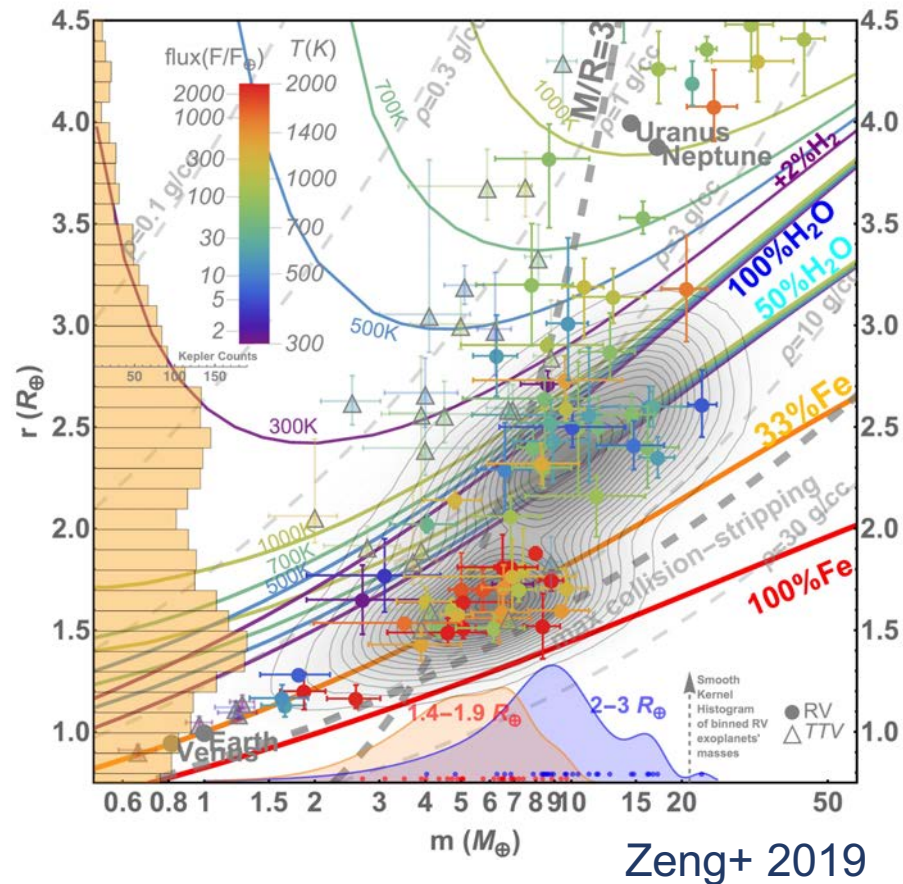# Direct discovery of planet masses for ARIEL with radial velocities

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Motivation

- Mass estimates required for bulk properties

Zeng+ 2019

- Uncertainties often large

 require $\Delta M_p \leq 50\%$ or better to distinguish planet types

Motivation

- Mass estimates are expected with atmospheric retrieval codes
- How feasible is the direct mass recovery with ground based RV facilities?

- For ARIEL, use

  Tier 1 sample of ~2100 planets from Edwards+ 2019

  How many observation epochs are needed to recover reliable masses for the lowest mass planets?

Potential Tier 1 Planets (2098 plotted)

Edwards+ 2019

- Not simple to answer – depends on many factors – stellar rotation activity, spectral type, orbital period, instrument precision
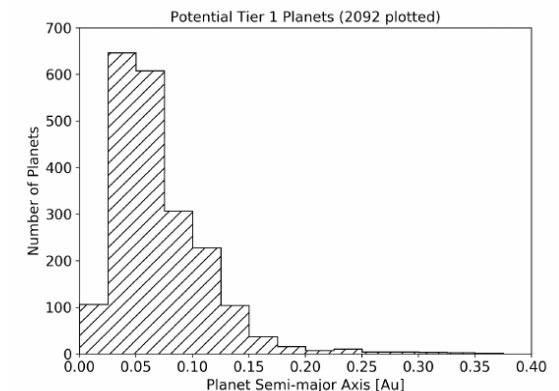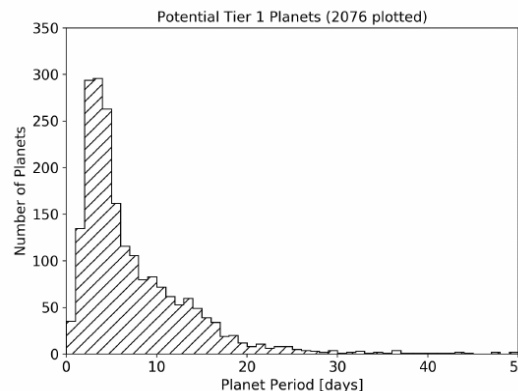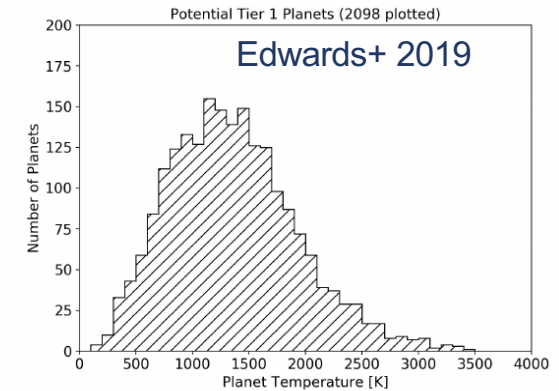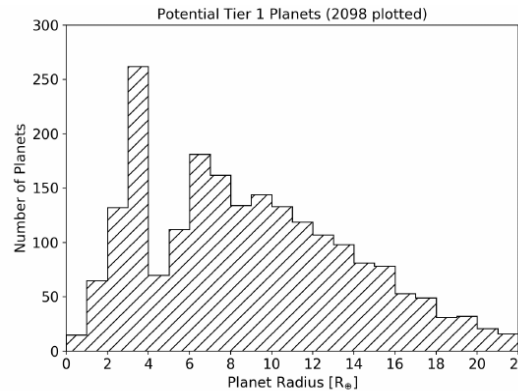
Spot Models

- Log-normal solar spot distribution models (Bogdan+ 1988)

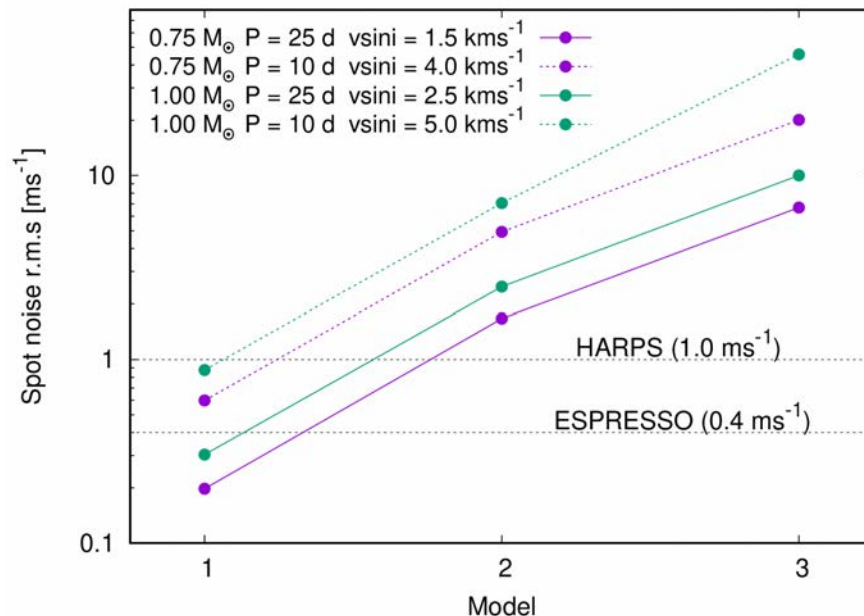|	Solar minimum	Solar maximum	Extreme solar maximum
	f = 0.02%	f = 0.3%	f = 2%
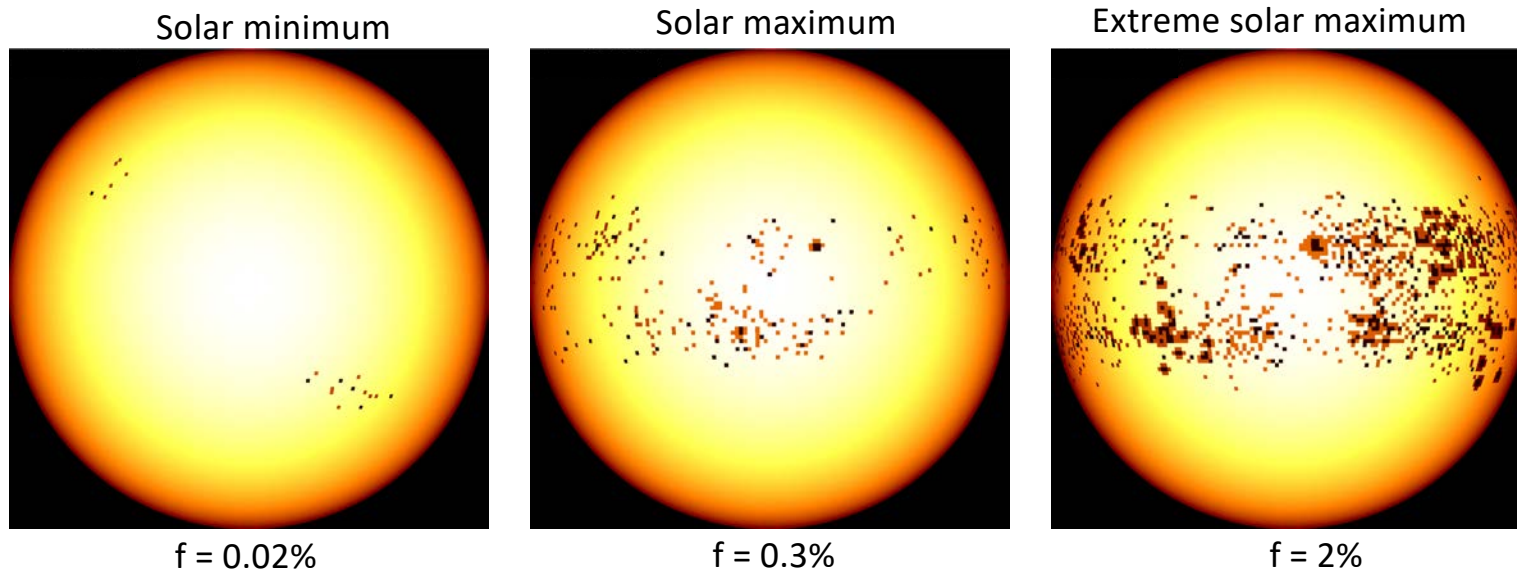
- Models scaled to match spot filling found from indirect imaging techniques (Solanki+ 1999)
- Umbral filling factors of 0.02% (solar min) – 2% (extreme solar max) used

Spot model 'Jitter'

- Stellar models: K2V / 0.75 $M_\odot$ & G2V / 1.0$M_\odot$ (SpT vs spot contrasts from Berdyugina+ 2005)
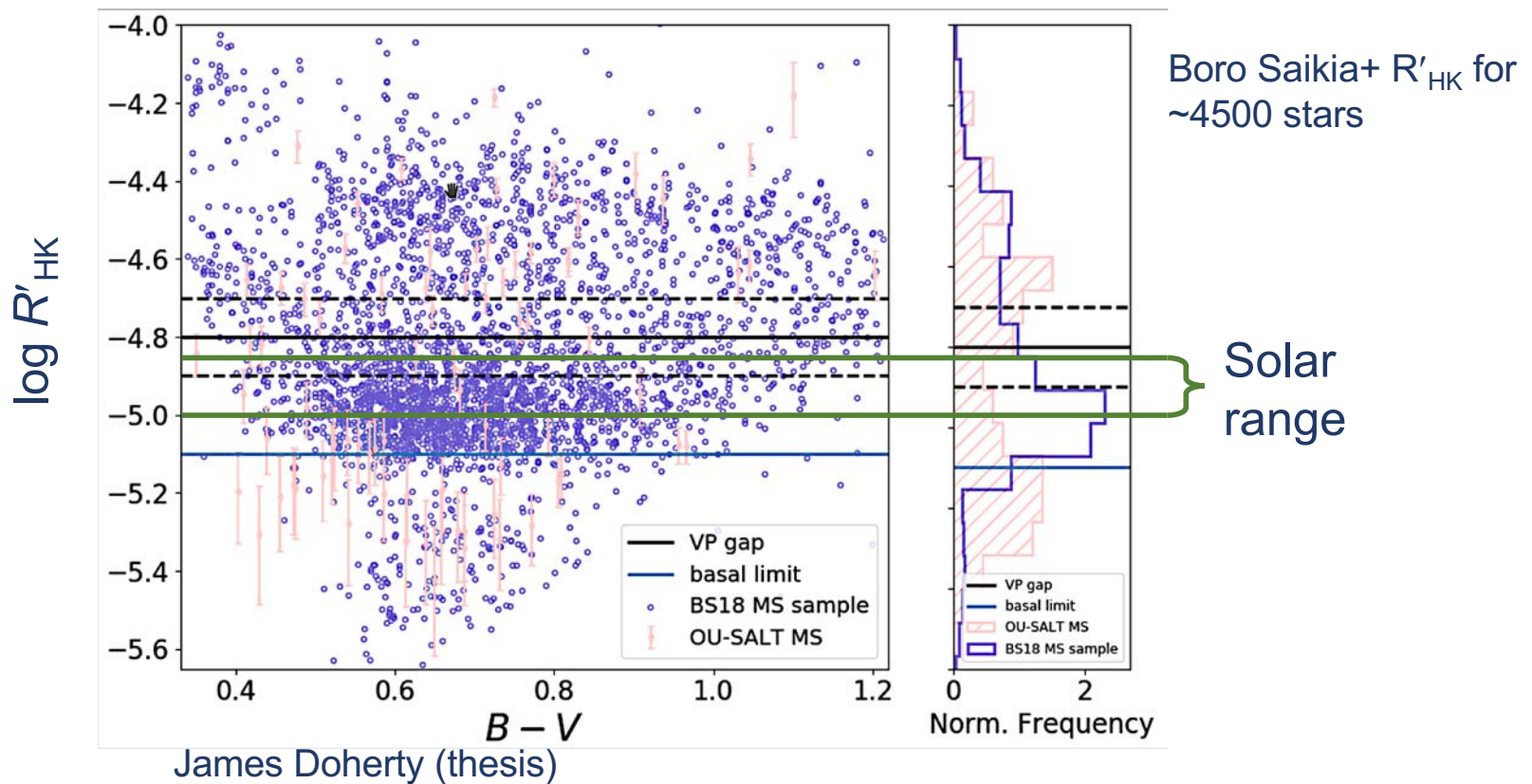
- P_{rot} = 10 d & P_{rot} = 25 d

	K2V - 0.75 $M_\odot$ T_{eff} = 5000K T_{sp} = 3750K	G2V - 1.0 $M_\odot$ T_{eff} = 5750K T_{sp} = 4000K
P_{rot} [d]	$v \sin i$ [km/s]	$v \sin i$ [km/s]
10	4.0	5.0
25	1.5	2.5

- HARPS spectral resolution R ~ 115,000
- Solar minimum activity – spot noise < 1 ms^{-1}
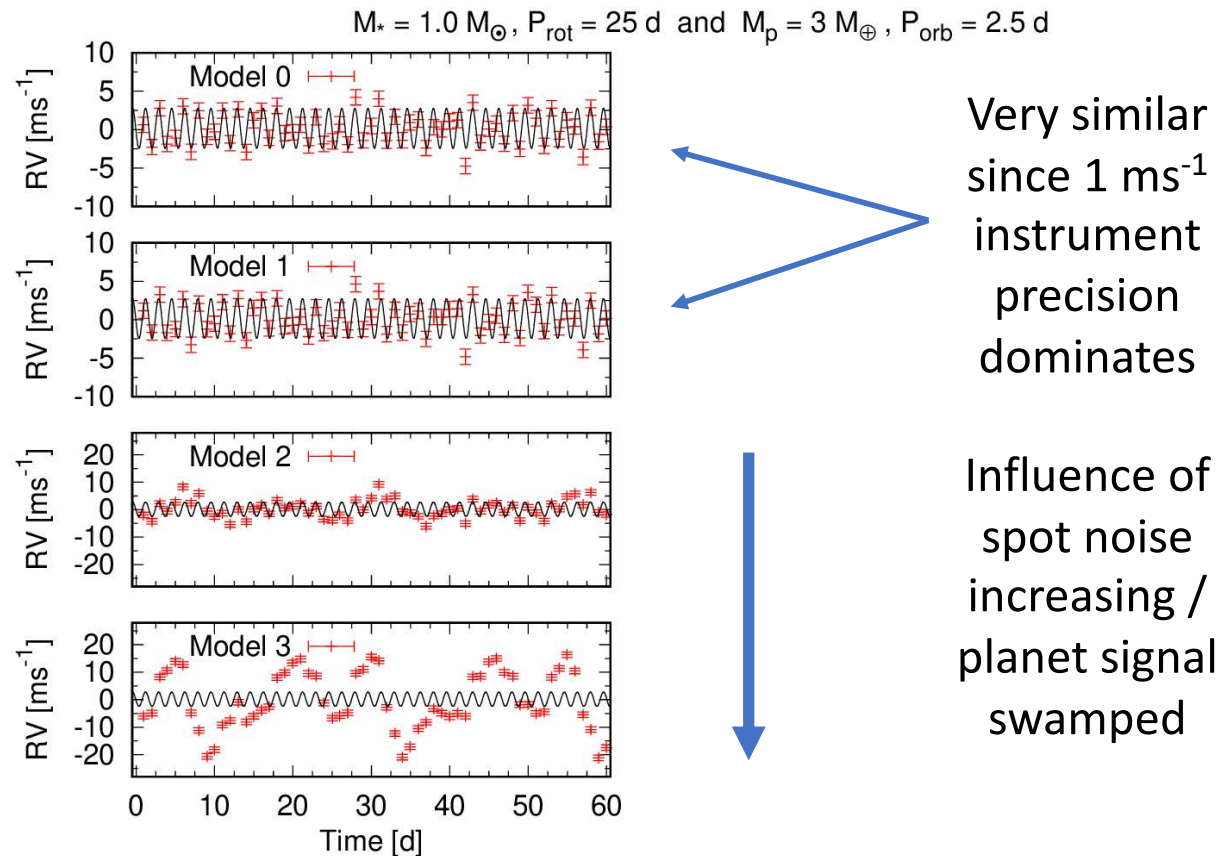- Dominated by instrumental precision of 1 ms^{-1}

Typical activity

- Solar min and max correspond to Ca II H&K chromospheric activity measures of log R'_{HK} ~ -5.0 and log R'_{HK} ~ -4.85

Boro Saikia+ R'$_{HK}$ for ~4500 stars

Solar range

James Doherty (thesis)

The simulation

- Simulate RVs for 1.25 d < P_{orb} < 20 d and 1.0 $M_\oplus$ < M_p < 50 $M_\oplus$

- Astrophysical noise Model 1, 2 & 3 and no spots (Model 0) case each using the two stellar P_{rot} / $v \sin i$ cases

- Instrumental precision of 1 ms^{-1} assumed (i.e. HARPS)

- Synthetic RVs – 1 observation per night for 30, 60, 90, 120, 180, 240 nights

$M_* = 1.0\ M_\odot$, $P_{rot} = 25$ d and $M_p = 3\ M_\oplus$, $P_{orb} = 2.5$ d

Very similar since 1 ms^{-1} instrument precision dominates

Influence of spot noise increasing / planet signal swamped

Signal recovery & mass estimate

- Recover signal without accounting for activity using likelihood model period search (Anglada-Escudé+ 2012, 2016)

  (Likelihood ratio periodograms give improvement in $\Delta \log L$ of a best fit including a planetary signal compared to the null hypothesis which is the best fit without a Keplerian signal)

- Posterior sampling → mass uncertainties

- Cases with 50% (1-sigma) mass uncertainties identified

$M_* = 1.0\ M_\odot$, $P_{rot} = 25\ d$ and $M_p = 3\ M_\oplus$, $P_{orb} = 2.5\ d$
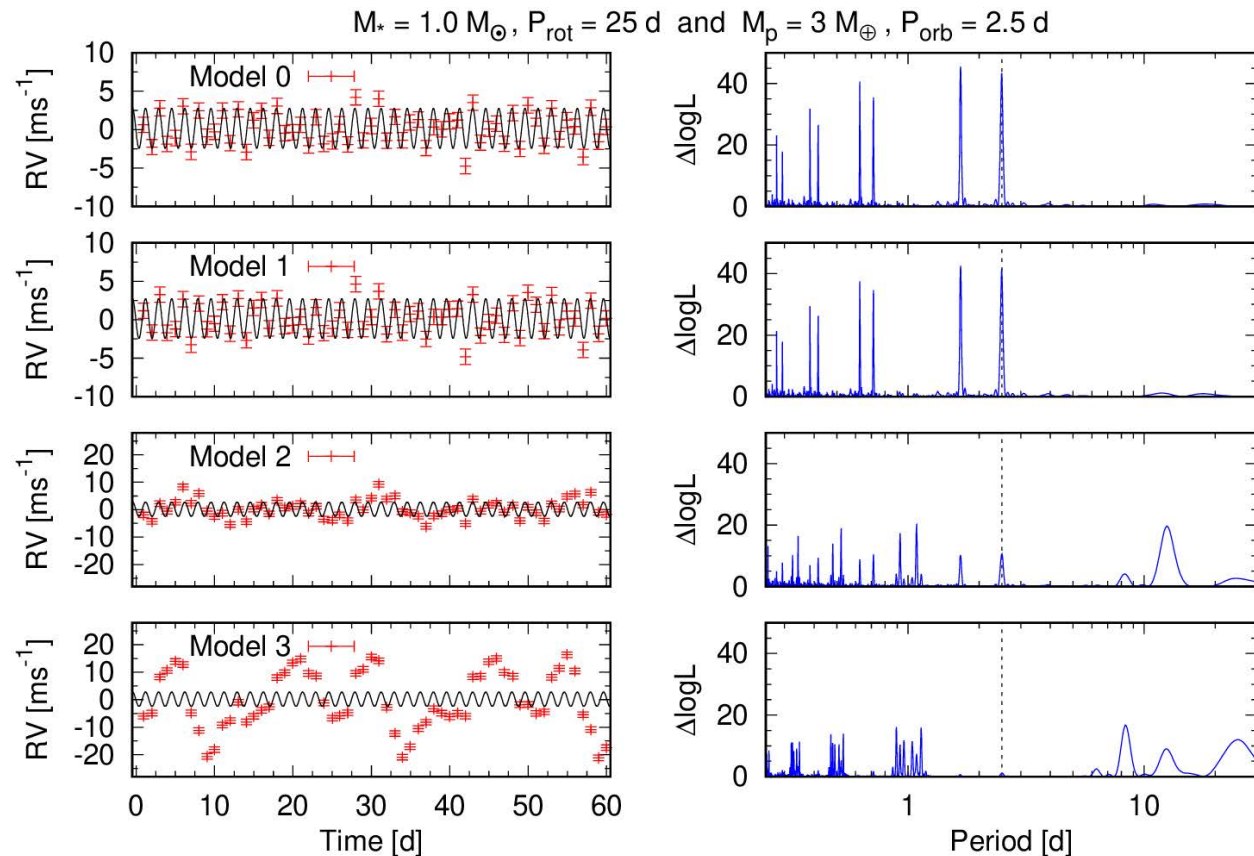
N_{obs} sensitivities

- Additional criterion: correct injected signal – i.e. P_{orb} - must be recovered (not alias peaks)

- Generally peak with $\Delta \mathrm{Log}\, L > 15$ is considered a significant detection

- In general ensures unambiguous period and mass recovery and yields mass uncertainties of order 10%
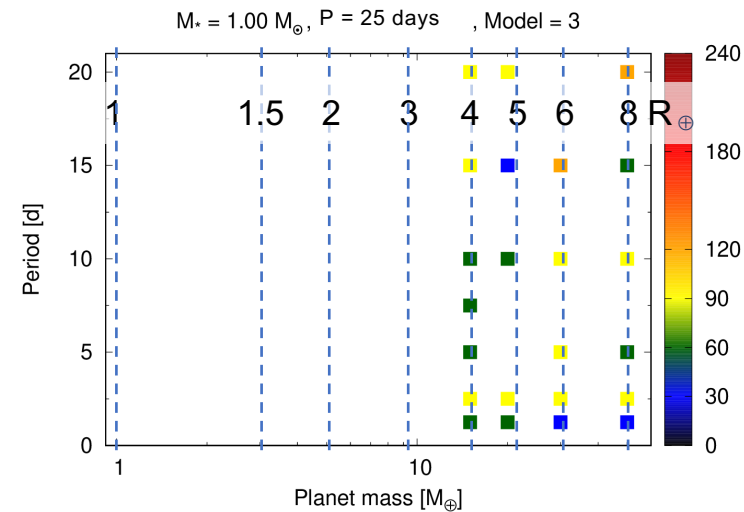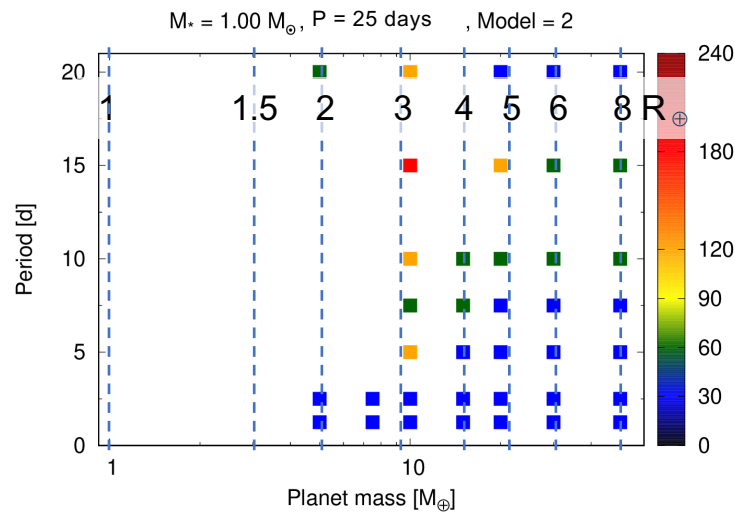

$M_* = 1.00\ M_\odot$, P = 25 days , Model = 0
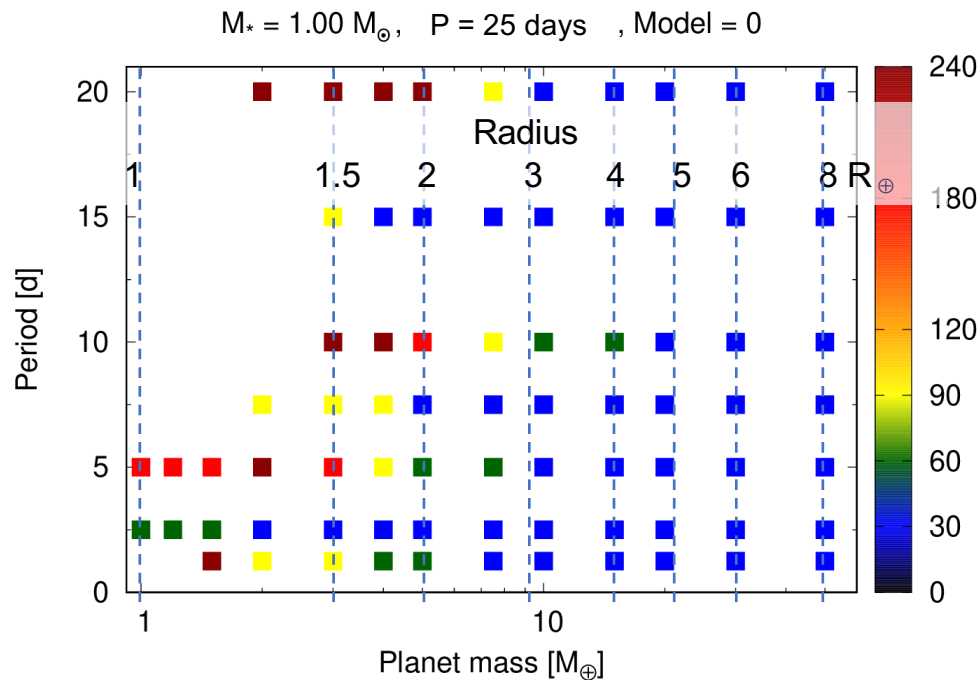
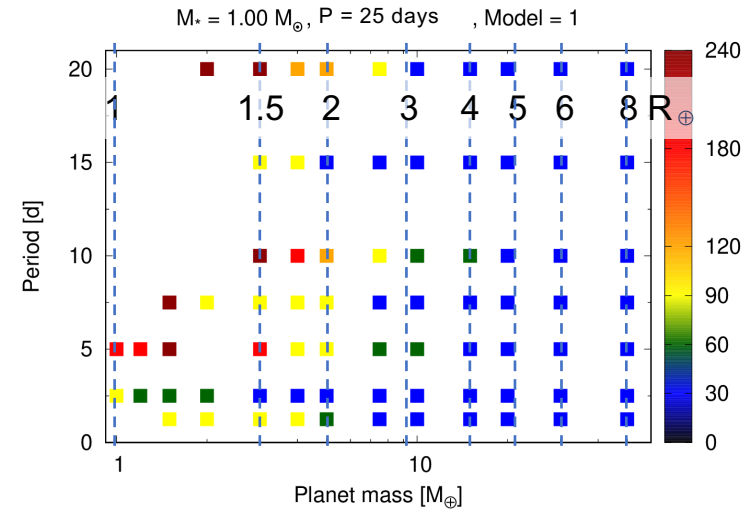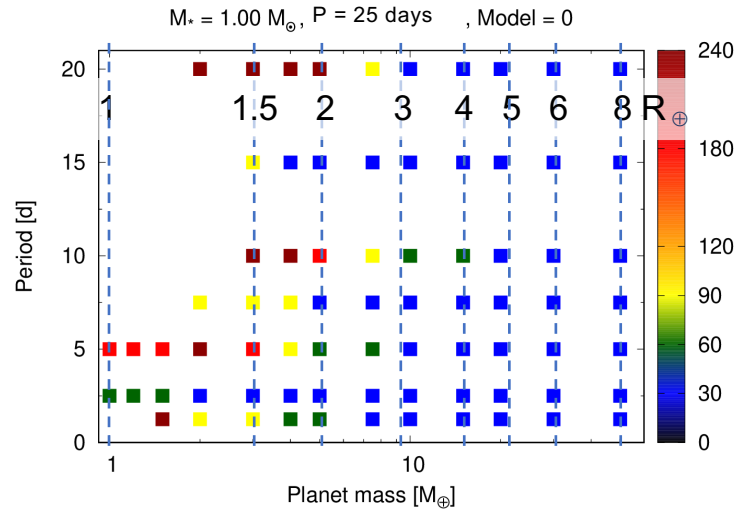Probabilistic radii from Cheng & Kipping 2017

Sensitivity

eg. Models 0 / 1 (sol min): 1.0 - 1.5 $M_\oplus$ in 2.5 d orbit with 60 - 90 obs

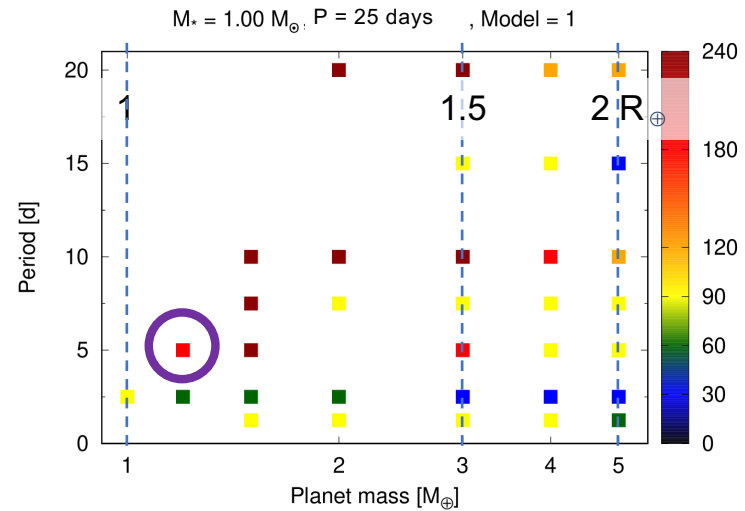Model 2 (sol max): 5 $M_\oplus$ limit for P <= 5 d ; 10 $M_\oplus$ limit for P >= 5 d

Model 3: 20 $M_\oplus$ limit
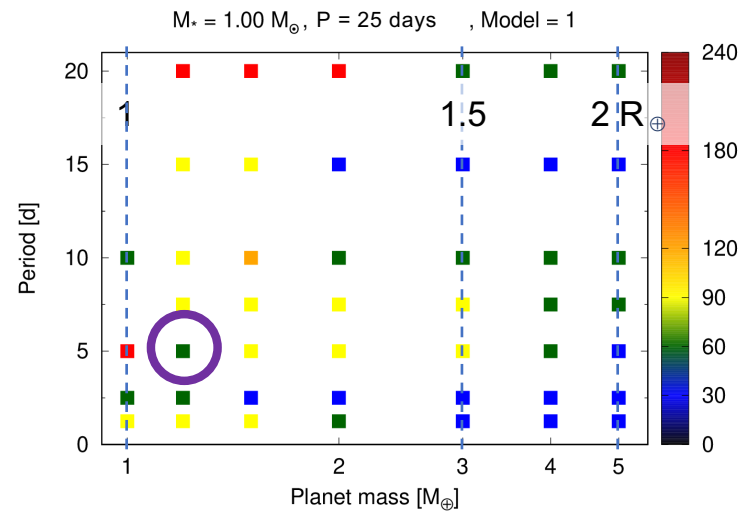
Instrumental precision

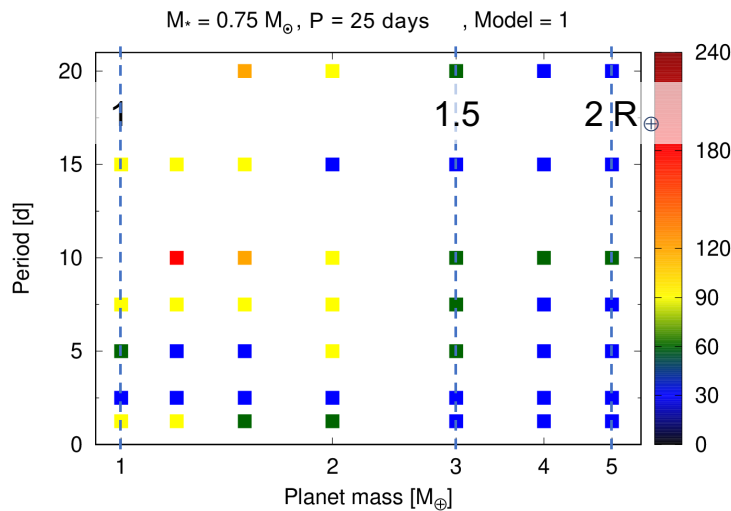0.4 ms^{-1} instrument precision → lowest mass planets feasible

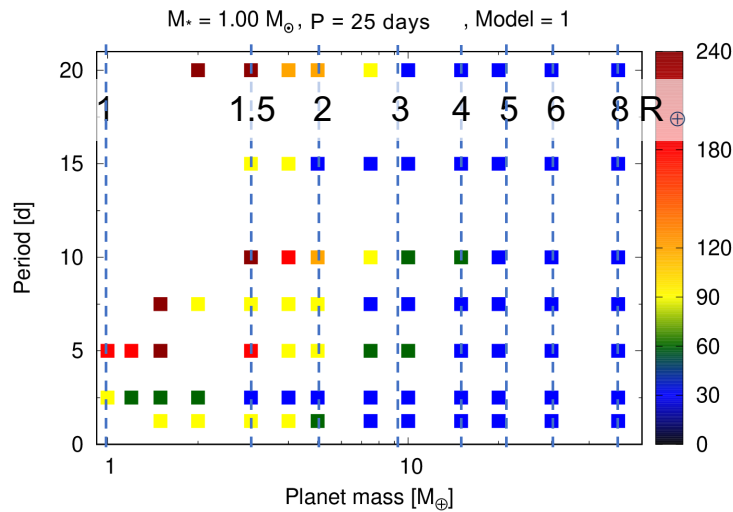eg 5 d, 1.2 M$_\oplus$ / 1.1 R$_\oplus$ requires 180 epochs with HARPS vs 60 epochs with ESPRESSO
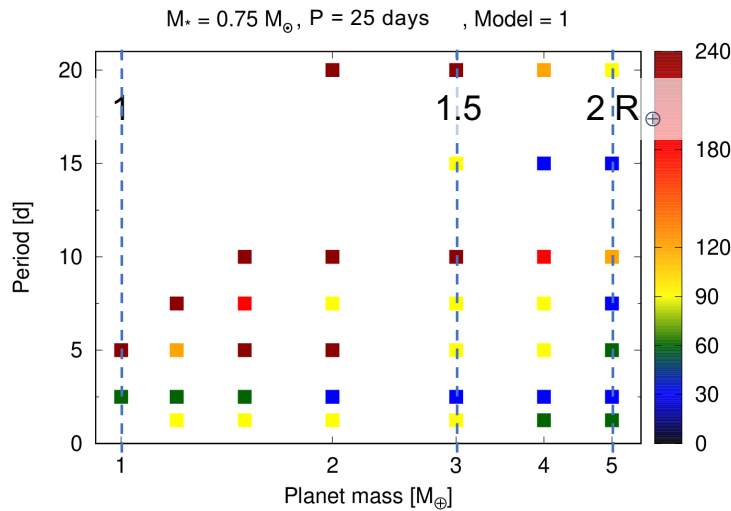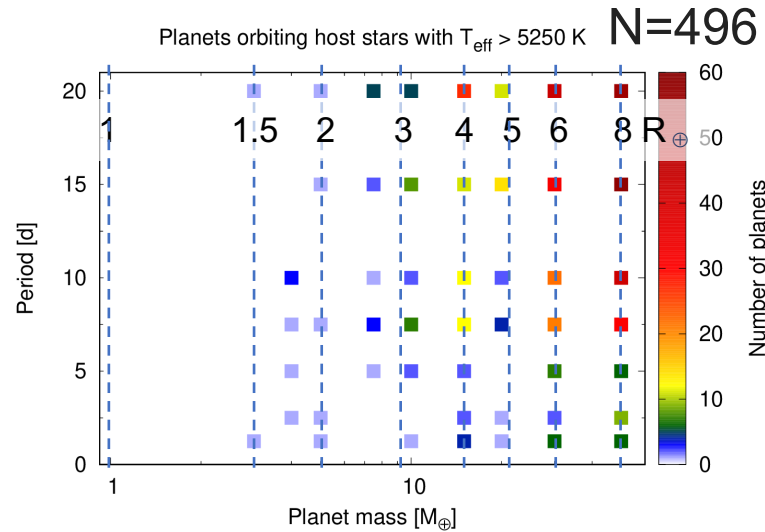
Number of observations

Assuming Model 1 / solar min stellar noise can be achieved

Sensitivities

$N_{planets}$ = 720 (Edwards+2019 sample)

$M_* = 1.00\ M_\odot$, P = 25 days, Model = 1

Planets orbiting host stars with $T_{eff} > 5250$ K   N=496

× = 16770 obsns

$M_* = 0.75\ M_\odot$, P = 25 days, Model = 1

Planets orbiting host stars with $T_{eff} < 5250$ K   N=224
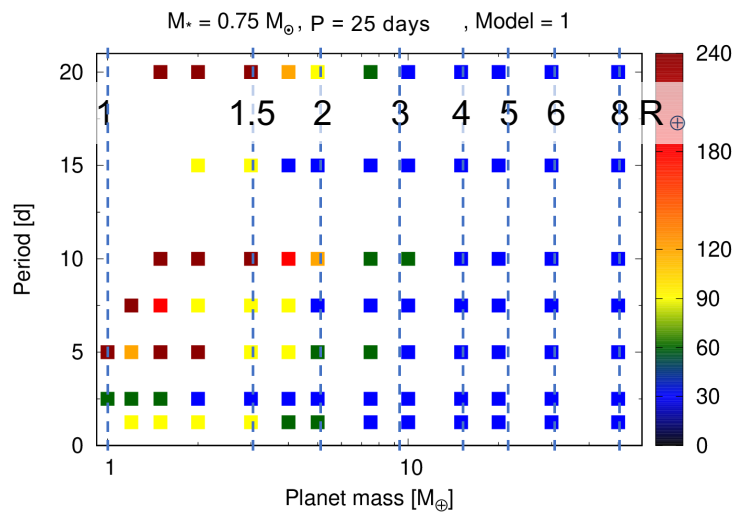
× = 11250 obsns

TOTAL ~28,000

Concluding estimates

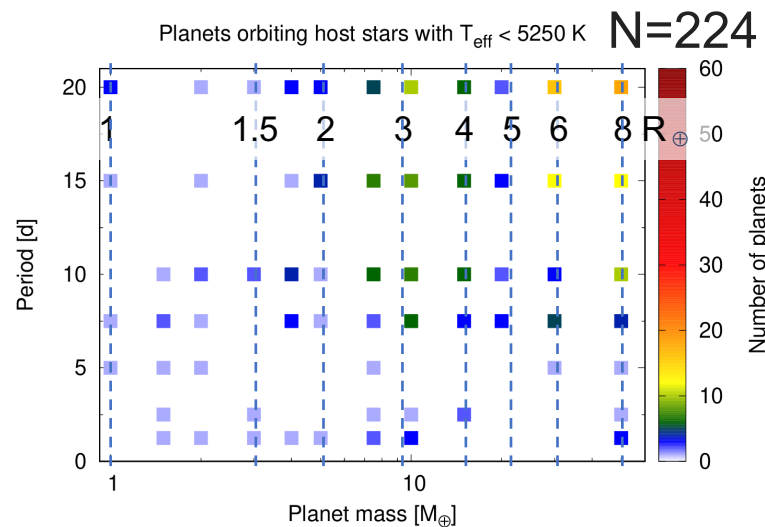- For 1ms^{-1} instrumental precision, assuming rough 900 sec exposures for all targets:

  TOTAL TIME = 292 days...assuming 8hr/night ---> **876 nights (~2.5 years)**

  ~1000 reference sample – 1.25 years   **!DON'T QUOTE TIMES!**

- To do:
  - Planets requiring >240 observations not included in estimate
  - Tier 1 sample contains a further ~1370 stars, extending mass to $M_p > 50\ M_\oplus$ ($R_p > 8\ R_\oplus$) and longer periods
  - Sub 1-ms^{-1} / ESPRESSO subset estimates needed

- Preliminary results indicate significant ground-based commitment is required for direct RV masses

- Facilities such ESPRESSO will be reserved for the lowest mass planets

- Selected targets with existing facilities and/or dedicated follow-up RV telescopes needed for larger / full sample

- Consider possibility of infrared RV facilities for fainter/redder targets