Exoplanet Yield Modeling

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NASA GSFC

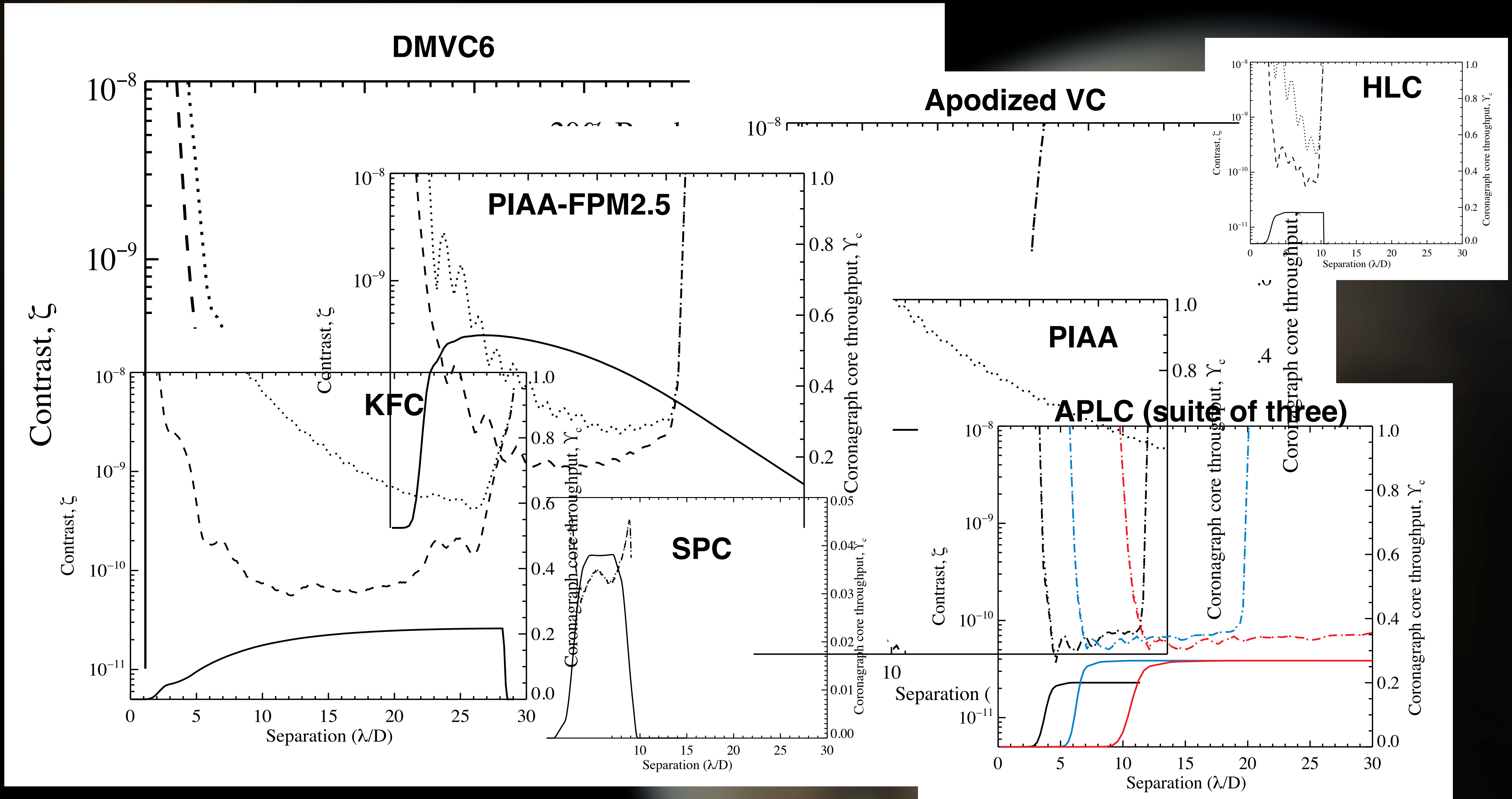
The Astro2020 Decadal Recommendation

Recommendation: After a successful mission and technology maturation program, NASA should embark on a program to realize a mission to search for biosignatures from a robust number of about ~25 habitable zone planets and to be a transformative facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade, with a target launch in the first half of the 2040s.

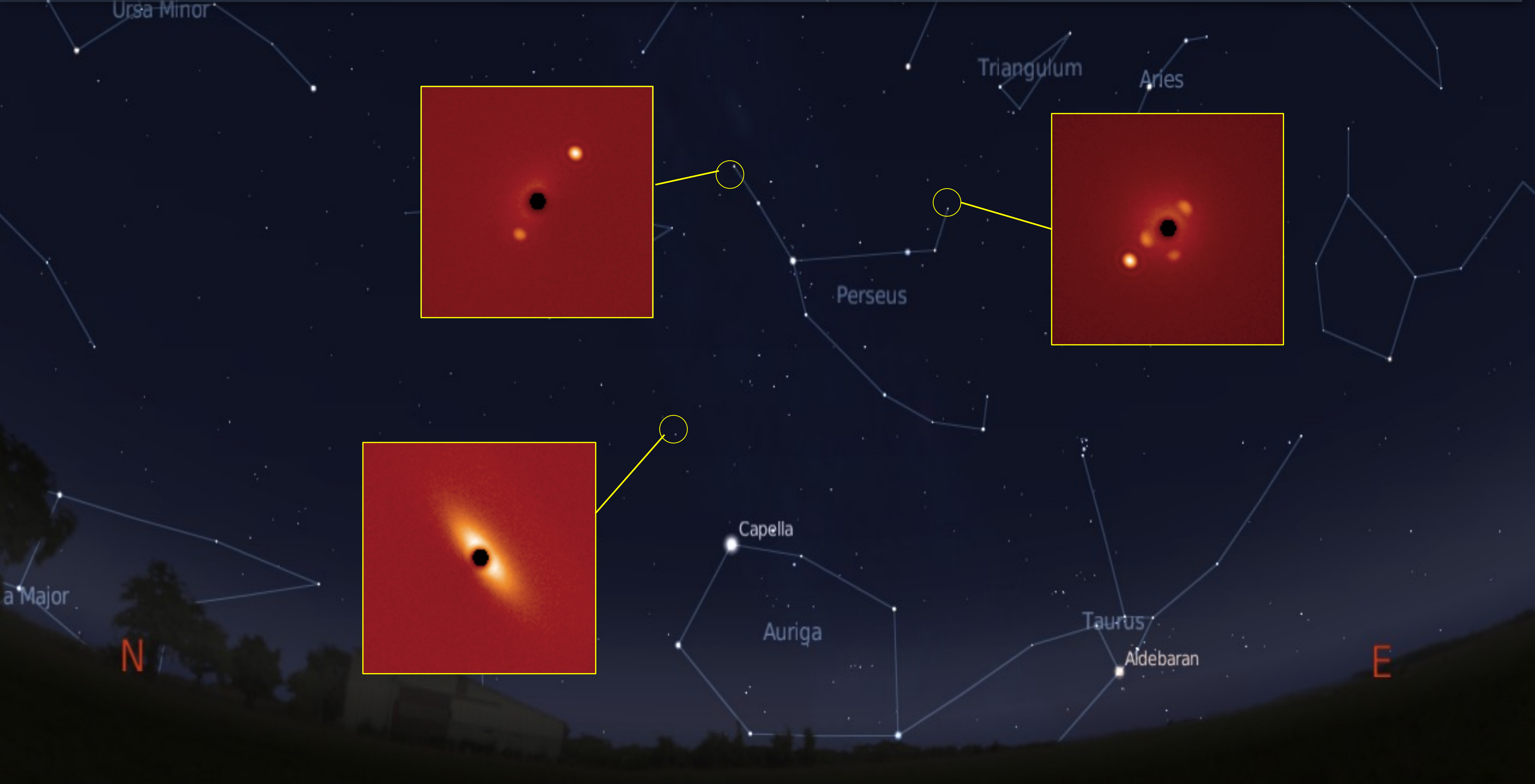
The mission the survey puts forward will combine a large, stable telescope with an advanced coronagraph intended to block the light of bright stars. It will be capable of surveying a hundred or more nearby Sun-like stars to discover their planetary systems and determine their orbits and basic properties. Then for the most exciting ~25 planets, astronomers will use spectroscopy at ultraviolet, visible, and near-infrared wavelengths to identify multiple atmospheric components that could serve as biomarkers (see

Astro2020 Final Report

Coronagraph performance is complex and trade space is coupled



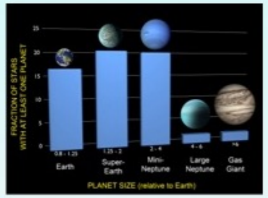
DRMs map coronagraph performance onto the stars around us



Exoplanet Yields Require Mission Simulations

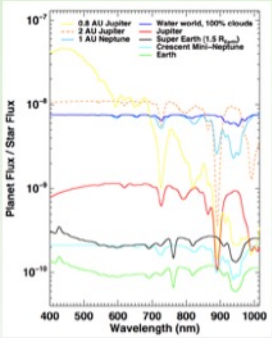
Astrophysical Constraints

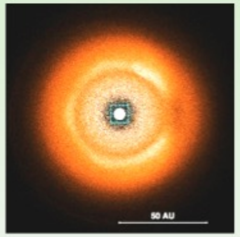
- η_{Earth}
- $\eta_{exozodi}$
- Planet sizes
- Albedos
- Phase functions



Observational Requirements

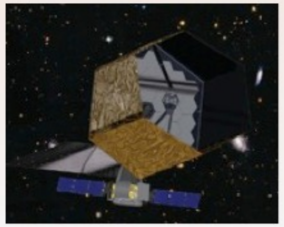
- Central wavelength
- Total bandpass
- Spectral resolution
- Signal-to-Noise
- Observing strategy





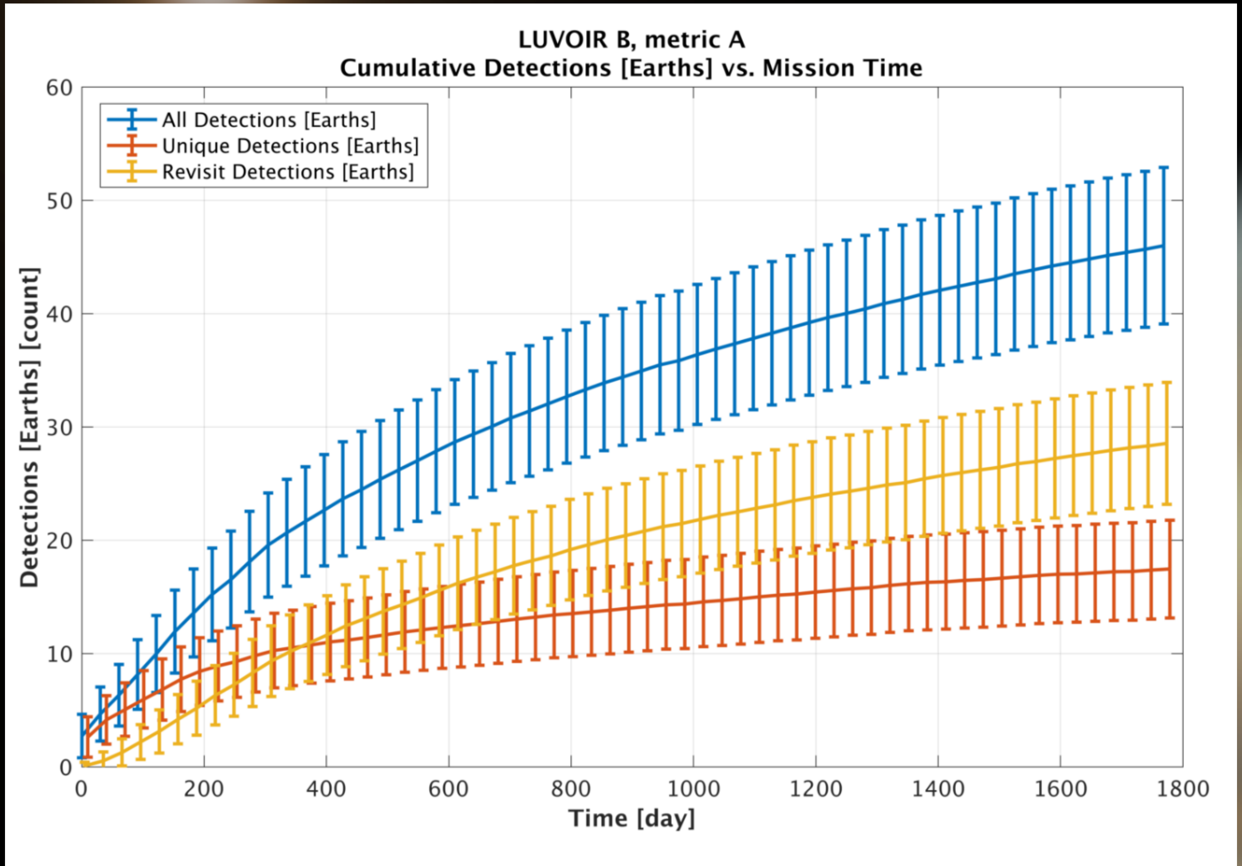
Technical Requirements

- Telescope diameter
- Contrast
- Contrast floor
- Inner working angle
- Outer working angle
- Total throughput
- Overheads

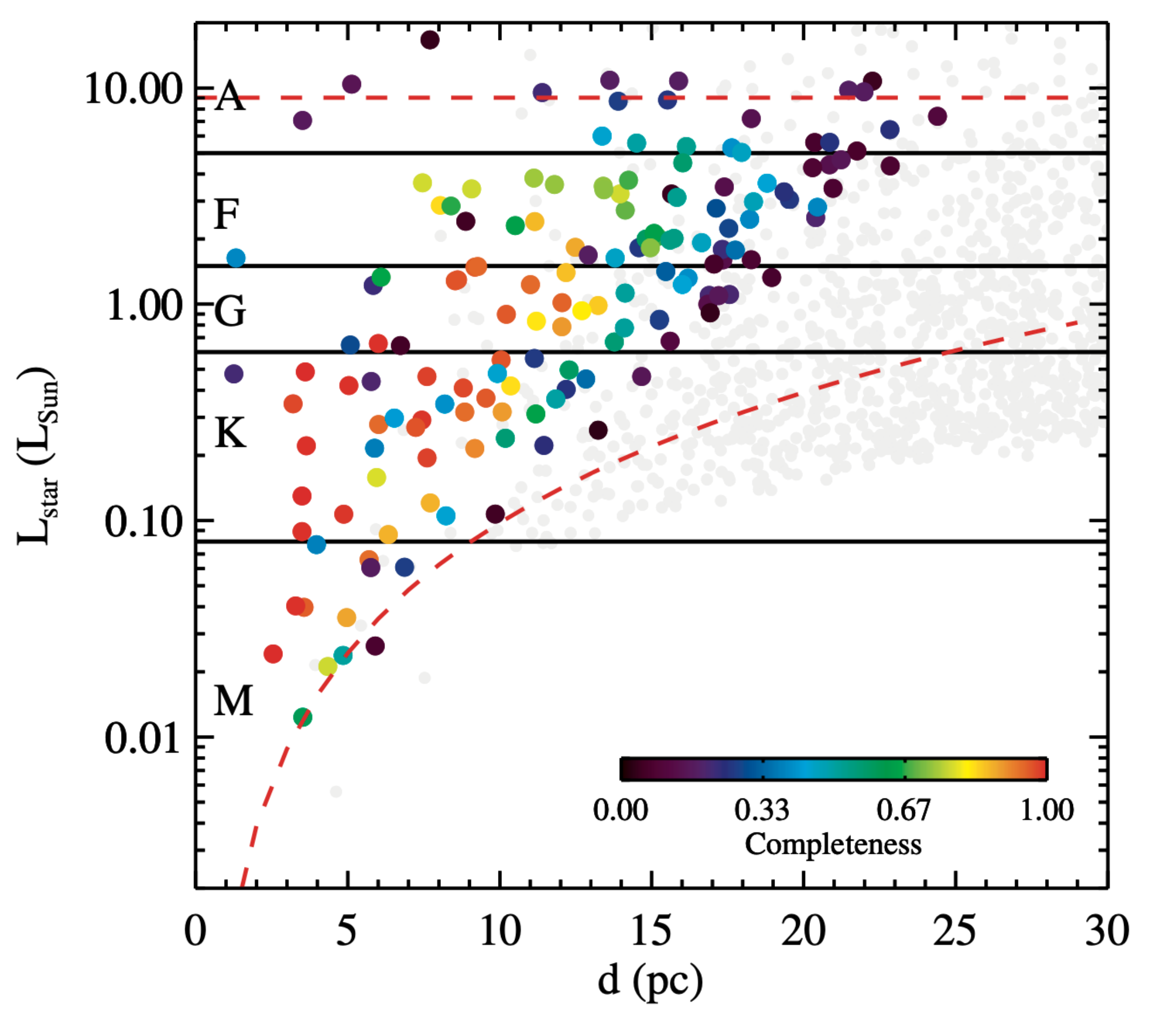


DRM

DRMs estimate scientific *productivity*



Morgan et al. (2019)



Stark et al. (in prep)

Spoiler alert: extended missions can improve data quantity/quality on high priority targets, but increasing yields is harder

“Completeness” is at the heart of yield calculations

THE ASTROPHYSICAL JOURNAL, 624:1010–1024, 2005 May 10

SINGLE-VISIT PHOTOMETRIC AND OBSCURATIONAL COMPLETENESS

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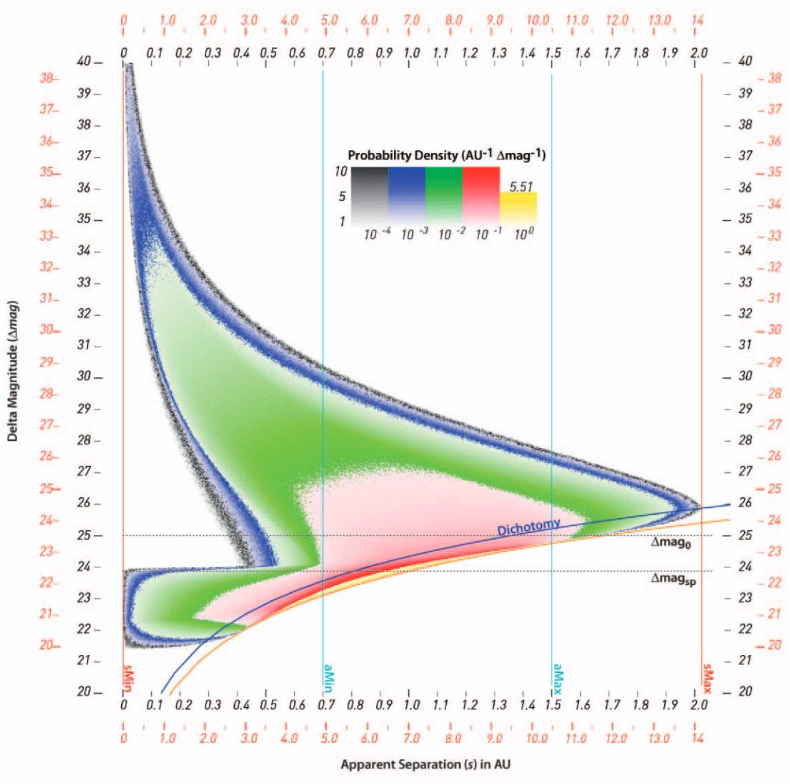
Received 2004 October 14; accepted 2005 January 7



Brown (2005)

First visit completeness

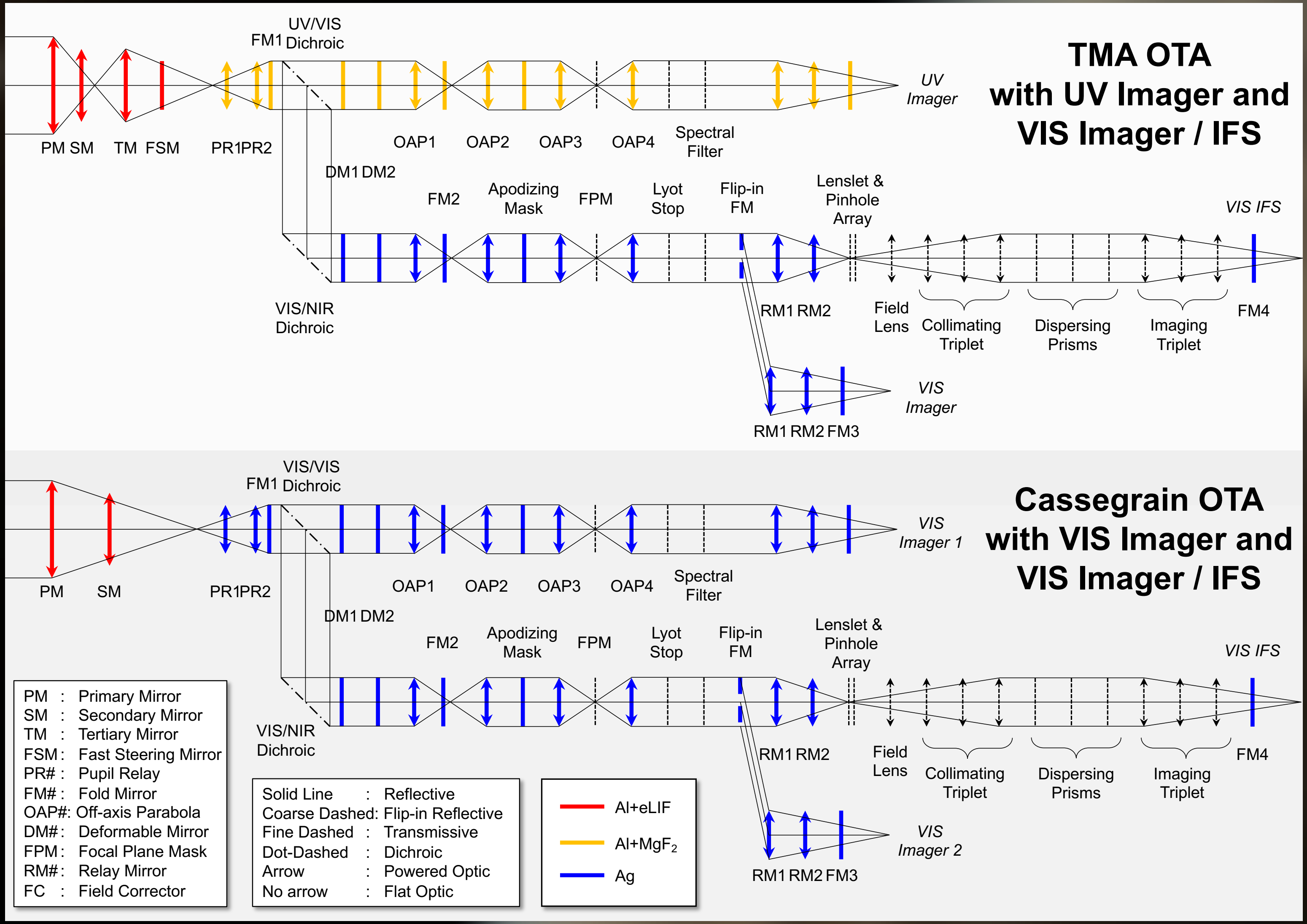
- Completeness, C = the chance of observing a given planet around a given star if that planet exists (Brown 2004)
- Yield = $\eta_{\text{Earth}}\,\Sigma\,C$
- Calculated using a large number of synthetic planets

If once wasn't enough, look again

Revisiting same star multiple times can increase total completeness

DRMs have come a long way: higher fidelity

LUVOIR & HabEx DRMs used realistic optical layouts

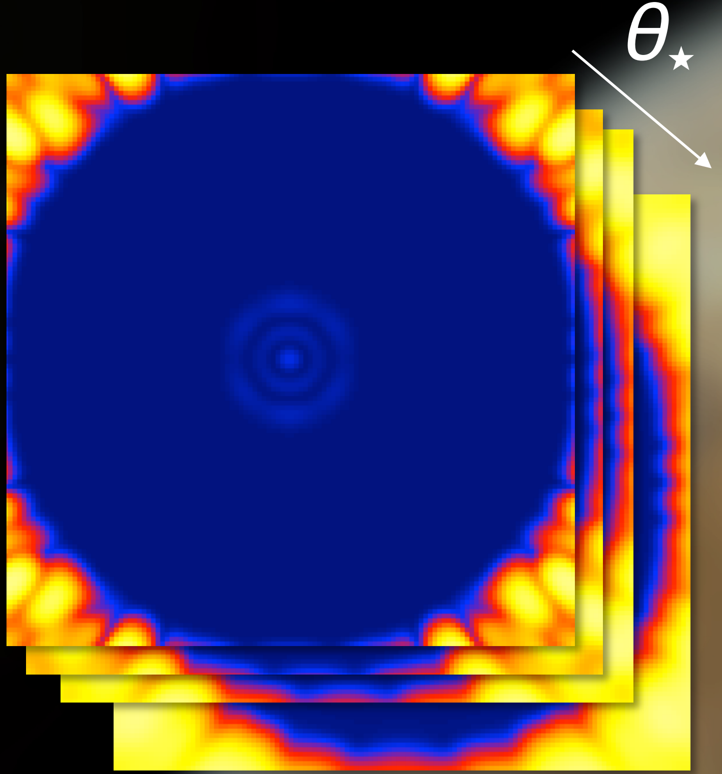


Stark et al. (2019)

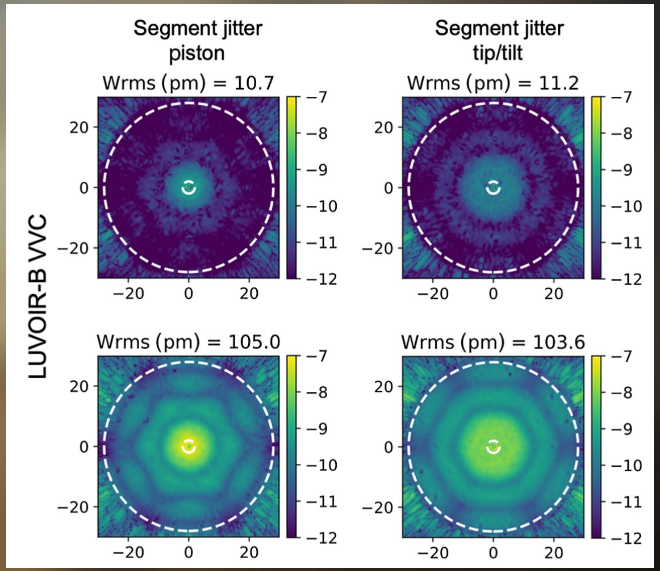
DRMs have come a long way: higher fidelity

We now use realistic coronagraph simulations

We have standardized the interface between coronagraph modelers and yield calculators

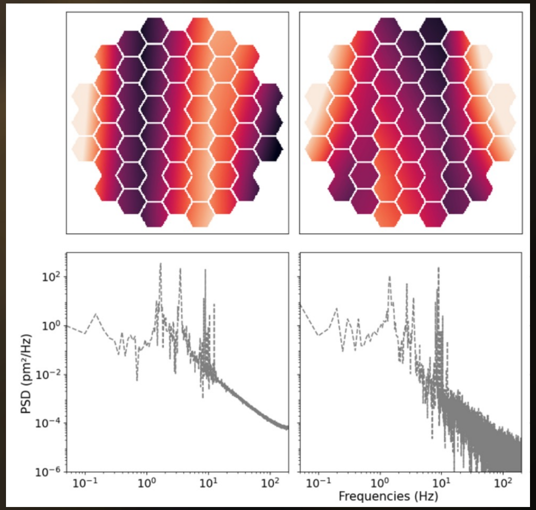


Zimmerman/Soummer/St. Laurent



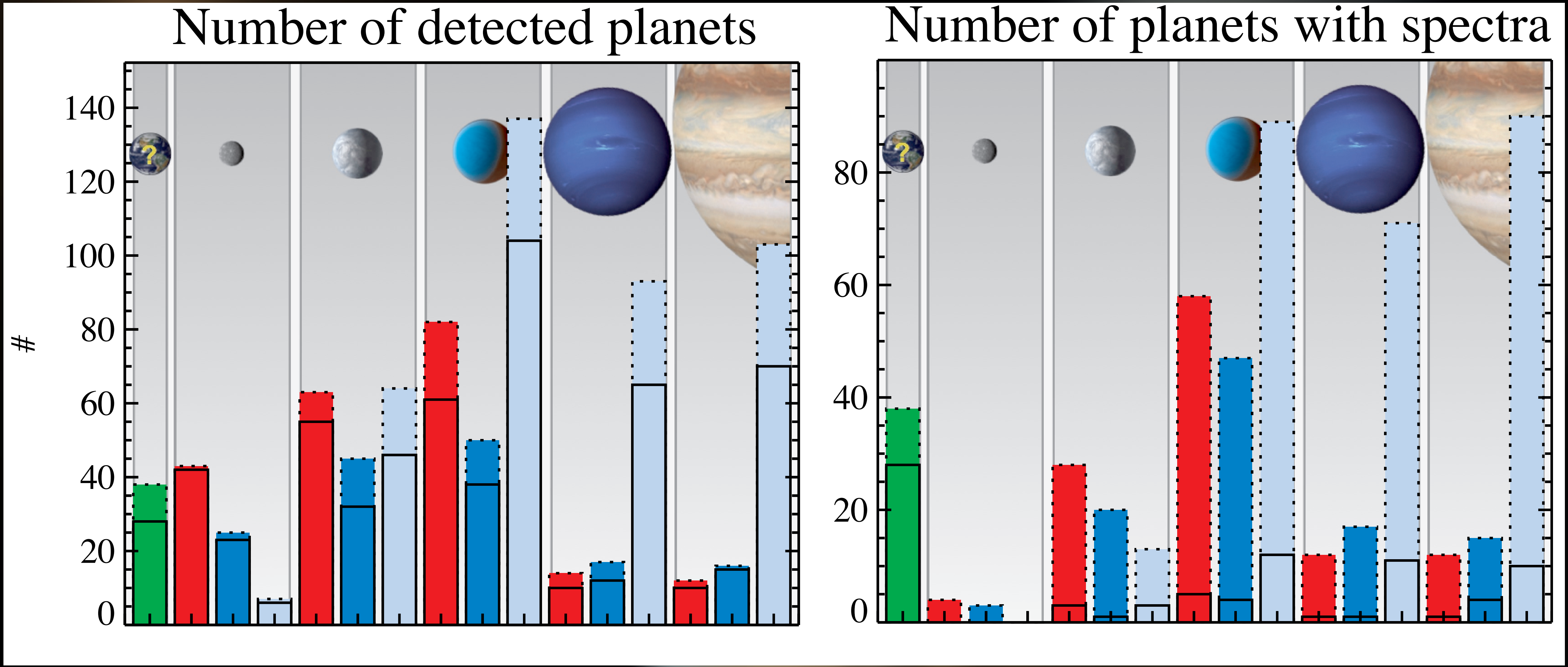
Juanola-Parramon et al. (2022)

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



Potier et al. (2022)

DRMs have come a long way: expanded science metrics



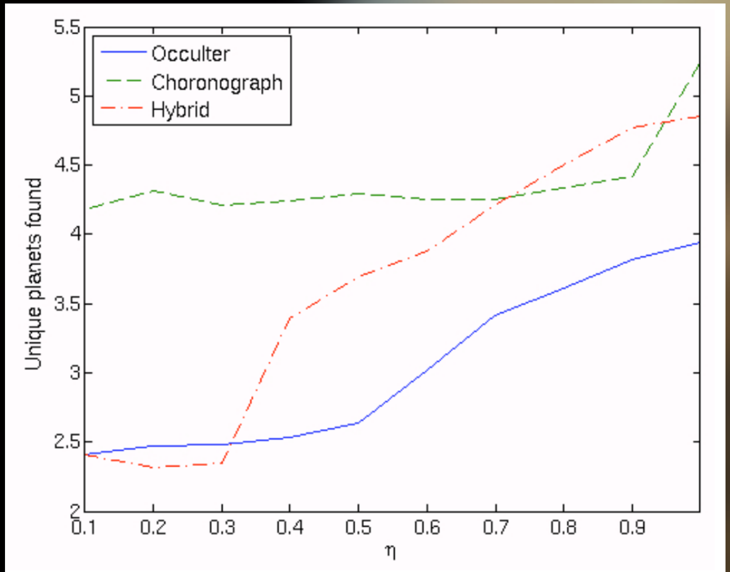
Howe et al. (submitted)
See also Kopparapu et al. (2018)

DRMs have come a long way: optimization

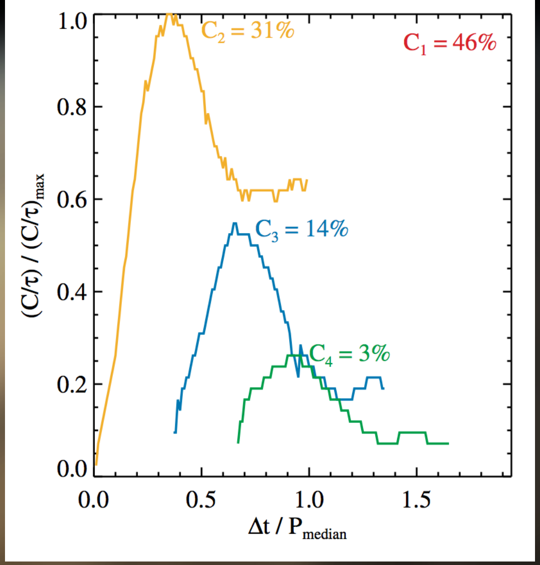
6. AN OPTIMIZATION OF Δmag_0 FOR ROUND AND ELLIPTICAL 8 m APERTURES

The purpose of this section is to illustrate the usefulness of our method of estimating the yield of search programs for instrument design. We use variations of the demonstrative observing program to explore the optimization of Δmag_0, perhaps the most critical specification of the instrument, for various values of grand total exposure time. Here we consider both round and elliptical 8 m apertures. In § 7 we use a simple model of an optimized coronagraph to provide one interpretation Δmag_0, in terms of wavefront stability.

Brown (2005)



Savransky & Kasdin (2008)



Stark et al. (2015)

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

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

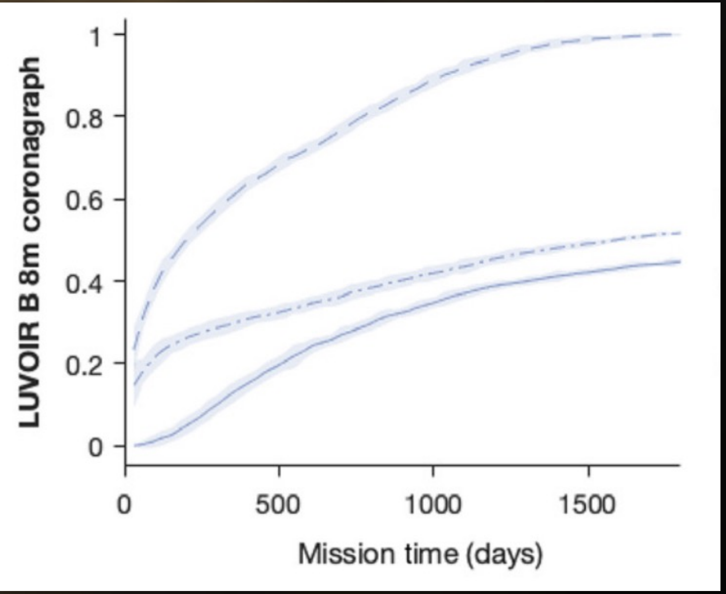
The total integration time is shared by N stars and is constrained by

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

We choose τ_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)

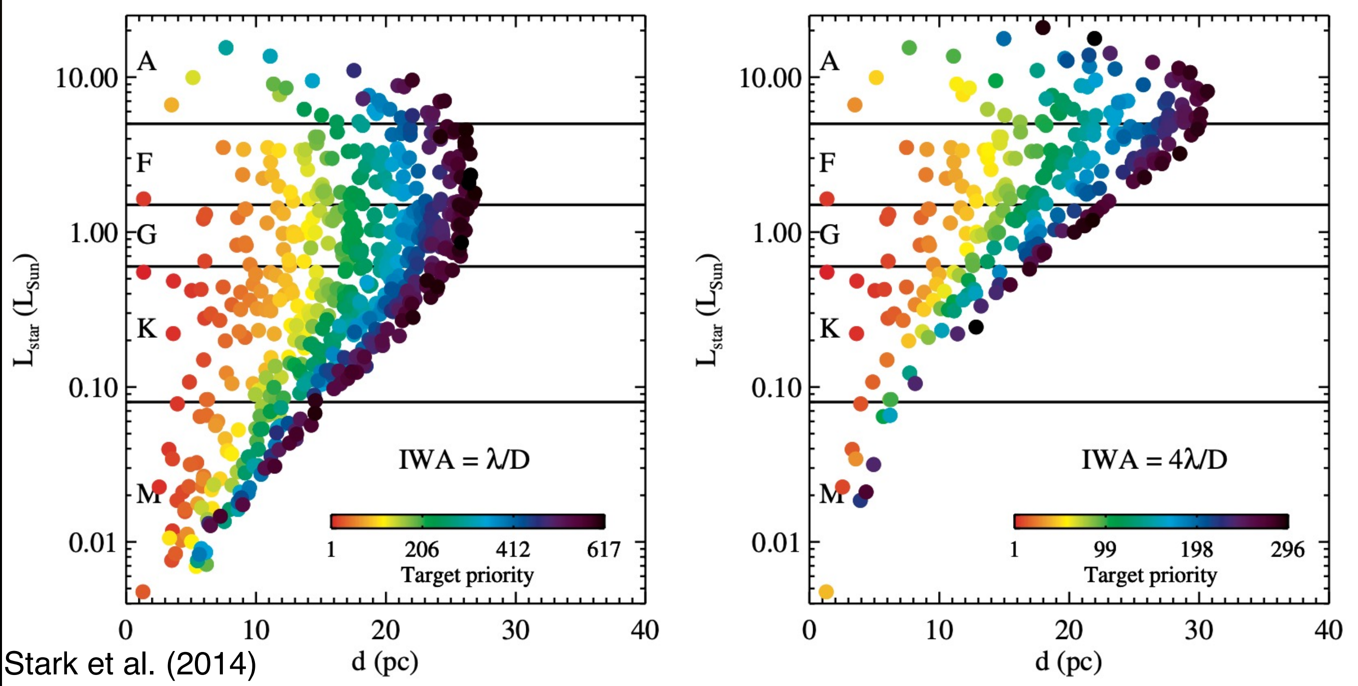


Morgan et al. (2021)

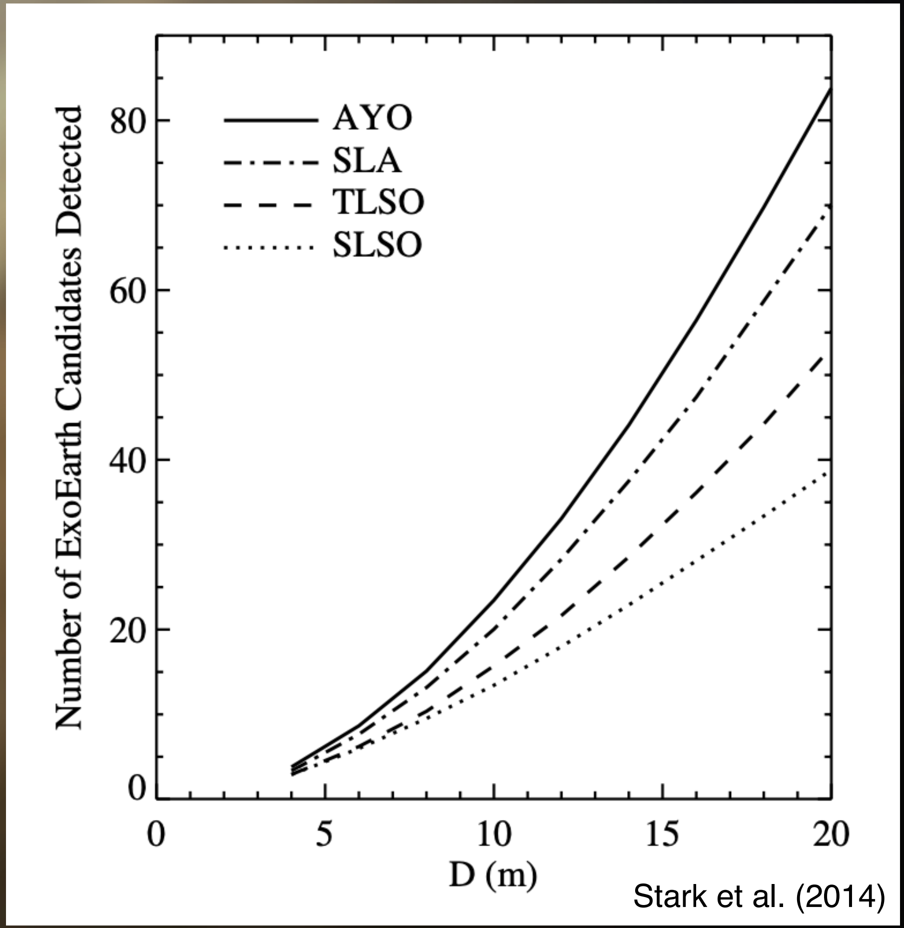
DRMs have come a long way: optimization

Why do we want to optimize?

- 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



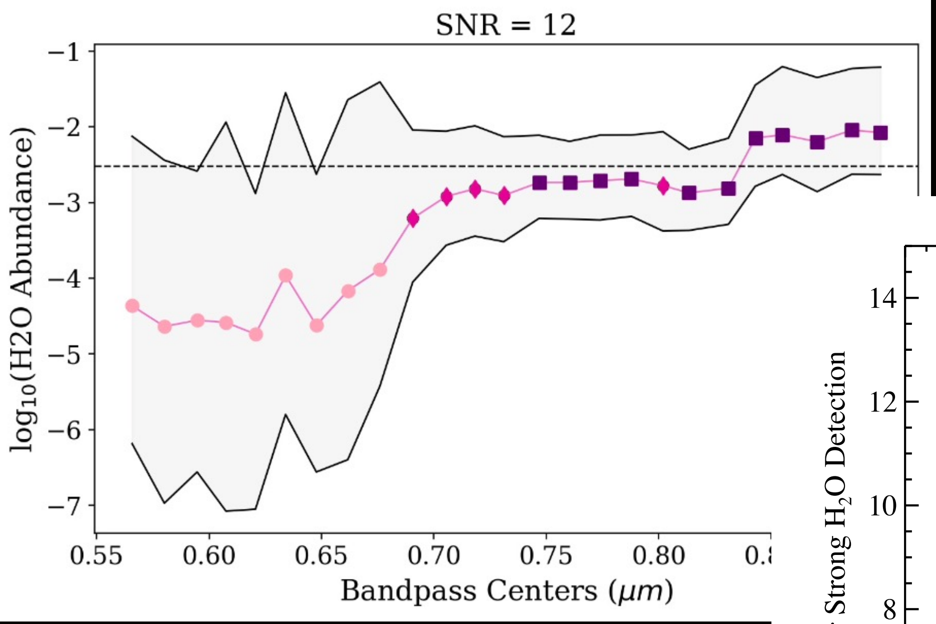
Target list adapts to changes in instrument



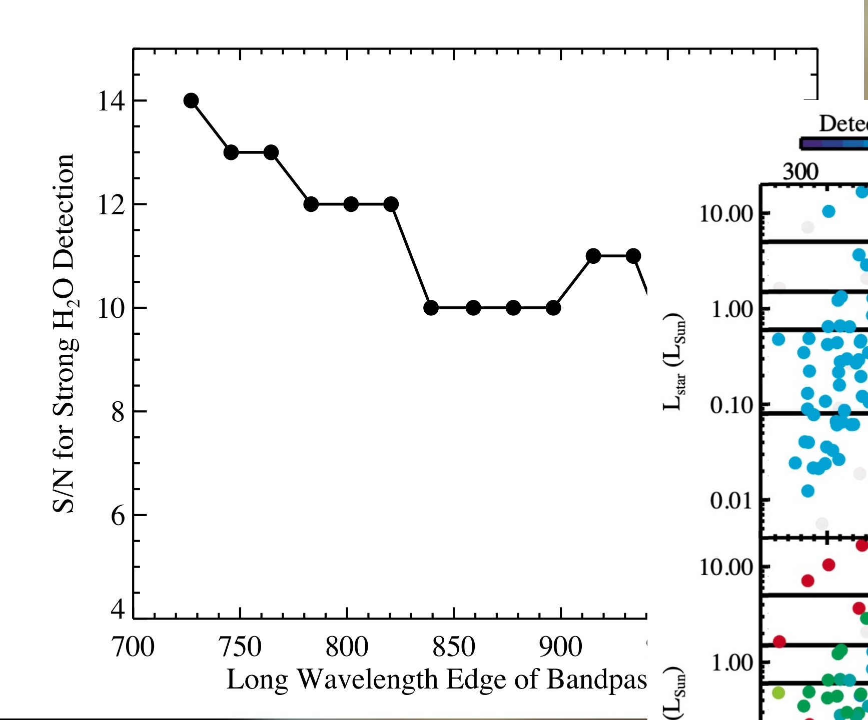
Optimization increases yields

DRMs have come a long way: optimization

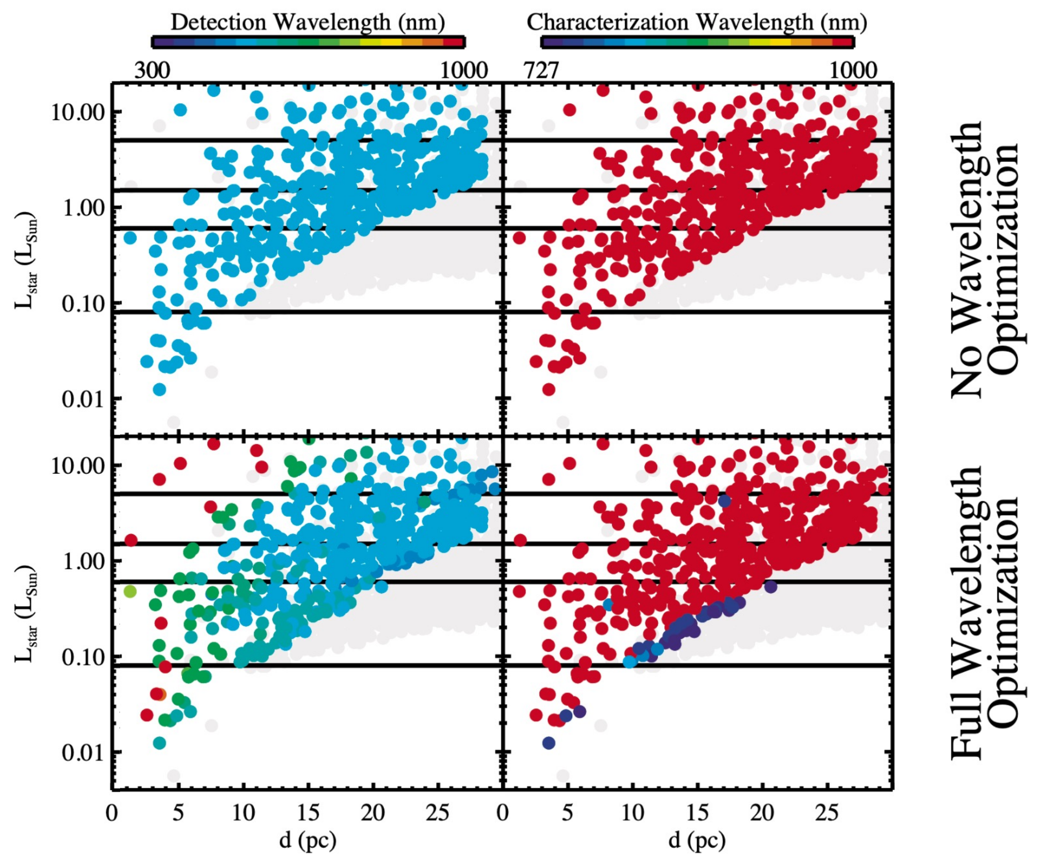
Wavelength optimization



Latouf et al. (submitted)

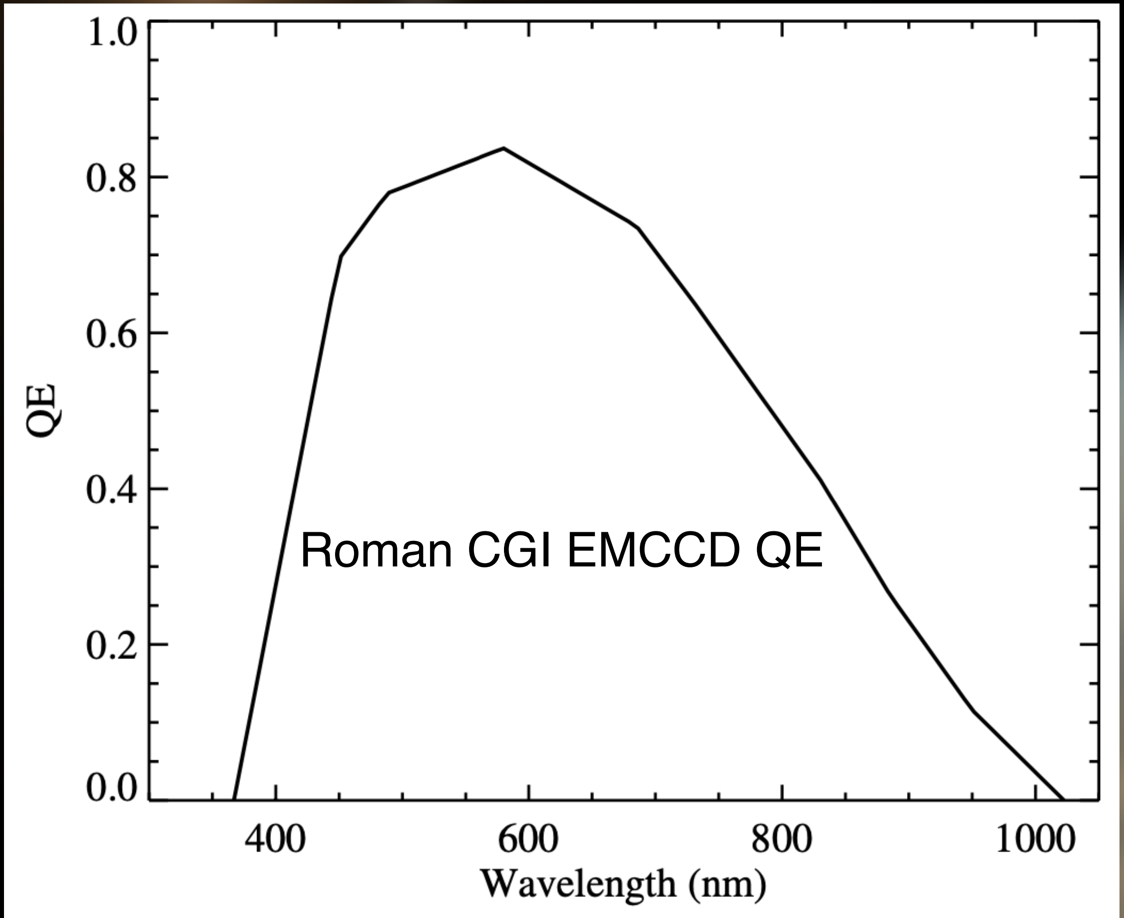


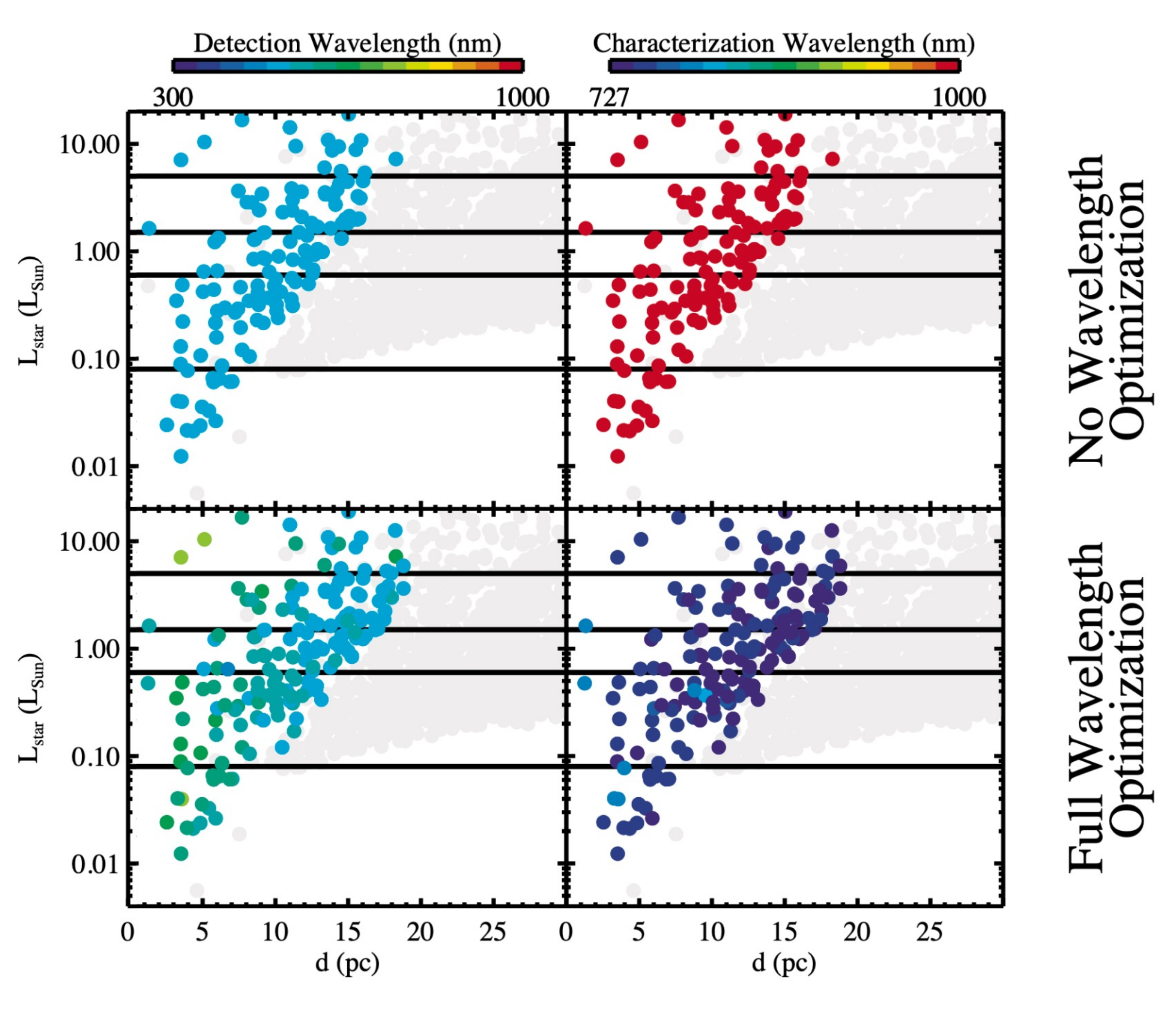
Stark et al. (submitted)



DRMs have come a long way: optimization

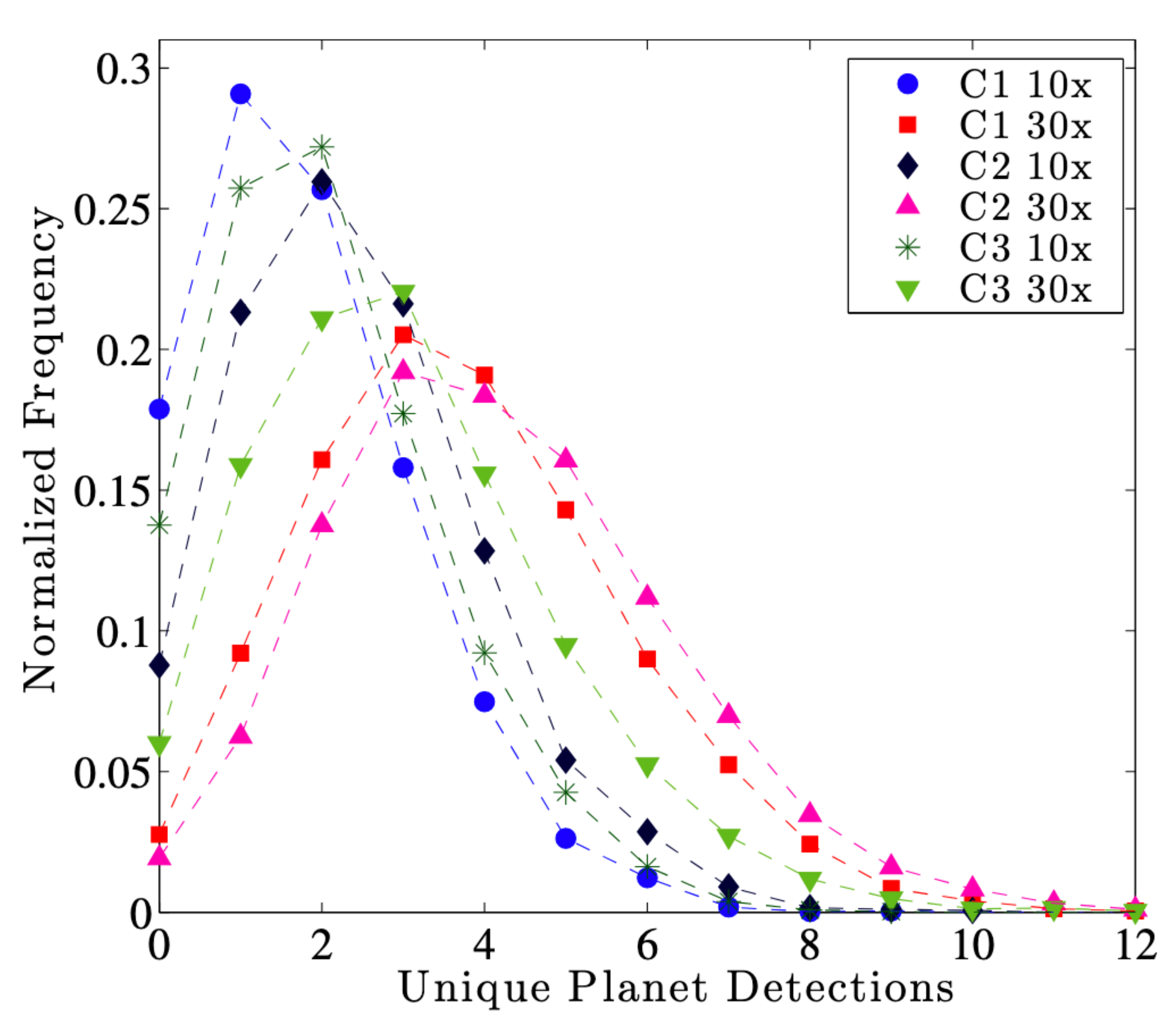
Wavelength optimization can be very important





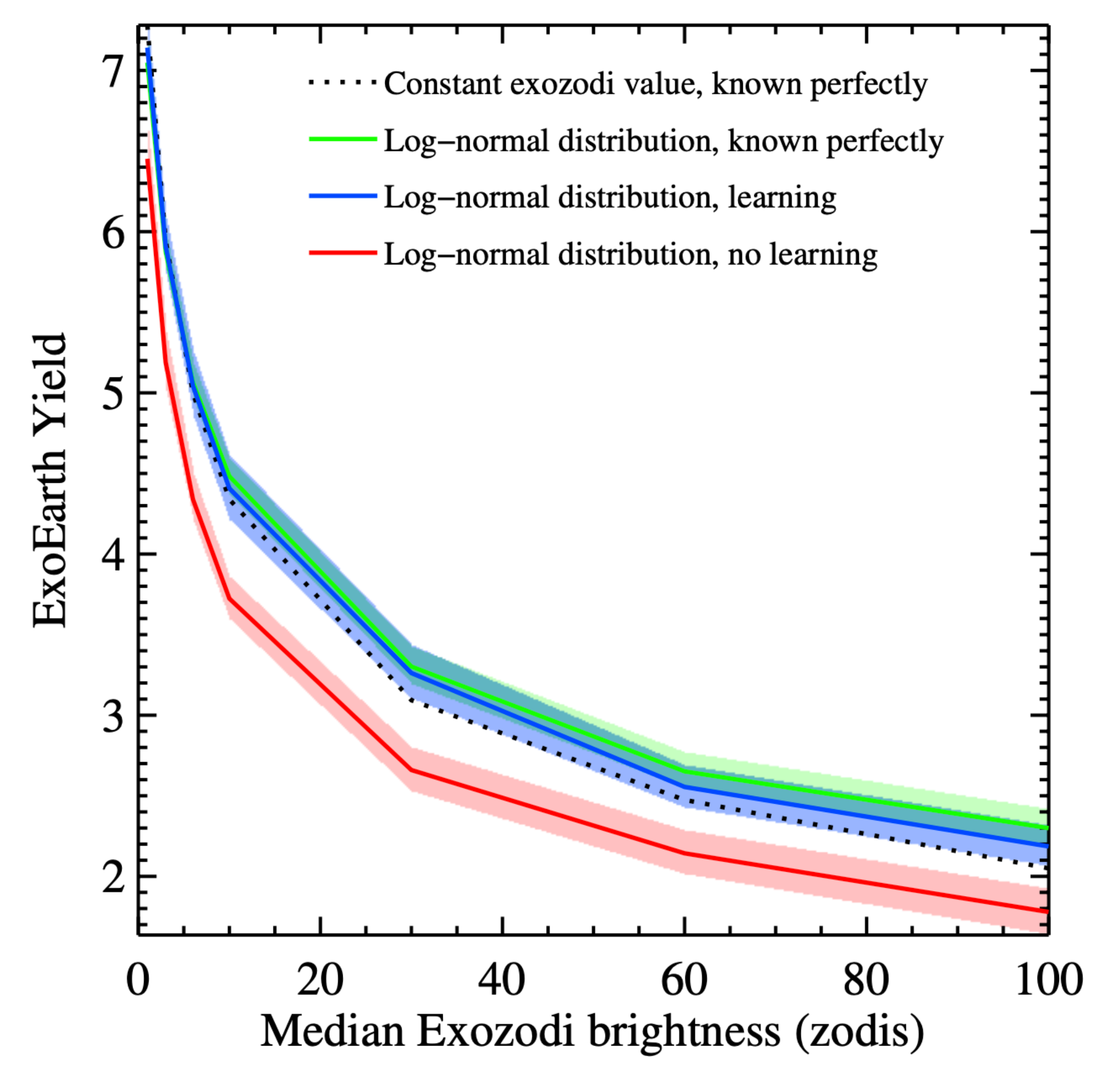
Wavelength optimization increased yields by 50% when adopting the Roman CGI EMCCD QE

What we've learned from DRMs: Yields are probabilistic

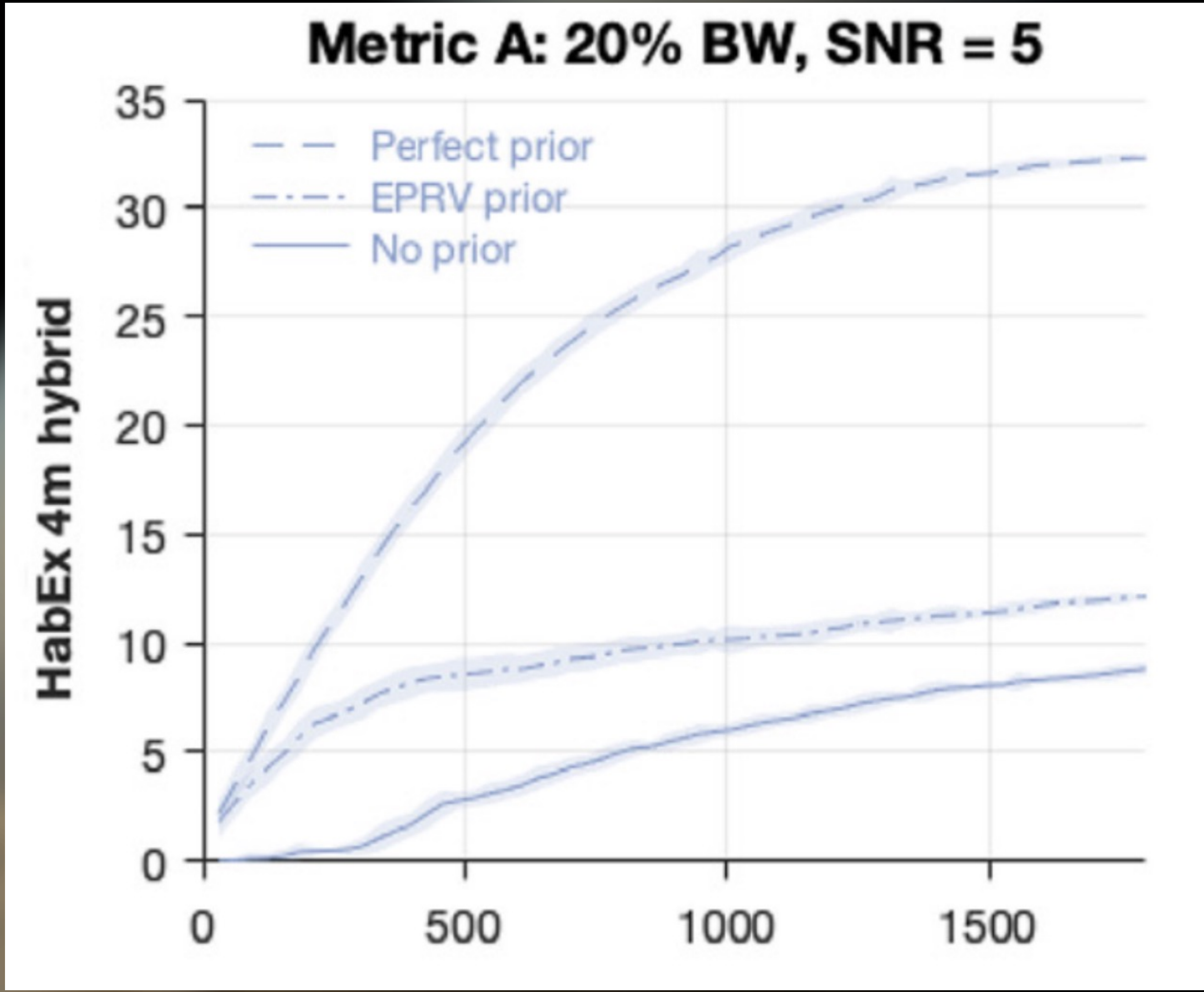


Savransky et al. (2016)

What we've learned from DRMs: Impact of prior knowledge

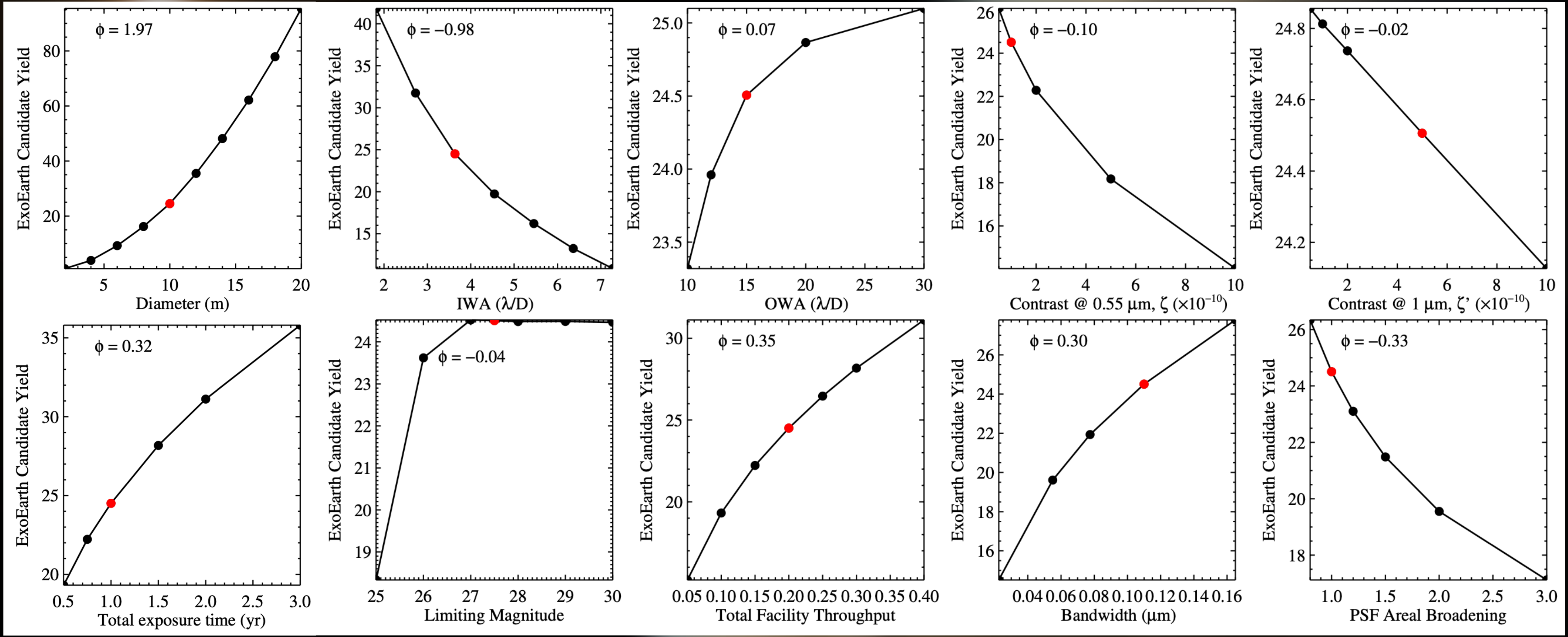


Stark et al. (2015)



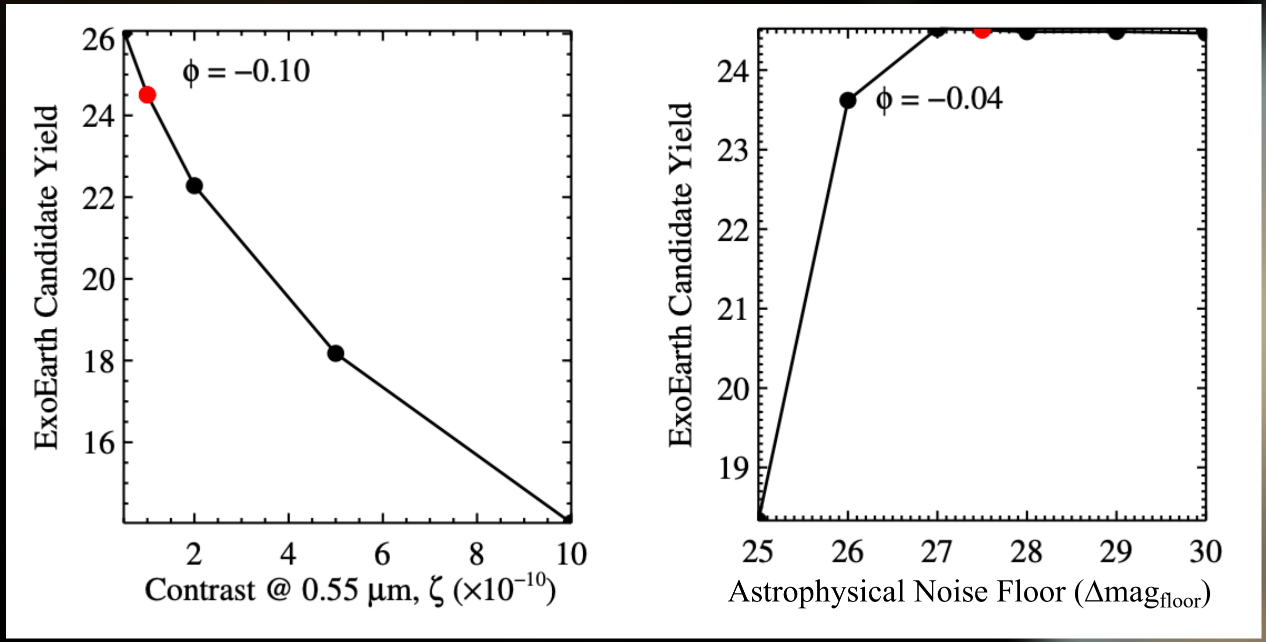
Morgan et al. (2021)

What we've learned from DRMs: Which parameters matter

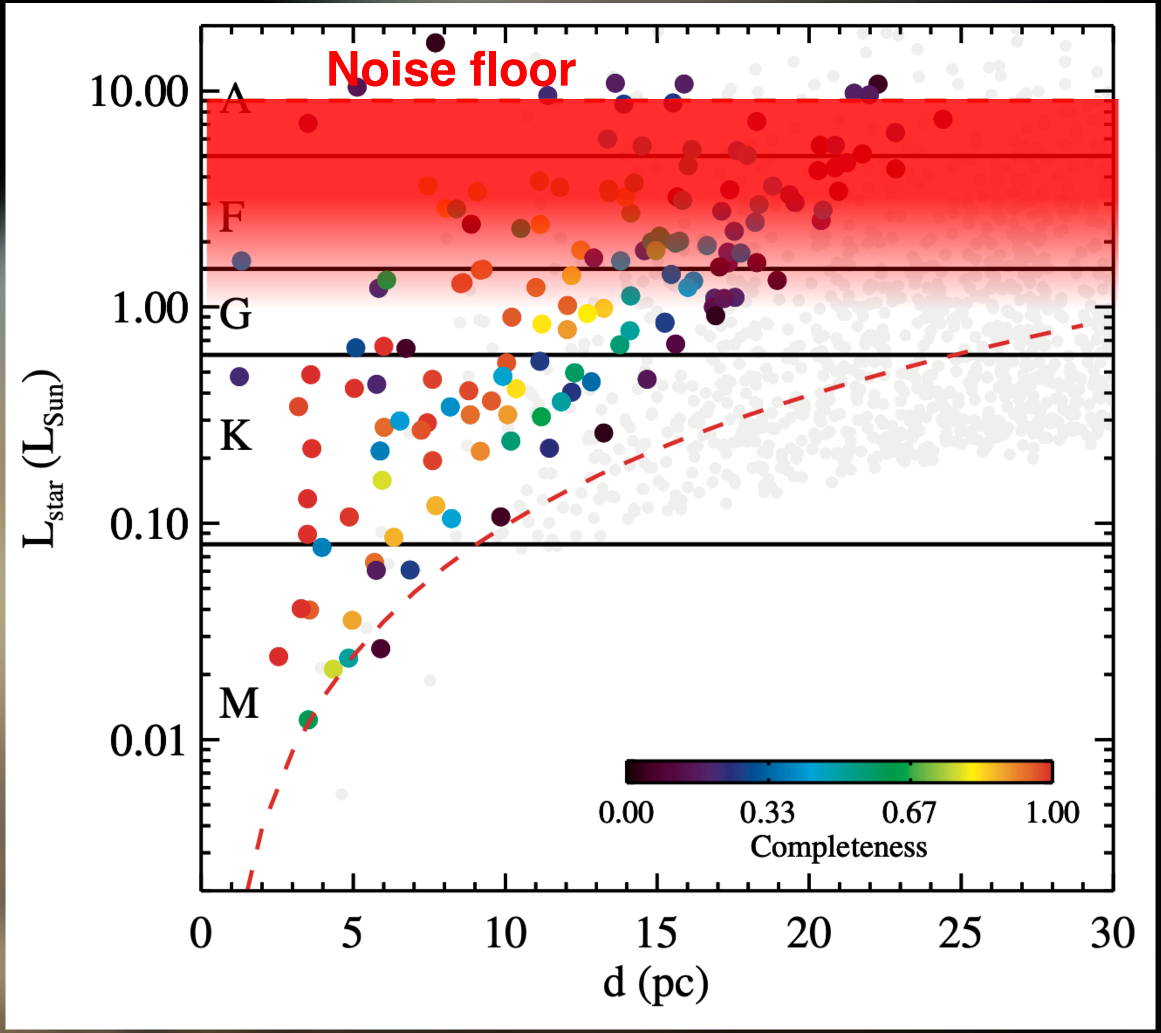


Stark et al. (2015)

What we've learned from DRMs: The noise floor is a critical parameter



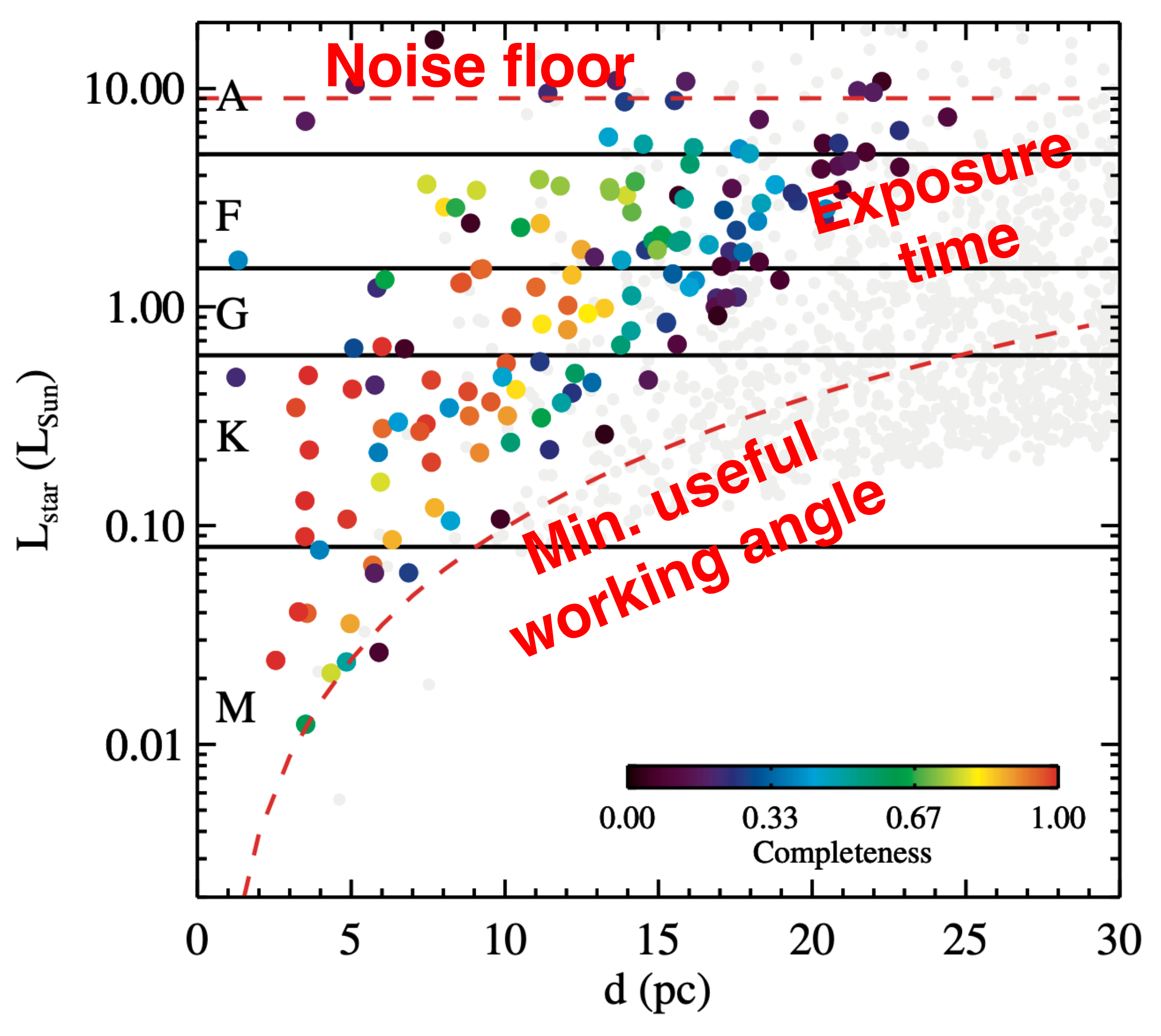
Stark et al. (2015)



Yield is relatively insensitive to raw contrast because of exozodi. But the *contrast floor after PSF subtraction is a critical* parameter.

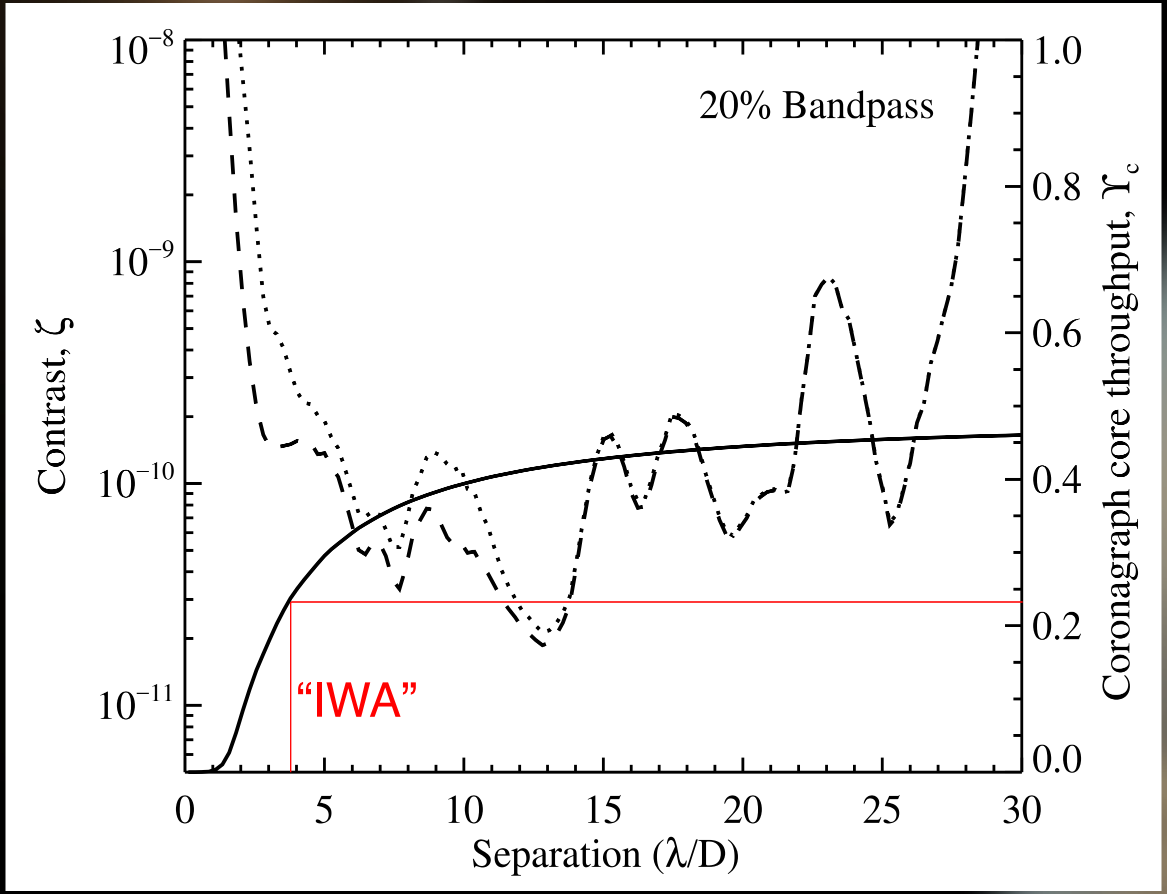
The noise floor directly limits the range of accessible targets

What we've learned from DRMs:
The range of accessible targets is set by ~three parameters

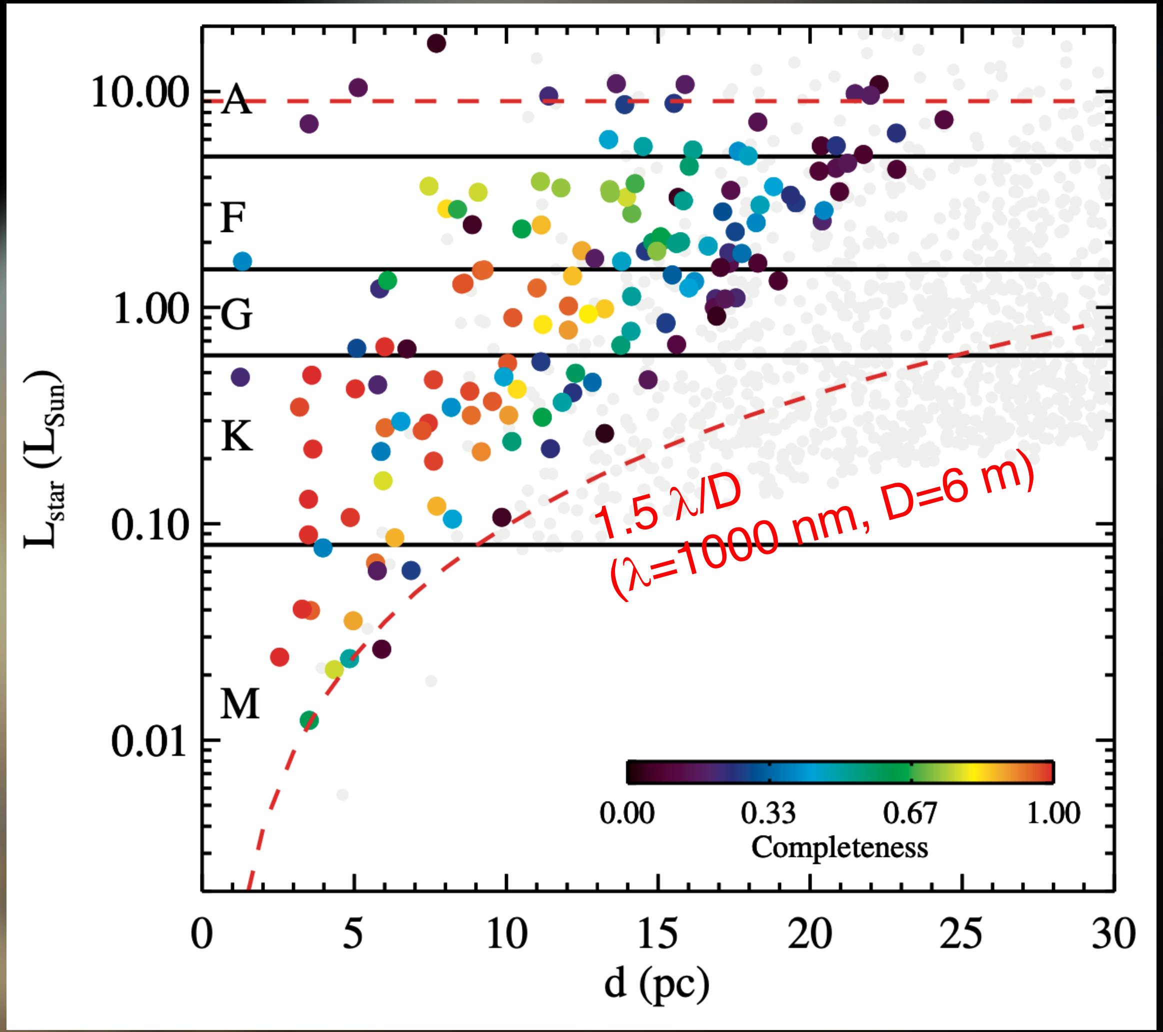


What we've learned from DRMs: How to use coronagraphs with HWO

DMVC6 azimuthally averaged performance

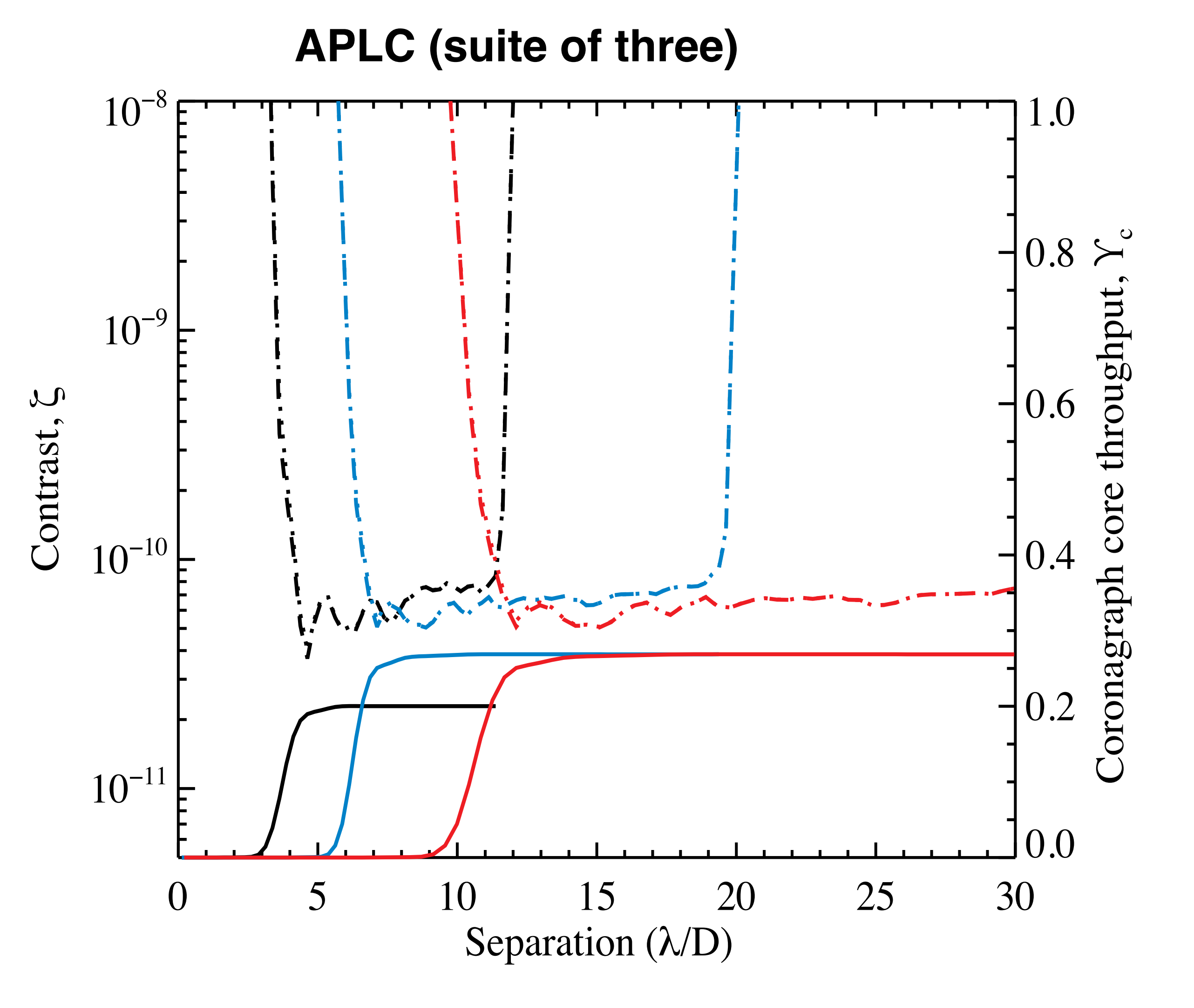


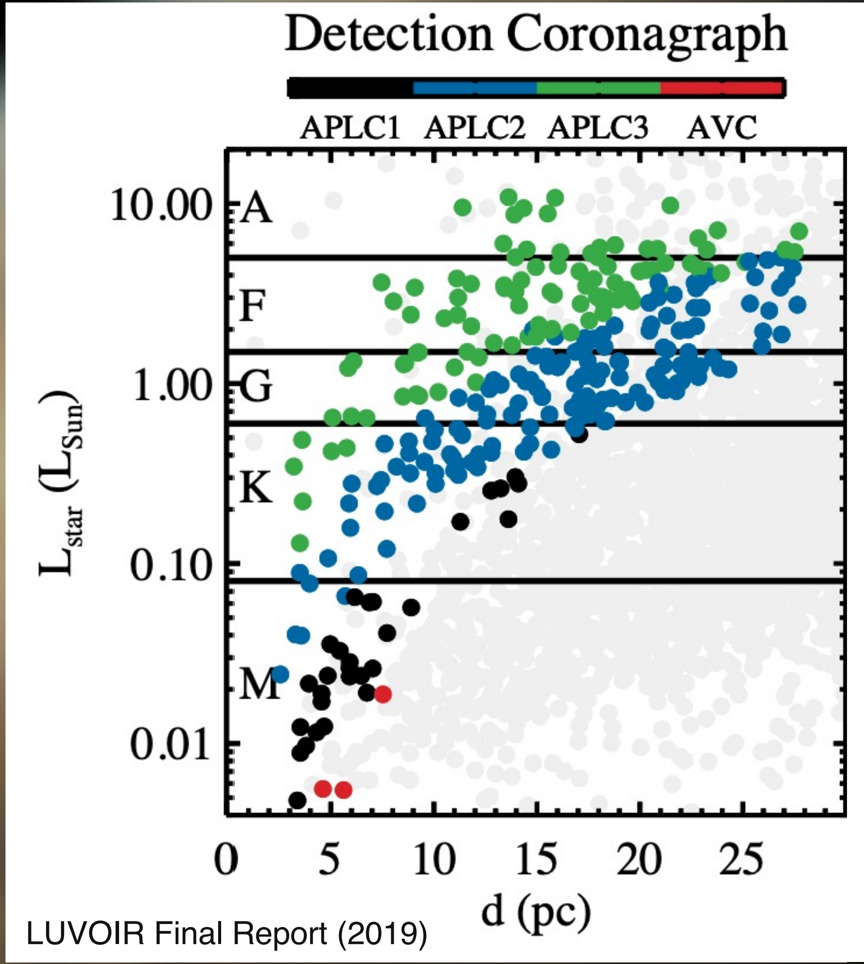
Useful throughput interior to "IWA" means coronagraphs can operate interior to IWA



Spatial resolution constraints to avoid planetary blending may be a critical limitation (Saxena 2022)

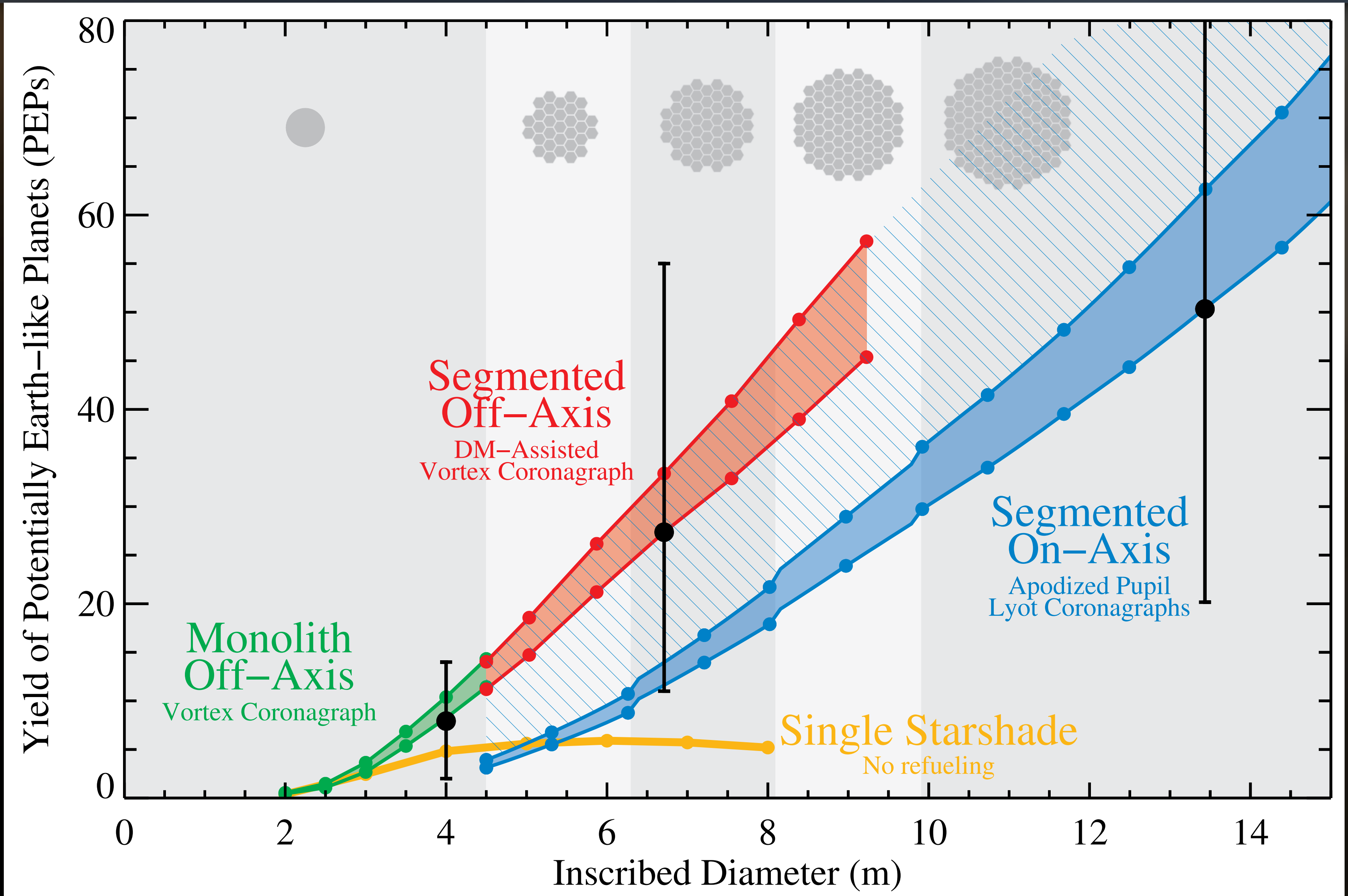
What we've learned from DRMs: How to improve coronagraph designs





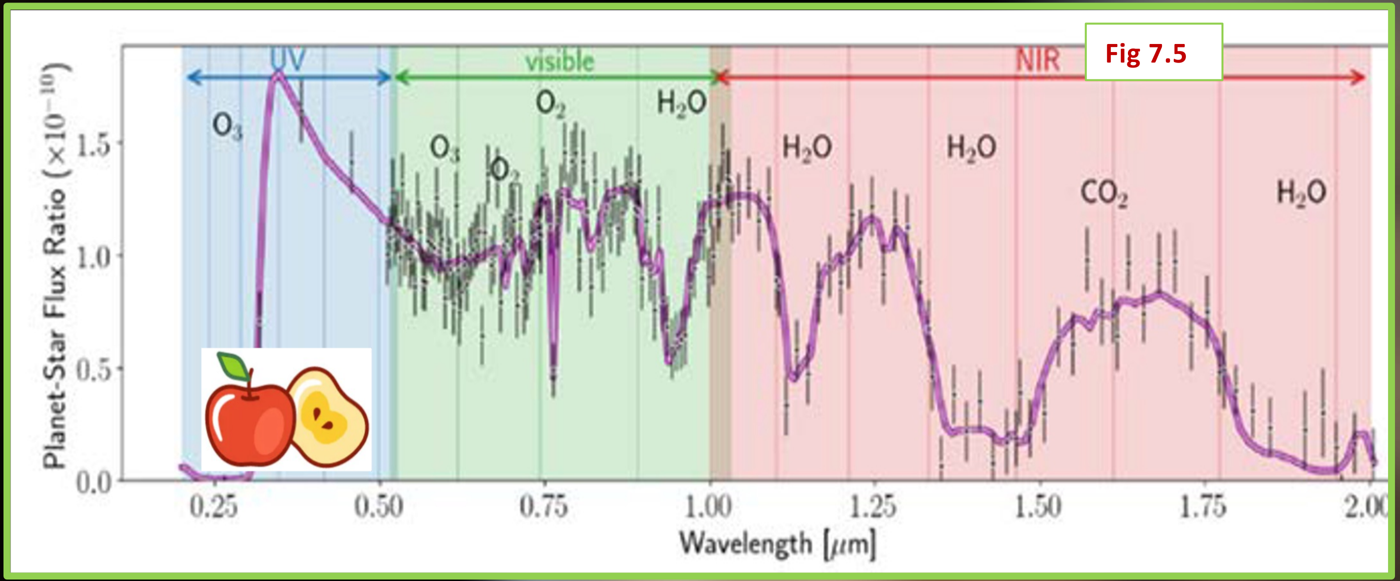
DRM optimally assigned LUVOIR-A's four coronagraph masks to each star.

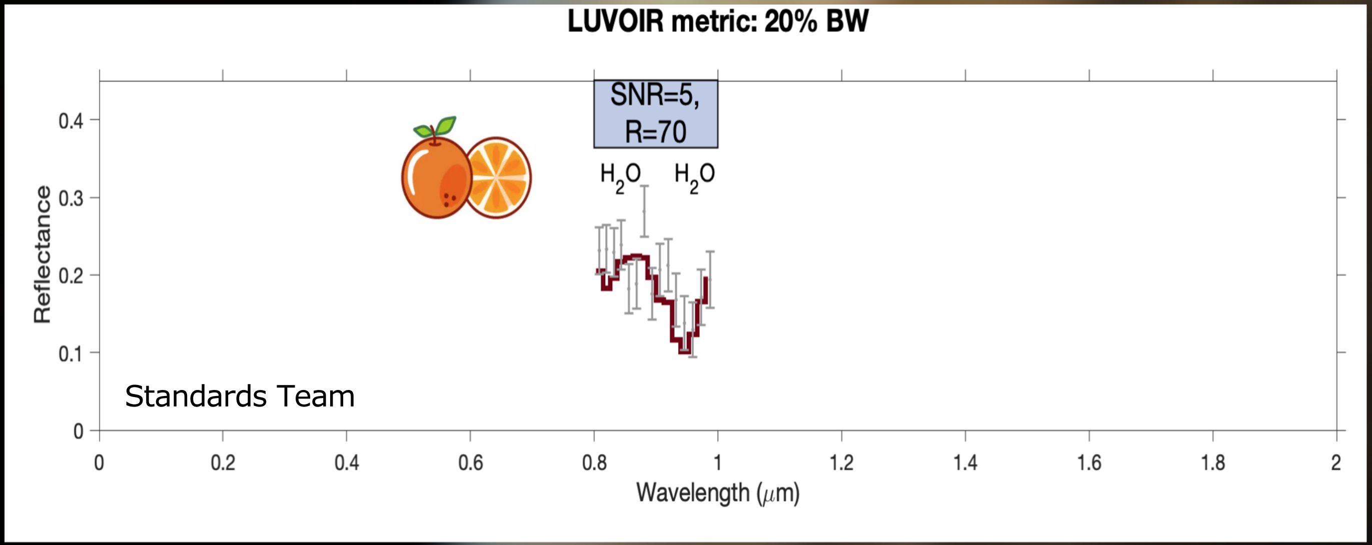
What we've learned from DRMs: The relative impacts of major design choices



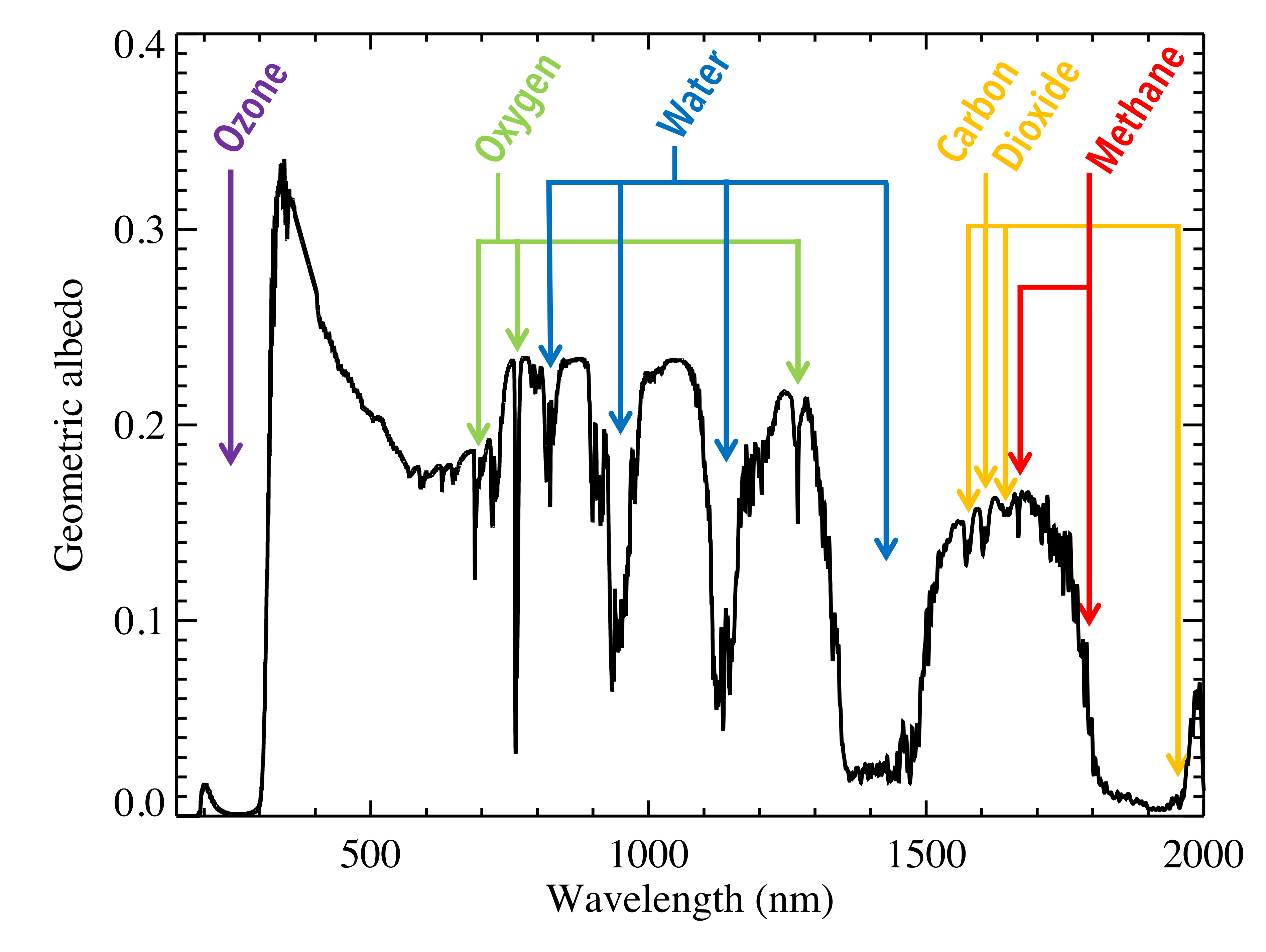
Stark et al. (2019)

Yield isn't everything: Data quality matters

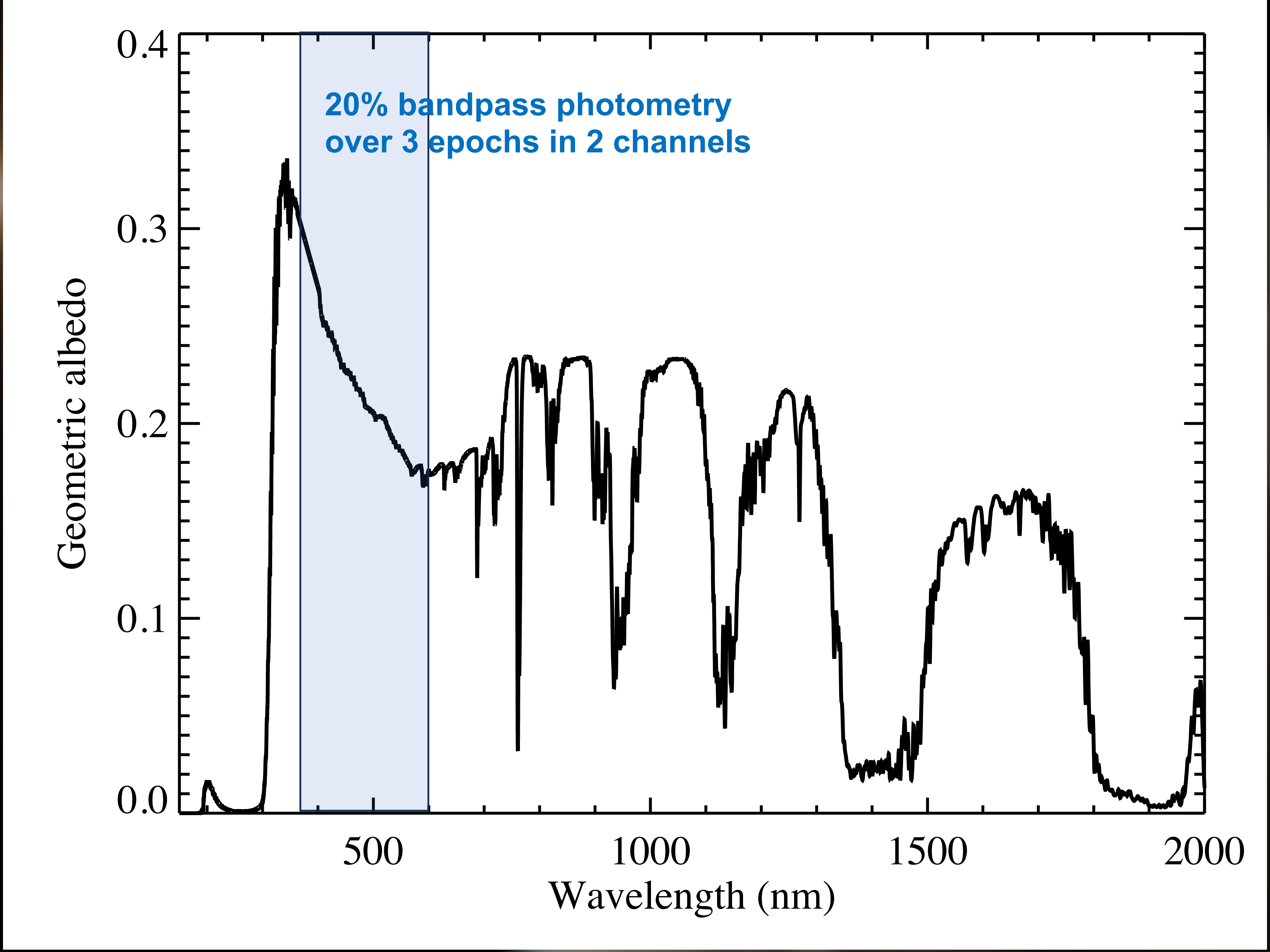




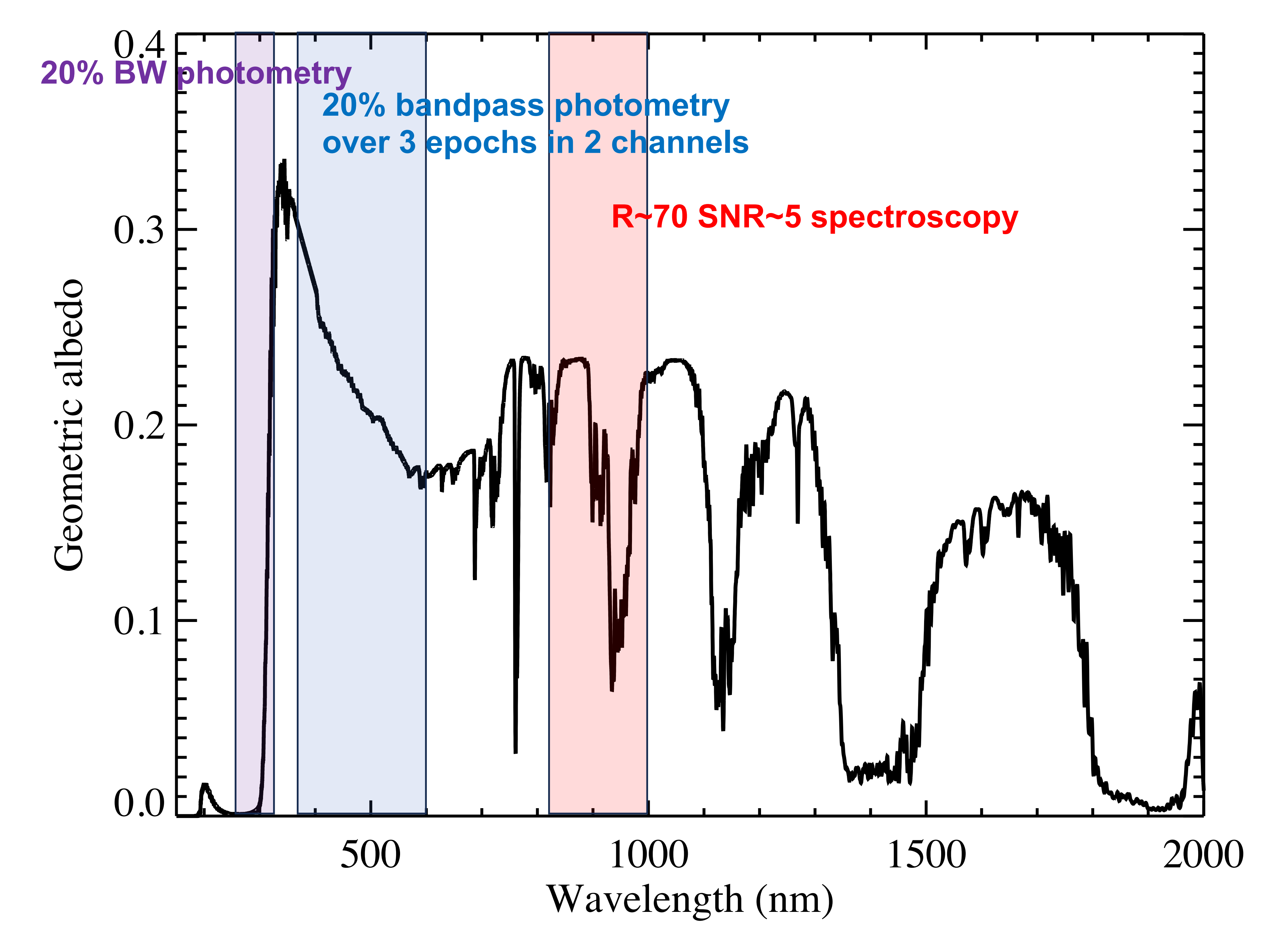
Slide from R. Morgan (2022)

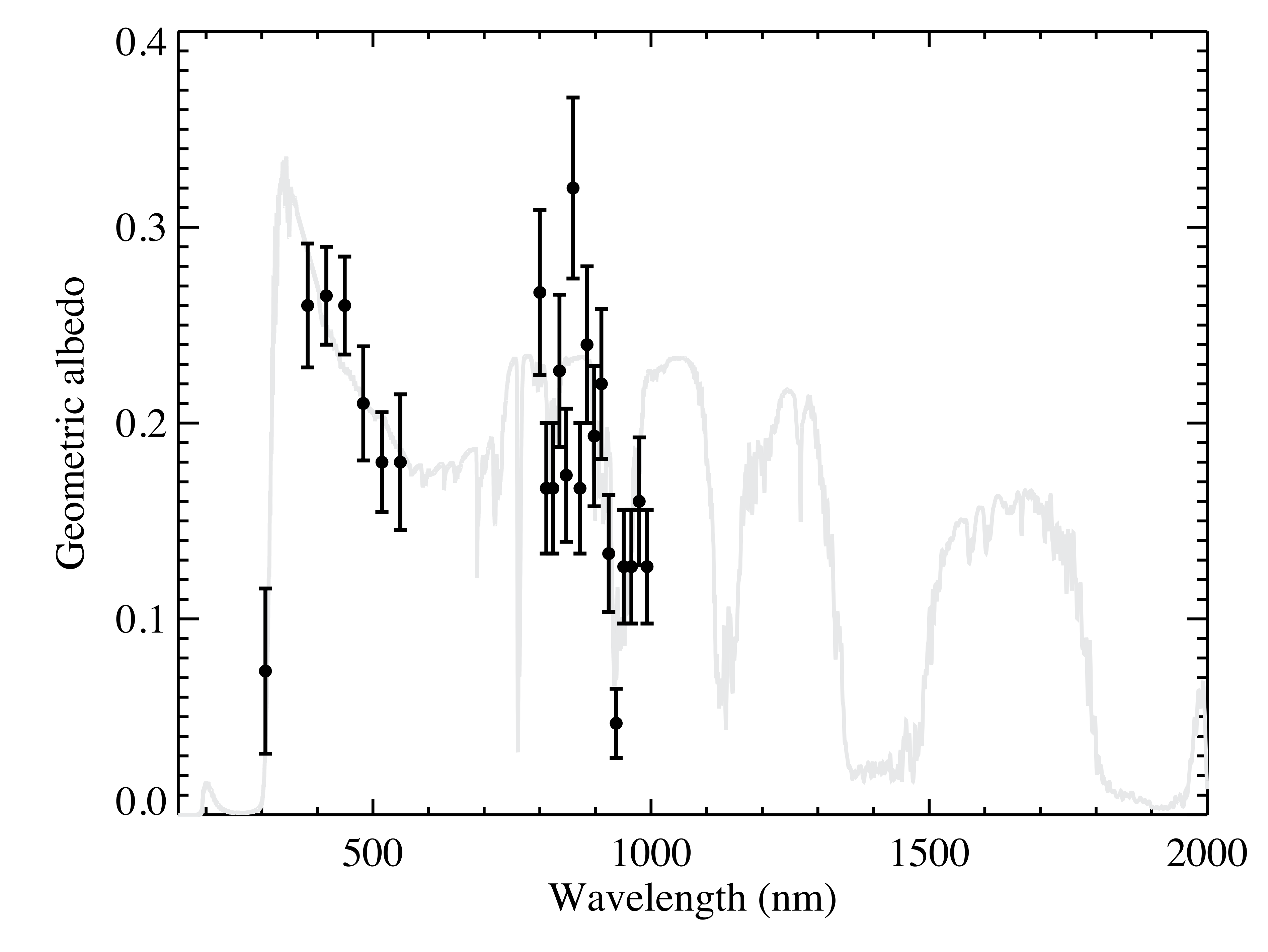


Ozone
Oxygen
Water
Carbon
Dioxide
Methane
Geometric albedo
0.0
0.1
0.2
0.3
0.4
500
1000
1500
2000
Wavelength (nm)



20% bandpass photometry
over 3 epochs in 2 channels
Geometric albedo
0.0
0.1
0.2
0.3
0.4
500
1000
1500
2000
Wavelength (nm)

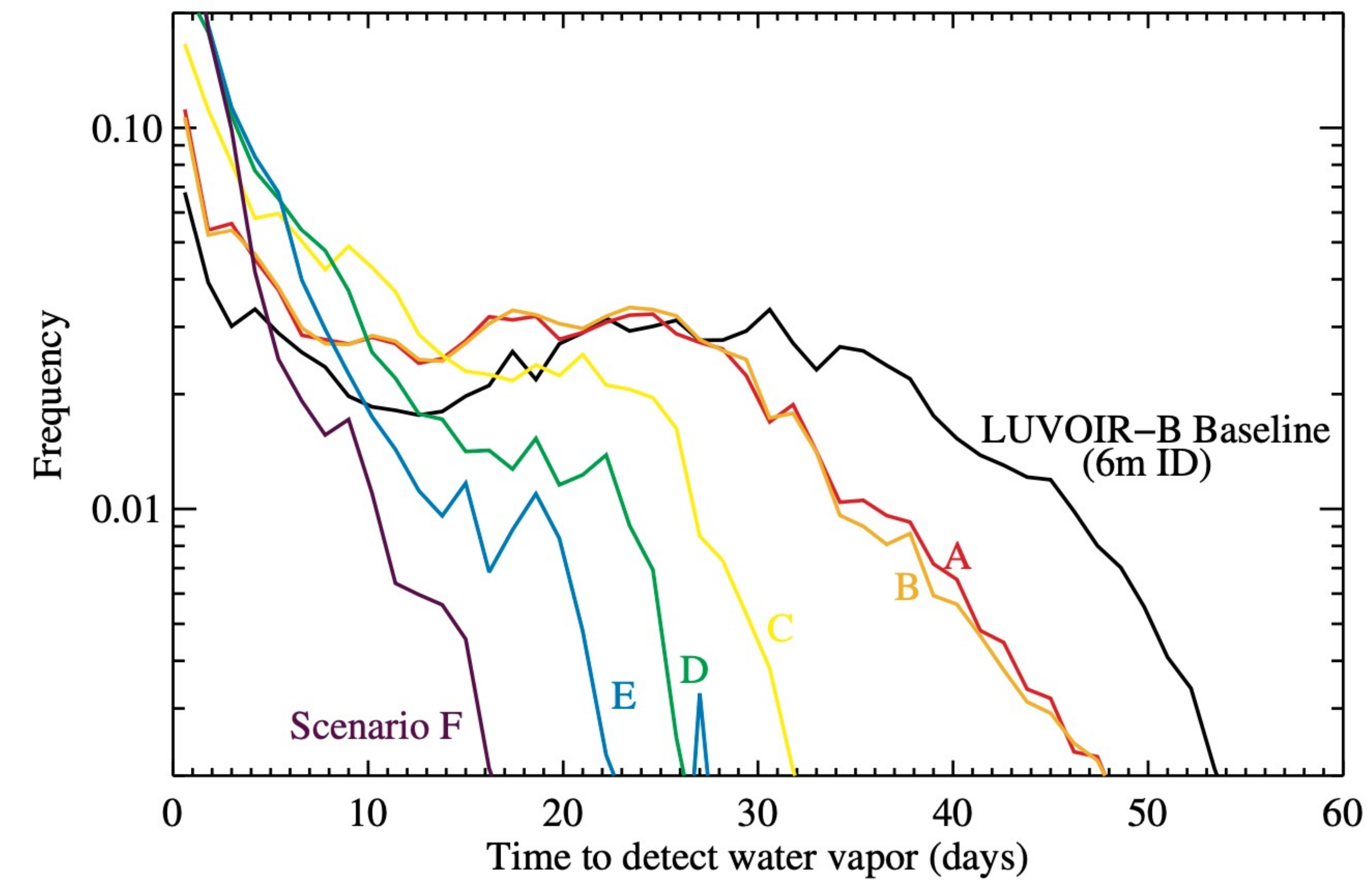

20% BW photometry
20% bandpass photometry
over 3 epochs in 2 channels
R~70 SNR~5 spectroscopy
Geometric albedo
0.0
0.1
0.2
0.3
0.4
500
1000
1500
2000
Wavelength (nm)



0.4
0.3
0.2
0.1
0.0
Geometric albedo
500
1000
1500
2000
Wavelength (nm)

Yield isn't everything: Exposure times matter

A month is too long to search for water vapor



Stark et al. (in prep)

There are paths to reducing exposure times by an order of magnitude without increasing telescope diameter.

Summary

Yield calculations can:

- Estimate scientific productivity
- Inform telescope & mission design
- Inform coronagraph design
- Inform observation methods
- Help identify performance risks through sensitivity analyses

Yield calculators should strive to:

- Optimize observations to play to strengths of mission and produce accurate trade studies
- Address additional metrics beyond exoplanet yields

Yield calculators *need help* to:

- Address underlying assumptions that could affect estimates (e.g., PSF subtraction method, exozodi subtraction, exozodi "leakage," etc.)

Much progress has been made

The Astrophysical Journal, 607:1003–1013, 2004 June 1

OBSCURATIONAL COMPLETENESS

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Brown (2004)

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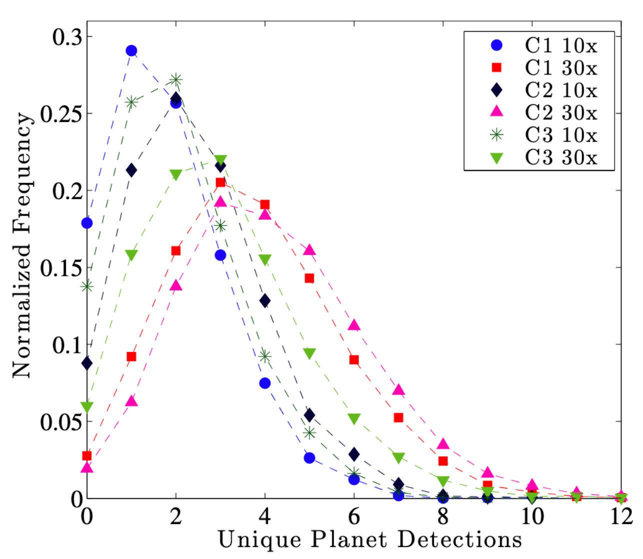

Savransky et al. (2016)

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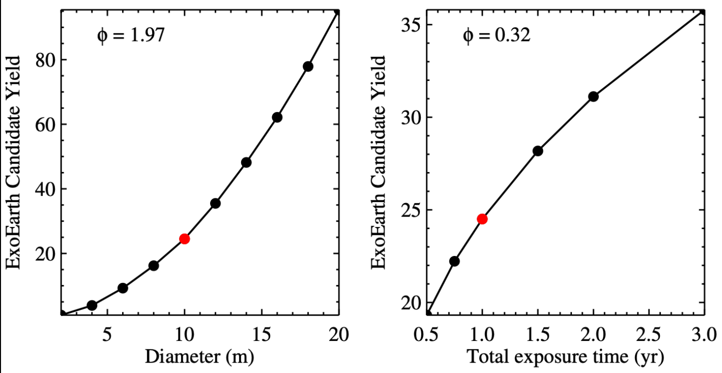
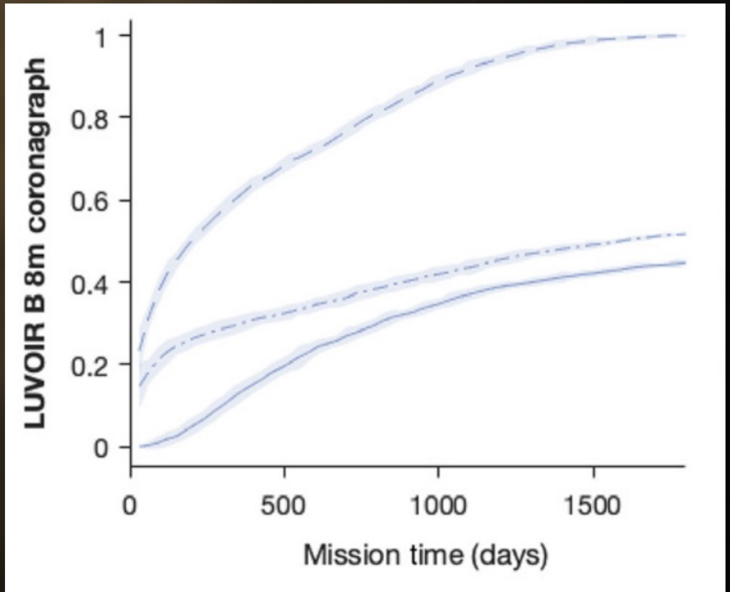
Brown (2005)



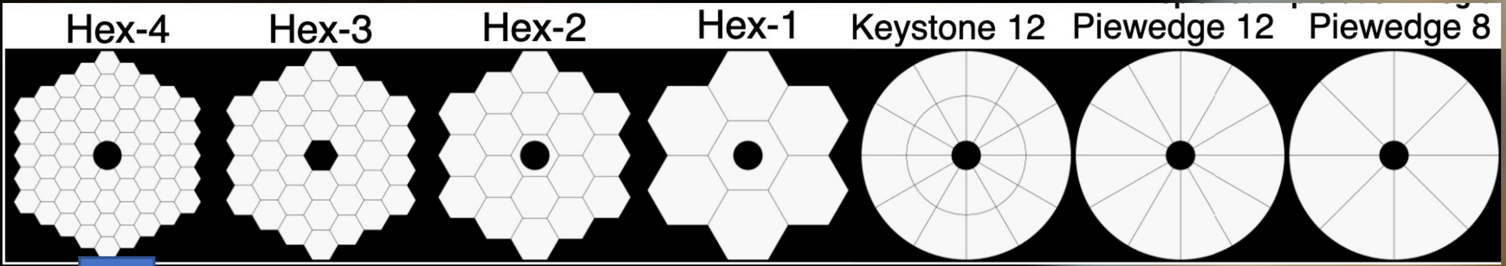
Stark et al. (2015)

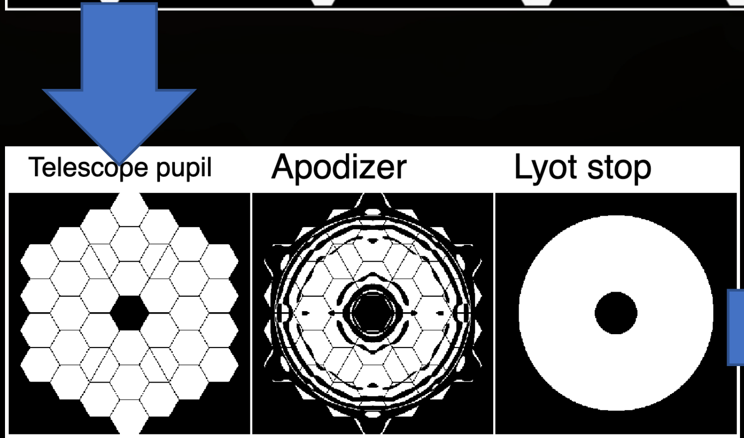


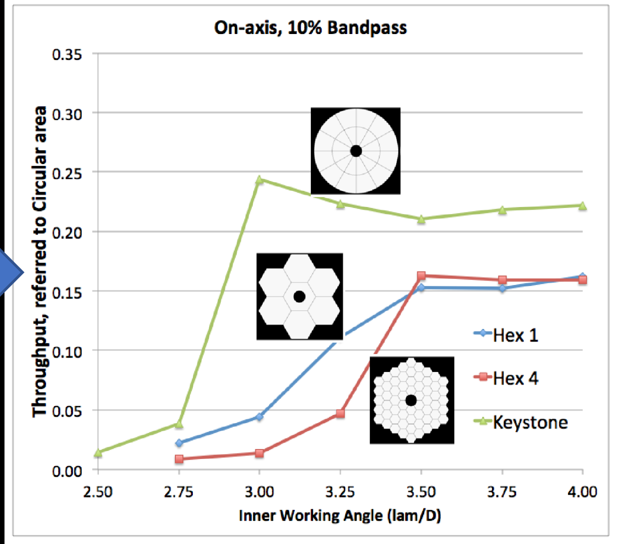
Morgan et al. (2021)

What we've learned from DRMs: How telescope geometry impacts coronagraphs & yield

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





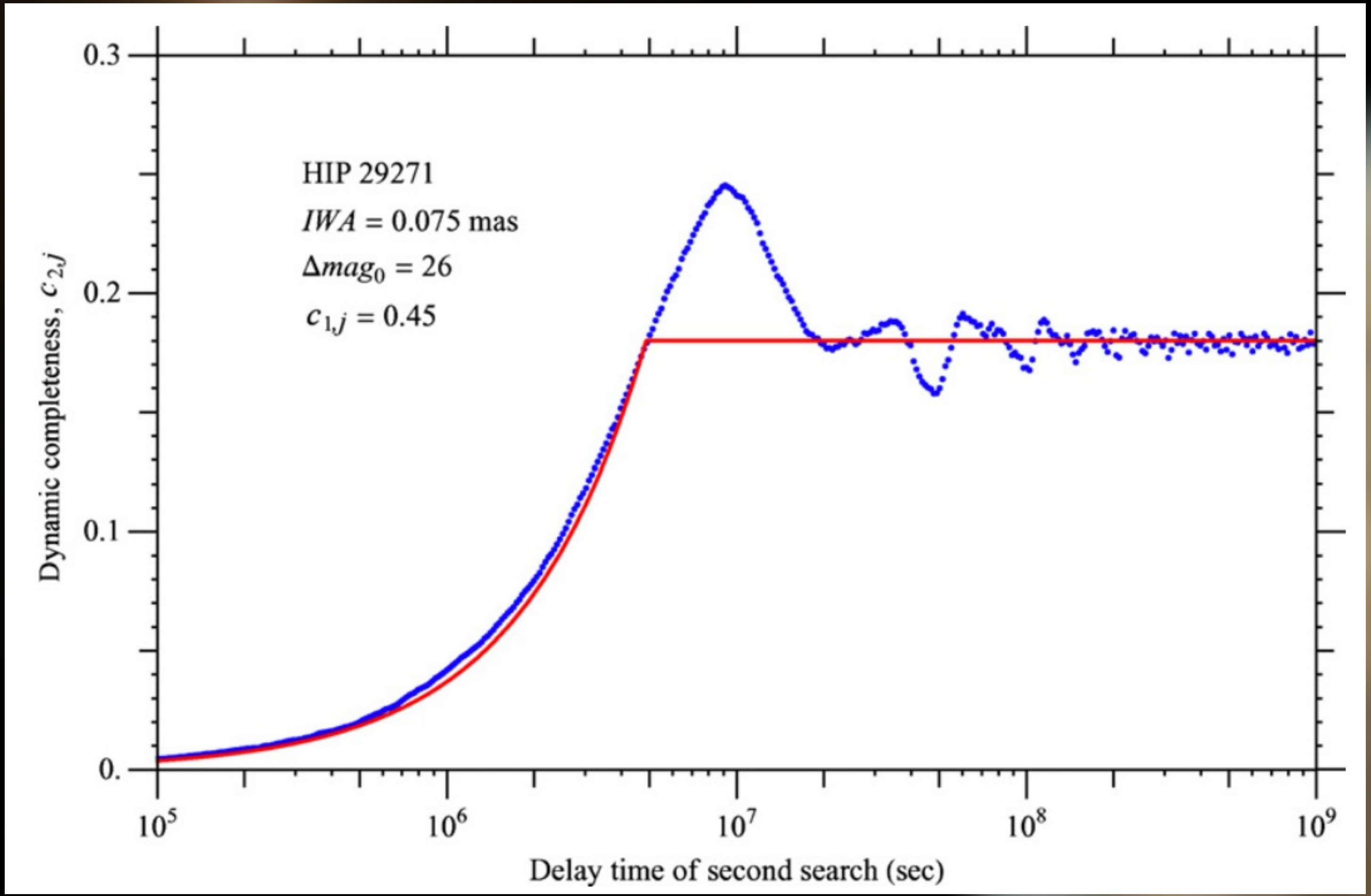


Slides from Shaklan (2016), many papers from SCDA Team

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.

Optimizing revisits

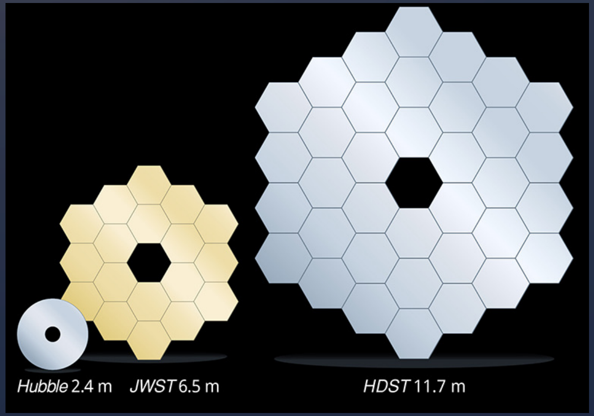


Brown & Soummer et al. (2010)

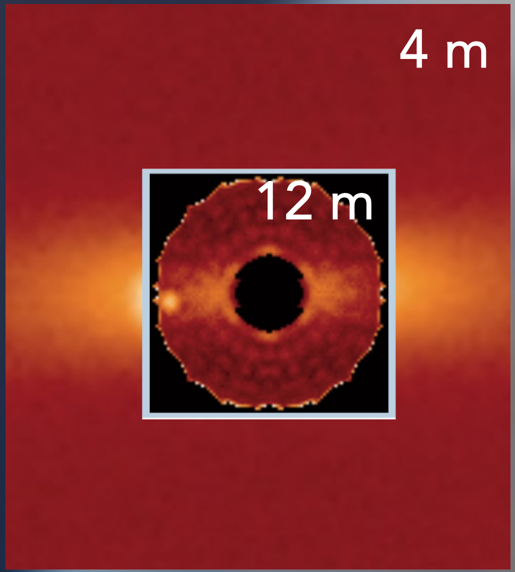
The most accurate, brute-force method would perform a blue-point-type calculation (see Figure 1) for every star in play every time a new observation is planned. The number of times would be of order the number of stars times the number of observations. For example, the number of blue-point-type calculations would exceed 10^5 for a program of 100 stars and 1000 LSOs, typical for a 4 m class instrument with IWA = 0.075 arcsec. Monte Carlo full-mission studies would be impractical, as each of the 400 blue points in Figure 1 took ~5 s to compute on a 3 GHz Intel Xenon processor running MATHEMATICA 6. Therefore, we must look at two approximate functions for $c_{i,j}(t)$, one of which

Why coronagraph yield is controlled by *D*

Larger photon bucket



Sharper PSF

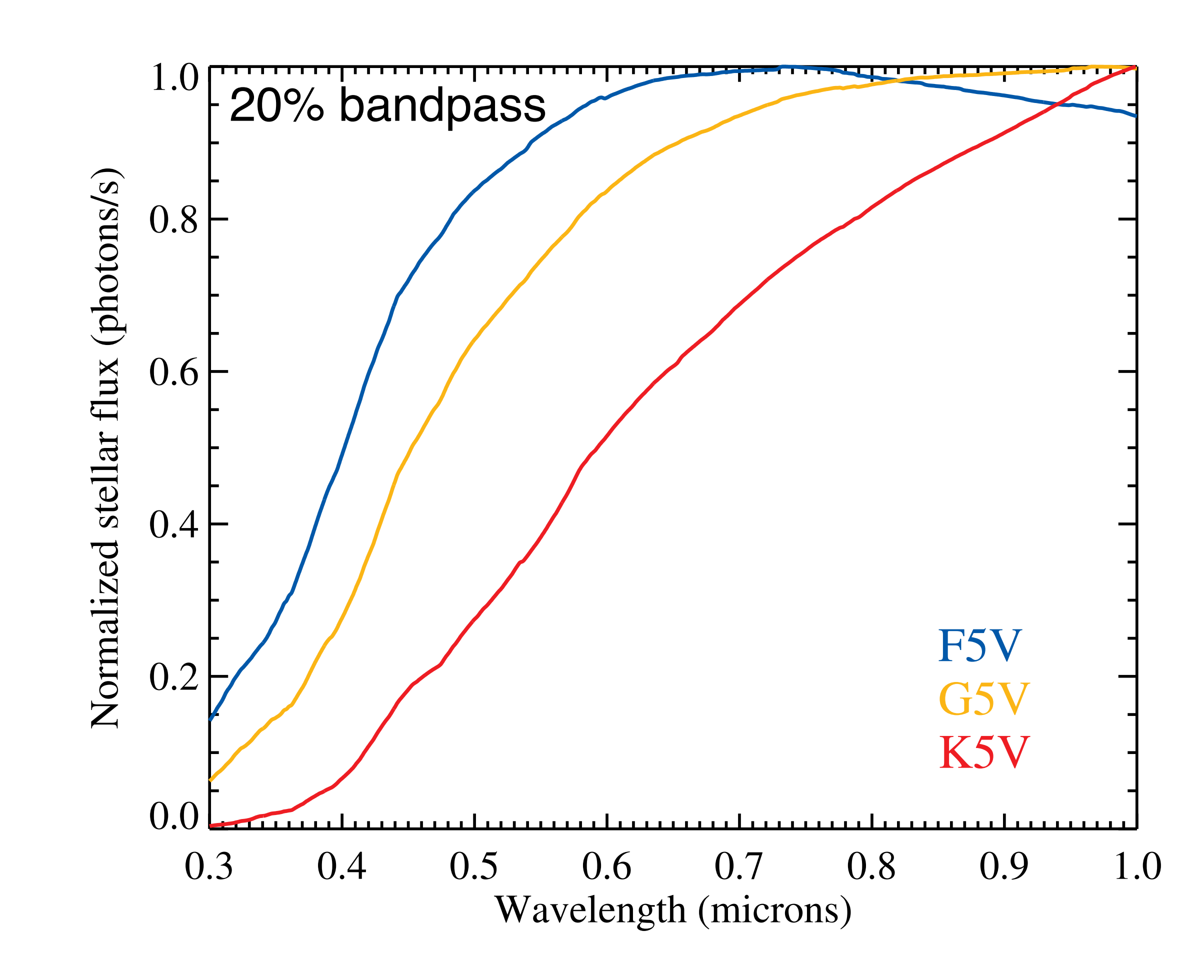


Smaller IWA $\sim \lambda/D$

Exposure time scales as D^{-4}

At what wavelength should we observe?

Star's Aren't "Brightest" at V Band



Stark et al. (submitted)

Which H_2O Feature Do We Pick?