Jet Propulsion Laboratory
California Institute of Technology

Introduction and importance of yield tools for science requirements and mission requirements

Rhonda Morgan
[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA

CL#23-2873

8 June 2023

Pre-decisional: for discussion purposes only

Agenda

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

Session 1 9:00 am - 11:00 am MT

Speaker	Description	Duration
Rhonda Morgan	introduction and importance of yield tools for science requirements and mission requirements	10 min
Dmitry Savransky	detailed overview of EXOSIMS open source mission simulation tool	30 min
Chris Stark	detailed overview of AYO (Altruistic Yield Optimization)	30 min
Felix A. Dannert, ETH Zurich	Yield prediction for space-based nulling interferometry	10 min
Samantha Hasler, MIT	Reducing Detection Confusion in Directly Imaged Multi-Planet Systems	10 min
Margaret Bruna, Mcgill University	Orbit Retrieval of Directly Imaged Exoplanets: When and How to Look	10 min
SIG2	Current progress in demographics	5 min
Rhonda Morgan (facilitator)	Q&A and discussion of priorities for future model improvement	15 min

Session 2 12:30 pm - 3:00 pm MT

Description	Duration
Interactive tutorial of EXOSIMS using GoogleCollab and at least two sample problems	60 min
Interactive tutorial of ExoVista	40 min
Open hack time for participants to start on their own problems with assistance from tool developers	50 min

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

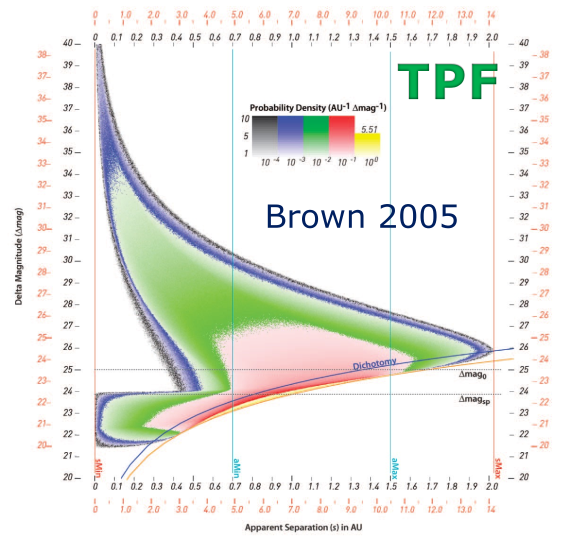
Mission model

- 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



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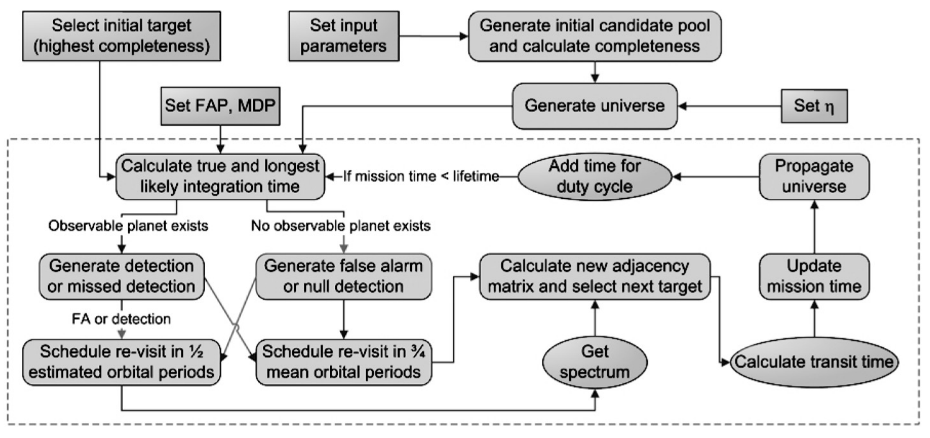
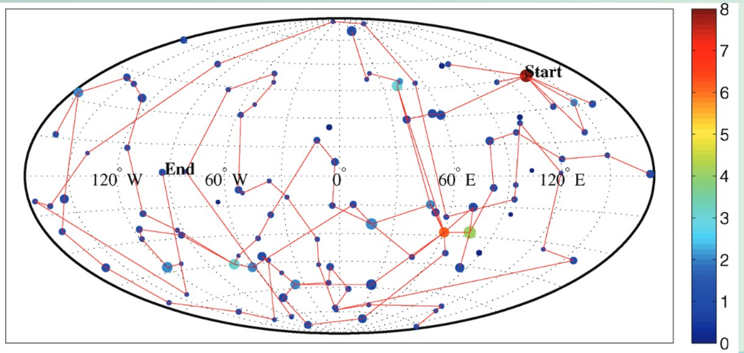
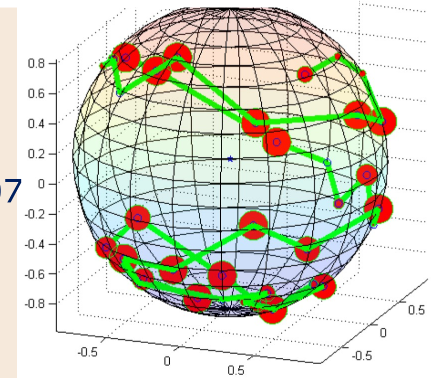
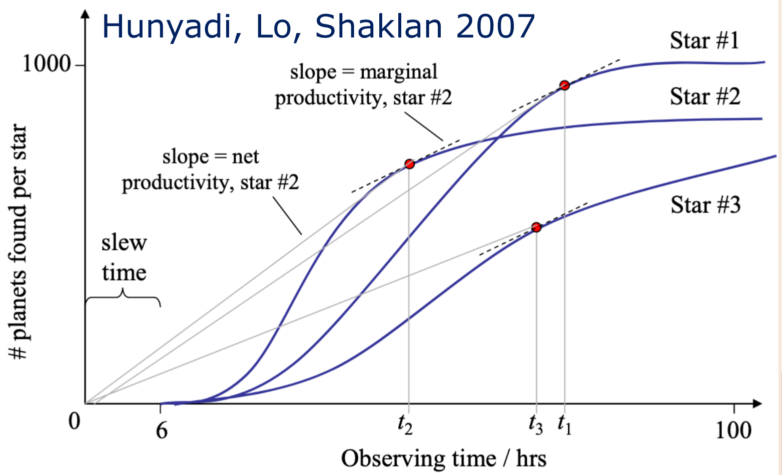


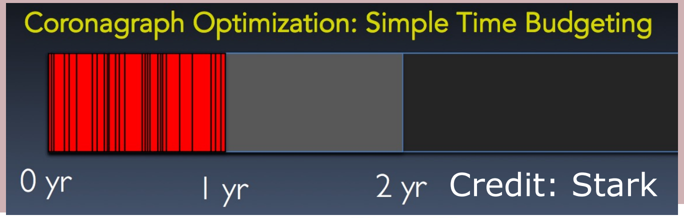
Savransky, Kasdin, Cady 2010

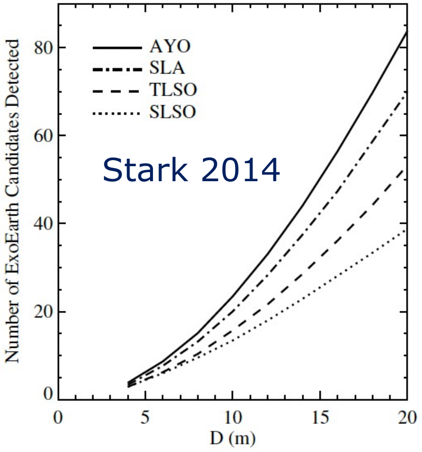


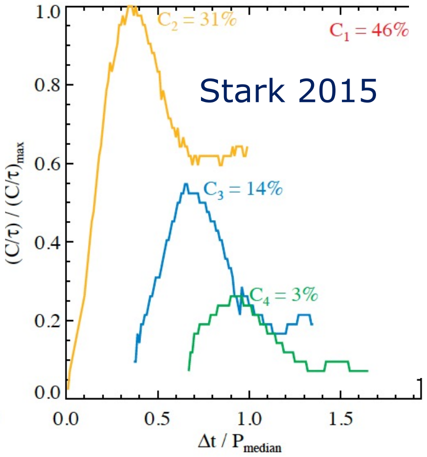
Hunyadi, Shaklan, Brown 2007





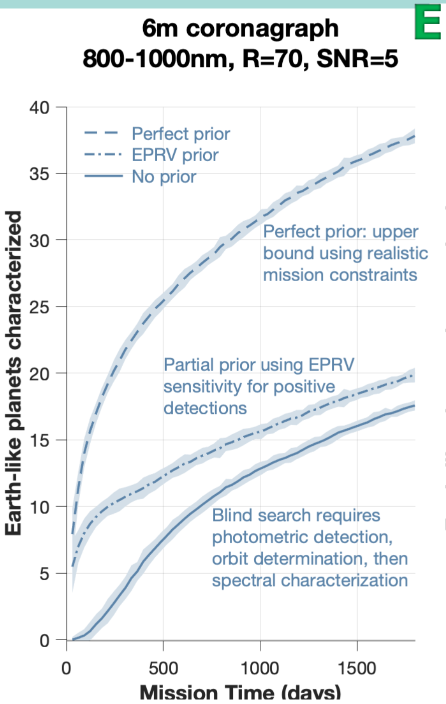


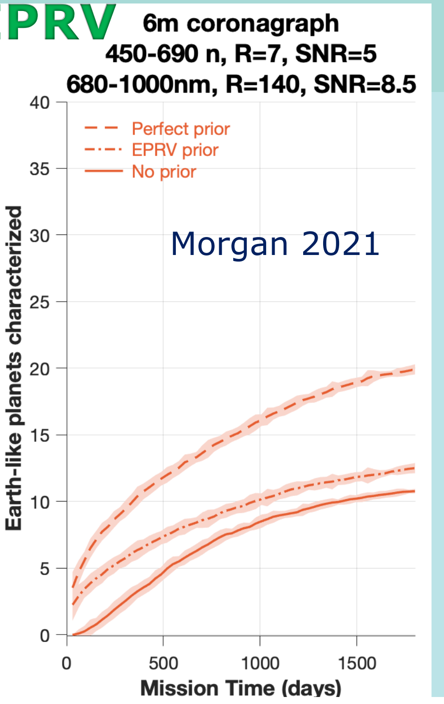


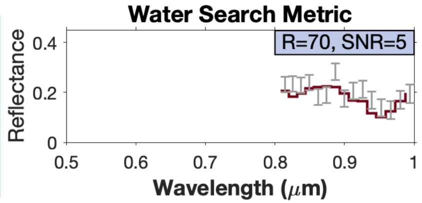


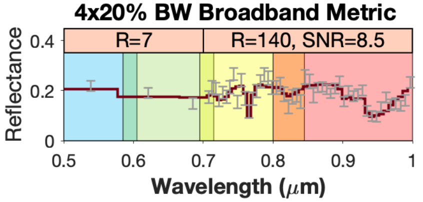
ATLAST, LUVOIR, HabEx

EPRV









Exoplanet Probe Studies (2015)

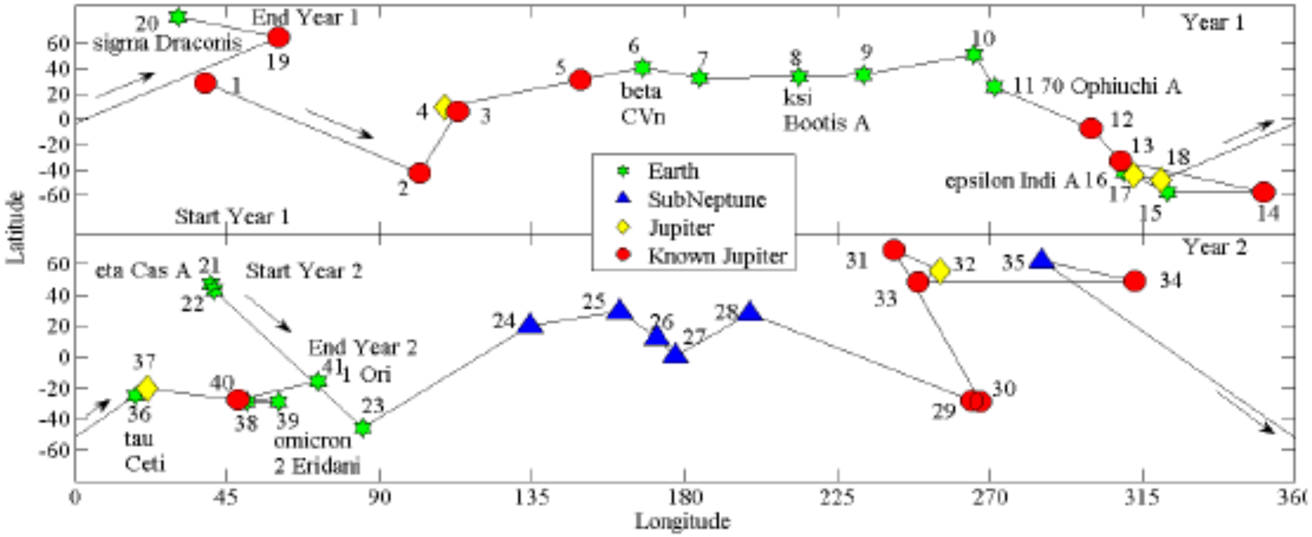


Figure 5.3-1. Observing sequence for Case 1, Dedicated Mission, Earth twins in HZ. Coordinates are ecliptic longitude and latitude.

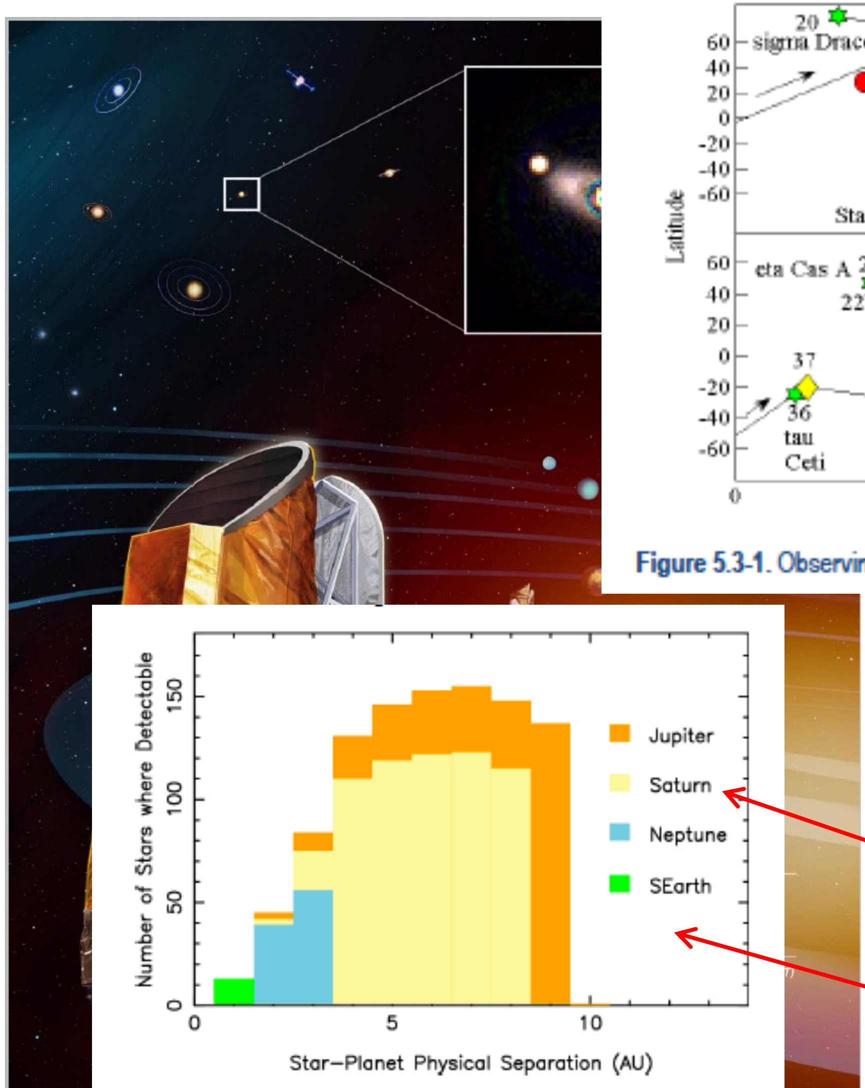


Figure ES-4. Exo-C exoplanetary search space among nearby stars, as a function of planet size and orbit.

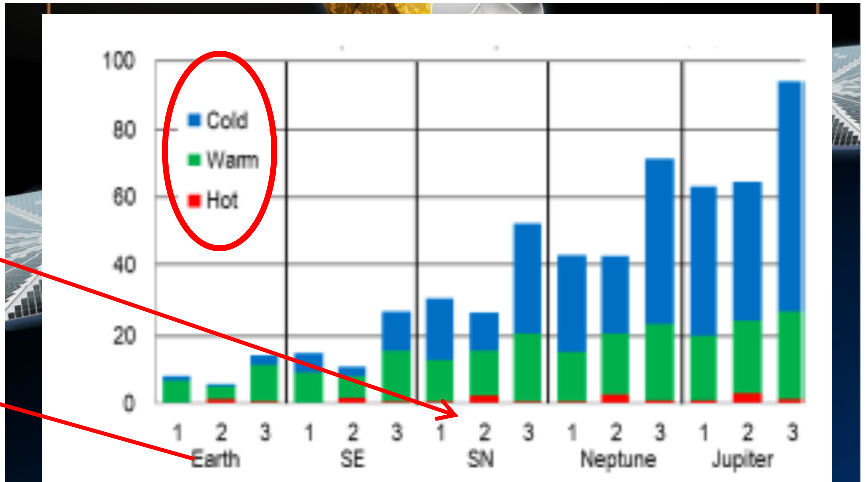
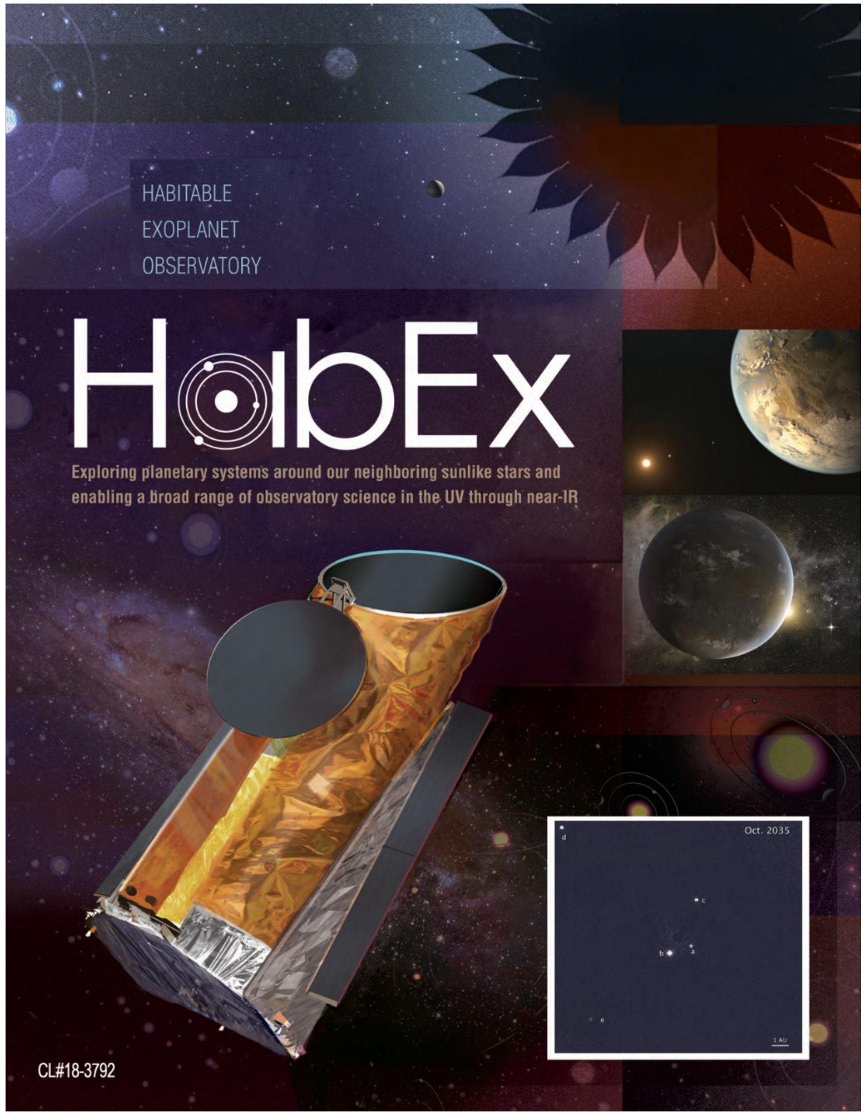
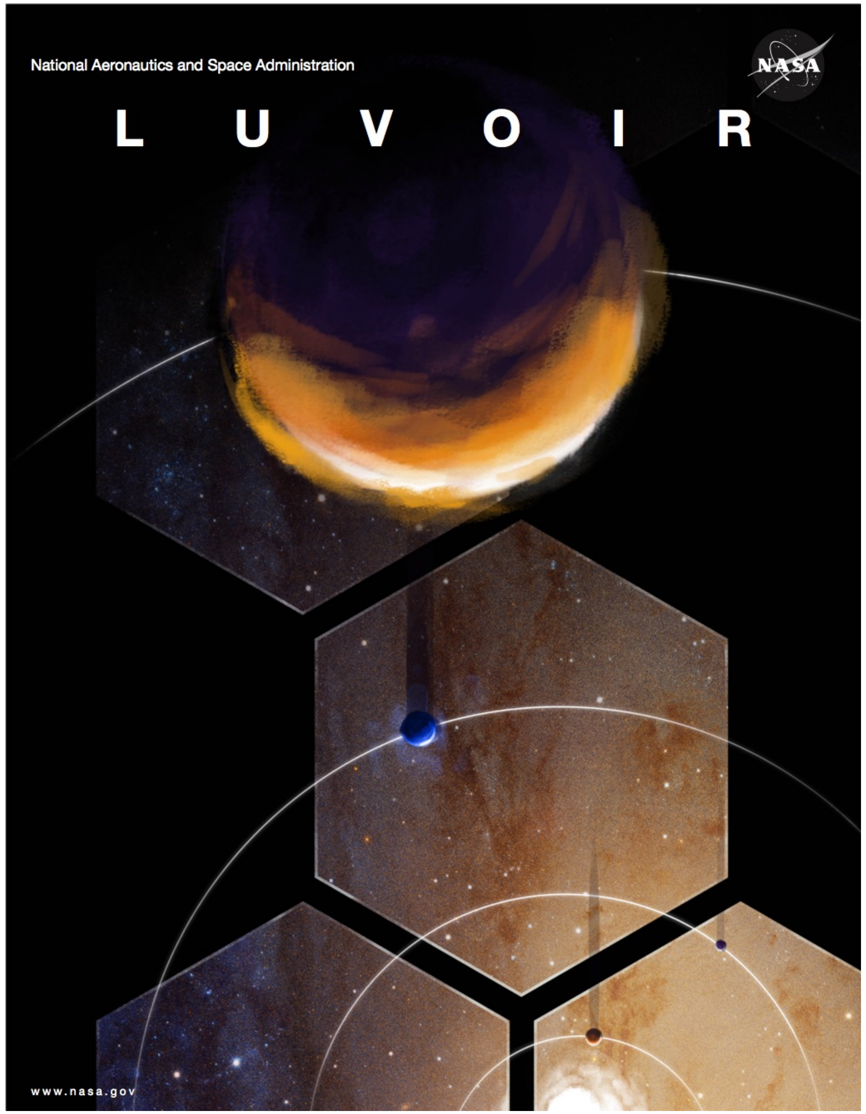
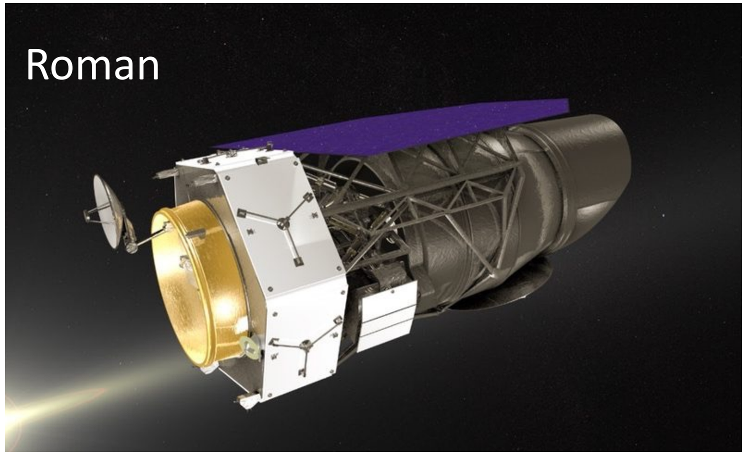


Figure 5.4-1. Observational completeness for the Case 1, 2, and 3 observation scenarios.

Exoplanet Direct Imaging Concept Missions



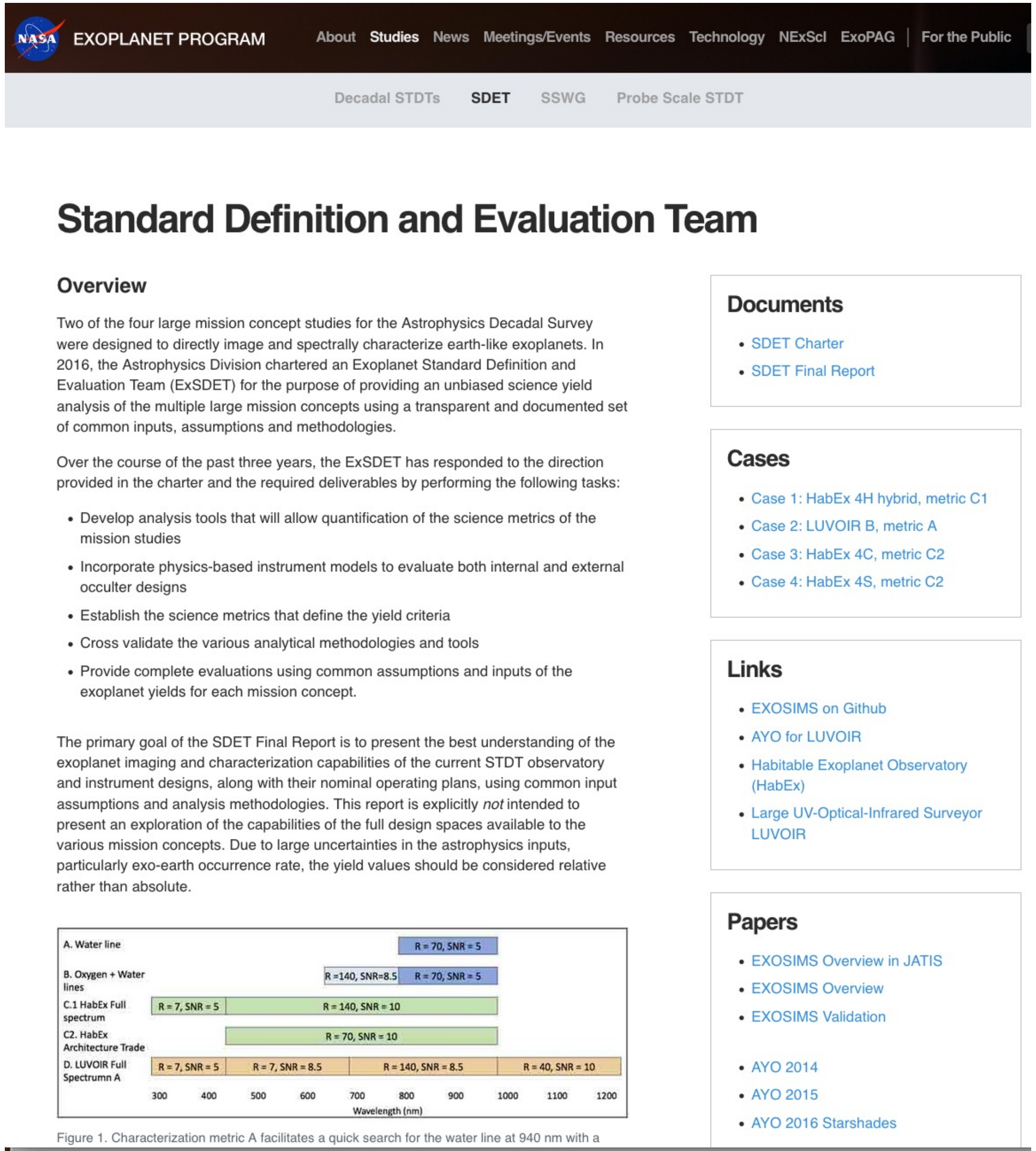




Standard Definitions and Evaluation Team

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

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



EXOPLANET PROGRAM

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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

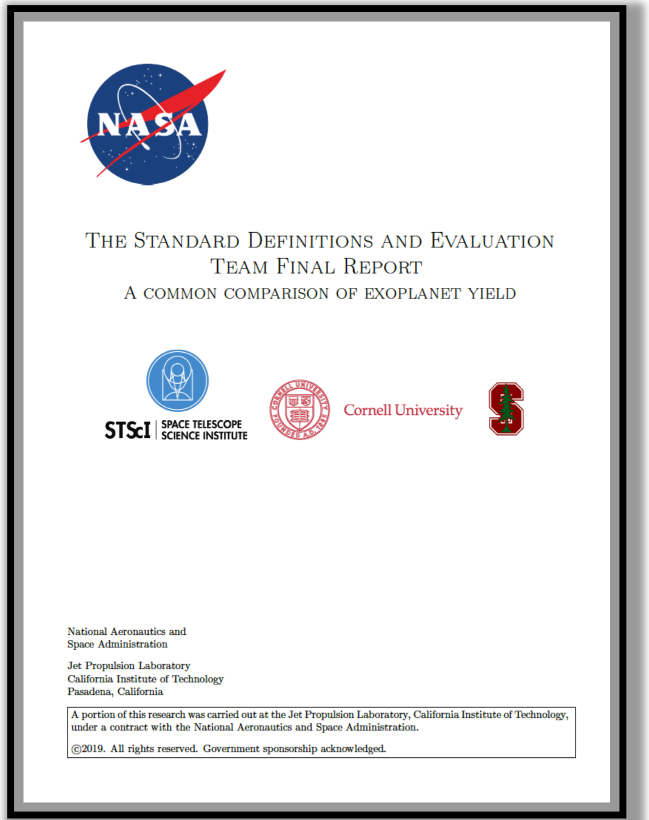
- Case 1: HabEx 4H hybrid, metric C1
- Case 2: LUVOIR B, metric A
- Case 3: HabEx 4C, metric C2
- Case 4: HabEx 4S, metric C2

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

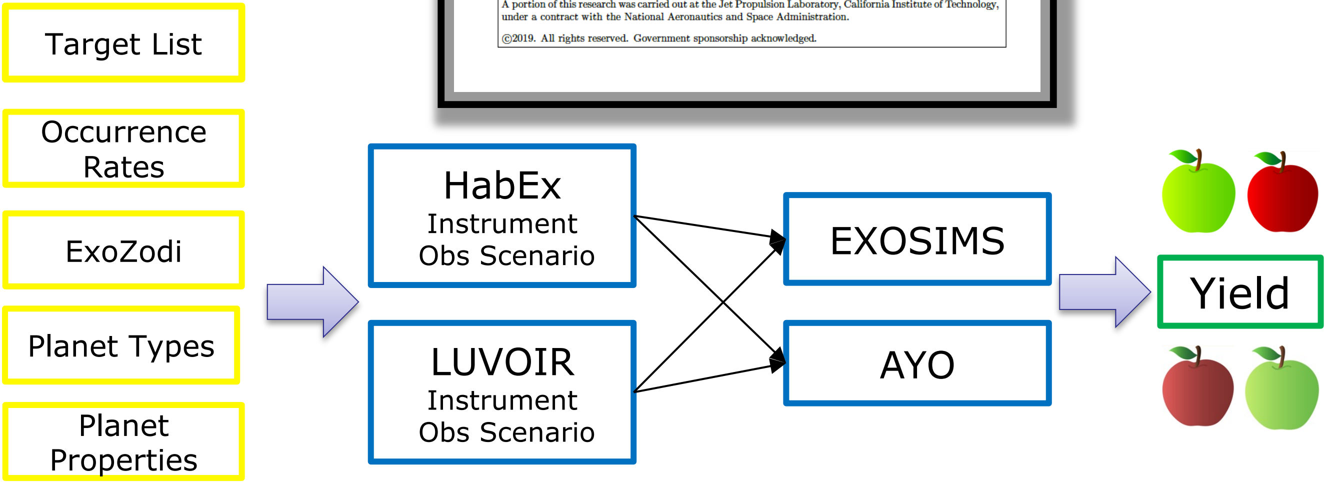
A COMMON COMPARISON OF EXOPLANET YIELD

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

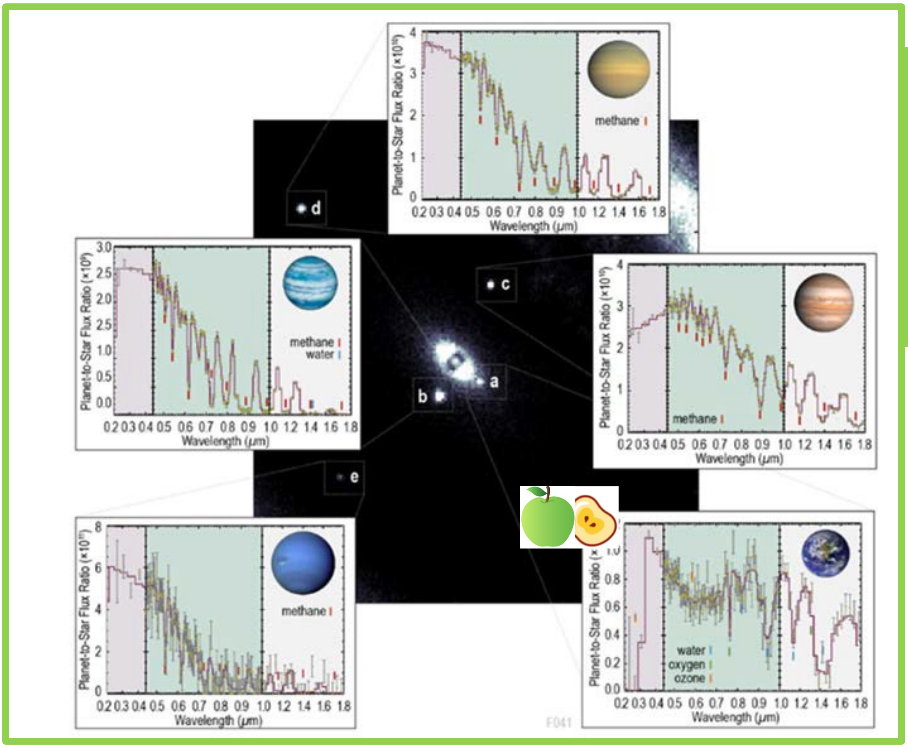
A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

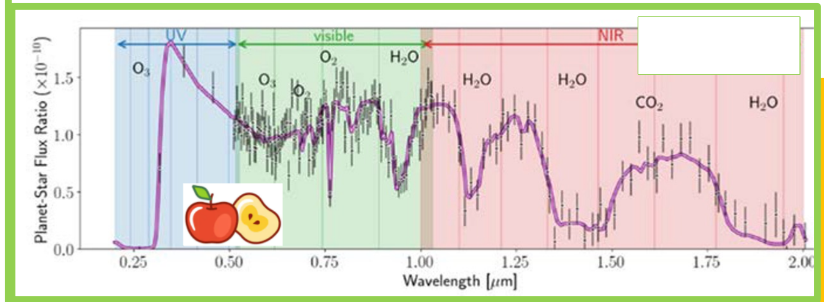
Thorough discussion of astrophysical inputs

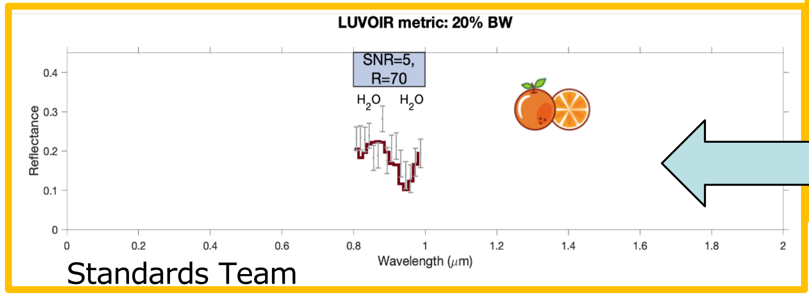


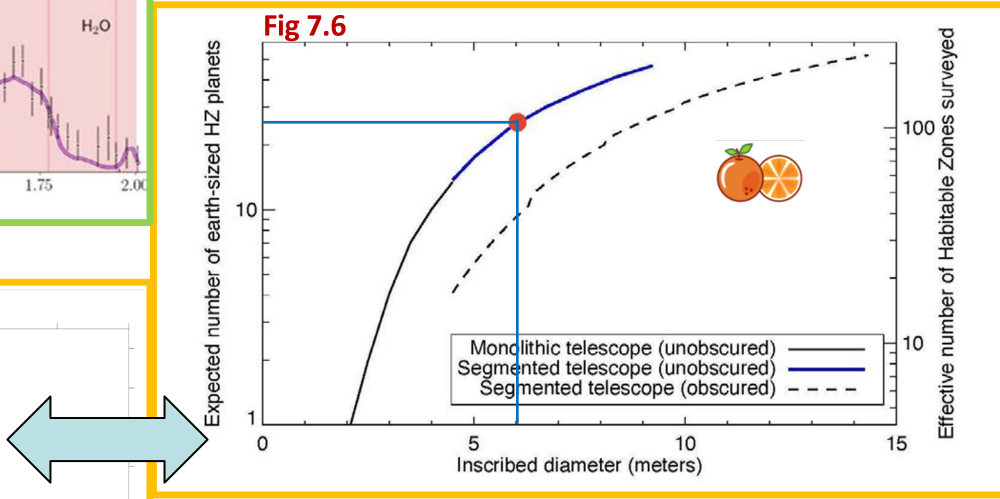
Astro2020 recommendation for exoplanets

- 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

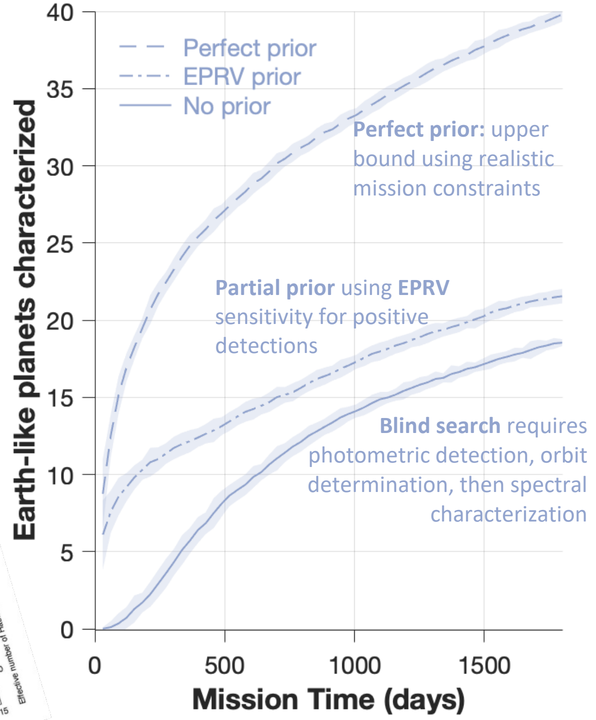
This will not be easy!

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

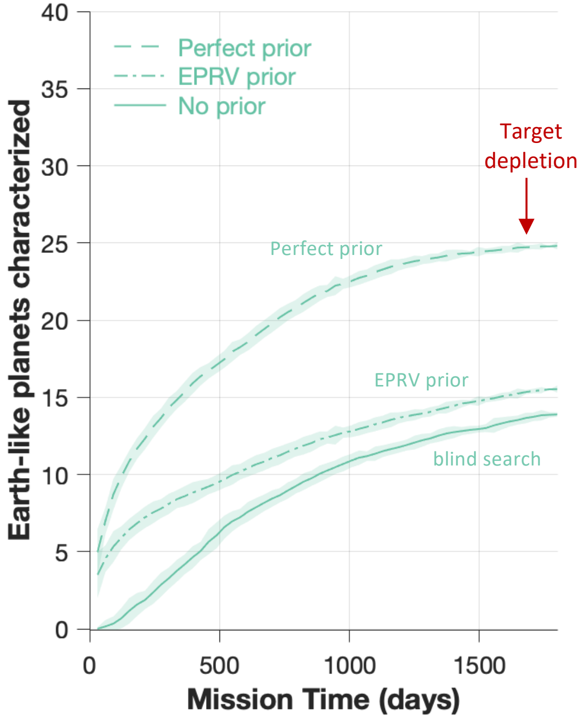
Different yield metrics reveal different sensitivities

Observing scenario, SNR, spectral resolution, number of sub-spectra, and precursor knowledge effect yield.

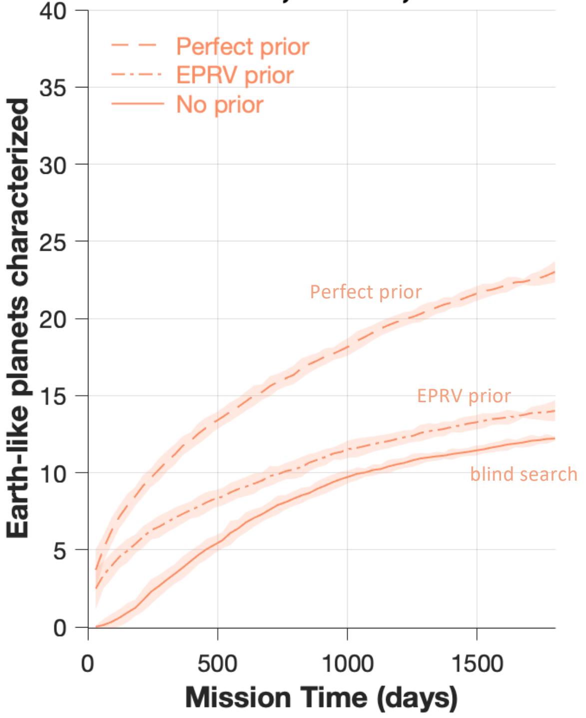
6m coronagraph
800-1000nm, R=70, SNR=5

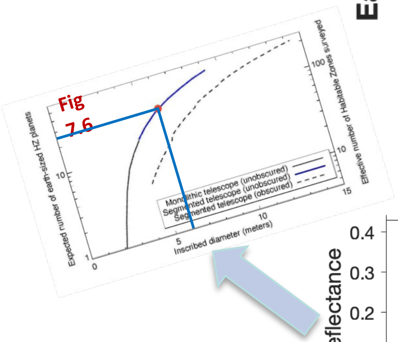


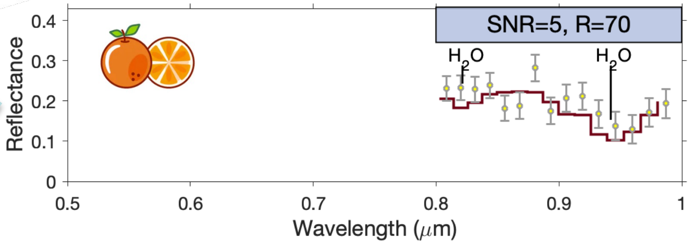
6m coronagraph
680-830nm, R=140, SNR=8.5

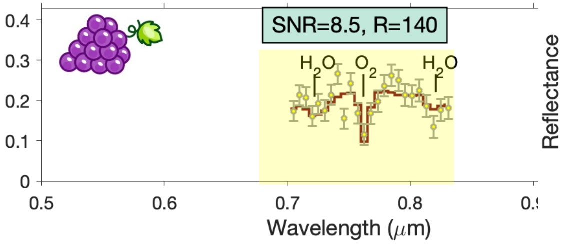


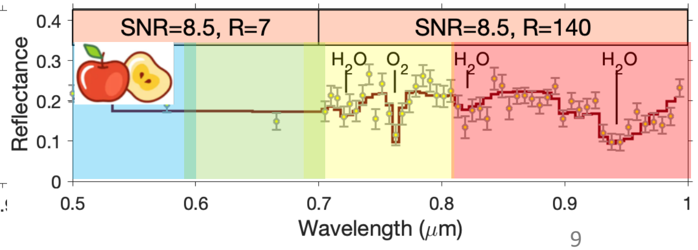
6m coronagraph
450-690 n, R=7, SNR=5
680-1000nm, R=140, SNR=8.5











More comparisons of metric impact on architectures in Morgan et al. 2021
https://doi.org/10.1117/1.JATIS.7.2.021220

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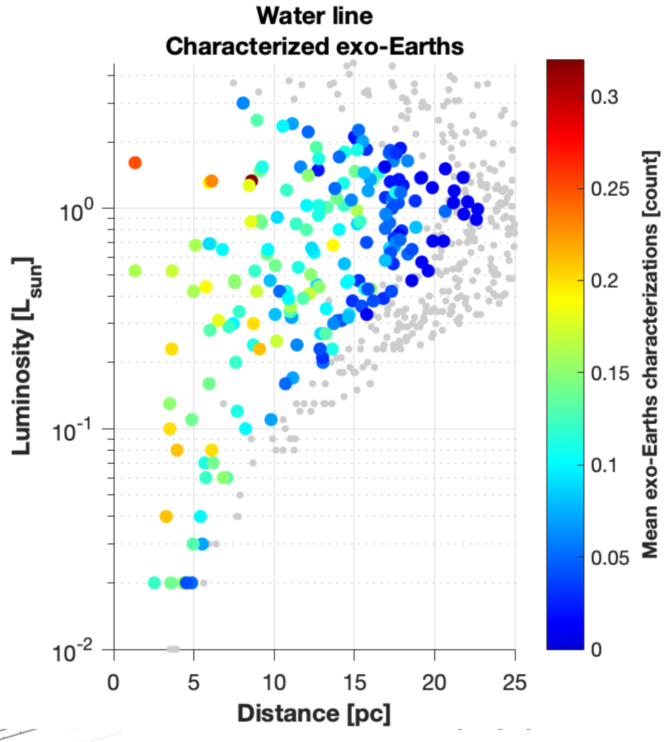
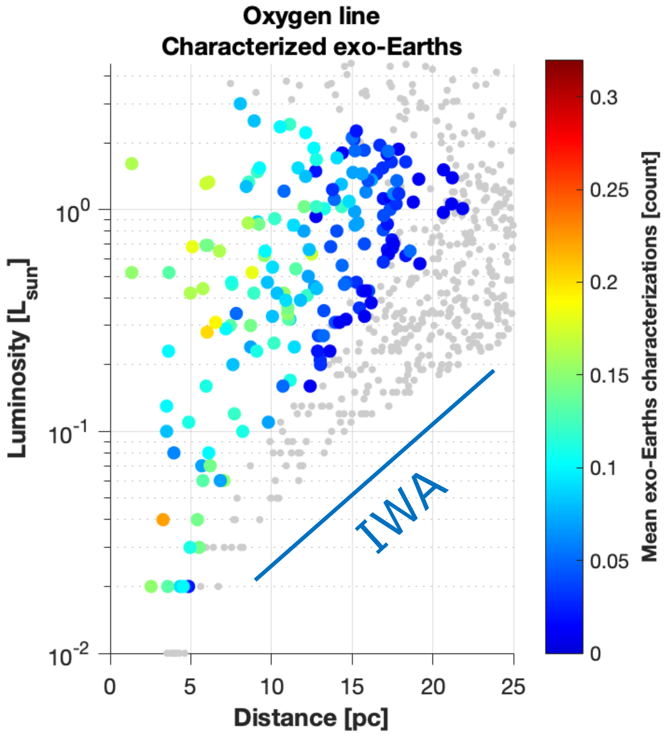
800-1000nm, R=70, SNR=5



6m coronagraph
680-830nm, R=140, SNR=8.5



6m coronagraph
450-690 n, R=7, SNR=5
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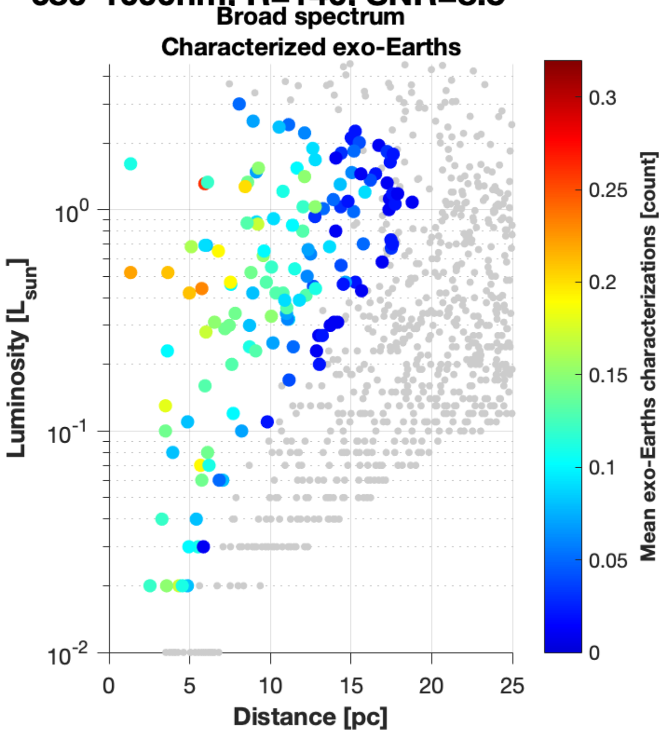

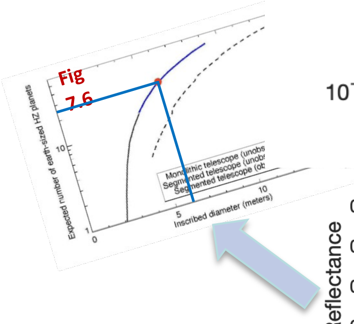

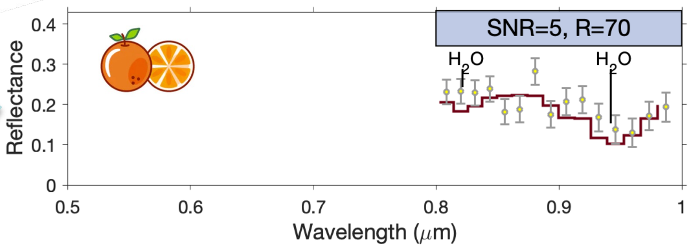

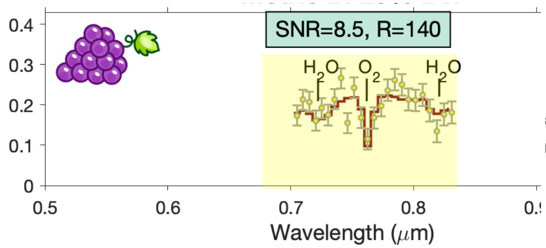

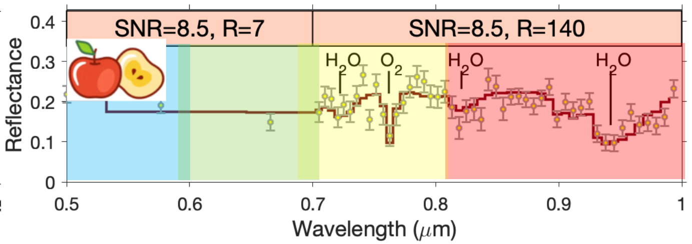

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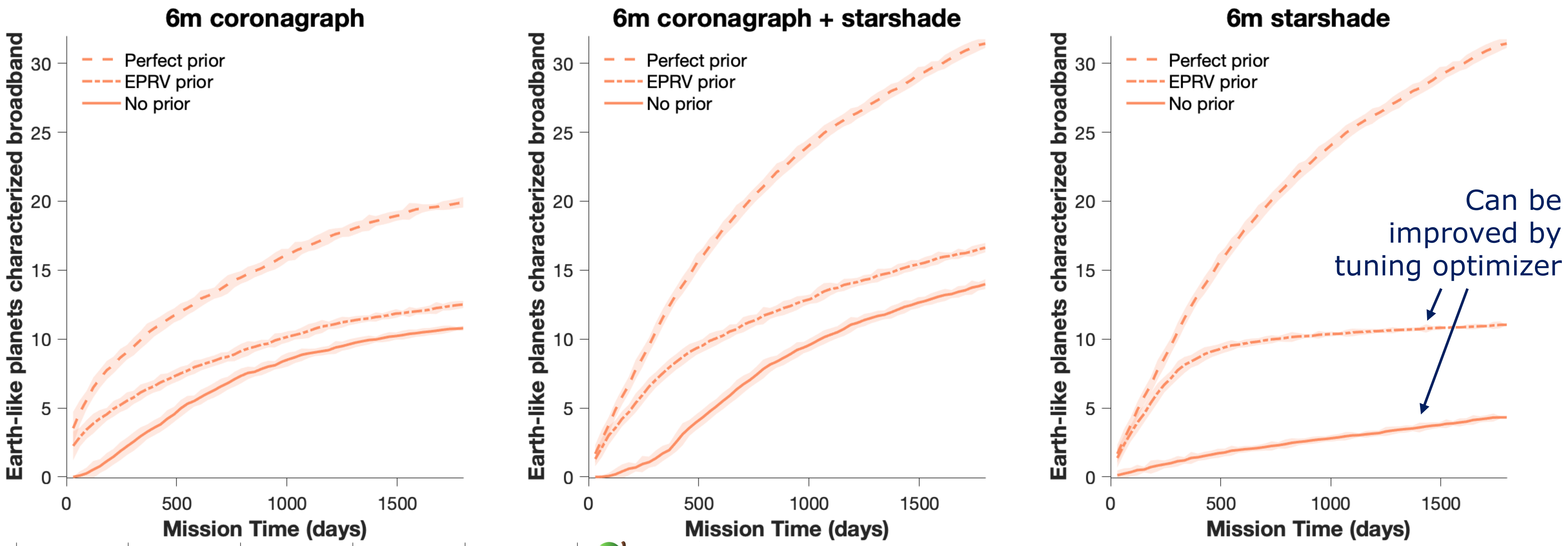
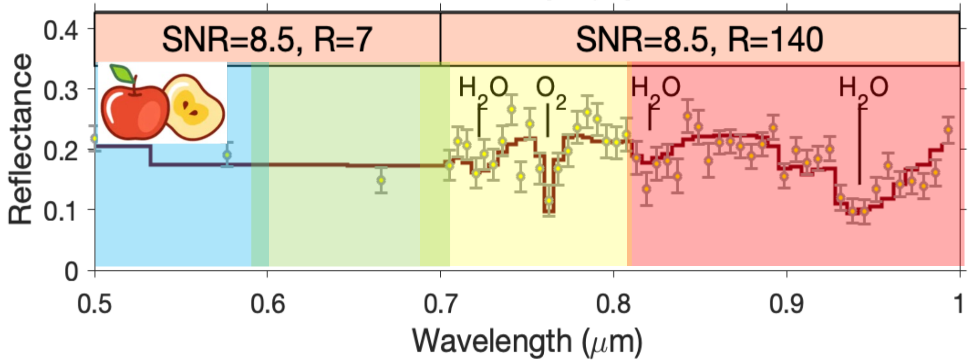
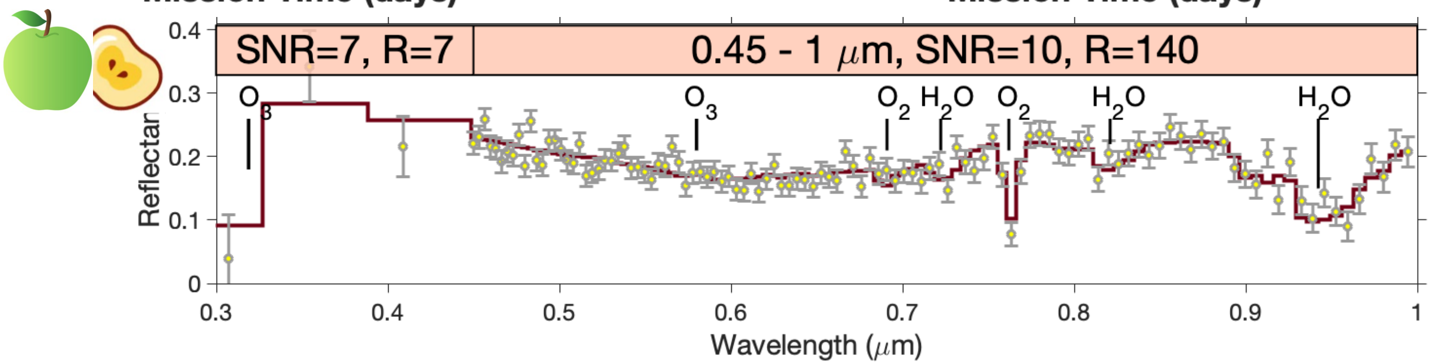
Yield with broadband metric for three architectures

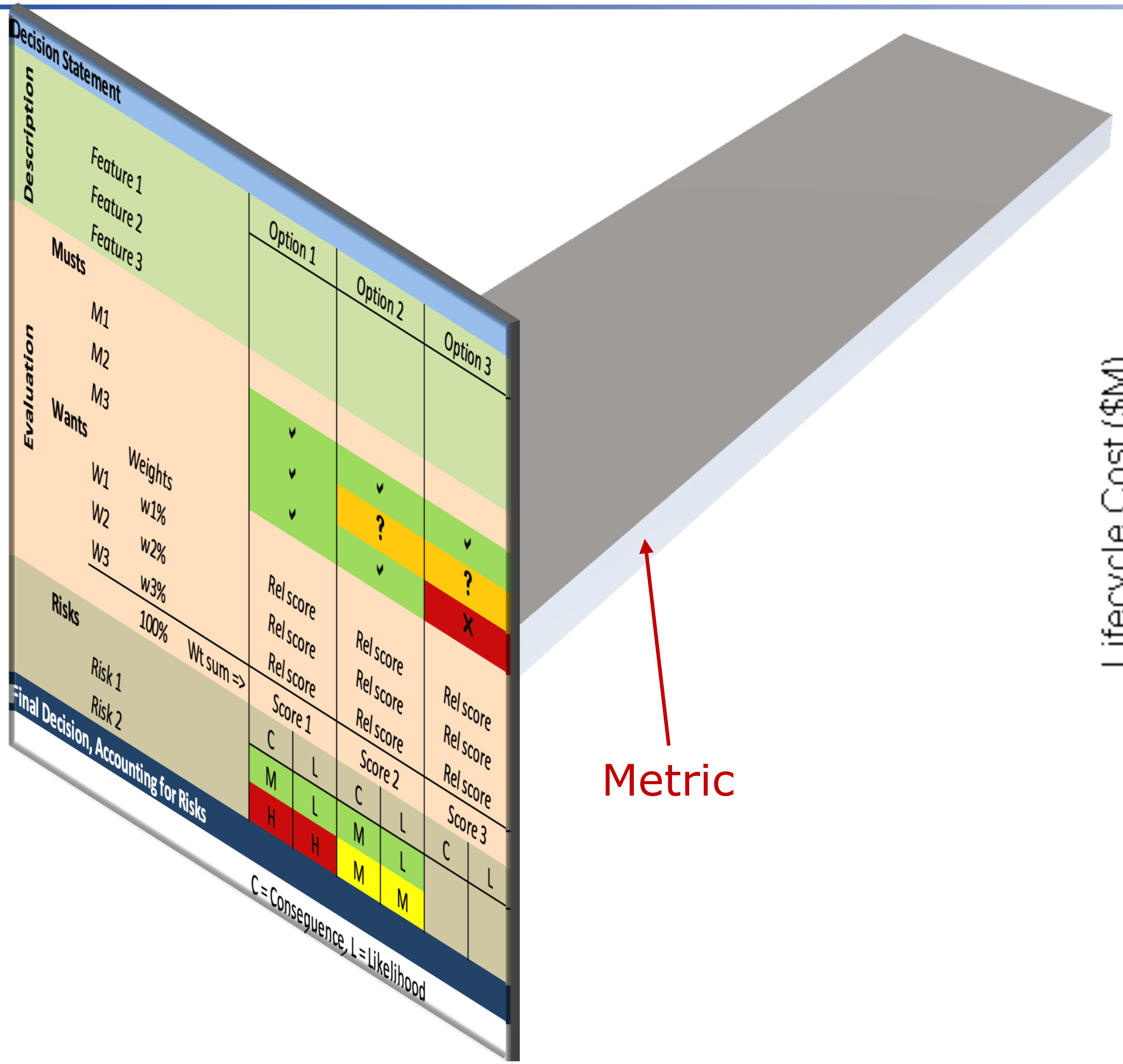
The HabEx 4m architectures were scaled to 6m and starshade from 52 m to 72m



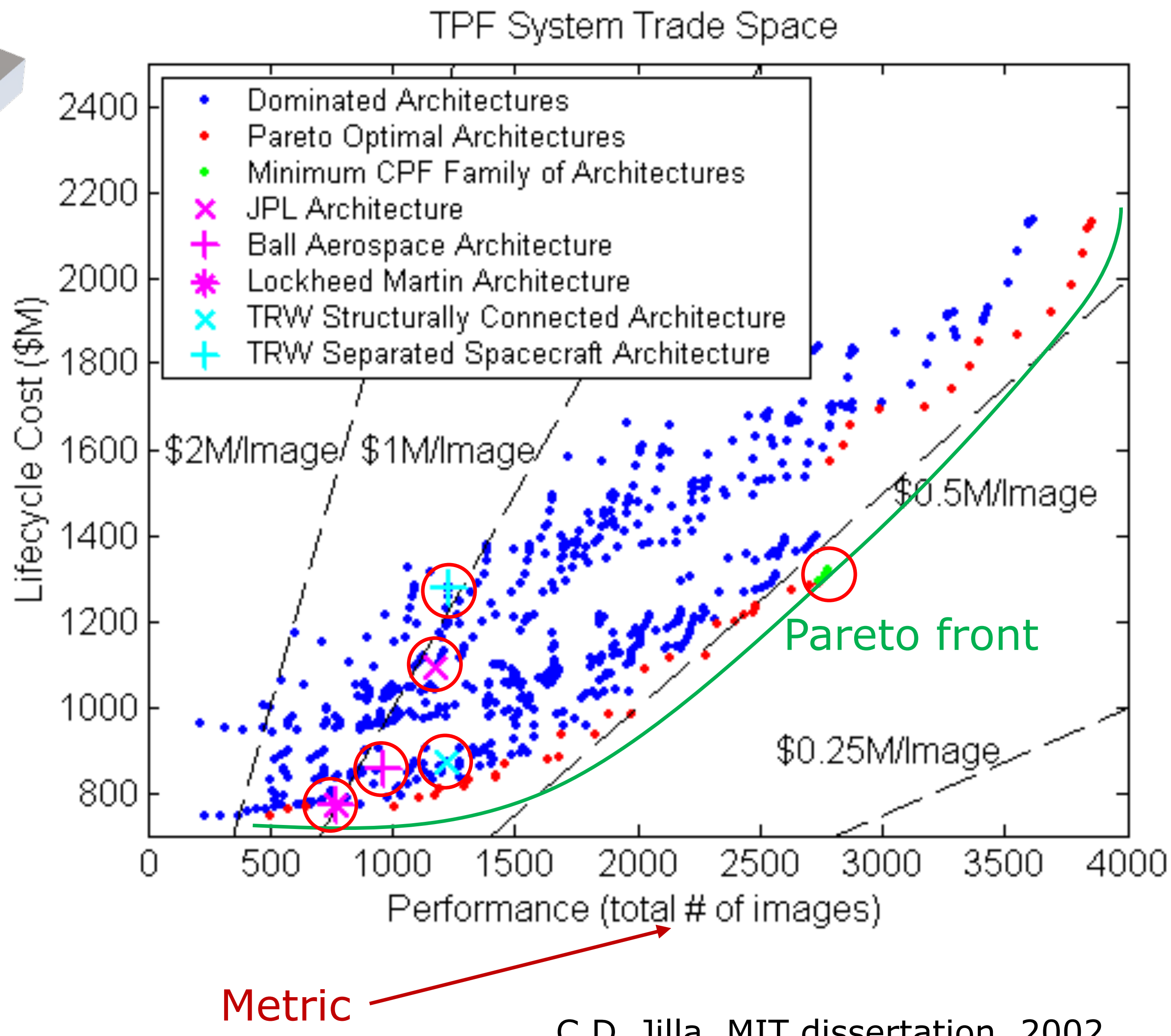




Metrics are used to quantify trades



Decision Matrix adapted from Kepner and Tregoe, 1965



C.D. Jilla, MIT dissertation, 2002

Science Traceability Matrix (STM)

- A tool to communicate how the science shapes the mission
- Flows the science goals and objectives to instrument and mission requirements
- Science objectives should be quantified

Yield tools link the flow of science observables to mission requirements

Science model → Measurement model → Instrument performance model → Mission model

Table 2: *Origins* Science Traceability Matrix

NASA Science Goals	*Origins* Science Goal/ Question	Science Objectives	Science Requirements: Science Observable	Science Requirements: Measurement Requirement	Instrument Requirements: Parameter	Instrument Requirements: Technical Requirement	Instrument Requirements: Instr	Instrument Requirements: CBE Performance	Mission Requirements: Driver	Mission Requirements: Parameter
How does the Universe work?	H... gala... sta... up... an... their central supermassive black holes from reionization to today?	... of reionization, down to a SFR of 1 $M_\odot$/yr at cosmic noon and 10 $M_\odot$/yr at z~5, performing the first unbiased survey of the co-evolution of stars and supermassive black holes over cosmic time. Measure the metal and dust content of at least 10^5 galaxies out to z=6 as a function of cosmic time, morphology, and environment tracing the rise of	... mid and far-IR emission lines.	... depths, respectively.	... (beam-capture field-of-view)				... ability and systematic error control	... 3.0m. • To meet Objectives #1-#3, a cold aperture with a temperature <6K. • Down to a line flux sensitivity of 10^{-19} W m^{-2} ability to map better than 0.15 deg²/hr and efficient scan mapping at a rate as high as 60 arcsec/sec. • To enable access to all targets of interest, the field of regard shall be 4π sr over the course of the
					Spectral line sensitivity	1.5×10^{-20} W m^{-2} at 250 μm (1 hr; 5σ)		8×10^{-21} W m^{-2} at 250 μm (1 hr; 5σ)		
			Multi-tiered survey leveraging a deep 1 deg² 2 μm imaging from JWST NIRCAM, a ~500 deg² medium depth survey for large-scale structure overlapping with WFIRST-HLS,	Extragalactic: In a deep integration the ability to resolve the CIB at 50 μm and de-blend the 250 μm map. Galactic: Ability to map star-forming regions, including point sources with	Wavelengths	50 and 250 μm	...continuum mapping	50 and 250 μm		
					Angular resolution	≤3" at 50 μm to resolve > 99% CIB		2.1"		
					Flux Density sensitivity	1.75 μJy (5σ) at 50 μm over 1 deg² in 400 hours. 3.8 μJy (5σ) at 250 μm over 1 deg² in 25 hours.		0.2 μJy (5σ) at 50 μm over 1 deg² in 400 hours. 0.6 μJy (5σ) at 250 μm over 1 deg² in 25 hours.		
					Polarization sensitivity	1% (3σ) in linear and circular polarization		0.1% (3σ), 1 degree in pol angle		

Agenda

Pre-Session:

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

Speaker	Title	Links
Eric Mamajek	Star Catalogs	Video I PDF
Jessie Christiansen	Occurrence rates and planet demographics	Video I PDF
Eric Nielsen	Planet generation Planet propagation and Orbit geometry	Video I PDF
Bertrand Mennesson	Zodiacal Light	Video I PDF
Bijan Nemati	Photometrics Part 1 - Coronagraph Parameters and SNR	Video I PDF Parts 1-3
	Photometrics Part 2 - SNR Structure	Video
	Photometrics Part 3 - Random Noise and Time to SNR	Video
John Krist	Starlight suppression system modeling	Video I PDF
Dmitry Savransky	Completeness Delta Mag and Integration Time	Video I PDF
Shannon Dulz	Bonus 1 - Population Demographics Modeling	Video I PDF
Bijan Nemati	Bonus 2 - Photon Counting with EMCCDs	Video I PDF

The purpose of this workshop is to:

- Bring together the vibrant communities of mission and instrument designers and yield modelers to share their expertise
- Introduce fundamental concepts in exoplanet imaging yield modeling
- Present state of the art yield modeling tools available for use today and provide basic instruction in their use
- Discuss gaps in yield modeling approaches and potential future efforts to close them

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Open hack time for participants to start on their own problems with assistance from tool developers	50 min

Starlight Suppression Workshop Aug 8-10

https://exoplanets.nasa.gov/exep/events/457/towards-starlight-suppression-for-the-habitable-worlds-observatory-workshop/

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MEETINGS & EVENTS

Towards Starlight Suppression for the Habitable Worlds Observatory Workshop

Date:
August 8, 2023 - August 10, 2023

Location:
400 S. Wilson Ave. Pasadena, CA 91106
›› view map

REGISTER

August 8-10, 2023 Time TBA

Chairs: Brendan Crill (NASA/JPL) and Laura Coyle (Ball Aerospace)

NASA has begun planning for an ambitious program to develop the Habitable Worlds Observatory (HWO) – the first in a panchromatic suite of Great Observatories recommended by the Astro2020

Downloads

Draft Block Agenda

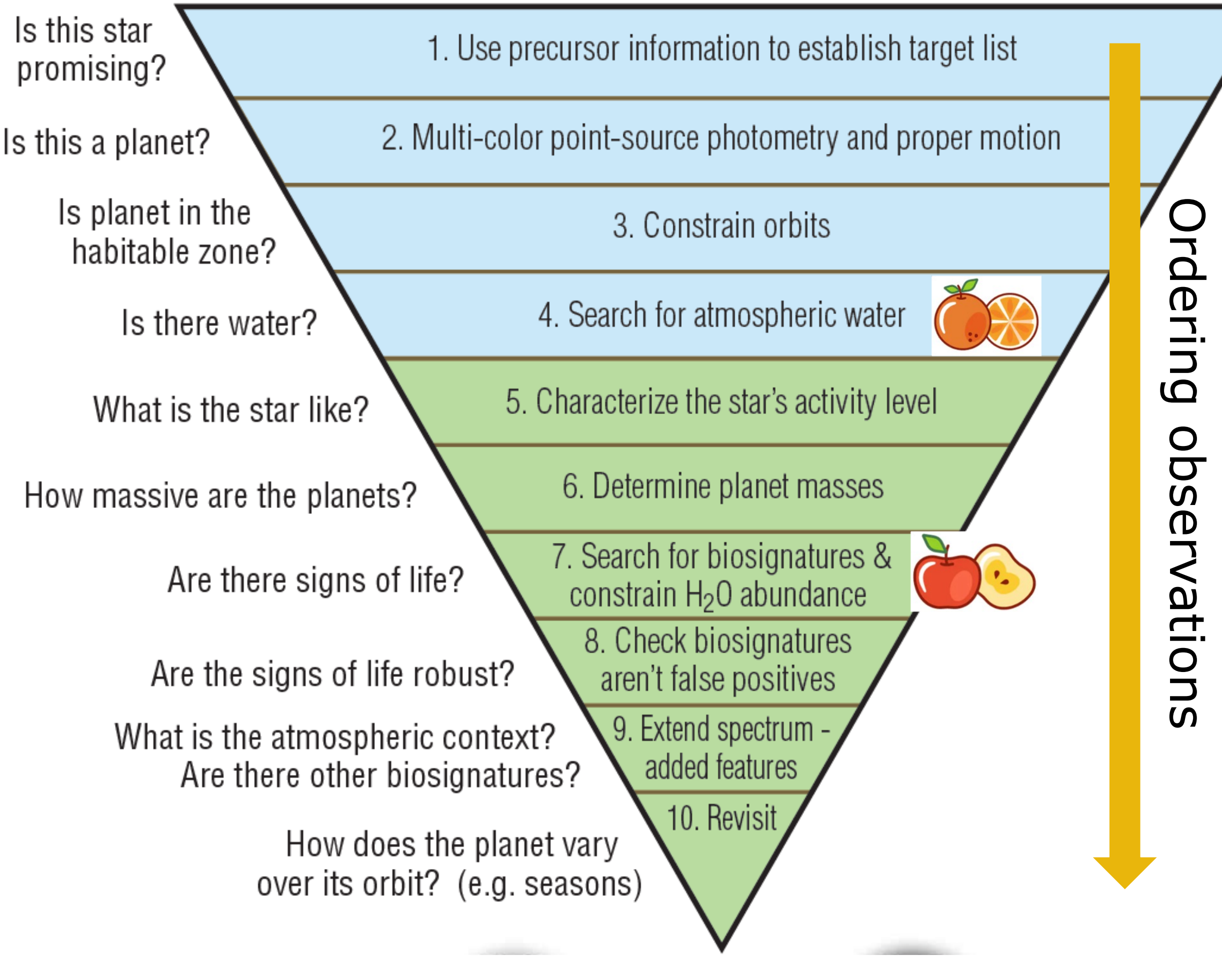
	Day 1 Tue Aug 8	Day 2 Wed Aug 9	Day 3 Thu Aug 10
Morning	Welcome Habitable Worlds Observatory Coronagraphy	Coronagraphy	Ultra-Stable Observatory
	Lunch	Lunch	Lunch
Afternoon	Coronagraphy	Starshade	Trades, Concerns, Plans Forward

Virtual Poster Abstract Submission (coming soon)

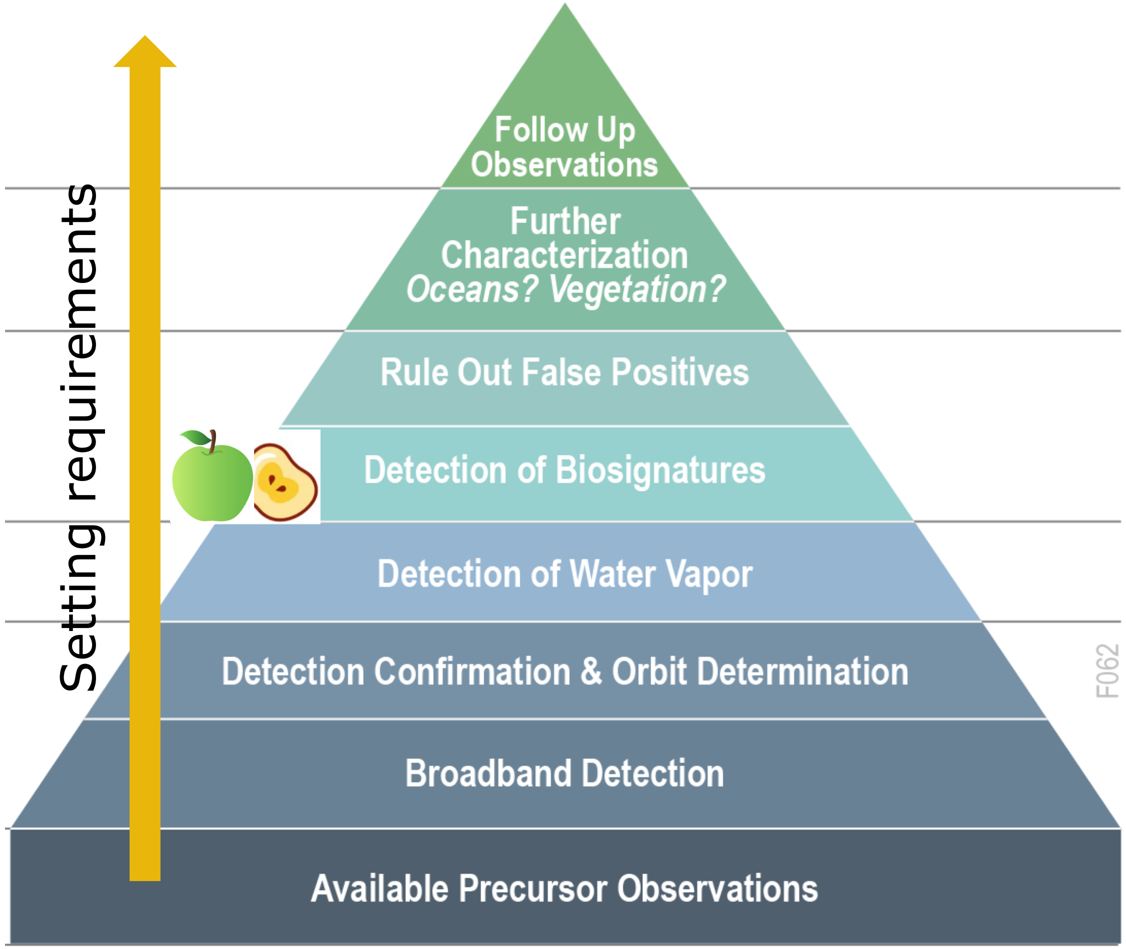
The agenda of talks will consist of invited summary talks, but we plan to accept

BACKUP

Observing Strategy impact on metrics



LUVOIR Final Report Fig. 3-11



HabEx Final Report Fig. 3.1-1

Exoplanet science yield model

NASA EXOPLANET EXPLORATION PROGRAM

Astrophysical Inputs
Star list
exozodi
Occurrence rate
Planet radii
albedo

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

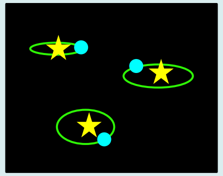
Mission Constraints
Lifetime
Observing allocation
Observatory orbit
Solar keepout
Observing scenario

Measurement model

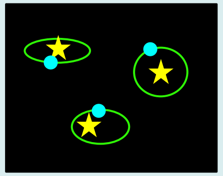
Instrument performance model

Mission model

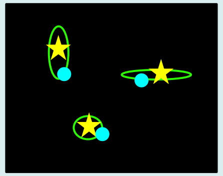
Universe n



Universe n+1



Universe n+2



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

Creates Monte Carlo ensembles of missions.

https://github/dsavransky/EXOSIMS

⟨n⟩ planets characterized

SNR =
Rs =
BW =
Wavelength =
In habitable zone