The KOI-94 Multi-Planet System
A Relation for Planet Radius, Mass, and Incident Flux

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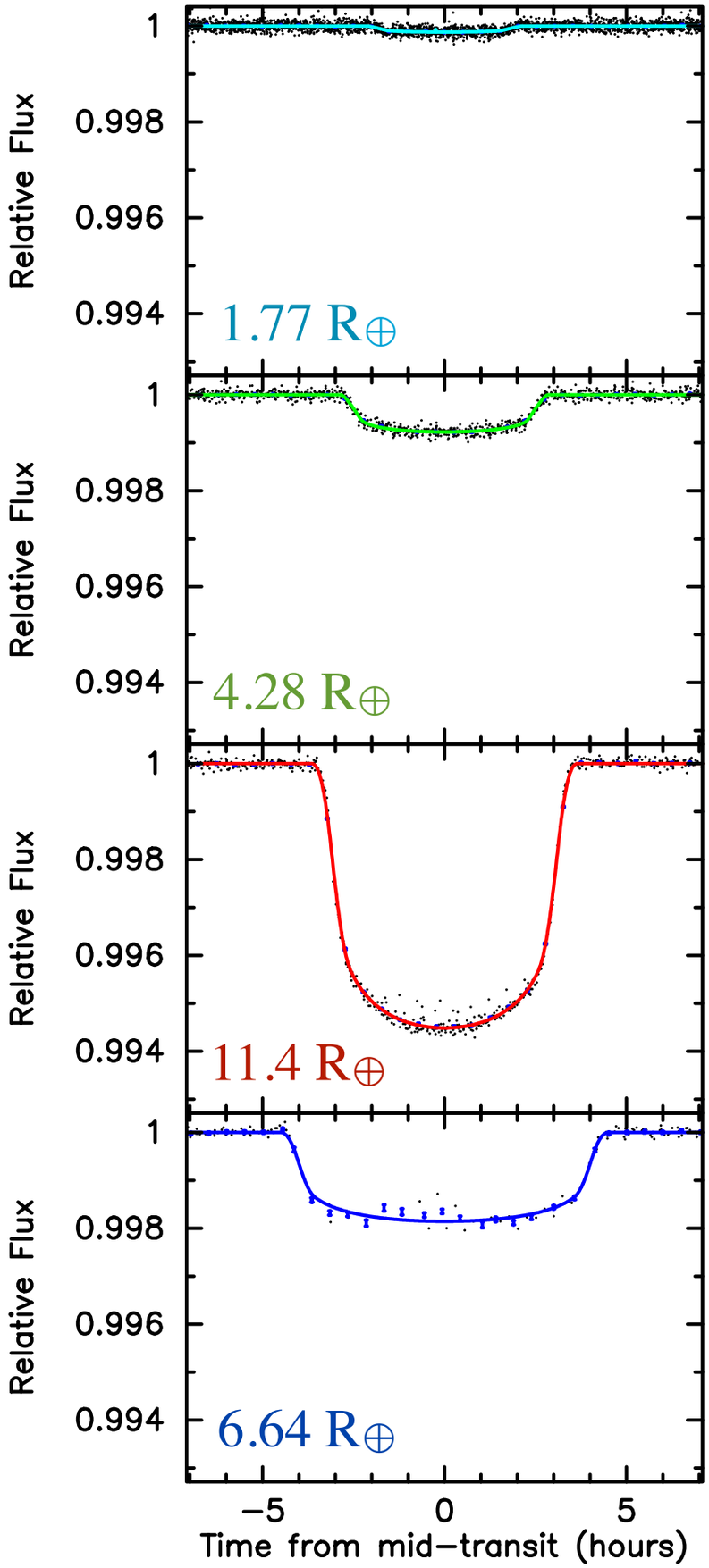
(submitted to ApJ)

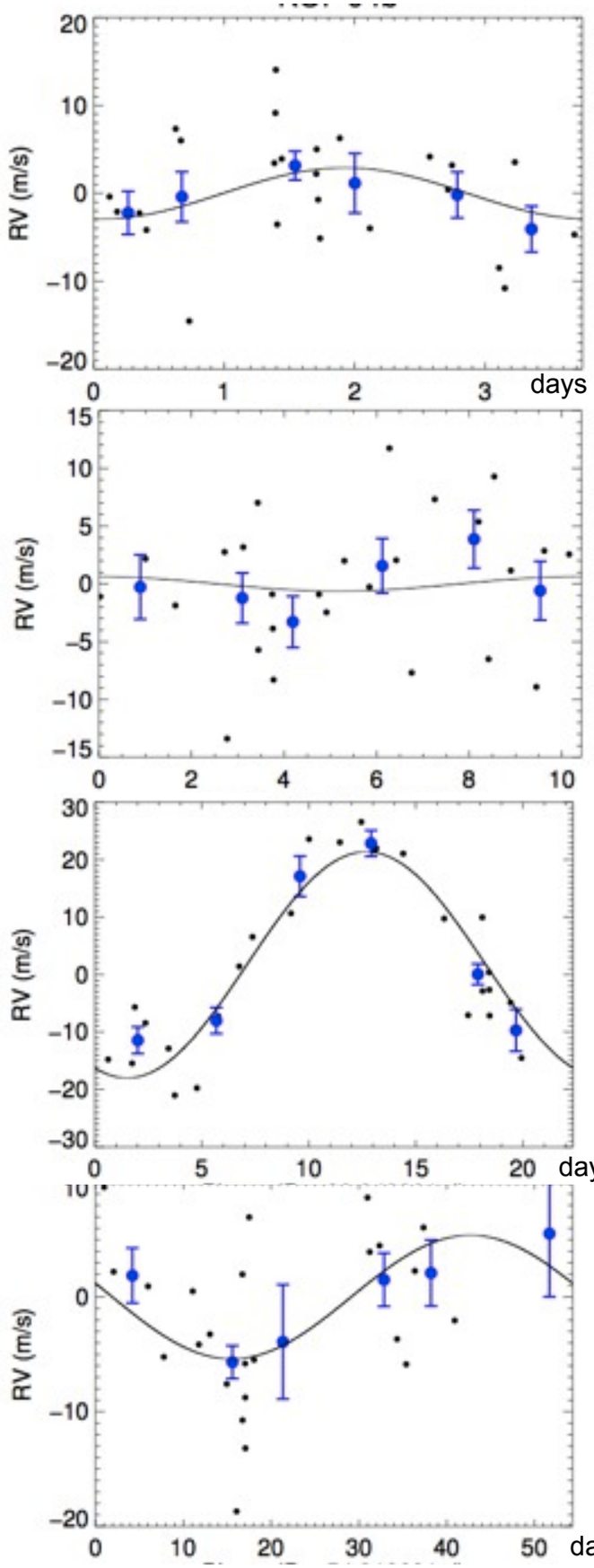
Planet	Period (d)	Radius ($R_\oplus$)	Mass ($M_\oplus$)
KOI-94 b	3.74	1.77	?
KOI-94 c	10.4	4.28	?
KOI-94 d	22.3	11.4	?
KOI-94 e	54.4	6.64	?

Is the giant planet KOI-94d inflated?

- ☑ Answered with 26 Keck/HIRES radial velocity measurements
- ☑ Established a new relation for planet radius, mass and incident flux

KOI-94 Planet	Orbital Period
b	3.74 days
c	10.4 days
d	22.3 days
e	54.4 days





10.5 ± 4.6 M⊕

15.6 ± 11 M⊕

106 ± 11 M⊕

Comparable to Saturn ...but less dense...is it inflated?

35 ± 23 M⊕

135 Exoplanets with Measured Mass and Radius

(exoplanets.org)

Table 4
Exoplanets with Measured Mass and Radius

Name	M_P ($M_\oplus$)	R_P ($R_\oplus$)	Incident Flux (erg s^{-1} cm^{-2})	Period (days)	First Ref.	Orbit Ref.
55 Cnc e	7.862	2.078	3.34E+09	0.737	McArthur et al. (2004)	Demory et al. (2011)
CoRoT-1 b	327.284	16.685	2.96E+09	1.509	Barge et al. (2008)	Barge et al. (2008)
CoRoT-10 b	875.699	10.862	5.39E+07	13.241	Bonomo et al. (2010)	Bonomo et al. (2010)
CoRoT-11 b	746.274	16.013	2.04E+09	2.994	Gandolfi et al. (2010)	Gandolfi et al. (2010)
CoRoT-12 b	292.131	16.125	9.86E+08	2.828	Gillon et al. (2010)	Gillon et al. (2010)
CoRoT-13 b	416.654	9.910	5.99E+08	4.035	Cabrera et al. (2010)	Cabrera et al. (2010)
CoRoT-14 b	2445.485	12.205	3.29E+09	1.512	Tingley et al. (2011)	Tingley et al. (2011)
CoRoT-17 b	781.832	11.422	1.32E+09	3.768	Csizmadia et al. (2011)	Csizmadia et al. (2011)
CoRoT-18 b	1108.075	14.669	1.23E+09	1.900	Hébrard et al. (2011)	Hébrard et al. (2011)
CoRoT-19 b	352.115	14.445	1.72E+09	3.897	Guenther et al. (2012)	Guenther et al. (2012)
CoRoT-2 b	1041.197	16.405	1.27E+09	1.743	Alonso et al. (2008)	Alonso et al. (2008)
CoRoT-4 b	228.008	13.325	3.02E+08	9.202	Moutou et al. (2008); Aigrain et al. (2008)	Moutou et al. (2008)
CoRoT-5 b	147.002	15.542	9.74E+08	4.038	Rauer et al. (2009)	Rauer et al. (2009)
CoRoT-6 b	938.715	13.057	2.43E+08	8.887	Fridlund et al. (2010)	Fridlund et al. (2010)
CoRoT-7 b	5.021	1.677	2.43E+09	0.854	Queloz et al. (2009); Léger et al. (2009)	Queloz et al. (2009)
CoRoT-8 b	68.673	6.383	1.21E+08	6.212	Bordé et al. (2010)	Bordé et al. (2010)
CoRoT-9 b	268.099	11.758	6.59E+06	95.274	Deeg et al. (2010)	Deeg et al. (2010)
GJ 1214 b	6.468	2.675	2.23E+07	1.580	Charbonneau et al. (2009)	Carter et al. (2011)
GJ 436 b	23.105	4.218	4.09E+07	2.644	Butler et al. (2004)	Maness et al. (2007)
HAT-P-1 b	169.196	13.908	6.58E+08	4.465	Bakos et al. (2007a)	Bakos et al. (2007a)
HAT-P-11 b	26.231	4.725	1.33E+08	4.888	Bakos et al. (2010)	Bakos et al. (2010)
HAT-P-12 b	66.997	10.739	1.91E+08	3.213	Hartman et al. (2009)	Hartman et al. (2009)
HAT-P-13 b	272.394	14.344	1.67E+09	2.916	Bakos et al. (2009b)	Winn et al. (2010)
HAT-P-14 b	710.648	12.877	1.37E+09	4.628	Torres et al. (2010)	Torres et al. (2010)
HAT-P-15 b	620.231	12.004	1.51E+08	10.864	Kovács et al. (2010)	Kovács et al. (2010)
HAT-P-16 b	1335.623	14.434	1.58E+09	2.776	Buchhave et al. (2010)	Buchhave et al. (2010)
HAT-P-17 b	168.493	11.310	8.91E+07	10.339	Howard et al. (2012)	Howard et al. (2012)
HAT-P-18 b	62.675	11.142	1.17E+08	5.508	Hartman et al. (2011a)	Hartman et al. (2011a)
HAT-P-19 b	92.889	12.676	2.36E+08	4.009	Hartman et al. (2011a)	Hartman et al. (2011a)
HAT-P-2 b	2819.241	12.956	1.10E+09	5.633	Bakos et al. (2007c)	Pál et al. (2010)
HAT-P-20 b	2316.734	9.708	2.02E+08	2.875	Bakos et al. (2011)	Bakos et al. (2011)
HAT-P-21 b	1296.160	11.466	6.12E+08	4.124	Bakos et al. (2011)	Bakos et al. (2011)
HAT-P-22 b	683.741	12.094	6.12E+08	3.212	Bakos et al. (2011)	Bakos et al. (2011)
HAT-P-23 b	666.163	15.318	4.03E+09	1.213	Bakos et al. (2011)	Bakos et al. (2011)
HAT-P-24 b	217.977	13.908	1.63E+09	3.355	Kipping et al. (2010)	Kipping et al. (2010)
HAT-P-26 b	18.640	6.327	2.23E+08	4.235	Hartman et al. (2011b)	Hartman et al. (2011b)
HAT-P-27 b	195.955	11.623	4.34E+08	3.040	Anderson et al. (2011b)	Anderson et al. (2011b)
HAT-P-28 b	199.536	13.572	8.27E+08	3.257	Buchhave et al. (2011a)	Buchhave et al. (2011a)

Table 4
Exoplanets with Measured Mass and Radius

HAT-P-29 b	247.580	12.396	5.70E+08	5.723	Buchhave et al. (2011a)	Buchhave et al. (2011a)
HAT-P-3 b	189.327	10.067	4.08E+08	2.900	Torres et al. (2007)	Torres et al. (2008)
HAT-P-30 b	225.996	15.005	1.63E+09	2.811	Johnson et al. (2011)	Johnson et al. (2011)
HAT-P-31 b	689.358	11.982	8.46E+08	5.005	Kipping et al. (2011)	Kipping et al. (2011)
HAT-P-32 b	302.182	22.810	2.62E+09	2.150	Hartman et al. (2011c)	Hartman et al. (2011c)
HAT-P-33 b	243.556	20.458	2.60E+09	3.474	Hartman et al. (2011c)	Hartman et al. (2011c)
HAT-P-34 b	1059.600	13.404	7.35E+08	5.453	Bakos et al. (2012)	Bakos et al. (2012)
HAT-P-35 b	335.047	14.915	1.41E+09	3.647	Bakos et al. (2012)	Bakos et al. (2012)
HAT-P-36 b	584.539	14.154	2.49E+09	1.327	Bakos et al. (2012)	Bakos et al. (2012)
HAT-P-37 b	372.996	13.191	6.01E+08	2.797	Bakos et al. (2012)	Bakos et al. (2012)
HAT-P-4 b	213.416	14.266	1.87E+09	3.057	Kovács et al. (2007)	Kovács et al. (2007)
HAT-P-5 b	335.490	14.042	1.27E+09	2.788	Bakos et al. (2007b)	Bakos et al. (2007b)
HAT-P-6 b	336.749	14.893	1.78E+09	3.853	Noyes et al. (2008)	Noyes et al. (2008)
HAT-P-7 b	572.656	15.262	5.57E+09	2.205	Pál et al. (2008)	Winn et al. (2009)
HAT-P-8 b	411.052	16.797	2.24E+09	3.076	Latham et al. (2009)	Latham et al. (2009)
HAT-P-9 b	246.817	15.677	1.24E+09	3.923	Shporer et al. (2009)	Shporer et al. (2009)
HD 149026 b	114.882	7.323	1.78E+09	2.876	Sato et al. (2005)	Carter et al. (2009)
HD 17156 b	1049.670	11.422	1.95E+08	21.217	Fischer et al. (2007)	Barbieri et al. (2009)
HD 189733 b	363.454	12.743	4.71E+08	2.219	Bouchy et al. (2005)	Bouchy et al. (2005)
HD 209458 b	219.181	15.218	9.93E+08	3.525	Henry et al. (2000); Charbonneau et al. (2000)	Torres et al. (2008)
HD 80606 b	1236.479	11.522	1.59E+07	111.437	Naef et al. (2001)	Moutou et al. (2009)
KOI-135 b	1027.001	13.437	1.63E+09	3.024	Borucki et al. (2011)	Bonomo et al. (2012)
KOI-196 b	156.857	9.417	1.40E+09	1.856	Borucki et al. (2011)	Santerne et al. (2011)
KOI-204 b	324.519	13.885	1.51E+09	3.247	Borucki et al. (2011)	Bonomo et al. (2012)
KOI-254 b	162.563	10.750	8.91E+07	2.455	Borucki et al. (2011)	Johnson et al. (2012)
KOI-428 b	691.836	13.101	1.54E+09	6.873	Santerne et al. (2011)	Santerne et al. (2011)
Kepler-10 b	4.539	1.415	4.88E+09	0.837	Batalha et al. (2011)	Batalha et al. (2011)
Kepler-11 b	4.298	1.968	1.86E+08	10.304	Lissauer et al. (2011)	Lissauer et al. (2011)
Kepler-11 c	13.500	3.147	1.36E+08	13.025	Lissauer et al. (2011)	Lissauer et al. (2011)
Kepler-11 d	6.100	3.427	6.50E+07	22.687	Lissauer et al. (2011)	Lissauer et al. (2011)
Kepler-11 e	8.401	4.515	4.11E+07	31.996	Lissauer et al. (2011)	Lissauer et al. (2011)
Kepler-11 f	2.298	2.607	2.48E+07	46.689	Lissauer et al. (2011)	Lissauer et al. (2011)
Kepler-12 b	137.283	18.980	1.09E+09	4.438	Borucki et al. (2011)	Fortney et al. (2011)
Kepler-14 b	2671.703	12.721	1.32E+09	6.790	Borucki et al. (2011)	Buchhave et al. (2011b)
Kepler-15 b	210.532	10.750	3.45E+08	4.943	Borucki et al. (2011)	Endl et al. (2011)
Kepler-16 b	105.833	8.441	4.84E+05	228.776	Borucki et al. (2011)	Doyle et al. (2011)
Kepler-17 b	788.004	14.893	2.10E+09	1.486	Borucki et al. (2011)	Désert et al. (2011)
Kepler-18 b	6.900	5.484	6.32E+08	3.505	Borucki et al. (2011)	Cochran et al. (2011)
Kepler-18 c	17.299	5.484	2.24E+08	7.642	Borucki et al. (2011)	Cochran et al. (2011)
Kepler-18 d	16.399	6.973	9.21E+07	14.859	Borucki et al. (2011)	Cochran et al. (2011)
Kepler-20 b	8.474	1.906	4.70E+08	3.696	Borucki et al. (2011)	Gautier et al. (2012b)
Kepler-20 c	15.734	3.064	1.12E+08	10.854	Borucki et al. (2011)	Gautier et al. (2012b)
Kepler-20 d	7.528	2.745	8.12E+06	77.612	Borucki et al. (2011)	Gautier et al. (2012b)
Kepler-4 b	24.544	3.998	1.54E+09	3.213	Borucki et al. (2010)	Borucki et al. (2010)
Kepler-5 b	672.699	16.024	2.42E+09	3.548	Koch et al. (2010)	Koch et al. (2010)
Kepler-6 b	212.739	14.815	1.16E+09	3.235	Dunham et al. (2010)	Dunham et al. (2010)
Kepler-7 b	139.127	16.550	1.33E+09	4.886	Latham et al. (2010)	Latham et al. (2010)
Kepler-8 b	186.158	15.890	1.73E+09	3.523	Jenkins et al. (2010)	Jenkins et al. (2010)
OGLE-TR-182 b	325.603	12.653	7.45E+08	3.979	Pont et al. (2008)	Pont et al. (2008)
OGLE-TR-211 b	240.675	15.229	2.01E+09	3.677	Udalski et al. (2008)	Udalski et al. (2008)
OGLE2-TR-L9 b	1453.828	18.028	3.89E+09	2.486	Snellen et al. (2009)	Snellen et al. (2009)
Qatar-1 b	346.352	13.034	8.45E+08	1.420	Alsubai et al. (2011)	Alsubai et al. (2011)
TrES-1 b	239.152	11.948	3.88E+08	3.030	Alonso et al. (2004)	Alonso et al. (2004)
TrES-2 b	381.607	13.706	1.14E+09	2.471	O'Donovan et al. (2006)	O'Donovan et al. (2006)
TrES-4 b	292.473	19.607	2.31E+09	3.554	Mandushev et al. (2007)	Mandushev et al. (2007)
TrES-5 b	565.109	13.538	1.09E+09	1.482	Mandushev et al. (2011)	Mandushev et al. (2011)
WASP-1 b	263.078	16.976	2.65E+09	2.520	Collier Cameron et al. (2007)	Simpson et al. (2011a)
WASP-10 b	1013.770	12.094	2.38E+08	3.093	Christian et al. (2009)	Christian et al. (2009)
WASP-11 b	171.543	10.190	1.87E+08	3.722	West et al. (2009b); Bakos et al. (2009a)	West et al. (2009b)
WASP-12 b	432.432	20.044	1.01E+10	1.091	Hebb et al. (2009)	Maciejewski et al. (2011)
WASP-13 b	152.357	15.554	1.12E+09	4.353	Skillen et al. (2009)	Skillen et al. (2009)
WASP-14 b	2444.754	14.344	2.75E+09	2.244	Joshi et al. (2009)	Joshi et al. (2009)
WASP-15 b	172.613	15.990	1.69E+09	3.752	West et al. (2009a)	West et al. (2009a)
WASP-16 b	267.695	11.287	6.64E+08	3.119	Lister et al. (2009)	Lister et al. (2009)
WASP-17 b	156.828	16.909	1.34E+09	3.735	Anderson et al. (2010)	Anderson et al. (2010)
WASP-18 b	3206.179	12.385	7.50E+09	0.941	Hellier et al. (2009b)	Hellier et al. (2009b)
WASP-19 b	360.211	15.520	4.13E+09	0.789	Hebb et al. (2010)	Hellier et al. (2011)
WASP-2 b	288.782	11.993	6.47E+08	2.152	Collier Cameron et al. (2007)	Charbonneau et al. (2007)
WASP-21 b	95.431	11.982	5.75E+08	4.322	Bouchy et al. (2010)	Bouchy et al. (2010)
WASP-22 b	177.678	12.541	9.25E+08	3.533	Maxted et al. (2010a)	Maxted et al. (2010a)
WASP-23 b	277.208	10.772	3.69E+08	2.944	Triaud et al. (2011)	Triaud et al. (2011)
WASP-24 b	346.738	14.557	2.22E+09	2.341	Street et al. (2010)	Simpson et al. (2011a)
WASP-25 b	183.847	13.661	5.06E+08	3.765	Enoch et al. (2011)	Enoch et al. (2011)
WASP-26 b	323.366	14.781	9.03E+08	2.757	Smalley et al. (2010)	Smalley et al. (2010)
WASP-29 b	77.261	8.869	2.04E+08	3.923	Hellier et al. (2010)	Hellier et al. (2010)
WASP-3 b	639.396	14.445	3.56E+09	1.847	Pollacco et al. (2008)	Tripathi et al. (2010)

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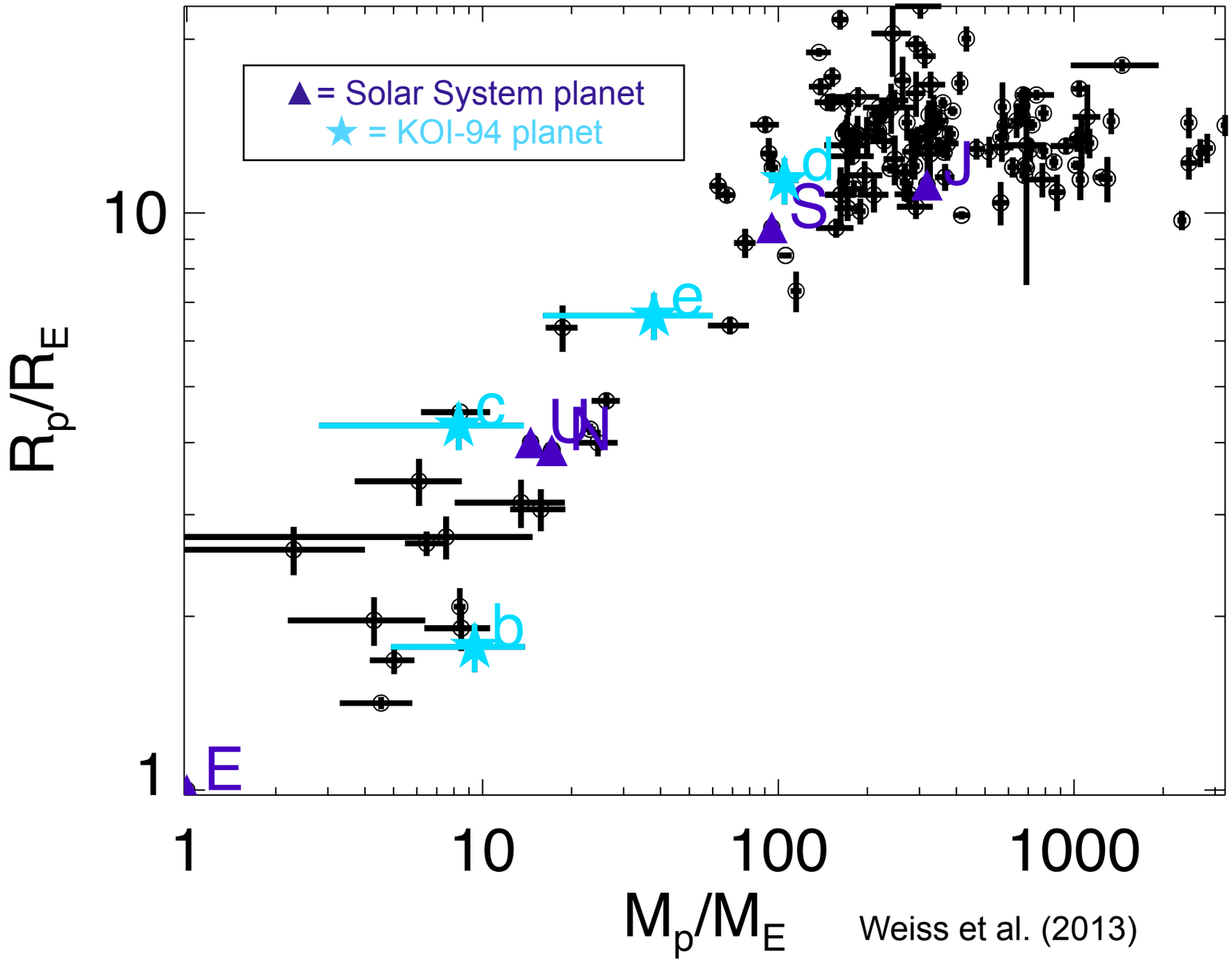
WASP-31 b	152.339	17.211	1.40E+09	3.406	Anderson et al. (2011a)	Anderson et al. (2011a)
WASP-32 b	1129.221	13.213	1.35E+09	2.719	Maxted et al. (2010b)	Maxted et al. (2010b)
WASP-34 b	185.399	13.661	4.13E+08	4.318	Smalley et al. (2011)	Smalley et al. (2011)
WASP-35 b	227.906	14.781	1.01E+09	3.162	Enoch et al. (2011)	Enoch et al. (2011)
WASP-36 b	721.220	14.210	1.89E+09	1.537	Smith et al. (2012)	Smith et al. (2012)
WASP-37 b	570.041	12.989	7.01E+08	3.577	Simpson et al. (2011b)	Simpson et al. (2011b)
WASP-38 b	854.794	12.250	5.49E+08	6.872	Barros et al. (2011)	Barros et al. (2011)
WASP-39 b	90.367	14.221	3.54E+08	4.055	Faedi et al. (2011)	Faedi et al. (2011)
WASP-4 b	388.827	15.352	1.77E+09	1.338	Wilson et al. (2008)	Wilson et al. (2008)
WASP-41 b	296.362	13.437	5.35E+08	3.052	Maxted et al. (2011)	Maxted et al. (2011)
WASP-43 b	564.470	10.414	8.11E+08	0.813	Hellier et al. (2011)	Hellier et al. (2011)
WASP-48 b	312.807	18.700	3.88E+09	2.144	Enoch et al. (2011)	Enoch et al. (2011)
WASP-5 b	516.398	13.112	2.09E+09	1.628	Anderson et al. (2008)	Anderson et al. (2008)
WASP-50 b	467.967	12.911	8.54E+08	1.955	Gillon et al. (2011)	Gillon et al. (2011)
WASP-6 b	165.697	13.706	4.46E+08	3.361	Gillon et al. (2009)	Gillon et al. (2009)
WASP-7 b	292.162	10.246	8.60E+08	4.955	Hellier et al. (2009a)	Hellier et al. (2009a)
WASP-8 b	679.482	11.623	1.76E+08	8.159	Queloz et al. (2010)	Queloz et al. (2010)
XO-1 b	291.903	13.504	4.82E+08	3.942	McCullough et al. (2006)	McCullough et al. (2006)
XO-2 b	180.056	11.007	6.93E+08	2.616	Burke et al. (2007)	Burke et al. (2007)
XO-5 b	366.286	11.534	4.82E+08	4.188	Burke et al. (2008)	Burke et al. (2008)
KOI-94 b	9.400	1.770	1.58E+09	3.743	Borucki et al. (2011)	Weiss et al. (2013)
KOI-94 c	8.300	4.280	4.03E+08	10.424	Borucki et al. (2011)	Weiss et al. (2013)
KOI-94 d	105.000	11.400	1.46E+08	22.343	Borucki et al. (2011)	Weiss et al. (2013)
KOI-94 e	38.000	6.640	4.46E+07	54.320	Batalha et al. (2012)	Weiss et al. (2013)
Earth	1.000	1.000	1.07E+06	365.250		
Jupiter	317.817	11.198	3.97E+04	4336.069		
Saturn	95.027	9.440	1.17E+04	10833.641		
Uranus	14.535	4.003	2.91E+03	30730.951		
Neptune	17.147	3.879	1.19E+03	60157.796		

What can we learn from these mass and radius measurements?

Planet Radius vs. Mass

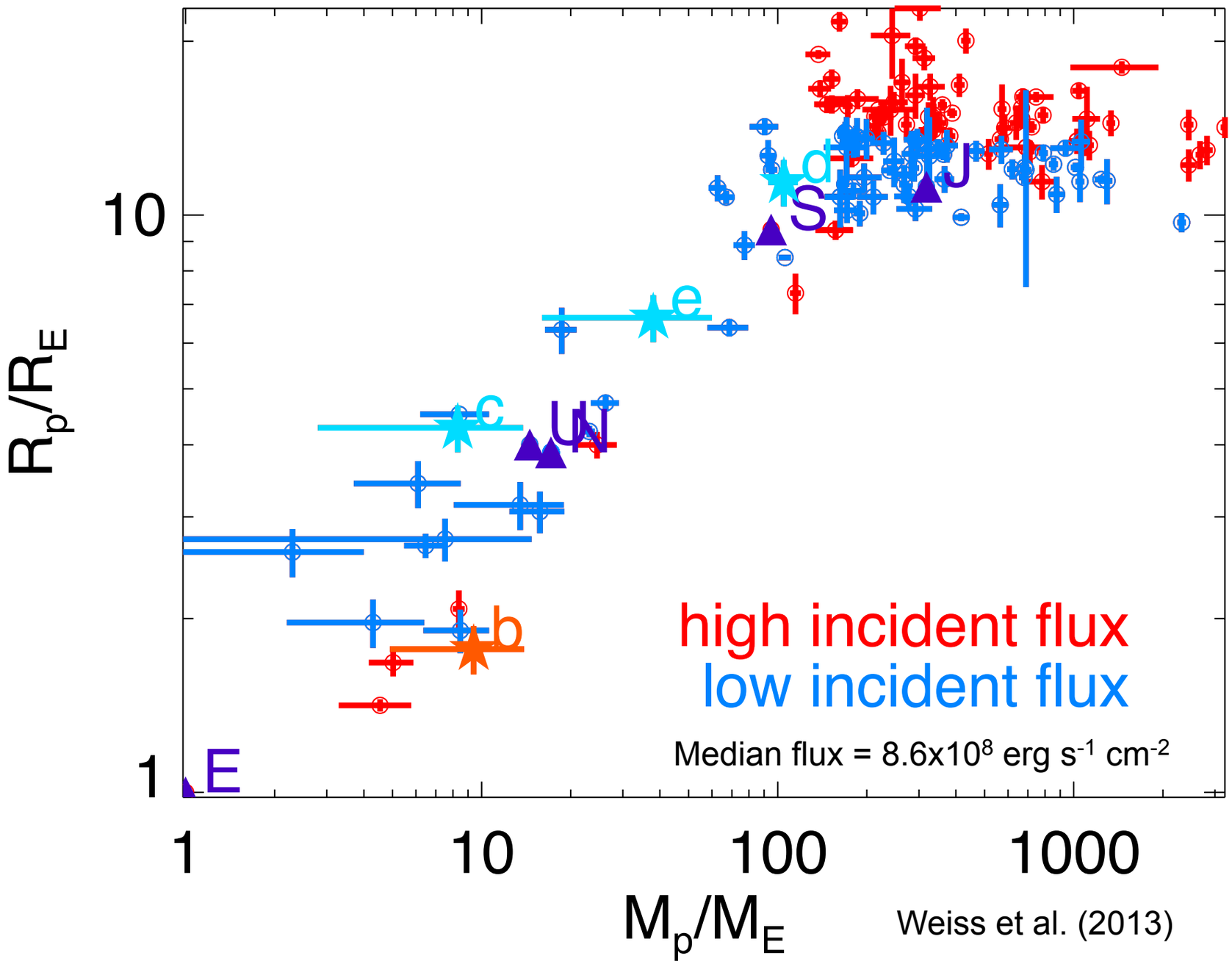
(exoplanets.org)



Planet Radius, Mass, and Incident Flux

(exoplanets.org)

$$\langle F \rangle = \sigma T_{\rm eff}^4 \frac{R_\star^2}{4\pi a^2} \sqrt{\frac{1}{1-e^2}}$$



▲= Solar System planet
★ = KOI-94 planet

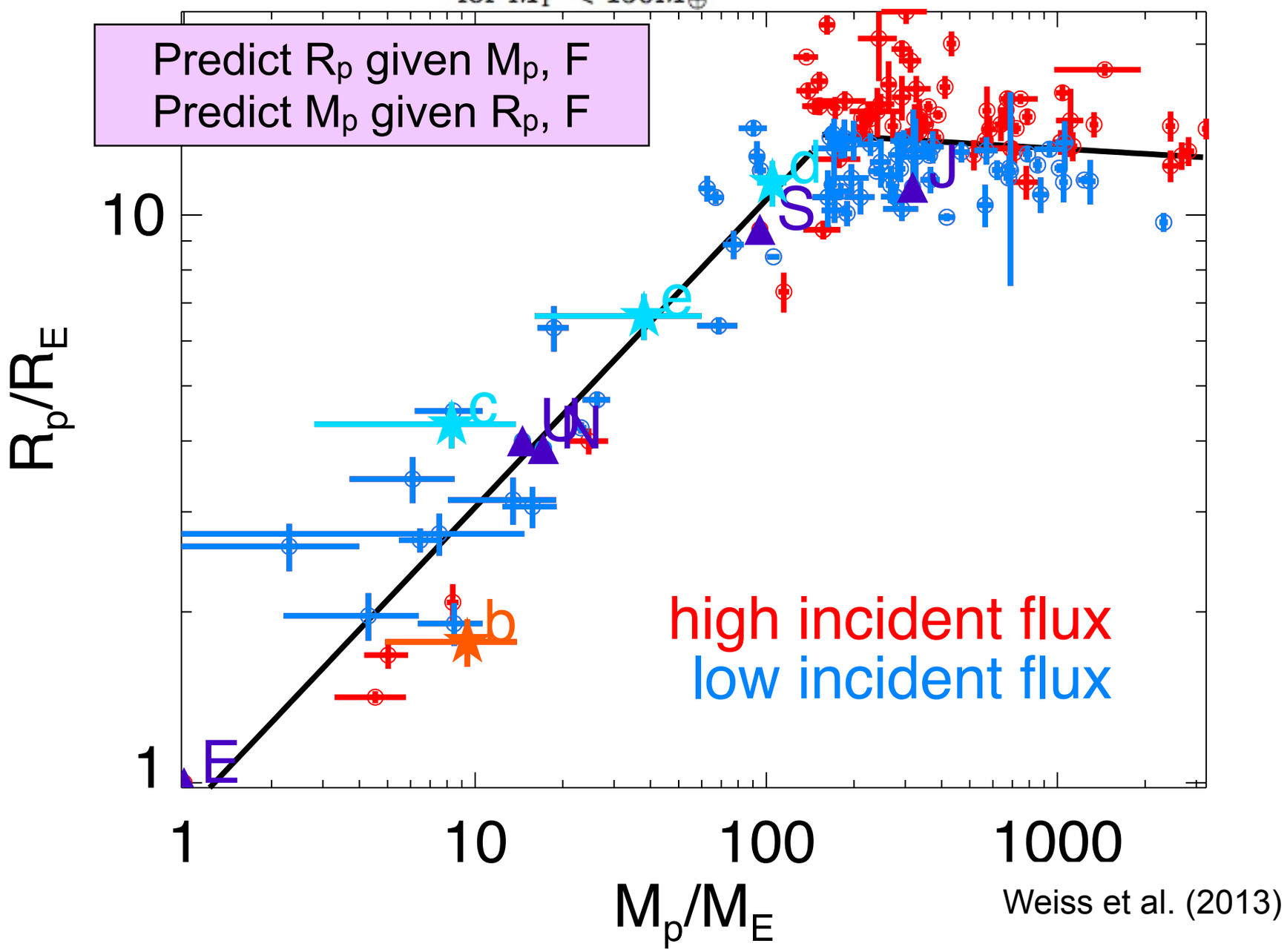
Relation between incident flux and radius for giant planets:
Fortney et al. (2011)
Miller & Fortney (2011)
Demory & Seager (2011)
Enoch et al. (2012)

A Relation for Planet Radius, Mass, and Incident Flux

(exoplanets.org)

$$\frac{R_P}{R_\oplus} = 1.78 \left(\frac{M_P}{M_\oplus}\right)^{0.53} \left(\frac{F}{\mathrm{erg\,s^{-1}\,cm^{-2}}}\right)^{-0.03} \quad \text{for } M_P < 150 M_\oplus$$

$$\frac{R_P}{R_\oplus} = 2.45 \left(\frac{M_P}{M_\oplus}\right)^{-0.039} \left(\frac{F}{\mathrm{erg\,s^{-1}\,cm^{-2}}}\right)^{0.094} \quad \text{for } M_P > 150 M_\oplus$$



Weiss et al. (2013)

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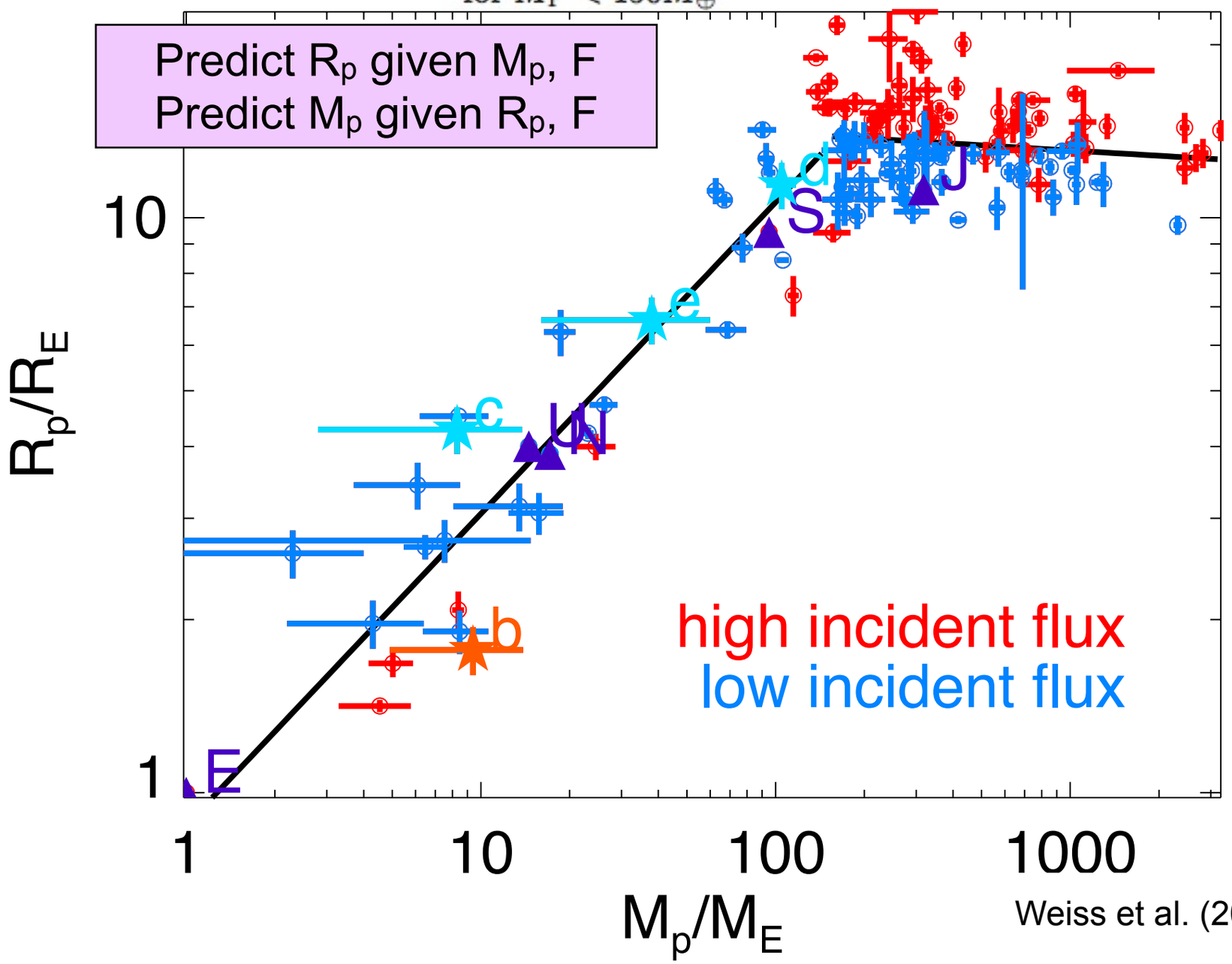
(exoplanets.org)

Uncertainties: 10% 60% 25% 5%

$$\frac{R_P}{R_\oplus} = 1.78 \left(\frac{M_P}{M_\oplus}\right)^{0.53} \left(\frac{F}{\mathrm{erg\,s^{-1}\,cm^{-2}}}\right)^{-0.03} \quad \text{for } M_P < 150 M_\oplus$$

$$\frac{R_P}{R_\oplus} = 2.45 \left(\frac{M_P}{M_\oplus}\right)^{-0.039} \left(\frac{F}{\mathrm{erg\,s^{-1}\,cm^{-2}}}\right)^{0.094} \quad \text{for } M_P > 150 M_\oplus$$

Predict R_p given M_p, F
Predict M_p given R_p, F



Weiss et al. (2013)

A Relation for Planet Radius, Mass, and Incident Flux

(exoplanets.org)

Uncertainties: 10% 60% 25% 5%

$$\frac{R_P}{R_\oplus} = 1.78 \left(\frac{M_P}{M_\oplus}\right)^{0.53} \left(\frac{F}{\mathrm{erg\,s^{-1}\,cm^{-2}}}\right)^{-0.03} \quad \text{for } M_P < 150 M_\oplus$$

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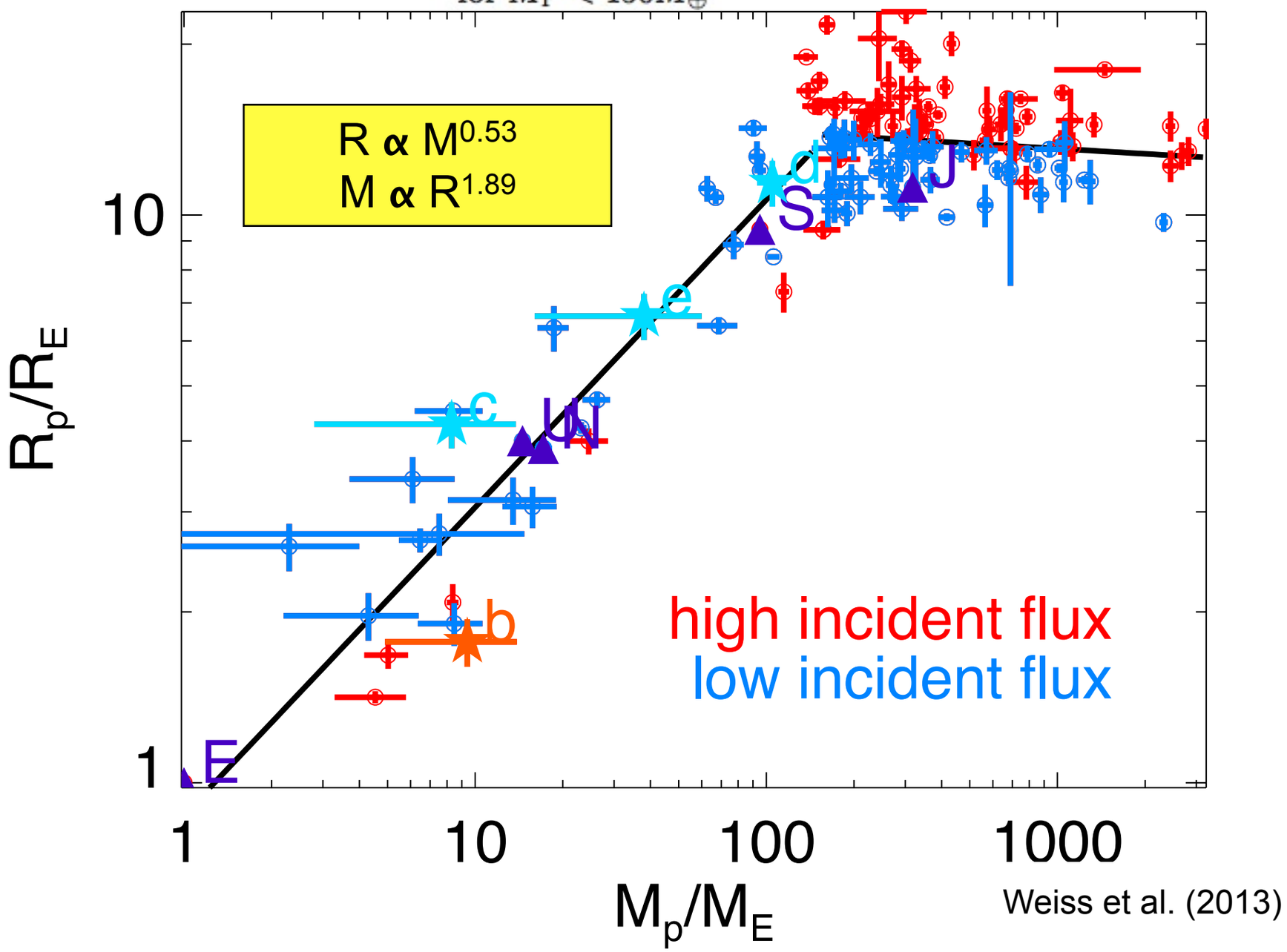

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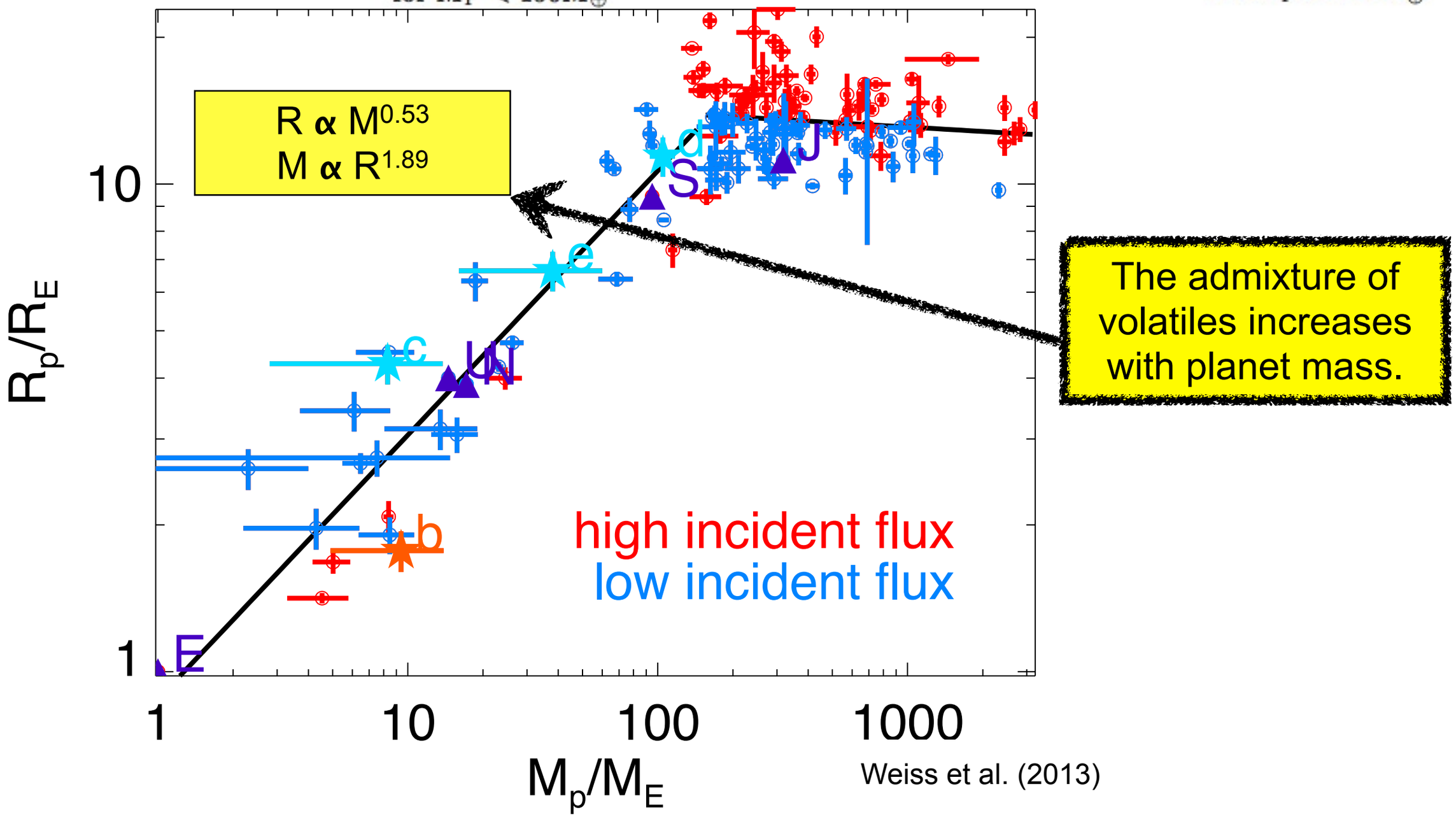
$$\frac{R_P}{R_\oplus} = 2.45 \left(\frac{M_P}{M_\oplus}\right)^{-0.039} \left(\frac{F}{\mathrm{erg\,s^{-1}\,cm^{-2}}}\right)^{0.094} \quad \text{for } M_P > 150 M_\oplus$$



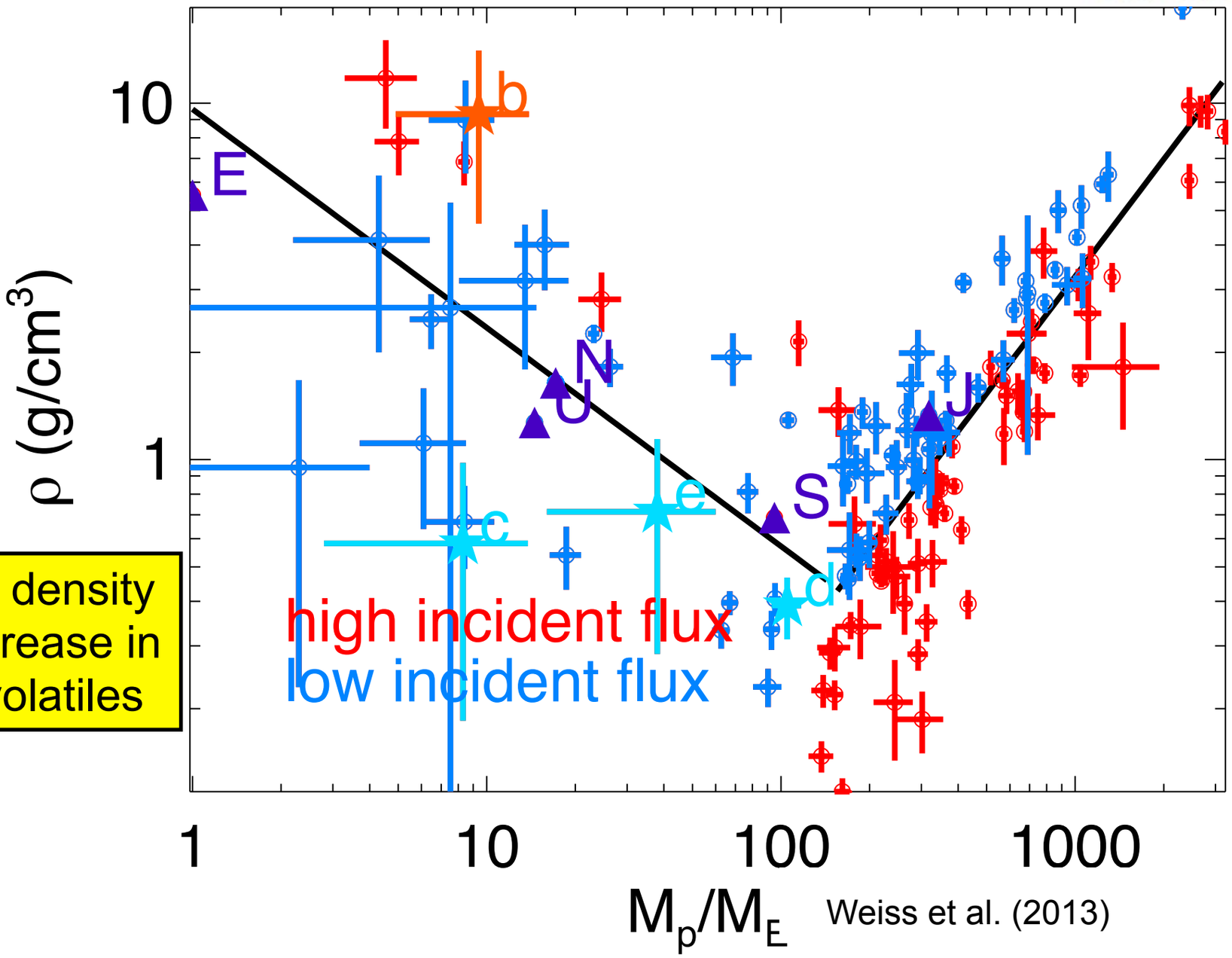
Weiss et al. (2013)

A Relation for Planet Radius, Density, and Incident Flux

(exoplanets.org).

$$\frac{\rho_{\rm P}}{\rm g\,cm^{-3}} = 1.29 \left(\frac{M_{\rm P}}{M_\oplus}\right)^{-0.60} \left(\frac{F}{\rm erg\,s^{-1}\,cm^{-2}}\right)^{0.09} \quad \text{for } M_{\rm P} < 150 M_\oplus$$

$$\frac{\rho_{\rm P}}{\rm g\,cm^{-3}} = 0.48 \left(\frac{M_{\rm P}}{M_\oplus}\right)^{1.10} \left(\frac{F}{\rm erg\,s^{-1}\,cm^{-2}}\right)^{-0.28} \quad \text{for } M_{\rm P} > 150 M_\oplus$$



Decrease in density indicates increase in fraction of volatiles

Weiss et al. (2013)

PRELIMINARY

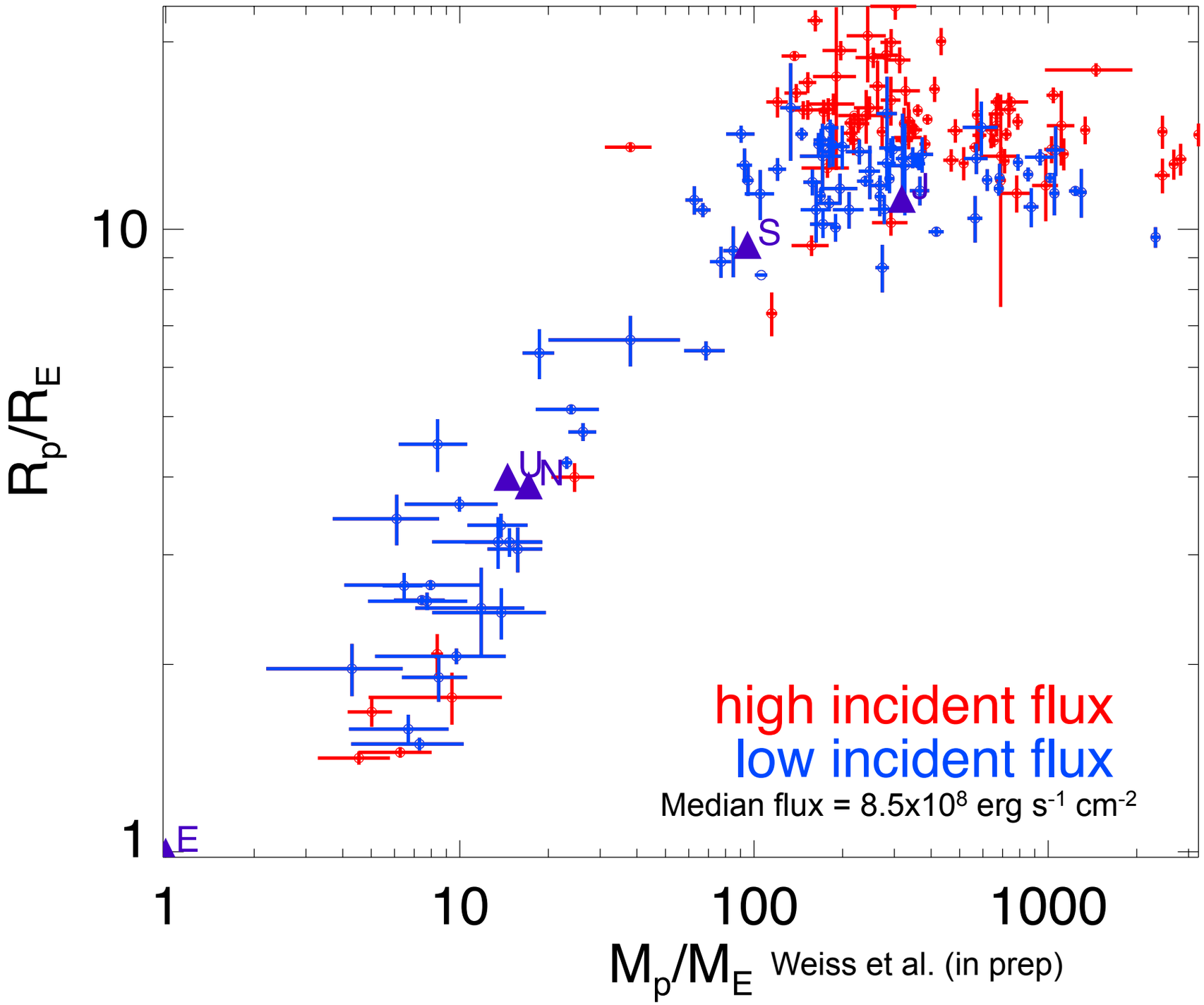
Improved MRF Relation:
+15 low-mass Kepler/Keck planets with $M_p > 2\sigma_{Mp}$

KOI	Period (d)	Rp ($R_\oplus$)	σ_{Rp}	Mp ($M_\oplus$)	σ_{Mp}	Flux (erg cm^{-2} s^{-1})	σ(Flux)
41.02	6.89000	1.49000	0.0350000	7.29000	3.02000	5.8974923e+08	3.8598701e+08
82.01	16.1500	2.52627	0.0823784	7.74000	2.86000	28335601.	5161990.6
104.01	2.51000	3.34674	0.145895	13.8000	3.19000	3.2060587e+08	2.3855669e+08
116.01	13.5700	2.46287	0.396625	11.8200	4.76000	1.2433703e+08	59014905.
122.01	11.5200	3.61715	0.0996954	9.97000	3.47000	2.4496492e+08	1.3682149e+08
148.02	9.67000	3.14292	0.166348	14.7500	4.34000	96377847.	23107909.
153.02	4.75000	2.06100	0.0600000	9.74000	4.59000	1.1415922e+08	42612801.
244.01	12.7200	5.13601	0.0902431	23.9000	5.78000	2.5332929e+08	92752952.
244.02	6.24000	2.68163	0.0471181	7.95000	3.90000	6.5477007e+08	3.8431331e+08
246.01	5.40000	2.53612	0.0387661	7.43000	1.46000	5.5595072e+08	3.4696649e+08
283.01	16.0900	2.42170	0.229301	13.8400	5.78000	86509387.	17598221.
299.01	1.54000	1.84855	0.206319	4.14000	2.10000	2.0972035e+09	1.6297212e+09
305.01	4.60000	1.57430	0.0860274	6.68000	2.48000	1.3670523e+08	96839175.
321.01	2.43000	1.44459	0.0283784	6.27000	1.75000	1.0015107e+09	8.4299629e+08

Used rp/rs from BangOgram, rstar from asteroseismology to rescale rp

Improved MRF Relation:
+15 low-mass Kepler/Keck planets with $M_p > 2\sigma_{Mp}$

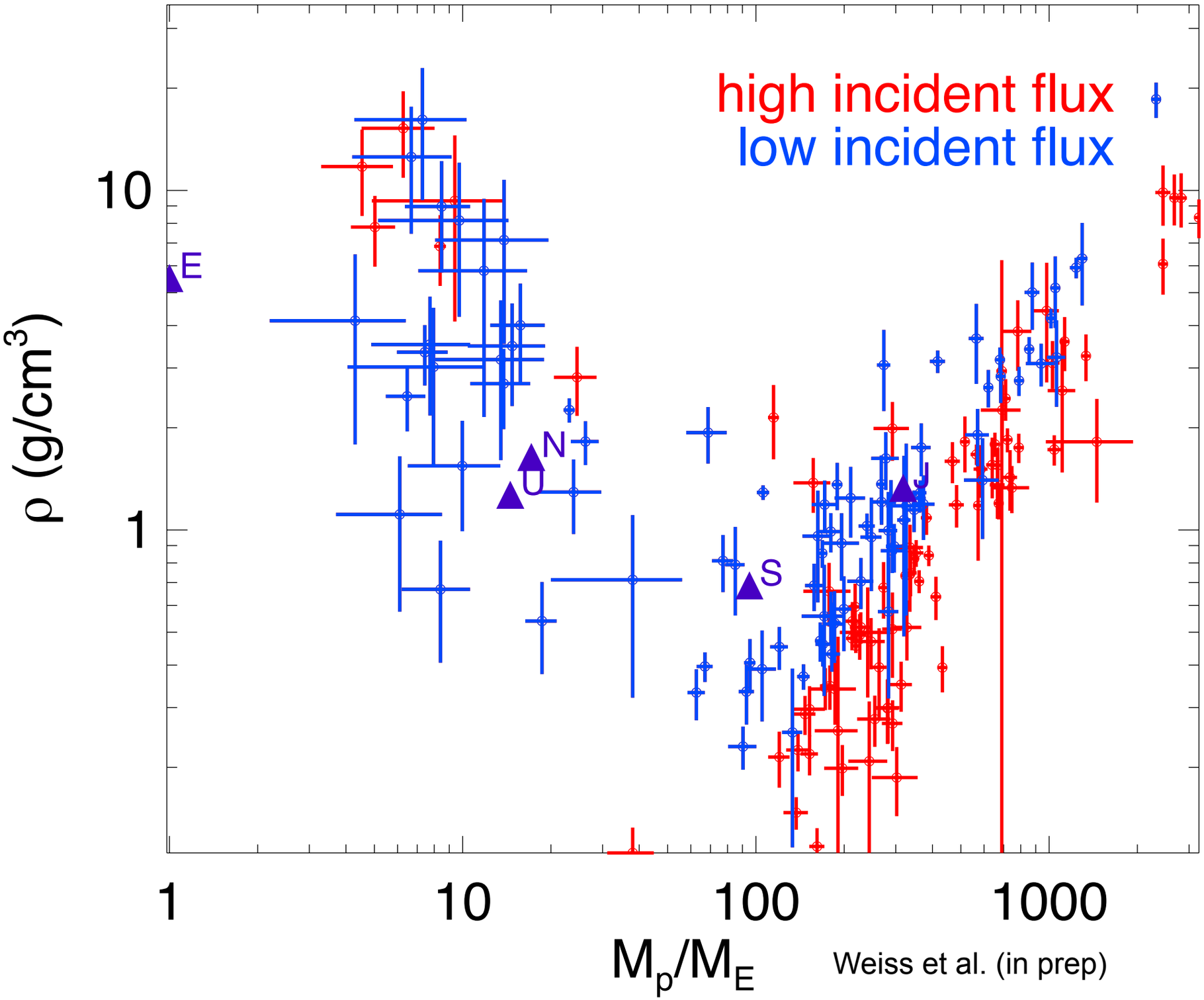
+26 new from exoplanets.org



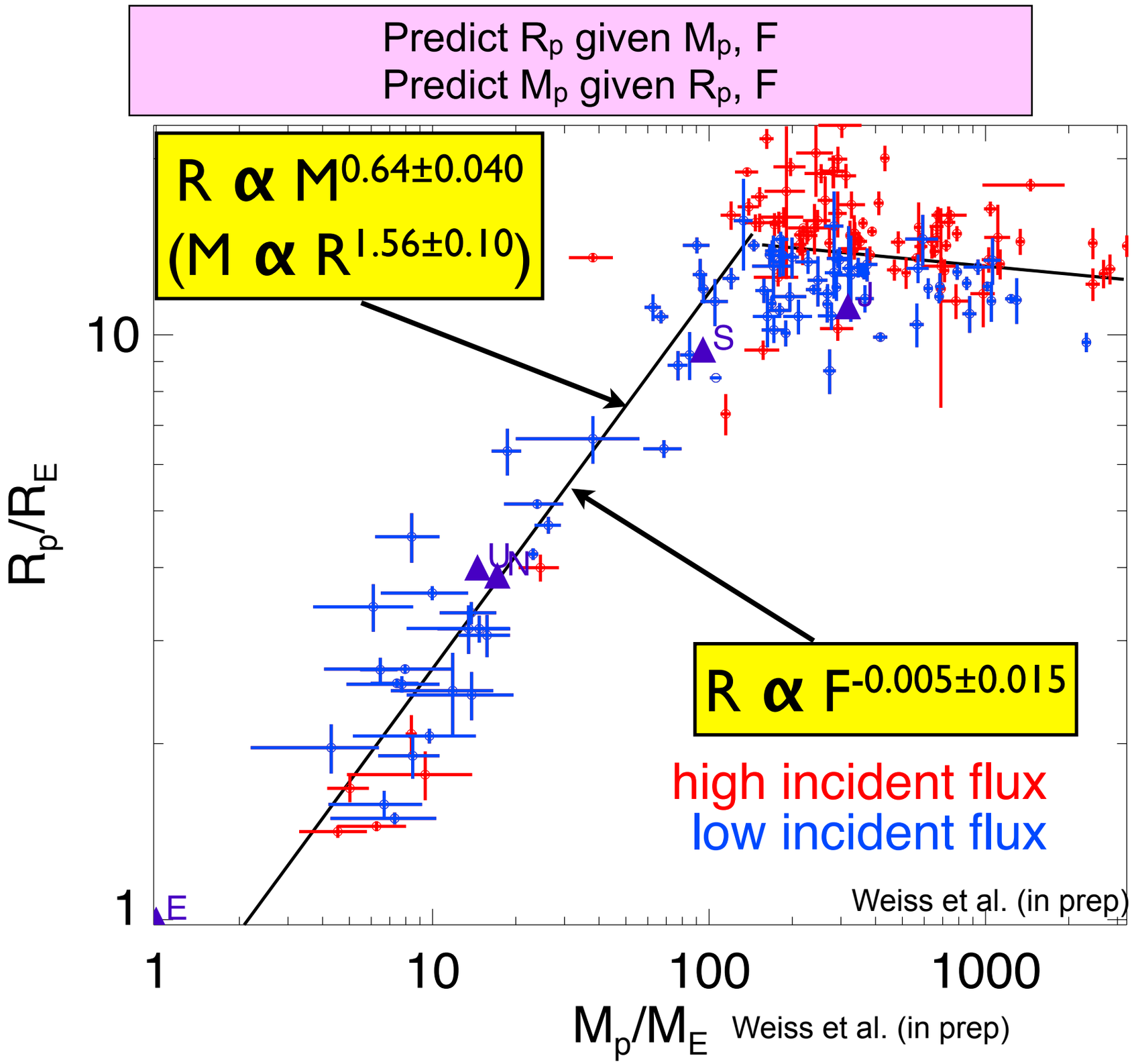
exoplanets.org 2013/2/11
Median flux = 8.45E8 erg cm-2 s-1
48 low-mass planets

Improved MRF Relation:
+15 low-mass Kepler/Keck planets with $M_p > 2\sigma_{Mp}$

+26 new from exoplanets.org



Improved MRF Relation: **176 Exoplanets**



Summary

KOI-94 has 4 transiting planets, including a "warm Jupiter:"

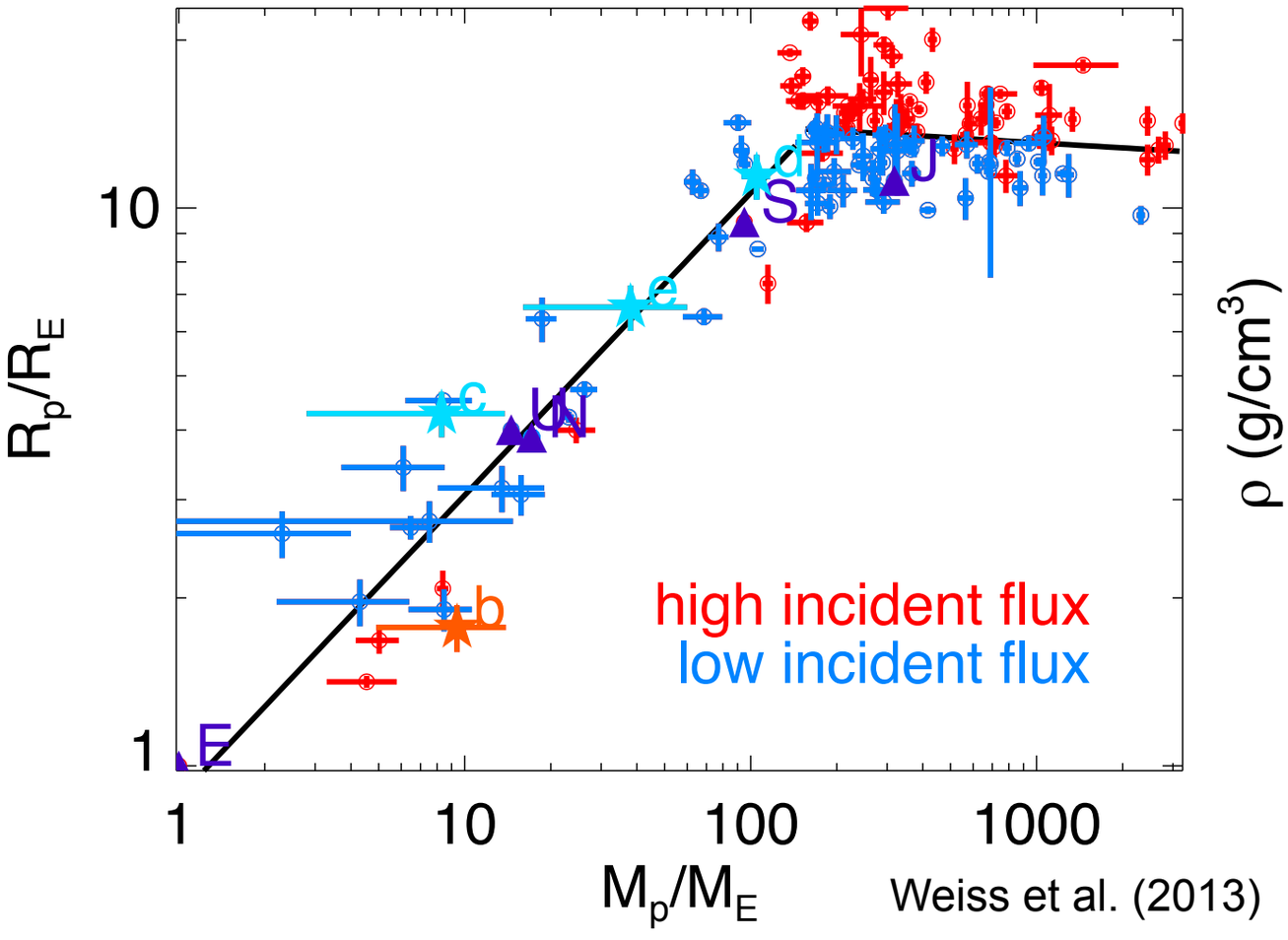
Planet	Period (d)	Radius ($R_\oplus$)	Mass ($M_\oplus$)
b	3.74	1.77	10.5 ± 4.6
c	10.4	4.28	15.6 ± 11
d	22.3	11.4	106 ± 11
e	54.4	6.64	35 ± 23

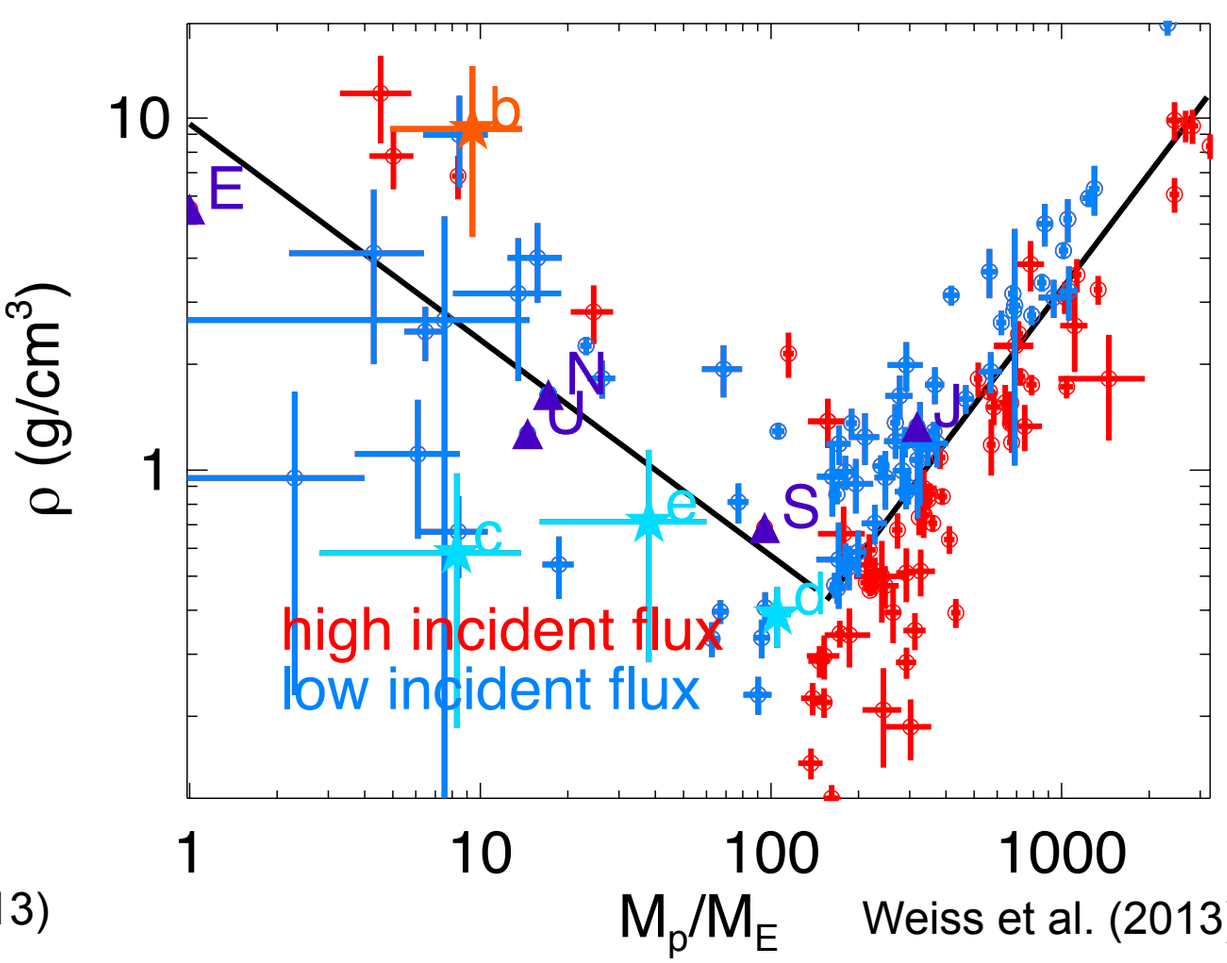
You can predict a planet's radius from its mass and incident flux:

$$M_P > 150 M_\oplus: \quad \frac{R_P}{R_\oplus} = 1.78 \left(\frac{M_P}{M_\oplus}\right)^{0.53} \left(\frac{F}{\mathrm{erg\,s^{-1}\,cm^{-2}}}\right)^{-0.03}$$

$$M_P < 150 M_\oplus: \quad \frac{R_P}{R_\oplus} = 2.45 \left(\frac{M_P}{M_\oplus}\right)^{-0.039} \left(\frac{F}{\mathrm{erg\,s^{-1}\,cm^{-2}}}\right)^{0.094}$$

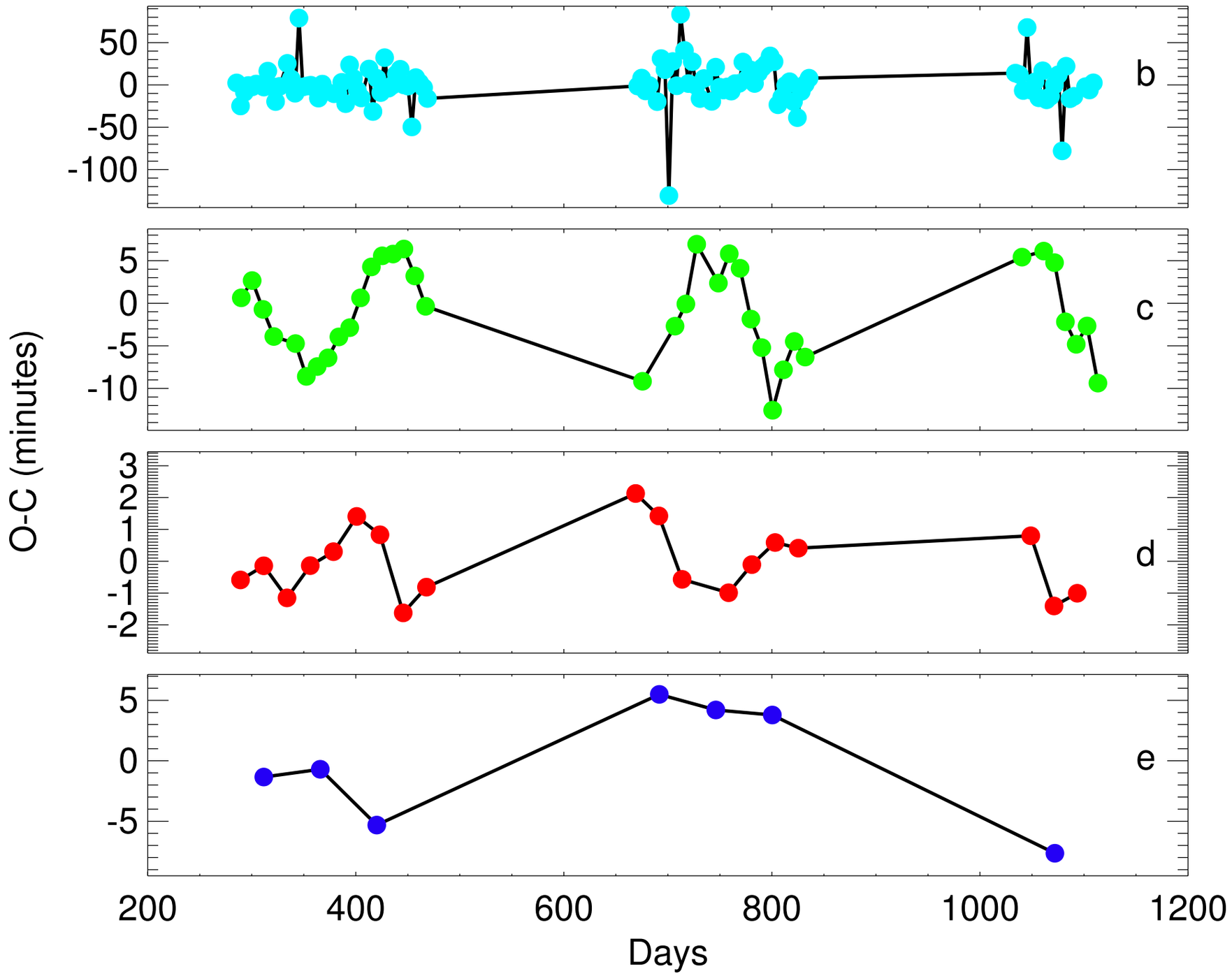
The admixture of volatiles increases with planet mass for M < 150 $M_\oplus$.





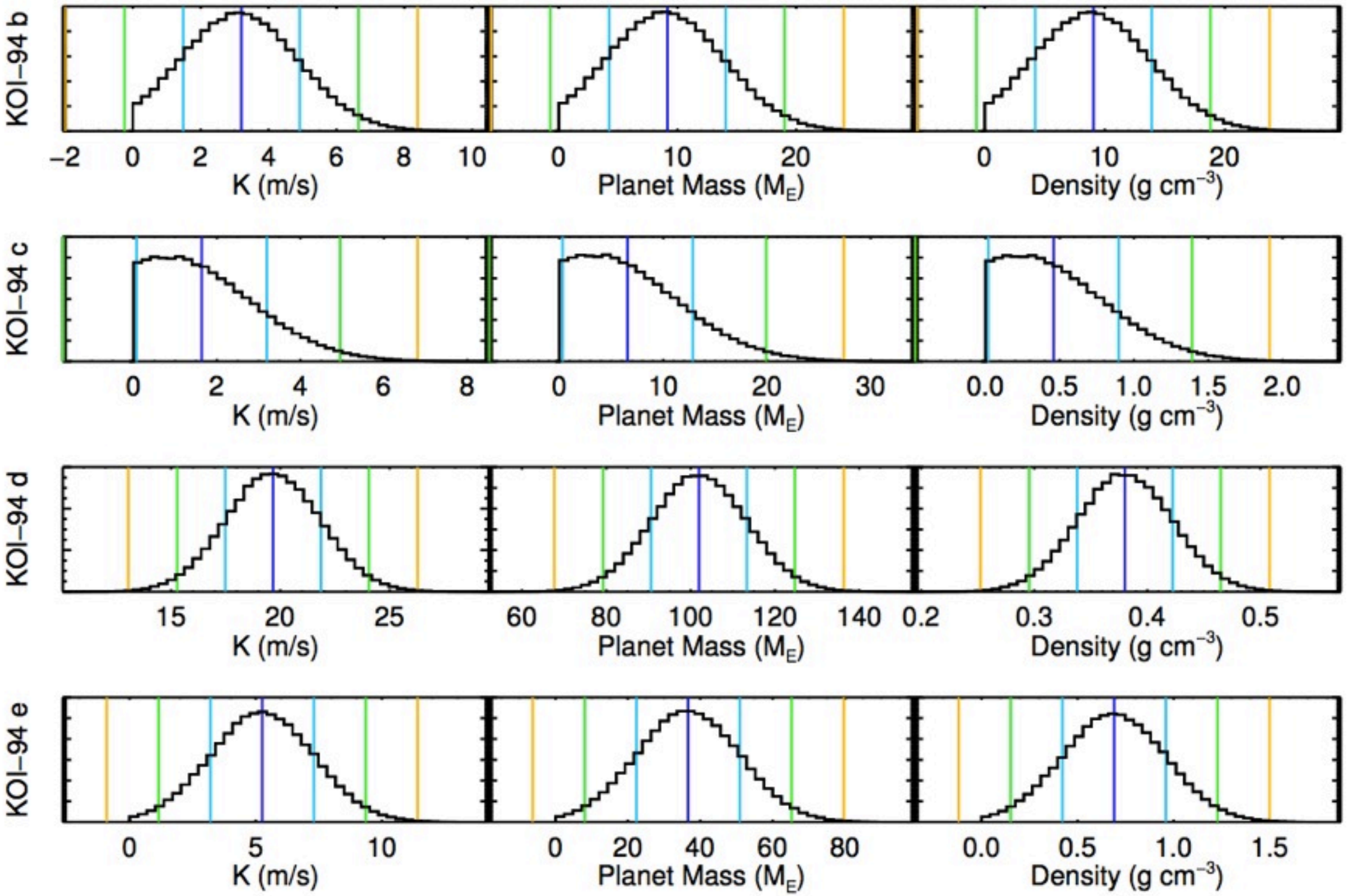
Extras

KOI-94 TTVs


O-C (minutes)
50
0
-50
-100
b
5
0
-5
-10
c
3
2
1
0
-1
-2
d
5
0
-5
e
200
400
600
800
1000
1200
Days

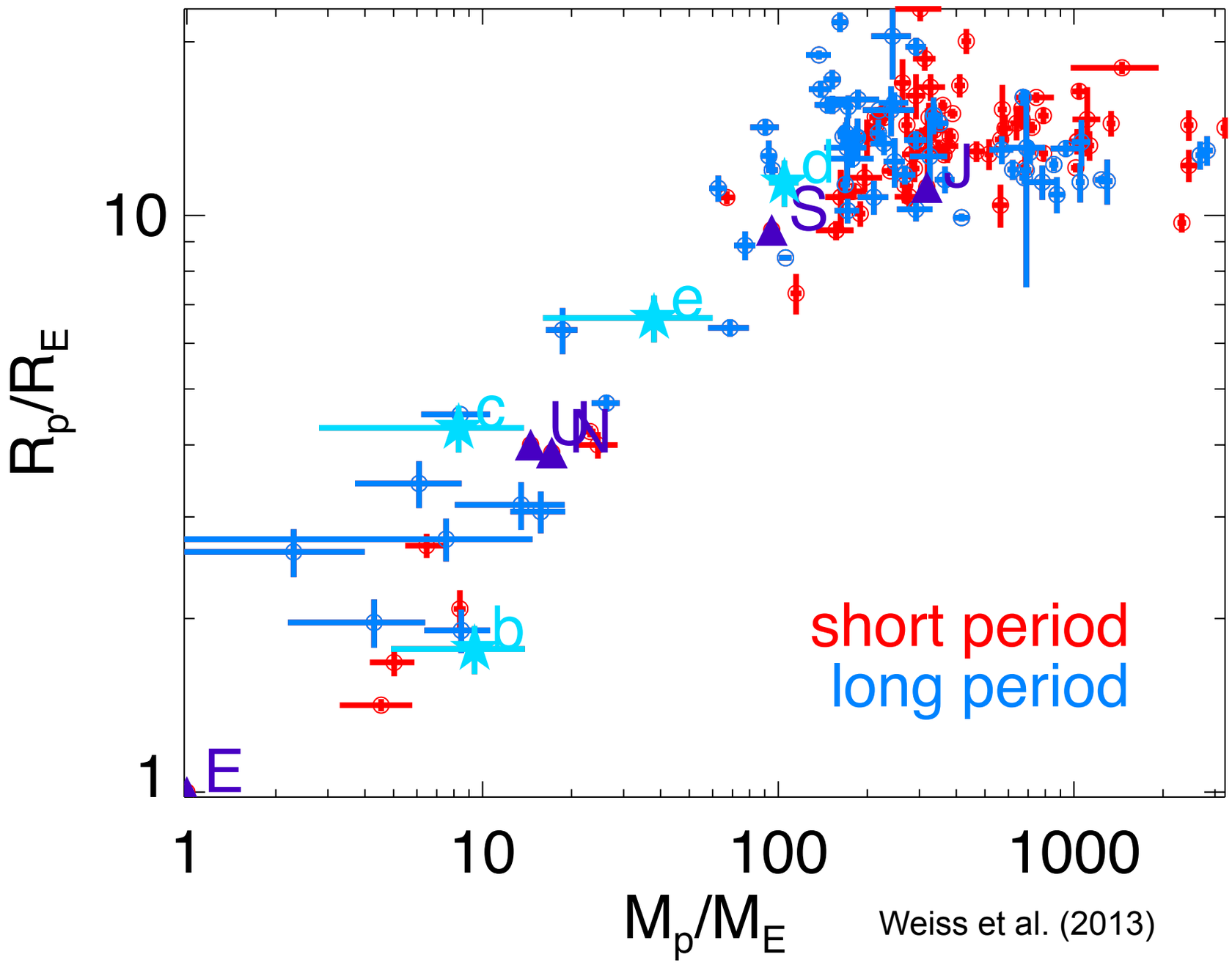
MCMC posterior distributions give mass, density, & errors of planets.

Significance:

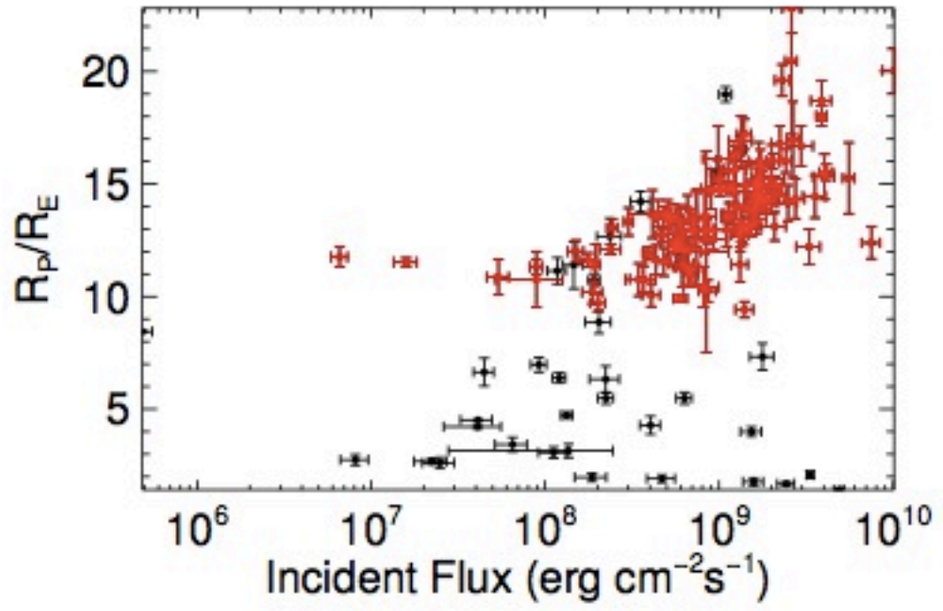


No Relation for Planet Mass, Radius and Orbital Period

(exoplanets.org).

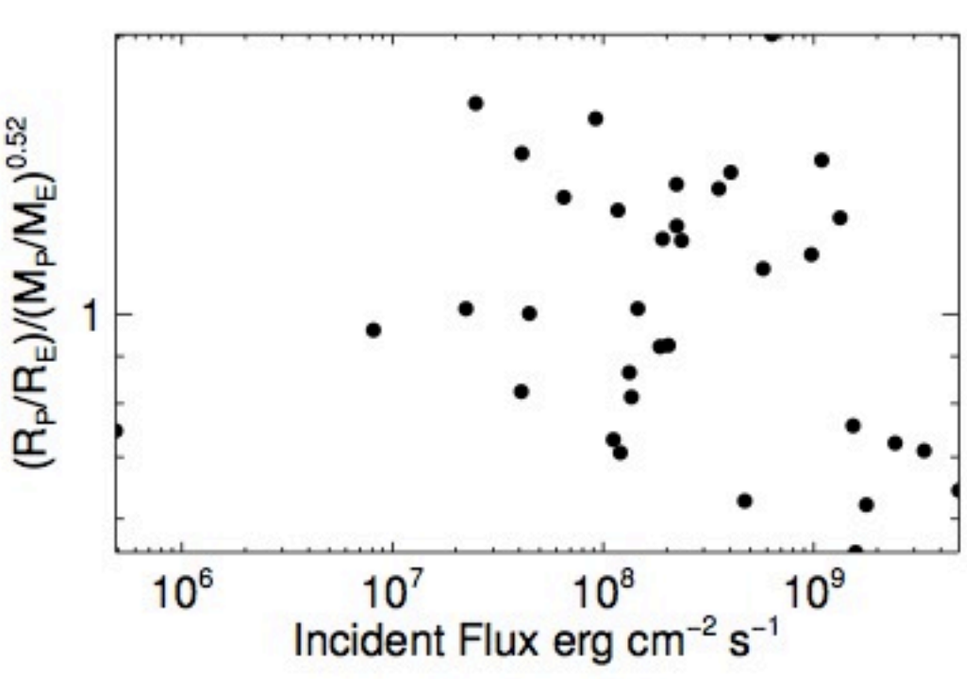


Radius-Incident Flux Relations



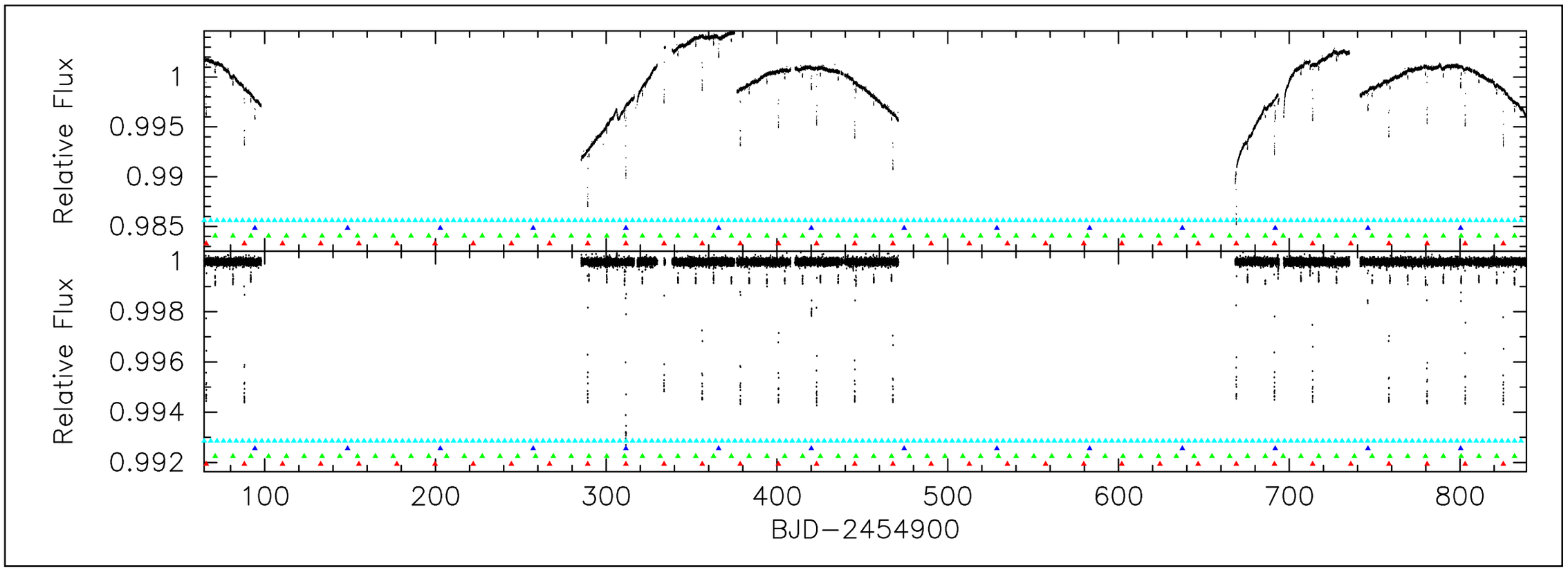
giant planets

low-mass planets



mass dependence removed for low-mass planets

KOI-94 raw Kepler photometry



$R_* = 1.52\ R_\odot$ (SME + YY)
KIC value = $1.2\ R_\odot$

Adaptive Optics

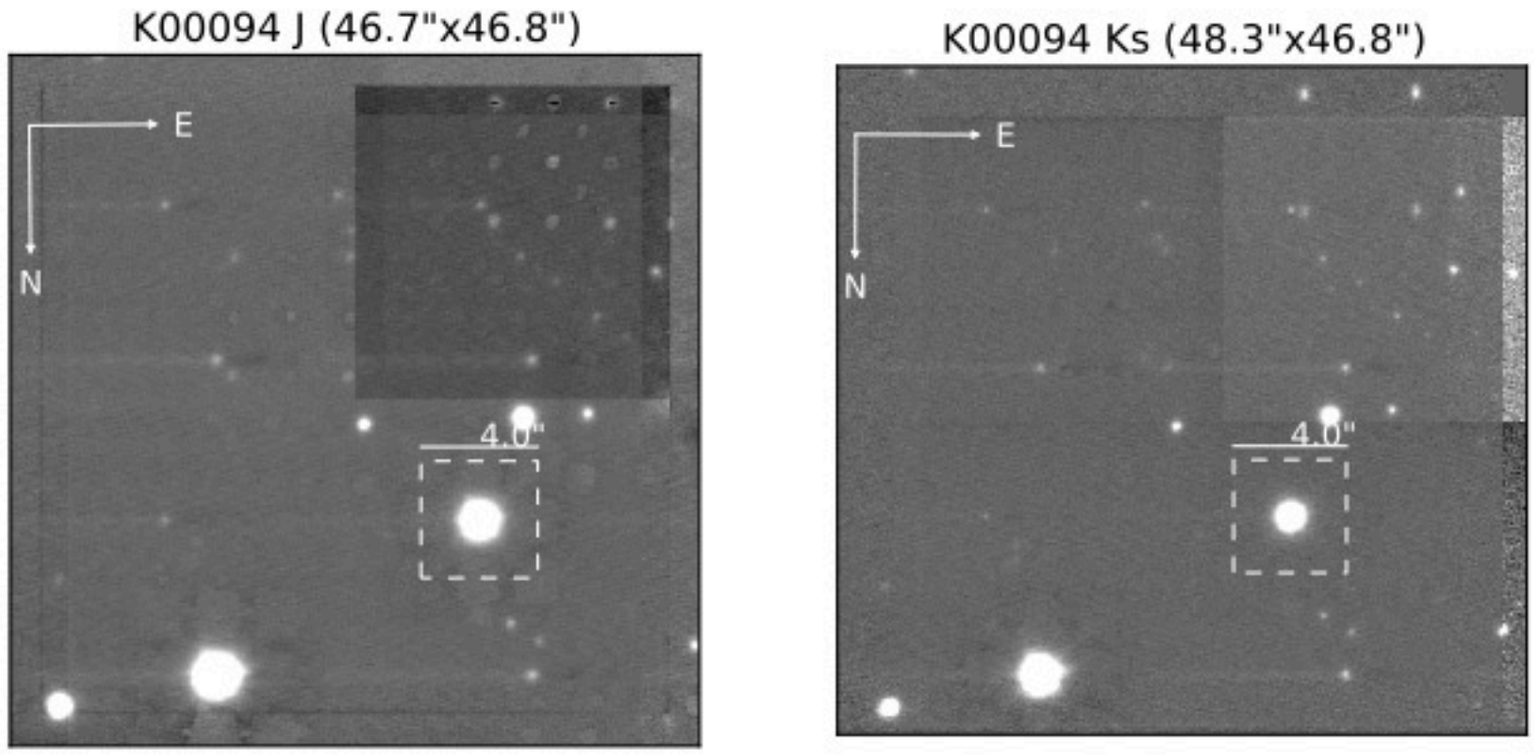


Fig. 4.1.— Adaptive optics image of KOI-94 in J and Ks. The closest companion is 7.5″ away. Note that several of the apparent faint sources are image artifacts; they are distinguishable from real stars because the artifacts form a box with a bright star at the bottom-left corner, and also show streaking to the left.

Speckle Imaging

2.76’

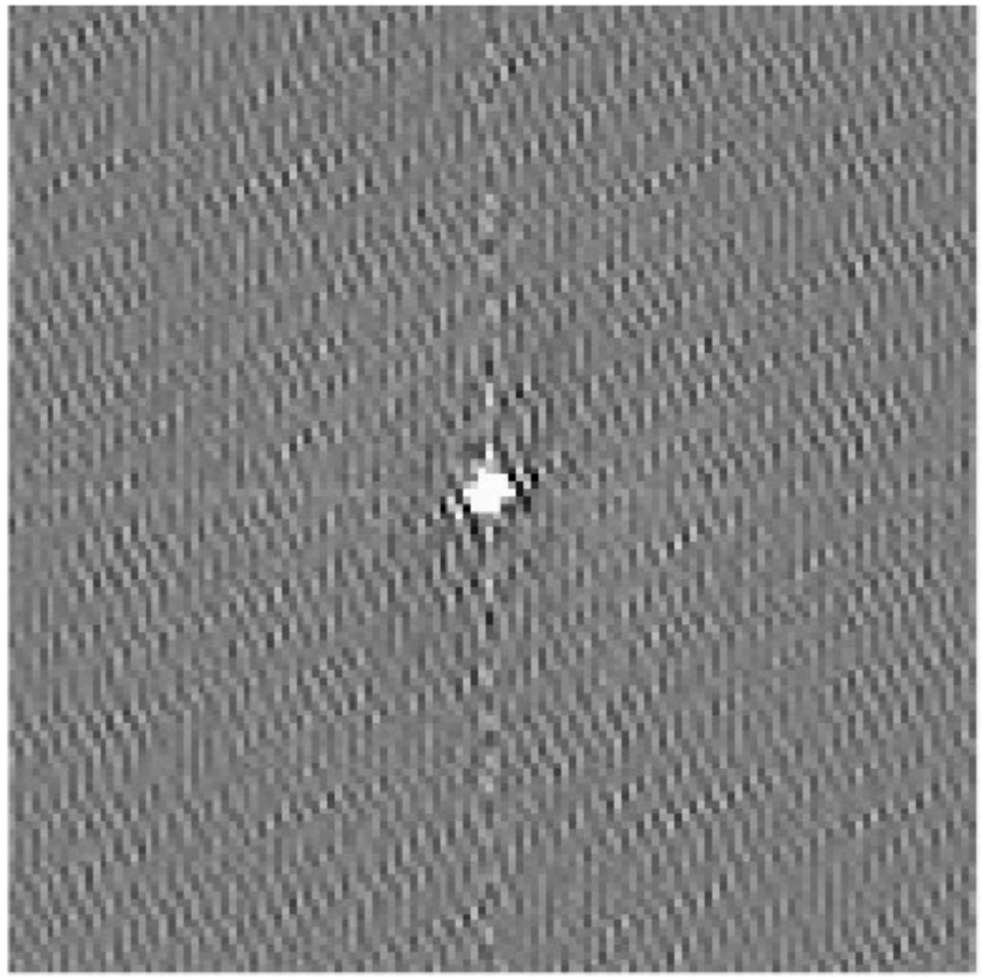


Fig. 4.2.— Speckle Image obtained 2012-10-23 at the WIYN telescope at 692 nm.

KOI-94 System Parameters

Star
(SME + YY)

Observed stellar parameters		
Effective temperature $T_{\rm eff}$ (K)	6182 ± 58	C
Spectroscopic gravity $\log g$ (cgs)	4.181 ± 0.66	C
Metallicity [Fe/H]	$+0.0228 \pm 0.0020$	C
Projected rotation $v \sin i$ ($\mathrm{km\,s^{-1}}$)	7.3 ± 0.5	C
Fundamental Stellar Properties		
Mass $M_\star (M_\odot)$	1.277 ± 0.050	D
Radius $R_\star (R_\odot)$	1.52 ± 0.14	D
Surface gravity $\log g_\star$ (cgs)	4.181 ± 0.66	D
Luminosity $L_\star$ ($L_\odot$)	3.01 ± 0.60	D
Kepler Magnitude K_p (mag)	12.2	D
Age (Gyr)	3.16 ± 0.39	D

Planets

Planetary parameters: KOI-94b		
Mass $M_{\rm P}$ ($M_\oplus$)	9.4 ± 4.5	A,B,C,D
Radius $R_{\rm P}$ ($R_\oplus$)	1.77 ± 0.17	A,B,C,D
Density $\rho_{\rm P}$ ($\mathrm{g\,cm^{-3}}$)	8.0 ± 4.7	A,B,C,D
Orbital semi-major axis a (AU)	0.05119 ± 0.00067	E
Equilibrium temperature $T_{\rm eq}$ (K)	1486	F
Planetary parameters: KOI-94c		
Mass $M_{\rm P}$ ($M_\oplus$)	$8.3^{+3.3}_{-7.7}$	A,B,C,D
Radius $R_{\rm P}$ ($R_\oplus$)	4.28 ± 0.40	A,B,C,D
Density $\rho_{\rm P}$ ($\mathrm{g\,cm^{-3}}$)	$0.5^{+0.19}_{-0.51}$	A,B,C,D
Orbital semi-major axis a (AU)	0.1013 ± 0.0013	E
Equilibrium temperature $T_{\rm eq}$ (K)	1012	F
Planetary parameters: KOI-94d		
Mass $M_{\rm P}$ ($M_\oplus$)	106 ± 11	A,B,C,D
Radius $R_{\rm P}$ ($R_\oplus$)	11.27 ± 1.06	A,B,C,D
Density $\rho_{\rm P}$ ($\mathrm{g\,cm^{-3}}$)	0.363 ± 0.101	A,B,C,D
Orbital semi-major axis a (AU)	0.1684 ± 0.0022	E
Equilibrium temperature $T_{\rm eq}$ (K)	806	F
Planet metallicity	0.17 ± 0.06	G
Planetary parameters: KOI-94e		
Mass $M_{\rm P}$ ($M_\oplus$)	43^{+17}_{-28}	A,B,C,D
Radius $R_{\rm P}$ ($R_\oplus$)	$6.64^{+0.56}_{-0.68}$	A,B,C,D
Density $\rho_{\rm P}$ ($\mathrm{g\,cm^{-3}}$)	$0.70^{+0.30}_{-0.49}$	A,B,C,D
Orbital semi-major axis a (AU)	0.3046 ± 0.0040	E
Equilibrium temperature $T_{\rm eq}$ (K)	584	F