Precursor Science for Metrics

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Pre-decisional: for discussion purposes only

PROCESS: Great Observatories Mission & Technology Maturation

INPUT

Flagship Proposals

- LCIT: Cost and schedule risk
- Concepts: Design options, capabilities
- Technology requirements & plans
- Targeted science

Decadal Survey

- Science prioritization
- Programmatic cost & timing box
- Execution risk box

Wavelength Coverage

- Capabilities: existing, planned, sun-setting

Burndown GO Program Risk:

- Iterate Science Goals using teams to trade science and performance.
- Perform scientific simulations to define key objectives
- Develop converging, mission-specific technical capabilities using development roadmaps, subsystem-level demonstrations, and demonstration of production processes of sufficient scale, with multi-functional teams of scientists, technologists & industrial partners
- Define Mission Architecture. Trade achievable capabilities
- Transition to design by supporting the Flagship Program Office

Leverage Technology & Build Foundations

- Enable smaller projects (Explorers to Probes) to address wavelength gaps, vet new technologies, mature Technology Readiness Level or Manufacturing Readiness Level
- Manage GO Grants Program to build science base for long-cycle capabilities

OUTPUT

- Mission Architecture with supporting technologies, science objectives, flagship capabilities that fit into decadal science per cost box
- Trades strategy to drive technology development to support Decadal constraints boxes
- Transition processes
- Technology roadmaps, timelines and mature technologies
- Wavelength gap forecasts & coverage strategy, incl. program size

Fig 7.3
Astro2020

Metrics are important
The Value and utility of metrics

- **Metrics provide a yardstick to iterate on science goals and objectives**
  - They quantify the science
    - Science goal -> observable -> science requirement
  - They include or can be used to derive SNR, wavelength range, sensitivity, spectral resolution, etc
  - Quantify the uncertainty in the measurement and the science
    - Particularly challenging for surveys (how much does uncertainty decrease for loss of the n+1 target?)
    - Propagate the uncertainty of astrophysics inputs through observing models to uncertainty in science performance

Uncertainty in astrophysical inputs

Table 2. Adopted Astrophysical Parameters

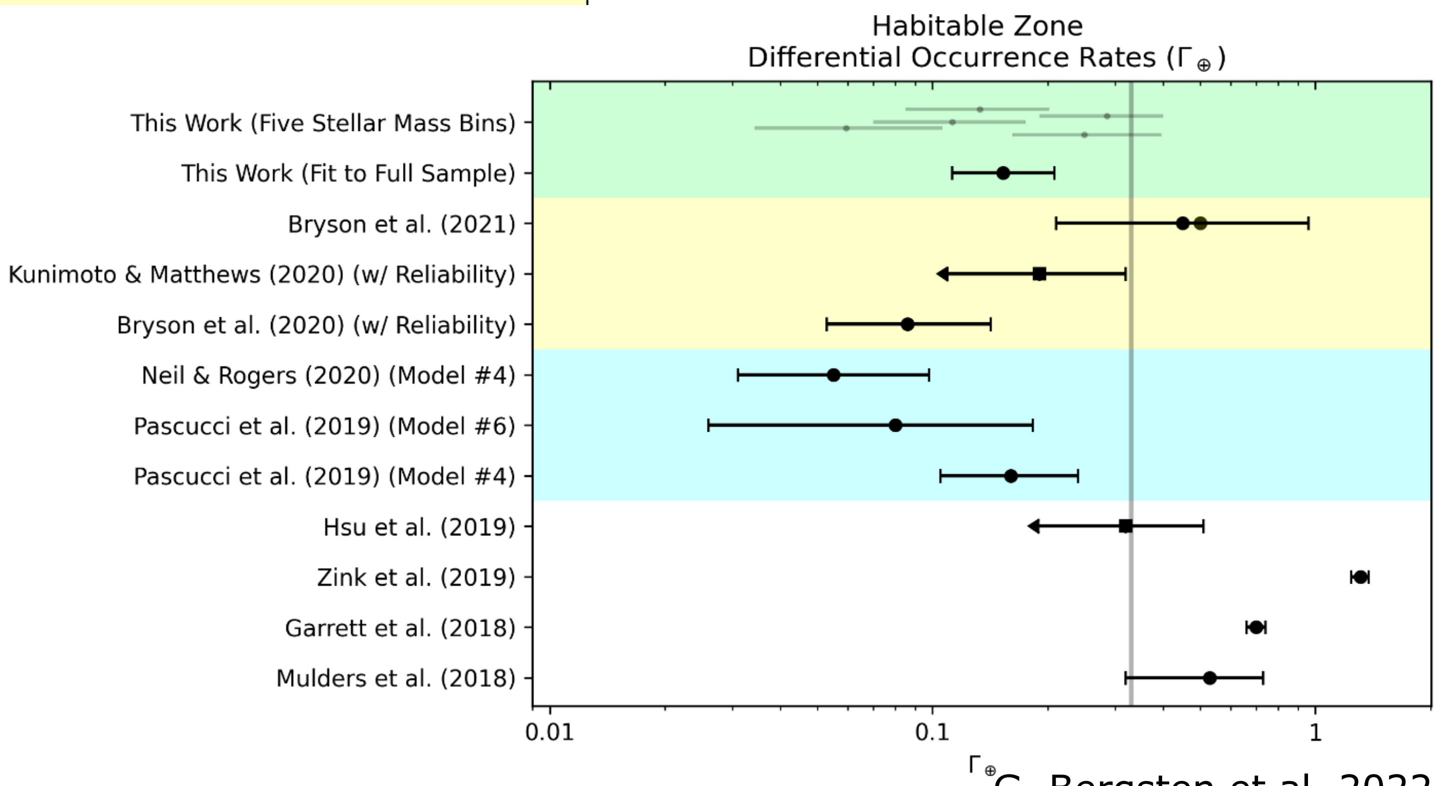
Parameter	Value	Description
$\eta_\oplus$	SAG13 power law	Fraction of sunlike stars w/exo-Earth candidate
R_p	$[R_p > 0.8/\sqrt{a}, 1.4]\ R_\oplus$	Exo-Earth candidate planet radius[a]
a	[0.95, 1.67] AU	Semi-major axis for solar twin
e	0	Eccentricity (circular orbits)
$\cos i$	$[-1, 1]$	Cosine of inclination (uniform distribution)
ω	$[0, 2\pi]$	Argument of pericenter (uniform distribution)
M	$[0, 2\pi]$	Mean anomaly (uniform distribution)
Φ	Lambertian	Phase function
A_G	0.2	Geometric albedo
A_G	0.5	Geometric albedo
z	Lindler model[b]	Average V band s
x	22 mag asec^{-2}	V band surface b
n	LBTI nominal distribution	Distribution of nu

[a] R_p lower bound is $R_p > 0.8/\sqrt{a}$ in units of $R_\oplus$, where a is the I

[b] Lindler zodiacal light model as a function of ecliptic latitude an

[c] For solar twin. Varied with spectral type, as zodi definition fix

High uncertainty astrophysical inputs



G. Bergsten et al. 2022

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x	22 mag asec^{-2}	V band surface brightness of 1 zodi of exozo
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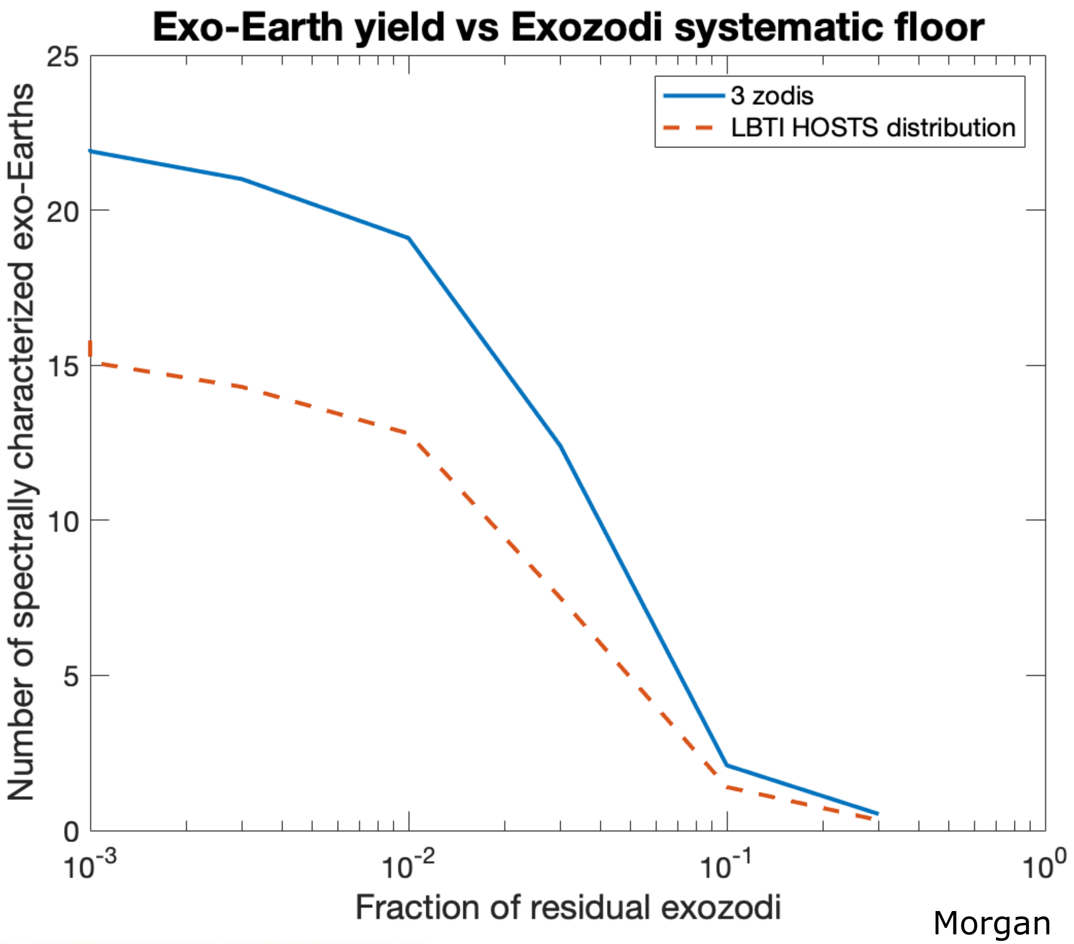
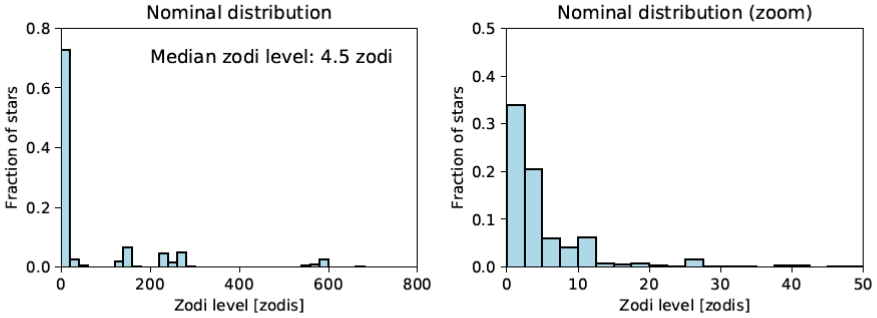
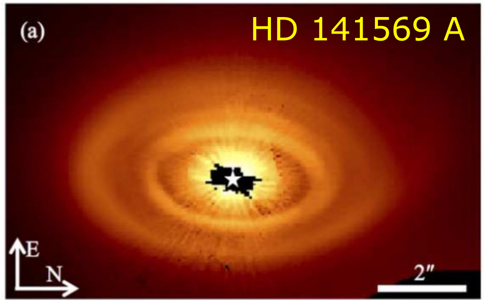


Morgan

High uncertainty astrophysical inputs



Ertel et al. 2019



Konishi et al. 2016

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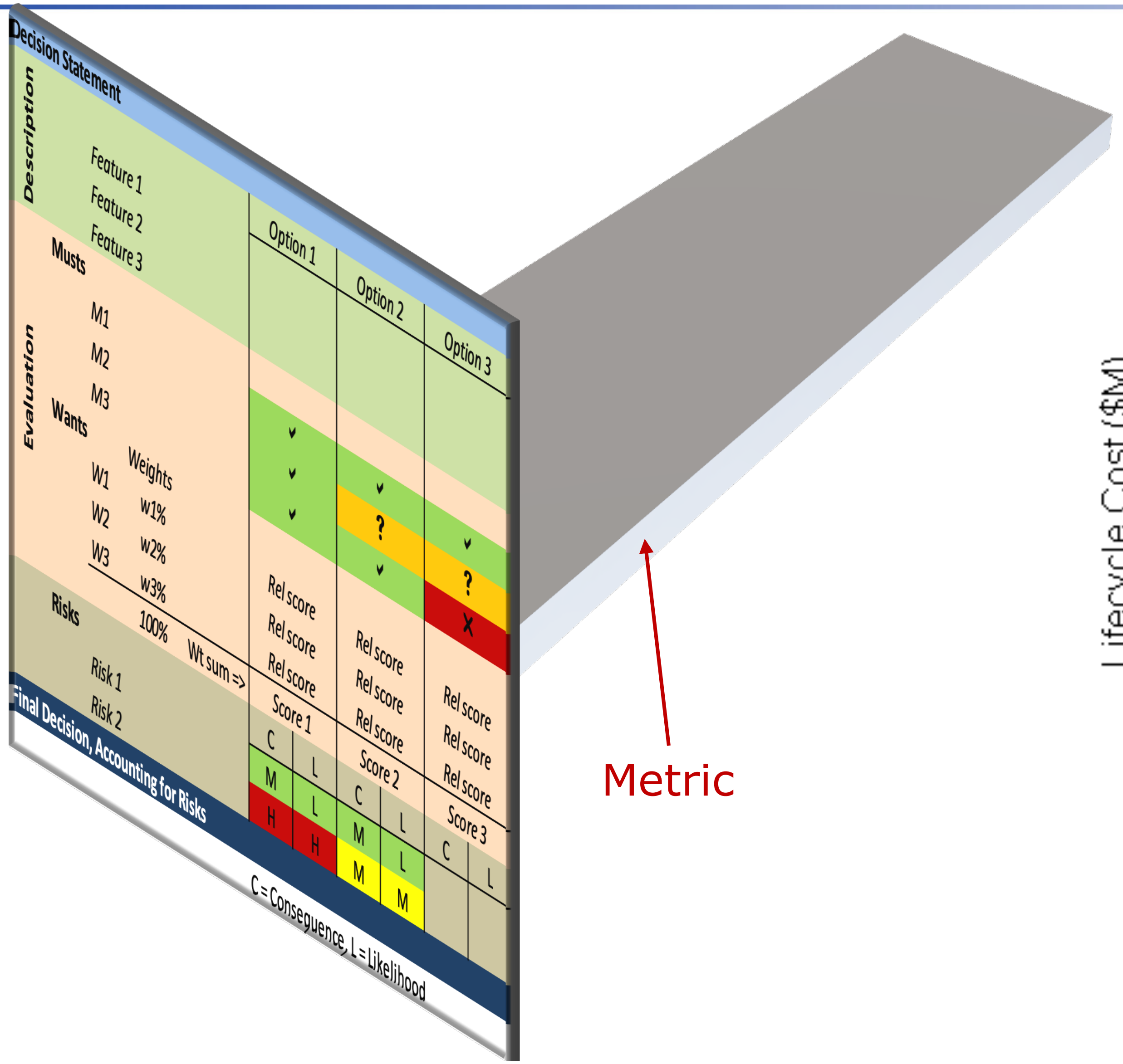
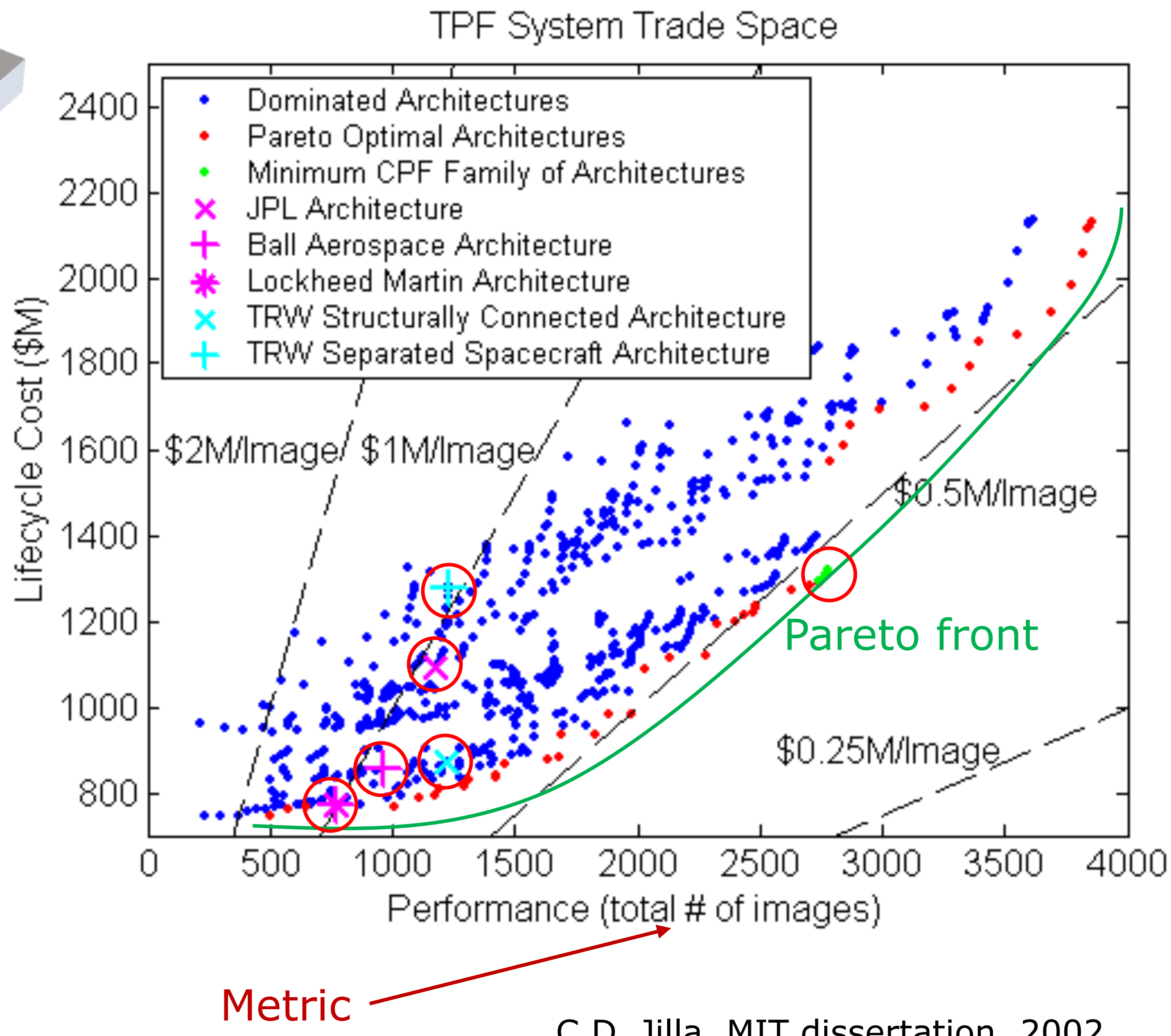
- **Metrics are the yardstick for architecture trades/trade space analysis**
  - Science requirements flow to instrument requirements flow to mission design
  - Metrics score subsystem trades, such as detector A vs detector B
  - Inform architecture trades, such as K-T decision matrix
  - Enable parametric exploration of the trade space to find the pareto front

Metrics are used to quantify trades



Decision Matrix adapted by G. Blackwood from Kepner and Tregoe, 1965



C.D. Jilla, MIT dissertation, 2002

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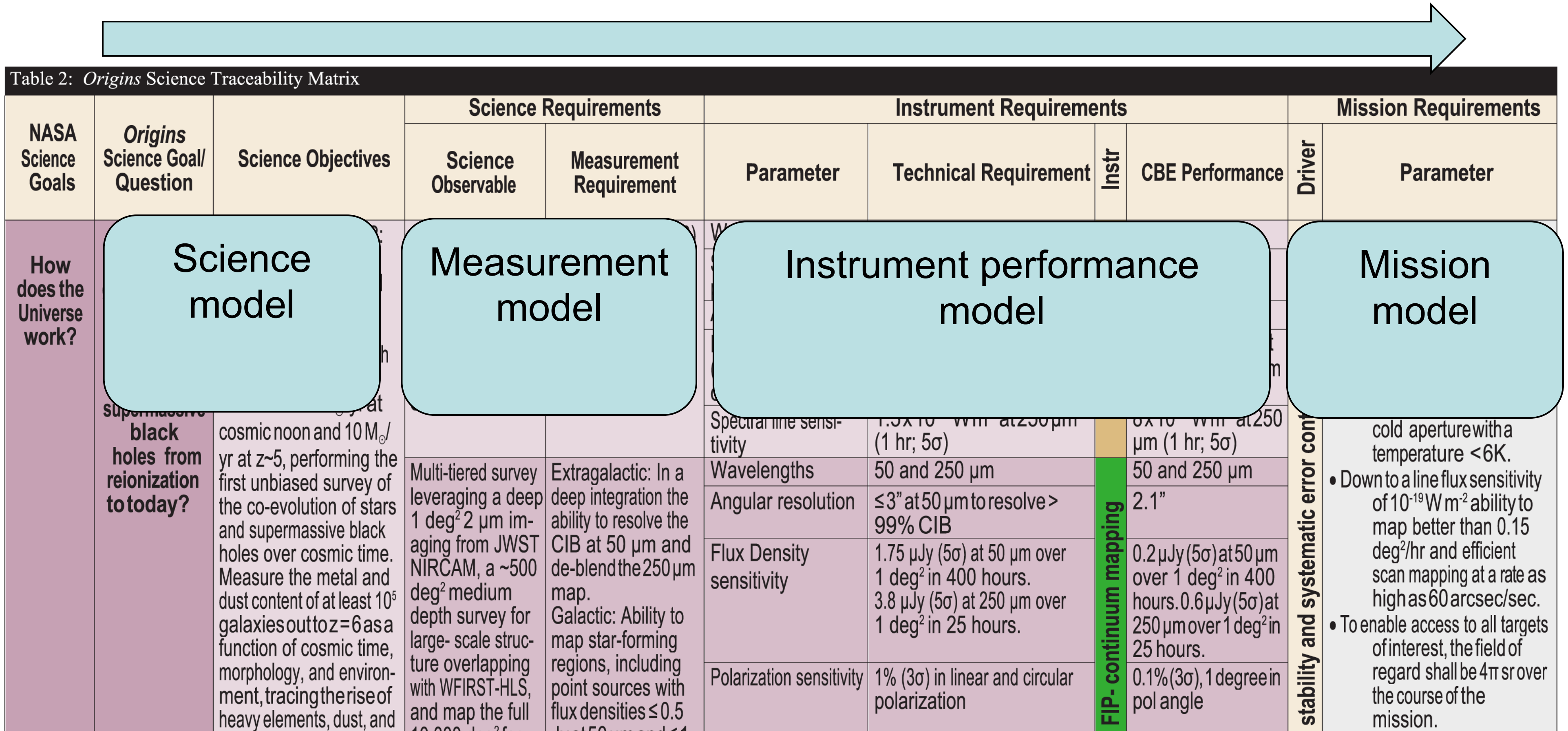
  - Enable parametric exploration of the trade space to find the pareto front
- **Metrics need to be defined early … and then iterated**
  - This is the connecting point/rod/joint from the left to right sides of the Science Traceability Matrix

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
- Shows a well-understood concept



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

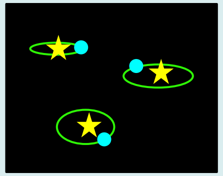
Mission Constraints
- Lifetime
- Observing allocation
- Observatory orbit
- Solar keepout
- Observing scenario

Measurement model

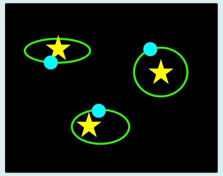
Instrument performance model

Mission model

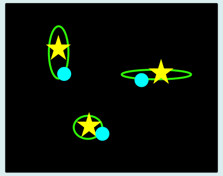
Universe n



Universe n+1



Universe n+2



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

Creates Monte Carlo ensembles of missions.

https://github/dsavransky/EXOSIMS

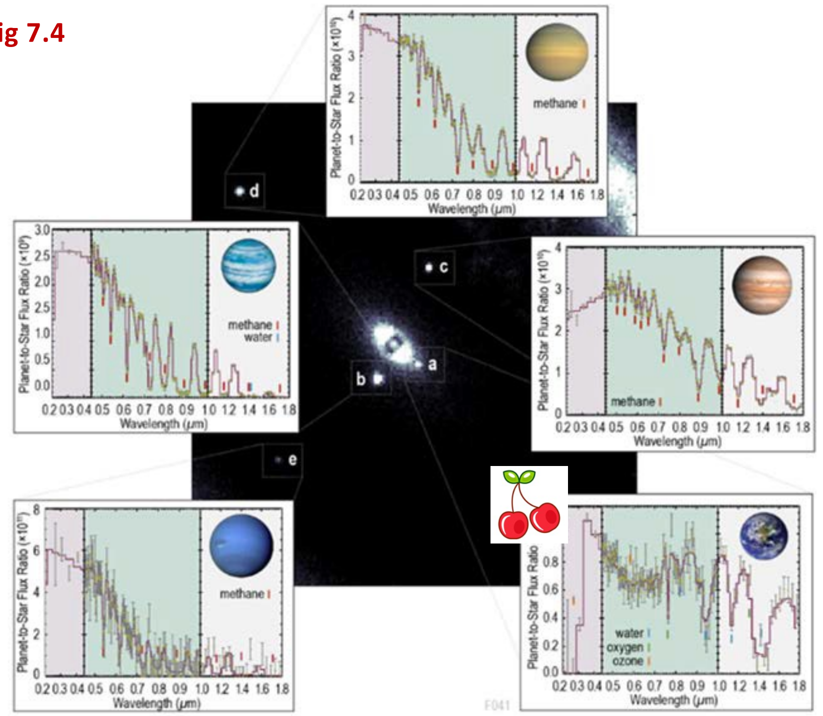
⟨n⟩ planets characterized

SNR =
Rs =
BW =
Wavelength =
In habitable zone

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”

Fig 7.4



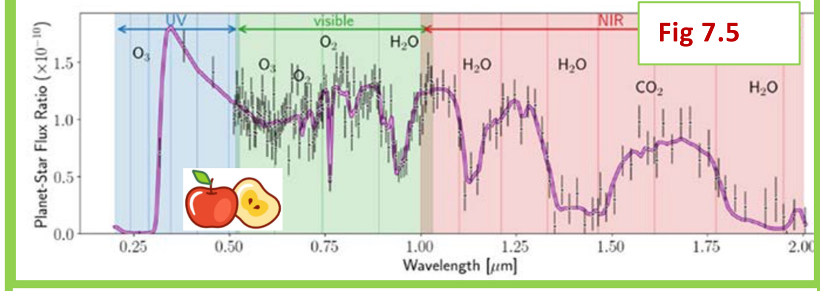
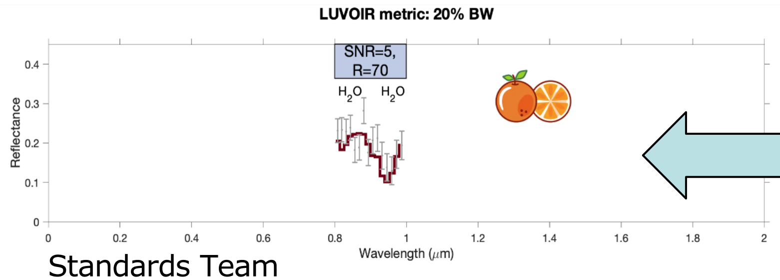
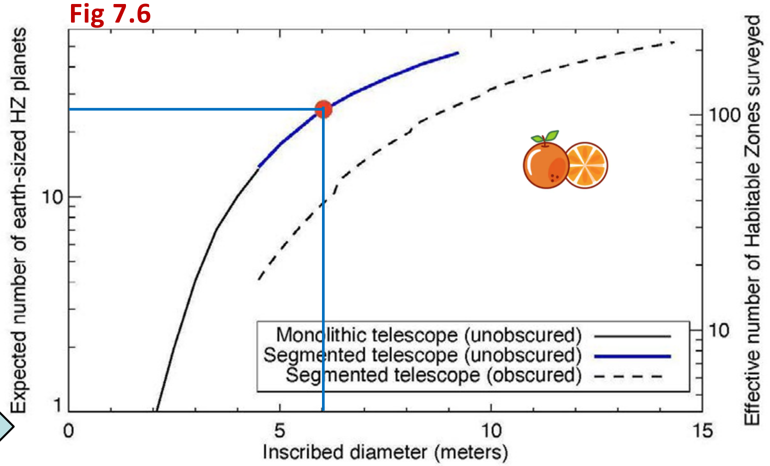


Fig 7.5



Standards Team

Fig 7.6

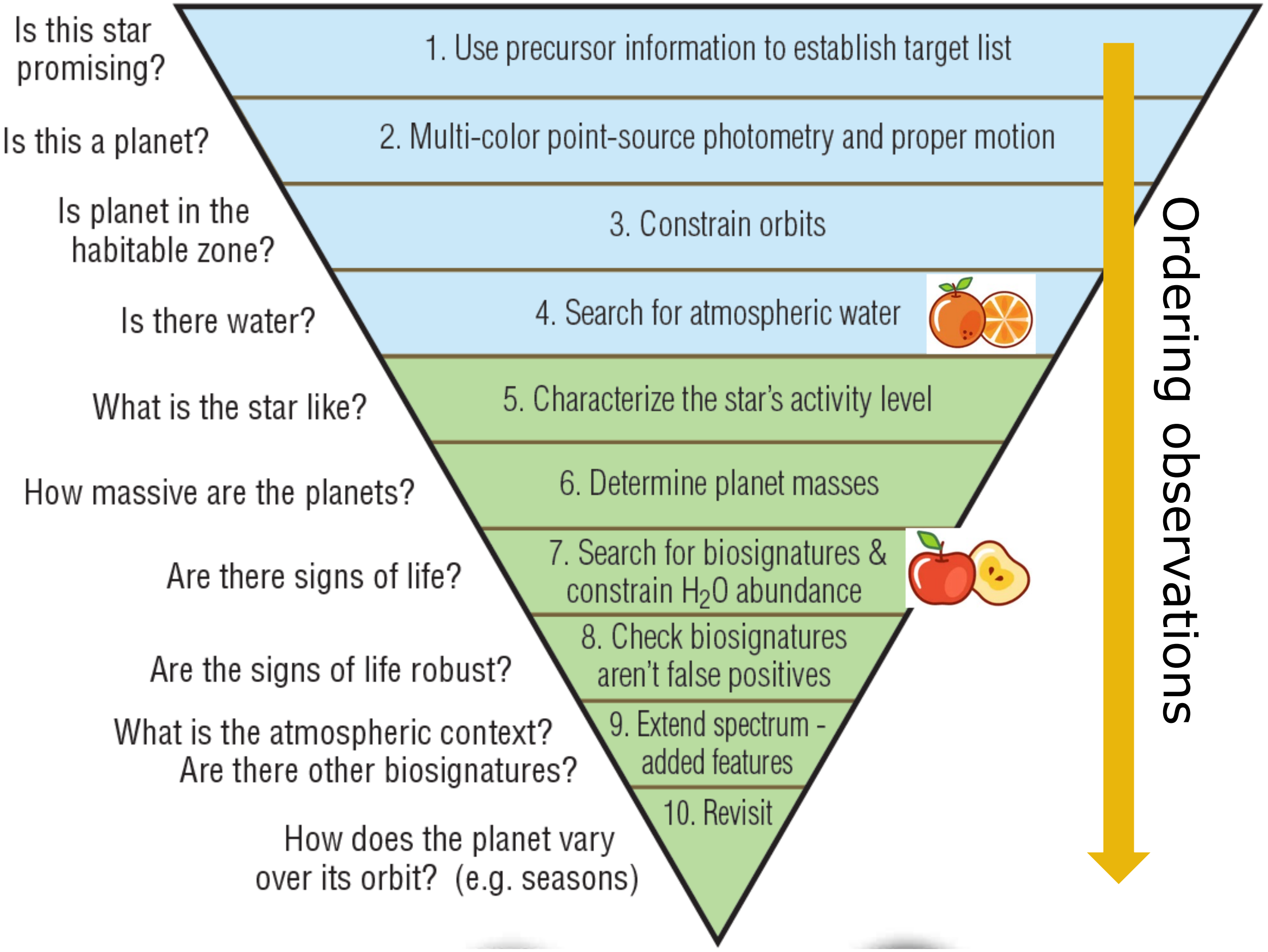


- Building on the work done by large concept studies and the Standards Evaluation Team, we can iterate, address nuances, and incorporate progress to map exoplanet science goals to planet characterization to metrics

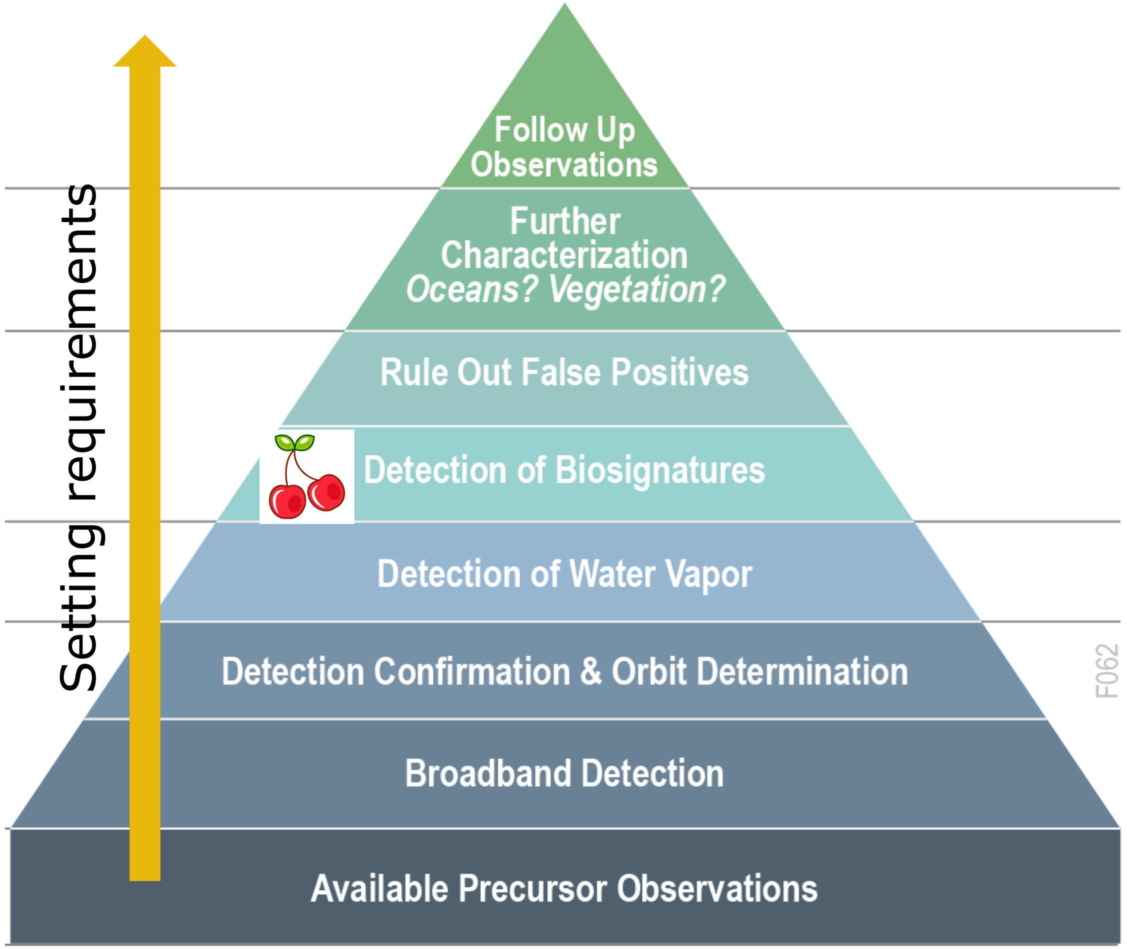
This will not be easy!

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

Observing Strategy impact on metrics



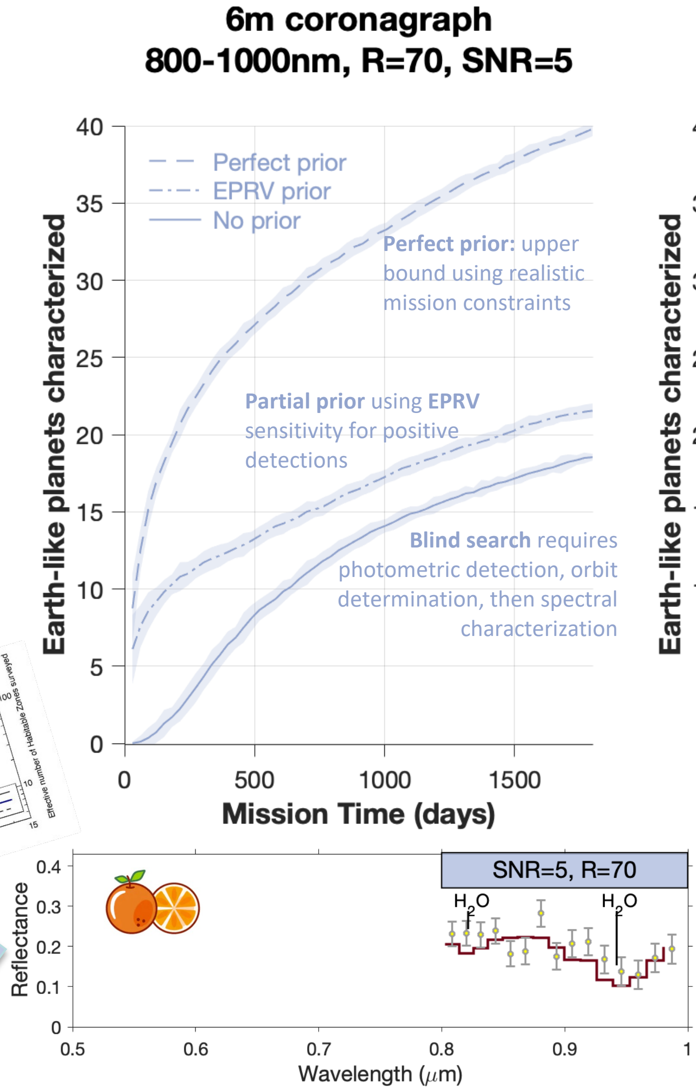
LUVOIR Final Report Fig. 3-11

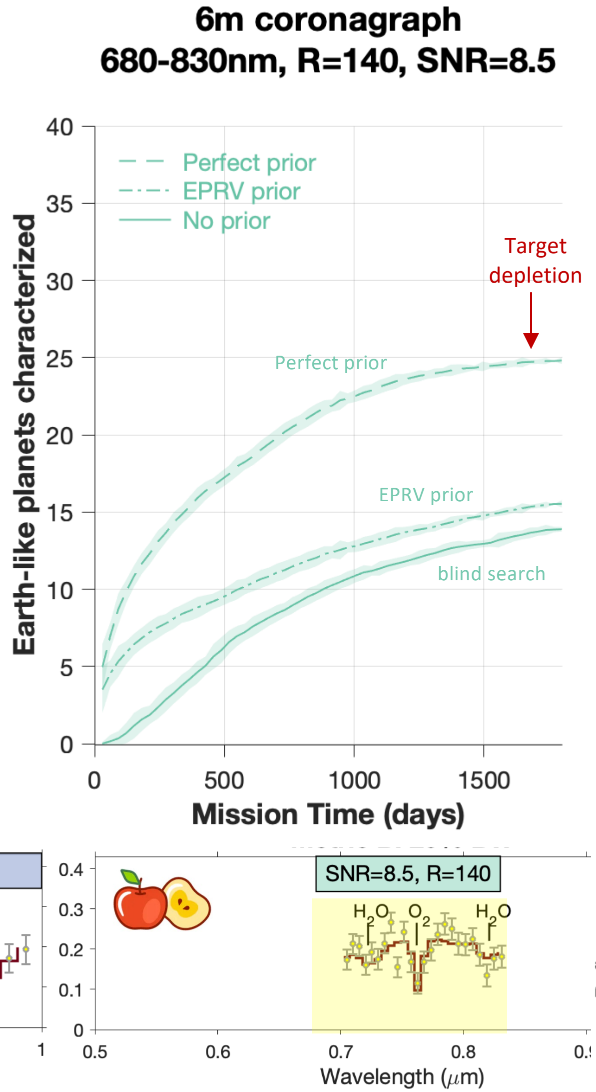


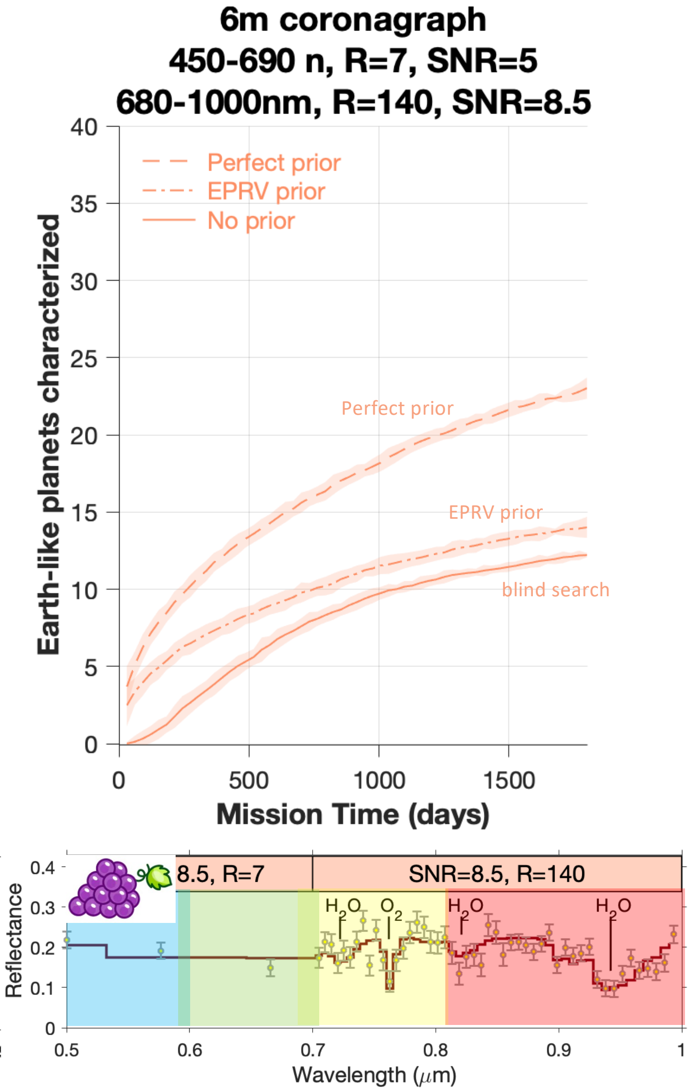
HabEx Final Report Fig. 3.1-1

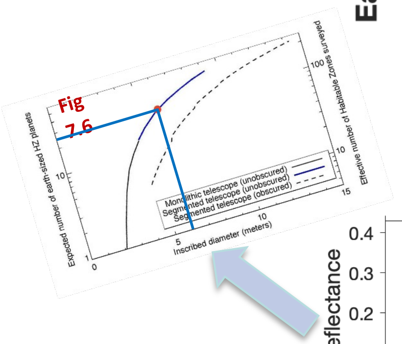
Different yield metrics reveal different sensitivities

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









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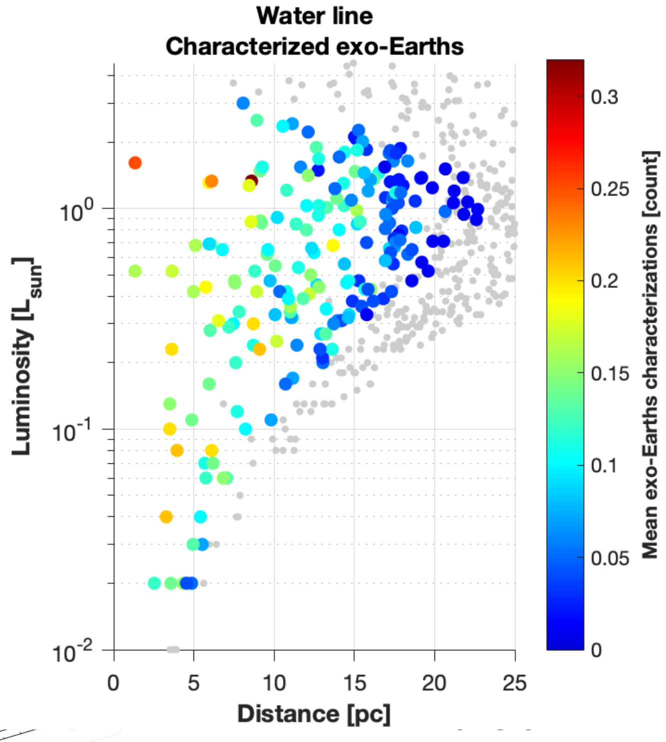
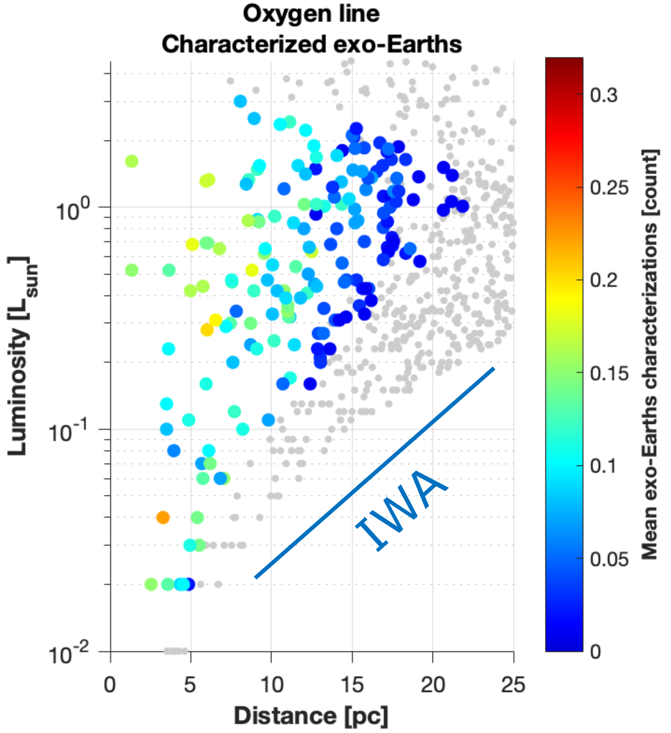
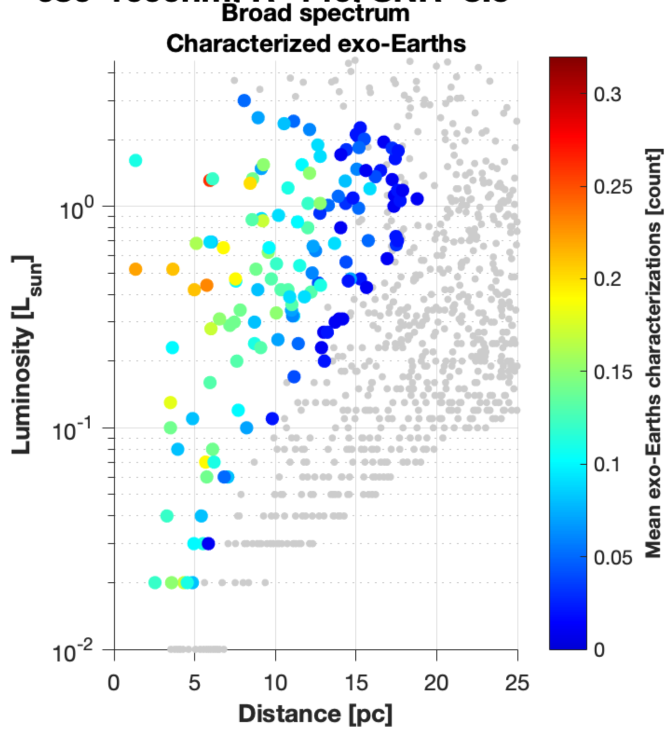
6m coronagraph
800-1000nm, R=70, SNR=5

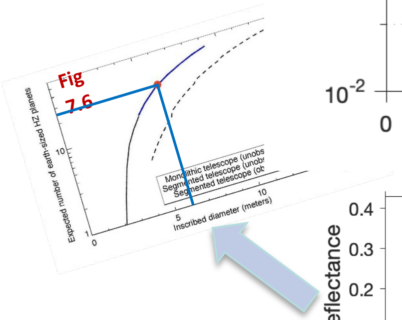


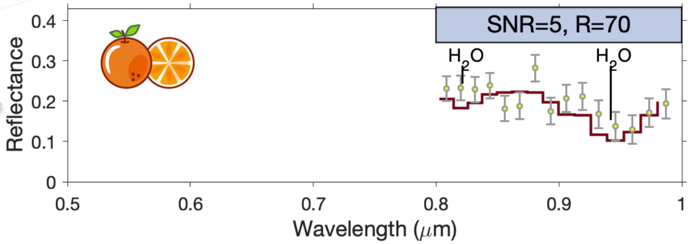
6m coronagraph
680-830nm, R=140, SNR=8.5

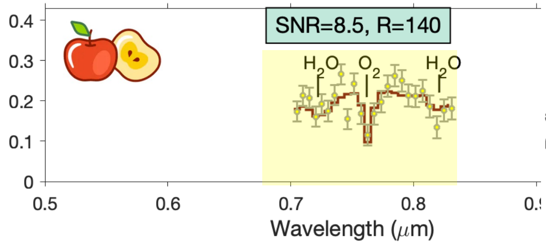


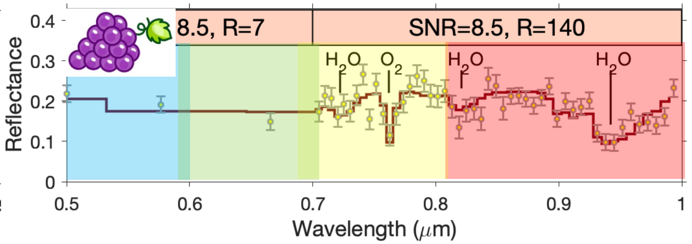
6m coronagraph
450-690 n, R=7, SNR=5
680-1000nm, R=140, SNR=8.5











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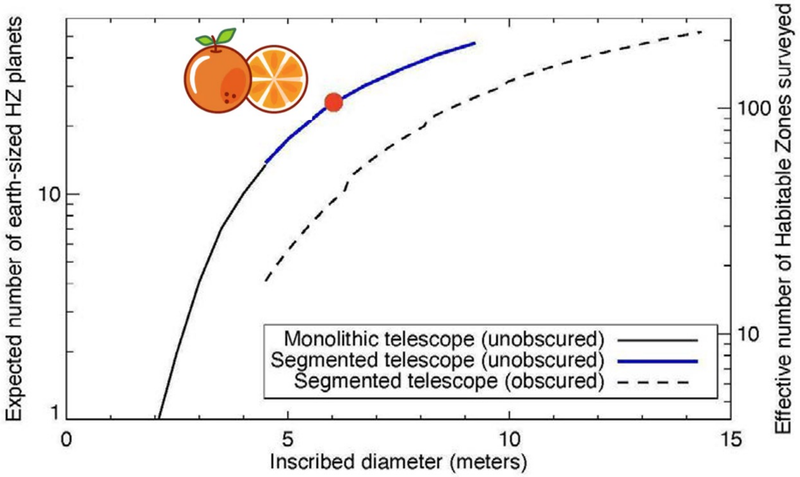
Metrics quantify performance sensitivity to key parameters

What is the shape of the curve for other metrics?
For tiered observing scenarios that combine metrics?



Stark, MacIntosh, Mawet 2017

? ? ?

? ? ?

$$\text{Yield} = 6 \times (D/5\text{m})^{1.97} (T_{int}/\text{yr})^{0.32} (41\text{mas}/IWA_d)^{0.98} \times (\eta_E/0.1)^{0.96} (A/0.2)^{0.65} (3/Zodi_{median})^{0.17}$$

Stark et al. 2014

What are good metrics going forward?

- **Represent the desired science measurable at a quality required to accomplish the science goal**
  - Clearly communicate apples from oranges
  - Computationally tenable for many iterations and trades
- **Defining the science metrics is work**
  - That will require iterating on the science performance models
  - That will likely require iterating on the measurement models
  - There are nuances that are worth understanding EARLY
  - There is an opportunity with this precursor science workshop to identify the work that needs to be done to design good metrics

We as a community need to be clear on which metric we are using so that there are not apples to oranges comparisons muddying the trades.

Resources

- **Standards Team Final Report detailing common yield inputs and assumptions**
  - **https://exoplanets.nasa.gov/exep/studies/sdet/**

- **EXOSIMS open source mission simulation tool: https://github.com/dsavransky/EXOSIMS**

Finding Science Gaps by Thinking about Metrics

- **Each mission's high-level science goals will require specific classes of observations to be carried out over some area of sky or some number of specific targets. Example major observing programs from other missions:**
  - Deep fields & wide area surveys by HST, Chandra & Spitzer
  - HST distance scale & other early key projects; large Treasury Programs
  - Exoplanet phase curves with warm Spitzer
  - Spitzer Legacy science programs
  - Herschel key programmes
  - IROUV's search for & characterization of temperate rocky exoplanets
- **While many such observing programs cannot be anticipated in advance, the key science questions from the Decadal & the Large Mission Studies can be used <u>to identify</u> fiducial large programs for each FGO today**
- **The time it takes to execute these large programs and the scope of the program achievable therein are two classes of metrics useful for evaluating mission architecture options**
- **Metrics will be <u>defined</u> for each future FGO through the Decadal's GOMaP process over the next few years. There are many subtleties involved. We are only starting the discussion today !**

Progress we can make today

- **Draft a few useful metrics that quantify the performance of each FGO in each of the four science areas: X-ray, far-IR, IROUV-astro, IROUV-exo**
- **Write down the attributes of each metric, but don't try to settle on their numerical values now !**
  - Sensitivity, wavelength range, spectral resolution, the temporal coverage - list all the things needed to define a successful observation program (the fine print that defines an observation program)
  - And then the overall "score" needed to achieve the science objective
- **The next thing to develop is the metric dependencies (all the assumptions about the astrophysics and the observatory system needed to calculate the metric score)**
  - Includes the above attributes
  - Parameters of the telescope and instruments are Interesting, but connects to technology issues that will be worked separately. So don't get caught up in these.
  - **Input astrophysical parameters needed to calculate values of the metric**
  - **Fidelity of modeling methods used to calculate values of the metric**
  - **Data processing methods needed to complete a successful observation**
- **If there is significant uncertainty in any of the latter three areas, it points to a science gap that could be addressed by precursor science work**

The example science metric so far

- **Astro 2020 recommended "a mission to search for biosignatures from a robust number of about ~25 habitable zone planets ..."**
- **The HabEx & LUVOIR studies, and the independent ExEP Science Evaluation Team, produced yield estimates calculated in similar ways to what the Decadal asked for … so infrastructure exists to work with science metrics for IROUV-exo. Additional IROUV metrics should be agreed on.**
  - Input astrophysical parameters eta_Earth and exozodi level clearly affect the calculated values of the metric, and point toward science gaps & precursor science to do
  - Mission simulation tools could use improved inputs and fidelity for scheduling visits at optimal times, which points to software development and EPRV precursor work
  - Data processing methods needed to accomplish a valid observation could use further development (subtraction of image speckles, structure in exozodi)
- **Astro 2020 did not specify science metrics for IROUV-Astro, Far-IR, or X-ray**
- **The community will need to develop the above through forums like this workshop, PAG working groups, GOMaP, and eventually mission science teams**

Breakout Instructions

- **Consider what science metrics should be used to evaluate the science performance of the FGO**
- **For the precursor science ROSES call, what is uncertain in calculating that metric that could be made more reliable through precursor science work? (astrophysics knowledge, model fidelity, instrument capability)**

- **Record notes in spreadsheet with headers (one table per breakout group):**
  - Science objective
  - Significance of the science objective, such as it's importance or portion of mission observing time
  - Metric name
  - Brief metric description
  - Components that should be included in the metric definition (such as SNRs, spectral resolution, etc), but their specific values don't have to be decided in this session
  - Astrophysical inputs (parameters needed to calculate the metric)
  - Inputs with major uncertainties (this will likely lead to a science gap)
  - (Optional) instrument parameters (not the focus of the session, this capture area is available for those compelled to provide them)

QUESTIONS