Jet Propulsion Laboratory
California Institute of Technology

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

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11 January 2024

Pre-decisional: for discussion purposes only

Yield Modeling Tools Resources

bit.ly/YieldTools_AAS234

EXOPLANET PROGRAM

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MEETINGS & EVENTS

Exoplanet Yield Modeling Tools Workshop Remix

Date:
January 11, 2024

Location:
Splinter Session of AAS in New Orleans, LA
›› view map

REGISTER

January 11, 2024; 9:00 – 11:00am CST

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

About this Workshop

Downloads

- Agenda (updated December, 4,2023)
- 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

Fundamental Concepts short-talks

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

Purpose

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

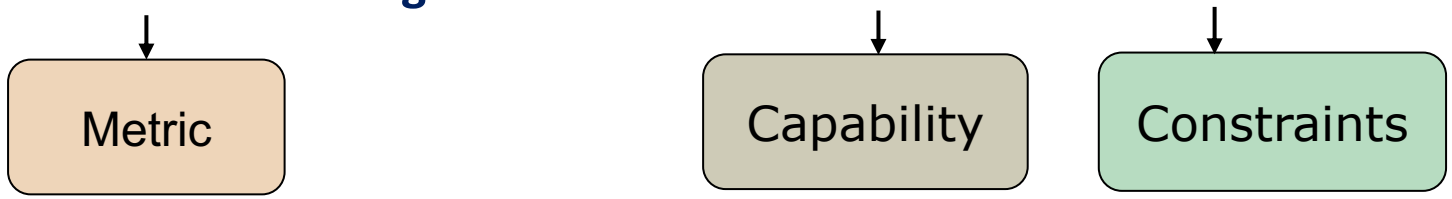
ExEP's Yield Modeling Tools Workshop Remix

bit.ly/YieldTools_AAS234

Time (CT)	Title	Speaker
9:00	Importance of yield tools for science and mission requirements	Rhonda Morgan (ExEP)
9:10	Detailed overview of EXOSIMS open-source mission simulation tool	Dmitry Savransky (Cornell)
9:40	Detailed overview of AYO (Altruistic Yield Optimization)	Chris Stark (GSFC)
10:00	Interactive tutorial of EXOSIMS	Rhonda Morgan (ExEP)
10:20	Interactive tutorial of ExoVista	Alexander Howe (GSFC)
10:50	Discussion of priorities for future model improvement	Rhonda Morgan (ExEP)

What is science performance (yield) modeling?

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



- **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

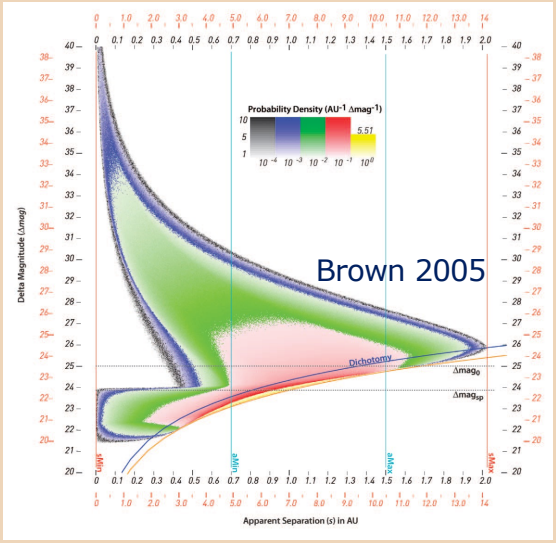
Instrument model

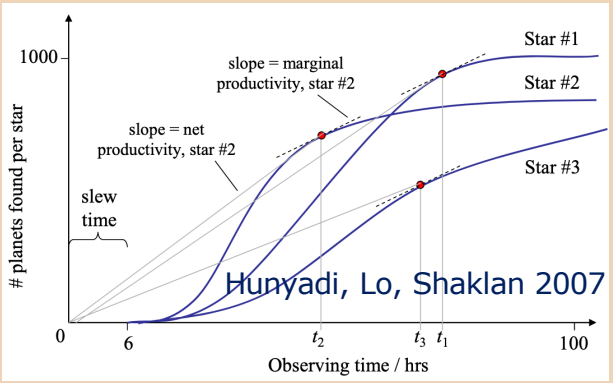
Optics
Photometry
Starlight suppression
~mission dynamics

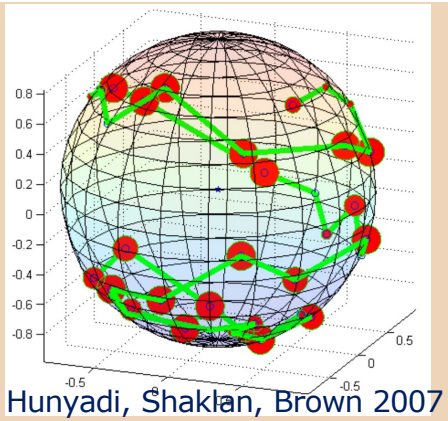
Mission model

- 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

TPF







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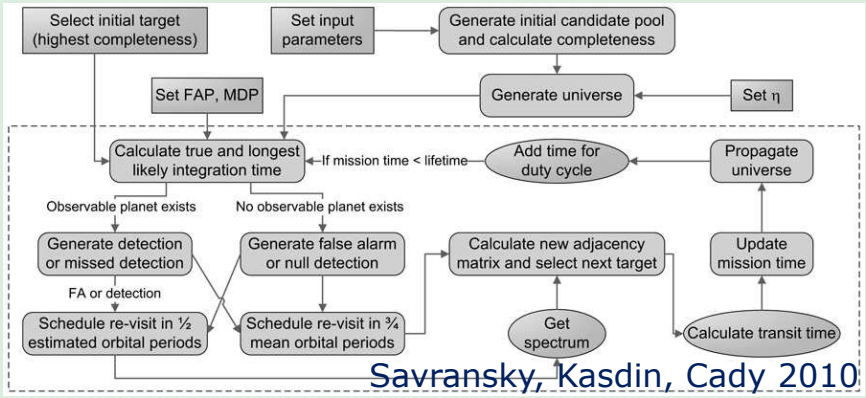
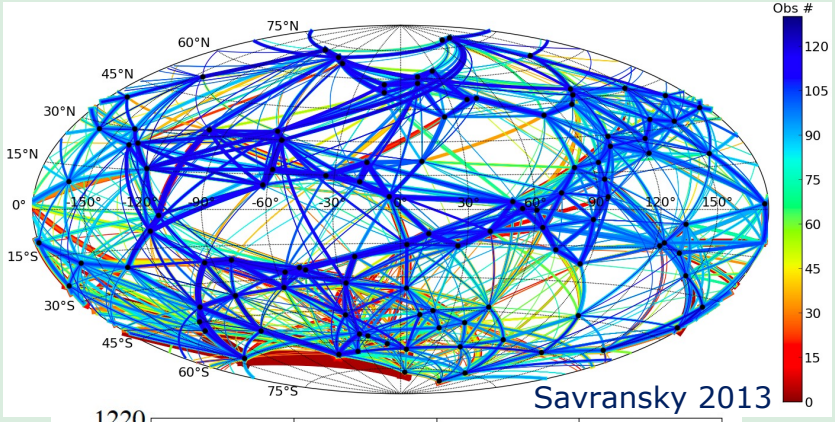
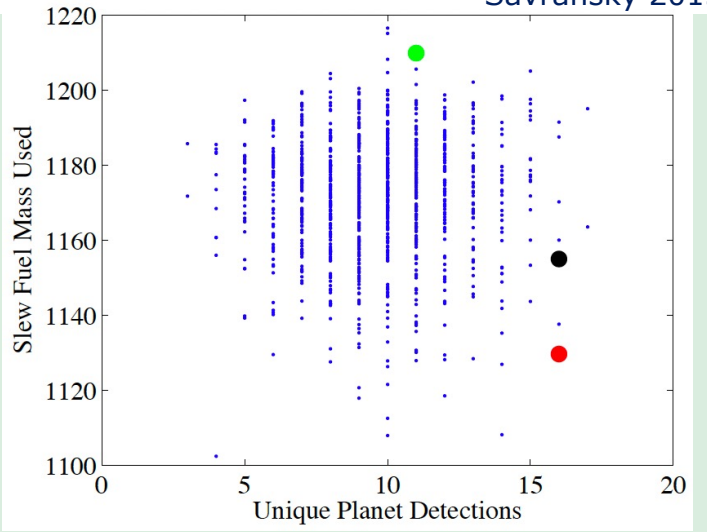
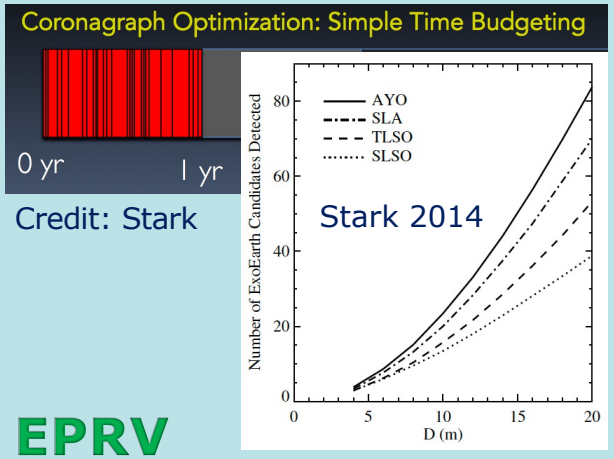
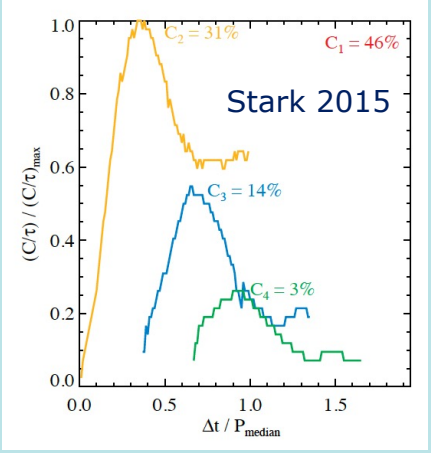




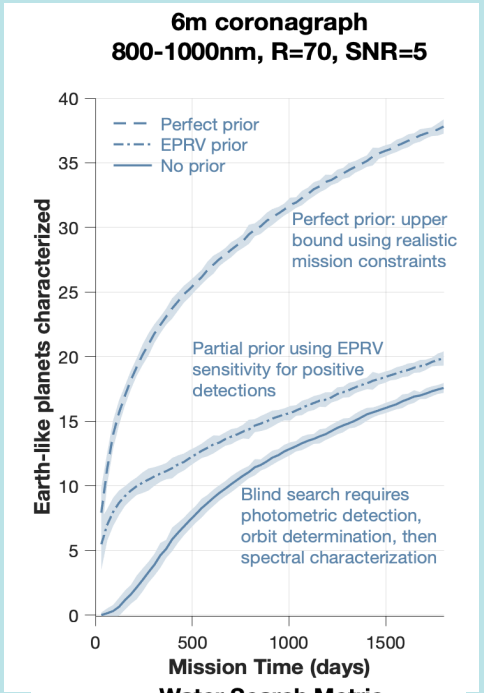


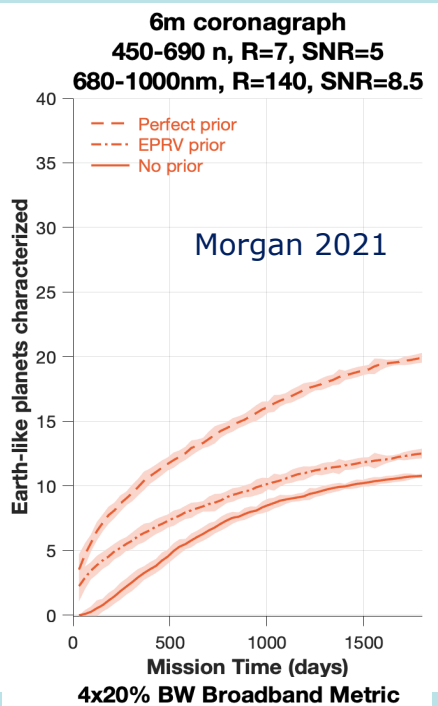
ATLAST, LUVOIR, HabEx



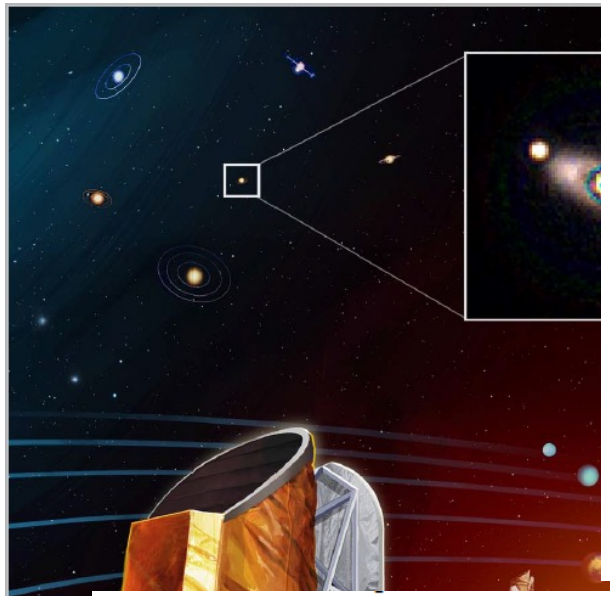


EPRV





Exoplanet Probe Studies (2015)



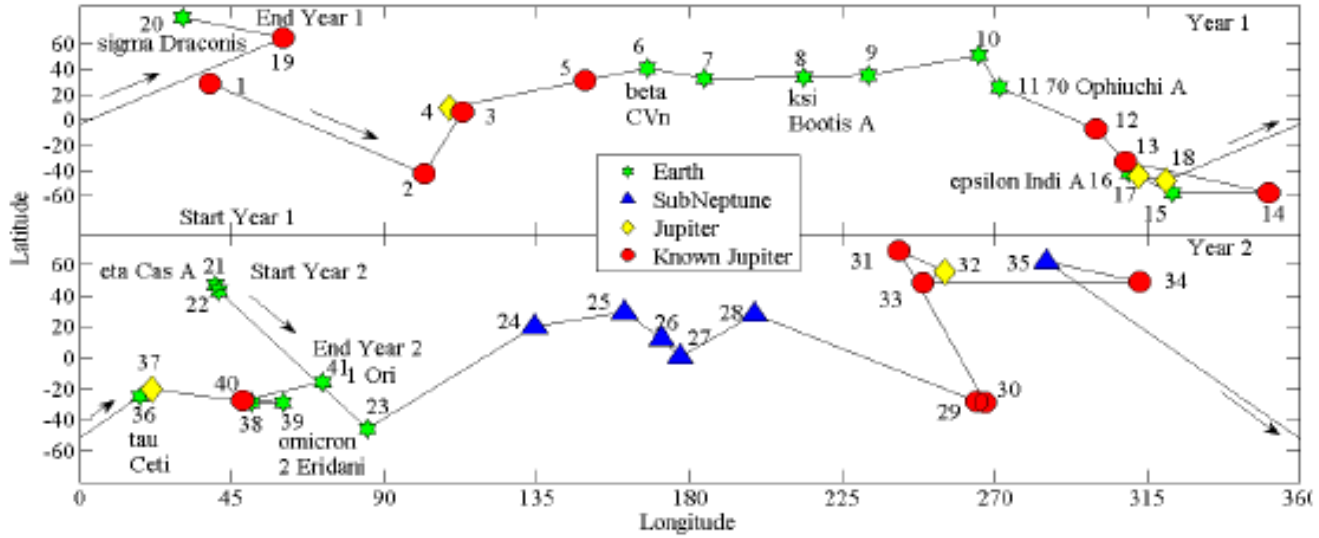


Figure 5.3-1. Observing sequence for Case 1, Dedicated Mission, Earth twins in HZ. Coordinates are ecliptic longitude and latitude.

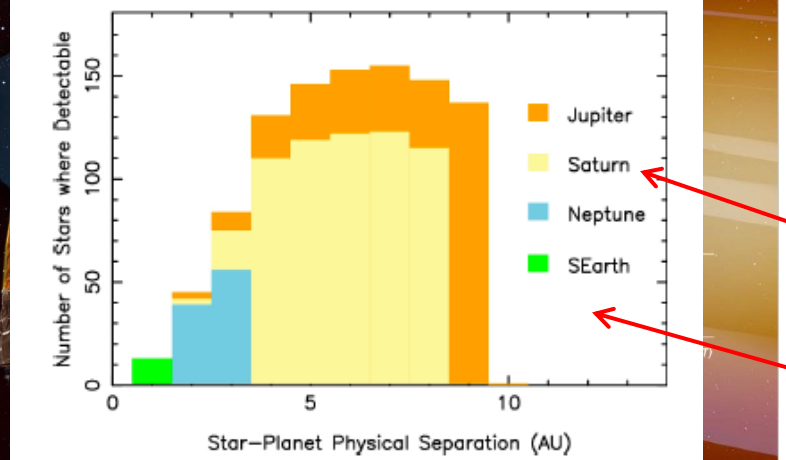


Figure ES-4. Exo-C exoplanetary search space among nearby stars, as a function of planet size and orbit.

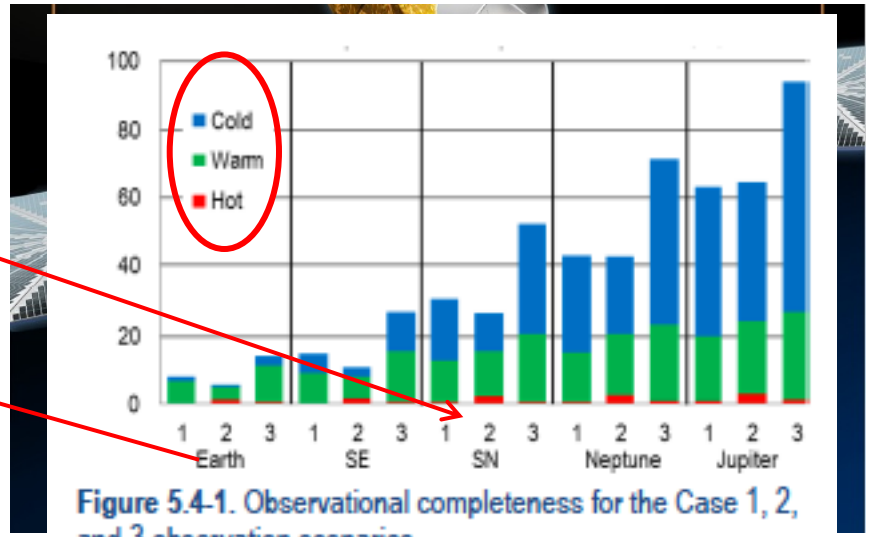
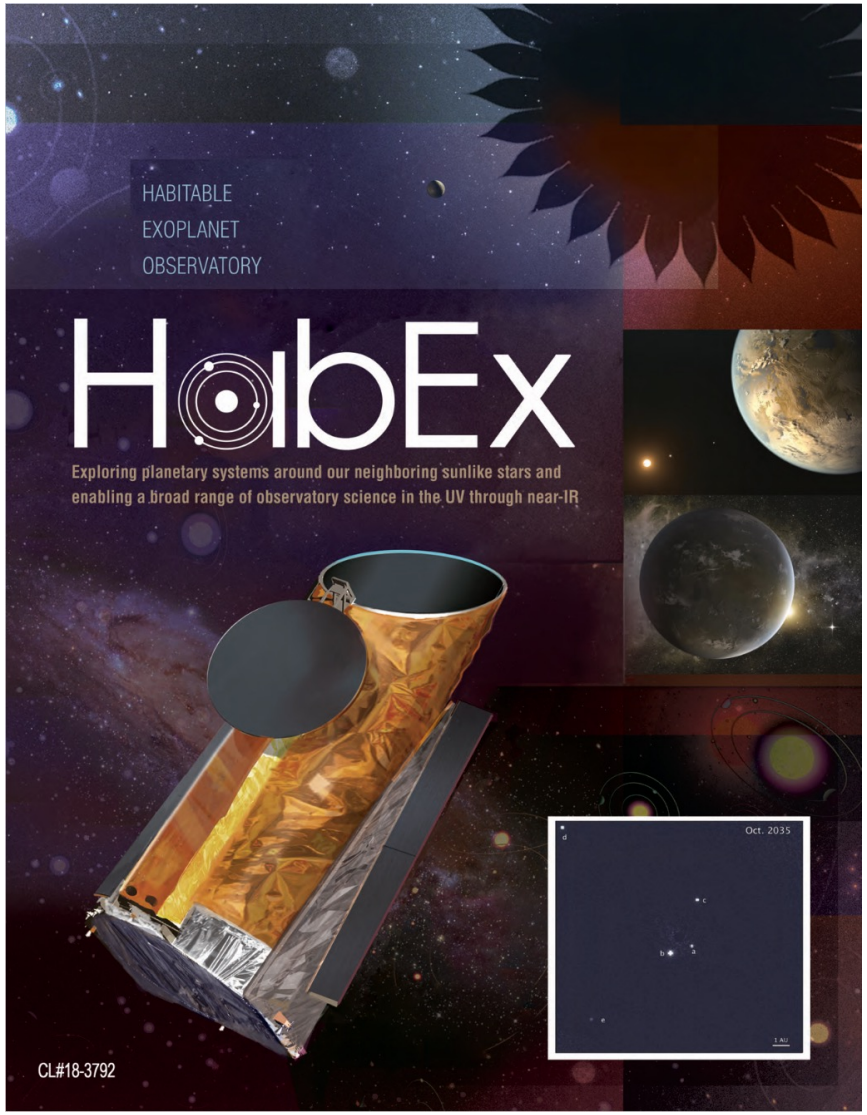
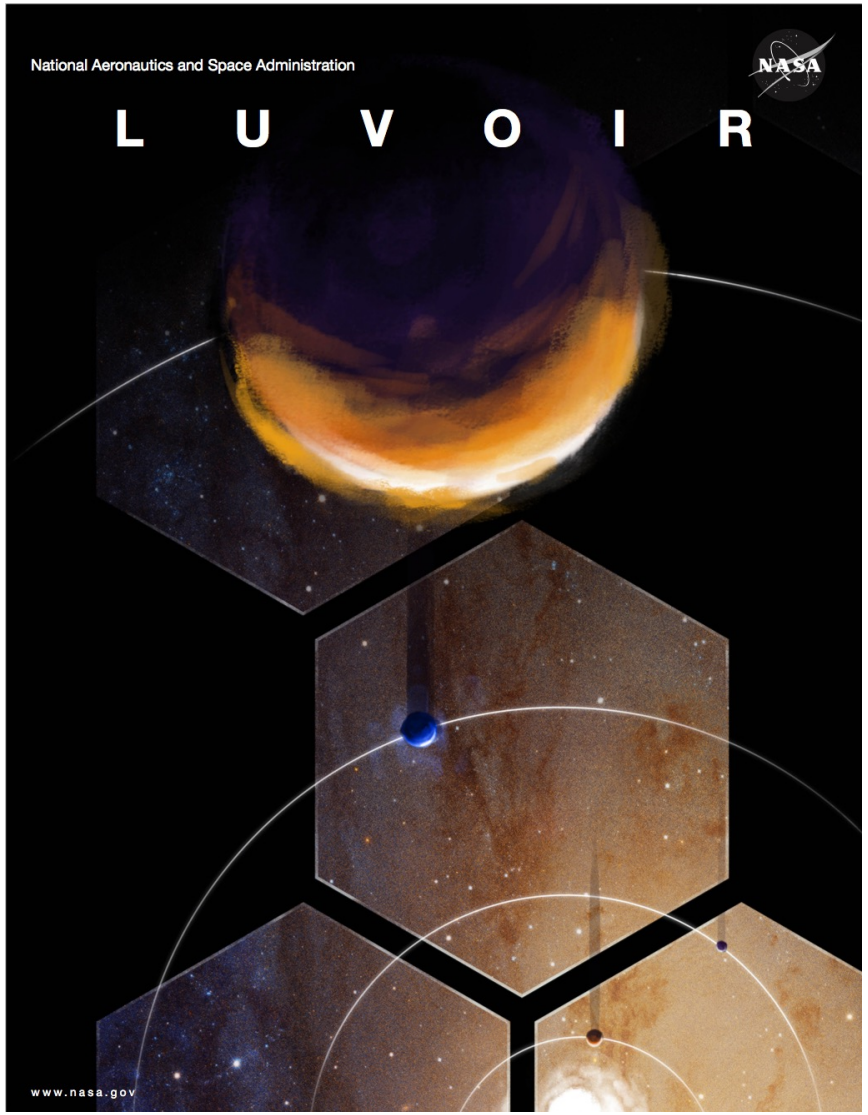
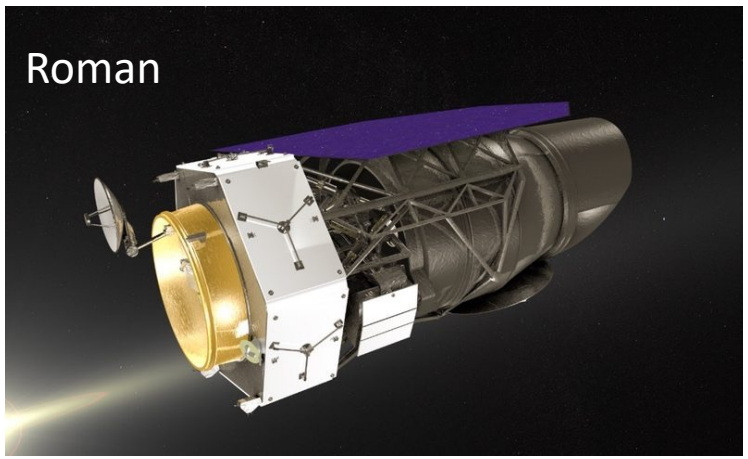


Figure 5.4-1. Observational completeness for the Case 1, 2, and 3 observation scenarios.

Exoplanet Direct Imaging Concept Missions







Standard Definitions and Evaluation Team

https://bit.ly/StandardsTeam

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

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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.

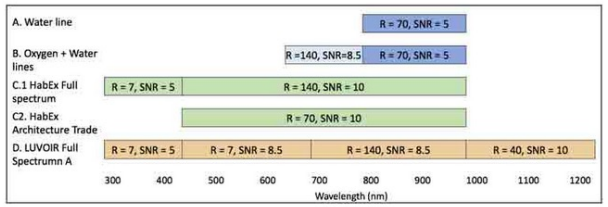


Figure 1. Characterization metric A facilitates a quick search for the water line at 940 nm with a

Documents

- SDET Charter
- SDET Final Report

Cases

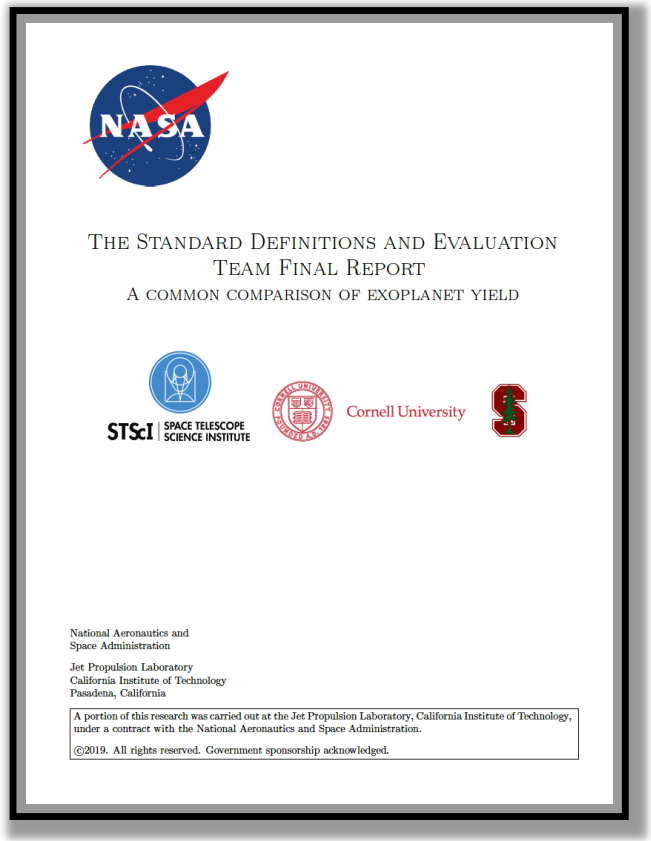
- Case 1: HabEx 4H hybrid, metric C1
- Case 2: LUVOIR B, metric A
- Case 3: HabEx 4C, metric C2
- Case 4: HabEx 4S, metric C2

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

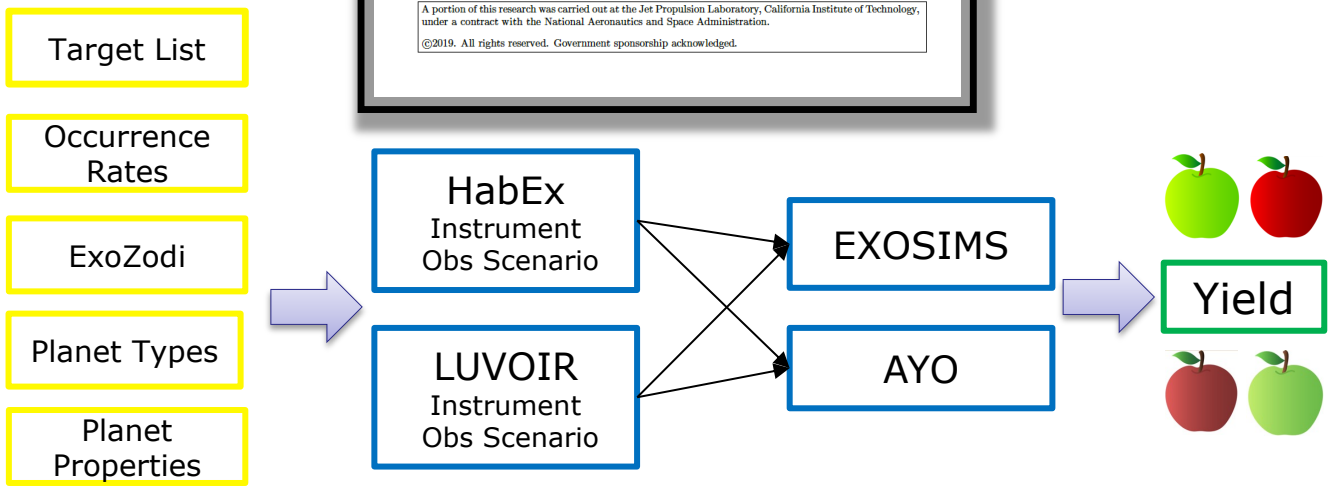
STScI SPACE TELESCOPE SCIENCE INSTITUTE | Cornell University

National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

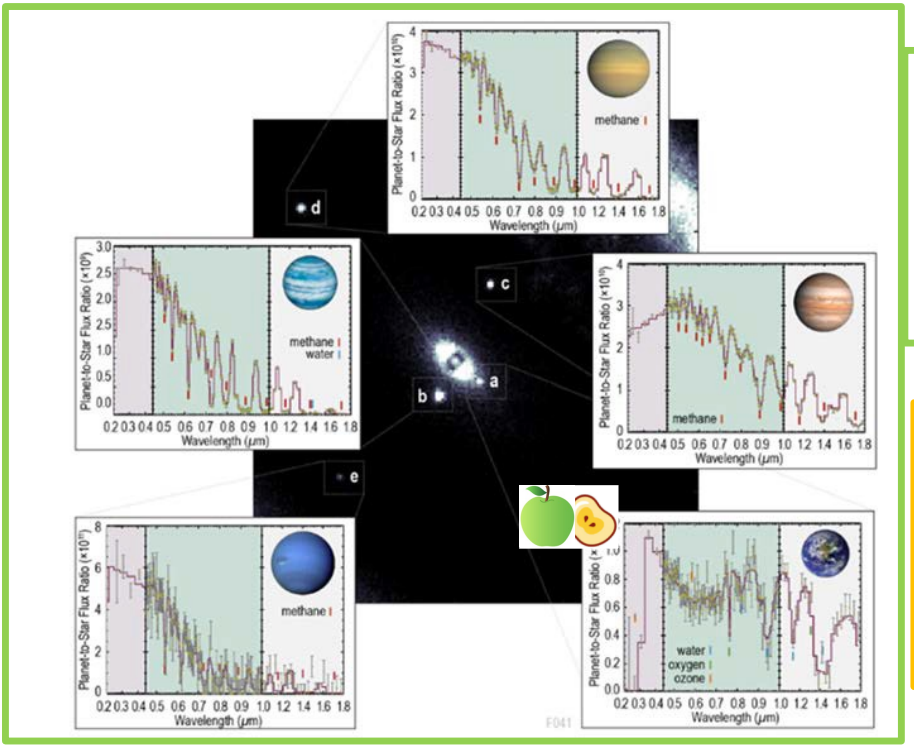
A portion of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

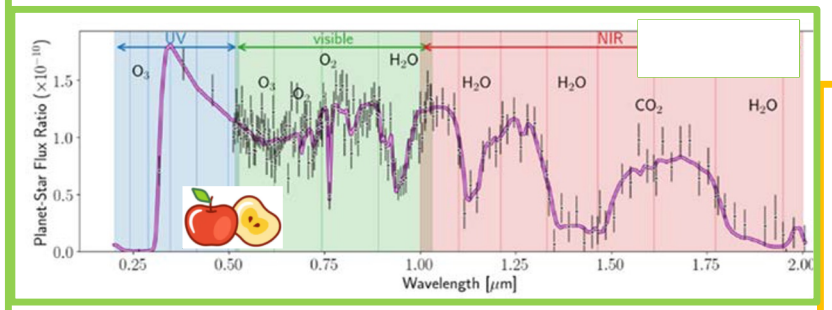
Thorough description of astrophysical inputs

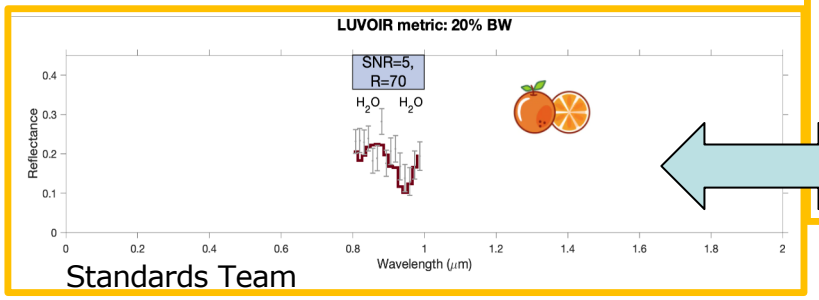


Astro2020 recommendation for exoplanets

- 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”

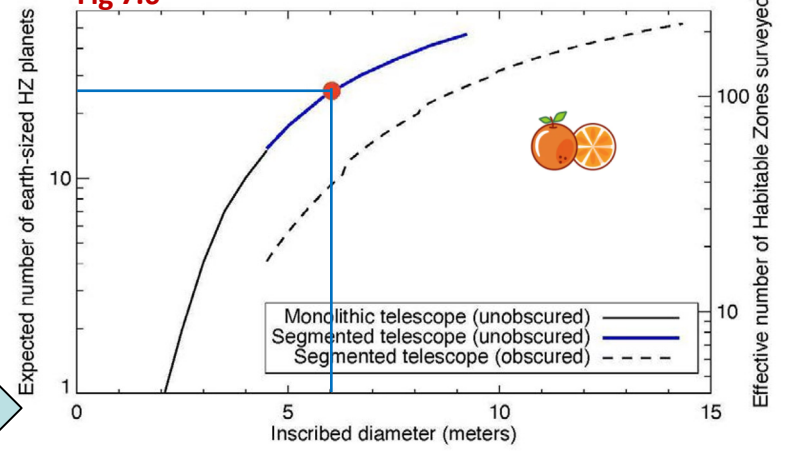






Standards Team

Fig 7.6



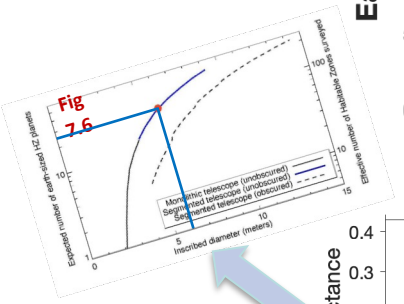
- Building on the work done by large concept studies and the Standards Evaluation Team, we can iterate, address nuances, and incorporate progress to map exoplanet science goals to planet characterization to metrics

This will not be easy!

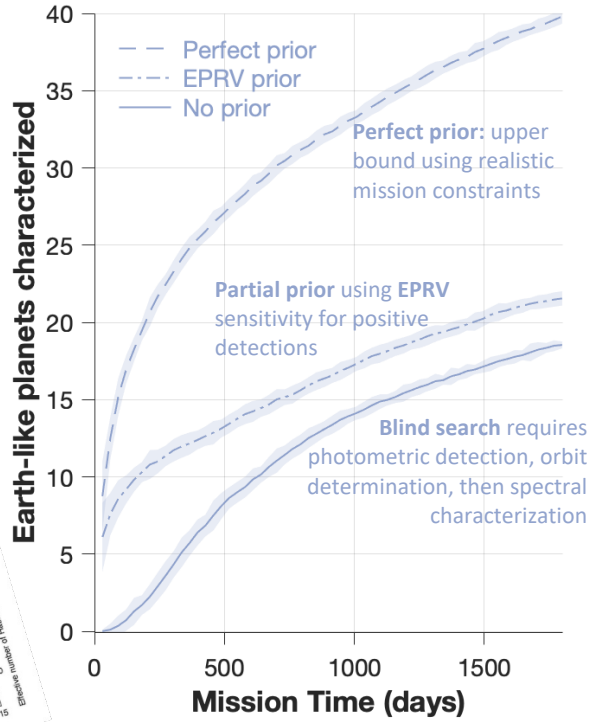
- Characterization is complicated and will likely involve multiple measurements. … This means we’ll have more than one metric

Different yield metrics reveal different sensitivities

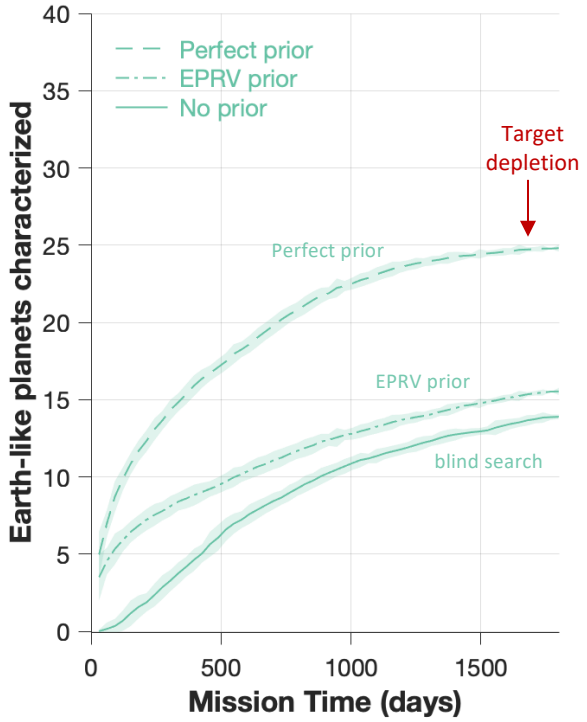
Observing scenario, SNR, spectral resolution, number of sub-spectra, and precursor knowledge effect yield.



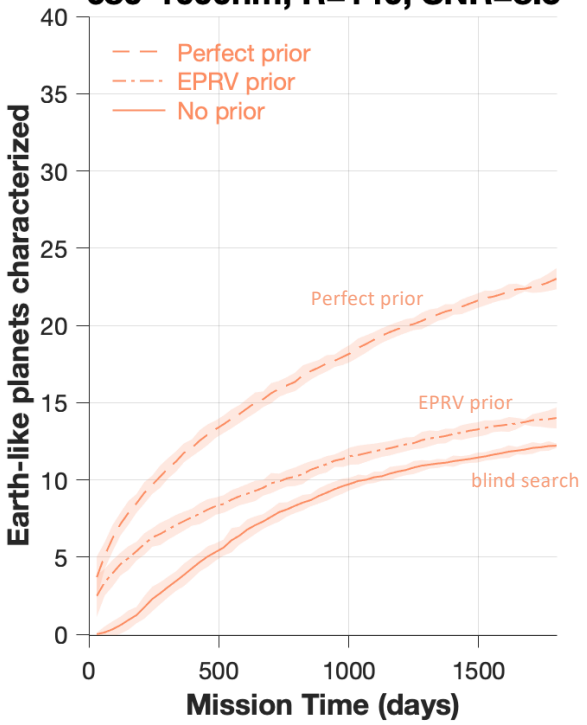
6m coronagraph
800-1000nm, R=70, SNR=5

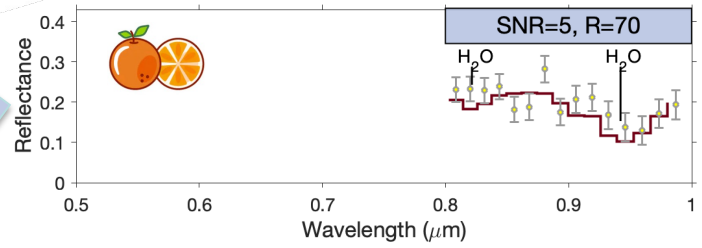


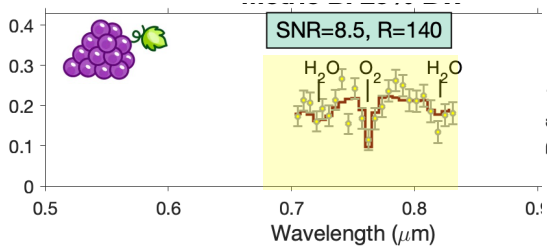
6m coronagraph
680-830nm, R=140, SNR=8.5

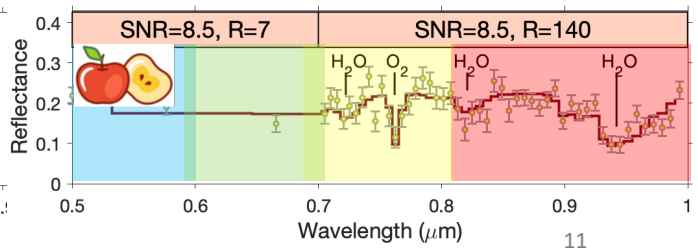


6m coronagraph
450-690 n, R=7, SNR=5
680-1000nm, R=140, SNR=8.5





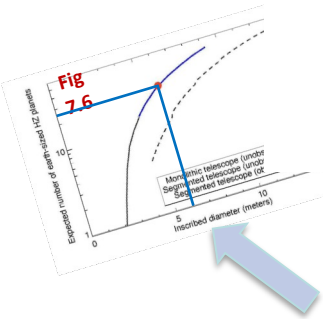




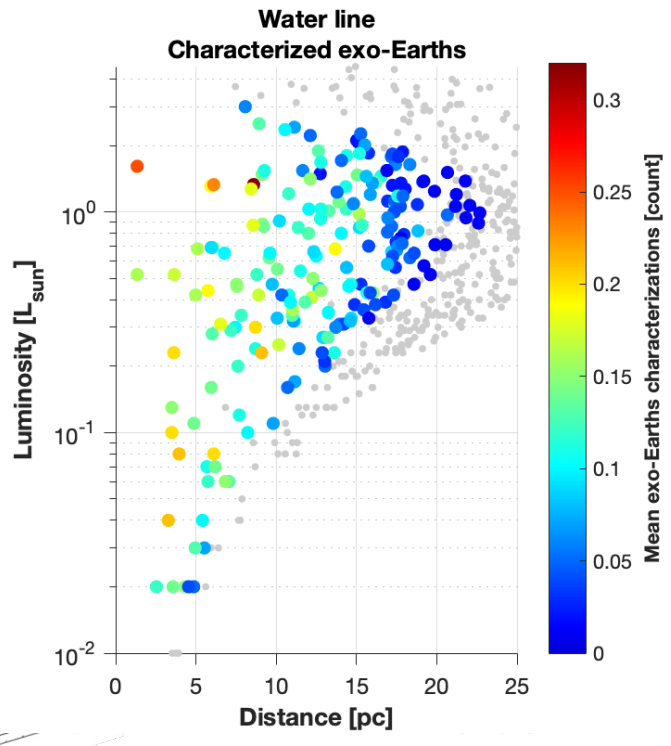
More comparisons of metric impact on architectures in Morgan et al. 2021
https://doi.org/10.1117/1.JATIS.7.2.021220

Different yield metrics reveal different sensitivities

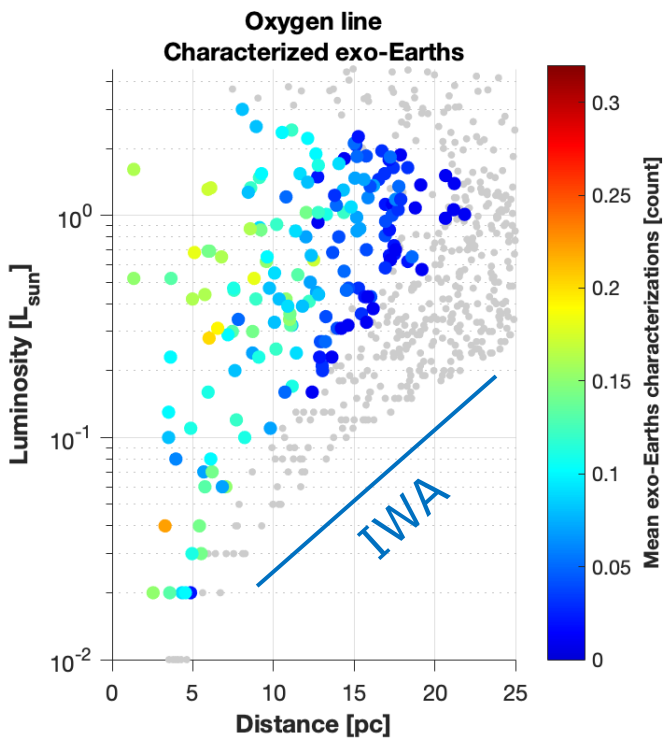
Observing scenario, SNR, spectral resolution, number of sub-spectra, and precursor knowledge effect yield.



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



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



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450-690 n, R=7, SNR=5
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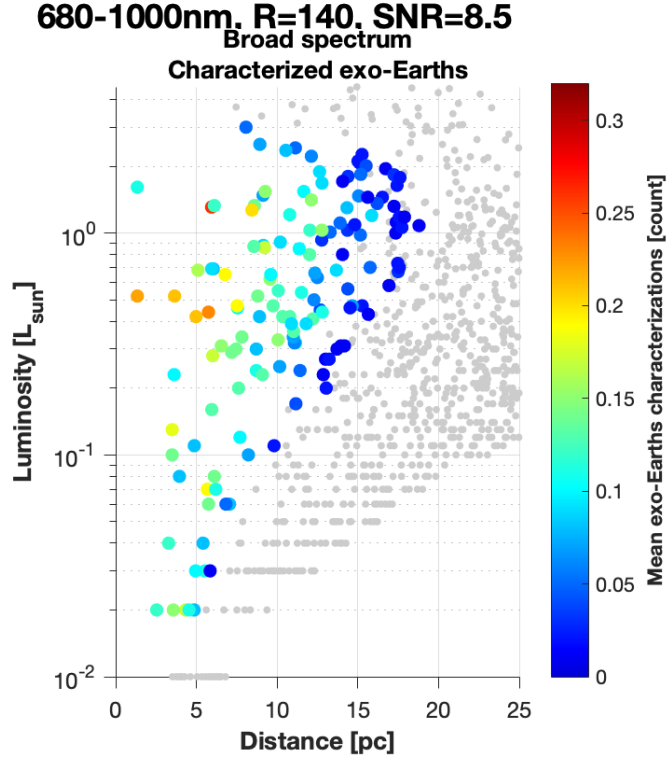
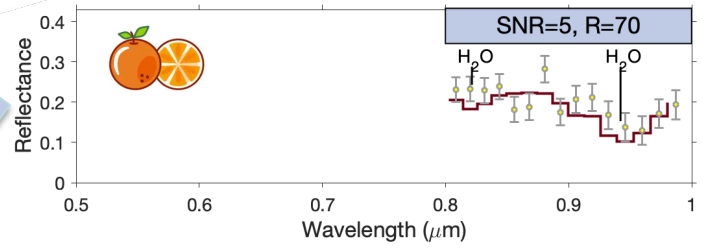
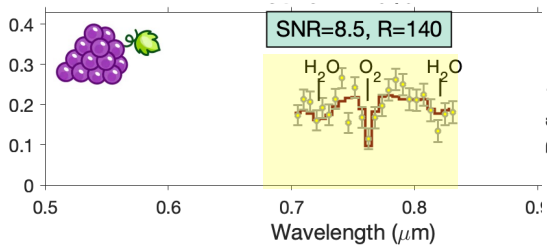
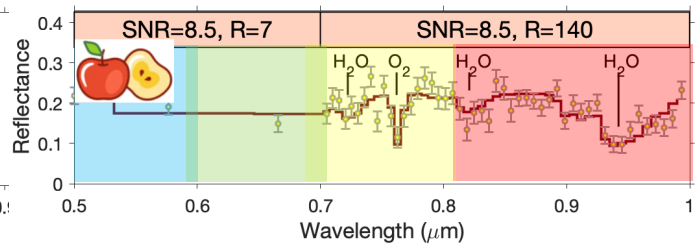




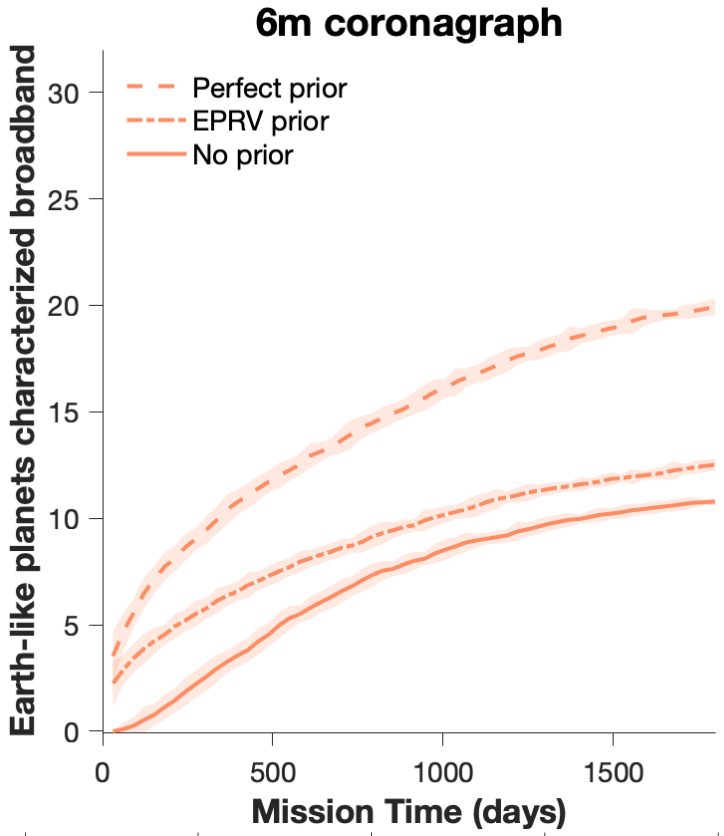


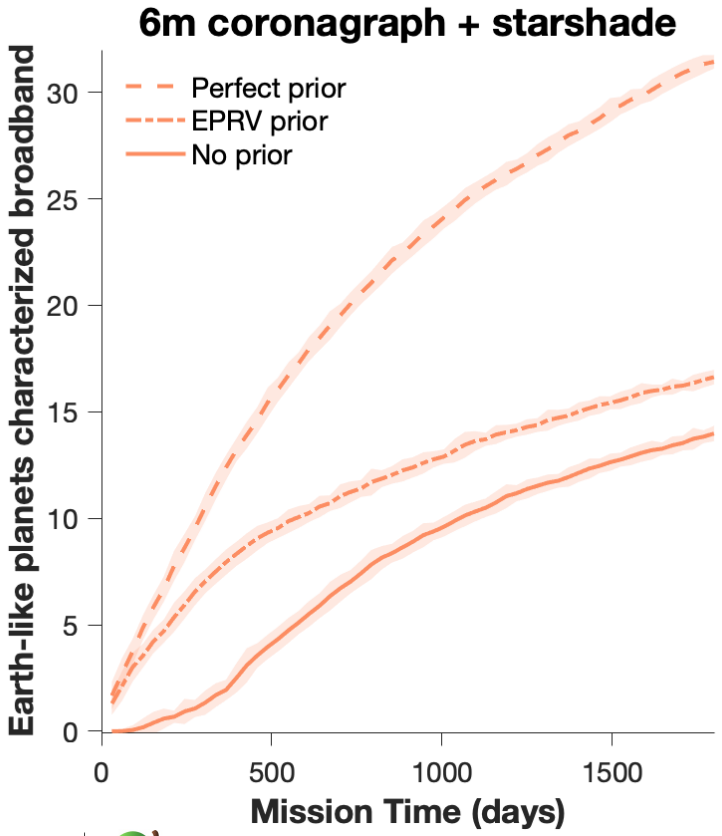


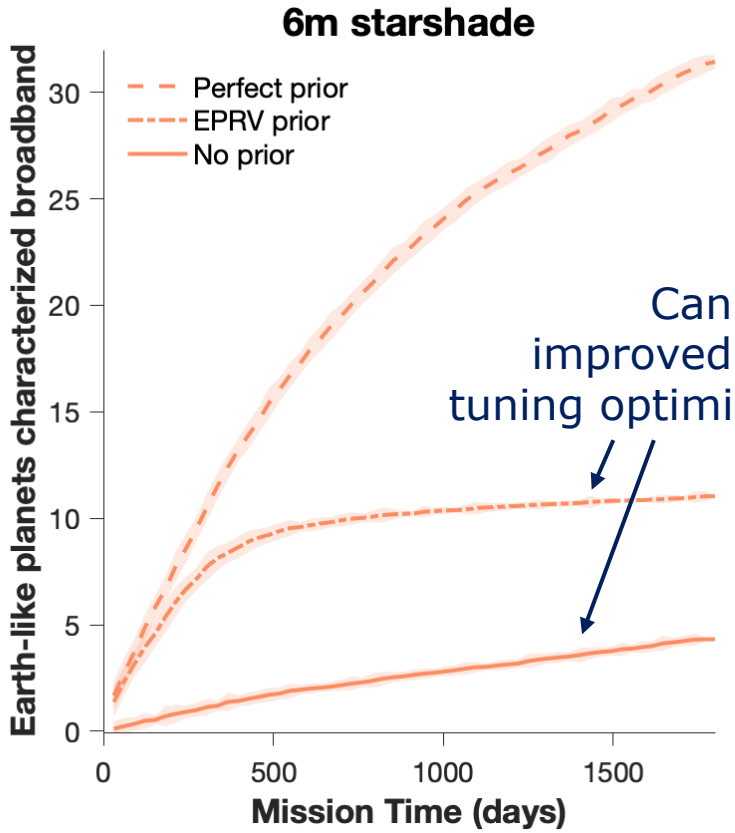
More comparisons of metric impact on architectures in Morgan et al. 2021
https://doi.org/10.1117/1.JATIS.7.2.021220

Yield with broadband metric for three architectures

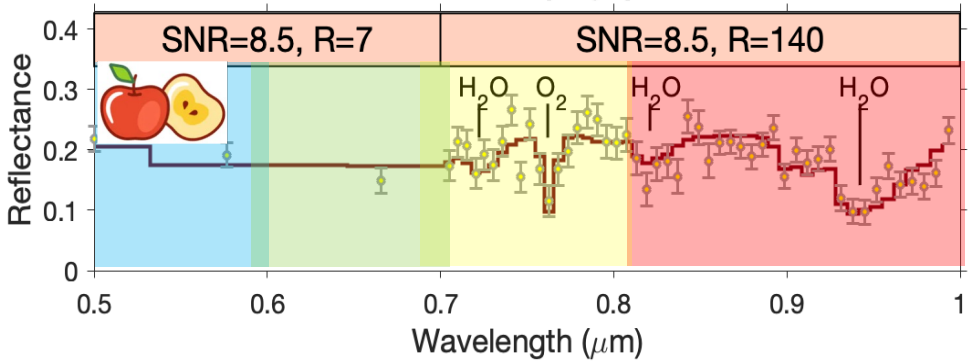
The HabEx 4m architectures were scaled to 6m and starshade from 52 m to 72m

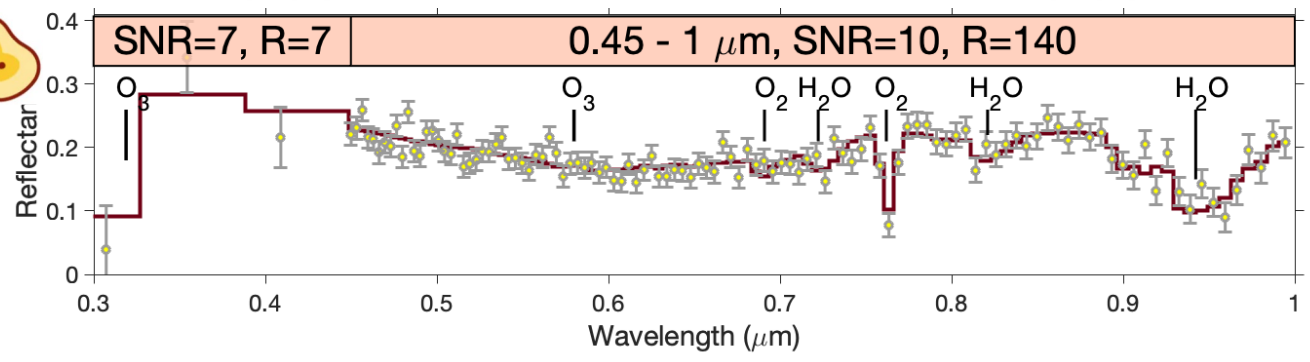




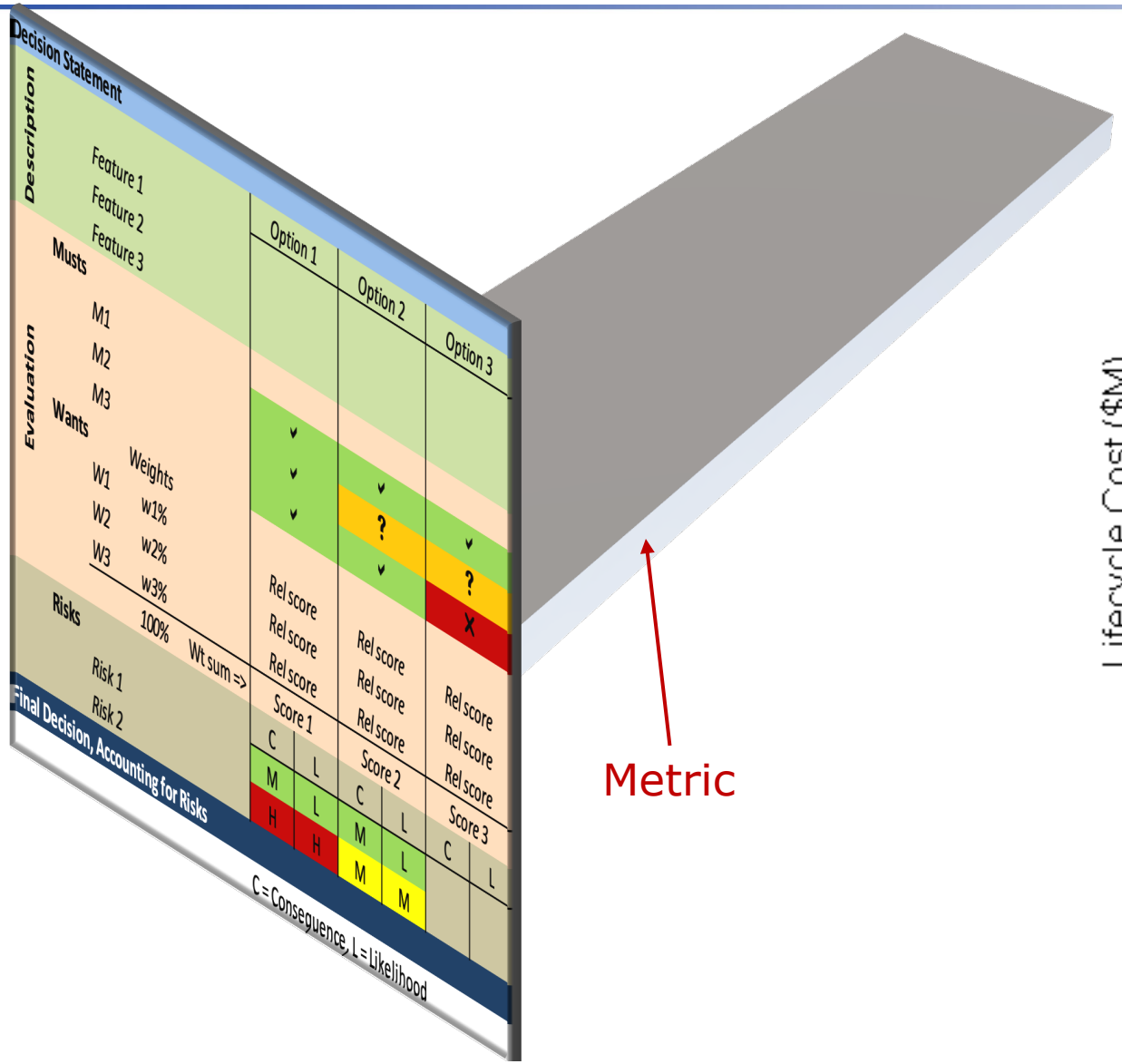


Can be improved by tuning optimizer



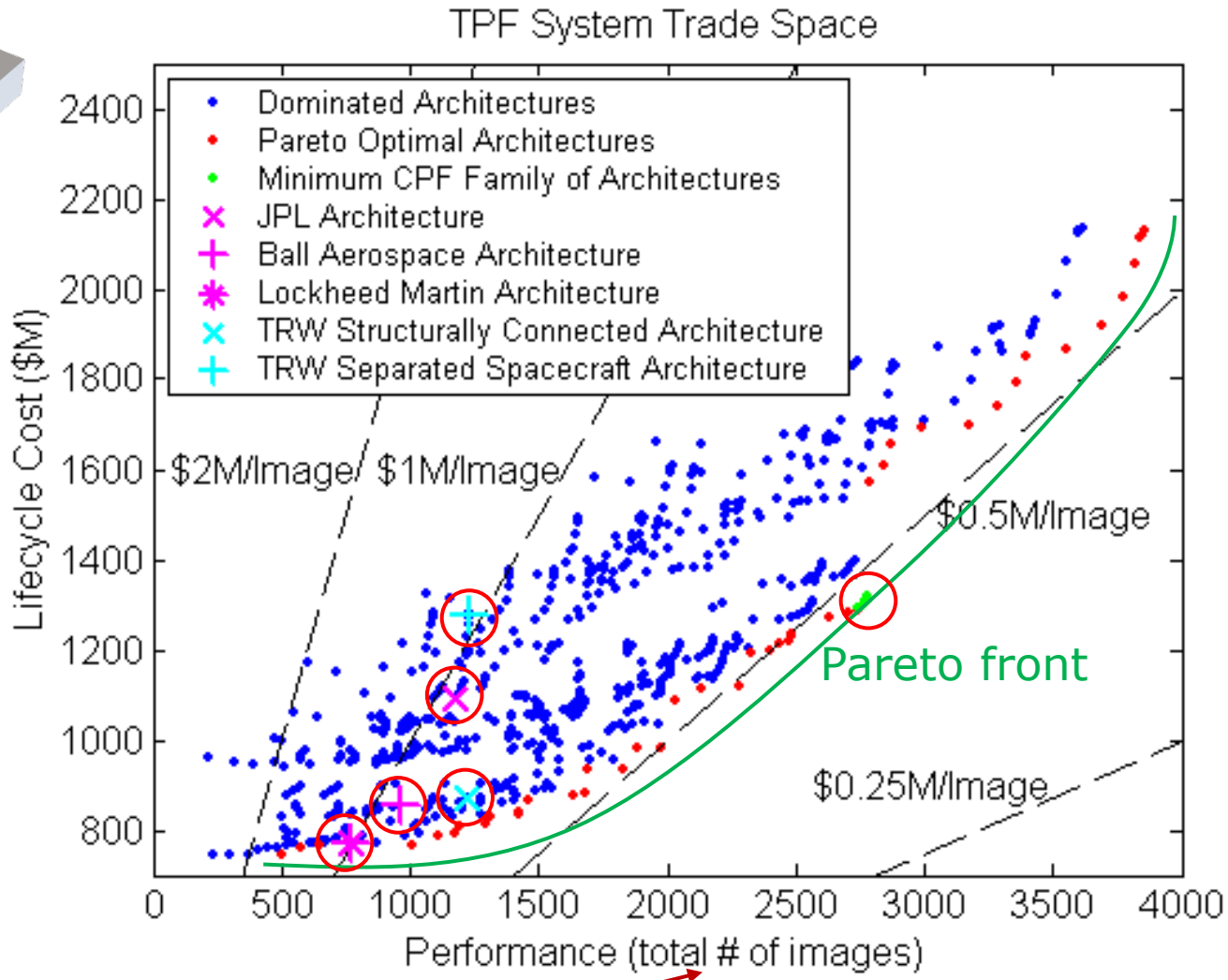


Metrics are used to quantify trades



Metric

Decision Matrix adapted from Kepner and Tregoe, 1965



Metric

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

Table 2: *Origins* Science Traceability Matrix

NASA Science Goals	*Origins* Science Goal/ Question	Science Objectives	Science Requirements		Instrument Requirements				Mission Requirements	
			Science Observable	Measurement Requirement	Parameter	Technical Requirement	Instr	CBE Performance	Driver	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 solid angle field-of-view)		O	3.0m.	ility and systematic error control	• 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 deg^2/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 deg^2 2 μm imaging from JWST NIRCAM, a ~500 deg^2 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 deg^2 in 400 hours. 3.8 μJy (5σ) at 250 μm over 1 deg^2 in 25 hours.		0.2 μJy (5σ) at 50 μm over 1 deg^2 in 400 hours. 0.6 μJy (5σ) at 250 μm over 1 deg^2 in 25 hours.		
					Polarization sensitivity	1% (3σ) in linear and circular		0.1% (3σ), 1 degree in		

Science model

Measurement model

Instrument performance model

Mission model

BACKUP

ExEP's Yield Modeling Tools Workshop Remix

AAS243 Thursday, June 11, 9-11 am Central

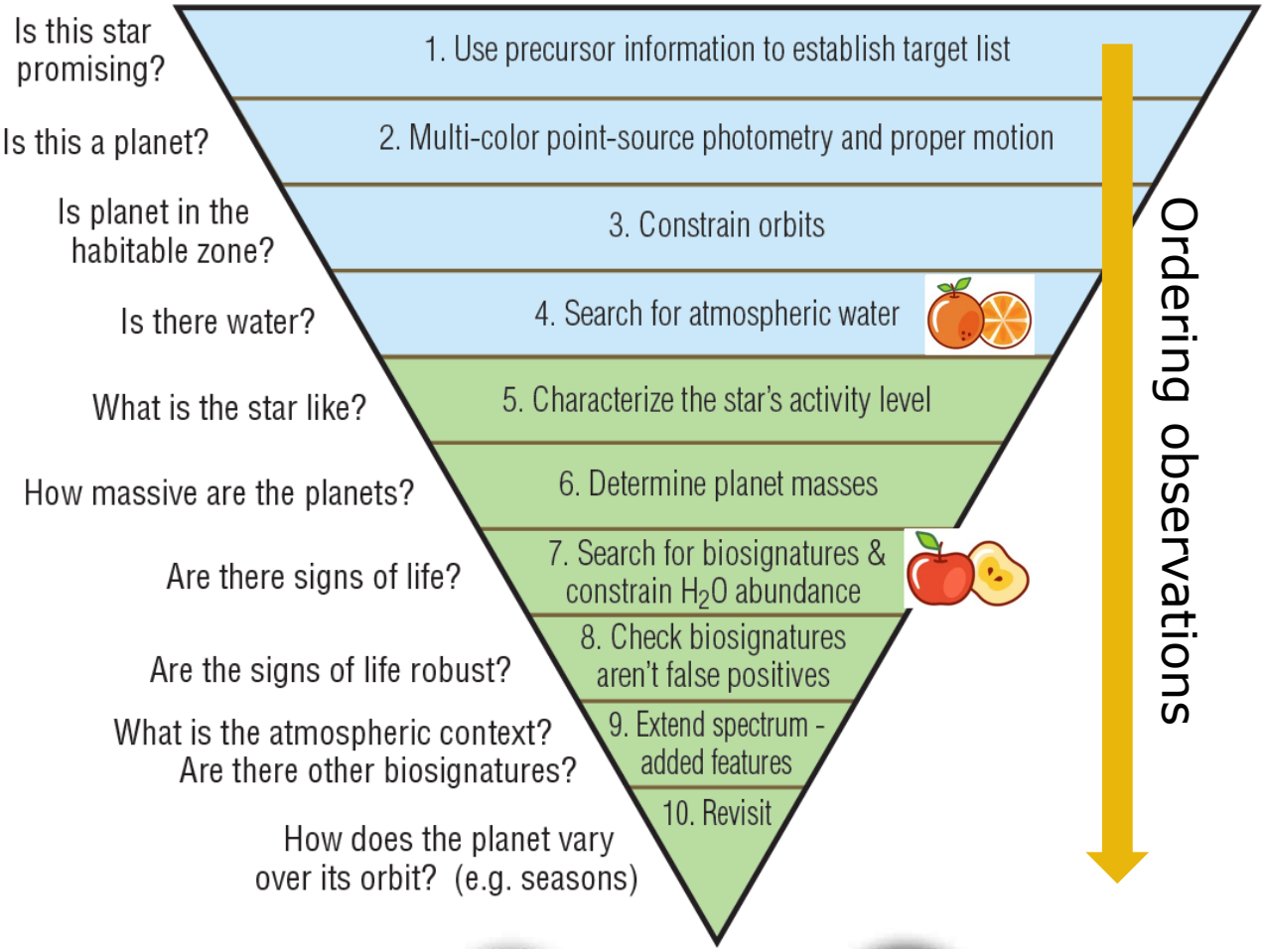
Time (CT)	Title	Speaker
9:00	Importance of yield tools for science and mission requirements	Rhonda Morgan (ExEP)
9:10	Detailed overview of EXOSIMS open-source mission simulation tool	Dmitry Savransky (Cornell)
9:40	Detailed overview of AYO (Altruistic Yield Optimization)	Chris Stark (GSFC)
10:00	Interactive tutorial of EXOSIMS	Rhonda Morgan (ExEP)
10:20	Interactive tutorial of ExoVista	Alexander Howe (GSFC)
10:50	Discussion of priorities for future model improvement	Rhonda Morgan (ExEP)

NEW ORLEANS

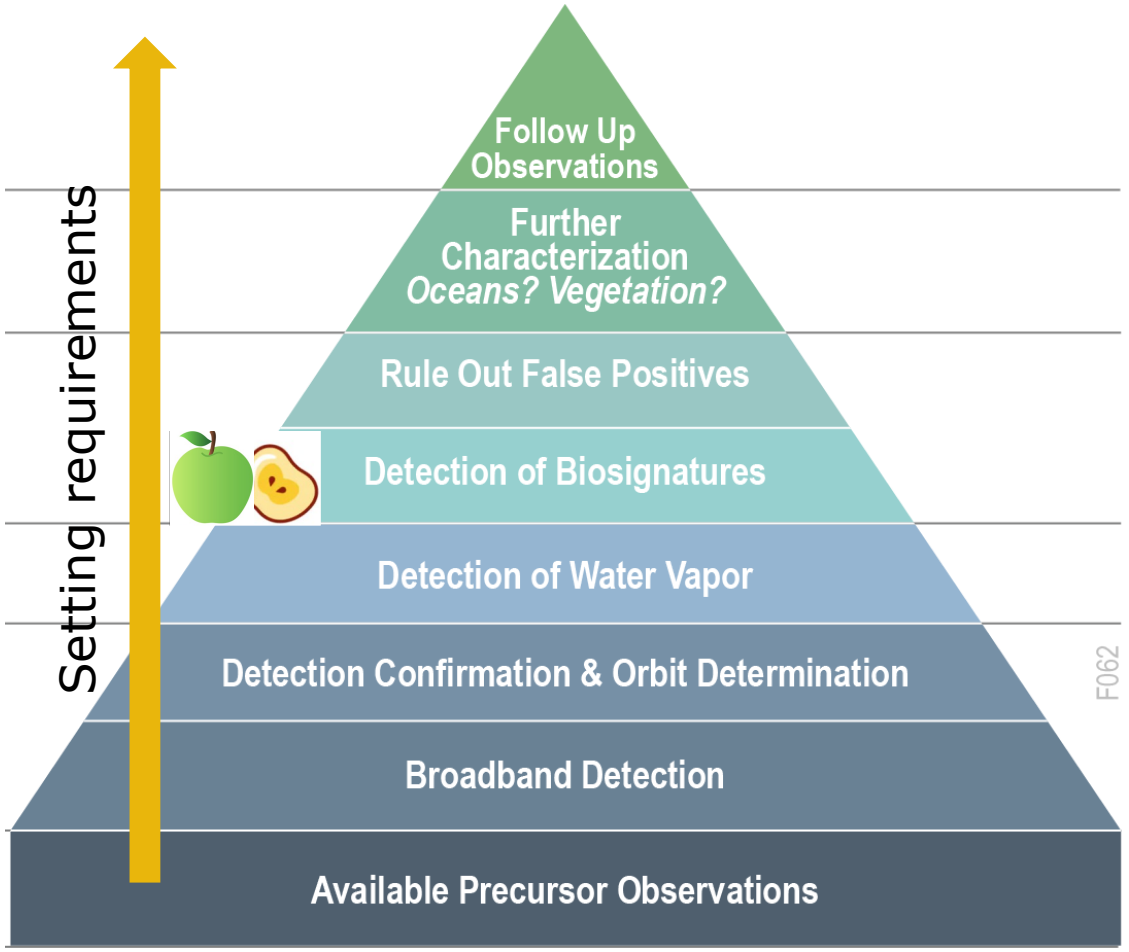
Convention Center Room : 219

Register & WebEx : bit.ly/YieldTools_AAS234

Observing Strategy impact on metrics



LUVOIR Final Report Fig. 3-11



HabEx Final Report Fig. 3.1-1

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

⟨n⟩ planets characterized

SNR =
Rs =
BW =
Wavelength =
In habitable zone

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

Creates Monte Carlo ensembles of missions.

https://github/dsavransky/EXOSIMS