

# A Comparison of Analytical Depth of Search Metrics with Mission Simulations for Exoplanet Imagers

[9904-59]

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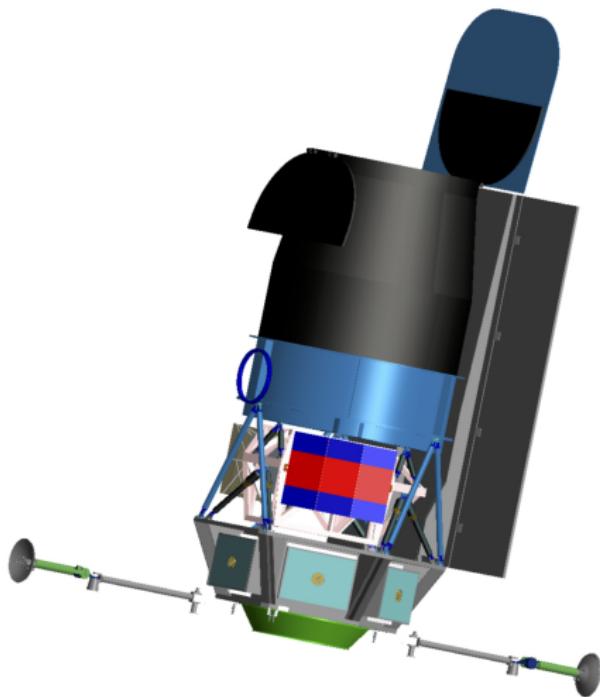


Cornell University



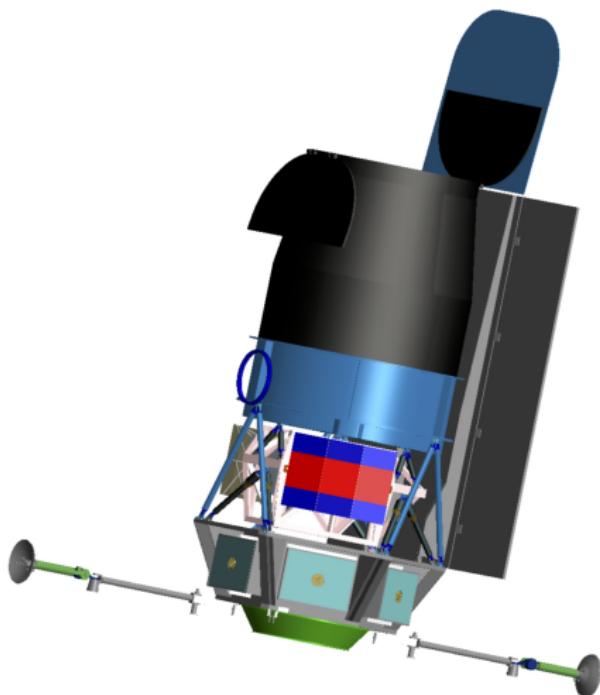
June 30, 2016

# What We Want



$\rightarrow N_{\text{planets}}, N_{\text{spectra}}, N_{\text{orbits}}$ , planet types, mass distribution, radius distribution, period distribution, ...

# What We Can Reasonably Expect



→  $E[N_{\text{planets}}], \text{Var}[N_{\text{planets}}]$



# This Has Been Exhaustively Studied



R. A. Brown.

Obscurational completeness.

*The Astrophysical Journal*, 607:1003–1017, 2004a.



R. A. Brown.

New information from radial velocity data sets.

*The Astrophysical Journal*, 610:1079–1092, 2004b.



R. A. Brown.

Single-visit photometric and obscurational completeness.

*The Astrophysical Journal*, 624:1010–1024, 2005.



S.L. Hunyadi, S.B. Shaklan, and R.A. Brown.

Single visit completeness optimization.  
2005.



D. J. Lindler.

TPF-O design reference mission.

*In Proc. SPIE*, volume 6687, 2007.



R.A. Brown and R. Soummer.

New completeness methods for estimating exoplanet discoveries by direct detection.

*The Astrophysical Journal*, 715:122, 2010.



E. Agol.

Rounding up the wanderers: optimizing coronagraphic searches for extrasolar planets.

*Monthly Notices of the Royal Astronomical Society*, 374 (4):1271–1289, 2007.



D. Savransky and N. Jeremy Kasdin.

Design reference mission construction for planet finders.

*In Proc. SPIE*, volume 7010, 2008.



D. Savransky, N. J. Kasdin, and E. Cady.

Analyzing the designs of planet finding missions.

*Publications of the Astronomical Society of the Pacific*, 122(890):401–419, April 2010.



T. Glassman, L. Newhart, W. Voshell, A. Lo, and G. Barber.

Creating optimal observing schedules for a starshade planet-finding mission.

*In Aerospace Conference, 2011 IEEE*, pages 1–19. IEEE, 2011.



Margaret C Turnbull, Tiffany Glassman, Aki Roberge, Webster Cash, Charley Noecker, Amy Lo, Brian Mason, Phil Oakley, and John Bally.

The Search for Habitable Worlds: 1. The Viability of a Starshade Mission.  
*Publications of the Astronomical Society of the Pacific*, 124(915):418–447, 2012.



Christopher C Stark, Aki Roberge, Avi Mandell, and Tyler D Robinson.

Maximizing the exoearth candidate yield from a future direct imaging mission.

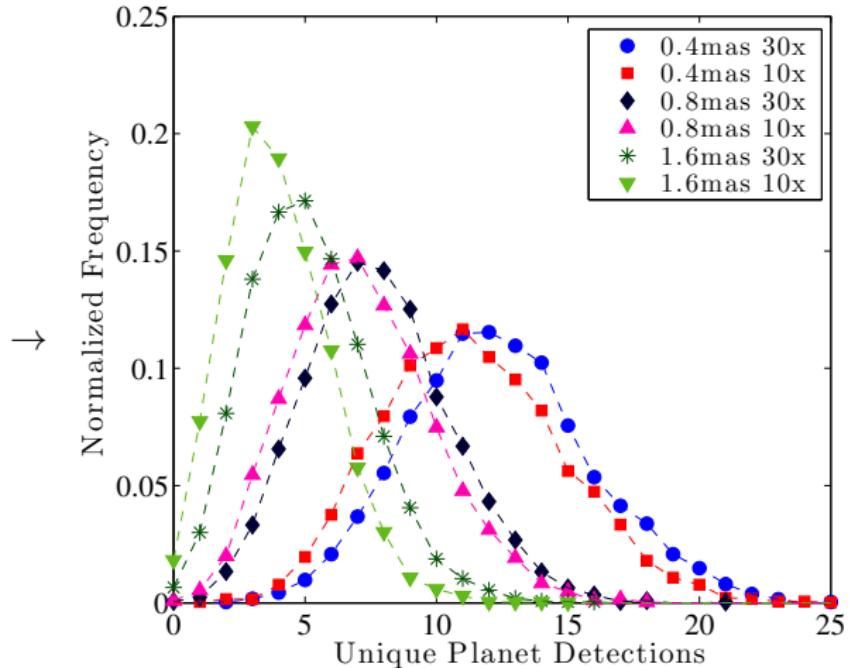
*The Astrophysical Journal*, 795(2):122, 2014.



Christopher C Stark, Aki Roberge, Avi Mandell, Mark Clampin, Shawn D Domagal-Goldman, Michael W McElwain, and Karl R Stapelfeldt.

Lower limits on aperture size for an exoearth detecting coronagraphic mission.  
*The Astrophysical Journal*, 808(2):149, 2015.

# One Solution: Monte Carlo Mission Simulation



As always: garbage in/garbage out

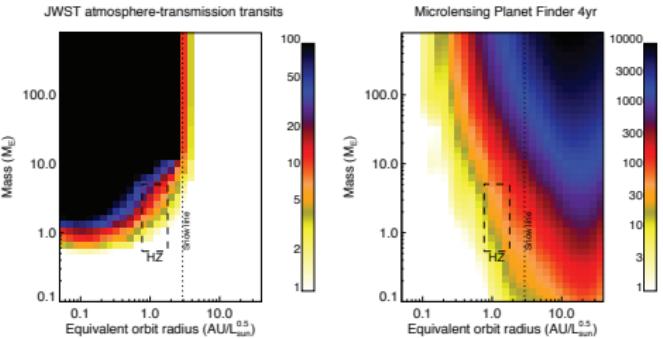
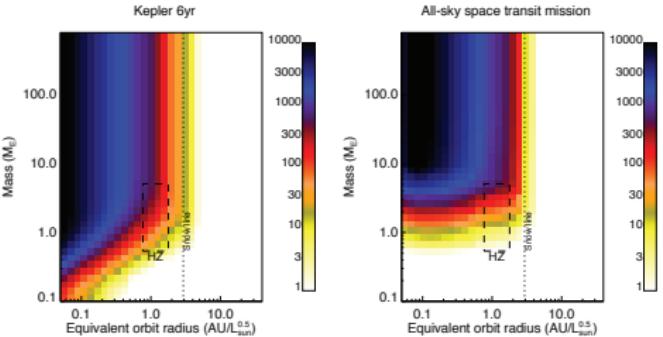
See: Delacroix: 9911-47; [github.com/dsavransky/EXOSIMS](https://github.com/dsavransky/EXOSIMS)

# An Alternate Approach: Depth of Search

## Worlds Beyond: A Strategy for the Detection and Characterization of Exoplanets

Report of the ExoPlanet Task Force

Astronomy and Astrophysics Advisory Committee



# Depth of Search

- ① Choose a grid of your favorite pair of parameters  $(M_P, a/\sqrt{L})$ ,  $(R_P, a)$ ,  $(s, \Delta\text{mag})$ , etc.
  - ② Calculate the portion of planets at each grid point that would be detectable by your instrument
  - ③ The depth of search of the survey is the sum of detection probabilities over the full grid for the full target list
- Provides a measure of ‘Statistical Robustness’ of the survey

These calculations are completely independent of any assumptions about the distributions of planetary properties

$$E[\text{detections}] = \eta \sum_{k=1}^n k \sum_{j \in {}_n C_k} \prod_{i \in j} p_i \prod_{i \notin j} (1 - p_i) = \eta \sum_{i=1}^n p_i$$



# Well, Except for the Target List...

Maximize:

$$J = \sum_{i \in T} c_i \quad c_i \rightarrow \text{Target Metric}$$

subject to:

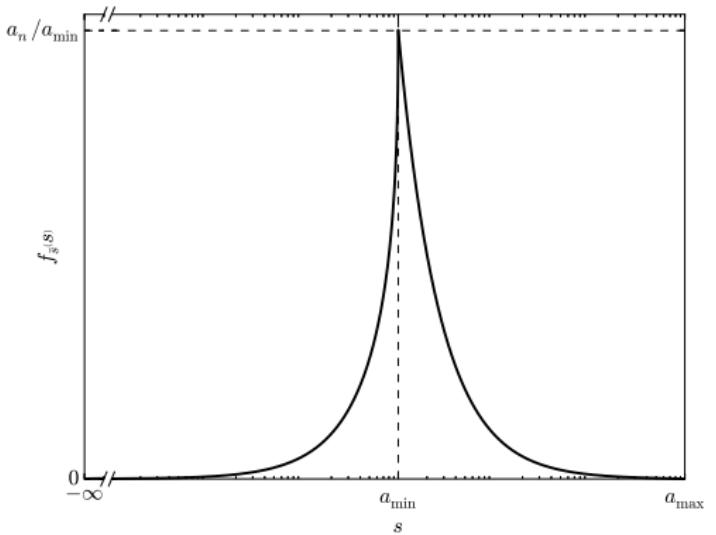
$$\sum_{i \in T} t_i \leq t_{\max} \quad t_i \rightarrow \text{Target Integration Time}$$

If your target metric is anything like completeness, you are building population assumptions into your calculation

# An Alternate Metric

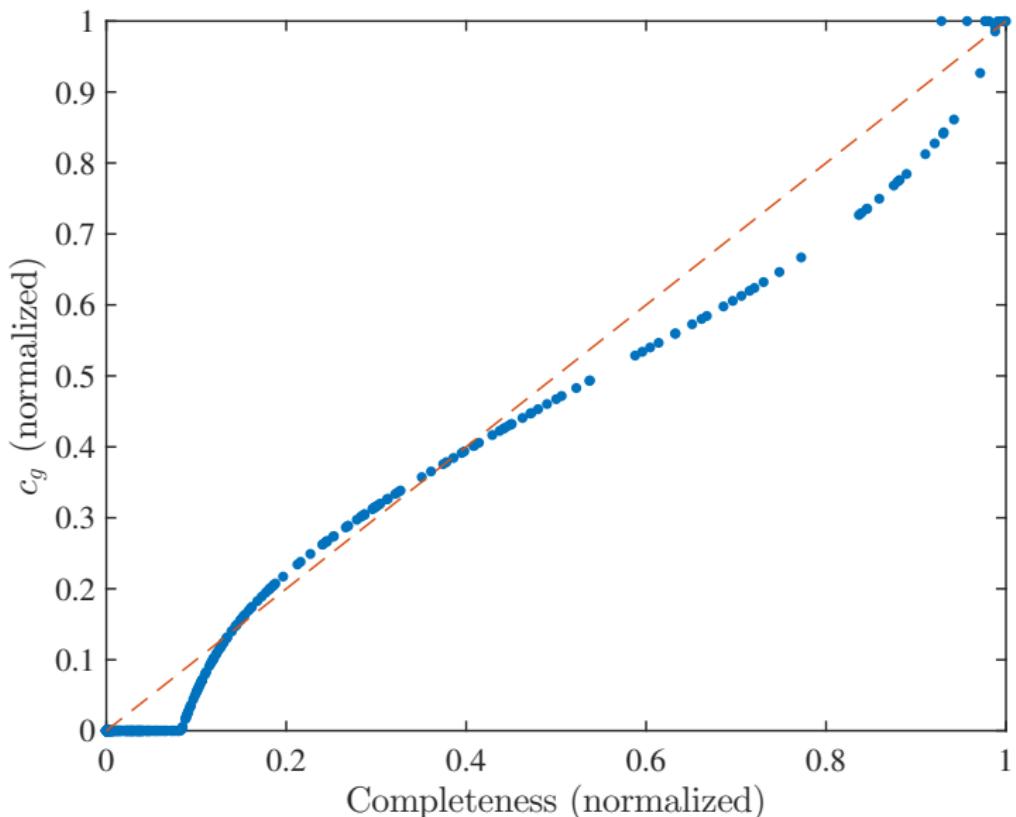


Consider a toy model population with only circular orbits and log-uniform distributed semi-major axes

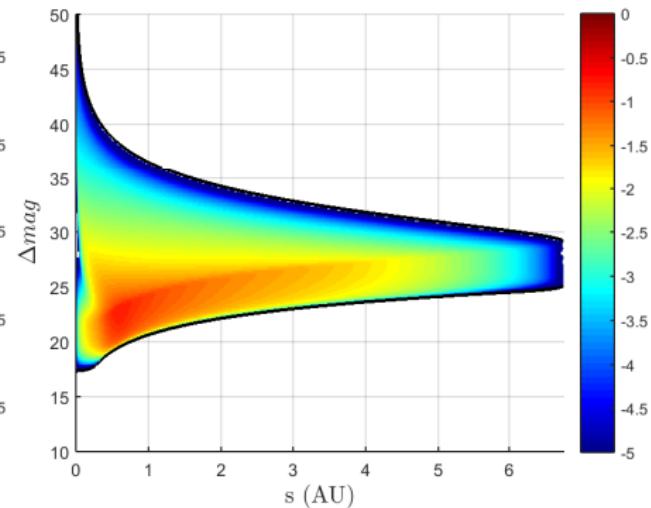
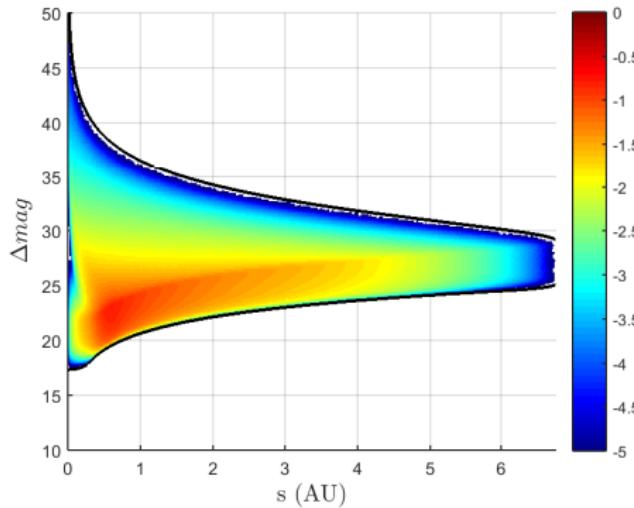


$$\begin{aligned} c_g &= \int_{\text{IWA}d}^{\min(\{\text{OWAd}, a_{\max}\})} \frac{a_n}{s} \sqrt{1 - \left(\frac{s}{a_{\max}}\right)^2} ds \\ &= a_n \left[ \left( \frac{a_{\max}}{s} - \frac{s}{a_{\max}} \right) \left( \sqrt{\left(\frac{a_{\max}}{s}\right)^2 - 1} \right)^{-1} - \cosh^{-1} \left( \frac{a_{\max}}{s} \right) \right] \Big|_{\text{IWA}d}^{\min(\{\text{OWAd}, a_{\max}\})} \end{aligned}$$

# Comparing to Completeness



# A Quick Note on Calculating Planetary Joint Probability Distributions



$$f_{\bar{s}, \overline{\Delta \text{mag}}} (s, \Delta \text{mag}) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} f_{\bar{s}, \overline{\Delta \text{mag}}, \bar{p}, \bar{R}} (s, \Delta \text{mag}, p, r) \, dR \, dp$$

Garrett and Savransky (ApJ submitted)  
see: [github.com/dgarrett622/FuncComp](https://github.com/dgarrett622/FuncComp)



# Solving for the Target List

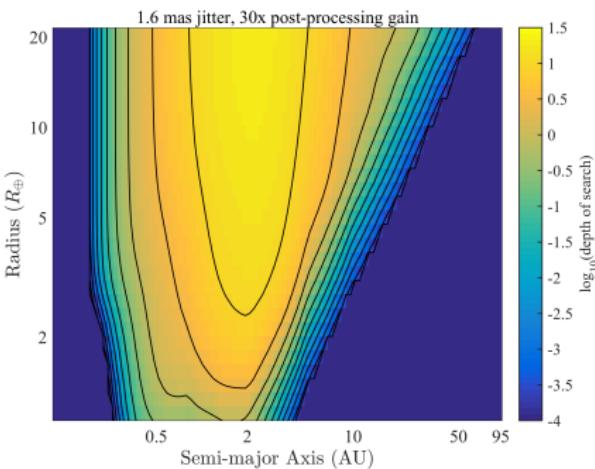
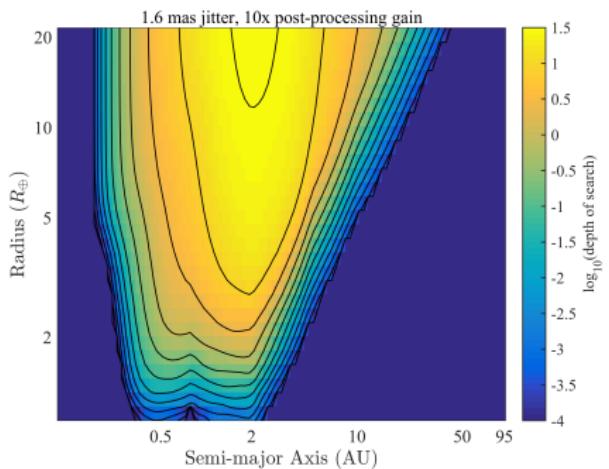
Use a GA, for no particular reason (but it actually works quite well)

$$T = \{i : x_i = 1, \forall x_i \in \mathbf{x}\}$$

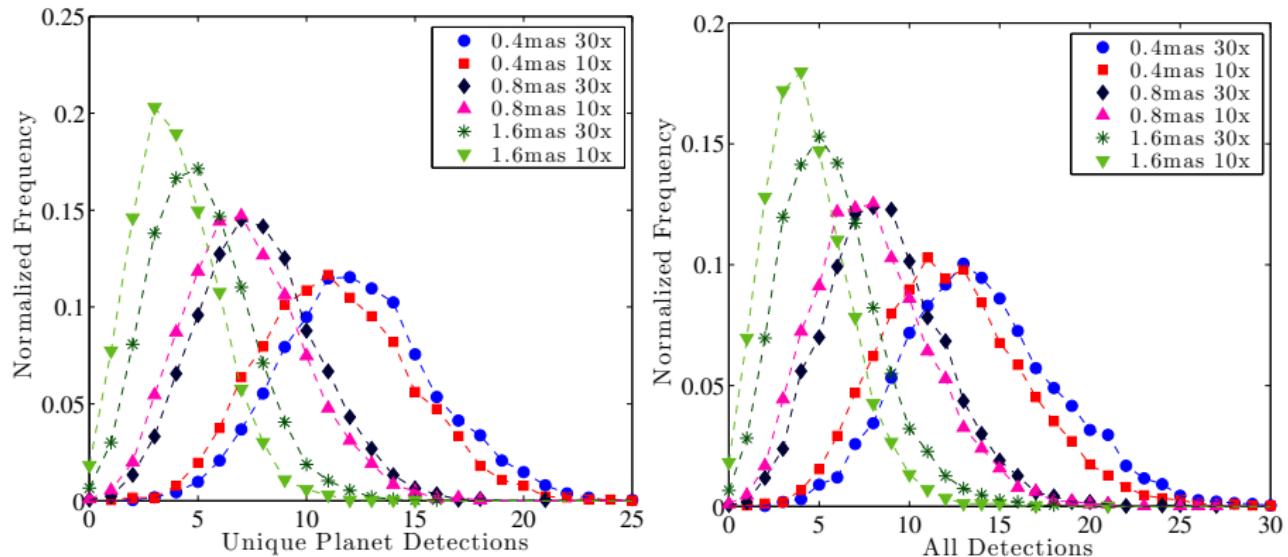
$$f(\mathbf{x}) = a_1 \frac{\sum_{i \in T} c_i}{\sum_i c_i} + \left(1 - \frac{|\sum_{i \in T} t_i - t_{\max}|}{t_{\max}}\right) - a_2 \left(\sum_{i \in T} t_i > t_{\max}\right)$$

$$a_2 > a_1 > 1$$

# WFIRST HLC Depth of Search

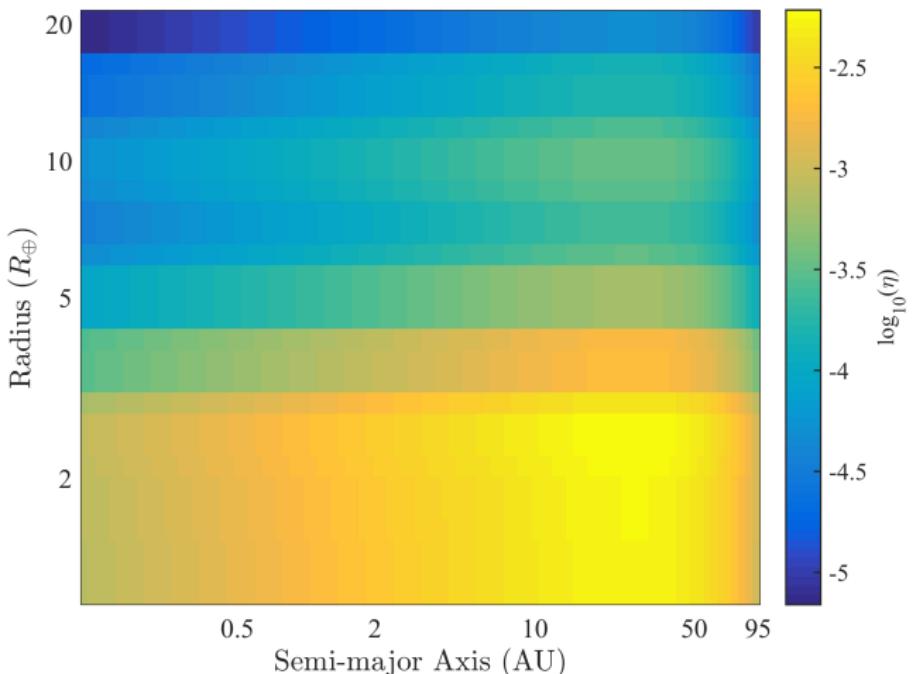


# Comparing with Mission Simulations



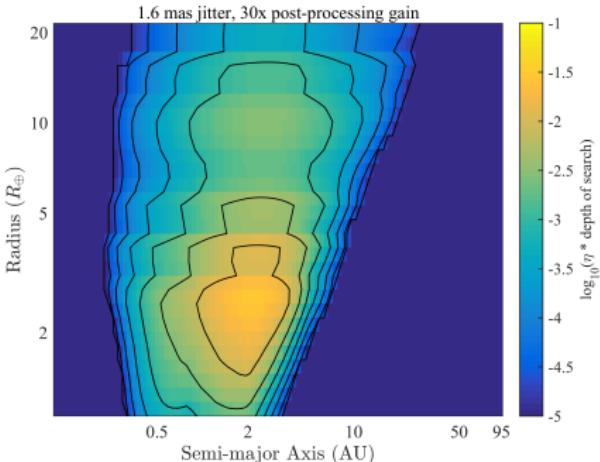
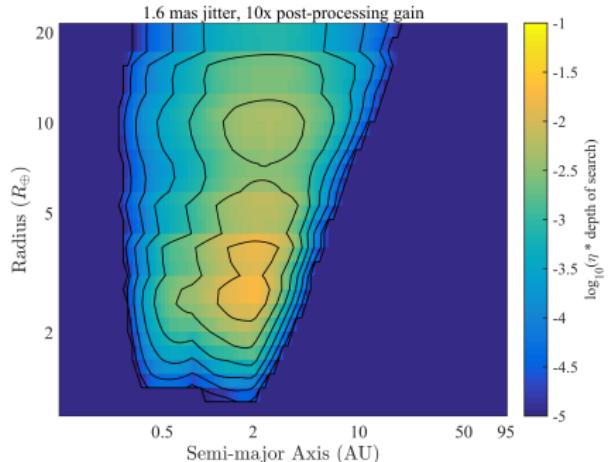
Savransky and Garrett (2015)

# Need an Occurrence Rate Grid



Note: Much better results coming soon from SAG13

# Depth of Search-Derived Detection Rates



Jitter (mas)	Contrast Factor	$\sum_i (\eta_i \text{DOS}_i)$	Unique Detections		All Detections	
			$\mu$	$1\sigma$	$\mu$	$1\sigma$
0.4	30x	12.53	12.4	3.5	14.0	4.4
	10x	11.93	11.4	3.5	12.5	4.2
0.8	30x	9.43	7.8	2.8	8.7	3.3
	10x	8.69	7.2	2.7	8.0	3.3
1.6	30x	4.10	5.1	2.3	5.7	2.7
	10x	2.57	4.0	2.0	4.4	2.4

# Conclusions



- Depth of Search is a powerful metric for fast mission concept evaluation
- Independent of planet population assumptions, and a single depth of search calculation can be used to forecast the number of detections based on multiple different populations
- Reproduces full mission simulation results (in terms of expected number of detections) to within  $1\sigma$  error bars
- But: cannot capture all of the constraints of a real mission, or provide all of the metrics of a full mission simulation