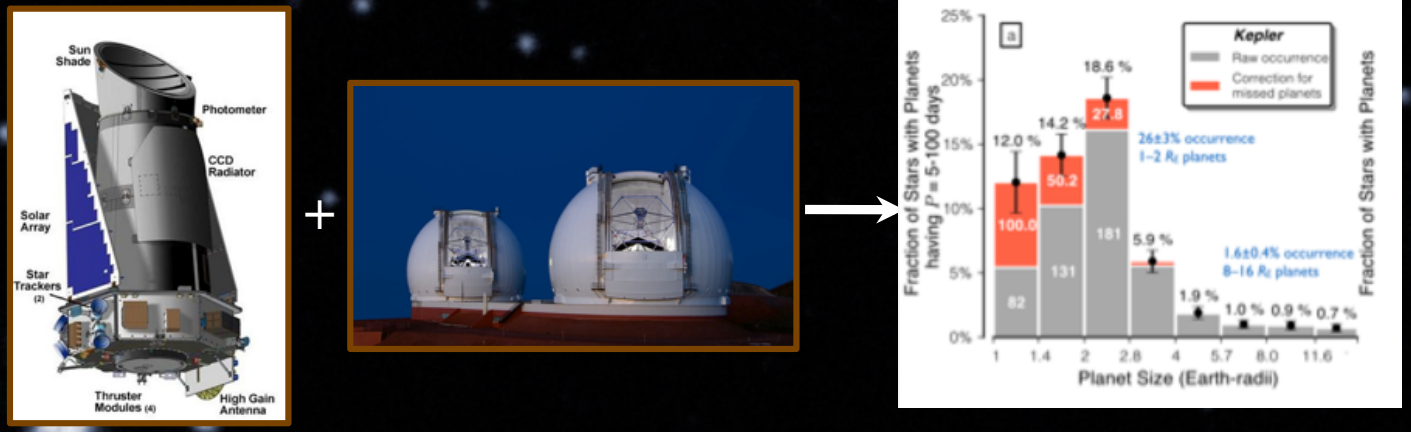
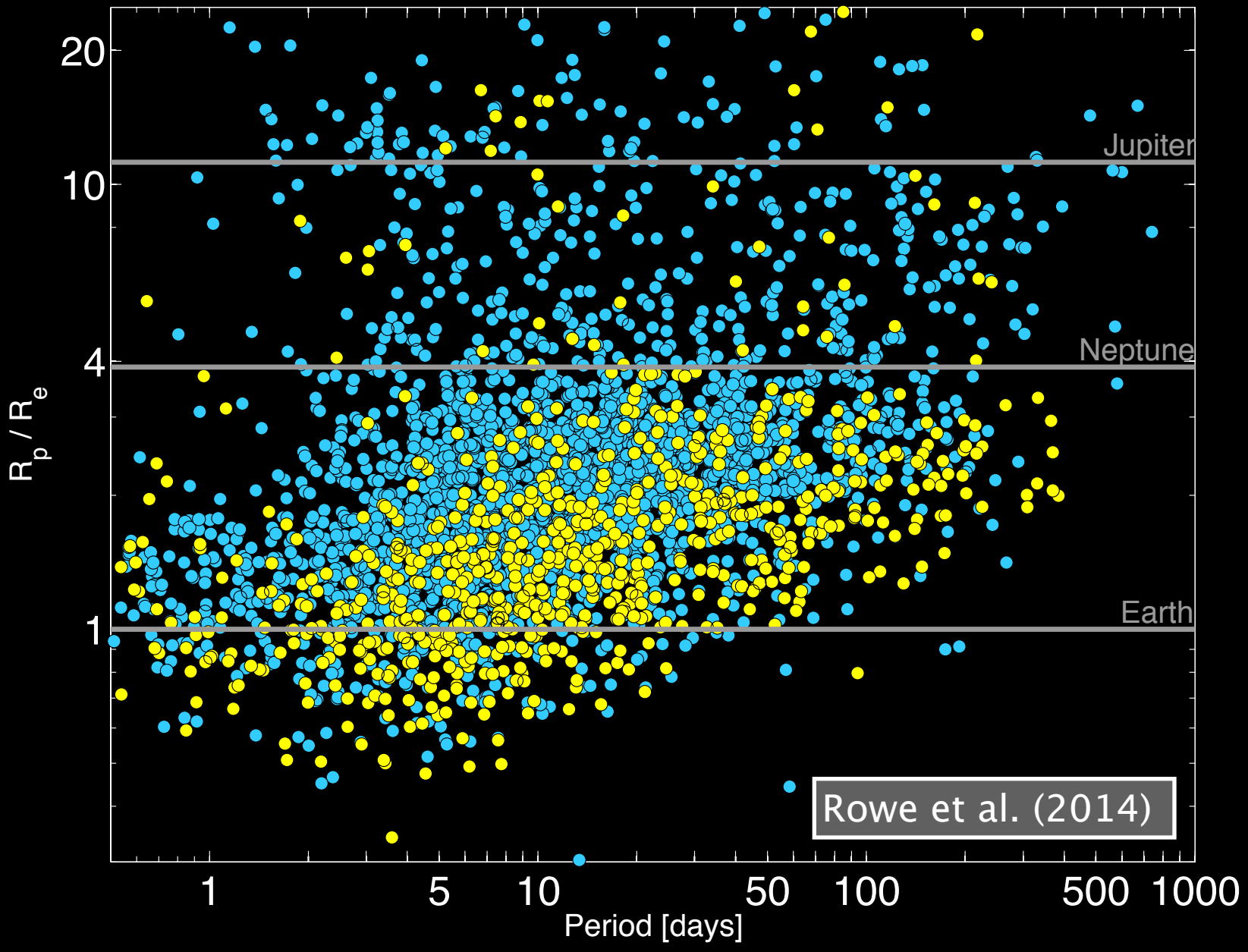
Occurrence of 1-4 R_{Earth} Planets Orbiting Sun-Like Stars

Geoff Marcy, Erik Petigura, Andrew Howard

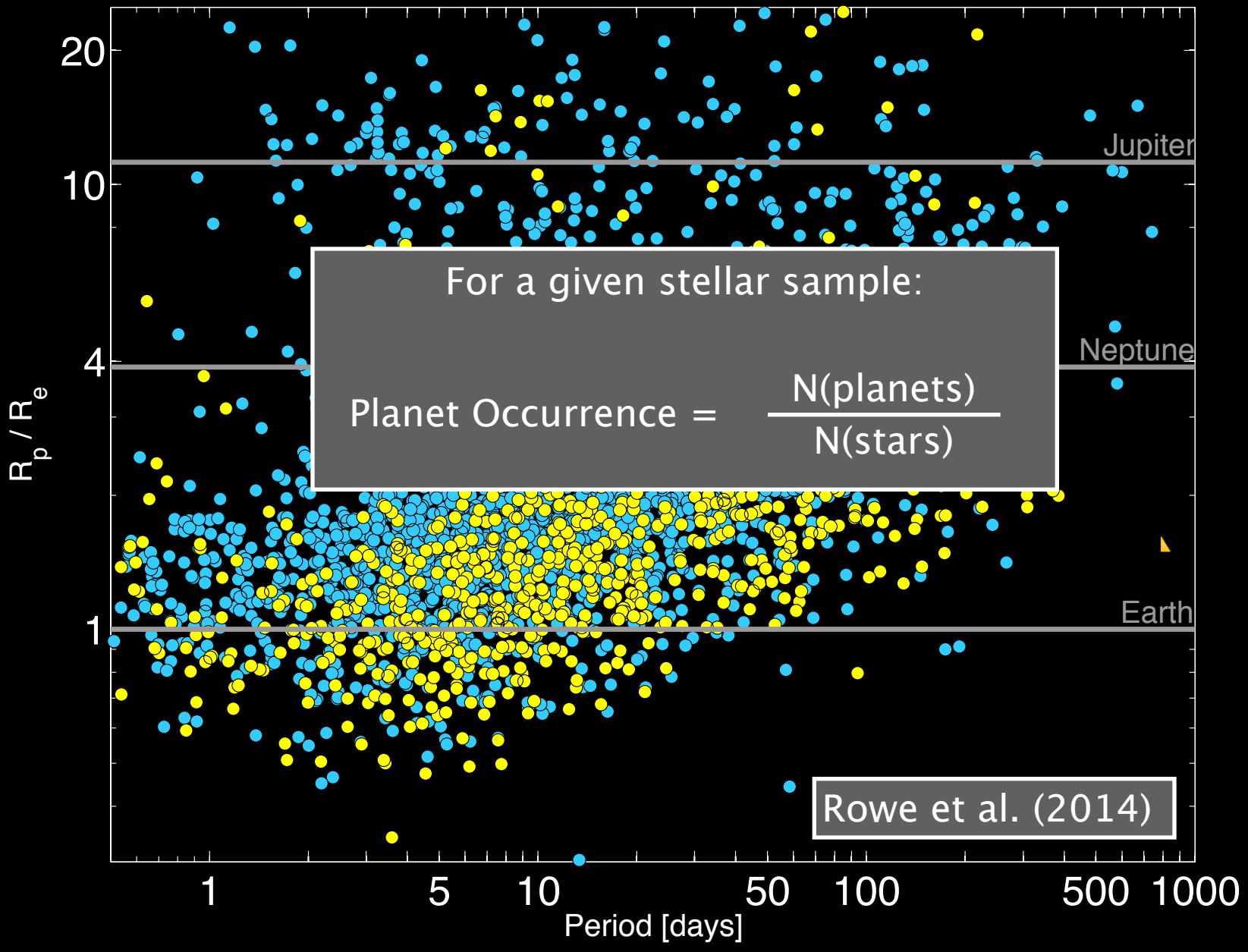


Collaborators: Lauren Weiss, Howard Isaacson, Rea Kolbl, Lea Hirsch
Thanks to: UC Berkeley, Univ. Hawaii, Keck Observatory, NASA

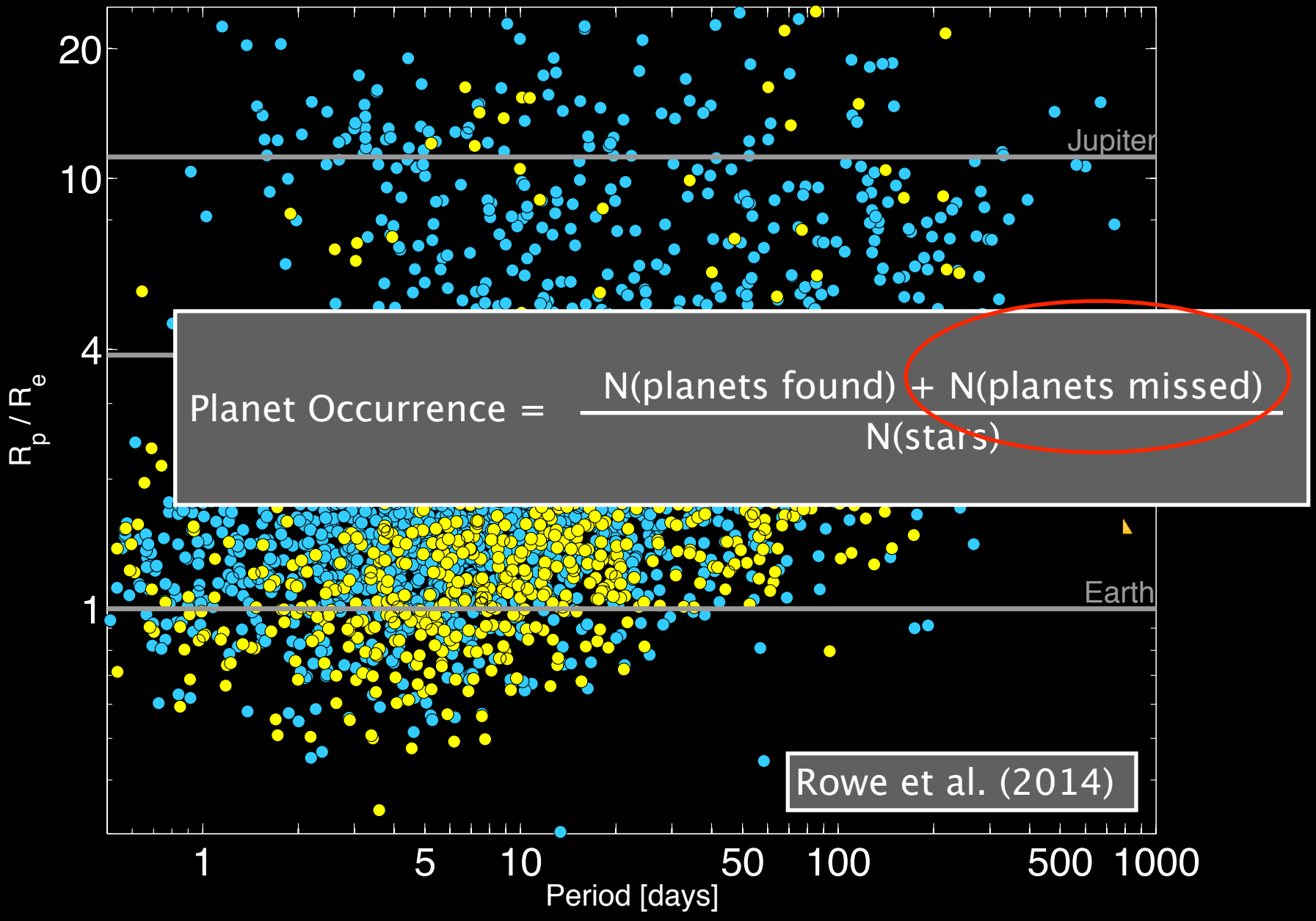
Kepler Planets



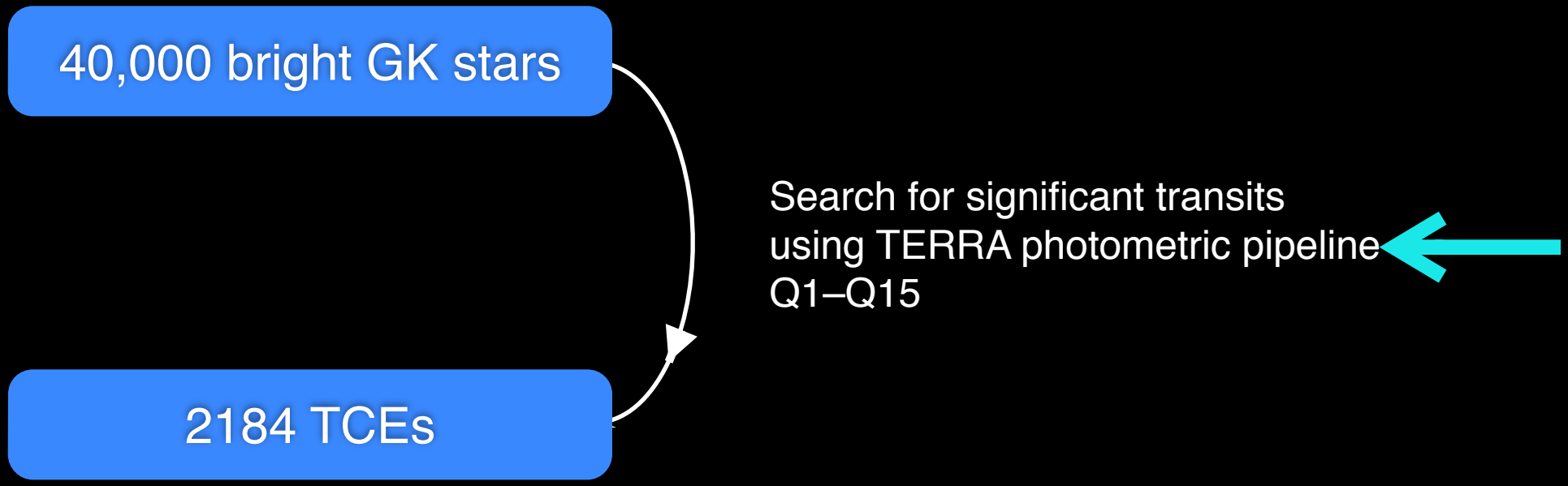
Kepler Planets



Kepler Planets



40,000 bright GK stars


40,000 bright GK stars
Search for significant transits
using TERRA photometric pipeline
Q1–Q15
2184 TCEs

TERRA

In-house photometric Transit Search: Optimized for small planet detection

Enables measurement of detection efficiency (completeness) using injection and recovery experiments

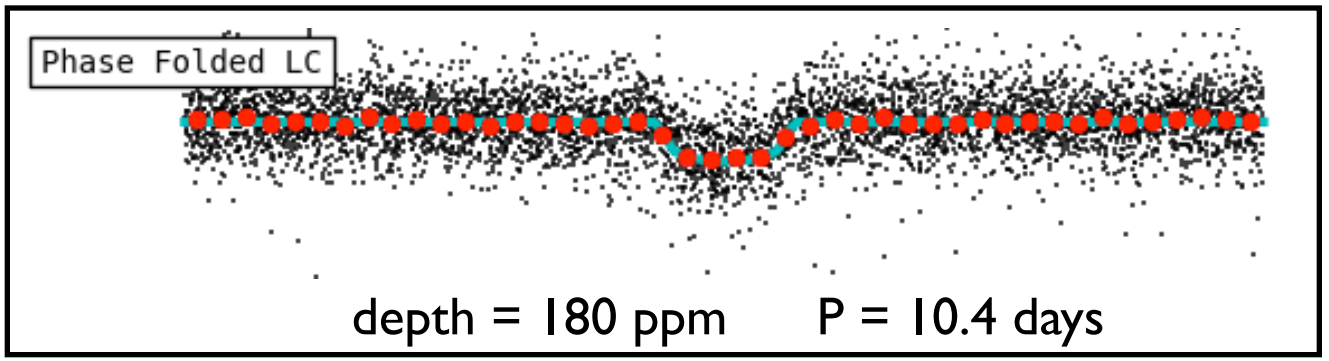
E.Petigura (2013)

TERRA – optimized for small planets

Time domain preprocessing

- Start with raw photometry
- Gaussian process detrending
- Calibration
- Petigura & Marcy 2012

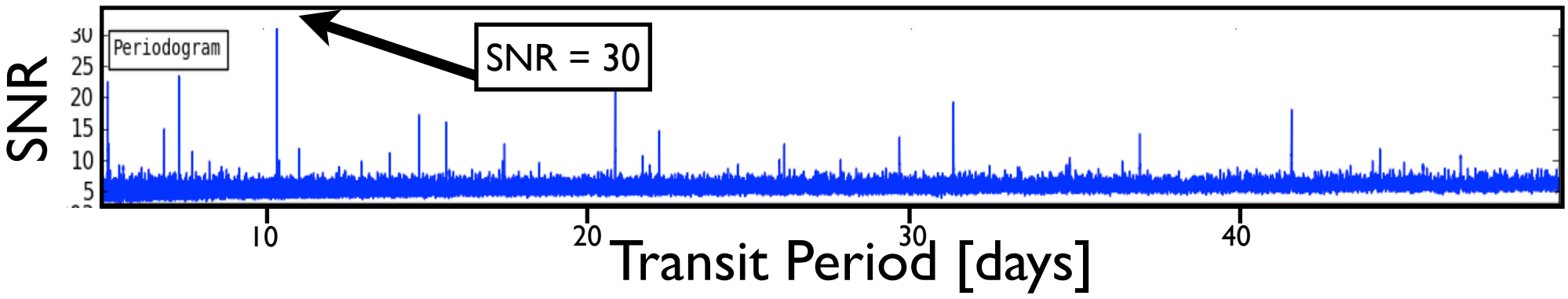
Earth-size planet found

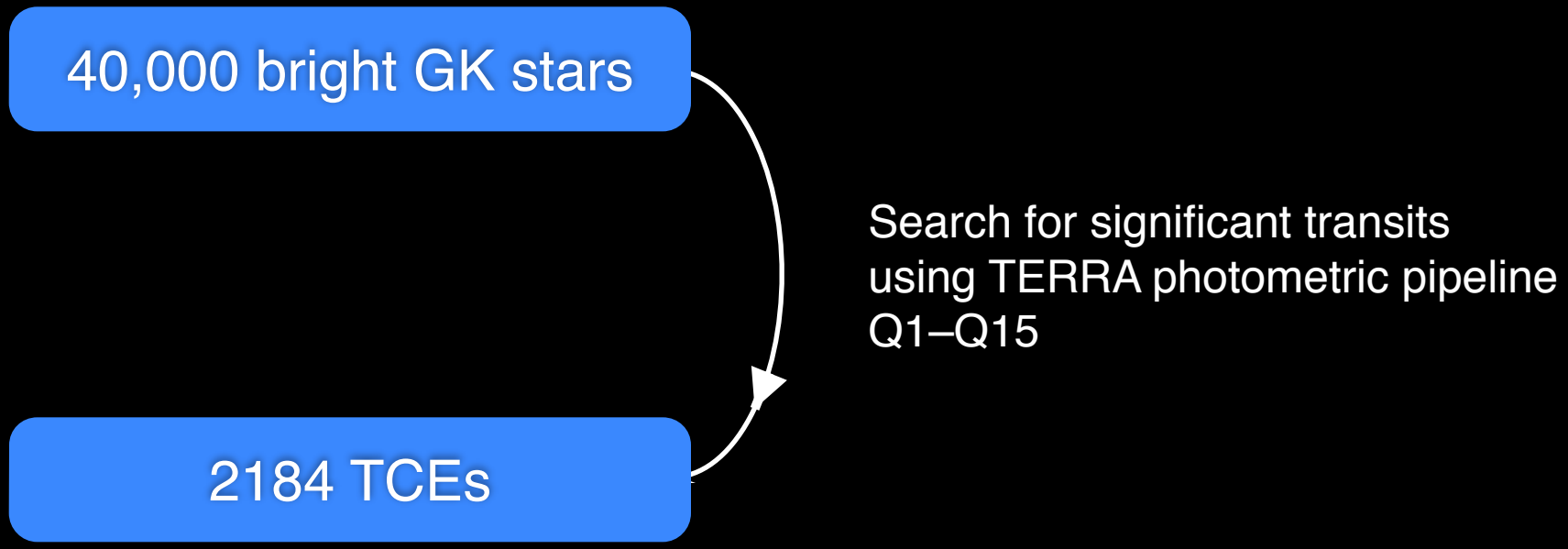


Transit search

- Matched filter
- Similar to BLS algorithm (Kovacs, Zucker, Mazeh 2002)
- Leverages Fast-Folding Algorithm (Staelin+ 68; Petigura+ 13, in prep)

Transit Periodogram

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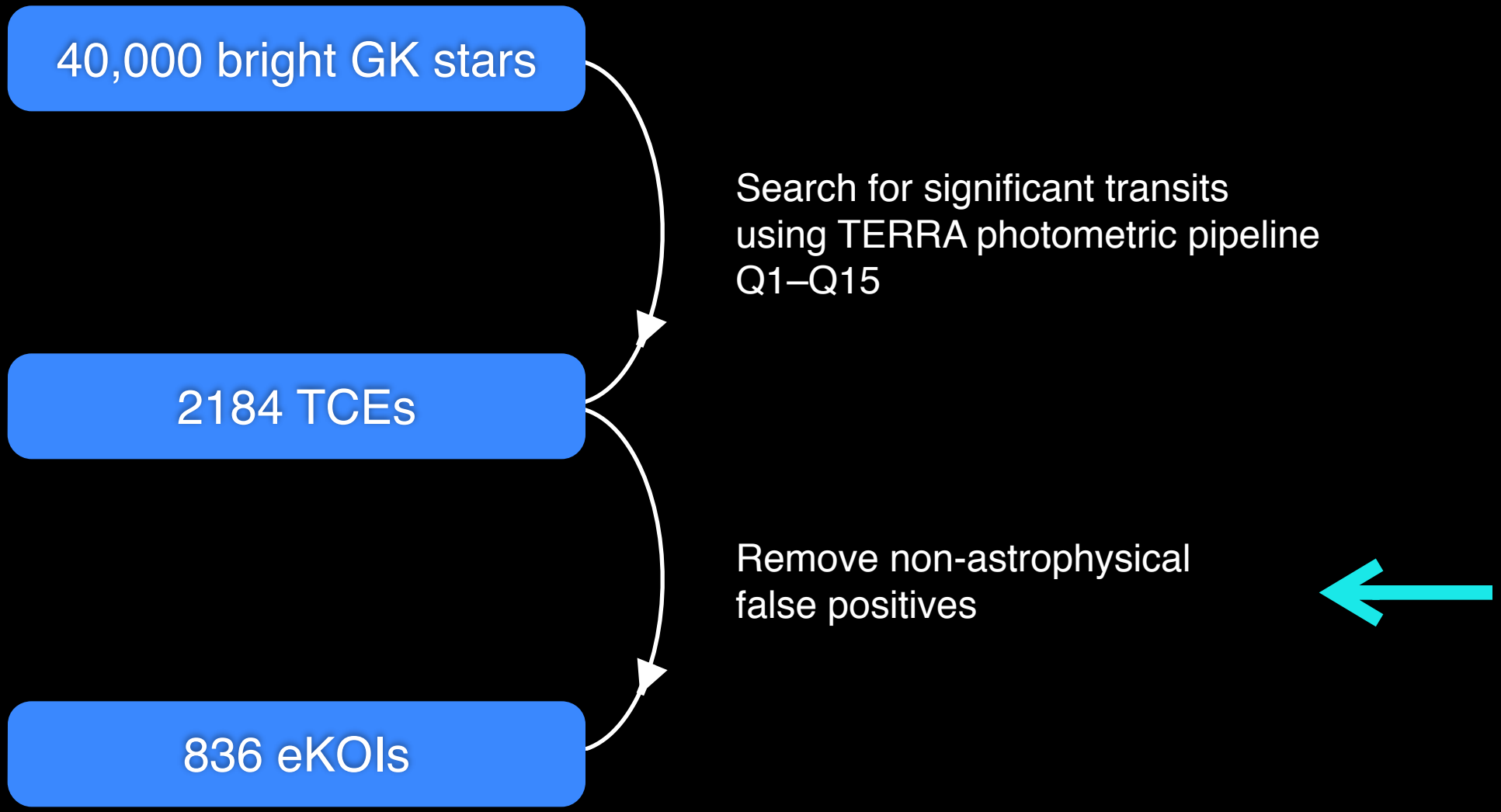
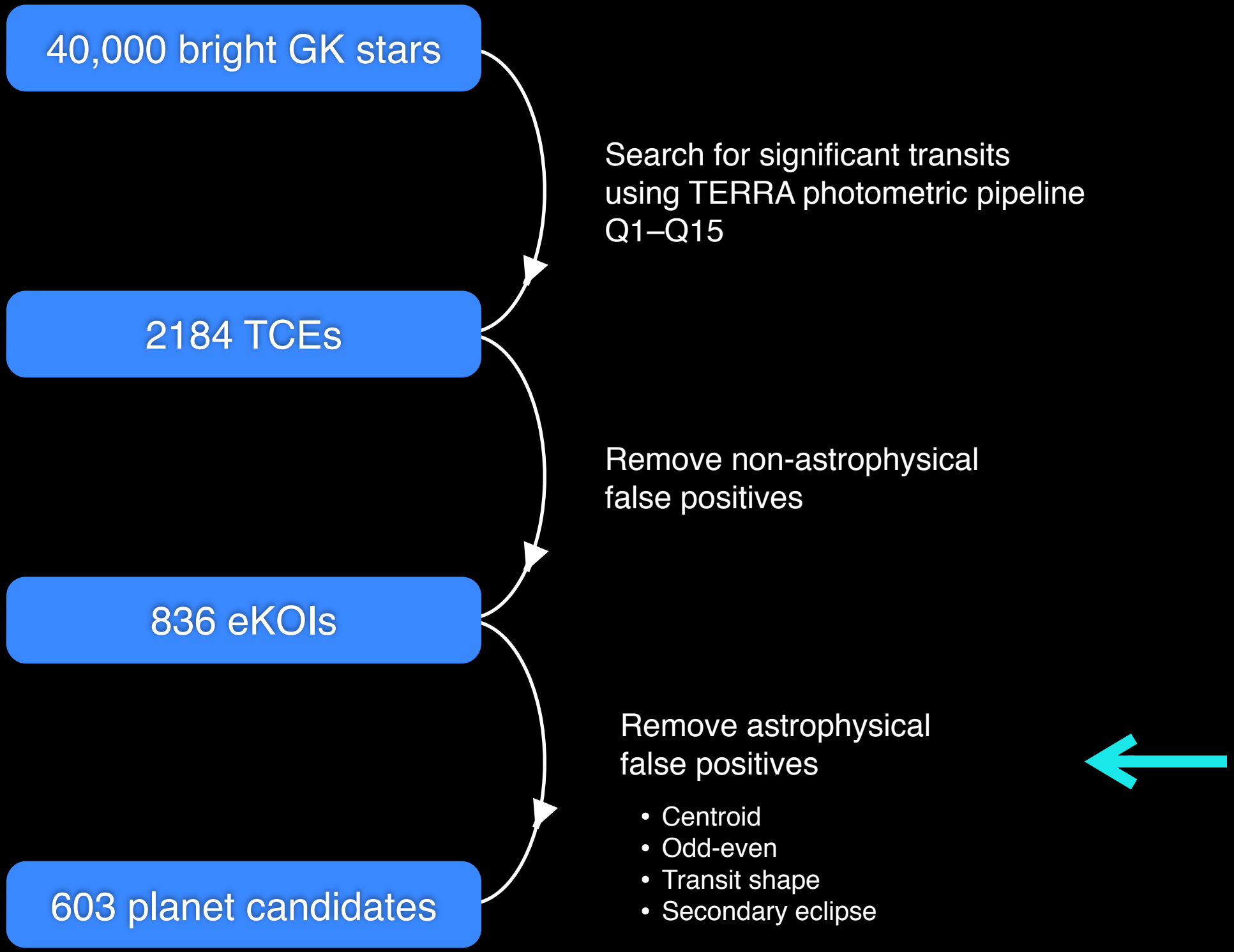
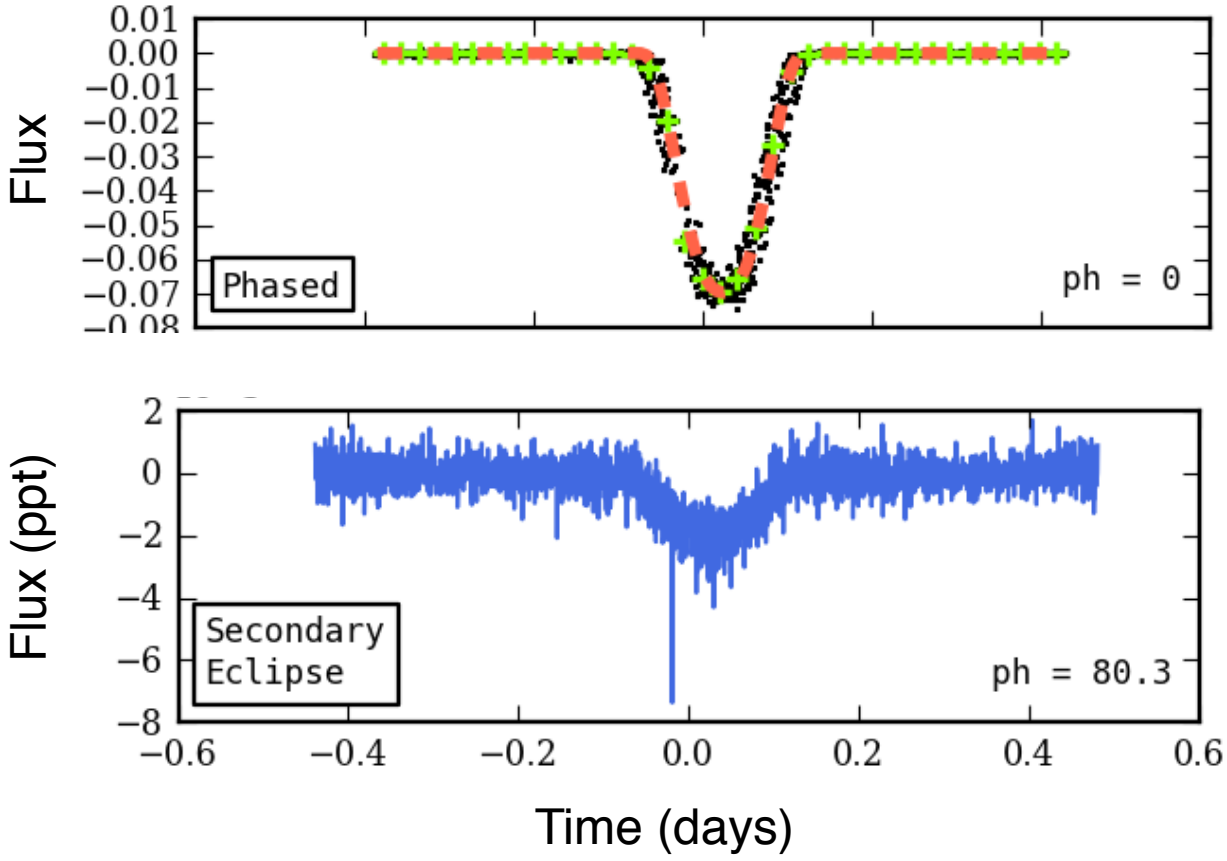

40,000 bright GK stars
Search for significant transits
using TERRA photometric pipeline
Q1–Q15
2184 TCEs
Remove non-astrophysical
false positives
836 eKOIs


40,000 bright GK stars
Search for significant transits
using TERRA photometric pipeline
Q1–Q15
2184 TCEs
Remove non-astrophysical
false positives
836 eKOIs
Remove astrophysical
false positives
• Centroid
• Odd-even
• Transit shape
• Secondary eclipse
603 planet candidates

Identifying eclipsing binaries using secondary eclipses

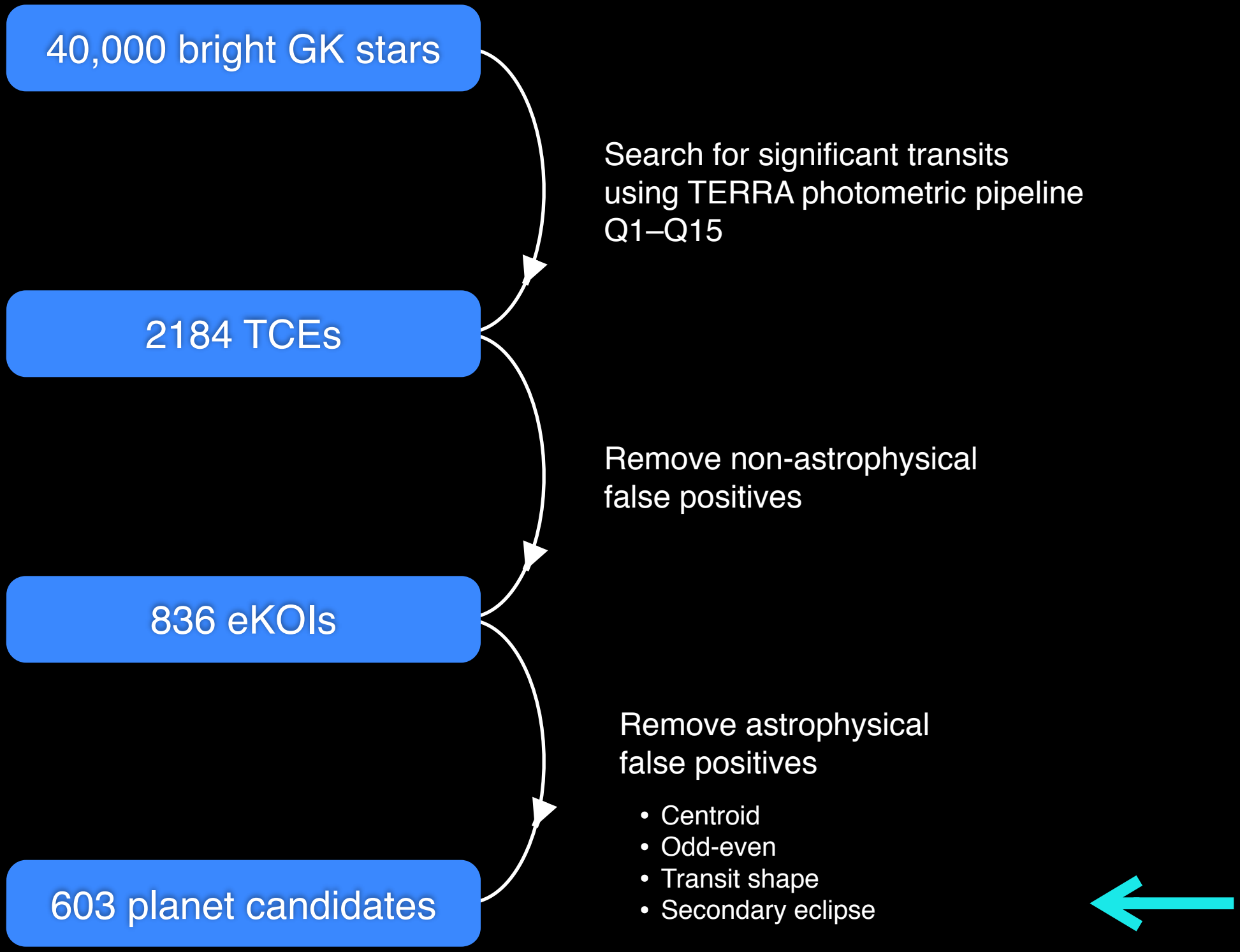


Primary 7% dimming

Secondary 0.2% dimming

T_{eff} = 2343 K

not a planet


40,000 bright GK stars
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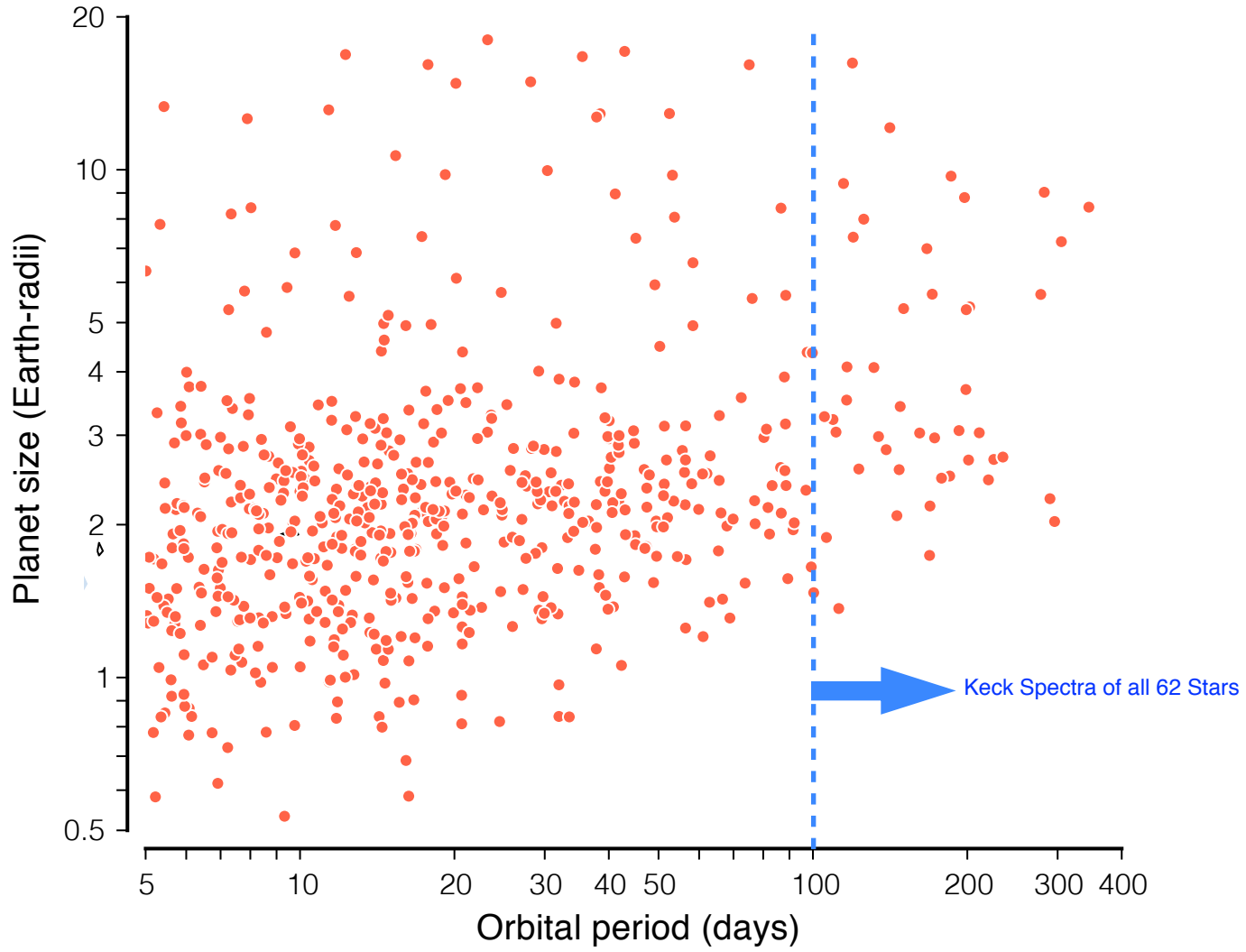
603 Planet Candidates

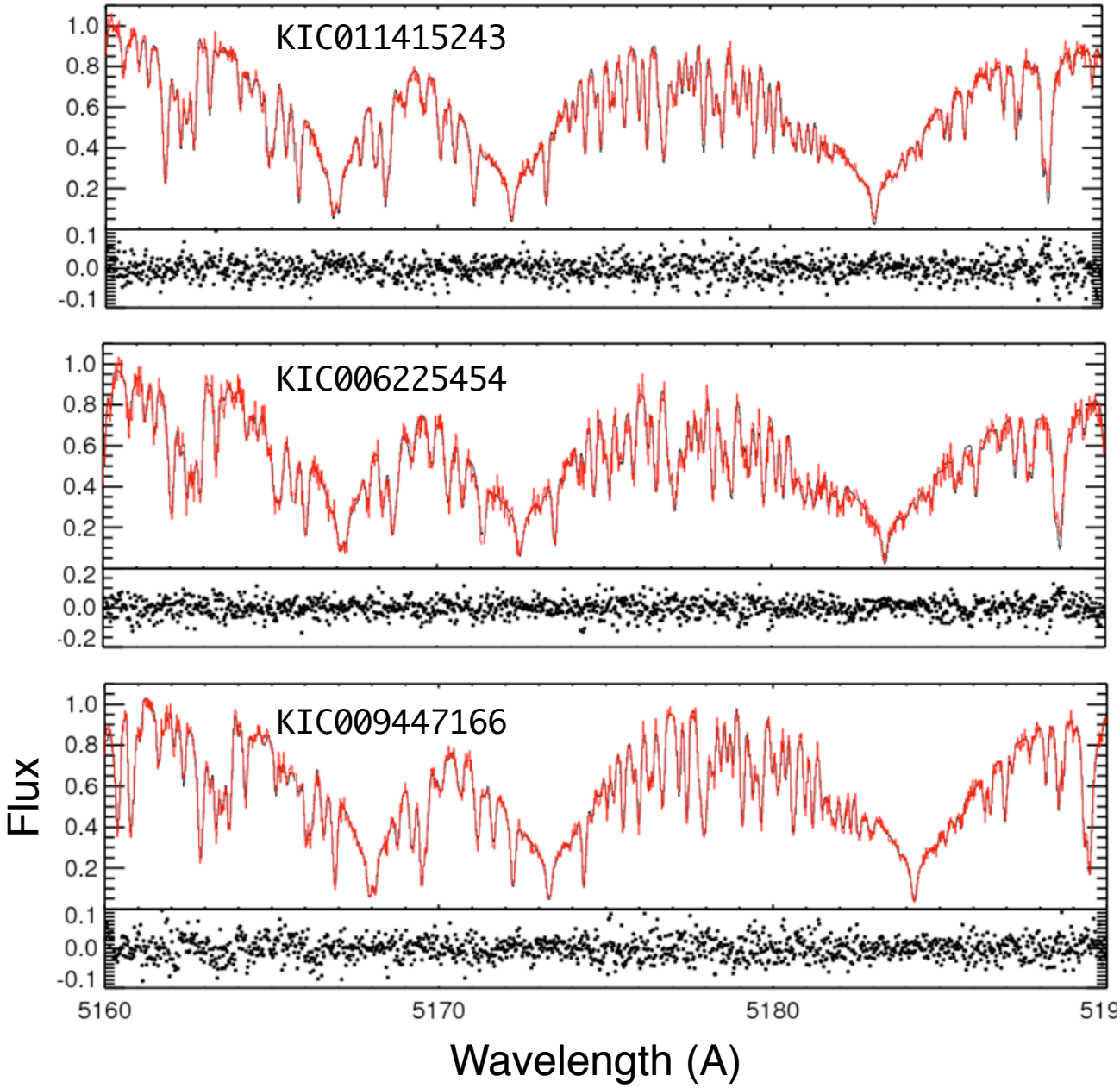


574 (95%) KOIs (Nov 2013)

597 (99%) KOIs (Jun 2014)

Keck HIRES spectra of 318 eKOIs

Keck spectra of all 62 candidates with P > 100 days



Keck HIRES Spectra

Better stellar parameters

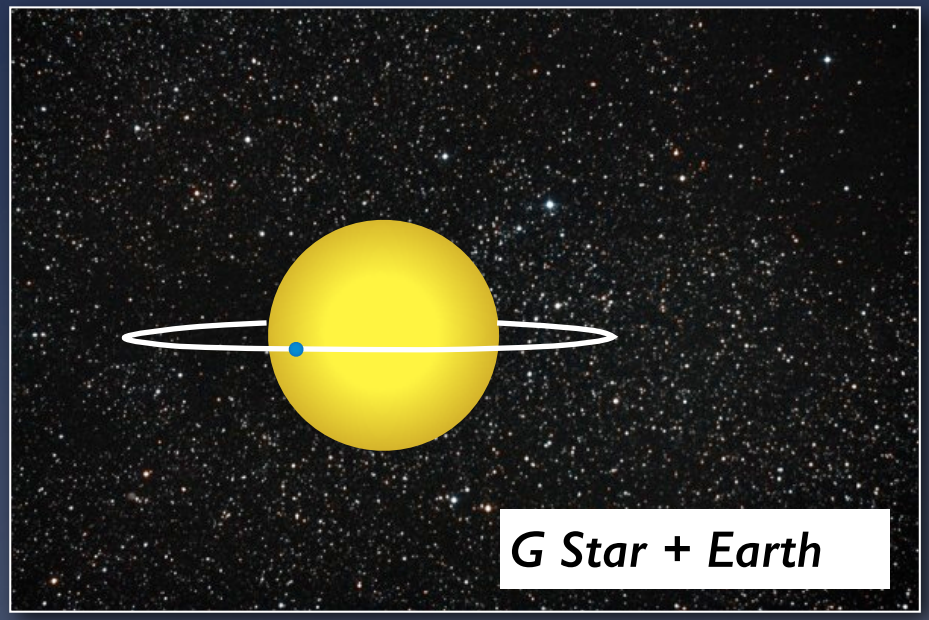
- $R_\star$ good to 10% (photometry: 40%)
- $L_\star$ good to 25% (photometry: 80%)

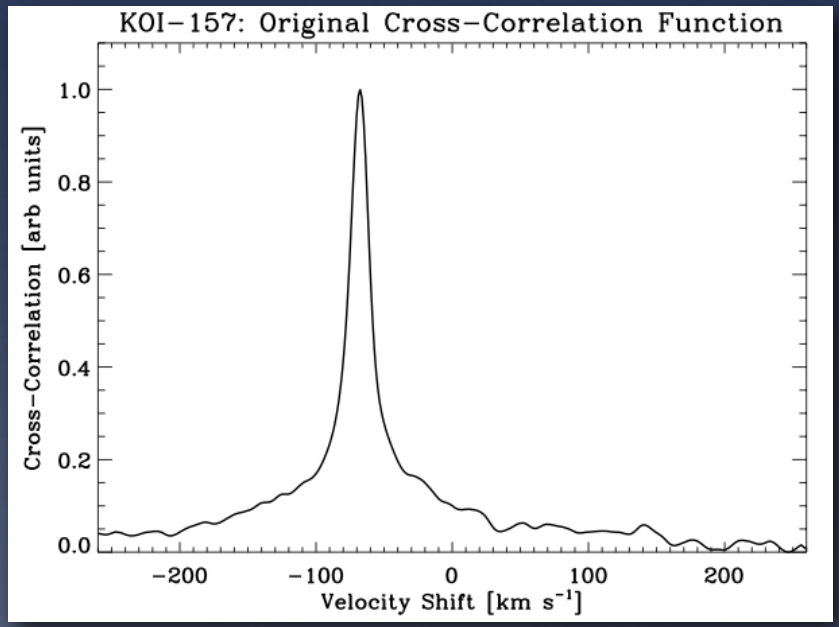
Find false positives

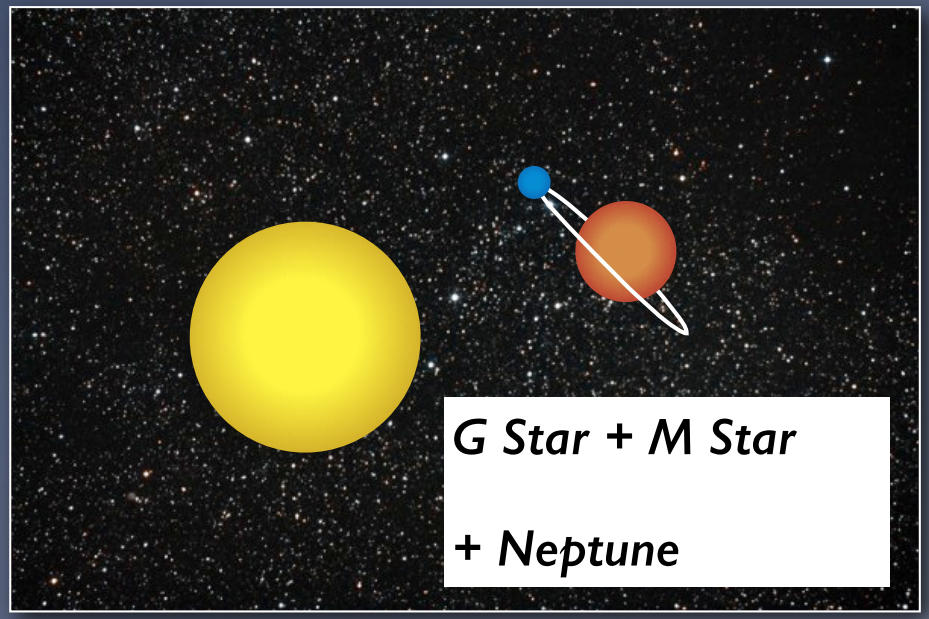
- Detect second set of lines
- Kolbl and Marcy (2014)

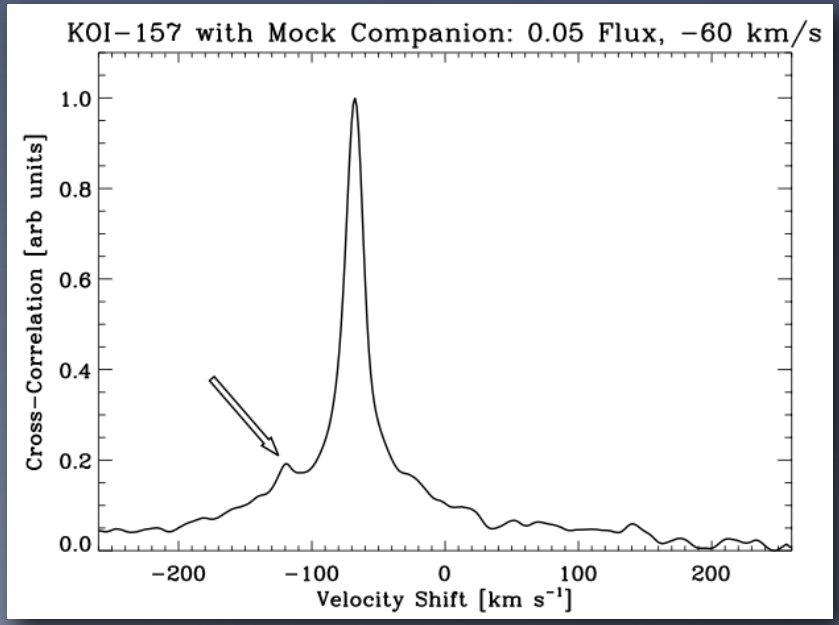
Petigura+ *in prep* (SpecMatch)

False positive vetting

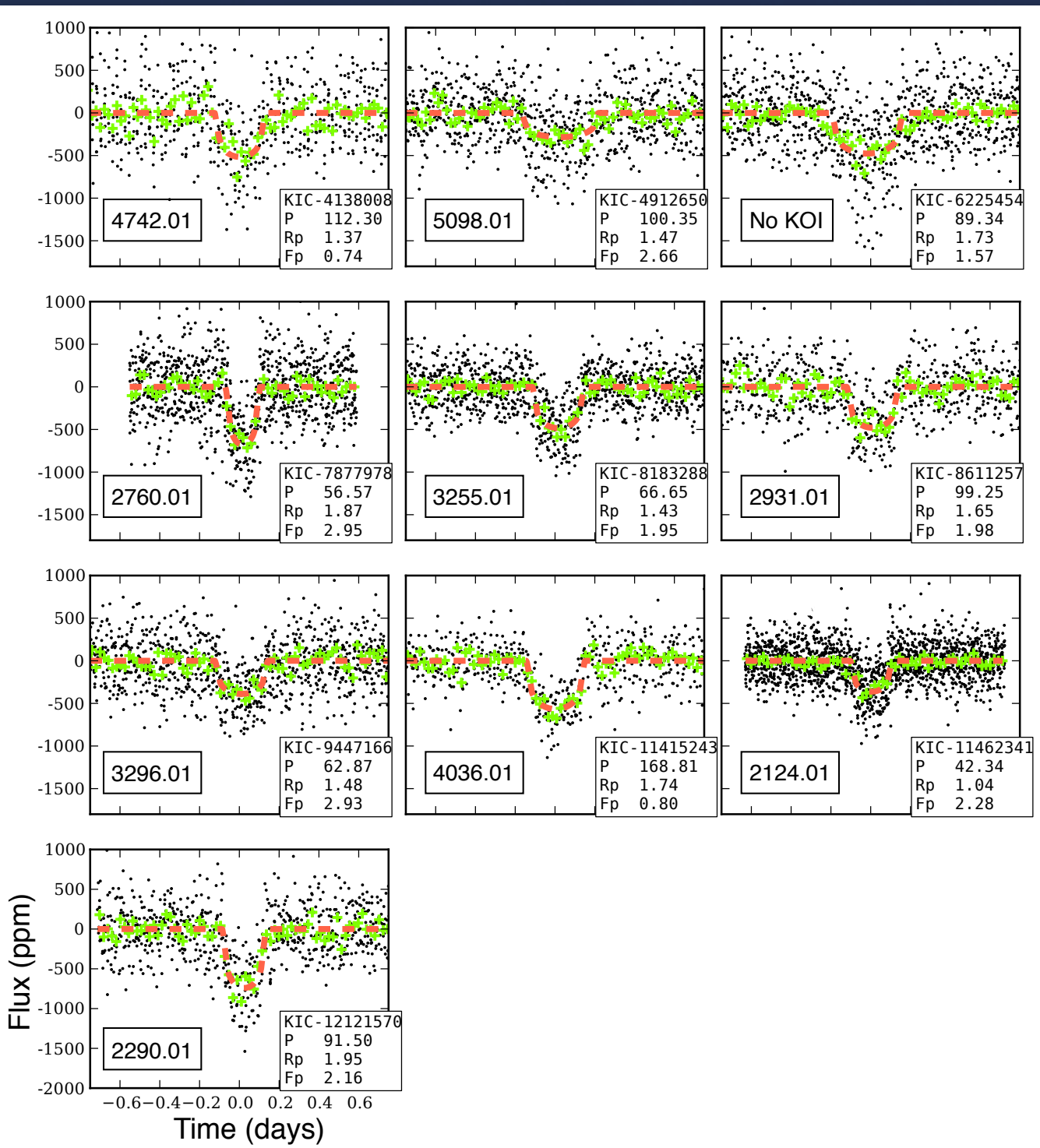








Kolbl and Marcy (2014)



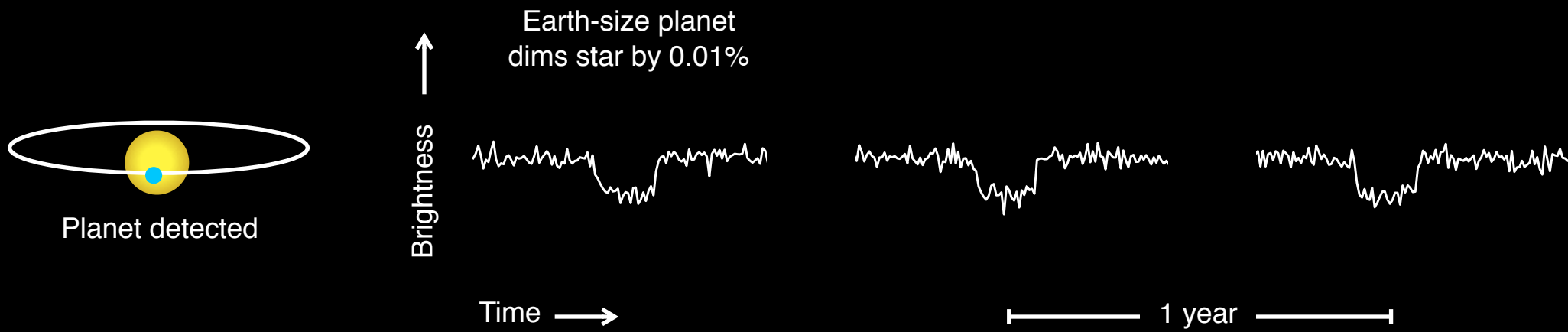
Representative Earth-size Candidates

Period > 40 days

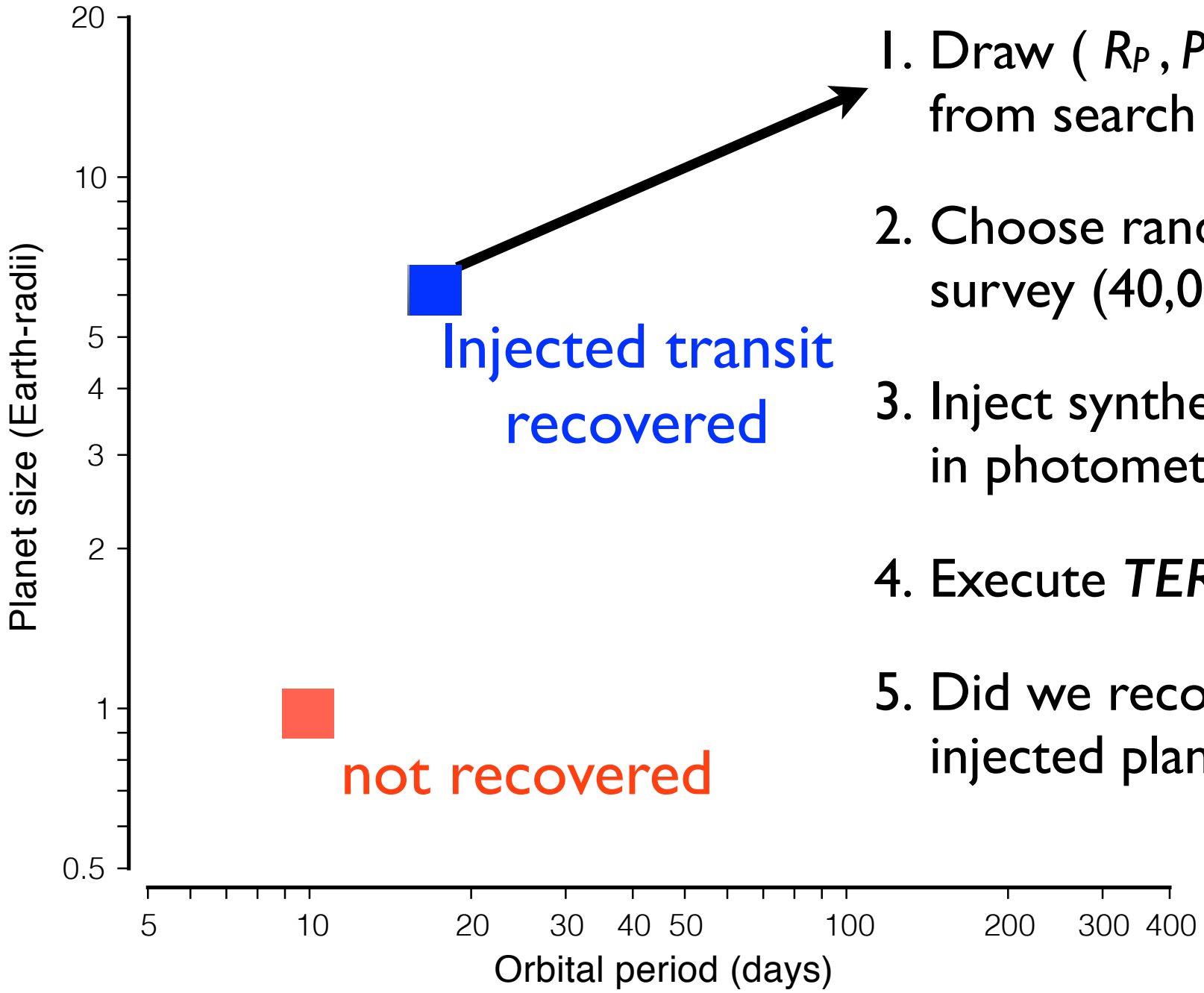
9/10 are KOIs.

Keck spectra of all.

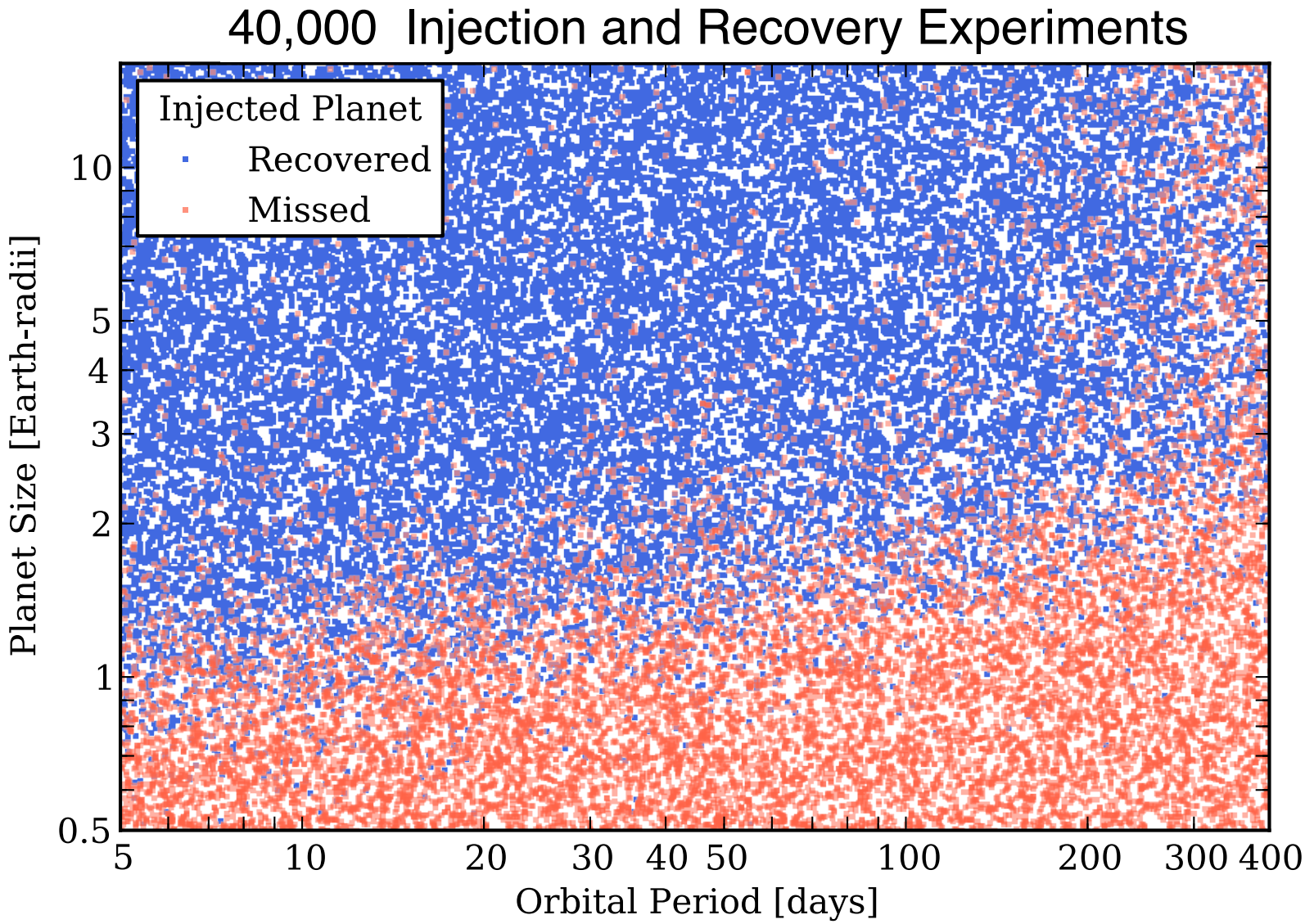
$$\text{Planet Occurrence} = \frac{\overset{\checkmark}{\text{N(planets found)}} + \overset{???}{\text{N(planets missed)}}}{\text{N(stars)}}$$


Earth-size planet
dims star by 0.01%
Brightness
Planet detected
Time
1 year

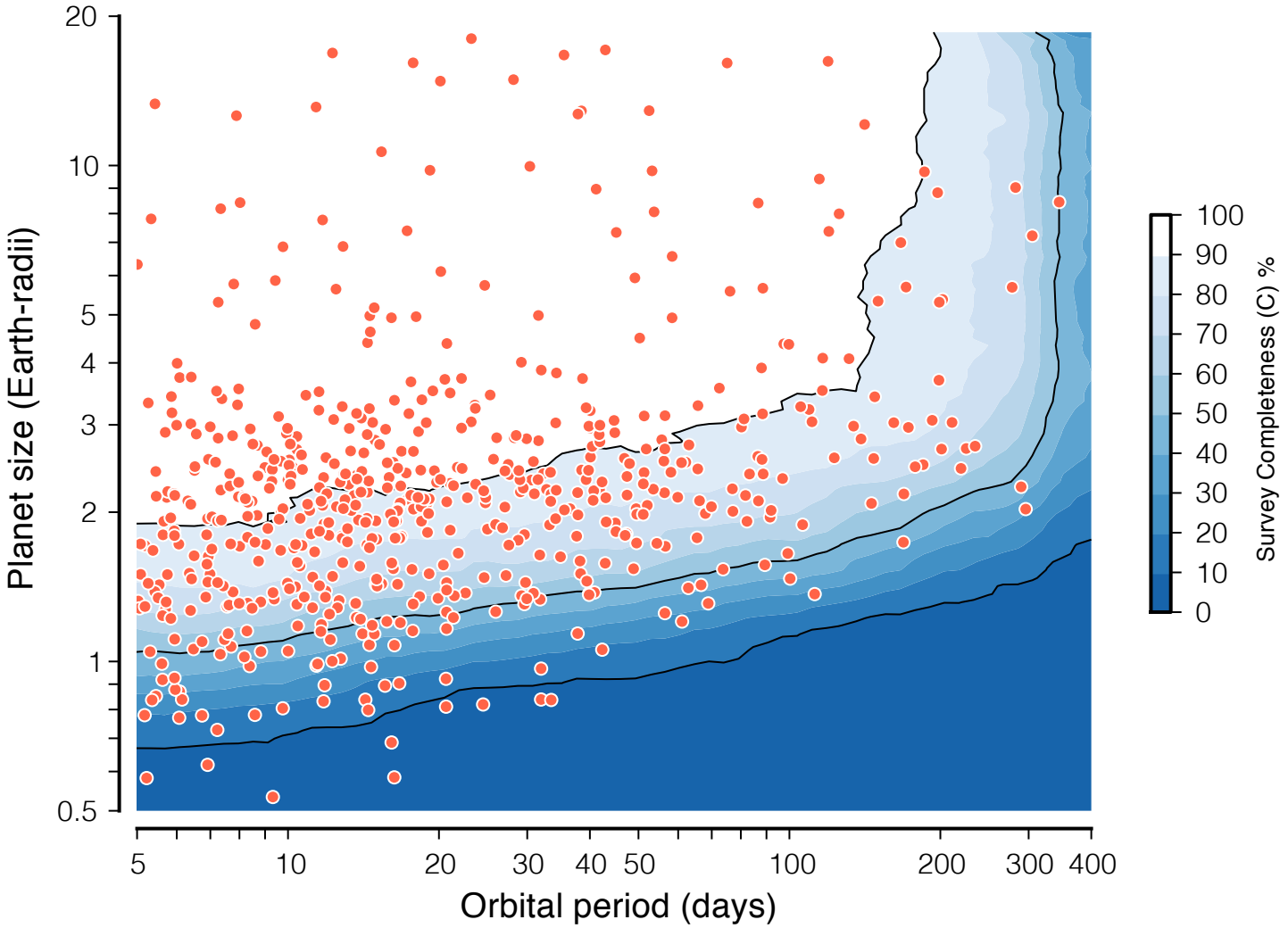
Injection and Recovery Determination: *Pipeline Completeness*



1. Draw (R_P , P) randomly from search domain
2. Choose random star from survey (40,000 GK stars)
3. Inject synthetic light curve in photometry (real noise)
4. Execute *TERRA pipeline*
5. Did we recover the injected planet?

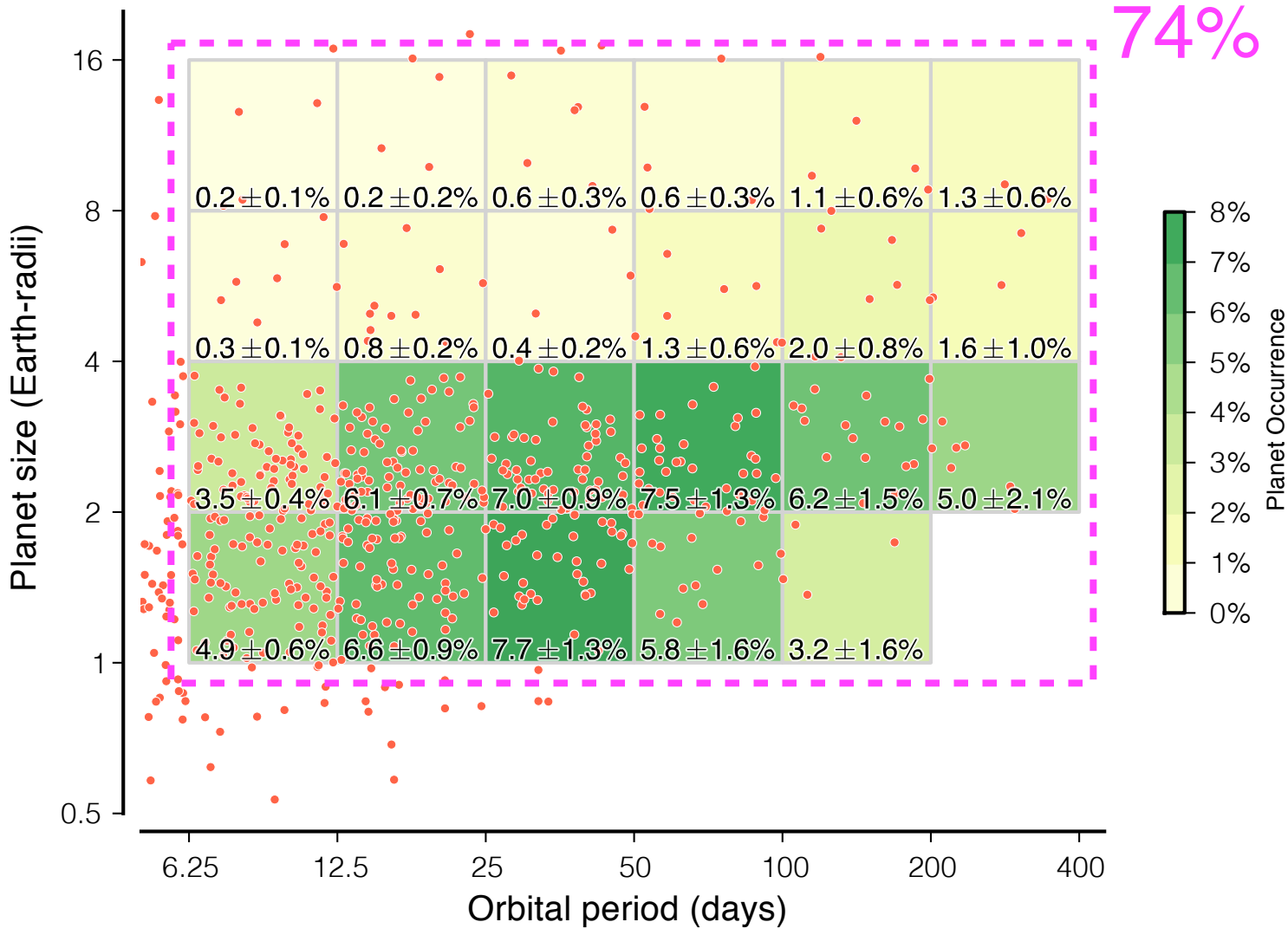

40,000 Injection and Recovery Experiments
Injected Planet
Recovered
Missed
Planet Size [Earth-radii]
10
5
4
3
2
1
0.5
5
10
20
30
40
50
100
200
300
400
Orbital Period [days]

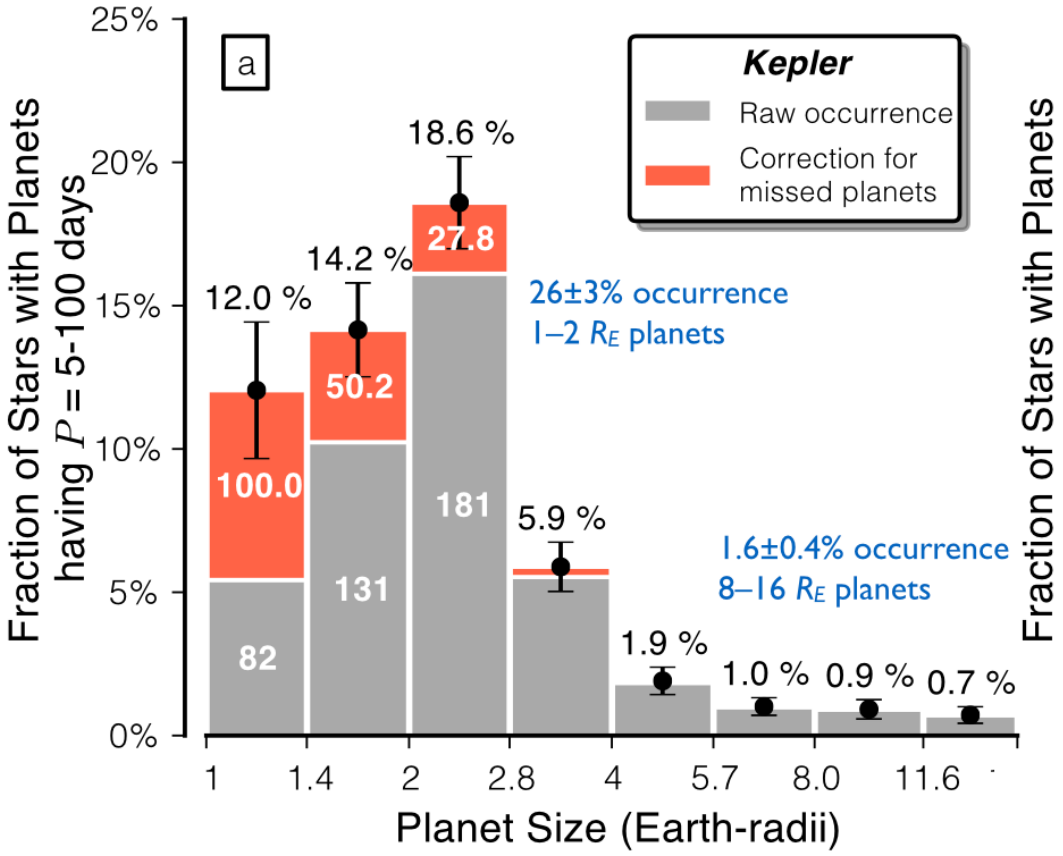
Completeness from Injection and Recovery



$$\text{Planet Occurrence} = \frac{\overset{\checkmark}{\text{N(planets found)}} + \overset{\checkmark}{\text{N(planets missed)}}}{\text{N(stars)}}$$

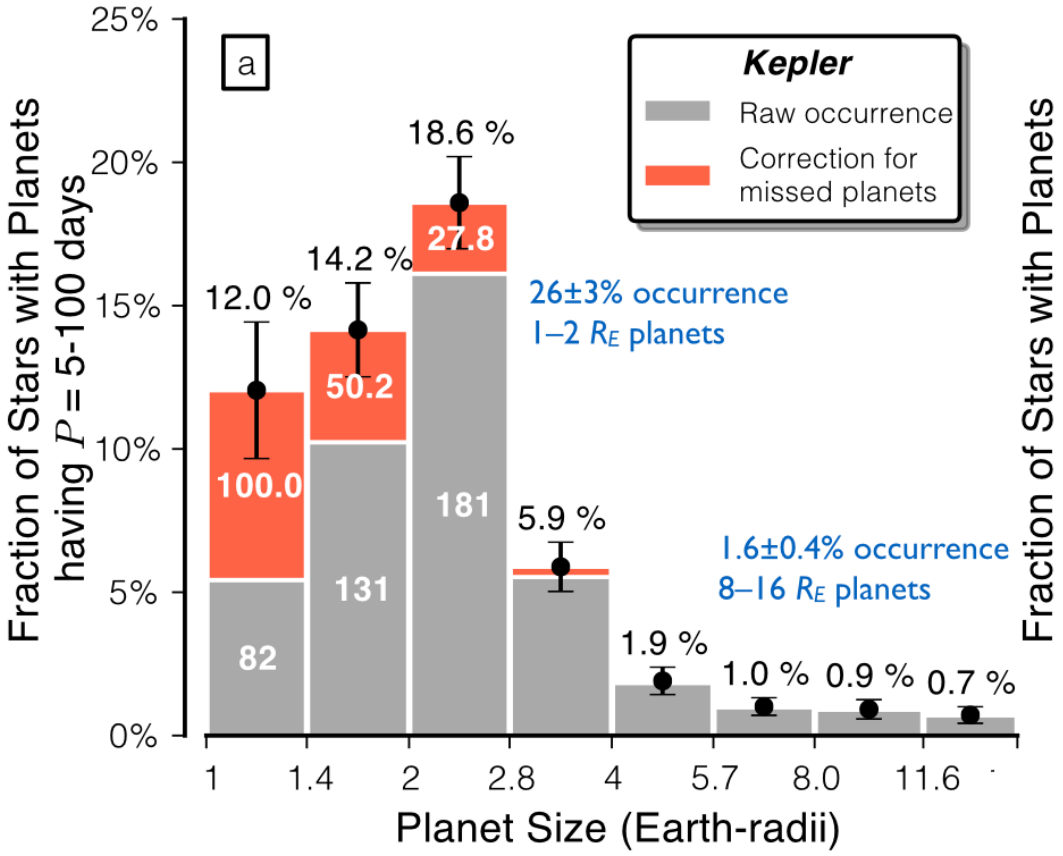
Planet Occurrence:
Planet Size and Orbital Period





Planet Size Distribution

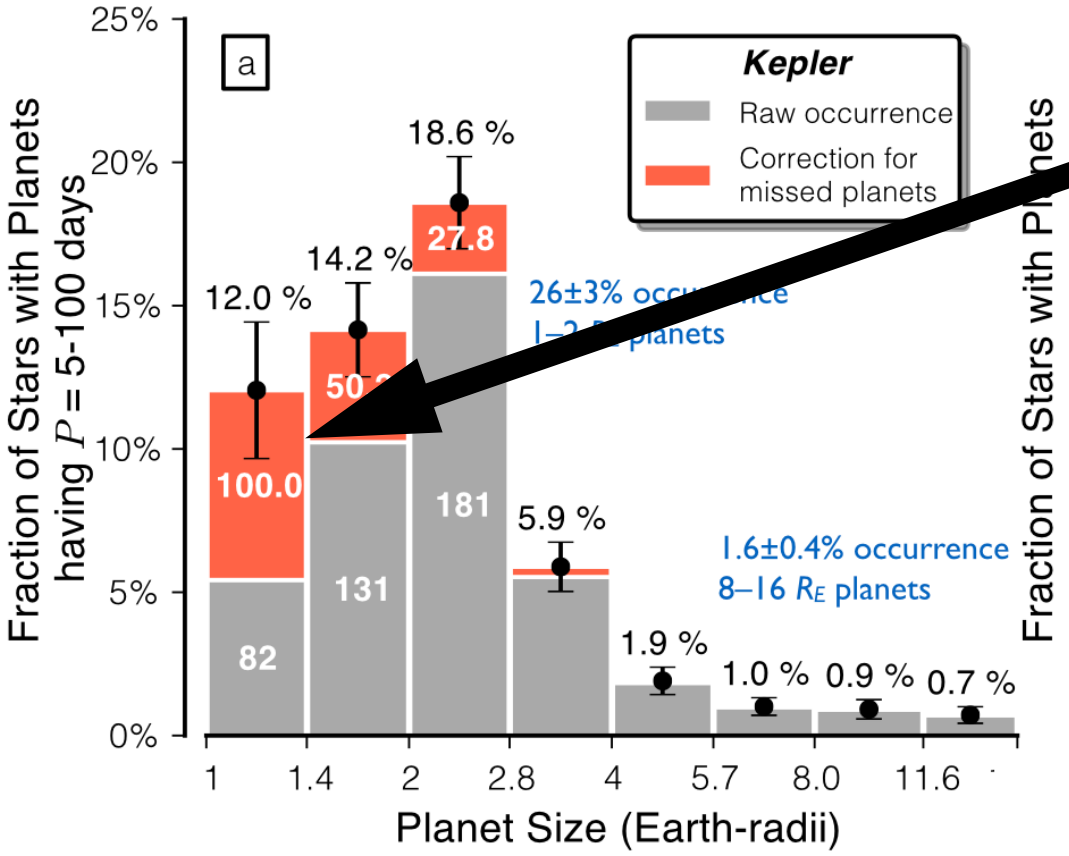
Petigura, Howard, & Marcy (2013)



26% of GK stars have Planets:
Radius: 1 - 2 R Earth
Period: < 100 days

Planet Size Distribution

Petigura, Howard, & Marcy (2013)



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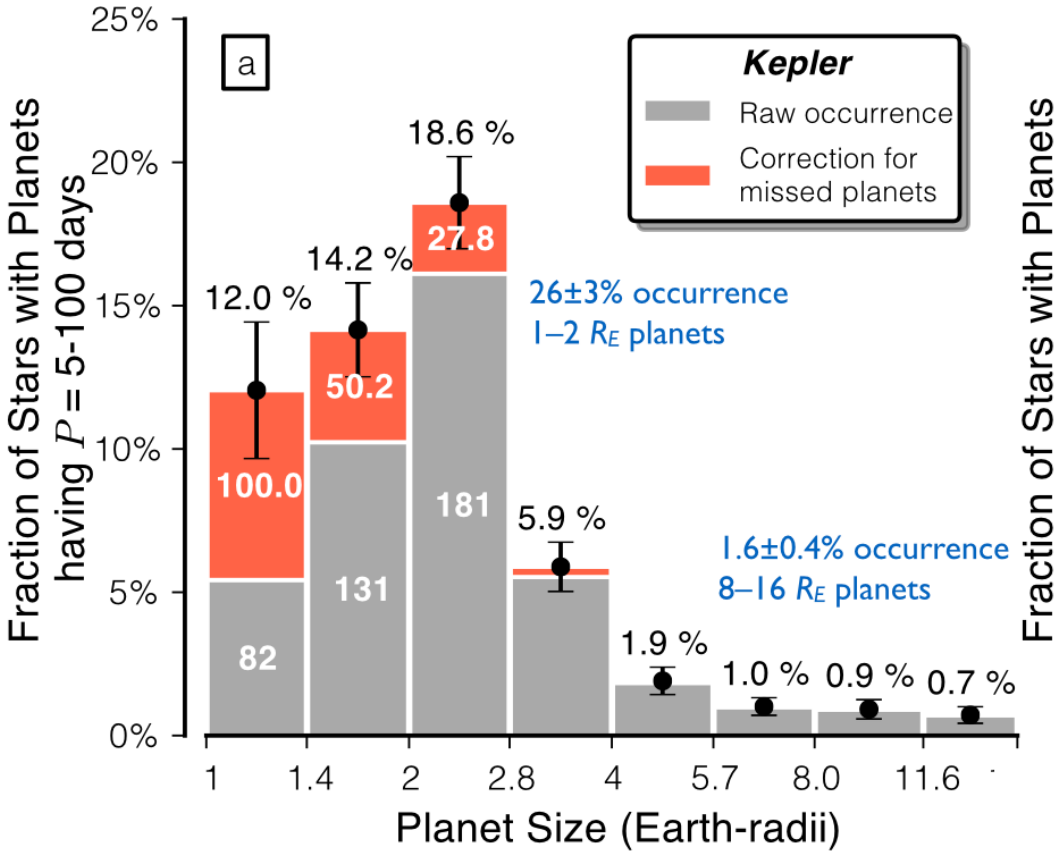

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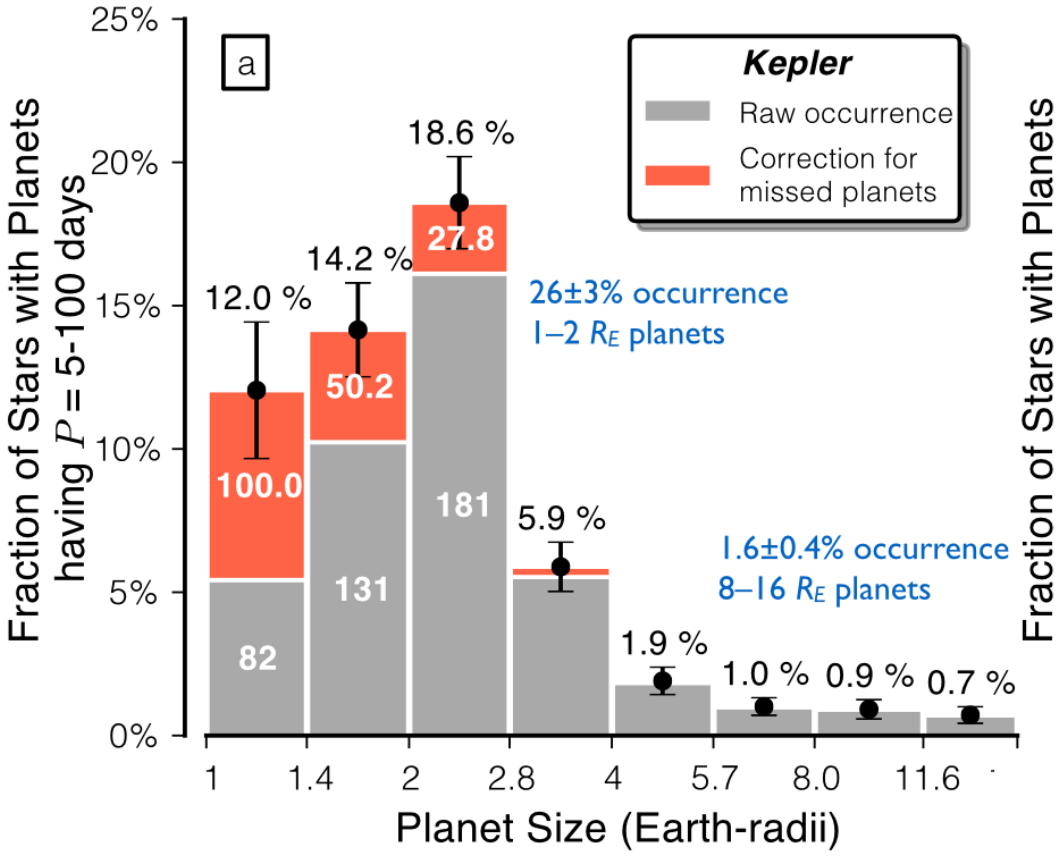
Period: < 100 days

Planet Size Distribution

Mullally, Batlaha, Burke, et al:
29% for 1-2 REarth, P < 50 d
60% for 1-2 REarth, P < 300 d

Charbonneau et al:

Petigura, Howard, & Marcy (2013)



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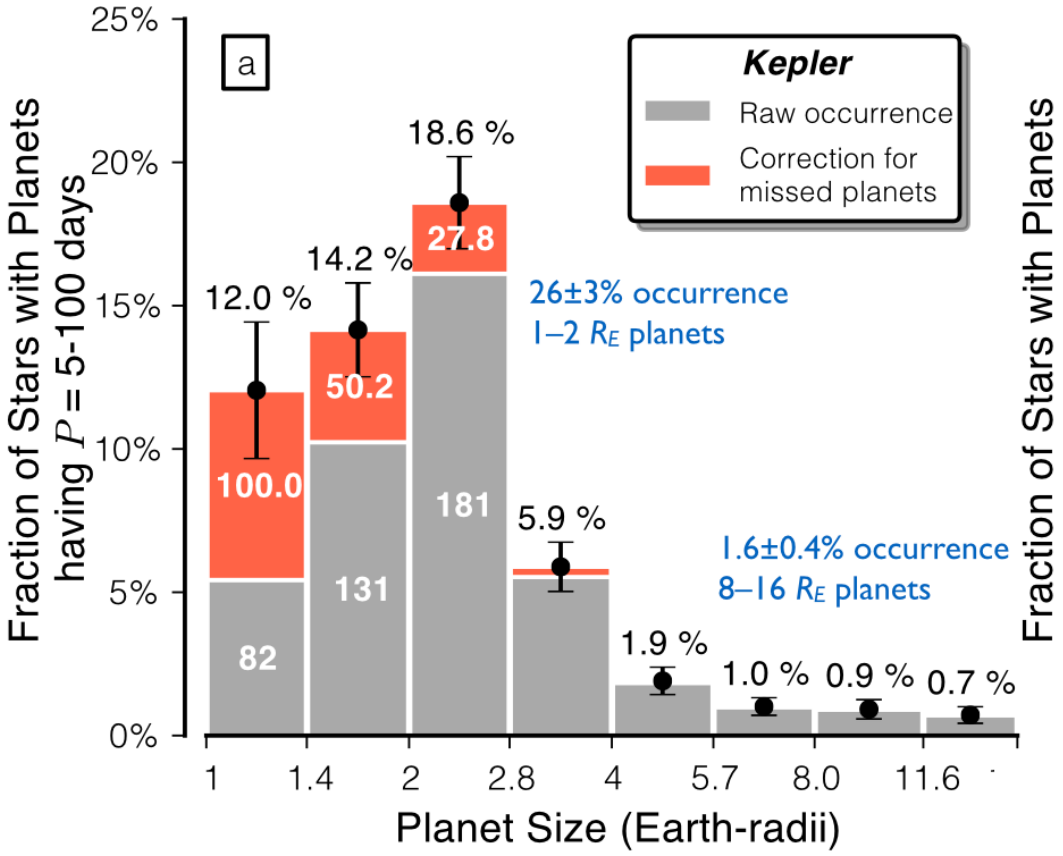
Charbonneau et al:

Our work: Only one planet included per host star.
==> 26% is a Lower limit to occurrence

Petigura, Howard, & Marcy (2013)



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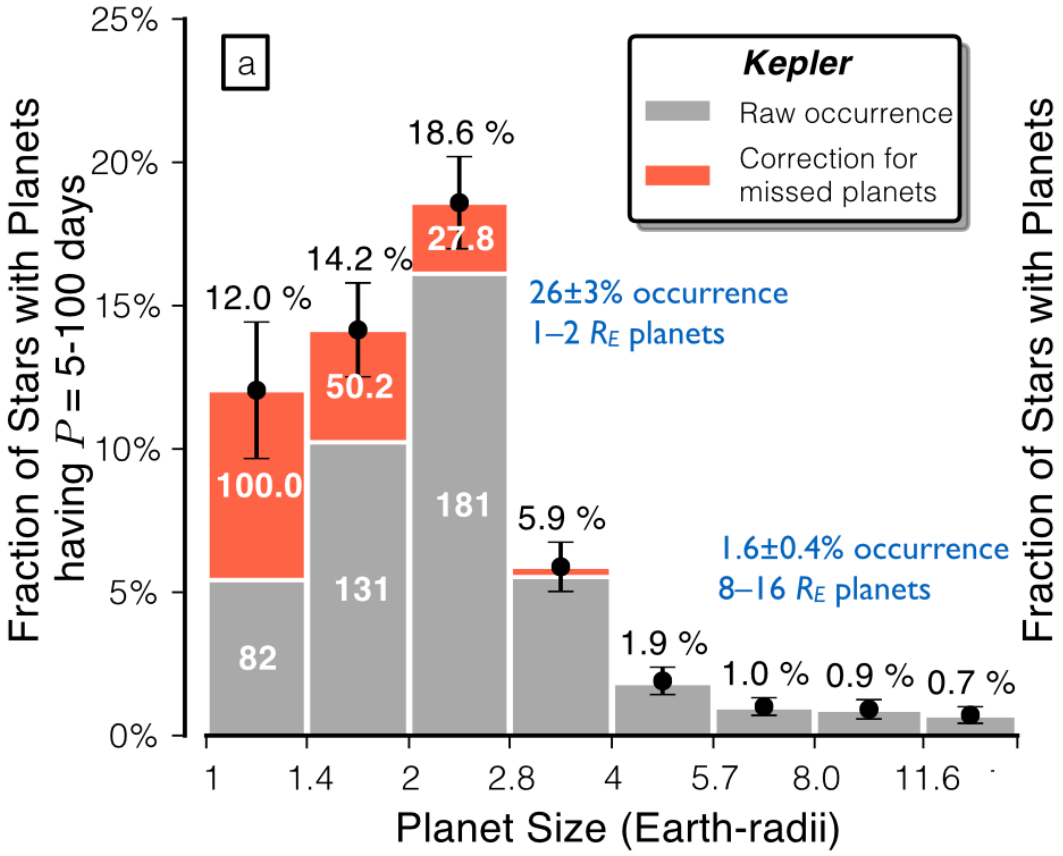
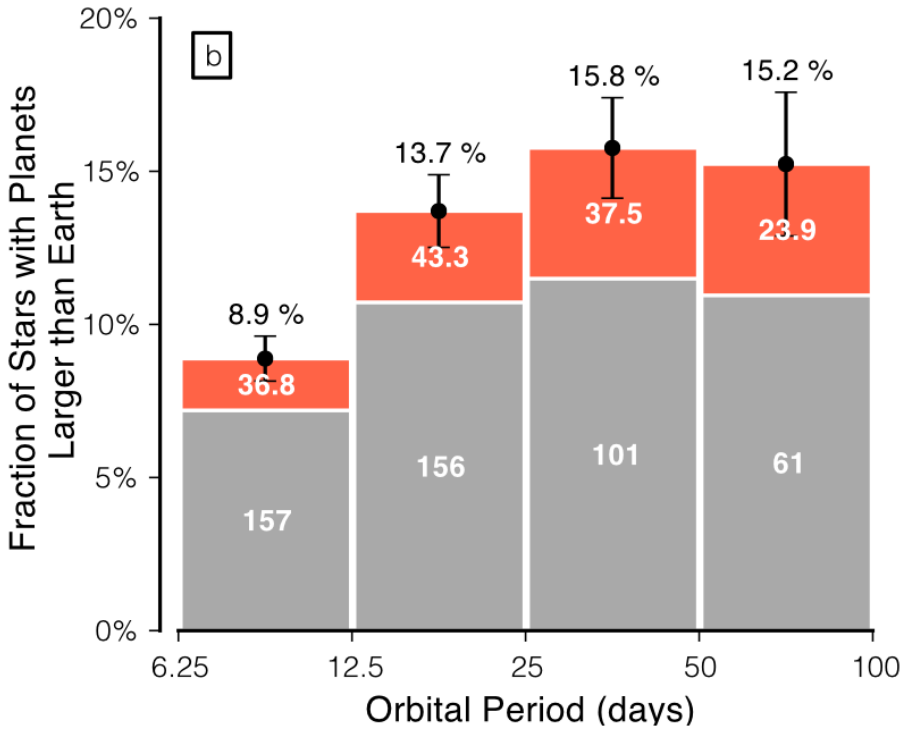


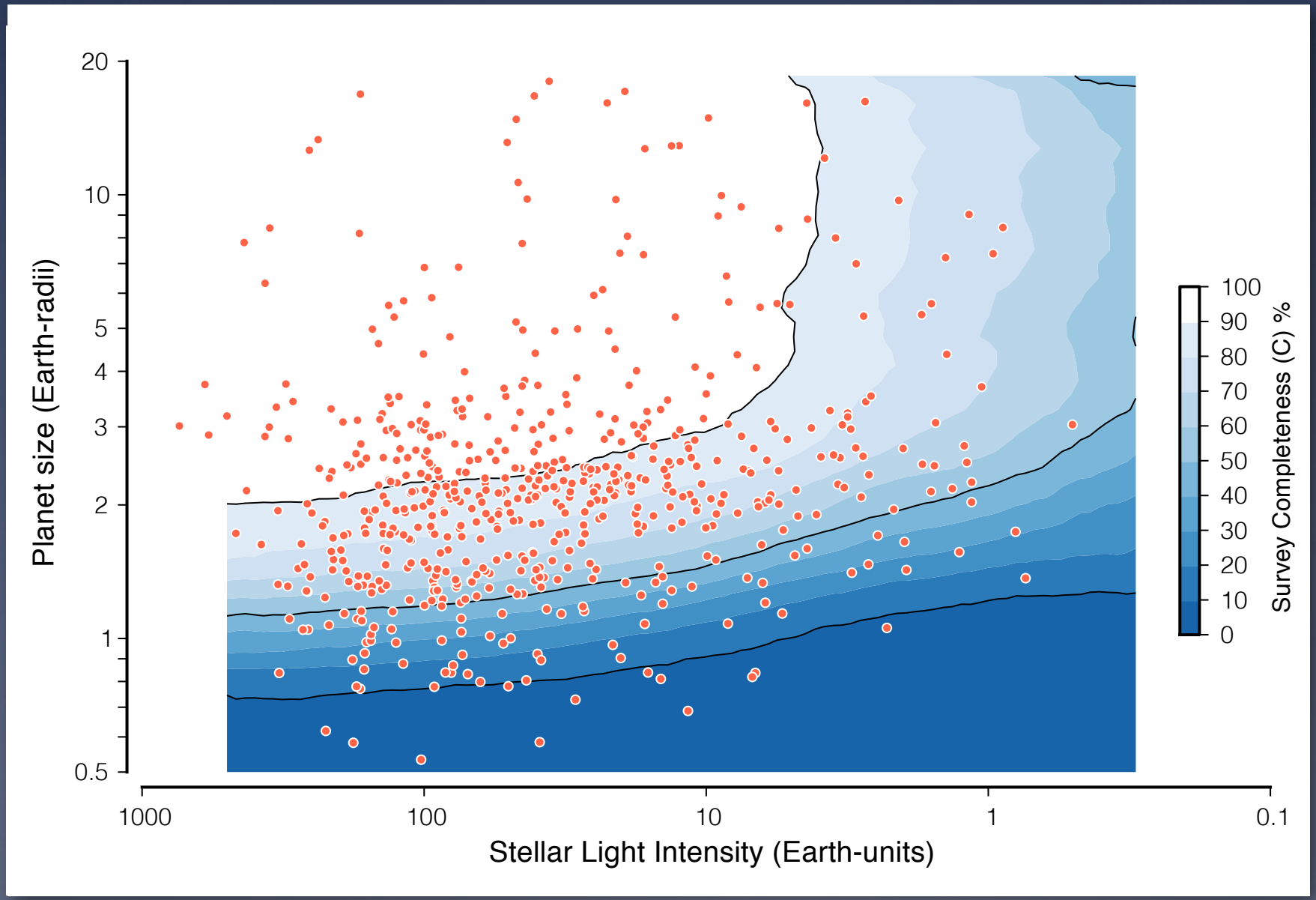
Planet Size Distribution

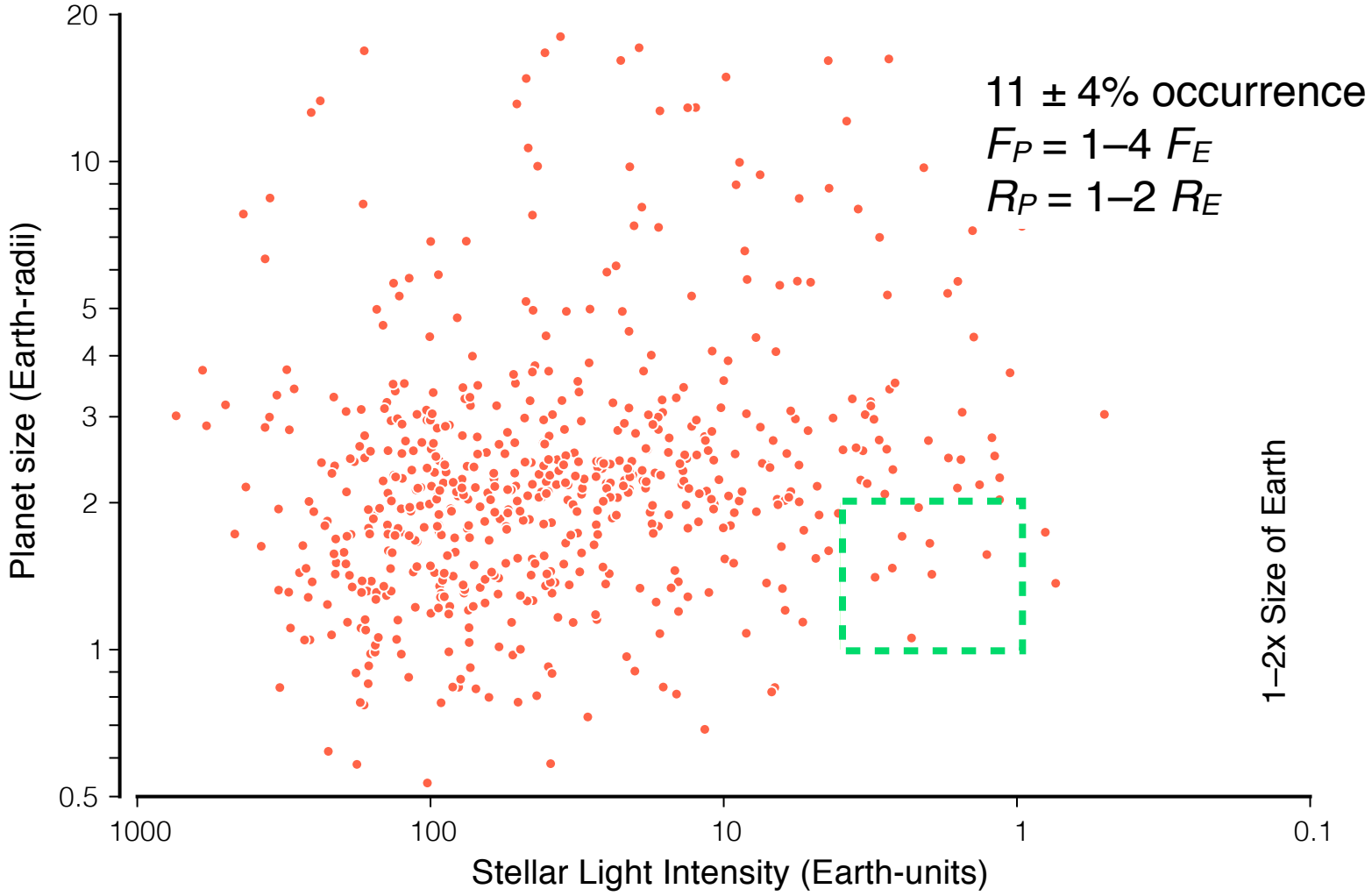
Planet Period Distribution



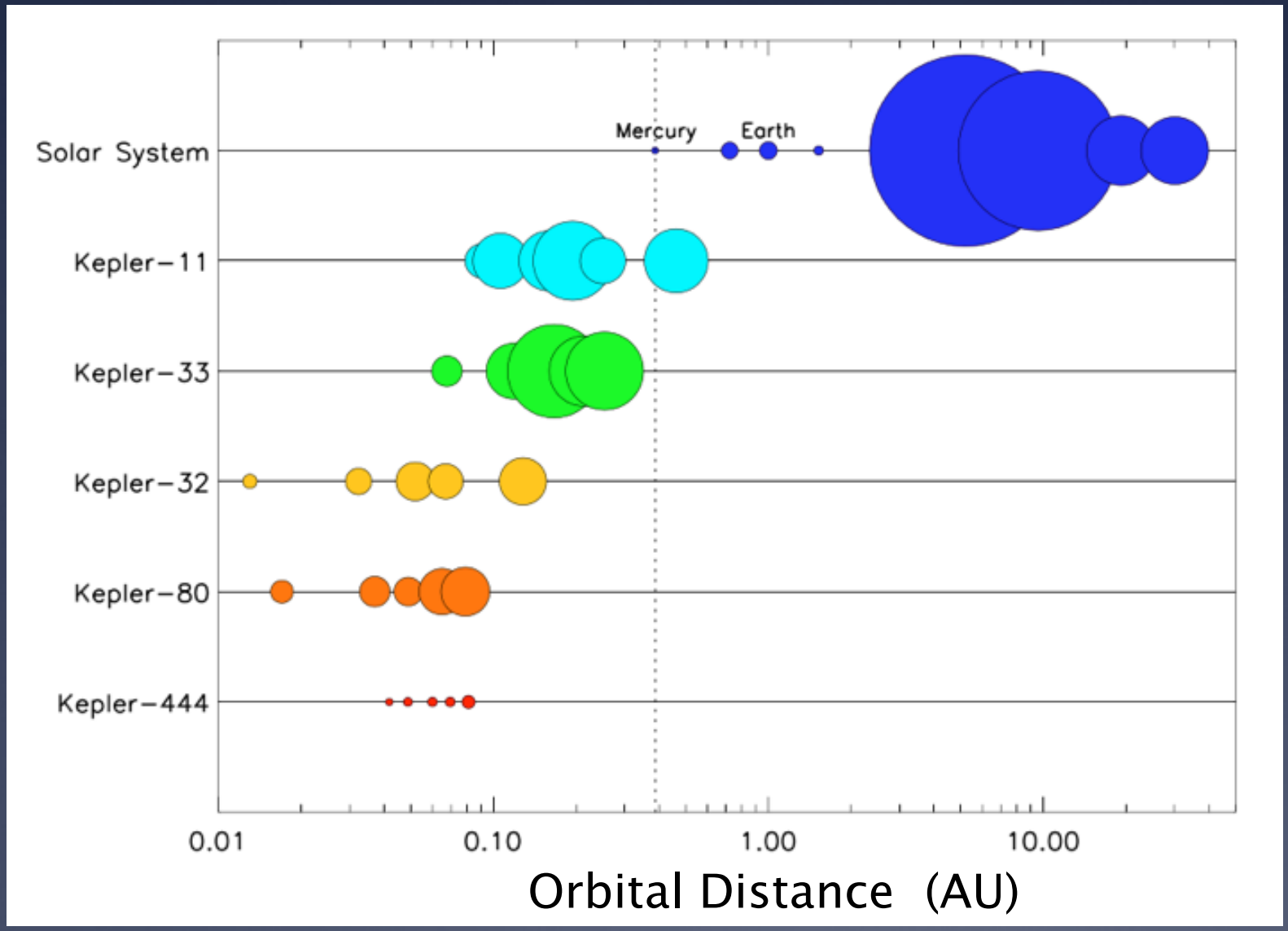
Petigura, Howard, & Marcy (2013)

Planet Occurrence:
Planet Radius and Incident Flux




11 ± 4% occurrence
F_P = 1–4 F_E
R_P = 1–2 R_E
1–2x Size of Earth
Planet size (Earth-radii)
20
10
5
4
3
2
1
0.5
1000
100
10
1
0.1
Stellar Light Intensity (Earth-units)

Multi-Planet Sub-Neptunes:
Formation Clue



Multi-Planet Sub-Neptunes:
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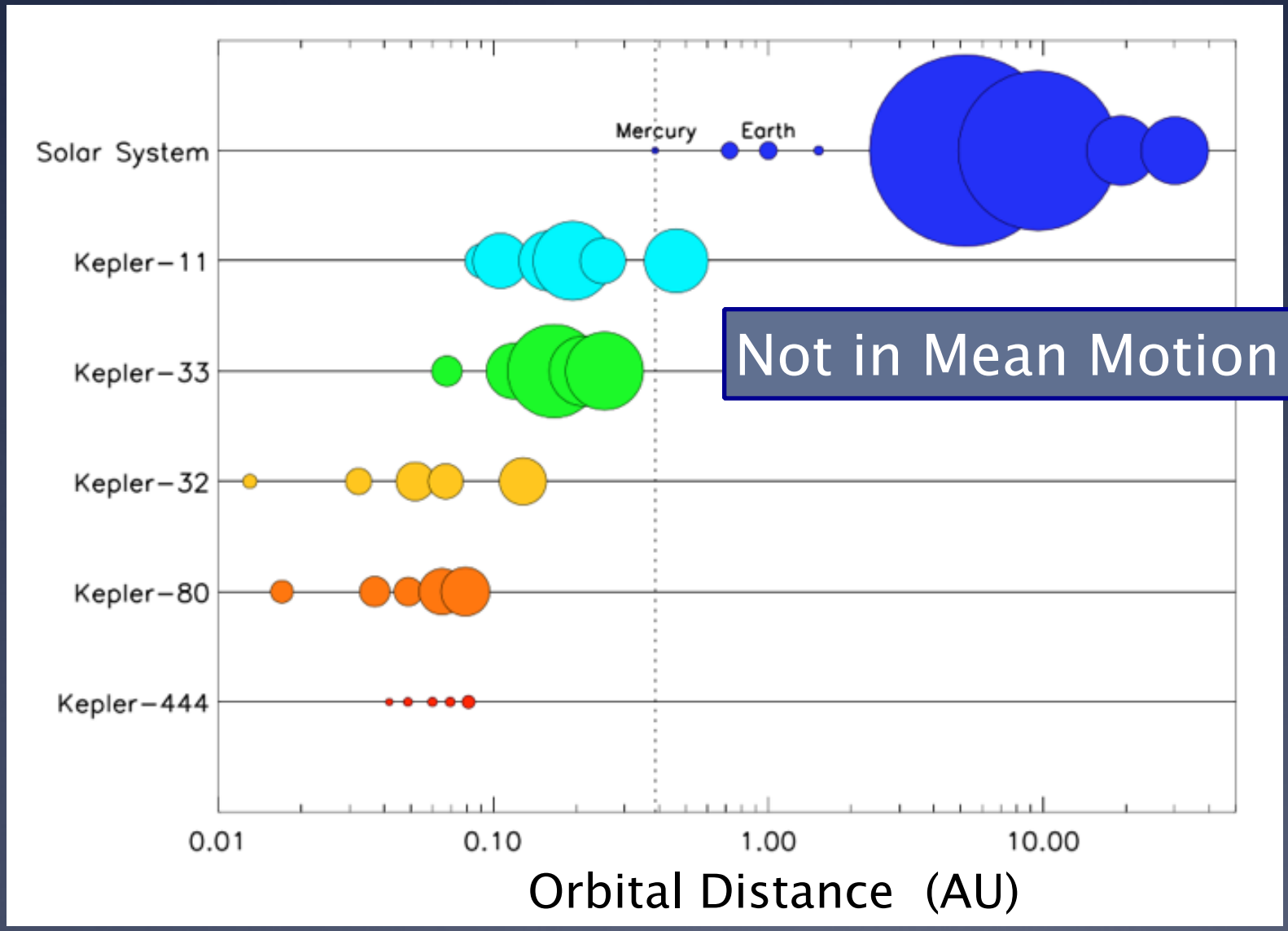
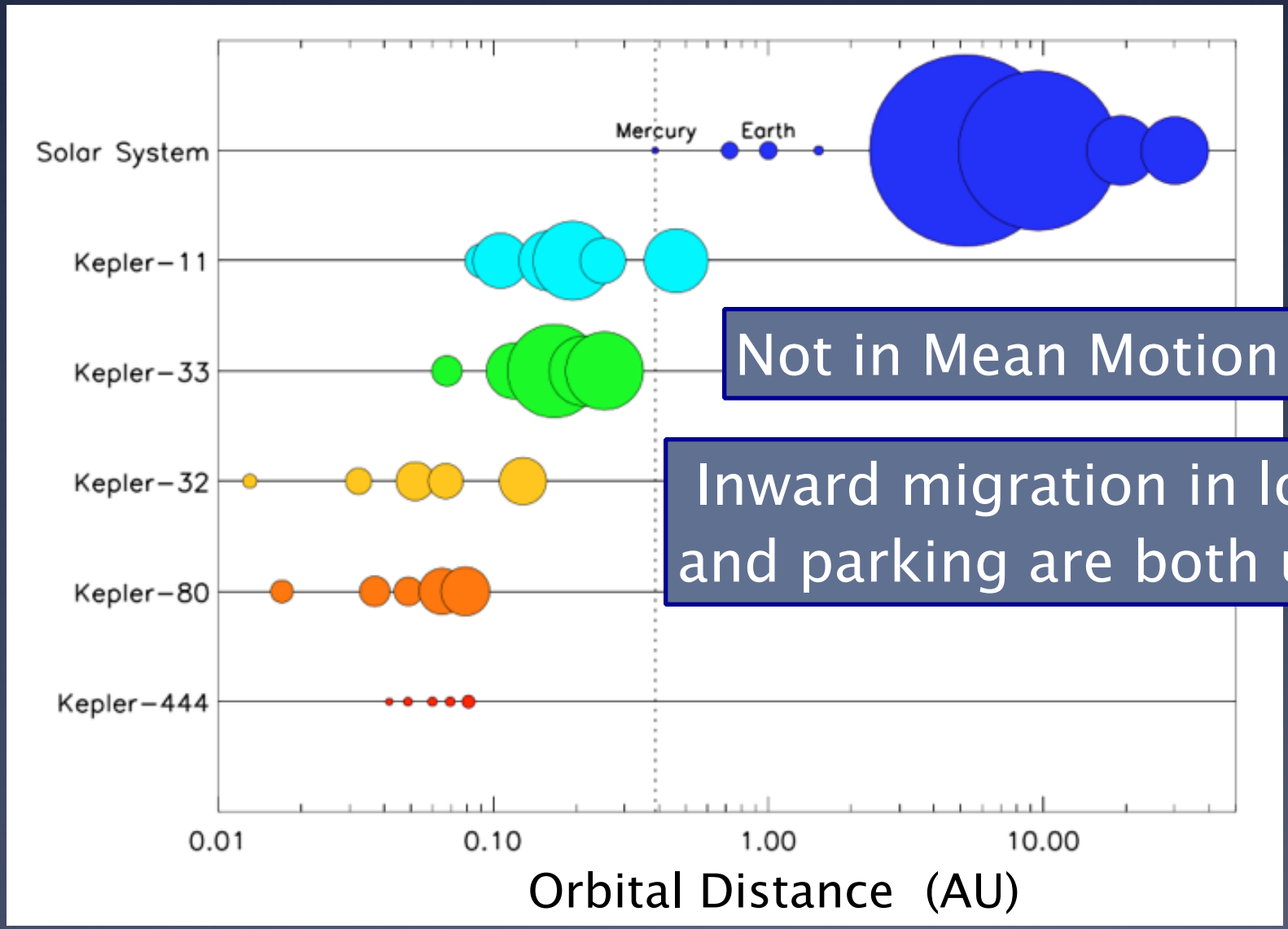


Not in Mean Motion Resonances

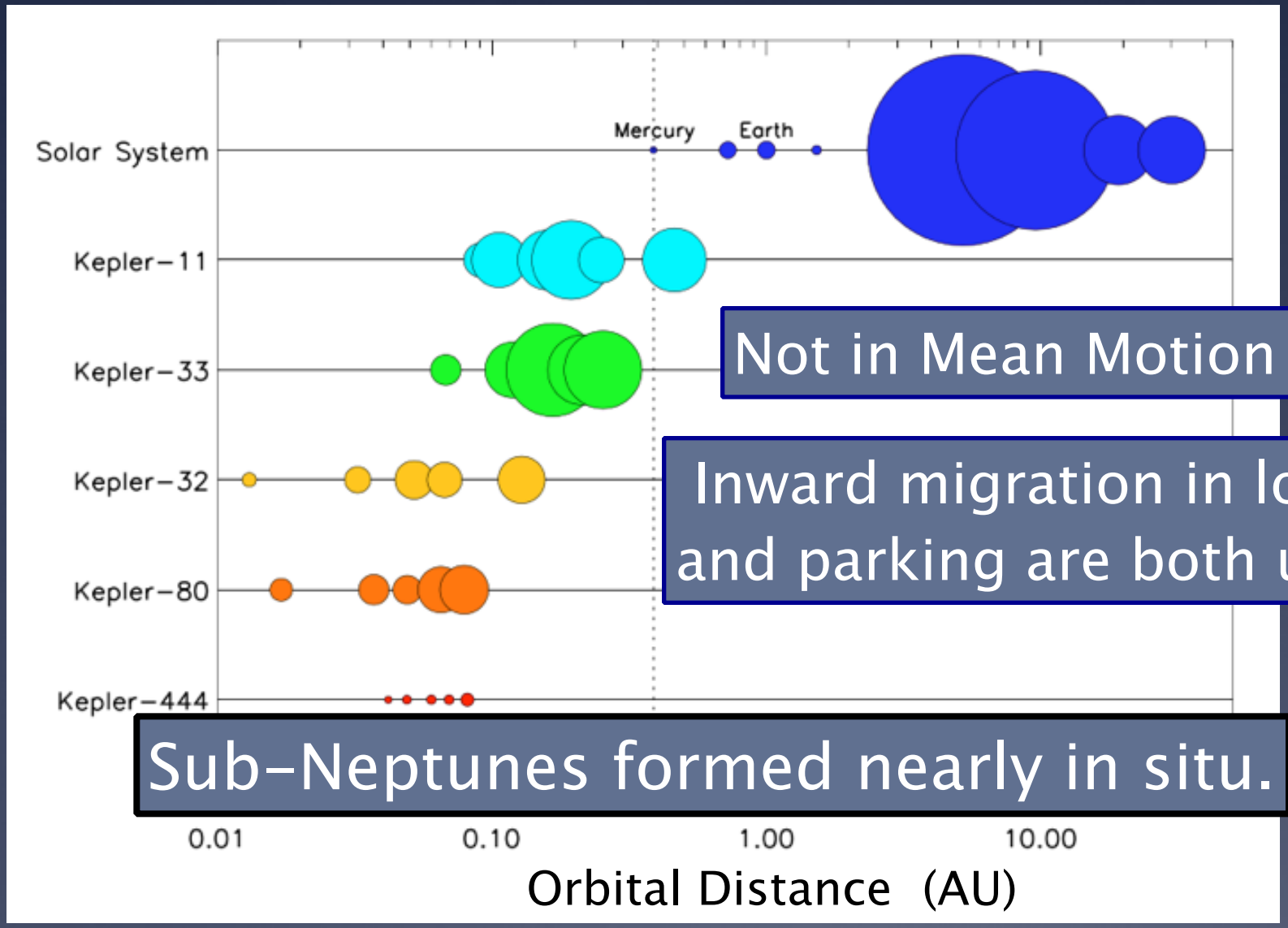
Multi-Planet Sub-Neptunes:
Formation Clue



Not in Mean Motion Resonances

Inward migration in lock-step, and parking are both unlikely.

Multi-Planet Sub-Neptunes:
Formation Clue

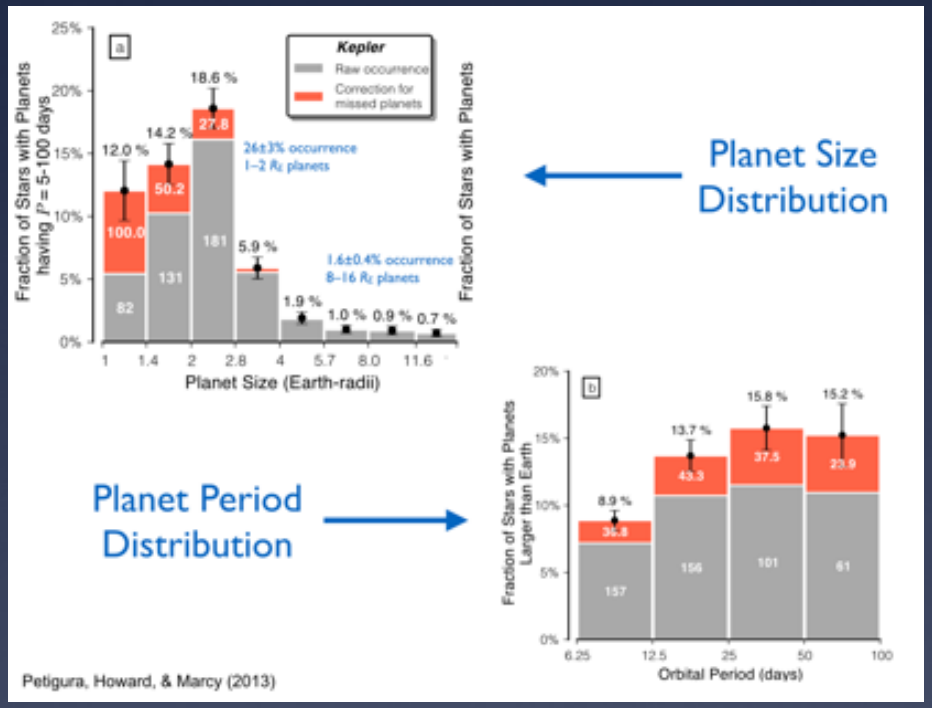
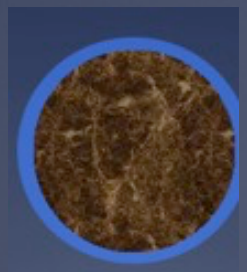
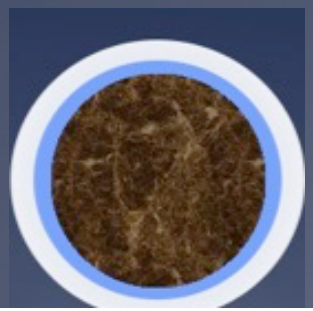
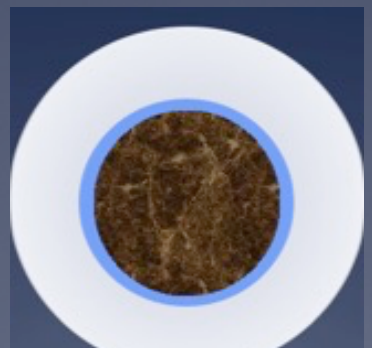
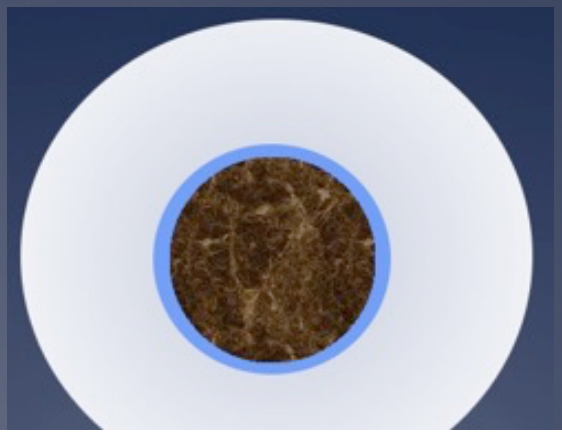


Not in Mean Motion Resonances

Inward migration in lock-step, and parking are both unlikely.

Sub-Neptunes formed nearly in situ.

Sub-Neptunes: Summary



* Probably Formed in close - Near where are they are now.