The Robo-AO KOI Survey:
Laser adaptive optics imaging of every *Kepler* exoplanet candidate

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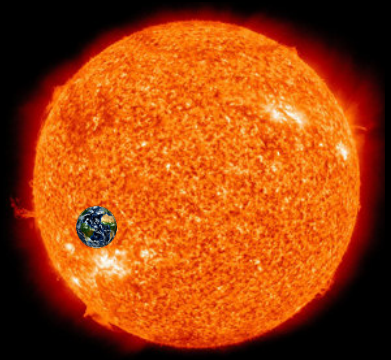
XRP grant NNX15AC91G

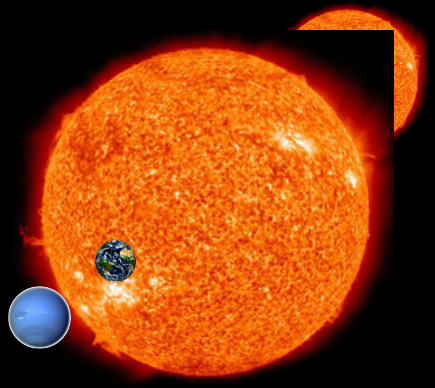
Kepler high-resolution follow-ups

Kepler discovers ~4000 planetary candidate hosts

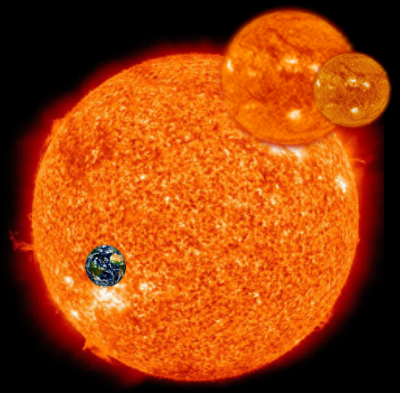
Every KOI needs ground follow-up for confirmation and characterization



Confirm no other sources

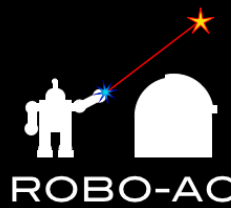


Correct the derived planetary radius



Identify astrophysical false positives

Kepler high-resolution follow-ups



Conventional high-resolution imaging (AO, speckle, lucky imaging)

Howell+ 2011, Lillo-Box+ 2012, 2014, Horch+ 2012, 2014, Adams+ 2012, 2013, Dressing+ 2014, Wang+ 2015abc, Everett+ 2015, Gilliland+ 2015, Cartier+ 2015, Kraus+ 2016, Furlan+ 2017a, Hirsch+ 2017, etc.

Robo-AO:

Fast and efficient LGS-AO observations

Fully robotic LGS-AO in the visible

Sub-minute observing overheads

~250 KOIs observed a night

Diffraction limited on majority of KOIs (V<17)

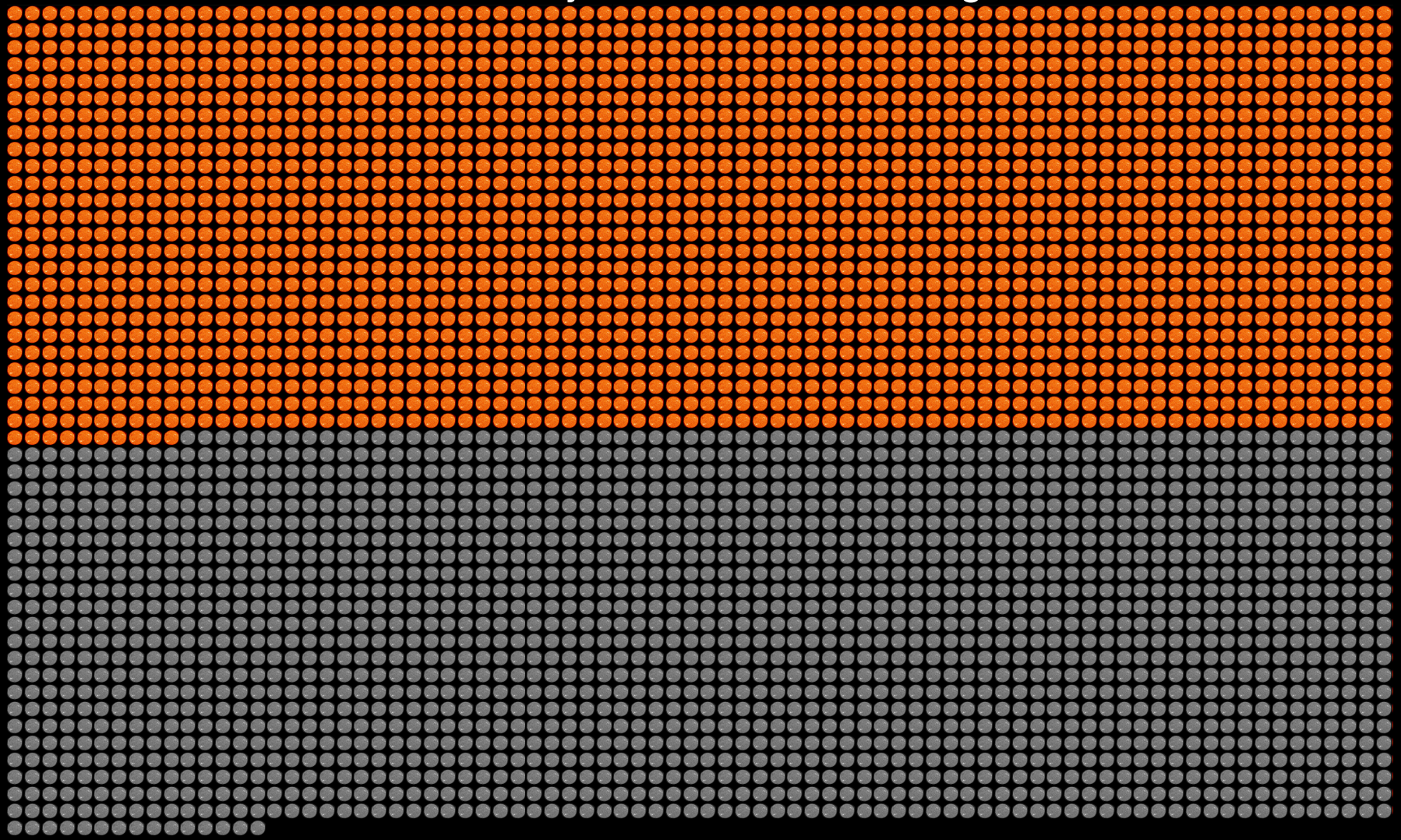
Kitt Peak 2.1m

Baranec, Riddle, Law, et al., ApJL, 790, L8 (2014)

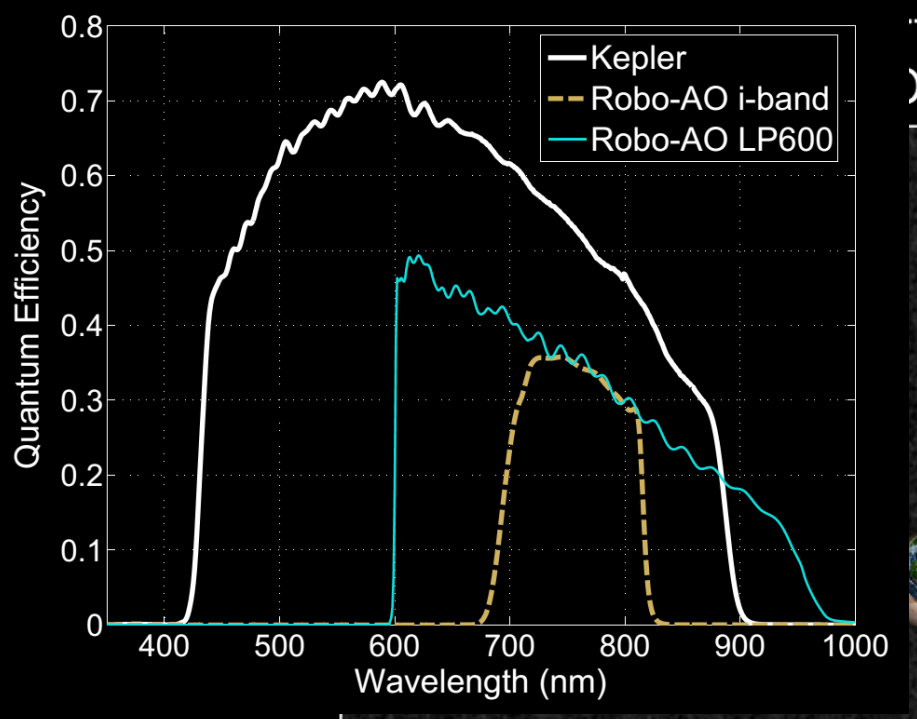
Robo-AO KOI Survey

More than half of KOIs have only been observed with high-resolution with Robo-AO

Robo-AO has observed 3857 KOIs

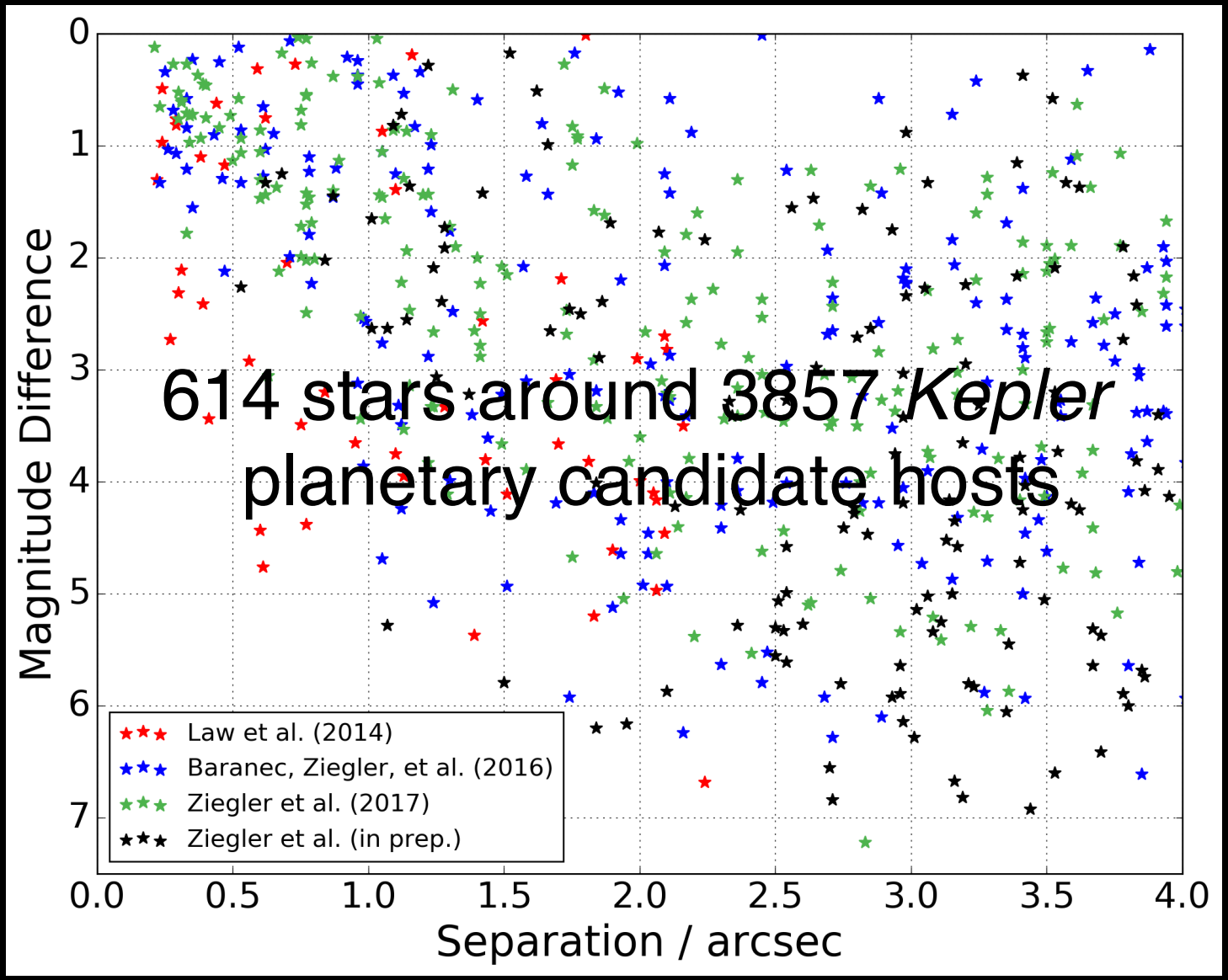


Robo-AO KOI Survey



Boyajian et al. 2013

Nearby stars to planetary candidates



KOI 346

Possible Nearby Companion

Open Observing Notes (9)

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2017-08-08 21:11:57

Jump to: Transit Params Orbital Params Planet Params Stellar Params Magnitudes Observations Summary Detections Files
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Summary of Stellar Parameters			
Star Name	KOI 346, KIC 11100383, Kepler-532		
Planet Name(s)	346.01 (Confirmed Planet), Kepler-532 b		
Possible False Positive?	No		Edit
Possible Nearby Companion?	Yes: 1.61" companion (Keck/NIRC2)		Edit
Position (J2000)	RA/Dec (h:m:s)	19:54:38.62	48:36:22.93
	RA/Dec (deg)	298.660919	48.606369
	Gal Lat/Long (deg)	10.476056	82.614204
Kepler mag	13.524		
V mag	13.804		
Ks mag	11.545		
Teff (K)	5103.00 ± 102.0		
log(g)	4.584 ± 0.020		
Radius (R_Sun)	0.7680 ± 0.0540		
Mass (M_Sun)	0.8250 ± 0.0370		
Vsini (km/s)			
[Fe/H]	0.000 ± 0.150		
Density (g/cm3)	2.569 ± 0.2825		

KOI	Radius (R_Earth)	Transit P
346.01	2.62 ± 0.18	12.9248

# Observations	
Spectroscopic	4
Imaging	5
Radial Velocity	0

Exoplanet Archive Host star: Overview page | Ligh
Exoplanet Archive KOIs: 346.01 (transits)
IRSA Finder Chart
SIMBAD for KOI-346 (if available)
exoplanets.org: 346.01 (if available)
MAST lightcurve
Eclipsing Binary Catalog (if available)

Transit Parameters (1) • Add new • Download all

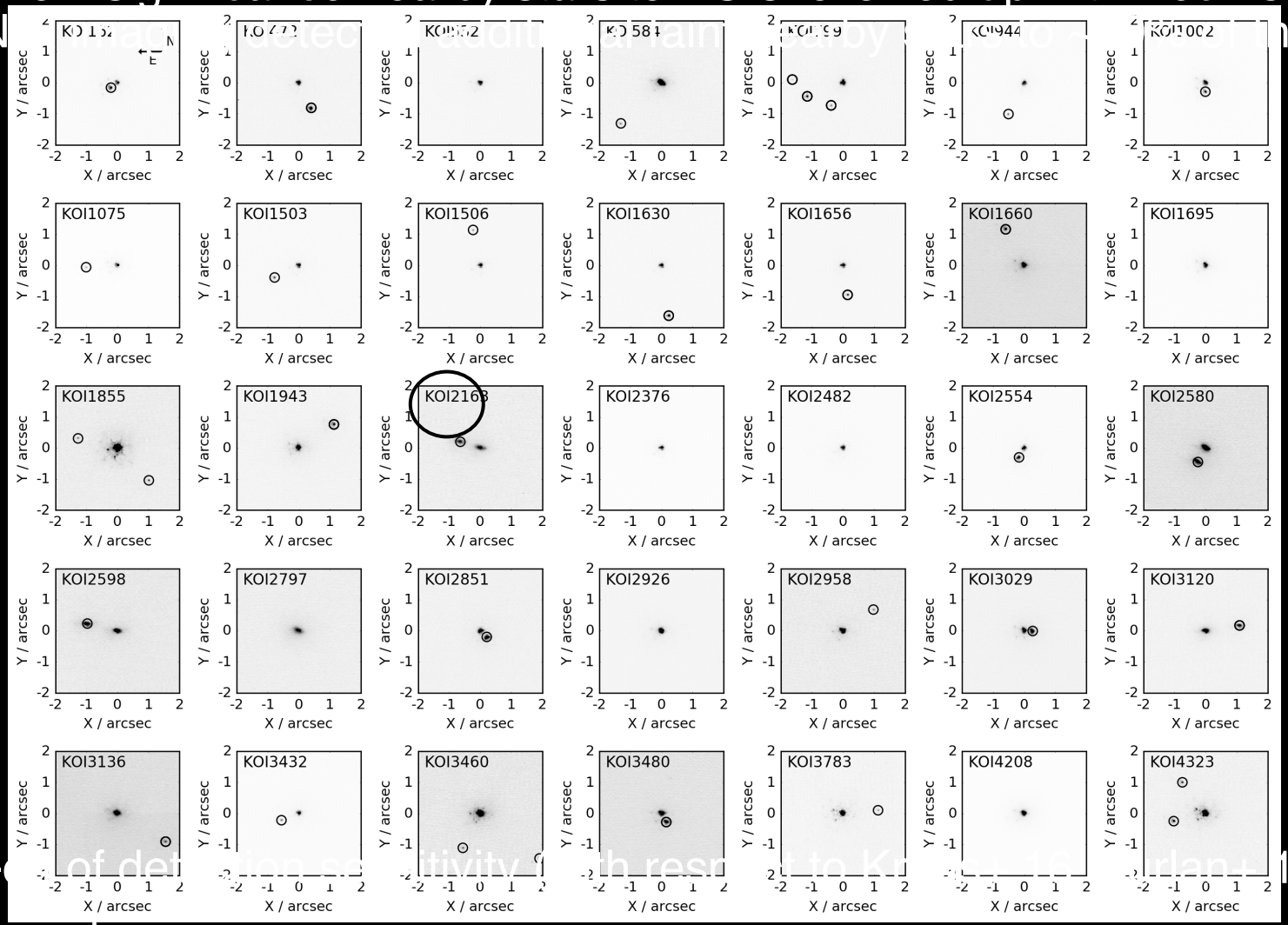
KOI	Epoch (BJD)	Period (days)	Depth (mmag)	Depth (ppm)	Duration (hrs)	R_planet/R_star	Fitted Stellar Density (g/cm3)	Pla Fit
346.01	2455003.78679000 ±0.0012700	12.924898030 ±0.000022460	1.04172061 ±0.02410361	959 ±22	2.6811 ±0.0614	0.031196 ±0.000653	1.84274 ±3.93543	LS+

Nearby stars to planetary candidates

ROBO-AO

120 low-significance nearby stars to KOIs followed up with Keck/Gemini

Deep N… …ese KOIs



Trade-… …of det… …sensitivity … …th resp… …to Ku… …16, Furlan+, 17a, etc.)

for comprehensiveness

Ziegler+, *in prep.*

Rocky, habitable zone planets

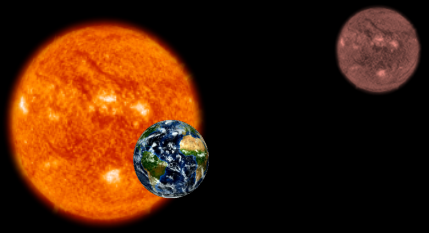
ROBO-AO

Habitable Zone Candidates with Robo-AO Detected Companions

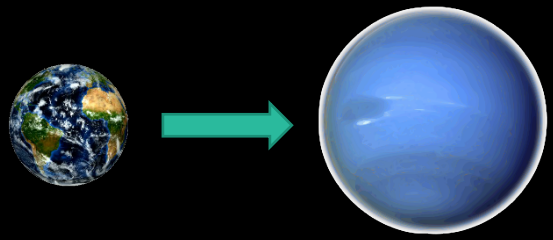
Planet candidate	Period (d)	$R_{p,i}$ [a] ($R_\oplus$)	$R_{p,c}$ [b] ($R_\oplus$)	Equil. Temp. (K)	Sep (″)	Δm (mag)
227.01[c]	17.7	2.45	2.96	350	0.33	0.84
255.01	27.5	2.51	2.67	313	3.36	2.14
438.02[c]	52.7	1.76	1.81	271	3.28	3.11
1503.01	150.2	3.79	4.23	291	0.76	1.52
1846.01	106.0	3.81	4.46	322	3.7	1.07
1989.01[c]	201.1	1.84	1.88	297	1.12	3.49
2174.02[c]	33.1	1.88	2.53	343	0.92	0.21
2744.01	109.6	2.46	2.63	340	3.44	2.12
2760.01	56.6	2.19	2.64	317	0.44	0.84
2862.01	24.6	1.79	2.44	321	0.67	0.17
2926.03	21.0	2.43	3.24	357	0.33	0.27
2926.04	37.6	2.09	2.79	294	0.33	0.27
3255.01[c]	66.7	1.37	1.38	294	3.15	4.87
3284.01[c]	35.2	0.98	1.03	272	3.94	2.42
3401.02[c]	326.7	2.20	2.64	283	0.65	0.89
3946.01[c]	308.5	2.36	2.37	298	4.27	5.26
4550.01	140.3	1.73	2.42	257	1.03	0.04
4810.01	115.2	2.07	2.13	353	2.32	3.16
5101.01	436.2	1.64	1.68	331	1.22	3.33
5553.01	120.9	2.59	2.71	333	0.95	2.52
5671.01	190.9	1.73	1.89	356	2.13	1.79
5707.01	208.8	2.88	3.03	347	2.67	2.43
5885.01	111.1	1.87	1.89	364	3.36	4.03
6120.02	205.4	1.67	1.75	323	3.78	2.48
6745.01	383.9	2.78	2.82	314	3.02	3.78
6745.01	383.9	2.78	2.82	314	2.81	3.92

26 candidate rocky, habitable-zone planets with nearby stars

11 nearby stars are likely associated

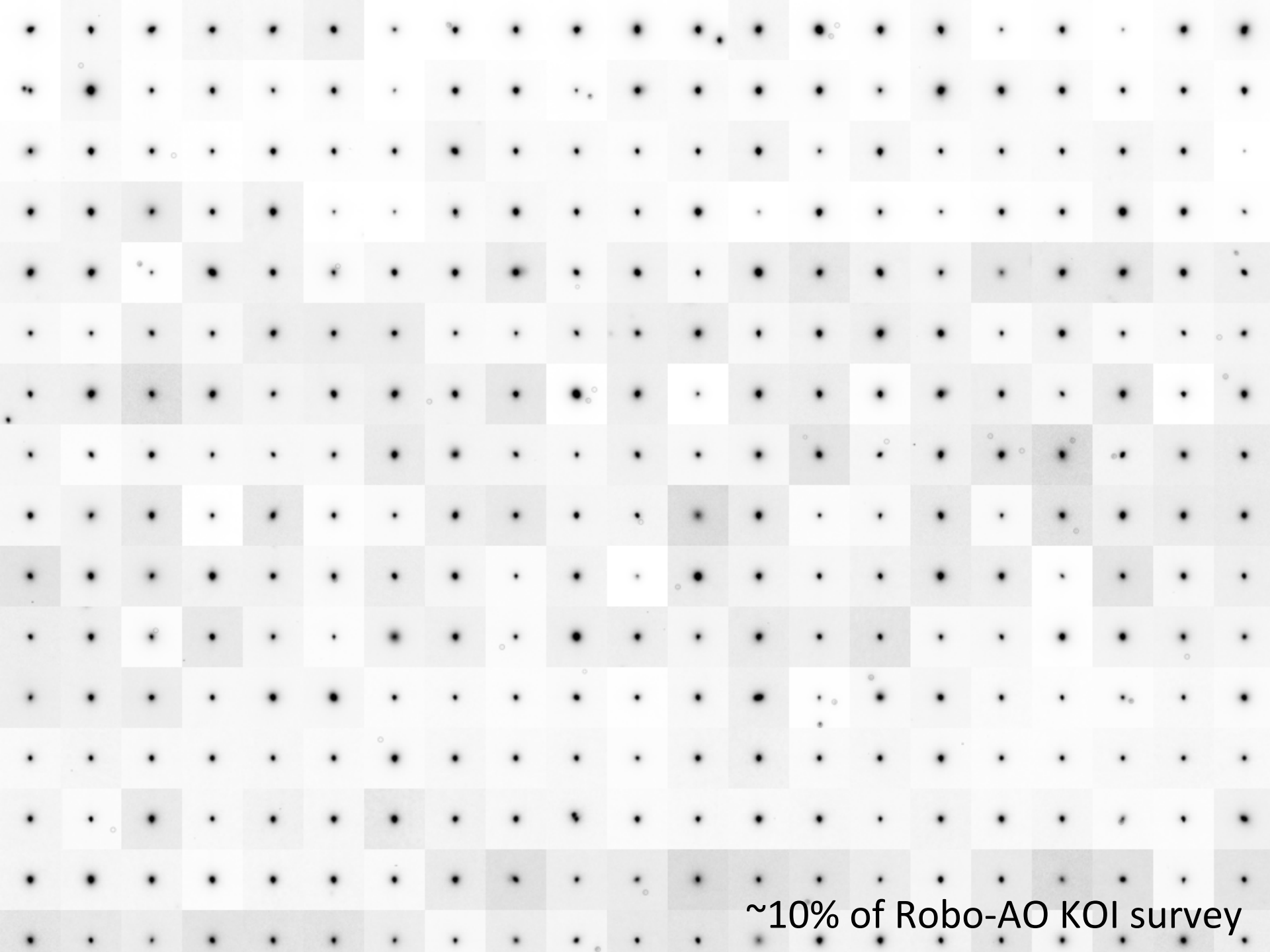


8 planets are now more likely to not be rocky



roboaokepler.org

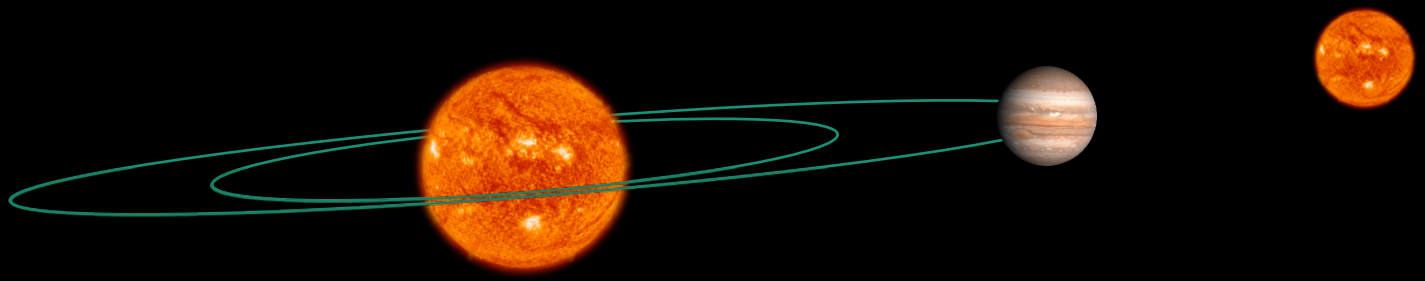
Ziegler et al. (2017)


~10% of Robo-AO KOI survey

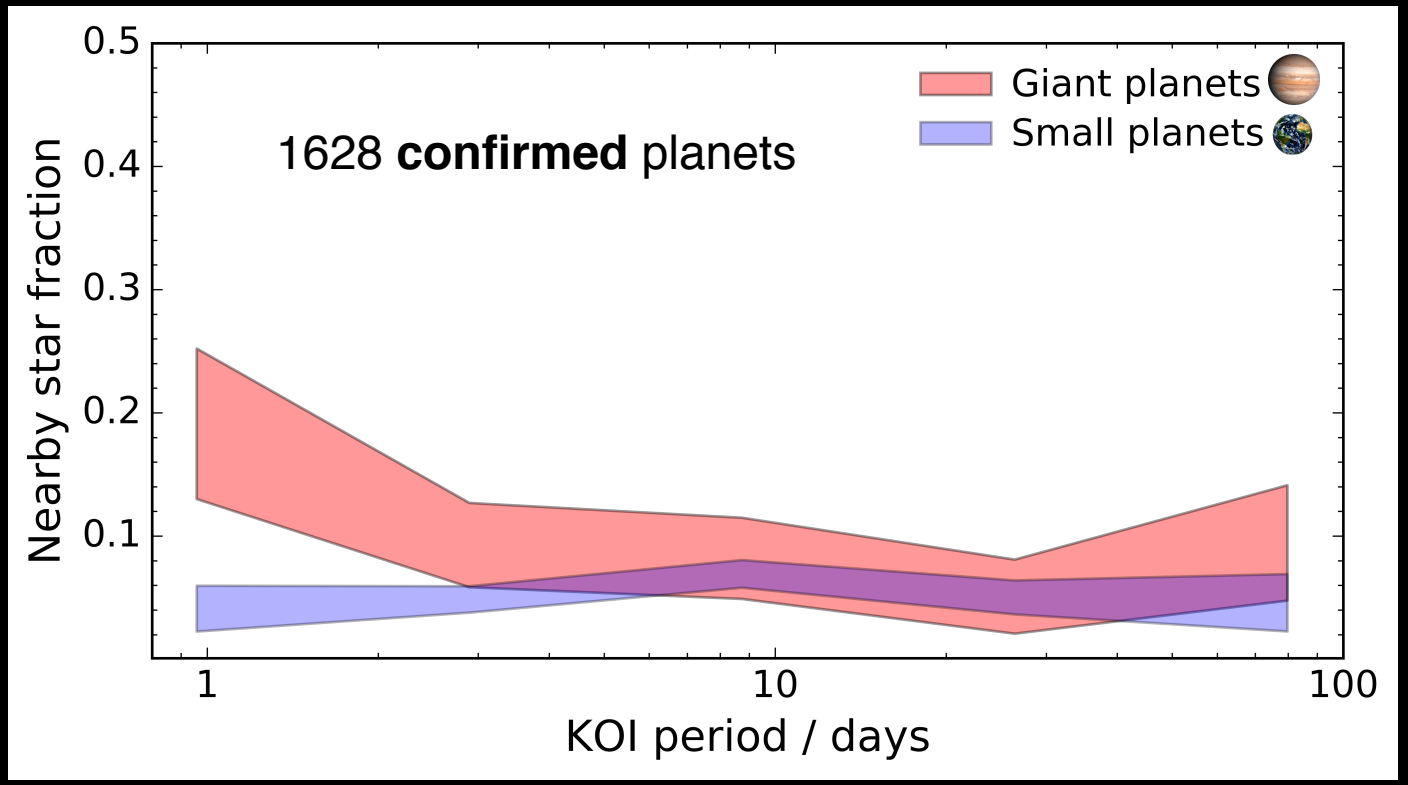
Stellar multiplicity and planetary systems

ROBO-AO

Perturbations from third body drive orbital migration
(Fabrycky+ 2011; Katz+ 2012; Noaz+ 2012)



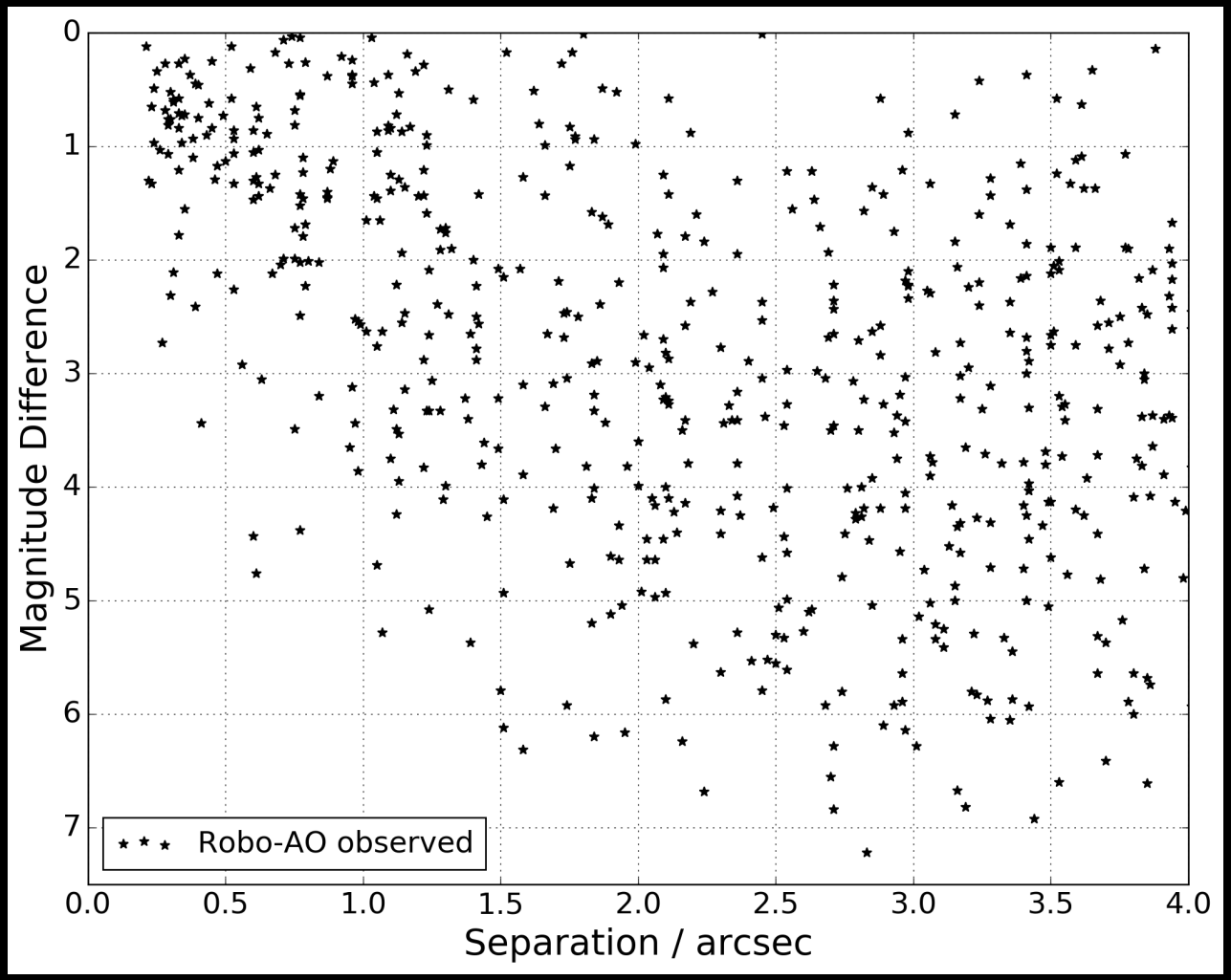
Binaries may lead to hot Jupiters



Ziegler et al., AJ 153, 66 (2017)

Association of nearby stars

Many of these nearby stars are not bound, but line of sight asterisms

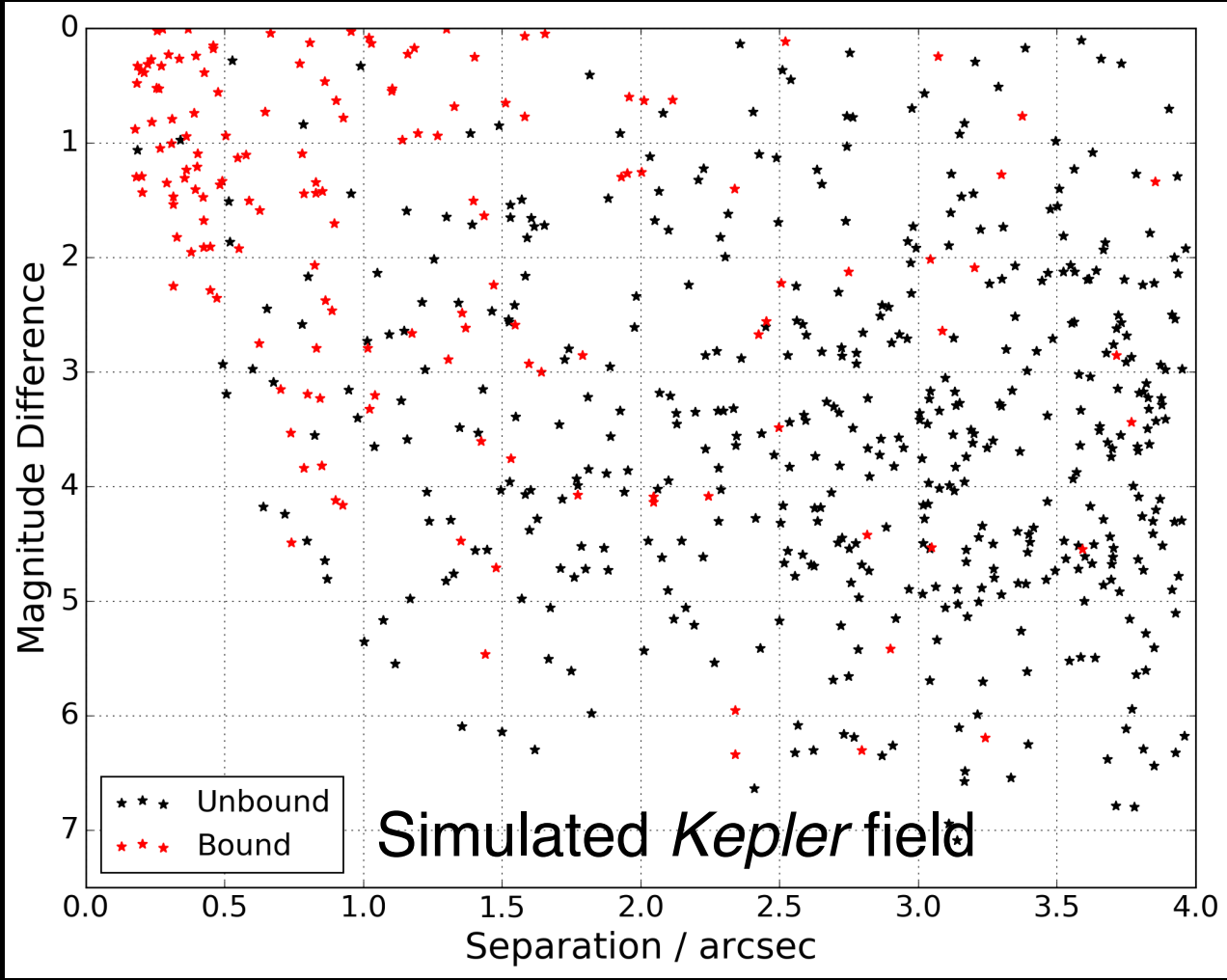


Ziegler+, *in prep.*

Association of nearby stars

ROBO-AO

Association probabilities as a function of separation estimated from Galactic stellar models (TRILEGAL, Girardi+ 2005), similar to Horch+ 2014



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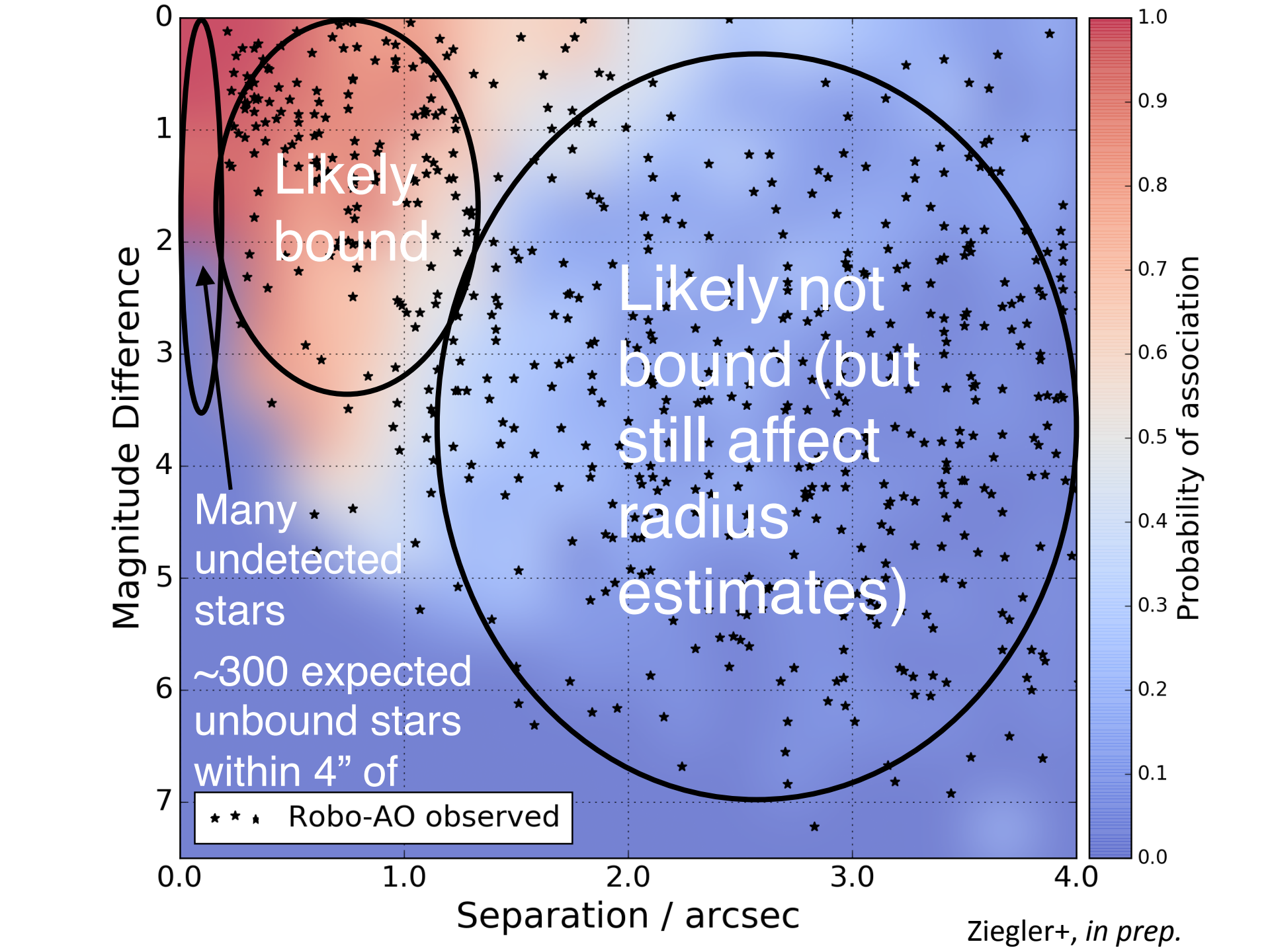
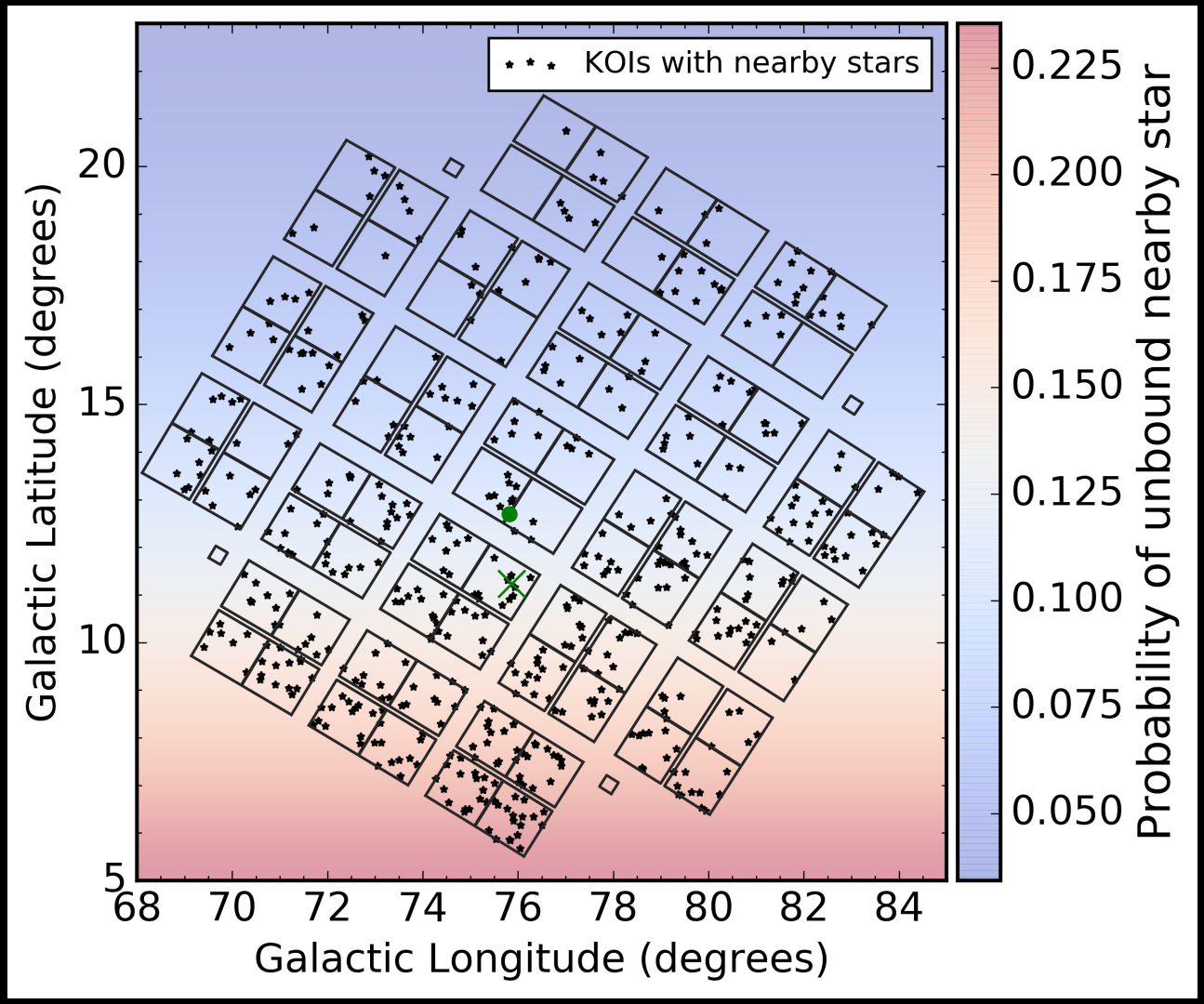
Ziegler+, *in prep.*


Likely bound
Likely not bound (but still affect radius estimates)
Many undetected stars
~300 expected unbound stars within 4” of
Robo-AO observed
Magnitude Difference
Separation / arcsec
Probability of association
0
1
2
3
4
5
6
7
0.0
1.0
2.0
3.0
4.0
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Ziegler+, *in prep.*

Observed stellar density



~320 expected unbound stars within 4” of KOIs

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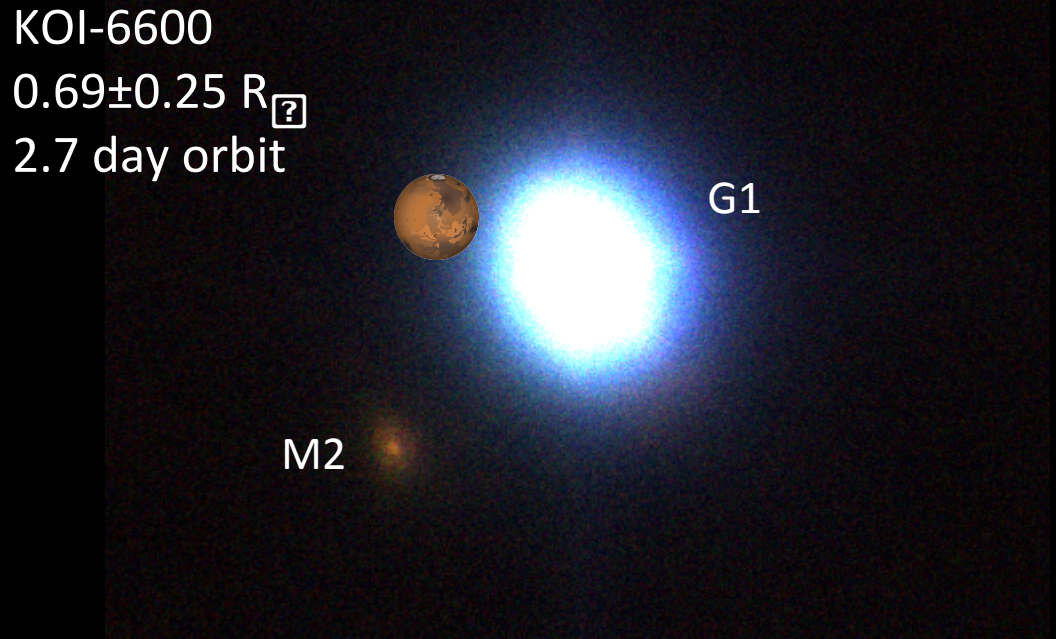
Ziegler+, *in prep.*

Characterization of nearby stars

Robo-AO allows us to perform multi-band imaging to access association of every planetary system with a nearby star



Robo-AO KP visible (Ziegler+, *in prep*) plus Palomar PHARO NIR (Furlan+ 2017)

$\Delta m_{i'}$=5.91 $\Delta m_{i'}$=5.19 $\Delta m_{z'}$=4.45 Δm_{J}=3.60 Δm_{K}=3.05

Isochrones (Morton 2015), SEDs (Kraus & Hillenbrand 2007)

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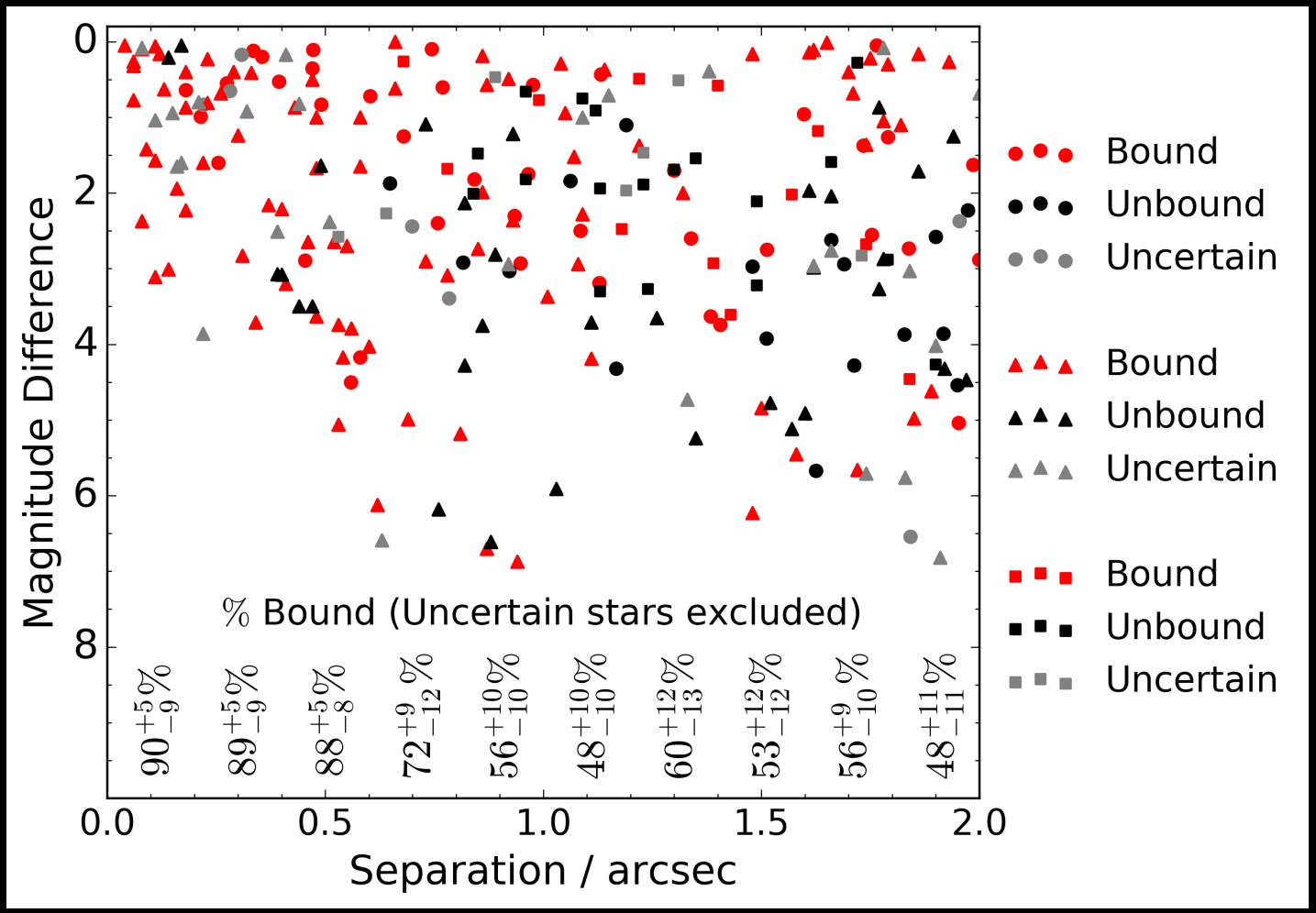
Association of nearby stars

ROBO-AO

Photometric observational evidence: most stars >1” are unbound

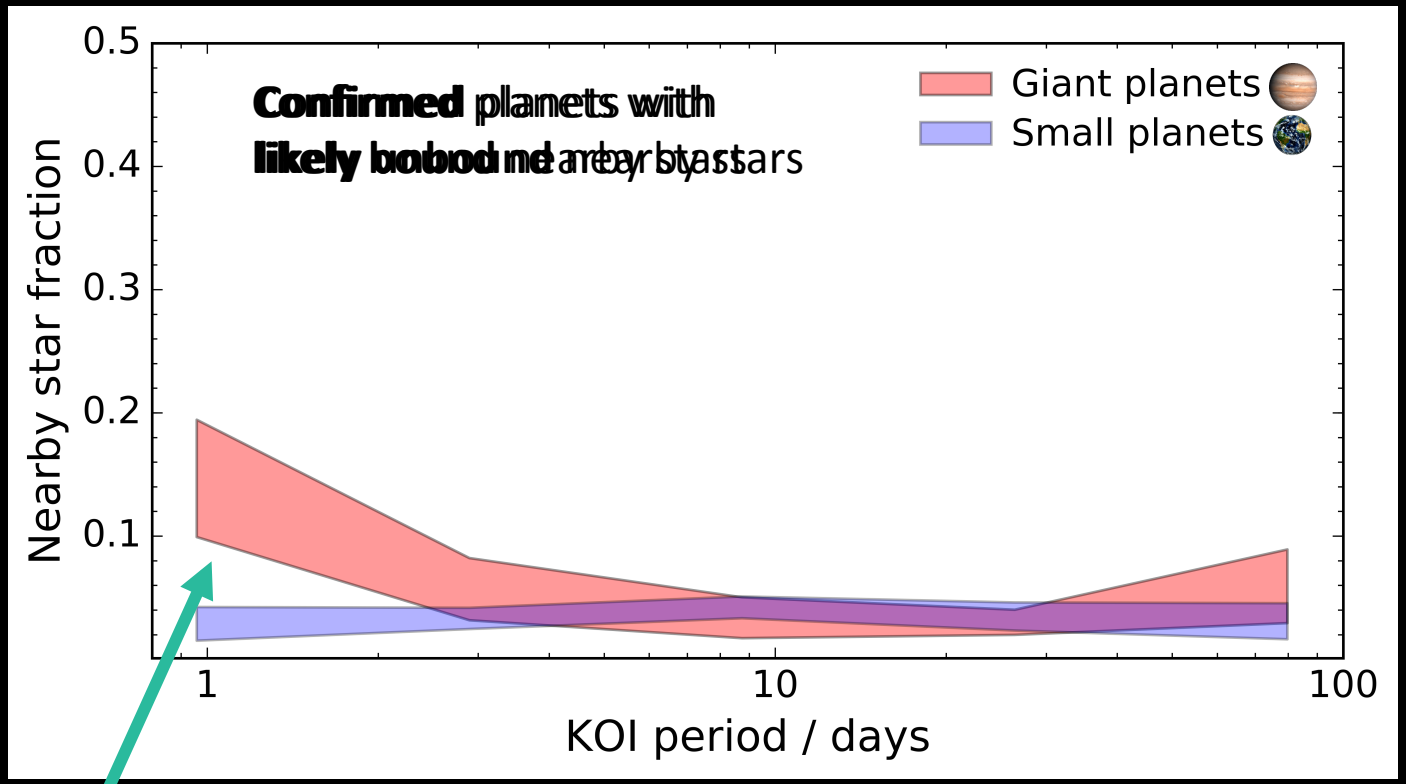


Atkinson+ 2017
(104 KOIs)

Hirsch+ 2017
(176 KOIs)

Ziegler+ (in prep)
(157 KOIs)

Binaries may lead to hot Jupiters

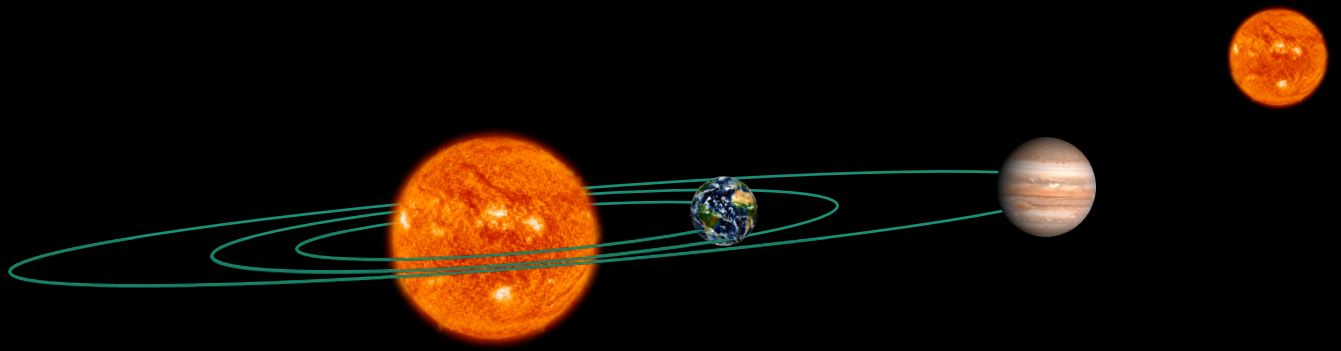


Hot Jupiters are ~4x more likely to have a nearby stellar companions (~2.5σ)

Stellar multiplicity and planetary systems

ROBO-AO

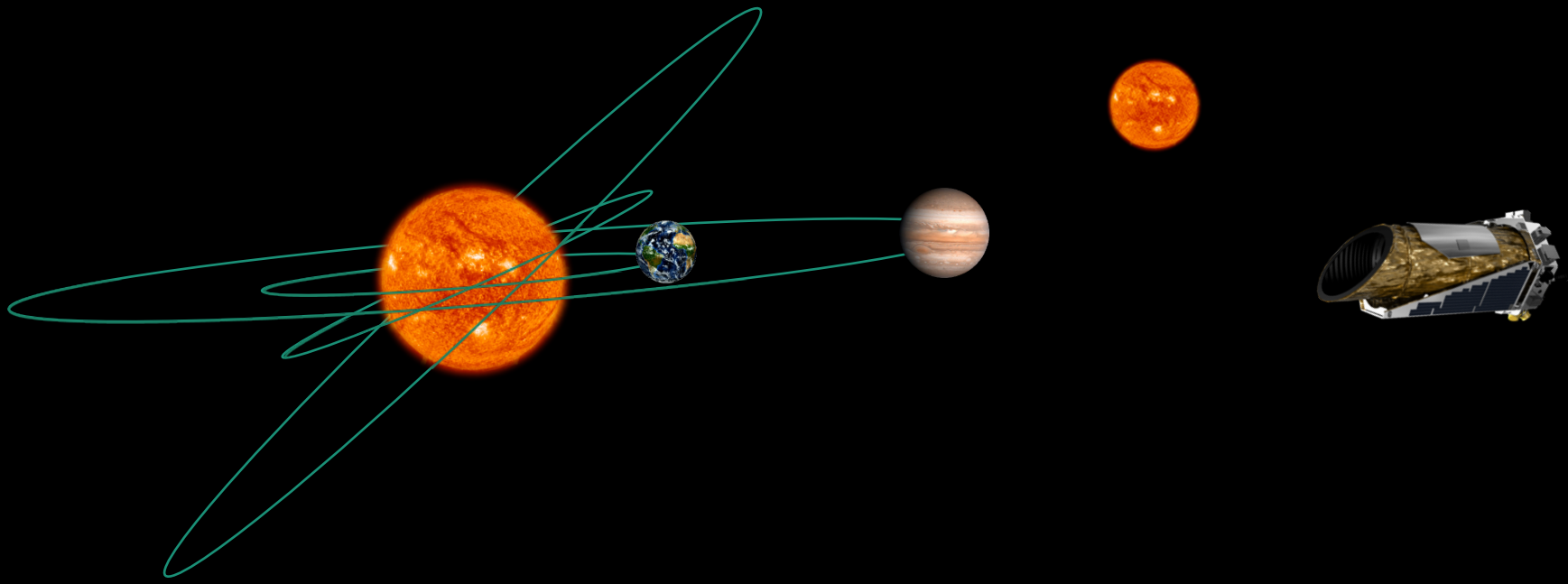
Dynamical interactions between small and large planets are thought to differentially eject smaller planets (Xie+ 2014)



Stellar multiplicity and planetary systems

ROBO-AO

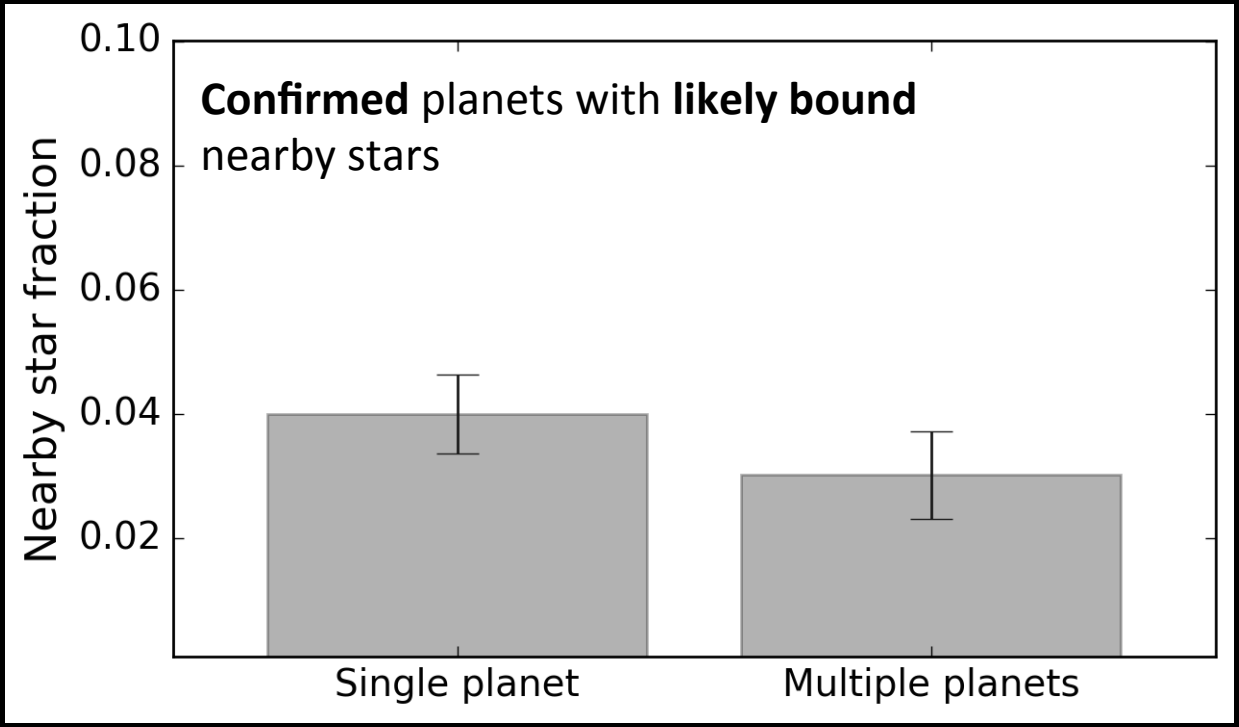
Nearby star may tilt mutual inclinations of planets
(Wang+ 2014; Batygin 2012)



Single transiting planet systems are thought to have more nearby stars than multiple transiting planet systems

Robo-AO KOI Survey

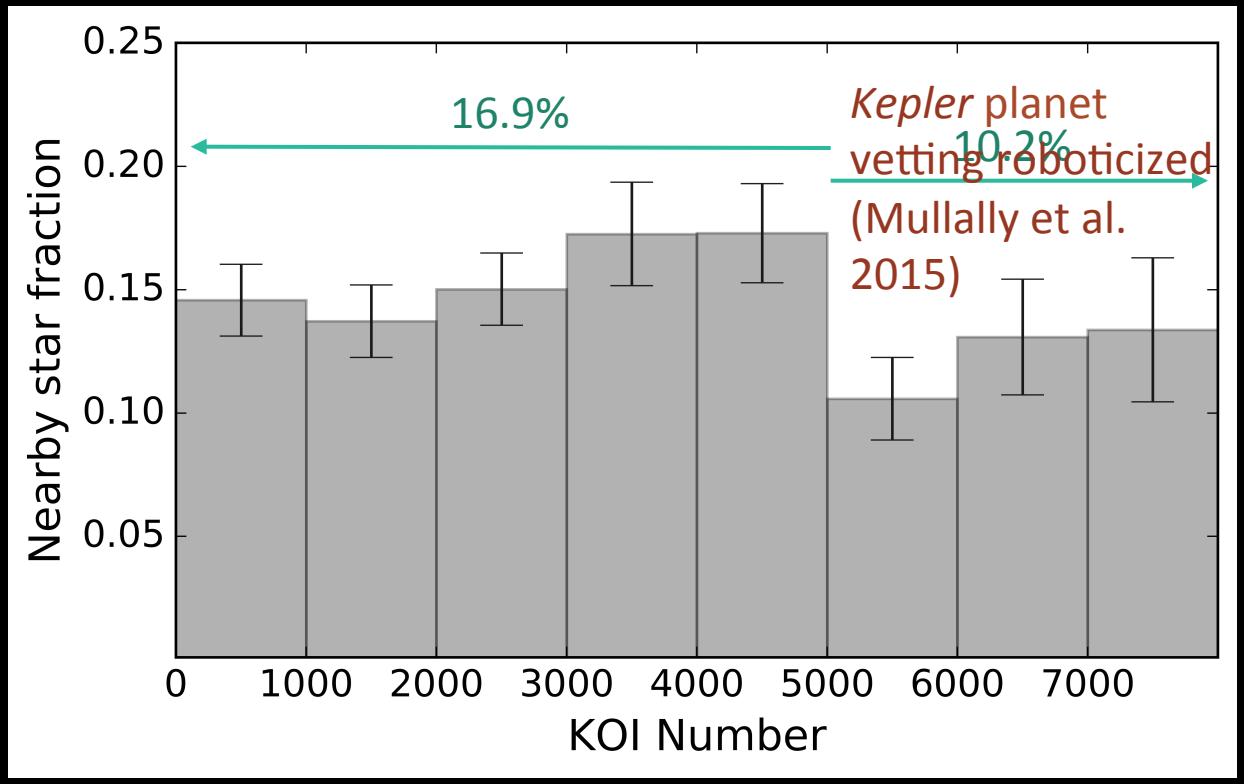
Nearby star fraction of single and multiple transiting planet systems



Ziegler+, 2017 *in prep.*

Robo-AO KOI Survey

KOIs numbered >5000 are less likely to have nearby stars

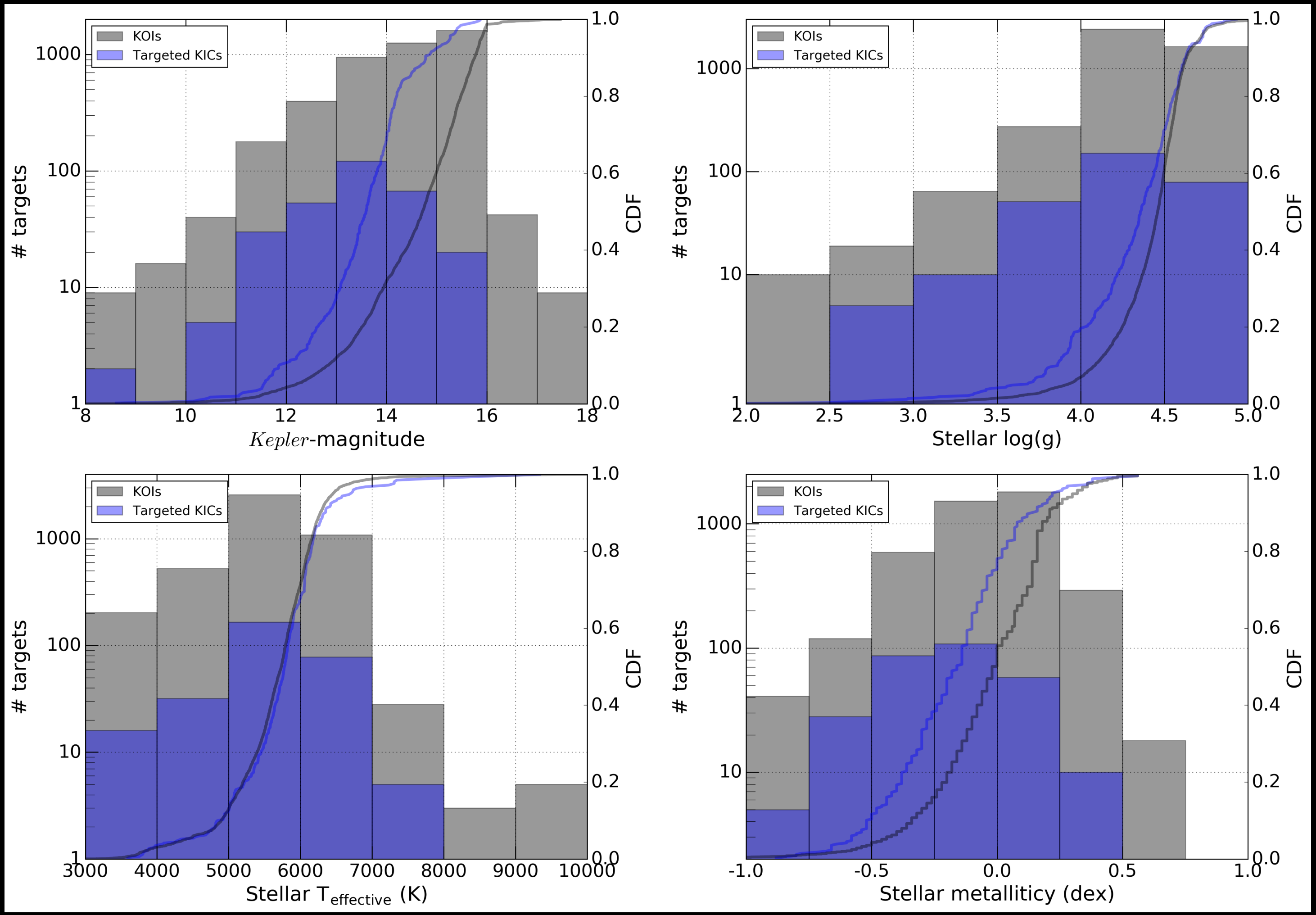


Ziegler et al., AJ 153, 66 (2017)

KIC control sample

Nearby-star fraction of KICs (15.1±1.2%) consistent with KOIs (14.6±.6%)

Robo-AO observed 1200 KICs with control sample



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Ziegler+, *in prep.*

~4000 high-resolution KOI observations with Robo-AO, ~600 contaminating nearby stars

Hot Jupiters are more likely than other types of planets to be in a binary system

Single and multi-planet systems show little difference in binary star rates

Robo-AO network will be able to observe and characterize transiting planets discovered from future all-sky missions

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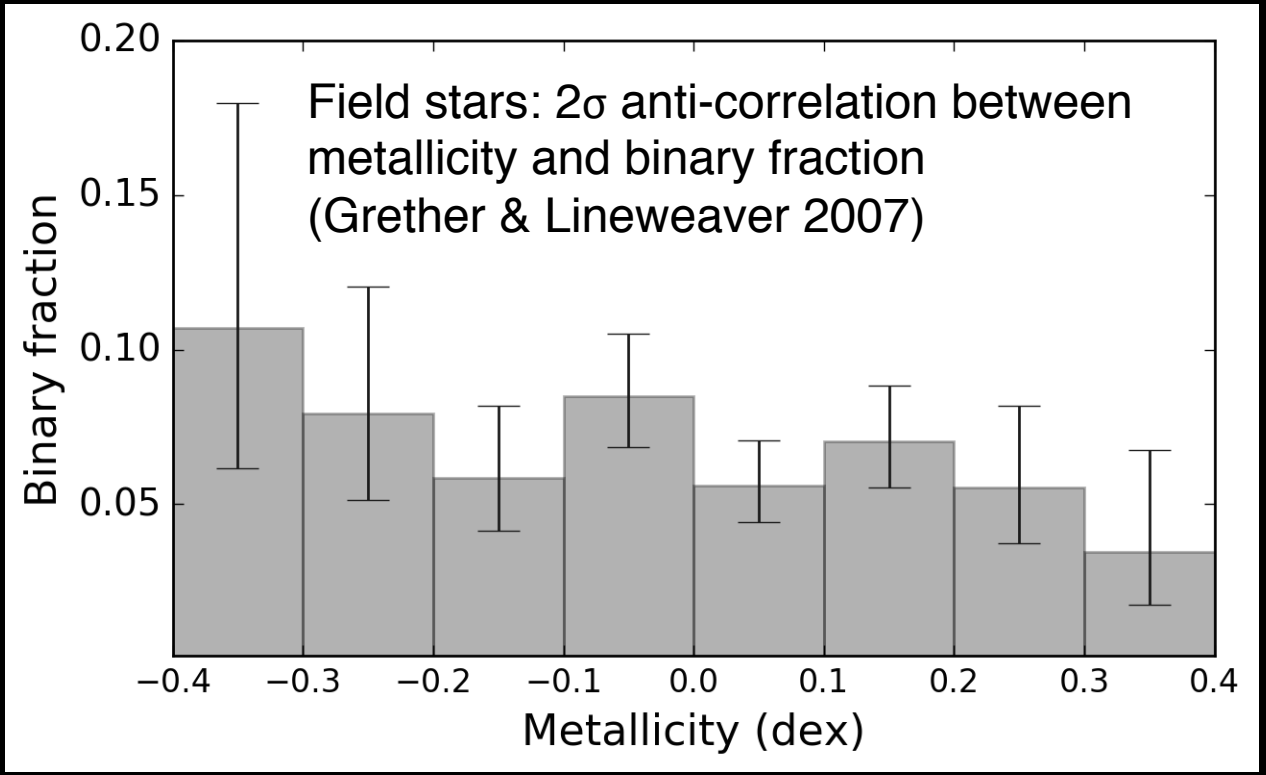
ROBO-AO

Ziegler+, SPIE 9909 2016

KOIs are similar to field stars

KOIs with lower metallicity have a slightly higher nearby star fraction

Likely associated stars



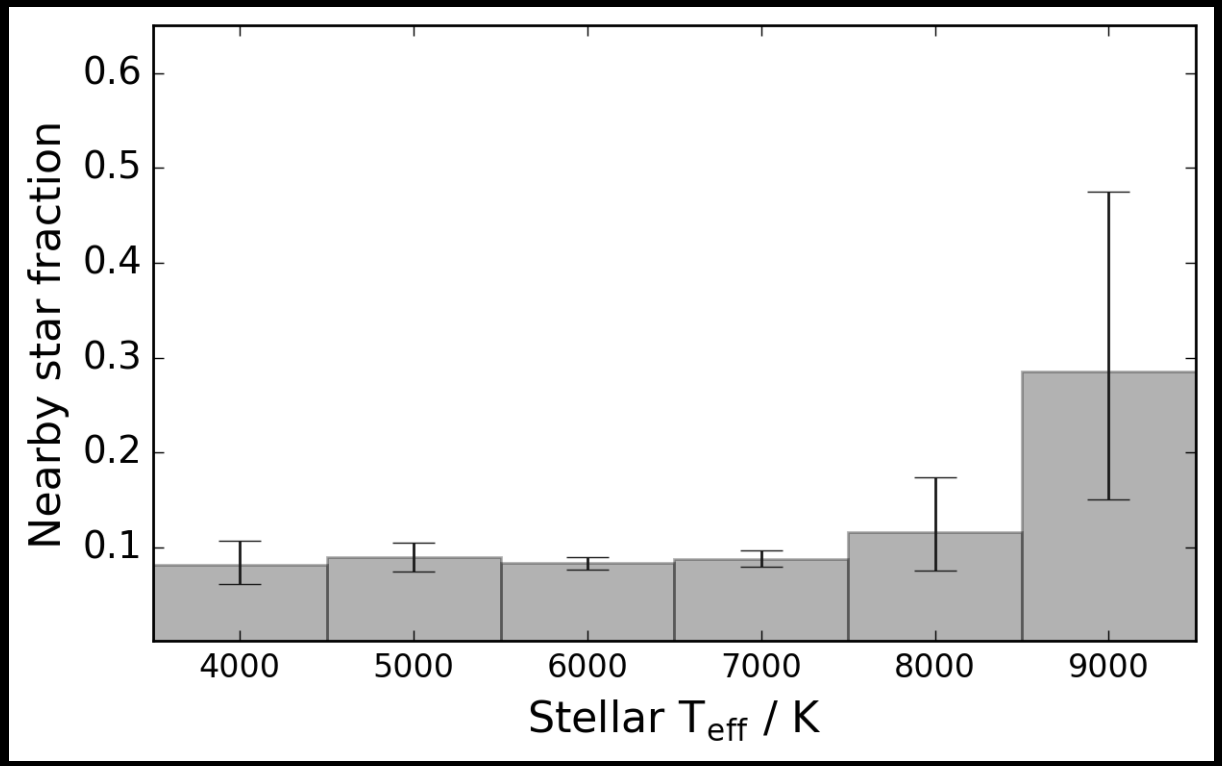
CKS stellar parameters (Johnson+ 2017)

Ziegler+, *in prep.*

KOIs are similar to field stars

KOIs follow trend of multiplicity correlating with T_{eff} (Duchêne & Kraus 2013)

Likely associated stars

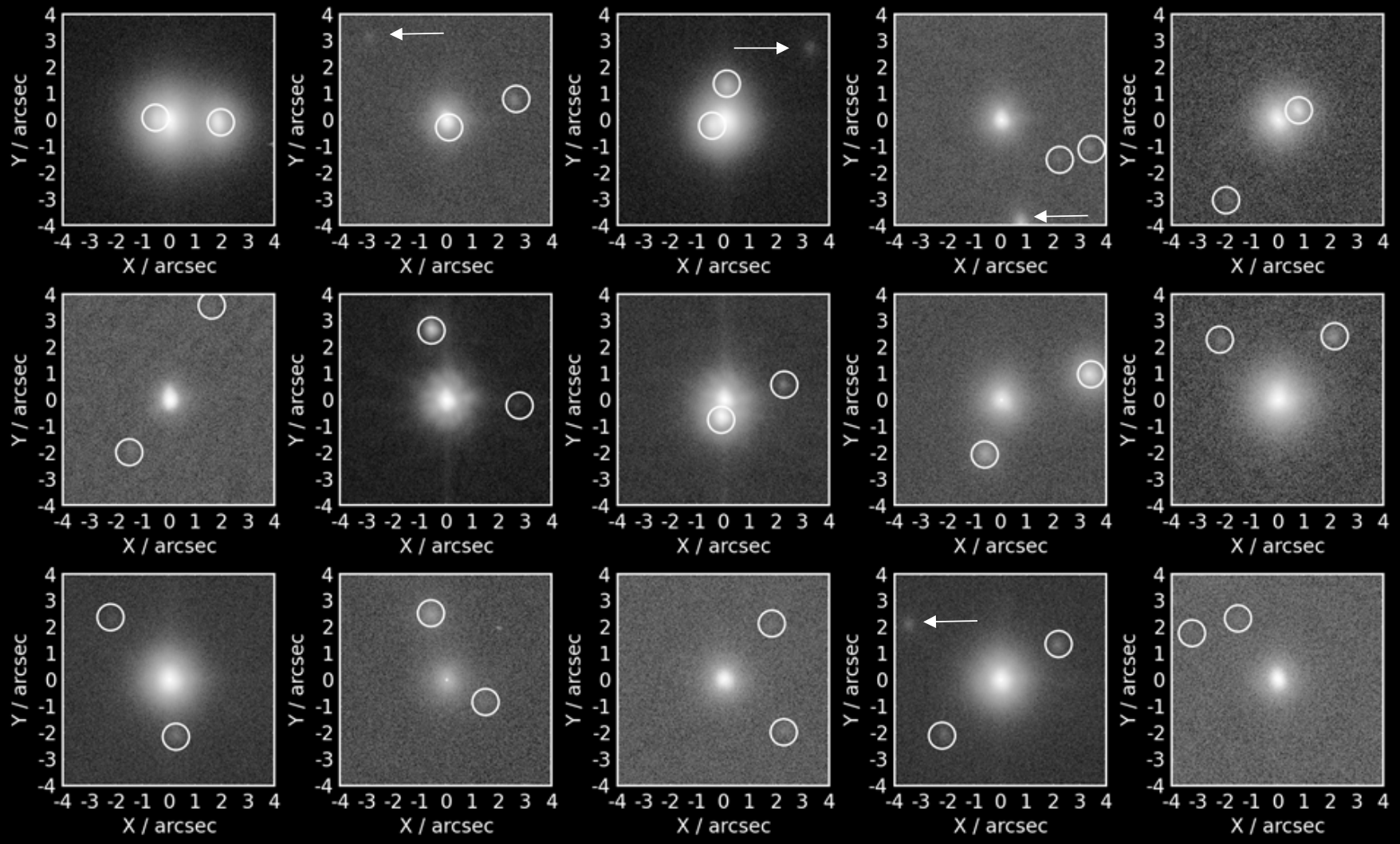


CKS stellar parameters (Johnson+ 2017)

Ziegler+, *in prep.*

Planets in multiple star systems

ROBO-AO



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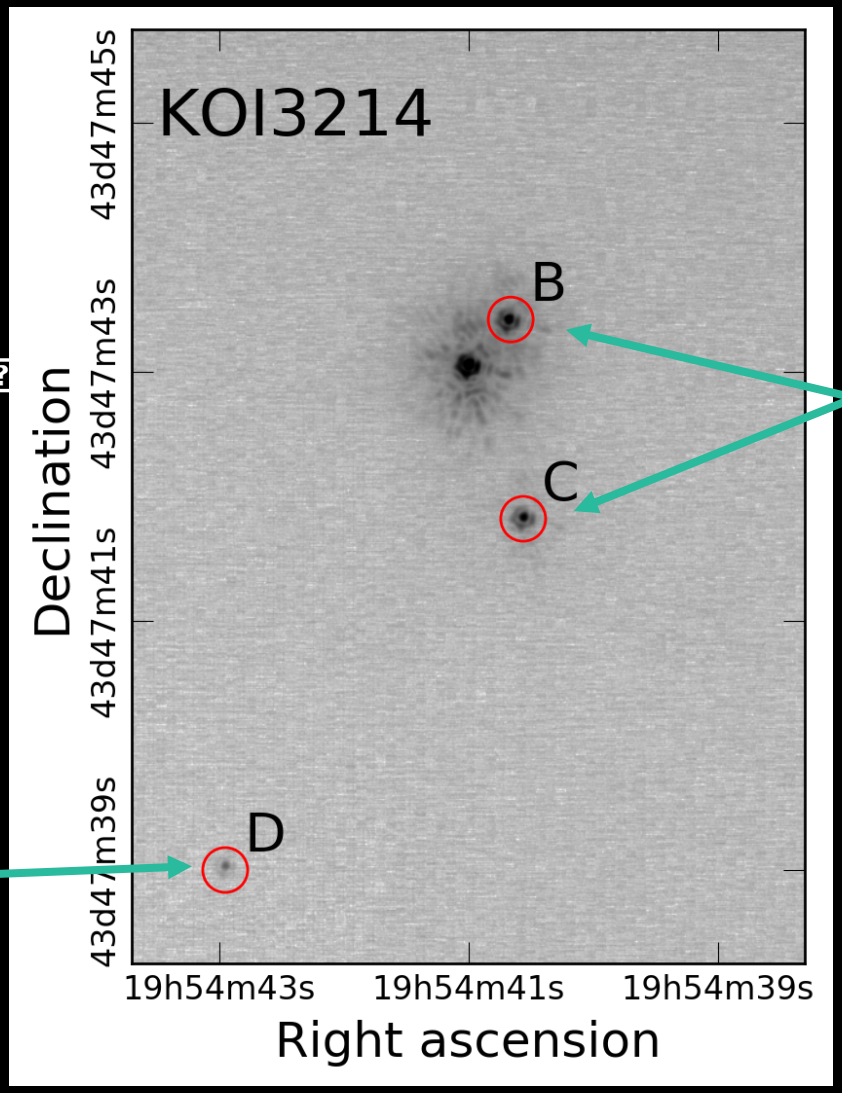
Ziegler et al., AJ 153, 66 (2017)

Planets in multiple star systems

ROBO-AO

1.35 $R_{?}$ and 1.53 $R_{?}$ planet system



Likely associated

Likely not associated

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Ziegler+, *in prep.*

Observed stellar density

The observed stellar density of the *Kepler* field can be estimated from the Robo-AO full frame images