Measuring Precise Masses of Ariel planets: Lessons Learned

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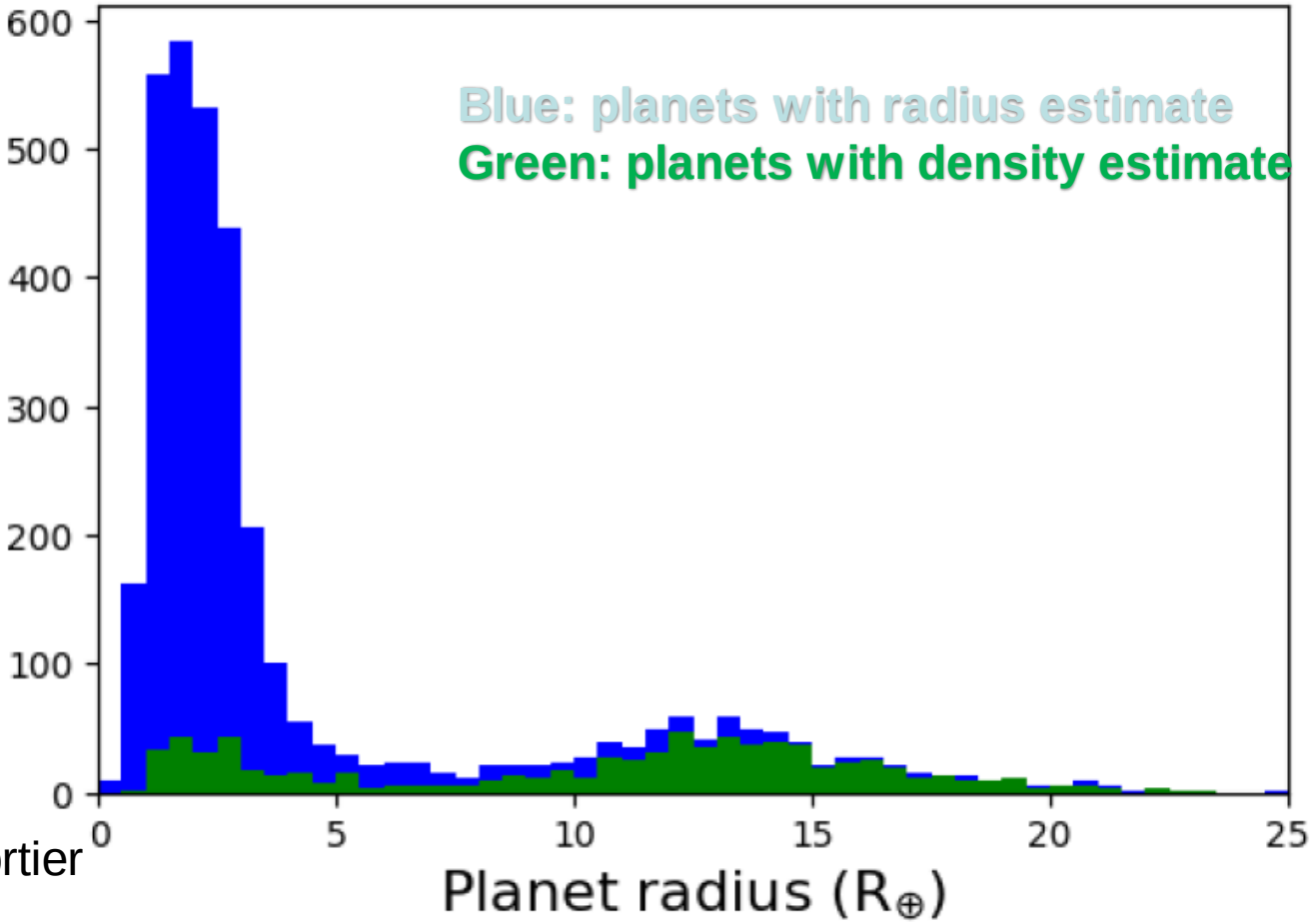
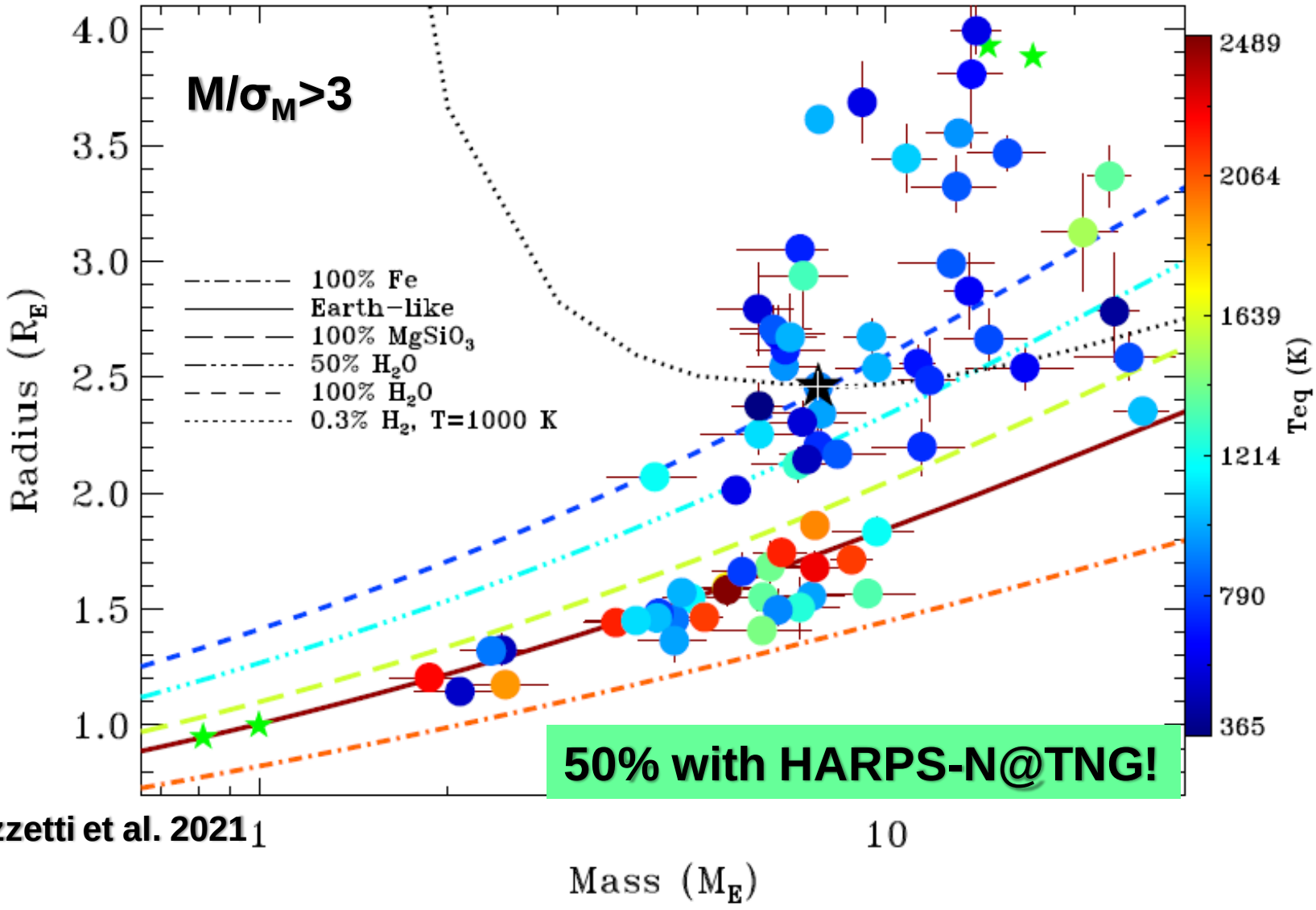
Densities of Small Planets



Credits: A. Mortier

Precise masses/densities of small planets are key to estimate their atmospheric scale heights and thus select those best suited for atmospheric characterization with JWST and Ariel.

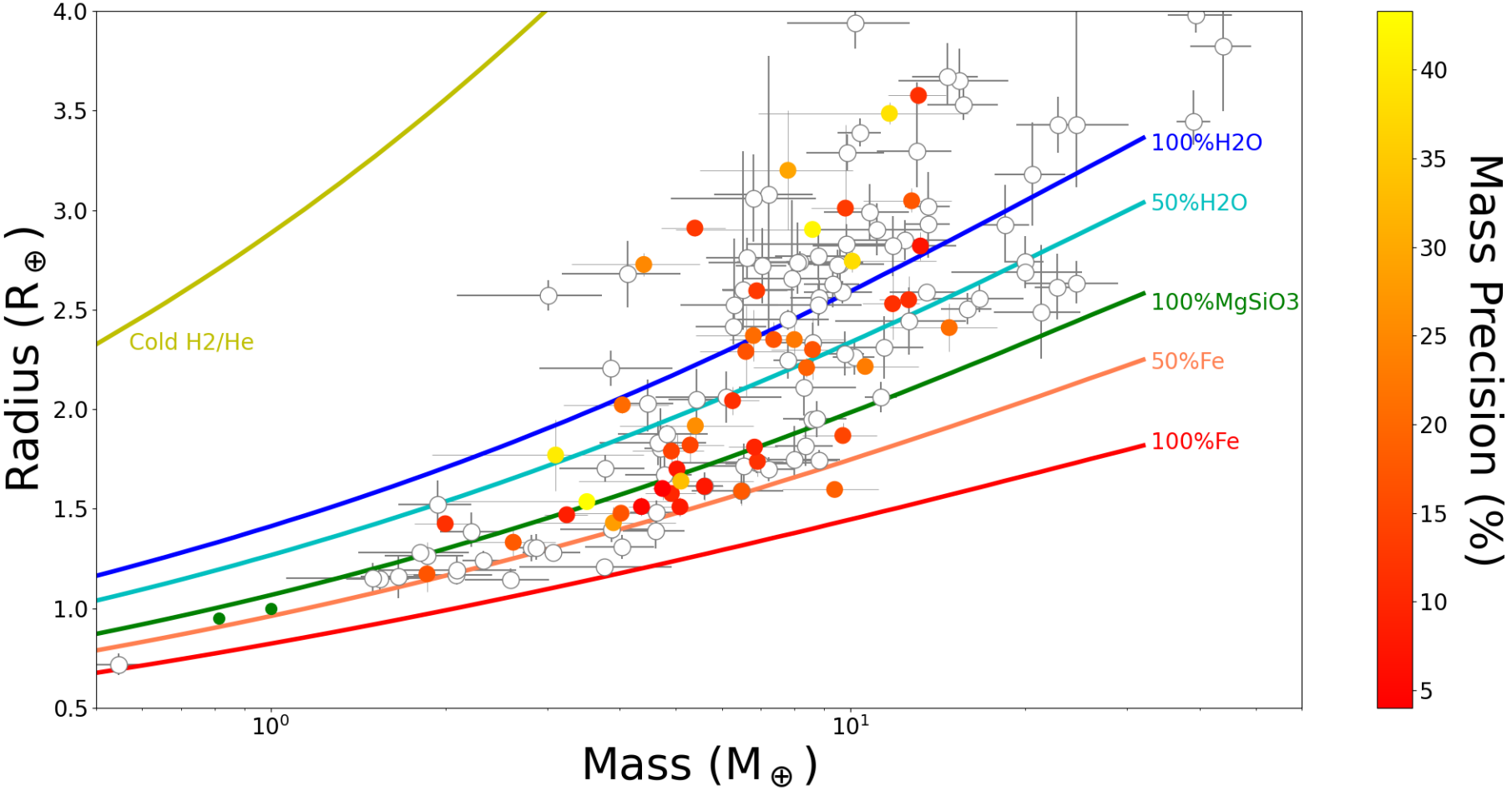
M-R Relation: Small Planets



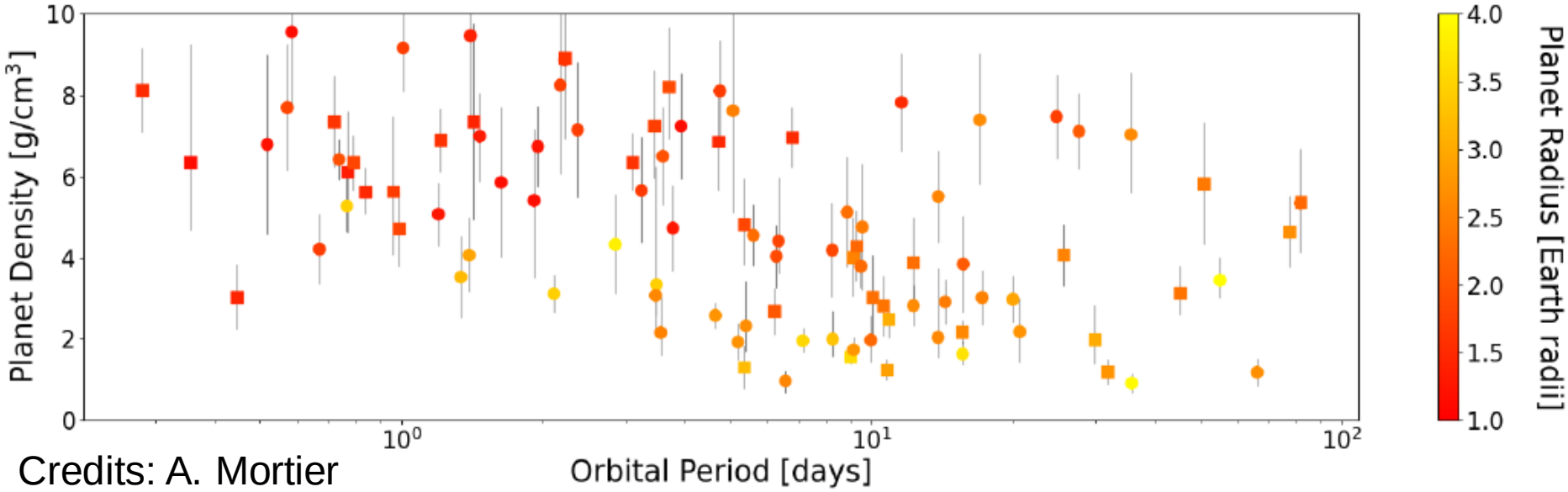
50% with HARPS-N@TNG!

Sozzetti et al. 2021

HARPS-N GTO


Radius ($R_\oplus$)
Mass ($M_\oplus$)
Mass Precision (%)
Cold H2/He
100%H2O
50%H2O
100%MgSiO3
50%Fe
100%Fe

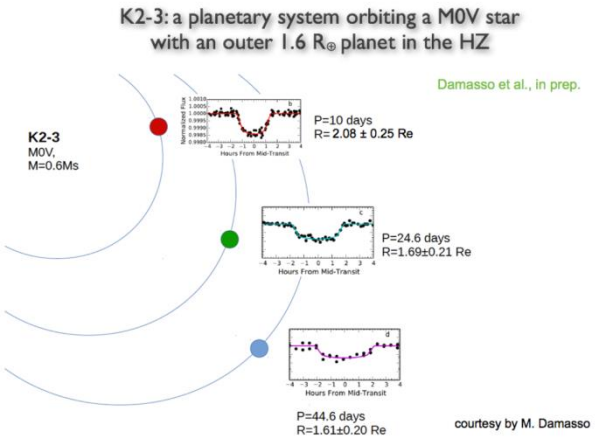
From Ultra-Short to Long Periods



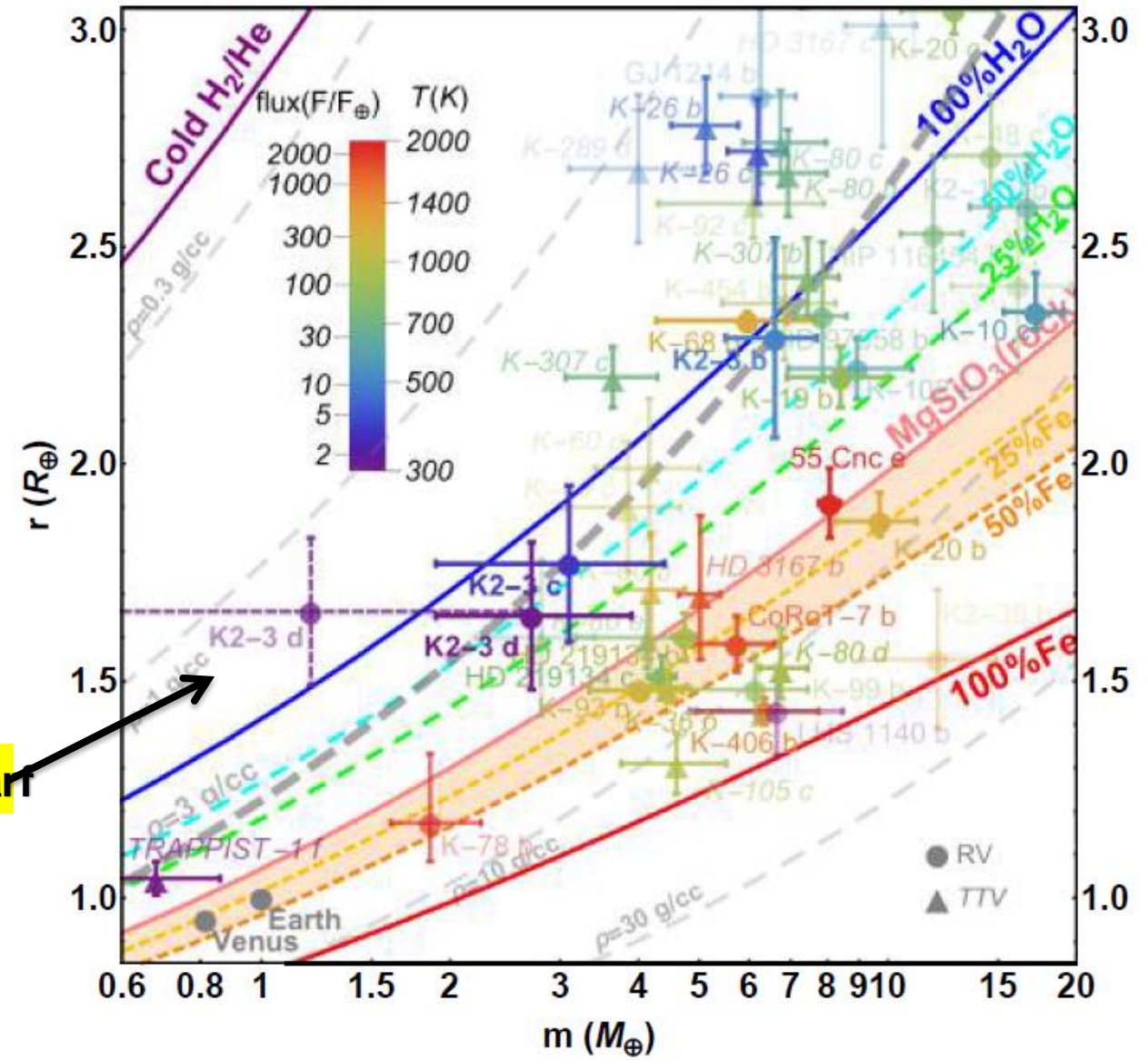
Credits: A. Mortier

K2-141b: 0.2803244 d - 1.51 $R_\oplus$ - 5.08$M_\oplus$ (Malavolta et al. 2018)
Kepler-78b: 0.3550 d - 1.173 $R_\oplus$- 1.86$M_\oplus$ (Pepe et al. 2013)
WASP-47e: 0.79 d - 1.81 $R_\oplus$- 6.83$M_\oplus$ (Vanderburg et al. 2017)
TOI-561b: 0.446578 d - 1.423 $R_\oplus$ - 1.59$M_\oplus$ (Lacedelli et al. 2021)
TOI-1634b: 0.989 d - 1.79 $R_\oplus$ - 4.91$M_\oplus$ (Cloutier et al. 2021)
K2-263b: 50.8 d - 2.41 $R_\oplus$ - 14.8$M_\oplus$ (Mortier et al. 2018)
TOI-561e: 77.2 d - 2.67 $R_\oplus$ - 16.0$M_\oplus$ (Lacedelli et al. 2021)
Kepler-538b: 81.73778 d - 2.215 $R_\oplus$ - 10.6$M_\oplus$ (Mayo et al. 2019)

Eyes on the K2-3 system of sub-Neptunes



In the HZ of a 0.6 $M_\odot$ dwarf



Damasso et al. A&A 2018

ESPRESSO GTO: TOI-178

Leleu et al. 2021

46 ESPRESSO RVs!

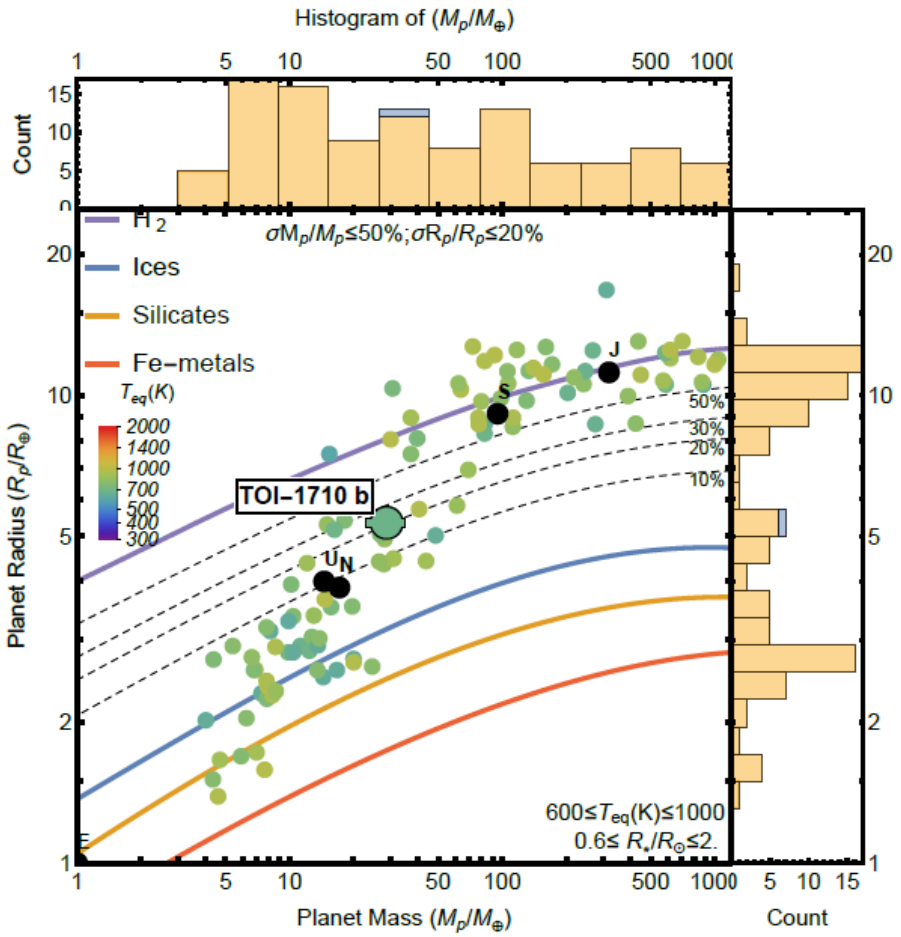
Parameter (unit)	b	c	d
Fitted parameters (photometry)			
$R_p/R_\star$	0.01623 ± 0.00097	$0.0235^{+0.0015}_{-0.0013}$	$0.03623^{+0.00087}_{-0.00091}$
b ($R_\star$)	$0.17^{+0.19}_{-0.13}$	$0.34^{+0.30}_{-0.23}$	$0.485^{+0.051}_{-0.060}$
T_0 (BJD-TBD)	$2458741.6365^{+0.0043}_{-0.0030}$	$2458741.4783^{+0.0034}_{-0.0029}$	$2458747.14623^{+0.00087}_{-0.00095}$
P (d)	1.914558 ± 0.000018	$3.238450^{+0.000020}_{-0.000019}$	6.557700 ± 0.000016
$\rho_\star$ ($\rho_\odot$)	2.35 ± 0.17 (same for all planets)		
Fitted parameters (spectroscopy)			
K (ms^{-1})	$1.05^{+0.25}_{-0.30}$	$2.77^{+0.22}_{-0.33}$	$1.34^{+0.31}_{-0.39}$
Derived parameters			
δ_{tr} (ppm)	263^{+32}_{-30}	551^{+68}_{-59}	1313^{+64}_{-65}
Detection SNR	8.2	8.1	20.2
$R_\star/a$	$0.1161^{+0.0030}_{-0.0027}$	$0.0818^{+0.0021}_{-0.0019}$	$0.0511^{+0.0013}_{-0.0012}$
$a/R_\star$	$8.61^{+0.21}_{-0.22}$	$12.23^{+0.29}_{-0.31}$	$19.57^{+0.47}_{-0.49}$
R_p ($R_\oplus$)	$1.152^{+0.073}_{-0.070}$	$1.669^{+0.114}_{-0.099}$	$2.572^{+0.075}_{-0.078}$
a (AU)	0.02607 ± 0.00078	0.0370 ± 0.0011	0.0592 ± 0.0018
i (deg)	$88.8^{+0.8}_{-1.3}$	$88.4^{+1.1}_{-1.6}$	$88.58^{+0.20}_{-0.18}$
[illegible]	[illegible]	[illegible]	[illegible]
T_{eq} (K)[a]	1040^{+22}_{-21}	873 ± 18	690 ± 14
M_p ($M_\oplus$)	$1.50^{+0.39}_{-0.44}$	$4.77^{+0.55}_{-0.68}$	$3.01^{+0.80}_{-1.03}$
ρ_p ($\rho_\oplus$)	$0.98^{+0.35}_{-0.31}$	$1.02^{+0.28}_{-0.23}$	$0.177^{+0.055}_{-0.061}$

Parameter (unit)	e	f	g
Fitted parameters (photometry)			
$R_p/R_\star$	$0.0311^{+0.0011}_{-0.0012}$	0.0322 ± 0.0014	$0.0404^{+0.0019}_{-0.0018}$
b ($R_\star$)	$0.583^{+0.046}_{-0.066}$	$0.765^{+0.027}_{-0.031}$	$0.866^{+0.017}_{-0.019}$
T_0 (BJD-TBD)	$2458751.4658^{+0.0016}_{-0.0019}$	$2458745.7178^{+0.0023}_{-0.0027}$	$2458748.0302^{+0.0023}_{-0.0017}$
P (d)	9.961881 ± 0.000042	$15.231915^{+0.000115}_{-0.000095}$	$20.70950^{+0.00014}_{-0.00011}$
$\rho_\star$ ($\rho_\odot$)	2.35 ± 0.17 (same for all planets)		
Fitted parameters (spectroscopy)			
K (ms^{-1})	$1.62^{+0.41}_{-0.34}$	$2.76^{+0.46}_{-0.42}$	$1.30^{+0.38}_{-0.59}$
Derived parameters			
δ_{tr} (ppm)	968^{+69}_{-71}	1037^{+94}_{-90}	1633^{+157}_{-139}
detection SNR	13.6	11.0	10.4
$R_\star/a$	$0.03866^{+0.00100}_{-0.00090}$	$0.02913^{+0.00075}_{-0.00068}$	$0.02373^{+0.00061}_{-0.00056}$
$a/R_\star$	$25.87^{+0.62}_{-0.65}$	$34.33^{+0.82}_{-0.87}$	$42.13^{+1.01}_{-1.06}$
R_p ($R_\oplus$)	$2.207^{+0.088}_{-0.090}$	$2.287^{+0.108}_{-0.110}$	$2.87^{+0.14}_{-0.13}$
a (AU)	$0.0783^{+0.0023}_{-0.0024}$	0.1039 ± 0.0031	$0.1273^{+0.0038}_{-0.0039}$
i (deg)	$88.71^{+0.16}_{-0.13}$	$88.723^{+0.071}_{-0.069}$	$88.823^{+0.045}_{-0.047}$
[illegible]	[illegible]	[illegible]	[illegible]
T_{eq} (K)[a]	600 ± 12	521 ± 11	470 ± 10
M_p ($M_\oplus$)	$3.86^{+1.25}_{-0.94}$	$7.72^{+1.67}_{-1.52}$	$3.94^{+1.31}_{-1.62}$
ρ_p ($\rho_\oplus$)	$0.360^{+0.143}_{-0.097}$	$0.65^{+0.21}_{-0.15}$	$0.166^{+0.065}_{-0.068}$

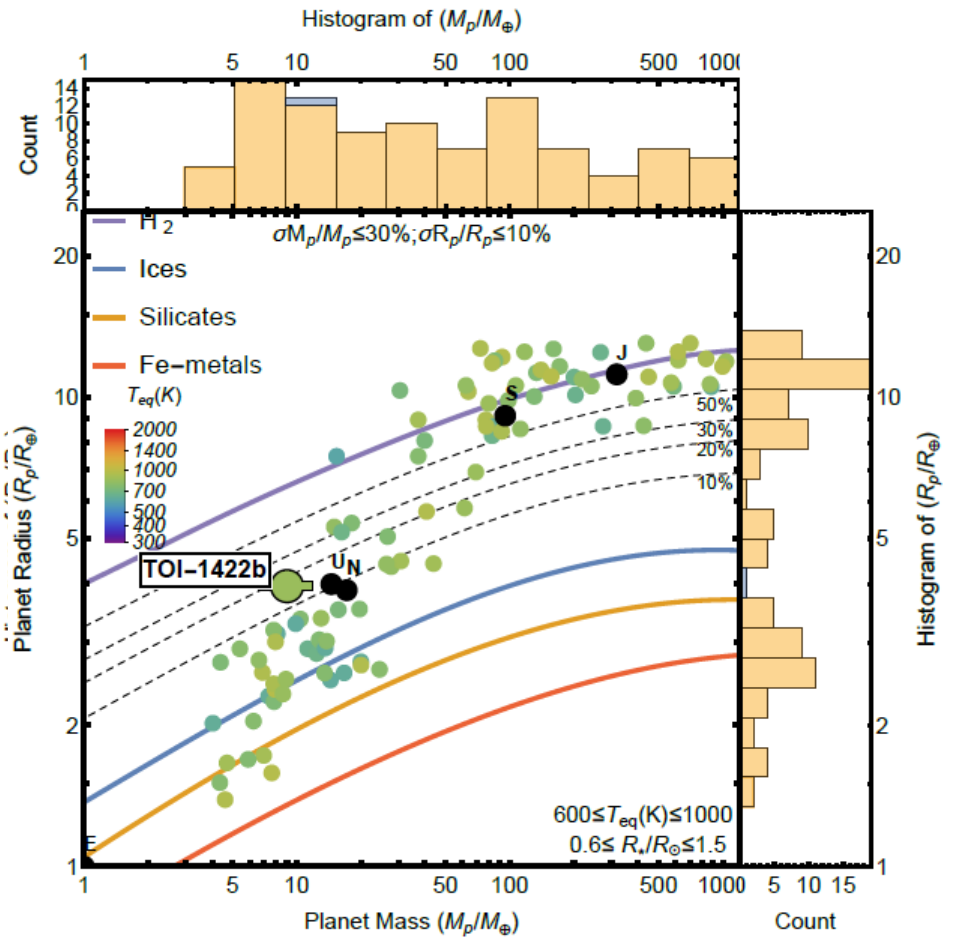
Six Super Earths and sub-Neptunes in a resonant chain!

P_c/P_b=5:3; P_d/P_c=2:1; P_e/P_d=3:2; P_f/P_e=3:2; P_g/P_f=4:3

GAPS2 – TESS Neptunians

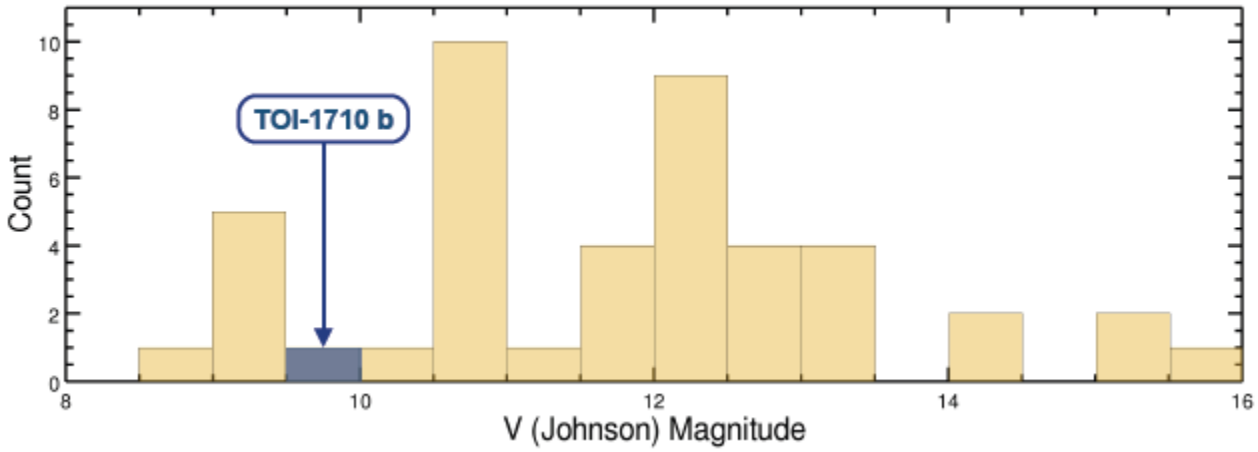


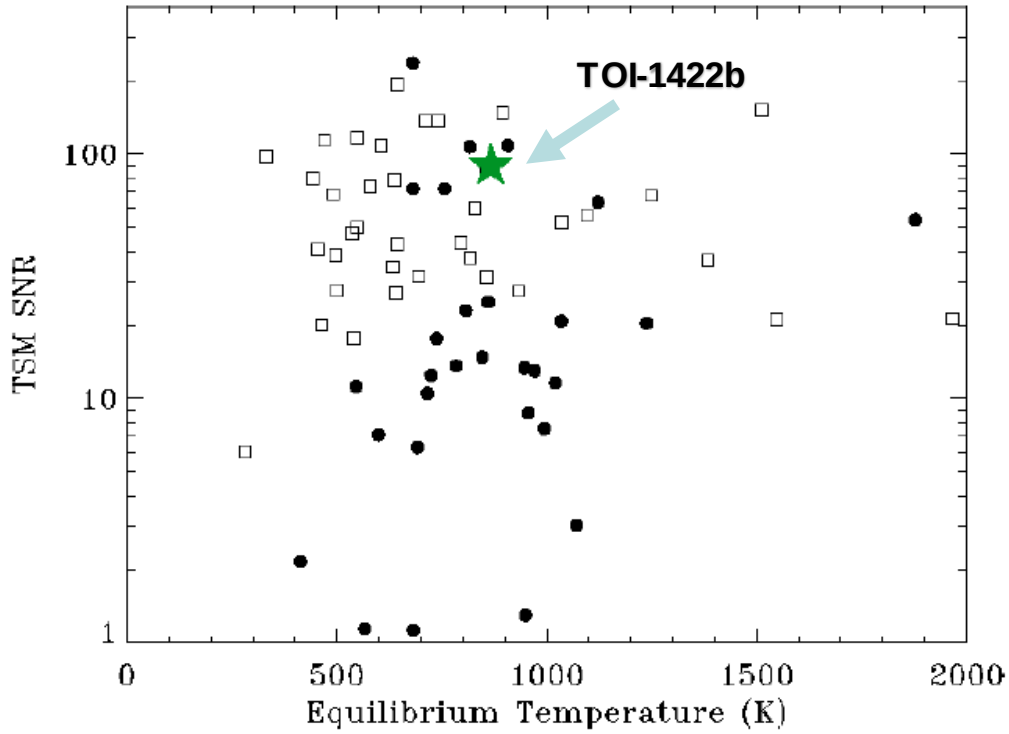
Konig, Damasso et al. 2022



Naponiello et al. 2022

HARPS-N follow-up of a sample of a dozen TESS candidates with R_p in the [3,6] R_J range


TOI-1710 b
Count
V (Johnson) Magnitude

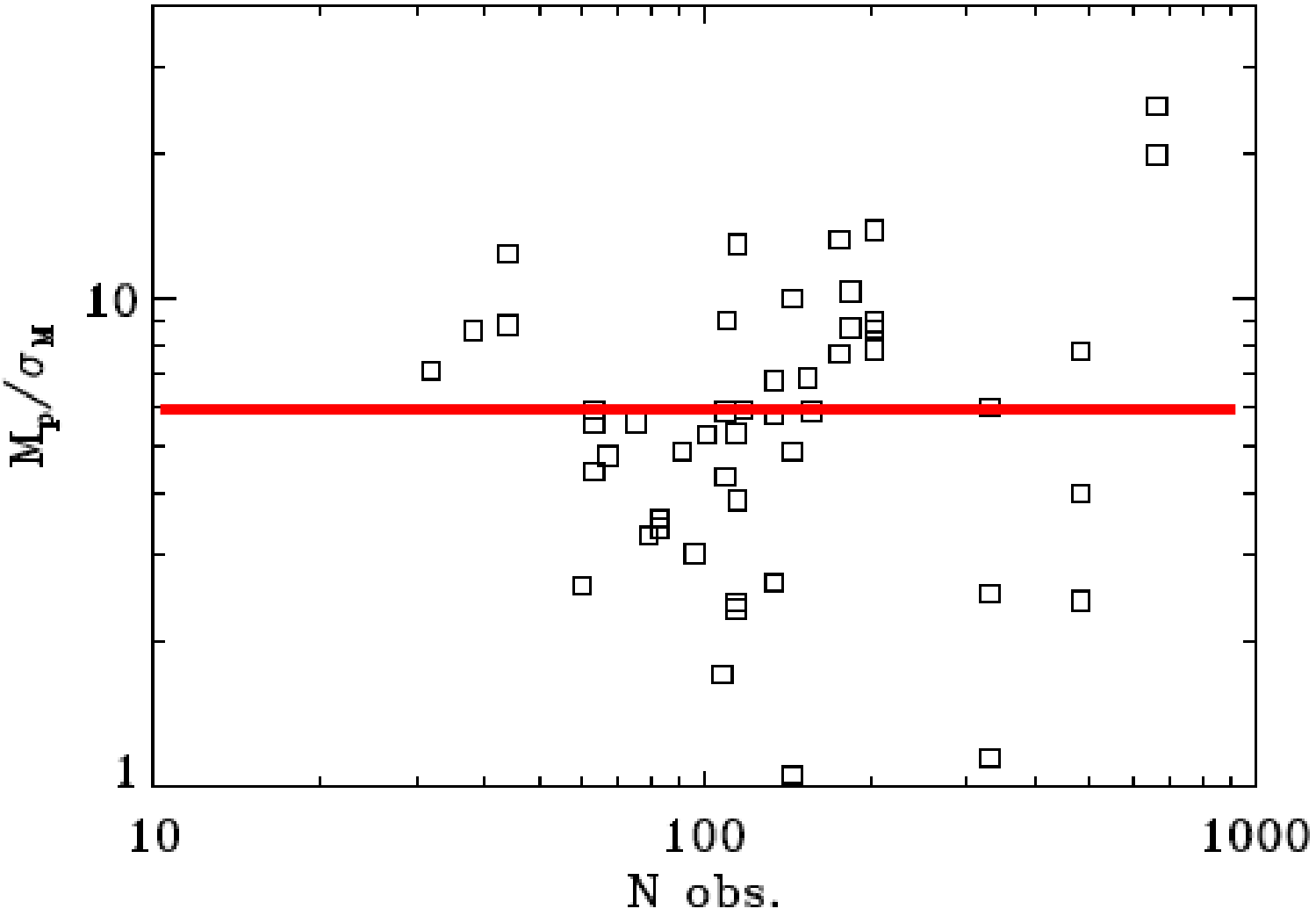

TOI-1422b
TSM SNR
Equilibrium Temperature (K)

HARPS-N GTO

σ_m/m_{pl} < 10% within 0.1 AU

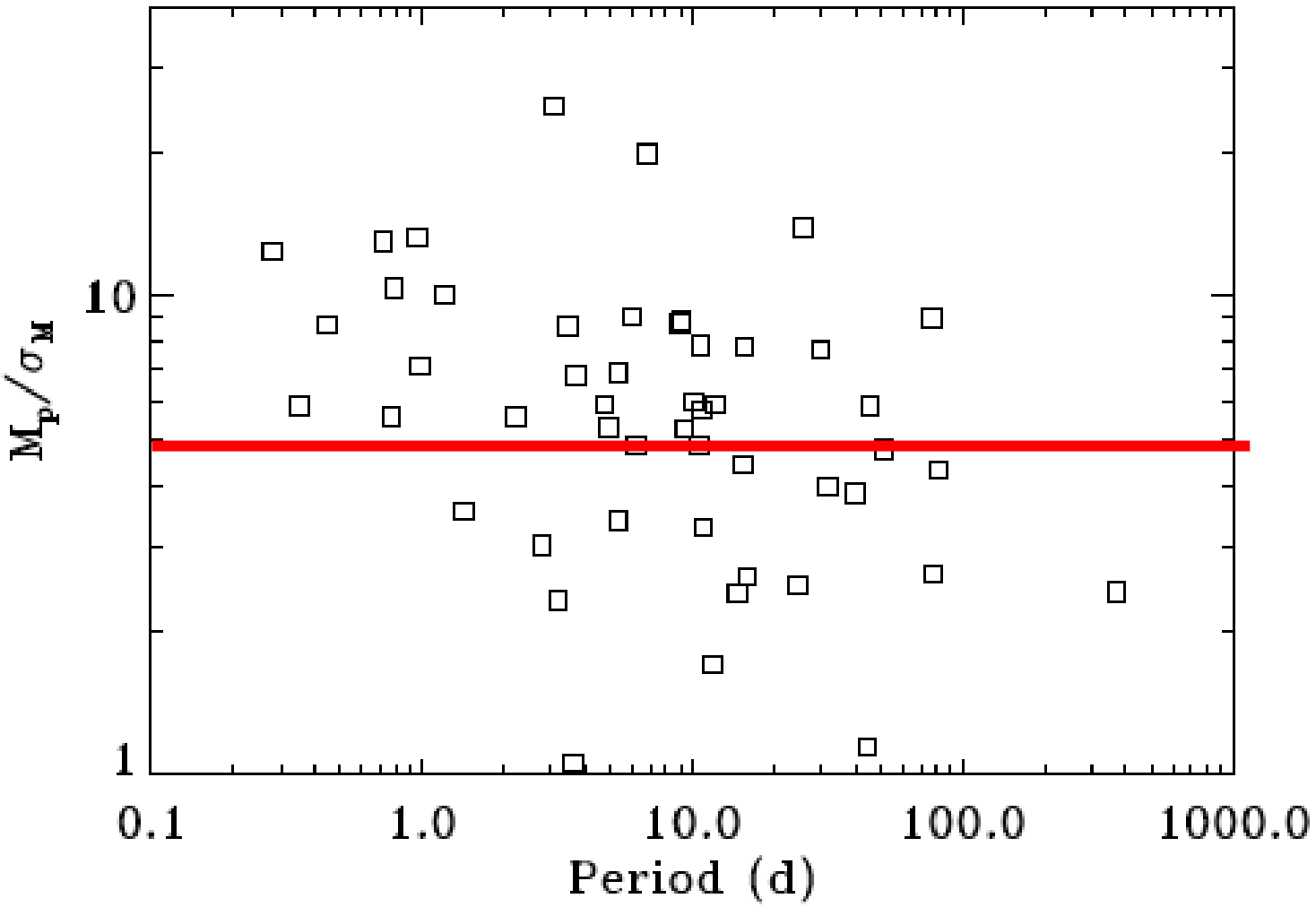
Star	5 M_{EARTH}	10 M_{EARTH}
F0 (1.60 M_{SUN})	158	40
G0 (1.05 M_{SUN})	104	26
K0 (0.79 M_{SUN})	78	20
M0 (0.51 M_{SUN})	50	13

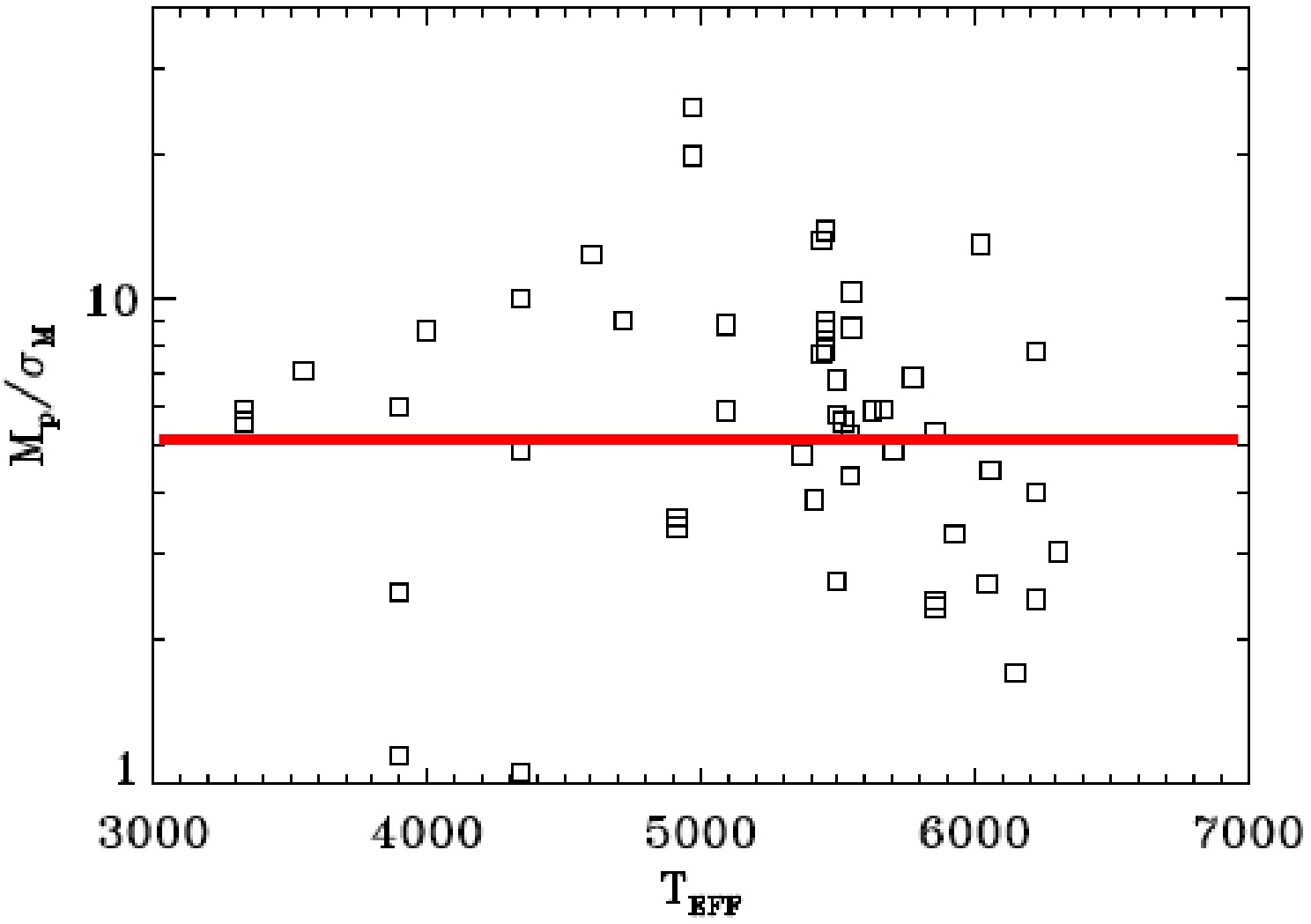
M-R relation for rocky Super Earths:
25 nights/yr for 40 targets

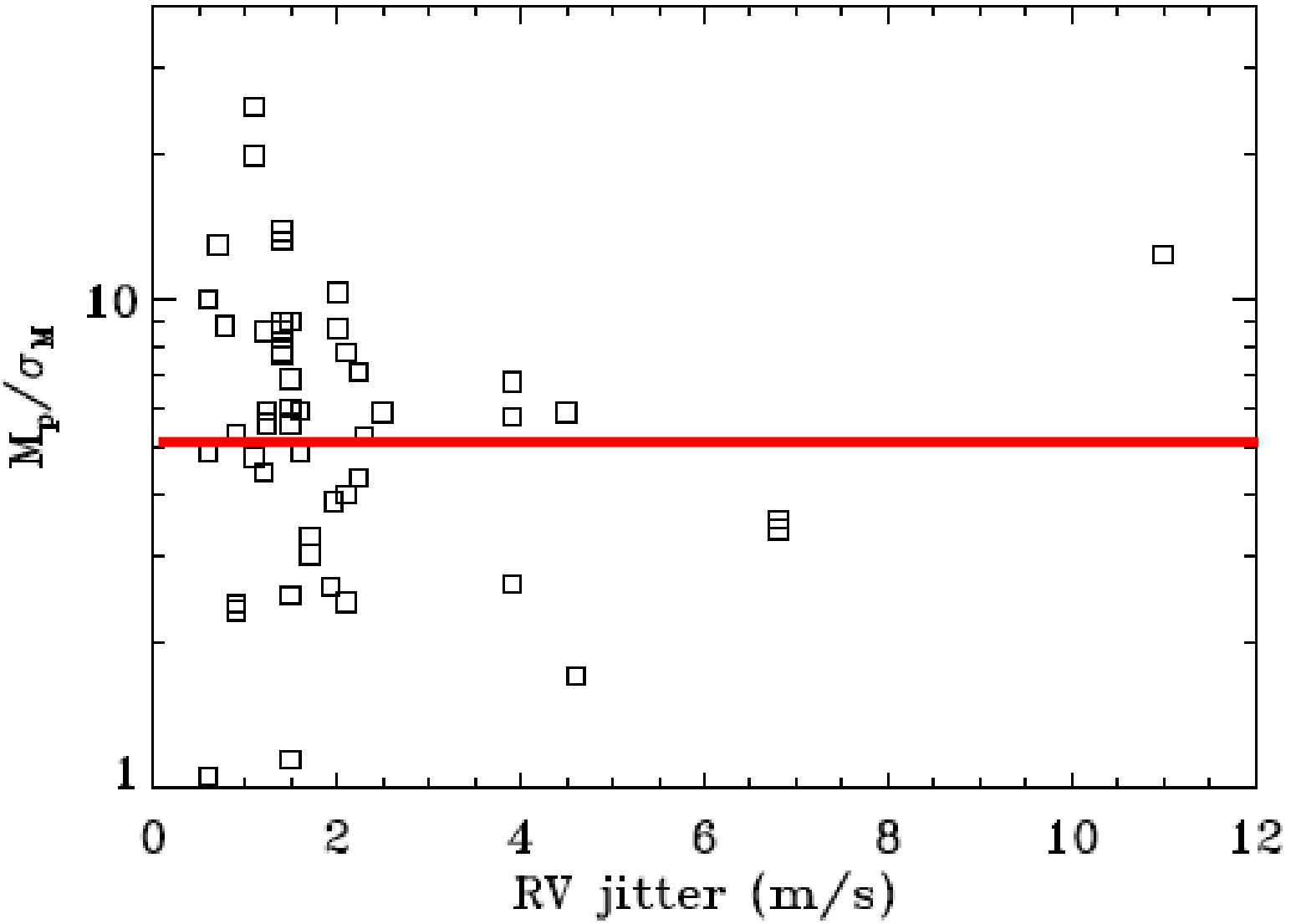


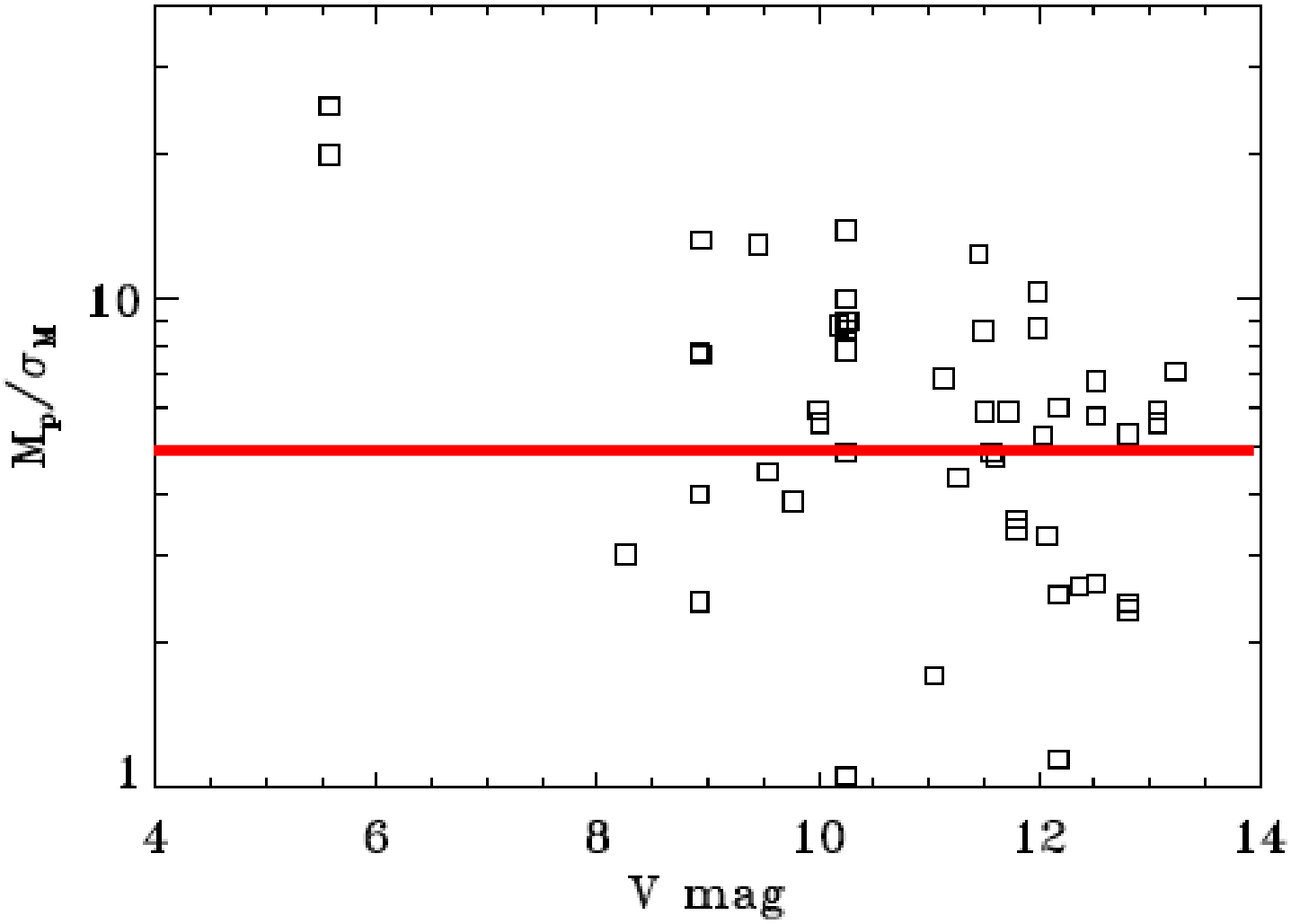
HARPS-N GTO: 62 planets in 35 systems (17 multiples)

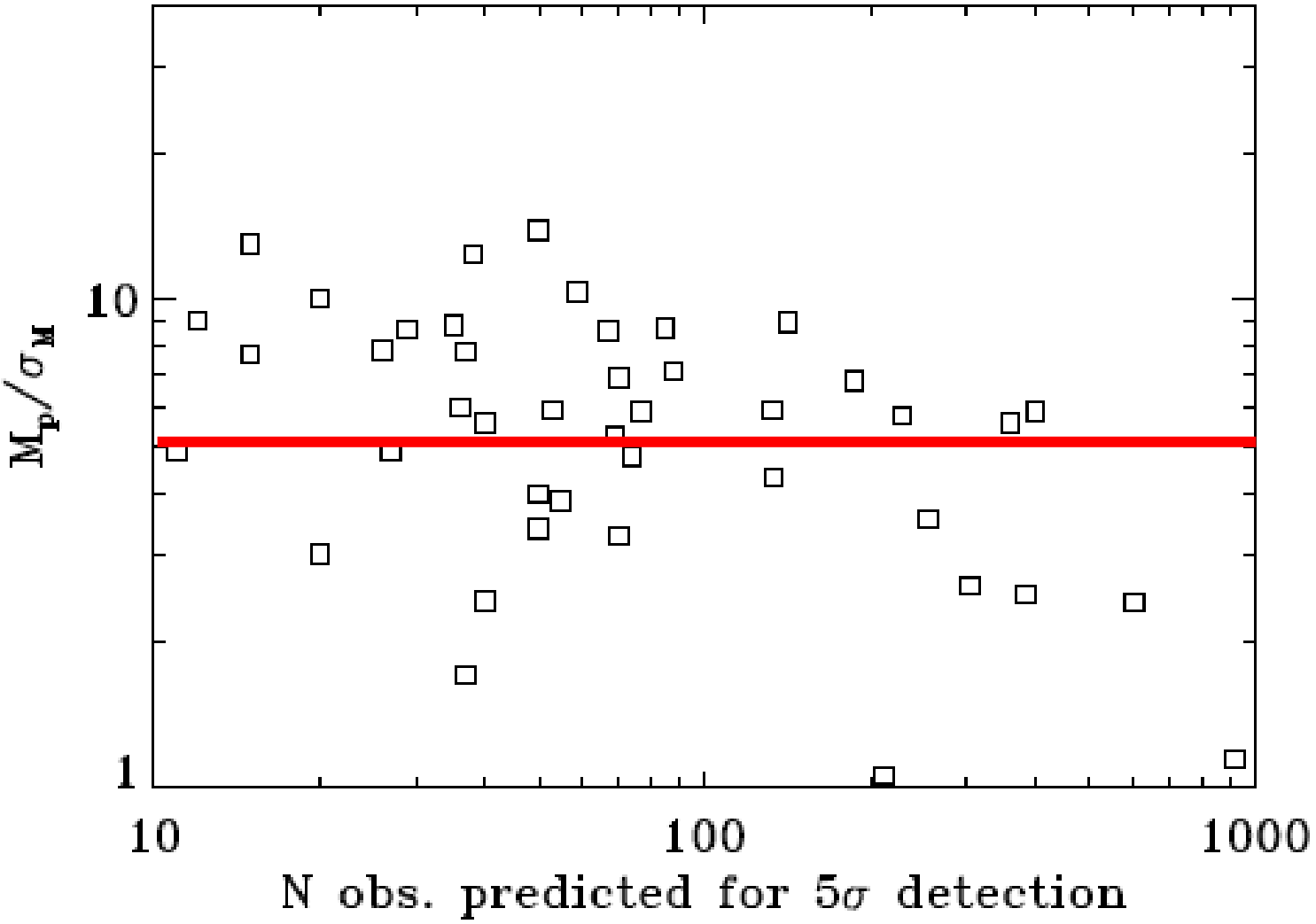
36 with mass determined to better than 20% precision


10
1
M_p/σ_M
0.1
1.0
10.0
100.0
1000.0
Period (d)


10
1
M_p/σ_M
3000
4000
5000
6000
7000
T_{EFF}


10
1
M_p/σ_M
0
2
4
6
8
10
12
RV jitter (m/s)


10
1
M_p/σ_M
4
6
8
10
12
14
V mag


10
1
M_p/σ_M
10
100
1000
N obs. predicted for 5σ detection

Agreement

Table 1 | Planetary system parameters of Kepler-78 b

Planetary system parameter	Kepler-78b
Reference epoch, T_0 (BJDUTC)	2,456,465.076392
Orbital inclination, I (°)*	79^{+9}_{-14}
Systemic radial velocity, γ (km s^{-1})†	-3.5084 ± 0.0008
Orbital period, P (d)†	0.3550 ± 0.0004
Mean longitude, λ_0, at epoch T_0 (°)†	293 ± 13
Eccentricity, e†	0
Radial-velocity semi-amplitude, K_p (m s^{-1})†	1.96 ± 0.32
Planetary mass, m_p ($M_\oplus$)‡	$1.86^{+0.38}_{-0.25}$
Planetary radius, R_p ($R_\oplus$)‡	$1.173^{+0.159}_{-0.089}$
Planetary mean density, ρ_p (g cm^{-3})‡	$5.57^{+3.02}_{-1.31}$
Semi-major axis, a (AU)†	0.0089
Surface temperature, T (K)*	1500-3000
Number of measurements, N_{meas}	109
Time span of observations (d)	97.1
Radial-velocity dispersion ($O-C$) (m s^{-1})†	2.34
Reduced χ^2†	1.12 ± 0.07

Planetary properties	
Name	Kepler-78b
Mass, M_{pl}	$1.69 \pm 0.41 M_\oplus$
Radius, R_{pl}	$1.20 \pm 0.09 R_\oplus$
Density, ρ_{pl}	$5.3^{+2.0}_{-1.6}$ g cm^{-3}
Surface gravity, g_{pl}	$11.4^{+3.5}_{-3.1}$ m s^{-2}
Iron fraction	0.20 ± 0.33 (two-component rock/iron model)
Orbital period, P_{orb} (from ref. 6)	0.35500744 ± 0.00000006 days
Transit epoch, t_c (from ref. 6)	2454953.95995 ± 0.00015 (BJD_{TBD})

Additional parameters	
$(R_{pl}/R_{star})^2$	217 ± 9 parts per million
Scaled semi-major axis, a/R_{star}	2.7 ± 0.2
Doppler amplitude, K	1.66 ± 0.40 m s^{-1}
Systemic radial velocity	-3.59 ± 0.10 km s^{-1}
Radial-velocity jitter, σ_{jitter}	2.1 ± 0.3 m s^{-1}
Radial-velocity dispersion	2.6 m s^{-1} (s.d. of residuals to best-fit model)

Disagreement (?)

Table 7
Kepler-10 Parameters in Different Studies

Parameter	Units	B11[a]	D14[b]	This Work HIRES only	2 pl. circ.	2 pl. ecc.	Best 3 pl.
Stellar							
$T_{\rm eff}$	K	5627 ± 44	5708 ± 28	same as D14			
log g	cgs	4.341 ± 0.012	4.344 ± 0.004	…	…	…	…
$M_\star$	$M_\odot$	0.895 ± 0.060	0.910 ± 0.0214	…	…	…	…
$R_\star$	$R_\odot$	1.056 ± 0.021	1.065 ± 0.009	…	…	…	…
$L_\star$	$L_\odot$	1.004 ± 0.059	1.004 ± 0.059	…	…	…	…
[Fe/H]	dex	−0.15 ± 0.04	−0.15 ± 0.04	…	…	…	…
$v \sin i$	m s^{-1}	0.5 ± 0.5	0.6 ± 0.5–2.04 ± 0.34	…	…	…	…
Age	Gyr	11.9 ± 4.5	10.6 ± 1.4	…	…	…	…
Kepler-10 b							
Period	days	0.837495 ± 4E-6	0.8374907 ± 2E-7	fixed, same as D14			
TT	BJD—2 454 900	64.57375 ± 0.0007	134.08687 ± 0.00018	fixed, same as D14			
K	m s^{-1}	3.3 ± 0.9	2.38 ± 0.35	3.31 ± 0.59	2.67 ± 0.3	2.70 ± 0.31	2.67 (fixed)
a	AU	0.01684 ± 0.00033	0.01685 ± 0.00013	fixed, same as D14			
$M_{\rm p}$	$M_\oplus$	4.56 ± 1.23	3.33 ± 0.49	4.61 ± 0.83	3.72 ± 0.42	3.76 ± 0.43 $M_\oplus$	3.70 (fixed)
$R_{\rm p}$	$R_\oplus$	1.416 ± 0.034	1.47 ± 0.03	fixed, same as D14			
$\rho_{\rm p}$	g cm^{-3}	8.8 ± 2.5	5.8 ± 0.8	8.0 ± 1.43	6.46 ± 0.72	6.53 ± 0.75	6.46 (fixed)
Kepler-10 c							
Period	days	45.29485 ± 0.0007	45.294301 ± 4.8E-5	fixed, same as D14			45.295
TT	BJD-2454900	71.6761 ± 0.0022	162.26648 ± 0.00081	fixed, same as D14			71.67
K	m s^{-1}	x	3.26 ± 0.36	1.09 ± 0.58	2.67 ± 0.34	2.83 ± 0.38	2.66
a	AU	0.2407 ± 0.0048	0.2410 ± 0.0019	fixed, same as D14			0.24
e		0 (fixed)	0 (fixed)	0 (fixed)	0 (fixed)	0.17 ± 0.13	0.09
ω	°	…	…	…	…	71 ± 20	79.7
$M_{\rm p}$	$M_\oplus$	<20	17.2 ± 1.9	$5.69^{+3.19}_{-2.90}$	13.98 ± 1.79	14.59 ± 1.90	13.94
$R_{\rm p}$	$R_\oplus$	2.277 ± 0.054	2.35 ± 0.06	fixed, same as D14			
$\rho_{\rm p}$	g cm^{-3}	<10	7.1 ± 1.0	$2.42^{+1.36}_{-1.24}$	5.94 ± 0.75	6.21 ± 0.81	6.20

Jump parameter	Best-fit value	
	TERRA	alternative pipeline
Stellar activity GP model		
h [m s^{-1}]	$2.9^{+0.4}_{-0.3}$	$3.1^{+0.5}_{-0.3}$
λ [days]	$40.0^{+10.4}_{-9.0}$	$43.5^{+9.8}_{-8.9}$
w	$0.18^{+0.11}_{-0.04}$	0.26 ± 0.07
θ [days]	$40.4^{+1.1}_{-1.9}$	$39.8^{+1.1}_{-0.9}$
Uncorrelated jitter		
$\sigma_{\rm jit,HARPS-N}$ [m s^{-1}]	1.4 ± 0.3	0.6 ± 0.4
$\sigma_{\rm jit,HARPS-pre}$ [m s^{-1}]	2.2 ± 0.5	2.5 ± 0.5
$\sigma_{\rm jit,HARPS-post}$ [m s^{-1}]	2.0 ± 0.6	1.6 ± 0.6
RV offset		
$\gamma_{\rm HARPS-N}$ [m s^{-1}]	$-0.06^{+0.54}_{-0.57}$	$30149.2^{+0.6}_{-0.7}$
$\gamma_{\rm HARPS-pre}$ [m s^{-1}]	$0.20^{+0.75}_{-0.79}$	$30480.2^{+0.8}_{-0.9}$
$\gamma_{\rm HARPS-post}$ [m s^{-1}]	$0.002^{+0.670}_{-0.688}$	30479.2 ± 0.8
Planetary orbital parameters		
$K_{\rm b}$ [m s^{-1}]	2.7 ± 0.4	2.9 ± 0.4
$P_{\rm b}$ [days]	10.05454 ± 0.00003	10.05454 ± 0.00003
$T_{0,\rm b}$ [BJD-24 00 000]	56813.42022 ± 0.00095	56813.42025 ± 0.00095
$K_{\rm c}$ [m s^{-1}]	0.95 ± 0.37	0.98 ± 0.34
$P_{\rm c}$ [days]	24.64638 ± 0.00017	24.64638 ± 0.00018
$T_{0,\rm c}$ [BJD-24 00 000]	56812.2777 ± 0.0026	56812.2778 ± 0.0026
$K_{\rm d}$ [m s^{-1}]	$0.29^{+0.34}_{-0.18}$ [<0.43 (68.3^{th} perc.)]	$0.31^{+0.35}_{-0.20}$ [<0.47 (68.3^{th} perc.)]
$P_{\rm d}$ [days]	44.55764 ± 0.00042	44.55766 ± 0.00043
$T_{0,\rm d}$ [BJD-24 00 000]	56826.2248 ± 0.0037	56826.2247 ± 0.0038
Planetary radii [a]		
$R_{\rm p,b}$ ($R_\oplus$)	2.29 ± 0.23	
$R_{\rm p,c}$ ($R_\oplus$)	1.77 ± 0.18	
$R_{\rm p,d}$ ($R_\oplus$)	1.65 ± 0.17	
Quantities derived from RVs [b]		
$M_{\rm p,b}$ ($M_\oplus$)	6.6 ± 1.1	7.0 ± 1.0
$M_{\rm p,c}$ ($M_\oplus$)	$3.1^{+1.3}_{-1.2}$	$3.2^{+1.2}_{-1.1}$
$M_{\rm p,d}$ ($M_\oplus$)	$1.2^{+1.4}_{-0.7}$ [<1.8 (68.3^{th} perc.)]	$1.3^{+1.5}_{-0.8}$ [<1.9 (68.3^{th} perc.)]
	$2.7^{+1.2}_{-0.8}$ (see Sect. 5.1)	
$\rho_{\rm p,b}$ [g cm^{-3}]	$3.0^{+1.3}_{-0.9}$	$3.2^{+1.3}_{-0.9}$
$\rho_{\rm p,c}$ [g cm^{-3}]	$3.1^{+1.9}_{-1.3}$	$3.2^{+1.8}_{-1.3}$
$\rho_{\rm p,d}$ [g cm^{-3}]	$1.6^{+2.1}_{-1.0}$ [<2.4 (68.3^{th} perc.)]	$1.6^{+2.1}_{-1.0}$
	$3.1^{+2.0}_{-1.2}$ (see Sect. 5.1)	
$a_{\rm p,b}$ [AU]	$0.0777^{+0.0024}_{-0.0026}$	
$a_{\rm p,c}$ [AU]	$0.1413^{+0.0044}_{-0.0047}$	
$a_{\rm p,d}$ [AU]	$0.2097^{+0.0065}_{-0.0070}$	

Disagreement?

ESPRESSO:

K_b= 3.3+/- 0.3 m/s

Different stellar behavior…

27/05/2022

Food for Thoughts

- Selecting a large sample of super Earths and Neptunes with precise *and* accurate masses and densities will be challenging (bright stars are few!)

- Do your observing time estimates as accurately as possible

- Then double or triple them

- **For Ariel:** large(r) coordination/collaboration efforts to become necessary (e.g., TESS follow-up program in GAPS2 continuing in the coming years and improving cross-talk with HARPS-N GTO)