# Properties of Sub-Neptune-Size Planets


## Andrew W. Howard - UC Berkeley

Photometry by: Greg Henry (TSU)

California Planet Search (CPS):
Geoff Marcy, Debra Fischer, John Johnson, Jason Wright, Howard Isaacson, more!

California Kepler Survey (CKS):
Geoff Marcy, John Johnson, Tim Morton, Howard Isaacson

Kepler Team

Photo credit: Laurie Hatch

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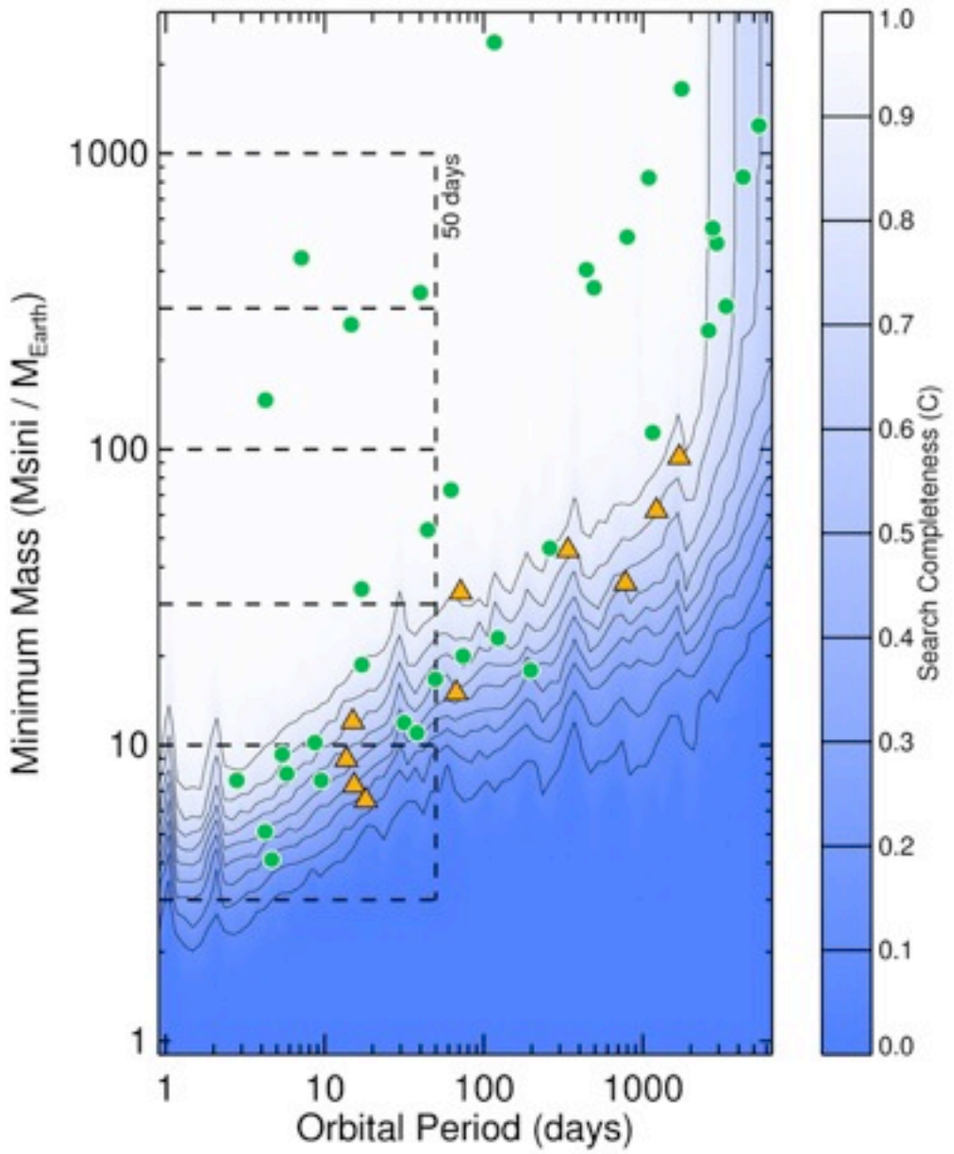
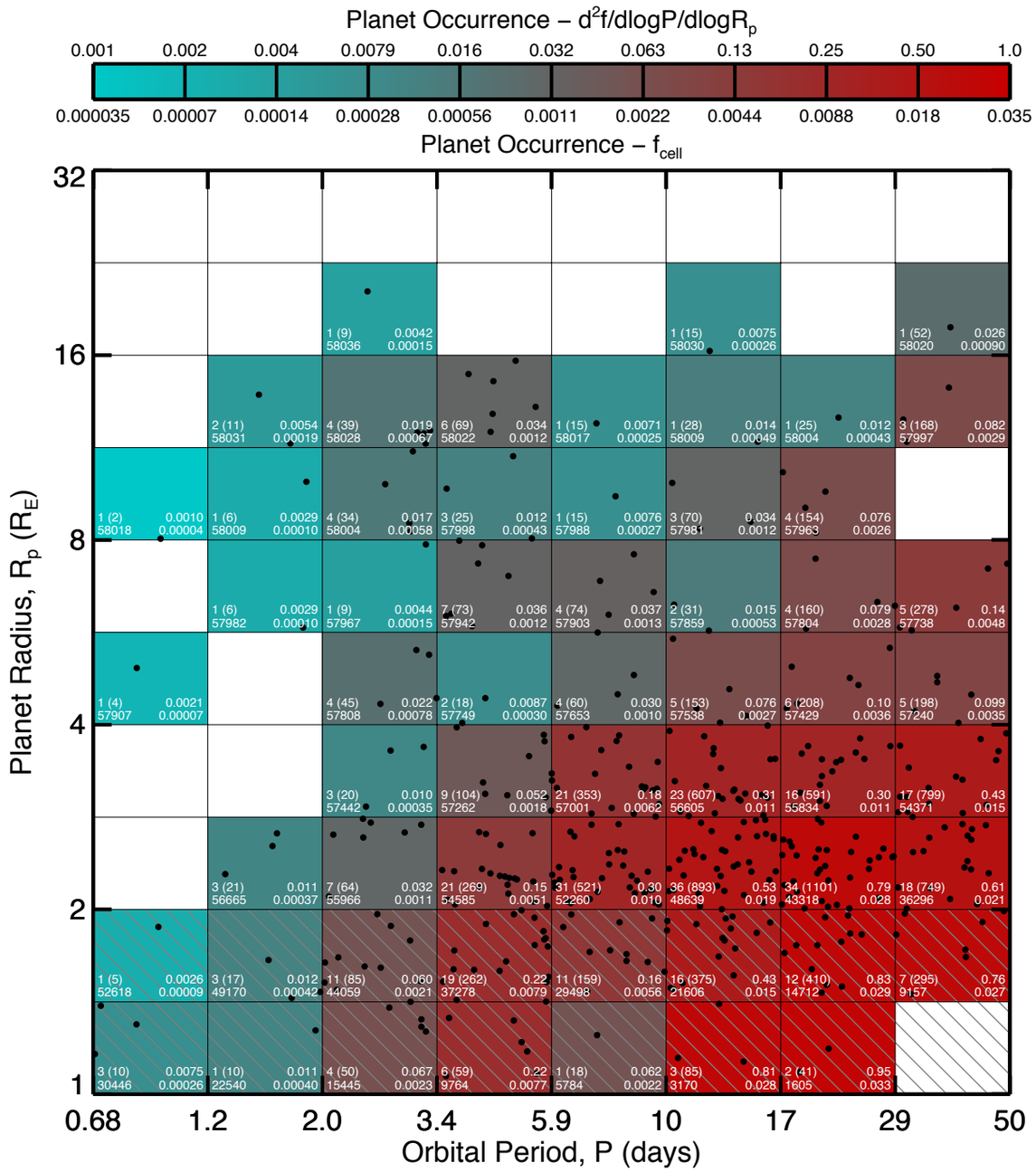
# Planet Occurrence from Doppler and Kepler




Eta-Earth Survey
(NASA/UC/Keck)

Howard et al. 21, Science, 33, 653

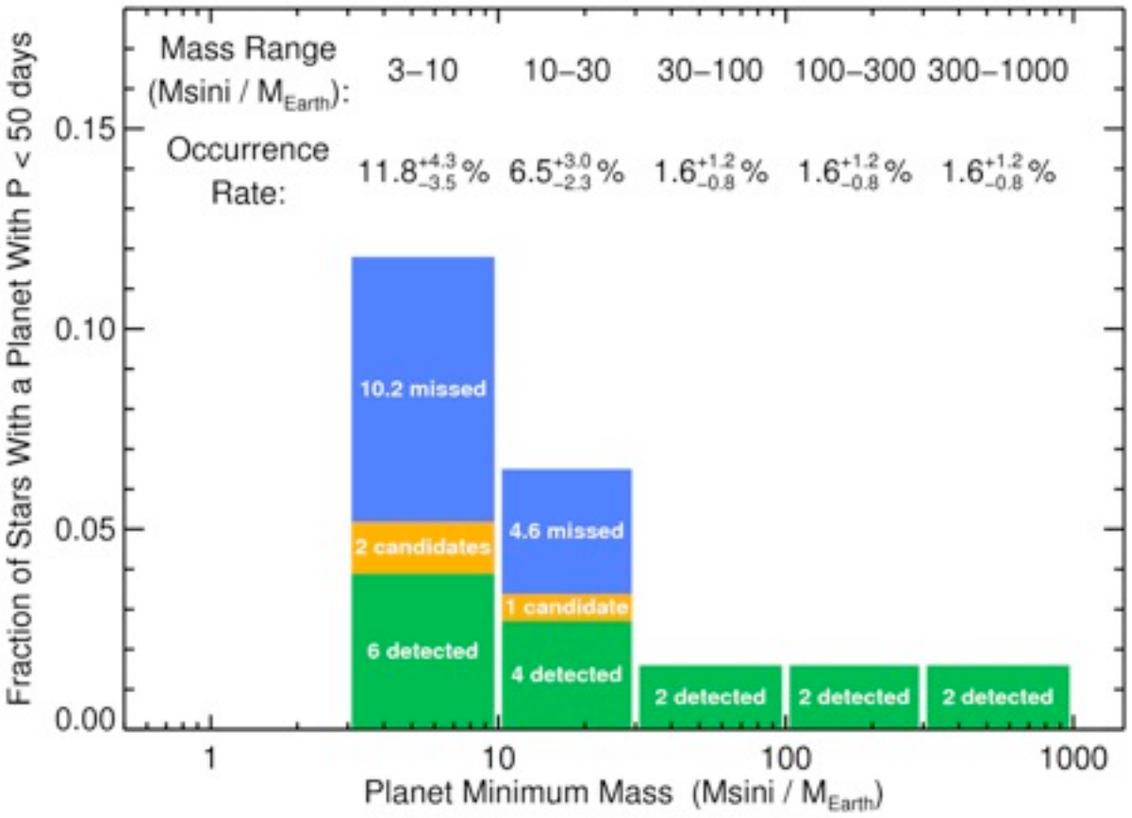



Kepler
(NASA)

Howard et al. 2011c, ApJ submitted, arXiv:1103.2541

# Planet Mass Distribution
# Eta-Earth Survey (*Doppler*)

Howard et al. 21, Science, 33, 653




**Power Law Mass Function**

$df/d\log M = kM^{\alpha}$

$k = 0.39^{+0.27}_{-0.16}$, $\alpha = -0.48^{+0.12}_{-0.14}$

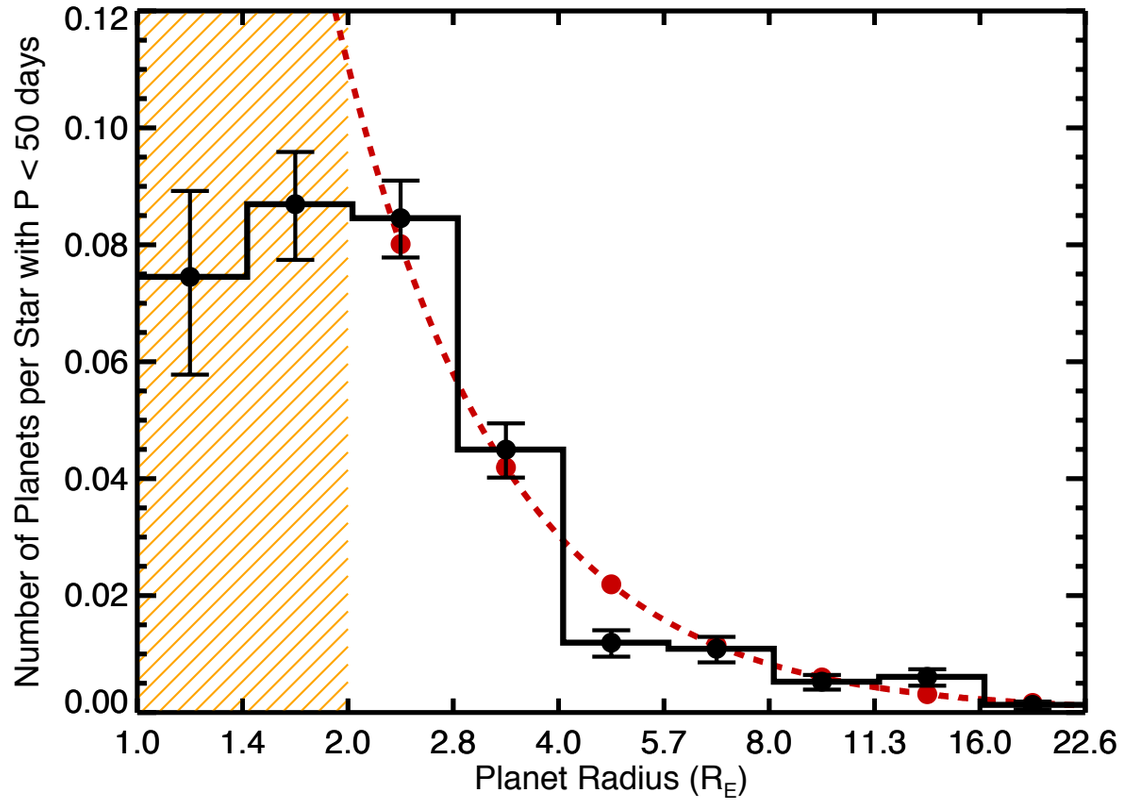
**Extrapolate:**

$\eta_{\mathbf{Earth}} = 23^{+16}_{-10}\%$

$M\sin i = 0.5\text{-}2.0\ M_E$, $P < 50$ days

# Planet Radius Distribution
# *Kepler*

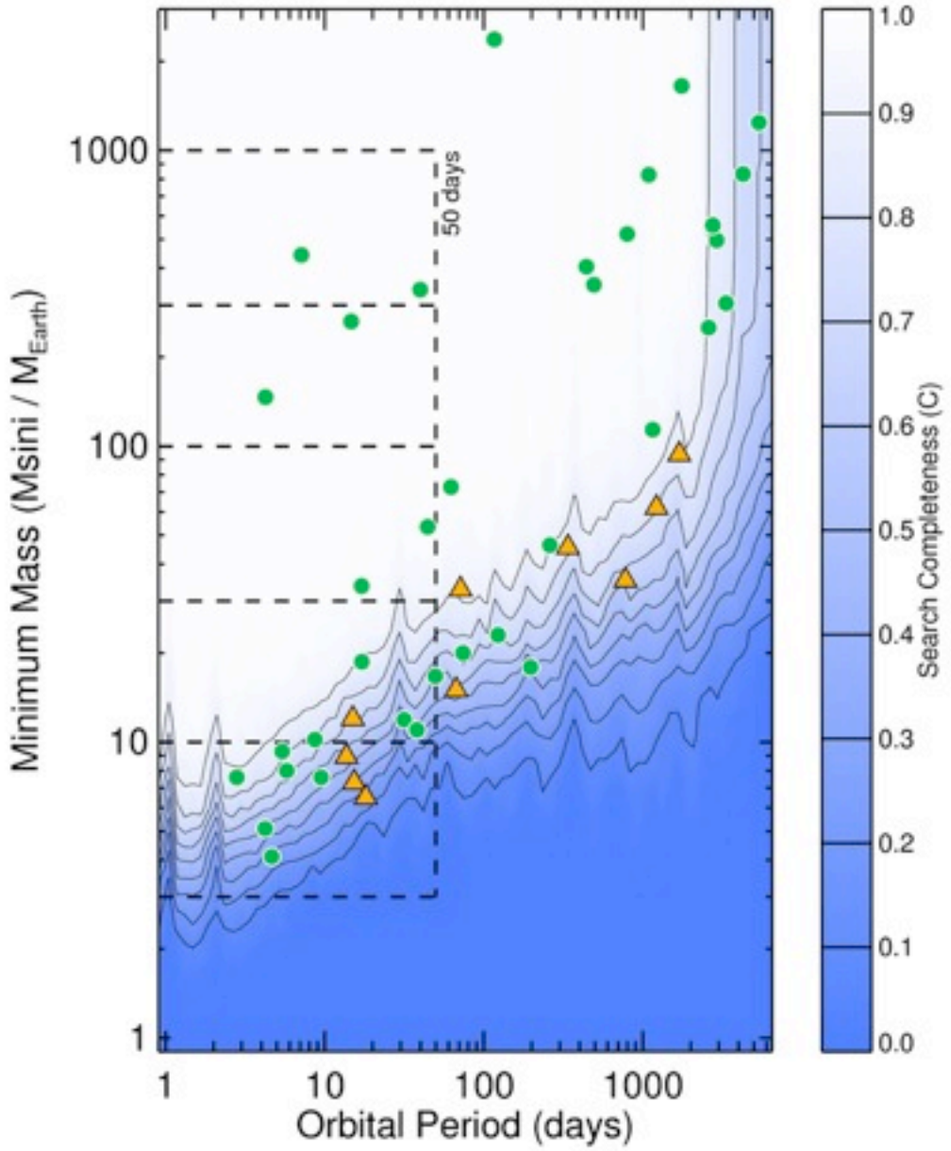
Howard et al. 2011c, ApJ submitted, arXiv:1103.2541




**Power Law Radius Function**

$df/d\log R = kR^{\alpha}$

$k = 2.9 \pm 0.5$, $\alpha = -1.92 \pm 0.11$

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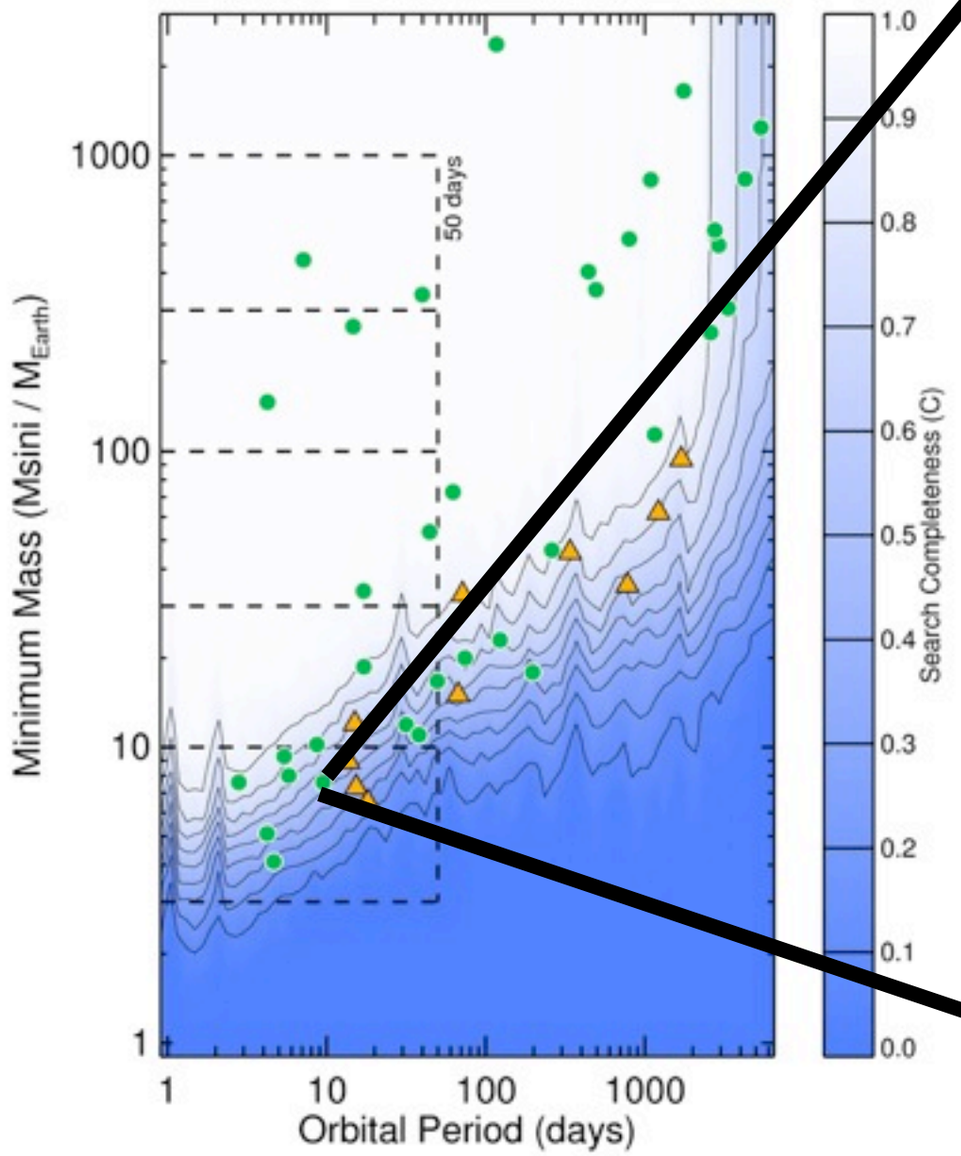
Howard, et al. (2011, ApJ, 731,10)

# HD 97658b - A New Transiting Super-Earth

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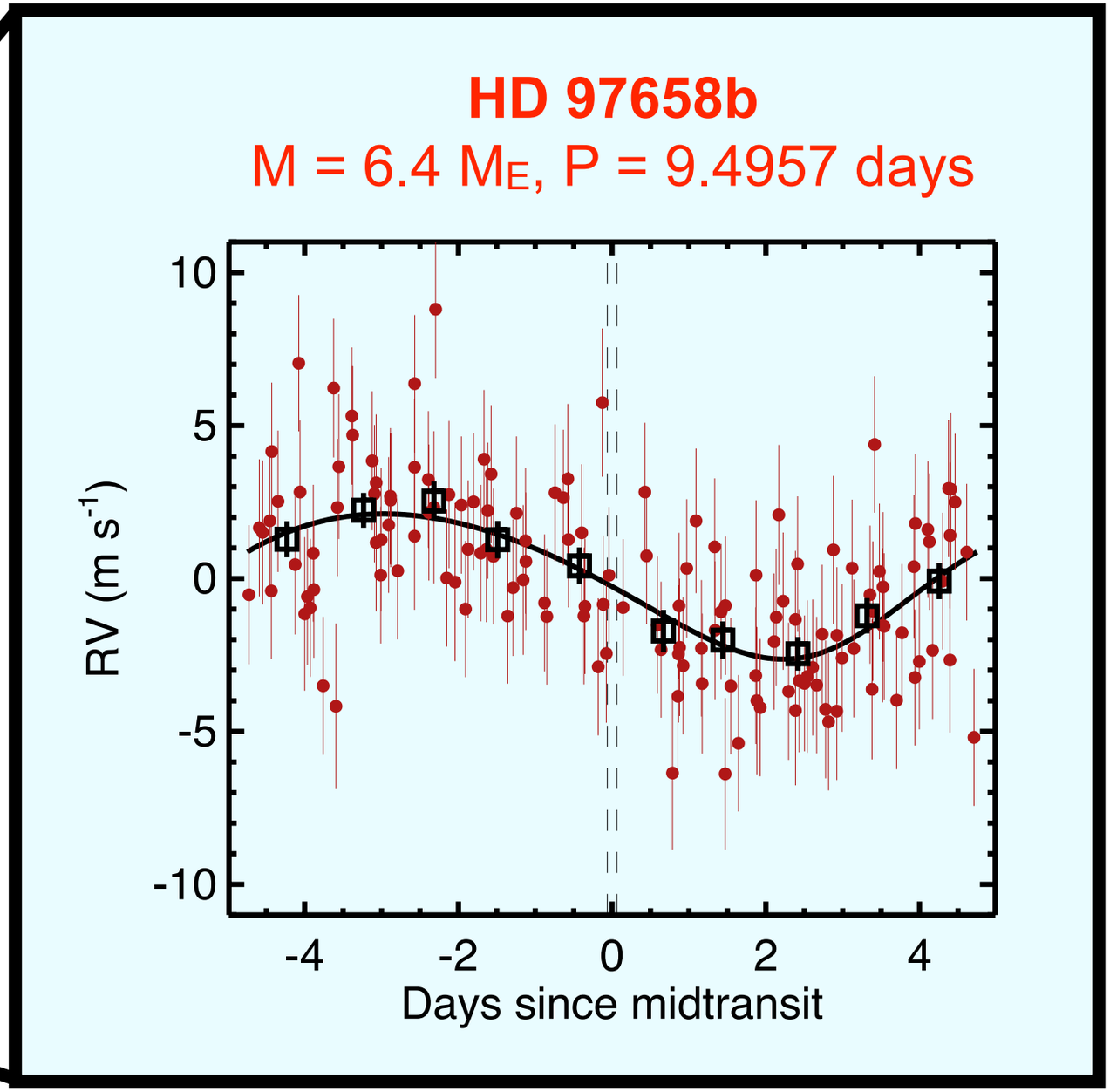
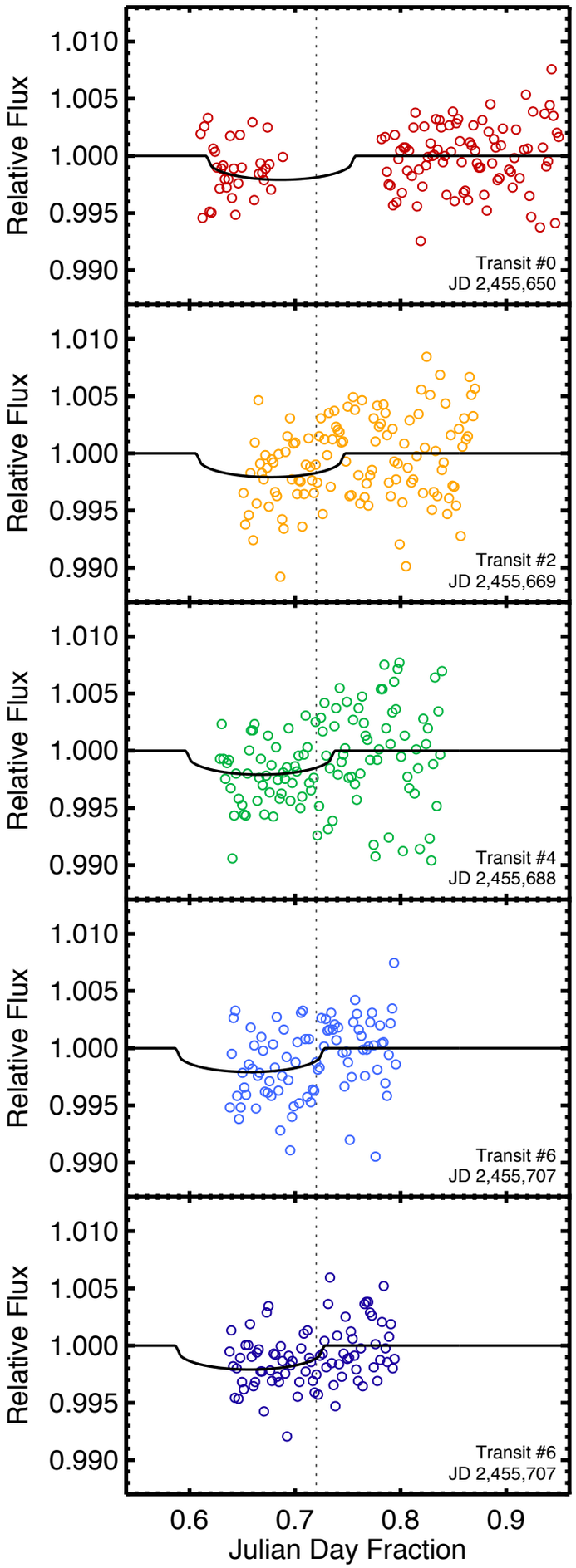



RVs from Keck-HIRES
RMS (binned) = 0.3 m/s

Howard, et al. (2011, ApJ, 731,10)

# Photometry
# by Greg Henry (TSU)

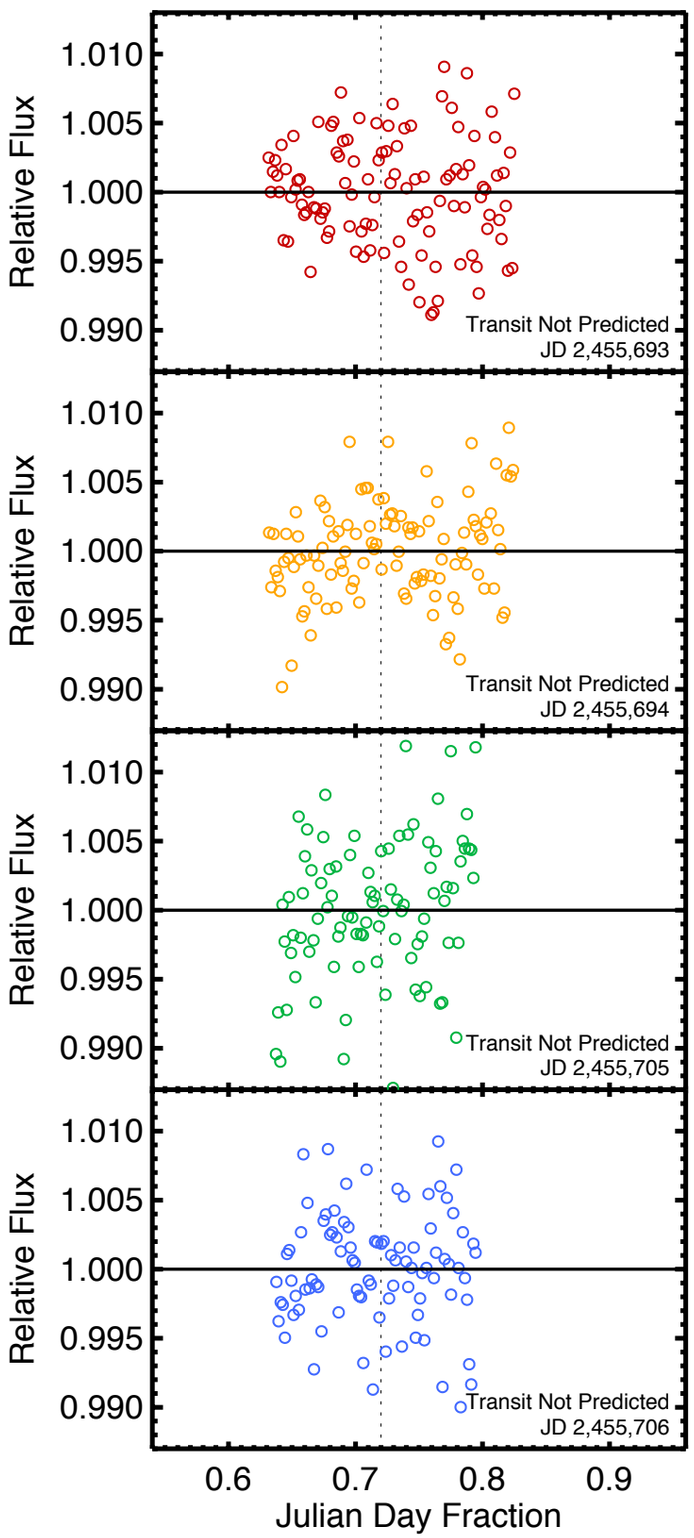



***Transits Predicted***

and detected with
2-3.5σ significance

***Transits NOT predicted***

or detected to 2σ

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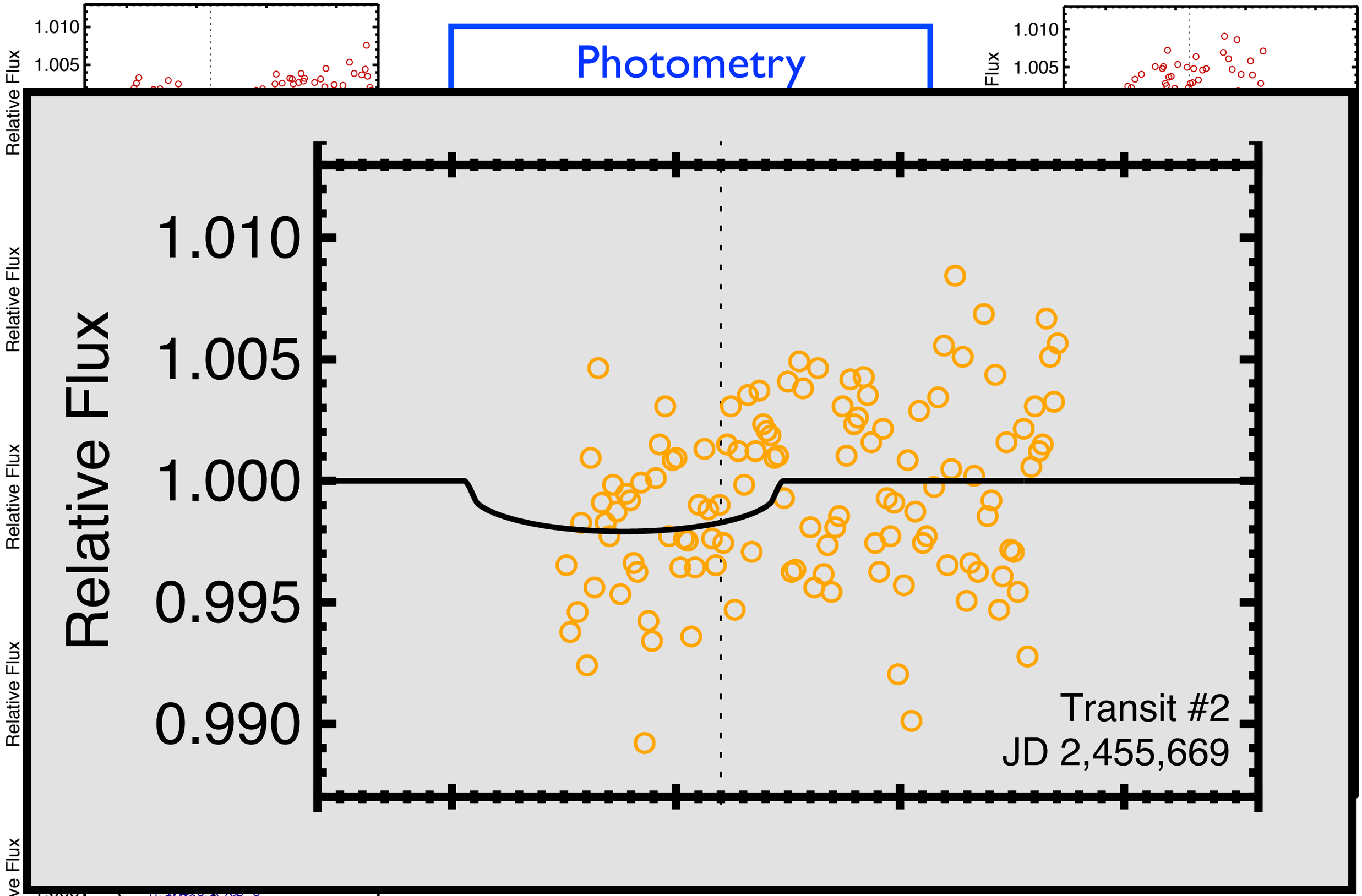


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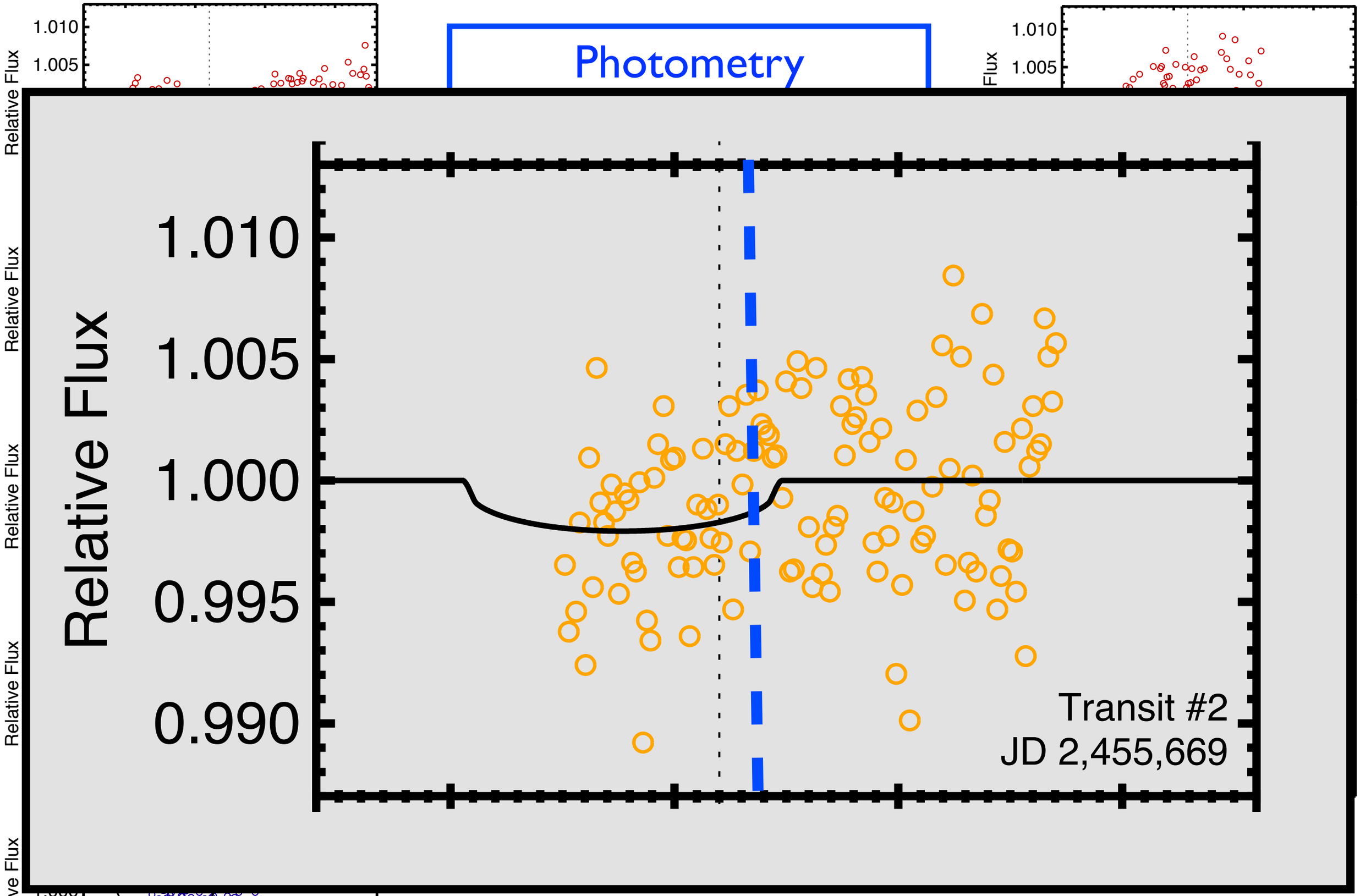


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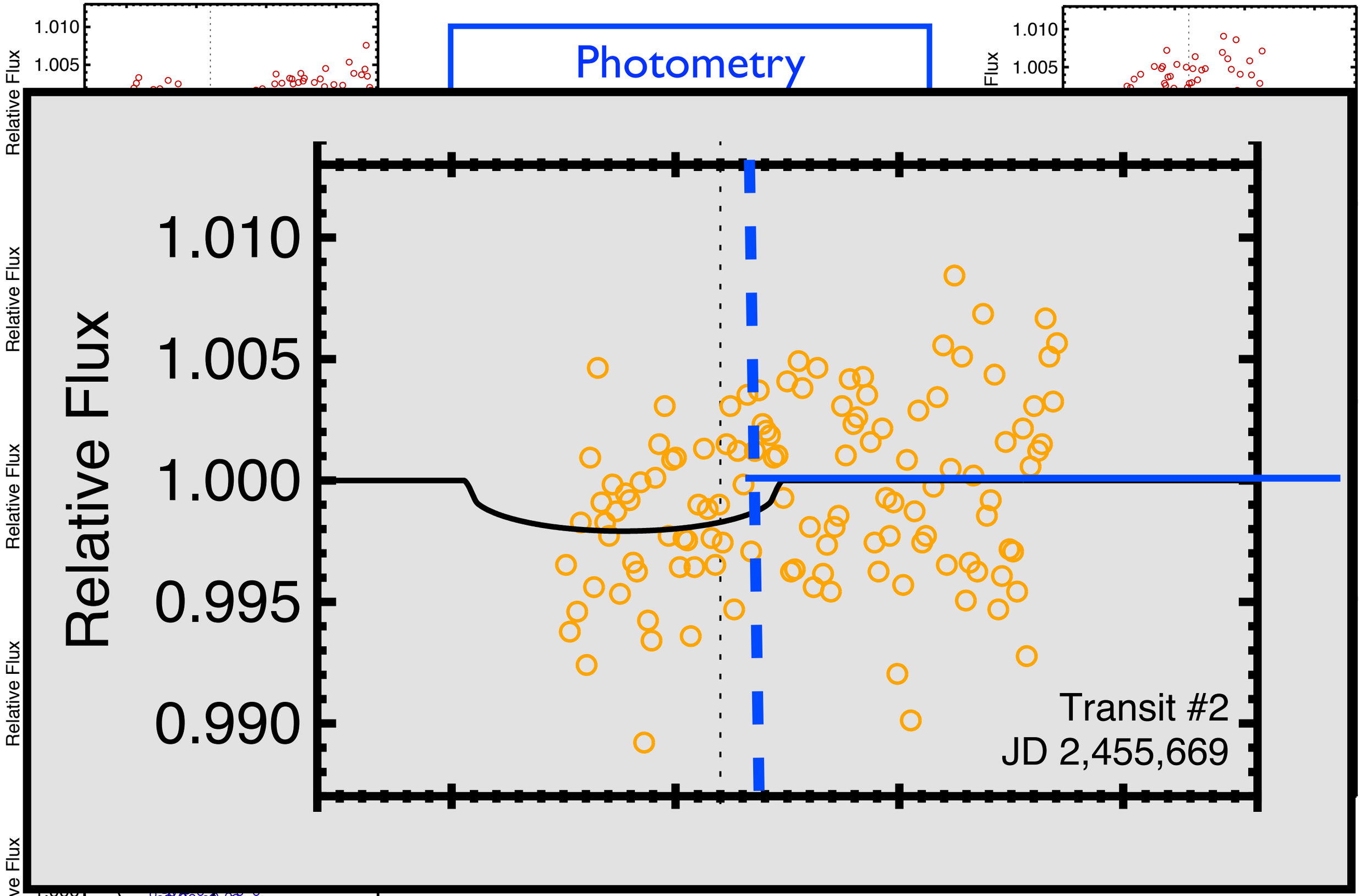


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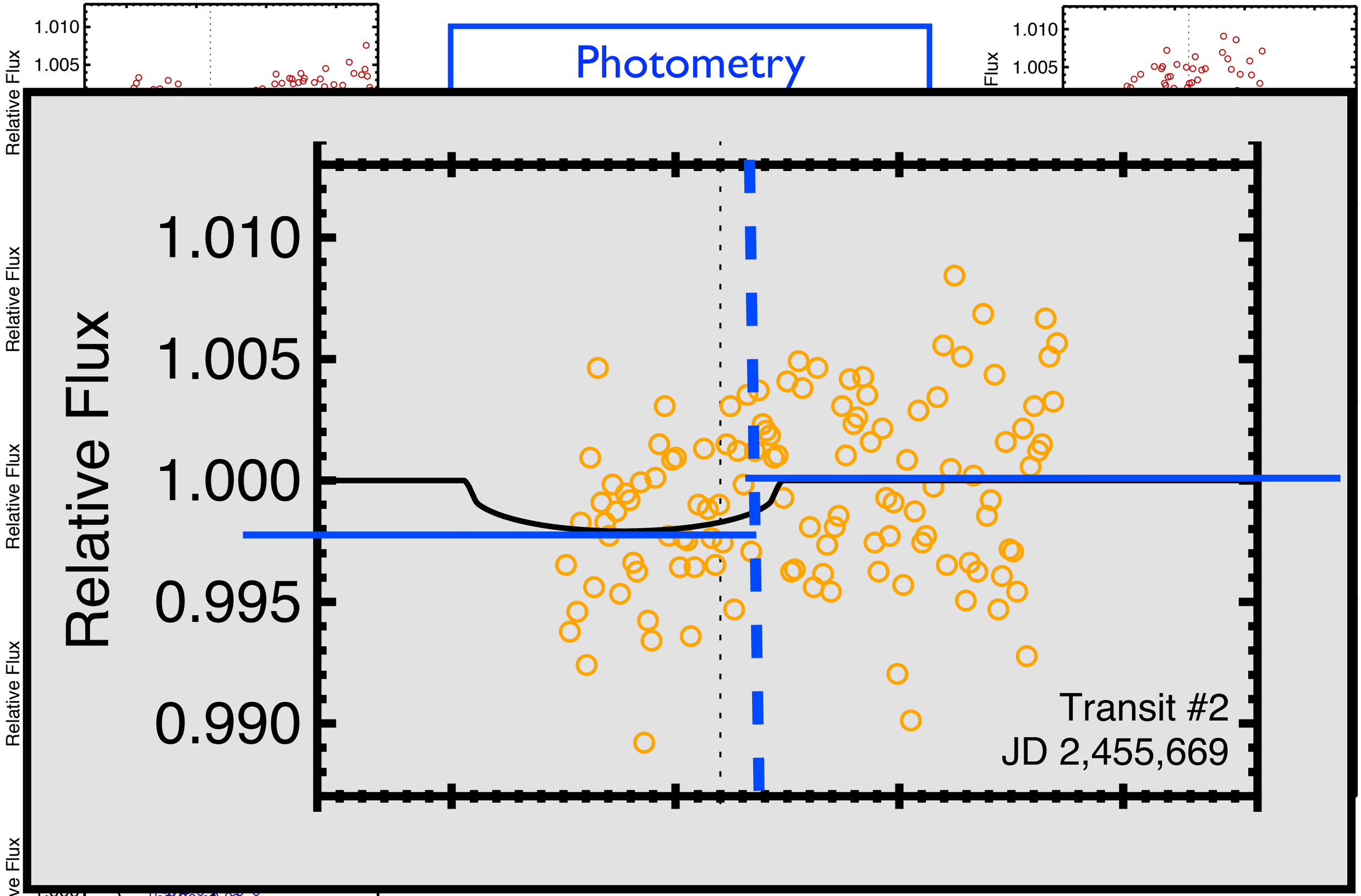


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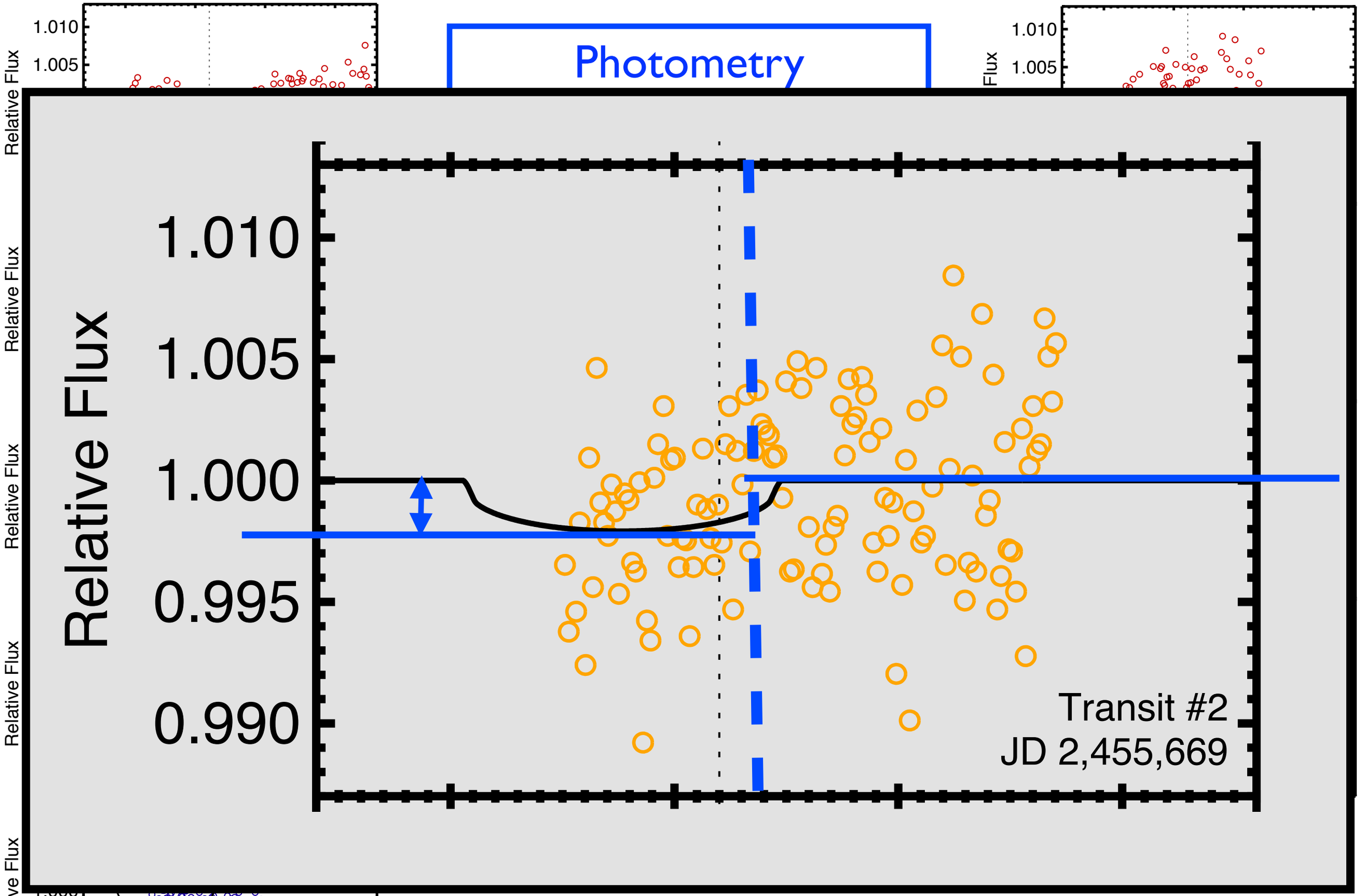


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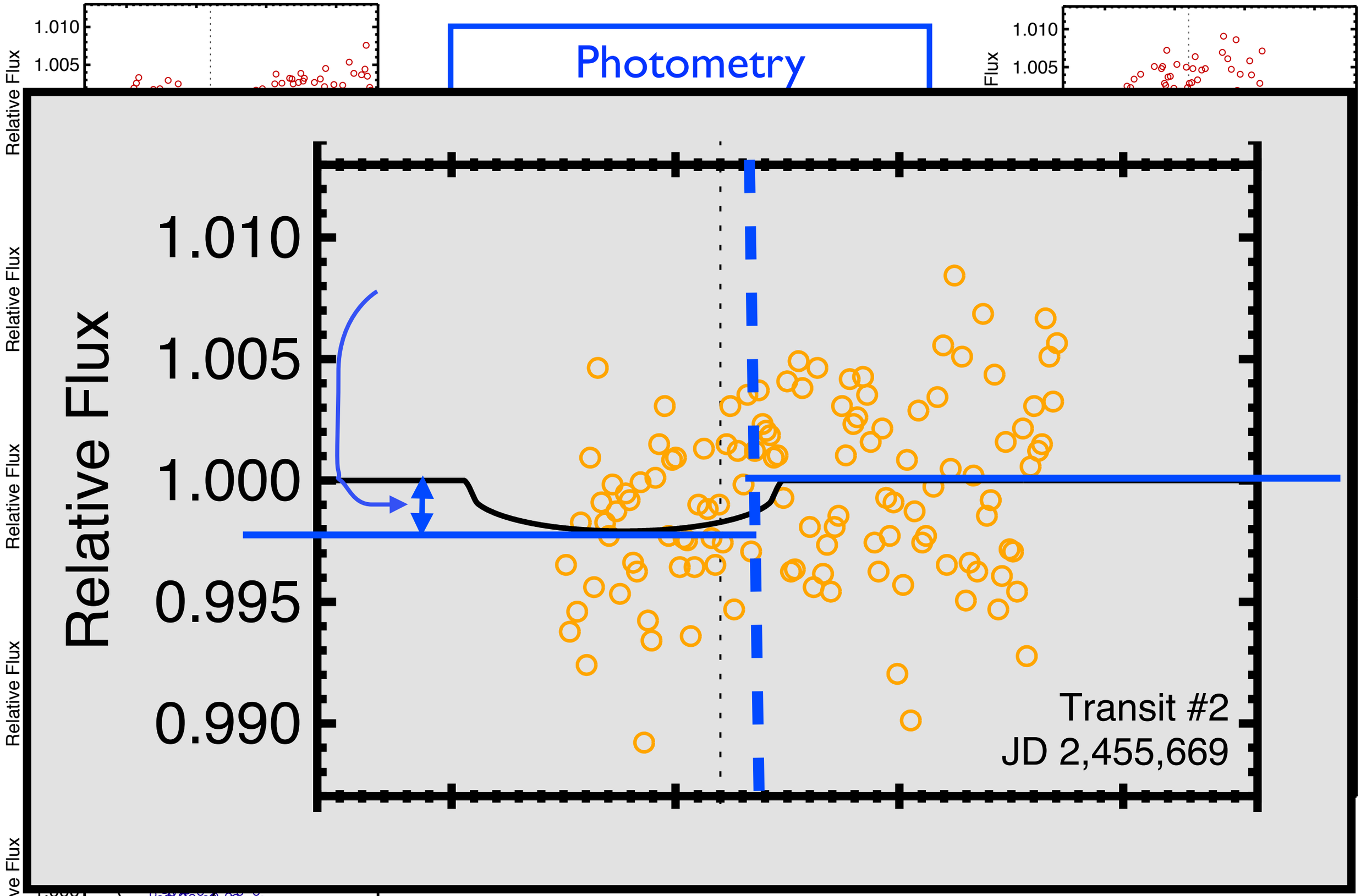


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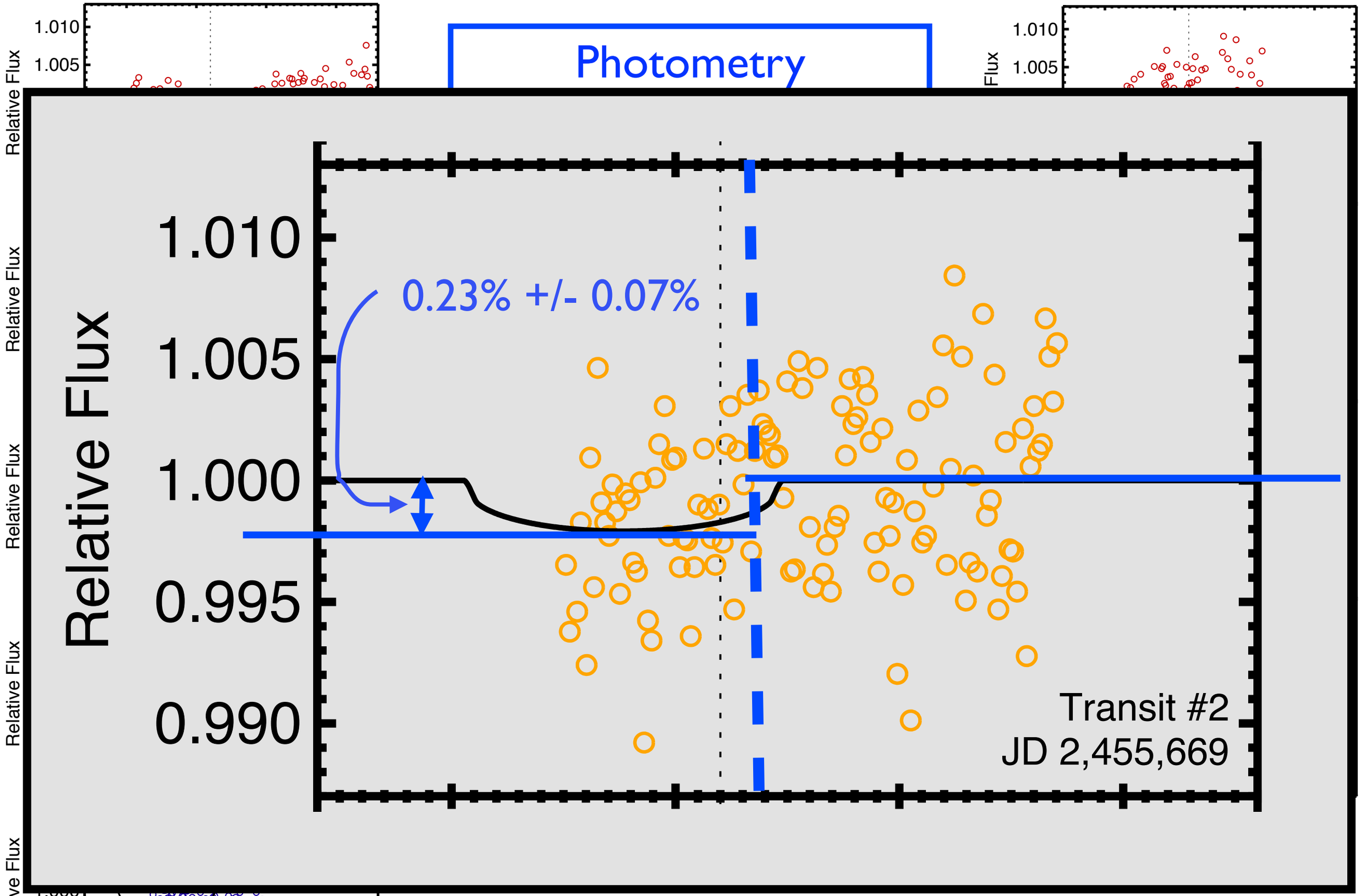


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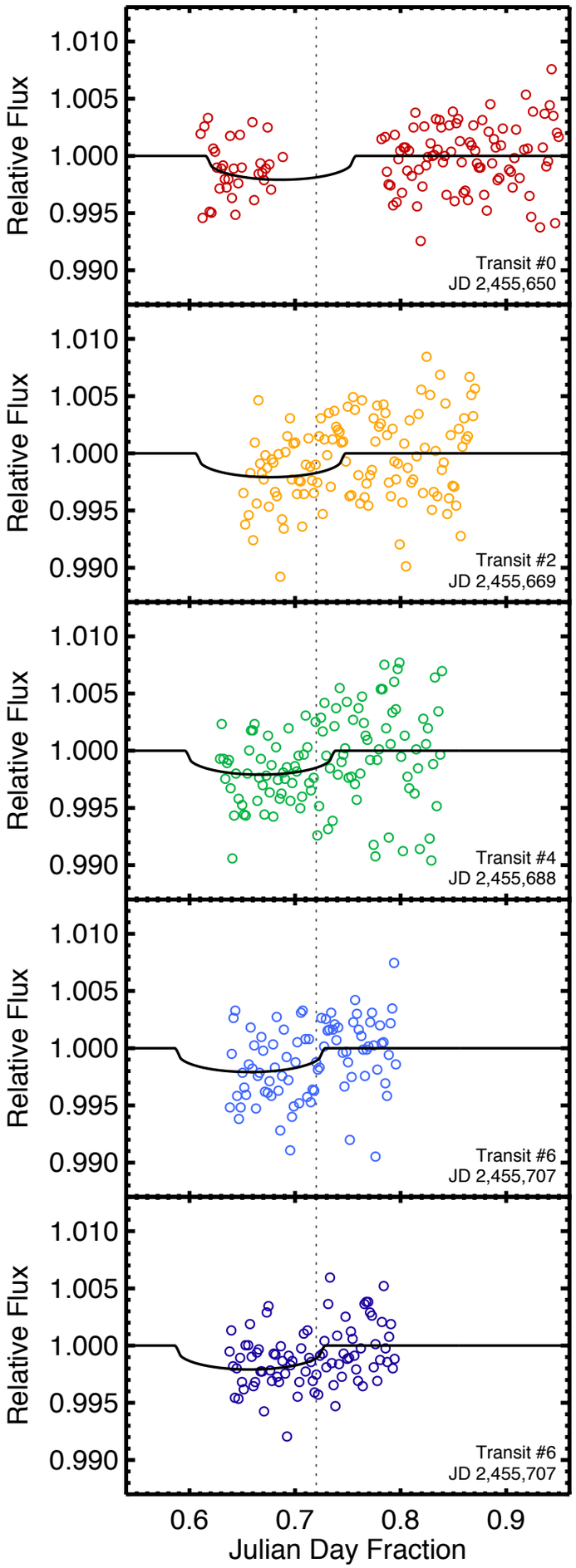
# by Greg Henry (TSU)




***Transits Predicted***

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2-3.5σ significance

***Transits NOT predicted***

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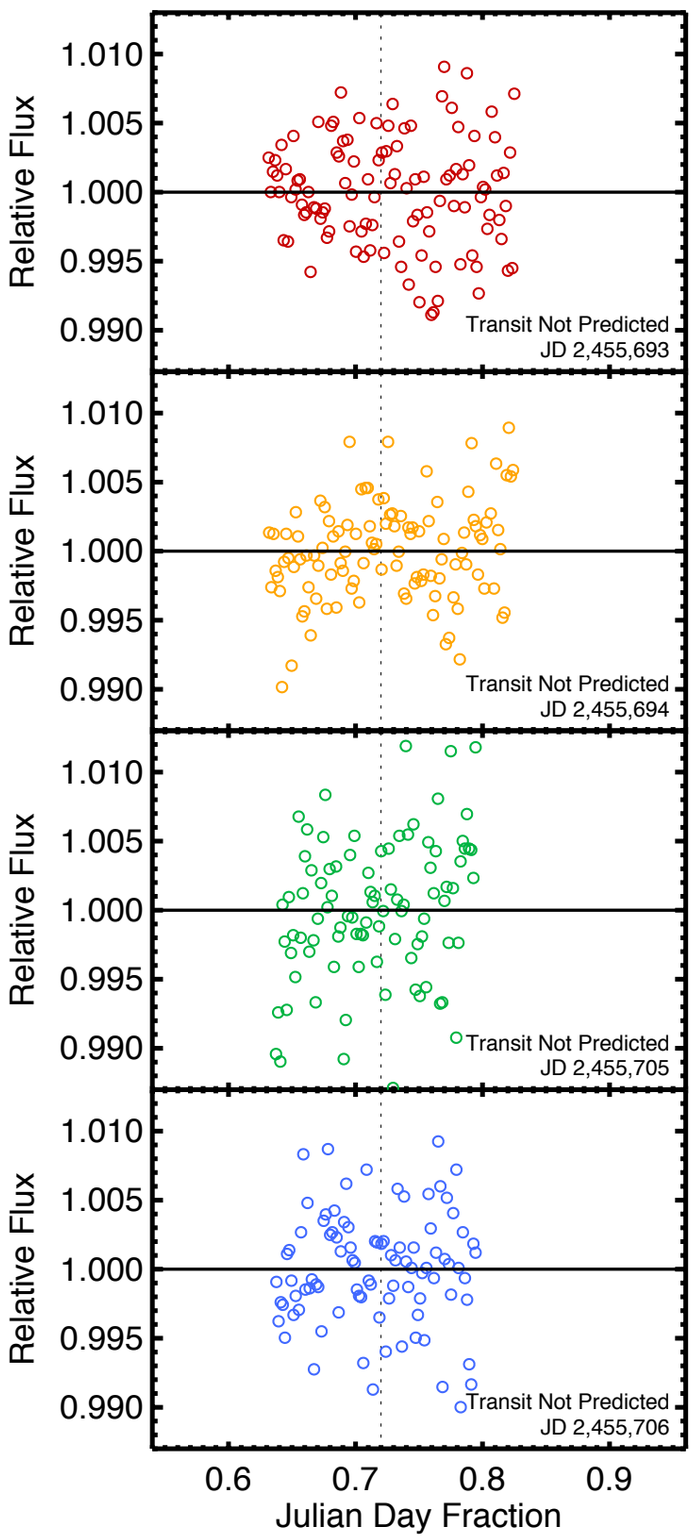
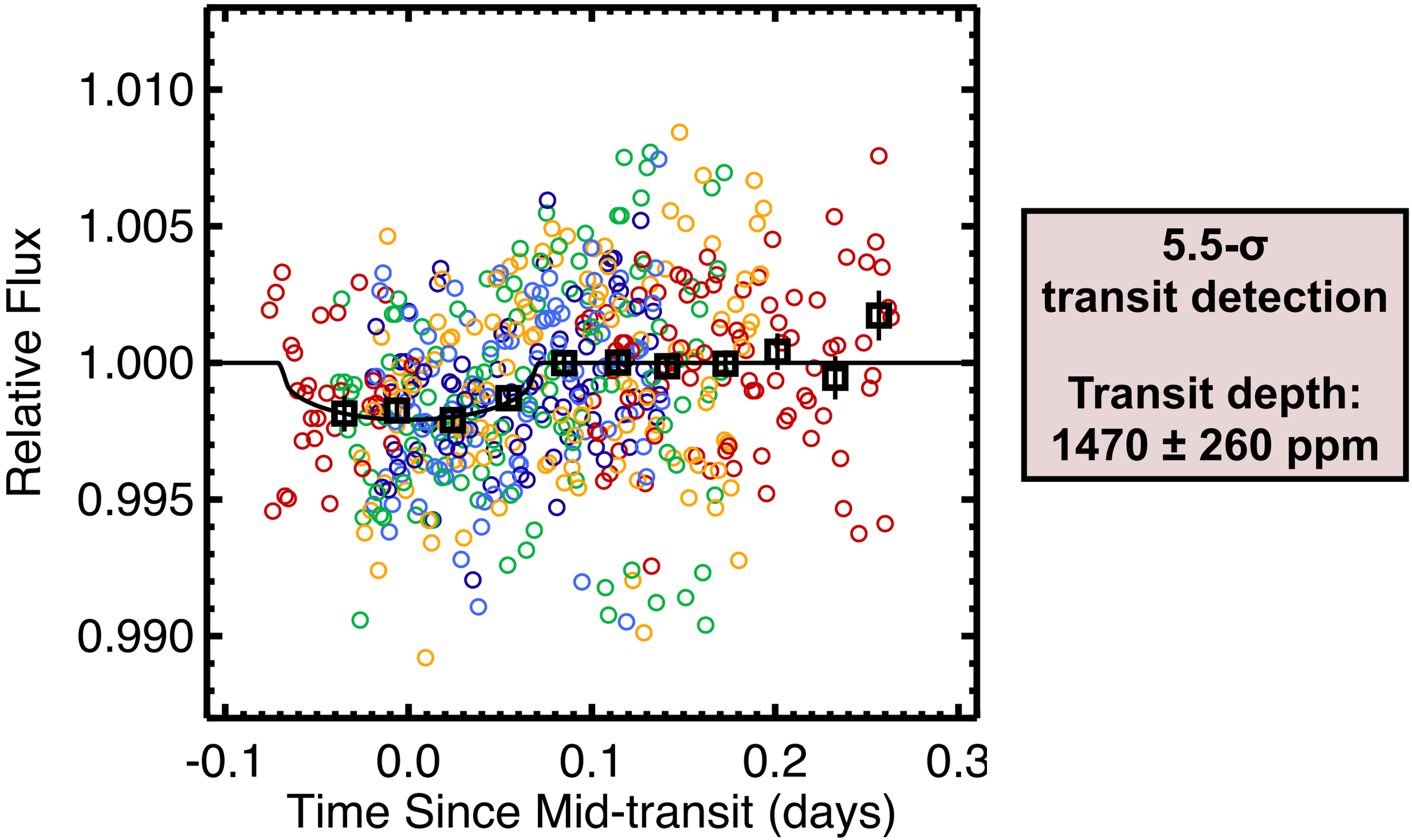



Henry, Howard, Marcy, Fischer, Johnson (2011, ApJ, submitted)

# Nights with predicted transits

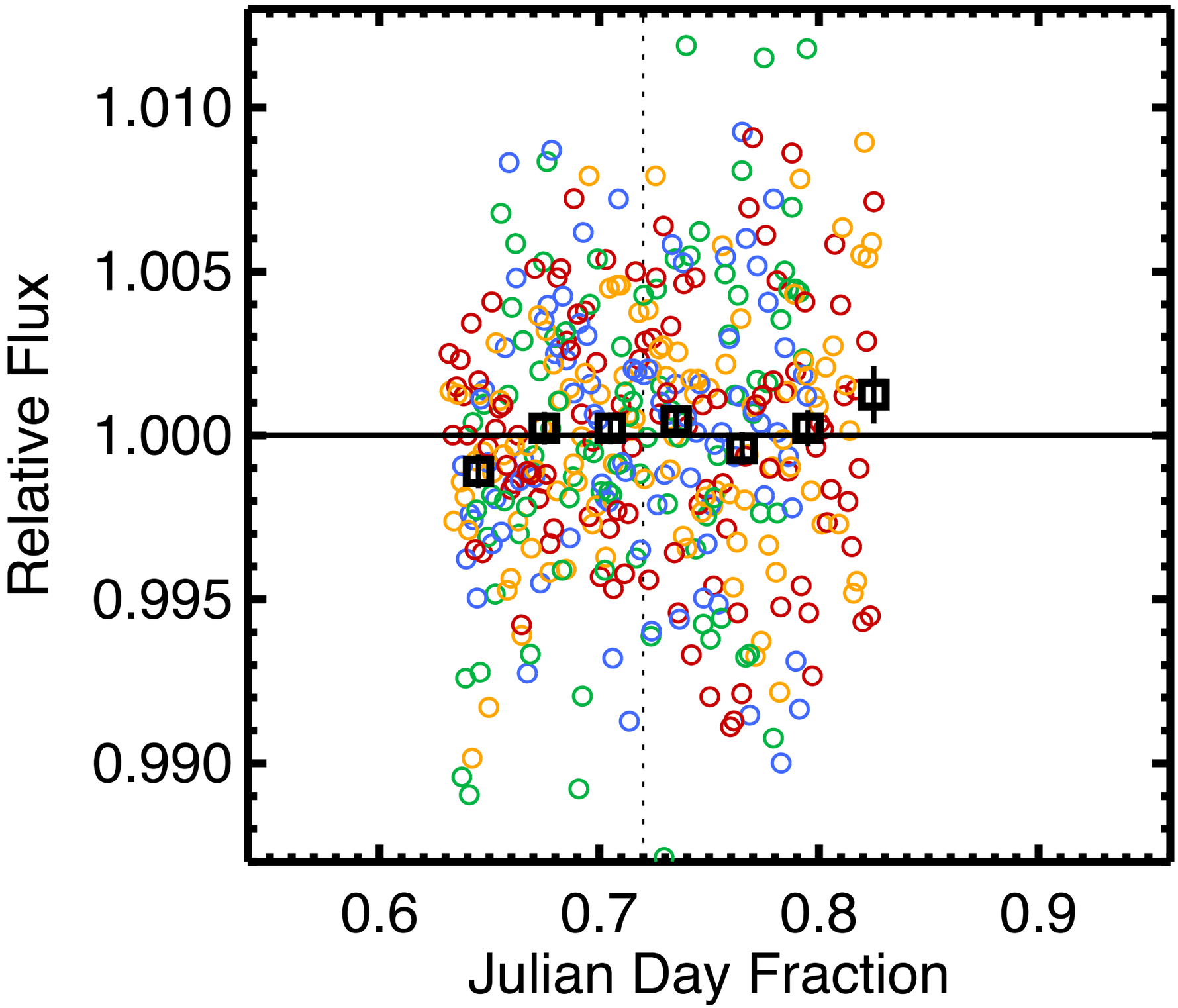



**5.5-σ transit detection**

**Transit depth: 1470 ± 260 ppm**

Henry, Howard, Marcy, Fischer, Johnson (2011, ApJ, submitted)

# Nights with transits *NOT* predicted




**Offset at JDF 0.72: 400 ± 398 ppm**

**Consistent with flat**

Henry, Howard, Marcy, Fischer, Johnson (2011, ApJ, submitted)

# HD 97658b

Mass = 6.4 ± 0.7 $M_E$

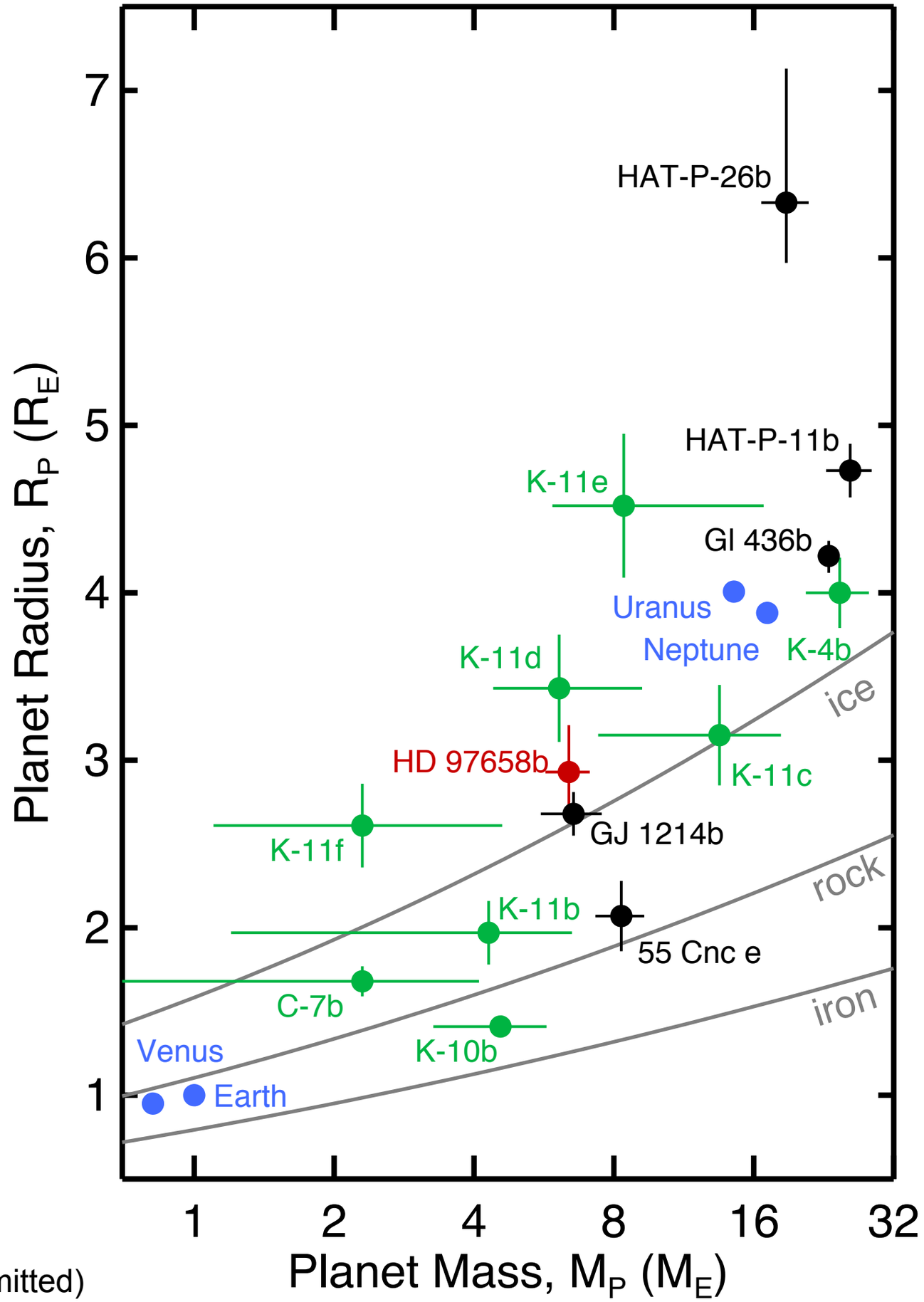
Radius = 2.93 ± 0.28 $R_E$

Density = $1.4^{+0.5}_{-0.4}$ g cm$^{-3}$

Period = 9.4957 ± 0.0022 days

$T_{eq}$ = 510-720 K

Star = K1 V

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# GJ 1214b

Mass = 6.55 ± 0.98 $M_E$

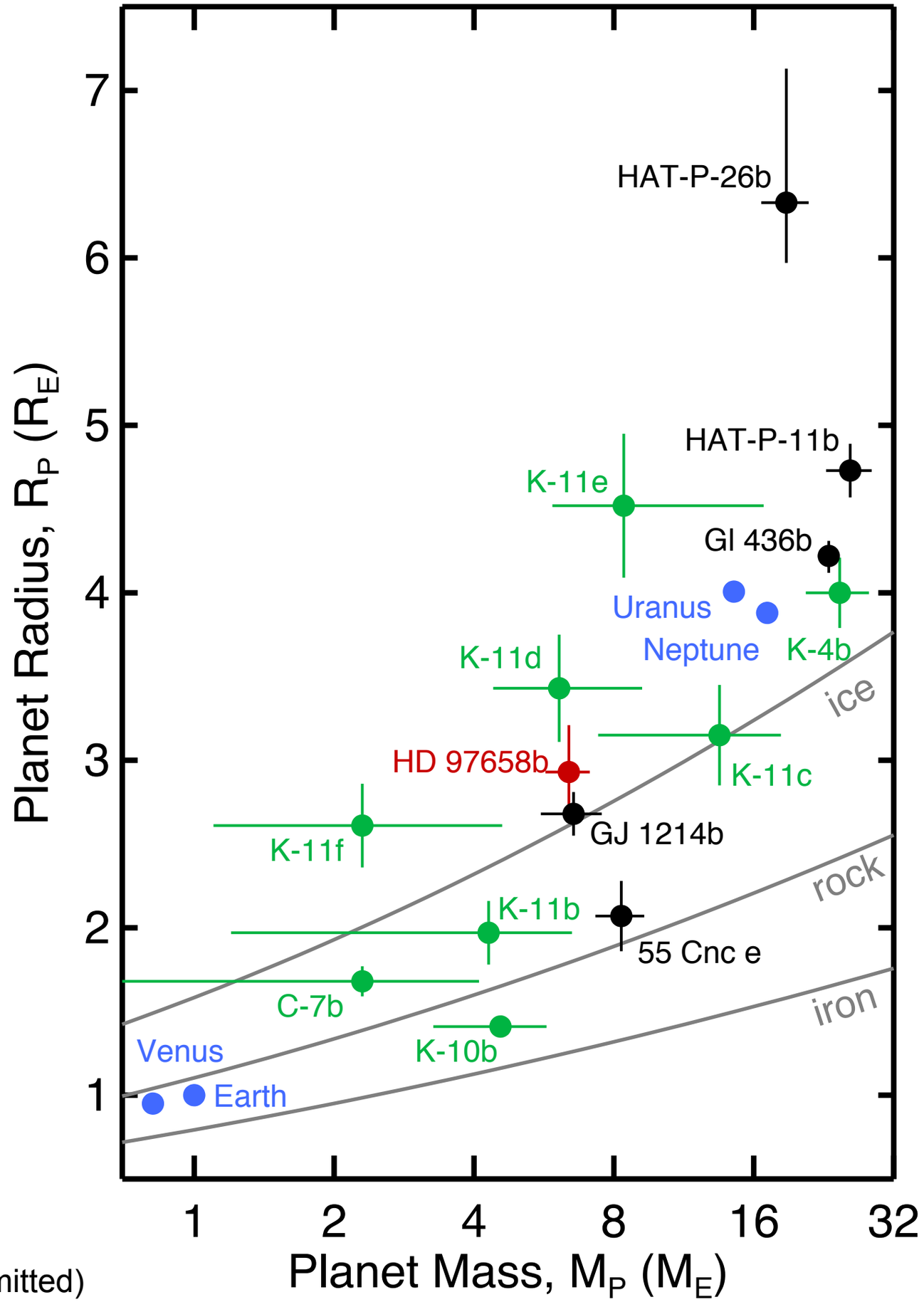
Radius = 2.68 ± 0.13 $R_E$

Density = 1.9 ± 0.4 g cm$^{-3}$

Period = 1.58... days

$T_{eq}$ = 393-555 K

Star = M4.5 V

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Star = K1 V

Bright star!
V = 7.8
K = 5.7

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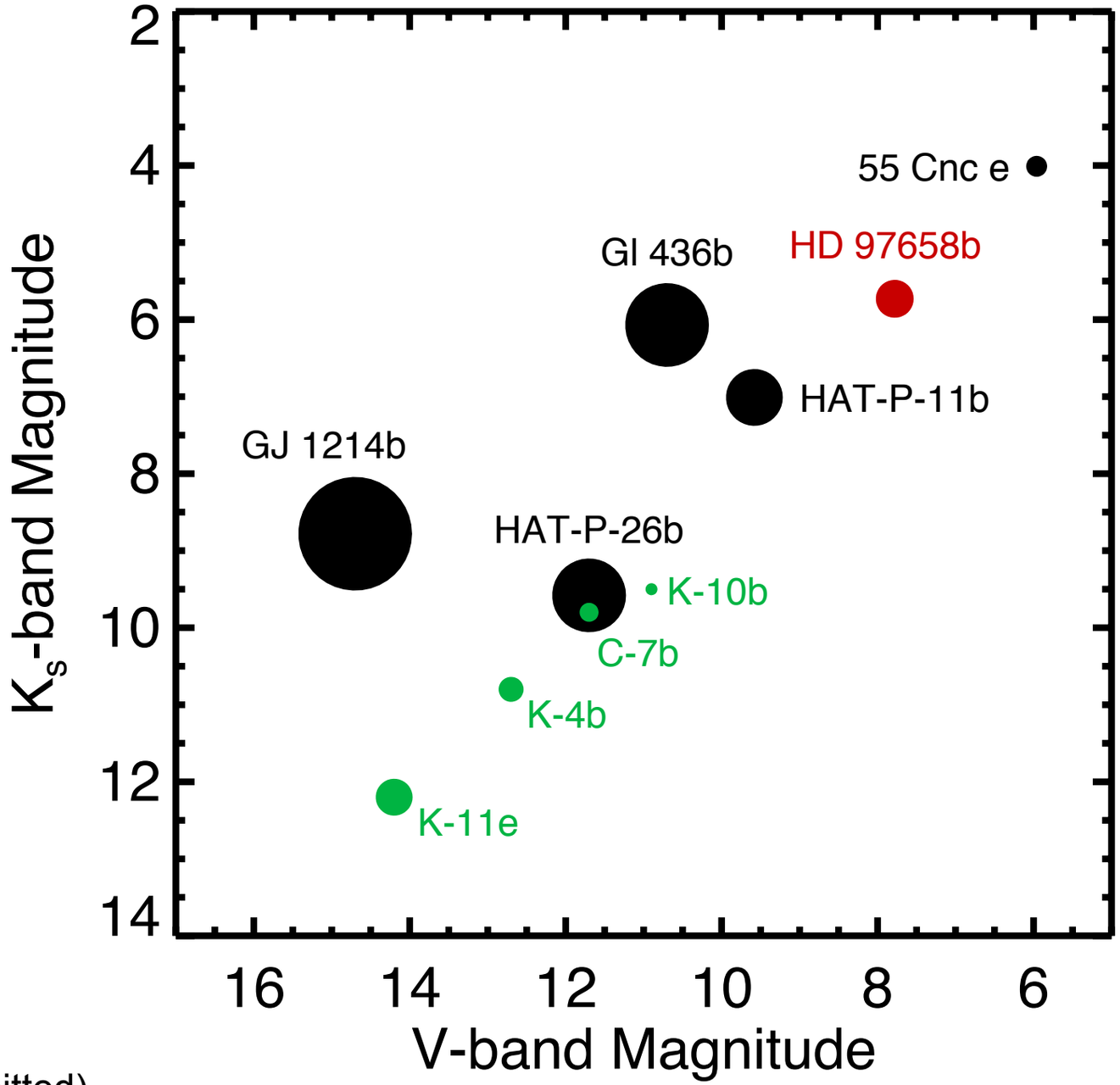
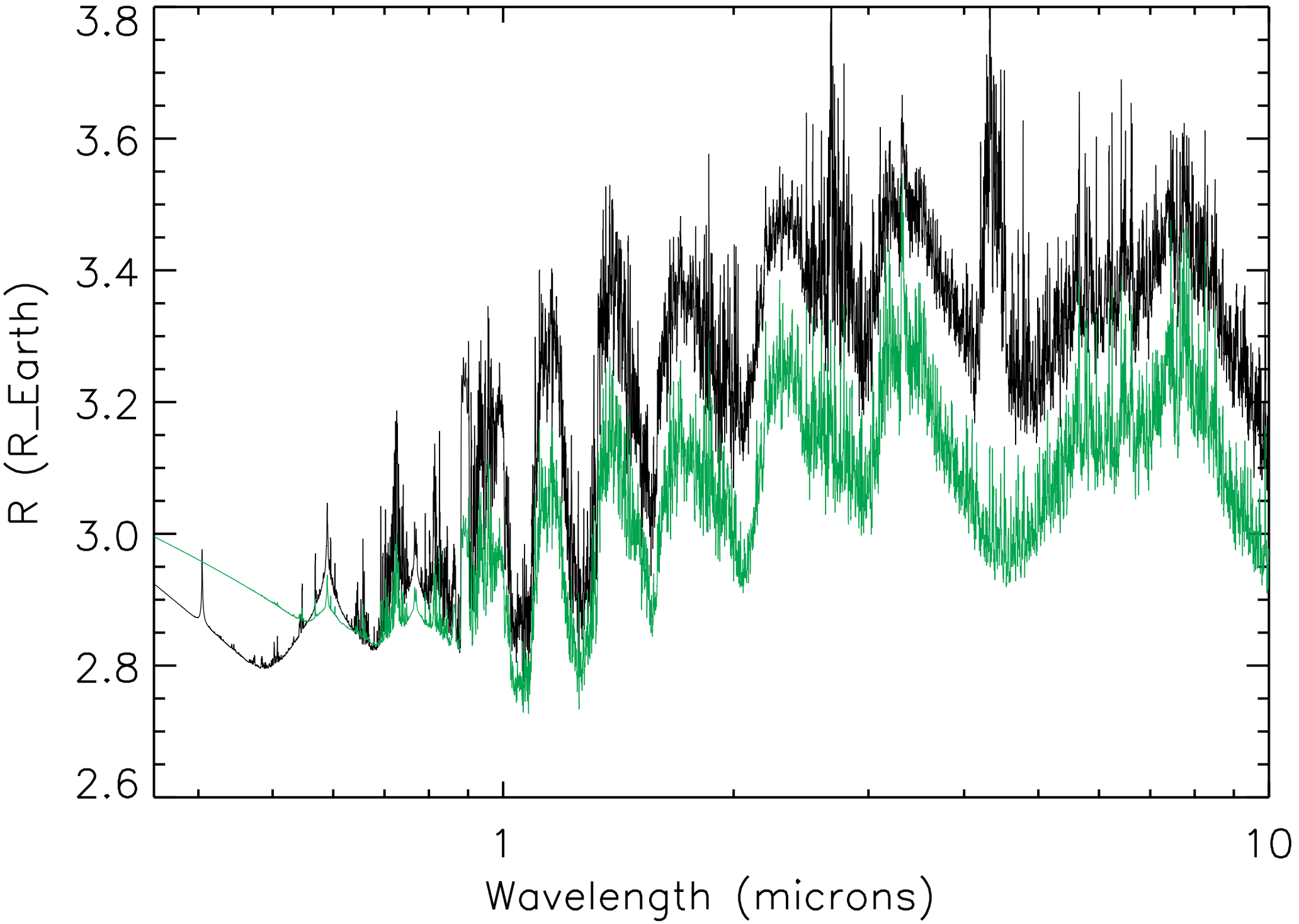



Henry, Howard, Marcy, Fischer, Johnson (2011, ApJ, submitted)

# Model Transmission Spectrum - HD 97658b
# by Jonathan Fortney



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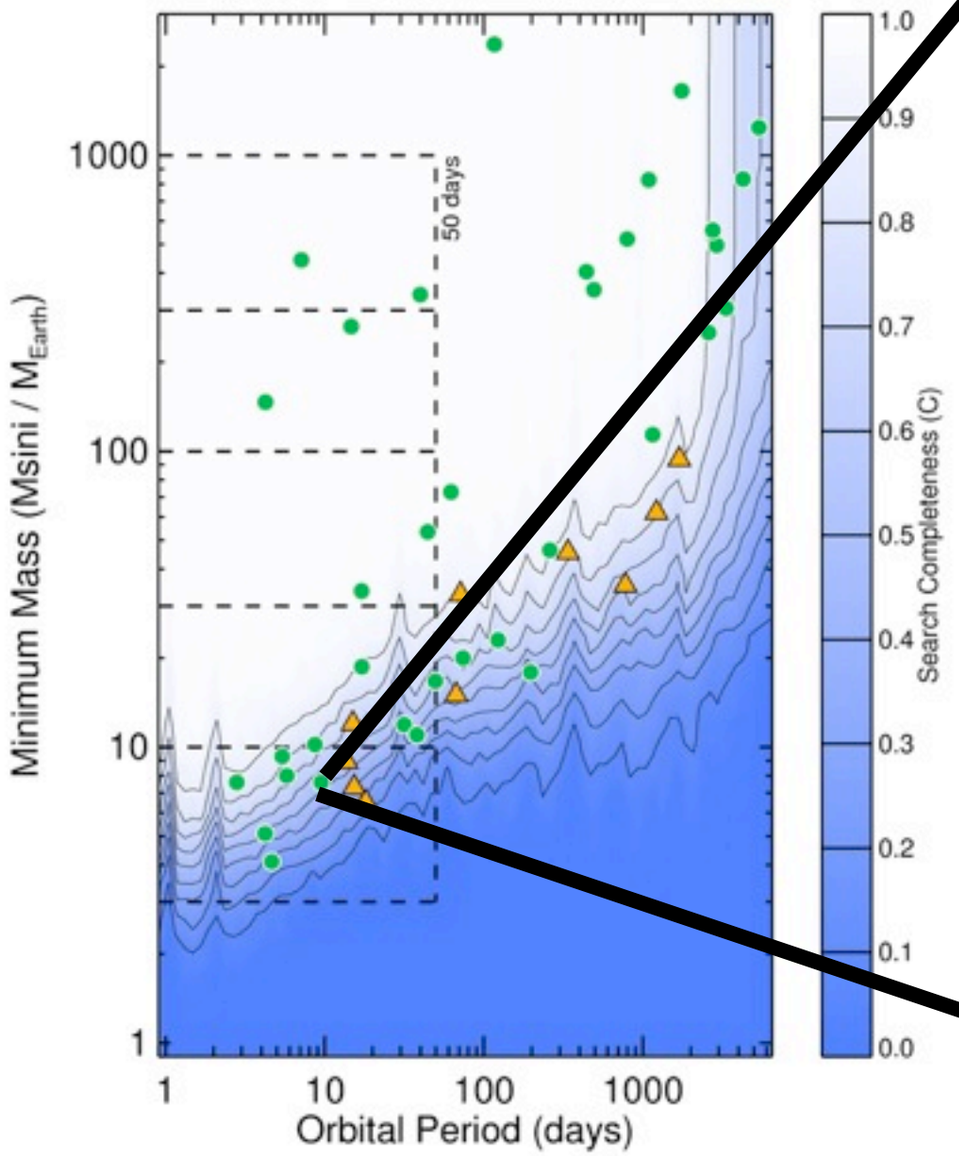
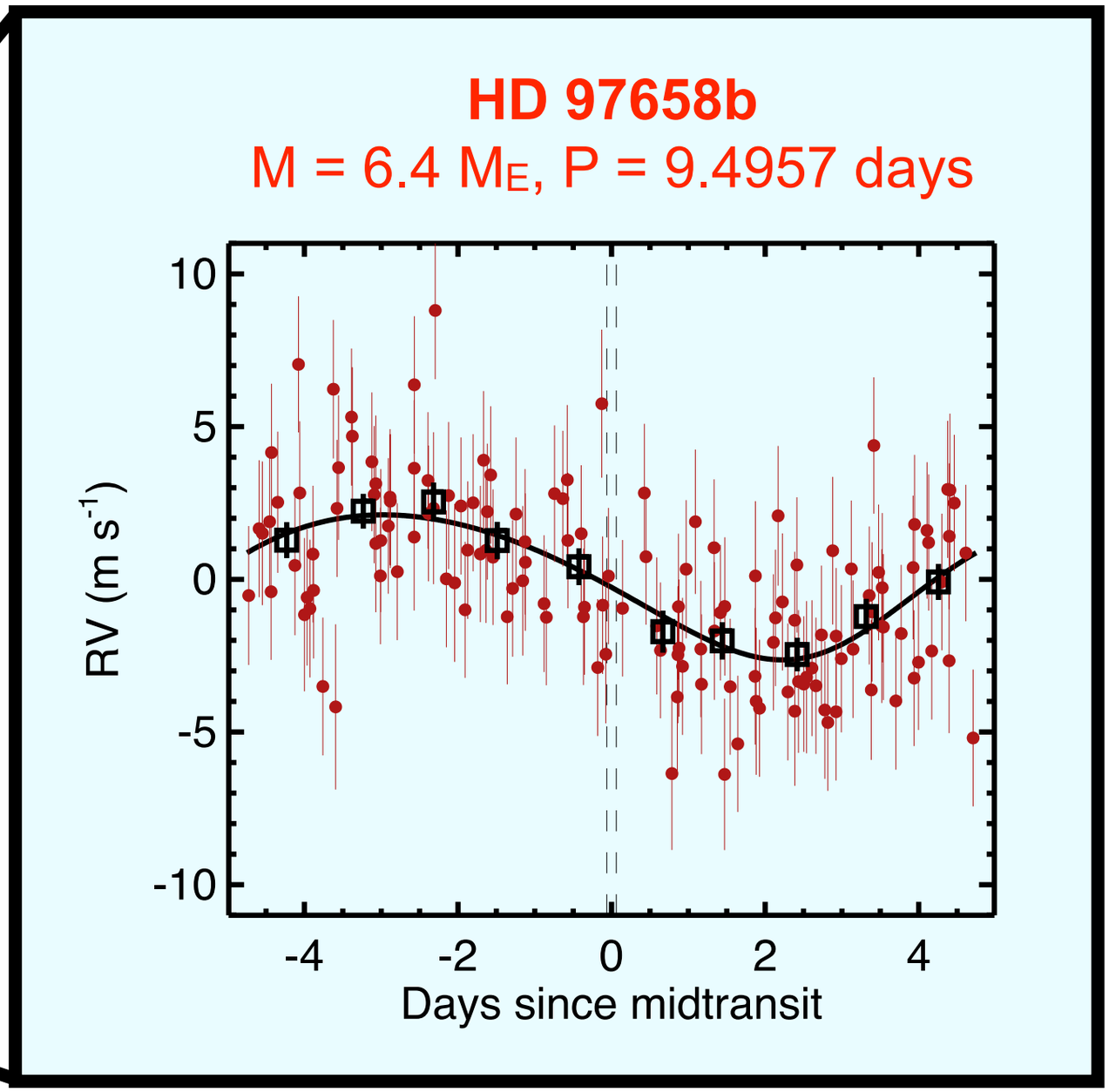
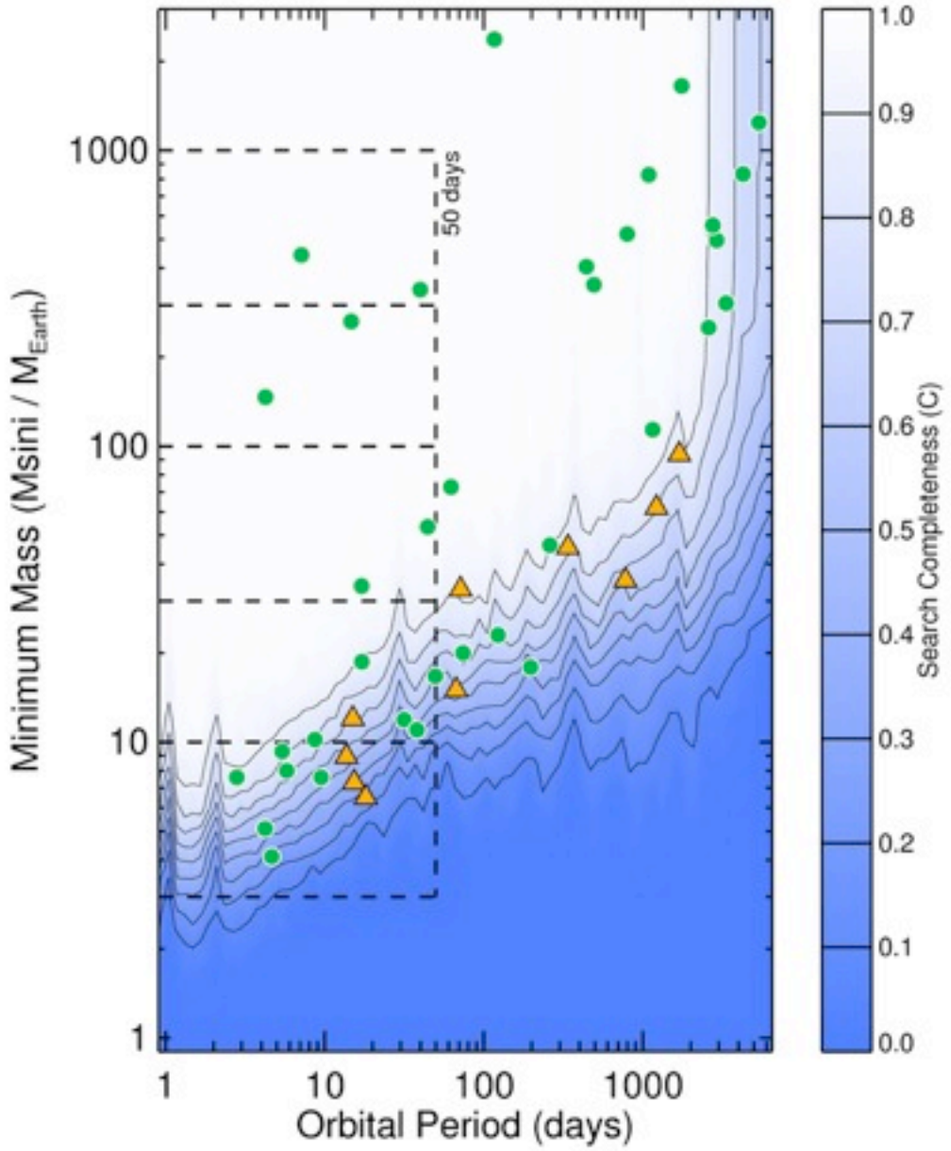



Eta-Earth Survey
(NASA/UC/Keck)




Howard, et al. (2011, ApJ, 731,10)




Eta-Earth Survey
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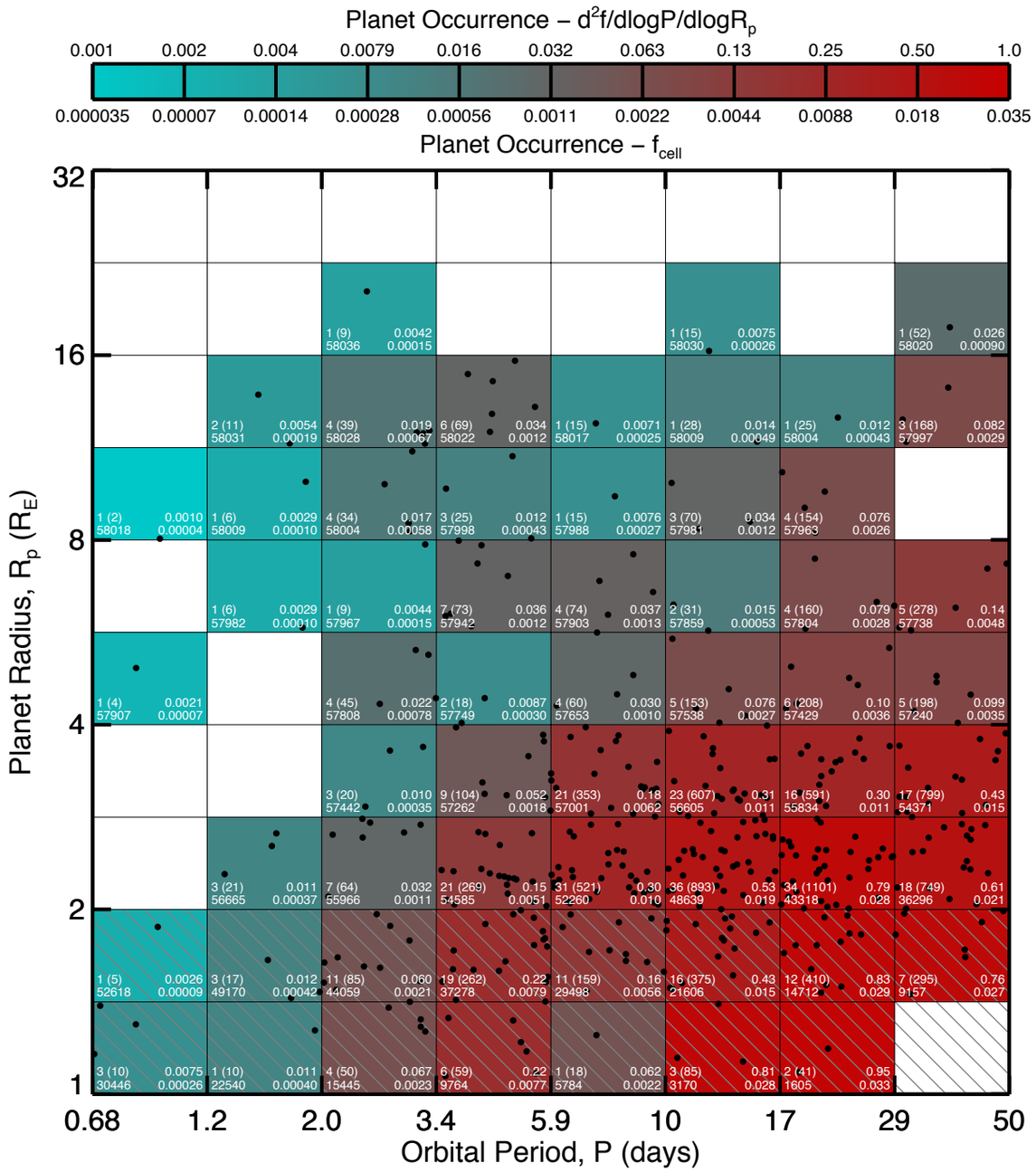
# Planet Occurrence from Kepler




Kepler
(NASA)

## How to Compute planet occurrence:

1. Select set of planets, stars, and SNR threshold
2. Correct for transit probabilities
3. Correct for noisy stars using actual noise measurements (CDPP)
4. Compute planet occurrence in grid of cells in $R_p$ and period

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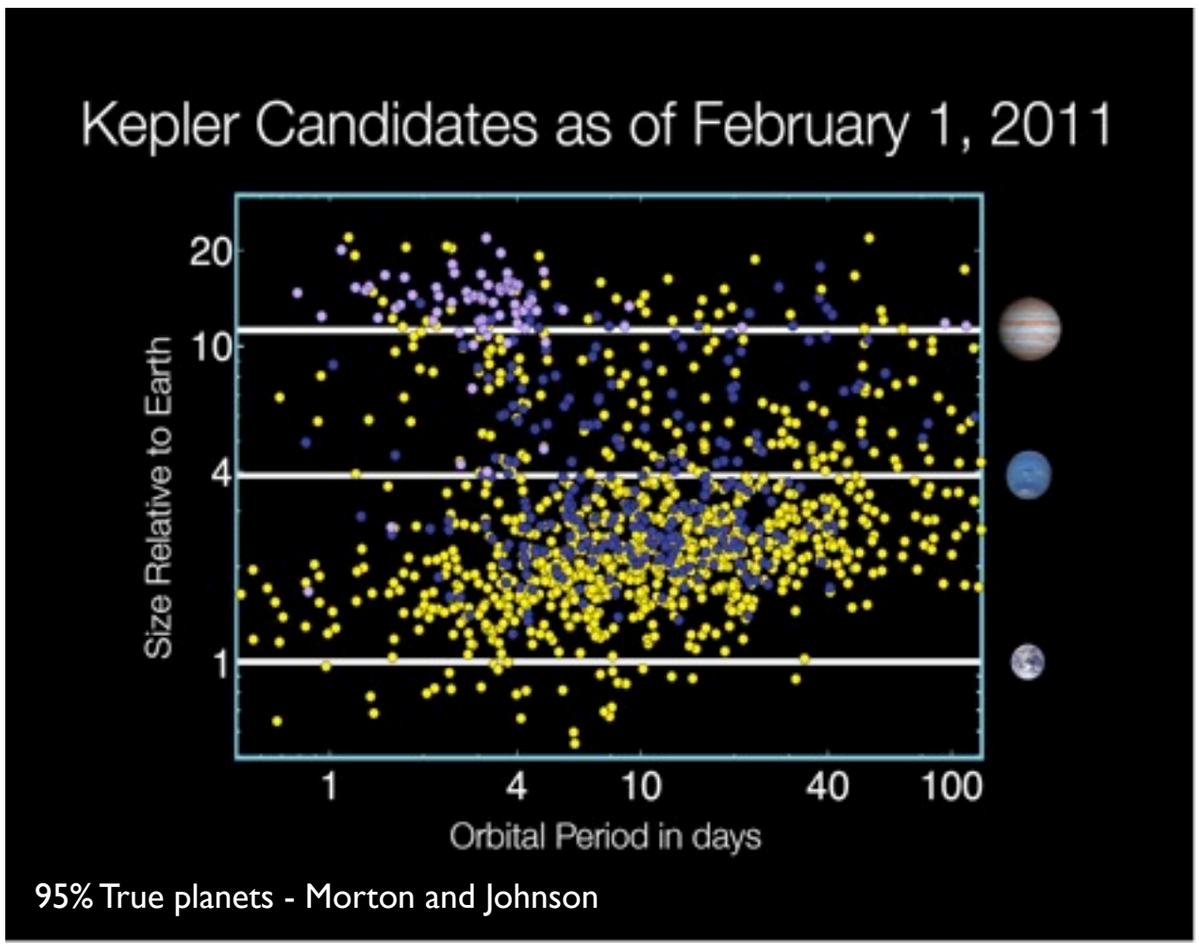

95% True planets - Morton and Johnson

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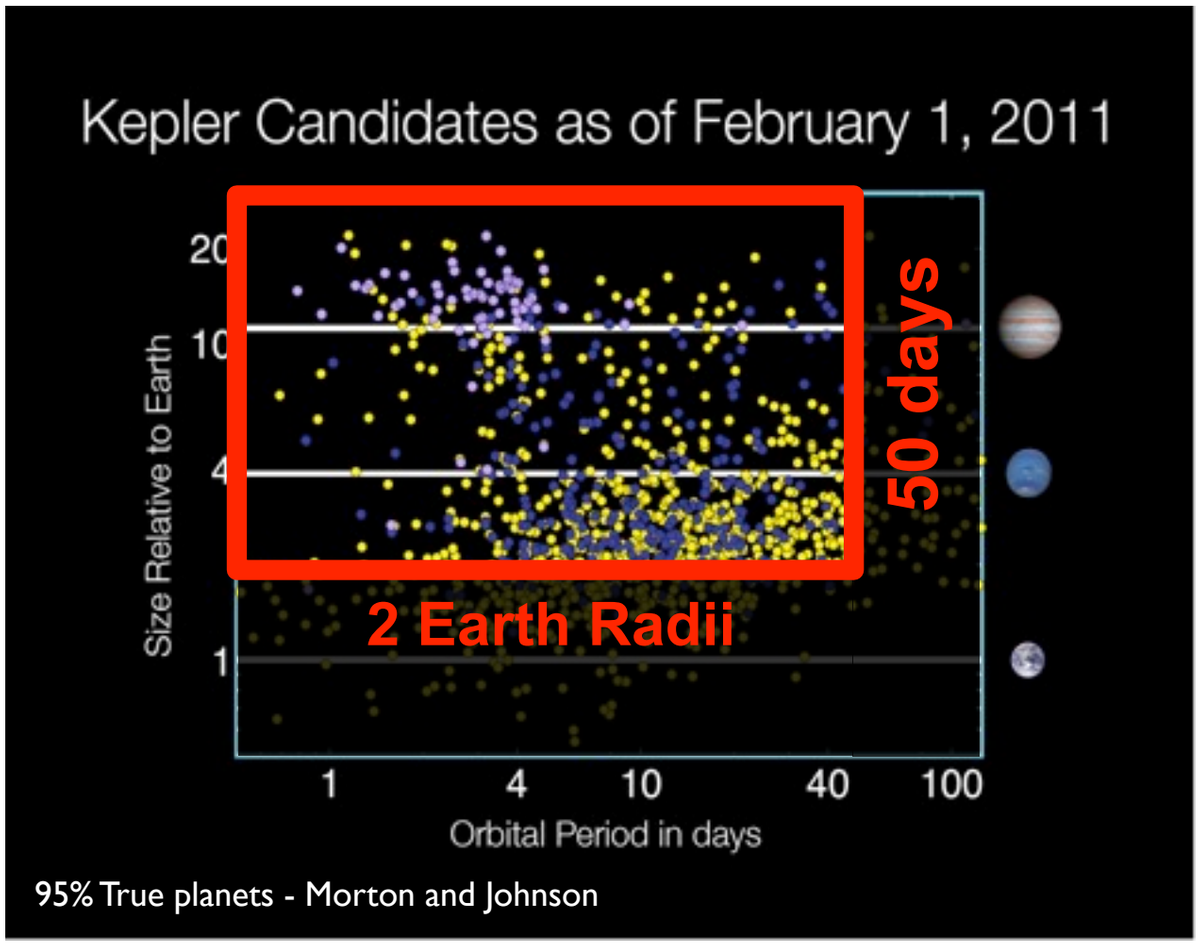


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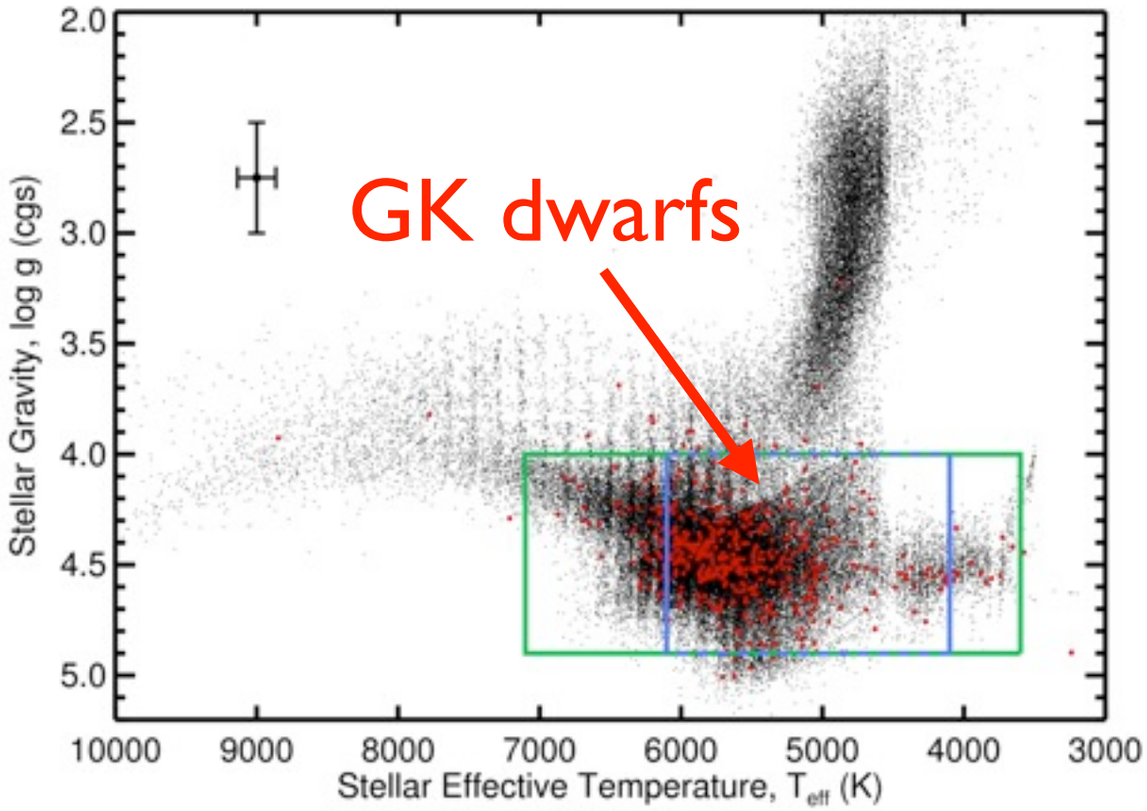


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| Full sample | | Restricted sample |
|---|---|---|
| ~156,000 stars | → | ~58,000 stars |
| 1,230 planets | | 438 planets |

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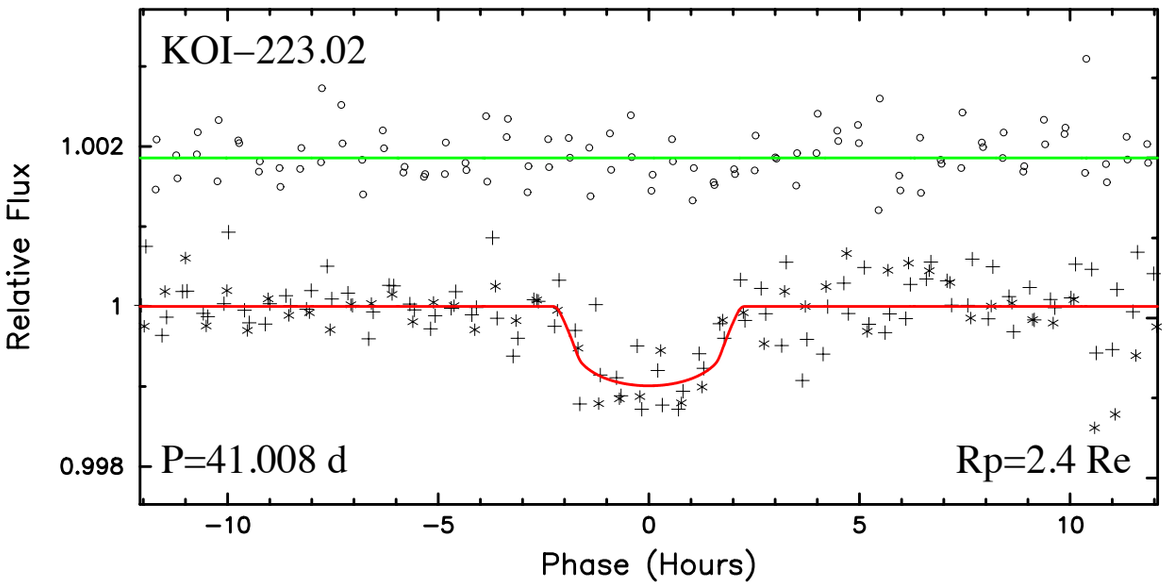


- Only GK dwarfs ($T_{eff}$/log$g$)
- Only bright stars ($Kp$ < 15)
- Only high SNR transits (SNR > 10 in 90 days)

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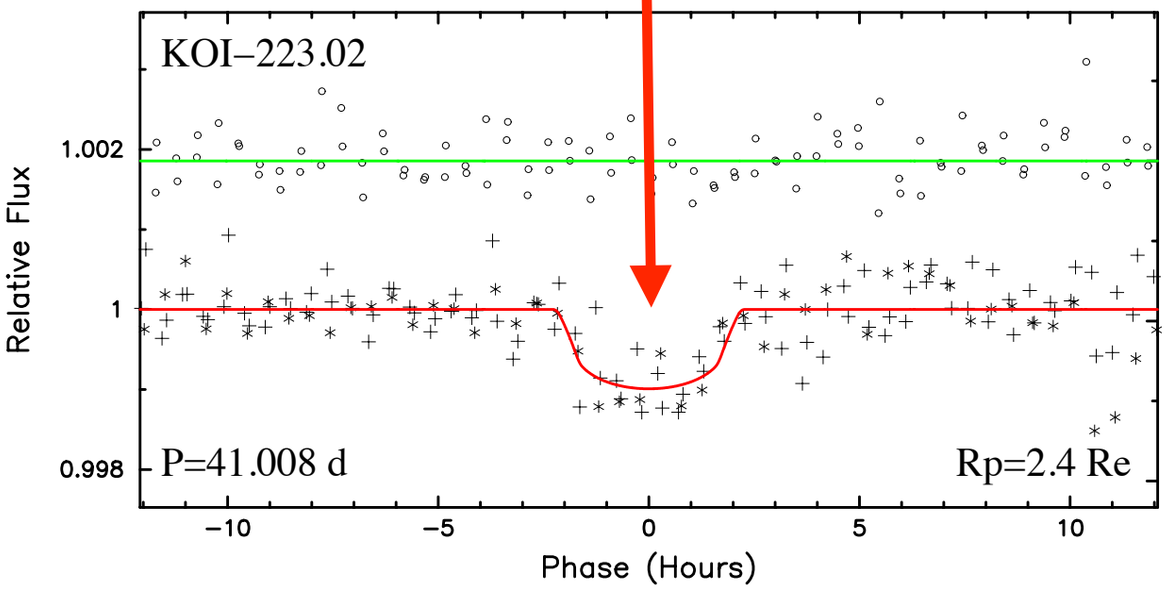
SNR ≈ 10

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Correct for:

Transit probabilities - $p_{transit} = R_\star/a$

Incompleteness - some stars lack the photometric sensitivity

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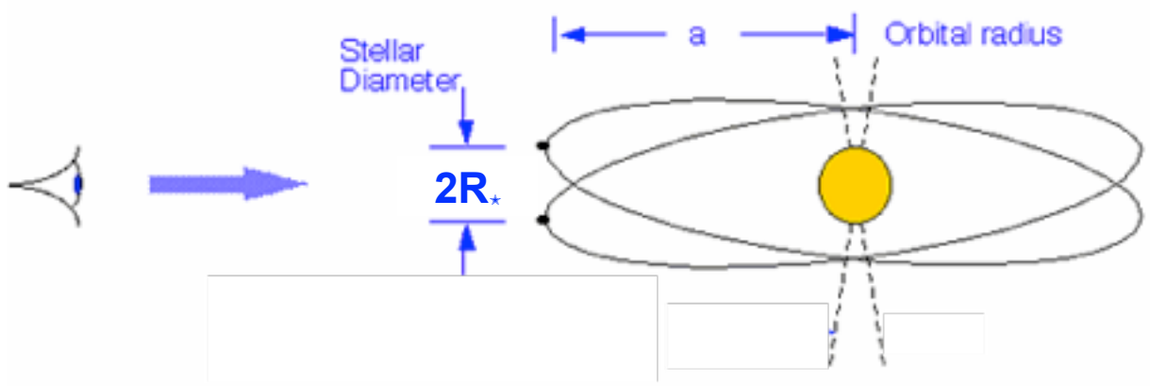


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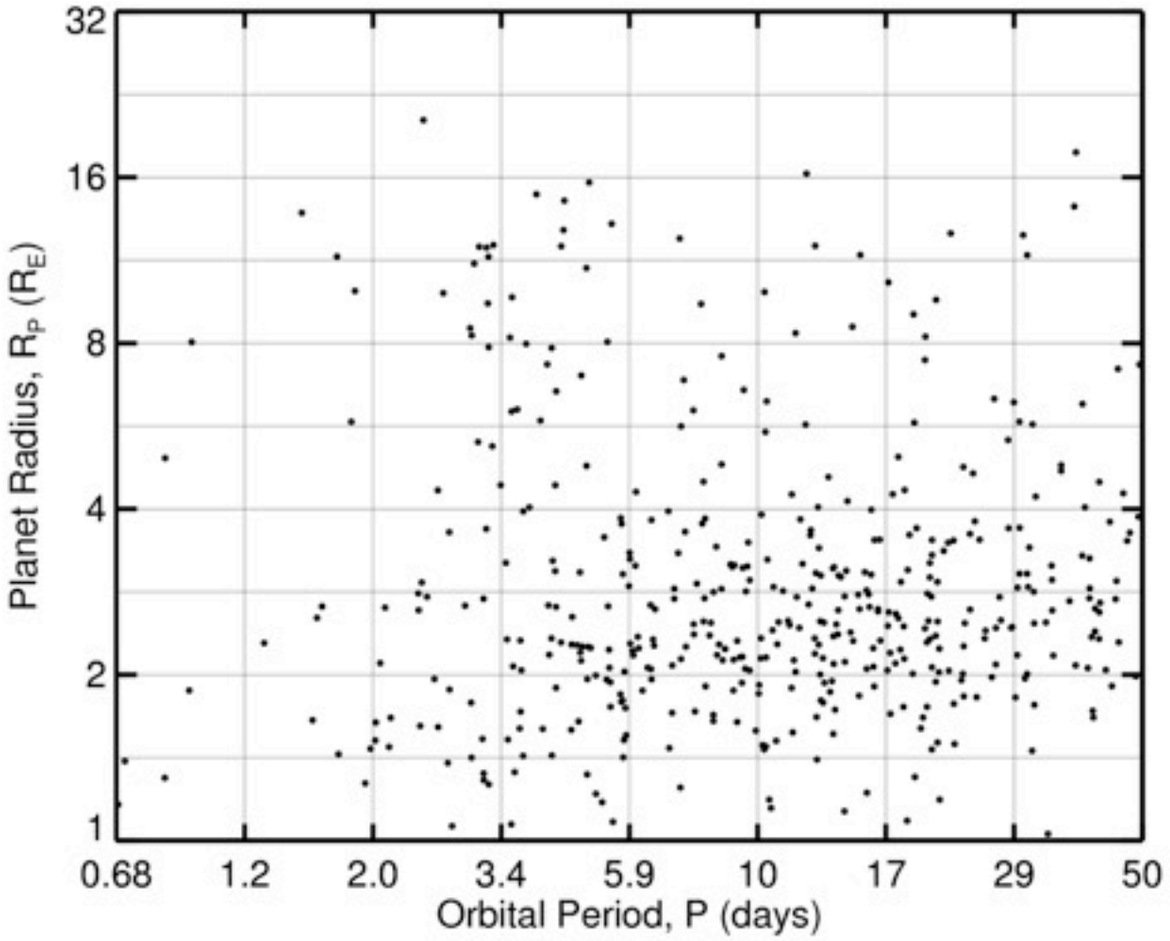


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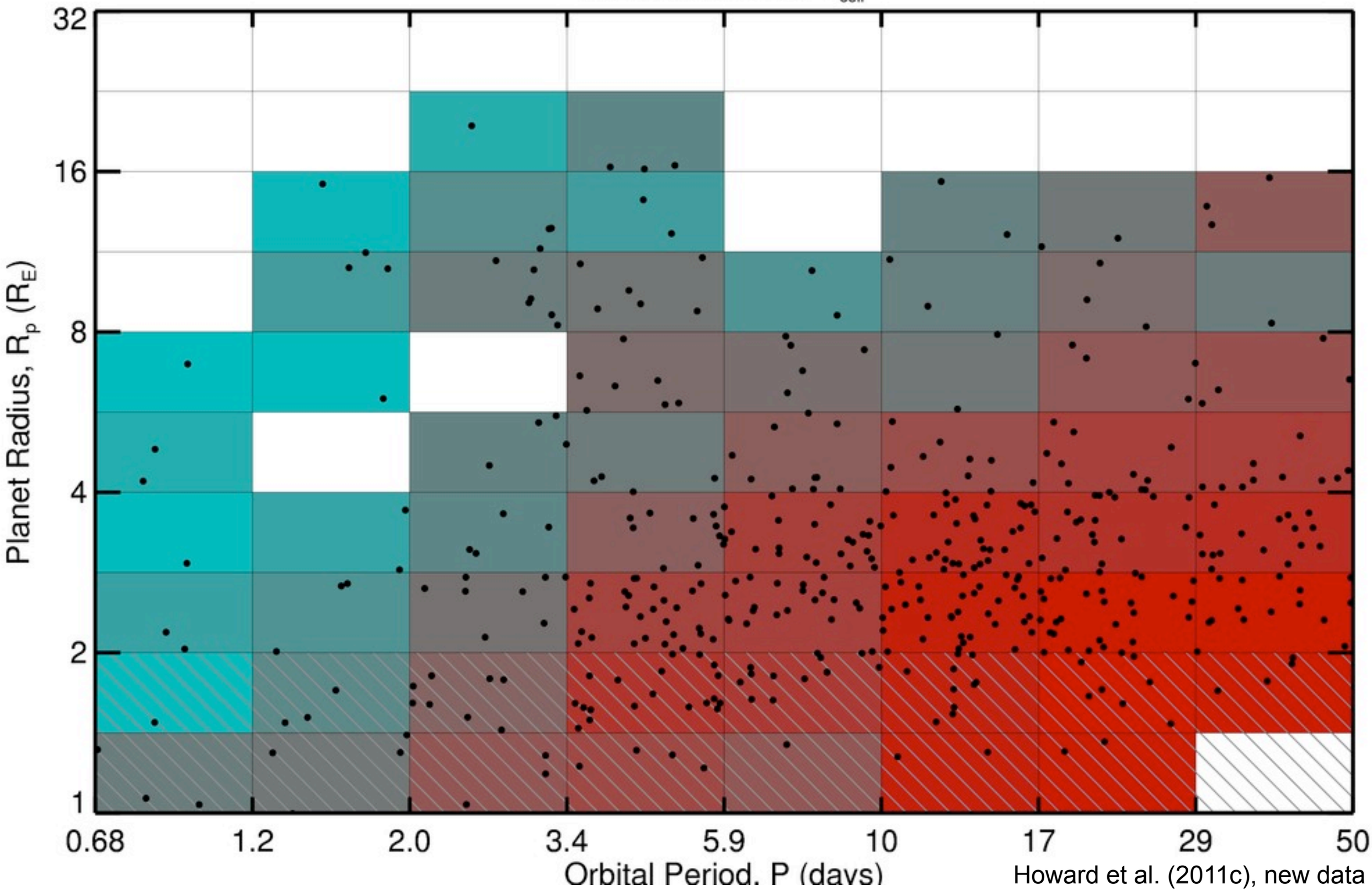
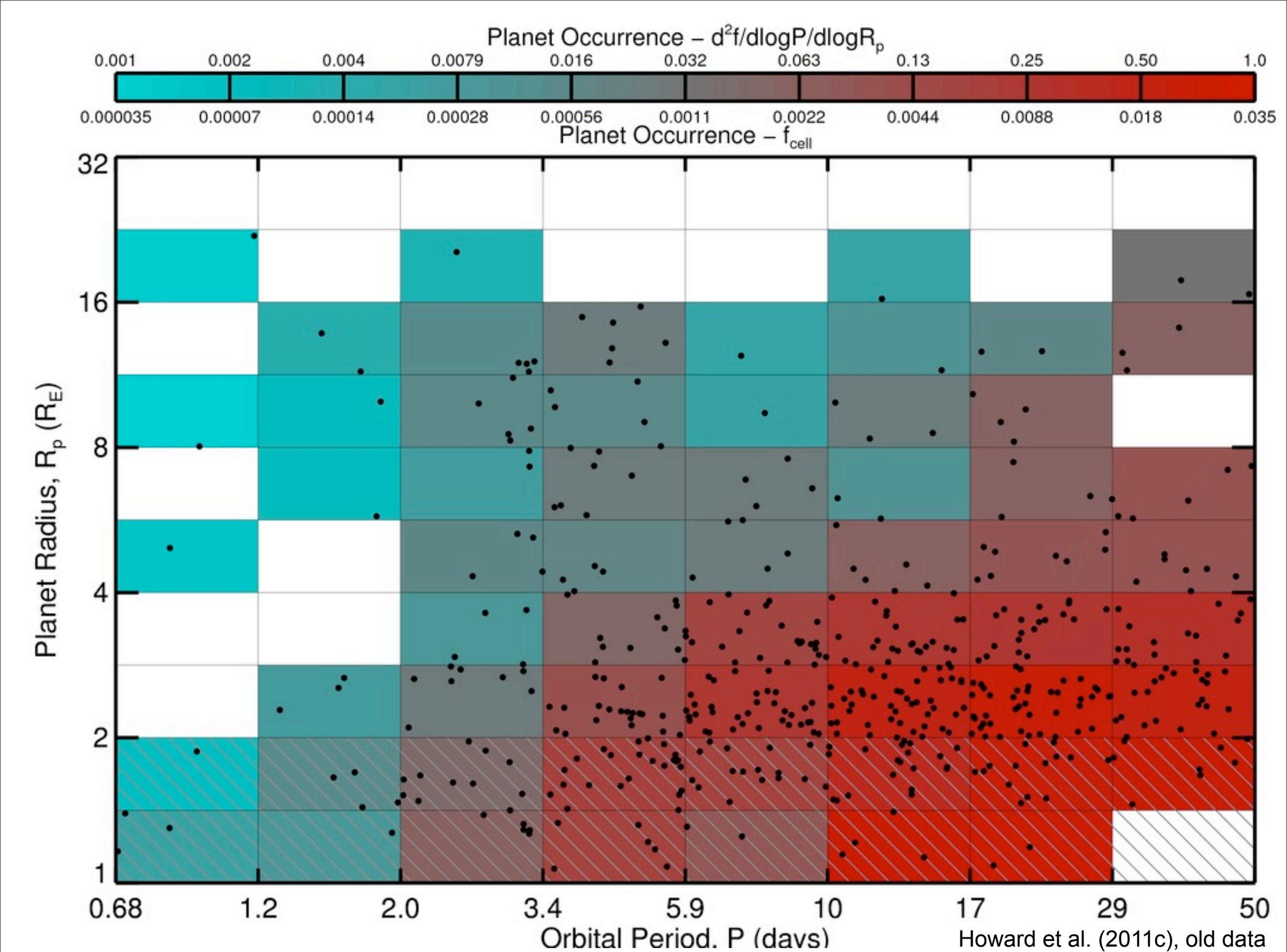
Planet Occurrence – $d^2f/d\log P/d\log R_p$

| 0.001 | 0.002 | 0.004 | 0.0079 | 0.016 | 0.032 | 0.063 | 0.13 | 0.25 | 0.50 | 1.0 |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.000035 | 0.00007 | 0.00014 | 0.00028 | 0.00056 | 0.0011 | 0.0022 | 0.0044 | 0.0088 | 0.018 | 0.035 |

Planet Occurrence – $f_{cell}$

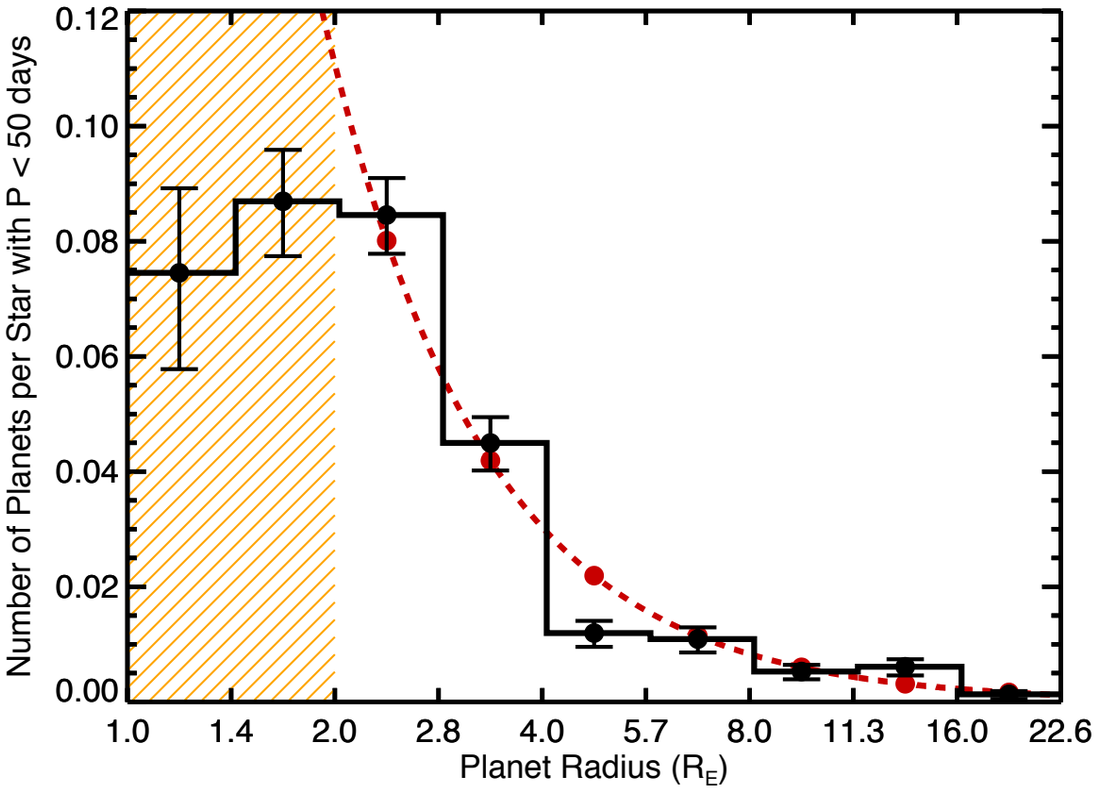



Howard et al. (2011c), new data


Planet Occurrence – d²f/dlogP/dlogR_p
0.001
0.002
0.004
0.0079
0.016
0.032
0.063
0.13
0.25
0.50
1.0
0.000035
0.00007
0.00014
0.00028
0.00056
0.0011
0.0022
0.0044
0.0088
0.018
0.035
Planet Occurrence – f_cell
32
16
8
4
2
1
Planet Radius, R_p (R_E)
0.68
1.2
2.0
3.4
5.9
10
17
29
50
Orbital Period, P (days)
Howard et al. (2011c), old data

# Planet Radius Distribution

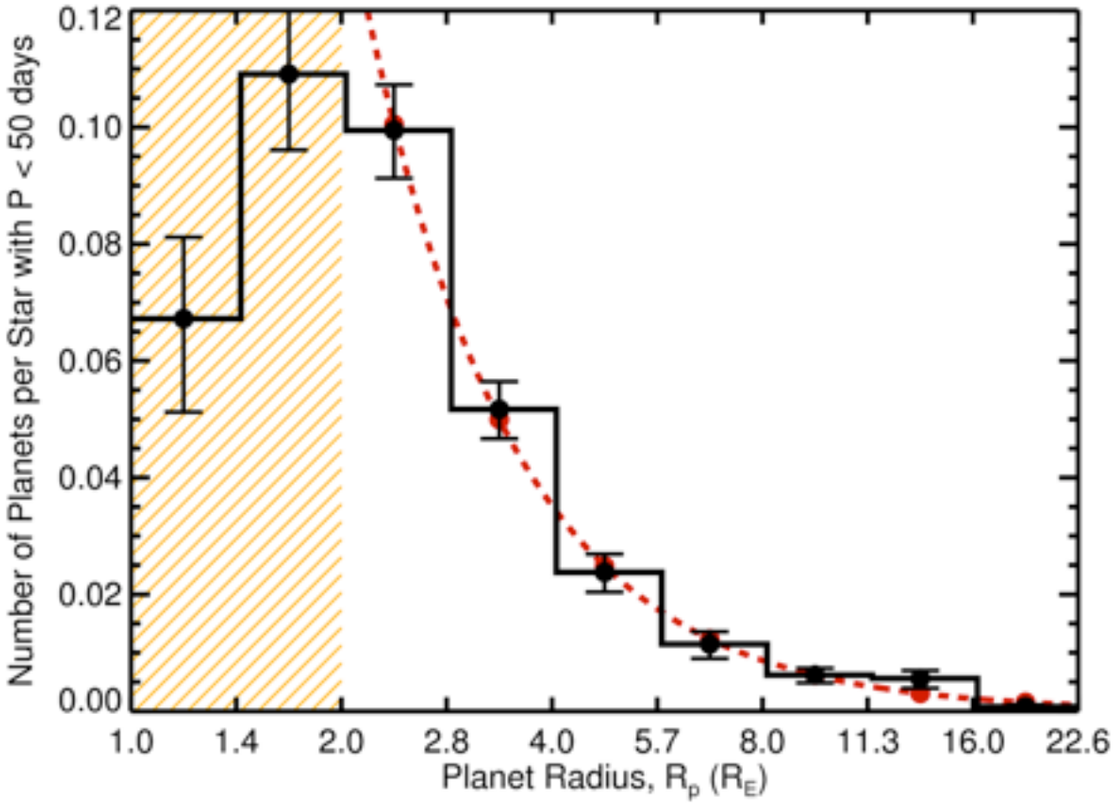
## Feb 2011 data (Borucki et al. 2011)




$k = 2.9 \pm 0.5$

$\alpha = -1.92 \pm 0.11$

## Sep 2011 data (N. Batalha's talk)




$k = 3.8 \pm 0.3$

$\alpha = -2.01 \pm 0.09$

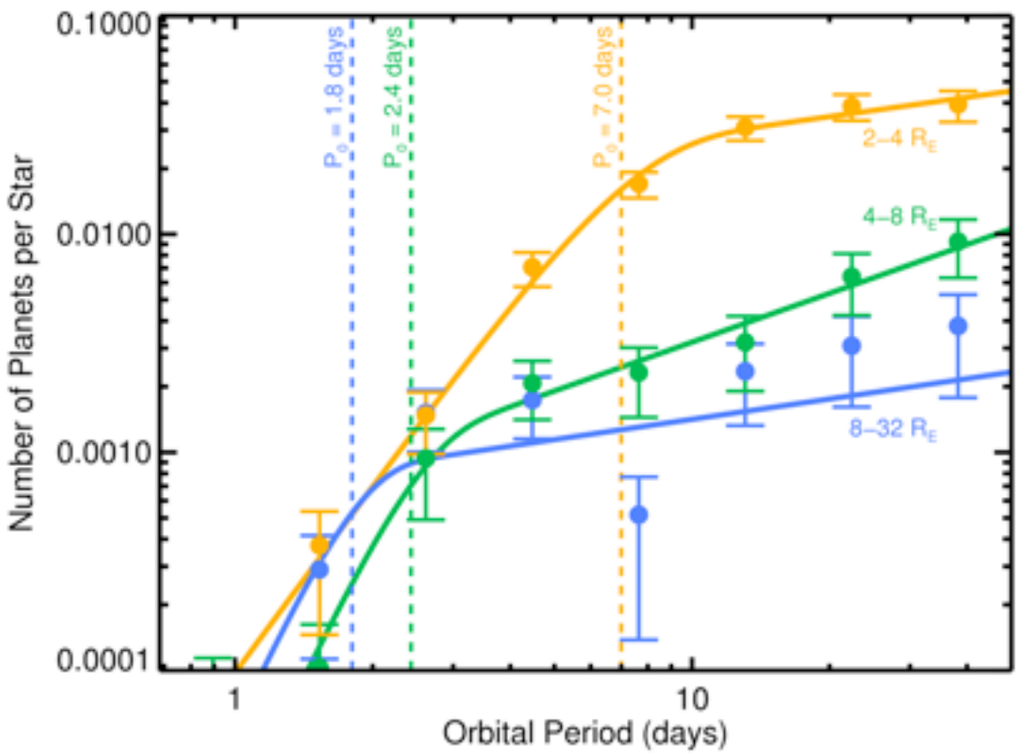
Power law:

$dN/d\log R = kR^{\alpha}$

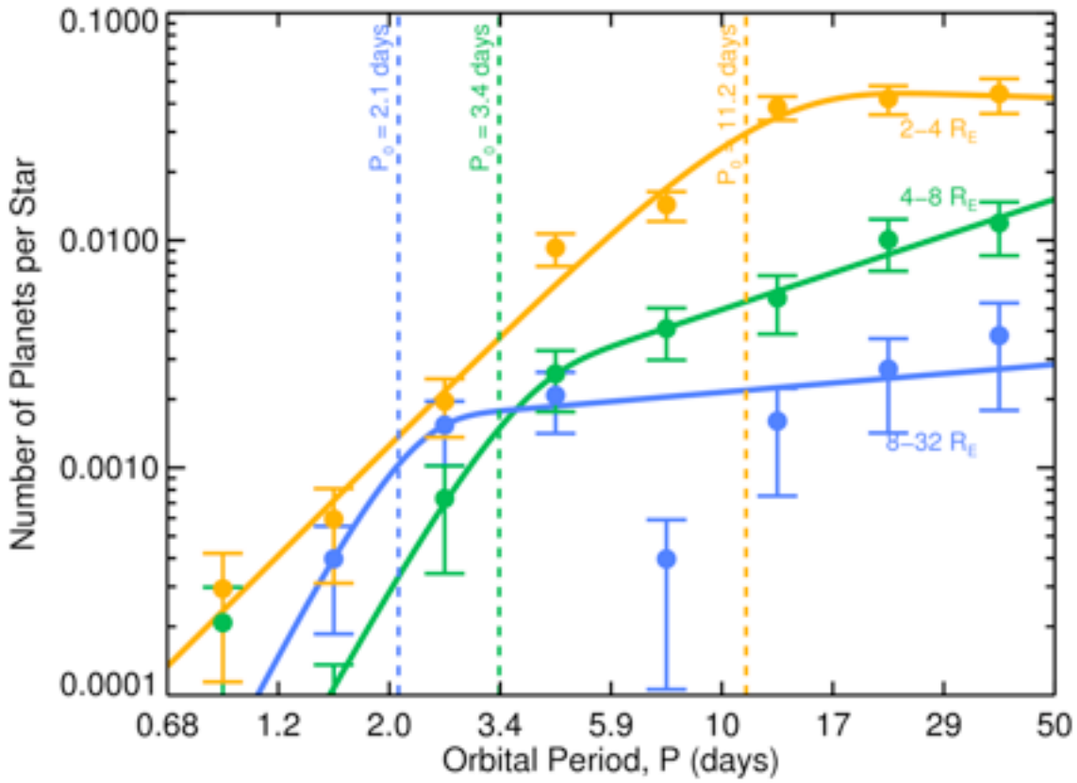
Howard et al. (2011c)

# Planet Period Distribution

## Feb 2011 data (Borucki et al. 2011)

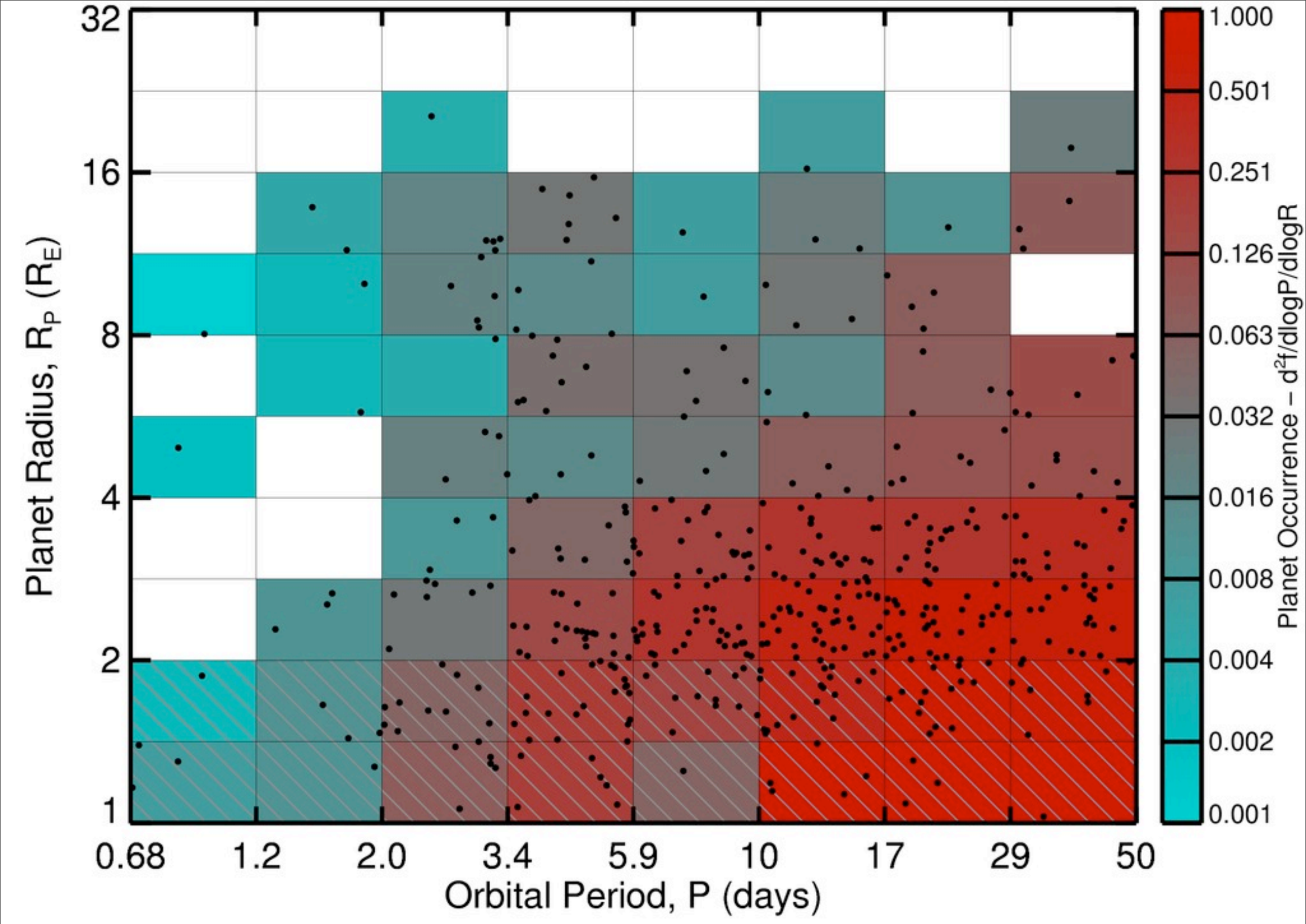



## Sep 2011 data (N. Batalha's talk)

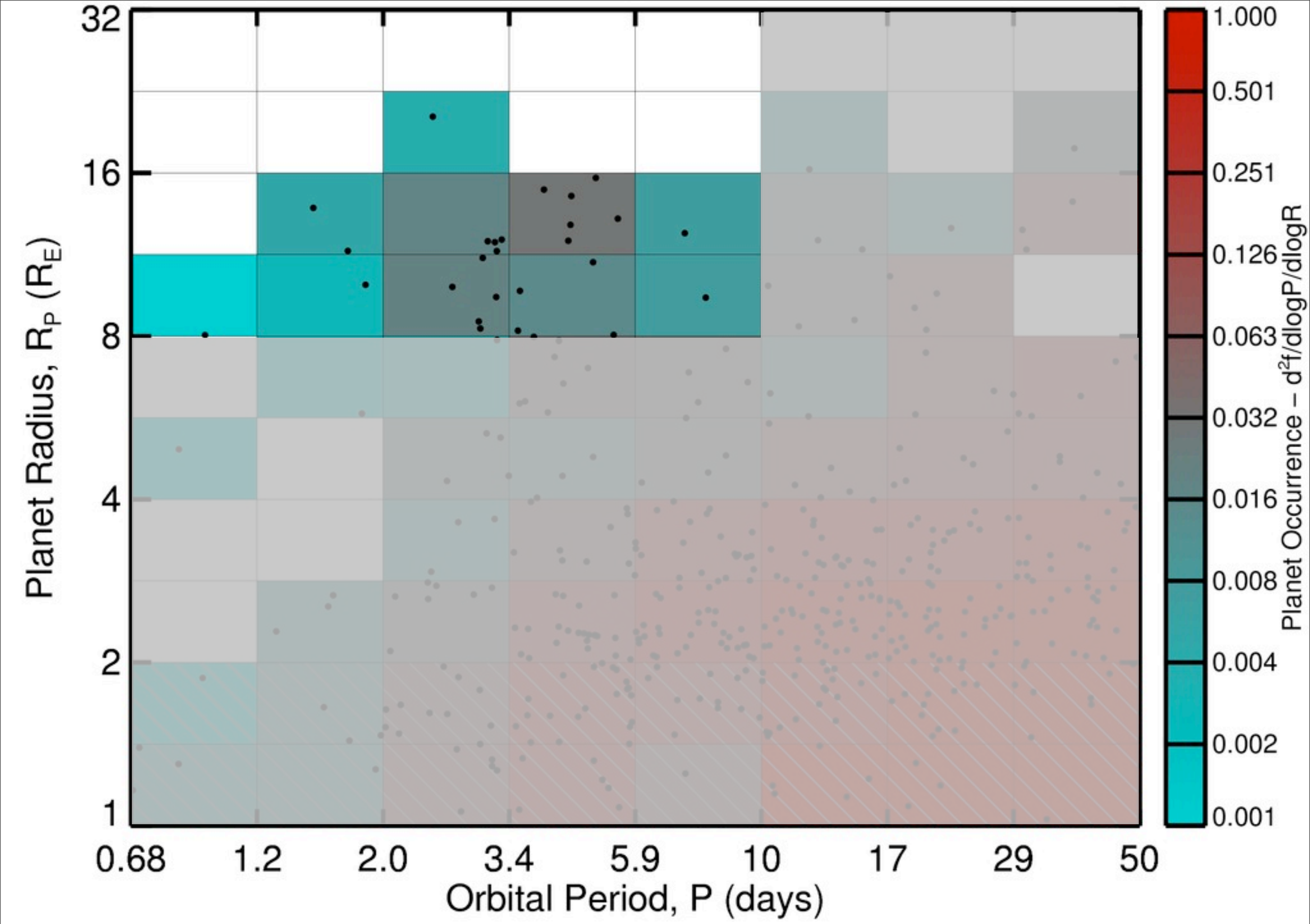



D. Tsang's theory for different pile-up radii (2011, arXiv:1107.4069):
Small planets pile-up farther out because density waves reflect off of inner disk boundary and stop small planets, but not large planets

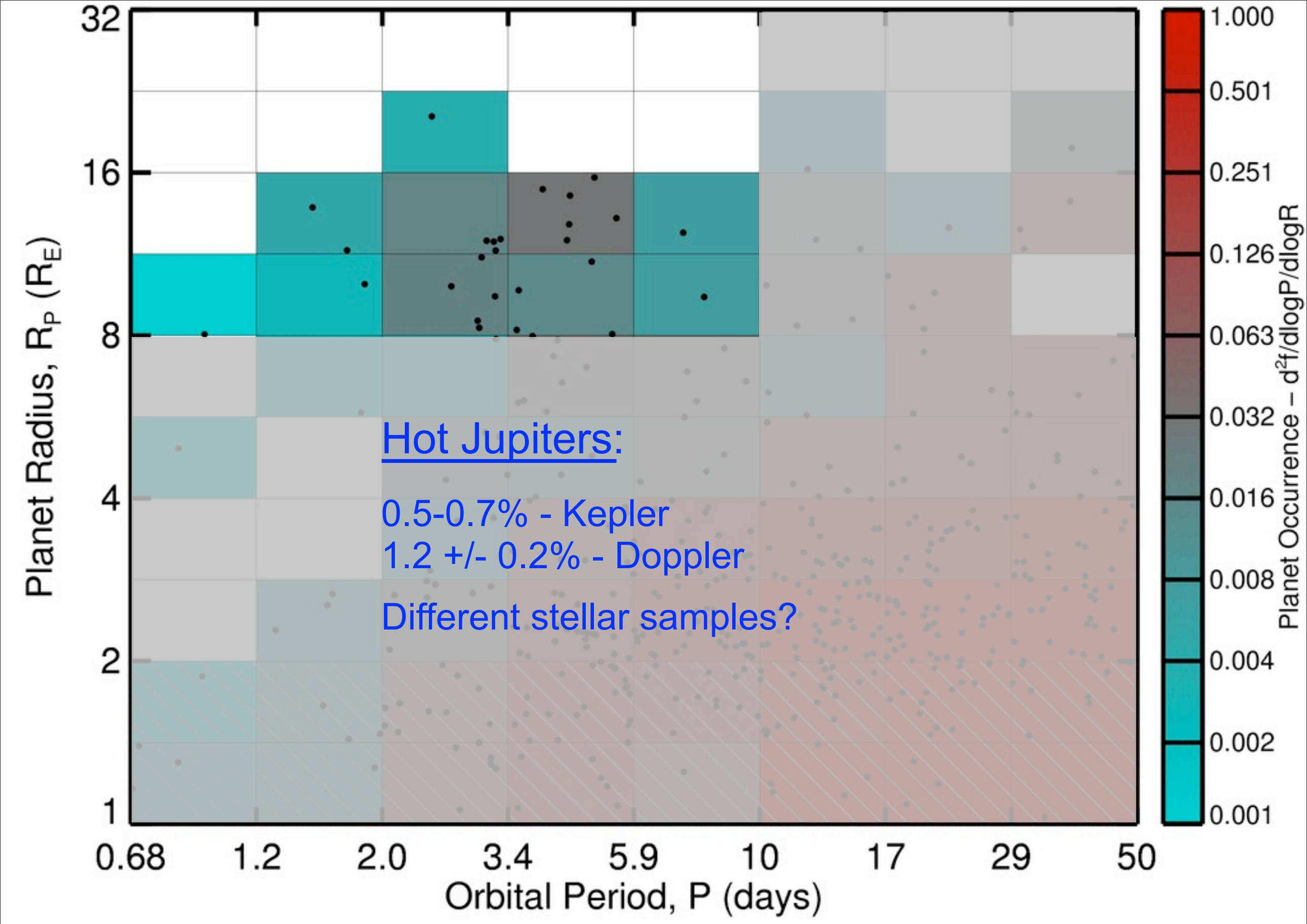
Howard et al. (2011c)




Howard et al. (2011c)



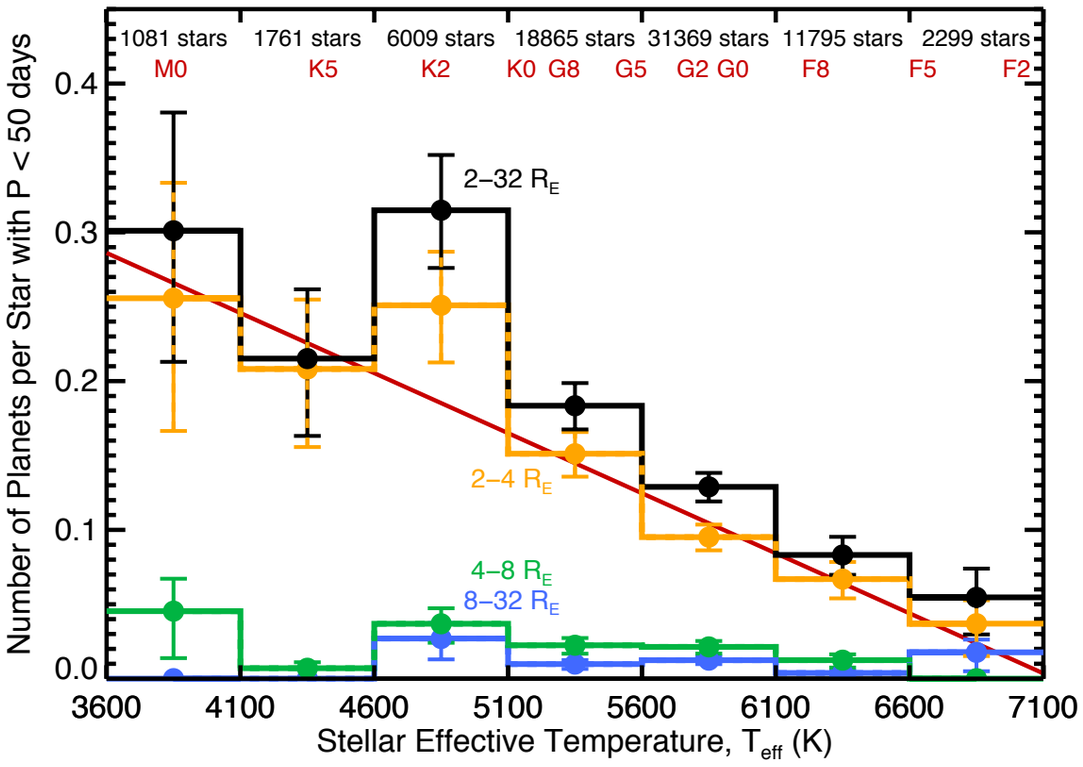

Howard et al. (2011c)



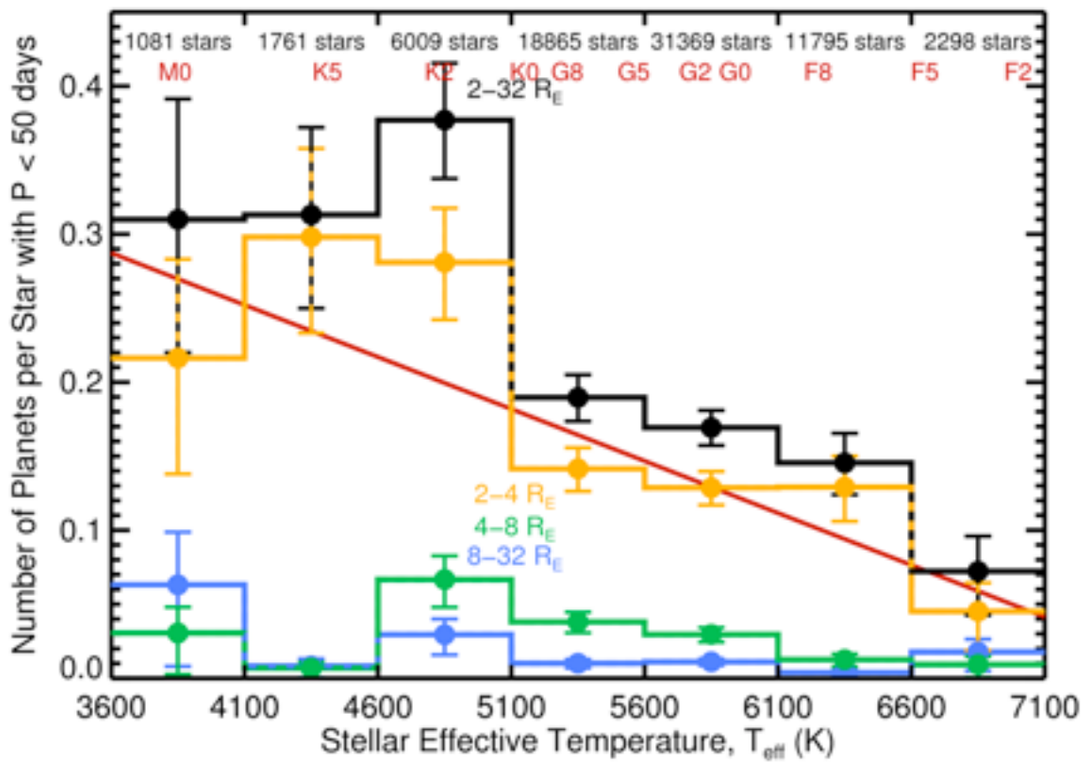

Howard et al. (2011c)

# Planet Occurrence vs. Stellar Temperature

## Feb 2011 data (Borucki et al. 2011)




## Sep 2011 data (N. Batalha's talk)

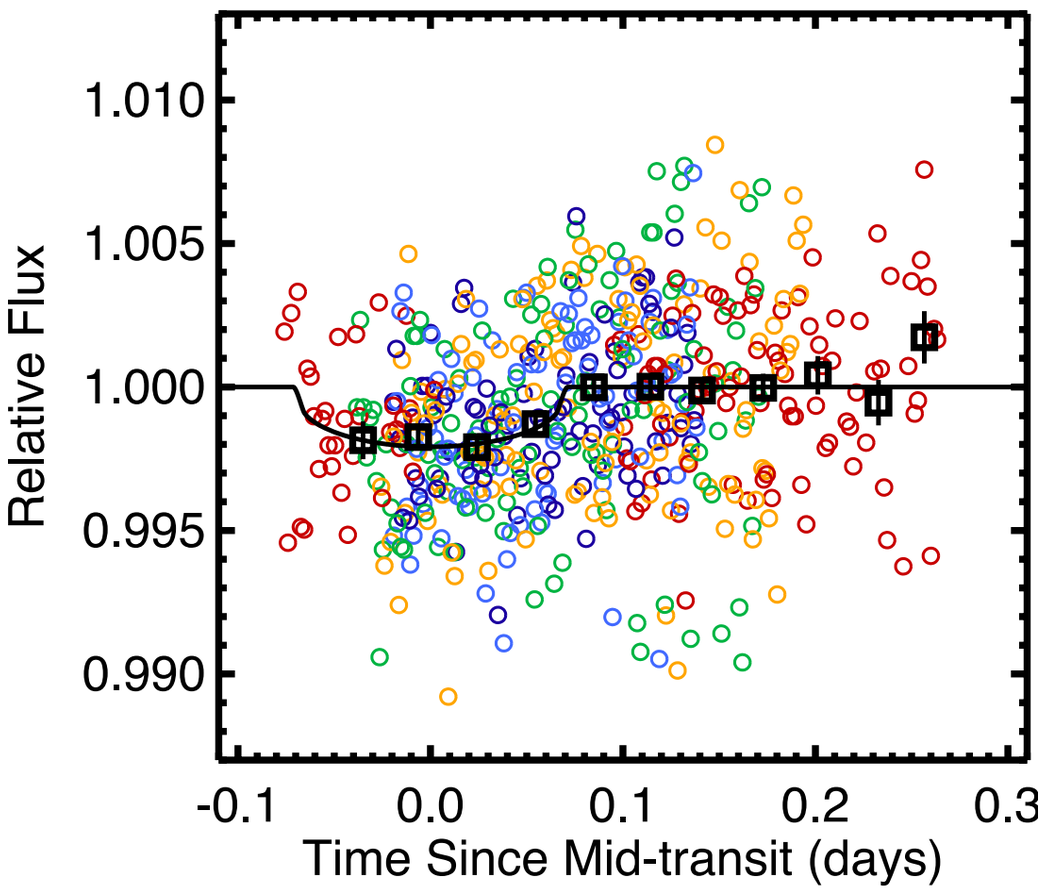


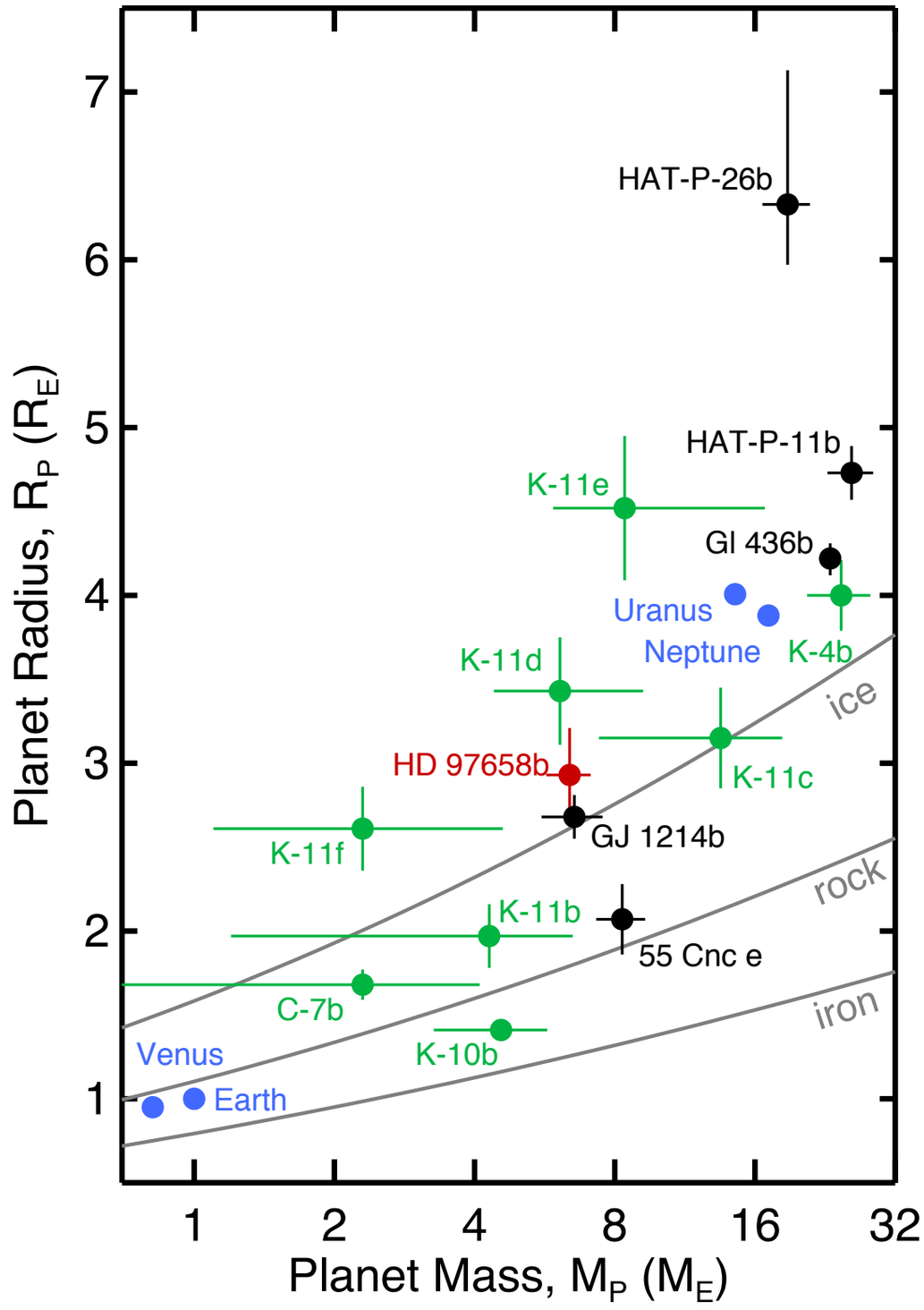

Howard et al. (2011c)

# HD 97658b - Photometry by Greg Henry (TSU)

## HD 97658b

Mass = 6.4 ± 0.7 $M_E$
Radius = 2.93 ± 0.28 $R_E$
Density = $1.4^{+0.5}_{-0.4}$ g cm$^{-3}$
Period = 9.4957 ± 0.0022 days
$T_{eq}$ = 510-720 K
Star = K1 V




Henry, Howard, Marcy, Fischer, Johnson (2011, ApJ, submitted)

Questions?

# Absolute Planet Occurrence

Teff=4100-6100 K
logg = 4.0-4.9
Kp < 15
SNR > 10 (90 days)

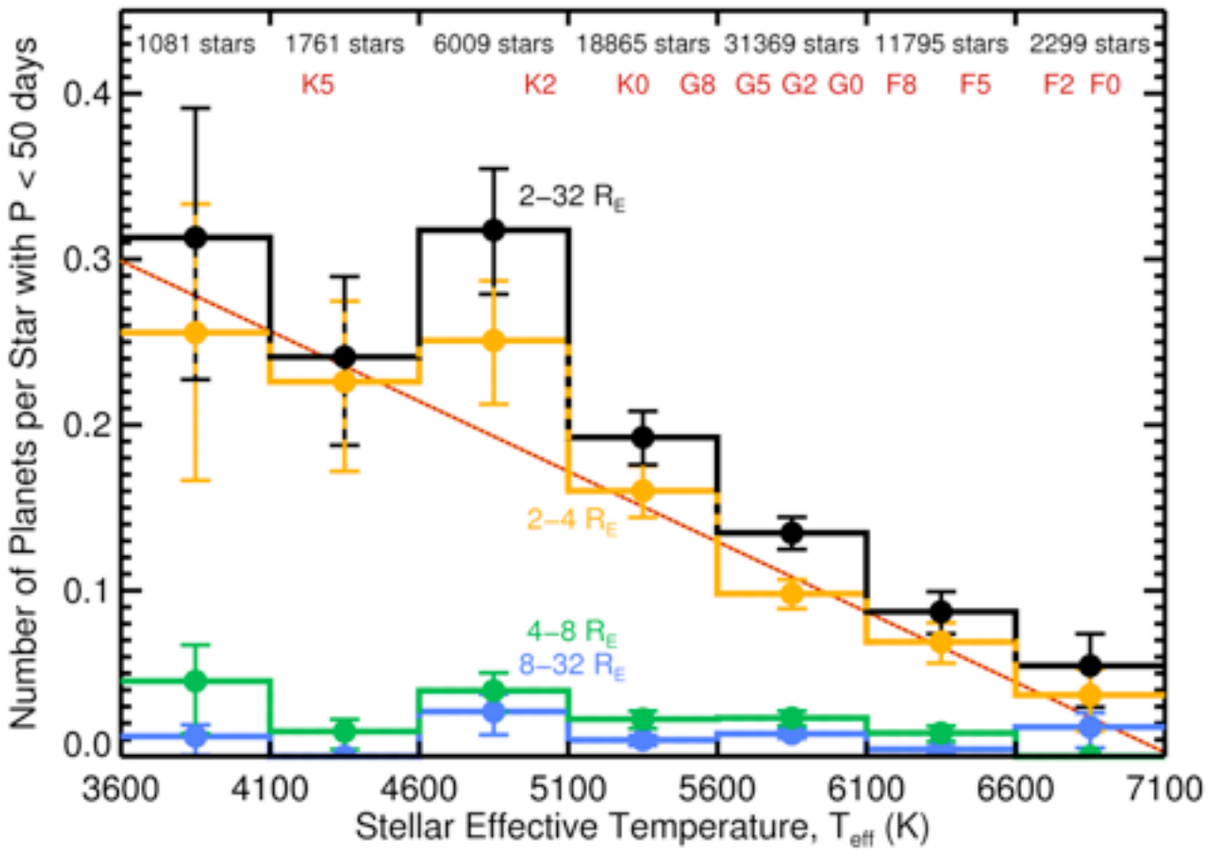
Feb 2011 data
(Borucki et al. 2011)

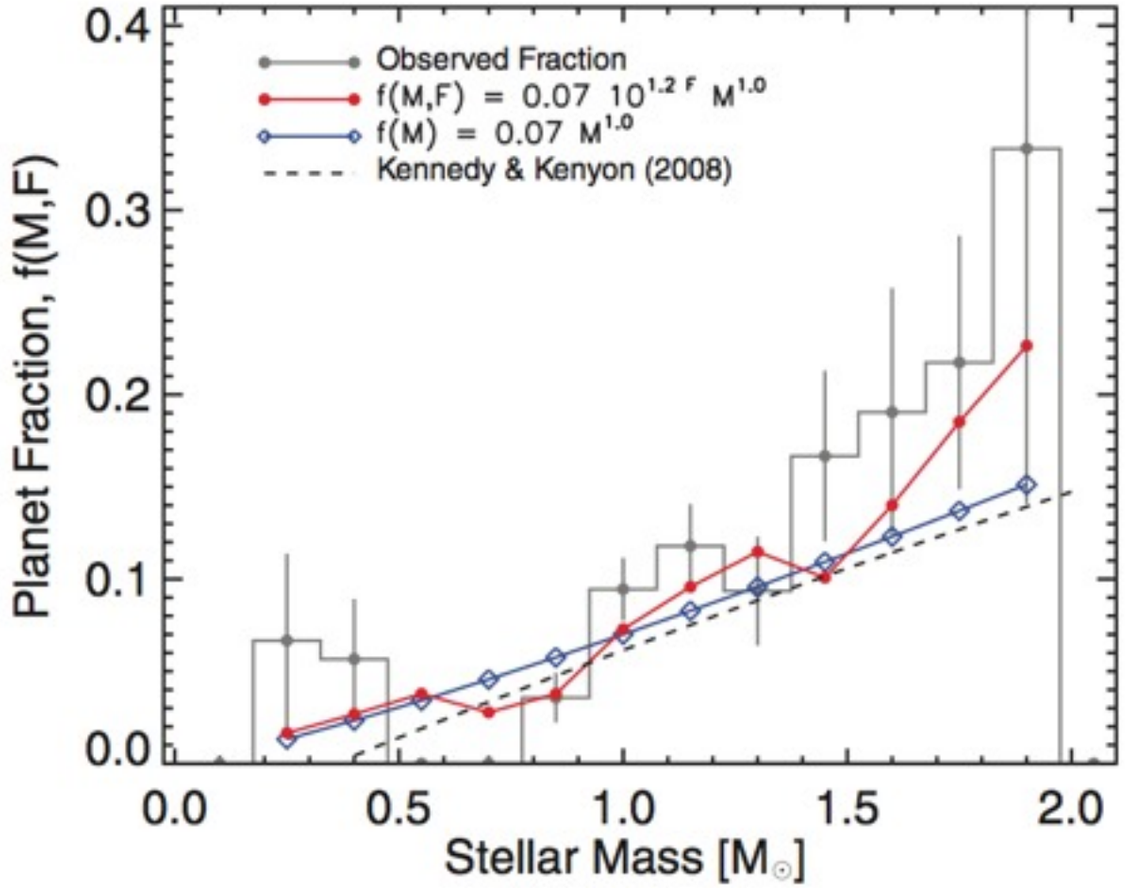
| Rp | occurrence |
|---|---|
| 2-4 Re | → 13% |
| >2 Re | → 16.5% |

Sep 2011 data
(N. Batalha's talk)

| Rp | occurrence |
|---|---|
| 2-4 Re | → 15% |
| >2 Re | → 20% |

# Planet Occurrence vs. $M_\star$



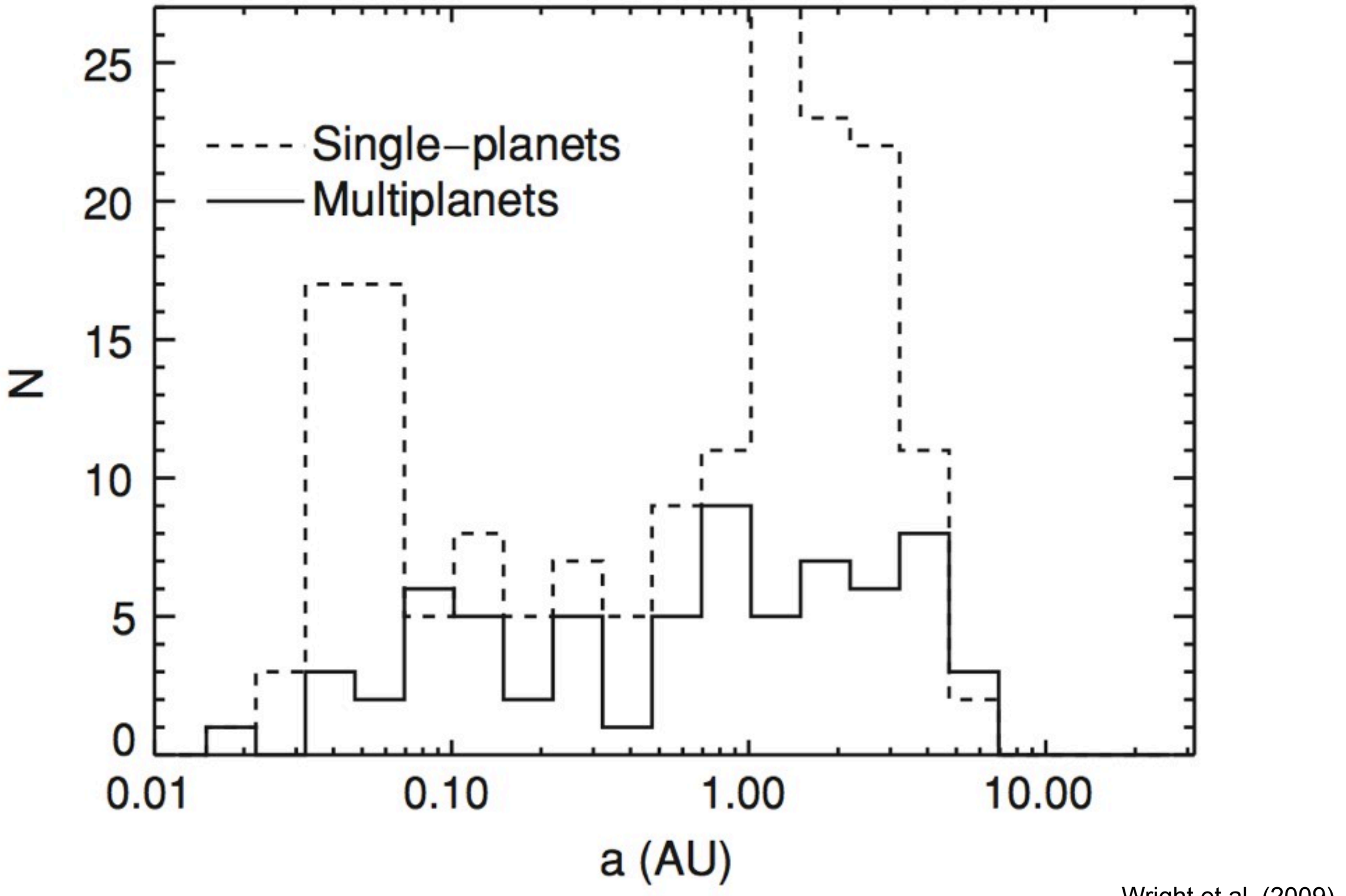

Occurrence within .25 AU of small planets *decreases* with $M_\star$

Howard et al. (2011c)

Occurrence within 2.5 AU of giant planets *increases* with $M_\star$

Johnson et al. (2010)

# Jovian Planets




Wright et al. (2009)