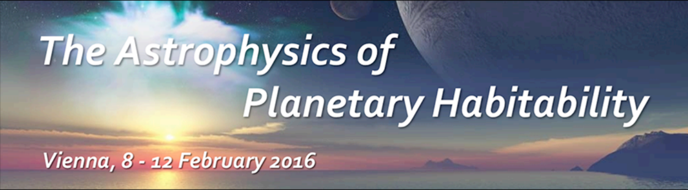
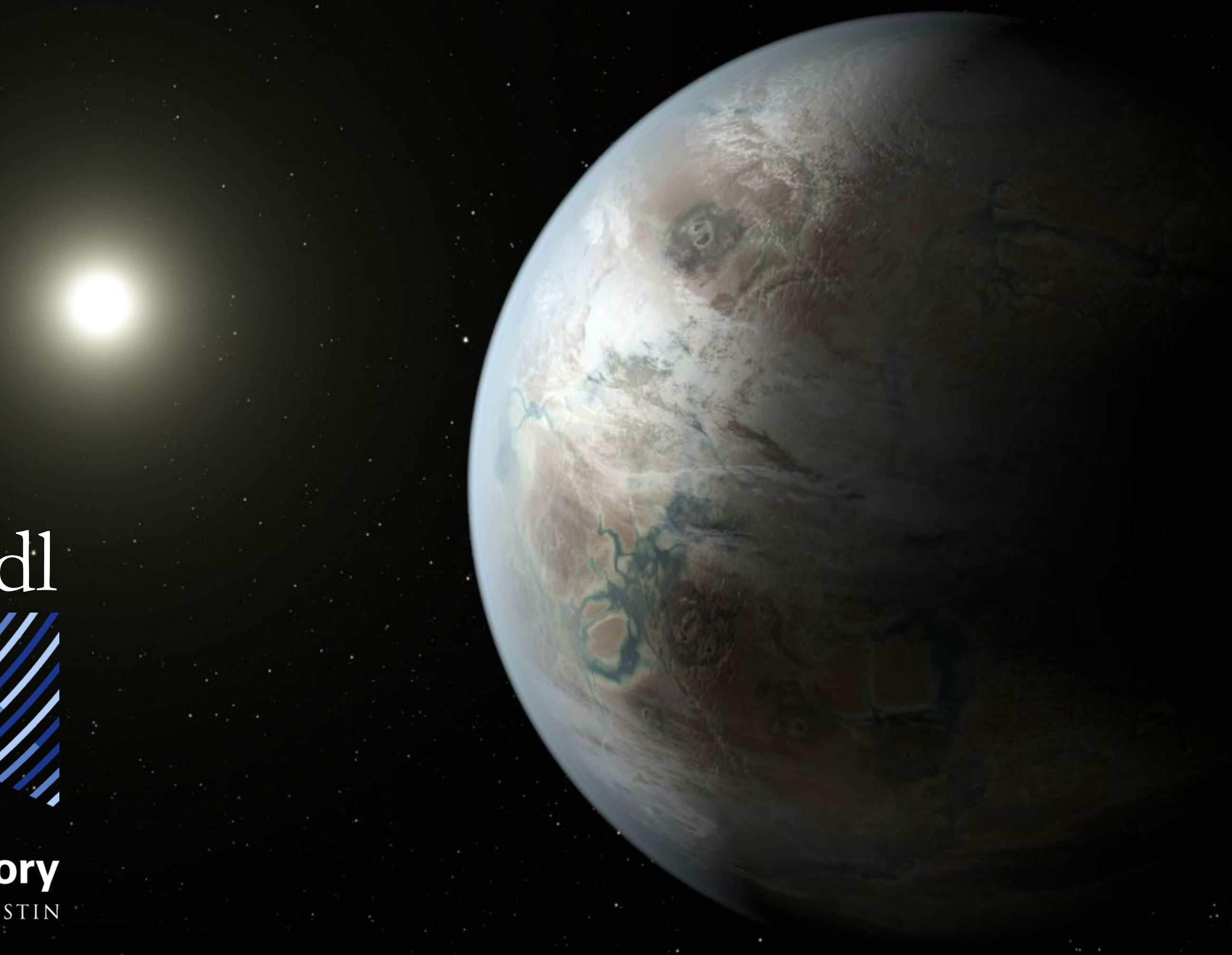


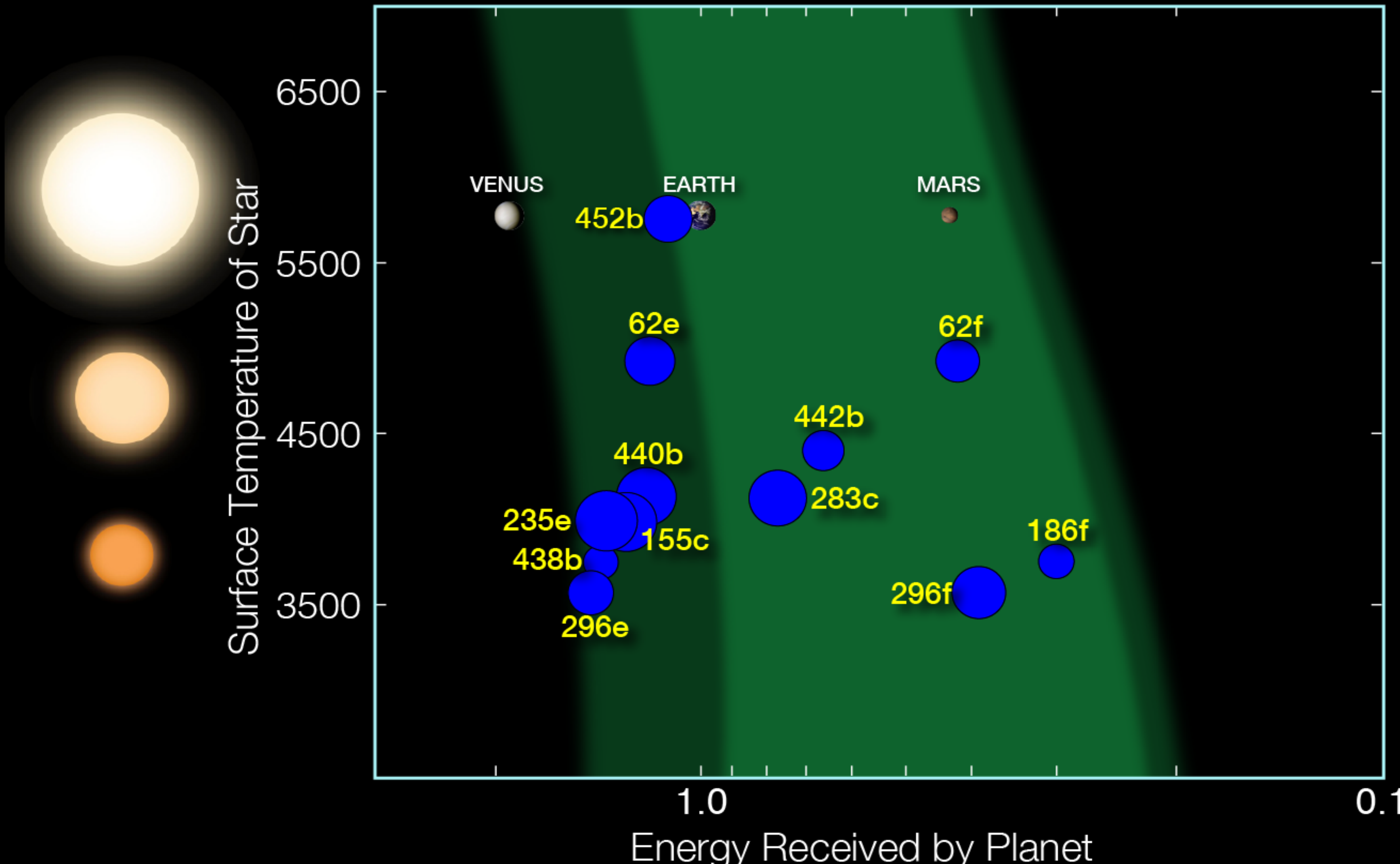
Characterization of the Kepler-452 system, the (currently) closest analog to the Sun-Earth system.



Michael Endl

McDonald Observatory
THE UNIVERSITY OF TEXAS AT AUSTIN

Kepler's Small HZ Exoplanets



The Astronomical Journal, 150:56 (19pp), 2015 August doi:10.1088/0004-6256/150/2/56

DISCOVERY AND VALIDATION OF Kepler-452b: A 1.6 $R_{\oplus}$ SUPER EARTH EXOPLANET IN THE HABITABLE ZONE OF A G2 STAR

Jon M. Jenkins[1], Joseph D. Twicken[1,2], Natalie M. Batalha[1], Douglas A. Caldwell[1,2], William D. Cochran[3], Michael Endl[3], David W. Latham[4], Gilbert A. Esquerdo[4], Shawn Seader[1,2], Allyson Bieryla[4], Erik Petigura[5], David R. Ciardi[6], Geoffrey W. Marcy[5], Howard Isaacson[5], Daniel Huber[2,7,8], Jason F. Rowe[1,2], Guillermo Torres[4], Stephen T. Bryson[1], Lars Buchhave[4,9], Ivan Ramirez[3], Angie Wolfgang[10], Jie Li[1,2], Jennifer R. Campbell[11], Peter Tenenbaum[1,2], Dwight Sanderfer[1], Christopher E. Henze[1], Joseph H. Catanzarite[1,2], Ronald L. Gilliland[12], and William J. Borucki[1]

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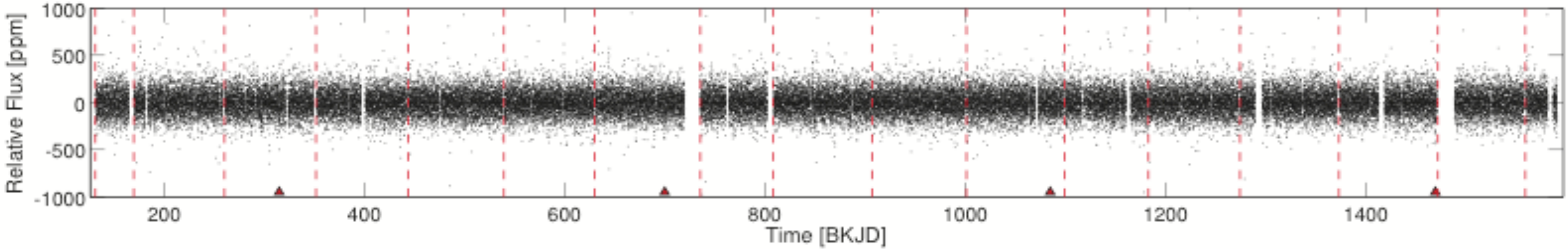
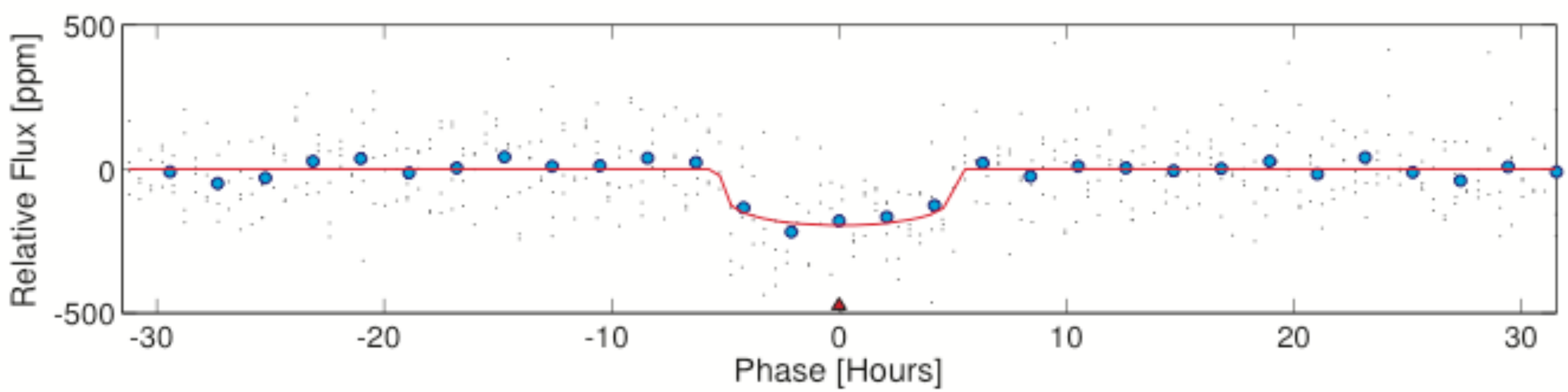
Received 2015 March 3; accepted 2015 May 23; published 2015 July 23

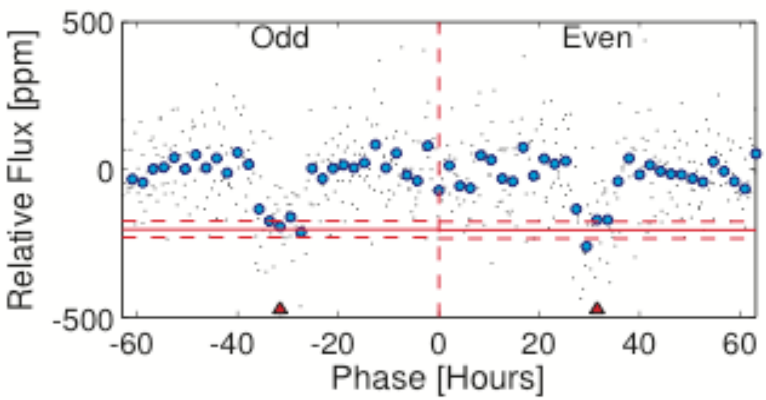
Discovery & Follow-up:

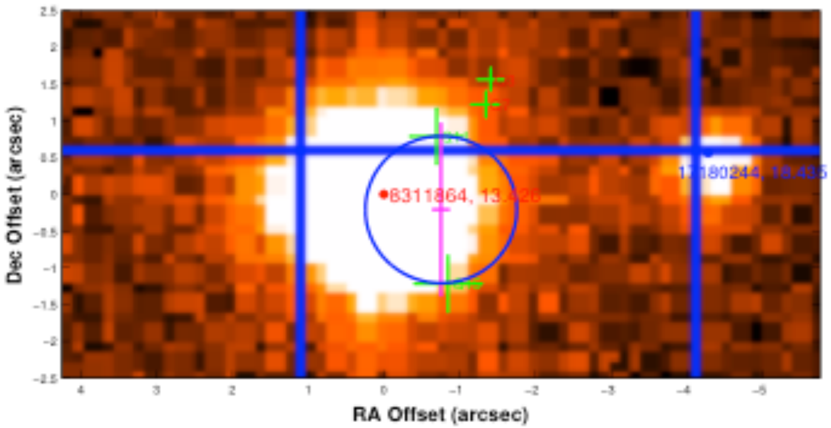
- Kepler-452b was discovered in a test run of the *Kepler* Science Operations Center (SOC) 9.2 codebase in 2014 May when one of us (J. Twicken) inspected the planet search pipeline results to assess performance of an enhanced pipeline codebase for small, cool planets.

Kepler Light Curve with P = 385 d!









Discovery & Follow-up:

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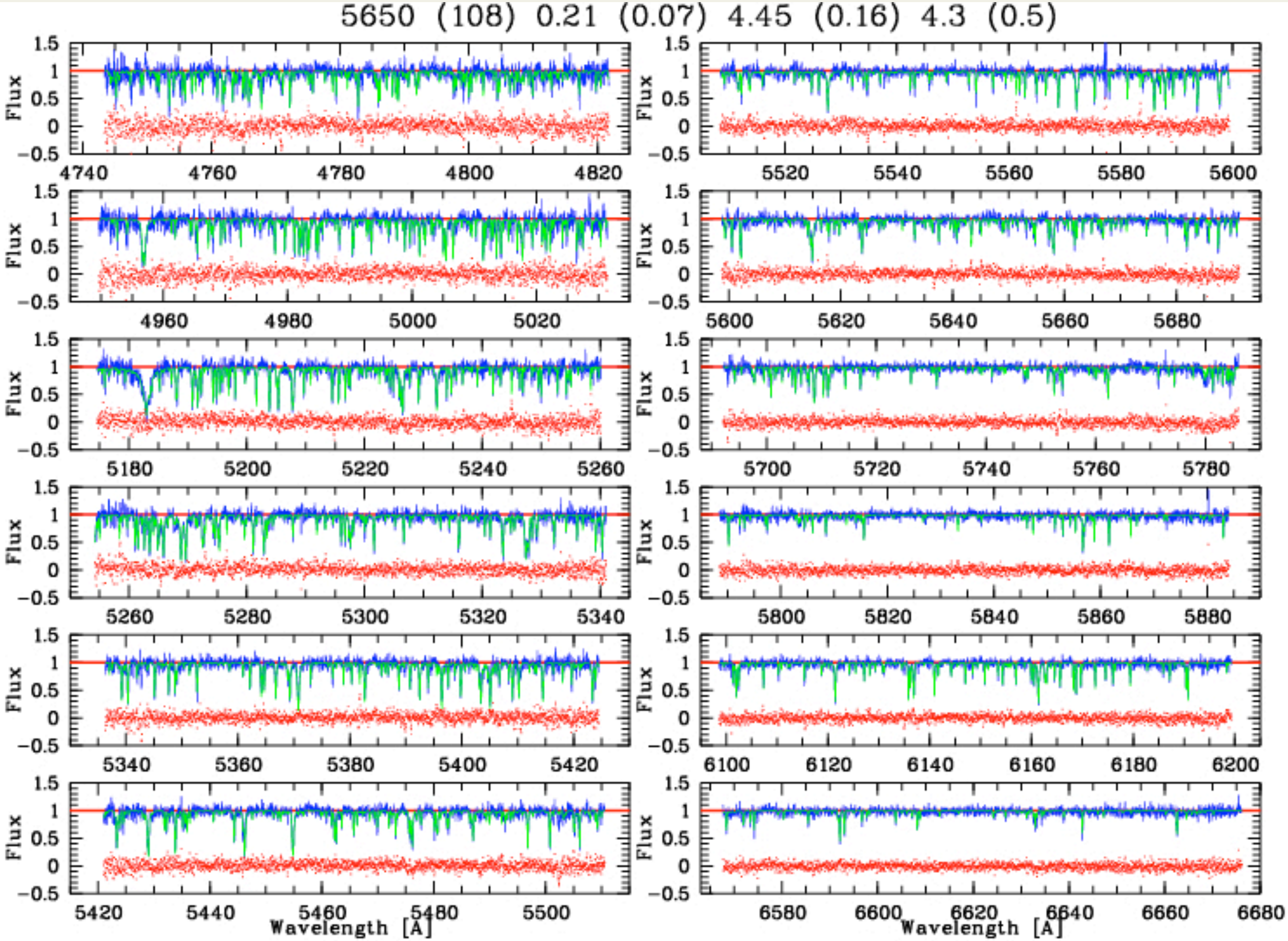
- McDonald Observatory first 2.7 m recon spectrum: May 2014

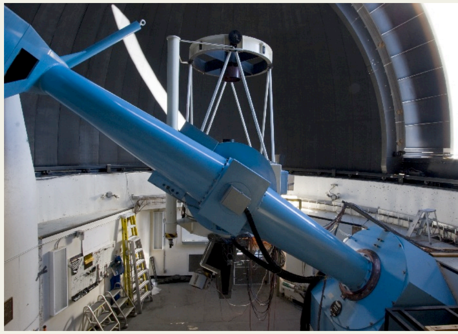

McDonald Observatory 2.7 m telescope

McDonald Observatory recon spectrum: 18 May 2014 S/N=31 (V=13.4)

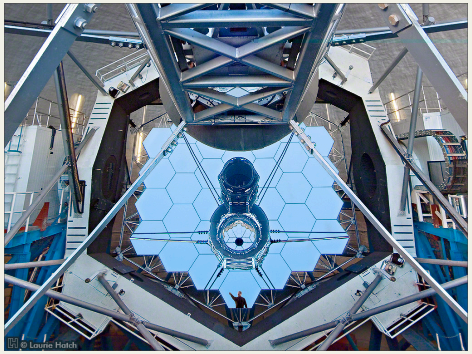


Discovery & Follow-up:

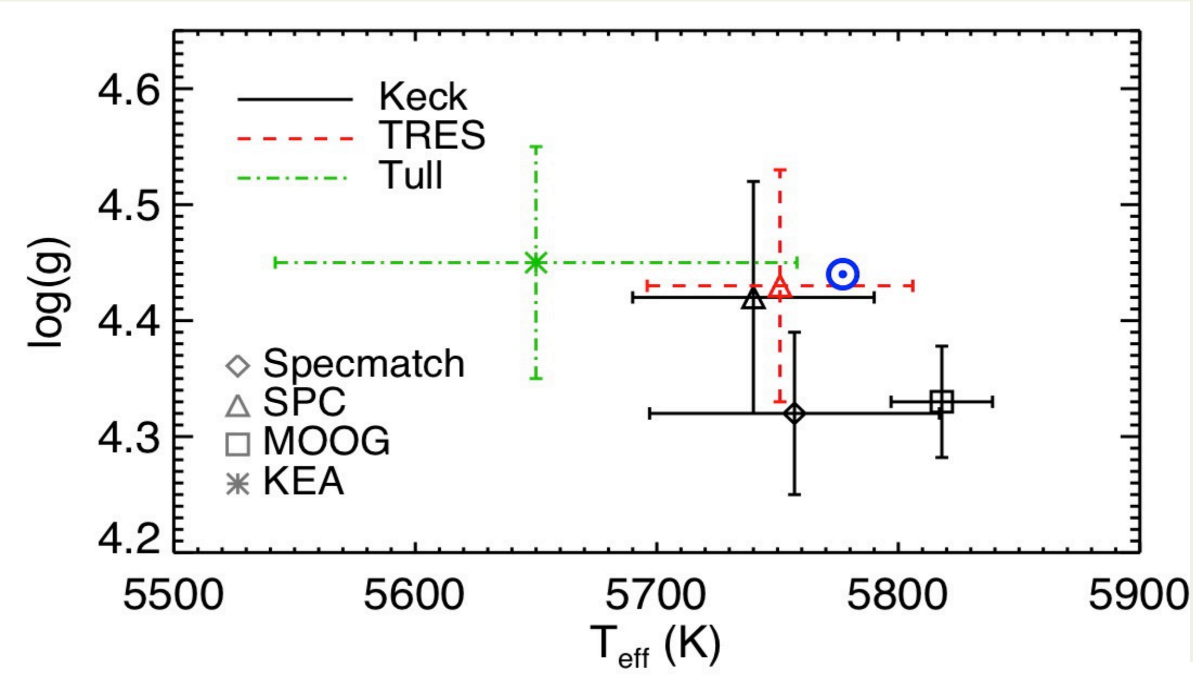
- Kepler-452b was discovered in a test run of the *Kepler* Science Operations Center (SOC) 9.2 codebase in 2014 May when one of us (J. Twicken) inspected the planet search pipeline results to assess performance of an enhanced pipeline codebase for small, cool planets.
- McDonald Observatory first 2.7 m recon spectrum: May 2014
- Whipple Observatory 1.5 m (TRES) 2 recons in June 2014
- Keck/NIRC2 AO-imaging in June 2014 (=> no nearby star)
- Keck/HIRES "high" S/N recon spectrum: July 2014

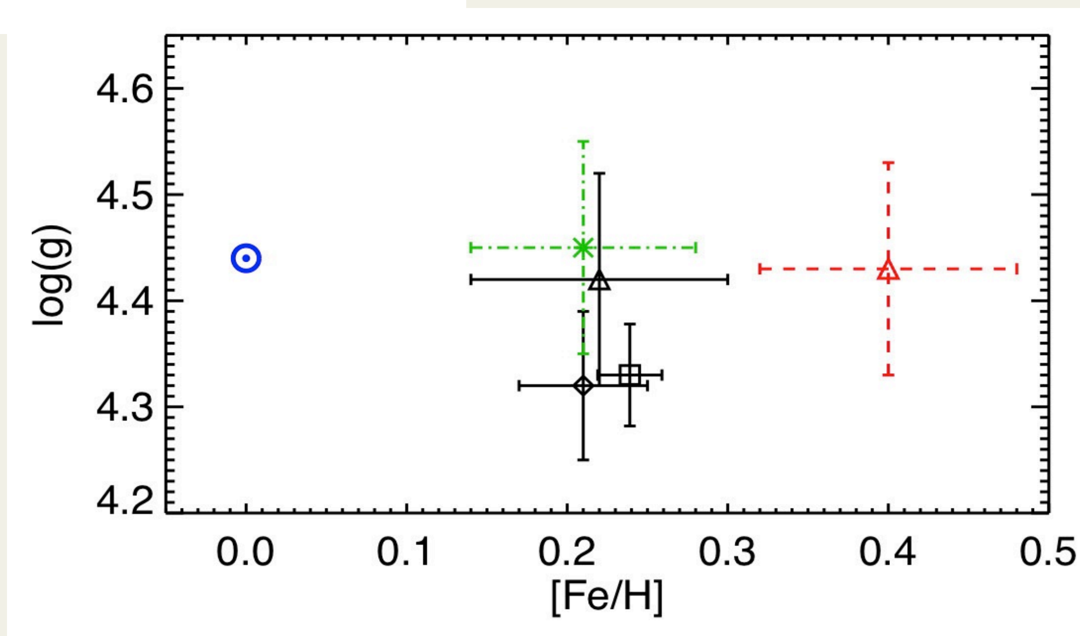


McDonald Observatory 2.7 m telescope

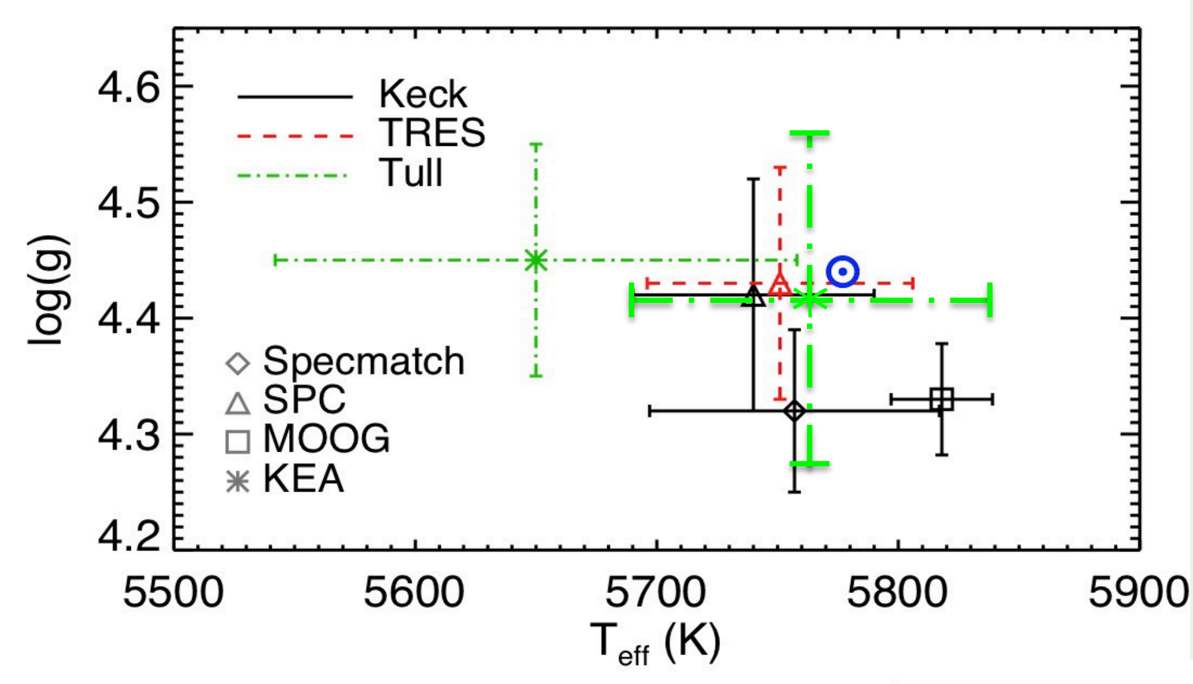


The "Battle of Spectroscopy":

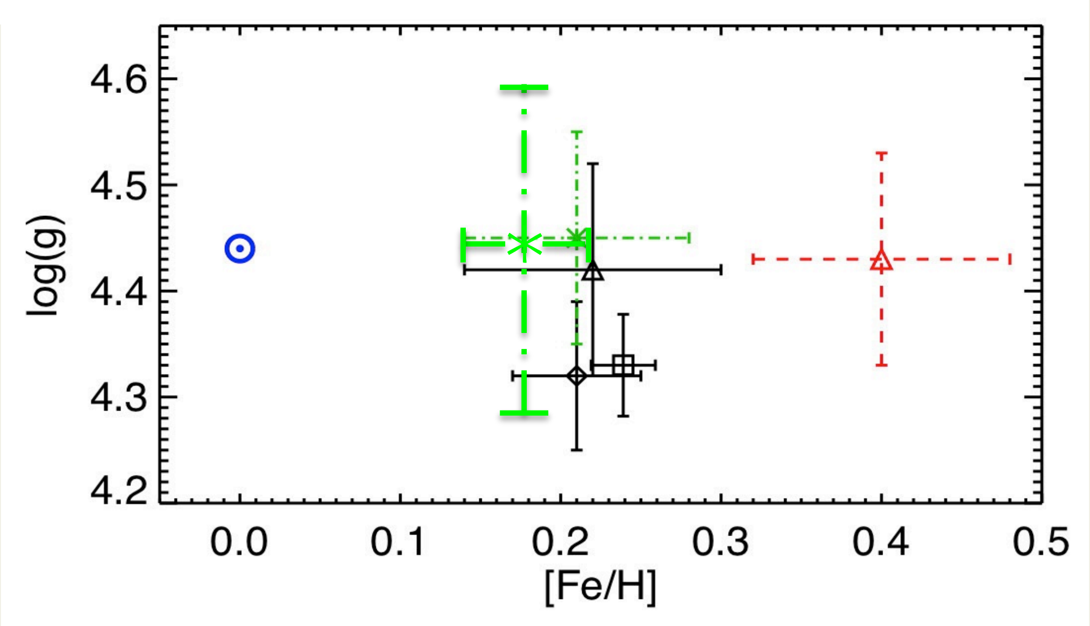




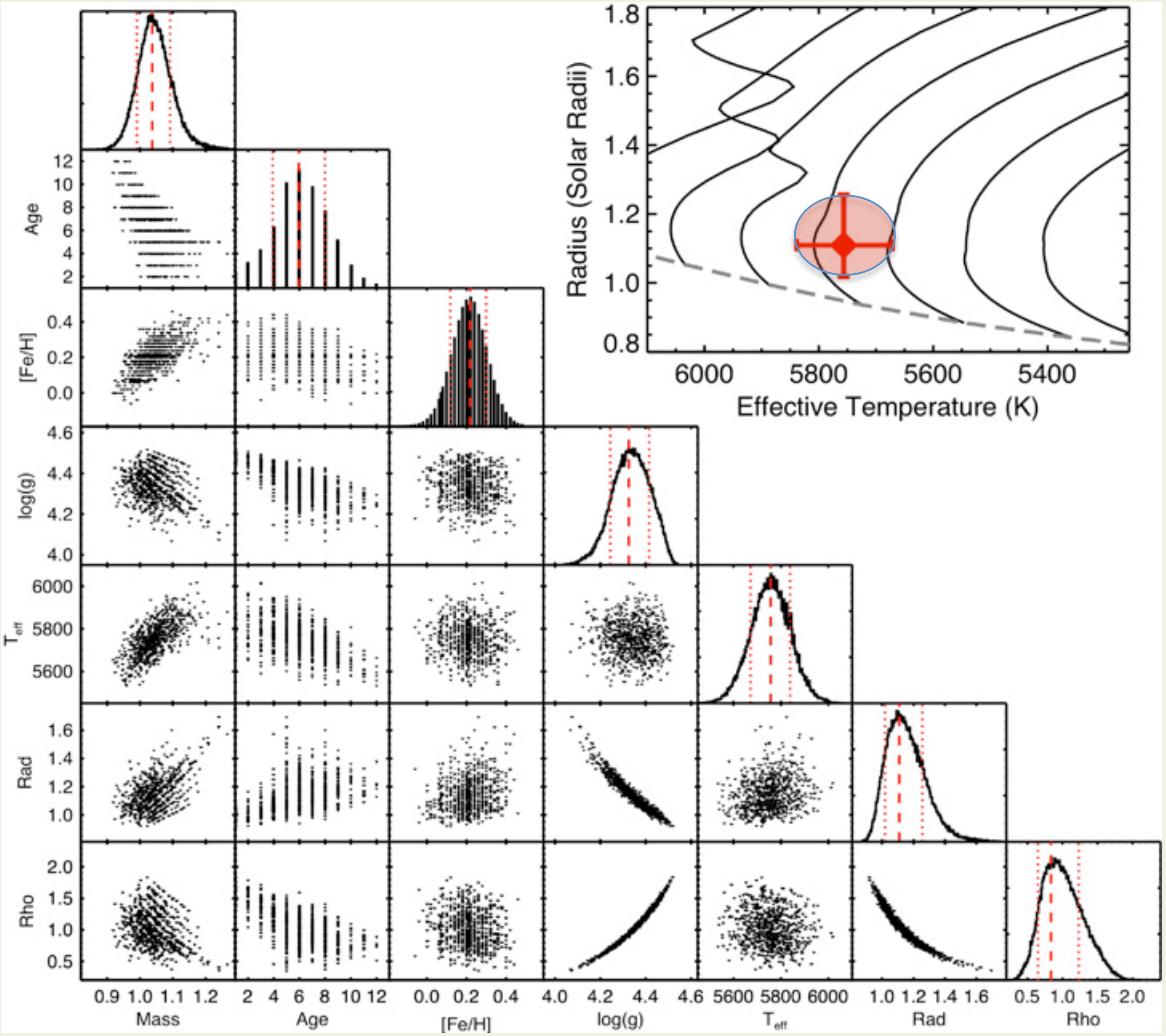
The “Battle of Spectroscopy”:



Absolute RV (-25km/s) stayed the same!



Stellar Properties:



To derive stellar properties: fitted T_{eff} , log *g*, and [Fe/H] to a grid of **Dartmouth isochrones** (Dotter et al. 2008), also compared to **Yonsei-Yale isochrones** (Yi et al. 2004)

$R_* = 1.1 \pm 0.15\ R_{sun}$

$M_* = 1.037 \pm 0.05\ M_{sun}$

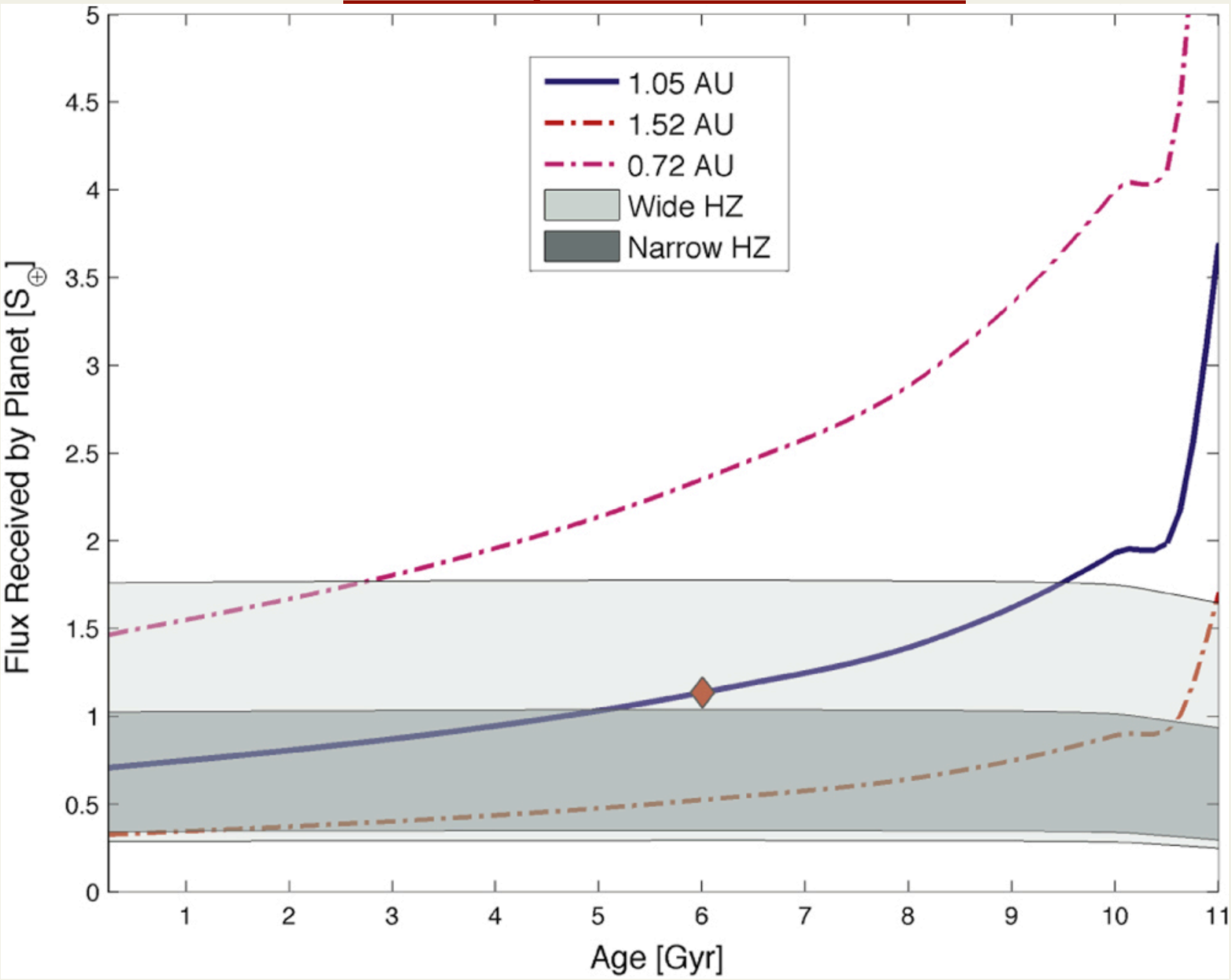
$\rho_* = 0.84 \pm 0.04\ g\ cm^{-3}$

Age ~ 6 ± 2 Gyr

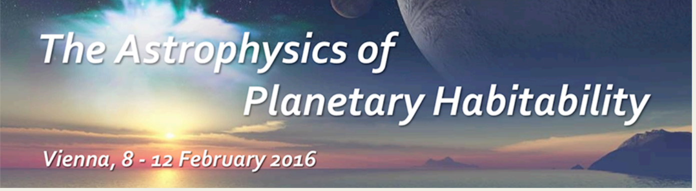
Planetary Properties:

Parameter	Value
Transit and orbital parameters	
Orbital period P (day)	$384.843^{+0.007}_{-0.012}$
Epoch (BJD—2454833)	$314.985^{+0.015}_{-0.019}$
Scaled planet radius $R_P/R_\star$	$0.0128^{+0.0013}_{-0.0006}$
Impact parameter $b \equiv a \cos i/R_\star$	$0.69^{+0.16}_{-0.45}$
Orbital inclination i (deg)	$89.806^{+0.134}_{-0.049}$
Transit depth T_{dep} (ppm)	199^{+18}_{-21}
Transit duration T_{dur} (hr)	$10.63^{+0.53}_{-0.60}$
Eccentricity $e \cos(\omega)$	$0.03^{+0.75}_{-0.39}$
Eccentricity $e \sin(\omega)$	$-0.02^{+0.31}_{-0.31}$
Planetary parameters	
Radius R_P ($R_\oplus$)	$1.63^{+0.23}_{-0.20}$
Orbital semimajor axis a (AU)	$1.046^{+0.019}_{-0.015}$
Equilibrium temperature T_{equ} (K)	265^{+15}_{-13}
Insolation relative to Earth	$1.10^{+0.29}_{-0.22}$

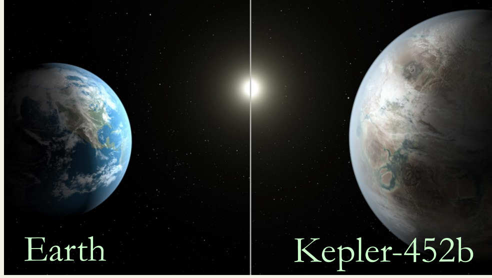
History of Insolation:



Note: This figure uses the updated Kopparapu HZ values for a 5-Mearth planet.



Summary:



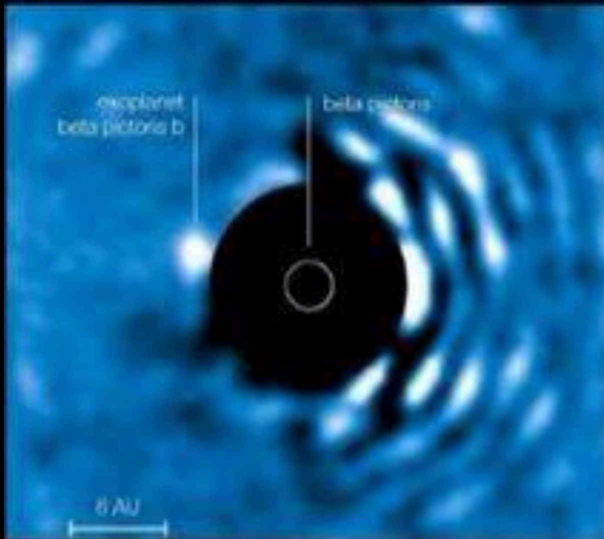
- Kepler-452b is the longest period transiting planet ≤2 $R_\oplus$
- Kepler-452b is the only small, possibly rocky exoplanet in the HZ of a G-type star very similar to the Sun
- It is the first (and only) transit on this target star (<10% chance of seeing an exo-Venus transit in this system)
- Final stellar parameters obtained from spectroscopy indicate a 1.1 $R_\odot$ star with

T_{eff} = 5757 ± 85 K, [Fe/H] = +0.2 ± 0.09, log g = 4.32 ± 0.09 and an age of ~6±2 Gyr

- => final planet parameters indicate a 1.6 ± 0.2 $R_\oplus$ planet in a 385-day period orbit with S_{eff} = 1.1 $S_\oplus$
- Outlook: SOC is currently finishing up analysis of all 4 years of *Kepler* data with 9.2 pipeline, next step: completeness study, next step: planet occurrence rates.

M. Endl acknowledges support by
NASA's *Kepler* Mission Participating Scientist Program

Every time there's an 'Earth 2.0' exoplanet announced.



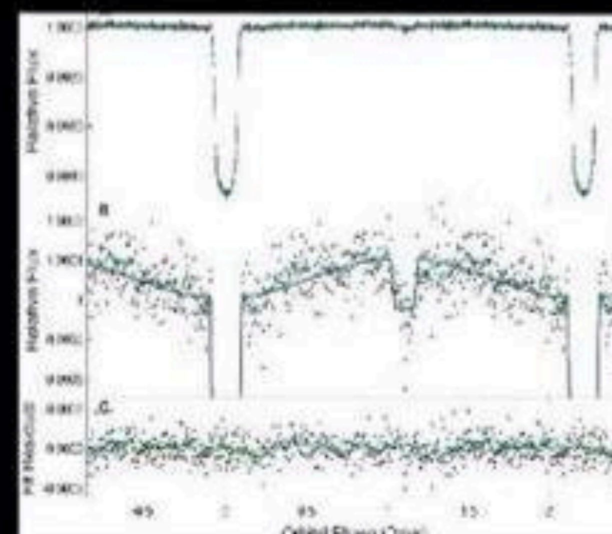
What Astronomers see.

What NASA see.

What Newspaper Artists see.

What Joe Public sees.

What conspiracy theorists see.



What we actually see.

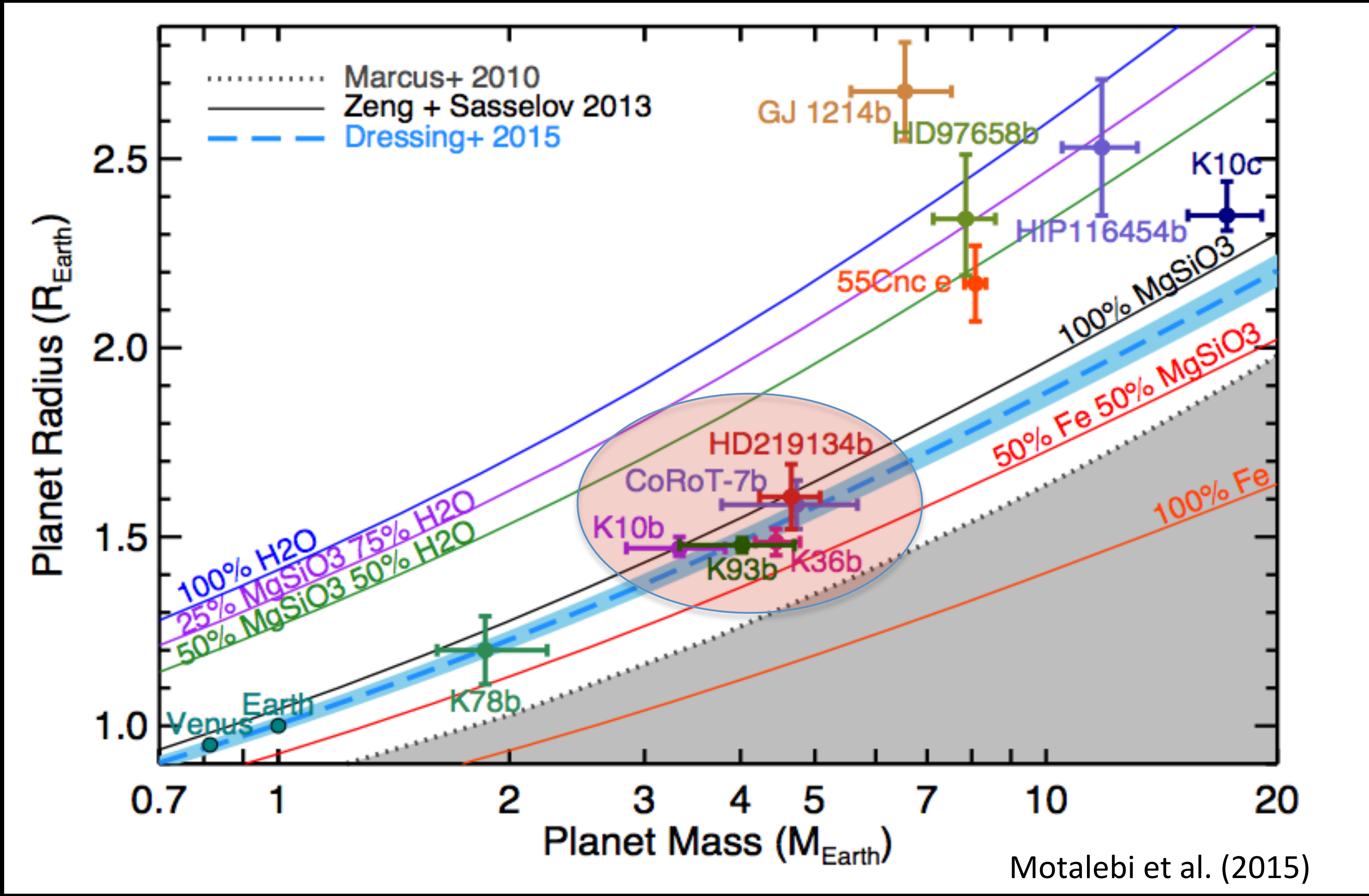
Spectroscopy:

Stellar Properties of KIC 8311864

Parameter	Value
Derived from high-resolution spectroscopy using SpecMatch	
Effective Temperature (K)	5757 ± 85
log [Surface gravity] (dex)	4.32 ± 0.09
Metallicity [Fe/H] (dex)	0.21 ± 0.09
Derived from fitting T_{eff}, log g and [Fe/H] to isochrones	
Radius ($R_\odot$)	$1.11^{+0.15}_{-0.09}$
Mass ($M_\odot$)	$1.037^{+0.054}_{-0.047}$
Mean Density (g cm^{-3})	$0.84^{+0.40}_{-0.19}$
Age (Gyr)	$\sim 6 \pm 2$

Jenkins et al. adopted SpecMatch results for HIRES data**; inflated errors according to scatter in analyses of HIRES data**

Mass-Radius Measurements For Small Planets



Motalebi et al. (2015)

There are now 5 exoplanets with 1.4 Re ≤ Rp≤ 1.6 Re with “rocky” densities

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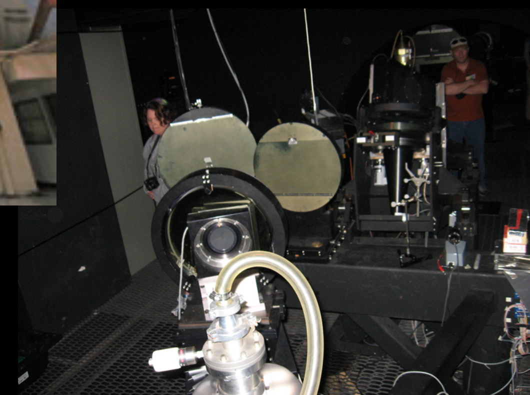
McDonald Observatory: Telescope & Instrument



Reconnaissance spectroscopy of KOIs:
2009 – 2015: 1130 KOIs observed

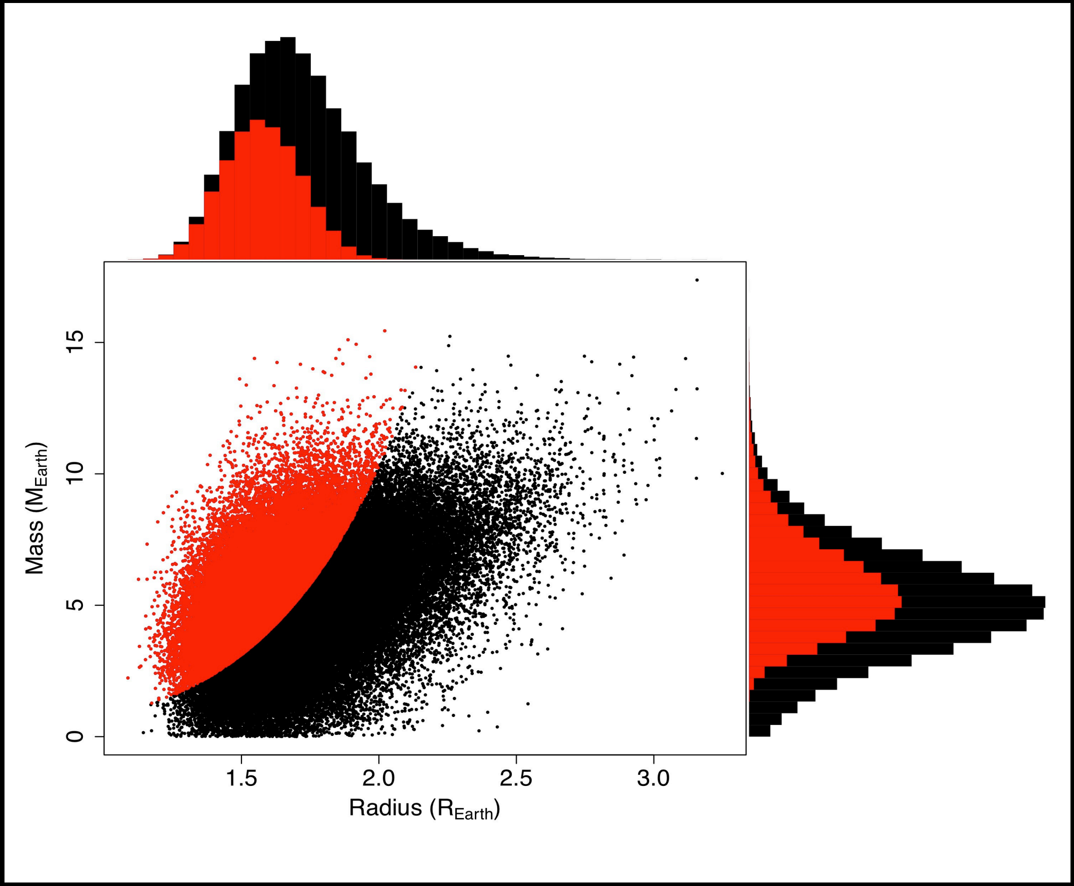
William Cochran, Phillip MacQueen, Marshall Johnson, Kevin Gullikson and Ivan Ramirez

Likelihood of Rocky Composition

Used probabilistic mass-radius relationship developed by Wolfgang, Rogers and Ford (submitted) to associate a mass with each radius in the MCMC chain.

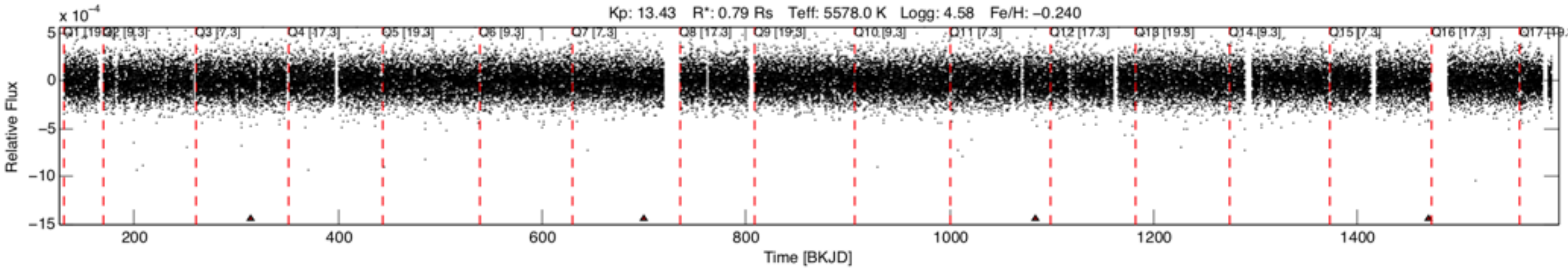
Compared densities against that expected for a pure silicate composition as per Fortney, Marley and Barnes (2007).

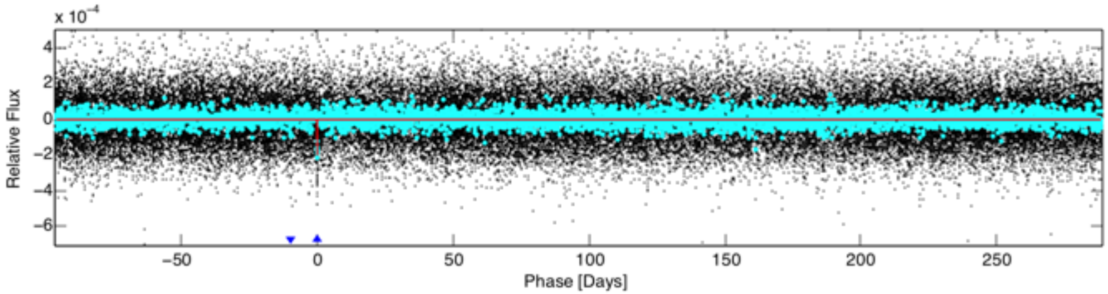
Measured fraction of MCMC realizations denser than pure silicate:

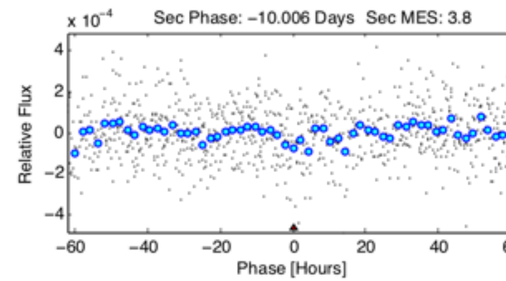


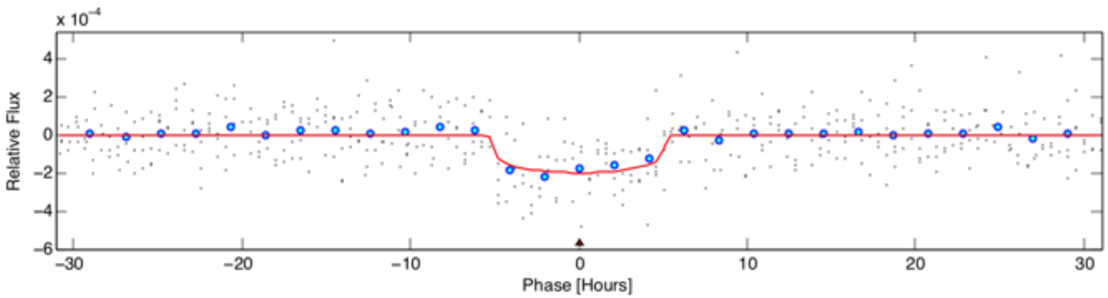
=> 49% chance of being rocky

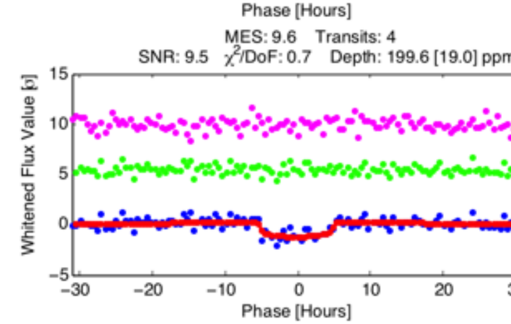
KIC: 8311864   Candidate: 1 of 1   Period: 384.846 d

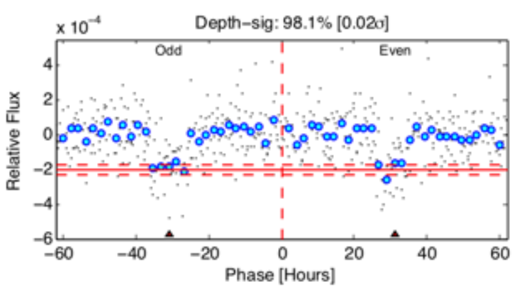


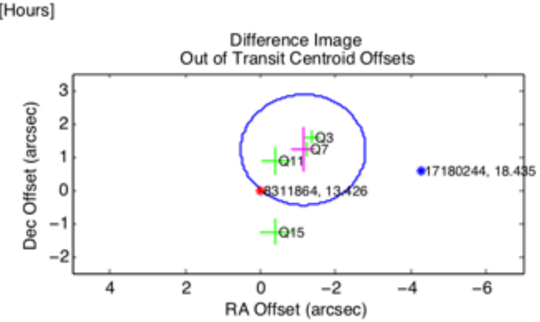












DV Fit Results:

Period = 384.84625 [0.00754] d
Epoch = 314.9787 [0.0146] BKJD
Rp/R* = 0.0129 [0.0248]
a/R* = 274.62 [2265.06]
b = 0.30 [25.06]

Teq = 221 K
Rp = 1.12 Re
a = 0.9888 AU

DV Diagnostic Results:

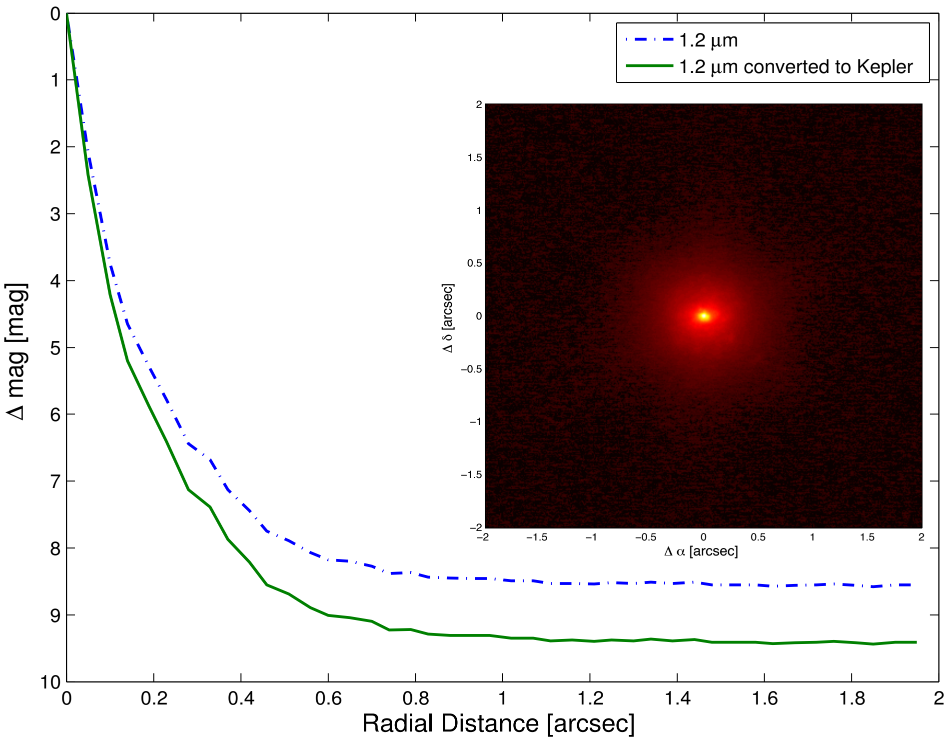
Epoch−sig: 92.0% [0.10σ]
ShortPeriod−sig: N/A
LongPeriod−sig: N/A
ModelChiSquare2−sig: 91.6%
Bootstrap−pfa: 4.79e−14

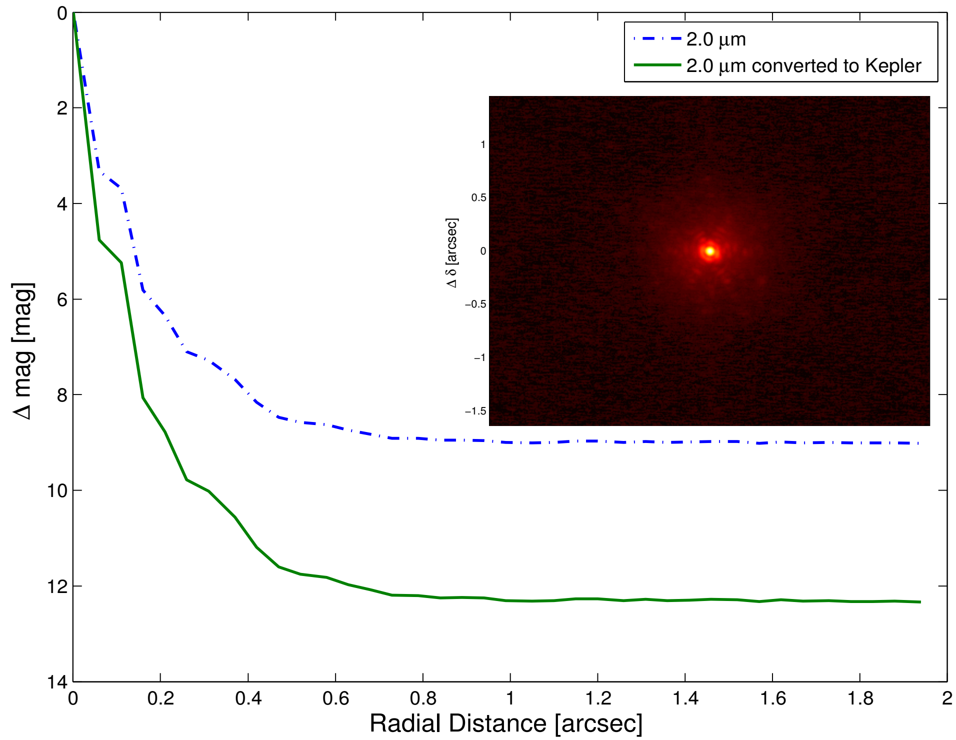
Centroid−sig: 1.1%
Centroid−so: 1.832 arcsec [1.63σ]
OotOffset−rm: 1.664 arcsec [3.00σ]
KicOffset−rm: 1.649 arcsec [3.61σ]
OotOffset−bf: N/A
KicOffset−bf: N/A
OotOffset−st: 0/4/0/0 [4]
KicOffset−st: 0/4/0/0 [4]
DiffImageQuality−fgm: 0.75 [3/4 of 4]

Software Revision: svn+ssh://murzim/repo/soc/branches/integ/ksop−1993@55984   —   Date Generated: 11−Jul−2014 01:49:44 Z

This Data Validation Report Summary was produced in the Kepler Science Operations Center Pipeline at NASA Ames Research Center

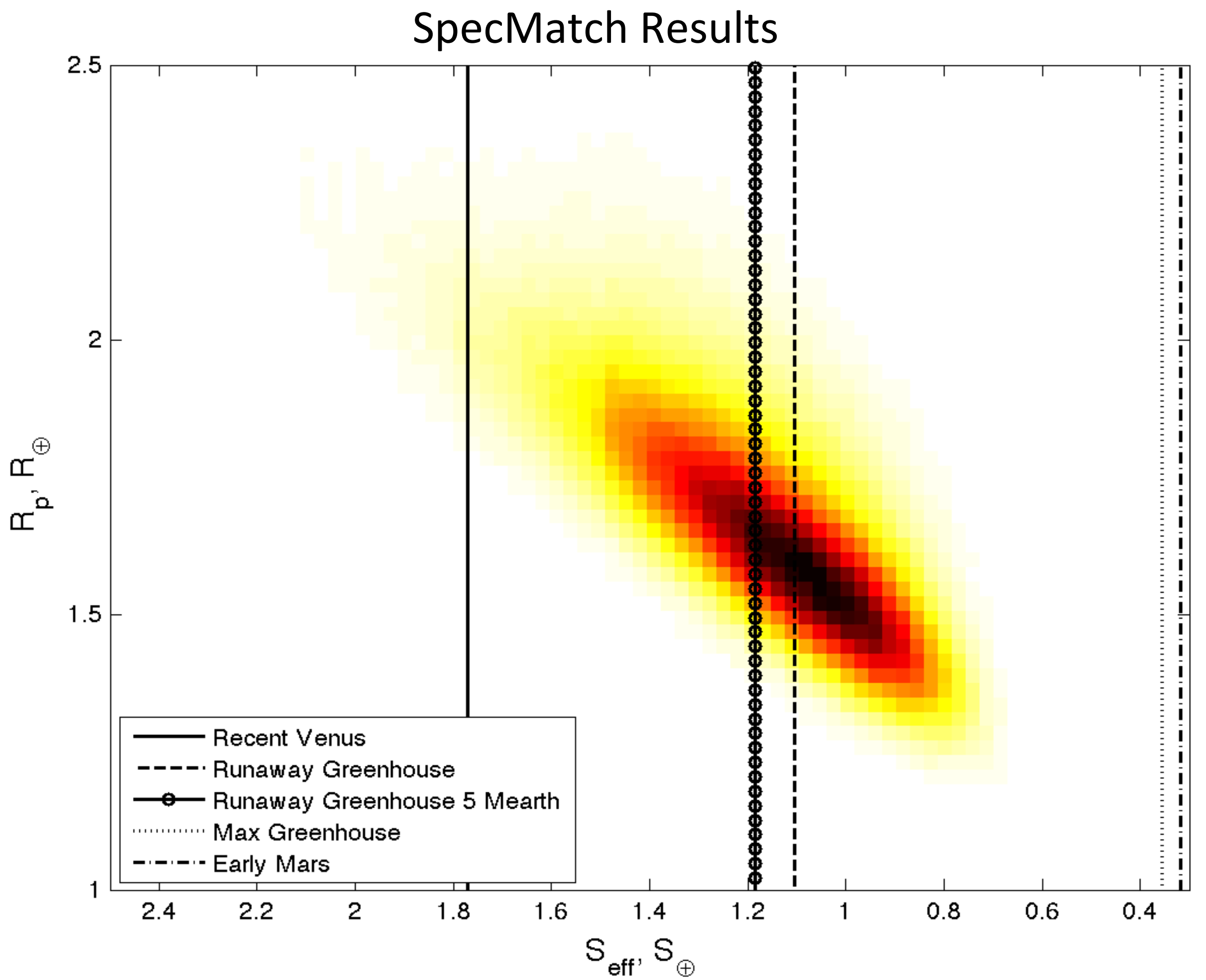
AO Observations:





No evidence for companions in AO images
(also ruled out contamination by optical ghosts and video crosstalk)

Likelihood of Habitability



HZ as per updated Kopparapu et al. (2013)

Generated realizations of planet radius and insolation for MCMC chain and compared against Kopparapu et al. (2013) habitable zone boundaries.

97% with Seff < Recent Venus
53% with Seff < 5 Mearth Runaway Greenhouse
39% with Seff < 1 Mearth Runaway Greenhouse

The "Battle of Spectroscopy":

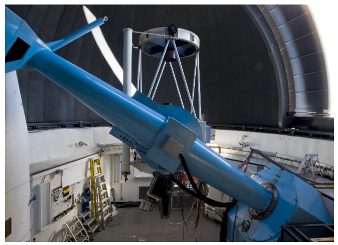


Table 1
Spectroscopy and Analysis Results for KIC 8311864

Parameter	Value	Notes
Tull/McDonald Observatory		
Effective temperature (K)	5650 ± 108	a
Surface gravity $\log g$ (cgs)	4.45 ± 0.16	a
Metallicity [Fe/H](dex)	0.21 ± 0.07	a
Projected rotation Velocity $v \sin i$ (km s^{-1})	4.3 ± 0.5	a
TRES/Whipple Observatory		
Effective temperature (K)	5751 ± 55	b
Surface gravity $\log g$ (cgs)	4.43 ± 0.10	b
Metallicity [Fe/H](dex)	0.40 ± 0.08	b
Projected rotation Velocity $v \sin i$ (km s^{-1})	4.2 ± 0.5	b
HIRES/Keck Observatory		
Effective temperature (K)	5757 ± 60	c
Surface gravity $\log g$ (cgs)	4.32 ± 0.07	c
Metallicity [Fe/H](dex)	0.21 ± 0.04	c
Projected rotation Velocity $v \sin i$ (km s^{-1})	<1	c

Notes.
a: Analyzed with *Kea*.
b: Analyzed with SPC.
c: Analyzed with SpecMatch.
d: Analyzed with MOOG.

The "Battle of Spectroscopy":

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Spectroscopy and Analysis Results for KIC 8311864

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Projected rotation Velocity v sin i (km s^{-1})	4.3 ± 0.5	a
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Effective temperature (K)	5751 ± 55	b
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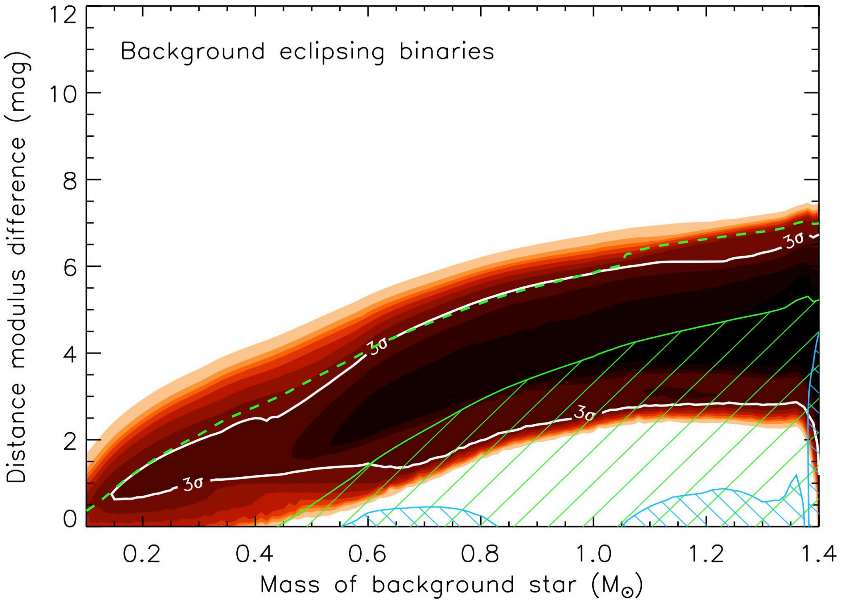
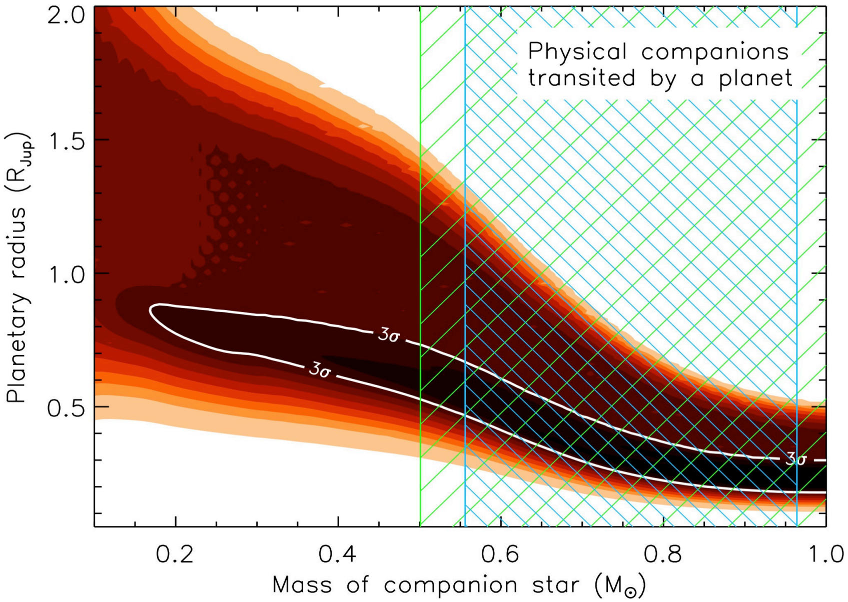
HIRES/Keck Observatory		
Effective temperature (K)	5757 ± 60	c
Surface gravity log g (cgs)	4.32 ± 0.07	c
Metallicity [Fe/H](dex)	0.21 ± 0.04	c
Projected rotation Velocity v sin i (km s^{-1})	<1	c
Effective temperature (K)	5740 ± 50	b
Surface gravity log g (cgs)	4.42 ± 0.10	b
Metallicity [Fe/H](dex)	0.22 ± 0.08	b
Projected rotation Velocity v sin i (km s^{-1})	0.8 ± 0.5	b
Effective temperature (K)	5818 ± 21	d
Surface gravity log g (cgs)	4.33 ± 0.05	d
Metallicity [Fe/H](dex)	0.24 ± 0.02	d

Notes.
a: Analyzed with *Kea*.
b: Analyzed with SPC.
c: Analyzed with SpecMatch.
d: Analyzed with MOOG.

Blender Analysis





BEB odds: 1.21×10^{-12}
BP odds: 2.56×10^{-10}
HTP odds: 2.35×10^{-6}

Vs: (Expected) Planet odds: 9.97×10^{-4}

Therefore, odds ratio is ~424:1