Workshop talk: False positives and shallow eclipsing binaries in transiting exoplanet services, PLATO Week, Porto, October 2017

Other

How to cite:

Rowden, Pamela; Kolb, Ulrich and Farmer, Rob Workshop talk: False positives and shallow eclipsing binaries in transiting exoplanet services, PLATO Week, Porto, October 2017. n/a, Porto.

False positives and shallow eclipsing binaries in transiting exoplanet surveys

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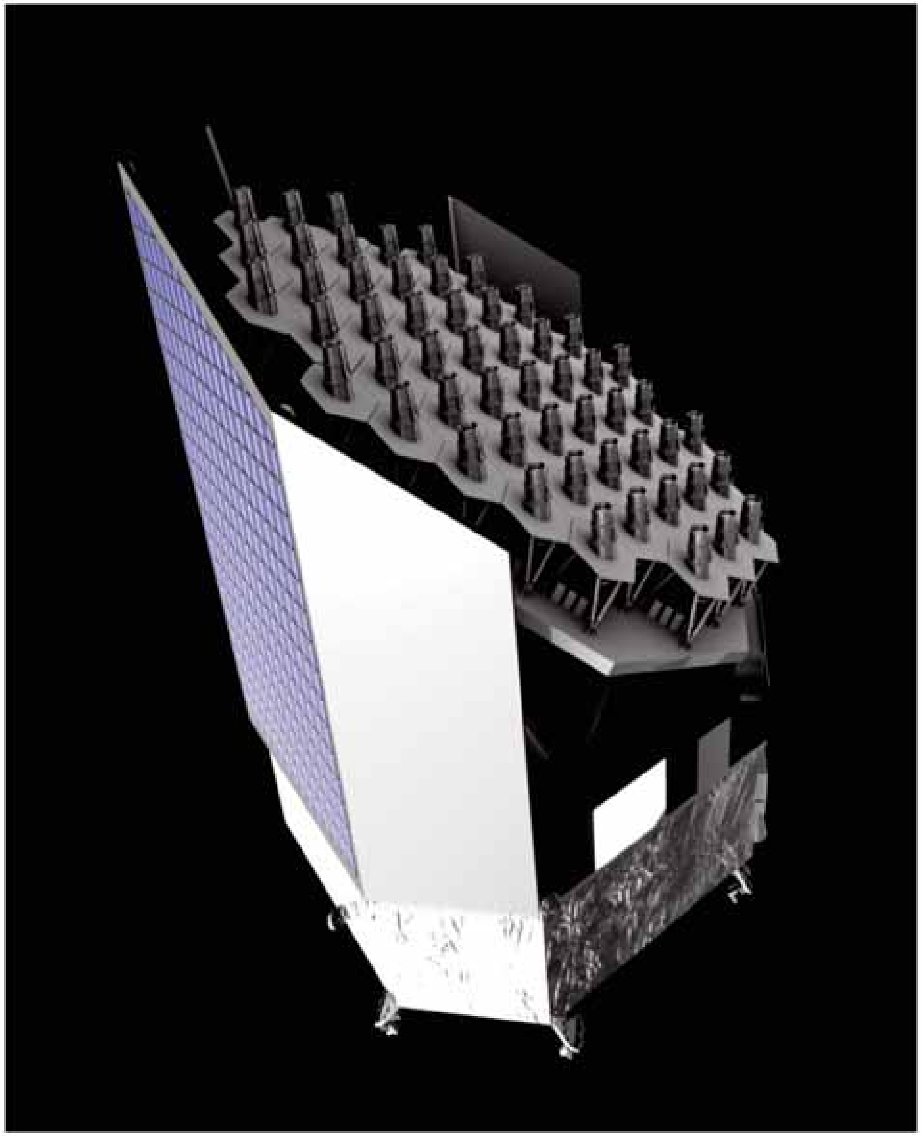
Life-changing Learning

OUTLINE

False Positives in Transiting Exoplanet Surveys



- Galaxy simulation
- Binary analysis
- Exoplanet distribution
- Results

Image credit: Thales Alenia Space
Image shows Thales Alenia Space concept, 18 February 2010, from assessment phase

METHODOLOGY

KIWI: *Kepler Information With Interest …*

- Take the Kepler observed output in both the eclipsing binary and the confirmed exoplanet populations
- Apply to a synthetic Galaxy
- Simulate an eclipsing binary and an exoplanet population
- Interpret using PLATO precision

Image credit: NASA JPL

BiSEPS

Binary Stellar Evolution Population Synthesis

- Based on stellar evolution fitting formulae of Hurley et al (2000) and binary evolution fitting formulae of Hurley et al (2002)
- Creates a synthetic population of both binary systems and single stars by evolving the stars self-consistently from formation
- These models are then seeded into a model of the Galaxy, which uses the fully evolved models as well as information on extinction

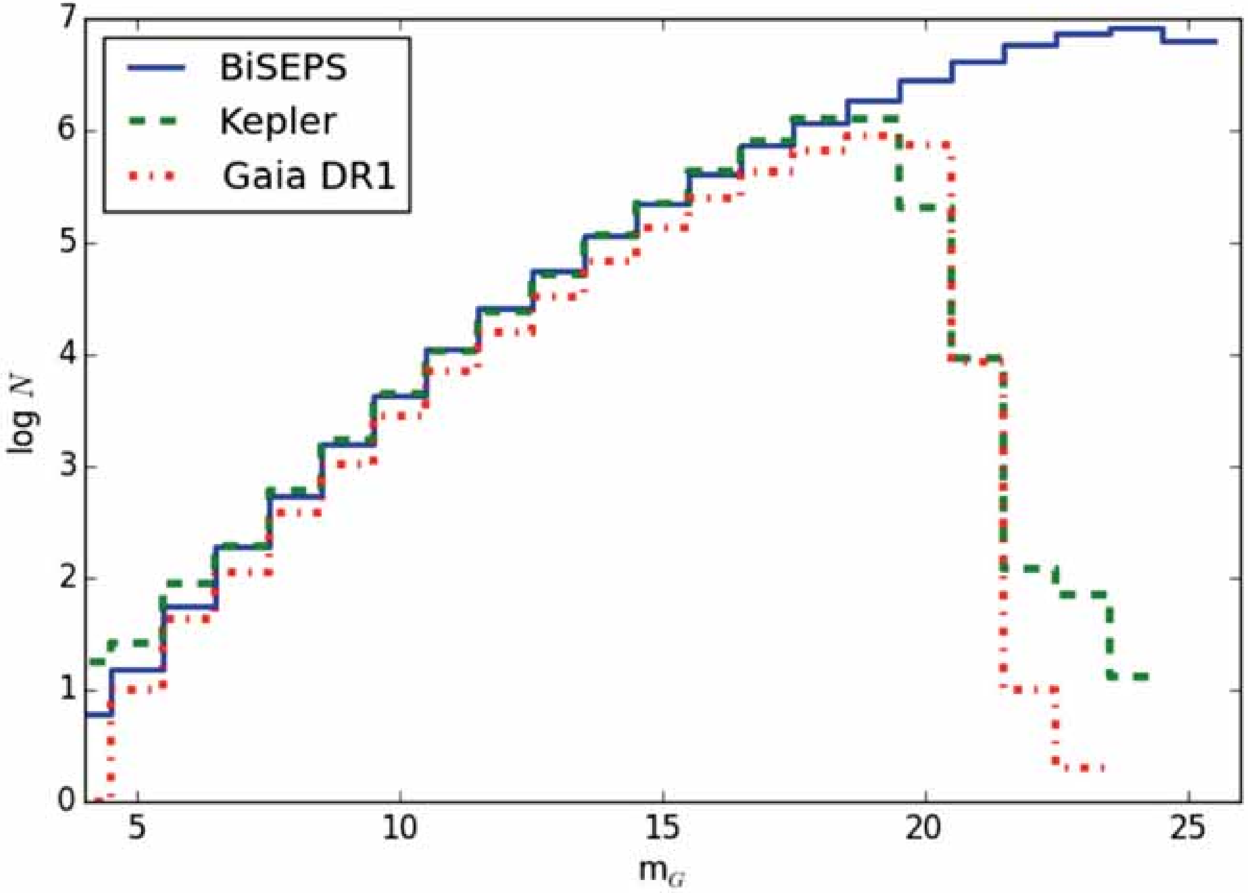
Galaxy model:

- Two-disc model (thin and thick) with each disc described by a double exponential
- Star formation is constant from 13-10 Gyr ago in the thick disc ($Z = 0.0033$)
- Star formation is constant over the past 10 Gyr in the thin disc ($Z = 0.02$)
- Kroupa initial mass function

BiSEPS

Synthetic Kepler and PLATO fields

- A synthetic Kepler field had previously been generated and calibrated (Farmer, Kolb & Norton, 2013)
- PLATO simulations focus on the proposed Long Look fields in Rauer et al (2014)
- PLATO field calibration verified against the current Kepler Input Catalogue hosted on MAST and Gaia DR1 (illustrated)



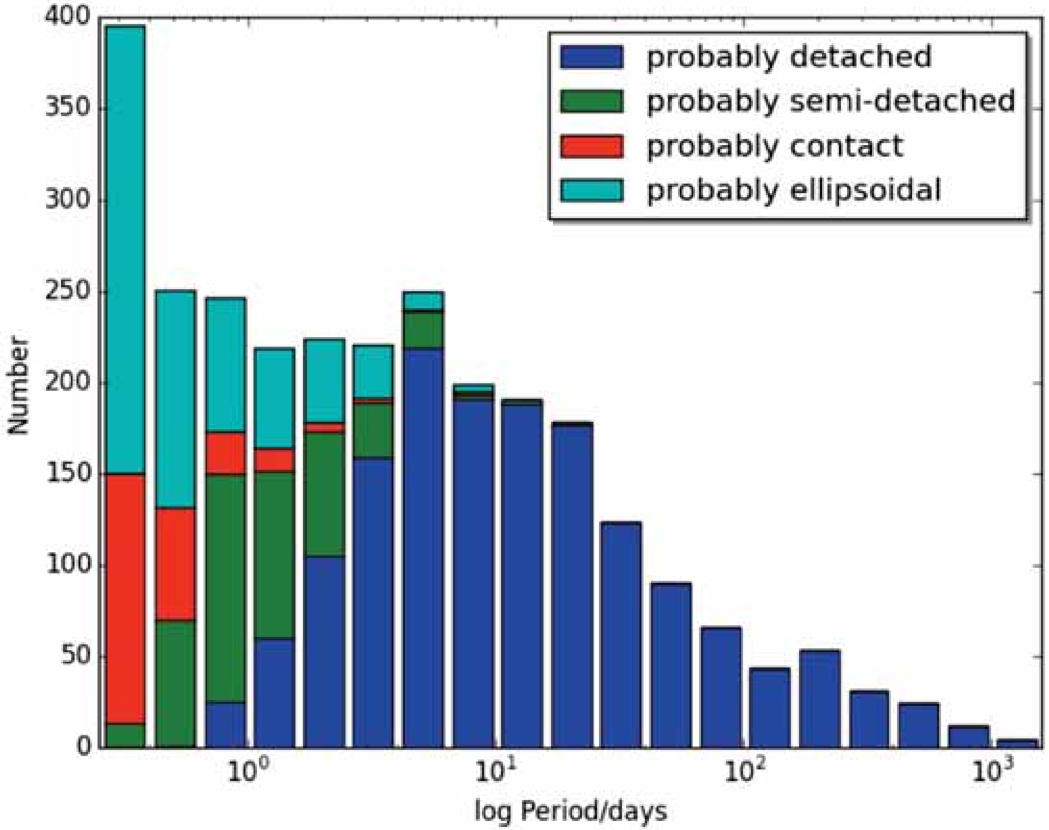
KEPLER OBSERVATIONS

NASA Exoplanet Archive (NExSci):

- Potential eclipsing binaries are identified by a “Significant Secondary” flag
- May be blended or unblended

Kepler Eclipsing Binary Catalogue:

- Unblended confirmed eclipsing binaries



The likely distribution of unblended eclipsing binaries by binary type from the morphology parameter in the Kepler Eclipsing Binary Catalogue. Interpretation of the parameter is from Matijevič et al (2012).

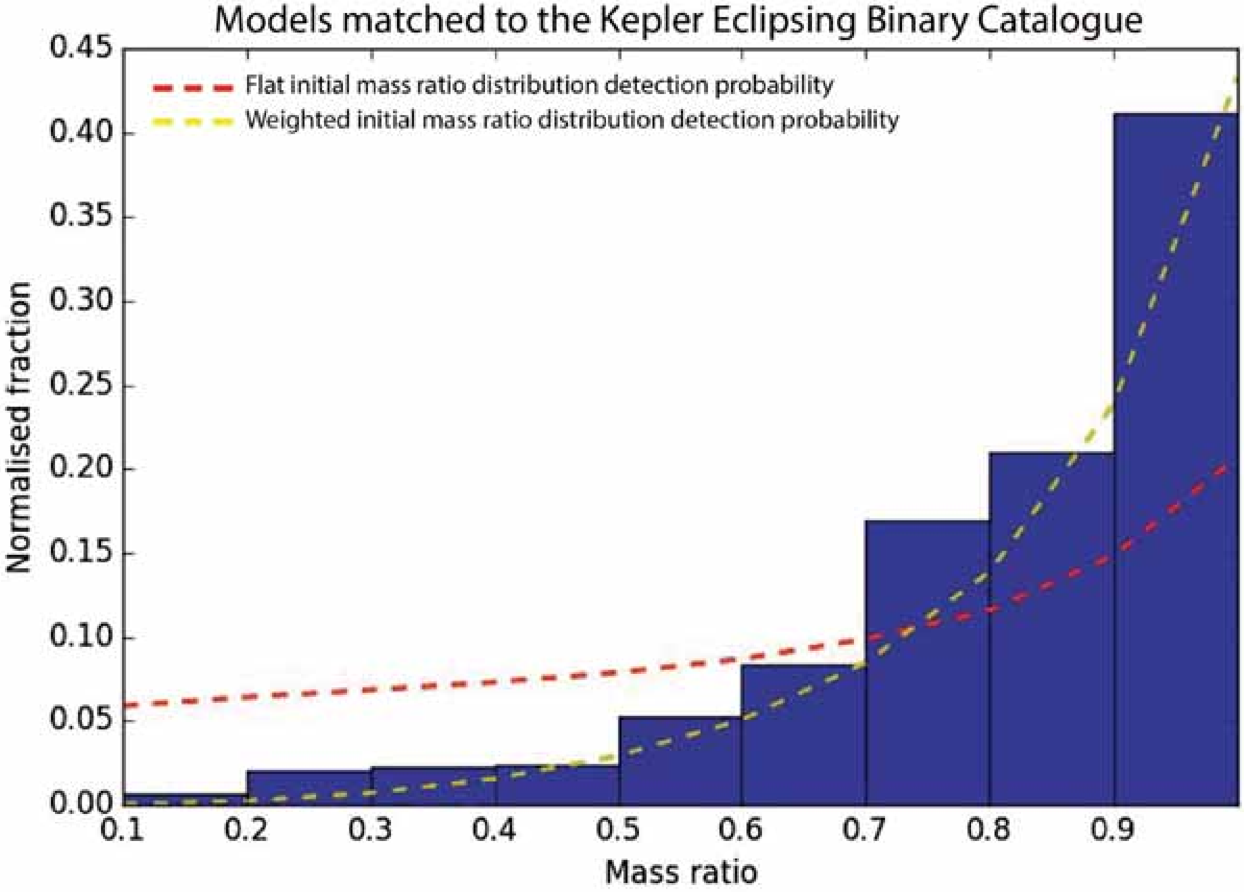
CALIBRATION

Eclipsing Binaries

- P < 10 days: use Kepler Eclipsing Binary Catalogue to calibrate the initial mass ratio

- Sample size: 971 systems

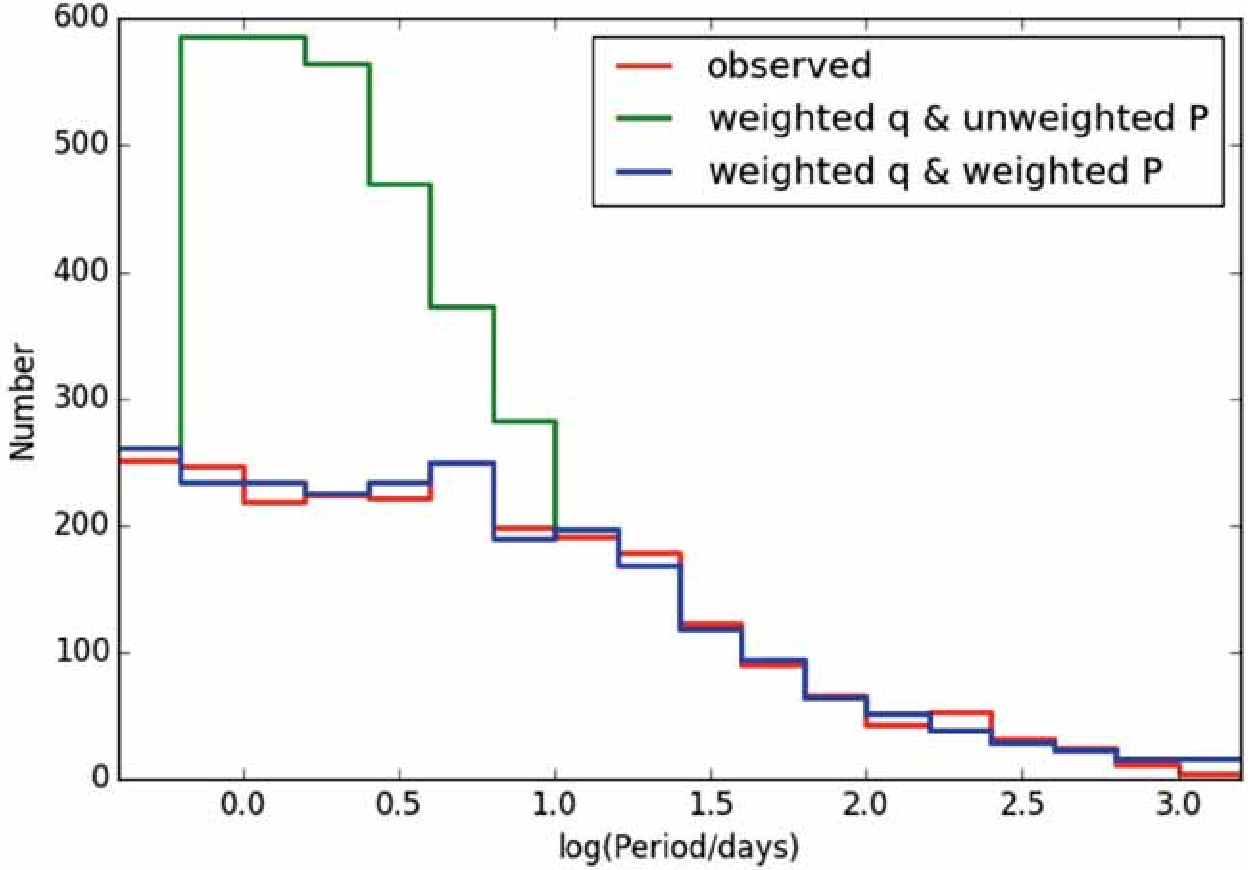
- Our simulations assume *e* = 0: binaries with *P* < 10 days are likely to have circularised



CALIBRATION

Eclipsing Binaries

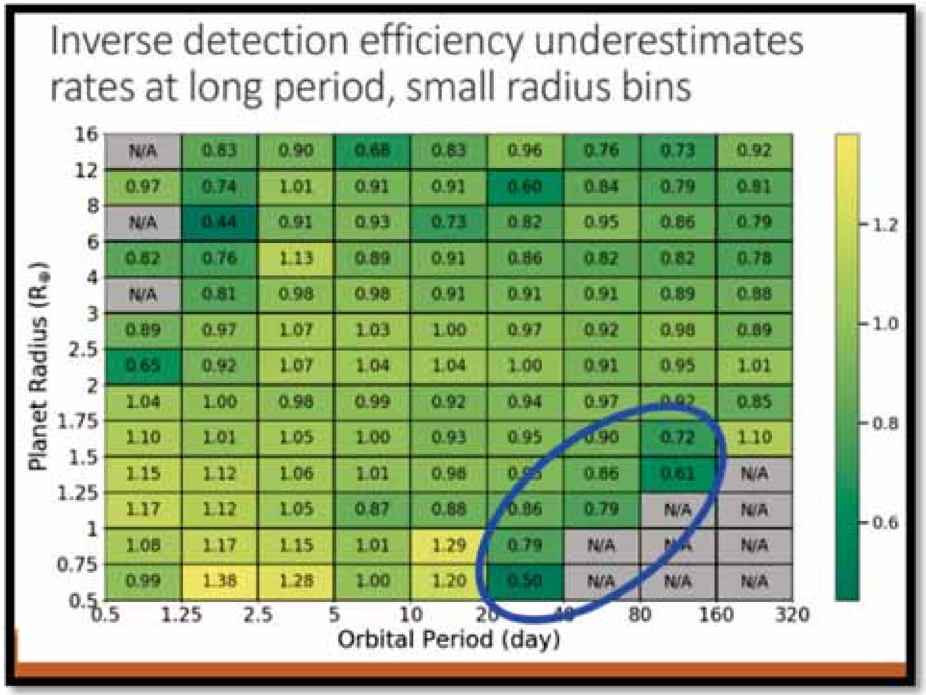
- All systems: use Kepler Eclipsing Binary Catalogue to further calibrate by orbital period
    - P < 10 days: calibrate by initial period distribution and initial mass ratio
    - P 10 to ≈ 64 days: calibrate by initial mass ratio, initial period distribution is flat
    - P > ≈ 64 days: both initial mass ratio and initial period distribution are flat



CALIBRATION

Intrinsic Exoplanet Distribution

- Our method: applying an Inverse Detection Efficiency Method (IDEM) to Kepler observations, DR25, using a synthetic galaxy modelled by BiSEPS
- IDEM uses the geometric transit probability to assess the likelihood of observing a given planet around a given star
- An alternative method is approximate Bayesian computation (ABC) demonstrated by Danley Hsu at the Kepler & K2 Science Conference, June 2017: his results (right) indicate general agreement between the two types of method except in the small radius/long period regime



Inverse detection efficiency underestimates rates at long period, small radius bins

N/A	0.83	0.90	0.68	0.83	0.96	0.76	0.73	0.92
0.97	0.74	1.01	0.91	0.91	0.60	0.84	0.79	0.81
N/A	0.44	0.91	0.93	0.73	0.82	0.95	0.86	0.79
0.82	0.76	1.13	0.89	0.91	0.86	0.82	0.82	0.78
N/A	0.81	0.98	0.98	0.91	0.91	0.91	0.89	0.88
0.89	0.97	1.07	1.03	1.00	0.97	0.92	0.98	0.89
0.65	0.92	1.07	1.04	1.04	1.00	0.91	0.95	1.01
1.04	1.00	0.98	0.99	0.92	0.94	0.97	0.92	0.85
1.10	1.01	1.05	1.00	0.93	0.95	0.90	0.72	1.10
1.15	1.12	1.06	1.01	0.98	[illegible]	0.86	0.61	N/A
1.17	1.12	1.05	0.87	0.88	0.86	0.79	N/A	N/A
1.08	1.17	1.15	1.01	1.29	0.79	N/A	N/A	N/A
0.99	1.38	1.28	1.00	1.20	0.50	N/A	N/A	N/A

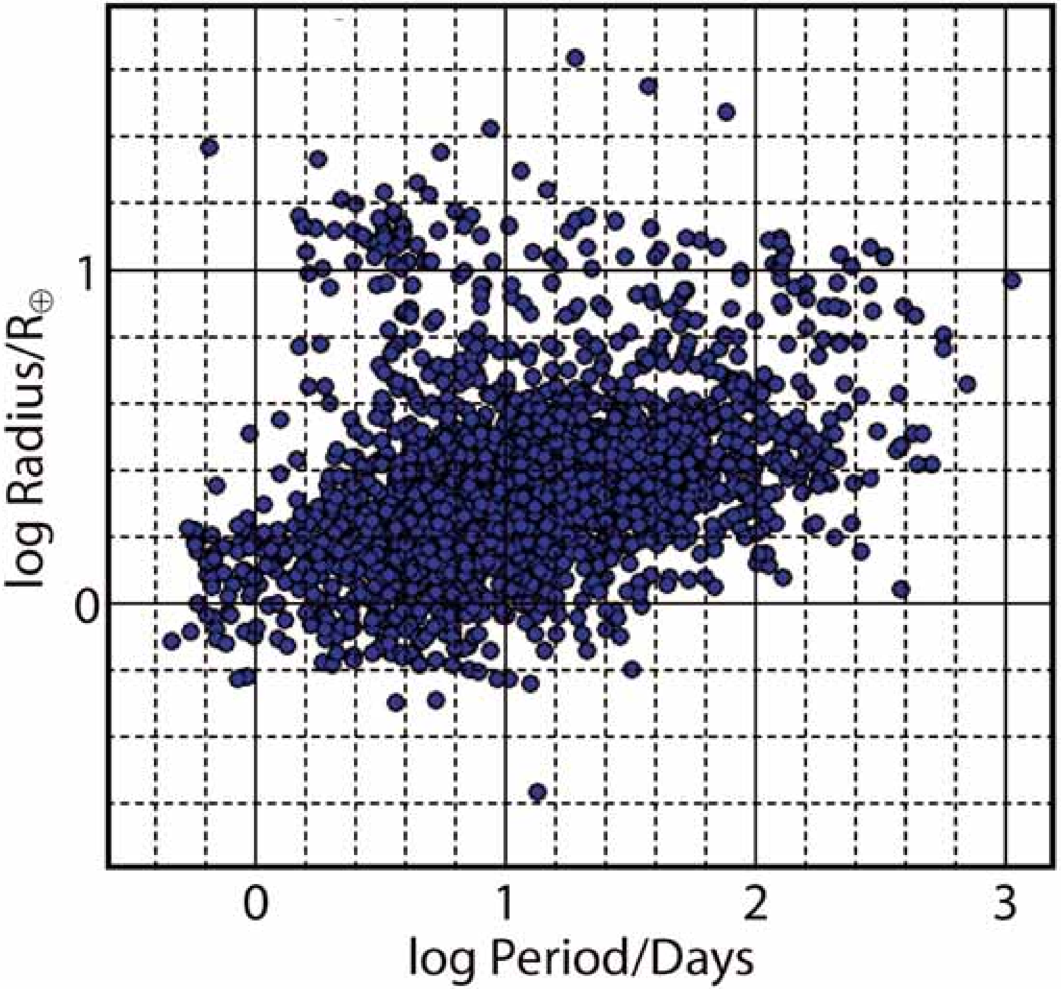
CALIBRATION

Intrinsic Exoplanet Distribution

- Confirmed planets, Kepler DR25, by radius and period

- DR25 uses updated stellar parameters, so planet radii are more accurate

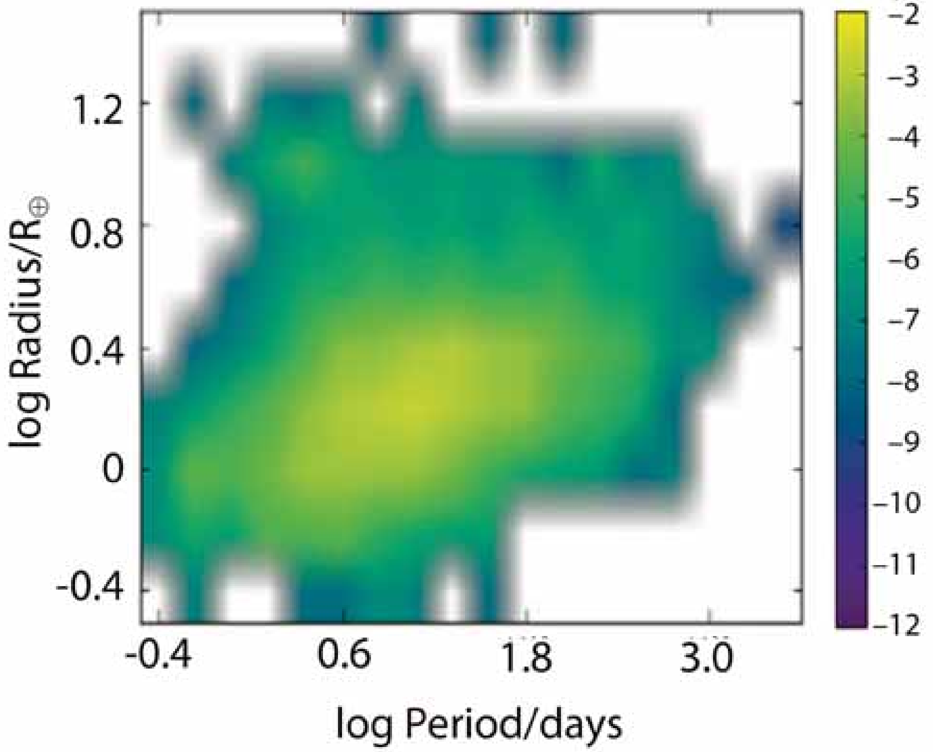
- Note
  - – sub-Jovian desert
  - – dependence of giant planet maximum radius on orbital distance



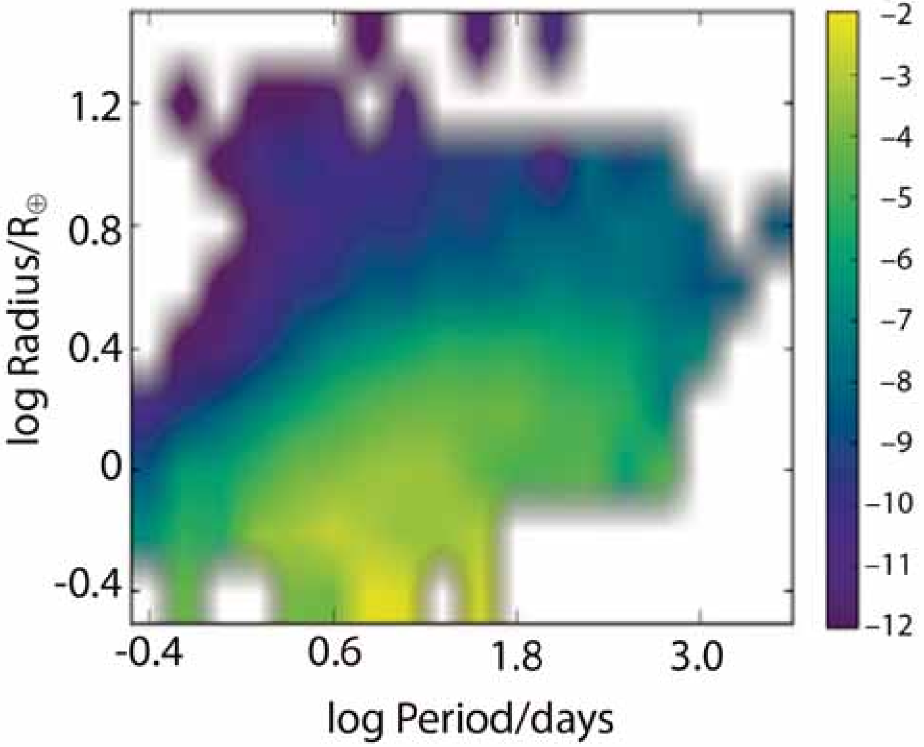
CALIBRATION

Intrinsic Exoplanet Distribution

Normalised observed distribution,
Kepler DR25,
non-zero bins only



Our normalised intrinsic
distribution, non-zero bins in
Kepler DR25 only (right)



RESULTS

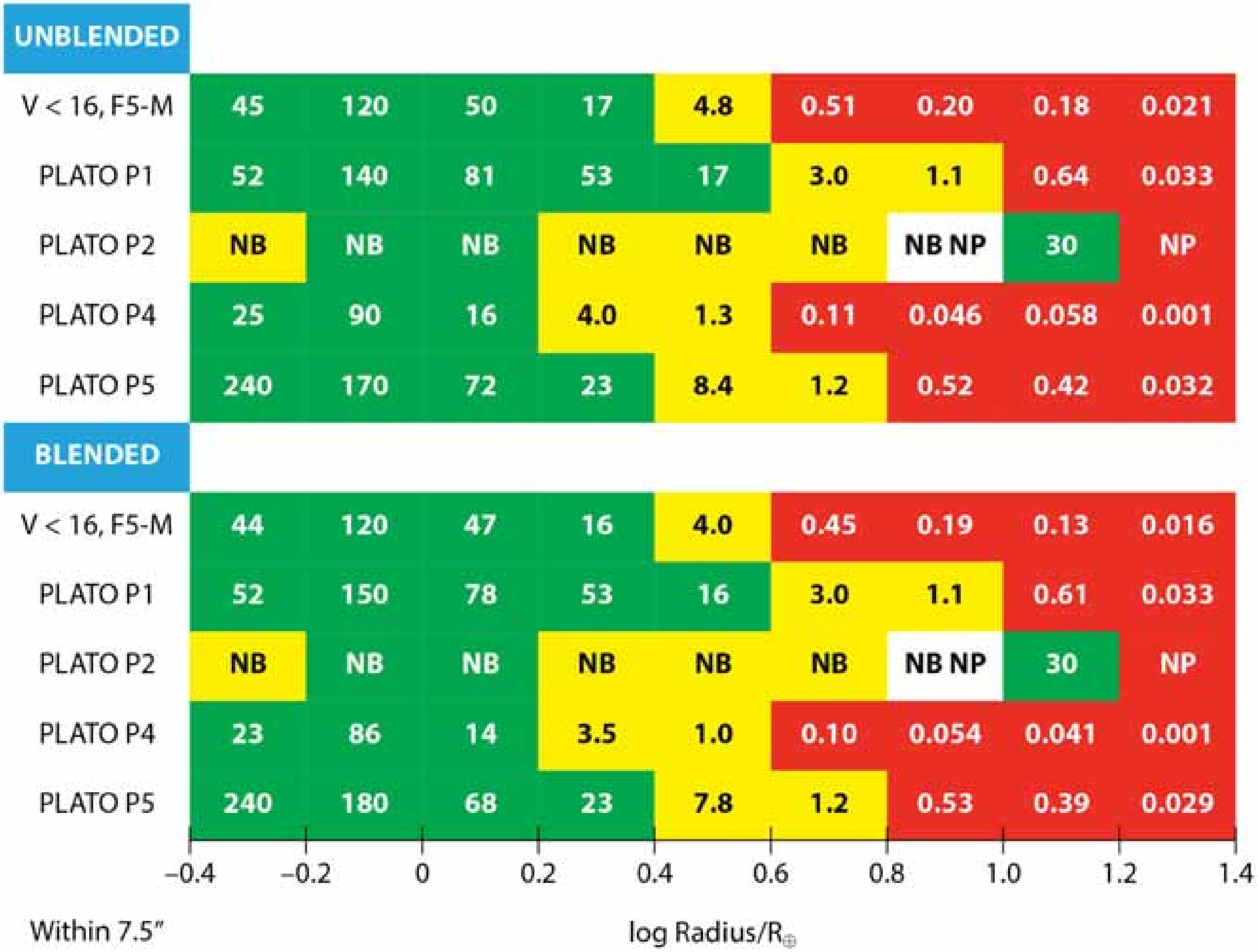
Ratio planets:binaries, LLN, same pixel

Full field, < 7.5”

- Green: More than 10 planets for each binary, so don’t worry!
- Yellow: 10 or fewer planets for each binary, so be careful …
- Red: More binaries than planets, be extremely careful!

Error is square root of *N*

NB: no binaries; NP: no planets



UNBLENDED

V < 16, F5-M	45	120	50	17	4.8	0.51	0.20	0.18	0.021
PLATO P1	52	140	81	53	17	3.0	1.1	0.64	0.033
PLATO P2	NB	NB	NB	NB	NB	NB	NB NP	30	NP
PLATO P4	25	90	16	4.0	1.3	0.11	0.046	0.058	0.001
PLATO P5	240	170	72	23	8.4	1.2	0.52	0.42	0.032

BLENDED

V < 16, F5-M	44	120	47	16	4.0	0.45	0.19	0.13	0.016
PLATO P1	52	150	78	53	16	3.0	1.1	0.61	0.033
PLATO P2	NB	NB	NB	NB	NB	NB	NB NP	30	NP
PLATO P4	23	86	14	3.5	1.0	0.10	0.054	0.041	0.001
PLATO P5	240	180	68	23	7.8	1.2	0.53	0.39	0.029

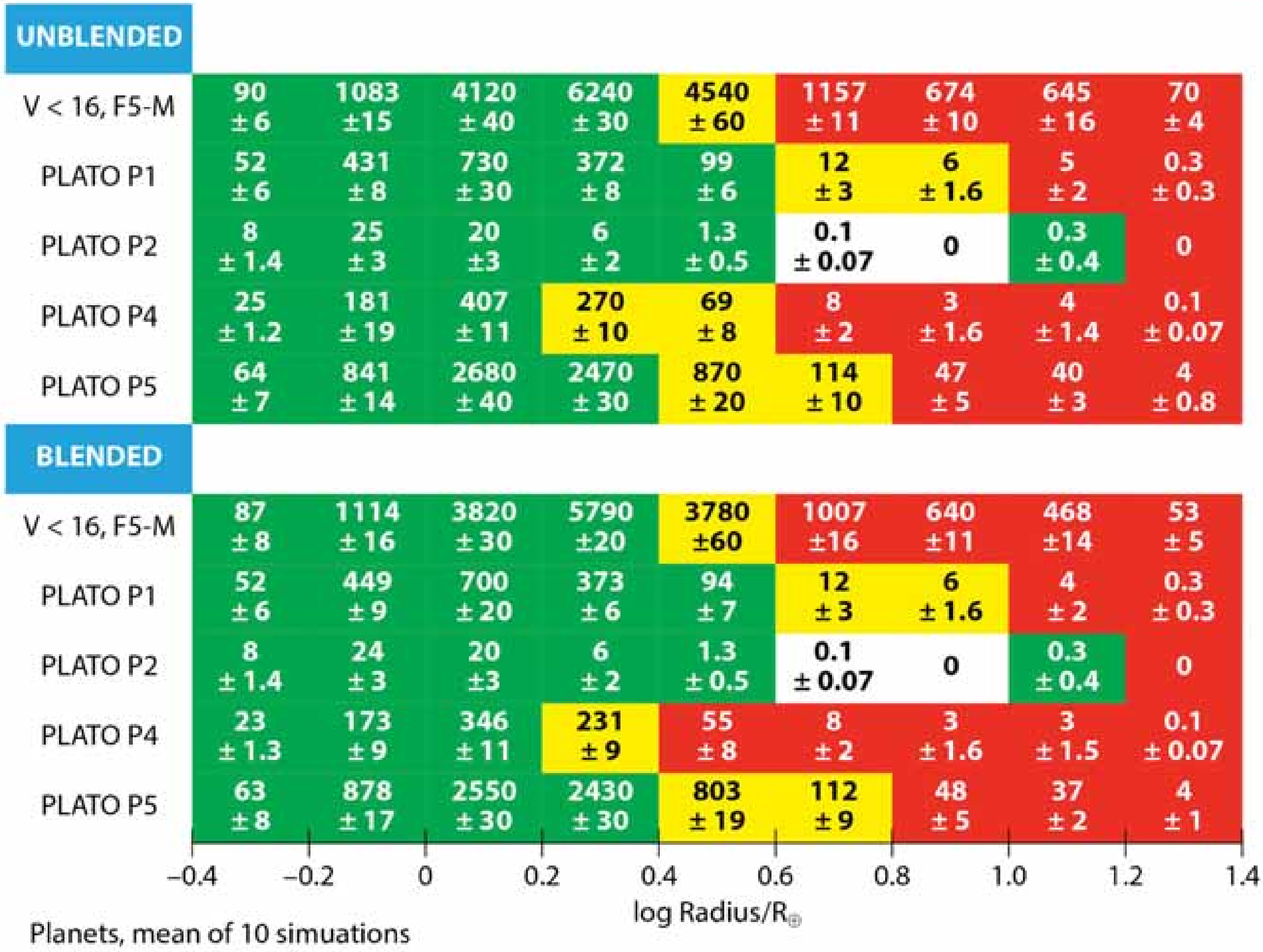
RESULTS

Planets, LLN, full field

Mean of 10 simulations

Error is square root of *N*

Colours matched to bins in previous slide



UNBLENDED

V < 16, F5-M	90 ±6	1083 ±15	4120 ± 40	6240 ± 30	4540 ± 60	1157 ± 11	674 ± 10	645 ± 16	70 ± 4
PLATO P1	52 ±6	431 ± 8	730 ± 30	372 ± 8	99 ± 6	12 ± 3	6 ± 1.6	5 ± 2	0.3 ± 0.3
PLATO P2	8 ± 1.4	25 ± 3	20 ±3	6 ± 2	1.3 ± 0.5	0.1 ± 0.07	0	0.3 ± 0.4	0
PLATO P4	25 ± 1.2	181 ± 19	407 ± 11	270 ± 10	69 ± 8	8 ± 2	3 ± 1.6	4 ± 1.4	0.1 ± 0.07
PLATO P5	64 ± 7	841 ± 14	2680 ± 40	2470 ± 30	870 ± 20	114 ± 10	47 ± 5	40 ± 3	4 ± 0.8

BLENDED

V < 16, F5-M	87 ± 8	1114 ± 16	3820 ± 30	5790 ±20	3780 ±60	1007 ±16	640 ±11	468 ±14	53 ± 5
PLATO P1	52 ±6	449 ± 9	700 ± 20	373 ± 6	94 ± 7	12 ± 3	6 ± 1.6	4 ± 2	0.3 ± 0.3
PLATO P2	8 ± 1.4	24 ± 3	20 ±3	6 ± 2	1.3 ± 0.5	0.1 ± 0.07	0	0.3 ± 0.4	0
PLATO P4	23 ± 1.3	173 ± 9	346 ± 11	231 ± 9	55 ± 8	8 ± 2	3 ± 1.6	3 ± 1.5	0.1 ± 0.07
PLATO P5	63 ± 8	878 ± 17	2550 ± 30	2430 ± 30	803 ± 19	112 ± 9	48 ± 5	37 ± 2	4 ± 1

Planets, mean of 10 simuations

RESULTS

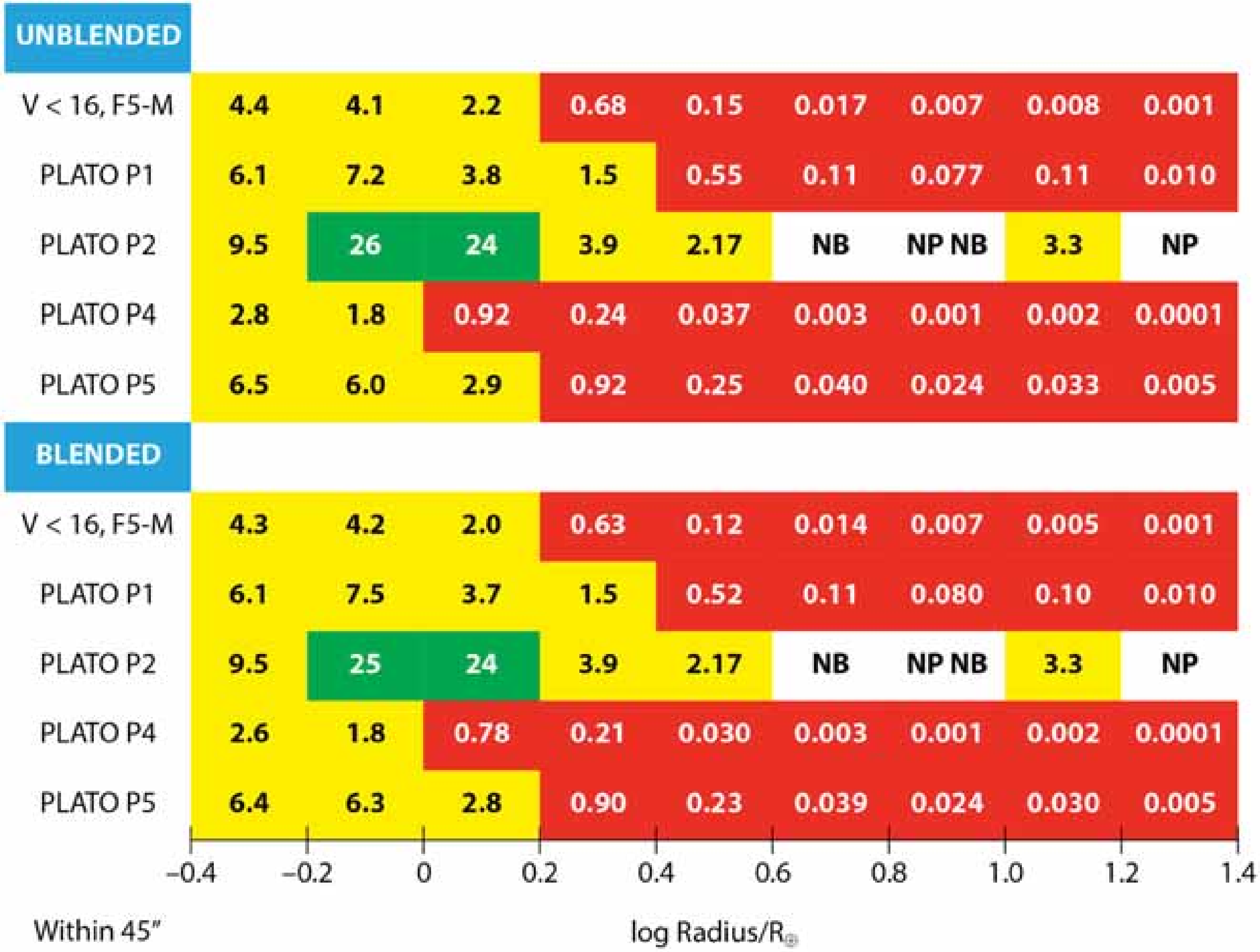
Ratio planets:binaries, LLN, same imagette

Full field, < 45”

- Green: More than 10 planets for each binary, so don’t worry!
- Yellow: 10 or fewer planets for each binary, so be careful …
- Red: More binaries than planets, be extremely careful!

Error is square root of *N*

NB: no binaries; NP: no planets



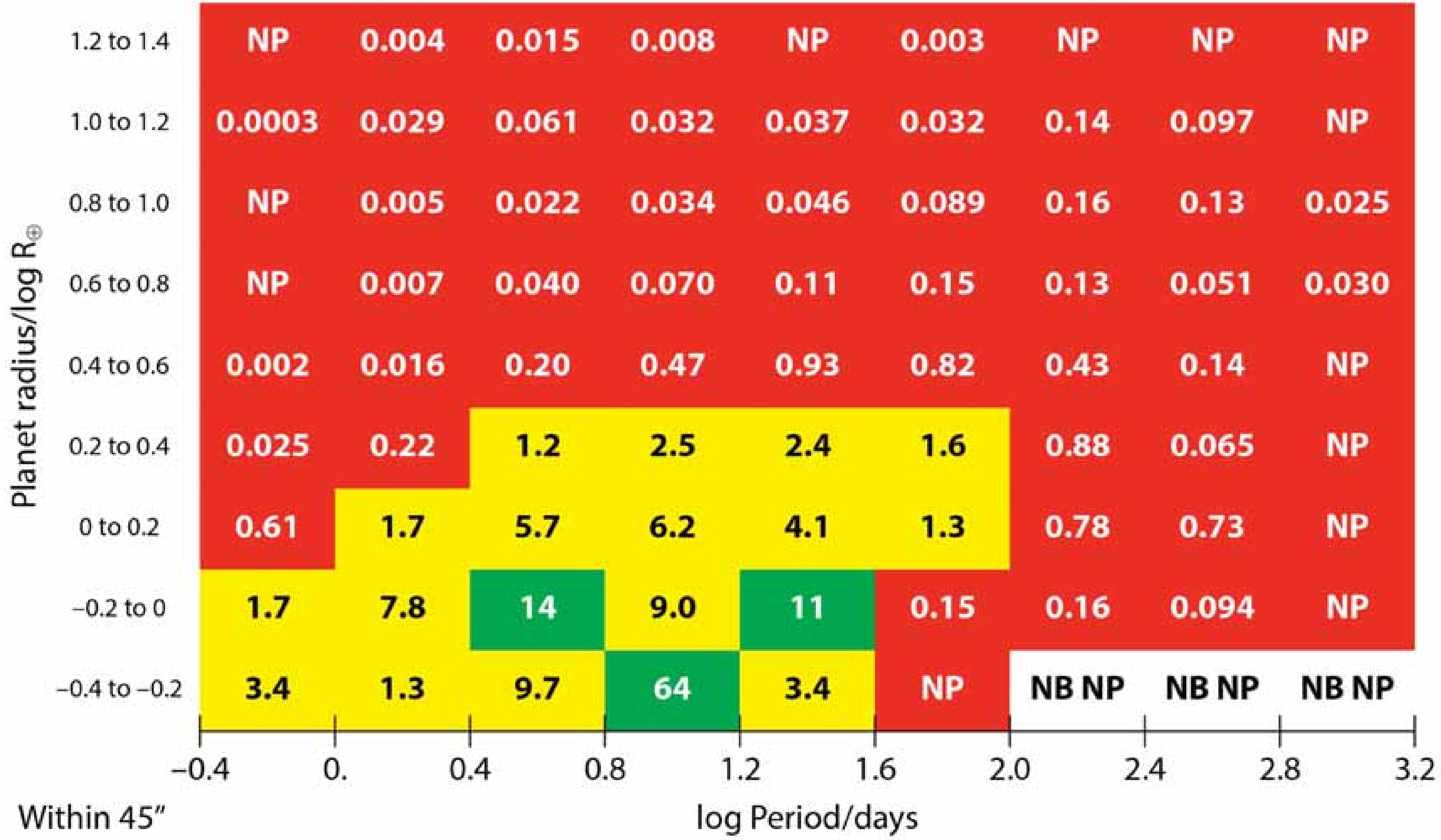
UNBLENDED									
V < 16, F5-M	4.4	4.1	2.2	0.68	0.15	0.017	0.007	0.008	0.001
PLATO P1	6.1	7.2	3.8	1.5	0.55	0.11	0.077	0.11	0.010
PLATO P2	9.5	26	24	3.9	2.17	NB	NP NB	3.3	NP
PLATO P4	2.8	1.8	0.92	0.24	0.037	0.003	0.001	0.002	0.0001
PLATO P5	6.5	6.0	2.9	0.92	0.25	0.040	0.024	0.033	0.005
BLENDED									
V < 16, F5-M	4.3	4.2	2.0	0.63	0.12	0.014	0.007	0.005	0.001
PLATO P1	6.1	7.5	3.7	1.5	0.52	0.11	0.080	0.10	0.010
PLATO P2	9.5	25	24	3.9	2.17	NB	NP NB	3.3	NP
PLATO P4	2.6	1.8	0.78	0.21	0.030	0.003	0.001	0.002	0.0001
PLATO P5	6.4	6.3	2.8	0.90	0.23	0.039	0.024	0.030	0.005

Within 45″

log Radius/$R_\oplus$

RESULTS

Ratio planets:binaries, P5, same imagette



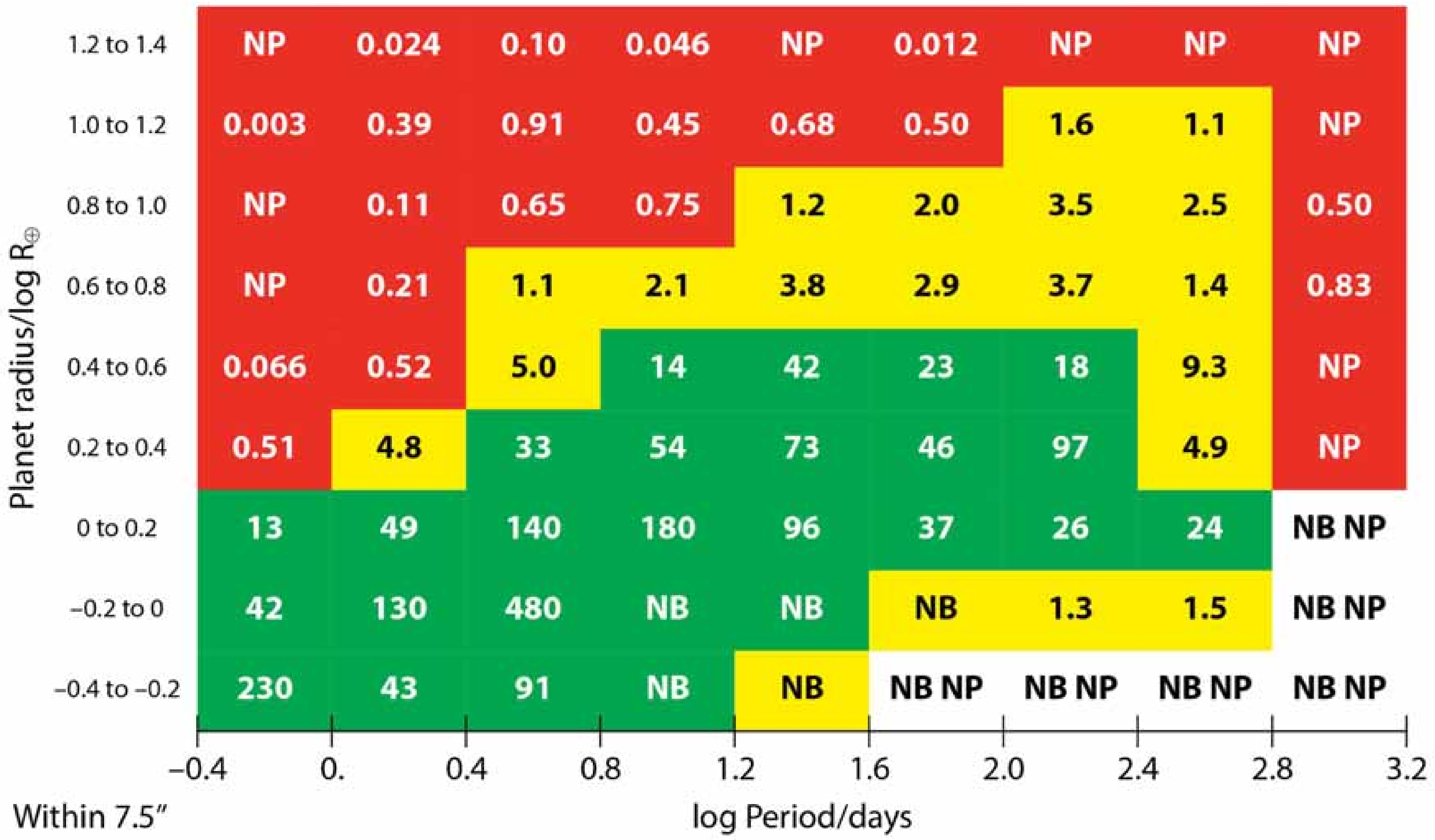
1.2 to 1.4	NP	0.004	0.015	0.008	NP	0.003	NP	NP	NP
1.0 to 1.2	0.0003	0.029	0.061	0.032	0.037	0.032	0.14	0.097	NP
0.8 to 1.0	NP	0.005	0.022	0.034	0.046	0.089	0.16	0.13	0.025
0.6 to 0.8	NP	0.007	0.040	0.070	0.11	0.15	0.13	0.051	0.030
0.4 to 0.6	0.002	0.016	0.20	0.47	0.93	0.82	0.43	0.14	NP
0.2 to 0.4	0.025	0.22	1.2	2.5	2.4	1.6	0.88	0.065	NP
0 to 0.2	0.61	1.7	5.7	6.2	4.1	1.3	0.78	0.73	NP
−0.2 to 0	1.7	7.8	14	9.0	11	0.15	0.16	0.094	NP
−0.4 to −0.2	3.4	1.3	9.7	64	3.4	NP	NB NP	NB NP	NB NP

Within 45″

NB: No binaries; NP: No Planets: NB NP: neither planets nor binaries

RESULTS

Ratio planets:binaries, P5, same pixel



1.2 to 1.4	NP	0.024	0.10	0.046	NP	0.012	NP	NP	NP
1.0 to 1.2	0.003	0.39	0.91	0.45	0.68	0.50	1.6	1.1	NP
0.8 to 1.0	NP	0.11	0.65	0.75	1.2	2.0	3.5	2.5	0.50
0.6 to 0.8	NP	0.21	1.1	2.1	3.8	2.9	3.7	1.4	0.83
0.4 to 0.6	0.066	0.52	5.0	14	42	23	18	9.3	NP
0.2 to 0.4	0.51	4.8	33	54	73	46	97	4.9	NP
0 to 0.2	13	49	140	180	96	37	26	24	NB NP
−0.2 to 0	42	130	480	NB	NB	NB	1.3	1.5	NB NP
−0.4 to −0.2	230	43	91	NB	NB	NB NP	NB NP	NB NP	NB NP

NB: No binaries; NP: No Planets: NB NP: neither planets nor binaries

RESULTS

Proportion in central region: planets

- Region covered by 4 cameras will give the best resolution, especially in achieving 34 ppm in P1 and 80 ppm in P5
- In P5, 1665 of the 6949 planets in the full field (24%) are in the region covered by 4 cameras in our simulation

			LLN					***LLS***		
Planet Class	**Centre**	**σ**	**Full field**	**σ**	**Ratio**	**Centre**	**σ**	**Full field**	**σ**	**Ratio**
Mars	22	4	63	8	35%	30	5	71	7	42%
Earth 1	289	17	878	17	33%	330	4	972	19	34%
Earth 2	672	11	2551	34	26%	741	22	2960	31	25%
Small Neptune 1	512	17	2427	26	21%	555	21	2801	43	20%
Small Neptune 2	134	7	803	19	17%	143	8	897	10	16%
Large Neptune	16	1.7	112	9	14%	20	5	127	4	16%
Giant Planet 1	7	1.7	48	5	15%	7	0.6	51	3	13%
Giant Planet 2	7	1.3	37	2	19%	6	1.0	42	3	14%
Giant Planet 3	0.8	0.9	4	1	20%	0.8	0.5	4	1.2	20%

RESULTS

Binary impostors in central region, LLN:

Number of binaries that would mimic a planet:

	Full field		Central region		Ratio centre/full	
Planet Size Class	7.5"	45"	7.5"	45"	7.5"	45"
Mars	0.3	10	0.2	1.5	67%	15%
Earth 1	5	139	1.4	23	28%	17%
Earth 2	37	929	4	116	11%	12%
Small Neptune 1	108	2695	14	231	13%	9%
Small Neptune 2	104	3466	8	204	8%	6%
Large Neptune	94	2832	9	167	10%	6%
Giant Planet 1	90	1932	9	116	10%	6%
Giant Planet 2	96	1223	12	83	13%	7%
Giant Planet 3	119	765	19	75	16%	10%

Error: square root of N

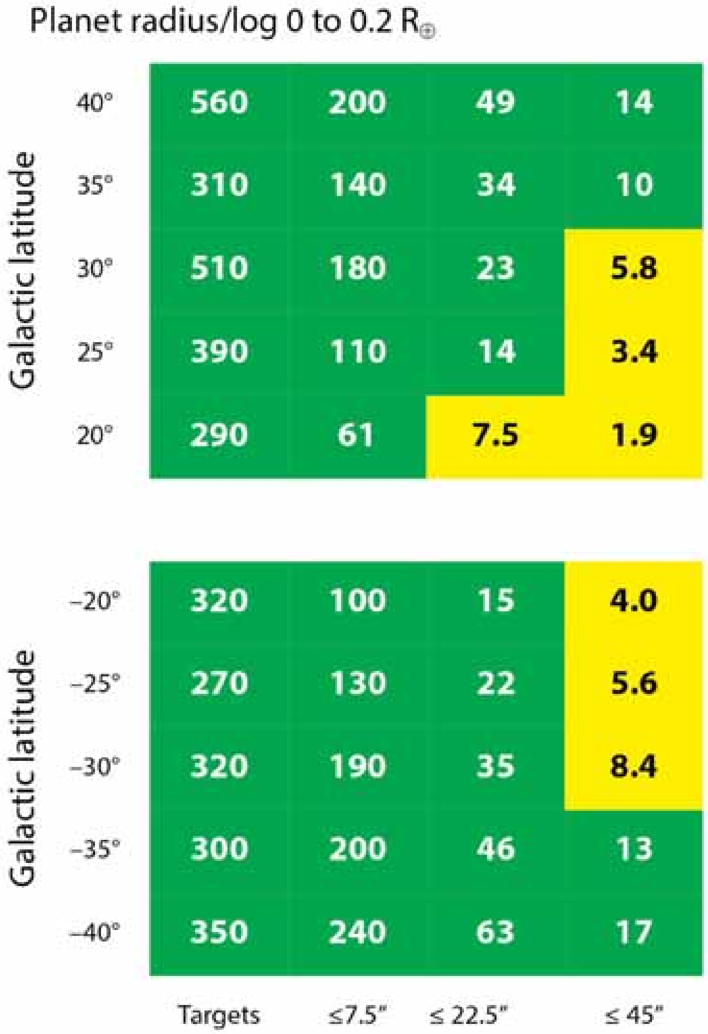
RESULTS

Ratio planets:binaries, central zone only, P5

Planet radius/log 0 to 0.2 $R_\oplus$

Galactic latitude	Targets	≤7.5″	≤ 22.5″	≤ 45″
40°	480	280	92	25
35°	1700	410	66	18
30°	3000	200	42	13
25°	2000	280	26	6.6
20°	1100	200	17	4.0

Galactic latitude	Targets	≤7.5″	≤ 22.5″	≤ 45″
−20°	4500	270	34	8.8
−25°	4300	100	49	11
−30°	4100	160	62	19
−35°	3800	150	100	27
−40°	1700	140	100	36



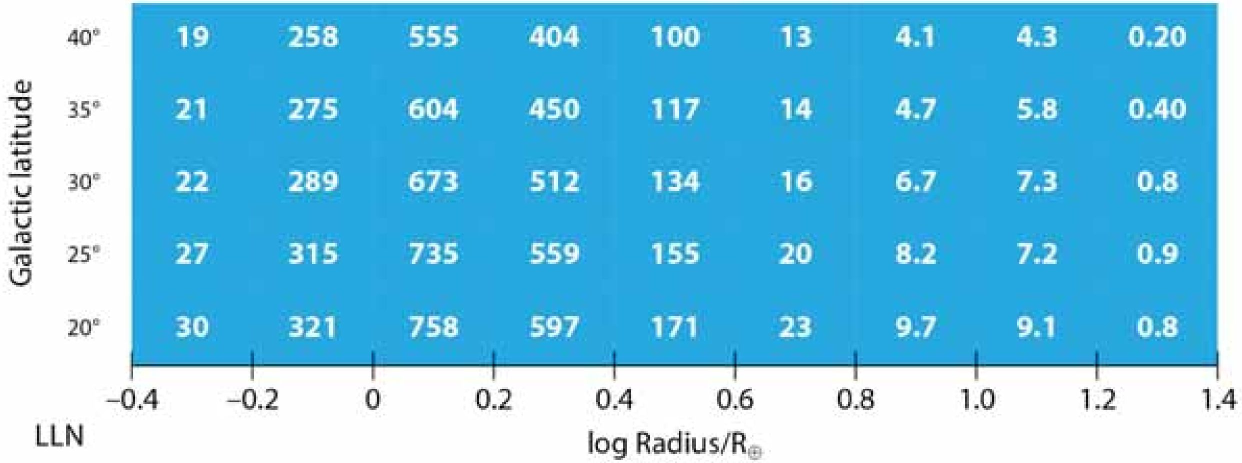
Planet radius/log 0 to 0.2 $R_\oplus$

Galactic latitude	Targets	≤7.5″	≤ 22.5″	≤ 45″
40°	560	200	49	14
35°	310	140	34	10
30°	510	180	23	5.8
25°	390	110	14	3.4
20°	290	61	7.5	1.9

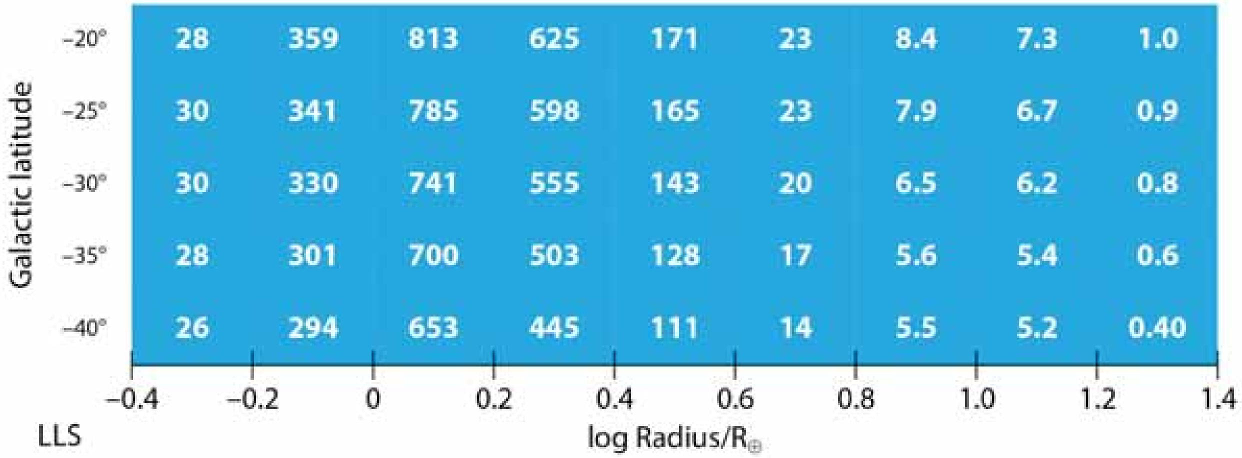
Galactic latitude	Targets	≤7.5″	≤ 22.5″	≤ 45″
−20°	320	100	15	4.0
−25°	270	130	22	5.6
−30°	320	190	35	8.4
−35°	300	200	46	13
−40°	350	240	63	17

RESULTS

Number of planets, central zone only, P5



40°	19	258	555	404	100	13	4.1	4.3	0.20
35°	21	275	604	450	117	14	4.7	5.8	0.40
30°	22	289	673	512	134	16	6.7	7.3	0.8
25°	27	315	735	559	155	20	8.2	7.2	0.9
20°	30	321	758	597	171	23	9.7	9.1	0.8



−20°	28	359	813	625	171	23	8.4	7.3	1.0
−25°	30	341	785	598	165	23	7.9	6.7	0.9
−30°	30	330	741	555	143	20	6.5	6.2	0.8
−35°	28	301	700	503	128	17	5.6	5.4	0.6
−40°	26	294	653	445	111	14	5.5	5.2	0.40

RESULTS

Provisional conclusions

- There is a larger fraction of planets in the region covered by four cameras than for background binaries.
- The proposed LLS field has a higher proportion of terrestrial planets to binaries, as well as a higher number of terrestrial planets, than equivalent latitudes in the LLN field …

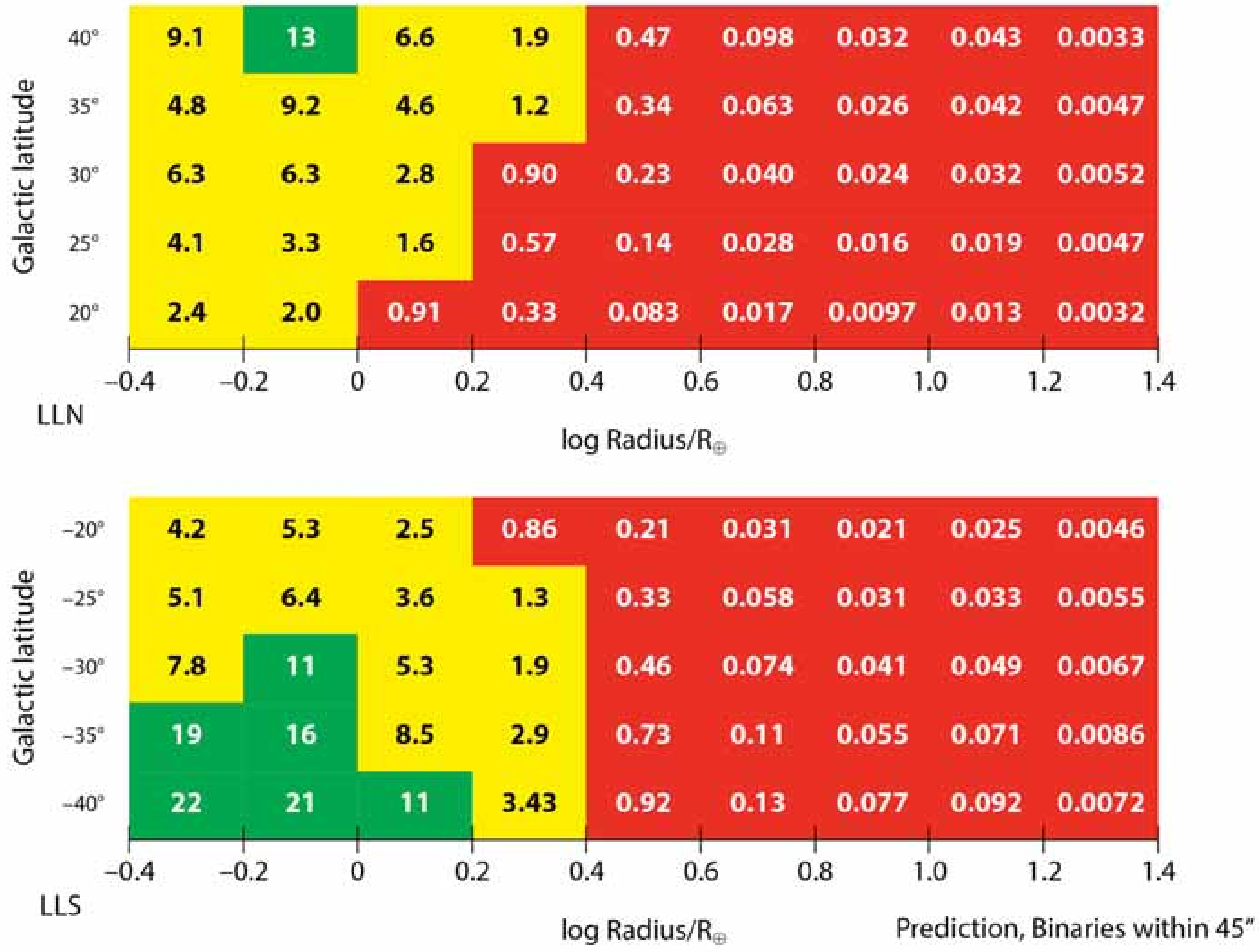
Why?

Blended binaries can be observed up to 10 kpc away:
terrestrial planets can be observed up to 0.3 kpc away.

LLS looks through the Galactic plane,
but is further from the Galactic centre than LLN:
so contains more nearby stars but fewer stars in the deep field
and hence fewer stars in total
in our simulations.

RESULTS

Prediction, P5, ratio planets:binaries, within same imagette



40°	9.1	13	6.6	1.9	0.47	0.098	0.032	0.043	0.0033
35°	4.8	9.2	4.6	1.2	0.34	0.063	0.026	0.042	0.0047
30°	6.3	6.3	2.8	0.90	0.23	0.040	0.024	0.032	0.0052
25°	4.1	3.3	1.6	0.57	0.14	0.028	0.016	0.019	0.0047
20°	2.4	2.0	0.91	0.33	0.083	0.017	0.0097	0.013	0.0032

−20°	4.2	5.3	2.5	0.86	0.21	0.031	0.021	0.025	0.0046
-25°	5.1	6.4	3.6	1.3	0.33	0.058	0.031	0.033	0.0055
-30°	7.8	11	5.3	1.9	0.46	0.074	0.041	0.049	0.0067
-35°	19	16	8.5	2.9	0.73	0.11	0.055	0.071	0.0086
-40°	22	21	11	3.43	0.92	0.13	0.077	0.092	0.0072

Prediction, Binaries within 45″

RESULTS

Next Steps

- Extend the full field deeper to verify the conclusions from the central field.
- Check the calibration of the synthetic fields with Gaia DR2, when available, to verify the conclusion that more terrestrial planets can be observed in the Southern hemisphere than the Northern hemisphere.
- Explore planetary population in multiple systems.
- Explore the role of higher order stellar multiplicity.
- Explore other fields of interest to the PLATO Input Catalogue.

SUMMARY

Kepler data, combined with a synthetic Galaxy, can provide valuable insights into the intrinsic distribution of both planets and binaries in exoplanet surveys.

Evidence to date indicates that, for observations of terrestrial planets, it would be safe to shift the centre of the field a few degrees closer to the Galactic plane.

Long Look South appears less contaminated than Long Look North.

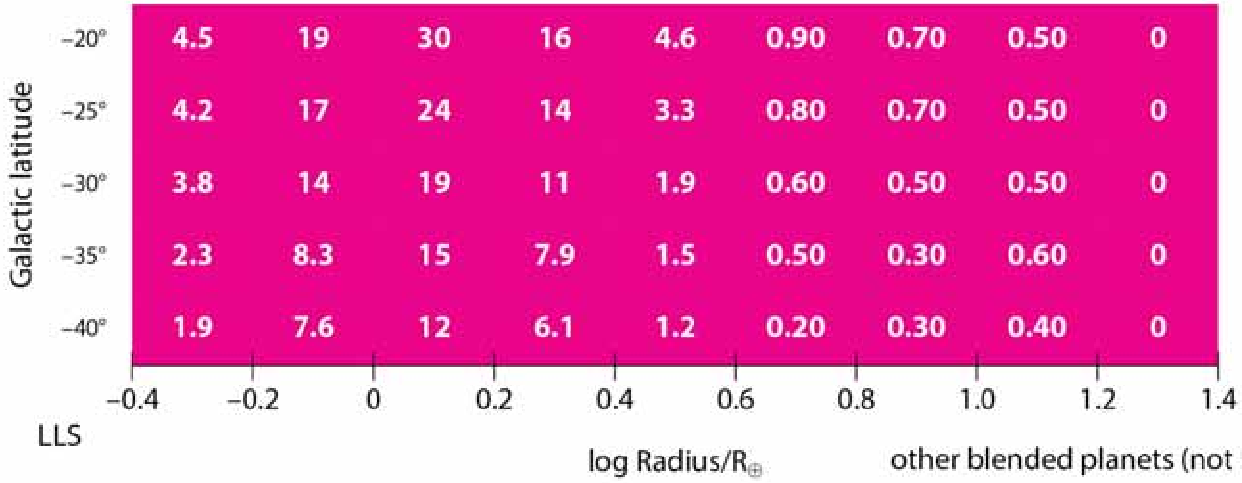
Further verification is required.

RESULTS

Non-P5 blended planets, central zone only

LLN

40°	0.9	4.2	5.8	2.3	0.5	0.5	0.2	0.2	0
35°	1.5	5.7	7.8	2.8	0.6	0.4	0.3	0.2	0
30°	1.8	7.3	10	5.5	1.5	0.60	0.60	0.30	0
25°	2.0	9.2	15	8.1	1.8	0.80	0.40	0.50	0.10
20°	3.7	13	23	11	2.9	1.3	0.60	0.60	0.10



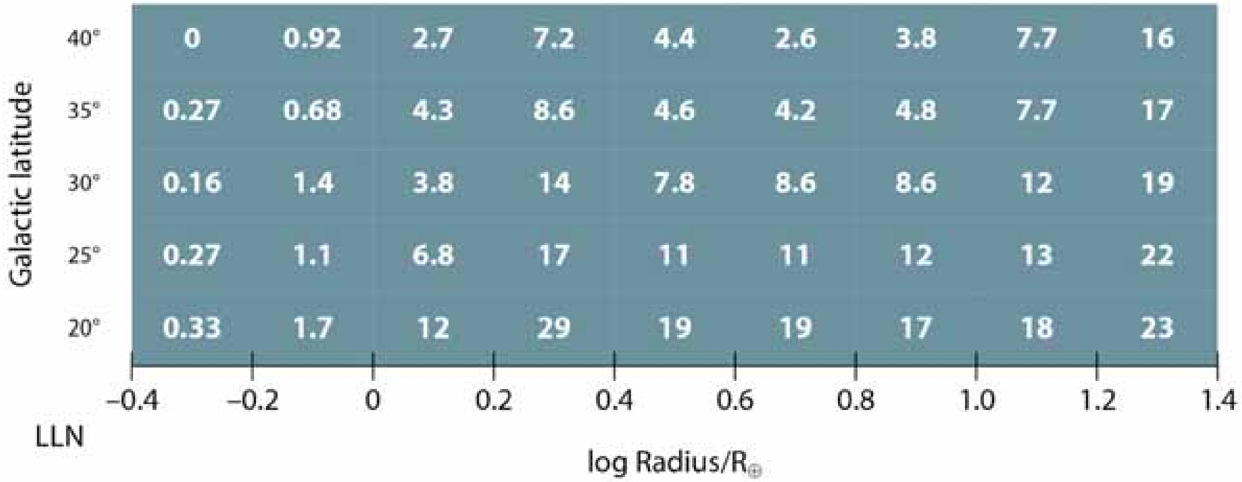
LLS

−20°	4.5	19	30	16	4.6	0.90	0.70	0.50	0
−25°	4.2	17	24	14	3.3	0.80	0.70	0.50	0
−30°	3.8	14	19	11	1.9	0.60	0.50	0.50	0
−35°	2.3	8.3	15	7.9	1.5	0.50	0.30	0.60	0
−40°	1.9	7.6	12	6.1	1.2	0.20	0.30	0.40	0

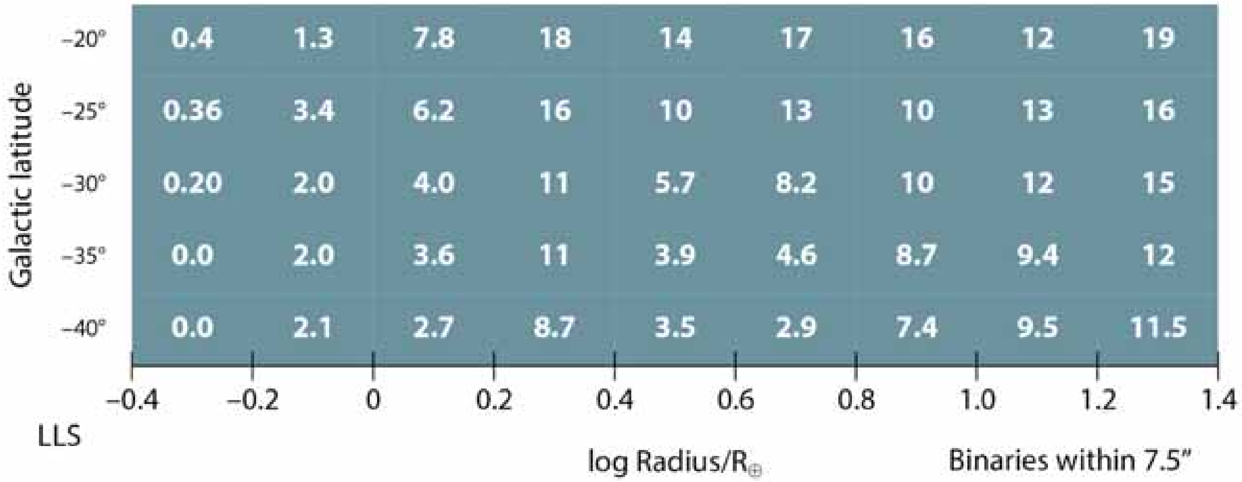
other blended planets (not P5)

RESULTS

Number of binaries < 7.5”, central zone only



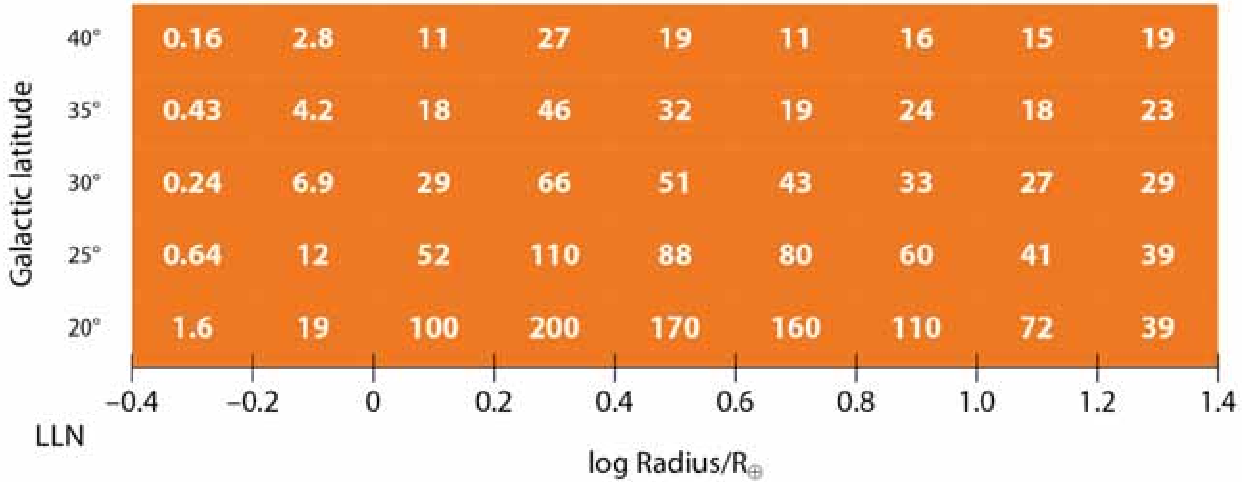
40°	0	0.92	2.7	7.2	4.4	2.6	3.8	7.7	16
35°	0.27	0.68	4.3	8.6	4.6	4.2	4.8	7.7	17
30°	0.16	1.4	3.8	14	7.8	8.6	8.6	12	19
25°	0.27	1.1	6.8	17	11	11	12	13	22
20°	0.33	1.7	12	29	19	19	17	18	23



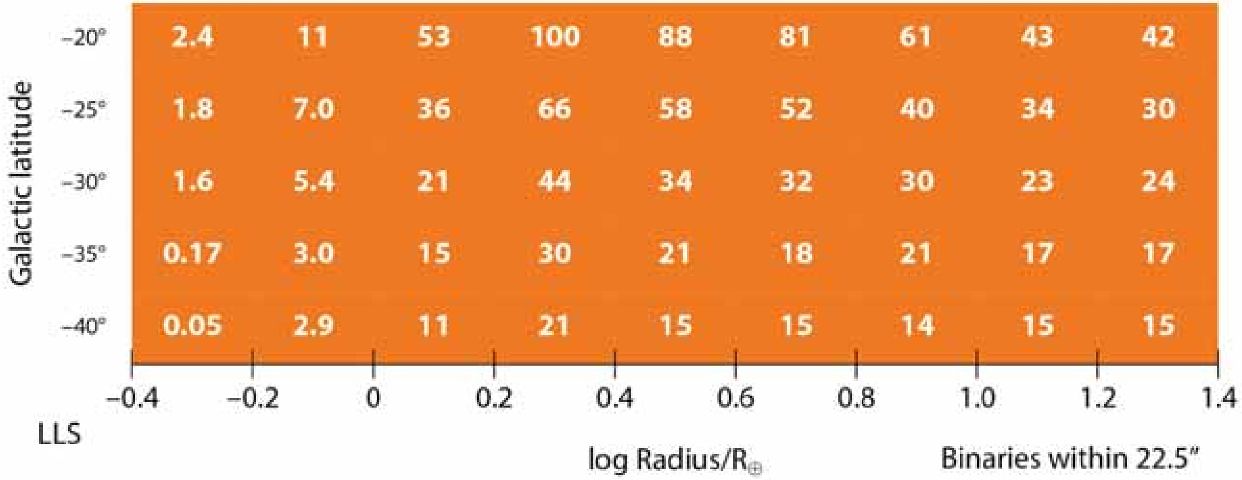
−20°	0.4	1.3	7.8	18	14	17	16	12	19
−25°	0.36	3.4	6.2	16	10	13	10	13	16
−30°	0.20	2.0	4.0	11	5.7	8.2	10	12	15
−35°	0.0	2.0	3.6	11	3.9	4.6	8.7	9.4	12
−40°	0.0	2.1	2.7	8.7	3.5	2.9	7.4	9.5	11.5

RESULTS

Number of binaries < 22.5”, central zone only



40°	0.16	2.8	11	27	19	11	16	15	19
35°	0.43	4.2	18	46	32	19	24	18	23
30°	0.24	6.9	29	66	51	43	33	27	29
25°	0.64	12	52	110	88	80	60	41	39
20°	1.6	19	100	200	170	160	110	72	39

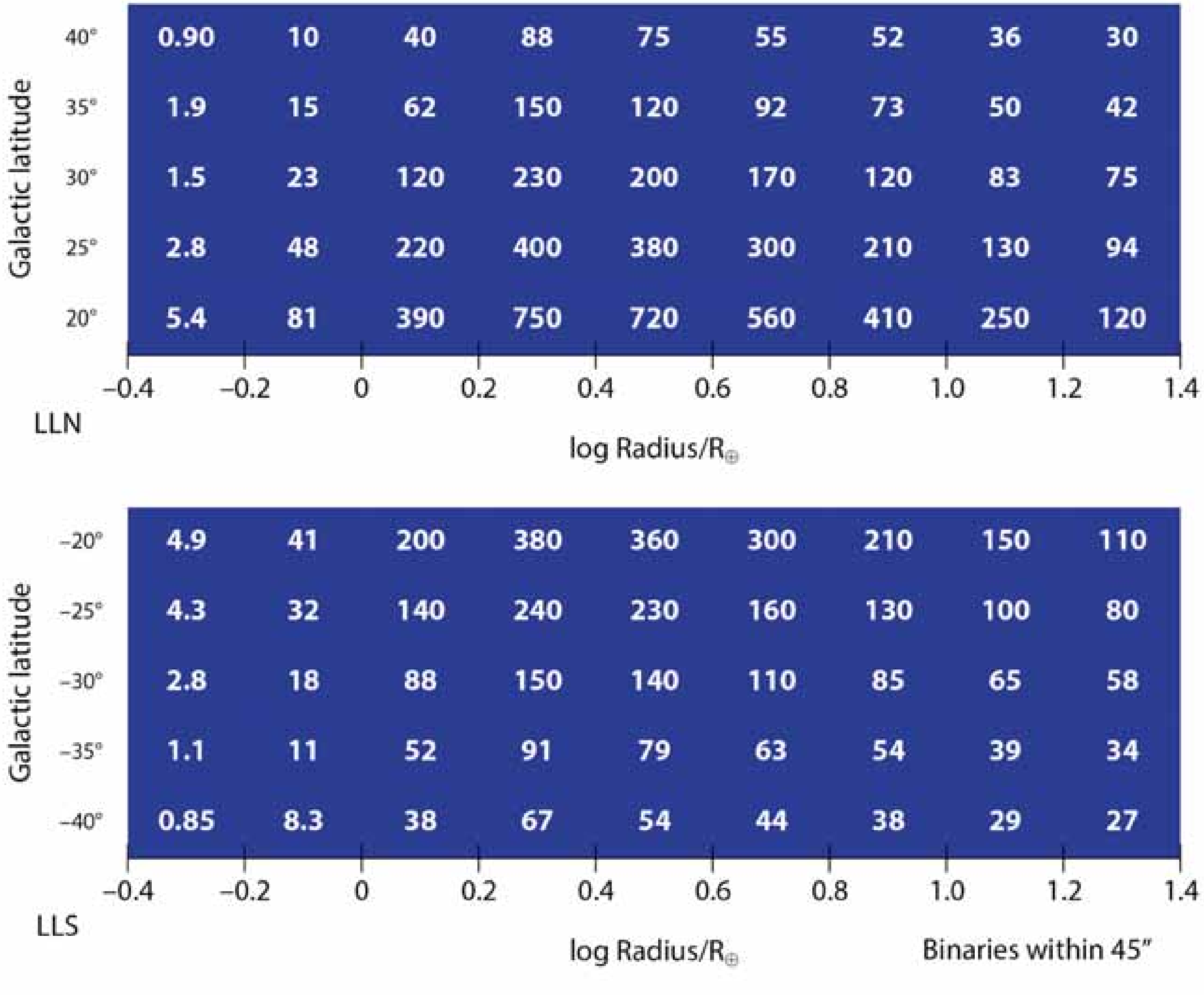


-20°	2.4	11	53	100	88	81	61	43	42
-25°	1.8	7.0	36	66	58	52	40	34	30
-30°	1.6	5.4	21	44	34	32	30	23	24
-35°	0.17	3.0	15	30	21	18	21	17	17
-40°	0.05	2.9	11	21	15	15	14	15	15

Binaries within 22.5″

RESULTS

Number of binaries < 45", central zone only



LLN

40°	0.90	10	40	88	75	55	52	36	30
35°	1.9	15	62	150	120	92	73	50	42
30°	1.5	23	120	230	200	170	120	83	75
25°	2.8	48	220	400	380	300	210	130	94
20°	5.4	81	390	750	720	560	410	250	120

LLS

−20°	4.9	41	200	380	360	300	210	150	110
−25°	4.3	32	140	240	230	160	130	100	80
−30°	2.8	18	88	150	140	110	85	65	58
−35°	1.1	11	52	91	79	63	54	39	34
−40°	0.85	8.3	38	67	54	44	38	29	27