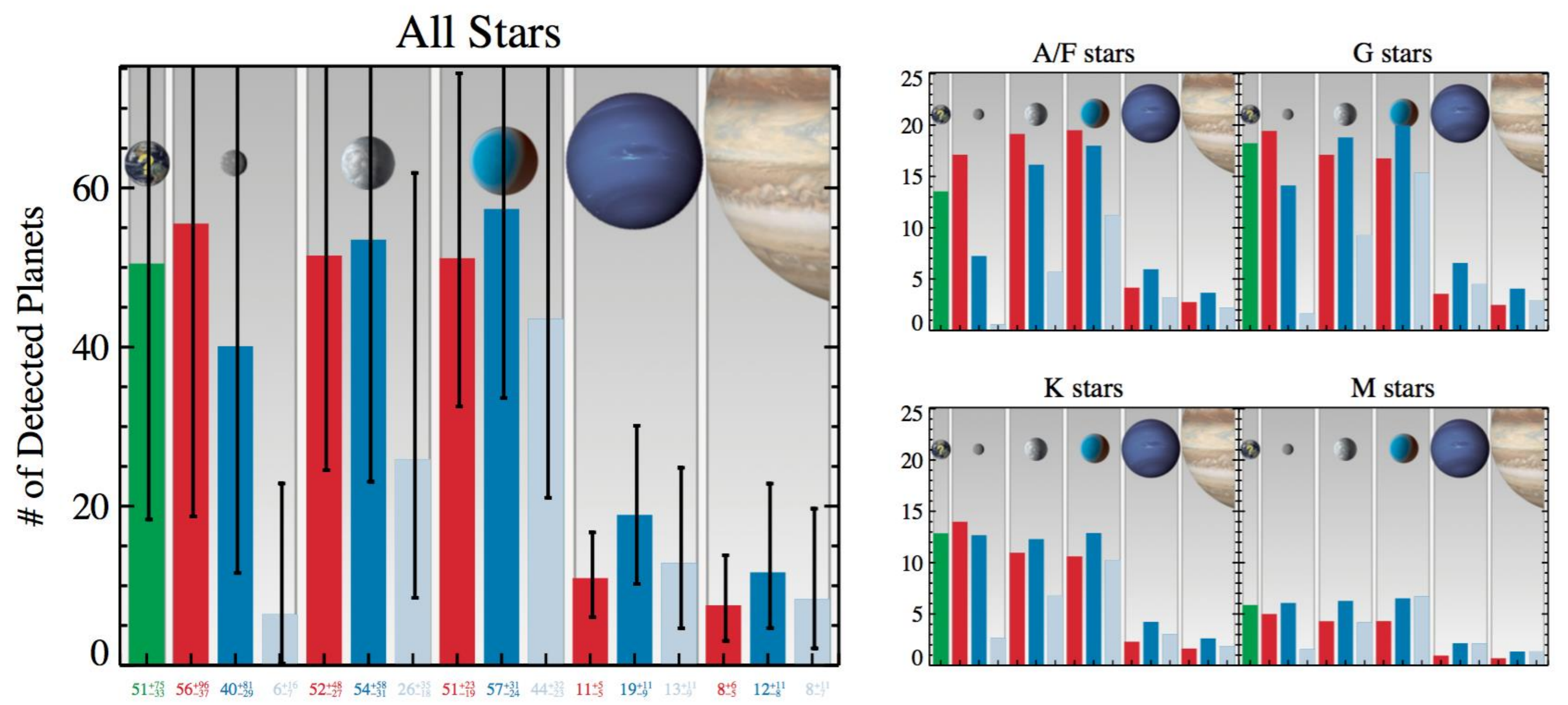
The Exoplanet Yield Landscape for Future Missions

Christopher

STScI

The Goal: Estimate the Exoplanet Science Yield for Direct Imaging Missions

This is where we'll end up:

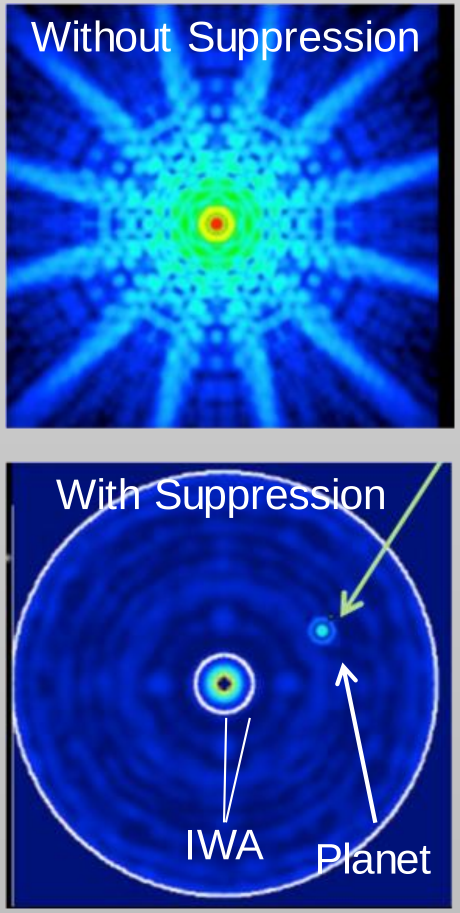


Note: future small adjustments are likely to hot/warm planets; cold planet yields are overestimated.

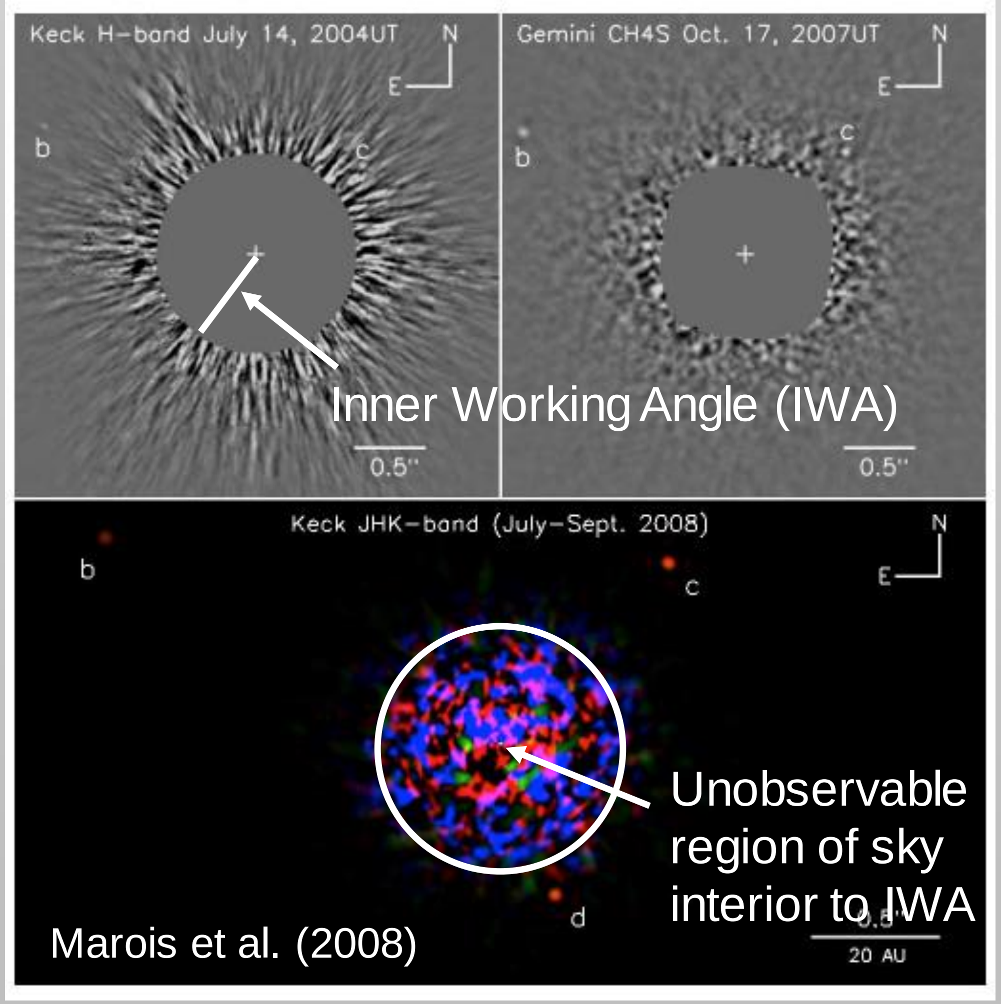
LUVOIR Interim Report

To Image an Earth-like Planet We Must Suppress Starlight

Model

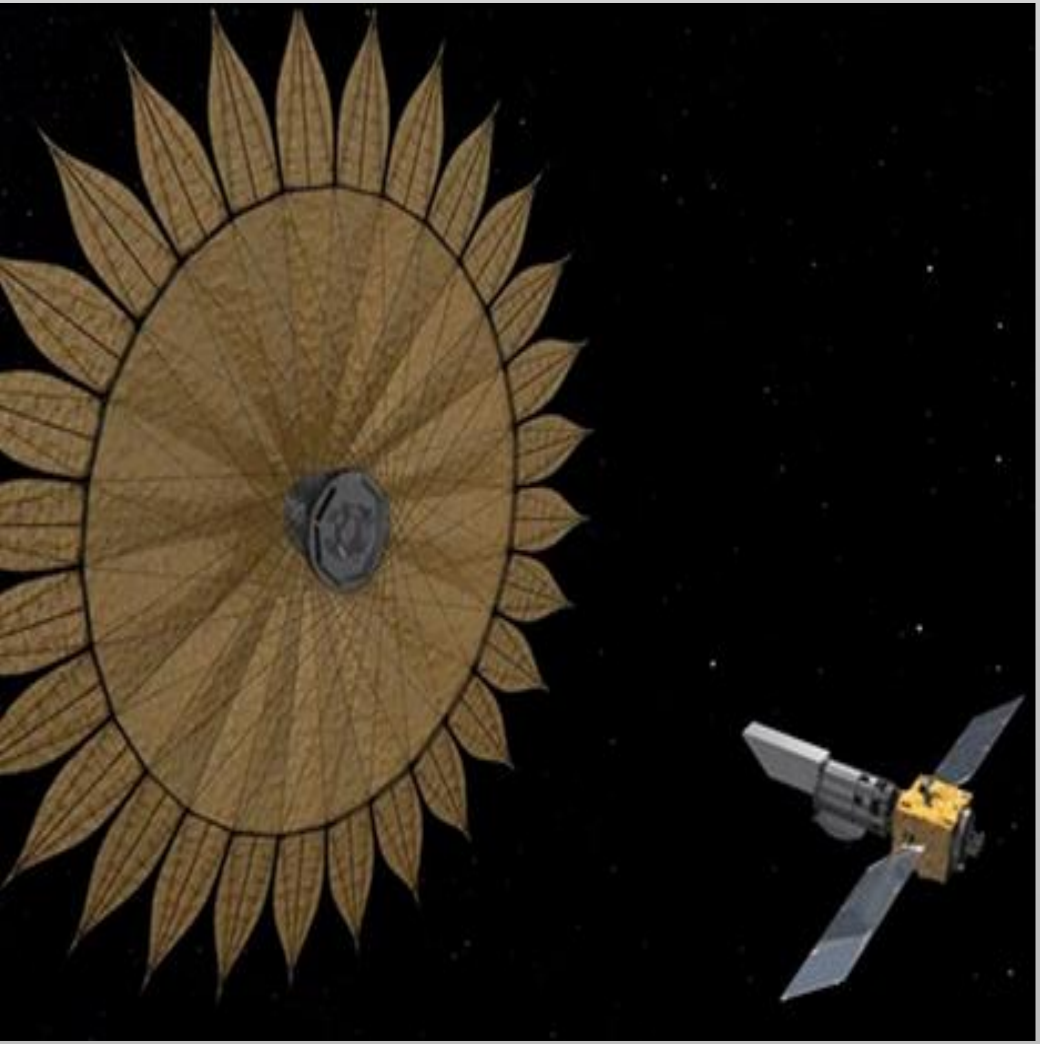


Actual Observations



Starshades

Blocking starlight before it reaches the telescope



NASA/JPL/Caltech

Observational Strengths

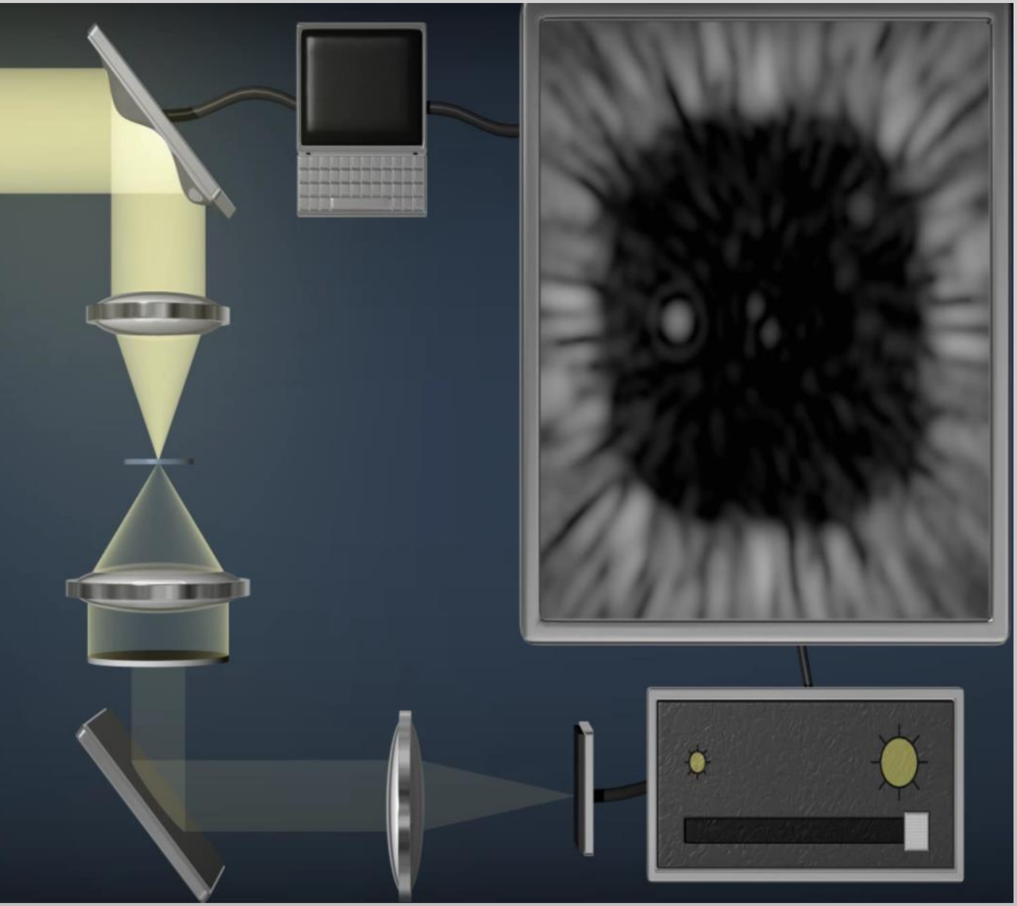
- Wide instantaneous bandpass
- High throughput
- IWA largely independent of λ
- OWA limited by detector
- Low overheads

Observational Limitations

- Yield limited by fuel—limited # of observations
- Repointing very costly
- Non-optimal scheduling constraints
- Brighter zodi

Coronagraphs

Using advanced optics to remove starlight inside of the telescope



NASA/JPL

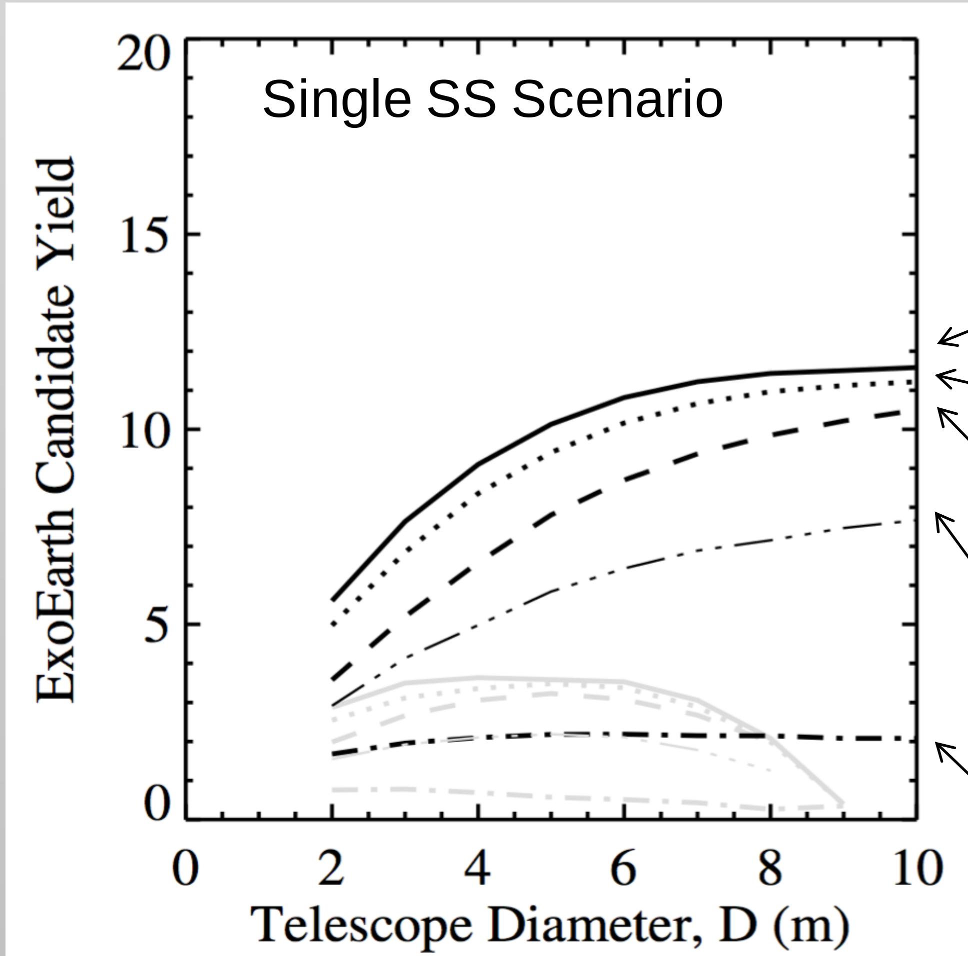
Observational Strengths

- Nimble
- Large field of regard
- Yield limited by time, not fuel

Observational Limitations

- Narrow instantaneous bandpass (~20%)
- Modest throughput
- IWA $\propto \lambda/D$
- OWA exists
- WFSC overheads

“Yield” Must be Defined by Science



Detection Only

2 Color Detection + Spectra on just the exoEarth candidates

Detection + Spectra after every observation

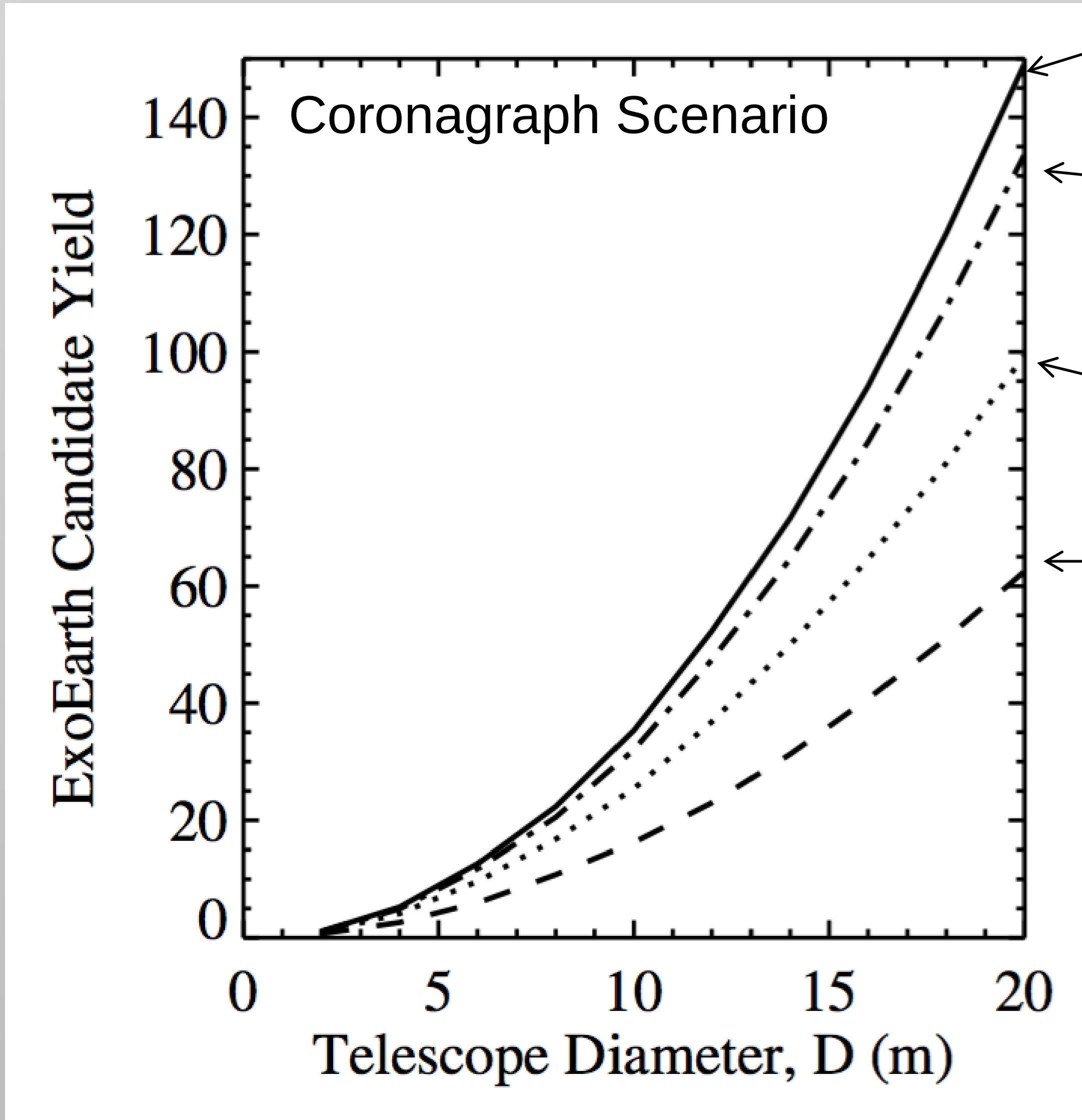
Detection + Spectra after every observation -> orbit determination of exoEarth candidates

Detection + Orbit determination -> spectra of exoEarth candidates

Stark et al. (2016 SPIE paper)

The “yield” depends on what science you want to obtain and how you go about obtaining it. This differs for starshades and coronagraphs! Data products, quantity, and quality will be

"Yield" Must be Defined by Science



Detection Only

Detection + Orbit determination -> spectra of exoEarth candidates

2 Color Detection + Spectra on just the exoEarth candidates

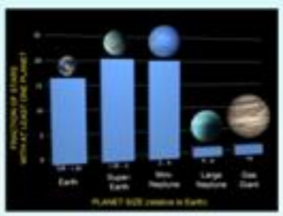
Detection + Spectra after every observation

Stark et al. (2016 SPIE paper)

Calculating Yield with a DRM Code

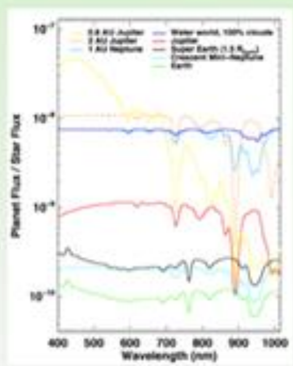
Astrophysical Constraints

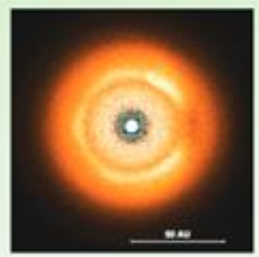
- η_{Earth}
- $\eta_{exozodi}$
- Planet sizes
- Albedos
- Phase functions



Observational Requirements

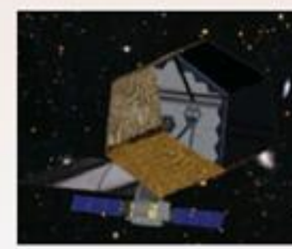
- Central wavelength
- Total bandpass
- Spectral resolution
- Signal-to-Noise
- Observing strategy





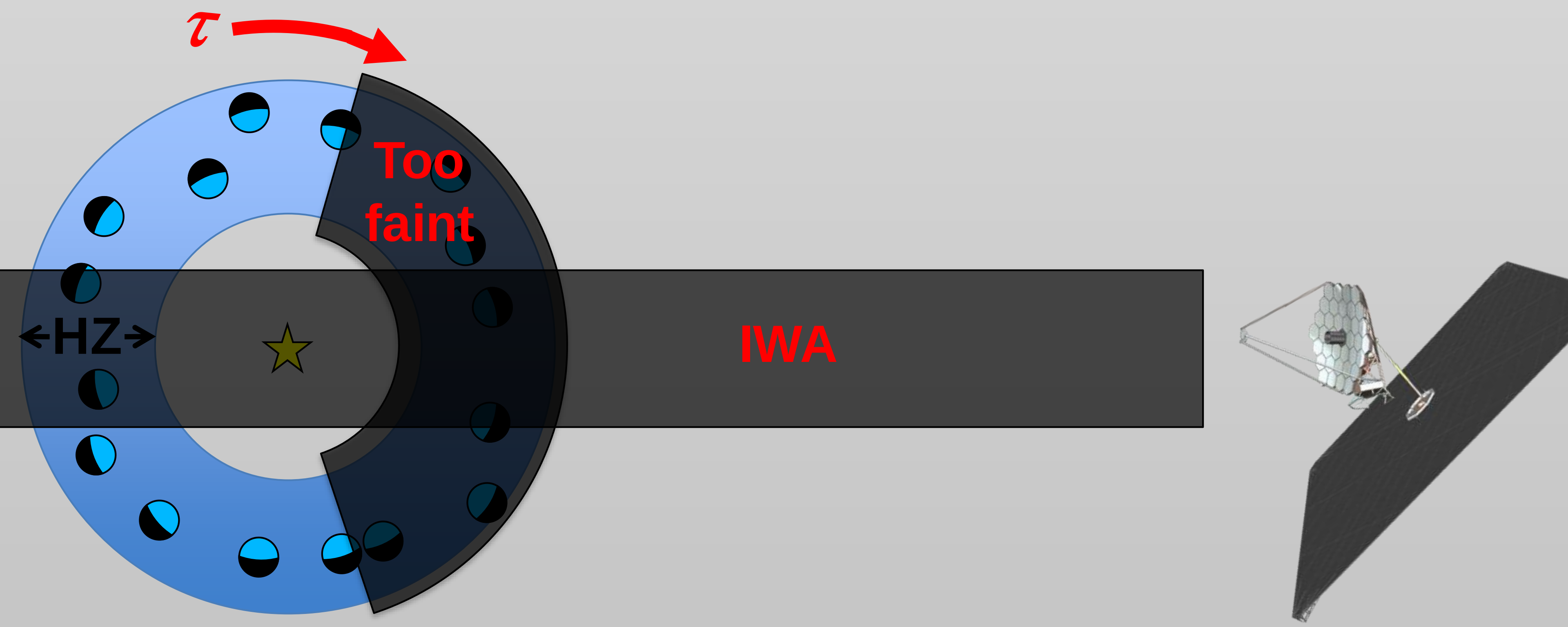
Technical Requirements

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



DRM

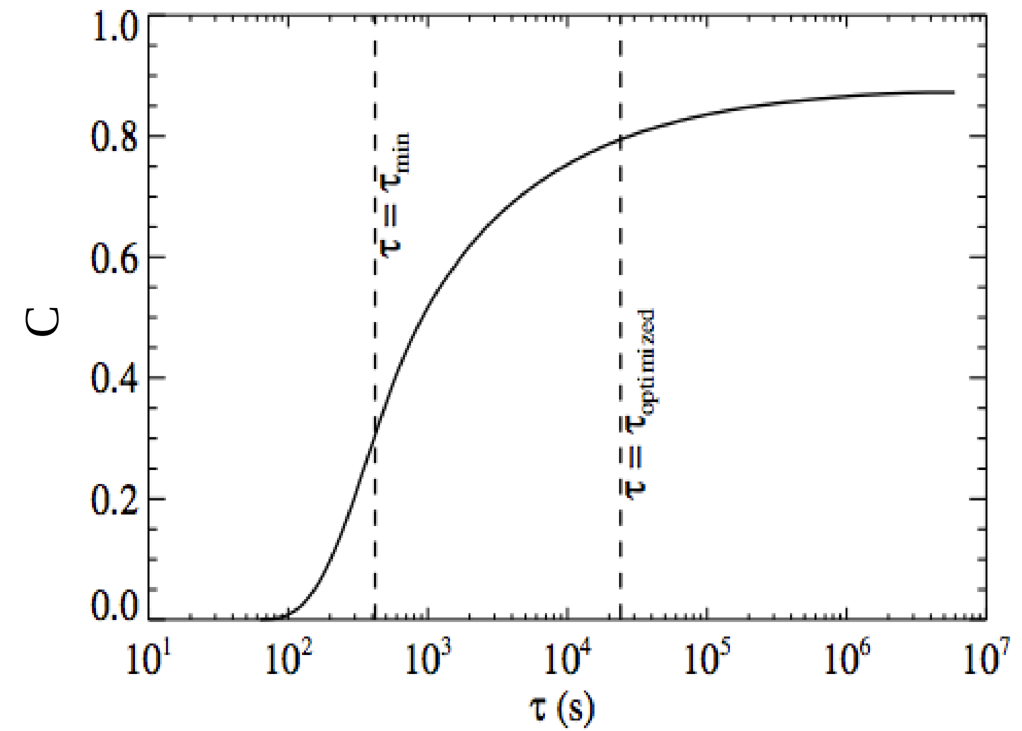
Calculating Yield via Completeness

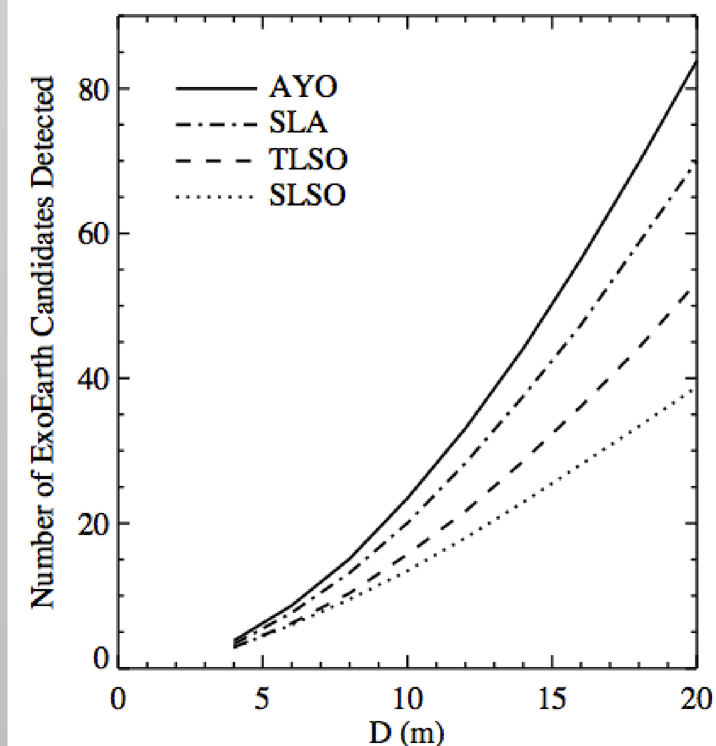


- Completeness, C = chance of observing a given planet "type" around a given star if that planet exists (Brown 2004)
- Yield = $\eta_{planet}\ \Sigma C$
- Calculated via Monte Carlo simulation with $\gtrsim 10^5$ synthetic planets per star

Maximizing Yield by Optimizing the Observations

Optimized Exposure Times

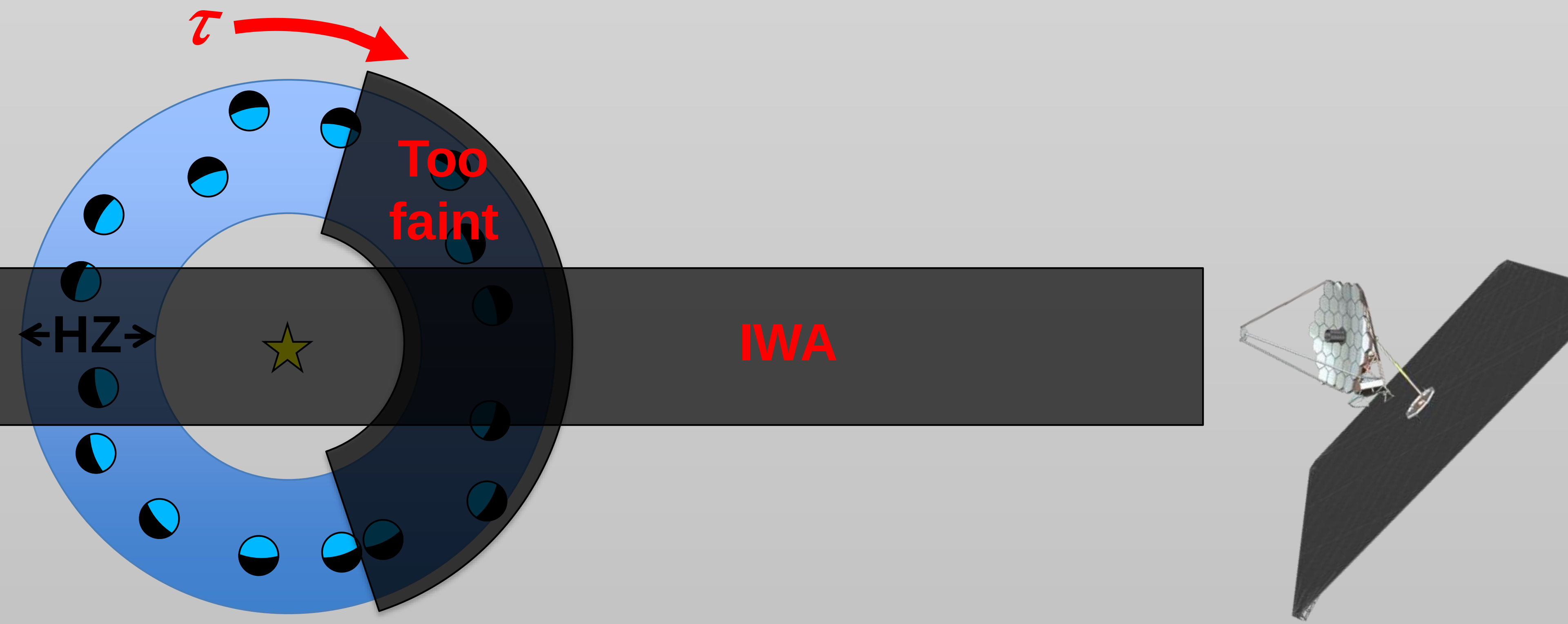




Stark et al. (2014)

Optimizing exposure times can potentially double yield

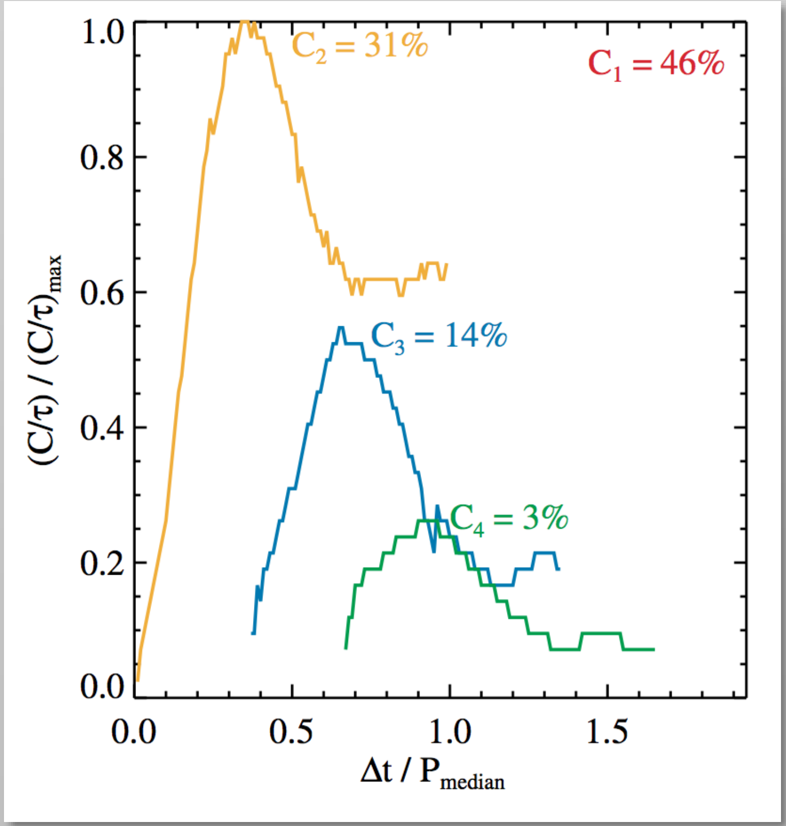
Calculating Yield via Completeness

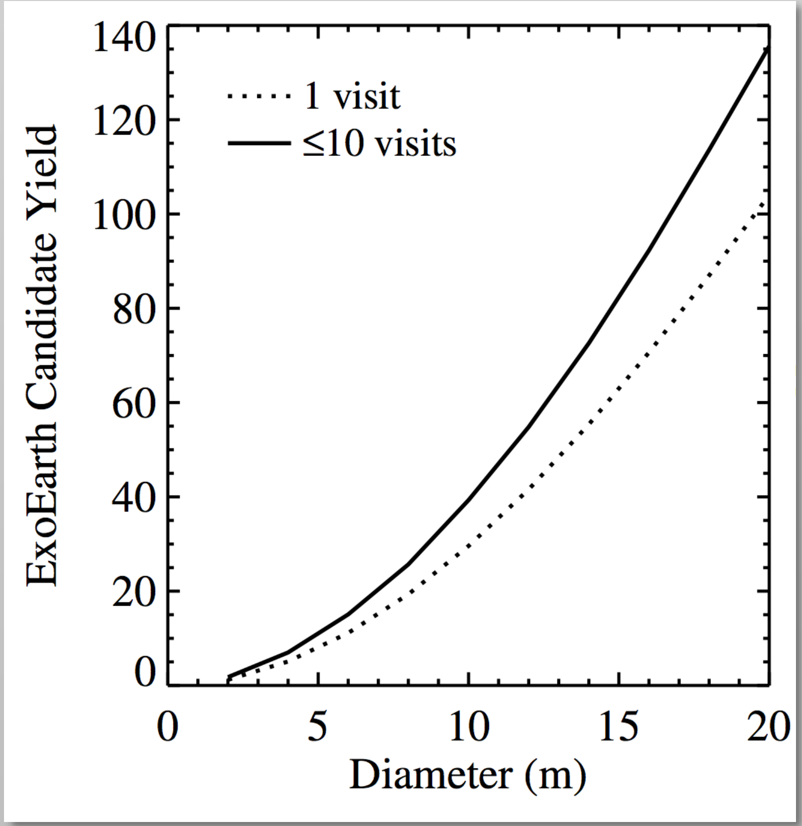


- Revisiting same star multiple times can increase total completeness
- Can optimize number of visits and delay time between visits

Maximizing Yield by Optimizing Revisits

Optimized Revisits



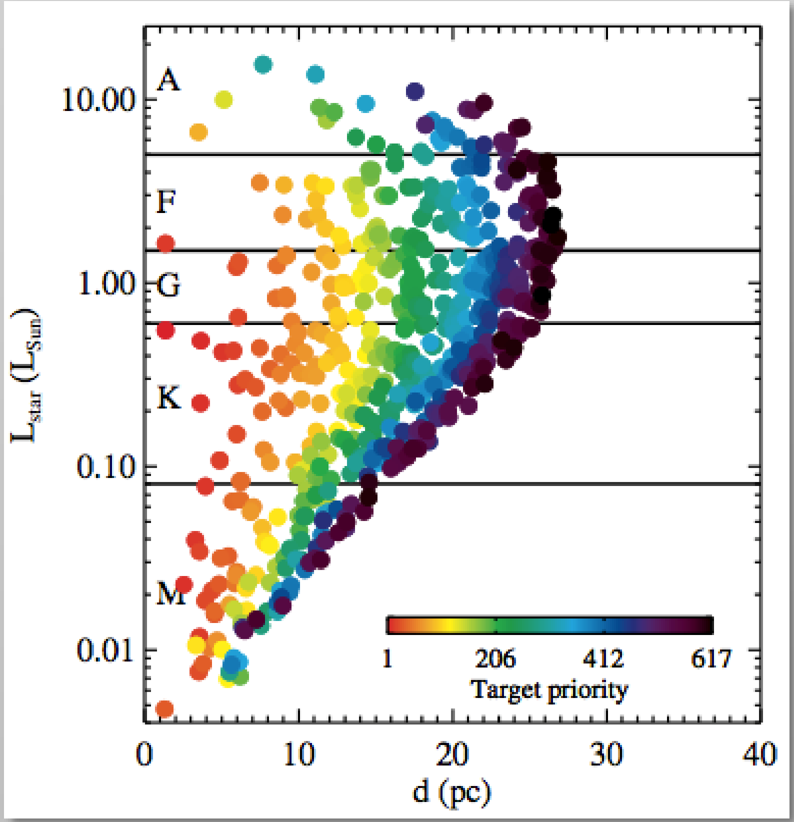


Stark et al. (2015)

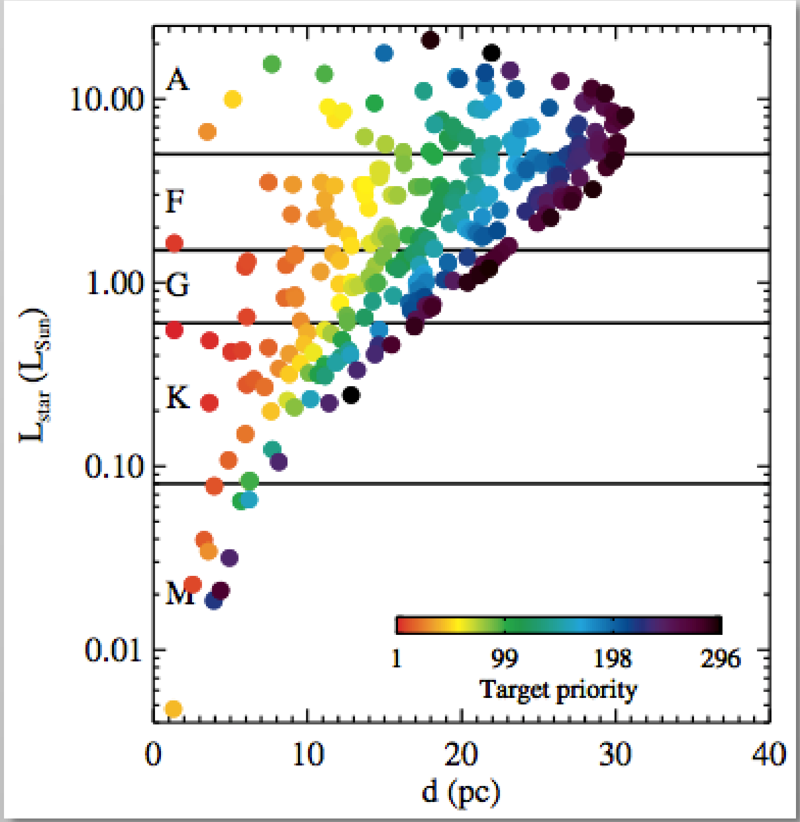
Optimizing revisits can increase yield by ~50%

Maximizing Yield by Optimizing Targets

IWA = λ/D

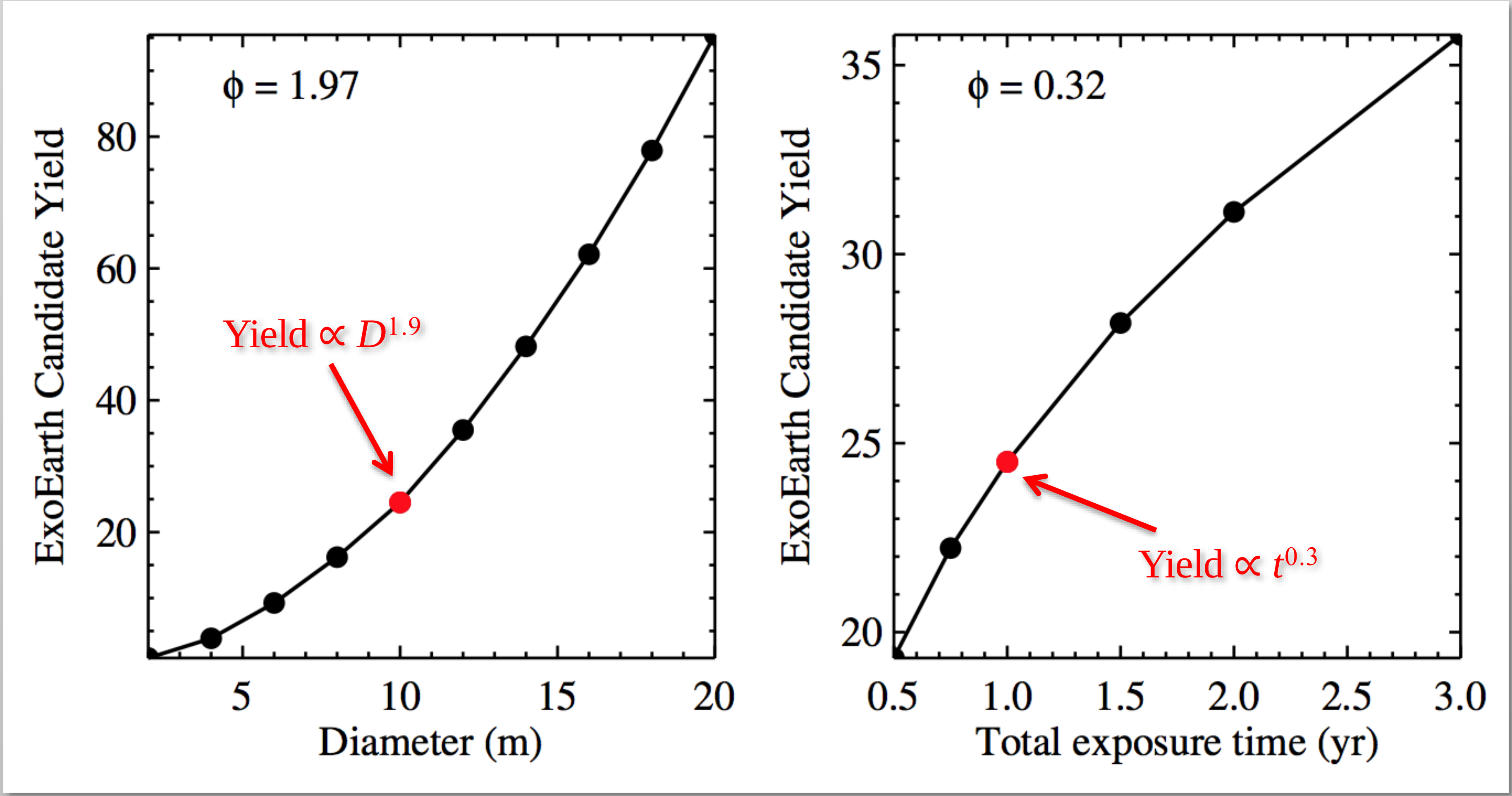


IWA = 4λ/D



Optimizing the observation plan is critical to yield estimates, as it ensures that we are always playing to the strengths of the mission

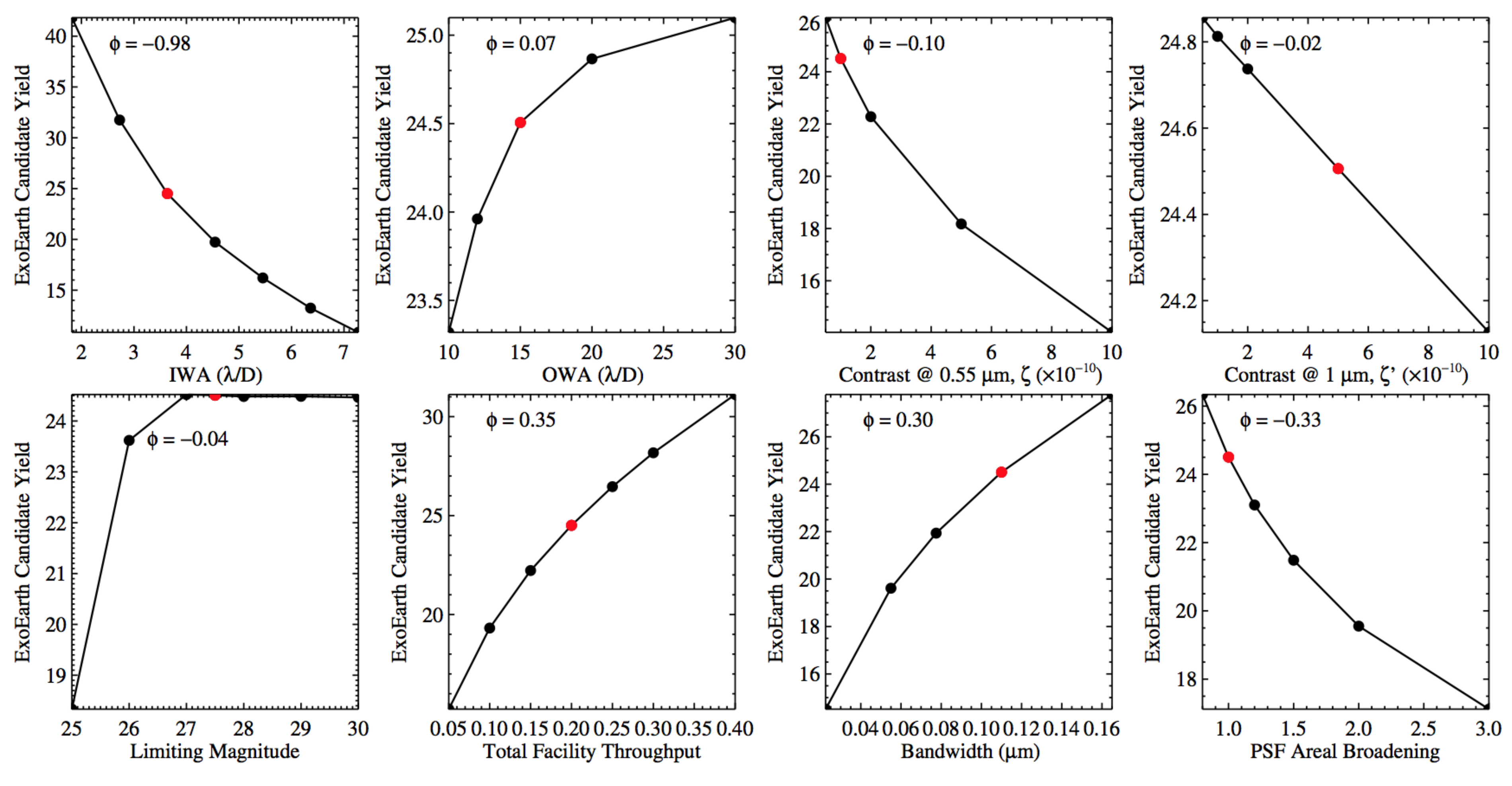
Lessons Learned from Toy Models



Stark et al. (2014)

Yield of a coronagraph-based mission is most sensitive to aperture size

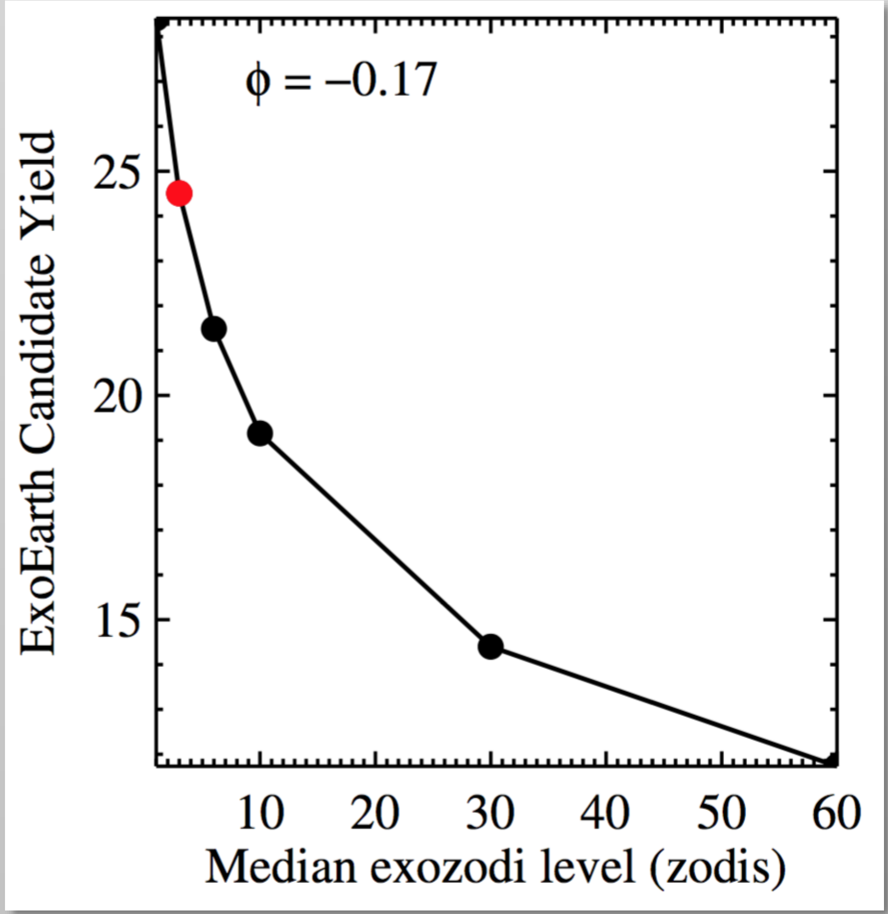
Lessons Learned from Toy Models



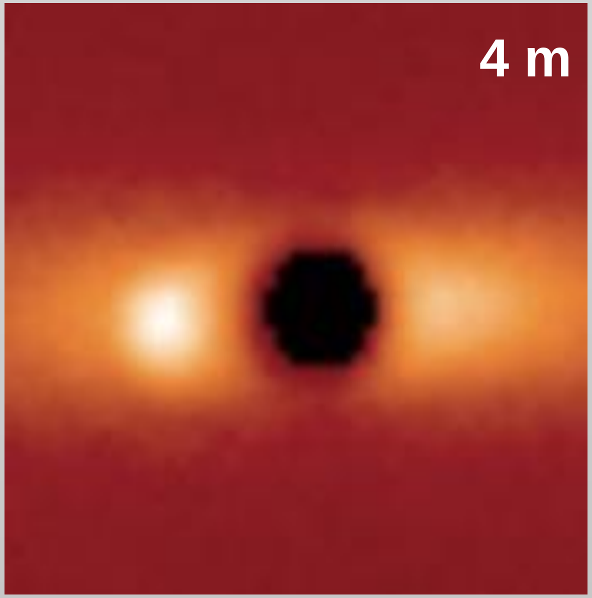
Stark et al. (2014)

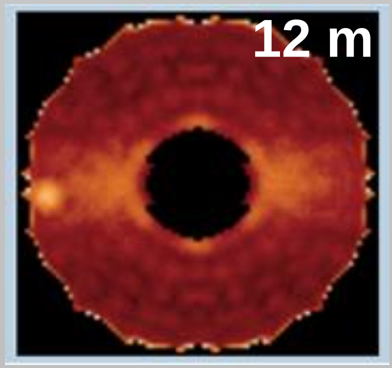
We have thoroughly explored phase space to understand yield scaling relationships.

Lessons Learned from Toy Models



Stark et al. (2014)





For reasonable mission parameters, yield is relatively insensitive to exozodi, assuming we can model/fit it and

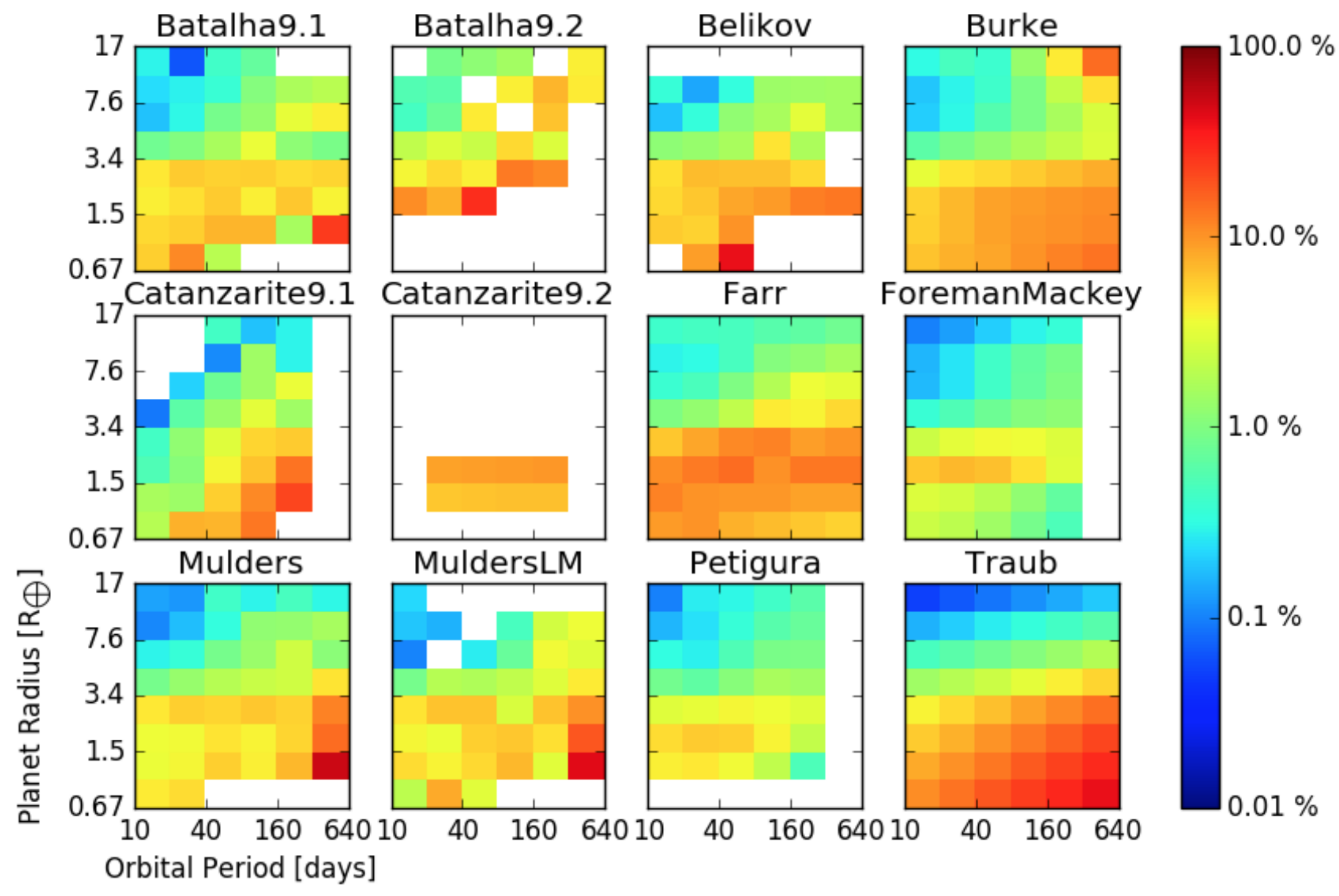
Updated Yield Estimates

We Are No Longer Using Toy Models

The Segmented Coronagraph Design and Analysis (SCDA), WFIRST, HabEx, LUVOIR, and SAG13 studies have significantly advanced the realism of the yield estimates…

Astrophysical Assumptions

Planet Occurrence Rate Distribution Taken from SAG13 Community Average



R. Belikov & SAG13

Astrophysical Assumptions

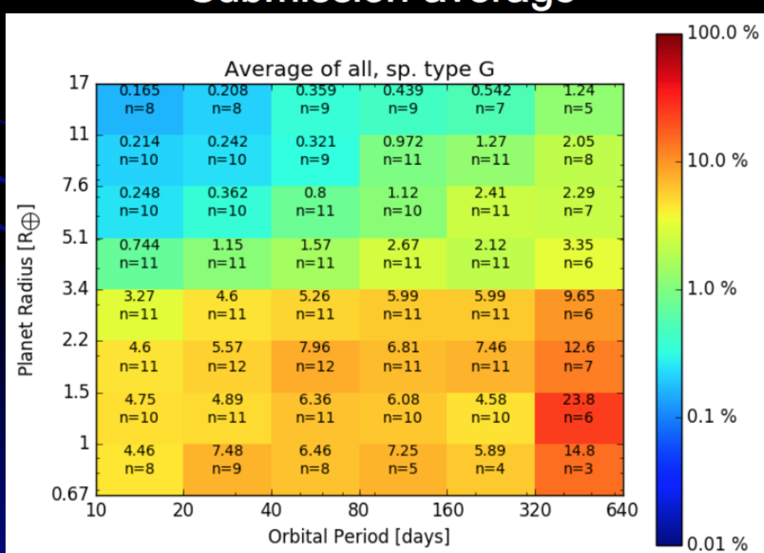
Planet Occurrence Rate Distribution Taken from SAG13 Community Average

$$\frac{\partial^2 N(R,P)}{\partial \ln R \, \partial \ln P} = \Gamma_i R^{\alpha_i} P^{\beta_i} \quad \text{in region } R_{i-1} \leq R < R_i$$

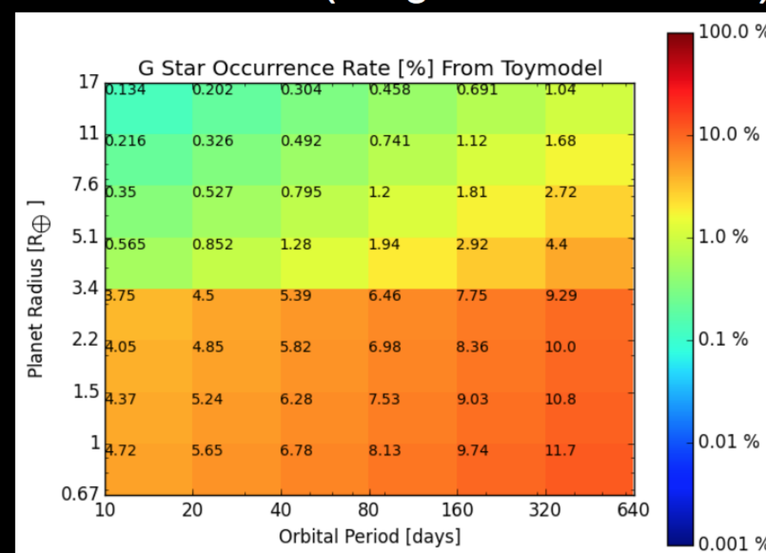
(R in Earth radius, P in years)

Γ_i	α_i	β_i	R_i
0.38	**-0.19**	**0.26**	**3.4**
0.73	-1.18	0.59	Inf

Submission average



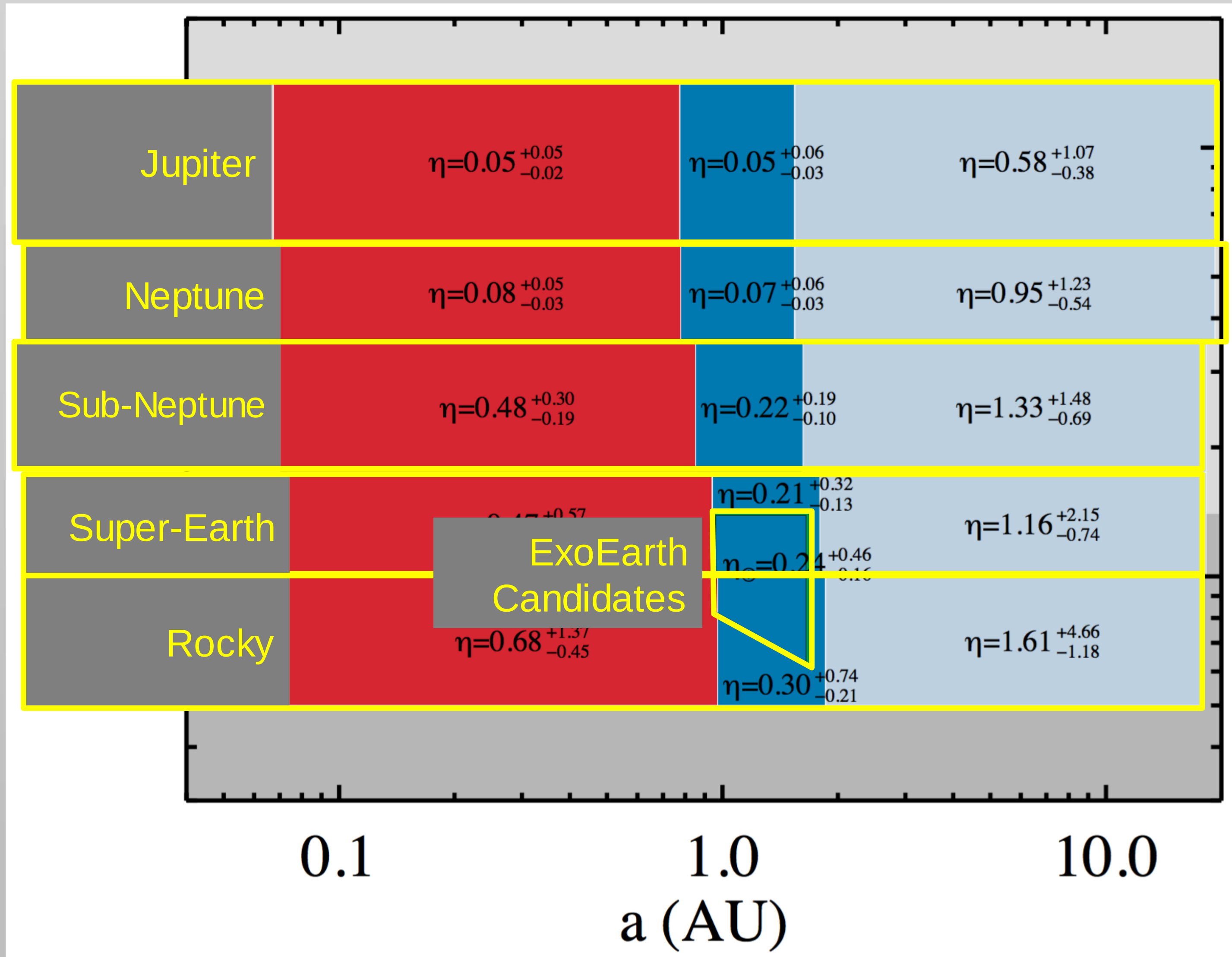
Parameteric fit (integrated across bins)



R. Belikov & SAG13

Astrophysical Assumptions

We use the SAG13 continuous distribution, but adopt coarse grid to communicate results:



Kopparapu et al. (2018) / Stark

Astrophysical Assumptions

Local Zodi

Stefan Seip

Color & pointing-dependent model from Leinert et al. (1998)

Exozodi

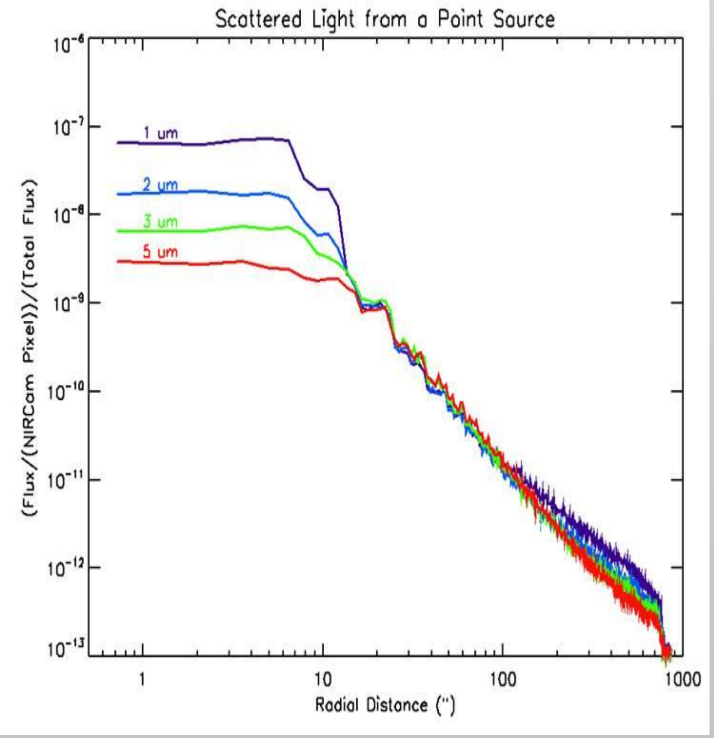
Kalas et al. 2005

Uniform optical depth **equal to 3 "zodis" of dust, illuminated by star. Color and brightness are dependent on spectral type.**

Astrophysical Assumptions

Stray Light from Binaries

NASA/Chris Gunn

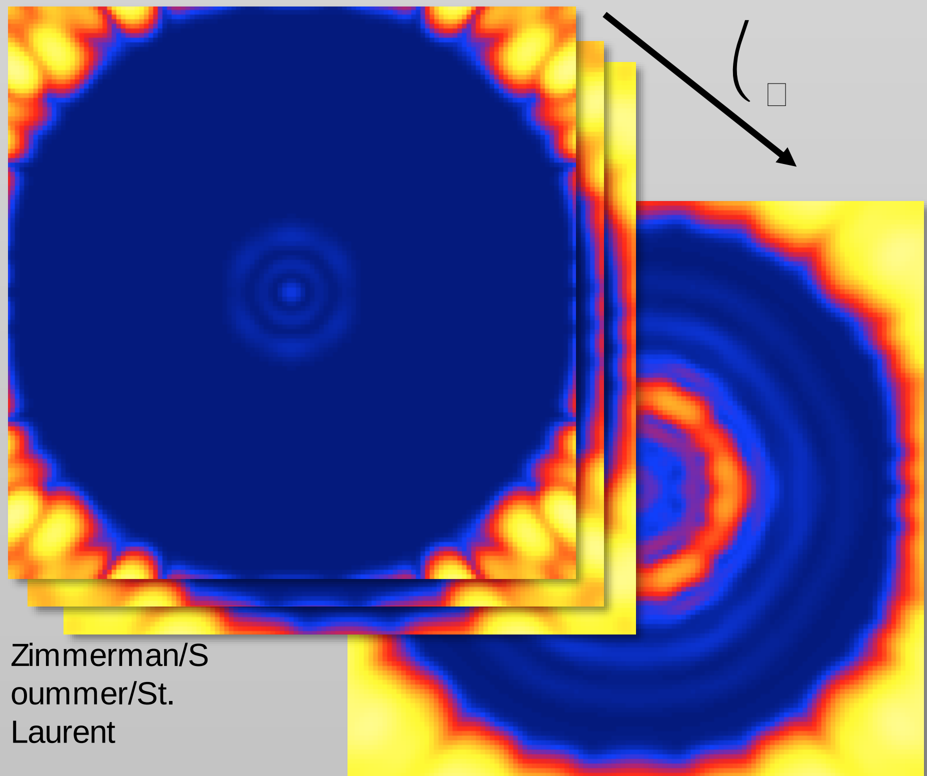


J. Stansberry

- Stray light: particulates on mirrors scatter light to far wings of the PSF
- Companion stars outside of the instrument field of view can produce stray light levels that exceed the suppressed starlight
- We include stray light using λ/20 RMS surface roughness, f^{-3}

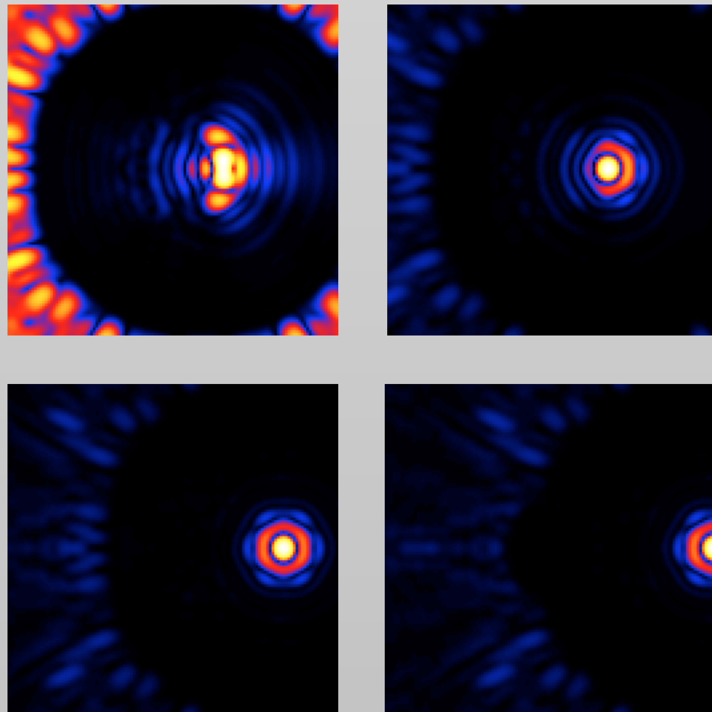
Instrument Modeling

We use detailed optical models of coronagraph & starshade



Zimmerman/Soummer/St. Laurent

- **2D leaked starlight simulations as a function of stellar diameter**
- **Contrast degradation due to instabilities currently modeled as 10^{-10} contrast floor**

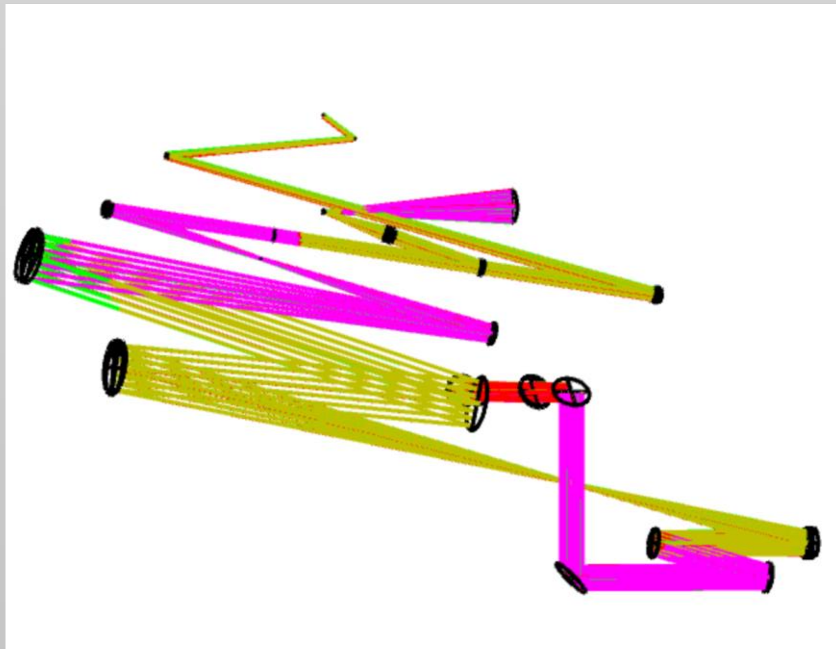


Zimmerman/Soummer/St. Laurent

Use large set of off-axis (planet) PSFs; interpolate to all separations

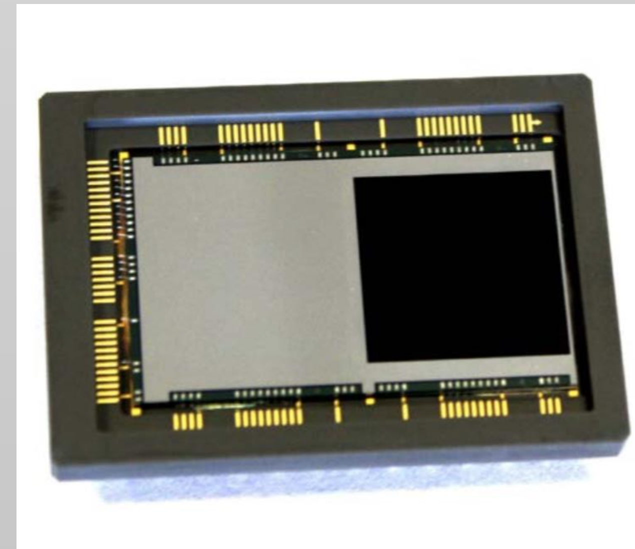
Instrument Modeling

Optics



- Adopt detailed optical layout from engineering designs defining each optical surface
- Wavelength-dependent reflectivities/transmissivities of all optics included

Detector



e2v

- Adopt a realistically-improved version of the WFIRST EMCCD
- Read noise, dark current, and clock induced charge
- QE & QE reductions due to readout inefficiencies

The Exoplanet Yield Landscape

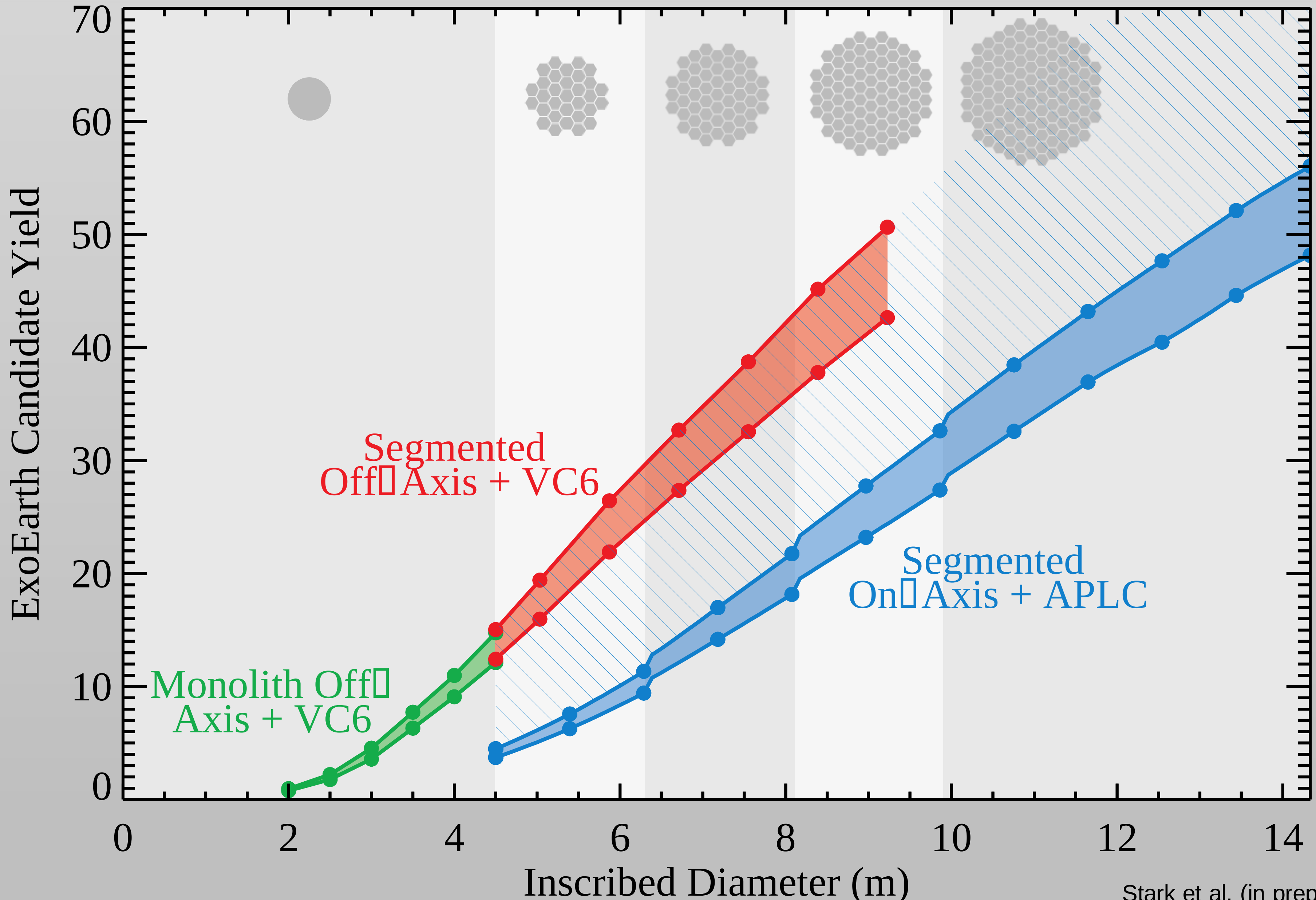
Three critical regimes

Monolith off-axis
Segmented off-axis
Segmented on-axis

For each of these, I adopted the *current* best-performing coronagraph and received yield inputs from their designers. Note that yields could increase a small amount by mixing different coronagraph designs.

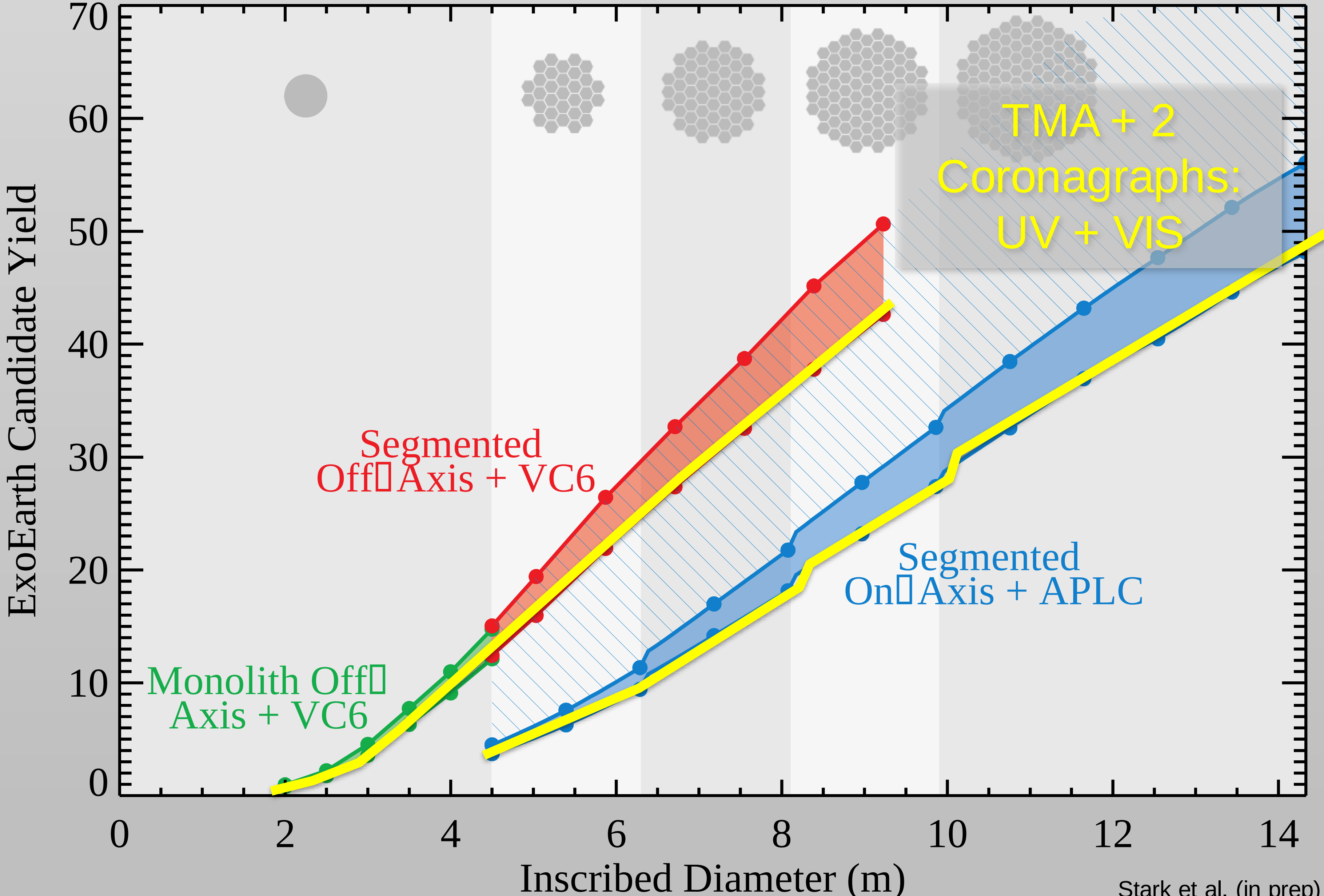
For each calculation, I assumed 6 observations per system on average (to measure orbits), simultaneous 2-channel detection at 500 nm, an R=70 SNR=5 spectrum on each exoEarth candidate @ 1 micron, and optimization of the planet's phase for characterization. I adopted LUVOIR's optical design.

The Exoplanet Yield Landscape



Stark et al. (in prep)

The Exoplanet Yield Landscape



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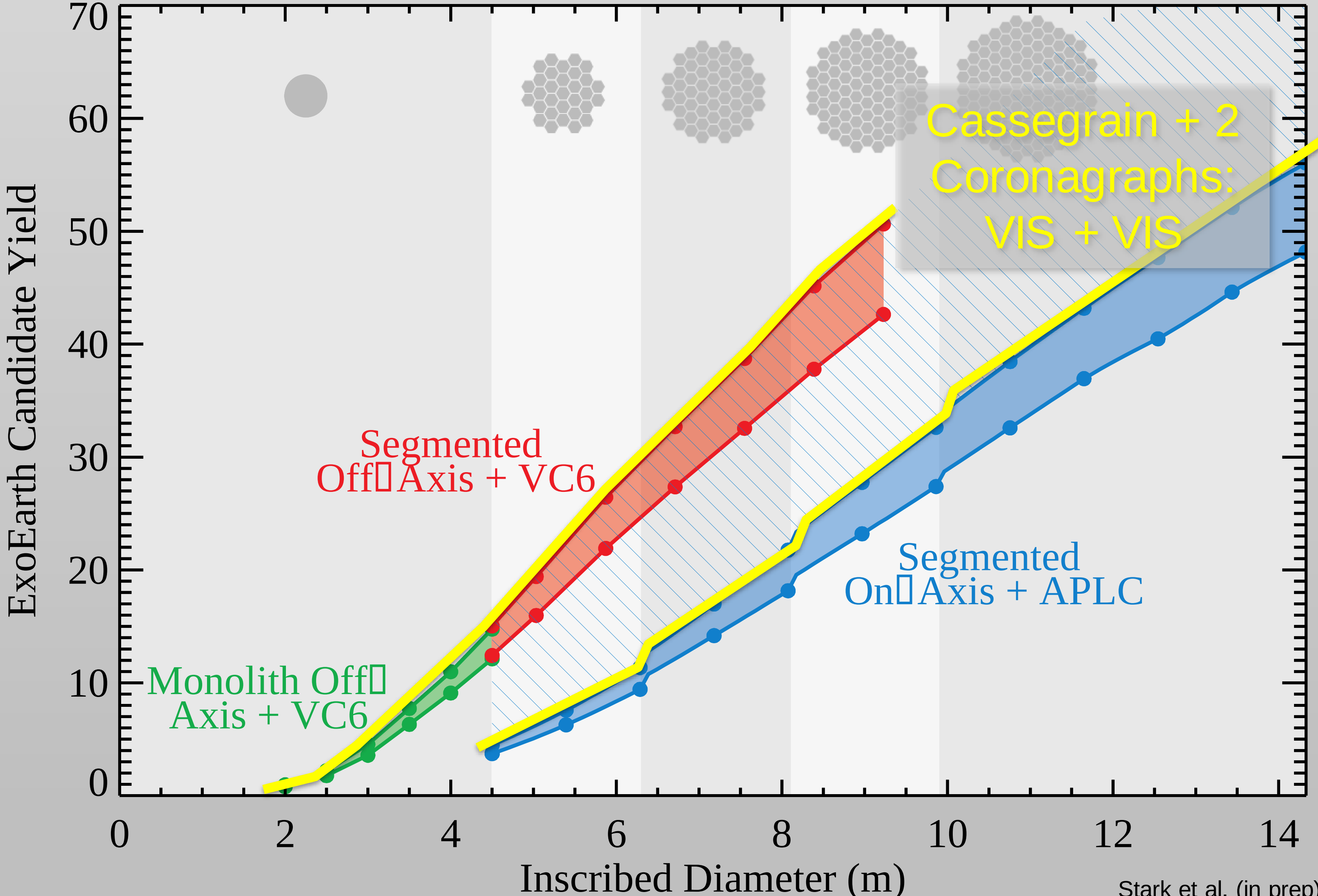

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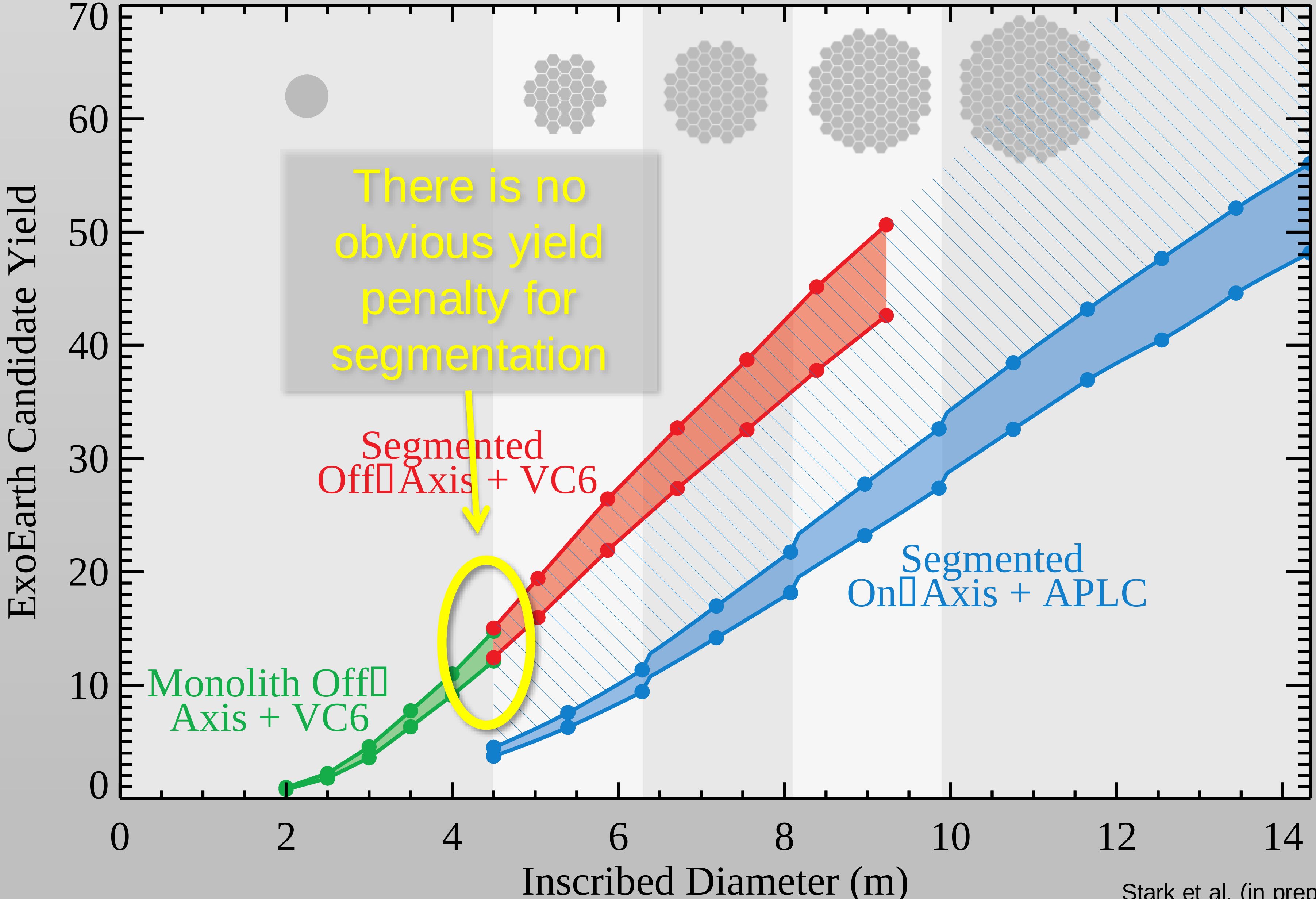

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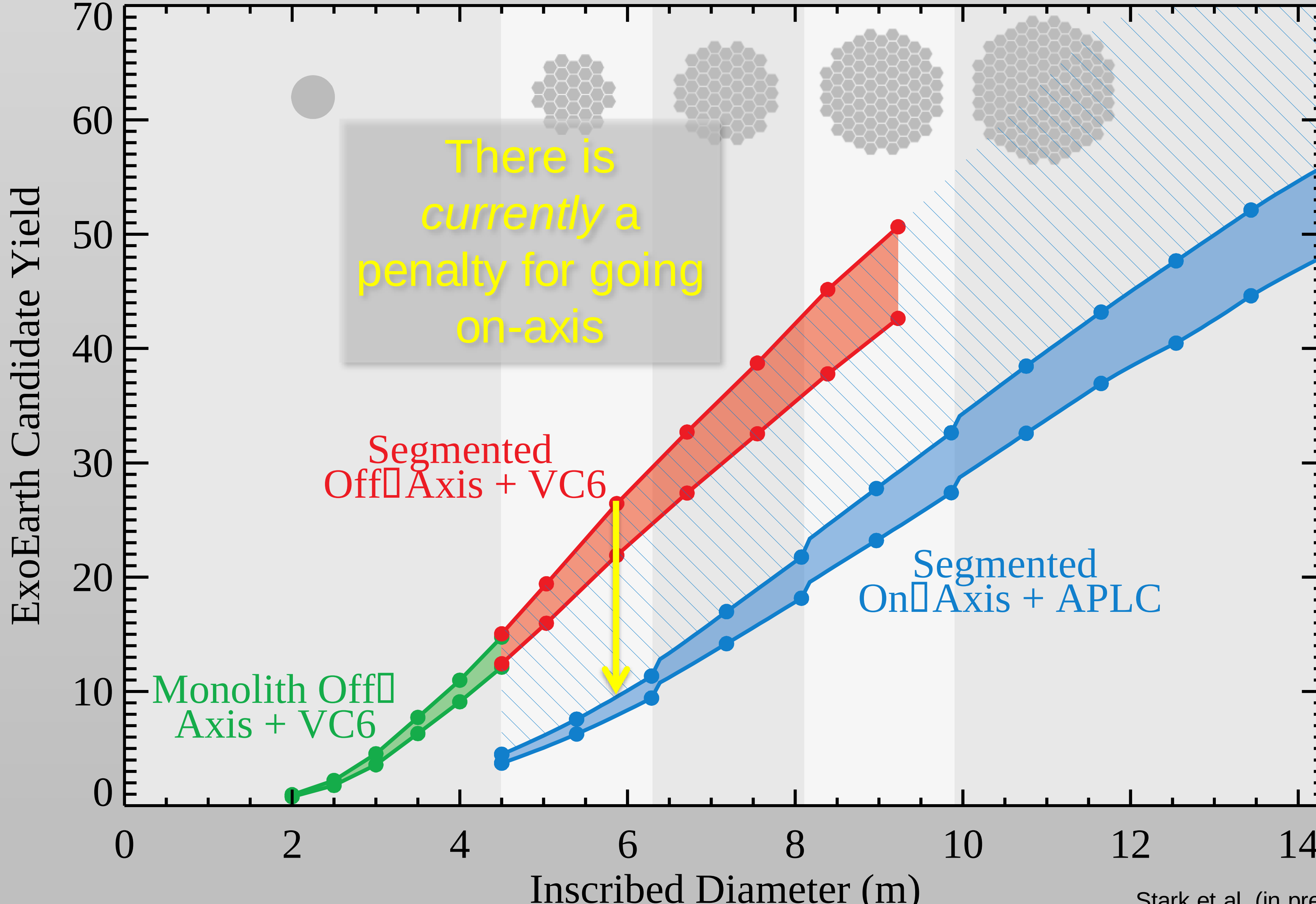

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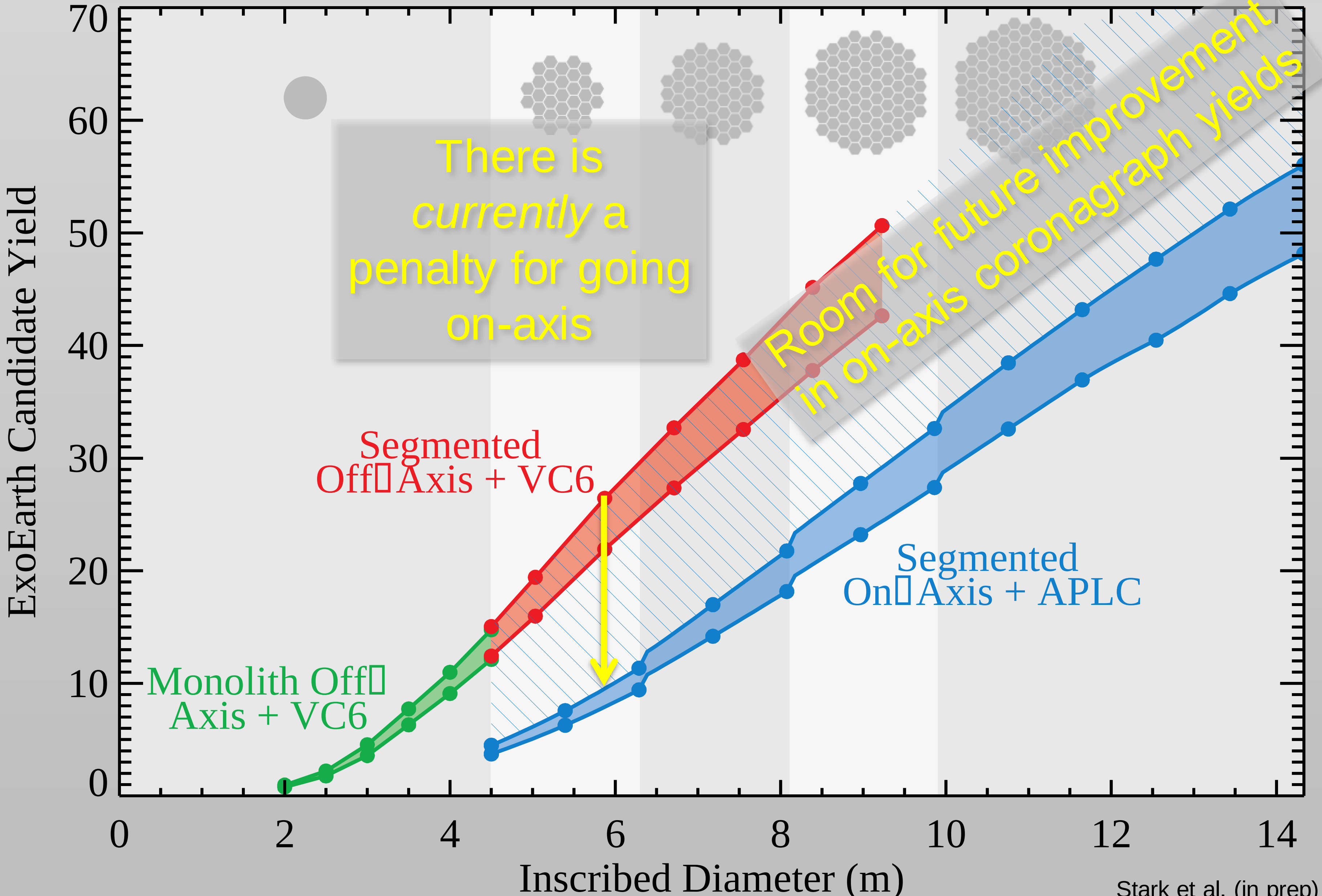

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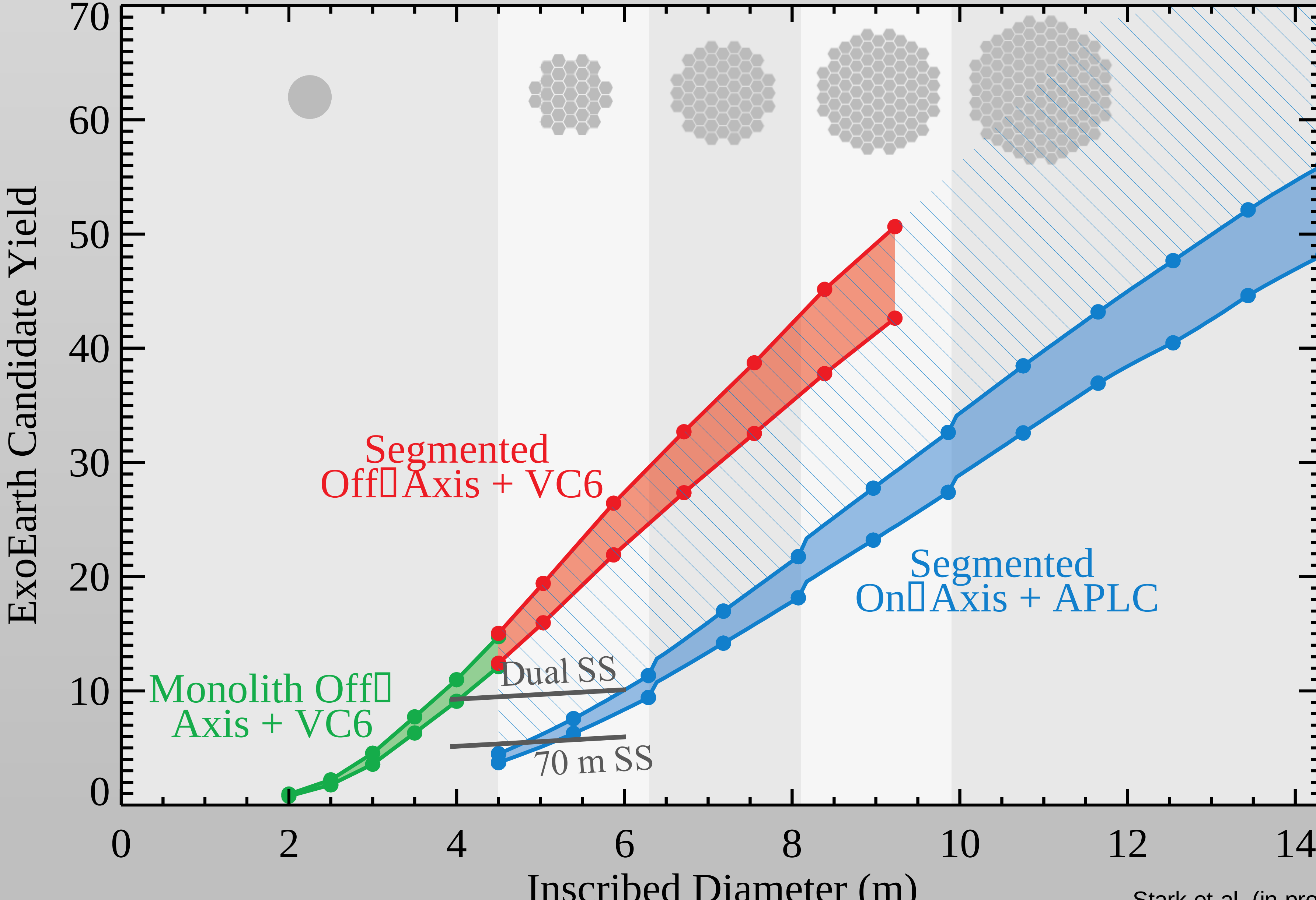

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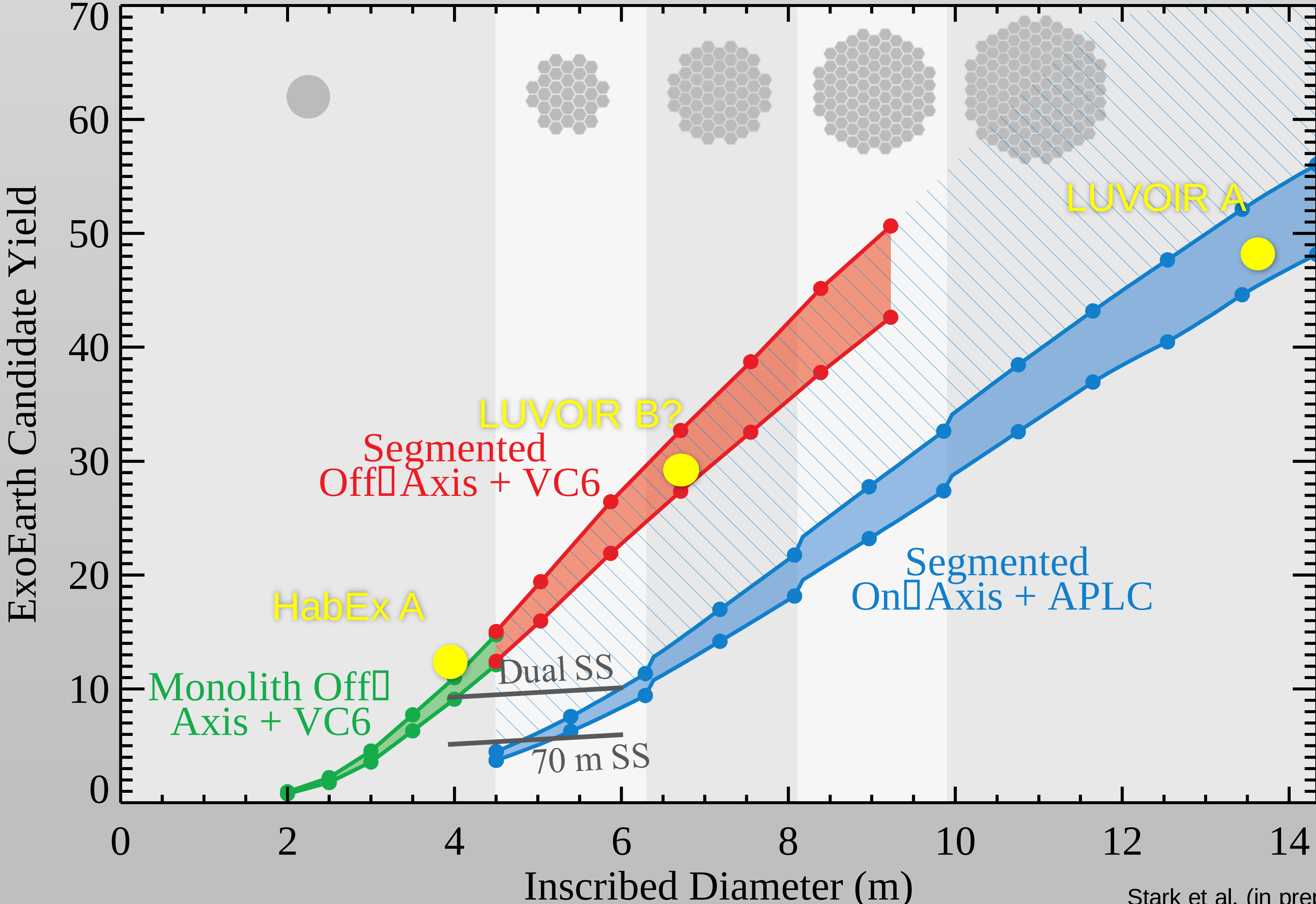
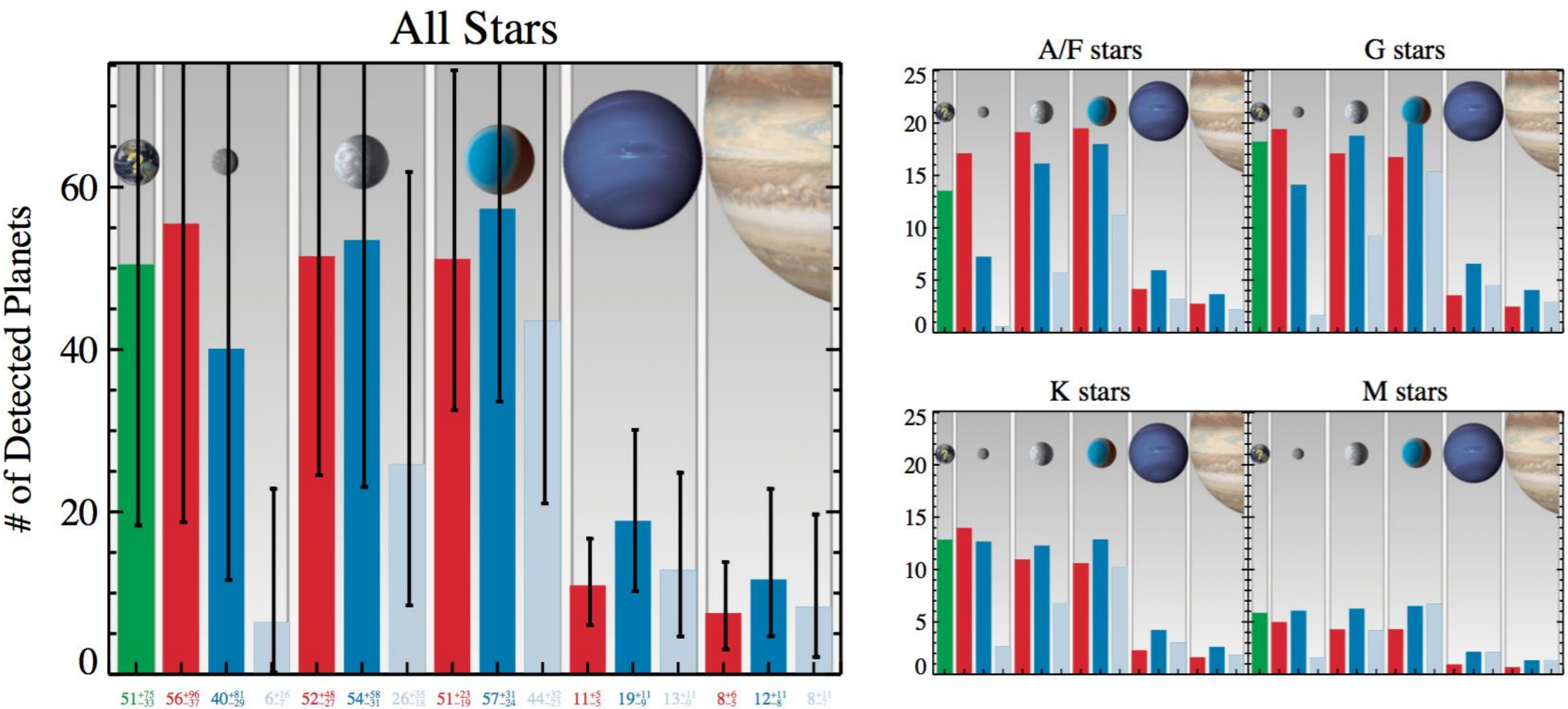


Stark et al. (in prep)

LUVOIR A Exoplanet Yield Diversity

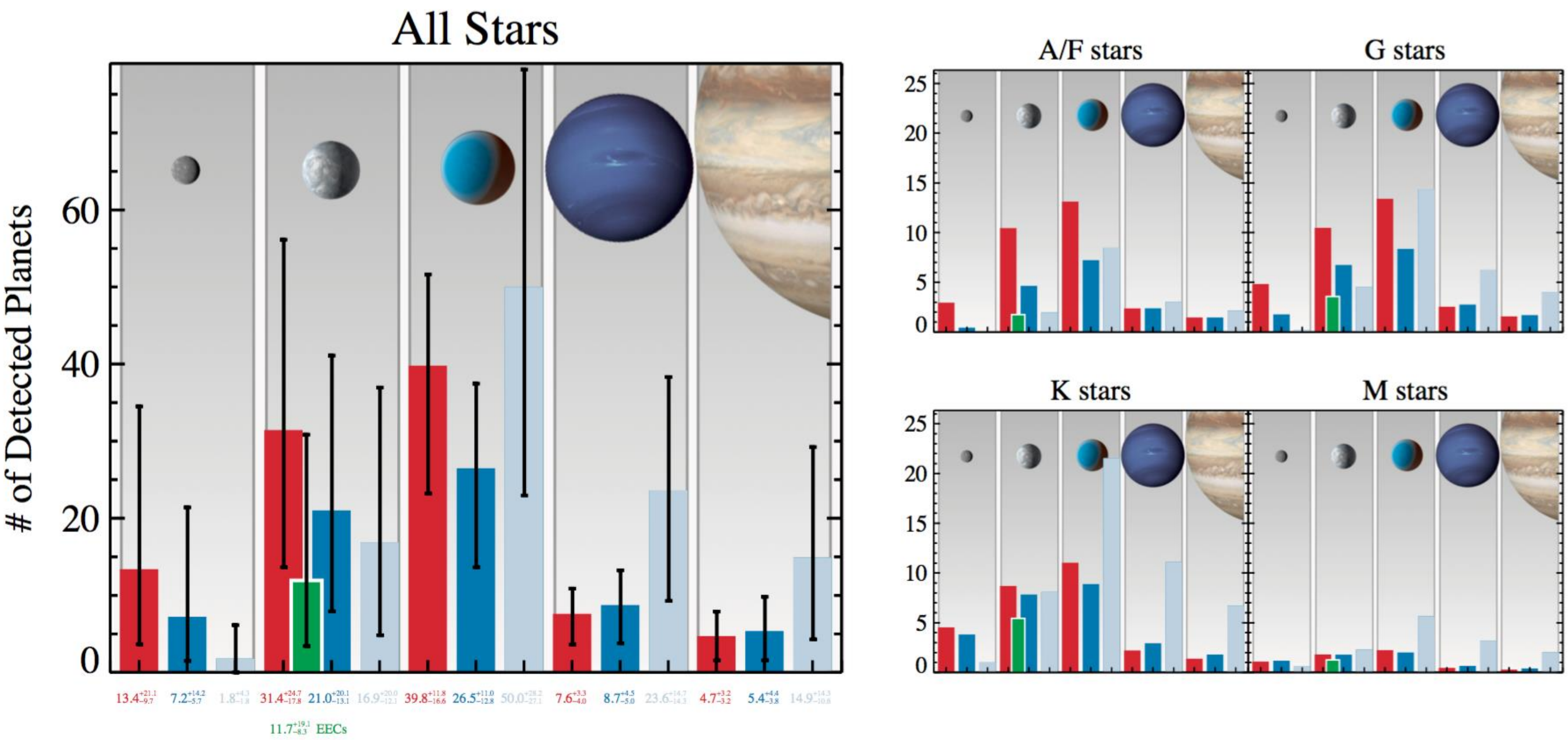


Note: future small adjustments are likely to hot/warm planets; cold planet yields are overestimated.

LUVOIR Interim Report

Error bars are 1-σ and include occurrence rate uncertainties and finite sampling statistics (randomness of planetary systems)

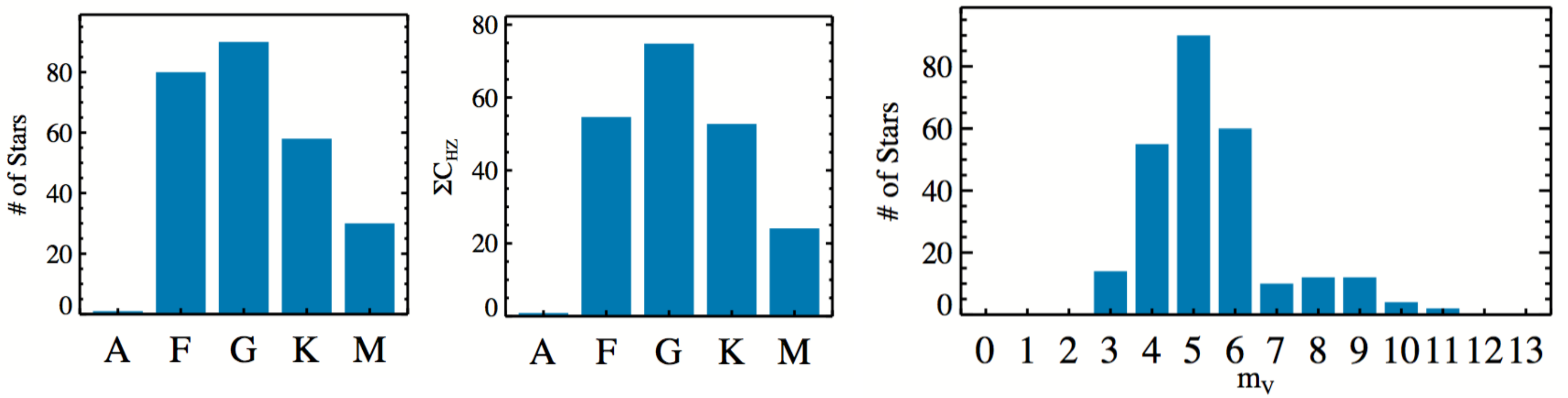
HabEx A Exoplanet Yield Diversity

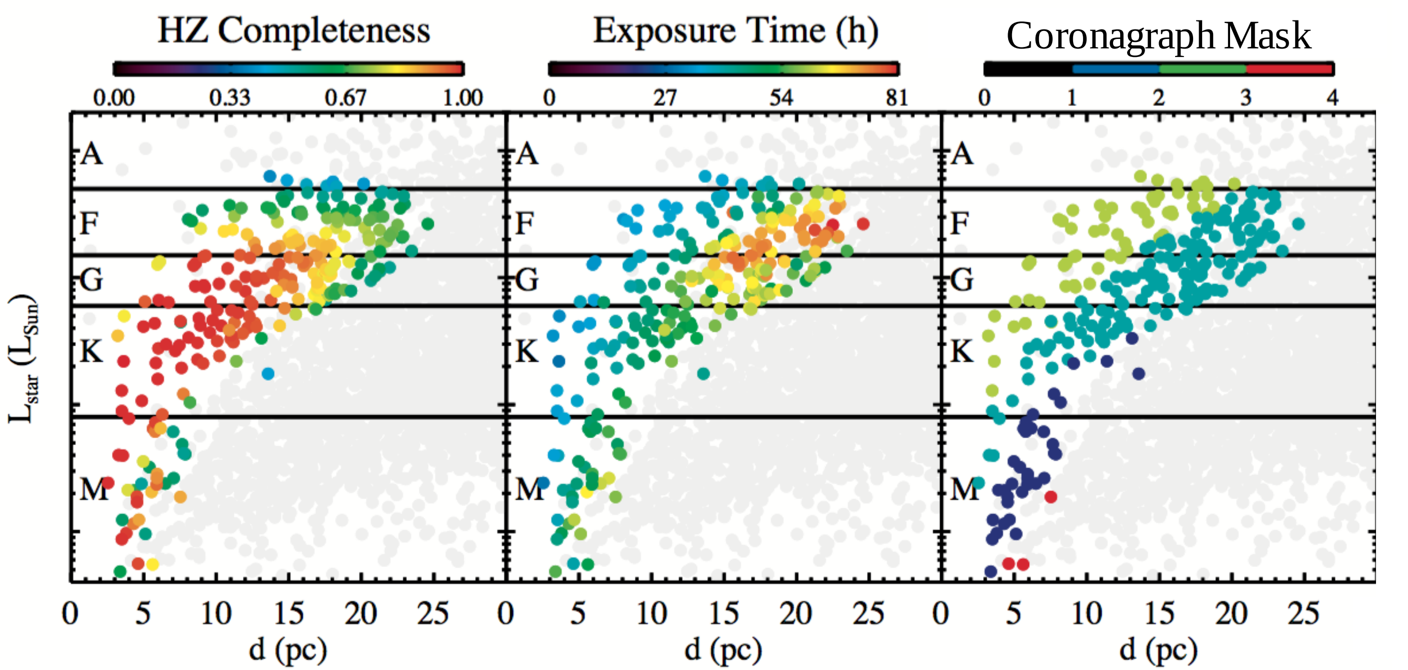


Note: future small adjustments are likely to hot/warm planets; cold planet yields are overestimated.

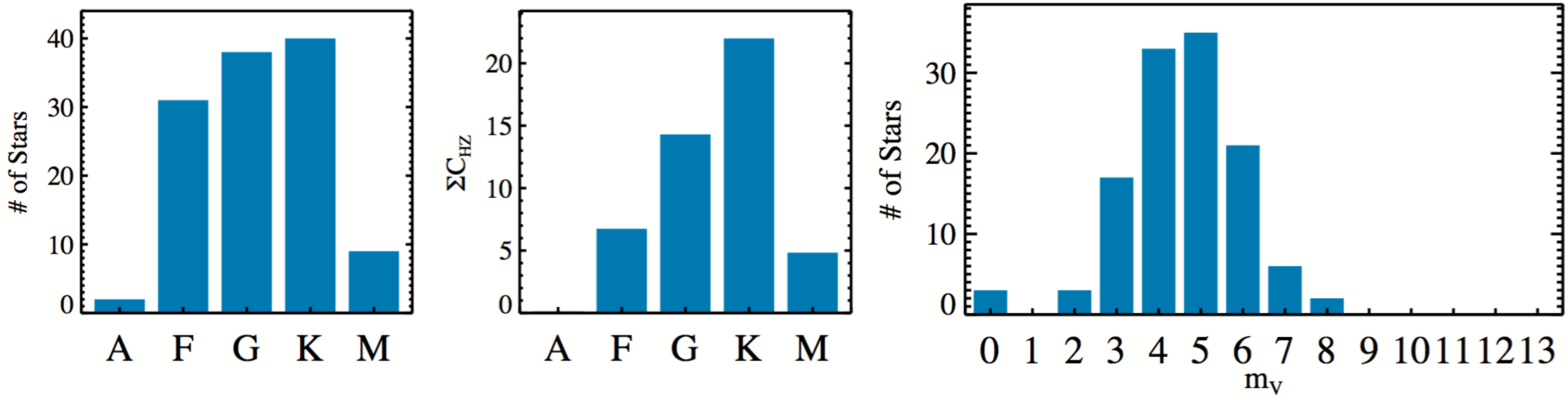
HabEx Interim Report

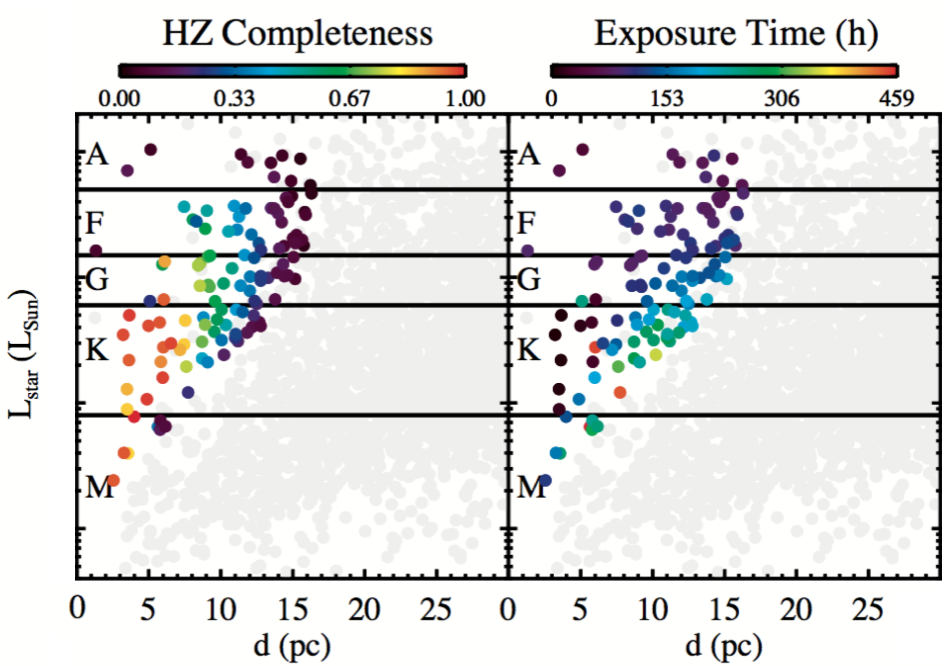
LUVOIR A Target List





HabEx A Target List





Summary

- We have a mature tool to estimate exoplanet yields (and uncertainties) that optimizes the observation plan and maximizes the yield
- The fidelity of the yield inputs are quickly approaching their limits
- “Yield” is defined/impacted by the science we want and how we go about getting it
- HabEx A will detect and characterize ~12 exoEarth candidates. LUVOIR A will detect and characterize ~50 exoEarth candidates. Both missions will detect a wide variety of other exoplanets.