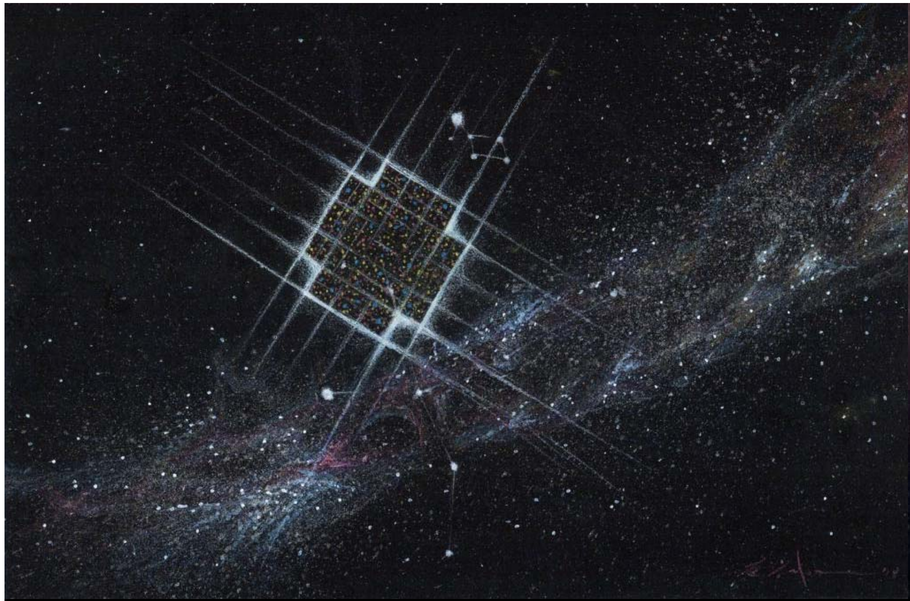

Images: Pale Blue Dots (K. Mora) & KOI-961 (NASA/JPL-Caltech)

The Prevalence of Small Planets Around Small Stars from Kepler

Courtney Dressing

& David Charbonneau

Harvard-Smithsonian Center for Astrophysics

Porto, Portugal

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& NASA Kepler PSP awarded to DC

15 September 2014


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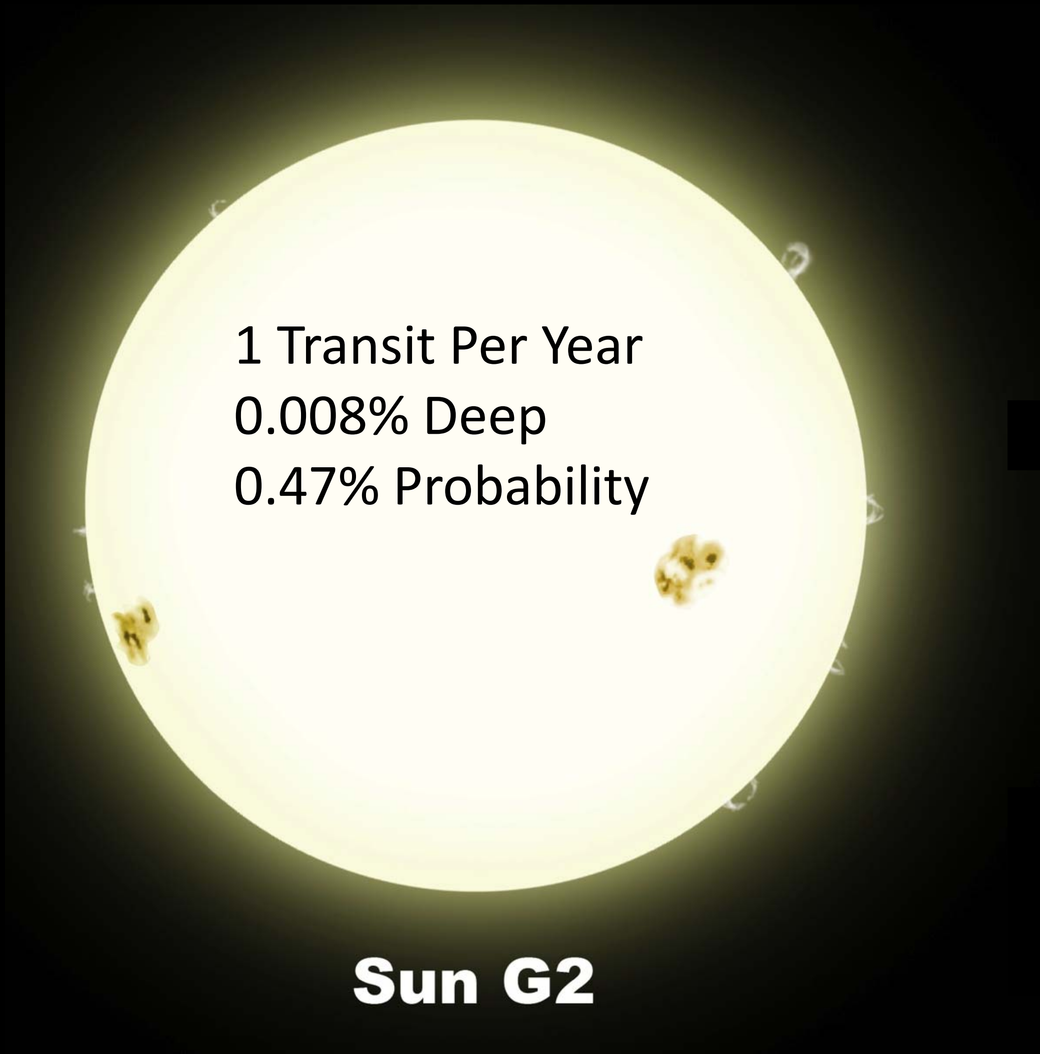
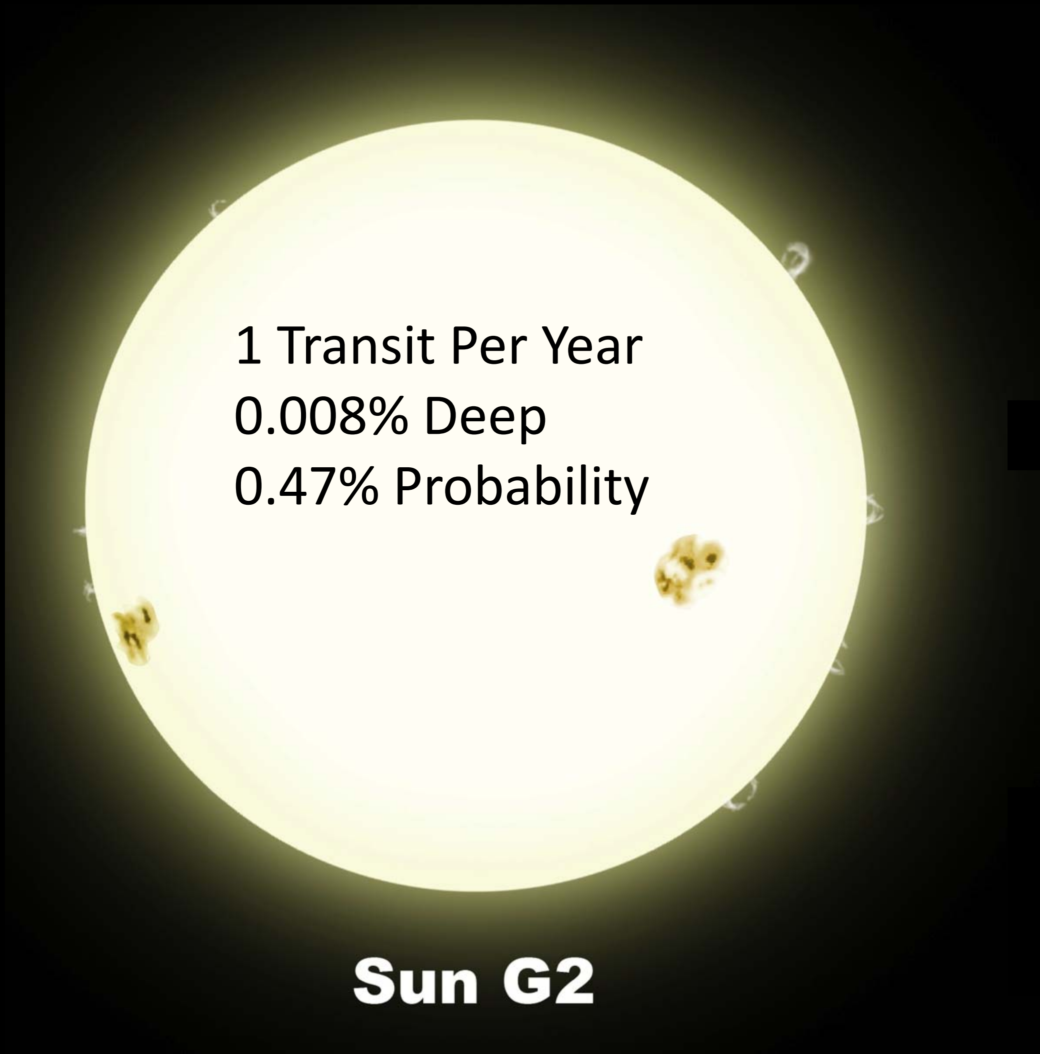
Targeting Planets
Around Small Stars
CARMENES
SPECULOOS
SPIRou
HPF
MEarth &
MEarth-South
ExTrA

The M Dwarf Advantage



The M Dwarf Advantage

1 Transit Per Year
0.008% Deep
0.47% Probability

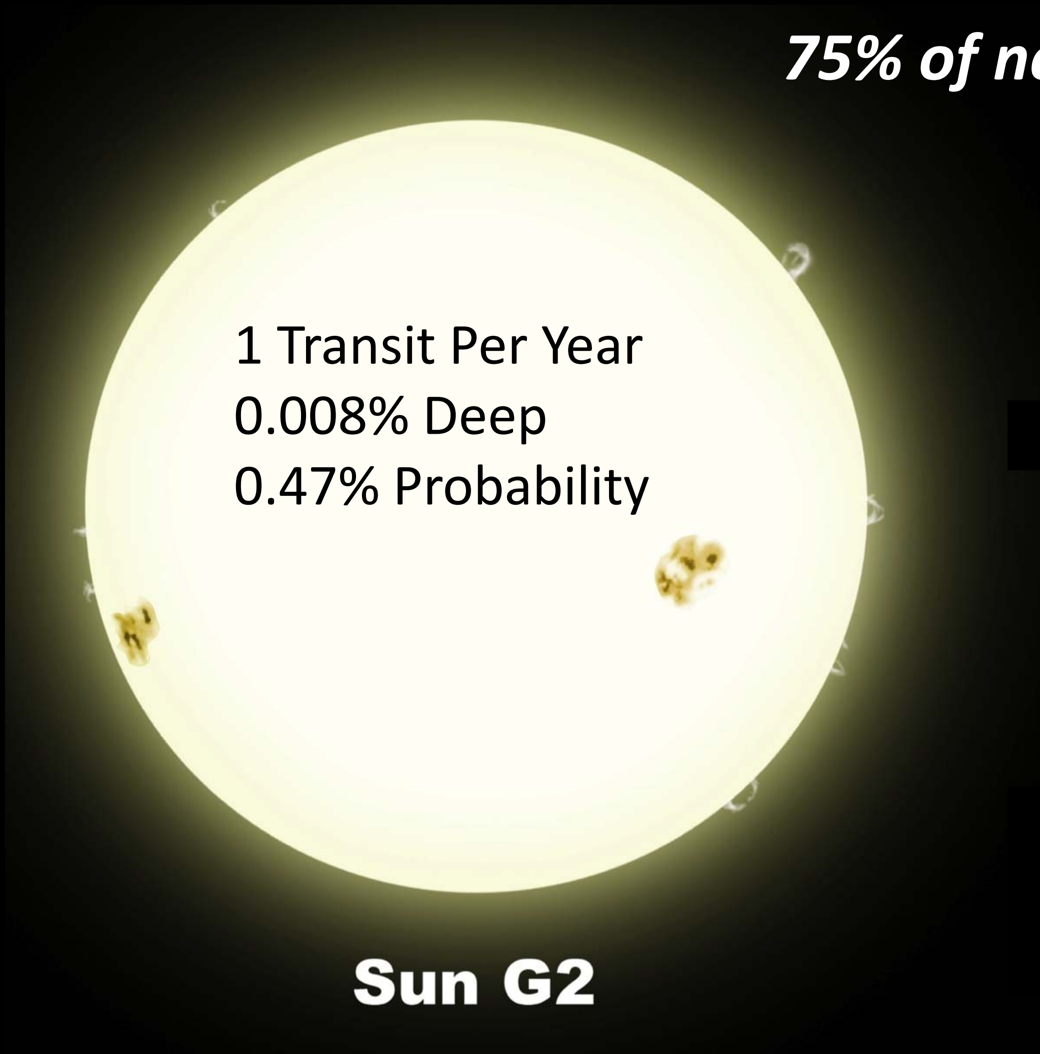


12 Transits Per Year
0.13% Deep
1.4% Probability

The M Dwarf Advantage

75% of nearby stars are M dwarfs

1 Transit Per Year
0.008% Deep
0.47% Probability



12 Transits Per Year
0.13% Deep
1.4% Probability

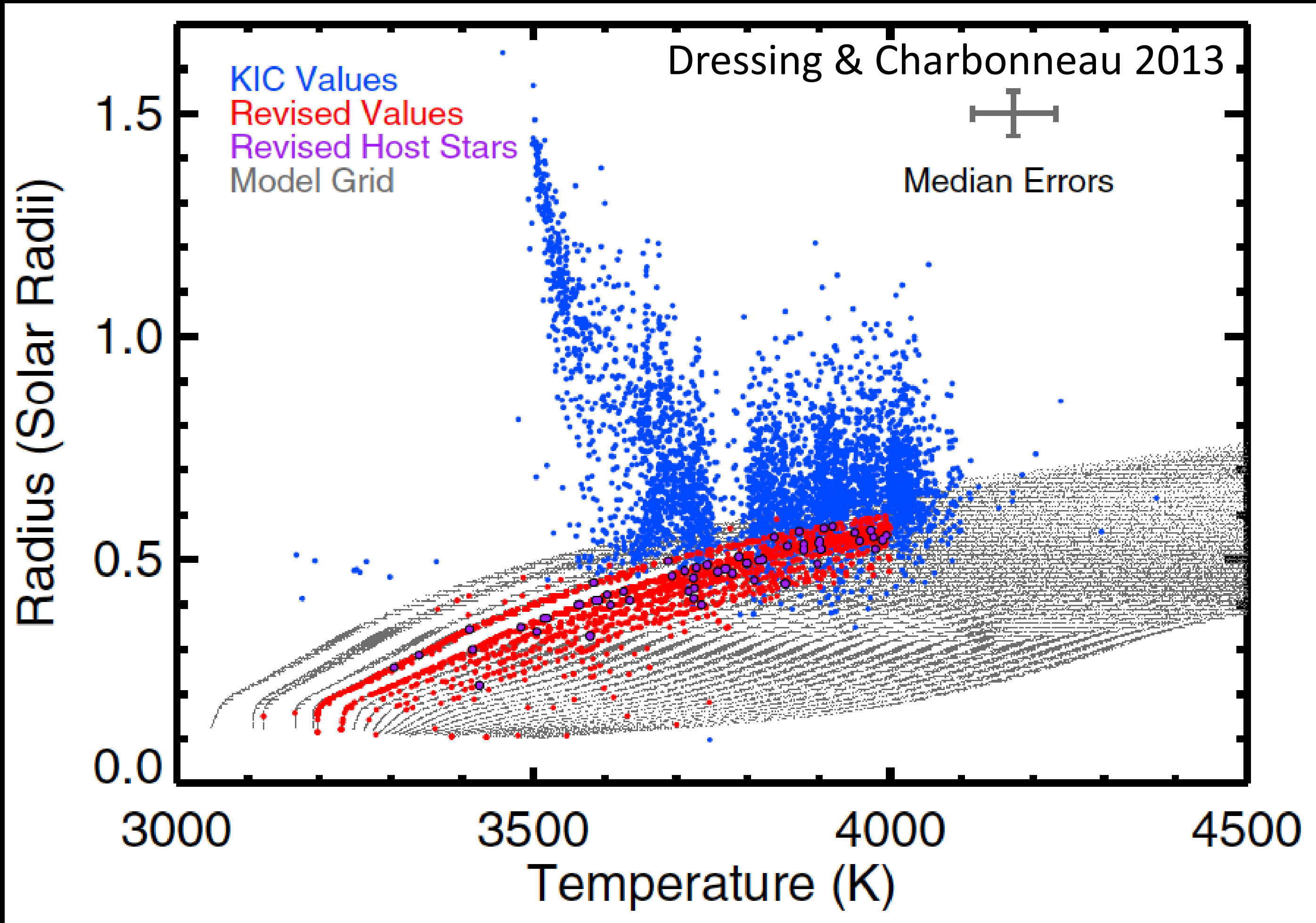
Computing the Planet Occurrence Rate

$$\text{Occurrence} = \frac{\overset{\text{Actual}}{\text{Number of Planets}}}{\underset{\text{Searched}}{\text{Number of Stars}}}$$

Important Corrections:

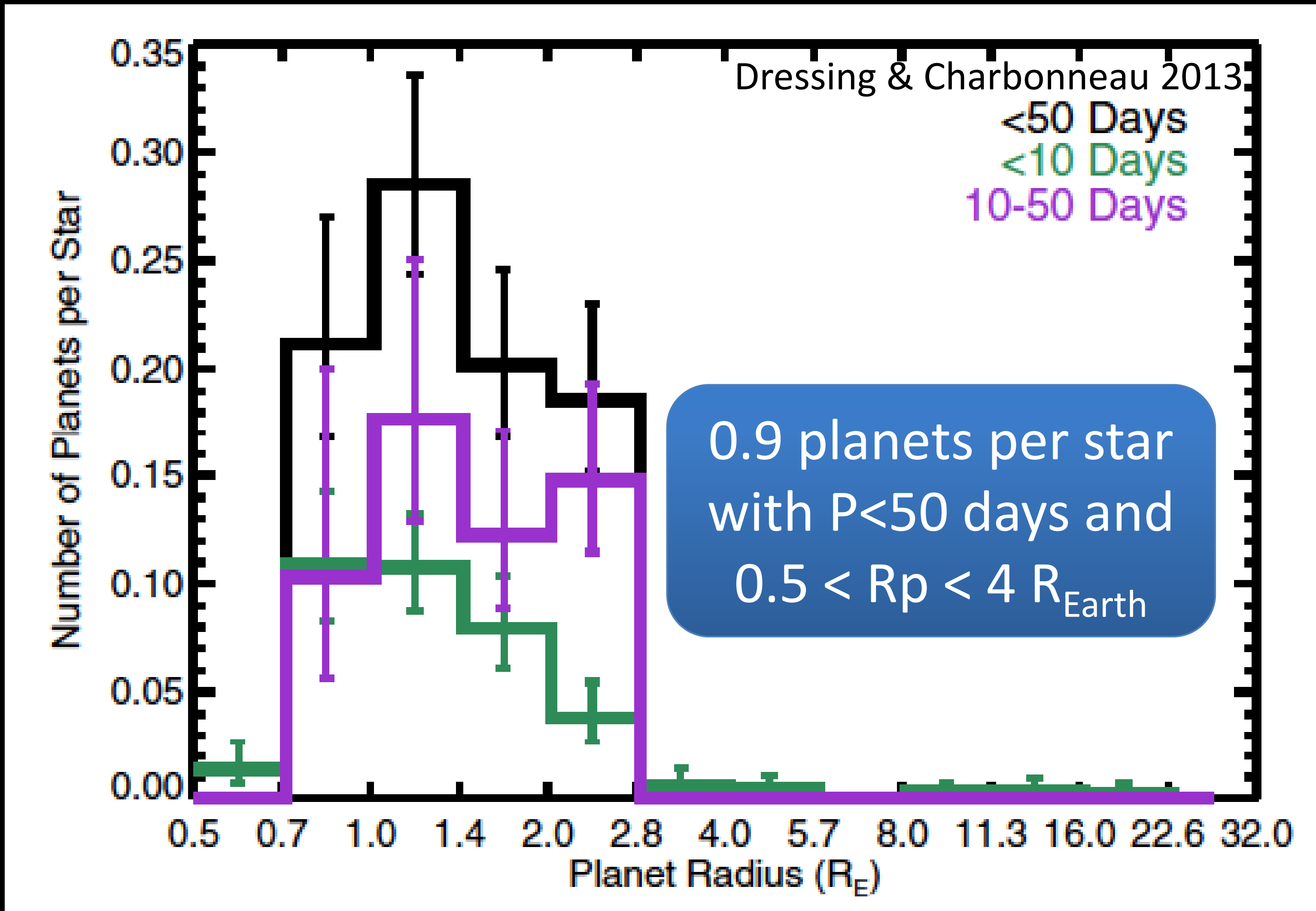
- ***We are not sensitive to all planets.***
- ***Some ``planets'' might be false positives.***

Revised Stellar Parameters for Kepler M Dwarfs



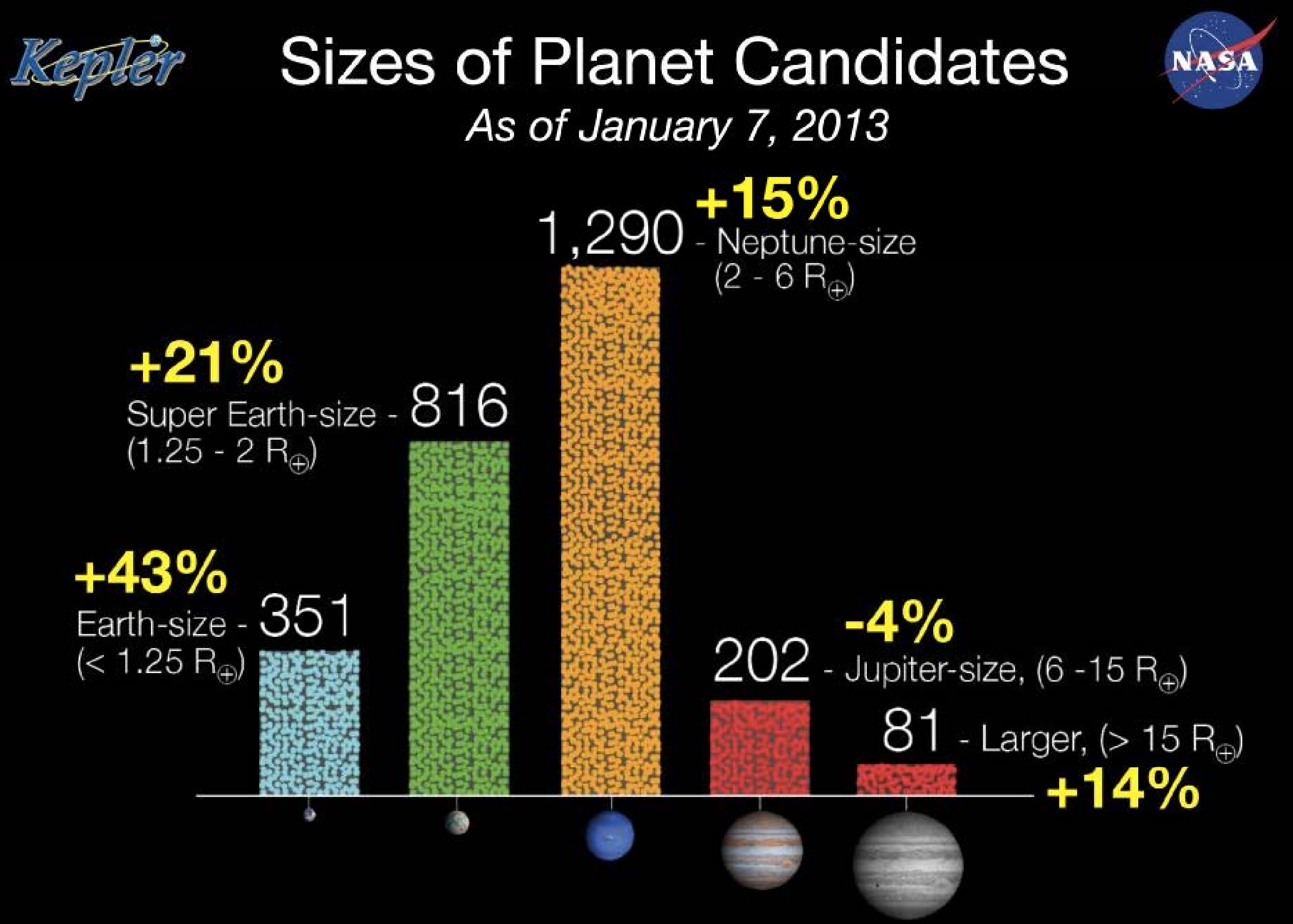
Fit KIC photometry (Brown+ 2011) to Dartmouth stellar models (Dotter+ 2008, Feiden+ 2011) using priors on [Fe/H] and galactic height (Casagrande+ 2008)

Our 2013 Planet Occurrence Estimate



0.15 (+0.13/-0.06) **Earth-size planets per HZ**

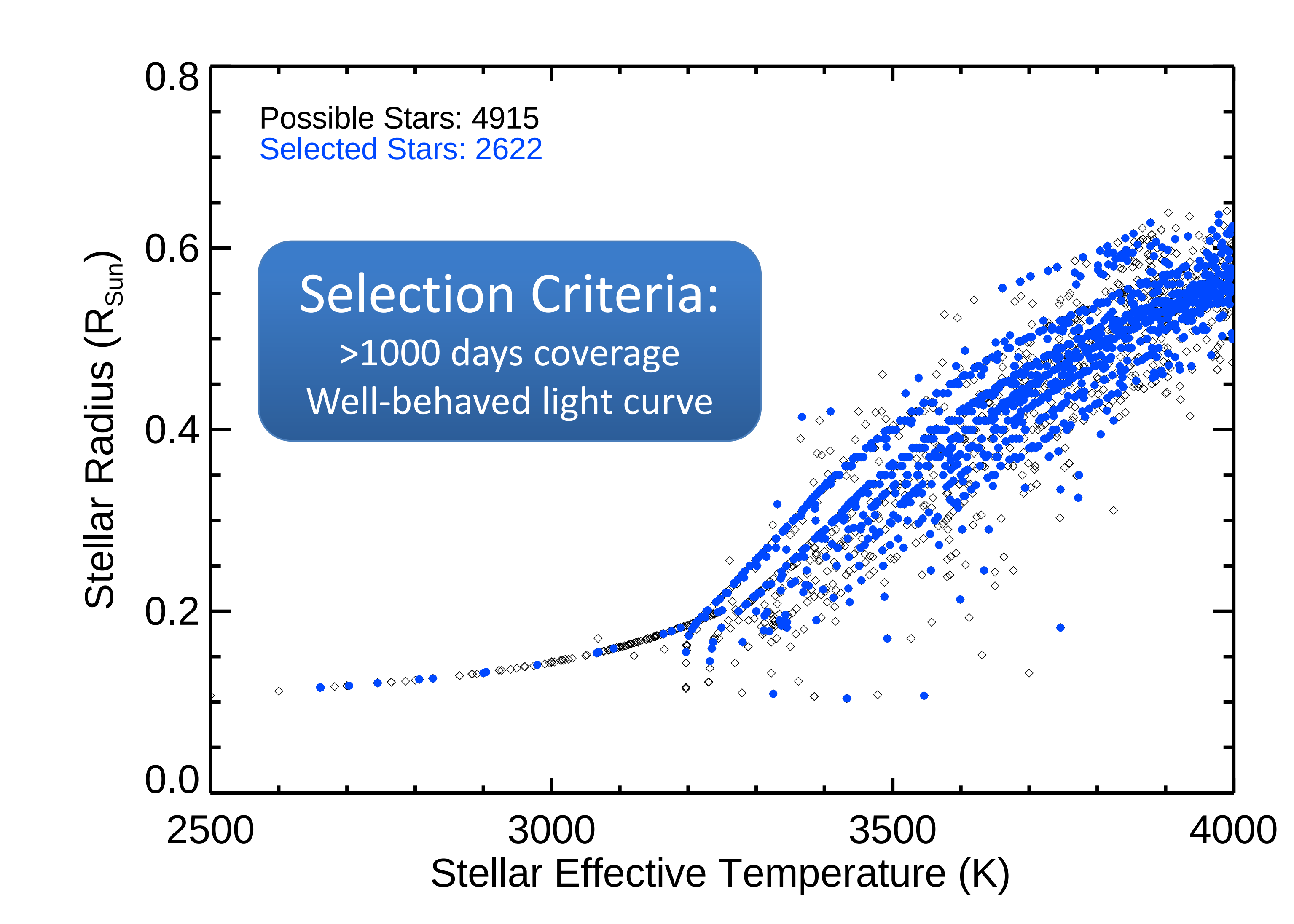
Improvement 1: **More Data**



Comparison of January 2013 and February 2012 KOI lists

Image Credit: NASA

Improvement 2: Refined Small Star Sample



Data from Kepler Stellar Properties Table at the NASA Exoplanet Archive (Huber et al. 2014)

Improvement 3:

MEASURED PIPELINE COMPLETENESS

Our Planet Detection Pipeline

Detrend & clean Kepler light curves

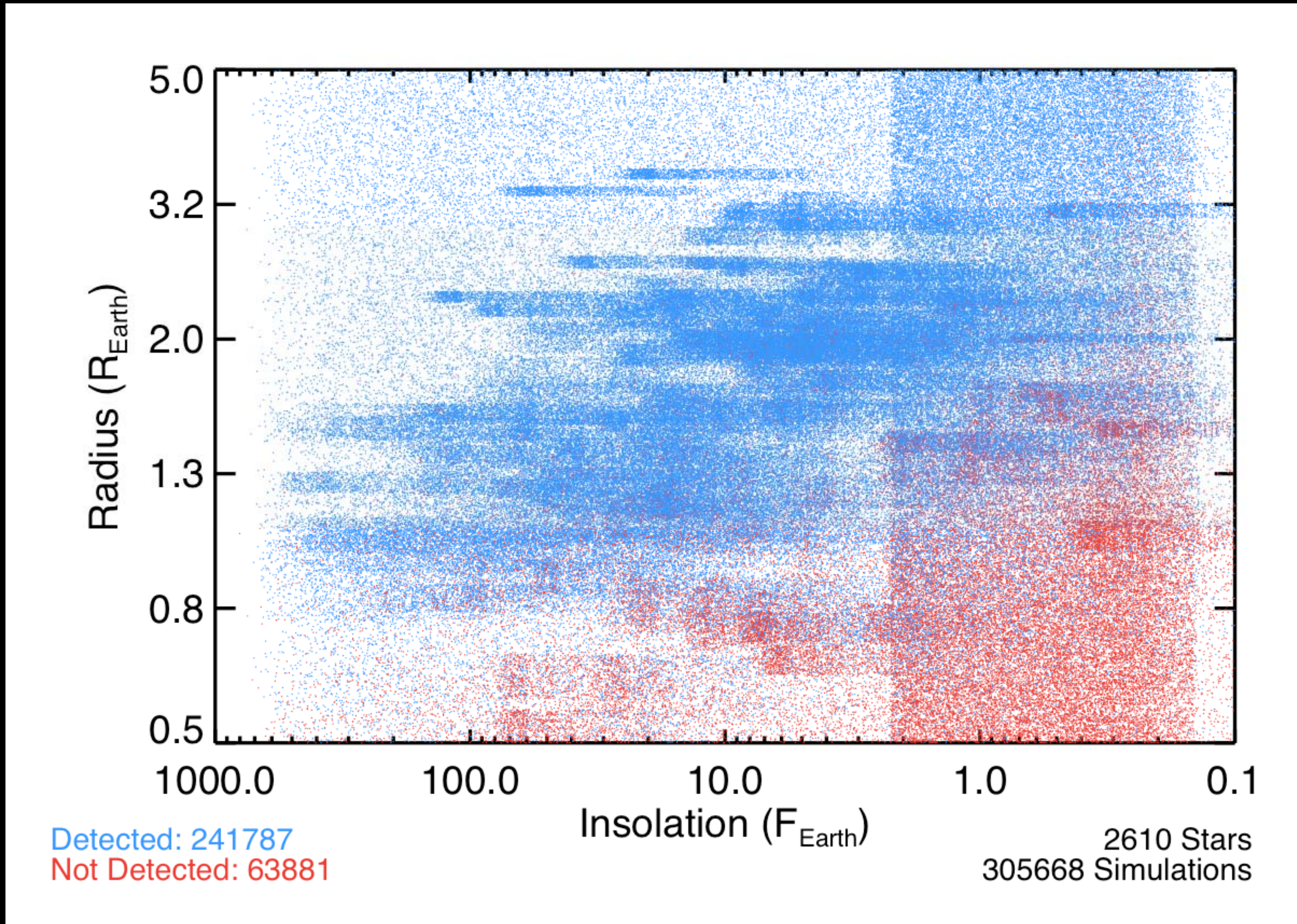
Generate Box-fitting Least Squares power spectrum for each star
(Scott Fleming's Fortran implementation of Kovacs et al. 2002)

Identify highest peaks & fit simple transit models

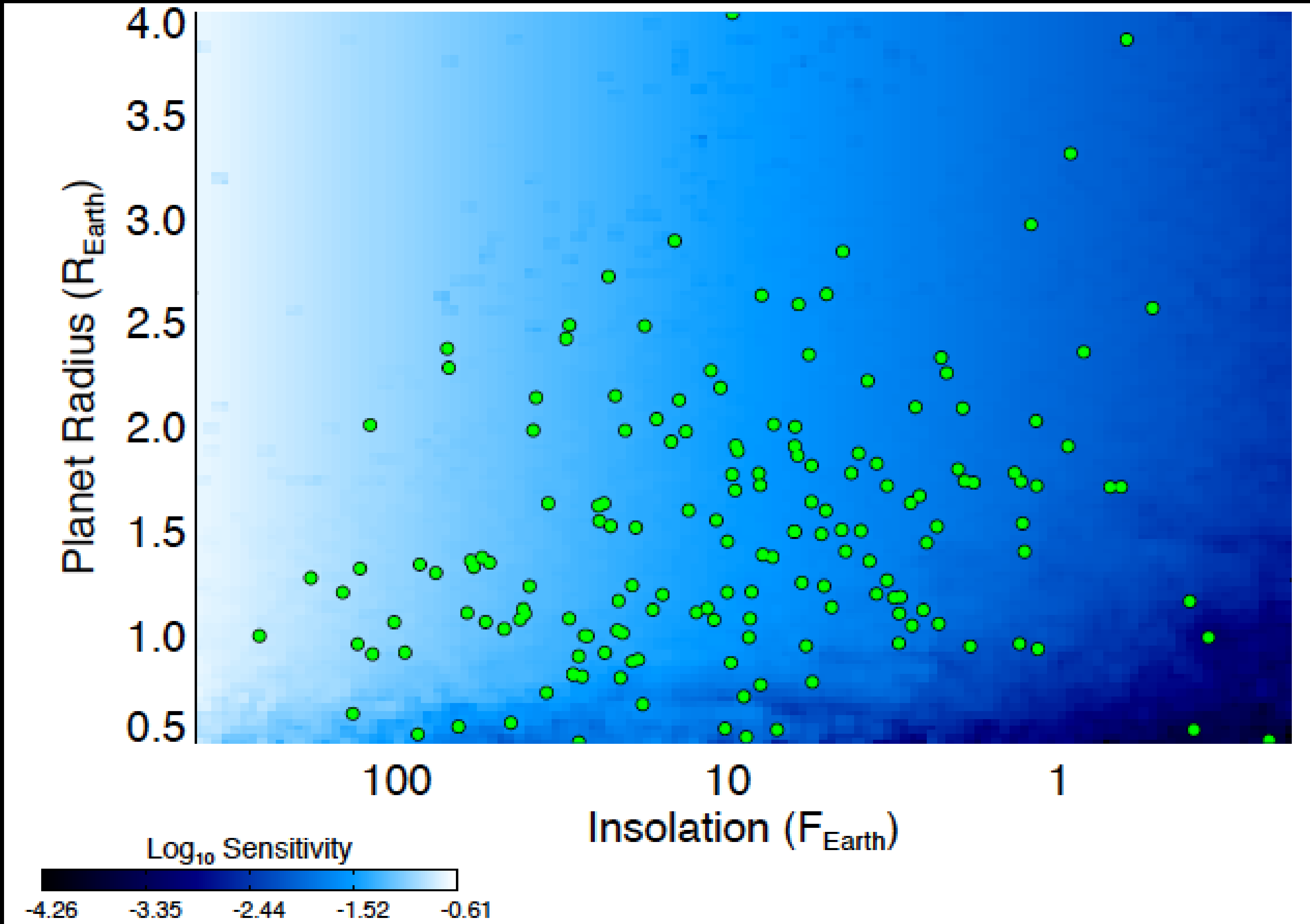
Excise data near accepted transits

Repeat until no new signals are detected

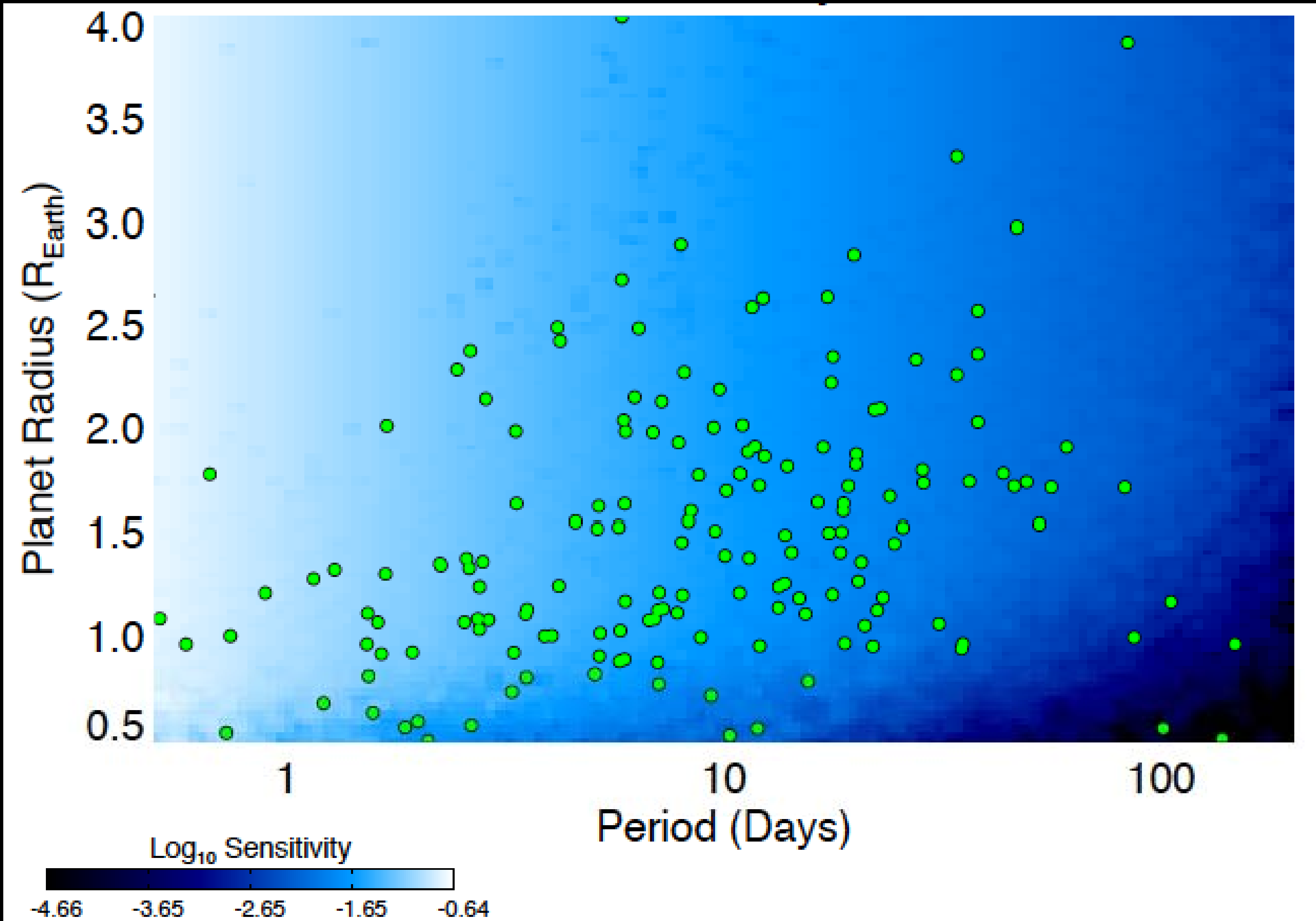
Pipeline Performance Versus Insolation



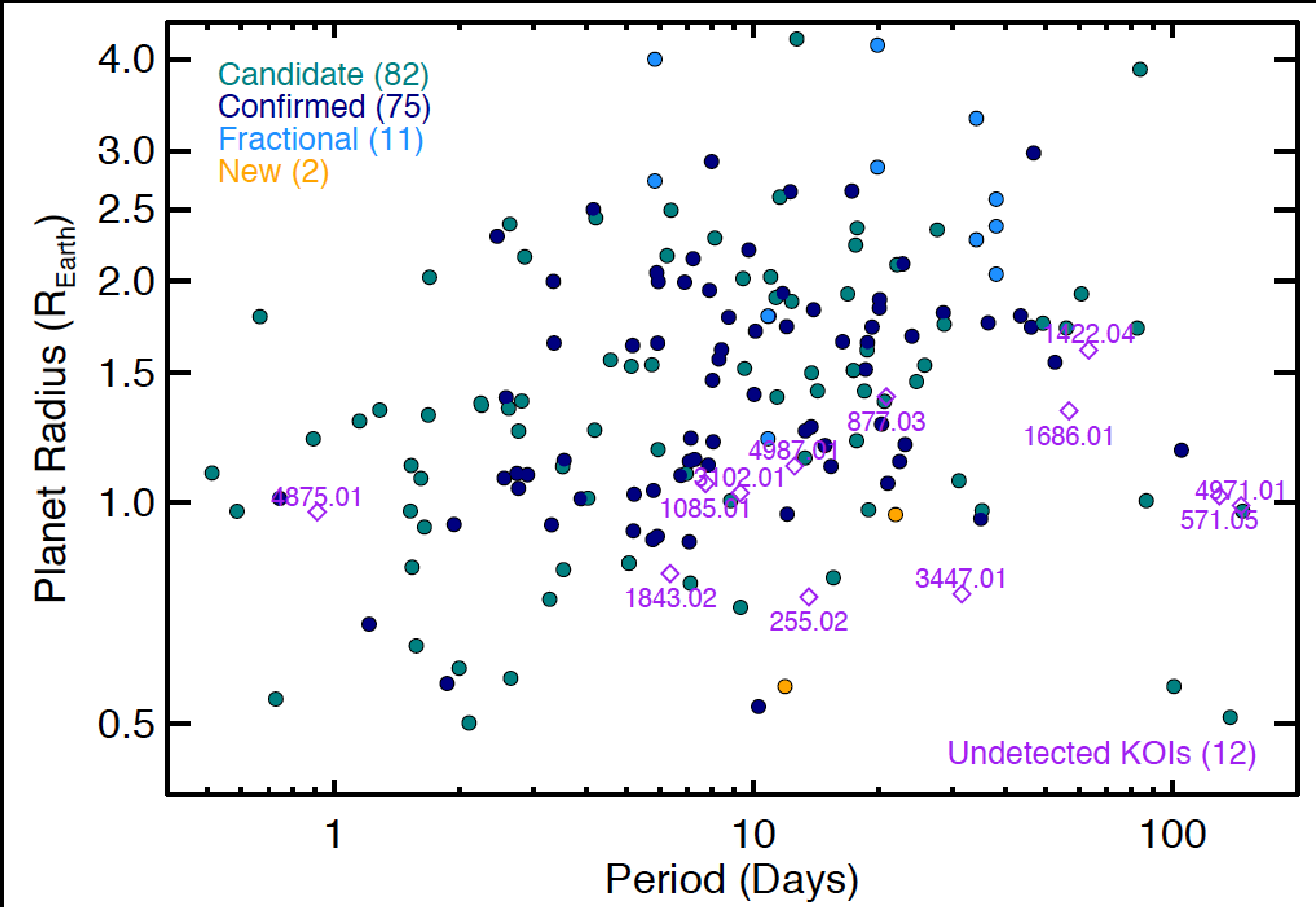
Smoothed Search Completeness



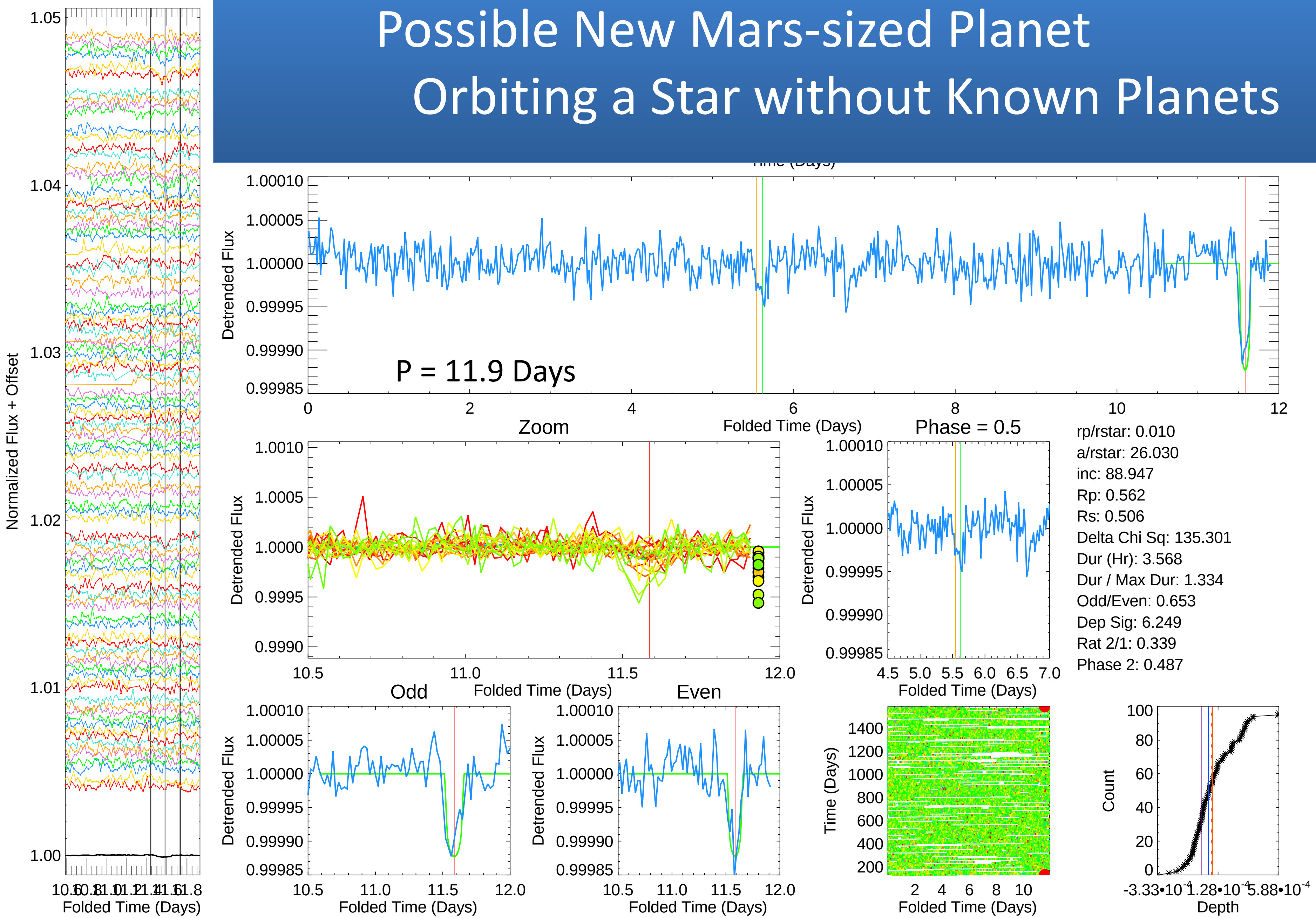
Search Completeness Versus Period



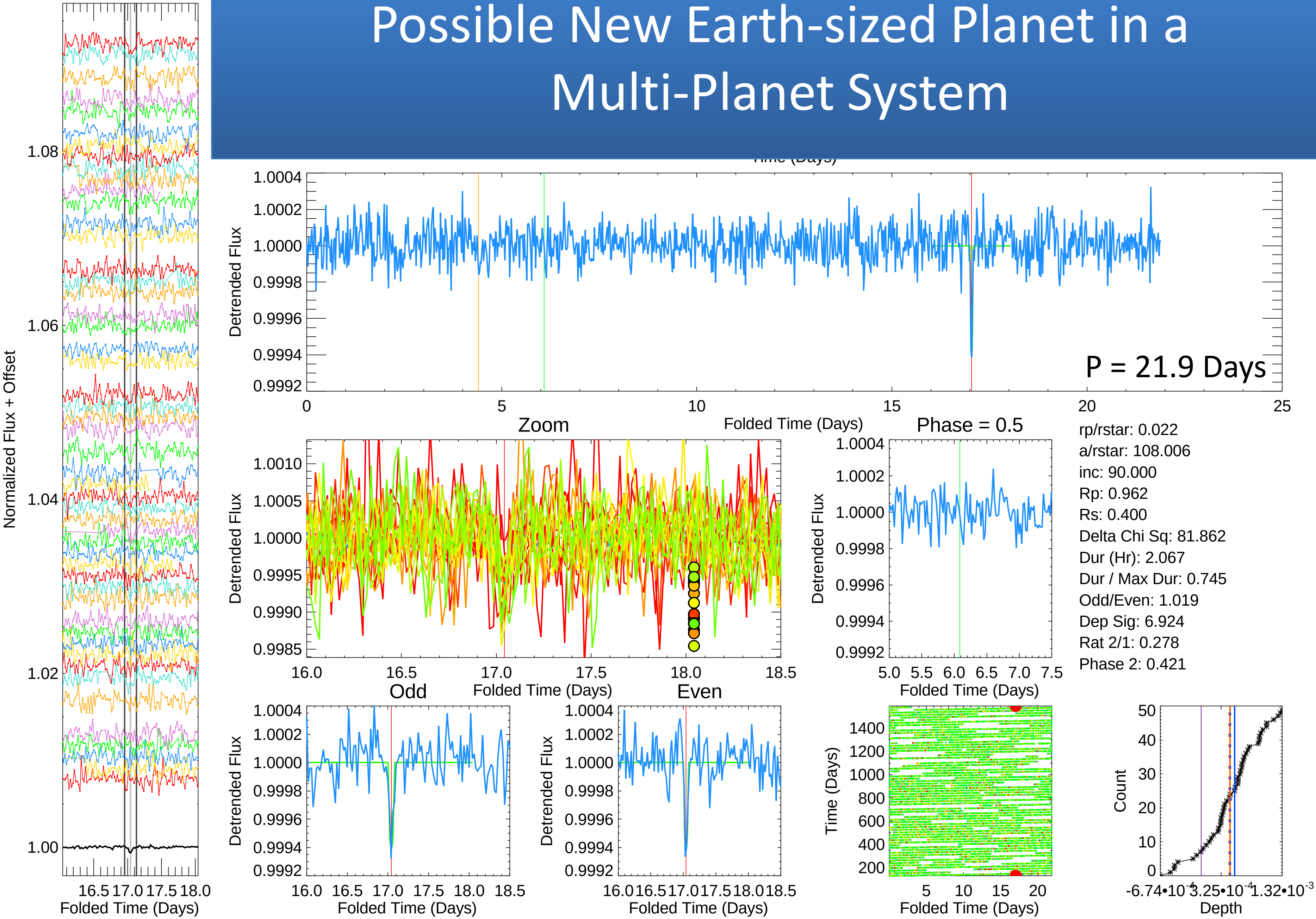
We Recover Most KOIs



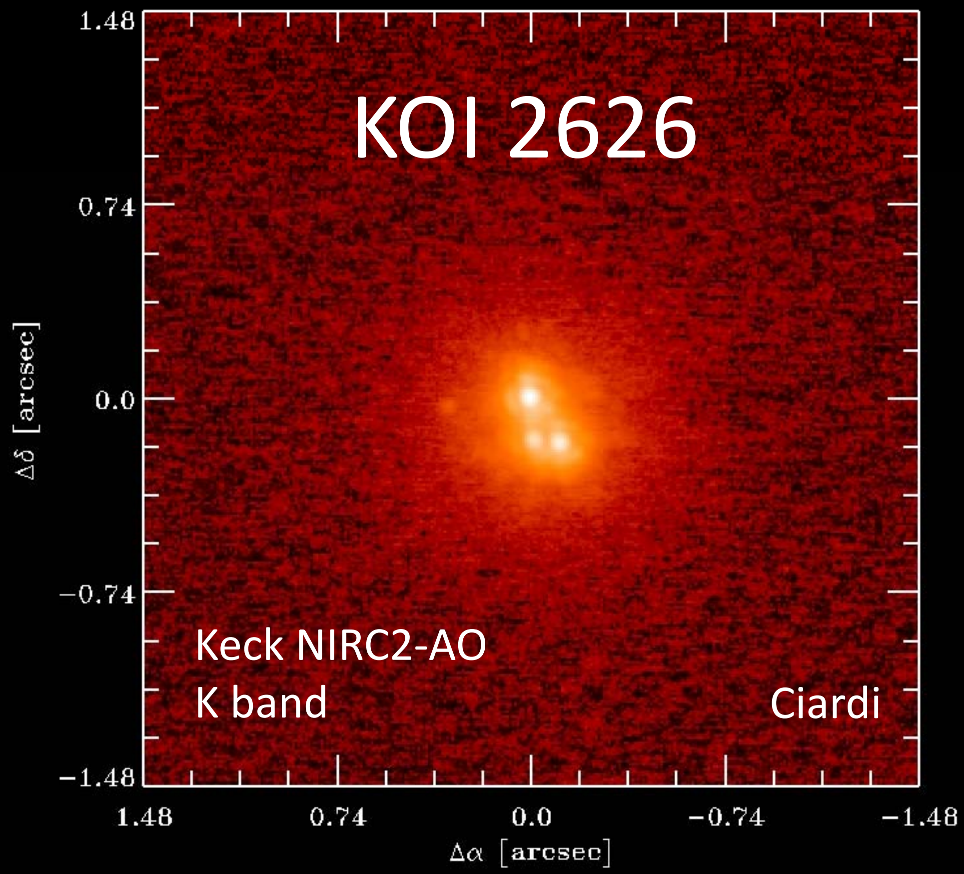
Possible New Mars-sized Planet Orbiting a Star without Known Planets

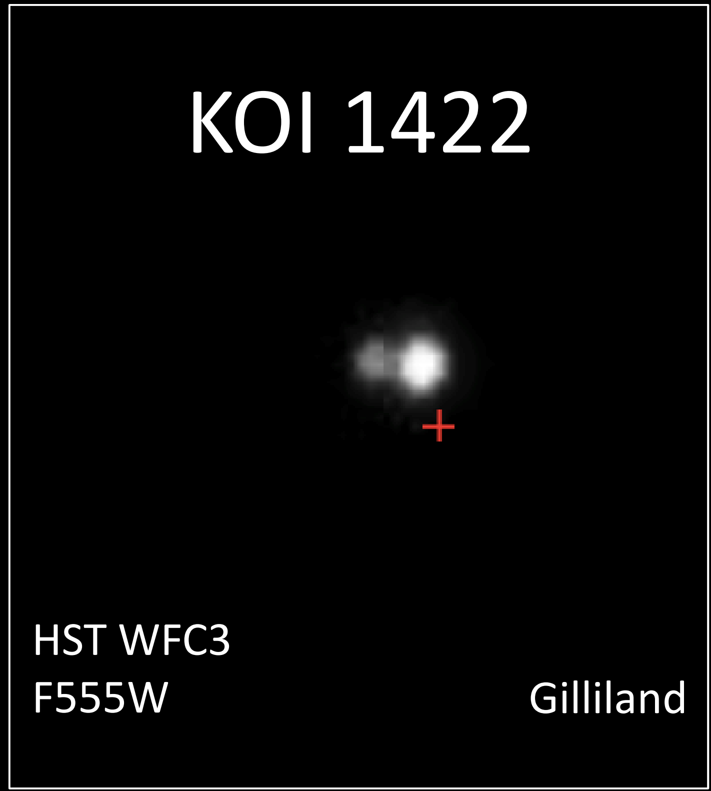


Possible New Earth-sized Planet in a Multi-Planet System



Improvement 4: **Inspected Follow-up Observations** of Planet Candidates





Revised System Properties in Star et al. (2014)

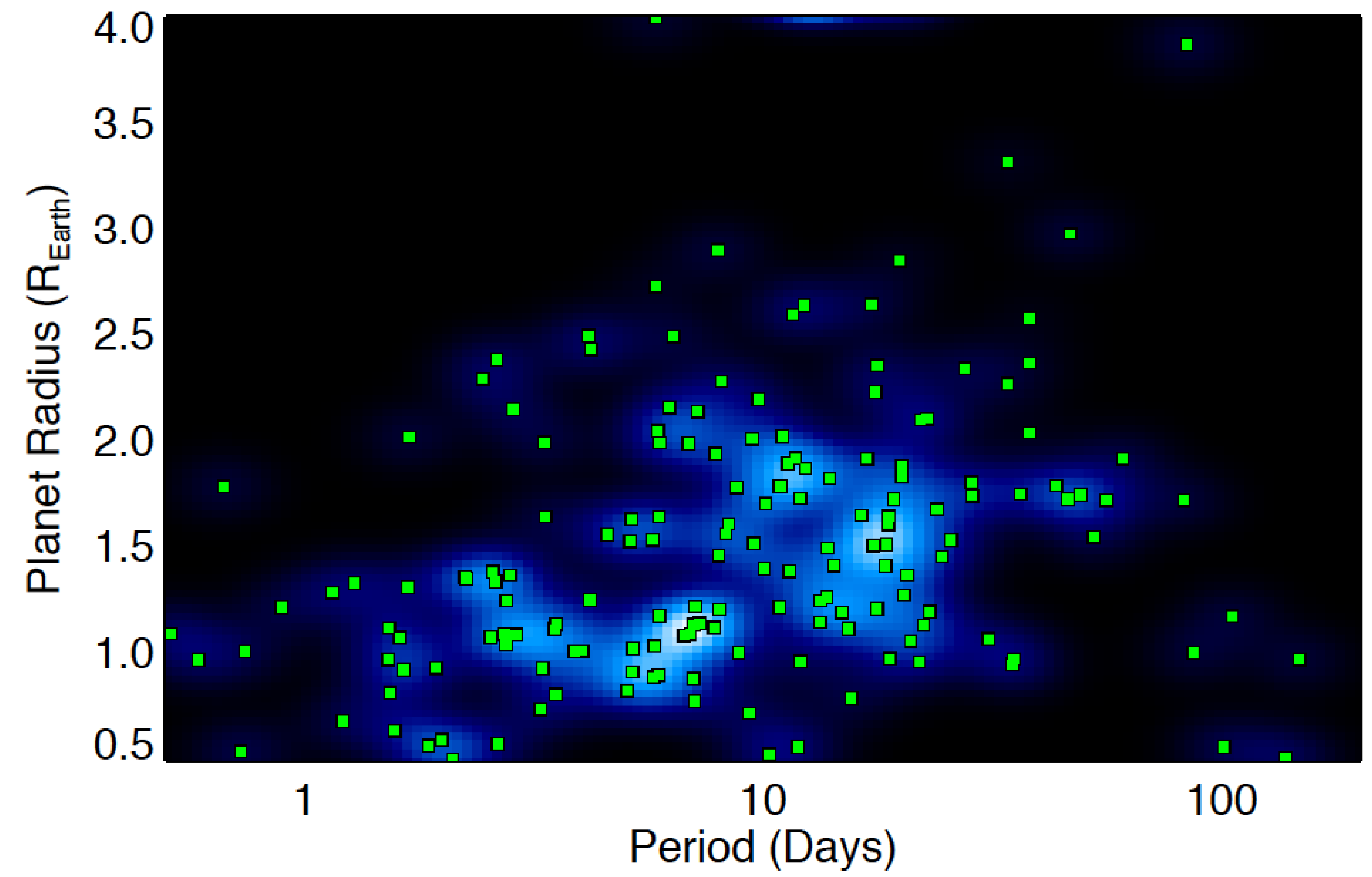
CFOP
Kepler Community Follow-up Observing Program

Improvement 5: False Positive Correction

Class	Radius (R_{Earth})	False Positive Rate
Earths	0.8-1.25	**12.3%** ± 3.0%
Super-Earths	1.25-2	**8.8%** ± 1.9%
Small Neptunes	2-4	**6.7%** ± 1.1%
Large Neptunes	4-6	**15.9%** ± 3.5%
Giants	6-22	**17.7%** ± 2.9%

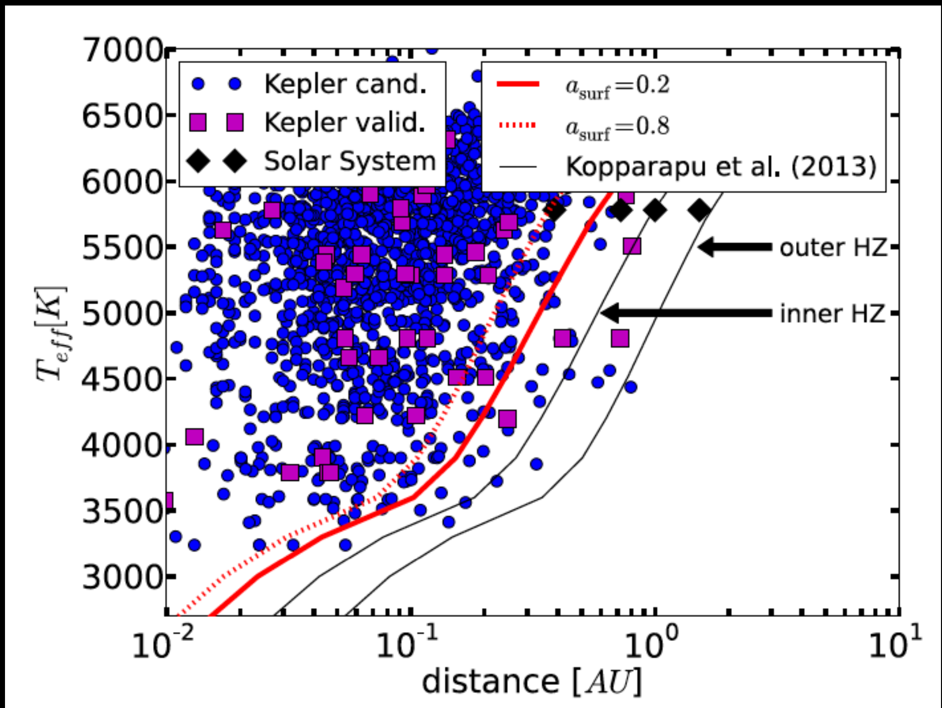
Rates from Fressin et al. (2013)

Smoothed Population of Planet Candidates

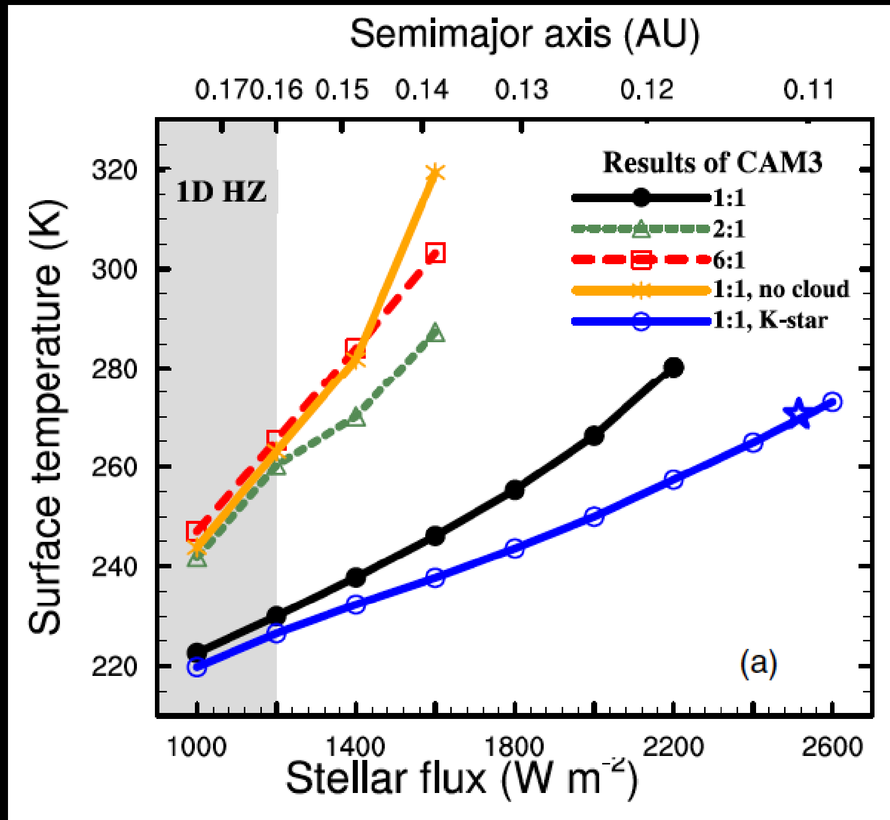


Improvement 6: More Sophisticated HZ Boundaries

- Moist & Maximum greenhouse limits from Kopparapu et al. 2013



Desert worlds (Zsom et al. 2013)

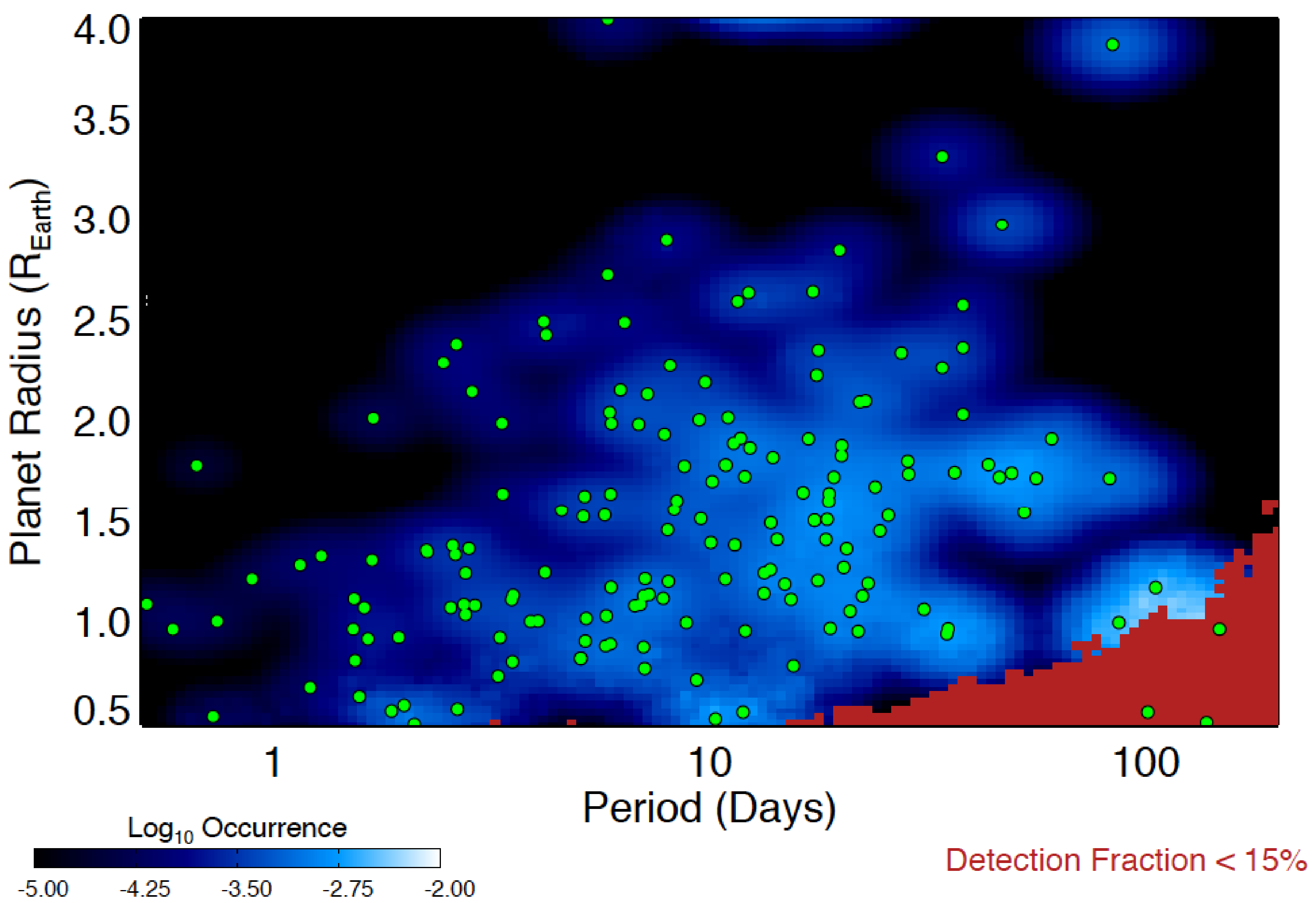


Clouds (Yang et al. 2013)

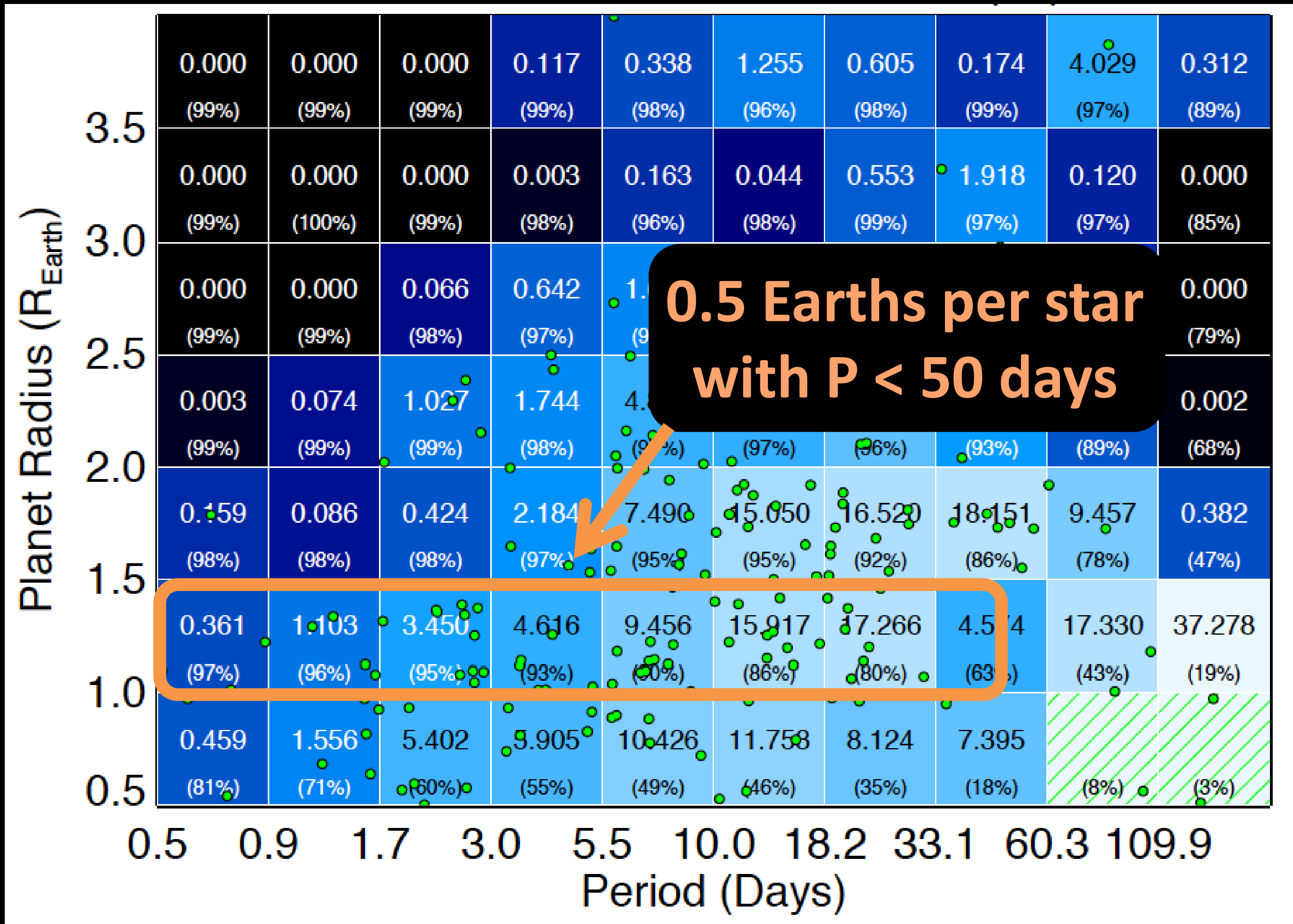
Interim Summary: List of Changes

1) Used all four years of Kepler data
2) Refined stellar sample
3) Measured pipeline completeness
4) Inspected follow-up observations
5) Applied a false positive correction
6) Used more sophisticated habitable zone boundaries

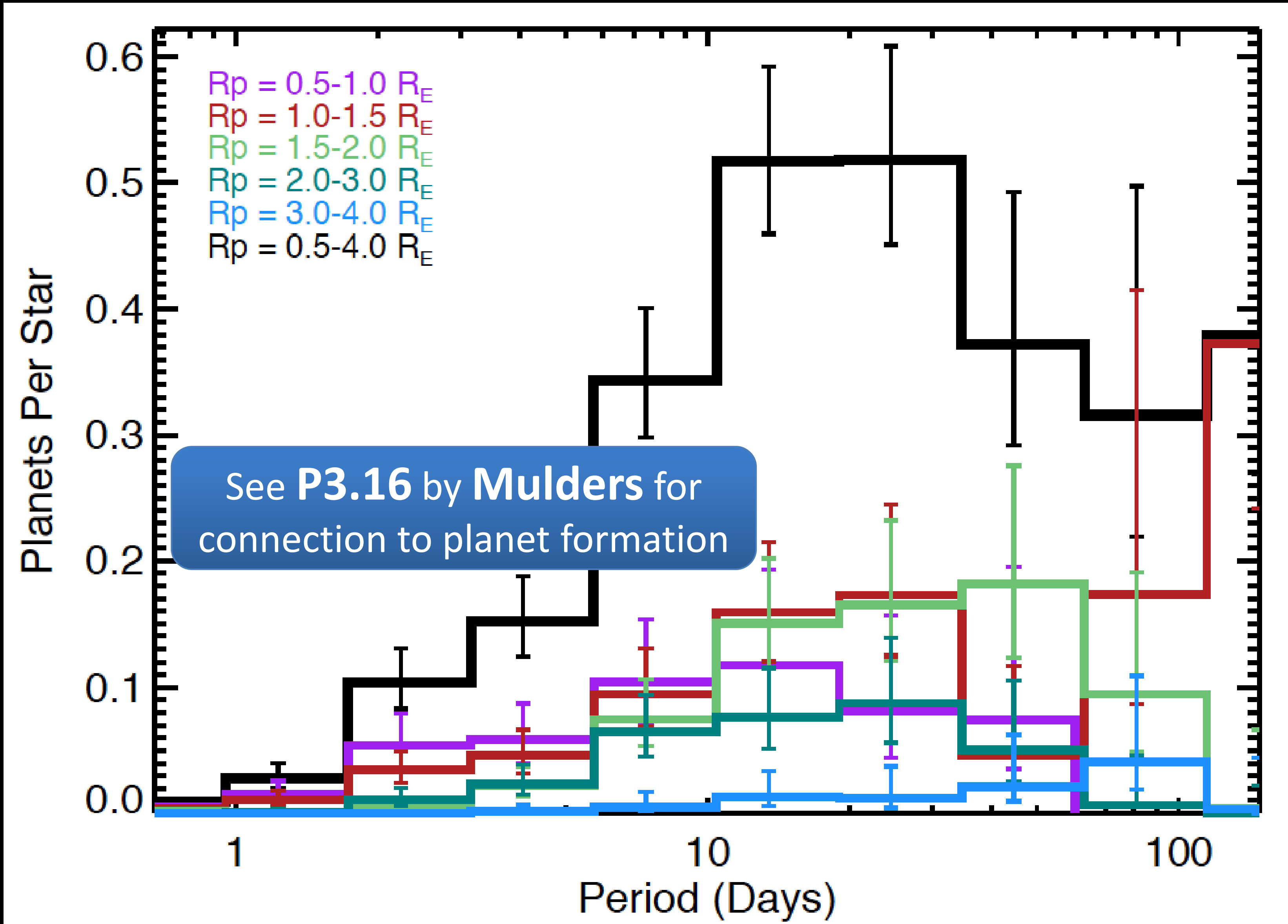
Resulting Occurrence Rate



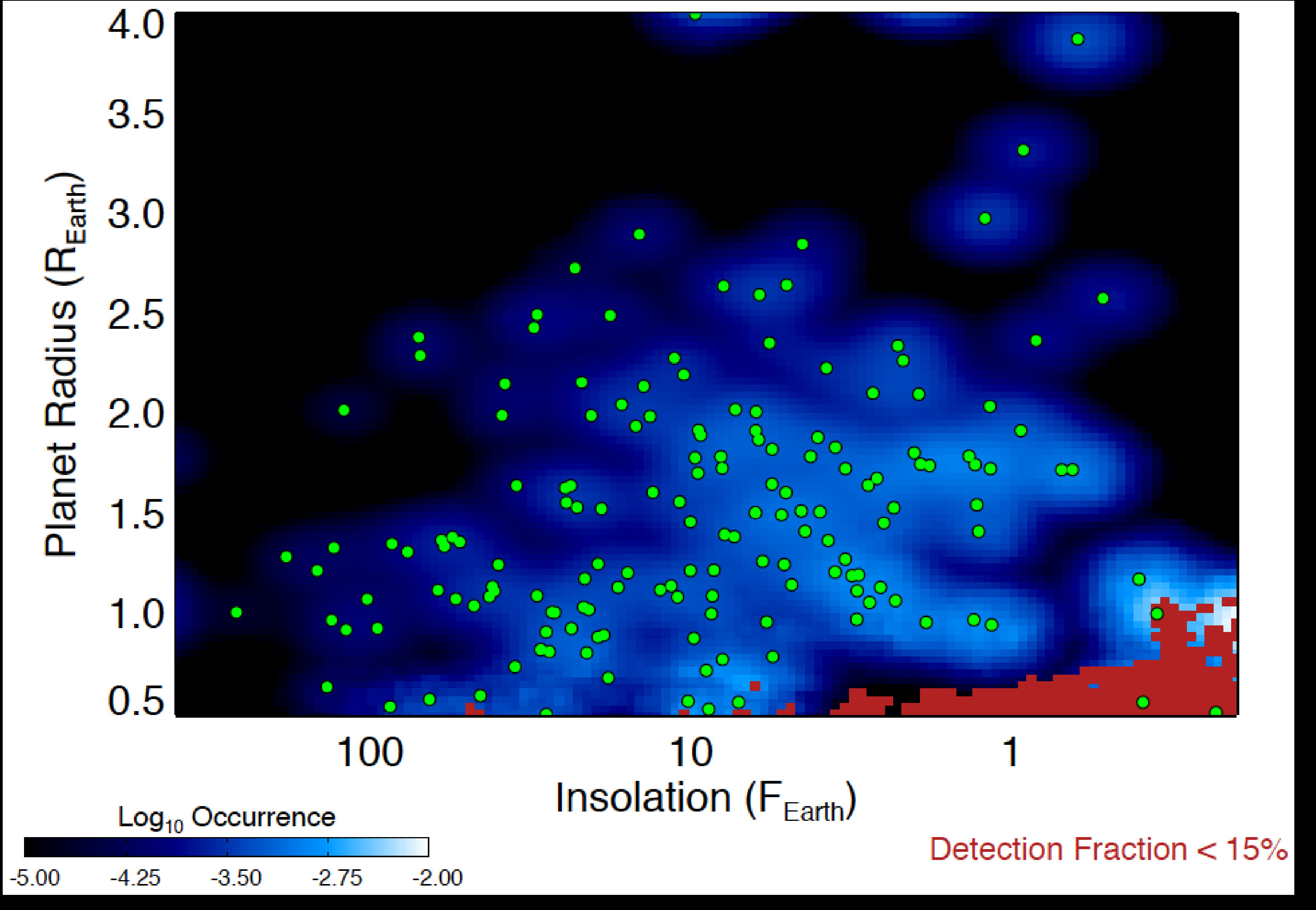
Estimated Planet Occurrence Rate (%)



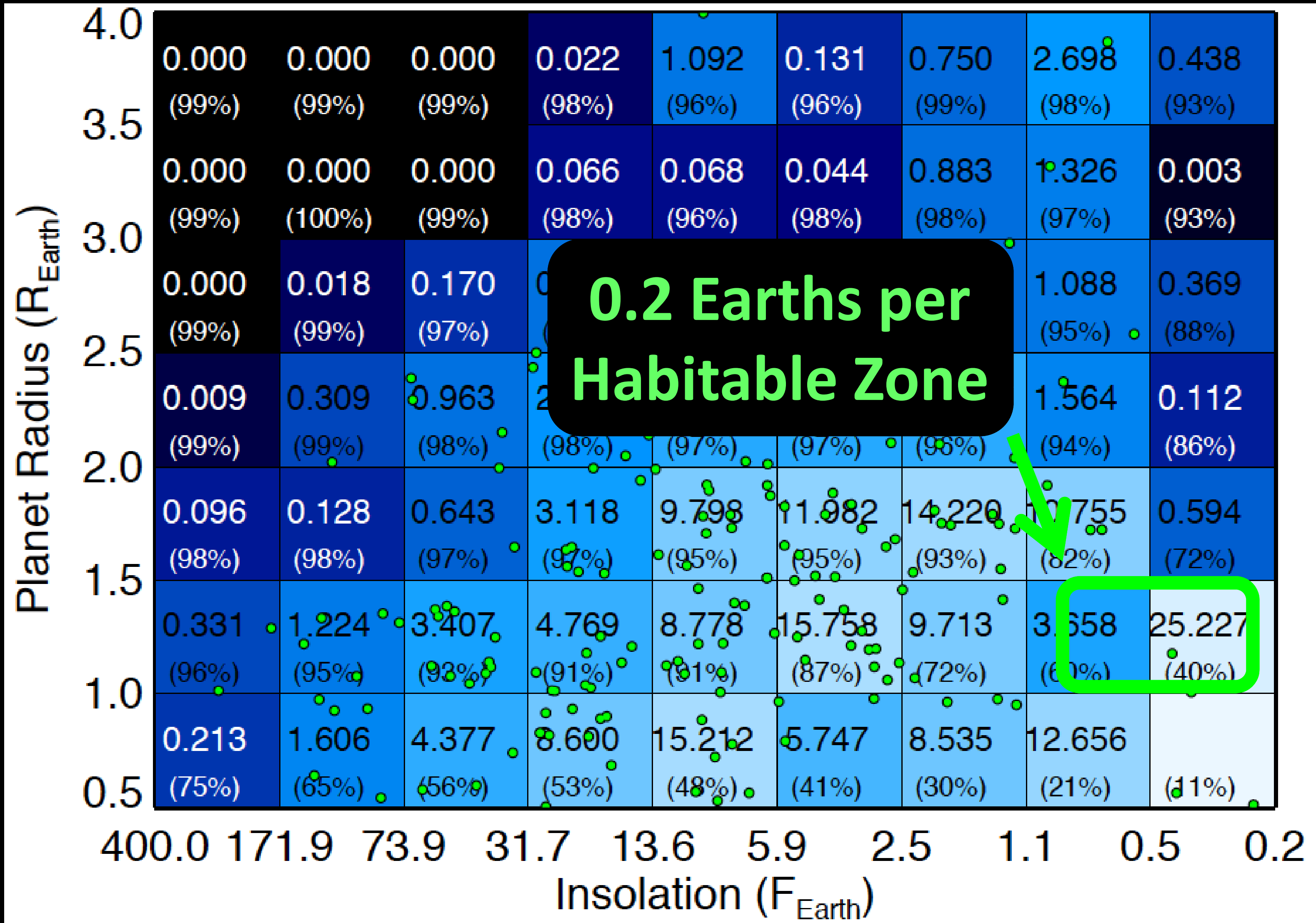
Planet Occurrence Versus Period



Smoothed Planet Occurrence Rate



Planet Occurrence (%) versus Flux



HZ from Kopparapu et al. 2013

Alternative HZ Choices

TABLE 7
HZ Occurrence Rates

$F_P(F_\oplus)$ / *Outer HZ:* / *Inner HZ:*	0.25 – 0.88 Max GH Moist GH	0.23 – 1.54 Mars Venus	0.25 – 4.00 Petigura Petigura	0.25 – 1.76 Max GH Cloudy Moist GH	0.25 – 2.78 Max GH Zsom (a=0.2)
$0.8 - 1.0\,R_\oplus$	$0.160^{+0.295}_{-0.088}$ (25%)	$0.239^{+0.248}_{-0.092}$ (28%)	$0.273^{+0.170}_{-0.087}$ (37%)	$0.227^{+0.211}_{-0.085}$ (30%)	$0.260^{+0.181}_{-0.089}$ (34%)
$1.0 - 1.5\,R_\oplus$	$0.186^{+0.214}_{-0.080}$ (51%)	$0.246^{+0.182}_{-0.091}$ (55%)	$0.394^{+0.112}_{-0.074}$ (64%)	$0.246^{+0.162}_{-0.088}$ (58%)	$0.324^{+0.127}_{-0.080}$ (61%)
$1.5 - 2.0\,R_\oplus$	$0.083^{+0.075}_{-0.036}$ (77%)	$0.172^{+0.083}_{-0.053}$ (81%)	$0.318^{+0.082}_{-0.059}$ (86%)	$0.206^{+0.085}_{-0.056}$ (82%)	$0.274^{+0.083}_{-0.059}$ (84%)
$2.0 - 2.5\,R_\oplus$	$0.011^{+0.034}_{-0.008}$ (91%)	$0.025^{+0.040}_{-0.014}$ (91%)	$0.083^{+0.048}_{-0.029}$ (93%)	$0.034^{+0.042}_{-0.016}$ (92%)	$0.067^{+0.047}_{-0.026}$ (93%)
$2.5 - 4.0\,R_\oplus$	$0.048^{+0.055}_{-0.025}$ (95%)	$0.074^{+0.062}_{-0.033}$ (95%)	$0.089^{+0.062}_{-0.034}$ (96%)	$0.079^{+0.061}_{-0.033}$ (96%)	$0.085^{+0.061}_{-0.033}$ (96%)
$1.0 - 2.0\,R_\oplus$	$0.269^{+0.164}_{-0.087}$ (64%)	$0.418^{+0.141}_{-0.086}$ (68%)	$0.712^{+0.093}_{-0.062}$ (75%)	$0.452^{+0.126}_{-0.083}$ (70%)	$0.598^{+0.108}_{-0.073}$ (73%)
$2.0 - 4.0\,R_\oplus$	$0.060^{+0.060}_{-0.027}$ (94%)	$0.099^{+0.067}_{-0.038}$ (94%)	$0.172^{+0.067}_{-0.047}$ (96%)	$0.114^{+0.066}_{-0.039}$ (95%)	$0.152^{+0.069}_{-0.044}$ (96%)

1.0 – 1.5 R_{Earth} in Mars – Venus HZ: 0.25

1.0 – 2.0 R_{Earth} in Petigura et al. (2013) HZ: 0.71

> 1 Planet Per Star for Pierrehumbert & Gaidos HZ

Nominal insolation boundaries from Kopparapu et al. 2014

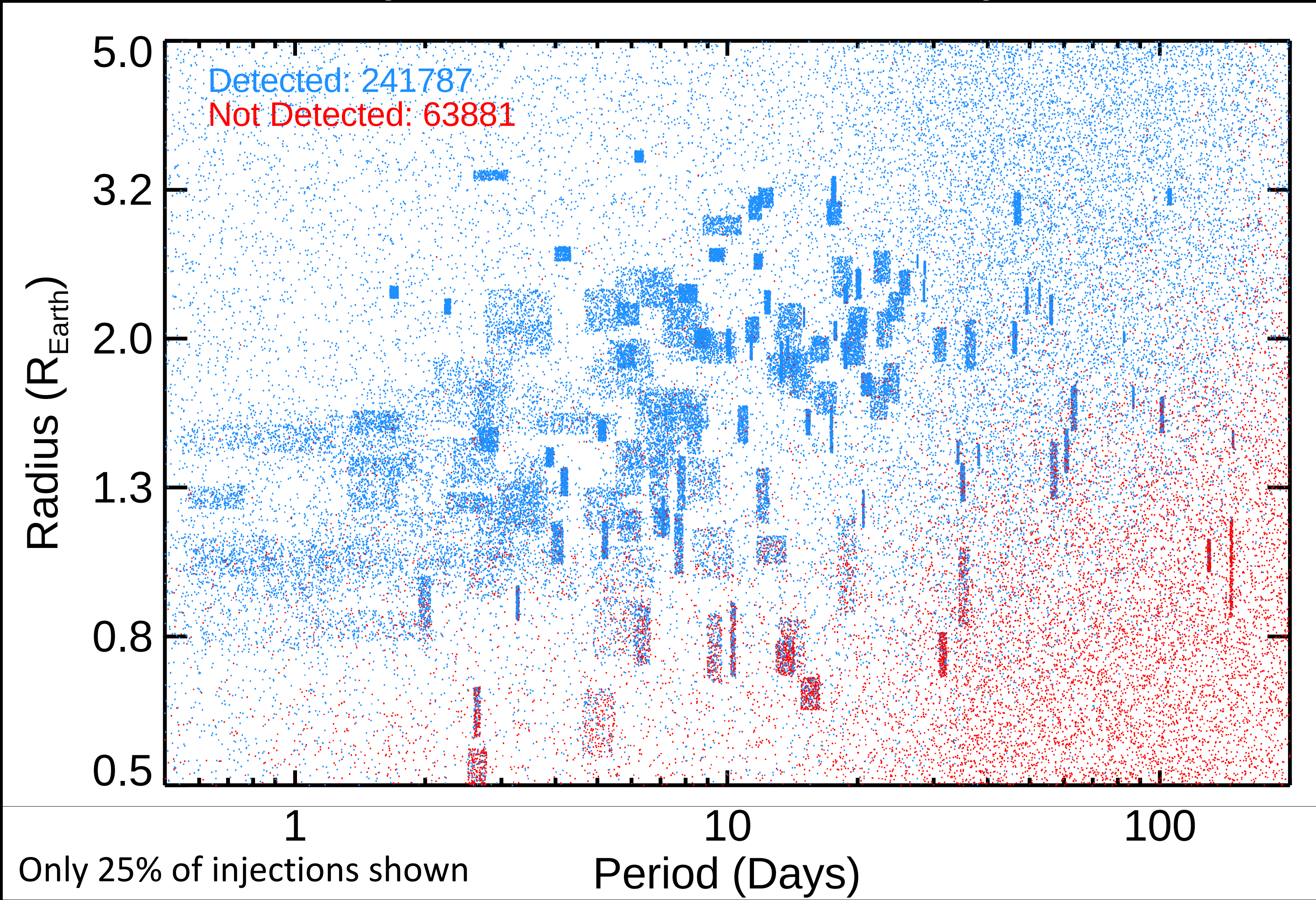
Summary & Conclusions

- We refined our estimate of M dwarf planet occurrence by:
  - Using all **four years of Kepler data**
  - Refining **stellar sample**
  - Explicitly **measuring pipeline completeness**
  - Inspecting **follow-up observations** & accounting for **dilution**
  - Applying a **false positive correction**
  - Incorporating **updated habitable zone boundaries**

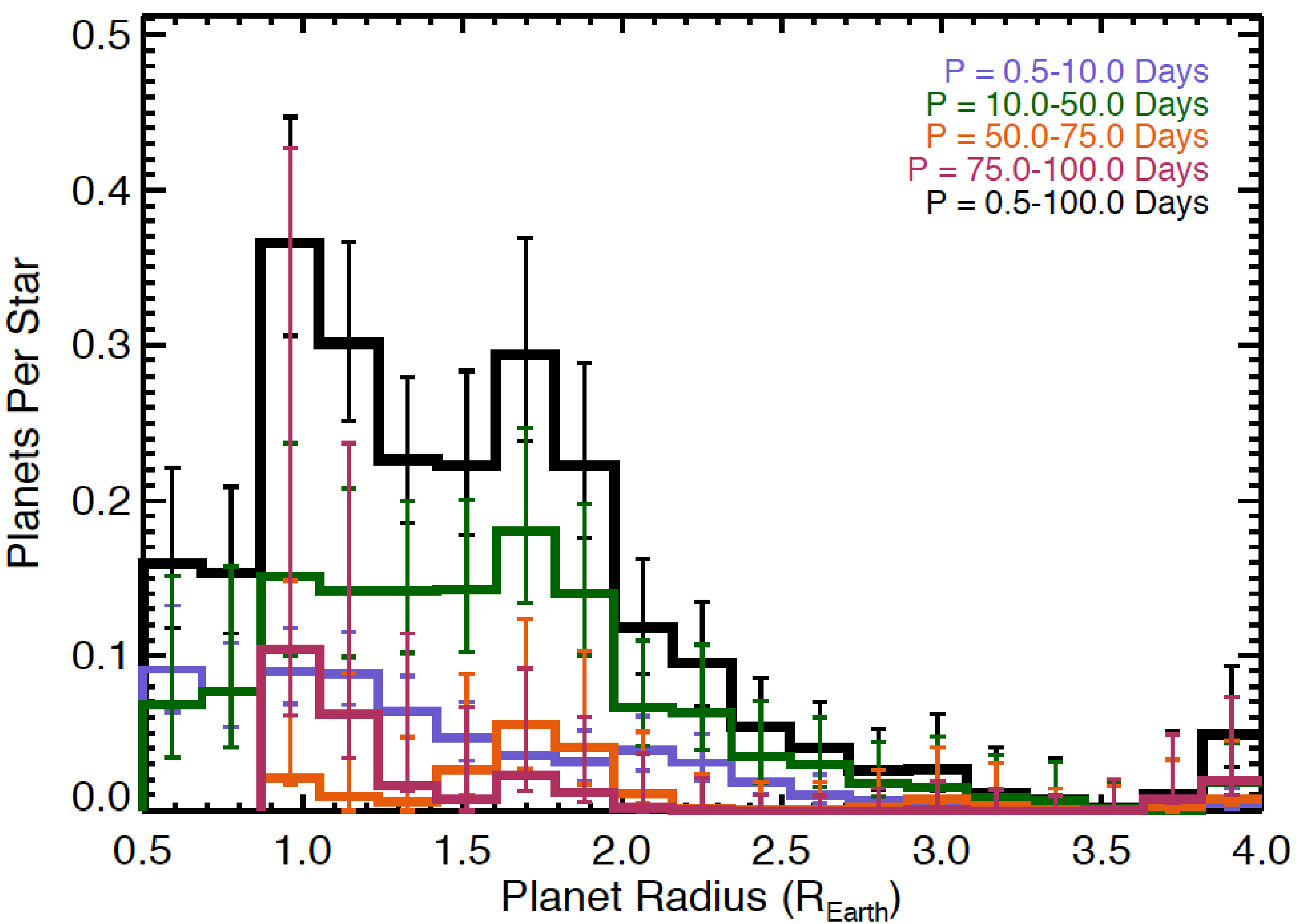
Radius (R_{Earth})	Period (Days)	Estimated Number per Star
1 – 1.5	0.5 – 50	**0.56** (+0.06/-0.05)
1.5 – 2	0.5 – 50	**0.53** (+0.07/-0.06)
1 – 1.5	Narrow HZ	**0.2** (+0.2/-0.1)
1-2	Venus – Mars HZ	**0.4** ± 0.1

ADDITIONAL SLIDES

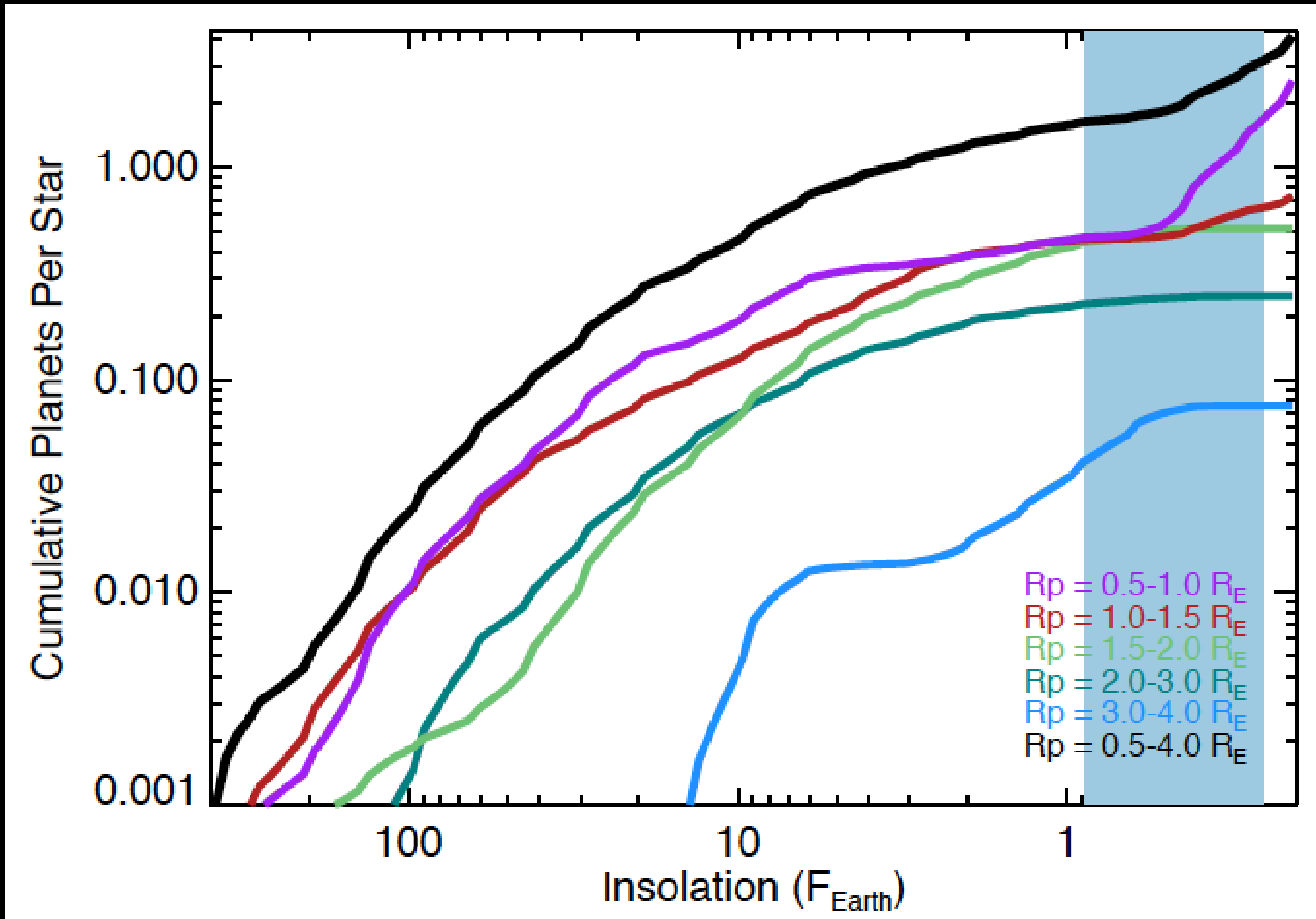
Pipeline Sensitivity



Smaller Planets Are More Common



Potentially Habitable Worlds are Common



HZ from Kopparapu et al. 2014