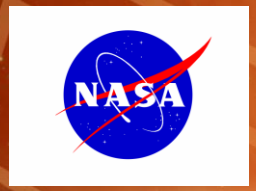
Terrestrial and Sub-Neptune Exoplanetary Systems from *Kepler*

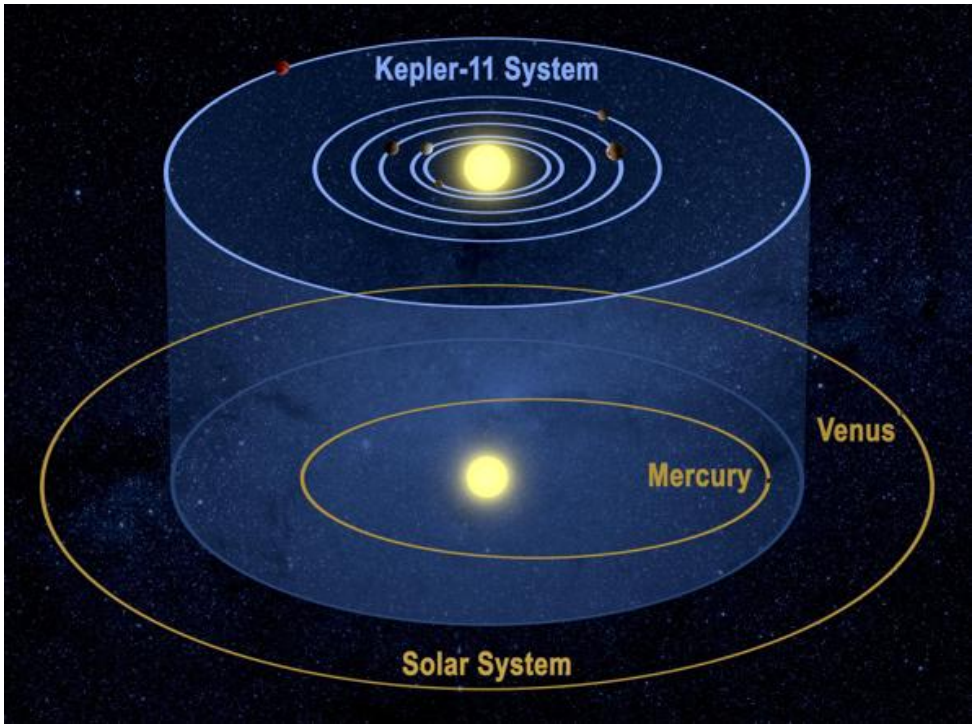


Daniel Fabrycky

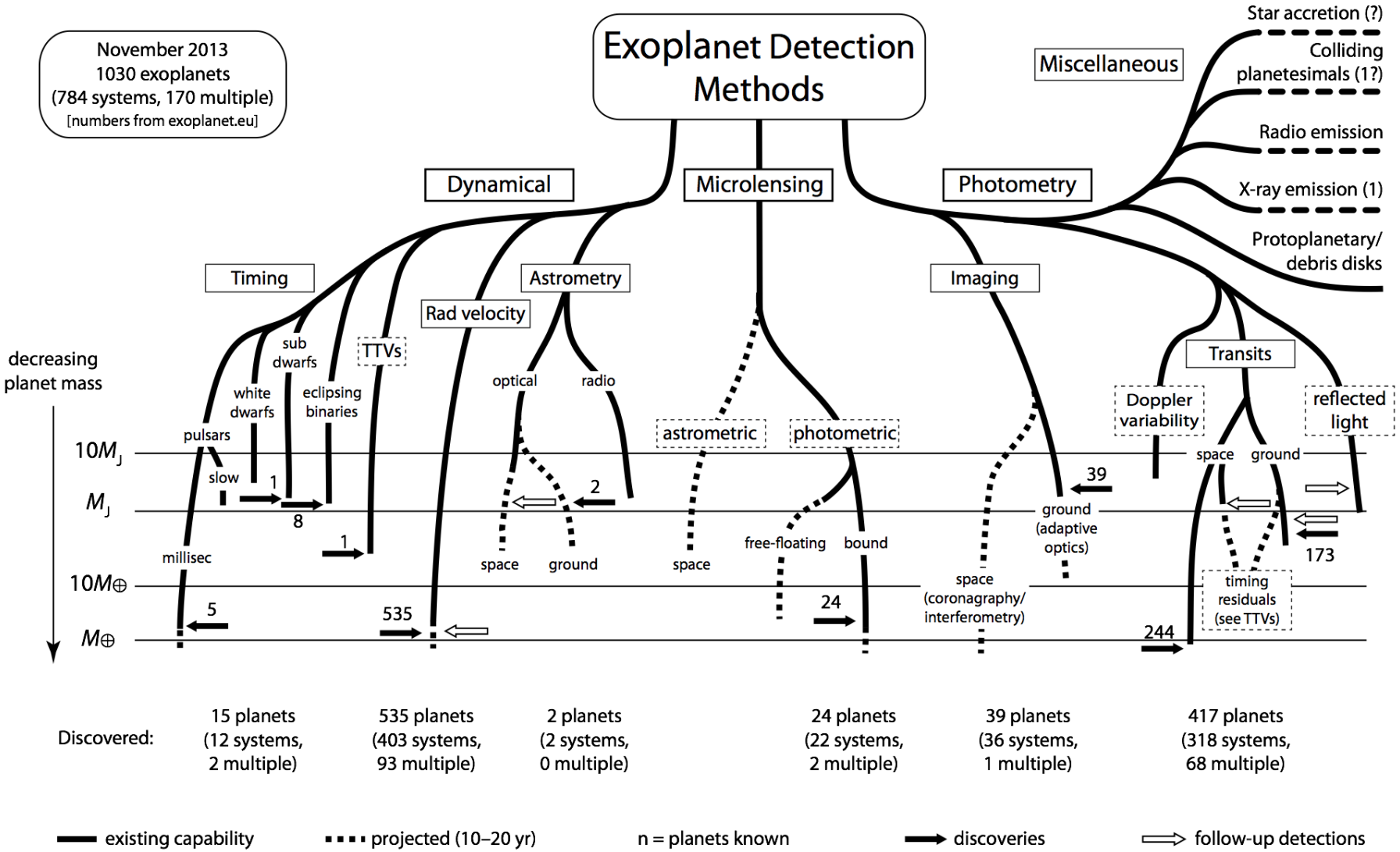
University of Chicago

Outline

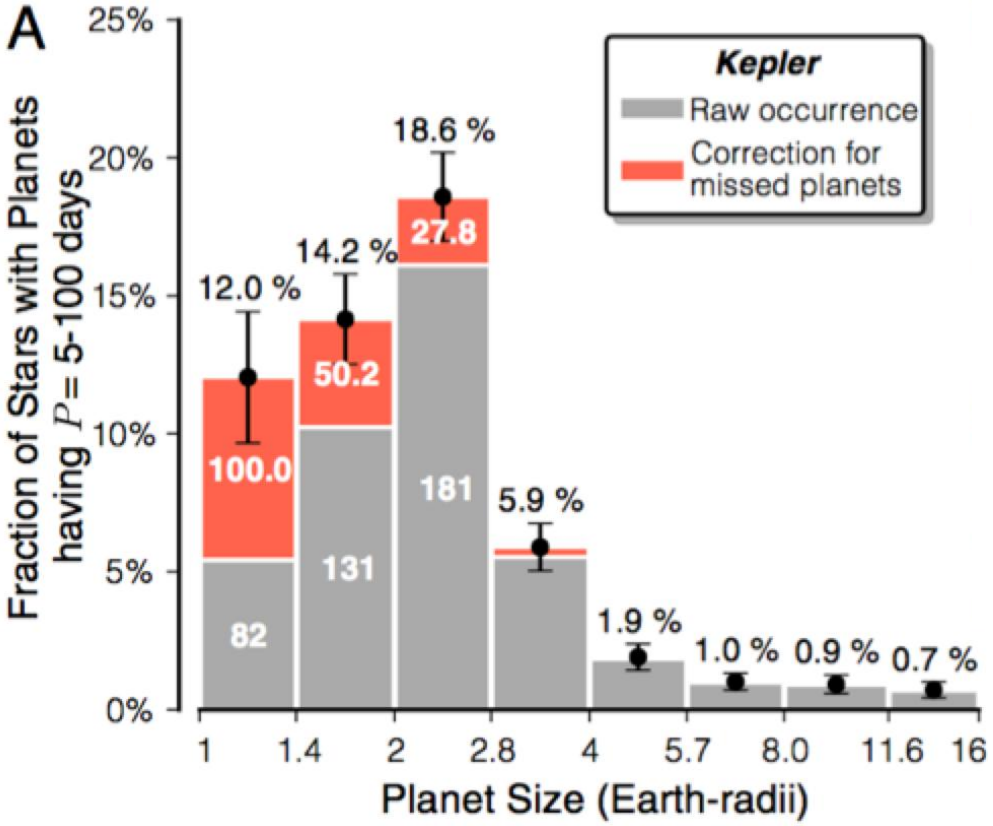
- Multi-transiting systems, Planet Types
- Mutual inclinations
- Period ratio distribution

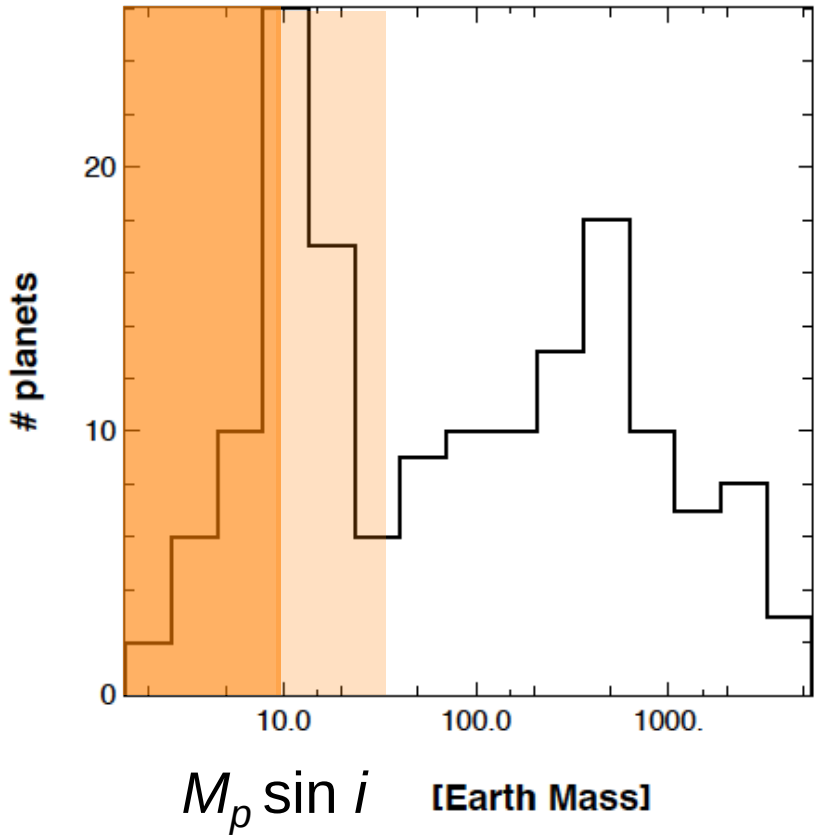


Perryman 2013



Reminder: Small Planets are Common





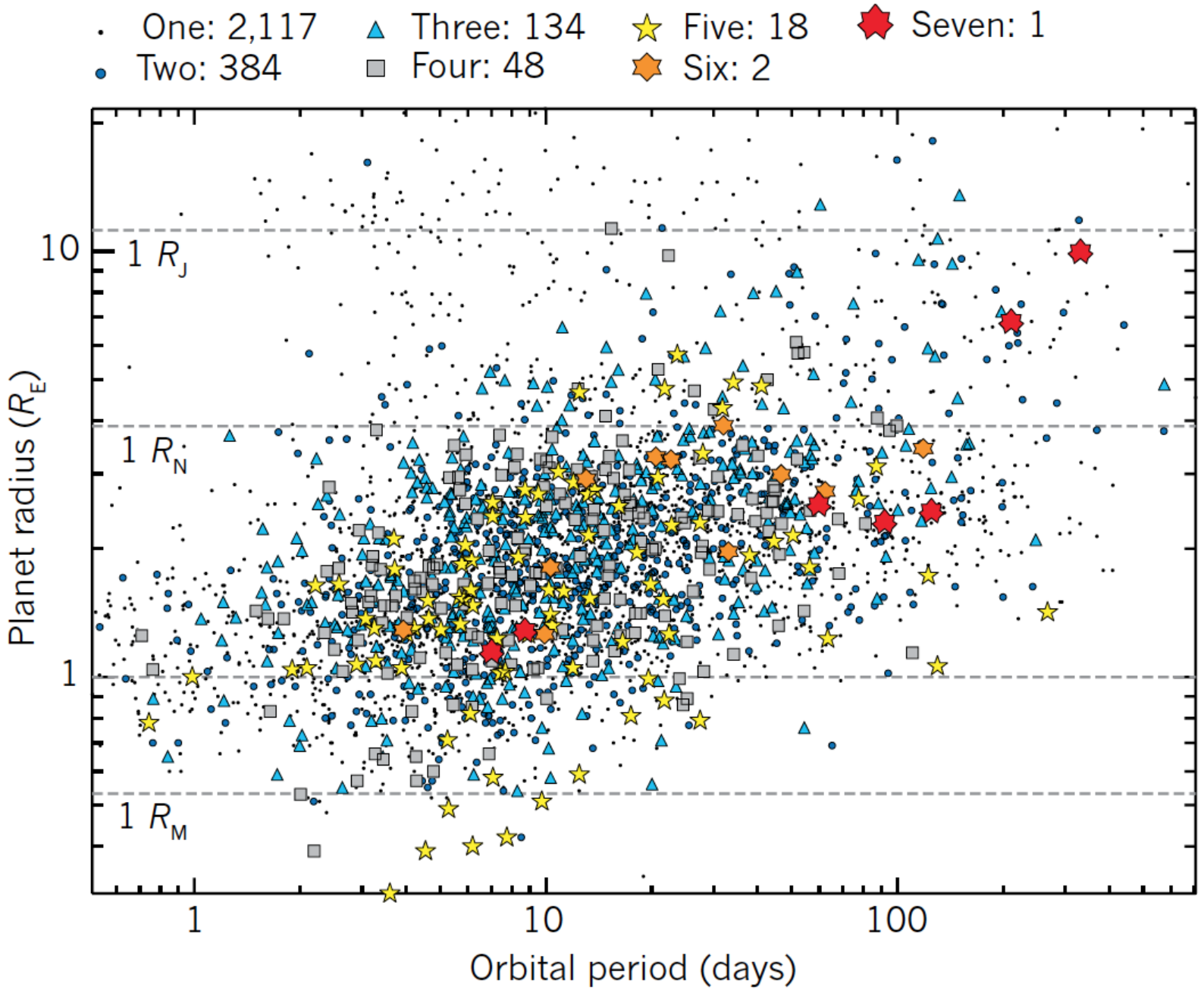
Transits/Kepler
(Petigura, Howard, Marcy 2013)

Doppler/HARPS
(Mayor et al. 2011)

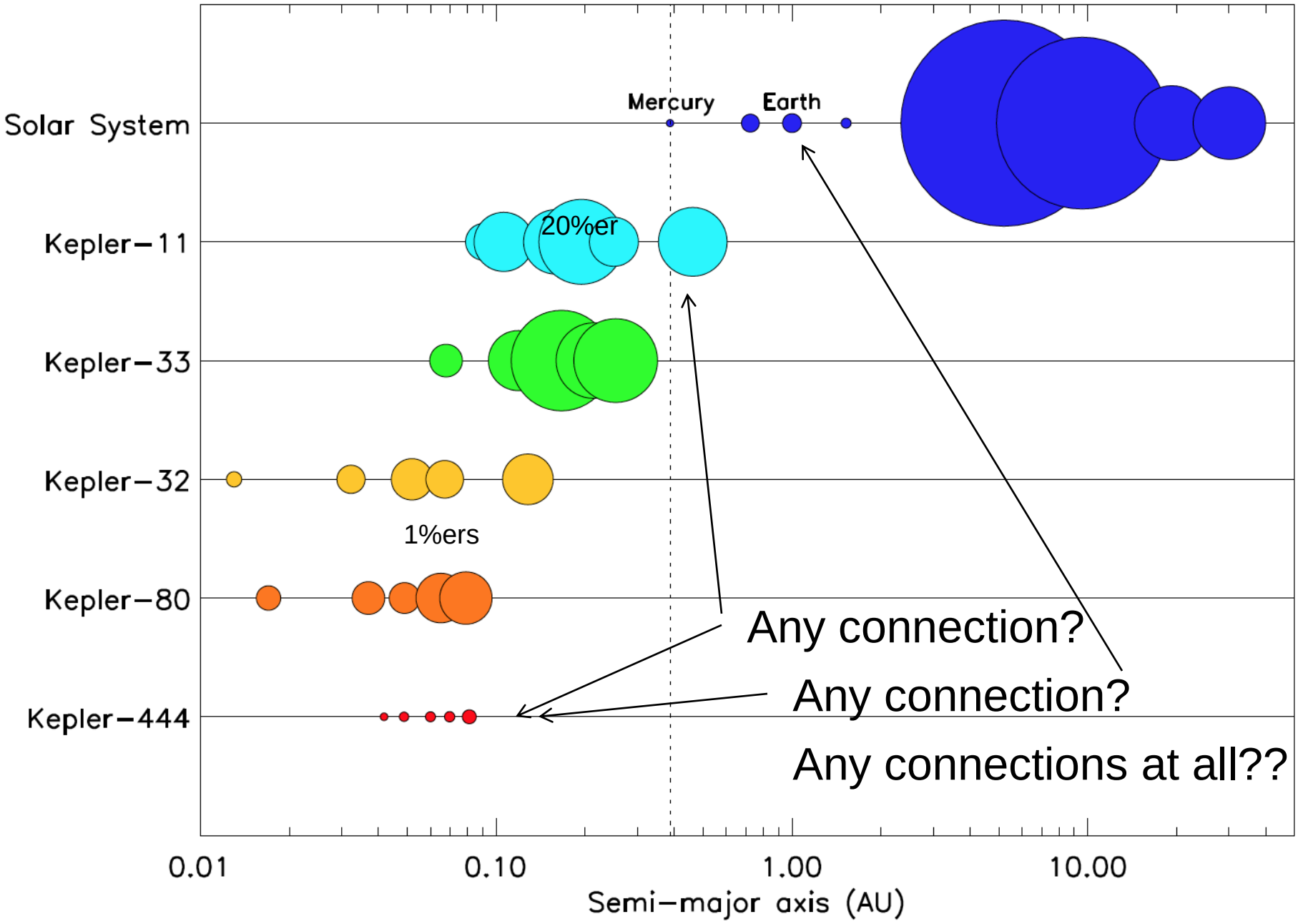
Kepler Mission (*NASA, 2009-2013**)

**resurrected as: K2*

- A search for Earth-like planets by the transit technique
- Brightness measurements of 150,000 stars
- In orbit around the Sun

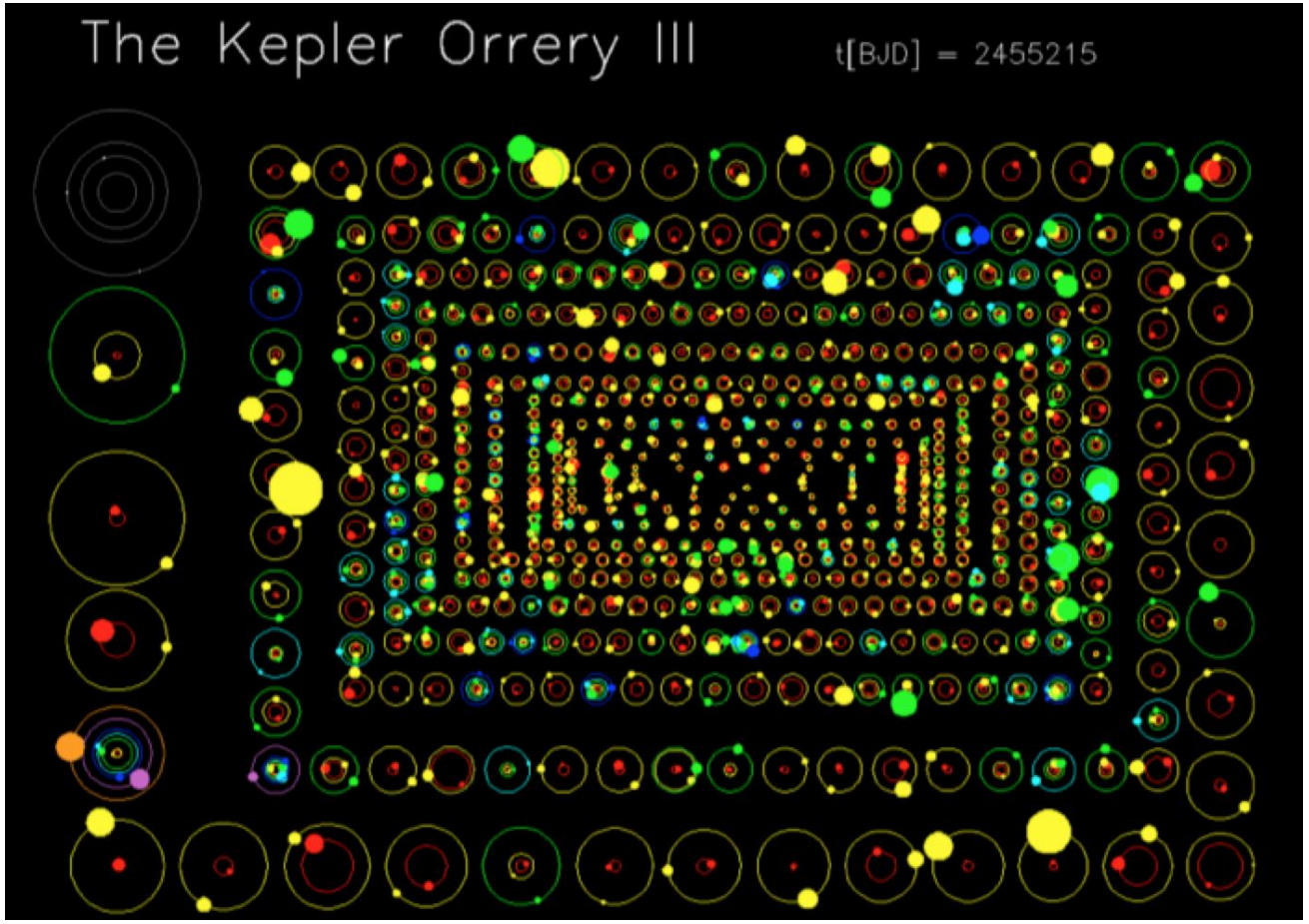


Courtesy J. Rowe., via Lissauer et al. 2014

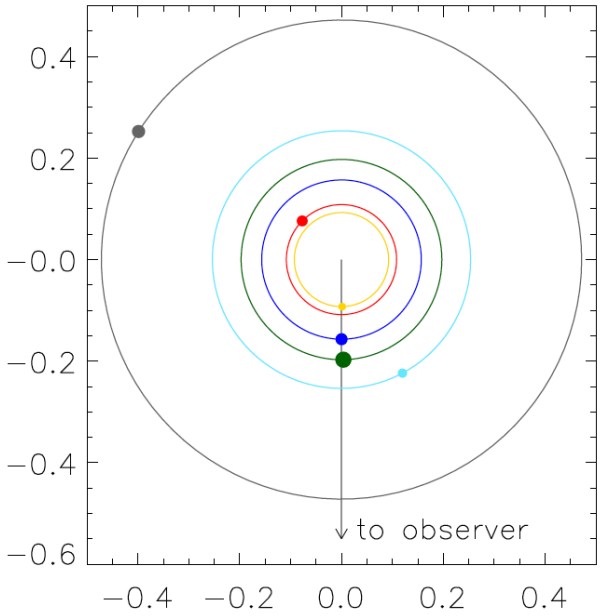


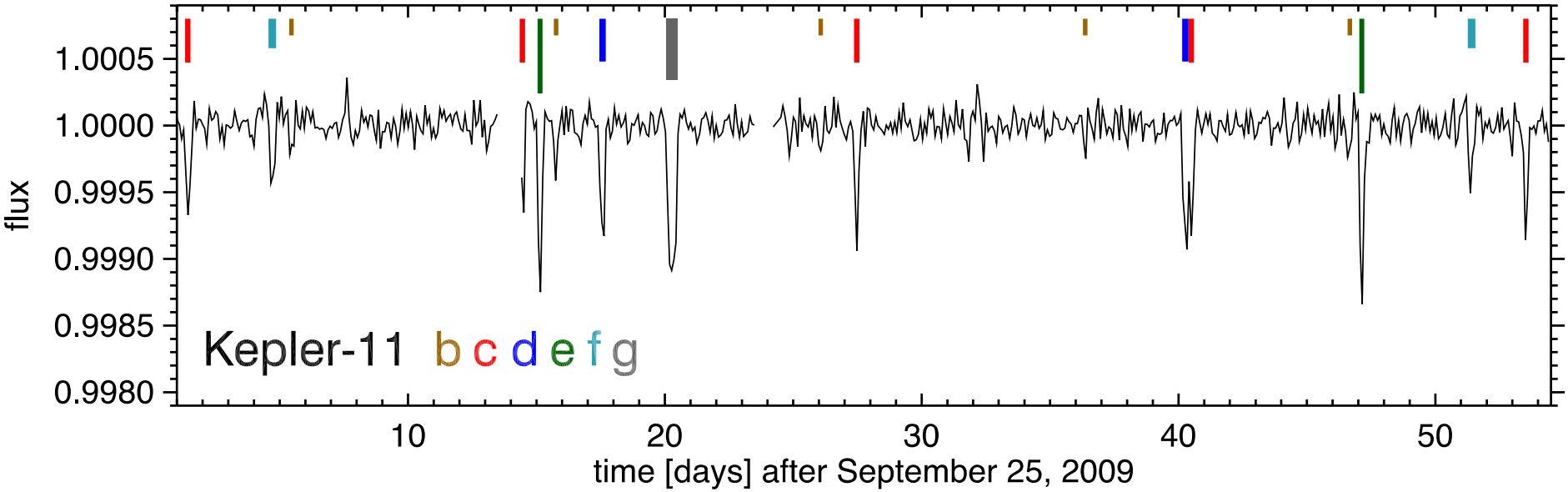
Campante et al. (2015)

https://www.youtube.com/watch?v=gnZVvYm6KKM
or
http://kepler.nasa.gov/multimedia/animations/orrery3/



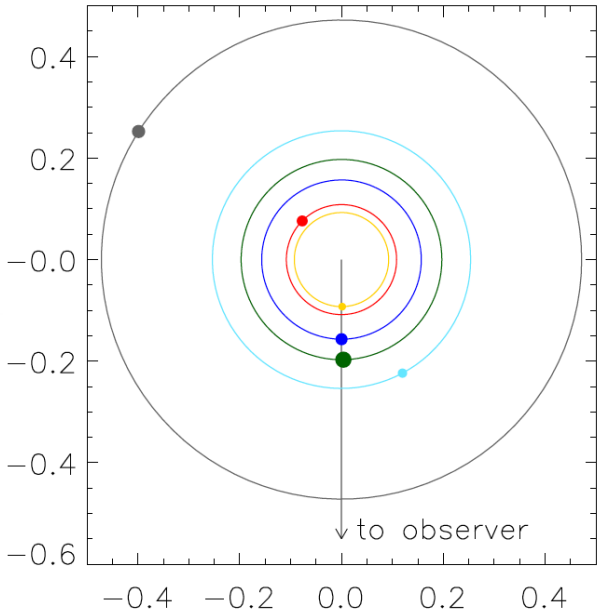
Kepler-11

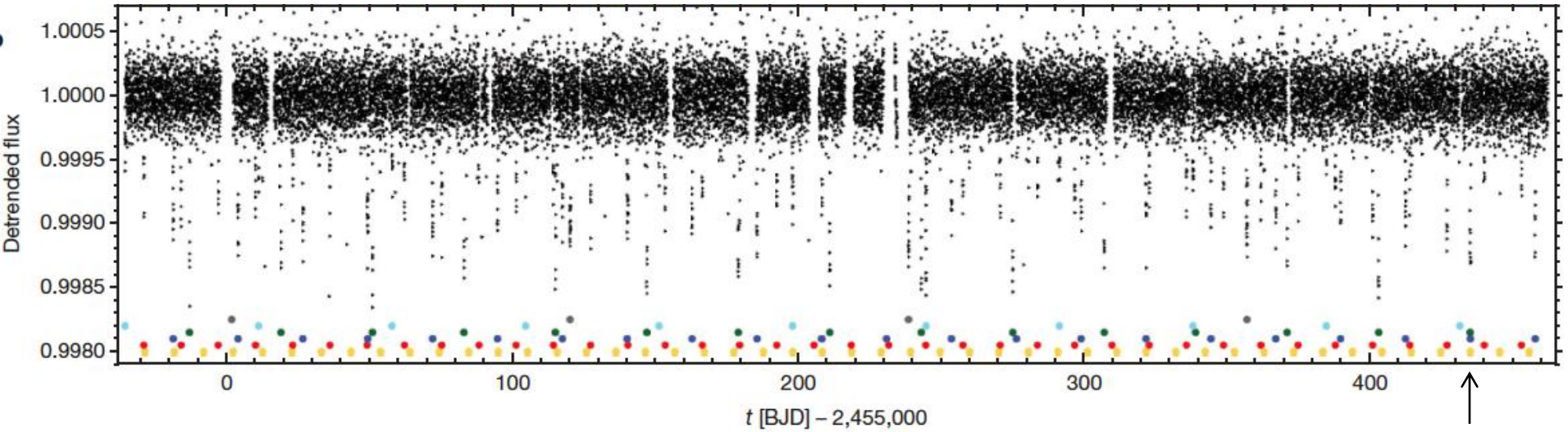




Lissauer, Fabrycky, Ford et al. 2011

Kepler-11





Lissauer, Fabrycky, Ford et al. 2011

nature
470, 1–134 3 FEBRUARY 2011
NATURE.COM/NATURE
NO. 7332 npg

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

SIX NEW WORLDS

Kepler telescope's edge-on view of compact planetary system around Sun-like star PAGE 53

POLICY

DEEP-SEA MINING

Regulate now to protect hydrothermal vent species

PAGE 31

DRUG DISCOVERY

TAKING THE LEAD

Debating how to keep the pipelines flowing

PAGE 42

ADAPTIVE IMMUNITY

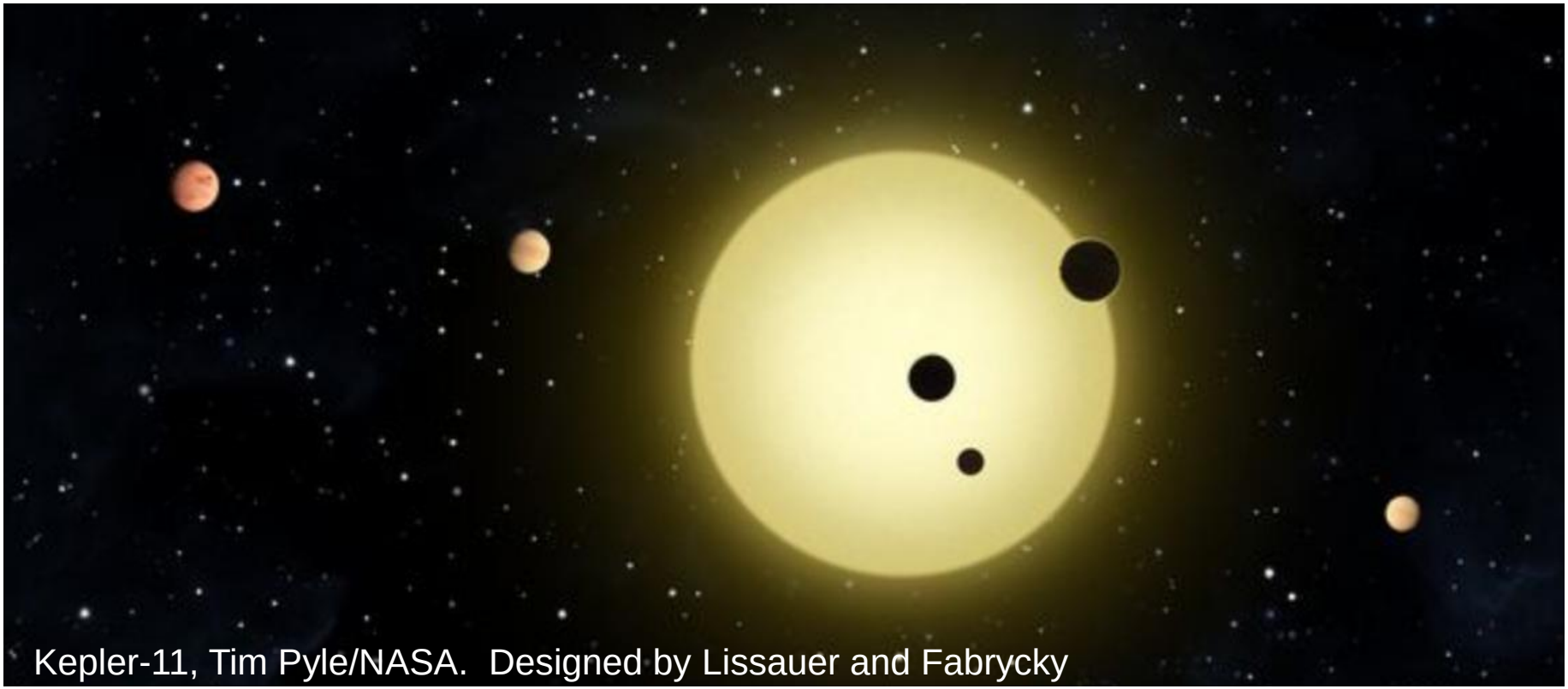
EARLY ORIGIN FOR A 'THYMUS'

Gill-based thymoid found in living-fossil lampreys

PAGE 90

NATURE.COM/NATURE
3 February 2011
$10.00US $12.99CAN
05
0 71486 03070 6

Image: NASA/Pyle
Designed by Lissauer and Fabrycky



Kepler-11, Tim Pyle/NASA. Designed by Lissauer and Fabrycky

** Available at Kepler’s website

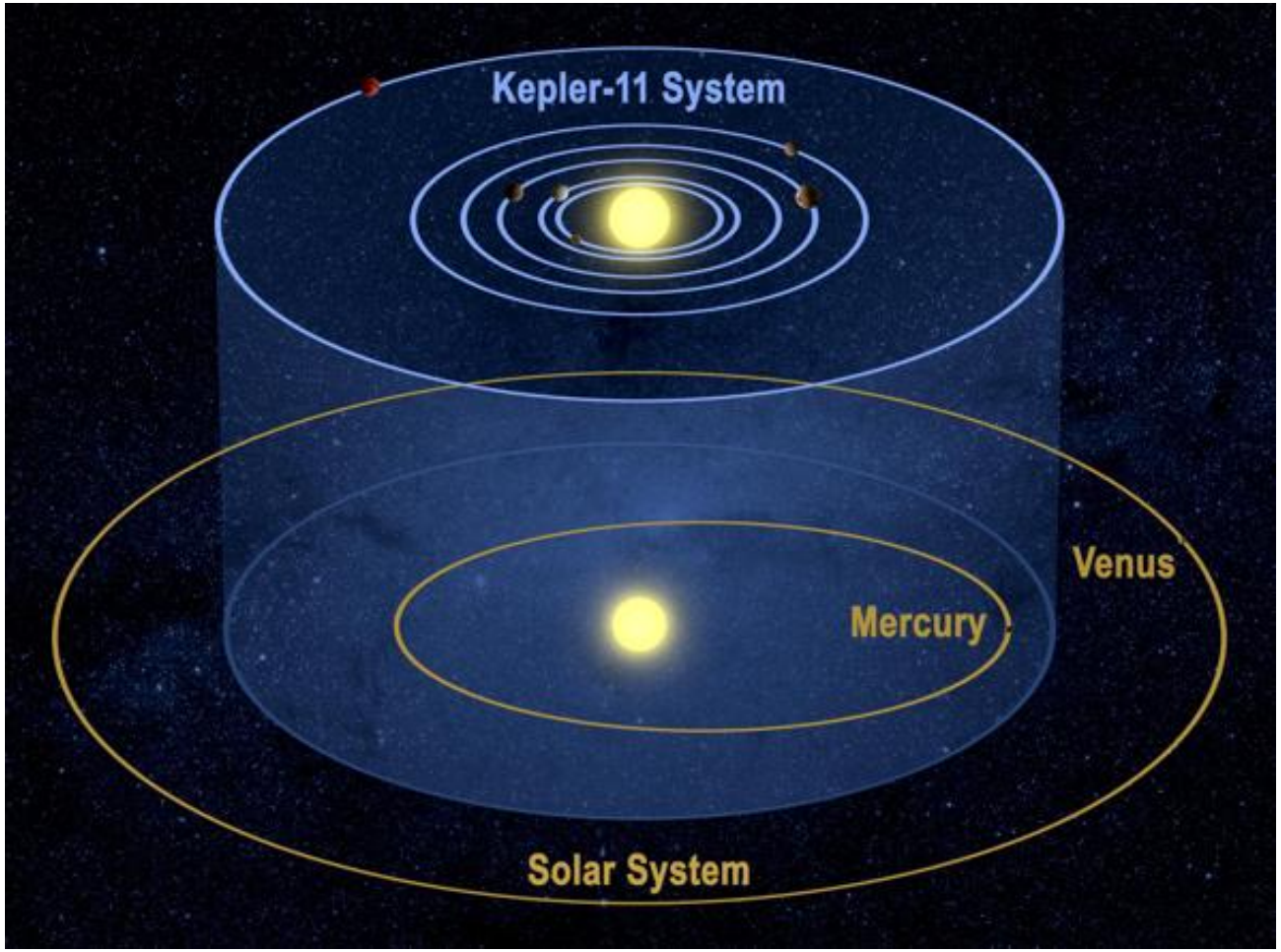
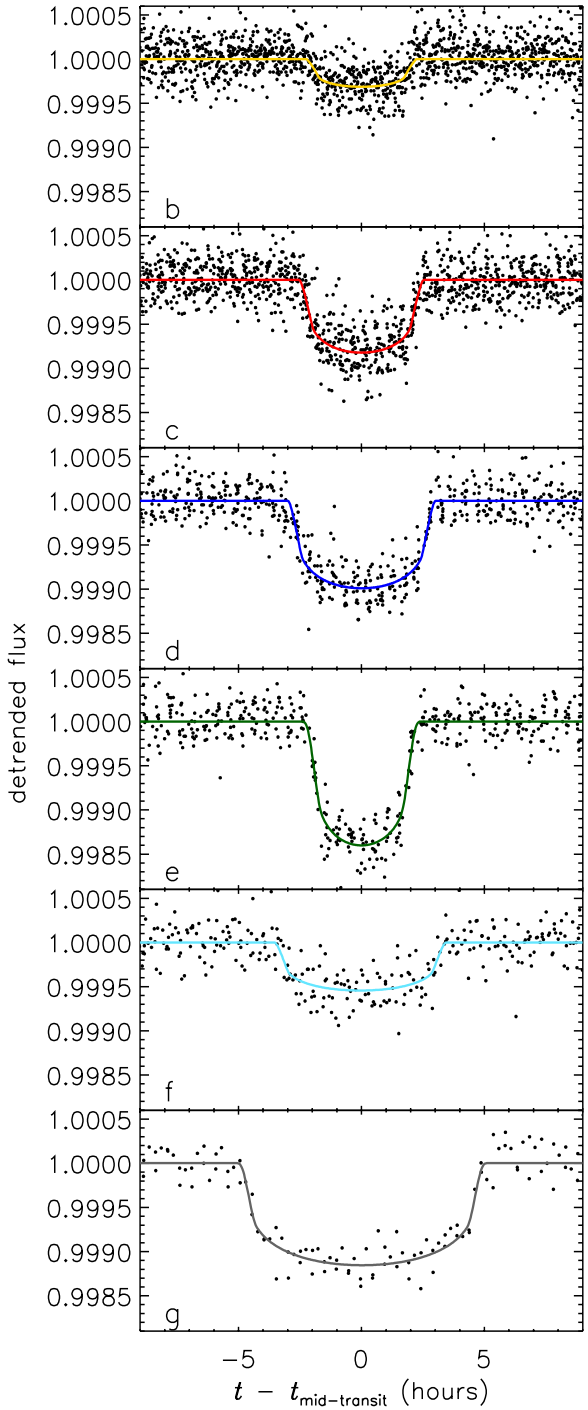
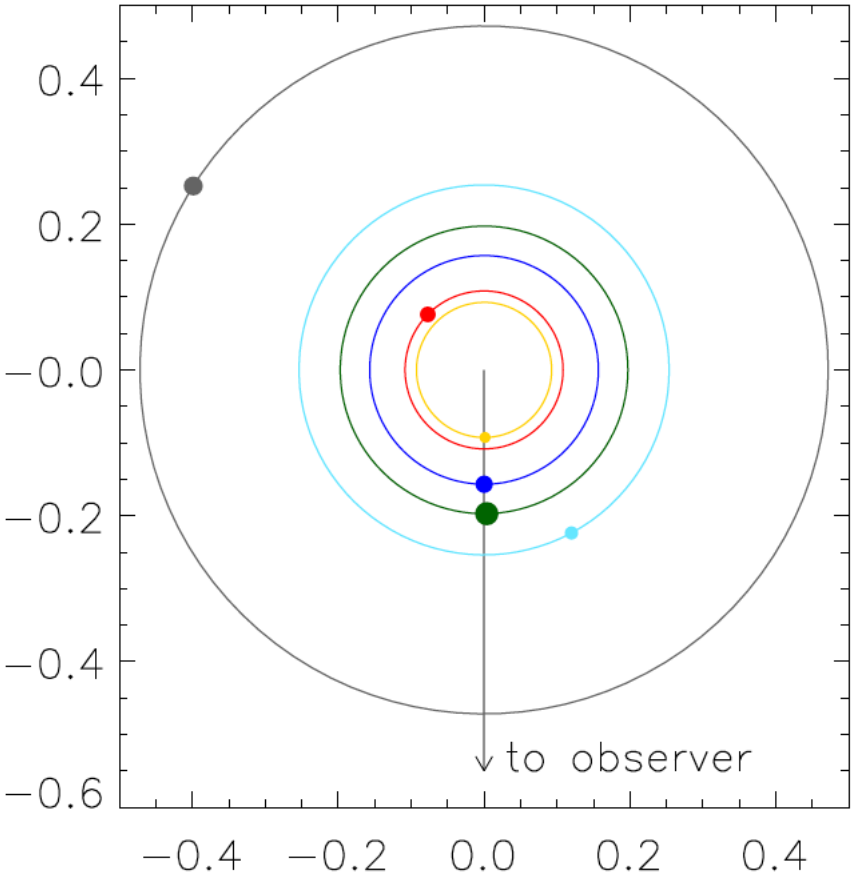


Image: NASA/Pyle


FINDING NEW
PLANETS
201
Kepler
NASA
Lathrop
DELLOSSO FAMILY FARM

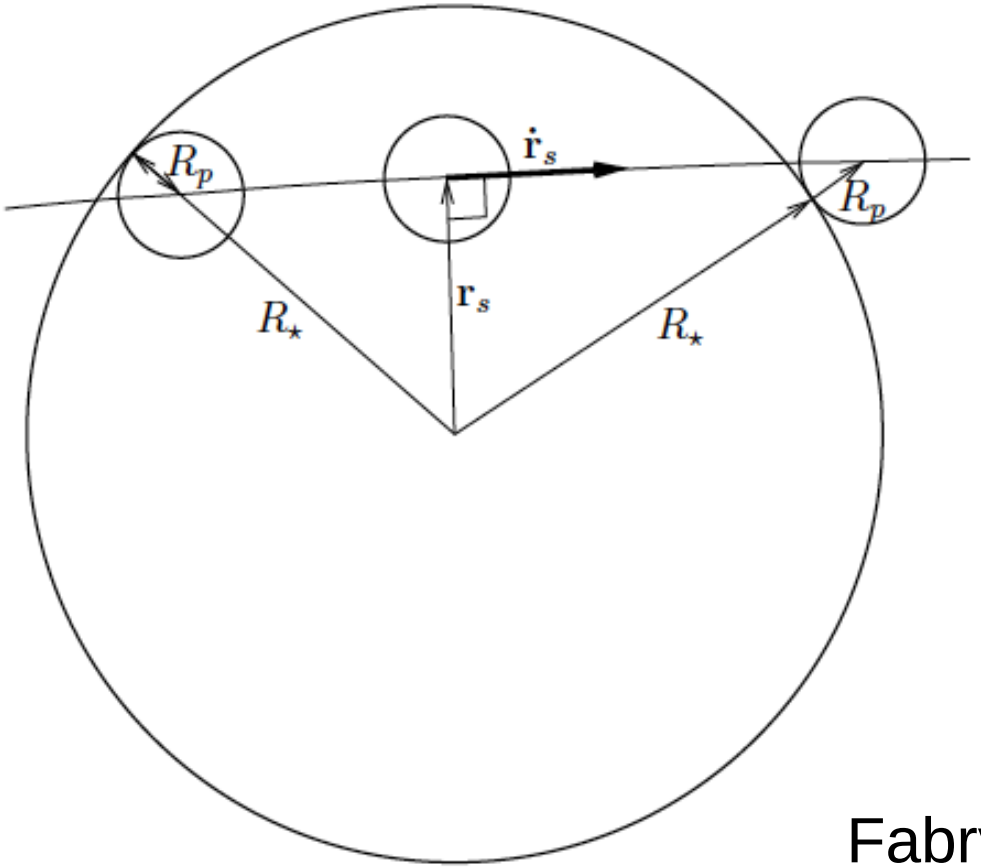

detrended flux
1.0005
1.0000
0.9995
0.9990
0.9985
b
c
d
e
f
g
−5
0
5
t − t_mid−transit (hours)


0.4
0.2
−0.0
−0.2
−0.4
−0.6
−0.4
−0.2
0.0
0.2
0.4
to observer

Dynamical Model of Transits

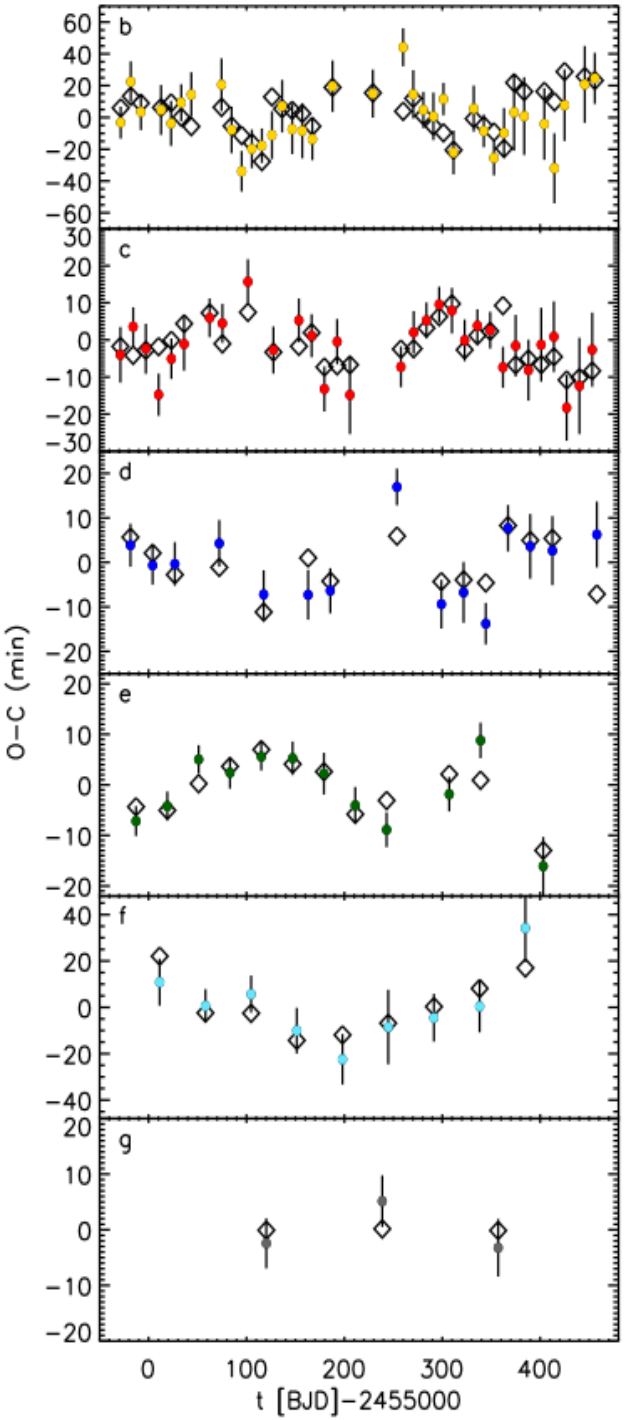
Use Newton's equations to integrate a 3-body system

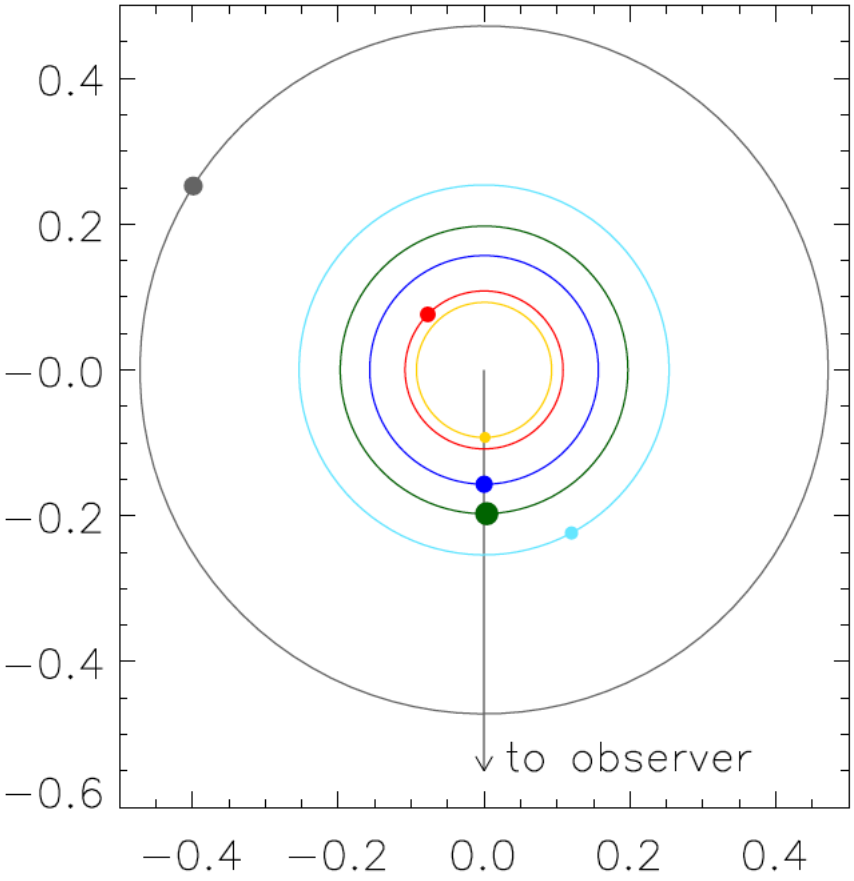
Numerical transit times and radial velocities

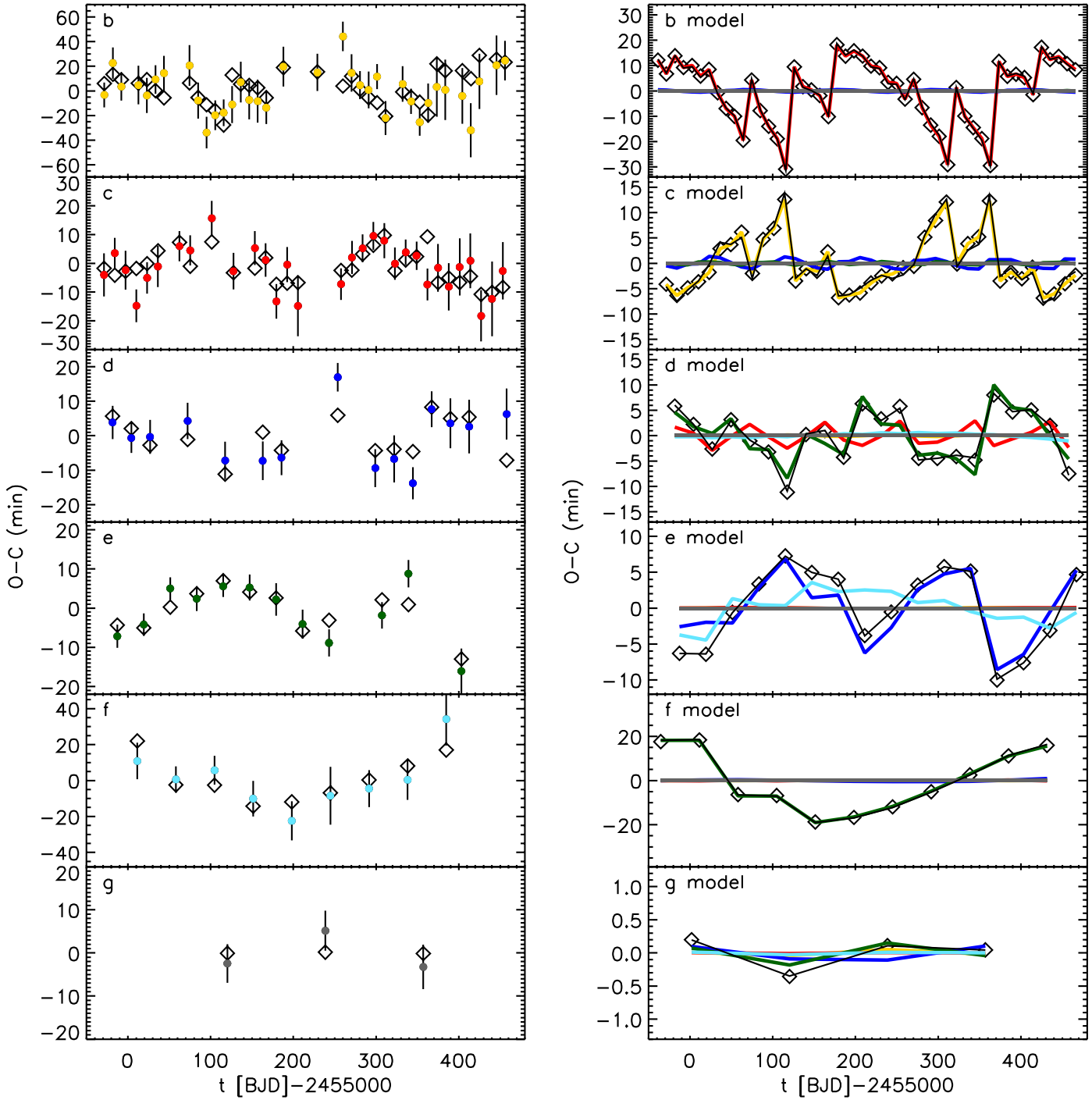


Fabrycky (2010)

Transit Timing Variations



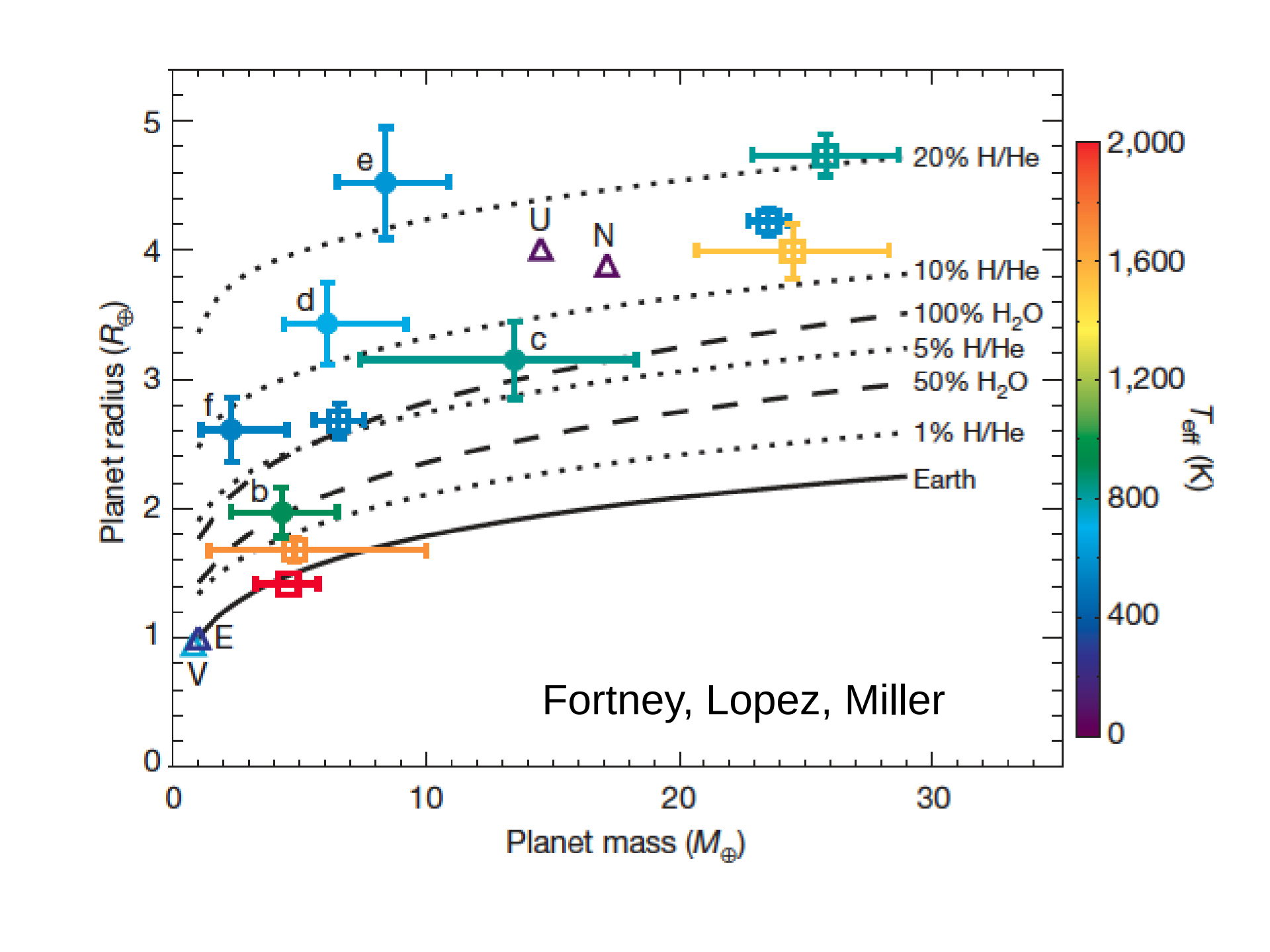



b
c
d
e
f
g
O−C (min)
t [BJD]−2455000
b model
c model
d model
e model
f model
g model
O−C (min)
t [BJD]−2455000

Kepler-11 parameters

Planet	P (days)	Mass ($M_\oplus$)	Radius ($R_\oplus$)	Density (g cm^{-3})
b	$\mathbf{10.3039}^{+0.0006}_{-0.0010}$	$\mathbf{1.9}^{+1.4}_{-1.0}$	$\mathbf{1.80}^{+0.03}_{-0.05}$	$\mathbf{1.72}^{+1.25}_{-0.91}$
c	$\mathbf{13.0241}^{+0.0013}_{-0.0008}$	$\mathbf{2.9}^{+2.9}_{-1.6}$	$\mathbf{2.87}^{+0.05}_{-0.06}$	$\mathbf{0.66}^{+0.66}_{-0.35}$
d	$\mathbf{22.6845}^{+0.0009}_{-0.0009}$	$\mathbf{7.3}^{+0.8}_{-1.5}$	$\mathbf{3.12}^{+0.06}_{-0.07}$	$\mathbf{1.28}^{+0.14}_{-0.27}$
e	$\mathbf{31.9996}^{+0.0008}_{-0.0012}$	$\mathbf{8.0}^{+1.5}_{-2.1}$	$\mathbf{4.19}^{+0.07}_{-0.09}$	$\mathbf{0.58}^{+0.11}_{-0.16}$
f	$\mathbf{46.6888}^{+0.0027}_{-0.0032}$	$\mathbf{2.0}^{+0.8}_{-0.9}$	$\mathbf{2.49}^{+0.04}_{-0.07}$	$\mathbf{0.69}^{+0.29}_{-0.32}$
g	$\mathbf{118.3807}^{+0.0010}_{-0.0006}$	< 25	$\mathbf{3.33}^{+0.06}_{-0.08}$	<4

Lissauer et al. (2013)


Planet radius ($R_\oplus$)
Planet mass ($M_\oplus$)
0
1
2
3
4
5
0
10
20
30
e
d
c
f
b
U
N
E
V
20% H/He
10% H/He
100% H_2O
5% H/He
50% H_2O
1% H/He
Earth
Fortney, Lopez, Miller
T_{eff} (K)
2,000
1,600
1,200
800
400
0

Other Extreme Sub-Neptunes

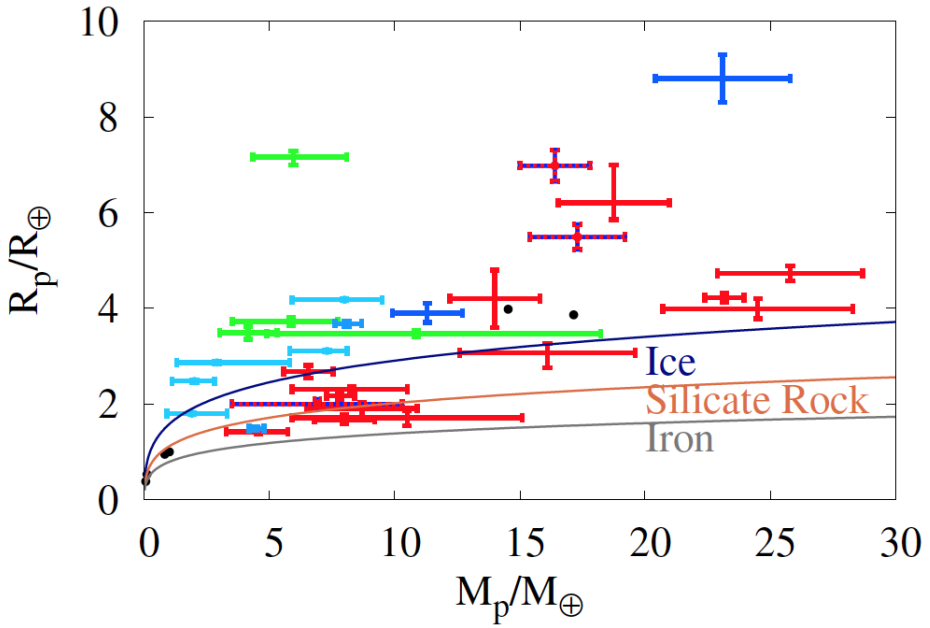
- Kepler-79 (Jontof-Hutter et al. 2014)

Planet	Mass ($M_\oplus$)	Radius ($R_\oplus$)	Density (g cm^{-3})
d	$\mathbf{6.0}^{+2.1}_{-1.6}$	$\mathbf{7.16}^{+0.13}_{-0.16}$	$\mathbf{0.09}^{+0.03}_{-0.02}$

Same density as the architypical puffy hot Jupiter, TrES-4 (Sozzeti et al. 2015)

- K

–



0.9 R_E

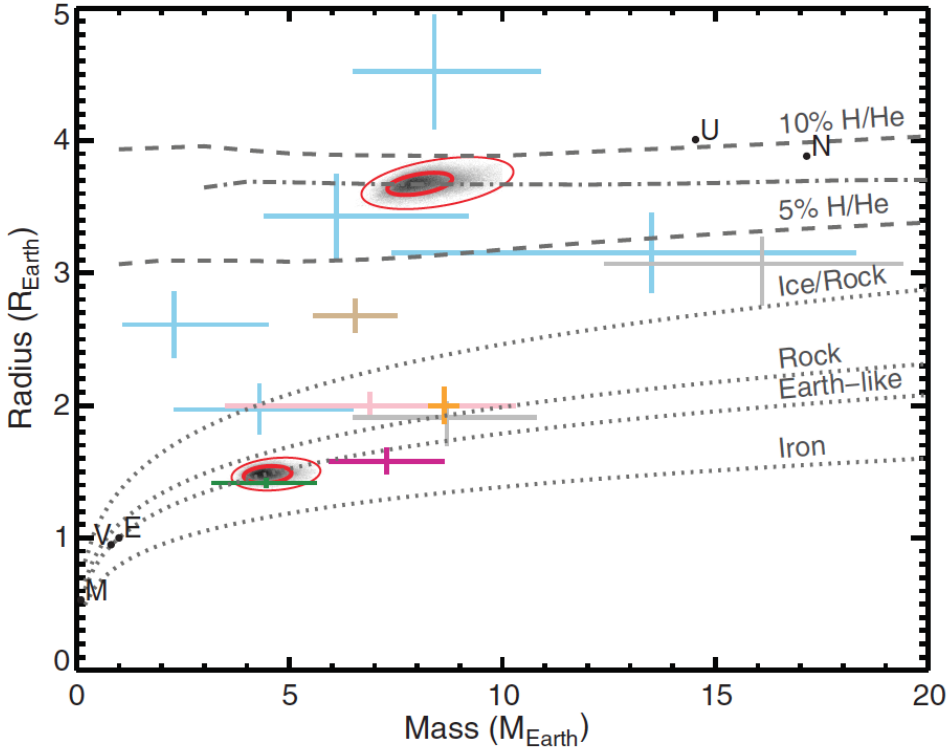
Most Constraining System for M/R models

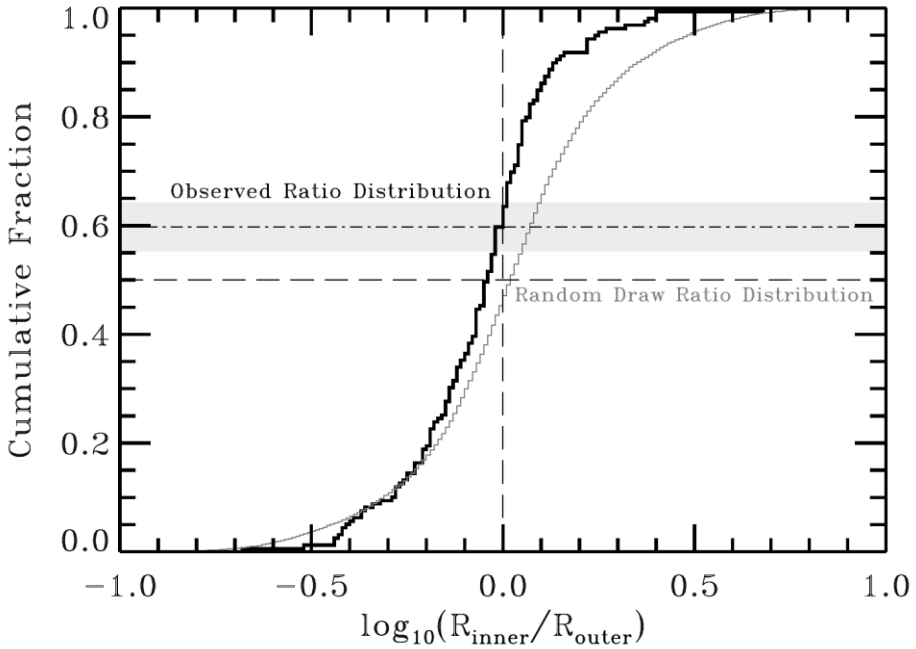
Kepler-36 (Carter, Agol, et al. 2013)

	Planet b	Planet c
P (days)	$13.83989^{+0.0082}_{-0.0060}$	$16.23855^{+0.0038}_{-0.0054}$
M_p (M_E)	$4.4^{+0.33}$	$^{+0.60}_{-0.46}$
R_p (R_E)	1.486 ± 0.035	3.679 ± 0.054

EXCEPTIONAL

The RULE: Adjacent planets similarly sized.



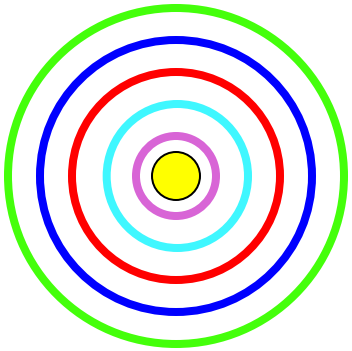


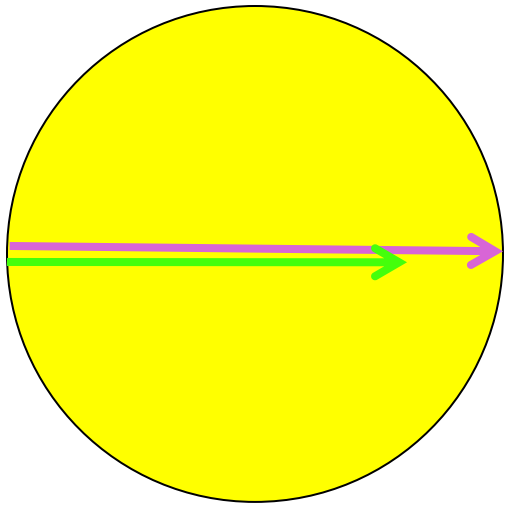
Ciardi et al. (2013)

Mutual inclinations

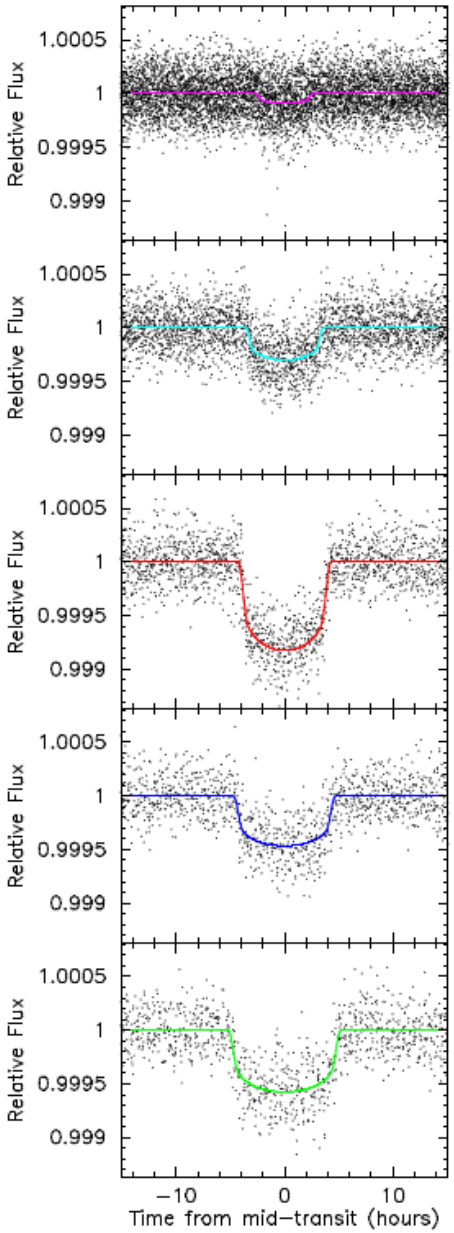
1) Matching RV's systems to Kepler's
   (Tremaine & Dong 2011, Figueria + 2012)
3) Duration Ratio Statistics, explained next

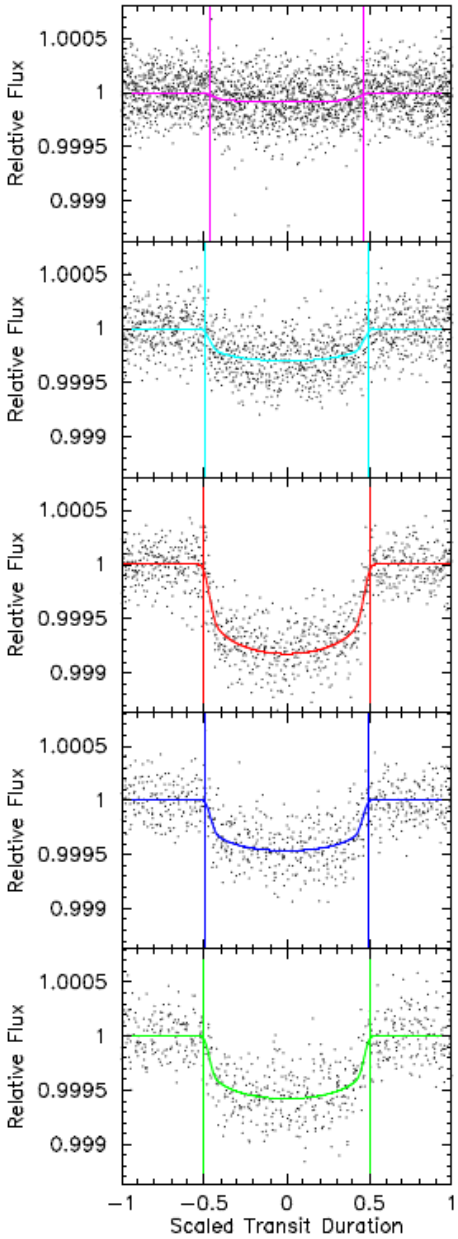
Durations in Systems



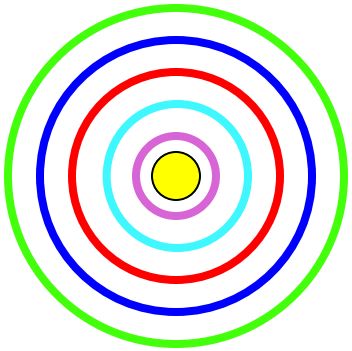


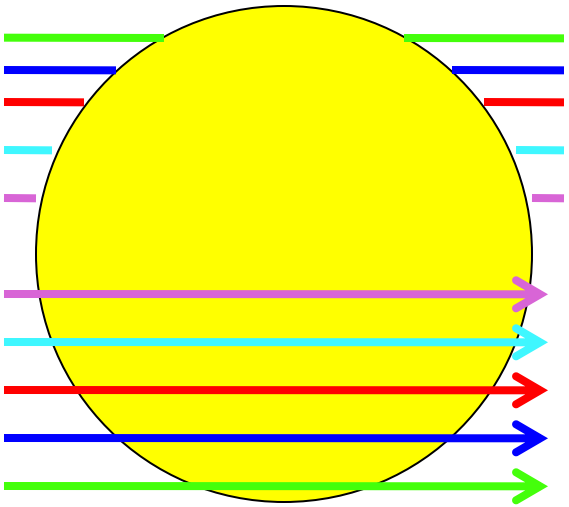
$$T_{\mathrm{dur}} \propto P^{1/3}$$

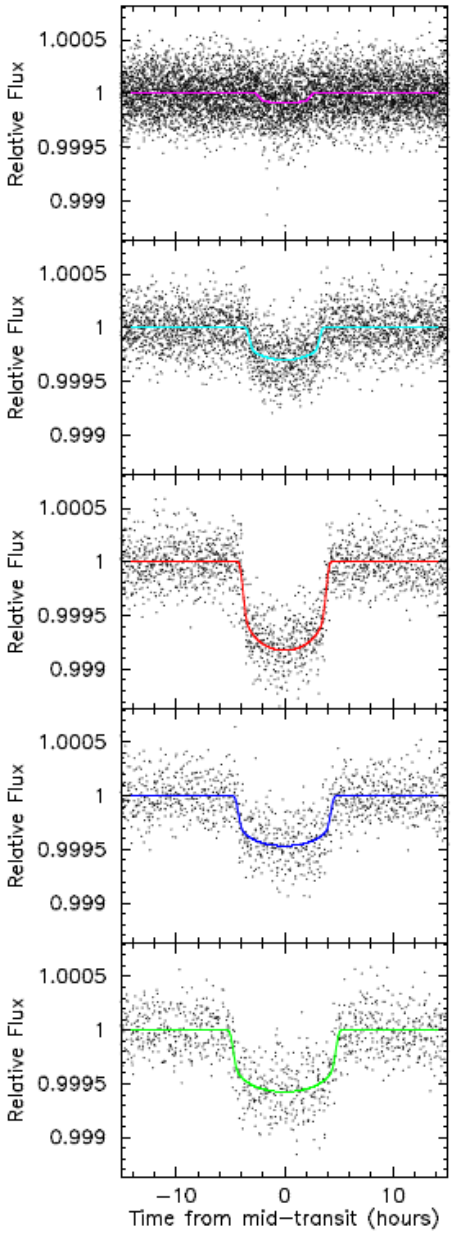


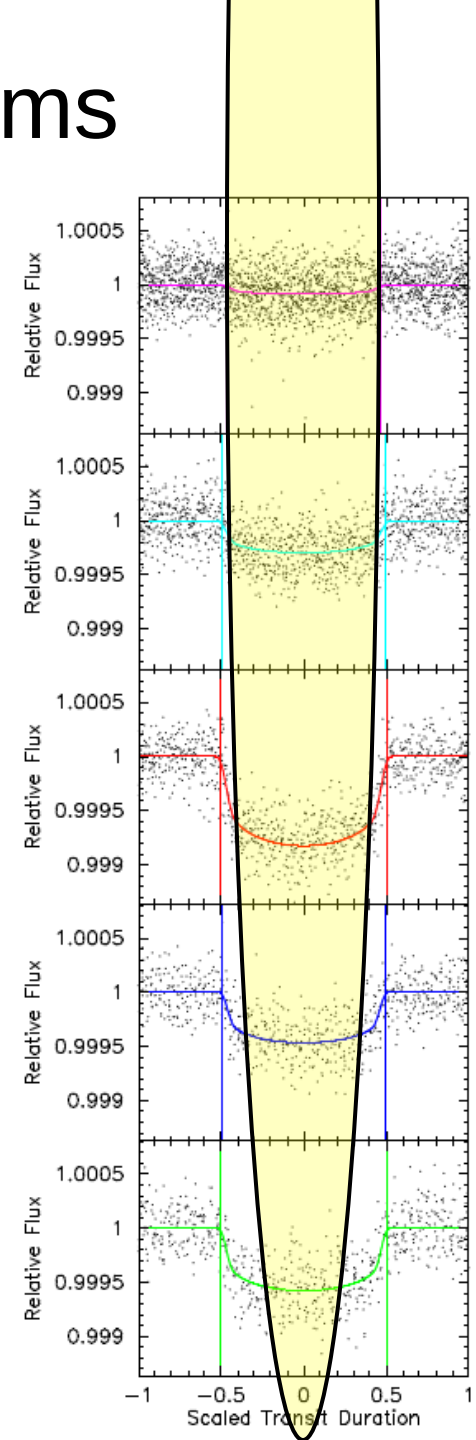


Durations in Systems







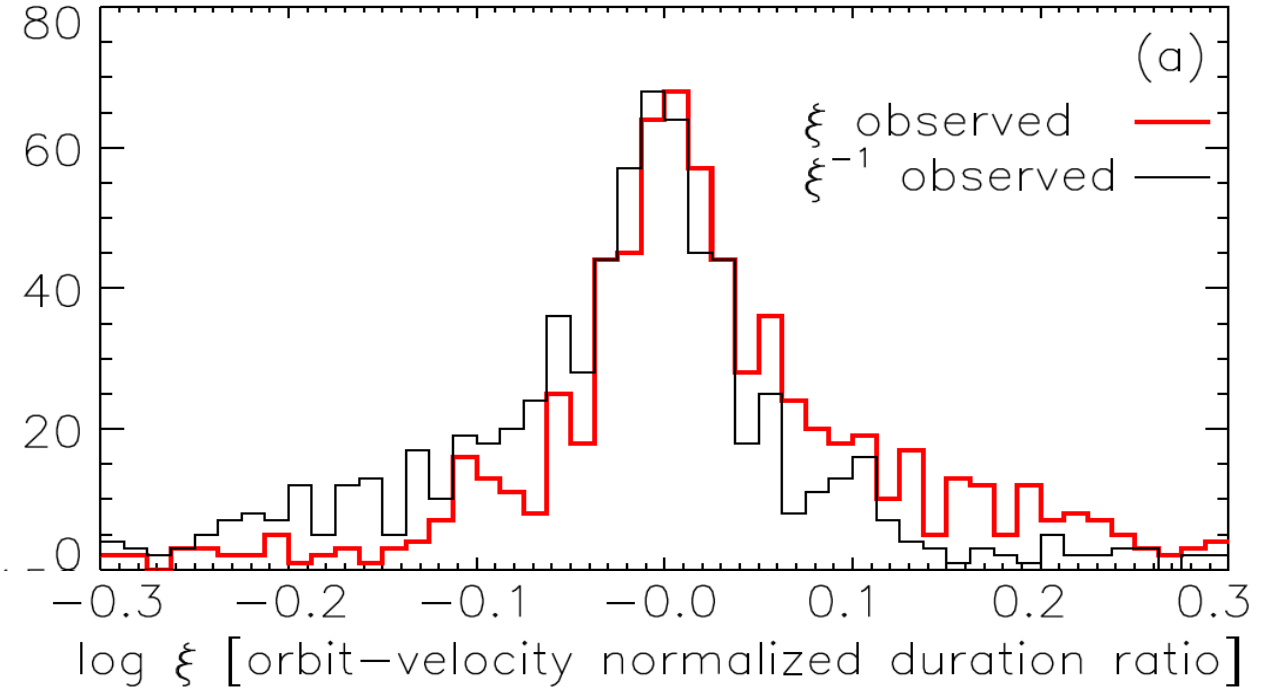


A variable to sense mutual inclinations:

$$\xi \equiv \frac{T_{\rm dur,1}/P_1^{1/3}}{T_{\rm dur,2}/P_2^{1/3}}$$

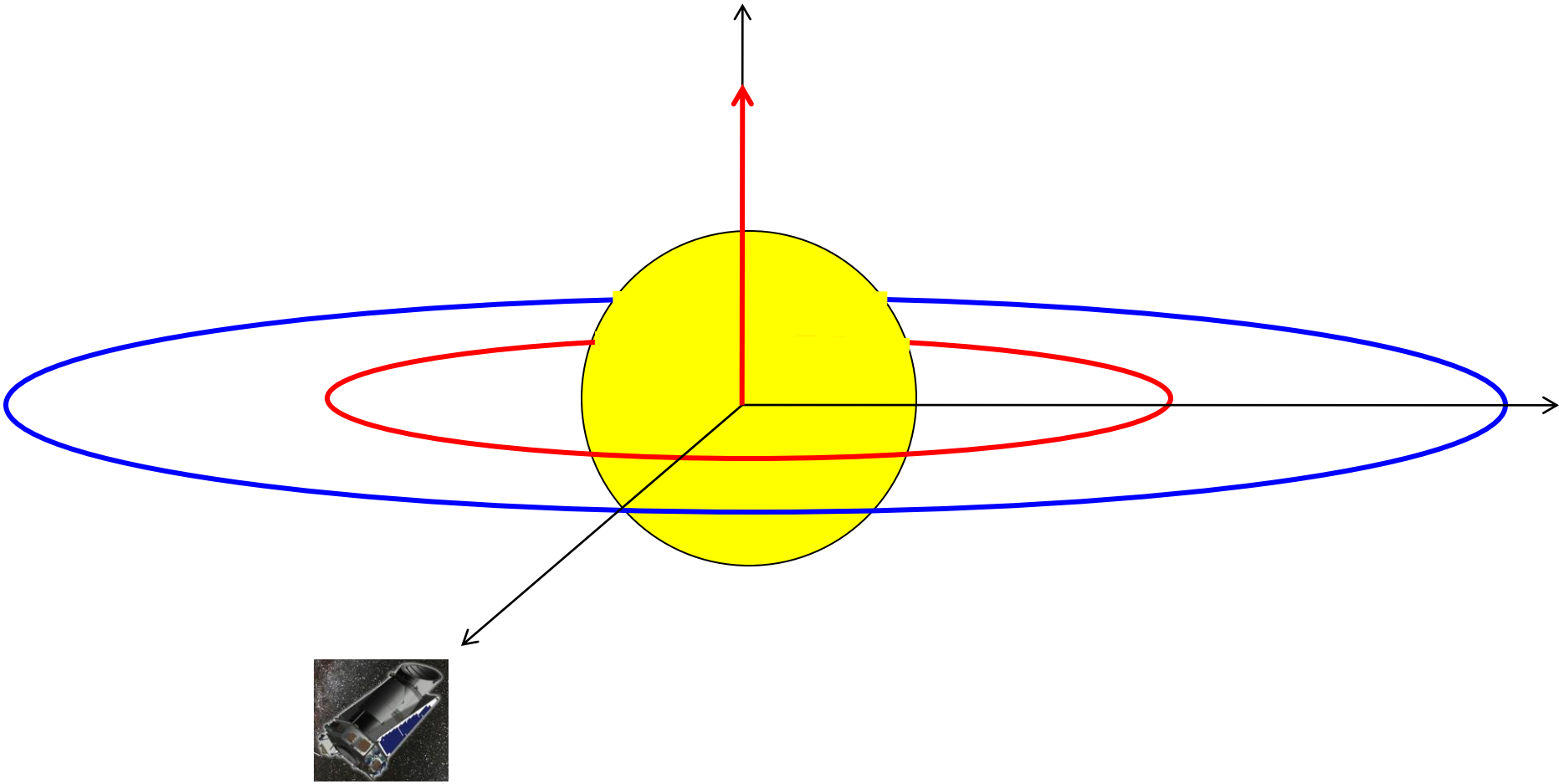
> 1 [circular, coplanar]

~ 1 [uncorrelated]



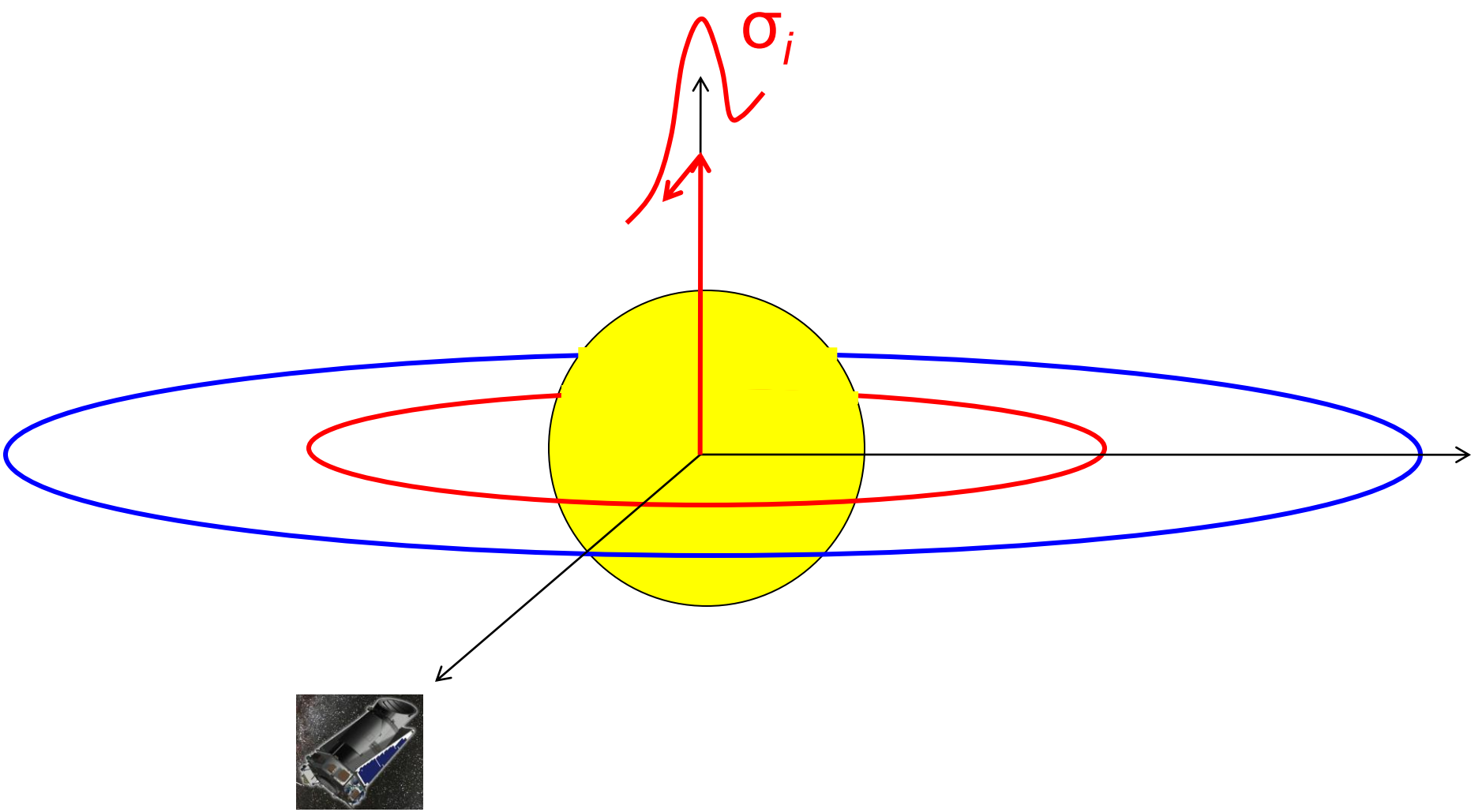
Architectures II; Fabrycky, Lissauer, et al. (2014)

Modeling mutual inclinations



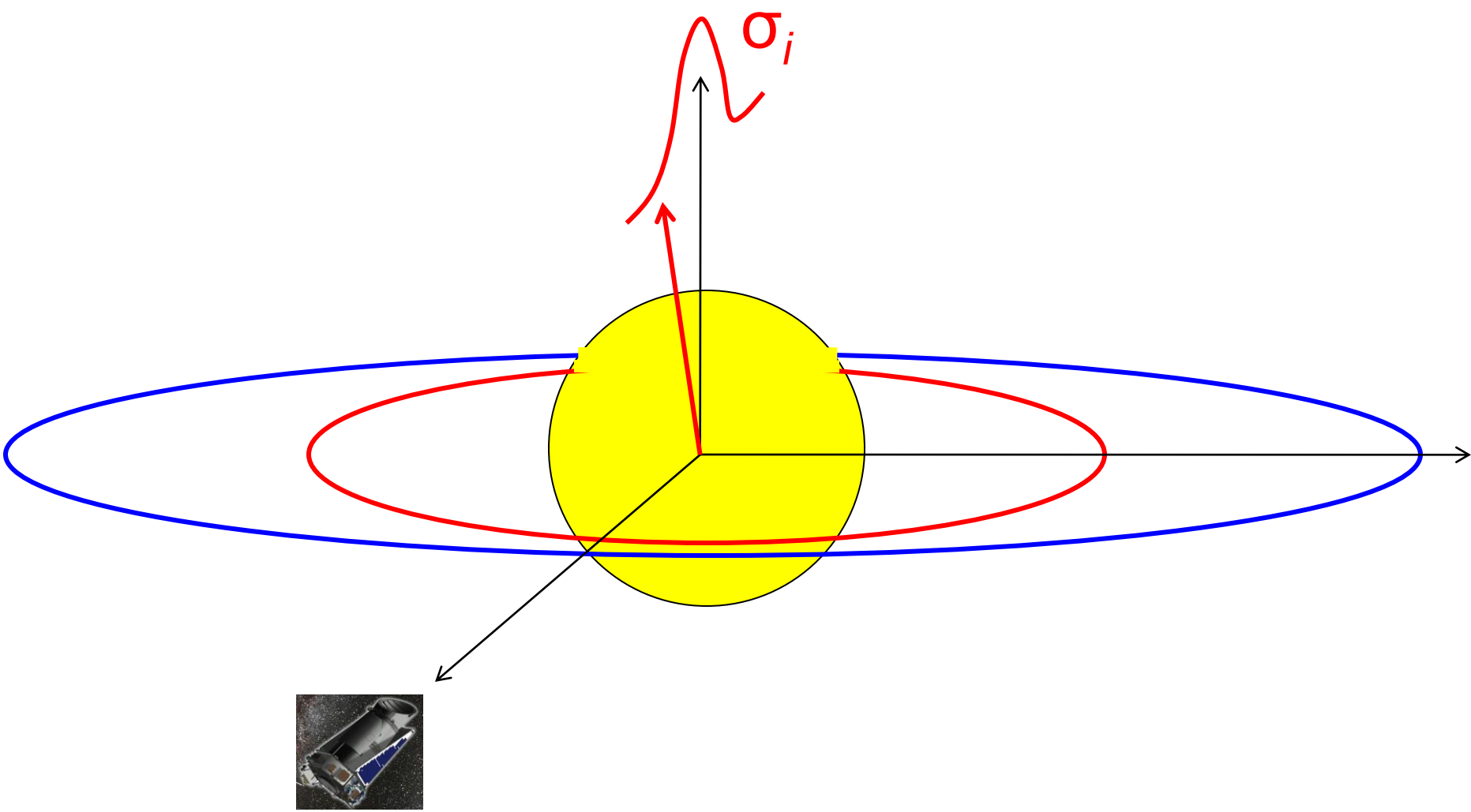
Architectures II; Fabrycky, Lissauer, et al. (2014)

Modeling mutual inclinations



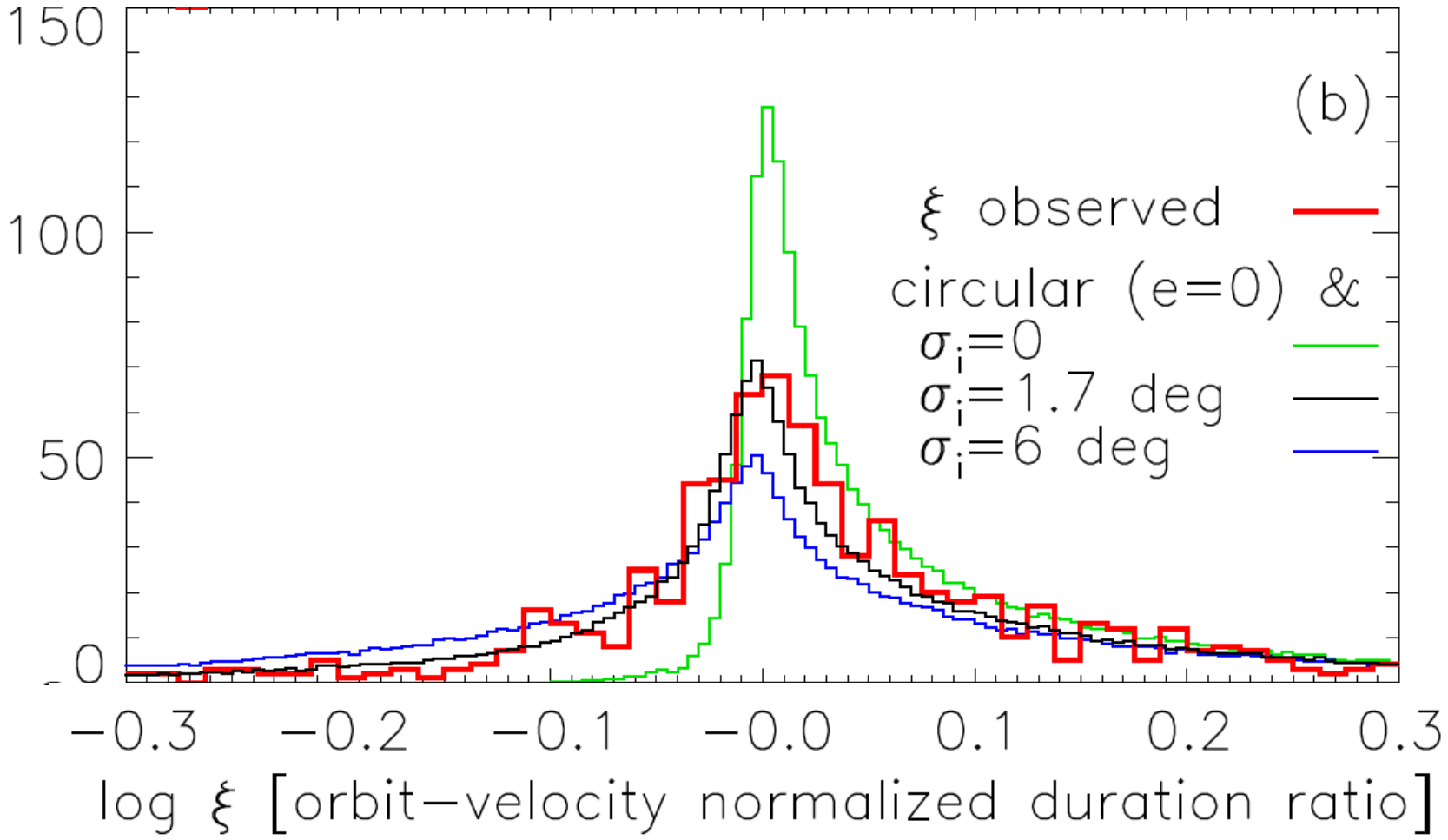
Architectures II; Fabrycky, Lissauer, et al. (2014)

Modeling mutual inclinations

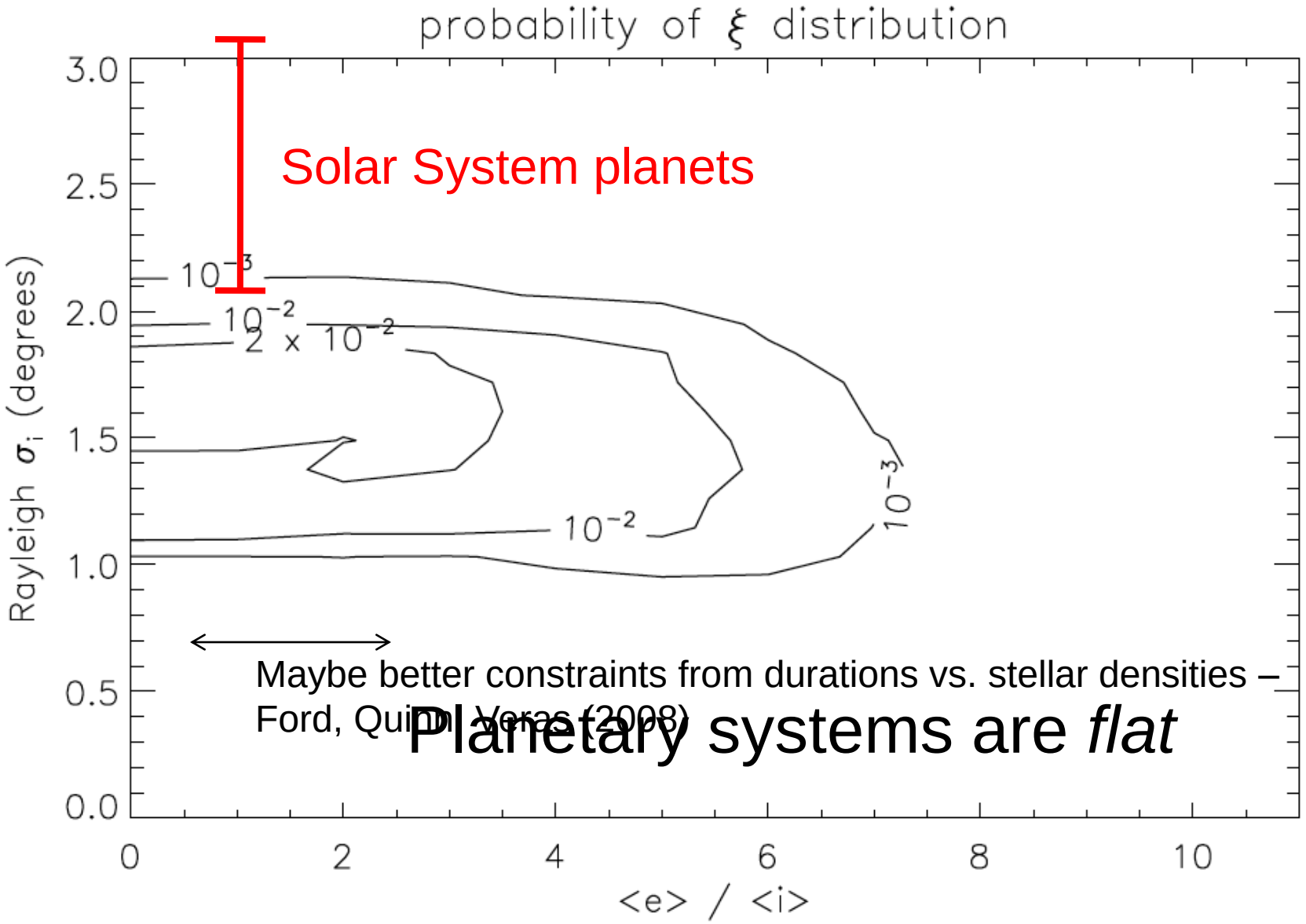


Architectures II; Fabrycky, Lissauer, et al. (2014)

Fitting Results



Architectures II; Fabrycky, Lissauer, et al. (2014)

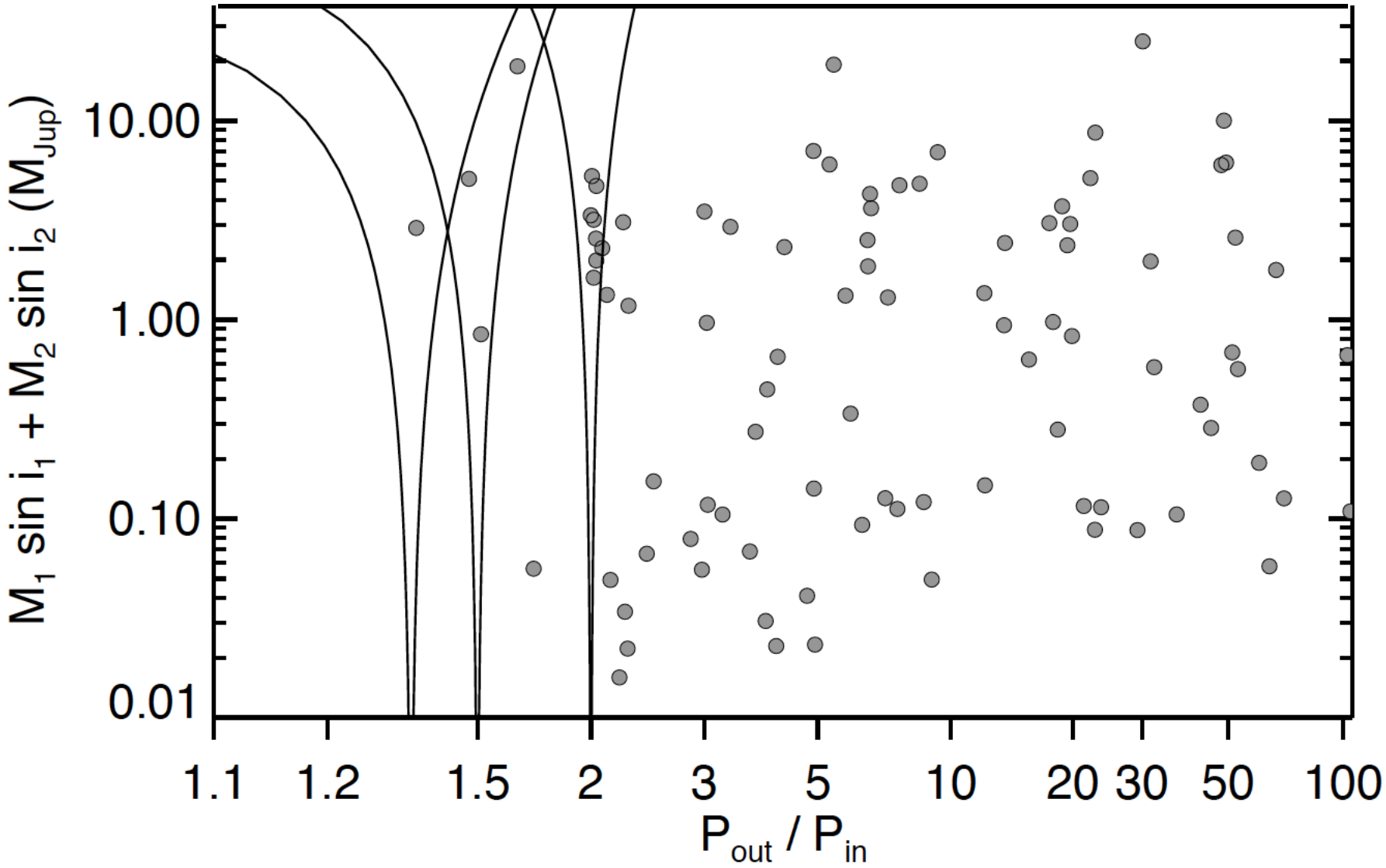


Maybe better constraints from durations vs. stellar densities – Ford, Quinn, Veras (2008)

Planetary systems are *flat*

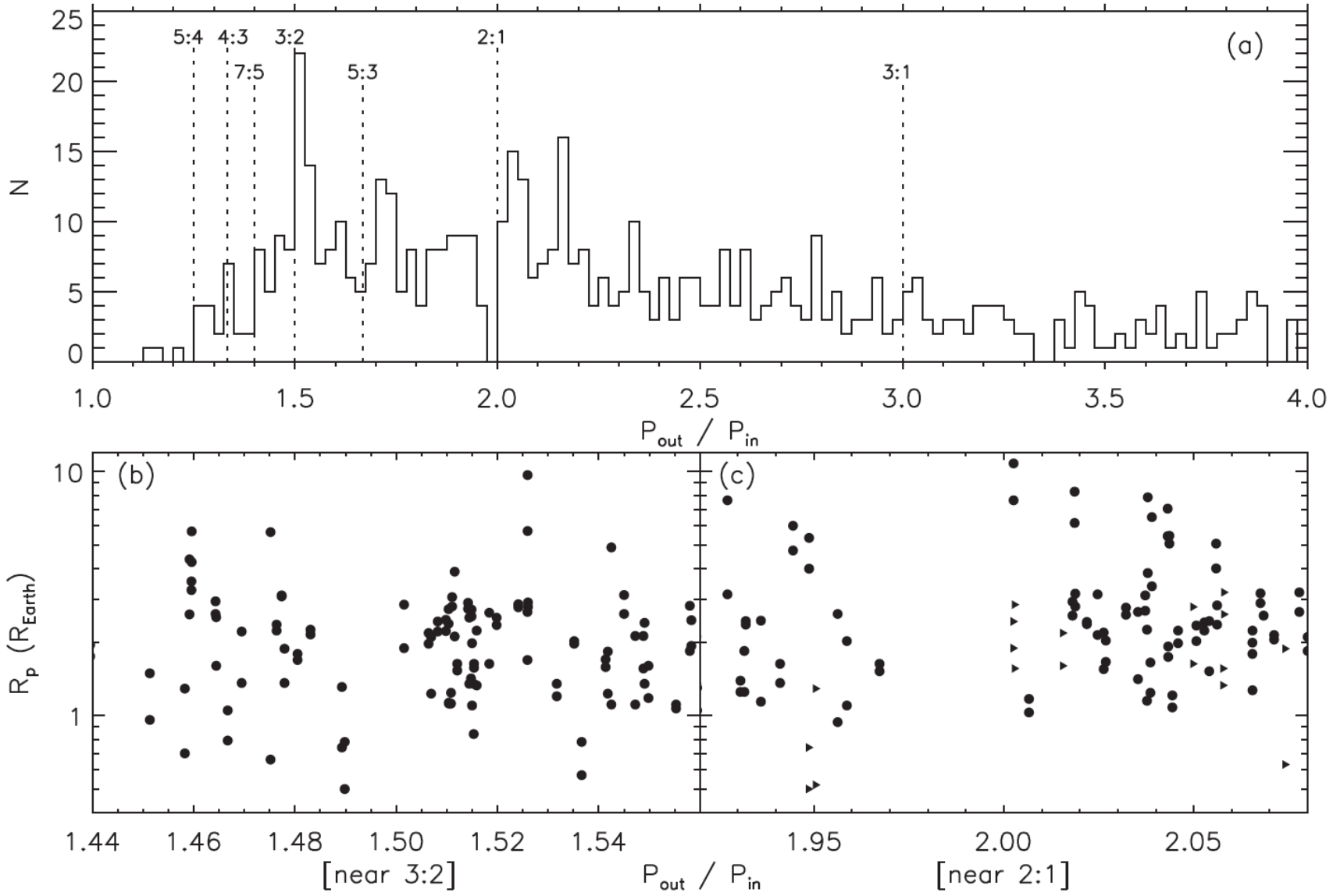
Fabrycky, Lissauer, et al. 2014

Period Ratios (RV)



Winn & Fabrycky (2015); see also Xie (2014)

Period Ratios (*Kepler*)



Architectures II; Fabrycky, Lissauer, et al. (2014)

Period Ratio Redistribution

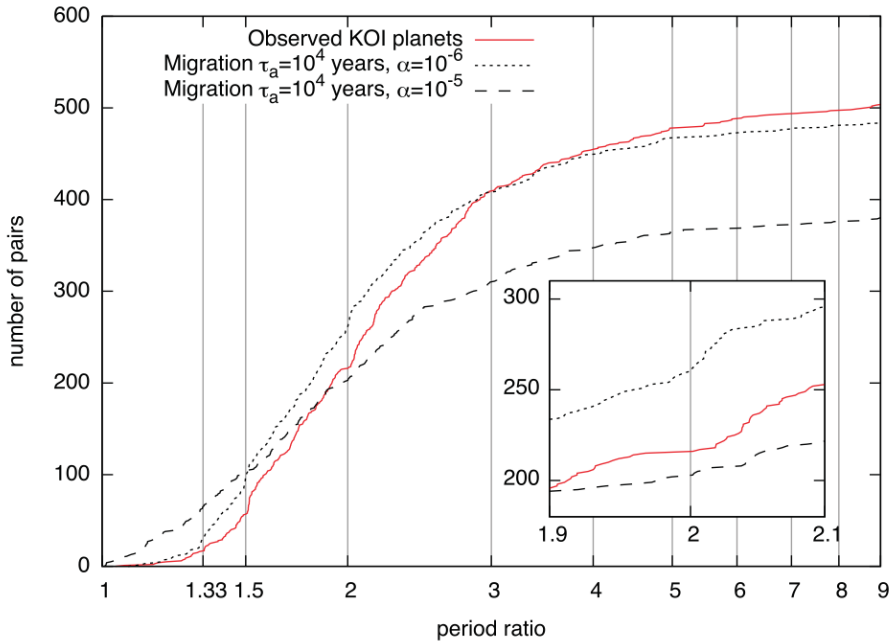
- Tidal dissipation on inner planet

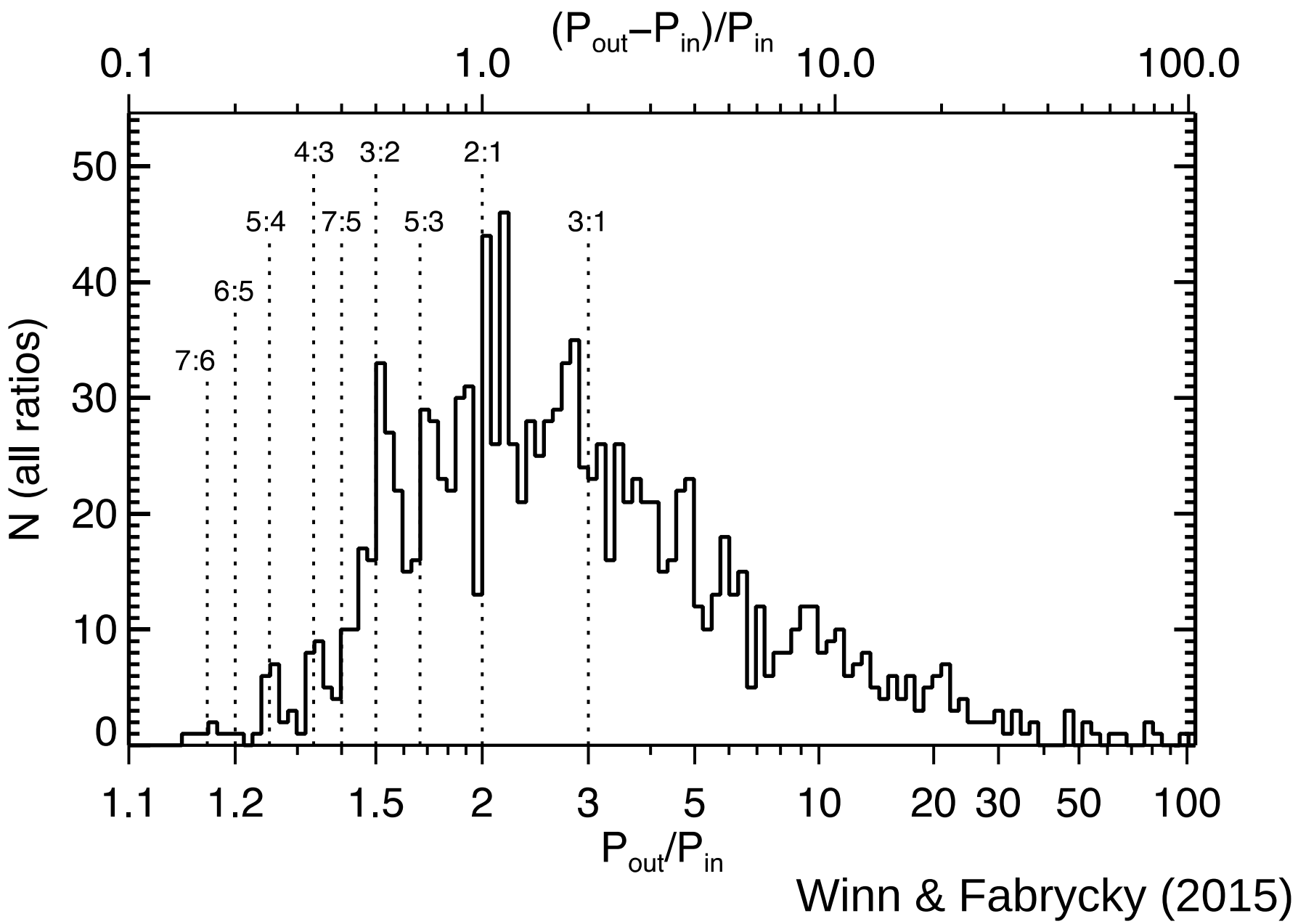
(Yes: Novak, Lai, Lin 2002, Terquem & Papaloizou 2007, Lithwick & Wu 2012, Batygin & Morbidelli 2012;

No: Lee, Fabrycky, Lin 2013;

Maybe so: Hansen & Murray 2014; Delisle & Laskar 2014)

- Planetesimal Scattering (Moore et al. 2013; Chatterjee & Ford 2014
- Turbulence in migration (Rein 2012)





Winn & Fabrycky (2015)

The Rule: Pairs are not in resonance

Exceptional Exceptions: Resonant chains

- A few multi-resonant systems:
- Kepler-223 (KOI-730; 4:3, 3:2, 4:3)
- Kepler-60 (KOI-2086; 5:4, 4:3)
- Kepler-80 (KOI-500; 1.518, 1.518, 1.350)

Summary

- *Kepler* found a host of multiplanet systems.
- Planet masses and system architectures are coming from transit measurements themselves
- Leaves challenges for planet formation, migration, etc.