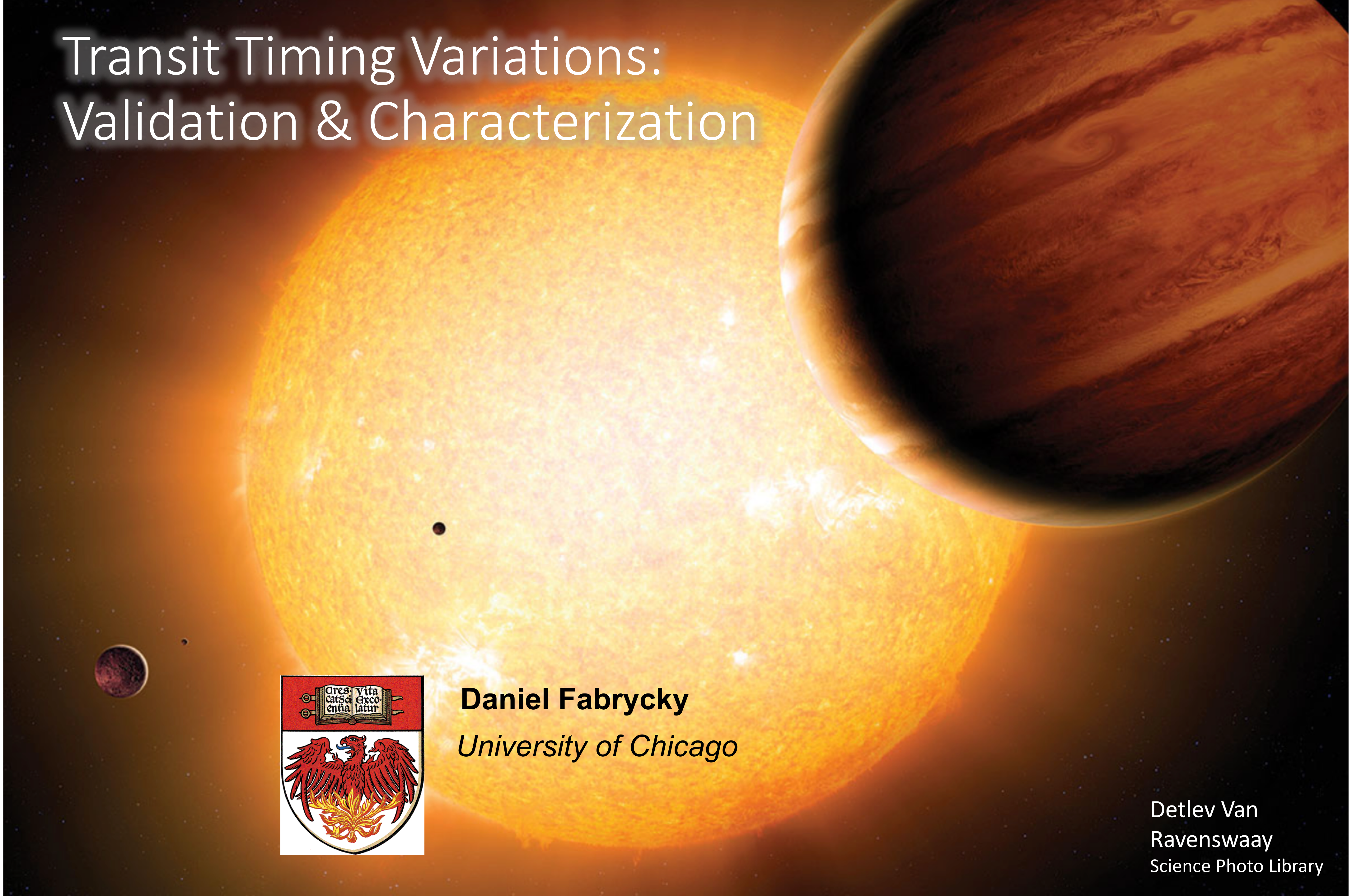
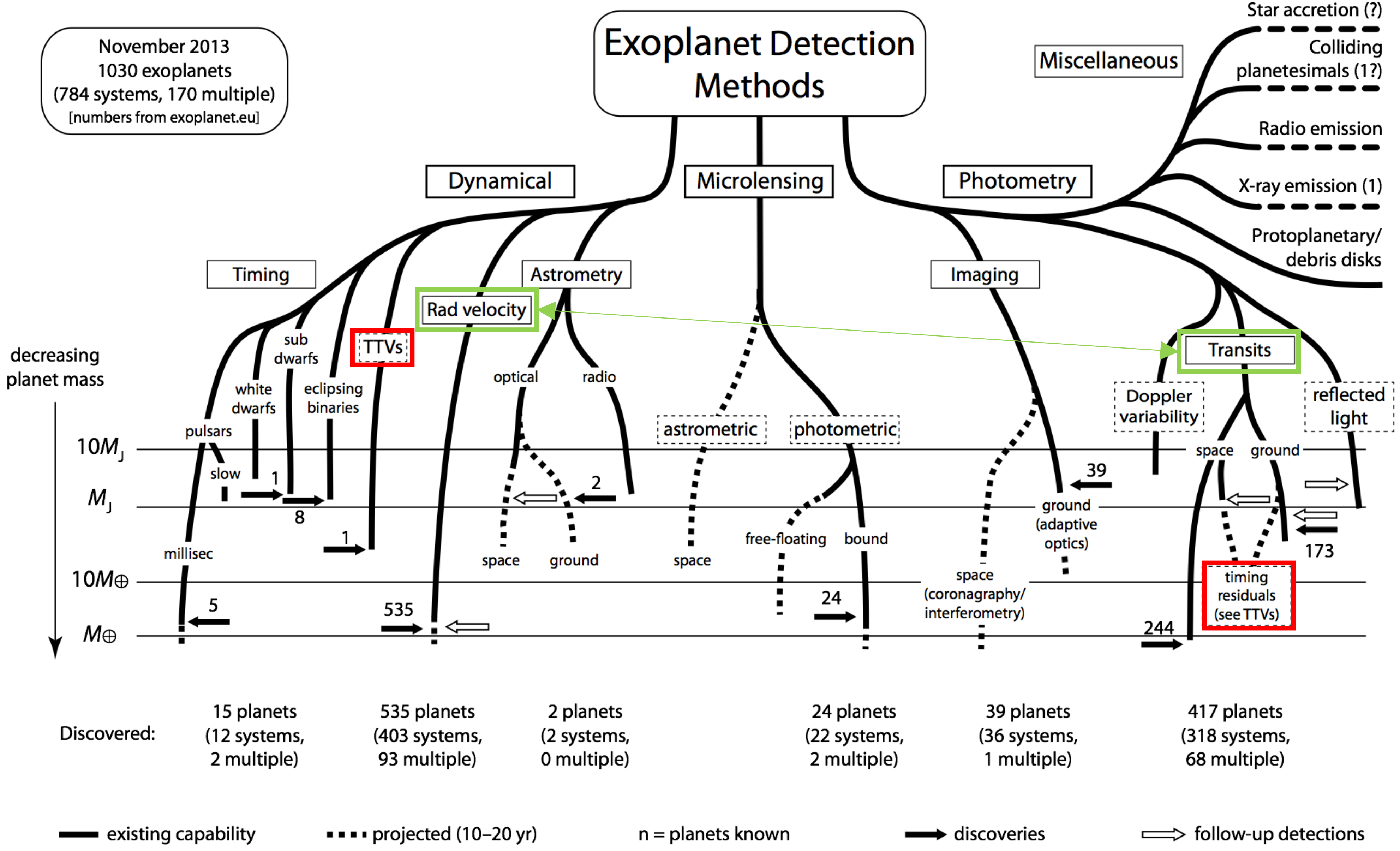
Transit Timing Variations: Validation & Characterization

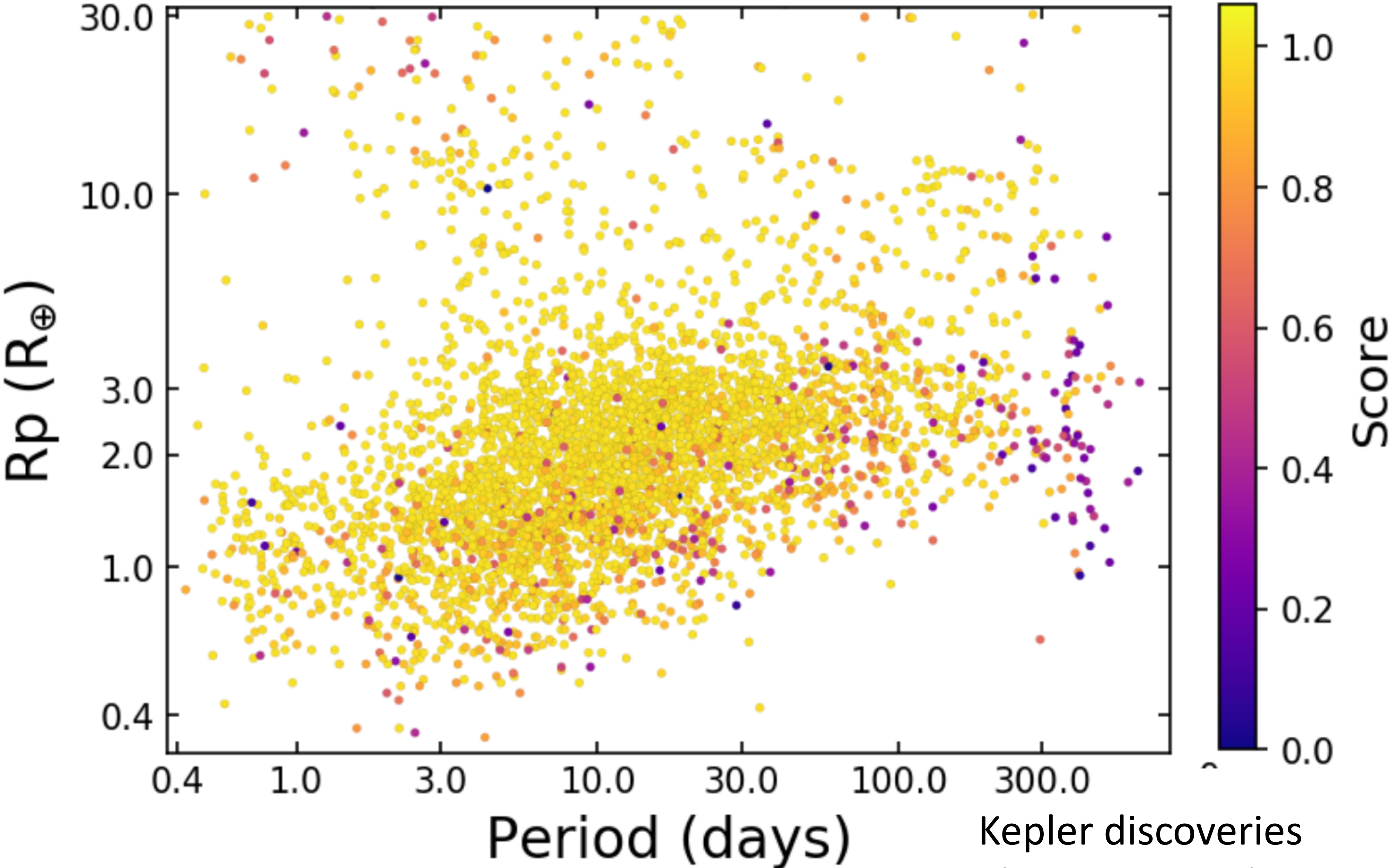
Daniel Fabrycky
University of Chicago



Detlev Van Ravenswaay
Science Photo Library

Perryman 2013

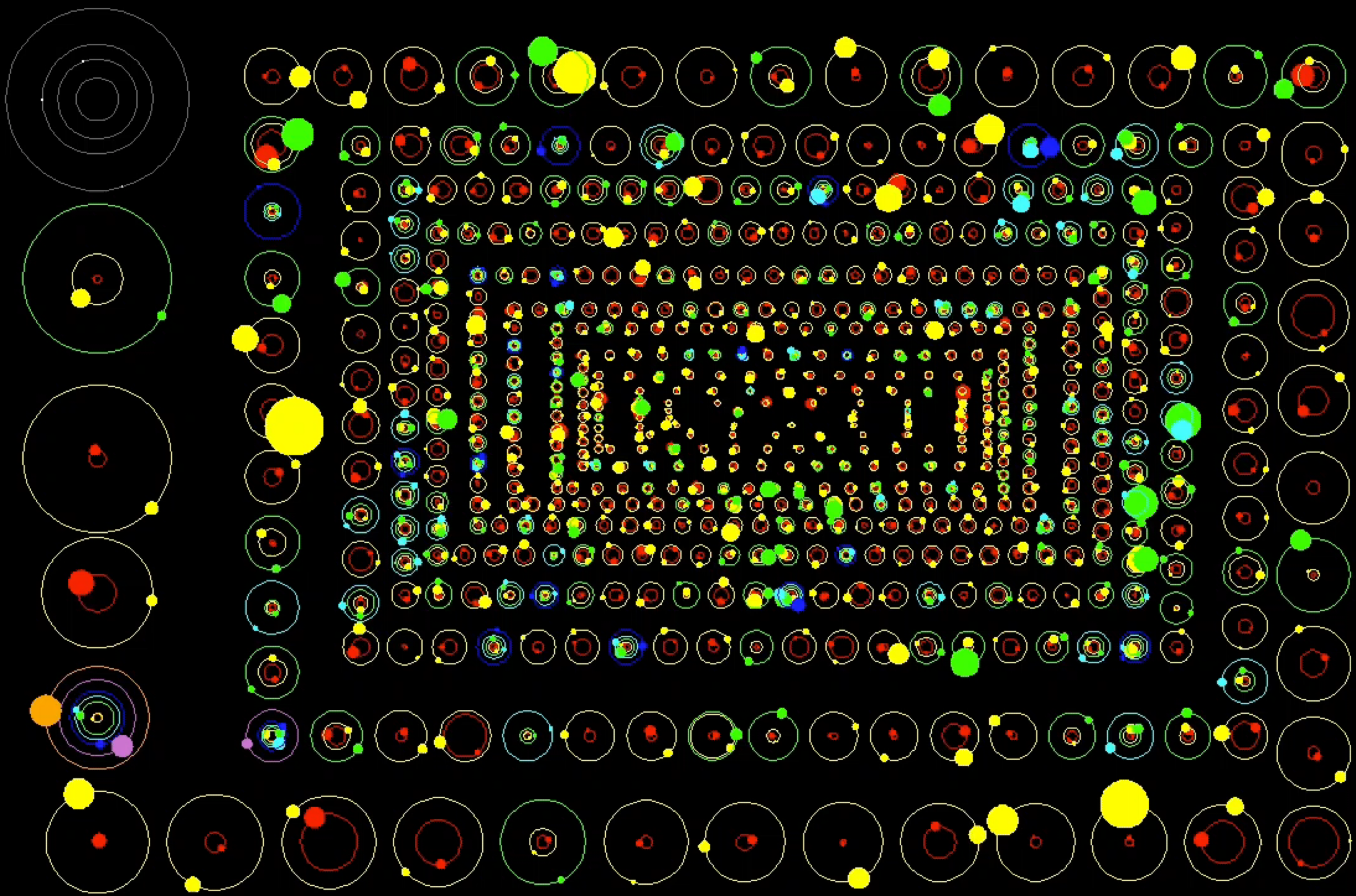




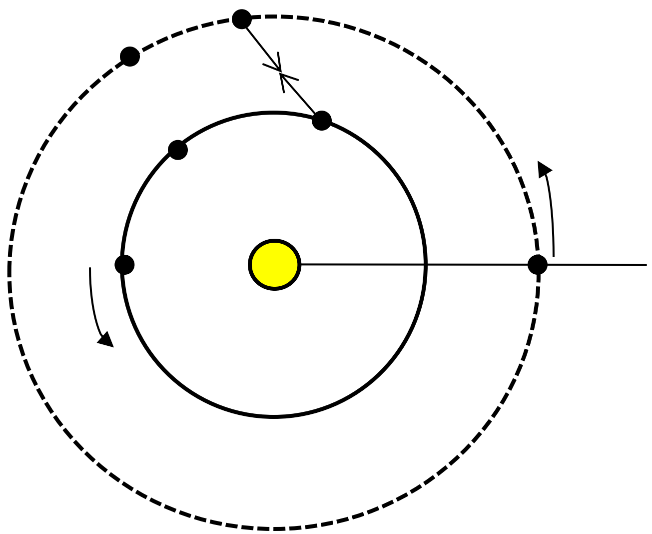
Kepler discoveries
Thompson et al. 2018

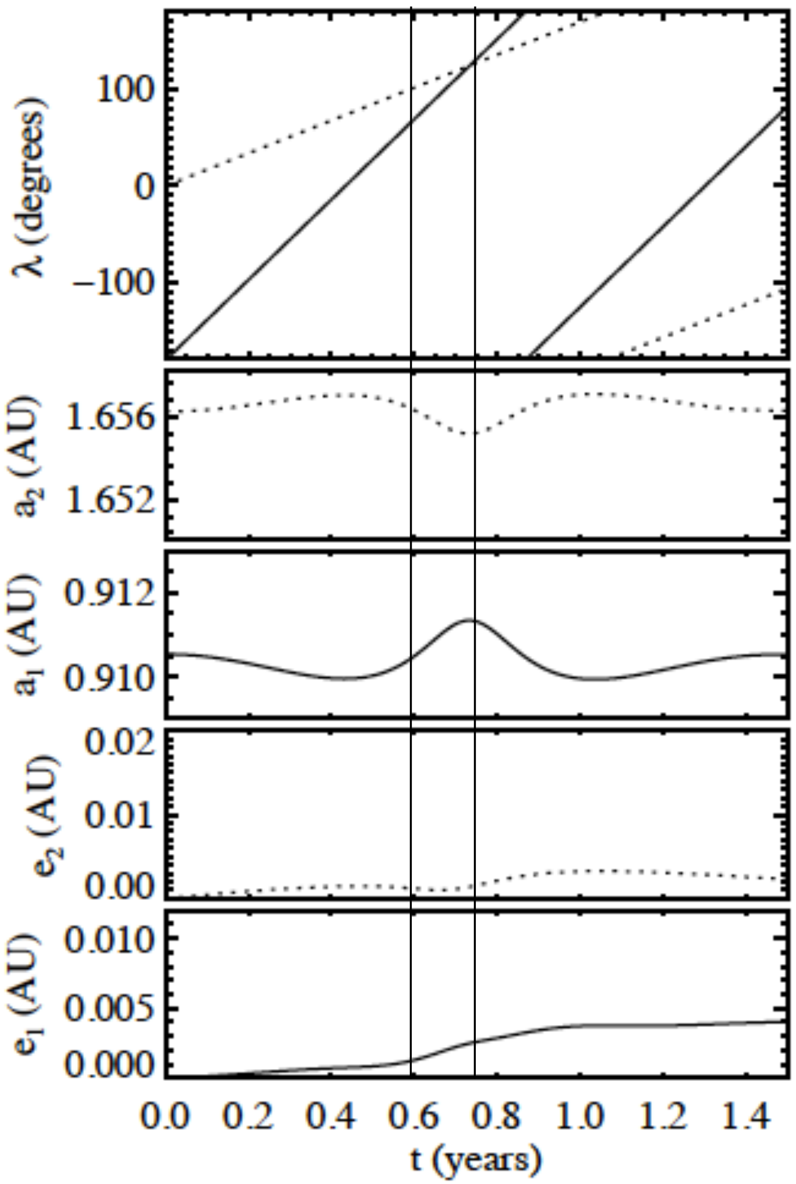
The Kepler Orrery III

t[BJD] = 2455215

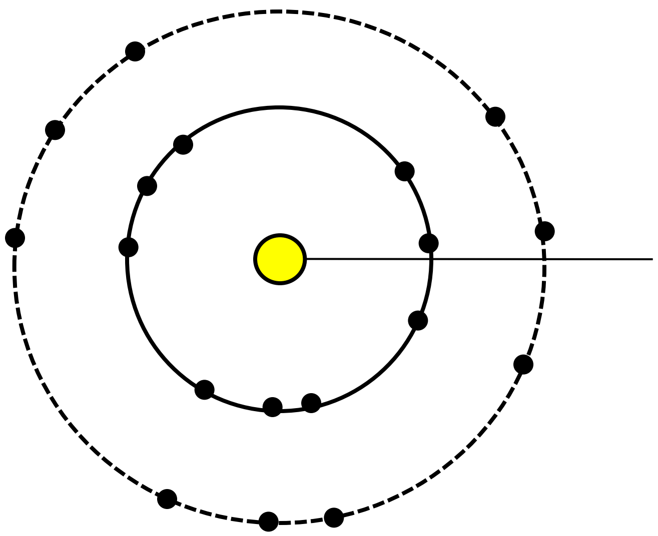


Dynamics: Orbital Timescales

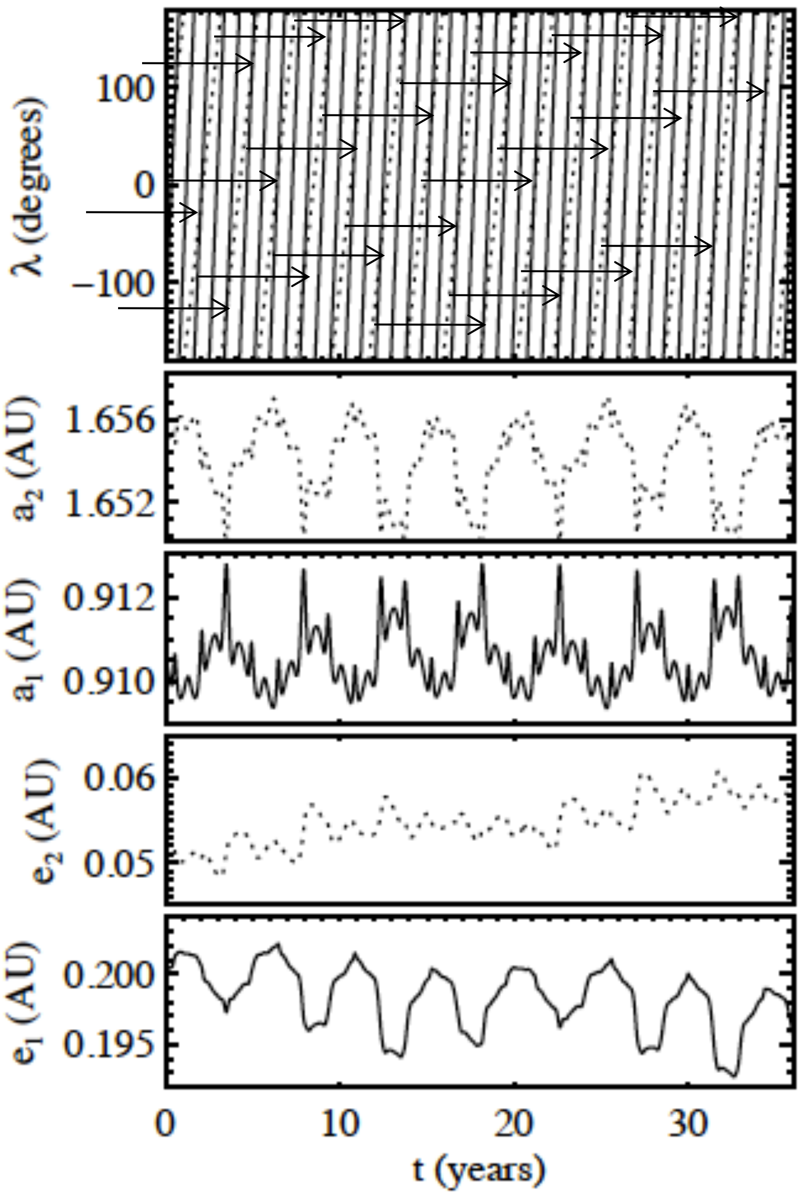




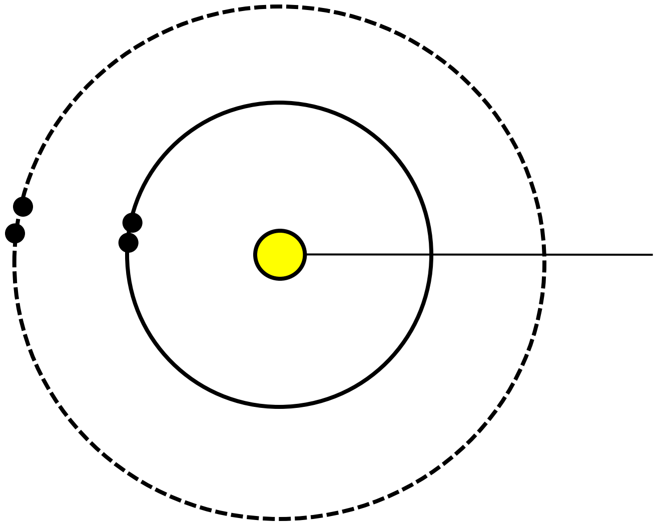
Dynamics: Secular Timescales



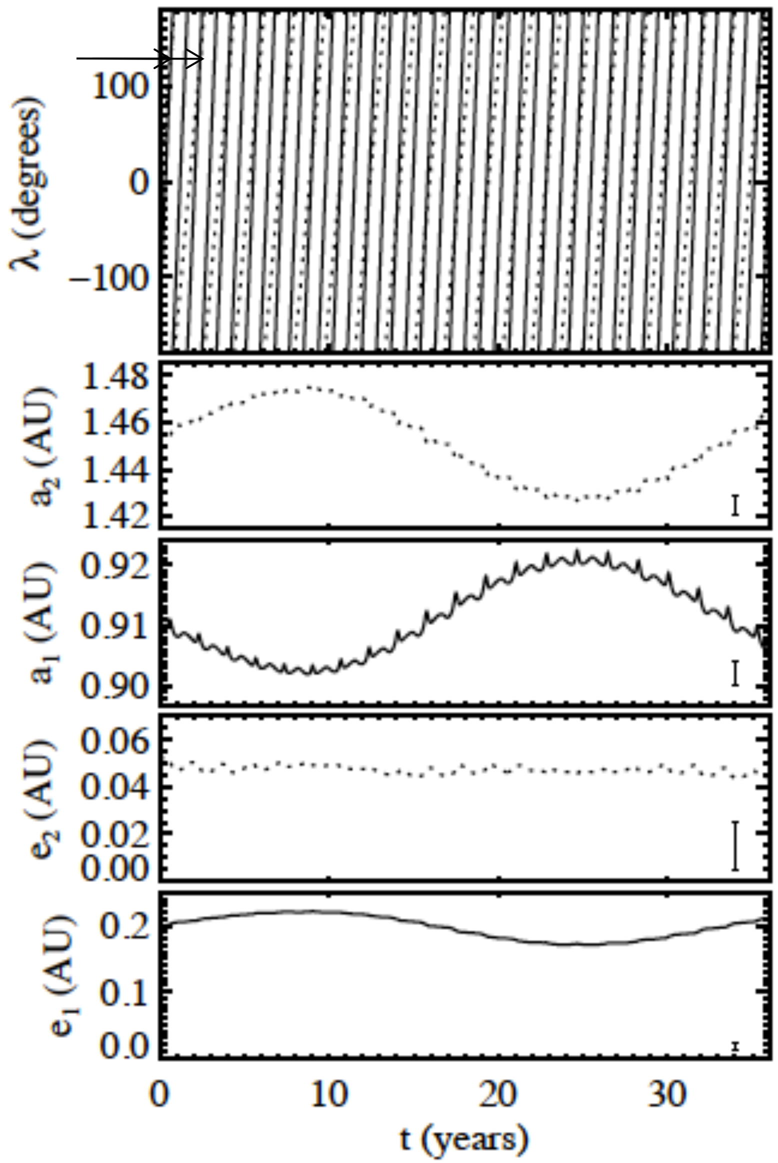
$P_2/P_1 = 2.44$
near 5:2



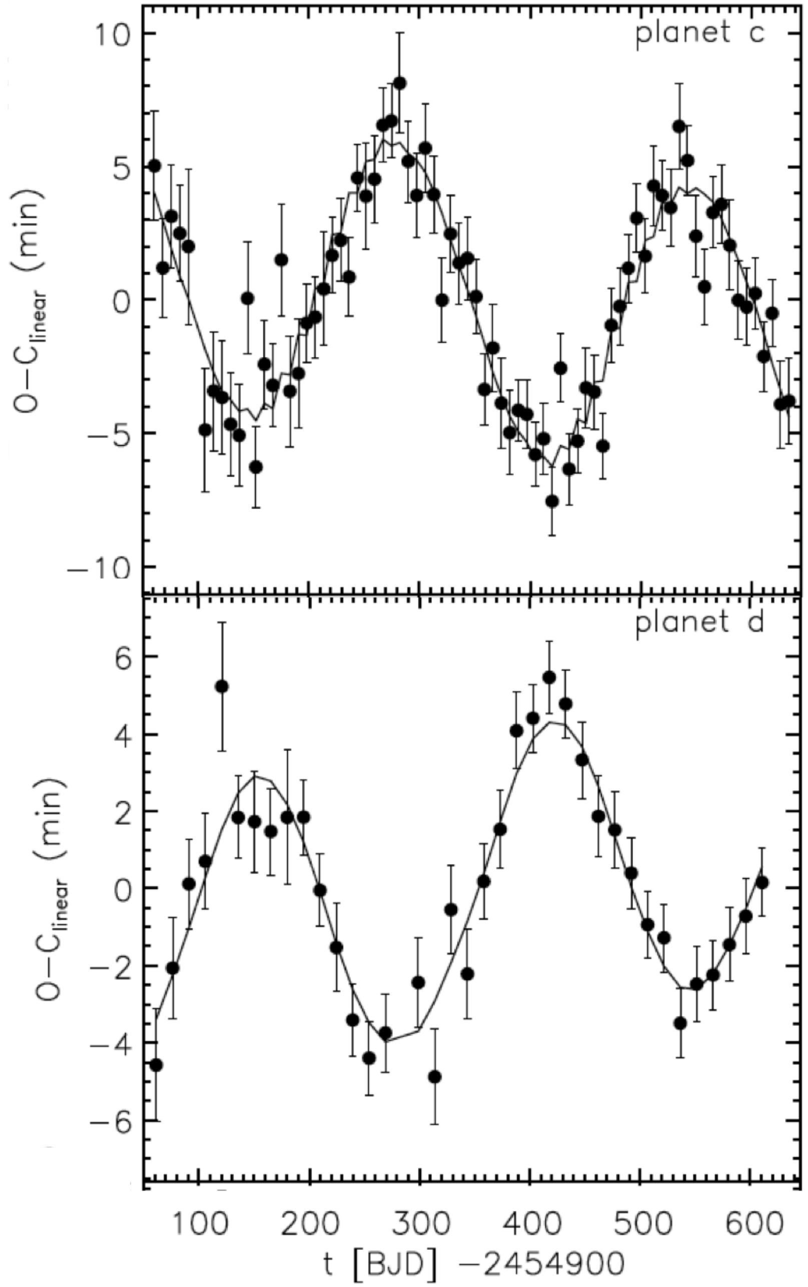
Dynamics: Resonant Orbits



$P_2/P_1 = 2.00$



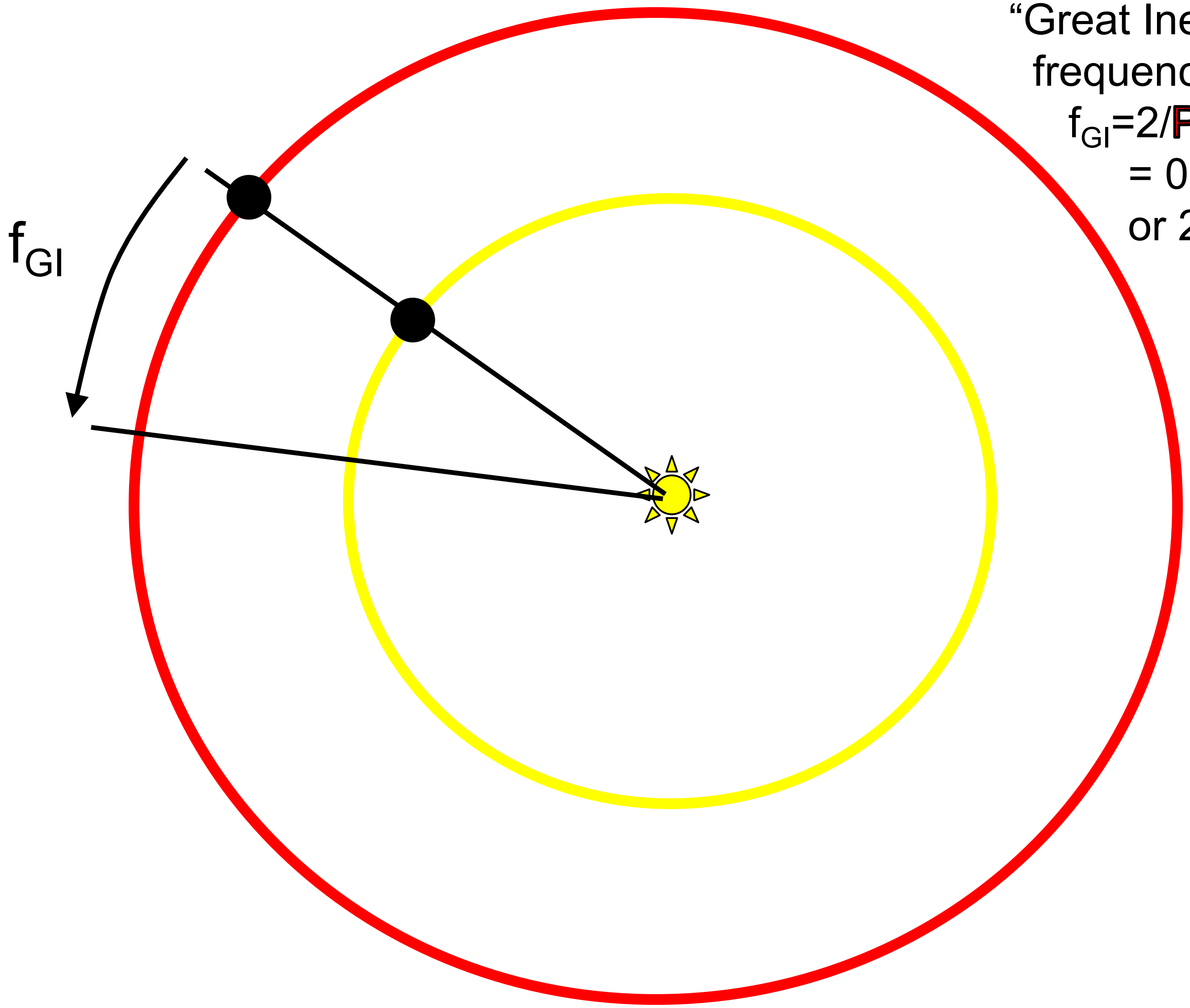
P = 7.6416 days



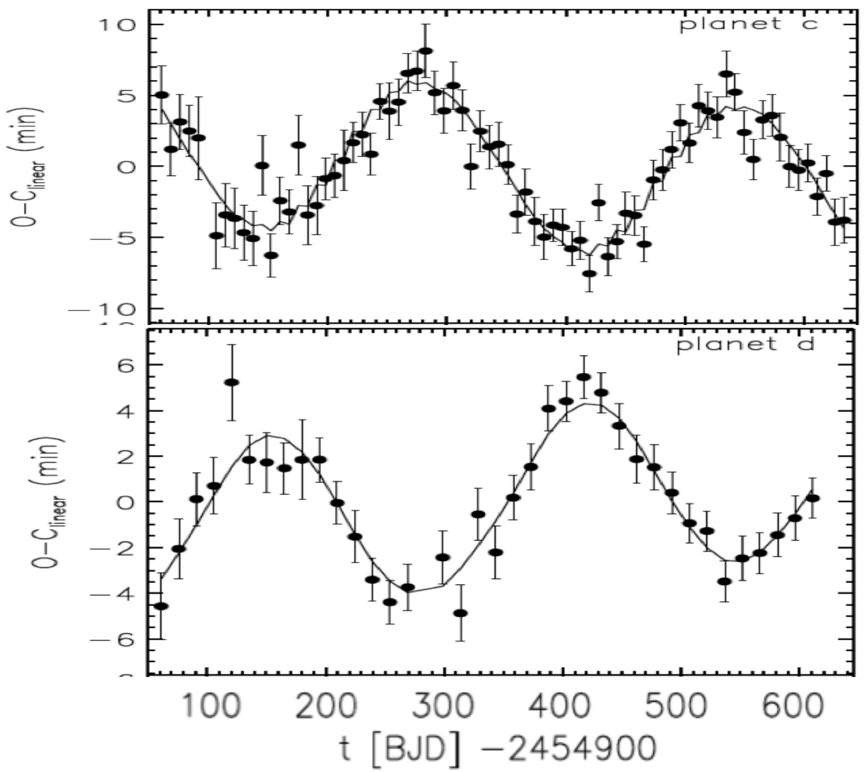
P = 14.8589 days

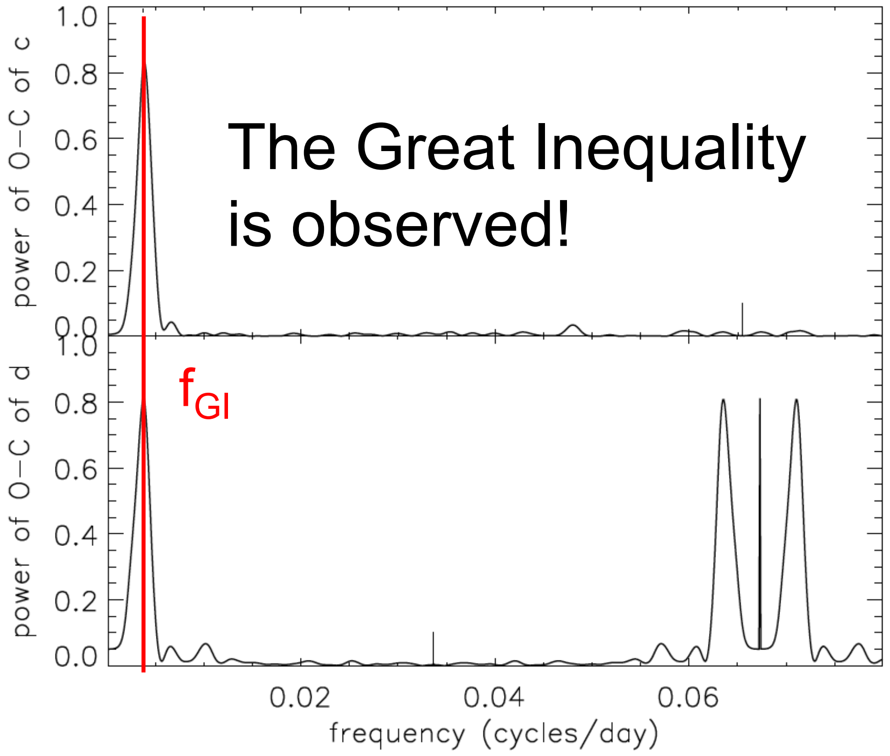
P/P=1.944 ~= 2/1

Kepler-18
Cochran, Fabrycky
et al. 2011



"Great Inequality"
frequency:
$f_{GI}=2/P-1/P$
= 0.0037 d-1
or 270 days





Planet	Period (days)	RV Mass (M_{Earth})	TTV Mass (M_{Earth})	e
b	3.5	12 ± 5	18 ± 9	n/a
c	7.6	15 ± 5	17.3 ± 1.7	0.00034 ±0.00014
d	14.9	28 ± 7	15.8 ± 1.3	0.00045 ±0.00052

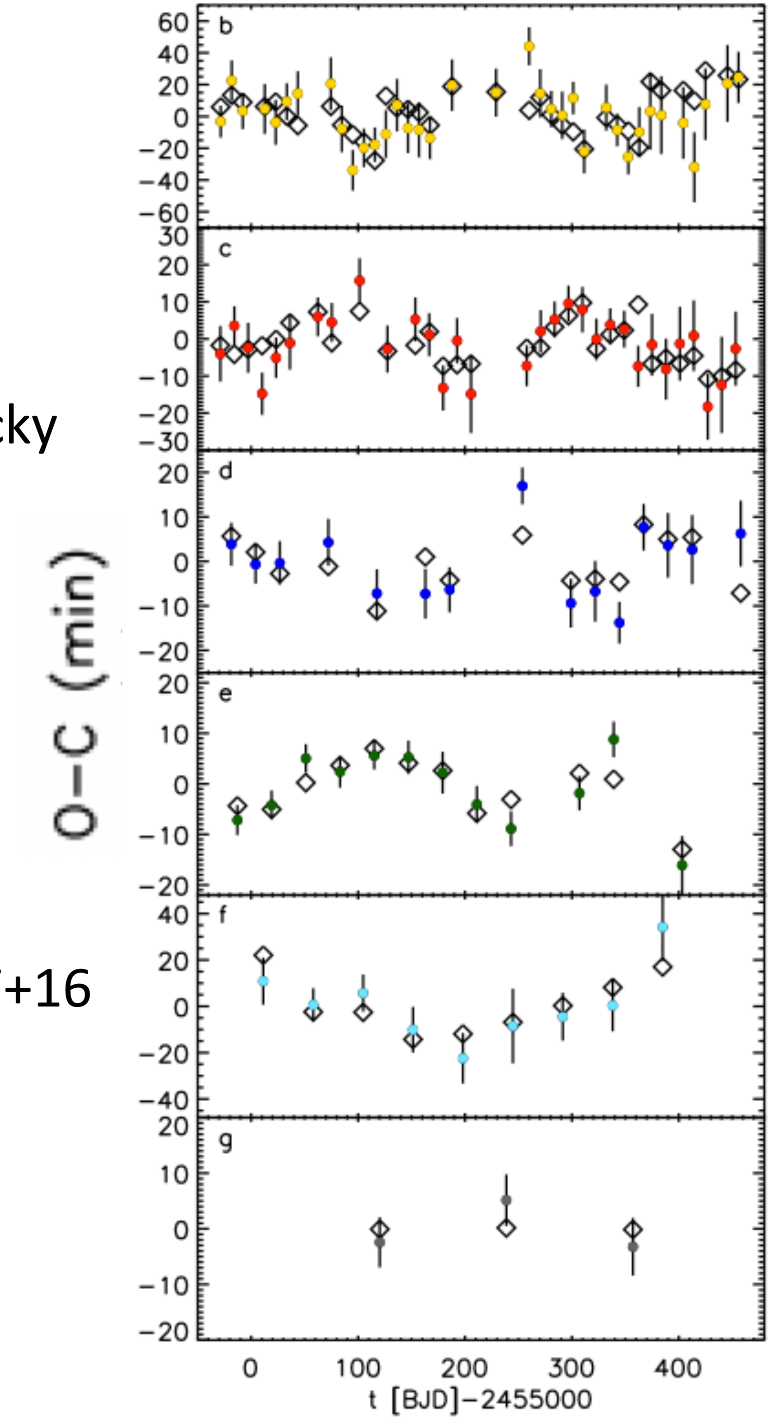
$$P_{TTV} = 1/|j/P_2 - k/P_1|.$$

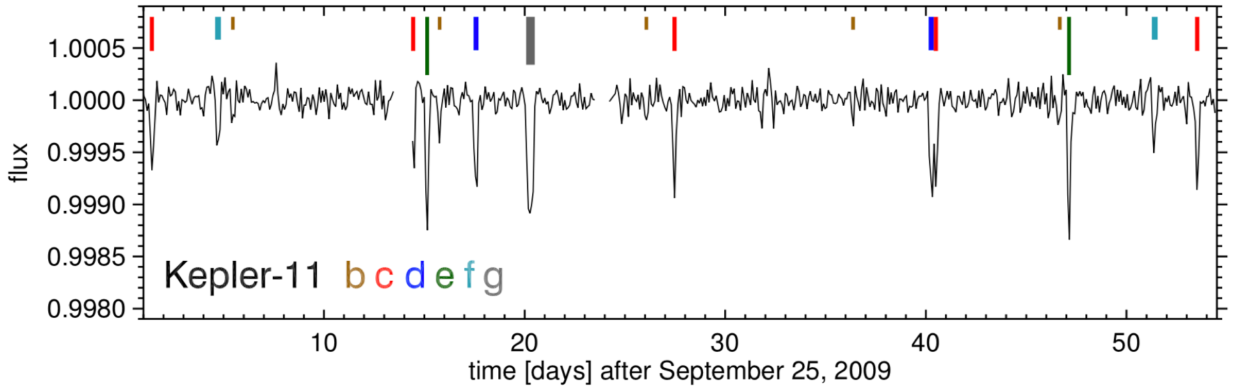
Cochran, Fabrycky et al. 2011
Fabrycky+12: We can use this timescale to be the validating signature of two transiting planets--> Kepler-23-32

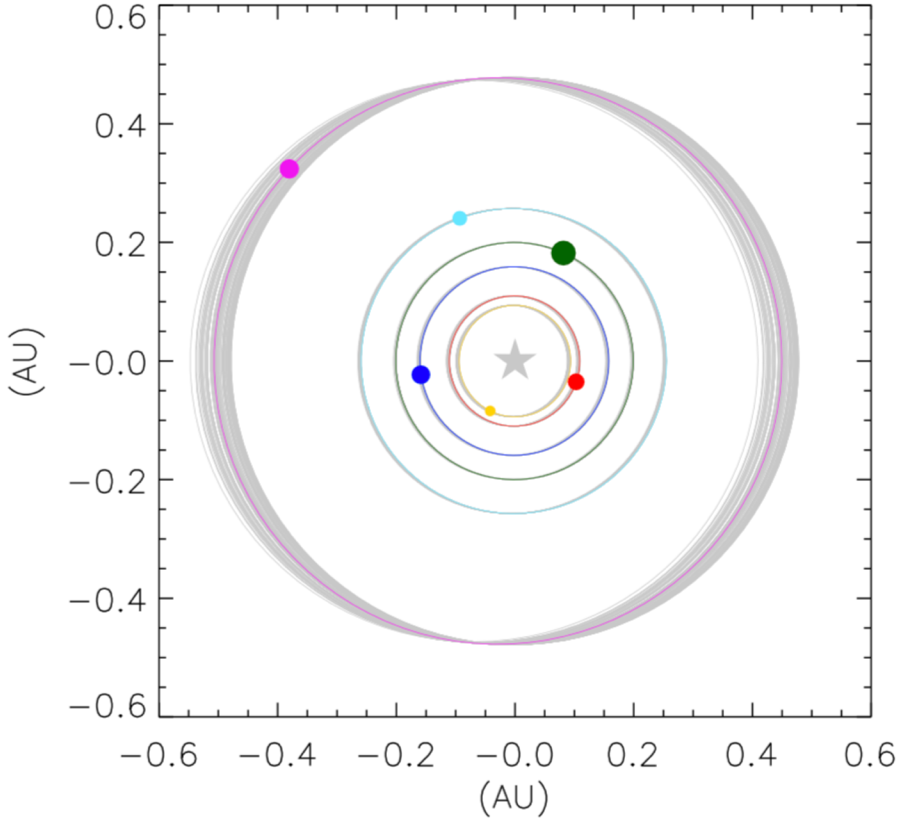
Kepler-11

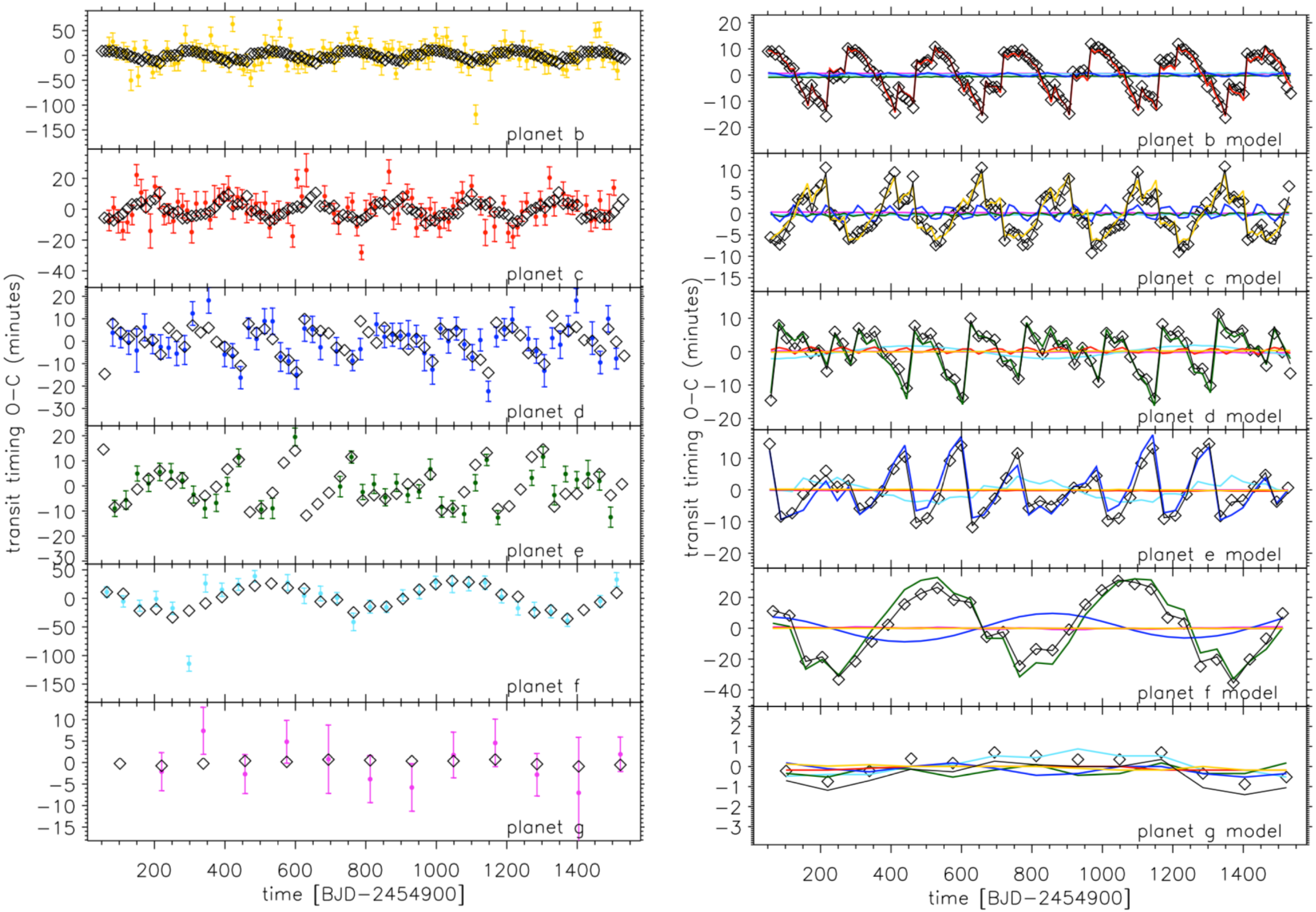
Lissauer, Fabrycky et al. 2011

Latest:
Borsato+14
Bedell/Mills/DF+16





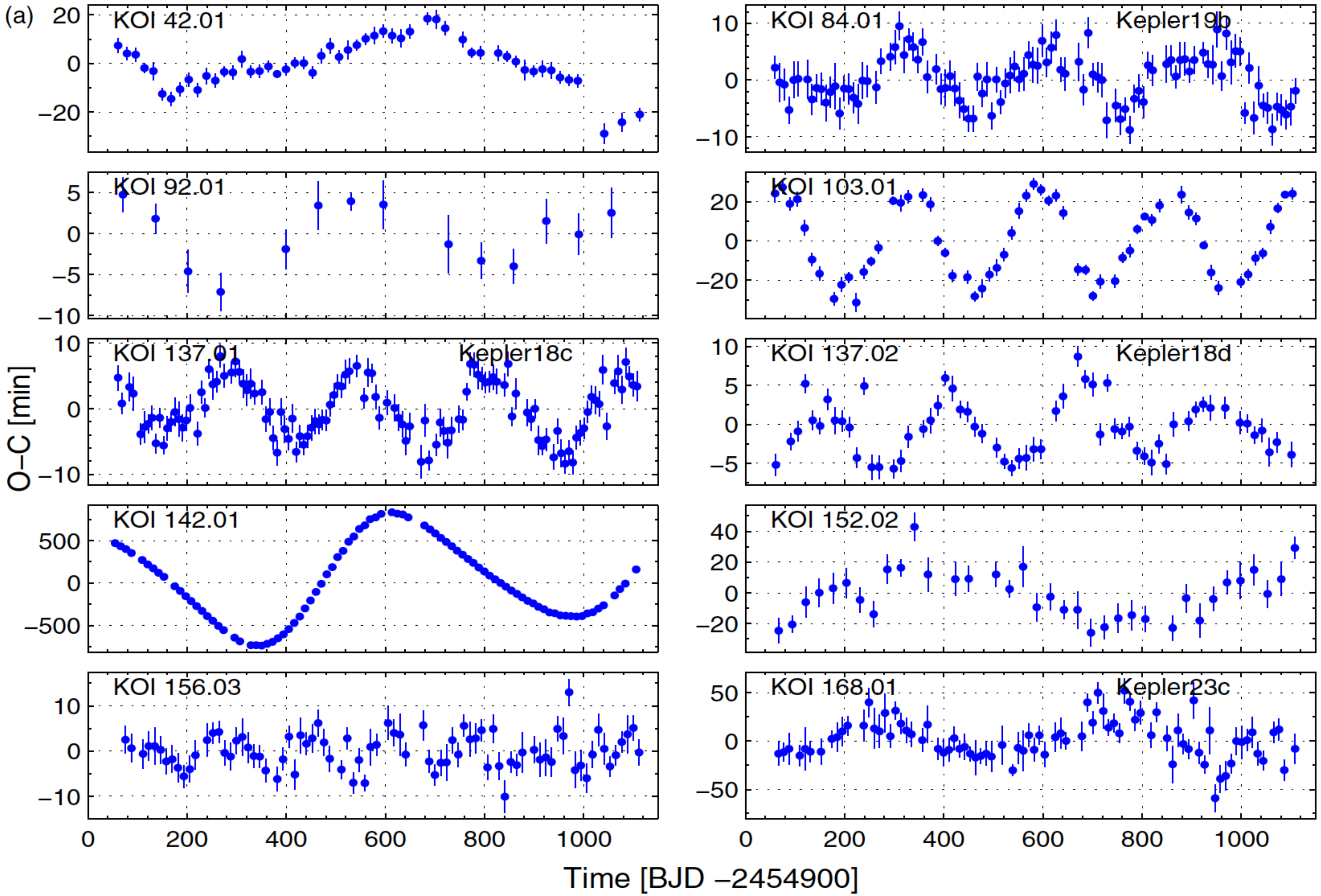




Note linearity of the signal – pairs' effect simply adds up to the 6-planet model.

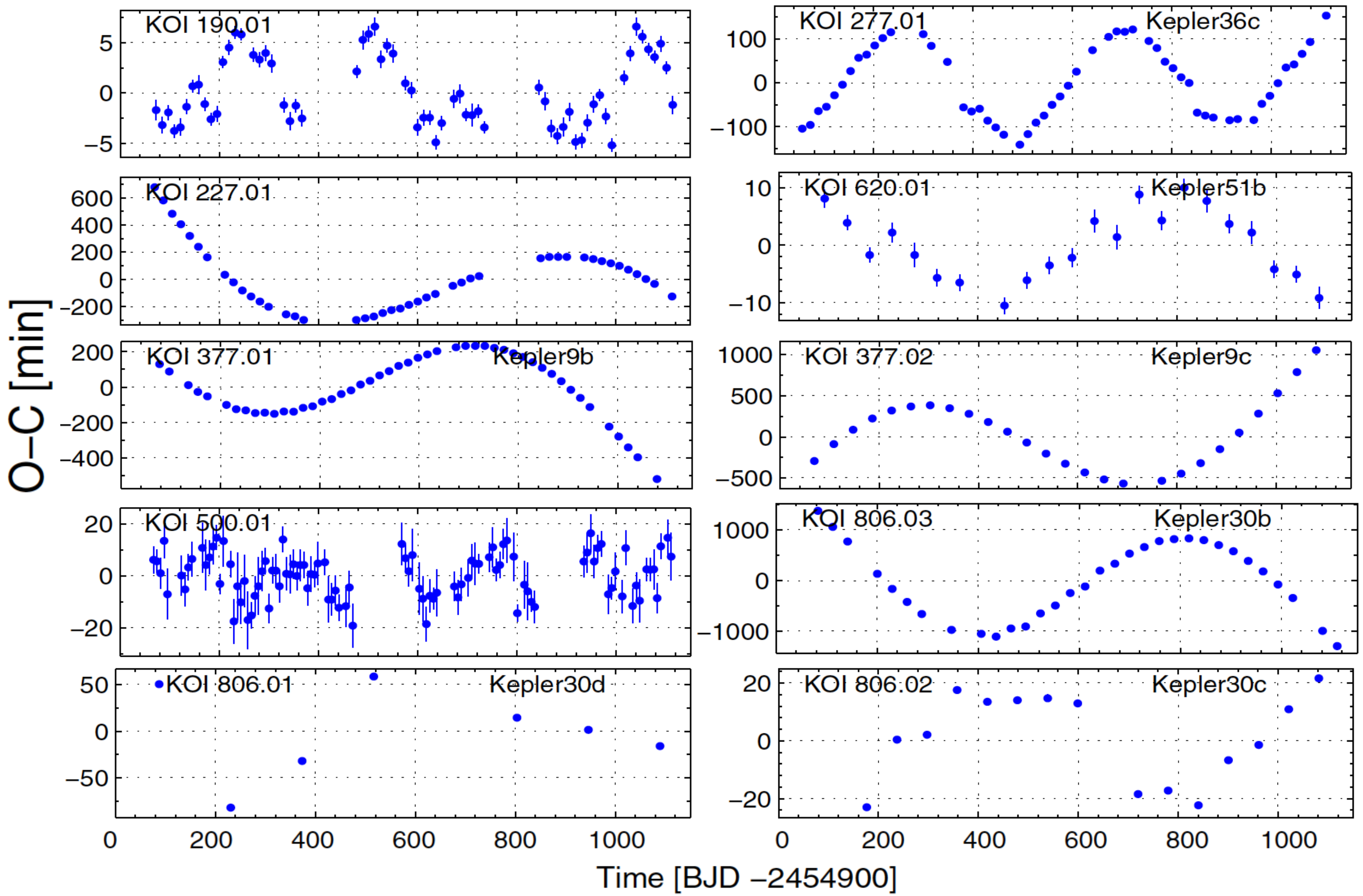
260 TTV detections

Holczer, Mazeh et al. 2013



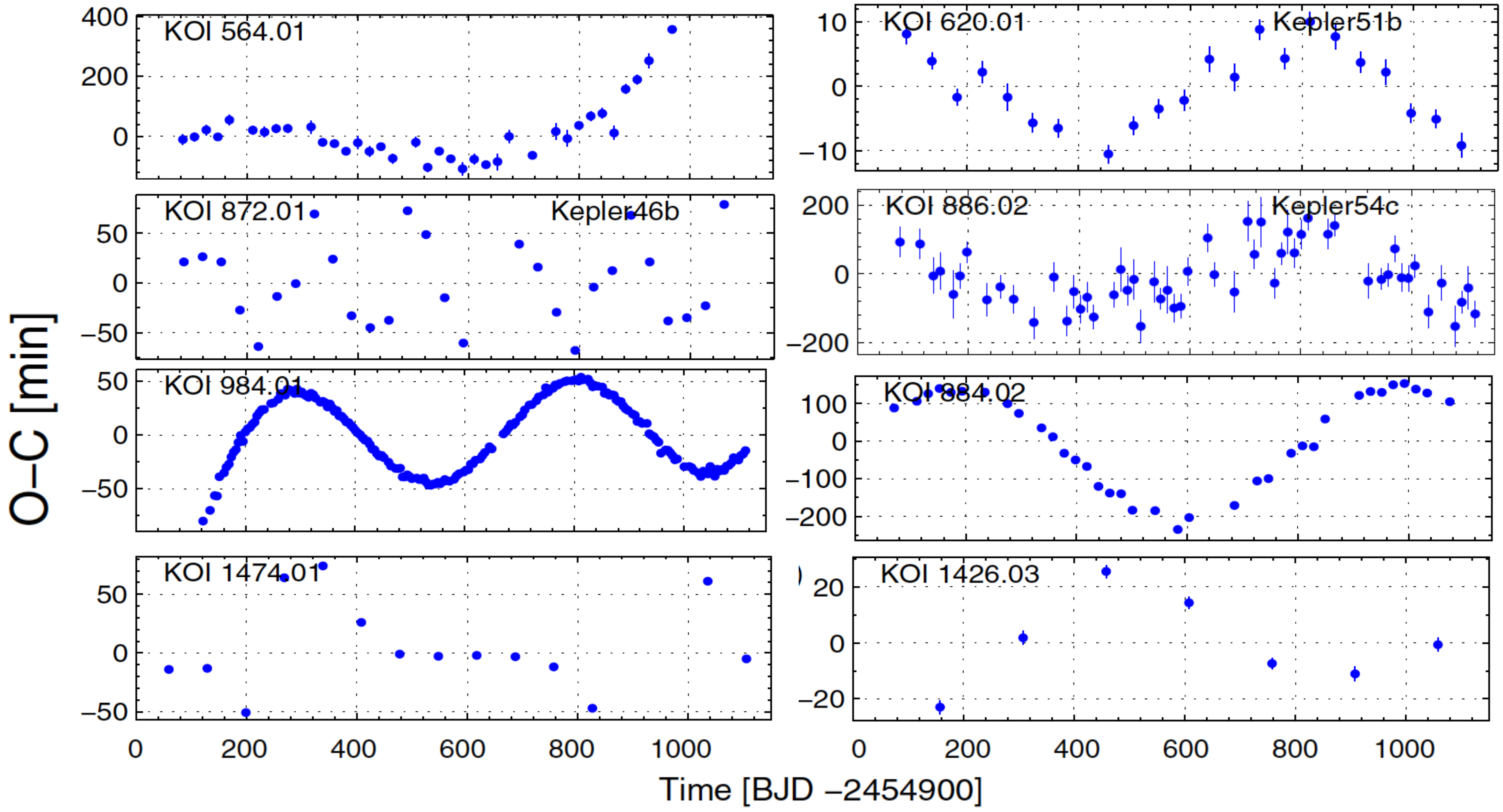
Cont'd

Holczer, Mazeh et al. 2013



Cont'd…

Holczer, Mazeh et al. 2013



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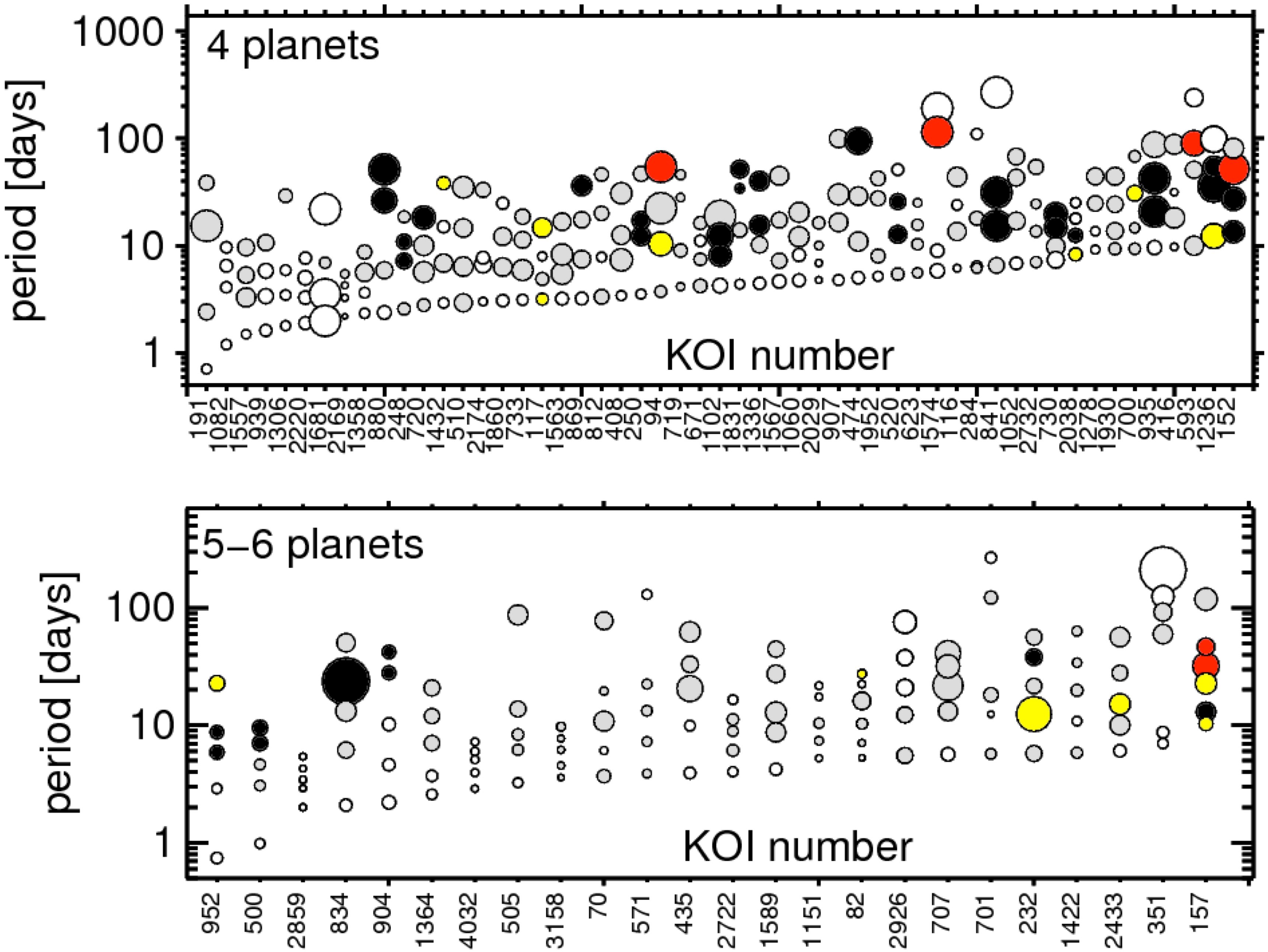


Sinusodal (strong)
Non-Sinusoidal (strong)
Either; weak but significant
Searched, but absent
Not searched

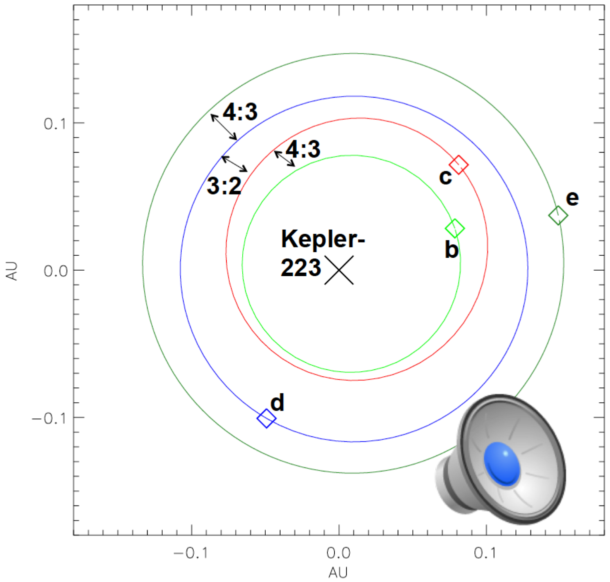
260 TTV detections out of 2599 with large individual transits (Holczer+16)

528 out of 4629 candidates, total (Ofir+18)

Architectures III: Lissauer et al. in prep

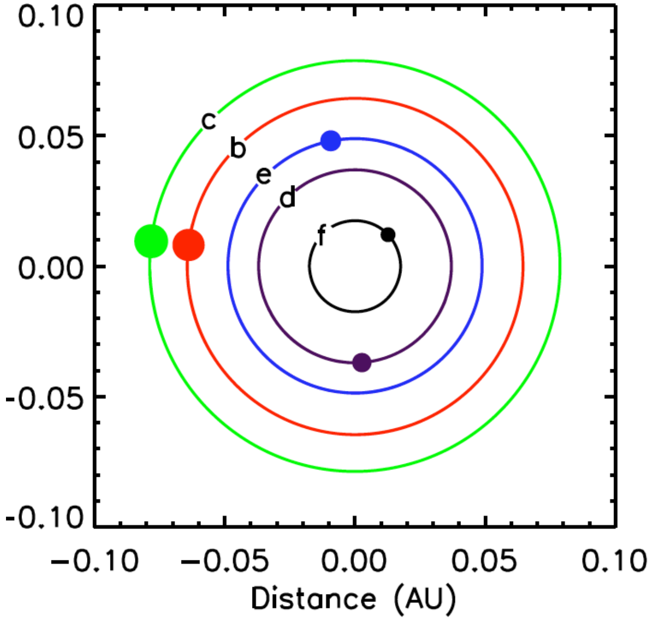
The Resonant Chains

Kepler-223



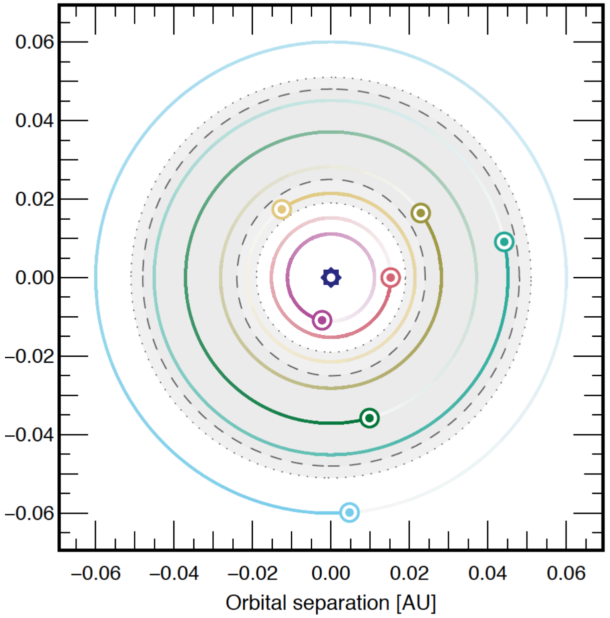
(4:3, 3:2, 4:3)

Kepler-80



(1.518, 1.518, 1.350)

TRAPPIST-1



(1.60293 (8:5), 1.67213 (5:3), 1.50622, 1.50939, 1.34174, 1.5192)

Also transiting:

Kepler-60 (Gozdziewski et al 2016, Jontof-Hutter et al. 2016)

K2-138 (Christiansen et al. 2017)

Doppler: GJ 876 (Rivera et al. 2010, Nelson et al. 2016)

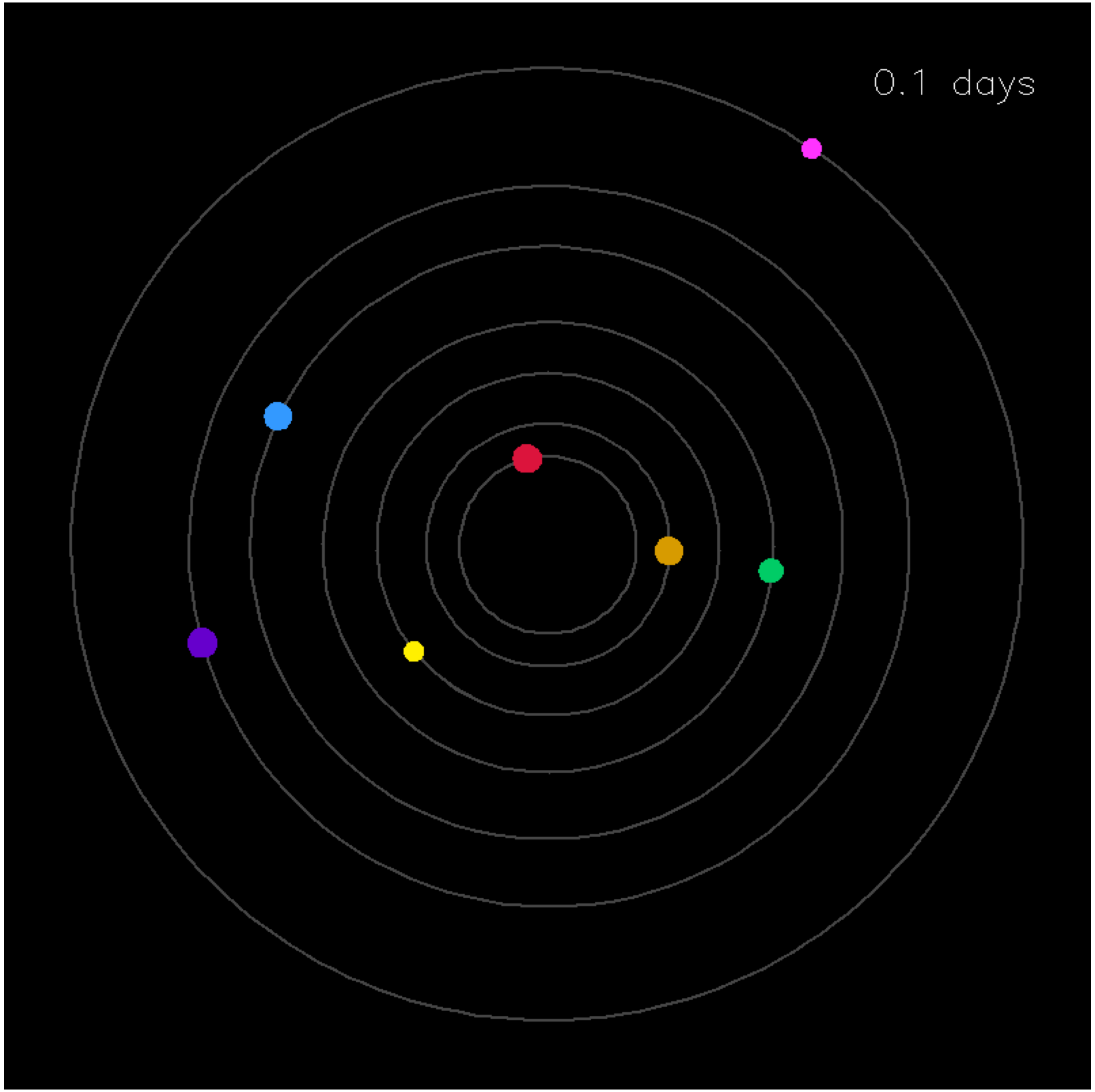
Imaging: HR 8799 (Fabrycky & Murray-Clay 2010, inferred from stability; Gozdziewski & Migaszewski 2014, migration simulation into correct phases)

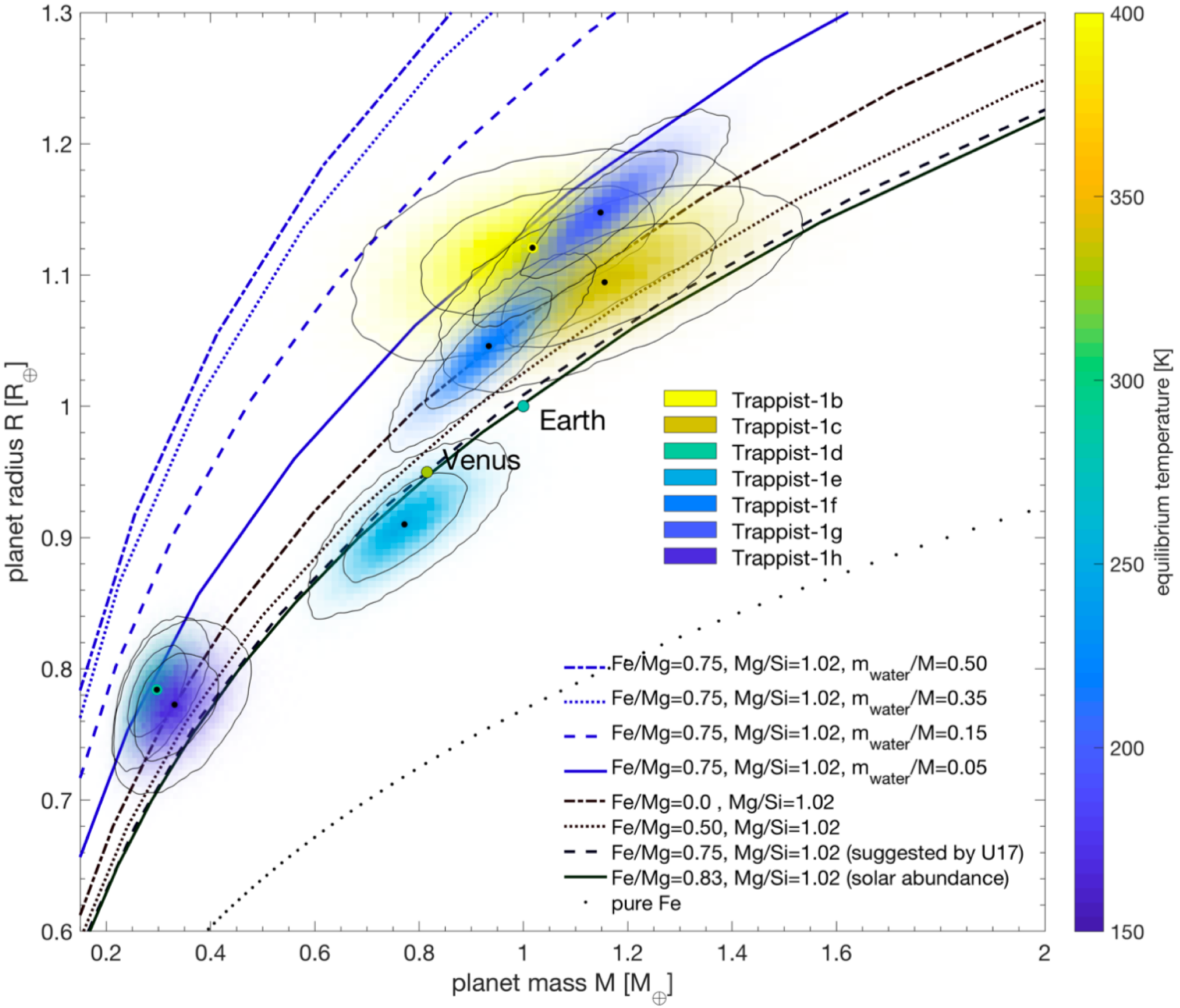
TRAPPIST-1

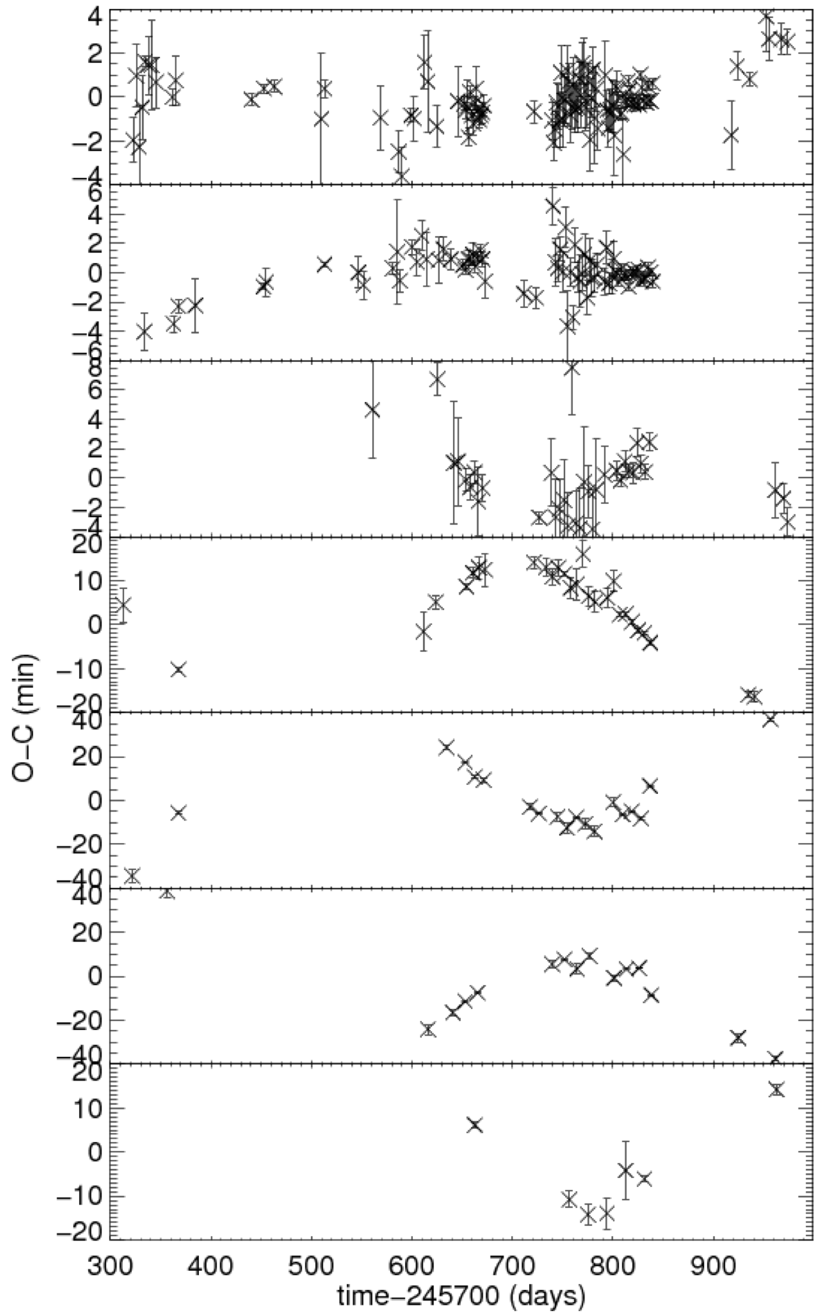
Planet	P (d)	P_{i+1}/P_i	n:m	$n/P_{i+1}-m/P_i$ (TTV freq., cycles/d)
b	1.51087081	1.60293	8:5	-0.0060535
c	2.4218233	1.67213	5:3	-0.0040494
d	4.049610	1.50622	3:2	-0.0020404
e	6.099615	1.50939	3:2	-0.0020395
f	9.206690	1.34174	4:3	-0.0020405
g	12.35294	1.5192	3:2	-0.002042
h	18.766			

Luger et al. 2017

Near-resonant super-period is 490 days.


0.1 days

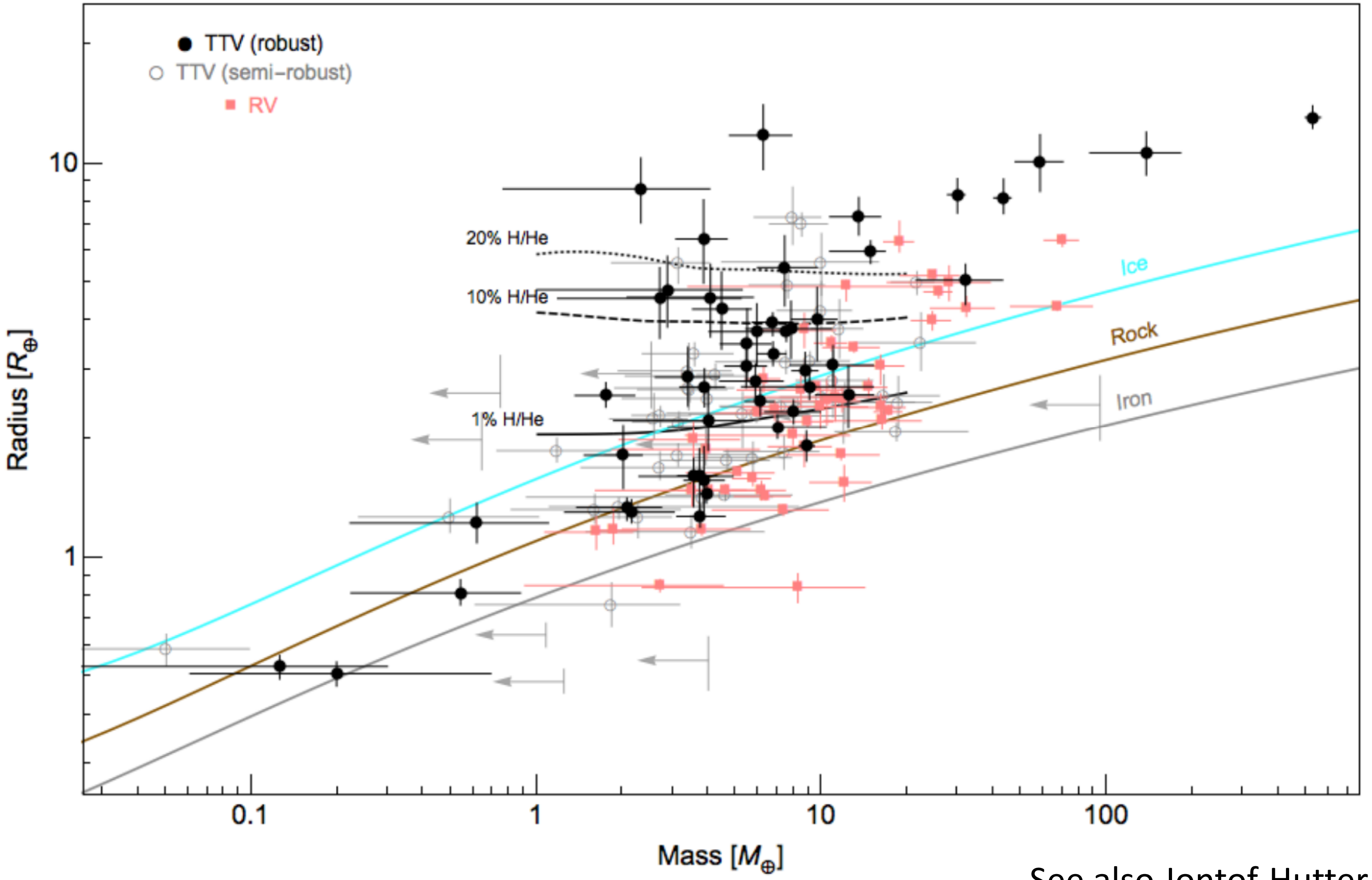




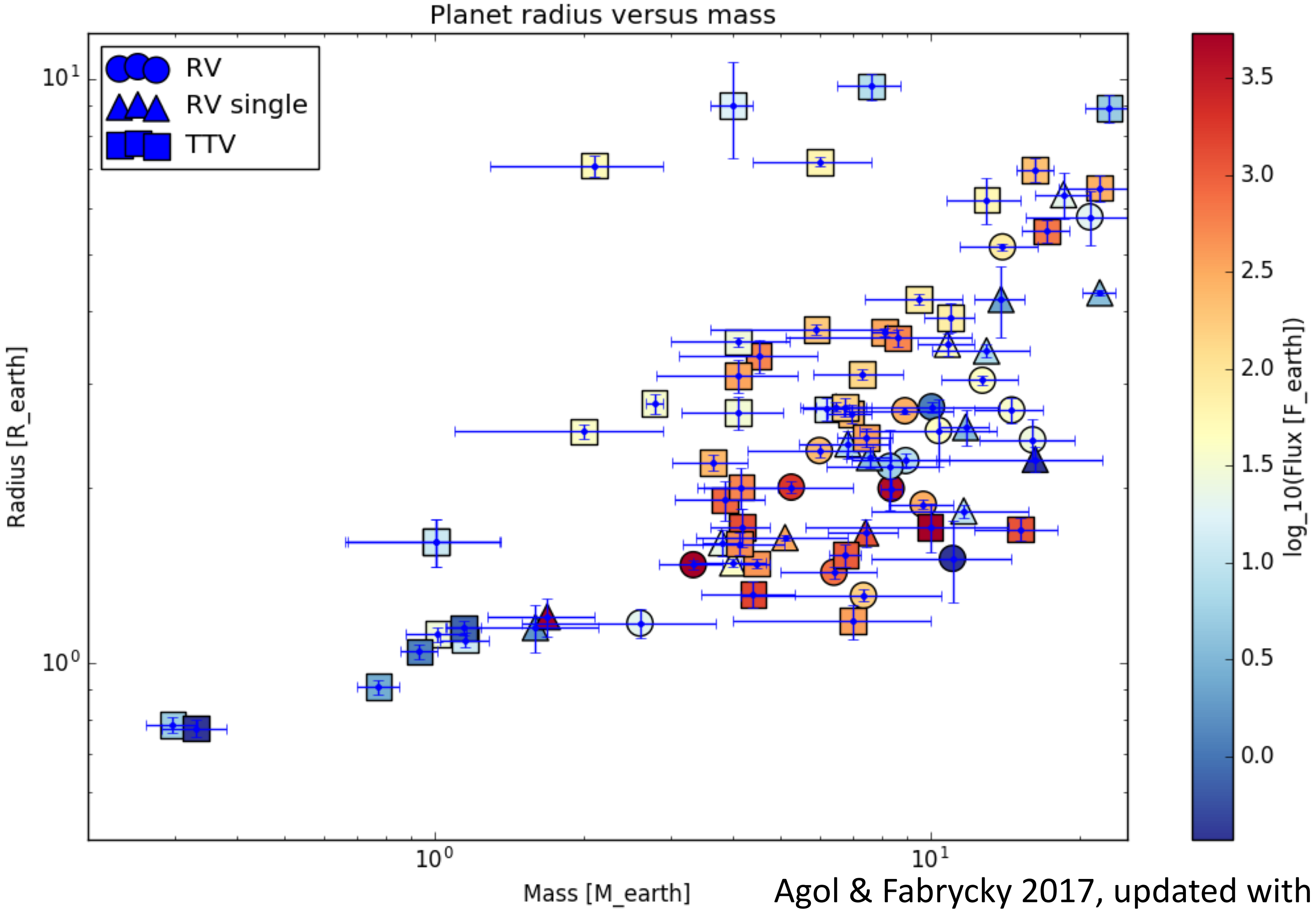
Grimm+18, leveraging Spitzer transit campaign of Delrez+18

Sub-Neptunes vs. Super-Earths

Hadden & Lithwick 2017



See also Jontof-Hutter et al. 2016



Scorecard for $M<25M_{Earth}$:

TTV: 44

RV: 33

Agol & Fabrycky 2017, updated with TRAPPIST-1

Detection of Exoplanets by TTV

First, a warning:

m/e degeneracy (Lithwick+12).

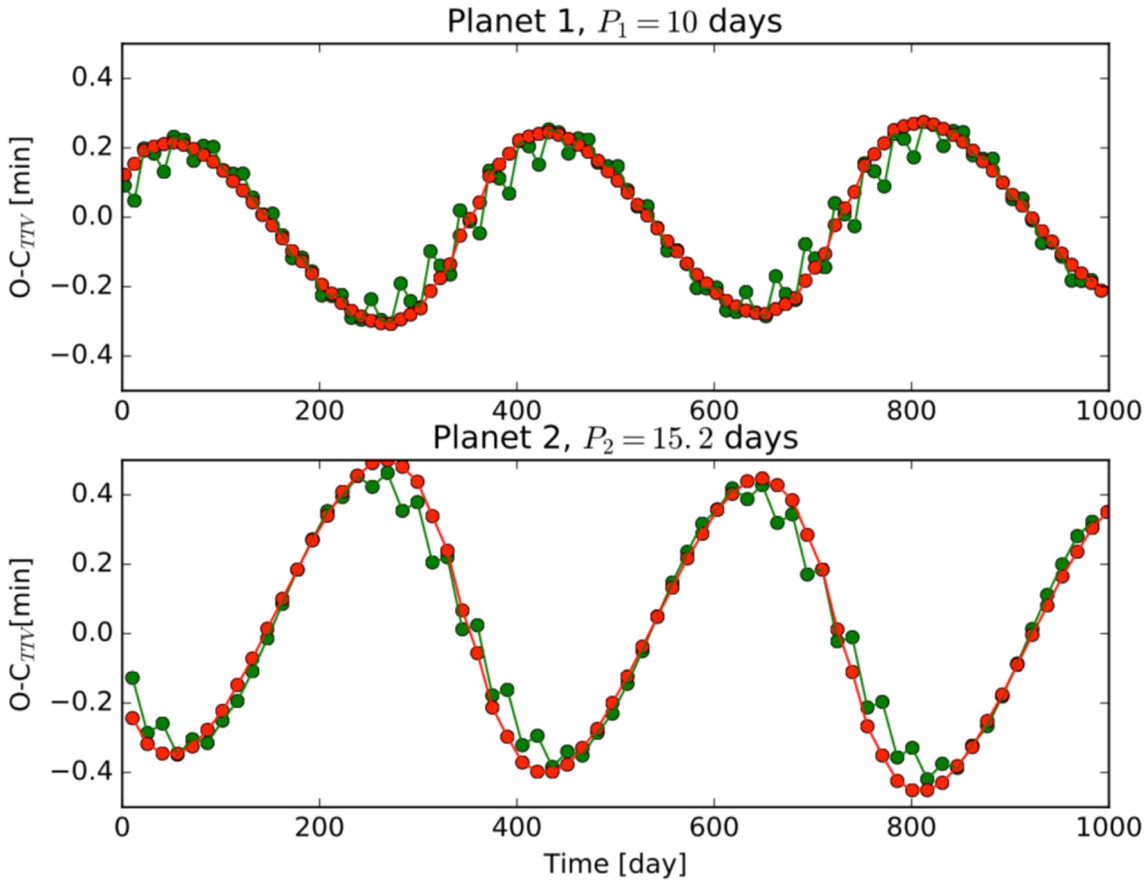
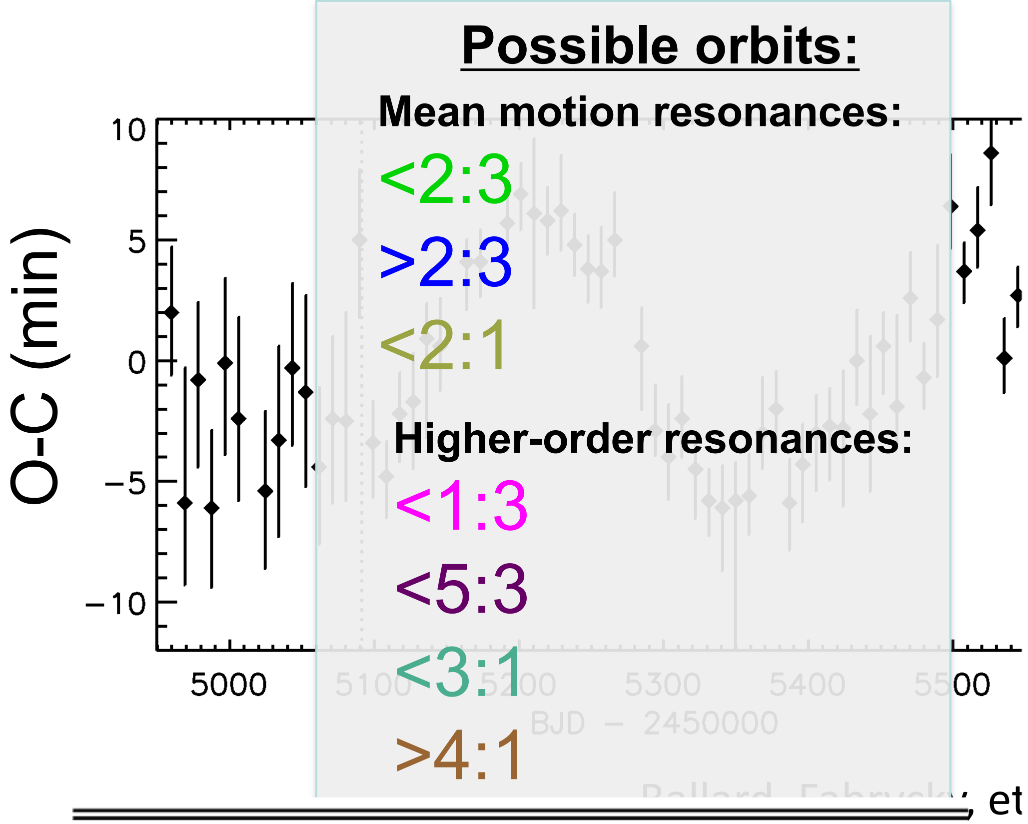


Fig. 2 Transit-timing variations of two low-eccentricity planets with larger mass ratios, $m_1 = m_2 = 10^{-6} m_*$ (green) compared with two higher eccentricity planets ($e_1 = e_2 = 0.04$) with smaller mass ratios $m_1 = m_2 = 10^{-7} m_*$. The zig-zag chopping component is apparent in the high-mass/low-eccentricity case, while less apparent in the low-mass/ high-eccentricity case.

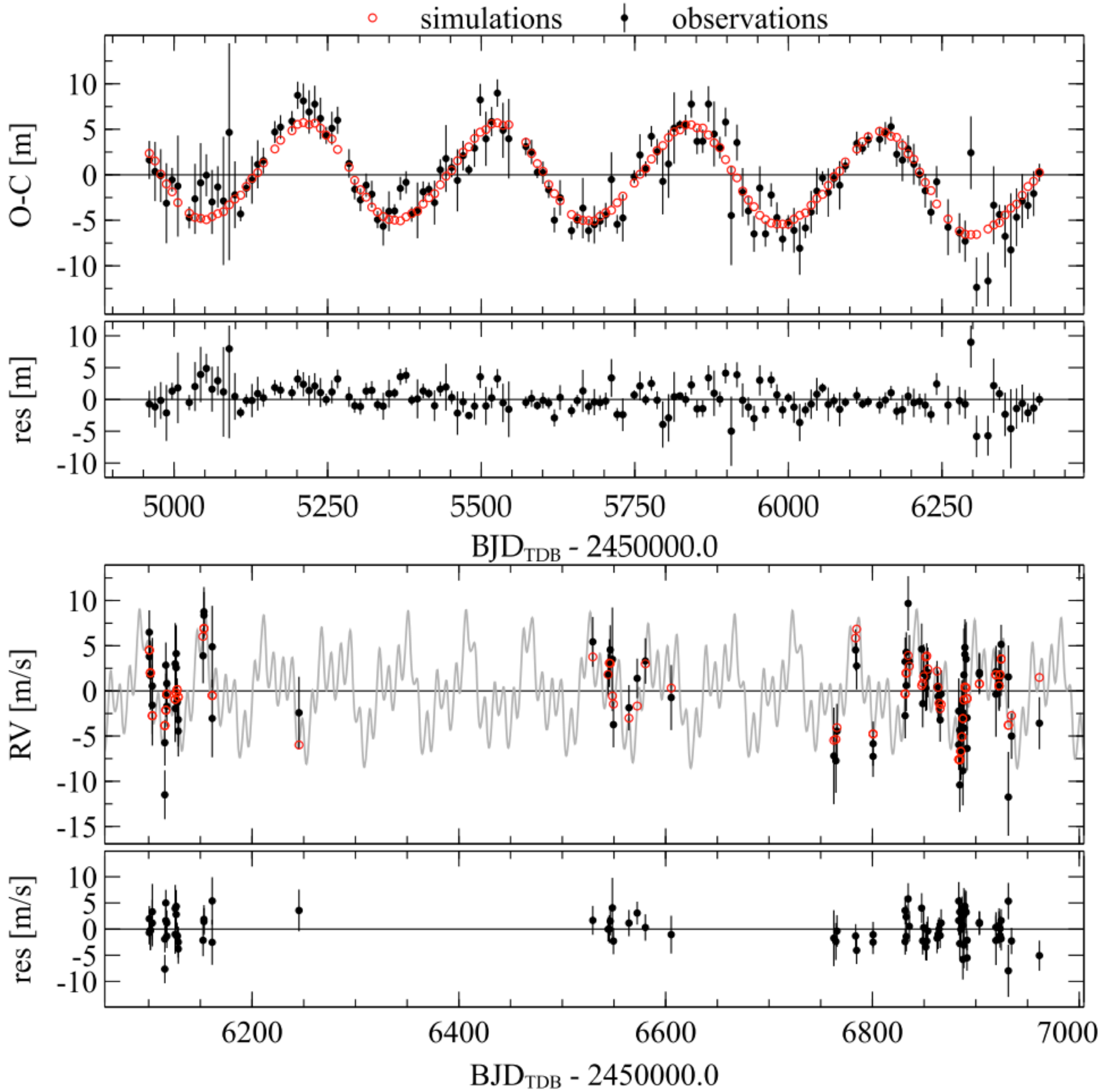
Agol & Fabrycky 2017

First successes: Kepler-19, first planet *apparent* through TTV



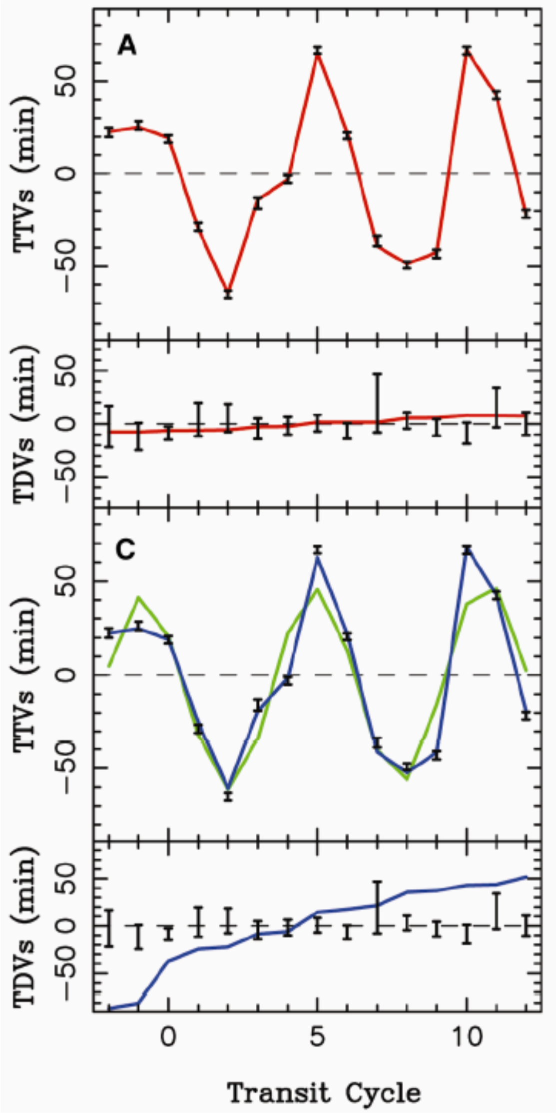
Planet	Period (days)	Mass [$M_\oplus$]
K19b	$9.28716^{+0.00004}_{-0.00006}$	$8.4^{+1.6}_{-1.5}$
K19c	$28.731^{+0.012}_{-0.005}$	$13.1^{+2.7}_{-2.7}$
K19d	$62.95^{+0.04}_{-0.30}$	$22.5^{+1.2}_{-5.6}$

>3:1 x3.09



Maltavolta+2017

First successes: KOI-872 = Kepler-46
First planet *discovered* through TTV/TDurationV

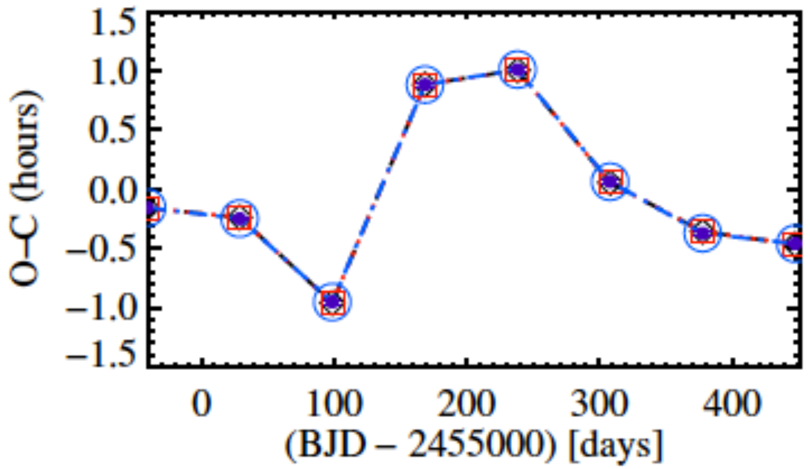


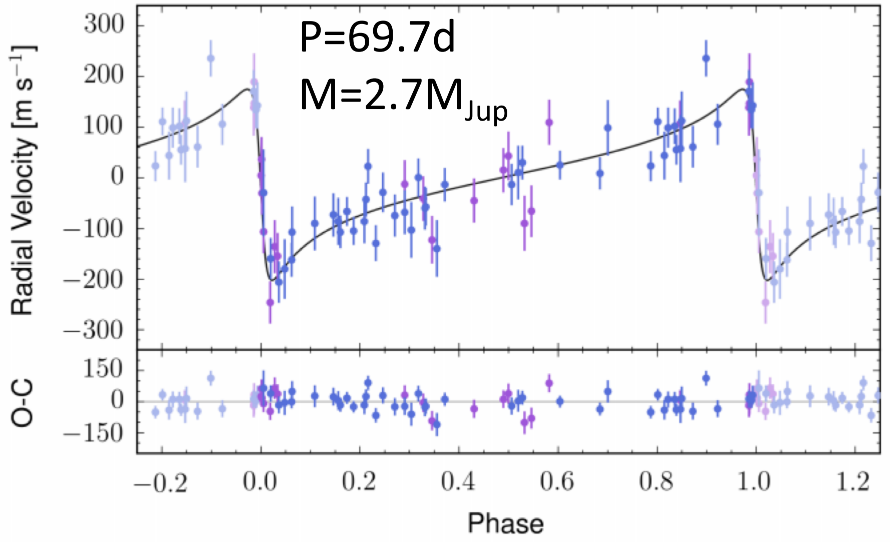
	KOI-872b	KOI-872c
τ_0 [BJD_{UTC}]	$2455053.2826^{+0.0013}_{-0.0014}$	–
P_P [days]	$33.60134^{+0.00021}_{-0.00020}$	$57.004^{+0.091}_{-0.100}$
R_P/R_*	$0.0887^{+0.0011}_{-0.0012}$	–
b_P	$0.759^{+0.022}_{-0.027}$	$3.1^{+1.1}_{-1.9}$
a_P/R_*	$44.9^{+2.1}_{-1.8}$	$63.9^{+2.9}_{-2.5}$
i_P [°]	$89.033^{+0.076}_{-0.069}$	$87.25^{+1.70}_{-0.95}$
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]	$0.812^{+0.043}_{-0.043}$	–

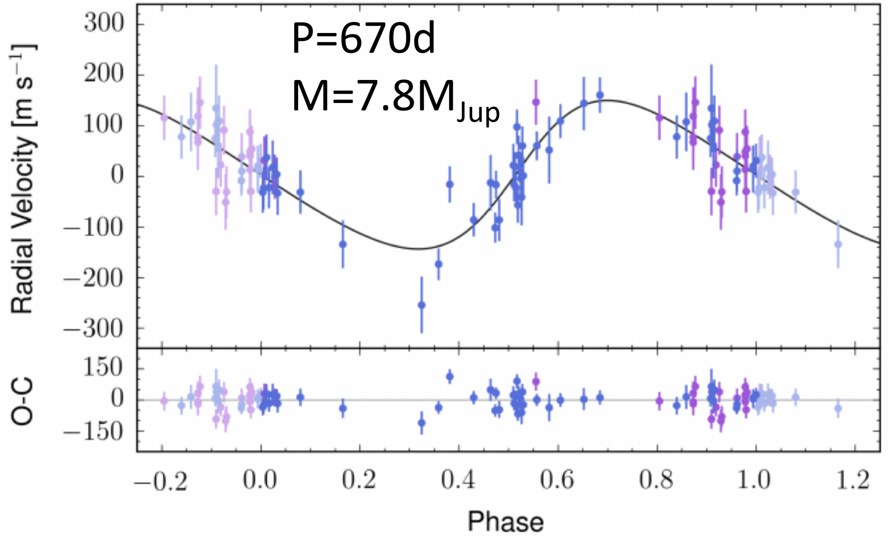
Nesvorny et al. 2012

Two more examples:

(1)



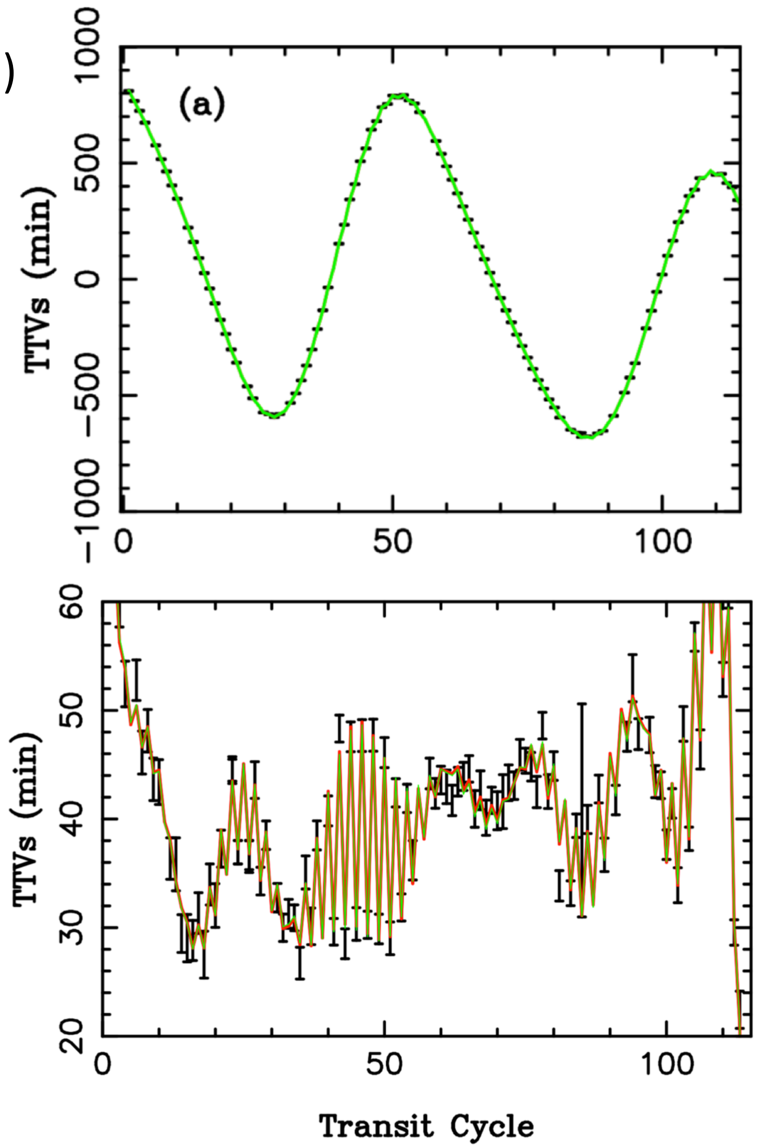




RV detection:
Almenara+18

Two more examples:

(2)



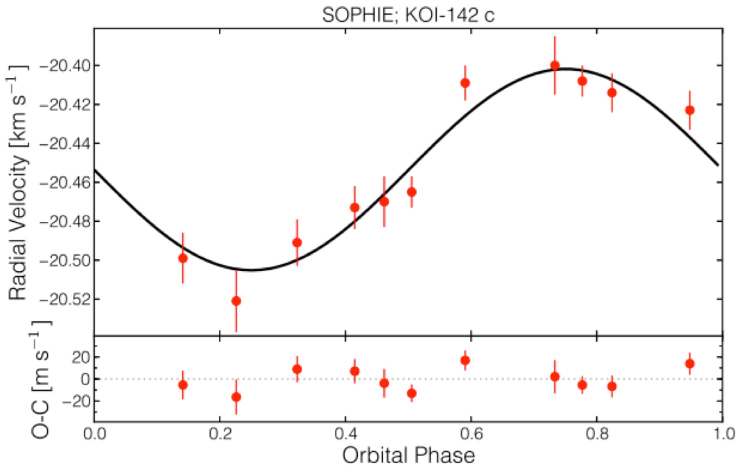
KOI-142

Nesvorny et al. (2012)

Neptune-size transiting planet strongly perturbed by a giant, resonant companion:

M_p= 0.675(+0.020/-0.013) M_{jup}

P = 22.338+/-0.003 days



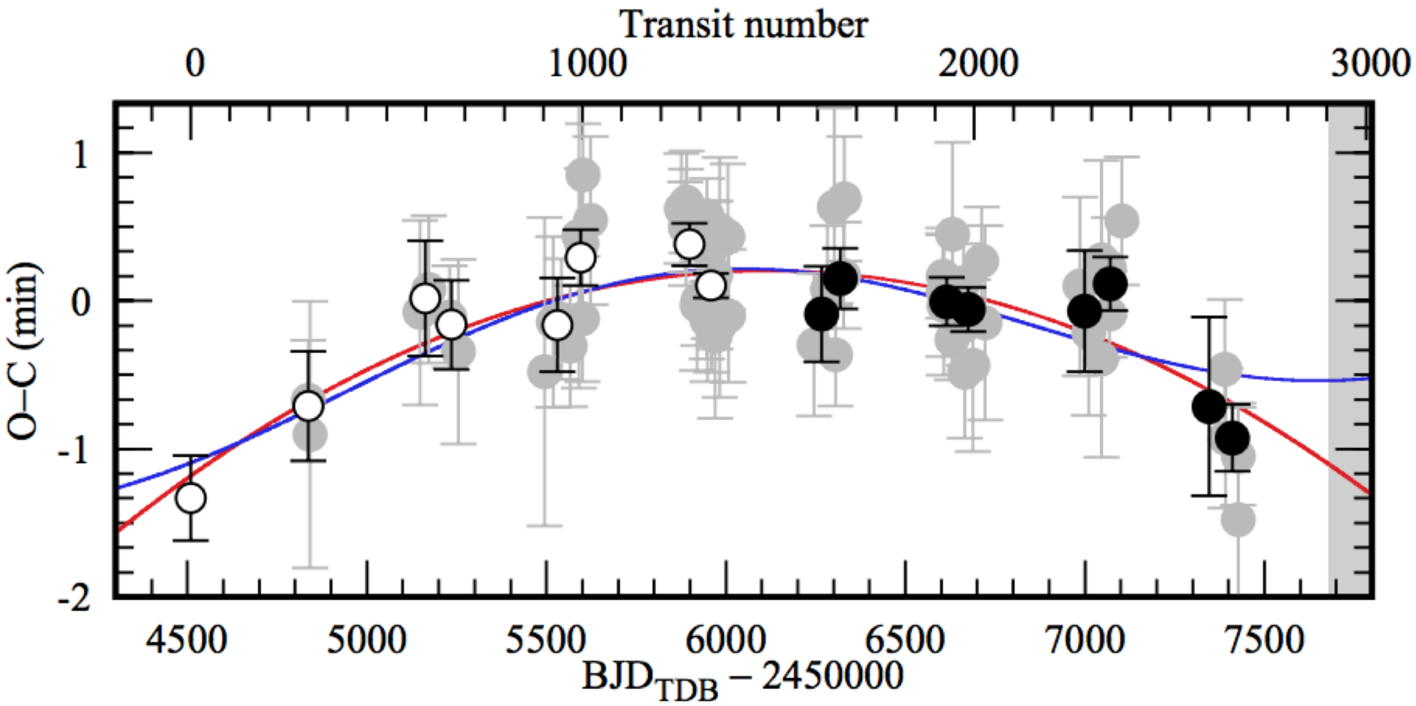
Barros et al. (2014)

$0.76^{+0.32}_{0.16}$

22.10 ± 0.25

A frontier: Tidal Decay

- Would characterize the *star*, not the planet. TTV of WASP-12b:



$dP/dt = (-2.56 \pm 0.40) \times 10^{-2}$ s yr^{-1}
$Q = 2.5 \times 10^5$

P=1.09days; M_p=1.41M_{Jup} Maciejewski+16

TTV – a characterization tool

- Several dozen transiting pairs have masses & eccentricities characterized, including a system of a few habitable planets (TRAPPIST-1)
- About 100 transit discoveries have been validated, but with only rough characterization
- The mass/radius results show a lack of atmospheres with higher effective temperature, leading to the differentiation of sub-Neptunes and super-Earths
- Tidal decay may be the next big discovery from TTV

TTV Bibliography

- First, inspiring papers:
  - Agol et al. 2005
  - Holman & Murray 2005
- A nice toolkit
  - Deck, Agol, Holman, Nesvorny 2014 (TTVFast)
- Largest batch analyses
  - Rowe et al. 2015
  - Holczer et al. 2016
  - Hadden & Lithwick 2017