Overview of *Kepler* Systems with Multiple Transiting Planet Candidates

Darin Ragozzine, CfA

Exploring Strange New Worlds

May 5, 2011

In collaboration with the *Kepler* TTV/Multiples Working Group

Quick Overview of *Kepler* Systems with Multiple Transiting Planet Candidates

Matt Holman

Jack Lissauer

Darin Ragozzine

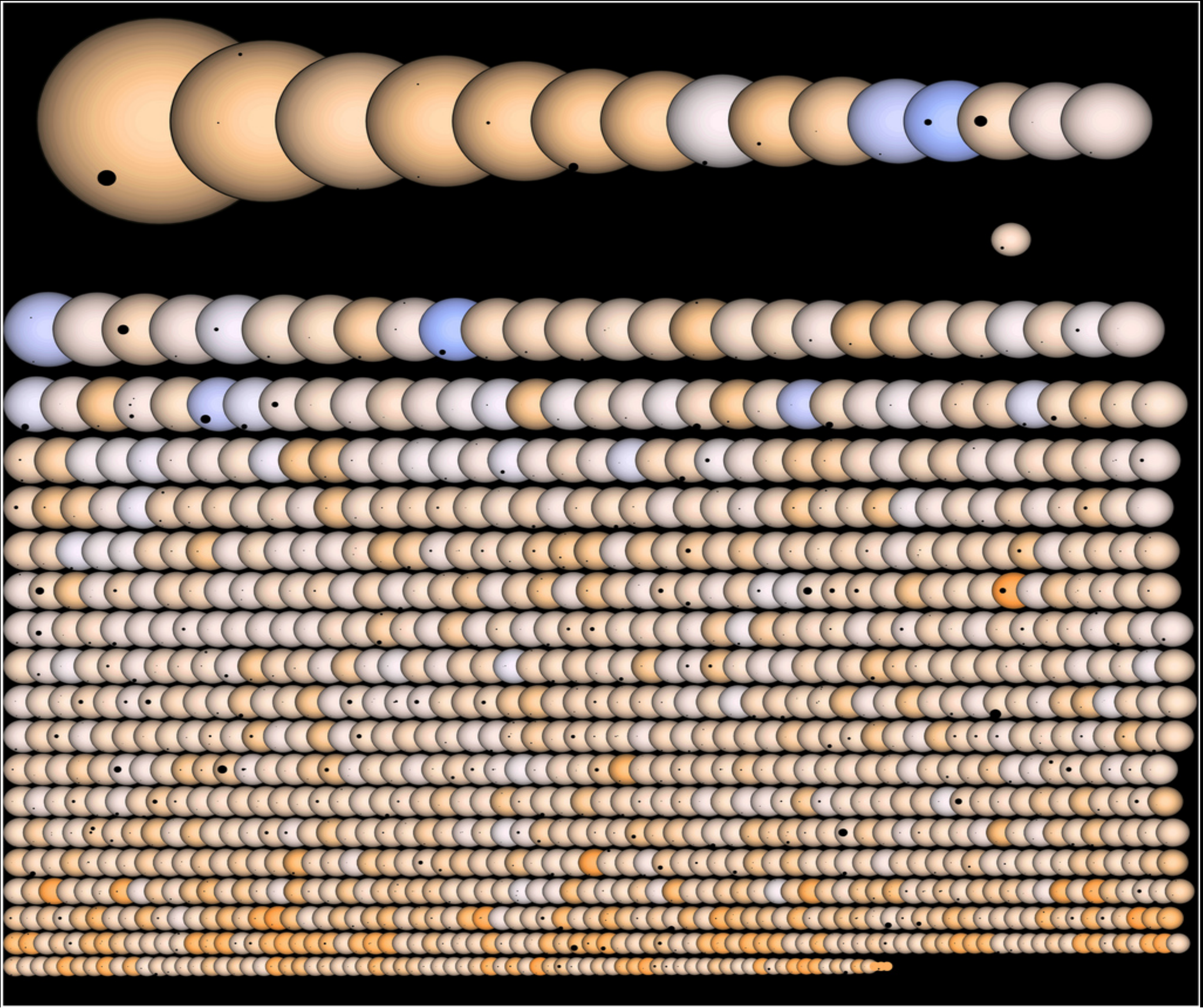
Dan Fabrycky

Eric Ford

Jason Steffen

And many many others on the NASA Kepler Science Team

NASA Watch / Spaceref



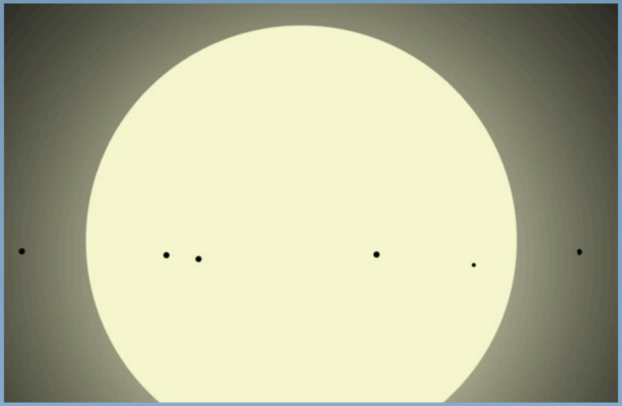
Which Strange New Worlds are most Explorable?

What kind of exoplanets tell us the most about the formation, evolution, and habitability of planets and planetary systems?

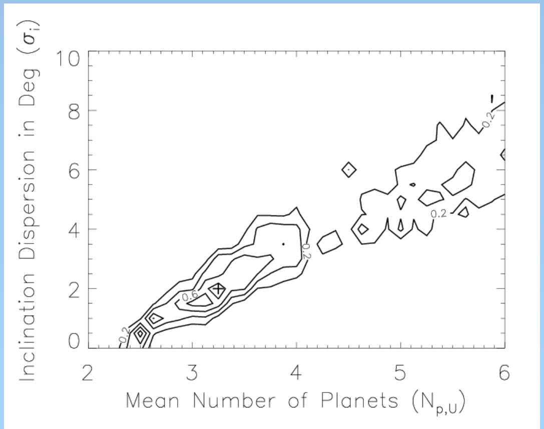
About Me

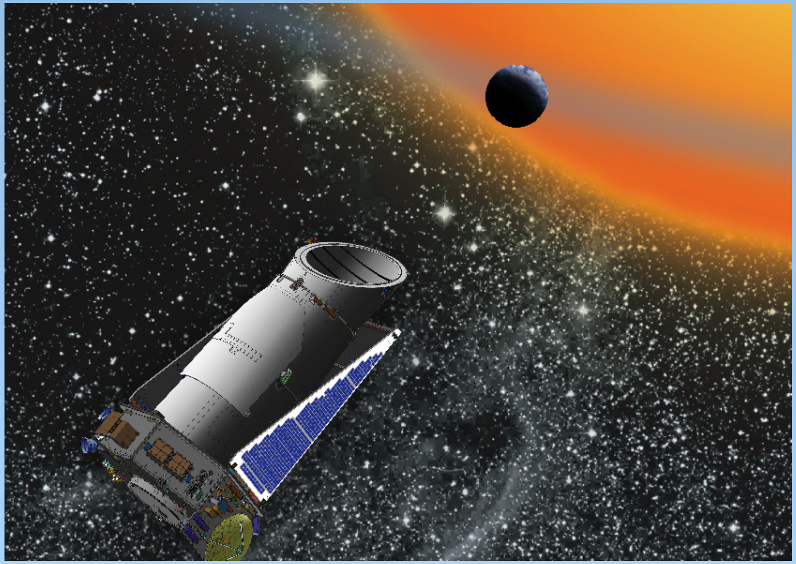
- Astrophysicist and/or Planetary Scientist
- Combine precise observations with orbital dynamics theory to improve our understanding of the formation and evolution of planetary systems
  - Observations from Kepler and Hubble Space Telescopes, as well as large ground-based telescopes
  - Applied to transiting extra-solar planets and Kuiper belt objects
- Doctorate from Caltech working with Mike Brown mostly on Kuiper Belt Objects in our solar system
- Currently postdoctoral researcher working with Matt Holman on the Smithsonian side of the Harvard-Smithsonian Center for Astrophysics on Harvard campus in Cambridge, MA
- Will be starting as an Harvard ITC (Institute for Theory and Computation) Fellow in July 2011

Outline



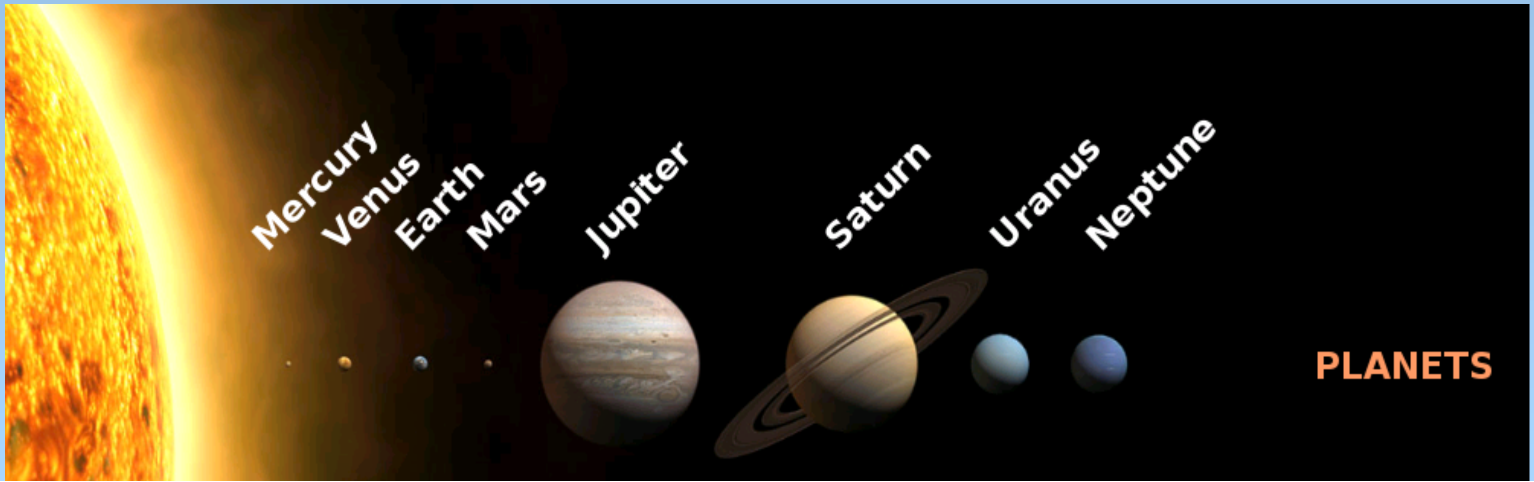
- Overview: exoplanets
- Exoplanetary gold?
- What did Kepler find?
- Why are multi-transiting systems valuable?
    - Kepler-9 and Kepler-11
- Some early statistical results
- Kepler's Future



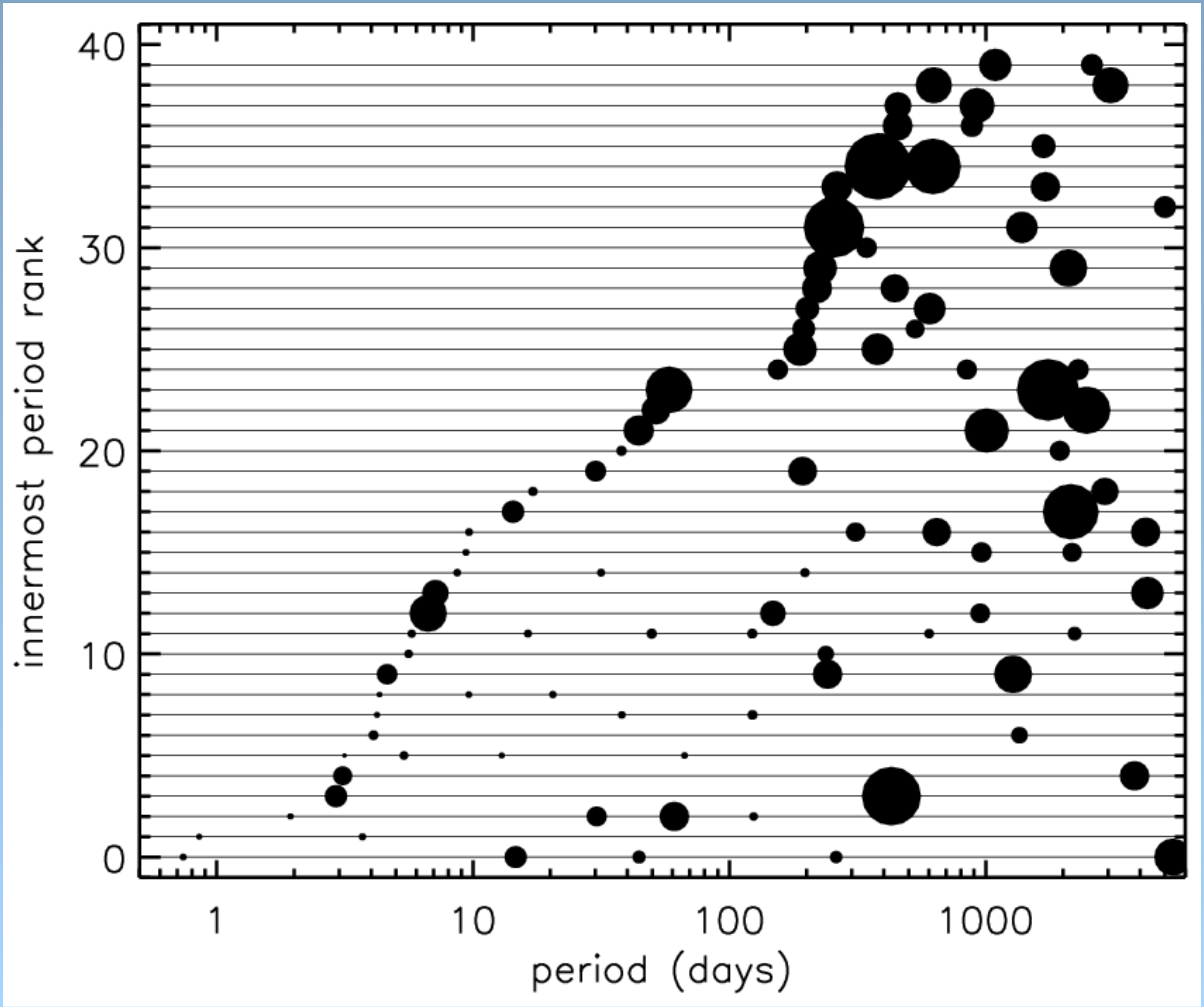


Multiples: Information-Rich

- Orbital architecture
  - Planet formation and evolution
- Planet-planet interactions (dynamics!)
  - Short-term interactions can be detected
  - Long-term interactions must be stable
- Comparative Planetology



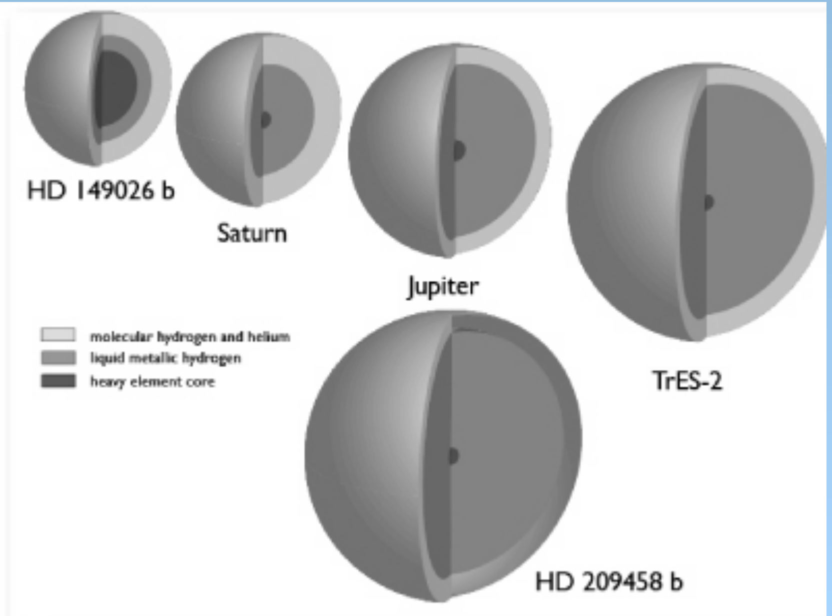
Radial Velocity Multiples



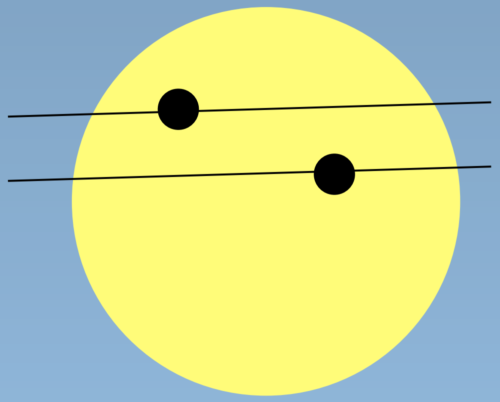
Transiting Planets: Information-Rich

- Resolves *sin i* ambiguity in Radial Velocities (Mass)
- Precise Measurement of Depth of Transit (Radius)
- Mass and Radius together give **Density**
    - Composition
    - Interior
    - Formation and Evolution
- Atmospheres
- Habitability
- (Drawback: rarer, fainter)

www.oklo.org



Multi-Transiting Systems



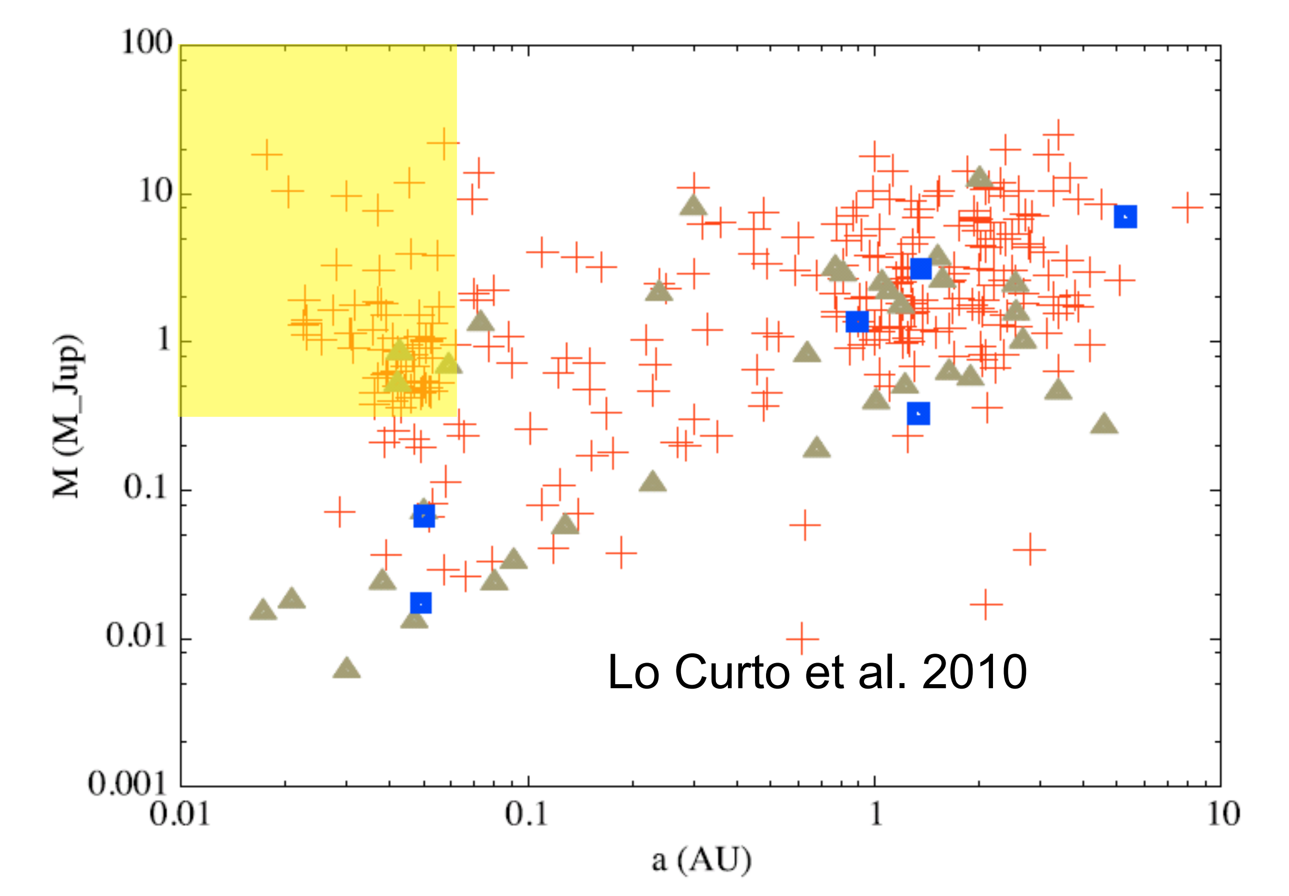
- Transiting Planets
  - Allow for physical characterization
  - Radius, Density, Atmosphere
  - (Interior, Composition, Habitability)
- Multiplanet systems
  - Determine orbital architecture
  - Bring tools of dynamicists to bear

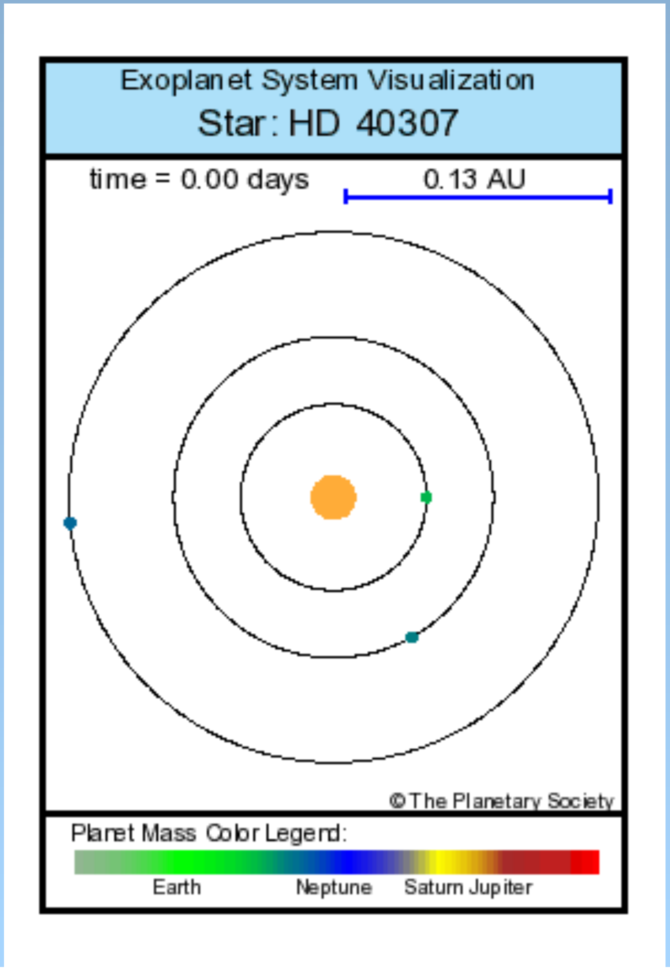
Multi-transiting systems are the most information-rich exoplanetary systems, combining the value of physical characterization with orbital architecture.

Ragozzine & Holman 2010

Multiples are Small

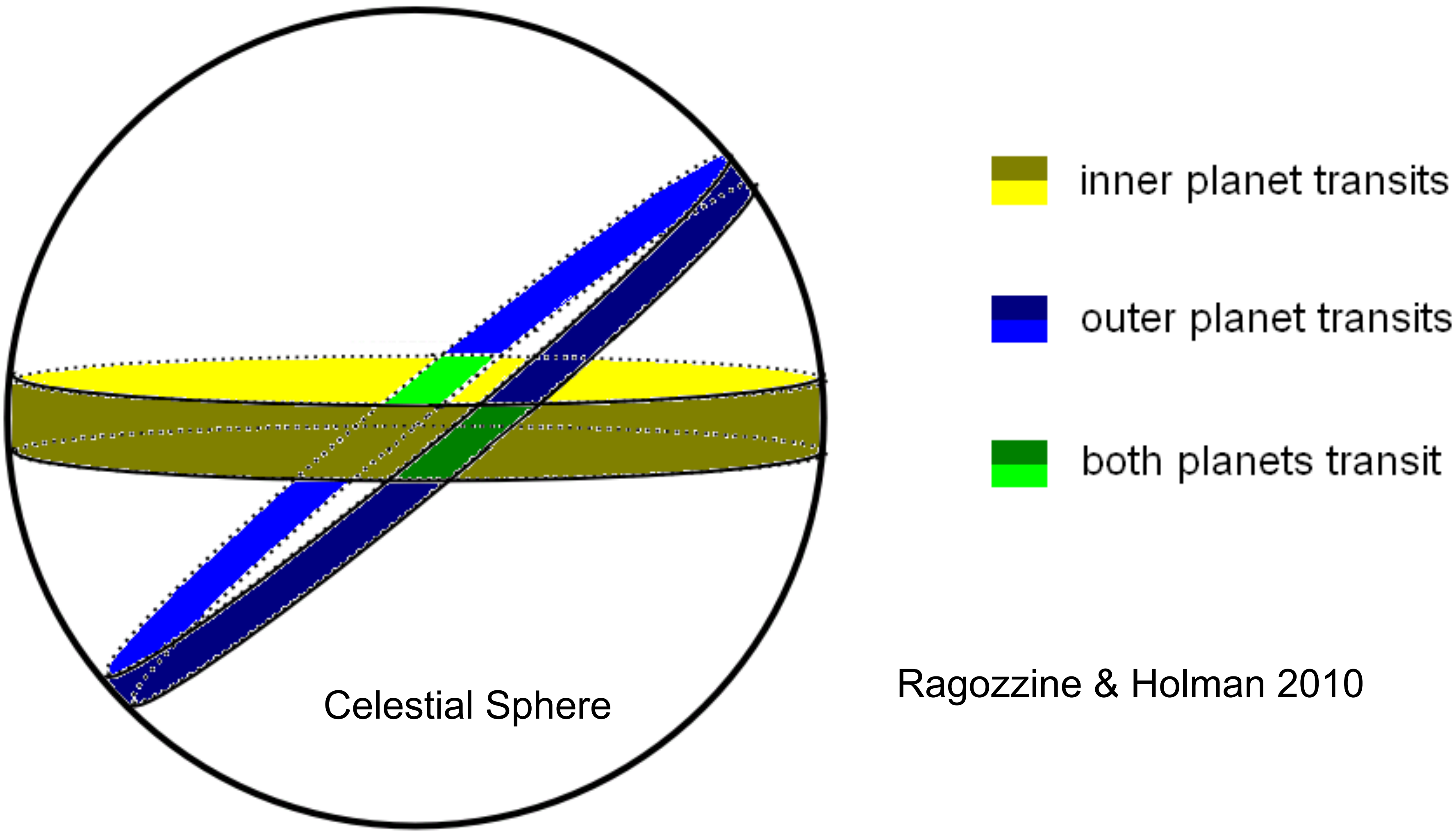
- From Radial Velocities: small close-in planets are frequent and tend to be in multiples





Are Multi-Tranisters common?

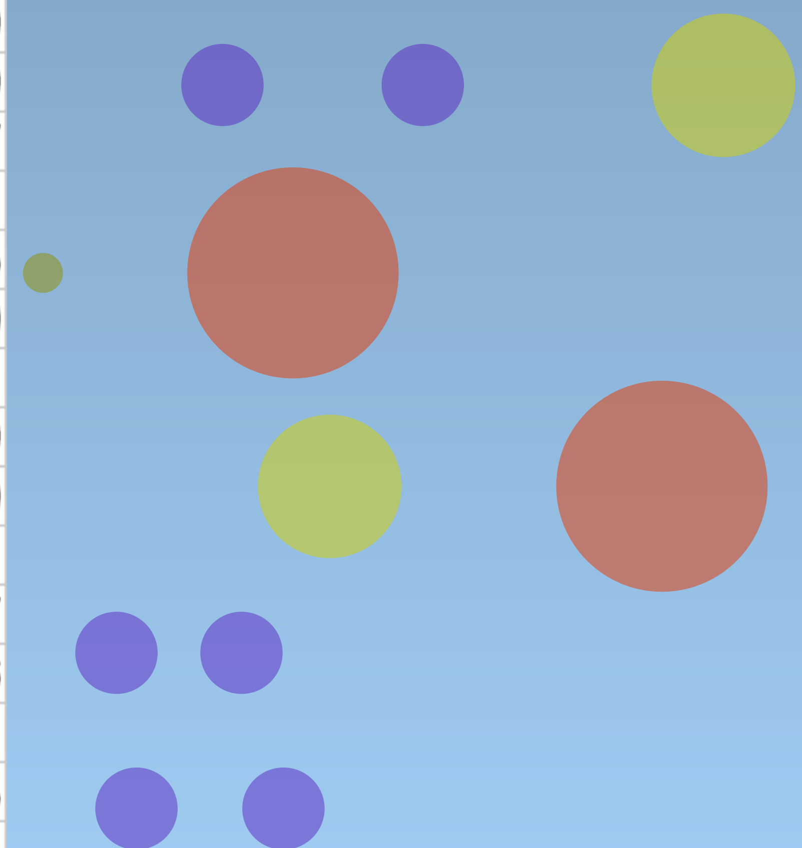
- Depends on (true) mutual inclination distribution



Ragozzine & Holman 2010

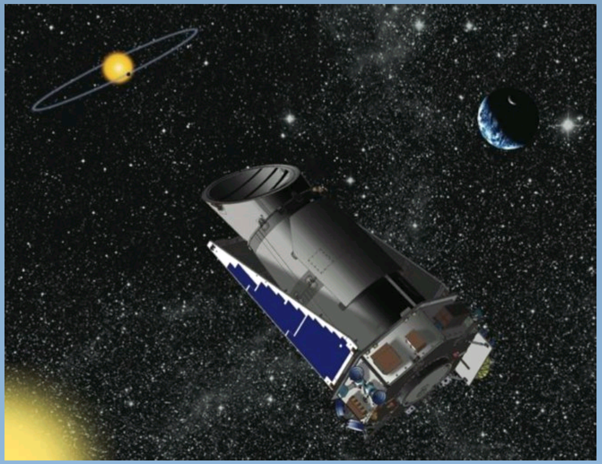
Kepler Multi-Transiting Candidates (Steffen et al. 2010)

Star	Mag	#	Per (d)	Dur (hr)	R (Nep)
KOI-152	13.9	.03	13.48	5.0	0.9
		.02	27.41	6.7	0.9
		.01	52	8.2	1.7
KOI-191	15.0	.02	2.42	2.3	0.5
		.01	15.36	3.6	3.0
KOI-209	14.2	.02	18.80	6.9	1.9
		.01	49	10.3	3.0
KOI-877	15.0	.01	5.95	2.3	0.7
		.02	12.04	2.9	0.6
KOI-896	15.3	.02	6.31	3.1	0.8
		.01	16.24	4.6	1.1



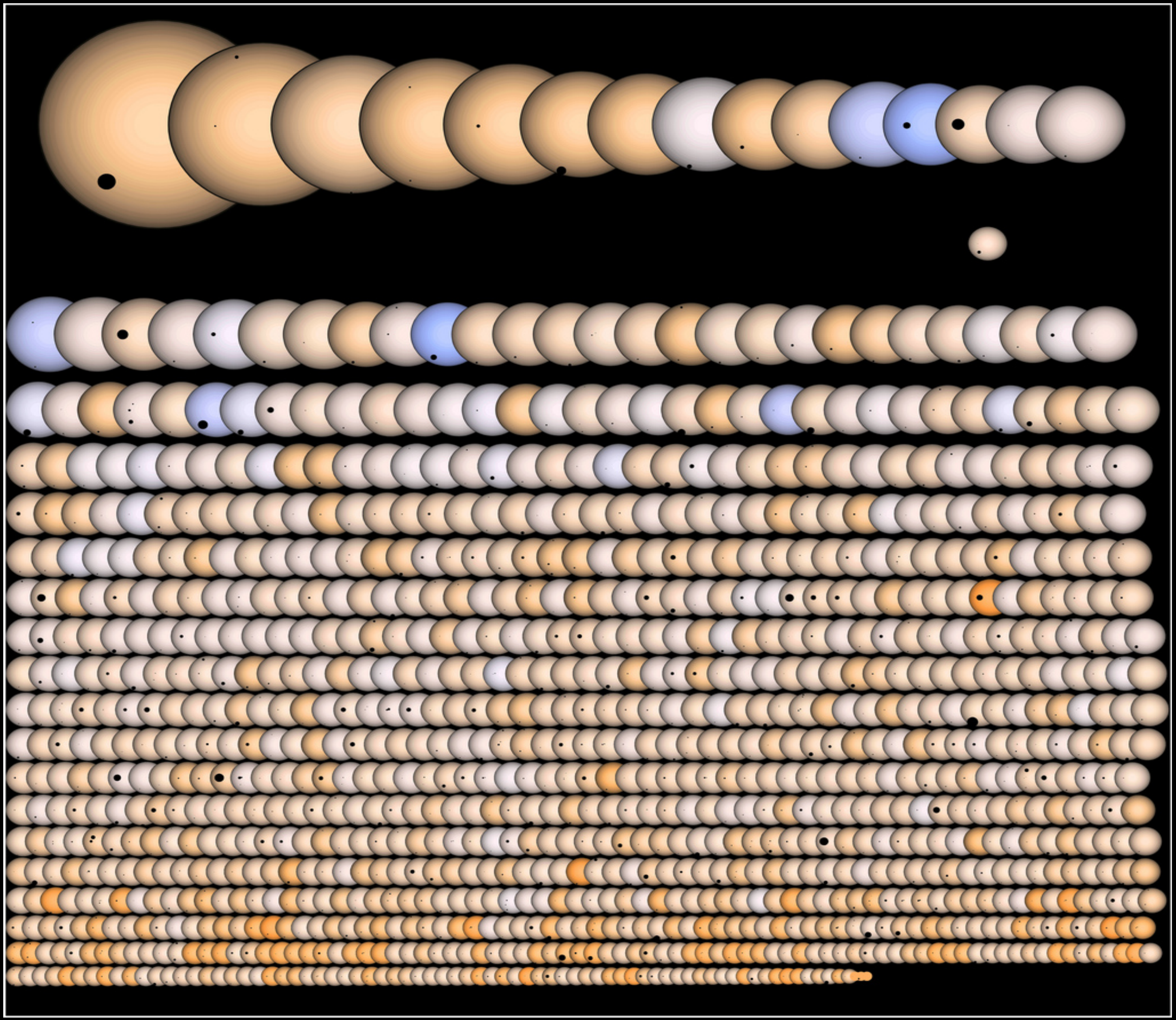
A faint *subset* of the (vetted) Kepler multi-transiting systems
CoRoT also has at least 2 candidates

Feb 2011 Kepler Data Release

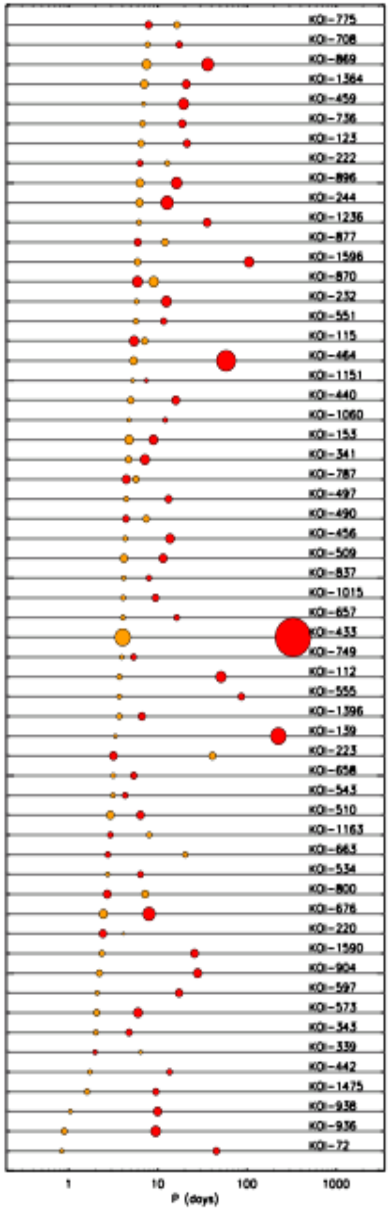


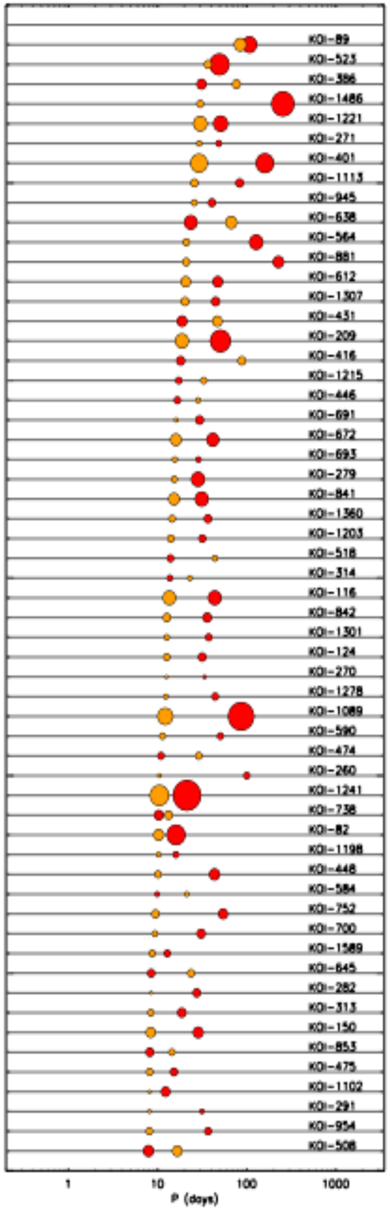
- All data from first 126 days
- Light curves generate candidates
  - Could be “false positives”
  - Most are likely (~90%) planets
- Search for your own candidates at planethunters.org
- Data and candidates in Borucki et al. 2011
- Various interpretation papers (available on arXiv): Lissauer et al. 2011b, Ford et al. 2011, Moorhead et al. 2011, Latham et al. 2011, Howard et al. 2011
- Everything in today's talk is public

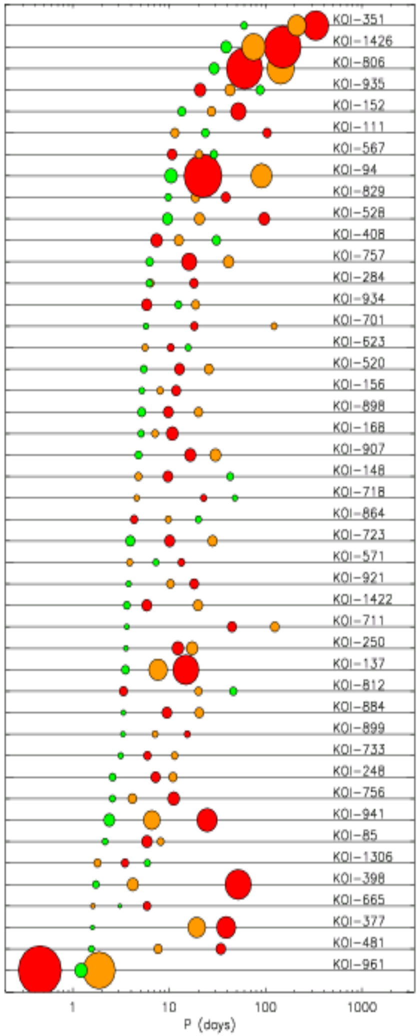
Over 1200 Exoplanet Candidates!

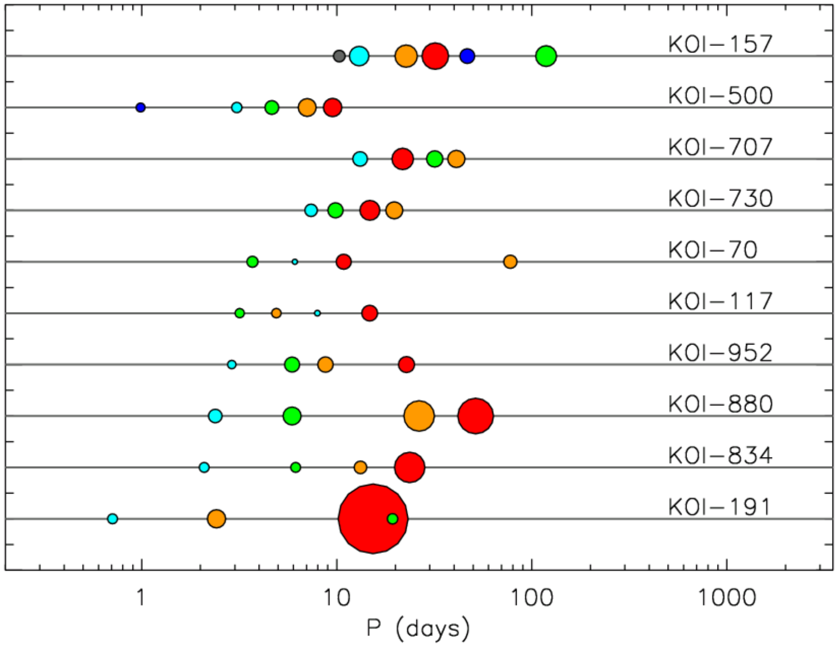


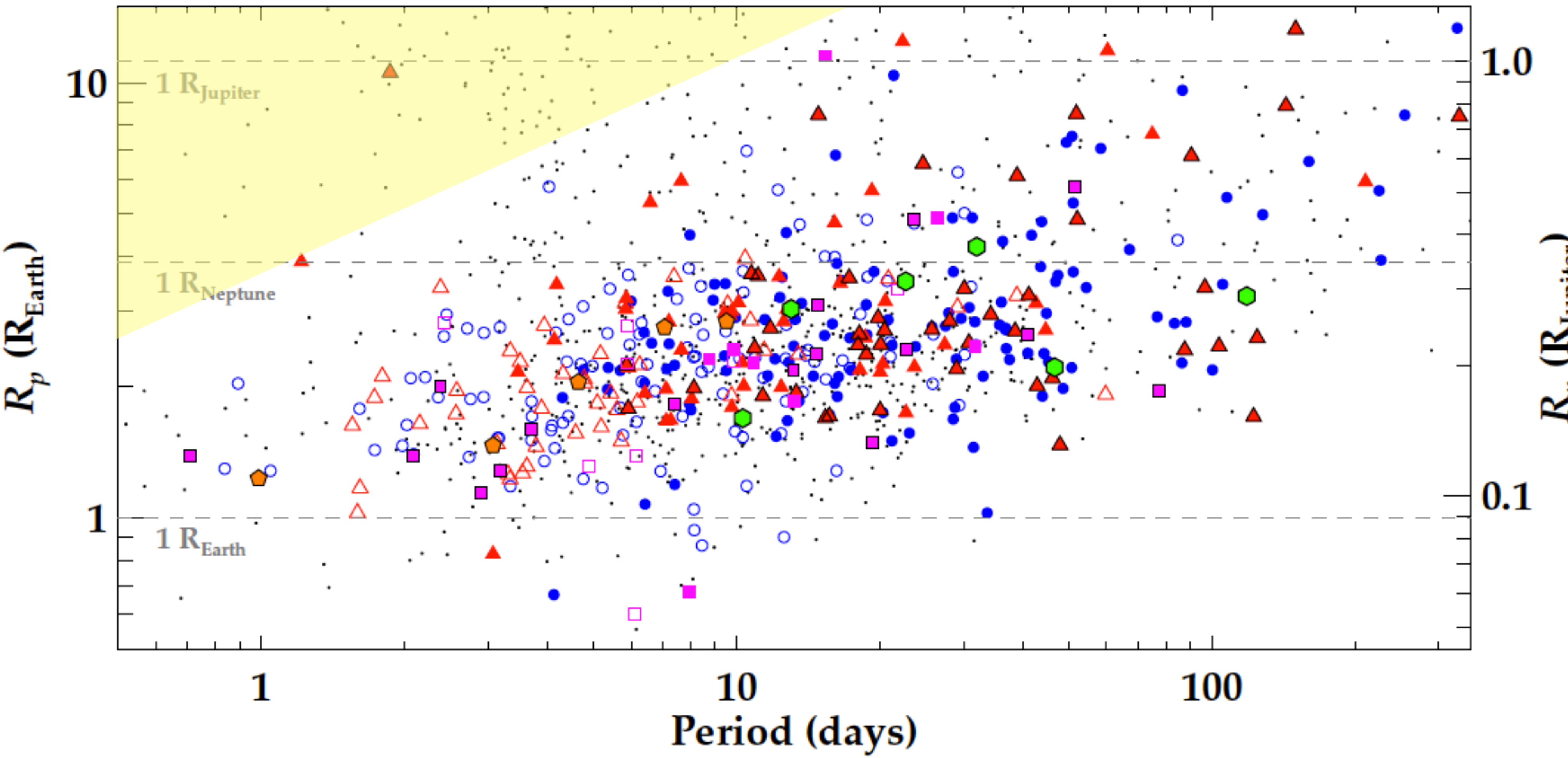
Multiple Candidate Systems!!!









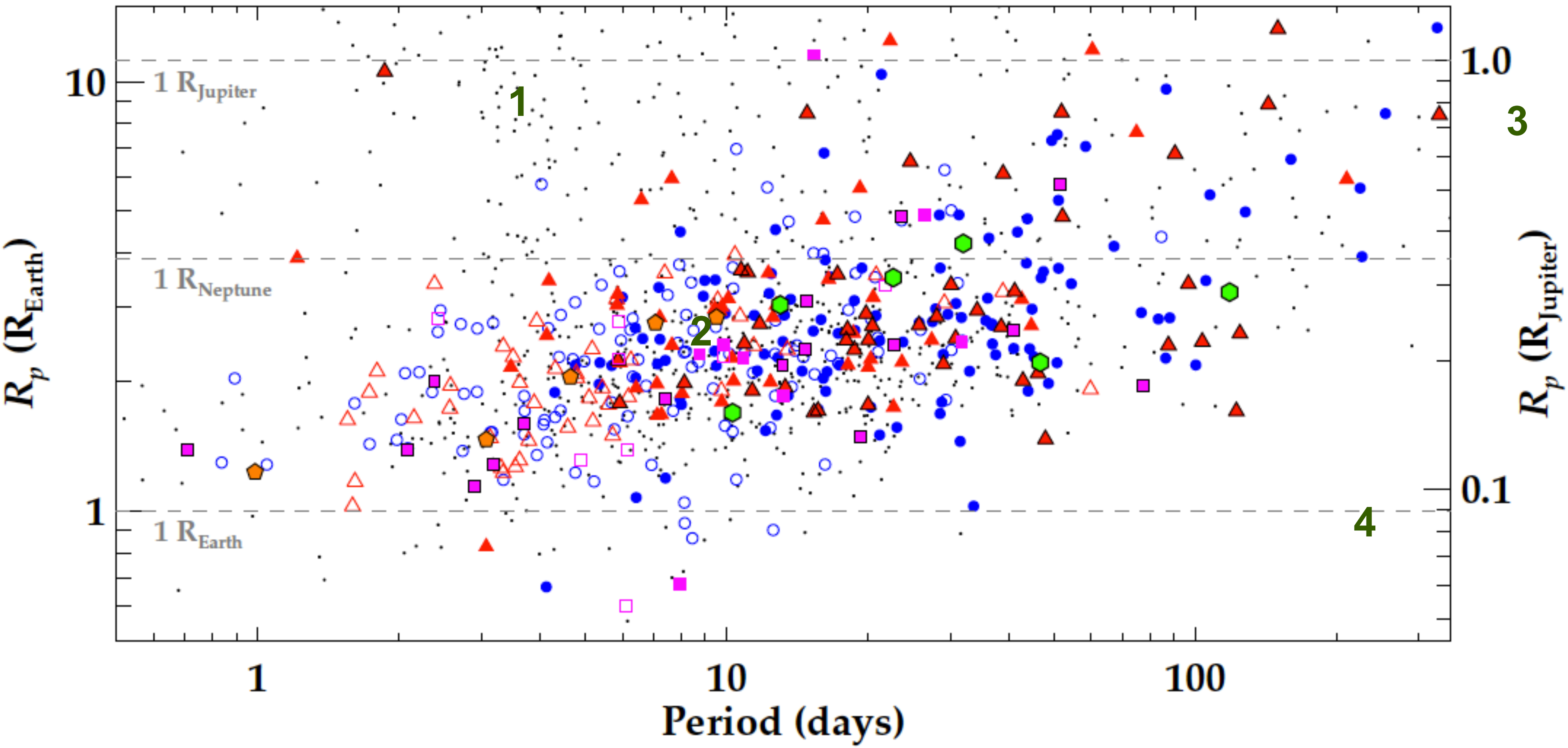


Numbers of multiplanets:

115 doubles, 45 triples, 8 quads,

1 & 1 of five and six

Borucki et al. 2011
Lissauer, Ragozzine,
Fabrycky et al. 2011b

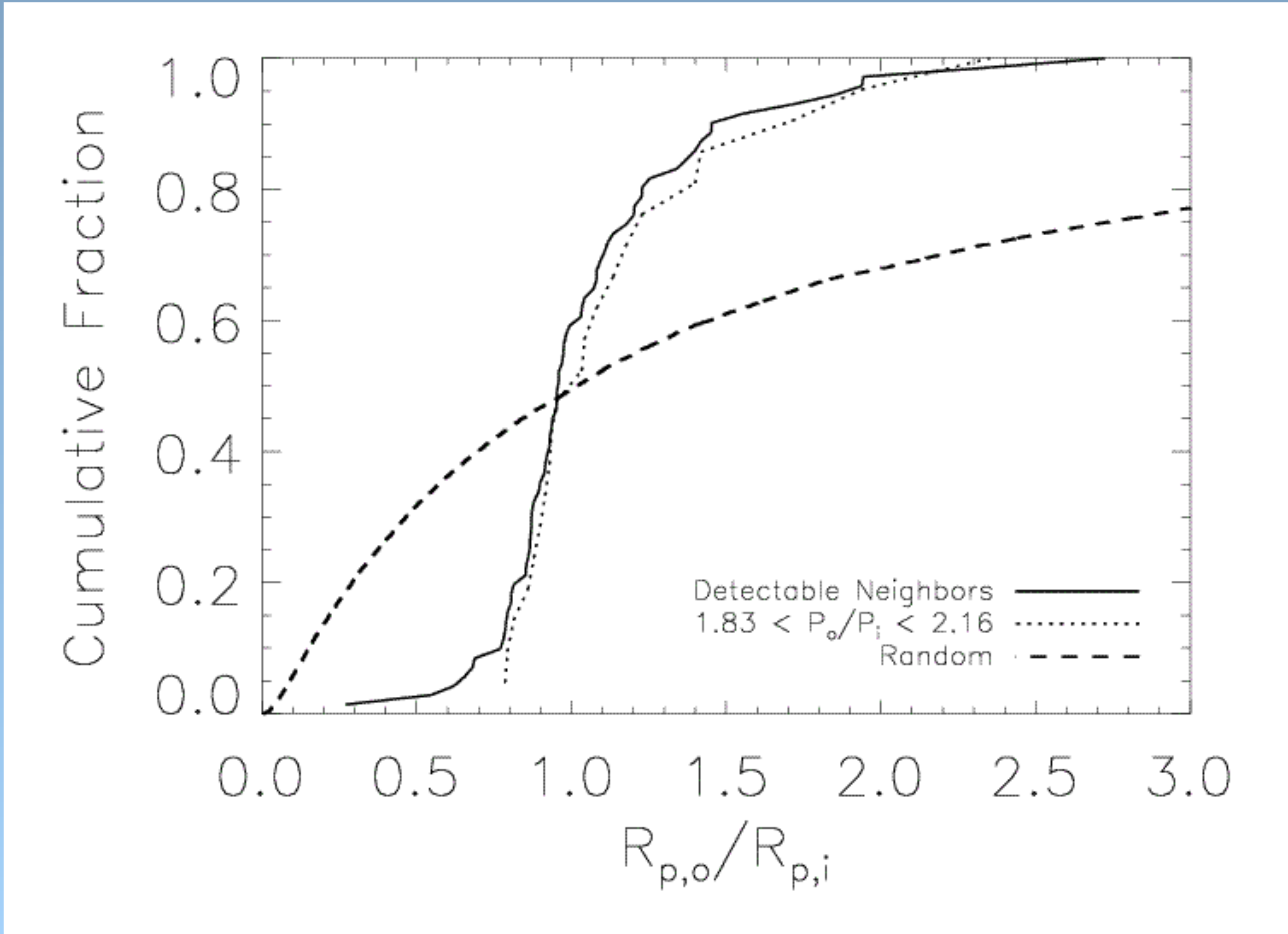


1. Single Hot Jupiters
2. Multiple short-period ~coplanar small planets
3. (Eccentric ~1 AU Jupiters)
4. (Solar System)

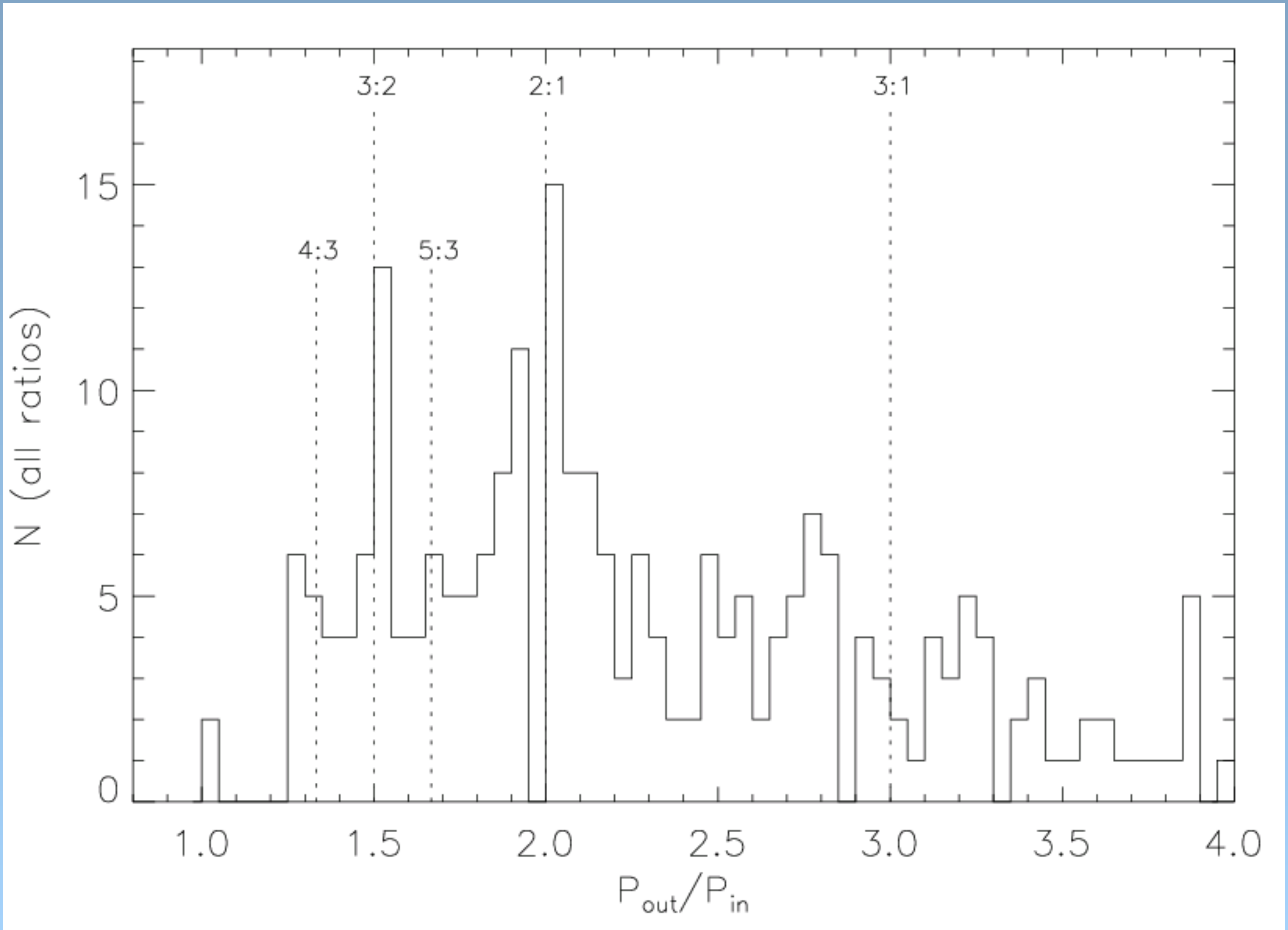
False Positives?

- Possible for each individual candidate
- All *Kepler* candidates get major vetting
- Multiples are more likely to be planets:
  - Planets tend to be in multiples (prob ↑)
  - Blends are **random** and have ~weak probabilities, that multiply (prob ↓)
- Inferred stellar properties must be consistent
  - Not a strong test, but these pass

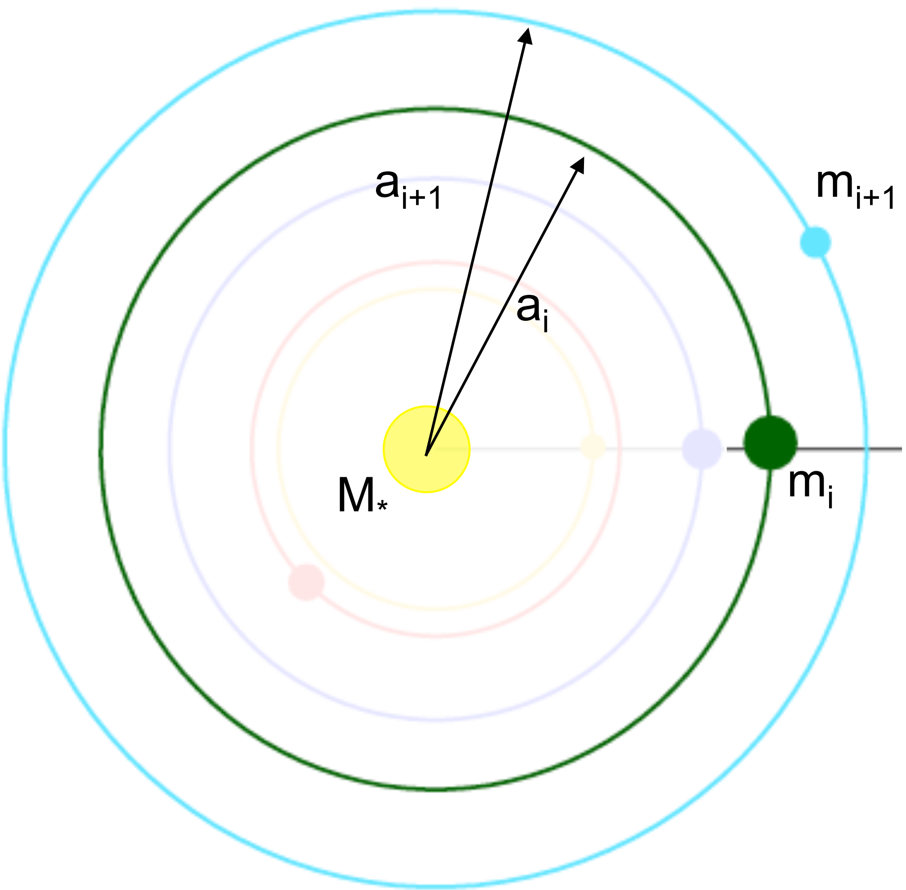
Non-Random 1: Radius Ratios



Non-Random 2: Period Ratios



Stability: Hill spacing



$$M_p = R_p^{2.06}$$

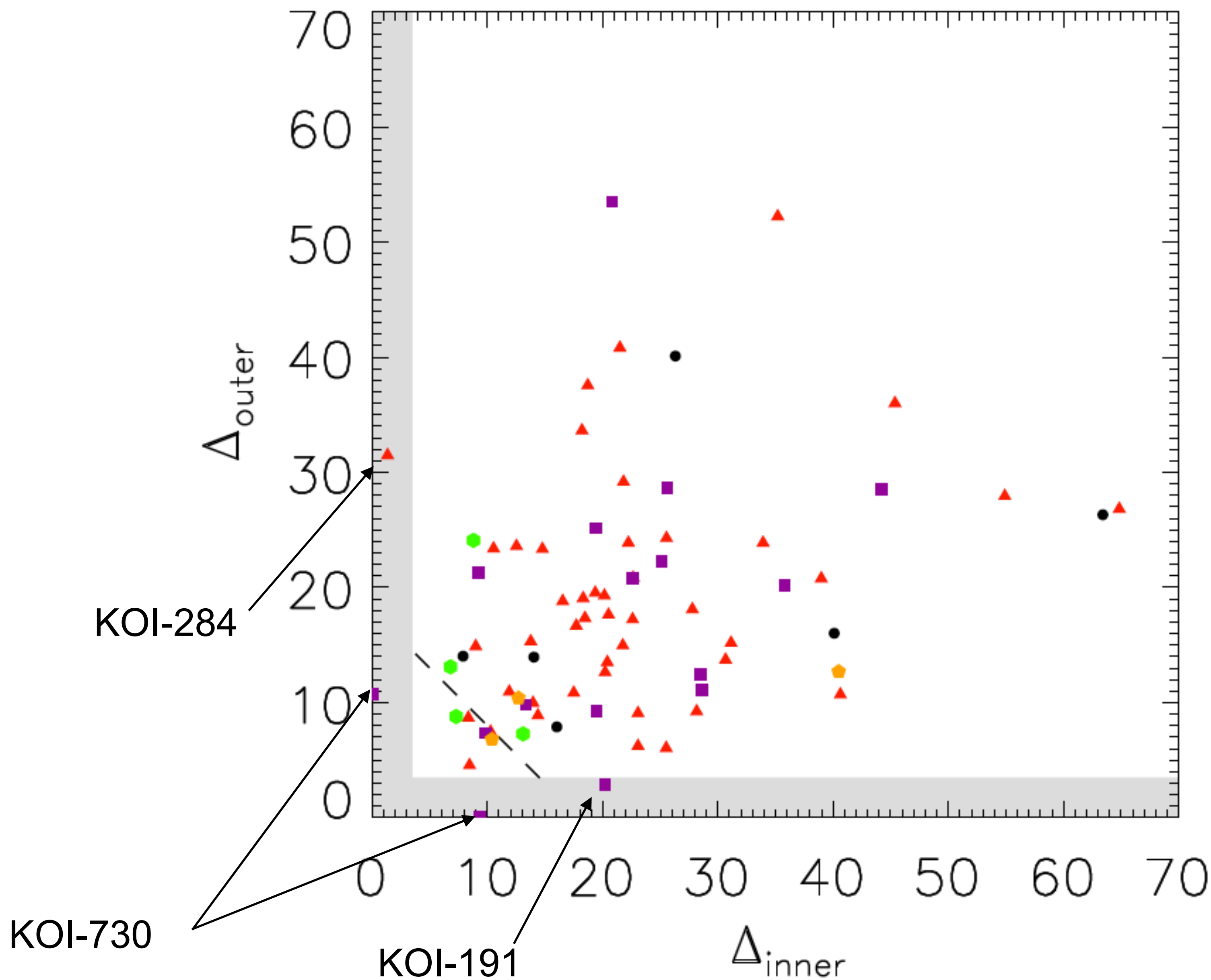
$$R_{H_{i,i+1}} = \left[\frac{m_i + m_{i+1}}{3M_\star}\right]^{1/3} \frac{(a_i + a_{i+1})}{2}$$

$$\Delta \equiv (a_o - a_i)/R_H > 2\sqrt{3} \approx 3.46$$

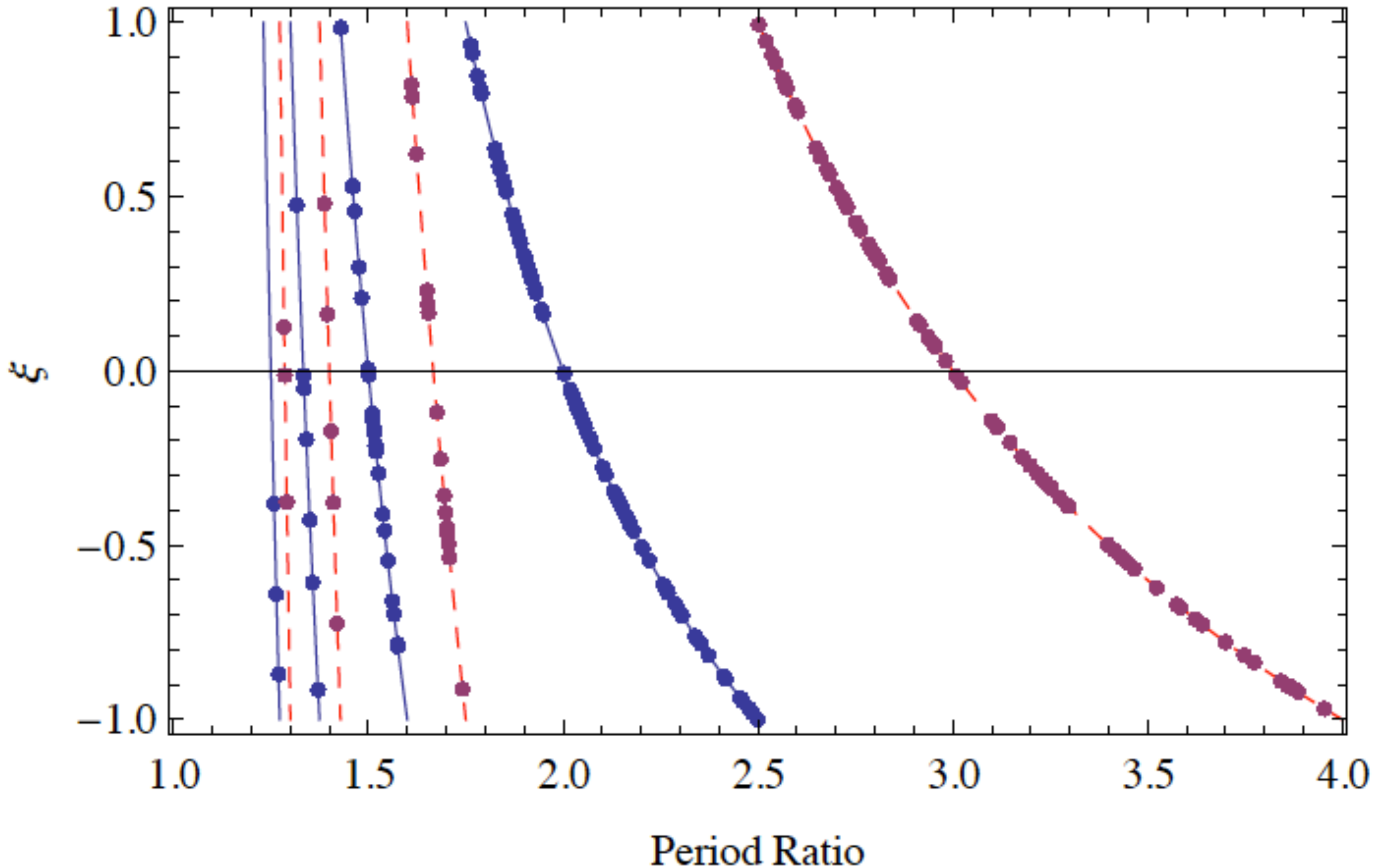
"Hill stable"

All 115 two-planet candidate systems are Hill stable!
With one exception, all 3+ candidate systems are stable as tested by dynamical integrations.

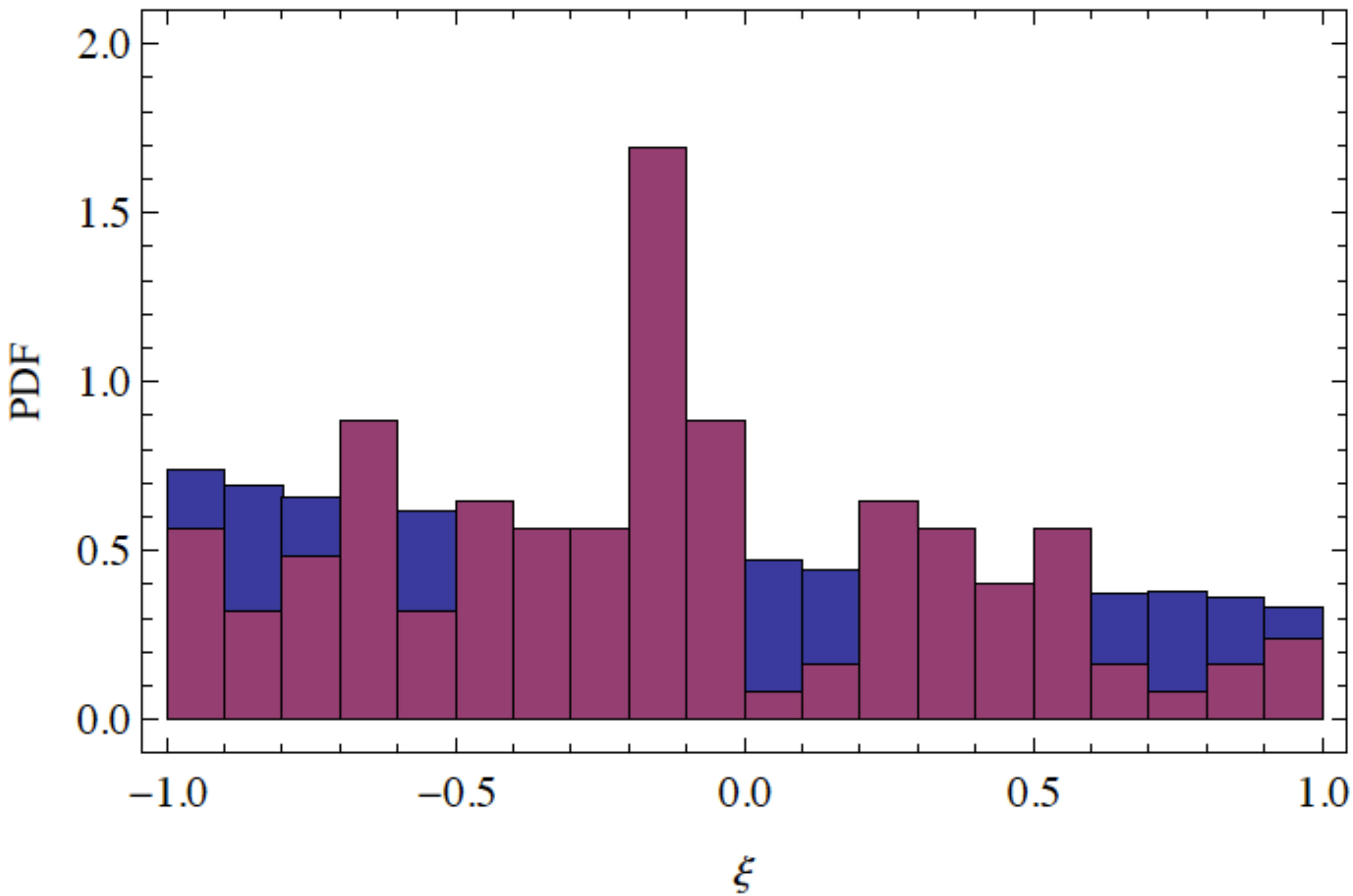
Long-term stability



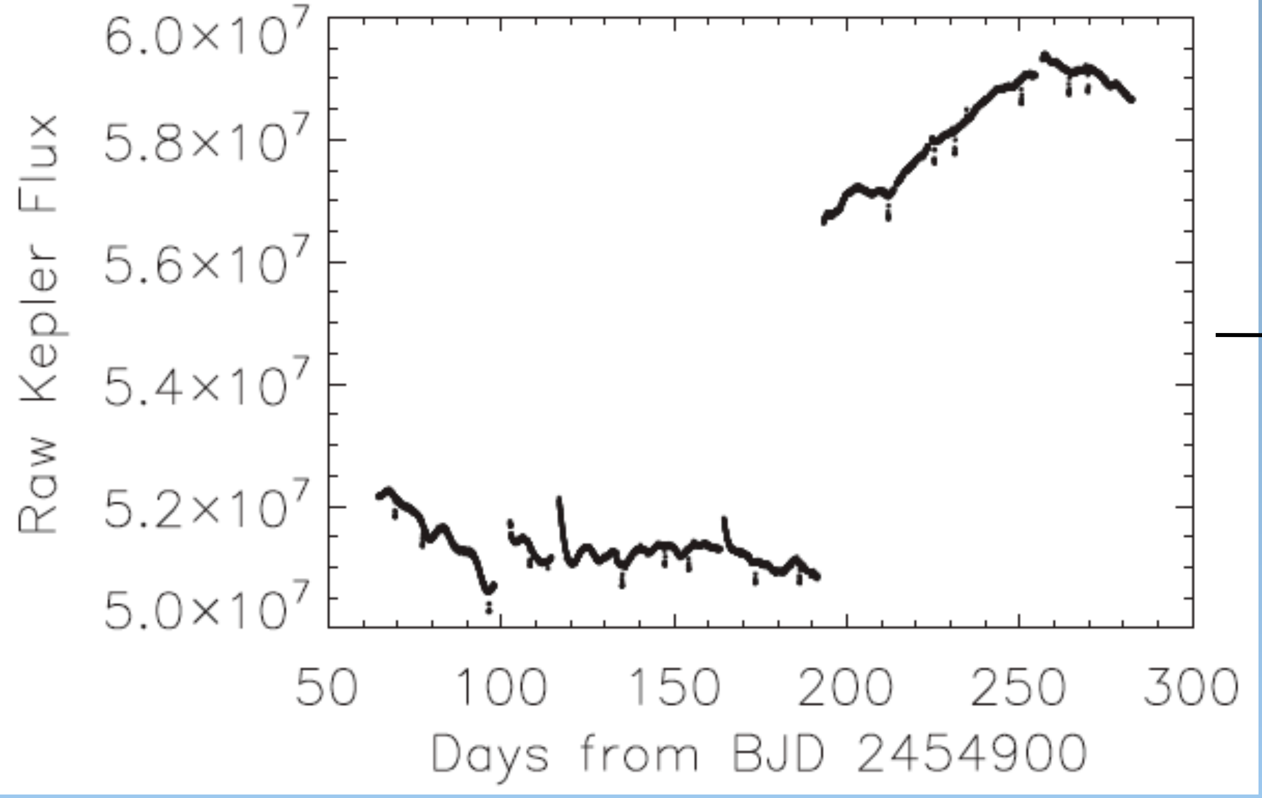
Resonance proximity



Clumping just wide of resonances



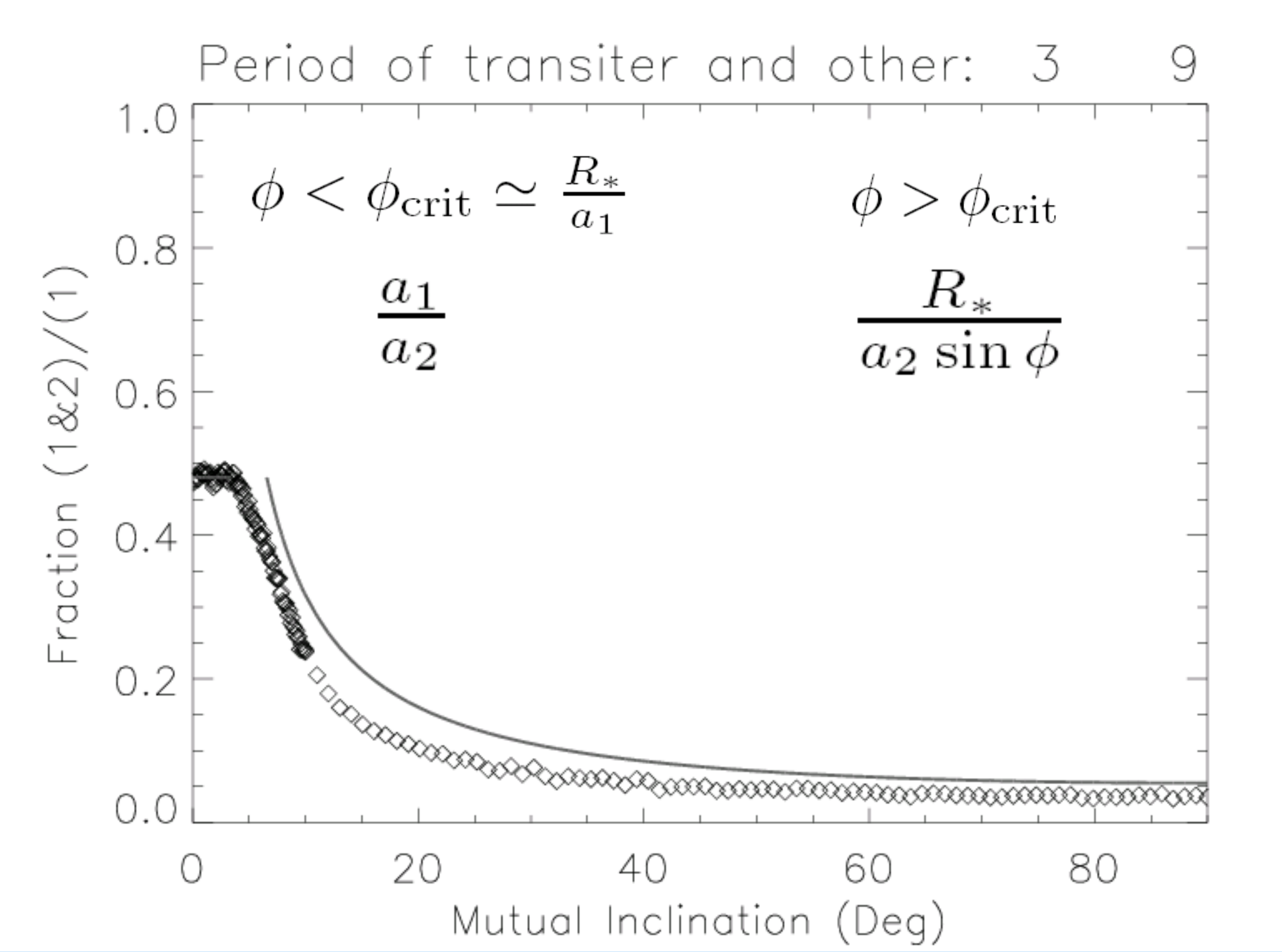
Confirming a planetary system



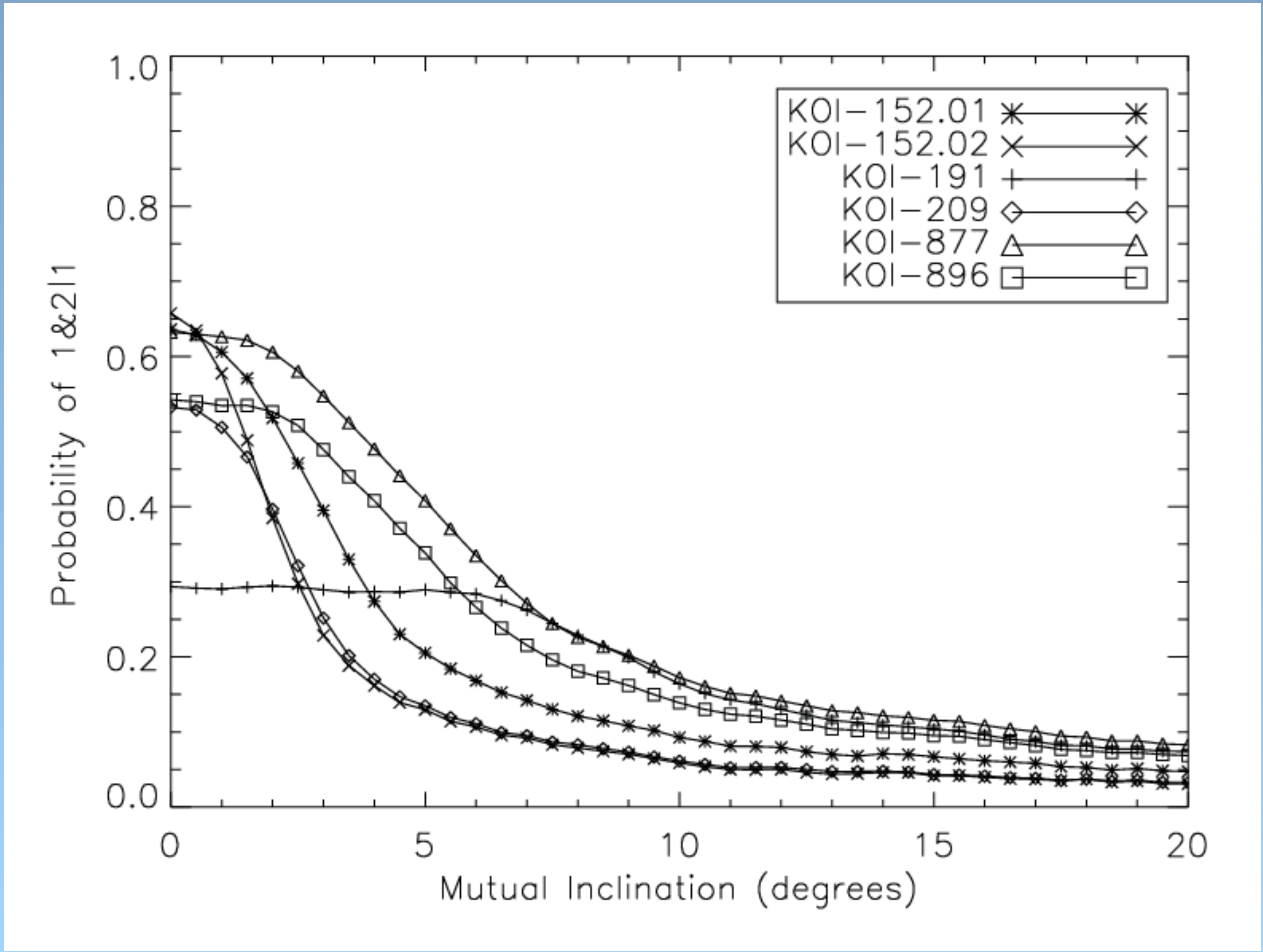
Kepler-9

Holman, Fabrycky, Ragozzine et al. 2010

Probability of MTS (if present)



Probabilities for Steffen systems



Two new aspects to TTVs (1)

- TTVs depend mostly on mass and conjunction distance of perturber (Holman & Murray 2005)
- If measured, TTVs an give an independent measurement of mass ratio of perturber to central mass (M_{pert}/M_*)

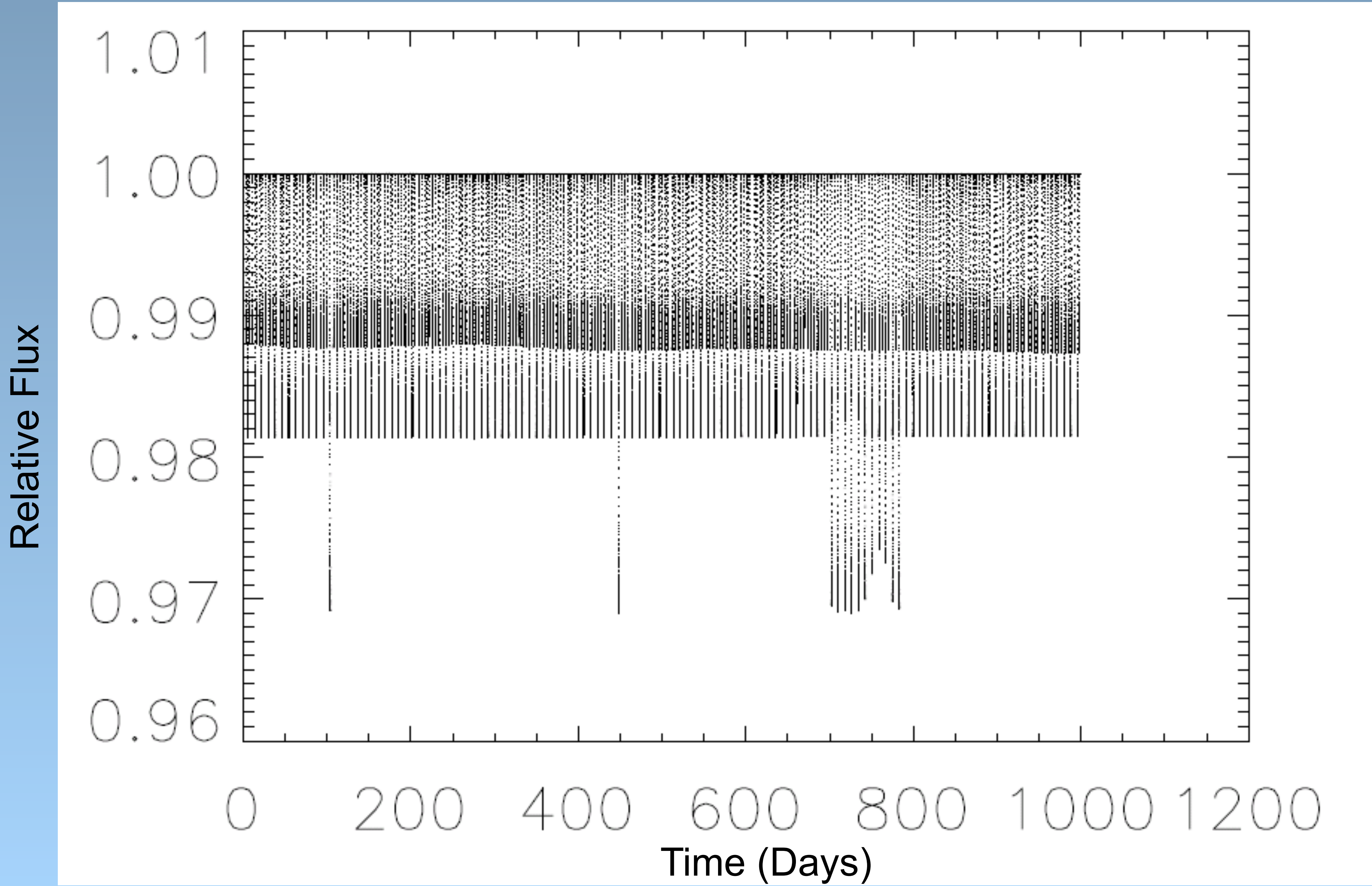
Radial Velocity amp = $K_{pert} \sim (M_{pert}/M_*)\, M_*^{1/3} \sin i_{pert}$

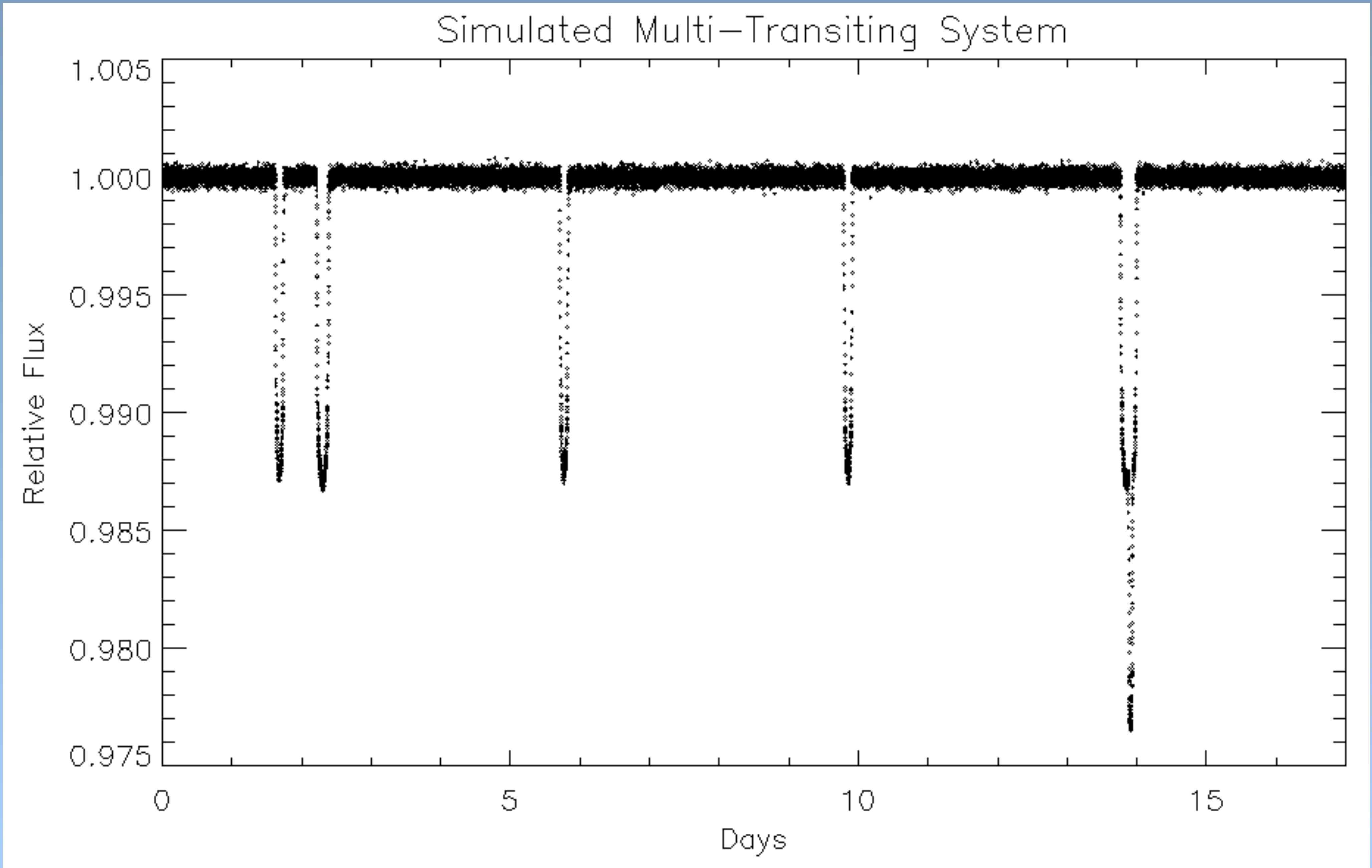
- *TTV + RV = Dynamical Masses (and Radii)*
- (Radial Velocity sets the length scale)

Two new aspects to TTVs (2)

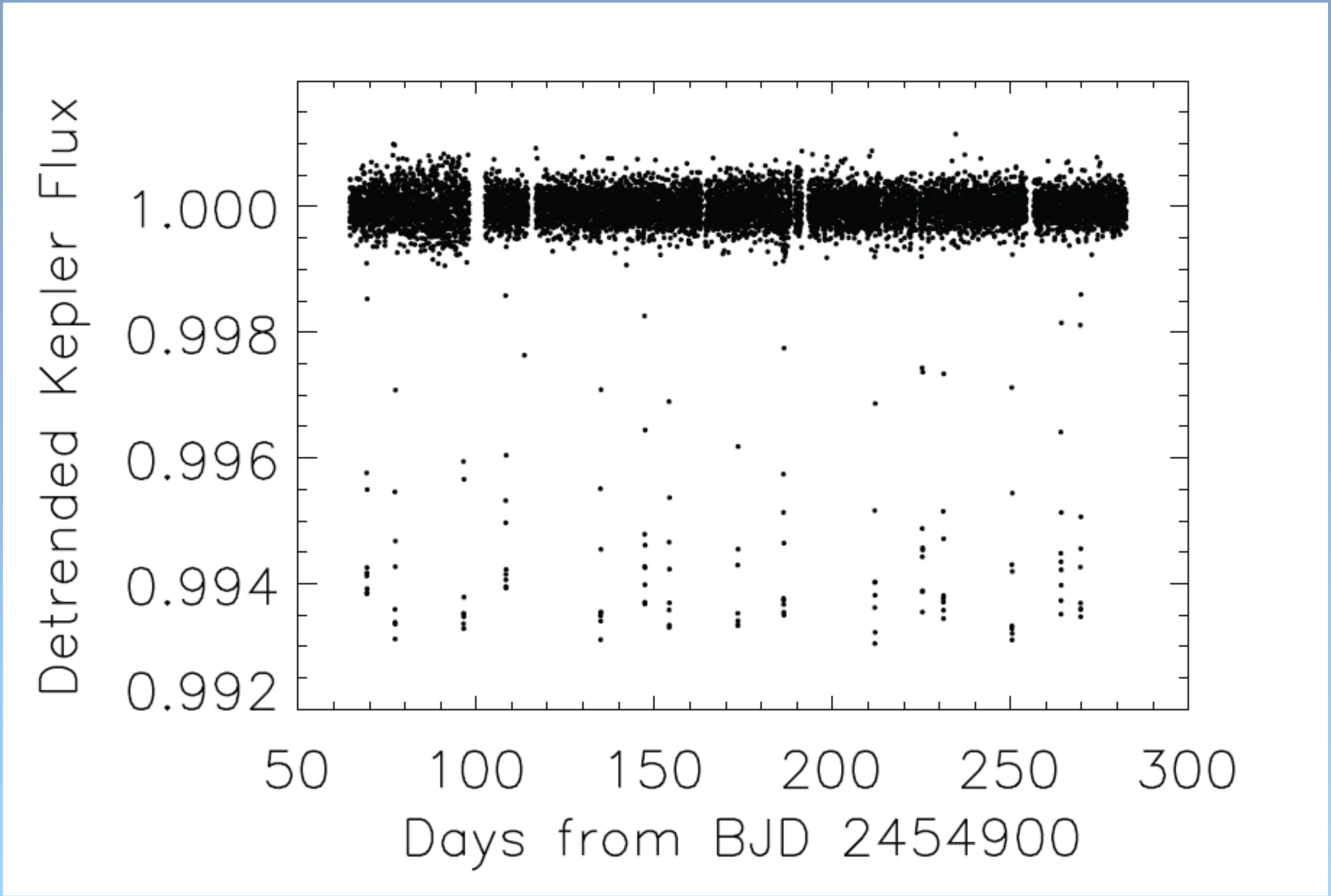
- TTVs are anomalies in along-track orbital phase
- TDVs are anomalies in cross-track positions or in apparent velocities
- Using a single number as the anomaly implicitly assumes that there is *no acceleration* during the transit
- TTVs/TDVs of HAT-P-13c are not well-defined
- True signal requires full coupled numerical integration and photometric model which encodes new information

2 Jupiters in 2:1 resonance, P = ~4,8 days

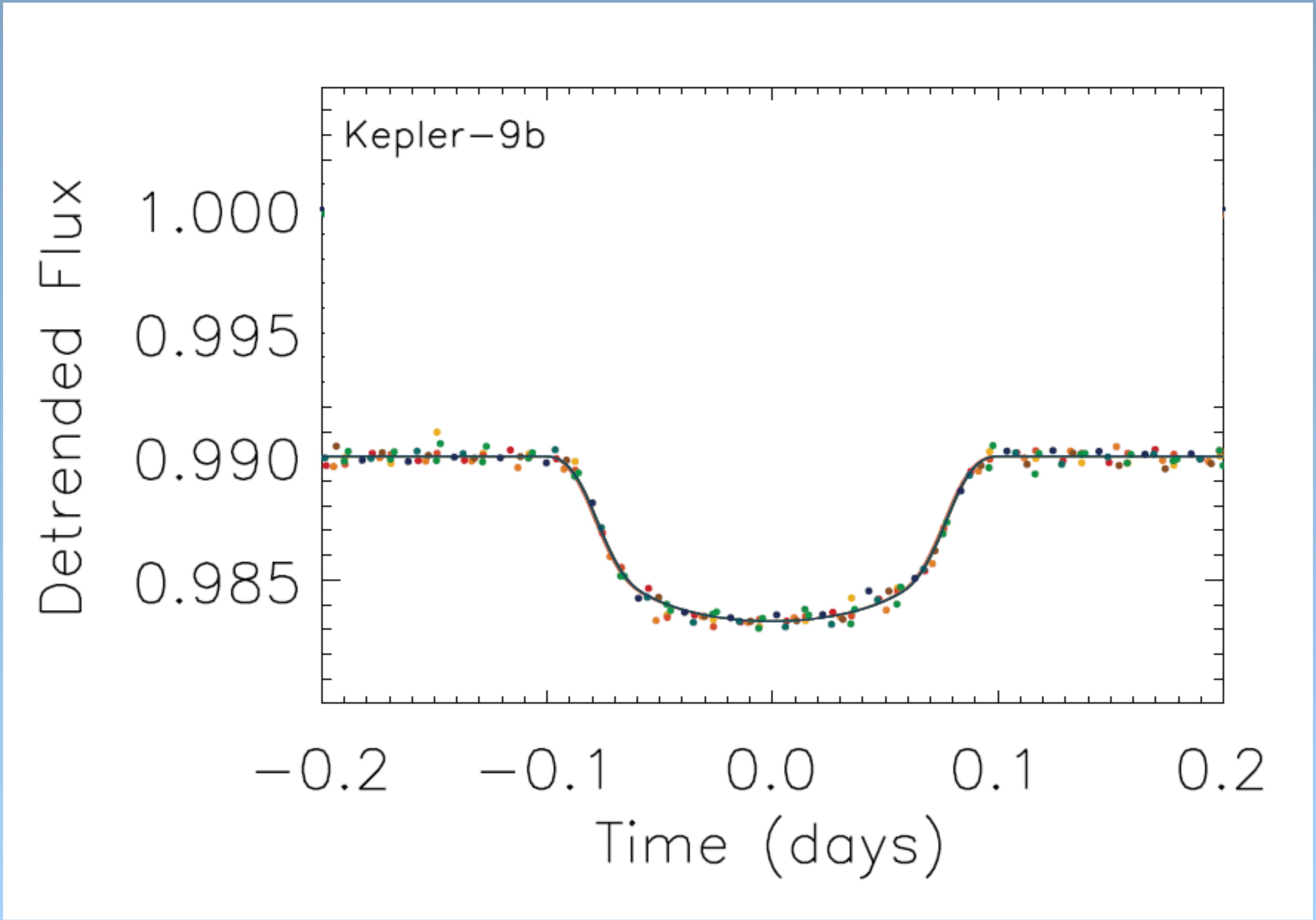



Simulated Multi-Transiting System
Relative Flux
1.005
1.000
0.995
0.990
0.985
0.980
0.975
0
5
10
15
Days

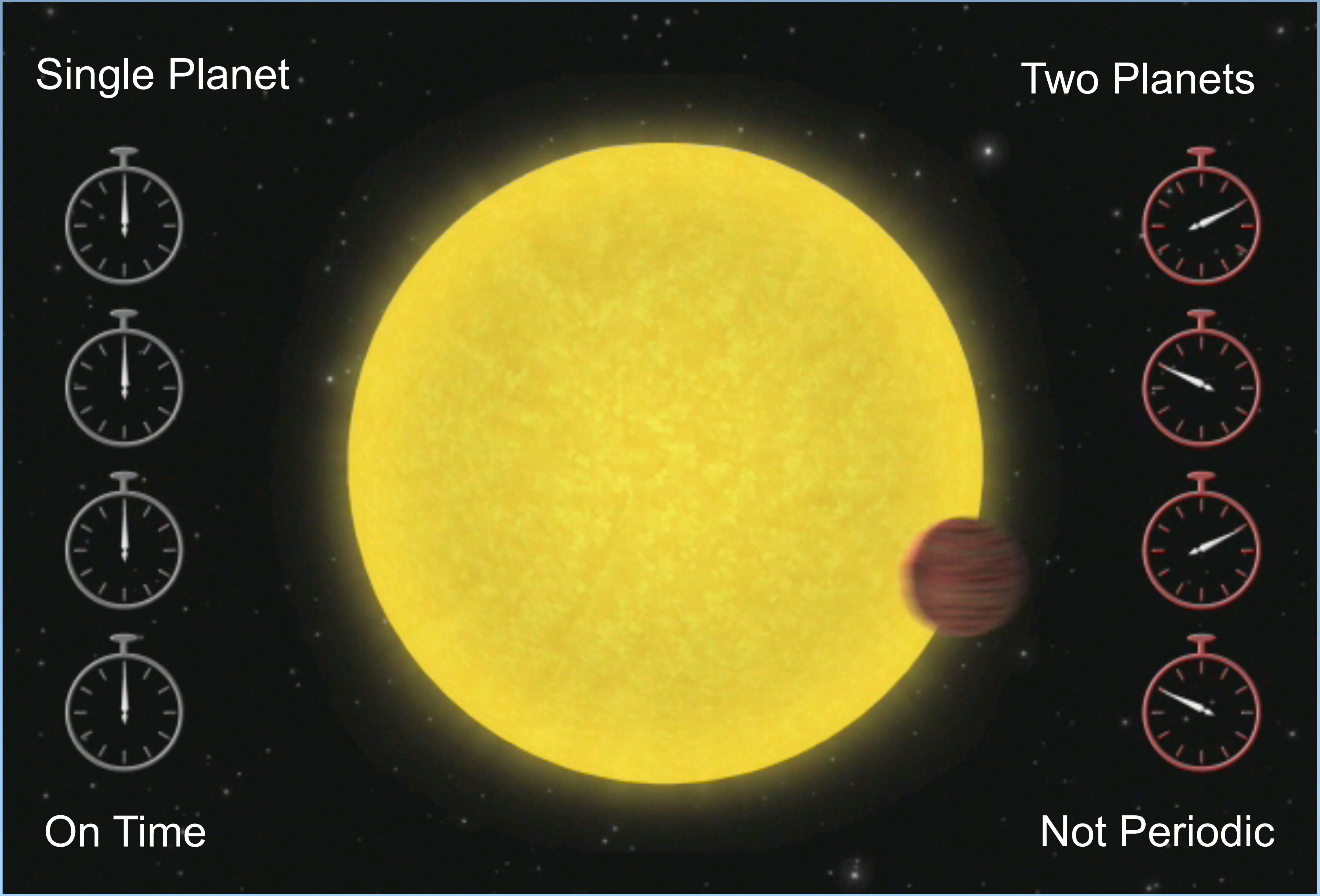
Detrend, Renormalize

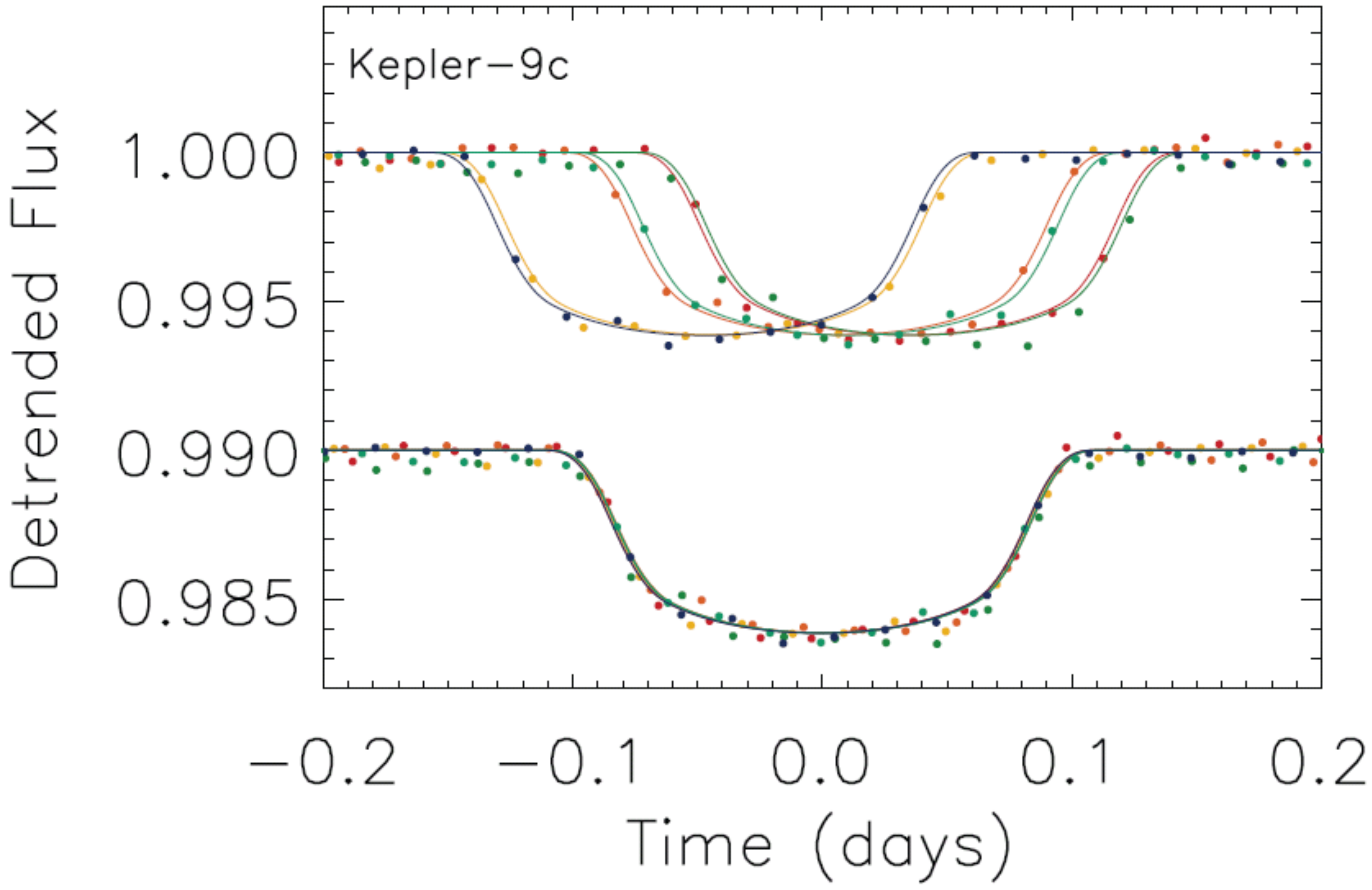


Fold on Observed Period



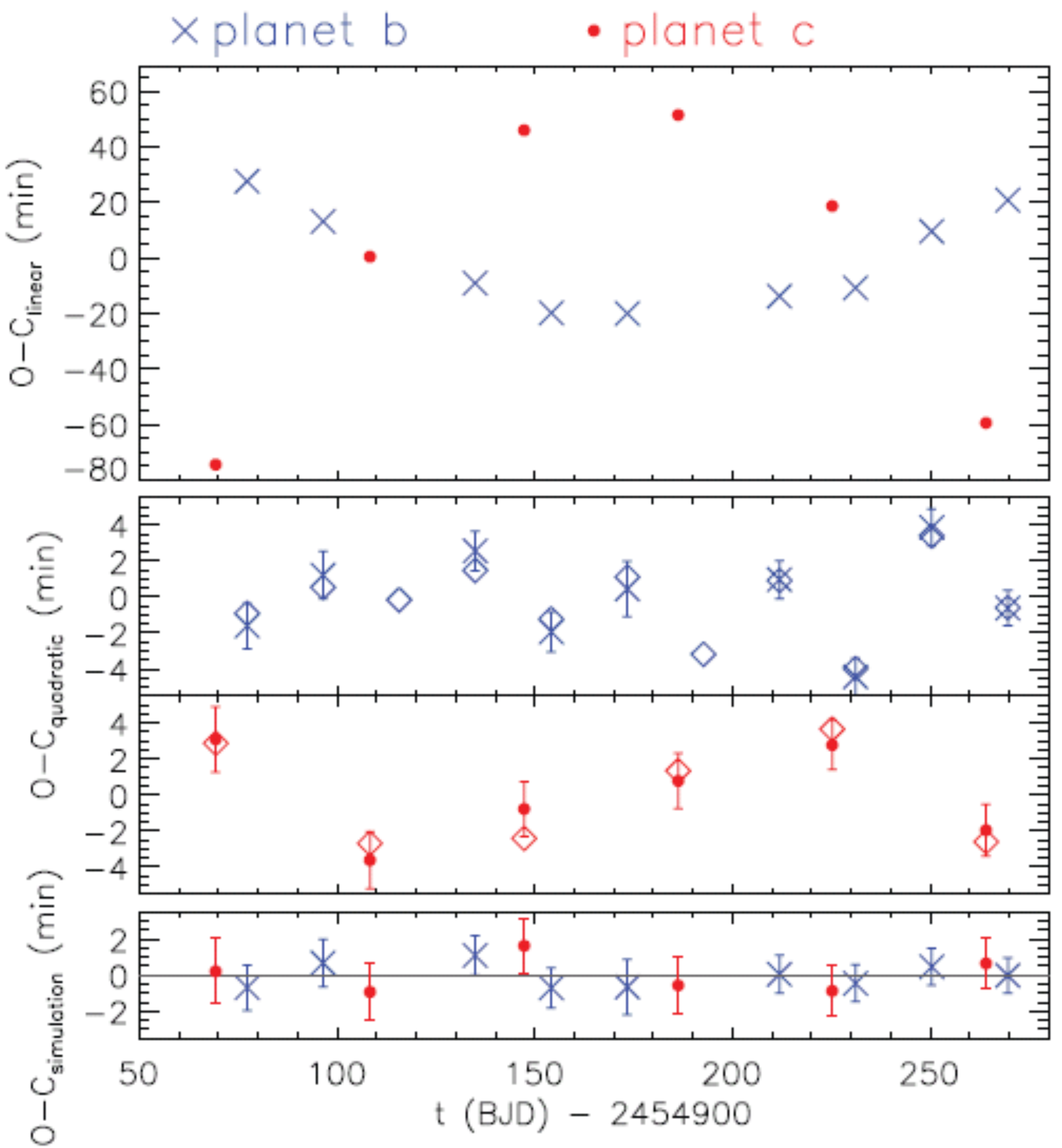
Transit Timing Variations (TTVs)




Kepler−9c
Detrended Flux
1.000
0.995
0.990
0.985
−0.2
−0.1
0.0
0.1
0.2
Time (days)

Value of Multi-Transiting TTVs

- TTVs proportional to perturber mass and period
- In MTS: TTV signal *much* easier to interpret and invert: know presence, period, phase, and radius
- Interdependent TTVs
- When RV signal is too weak (Earth) or hard, TTVs may measure masses better
  - So far, more Kepler planets confirmed by TTVs than any other means!

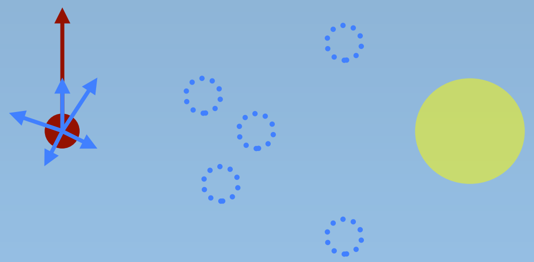


planet b
planet c
O−C_linear (min)
O−C_quadratic (min)
O−C_simulation (min)
60
40
20
0
−20
−40
−60
−80
4
2
0
−2
−4
50
100
150
200
250
t (BJD) − 2454900

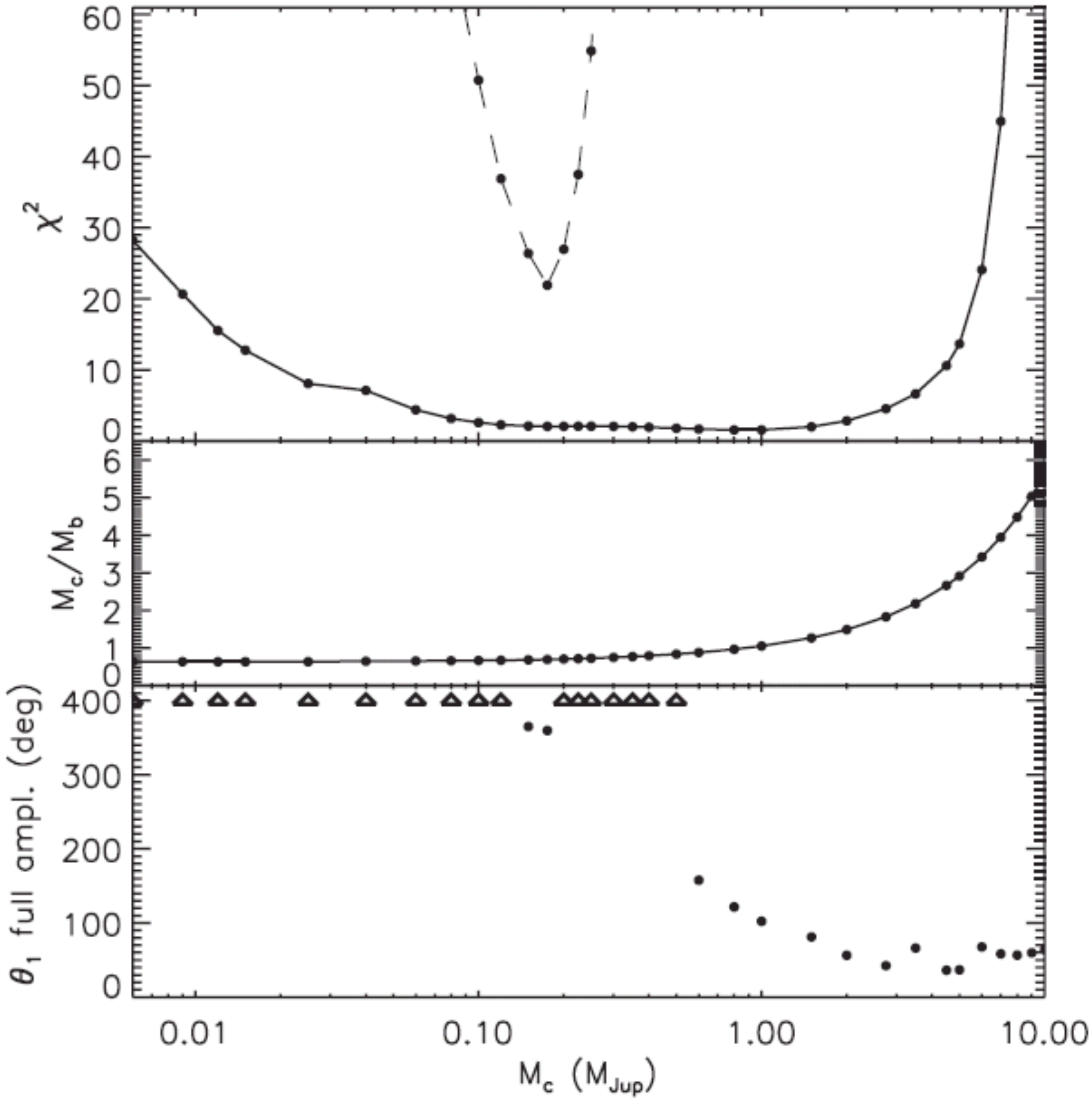
Resonance

Resonance implies a specific commensurability between two periodic forcings

- No resonance: if the ratio of periods implies that the long-term forcing is not coherent

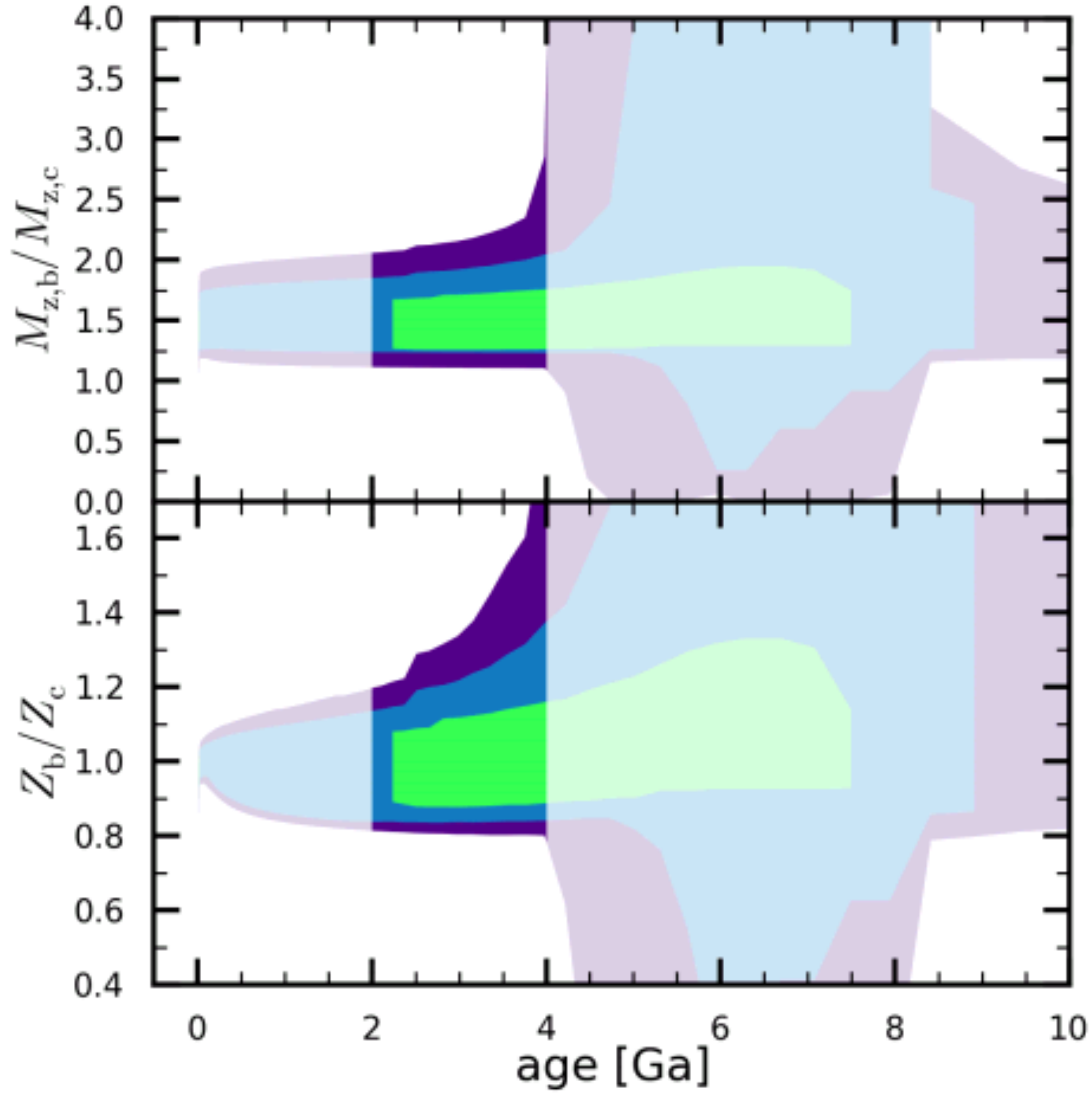


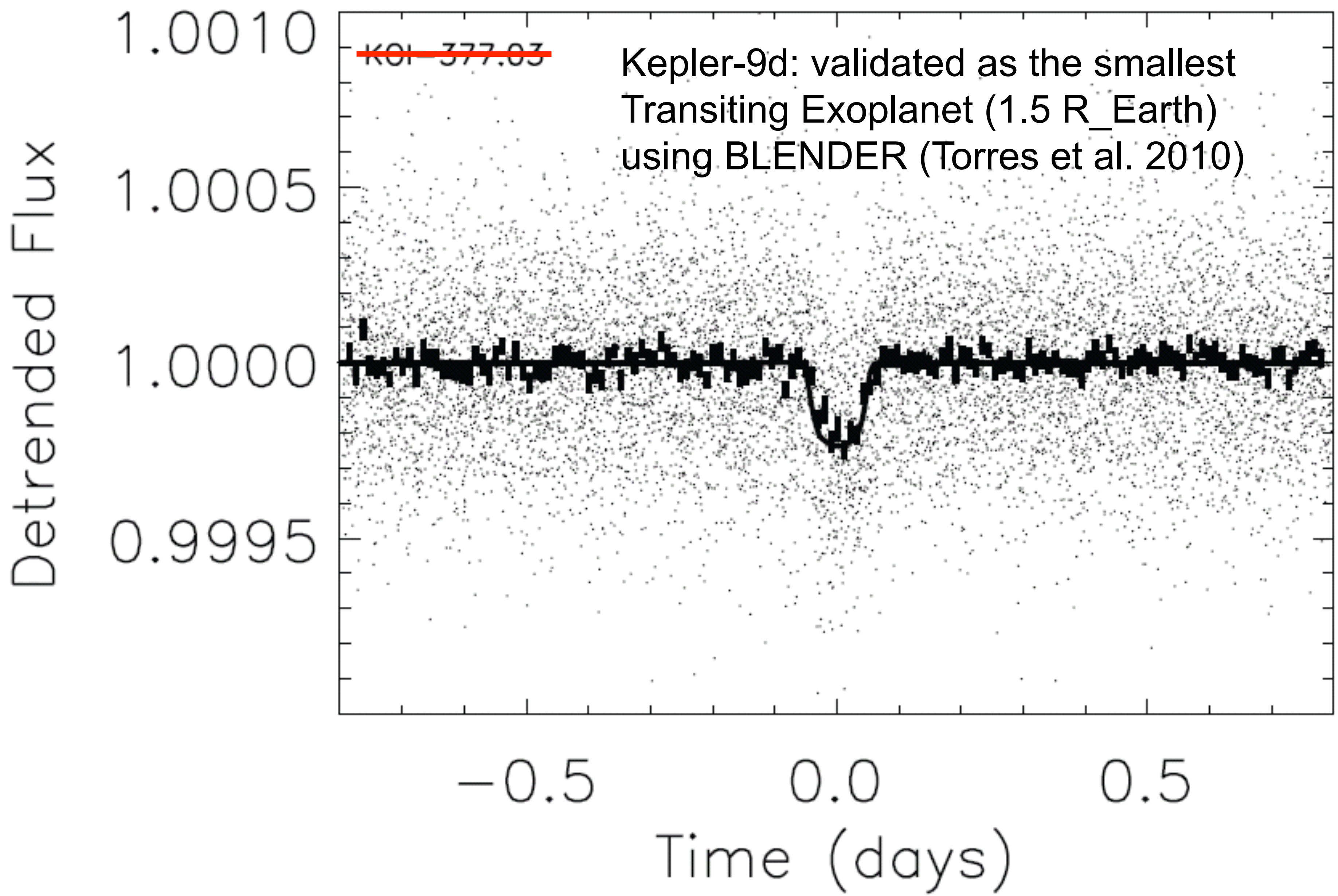
- Resonance: if the ratio of periods is a ratio of small integers, then the relative positions of the objects will often be the same, and the long-term forcing is coherent and **important**



60
50
40
30
20
10
0
χ^2
6
5
4
3
2
1
0
M_c/M_b
400
300
200
100
0
θ_1 full ampl. (deg)
0.01
0.10
1.00
10.00
M_c (M_{Jup})

Havel et al.: Kepler-9: stellar properties and composition of the planets




~~KOI 377.03~~
Kepler-9d: validated as the smallest
Transiting Exoplanet (1.5 R_Earth)
using BLENDER (Torres et al. 2010)
1.0010
1.0005
1.0000
0.9995
Detrended Flux
−0.5
0.0
0.5
Time (days)

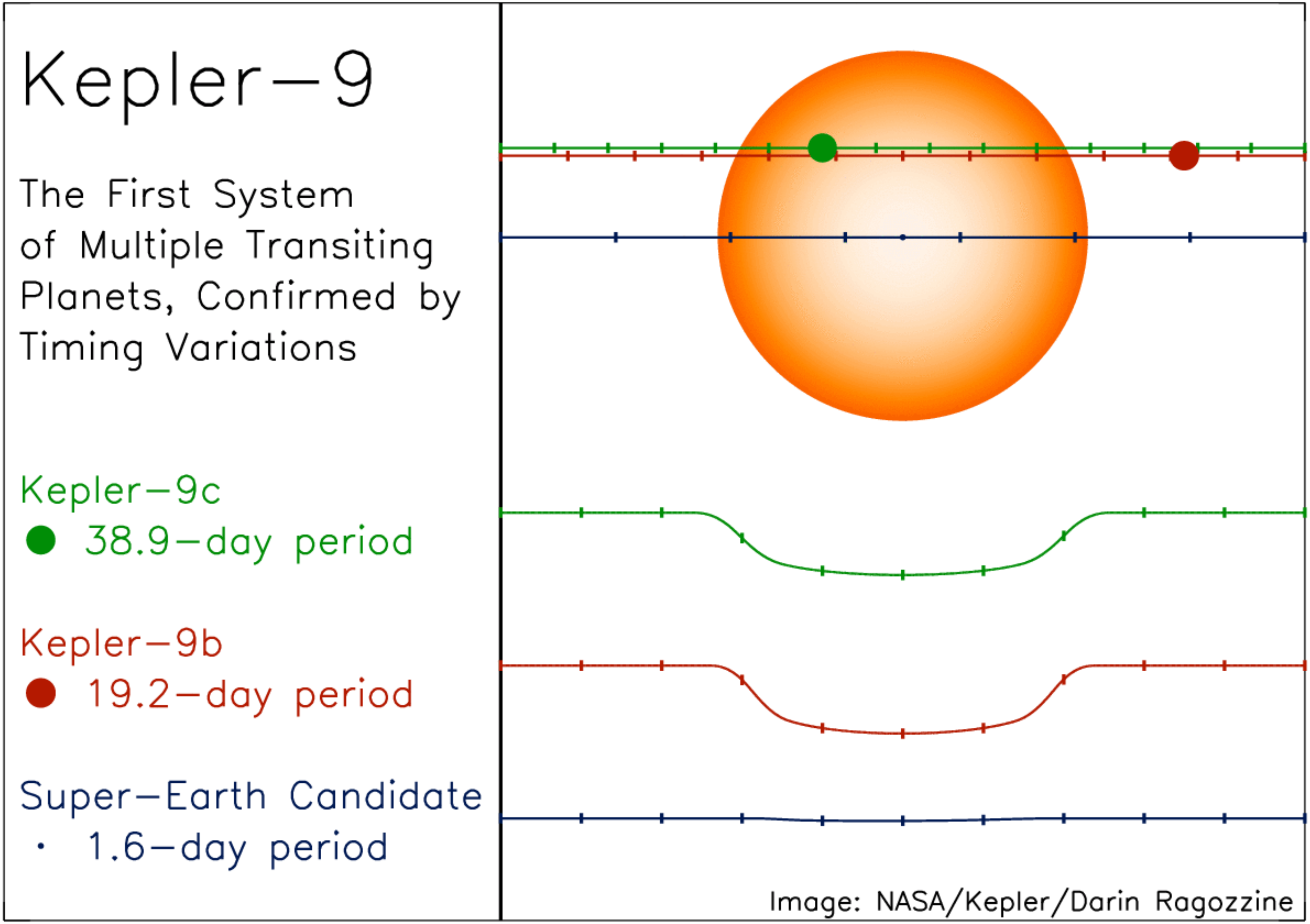
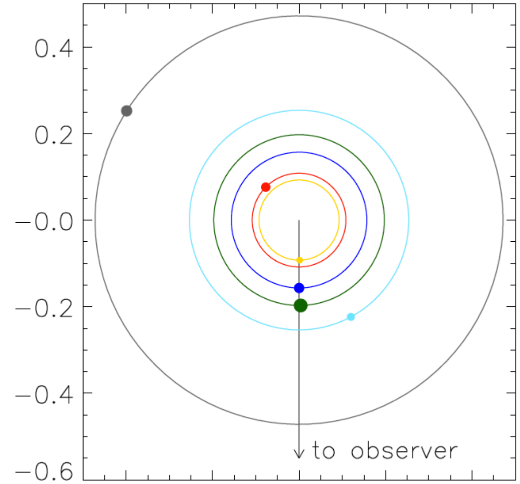
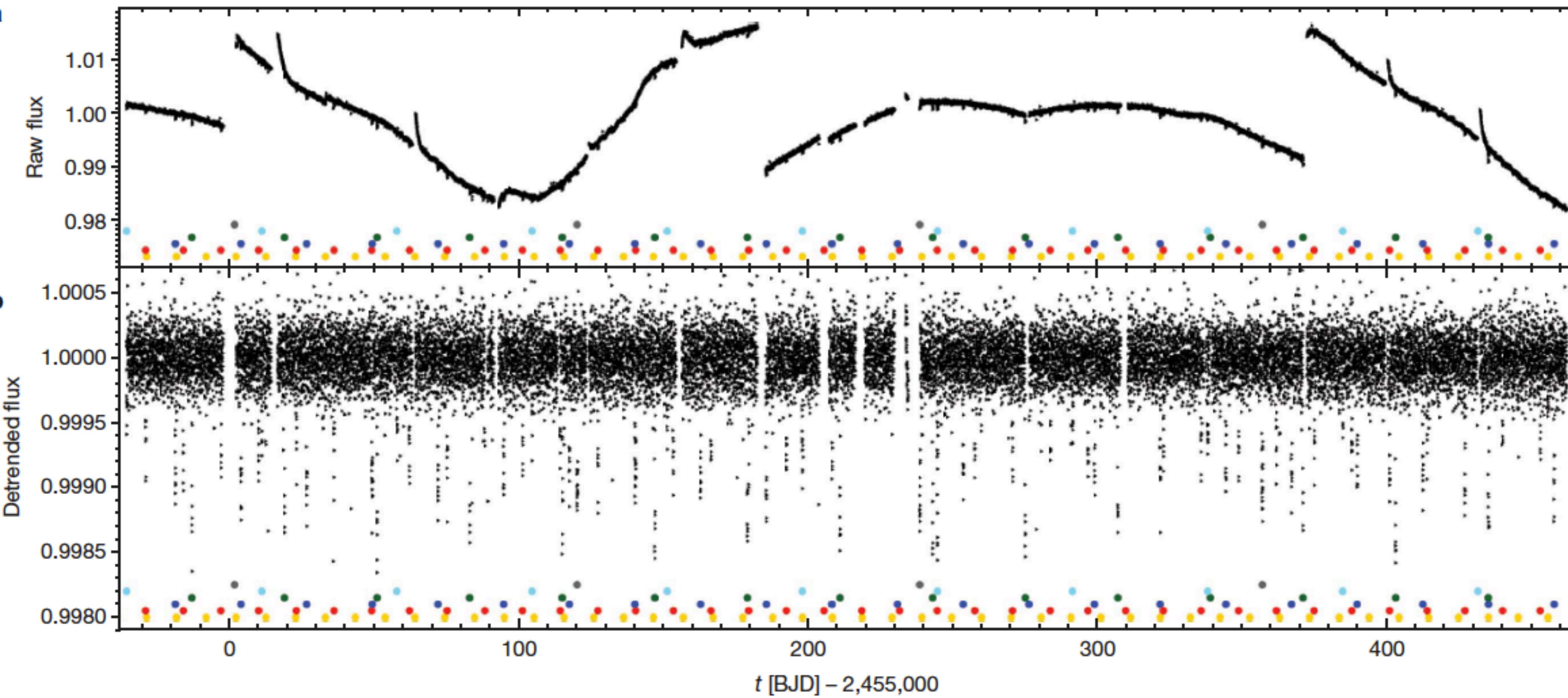

Kepler-9
The First System of Multiple Transiting Planets, Confirmed by Timing Variations
Kepler-9c
38.9-day period
Kepler-9b
19.2-day period
Super-Earth Candidate
1.6-day period
Image: NASA/Kepler/Darin Ragozzine

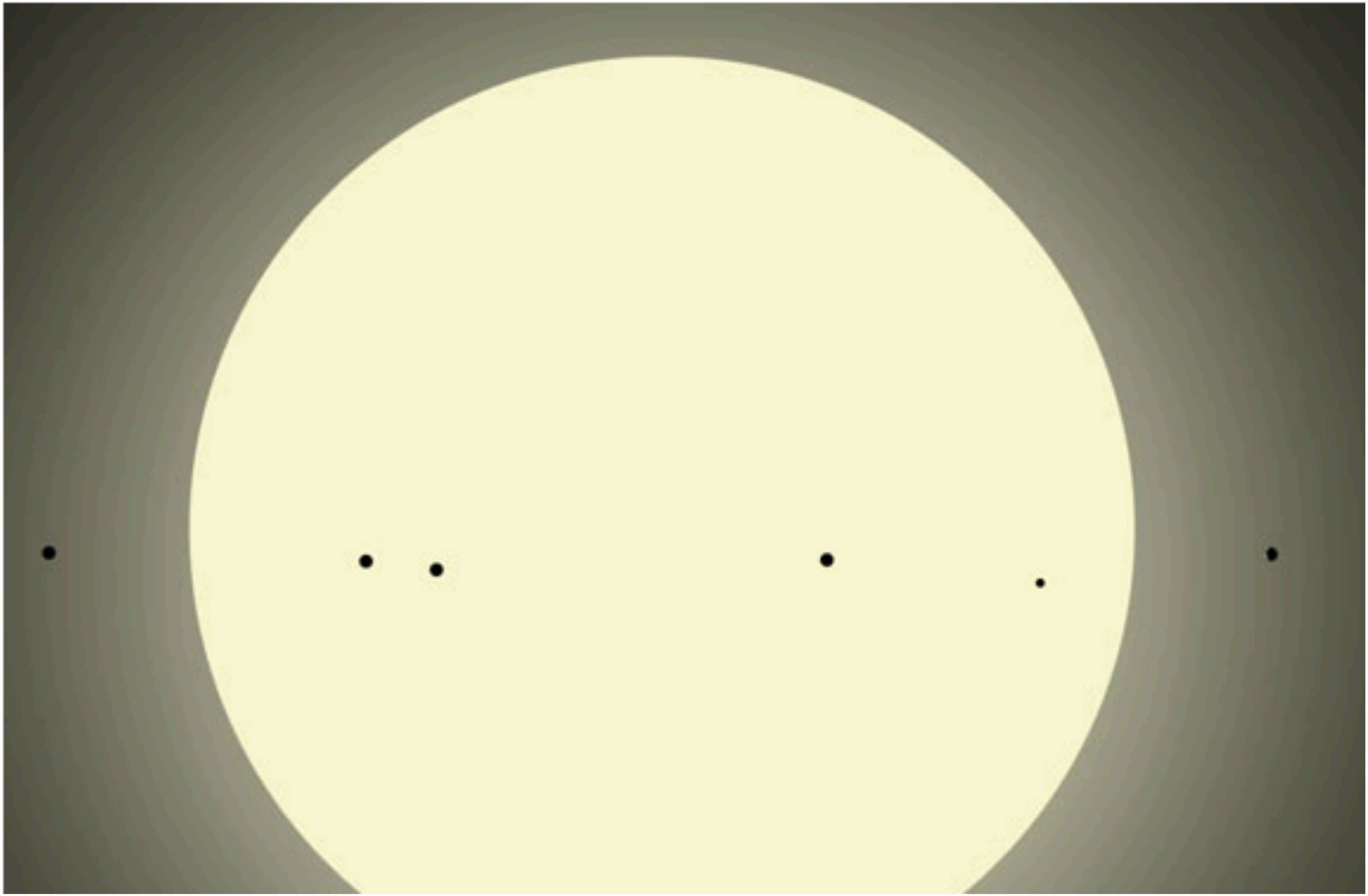
Image: NASA/Pyle

Kepler-11

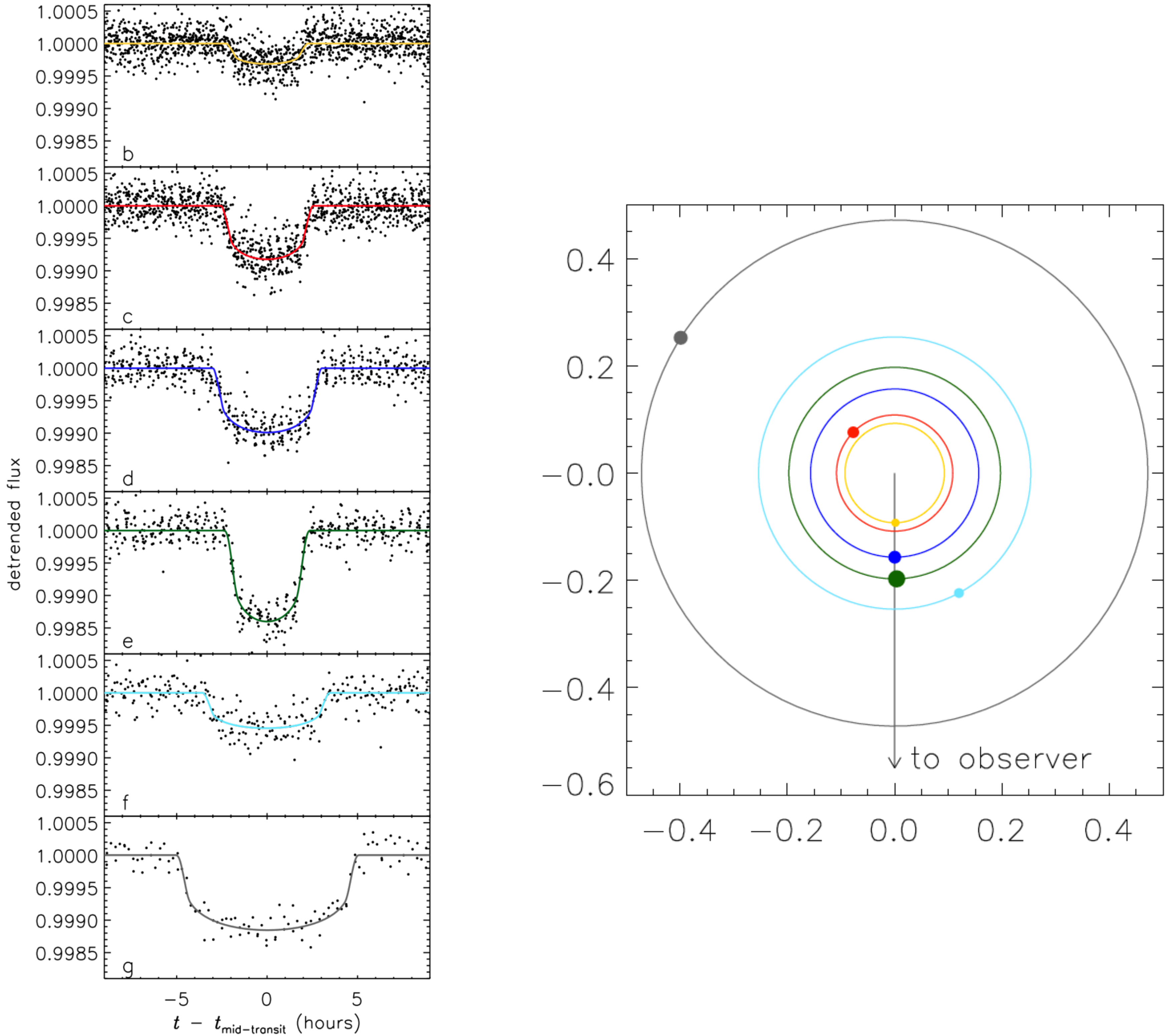




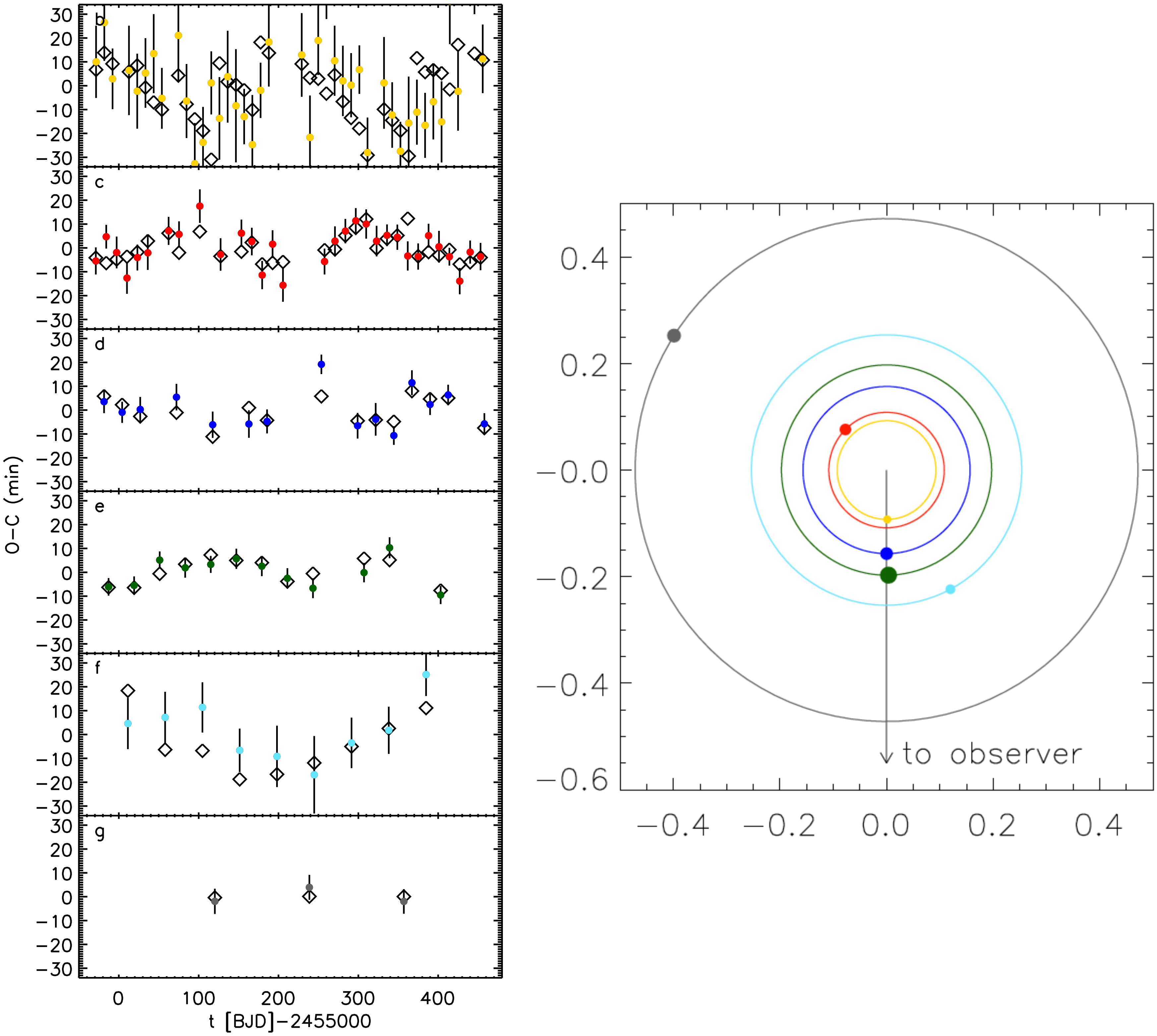
Lissauer, Fabrycky, Ford et al. 2011



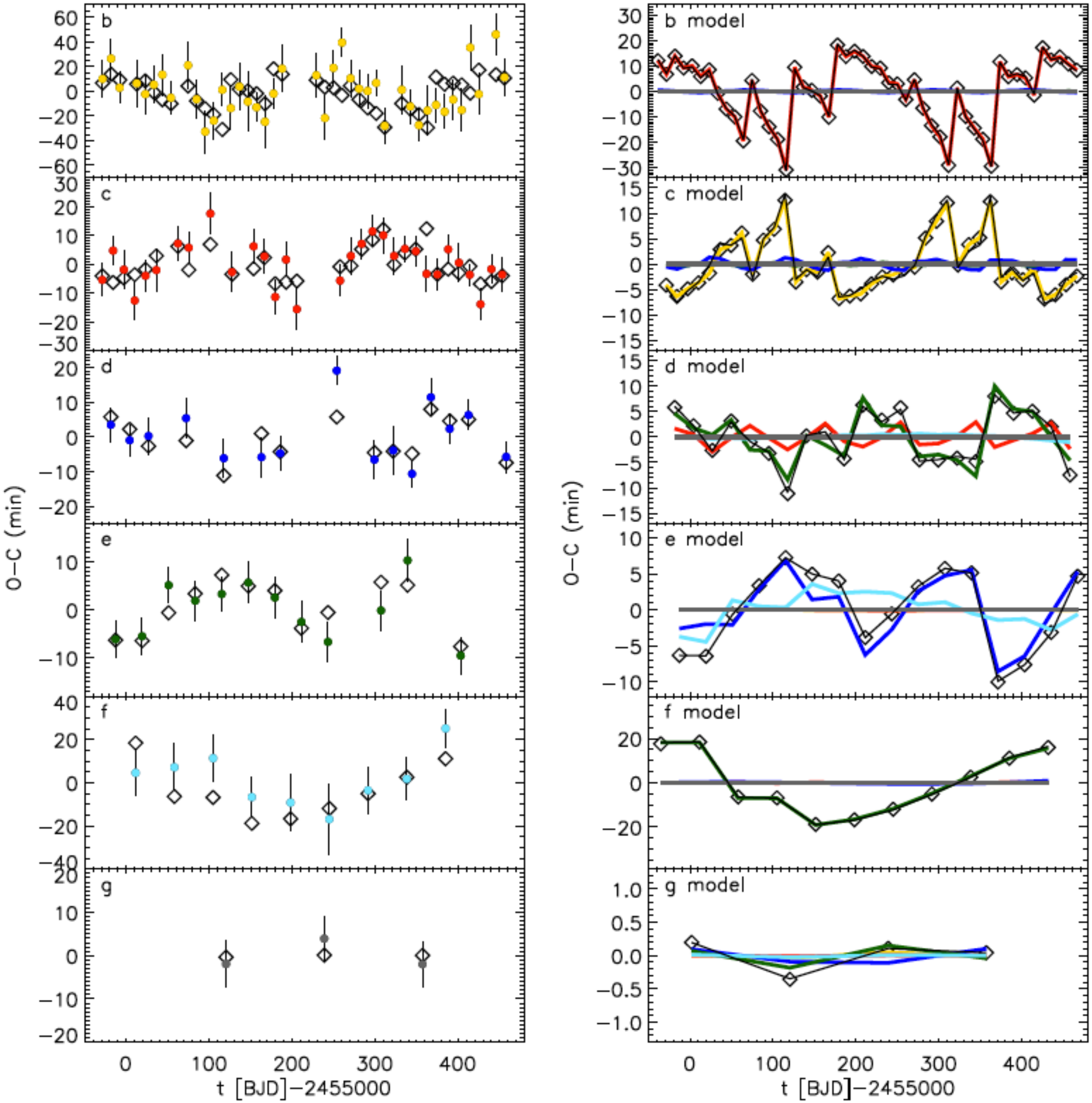
NASA Watch / Spaceref



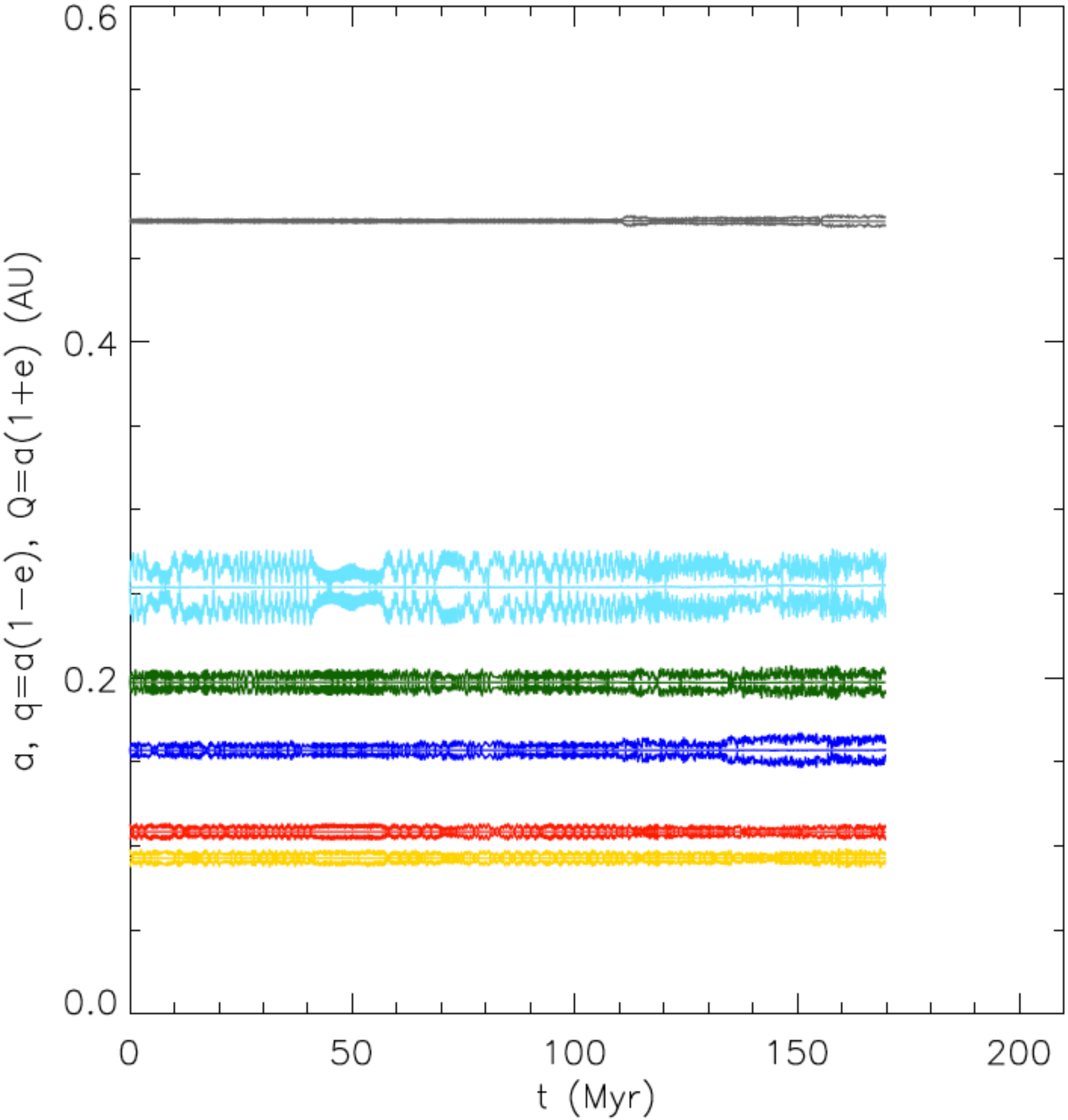
1.0005
1.0000
0.9995
0.9990
0.9985
b
c
d
e
f
g
detrended flux
−5
0
5
t − t_mid−transit (hours)
0.4
0.2
−0.0
−0.2
−0.4
−0.6
−0.4
−0.2
0.0
0.2
0.4
to observer



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



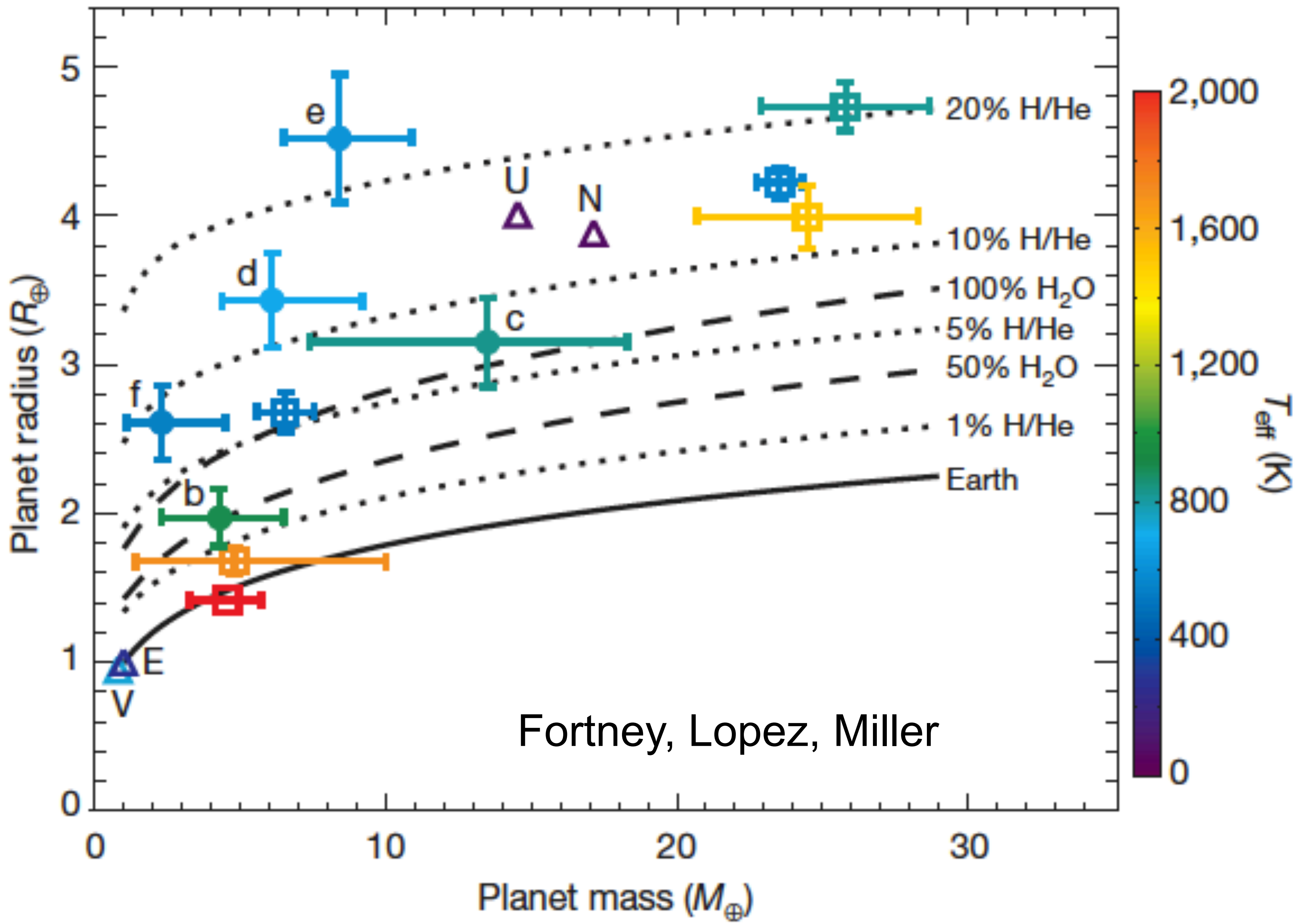
b
c
d
e
f
g
b model
c model
d model
e model
f model
g model
O−C (min)
t [BJD]−2455000



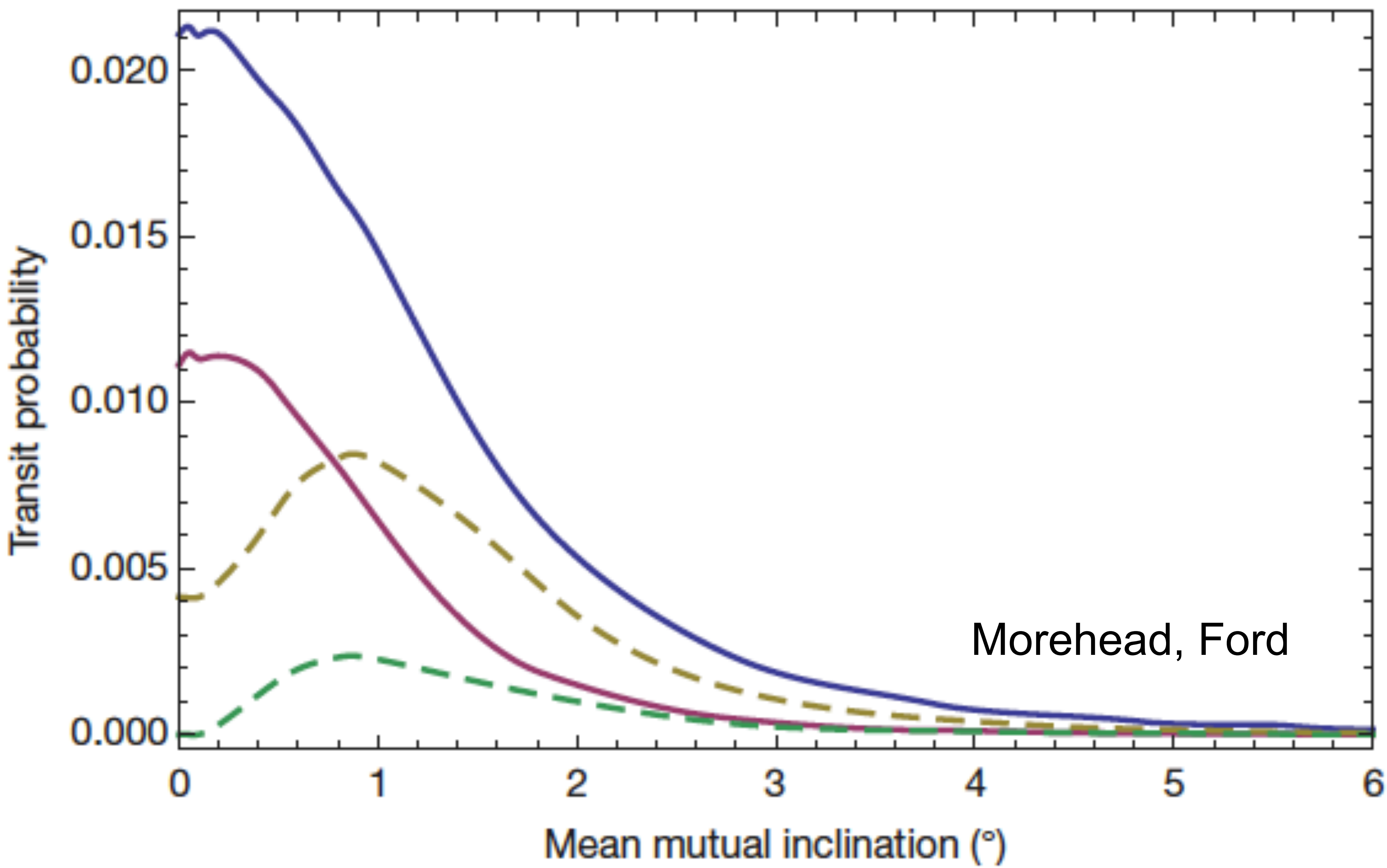
0.6
0.4
0.2
0.0
0
50
100
150
200
t (Myr)
a, q=a(1−e), Q=a(1+e) (AU)

Kepler-11 parameters

Planet	Period (days)	Radius ($R_\oplus$)	Mass ($M_\oplus$)	Density (g/cm³)
b	**10.30375** ± 0.00016	**1.97** ± 0.19	**4.3** +2.2,-2.0	**3.1** +2.1,-1.5
c	**13.02502** ± 0.00008	**3.15** ± 0.30	**13.5** +4.8,-6.1	**2.3** +1.3,-1.1
d	**22.68719** ± 0.00021	**3.43** ± 0.32	**6.1** +3.1,-1.7	**0.9** +0.5,-0.3
e	**31.99590** ± 0.00028	**4.52** ± 0.43	**8.4** +2.5,-1.9	**0.5** +0.2,-0.2
f	**46.68876** ± 0.00074	**2.61** ± 0.25	**2.3** +2.2,-1.2	**0.7** +0.7,-0.4
g	**118.37774** ± 0.00112	**3.66** ± 0.35	< 300	-



5
4
3
2
1
0
0
10
20
30
Planet radius ($R_\oplus$)
Planet mass ($M_\oplus$)
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
2,000
1,600
1,200
800
400
0
T_{eff} (K)
Fortney, Lopez, Miller


0.020
0.015
0.010
0.005
0.000
Transit probability
0
1
2
3
4
5
6
Mean mutual inclination (°)
Morehead, Ford

Formation / Evolution

- Comparative Planetology

Inclinations

- Much easier with *Kepler* Multi-Transiting Systems
- Inclination distribution
  - High inc from planet-planet scattering
  - Low inc if disk is important
  - Couple with eccentricity distribution
- Seeing both planets transit does not give true mutual inclination (though it is suggestive)

$$\underbrace{\cos\phi_{12}}_{\text{Want}} = \underbrace{\cos i_1 \cos i_2 + \sin i_1 \sin i_2}_{\text{Have}} \cos \underbrace{\Delta\Omega_{12}}_{\text{Unknown}}$$

True Mutual Inclinations

- Not impossible from RV or astrometry
- TTVs give true mutual inclinations, but it's tough
- MTS have 3 unique new ways
  - Statistically (from discovery fractions)
  - Multi-Rossiter-McLaughlin
  - Mutual Events

Multi-Rossiter-McLaughlin

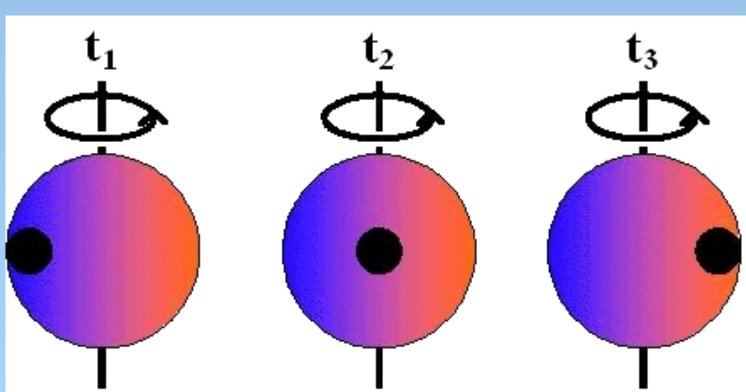
Want $\Delta\Omega_{bc}$

Measure the projected spin-orbit angle, λ

In terms of orbital-element-like angles, $\lambda_b = \Delta\Omega_{b*}$

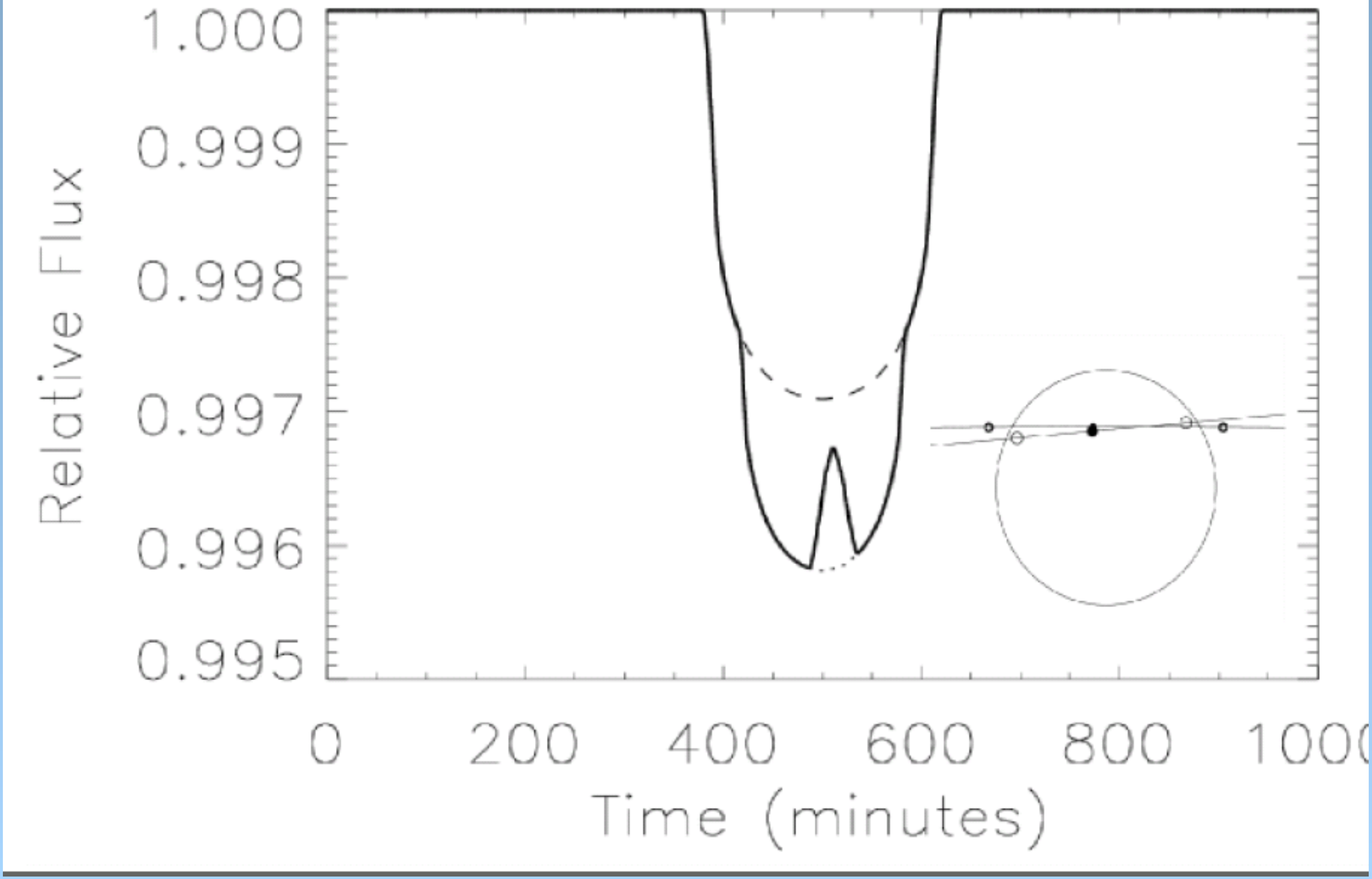
- Double-RM (Fabrycky 2009) gives two-way solution for mutual inclinaiton
  - Triple-RM removes degeneracy

$$\Delta\Omega_{bc} \equiv |\lambda_b \pm \lambda_c|$$

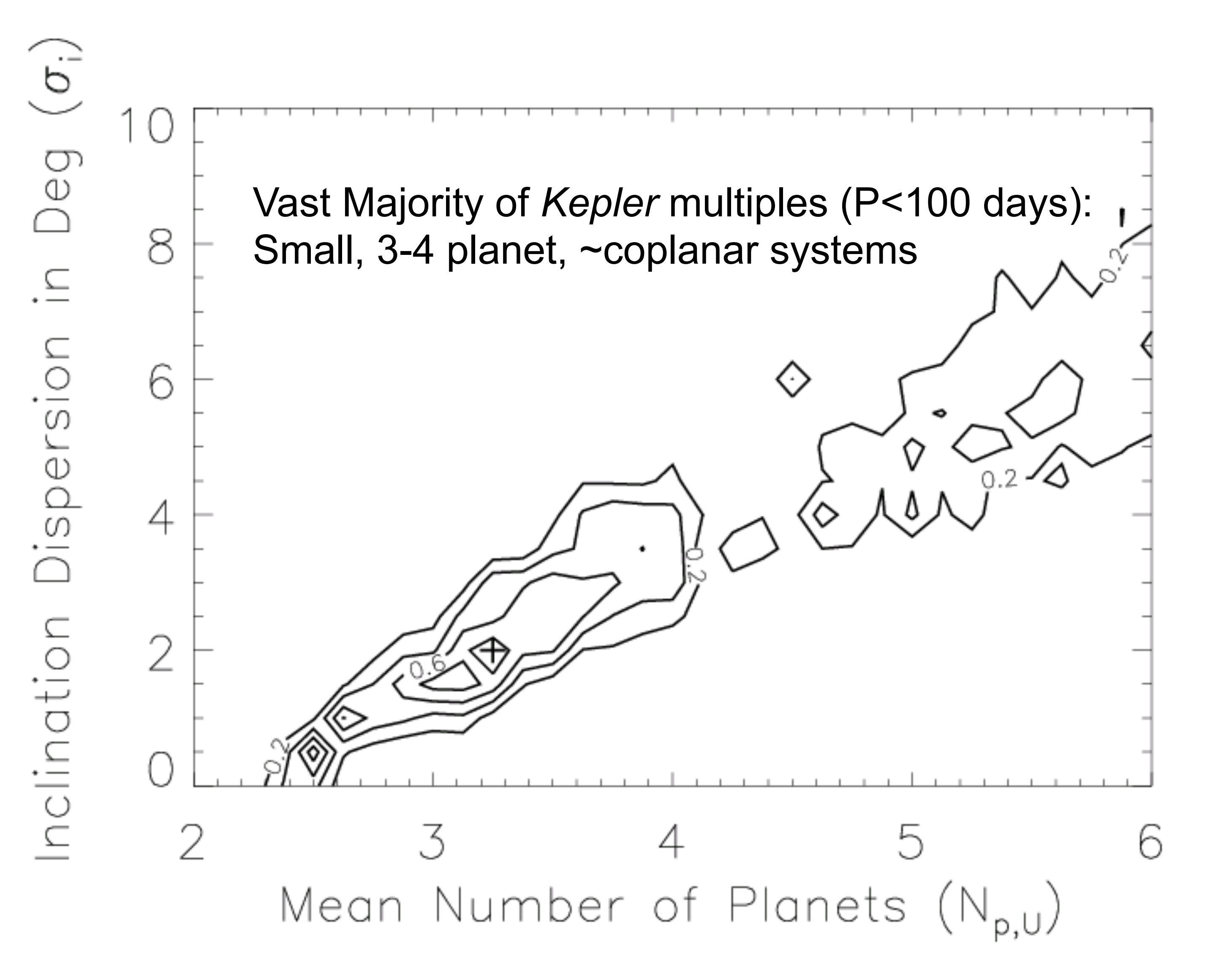


Exoplanet Mutual Events!

- Mutual events: when planets cross

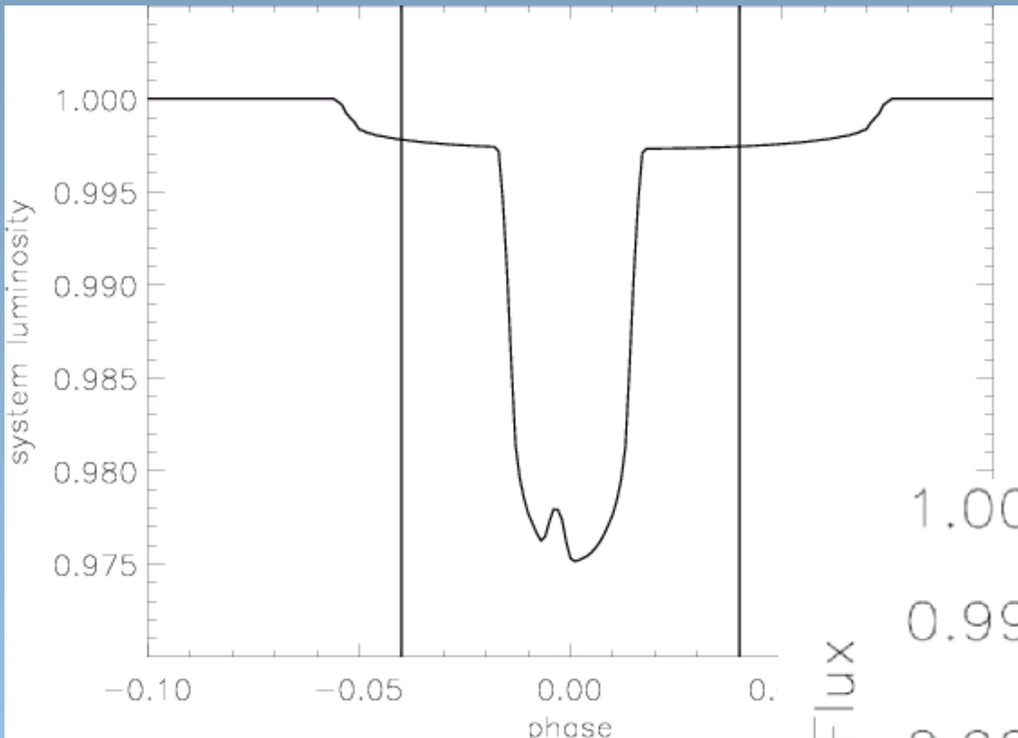


Statistically from Multiplicities



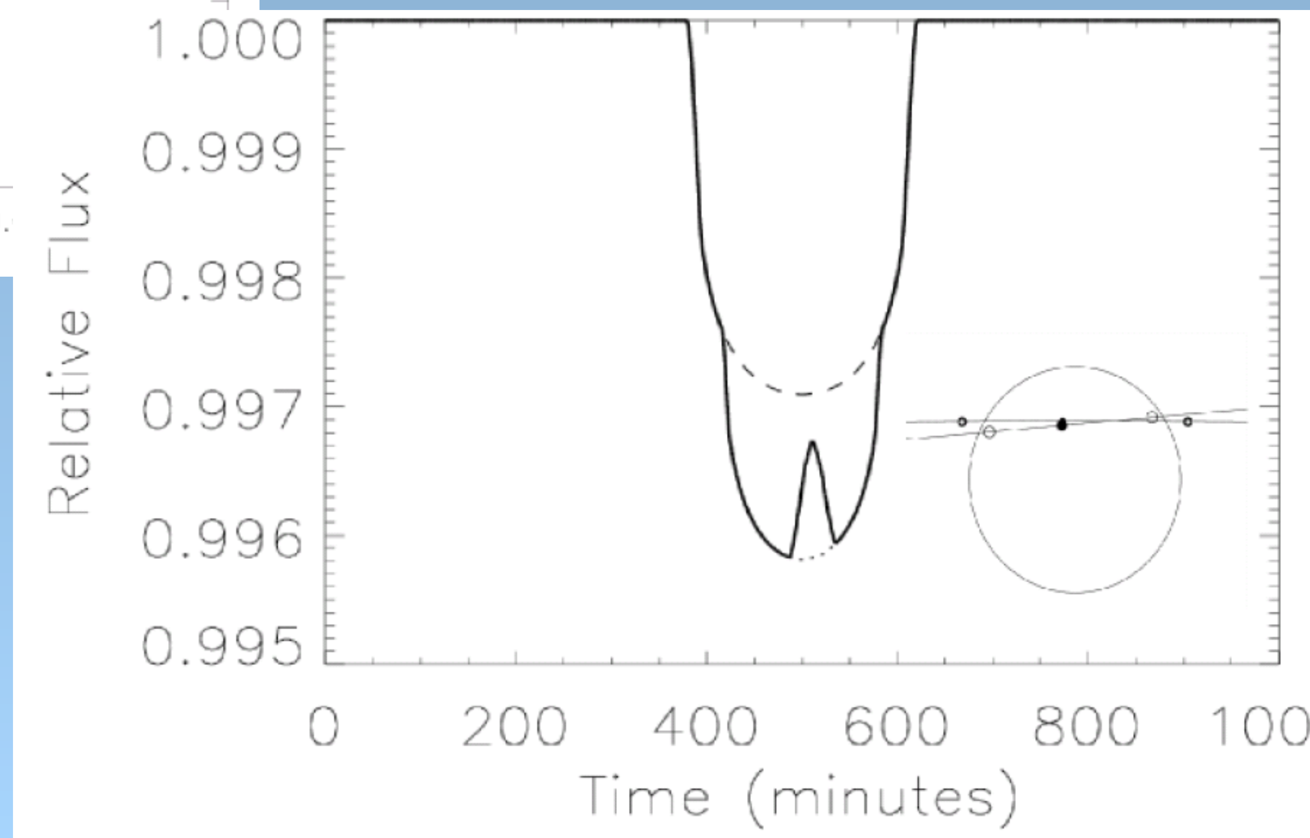
Lissauer, Ragozzine, et al. 2011b

Mutual Events!

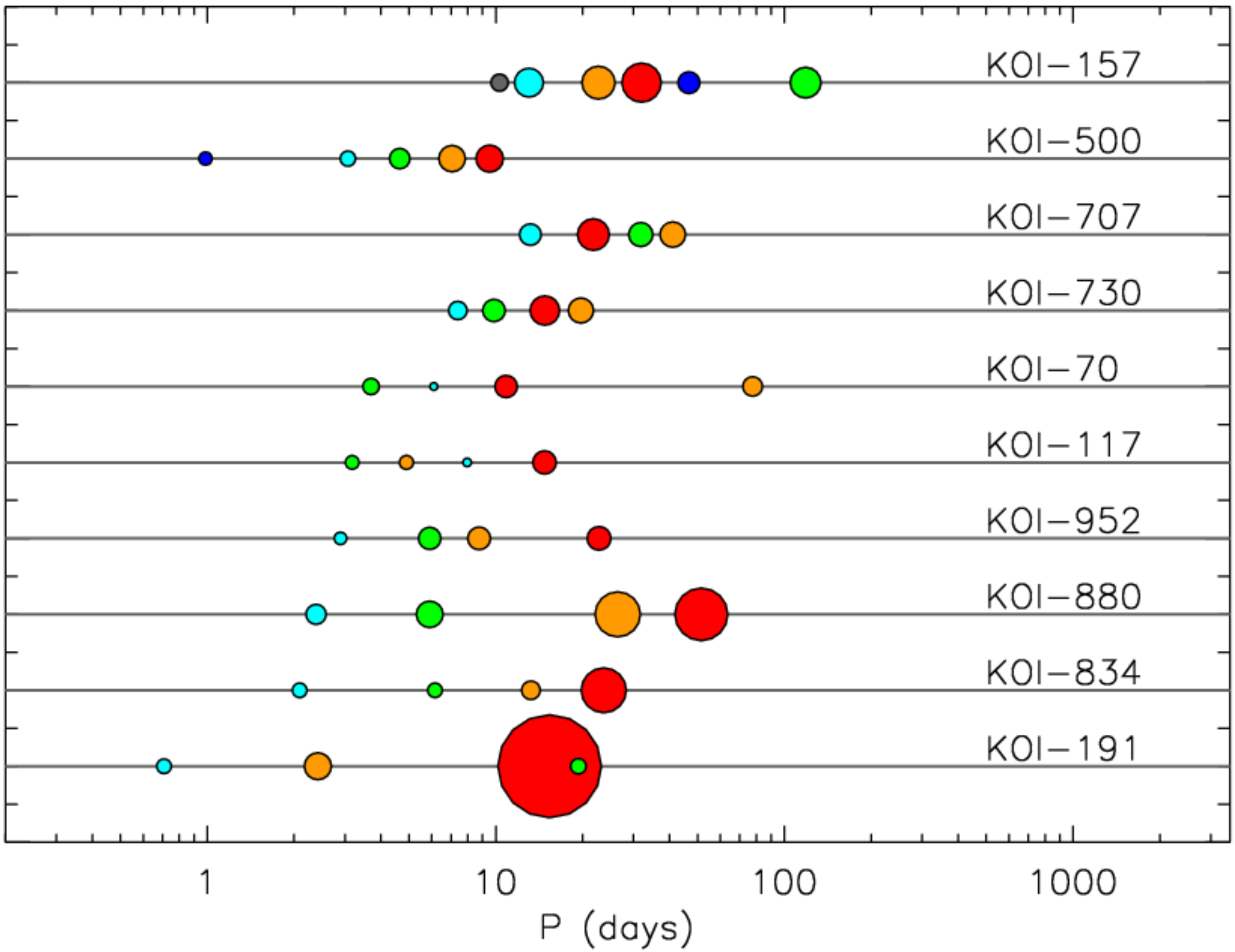


Rabus et al. 2008

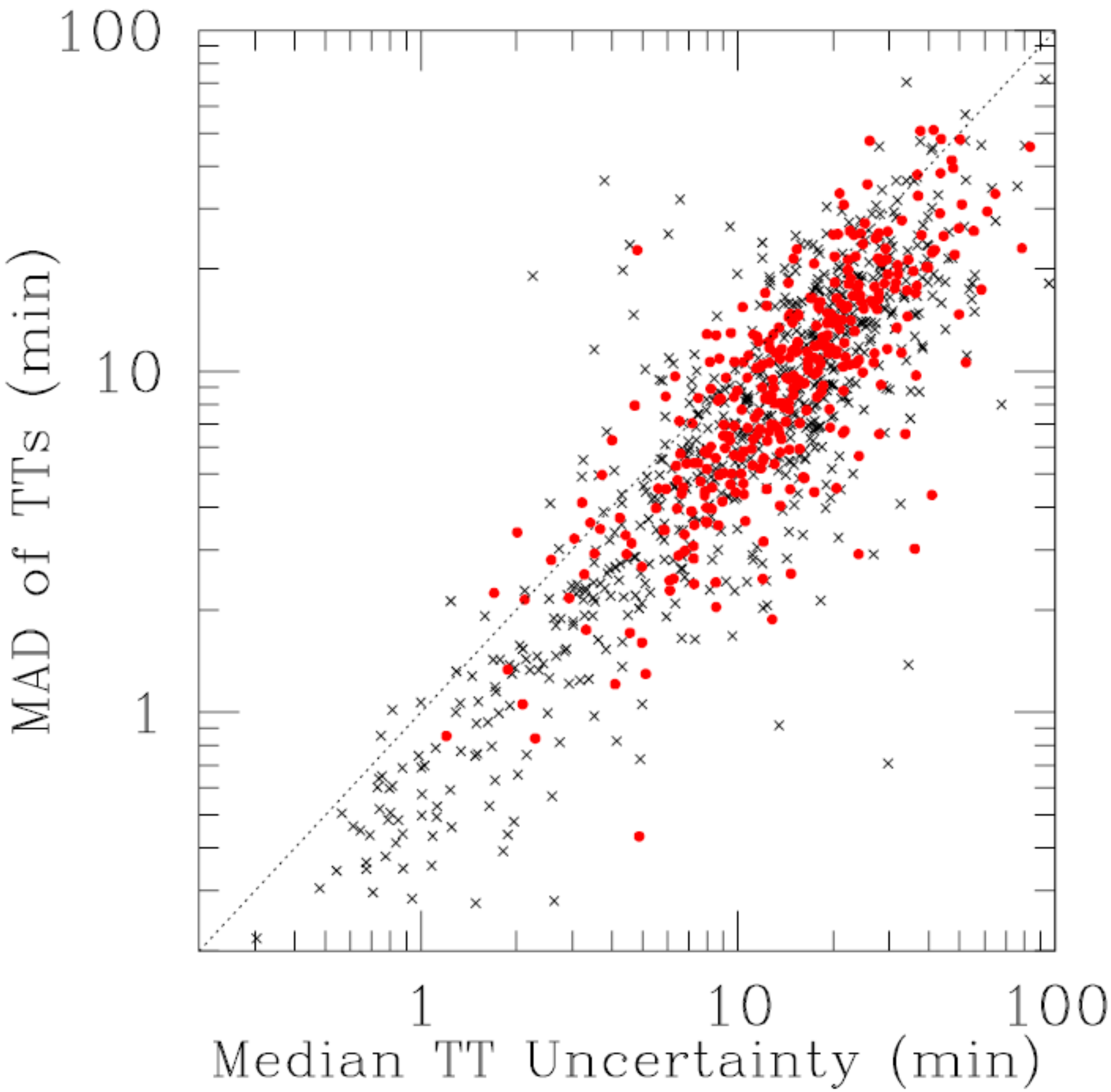
Ragozzine & Holman 2010



Strange New Worlds to Explore



Transit Timing Variations



Ford et al. 2011

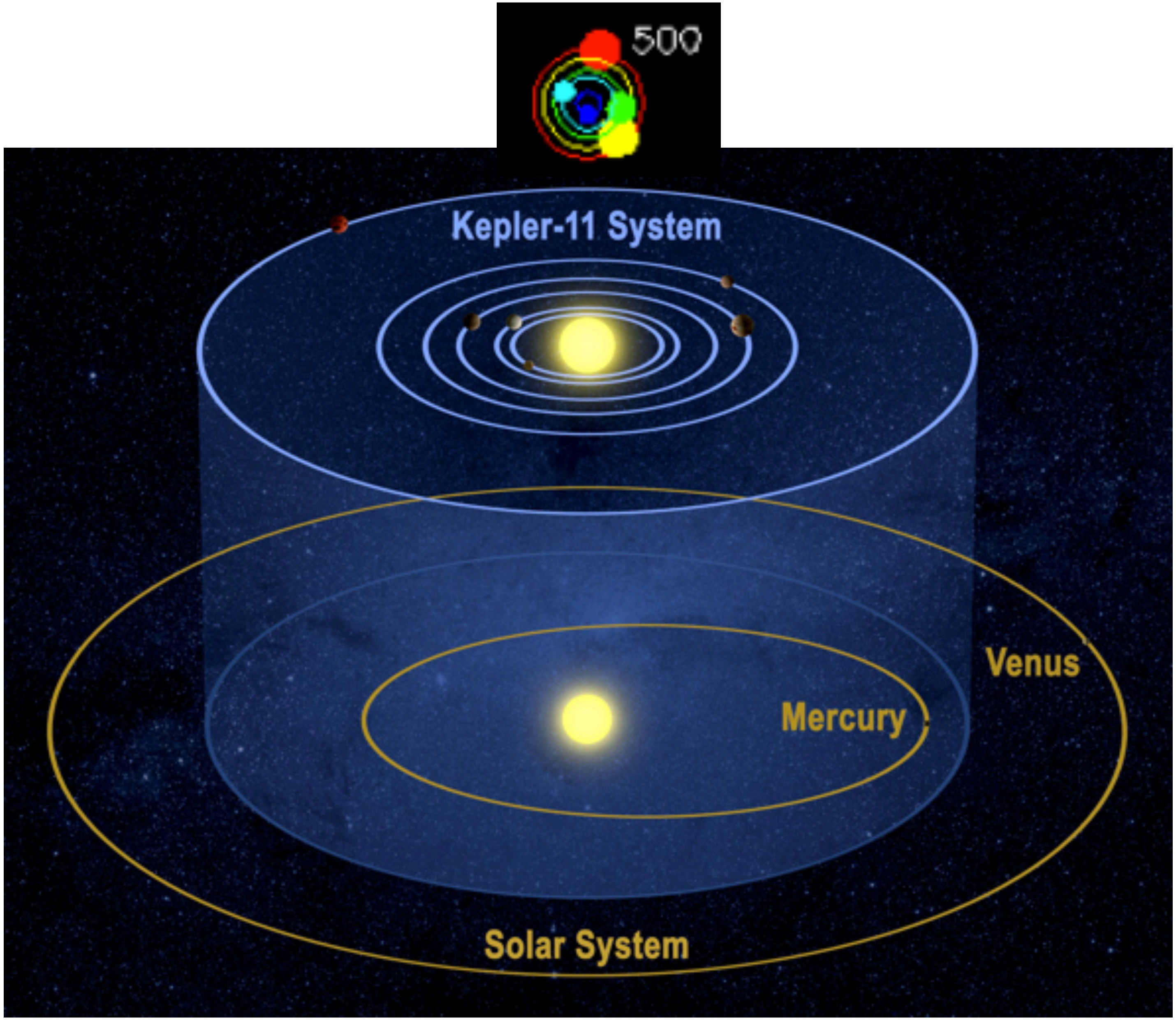
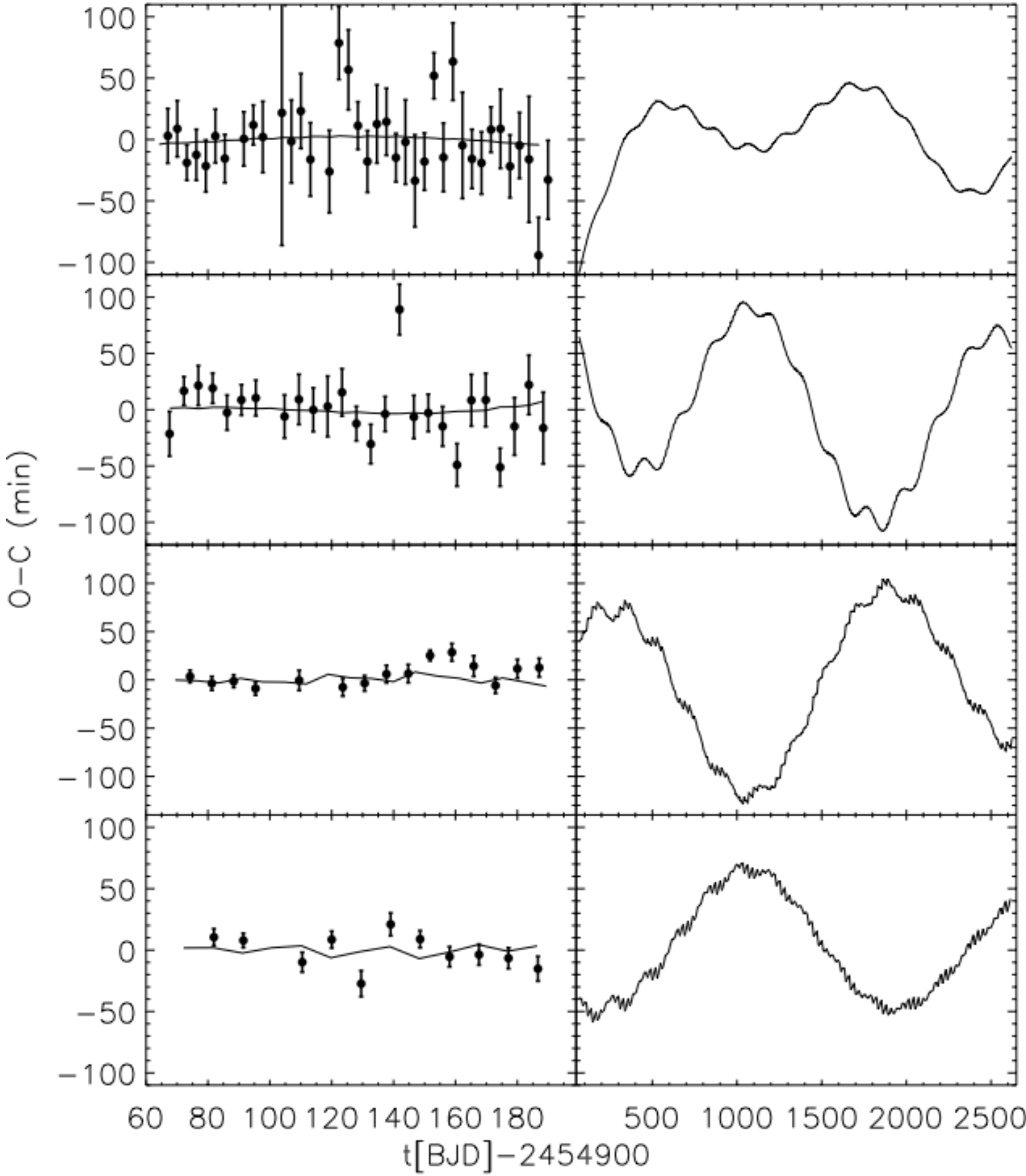


Image: NASA/Pyle

KOI-500

planet	P (days)	Mp(Mearth)
500.05	0.9867790	1.5
500.03	3.0721660	2.2
500.04	4.6453530	4.4
500.01	7.0534780	8.0
500.02	9.5216960	8.5



Ford, Rowe, Fabrycky et al. 2011

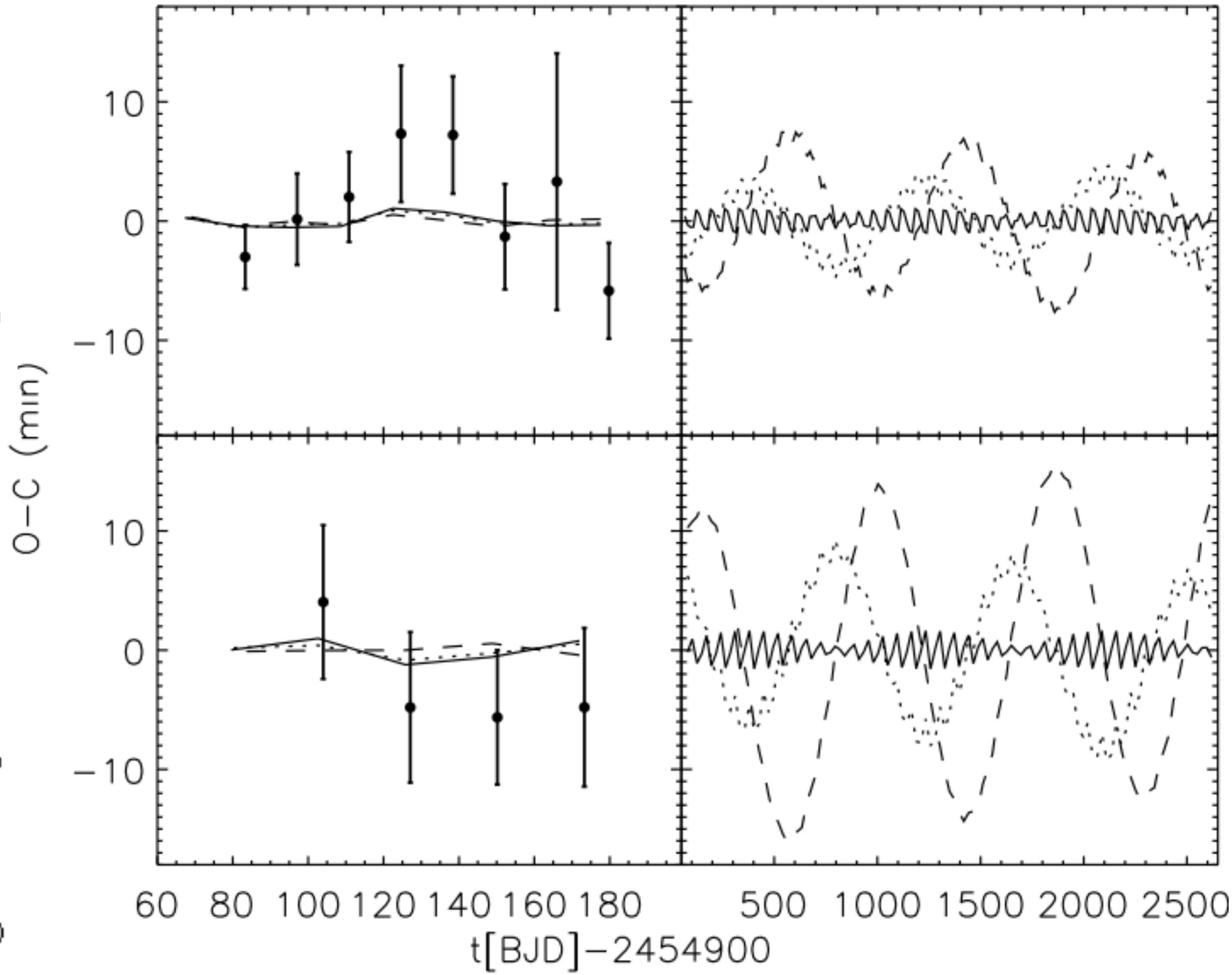
KOI-314

ms(sol)	rs(sol)
0.53	0.61

planet	P (days)	Mp(Mearth)
314.01	13.781048	4.0
314.02	23.090398	2.5

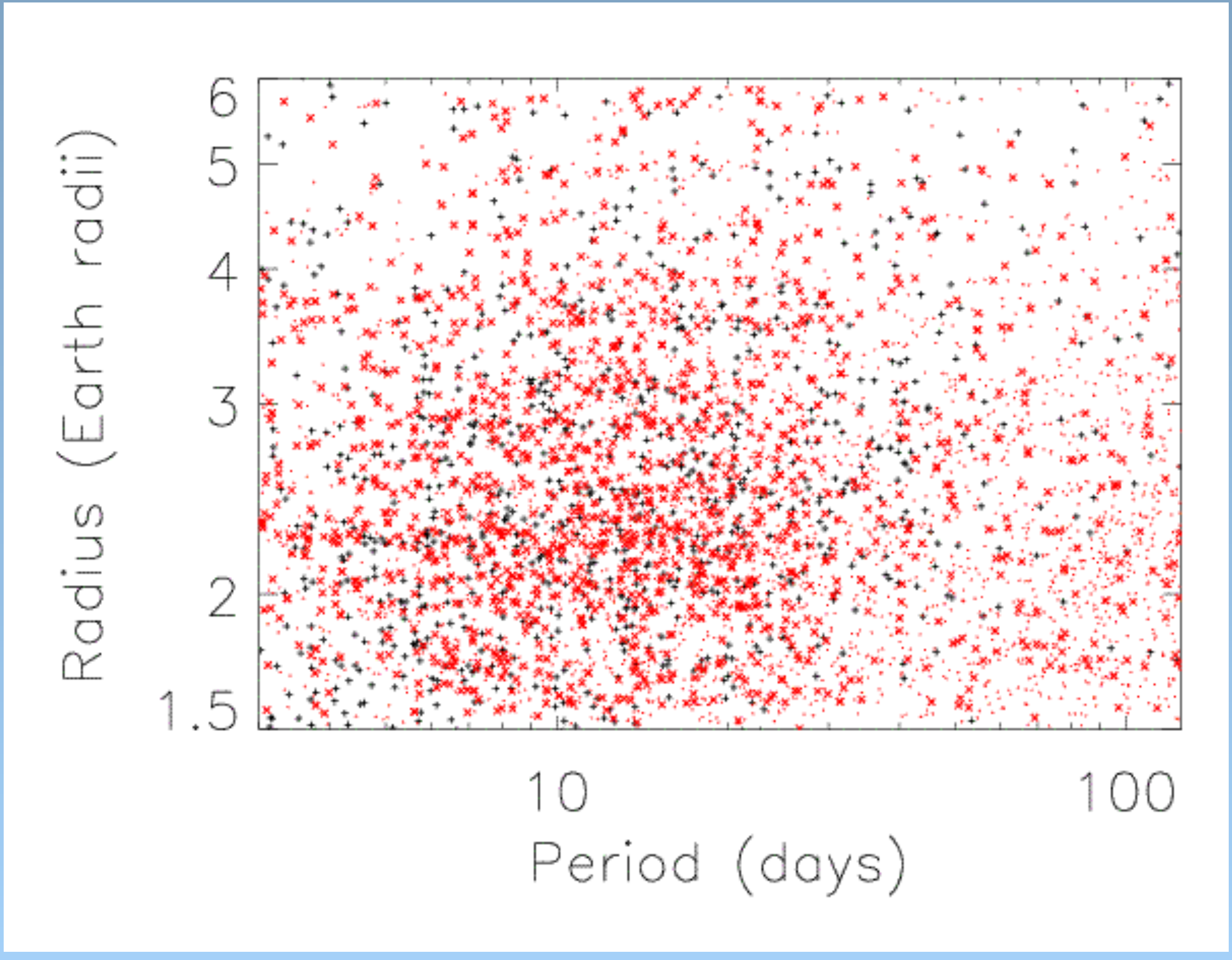
.02: near-habitable-zone candidate

	e	omega(deg)
Solid:	0.00000	0.0000
	0.00000	0.0000
Dotted:	0.15000	90.0000
	0.15000	90.0000
Dashed:	0.02000	0.0000
	0.02000	90.0000



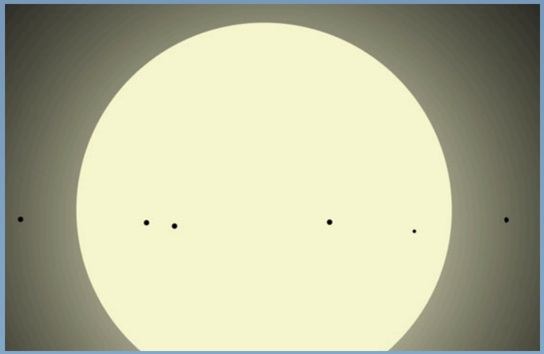
Ford, Rowe, Fabrycky et al. 2011

Kepler, the Multi-Transiting Machine

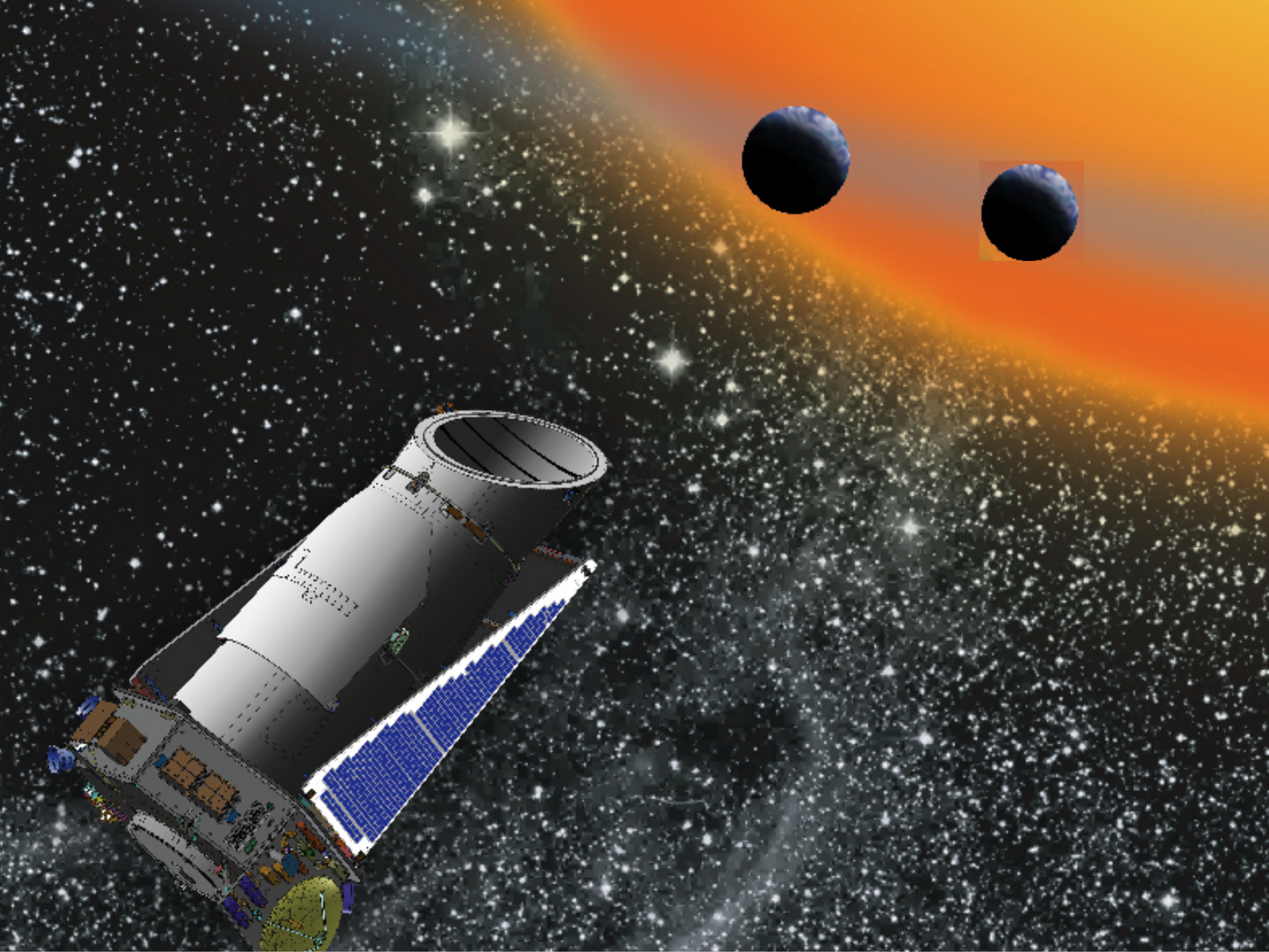


Lissuaer, Ragozzine, et al. 2011b

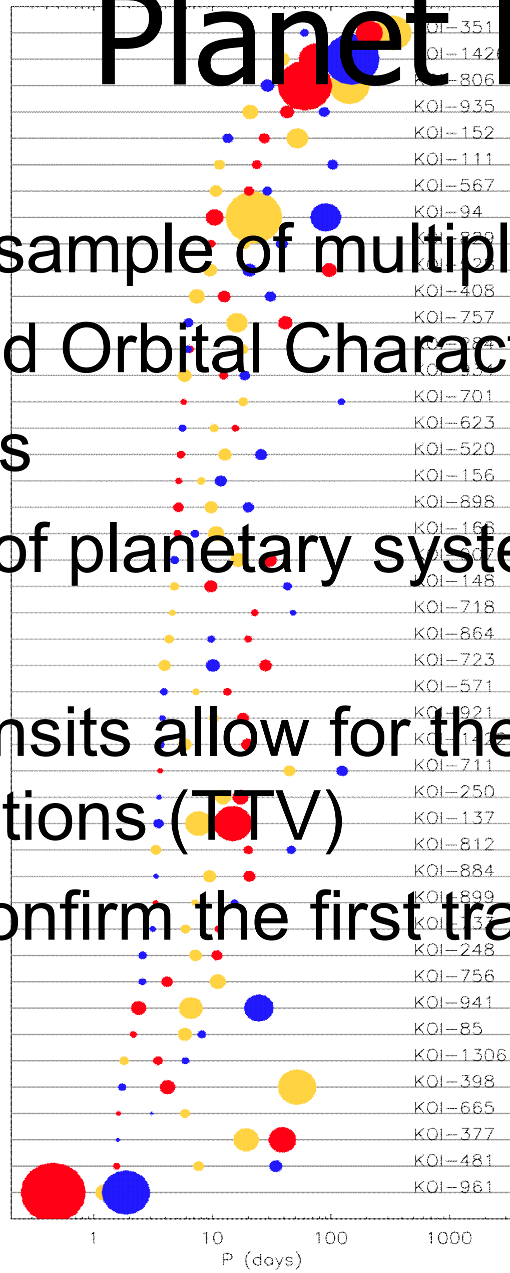
Conclusions

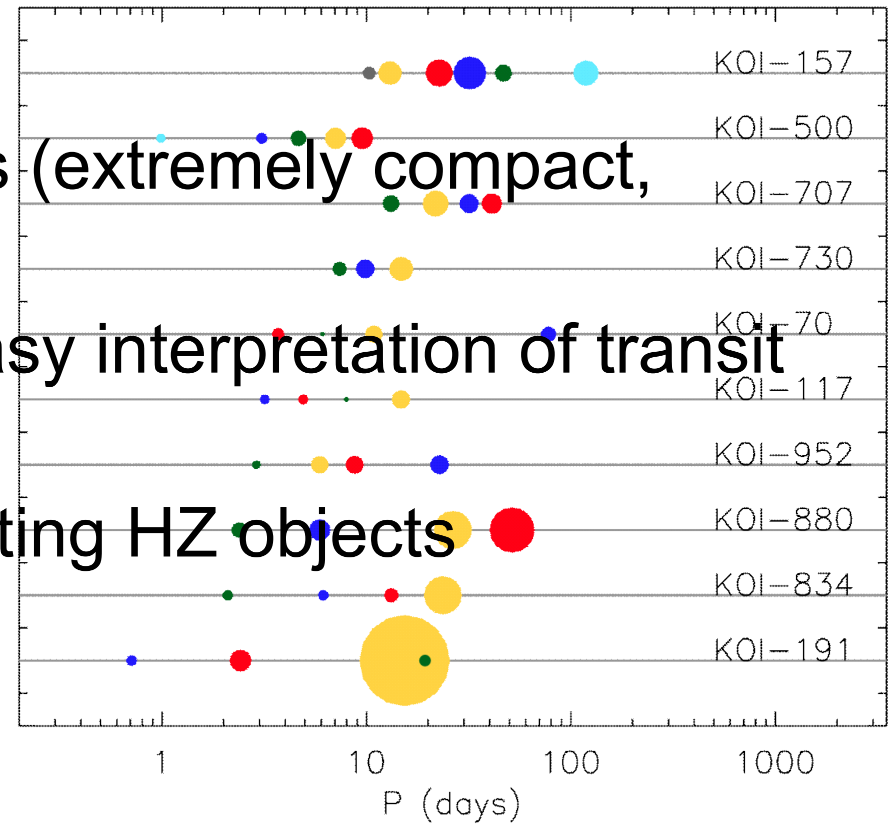


- Multi-transiting systems are *the most information-rich planetary systems outside of our solar system.*
- Kepler has discovered almost 200 (!!) multi-transiting systems
- Best Strange New Worlds for Exploring:
  - Fewer false positives
  - Masses without radial velocity (easier TTVs)
  - True mutual inclinations
  - Comparative planetology
- Kepler-9, 10, and 11 are examples of the value of MTS
- More information in **Ragozzine & Holman 2010; Lissuaer et al. 2011b**,a; Holman et al. 2010; Borucki et al 2011; Ford et al. 2011; Latham et al. 2011 with much much more to come



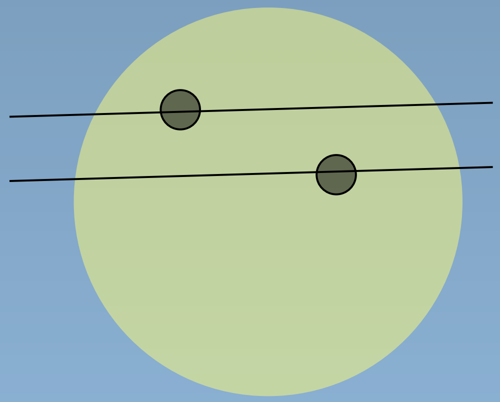
Kepler, the Multiple-Transiting Planet Machine

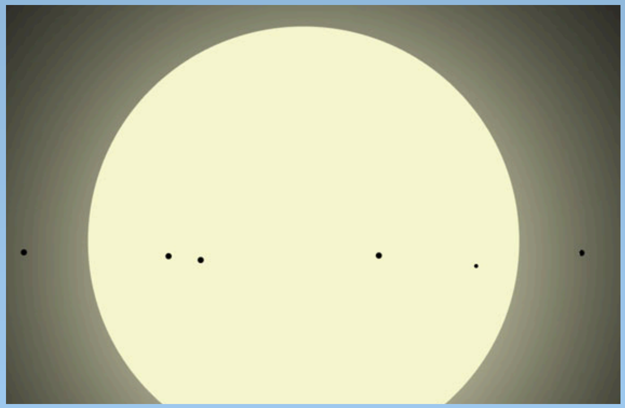




- Tripled the sample of multiplanets
- Physical and Orbital Characterization
- Resonances
- New types of planetary systems (extremely compact, Trojans)
- Multiple-transits allow for the easy interpretation of transit timing variations (TTV)
- TTV may confirm the first transiting HZ objects

Pics





Sciencexpress Research Article

Kepler-9: A System of Multiple Planets Transiting a Sun-Like Star, Confirmed by Timing Variations

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