Towards starshade yields for a 6m HWO telescope

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[3]Lunar and Planetary Lab, University of Arizona

8 August 2023
CL#23-4384

What is science performance (yield) modeling?

- **How much science can we get out of our instrument and mission?**

Metric | Capability | Constraints

- **We'll want to iterate, so be parametric to be computationally fast**

Measurement model

What you want to observe (and not observe): definition of an 'Earth-like' exoplanet, star list
occurrence rate
noise and confusion sources

Instrument model

Optics
Photometry
Starlight suppression
~mission dynamics

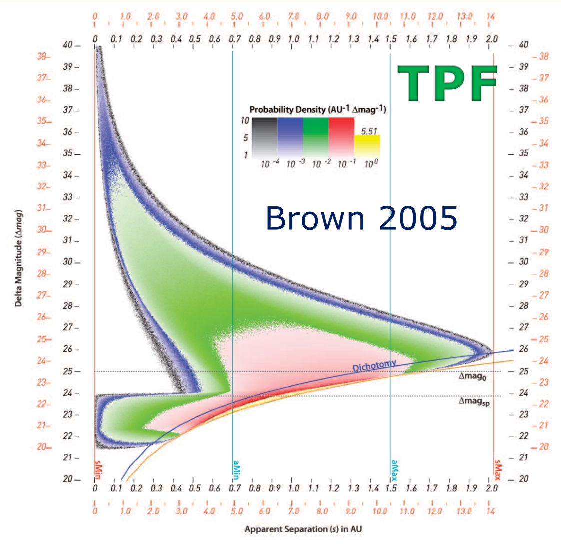
Mission model

- Allocating resources: exposure time, mission time, fuel.
- Allocation strategies would be different for target-limited or time-limited scenarios.
- For time-limited, efficiency concerns lead to desire for optimization schemes.
- Optimization and scheduling is its own field

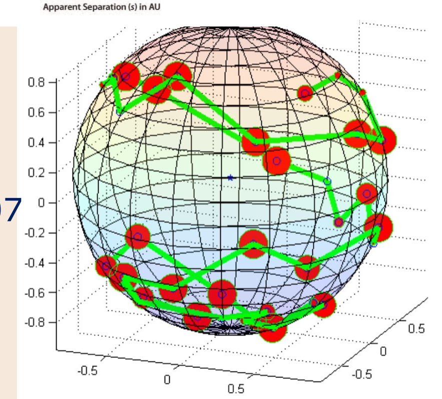
Historical Approaches

NASA EXOPLANET EXPLORATION PROGRAM

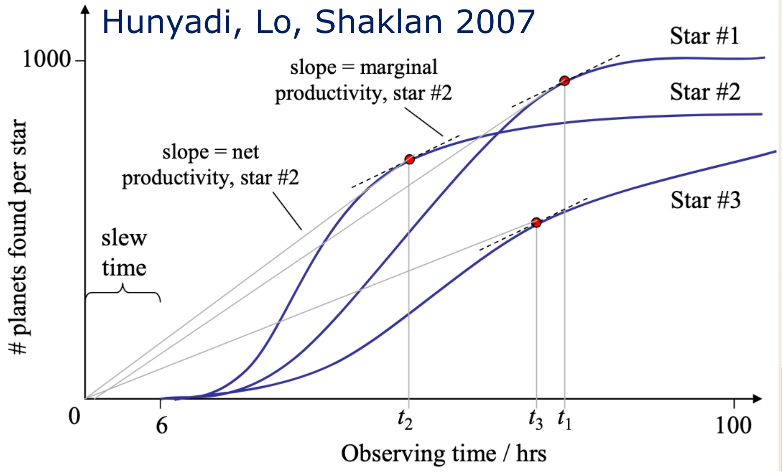
TPF



Brown 2005

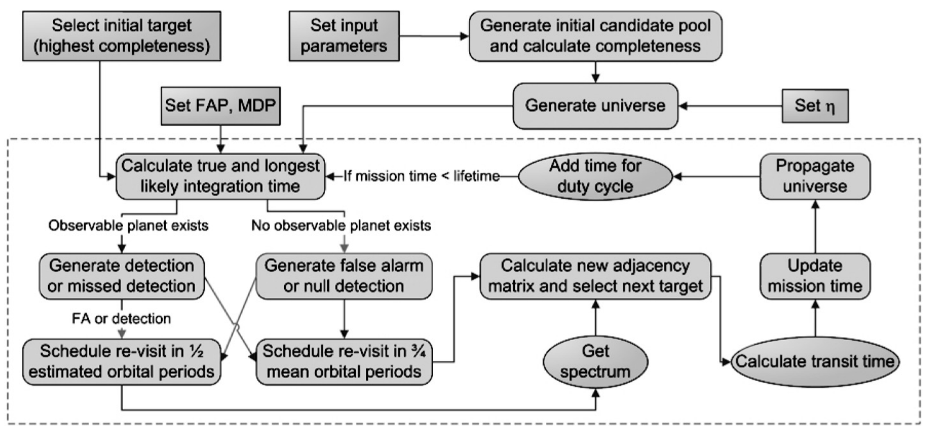


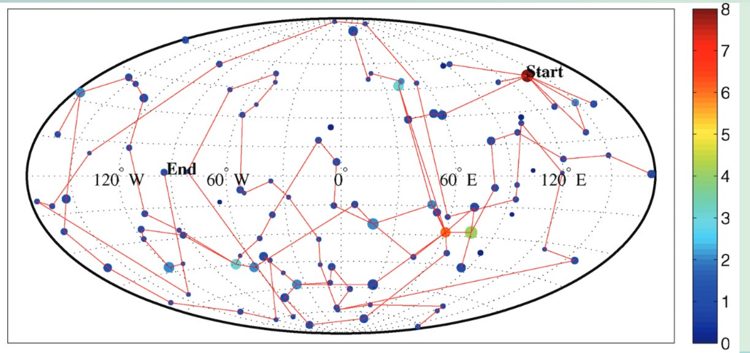
Hunyadi, Shaklan, Brown 2007



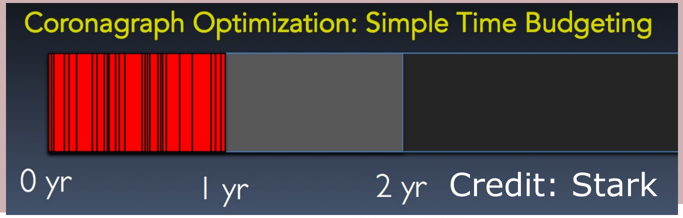
Hunyadi, Lo, Shaklan 2007

THEIA

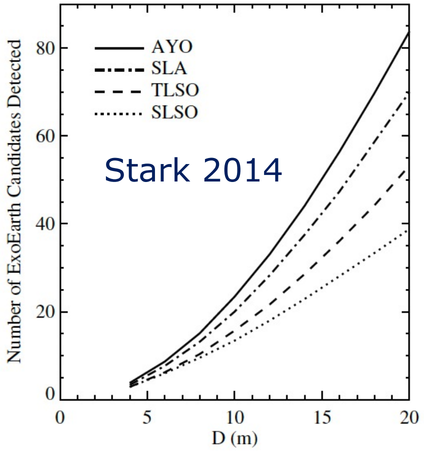




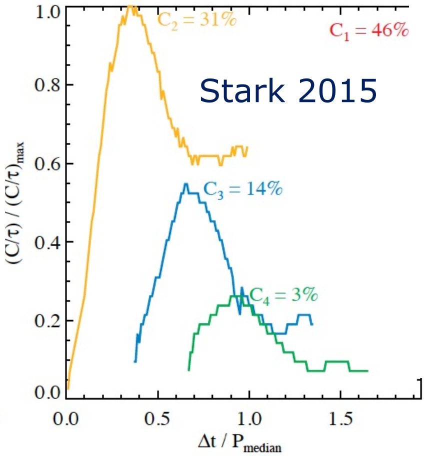
Savransky, Kasdin, Cady 2010



Credit: Stark



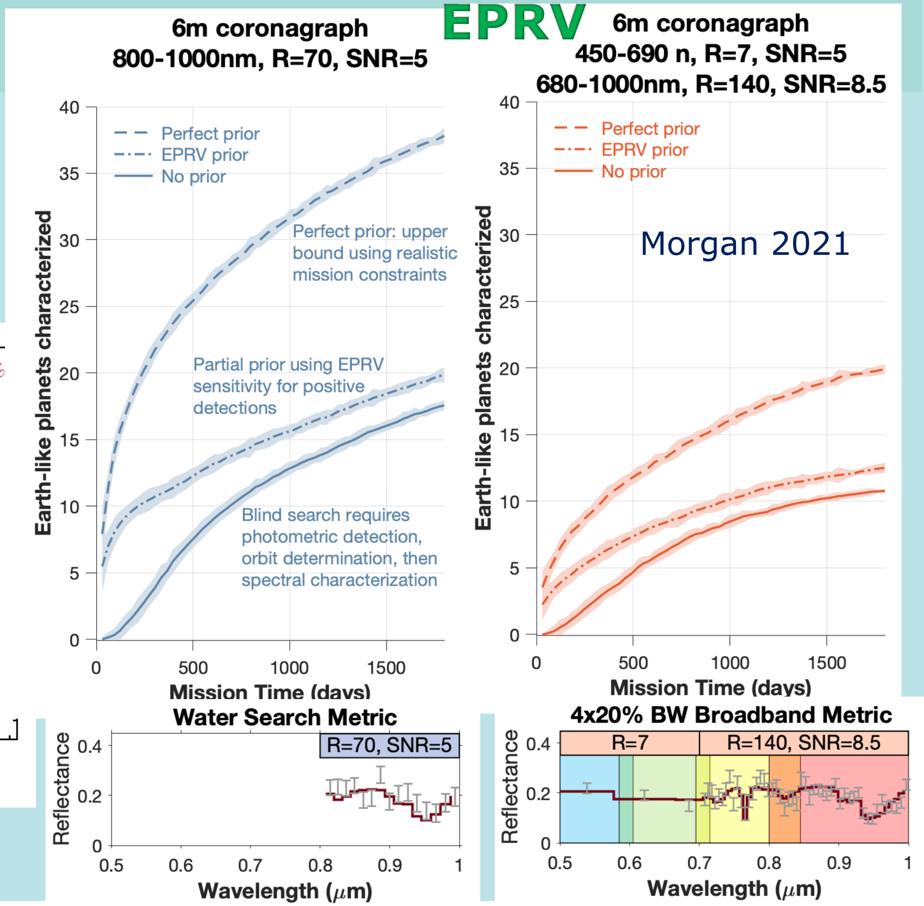
Stark 2014



Stark 2015

ATLAST, LUVOIR, HabEx

EPRV



Morgan 2021

https://exoplanets.nasa.gov/exep/events/456/exoplanet-yield-modeling-tools-workshop/

MEETINGS & EVENTS

Exoplanet Yield Modeling Tools Workshop

Date:
June 8, 2023

Location:
Splinter Session of AAS in Albuquerque, NM
›› view map

Agenda:
AAS242_splinter_agenda_yield_tools.pdf (127 KB)

REGISTER

June 8, 2023; 9am – 11am, 12:30 – 3:00pm

Chairs: Rhonda Morgan (NASA ExEP) and Dmitry Savransky (Cornell University)

About this Workshop

Downloads

- Agenda
- ExoVista Tutorial Materials
- EXOSIMS Tutorial Materials

Fundamental Concepts Videos

Pre-Session: Pre-recorded short talks on the fundamental concepts of yield modeling

Other Resources

Starlight suppression technologies from LUVOIR and HabEx reports
- Rhonda Morgan

Exoplanet science yield model

Astrophysical Inputs
- Star list
- exozodi
- Occurrence rate
- Planet radii
- albedo

Instrument Parms
- Aperture
- Throughput, QE
- Contrast, IWA, OWA
- Spectral Resolution
- Bandwidth, SNR

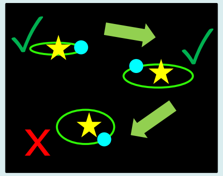
Mission Constraints
- Lifetime
- Observing allocation
- Observatory orbit
- Solar keepout
- Observing scenario

Measurement model

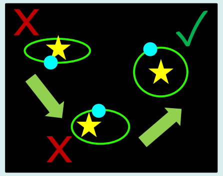
Instrument performance model

Mission model

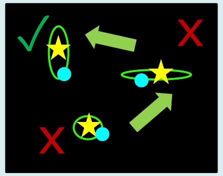
Universe n



Universe n+1



Universe n+2



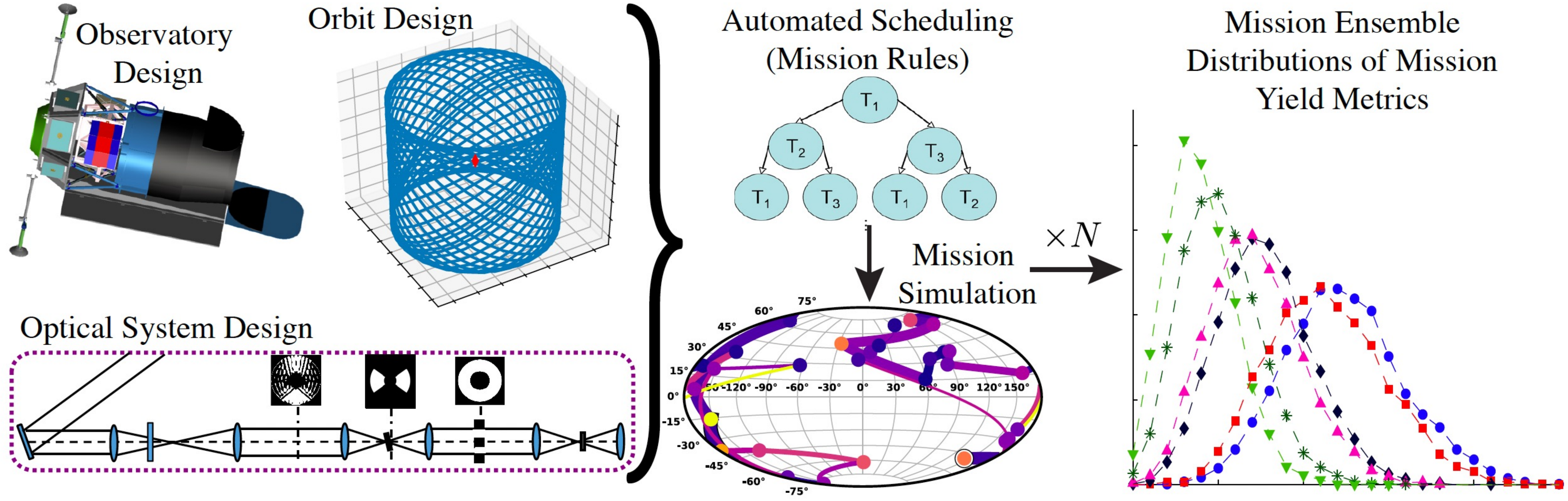
⟨n⟩ planets characterized

EXOSIMS: Open source. Python. Parametric. Probabilistic. Modular.

– Creates Monte Carlo ensembles of missions.

https://github/dsavransky/EXOSIMS

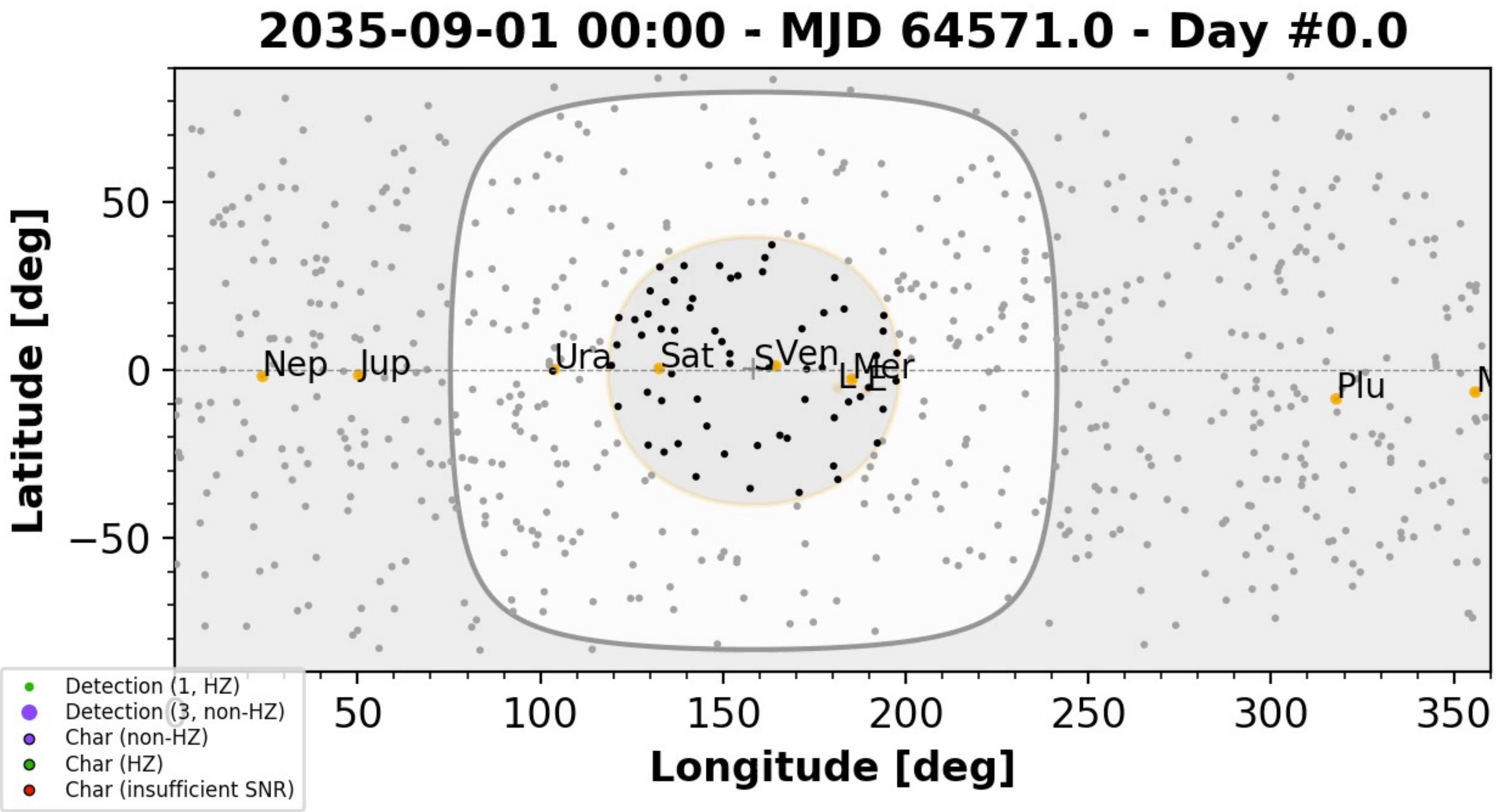
Predicting Exoplanet Yield: Monte Carlo Mission Modeling



- Pro: Can extract effectively *any* metric of performance with errorbars
- Con: Computationally costly
- Pro and Con: Requires a mission schedule

See: Savransky, Kasdin, and Cady, "Analyzing the designs of planet finding missions", 2010; Savransky and Garrett, "WFIRST-AFTA coronagraph science yield modeling with EXOSIMS", 2015

Coronagraph + Starshade example DRM



Standard Definitions and Evaluation Team

https://exoplanets.nasa.gov/exep/studies/sdet

NASA EXOPLANET EXPLORATION PROGRAM

Chartered to provide a consistent, transparent yield analysis using common input parameters

EXOPLANET PROGRAM — About | Studies | News | Meetings/Events | Resources | Technology | NExScI | ExoPAG | For the Public

Decadal STDTs | SDET | SSWG | Probe Scale STDT

Standard Definition and Evaluation Team

Overview

Two of the four large mission concept studies for the Astrophysics Decadal Survey were designed to directly image and spectrally characterize earth-like exoplanets. In 2016, the Astrophysics Division chartered an Exoplanet Standard Definition and Evaluation Team (ExSDET) for the purpose of providing an unbiased science yield analysis of the multiple large mission concepts using a transparent and documented set of common inputs, assumptions and methodologies.

Over the course of the past three years, the ExSDET has responded to the direction provided in the charter and the required deliverables by performing the following tasks:

- Develop analysis tools that will allow quantification of the science metrics of the mission studies
- Incorporate physics-based instrument models to evaluate both internal and external occulter designs
- Establish the science metrics that define the yield criteria
- Cross validate the various analytical methodologies and tools
- Provide complete evaluations using common assumptions and inputs of the exoplanet yields for each mission concept.

The primary goal of the SDET Final Report is to present the best understanding of the exoplanet imaging and characterization capabilities of the current STDT observatory and instrument designs, along with their nominal operating plans, using common input assumptions and analysis methodologies. This report is explicitly *not* intended to present an exploration of the capabilities of the full design spaces available to the various mission concepts. Due to large uncertainties in the astrophysics inputs, particularly exo-earth occurrence rate, the yield values should be considered relative rather than absolute.

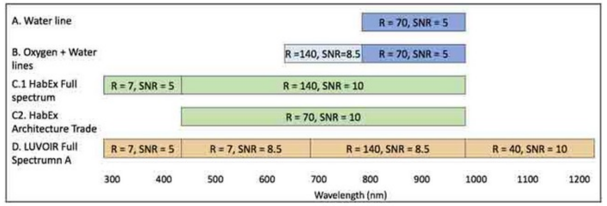


Figure 1. Characterization metric A facilitates a quick search for the water line at 940 nm with a

Documents

- SDET Charter
- SDET Final Report

Cases

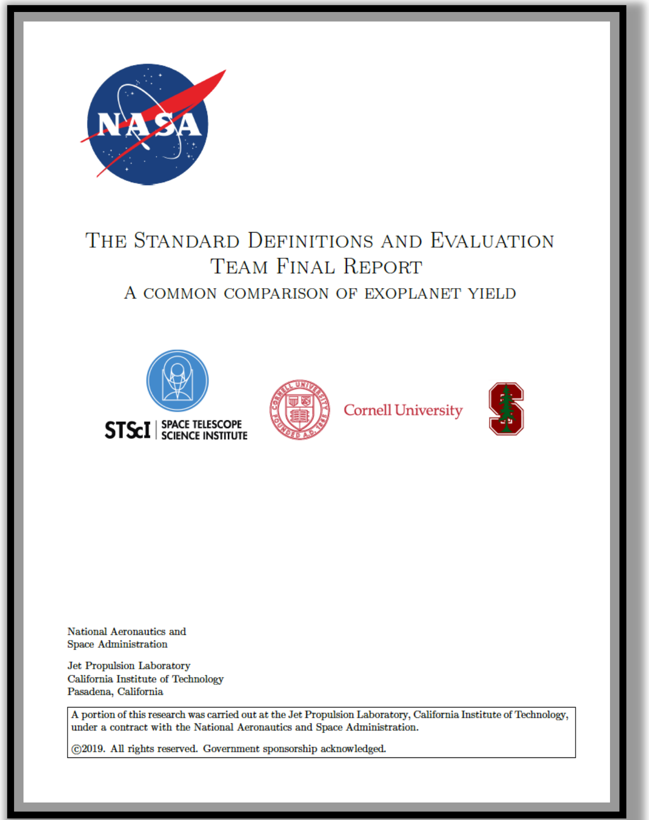
- Case 1: HabEx 4H hybrid, metric C1
- Case 2: LUVOIR B, metric A
- Case 3: HabEx 4C, metric C2
- Case 4: HabEx 4S, metric C2

Links

- EXOSIMS on Github
- AYO for LUVOIR
- Habitable Exoplanet Observatory (HabEx)
- Large UV-Optical-Infrared Surveyor LUVOIR

Papers

- EXOSIMS Overview in JATIS
- EXOSIMS Overview
- EXOSIMS Validation
- AYO 2014
- AYO 2015
- AYO 2016 Starshades



THE STANDARD DEFINITIONS AND EVALUATION TEAM FINAL REPORT

A COMMON COMPARISON OF EXOPLANET YIELD

STScI | SPACE TELESCOPE SCIENCE INSTITUTE — Cornell University

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

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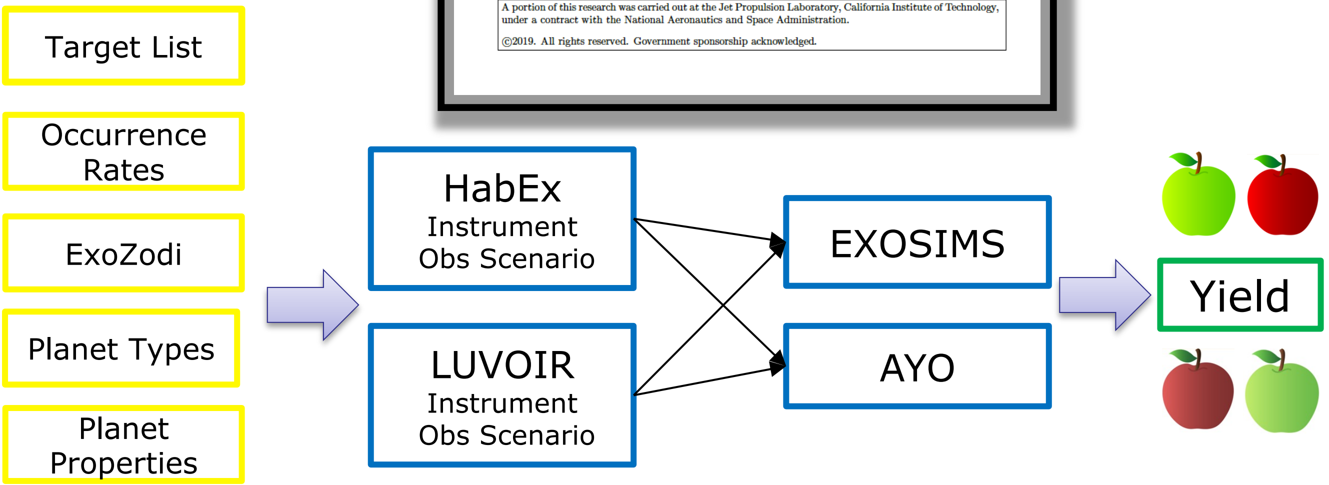
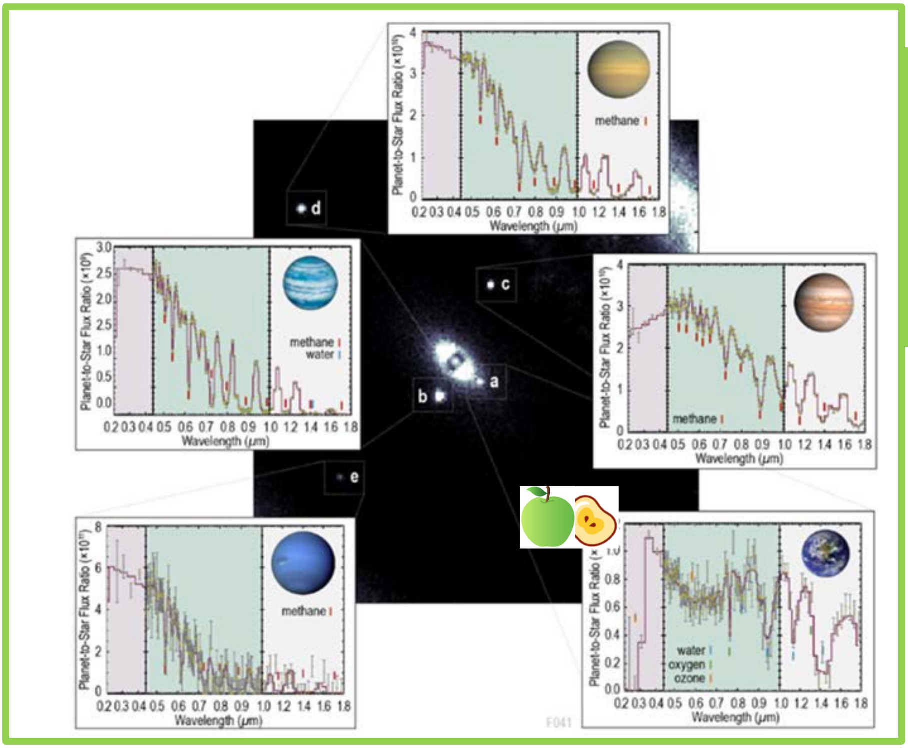
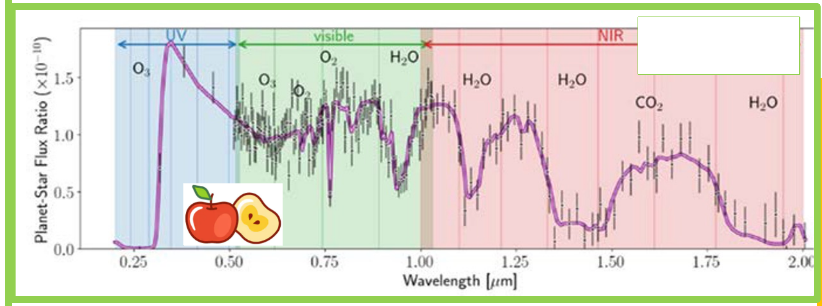
Thorough discussion of astrophysical inputs

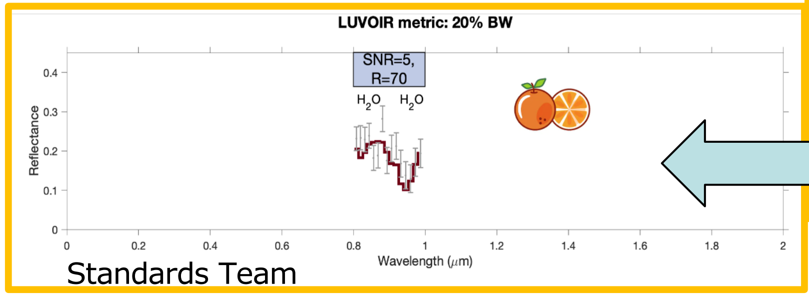


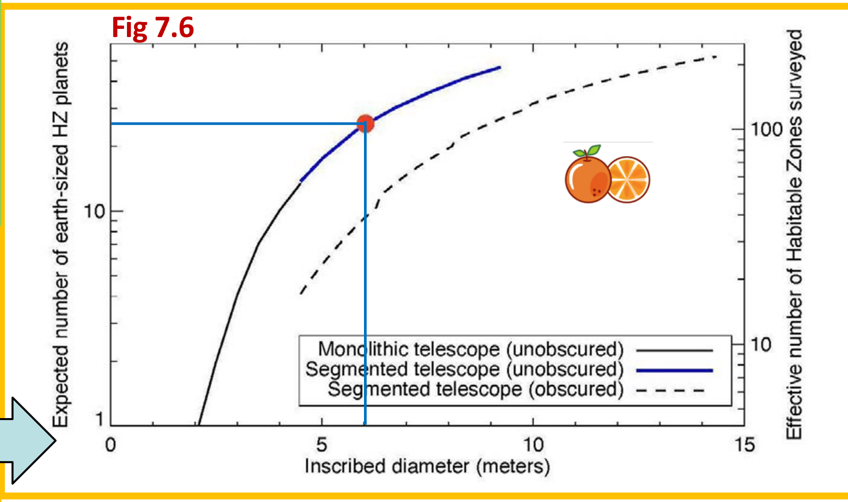
Astro2020 recommendation for exoplanets

- Astro2020 recommended a “future large IR/O/UV telescope optimized for observing habitable exoplanets and general astrophysics” to be **ready by end of the decade**
- Astro2020 recommended “to search for **biosignatures** from a **robust number** of about ~25 habitable zone [exo]planets”









- Building on the work done by large concept studies and the Standards Evaluation Team, we can iterate, address nuances, and incorporate progress to map exoplanet science goals to planet characterization to metrics

This will not be easy!

- Characterization is complicated, and will likely involve multiple measurements. … This means we’ll have more than one metric

Metrics

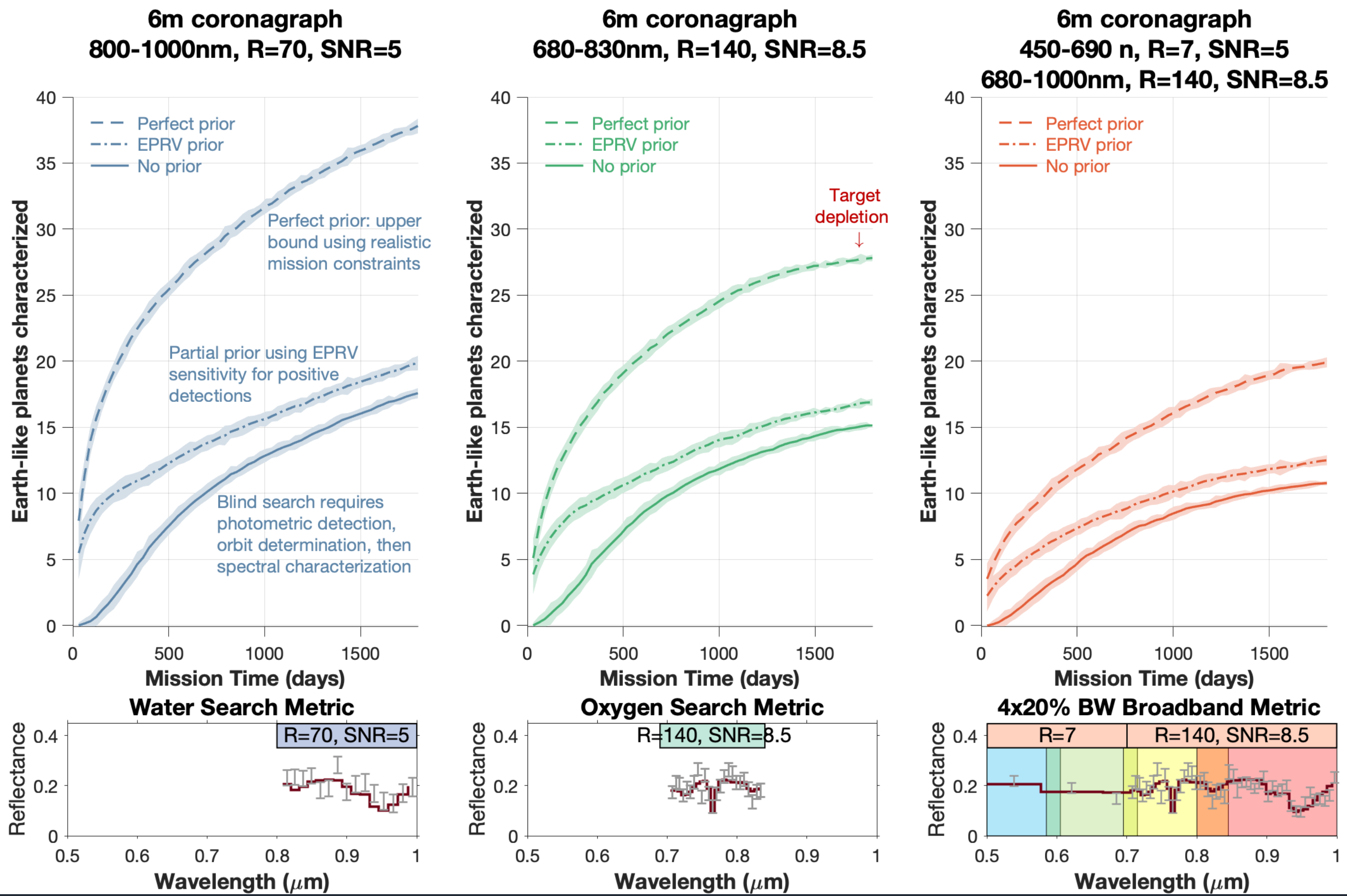
Bandwidth, SNR, R_s

Architecture

Observing Scenario

Prior Knowledge

Different yield metrics reveal different sensitivities



Different yield metrics reveal different sensitivities

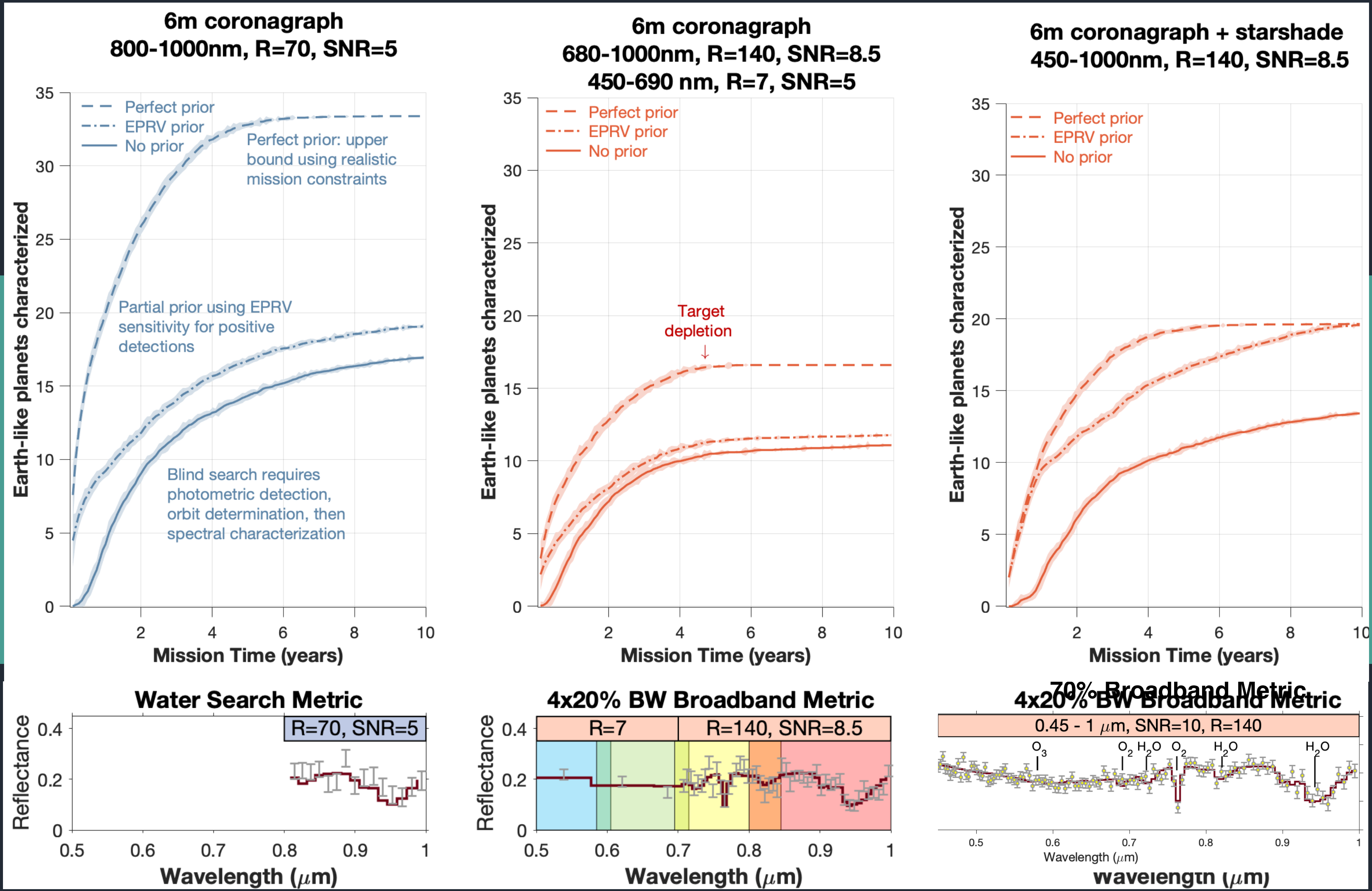
Metrics

Bandwidth, SNR, R_s

Coronagraph – Water Search

Coronagraph – Broadband

Coronagraph
+
Starshade



Three characterizations per target is target limited

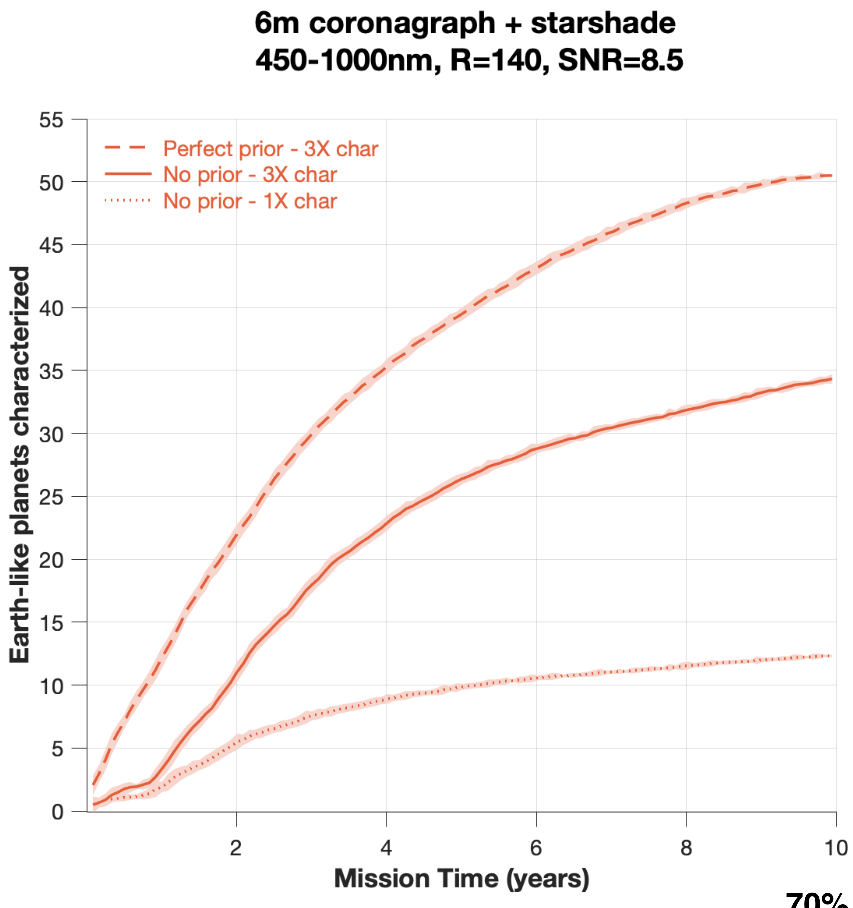
Metrics

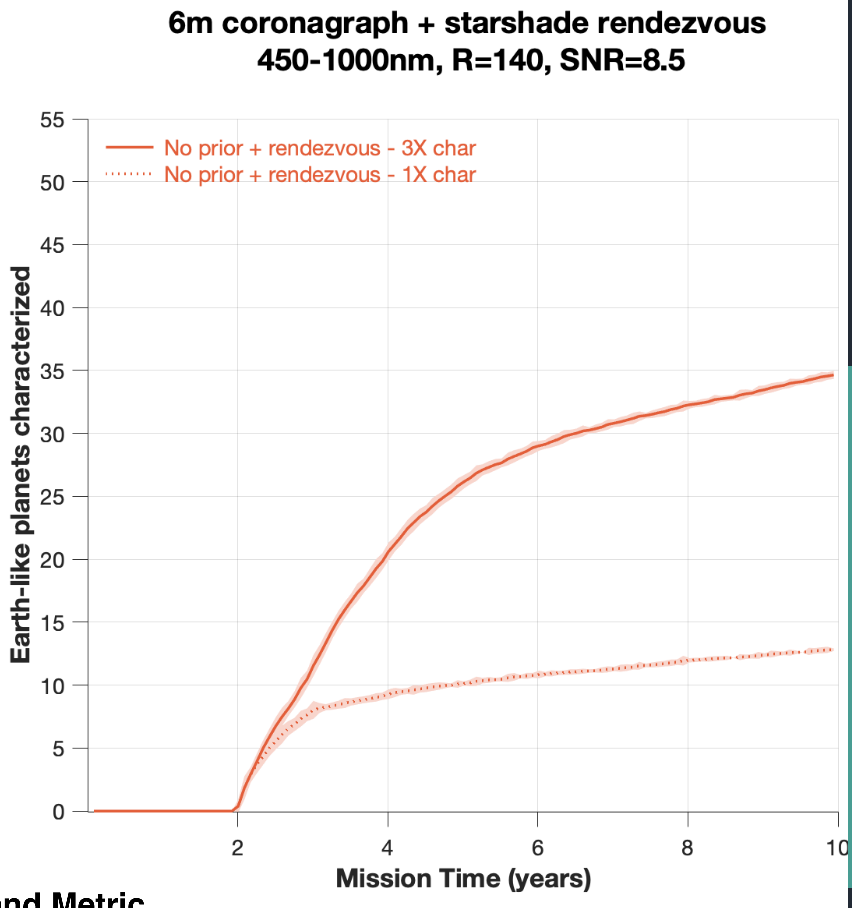
Bandwidth, SNR, R_s

Triple characterizations

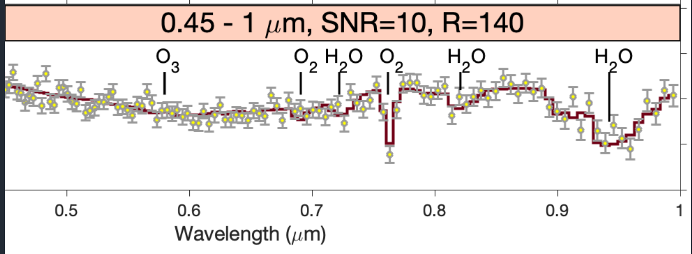
Starshade rendezvous at 2 yrs

Coronagraph
+
Starshade

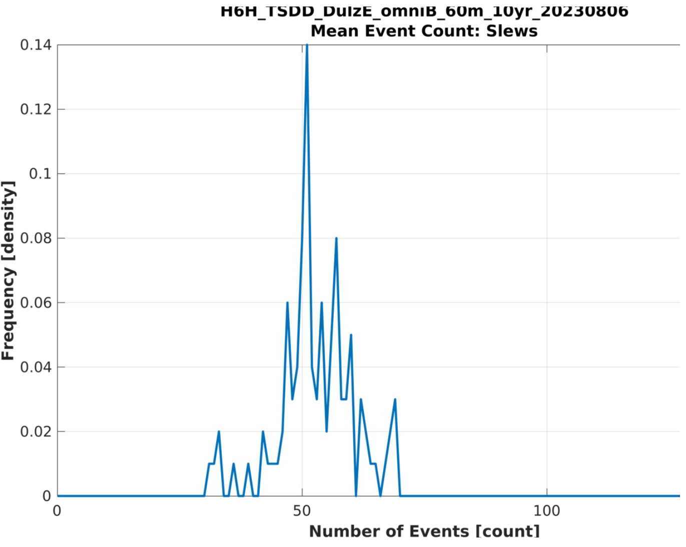


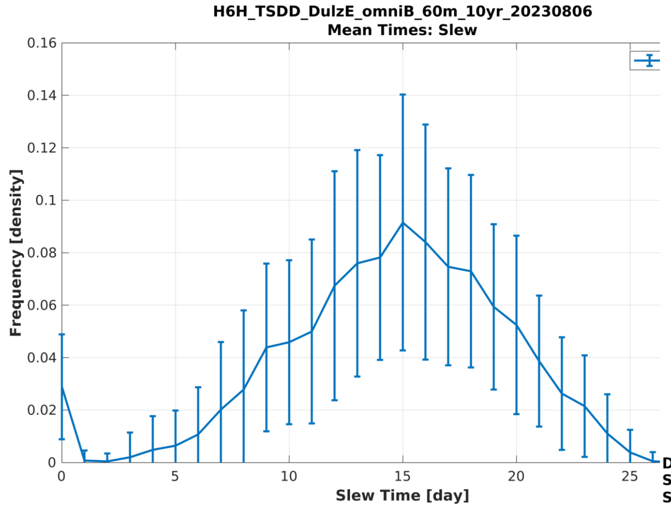


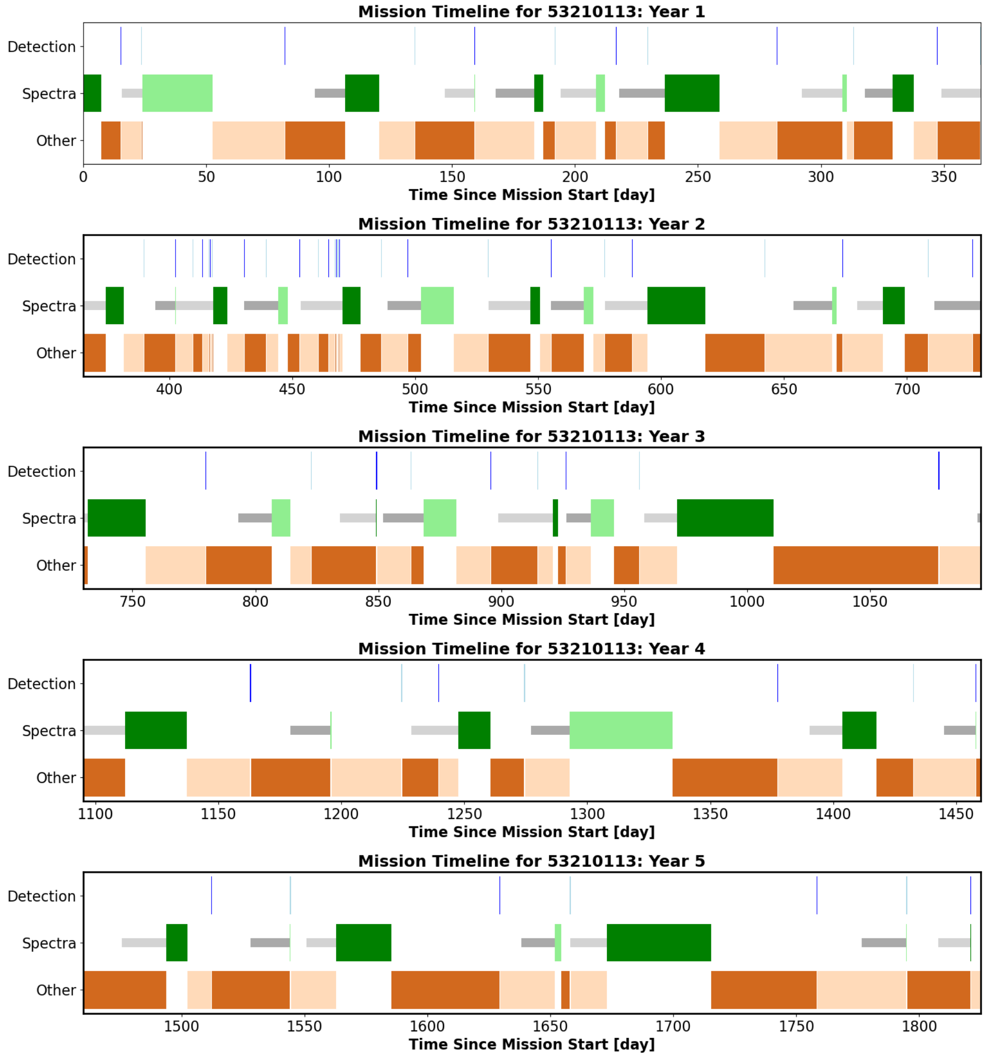
70% Broadband Metric



Triple characterizations are target and integration time limited

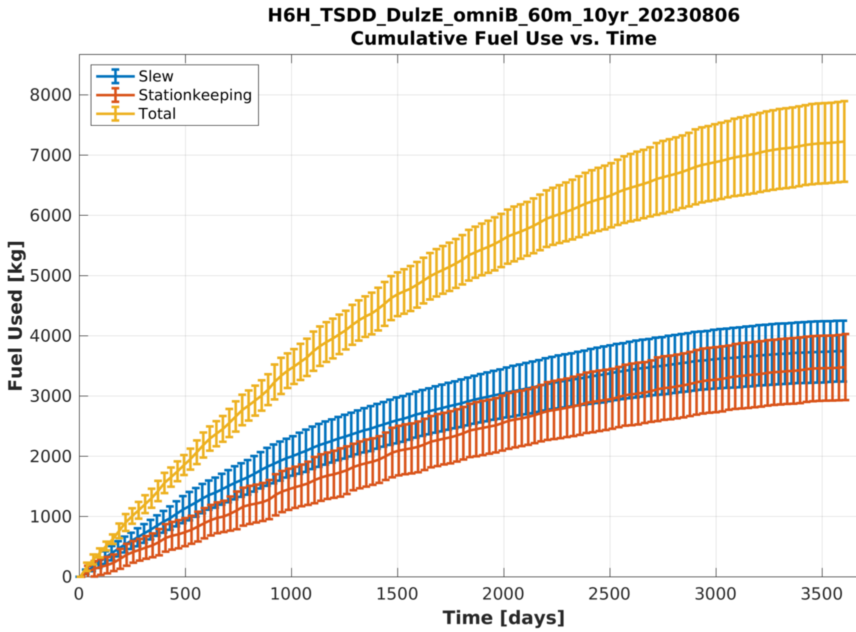






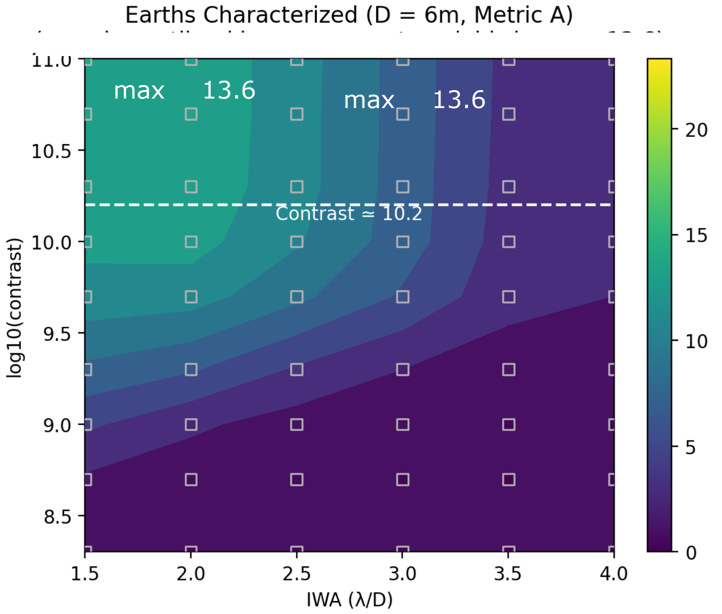
Detection: 41 days = 1.1%
Spectra: 844 days = 23.1%
Slew: 793 days = 21.7%
Other: 2538 days = 69.5%

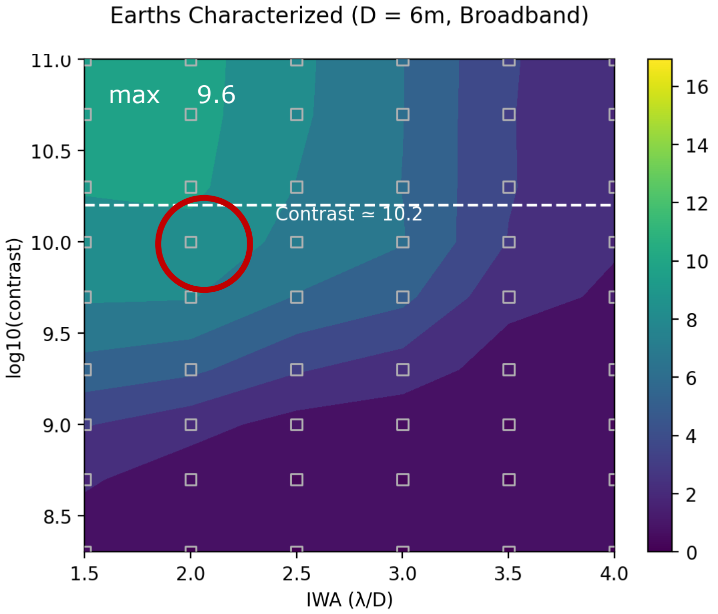
This is the most intensive case, but only 20% time is transiting and 23% time is spectra
70% to astrophysics



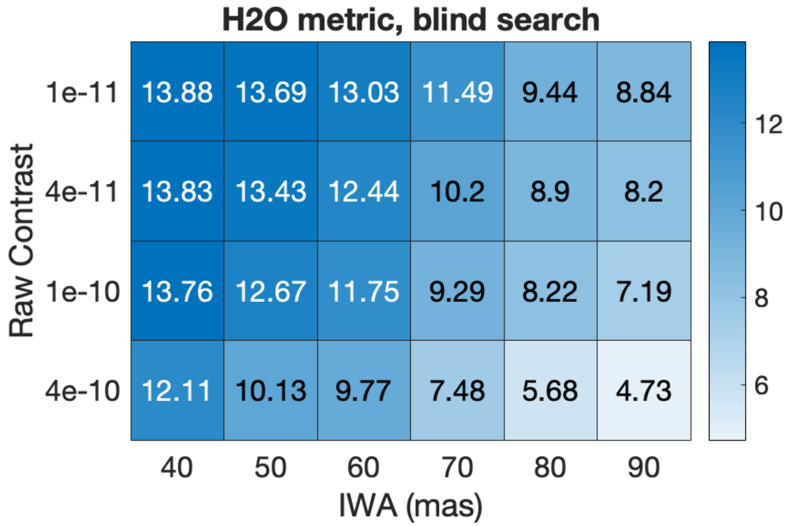
Water search and broadband: sensitivity to contrast, IWA

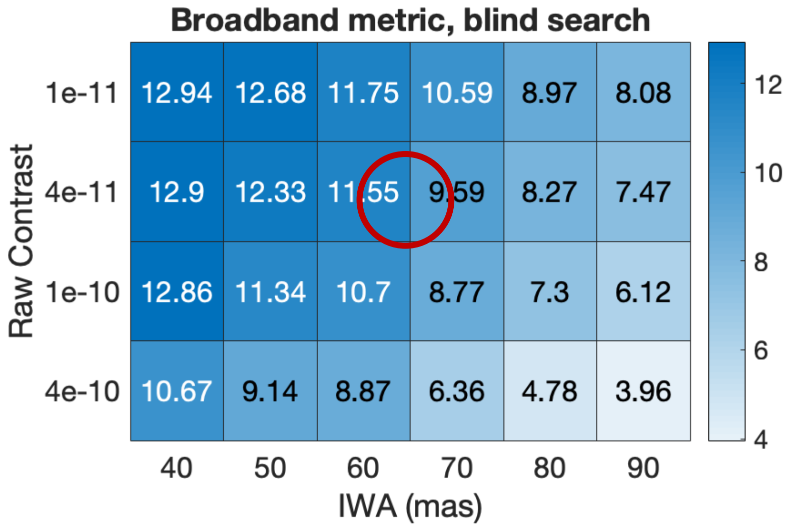
Coronagraph





Starshade





Summary

- **Coronagraph + starshade has high complementarity that provides high-quality, instantaneous 70% bandwidth spectra**
- **The initial point design concept of 65 mas IWA_{tips} is target limited, even for triple characterizations.**
  - Plenty of slew transits remain available.
  - Rendezvous two years into the mission achieves equivalent yield
- **Yield can be improved with smaller IWA**

BACKUP

Passband versus properties

- **LUVOIR and HabEx requirements based on modern Earth atmosphere**
- **Since then, Archean earth, preterozoic Earth with 1% O2 and 0.1% O2, Venus-like atmospheres studied**

Take home messages

- Linking the molecular volume mixing ratio to the cloud properties is important for reflected light spectroscopy
  - To measure the above-cloud gas abundance
  - To constrain the cloud composition
  - To explore the chemical composition of deeper atmospheric layers
- Near-IR wavelength band is crucial for the overall characterization of the atmosphere (CO_2 cannot be constrained with optical wavelength only)
- UV will be useful to detect and quantify O_2 and O_3 in those scenarios in which the contribution in the VIS wavelength band is not significant

Papers Spotlight

Hu 2019 - ApJ 887, 166
Damiano & Hu 2020 - AJ 159,175
Damiano et al. 2020 - AJ 160,206
Damiano & Hu 2021 - AJ 162,200
Damiano & Hu 2022 - AJ 163,299

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California Institute of Technology

H2O metric, blind search

Raw Contrast \ IWA (mas)	40	50	60	70	80	90
1e-11	13.88	13.69	13.03	11.49	9.44	8.84
4e-11	13.83	13.43	12.44	10.2	8.9	8.2
1e-10	13.76	12.67	11.75	9.29	8.22	7.19
4e-10	12.11	10.13	9.77	7.48	5.68	4.73

Broadband metric, blind search

Raw Contrast \ IWA (mas)	40	50	60	70	80	90
1e-11	12.94	12.68	11.75	10.59	8.97	8.08
4e-11	12.9	12.33	11.55	9.59	8.27	7.47
1e-10	12.86	11.34	10.7	8.77	7.3	6.12
4e-10	10.67	9.14	8.87	6.36	4.78	3.96

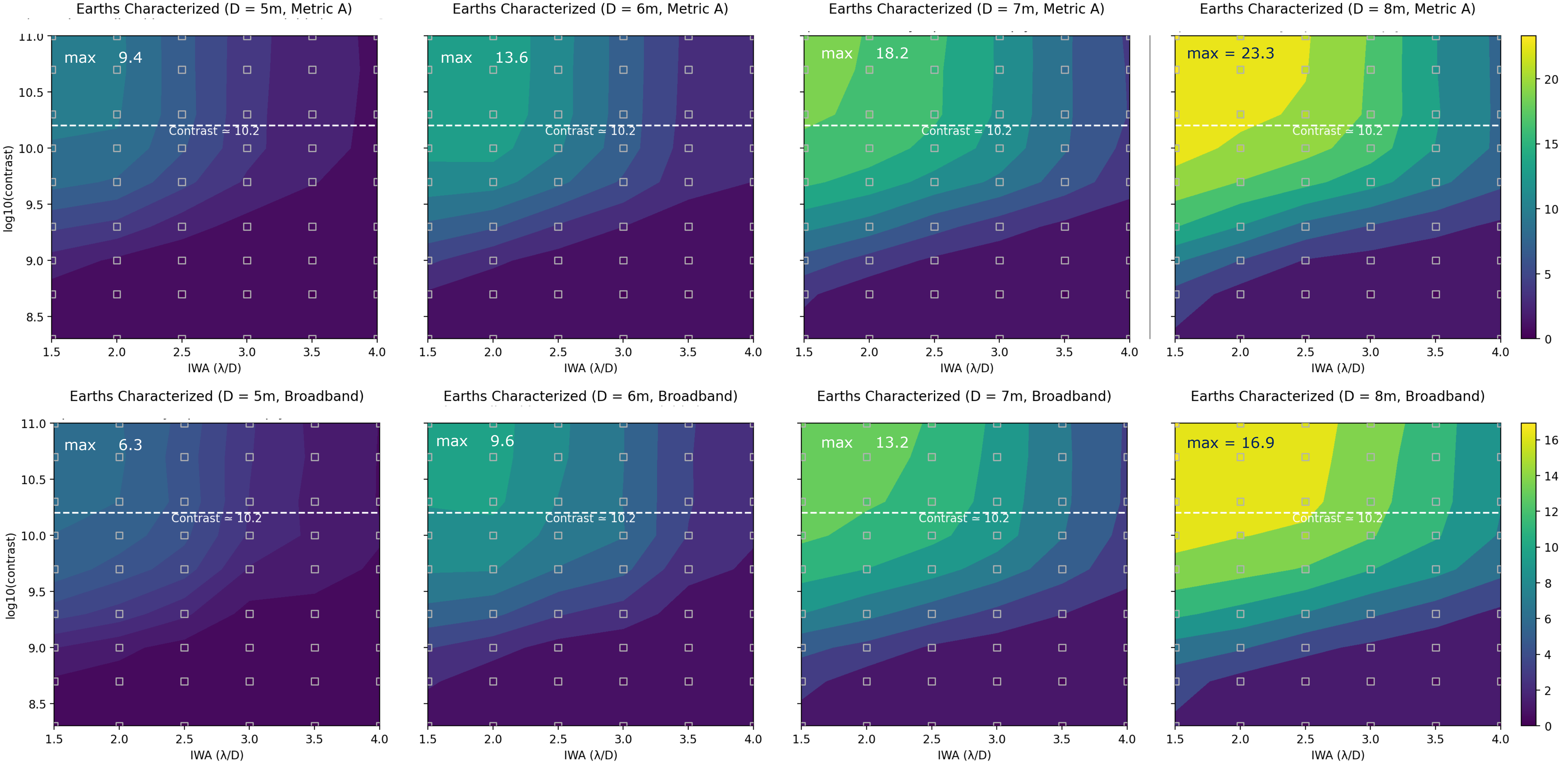
H20 metric, perfect prior

Raw Contrast \ IWA (mas)	40	50	60	70	80	90
1e-11	60.64	52.81	45.41	37.2	31.71	28.39
4e-11	60.26	49.75	43.03	32.49	28.39	24.08
1e-10	56.78	39.24	35.32	28.44	23.24	19.08
4e-10	34.91	26.66	26.58	19.12	13.46	11.33

Broadband metric, perfect prior

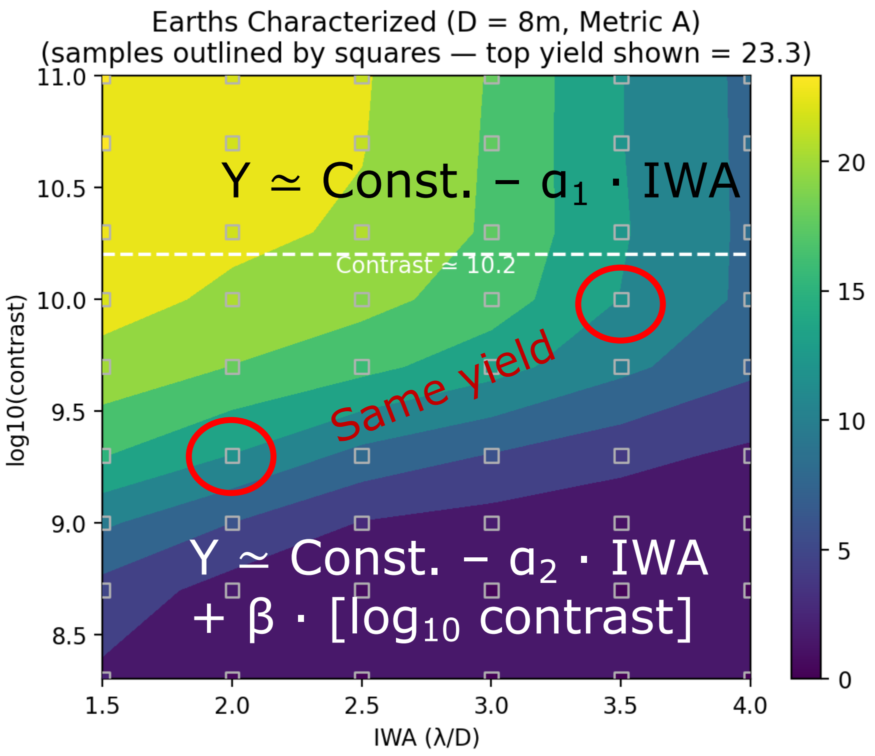
Raw Contrast \ IWA (mas)	40	50	60	70	80	90
1e-11	33.41	29.66	26.51	23.52	20.6	18.49
4e-11	33.29	27.77	25.65	21.16	18.63	16.15
1e-10	30.8	23.5	22.21	18.75	14.95	12.57
4e-10	21.44	17.22	17.08	12.55	8.66	7.46

Two metrics: sensitivity to diameter, contrast, IWA



Joint distribution fit via Linear response surface models

A linear model (or fit) for yield works reasonably well, and reveals partial derivatives w/r/t contrast and IWA



Broadband	α_1	RMSE	α_2	β	RMSE
5m	2.5	2%	2.2	3.7	3%
6m	3.3	6%	2.7	5.7	5%
7m	3.8	6%	3.1	7.4	4%
8m	3.6	7%	3.3	9.9	4%

- For water search metric, exo-Earth yield increases by about 4-6 for each λ/D drop in IWA (column 2)
- And exo-Earth yield increases by 6-13 for each decade in contrast (column 5)
- At or below log-contrast of 10, each decade in contrast is similar to 2·λ/D in IWA (i.e., β/α ~ 2)

Sensitivity of linear surface model to diameter