Tracing Exoplanet Science Requirements to Mission Requirements for HWO

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The Science Traceability Matrix (STM)

Define Science Goal → Flow Down to Instrument Requirements

Table 5.1-2. Science Traceability Matrix. Baseline science objectives and requirements appear in black typeface, while threshold objectives and requirements appear in grey, italic typeface. Driving requirements appear in the payload functional requirements in blue, bold typeface.

Goal	Science Objectives	Scientific Measurement Requirements		Payload Functional Requirements	Baseline Projected Performance
		Physical Parameters	Observables		
To seek out nearby worlds and explore their habitability.	**O1:** To determine if rocky planets (0.5–1.75 $R_\oplus$) continuously orbiting within the habitable zone (HZ) exist around nearby sunlike stars, surveying enough stars to detect and measure the orbits of at least 20 exo-Earth candidates (EECs) if each observed star hosted one EEC. To detect and measure the orbit of at least one EEC with ≥95% confidence. *Threshold: To determine if rocky planets (0.5–1.75 $R_\oplus$) continuously orbiting within the habitable zone (HZ) exist around nearby sunlike stars, surveying enough stars to detect and measure the orbits of at least 12 exo-Earth candidates (EECs) if each observed star hosted one EEC. To detect and measure the orbit of at least one EEC with ≥90% confidence.*	Planet position with respect to the central star over time to determine the orbit semi-major axis, eccentricity, and inclination to ≤10% accuracy. Planet radius determined within a factor of 2 of the true value.	Star-to-planet separation measured at ≥4 different orbital positions. Broadband planetary flux centered at 0.5 µm measured at ≥4 different orbital positions.	**F1.1 Broadband high contrast visible imaging with an $IWA_{0.5}$ ≤ 80 mas at 0.5 µm.** **F1.2 Angular positional accuracy ≤5 milliarcseconds (mas) root mean square (RMS).** **F1.3 Ability to visit target star ≥4 times.** **F1.4 Signal-to-noise ratio SNR ≥ 7 on a point source that is ≥ 10^{10} times fainter than a solar twin star located at 9 pc (V = 4.6 mag)** and at ≤80 mas from it using broadband photometry centered at 0.5 µm **in an exposure time of ≤20 hours (h).** See **Figure 5.2-1** for the baseline coronagraph instrument error budget. *Threshold: $IWA_{0.5}$ ≤105 mas at 0.5 µm.*	Coronagraph broadband high contrast visible imaging with an $IWA_{0.5}$ = 62 mas at 0.5 µm. Angular positional accuracy: 0.7 mas at 100 Hz Ability to visit target star: 6 times, as necessary SNR = 7 on a point source that is 10^{10} times fainter than a solar twin star located at 9 pc (V = 4.6 mag) and at 80 mas from it using broadband photometry centered at 0.5 µm in an exposure time of 9.6 h.
	O2: To determine if planets identified in Objective 1 have potentially habitable conditions (an atmosphere containing water vapor). Also, to determine if rocky planets outside the "2D EEC zone" have potentially habitable conditions, surveying an equivalent number of rocky planets outside the 2D EEC zone to those within it. *Threshold: To determine if the planets identified in the threshold requirement of Objective 1 have potentially habitable conditions (an atmosphere containing water vapor). Also, to determine if rocky planets that do not fit into Objective 1 have potentially habitable conditions, surveying ≥1 rocky planet interior and ≥1 rocky planet exterior to the HZ.*	The abundance of atmospheric H_2O if the column density is ≥0.4 g/cm² (modern Earth at the outer edge of the HZ). *Threshold: The abundance of atmospheric H_2O if the column density is ≥2.9 g/cm² (Modern Earth).*	Planetary spectrum, including ≥2 H_2O absorption features in the visible–near-IR. *Threshold: Planetary spectrum, including ≥1 H_2O absorption feature in the visible.*	**F2.1** Visible–near-IR spectroscopy with an **$IWA_{0.5}$ ≤ 80 mas at 1.0 µm.** **F2.2** Spectral range ≤0.7 µm to ≥1.0 µm. **F2.3** Spectral resolution (R): R ≥ 35 at 0.82 µm with SNR ≥ 10 and R ≥ 17 at 0.94 µm with SNR ≥ 10. Or R ≥ 17 at 0.94 µm with SNR ≥ 10 and R ≥ 19 at 1.13 µm with SNR ≥ 10. *Threshold:* *Visible spectroscopy with an $IWA_{0.5}$ ≤ 105 mas at 0.75 µm.* *Spectral range ≤ 0.7 µm to ≥ 1.0 µm.* *R ≥ 35 at 0.72 µm with SNR ≥ 5.*	Starshade UV–near-IR spectroscopy with an $IWA_{0.5}$ = 58 mas at 1.0 µm. Spectral range: 0.2–1.8 µm. R = 7 with SNR = 10 from 0.2–0.45 µm. R = 140 with SNR = 10 from 0.45–0.975 µm. R = 40 with SNR = 10 from 0.975–1.8 µm.
	O3: To determine if planets identified in	The abundance of atmospheric	Planetary spectrum from the UV–	**F3.1 UV–near-IR spectroscopy** $IWA_{0.5}$ ≤ 80 mas at 0.8 µm.	Starshade UV–near-IR spectroscopy with an

HabEx Final Report (2019)

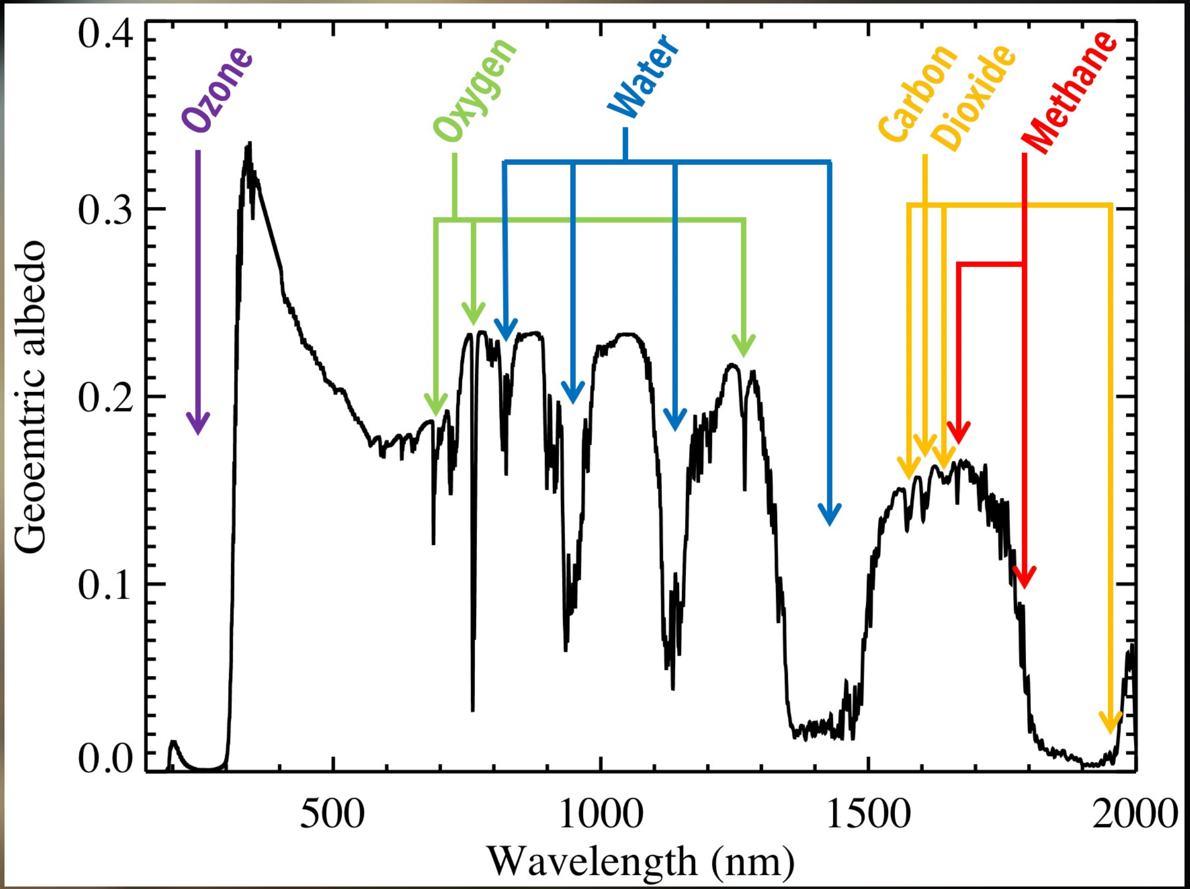
Ballparking HWO instrument requirements for exoplanet spectroscopy

Contrast ~ ratio of Earth's flux to Sun's flux at quadrature
~ g Φ(quadrature) $(R/r)^2$
~ 0.2 * 0.3 * $(4e\text{-}5)^2$
~ 1e-10

Noise floor ~ Contrast / SNR
~ 1e-10 / 10
~ 1e-11

IWA ~ Scale of HZ around Sun-like star at 10 pc
~ 1 AU / 10 pc
~ 100 mas
~ 3 λ/D @ 1 micron for 6 m aperture

OWA ~ Outer edge of Alpha Cen A's HZ
~ 1.7*sqrt($L_{\mathrm{AlphaCenA}}$) / $d_{\mathrm{AlphaCenA}}$
~ 2.1 AU / 1.3 pc
~ 1600 mas
~ 50 λ/D @ 1 micron for 6 m aperture



Bandwidth ~ range of interesting spectral features
~ 0.2 – 2 microns

The need for a flexible Design Reference Mission (DRM)

Problems with this approach

- Fiducials that define requirements can mislead. Not all stars are solar twins!
- What we really care about is scientific *productivity*
- The flow from science to mission requirements goes both ways

STMs & science req. docs are a critical formalization, but...

- They are relatively static
- They do not show all of the sensitivities of science to performance parameters
- They do not show the interdependency of performance parameters

DRMs are the machinery to establish/maintain science & mission requirements, and perform trade studies

DRMs are the science traceability machinery

A DRMs is a critical tool at the mission level for evaluating potential architectural concepts. Without a well thought out DRM, a conceptual mission design is at risk for not optimizing system trades, identifying necessary technology development, managing resources, and achieving a balanced design.

The DRM provides the traceability from science objectives to engineering requirements and can be used to examine options and implications for observations; finding "tall poles" and drivers and identifying the ultimate limits of performance. In this manner, it is a crucial tool for recognizing and nourishing the major strengths of the observatory and ranking design drivers.

Lightsey & Wilkinson (white paper, 2015)

Exoplanet imaging DRMs started with TPF

THE ASTROPHYSICAL JOURNAL, 607:1003–1013, 2004 June 1

OBSCURATIONAL COMPLETENESS

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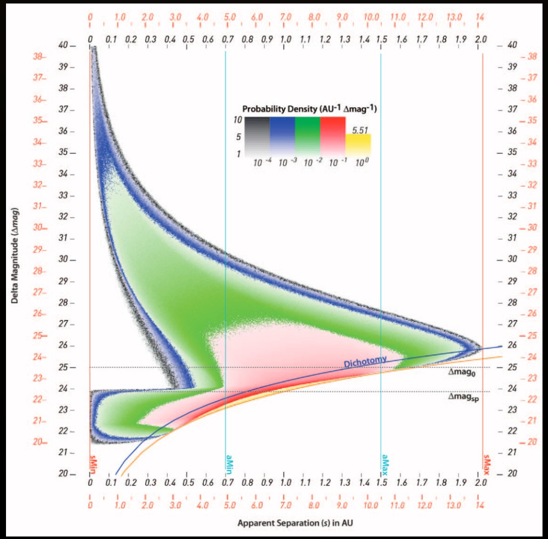
Brown (2004)



Brown (2005)

4. OPTIMIZATION

Our goal is to maximize the completeness integrated over all stars, subject to two constraints:
1) The maximum completeness on any star is limited by the instrument sensitivity floor.
2) The total integration time is limited by the allotted mission planet search duration.

The first constraint is folded into the functional form of completeness, which is given by:

$$C = \sum_{i=1}^{N} C_i(\tau_i),$$

where $C_i(\tau_i)$ is the completeness obtained on the ith star after integrating for time τ_i, and

$$\tau_i < \tau_{MAX,i}.$$

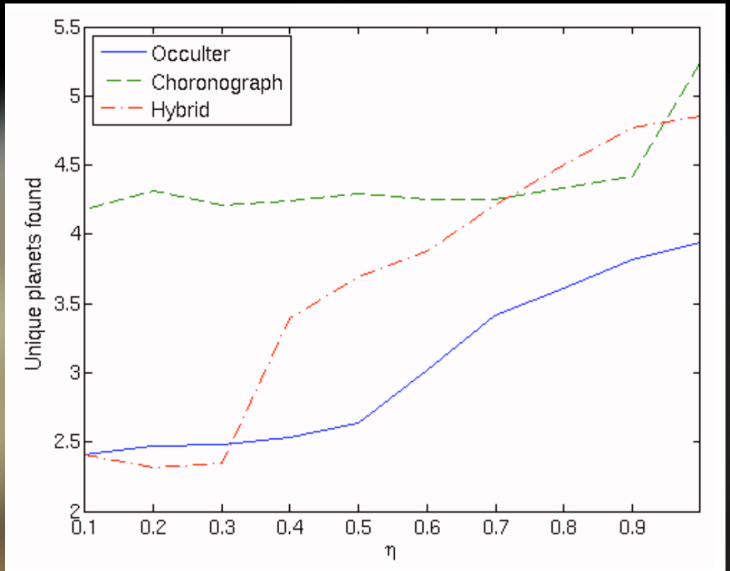
The total integration time is shared by N stars and is constrained by

$$\tau_m \geq \sum_{i=1}^{N} \tau_i.$$

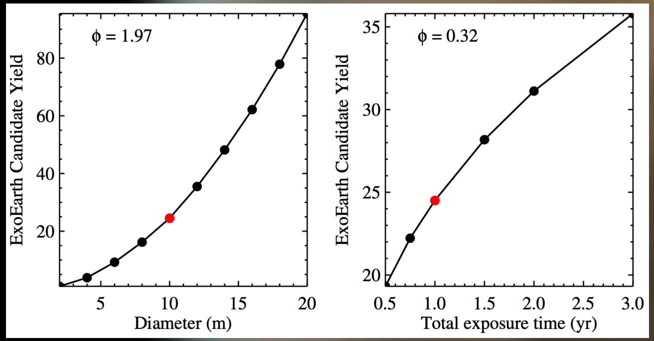
We choose $\tau_m = 1$ year to represent the integration time available during a three year mission.

In order to satisfy this optimization problem we observe all stars to the point where they have equal slopes,

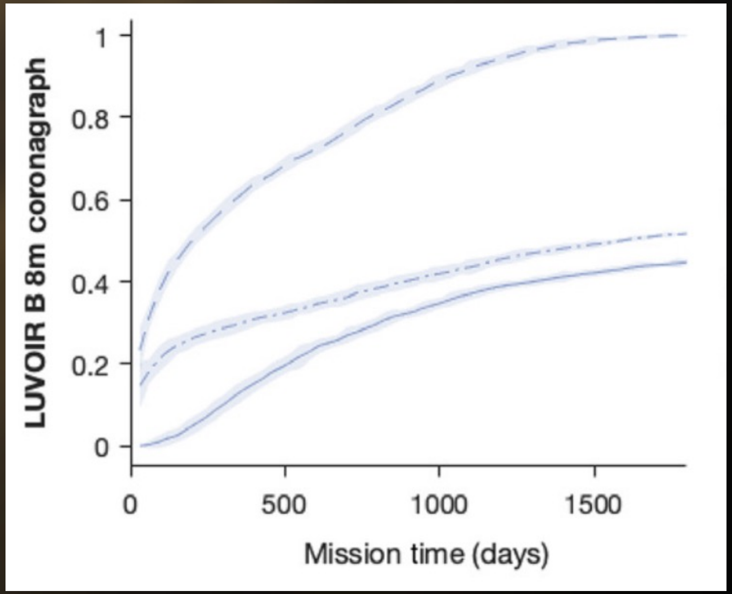
Hunyadi, Lo, & Shaklan (2007)



Savransky & Kasin (2008)



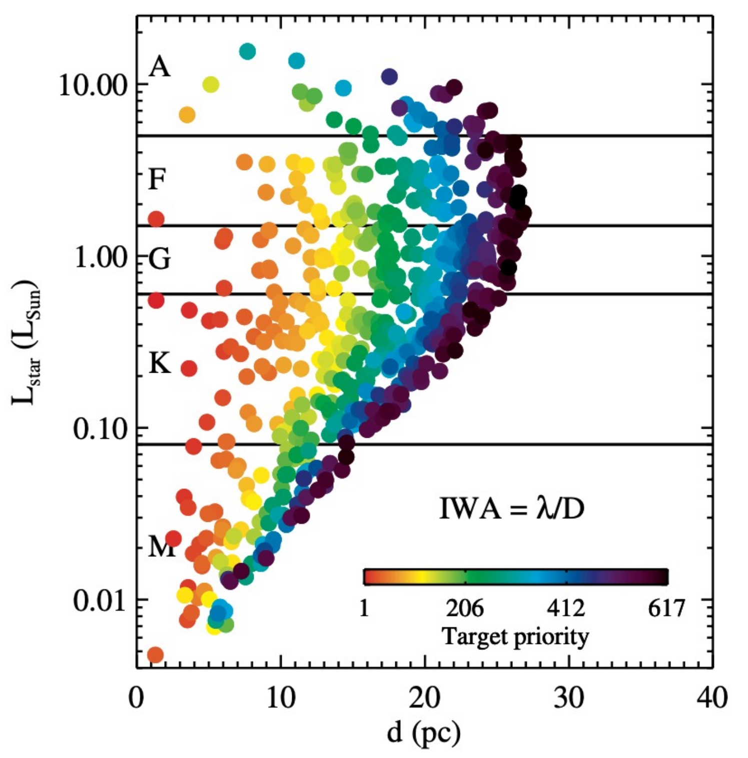
Stark et al. (2015)

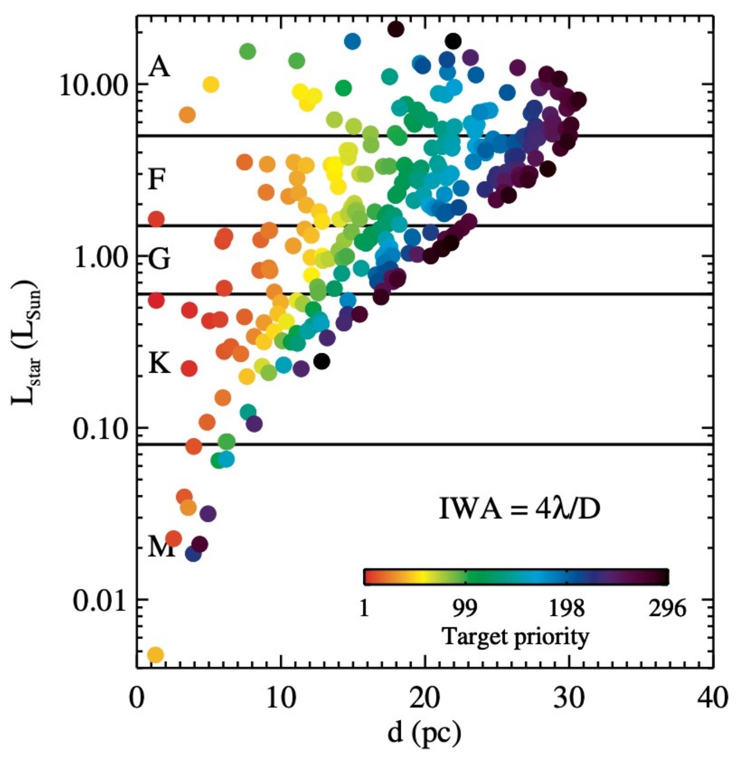


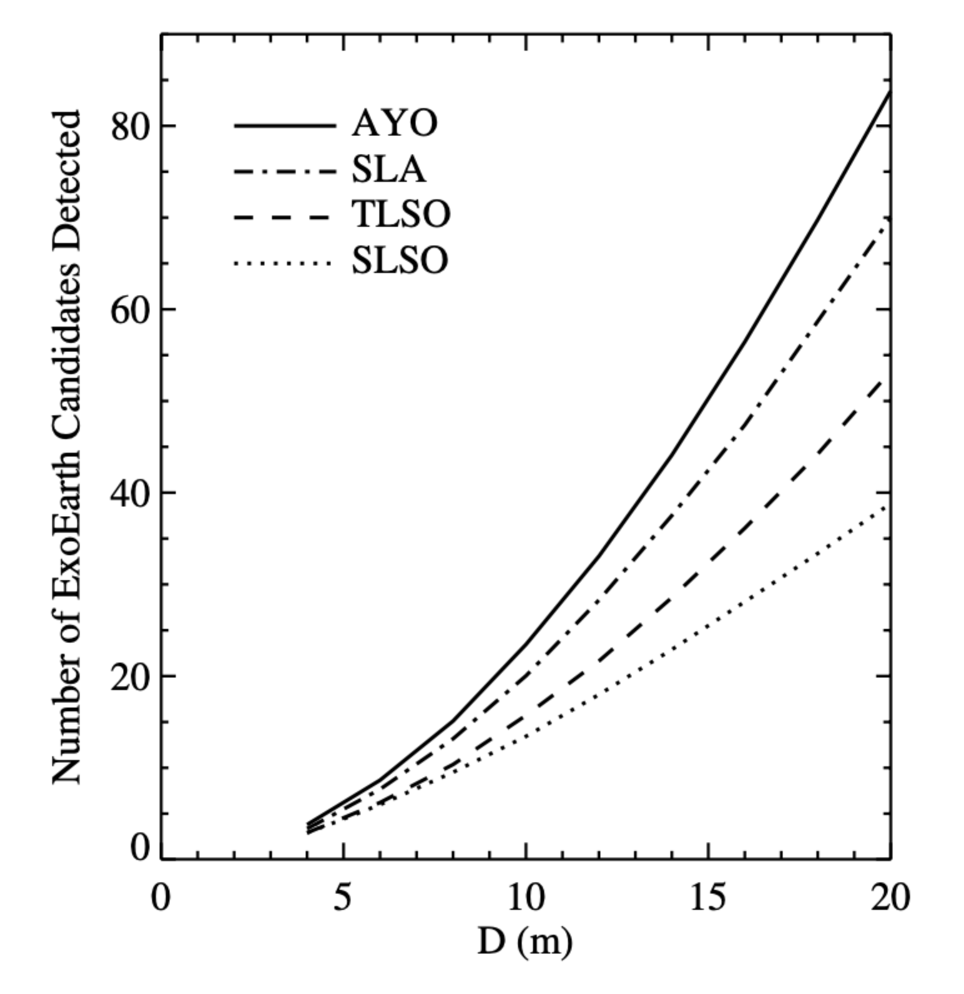
Morgan et al. (2021)

DRMs *must* optimize observations

- Assumptions/prescriptions re how to observe can lead to unintended bias, or worse—**incorrect trade studies**
- Pick a metric, then get out of the way and let your code tell you how to use the mission



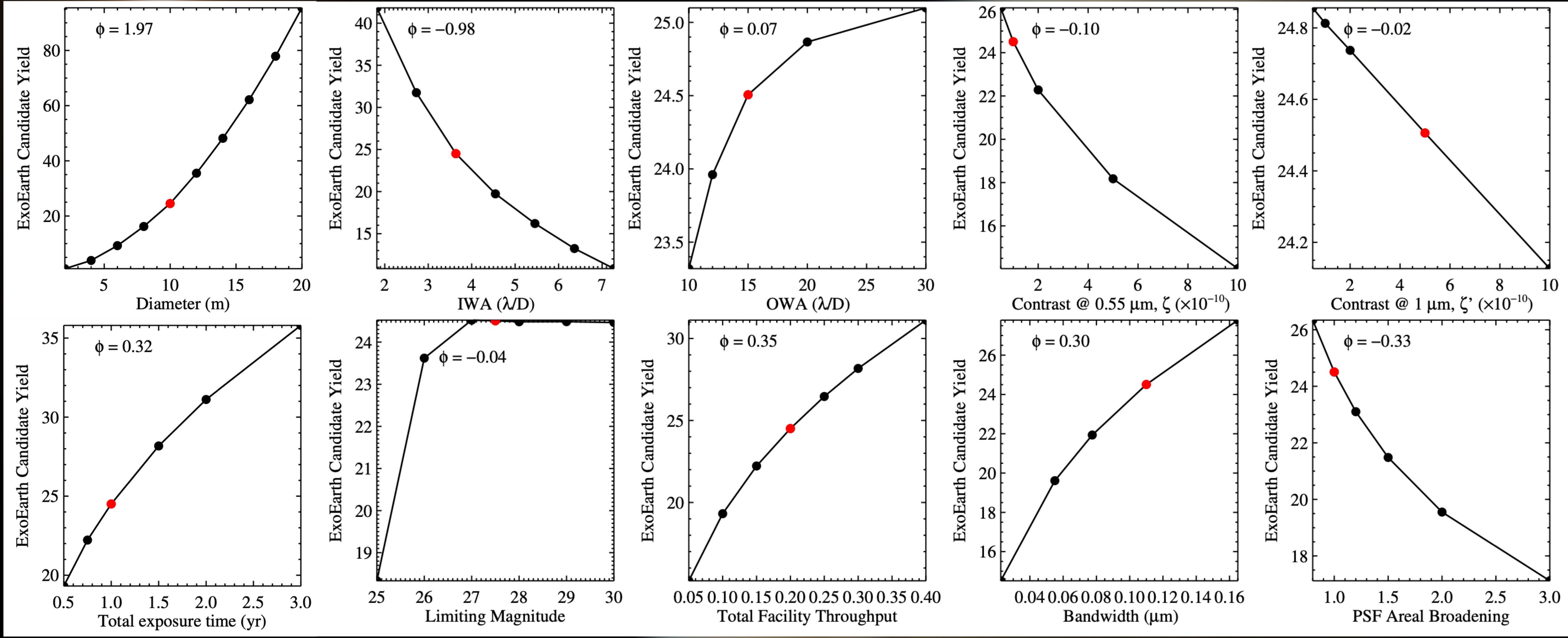




Target list adapts to changes in instrument

Stark et al. (2014)

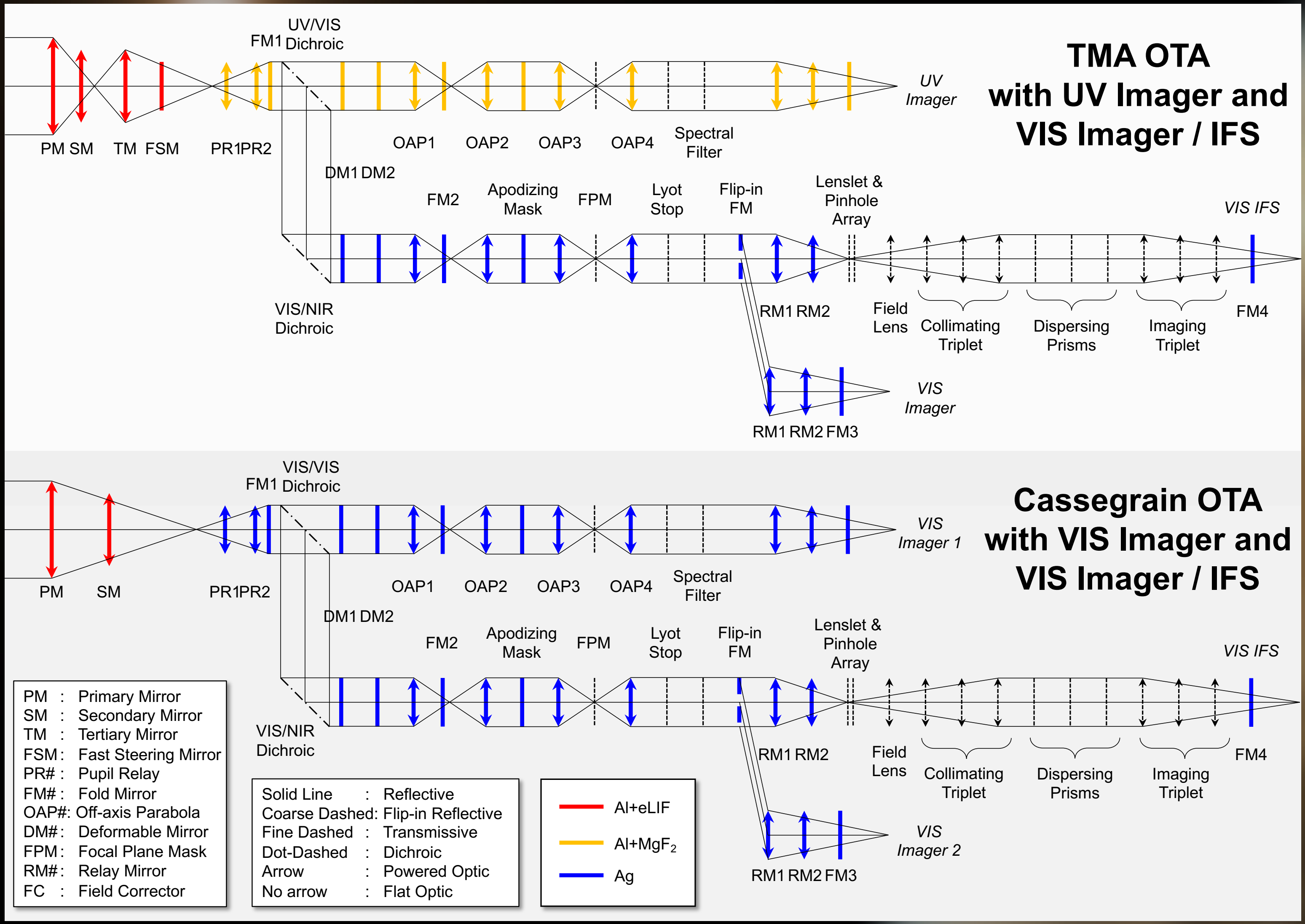
DRMs can estimate sensitivity of science performance to mission parameters



Stark et al. (2015)

DRMs have come a long way

LUVOIR & HabEx DRMs used realistic optical layouts



Stark et al. (2019)

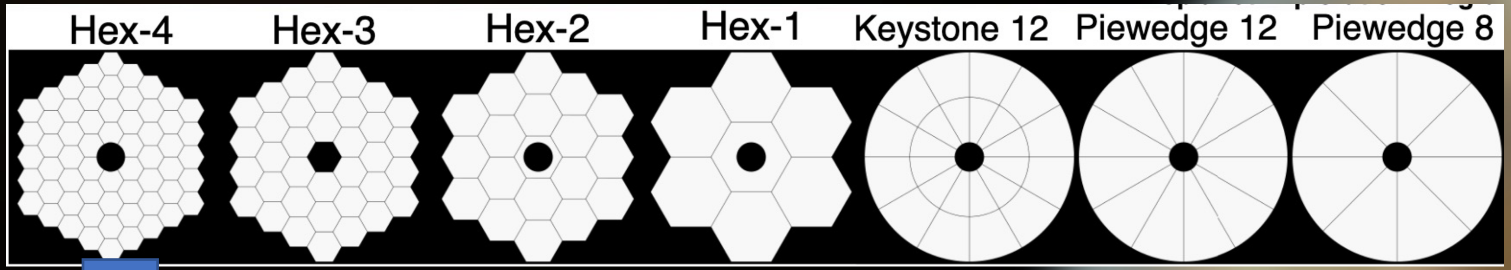
Key points:

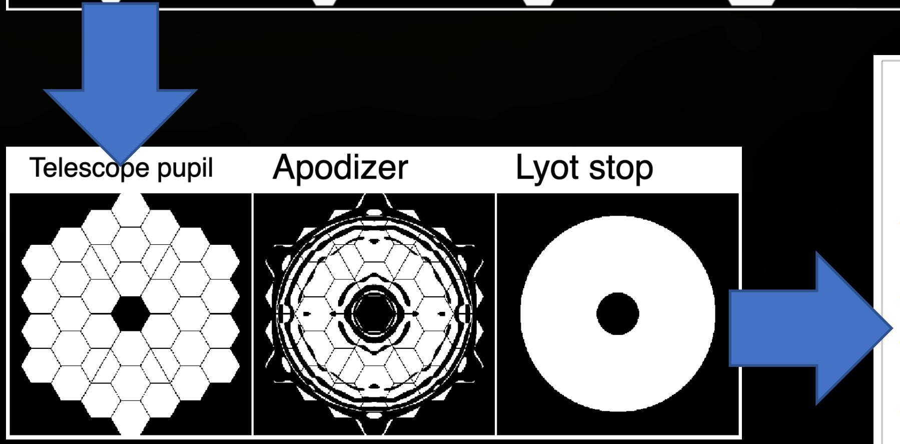
- The reflectivity of coatings matters a lot!
  i.e., 0.95^12 = 0.5
- We will likely have to trade bandwidth for throughput. UV coronagraphy reduces throughput at all wavelengths by up to ~0.5
- Efficiently parallelizing coronagraphs may be essential for wavelength coverage

DRMs have come a long way

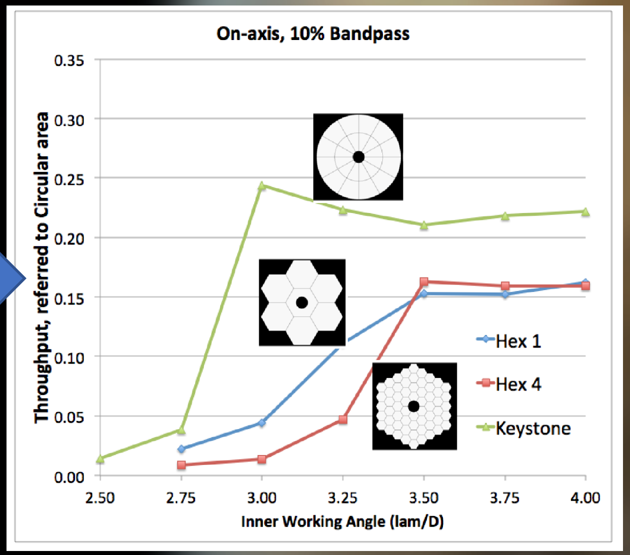
LUVOIR & HabEx DRMs used realistic coronagraph simulations

ExEP’s SCDA Study was essential to understanding the coronagraph design trade space and system-level requirements.





Slides from Shaklan (2016), many papers from SCDA Team

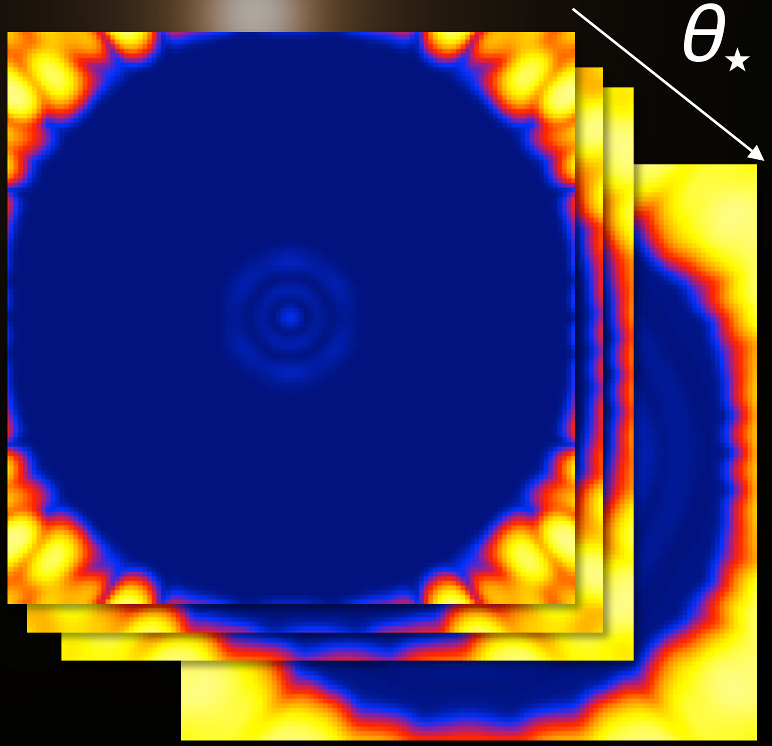


Key points:

- PM & SM geometry matters a lot—must design at system level!
- Coronagraph mask design has non-intuitive trades (OWA vs bandwidth, contrast vs IWA, etc.). Improving one parameter often comes at the expense of others.

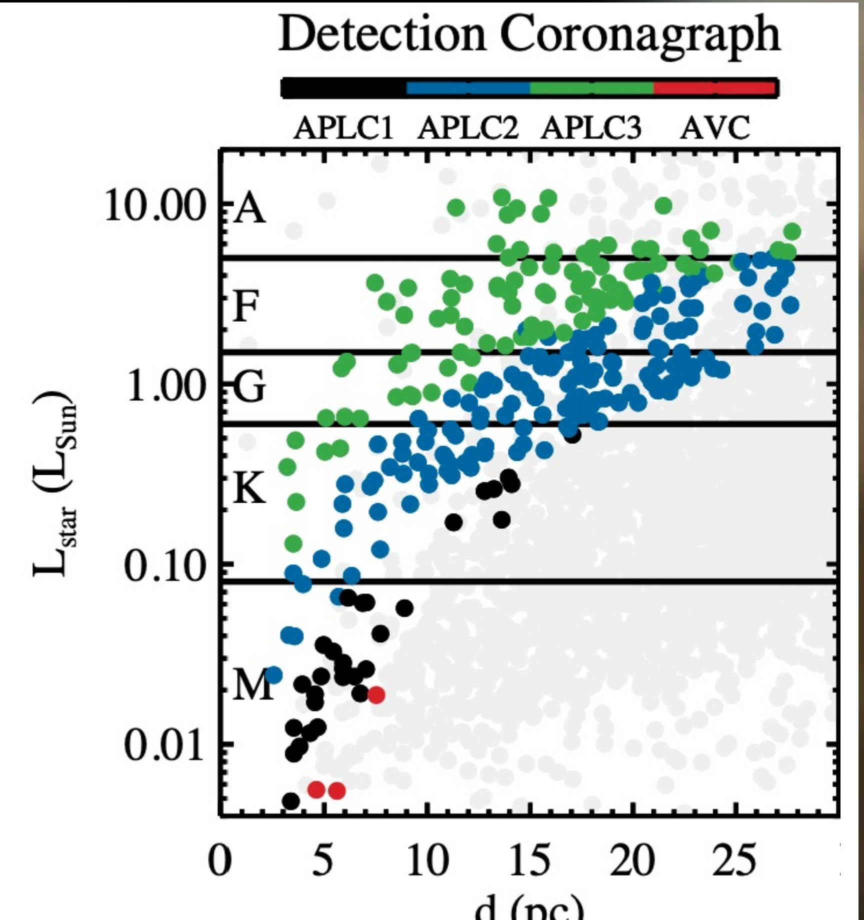
DRMs have come a long way

LUVOIR & HabEx DRMs used realistic coronagraph simulations



Zimmerman/Soummer/St. Laurent

- We assigned simulated 2D leaked starlight to each star as a function of stellar diameter
- We used 2D off-axis simulated PSFs to calculate planet's flux



LUVOIR Final Report (2019)

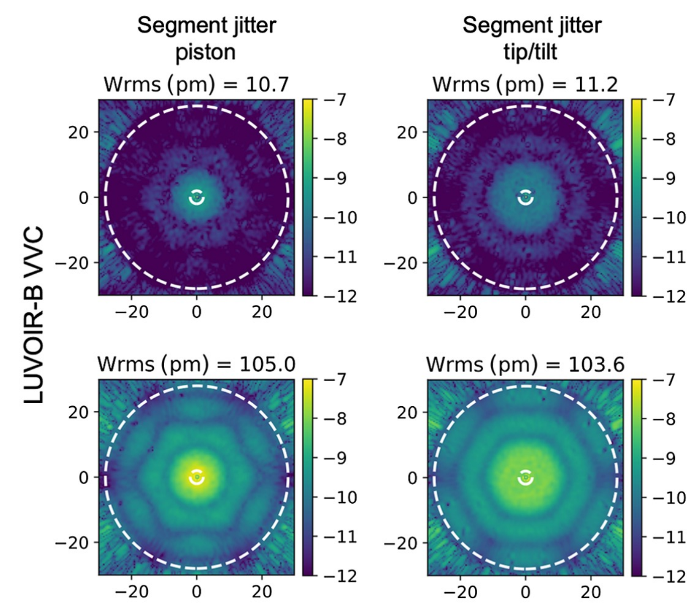
DRM optimally assigned LUVOIR-A's 4 coronagraph masks to stars.

Key points:

- One coronagraph doesn't have to do it all. We can design different coronagraphs for different stars
- Working within the IWA is not out of the question for some coronagraphs

DRMs have come a long way

Recent DRMs include simulated noise floors via dynamic aberrations

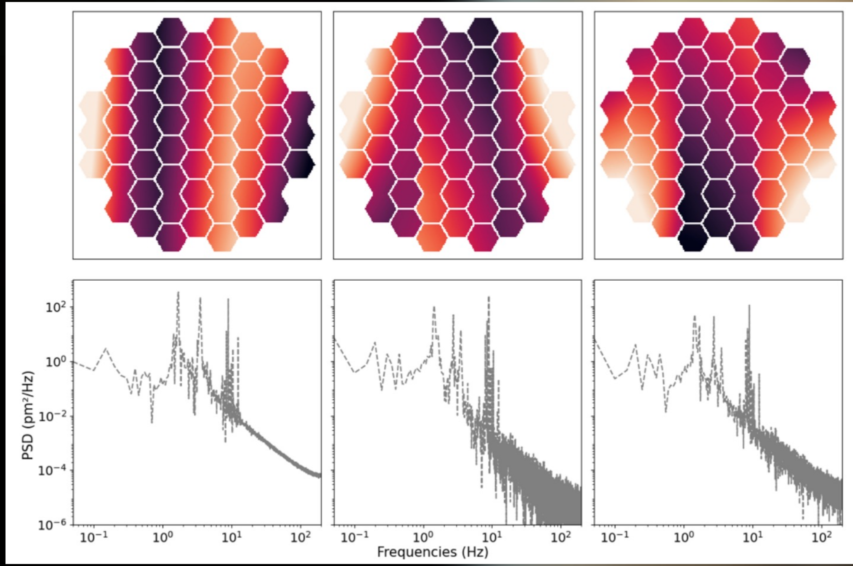


Juanola-Parramon et al. (2022)

Parameterized impact of dynamic disturbances on LUVOIR B.

Potier et al. (2022)

Used the WFE time series from ULTRA study to model noise floor of LUVOIR B.



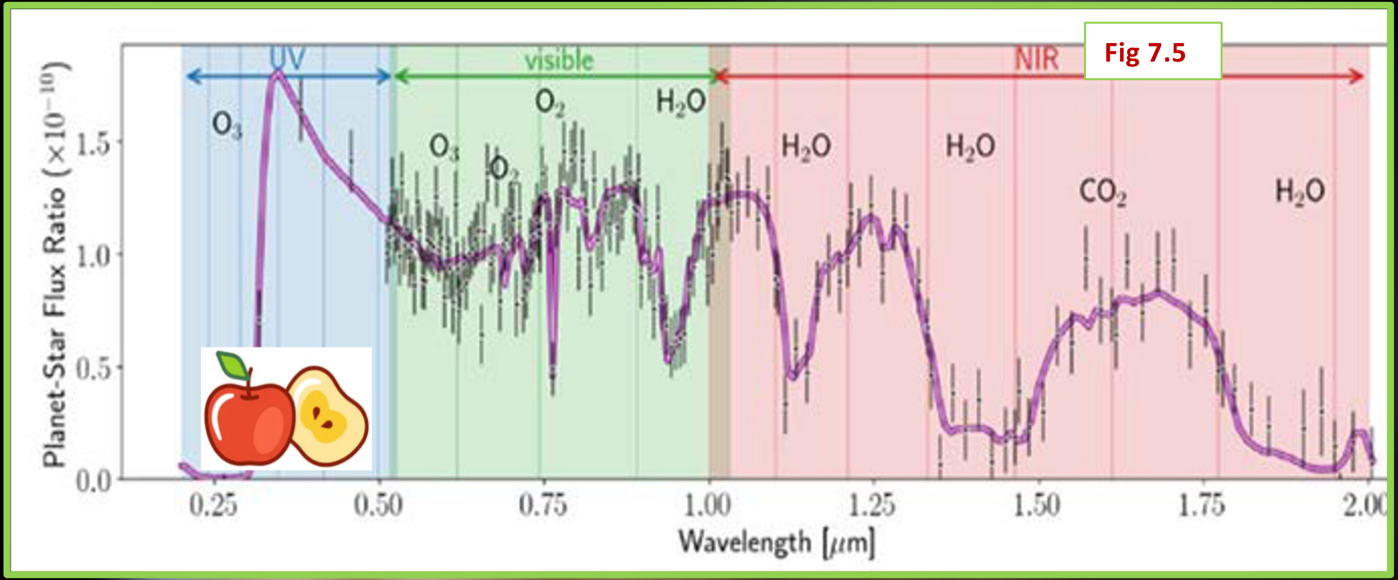
Key points:

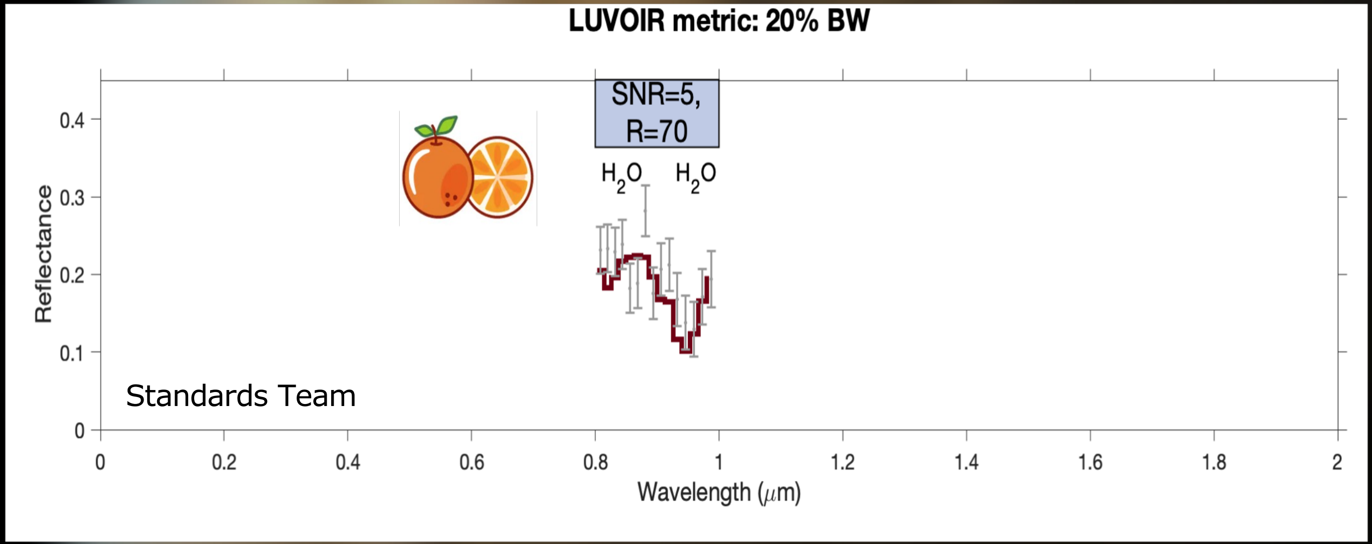
- **The noise floor is one of the most important instrument requirements to get right. We need confidence in these simulations.**
- We can now iterate between engineering simulations and coronagraph simulations to minimize key aberrations

Exoplanet "yields" aren't everything

DRMs can track additional metrics

- Spectral quality/coverage
- Exposure times
- WFSC times
- Orbit retrieval
- Schedulability
- Etc.





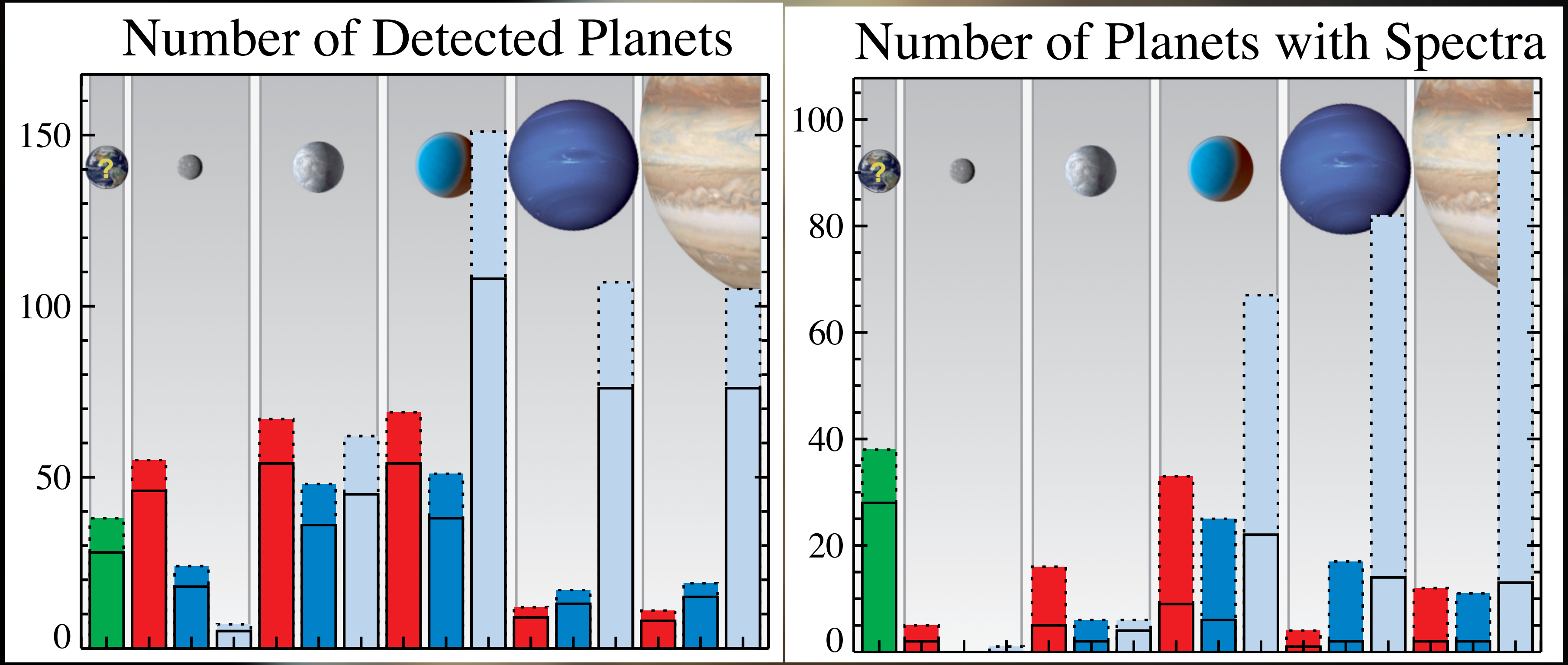
Slide from R. Morgan (2022)

There are many opportunities for improvement!

There are a multitude of low TRL technologies that could radically change our ability to achieve science requirements.

- Improved observation optimization
- Detector technologies:
  - Skipper CCDs & TES arrays
- WFS-based PSF subtraction a la Guyon et al. (2022)
- PIAA & other high throughput coronagraph designs
- Parabolic DMs
- Multi-star WFC
- Etc.

Howe & Stark (preliminary results)



Just one example: A mission with energy resolving TES arrays (dashed lines) could increase exoEarth detection yields by **~30%** compared to LUVOIR/HabEx baselined EMCCDs (solid lines) and would characterize **hundreds** of additional planets for free.

In summary...

Science requirements flow down to mission requirements. However, iteration is key to arriving at an optimized architecture. **DRMs provide the machinery to do that, to estimate science productivity, and to map out science yield sensitivities.**

The exoplanet science performance of HWO is dependent on a large number of parameters that are all tied together/traded. **Design must be thought of at the system level, from the PM to the detector, and from the spacecraft *to the observing strategy*.**

The trade space is enormous and there are many exciting ideas that can improve science yield/quality. **Small investments in low TRL technologies may have enormous benefits.**

We have a lot of work to do, but a lot to be excited about!

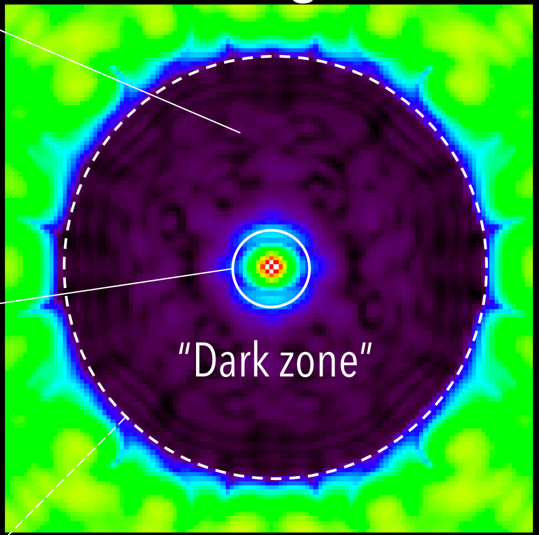
Coronagraphic Terms

"Raw" Contrast
Residual "dark zone" starlight in a photometric aperture at (x,y) divided by the star's flux if placed at (x,y). Varies with stellar diameter & WF aberrations.

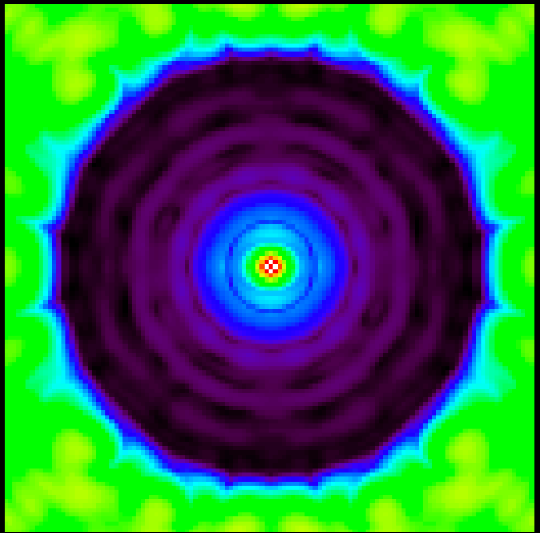
Inner Working Angle (IWA)
Radius interior to which exoplanet detection is difficult. Mathematically defined as radius where throughput reaches half-max in units of λ/D.

Outer Working Angle (OWA)
Radius beyond which exoplanets cannot be detected. Usually set by residual starlight in units of λ/D.

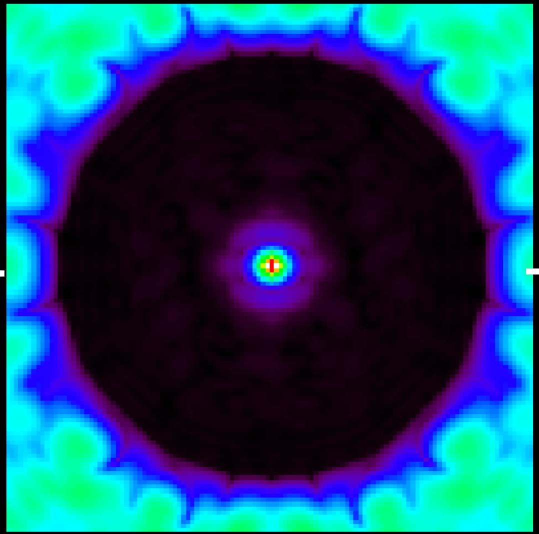
Science Image



Reference PSF



PSF-subtracted Image
Subtract reference star from science star to form final image



Noise floor/contrast floor
Estimated via stddev of remaining speckles, i.e. what varies between observations