Small-Planet Densities and System Architectures through Photodynamic Variations

Daniel Fabrycky

University of Chicago

NASA Kepler Participating Scientist

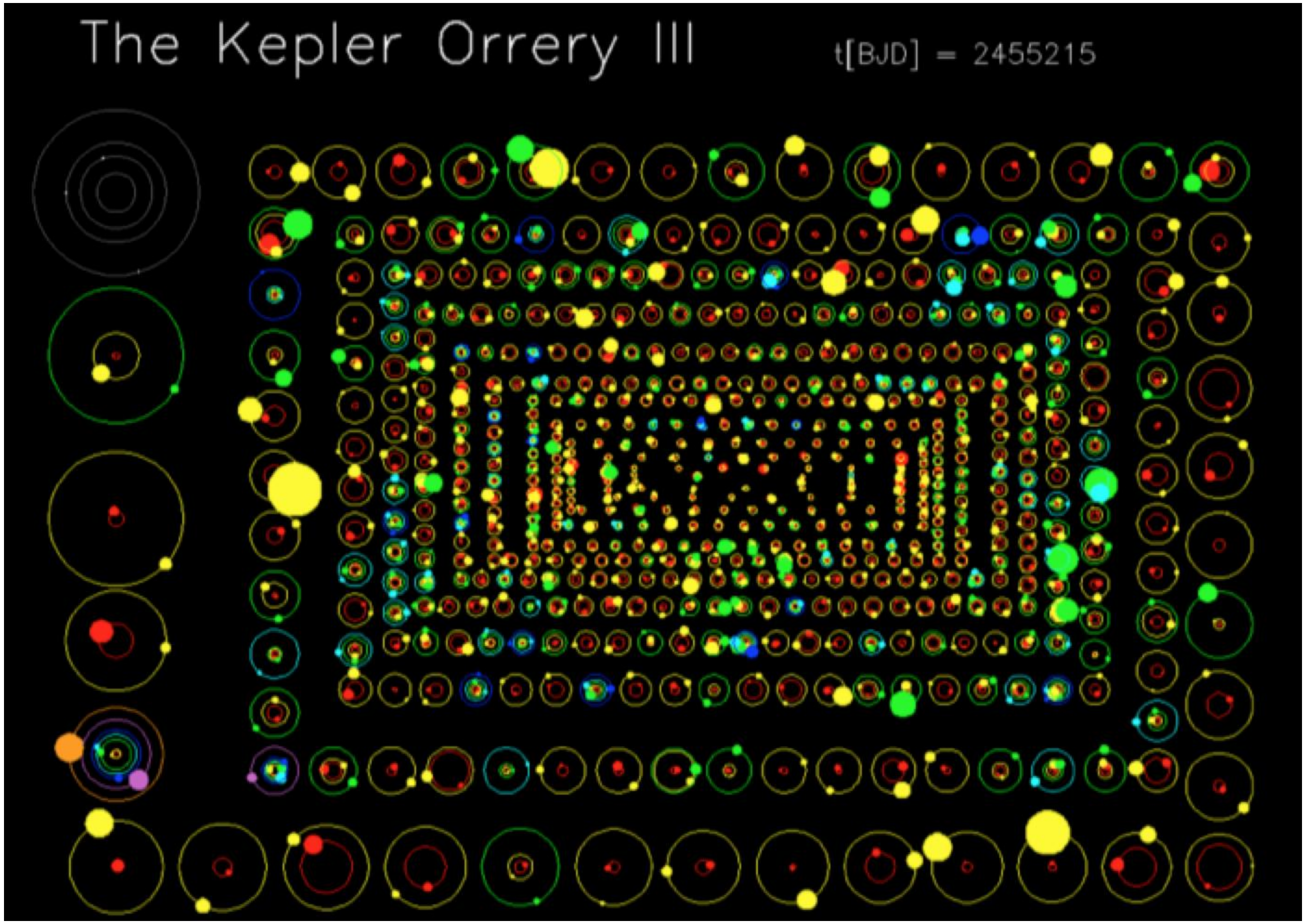
Sloan Research Fellow

Image: Pyle/N

https://www.youtube.com/watch?v=gnZVvYm6KKM

or

http://kepler.nasa.gov/multimedia/animations/orrery3/



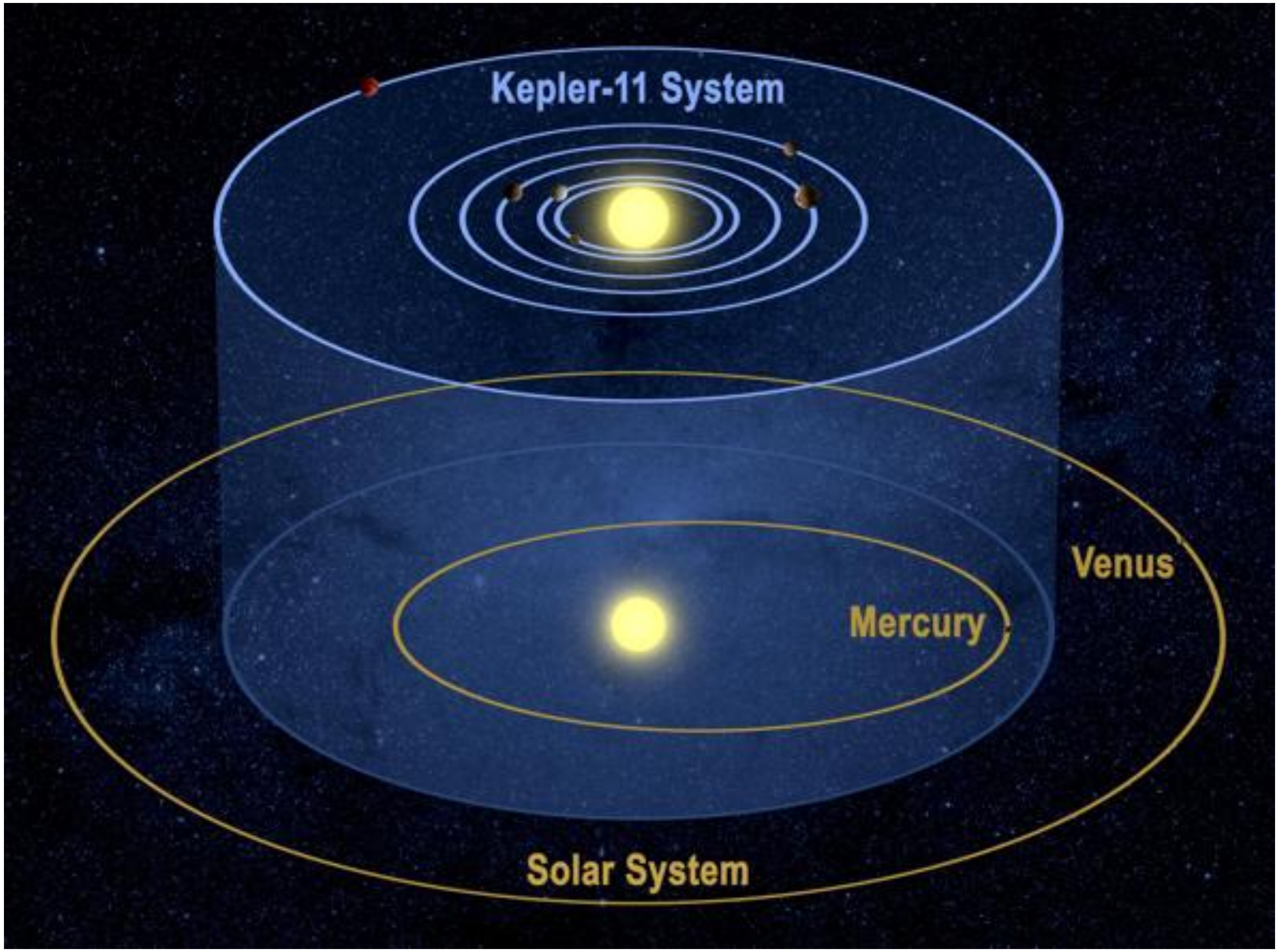


Image: NASA/Pyle

Kepler-11: Six Transiting Planets

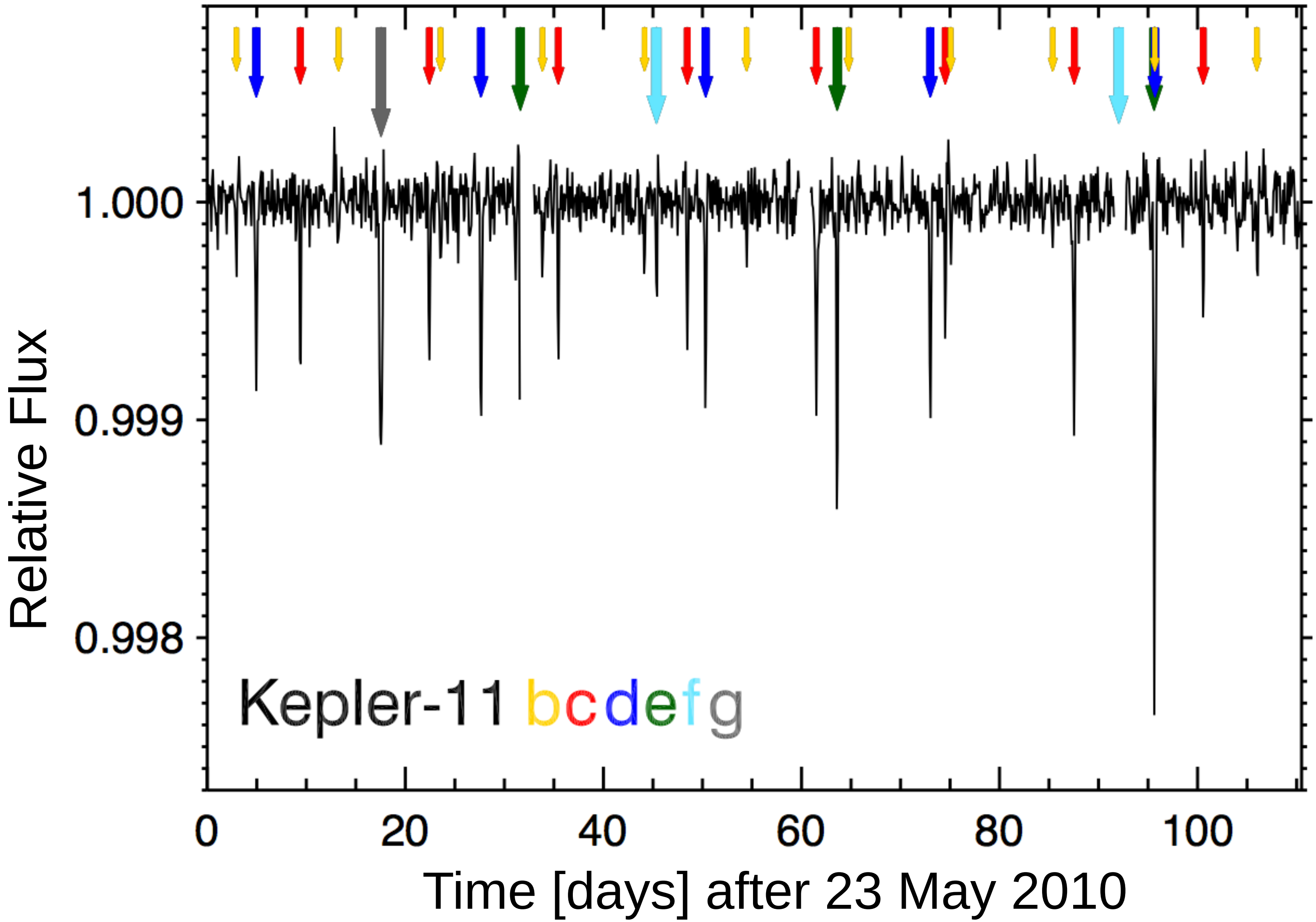
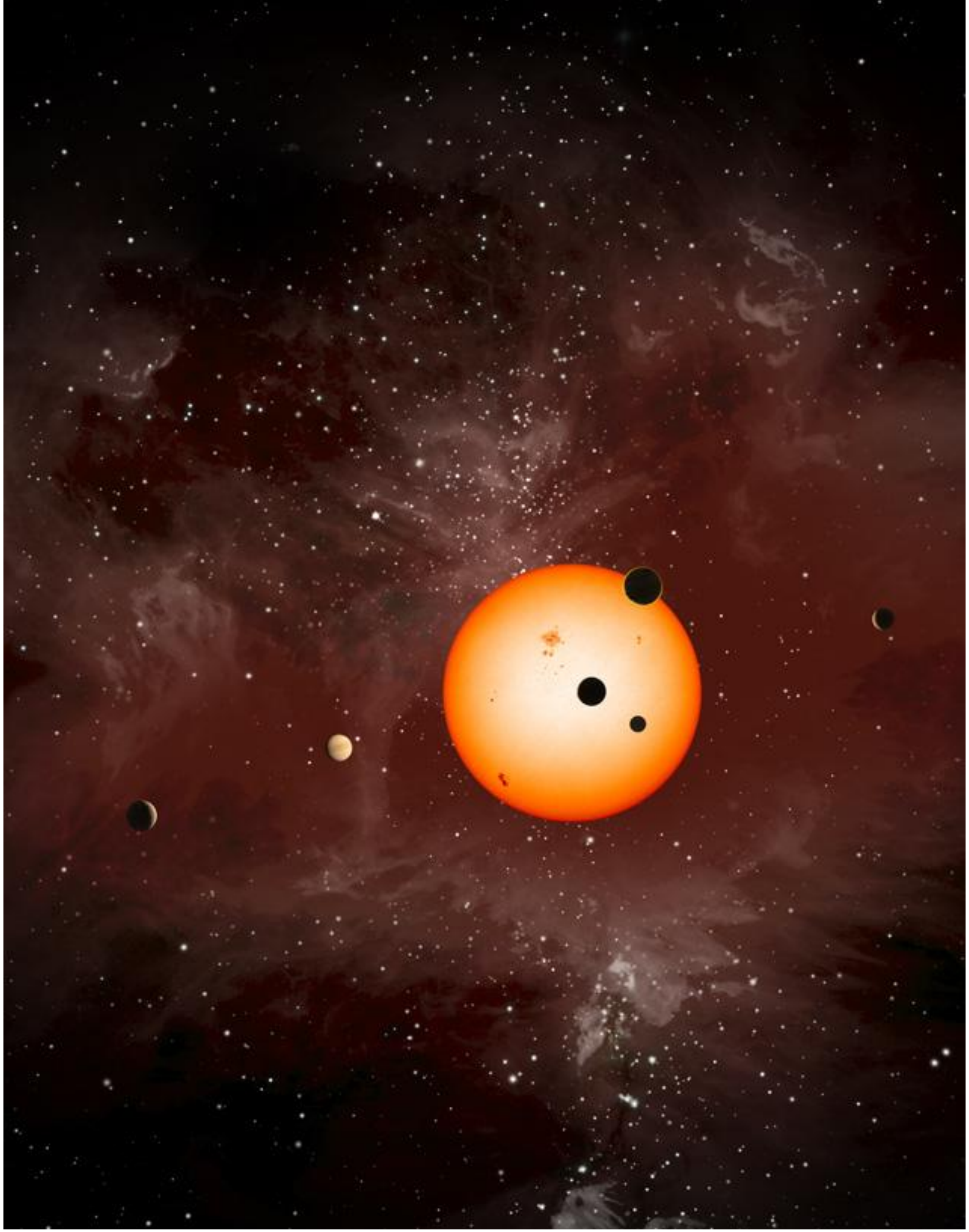
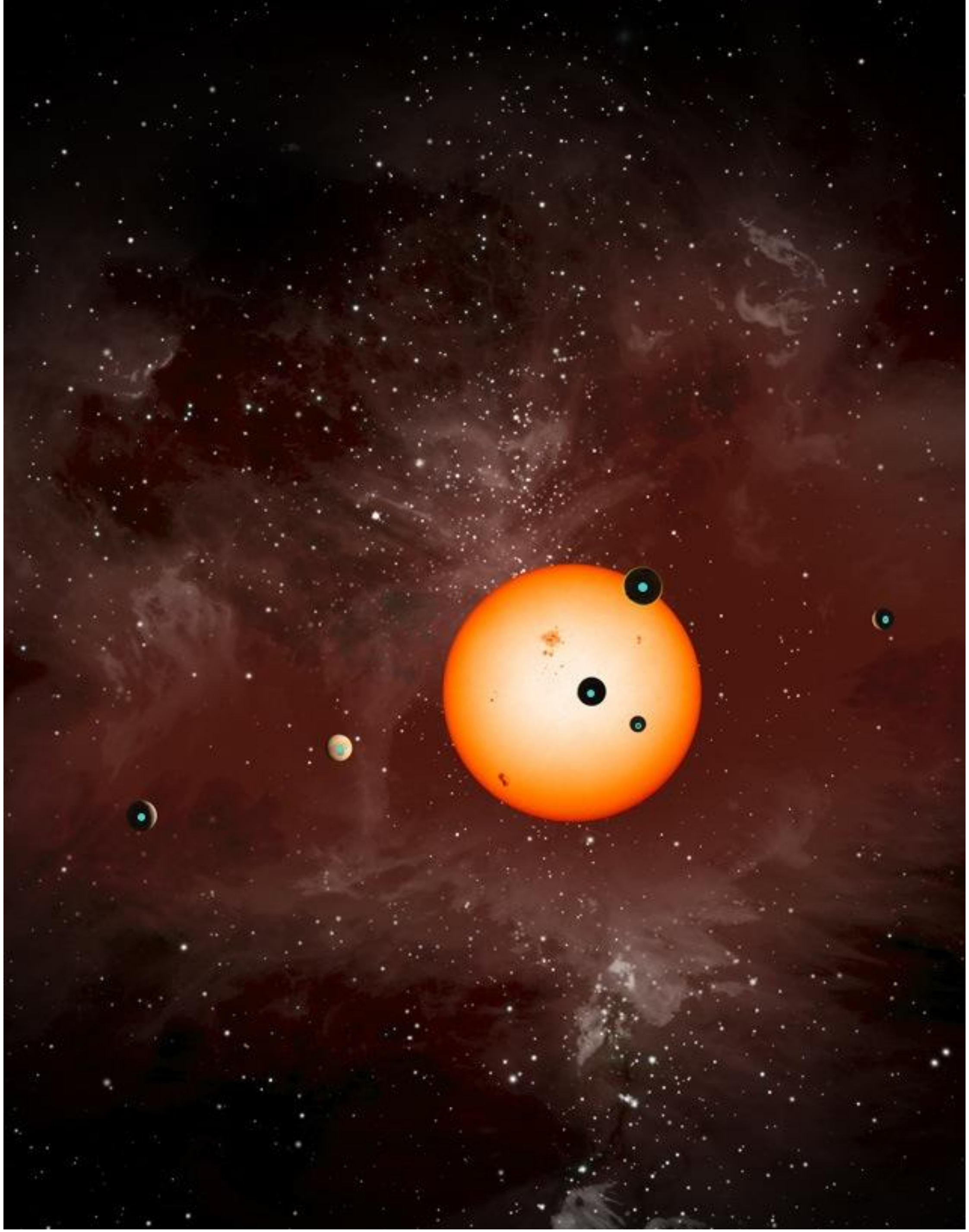
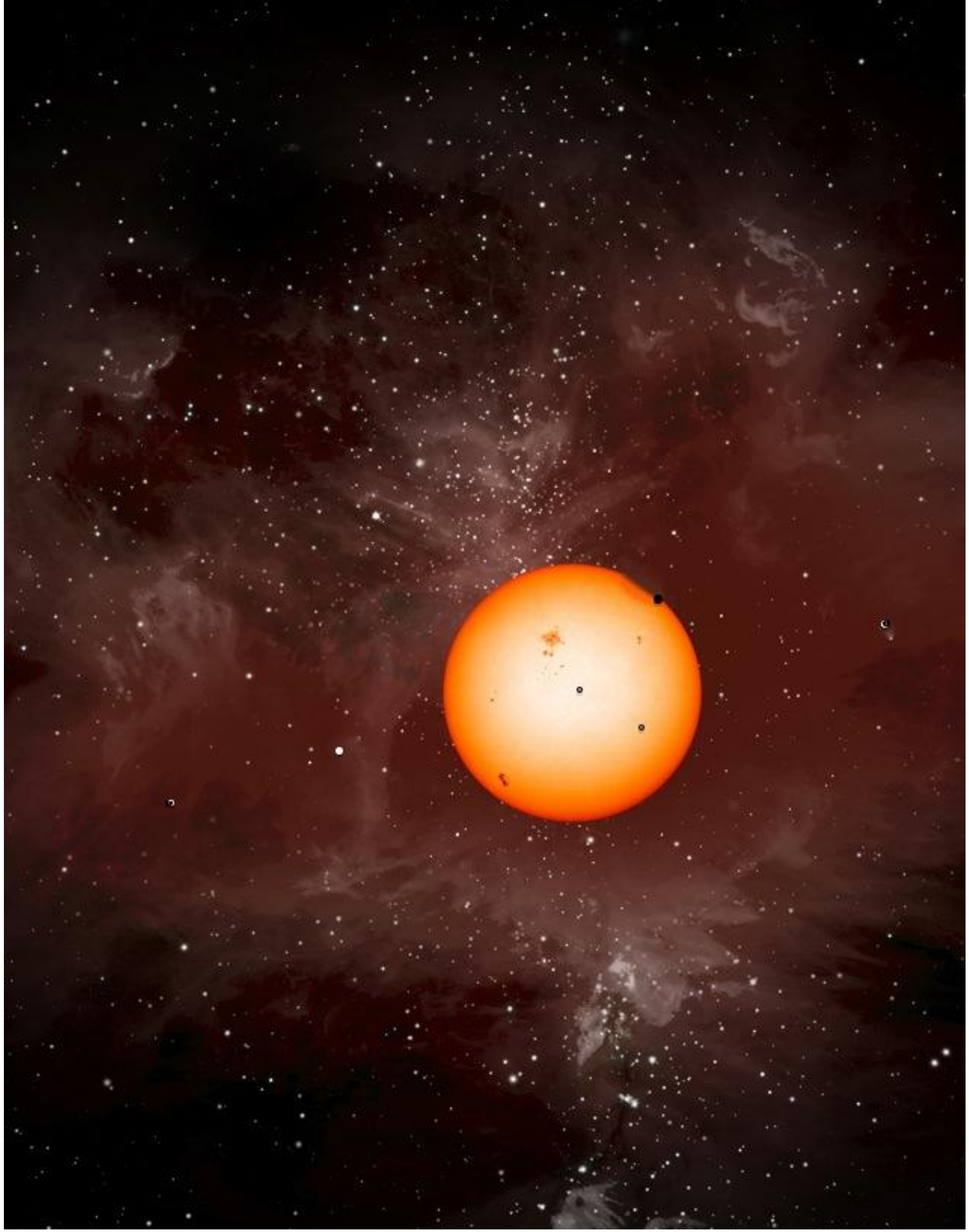


Image: NASA/Pyle







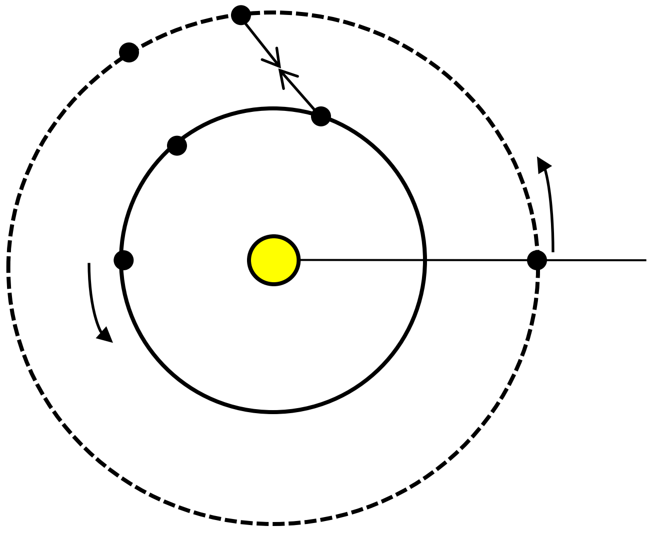
Outline: Small-Planet Densities and System Architectures through Photodynamic Variations

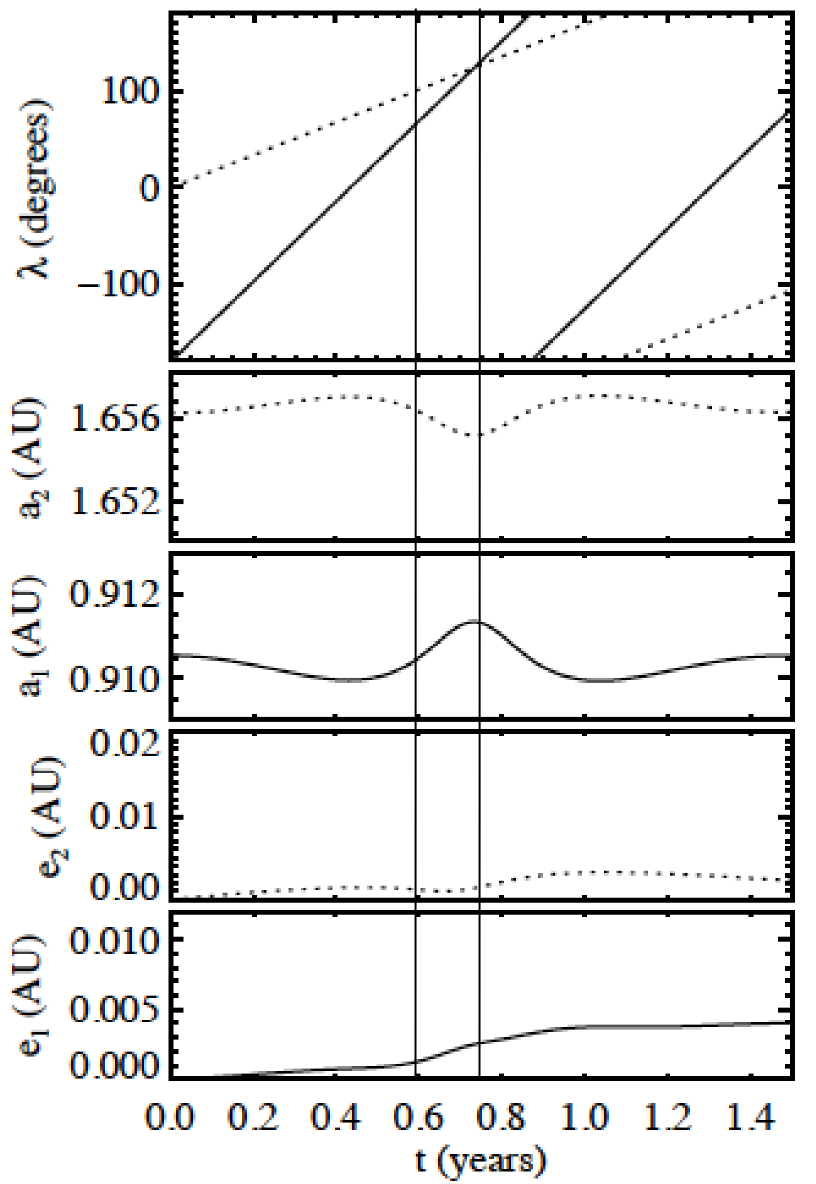
- Transit Timing Variations (TTV) → M_p
- Photometric Approaches to TTV
- Eccentricities to Probe Formation

"small"
1-6 M_E
2-8 R_E

0.5-2 R_E
rocky

Dynamics: Orbital Timescales

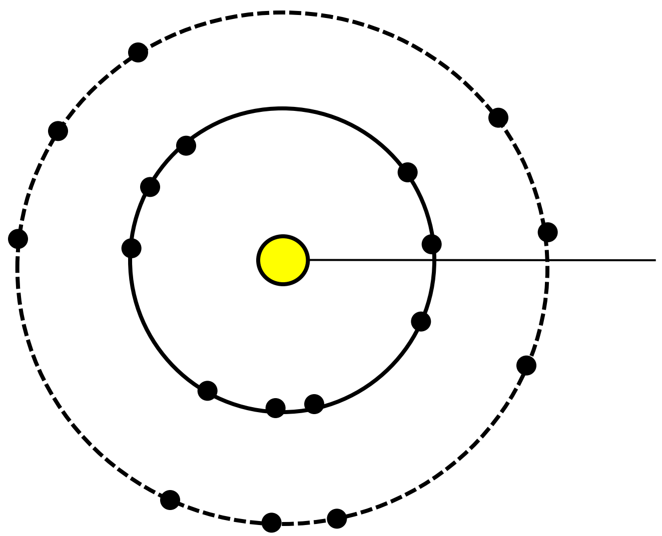


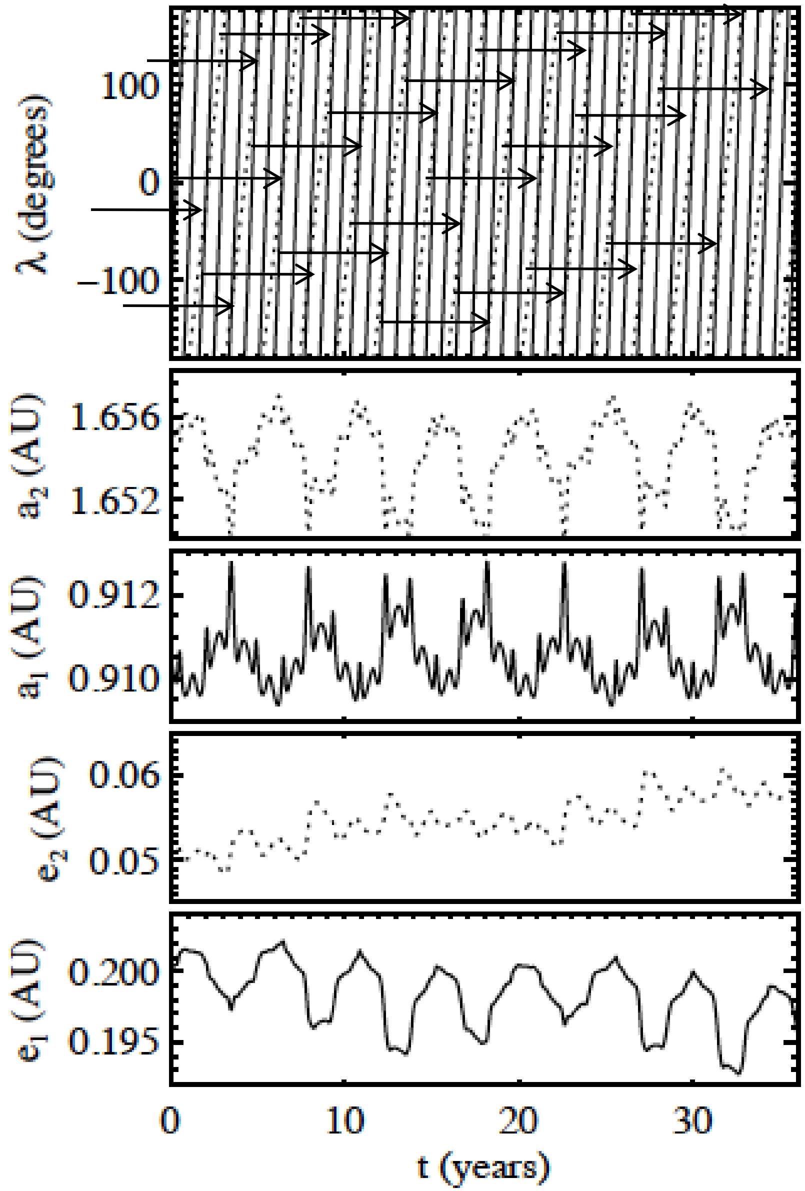


Transit timing variations

Agol et al. 2005,
Murray & Holman 2005

Dynamics: Secular Timescales





$P_2/P_1 = 2.44$

Non-resonant

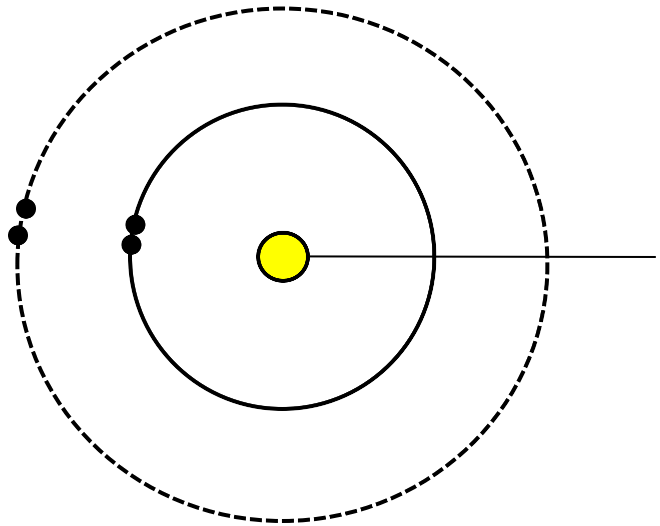
→ "Chopping" timing signal of Eric's talk, next

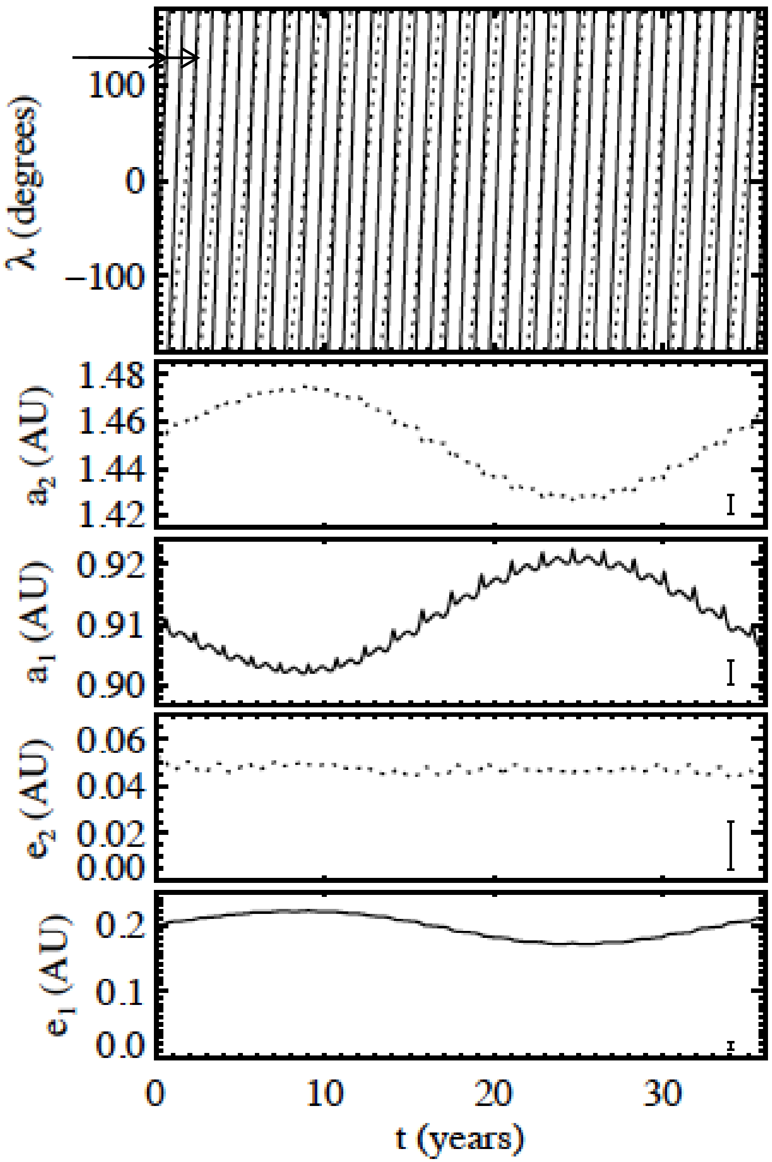
Transit timing variations

Agol et al. 2005,

Murray & Holman 2005

Dynamics: Resonant Orbits





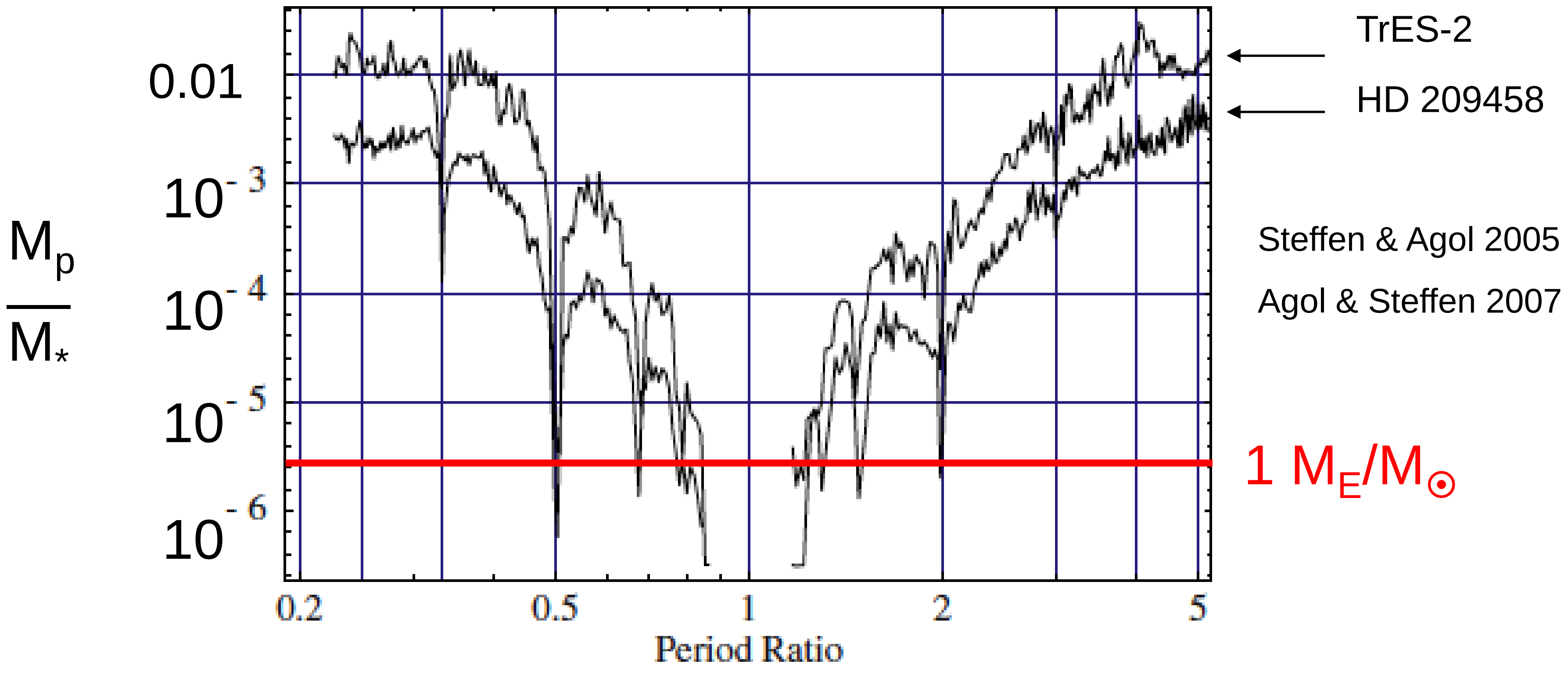
$P_2/P_1 = 2.00$

Transit timing variations

Agol et al. 2005,

Murray & Holman 2005

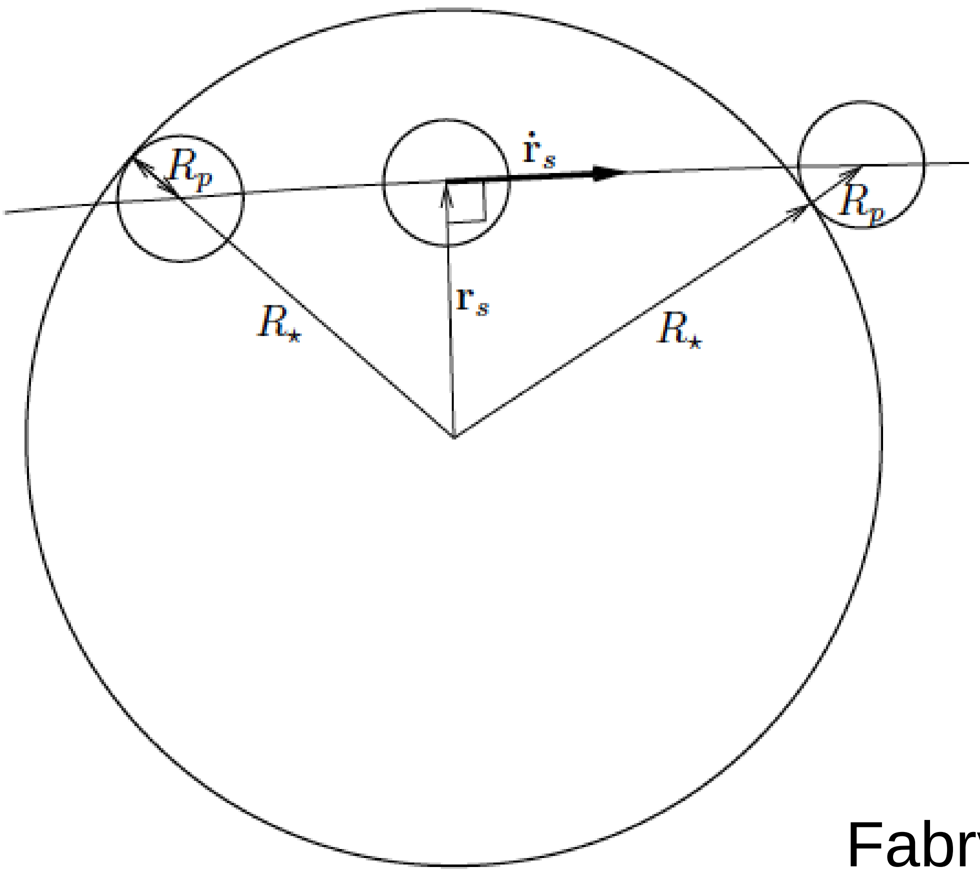
Sensitivity



TTV signal scales as orbital periods – *better* for relatively distant planets.

Dynamical Model of Transits

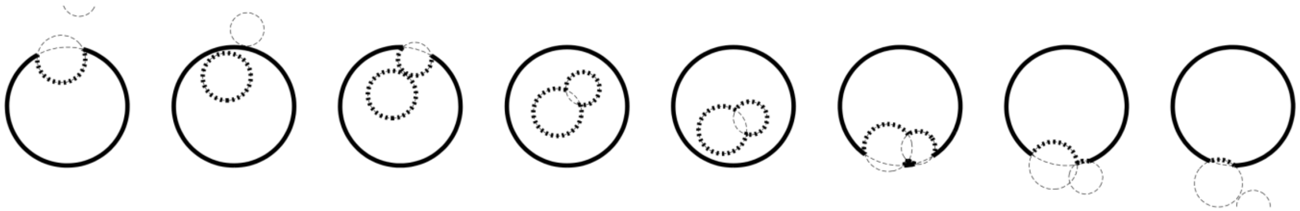
Use Newton's equations to integrate a 3-body system
Numerical transit times and radial velocities



Fabrycky (2010)

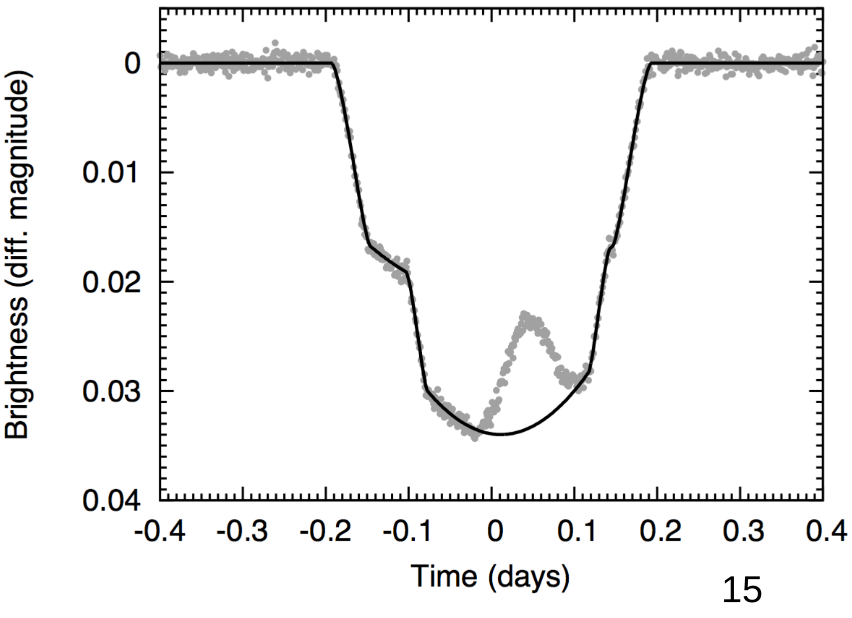
Transit Computation

- Semi-analytical solutions, using basic limb darkening (Pal 2011)



$$I[\mu] = 1 - c_1(1-\mu) - c_2(1-\mu)^2$$

$$\mu = \mu[x,y] = (1-(x^2+y^2))^{\frac{1}{2}}$$

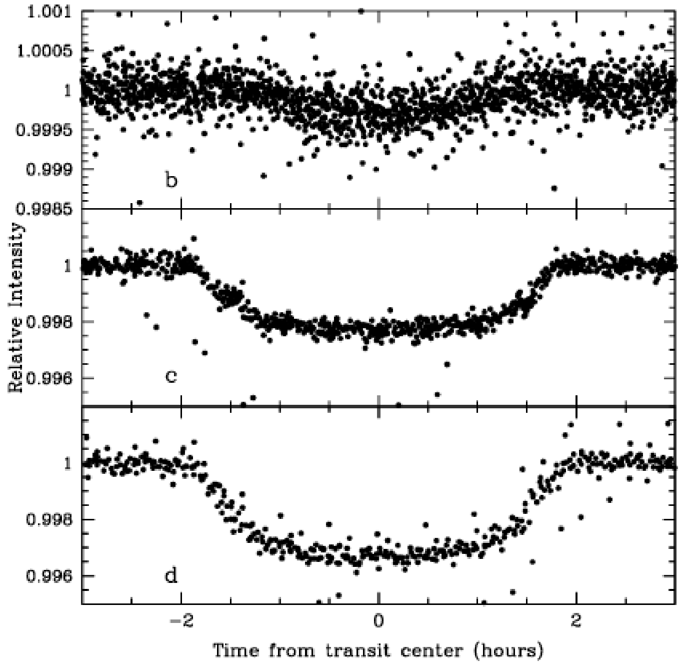


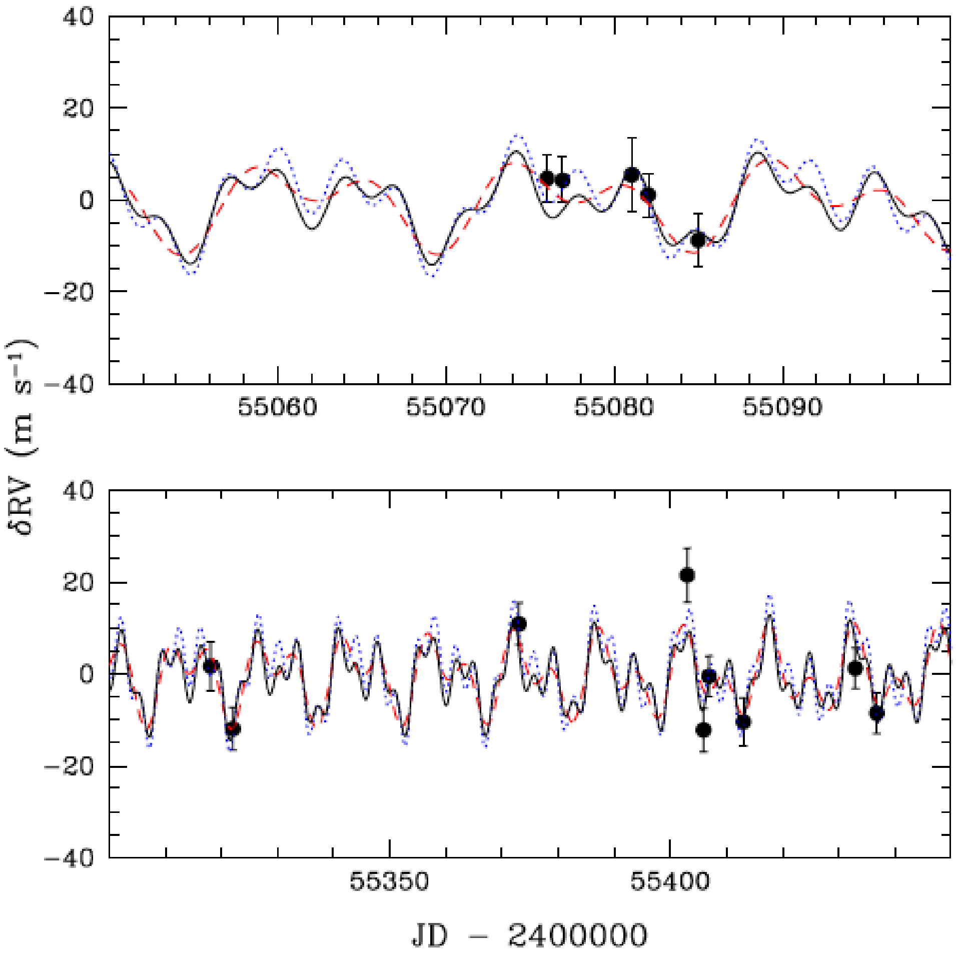
(slide courtesy UChicago graduate student Sean Mills)

“Ground truth”

- Neptune’s discovery
- Checking TTV masses by Radial Velocity
  - Kepler-18 (Multi-transiting)
  - KOI-142 (TTV discovery)
  - Lauren Weiss’ poster on Kepler-11

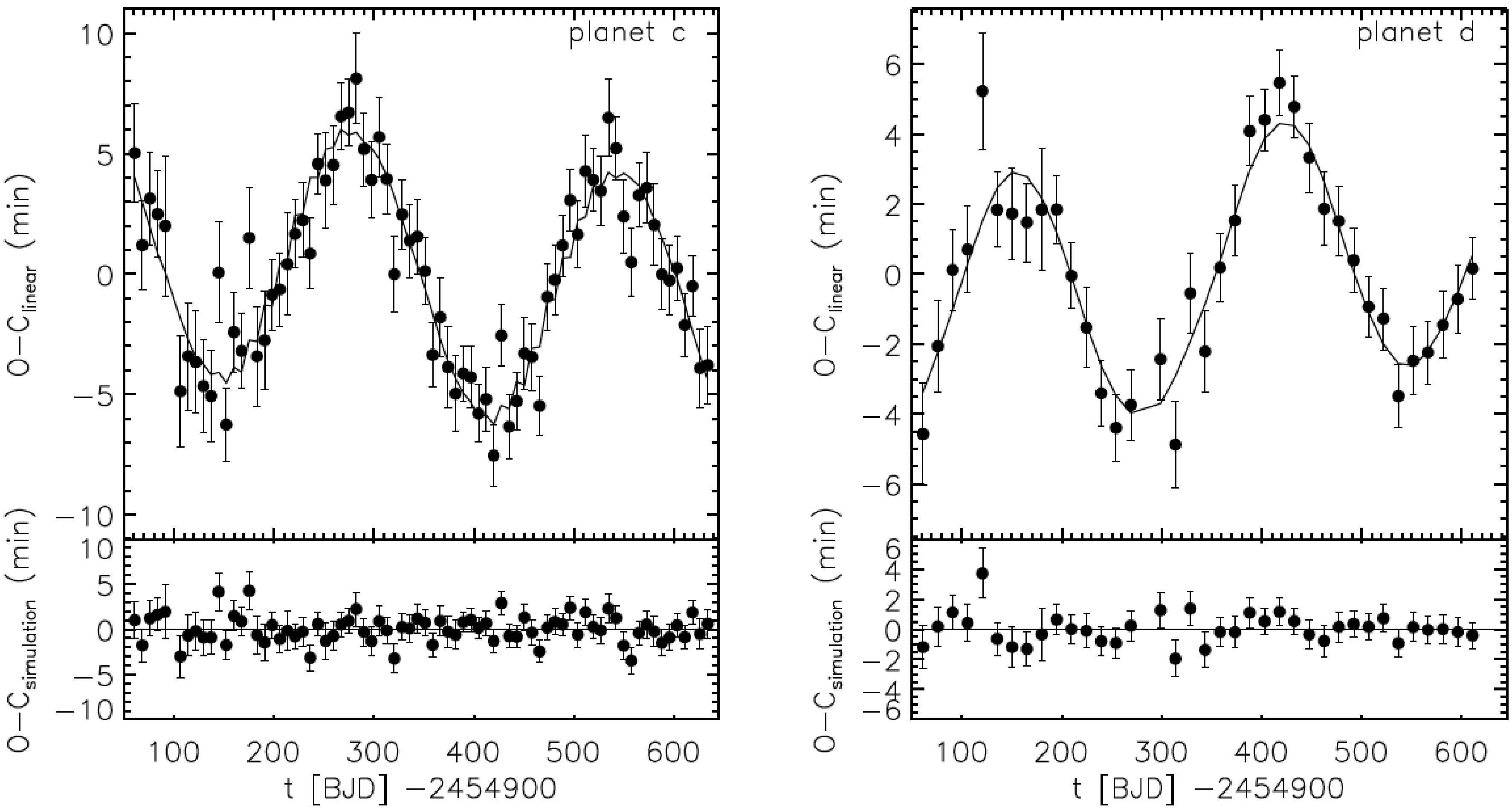
Kepler-18 (Cochran, Fabrycky, et al. 2011)





Planet	Period (days)	Mass (M_{Earth})
b	3.5	12 ± 5
c	7.6	15 ± 5
d	14.9	28 ± 7

P = 7.6416 days   P = 14.8589 days



P/P=1.944 ~= 2/1

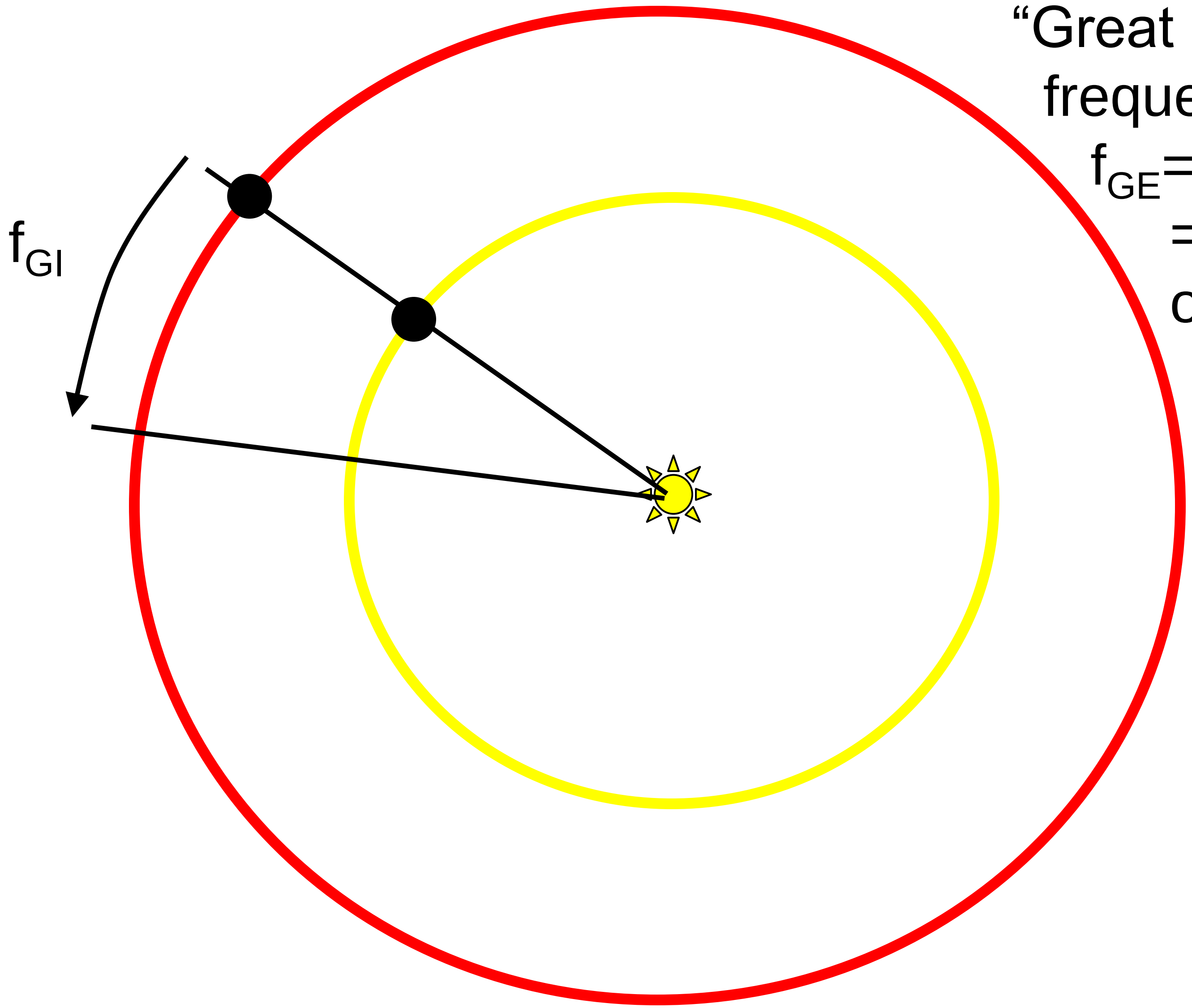
Fit adjusts: P, T_0 (phase), e*cos*w, e*sin*w, M_p of each planet

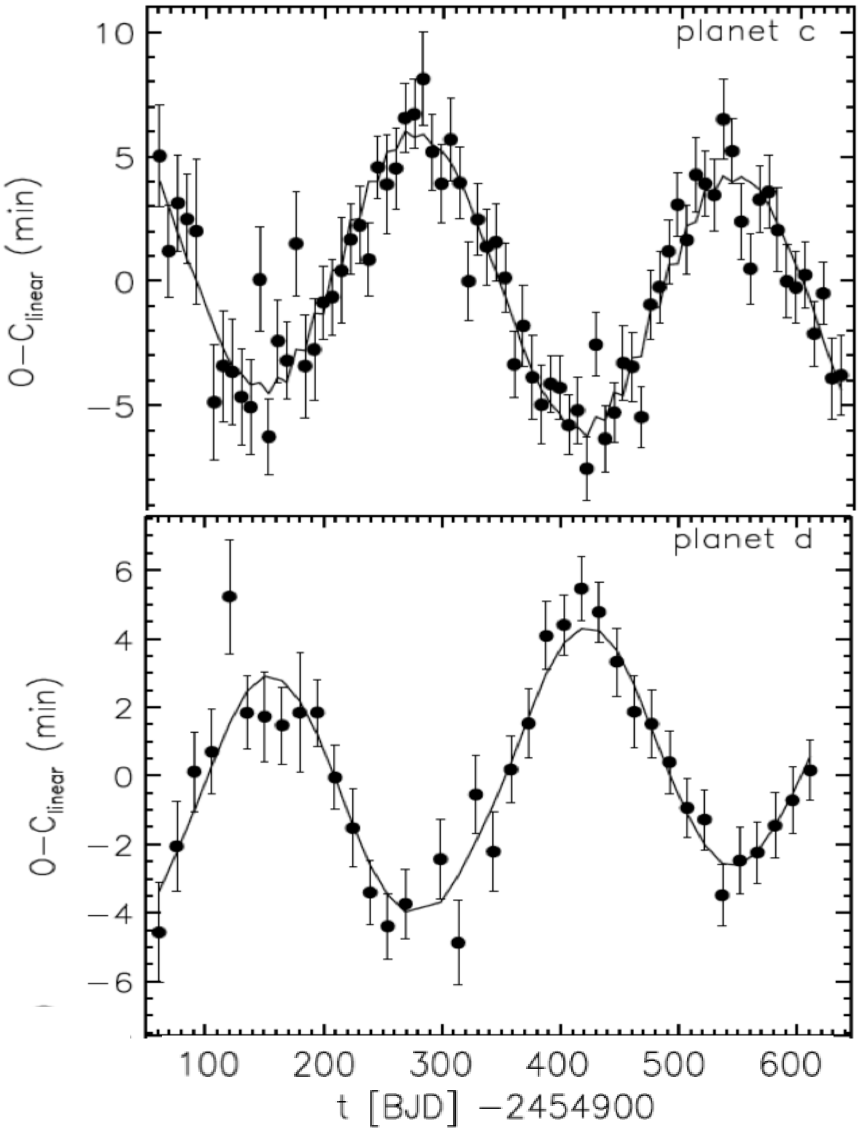
“Great Inequality” frequency:

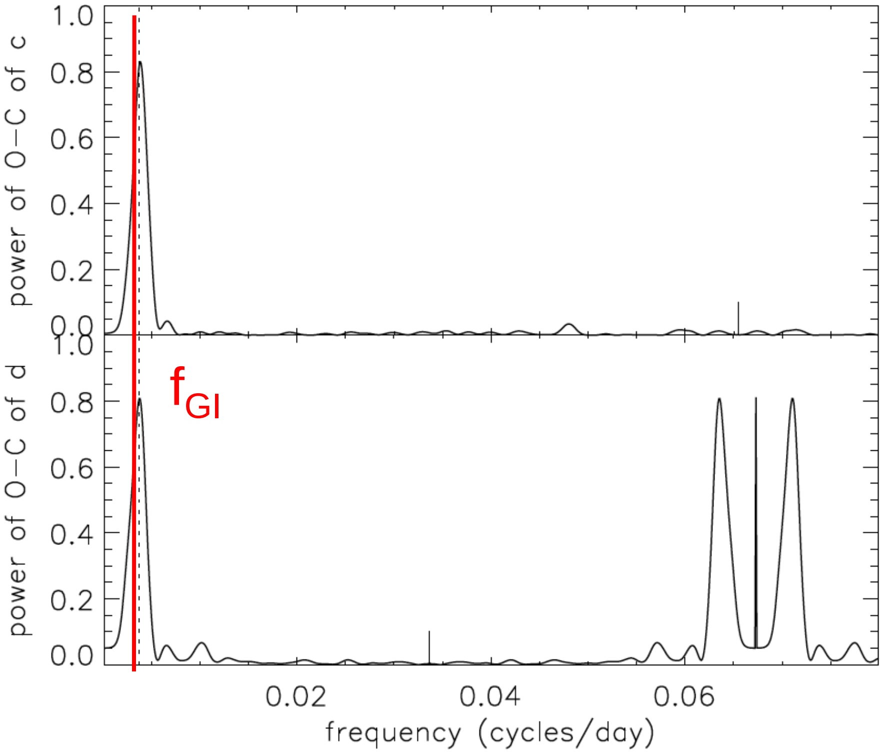
$f_{GE}=2/P-1/P$

$= 0.0037\ d^{-1}$

or 270 days







The Great Inequality is observed!

Kepler-18 tests TTV masses

Planet	Period (days)	RV Mass (M_{Earth})	TTV Mass (M_{Earth})
b	3.5	12 ± 5	18 ± 9
c	7.6	15 ± 5	17.3 ± 1.7
d	14.9	28 ± 7	15.8 ± 1.3

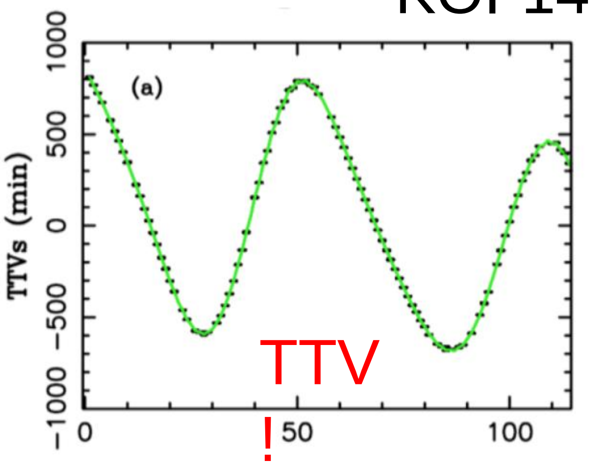
Other multi-transiting test?

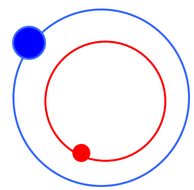
Kepler-9: published RV dataset has 6 points for 3 planets, an insufficient test;

(see Dreizler & Ofir (2014), Borsato+14 for TTV mass)

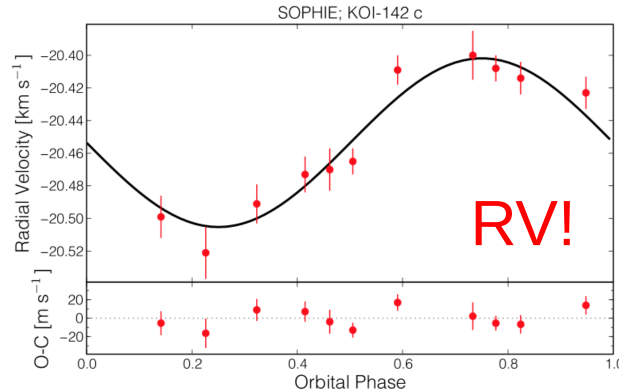
TTV-discovered Planet, Checked by RV

- KOI-142 (Nesvorny et al. 2013)



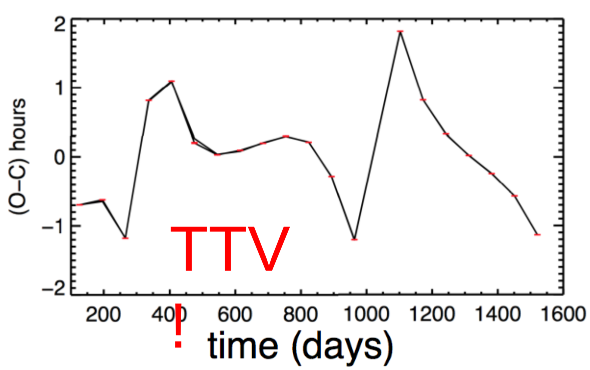


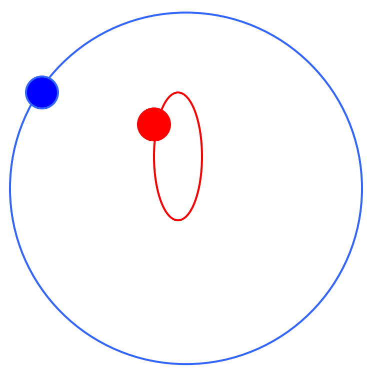
Barros et al. (2014)

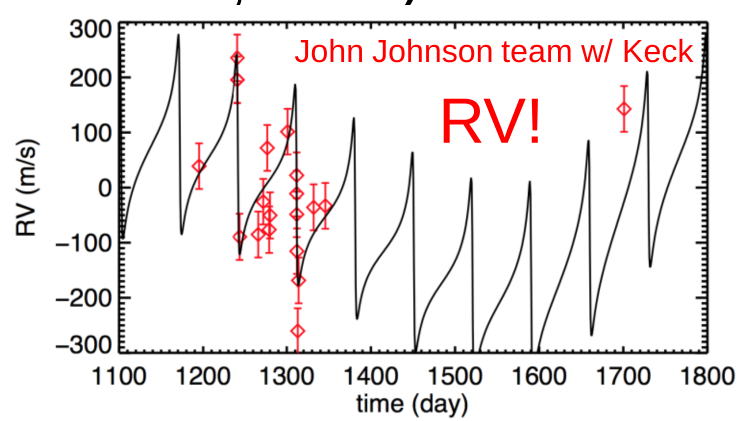


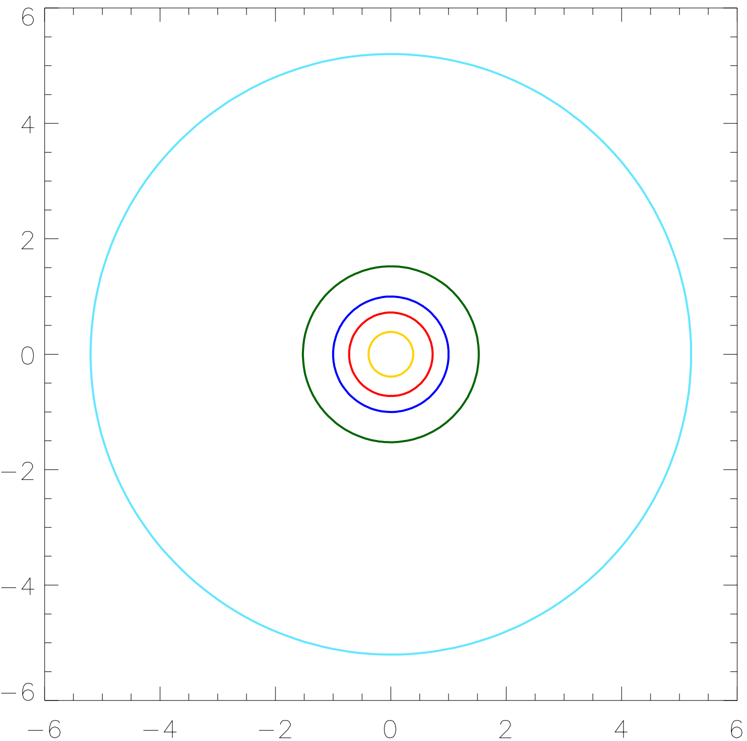
	Fitted parameters
22.340 +/-0.002	Orbital period, P [days]
0.0559 +/-0.0004	Orbital eccentricity
0.63 +/-0.03	Minimum planet mass [M_J]

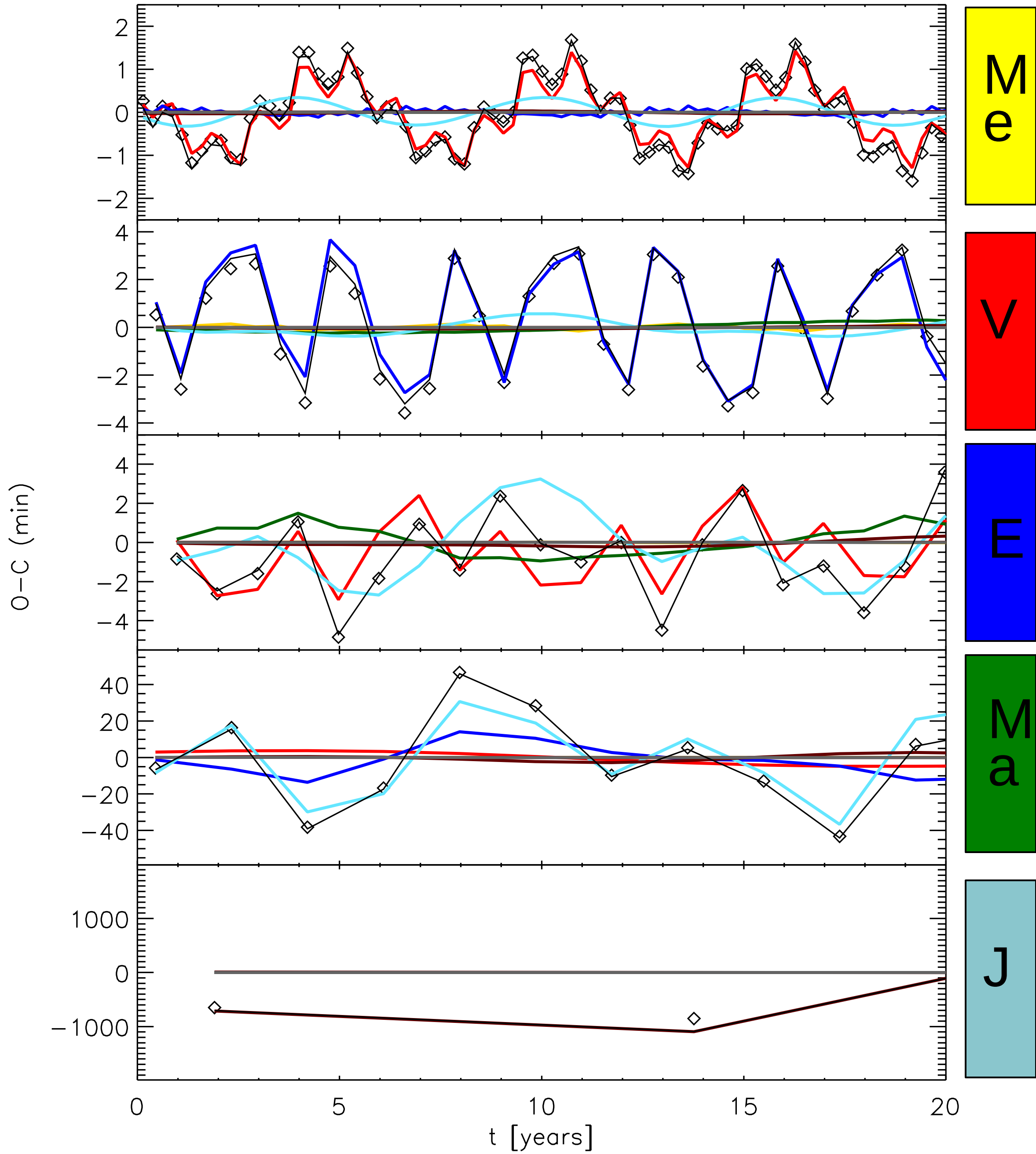
- KOI-1474 (Dawson et al. 2012, 2014)







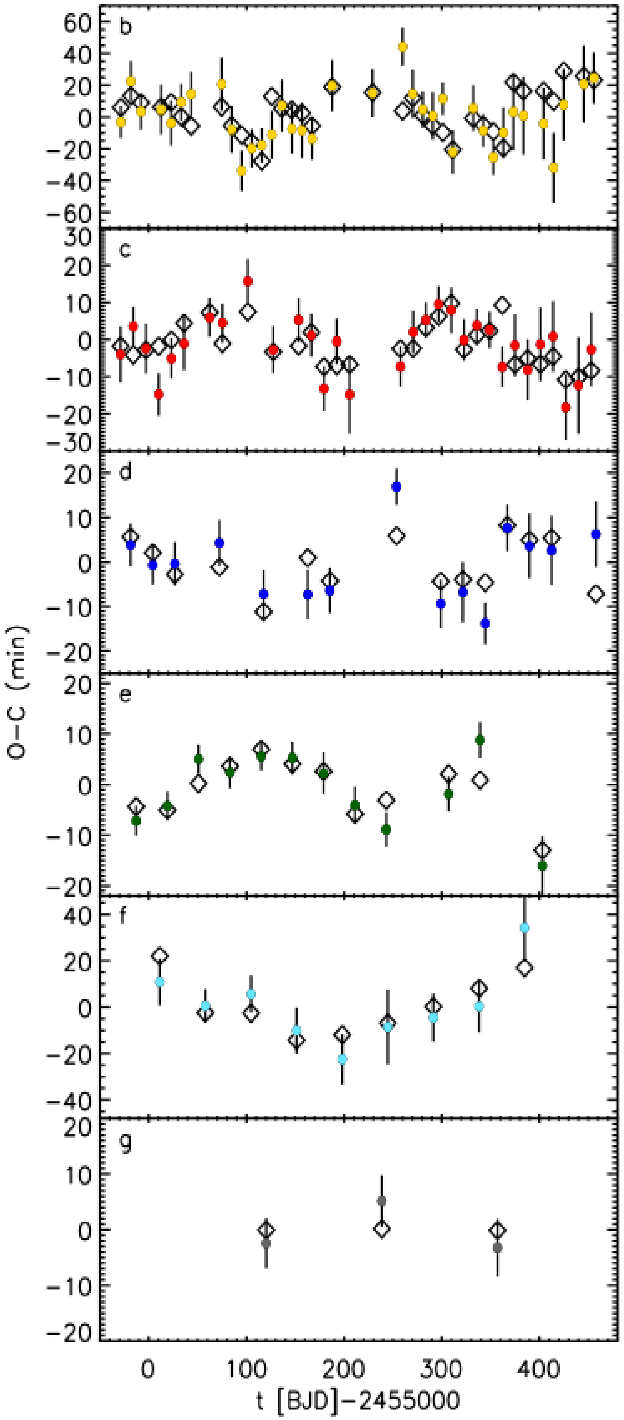


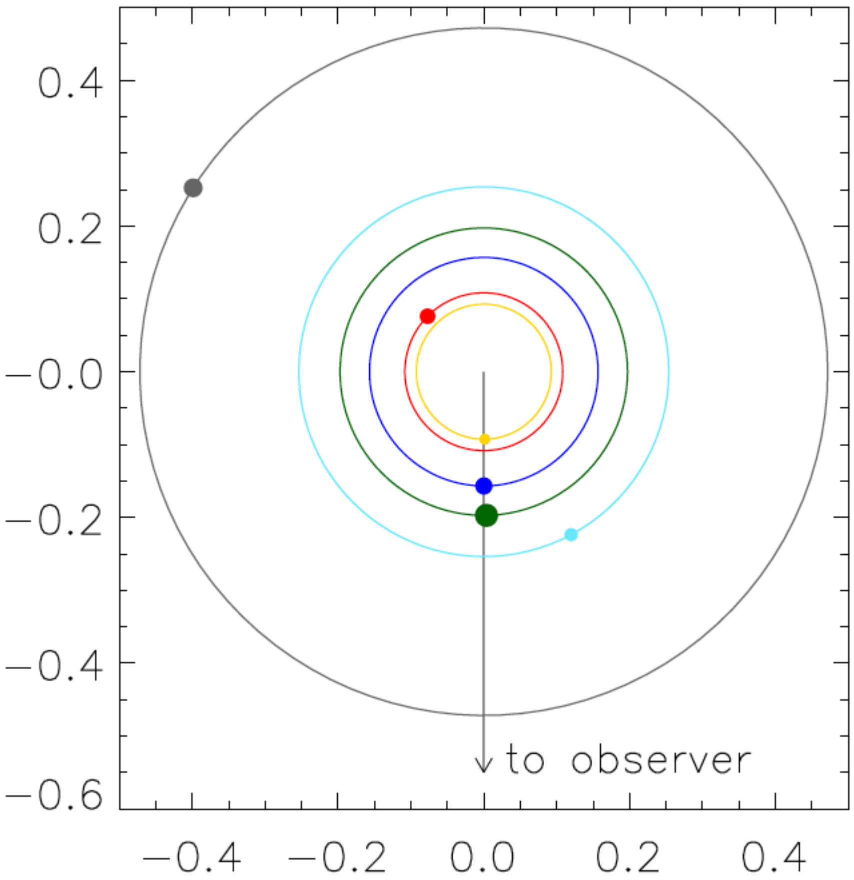


Mercury-through-Jupiter mutual perturbations.

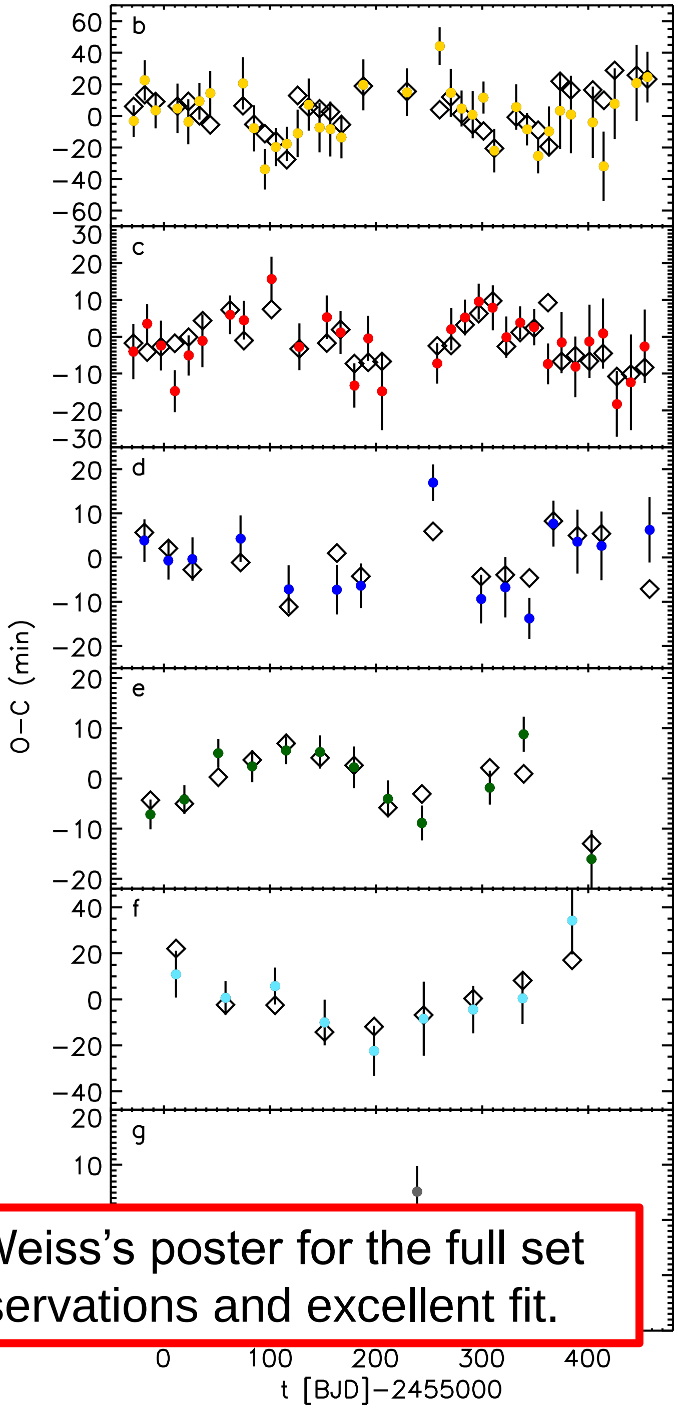
Concept: Holman & Murray 2005

Kepler-11

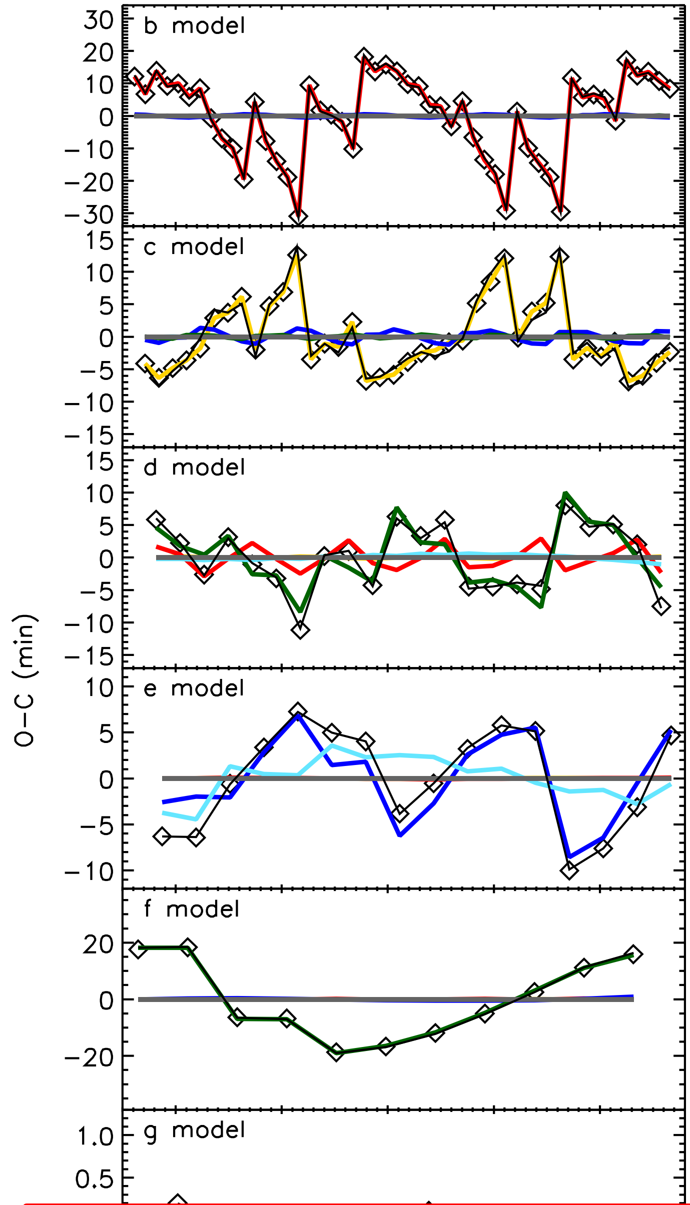




Lissauer, Fabrycky, et al. 2011

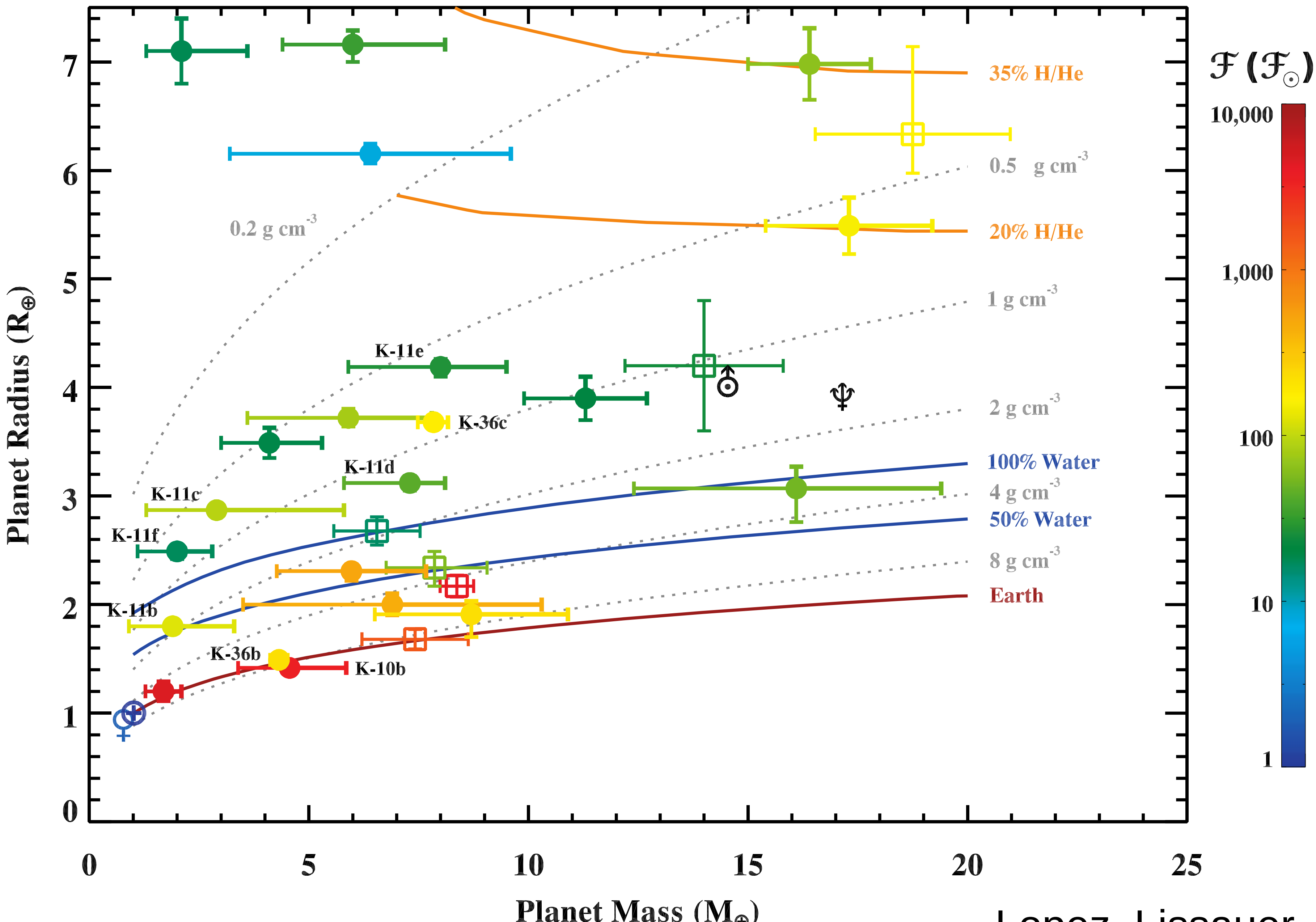


See Weiss's poster for the full set of observations and excellent fit.



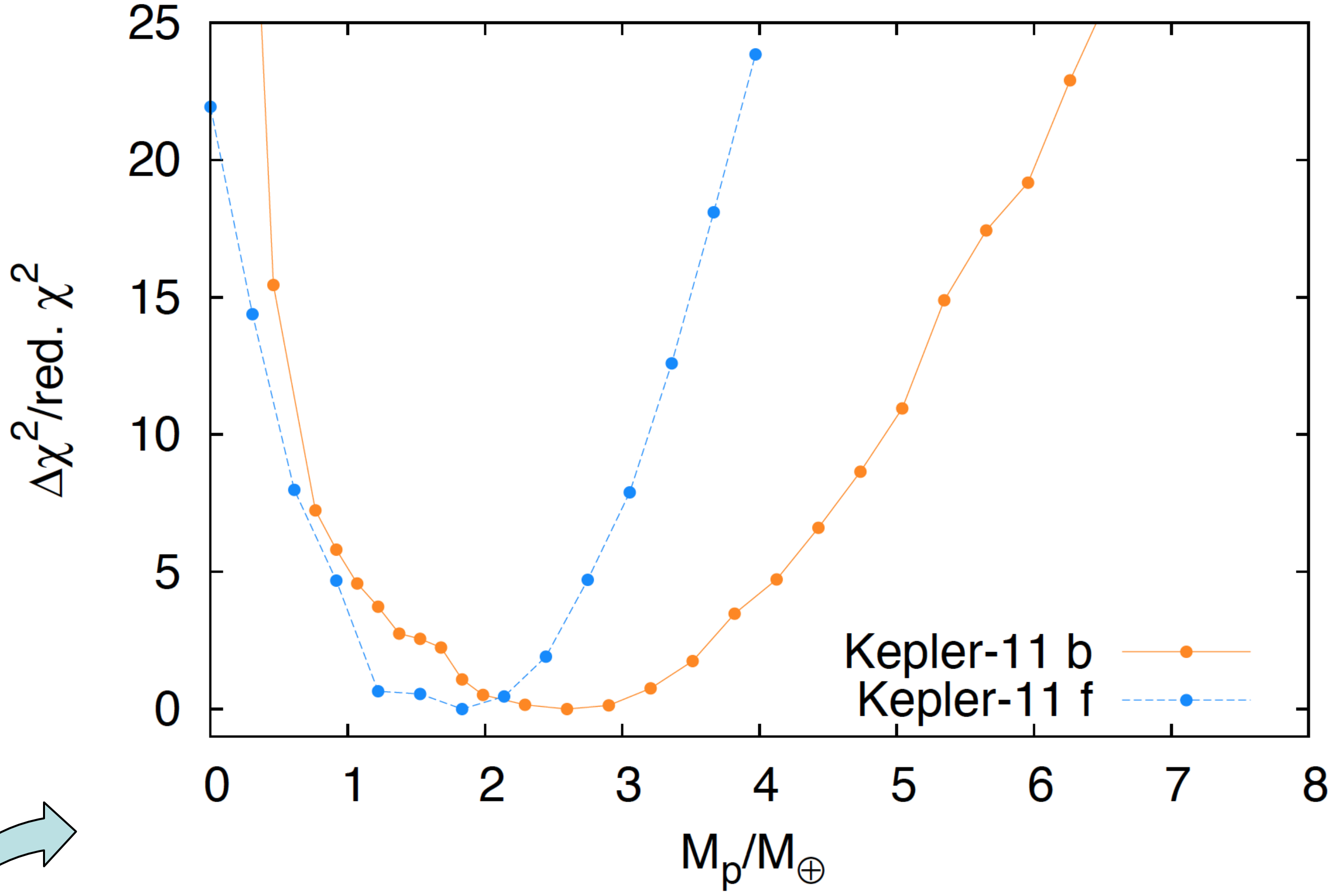
Measure *Radius* from the transit depth.
Measure *Mass* from the neighbor's transit timing.

From Earth-sized to Mini-Neptunes



Lopez, Lissauer

"Have you tried taking the smallest two Kepler-11 planets, fixing them at higher masses, and actually seeing if you can't find *a* solution… that isn't offensive?" --Dave Charbonneau on Monday



Quick work by Daniel Jontof-Hutter!

(Lissauer, Jontof-Hutter, et al. 2013 updated analysis of Kepler-11)

More Extreme Sub-Neptunes

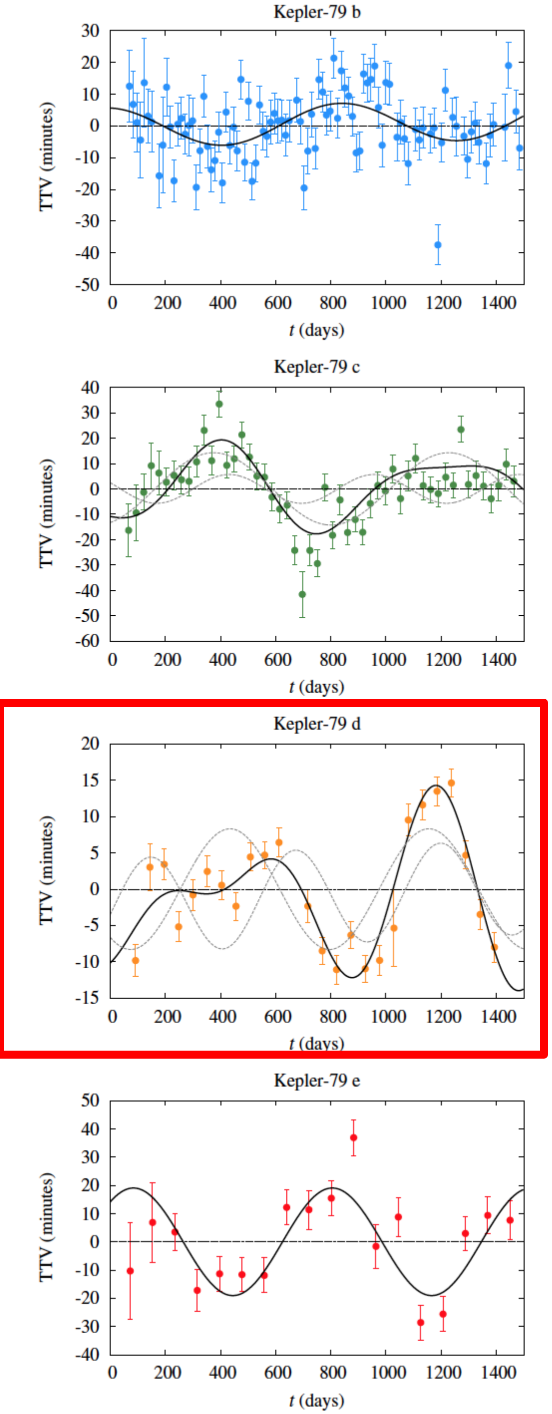
(don't ignore them – they're real!)

See Daniel Jontof-Hutter's poster and talk with him!

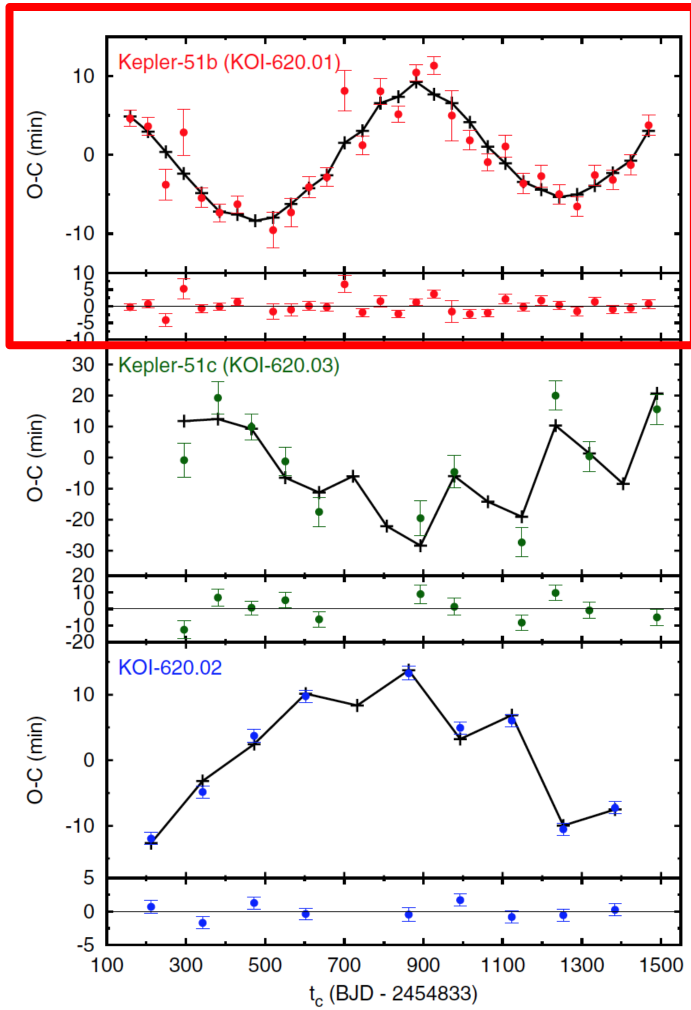
Kepler # Planet	T_{eq} (K)	TTV Mass (M_{Earth})	Transit Radius (R_{Earth})	Ref.
79 d	634	$6.0^{+2.1}_{-1.6}$	$7.16^{+0.13}_{-0.16}$	Jontof-Hutter + 2014
51 b	543	$2.1^{+1.5}_{-0.8}$	7.1 ± 0.9	Masuda 2014
87 c	403	6.4 ± 0.8	6.1 ± 0.3	Ofir + 2014

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

More Extreme Sub-Neptunes

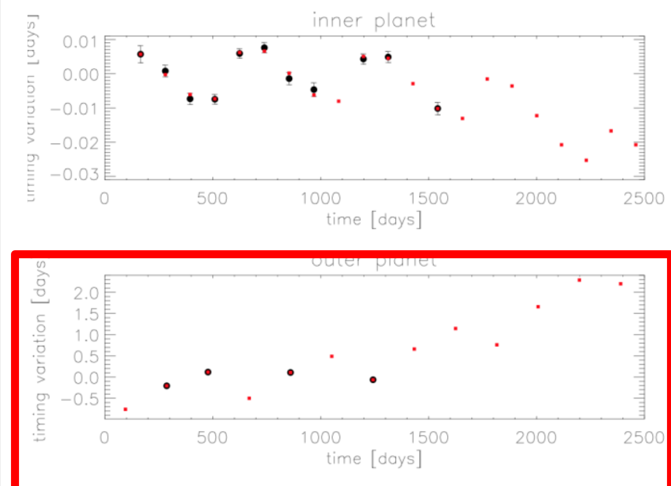


<< Jontof-Hutter+14

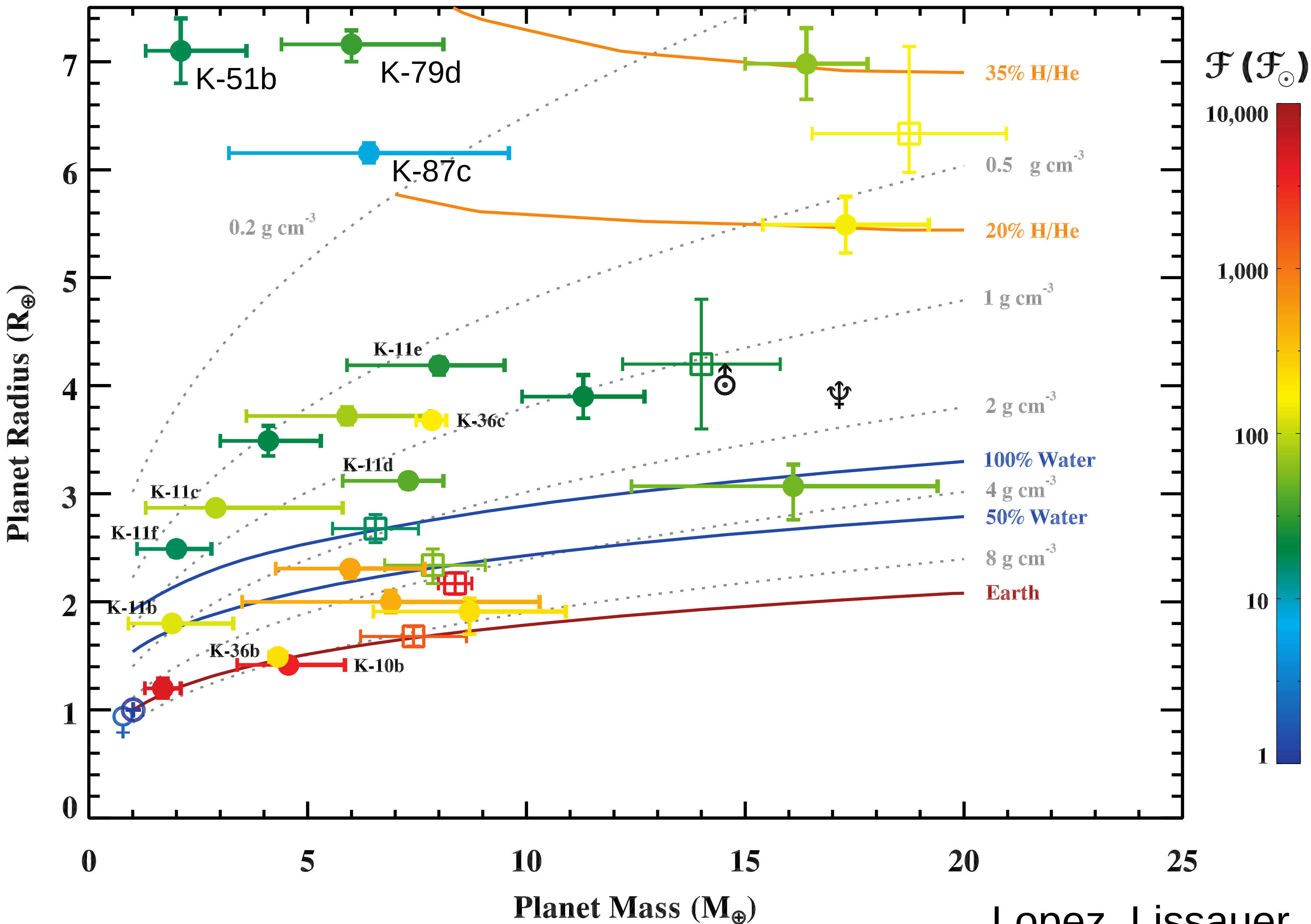


< Masuda 14

VV Ofir+14



From Earth-sized to Mini-Neptunes



Lopez, Lissauer

Exoplanetary System Architectures

Basic facts:

- Planet number
- Masses
- Radii

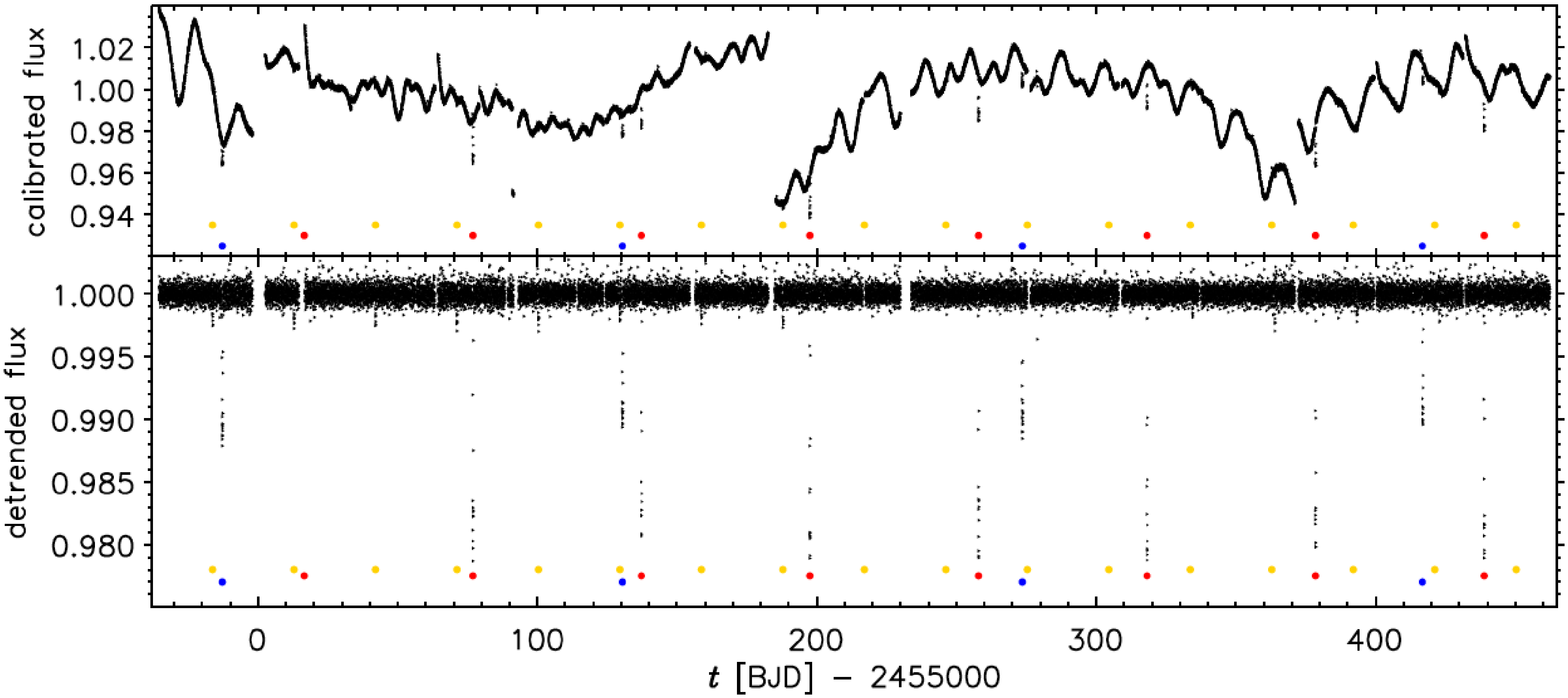
Dynamical properties:

- Periods (n.b.: their ratios)
- Eccentricities
- Mutual Inclinations

Transits	Radial Velocities
w/ TTV	✔
w/ TTV	✔
✔	
✔✔	✔
w/ TTV	✔
w/ TDV	

Clearinghouse of TTV and TDV curves: Mazeh et al. 2013
ftp://wise-ftp.tau.ac.il/pub/tauttv/TTV
Version 112 sub-directory for the latest

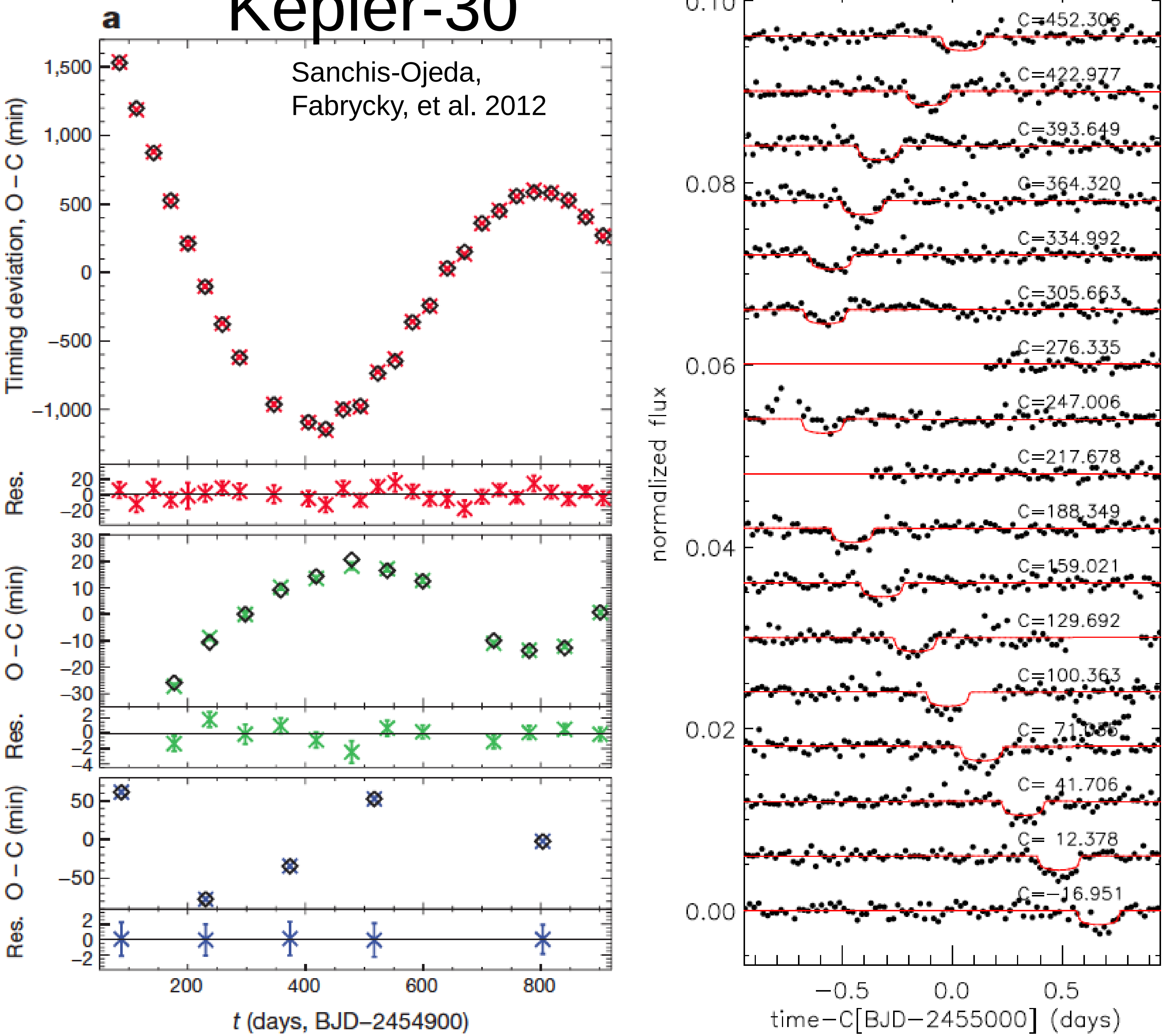
Kepler-30

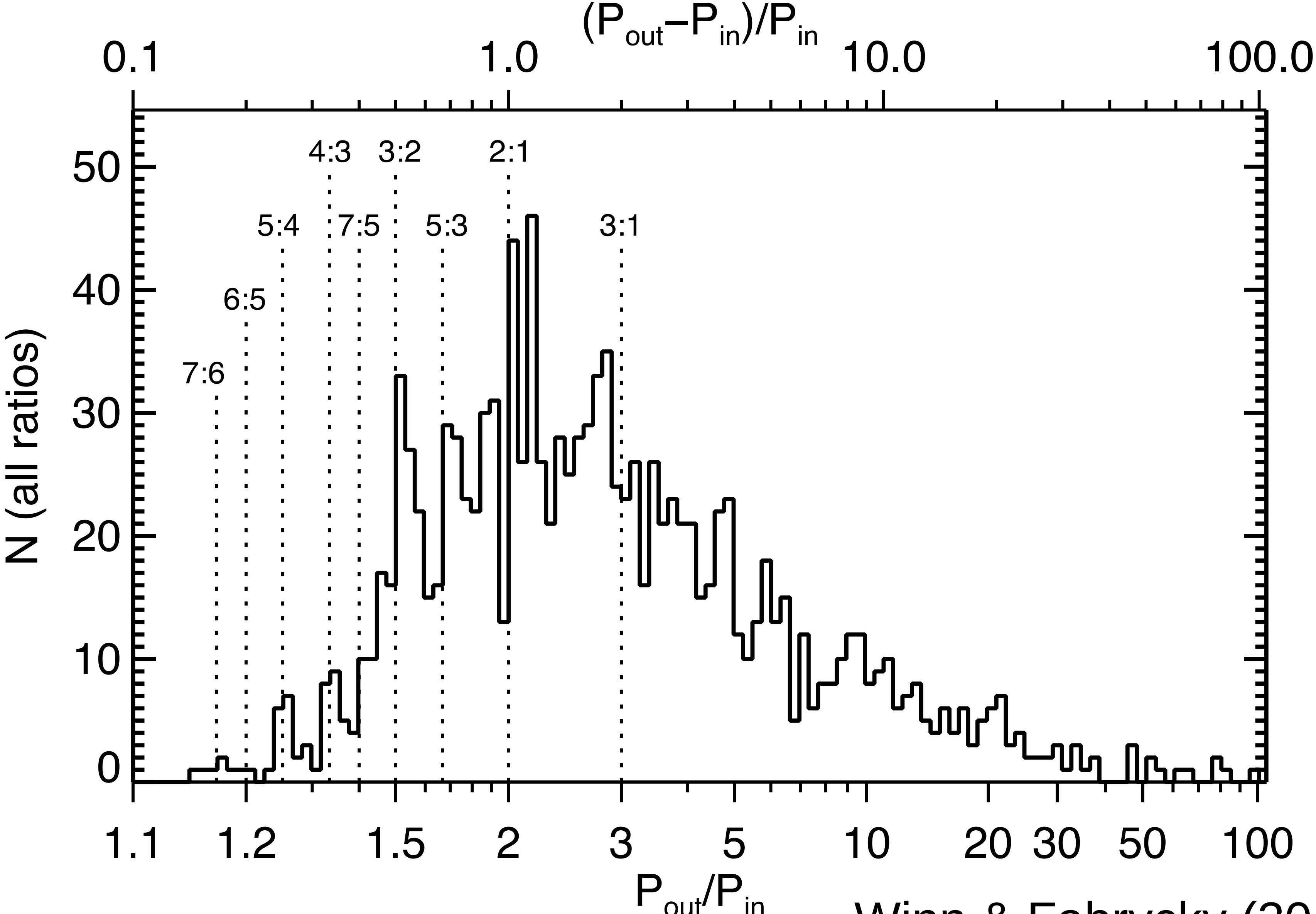


Fabrycky, Ford, Steffen et al. 2012

Kepler-30

Sanchis-Ojeda, Fabrycky, et al. 2012



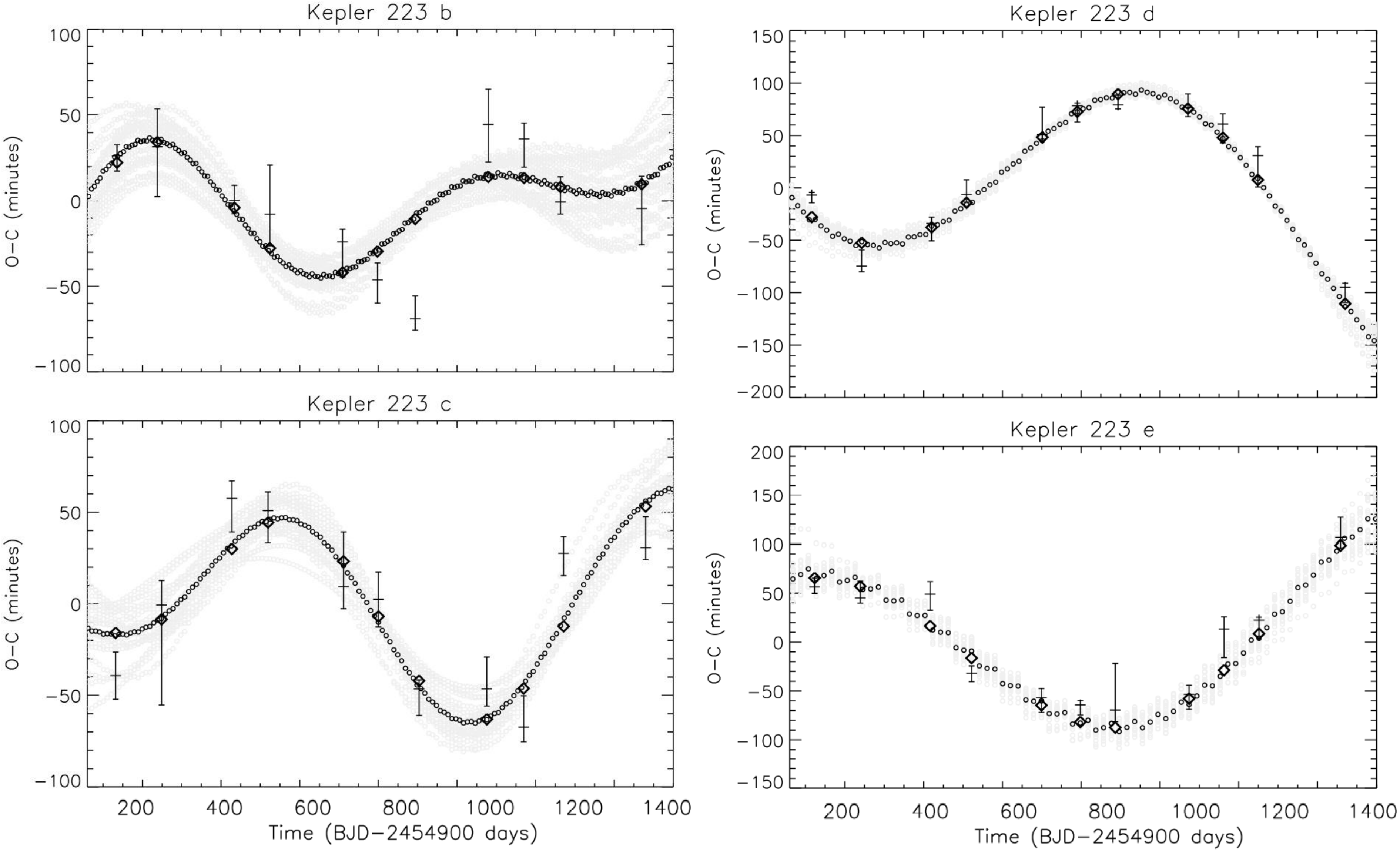


Winn & Fabrycky (2015)
Following Fabrycky+14,
“Architectures II”

A few Resonant chains

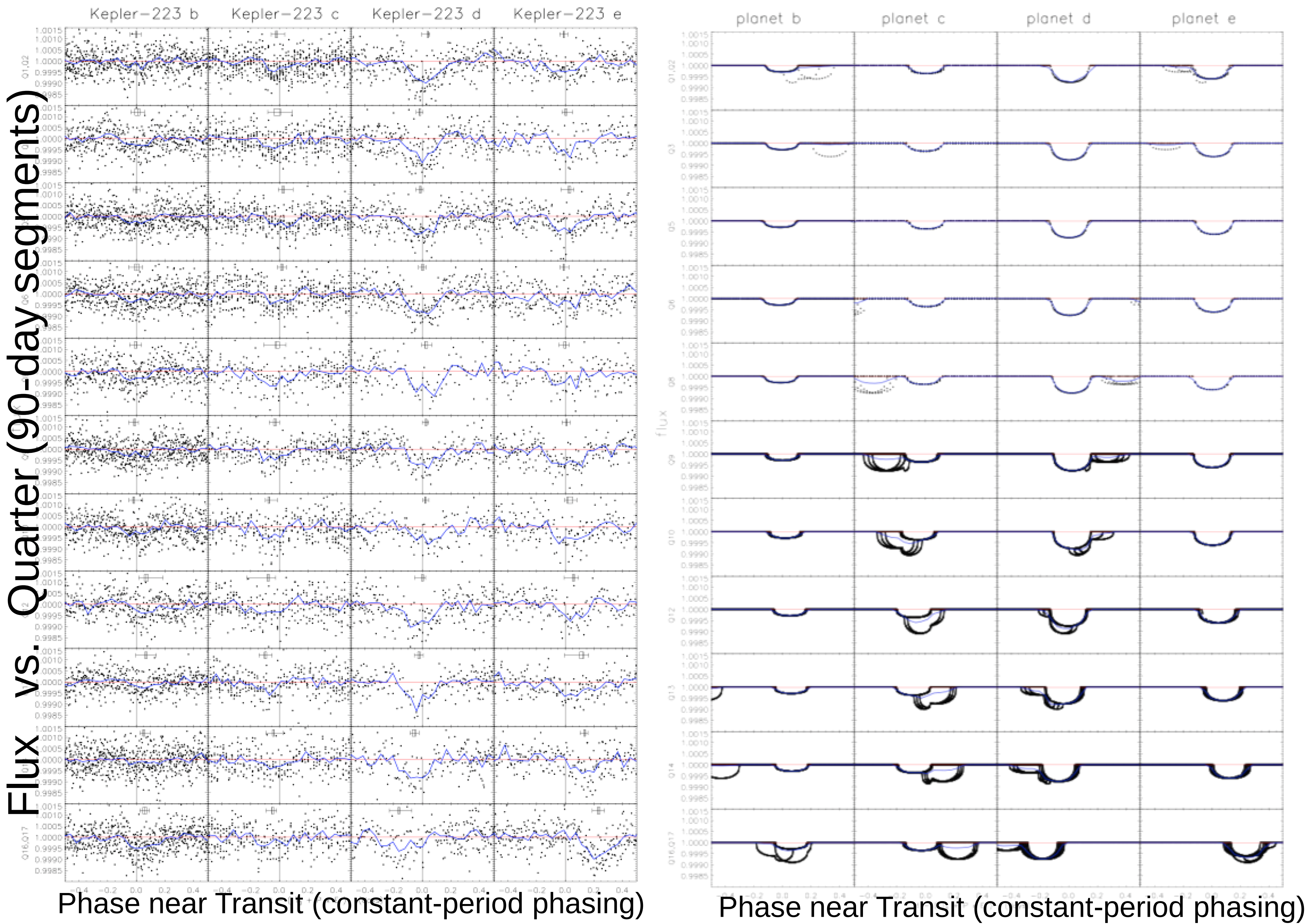
- Kepler-223 (KOI-730; 4:3, 3:2, 4:3)
- Kepler-60 (KOI-2086; 5:4, 4:3)
- Kepler-80 (KOI-500; 1.518, 1.518, 1.350)

KOI-730 TTVs, detected at last!



See Sean Mills' poster!

KOI-730 DATA Photodynamic MODEL



Sinusoidal Photodynamics

- Work in progress: Fitting photometry of all multitransiting systems with transit phase

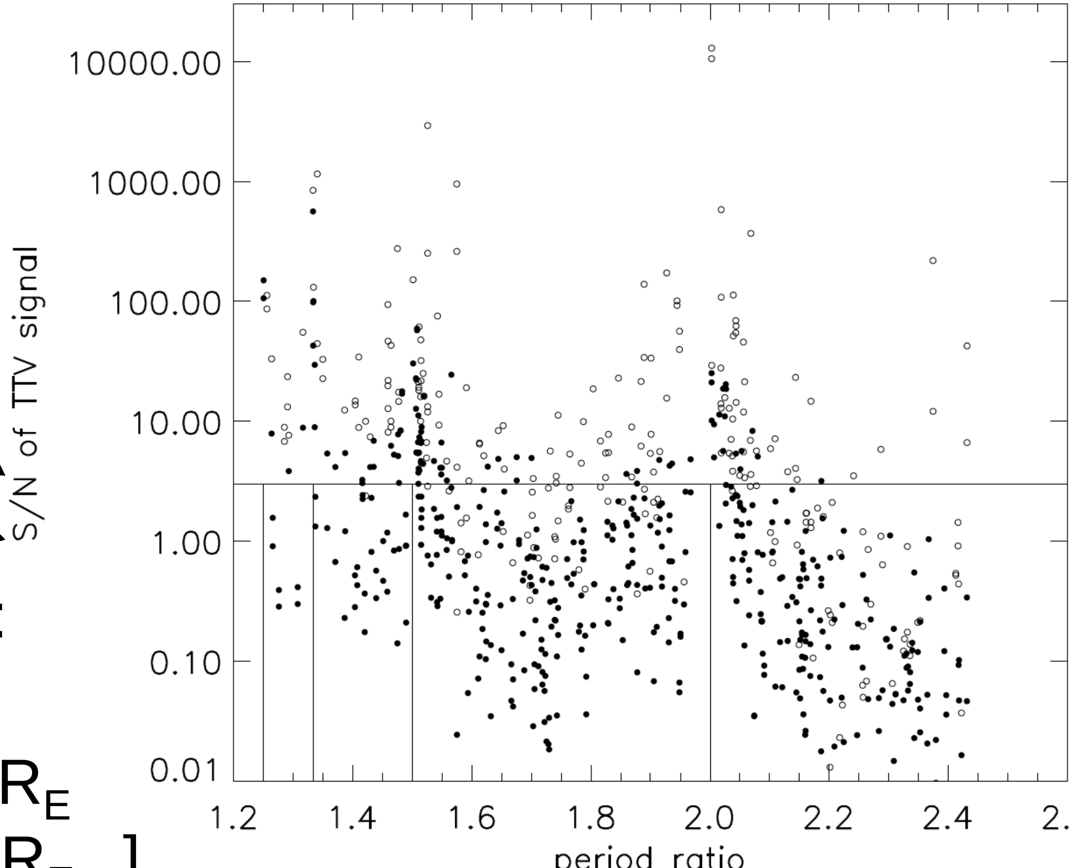
$$\Phi = T_0 + PxE + A_{ttv} \sin(2\pi\, t/P_{ttv} + \phi_{ttv})$$

Carter et al. (2008) [yes, idealized!]

Lithwick et al. (2012) [for plot amplitudes: e=0,

$M_{p,e} = R_{p,e}^{3.7}$ ● $R_p < 2\, R_E$

$R_{p,e}^{2.06}$ ○ $R_p > 2\, R_E$]



Eccentricities of Terrestrials?

- Planet formation options:
  - Within gas disk → low eccentricities
  - Giant Impacts → orbits cross, eccentricities much larger than the Hill sphere

  caveat: there may be some damping on residual or secondary debris (e.g., Schlichting et al. 2012)

Eccentricities of Terrestrials?

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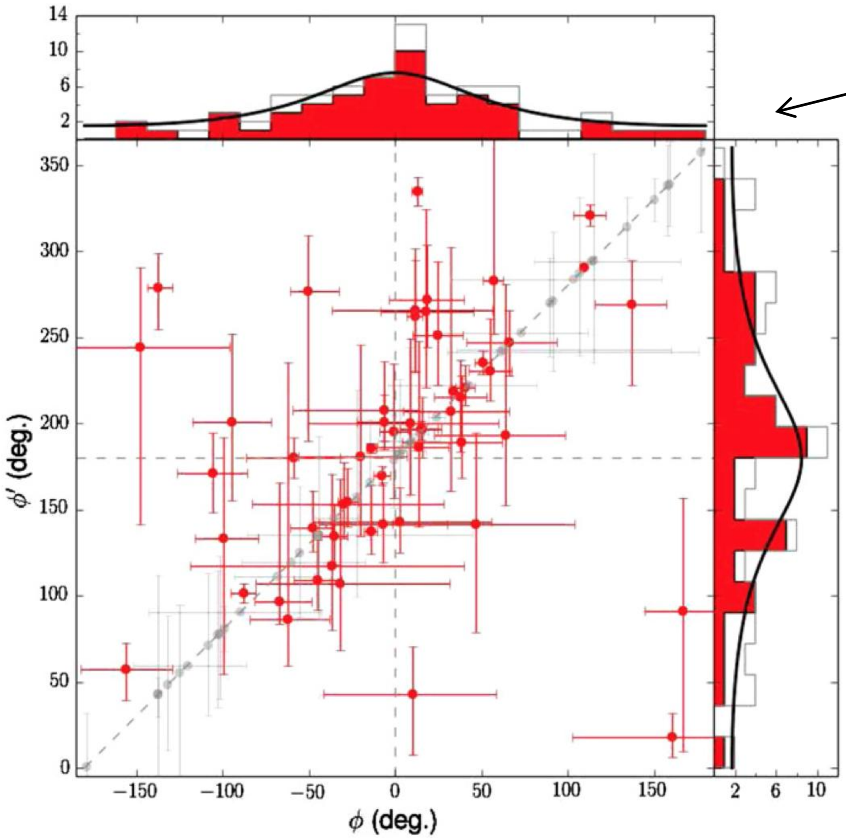

TTV phases of 54 systems: Hadden & Lithwick (2014) analyzing Mazeh+13 TTs.

Near - 2:1, 3:2, 4:3 resonant perturbation relates: ϕ_{ttv} / e_{free}

$$\sigma_e = \begin{cases} 0.017^{+0.009}_{-0.005}, & \text{for } R \text{ and } R' < 2.5\ R_\oplus \\ 0.008^{+0.003}_{-0.002}, & \text{for } R \text{ and } R' > 2.5\ R_\oplus. \end{cases}$$

Summary

- *Kepler* found a host of multiplanet systems.
- TTV masses reveal Super-Puffy Sub-Neptunes
- Photodynamics opens a new window on *exo*terrestrial planet formation