Two New Kepler Circumbinary Planets

Bill Welsh

San Diego State University

and the

Kepler Team

with special thanks to:

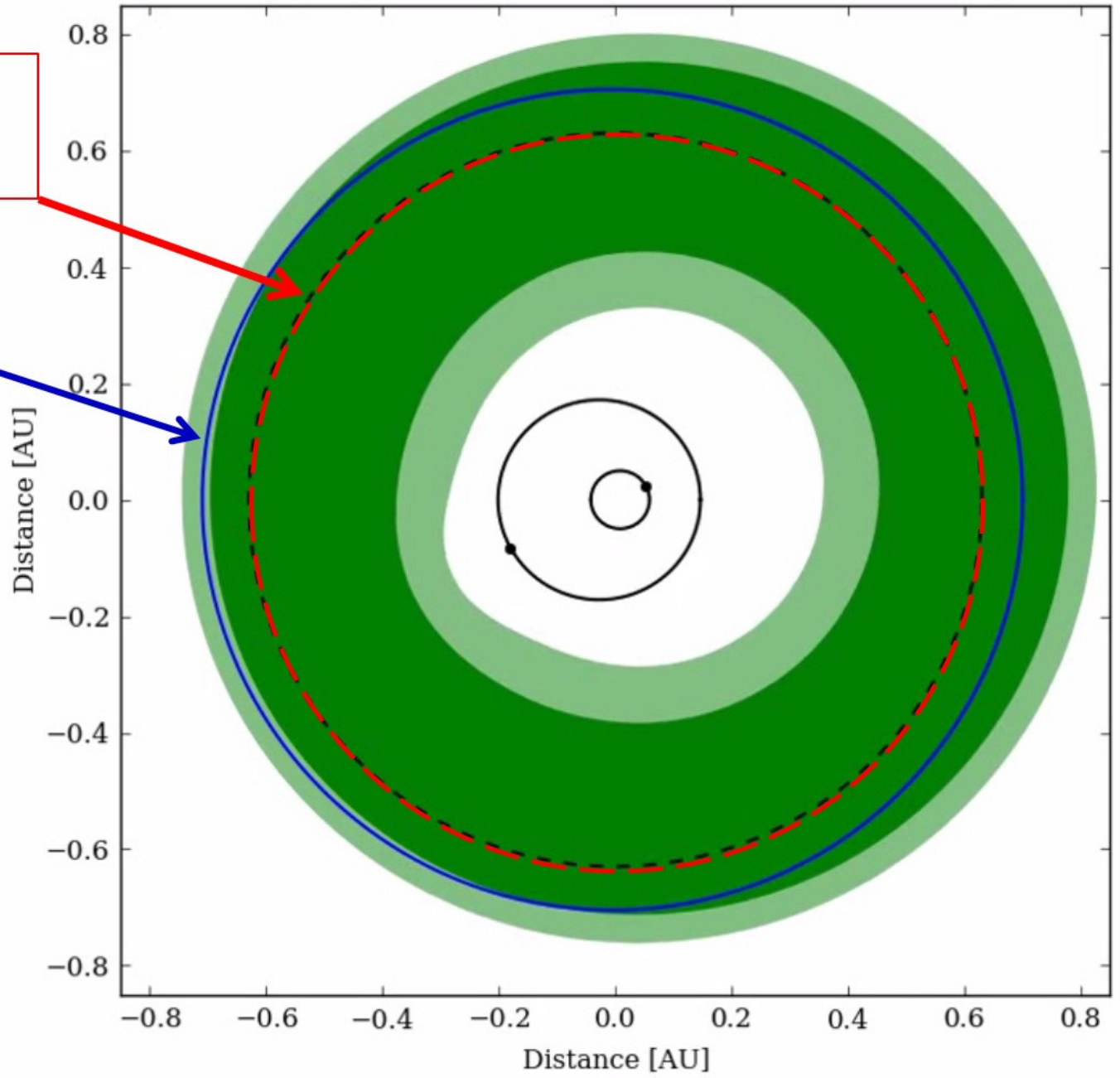
Jerry Orosz, Don Short, Nader Haghighipour, Dan Fabrycky, and the *Kepler EB & TTV Working Groups*

Credit: Ron Miller & Scientific American
(Welsh & Doyle 2013 November)


Exactly 3 years ago today: Kepler-16: the first *transiting* circumbinary planet was announced (Doyle et al. 2012)
Saturn-size planet orbiting a K+M eclipsing binary P=229 d, just inside the habitable zone (HZ).
Illustration credit:
NASA/JPL-Caltech/T. Pyle

critical radius
$a_{crit} \sim 2\text{-}4\ a_{binary}$

planet orbit
$a = 1.09\ a_{crit}$

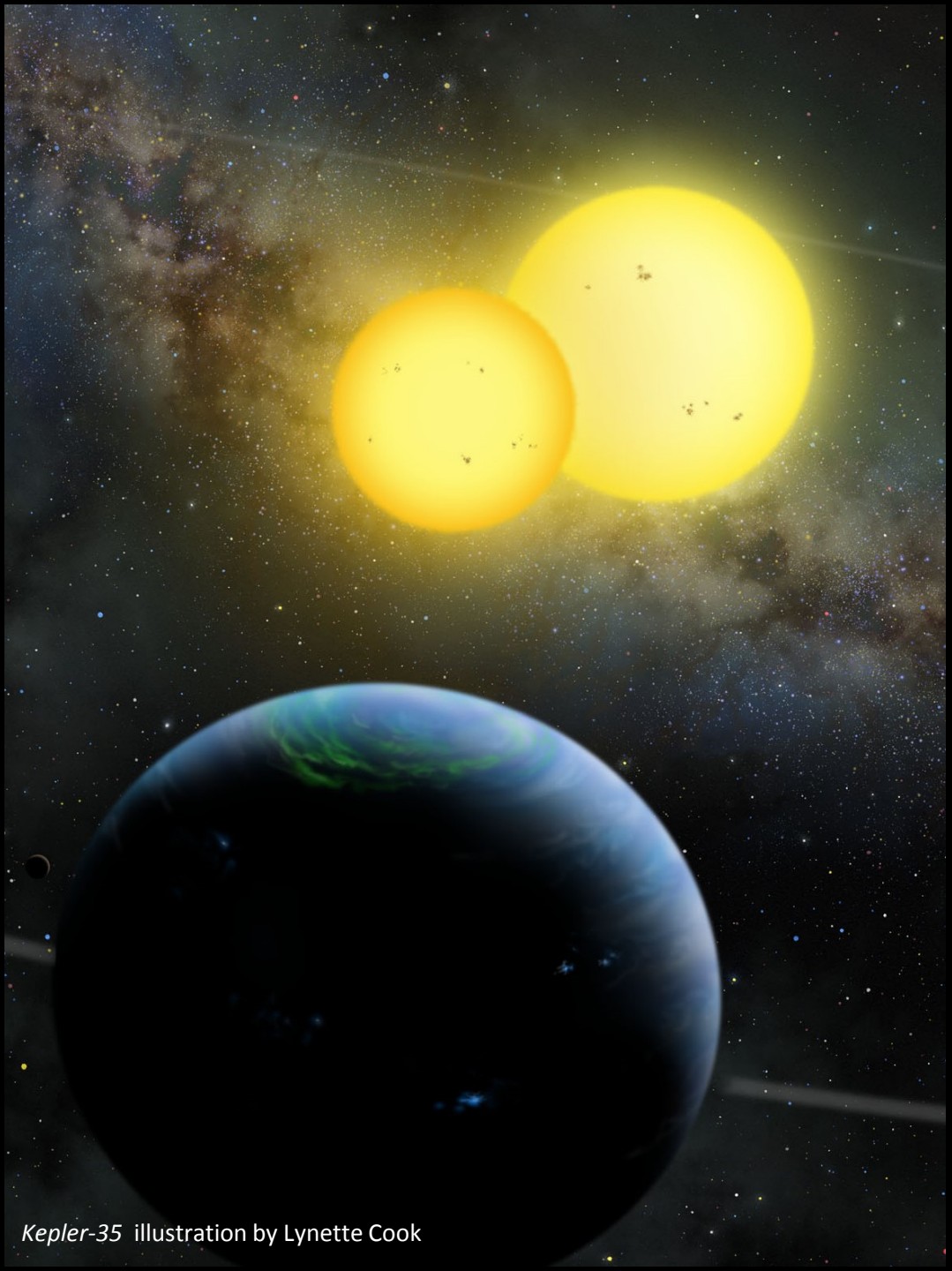


Kepler 16

animation courtesy of Tobias Müller (IfA & Univ. Tübingen)

using HZ calculator of Kaltenegger & Haghighipour (2013) and Haghighipour & Kaltenegger (2013)

http://astro.twam.info/hz-ptype



Kepler-35 illustration by Lynette Cook

10 known TCBP

- Kepler-16
  Doyle et al. 2011
- Kepler-34 & Kepler-35
  Welsh et al. 2012
- Kepler-38
  Orosz et al. 2012
- Kepler-47 b,c
  Orosz et al. 2012
- PH-1/ KIC4862625/Kepler-64
  Schwamb et al. 2013
  Kostov et al. 2013

illustration copyright by
Mark Garlick

- Kepler-413 b
  Kostov et al. 2014
- Kepler-47 d
  Orosz et al. (in prep)
- KIC 9632895 b
  Welsh et al. (submitted)

Kepler-47 Orosz et al. (2012)

establishes that planetary *systems can form and persist* around close binary stars

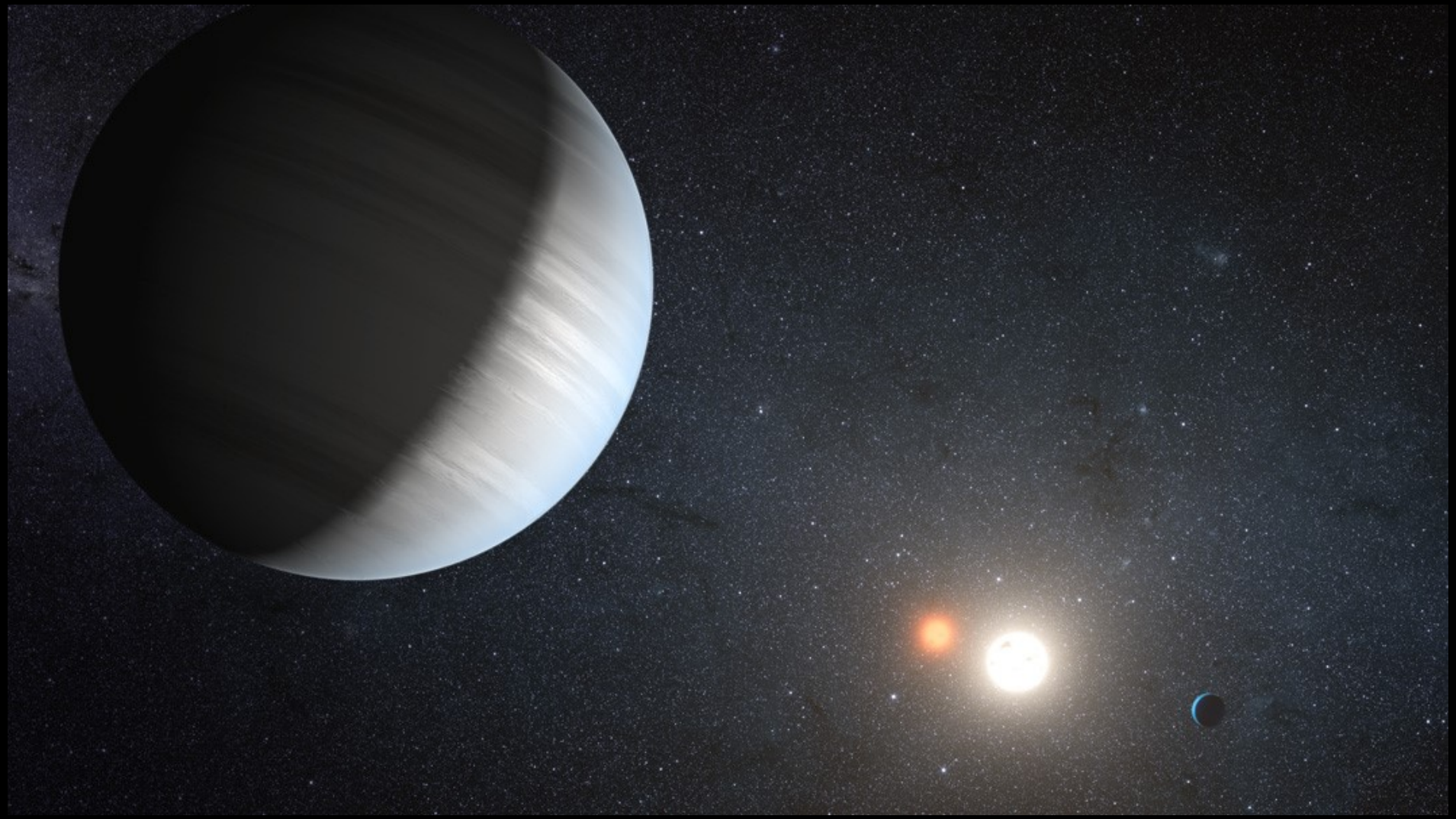


Illustration credit: *NASA/JPL-Caltech/T. Pyle*

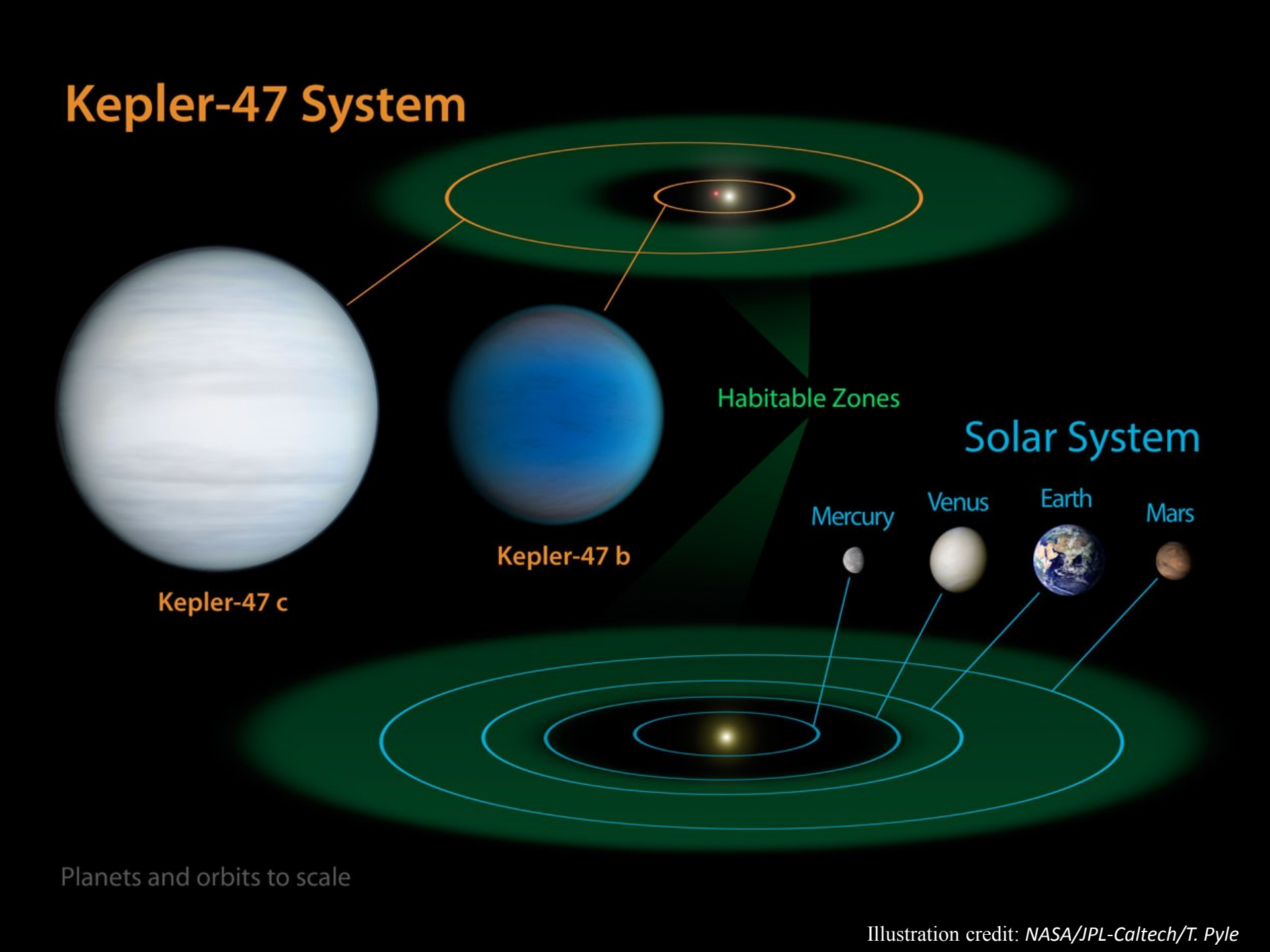
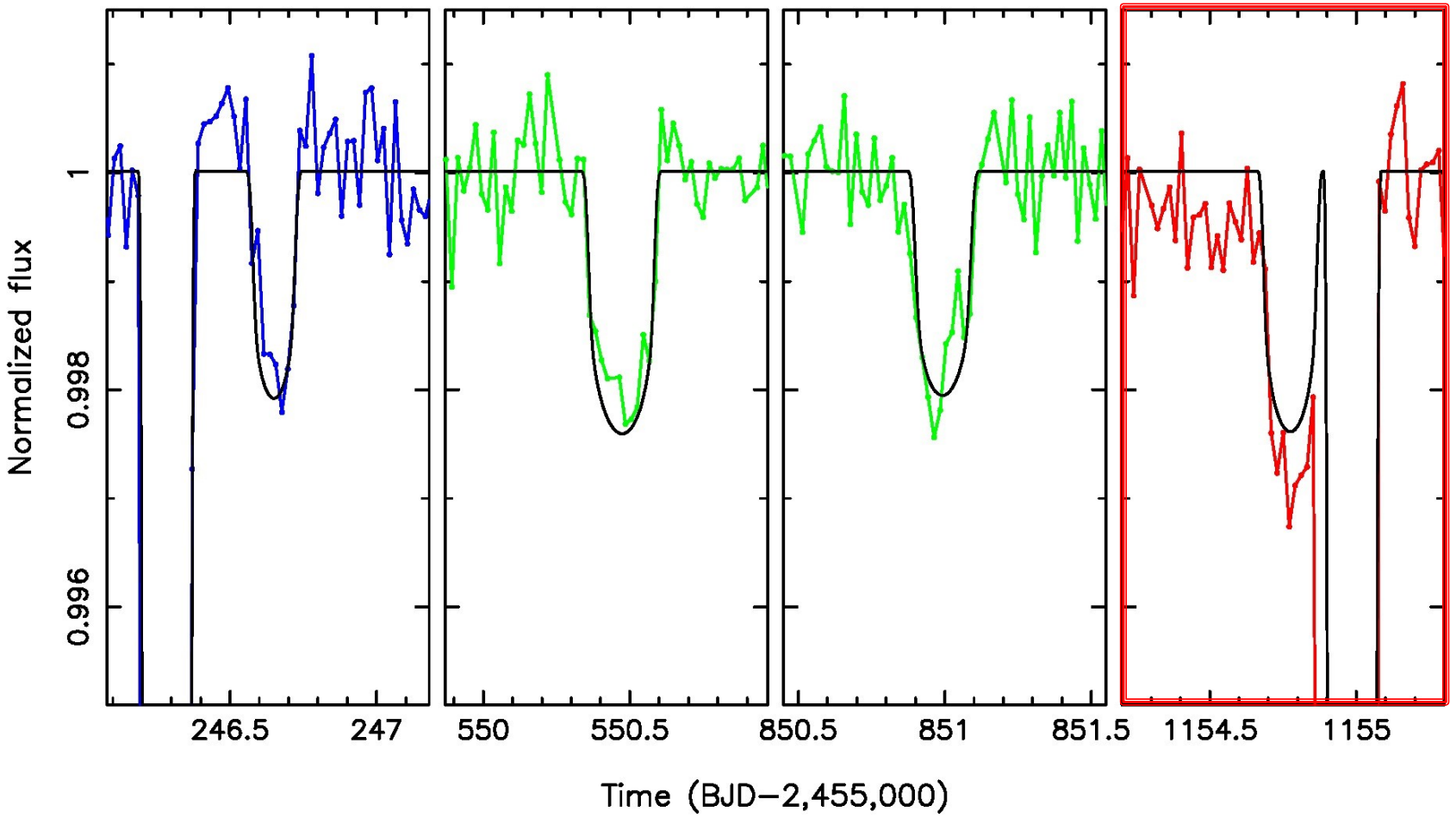


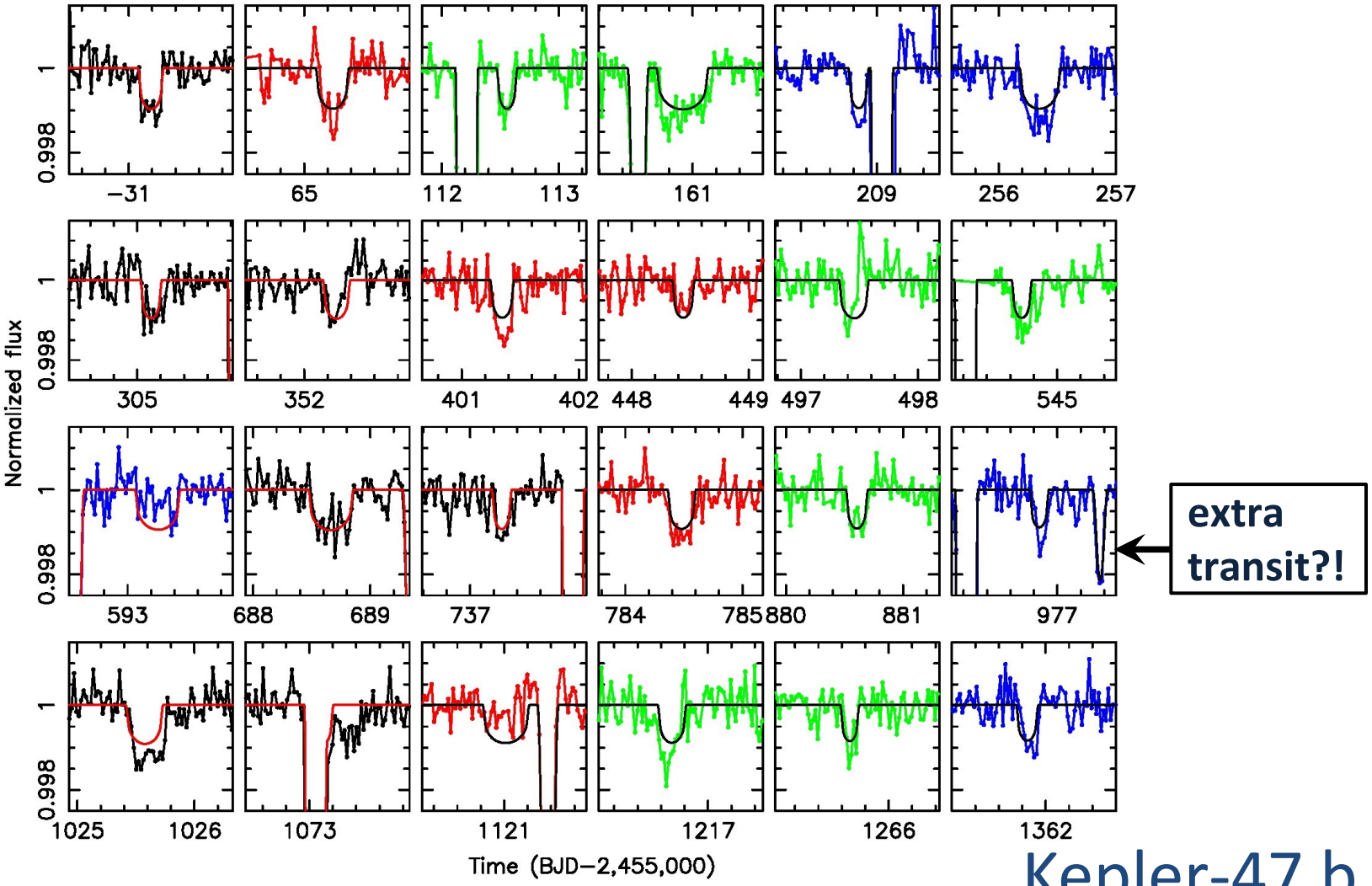
Illustration credit: *NASA/JPL-Caltech/T. Pyle*



Kepler-47 c

UPDATE:

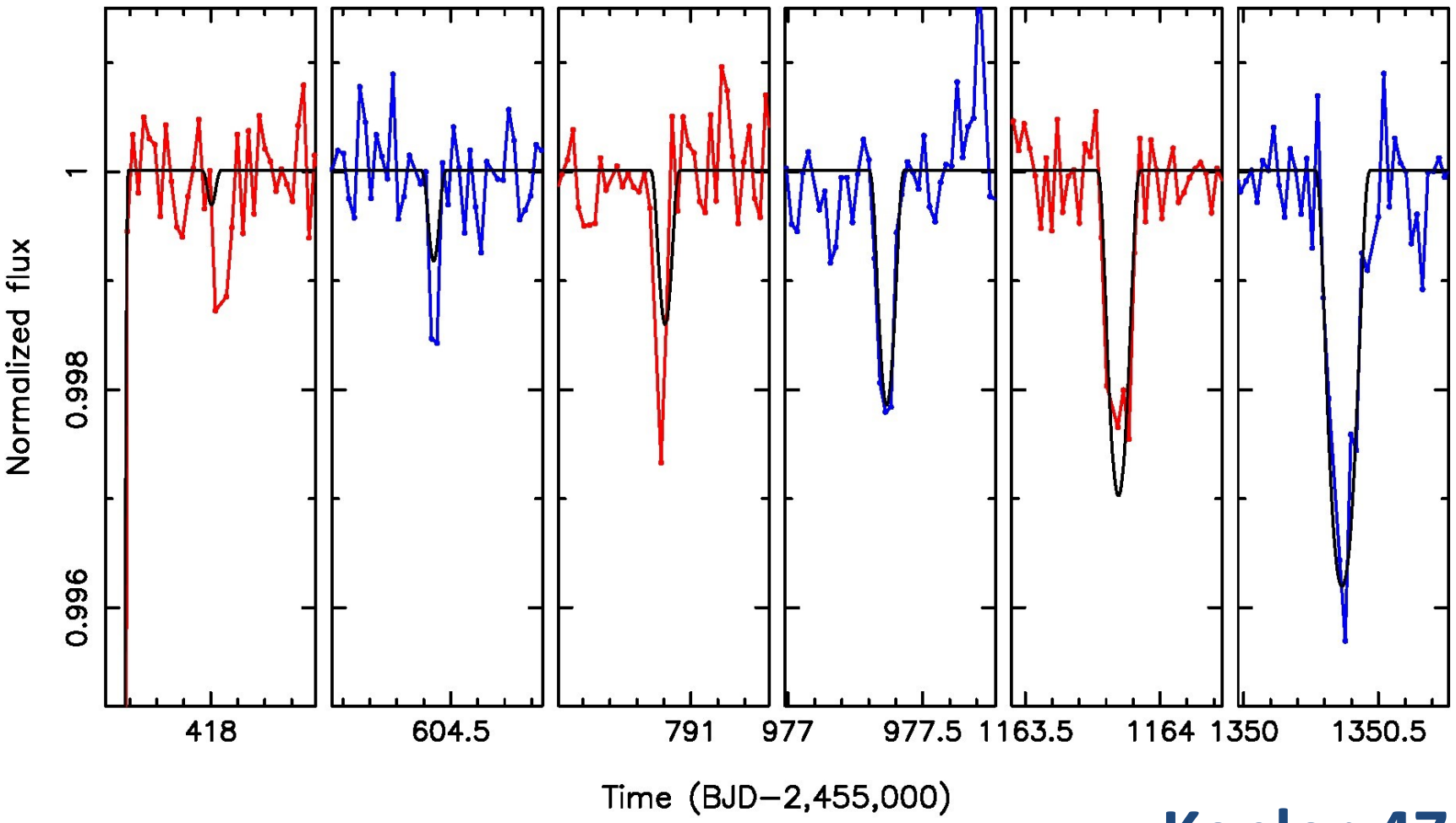
- 1 more transit of the outer planet (c) = 4 total
- 6 more transits of the inner planet (b) = 24 total



Kepler-47 b

UPDATE:

- 1 more transit of the outer planet (c) = 4 total
- 6 more transits of the inner planet (b) = 24 total

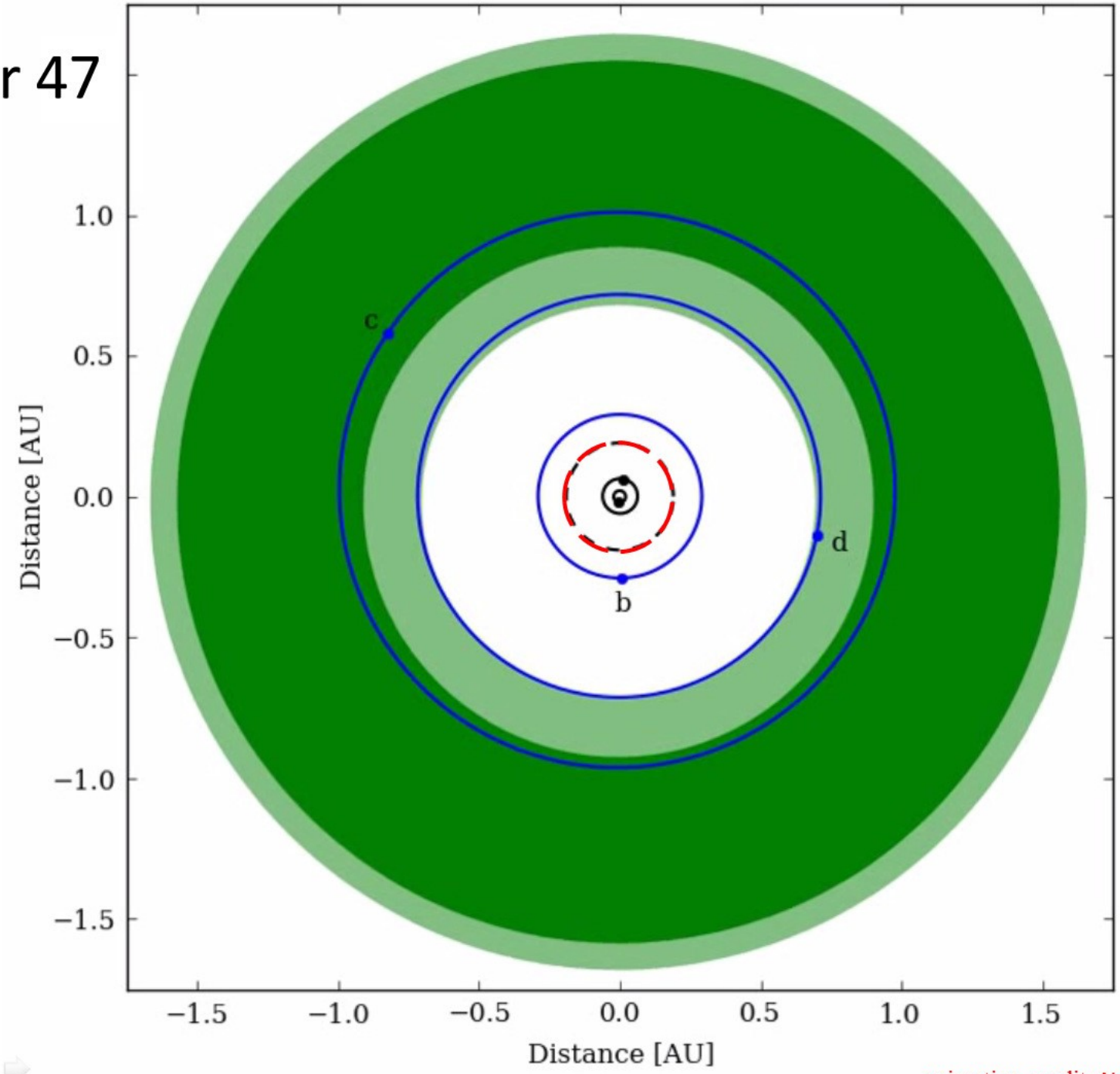


Kepler-47 d

UPDATE:

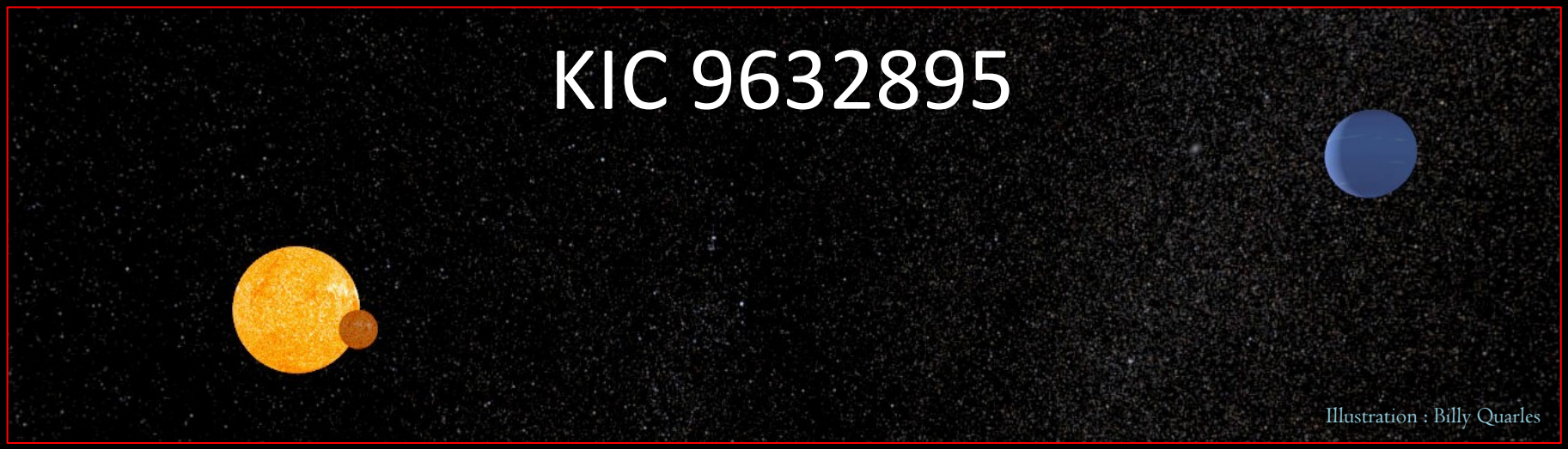
- 1 more transit of the outer planet (c) = 4 total
- 6 more transits of the inner planet (b) = 24 total
- *And 6 transits of the new middle planet (d):*
- *P=187.4 d e=0.02 R=7.3* R_{Earth}

Kepler 47



animation credit: *Nader Haghighipour*

KIC 9632895

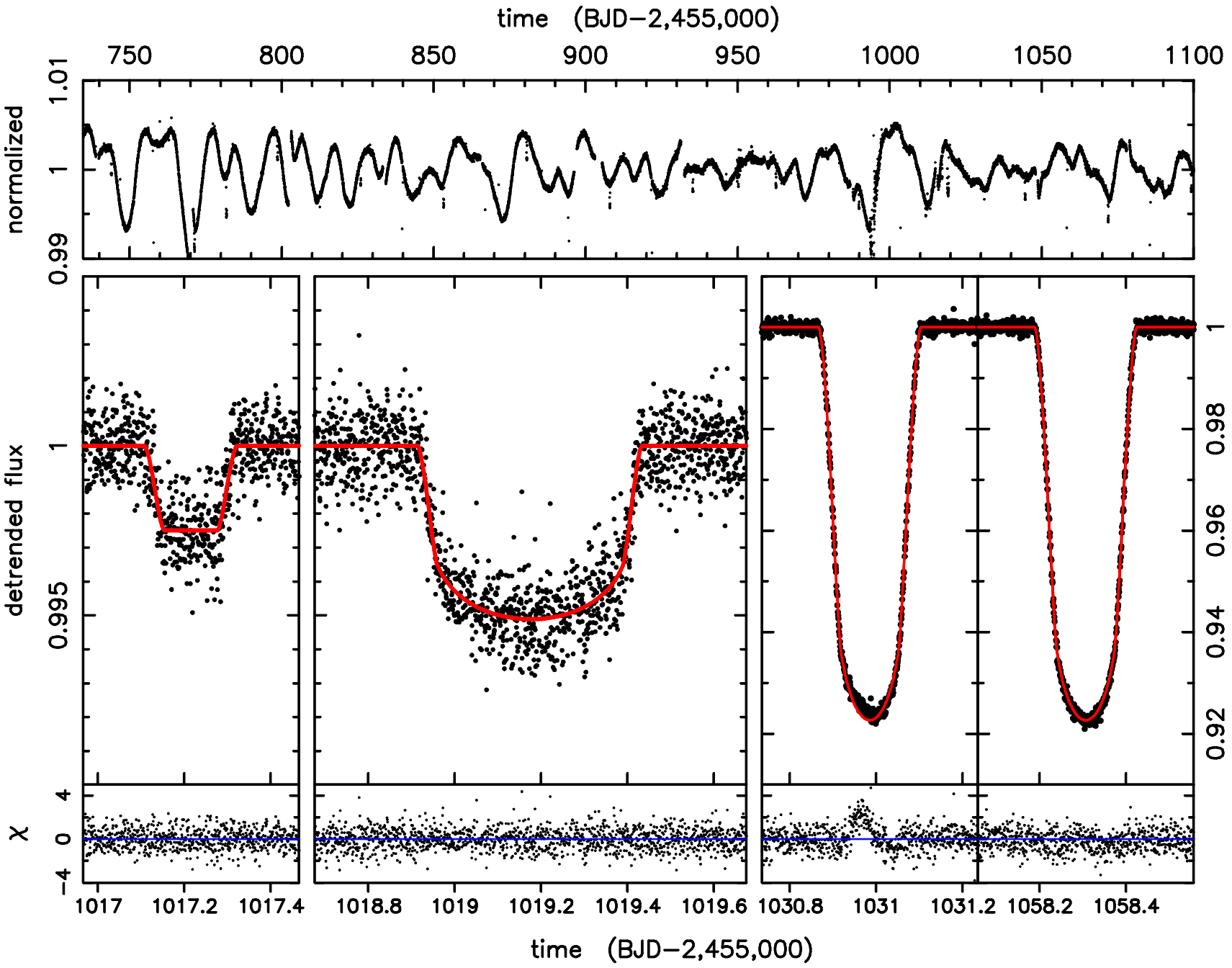


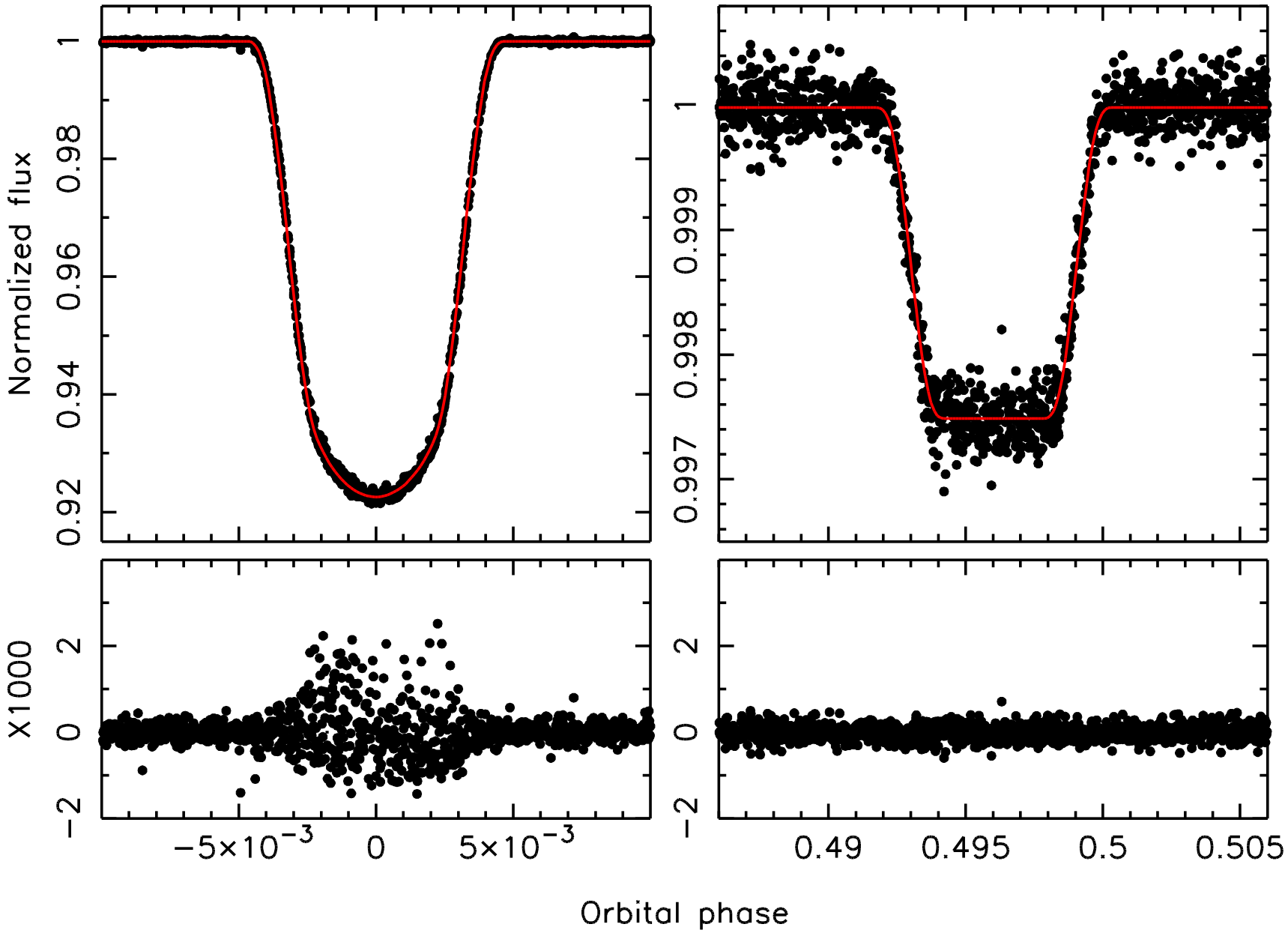
Eclipsing Binary

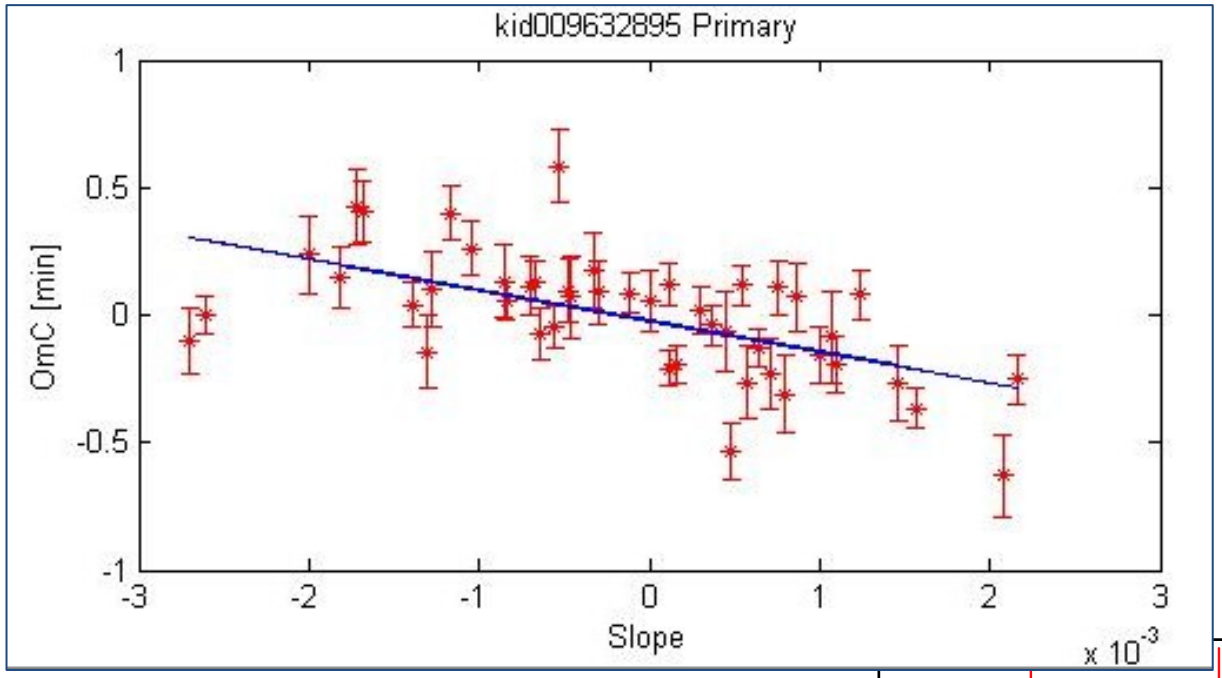
- P = 27.3220 d
- e = 0.05
- M_1 = 0.93 M_{Sun}
- M_2 = 0.194 M_{Sun}
- T_1 = 5527 K

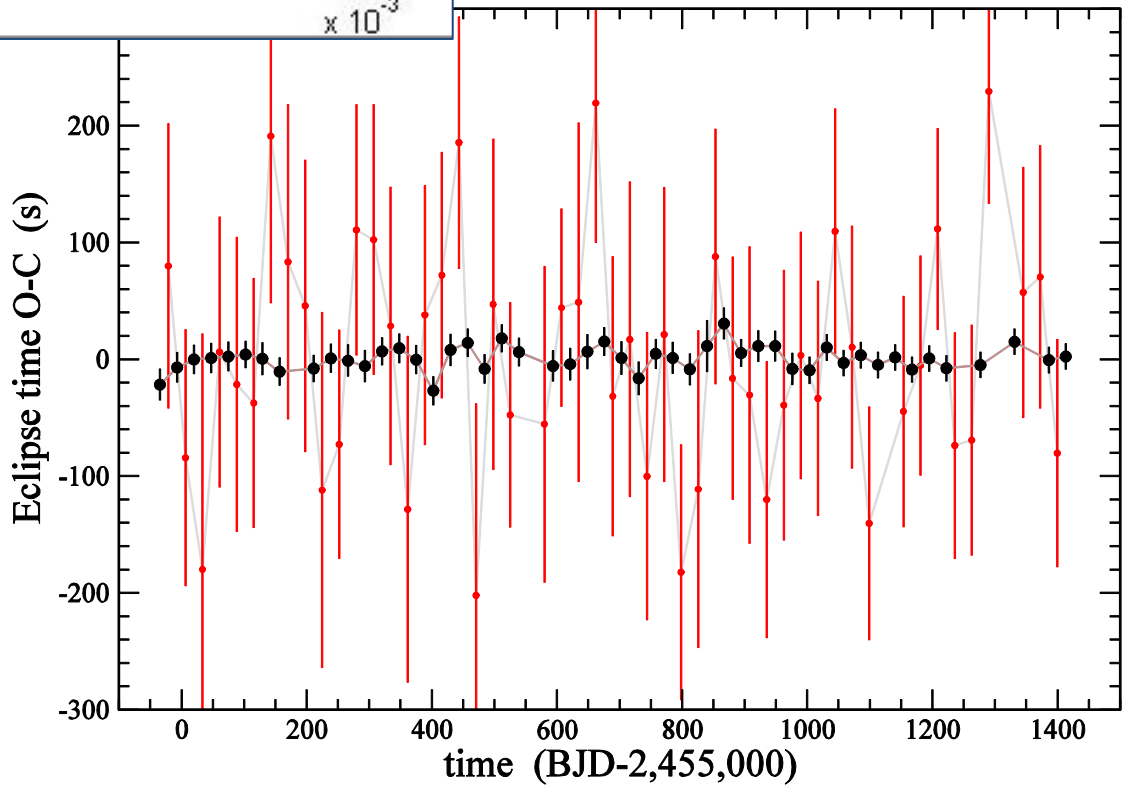
Planet

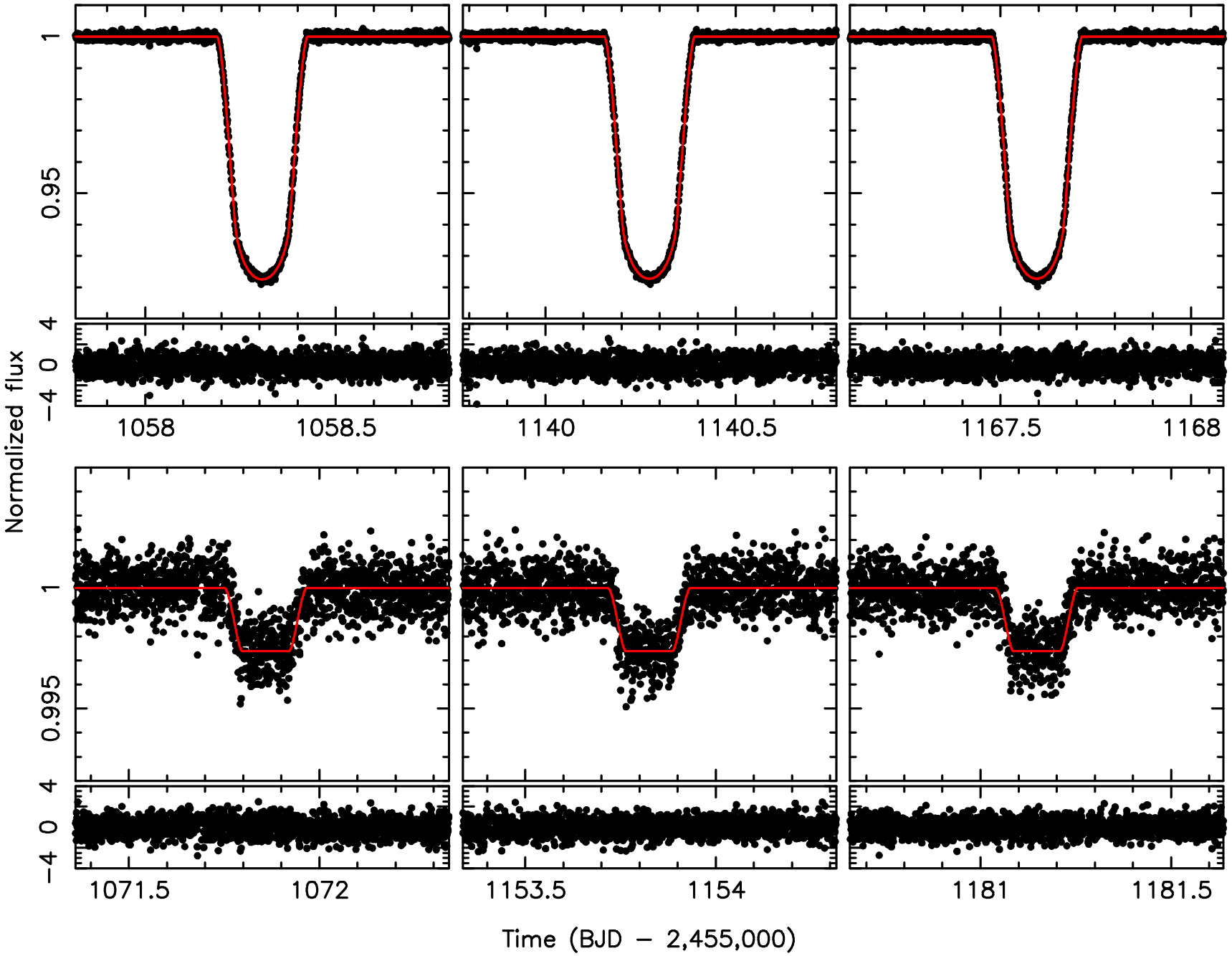
- P_p = 240.5 d (=0.79 au)
- e = 0.04
- R_p = 6.2 R_e
- M_p < 16 M_e at 1-σ
- mutual incl. 2.3 deg

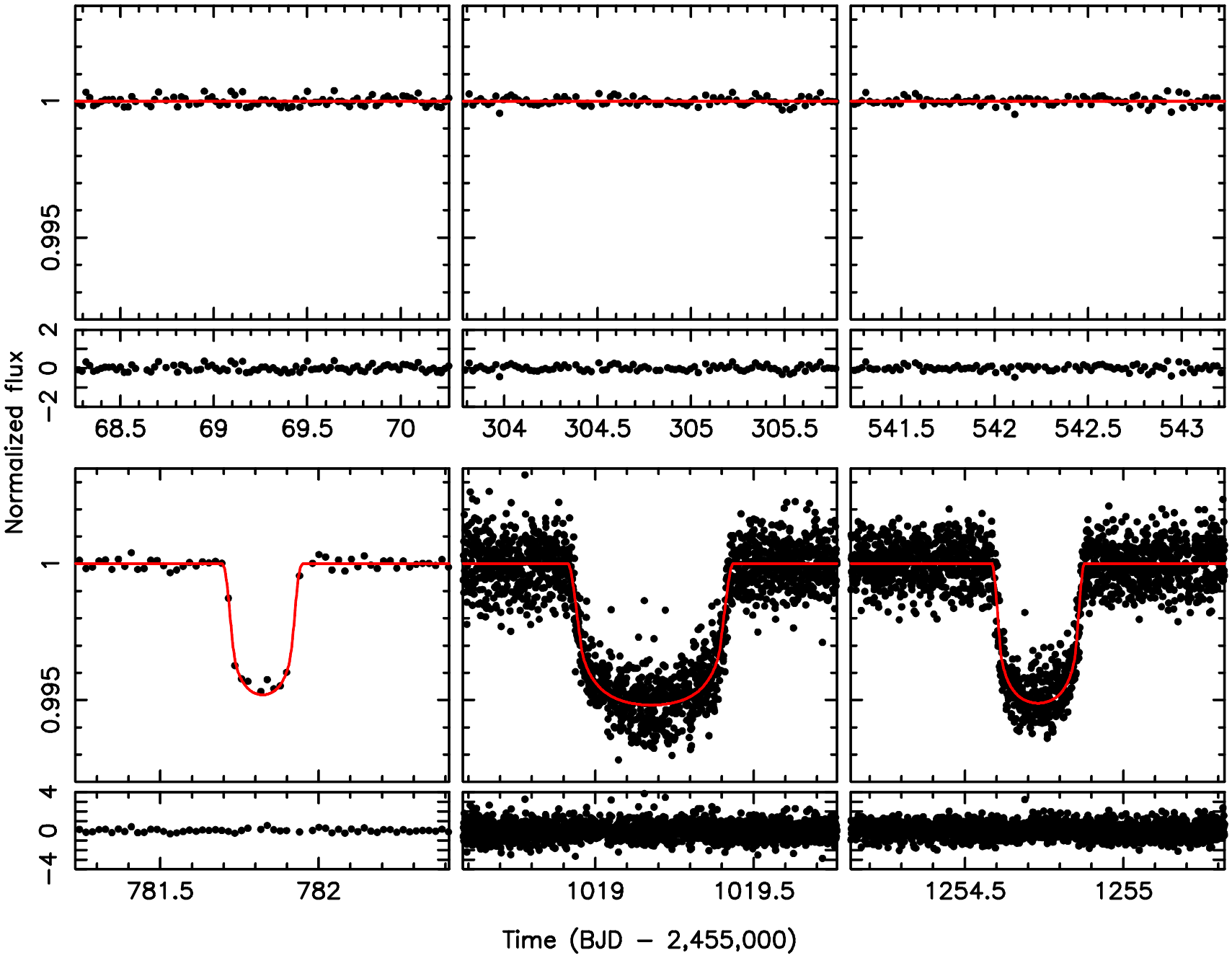

time (BJD−2,455,000)
750
800
850
900
950
1000
1050
1100
normalized
1.01
1
0.99
detrended flux
1
0.995
0.98
0.96
0.94
0.92
χ
4
0
−4
1017
1017.2
1017.4
1018.8
1019
1019.2
1019.4
1019.6
1030.8
1031
1031.2
1058.2
1058.4
time (BJD−2,455,000)

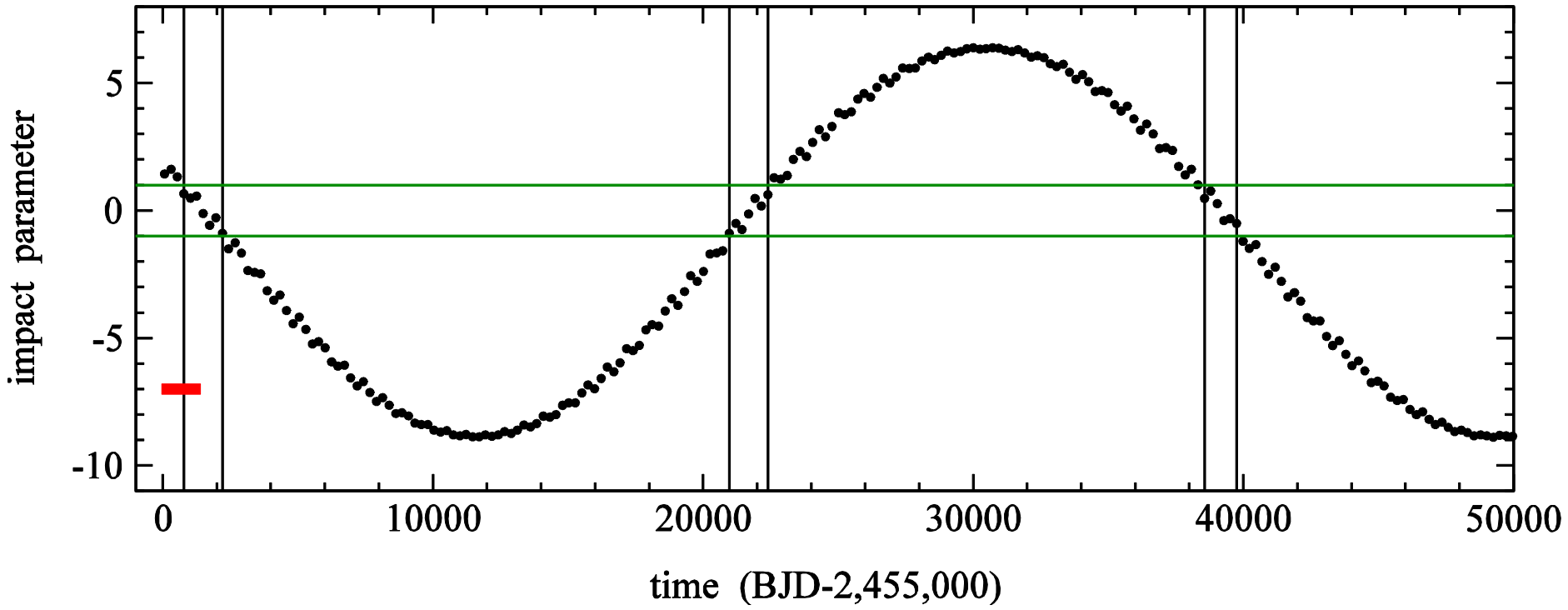

Normalized flux
0.92
0.94
0.96
0.98
1
0.997
0.998
0.999
1
X1000
−2
0
2
−5×10^−3
0
5×10^−3
0.49
0.495
0.5
0.505
Orbital phase


kid009632895 Primary
OmC [min]
Slope
x 10^-3


Eclipse time O-C (s)
time (BJD-2,455,000)

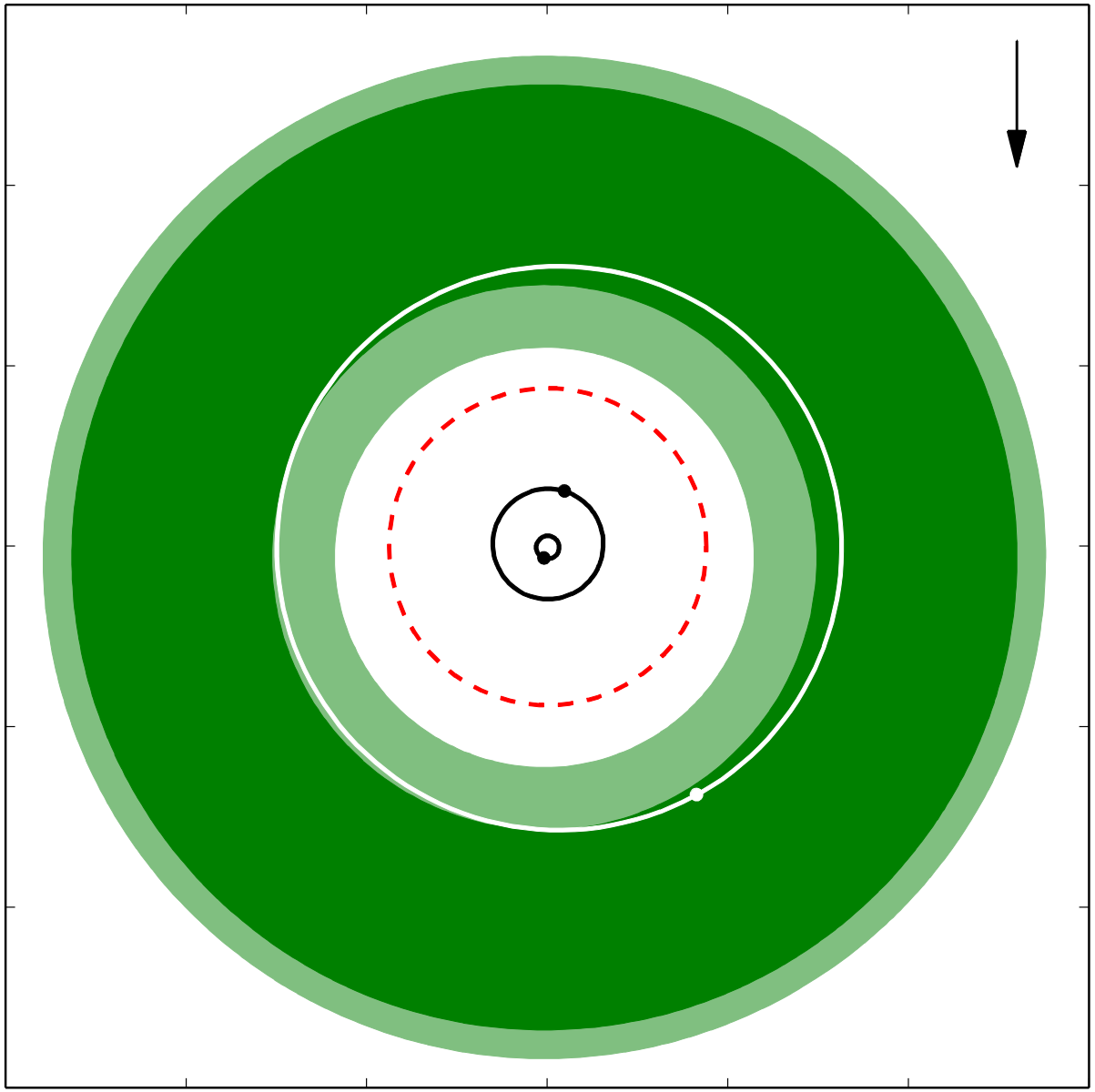

Normalized flux
1
0.95
4
0
−4
1058
1058.5
1140
1140.5
1167.5
1168
1
0.995
4
0
−4
1071.5
1072
1153.5
1154
1181
1181.5
Time (BJD − 2,455,000)


Normalized flux
1
0.995
2
0
−2
68.5
69
69.5
70
304
304.5
305
305.5
541.5
542
542.5
543
1
0.995
4
0
−4
781.5
782
1019
1019.5
1254.5
1255
Time (BJD − 2,455,000)



- 103-year precession cycle
- transits only ~8% of the time
- please observe transit on 2015 July 02,
  last one until 2066!

KIC 9632895



For every transiting circumbinary planet, there should be *many* more non-transiting cases.

Search for large NTCBP via *dynamical* perturbations of the binary stars' orbits *(not light-travel time effect)*

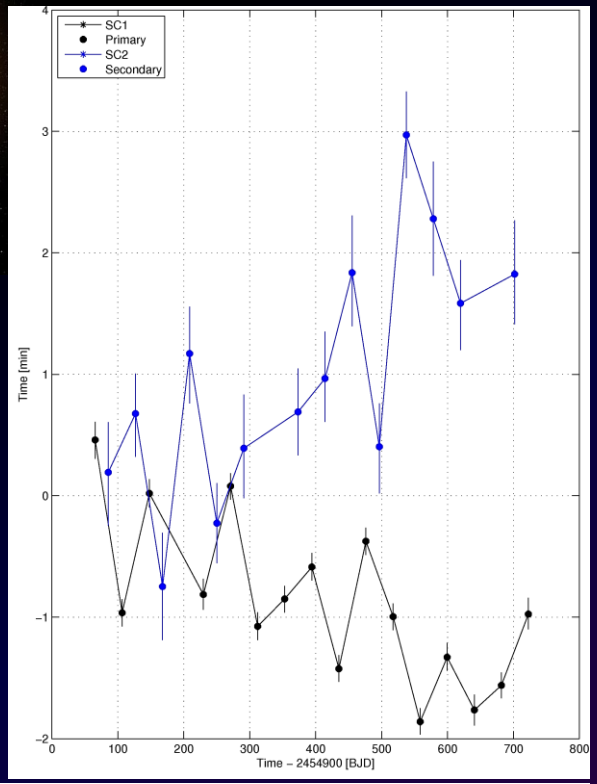
➔ eclipse timing variations (ETVs)

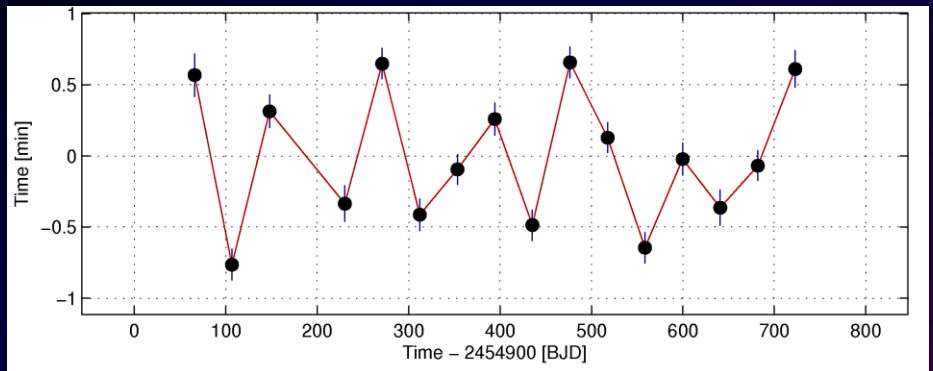
Non-Transiting CBP Search Strategy:

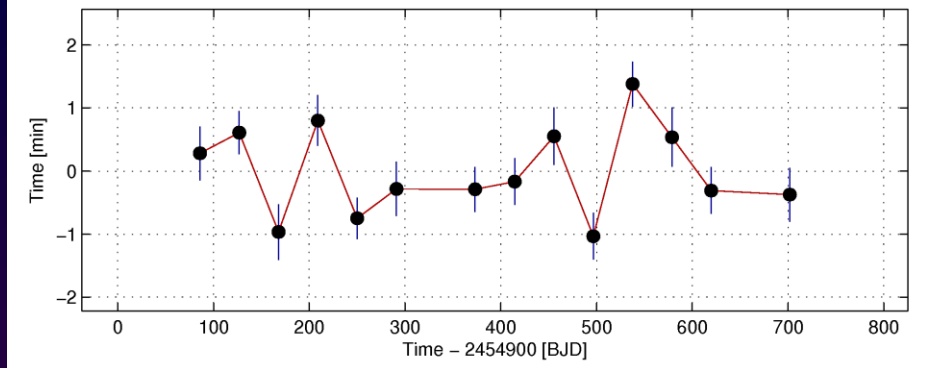
- Need at least one cycle in the O-C
- Need small O-C: amplitude < few minutes

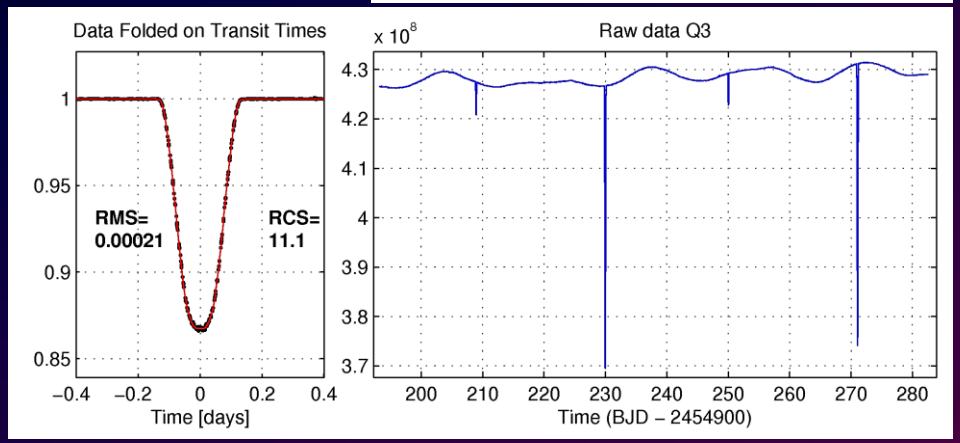
  could be massive + far away, or low-mass + close
- Need *short-period* variation → small orbit
- Borkovits-type periodic "wiggle"
- *CPOC divergence* (if e>0) → dynamical interaction

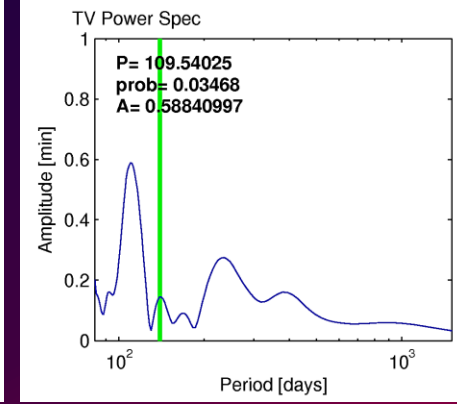
Kepler-16 passes our search criteria.

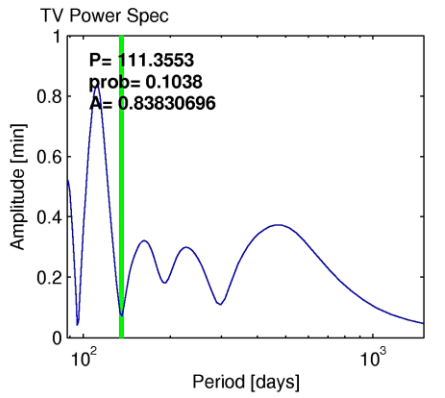


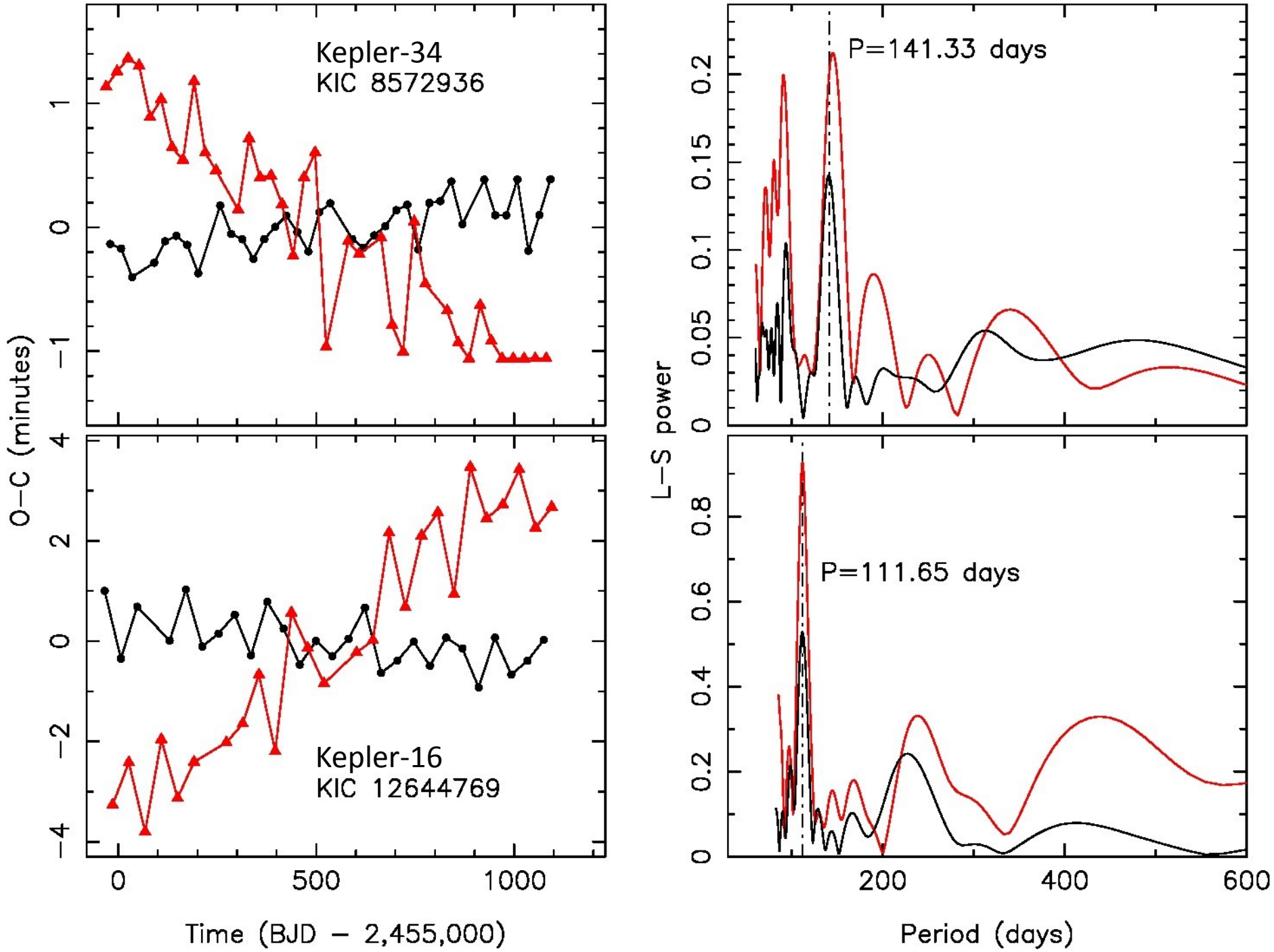


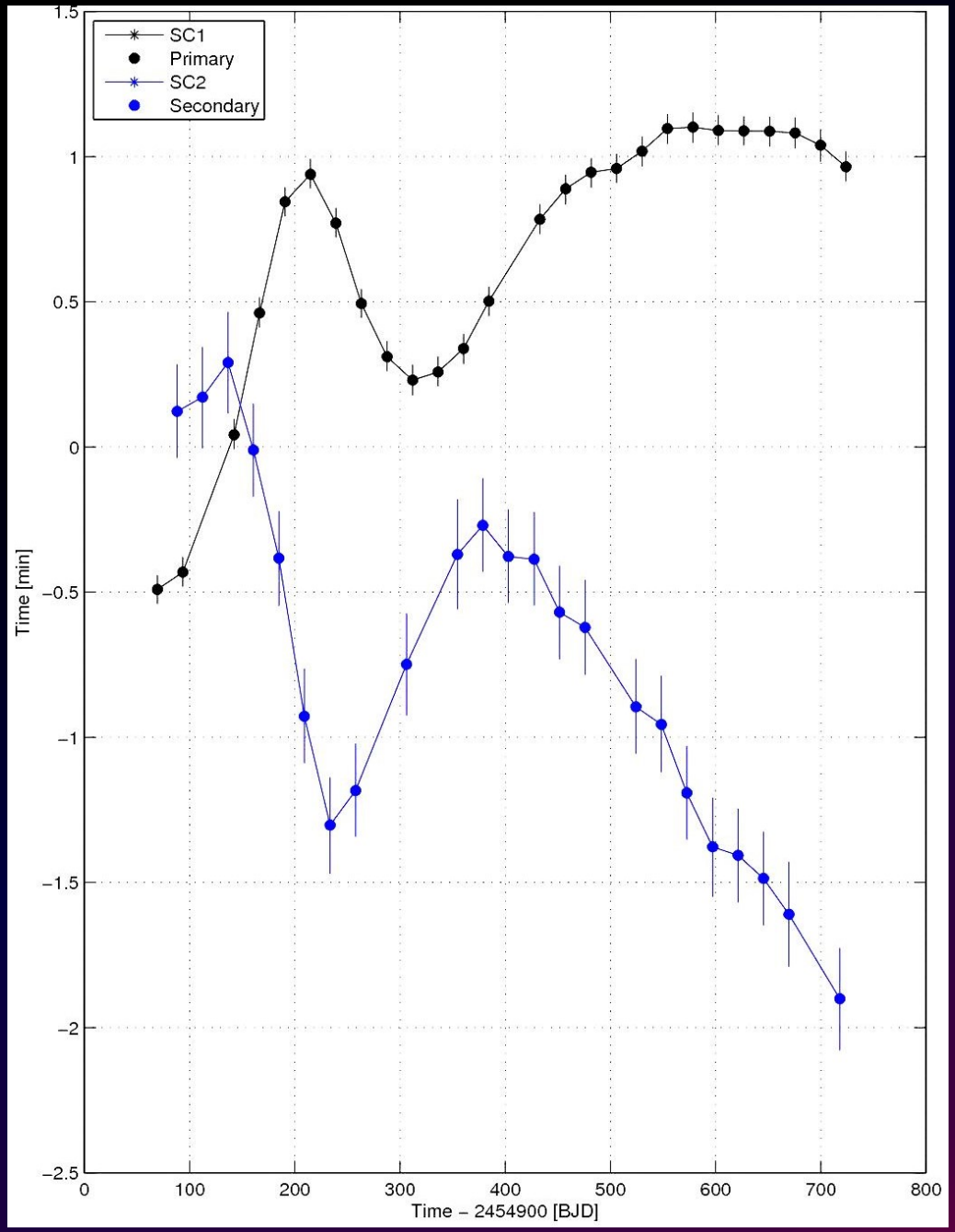









Kepler-34
KIC 8572936
Kepler-16
KIC 12644769
O−C (minutes)
Time (BJD − 2,455,000)
L−S power
P=141.33 days
P=111.65 days
Period (days)



KOI-2938 = KIC7821010

- clean, high S/N
- good fit to eclipses
- low amplitude O-C
- periodogram shows lots of power
- “Borkovits wiggle”
- diverging CPOC

→ Very strong candidate

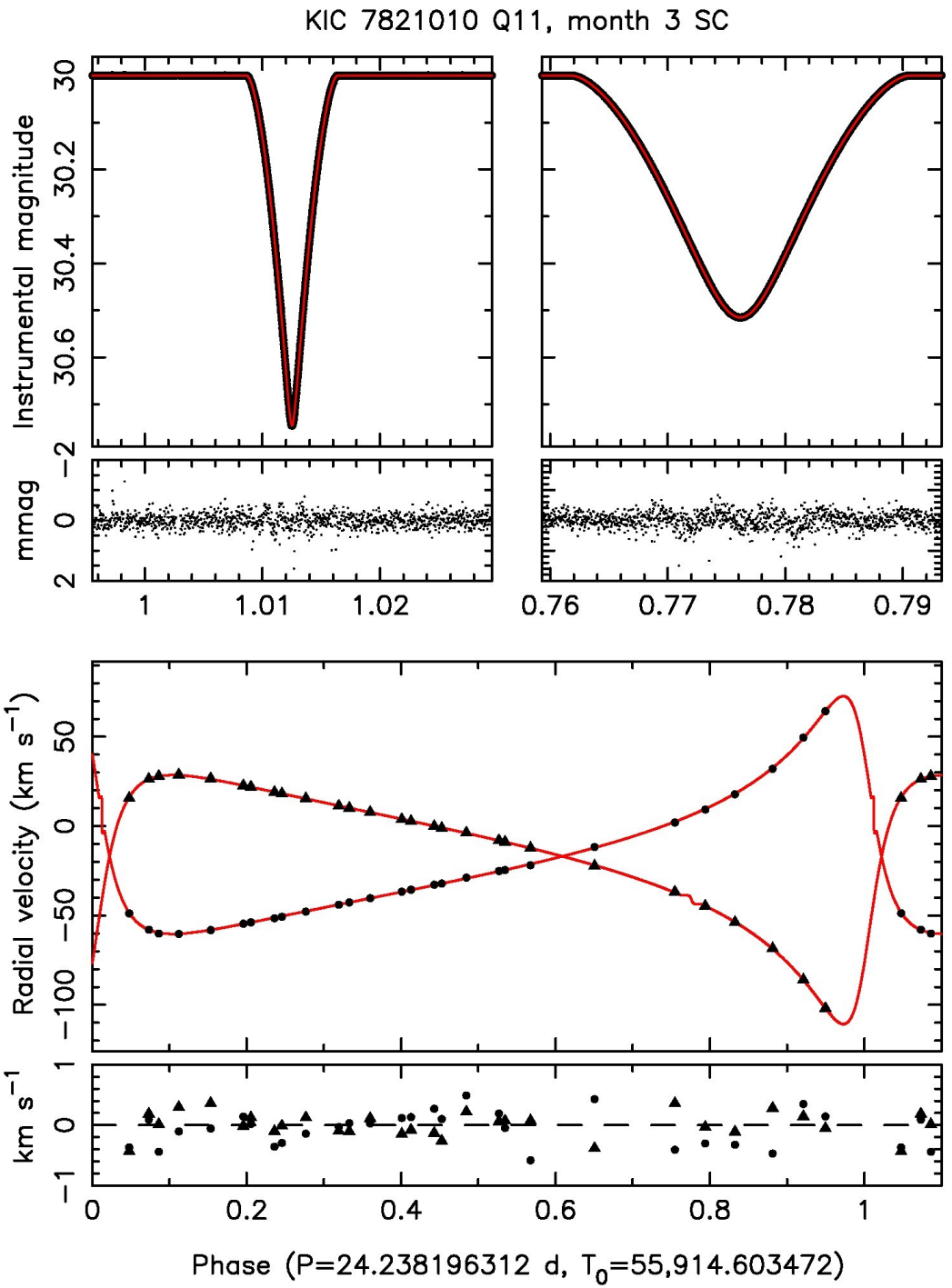
KOI 2938 = KIC 7821010

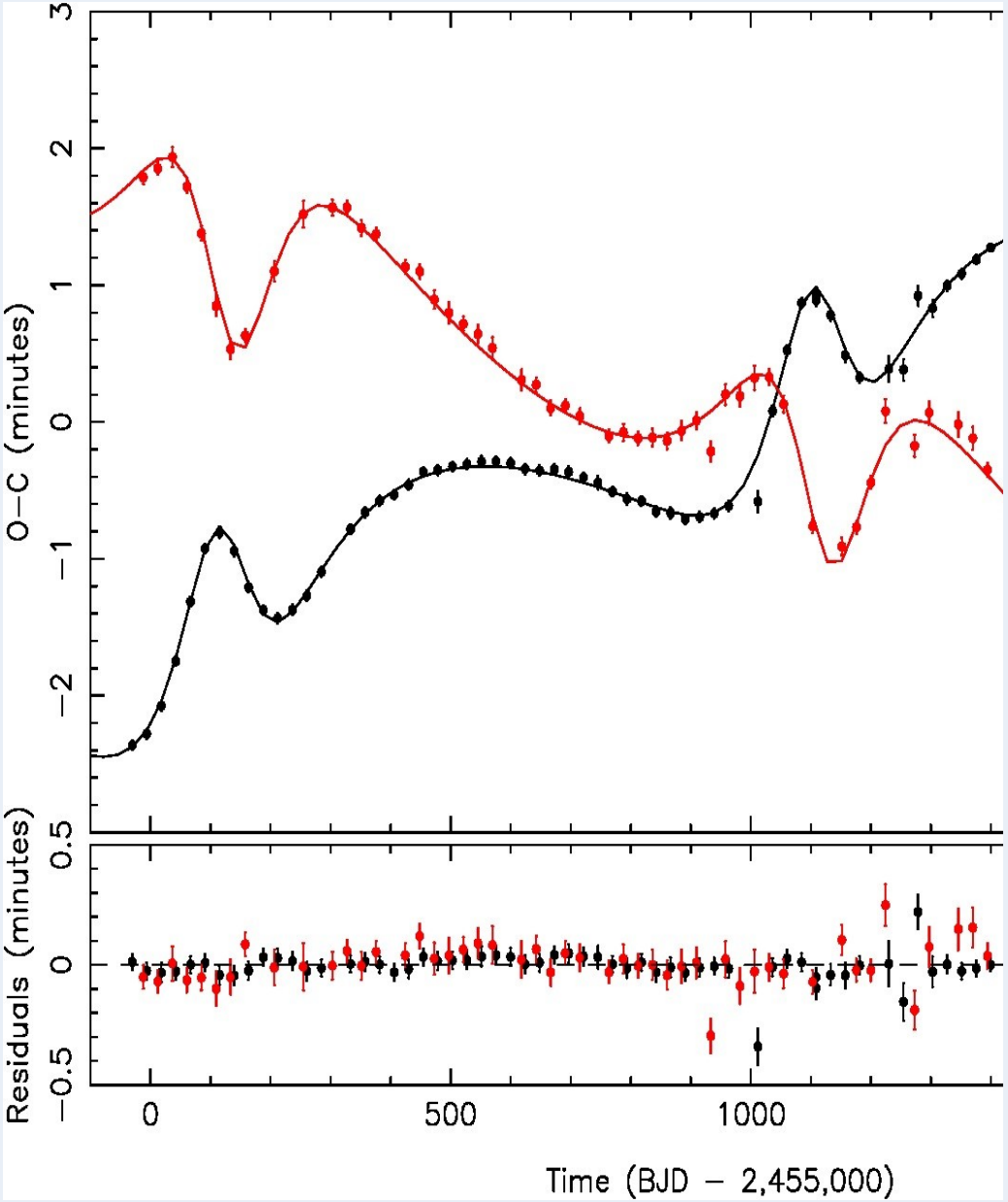
P_{EB} = 24.23820 d

e_{EB} = 0.6791

M_1= 1.29 M_2=1.23 $M_\odot$

L_1 = 2.33 L_2 =2.12 $L_\odot$





KOI 2938 = KID 7821010

The first Kepler non-transiting CBP

P_p = 994.14 d

e_p = 0.358

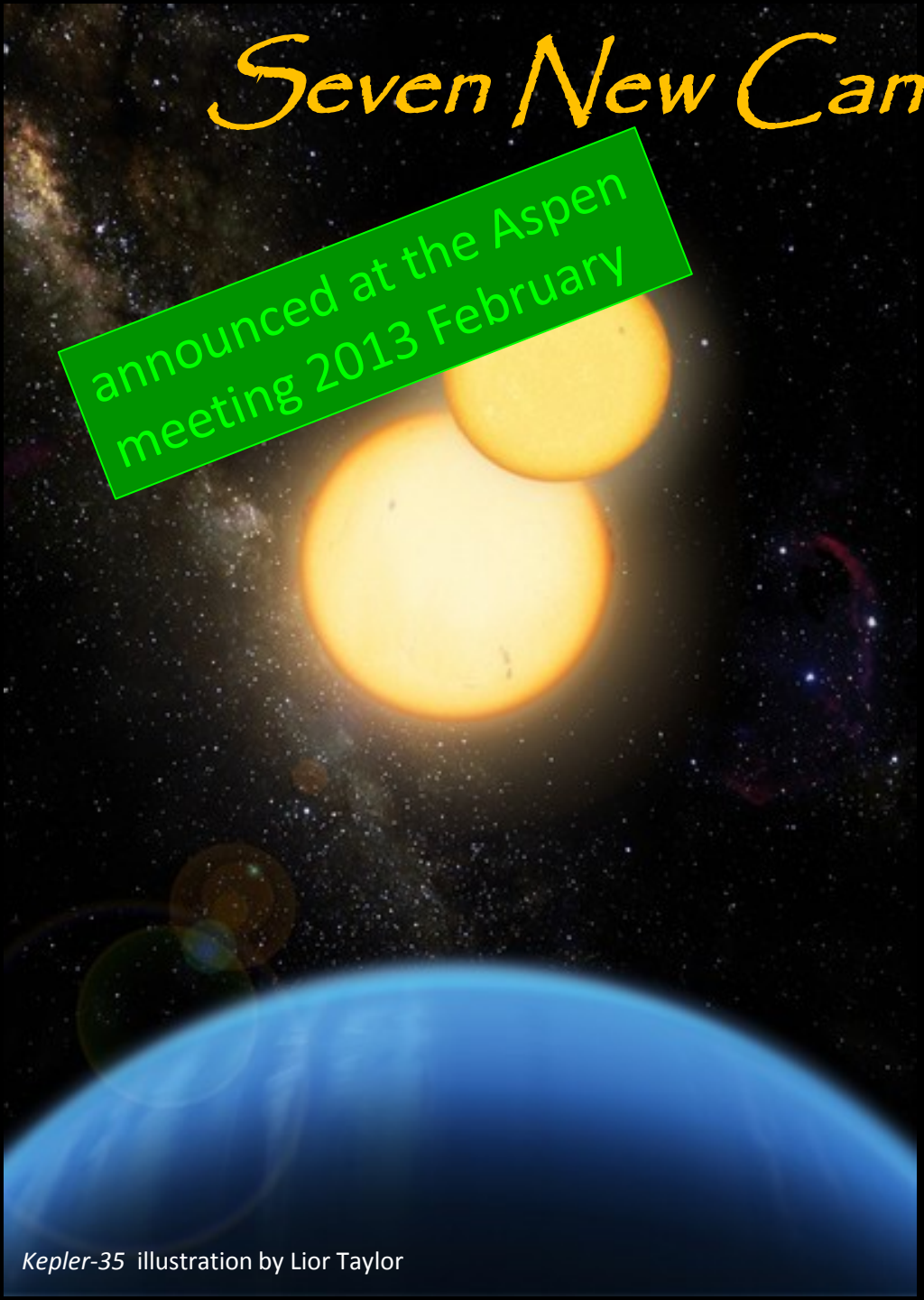
M_p = 2.6 M_{Jup}

mutual i ~ 4.9°

Average insolation puts planet in the habitable zone

credit:
D. Fabrycky

Seven New Candidate CBPs



Kepler-35 illustration by Lior Taylor

KIC 12351927 = Kepler-413
- Kostov et al. (in prep) (→2014)

Kepler-47 d
- Orosz et al. (in prep)

KIC 9632895 / KOI-3151
- Welsh et al. (in prep) (→submitted)

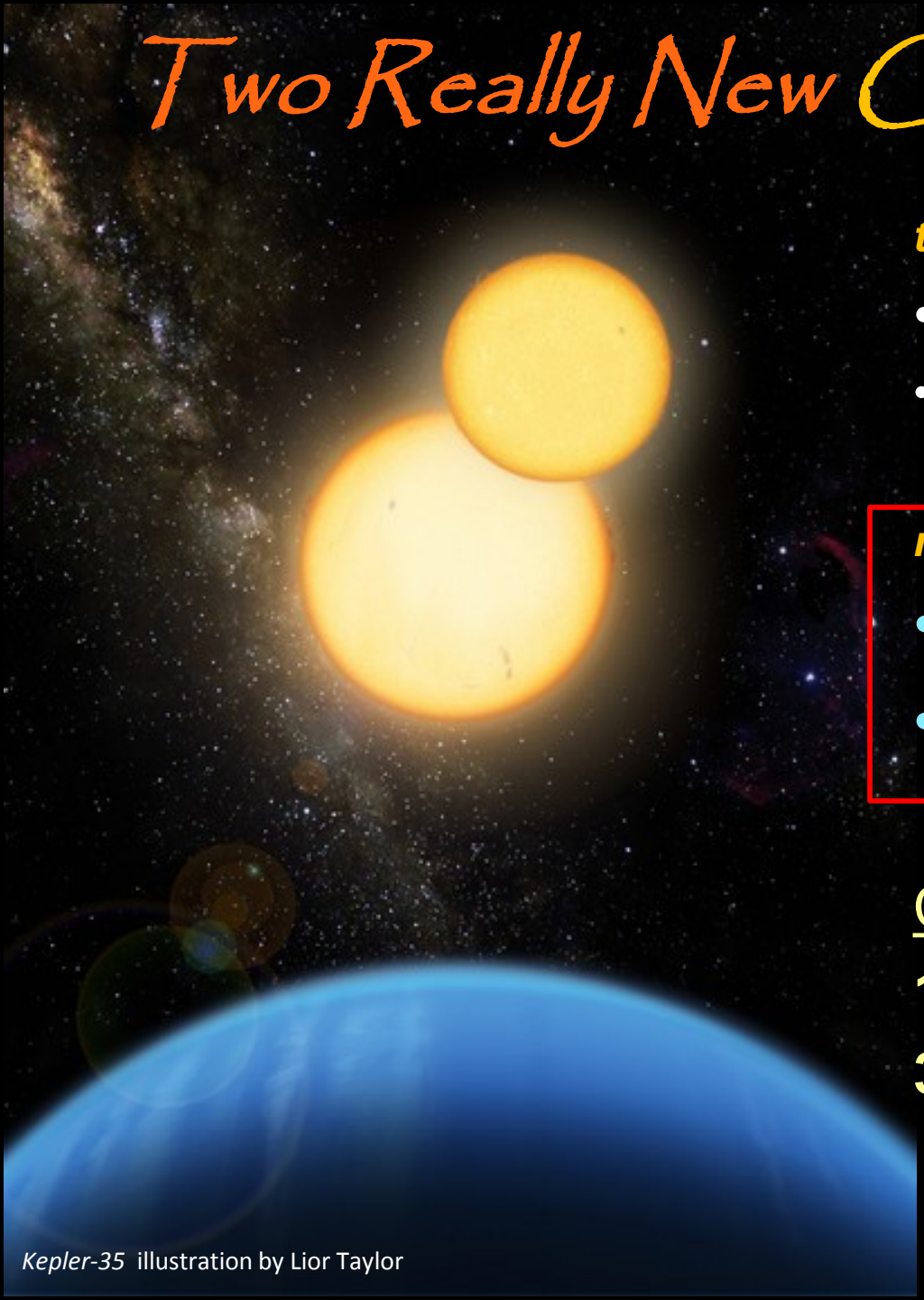
KOI-2938 / KIC 7821010
- Fabrycky et al. (in prep)

KOI-3152 / KIC 6504534
- Carter et al. (in prep)

KOI-2939 / KIC 5473556

KOI-1741 / KIC 8180020

Two Really New Candidate CBPs



Kepler-35 illustration by Lior Taylor

transiting:

- **KIC 10753734**
- **(KIC 5015913 ?)**

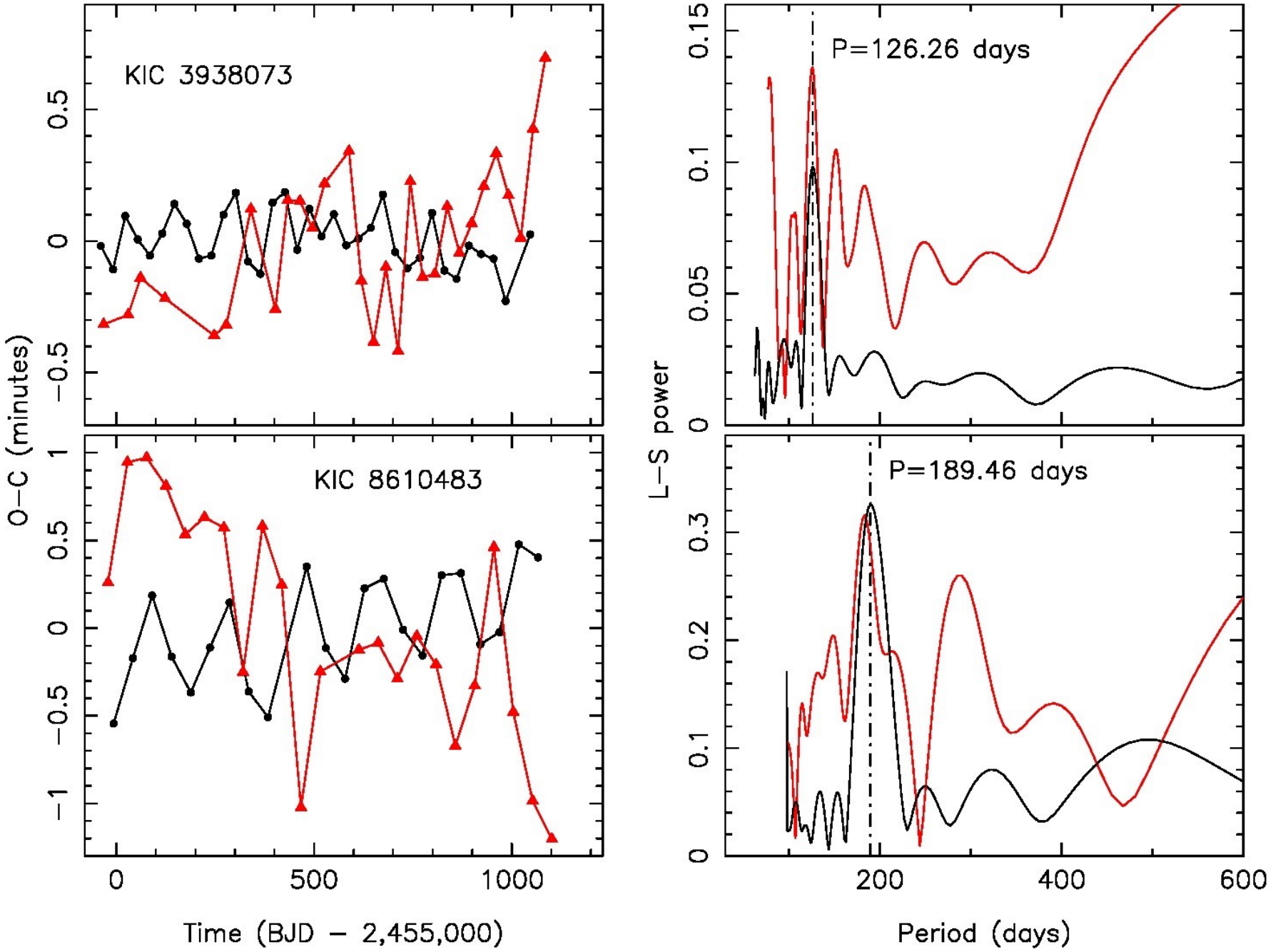
non-transiting:

- **KIC 8610483**
- **KIC 3938073**

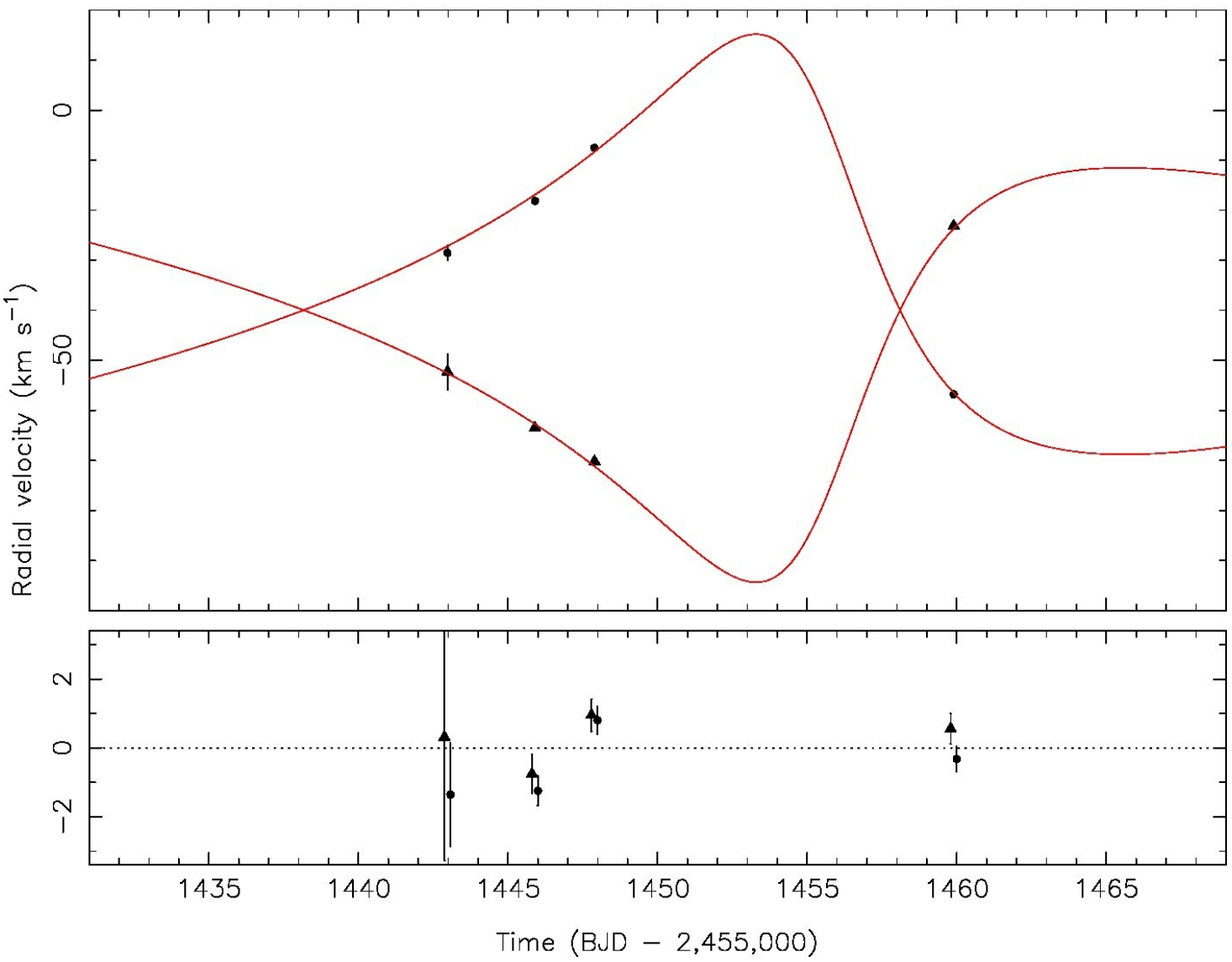
Current tally:

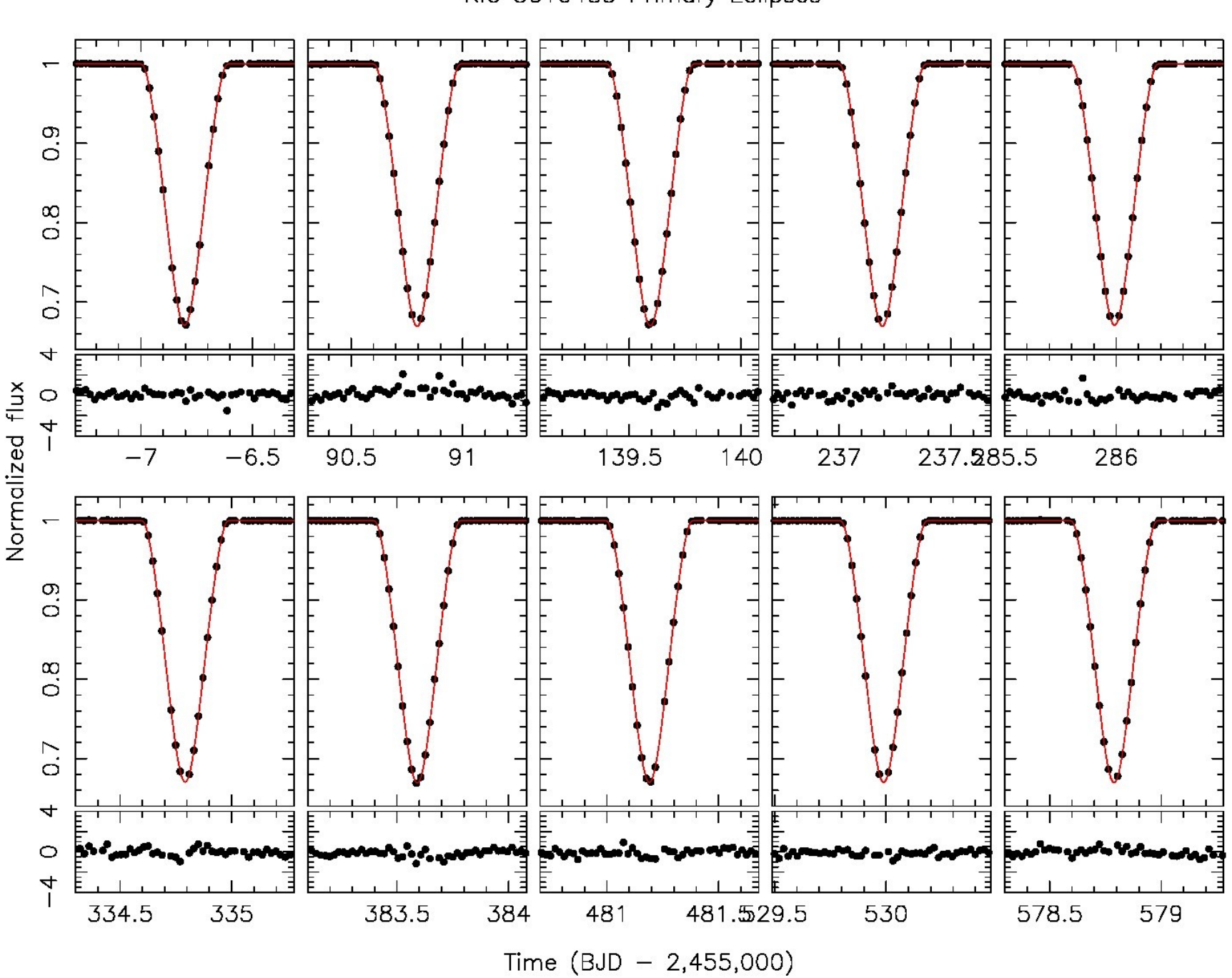
10 transiting + 4 candidates

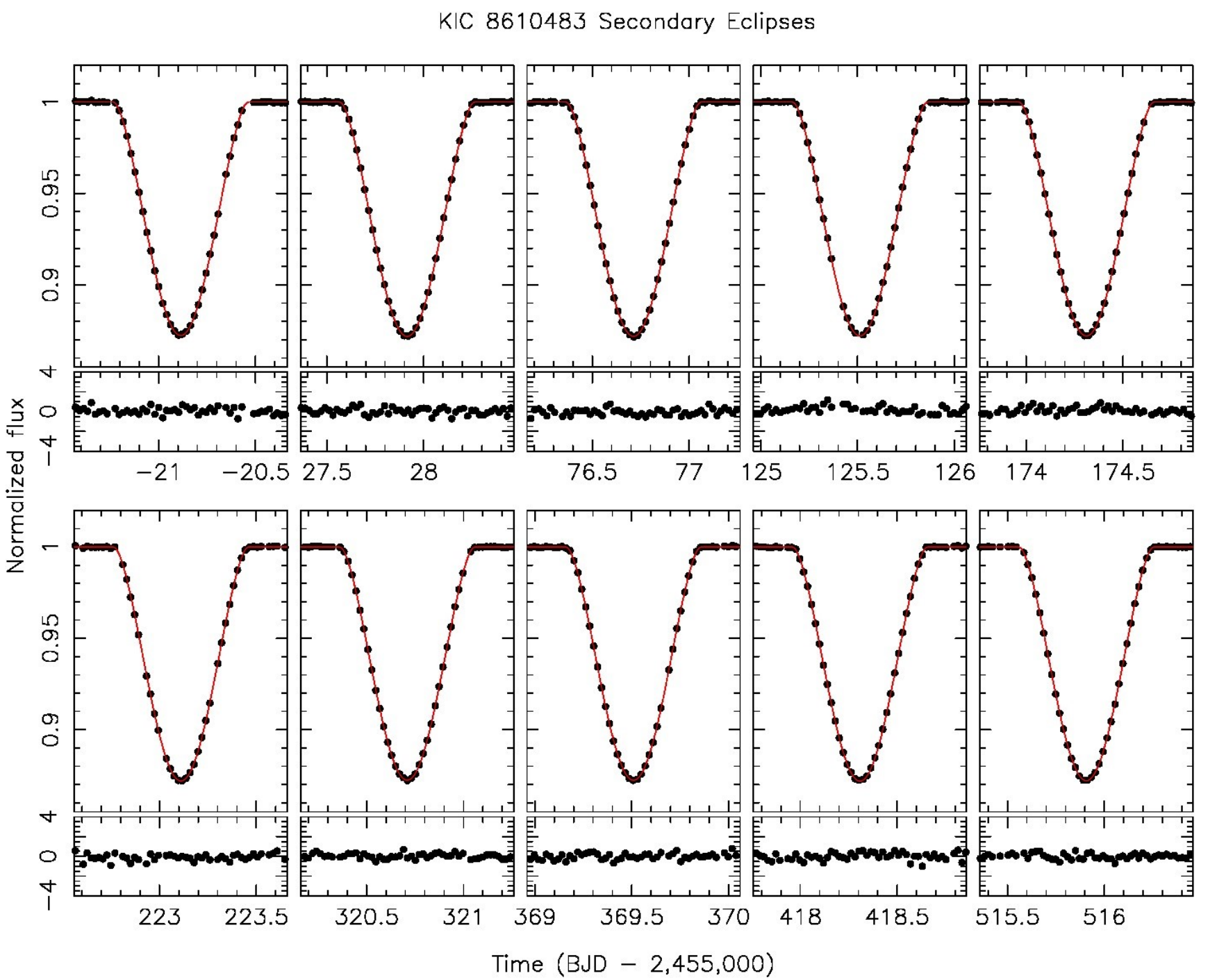
3 non-transiting candidates

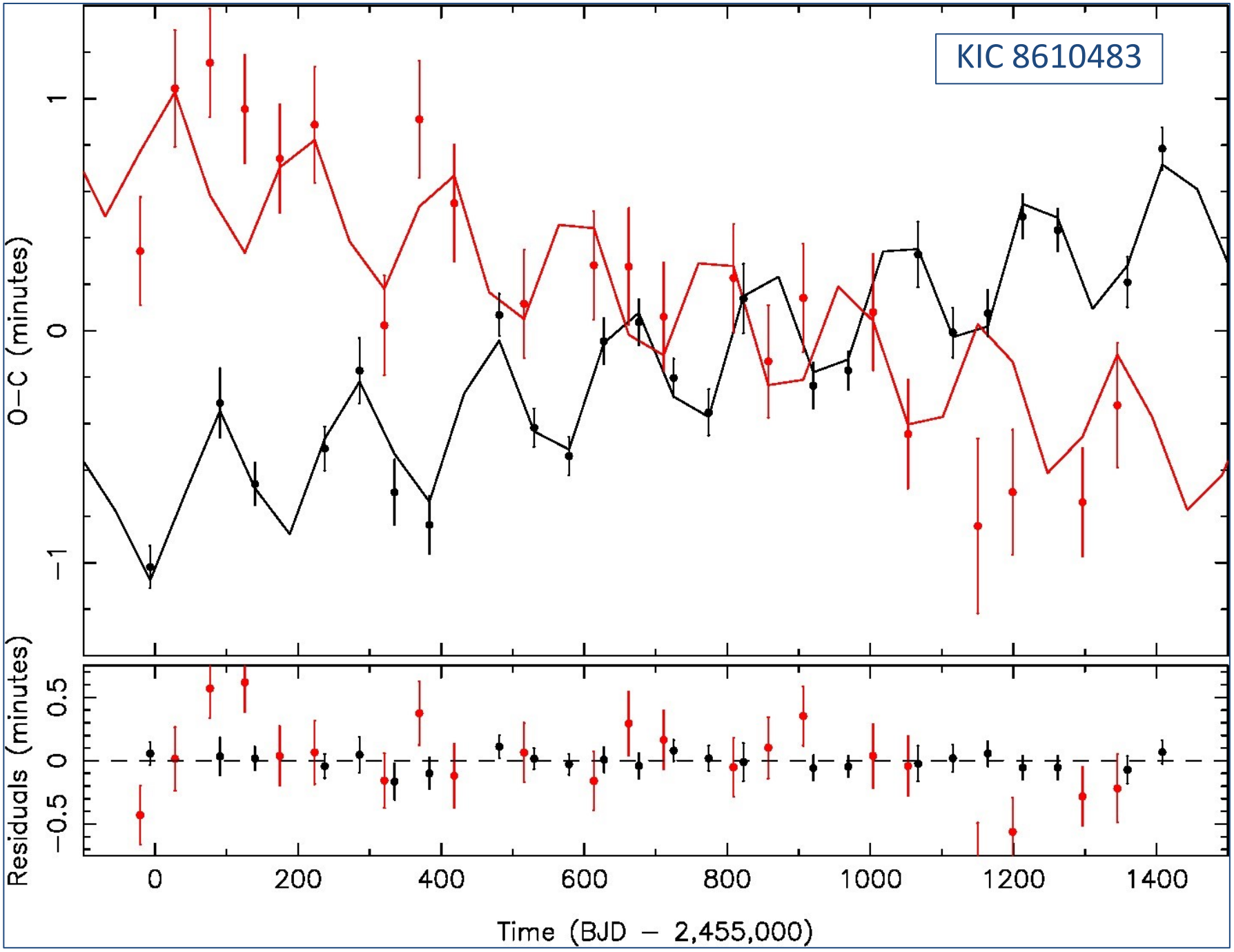

KIC 3938073
KIC 8610483
O−C (minutes)
Time (BJD − 2,455,000)
P=126.26 days
P=189.46 days
L−S power
Period (days)

KIC 8610483


KIC 8610483 One Planet Model
Radial velocity (km s^{-1})
0
−50
2
0
−2
1435
1440
1445
1450
1455
1460
1465
Time (BJD − 2,455,000)


KIC 8610483 Primary Eclipses
Normalized flux
1
0.9
0.8
0.7
4
0
−4
−7
−6.5
90.5
91
139.5
140
237
237.5
285.5
286
334.5
335
383.5
384
481
481.5
529.5
530
578.5
579
Time (BJD − 2,455,000)


KIC 8610483 Secondary Eclipses
Normalized flux
1
0.95
0.9
4
0
−4
−21
−20.5
27.5
28
76.5
77
125
125.5
126
174
174.5
223
223.5
320.5
321
369
369.5
370
418
418.5
515.5
516
Time (BJD − 2,455,000)


KIC 8610483
O−C (minutes)
1
0
−1
Residuals (minutes)
0.5
0
−0.5
0
200
400
600
800
1000
1200
1400
Time (BJD − 2,455,000)

(preliminary) Derived Parameters of KIC 8610483

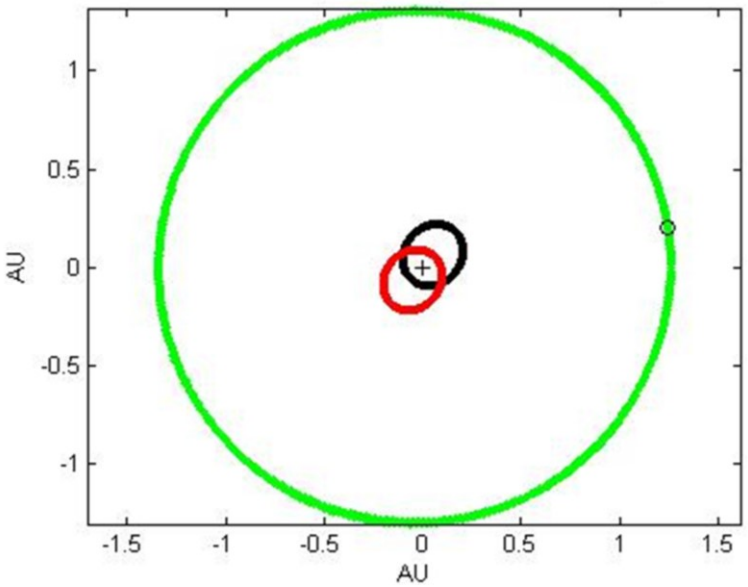
parameter	value
M_1 $(M_\odot)$	0.961 ± 0.020
M_2 $(M_\odot)$	0.974 ± 0.015
M_3 $(M_\oplus)$	45.069 ± 3.496
R_1 $(R_\odot)$	1.450 ± 0.023
R_2 $(R_\odot)$	1.371 ± 0.016
R_3 $(R_\oplus)$	...
$\log g_1$ (cgs)	4.097 ± 0.013
$\log g_2$ (cgs)	4.152 ± 0.013
a_2 (AU)	0.3257 ± 0.0027
a_3 (AU)	1.3179 ± 0.0087
e_2	0.4926244 ± 0.0011450
ω_2 (deg)	50.52567 ± 0.14558
e_3	0.0286155 ± 0.0147505
ω_3 (deg)	27.94829 ± 29.00059
$I_{2,3}$ (deg)	11.4412 ± 2.9777

P binary = 48.799 d
incl. binary = 88.83 deg

P planet = 397.3 d
incl. planet ~ 77.6 deg

$a/a_{crit} = 1.13$

(P/Pcrit = 1.20)



KIC 3938073 *(preliminary)*

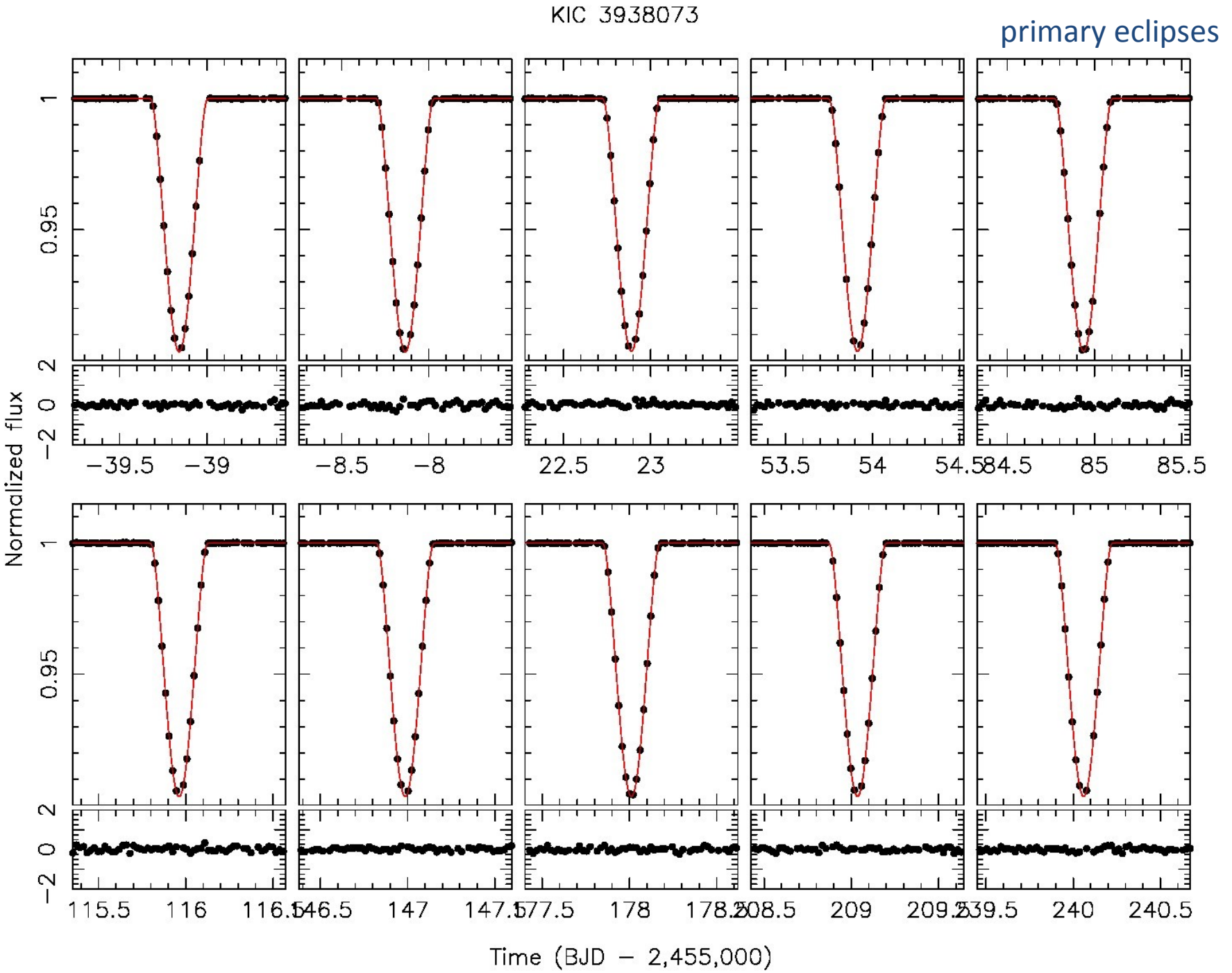
Eclipsing Binary

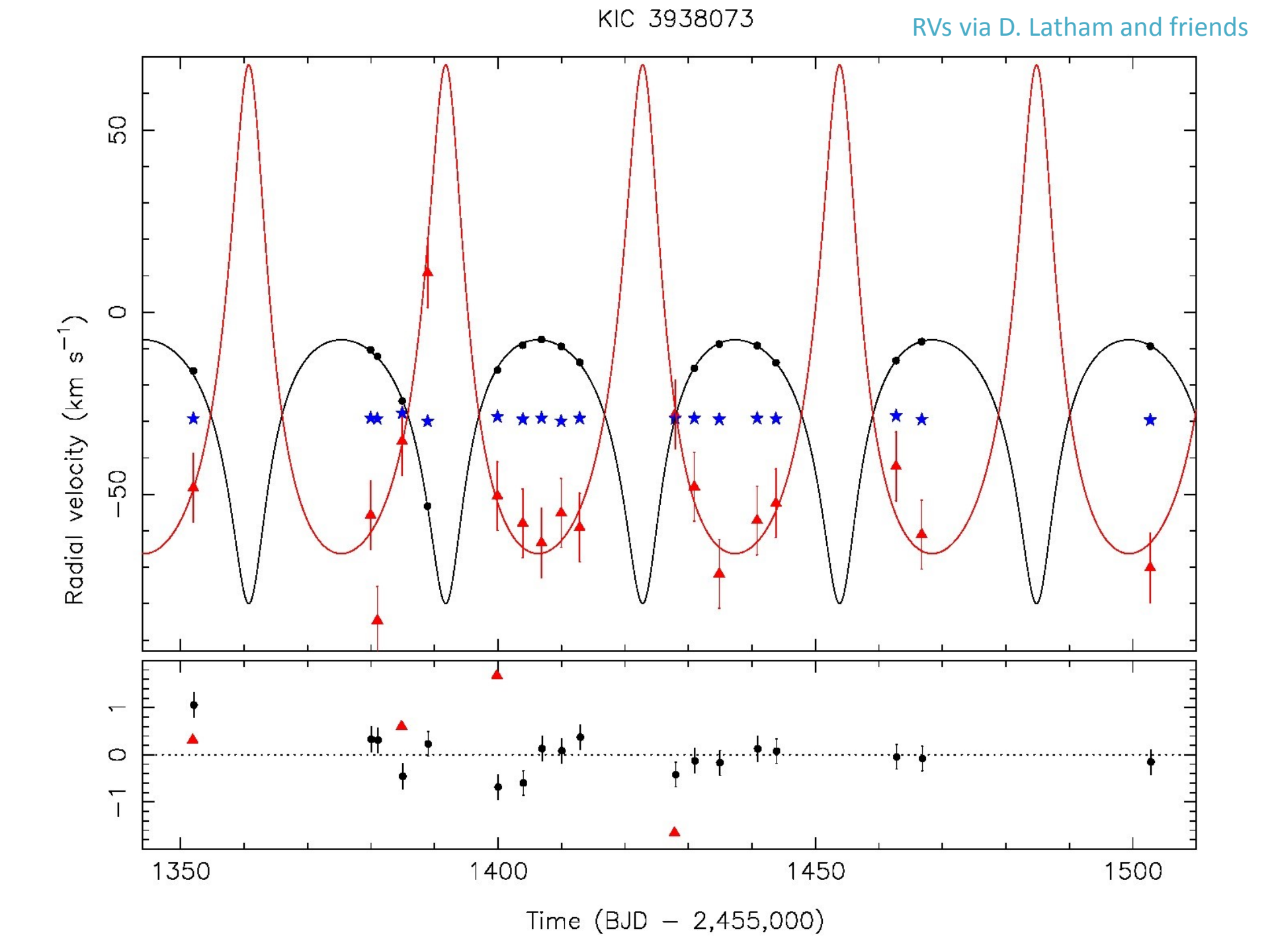
- P = 31.024 d
- e = 0.433
- M_1 = 1.98 M_{Sun}
- M_2 = 0.97 M_{Sun}
- R_1 = 1.71 R_{sun}
- R_2 = 0.86 R_{sun}

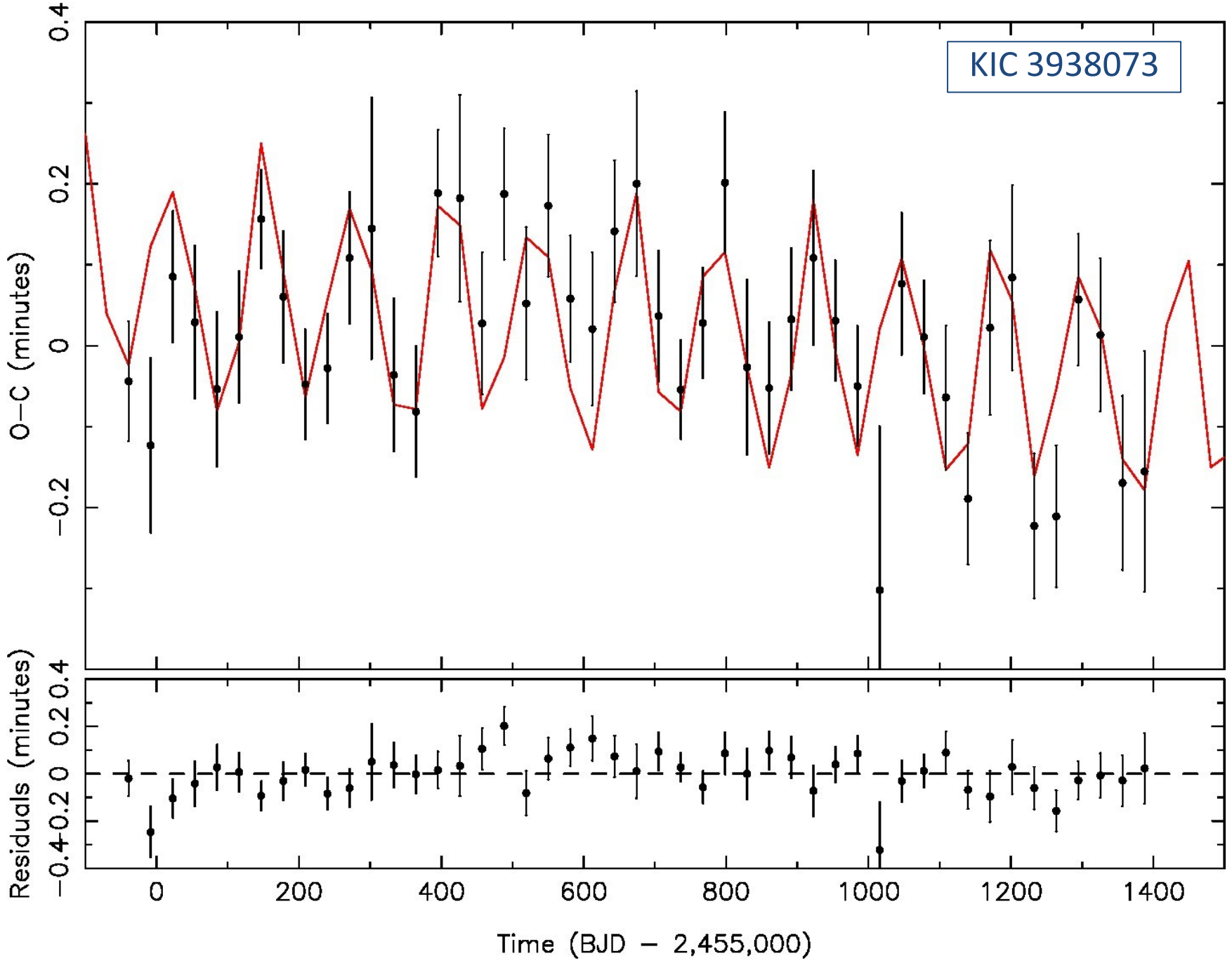
(but light from 3rd star...)

Planet

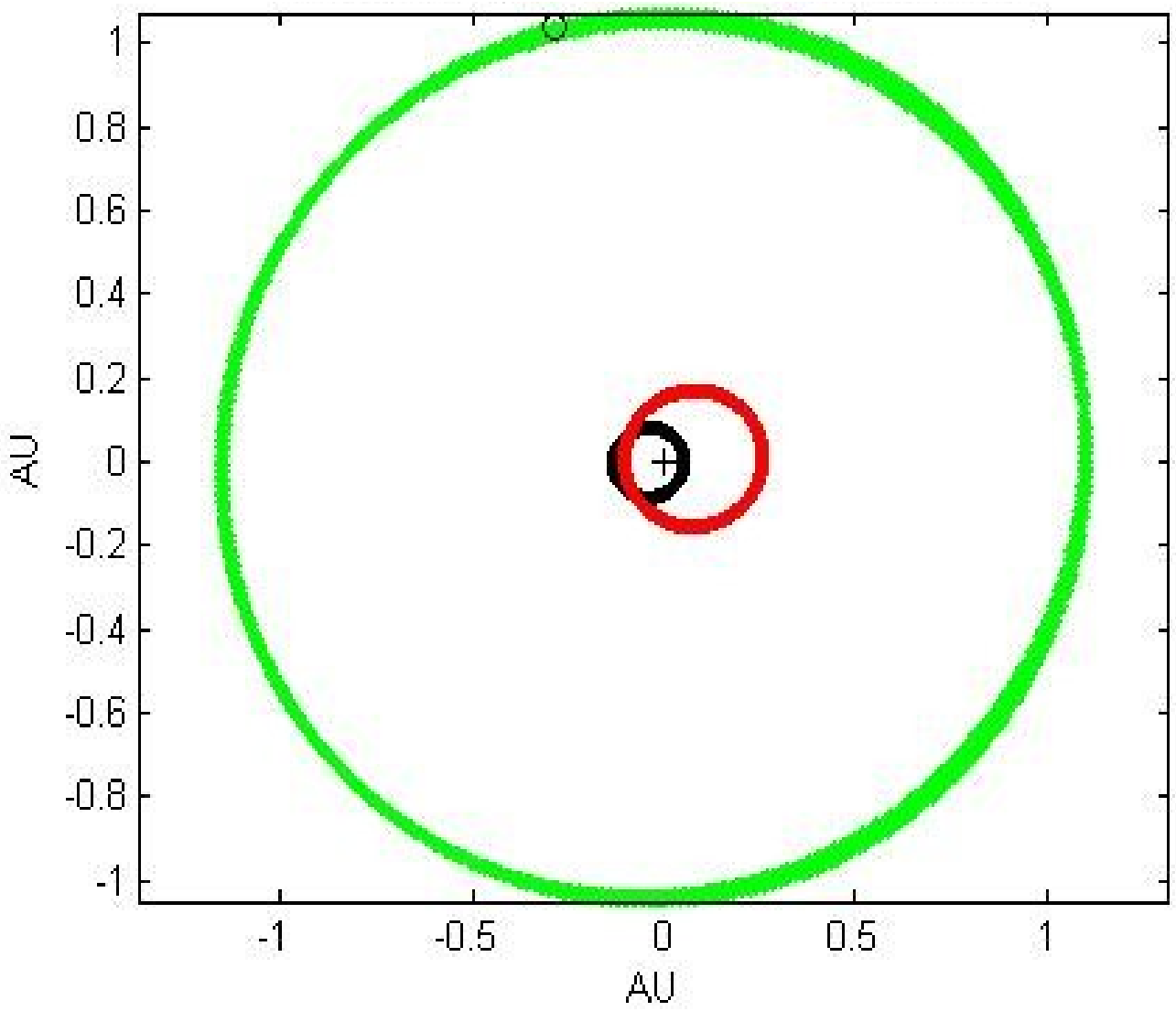
- P_p ~ 269.6 d
- e ~ 0.07
- M_p ~ 46 M_{Earth}
- R_p = ----
- inclination ~ 71 deg
- mutual incl. ~ 14 deg


KIC 3938073
primary eclipses
Normalized flux
1
0.95
2
0
−2
−39.5
−39
−8.5
−8
22.5
23
53.5
54
54.5
84.5
85
85.5
115.5
116
116.5
146.5
147
147.5
177.5
178
178.5
208.5
209
209.5
239.5
240
240.5
Time (BJD − 2,455,000)


KIC 3938073
RVs via D. Latham and friends
Radial velocity (km s^{-1})
50
0
−50
−1
0
1
1350
1400
1450
1500
Time (BJD − 2,455,000)


KIC 3938073
O−C (minutes)
0.4
0.2
0
−0.2
Residuals (minutes)
−0.4
−0.2
0
0.2
0.4
0
200
400
600
800
1000
1200
1400
Time (BJD − 2,455,000)

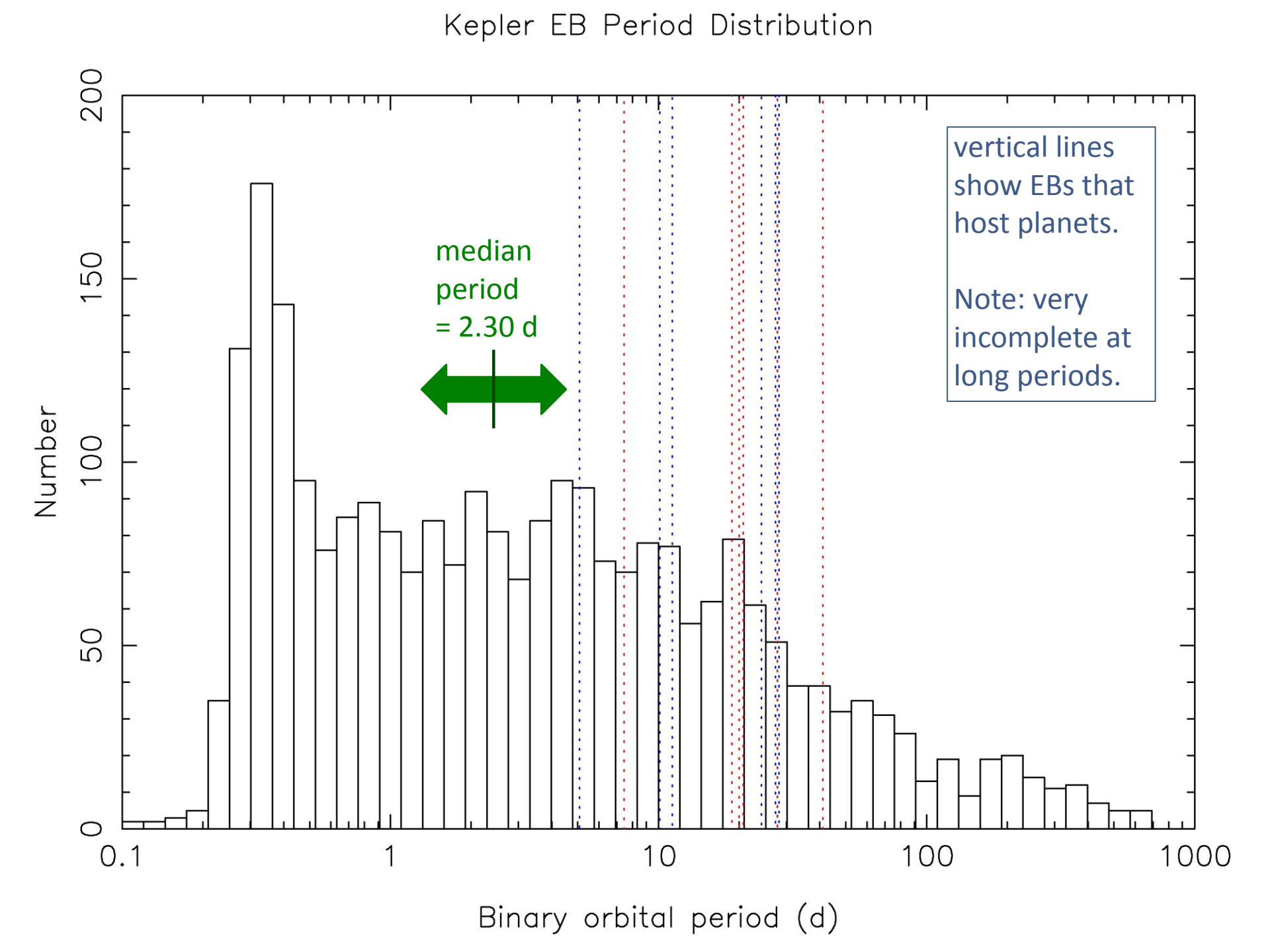
KID 3938073

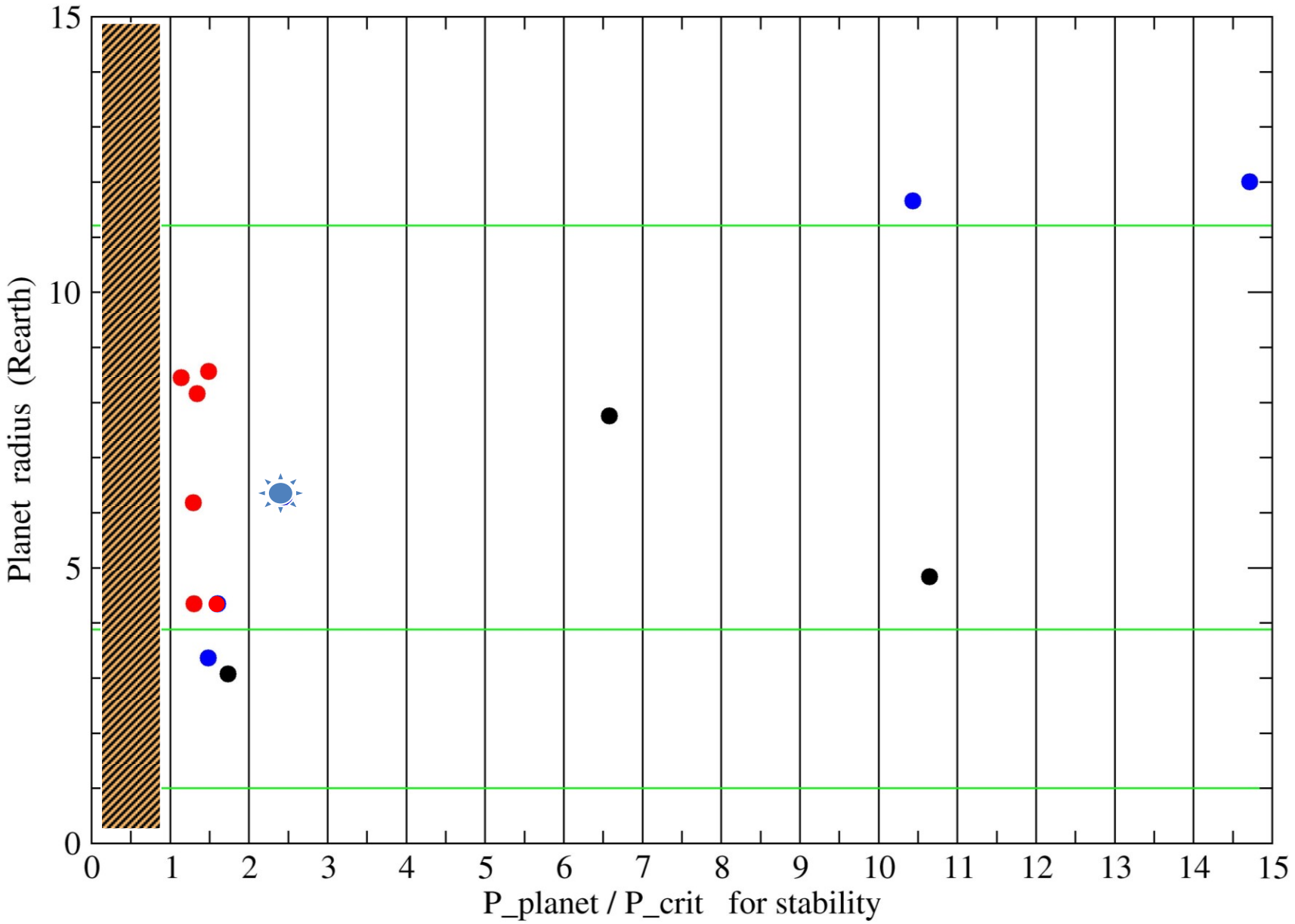


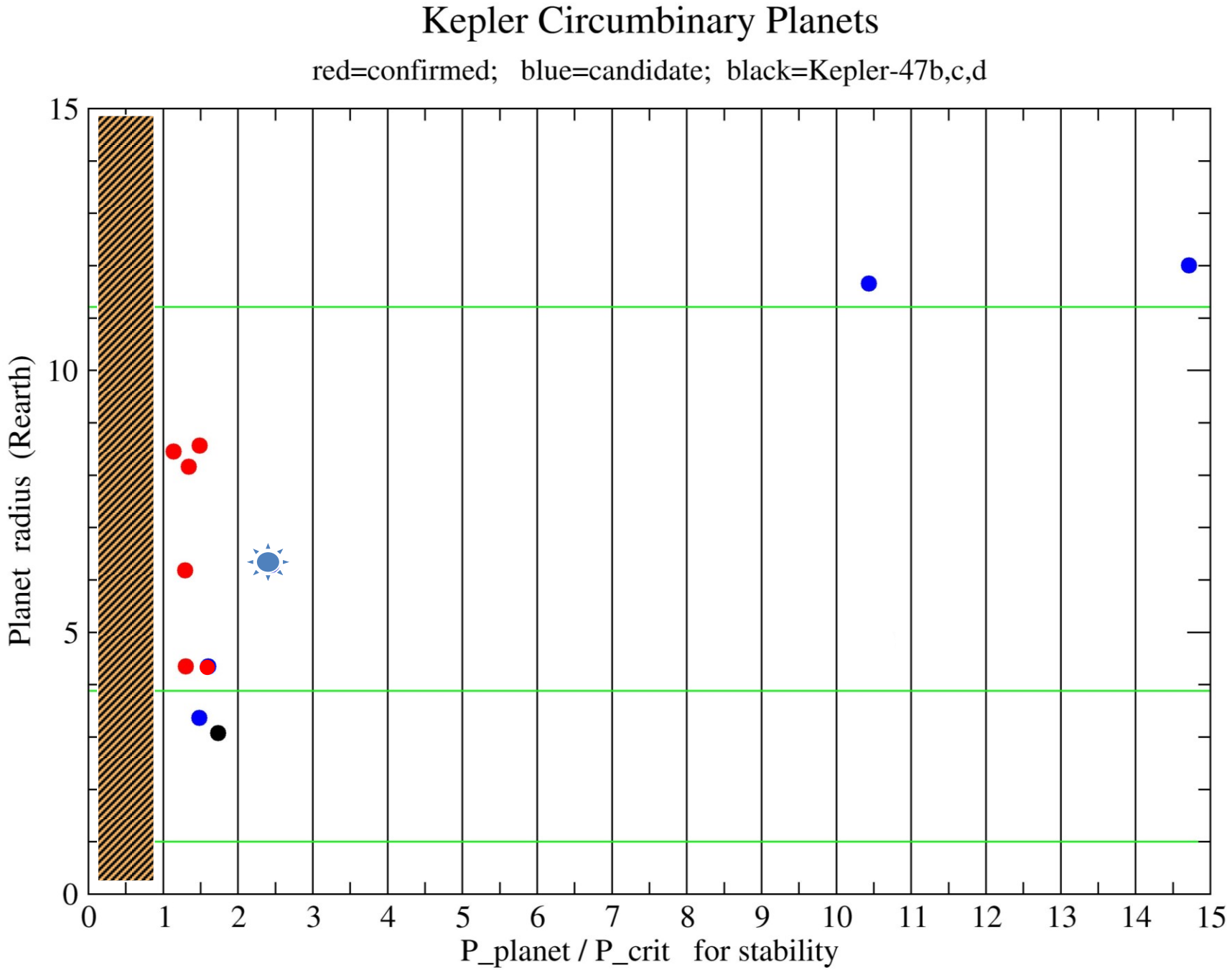
credit:
D. Short

Some emerging trends:

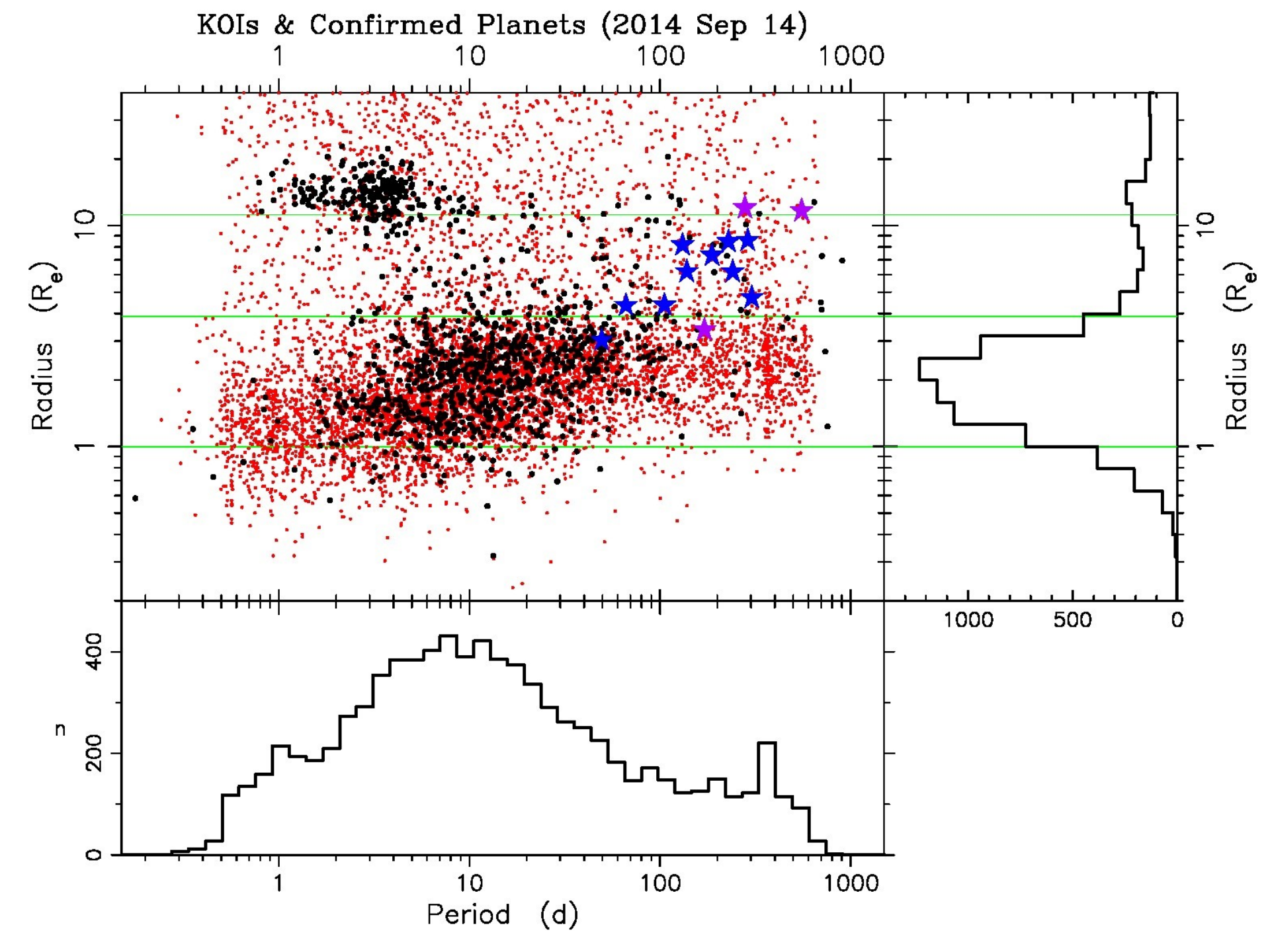
- *CBP not seen in short P binaries*
  - *why not? past 3rd body interaction?*
- *Planets are close to the critical orbital radius*
  - *8 out of 11 systems have $P < 2\ P_{crit}$*
  - *observational bias or migration pile-up?*


Kepler EB Period Distribution
Number
0
50
100
150
200
0.1
1
10
100
1000
Binary orbital period (d)
median
period
= 2.30 d
vertical lines
show EBs that
host planets.
Note: very
incomplete at
long periods.


Kepler Circumbinary Planets
red=confirmed; blue=candidate; black=Kepler-47b,c,d
Planet radius (Rearth)
P_planet / P_crit for stability
0
5
10
15
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15


Kepler Circumbinary Planets
red=confirmed; blue=candidate; black=Kepler-47b,c,d
Planet radius (Rearth)
P_planet / P_crit for stability
0
5
10
15
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

- As a consequence of being close to critical radius, *Kepler* CBPs are close to the HZ.
  - *With the new circumbinary planet KIC 9632895, 3 out of 10 CBPs are in the HZ*
  - *5 out of 12 candidates are in wide HZ (~42%)*


KOIs & Confirmed Planets (2014 Sep 14)
1
10
100
1000
Radius (R_e)
10
1
1000
500
0
n
400
200
0
Period (d)

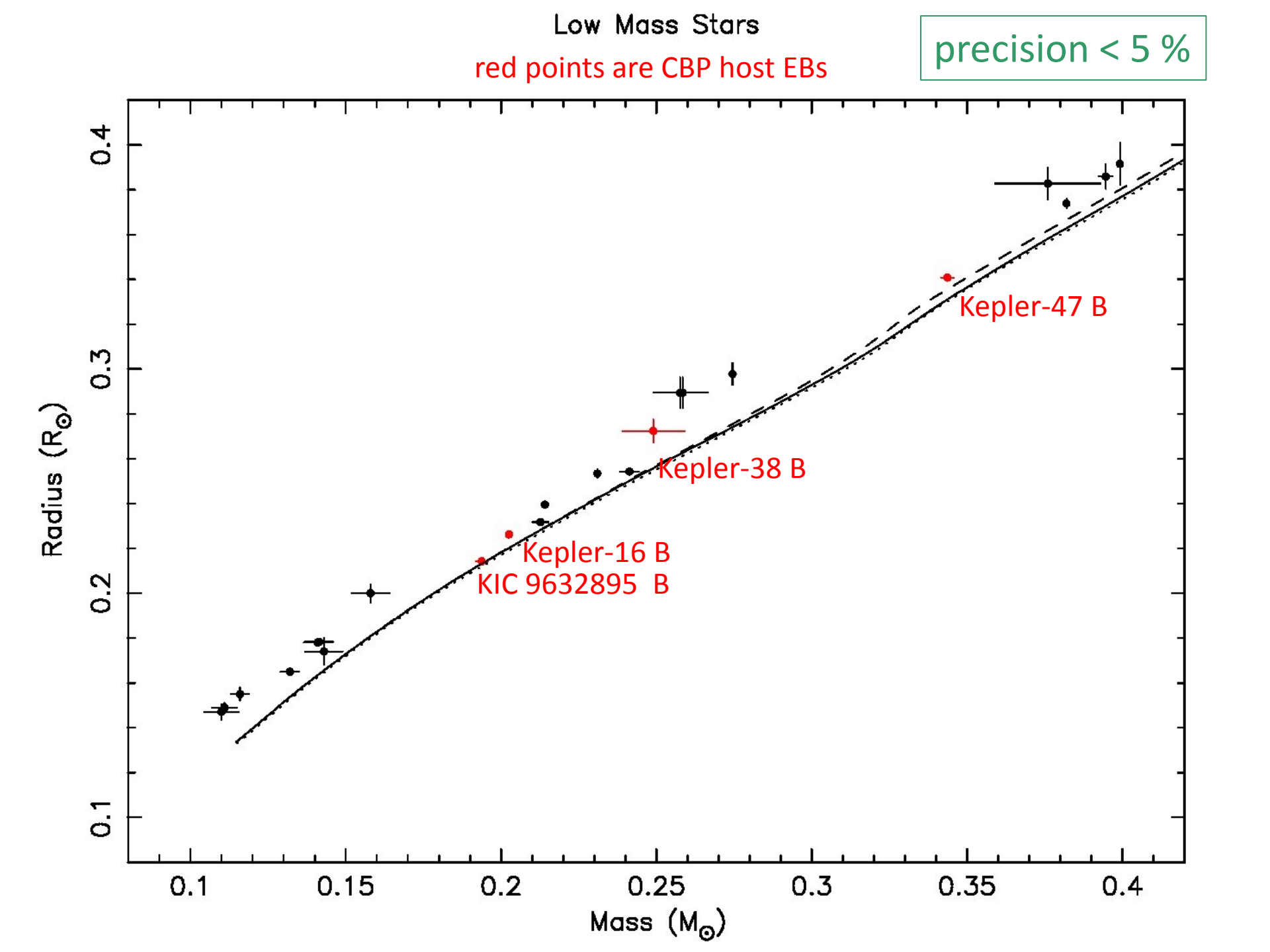
SUMMARY: Kepler Circumbinary Planets

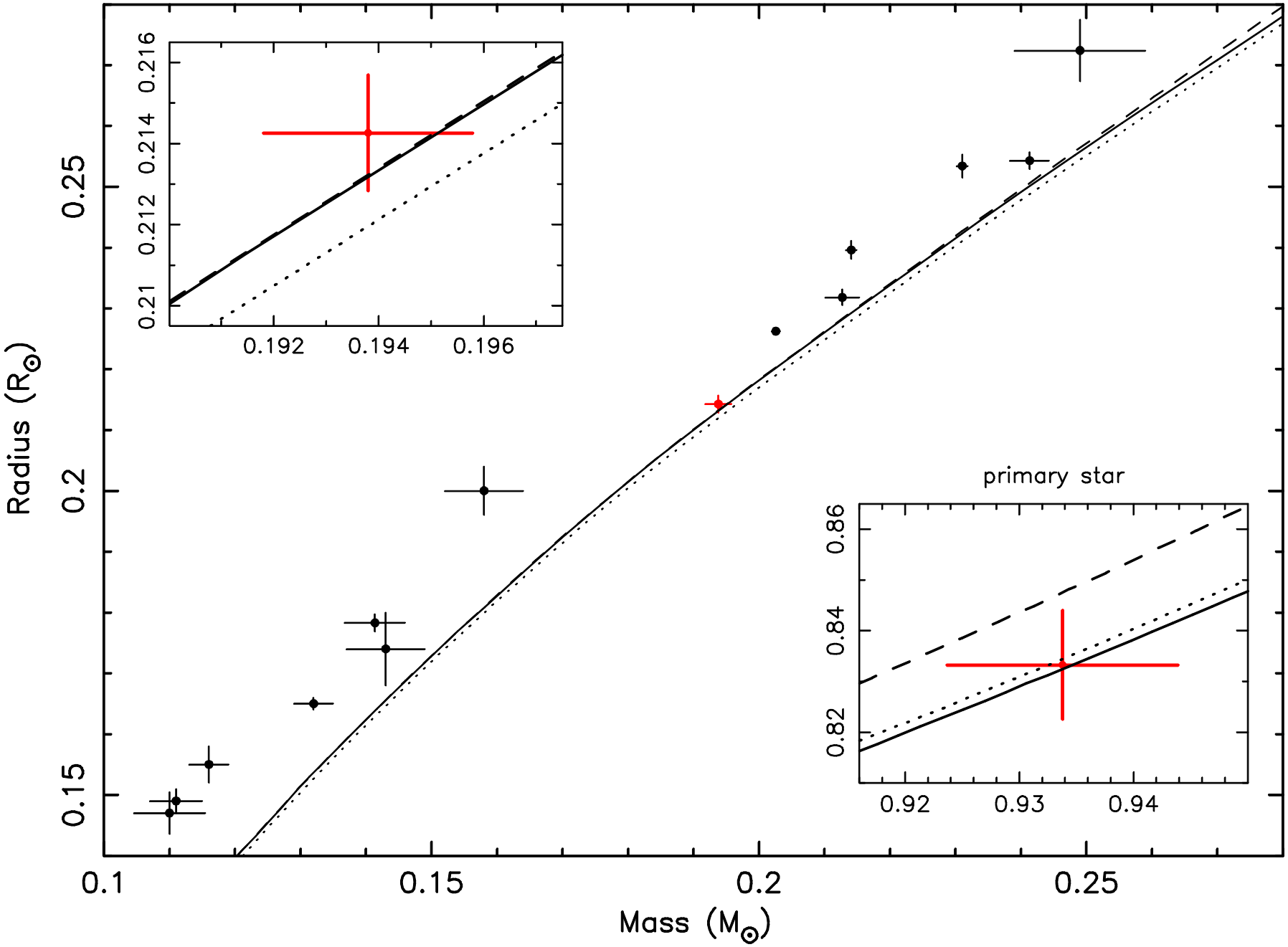
Much more difficult to find, but offer rich rewards.

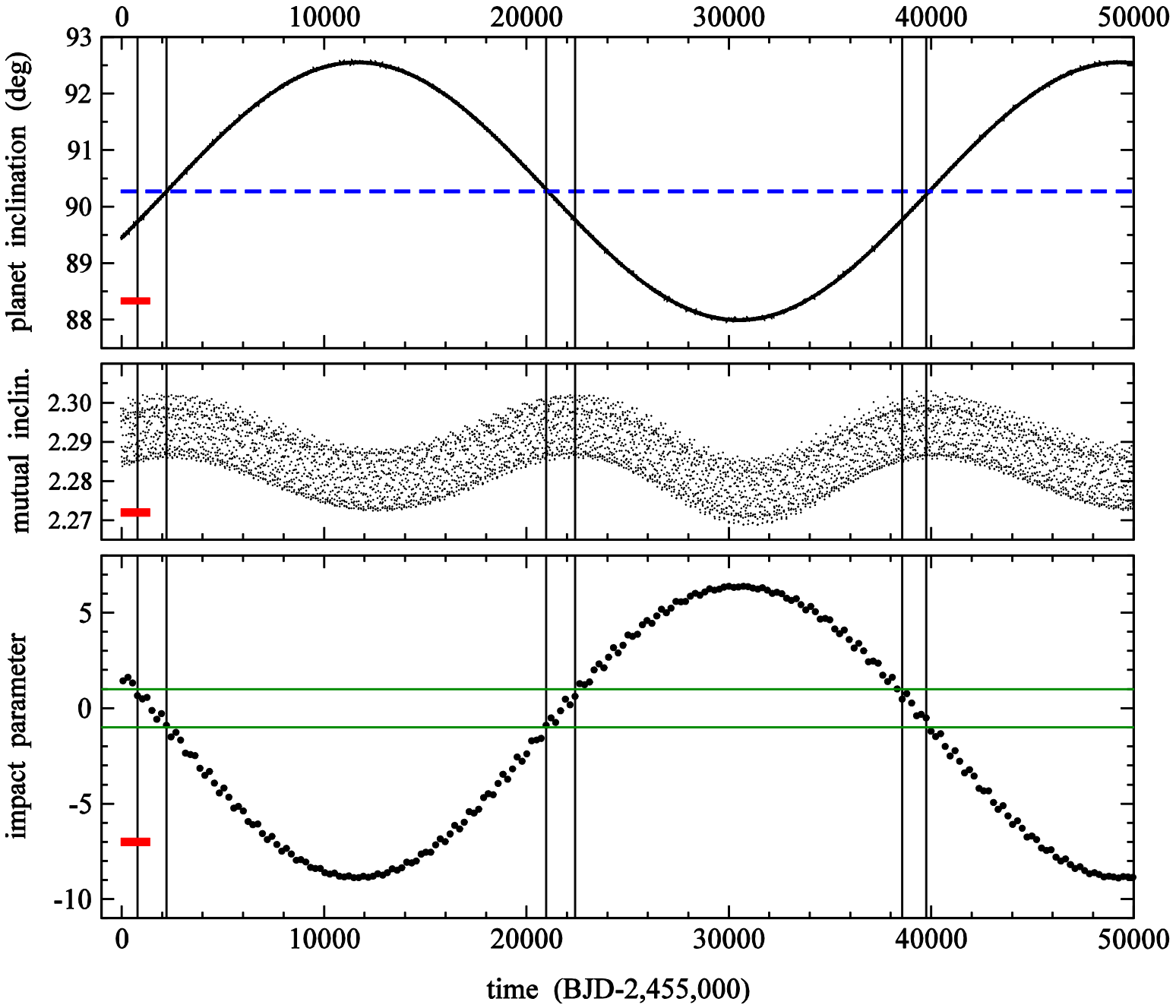
- 10+ transiting & 3 non-transiting cases
- diverse planet and stellar orbits
- but no very short-period EB cases

- planets tend to be close to unstable region → HZ

- provide very precise masses & radii (for planets & stars)
- challenges for planet formation theory and insight into binary star formation

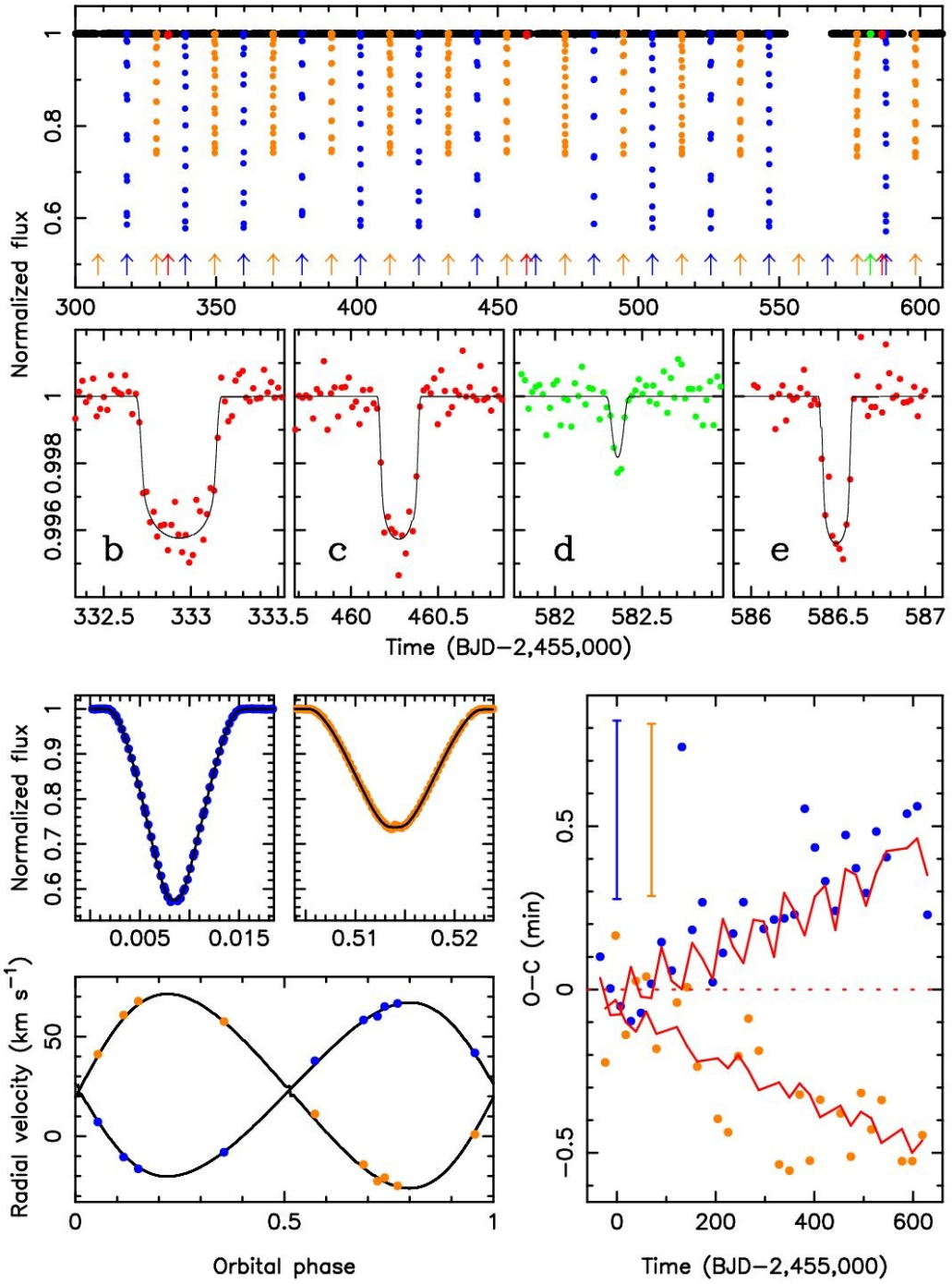

Low Mass Stars
red points are CBP host EBs
precision < 5 %
Kepler-47 B
Kepler-38 B
Kepler-16 B
KIC 9632895 B
Radius ($R_\odot$)
Mass ($M_\odot$)
0.1
0.2
0.3
0.4
0.1
0.15
0.2
0.25
0.3
0.35
0.4


Radius ($R_\odot$)
Mass ($M_\odot$)
0.1
0.15
0.2
0.25
0.15
0.2
0.25
0.21
0.212
0.214
0.216
0.192
0.194
0.196
primary star
0.82
0.84
0.86
0.92
0.93
0.94


0
10000
20000
30000
40000
50000
93
92
91
90
89
88
planet inclination (deg)
2.30
2.29
2.28
2.27
mutual inclin.
5
0
-5
-10
impact parameter
time (BJD-2,455,000)

Kepler-35

	Kepler-35
Planet	
Mass of planet, $M_p(M_{\rm Jupiter})$	$0.127^{+0.020}_{-0.020}$
Radius of planet, $R_p(R_{\rm Jupiter})$	$0.728^{+0.014}_{-0.014}$
Mean Density of planet, ρ_p (g cm^{-3})	$0.410^{+0.070}_{-0.069}$
Properties of it	
Reference Epoch (BJD)	2,454,965.85000
Period, P (days)	$131.458^{+0.077}_{-0.105}$
Semi-major axis length, a (AU)	$0.60347^{+0.00101}_{-0.00103}$
Eccentricity, e	$0.042^{+0.007}_{-0.004}$
Eccentricity Times Sine of Arg. of Periapse, $e\sin(\omega)$	$0.035^{+0.009}_{-0.011}$
Eccentricity Times Cosine of Arg. of Periapse, $e\cos(\omega)$	$0.017^{+0.021}_{-0.018}$
Mean Longitude, $\lambda \equiv M + \omega$ (deg)	$136.4^{+2.1}_{-2.7}$
Inclination i (deg)	$90.76^{+0.12}_{-0.09}$
Relative Nodal Longitude, Ω (deg)	$-1.24^{+0.24}_{-0.33}$
Properties of the Binary	
Mass of A, $M_A(M_\odot)$	$0.8877^{+0.0051}_{-0.0053}$
Radius of A, $R_A(R_\odot)$	$1.0284^{+0.0020}_{-0.0019}$
Mass of B, $M_B(M_\odot)$	$0.8094^{+0.0042}_{-0.0045}$
Radius of B, $R_B(R_\odot)$	$0.7861^{+0.0020}_{-0.0022}$
Flux ratio in the Kepler bandpass, F_B/F_A	$0.3941^{+0.0011}_{-0.0010}$
Properties of the orbit	
Period, P (days)	$20.733666^{+0.000012}_{-0.000012}$
Semi-major axis length, a (AU)	$0.17617^{+0.00029}_{-0.00030}$
Eccentricity, e	$0.1421^{+0.0014}_{-0.0015}$
Eccentricity Times Sine of Arg. of Periapse, $e\sin(\omega)$	$0.1418^{+0.0014}_{-0.0015}$
Eccentricity Times Cosine of Arg. of Periapse, $e\cos(\omega)$	$0.0086413^{+0.0000031}_{-0.0000031}$
Mean Longitude, $\lambda \equiv M + \omega$ (deg)	$89.1784^{+0.0011}_{-0.0012}$
Inclination i (deg)	$90.4238^{+0.0076}_{-0.0073}$



Kepler-47 *update*

Eclipsing Binary

- Kp = 15.2 mag
- P = 7.448374 d
- e = 0.028

Sun-like primary

- T_1 = 5640 K
- M_1 = 0.966 M_{Sun}
- R_1 = 0.936 R_{sun}

- M_2 = 0.344 M_{Sun}
- R_2 = 0.341 R_{sun}

Inner planet "b"

- P_b = 49.45 d
- R_b = 3.0 R_e
- M_b < 2.0 M_J

Outer planet "c"

- P_c = 303.2 d
- R_c = 4.7 R_e
- M_c < 28 M_J

KOI 2938 = KID 7821010

first non-transiting CBP

P_p = 994 d

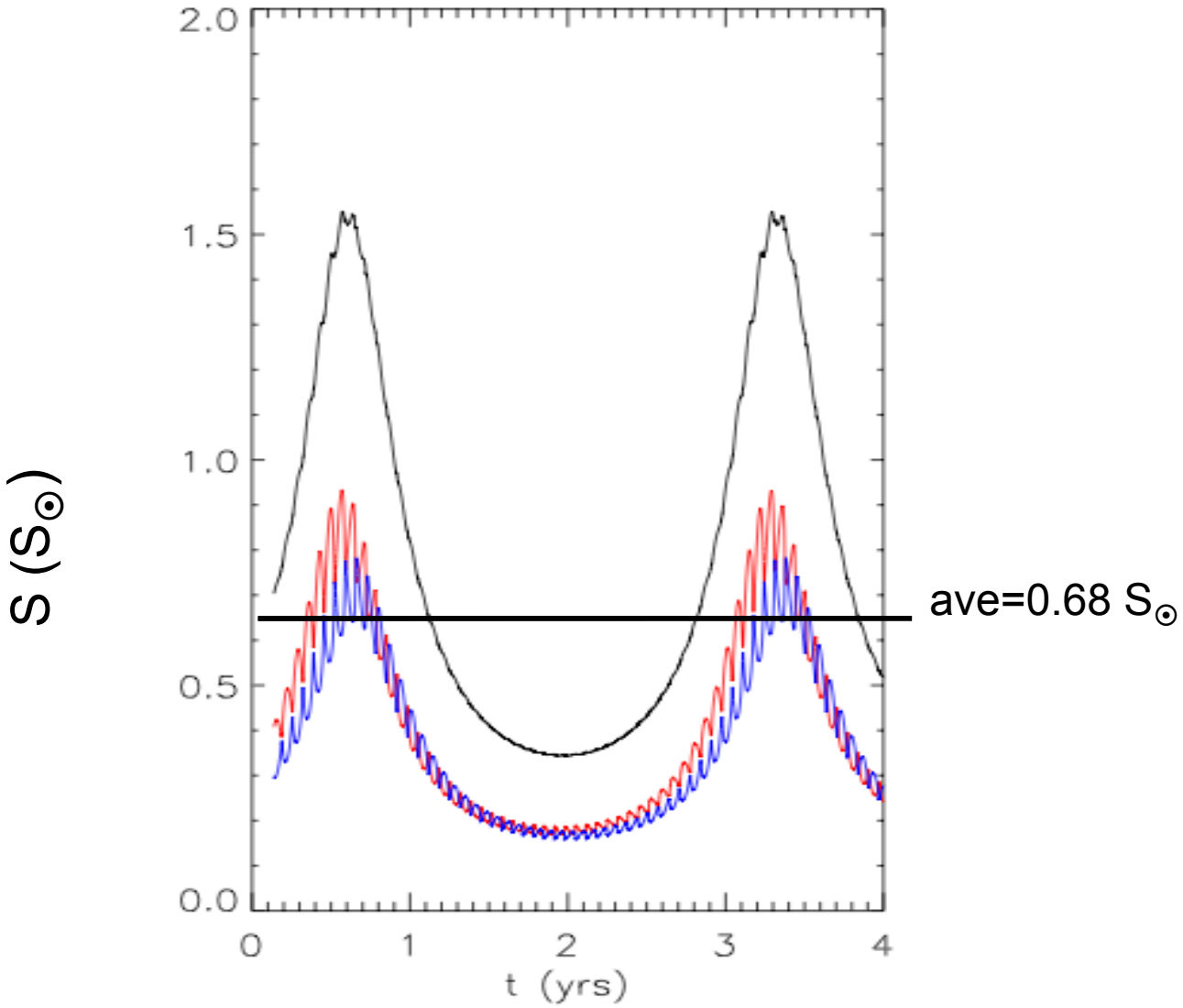
e_p = 0.36

M_p = 2.6 M_{Jup}

mutual i ~5°

Also used GR precession and solved k_2=0.0077 (for each star)

Average insolation puts planet in the habitable zone



credit:
D. Fabrycky