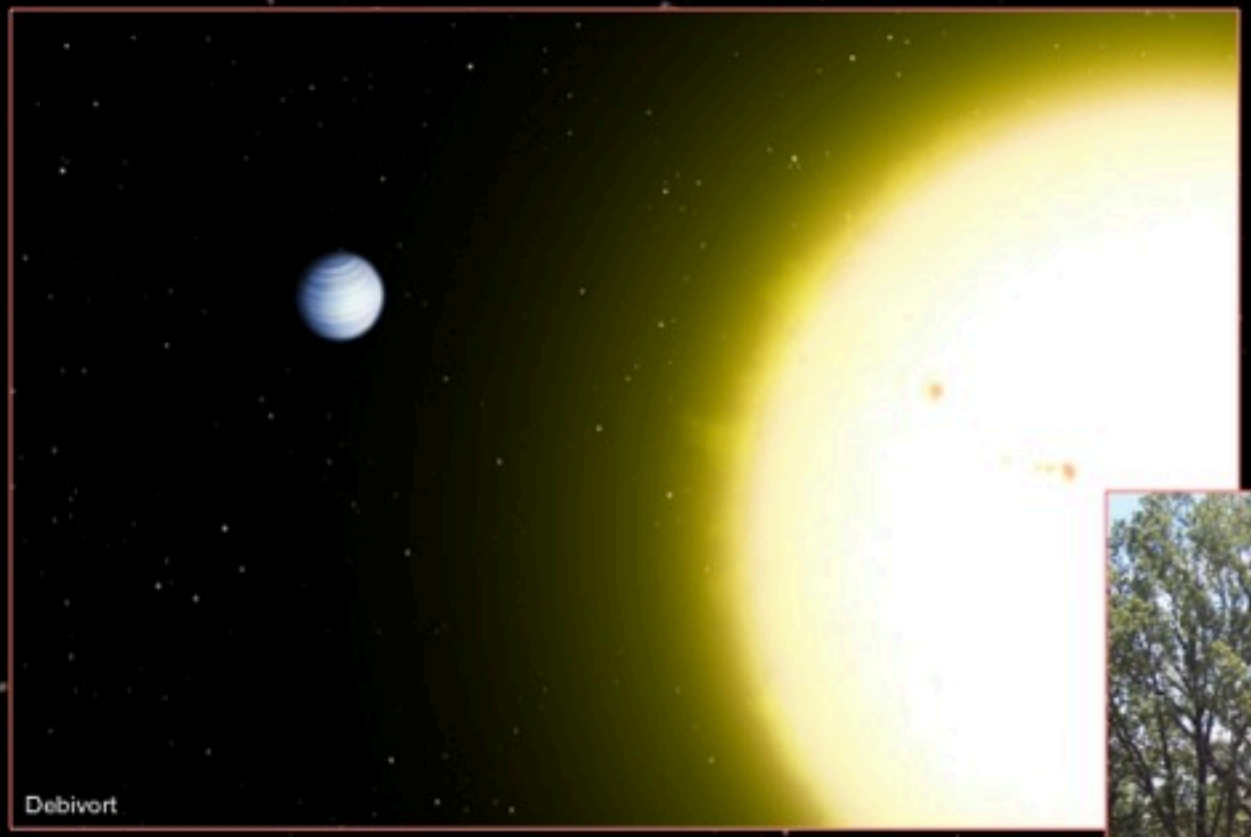
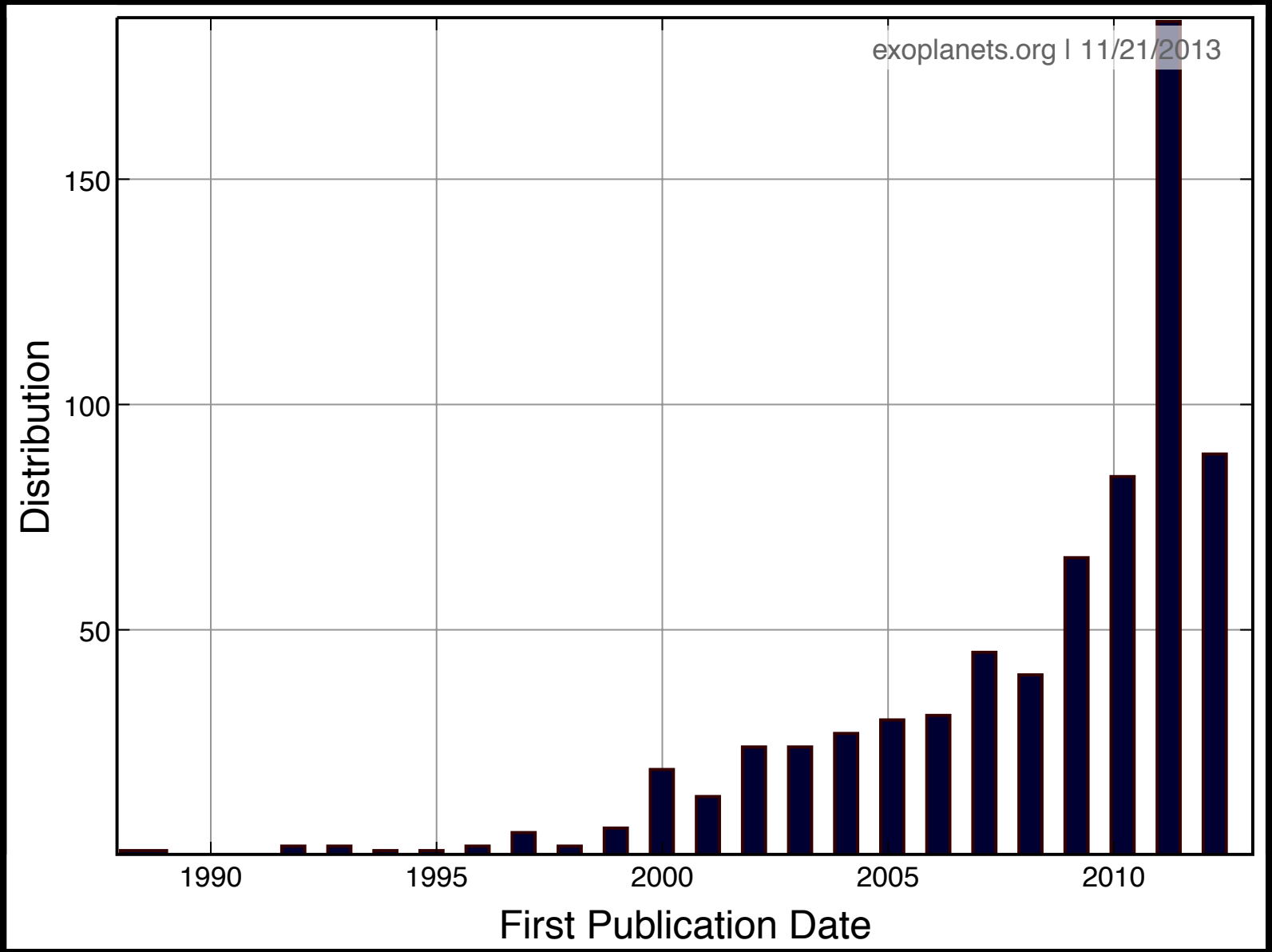
Exoplanet around a Sun-like Star



51 Peg b
OHP
France

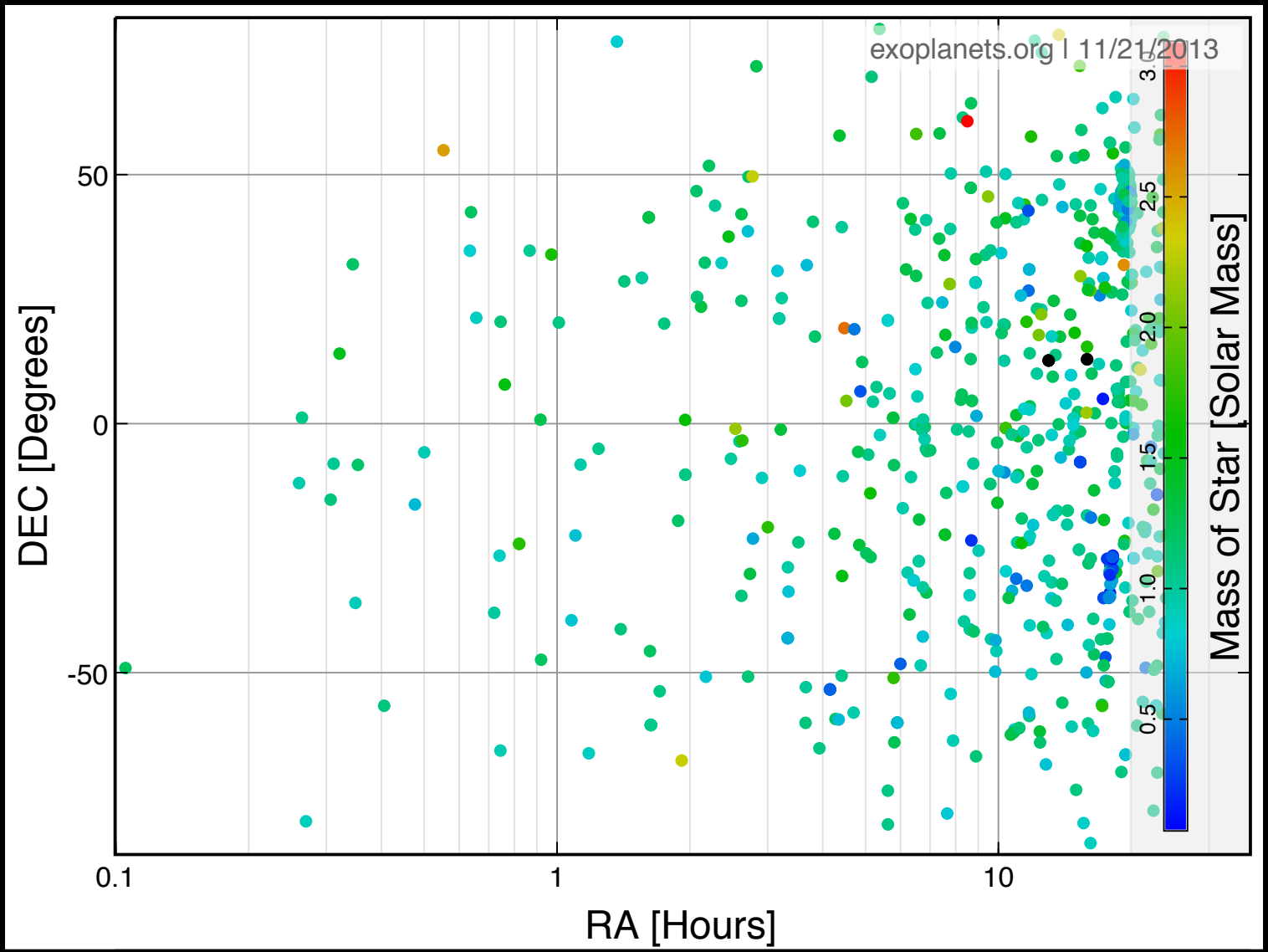
1543 — 1609 — 1781 — 1846 — 1993 — 1995 — 1999 — 2001 — 2009

Planet Detection Timeline

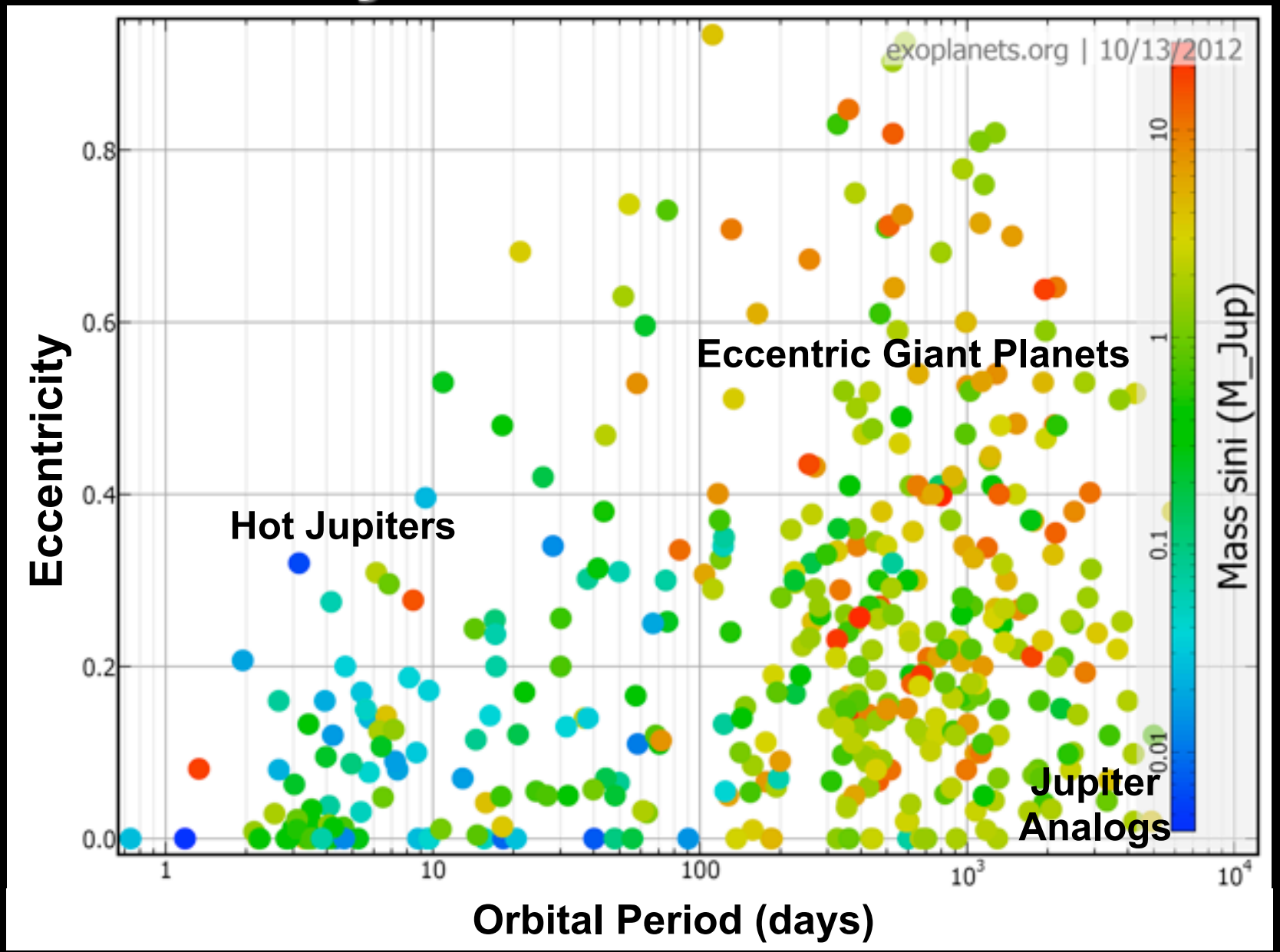


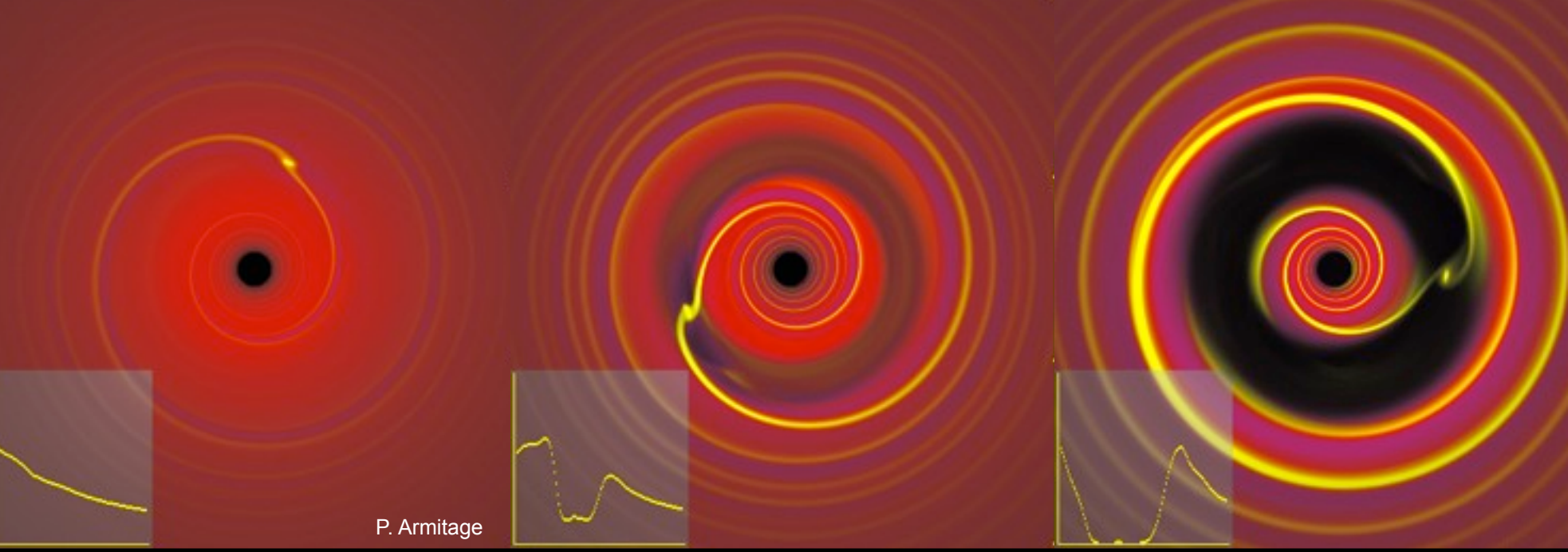
Exoplanet around a Sun-like Star

They are everywhere!



Diversity of Extrasolar Planets





New Theories of Planet Formation

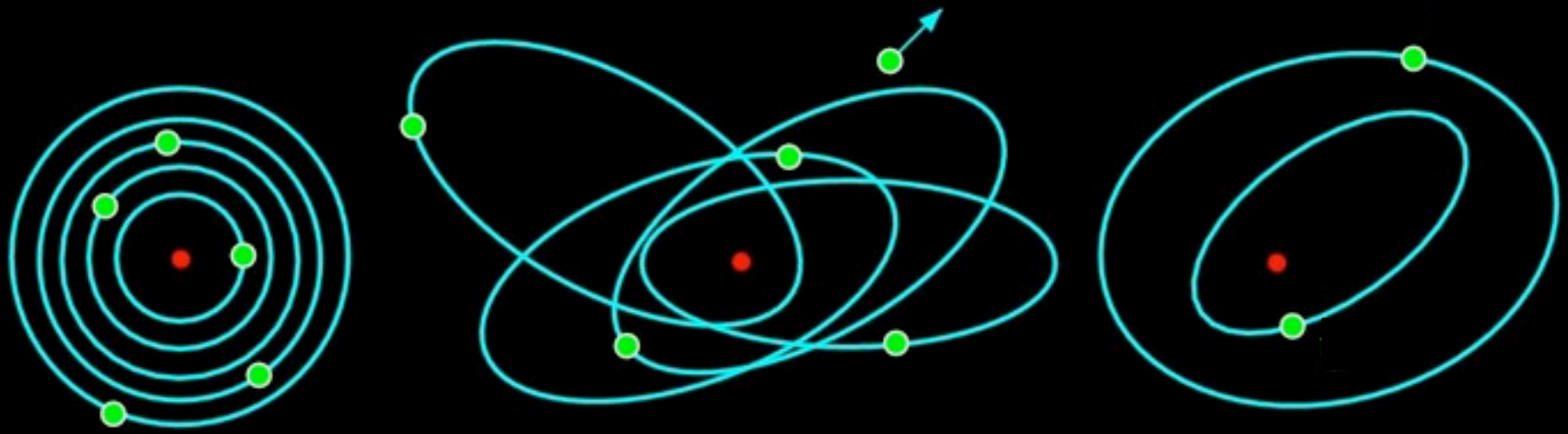


Illustration by E. Chiang; Adaptations E. Ford

Hot Jupiters via Disk Migration

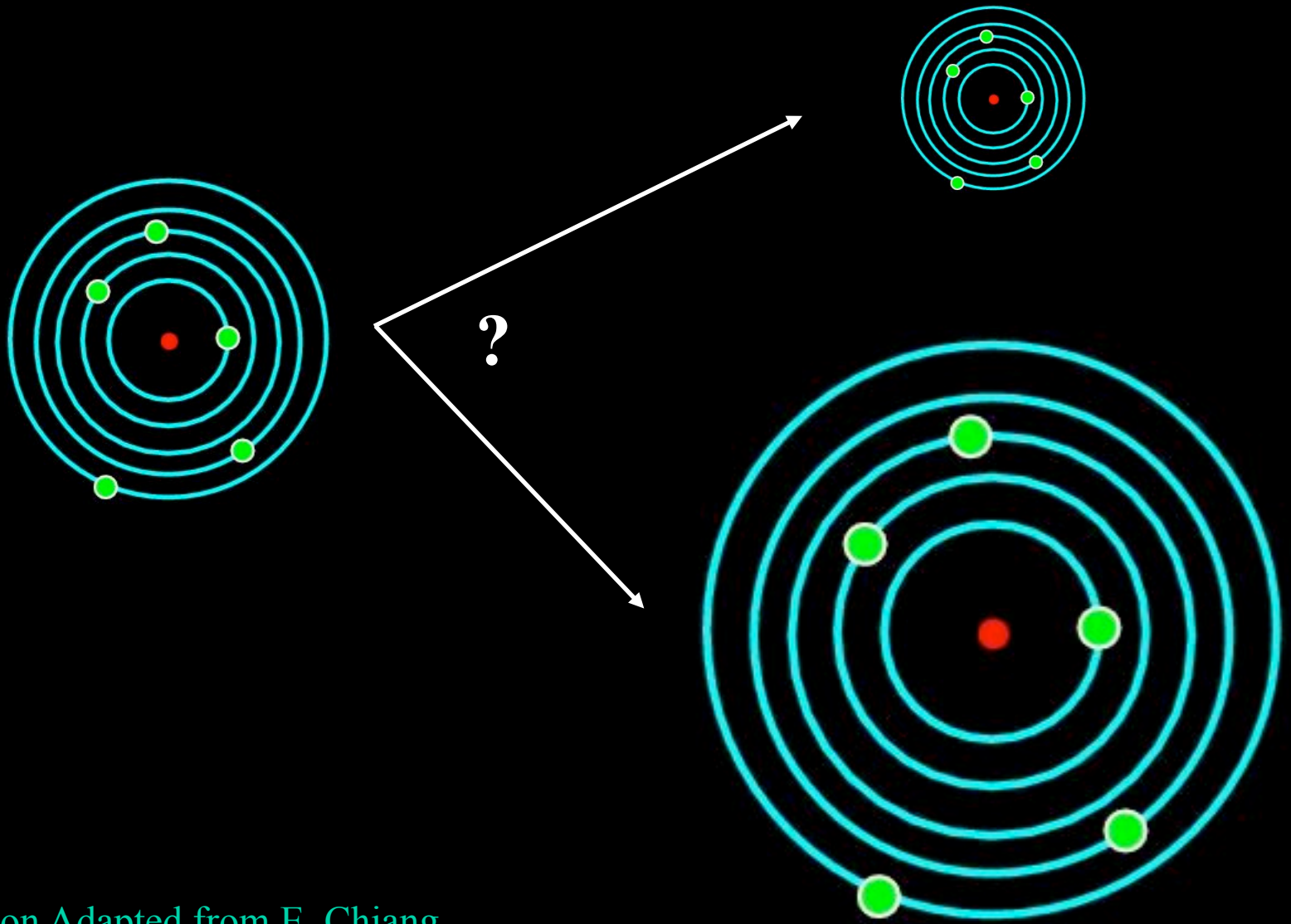
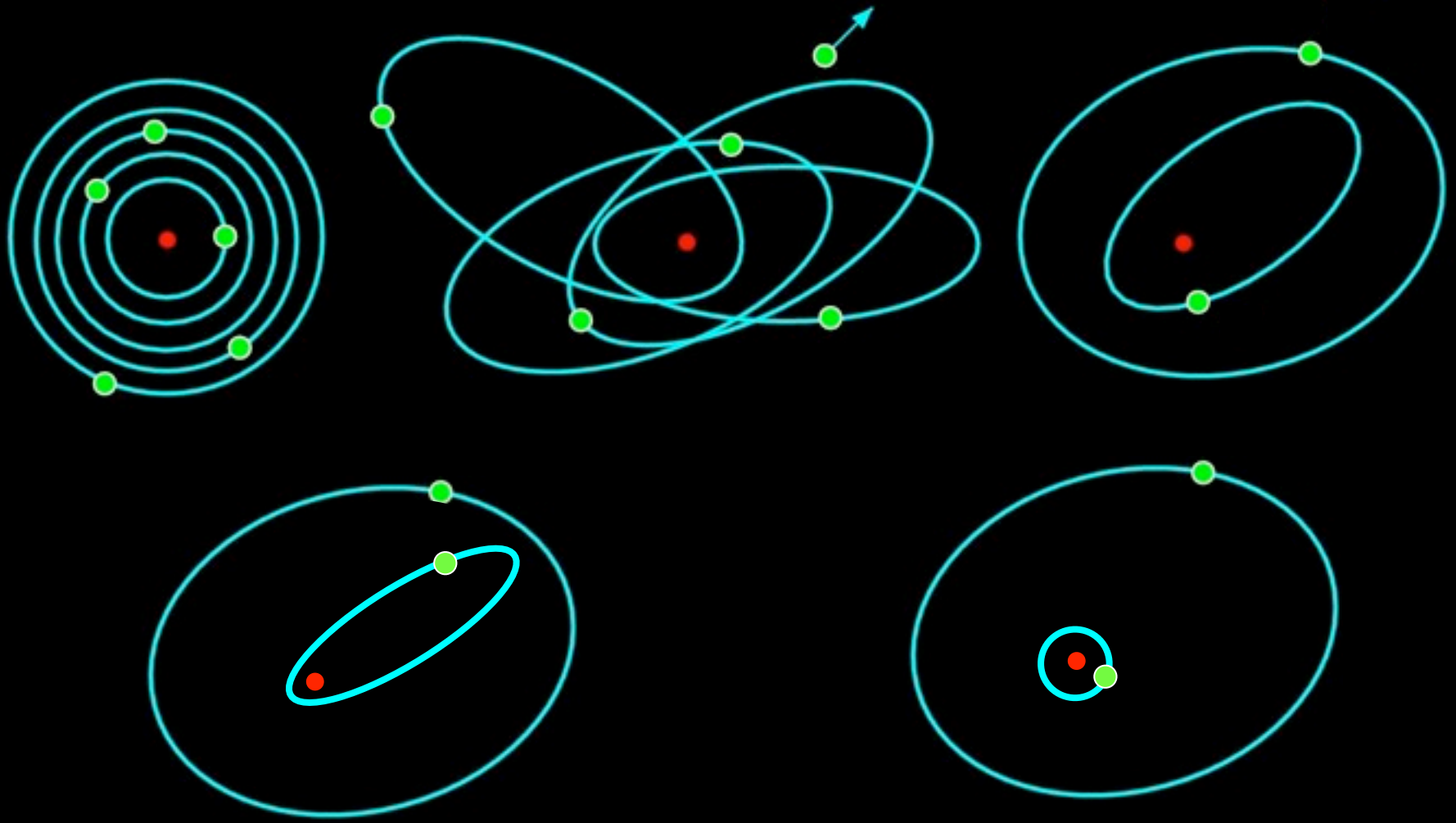


Illustration Adapted from E. Chiang

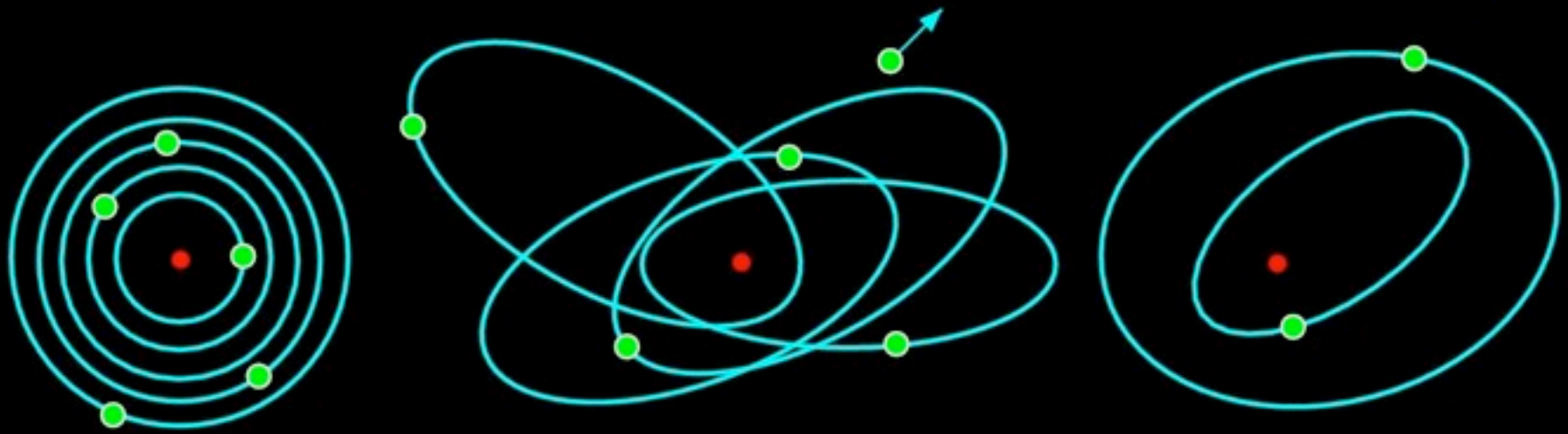
Hot Jupiters via Planet Scattering + Tidal Circularization



Rasio & Ford 1996

Illustration adapted from E. Chiang

Eccentric Giant Planets via Planet Scattering



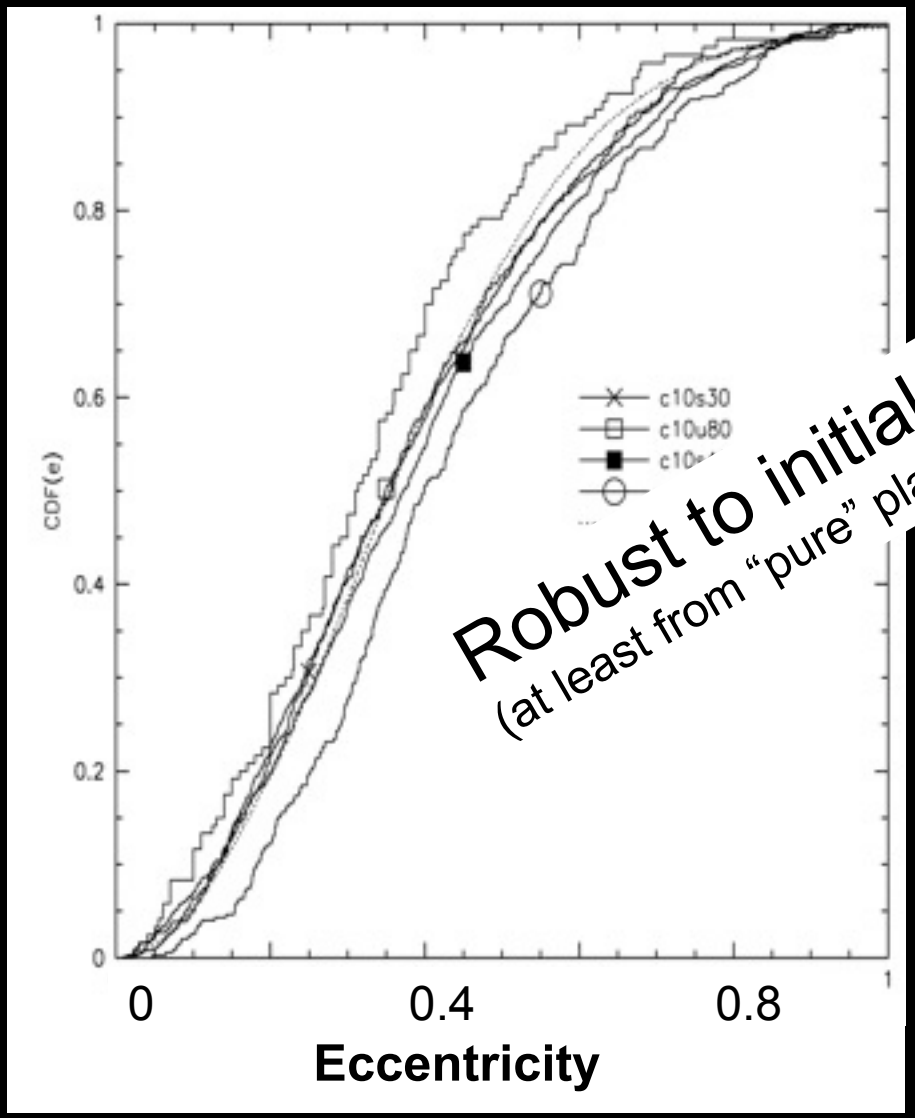
Rasio & Ford 1996; Weidenschilling & Marzari 1996

Illustration Adapted from E. Chiang

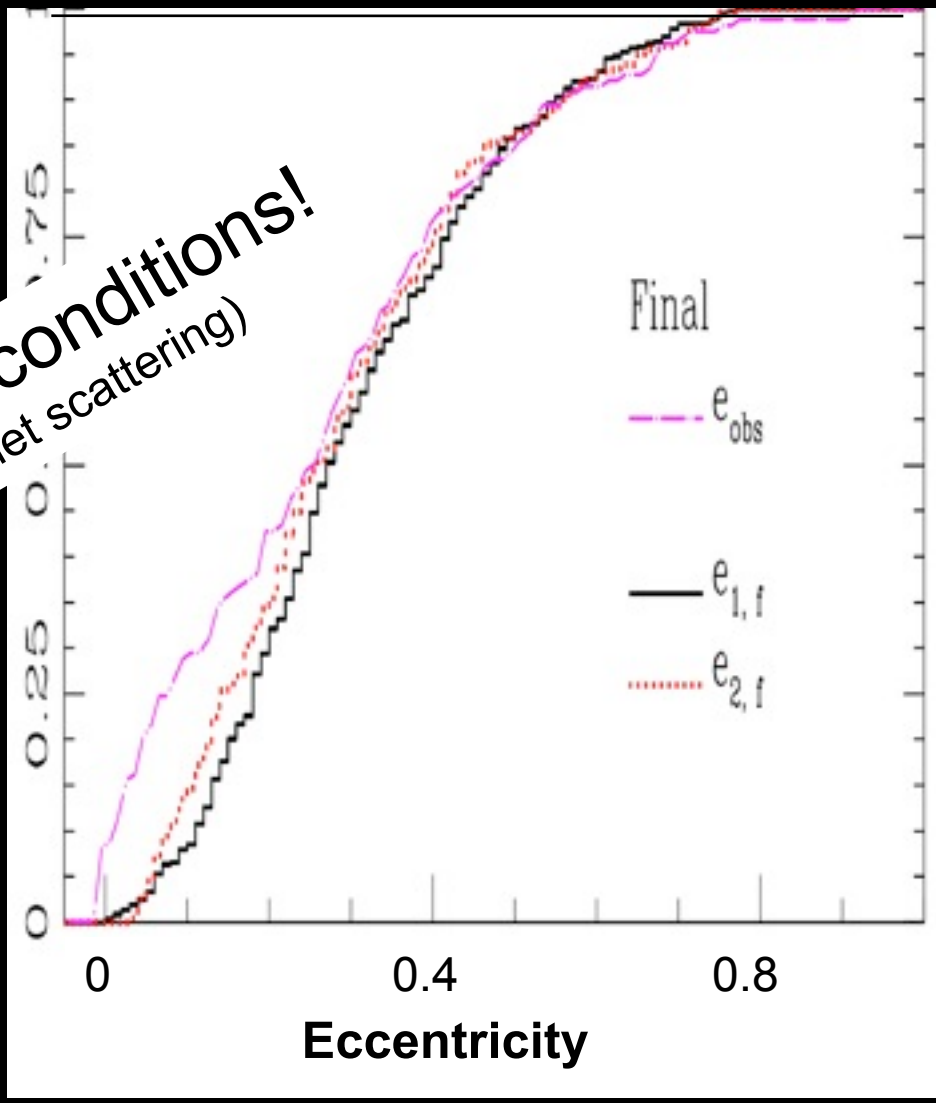
Eccentricity Distribution Predicted by Planet Scattering

Many Planets

Three Planets



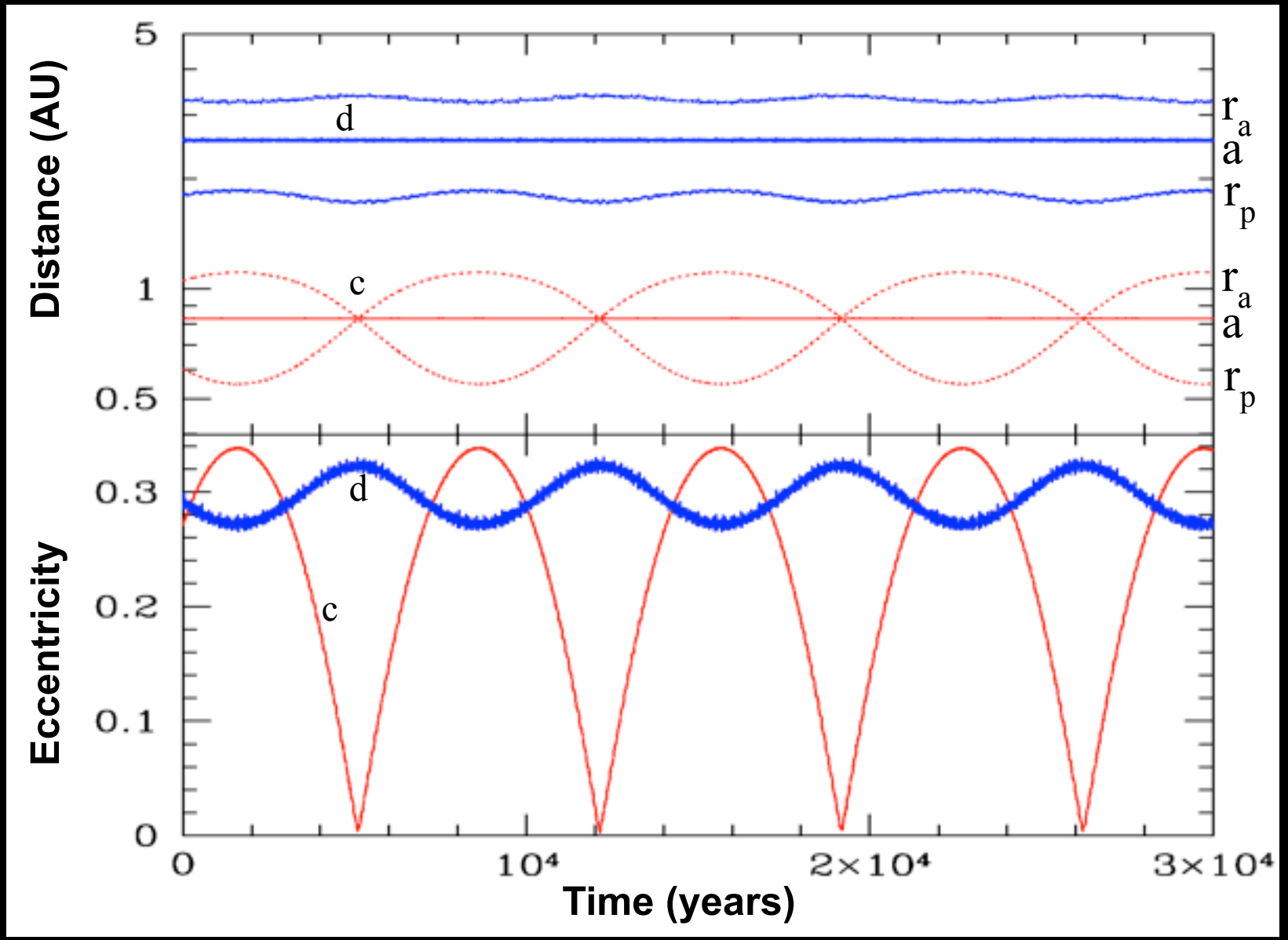
Robust to initial conditions!
(at least from "pure" planet scattering)



Juric & Tremaine 2007

Chatterjee et al. 2007

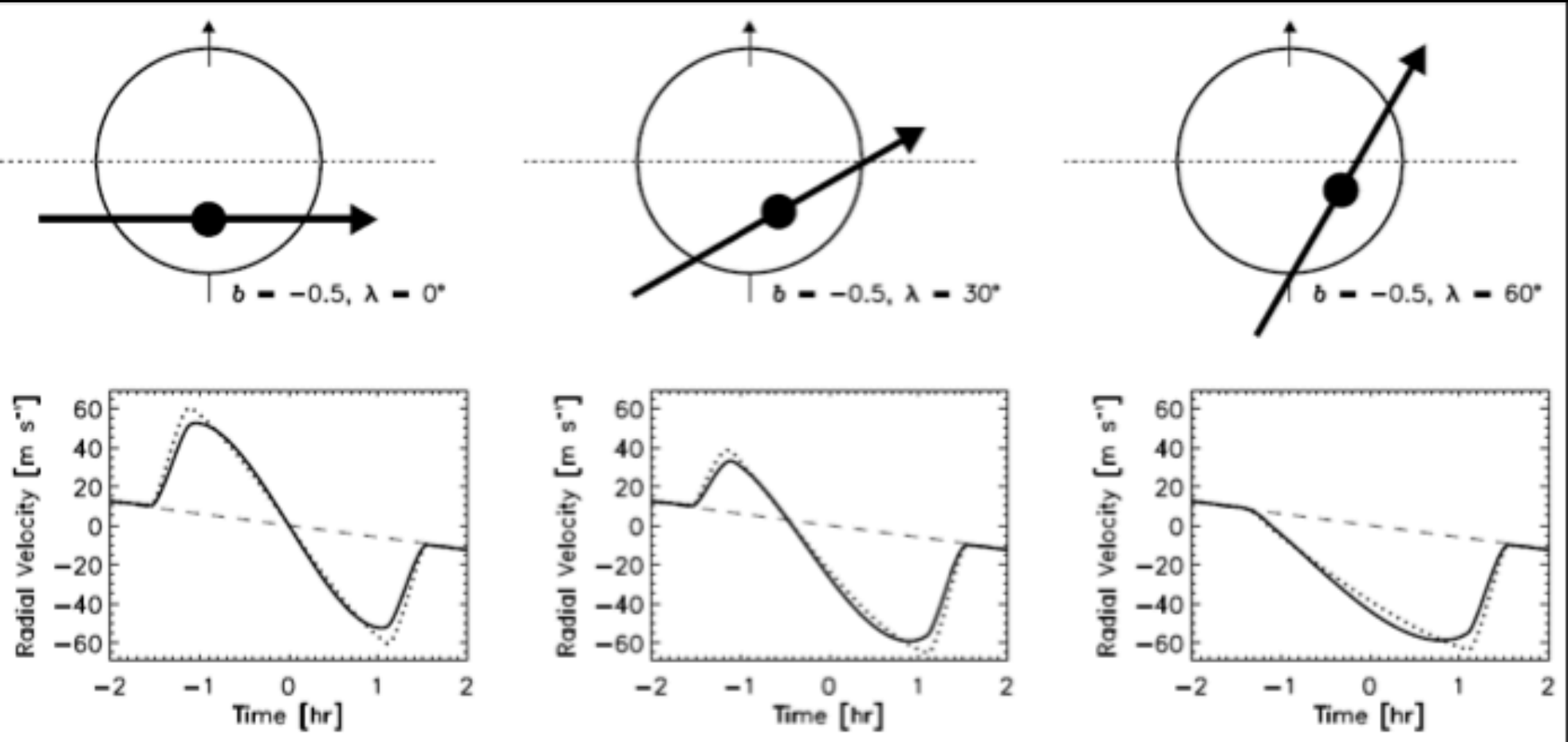
Secular Evolution of Ups And



Ford, Lystad, Rasio 2005; see also Malhotra (2002), Chiang et al. (2002); Barnes & Greenberg (2006); Veras & Ford 2009

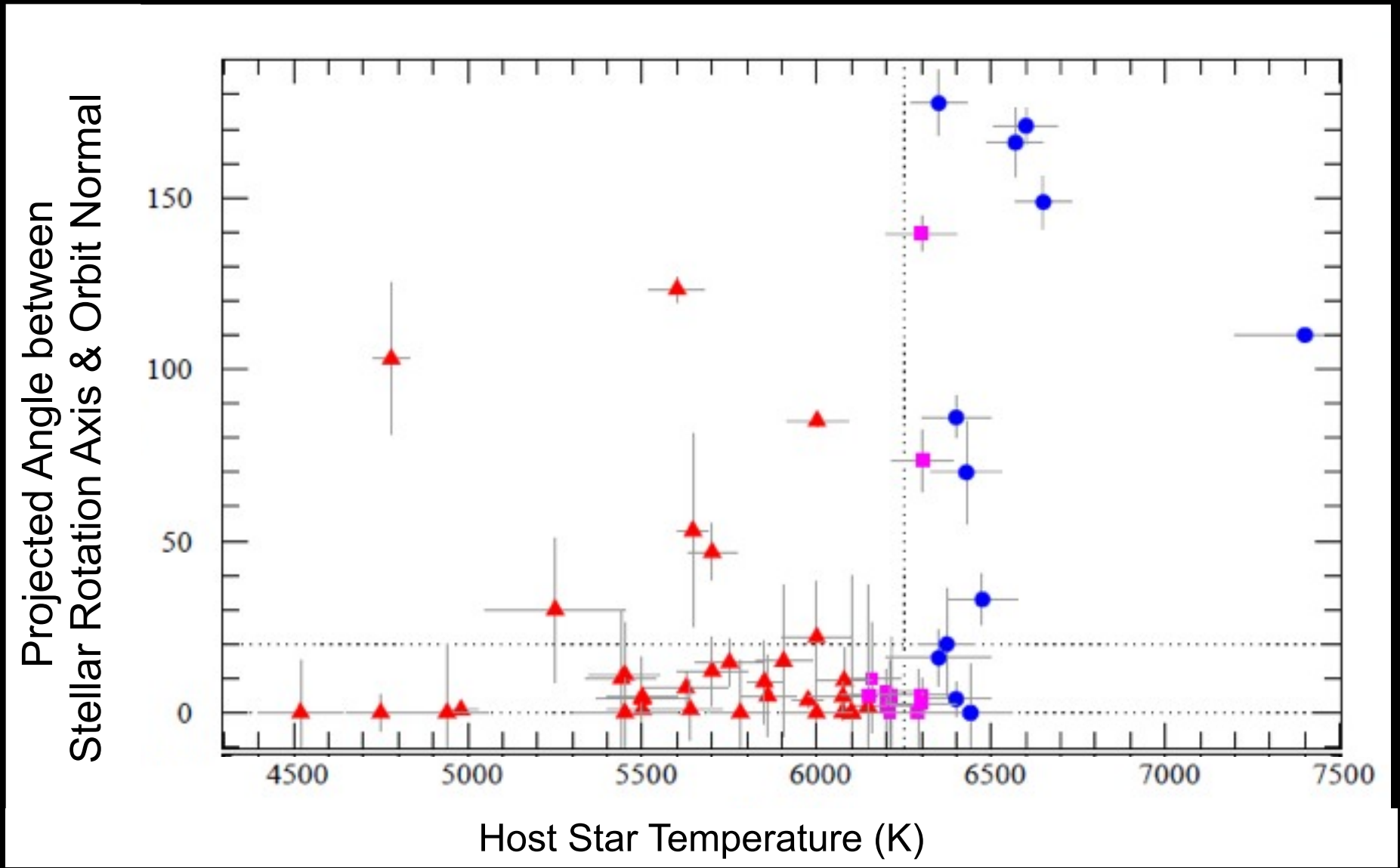
Measuring Exoplanet Inclinations

- Tidal dissipation in the planet rapidly damps eccentricity
- Search for planets with inclination excited by strong scattering
  (Chatterjee et al. 2008; Fabrycky & Tremaine 2007; Nagasawa et al. 2007)



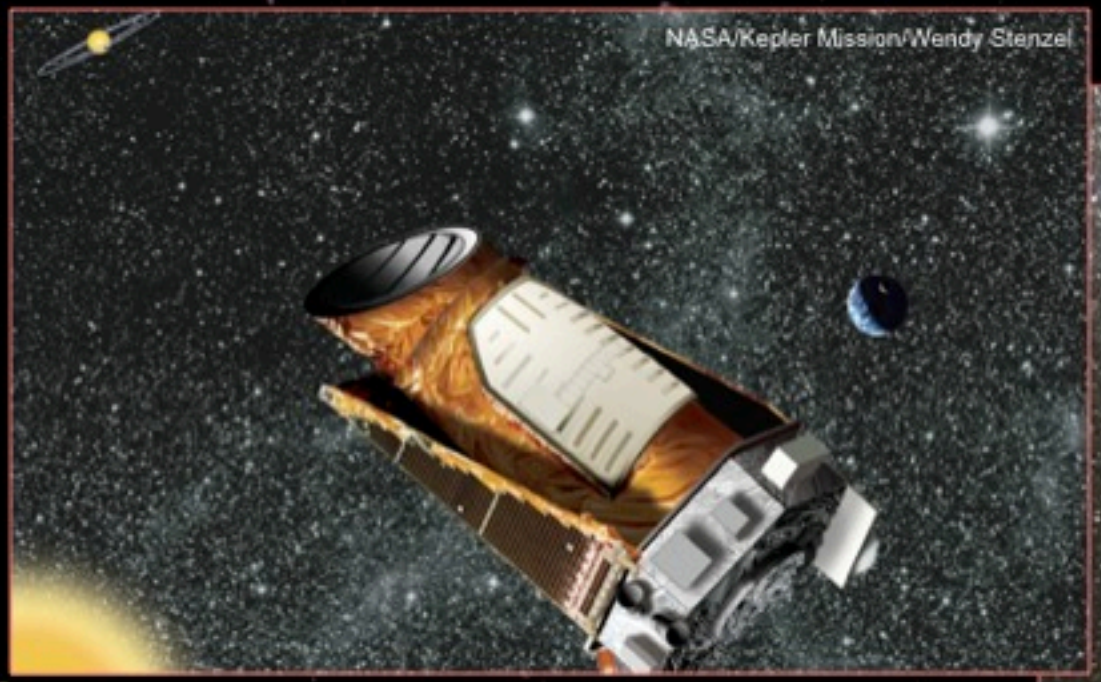
Gaudi & Winn 2006

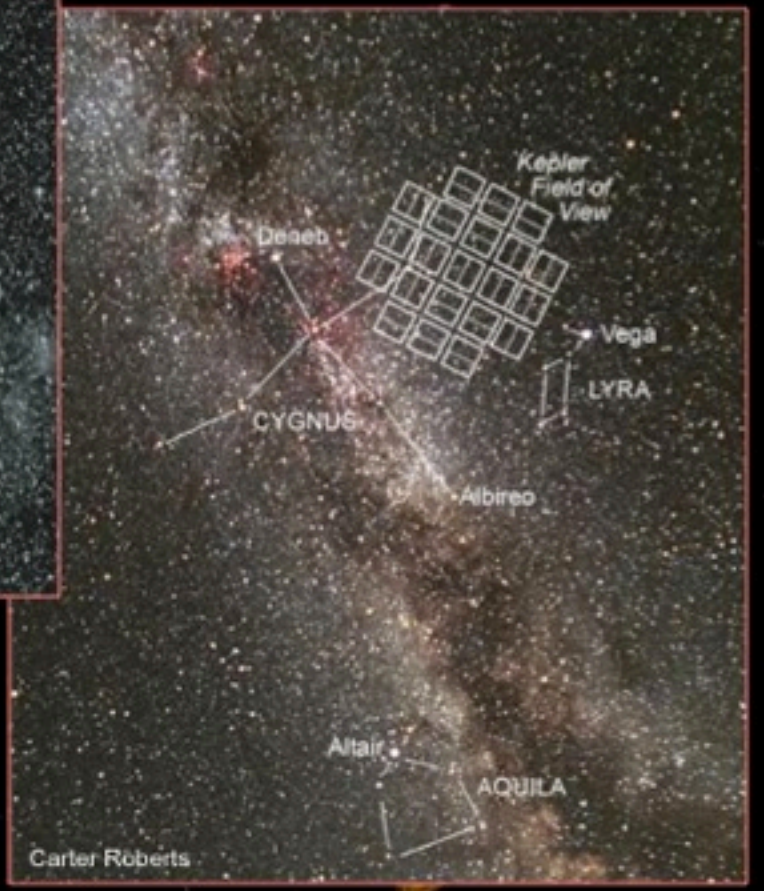
Stars & Hot-Jupiter's can be Misaligned



Amaury Triaud; adapted from Winn et al. 2010

Launch of *Kepler* Mission

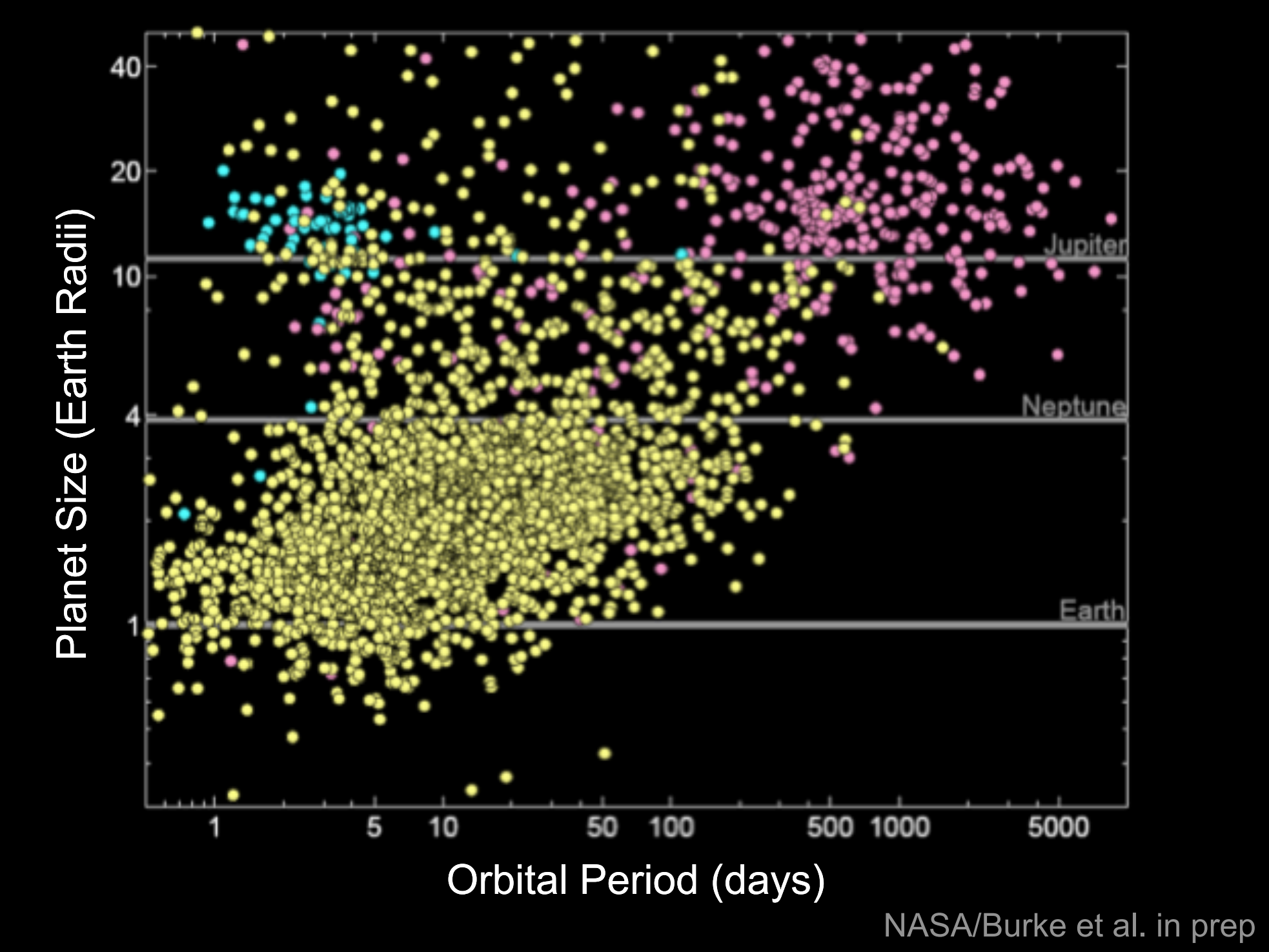


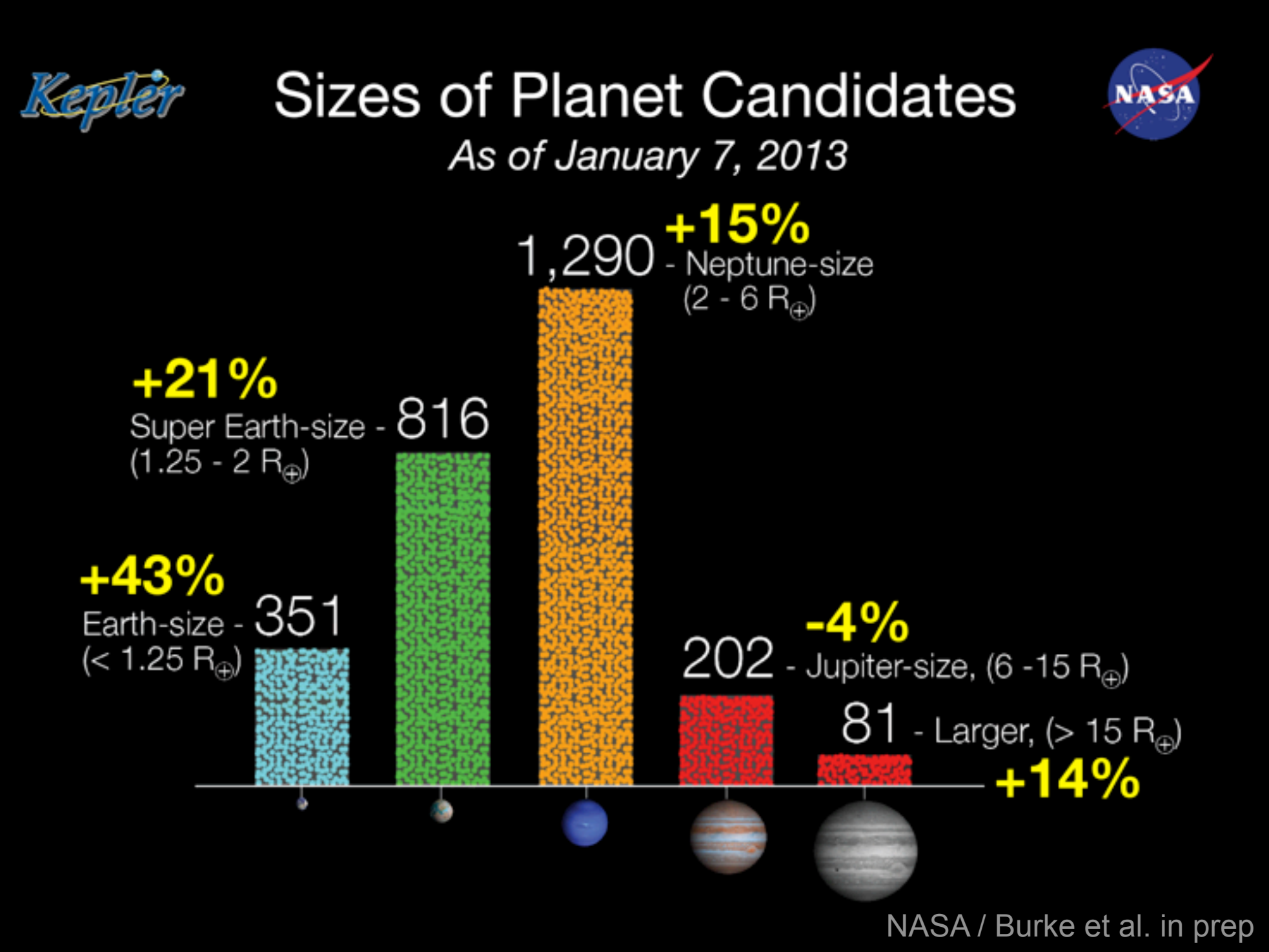


Frequency of Earth-like planets

Kepler

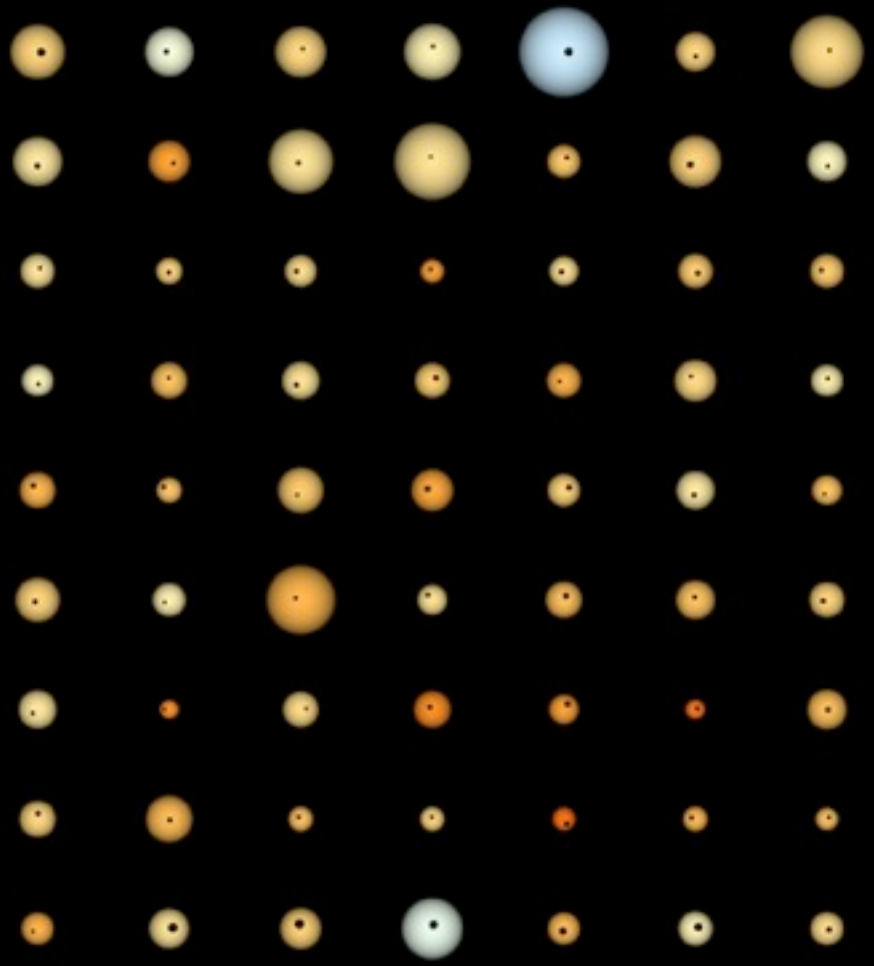
Solar Orbit


Planet Size (Earth Radii)
40
20
10
4
1
Jupiter
Neptune
Earth
1
5
10
50
100
500
1000
5000
Orbital Period (days)
NASA/Burke et al. in prep


Kepler
Sizes of Planet Candidates
As of January 7, 2013
NASA
1,290
+15%
- Neptune-size
(2 - 6 R⊕)
+21%
Super Earth-size - 816
(1.25 - 2 R⊕)
+43%
Earth-size - 351
(< 1.25 R⊕)
202
-4%
- Jupiter-size, (6 -15 R⊕)
81
- Larger, (> 15 R⊕)
+14%
NASA / Burke et al. in prep

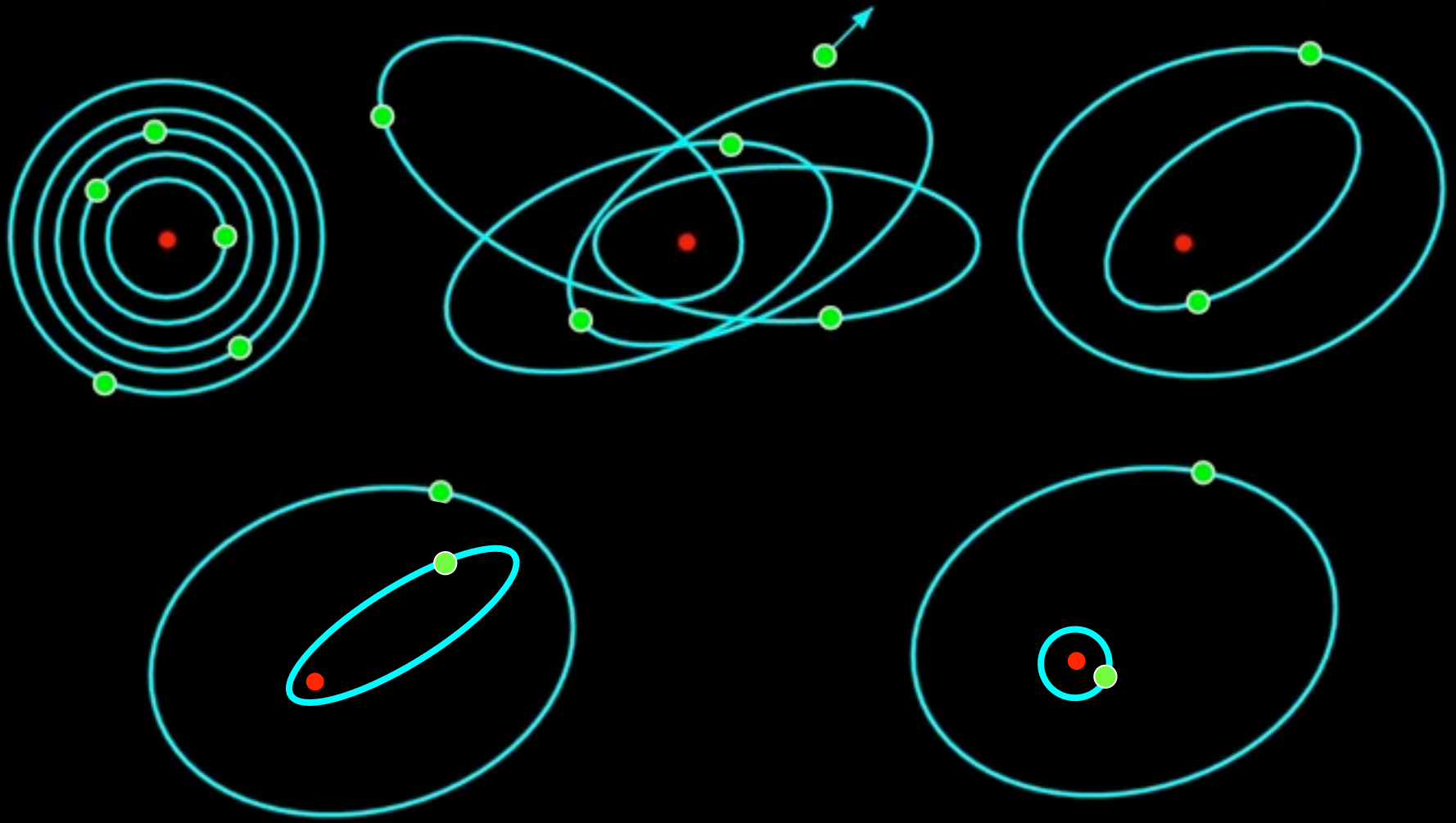
Hot Jupiters are Lonely

- 63 Hot Jupiters
- No other transiting planets
- No TTV signals
- Consistent with eccentricity excitation followed by tidal circularization



(Steffen et al. 2012 PNAS;
see Szabo et al. arxiv)

Hot Jupiters via Planet Scattering + Tidal Circularization



Rasio & Ford 1996

Illustration adapted from E. Chiang

Hot Jupiters via Disk Migration?

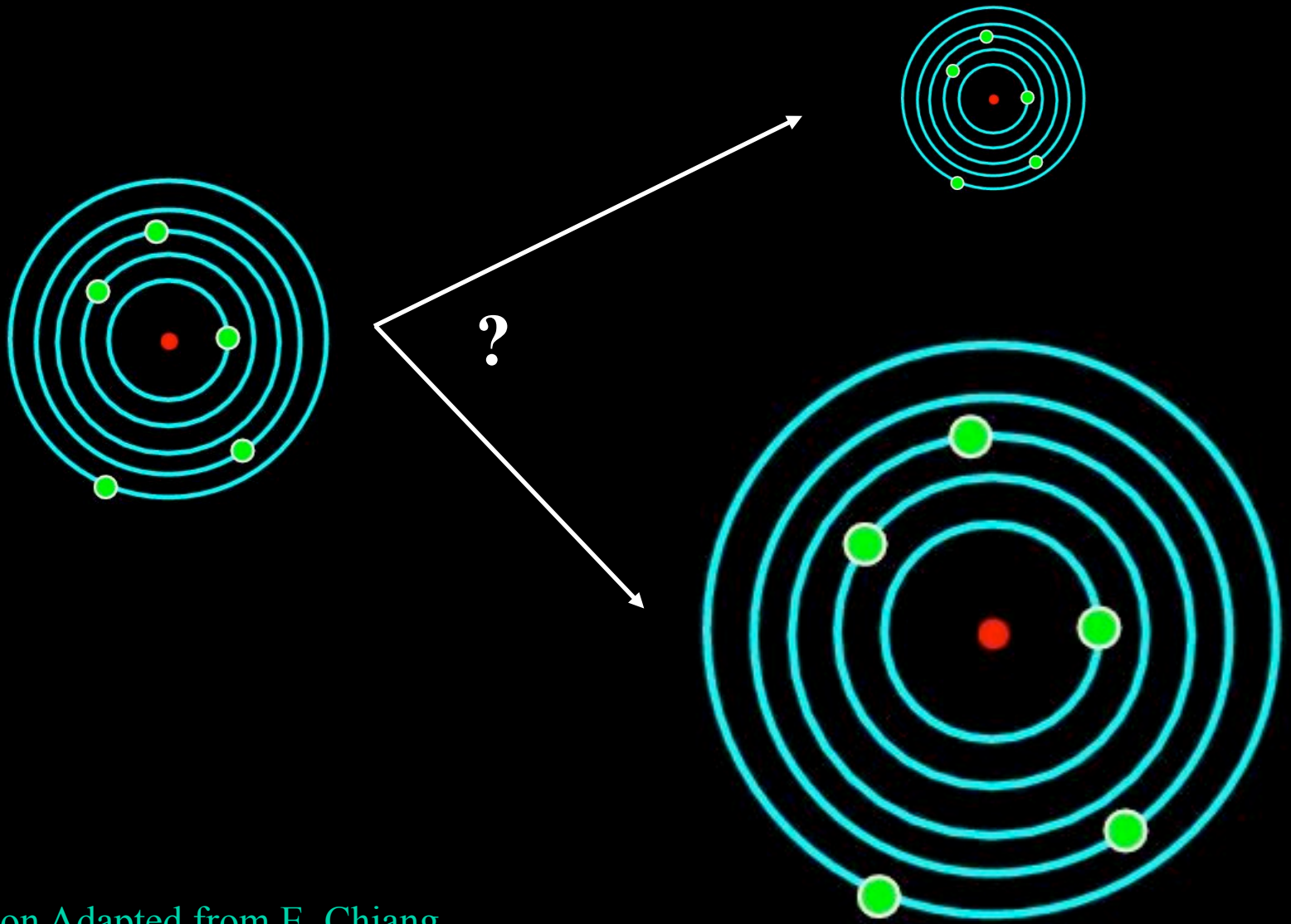
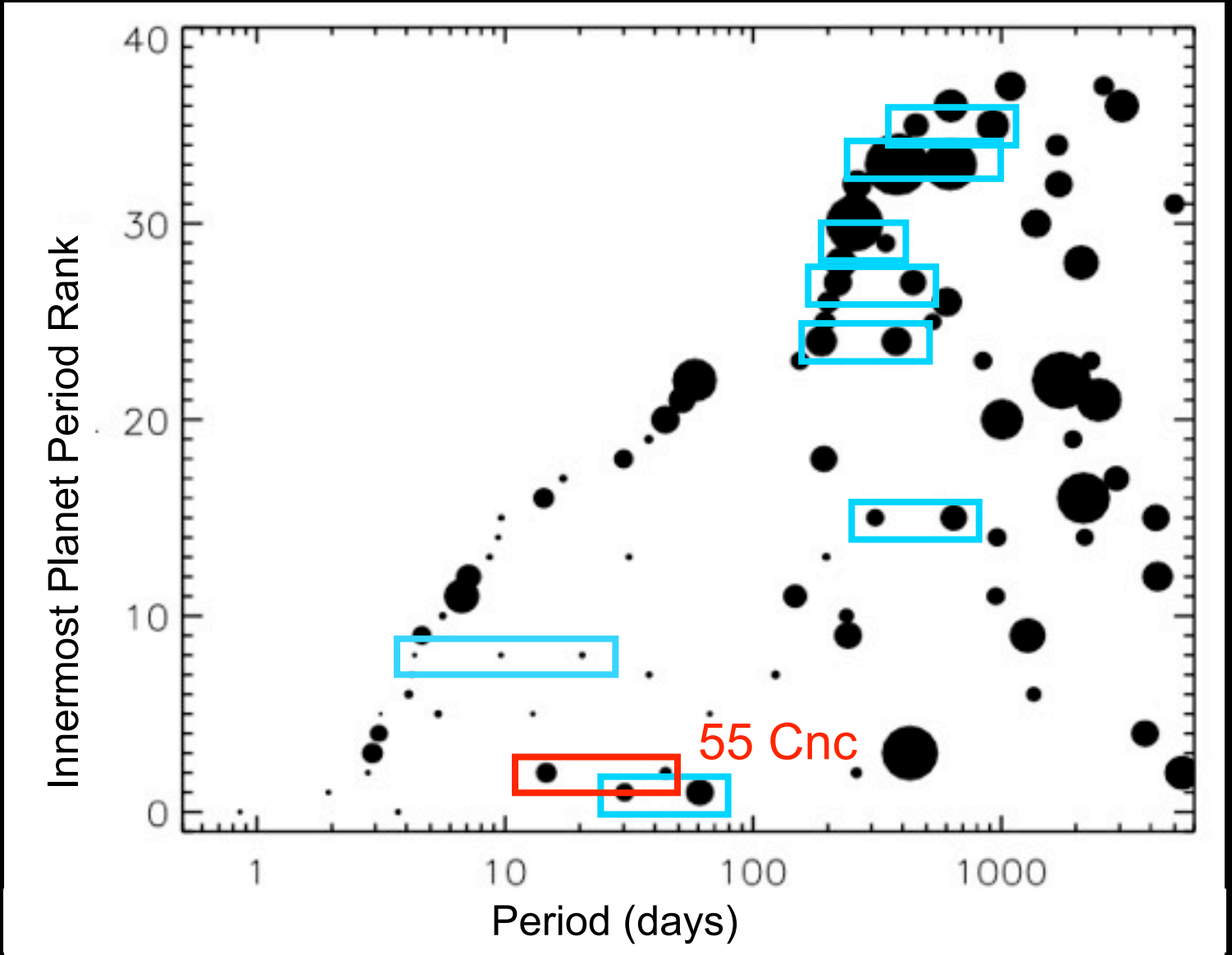


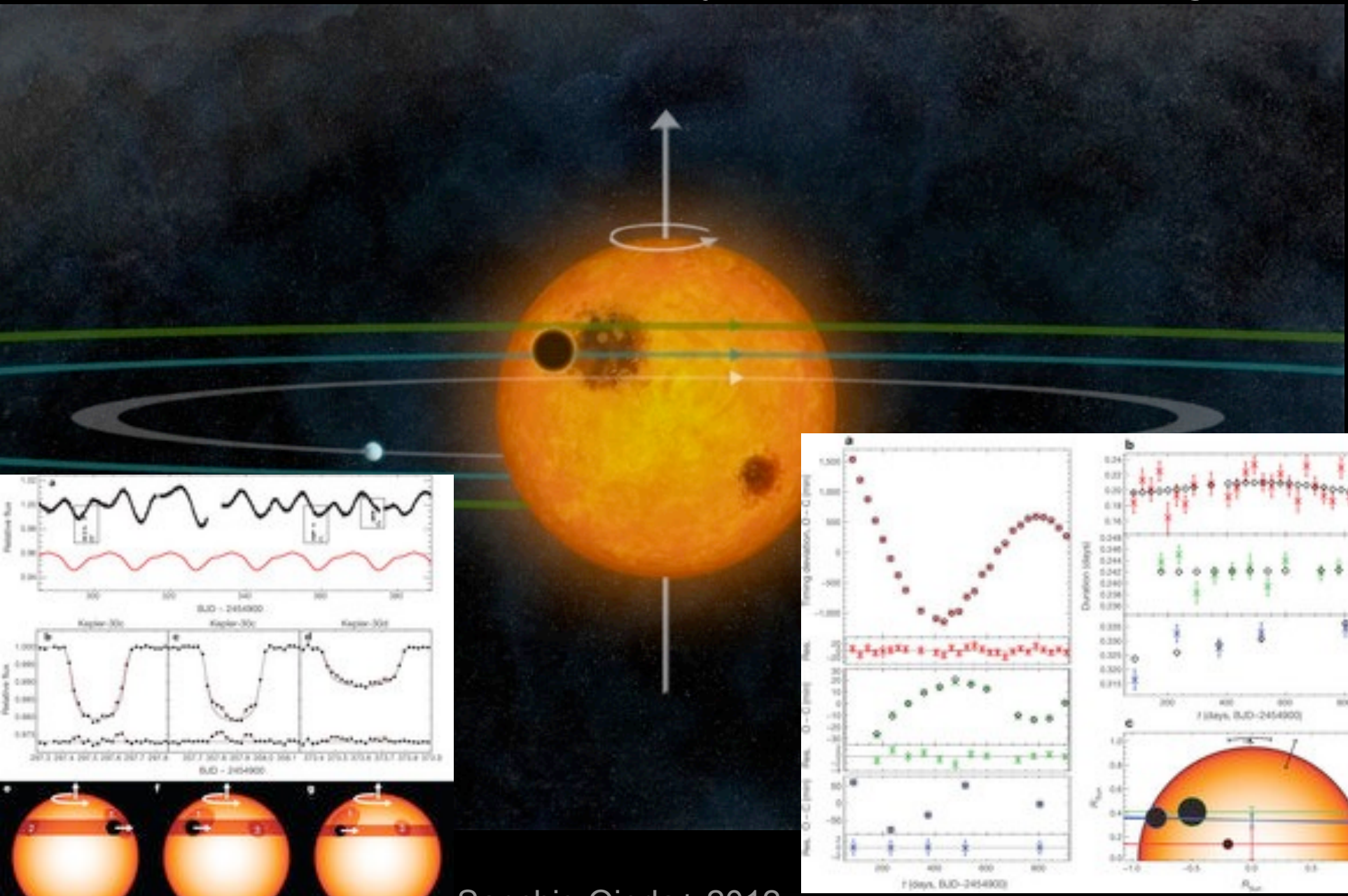
Illustration Adapted from E. Chiang

Orbital Resonances Among Multi-Planet Systems Disovered via RVs

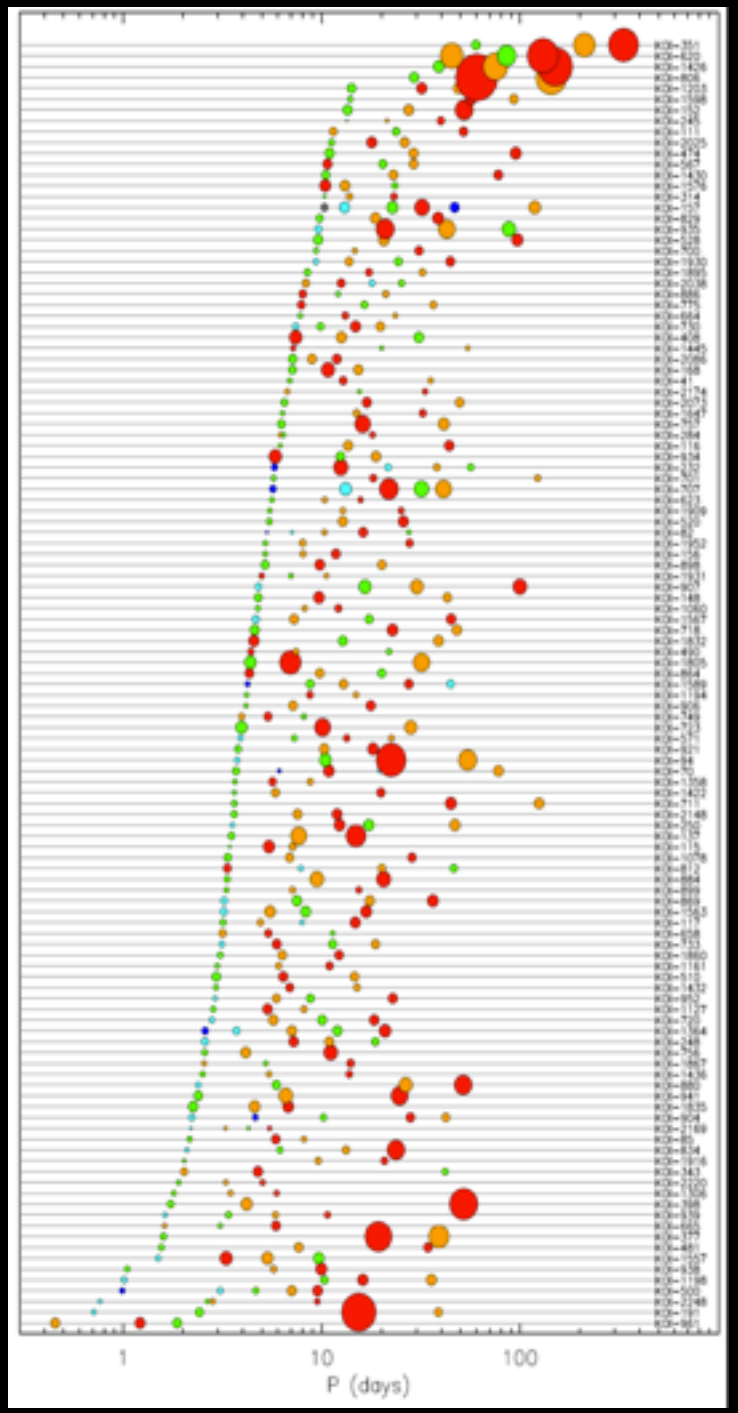


Fabrycky

Kepler-30: Coplanarity via Spot Crossings

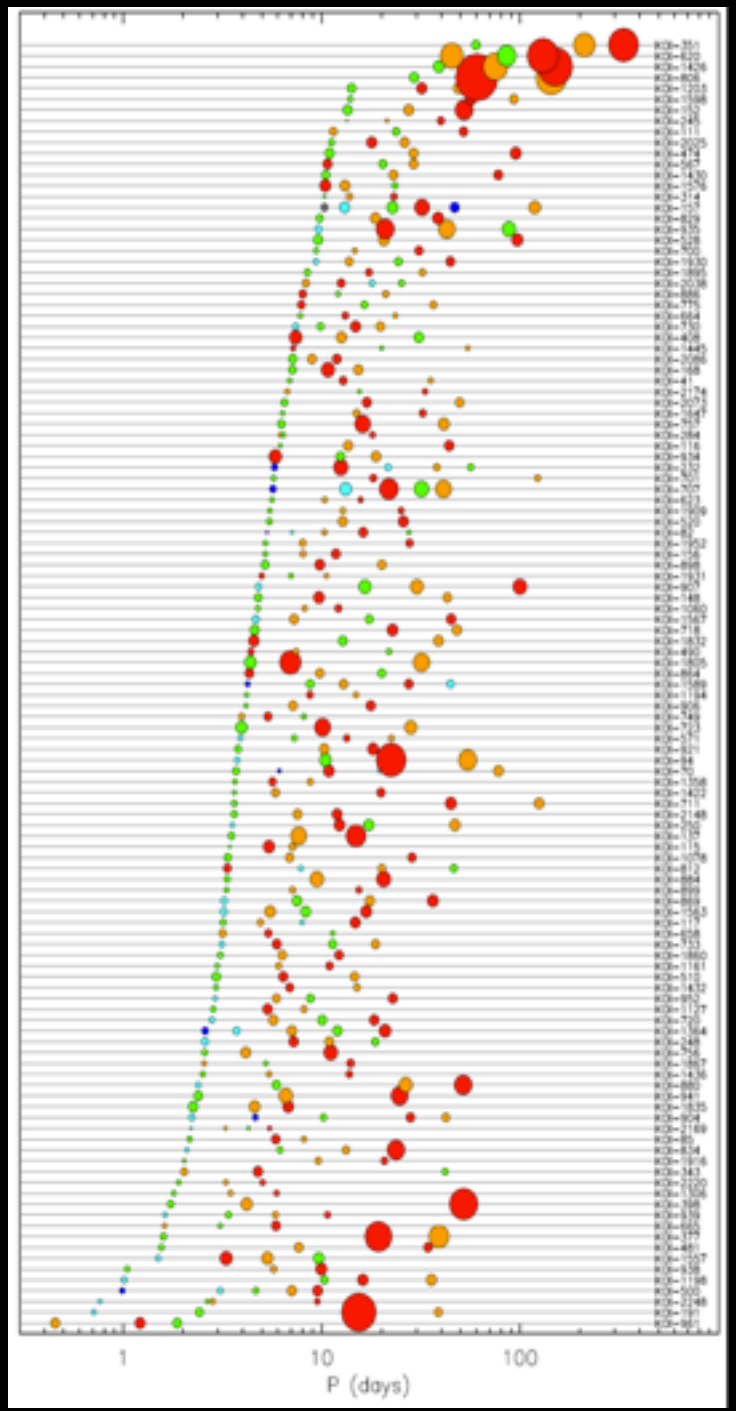


Sanchis-Ojeda+ 2012



Extremely Compact Multi-transiting Planetary Systems

Fabrycky et al. 2012



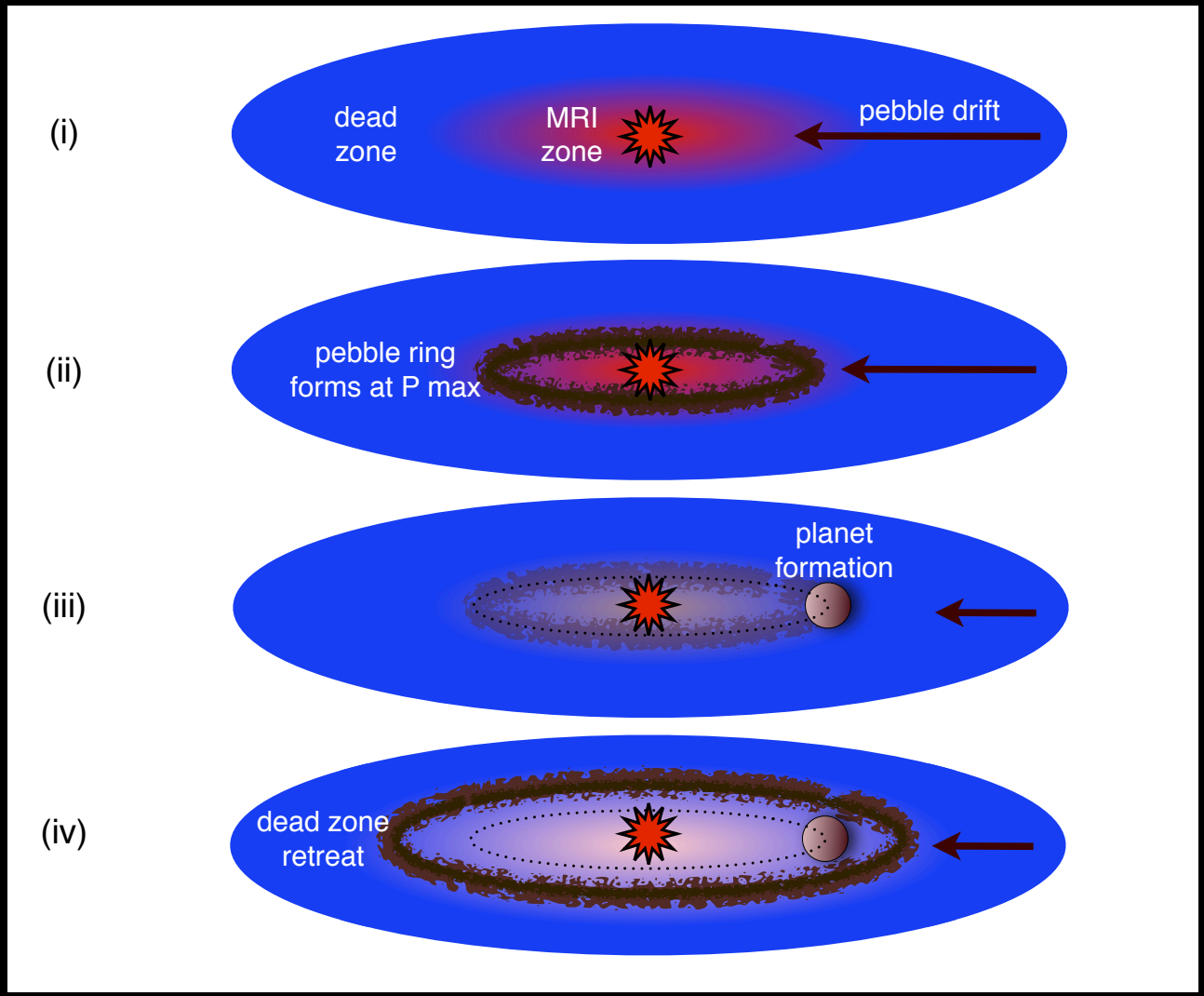
Extremely Compact Multi-transiting Planetary Systems

Higher solid density close to star- idea of minimum mass extrasolar nebula (Laughlin et al. 2012, also see Hansen & Murray 2012)

Inside-out planet formation (Chatterjee & Tan)

Fabrycky et al. 2012

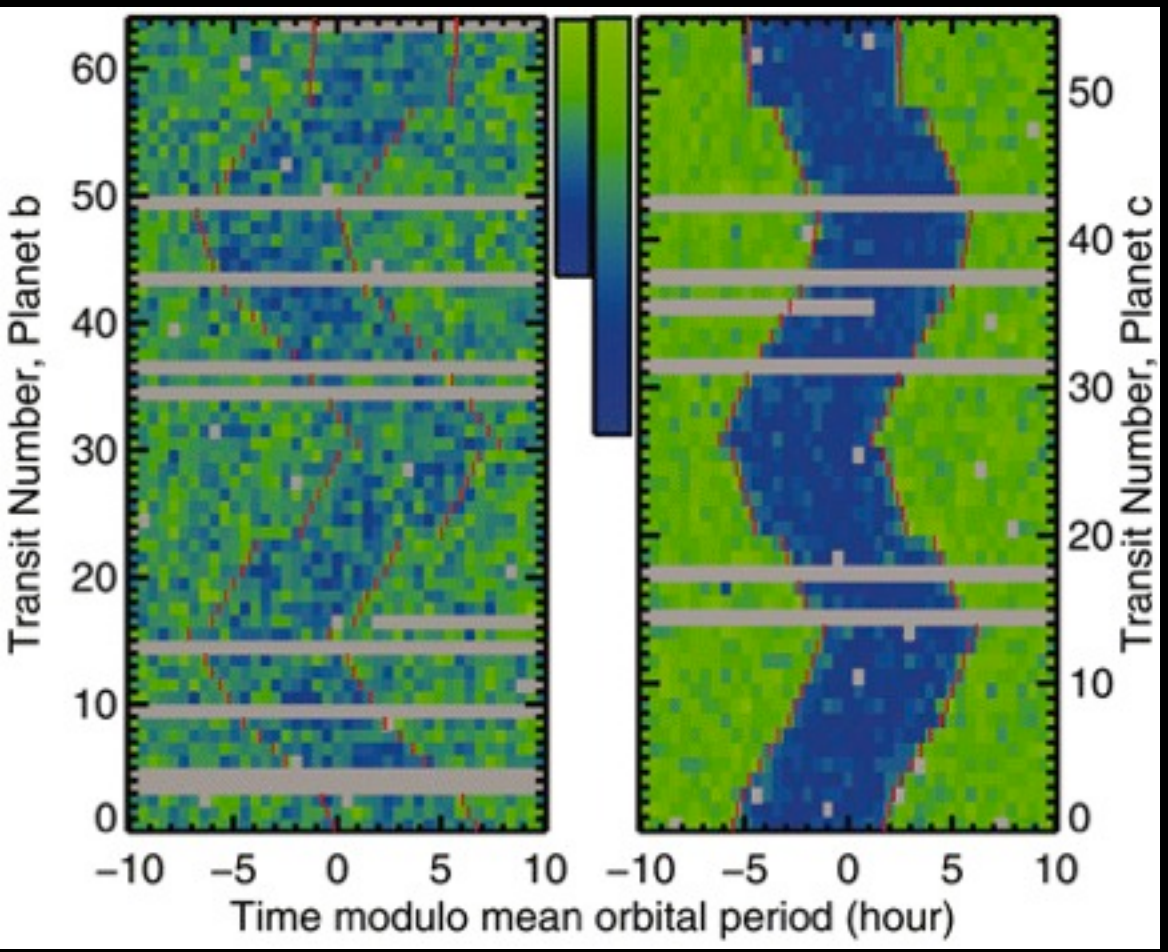
Extremely Compact Multi-transiting Planetary Systems



Chatterjee & Tan 2013

Very Tightly Packed Planetary Systems

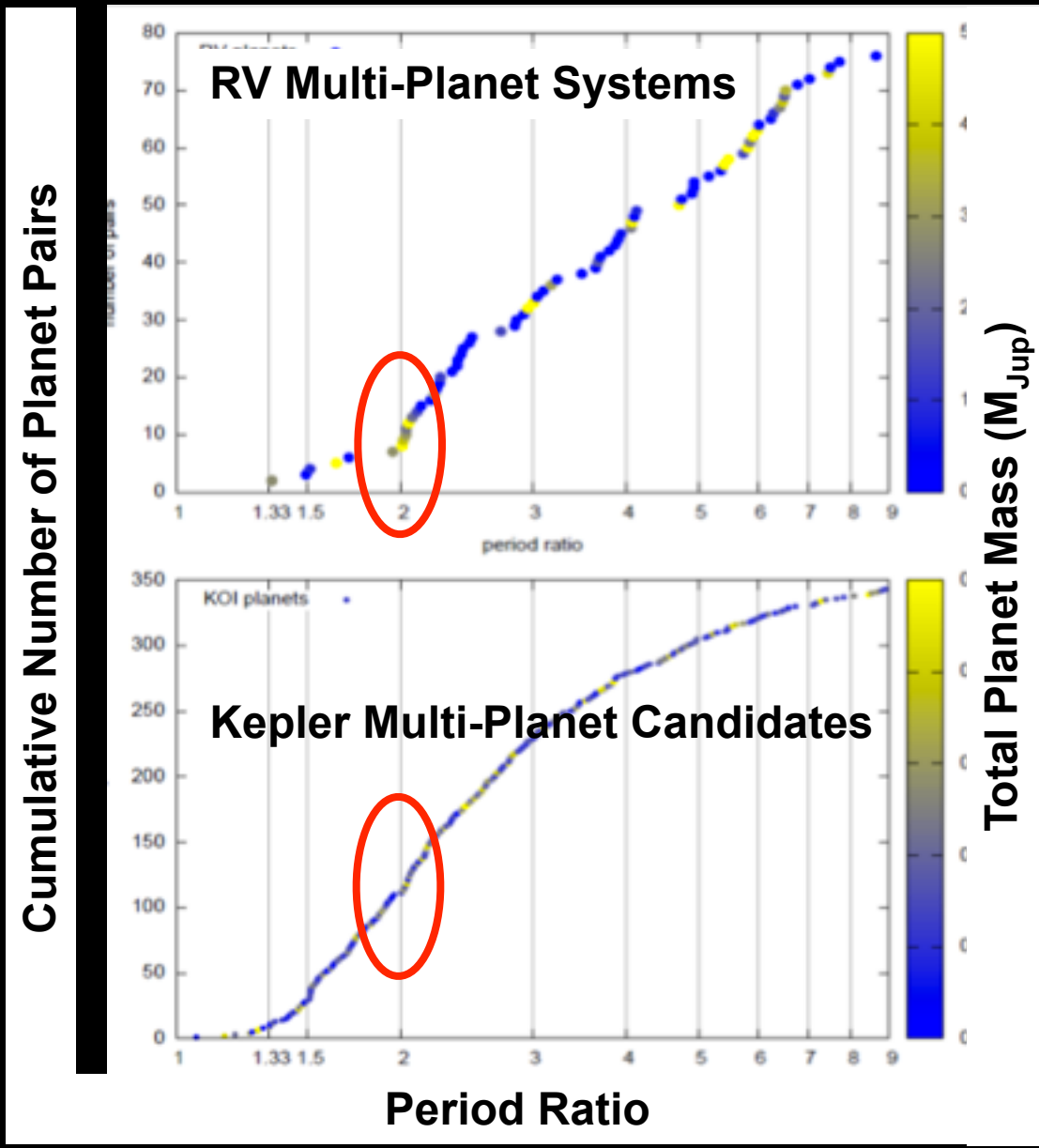
Kepler-36b&c: Chaotic due to 29:34 and 6:7 MMRs!



Carter et al. 2012; Deck et al. 2012

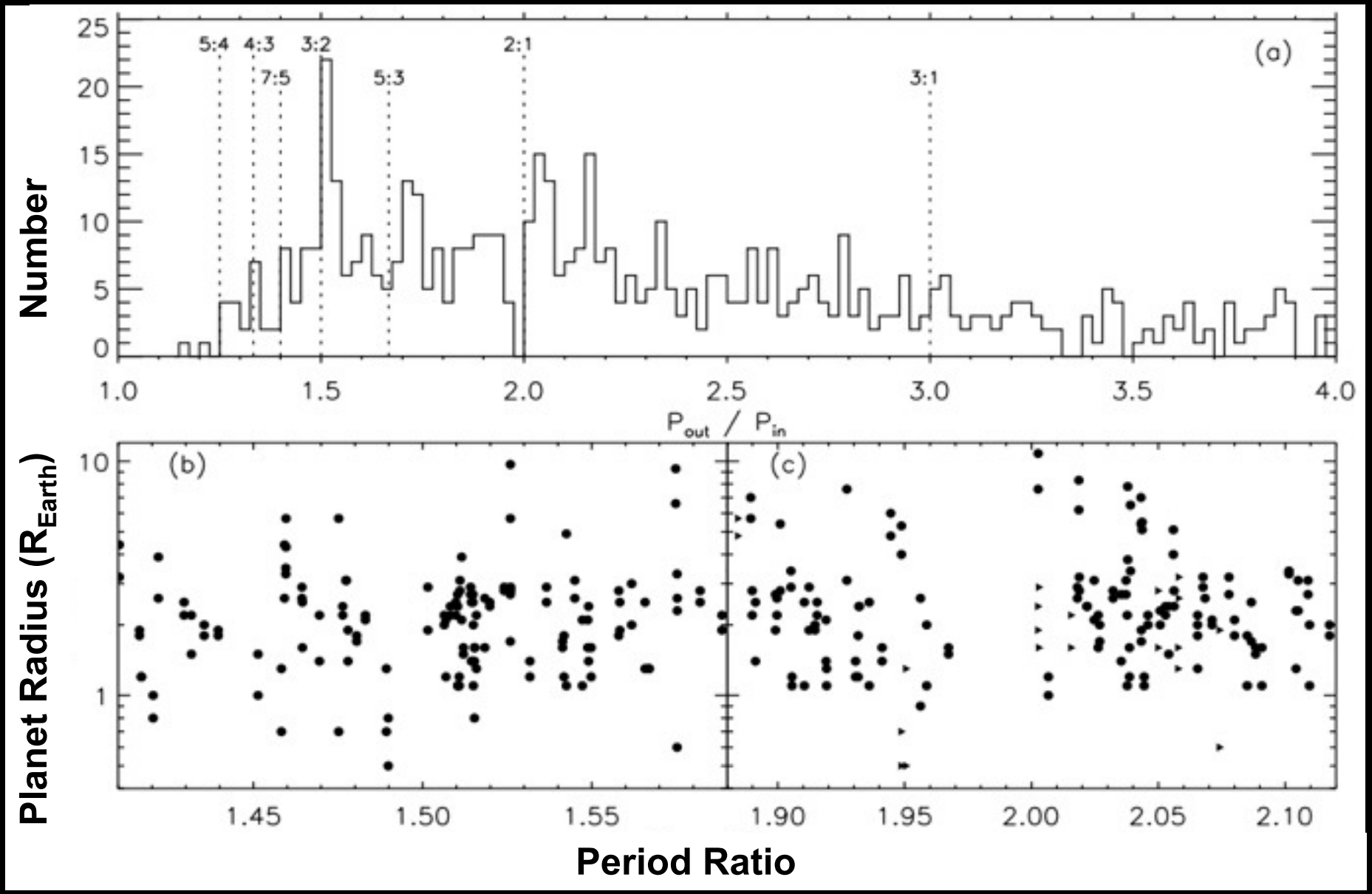
Resonances in Kepler Multi-Planet Systems

- Rarer than in RV systems
  - Predicted!
- Most near, but not in resonance
- Near resonant great for TTVs
  - esp. closely spaced pairs!



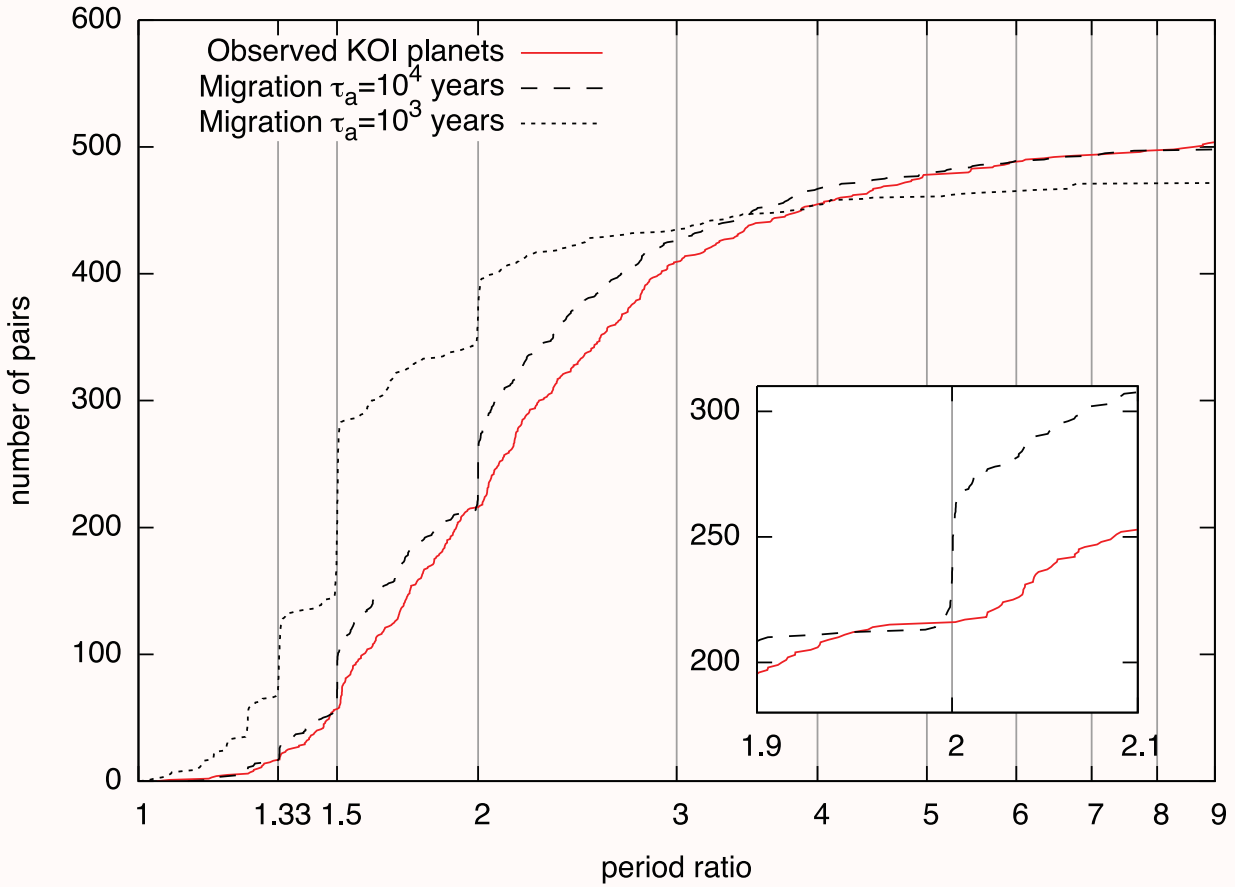
Rein et al. 2012;
Ford & Rasio 2008; Veras et al. 2012

Kepler's Near Resonant Systems



Fabrycky et al. 2012; see also Rein et al. 2012; Ford & Rasio 2008; Veras et al. 2012

Kepler's Near Resonant Systems



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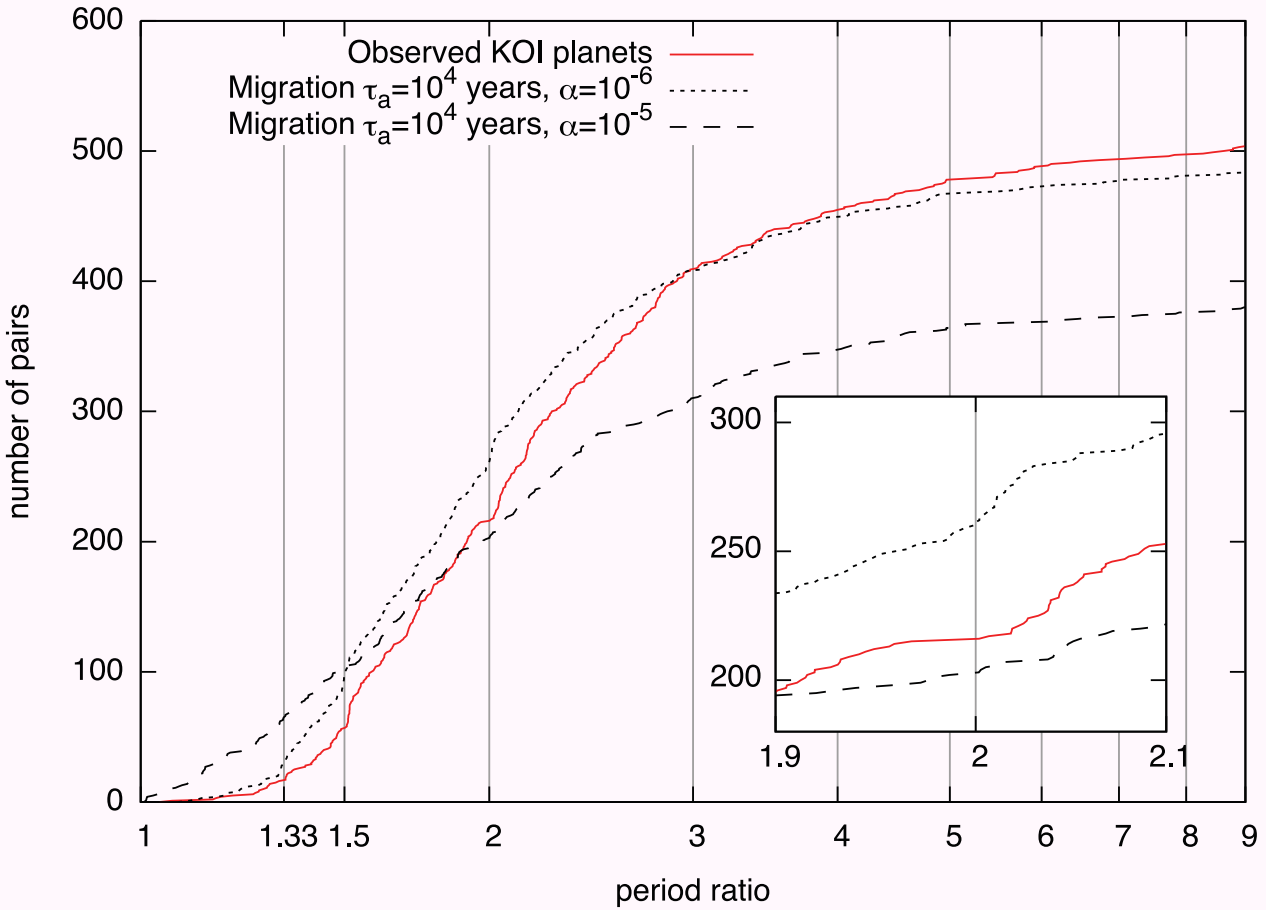
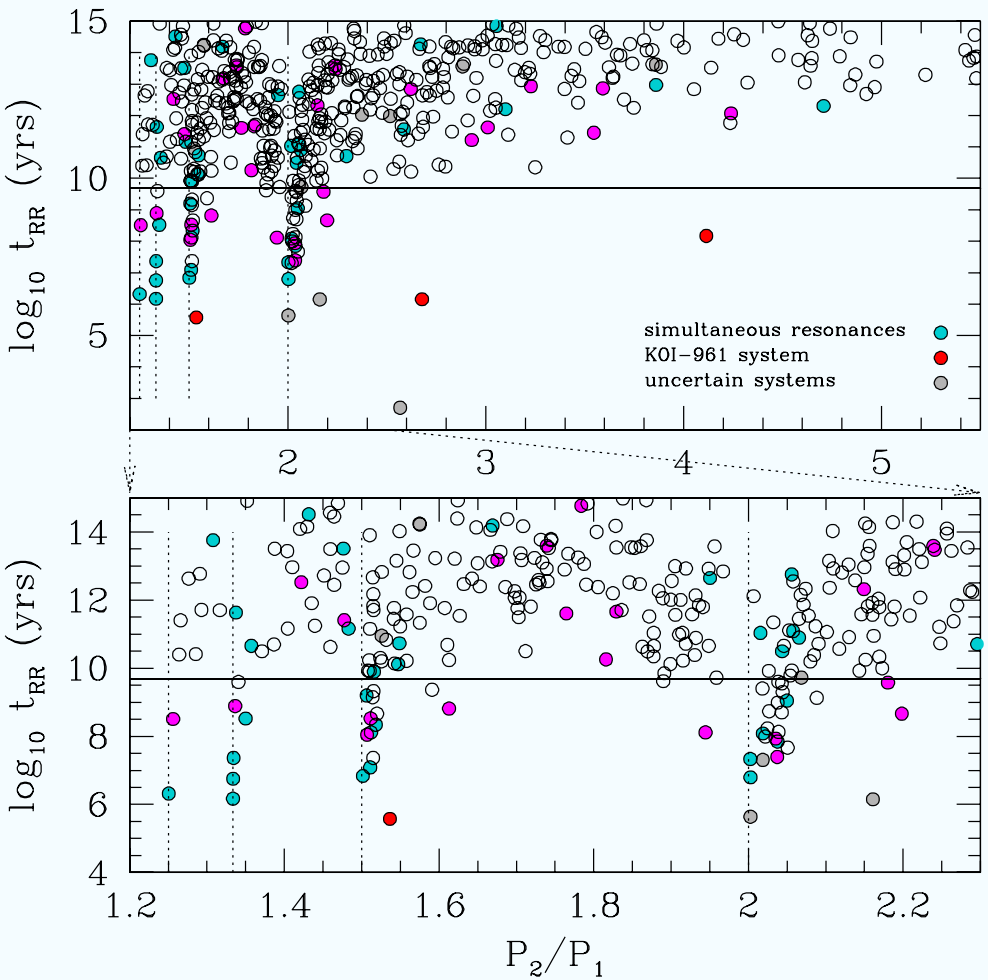
Kepler's Near Resonant Systems



Rein et al. 2012; see also Ford & Rasio 2008; Veras et al. 2012

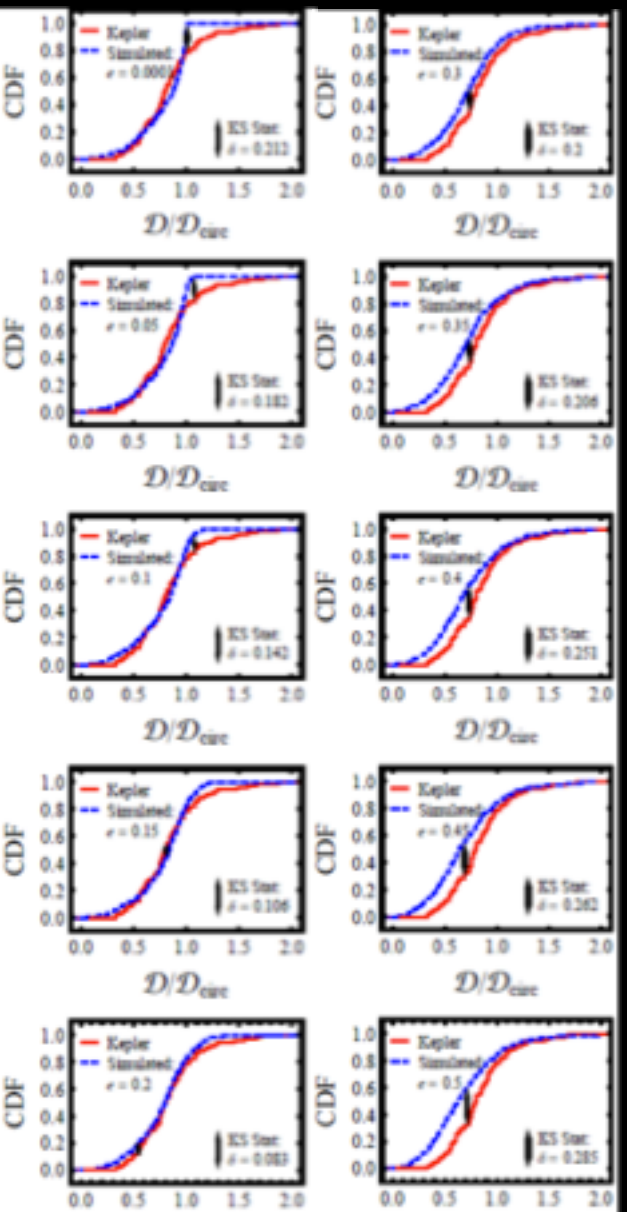
Kepler's Near Resonant Systems

resonant repulsion

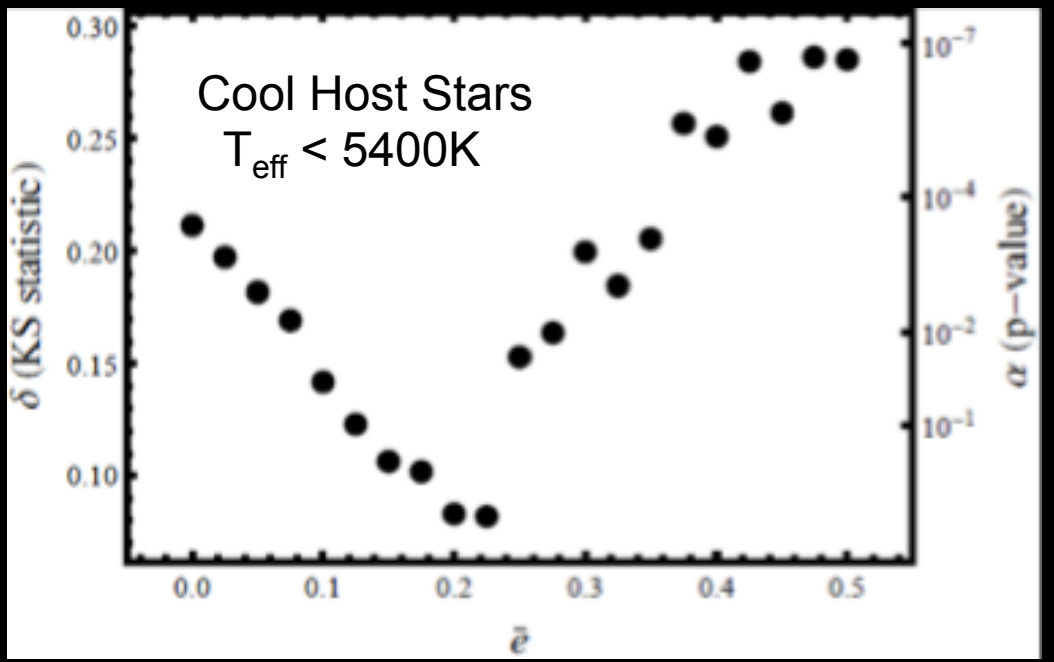


Lithwick et al. 2012; see also Ford & Rasio 2008; Veras et al. 2012

Eccentricities of Transiting Planets via Transit Duration Distribution



- Consistent w/ RV distribution
- Smaller planets have smaller eccentricities
- Subject to uncertainties in stellar properties (A. Moorhead+ 2011)



A. Moorhead+ 2011; see also Dawson+ 2012, Kane+ 2012

Testing Planet Formation Theory with Kepler

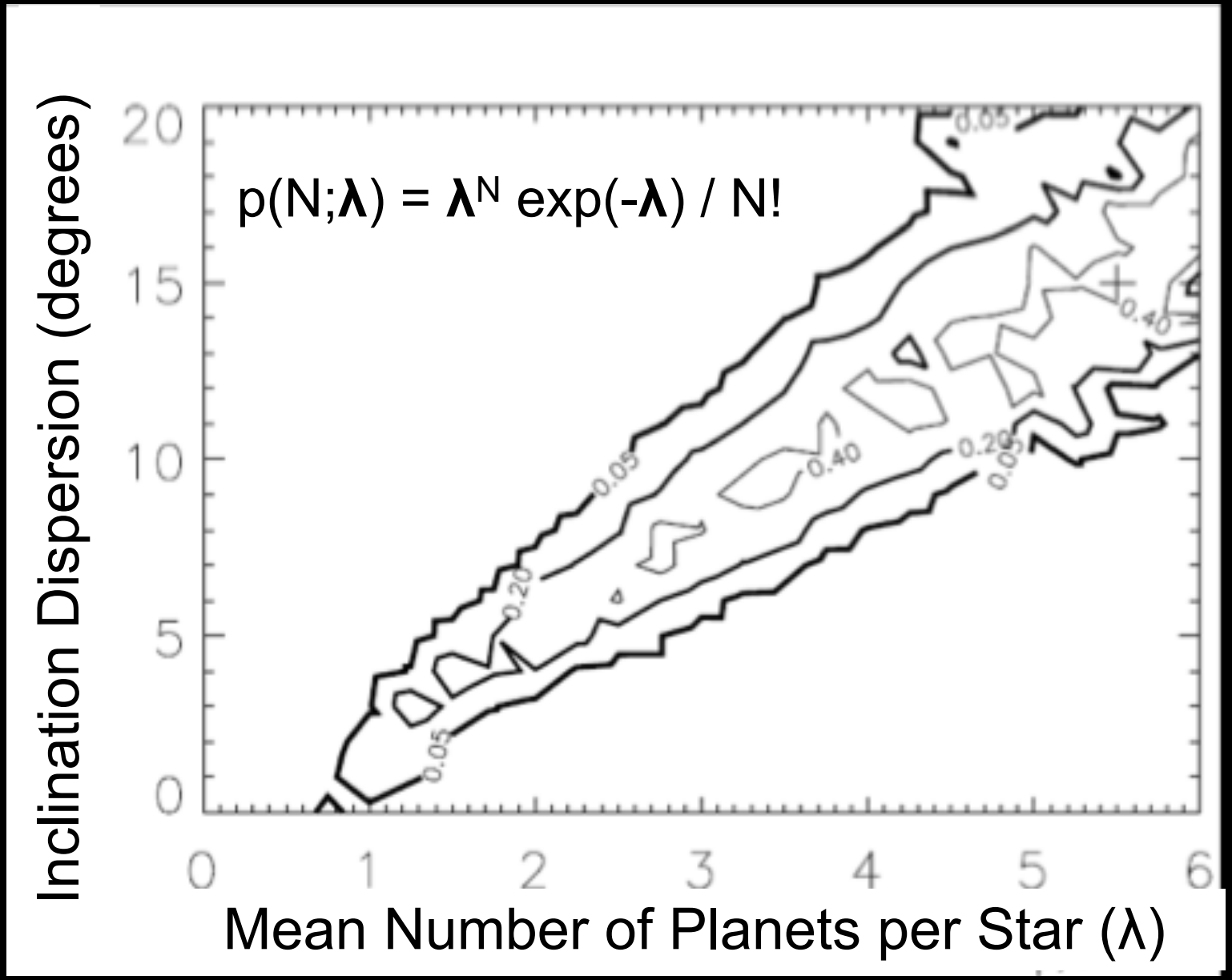
Orbital eccentricities, inclinations & multiplicity are key probes of planet formation:

- Eccentricity distribution (+ stellar densities) → Transit duration distribution
- Inclination distribution + Frequency of multiple planet systems (+ period distribution) → Frequency of multiply transiting systems & transit duration variations
- Frequency of multiple planet systems + Eccentricity distribution (+ period distribution) → Distribution of TTV signatures

One complex inverse problem!

(Observables, Desired Distributions, Both)

Planet Multiplicity & Mutual Inclinations

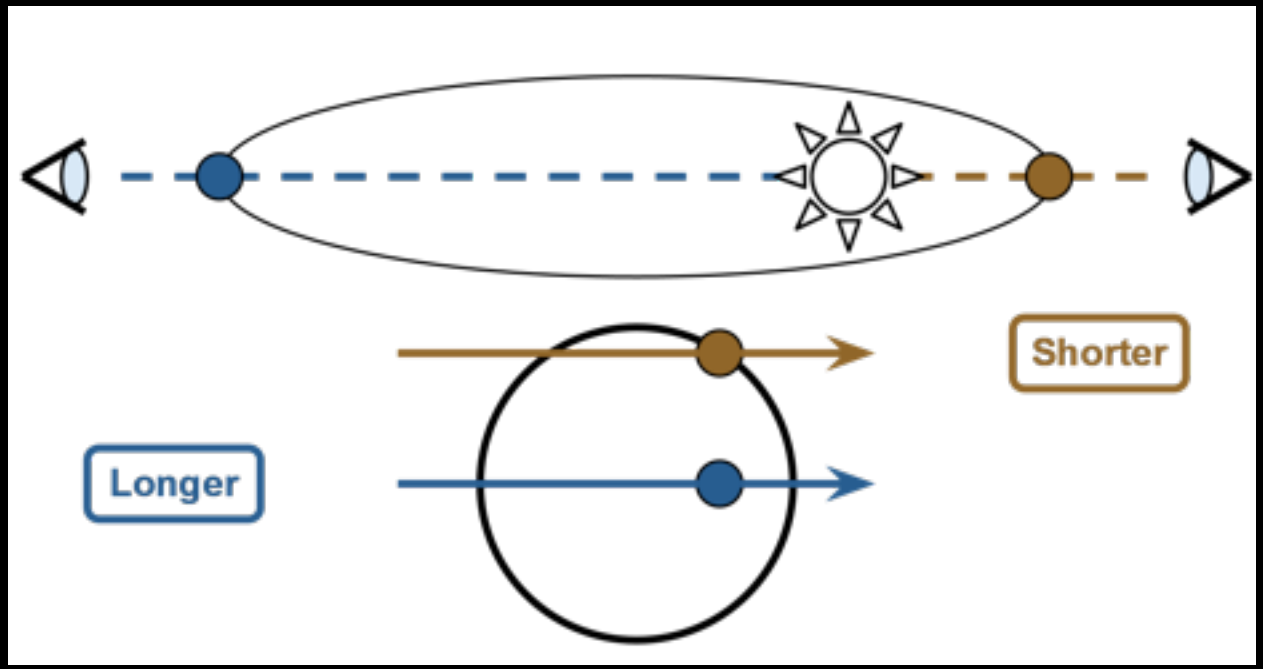


Ragozzine

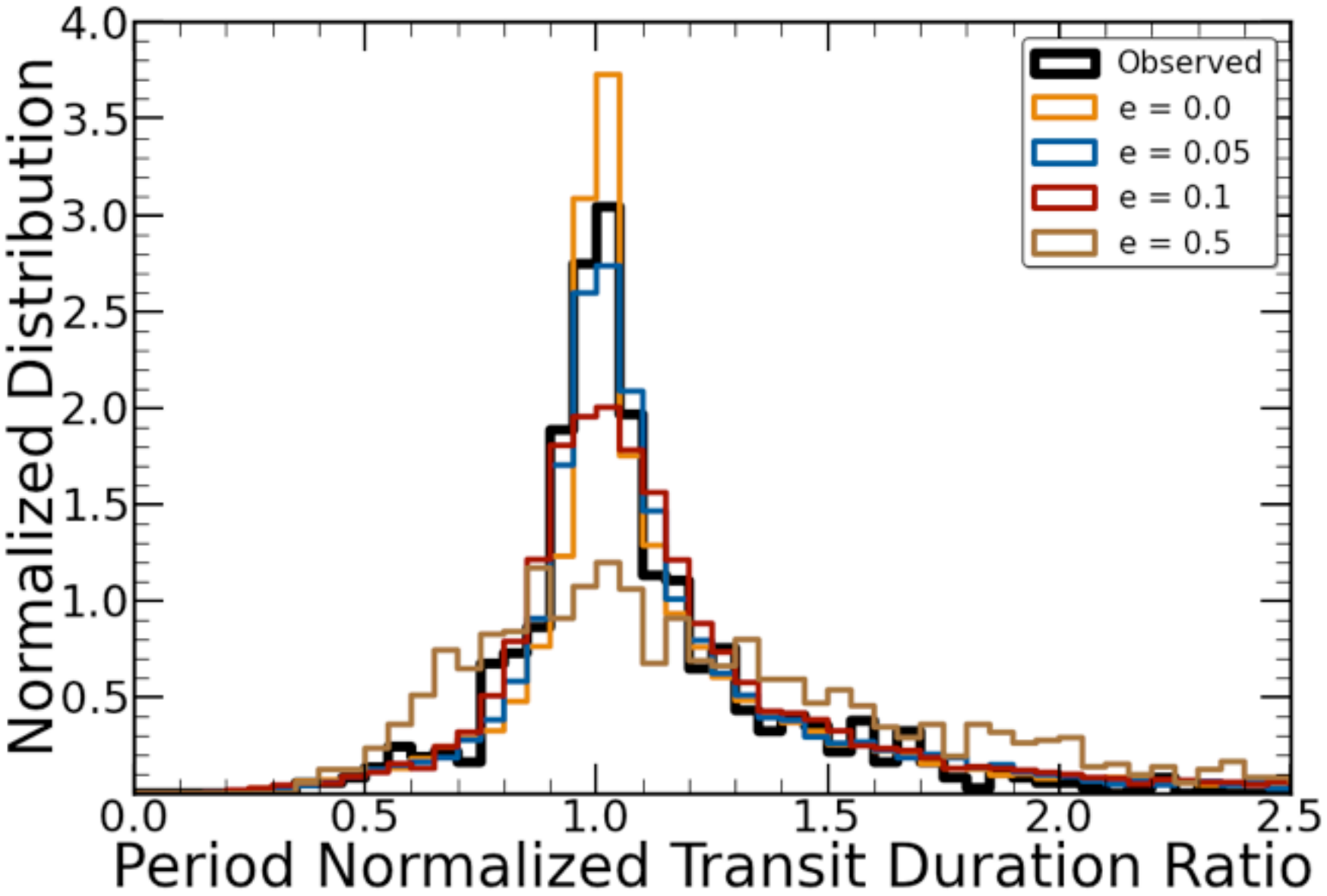
see also Lissauer+ 2011; Tremaine & Dong 2011; Fang et al. 2012

Period-Normalized Transit Duration Ratio

$$\xi \equiv \left(D_{in} \right.$$



R. Morehead; see poster 343.04



R. Morehead in prep.; see also Fabrycky et al. 2012; Fang et al. 2012; poster 343.04

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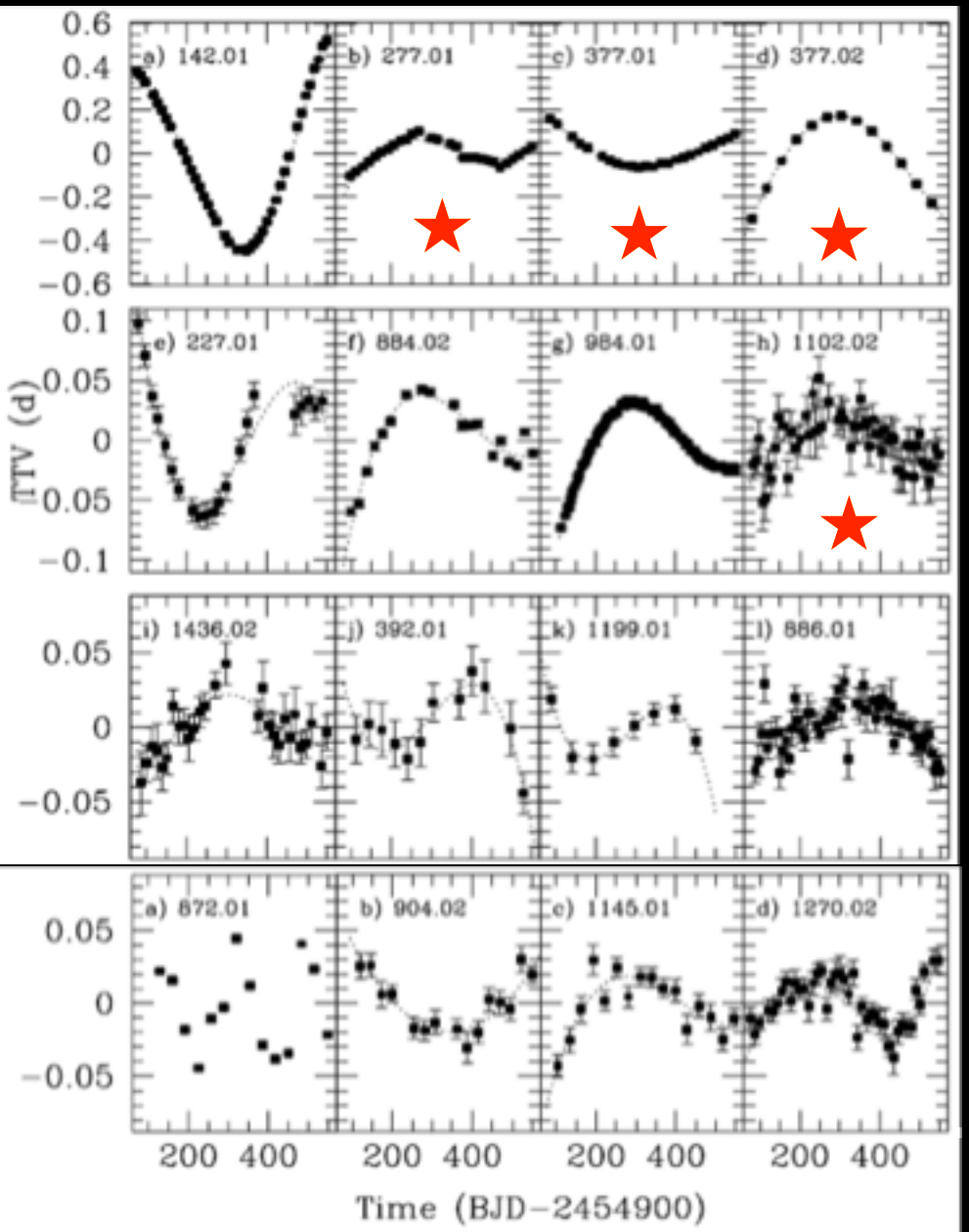
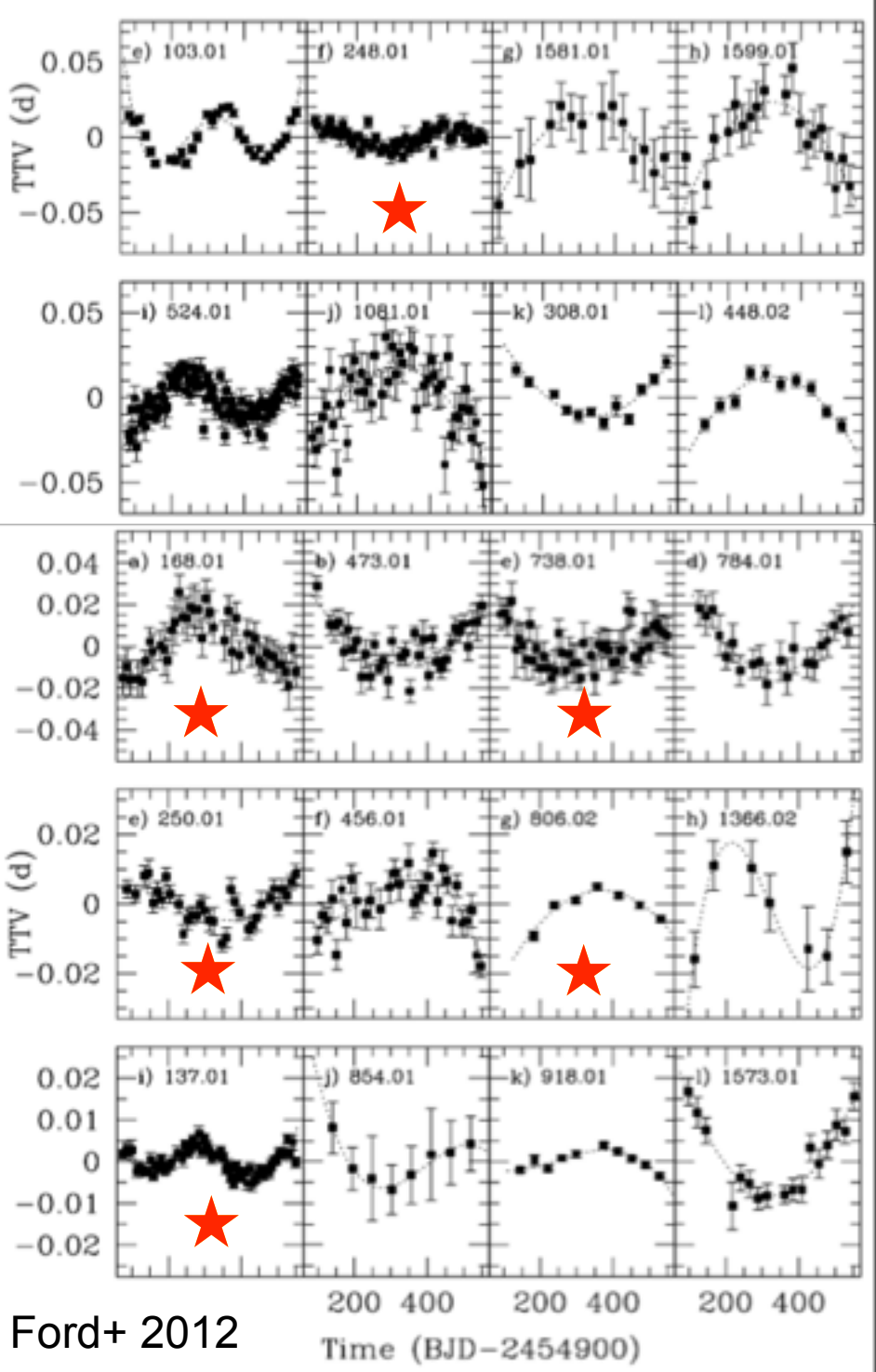
- Frequency of multiple planet systems + Eccentricity distribution (+ period distribution) → Distribution of TTV signatures

One complex inverse problem!

(Observables, Desired Distributions, Both)

Long-Term TTVs



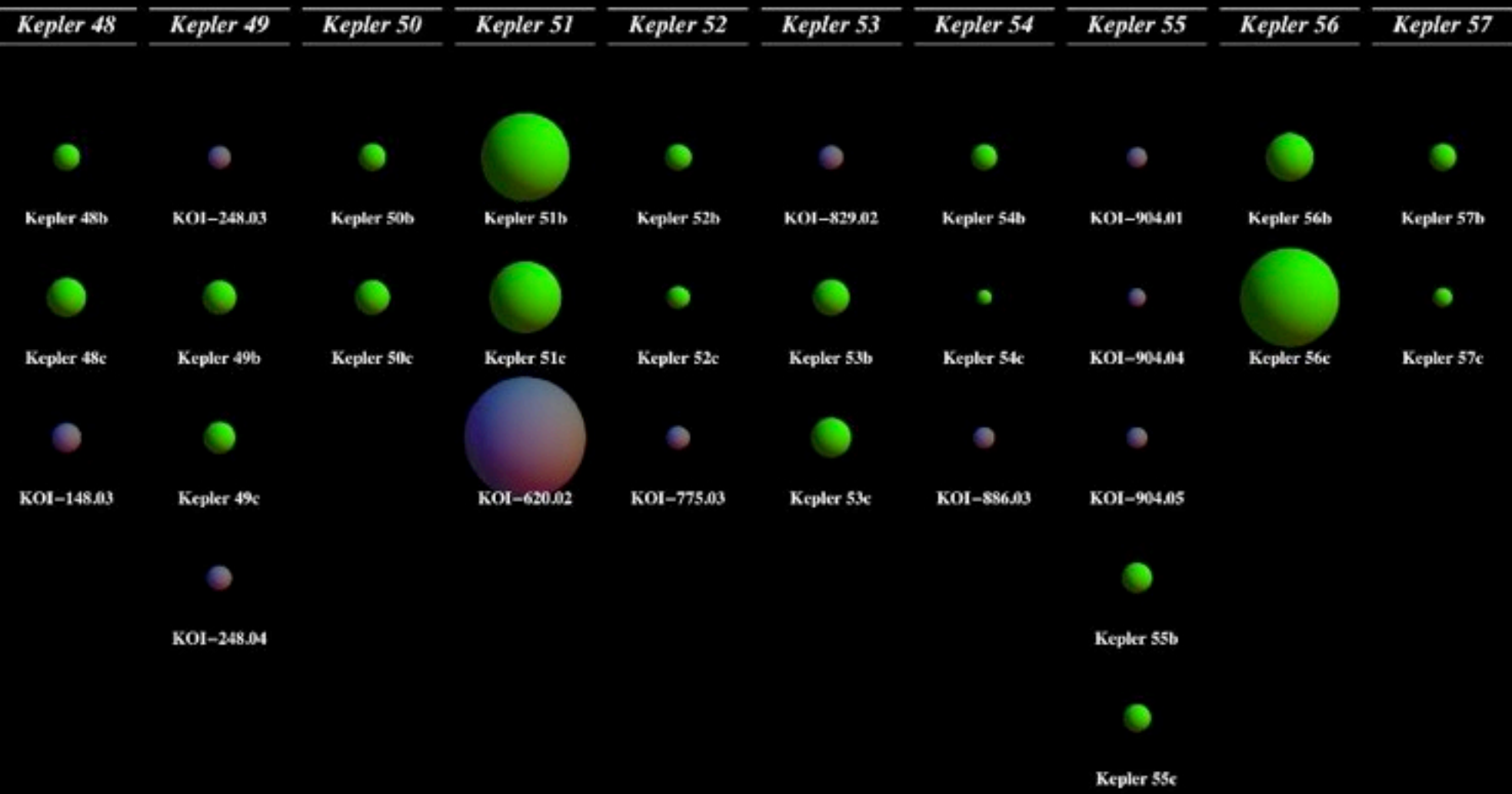


Ford+ 2012

Kepler's Multiple Planet Systems

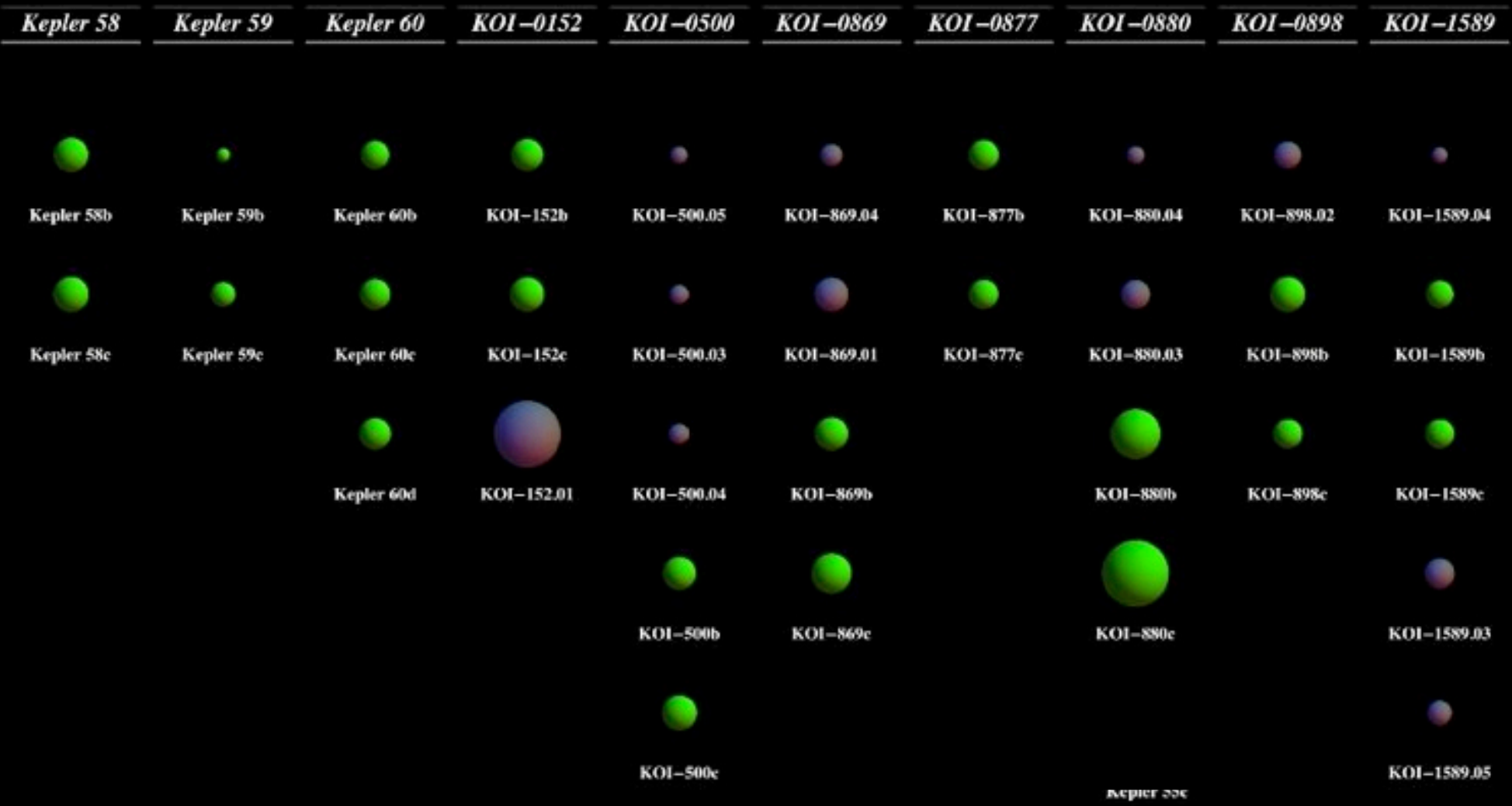
Holman+ 2011; Batalha+ 2010; Torres+ 2010; Lissauer+ 2011; Cochran+ 2011; Ford+ 2012; Steffen+ 2012ab; Fabrycky+ 2012; Fressin+ 2012; Muirhead+ 2012; Nesvorny+ 2012; Xie 2012; Orosz+ 2012

Kepler's Multiple Planet Systems



Holman+ 2011; Batalha+ 2010; Torres+ 2010; Lissauer+ 2011; Cochran+ 2011; Ford+ 2012; Steffen+ 2012ab; Fabrycky+ 2012; Fressin+ 2012; Muirhead+ 2012; Nesvorny+ 2012; Xie 2012; Orosz+ 2012

Kepler's Multiple Planet Systems



Holman+ 2011; Batalha+ 2010; Torres+ 2010; Lissauer+ 2011; Cochran+ 2011; Ford+ 2012; Steffen+ 2012ab; Fabrycky+ 2012; Fressin+ 2012; Muirhead+ 2012; Nesvorny+ 2012; Xie 2012; Orosz+ 2012

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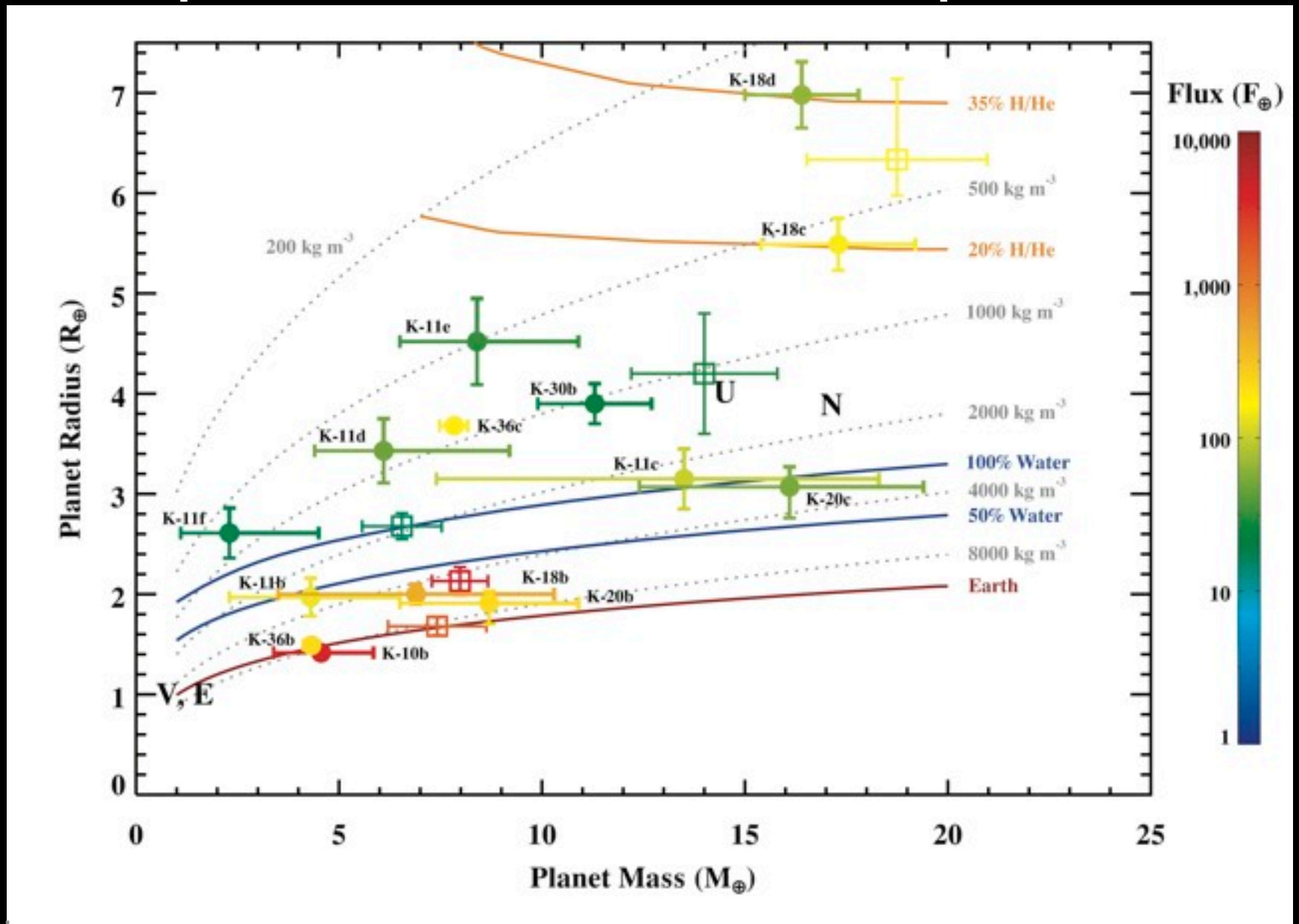
How Common are TTVs?

- First 16 months of Kepler data (Ford+ 2012):
  - 39 – 175 TTV candidates
  - 8% – 18% of suitable KOIs show TTVs
  - More for multis & long period planets
- Planets Confirmed by TTVs: 73 of ~105
- Sensitivity to long-term TTVs grows $\sim t^{5/2}$
  - Many more KOIs w/ TTVs in extended mission

Super-Earths or Mini-Neptunes?

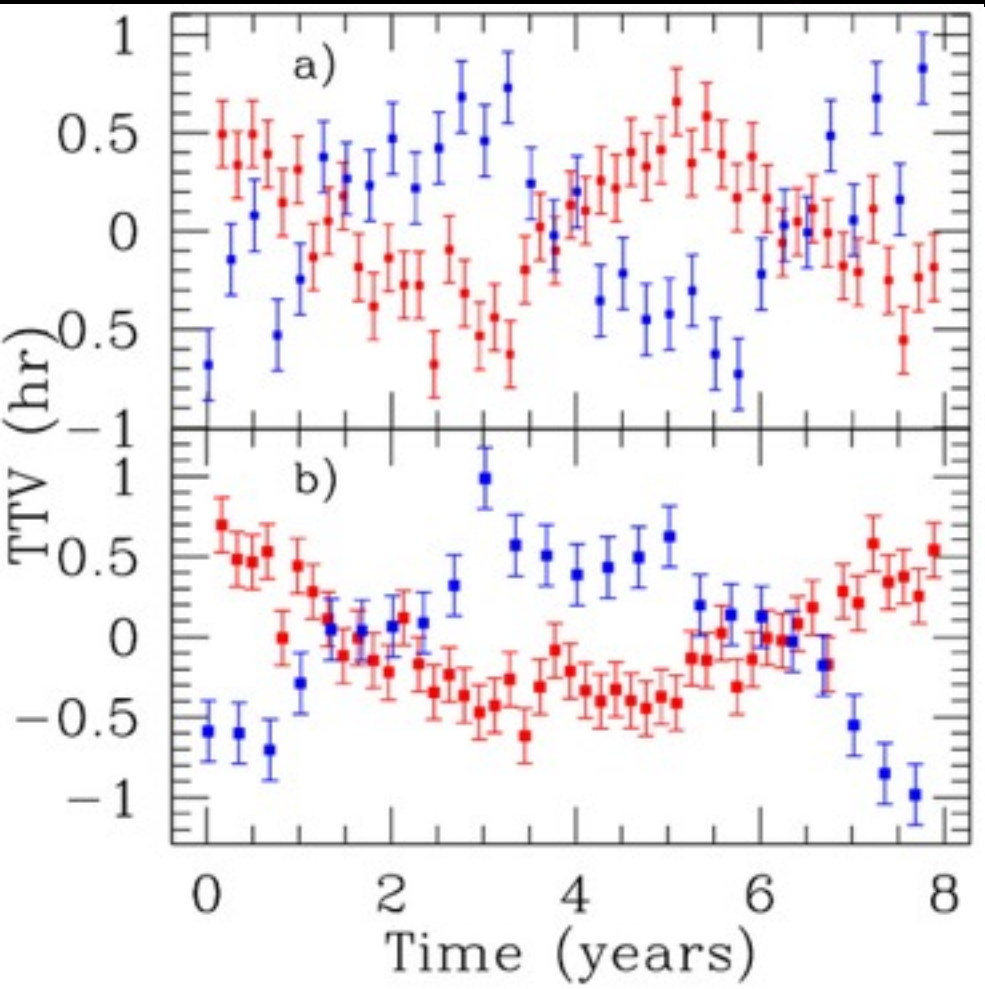


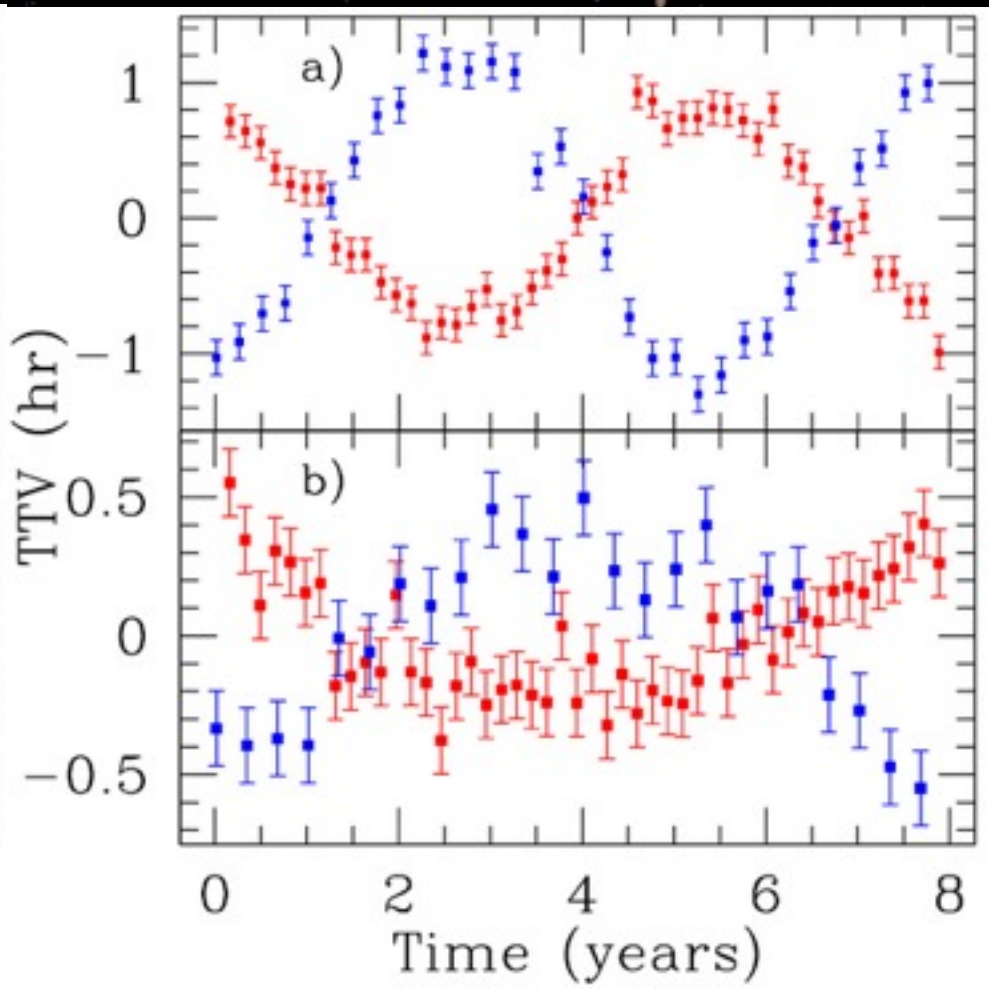
Eric Lopez

Future Prospects for Measuring Masses via TTVs

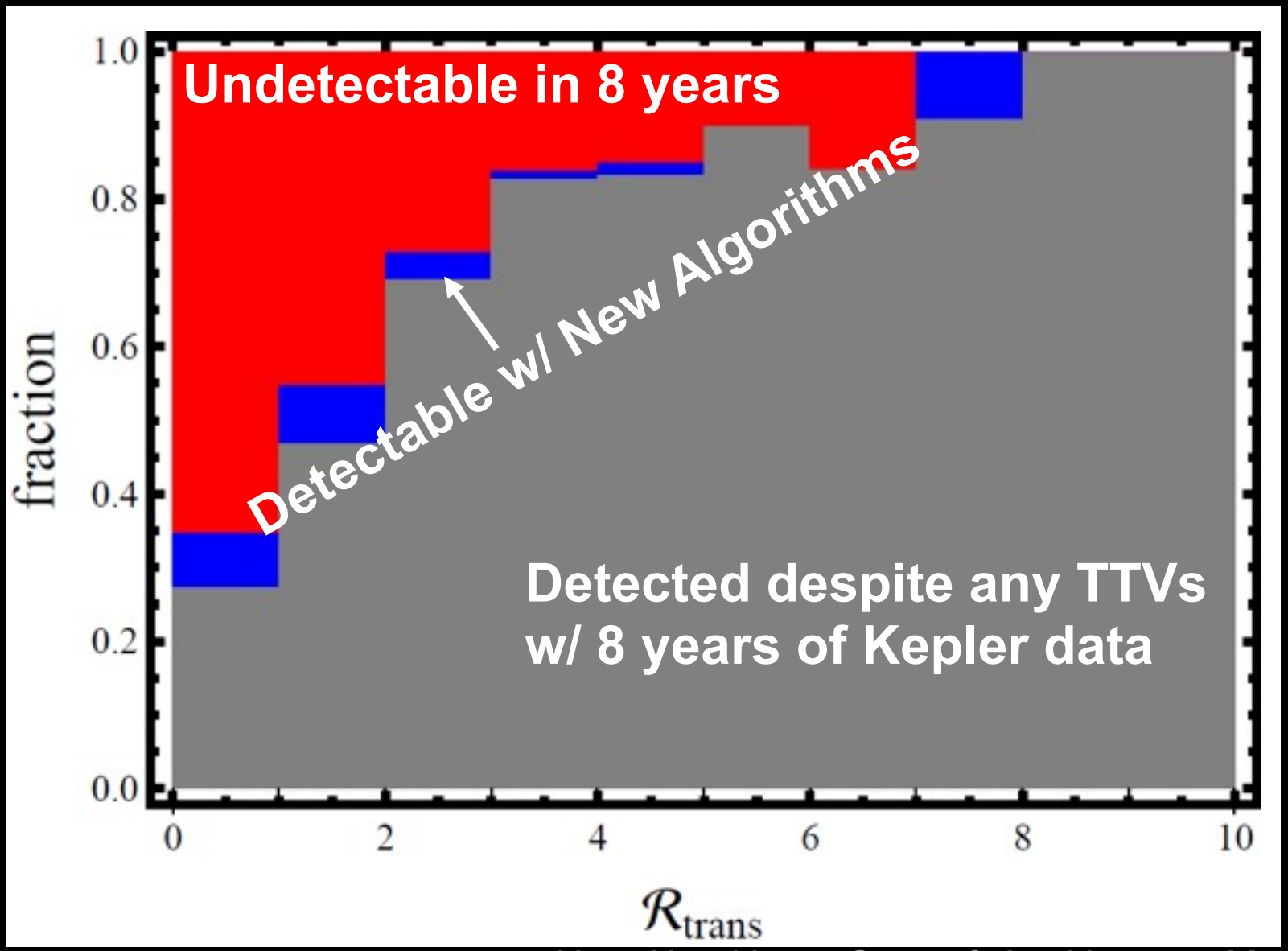
1 Earth-mass, 3:2 MMR, Kp=13

2 Earth-mass, 3:2 MMR, Kp=13





Detecting Small Planets w/ Large TTVs



Ford+ 2012

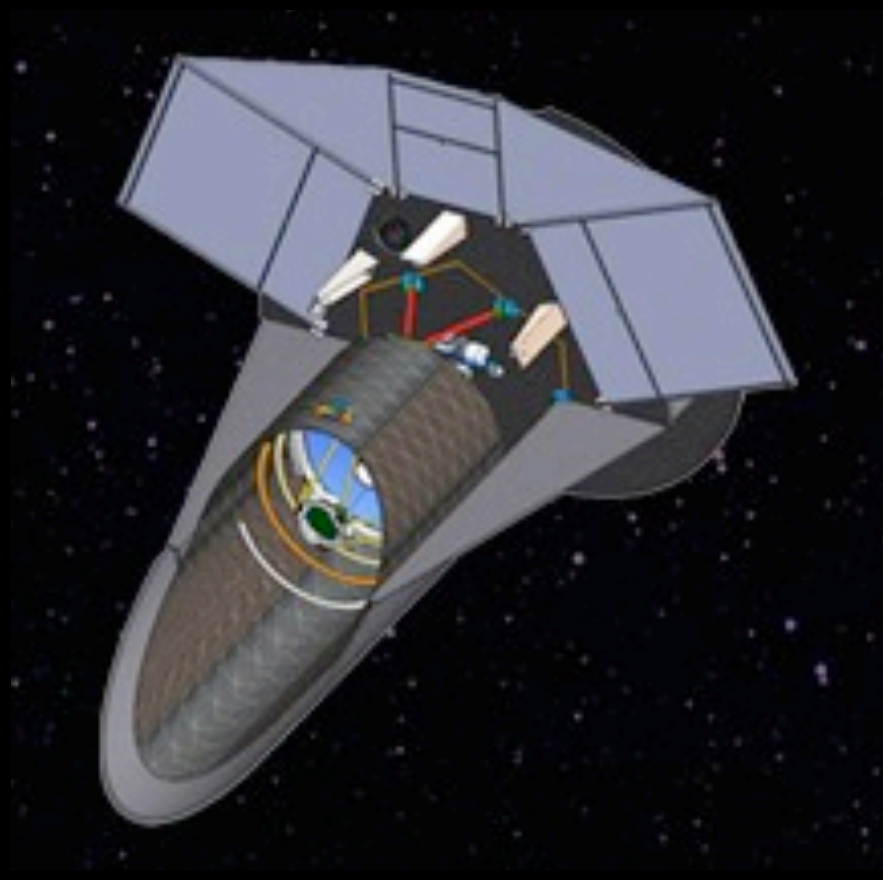
New Algorithms: Carter & Agol in prep; Moorhead+ in prep

Testing Planet Formation Theory with Kepler

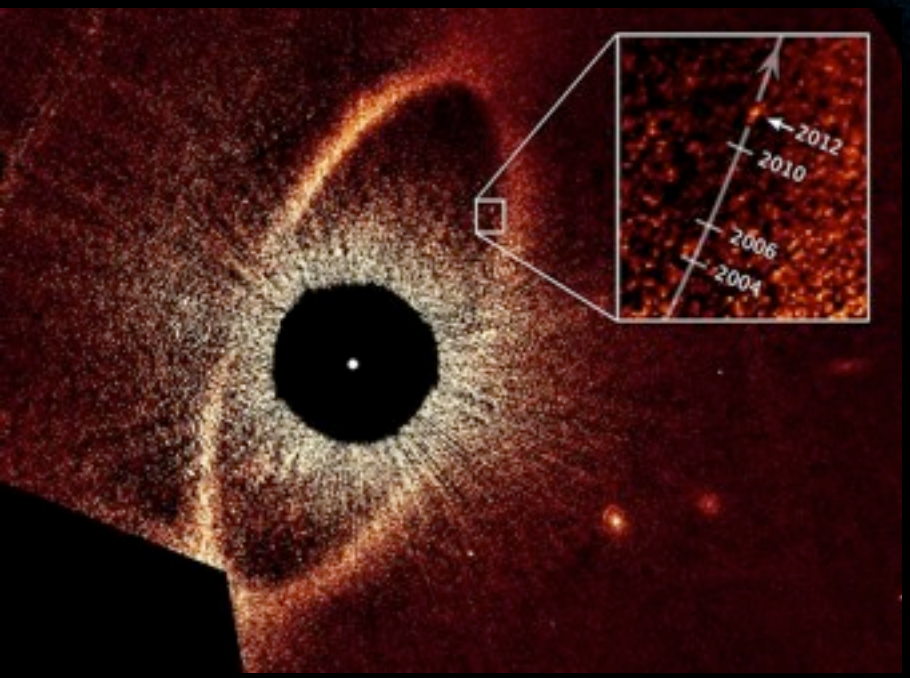
Must combine many elements simultaneously:

- Detection efficiency/completeness
- Planetary systems
  (not just superposition of individual planets)
- Variety of observational constraints
  (e.g., RV, TTV, spectra, imaging, seismology)
- Observational uncertainties
- How planets were chosen for follow-up observations or more detailed analyses

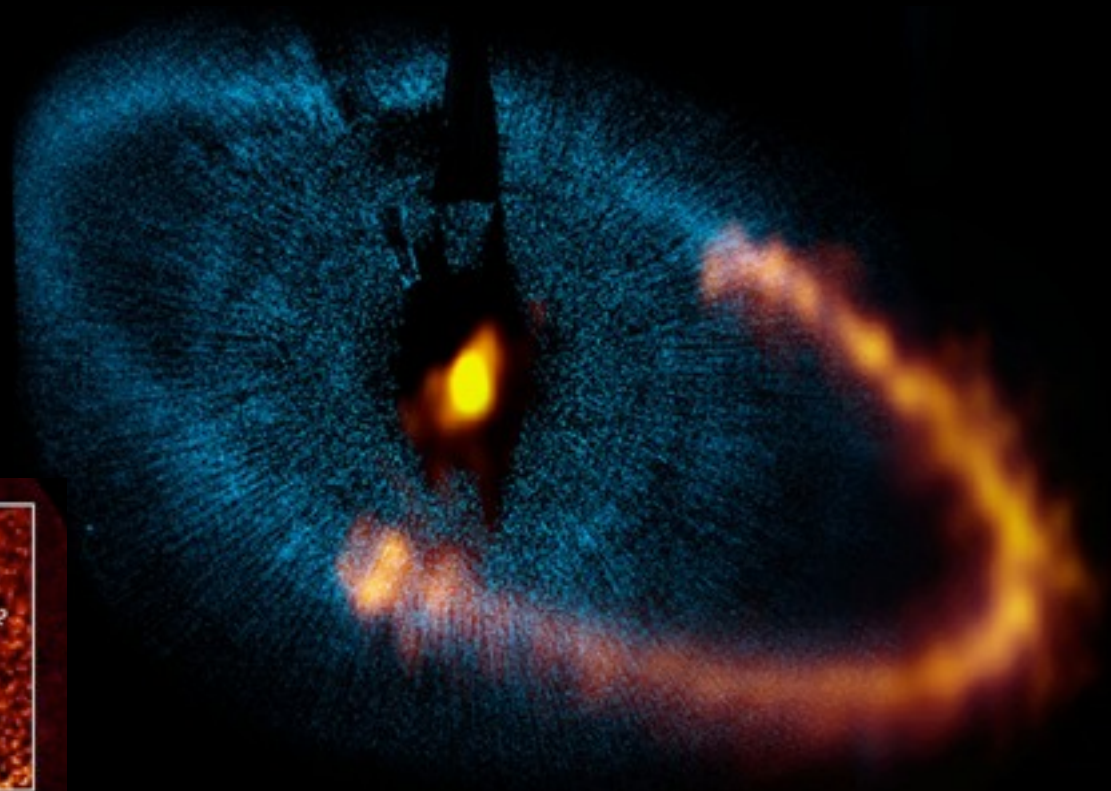
Future Space Missions



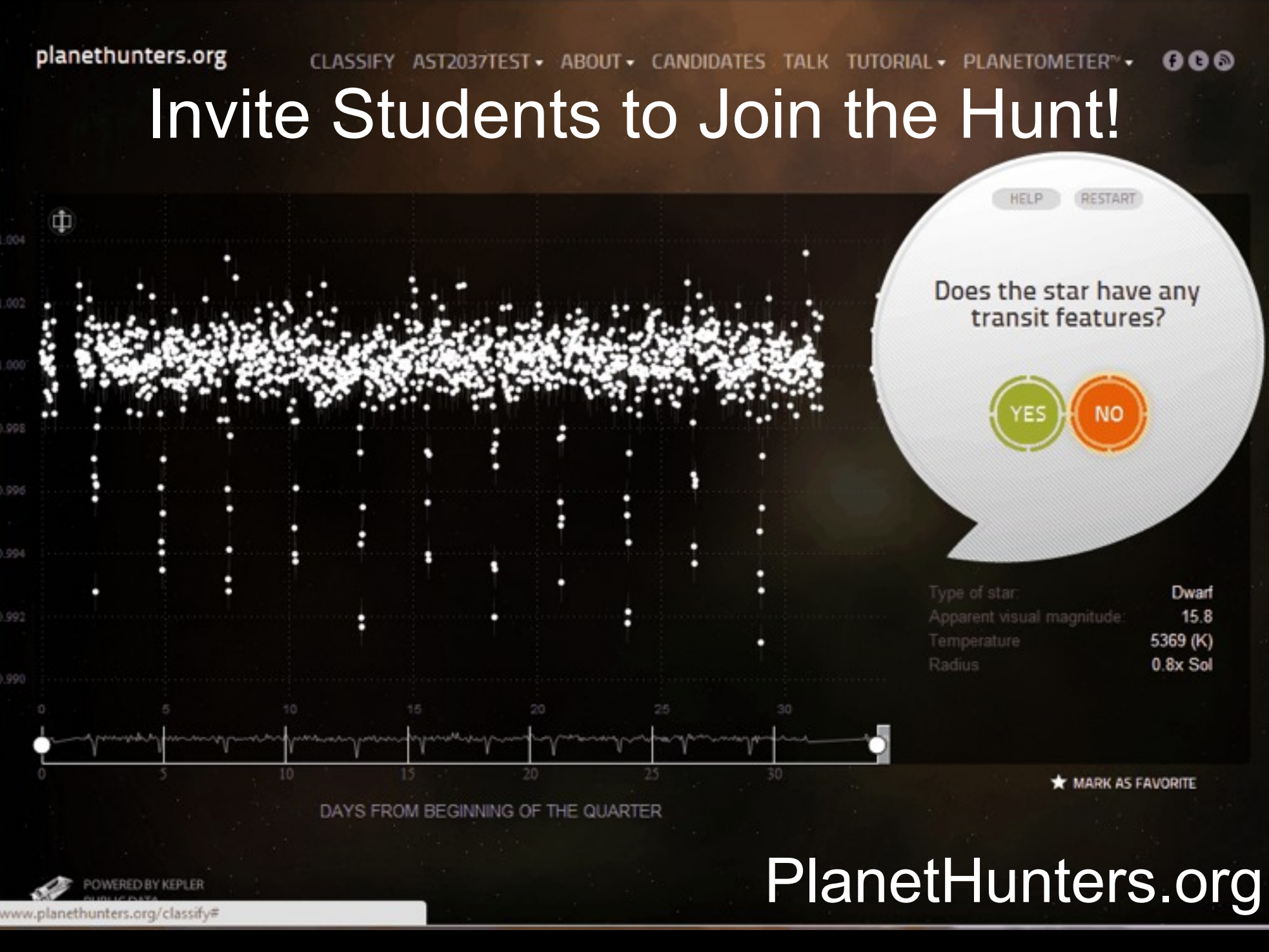
Direct Imaging & ALMA

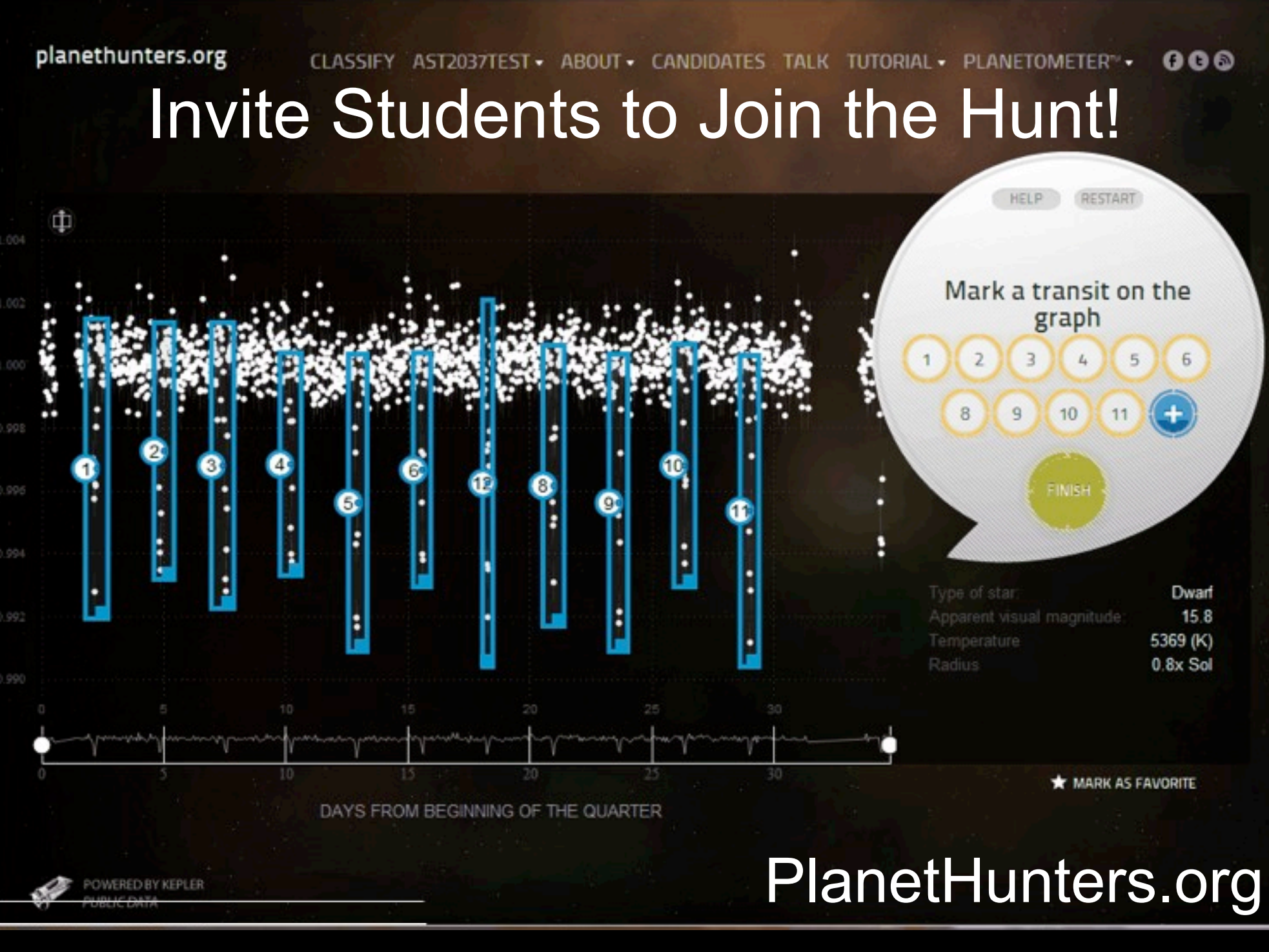


NASA, ESA, & Kalas (UC, Berkeley & SETI Institute)



Boley et al. 2012
ALMA: ESO/NAOJ/NRAO + HST: NASA/ESA


planethunters.org
CLASSIFY AST2037TEST ABOUT CANDIDATES TALK TUTORIAL PLANETOMETER
Invite Students to Join the Hunt!
HELP
RESTART
Does the star have any transit features?
YES
NO
Type of star: Dwarf
Apparent visual magnitude: 15.8
Temperature 5369 (K)
Radius 0.8x Sol
MARK AS FAVORITE
DAYS FROM BEGINNING OF THE QUARTER
POWERED BY KEPLER
www.planethunters.org/classify#
PlanetHunters.org


planethunters.org
CLASSIFY
AST2037TEST
ABOUT
CANDIDATES
TALK
TUTORIAL
PLANETOMETER
Invite Students to Join the Hunt!
HELP
RESTART
Mark a transit on the graph
1
2
3
4
5
6
8
9
10
11
FINISH
Type of star
Dwarf
Apparent visual magnitude
15.8
Temperature
5369 (K)
Radius
0.8x Sol
MARK AS FAVORITE
DAYS FROM BEGINNING OF THE QUARTER
POWERED BY KEPLER
PUBLIC DATA
PlanetHunters.org

Questions

Movie of Collapse & Fragmentation