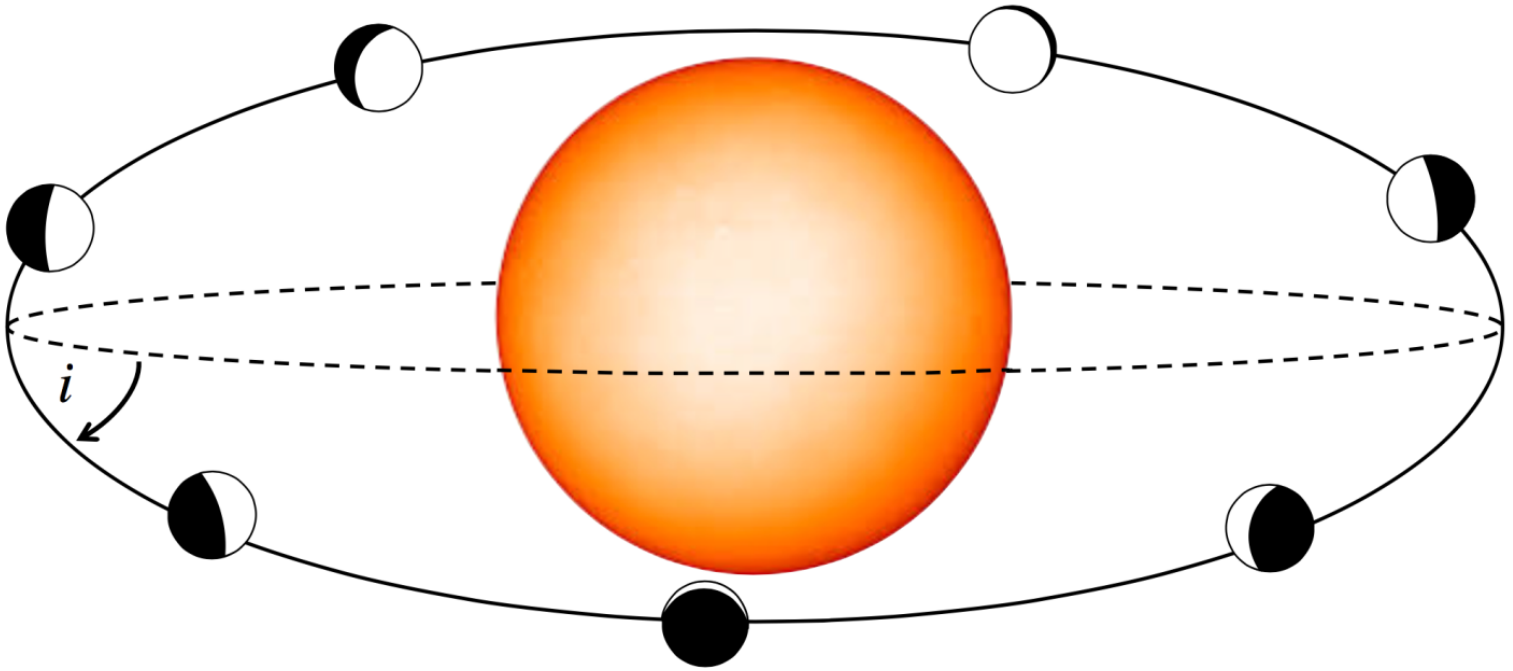
Supervised Learning Detection of Sixty Non-Transiting Hot Jupiter Candidates



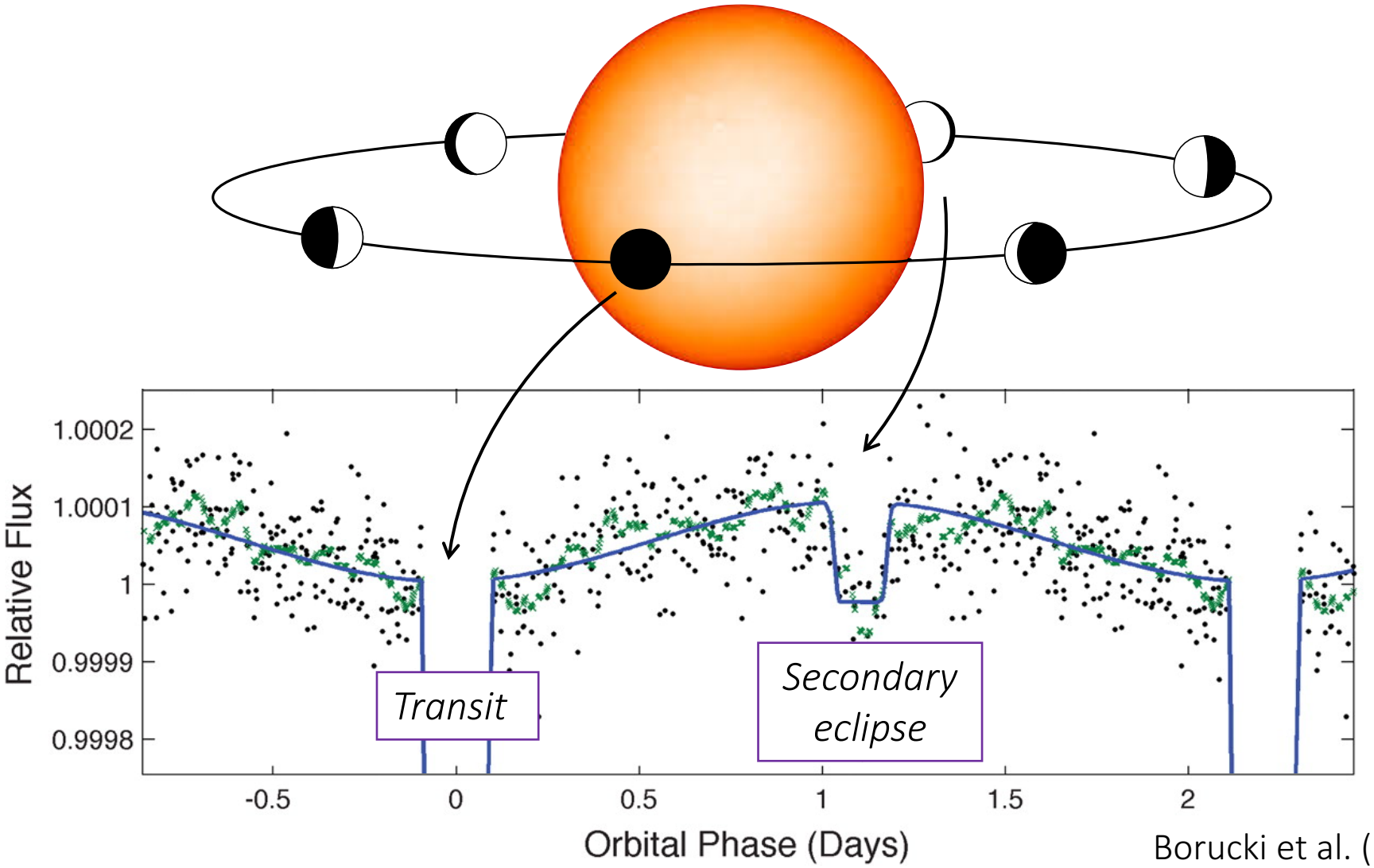
Sarah Millholland – Yale University

Advisor: Greg Laughlin

ERES III, June 13, 2017

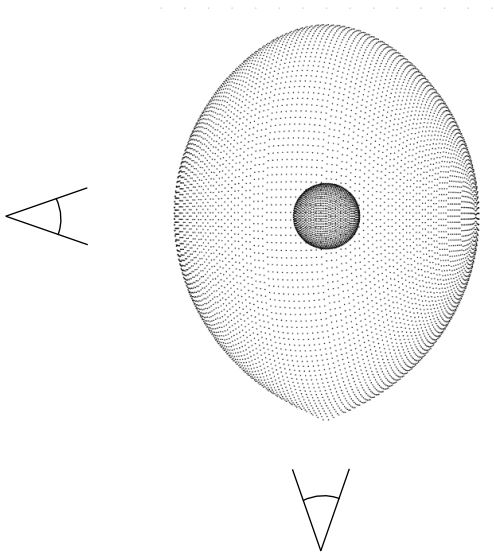
Background

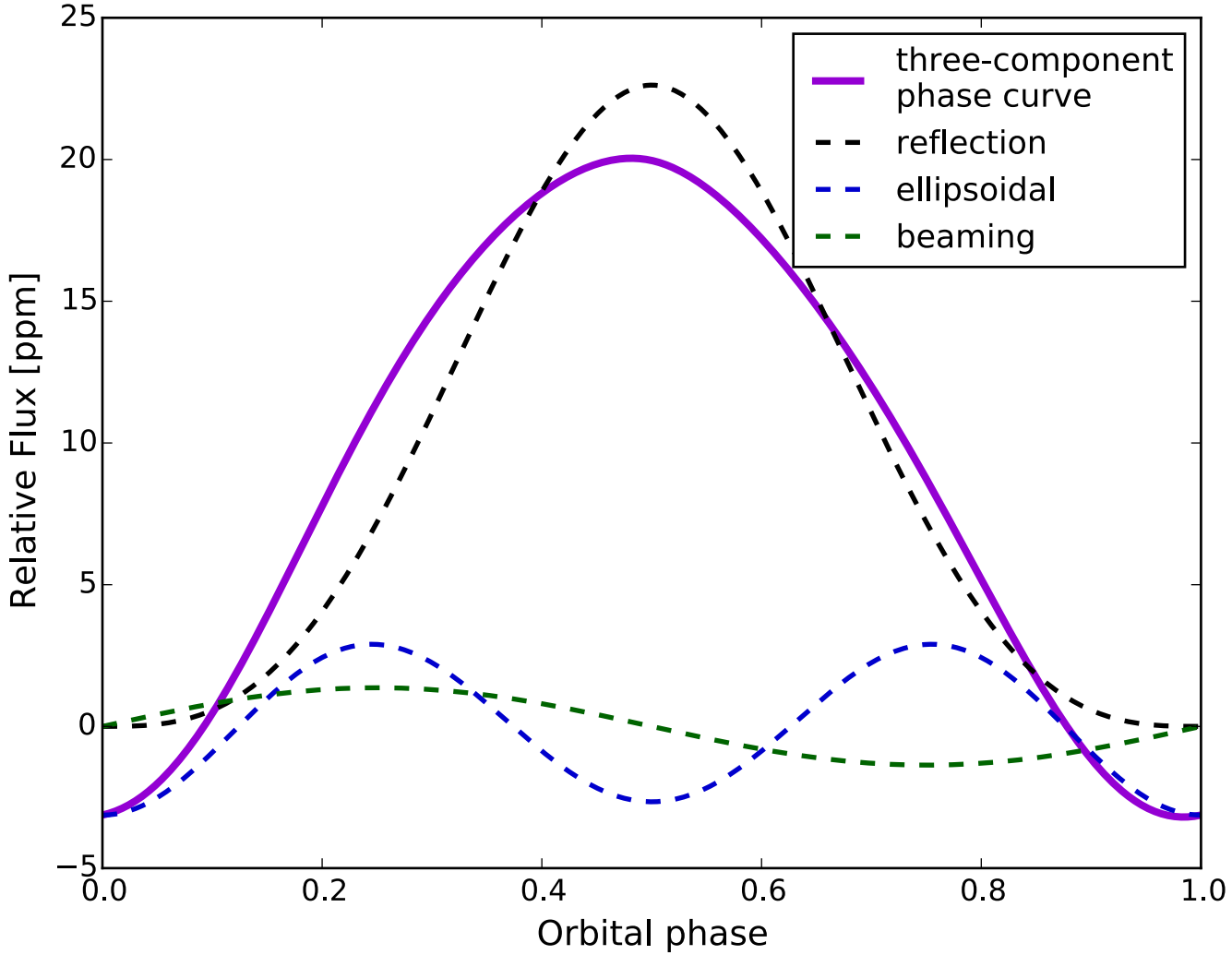
First *Kepler* phase curve: HAT-P-7b



Borucki et al. (2009)

Optical phase curve components





$M_\star = M_\odot$

$R_\star = R_\odot$

$T_{\rm eff} = 6000$ K

$P = 2$ d

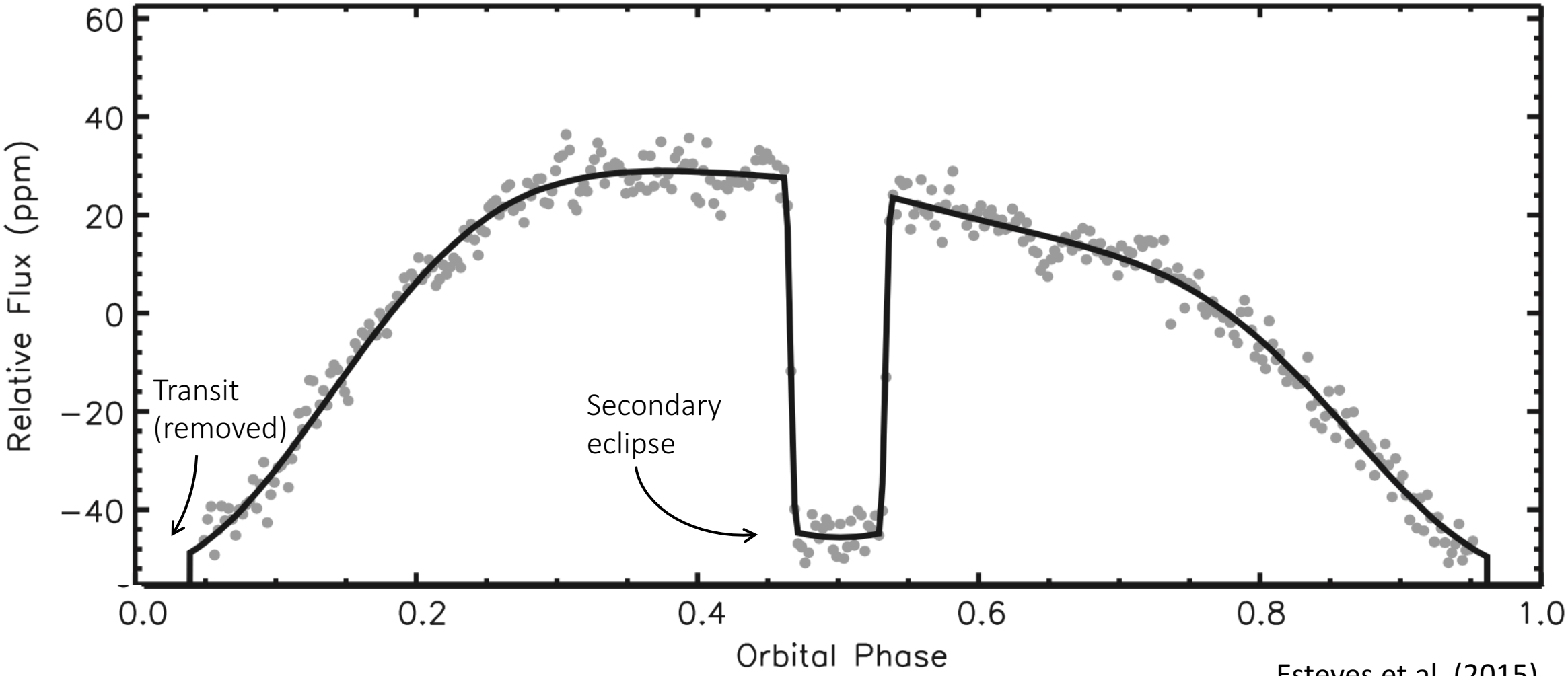
$M_p = 0.7\ M_{\rm Jup}$

$R_p = R_{\rm Jup}$

$i = 85°$

$A_g = 0.1$

HAT-P-7b (again)

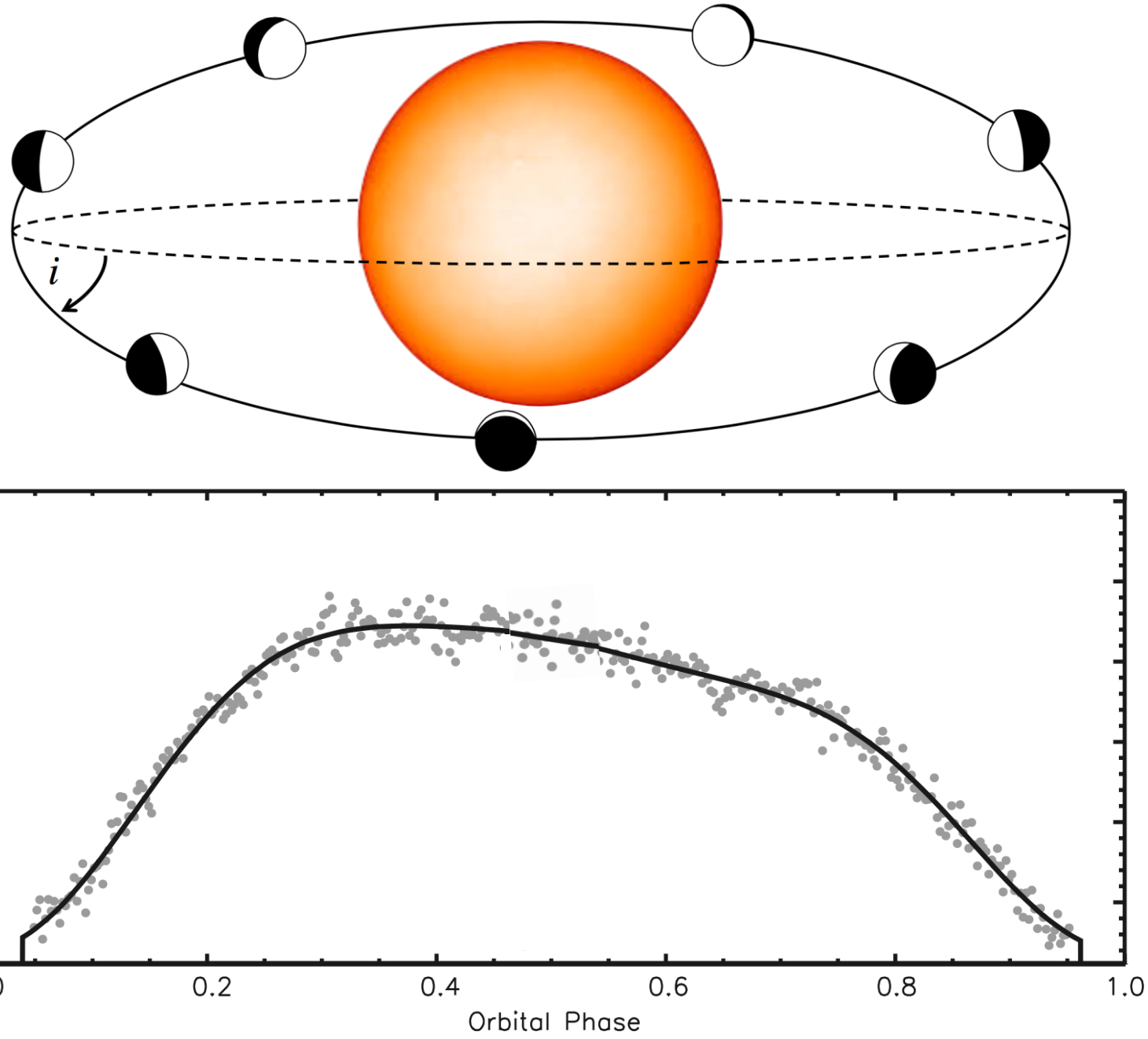


Esteves et al. (2015)

Motivation & Goals

Motivation

1. Phase curves are probes of a wide range of planet atmospheric properties.
2. There are only ~15 planets with well-characterized optical phase curves.
3. Expand the search to non-transiting planets.


i
60
40
20
0
−20
−40
Relative Flux (ppm)
0.0
0.2
0.4
0.6
0.8
1.0
Orbital Phase

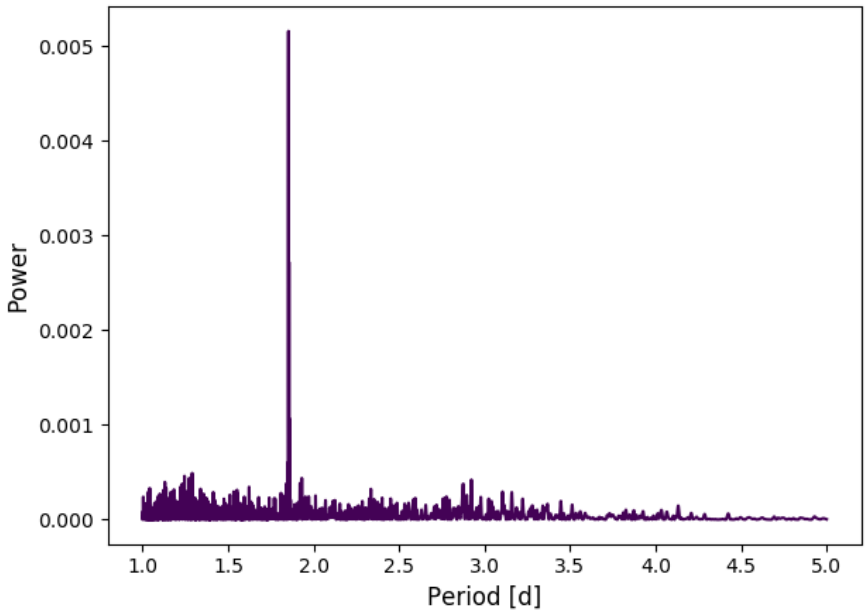
Goal

Perform a systematic search through Kepler light curves to detect the optical phase curves of non-transiting planets.

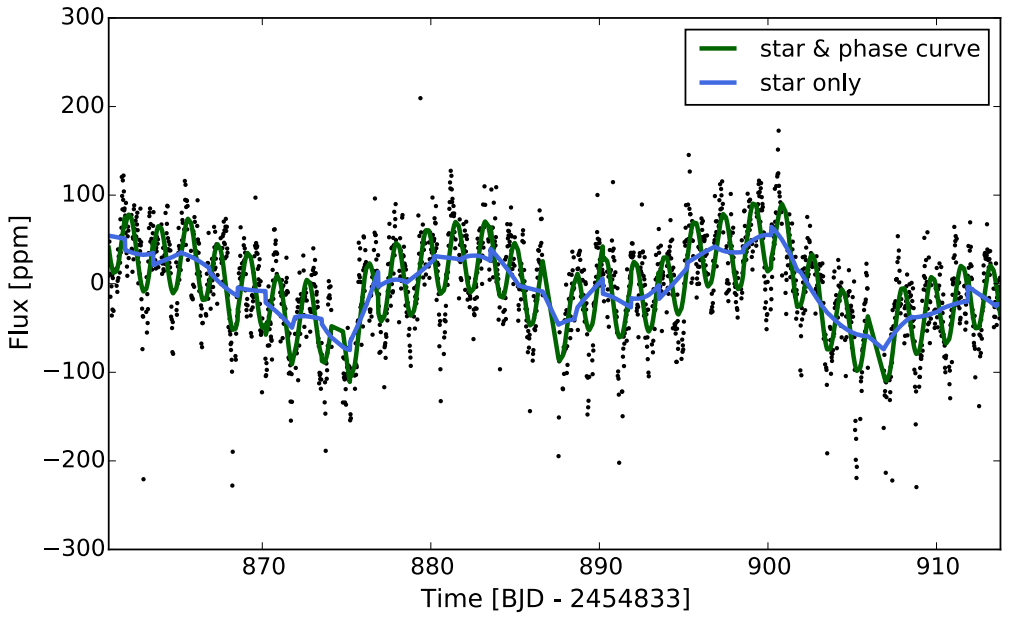
Methodology

Part 1: Identification
Identify candidate phase curves in Kepler light curves

Periodogram search

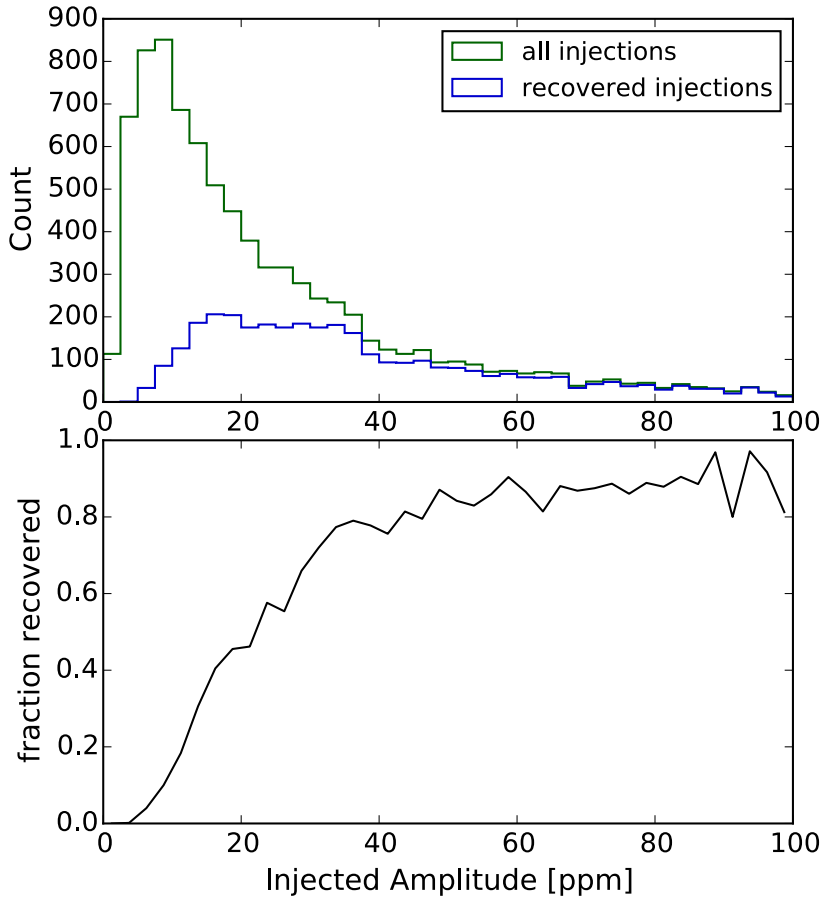


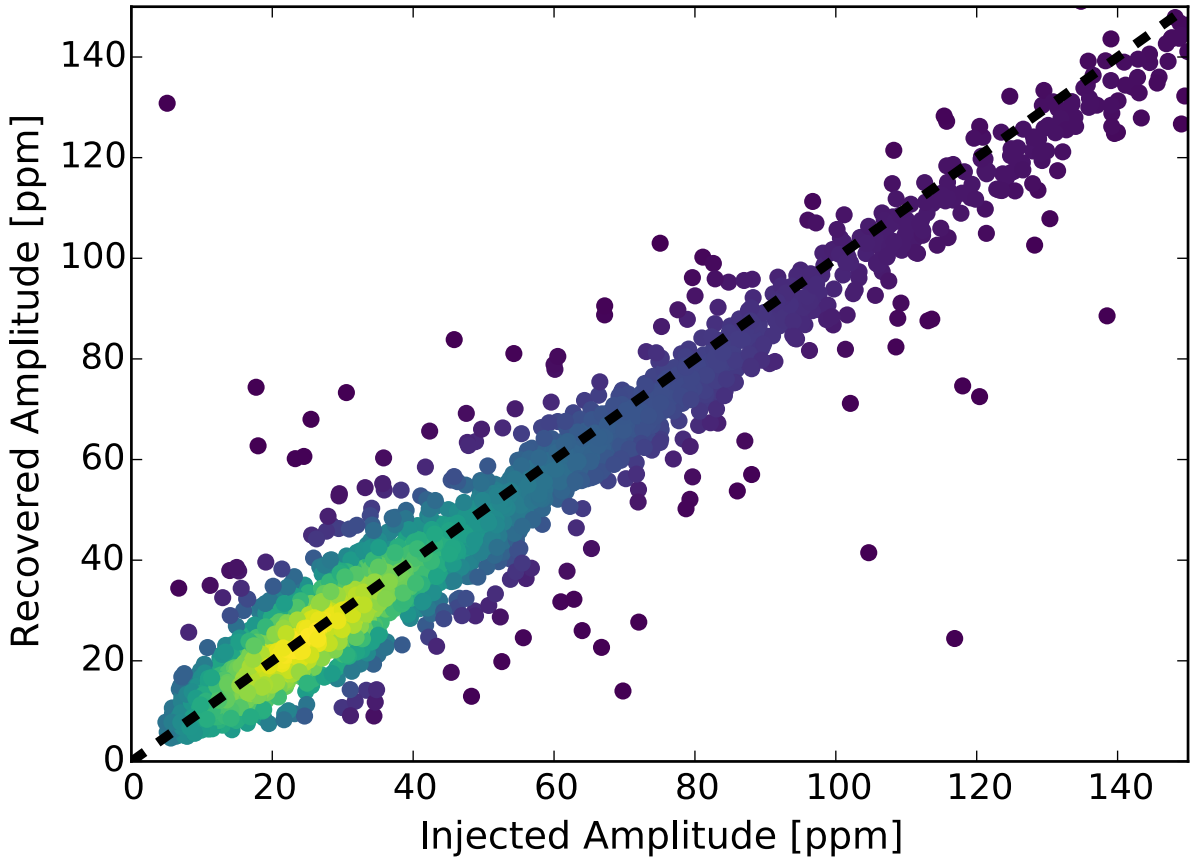
Phase curve fitting



Millholland & Laughlin (2017, submitted)

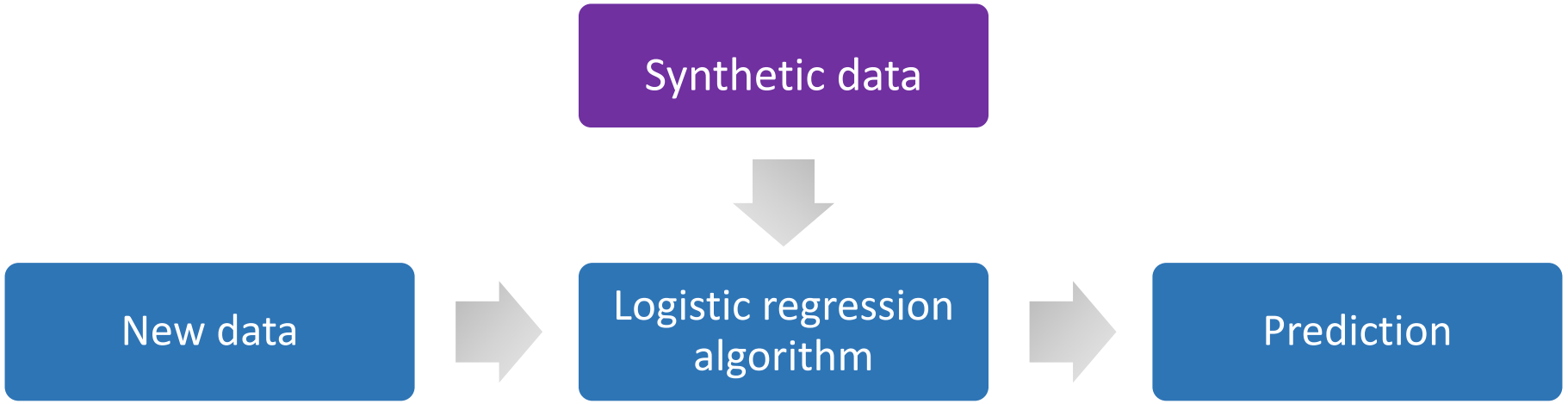
Synthetic phase curve injection & recovery



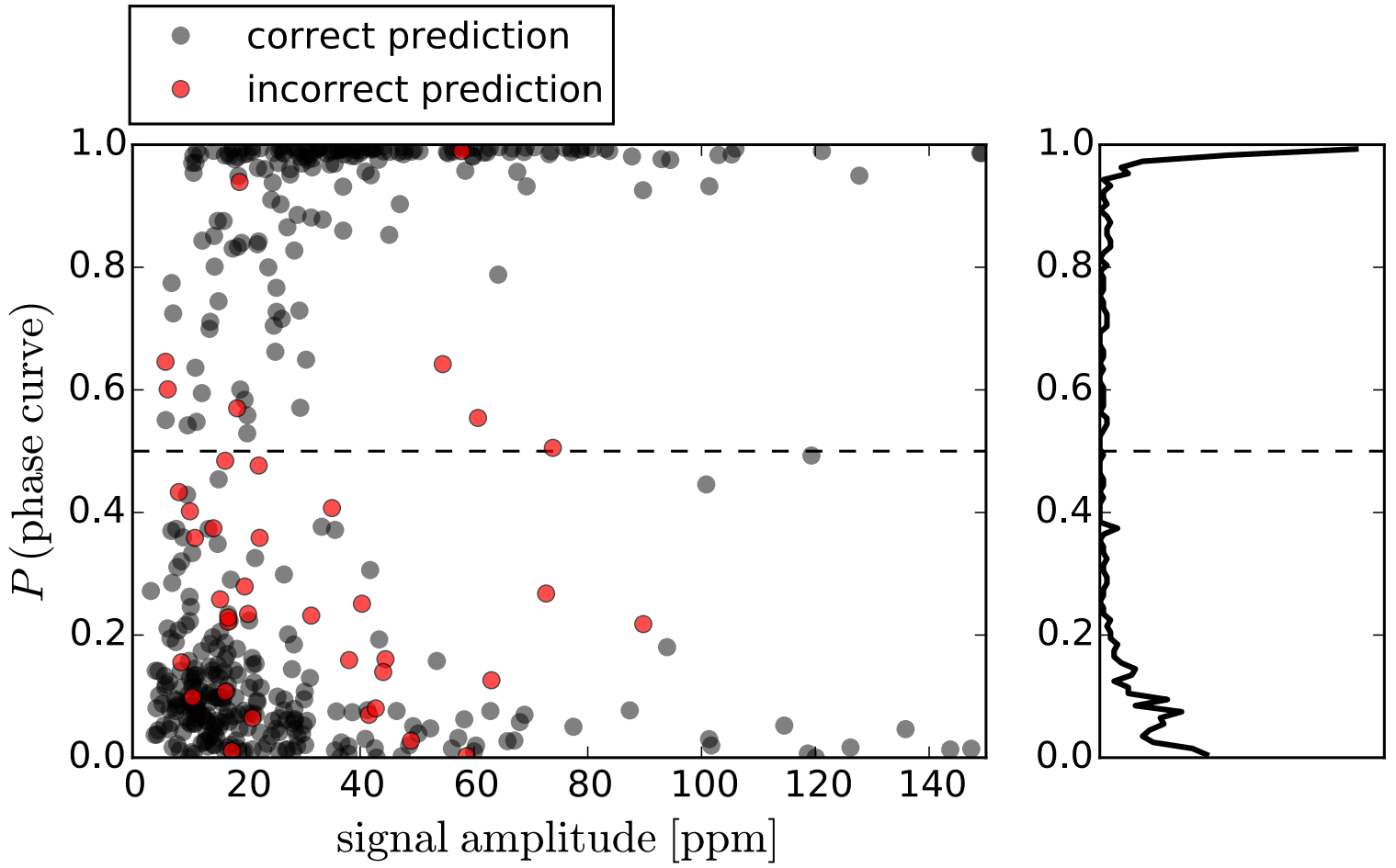


Part 2: Classify signals using a logistic regression supervised machine learning algorithm

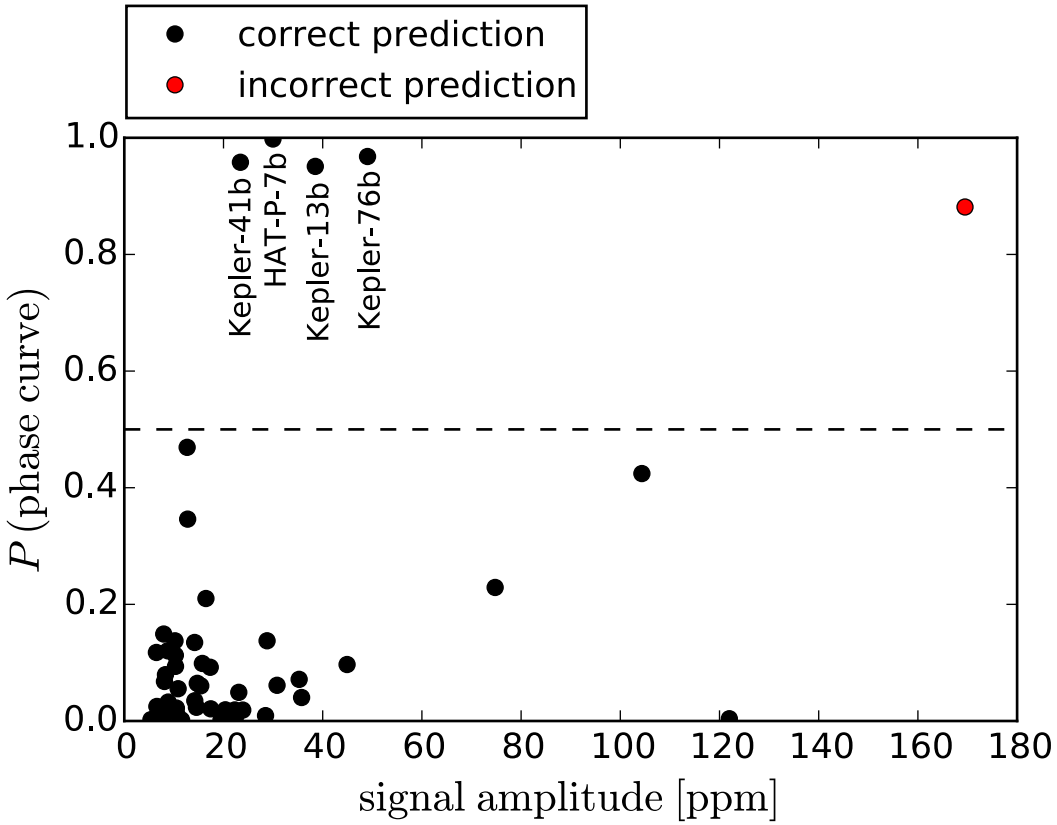
- Question: Is this candidate signal a true planet phase curve? (Yes/No)
- Predictors:
  - E.g. signal coherence, significance of other periods in the periodogram, etc.
- Regress on synthetically generated phase curves "learning"
- Predict phase curve existence in new light curves



Train and test on synthetic phase curve data

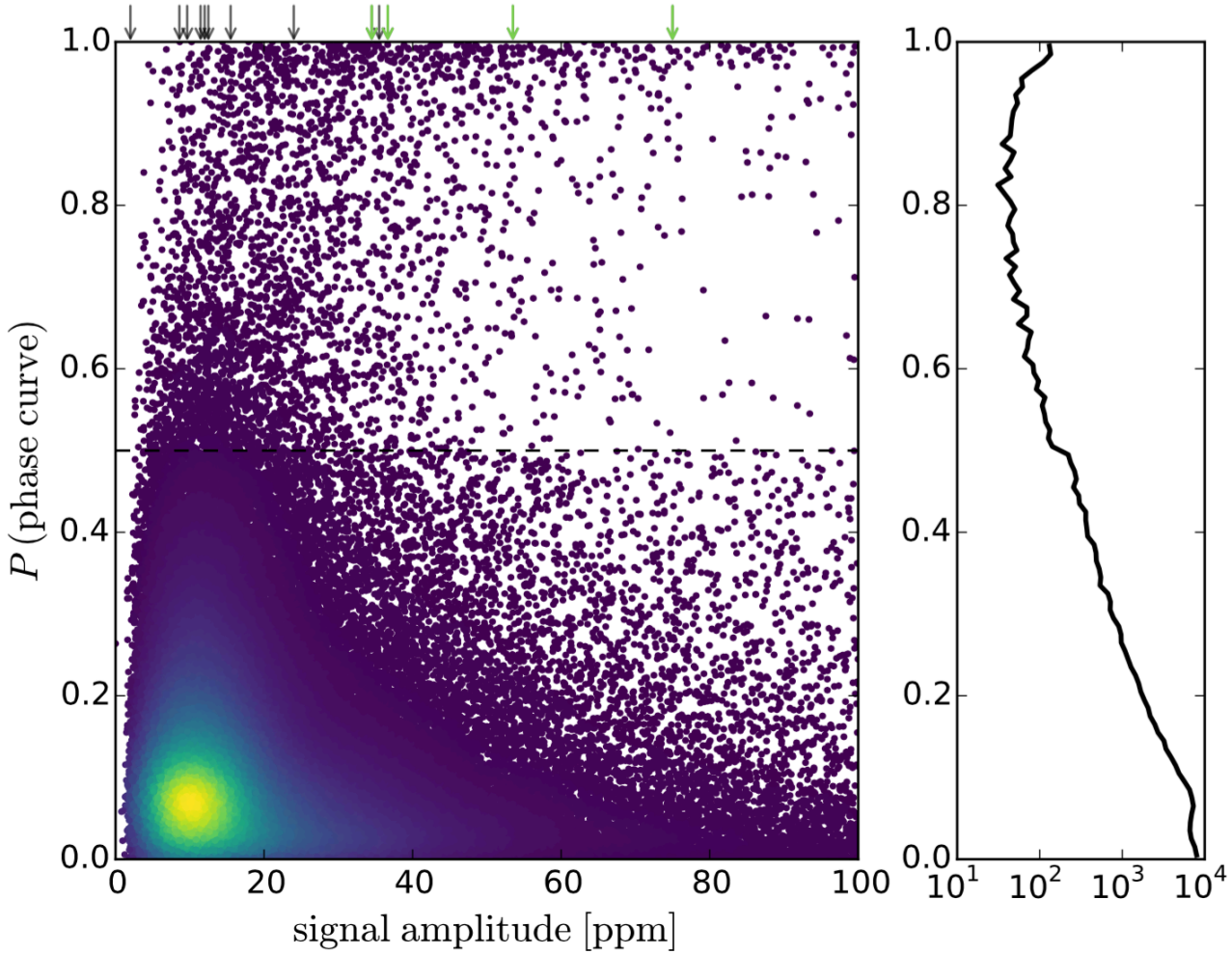


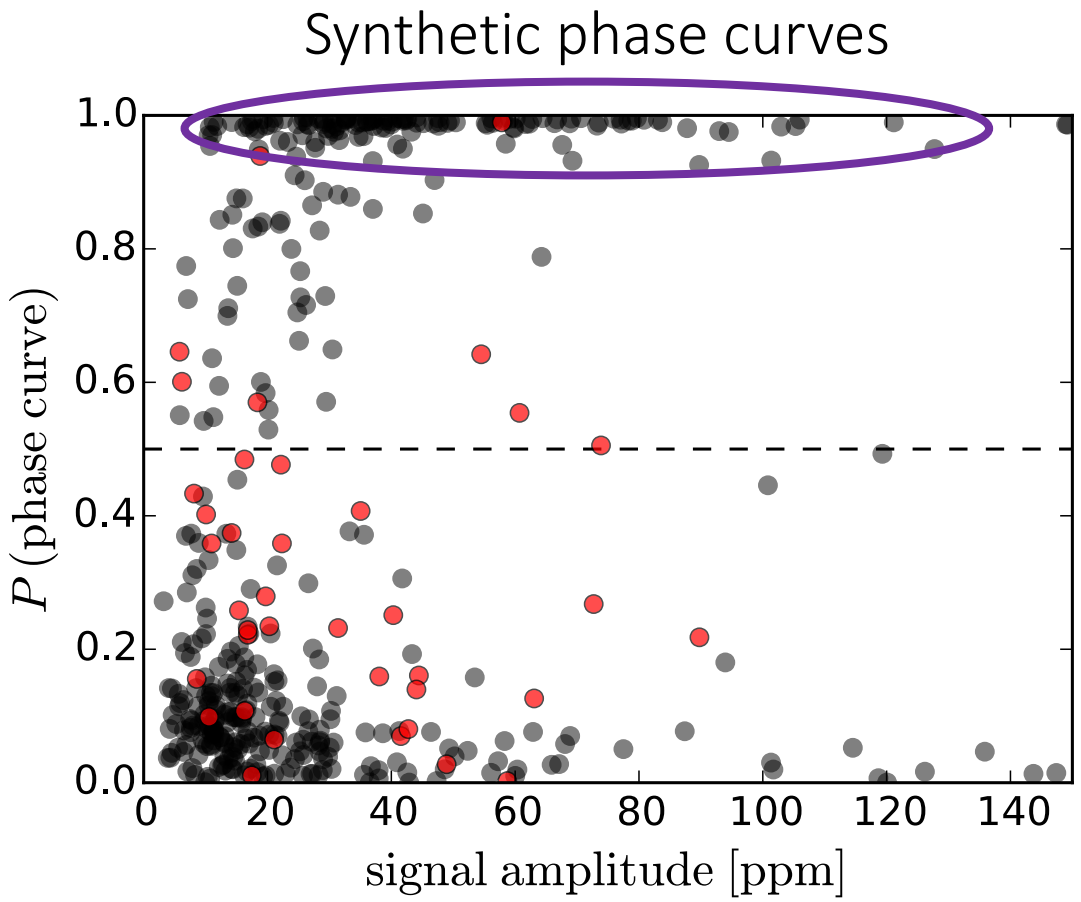
Test on known transiting hot Jupiters

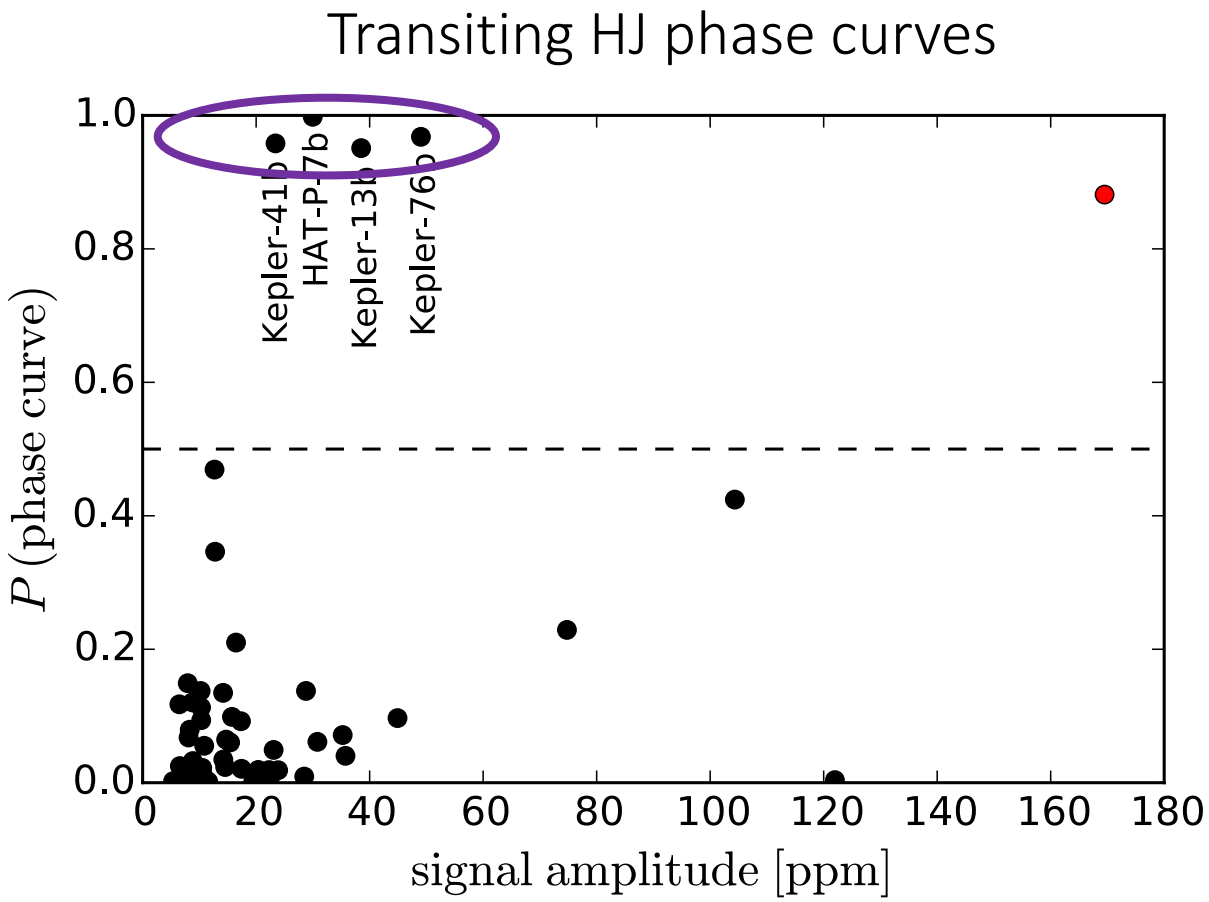


Application to *Kepler* FGK Stars

Application to *Kepler* FGK stars without KOIs

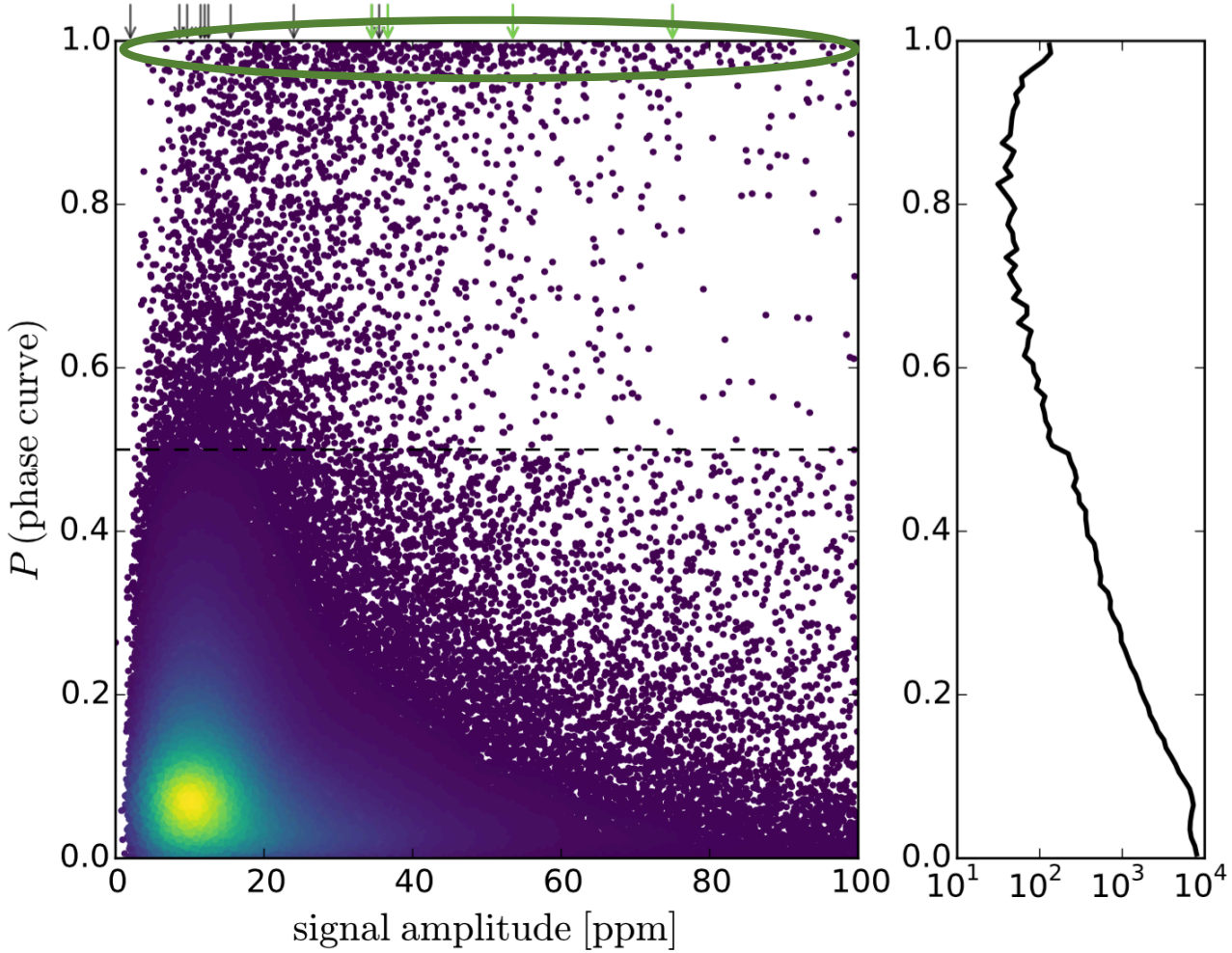






Focus on candidates with large probabilities

Application to *Kepler* FGK stars without KOIs

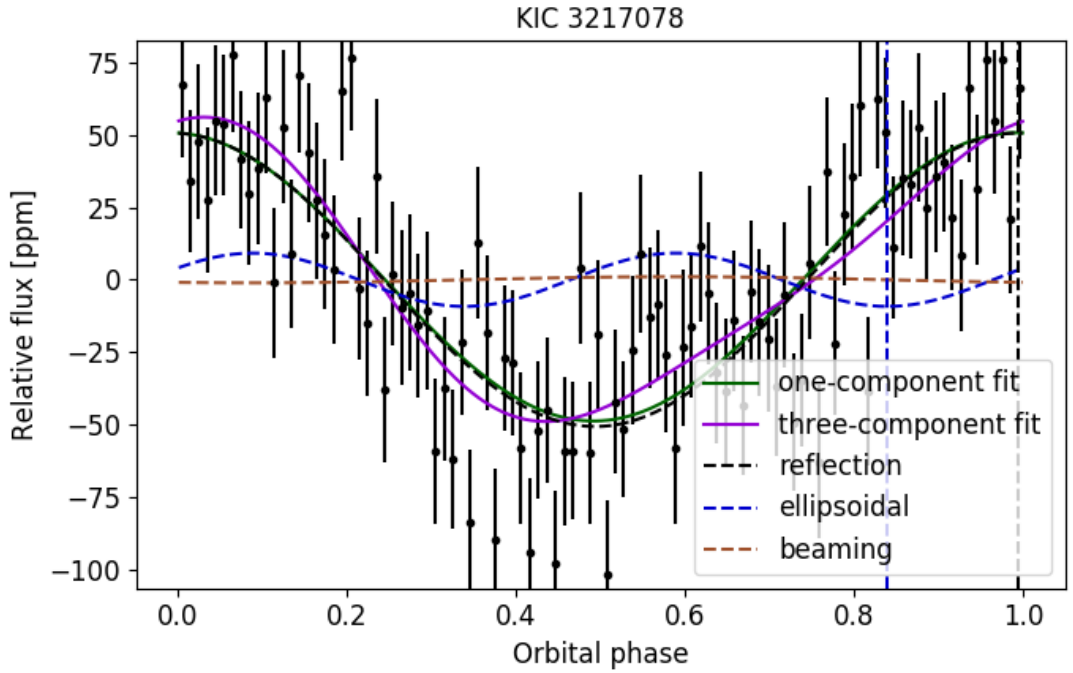


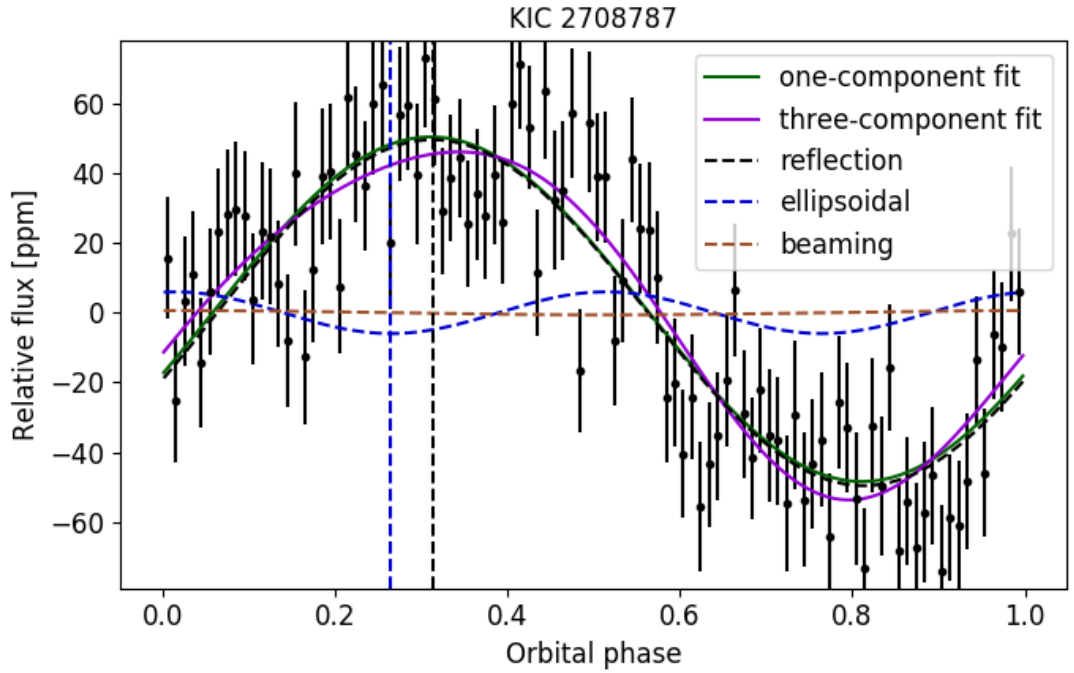
Sixty high probability planet candidates

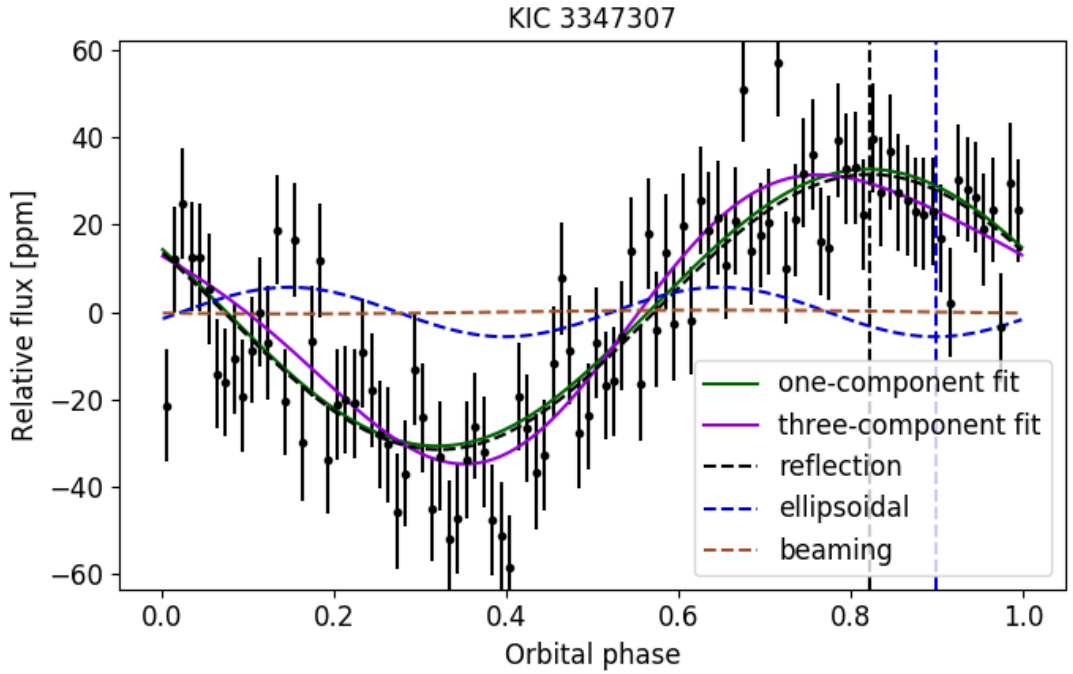
Table 2. A catalog of 60 high probability non-transiting hot Jupiter candidates

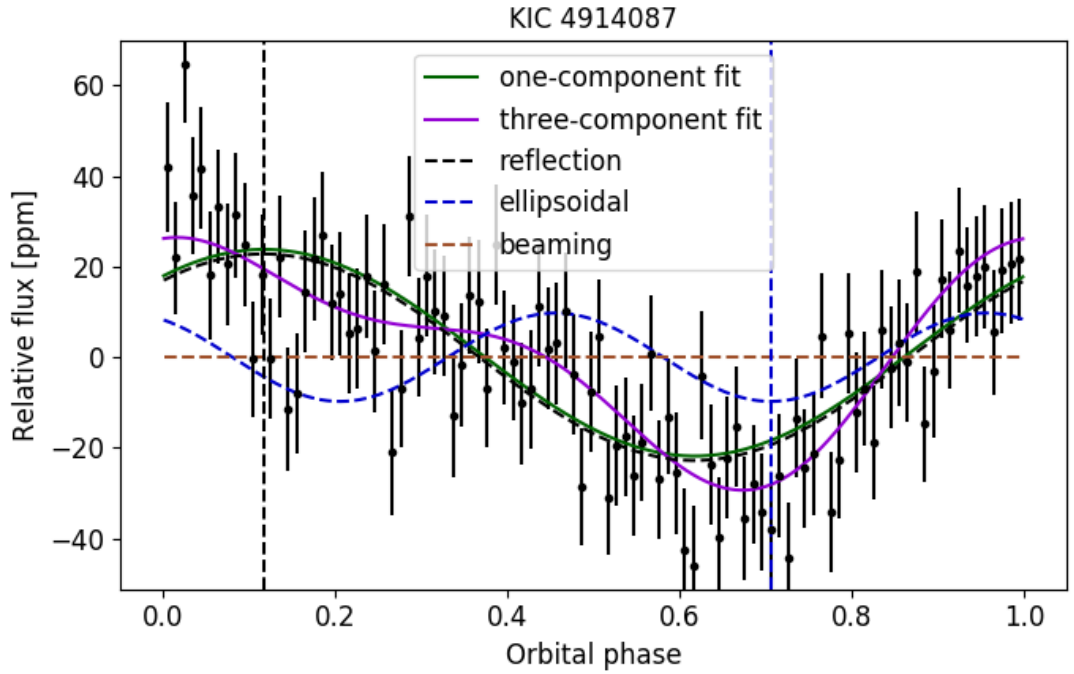
KIC	K_p	$T_{\rm eff}$ [K]	$R_\star$ [$R_\odot$]	$M_\star$ [$M_\odot$]	Fe/H	P [days]	$A_{\rm refl}$	$A_{\rm ellip}$	$K \sin i$ [m/s]	Prob
2706947	13.7	6771	1.29	1.15	-0.44	2.5762±0.0018	48.0	3.9	150±144	0.981
2708787	15.1	4243	0.63	0.62	-0.12	1.8296±0.0008	49.6	6.0	326±188	0.987
3217078	15.7	4780	0.77	0.75	0.14	1.8530±0.0008	50.7	9.2	389±200	0.984
3347307	14.6	5955	0.91	1.00	-0.16	1.8329±0.0008	31.5	5.7	251±248	0.992
3539728	15.3	6075	0.97	1.05	-0.12	1.6002±0.0006	42.9	8.1	257±268	0.982
3964318	14.1	4544	0.64	0.71	-0.08	1.7412±0.0007	28.0	2.3	133±108	0.977
4753174	14.3	6592	1.19	1.21	-0.12	1.6850±0.0008	47.4	2.2	55±63	0.981
4914087	15.0	5505	0.88	0.83	-0.18	2.2909±0.0017	22.8	9.8	496±372	0.984

Millholland & Laughlin (2017, submitted)


KIC 3217078
Relative flux [ppm]
Orbital phase
one-component fit
three-component fit
reflection
ellipsoidal
beaming


KIC 2708787
Relative flux [ppm]
Orbital phase
one-component fit
three-component fit
reflection
ellipsoidal
beaming


KIC 3347307
Relative flux [ppm]
Orbital phase
one-component fit
three-component fit
reflection
ellipsoidal
beaming


KIC 4914087
Relative flux [ppm]
Orbital phase
one-component fit
three-component fit
reflection
ellipsoidal
beaming

Kepler Non-Transiting Hot Jupiter Candidates

Note: This webpage is best viewed using Google Chrome or Safari.

This repository contains information about non-transiting, short-period, giant planet candidates presented in the following paper: "Supervised Learning Detection of Sixty Non-Transiting Hot Jupiter Candidates," Millholland, S. & Laughlin, G. 2017, AJ, submitted.

The candidates were identified using a logistic regression algorithm in a supervised learning context. The algorithm was trained to recognize the properties of optical, full-phase photometric variations of short-period planets. It was then applied to search for planetary phase curves within lightcurves of Kepler FGK stars without known planets or planet candidates.

Here we provide the details of the 60 planet candidates presented in the paper.
Click here to view/download a CSV catalog of all candidates.
Click on the individual candidate pages below for plots and further information.

KIC 2706947 , RA = 290.01038°, Dec = 37.92576°, Kp = 13.731

KIC 2708787 , RA = 290.44894°, Dec = 37.98871°, Kp = 15.096

KIC 3217078 , RA = 285.78048°, Dec = 38.34582°, Kp = 15.691

KIC 3347307 , RA = 292.73237°, Dec = 38.44221°, Kp = 14.554

KIC 3964318 , RA = 294.08643°, Dec = 39.04128°, Kp = 14.144

KIC 4753174 , RA = 293.64125°, Dec = 39.8735°, Kp = 14.316

KIC 4914087 , RA = 288.88971°, Dec = 40.08975°, Kp = 15.041

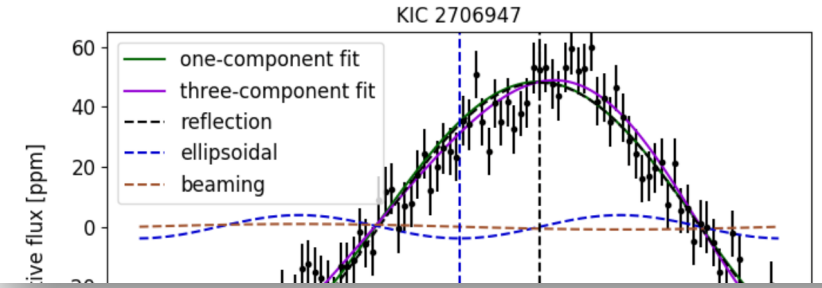
KIC 2706947

Stellar parameters[1]:
RA = 290.0103795°
Dec = 37.92576°
Kp = 13.731
$M_\star = 1.15^{+0.18}_{-0.15}\ M_\odot$
$R_\star = 1.29^{+0.18}_{-0.15}\ R_\odot$
$T_{eff} = 6771^{+188}_{-235}$ K
$Fe/H = -0.44^{+0.25}_{-0.3}$

[1] From the Kepler Stellar Catalog Q1-Q17 DR 25

Candidate planet & phase curve parameters:
P = 2.5762 ± 0.0018 days
A_{refl} = 48.0 ppm
A_{ellip} = 3.88 ppm

Candidate phase curve:

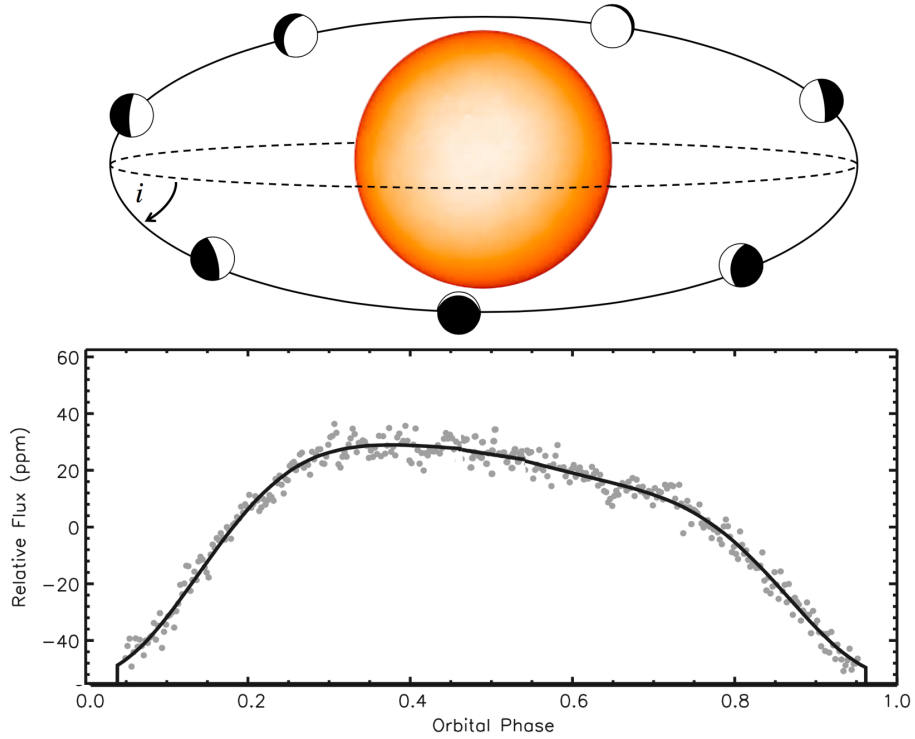


https://smillholland.github.io/Non-transiting_HJs/

Conclusions

Conclusions

1. Optical phase curves can be used a method for the detection of non-transiting planets.



Conclusions

1. Optical phase curves can be used a method for the detection of non-transiting planets.
2. I used a supervised machine learning algorithm to detect sixty non-transiting hot Jupiter candidates.

Table 2. A catalog of 60 high probability non-transiting hot Jupiter candidates

KIC	K_p	$T_{\rm eff}$ [K]	$R_\star$ [$R_\odot$]	$M_\star$ [$M_\odot$]	Fe/H	P [days]	$A_{\rm refl}$	$A_{\rm ellip}$	$K \sin i$ [m/s]	Prob
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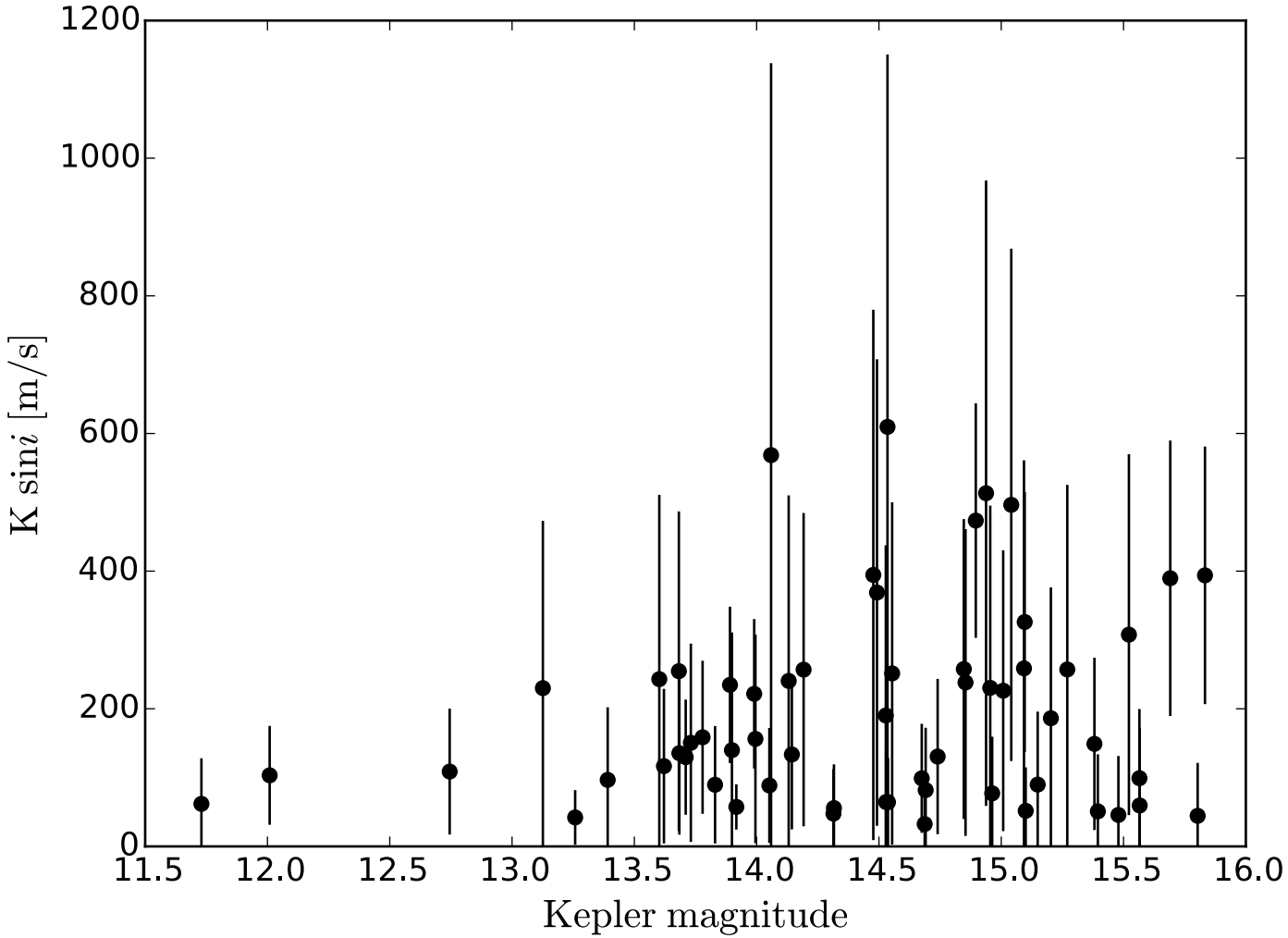
Conclusions

1. Optical phase curves can be used a method for the detection of non-transiting planets.
2. I used a supervised machine learning algorithm to detect sixty non-transiting hot Jupiter candidates.
3. RV follow-up is underway.

Extra Slides

Expected RV semi-amplitudes

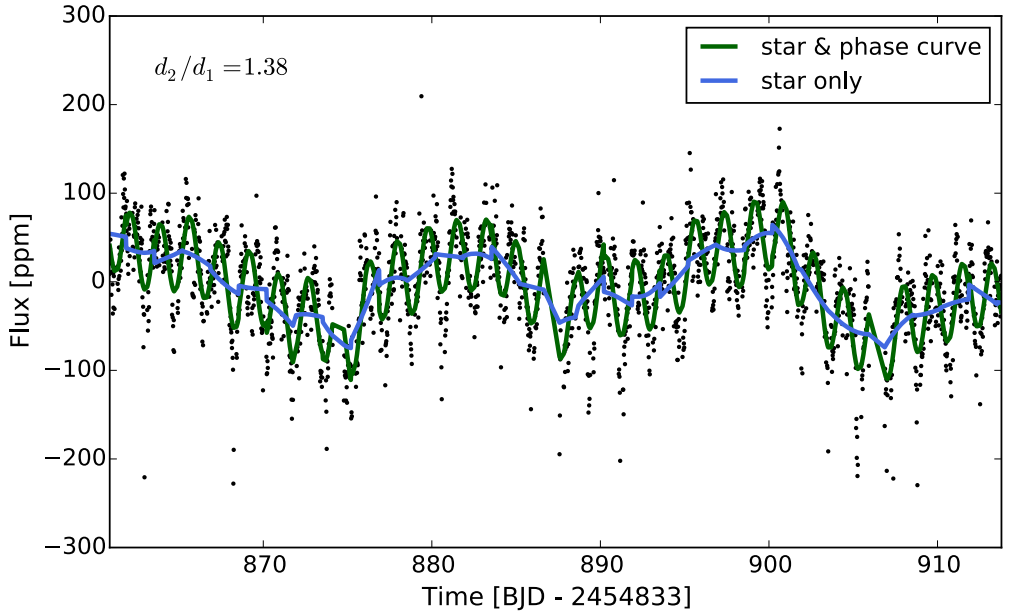


Detecting non-transiting planet phase curves

- Big idea #1: A planetary phase curve is more coherent than other forms of light curve variability.

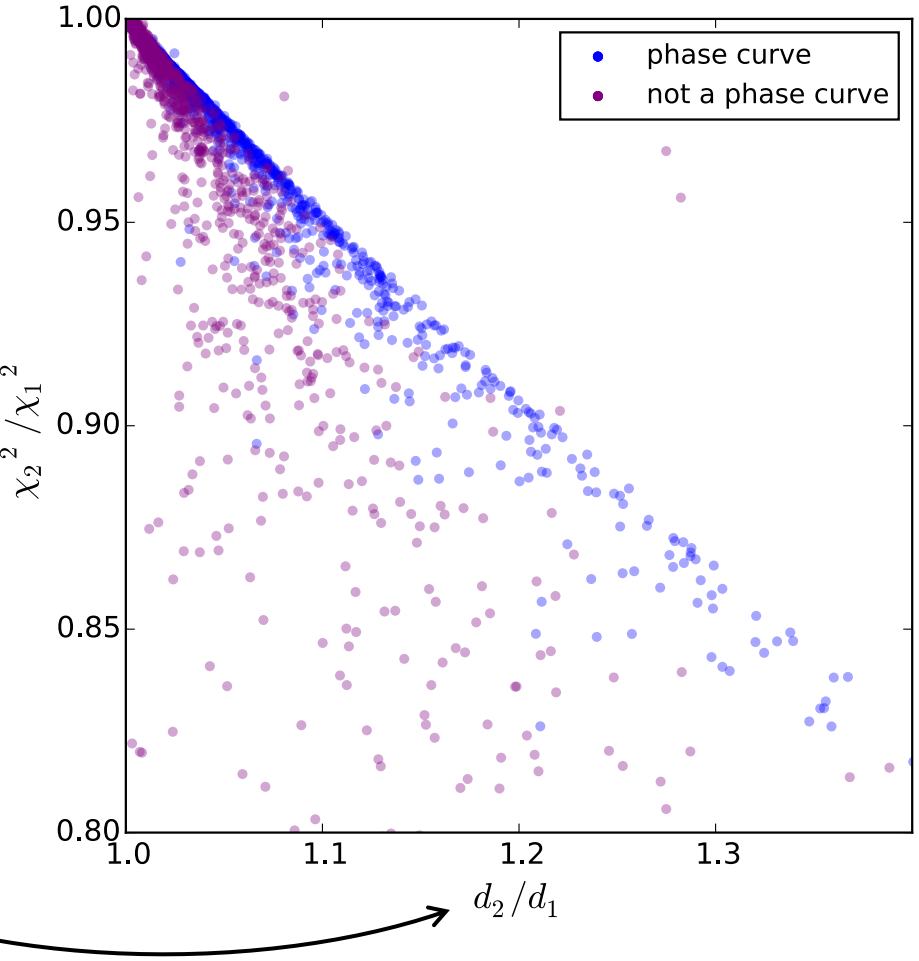
- Big idea #2: We can train an algorithm to recognize the signatures of planetary phase curves. We can then apply the algorithm to search for phase curves in new light curves.

Example predictors: chi-square of the fit and residual autocorrelation

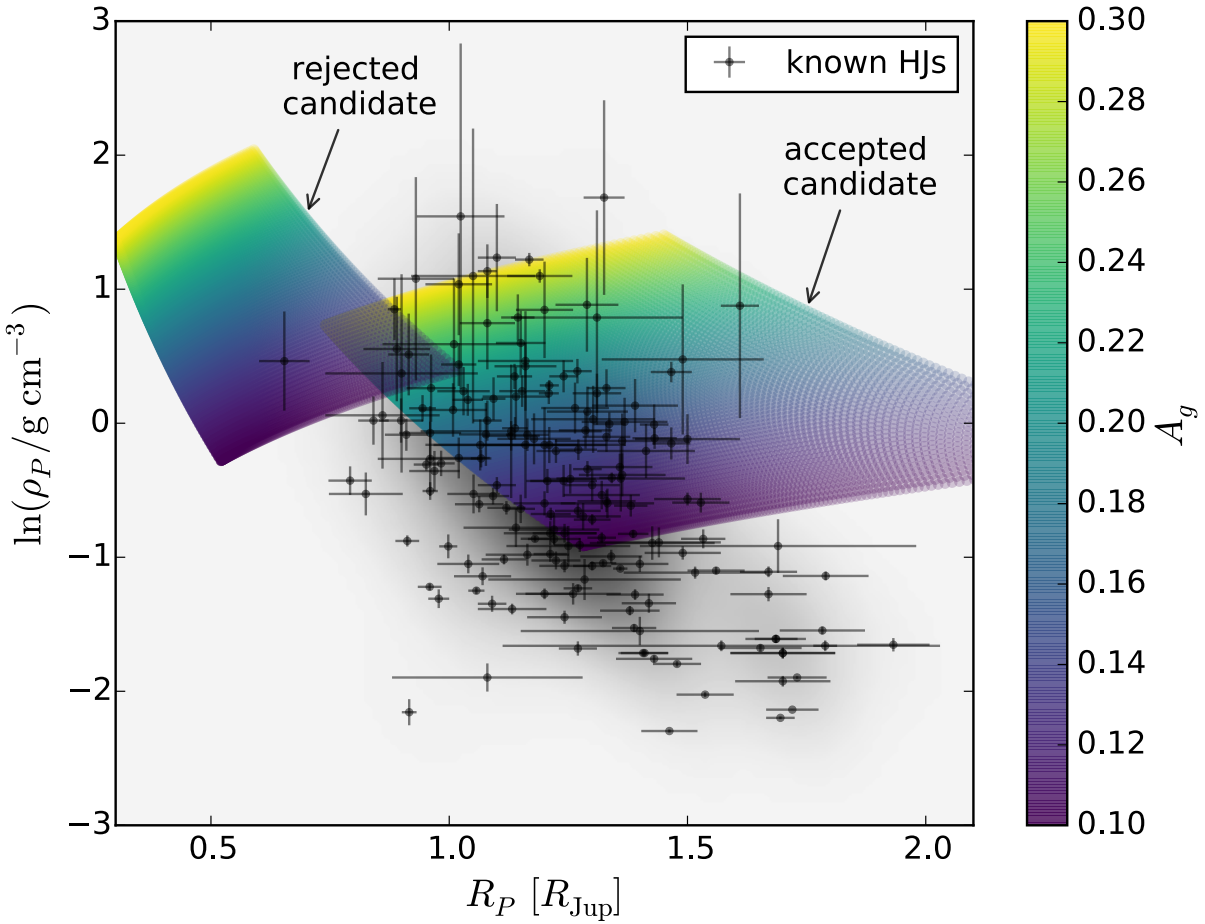


Durbin-Watson statistic

$$d = \frac{\sum_{i=2}^{N} (r_i - r_{i-1})^2}{\sum_{i=1}^{N} r_i^2}$$

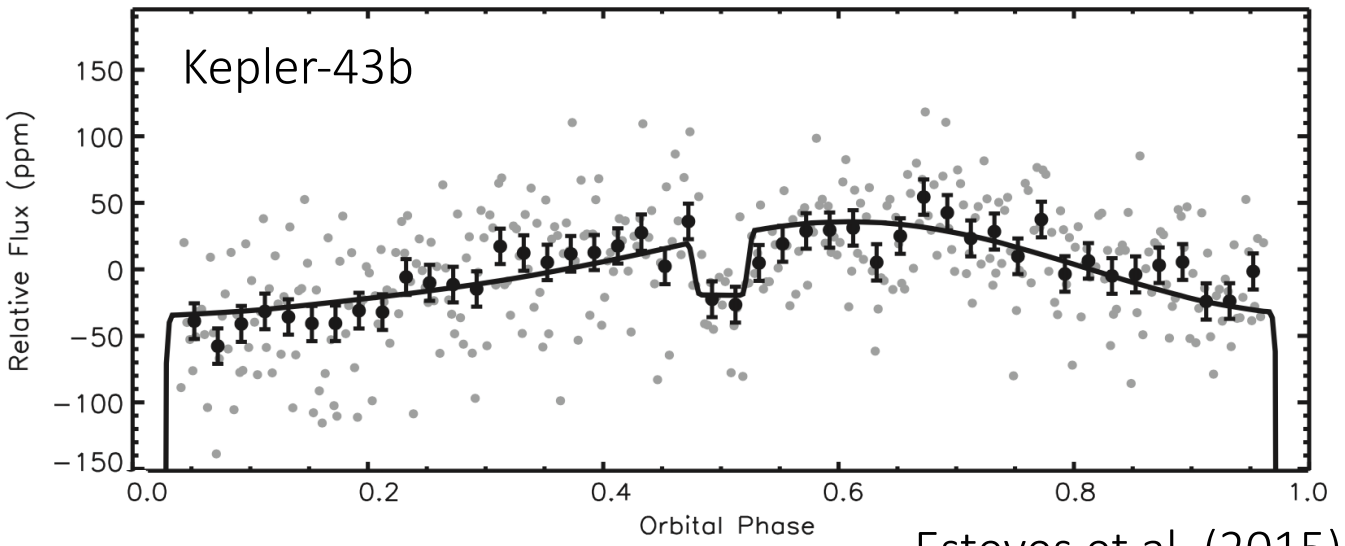


Additional candidate vetting

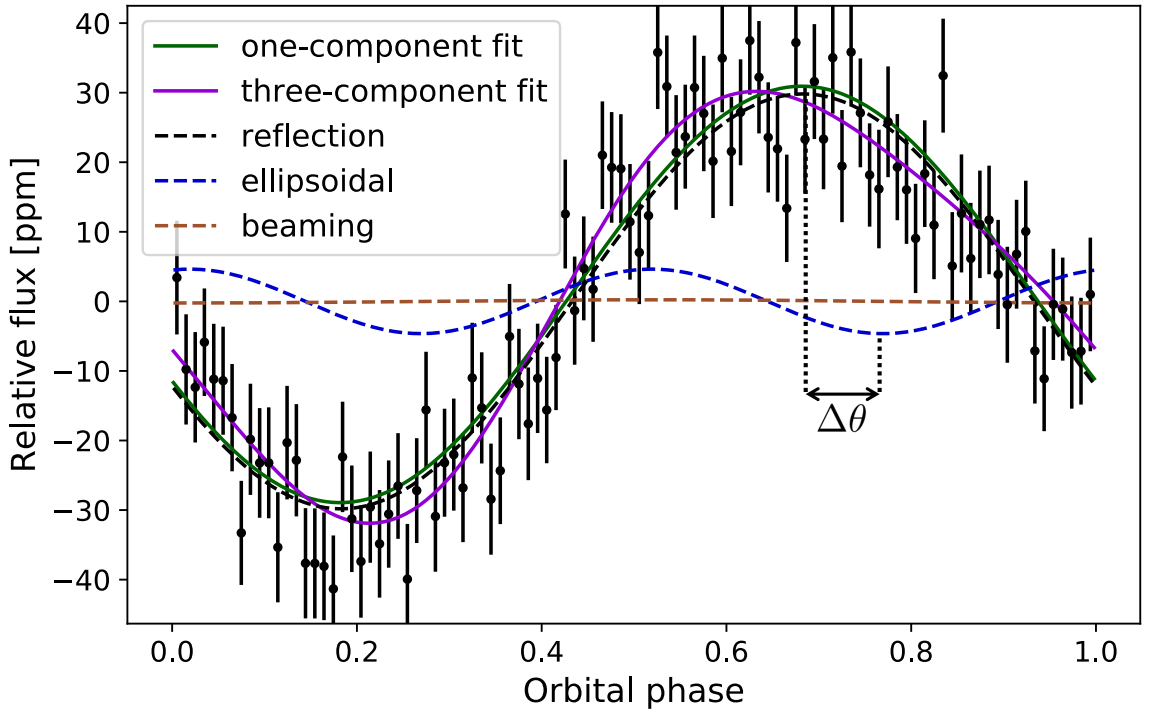


Offsets of the phase curve maxima

Probe of atmospheric dynamics and reflective properties.

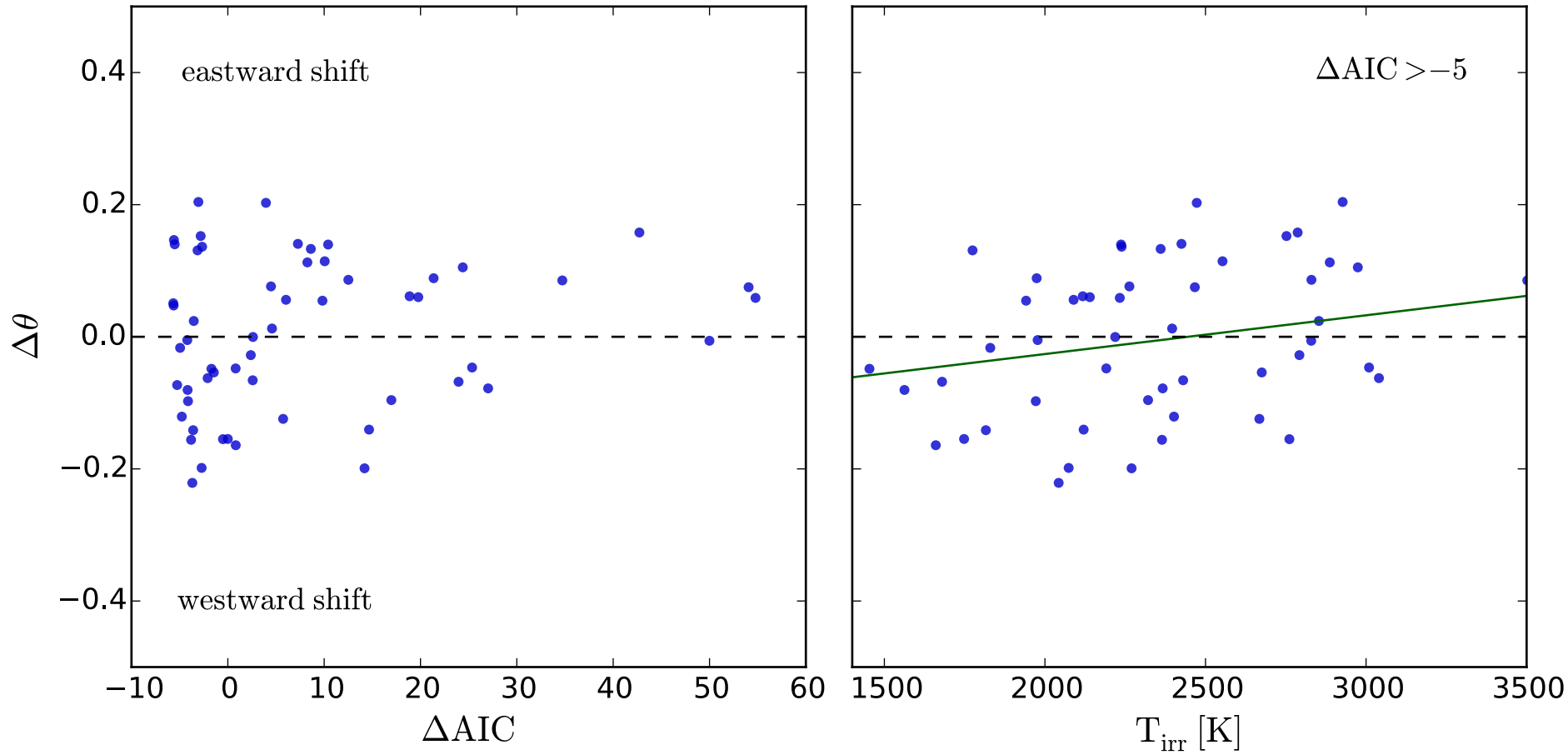


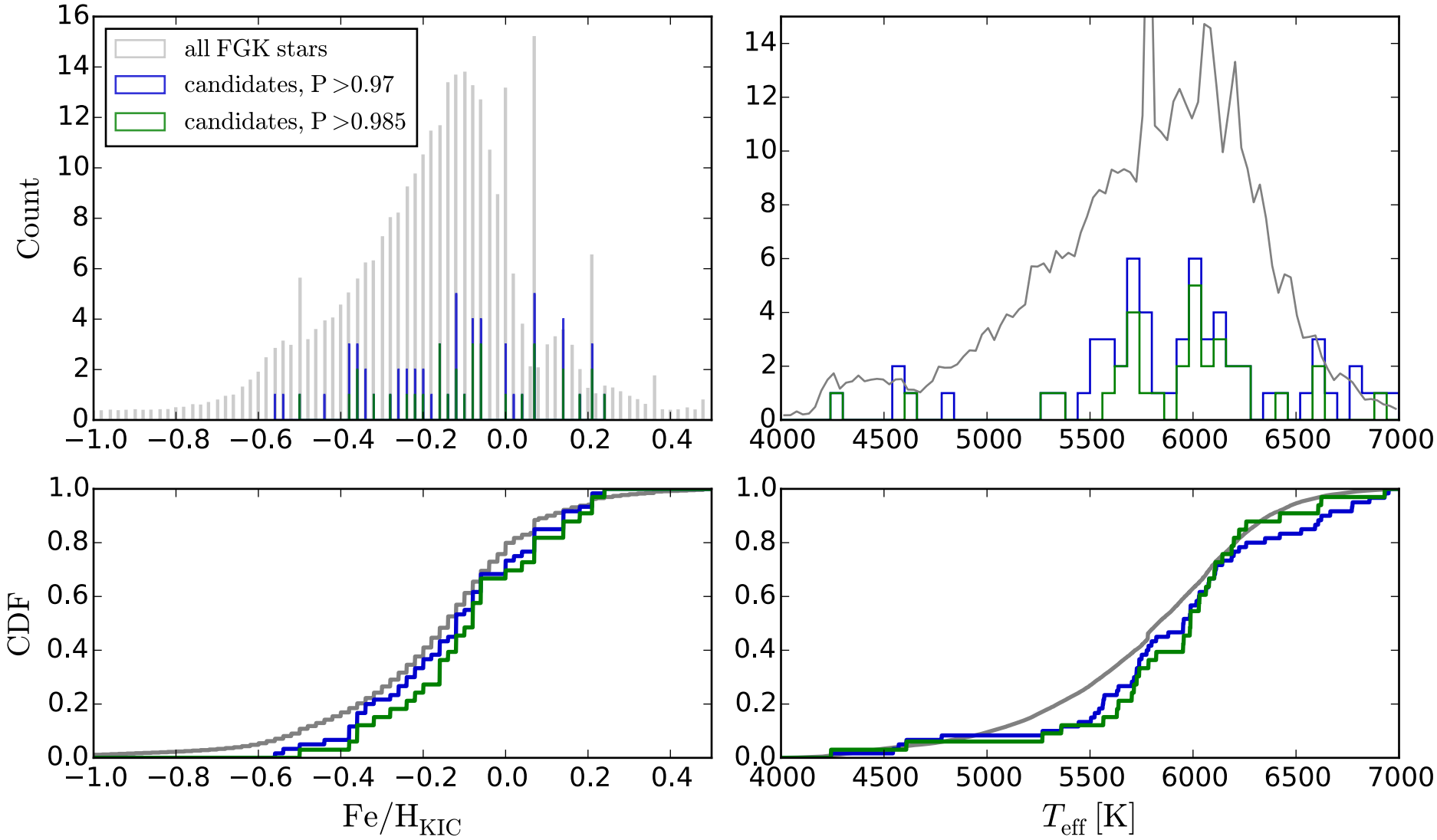
Esteves et al. (2015)

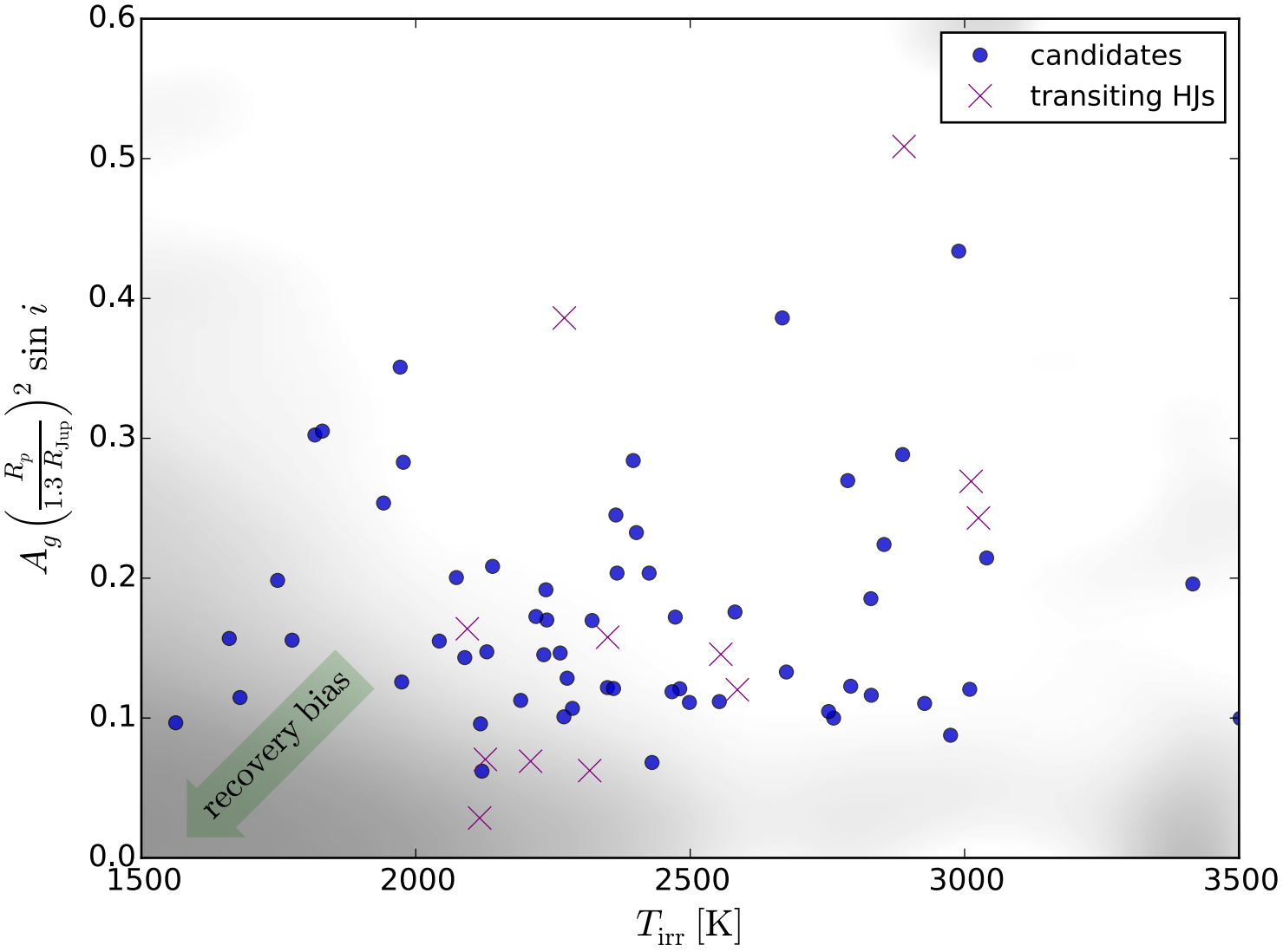


Offsets of the phase curve maxima

Probe of atmospheric dynamics and reflective properties.




all FGK stars
candidates, P >0.97
candidates, P >0.985
Count
CDF
Fe/H$_{\rm KIC}$
$T_{\rm eff}$ [K]


candidates
transiting HJs
recovery bias
$A_g \left(\frac{R_p}{1.3\,R_{\rm Jup}} \right)^2 \sin i$
$T_{\rm irr}$ [K]
0.0
0.1
0.2
0.3
0.4
0.5
0.6
1500
2000
2500
3000
3500