Insights from Kepler

David W. Latham
For the Kepler Team
24 February 2011

In March Kepler rose,
seeking shadows of planets.
Are any like Earth?

Multiples!

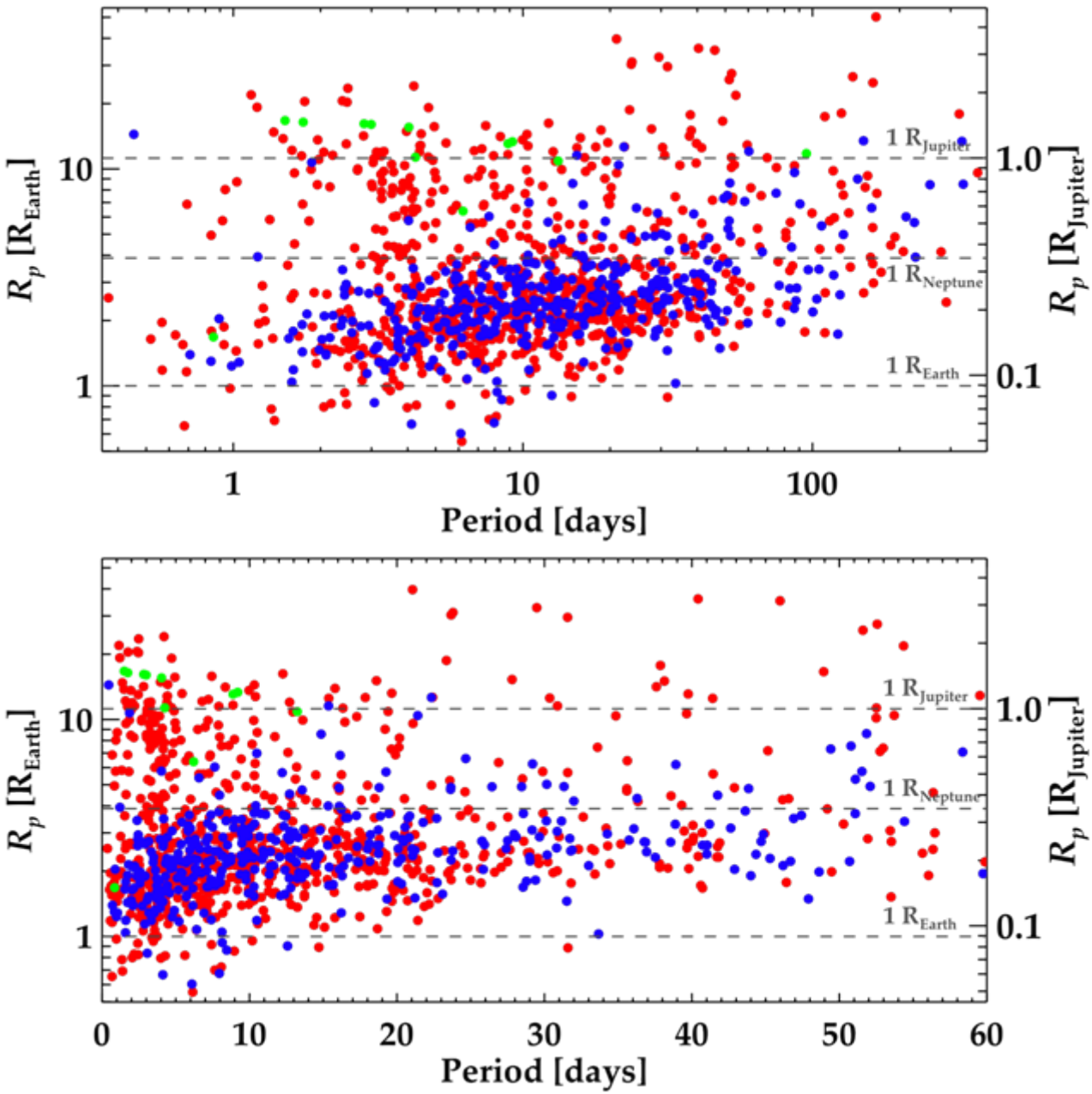
Single: one periodic sequence of transits

Multiple: two or more sequences of transits (different periods and different depths)

827 singles (red)
408 in multiples (blue)
- 115 two planets
- 45 three
- 8 four
- 1 five
- 1 six

170 multiple systems

1235 Vetted Candidates



Multiples!

Rejected:
498 false positives 29%
486 singles 98%
12 in multiples 2%

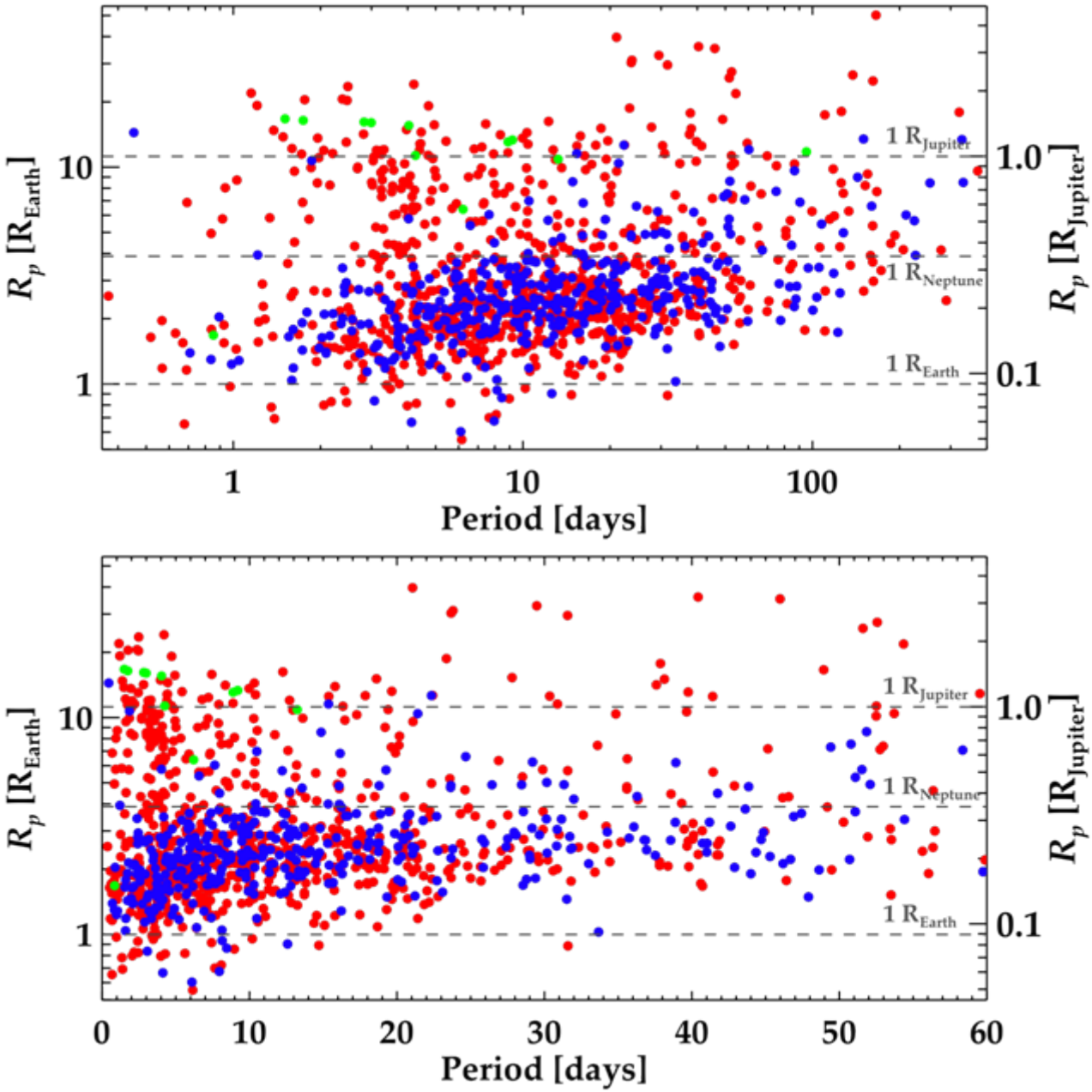
Candidates in multiples (about 1/3 of total) are almost all planets!

Multiple systems are coplanar to ~1 degree, flatter than Solar System!

Giant planets are less common in multiples

Why didn't CoRoT find multiples? (green points)

1235 Vetted Candidates



Rejecting False Positives

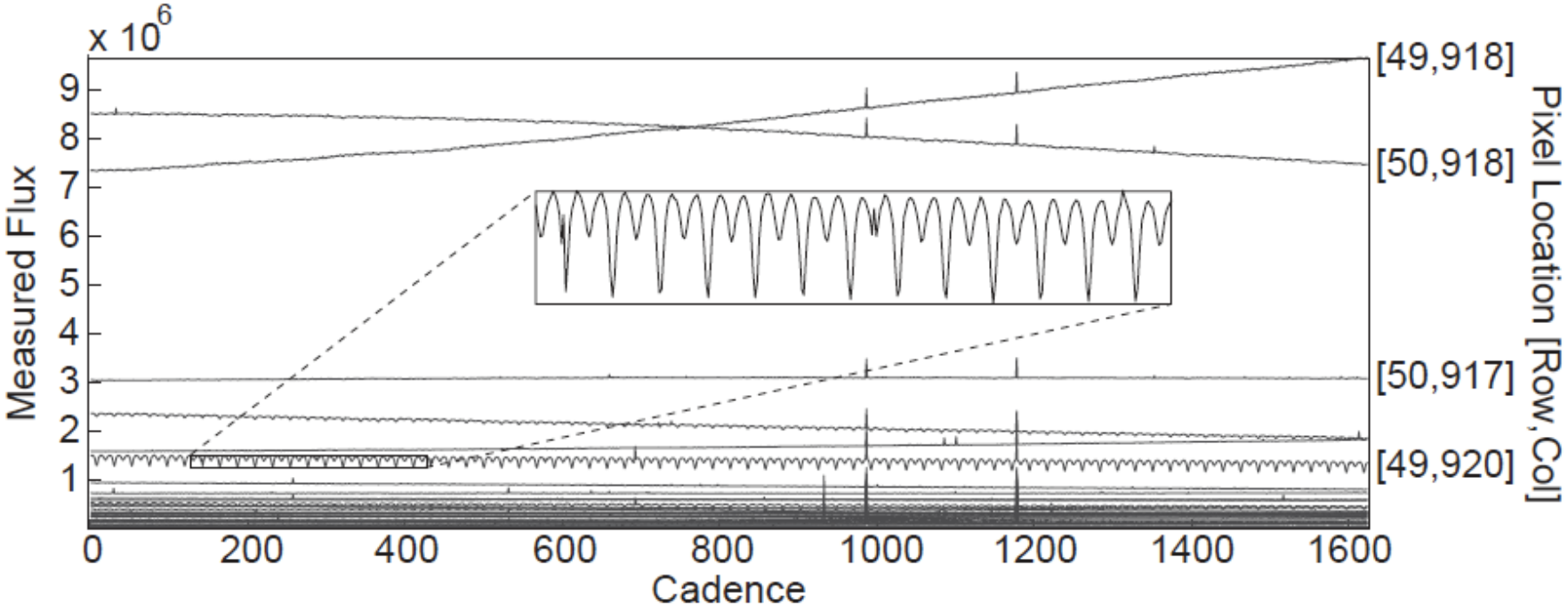
- Motion of image centroid during transit (60%)
  - Background eclipsing binaries, misaligned by more than ~1 or 2 arcseconds
  - Need high-resolution images to see inside ~1”
- Light curve features (35%)
  - Secondary eclipses, ellipsoidal variations, ETVs
- Large radial velocity variations (5%)
  - At least two stars in the target system

Centroid Motion

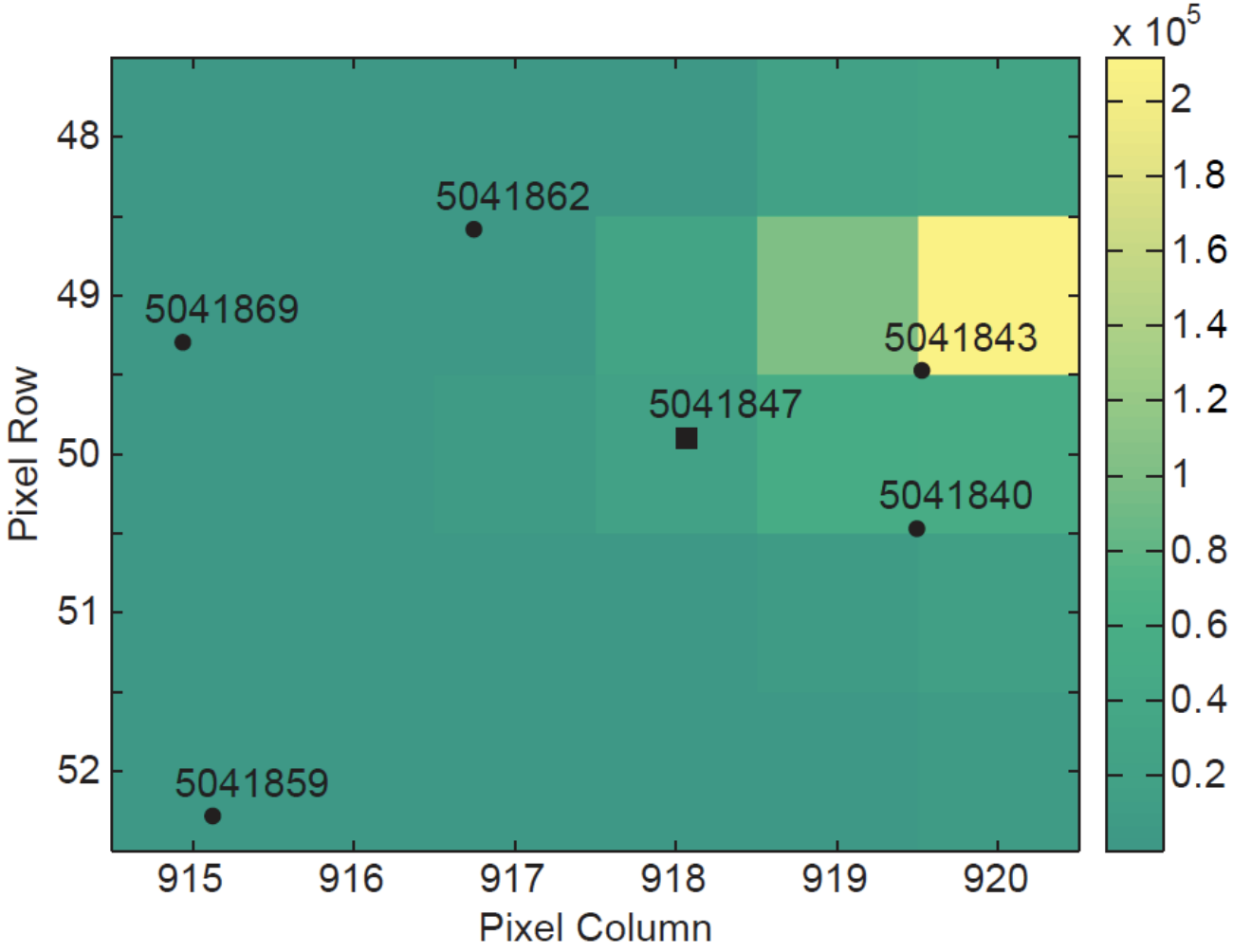
KIC 5041847 -- An extreme example:

Most of the signal comes from the selected target (KIC 5041847) on two pixels [49,918] & [50,918]

The “transit” signal comes from a nearby fainter star (KIC 5041843) on pixel [49,920] (4 arcsec pixels)



Difference of two images:
-- One during (all) the transits,
-- One outside (but nearby) the transits



ON THE LOW FALSE POSITIVE PROBABILITIES OF *KEPLER* PLANET CANDIDATES

TIMOTHY D. MORTON[1], JOHN ASHER JOHNSON[1,2]

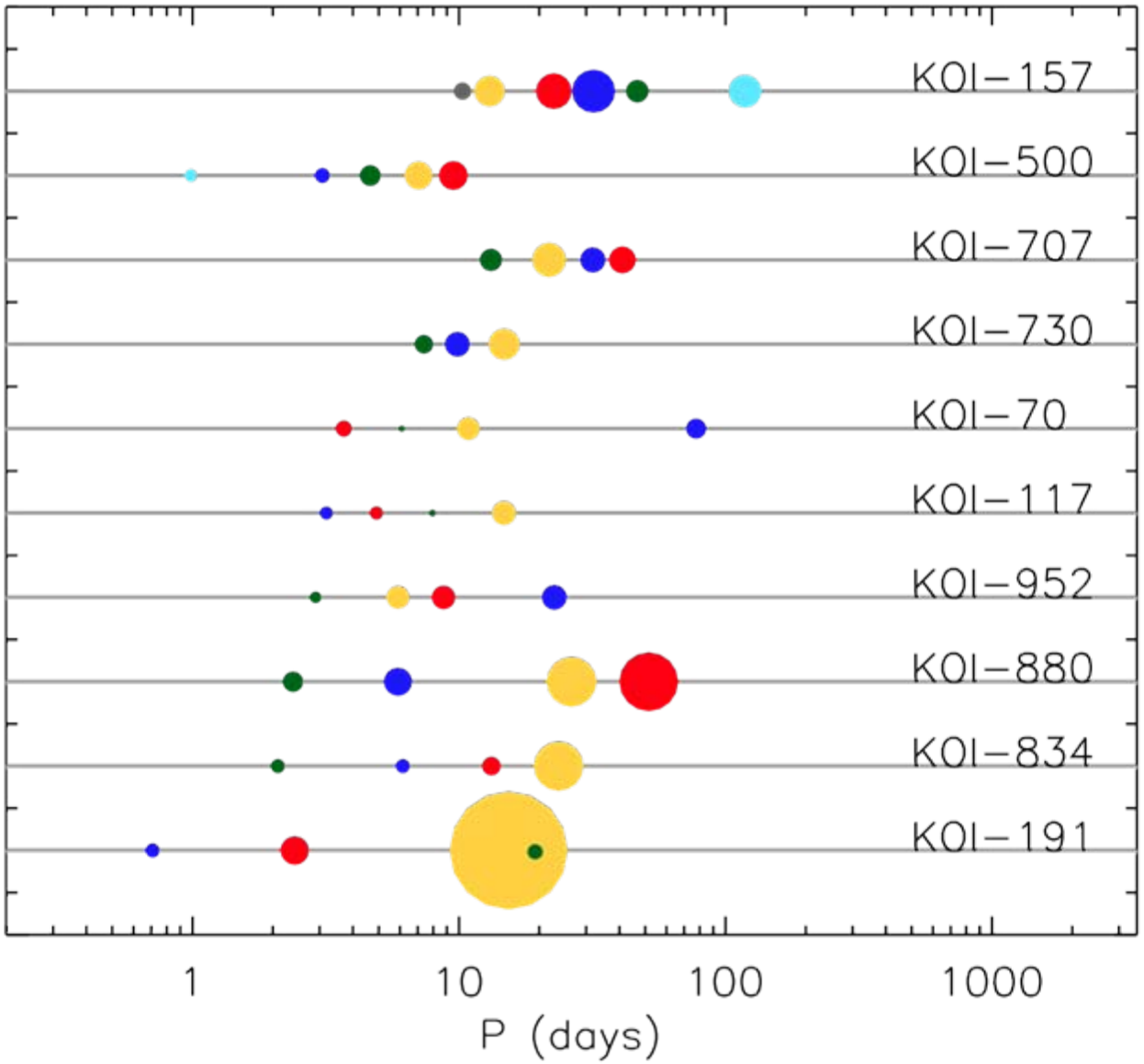
Draft version February 1, 2011

ABSTRACT

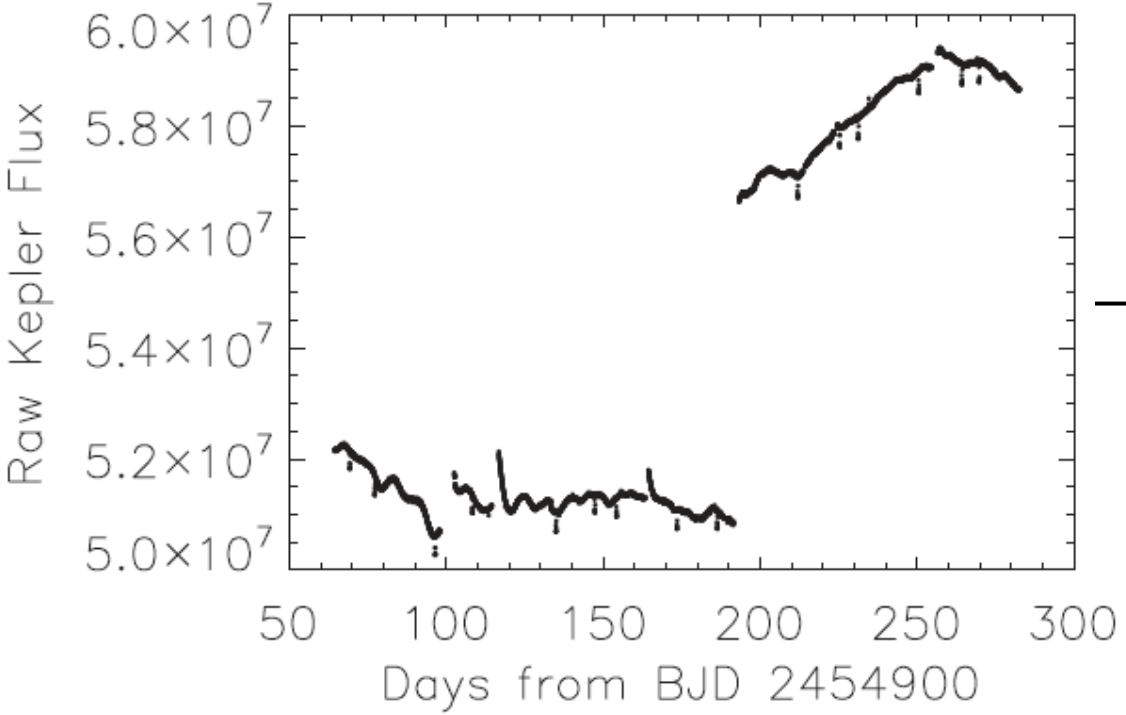
We present a framework to conservatively estimate the probability that any particular planet-like transit signal observed by the *Kepler* mission is in fact a planet, prior to any ground-based follow-up efforts. We use Monte Carlo methods based on stellar population synthesis and Galactic structure models, and we provide empirical analytic fits to our results that may be applied to the as-yet-unconfirmed Kepler candidates. We find that the false positive probability for candidates that pass preliminary *Kepler* vetting procedures is generally <10% and often <5%, assuming a 20% occurrence rate of close-in planets in the mass range $0.5\ M_\oplus < M_p < 10\ M_{\rm Jup}$. This probability varies most strongly with the magnitude and Galactic latitude of the *Kepler* target star, and more weakly with transit depth. We establish that a single deep high-resolution image may be an extremely effective follow-up tool for shallow transit signals. By reducing the radius around the target star where a blend might exist, the false positive probability of an earth-sized transit around a faint star decreases from >20% to <2%, assuming a continuous power law for the planet mass function with index $\alpha = -1.5$. Since *Kepler* will detect many more planetary signals than can be positively confirmed with ground-based follow-up efforts in the near term, these calculations will be crucial to using the ensemble of *Kepler* data to determine population characteristics of planetary systems.

"We find that the false positive probability for candidates that pass preliminary Kepler vetting procedures is generally <10% and often <5%,"

Gallery of Candidate Multiply-Transiting Planetary Systems



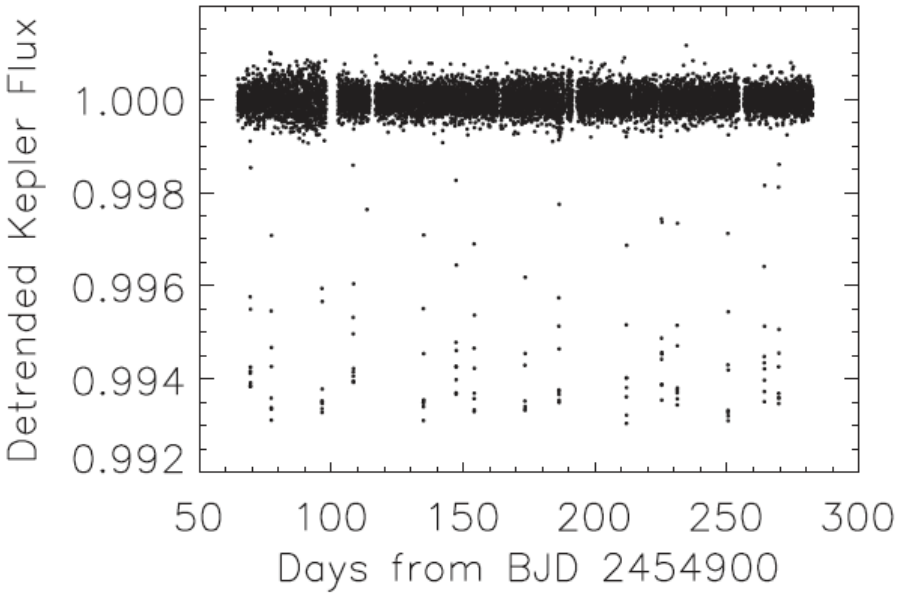
Kepler-9

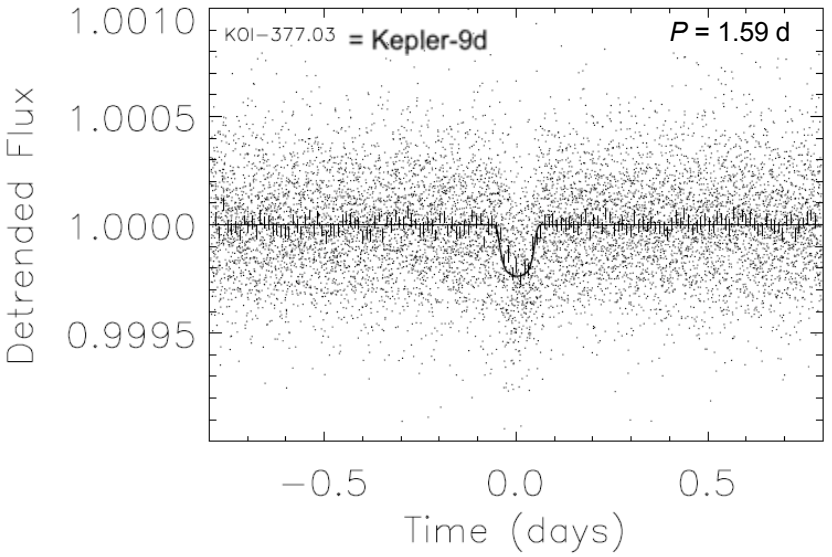


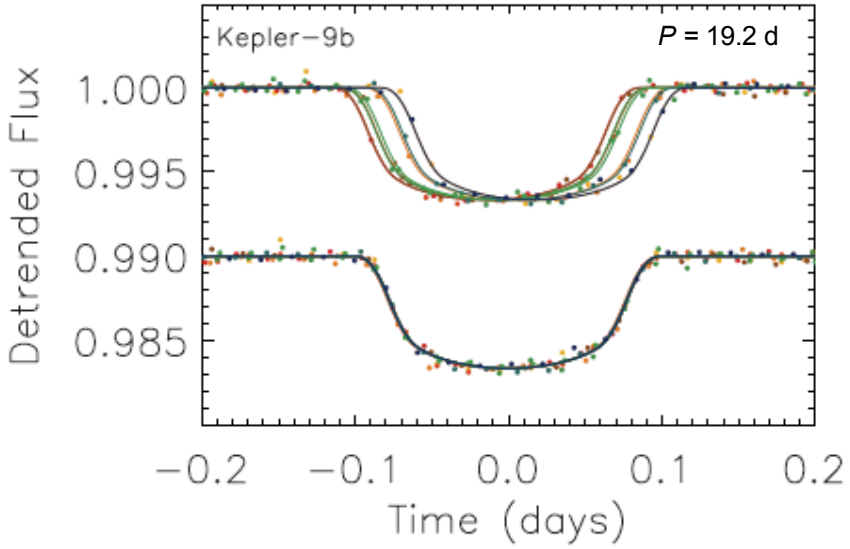
Holman, Fabrycky, Ragozzine et al. 2010

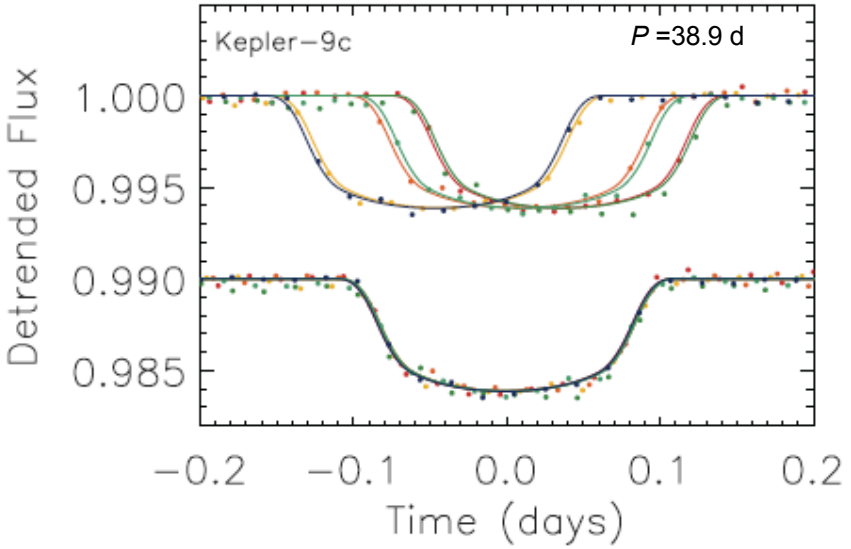
Kepler-9 b/c/d

Ragozzine

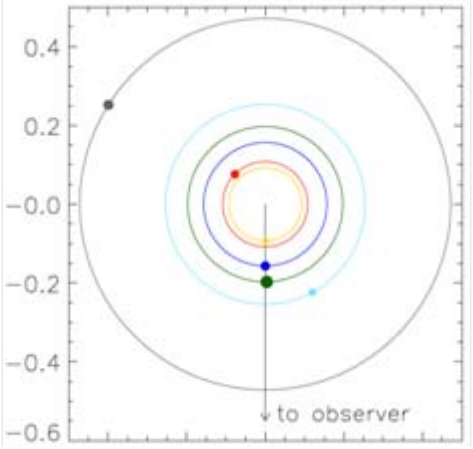


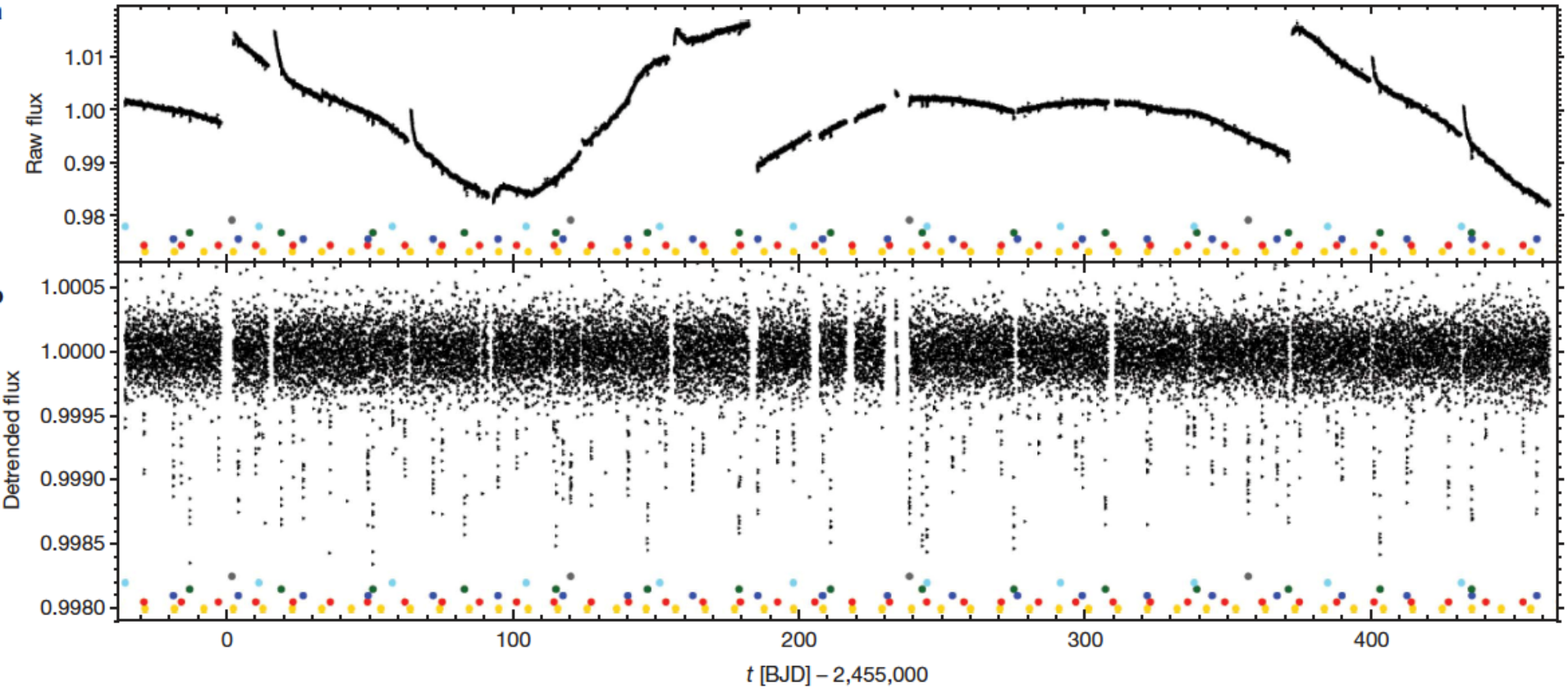




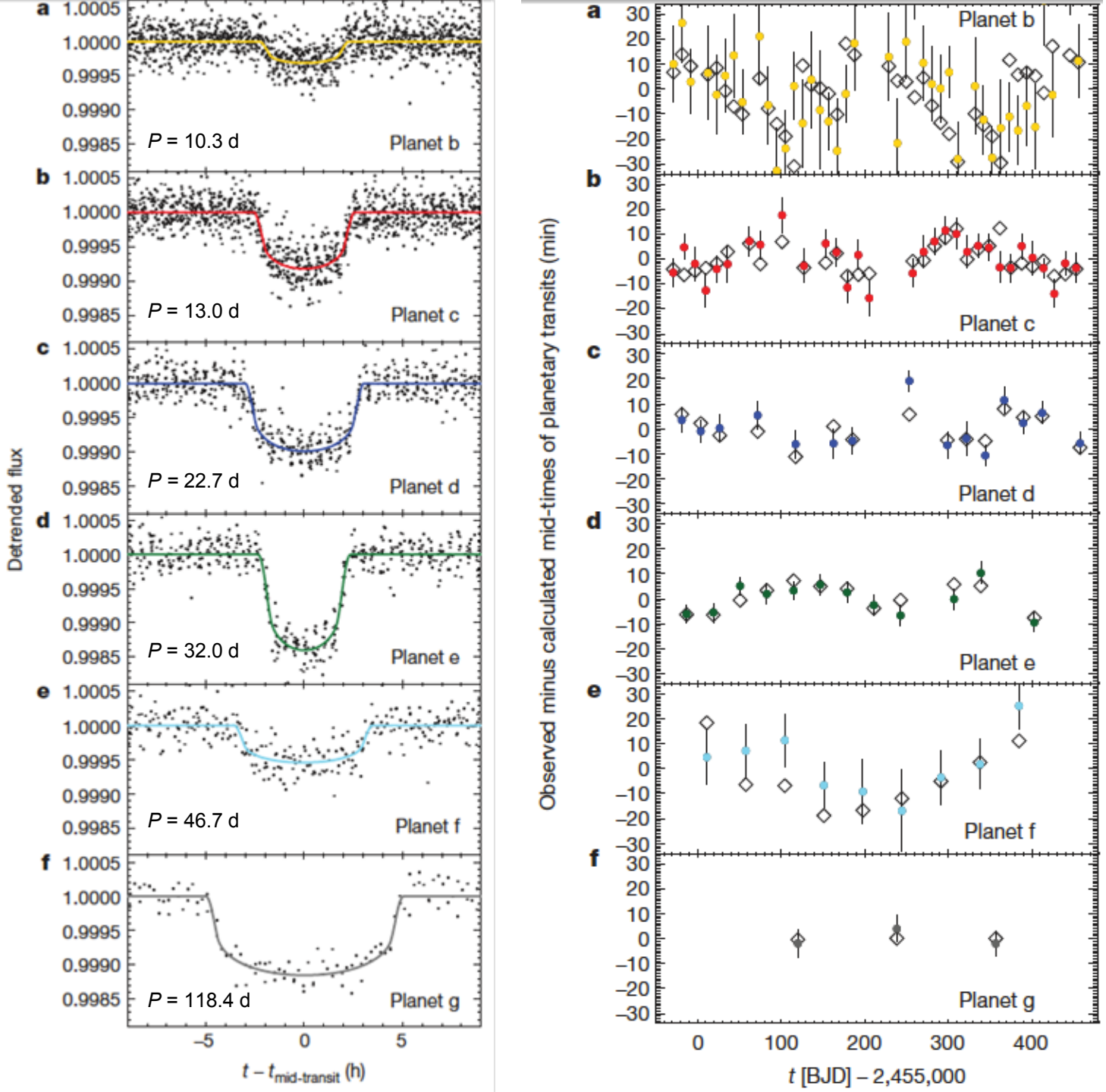


Kepler-11





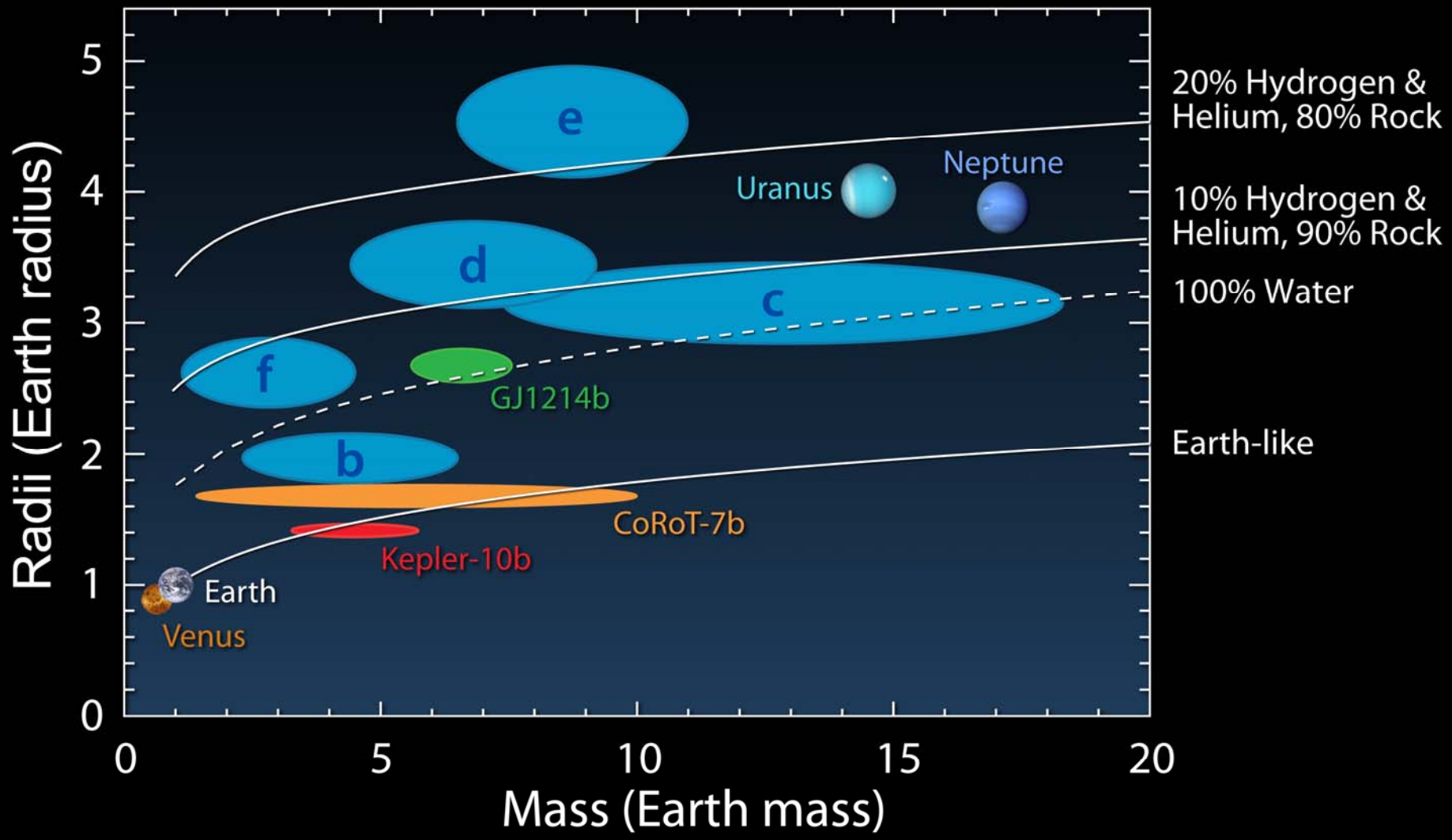
Lissauer, Fabrycky, Ford et al. 2011


a
b
c
d
e
f
Detrended flux
1.0005
1.0000
0.9995
0.9990
0.9985
P = 10.3 d
Planet b
P = 13.0 d
Planet c
P = 22.7 d
Planet d
P = 32.0 d
Planet e
P = 46.7 d
Planet f
P = 118.4 d
Planet g
–5
0
5
t – t mid-transit (h)
Observed minus calculated mid-times of planetary transits (min)
30
20
10
0
–10
–20
–30
Planet b
Planet c
Planet d
Planet e
Planet f
Planet g
0
100
200
300
400
t [BJD] – 2,455,000

Kepler-11 parameters

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

Composition of Kepler-11 Planets

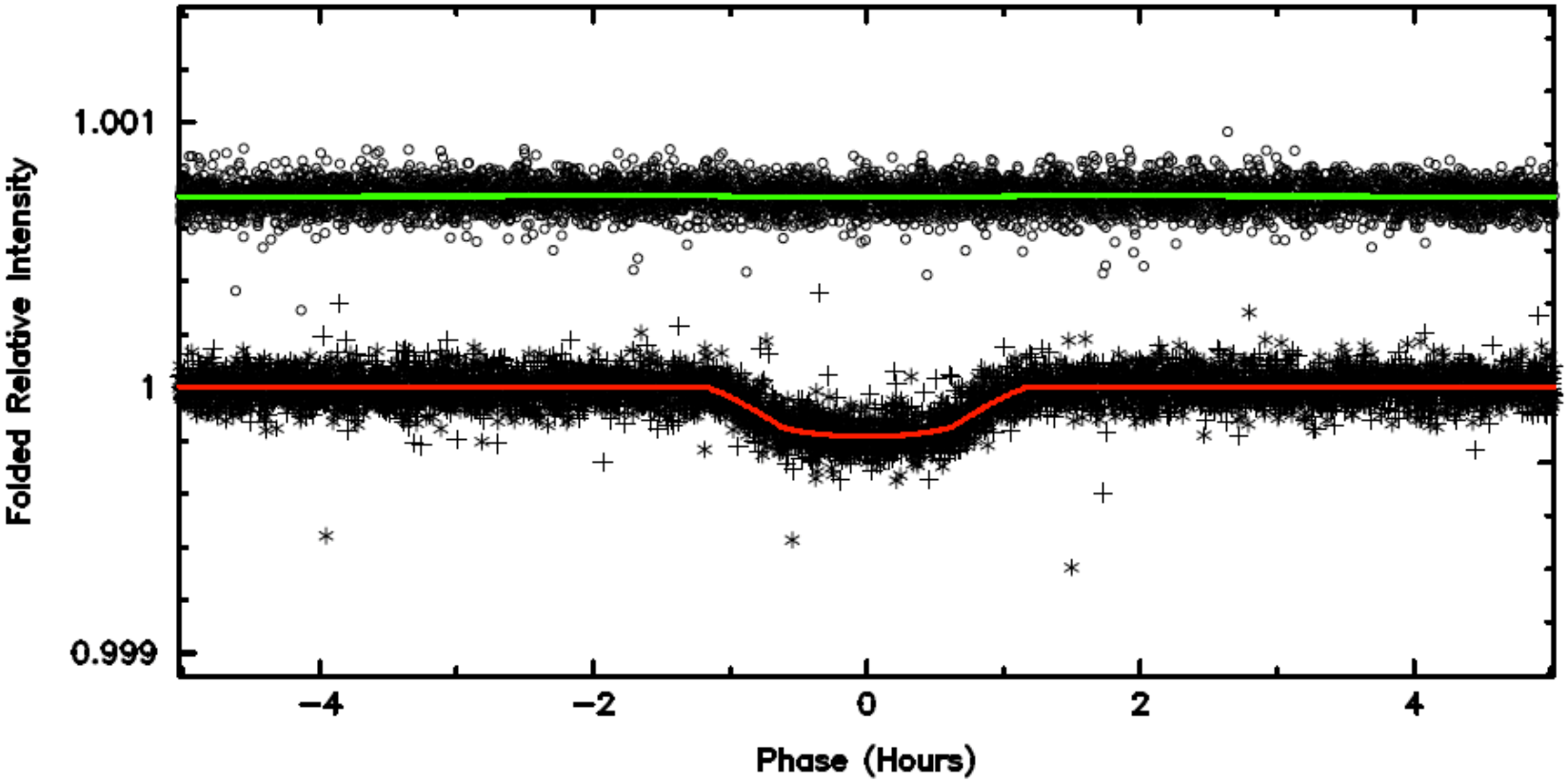


Summary

- Kepler-11 is a surprisingly flat system of six planets.
- The five inner planets comprise the most closely-spaced planetary system known.
- The planets are mid-sized: 2-5 times as large as Earth.
- Most have low densities, implying mixtures of solids and light gases.

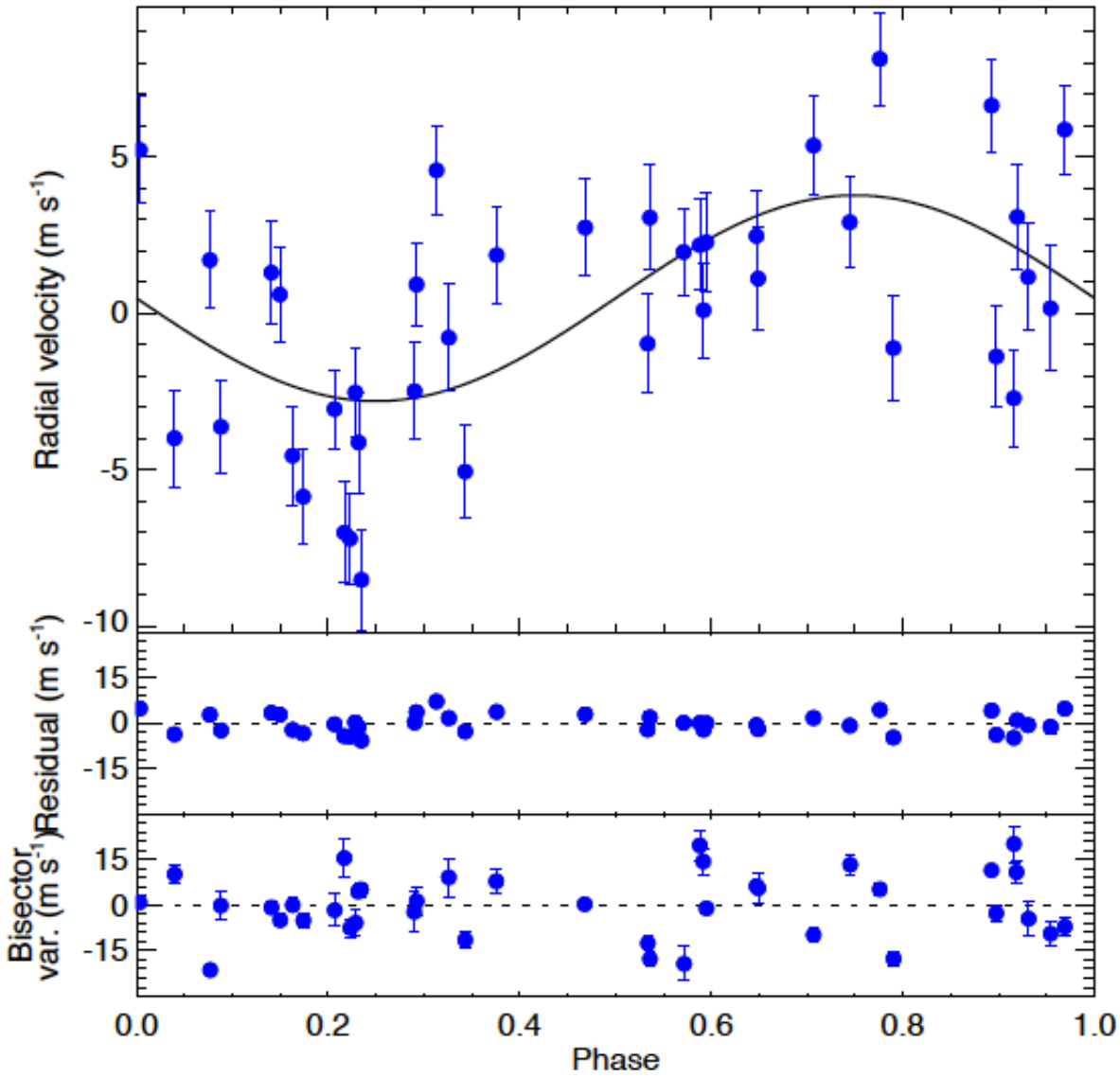
Kepler-10: Kepler hits solid ground

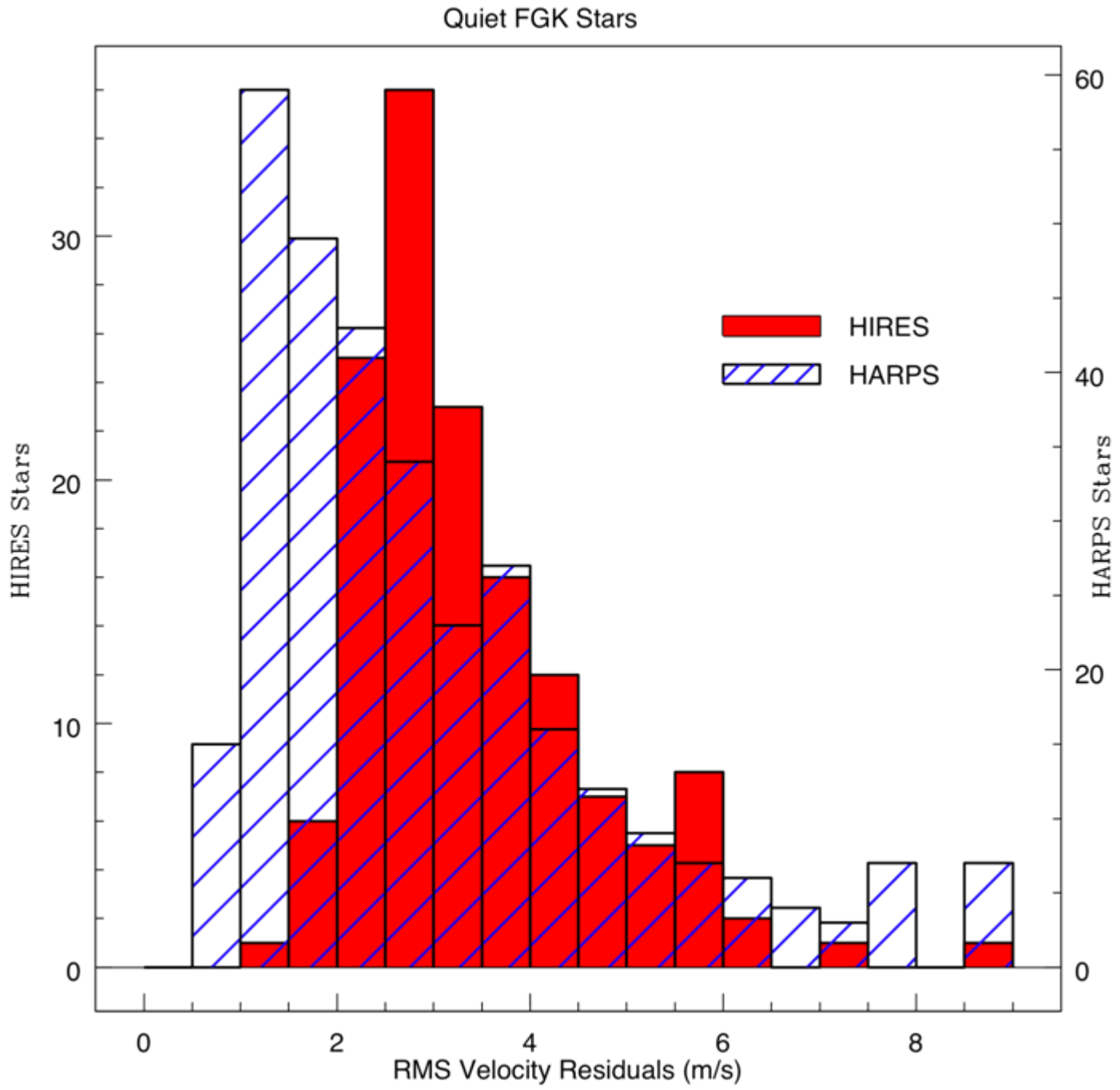
- Batalha et al. 2011, ApJ, 729, 27
- Bright enough (Kp=11) for good spectroscopy
- A multiplanet host: a second candidate at 45.3 days
- Period = 0.84 d



Orbital Solution – Keck HIRES

- R_p = 1.4 R_E
- M_p = 4.6 M_E
- Density = 9 g/cm^3
- Period = 0.84 d
- 11th Kepler mag
- Quiet G dwarf
- Near HIRES limit
- Need HARPS-N
- TTVs may be the best way to confirm small planets in HZ




Quiet FGK Stars
HIRES
HARPS
HIRES Stars
HARPS Stars
RMS Velocity Residuals (m/s)
0
10
20
30
0
20
40
60
0
2
4
6
8

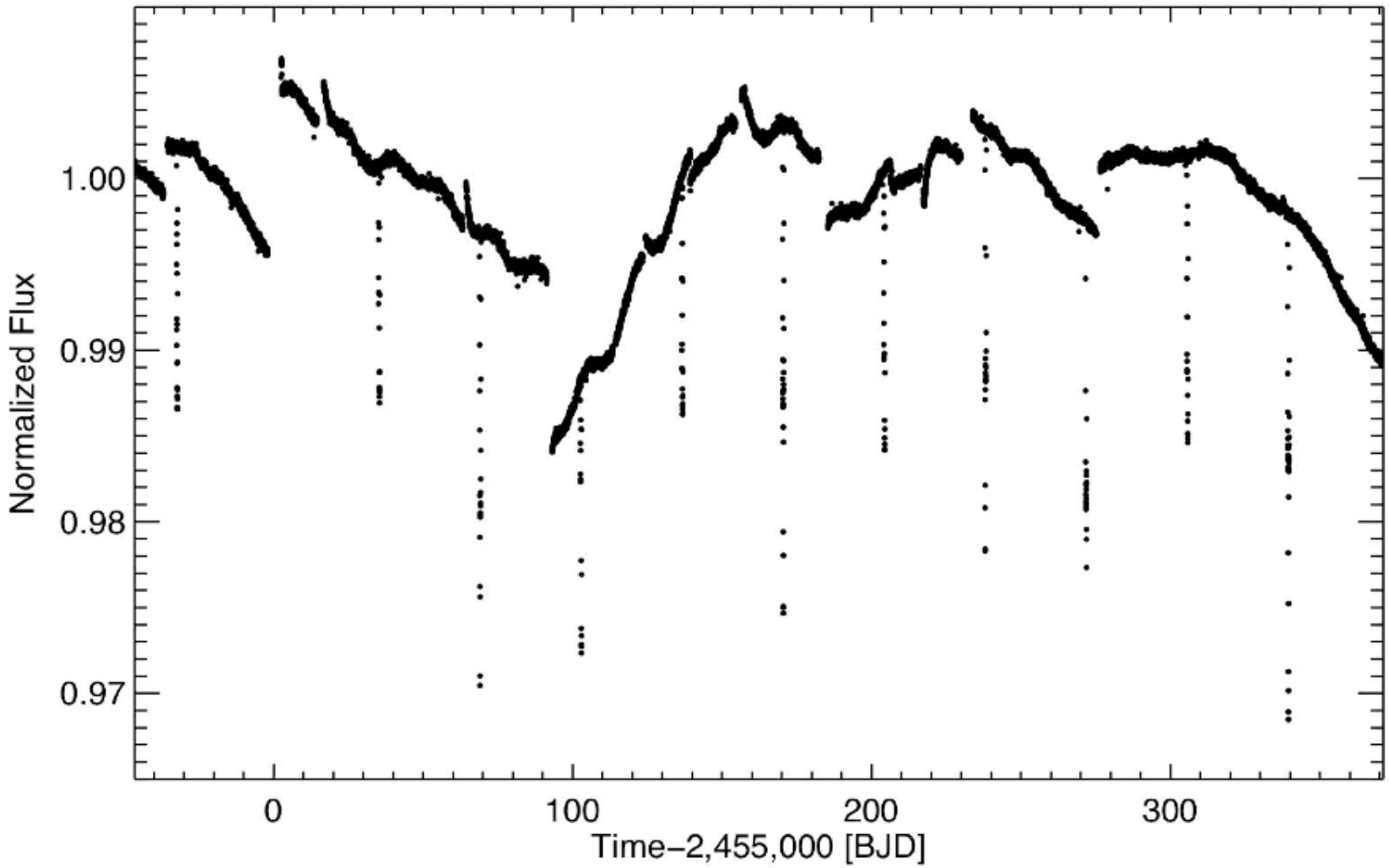
HARPS-N Collaboration


HARPS-N Collaboration:
Geneva, CfA, UK, INAF-TNG

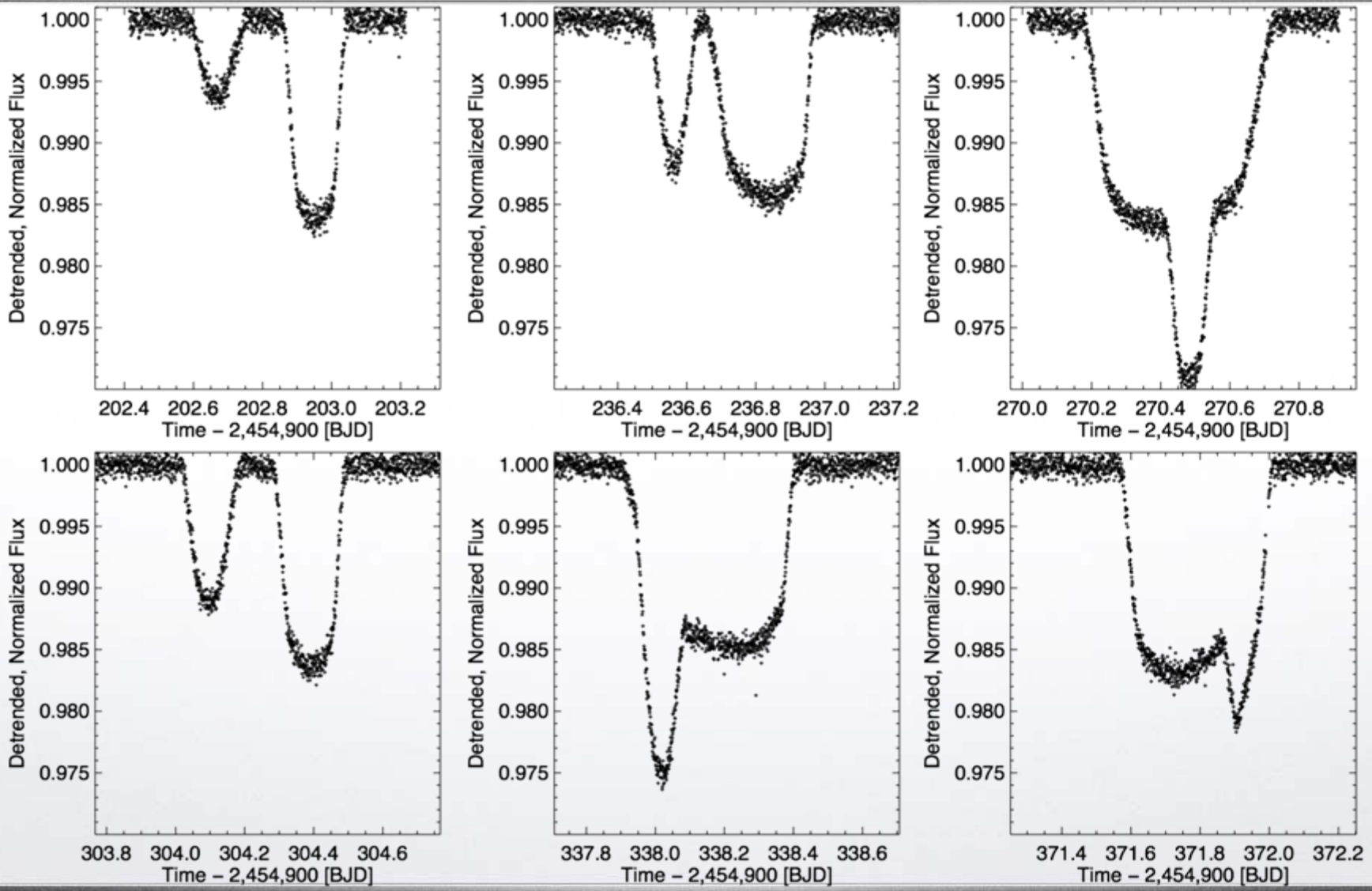
Eclipsing Hierarchical Triple with Two Low-Mass Stars

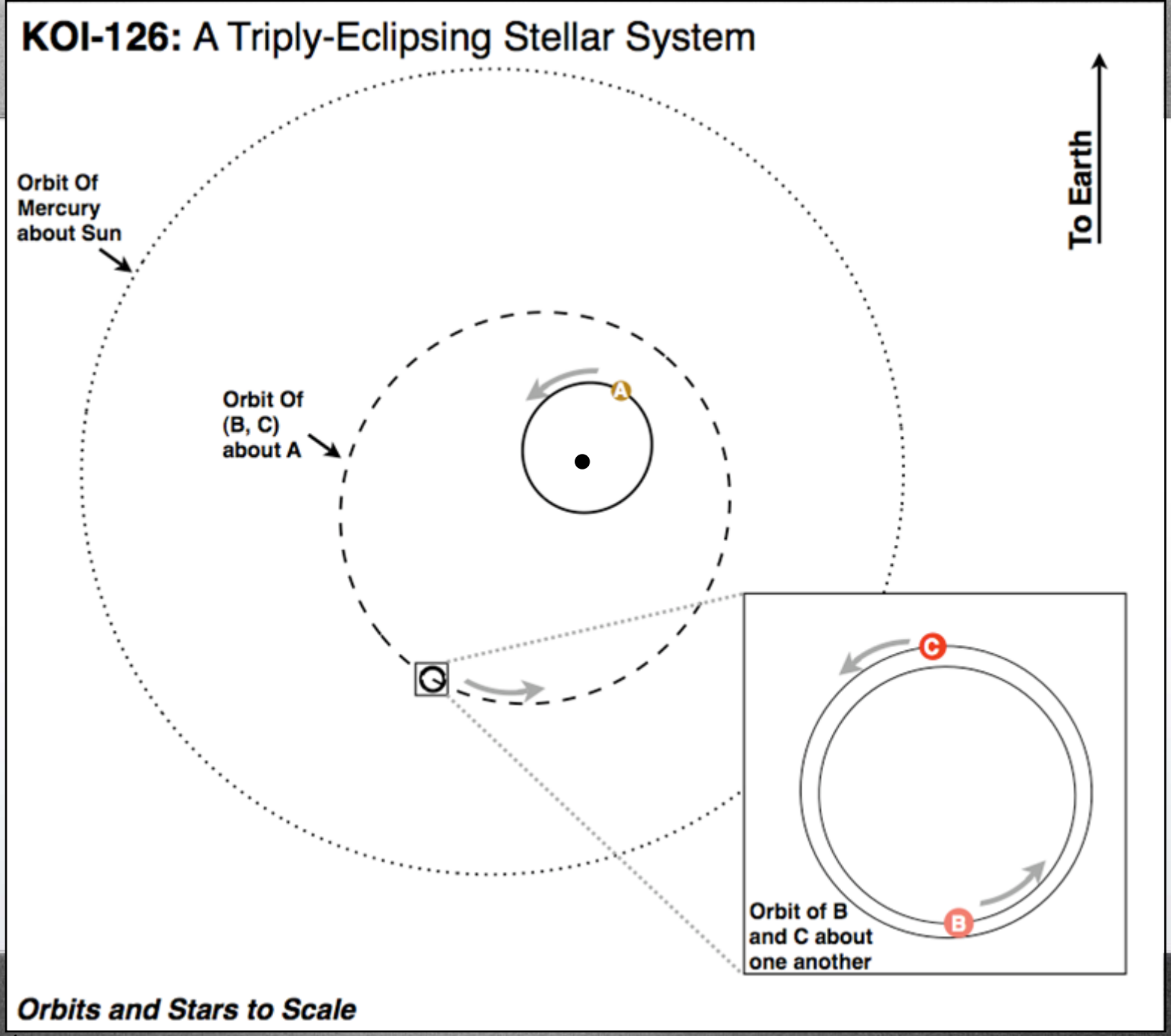
Josh Carter, Daniel Fabrycky, Darin Ragozzine, Matthew Holman, Sam Quinn, David Latham, Lars Buchhave, Jeffrey Van Cleve, William Cochran, Miles Cote, Michael Endl, Eric Ford, Michael Haas, Jon Jenkins, David Koch, Jie Li, Jack Lissauer, Phillip MacQueen, Christopher Middour, Jerome Orosz, Jason Rowe, Jason Steffen, William Welsh

“KOI-126:” Long Cadence Kepler Photometry

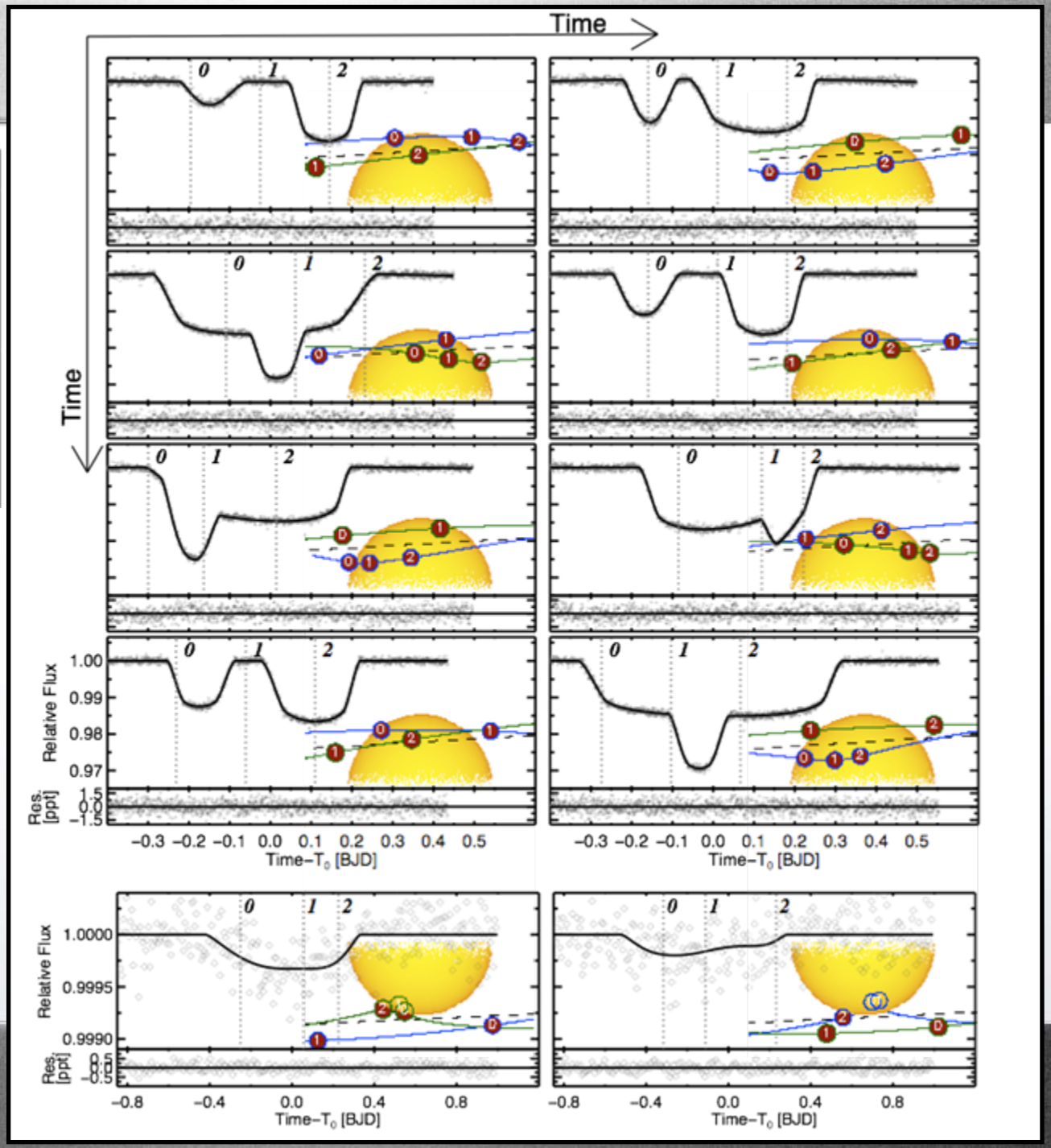


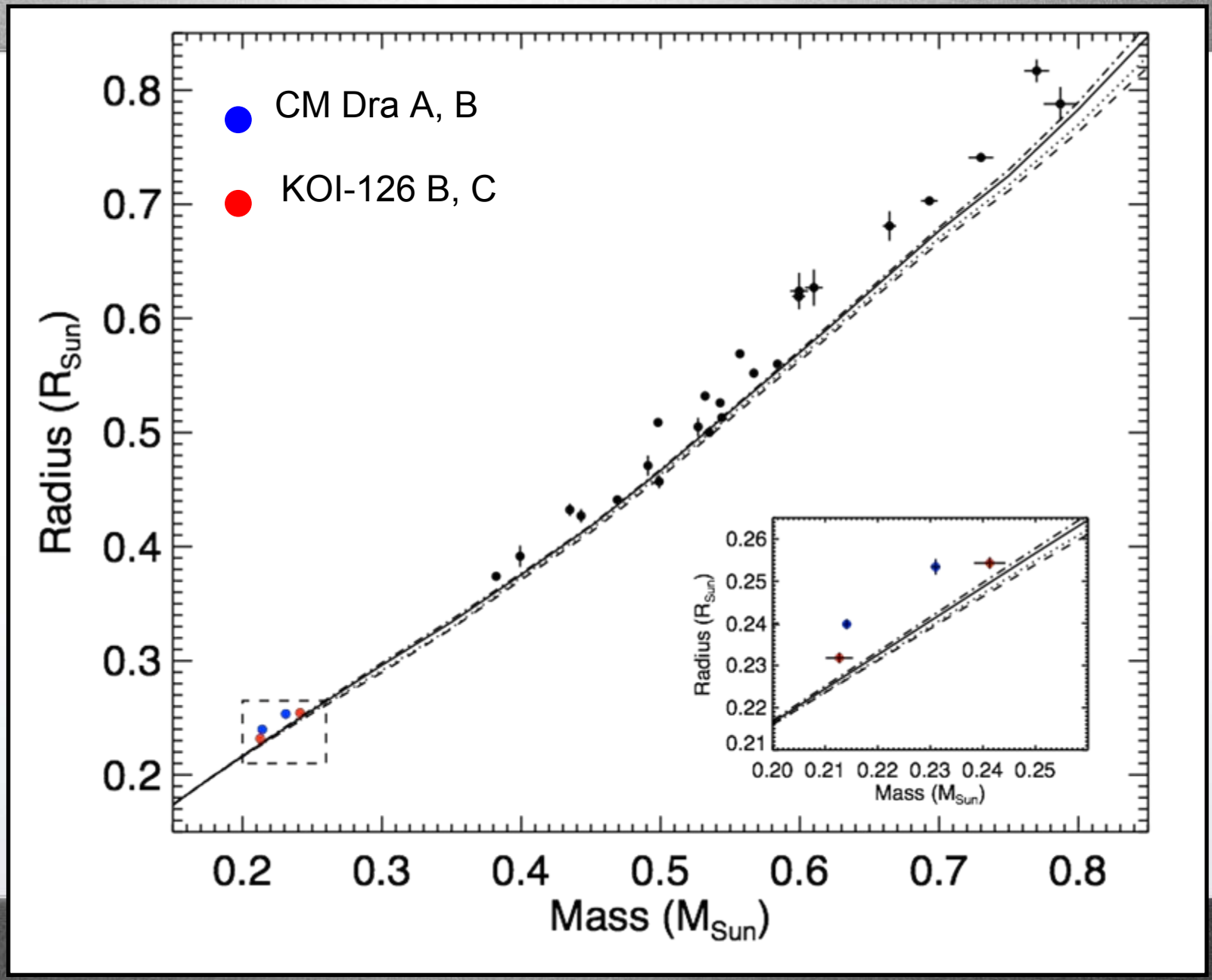
Short Cadence Kepler Photometry Near Events

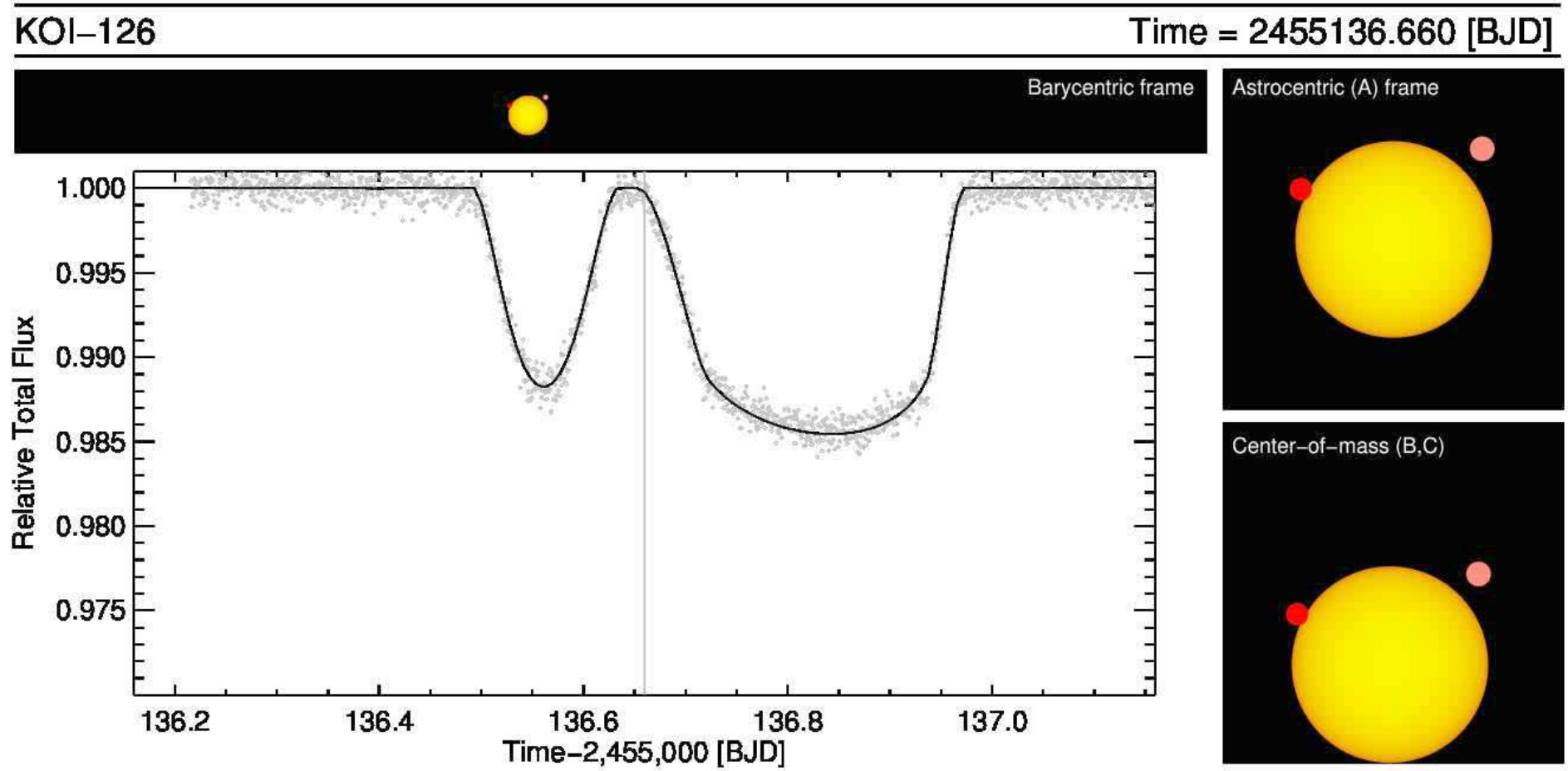



KOI-126: A Triply-Eclipsing Stellar System
Orbit Of Mercury about Sun
To Earth
Orbit Of (B, C) about A
A
C
B
Orbit of B and C about one another
Orbits and Stars to Scale

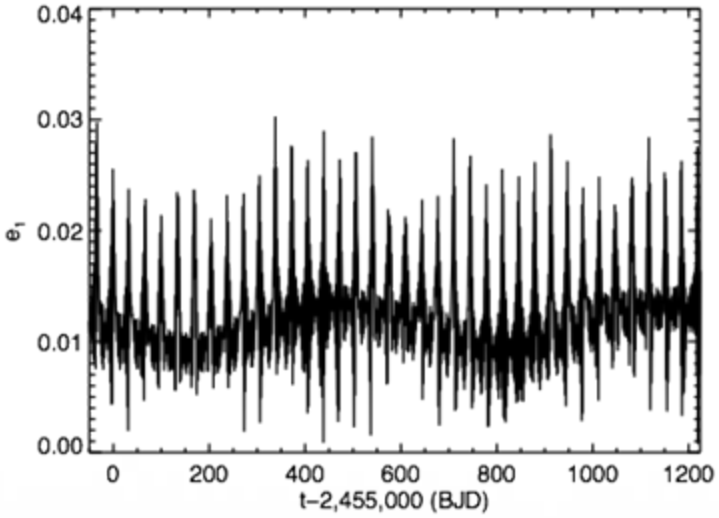
Parameter	Value
Masses	
M_A	$1.347 \pm 0.032\ M_\odot$
M_B	$0.2413 \pm 0.0030\ M_\odot$
M_C	$0.2127 \pm 0.0026\ M_\odot$
Radii	
R_A	$2.0254 \pm 0.0098\ R_\odot$
R_B	$0.2543 \pm 0.0014\ R_\odot$
R_C	$0.2318 \pm 0.0013\ R_\odot$

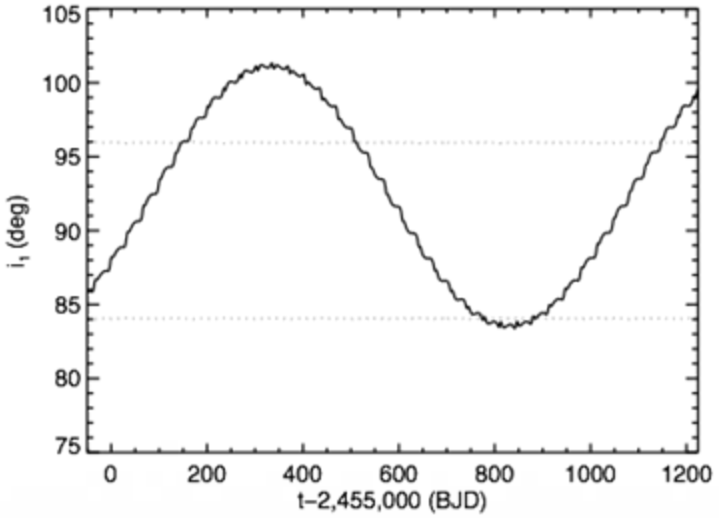


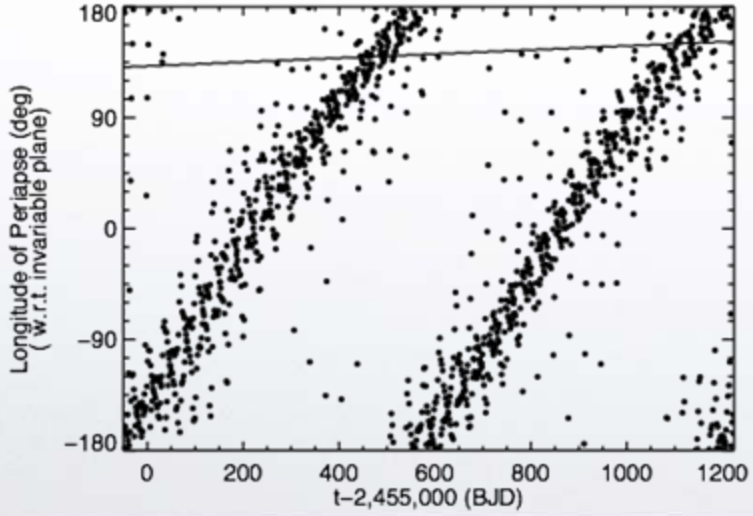

CM Dra A, B
KOI-126 B, C
Radius (R_{Sun})
Mass (M_{Sun})
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.21
0.22
0.23
0.24
0.25
0.26
0.20 0.21 0.22 0.23 0.24 0.25

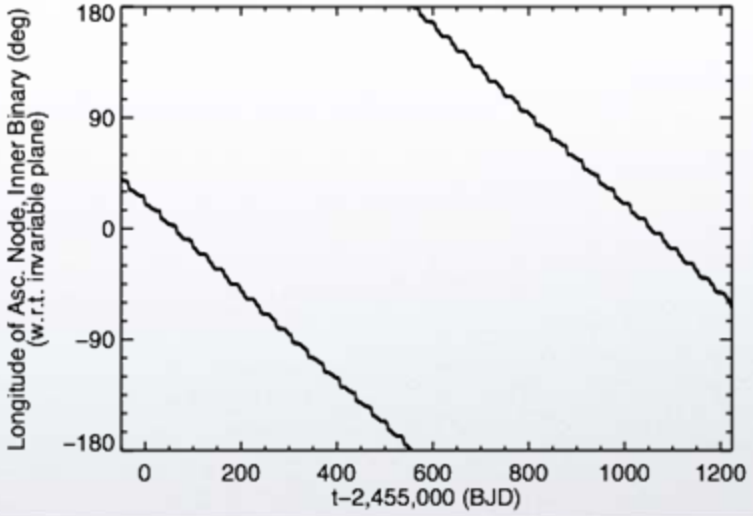

KOI–126
Time = 2455136.660 [BJD]
Barycentric frame
Astrocentric (A) frame
Center–of–mass (B,C)
Relative Total Flux
1.000
0.995
0.990
0.985
0.980
0.975
136.2
136.4
136.6
136.8
137.0
Time–2,455,000 [BJD]

Evolution of Keplerian Orbital Elements





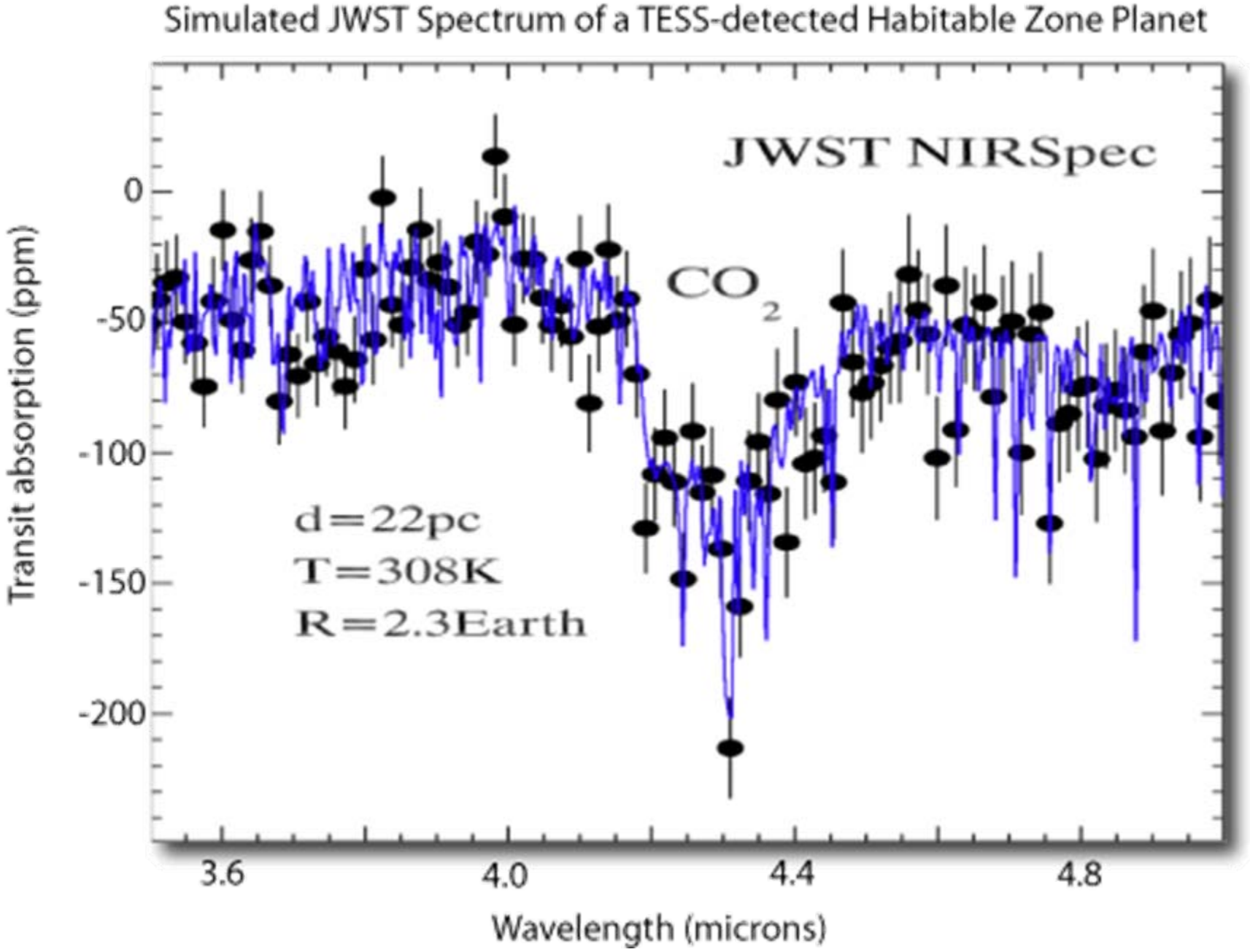




TESS (SMEX version shown here)

Transiting Exoplanet Survey Satellite

Explorer proposal submitted last week. New partners, more capable mission.



Drake Deming