Multiplanet systems from the Dispersed Matter Planet Project

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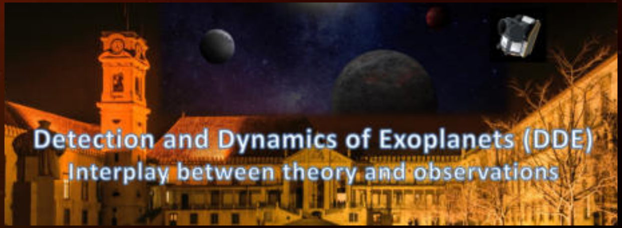


Artwork – DMPP-2 by Mark Garlick

The Dispersed Matter Planet Project hypothesis

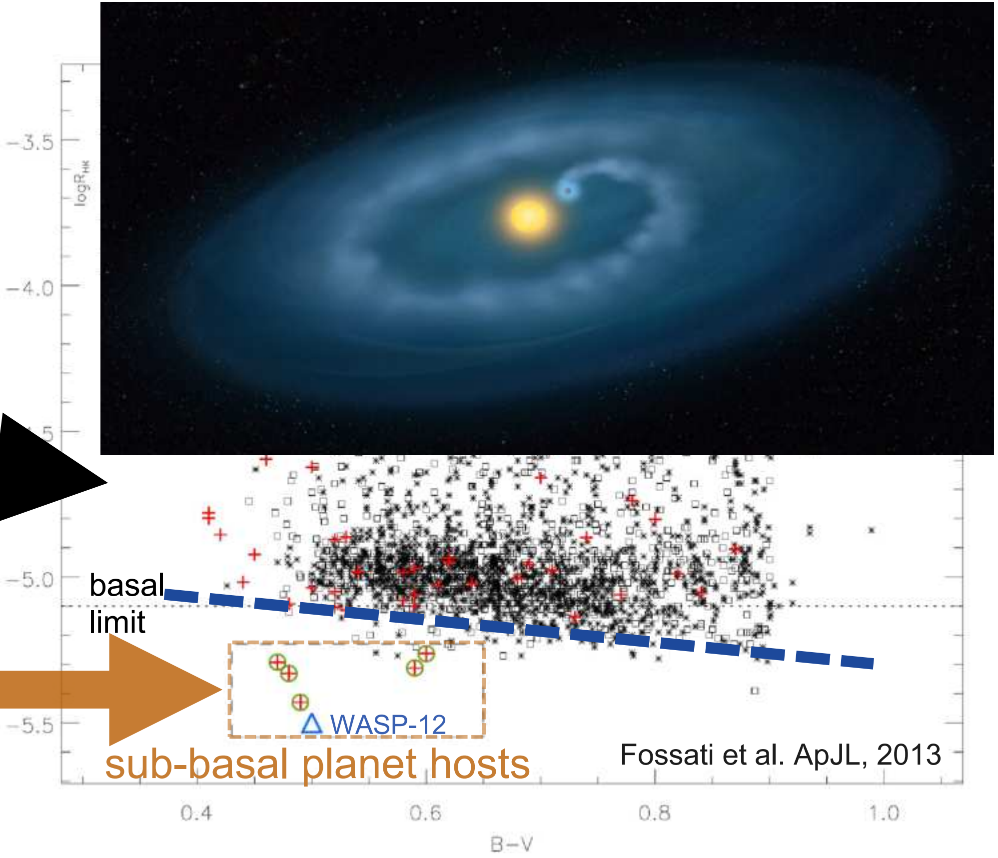
Basal flux due to dissipation of acoustic wave energy in the turbulent chromosphere

Ca II H&K basal flux

log R'_{HK} = -5.1 (on average)

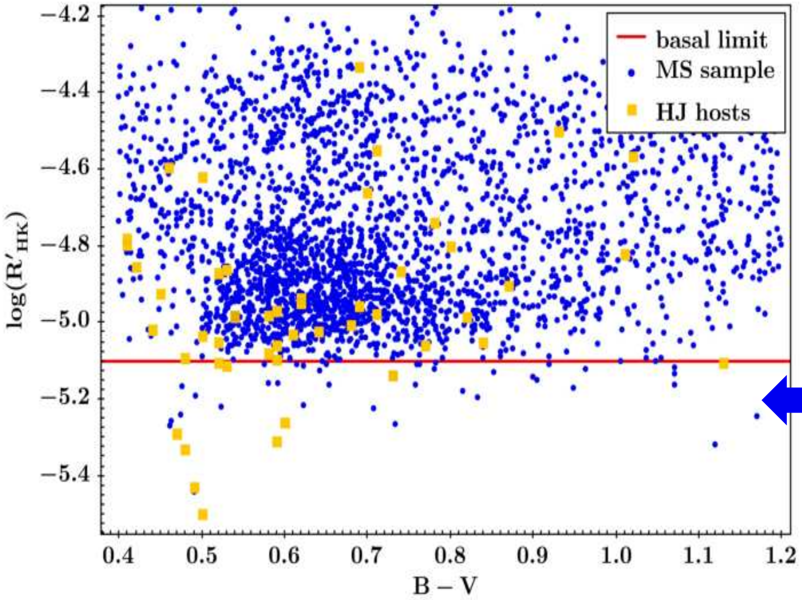
Energy released by magnetic activity phenomena results in excess emission above basal flux level

DMPP Hypothesis: continuing mass loss from close orbiting exoplanets may quench chromospheric emission below the basal flux level



The Dispersed Matter Planet Project- target identification

- Unevolved MS 0.4 < B-V < 1.2 sample of 2716 stars drawn from catalogue of Pace et al. (2013)



DMPP sample

39 targets,
all d ≤100pc

Potential BRIGHT hosts of mass-losing, low-mass(?), short period planets

- DMPP systems have 5 < *V* < 11 → more amenable to follow-up characterisation than e.g. Kepler planets
- Higher than average chance of transiting

DMPP: Radial velocity Survey

- High cadence monitoring –> increased sensitivity to short period low-mass planets

  RVs from HARPS, HARPS-N, SOPHIE

- RV periodogram searches

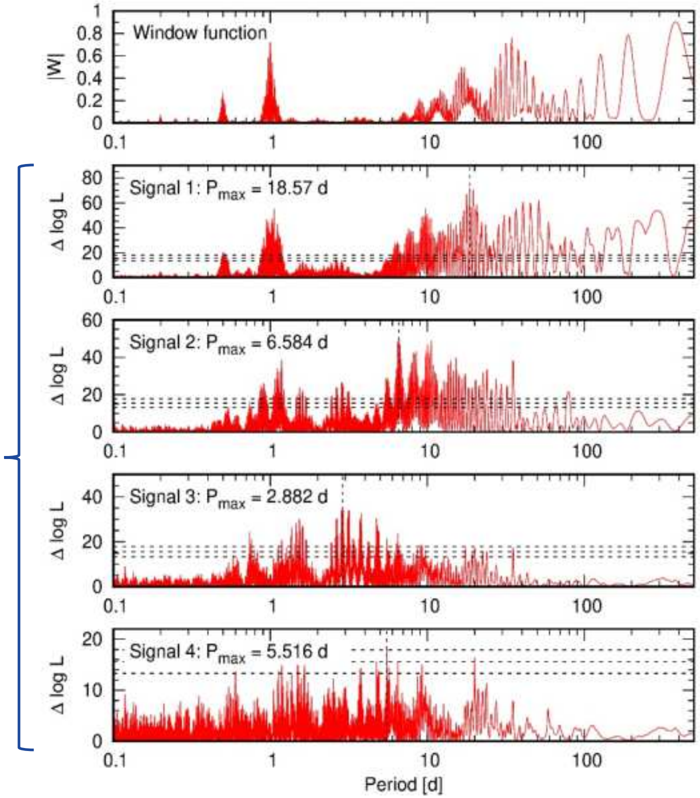
  Likelihood model with N_p Keplerians

  recursive addition of signals N_p vs N_{p-1} assessed via ΔLogL

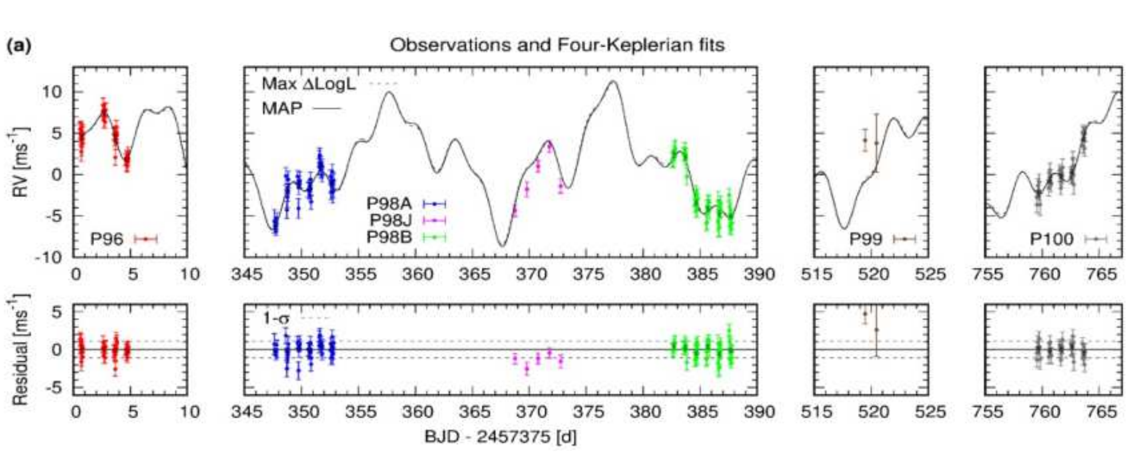
  Anglada-Escudé+ (2013, 2016)

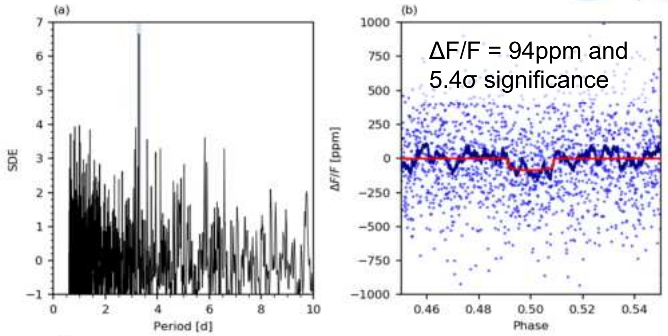
DMPP-1 148 HARPS RVs over 3 years

Four significant Keplerians



DMPP-1: compact multi-planet system with a transit





R_P $[R_\oplus]$	$1.38^{+0.29}_{-0.32}$
P (days)	$3.2854^{+0.0032}_{-0.0025}$
T_0 [BTJD]	1469.982 ± 0.010
i	$83.4^\circ{}^{+1.0^\circ}_{-0.4^\circ}$
a (au)	0.0461 ± 0.0008
T_{dur} (days)	$0.06^{+0.03}_{-0.01}$
b	$0.90^{+0.04}_{-0.13}$
δ (ppm)	87^{+25}_{-30}
$M_{P,\text{Earth-like}}$ $(M_\oplus)$	$3.2^{+3.6}_{-2.0}$

DMPP-1 F8V, V = 7.98 – Number of Planets: $\boldsymbol{N_p}$ **= 4**

Planet	b	c	d	e
P_{orb} [d]	18.6	6.58	2.88	5.52
m_p sin i [$M_\oplus$]	24	9.6	3.4	4.1

Staab+ Nat. Astron. 4, 399, 2020

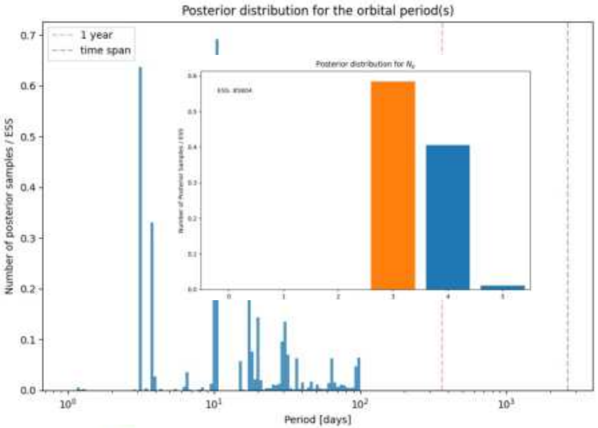
- Transiting 3.28 d planet is not detected in RVs. I insolation flux would be 990 $S_\oplus$, typical for a CDE

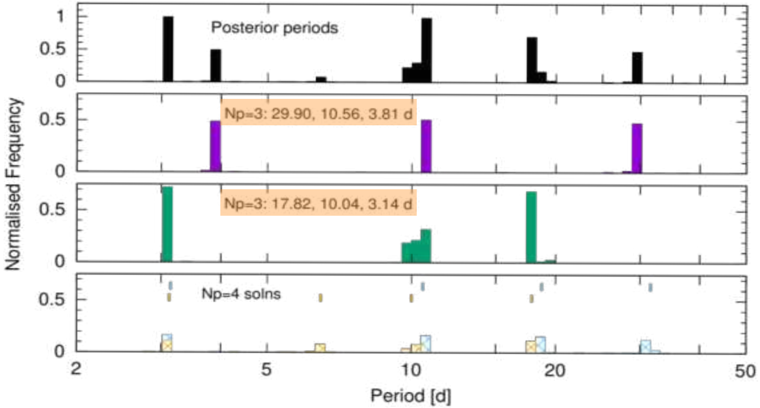
  Transit signature of low mass planet is likely due to transit signature of a dust/gas cloud

CHEOPS data under analysis

Jones+ ApJ, 895, L17, **2020**

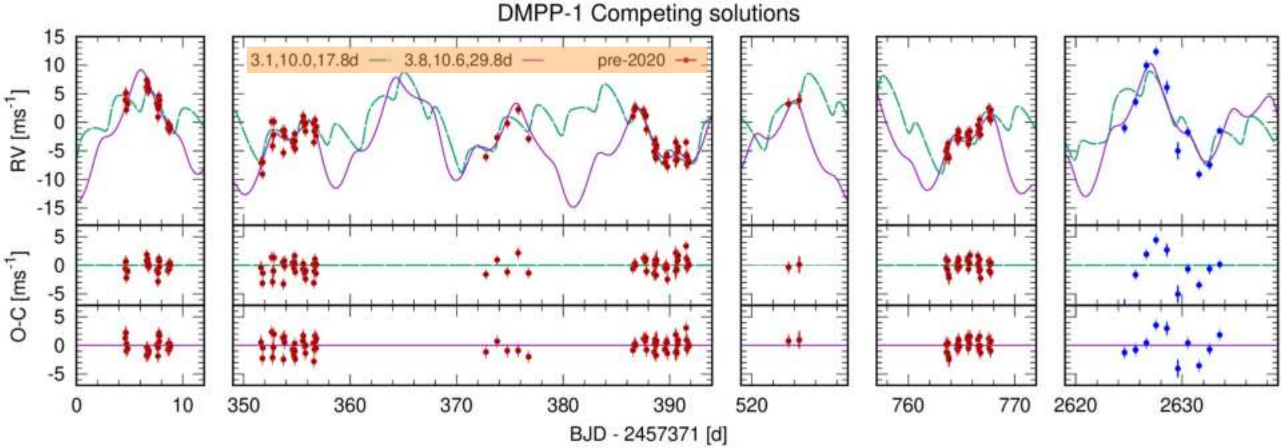
DMPP-1: Nested sampling with Kima – $N_p = 3$





Powered by kima

Faria et al. 2018



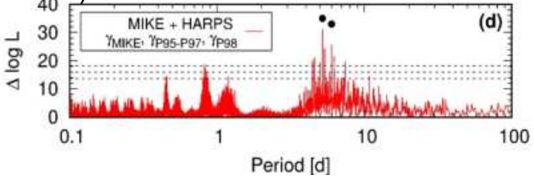
- Bayesian approach to identifying Keplerian signals

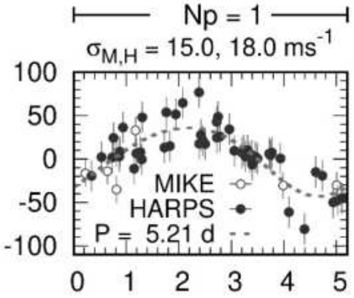
  Likelihood model includes Np as free parameter

  Diffusive nested sampling enables assessment of competing solutions

DMPP-2: two very different planetary systems

- **DMPP-2 :** F5V, *V* = 8.6 Haswell, Staab, Barnes et al. (*Nat. Astron.* 4, 408, 2020)





- **Kima :**

  Np = 3

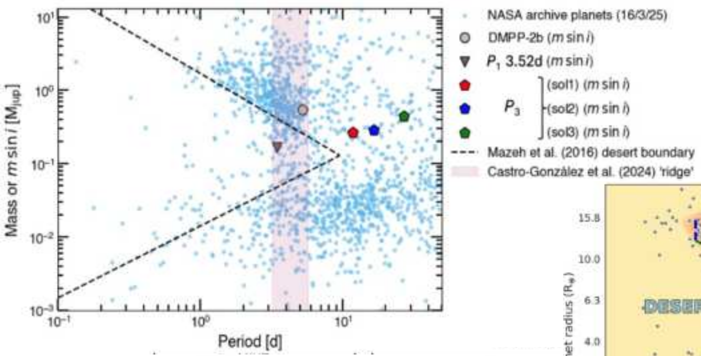
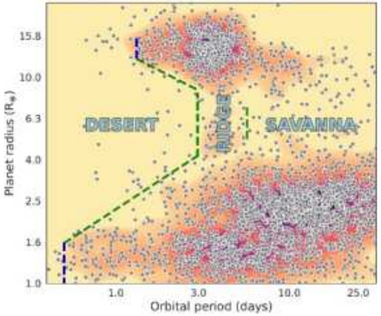
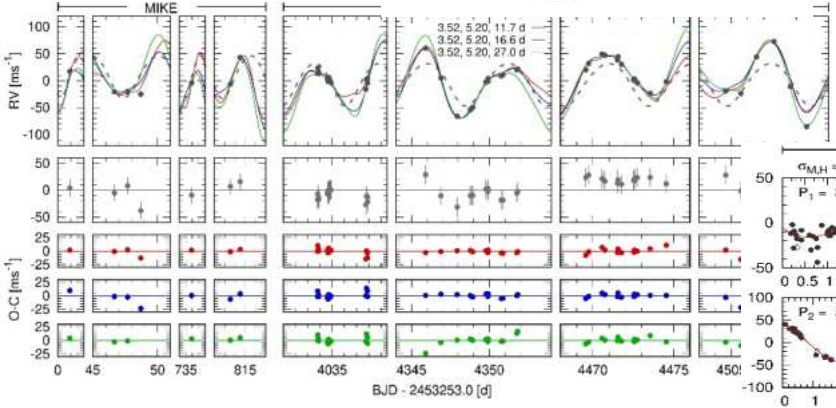
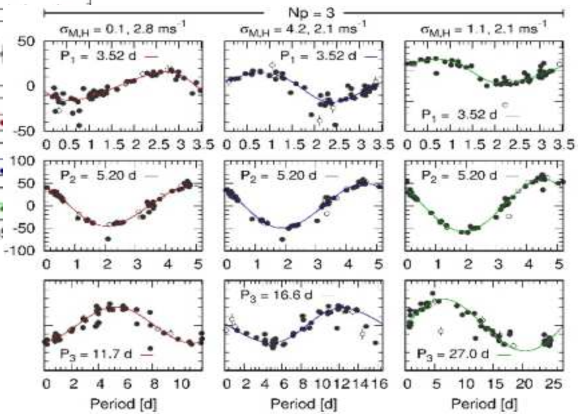


Fig 1: Short period exoplanets. The newly identified "Ridge" is indicated in pink. The "Savannah" is at P > ~6d and intermediate masses.







- High jitter originally interpreted as due to stellar non-radial gravity-mode pulsations γ-Doradus pulsator

P_{orb} = 5.207 d $M_p \sin i$ = 0.469 M_J

DMPP-4: A naked-eye F star - Keplerian solutions

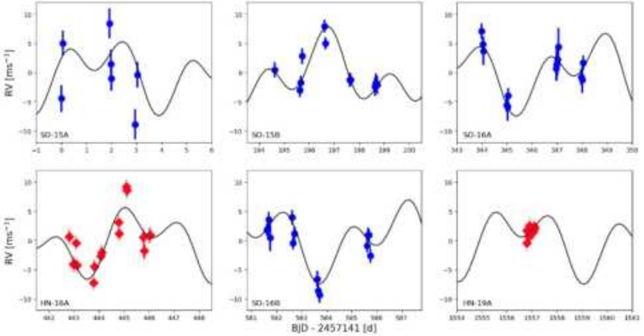
	$N_p = 2$
$T_{0,b}$ [d]	$2457140.26^{+0.81}_{-0.65}$
P_b [d]	$2.4570^{+0.0026}_{-0.0462}$
K_b [ms^{-1}]	$3.26^{+0.46}_{-0.57}$
e_b	<0.065
ω_b [rad]	$2.7^{+2.4}_{-1.6}$
a_b [AU]	$0.03836^{+0.00039}_{-0.00044}$
$m_p \sin i_b$ [M$_\oplus$]	$8.0^{+1.1}_{-1.5}$
	Planet candidate c
$T_{0,c}$ [d]	$2457138.9^{+1.6}_{-1.8}$
P_c [d]	$5.4196^{+0.6766}_{-0.0030}$
K_c [ms^{-1}]	$3.81^{+0.43}_{-0.50}$
e_c	<0.064
ω_c [deg]	$2.8^{+2.2}_{-1.7}$
a_c [AU]	$0.06514^{+0.00469}_{-0.00041}$
$m_p \sin i_c$ [M$_\oplus$]	$12.2^{+1.4}_{-1.6}$

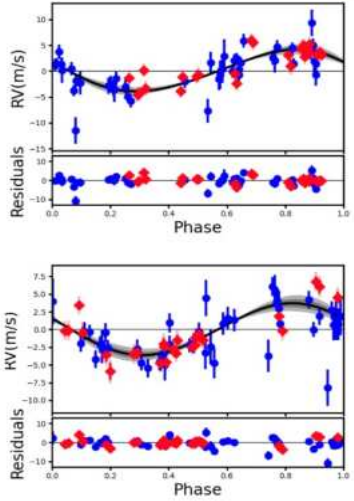
Recursive

2.459 d

3.498 d

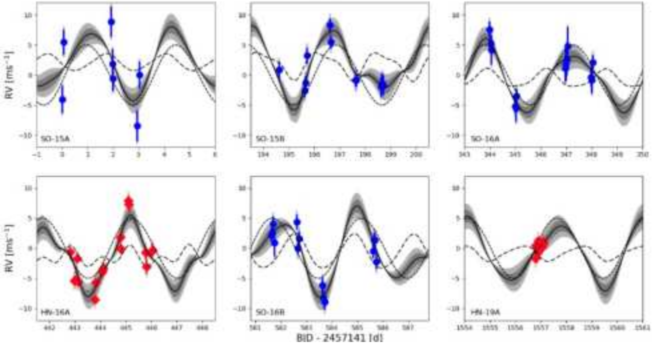
Keplerian only : $N_p = 2$



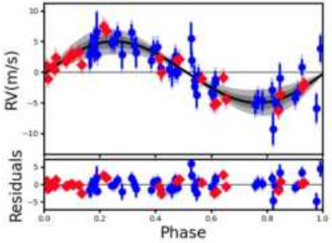


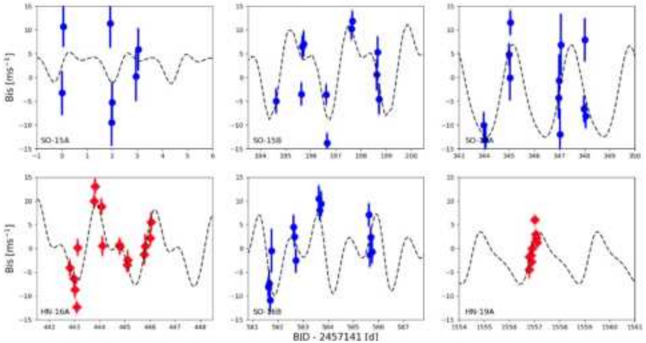
Barnes+ **2023**

Kepleriain + GP with simultaneous fit to BIS timeseries : $N_p = 1$



P = 3.498 d



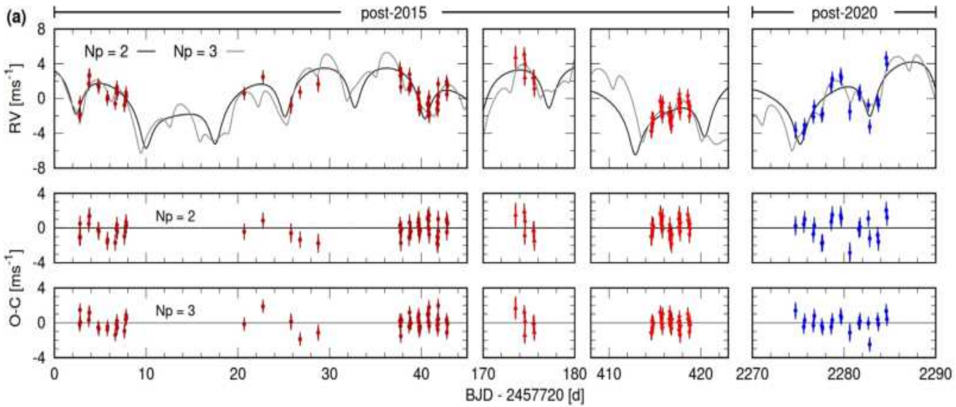


Another DMPP system

- Long term coherent signals --> dynamical signals

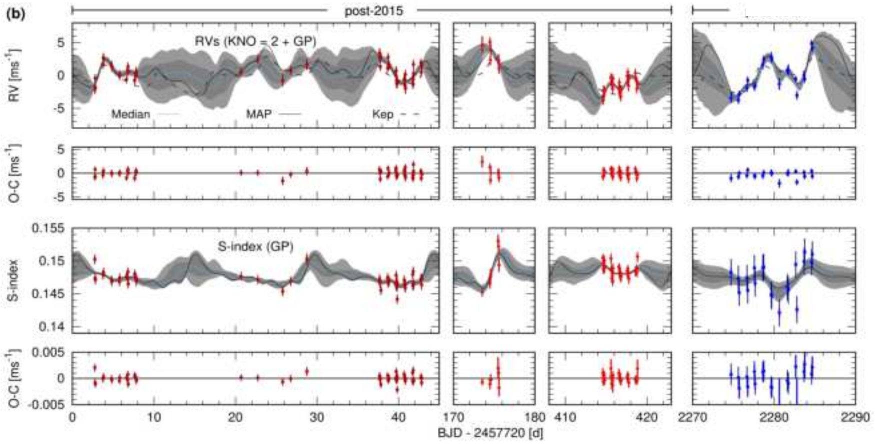
  Strong evidence for $N_p = 2$

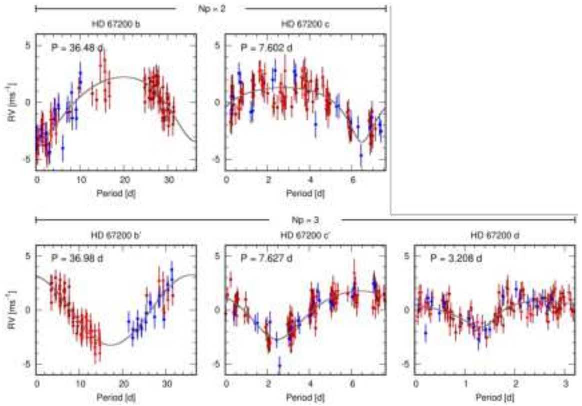
  moderate for $N_p = 3$ (BF = 38)



- Tentative activity evidence

  Keplerian + GP fitting





Need more data with better sampling!

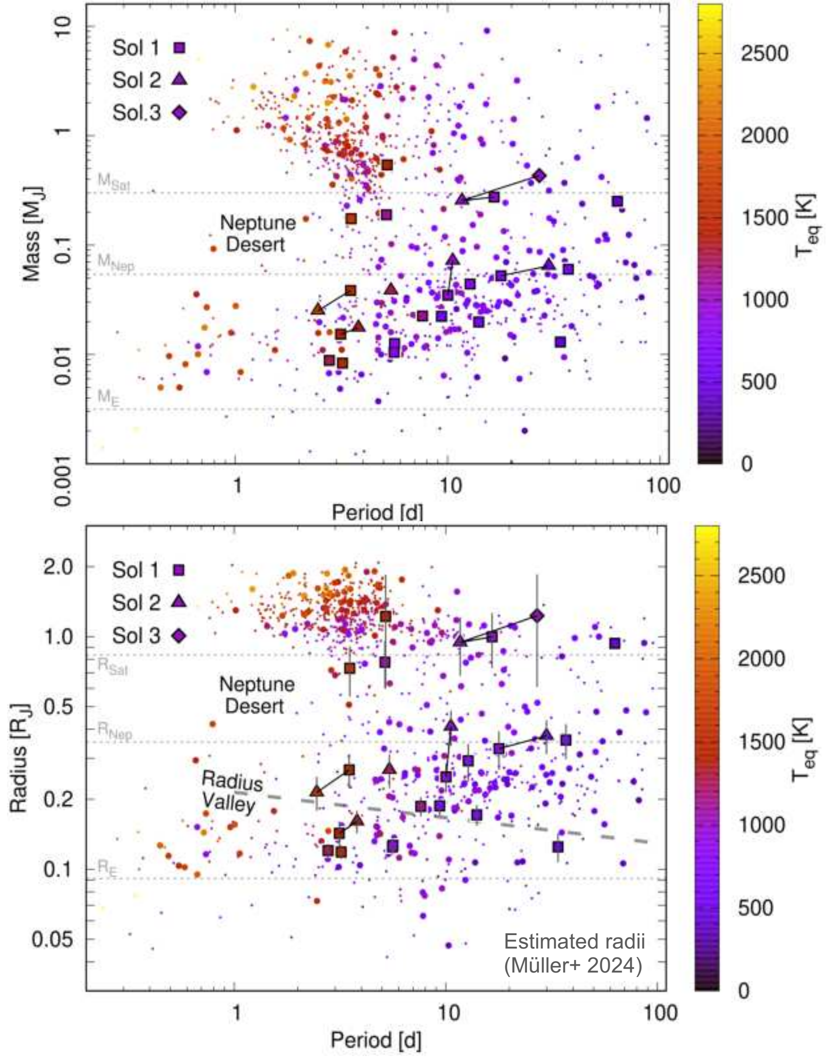
DMPP: Demographics

Moderate-Strong evidence for 23-24 exoplanets

- Majority of planets are sub-Neptune-mass
  - around half have T_{eq} > 1000 K (9 for A = 0.36 / 11 for A = 0)
  - radii suggest H_2 dominated atmospheres (Zeng et al. 2019)

- Masses indicate likely rocky bodies for DMPP-1, DMPP-3Ab, HD39194 (Mayor+2011, Unger+2021), HD2134 and HD67200
  - mass loss via sputtering --> refractory-rich atmospheres esp. for O and Mg (Vidotto+ 2016)

- HD181433 – N_p = 3 (Bouchy+ 2009, Horner+2019) and other systems HD89839 mostly have long period planets 1000d – 7000d
  - undetected interior planets – HD181433b (P=9.4d), but no evidence for interior planets (yet)

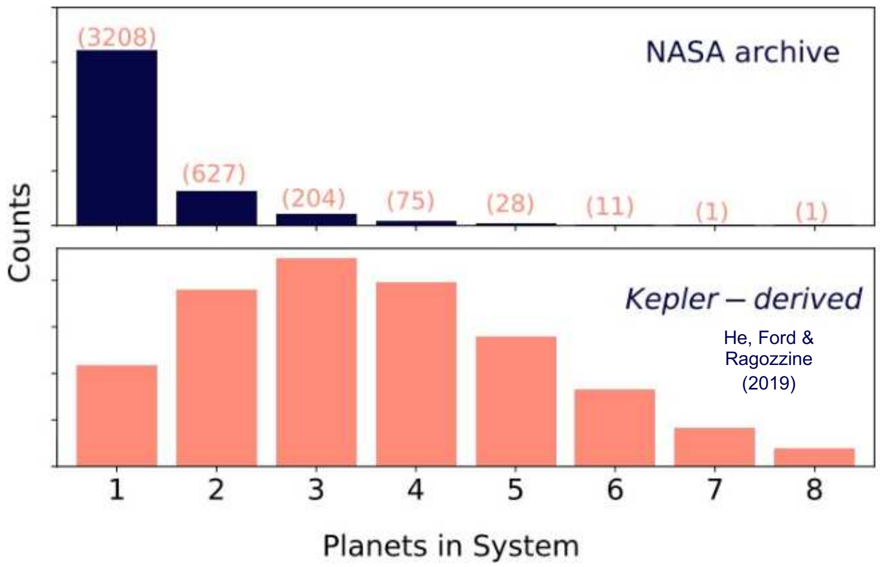


Multiplicity

- Kepler revealed ubiquity of low-mass planets
- 23% of exoplanet systems are *observed* to be in multiples
- Forward models based on Kepler systems (He+ 2019) predict far more multiplanet systems than are present in exoplanetary catalogues

90% of systems multiples

$<N_p>$ ~ 4.5 (He+ 2021)



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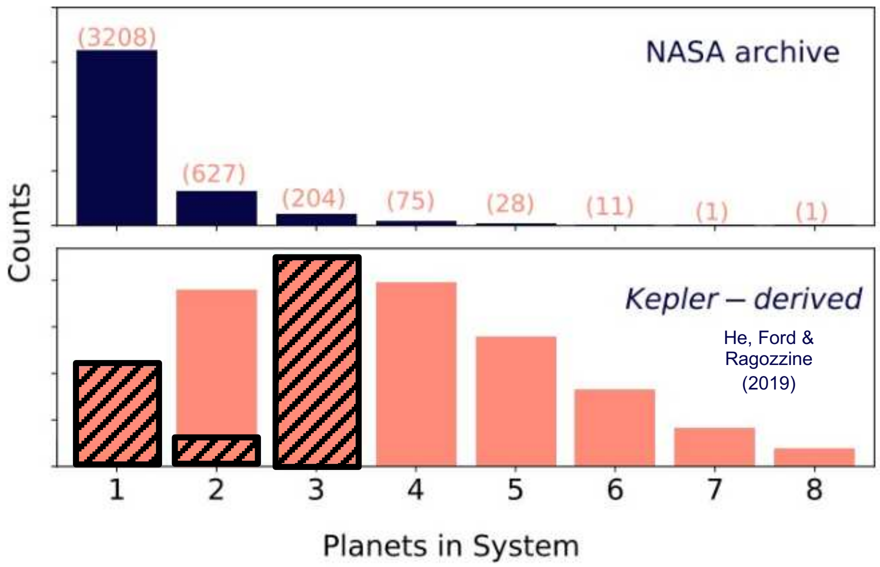


DMPP: $f(N_p=3) = 2 \times f(N_p=1)$

- RVs less sensitive to inclination effects

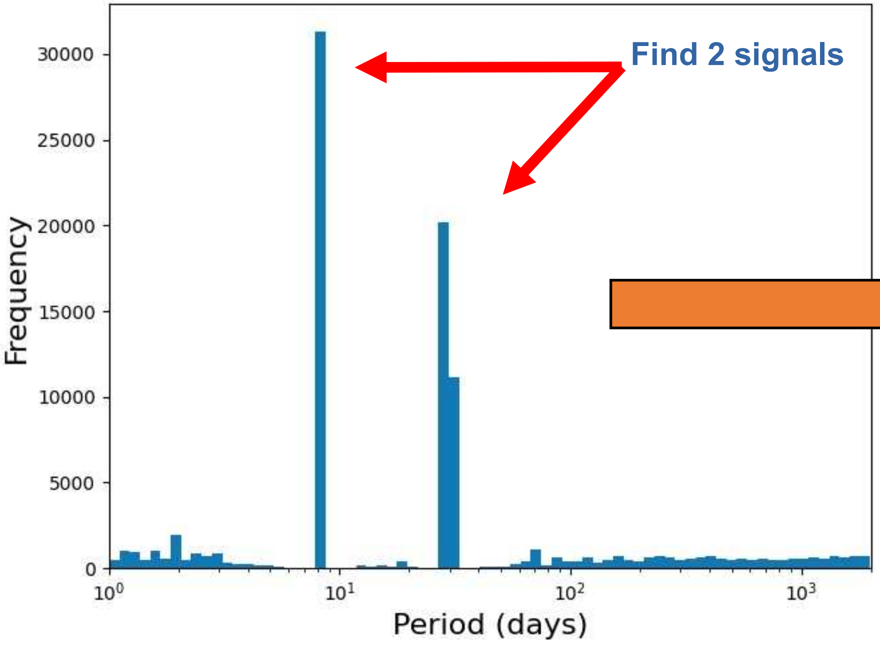
still need robust characterisation of signals

Detection sensitivities with a diffusive nested sampler

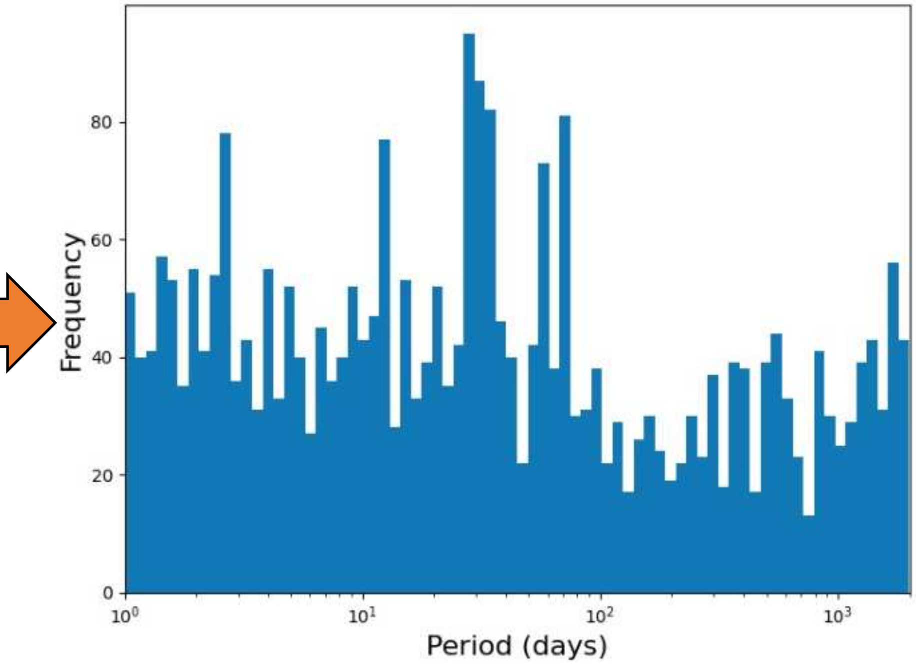
- Produces map of all signals compatible with data when forced to explore Np higher than formally detected (BF = 150) “what is compatible with the data?”
- Since those proposed signals remain formally undetected, the posterior naturally produces a detection threshold

Methodology outlined in Standing+ (2022) & Standing+ (2025, in prep)

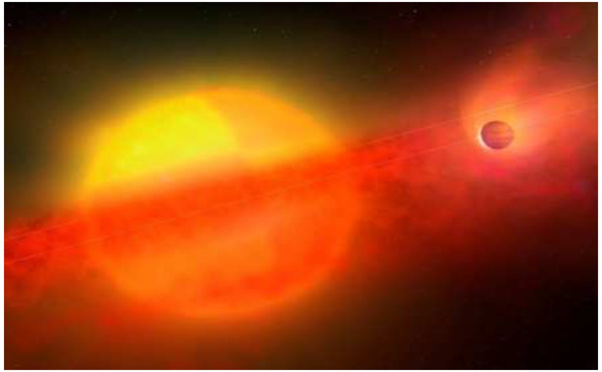
Initial run to establish any signals present



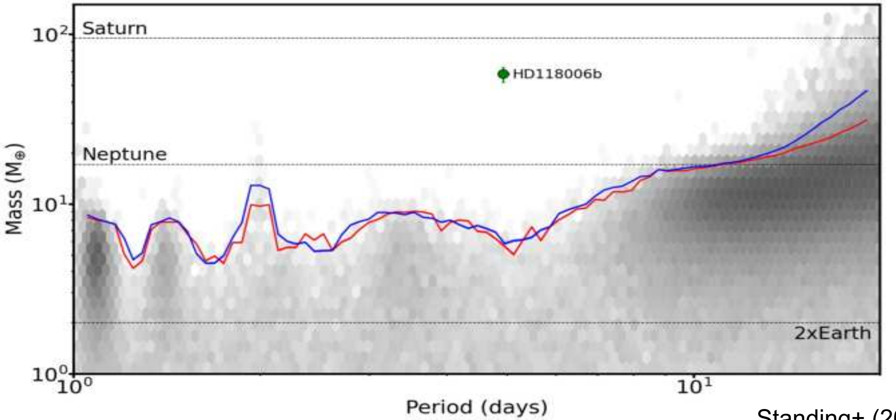
Np = 1 (fixed)



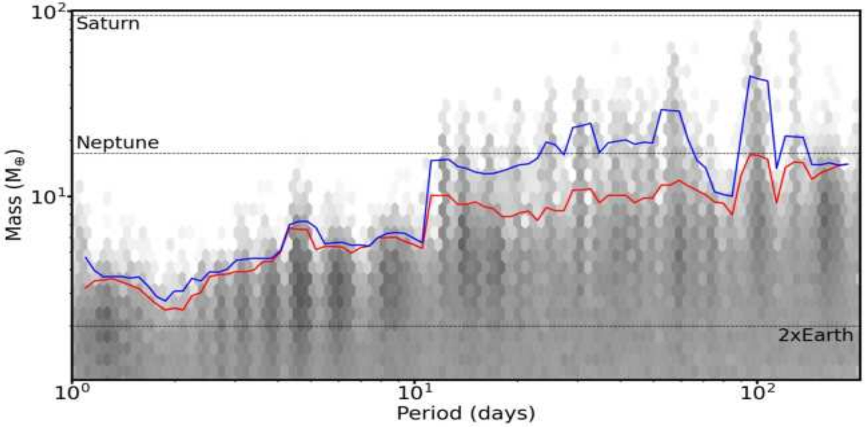
Detection sensitivities in the DMPP sample



DMPP-2 system Image credit: Mark A. Garlick

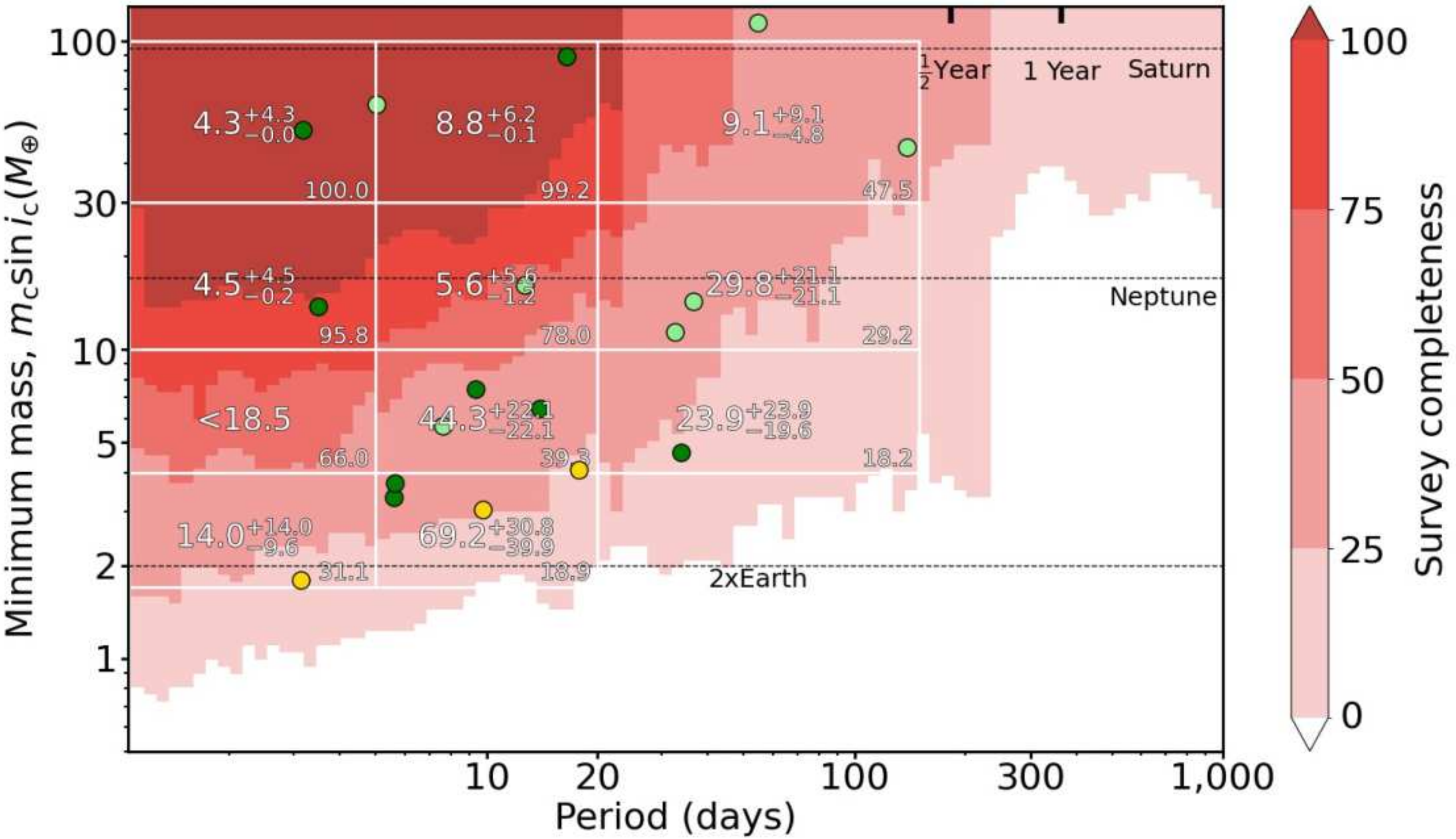


Standing+ (2025, in prep)



- Assuming circular orbits affects sensitivities e.g. Endl+ 2002) and see Standing+ (2022).
- *e*=0 not necessary with this method
- **Overestimates sensitivity by ~8%!**

DMPP completeness

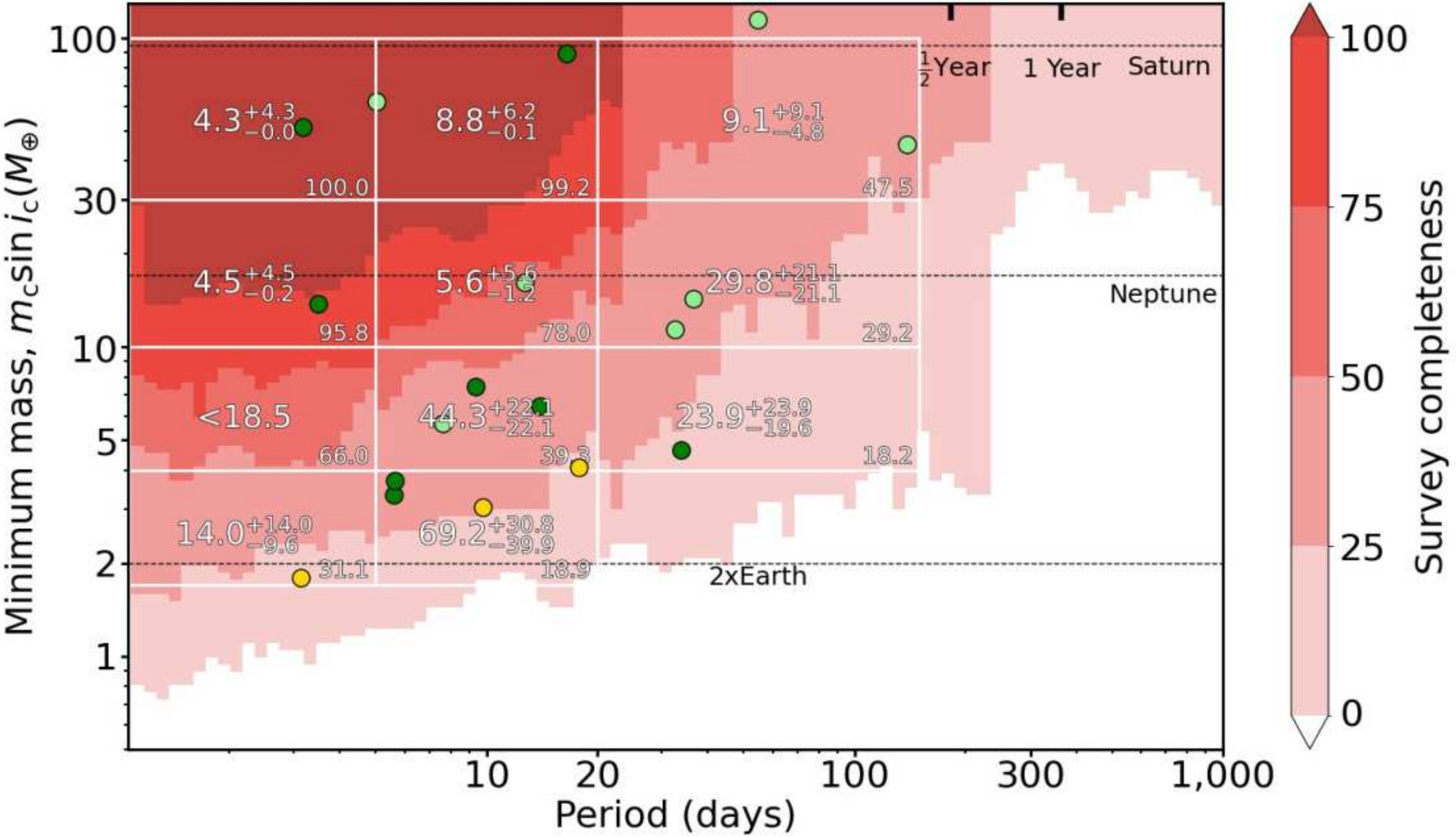


DMPP occurrence rates

$$\mathcal{N}_p = \frac{1}{n_{stars}} \sum_{i=1}^{n_{det}} \frac{1}{C(P_b, m_b \sin i_b)}$$

$$\sigma = 2\frac{\mathcal{N}_p}{\sqrt{n_{det}}}$$

Mayor et al. (2011)



Comparison of occurrence rates with other RV surveys

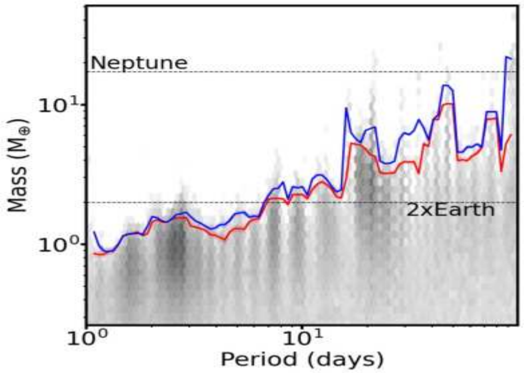
		$3 - 10\ M_\oplus$	$10 - 30\ M_\oplus$	$30 - 100\ M_\oplus$
Eta-Earth survey (Keck) - 166★	Howard et al. (2010)	11.8 ± 4.3 %	6.5 ± 3 %	1.6 ± 1.2 %
HARPS GTO - 822 ★	Mayor et al. (2011)	16.6 ± 4.4 %	11.1 ± 2.4 %	1.2 ± 0.5 %
HARPS Archive - 693 ★	Bashi et al. (2020)	10.0 ± 2.0 %	6.0 ± 1.0 %	-
DMPP Survey - 23 ★	This work	$82.8^{+17.2}_{-29.3}$ %	$23.0^{+11.5}_{-5.6}$ %	$14.5^{+8.4}_{-1.4}$ %
	This work (circular)	69.6 ± 24.6 %	$20.8^{+10.4}_{-3.4}$ %	$13.3^{+7.7}_{-0.3}$ %

Standing+ (2025, in prep)

Consistent with the DMPP hypothesis!

DMPP: Summary and Future Work

- Highly efficient recovery of diverse planetary systems orbiting host stars with below basal flux chromospheric emission
  - likely (near) edge on systems
- TESS analysis in progress to search for transits and stellar periodicities
  - challenging : $d_{transit} \leq 100$ ppm
- First epoch RVs for remaining systems with few or no observations
  - evidence for signals in many/most systems
- Occurrence rates in agreement with DMPP hypothesis



Nested sampling with N_p as a free parameter more reliable than frequentist methods where Keplerians are added recursively