Are the Kepler-11 planets ultra-low density?





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Who's Who IAP, Paris, 2015

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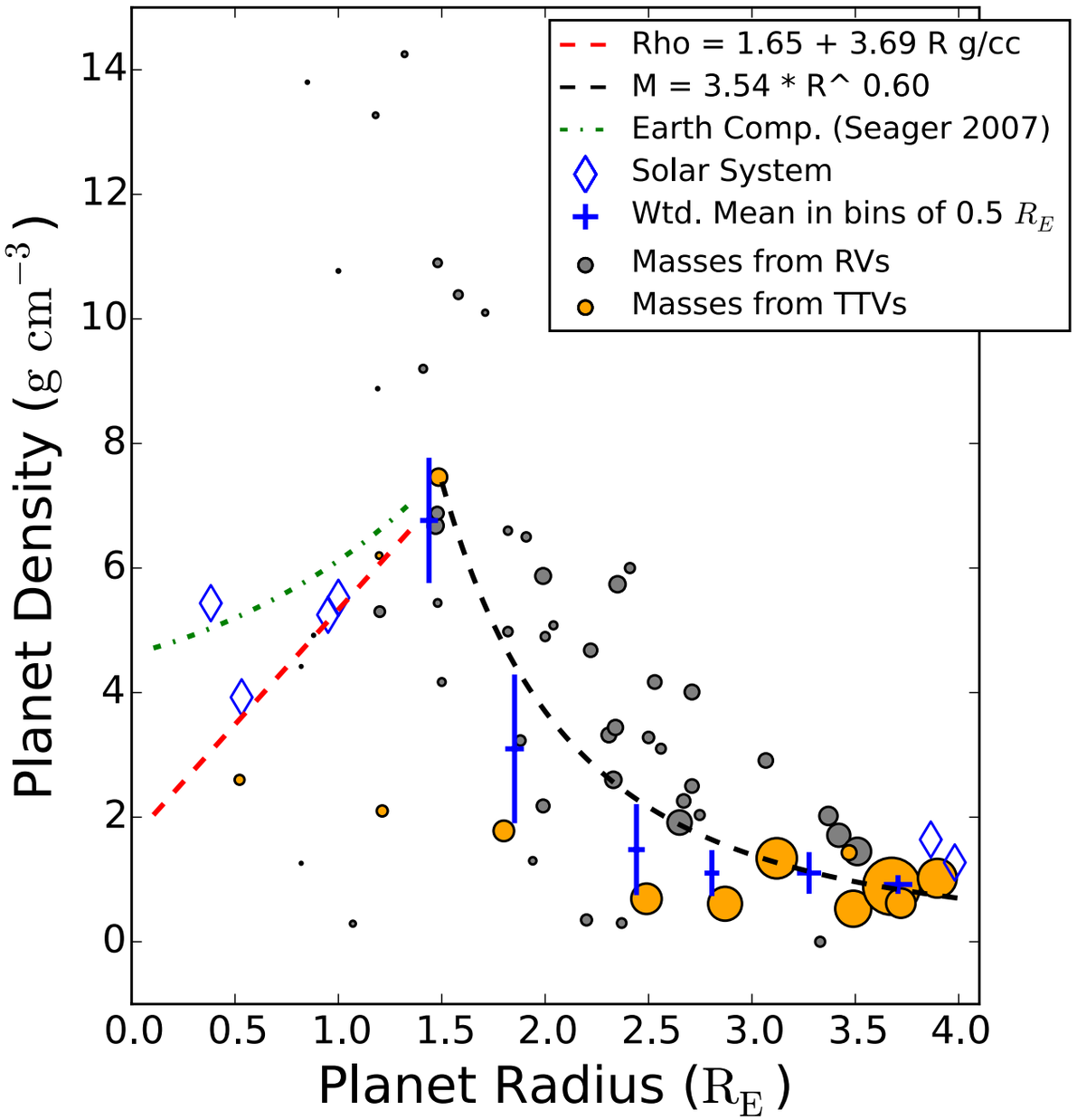
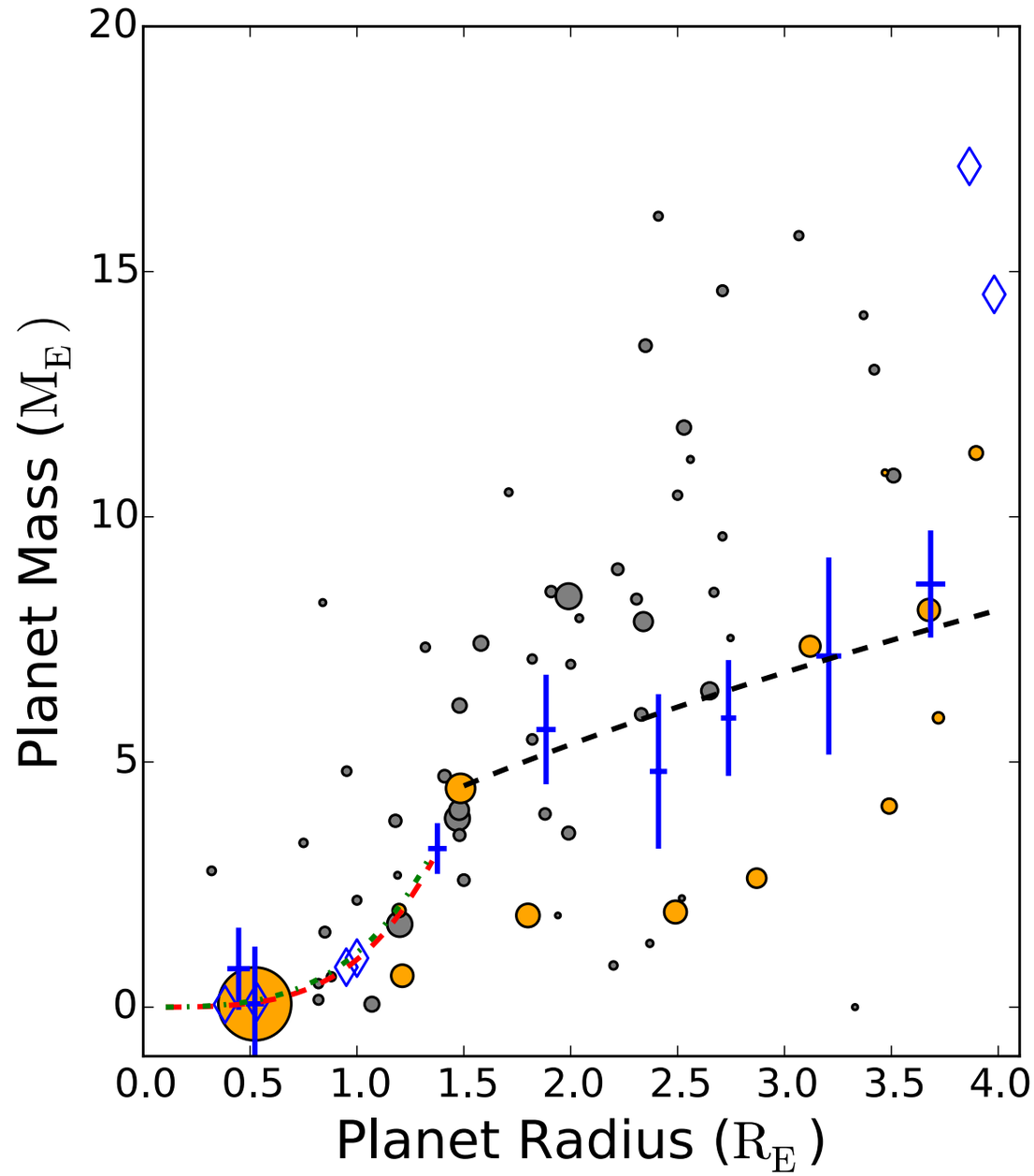
Masses, densities of 70 planets smaller than 4 R_E

Weiss & Marcy 2014





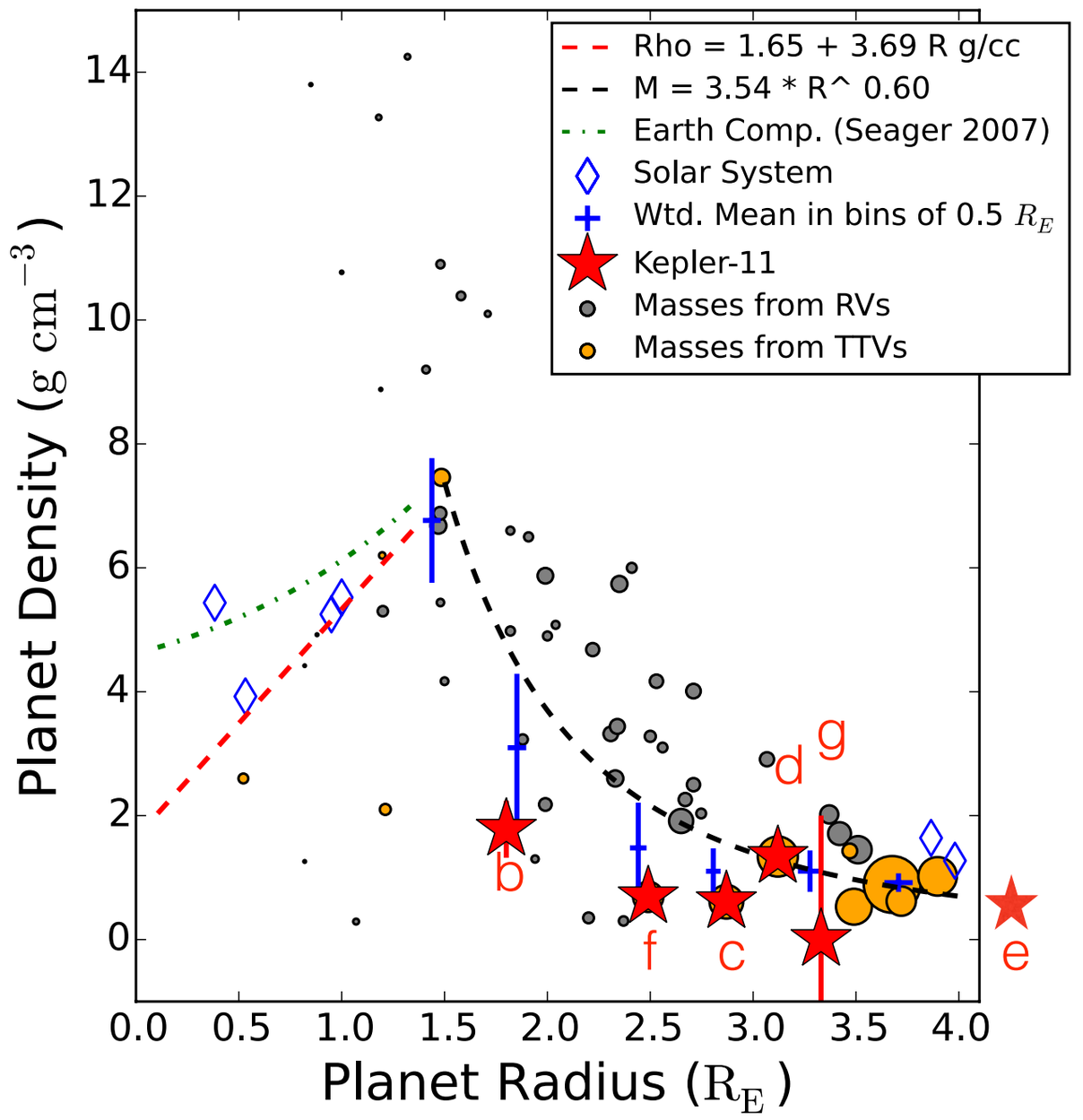
Lissauer+ 2013:
"All Six Planets Known to Orbit Kepler-11 Have Ultra-Low Densities"

Table 4
The Planets of Kepler-11

Planet	Mass ($M_\oplus$)	Radius ($R_\oplus$)	Density (g cm^{-3})
b	$1.9^{+1.4}_{-1.0}$	$1.80^{+0.03}_{-0.05}$	$1.72^{+1.25}_{-0.91}$
c	$2.9^{+2.9}_{-1.6}$	$2.87^{+0.05}_{-0.06}$	$0.66^{+0.66}_{-0.35}$
d	$7.3^{+0.8}_{-1.5}$	$3.12^{+0.06}_{-0.07}$	$1.28^{+0.14}_{-0.27}$
e	$8.0^{+1.5}_{-2.1}$	$4.19^{+0.07}_{-0.09}$	$0.58^{+0.11}_{-0.16}$
f	$2.0^{+0.8}_{-0.9}$	$2.49^{+0.04}_{-0.07}$	$0.69^{+0.29}_{-0.32}$
g	<25	$3.33^{+0.06}_{-0.08}$	<4

Notes. The mass and eccentricity of Kepler-11 g are 2σ upper bounds

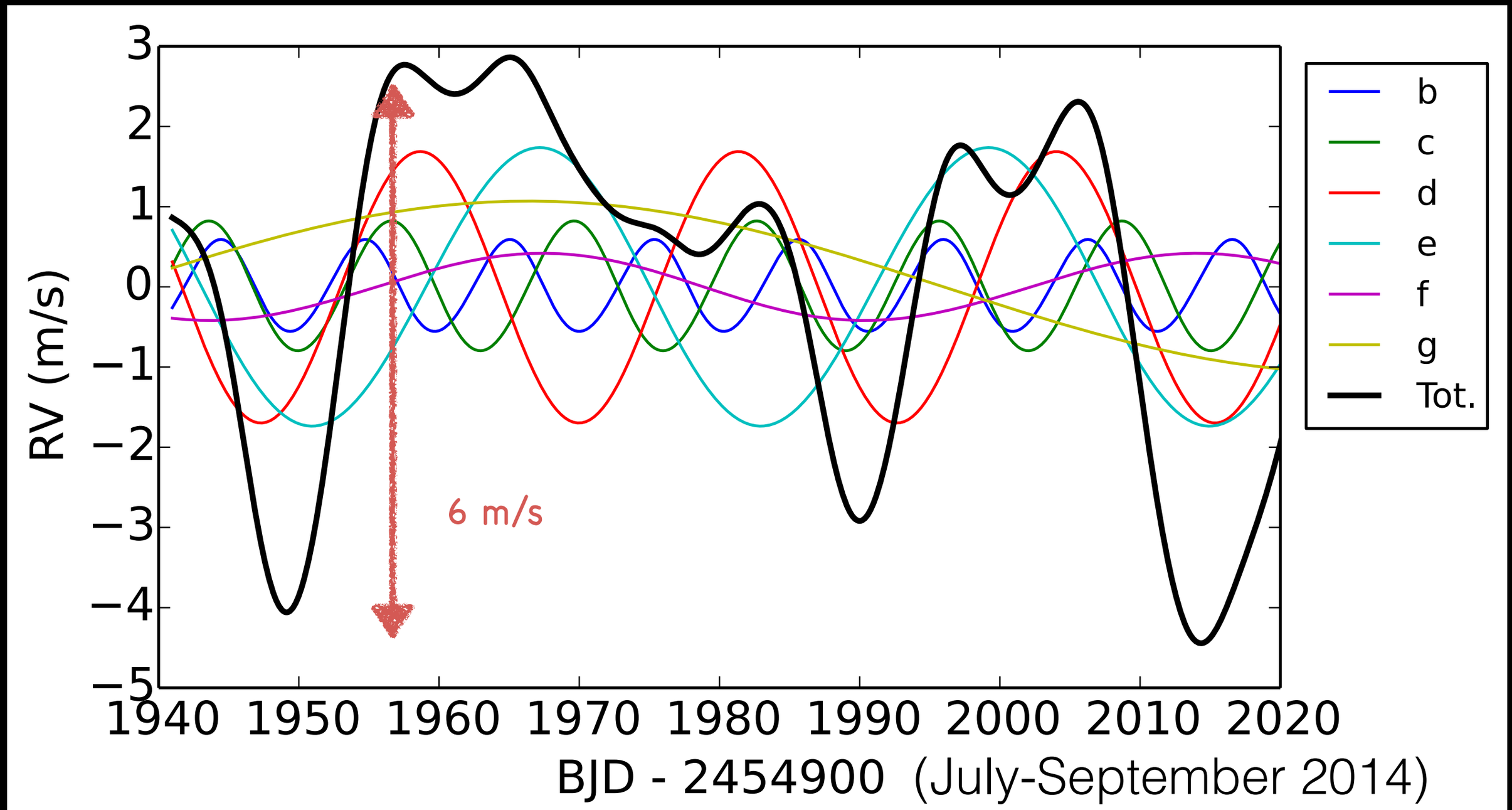
0.7 g/cc



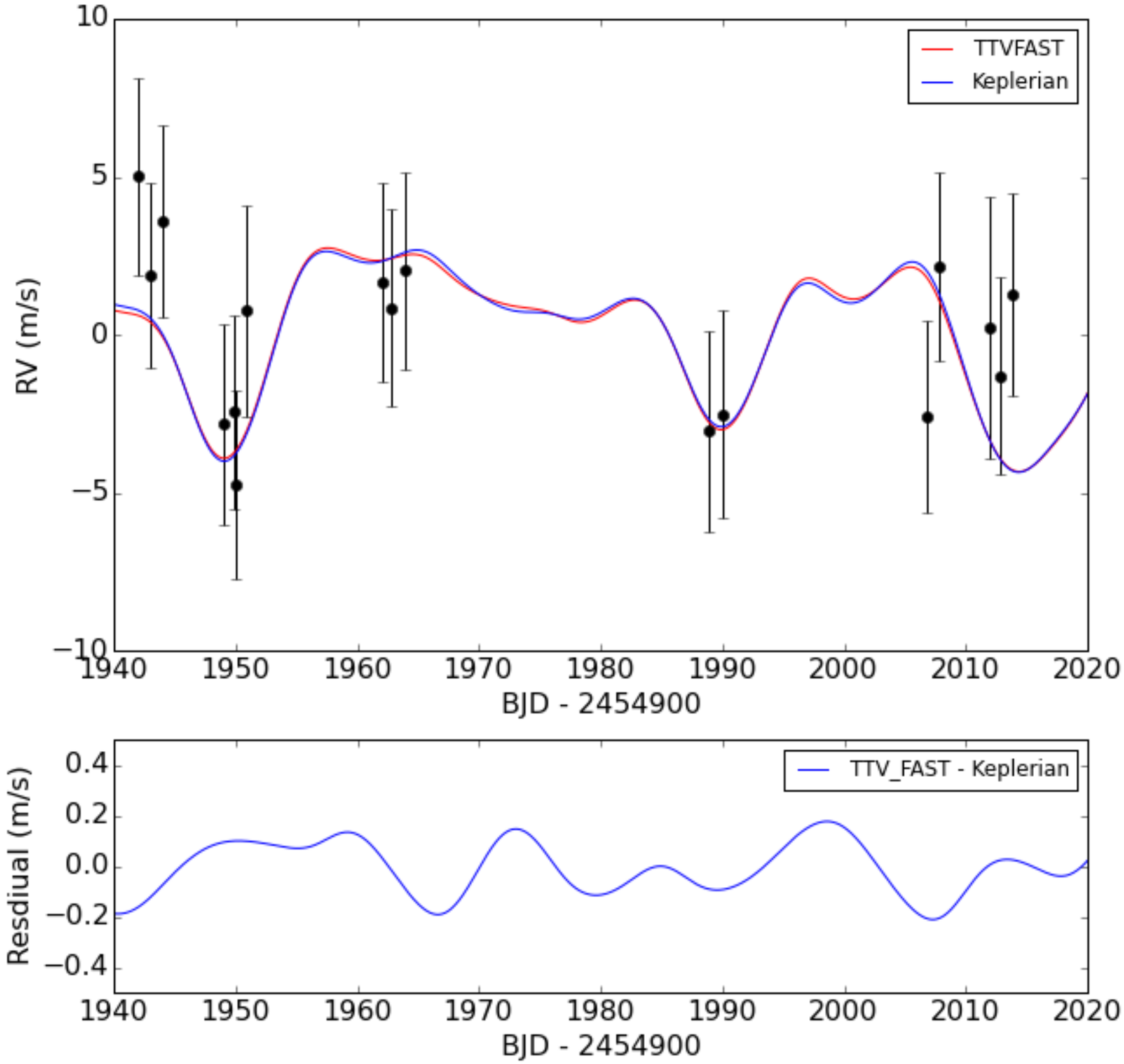
L. M. Weiss

IAP June 30, 2015

Timed observations at predicted large RV changes based on Lissauer+ 2013 ephemerides

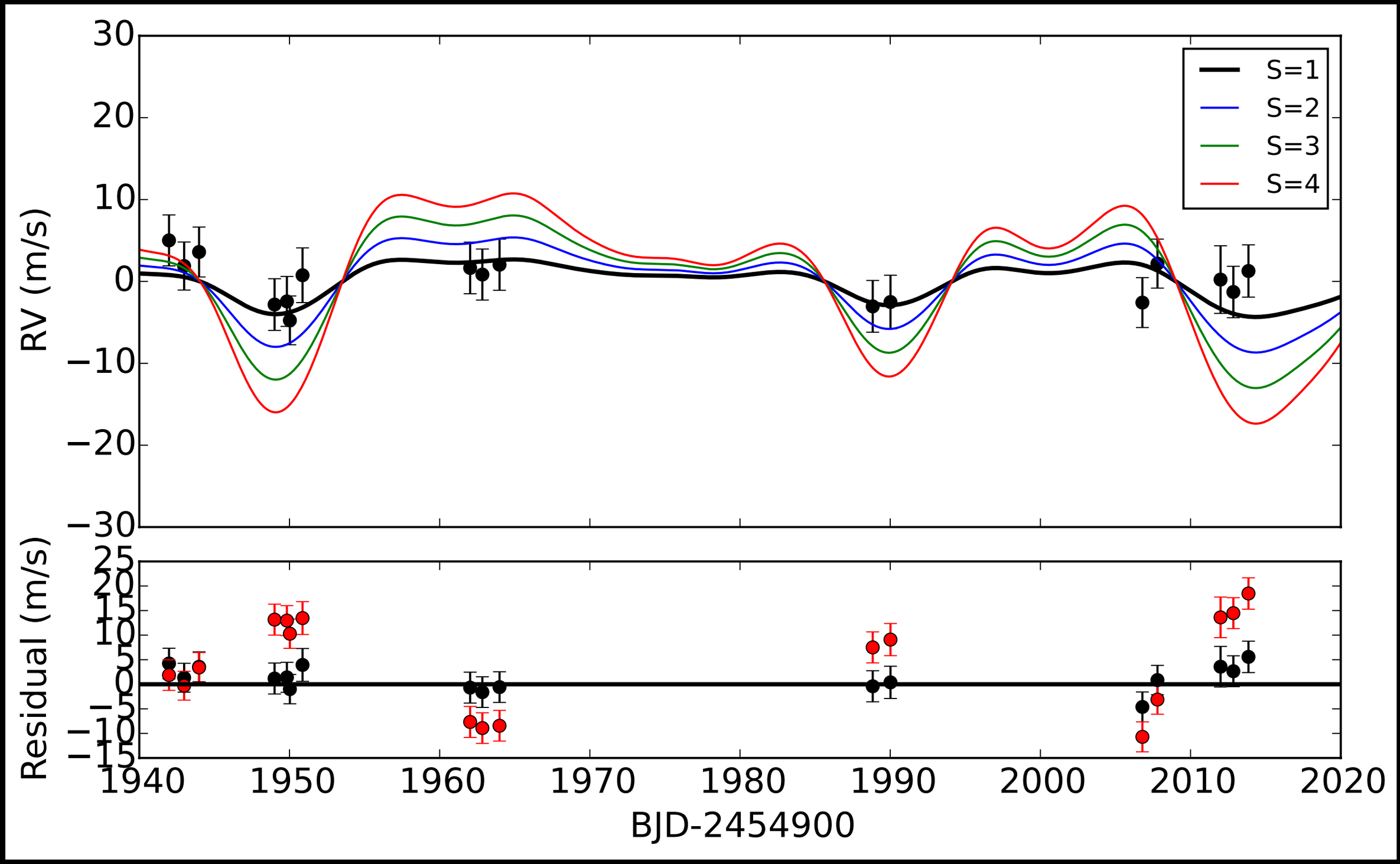


We acquired 17 HIRES RVs of Kepler-11

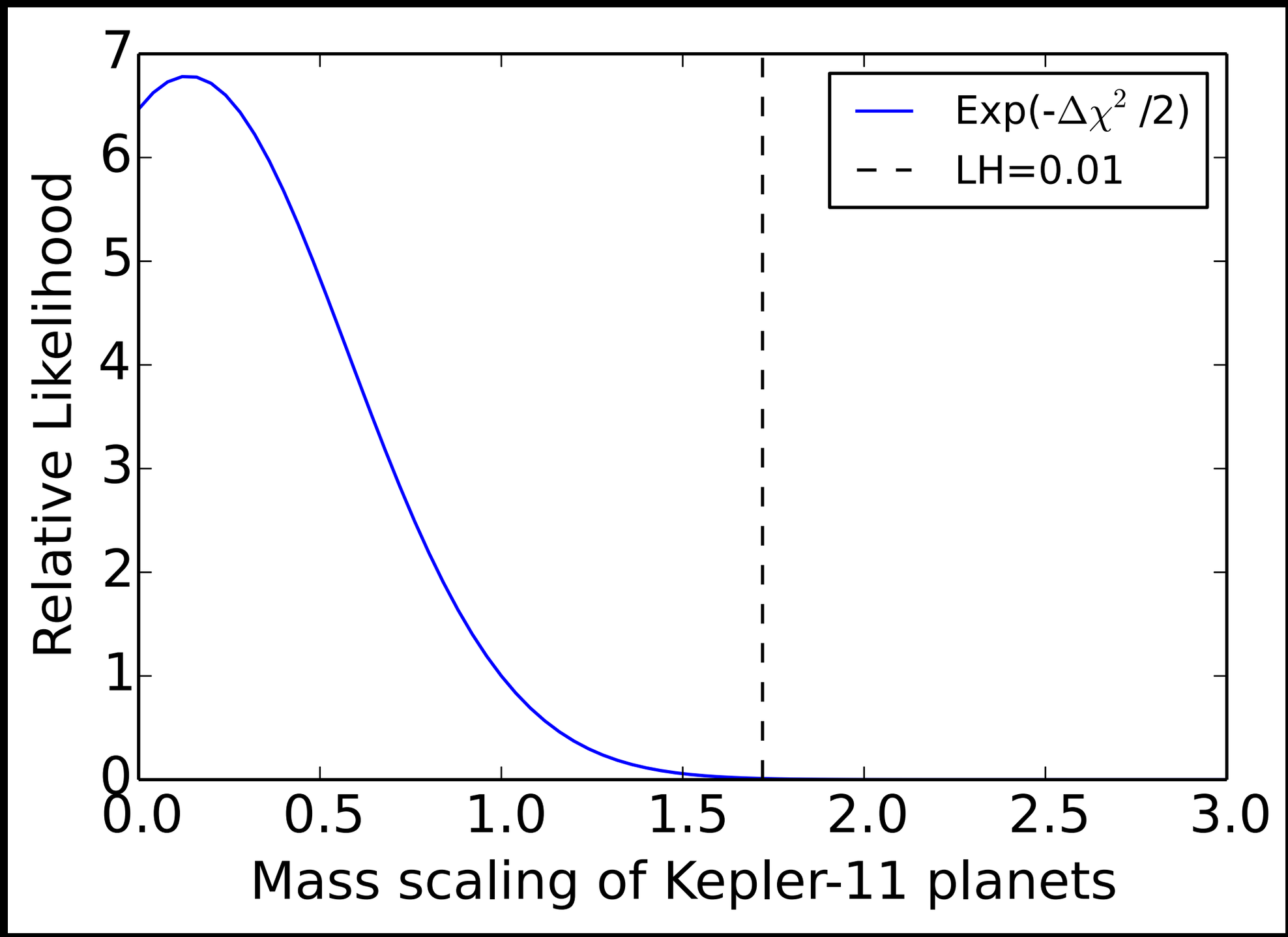


July-September 2014

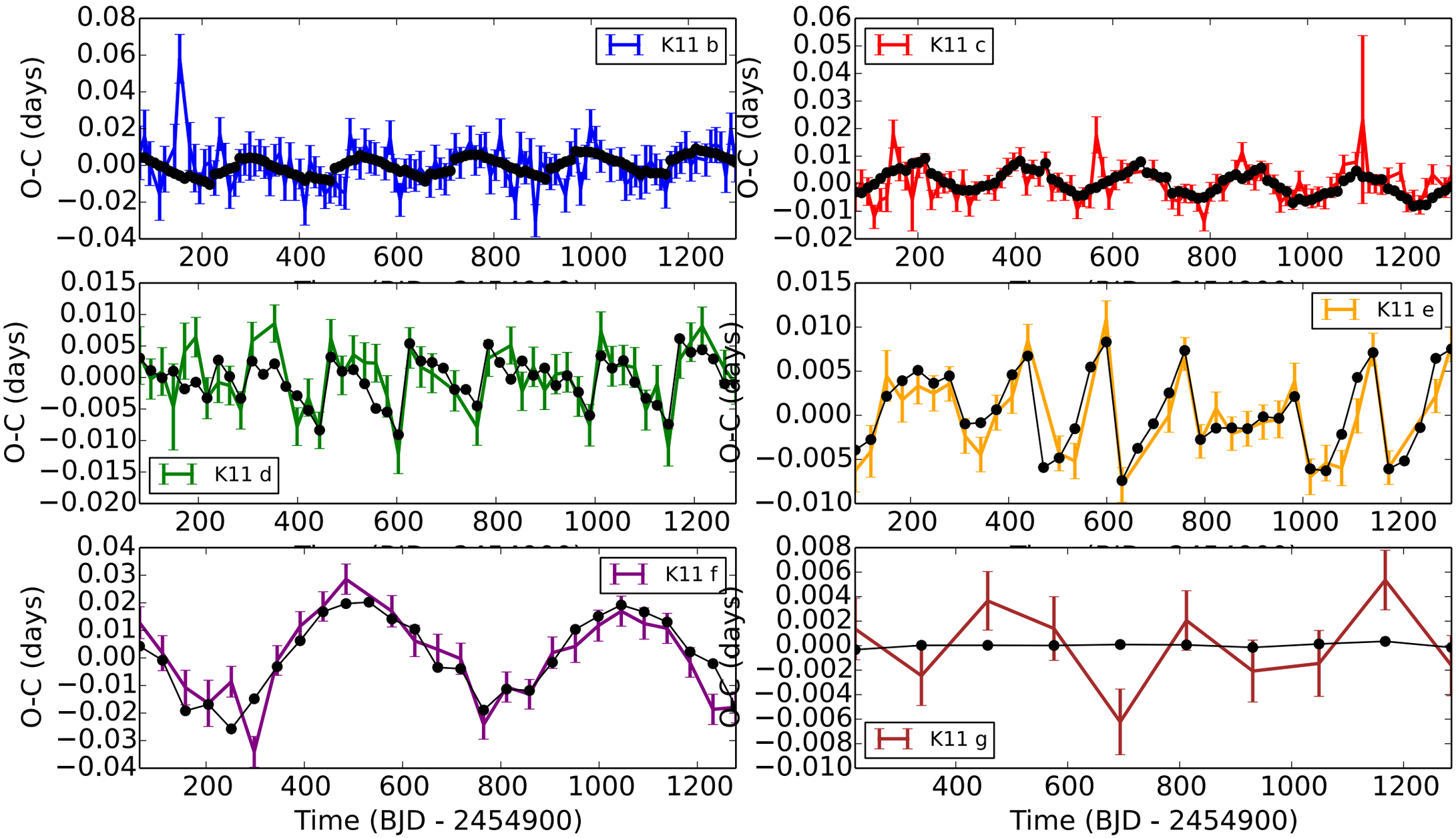
Test Scaling the Masses of all 6 Planets by Factor S



RVs rule out mass scalings > 2x the TTV-determined masses with > 2-sigma confidence



L-M Minimization with TTVFAST applied to TTVs + RVs: Ndata = 330, Chi^2 = 380



RV-constrained Kepler-11 Dynamical Parameters:

Table 2
Kepler-11 Best Fit Dynamical Properties

Planet	Period (d)	Ecc.	Inc. (°, fixed)	Ω (°, fixed)	ω (°)	M.A. (°)	Mass ($M_\oplus$)	Radius[a] ($R_\oplus$)	Density (g/cc)
Kepler-11b	10.30483	0.045	89.64	0	45.54	127.15	$1.87^{+0.43}_{-0.53}$	1.80 ± 0.04	1.76 ± 0.46
Kepler-11c	13.02386	0.025	89.59	0	51.32	189.72	$2.63^{+0.80}_{-0.63}$	2.87 ± 0.05	0.61 ± 0.17
Kepler-11d	22.69197	0.003	89.67	0	146.29	21.97	$7.36^{+0.03}_{-1.16}$	3.12 ± 0.06	1.34 ± 0.12
Kepler-11e	31.99412	0.013	89.89	0	228.40	318.26	$8.19^{+0.77}_{-0.66}$	4.19 ± 0.08	0.61 ± 0.06
Kepler-11f	46.69292	0.013	89.47	0	335.55	105.43	$1.94^{+0.32}_{-0.88}$	2.49 ± 0.05	0.69 ± 0.21
Kepler-11g	118.3973	0.039	89.87	0	34.51	295.63	$< 27.6^b$	3.33 ± 0.07	$< 4.11^b$

Note. — Osculating Elements determined at epoch BJD - 2454900 = 64.67

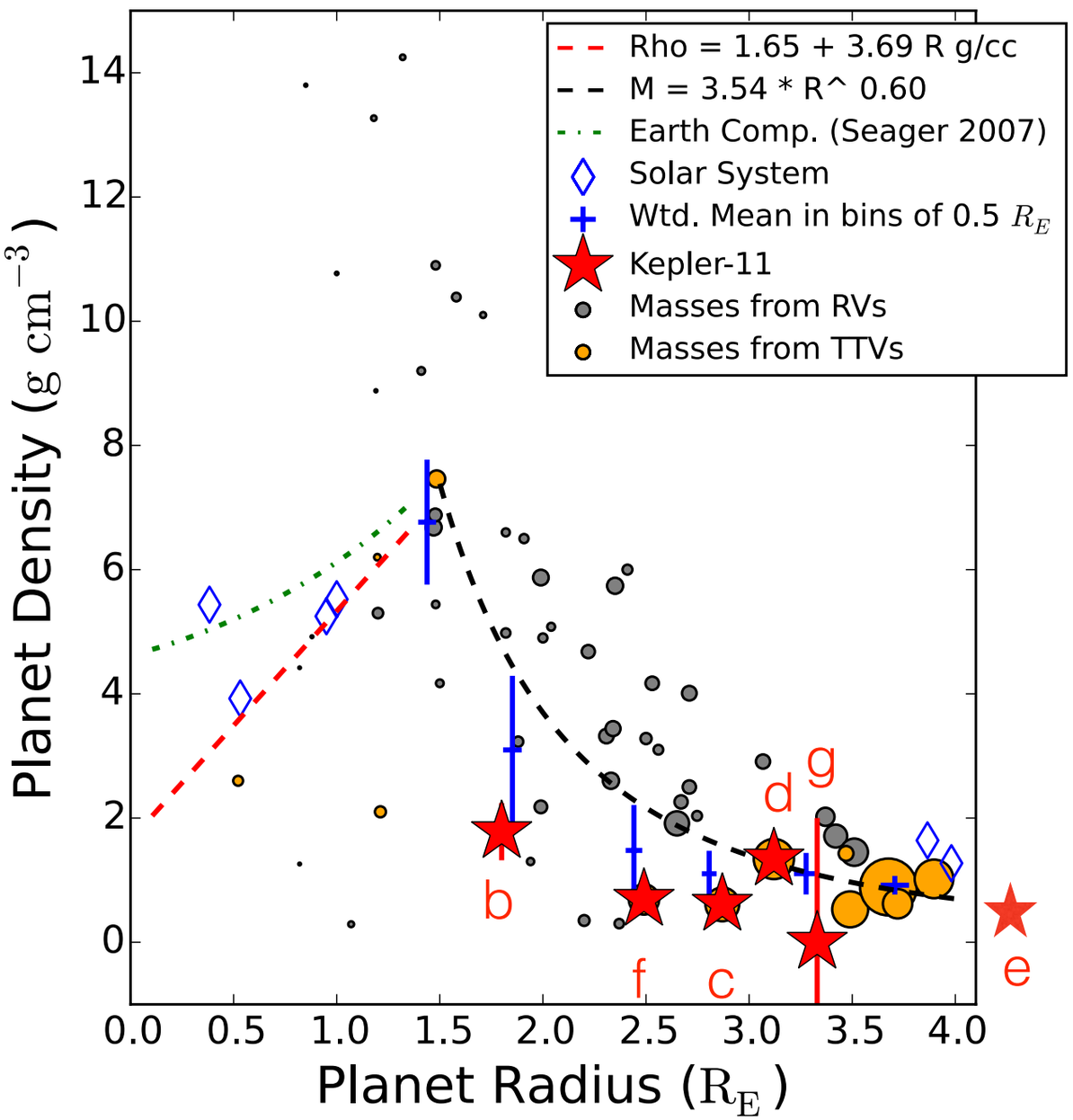
[a] From Lissauer et al. (2013)

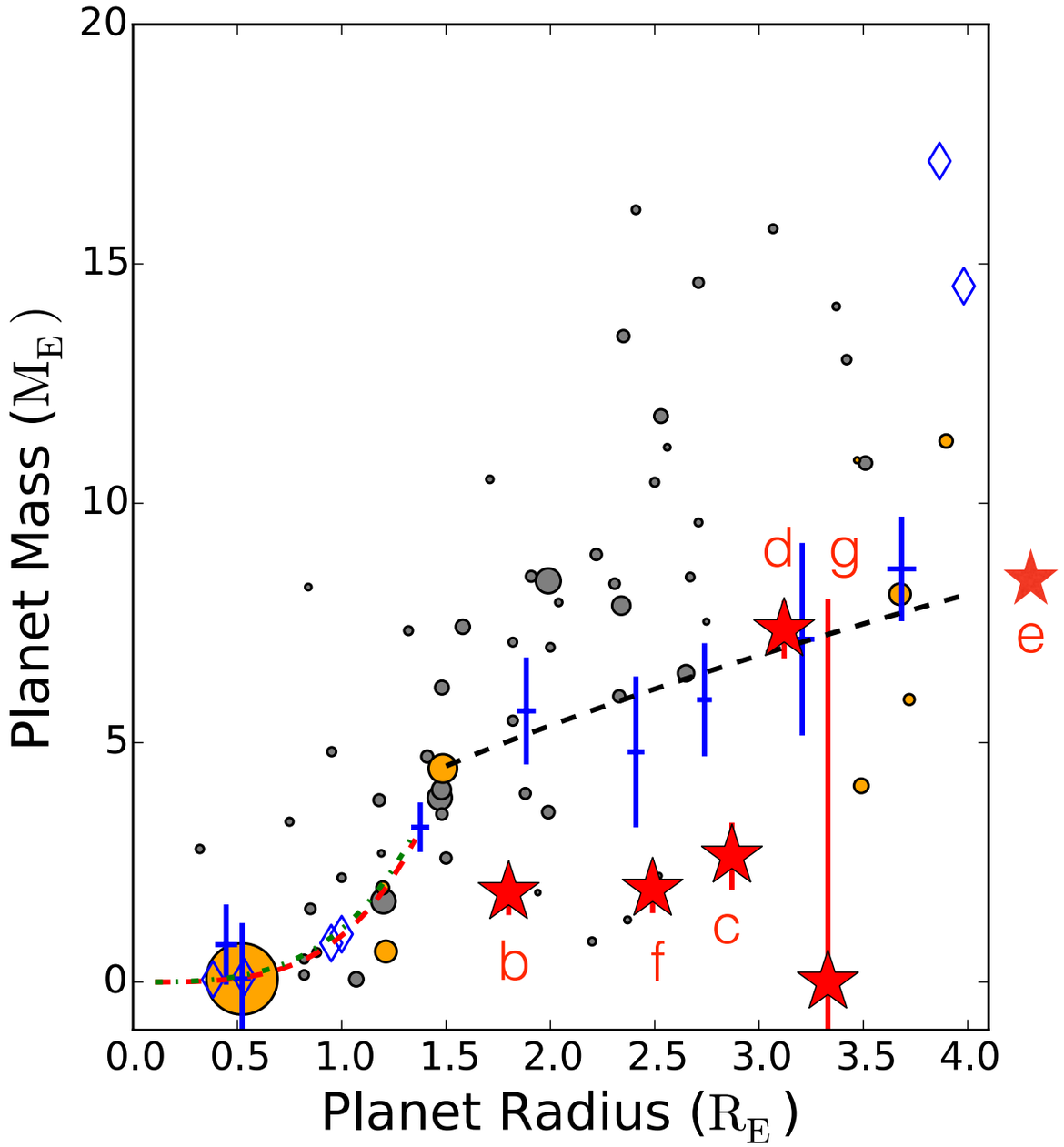
[b] 2σ upper limit.

Masses and densities are within +/-10% of Lissauer et al. 2013 values

RV measurements of Kepler-11 are consistent with ultra-low density planets

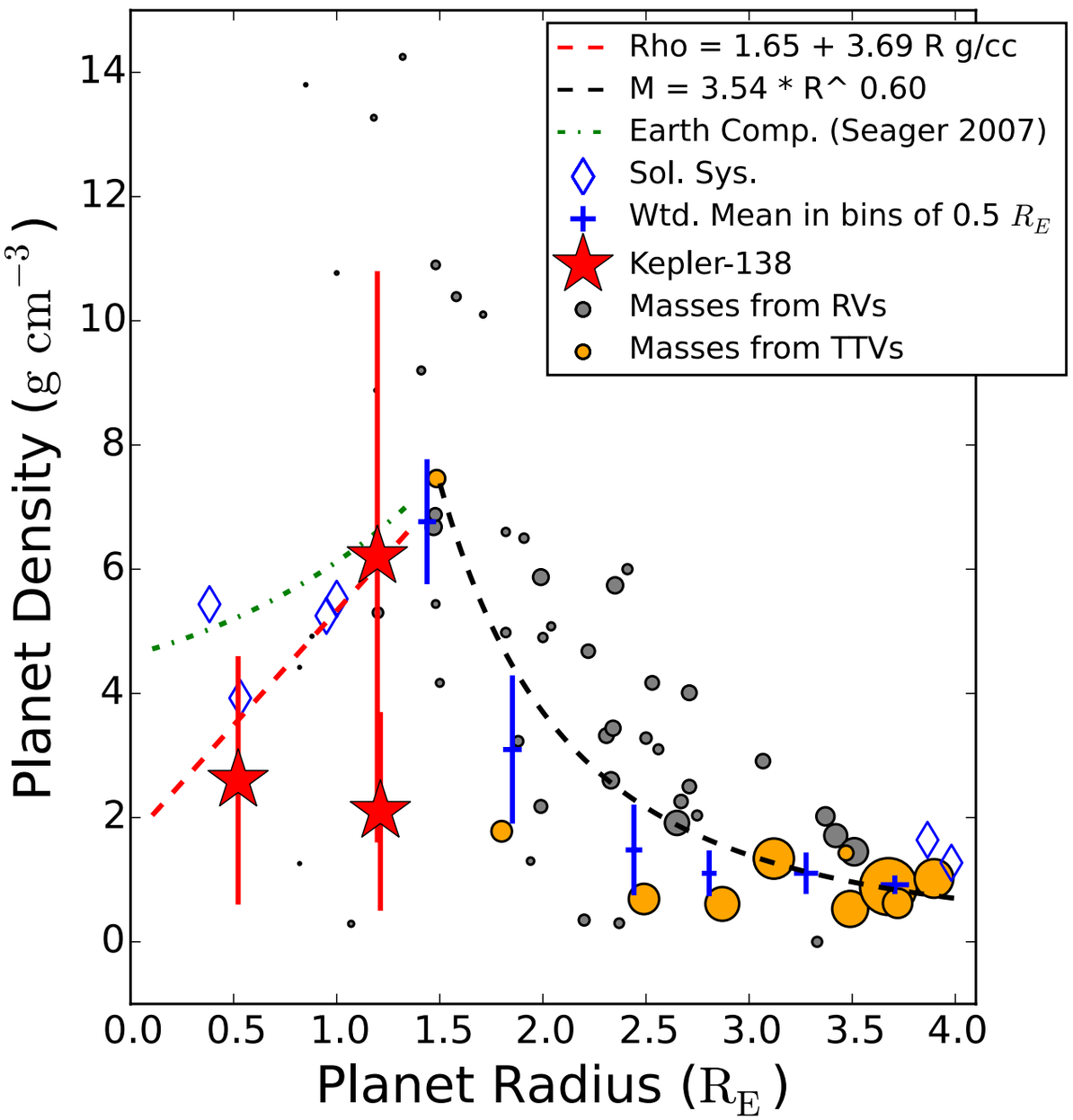
Weiss+ 2015 (in prep.)

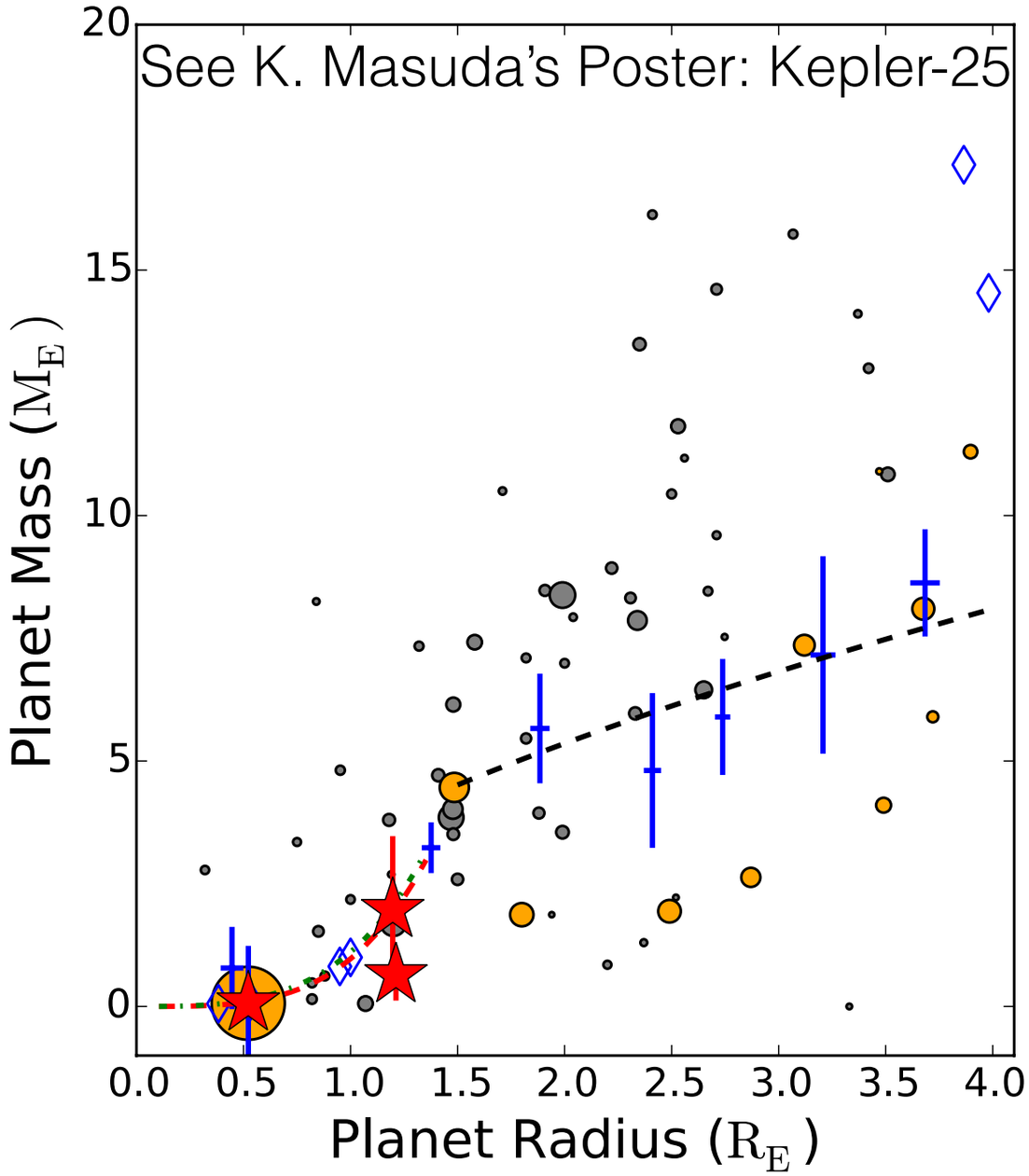




Kepler-138 c is low density.
Ultra-low density planets exist at small radii too!

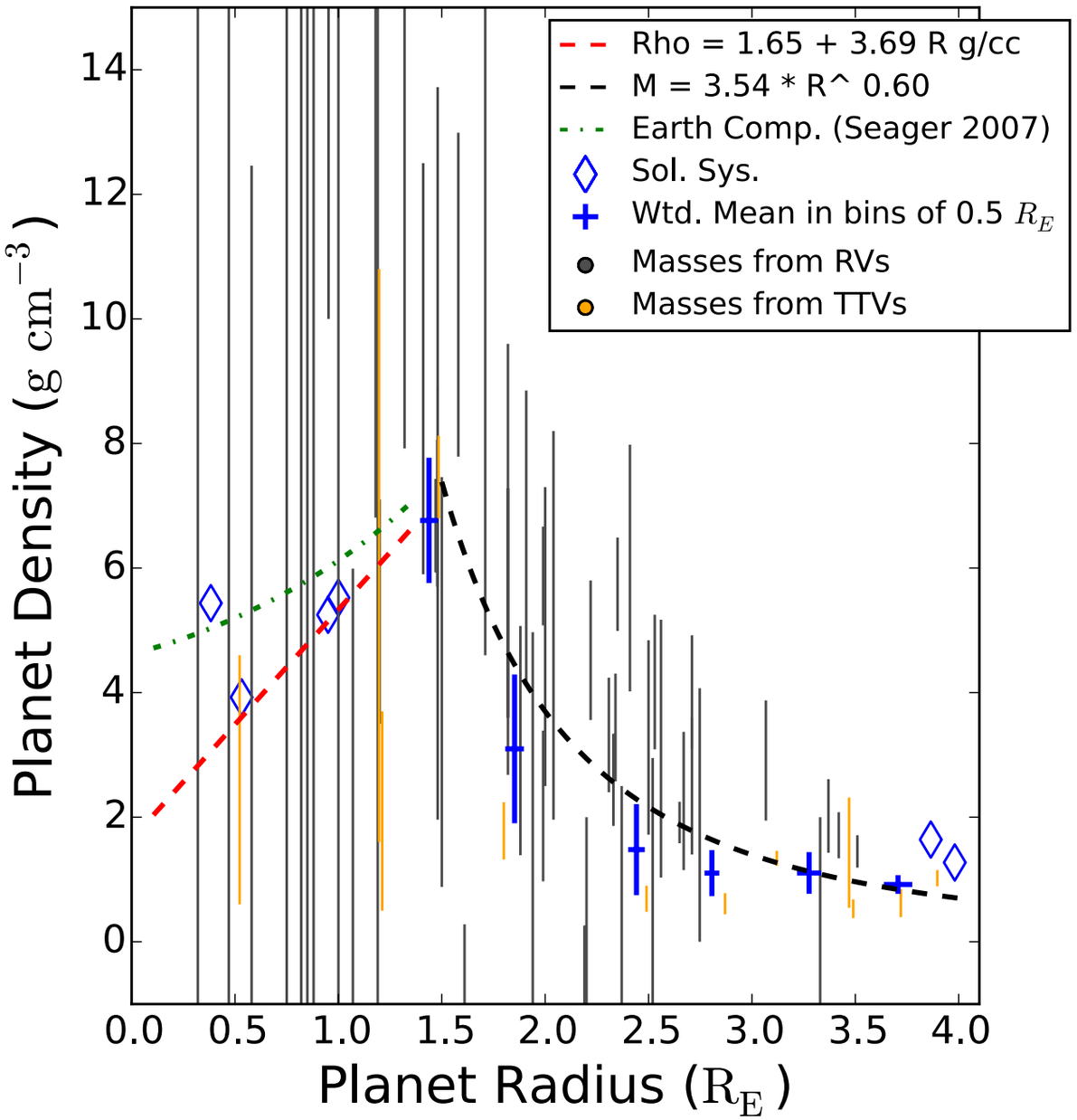
Weiss+ 2015 (in prep.)

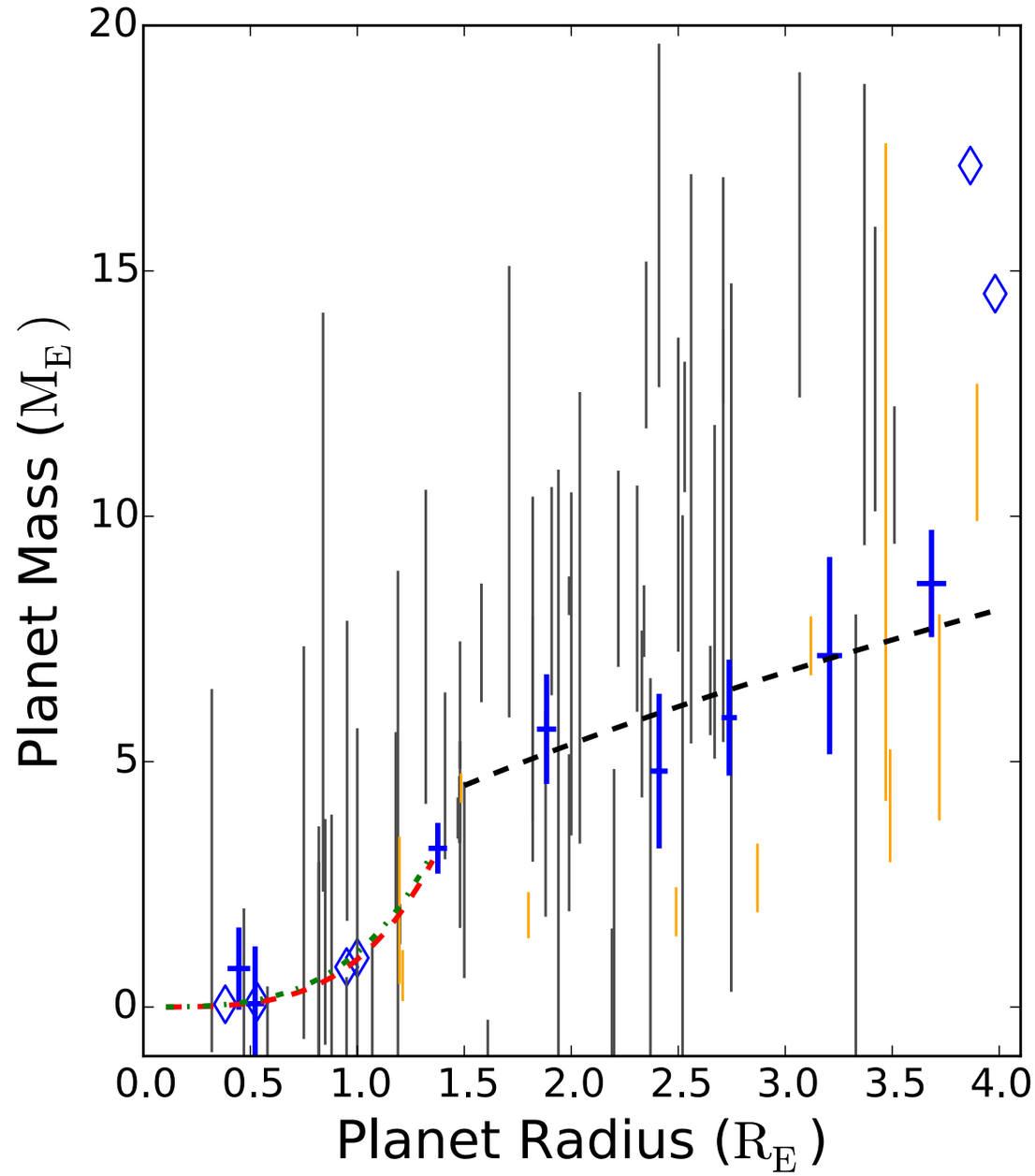


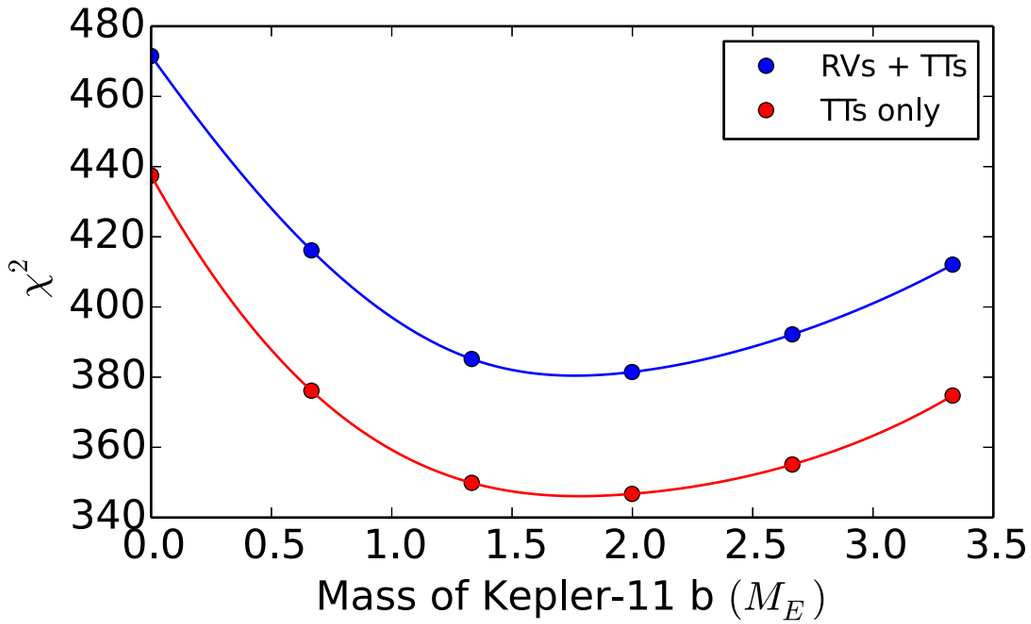


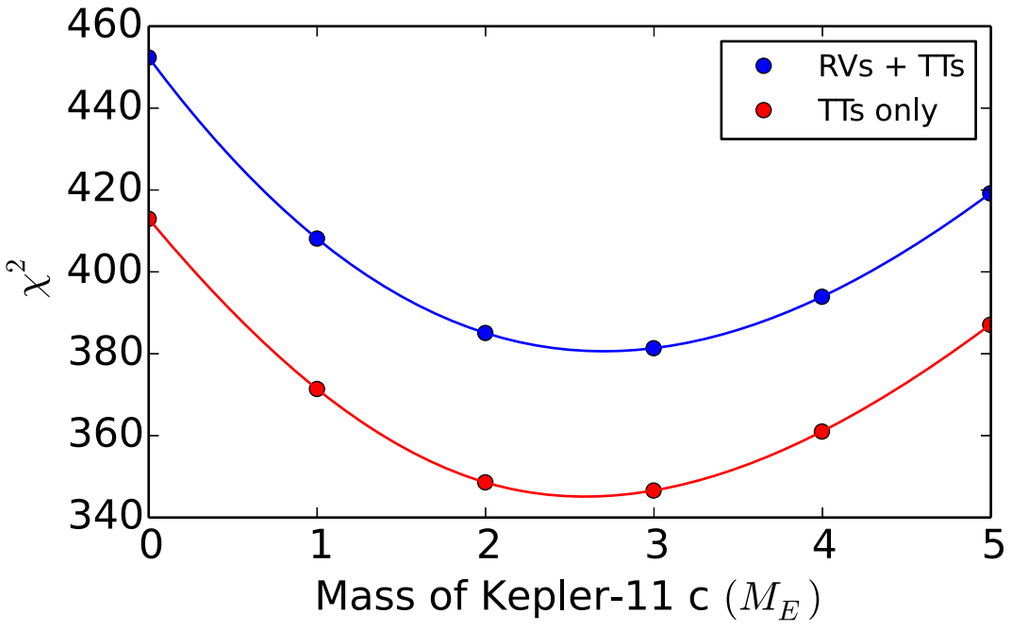
Extras

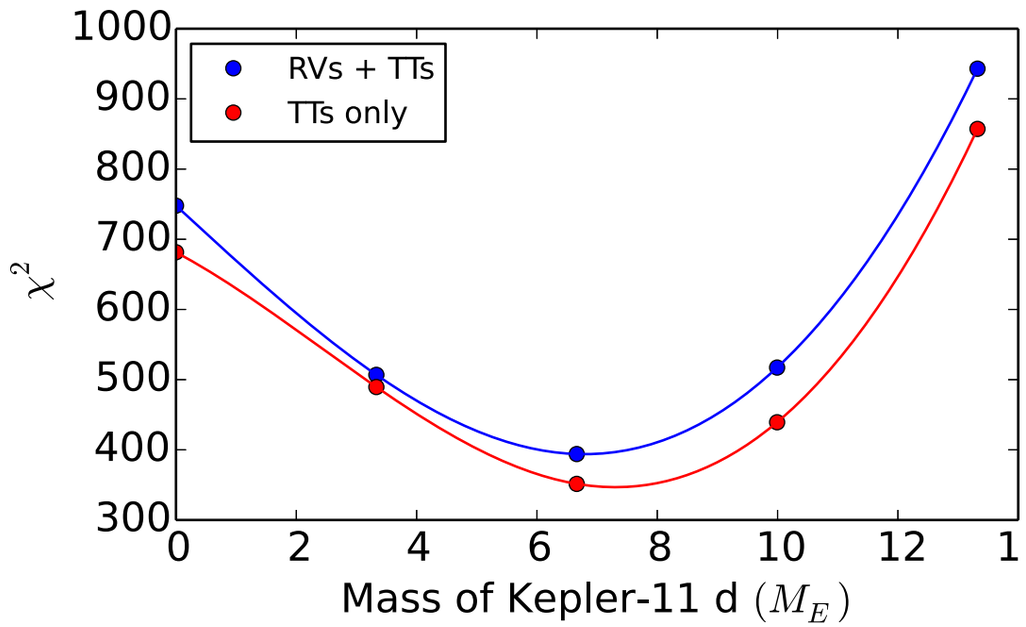
Masses, densities of planets smaller than 4 RE

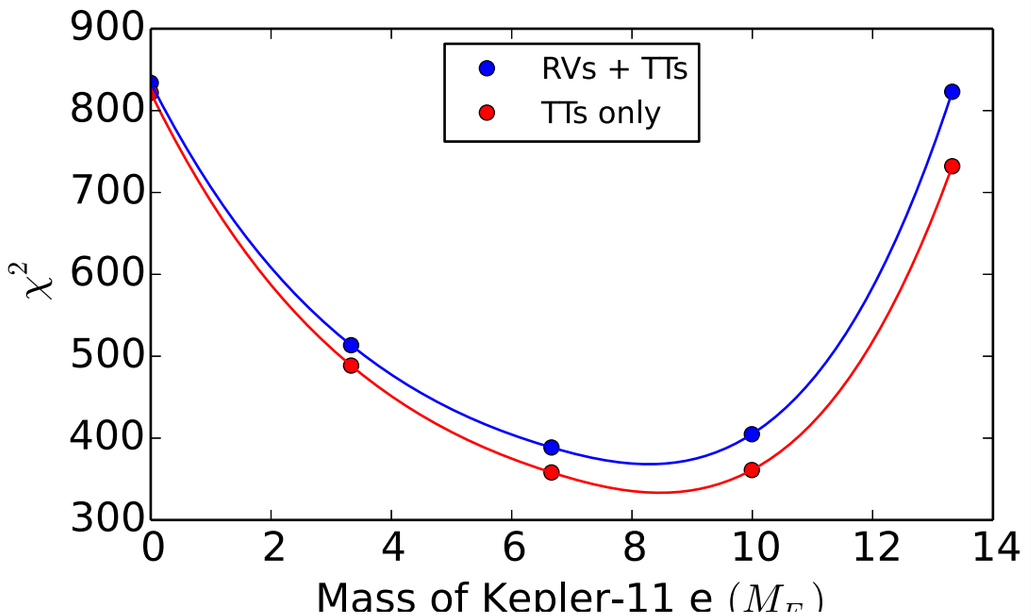


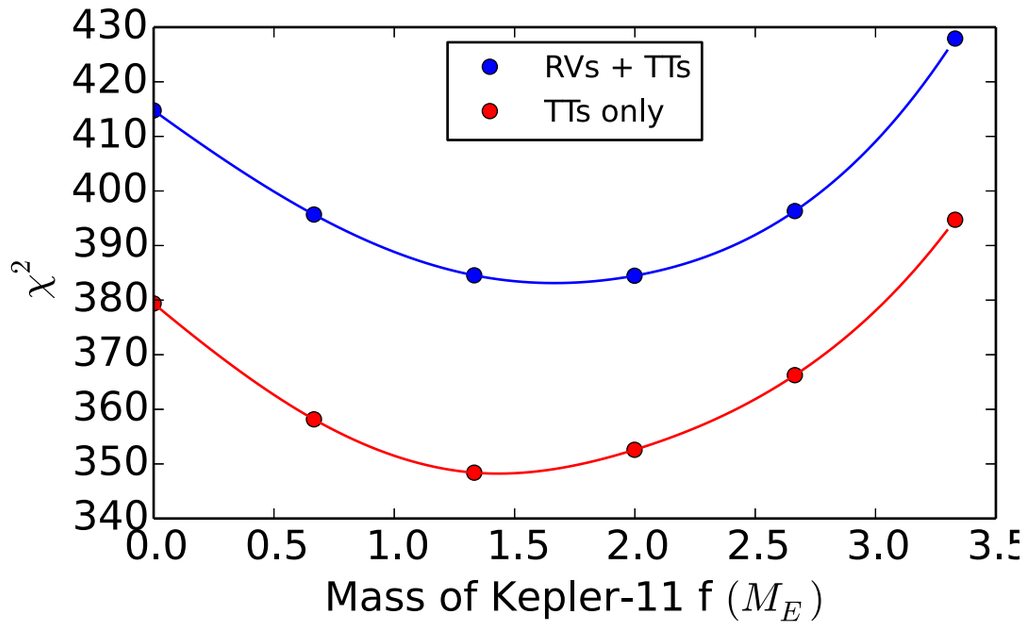


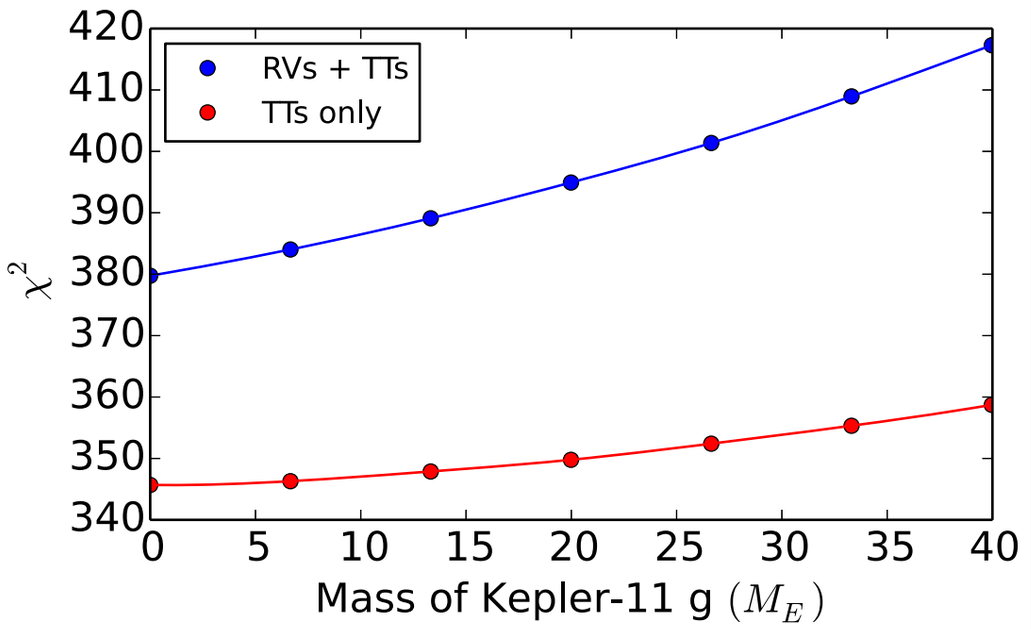

RVs + TTs
TTs only
χ^2
Mass of Kepler-11 b (M_E)

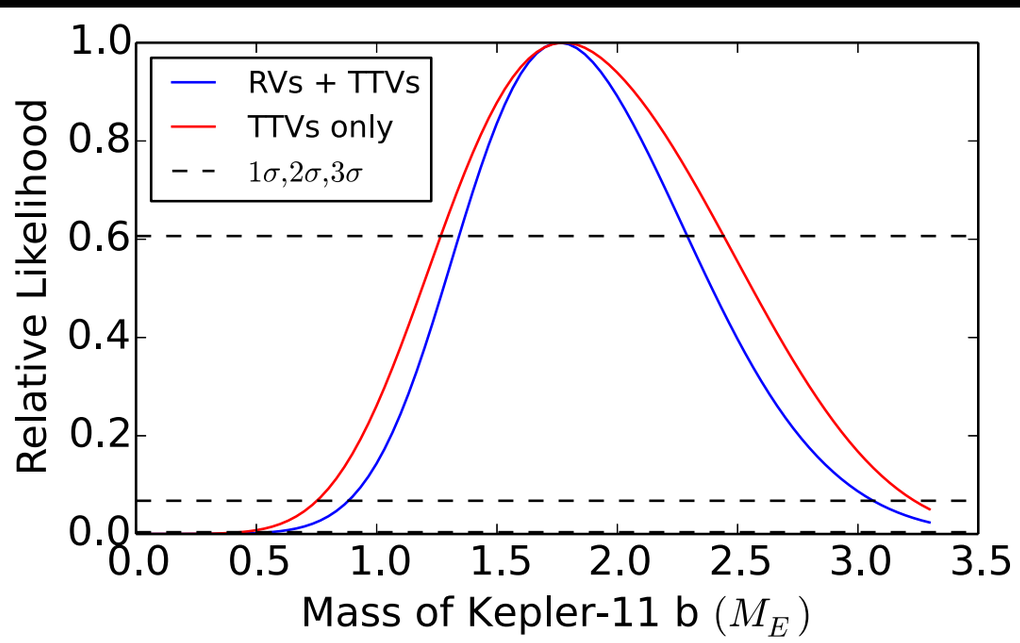

RVs + TTs
TTs only
χ^2
Mass of Kepler-11 c (M_E)

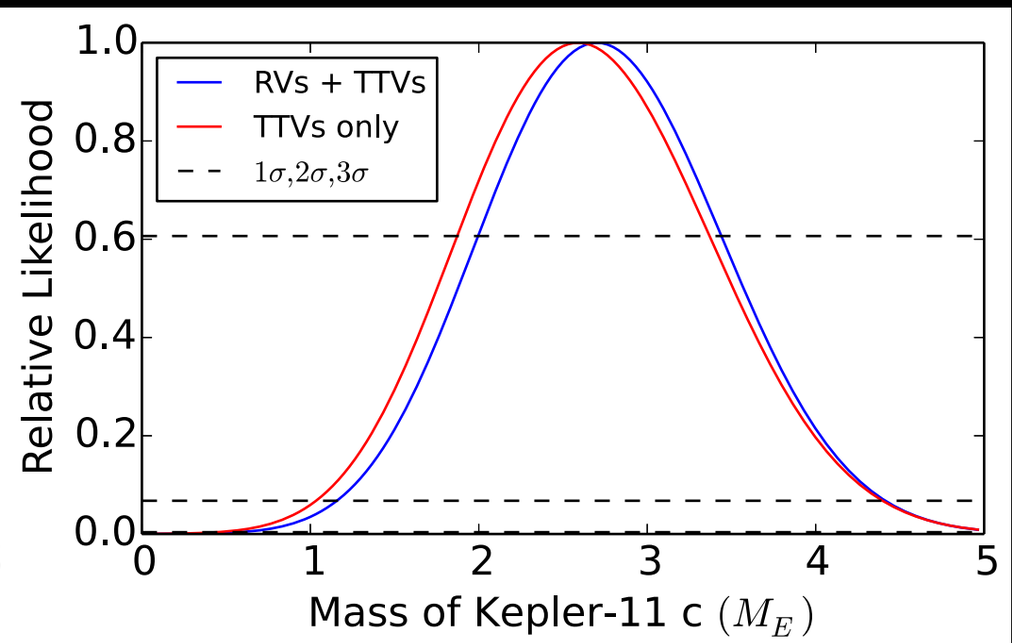

RVs + TTs
TTs only
χ^2
Mass of Kepler-11 d (M_E)

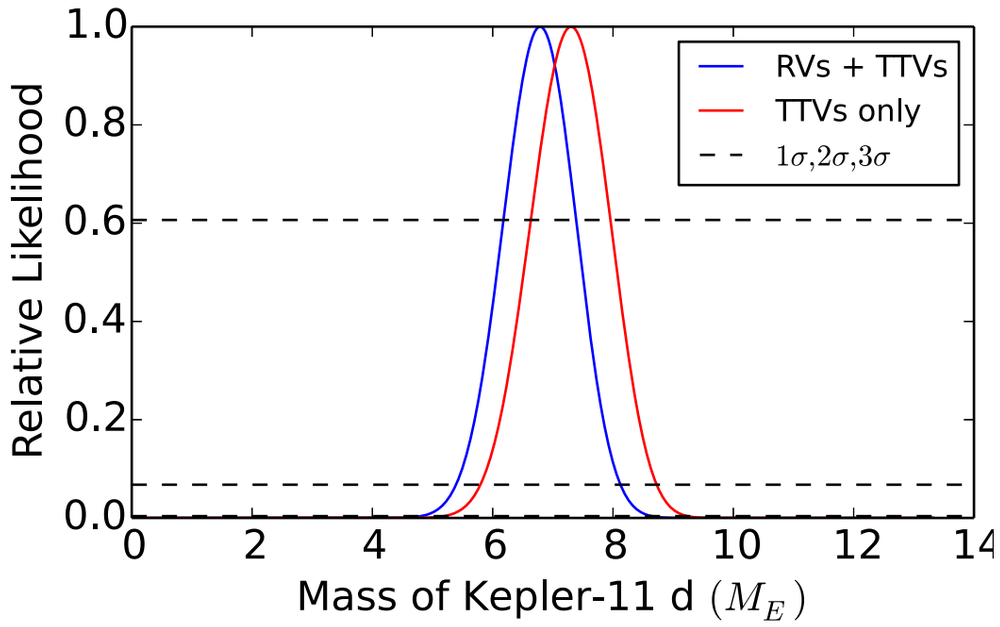

RVs + TTs
TTs only
χ^2
Mass of Kepler-11 e (M_E)

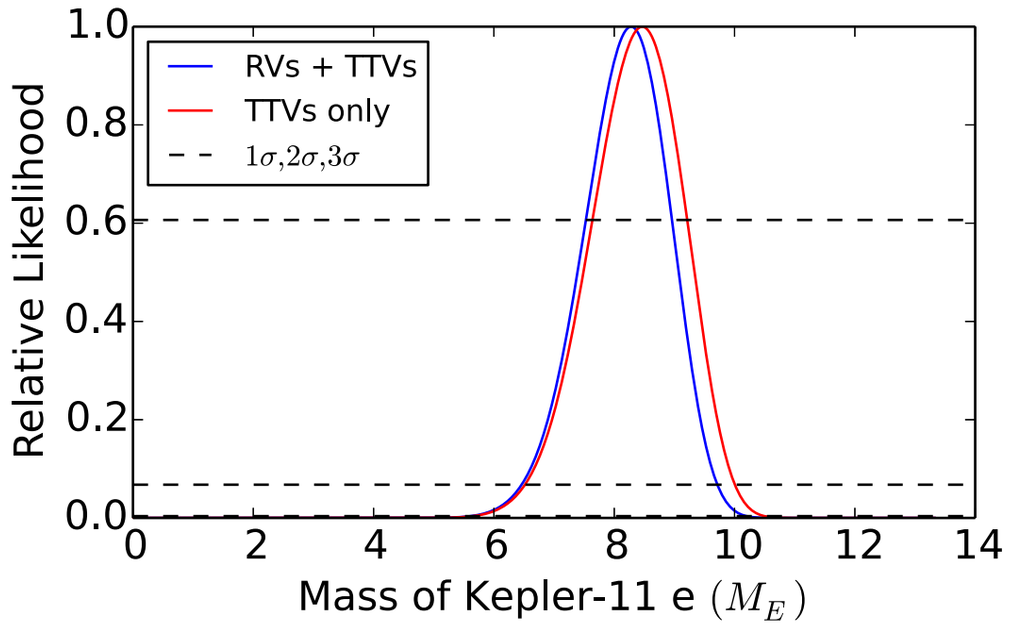

RVs + TTs
TTs only
χ^2
Mass of Kepler-11 f (M_E)

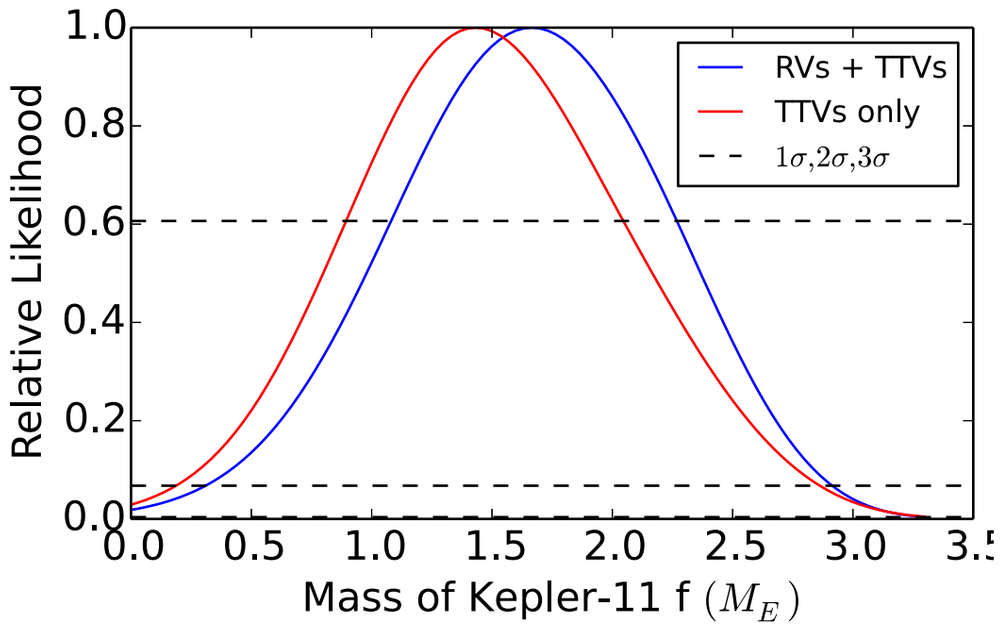

RVs + TTs
TTs only
χ^2
Mass of Kepler-11 g (M_E)

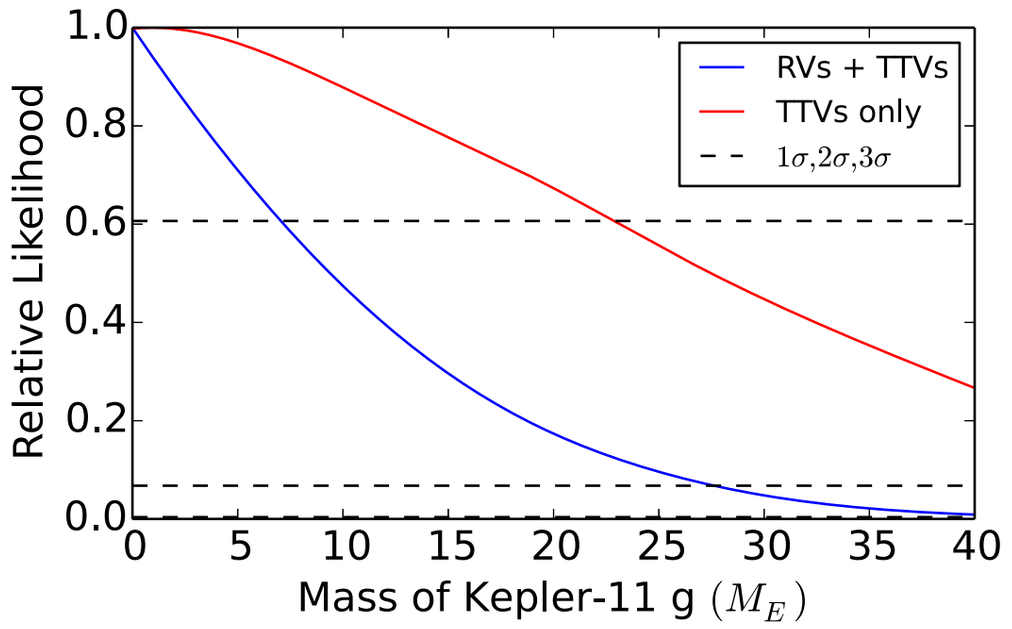

RVs + TTVs
TTVs only
1σ,2σ,3σ
Relative Likelihood
Mass of Kepler-11 b (M_E)


RVs + TTVs
TTVs only
1σ,2σ,3σ
Relative Likelihood
Mass of Kepler-11 c (M_E)


RVs + TTVs
TTVs only
1σ,2σ,3σ
Relative Likelihood
Mass of Kepler-11 d (M_E)


RVs + TTVs
TTVs only
1σ,2σ,3σ
Relative Likelihood
Mass of Kepler-11 e (M_E)


RVs + TTVs
TTVs only
1σ,2σ,3σ
Relative Likelihood
Mass of Kepler-11 f (M_E)


RVs + TTVs
TTVs only
1σ,2σ,3σ
Relative Likelihood
Mass of Kepler-11 g (M_E)