equi-mass Jovian planets
  - a_1=5AU or 3AU or 7AU, $a_2>1.5a_1$,..
  - e=0
  - mutual inclination = 0.5º, 1º, 1.5º
  - Radius: R=1R_J or 2R_J or 0.5R_J
  - mass: m= 1M_J or 0.5M_J or 2M_J
  - GR (on/off)
  - Rotation: pseudo-synchronization or non-rotating



- Orbital integration: Hermite code, 10^7-10^9y
  100 runs for one parameter set

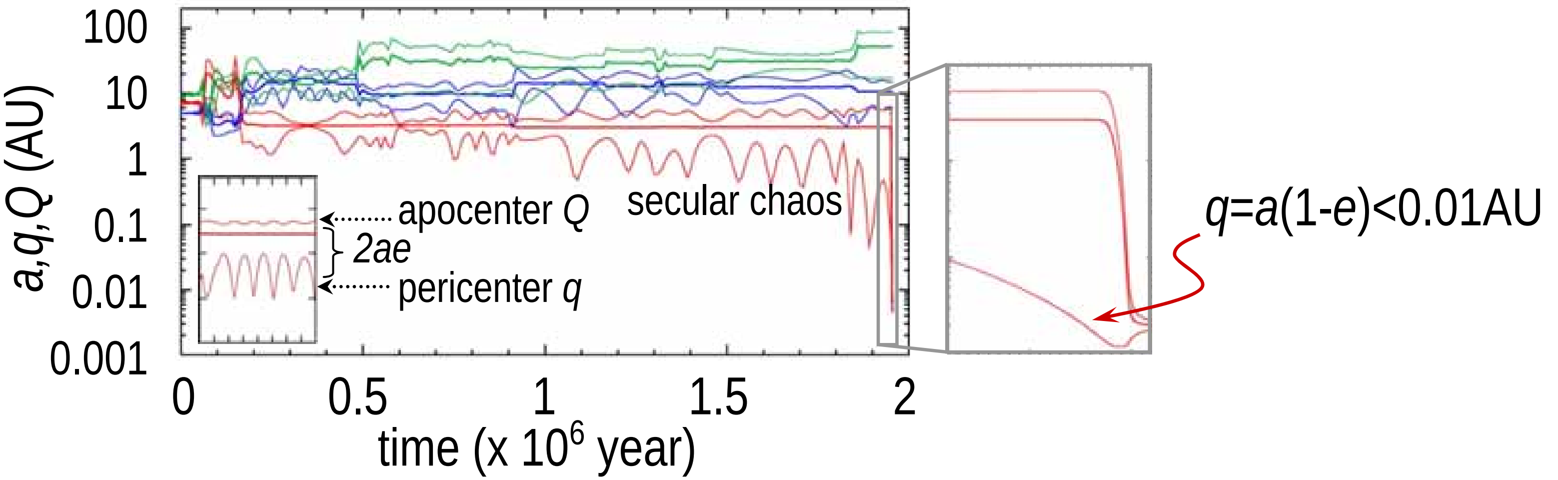
- Tidal force
  Dynamic tides, l =2 f mode+ g,p modes (on/off)
  given by Ivanov & Papaliozou (2007)
  Effective for eccentric gas planets



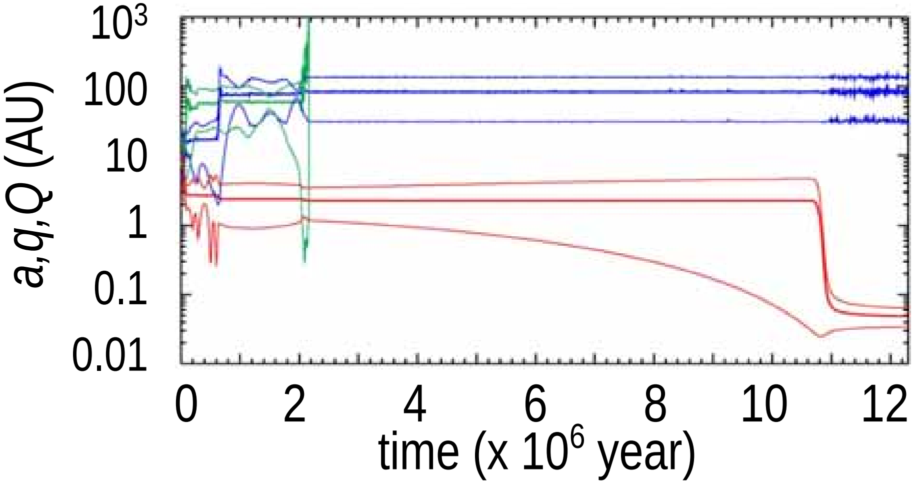
(~1000 runs in total)

Orbital Evolution to Close-in Planets

- Random circularization (HJ formation during 3-planet interaction): 20-30%



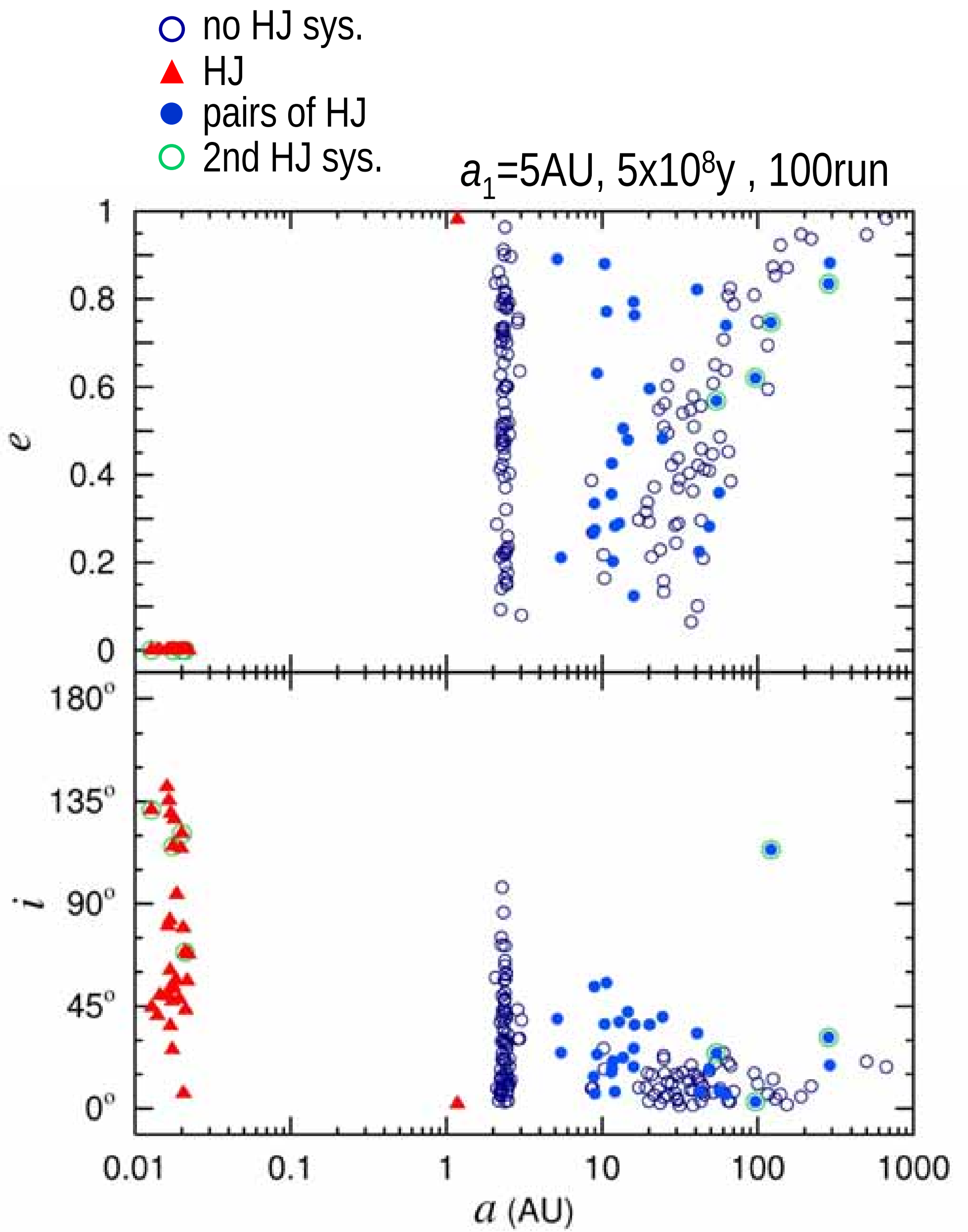
- Stable circularization (HJ formation after an ejection of a planet): ~4%



exchange of $e_k \Leftrightarrow i_k$
→ Kozai mechanism
exchange of $e_k \Leftrightarrow e_j$
→ Secular mechanism

Longer circularization timescale

Final Distribution

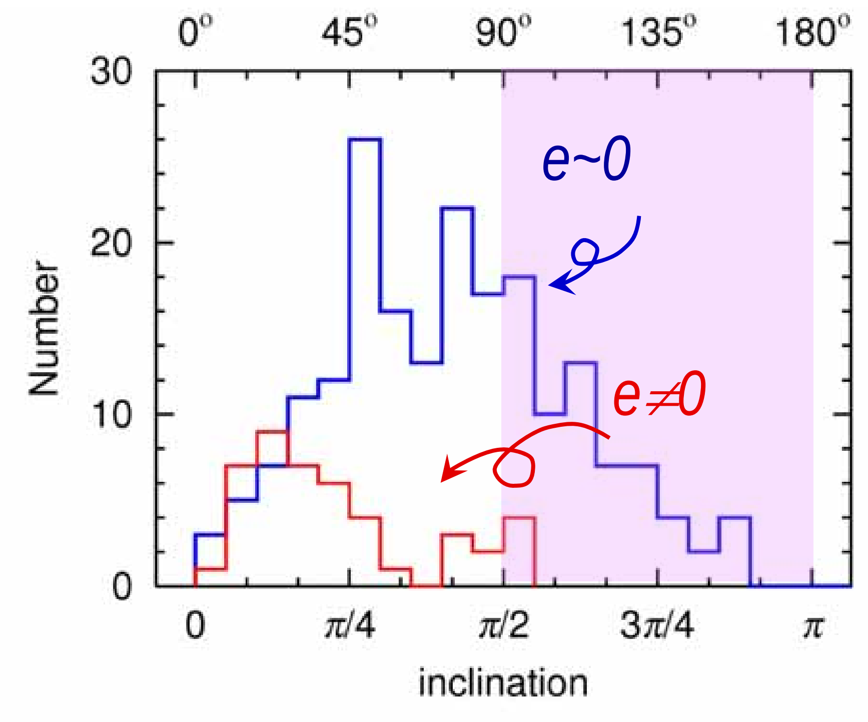


- Formation of HJs
  → *outer pairs >10AU*
- Formation of distant planets.
  But their eccentricities are large.
- Since *e* & *i* of remaining planets are large, 2nd HJ is formed easier than the first one.
- Eccentric HJ is formed by stable circularization.
  It has small i. Rare.

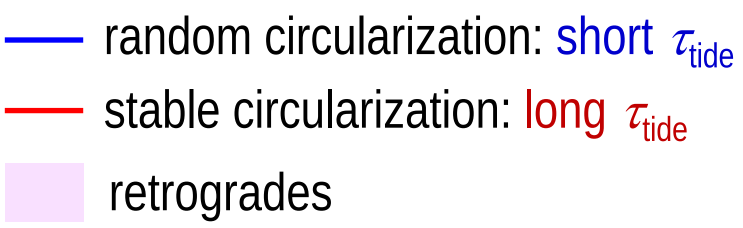
  (If we start from more stable systems, the situation would be changed.)

  → *previous talk by Dr. Naoz and tomorrow talk by Dr. Lithwick*

Inclinations



Results of 1100runs



- Retrograde:28%. i>30°:84%.
- HJs formed by random circularization: totally circularized (e=0, larger i).
- HJs formed by stable circularization;
  - have longer tidal circularization timescale (non-zero e is possible)
  - have smaller i (~ progrades)

= Eccentric planets with high i or retrograde orbits would be rare.

Summary

When multiplanets cause orbital instability,

- Inclined close-in-Jupiters tend to be formed by random circularization. The probability is *P* ~20-30%.
  They tend to be circular.

- Eccentric close-in Jupiters (τ_e>1Gyr) tend to be formed by stable circularization. *P* ~4%.
  They tend to have prograde orbits (small/moderate i).

= Eccentric retrograde planets would be rare.

- Related theory Posters: 34.07 F. Rasio, 34.02 Y. Matsumoto

A paper coming; *Orbital Distributions of Close-In Planets and Distant Planets Formed by Scattering and Dynamical Tides* by MN & Ids. Will appear on ApJ in next month :)