Astro2020 Science White Paper

Optimal Architectures and Survey Designs for Maximizing the Yields of Direct-Imaging Exoplanet Missions

Thematic Areas: ✓ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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Abstract: Our ability to answer fundamental scientific questions about extrasolar planets hinges on satisfying an age-old astronomical requirement: a sufficient sample size. Thus, the expected yield of exoplanets is critical to understanding the scientific impact of future missions. With $\eta_{\oplus}$ measured by the *Kepler* mission and the exozodiacal dust distribution from LBTI, we can now provide absolute estimates, with propagated uncertainties, of the exoplanet yields of future missions. From yield studies we now know that the most efficient way to use coronagraphs and starshades differs, and requires focusing on different science products. By closing the loop between mission design and astronomical productivity, yield studies have allowed the design process to take advantage of astronomical degrees of freedom to relax requirements and distribute risk. This newly appreciated astronomical "flexibility," together with exposure time scaling relationships, mean that the number of potentially Earth-like planets that can be detected and characterized with a future direct-imaging space telescope is a relatively weak function of almost all mission design parameters, except one: telescope diameter. Large samples of exoplanets requires a large aperture.

1 Introduction

Over the last few decades we have witnessed the birth and rapid growth of extrasolar planets as a new field of astronomy. The radial velocity and transit techniques have detected an astonishing diversity of exoplanets and revealed that there are more planets than stars in the universe. The *Kepler* mission showed that potentially Earth-like planets (PEPs) may be common, nothing less than a pivotal moment for understanding our place in the universe[1]. We can now plan the next generation of telescopes to find and characterize these planets, and address profound scientific questions, like how common are water-rich terrestrial-mass planets? What makes a planet habitable? Is life an inevitable outcome of habitability? However, **we can only answer these questions if we satisfy an age-old astronomical requirement: a sufficient sample size.** Thus, the expected number of exoplanets detected and characterized is a critical metric for future missions aiming to study exoplanets. Other works estimate the sample sizes of planets required to answer some of these questions, generally ranging from a dozen to dozens[2, 3, 4]. This white paper discusses how the sample size, or yield, of directly-imaged exoplanets depends on mission scale and survey design.

2 Observational goals

To answer the questions posed above we must go beyond the mere detection of exoplanets: we need to measure as many of the relevant physical properties of the planet as possible and understand the ecosystem in which it resides. Specifically, we must measure the planet's mass and radius to determine its bulk composition and surface gravity, its orbit to constrain insolation and atmospheric photochemistry, and its spectrum to understand atmospheric and surface composition. Finally, we must characterize the system in which that planet resides, including the host star and any other planets present, to build confidence in our interpretation and rule out false positive scenarios.

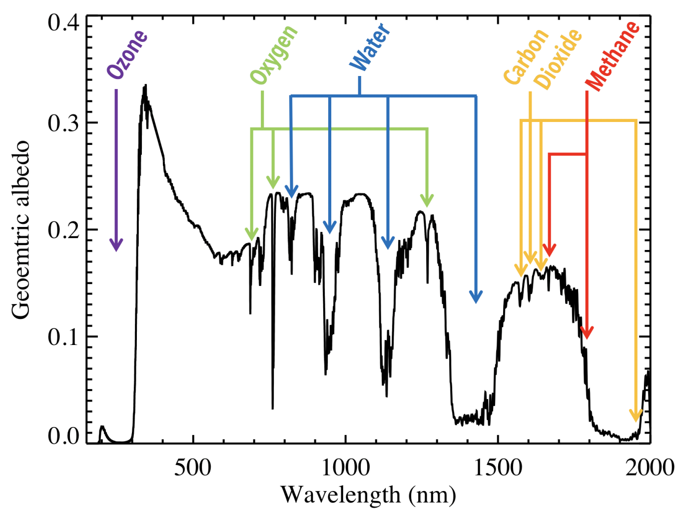

Figure 1: Earth's UVOIR reflected light spectrum reveals key atmospheric molecules.

Though it is naive to think that all potentially habitable or even habitable planets are Earth-twins, or that all life resembles that on Earth, there are many reasons why we believe that Earth-size planets in the habitable zones of Sun-like stars are the best candidates to detect and *recognize* habitability and life as we know it[5, 6, 7]. Figure 1 shows the Earth's reflected light spectrum; coverage from the UV to NIR reveals Rayleigh scattering and absorption features from O_3, O_2, and CH_4 (potential biosignatures), as well as H_2O and CO_2[8]. With this spectrum and measurements of our orbit, mass/radius, and Sun, an external observer could infer the presence of life on our planet[9]. While modern Earth is only a brief slice of Earth history, this same wavelength range would also allow us to understand past eras, like anoxic Archean Earth[10] and Proterozoic Earth[11].

3 Making those observations with coronagraphs and starshades

The detection and characterization of PEPs around Sun-like stars is a major science driver for the field of exoplanets[12]. The only method capable of enabling this for a large number of stars is direct high-contrast imaging in reflected light[12]. To directly image such planets in reflected light, starlight must be suppressed by a factor $\sim 10^{-10}$ while planets, separated by a few tens of milliarcseconds, remain visible (this defines the instrument's inner working angle, or IWA). Currently there are two technologies that could achieve this: coronagraphs and starshades. **These instruments differ in their implementation, as well as in their advantages and limitations, and would produce different data sets**.

Coronagraphs are instruments internal to the telescope that block starlight using shaped and apodized mirrors/masks[13, 14]. Modern high-contrast coronagraphs have a wavefront sensing and control (WFSC) system to maintain the contrast using deformable mirrors (DMs). A coronagraph's IWA scales as λ/D; planets detected at shorter wavelengths may not be visible at longer wavelengths. While some coronagraphs have bandpasses of 10-20% by design and others are achromatic, WFSC for all designs has been limited to $\sim$20% in the lab (future techniques may improve this)[15]. Coronagraphs can have large instantaneous fields of regard and have no direct consumables; they are relatively nimble and yields are typically limited by time. Together, these pros and cons mean that coronagraphs are well-suited for the many observations needed to conduct a blind survey for exoplanets and measure their orbits. However, without improvements to the WFSC bandwidth, they are not ideally suited to obtain wide bandpass spectra on the majority of detected exoplanets.

The optimal imaging strategy for a coronagraph-based mission is to exploit their agility and perform multi-epoch observations of every planetary system, exposing deep enough to detect planets at quadrature or gibbous phases, and measure their orbits[16]. Once planets are found and orbits are determined, cursory spectral characterizations will be performed on some to search for key atmospheric species like H_2O and O_3. Finally, high-priority systems will be spectrally characterized in more detail, requiring multiple observations with different coronagraphic filters to cover a broad bandpass. **Coronagraph-based missions are most well-suited to produce data sets with detections, measured colors, measured orbits, measured phase variations, and cursory spectral "snippets" of most exoplanets observed, but with broad-wavelength spectra for a fraction of those planets**. An extended mission could provide additional time for spectral characterizations.

Starshades are spacecraft separated from the telescope by tens to hundreds of thousands of km that cast a shadow over the telescope. Repointing requires slewing the starshade across the sky, typically taking days to weeks[17]. While the slew time itself is not wasted (the telescope can perform other observations), the propellent consumed typically limits starshades to $\sim$100 pointings for a 5 yr mission[17]. Starshades can have smaller *wavelength-independent* IWAs (but are ultimately limited to $\gtrsim \lambda/D$), broader bandpass ($\sim$100%), and higher throughput than current coronagraphs, but are limited to smaller instantaneous fields of regard, complicating observation timing[18]. Together, these pros and cons mean that starshades are well-suited for taking broad spectra of exoplanets, but without refueling they are not ideally suited for the many observations required for blind surveys or measuring orbits.

The optimal imaging strategy for a starshade-based mission will take advantage of their high throughput and avoid revisiting systems, exposing deep enough on the first visit to obtain cursory spectra on planets in crescent phase[16]. High-priority targets will be followed up for orbit determination and higher SNR spectra. **Starshade-based missions are most well-suited to produce data sets with spectra for most exoplanets detected, but with measured orbits and phase variations for a fraction of those planets.** An extended mission would require refueling the starshade.

Hybrid missions that use both coronagraphs and starshades benefit from the agility of coronagraphs and the throughput and bandpass of starshades. The optimal use of such a system will be an initial blind survey with orbit determination using the coronagraph, followed by spectral characterizations using the starshade[18]. **Hybrid missions will produce data sets with measured orbits, phase variations, and spectra for most exoplanets detected.** Without refueling of the starshade, an extended mission could continue using only the coronagraph.

4 Modeling the observations and estimating yield

The performance of coronagraphs and starshades are often presented as 2D plots of contrast vs. separation, which suggests that if we can observe Earth-like contrasts at Earth-like separations for nearby stars, then we can search for habitability and life. However, this is not true if the throughput is too low, the PSF is too broad, etc. The performance of these instruments is multivariate, complex, and depends on the design of the telescope[19]. **It is not enough to discuss the capabilities of a mission or instrument; we must model the *productivity* of the mission as a complete system. Exoplanet yield calculations close the design loop by mapping the performance of an instrument onto the sky to calculate the number of exoplanets detectable/characterizable within a given resource budget (time or fuel).** Details on how yield calculations are performed and observations are optimized can be found in the literature[2, 20, 21, 22, 23, 24, 25, 26]. We note that while much of the literature focuses on "toy" instrument models, the fidelity of yield calculations has recently improved dramatically, and can now include simulated instrument performance, sensitivity to stellar diameter, jitter, optical surface figure errors, etc.[18, 27, 26]

4.1 Astrophysical uncertainties: $\eta_\oplus$ and the exozodi distribution

Astrophysical uncertainties significantly impact the precision of yield estimates and should be considered when designing a mission—in particular $\eta_\oplus$, the occurrence rate of PEPs. While the *Kepler* mission allowed measurement of $\eta_\oplus$ for M stars[28], for Sun-like stars we must extrapolate from shorter periods and larger planets[1]. Published estimates of $\eta_\oplus$ range from $\sim$1% to $>$100%[29, 30, 31, 32, 33]. The ExoPAG SAG13 study recently standardized a grid for occurrence rates to understand the differences in the many published values[34, 35]; the result was a community consensus average of $\eta_\oplus = 0.24^{+0.46}_{-0.16}$. We adopted this value of $\eta_\oplus$ for the yield results presented here. We note that this estimate is consistent with the most recent values published by the *Kepler* team[1], as well as the most recent independent estimates which include the *Kepler* DR25 catalog and GAIA DR2 distances[36].

Another source of astrophysical uncertainty is the amount of dust, or exozodi, around other stars. Recently the LBTI HOSTS survey constrained the distribution of exozodi around Sun-like stars (most likely median value of $4.5\times$ the solar zodiacal light), and produced a best fit free-form exozodi distribution with estimated uncertainties[37, 38]. Both of these sources of uncertainty are propagated through the yield calculations presented here.

4.2 The exoplanet yield landscape

As a result of the WFIRST CGI SITs, WFIRST Starshade Rendezvous Probe, HabEx, LUVOIR, Segmented Coronagraph Design and Analysis, Exoplanet Standard Definitions Team, and S5 Starshade Technology Advancement studies, we now have a solid understanding of how exoplanet yields depend on mission design choices. Figure 2 shows the yield of PEPs (defined as $0.5 < R < 1.4\ R_\oplus$ and within the conservative HZ[39, 18, 27]) for coronagraph-based missions in green, blue, and red. These curves cross two key technological thresholds: the diameter beyond which monolithic mirrors are difficult to manufacture ($\sim$4 m) and beyond which the primary-secondary mirror distance may be too large for an off-axis space telescope assembled on the ground ($\sim$9 m). Dozens of coronagraph designs were assessed for these calculations; shown are the best performing designs to date for each region. Currently there is a large penalty for on-axis telescopes. Future improvements in coronagraph designs may close this gap, though by how much is unclear. The spread in the colored curves represents different instrument design choices, ranging from a low-throughput scenario (extra fold mirrors and aluminum coatings enabling UV coronagraphy) to a high-throughput scenario (few aluminum coated mirrors). Thin black error bars, shown for only a few point designs, express the 1σ astrophysical uncertainties, including occurrence rate and exozodi uncertainties and Poisson noise due to the exozodi and planetary systems of individual stars.

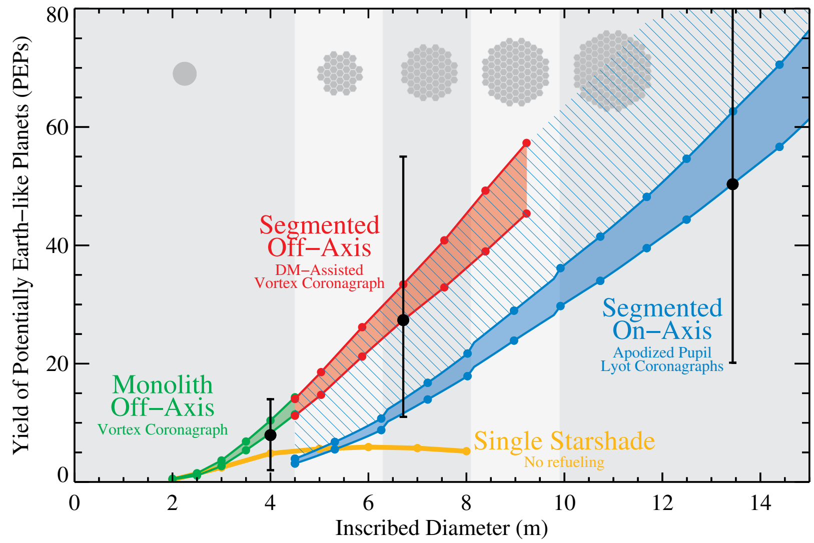

Figure 2: Yield of PEPs for future direct-imaging space telescopes[26]. Spread in colored curves corresponds to high and low throughput scenarios. Three point designs (black dots) are shown with astrophysical uncertainties. There is potentially little yield penalty for segmentation, but currently a substantial penalty for on-axis telescope designs (blue hashed region shows room for improvement). Large yields require a large telescope.

Figure 2 shows estimated yields for starshade-based missions in orange. **Unlike coronagraphs, starshade yields turn over as diameter increases** because 1) starshade size, mass, and separation must also increase (to maintain an IWA$\sim\lambda/D$ at the longest wavelength), leading to more costly slews, and 2) as the mission succeeds in discovering PEPs, it must devote slews to measuring their orbits[24]; i.e., starshade-based missions are at the mercy of the rocket equation. Figure 2 does not show the yields of hybrid missions; they would be only slightly higher than their coronagraphic counterparts, but would produce significantly higher quality and quantity of spectra (unless the bandwidth of coronagraphy can be improved substantially in the future).

Figure 2 only shows the yield of PEPs assuming a PEP-optimized two year survey. **Along the way, many other diverse exoplanets will be discovered, and some also characterized.** Figure 3 shows the diversity of exoplanets expected for the two black points shown in Figure 2. Because the exposure times for warm and cold gas giants can be substantially shorter than that for PEPs, their yields could be increased at little cost, via additional observations optimized for such planets.

Sensitivity analyses have demonstrated that the yields of PEPs for coronagraph-based and hybrid missions are weakly dependent on almost all mission and instrument parameters, except for telescope diameter (Figure 4)[2]. This weak dependence is in part because the target list and observations can be optimized to adapt to the strengths/weaknesses of a given mission[2]. E.g., missions with small IWA and poor contrast would be matched to later type stars, and starshade-based missions are matched to stars that can be searched well in a single observation; **yield optimization has provided new astronomical degrees of freedom to the mission design process.** On the other hand, the strong sensitivity to telescope diameter comes about because the required exposure times typically scale as D^{-4} (in the background limited regime) and the IWA scales as λ/D, such that larger telescopes can observe more targets, more quickly. **Therefore, for a given space telescope design (on- or off-axis), the yield is essentially set by the telescope diameter.**

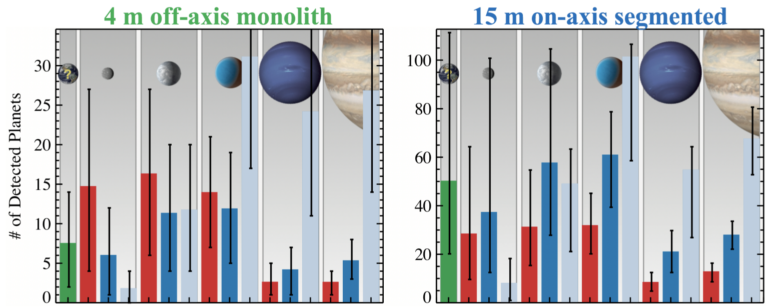

Figure 3: Yields of hot (red), warm (blue), and cold (ice blue) planets for a PEP-optimized (green) 2 yr survey with a coronagraph-based mission. Giant planet yields could be increased via their own optimized survey.

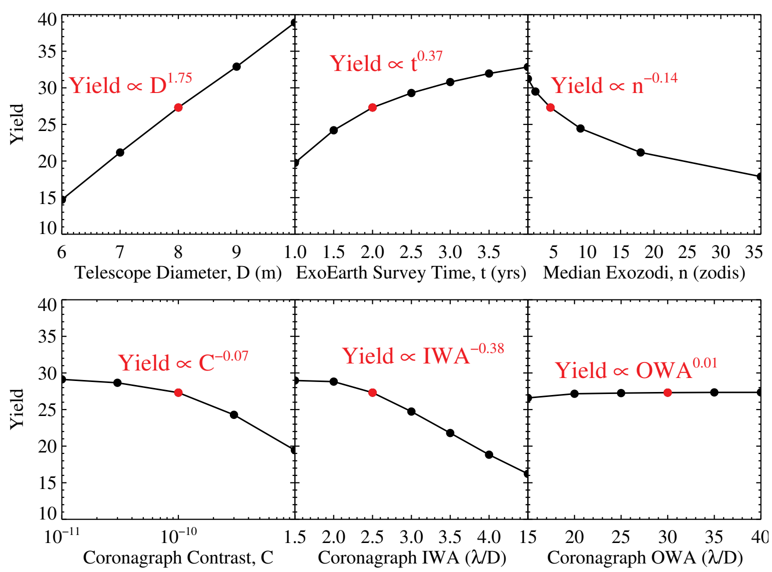

Figure 4: Sensitivity of PEP yield to changes in individual mission parameters for an 8 m off-axis coronagraph-based mission[26]. Yield is a weak function of most parameters, but strongly depends on aperture size[2].

5 Conclusion

Yield calculations are a critical part of mission design, allowing us to quantify the scientific return, guide design choices and trades, and understand efficient mission operation. Observation optimization has made astronomical degrees of freedom available to mission design, distributing risk among individual requirements. These same tools could and should be used to assess yields of future complementary ground-based facilities (ELTs). With measurements of $\eta_\oplus$ and the exozodi distribution, we can now predict absolute numbers, with propagated uncertainties, of exoplanets detected/characterized by future direct-imaging space telescopes. As a result, we now know that a large aperture is a requirement to achieving large samples of potentially Earth-like exoplanets for statistical studies.

References

[1] C. J. Burke, J. L. Christiansen, F. Mullally, S. Seader, D. Huber, J. F. Rowe, J. L. Coughlin, S. E. Thompson, J. Catanzarite, B. D. Clarke, T. D. Morton, D. A. Caldwell, S. T. Bryson, M. R. Haas, N. M. Batalha, J. M. Jenkins, P. Tenenbaum, J. D. Twicken, J. Li, E. Quintana, T. Barclay, C. E. Henze, W. J. Borucki, S. B. Howell, and M. Still, "Terrestrial Planet Occurrence Rates for the Kepler GK Dwarf Sample," *ApJ* **809**, 8 (2015).

[2] C. C. Stark, A. Roberge, A. Mandell, and T. D. Robinson, "Maximizing the ExoEarth Candidate Yield from a Future Direct Imaging Mission," *ApJ* **795**, 122 (2014).

[3] J. H. Checlair et al., "A Statistical Comparative Planetology Approach to Maximize the Scientific Return of Future Exoplanet Characterization Efforts." Astro2020 White Paper (2019).

[4] R. Ramirez et al., "Habitable Zone Predictions and How to Test Them." Astro2020 White Paper (2019).

[5] R. Luger and R. Barnes, "Extreme Water Loss and Abiotic O2Buildup on Planets Throughout the Habitable Zones of M Dwarfs," *Astrobiology* **15**, 119–143 (2015).

[6] K. Garcia-Sage, A. Glocer, J. J. Drake, G. Gronoff, and O. Cohen, "On the Magnetic Protection of the Atmosphere of Proxima Centauri b," *ApJ* **844**, L13 (2017).

[7] G. Arney et al., "The Sun-like Stars Opportunity." Astro2020 White Paper (2019).

[8] A. Roberge, M. J. Rizzo, A. P. Lincowski, G. N. Arney, C. C. Stark, T. D. Robinson, G. F. Snyder, L. Pueyo, N. T. Zimmerman, T. Jansen, E. R. Nesvold, V. S. Meadows, and M. C. Turnbull, "Finding the Needles in the Haystacks: High-fidelity Models of the Modern and Archean Solar System for Simulating Exoplanet Observations," *PASP* **129**, 124401 (2017).

[9] E. W. Schwieterman, N. Y. Kiang, M. N. Parenteau, C. E. Harman, S. DasSarma, T. M. Fisher, G. N. Arney, H. E. Hartnett, C. T. Reinhard, S. L. Olson, V. S. Meadows, C. S. Cockell, S. I. Walker, J. L. Grenfell, S. Hegde, S. Rugheimer, R. Hu, and T. W. Lyons, "Exoplanet Biosignatures: A Review of Remotely Detectable Signs of Life," *Astrobiology* **18**, 663–708 (2018).

[10] J. Krissansen-Totton, S. Olson, and D. C. Catling, "Disequilibrium biosignatures over Earth history and implications for detecting exoplanet life," *Science Advances* **4**, eaao5747 (2018).

[11] C. T. Reinhard, S. L. Olson, E. W. Schwieterman, and T. W. Lyons, "False Negatives for Remote Life Detection on Ocean-Bearing Planets: Lessons from the Early Earth," *Astrobiology* **17**, 287–297 (2017).

[12] E. National Academies of Sciences and Medicine, *Exoplanet Science Strategy*, The National Academies Press, Washington, DC (2018).

[13] G. Ruane, A. Riggs, J. Mazoyer, E. H. Por, M. N'Diaye, E. Huby, P. Baudoz, R. Galicher, E. Douglas, J. Knight, B. Carlomagno, K. Fogarty, L. Pueyo, N. Zimmerman, O. Absil,

M. Beaulieu, E. Cady, A. Carlotti, D. Doelman, O. Guyon, S. Haffert, J. Jewell, N. Jovanovic, C. Keller, M. A. Kenworthy, J. Kuhn, K. Miller, D. Sirbu, F. Snik, J. K. Wallace, M. Wilby, and M. Ygouf, "Review of high-contrast imaging systems for current and future ground- and space-based telescopes I: coronagraph design methods and optical performance metrics," in *Space Telescopes and Instrumentation 2018: Optical, Infrared, and Millimeter Wave*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10698**, 106982S (2018).

[14] L. Pueyo, "Direct Imaging as a Detection Technique for Exoplanets," *Handbook of Exoplanets* , 10 (2018).

[15] J. Trauger, D. Moody, B. Gordon, J. Krist, and D. Mawet, "Complex apodization Lyot coronagraphy for the direct imaging of exoplanet systems: design, fabrication, and laboratory demonstration," in *Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave*, *Proc. of SPIE* **8442**, 84424Q (2012).

[16] C. C. Stark, E. J. Cady, M. Clampin, S. Domagal-Goldman, D. Lisman, A. M. Mandell, M. W. McElwain, A. Roberge, T. D. Robinson, D. Savransky, S. B. Shaklan, and K. R. Stapelfeldt, "A direct comparison of exoEarth yields for starshades and coronagraphs," **9904**, 99041U (2016).

[17] S. Seager and the Exo-S Team, "Exo-S Final Report." Online document, https://exoplanets.nasa.gov/exep/about/exos/ (2015).

[18] B. S. Gaudi, S. Seager, and the HabEx Team, "The Habitable Exoplanet Observatory (HabEx) Mission Concept Study Interim Report," *ArXiv e-prints* (2018).

[19] K. St. Laurent, K. Fogarty, N. T. Zimmerman, M. N'Diaye, C. C. Stark, J. Mazoyer, A. Sivaramakrishnan, L. Pueyo, S. Shaklan, R. Vanderbei, and R. Soummer, "Apodized pupil lyot coronagraphs designs for future segmented space telescopes," *Proc. of SPIE* **10698**, 10698 – 10698 – 17 (2018).

[20] R. A. Brown, "Single-Visit Photometric and Obscurational Completeness," *ApJ* **624**, 1010–1024 (2005).

[21] D. Savransky, N. J. Kasdin, and E. Cady, "Analyzing the Designs of Planet-Finding Missions," *PASP* **122**, 401–419 (2010).

[22] C. C. Stark, A. Roberge, A. Mandell, M. Clampin, S. D. Domagal-Goldman, M. W. McElwain, and K. R. Stapelfeldt, "Lower Limits on Aperture Size for an ExoEarth Detecting Coronagraphic Mission," *ApJ* **808**, 149 (2015).

[23] D. Savransky and D. Garrett, "WFIRST-AFTA coronagraph science yield modeling with EXOSIMS," *Journal of Astronomical Telescopes, Instruments, and Systems* **2**, 011006 (2016).

[24] C. C. Stark, S. Shaklan, D. Lisman, E. Cady, D. Savransky, A. Roberge, and A. M. Mandell, "Maximized exoEarth candidate yields for starshades," *Journal of Astronomical Telescopes, Instruments, and Systems* **2**, 041204 (2016).

[25] R. Morgan, M. Turmon, C. Delacroix, D. Savransky, D. Garrett, P. Lowrance, X. C. Liu, and P. Nunez, "ExEP yield modeling tool and validation test results," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10400**, 104001K (2017).

[26] C. C. Stark et al., "The ExoEarth Yield Landscape for Future Direct Imaging Space Telescopes." Submitted (2019).

[27] The LUVOIR Team, "The LUVOIR Mission Concept Study Interim Report," *ArXiv e-prints* (2018).

[28] C. D. Dressing and D. Charbonneau, "The Occurrence of Potentially Habitable Planets Orbiting M Dwarfs Estimated from the Full Kepler Dataset and an Empirical Measurement of the Detection Sensitivity," *ApJ* **807**, 45 (2015).

[29] J. Catanzarite and M. Shao, "The Occurrence Rate of Earth Analog Planets Orbiting Sun-like Stars," *ApJ* **738**, 151 (2011).

[30] A. N. Youdin, "The Exoplanet Census: A General Method Applied to Kepler," *ApJ* **742**, 38 (2011).

[31] E. A. Petigura, A. W. Howard, and G. W. Marcy, "Prevalence of Earth-size planets orbiting Sun-like stars," *Proceedings of the National Academy of Science* **110**, 19273–19278 (2013).

[32] D. Foreman-Mackey, D. W. Hogg, and T. D. Morton, "Exoplanet Population Inference and the Abundance of Earth Analogs from Noisy, Incomplete Catalogs," *ApJ* **795**, 64 (2014).

[33] W. A. Traub, "Kepler exoplanets: a new method of population analysis," *arXiv e-prints* (2016).

[34] R. Belikov, C. C. Stark, N. Batalha, C. Burke, and SAG13 Members, "ExoPAG SAG13: Exoplanet Occurrence Rates and Distributions, Closeout Report," (2017).

[35] R. K. Kopparapu, E. Hébrard, R. Belikov, N. M. Batalha, G. D. Mulders, C. Stark, D. Teal, S. Domagal-Goldman, and A. Mandell, "Exoplanet Classification and Yield Estimates for Direct Imaging Missions," *ApJ* **856**, 122 (2018).

[36] D. C. Hsu, E. B. Ford, D. Ragozzine, and K. Ashby, "Occurrence Rates of Planets orbiting FGK Stars: Combining Kepler DR25, Gaia DR2 and Bayesian Inference," *arXiv e-prints* (2019).

[37] S. Ertel, D. Defrère, P. Hinz, B. Mennesson, G. M. Kennedy, W. C. Danchi, C. Gelino, J. M. Hill, W. F. Hoffmann, G. Rieke, A. Shannon, E. Spalding, J. M. Stone, A. Vaz, A. J. Weinberger, P. Willems, O. Absil, P. Arbo, V. P. Bailey, C. Beichman, G. Bryden, E. C. Downey, O. Durney, S. Esposito, A. Gaspar, P. Grenz, C. A. Haniff, J. M. Leisenring, L. Marion, T. J. McMahon, R. Millan-Gabet, M. Montoya, K. M. Morzinski, E. Pinna, J. Power, A. Puglisi, A. Roberge, E. Serabyn, A. J. Skemer, K. Stapelfeldt, K. Y. L. Su, V. Vaitheeswaran, and M. C. Wyatt, "The HOSTS Survey–Exozodiacal Dust Measurements for 30 Stars," *AJ* **155**, 194 (2018).

[38] S. Ertel et al., "The HOSTS survey for exozodiacal dust: Observational results from the complete survey." In prep (2019).

[39] R. K. Kopparapu, R. Ramirez, J. F. Kasting, V. Eymet, T. D. Robinson, S. Mahadevan, R. C. Terrien, S. Domagal-Goldman, V. Meadows, and R. Deshpande, "Habitable Zones around Main-sequence Stars: New Estimates," *ApJ* **765**, 131 (2013).