What is Needed to Measure η_{Earth} from Kepler?

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With support from:
Previous briefings to the Kepler Exoplanet Council
Community Follow-up Observing Program (David Ciardi)
SAMSI Kepler Working Groups: Planet Detection (Bekki Dawson)
& Planet Populations (Darin Ragozzine, Angie Wolfgang)

This Talk is Not

- NASA's position
- Kepler Project's position
- Kepler Exoplanet Council's position
- Follow-up Observing Program position
- Kepler Trasnit Timing & Multi-body Working Group's position
- SAMSI Kepler Working Groups' position

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- Kepler Transit Timing & Multi-body Working Group's position
- SAMSI Kepler Working Groups' position

- Penn State/CEHW's position
- Eric Ford's opinion

Main Points

- Best science from Kepler is yet to come

- Existing Kepler data will remain the key dataset for addressing many key scientific questions, including η_{Earth}, for decades.

What's the Catch?

NASA needs a realistic, stable plan for significant long-term support, including:

- Algorithm/software development,
- Kepler Data analysis,
- Follow-up observations,
- Providing and documenting data products to the community,
- Statistical methods/analyses and
- Scientific interpretation.

Requirements for η_{Earth}

1) Sensitivity to earth-size planets in the HZ *for a range of stellar types*
2) Uniform & reliable catalog of planets *& target stars* with well-understood *planet* sizes, orbital periods & insolation fluxes
3) Understanding of sample completeness terms
   – Sensitivity, geometry, pipeline, *vetting…*
4) Knowledge of sample reliability terms:
   – Astrophysical, instrumental, pipeline
5) Well-documented and accessible data products*, algorithms and software tools* for continued analysis by the community as the state of information improves.

Here and afterwards italics indicate modifications by EBF

A First Step Towards η_{Earth}

Occurrence rates expressed as a distribution over planet size, period, insolation flux, and star type with corrections for both catalog reliability and catalog incompleteness.

sensitivity → $\frac{1}{N_*}$; *indicator function* → I

$$\text{Number of Planet per Star} = NPPS = \frac{1}{N_*}\sum_{i=1}^{n_p}\frac{r_i}{c_i}\times I[P_i, Rp_i, S_i, T_{\mathrm{eff}\,i}]$$

$$r_i = r_{astro} \times r_{instr} \times \ldots$$ ← reliability

$$c_i = c_{geom} \times c_{sens} \times c_{pipeline} \times \ldots$$ ← completeness

Kepler *project's* initial analyses will follow the methodology of Burke et al 2006 and Youdin 2013.

SAMSI Populations Working Group is developing a more powerful statistical framework and computational tools.

Improve Detection Efficiency

- Increase sensitivity to small planets in long period orbits
  - Analyze the full set of mission data that has been collected using existing and future pipeline tools
  - Identify new candidates early enough to initiate follow-up observations
  - Improve spatial resolution and time dependence of the PRF *(Pixel Response Function)* model
  - Implement PRF fitting in PA *(Photometric Analysis)*
  - Tune the TPS *(Transiting Planet Search)* vetoes and understand pre-veto vulnerabilities to increase the detection probability in TPS

Occurrence rates of Earth-size planets in the HZ of G-type stars will have to be extrapolated from other populations unless we increase sensitivity to this part of parameter space. *I am confident we can.*

R. Dawson

Earth-size signals are being detected by pipeline

Kepler Threshold Crossing Events

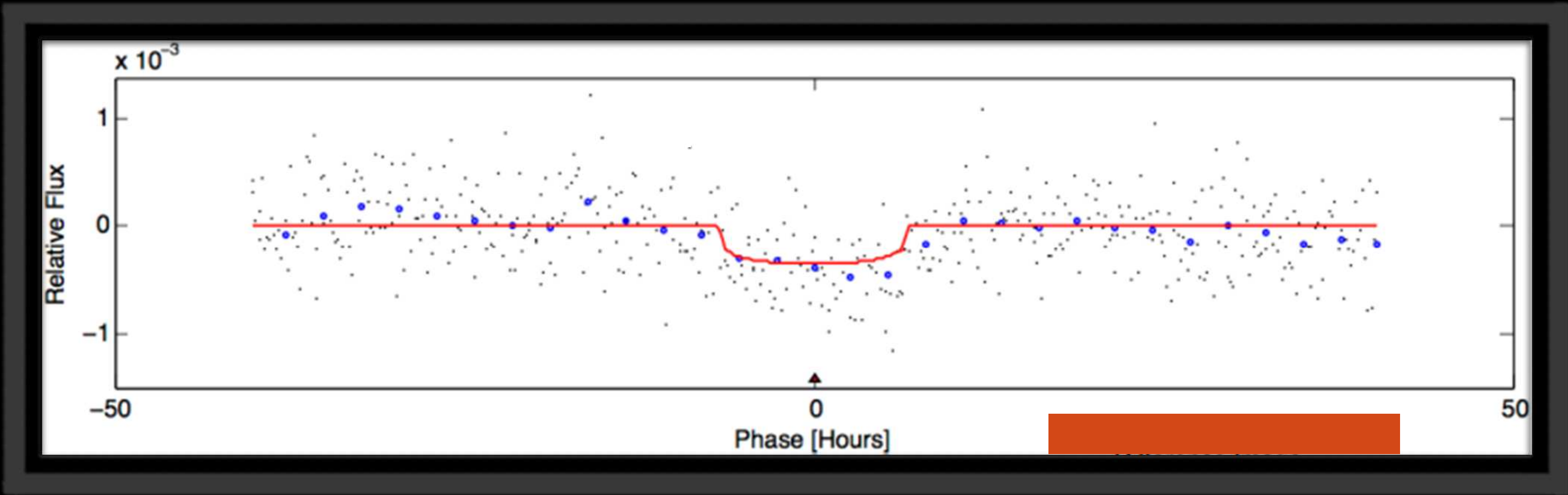
KepID	Planet Number	Orbital Period [days]	Planetary Radius [Earth]	Trans
		between 200 and 400	between 1 and 2	
9893468	1	201.338±0.00505155	1.866±2.237	174.724
6516734	1	201.608±0.0106736	1.599±3.637	273.28
6308539	1	201.953±0.0139061	1.237±5.584	171.697
4934928	1	202.245±0.0147445	1.307±4.266	170.851
10532378	1	202.77±0.00516909	1.96±2.637	230.541
8110733	5	203.504±0.00488337	1.95±3.77	329.502
8613497	1	203.843±0.0119426	1.481±4.159	196.971
10538299	2	204.087±0.00909437	1.345±9.948	168.92
4914162	1	205.12 [illegible]	[illegible]	[illegible]
6685646	2	205.17 [illegible]	[illegible]	[illegible]
8681776	1	206.04 [illegible]	[illegible]	[illegible]
11389908	1	206.72 [illegible]	[illegible]	[illegible]
11284772	1	207.24 [illegible]	[illegible]	[illegible]
6680911	1	207.47 [illegible]	[illegible]	[illegible]
5446285	8	208.12 [illegible]	[illegible]	[illegible]
4451099	3	208.61 [illegible]	[illegible]	[illegible]
9832155	2	209.09 [illegible]	[illegible]	[illegible]

1 to 17 of 841 (18406 total)

e.g. Currently (through Q12) 841 "threshold crossing events“ corresponding to 1-2 Earth radii and periods between 200-400 days.

NExScI

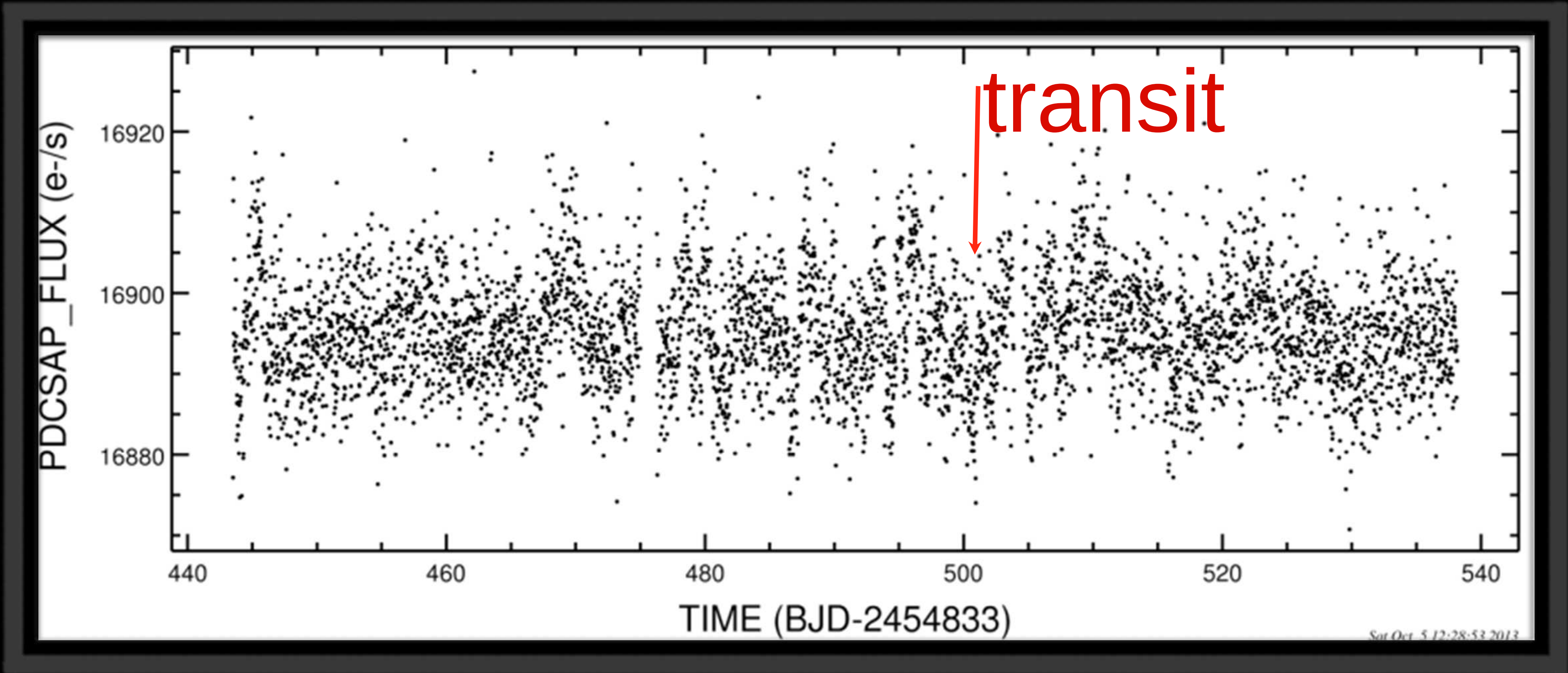
Example Threshold Crossing Event



- One of 841 Earth-like signals in Q1-Q12
- Cleanly passes all validation tests
- Signal-to-noise = 6.5, just below 7-σ cut-off

R. Dawson

Unfolded Light Curve: Correlated (Stellar & Instrumental) Noise Can Mimic Transits



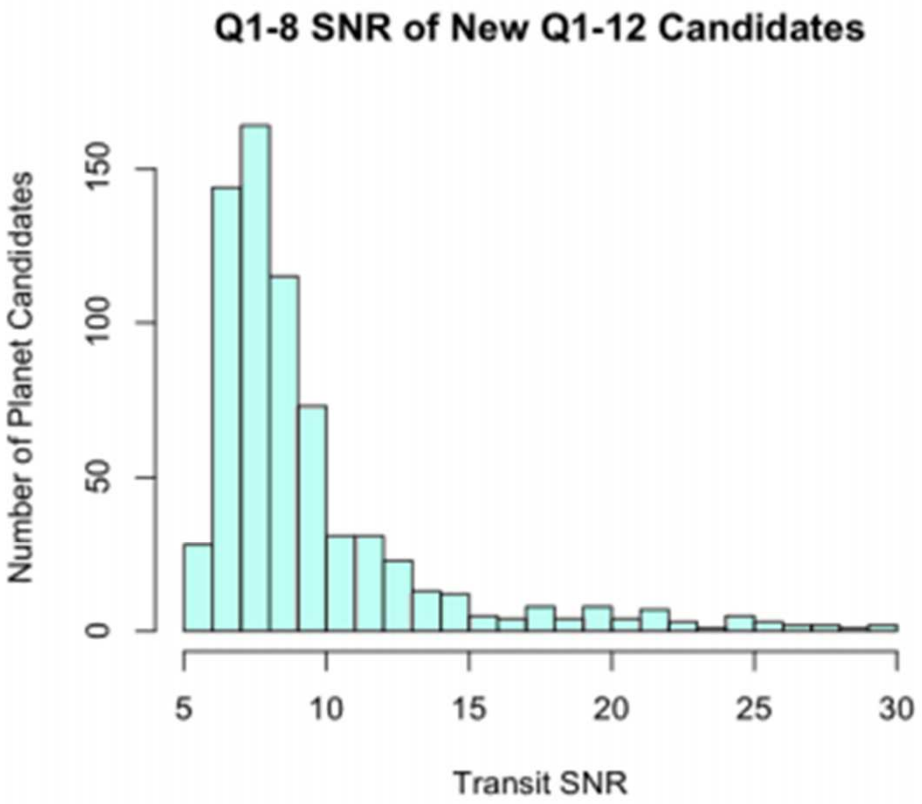
A signal buried in the noise or three non-planetary dips that lined up?

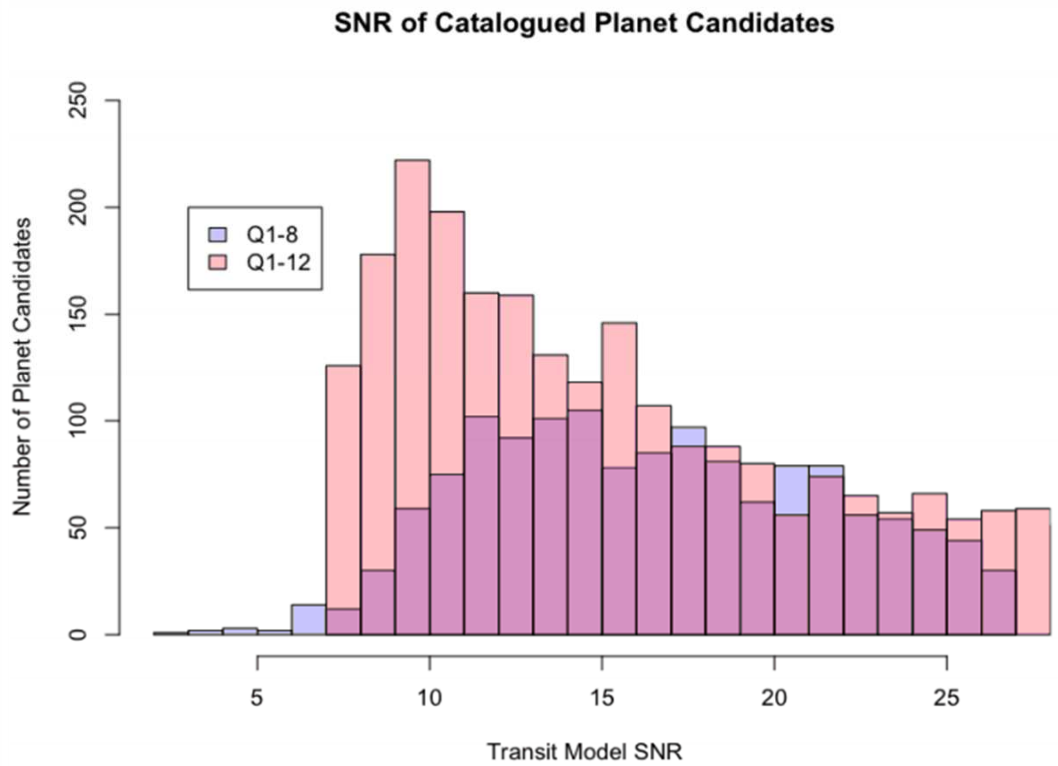
R. Dawson

Detection of Earth twins demands better noise models

- With sixteen quarters of data, Earth-size planets in HZ of G stars lie very near the detection threshold
- Modest improvements in analysis can significantly increase sensitivity, completeness & reliability
- Noise is not white: Gaussian processes, wavelets, and other techniques hold promise
- Much more research necessary to better model noise and robustly detect these signals that are of great scientific interest
- Several efforts underway, incl. Kepler Project, SAMSI Planet Detection Working Group, and individual postdocs/grad students

Planet Detection Algorithms Still Improving





Quantify Detection Efficiency

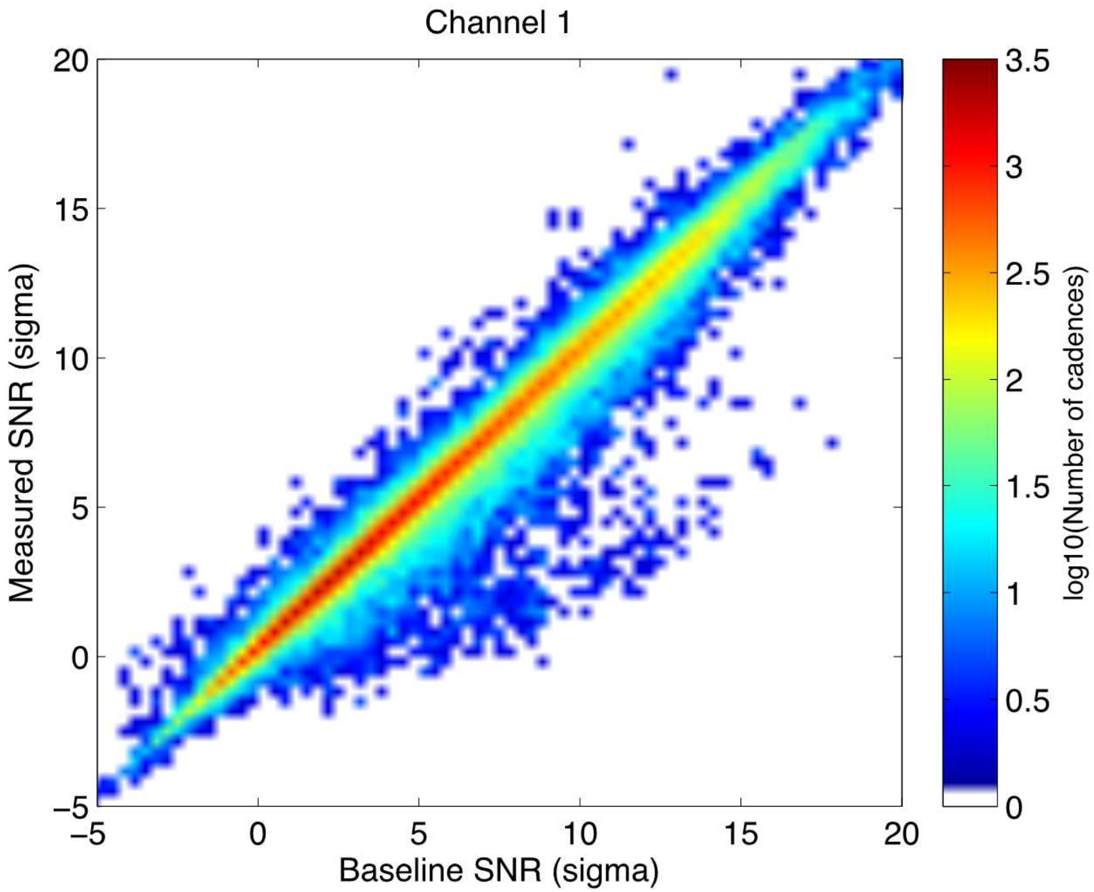
- Perform transit injection studies to quantify the detection efficiency of the pipeline ("pipeline completeness").
  - Compute detection efficiency over planet and star properties as well as planet multiplicity
  - Utilize both pixel-level and flux-level transit injection as necessary
  - Test the efficiency of the vetting procedures
  - Make a challenge set for independent performance studies

Pipeline incompleteness, if left unaccounted for, will lead to underestimates in the planet occurrence rates. Detection efficiency is dependent on planet and star properties. Failure to map out these dependencies will bias occurrence rate parameterizations.

Completeness: pipeline front end

Cal → Phot → Sys Err Corr → Harmonic Rem → White → Sig Det

98% fidelity in preserving single transit SNR with a ~3% scatter in the SNR.



MS = 0.9972(+/- 0.0013) x BS - 0.0129(+/- 0.0052)

Christiansen et al 2013, ApJS, 207, 35

Improve Catalog Uniformity

- Produce a uniformly vetted planet catalog (based on the complete set of uniformly processed Kepler data) that is suitable for statistical studies
  - Apply machine learning algorithms to replace or compliment manual processes
  - Utilize machine learning algorithms to support end-to-end tests of detection efficiency and overall performance

The current triage + vetting process includes manual inspection and decision gates that are subjective. Quantifying the accuracy of manual processes and the biases they introduce into planet occurrence rates is prohibitively costly and time consuming. Auto-vetting will facilitate catalog uniformity and testing.

Increase & Quantify Catalog Reliability

- Eliminate astrophysical and instrumental false positives in the planet catalog as a function of planet radius, orbital period, and star properties (Kp, galactic latitude, CDPP,…) by performing ancillary data analysis and ground-based follow-up observations
- Approximately 15% of the earth-size planet candidates at short orbital periods are expected to be astrophysical false positives (may be larger at longer periods). This number can be reduced to < 5% by targeted follow-up observations thereby increasing the reliability of planet occurrence rates.
- Failure to account for catalog reliability will lead to overestimates in occurrence rates. Current estimates range from 5% to 20% but have only been computed out to P=85 days.

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- Failure to account for catalog reliability will lead to overestimates in occurrence rates. Current estimates range from 5% to 20% but have only been computed out to P=85 days.
- High reliability will be more important for few Earth-size planet candidates at long orbital periods, since few are expected even if such planets are common.

Kepler Project Funded Observing Efforts

Site	Telescope	Role	Notes
Mt. Hopkins	Tillinghast 1.5m	Spectroscopy: Radial velocities, stellar classification	KFOP and XMFOP
McDonald	Smith 2.7m	Spectroscopy: Radial velocities, stellar classification	KFOP and XMFOP
Mt. Hamilton	Shane 3m	Spectroscopy: Radial velocities, stellar classification	KFOP only
La Palma	NOT 2.m	Spectroscopy: Radial velocities, stellar classification	KFOP only
Kitt Peak	Mayall 4m	Spectroscopy: Radial velocities, stellar classification	KFOP and XMFOP
Mauna Kea	Keck I 10m	Spectroscopy: Radial velocities, stellar classification	KFOP and XMFOP
Kitt Peak	WIYN 3.5m	Imaging: Speckle	KFOP and XMFOP - to be replaced with DCT 4m
Mt. Hopkins	MMT 6.5m	Imaging: Near-infrared Adaptive Optics	KFOP only
Mt. Hamilton	Shane 3m	Imaging: Near-infrared Adaptive Optics	KFOP and XMFOP
Mt. Palomar	Hale 5m	Imaging: Near-infrared Adaptive Optics	KFOP and XMFOP
Mauna Kea	Keck II 10m	Imaging: Near-infrared Adaptive Optics	XMFOP only
Mauna Kea	Gemini 8m	Imaging: Speckle	XMFOP only
Earth Orbit	HST 2.4m	Imaging: Diffraction limited optical	KFOP only

Follow-Up Observing “Modes”

1. "Survey Mode" - aimed @ eta_planet
   a. Concentrating on systems containing small planets (e.g., R < 2.5 Rearth)
   b. Spectroscopy and imaging of as many systems as possible to support validation efforts

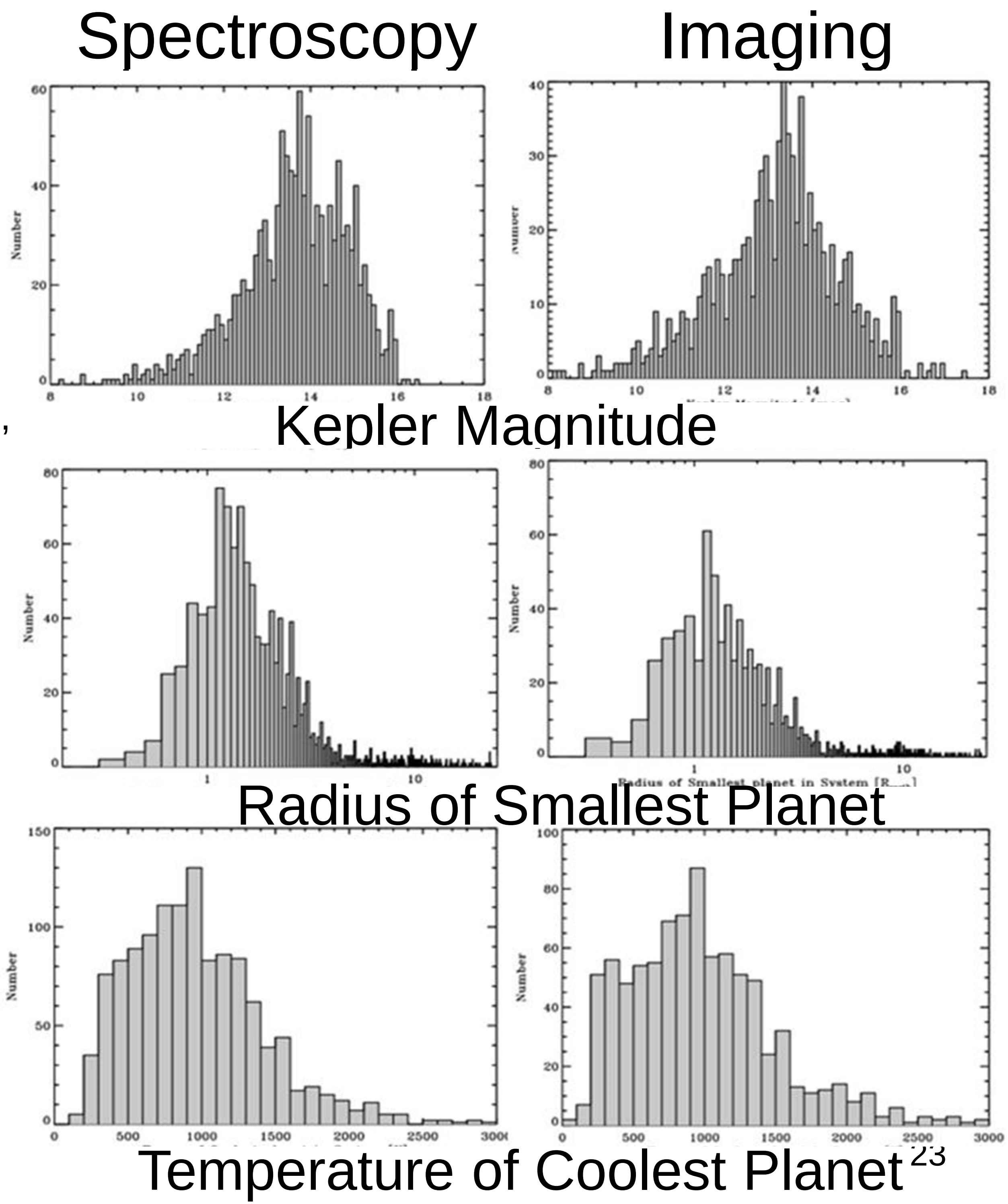
2. "Dedicated mode" – aimed @ individual systems
   a. Concentrating on most “strategic” systems (e.g., small and cool planets, precision RVs) to support confirmation and validation
   b. Higher sensitivity and higher resolution spectroscopy and imaging

KFOP/XMFOP observed systems

- All KFOP and XMFOP data available on CFOP website
- 9 semesters of observing: 2009B, 2010AB, 2011AB, 2012AB, 2013AB

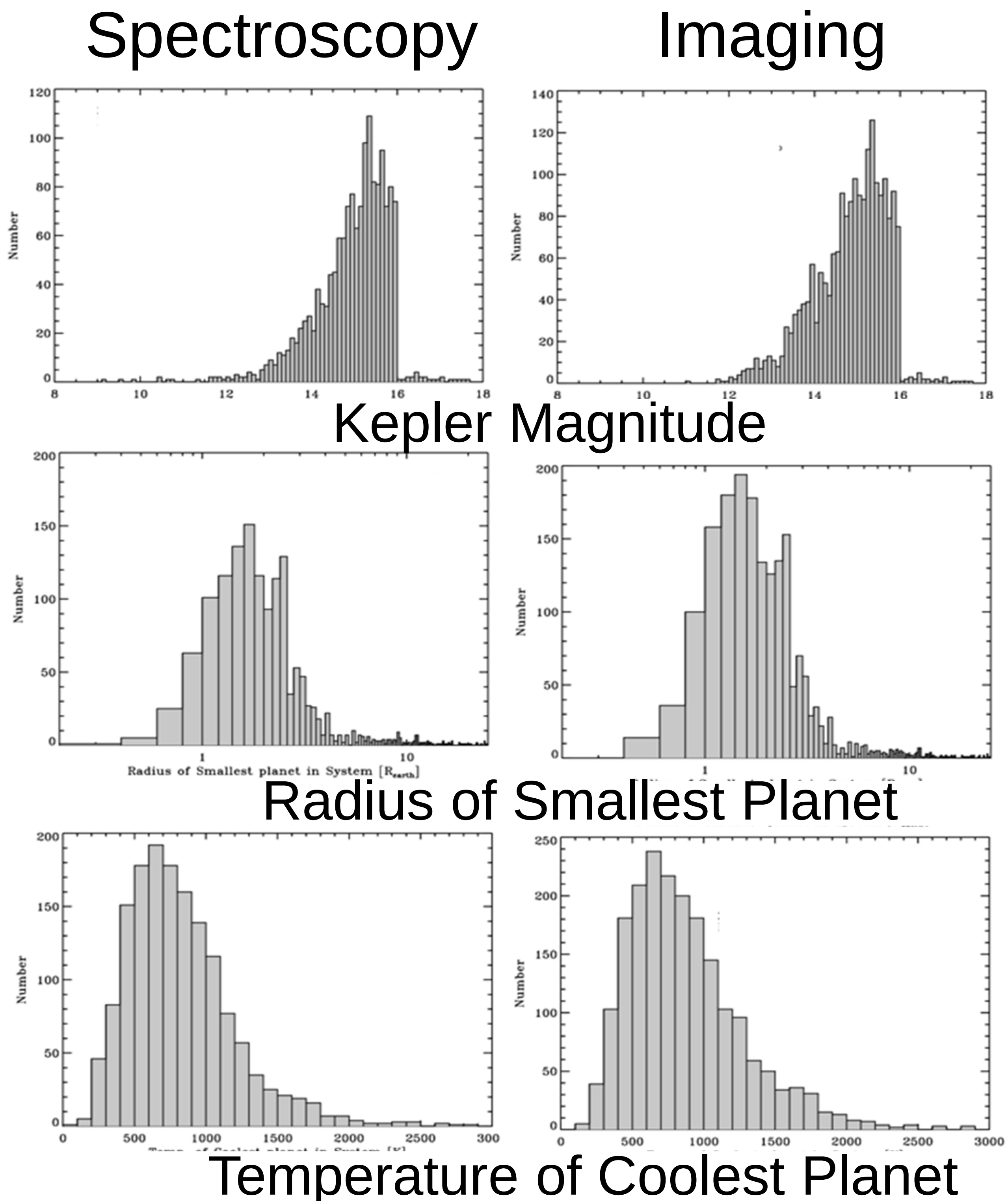
Spectroscopic Observations	All Observations	Unique Systems
All Systems	3928	1911
Candidates Only	3349	1181
Mt. Hopkins	980	515
McDonald	759	610
Lick	139	124
NOT	78	44
KPNO	555	486
Keck	1417	132

Imaging Observations	All Observations	Unique Systems
All Systems	3794	1274
Candidates Only	2015	779
WIYN-Speckle	1085	512
Palomar-AO	180	135
MMT-AO	173	128
Lick-AO	277	236
Keck-AO	240	205
Gemini-Speckle	84	38
HST	40	20



KFOP/XMFOP unobserved systems

- About half of the "strategic" systems unobserved
- Proposed to Kepler project to finish the follow-up observing program as part of the Kepler close-out plan



Draft Proposal

- Complete spectroscopy and imaging of
  - Systems with $R < 2.5 R_{Earth}$ planets,
  - Systems with relatively cool (T < 320 K) planets and/or
  - Systems with long period planets (P > 50 days)

Category	Mode	Number of Stars
Systems with R < 1.5 Rearth	Survey	Spectra: 383, Imaging: 554
Systems with 1.5 < R < 2.5 Rearth	Survey	Spectra: 654, Imaging: 859
Systems with Teq < 320 K	Dedicated	Spectra: 82, Imaging: 90
Systems with R < 3 Rearth P > 50 days	Dedicated	Spectra: 122, Imaging: 161

- Kepler's most anticipated discoveries – small HZ planets orbiting G-type stars – will be made once the entire data volume is analyzed *with improved algorithms*. Since they haven't yet been identified, no follow-up observations have been made.

Improve Accuracy of Planet & Star Properties

- Systematic errors in the Kepler Input Catalog lead to errors ranging from 20% to 400% in stellar radii and planet properties. Such errors propagate to planet occurrence rate calculations.
- *Star Properties Working Group is asked to* generate a homogeneous catalog of star properties sufficient for computing homogeneous planet properties and understand its biases and uncertainties.
  - Recompute star properties using newly available photometric catalogs (Greiss et al 2012, Everett et al 2012), new knowledge of reddening in the Kepler FOV, and improved isochrones.
  - Compute systematic errors via comparison with spectroscopic and asteroseismic star properties of KOI host stars
  - Evaluate differences between the KOI host star sample and the parent population of target stars via control group campaigns *(e.g., SDSS/APOGEE, HET/VIRUS, MMT/Hectochelle)*.

Compute Planet Occurrence Rates

- *Combine all previous elements:*
  - Improved detection sensitivity,
  - Kepler's planet catalog,
  - Estimates of completeness & reliability, and
  - Planet properties derived from the star properties catalog

  to compute planet occurrence rates

  (as a function of planet radius, period, insolation flux, and star type).

- Provide initial estimates based on existing methodologies
- *Future data analysis, catalogs and follow-up observations will enable future improvements in measurements of η_{Earth}.*
- *Develop statistical framework and practical computational tools for analyzing Kepler planets with Bayesian hierarchal models to provide more accurate estimates of η_{Earth} and to enable more complex populations studies.*

Debias Planetary Systems, not Planets

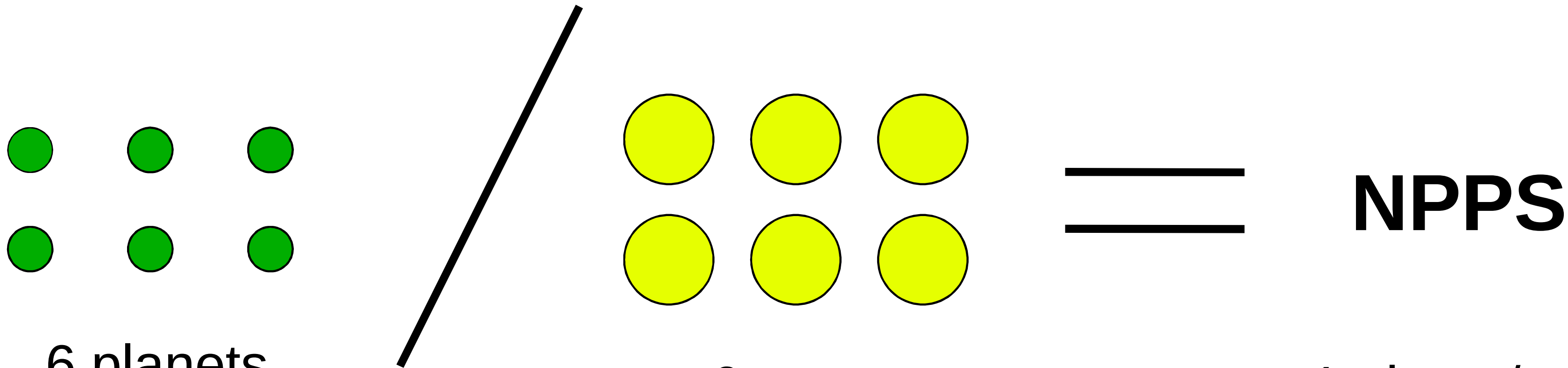
- Preserve rich information about orbital architecture that is available from multi-transiting systems
- Enables investigations of an enormous number of science questions: multiplicity, spacing between planets, mutual inclinations, orbital eccentricies, etc.

- Convert average Number of Planets Per Star (NPPS) into Fraction of Stars with Planetary systems (FSWP)

- Recently begun via “SysSim” grant (PIs: Ragozzine/Ford) and SAMSI Kepler Populations Working Group and

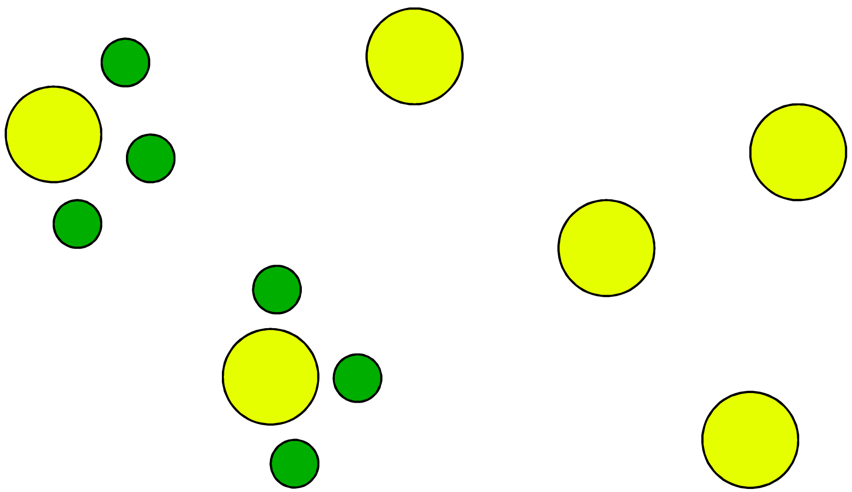
Average Number of Planets Per Star (NPPS)

- Most frequency/occurrence studies
- Frequency calculated planet by planet
- Example scientific questions:
  - What is distribution of planetary radii?



Fraction of Stars with Planetary Systems (FSWP)

- More difficult, requires specific analysis
- Frequency calculated system by system
- Example scientific questions:
  - What is efficiency of planet formation?
  - How do I design a future planet survey?



FSWP

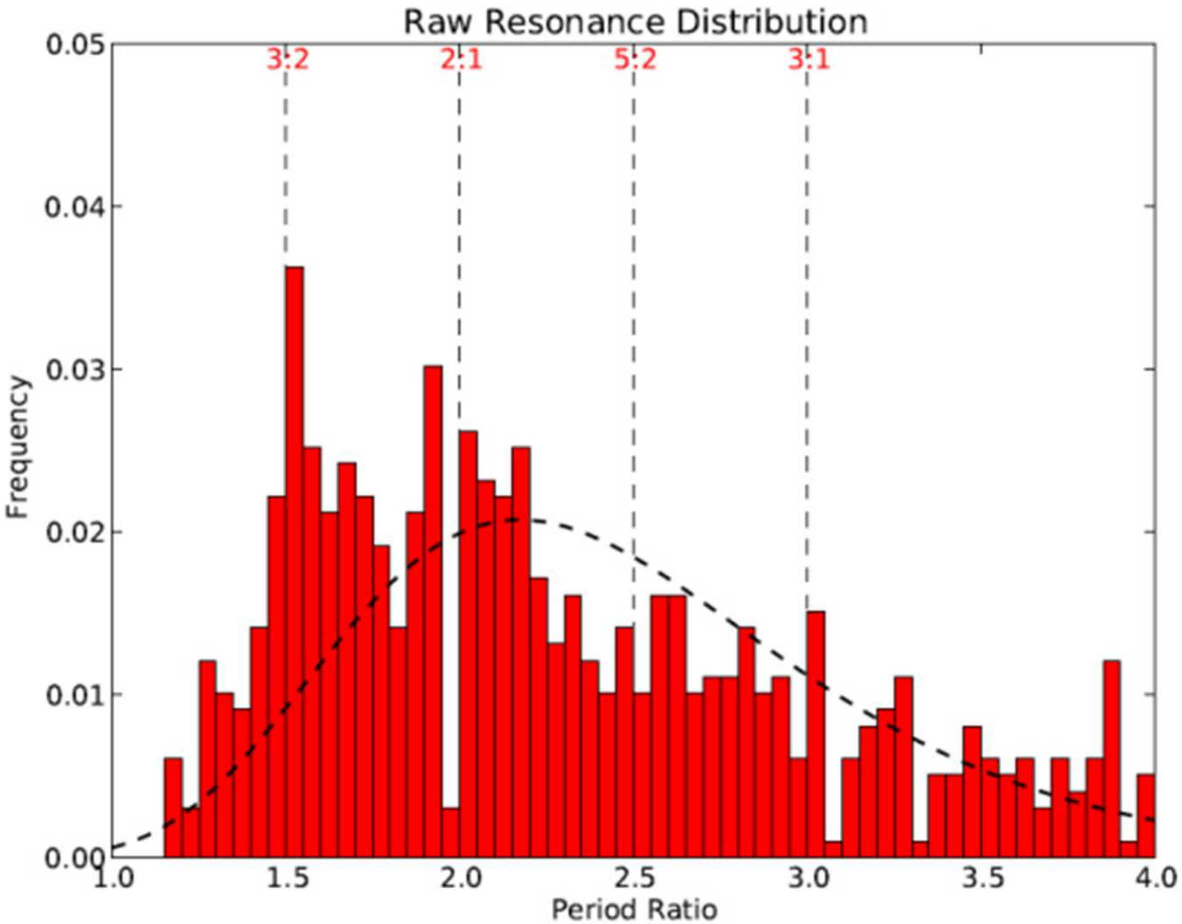
1/3
1 out of 3 stars
have planet(s)

NPPS

1 planet/star

Period Ratio Distribution

Ratio of outer planet period (“year”) to inner period
Spikes near ratios of integers (“resonances”)



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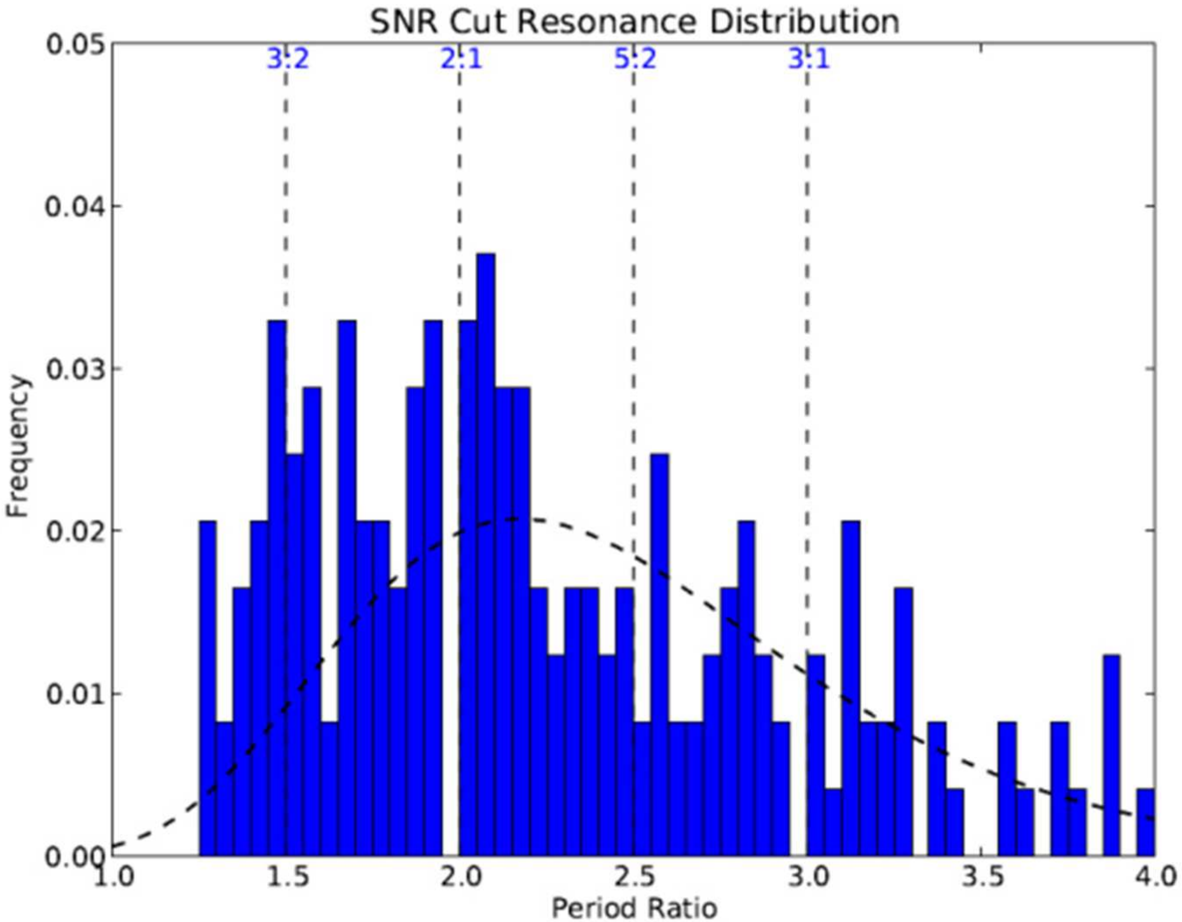

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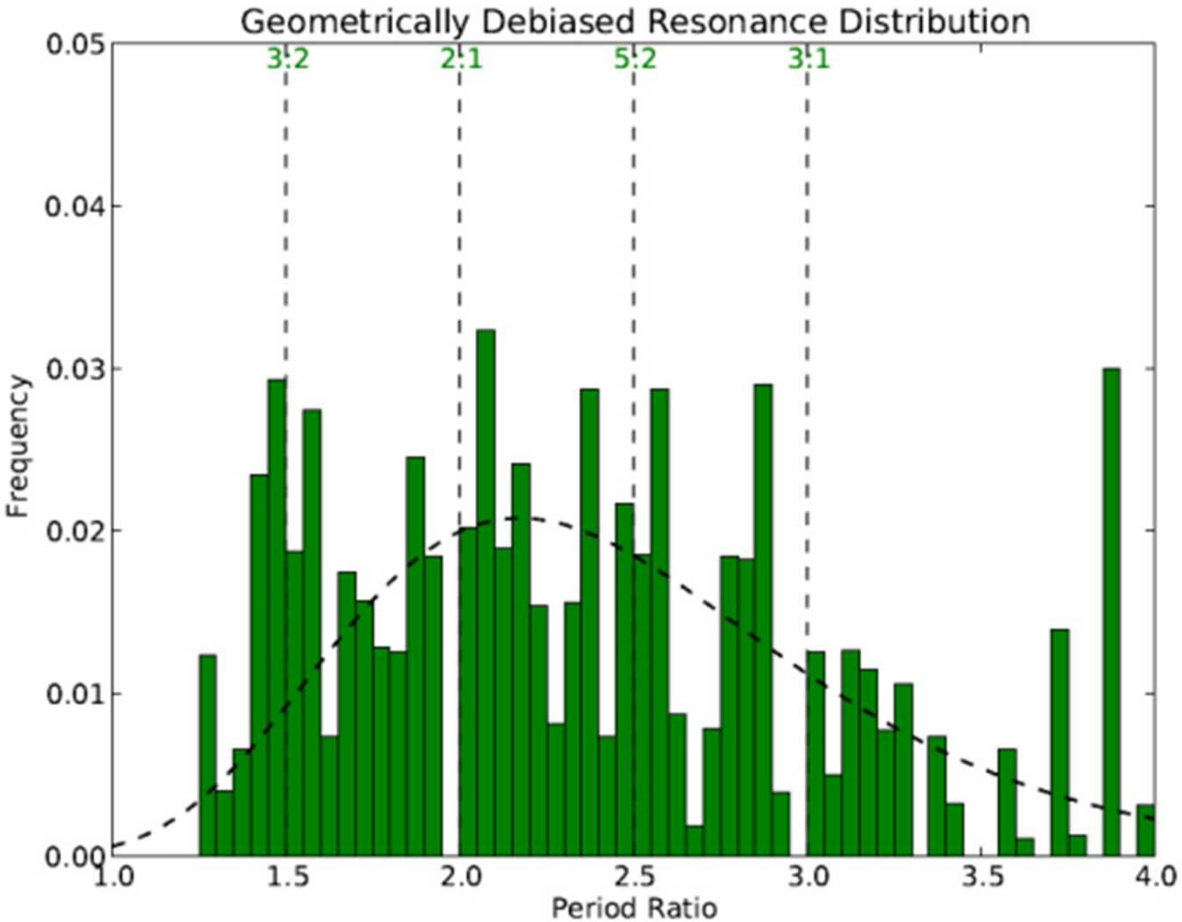


Other *Needed Transition* Activities

- Determine the fraction of *rocky* planets as a function of planet radius
  - Measure masses of small planets via high precision RV and TTV
  - Test theoretical models against the empirical mass/radius relation
  - *Combine Transit, TTV and RV planet statistics* to determine the planet density distribution
- Assess stellar multiplicity
  - Produce reliable and complete Kepler EB catalog
  - Quantify biases in planet occurrence rates due to unknown flux dilution amongst the parent population of target stars.
- Archive products for future studies
  - Legacy products *(e.g., CFOP, Exoplanet Archive, Posterior Samples, Software)*

Conclusions

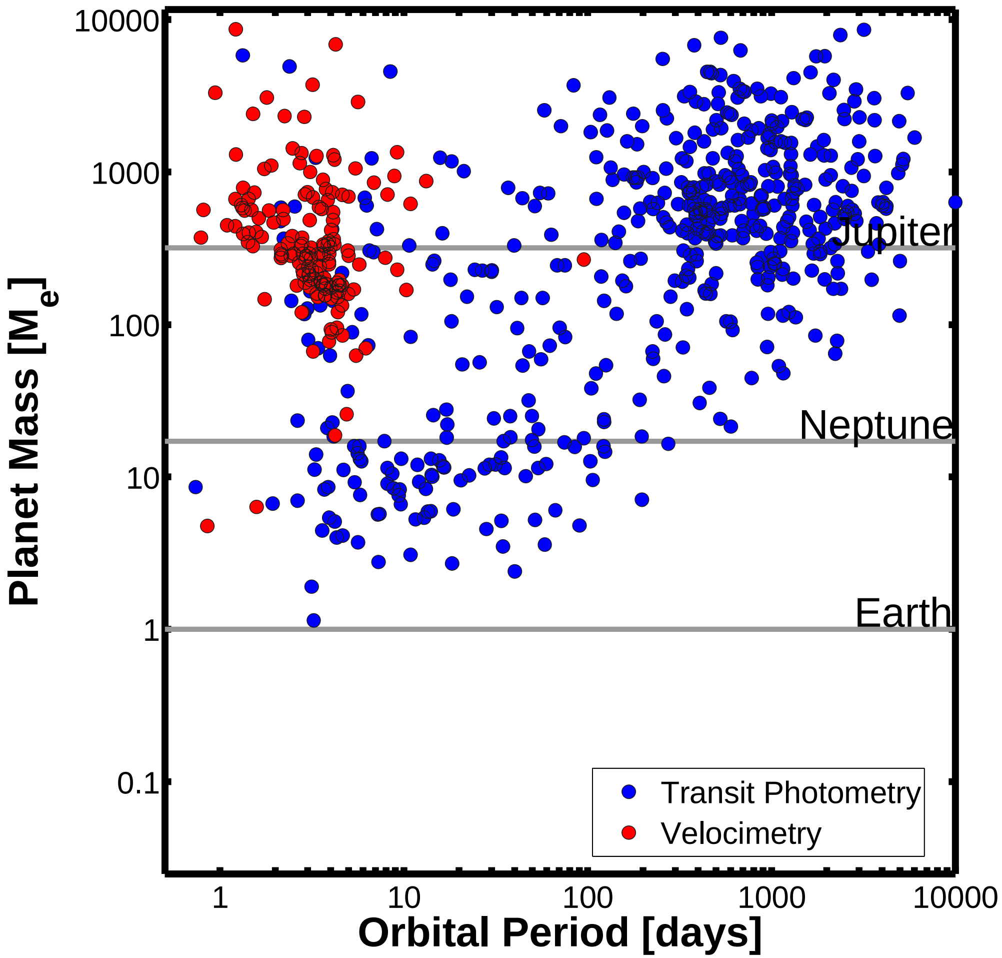
- Best science from Kepler is yet to come
- Existing Kepler data will remain the key dataset for addressing many key scientific questions, including η_{Earth}, for decades.
- Require a realistic, stable plan for significant long-term support, including:
  - Algorithm/software development,
  - Kepler Data analysis,
  - Follow-up observations,
  - Providing data products to the community,
  - Statistical methods and
  - Scientific interpretation.

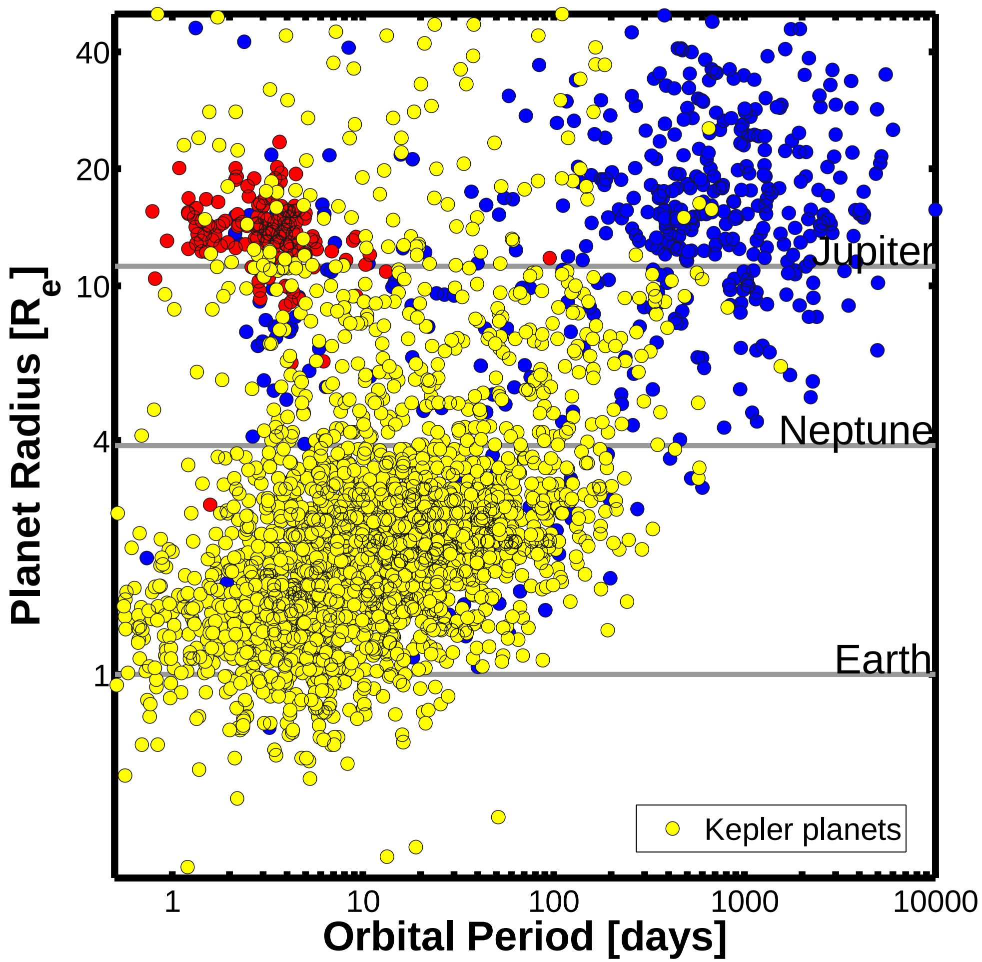
Questions?

Supplemental Slides

Known Exoplanets as of April 2013

Based on ~ 2 years of data





663 non-Kepler planets
85% larger than Neptune

~2700 Kepler planets
84% smaller than Neptune

Planet Occurrence Rates in the Literature

Occurrence rate measurements to date are based on the analysis of <= 2 years of data and, consequently, focus on orbital periods < 85 days.

NPPS for 1 <= Rp < 2 Re and 0.68 <= P < 50 days:

Borucki: 0.122 (1235 candidates)
Howard: 0.16 +/- 0.04 (1235 candidates)
Fressin: 0.27 +/- 0.02 (2320 candidates)
Dressing: 0.49 +/- 0.13 (cool stars from the 2320 candidates)

NPPS for 1 <= Rp < 22.6 Re and 0.68 < P < 50 days:

Traub: 0.29 +/- 0.02 (P < 42 days)
Borucki: 0.341 with very high uncertainty
Howard: 0.3264 +/- 0.0463
Youdin: 0.72 (extrapolates to smaller radii)
Fressin: 0.4802 +/- 0.0172 (larger sample)
Dressing: 0.6919 +/- 0.1332 (larger sample, cool stars)

Occurrence of Small HZ Planets

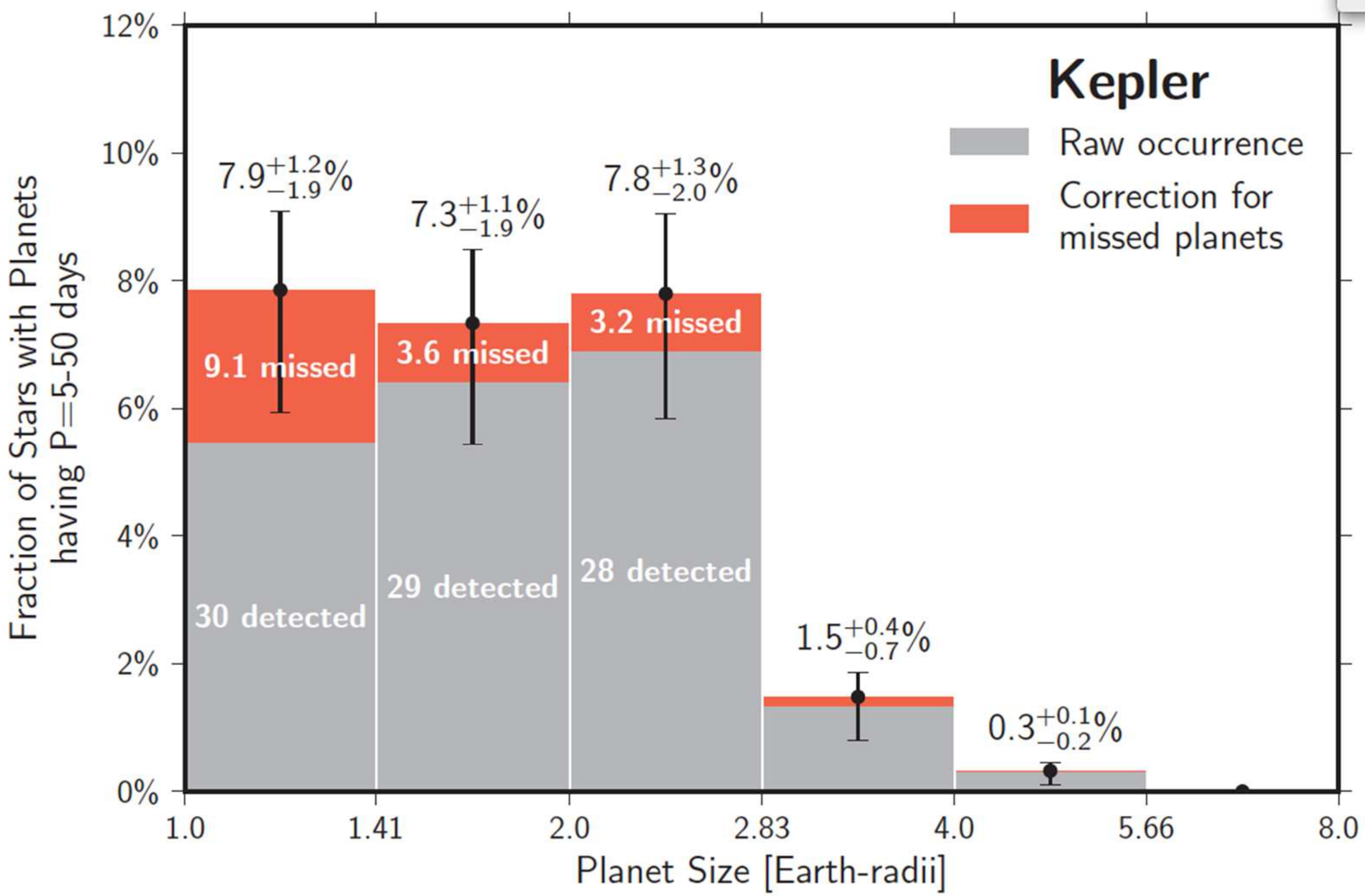
The only η_{Earth} estimates not based on extrapolations are for M-type stars.

- Dressing & Charbonneau 2013
  - Used Kasting et al 1993 HZ def'n for M0 stars: 0.46 to 1.0 F_e
  - NPPS = 0.15 +0.13 -0.06 (R_p < 1.4 R_e)
- Kopparapu 2013
  - Updated analysis & HZ definition from Kopparapu et al 2013
  - NPPS = 0.53 +0.08 -0.17 (R_p < 1.4 R_e)

Existing Kepler data can extend this to G & K stars.

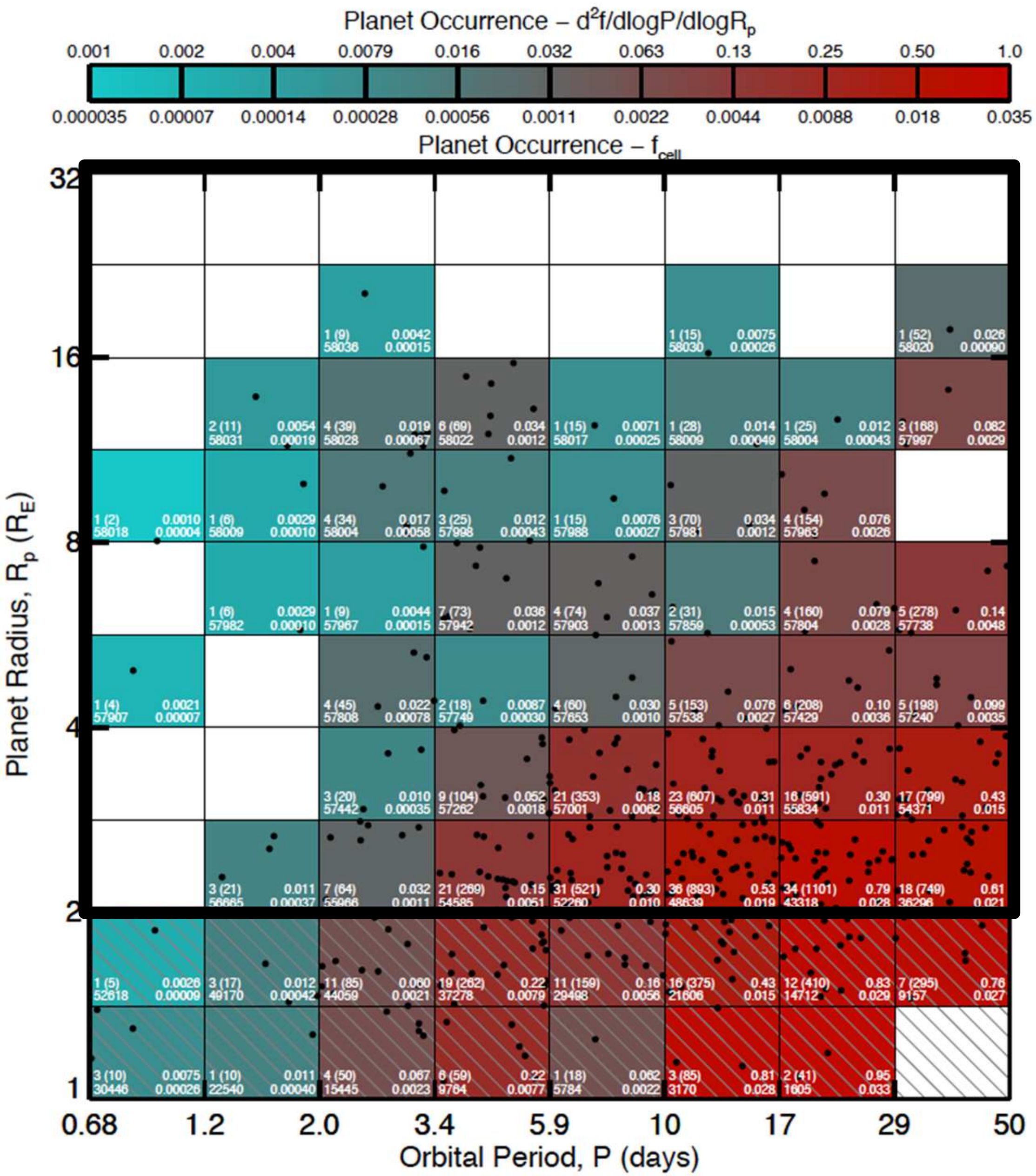
Completeness: pipeline

Pipeline completeness is a function of planet size, orbital period, and star properties.

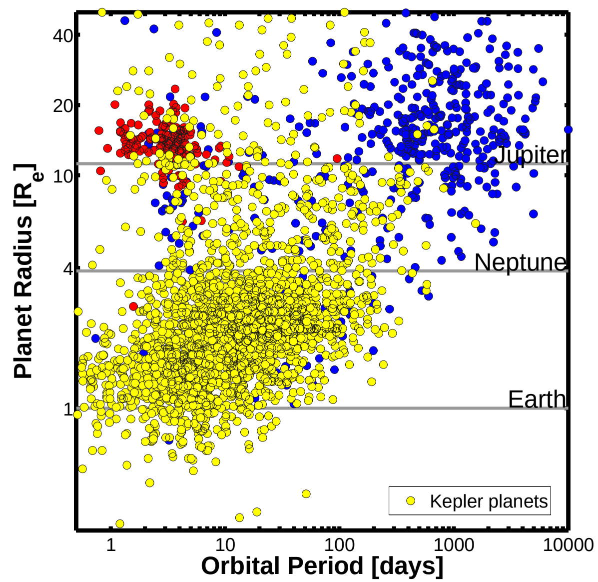


Petigura et al 2013

Observed versus Intrinsic Distributions



Observed

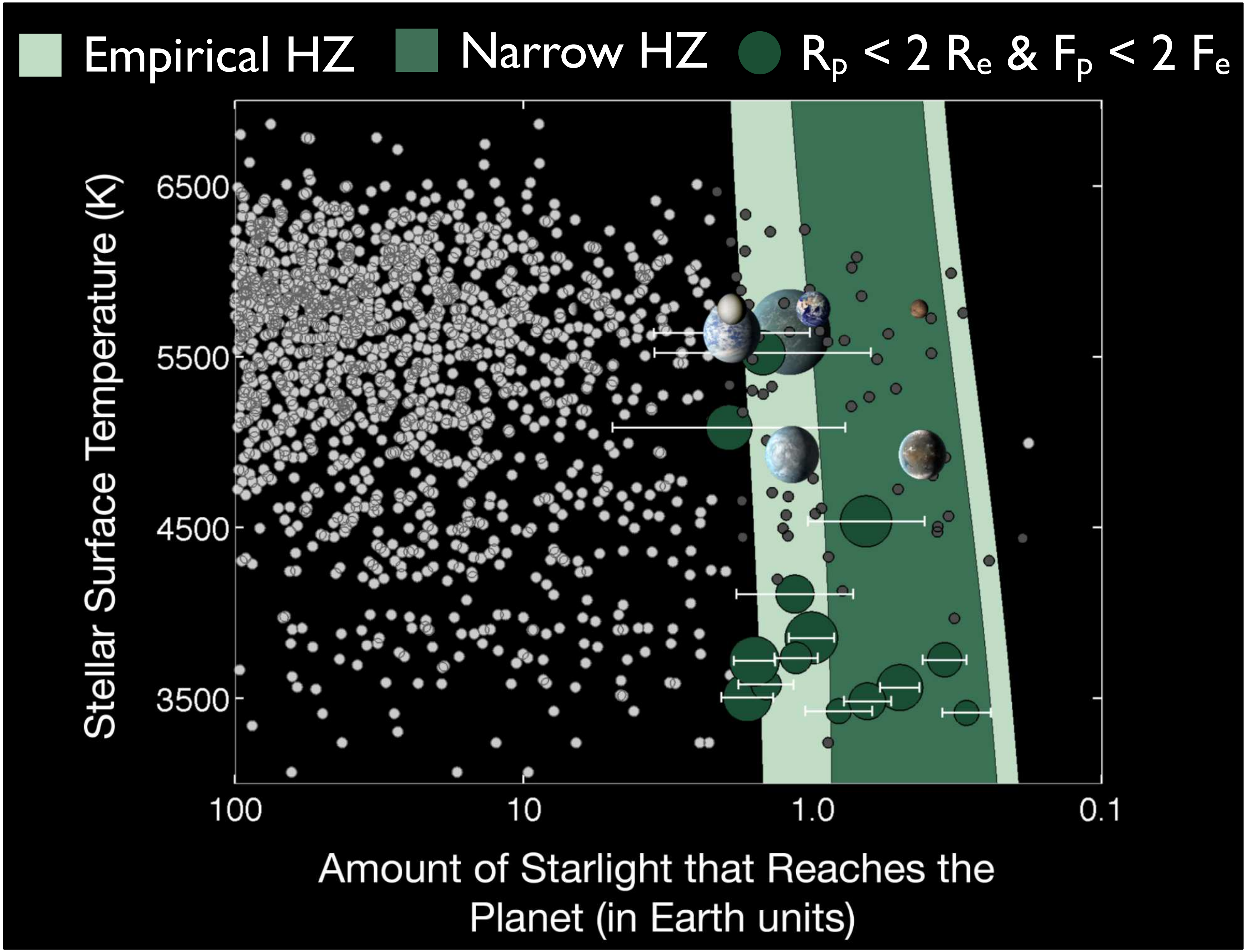


P < 50 days

Howard et al 2012

Note: cannot perform bias corrections on "zero" detections

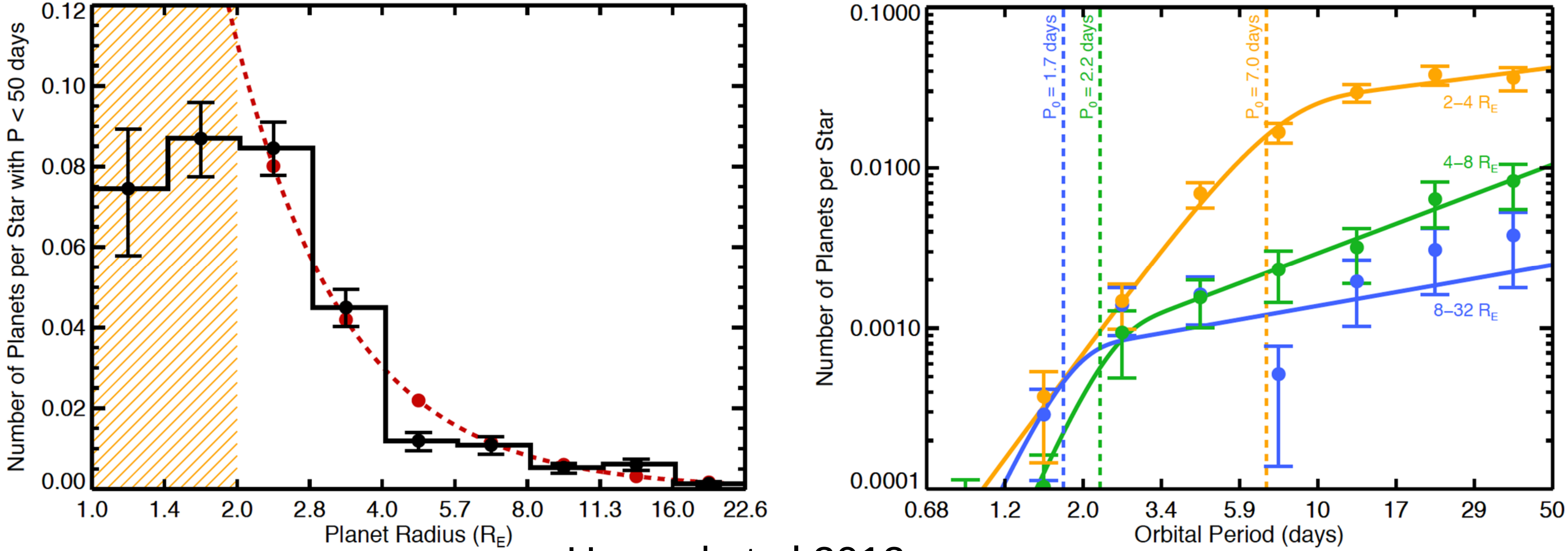
Occurrence of Small HZ Planets



Kepler Occurrence Rate Studies

- Borucki et al. 2011 ApJ 736 19, Characteristics of Planetary Candidates Observed by Kepler. II.
- Catanzarite & Shao 2011 ApJ 738 151, The Occurrence Rate of Earth Analog Planets Orbiting Sun-like Stars
- Youdin 2011 ApJ 742 38, The Exoplanet Census: A General Method Applied to Kepler
- Gould & Eastman 2011 arXiv:1102.1009
- Traub 2012 ApJ 745 20, Terrestrial, Habitable-Zone Exoplanet Frequency from Kepler
- Howard et al. 2012 ApJS 201 15, Planet Occurrence within 0.25 AU of Solar-type Stars from Kepler
- Dong & Zhu 2012 arXiv:1212.4853, Statistics of Kepler Planet Candidates Up to 0.75 AU
- Mann et a. 2012 ApJ 753 90, The May be Giants: Luminosity Class, Occurrence, and Metallicity Relations
- Gaidos & Mann 2013 ApJ 762 41, Objects in Kepler's Mirror May be Larger than they Appear
- Beaugé & Nesvorny 2013 ApJ 763 12, Emerging Trends in a Period-Radius Distribution of Close-In Planets
- Fressin et al 2013 ApJ 766 81, The False Positive Rate of Kepler and the Occurrence of Planets
- Dressing & Charbonneau 2013 ApJ 767 95, The Occurrence Rate of Small Planets around Small Stars
- Swift et al. 2013 ApJ 764 105, Characterizing the Cool KOIs. IV
- Petigura et al 2013 ApJ 770 69, A Plateau in the Planet Population Below Twice the Size of Earth
- Gaidos 2013 ApJ 770 90, Candidate Planets in the Habitable Zones of Kepler Stars
- Kopparapu 2013 ApJ 767 8, A Revised Estimate of the Occurrence Rate of Terrestrial Planets in the HZ around Kepler M-dwarfs
- Morton & Swift arXiv:1303.3013, The Radius Distribution of Small Planets Around Cool Stars
- Gaidos 2013 ApJ 771 18, An Understanding of the Shoulder of Giants: Jovian Planets…

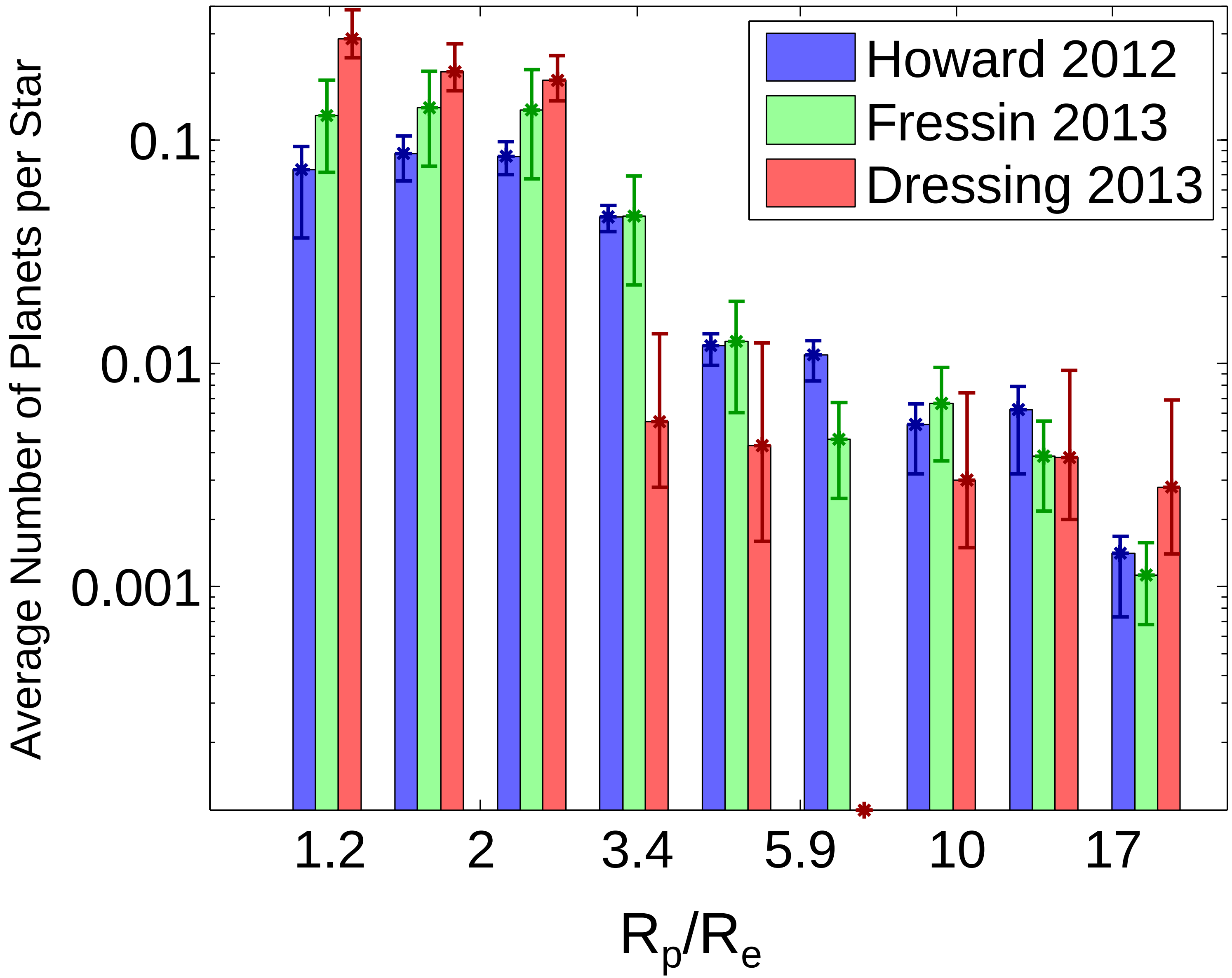
Period and Radius Distributions



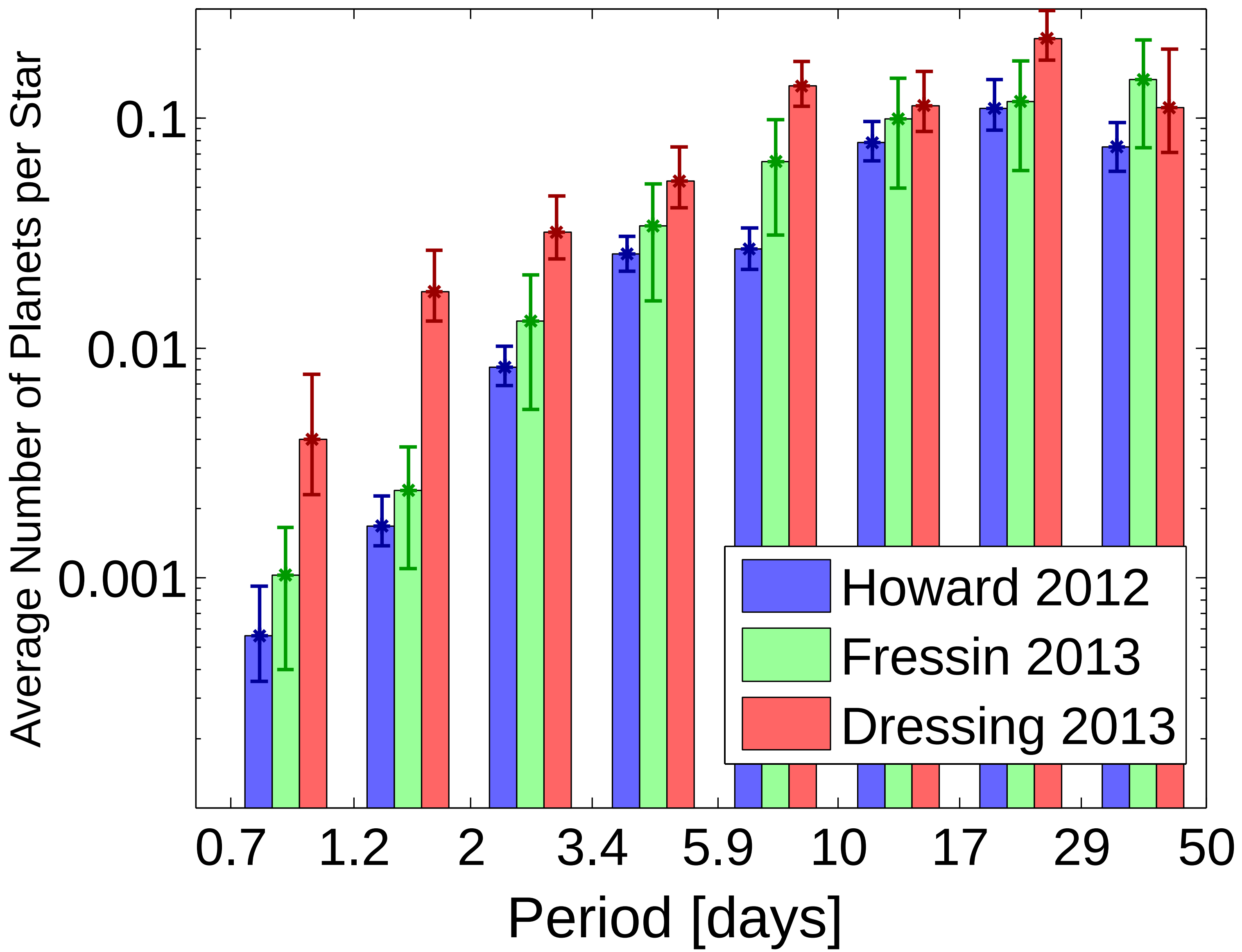
Howard et al 2012

- Order of magnitude jump in occurrence rates between giants and super-earths with P < 50 days.
- Sharp break in radius distribution at ~ 3 Re.
- Radius distribution flattens out from 3 Re down to 1 Re.
- Flat (log) period distribution beyond P=10 days for planets smaller than 4 Re.
- Results are reproduced by independent groups.

Comparing Results



Comparing Results

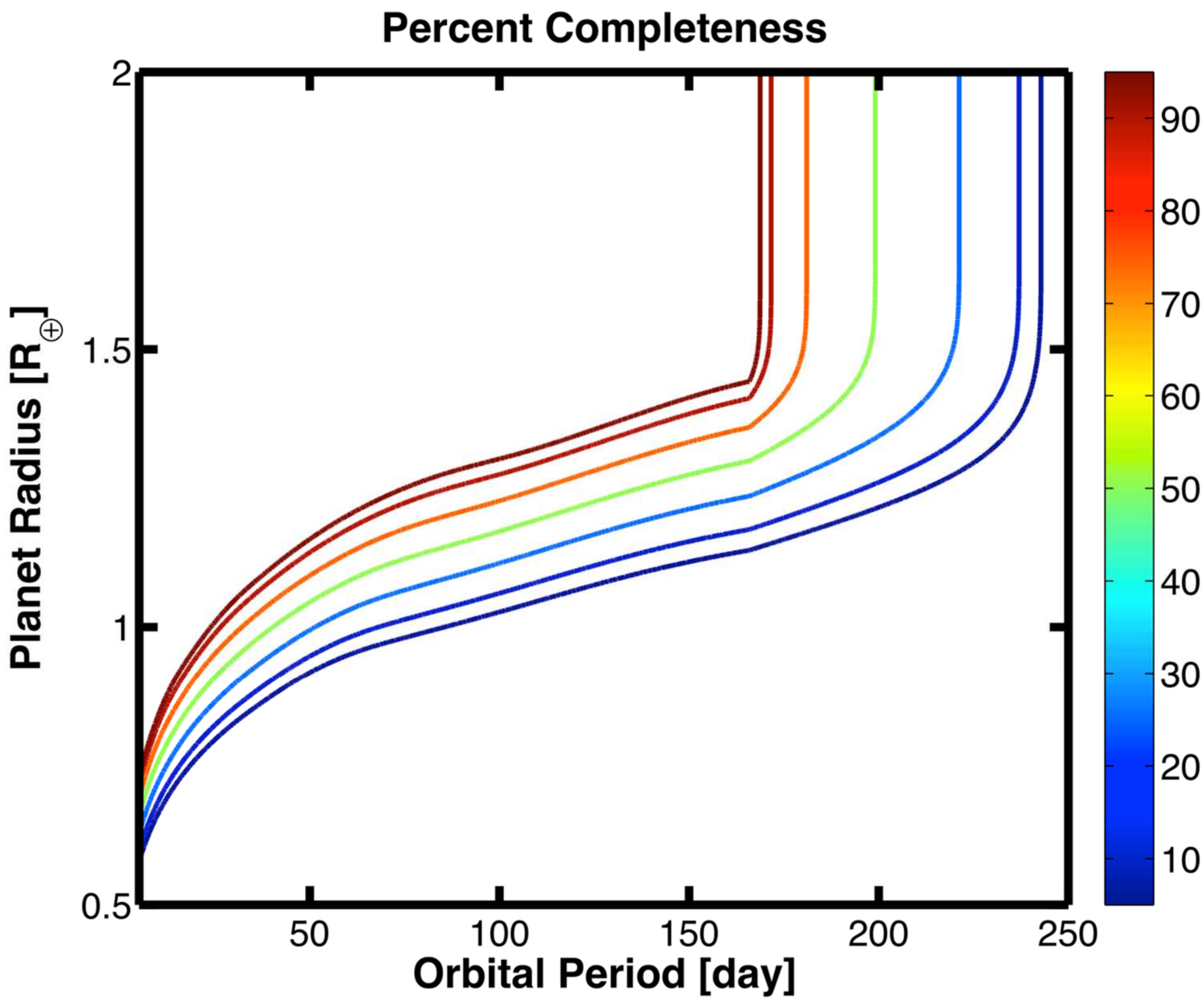


Completeness: sensitivity

- Borucki et al 2011: Gaussian probability of detection with unit variance around the stated detection threshold of 7.1σ (50% chance of detection)
- Howard et al. (2012) assumed a 100% detection efficiency for transiting signals with an SNR > 10σ, $R_p > 2R_\odot$, and P_orb < 50 days.
- Youdin (2011) assumed a 100% detection efficiency for transiting signals with an SNR > 10σ, $R_p > 0.5R_\odot$, and P_orb < 50 days.
- Dong & Zhu (2012) assumed a 100% detection efficiency for transit signals with an SNR > 8σ, no size limit, and P_orb < 250 days.
- Fressin et al. (2013) find a linear increase in detection efficiency from 0% at 6σ to 100% at 16σ.

Completeness: Sensitivity

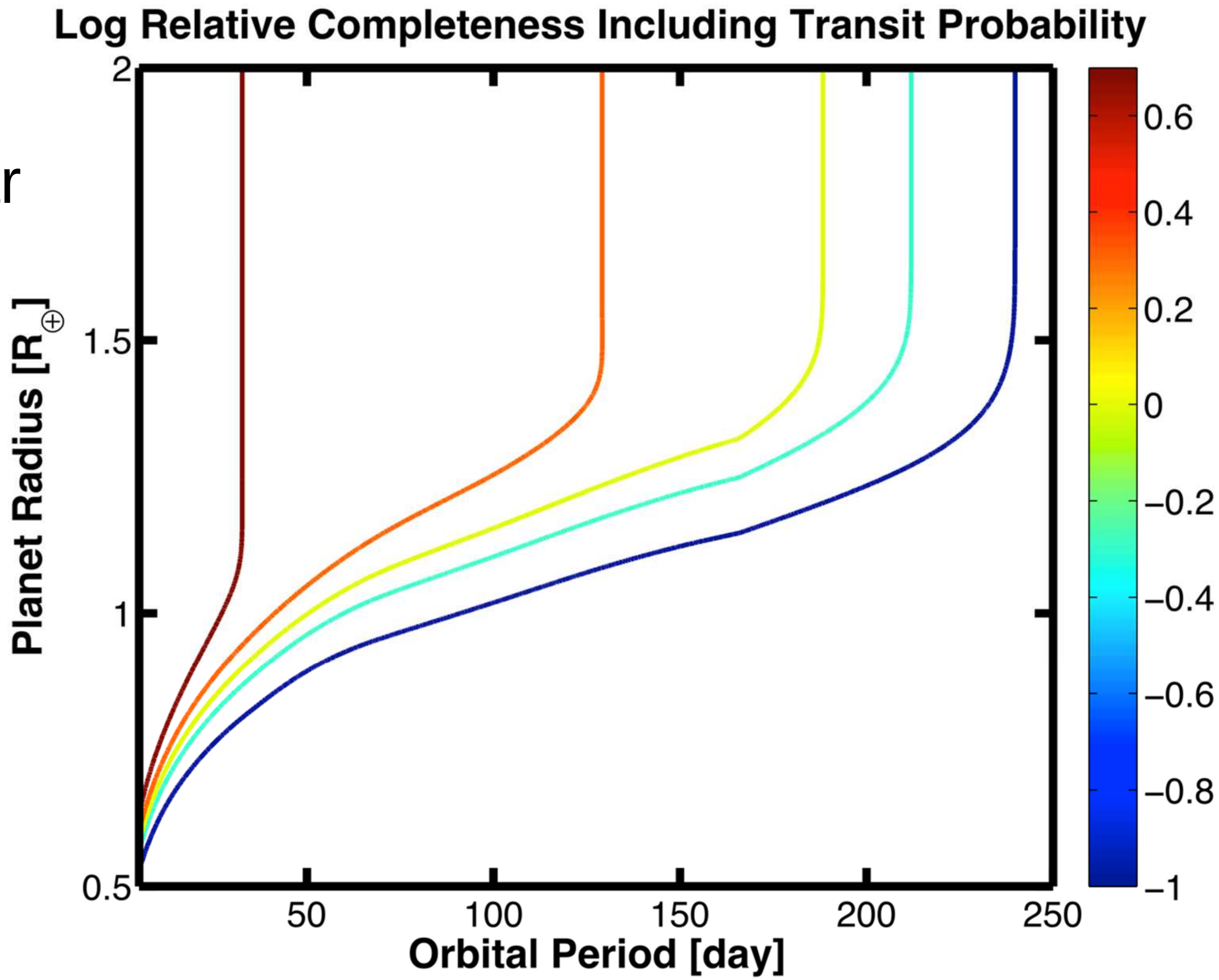
Typical G-type star
Kpmag=12
Q1- Q5
Threshold=7.1
95% duty cycle
Gaussian detector response.



Burke et al 2006; Youdin 2013

Completeness: sensitivity + geometry

Typical G-type star
Kpmag=12
Q1- Q5
Threshold=7.1
95% duty cycle
Gauss detector response.



Burke et al 2006; Youdin 2013

Questions?

Completeness: pipeline backend

Cal → Phot → Sys Err Corr → Harmonic Rem → White → Sig Det

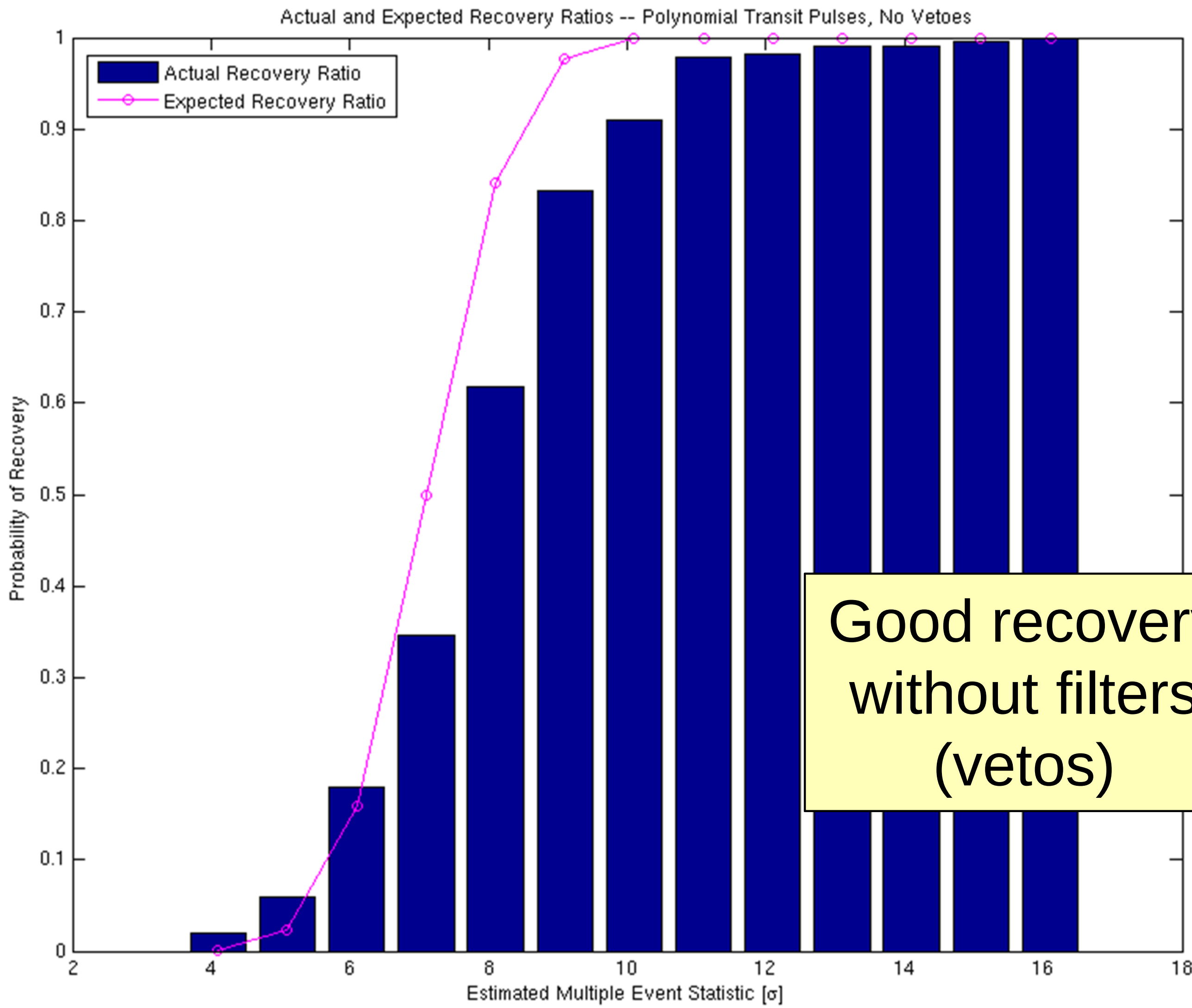
Monte Carlo transit injection in 10,080 flux timeseries.

Planets with sizes ranging from 0.5 to 3.0 Re

Periods ranging from 50 to 150 days

Pink: Gaussian error function

Without filters



Good recovery without filters (vetos)

Tenenbaum, in progress

Completeness: pipeline backend

Cal → Phot → Sys Err Corr → Harmonic Rem → White → Sig Det

Monte Carlo transit injection in 10,080 flux timeseries.

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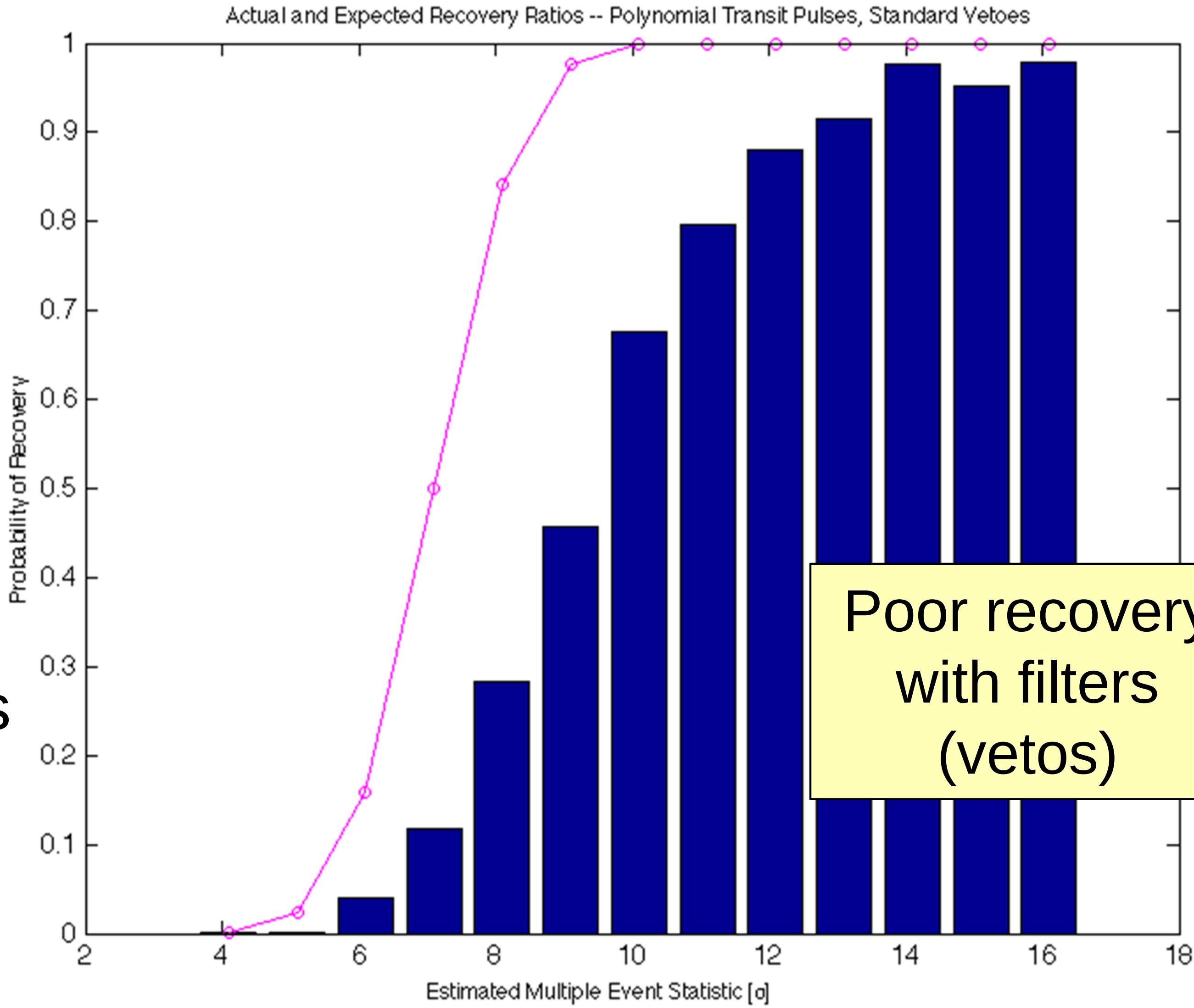


Poor recovery with filters (vetos)

Tenenbaum, in progress

Questions?

Goals of the Follow-Up Program

- FOP was part of the original level 1 mission requirements to support the determination of
  - Frequency of planets (η_{planet})
  - Distribution/frequency of planet/orbit characteristics
  - Properties of planet hosting stars
  - Existence of additional (non-transiting) planets
- FOP observing centered around
  - Stellar spectroscopy
  - High spatial resolution imaging
- With limited resources, concentrated efforts on Earth-sized and Earth-like planets
  - Small planets: R < 2.5 Rearth
  - In or near habitable zone (T < 300 – 400 K)

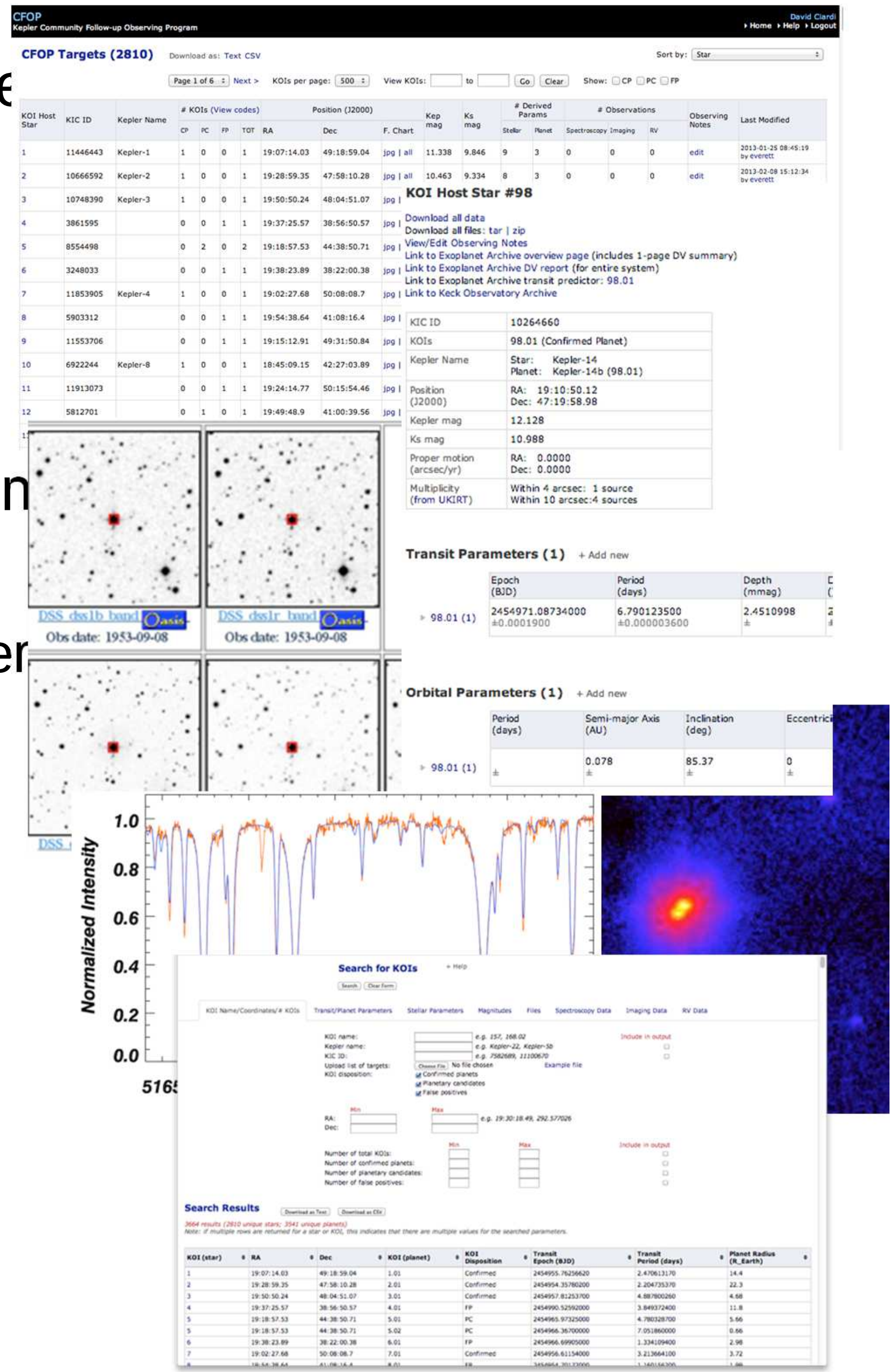
KFOP and XMFOP/CFOP

- Kepler Prime Mission
  - Proprietary KOIs and observations
  - Prime mission science team responsible for the Kepler follow-up observation program (KFOP)
- Extended Mission
  - All identified KOIs (and transit events) publicly available
  - Various working groups established and open to the public
  - Kepler-funded Extended Mission Follow-Up Observation Program (XMFOP)
    - Concentrate on systems with small and/or cool planets
    - Open to the general community
    - No proprietary KOIs or observations
  - Community Follow-up Observation Program (CFOP) website
    - Open to entire astronomical community
    - All KFOP and XMFOP data available through CFOP website

CFOP Website

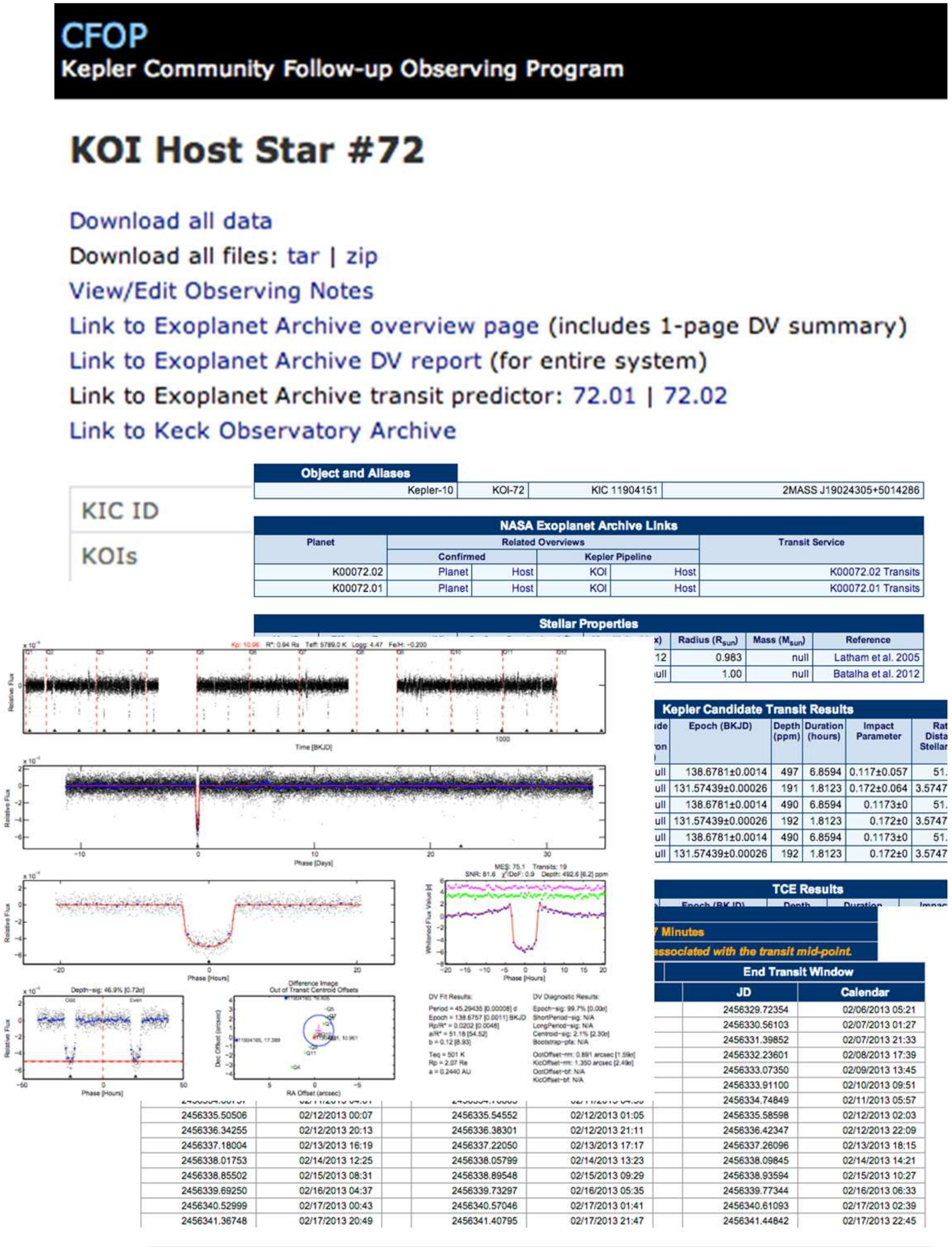
- KOIs as delivered to Exoplanet Archive by Kepler Project
  - Confirmed planets
  - Planet candidates
  - Known False Positives
- Spectroscopic and imaging observation
  - Individual files
  - Derived stellar and planetary parameter
  - Orbital parameters
  - Observing Notes – freeform
  - Comprehensive search page
- Open to the entire community
  - All data tagged with ownership

- https://cfop.ipac.caltech.edu



CFOP Connected to Exoplanet Archive

- Updates to EA are synchronized for CFOP
- EA overpage page linked from CFOP
- Data validation reports and summary report for each KOI directly linked from CFOP
- Transit prediction tool has direct link from CFOP
- Direct search to Keck Observatory Archive



CFOP KOI Summary

- Currently contains only KOIs as identified by the Kepler pipeline
- Numbers fluctuate as new observations and/or analysis is performed

	Systems	Planets
All KOIs	4799	5779
Confirmed KOIs	74	139
Candidate KOIs	2657	3449
False Positive KOIs	2147	2191
R < 1.5 Re	884	1057
R < 2.5 Re	1836	2365
T < 320 K	189	204

Community Involvement

- CFOP is open to all community members
- All data from the KFOP and XMFOP are publicly available through CFOP
- For more information:
  - Follow-up observation program and CFOP website: David Ciardi (ciardi@ipac.caltech.edu)
  - NASA Exoplanet Archive: Rachel Akeson (rla@ipac.caltech.edu)