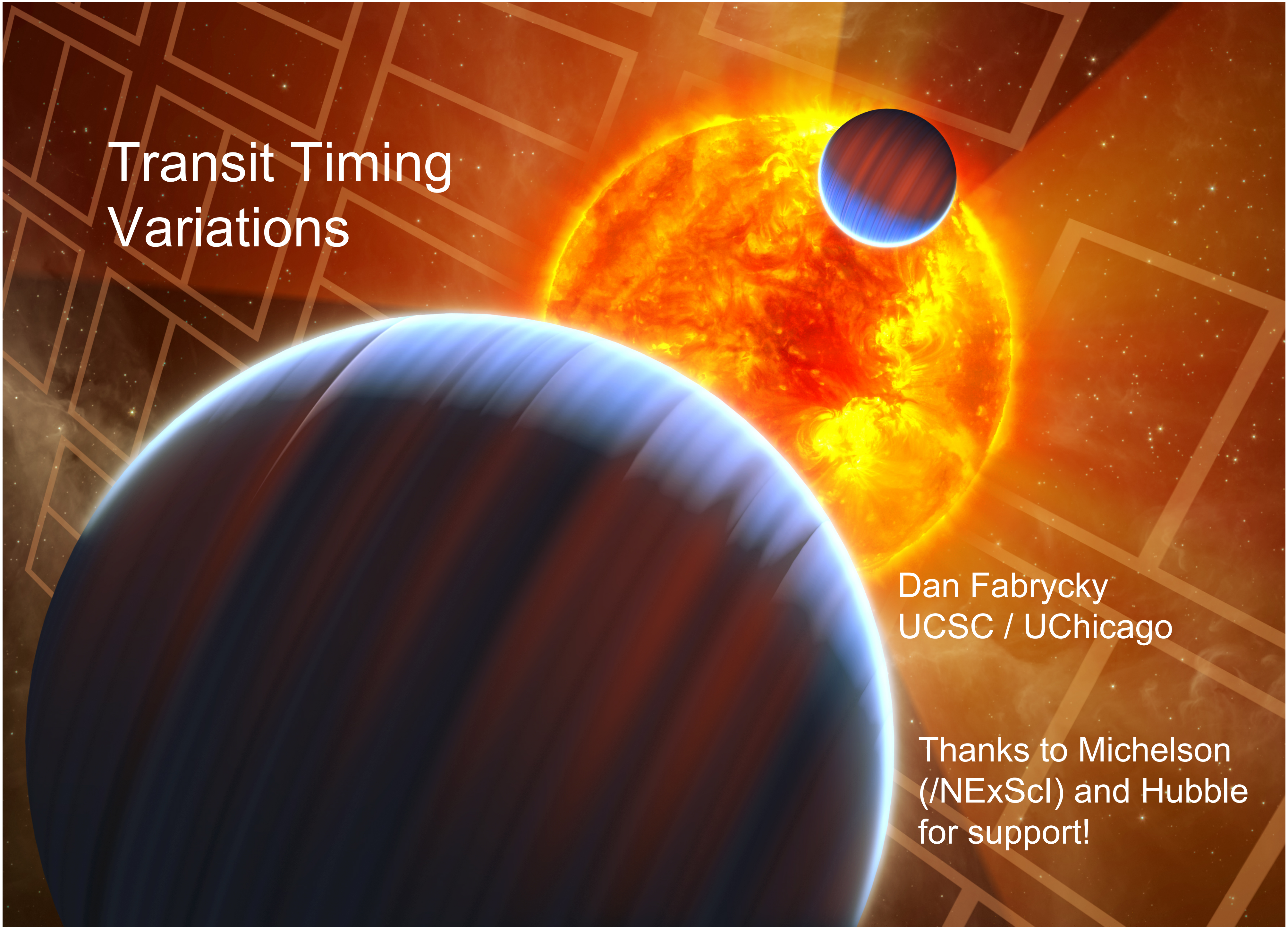
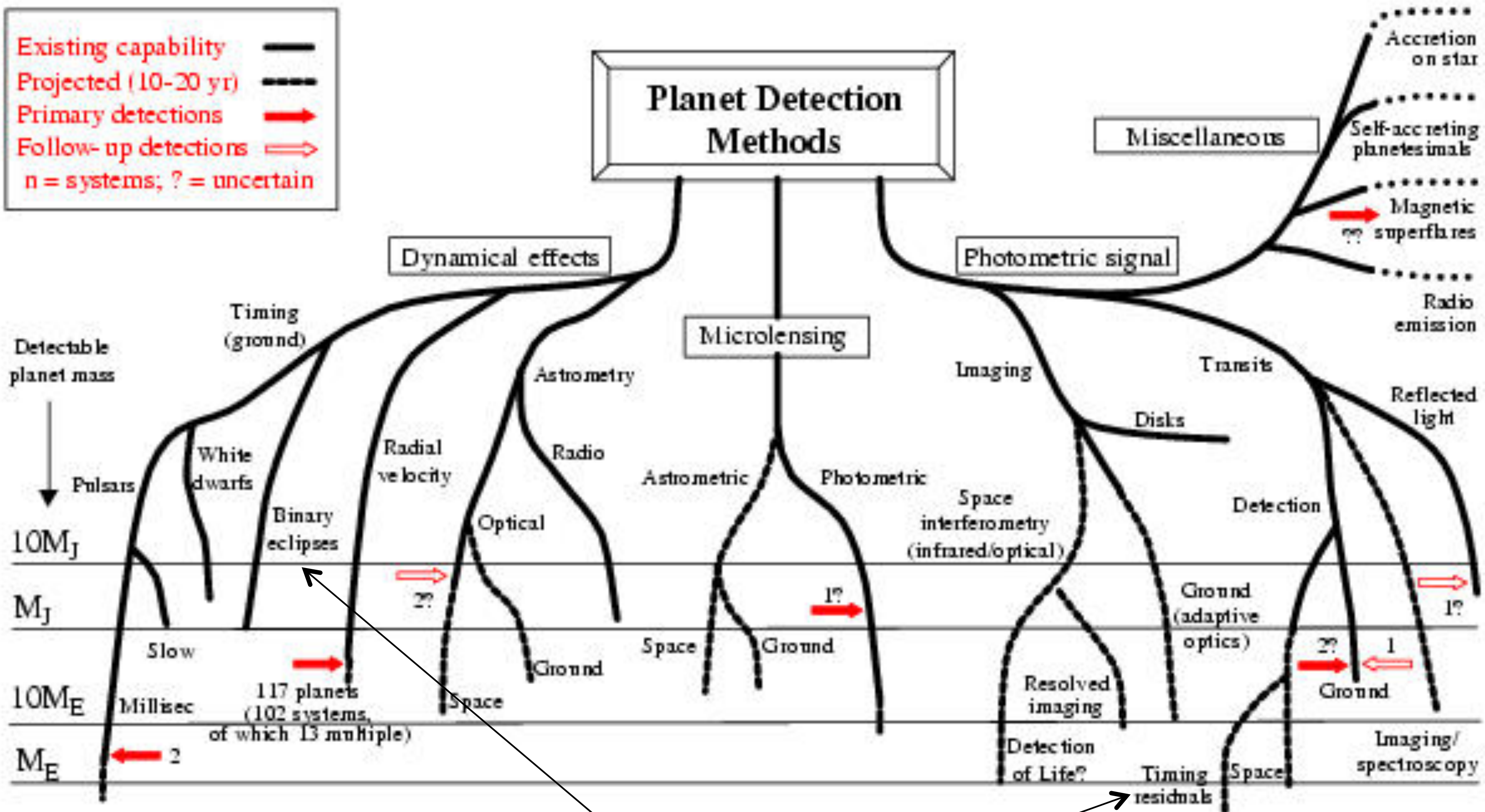

Transit Timing
Variations
Dan Fabrycky
UCSC / UChicago
Thanks to Michelson
(/NExScI) and Hubble
for support!

Planet Detection Methods

Michael Perryman, Rep. Prog. Phys., 2000, 63, 1209 (updated September 2003)



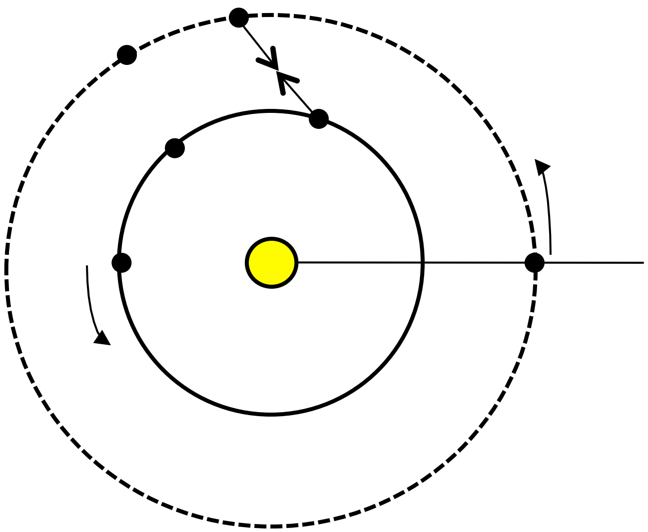
ETVs !

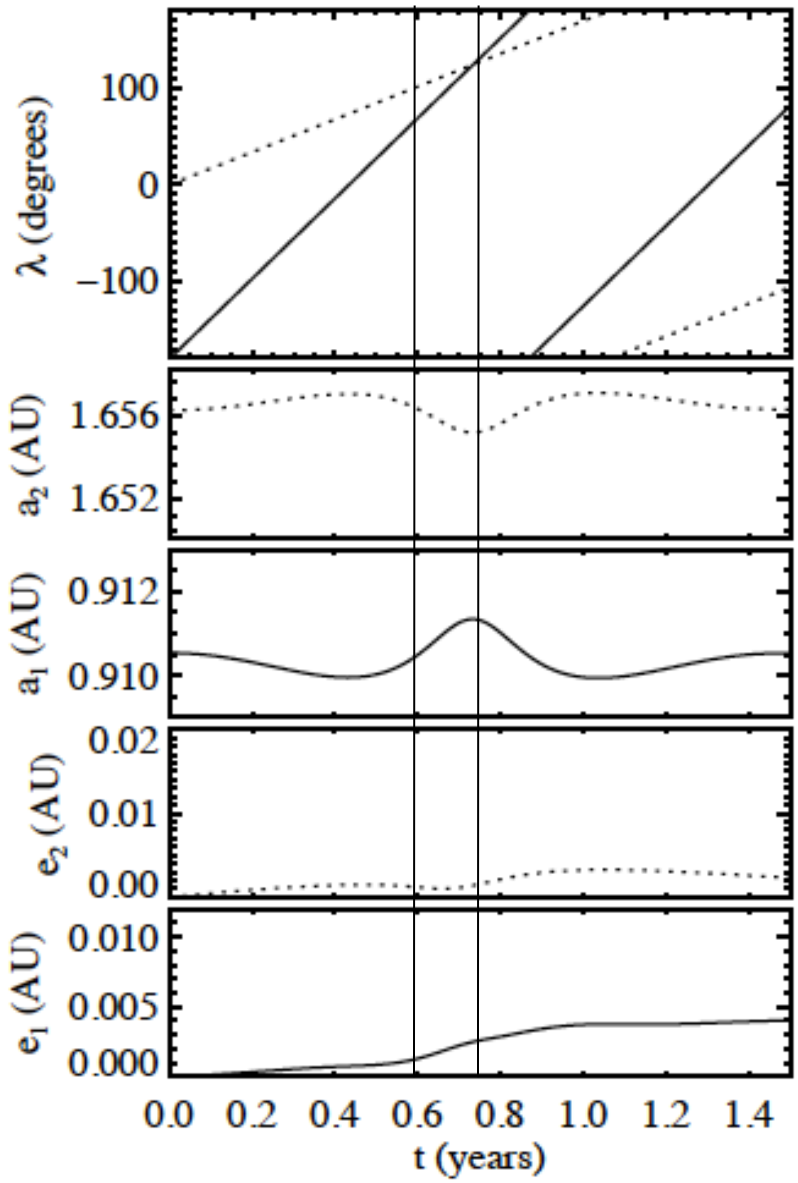
TTVs!

Overview

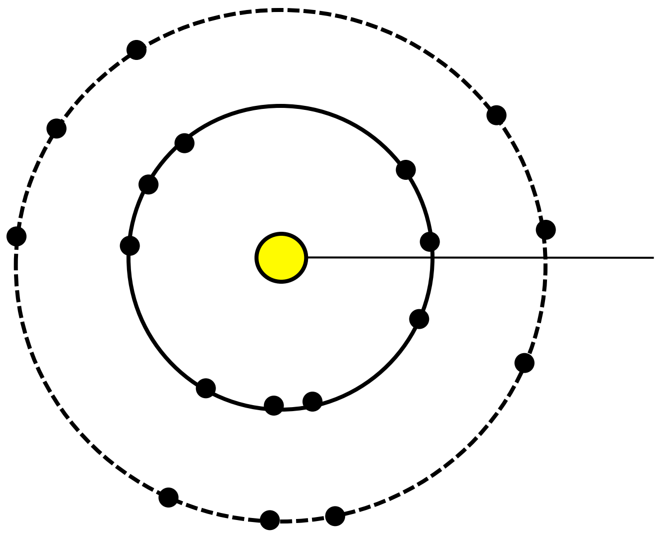
- The dynamics that give rise to TTV
- Sensitivity to Architecture
  - Upper limits and the lonliness of hot Jupiters
  - Prevalence of near-resonances
- Multi-transiting planets
  - Measurements of masses
  - Determination of full 3-D architecture

Dynamics: Orbital Timescales

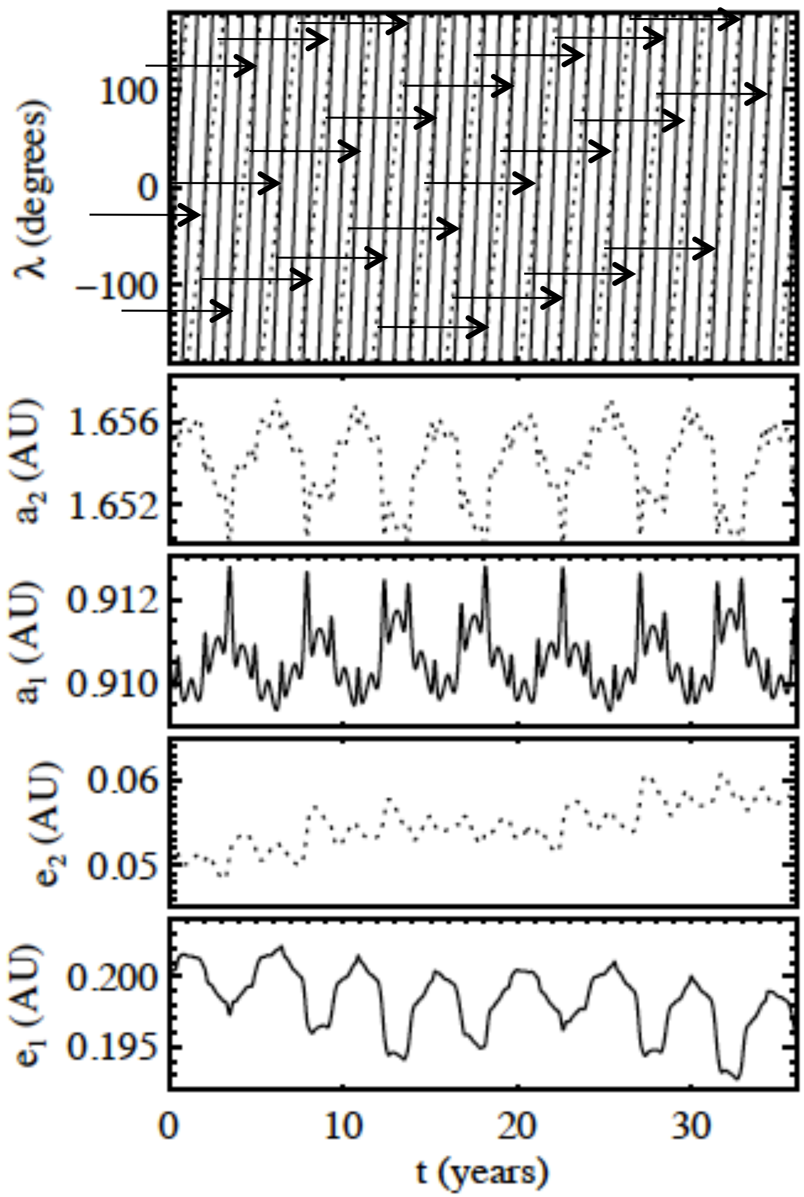




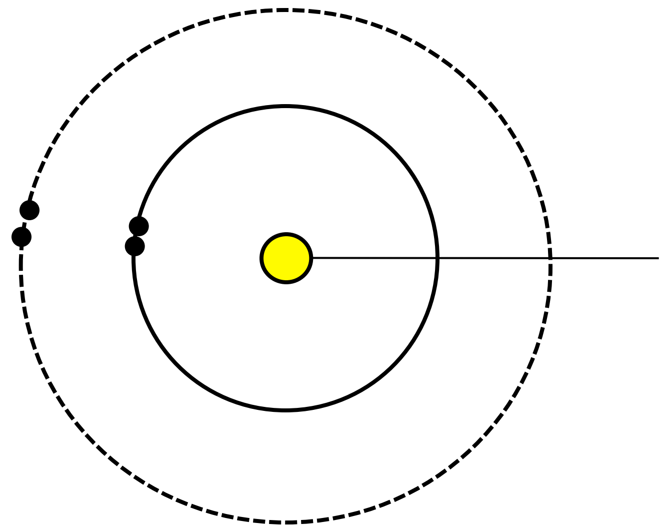
Dynamics: Secular Timescales



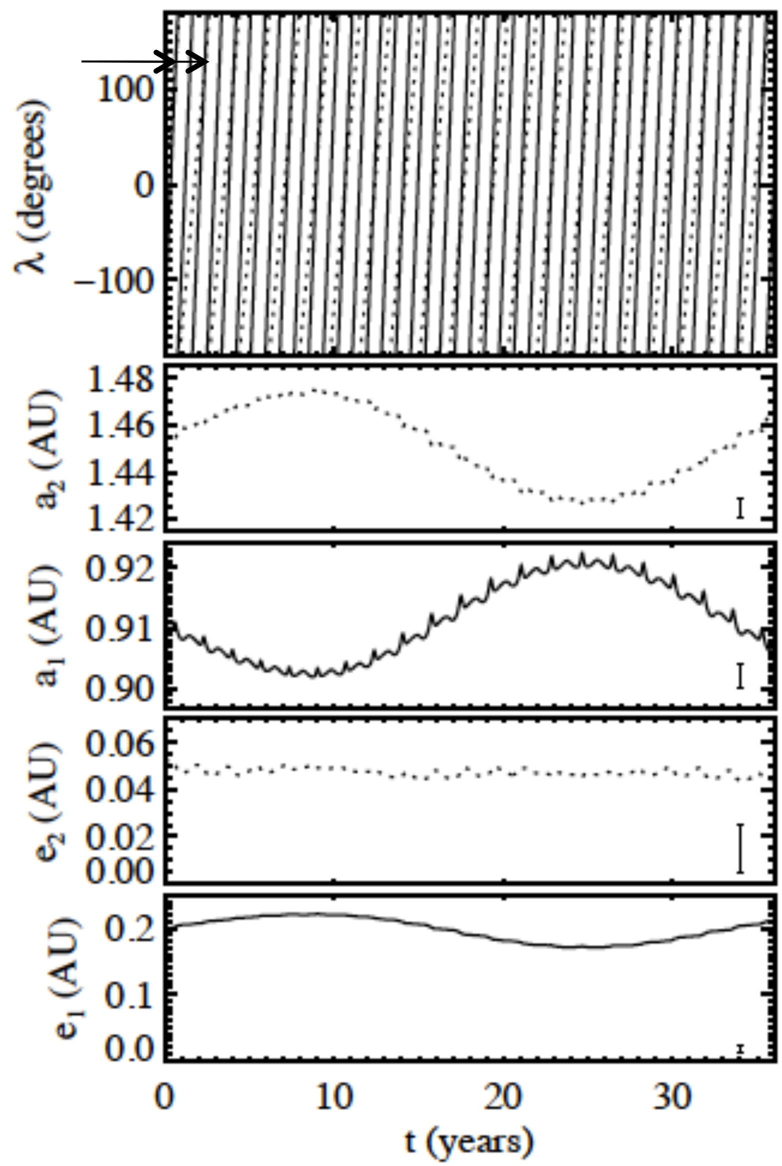
$P_2/P_1 = 2.44$
near 5:2



Dynamics: Resonant Orbits

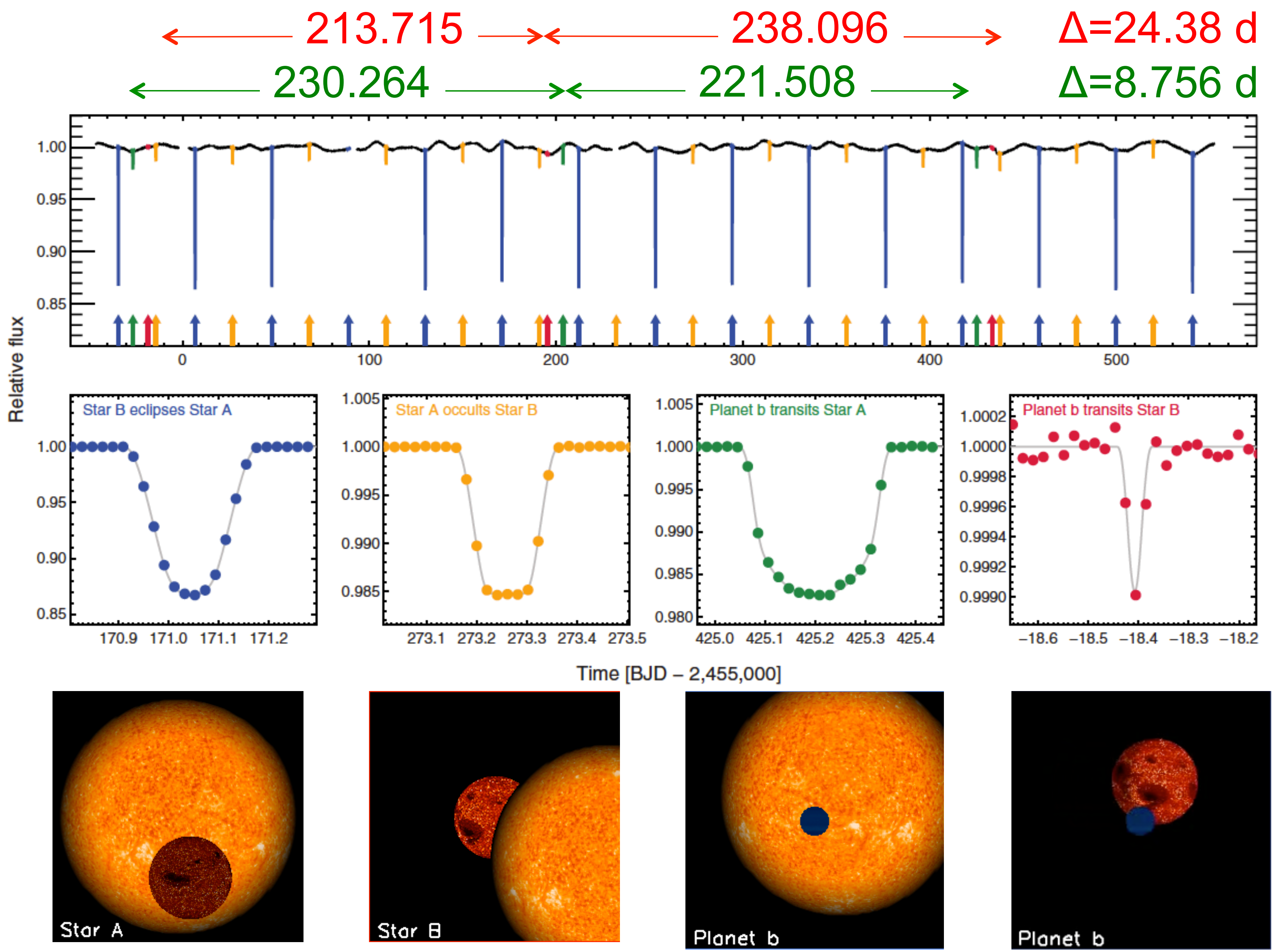


$P_2/P_1 = 2.00$



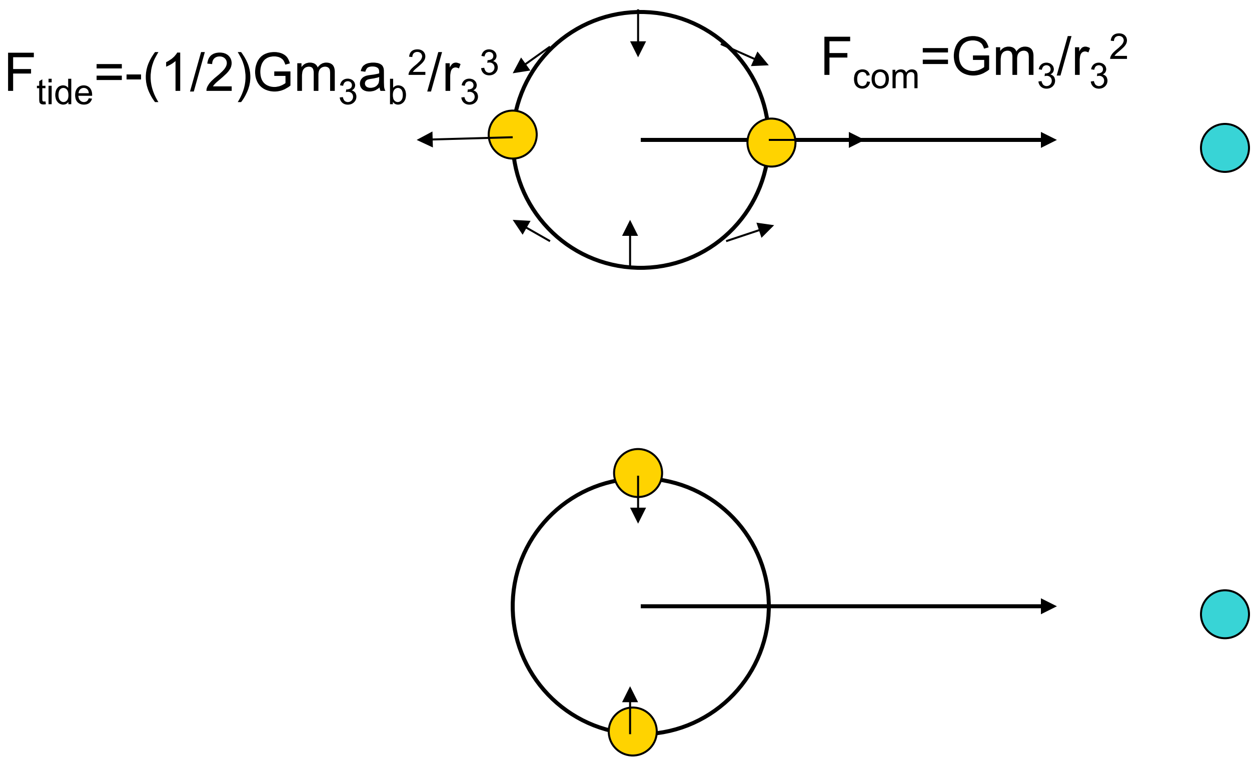
Keplerian Offsets

Kepler-16: Doyle, Carter, Fabrycky et al. 2011

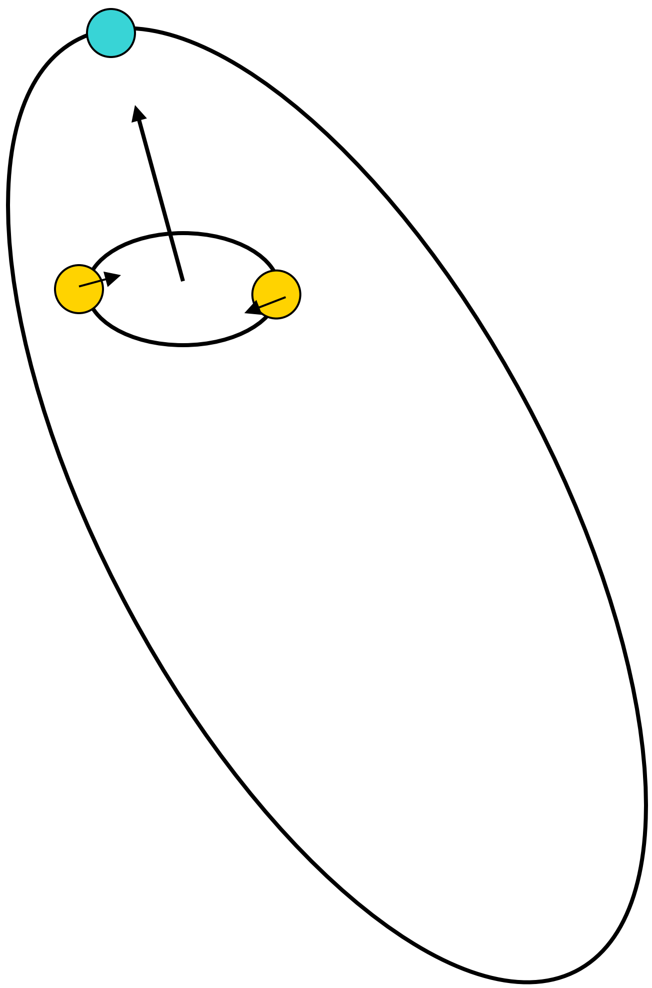


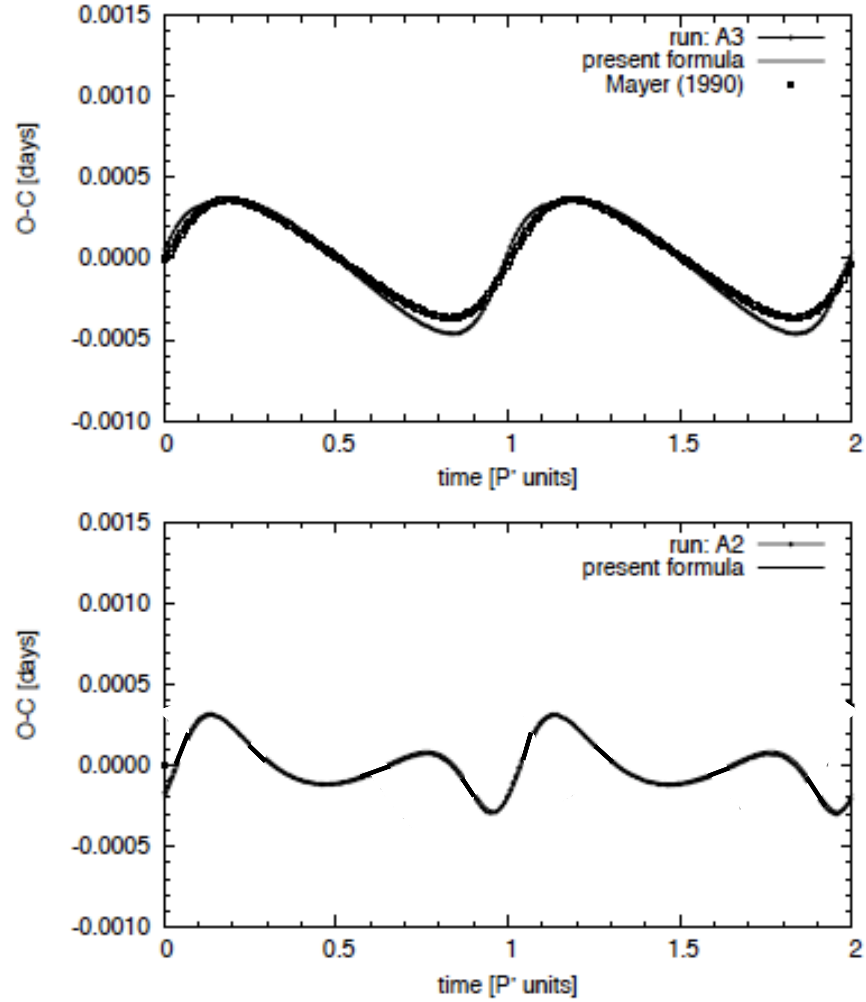
213.715
238.096
Δ=24.38 d
230.264
221.508
Δ=8.756 d
Relative flux
Star B eclipses Star A
Star A occults Star B
Planet b transits Star A
Planet b transits Star B
Time [BJD – 2,455,000]
Star A
Star B
Planet b
Planet b

Outer-Period Variation: Tidal period shift



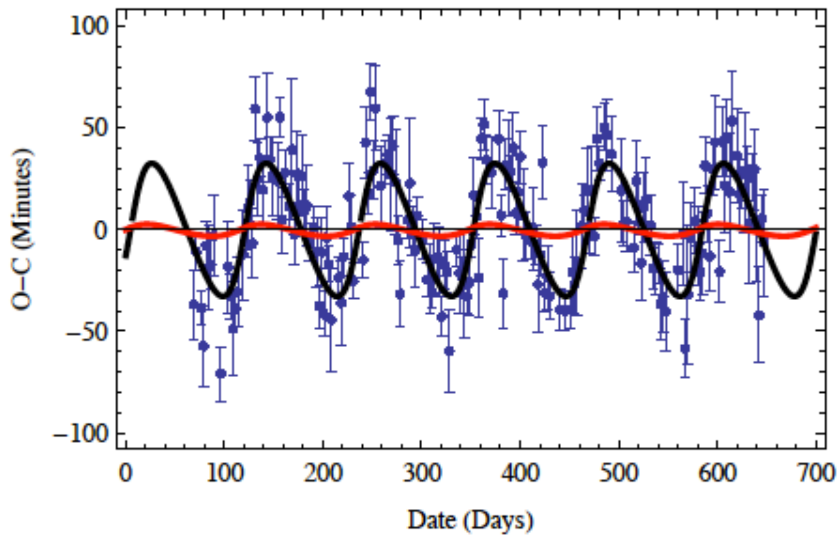
Outer-Period Variation: Inclination

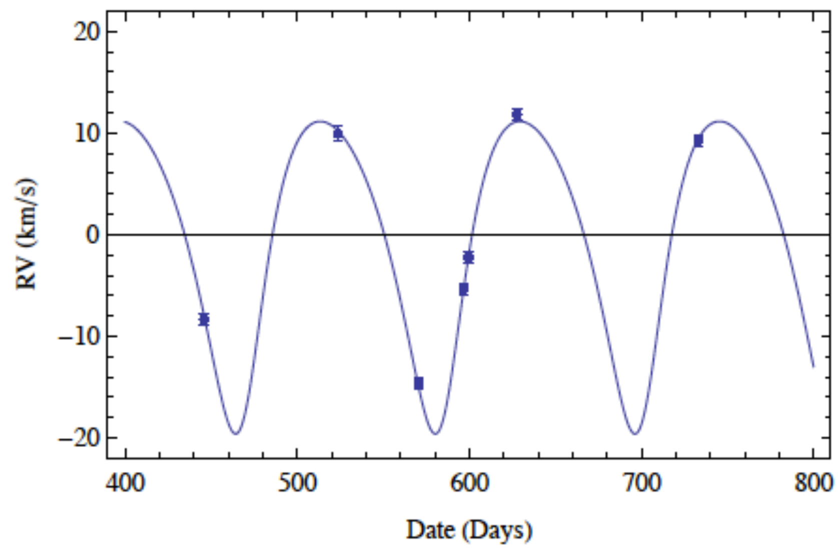




Borkovits et al. 2003

Tidal TTV examples





KOI-928

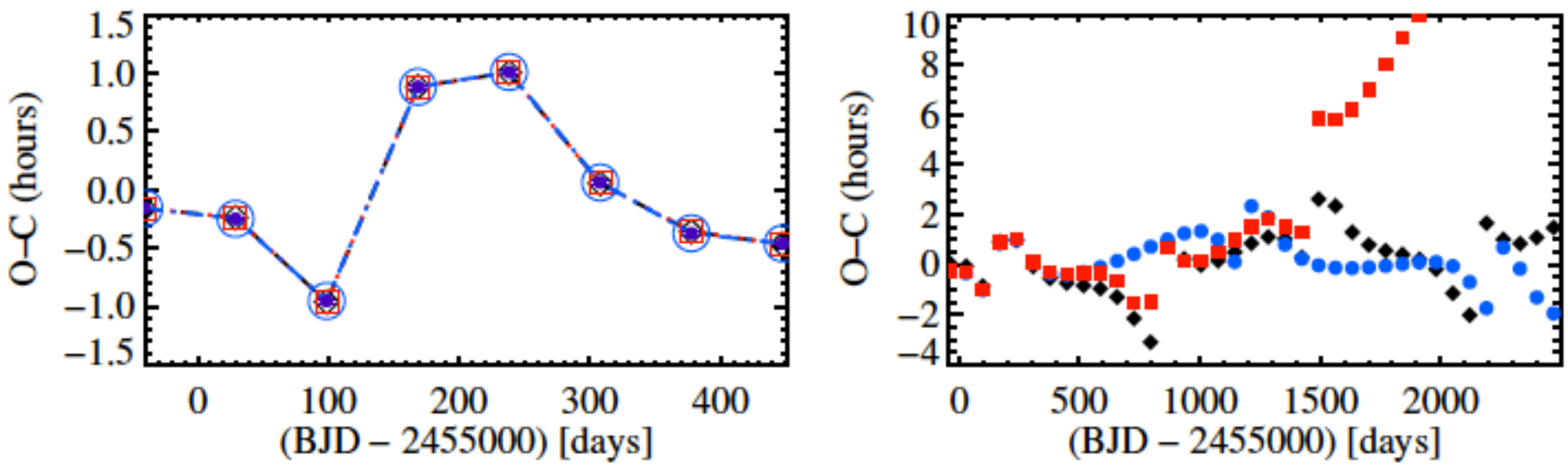
Steffen et al. (2011)

Solar-type primary star.

5.0 day binary of M-stars

orbiting it every 116 days.

Tidal TTV examples



KOI-1474

Dawson et al. (2012)

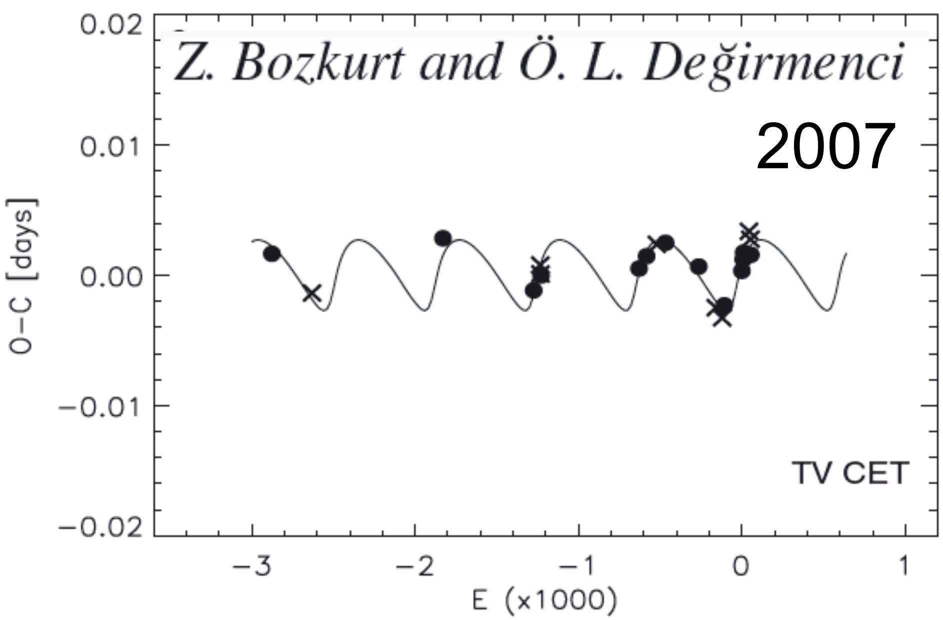
Jupiter-size transiting planet on an e=0.74-0.91 orbit. Strongly perturbed by a sub-stellar companion.

Light travel-time effect

$$T_{\min}(E) = T_0 + P_{\rm bin}E + K\left[\frac{1-e_3^2}{1+e_3\cos\nu_3}\sin(\nu_3+\omega_3) + e_3\sin\omega_3\right]$$

$$K = \frac{a_{12}\sin i_3}{c}$$

Irwin (1952)
Prsa et al. in prep.
Orosz et al. in prep.



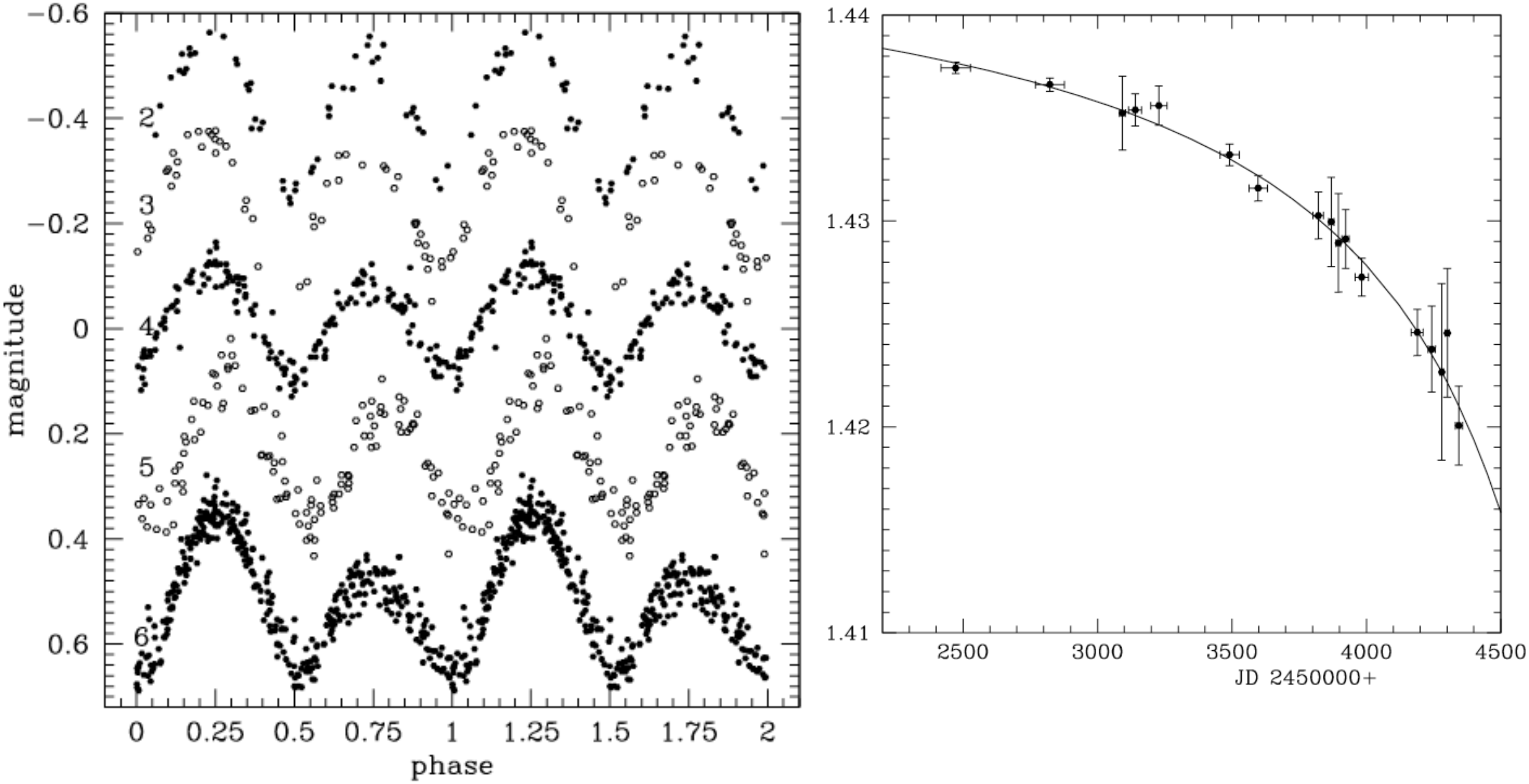
Parameters	TV Cet
M_1 ($M_\odot$)	1.39
M_2 ($M_\odot$)	1.27
R_1 ($R_\odot$)	1.47
R_2 ($R_\odot$)	1.27
$f(M_{3,4})$ ($M_\odot$)	0.0007
$M_{3,4,\min}$ ($M_\odot$)	0.18
$a_{3,4}$ (au)	8.19

Tidal Evolution?

- Close-in planets raise a tidal bulge on their host, as it dissipates the planet will be torqued into the star (Rasio+95, Sasselov02)
- It happens; will we observe it?

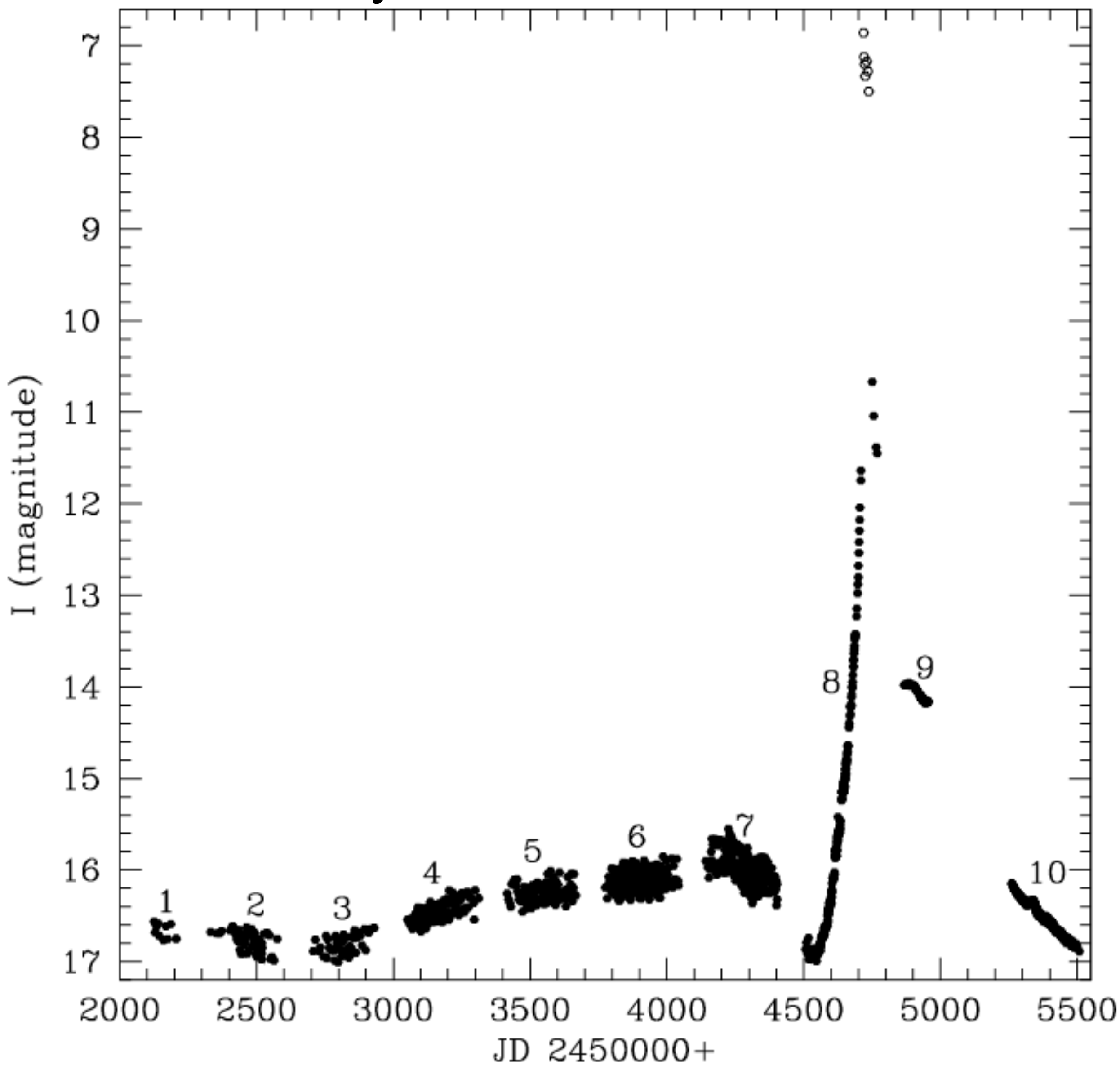
V1309 Scorpii: Merger of a Contact Binary

Tylenda et al. 2011



V1309 Scorpii: Merger of a Contact Binary

Tylenda et al. 2011

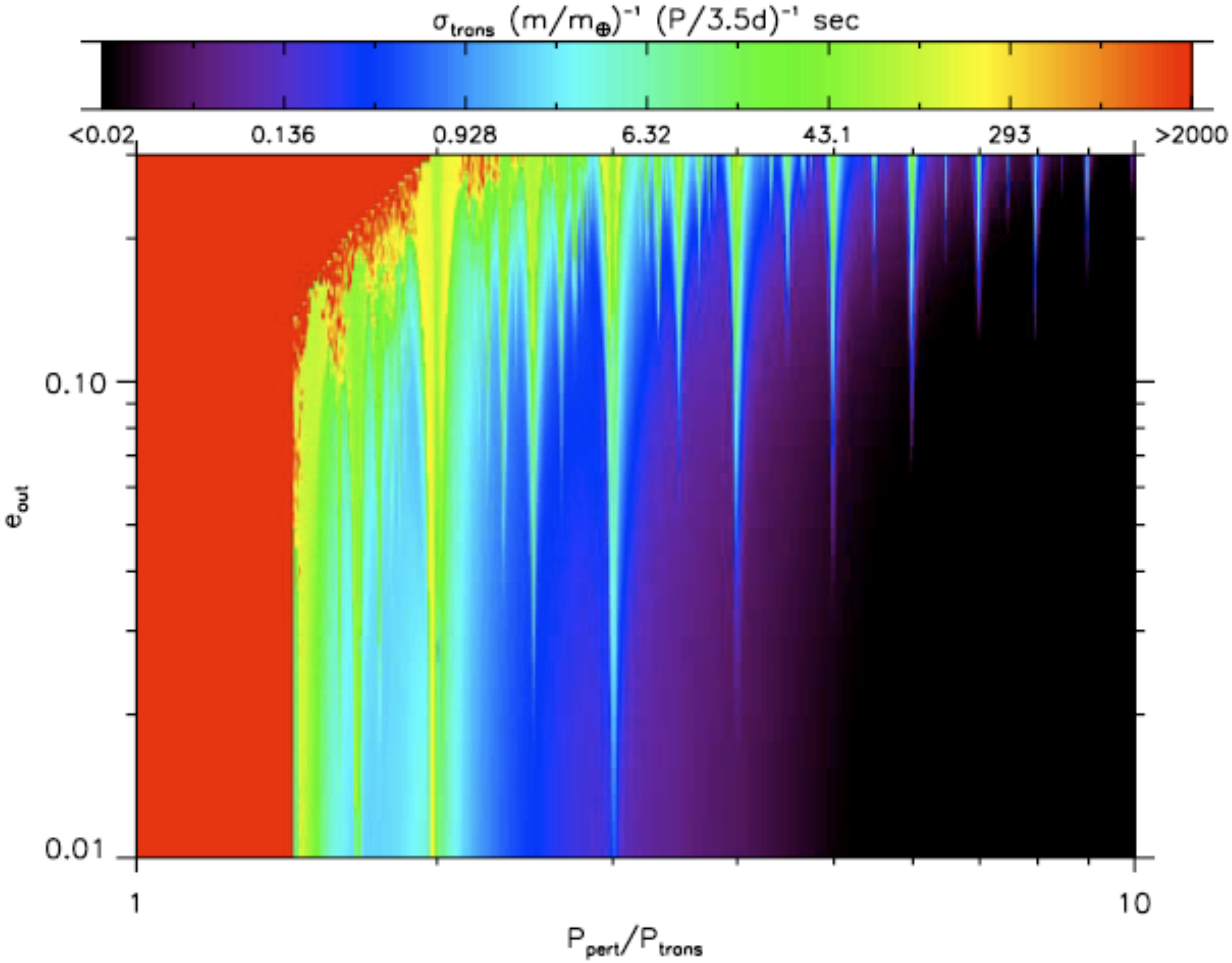


Additional Theory

- Secular (Miralda Escude 2002, Heyl & Gladman 2007 (in-plane), Pal & Kocsis 2007 (GR), Ragozzine & Wolf 2008 (tidal)) -- TDV
- Long-period (Borkovits et al. 2003)
- Moons (Kipping 2009ab, Simon 2007, Sato & Asada 2009) -- TDV again
- Trojans (Ford & Gaudi 2006, Ford & Holman 2007)
- Motion (Rafikov 2008 (Proper motion), Scharf 2007 (Parallax), Irwin 1952 (light-time))
- Stellar variability (Alonso+2008 (spots), Loeb 2009 (stellar size))
- Watson 2010 (oblateness, Applegate effect)
- Planetary Spin Precession (Carter and Winn 2010)
- Planetary consumption (Sasselov 2003)
- Clocks wrong (Eastman et al. 2010)

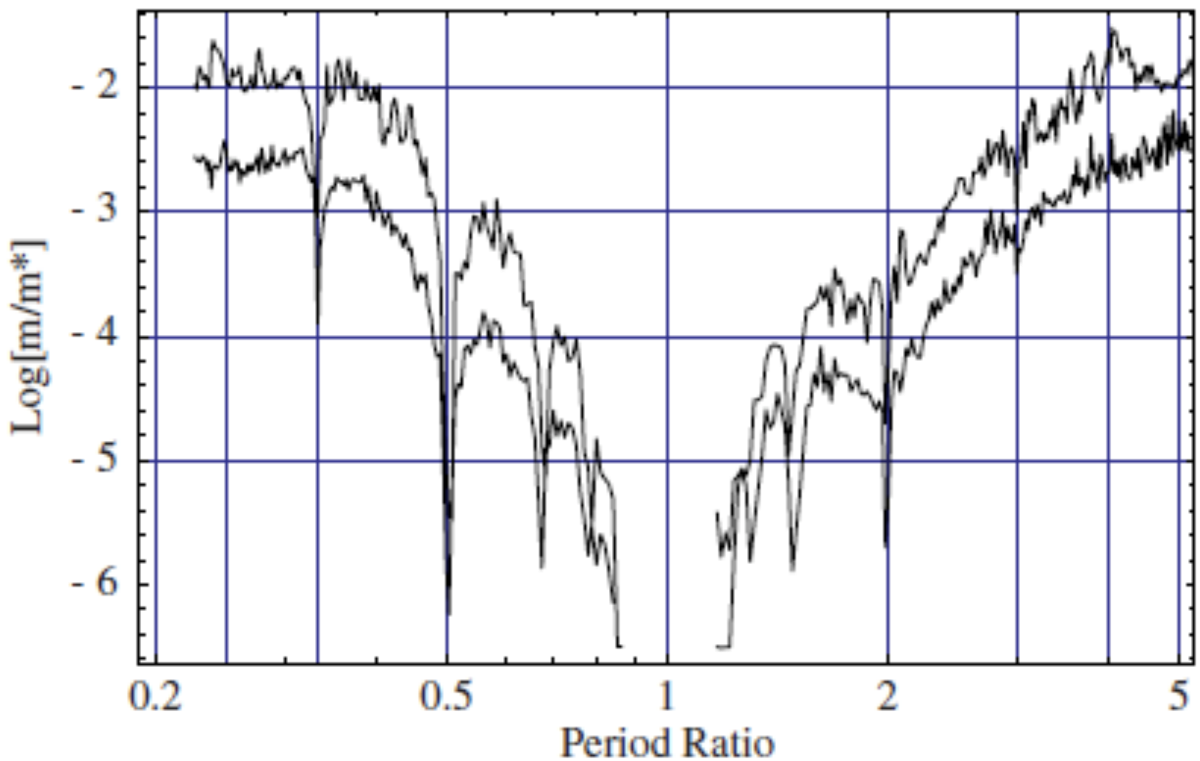
- Exciting papers (Agol et al., Holman & Murray 2005), emphasizing resonant effect

The Promise



Agol, Steffen, Sari, Clarkson (2005)

The Frustration



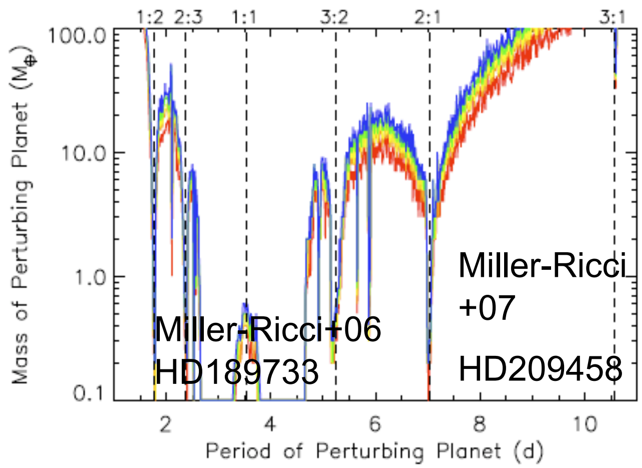
TrES-2

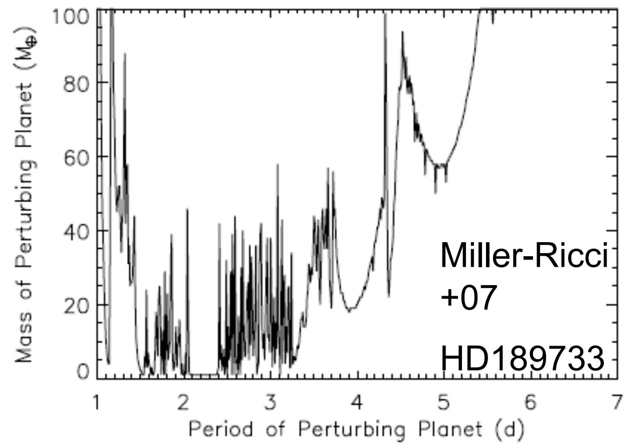
HD 209458

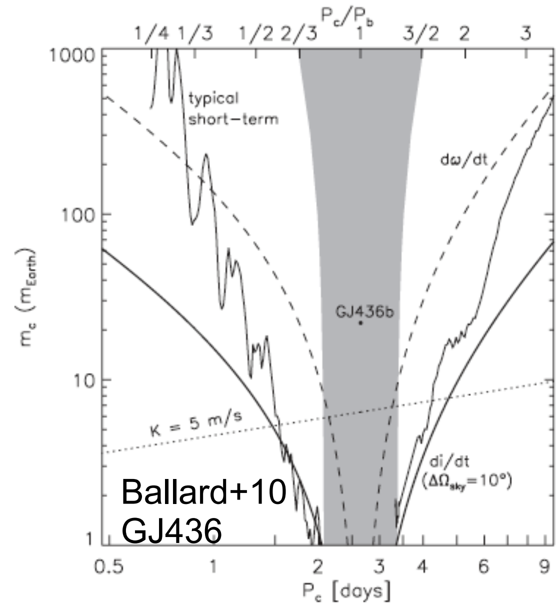
Steffen & Agol 2005

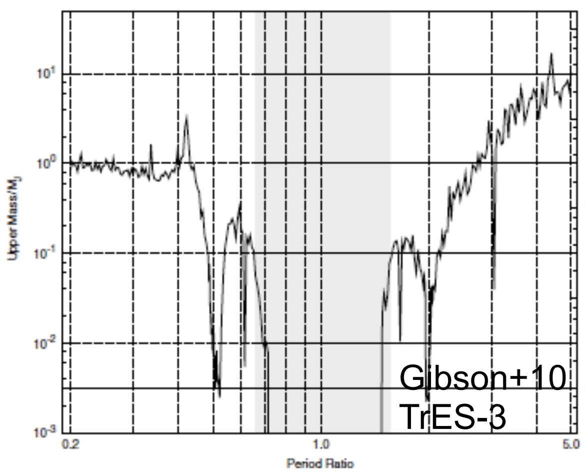
Agol & Steffen 2007

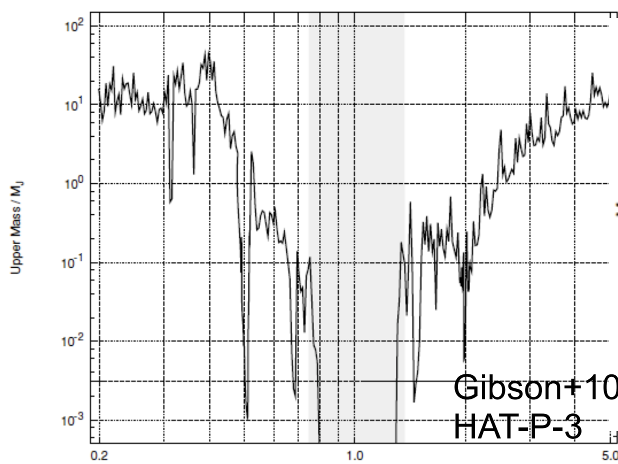
The Frustration

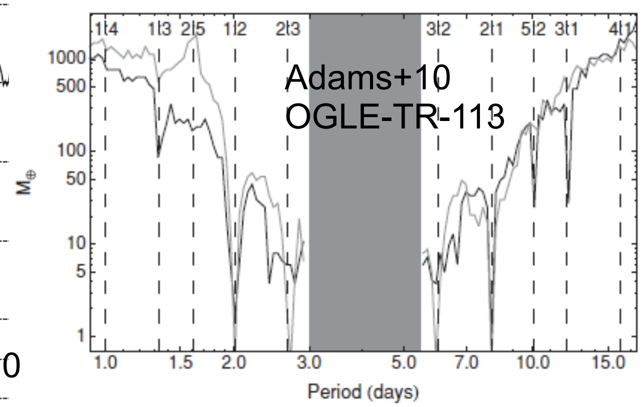


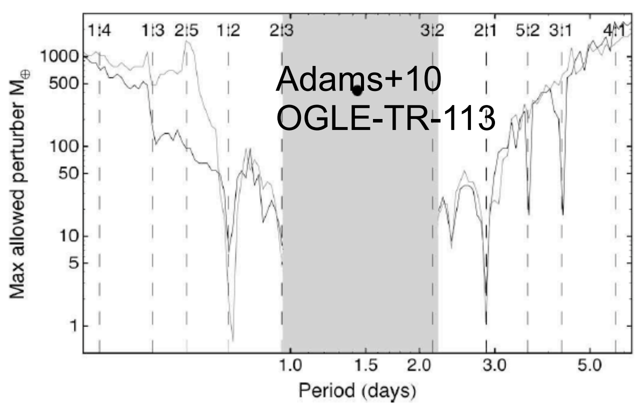


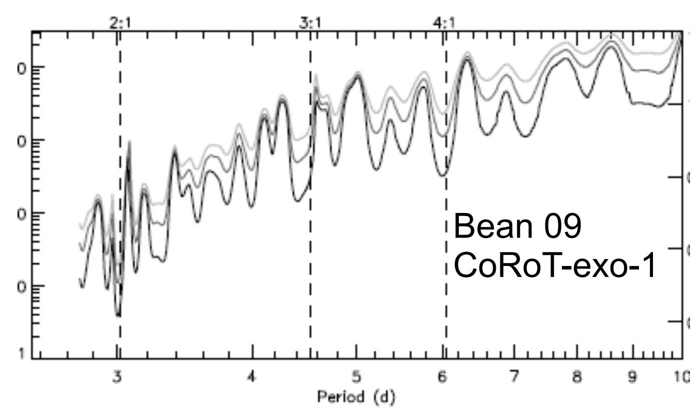


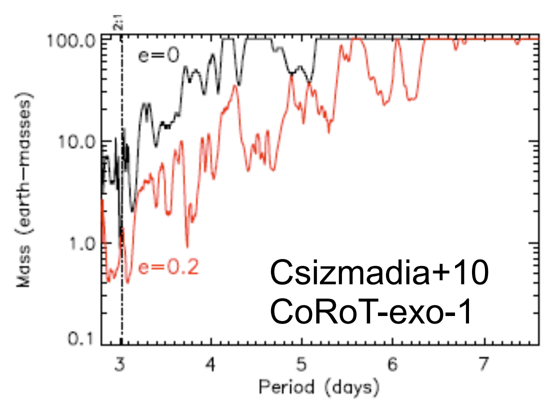








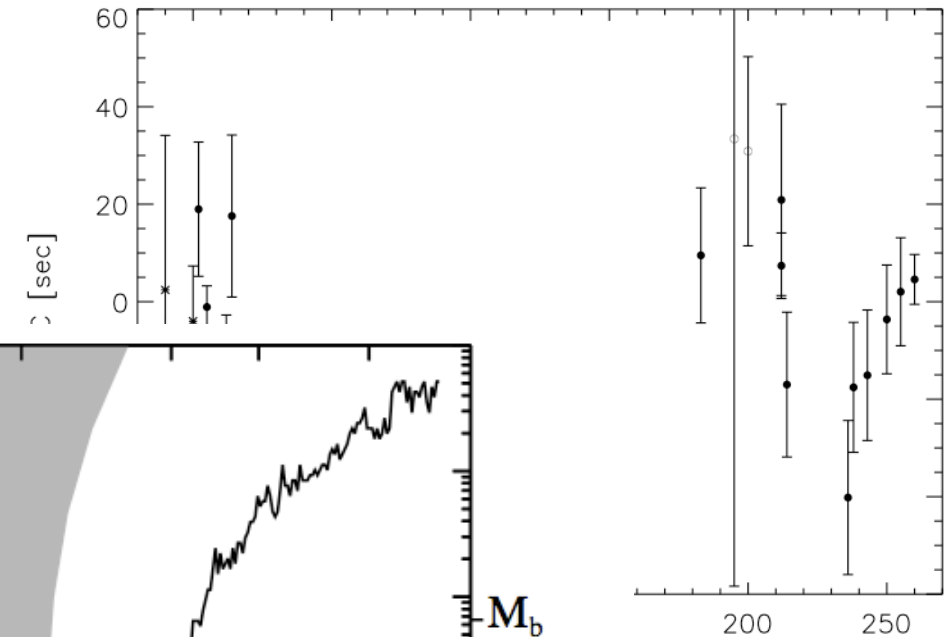


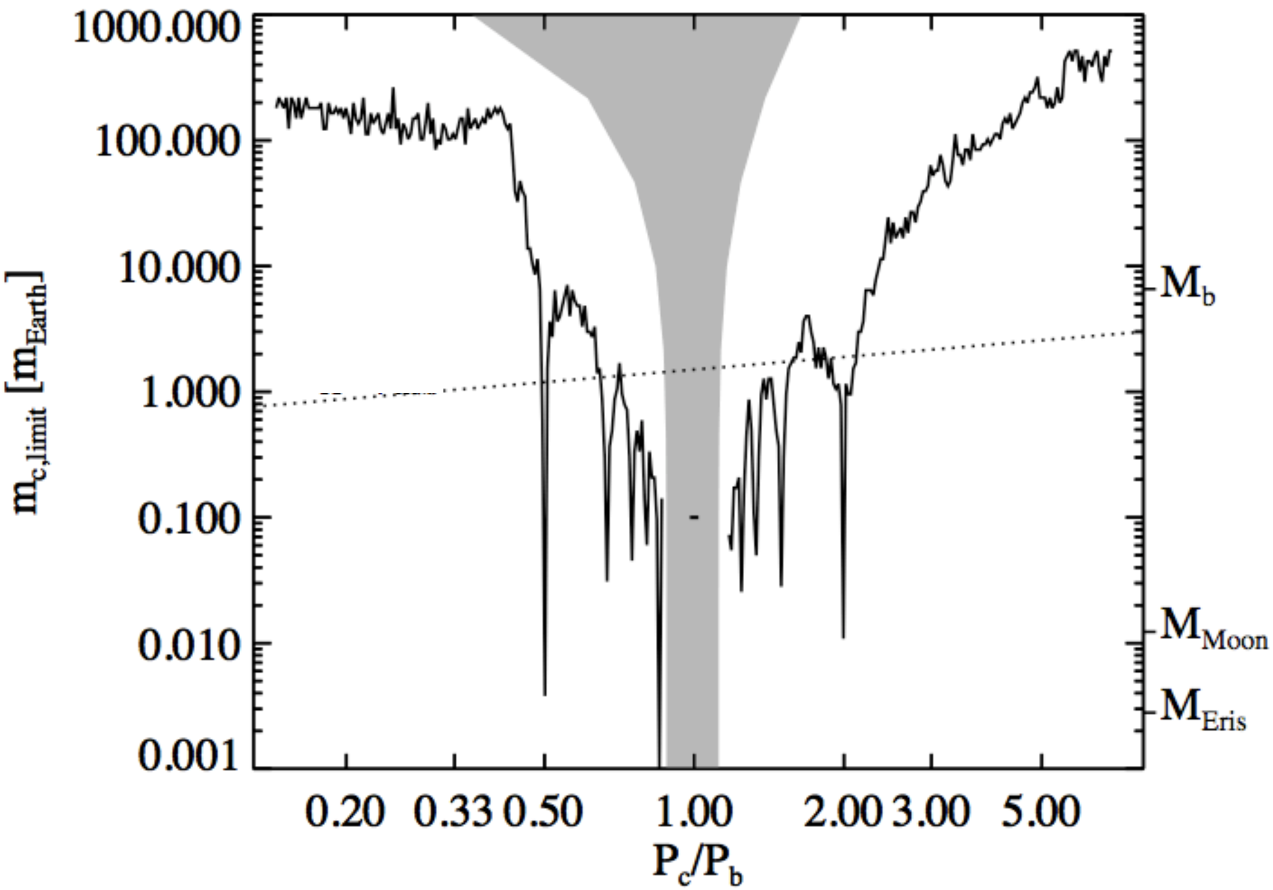


The Frustration

GJ 1214

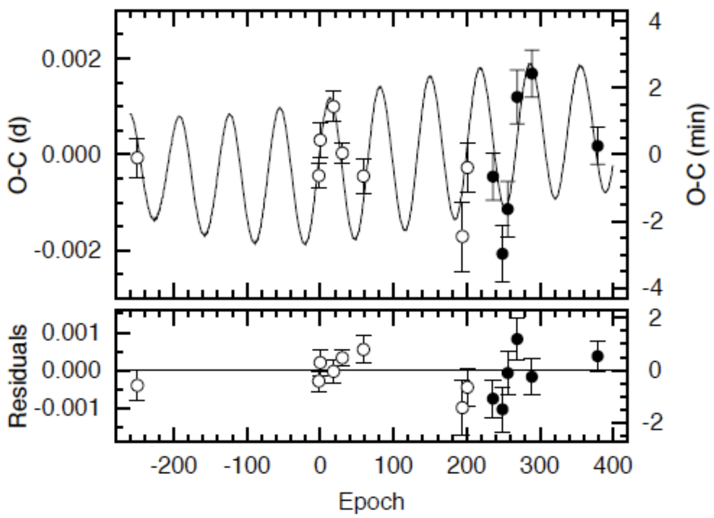
Carter et al. 2010

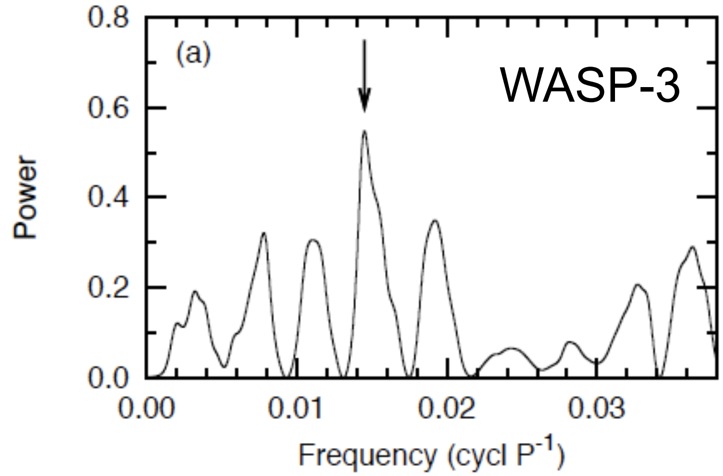


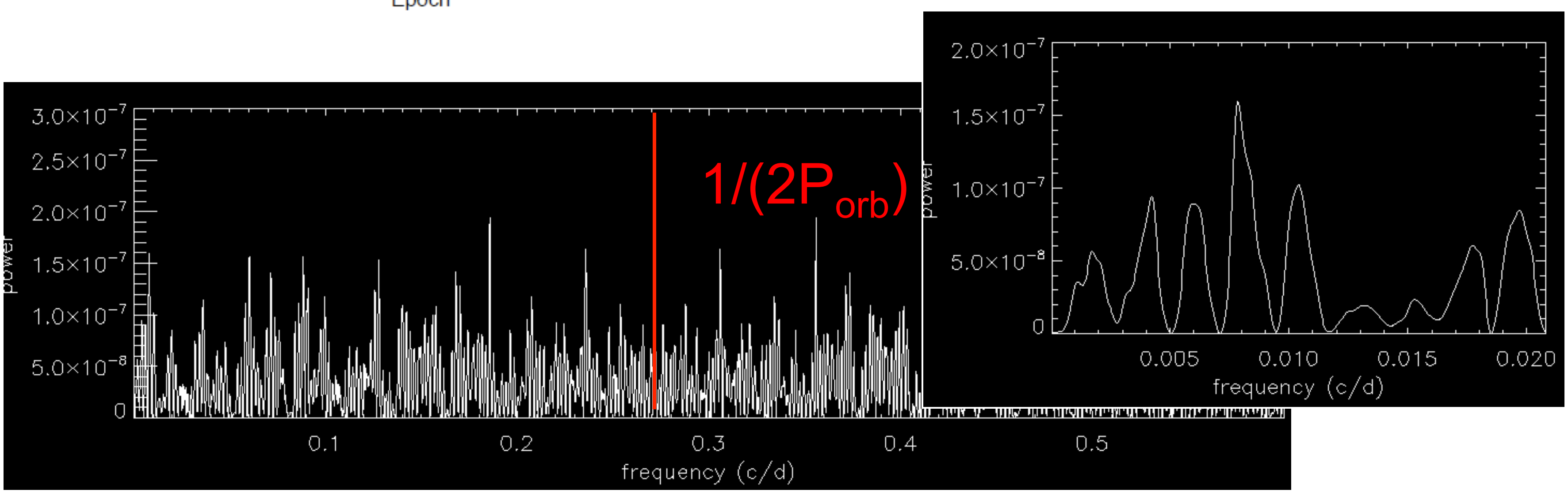


Periodograms

Steffen's 2006 thesis, Maciejewski et al. 2010, Kipping & Bakos 2010

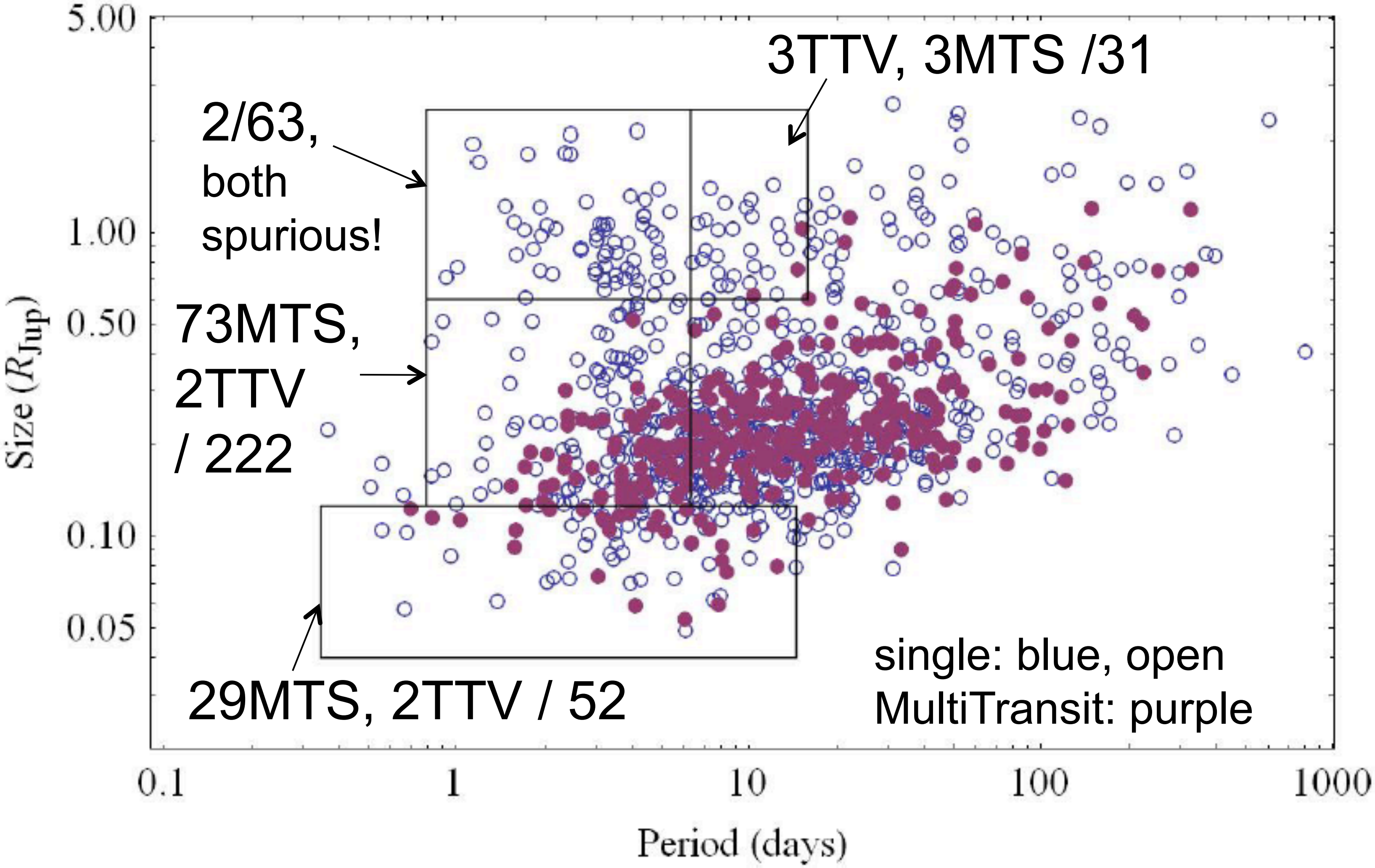






Kepler says: Hot Jupiters are Lonely

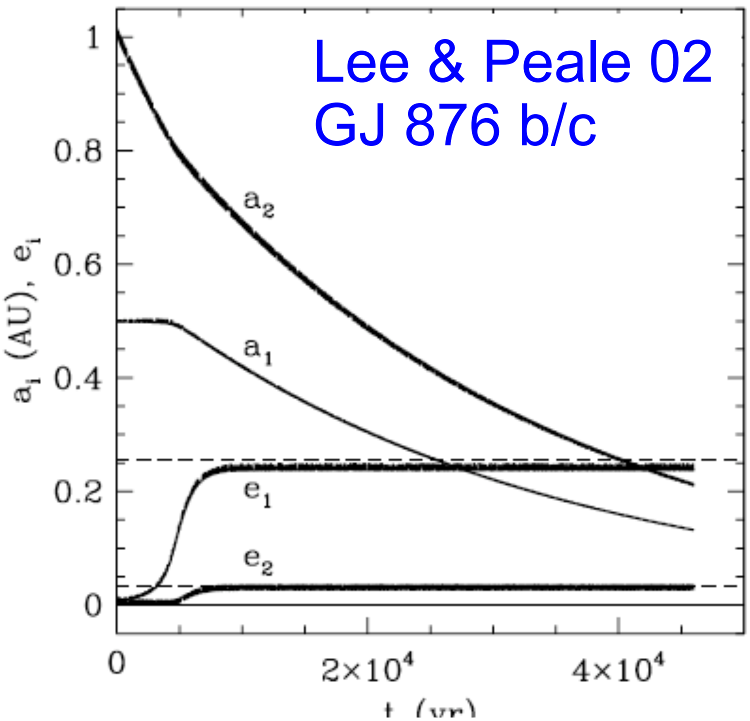
Steffen et al. 2012



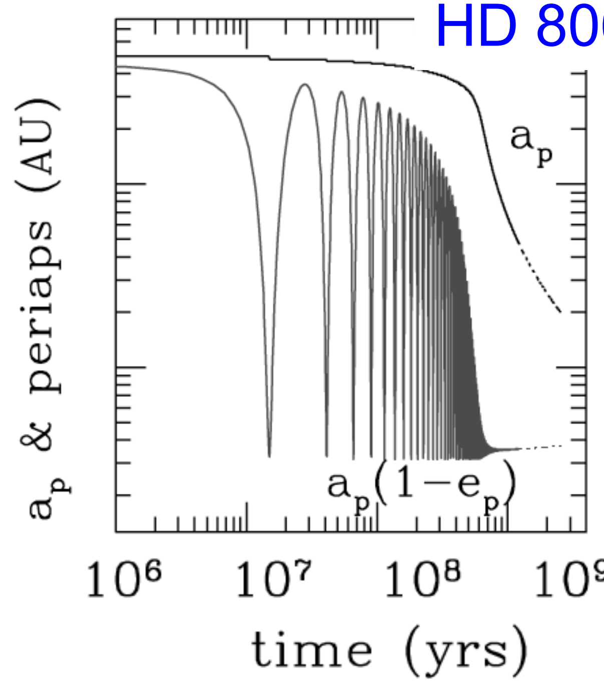
Why?

Disk migration theory

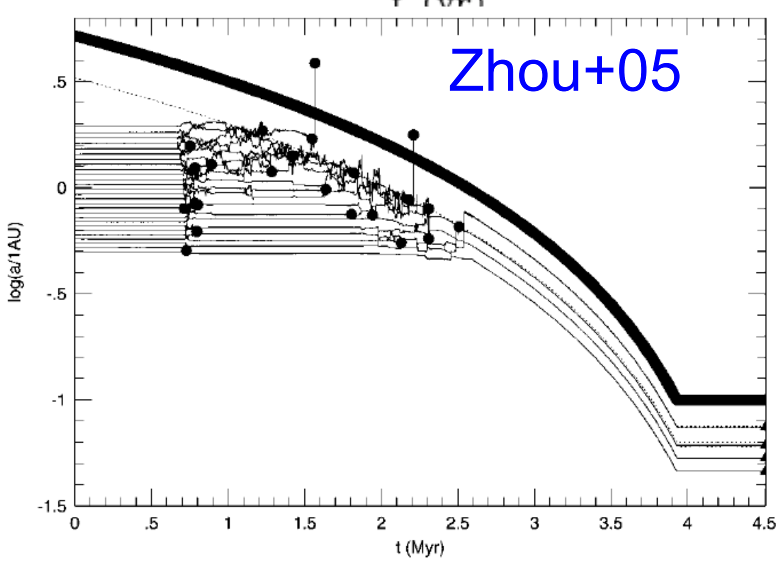
Lee & Peale 02
GJ 876 b/c

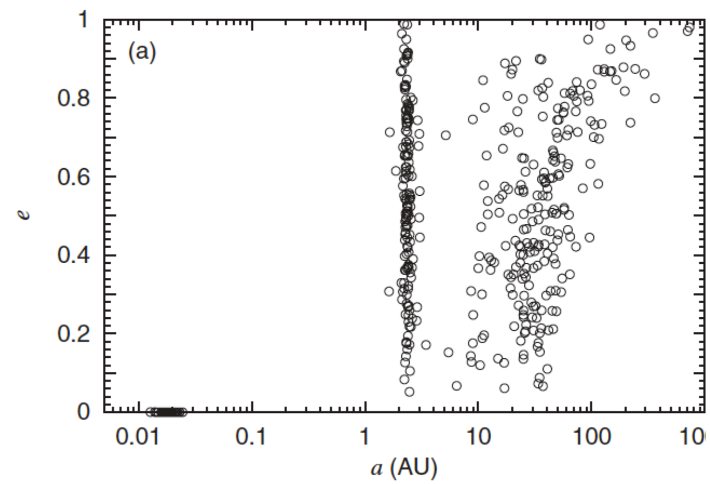


Wu & Murray 03
HD 80606b



Zhou+05



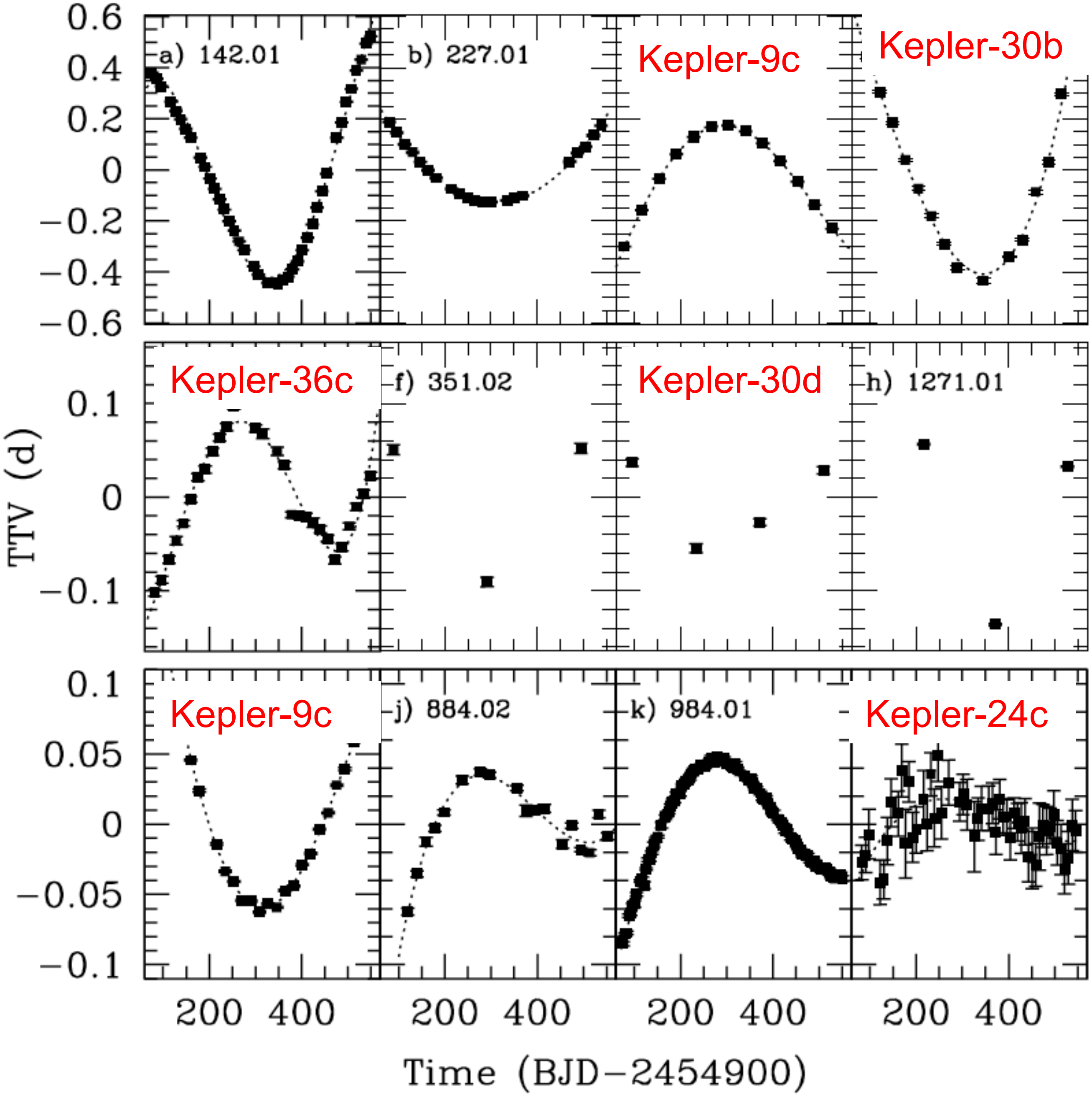


Nagasawa+08/11

High-eccentricity migration

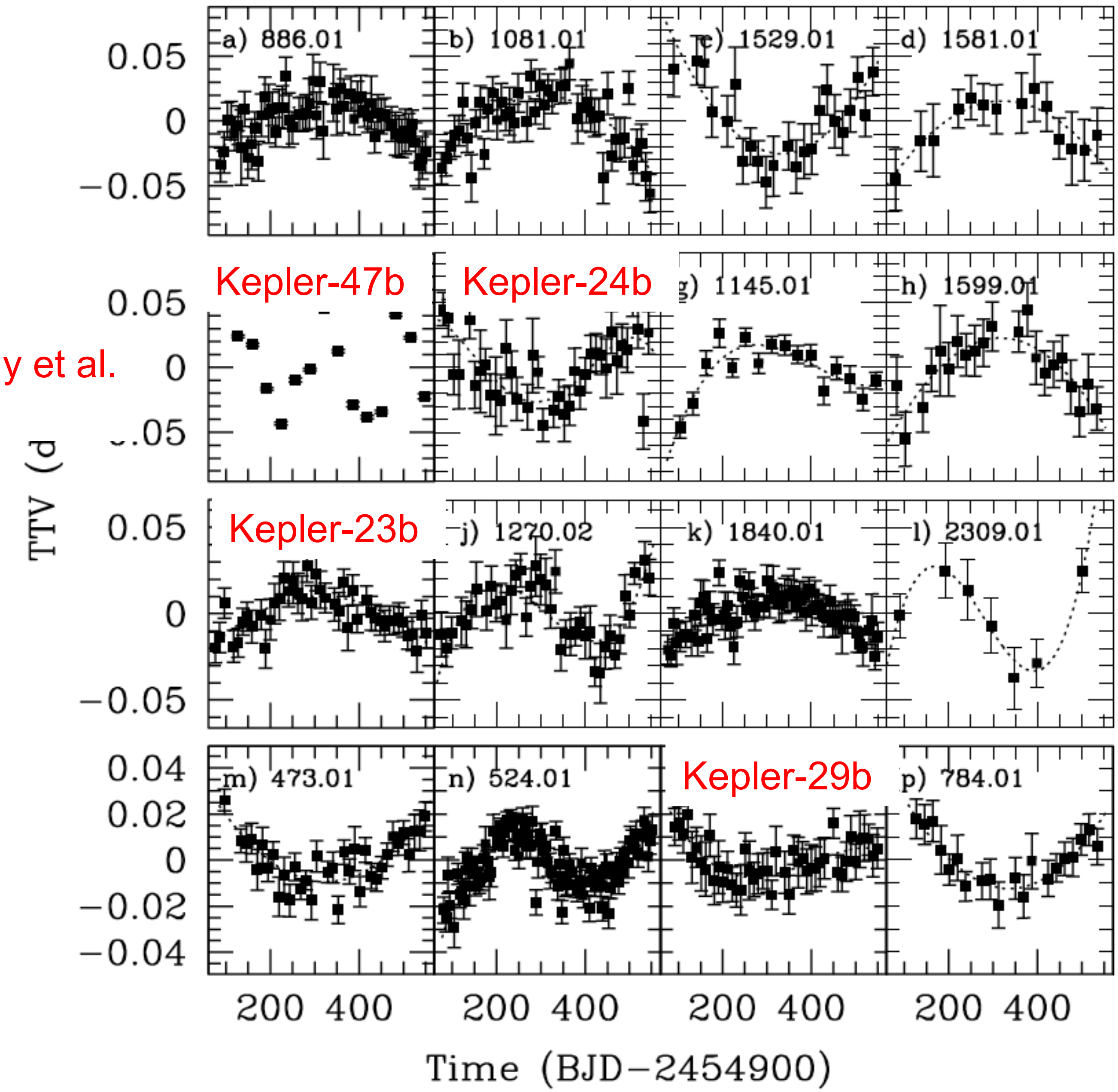
✔ Hot Jupiters

Embarrassment of Riches of TTV

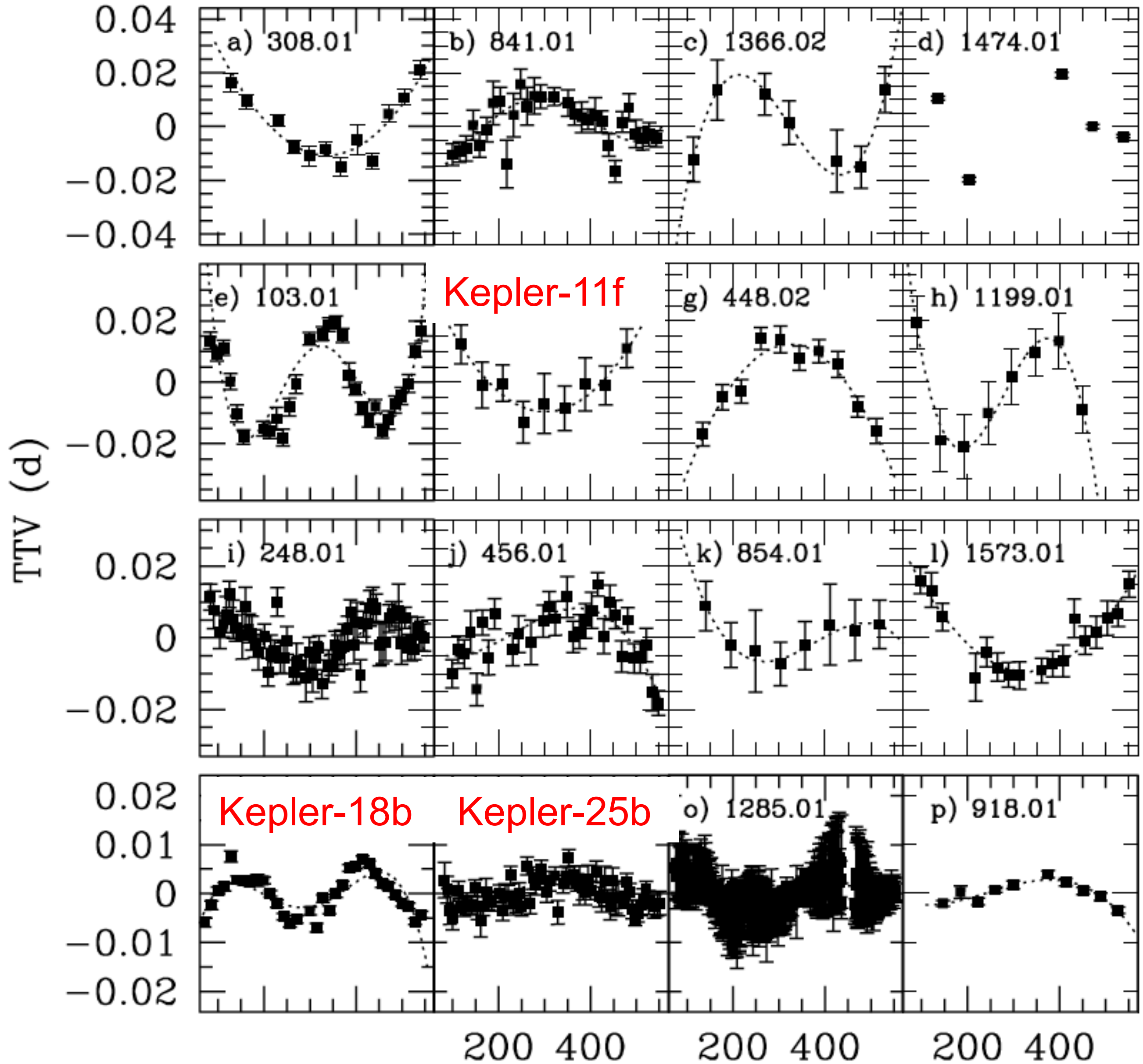


Embarrassment of Riches of TTV

Nesvorny et al. 2012



Embarrassment of Riches of TTV



Dawson et al. 2012
Awaiting acceptance /adoption

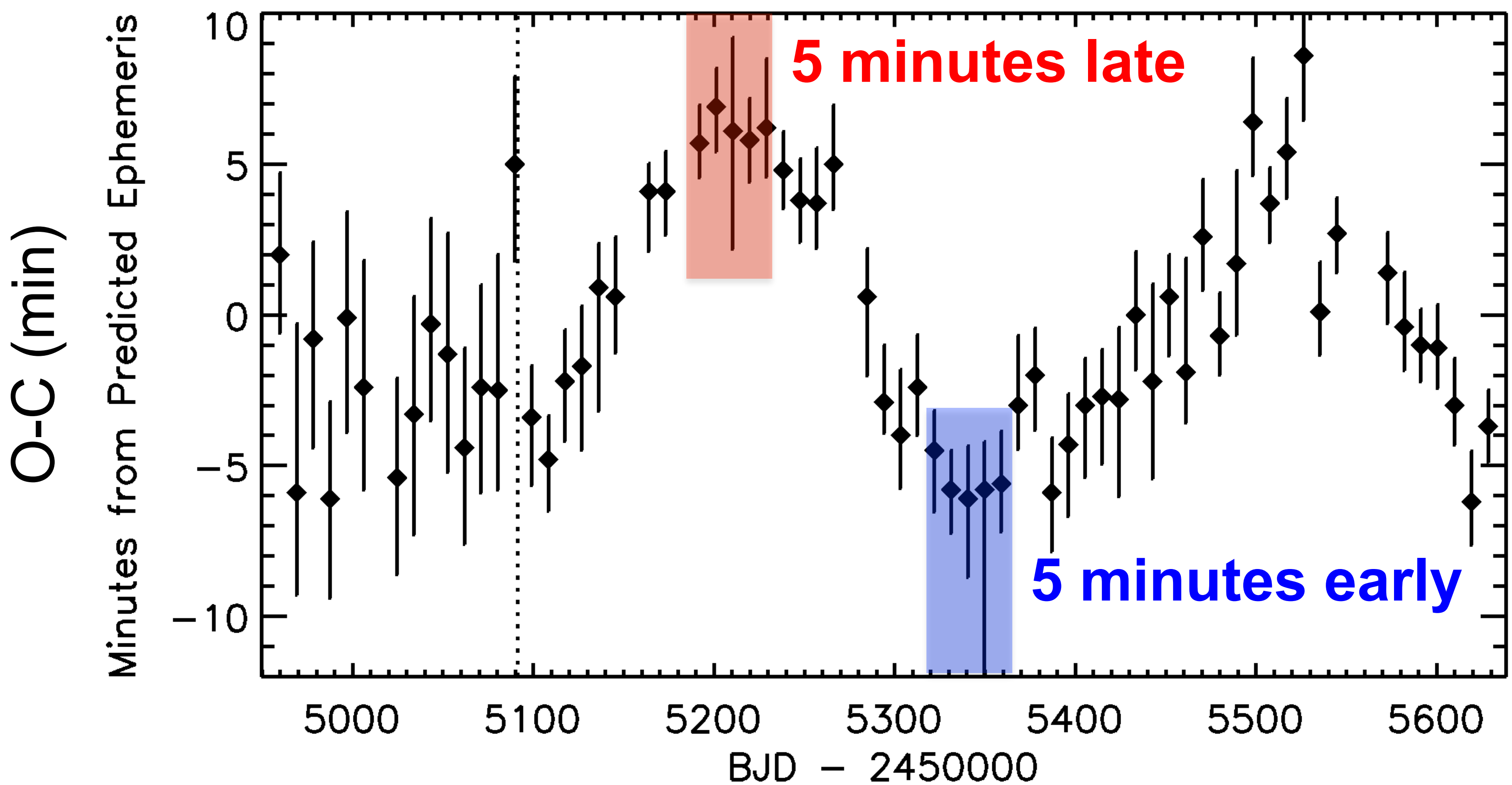
The Inverse Problem

- Perturbation theory (Agol et al. 2005 Appendix, Nesvorny & Morbidelli 2008, Nesvorny 2009, Nesvorny & Beauge 2009)
- Numerical approach (Meschari et al. 2009, Meschari & Laughlin 2010)
- Effects of Inclination near resonance (Payne et al. 2009)
- Extreme phase sensitivity (Veras et al. 2010)

- In general, difficult degeneracies plague TTV inversions.

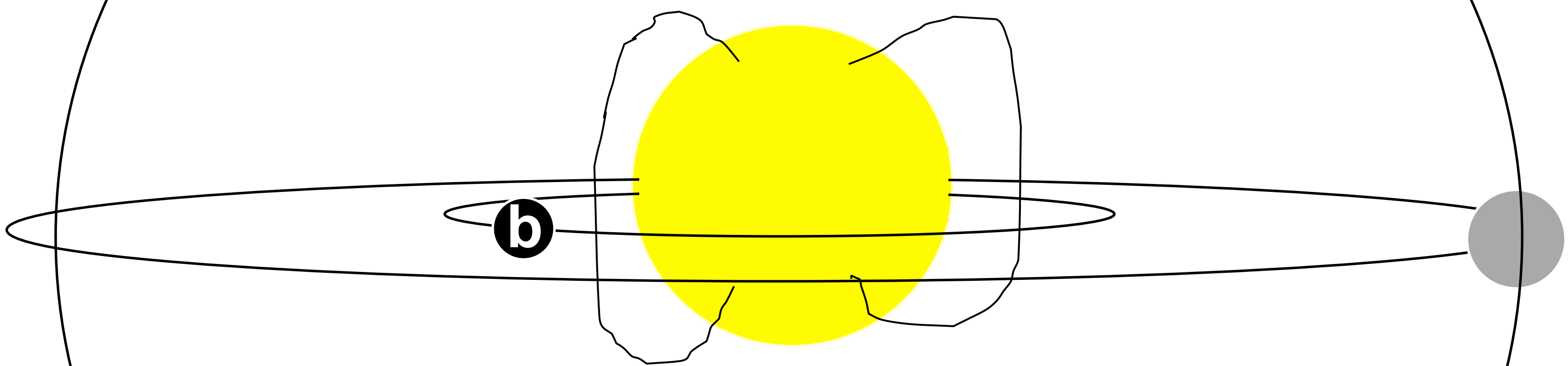
Kepler-19

Ballard, Fabrycky, Fressin et al. 2011



thanks to Sarah for slides

What's causing the TTV?



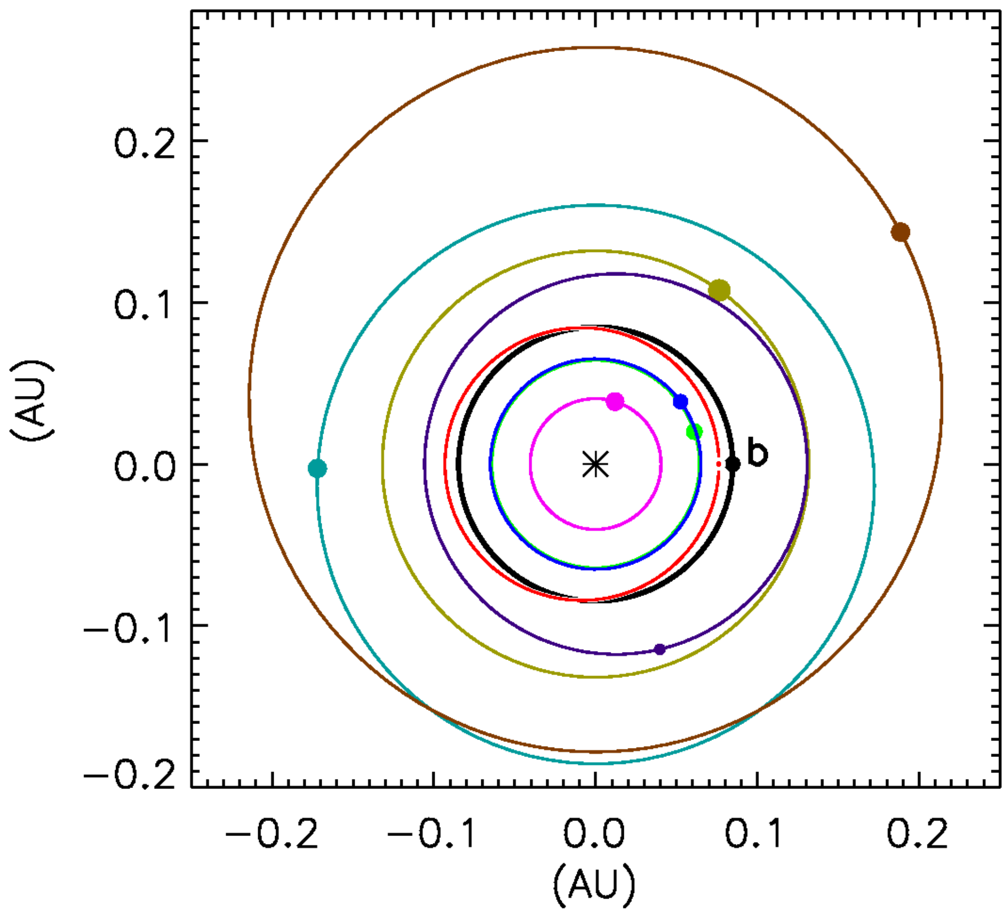
Light travel time hypothesis: would induce km/s Doppler shift (ruled out by order of magnitude)

Applegate effect: TTV amplitude too small, quiet star

Rotation of apsidal line: Timescales >> P_{TTV}

Tidal effect of star at $P=2P_{TTV}$: ruled out by RV, except for unlikely face-on inclination

Lots of possible orbits for the planet Kepler-19c



Possible orbits:

Mean motion resonances:

<2:3

>2:3

<2:1

Higher-order resonances:

<1:3

<5:3

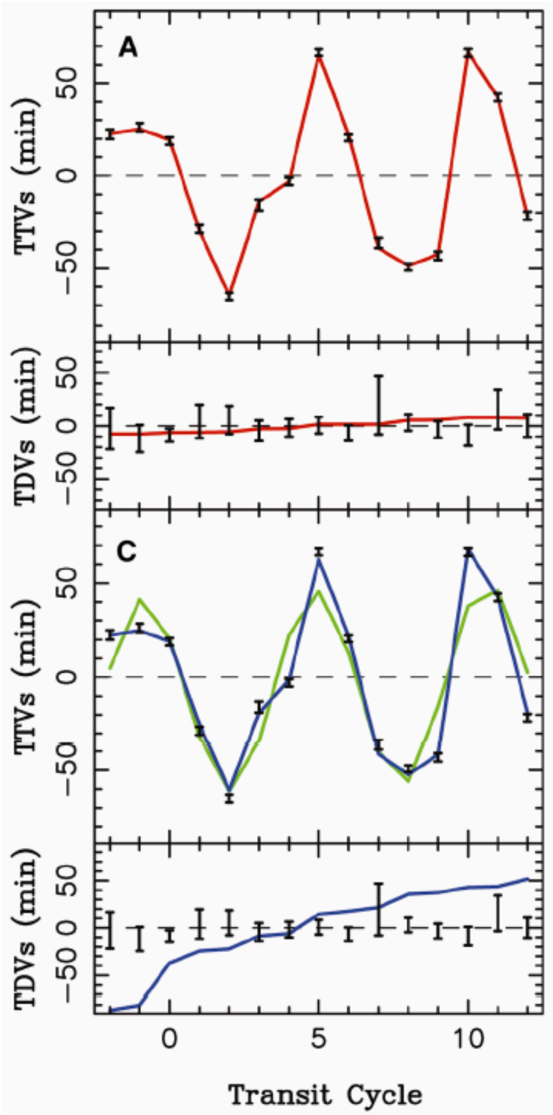
<3:1

>4:1

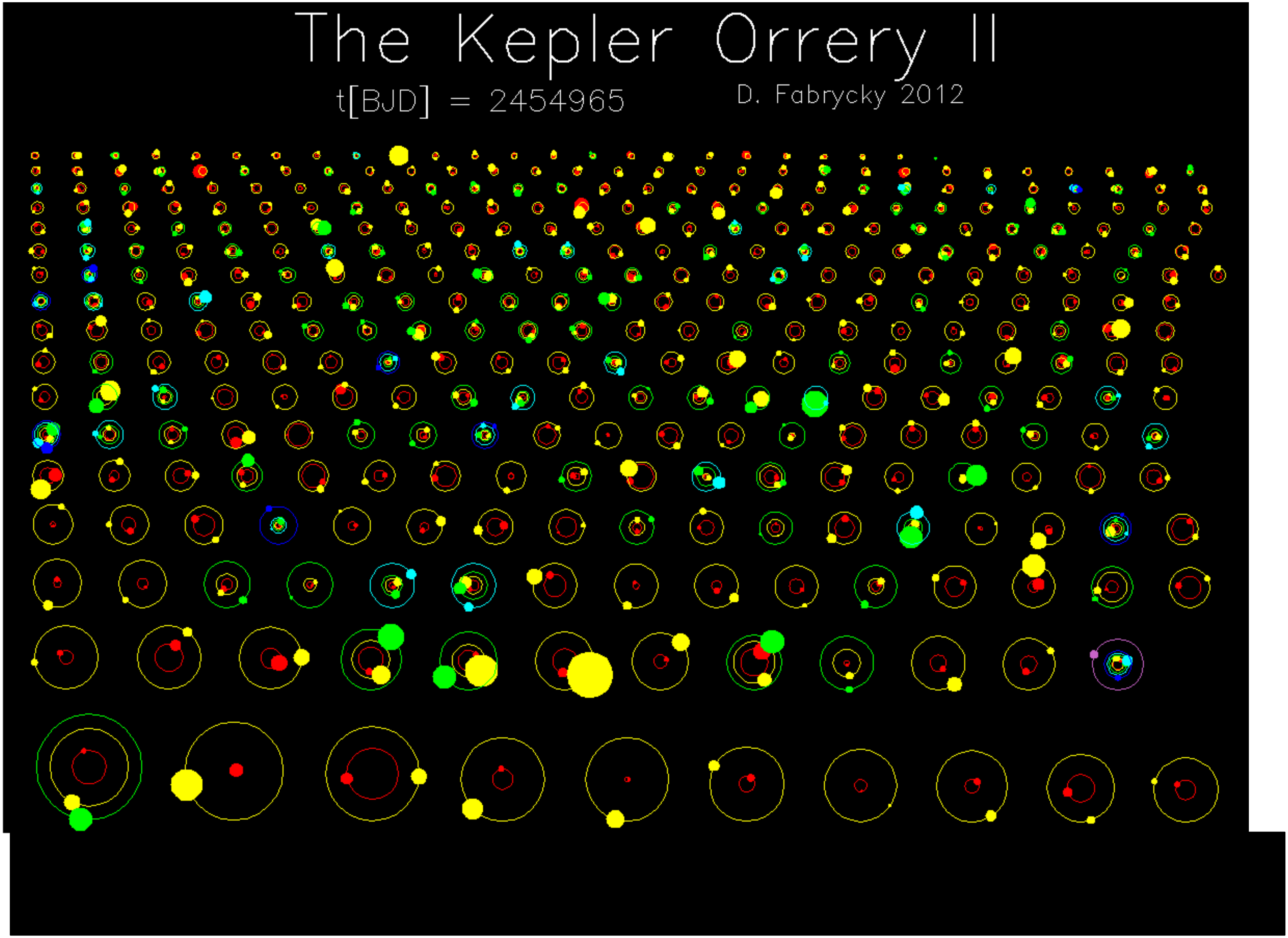
Co-orbital planet? Distant retrograde moon?

1:1

KOI-872 Nesvorny et al. 2012



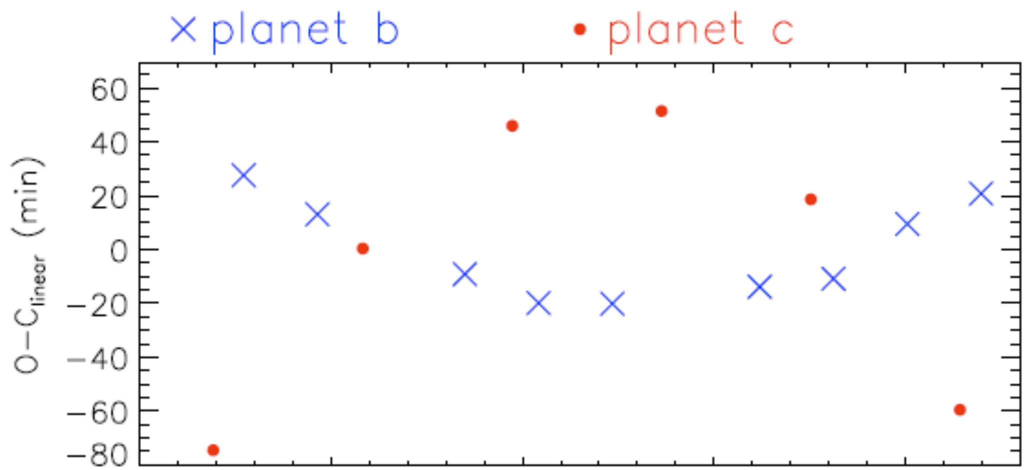
	KOI-872b	KOI-872c
τ_0 [BJD_{UTC}]	$2455053.2826^{+0.0013}_{-0.0014}$	–
P_P [days]	$33.60134^{+0.00021}_{-0.00020}$	$57.004^{+0.091}_{-0.100}$
R_P/R_*	$0.0887^{+0.0011}_{-0.0012}$	–
b_P	$0.759^{+0.022}_{-0.027}$	$3.1^{+1.1}_{-1.9}$
a_P/R_*	$44.9^{+2.1}_{-1.8}$	$63.9^{+2.9}_{-2.5}$
i_P [°]	$89.033^{+0.076}_{-0.069}$	$87.25^{+1.70}_{-0.95}$
a_P [AU]	$0.1967^{+0.0029}_{-0.0028}$	$0.2799^{+0.0041}_{-0.0040}$
e_P	$0.01^{+0.01}_{-0.01}$	$0.0145^{+0.0035}_{-0.0039}$
Ω_P [°]	270	303^{+20}_{-34}
ϖ_P [°]	–	$329.4^{+11}_{-9.2}$
λ_P [°]	0	$338.3^{+1.3}_{-1.4}$
M_P/M_*	$<6.4\times10^{-3}$	$3.97^{+0.17}_{-0.14}\times10^{-4}$
M_P [M_J]	<6	$0.376^{+0.023}_{-0.020}$
R_P [R_J]	$0.812^{+0.043}_{-0.043}$	–

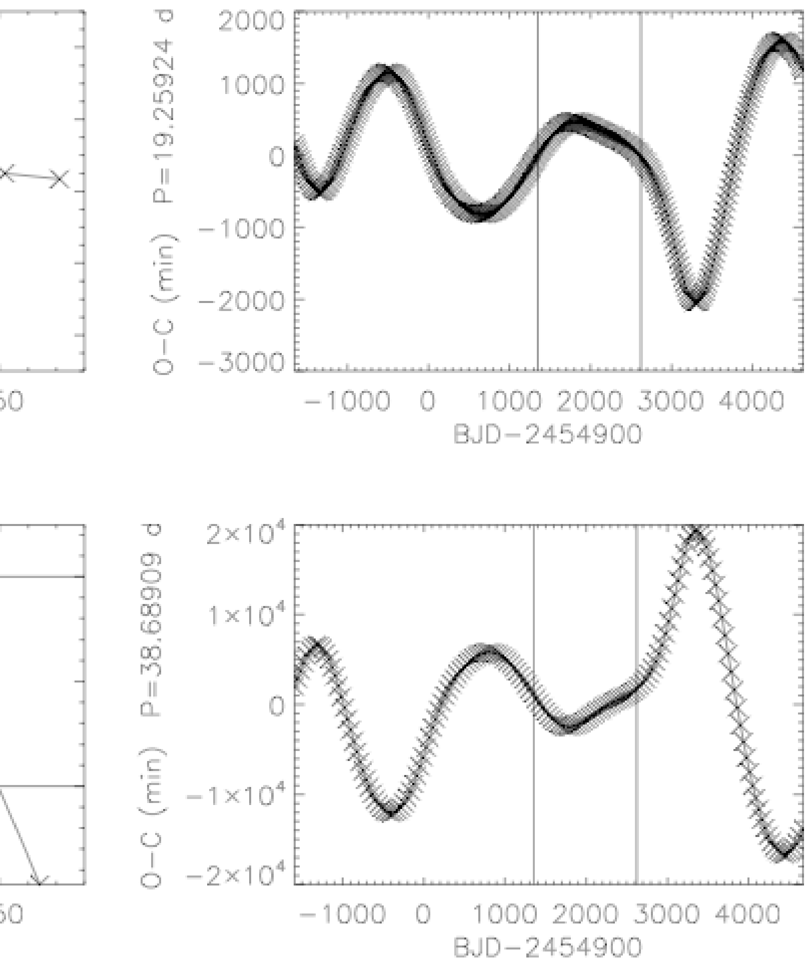

The Kepler Orrery II
t[BJD] = 2454965
D. Fabrycky 2012

Pairs of TTV'ing planets

- Kepler-9b/c, 11b/c and 11c/d/e, 18b/c
- Kepler-23-32 b/c
- ~10 more systems on the way

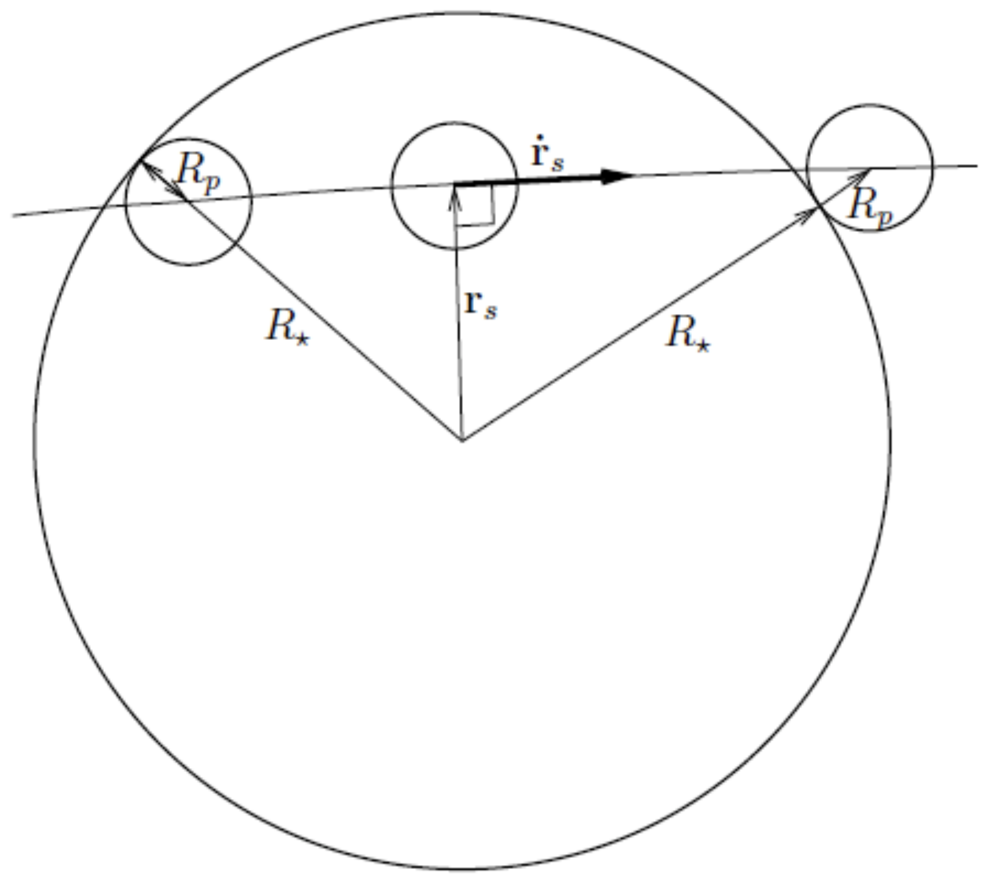
Kepler-9: First Impressions



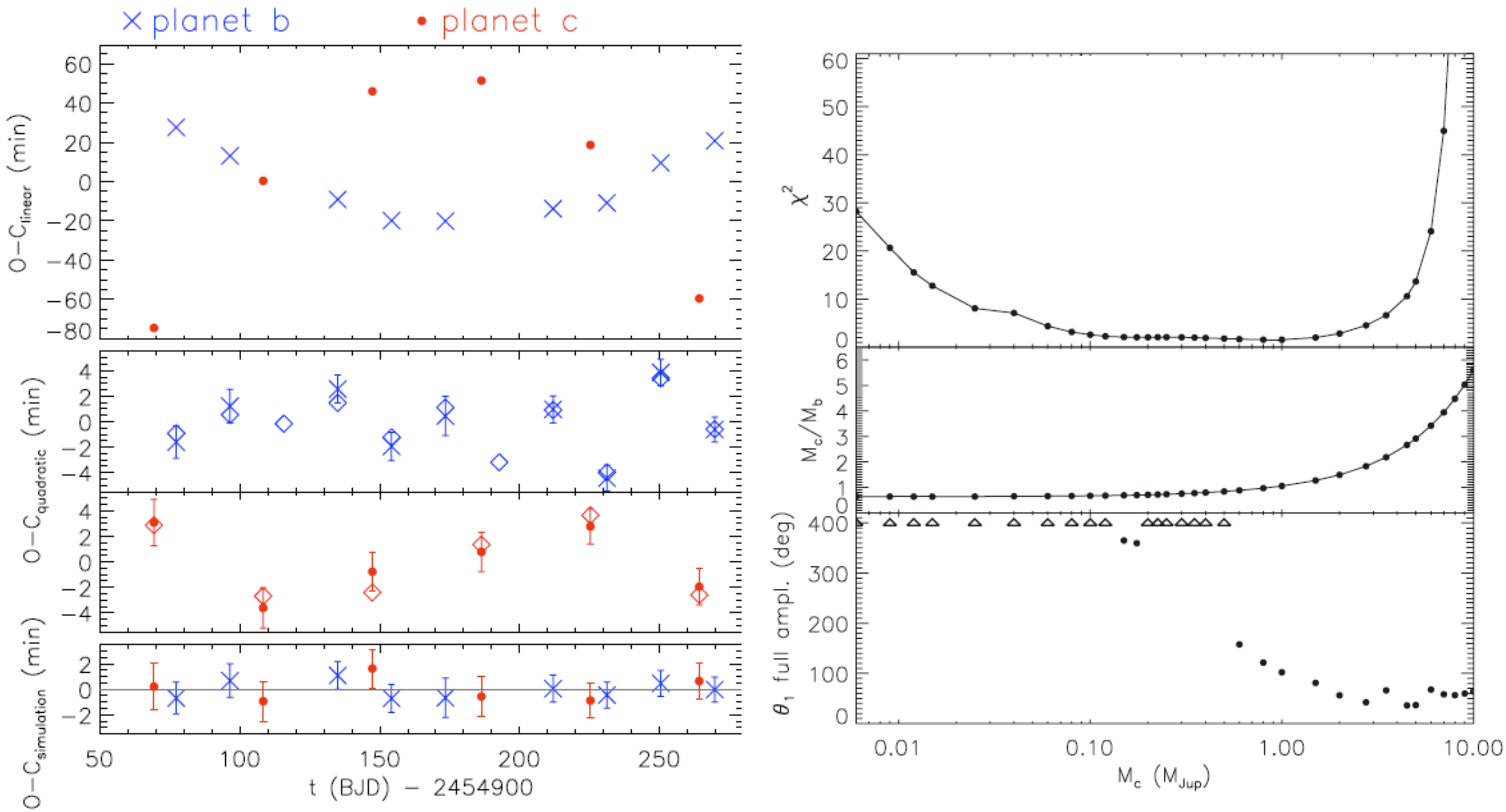


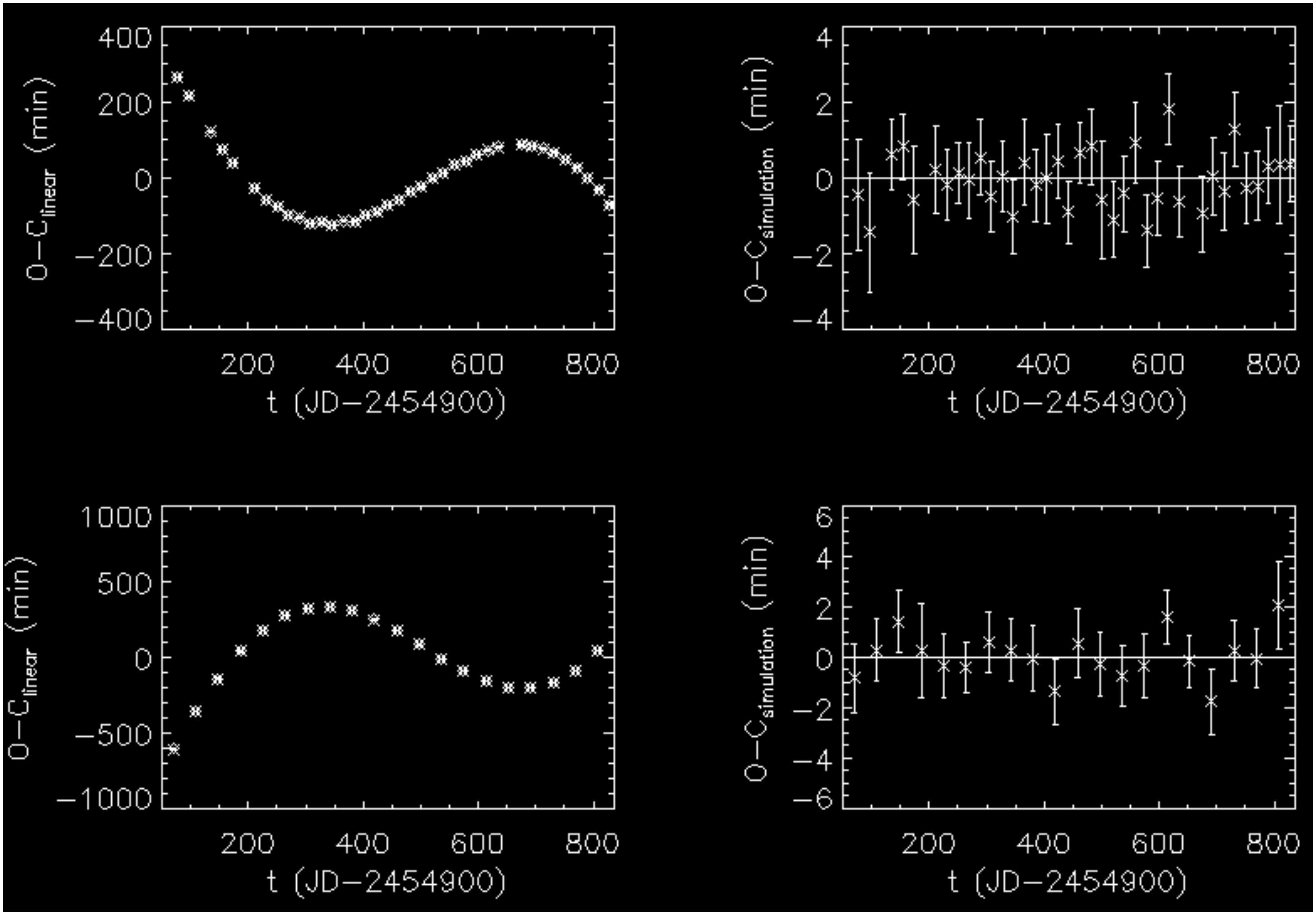
The Numerical Model

- Newton's equations, using high-order Runge-Kutta. Prints out at times of RV and transit t, b, v. Found by Newton's method on **r•v**



Fits of the data obtained





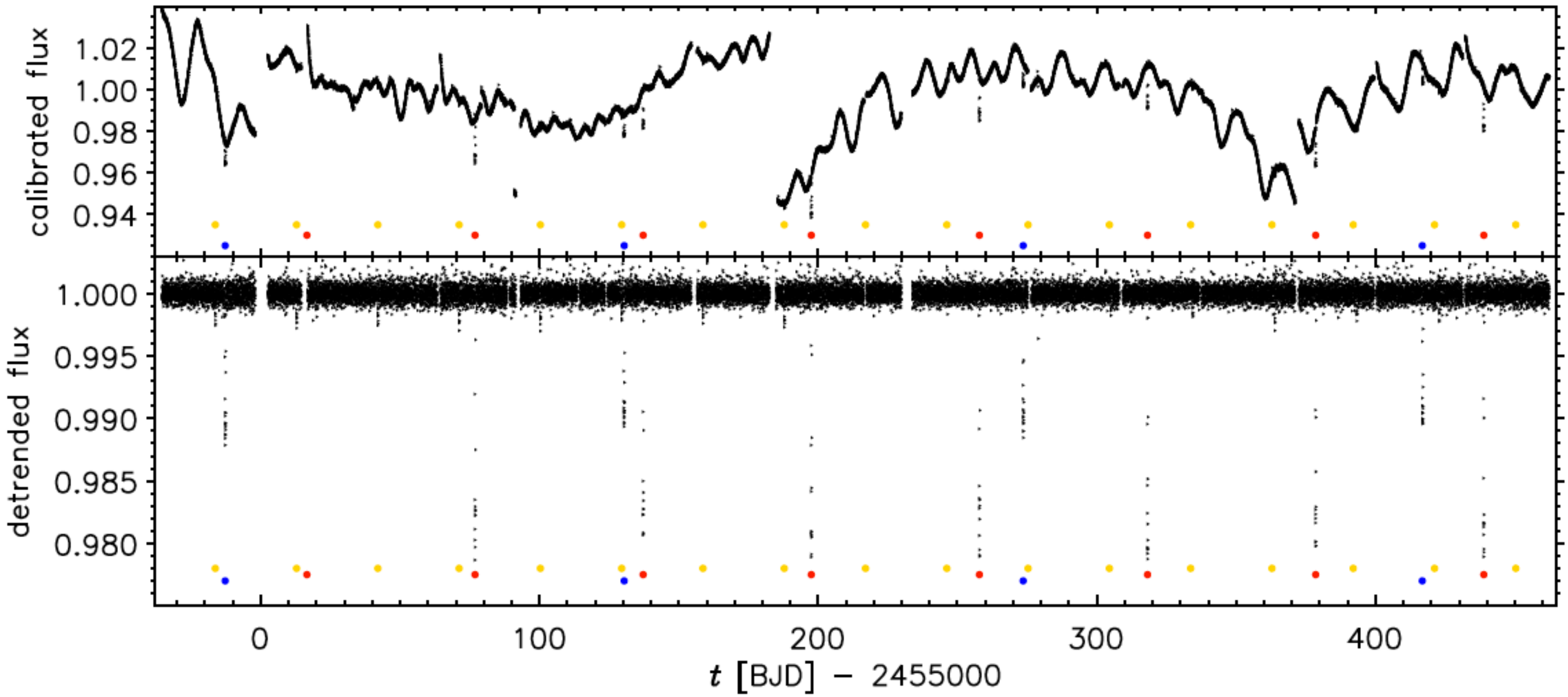
chi^2=28.1

49 d.o.f.

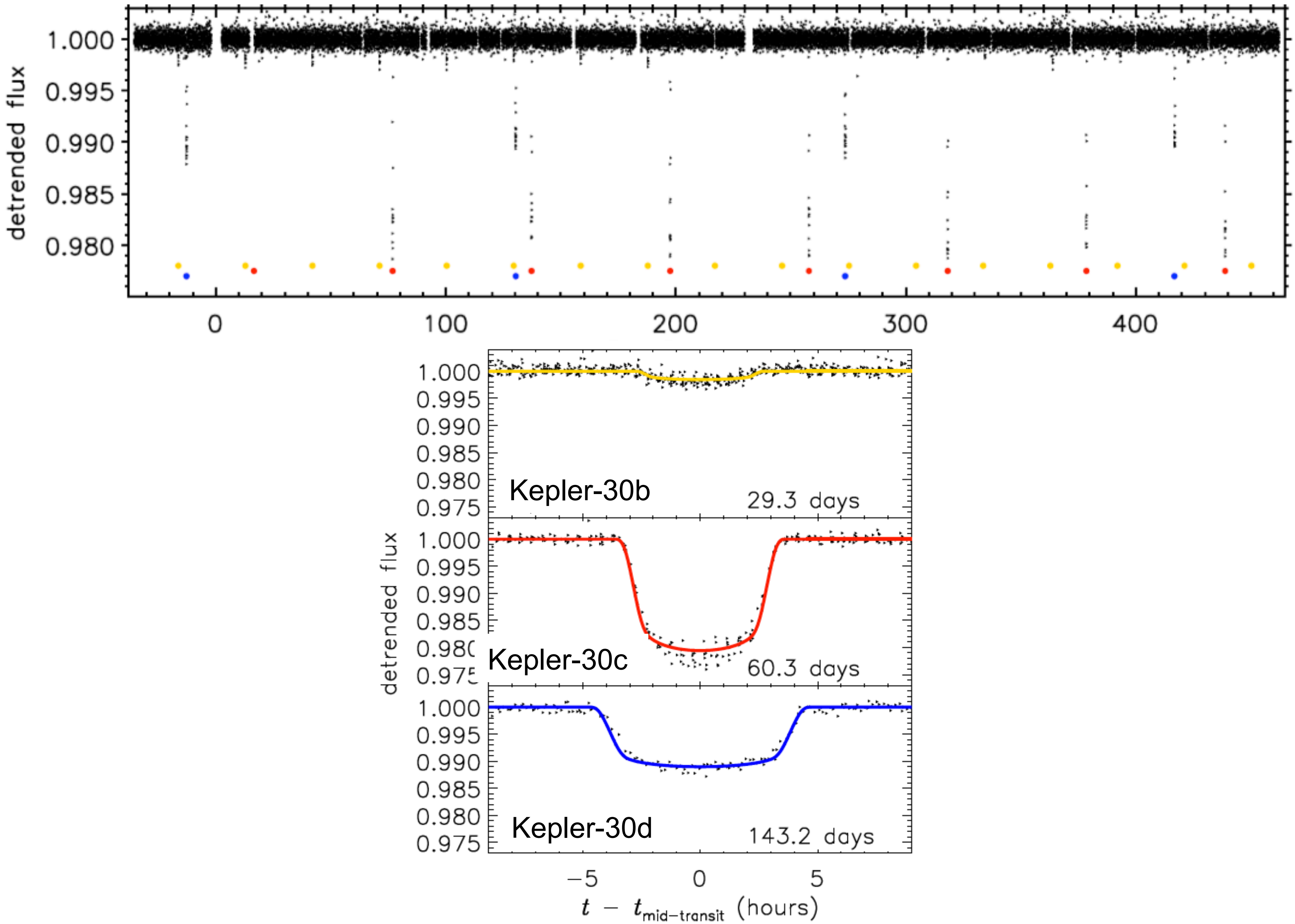
M_b=0.13±0.01 M_J

M_c=0.09±0.01 M_J

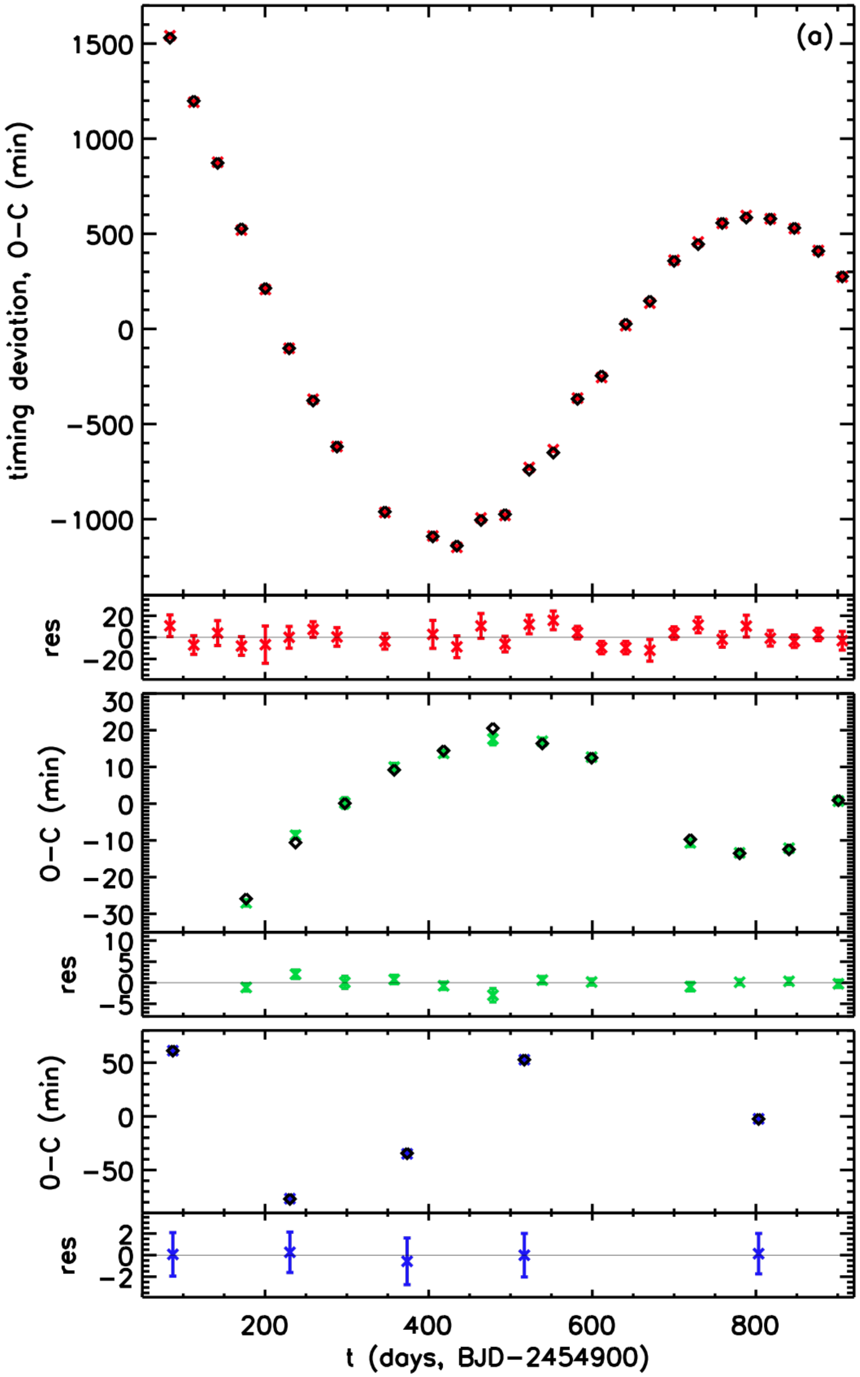
Kepler-30



- 3-planet system
- Tingley et al. 2011 observed a *ground-based* transit, found a 1-hour TTV

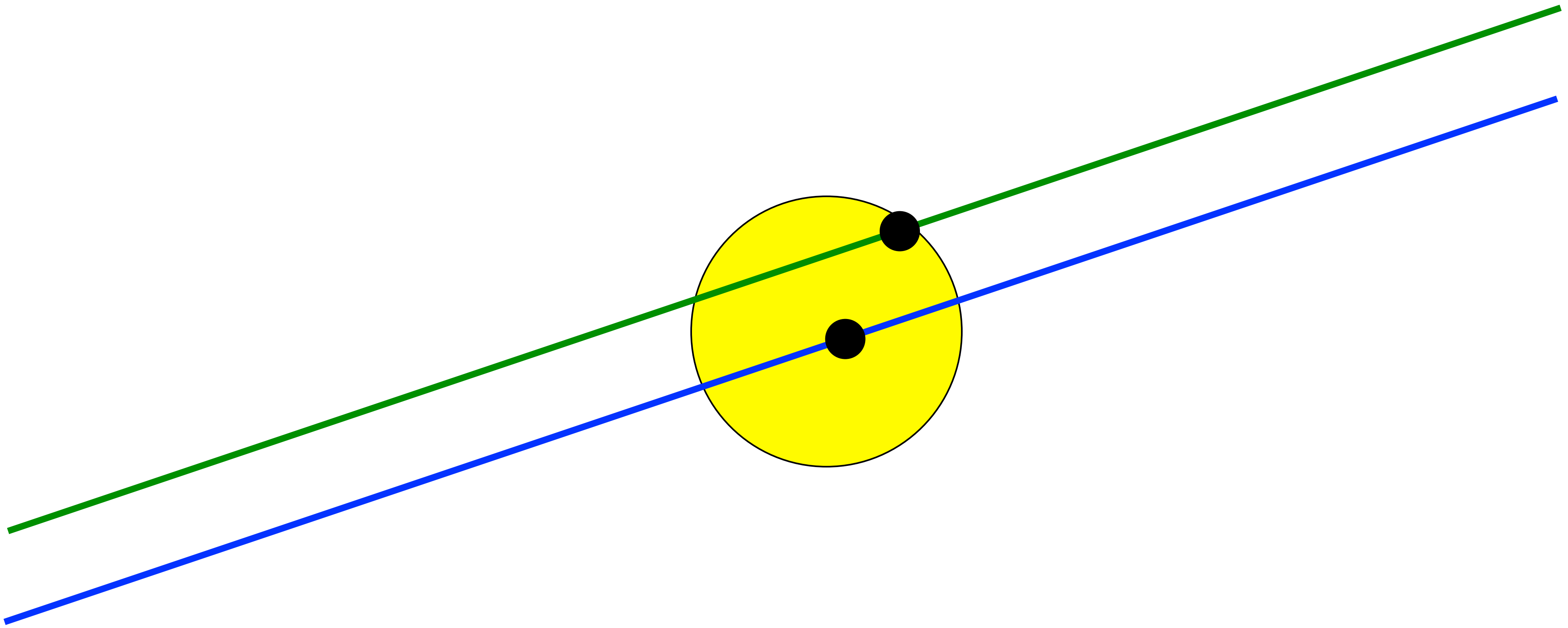


detrended flux
1.000
0.995
0.990
0.985
0.980
0
100
200
300
400
Kepler-30b
29.3 days
Kepler-30c
60.3 days
Kepler-30d
143.2 days
0.975
−5
0
5
$t - t_{\text{mid-transit}}$ (hours)

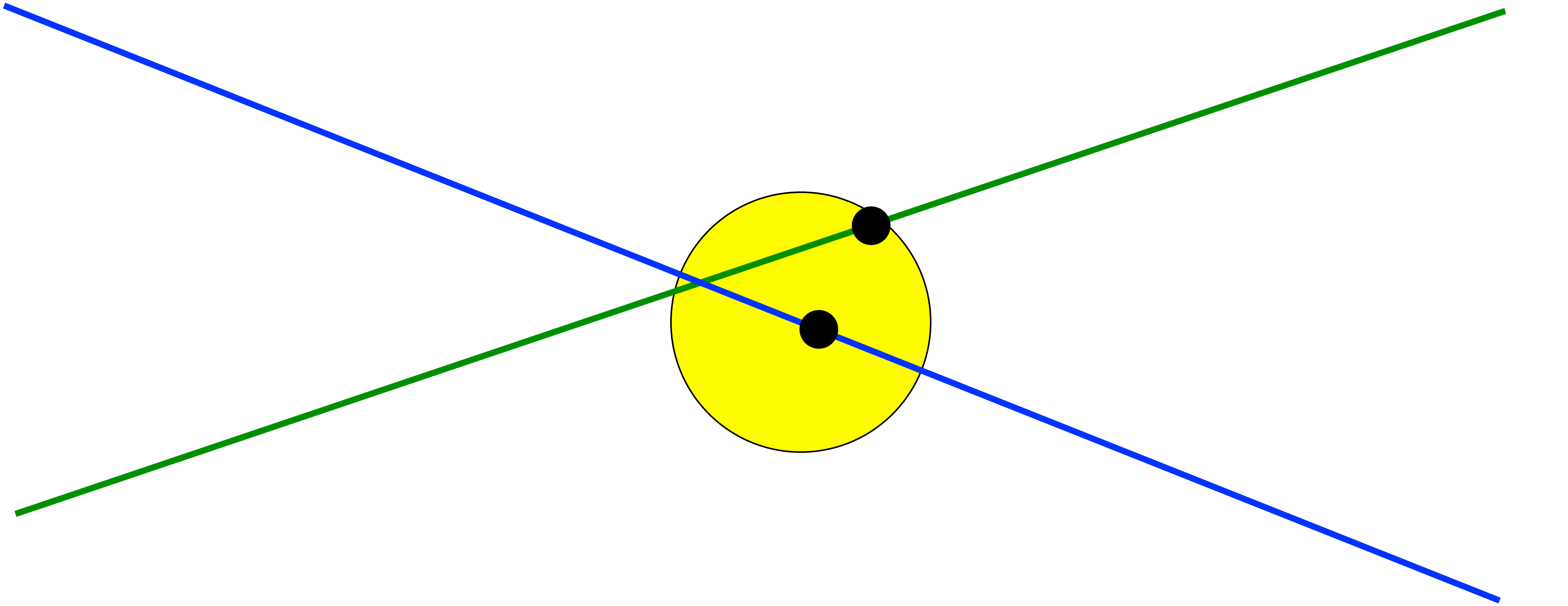


Kepler-30 through Q10

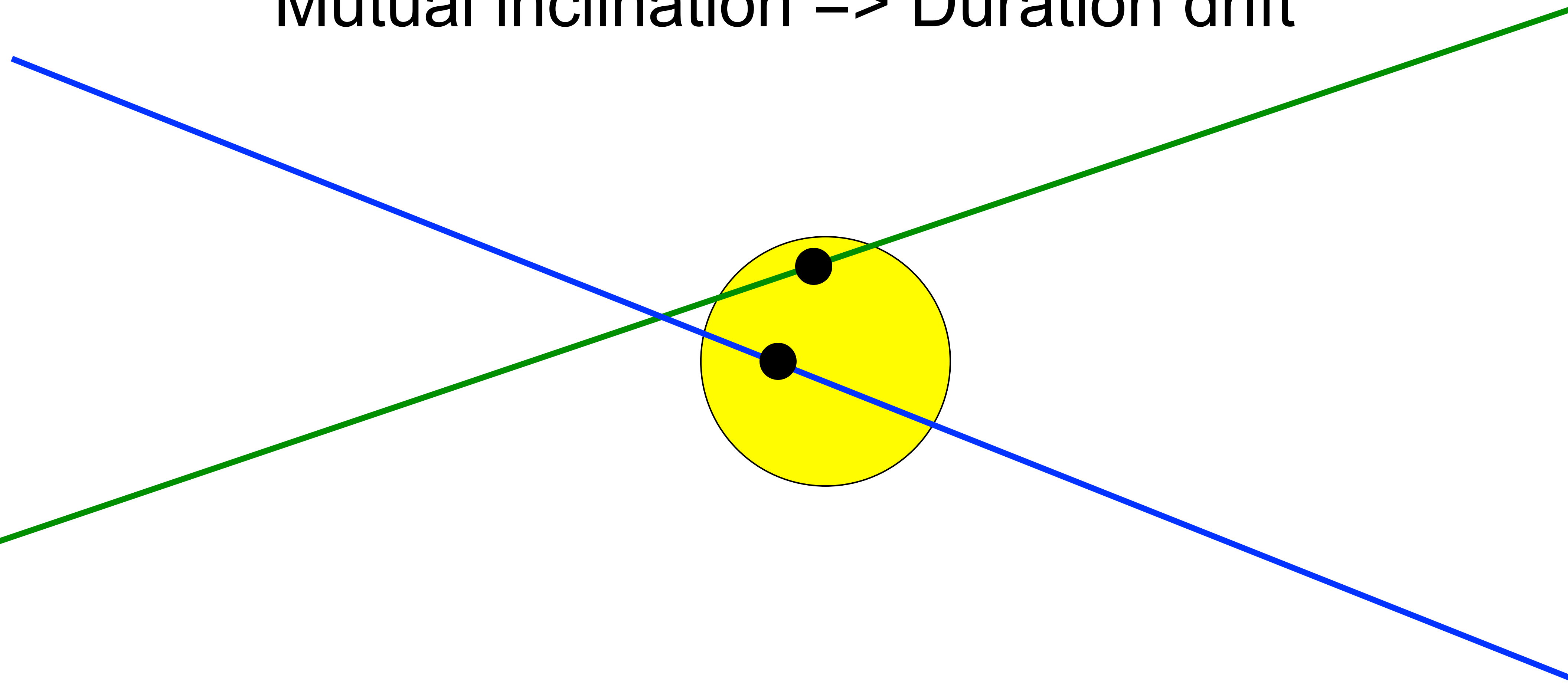
Mutual inclination => Duration drift



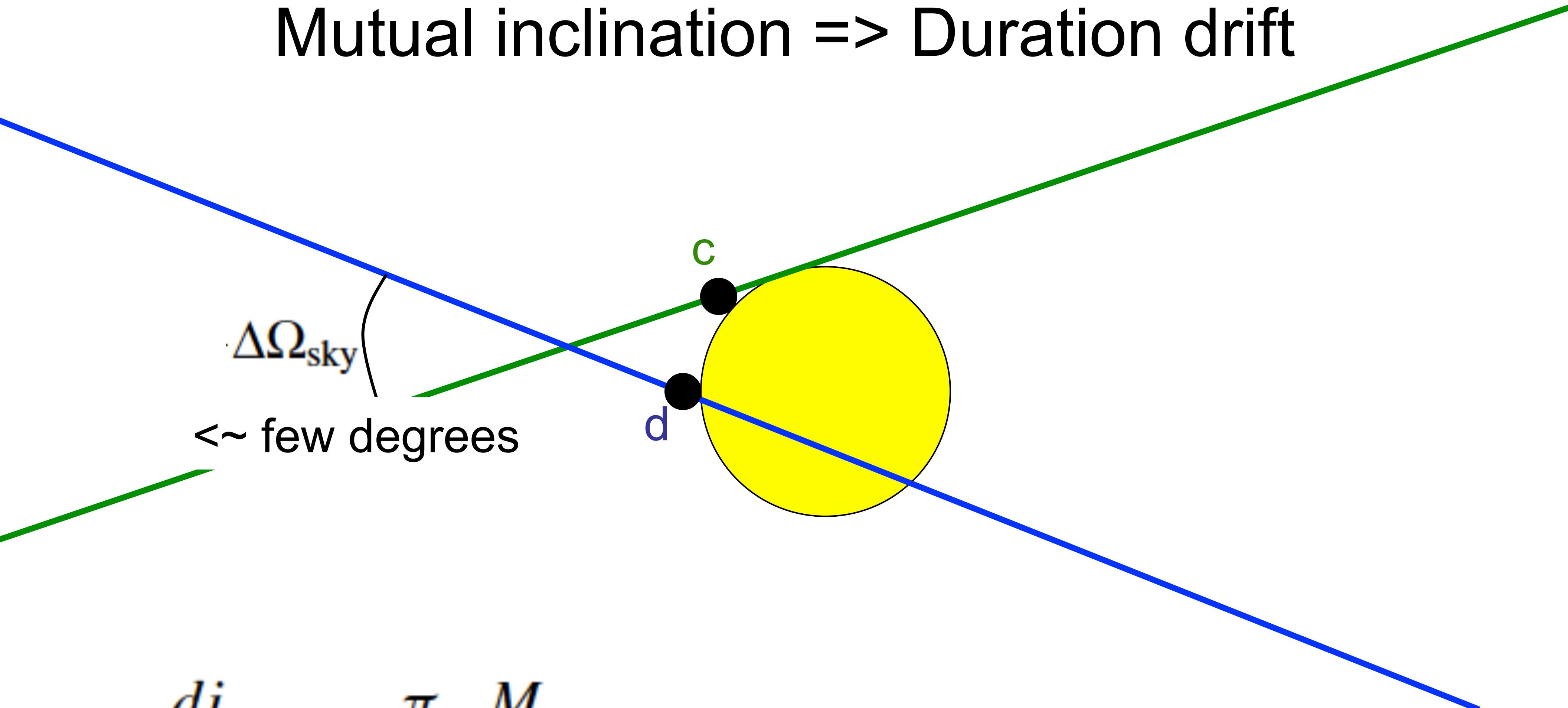
Mutual inclination => Duration drift



Mutual inclination => Duration drift



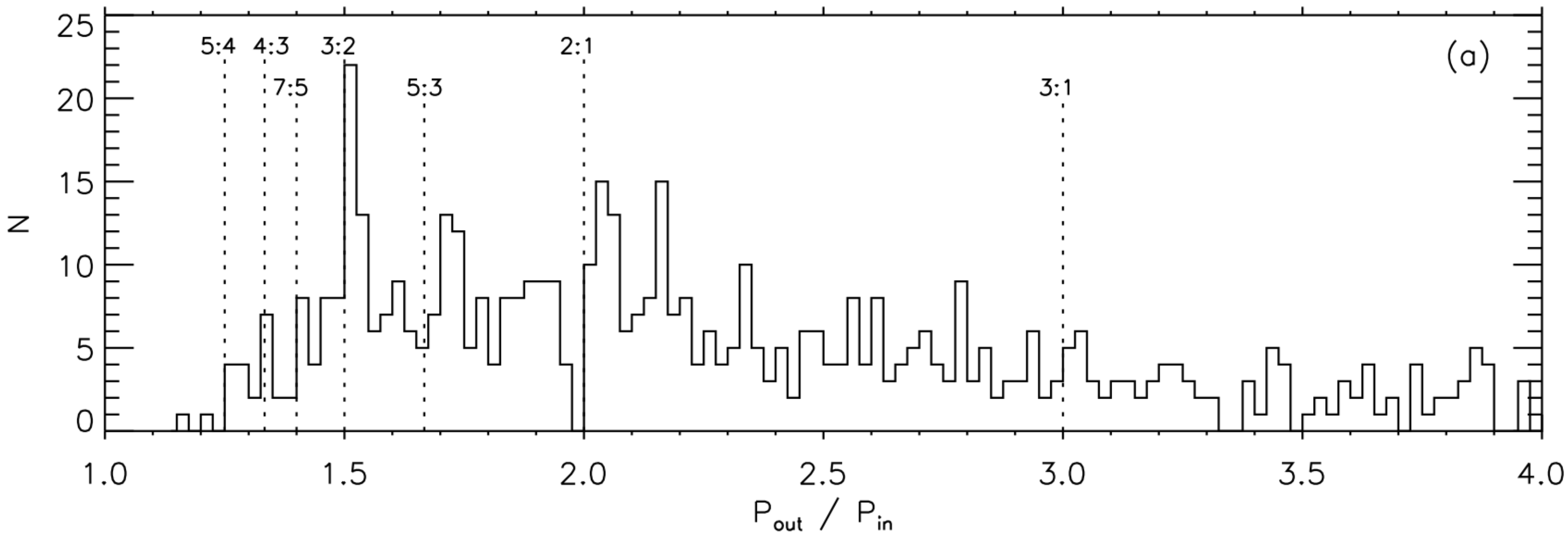
Mutual inclination => Duration drift



$$\frac{di}{dt} = -\frac{\pi}{2P_c}\frac{M_c}{M_\star}\, f(a_c/a_d)\, \Delta\Omega_{sky}$$

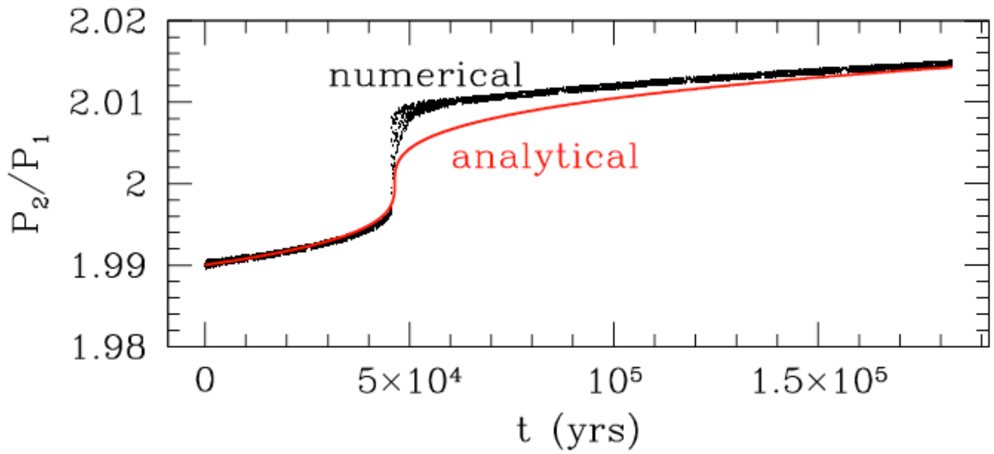
Miralda-Escude 2002
Ballard et al. 2010

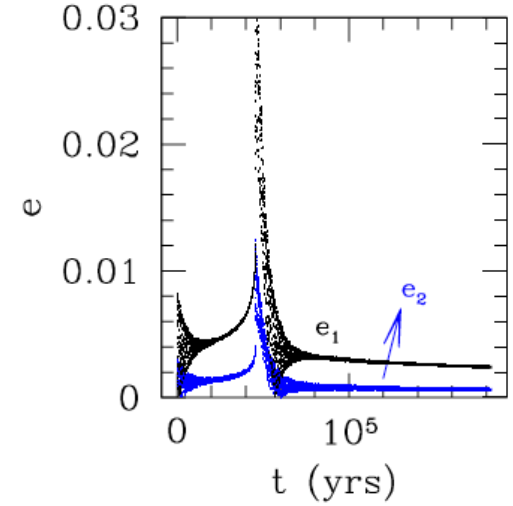
Architecture of Multiples



Lissauer et al. 2011, Fabrycky et al. 2012

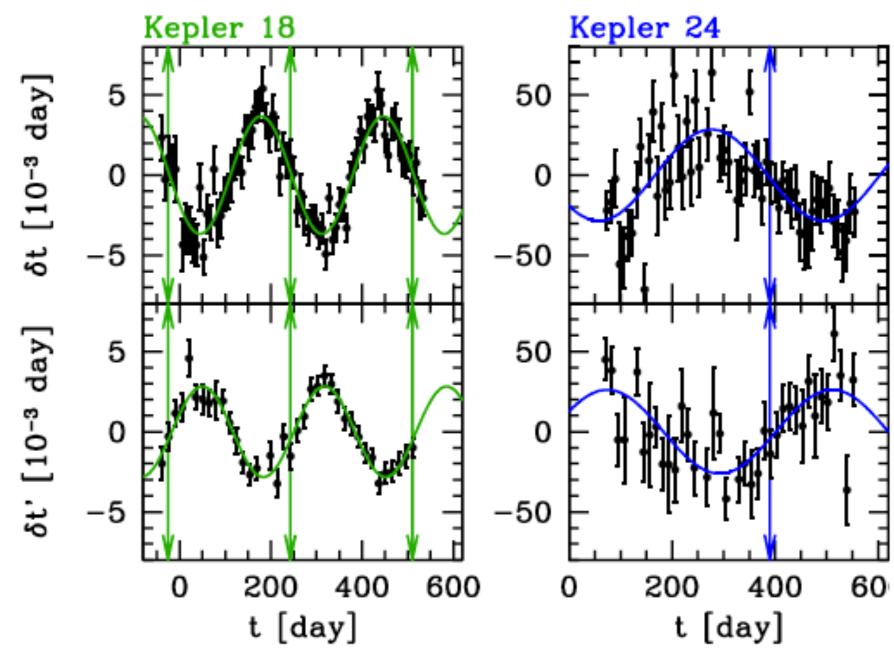
Resonant Repulsion



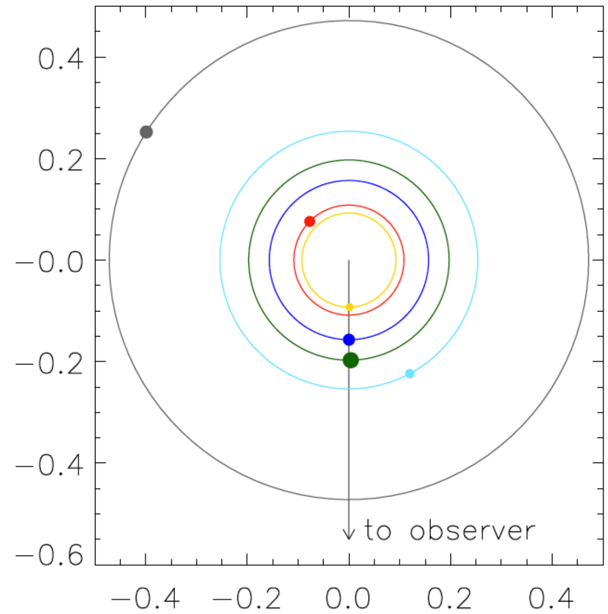


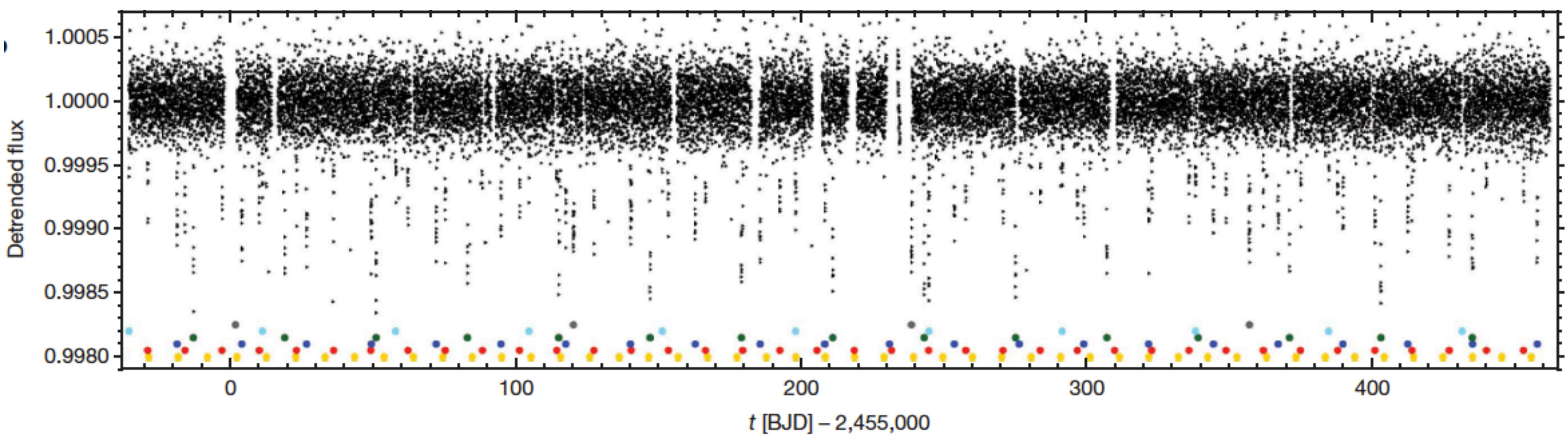
Lithwick & Wu 12 a
see also: Batygin & Morbidelli 12, Delisle+12

Lithwick & Wu 12 b
→ Correctly predicts the TTV *phase* of *some* pairs of planets.

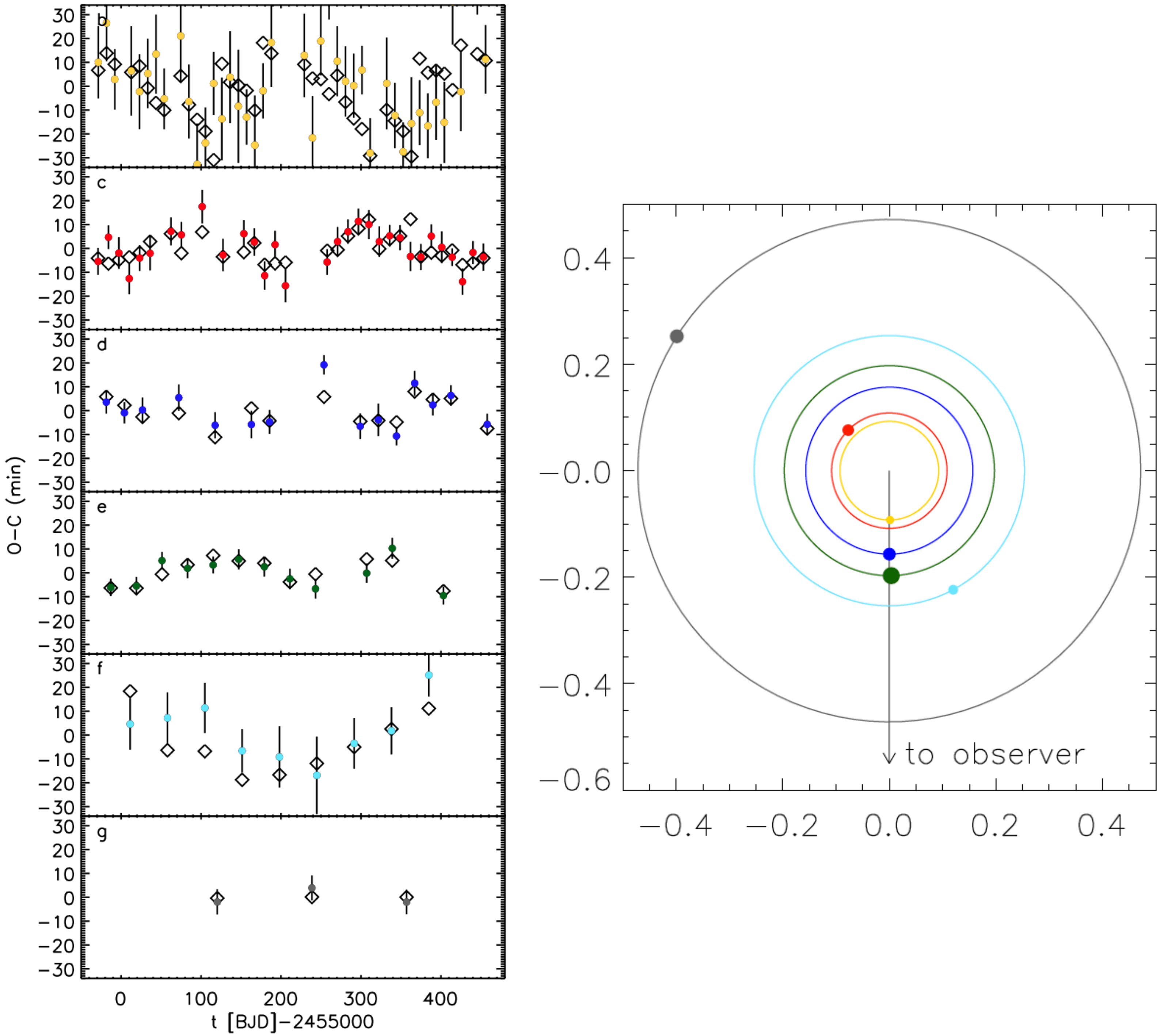


Kepler-11

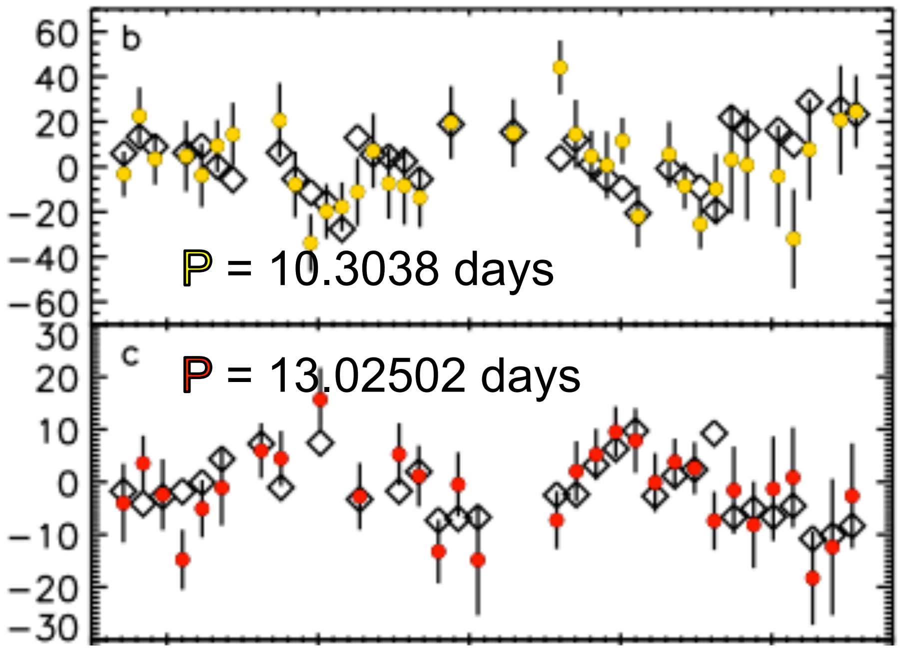


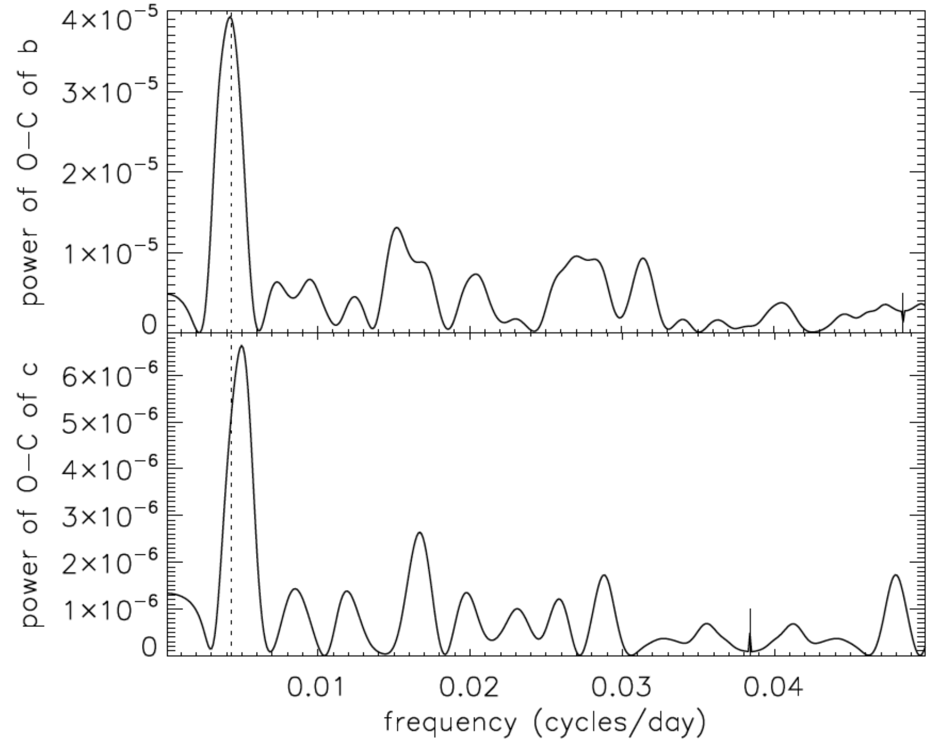


Lissauer, Fabrycky, Ford et al. 2011



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

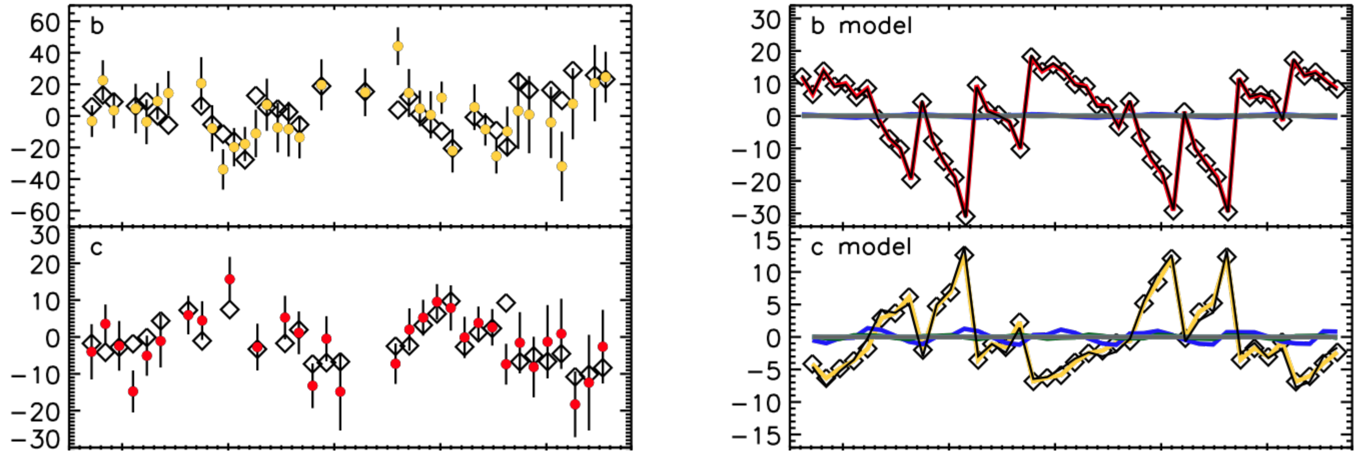




“Great Inequality” timescale:
1/(4/P-5/P) = 231 days

It is observed!

See also: Kepler-18 by Cochran, Fabrycky, et al.



b
c
b model
c model

Photodynamics

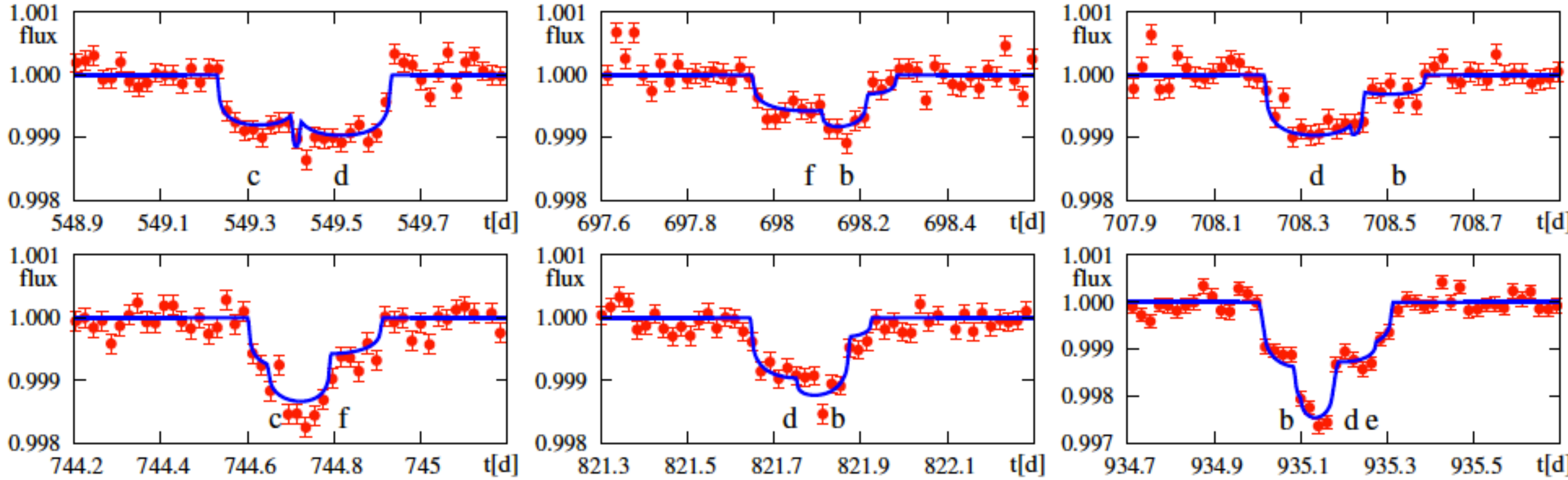
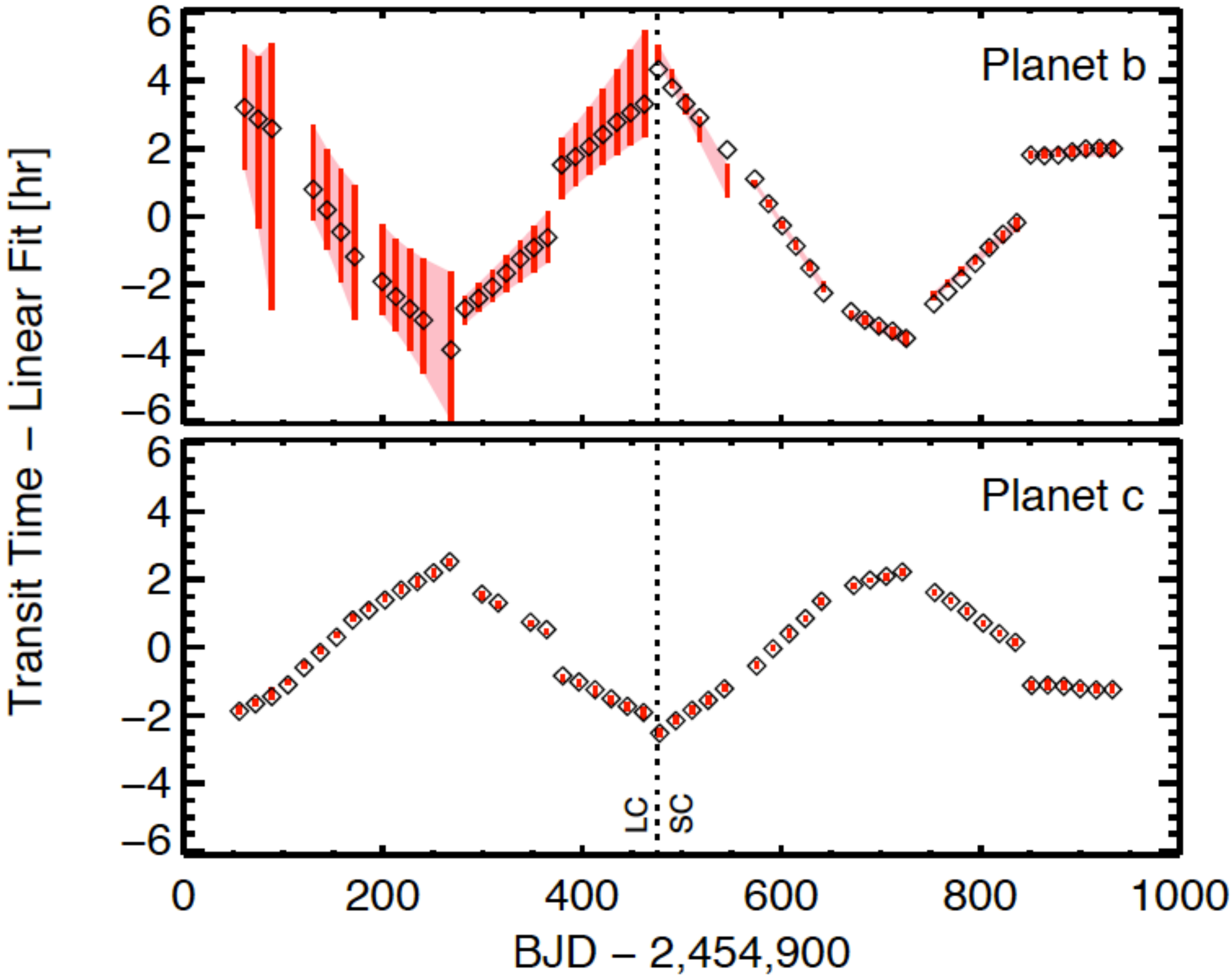


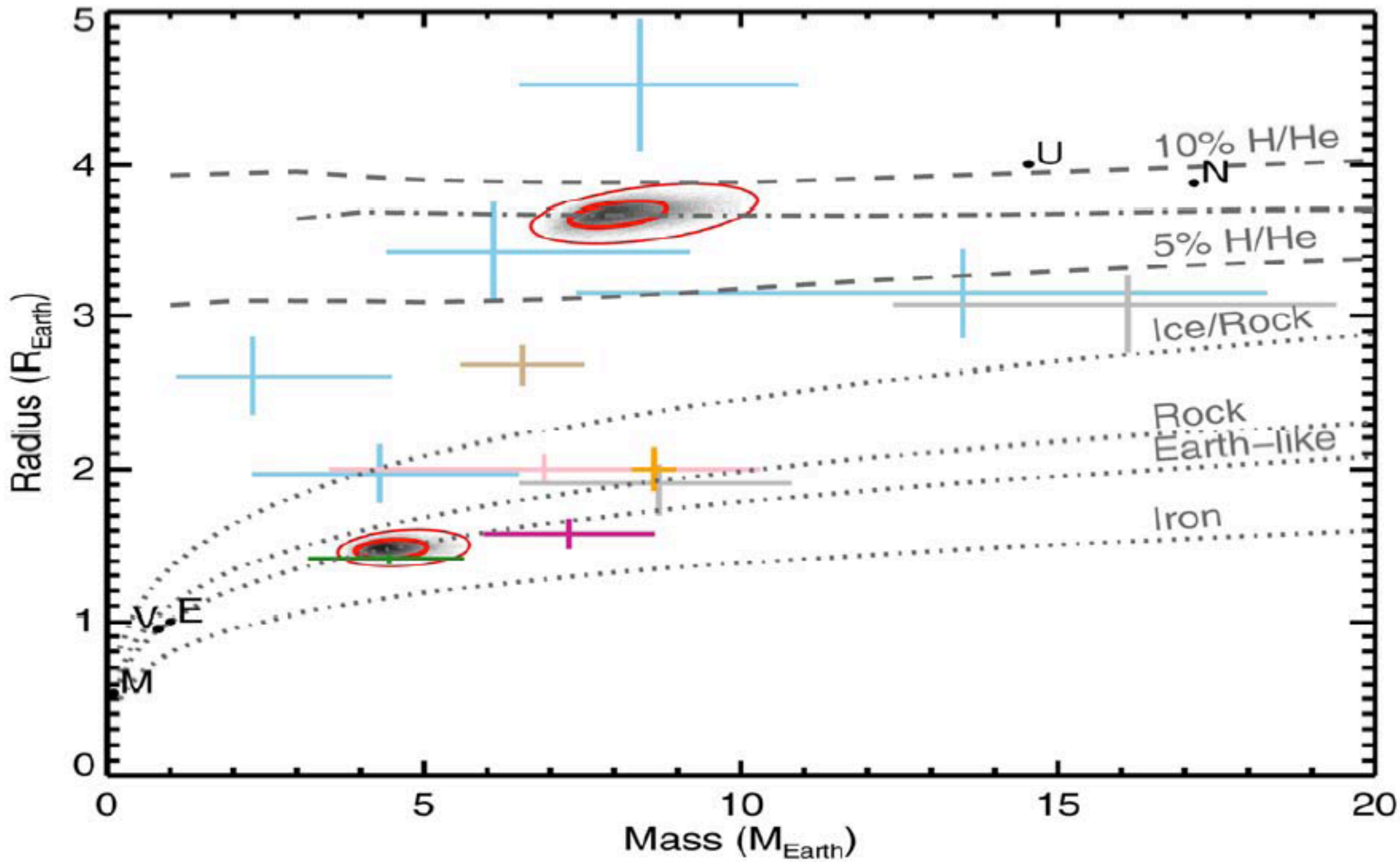
Table 4. Bootstrap results for model IV ($e_g = 0, \Omega_i = 0, i = b,c,d,e,f,g$). Mass of the star is $0.95\,\mathrm{m}_\odot$ (fixed). The best–fit stellar parameters: $R_0 = 1.140^{+0.026}_{-0.024}$, $\gamma_1 = 1.14^{+0.14}_{-1.21}$, $\gamma_2 = -0.42^{+0.78}_{-0.14}$, $\gamma_1 + \gamma_2 = 0.72^{+0.22}_{-0.25}$. Osculating Poincaré elements are given at the epoch of the first observation JD 2455964.51128.

parameter/planet	b	c	d	e	f	g
$m\,[\mathrm{m}_\oplus]$	$3.3^{+2.4}_{-1.8}$	$8.8^{+4.0}_{-5.0}$	$8.9^{+2.3}_{-3.4}$	$10.3^{+1.9}_{-1.5}$	$4.1^{+3.8}_{-2.4}$	< 21
$R\,[\mathrm{R}_\oplus]$	$2.01^{+0.13}_{-0.13}$	$3.23^{+0.12}_{-0.12}$	$3.59^{+0.15}_{-0.13}$	$4.70^{+0.21}_{-0.15}$	$2.82^{+0.15}_{-0.15}$	$3.85^{+0.12}_{-0.12}$
$\bar{\rho}\,[\rho_\oplus]$	$0.40^{+0.33}_{-0.19}$	$0.26^{+0.13}_{-0.18}$	$0.19^{+0.07}_{-0.08}$	$0.10^{+0.03}_{-0.03}$	$0.18^{+0.20}_{-0.10}$	< 0.35
a [au]	$0.091088\,\left(^{+13}_{-11}\right)$	$0.106514\,\left(^{+6}_{-8}\right)$	$0.154234\,\left(^{+18}_{-7}\right)$	$0.193927\,\left(^{+19}_{-10}\right)$	$0.249507\,\left(^{+35}_{-26}\right)$	$0.463913\,\left(^{+57}_{-39}\right)$
$e\cos\omega$	$-0.002^{+0.015}_{-0.021}$	$-0.006^{+0.015}_{-0.016}$	$-0.012^{+0.009}_{-0.019}$	$-0.018^{+0.006}_{-0.017}$	$-0.007^{+0.015}_{-0.020}$	0 (fixed)
$e\sin\omega$	$0.049^{+0.020}_{-0.050}$	$0.050^{+0.020}_{-0.044}$	$-0.010^{+0.008}_{-0.018}$	$-0.016^{+0.006}_{-0.017}$	$-0.017^{+0.011}_{-0.021}$	0 (fixed)
$I^\star$ [deg]	$88.76^{+0.96}_{-0.41}$	$91.00^{+0.40}_{-0.25}$	$90.89^{+0.17}_{-0.18}$	$88.743^{+0.043}_{-0.049}$	$89.30^{+0.10}_{-0.09}$	$89.719^{+0.061}_{-0.068}$
$\mathcal{M} + \omega$ [deg]	$205.8^{+2.4}_{-2.1}$	$266.4^{+1.7}_{-1.9}$	$182.7^{+2.1}_{-1.2}$	$197.2^{+1.8}_{-0.9}$	$89.6^{+2.6}_{-1.3}$	$336.286^{+0.066}_{-0.057}$
P [d]	$10.3021\,\left(^{+24}_{-18}\right)$	$13.0269\,\left(^{+10}_{-17}\right)$	$22.6986\,\left(^{+43}_{-13}\right)$	$32.0027\,\left(^{+41}_{-30}\right)$	$46.7044\,\left(^{+88}_{-59}\right)$	$118.411\,\left(^{+14}_{-15}\right)$
T_0 [JD]	$471.505\,\left(^{+20}_{-7}\right)$	$471.177\,\left(^{+18}_{-3}\right)$	$481.452\,\left(^{+17}_{-6}\right)$	$487.176\,\left(^{+22}_{-6}\right)$	$464.670\,\left(^{+14}_{-9}\right)$	$501.914\,\left(^{+26}_{-11}\right)$

Kepler-36 Carter, Agol, et al. 2012



Kepler-36

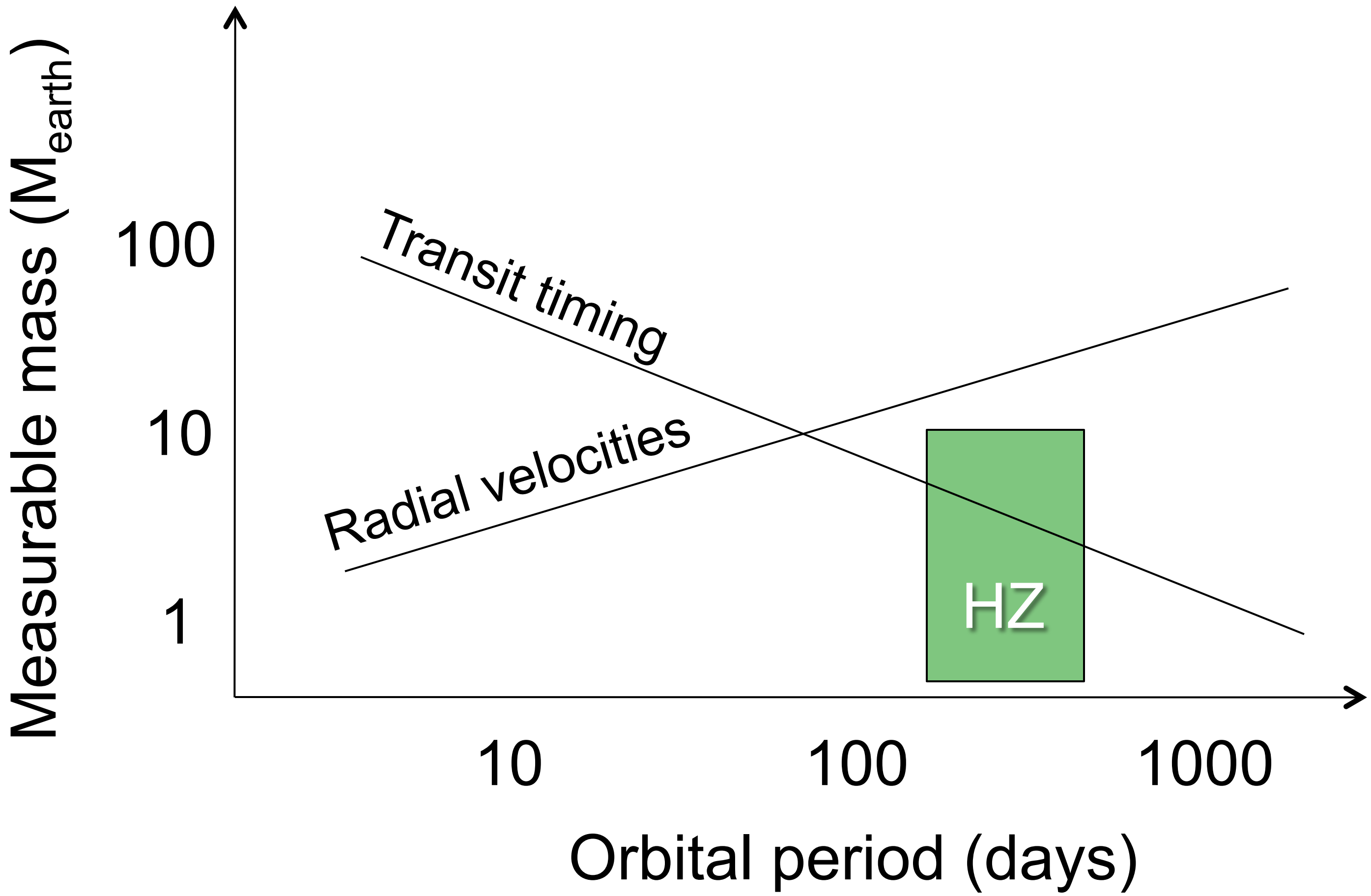


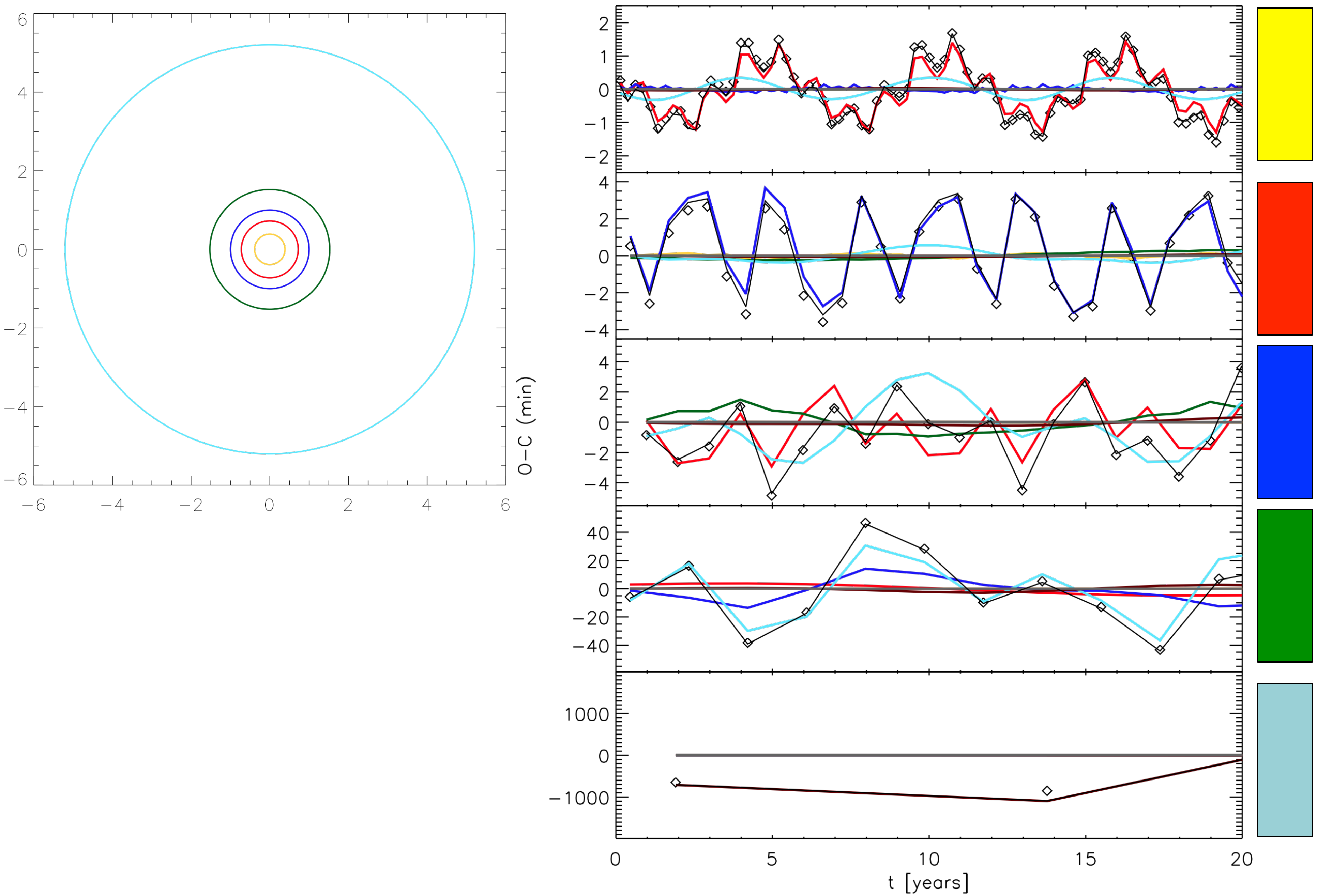
- Josh Carter's photodynamics have given us all the circumbinary planets, too.

Promise of TTVs??

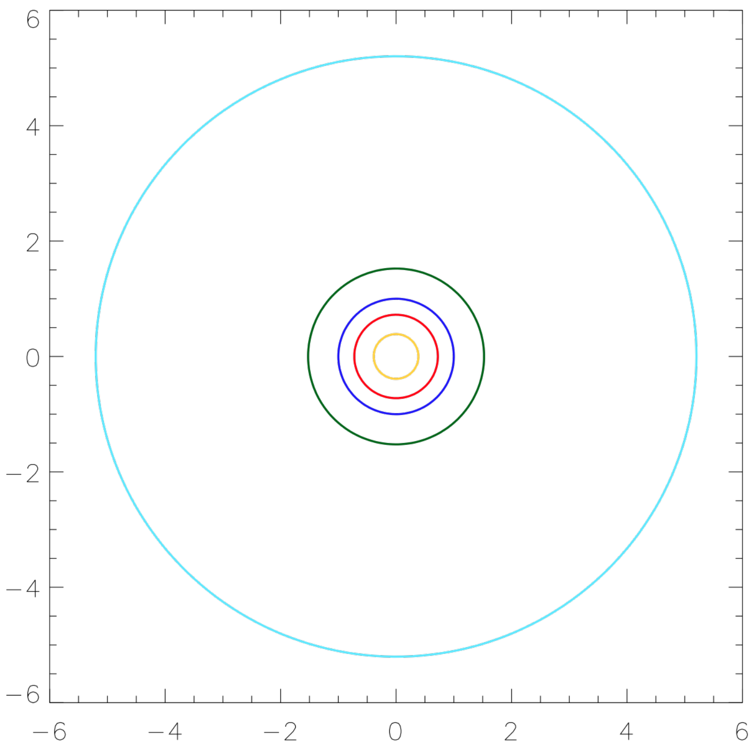
Promise of TTVs??

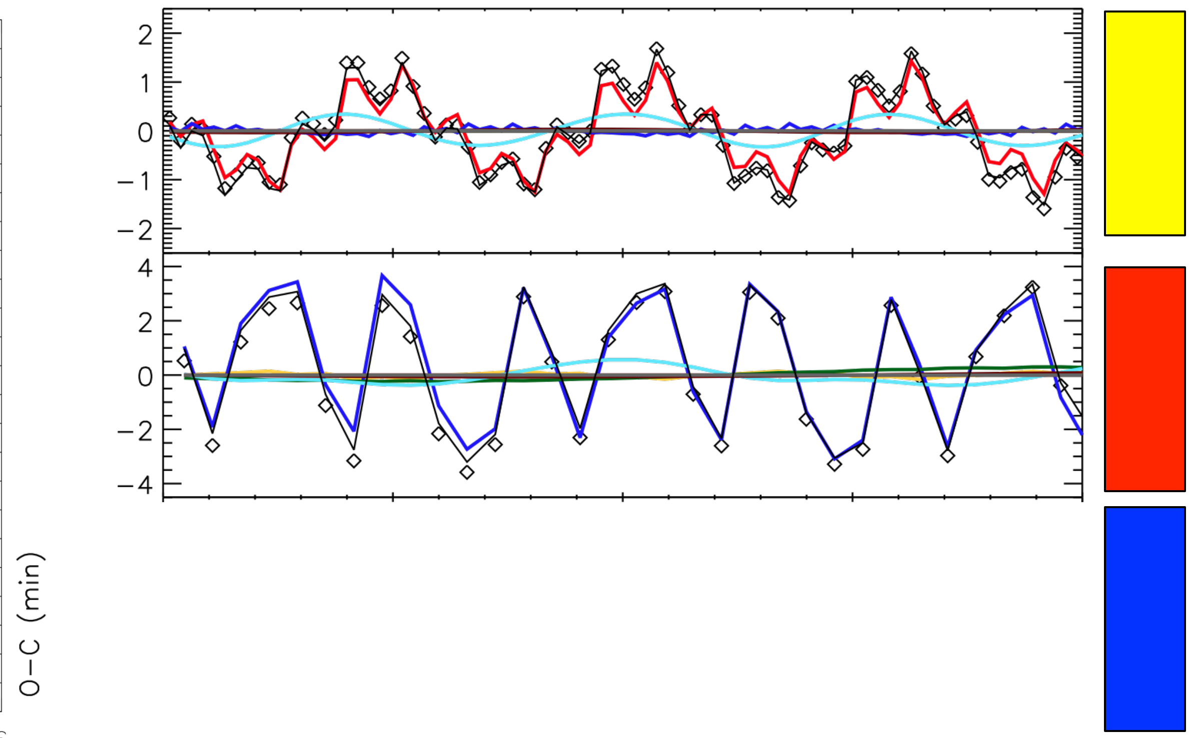
Route to weighing habitable planets



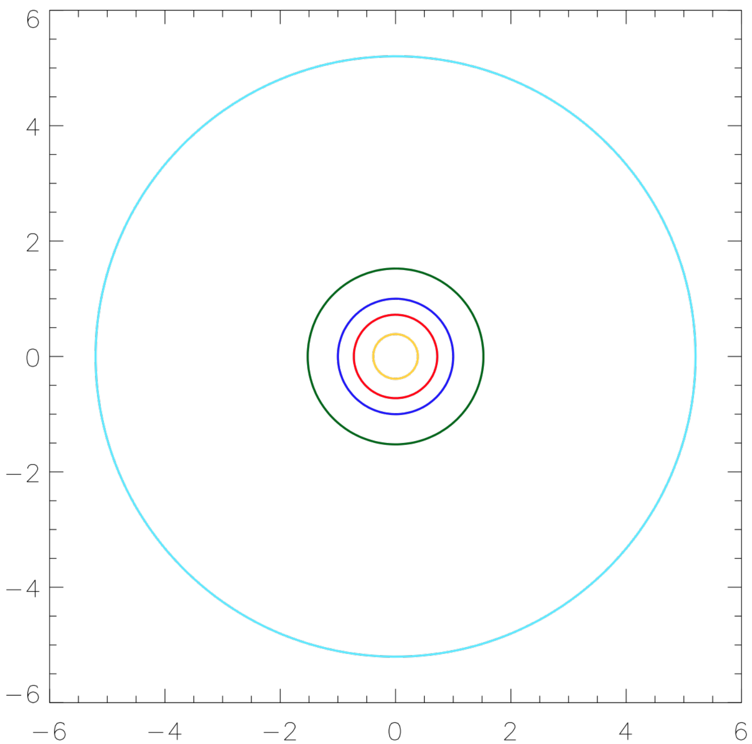


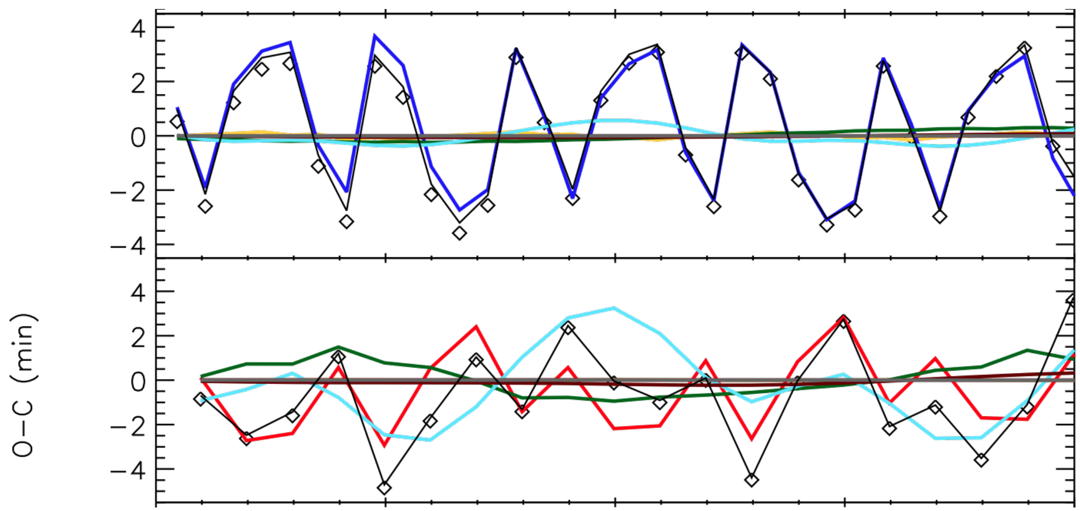
O−C (min)
t [years]



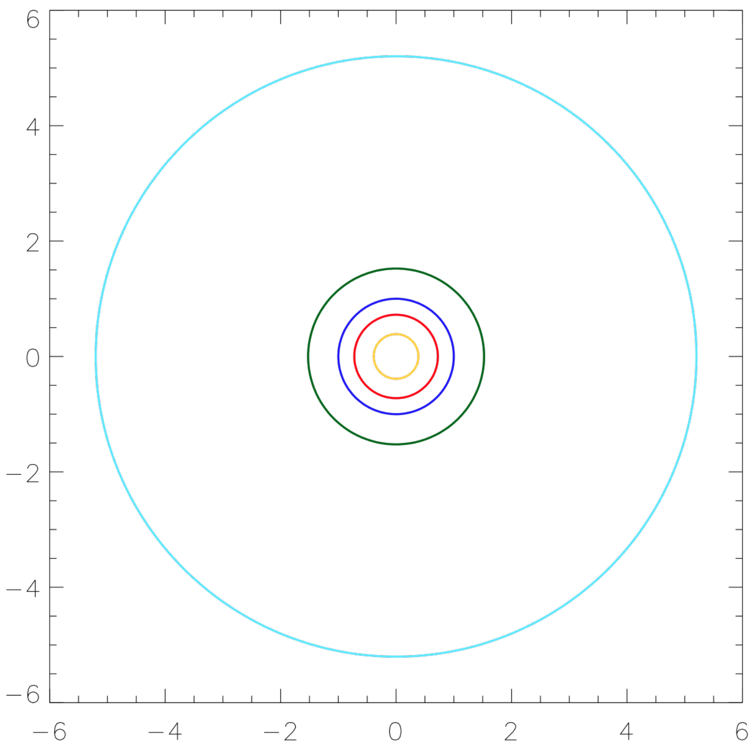


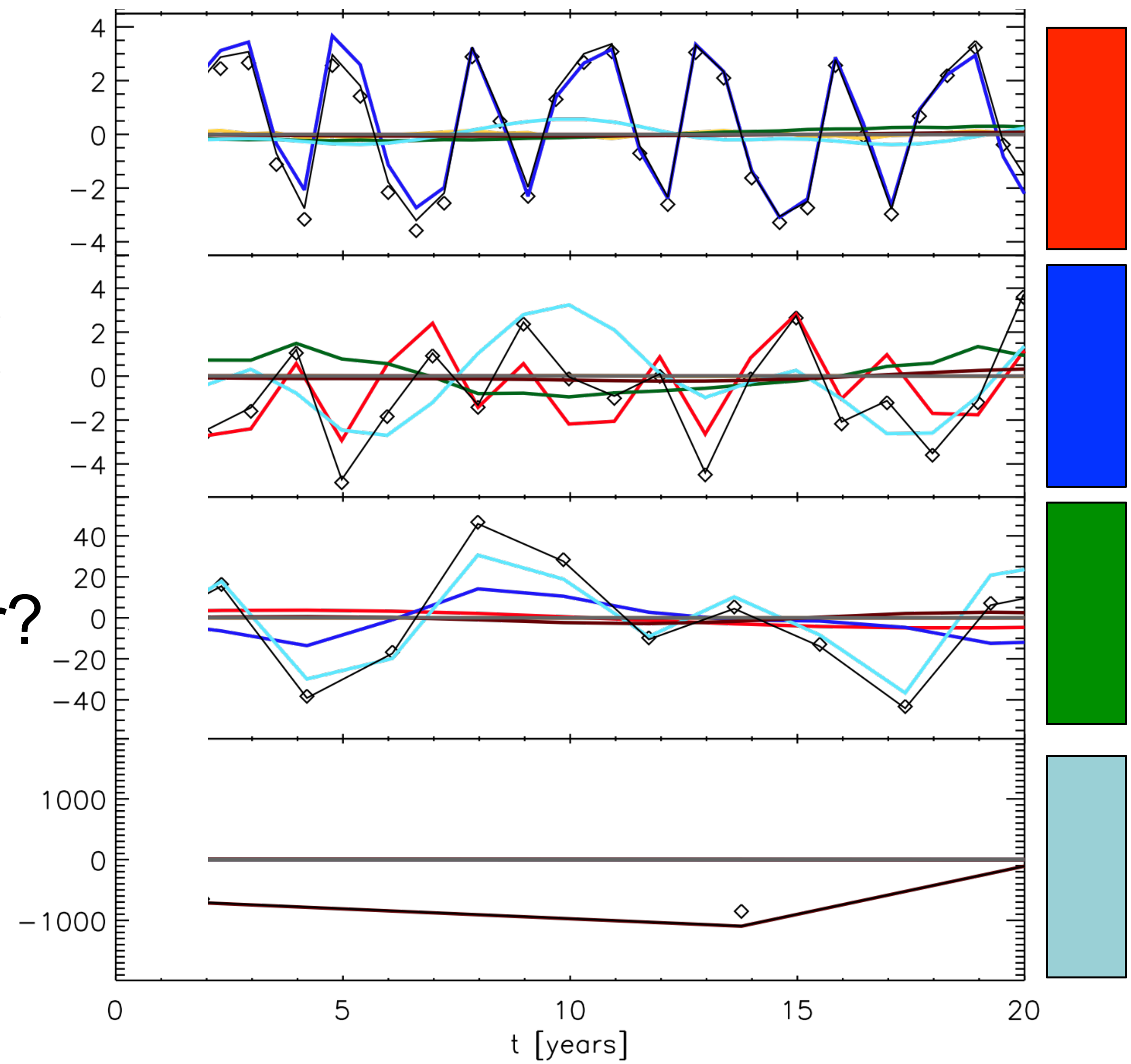
Only Mercury & Venus transit:
-- measure Venus' mass
-- infer Earth's existence





Only Venus & Earth transit:
-- measure both mass
-- infer Jupiter's existence





Venus through 1-Jupiter?
-- measure V,E,M mass
-- double-check Earth's
-- infer Jupiter's period
 and mass(?)

Questions?

- Nota bene: plenty more to talk about at the TTV hands on session later this morning!