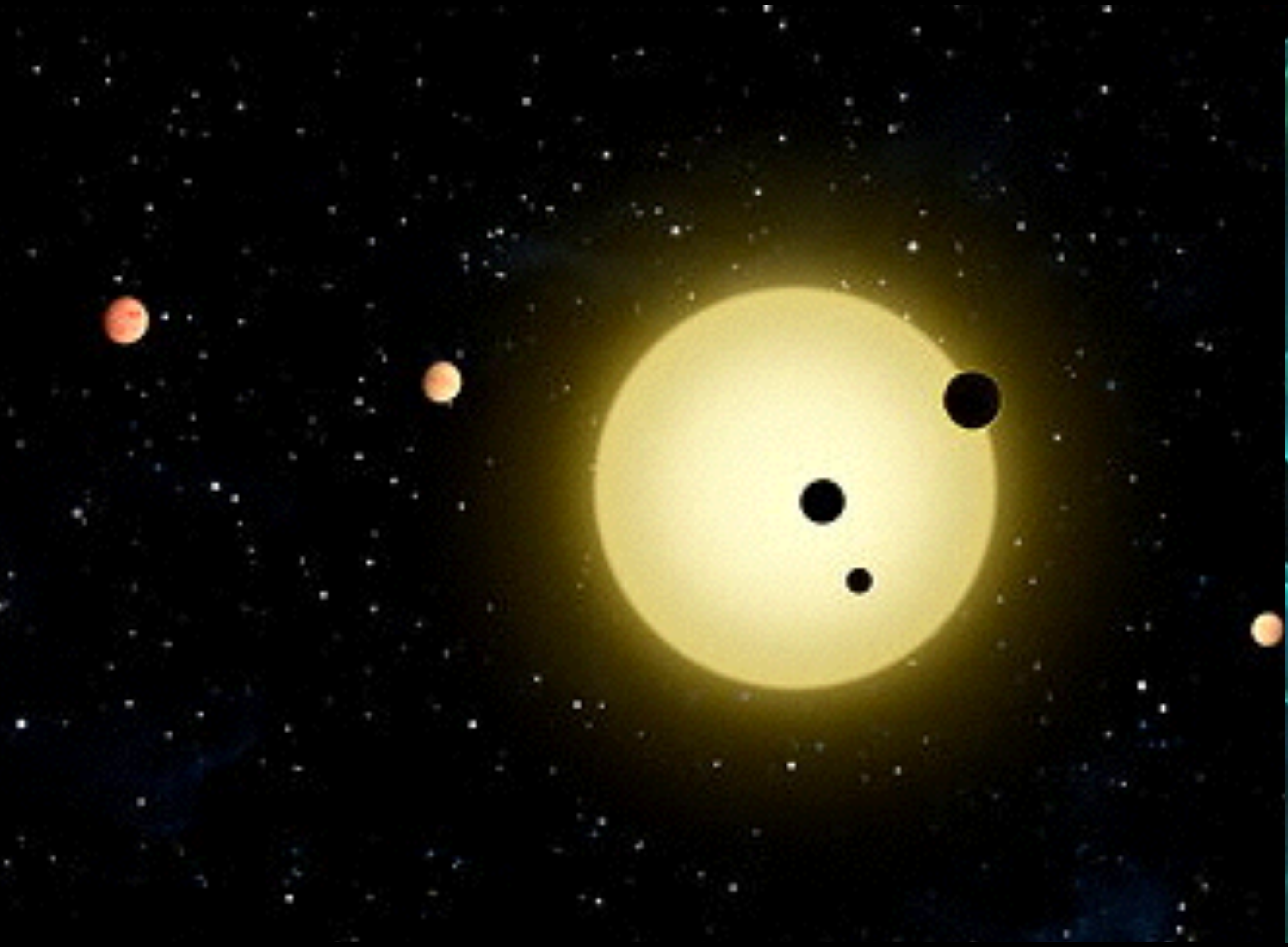
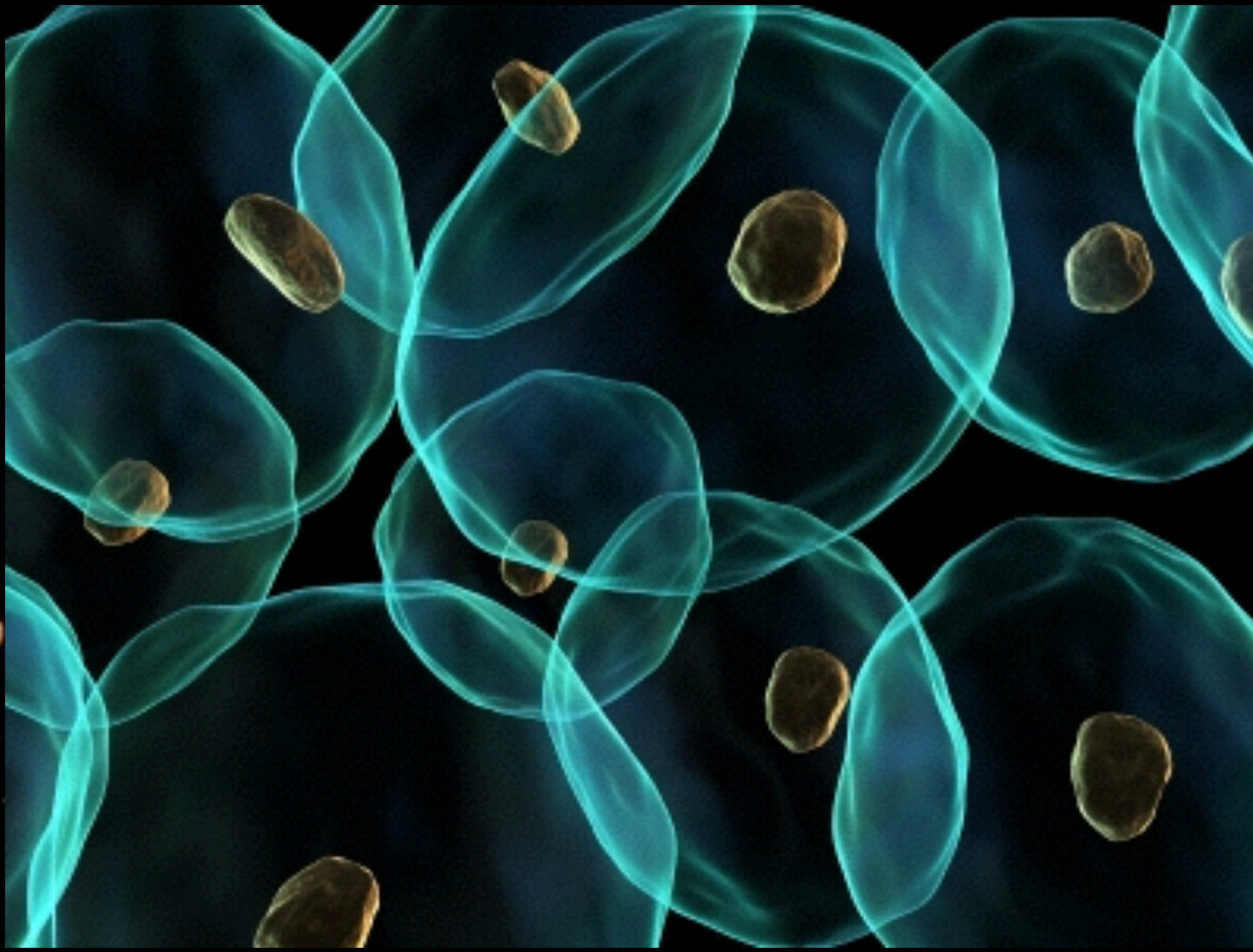
Kepler Planets — back to the origin





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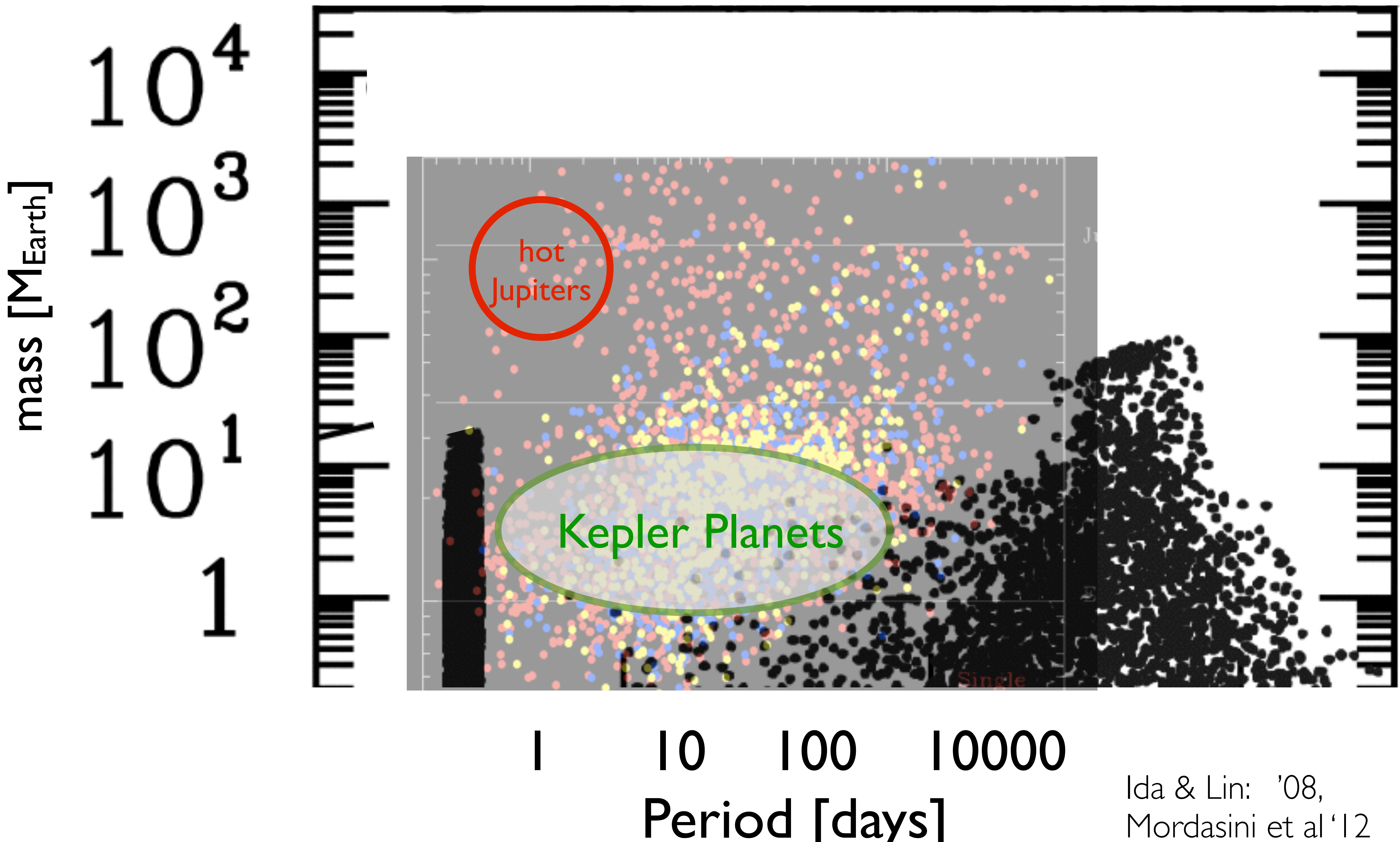
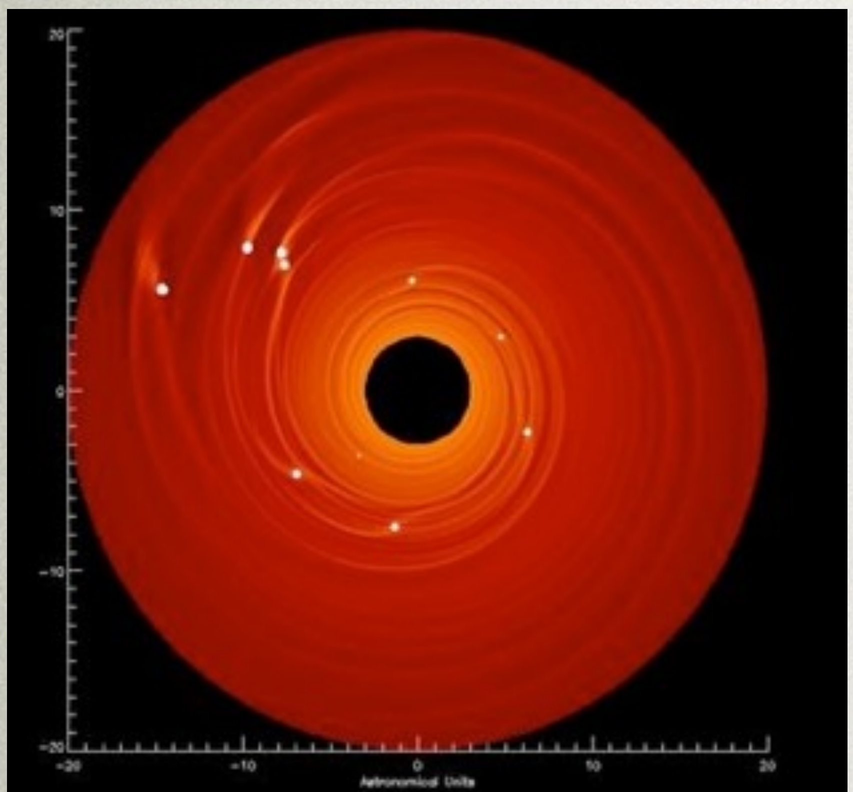
ACKNOWLEDGEMENTS TO THE KEPLER TEAM

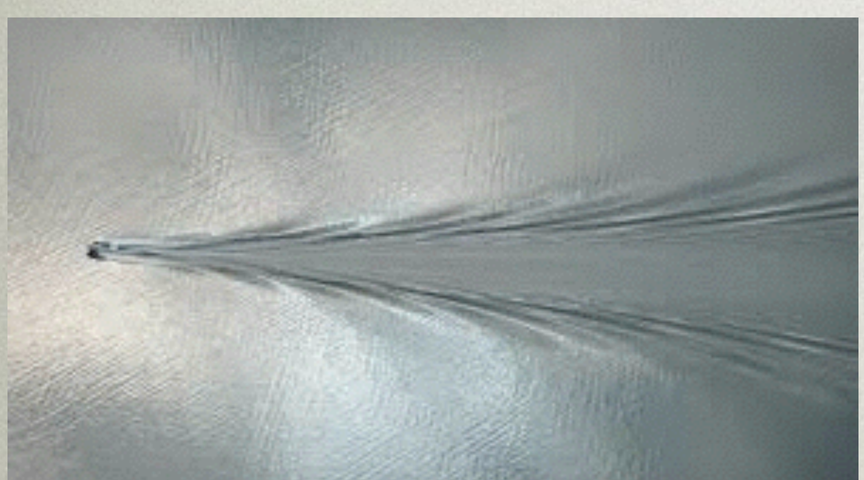
Kepler planets: an Unexpected population



Ida & Lin: '08, Mordasini et al '12

Difficult to retain these planets in gas disks.





The rapid Type I migration

(Ward '97, Tanaka & Ward '04)

$$\tau_a \equiv \frac{a}{\dot{a}} \sim \left(\frac{M_*}{M_p}\right)\left(\frac{M_*}{M_{\rm disk}}\right)\left(\frac{H}{a}\right)^2 \times P_{\rm orb}$$

$$\approx 1000 \text{ yrs } \left(\frac{1M_{\rm Earth}}{M_p}\right) \left(\frac{a}{0.1{\rm AU}}\right)^2$$

for MMSN type gas disk

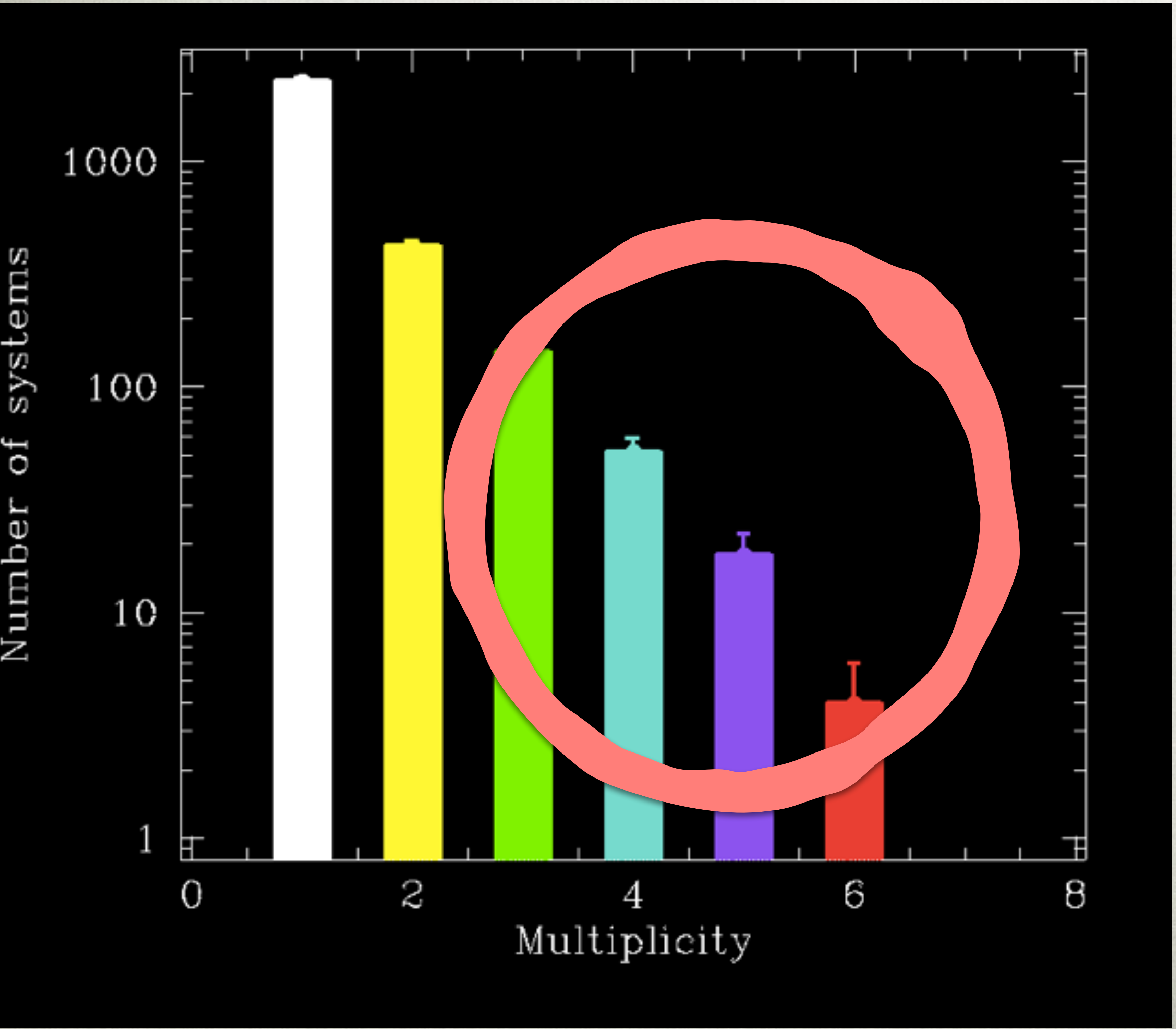
$$\tau_e = \frac{\dot{e}}{e} \approx 3\,{\rm yrs}$$

.torque reversal? disk edge? — get stuck in resonances.

.born after gas disk dissipation?

Npl	1	2	3	4	5	6	7
Nsys	2302	425	144	52	18	4	0

Oct '14

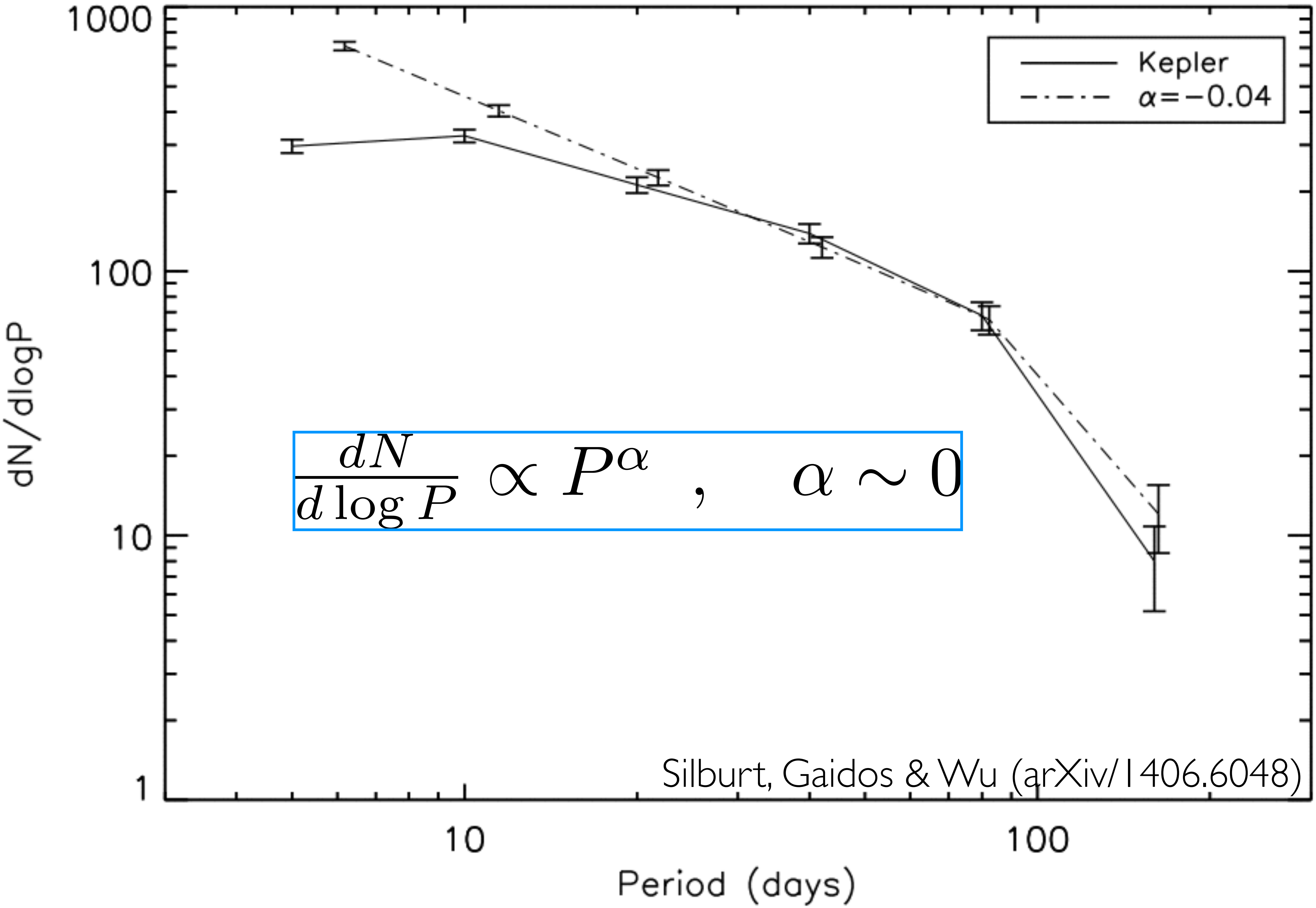


each star has in average ~ 0.8 planets;

some systems contain large number of planets (N ~ 10)

Howard et al '10,
Youdin '11,
Petigura et al '13
Fressin et al '13

This population extends from 0.05 to (at least) 1AU



$$\frac{dN}{d\log P} \propto P^{\alpha}\ , \quad \alpha \sim 0$$

"Back to the origin"

1. current composition ⇒ primordial composition

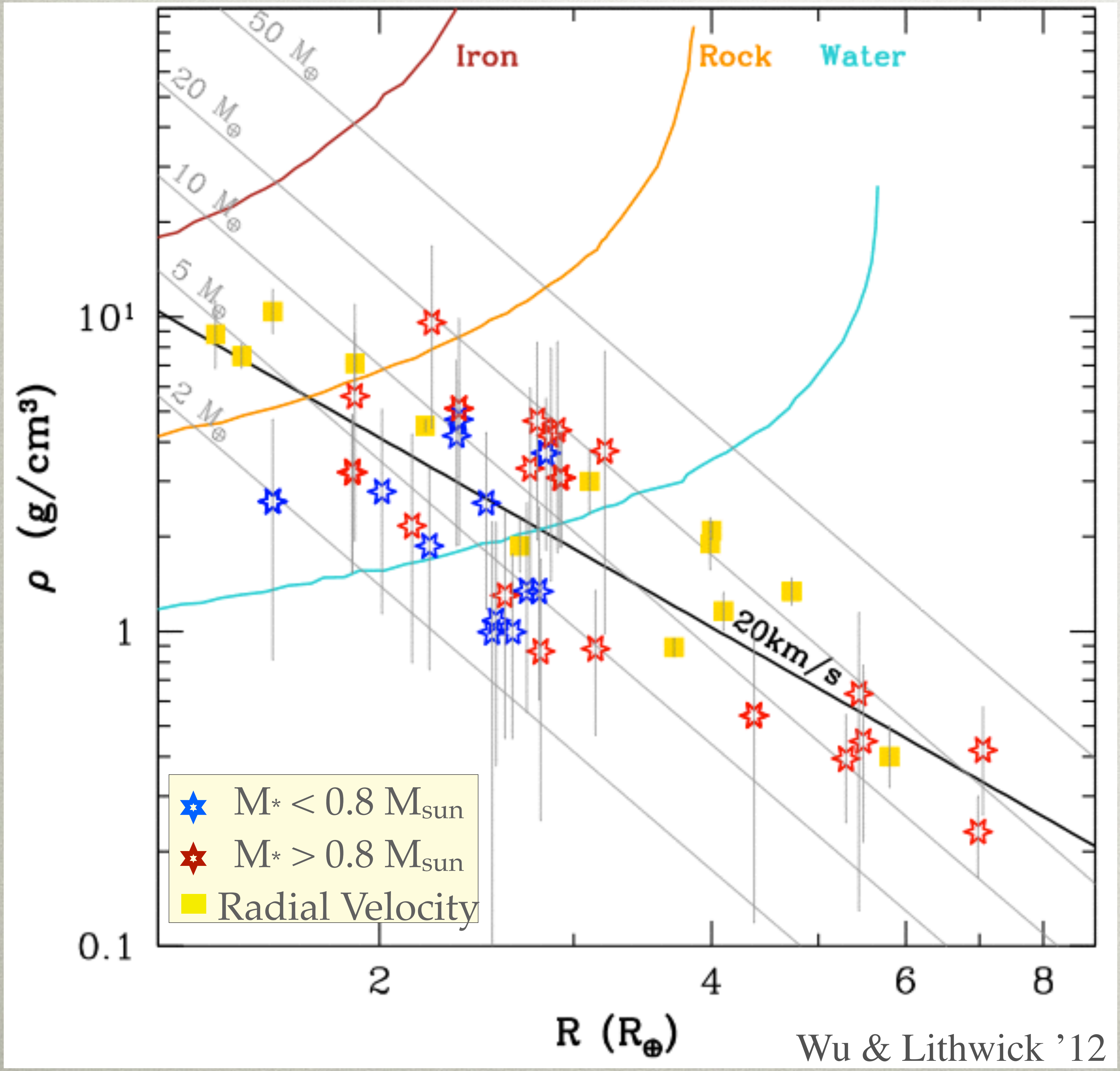
TTV (Agol et al '05, Holman & Murray '05, Lithwick et al '12)
+ RV mass measurements

2. current orbits ⇒ initial orbital arrangements

period, eccentricity, inclination measurements

Questions:
source of planetary materials?
gas accretion framework correct?
formed in gas disks?
migration? in-situ?

32 planet densities measured using TTV (statistical)



TTV-masses 2 - 20 M_E

Mass-Radius Relation:

$$M \sim 3M_\oplus \frac{R}{R_\oplus}$$

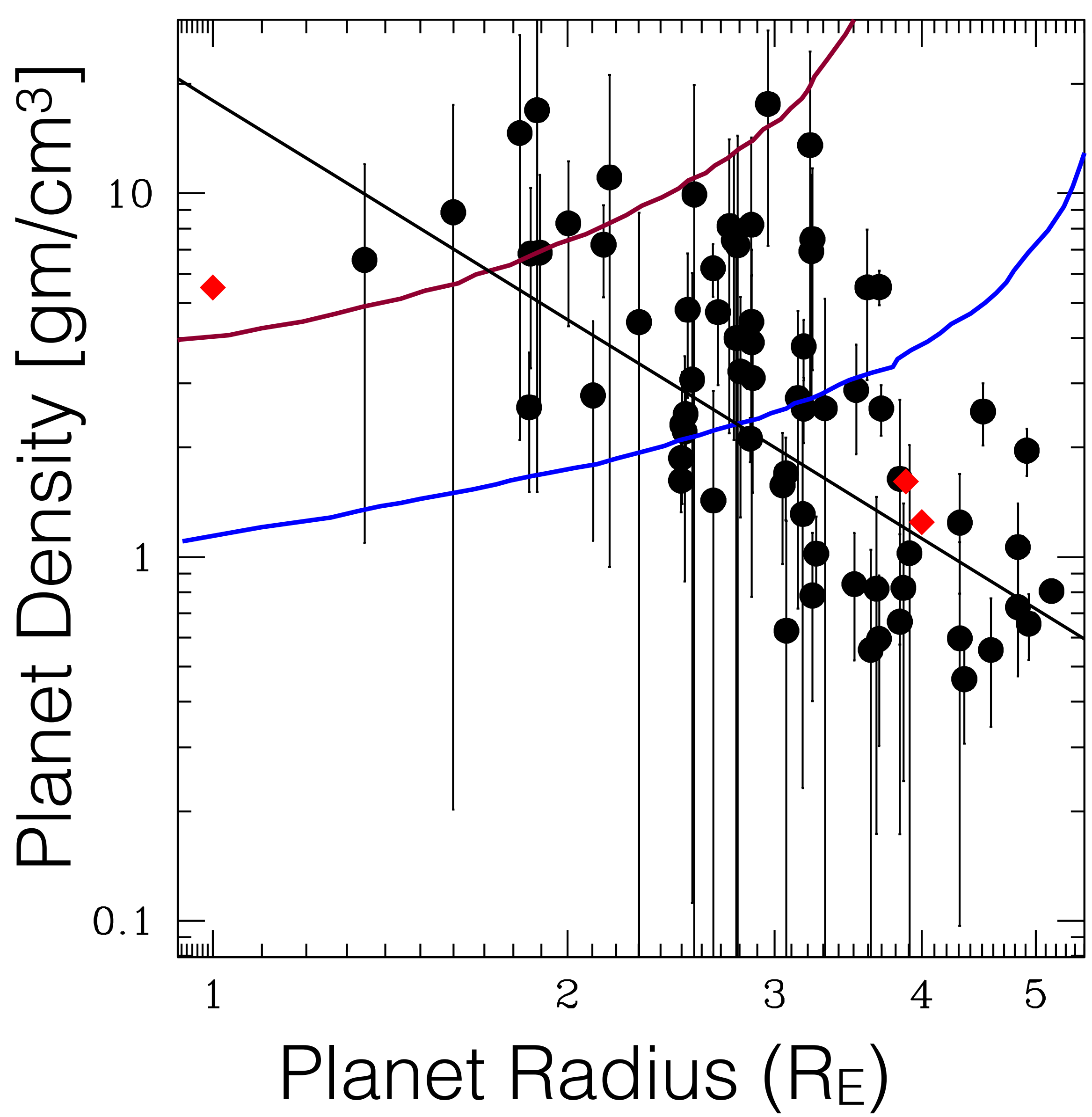
sign of volatile?

More density measurements…

~140 TTV planets

$$\rho \approx 3\rho_\oplus (R/R_\oplus)^{-2}$$

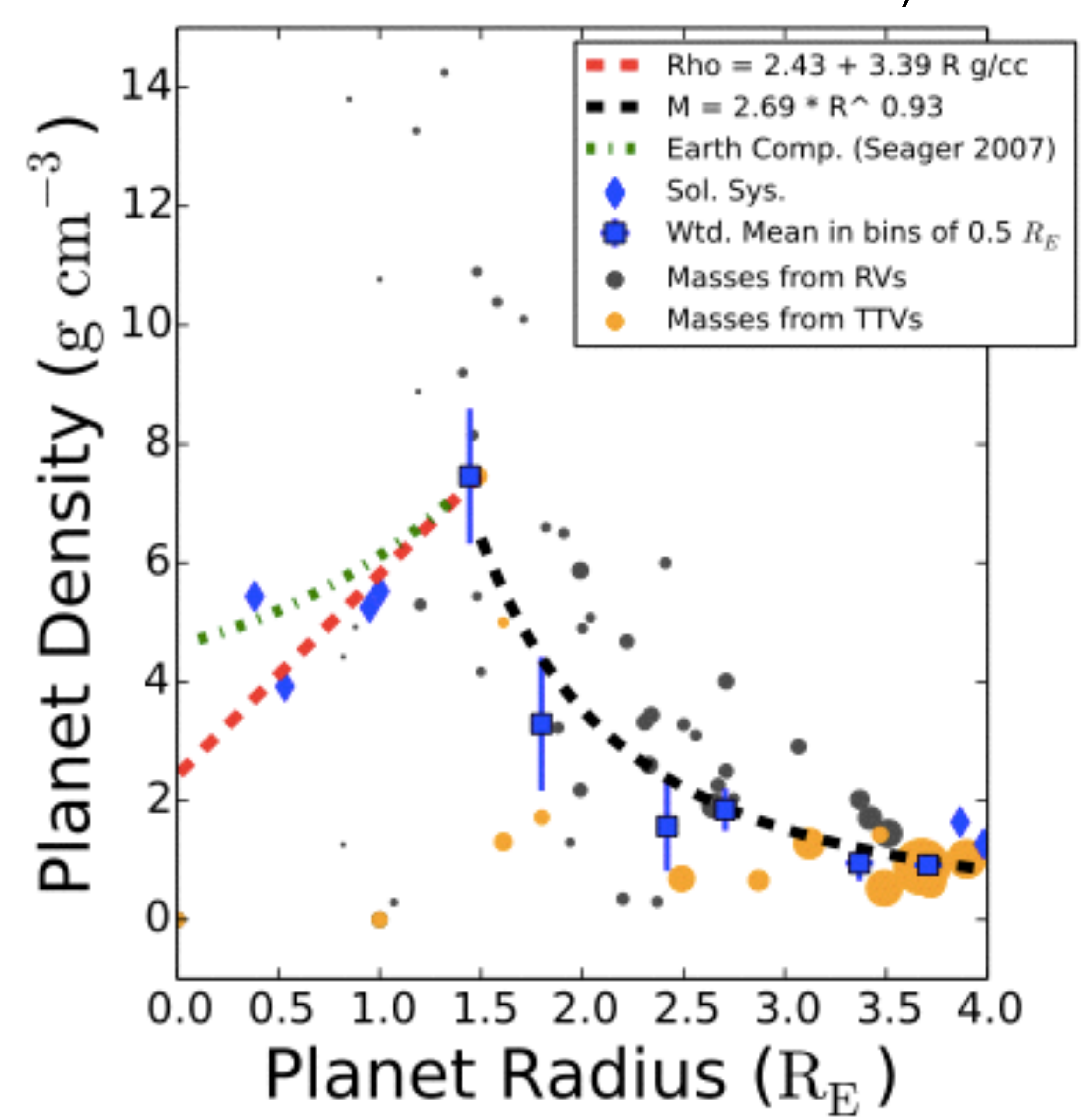
Hadden & Lithwick '14



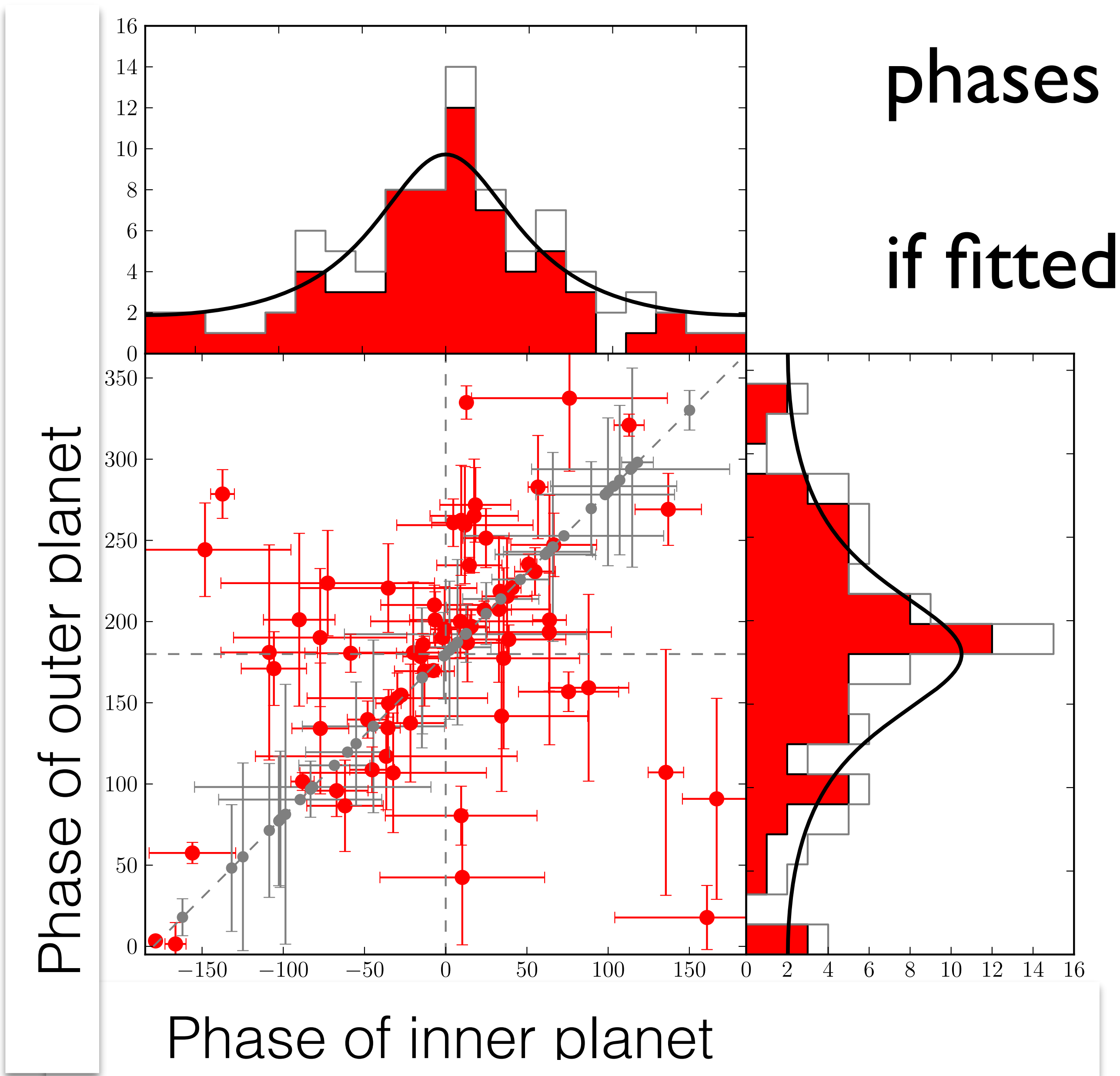
~20 RV planets

$$\rho \approx 2.4\rho_\oplus (R/R_\oplus)^{-2.1}$$

Weiss & Marcy '14



Eccentricity measurements for 70 planet pairs:



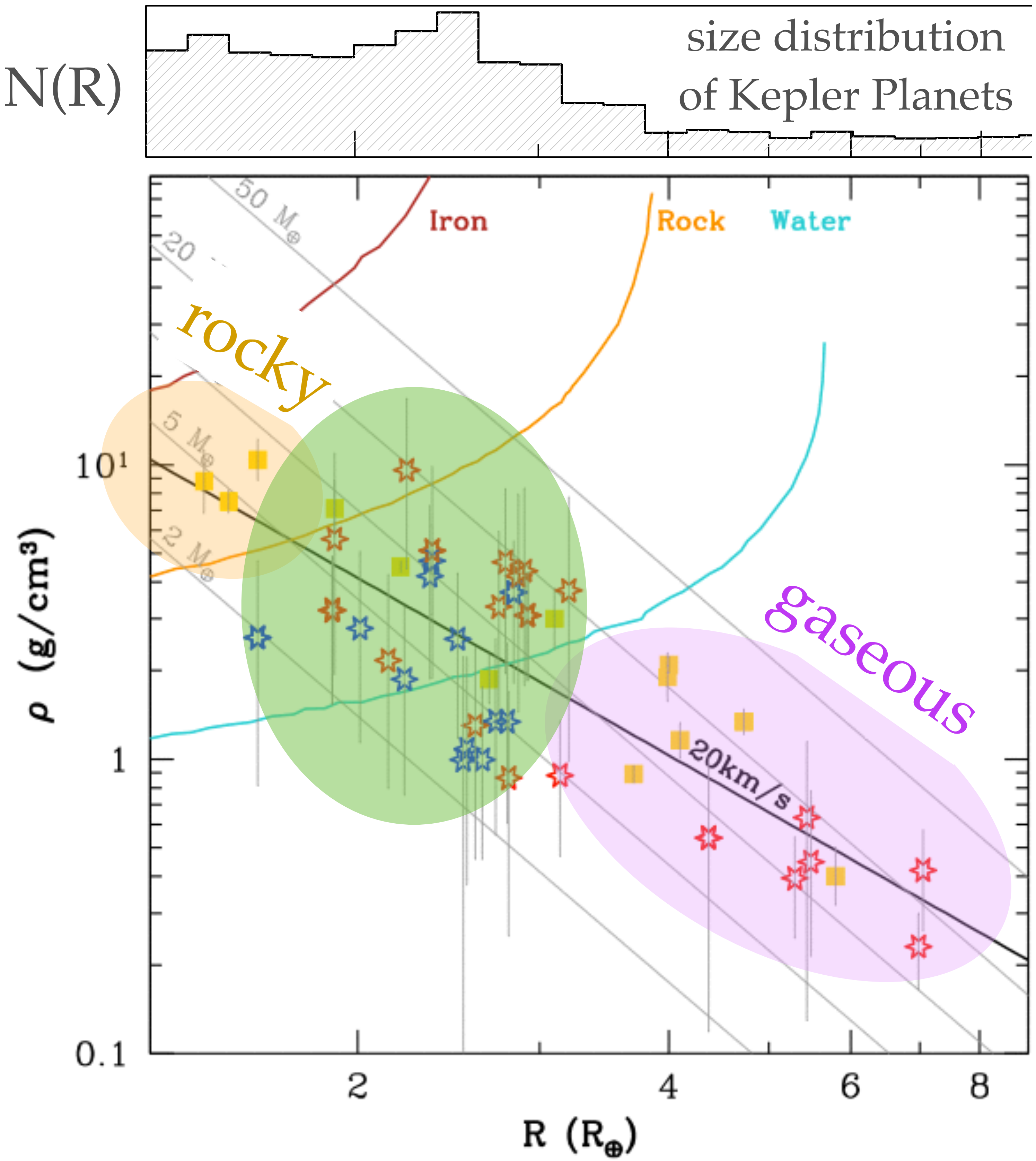
phases of TTV affected by eccentricity.

if fitted with a Rayleigh distribution

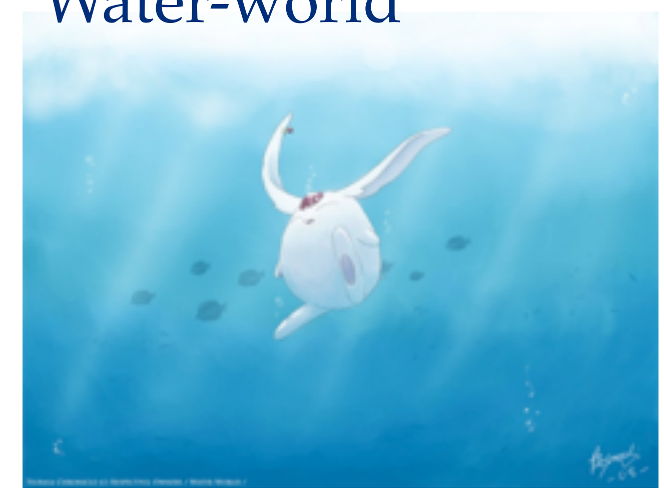
$$\sigma_e = 0.018^{+0.004}_{-0.008}$$

(Hadden & Lithwick '13,
Wu & Lithwick '12)

Degeneracy in internal composition

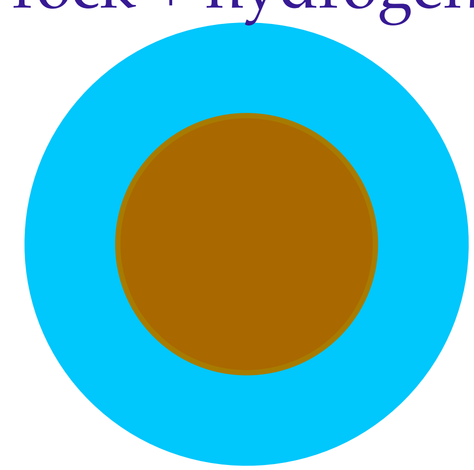


Water-world

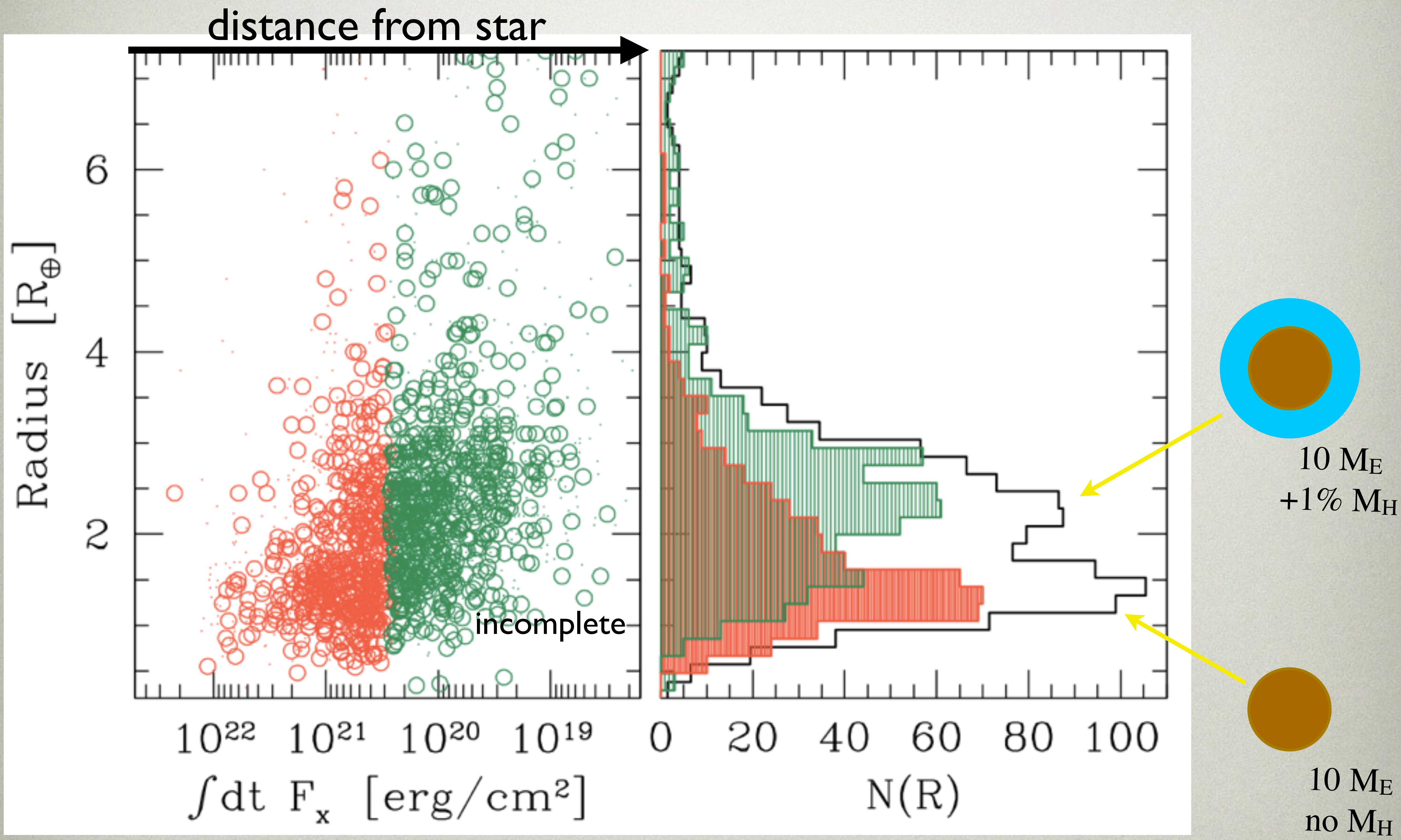


or

rock + hydrogen



Closer-in planets tend to be smaller & denser



size correlate strongly with X-ray exposure

Owen & Wu '13

photo-evaporation of hydrogen envelope

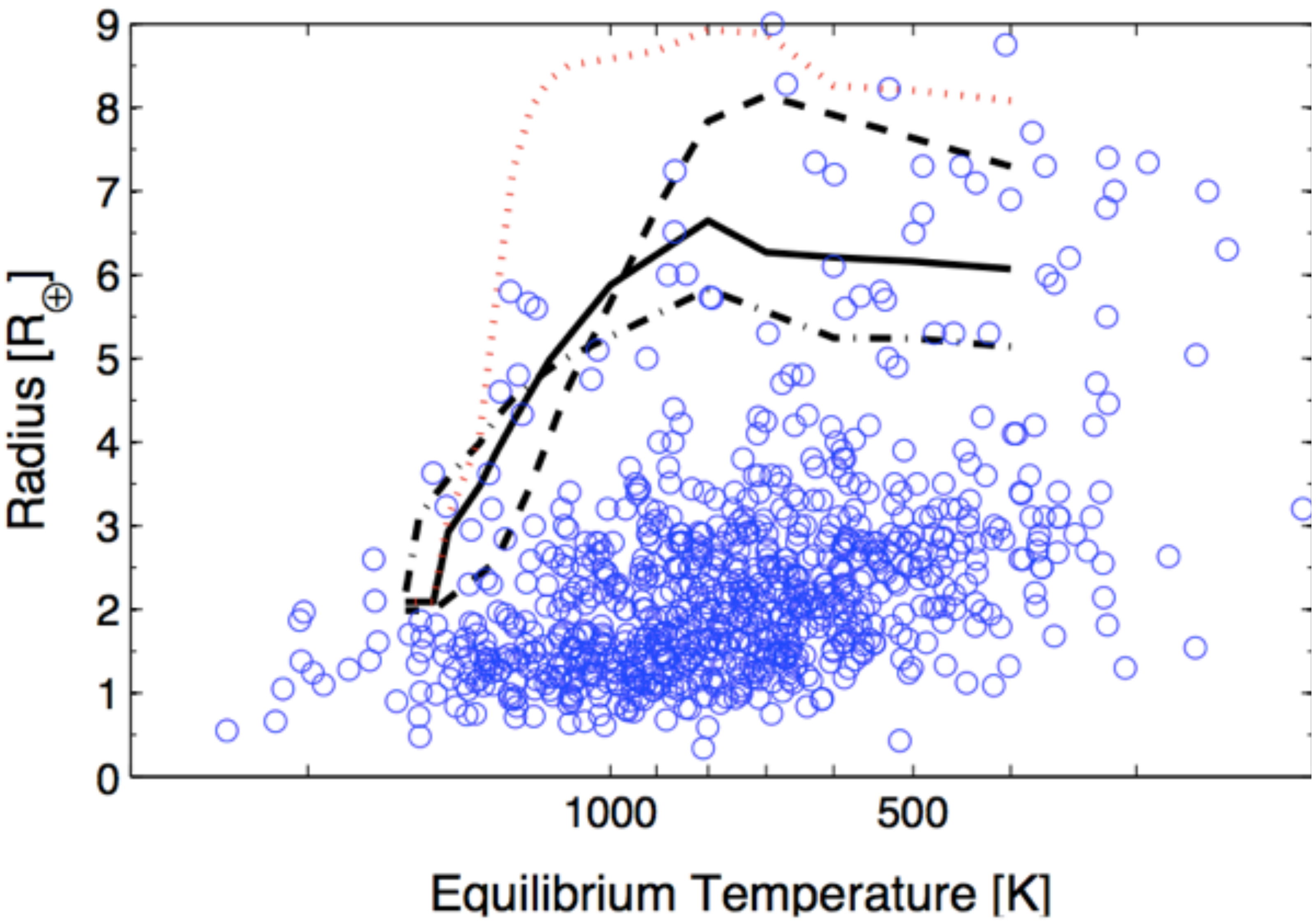
(Owen & Wu '13, also see Lopez et al '12)

back-of-the-envelope...

$$\dot{m} \times \frac{GM_p}{R_p} = \eta \frac{L_X}{4\pi a^2} \times \pi R_p^2$$

$$\frac{\Delta m}{M_p} \approx 0.05\% \ \left(\frac{\eta}{1}\right) \left(\frac{L_X}{10^{27}\mathrm{erg/s}}\right) \times \left(\frac{0.1\mathrm{AU}}{a}\right)^2 \left(\frac{R_p}{3R_\oplus}\right)^3 \times \left(\frac{10M_\oplus}{M_p}\right)^2 \left(\frac{t}{5\mathrm{Gyrs}}\right)$$

...and beyond



- stellar X-ray ionize metals in atmosphere; gas thermalized to ~ 8000K; hydrodynamic outflow
- planet thermal contraction (MESA, Paxton et al '11)
- Most evaporation occurs in the first 100 Myrs.
- low-mass planets inward of 0.1AU are strongly affected; can lose up to 50% of total mass

"Back to the origin"

1. current composition ⇒ primordial composition

majority planets = <u>10 M_E</u> refractory + <u>1%</u> Hydrogen envelope
formed before gas fully dissipated;
no sign of volatiles

2. current orbits ⇒ initial orbital arrangements

Questions:
source of planetary materials?
gas accretion framework correct?
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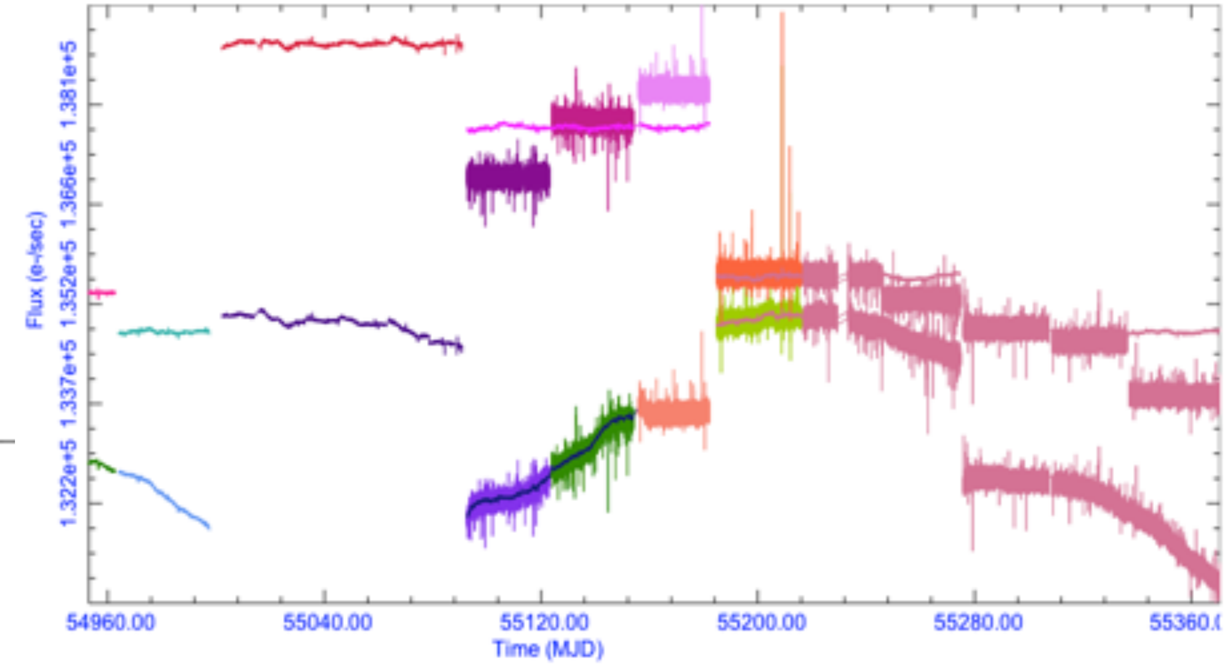
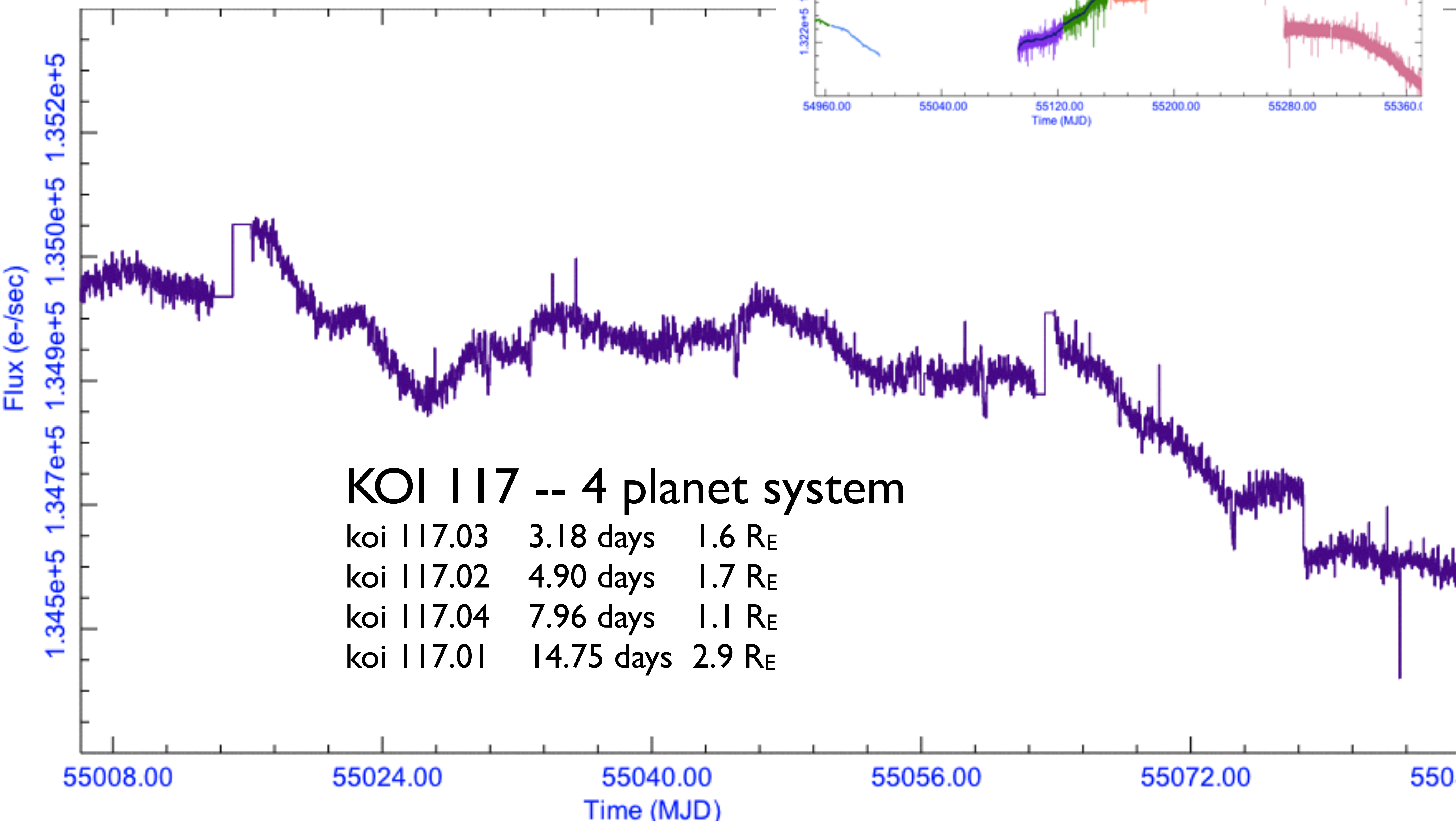
Orbits, orbits…





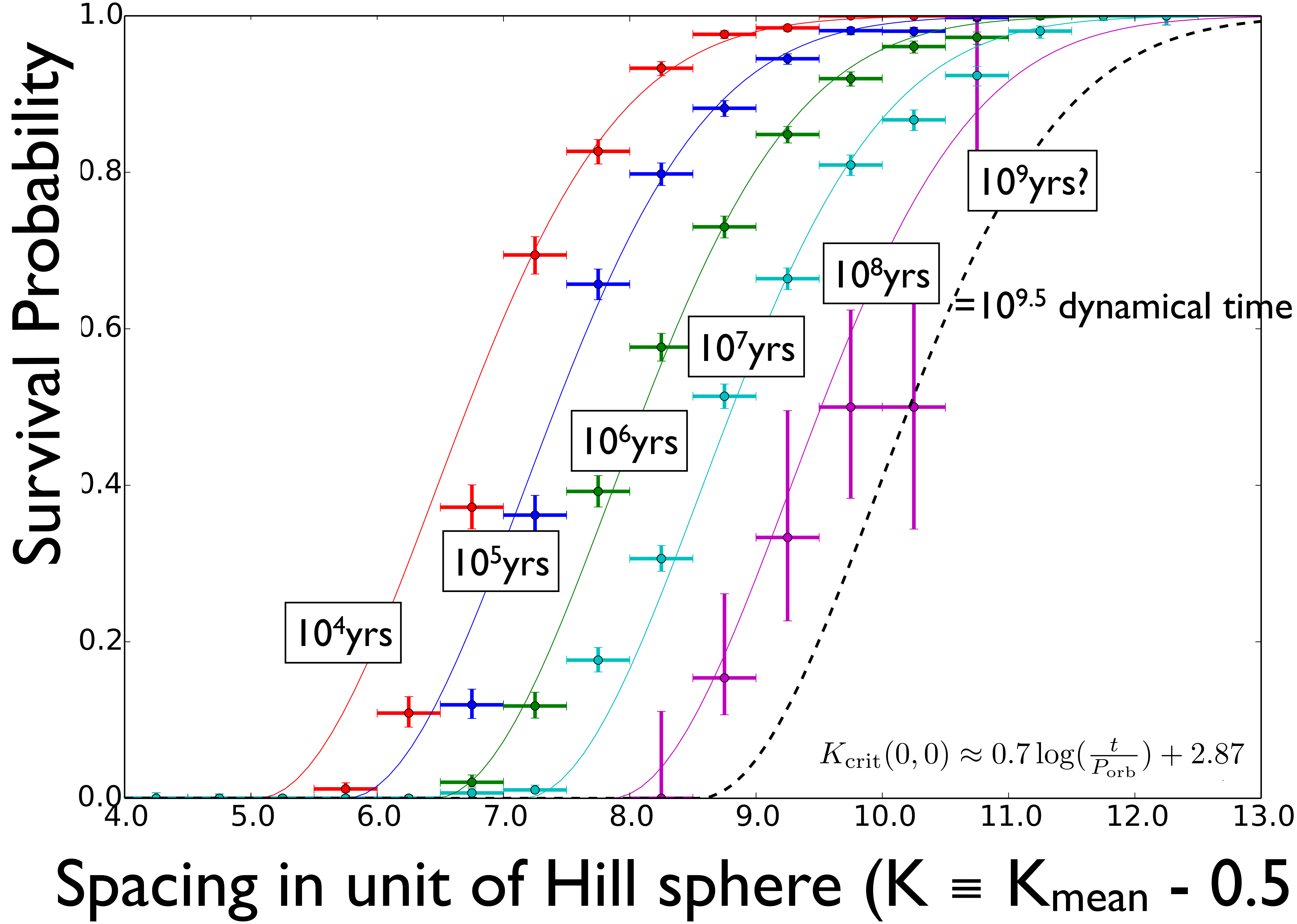
KOI 117 -- 4 planet system

koi 117.03	3.18 days	1.6 R_E
koi 117.02	4.90 days	1.7 R_E
koi 117.04	7.96 days	1.1 R_E
koi 117.01	14.75 days	2.9 R_E

Continuous Destabilization of Planetary Systems

Pu & Wu (in prep)

also Chambers et al '96. Smith & Lissauer '09, Funk et al '10, Zhou et al '07 '



Minimum spacing for a ladder of planets

- Coplanar,circular: K_{crit} = 10 @ 1 Gyrs

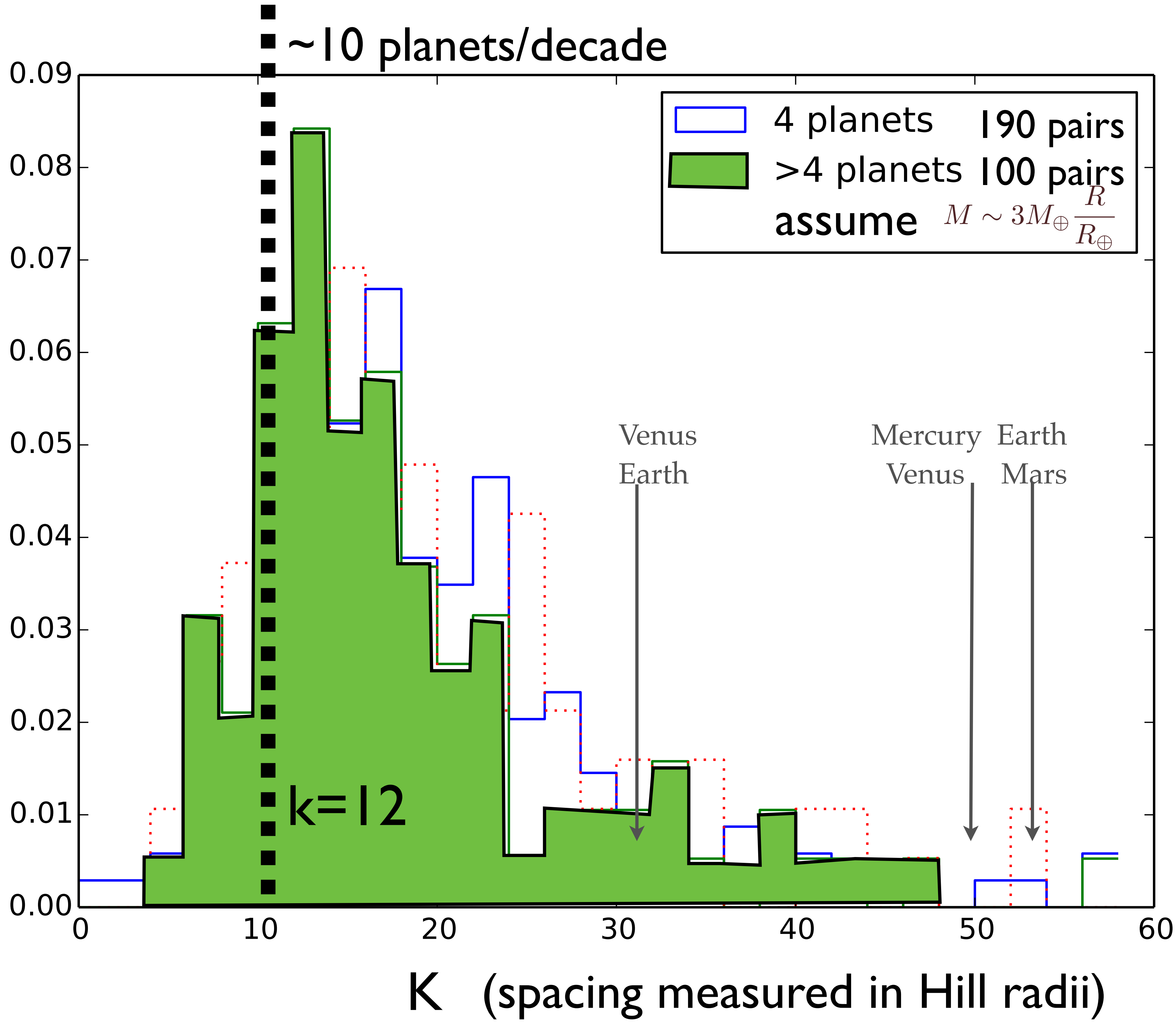
- Eccentric, inclined: need more elbow-room

$$K_{\rm crit}(\sigma_e, \sigma_{\rm inc}) \approx K_{\rm crit}(0,0) + \left(\frac{\sigma_e}{0.01}\right) + \left(\frac{\sigma_{\rm inc}}{0.04}\right)$$

TTV determinations: σ_e = $0.018^{+0.004}_{-0.008}$

⇒ To survive 1 Gyrs: K_{crit} = 12

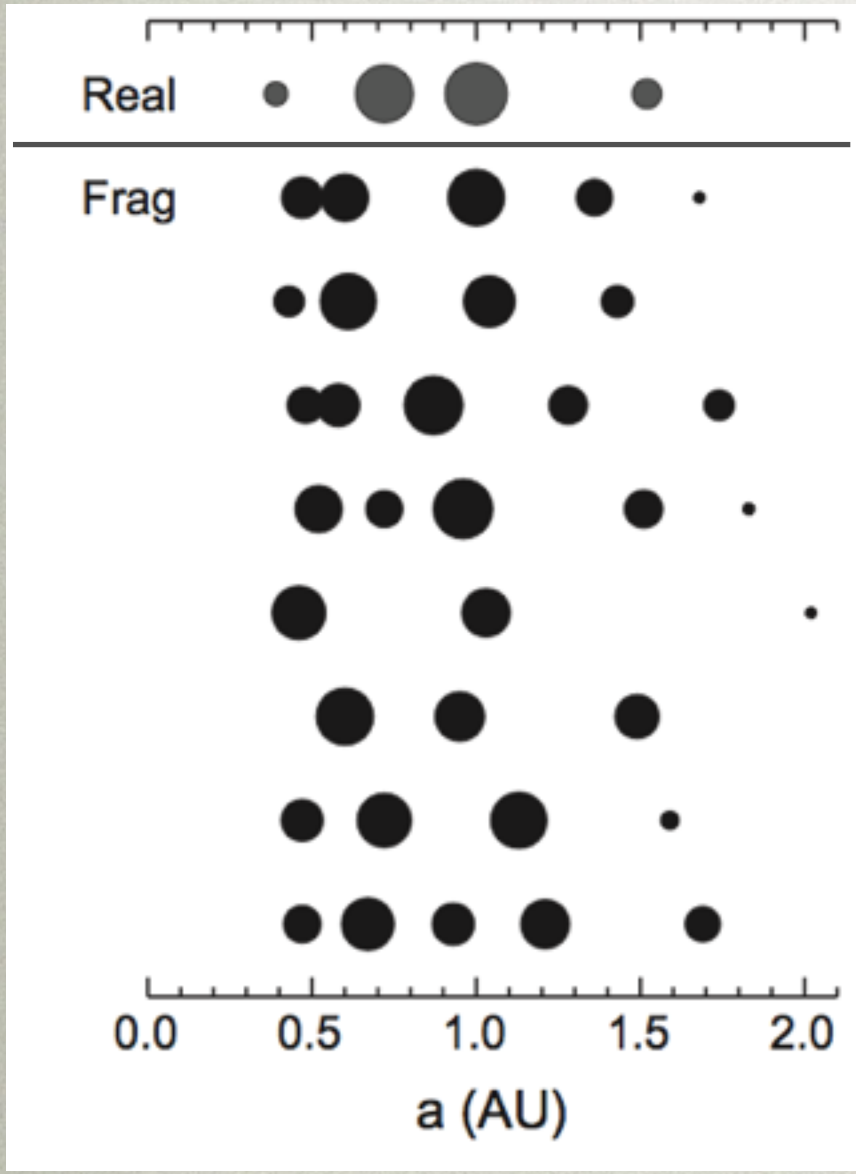
Observed Spacing of high-N Kepler systems



How to form such tightly spaced systems?

— Migration? (talk by Nelson)
— In-situ conglomeration?

terrestrial planets

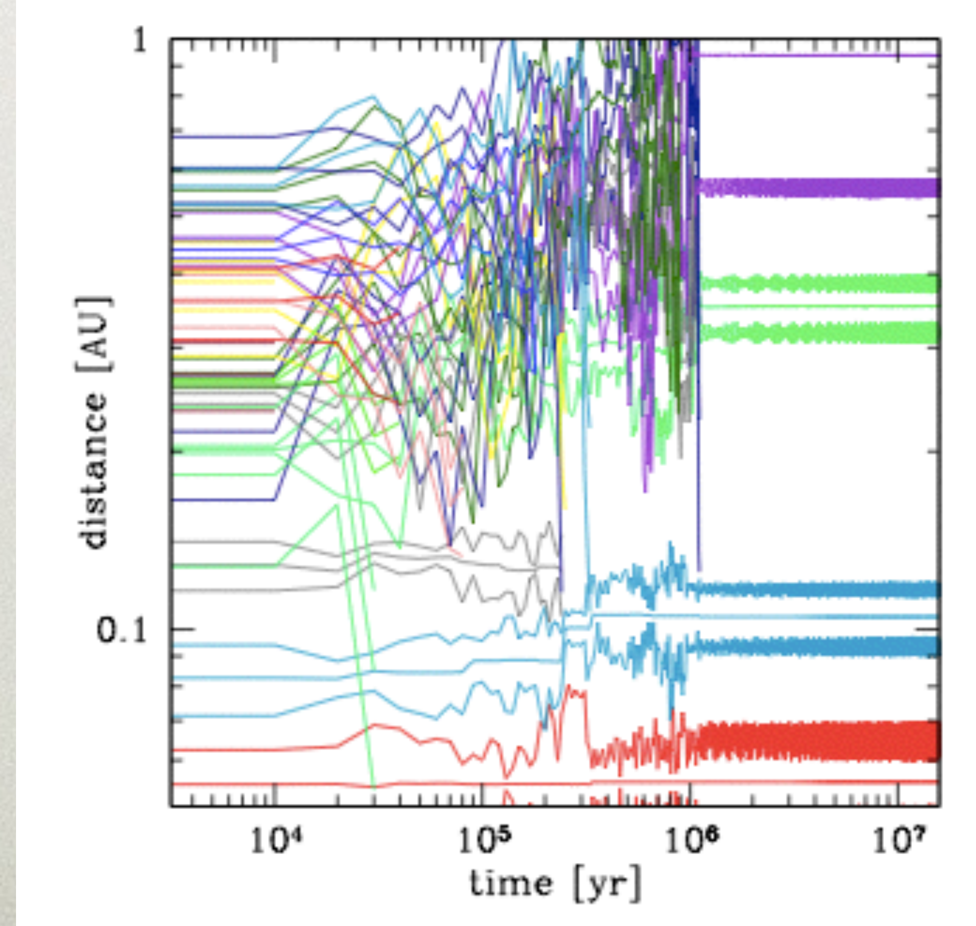


Chambers ’13; also
Chambers ’98, ’00, ’13,
Kokubo & Ida ’95, ’00, ’12...
Morishima et al ’08

“success”:
~ **4**/a-decade

because
e ~ inc ~ 0.2

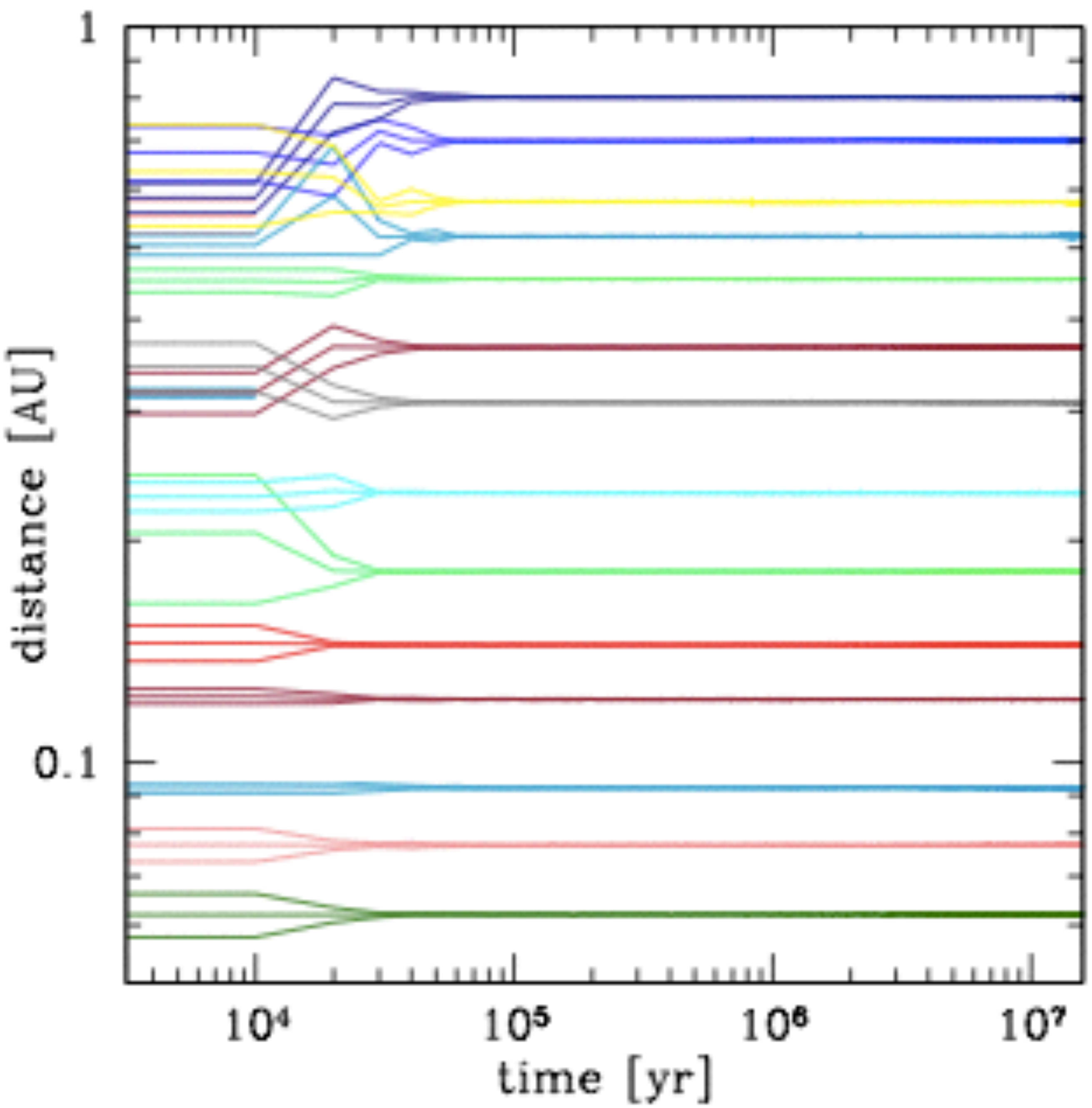
Kepler systems



Hansen & Murray ‘12

How to form such tightly spaced systems?

Repeat merging simulation, but with eccentricity damping

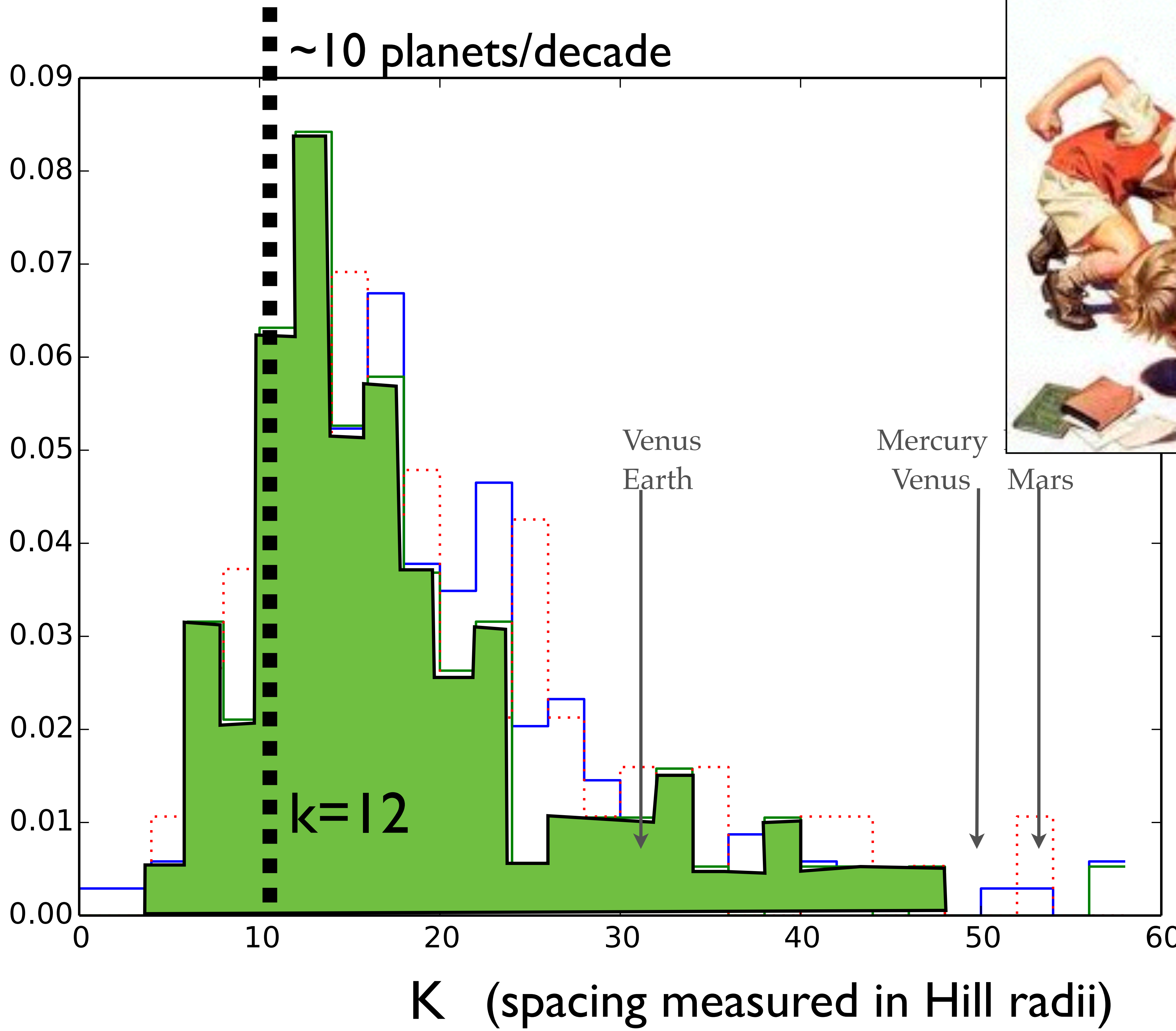


$t_{damp}=10^5$ yr for 10^7 yr: perfect merging

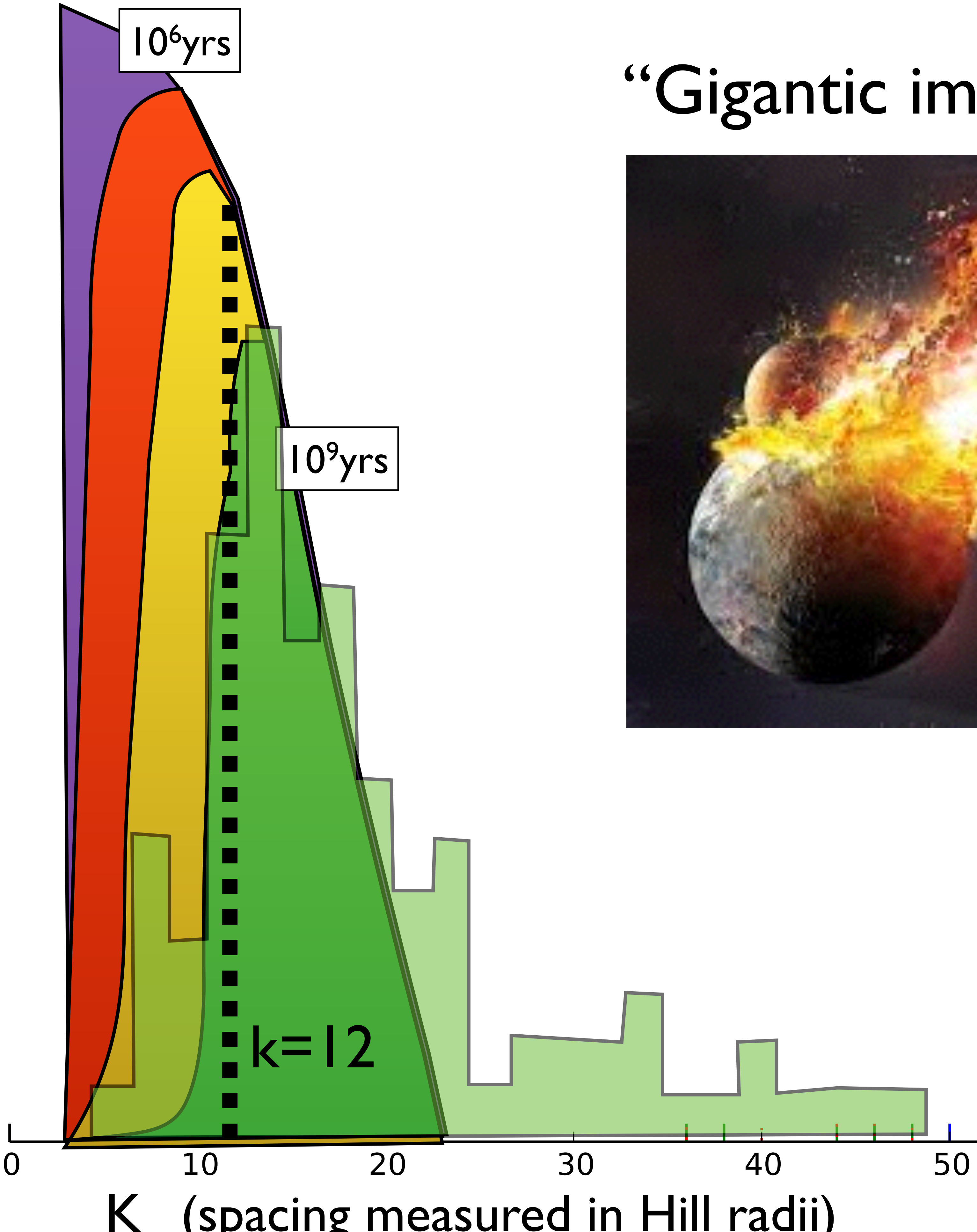
Result: high-multi systems ~ 10 planets/decade

Kominami & Ida ‘02
Lithwick & Wu ‘in prep

Two types of planetary systems:



“Gigantic impacts”

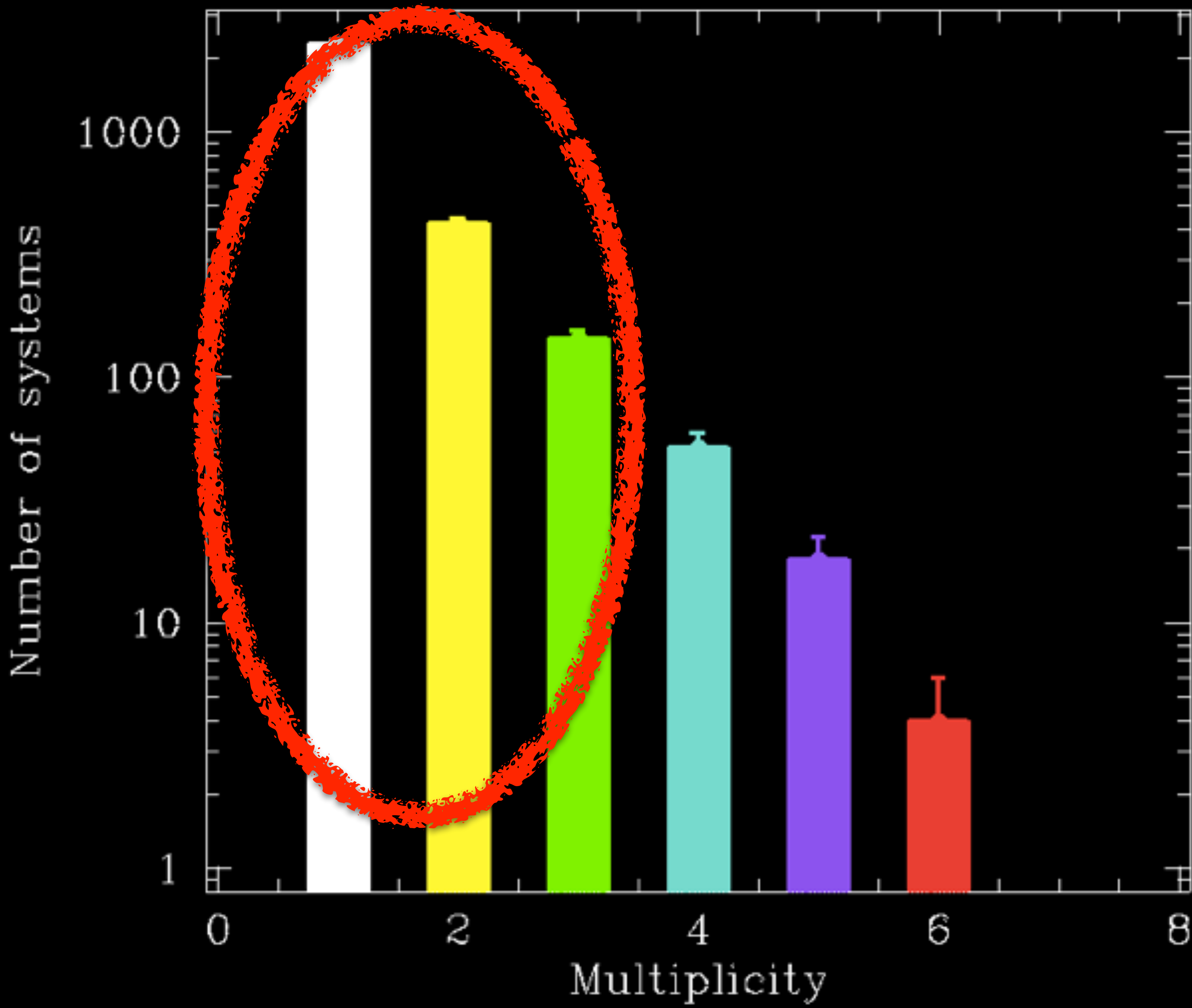


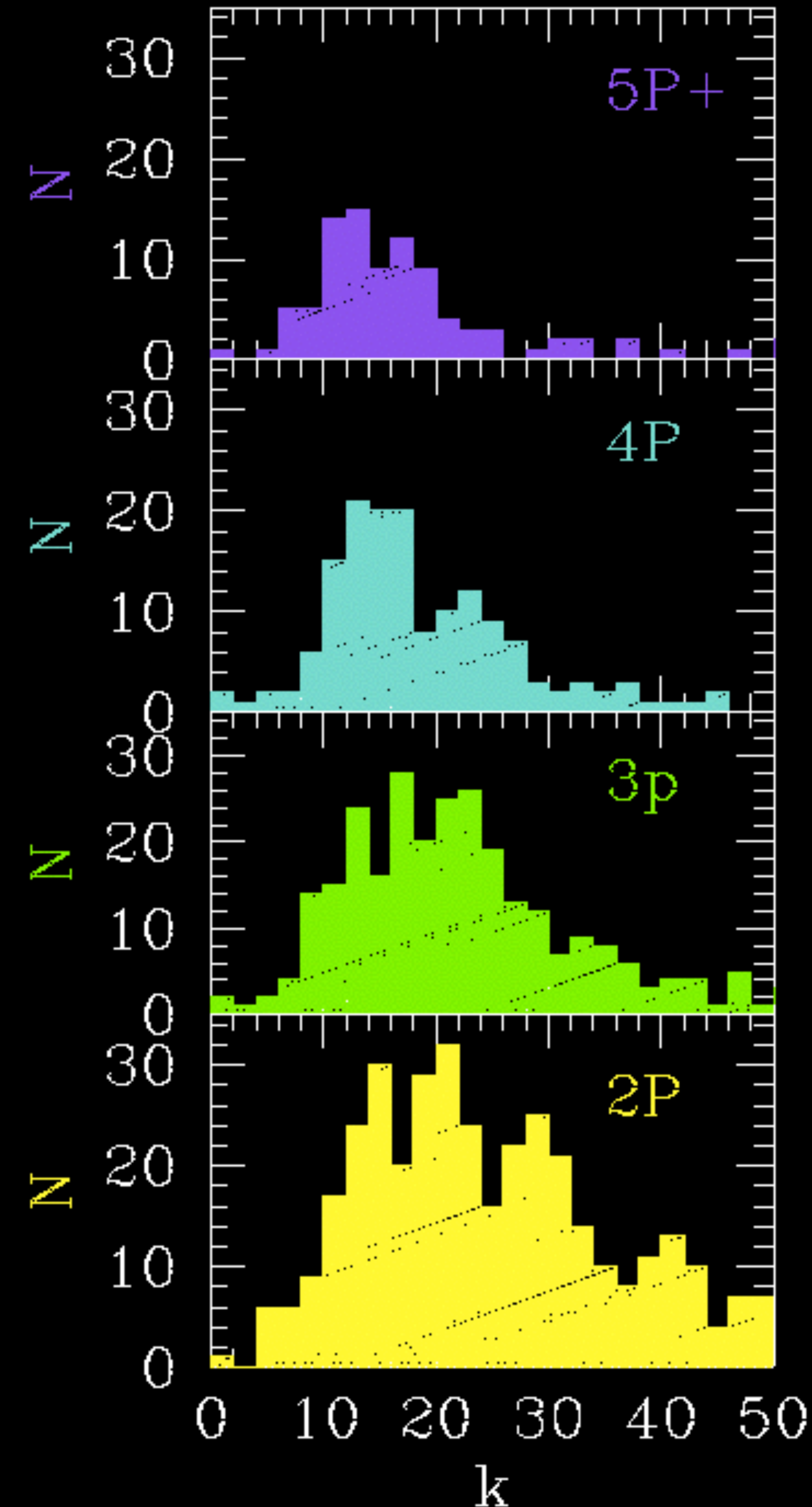
Low-N Kepler systems:

~ 75% of all systems

e ~ inc ~ 0.1

K ~ 30





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1. current composition ⇒ primordial composition

majority planets = <u>10 M_E</u> refractory + <u>1%</u> Hydrogen envelope
formed before gas fully dissipated;
no signature of volatiles

2. current orbits ⇒ initial orbital arrangements

majority system formed compact (~ 10 planets/decade);
but many trimmed down by 'gigantic impacts'
'extreme debris disks',

Questions:
source of planetary materials?
gas accretion framework?
formed in gas disks?
migration? in-situ?