ExoPAG SAG13:
Exoplanet Occurrence Rates and Distributions

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Gould, Andy
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Hsu, Danley
Kane, Stephen
Kasting, Jim
Kopparapu, Ravi
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Roberge, Aki
Rogers, Leslie
Savransky, Dmitry
Serabyn, Gene
Shabram, Megan
Shao, Mike
Solmaz, Arif
Sparks, William
Stahl, Philip
Stapelfeldt, Karl
Still, Martin
Suzuki, Daisuke
Swain, Mark
Traub, Wes
Turnbull, Margaret
Unwin, Stephen
Vanderbei, Bob
Walkowicz, Luzianne
Weiss, Lauren M.
Wolfgang, Angie
Youdin, Andrew
Ziemer, John K.

**** DRAFT ****

Charter

Over 5000 exoplanets and exoplanet candidates have been discovered to date. Many studies have been published and are on-going to determine exoplanet occurrence rates and distributions, particularly for potentially habitable worlds. These studies employ different statistical and debiasing methods, different definitions of terms such as eta_Earth and habitable zone, different degrees of extrapolation, and present distributions in different units from each other. The primary goal of this SAG is to evaluate what we currently know about planet occurrence rates, and especially eta Earth, by consolidating, comparing, and reconciling discrepancies between different studies. A secondary goal is to establish a standard set of occurrence rates accepted by as much of our community as possible to be used for mission yield estimates for missions to be considered by the decadal survey.

Key objectives and questions:

1. Propose standard nominal conventions, definitions, and units for occurrence rates/distributions to facilitate comparisons between different studies.

2. Do occurrence estimates from different teams/methods agree with each other to within statistical uncertainty? If not, why?

3. For occurrence rates where extrapolation is still necessary, what values should the community adopt as standard conventions for mission yield estimates?

Outline

1. Survey of occurrence rates from community-sourced and published submissions, integrated across a standard grid of bins

2. Analysis of variances between submissions and possible reasons for these variances

3. Analysis of which parts of exoplanet parameter space still requires extrapolation, particularly in the potentially habitable planet range

4. Parametrized distributions that can be used as inputs to EXOSIMS and other mission yield codes

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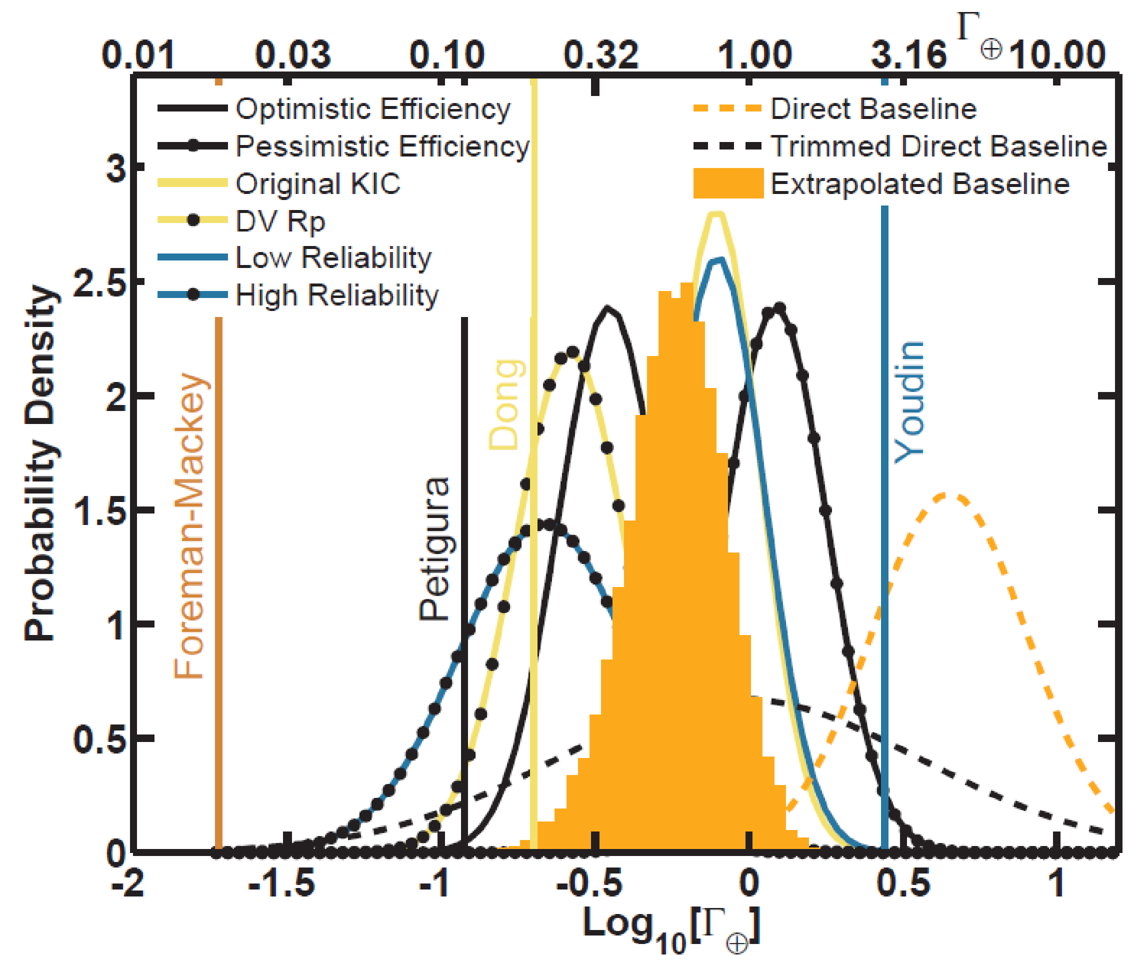
From Burke et al. 2015



$$\Gamma_{\mathrm{earth}} = \left.\frac{\partial^2 N(R,P)}{\partial \ln R\ \partial \ln P}\right|_{R=1,P=1\mathrm{y}}$$

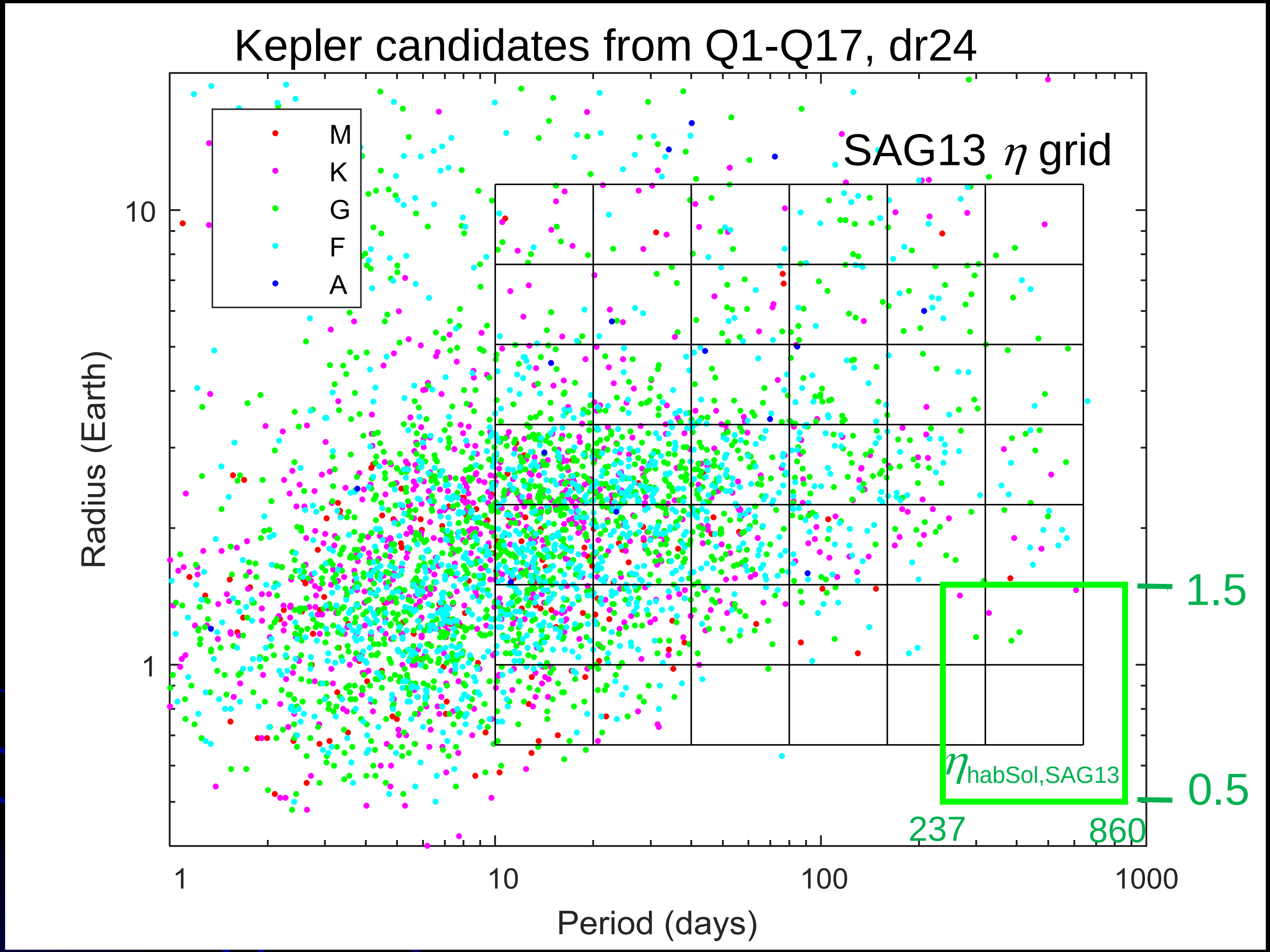
Γ_{earth} is independent of definitions of HZ or habitable size range

For most definitions of η_{Earth}, $\Gamma_{\mathrm{earth}} \sim \eta_{\mathrm{Earth}}$

“We generally find higher planet occurrence rates and a steeper increase in planet occurrence rates towards small planets than previous studies of the Kepler GK dwarf sample”

Standardized eta grid

[need to update to DR25]



12 community sourced occurrence tables

Batalha, Natalie (2)
Belikov, Rus
Burke, Chris
Catanzarite, Joe
Dressing, Courtney*
Farr, Will
Foreman-Mackey, Daniel*
Fulton, BJ
Kopparapu, Ravi
Mulders, Gijs
Petigura, Erik*
Traub, Wes*

*dataset was based on prior publications and re-integrated across SAG13 bins by Burke

All datasets and documents can be found on SAG13 repository: https://drive.google.com/drive/folders/0B520NCfkP4aOQUJYdmUzQTJkdkE

- $\eta_{habSol,SAG13}$
  - R = [0.5 – 1.5], P = [237 860] (Kopparapu optimistic HZ for Sol twin)
  - This is not exactly η_{Earth} , just a rough representation

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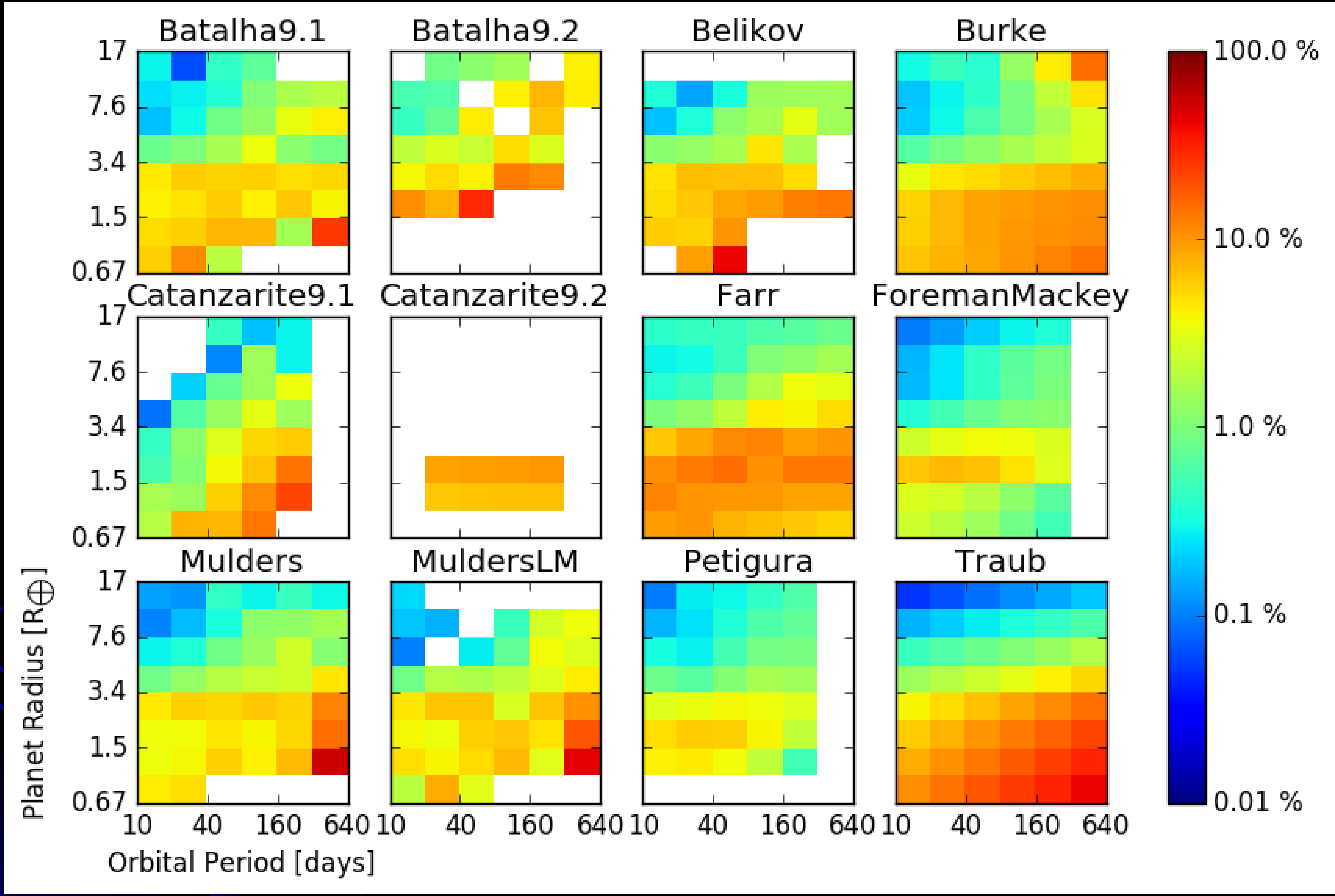
Example: submitted occurrence rates for G-dwarfs



**** DRAFT ****

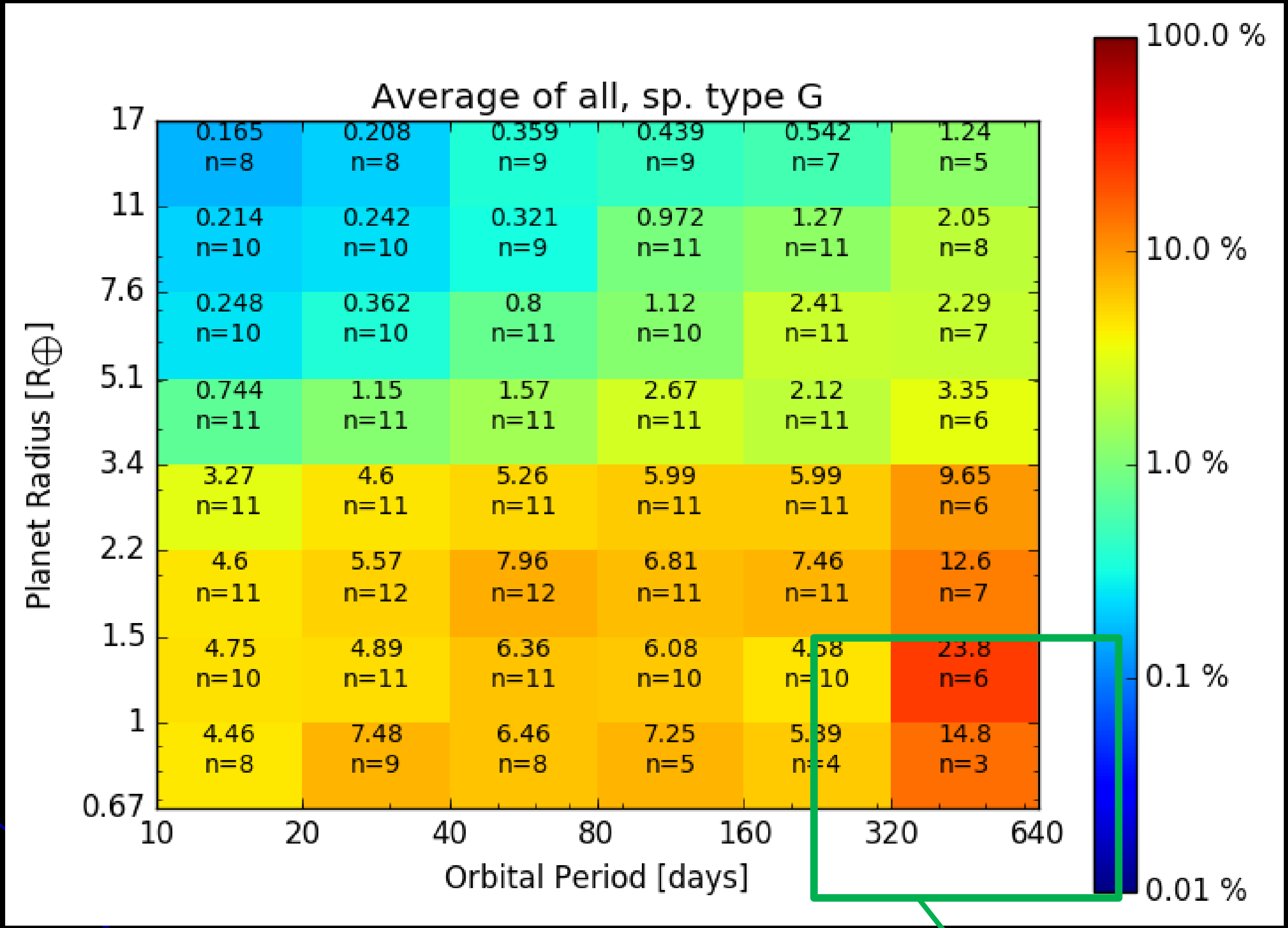
Plots and analysis are generated with the make_plots.py scriptby Gijs Mulders.
Full data and plots available online at http://[...]

Closer look at G-dwarf average

legend

% occurrence

# of submissions



$\eta_{habSol,SAG13} \sim 0.58$

(based on best power law fit)

Note: this is a simple geometric average across submissions, which does not account for dependencies. A combination based on an analysis of dependencies is challenging to formalize, but will be included in the final report.

Plots and analysis are generated with the make_plots.py script in the SAG13 Google drive, code by Gijs Mulders.

**** DRAFT ****

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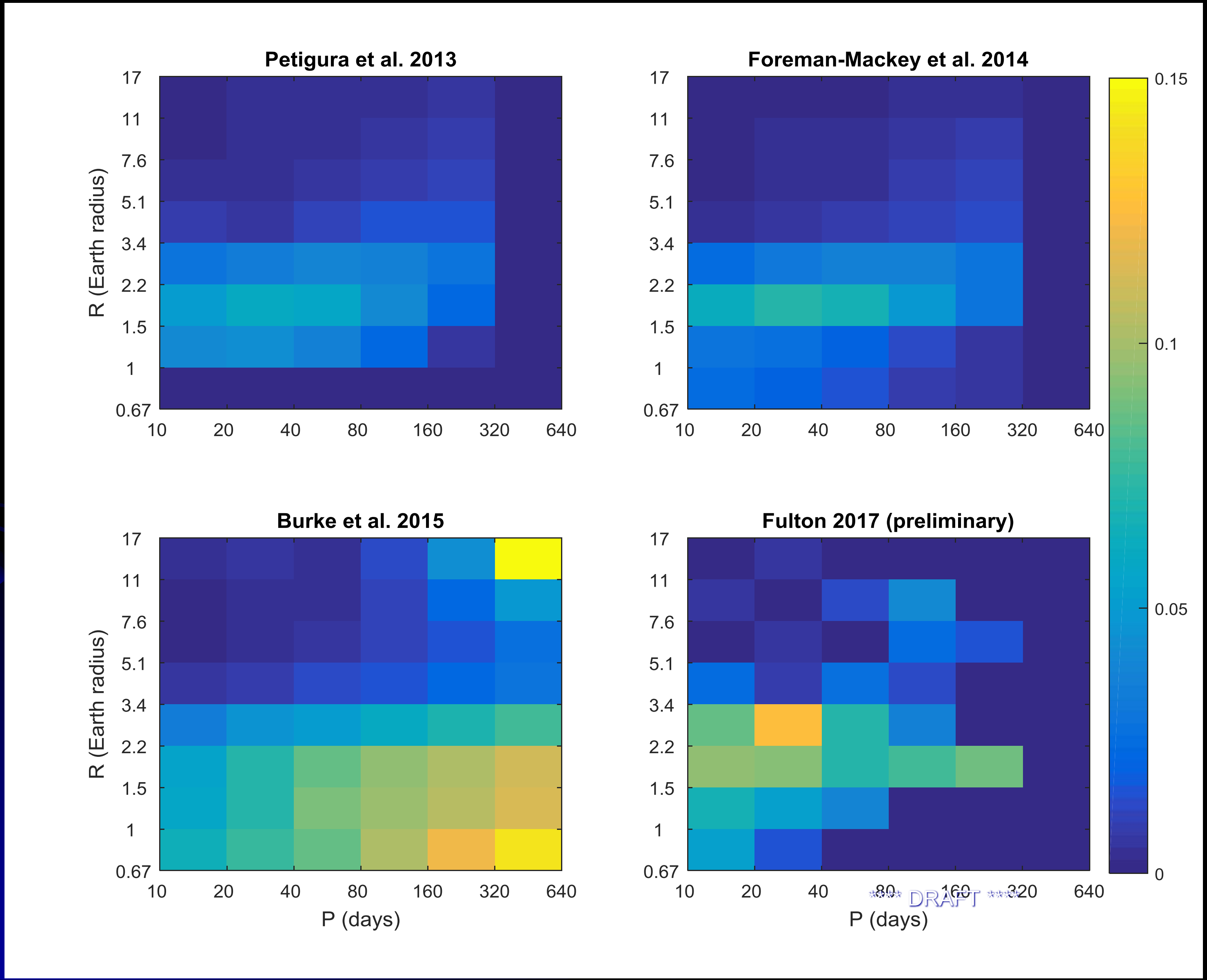
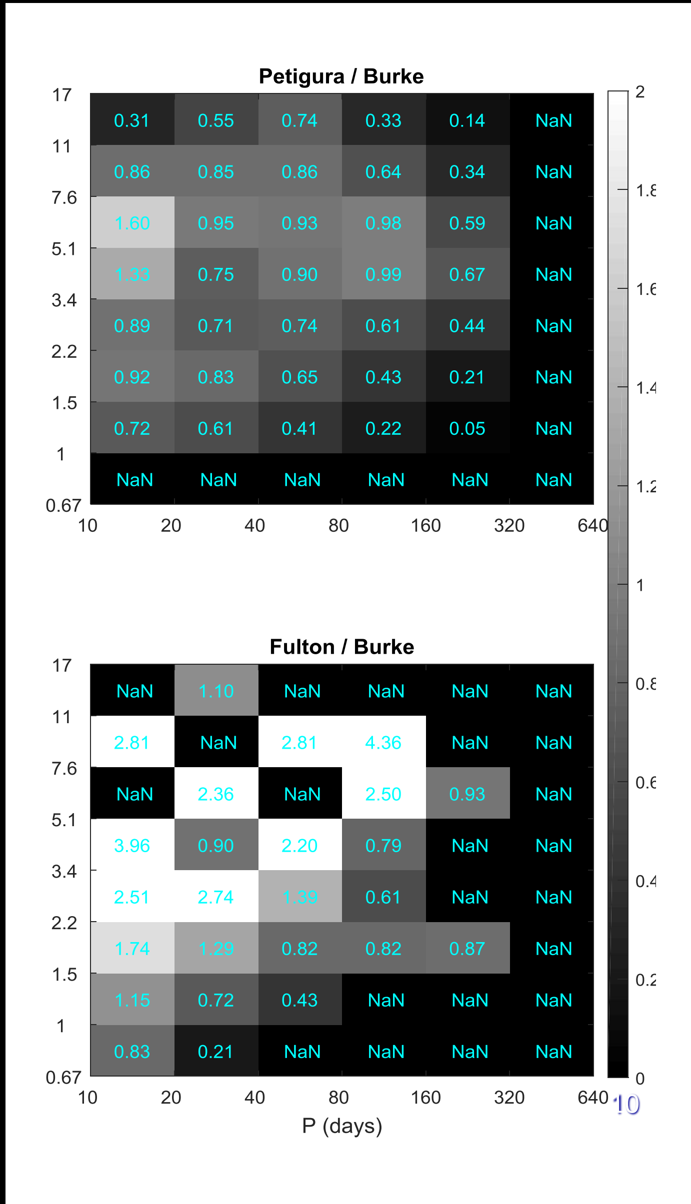
Comparison of four selected occurrence rates

Occurrence rates for G-dwarfs from different studies



Ratios



Closing the factor of ~4 gap between Petigura 2013 and Burke 2015

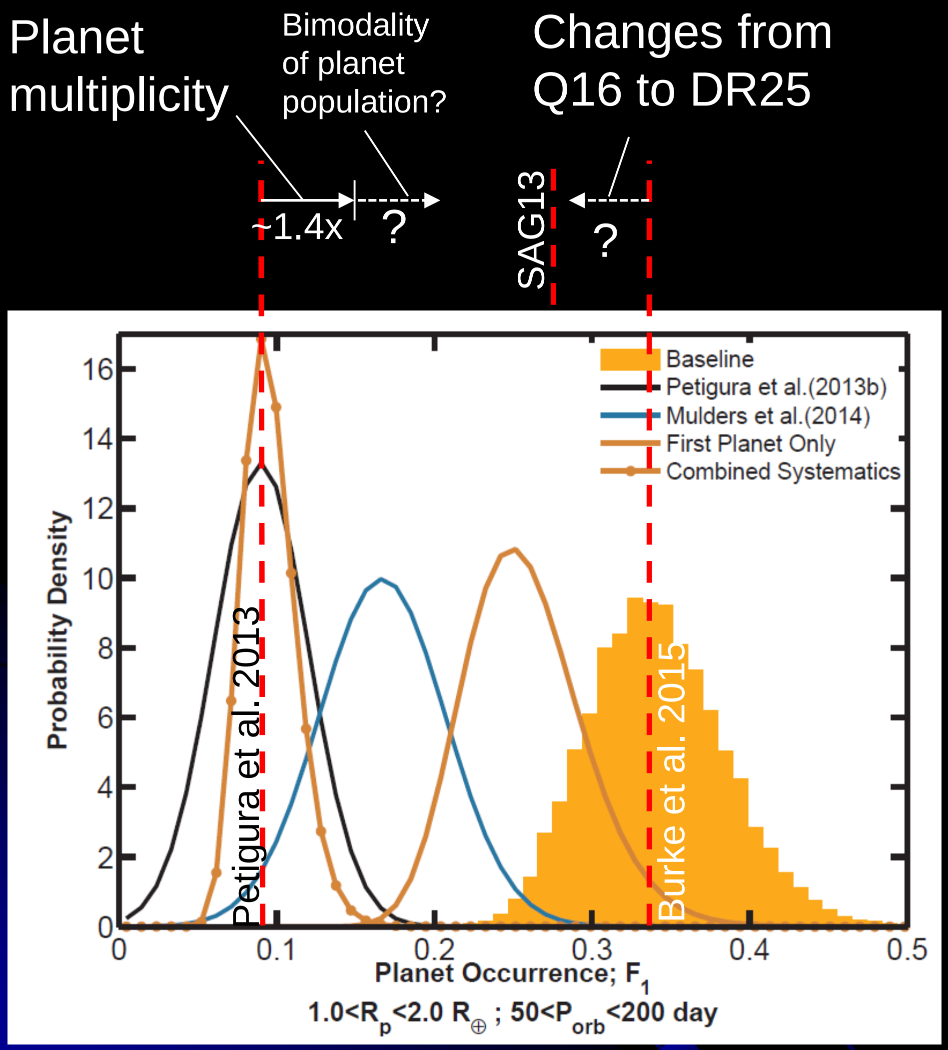


figure from Burke et al. 2015

- Petigura 2013 counted the largest planet in the system, while Burke 2015 considered all planets (a factor of 1.4 difference)
- Changes from Q16 to DR25 may slightly decrease the rates in Burke et al. 2015:
  - Star sizes are slightly larger, hence planets are slightly larger
    - # of {50<P<300, 0.75<R<2.5} planet candidates decreased from 156 to 118
  - Detection contours have slightly better recovery than Q16
- Remaining factor of 2 gap remains unexplained (several effects are being investigated)

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Sensitivity of occurrence rates to methodologies and assumptions

- Completeness curves and catalog seem to make the largest systematic differences for potentially habitable planets
  - DR24 lead to systematically higher numbers than many prior studies (~3-4x)
  - DR25 is likely to be a little bit lower than DR24 (perhaps ~1.5x)

- Other things (estimation method, details of the code, extrapolation) usually result in occurrence rates that are consistent to better than a factor of 2, usually much better

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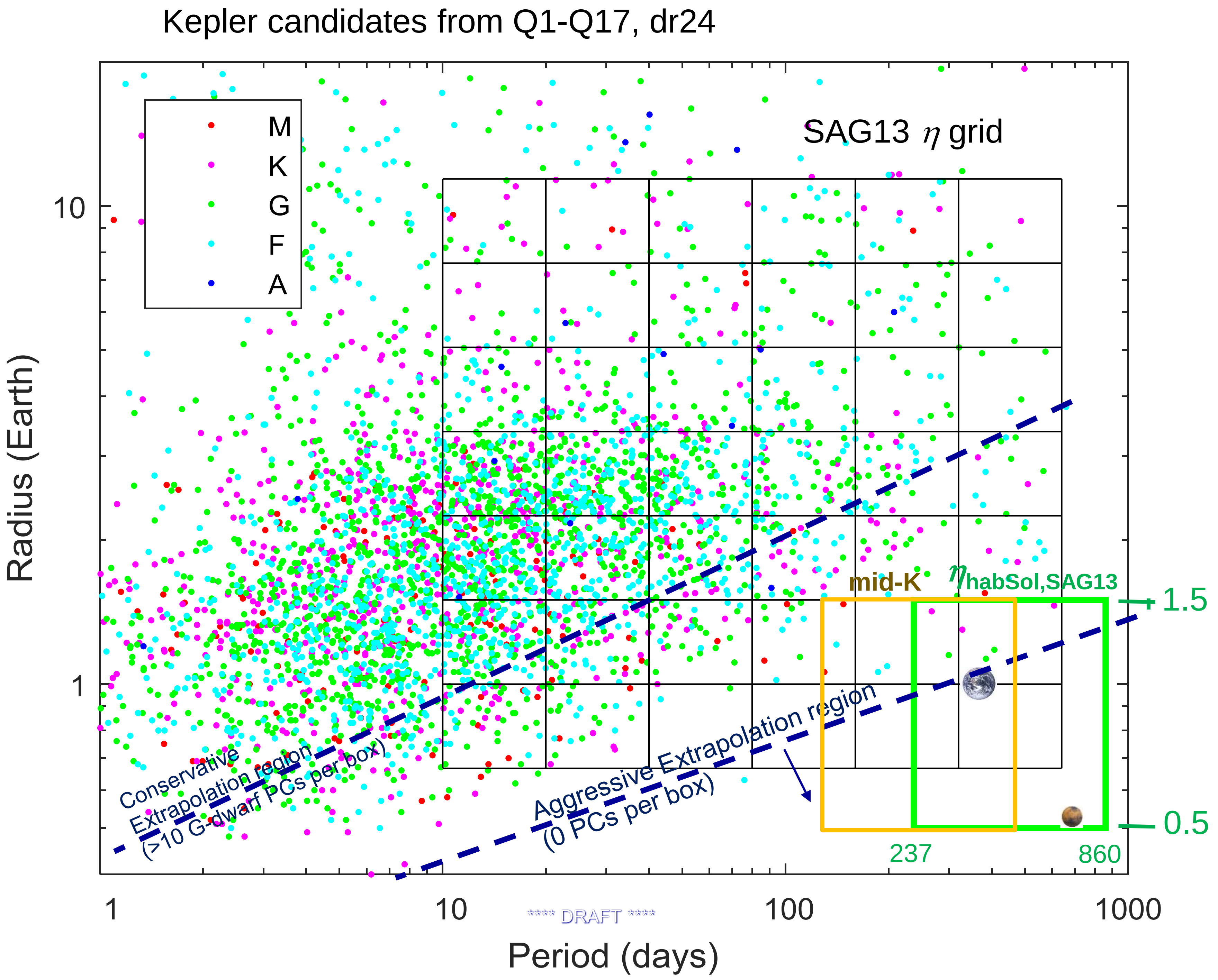
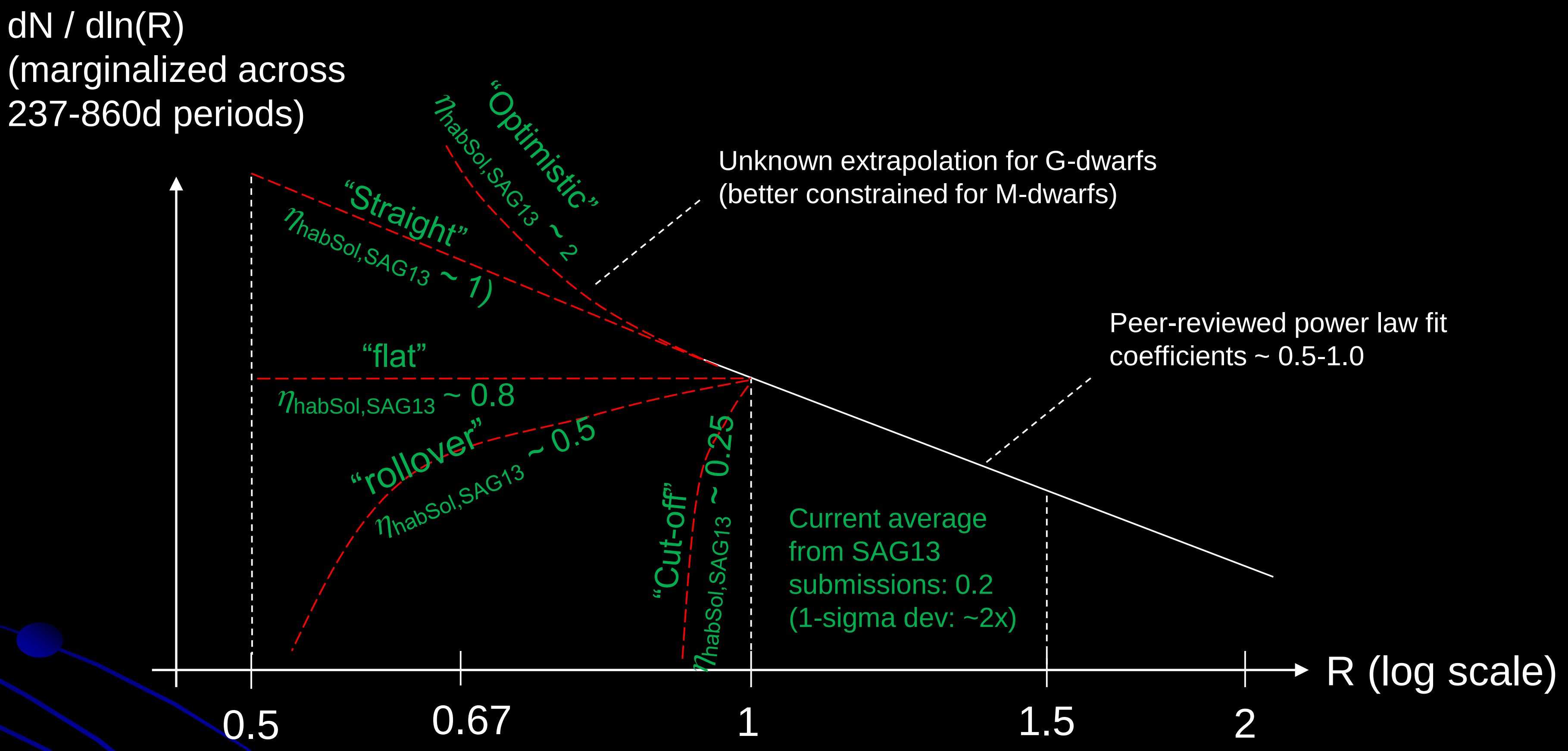

Kepler candidates from Q1-Q17, dr24
M
K
G
F
A
SAG13 η grid
Radius (Earth)
10
1
1.5
0.5
mid-K
η habSol,SAG13
Conservative Extrapolation region (>10 G-dwarf PCs per box)
Aggressive Extrapolation region (0 PCs per box)
237
860
1
10
100
1000
**** DRAFT ****
Period (days)

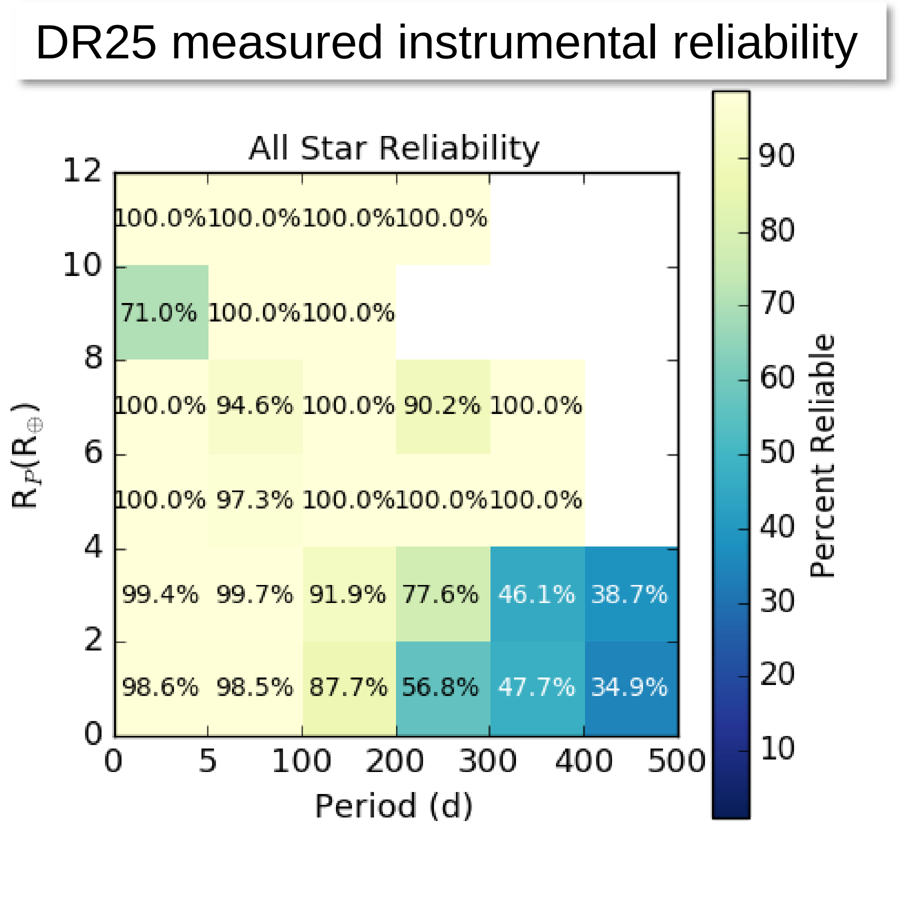
Importance of 0.5-1.0 Earth size bin



- Any estimate of eta_Earth should always very clearly specify:
  - What parameter bin it uses, and whether the ~0.5-1.0 bin is included or not
  - What extrapolation assumption was made
- Many discrepancies in eta_Earth estimates can be traced to inclusion or exclusion of 0.5-1.0 bin
- Mission study teams may want to consider the possibility of a large number of potentially habitable planets in the 0.5-1.0 bin

Reliability

- For Rp < 4 Re, P > 100 days you must account for reliability
  - Some PCs are not real planets
- DR25 is the first catalog to measure reliability
  - *Inverted* and *Scrambled* data measure instrumental reliability
  - Offset and EB injections provide insight into which astrophysical false positives are undetectable
- FPP table measures astrophysical reliability
- Accounting for reliability in occurrence rate estimates is an open problem



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Parametric fit (for G-dwarfs)

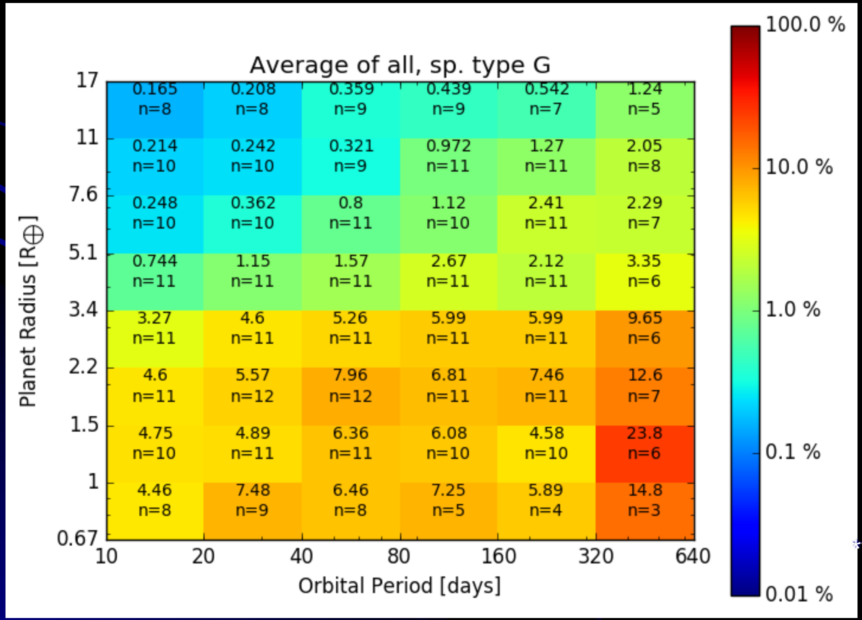
$$\frac{\partial^2 N(R,P)}{\partial \ln R \, \partial \ln P} = \Gamma_i R^{\alpha_i} P^{\beta_i} \qquad \text{in region } R_{i-1} \le R < R_i$$

(R in Earth radius, P in years)

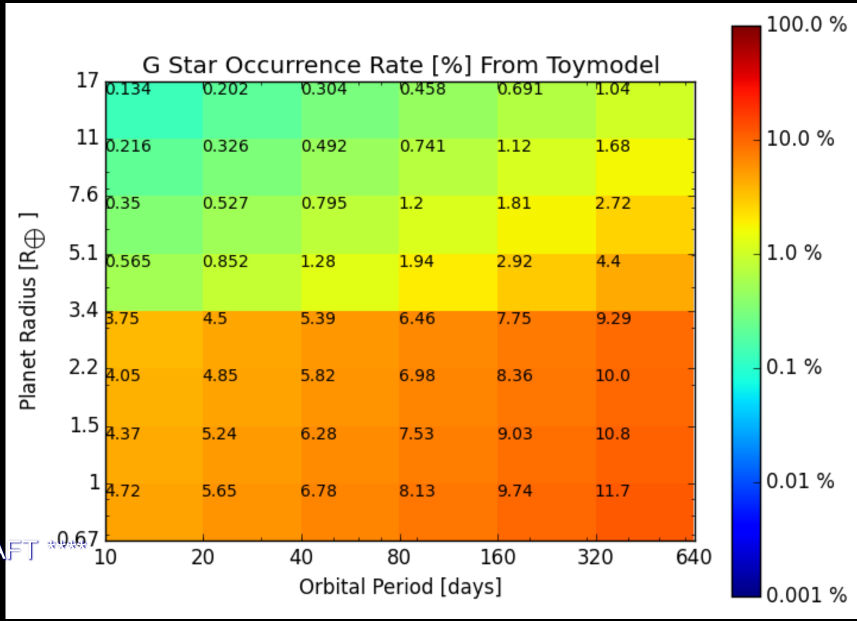
Γ_i	α_i	β_i	R_i
0.38	**-0.19**	**0.26**	**3.4**
0.73	-1.18	0.59	Inf

[to be updated to include uncertainties]

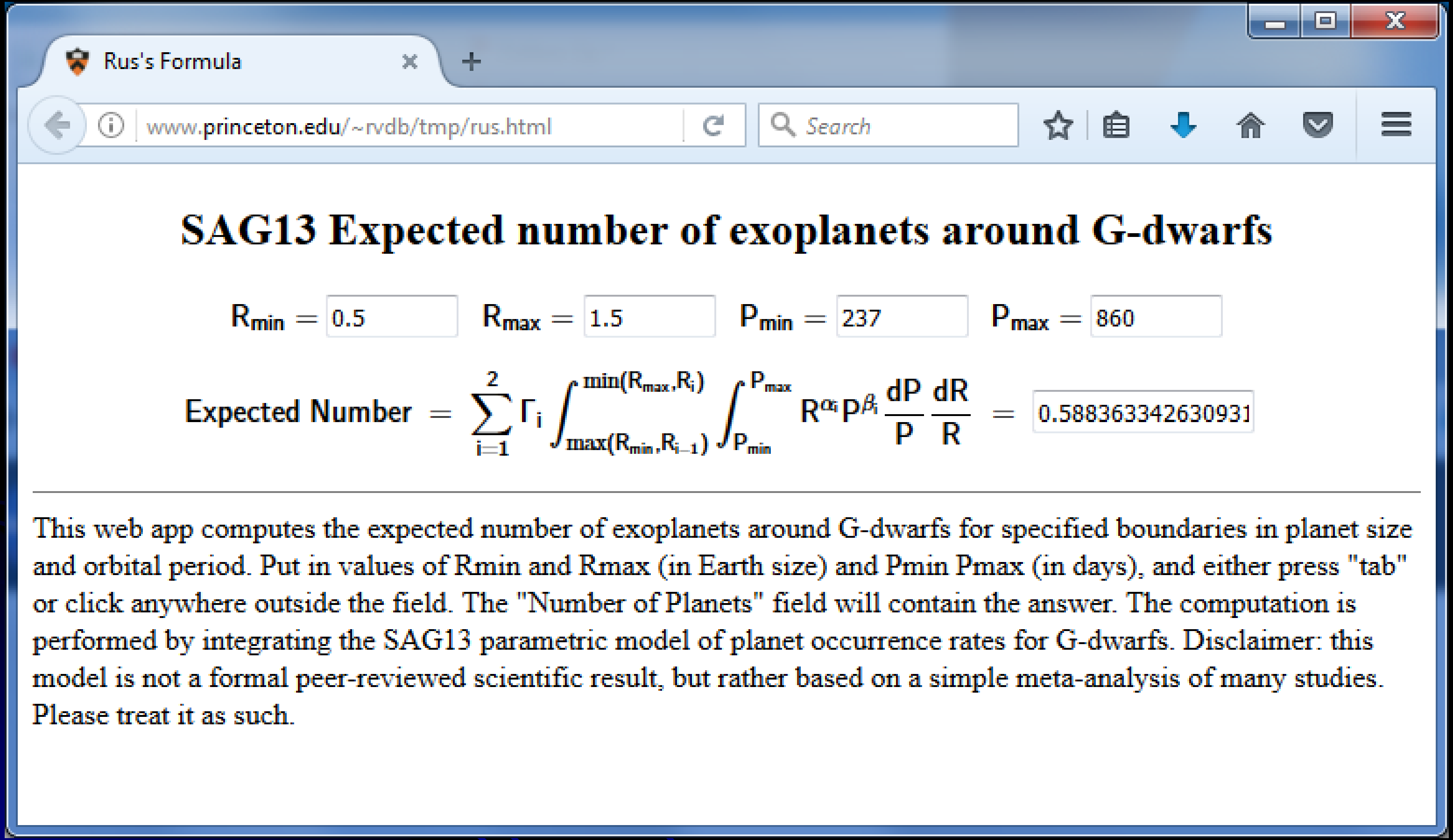
Submission average



Parameteric fit (integrated across bins)



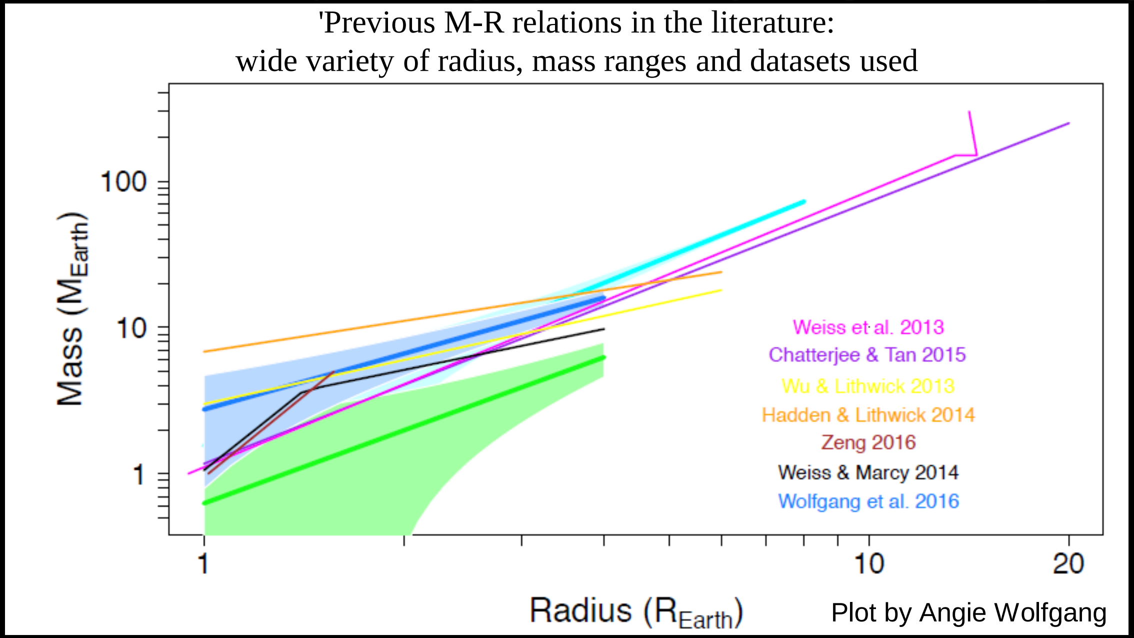
Online occurrence rate calculator (live demo)

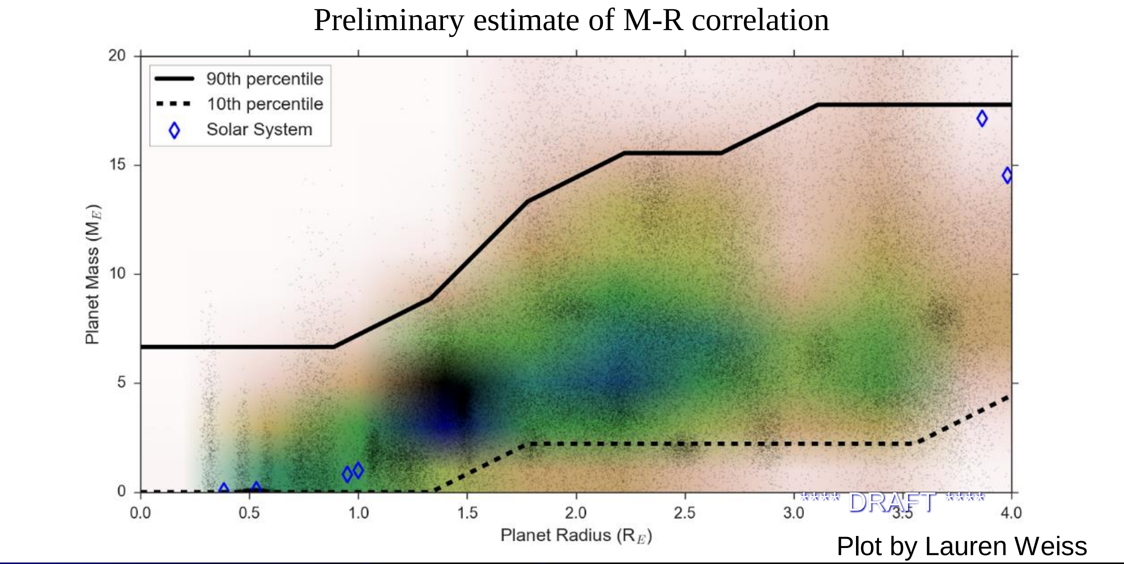


- Preliminary online implementation (by Bob Vanderbei)
- If there is interest, other SAG13 tools and code can be deployed as web apps
- Disclaimer: the SAG13 model used in this tool is NOT a formal peer-reviewed scientific result, but rather based on a simple meta-analysis of many studies. Please treat it as such.

Converting between Mass and Radius

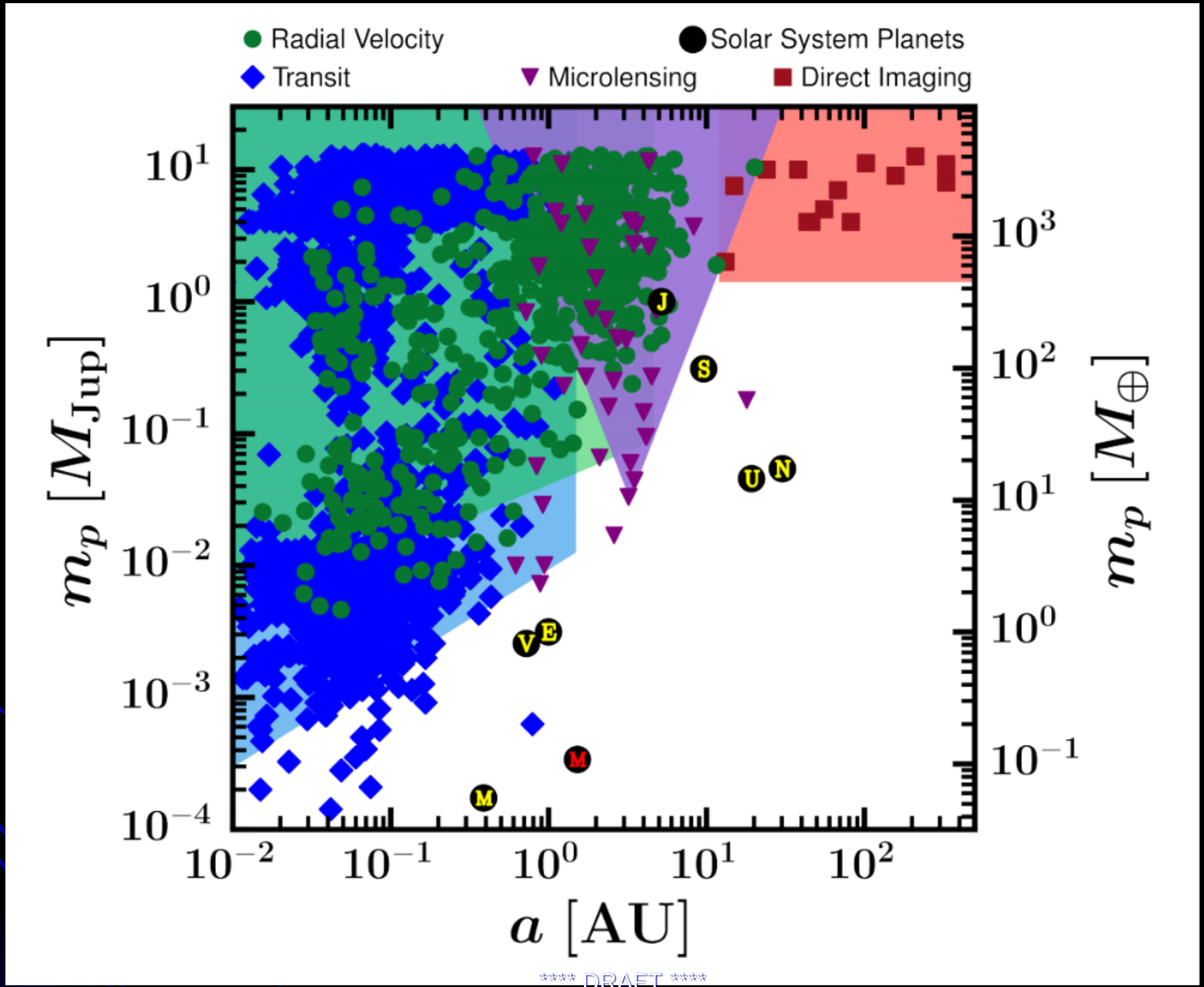
(focus group led by Angie Wolfgang and Lauren Weiss)





- Purpose: enable SAG13 occurrence rate submissions based on RV planets
- M-R relationship is fundamentally not a 1-1 map (e.g. M = f(R)), but a correlation (e.g. density function C(M,R))
- M-R focus group deliverables
  - an estimate of this correlation based on open community input
  - analysis of uncertainties and dependency on period and other parameters
- Notes about plots / methods
  - TTV data is included
  - Black dots: MC posterior simulation accounting for uncertainties on currently known M-R planets
  - Color map: estimate of the 2D correlation density function (using Gaussian kernel density estimator)

Linking to results from non-Transit techniques (Christian Clanton)



Conclusions

- The average SAG13 occurrence rates may be higher than what has been commonly adopted in the past, and eta_Earth is very sensitive to the boundaries chosen
  - Eta_habSolSAG13 ~ 0.6 (i.e. for 0.5-1.5 Earth size, Kopparapu extended HZ, and G-dwarfs)
  - SAG13 results represent a point in time; DR25 may lower it

- Although many orders of magnitude of Gamma_Earth (or eta_Earth) are possible, only a small range (~ few octaves) within that is “likely”

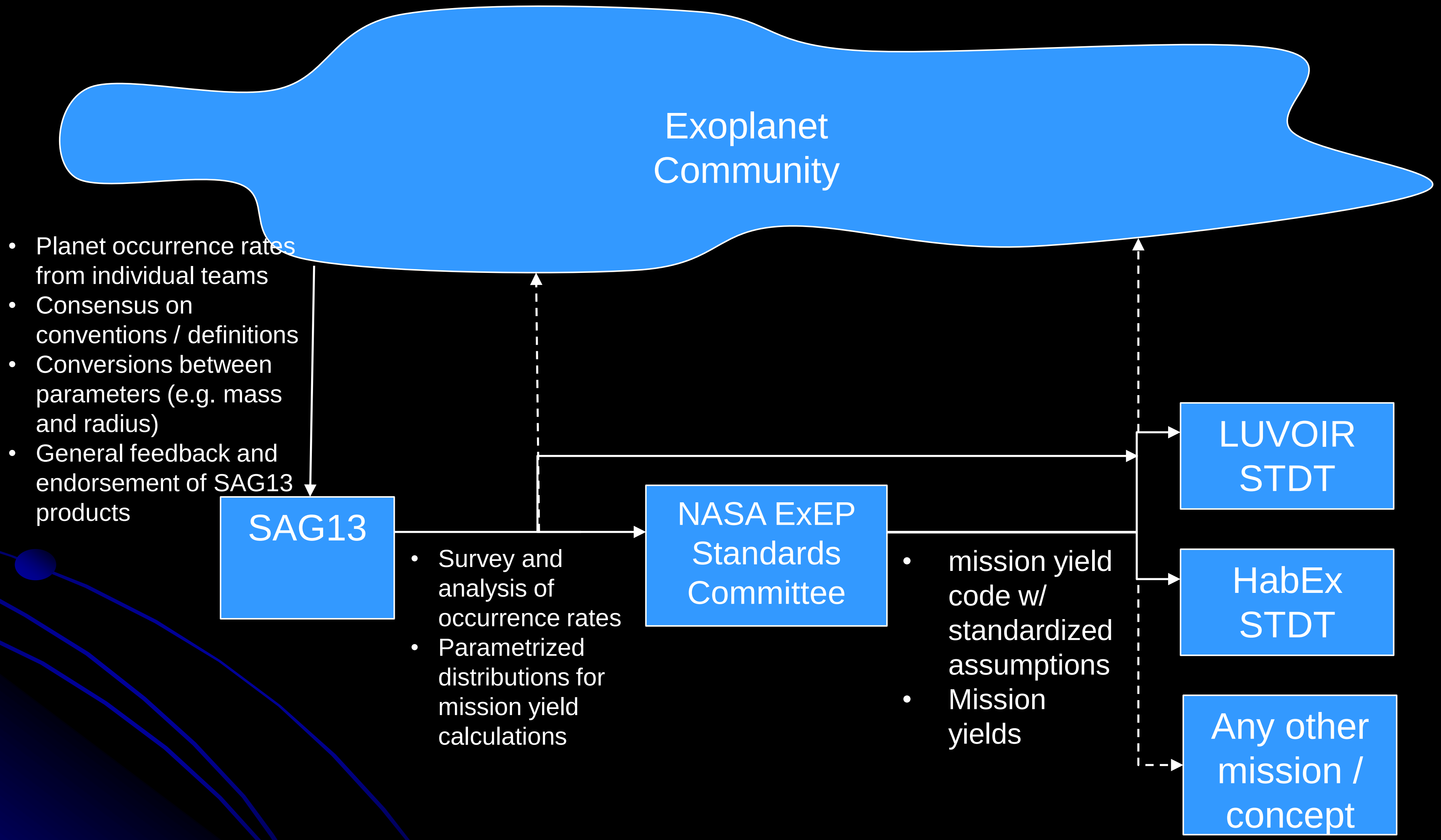
- Future work is still necessary to reduce systematics and uncertainties
  - DR25 may reduce potentially habitable occurrence rates, but not dramatically
  - Reliability remains a concern

SAG 13 products:

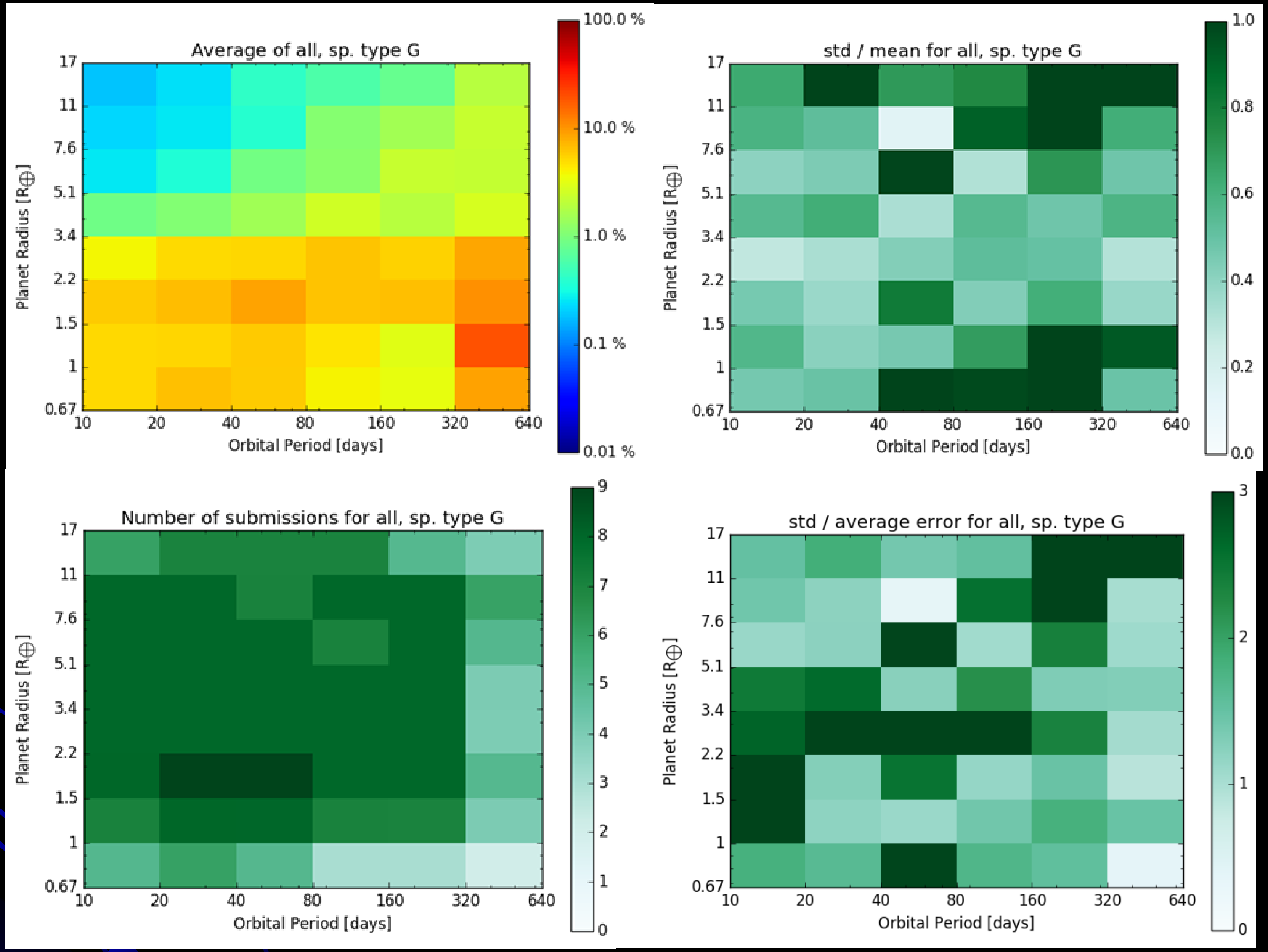
1. Proposed standard grid of bins.
2. Tables of combined occurrence rates and uncertainties from different studies across that grid.
3. Analysis of differences between studies and any known explanations
4. Parametric model to be used for mission yield simulations
5. Online tools to plot SAG13 tables and compute occurrence rates

Backup slides

SAG13 role [possibly backup slide]



Analysis of variations in submissions (for G-dwarfs)

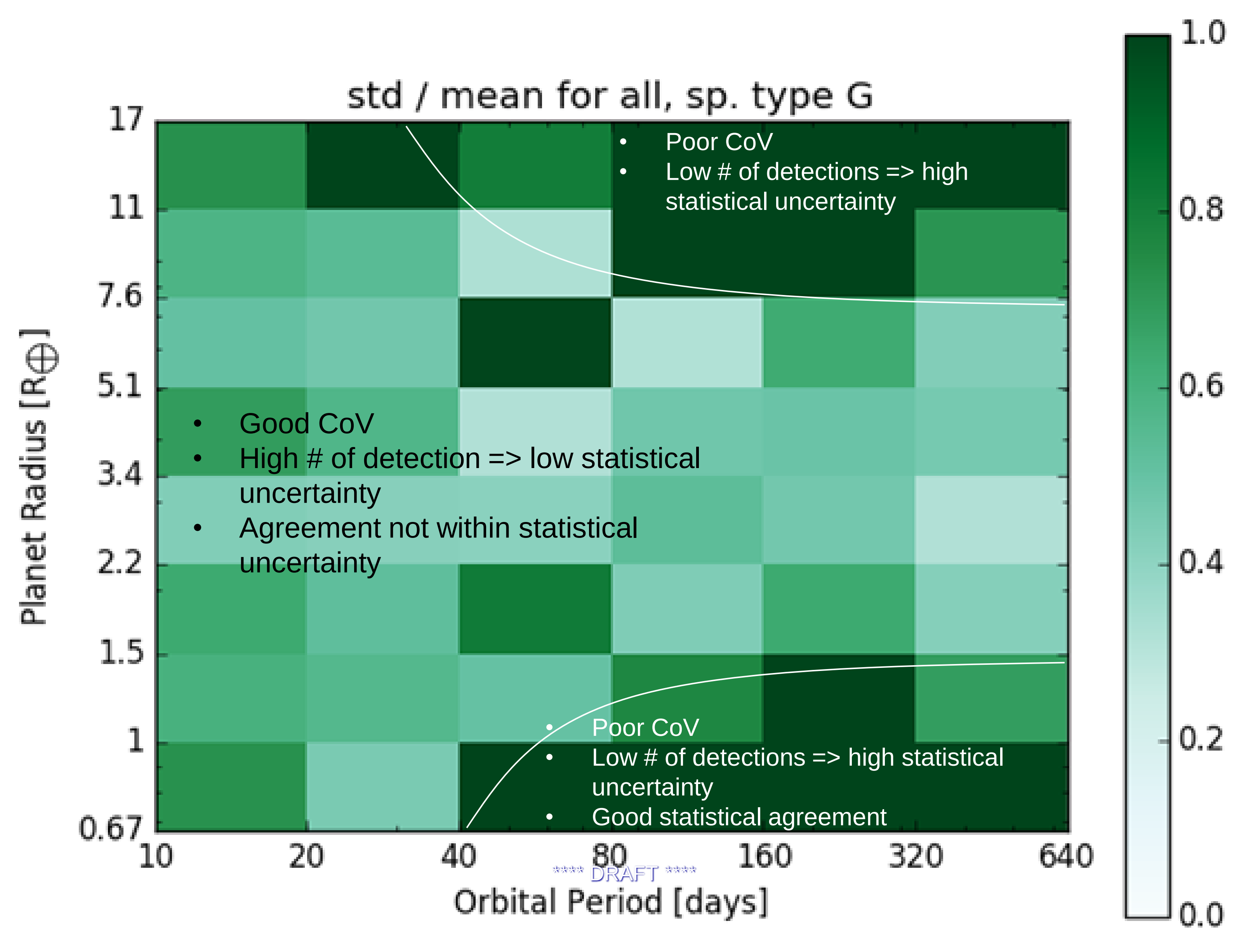


by Gijs Mulders

**** DRAFT ****

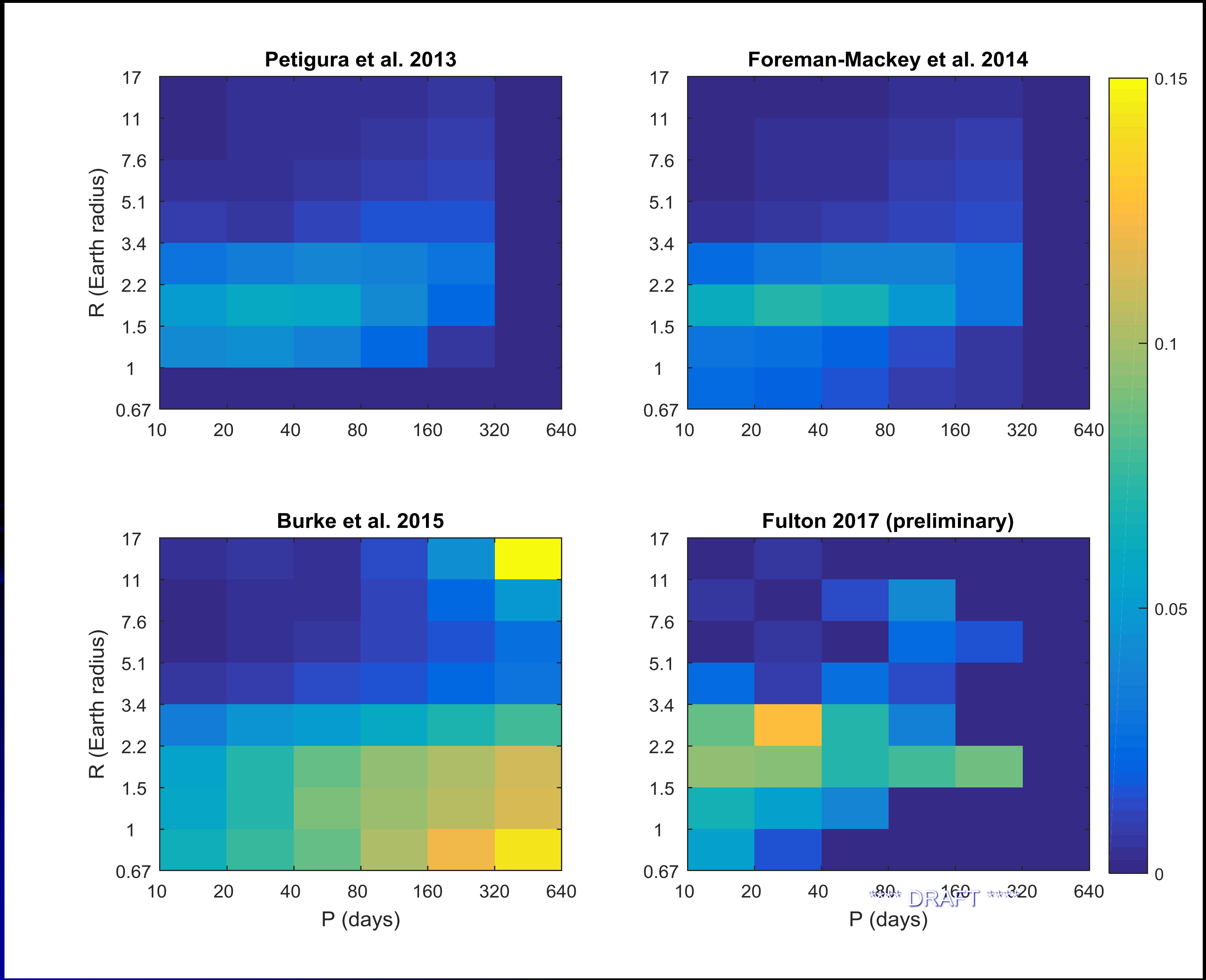
Coefficient of Variation

(aka relative standard deviation = std / mean)

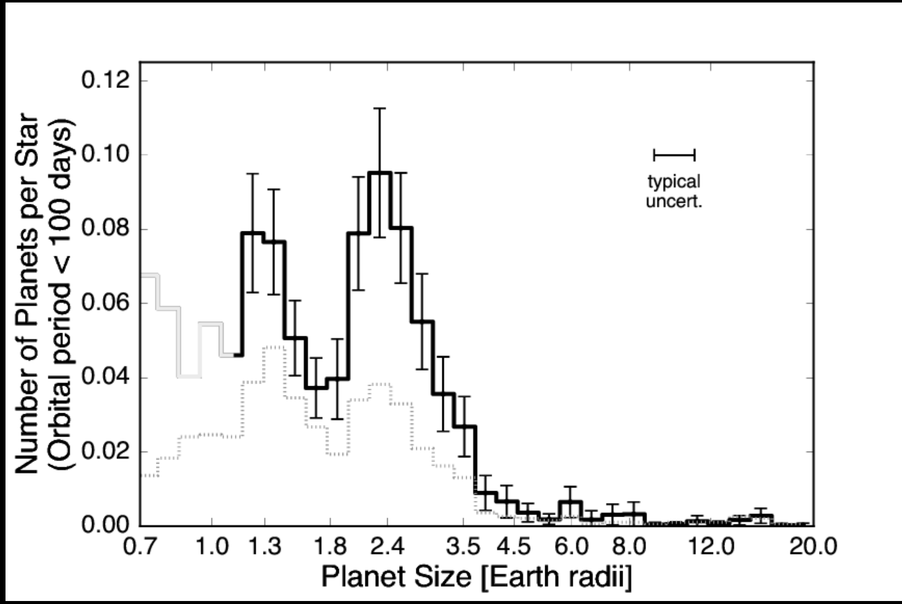


Selected occurrence rates on standard SAG13 grid

Occurrence rates for G-dwarfs from selected studies



Fulton et al. 2017



Calculations of habitable occurrence rates (example for G-dwarfs)

Integrating SAG13 parametric fit

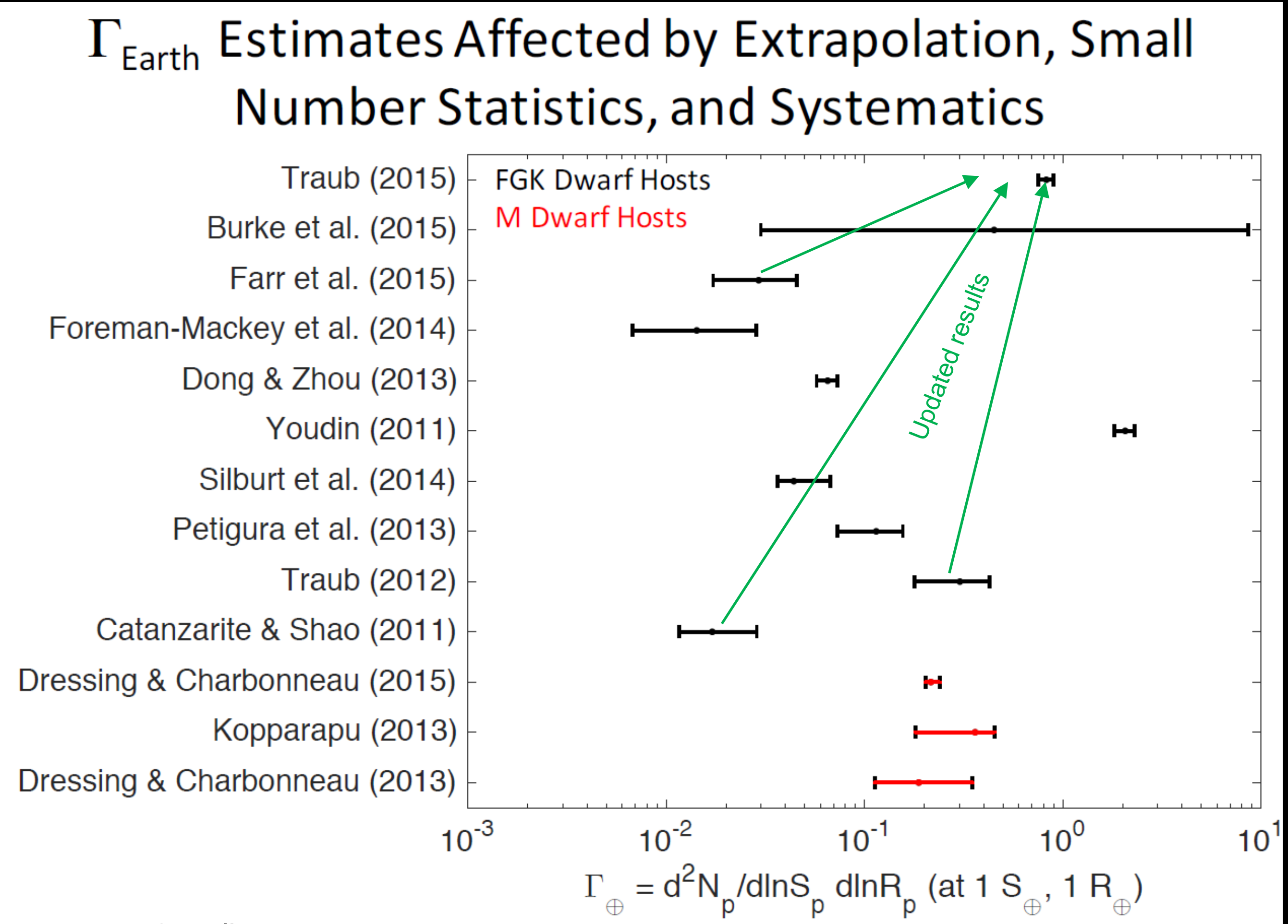
		HZ (from Kopparapu 2013)	
		Conservative	Optimistic
Planet radius range	1.0-1.5	**0.14**	**0.20**
	0.5-1.5	**0.40**	**0.58**

$\eta_{\mathrm{habSol,SAG13}}$

Using Burke et al. 2015 posterior tool
https://github.com/christopherburke/KeplerPORTs

		HZ (from Kopparapu 2013)	
		Conservative	Optimistic
Planet radius range	1.0-1.5	$\mathbf{0.21^{+0.08}_{-0.08}}$	$\mathbf{0.31^{+0.1}_{-0.1}}$
	0.5-1.5	$\mathbf{0.5^{+0.4}_{-0.2}}$	$\mathbf{0.73^{+0.6}_{-0.3}}$

Comparison of Γ_{earth} from different publications



Courtesy of Leslie Rogers

- Initially, it appears that the possible range of Γ_{earth} spans 2-3 orders of magnitude
- This is true, but conservative: only the middle ~couple of octaves are "likely"

Original proposed process

✓ 1. SAG defines a standard set of parameters representing occurrence rates and/or distributions. (Examples are in "occurrence_table_options.xlsx").

η_1: [rigorous definition]
η_2: [rigorous definition]
…
η_N: [rigorous definition]

✓ 2. Crowdsourcing: "focus group" members estimate parameters and their uncertainties
   1. Focus group members are meant to be those who have done occurrence estimates already

FG member 1 :

η_1 = [value] +/- [uncertainty]
η_2 = [value] +/- [uncertainty]
...
η_N =[value] +/- [uncertainty]

. . .

FG member N :

η_1 = [value] +/- [uncertainty]
η_2 = [value] +/- [uncertainty]
...
η_N =[value] +/- [uncertainty]

3. Organize / analyze the data from #2
   1. Check for statistical agreement
   2. Trace and attempt to resolve any outliers and discrepancies
   3. Document reasons for unresolvable discrepancies

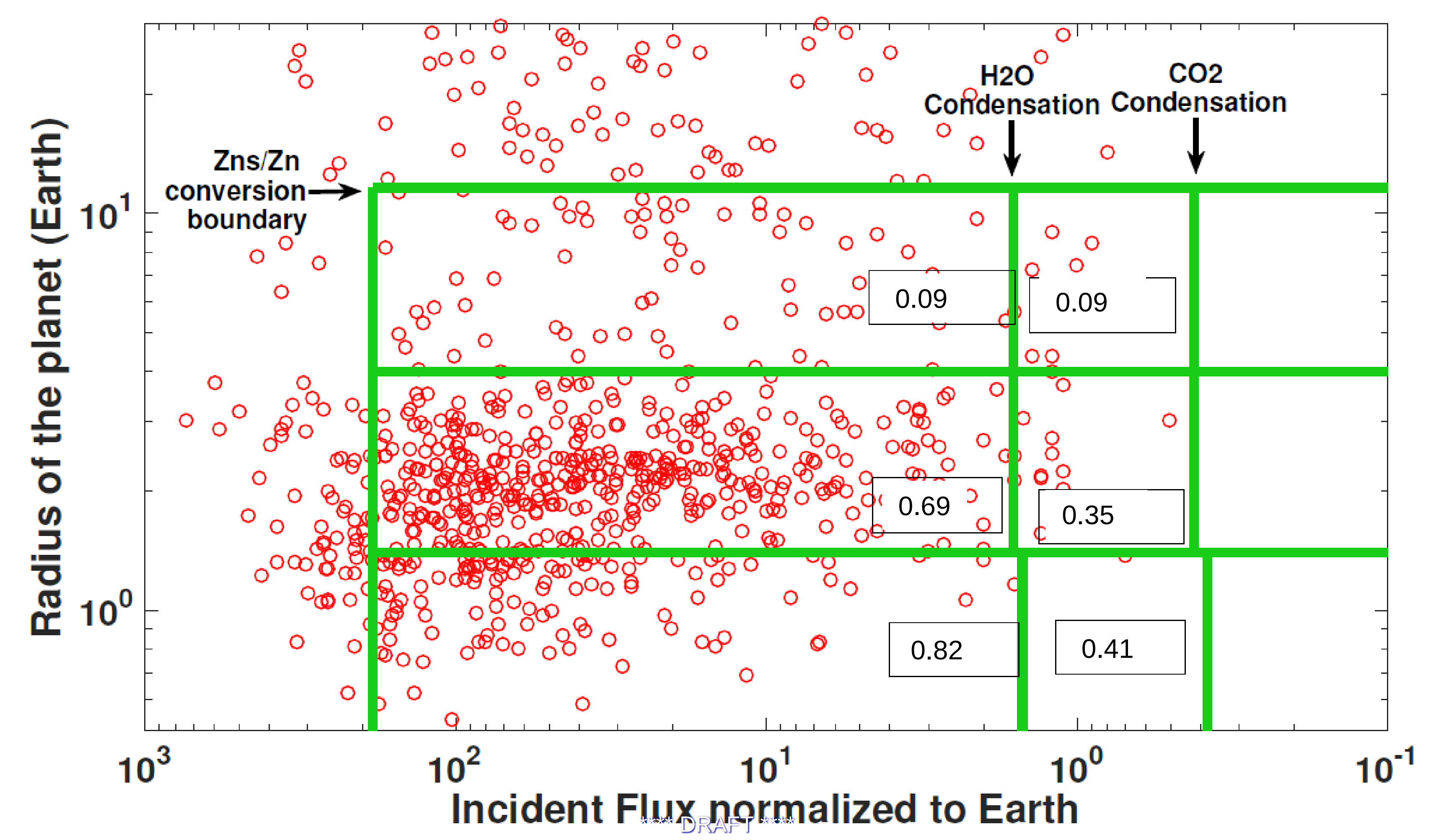
4. Final product:
   1. Mean and variance of each parameter estimate across FG members
   2. Explanation for any discrepancies
   3. Recommendation of what values to use for ExEP

η_1: = [mean] +/- [variance]
η_2: = [mean] +/- [variance]
…
η_N: = [mean] +/- [variance]

Occurrence rates for new proposed planet classification

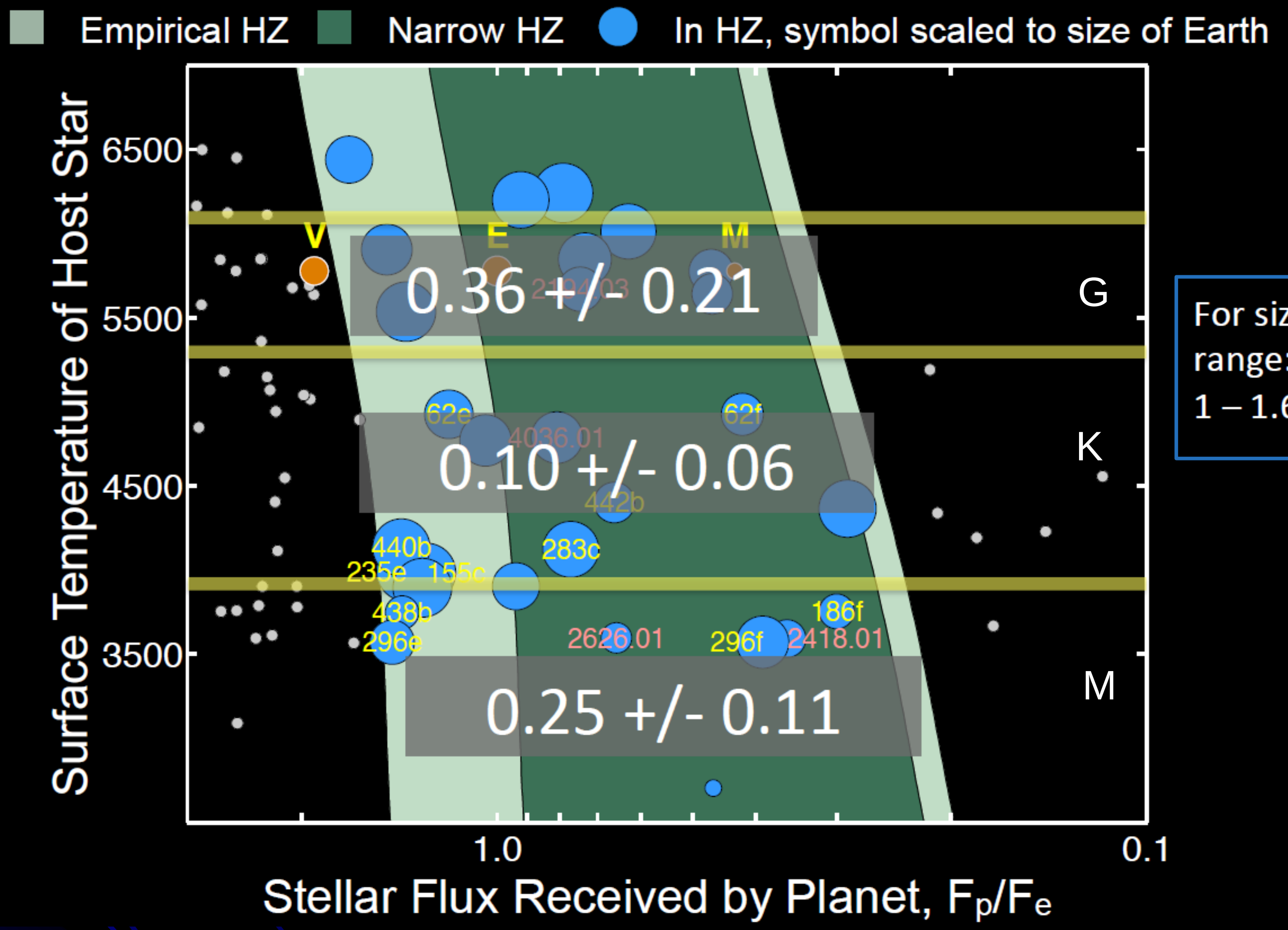
(from Kopparapu, Domagal-Goldman, et al., in prep)

Numbers based on integrating SAG13 parametric fit



Courtesy of Natalie Batalha

Small (< 2 R_e) Planets in the HZ: 4 yr



For size range: 1 – 1.6 R_e

Note: for planet size range of 0.5 – 1.6 R_e , expected # of planets may be a factor of ~2-3 higher
(based on extrapolation)

Rough idea for slide

Definition of SAG13 parametrized distribution:
(rough example)

d^2 N / (dlnSMA dlnR_planet) =

Gamma1 * R^alpha1 SMA^beta1 [for R < R_break]
Gamma2 * R^alpha2 SMA^beta2 [for R > R_break]

Plot of parametrized distribution
(for e.g. G star)

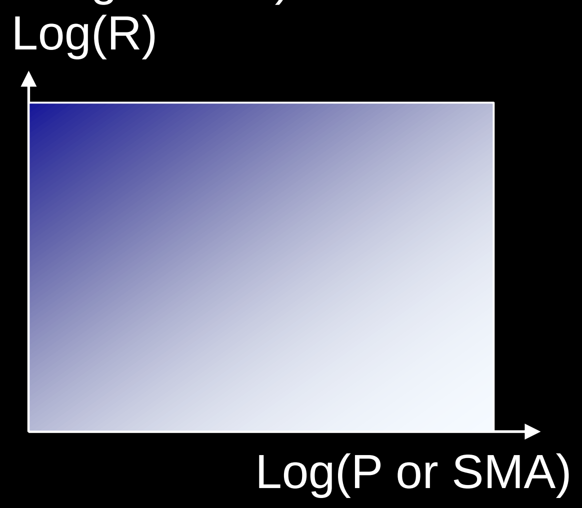
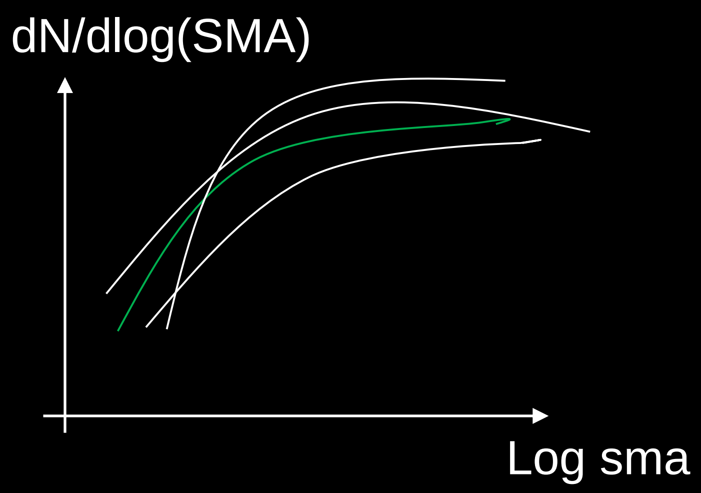
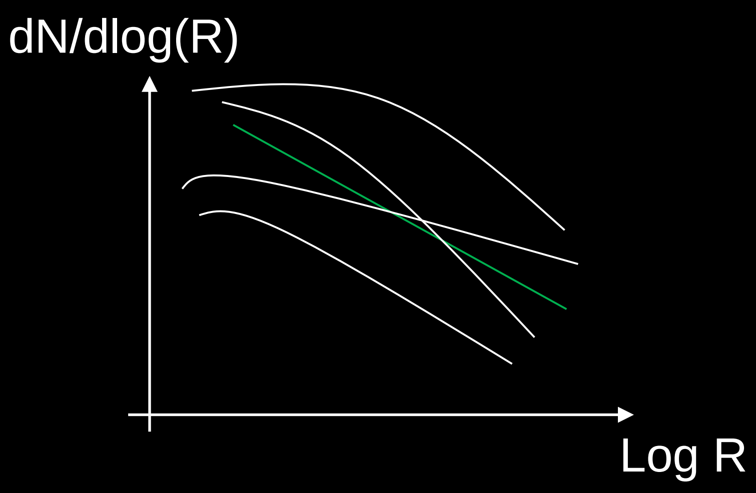


Table for G stars, and other ones for F, K, M stars

	alpha 1	alpha 2	beta 1	beta 2	Gamma1	Gamma2	R_break
“baseline”							
“optimistic							
Pessimisitic							

Variances between individual parameterized distributions

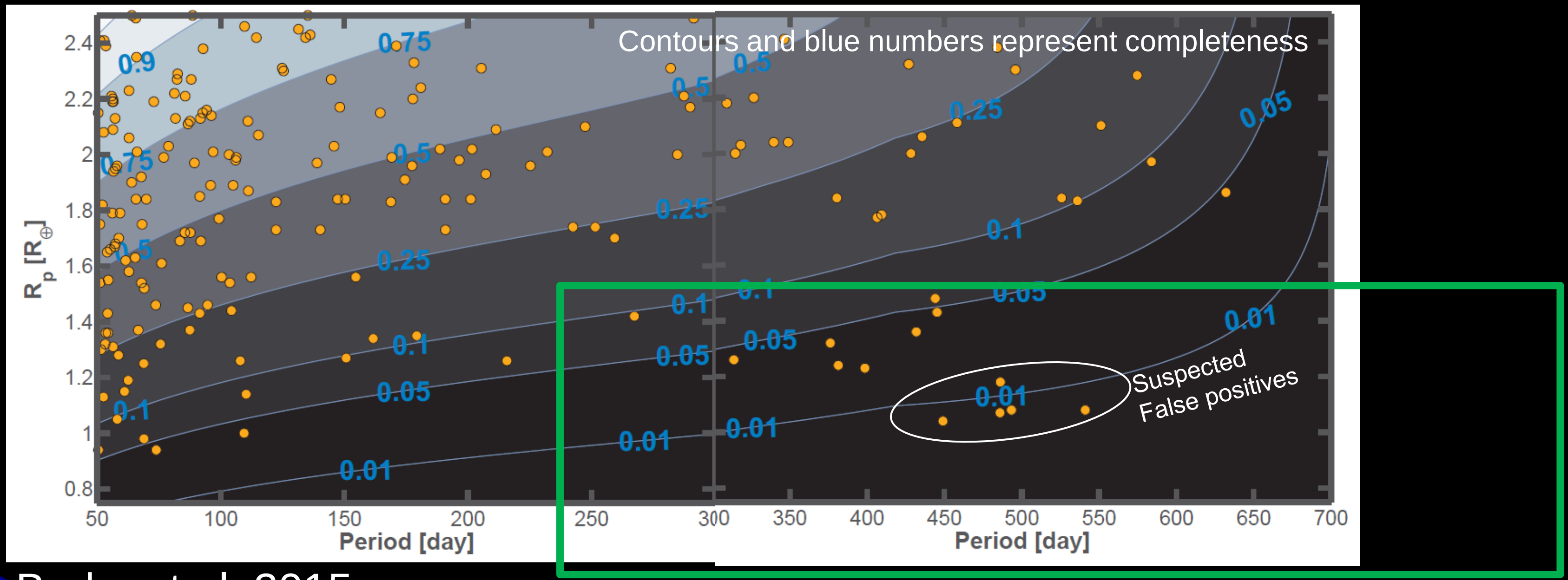




Current edge of planet candidates

[potential slide, meant to show actual planets and thus better visualize Poisson uncertainty]

Shorter periods, more reliable   Longer periods, less reliable



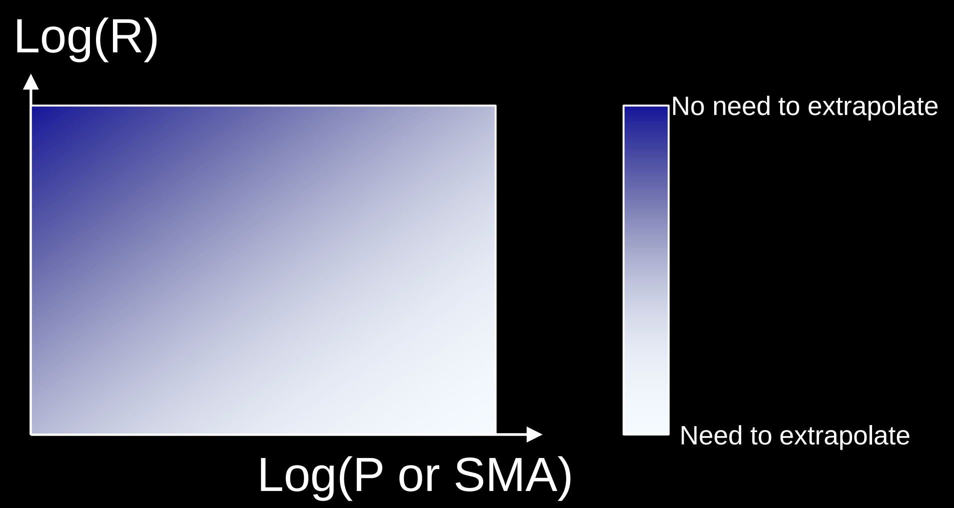
Burke et al. 2015

0.5-1.5 Earth size
237-860 days (Kopparapu extended HZ for Sun)

**** DRAFT ****

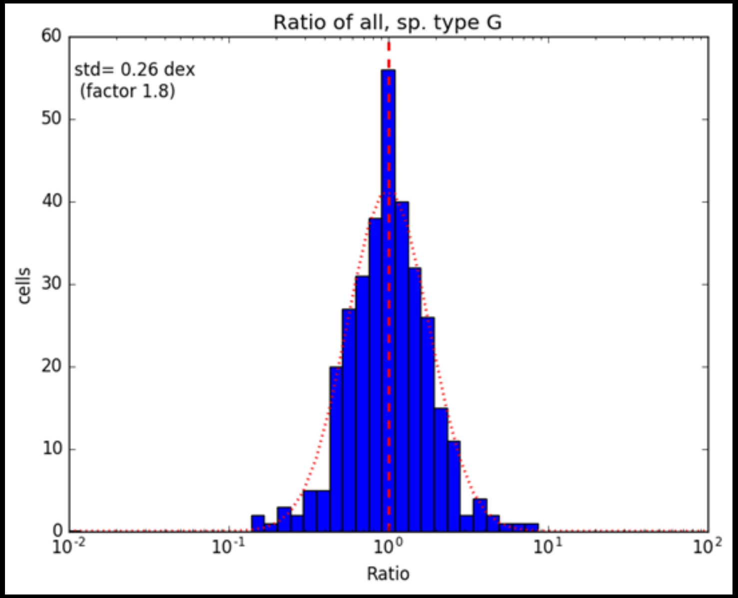
Analysis of extrapolation

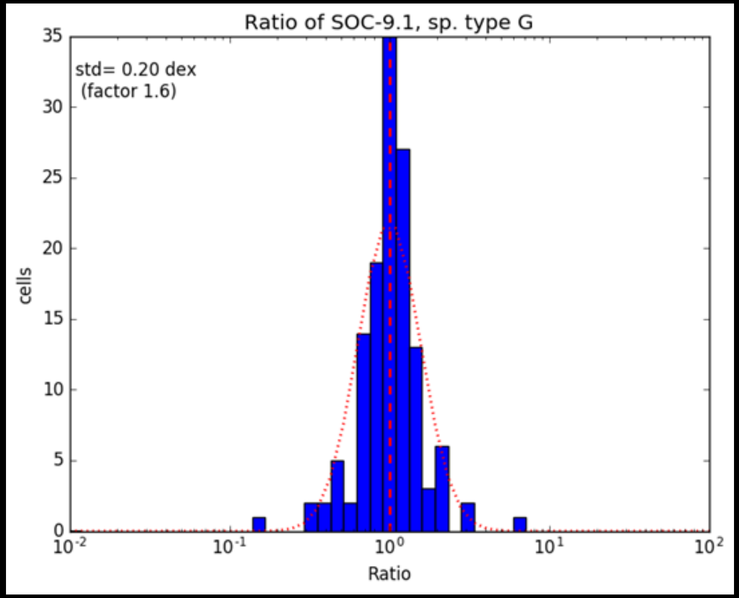
(Rough idea for slide)

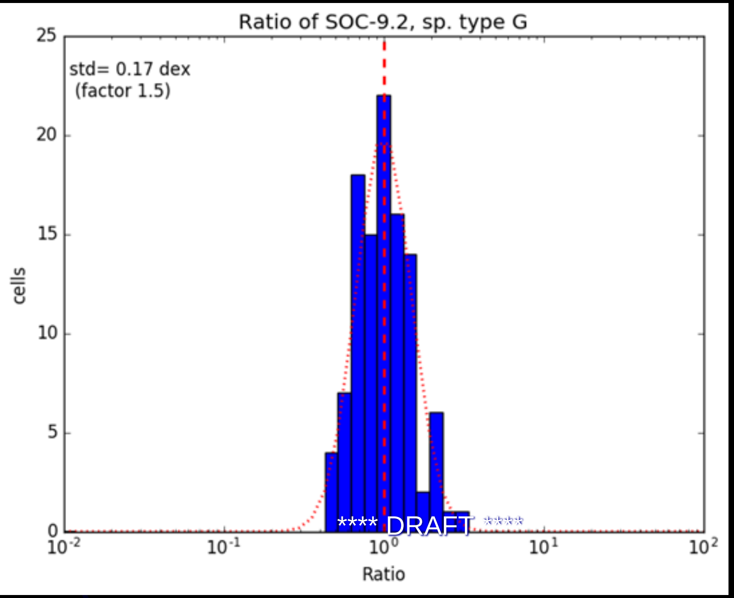


[Is there a standard metric that is a good measure of the need to extrapolate? Perhaps we can define something useful if one does not already exist – ideas?]

Variance in submissions







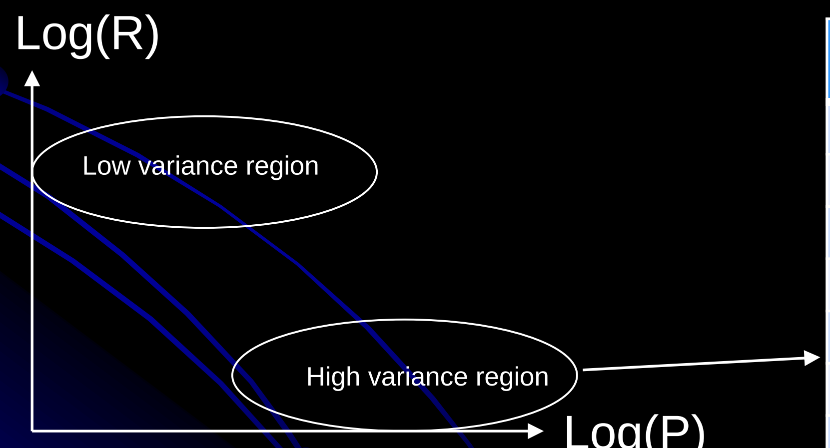
**** DRAFT ****

Courtesy of Gijs Mulders

Slide which shows any key correlations we found between variances / outliers and submission parameters (catalog, method, etc.)

[Goal is to show status and any key preliminary patterns we found in the most clear and concise way but emphasize that this is still a work in progress]

Rough idea for visualization:



Value of Γ_{earth}	catalog	Completeness ?	Methodology ?
Lowest value	Early catalog ?		
Highest value	More recent catalog ?		

[Note – for now, table entries are purely illustrative, not necessarily ones that we will have in the final slide]

ROUGH DRAFT

Details of submitted rates

	Catalog	Filters	Completeness model	Vetting efficiency	Reliability	Methodology	Value of Γ_{earth}
Batalha, Natalie (2)							
Belikov, Rus							
Burke, Chris							
Catanzarite, Joe							
Dressing, Courtney*							
Farr, Will							
Foreman-Mackey, Daniel*							
Kopparapu, Ravi							
Mulders, Gijs							
Petigura, Erik*							
Traub, Wes**							

ROUGH DRAFT / SLIDE IDEA

Original proposed process

1. SAG defines a standard set of parameters representing occurrence rates and/or distributions. (Examples are in "occurrence_table_options.xlsx").

η_1: [rigorous definition]
η_2: [rigorous definition]
…
η_N: [rigorous definition]

2. Crowdsourcing: "focus group" members estimate parameters and their uncertainties
   1. Focus group members are meant to be those who have done occurrence estimates already

FG member 1 :

η_1 = [value] +/- [uncertainty]
η_2 = [value] +/- [uncertainty]
…
η_N =[value] +/- [uncertainty]

. . .

FG member N :

η_1 = [value] +/- [uncertainty]
η_2 = [value] +/- [uncertainty]
…
η_N =[value] +/- [uncertainty]

3. Organize / analyze the data from #2
   1. Check for statistical agreement
   2. Trace and attempt to resolve any outliers and discrepancies
   3. Document reasons for unresolvable discrepancies

4. Final product:
   1. Mean and variance of each parameter estimate across FG members
   2. Explanation for any discrepancies
   3. Recommendation of what values to use for ExEP

η_1: = [mean] +/- [variance]
η_2: = [mean] +/- [variance]
…
η_N: = [mean] +/- [variance]

How do we combine different submissions into one occurrence table?

Accounting for “dependency” between submissions

Full accounting:
Only “independent” submissions are averaged

No accounting:
Simply average all submissions

- Best for producing an actual scientific measurement
- Measuring “dependency” is not trivial (and may be impossible in principle)
- Consensus on method can be challenging
- Psychological biases are challenging to identify and control

- Will not generate a scientific measurement, but possibly best for predictions?
- Simple method
- Easier consensus: all submissions are automatically fairly represented
- Crowdsourcing / Prediction market philosophy: psychological biases are in theory averaged out

The question of which method is “correct” is possibly philosophical
Will probably do both, explicitly describe the process, and leave interpretation to the reader
Feedback on our strategy is welcome and encouraged

Coordination with ExEP Standards Committee

- Schedule
  - Standards team needs to have final consensus by Aug 2017
  - Standards committee product by end of 2016
  - August 2016
    - Define what the product is going to contain
- How do we extrapolate to long periods
- Mass-radius relationship
- Two versions of the green box
  - One that does not need extrapolating
  - One that does
- Pick a milestone date where the Kepler team thinks there would be no more updates

Sensitivity of occurrence rates to methodologies and assumptions

- Completeness curves and catalog seem to make the largest systematic differences
  - More recent completeness curves and catalogs seem to lead to systematically higher numbers

- Other things (estimation method, details of the code, extrapolation) usually result in occurrence rates that are consistent to better than a factor of 2, usually much better