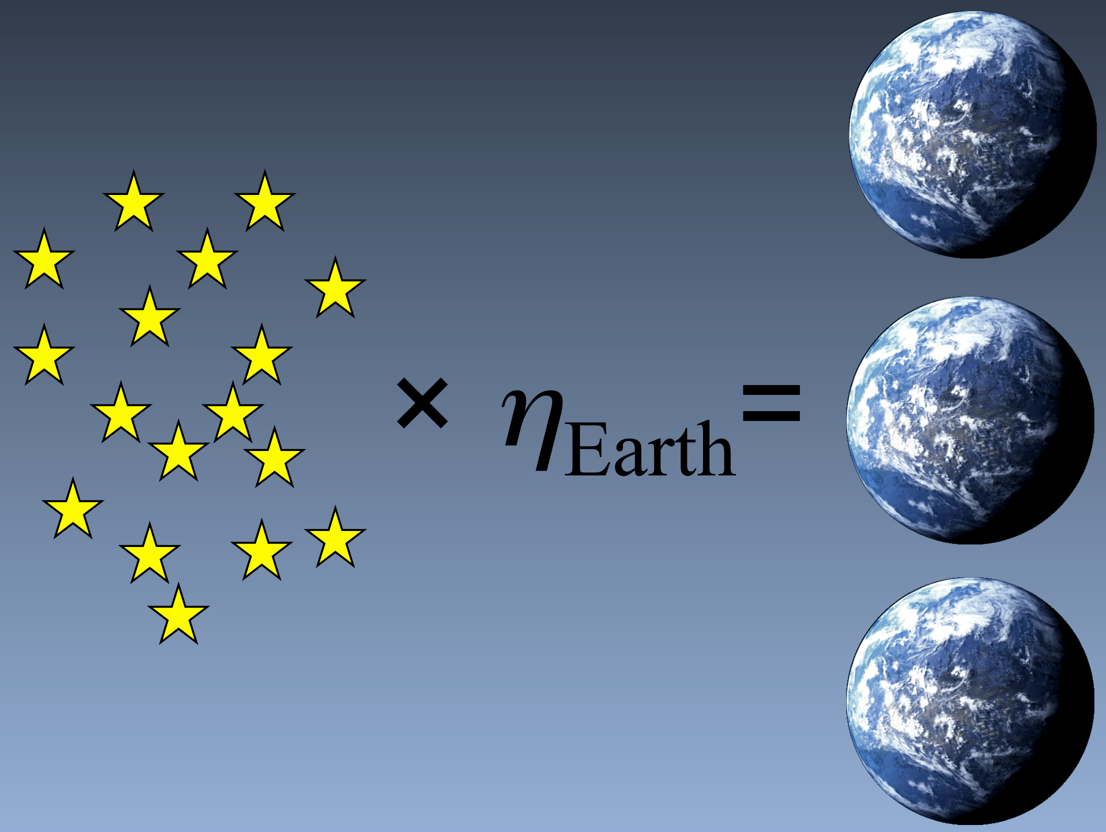
The Aperture of Future UVOIR Space Telescopes: Constraints Derived from ExoEarth Yield Calculations

Christopher Stark
GSFC NPP Fellow
christopher.c.stark@nasa.gov

Aki Roberge
Avi Mandell
Mark Clampin
Shawn Domagal-Goldman
Karl Stapelfeldt

How Does One Choose a Yield Goal?



…but at what confidence level?

How Does One Choose a Yield Goal?

Must rely on blind selection counting. The probability P of x successes out of n tries, each with probability p of success, is given by the binomial distribution function…

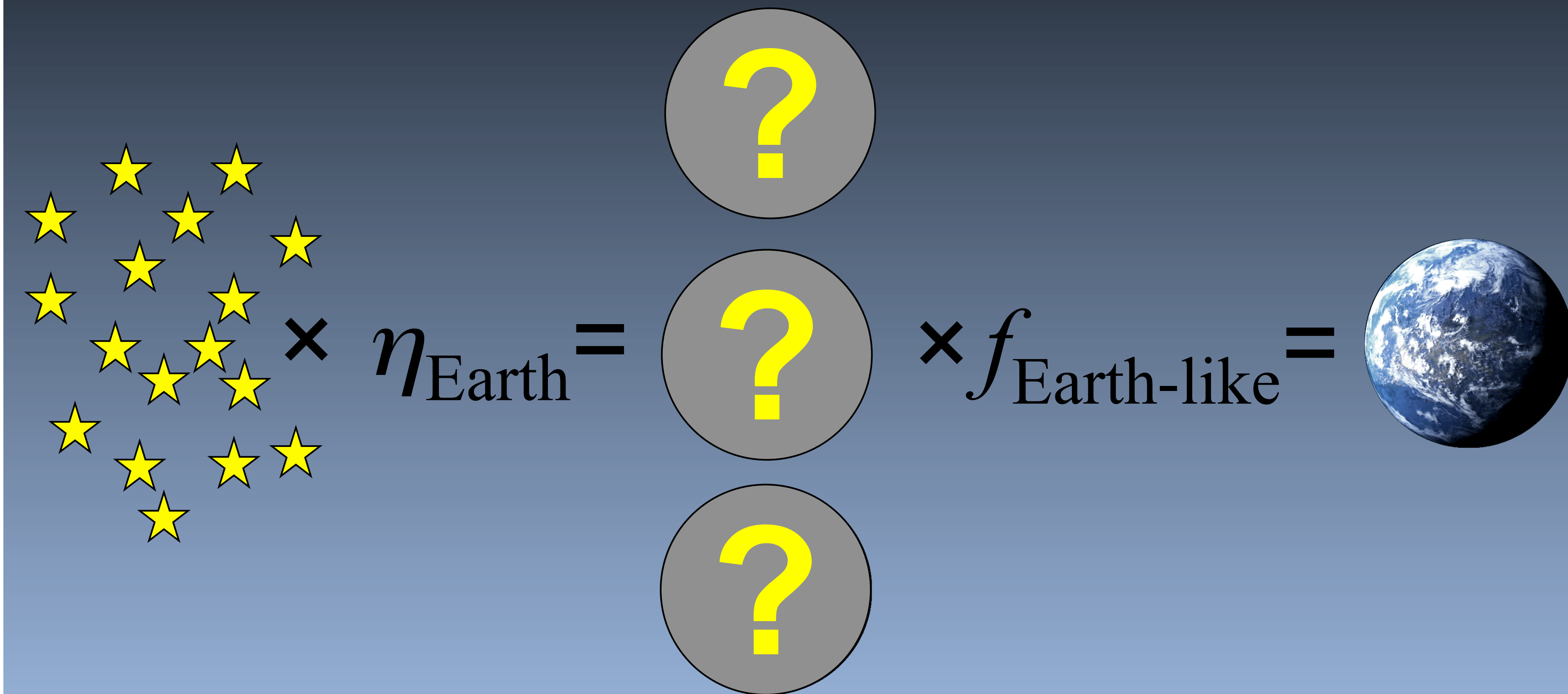
$$P\left(x,n,p\right)=\frac{n!}{x!(n-x)!}\,p^{x}\,\left(1-p\right)^{n-x}$$

Translating to require ≥ 3 ExoEarth Candidates (EC) gives…

$$C\left(N_{\rm EC}\geq 3,N_{\rm HZ},\eta_{\oplus}\right)=\sum_{N_{\rm EC}=3}^{N_{\rm HZ}}\frac{N_{\rm HZ}!}{N_{\rm EC}!(N_{\rm HZ}-N_{\rm EC})!}\,\eta_{\oplus}^{N_{\rm EC}}\,\left(1-\eta_{\oplus}\right)^{N_{\rm HZ}-N_{\rm EC}}$$

If you want 3 Earth-sized HZ planets with 95% confidence, you'd better budget for 6.

How Does One Choose a Yield Goal?



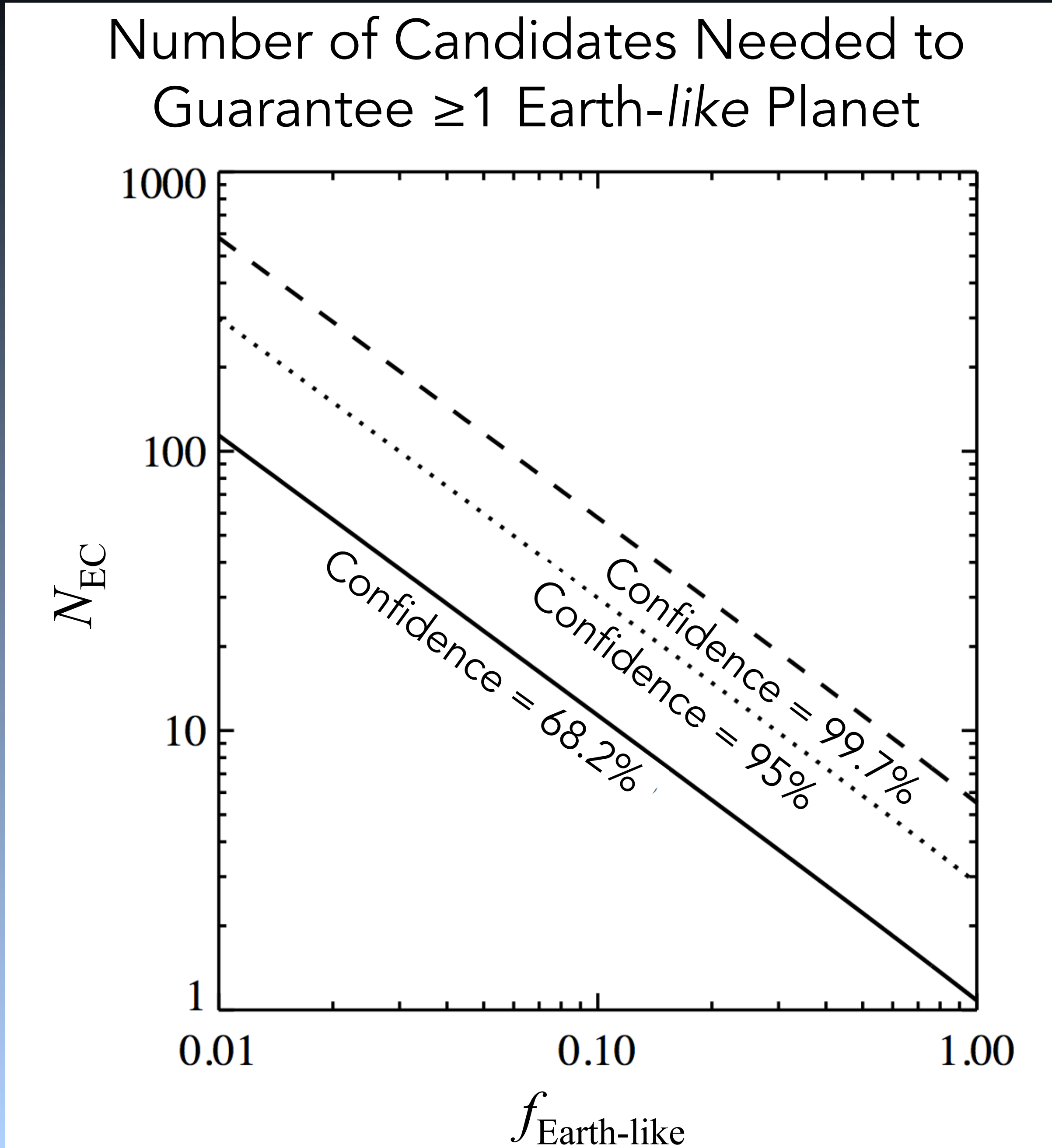
η_{Earth} does not express the number of Earth-*like* planets per star.

How Does One Choose a Yield Goal?

To guarantee at least 1 Earth-like planet at confidence level C

$$N_{\rm EC} = \eta_{\oplus} \frac{\log\left(1 - C\right)}{\log\left(1 - \eta_{\oplus} f_{\rm Earth\text{-}like}\right)}$$

How Does One Choose a Yield Goal?



How Does One Choose a Yield Goal?

Two example yield goals, summarized:

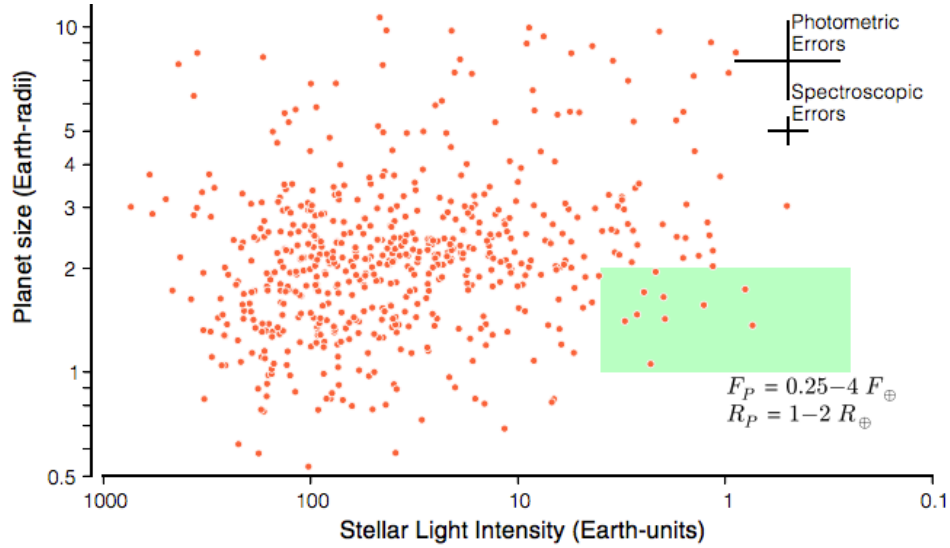
6 ExoEarth Candidates

- Guarantees 3 Earth-sized planets in the HZ at the 95% confidence level
- Does not help constrain $f_{\text{Earth-like}}$

30 ExoEarth Candidates

- Guarantees 1 Earth-*like* planet in the HZ at the 95% confidence level if $f_{\text{Earth-like}} \geq 0.1$
- In the event of a null result, we can constrain $f_{\text{Earth-like}} \leq 0.1$ at the 95% confidence level

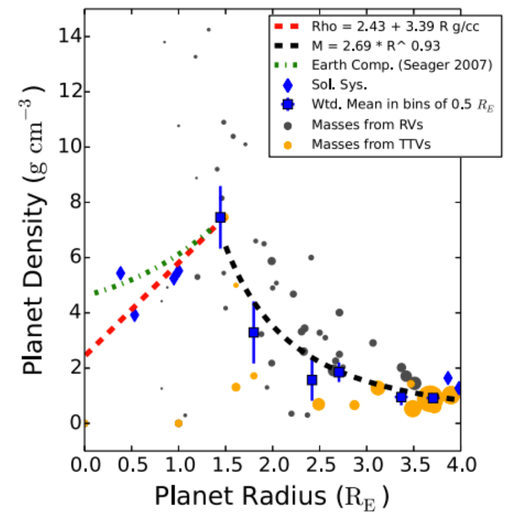
What Value of η_{Earth} Should We Use?



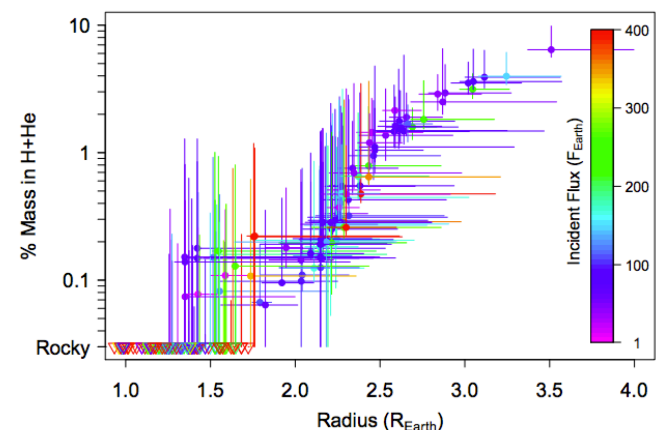
HZ definition	a_{inner}	a_{outer}	η_{Earth} (%)
Simple	0.5	2	22
Kasting (1993)	0.95	1.37	5.8
Kopparapu et al. (2013)	0.99	1.70	8.6

Petigura et al. (2013); see also Silburt et al. (2014)

Transition To Rocky Planets @ 1.5 R_{Earth}



Weiss & Marcy (2014)



Wolfgang & Lopez (2014)

η_{Earth} depends on definitions of HZ and "Earth-sized."

What Value of η_{Earth} Should We Use?

Table 3. $\eta_\oplus$ for Planet Radii 0.66 – 1.5 $R_\oplus$

HZ Definition	Acronym	a_{inner}[1] (AU)	a_{outer}[1] (AU)	$\eta_\oplus$[2]
Brown (2005)	BHZ	0.7	1.5	0.14 ± 0.05
Optimistic Kopparapu et al. (2013)	OKHZ	0.75	1.77	0.16 ± 0.06
Pessimistic Kopparapu et al. (2013)	PKHZ	0.99	1.67	0.10 ± 0.04

[1]For a Sun-like star.

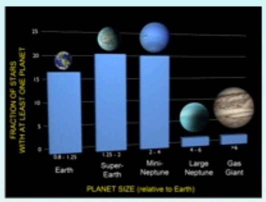
[2]Based on results and scaling relations from Petigura et al. (2013a).

I adopt the optimistic Kopparapu et al. (2013) HZ definition and $0.66 < R_p < 1.5\ R_{Earth}$, such that $\eta_{Earth} = 0.16 \pm 0.06$.

Calculating Yield with a DRM Code

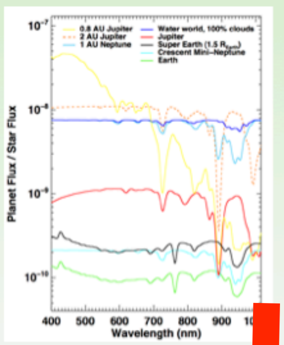
Astrophysical Constraints

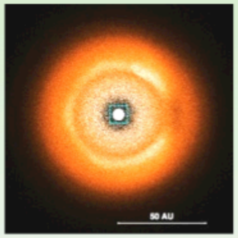
- η_{Earth}
- $\eta_{exozodi}$
- Planet sizes
- Albedos
- Phase functions



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

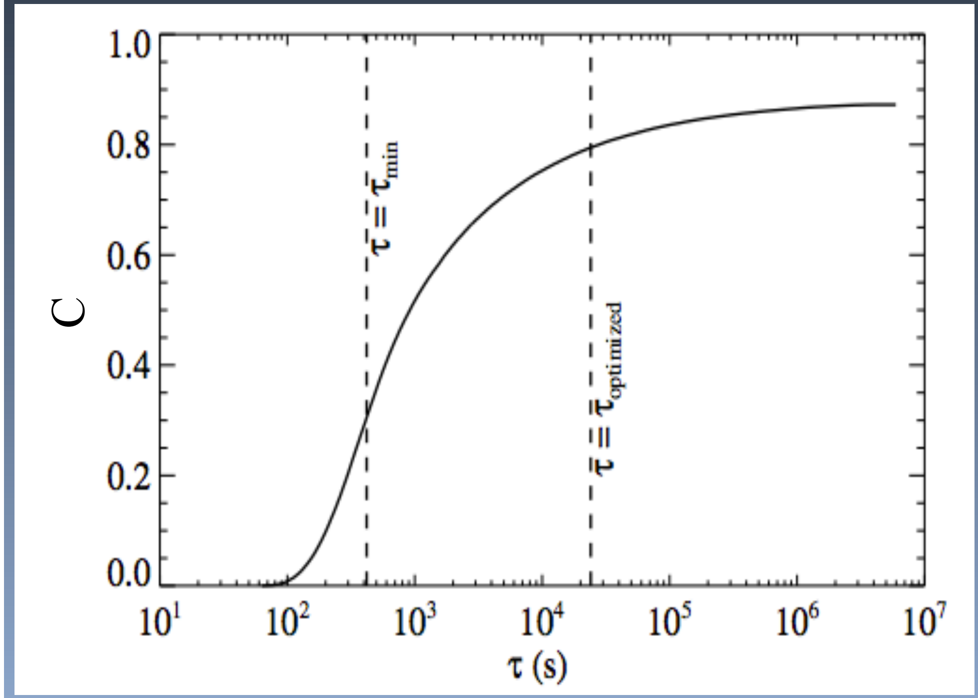
ExoEarth Candidate Yield

ExoEarth Yield Estimated via Completeness

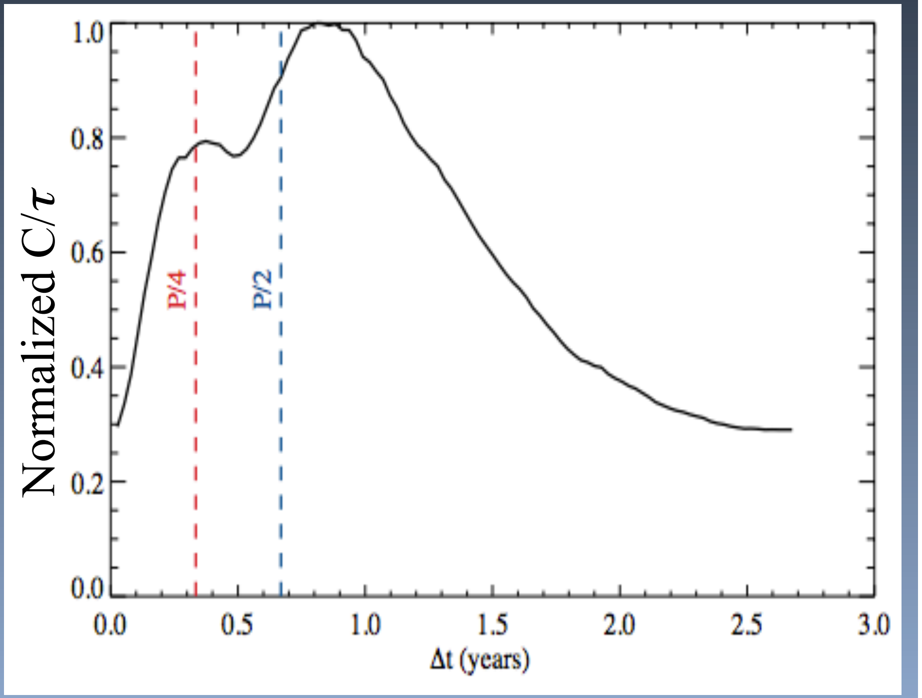
- Completeness, C = the chance of observing a given planet around a given star if that planet exists (Brown 2004)
- Yield = $\eta_{\mathrm{Earth}} \Sigma C$
- Calculated via a Monte Carlo simulation with synthetic planets
- Can revisit same star multiple times to increase total completeness

Maximizing Yield by Optimizing Observations

Optimize Exposure Time



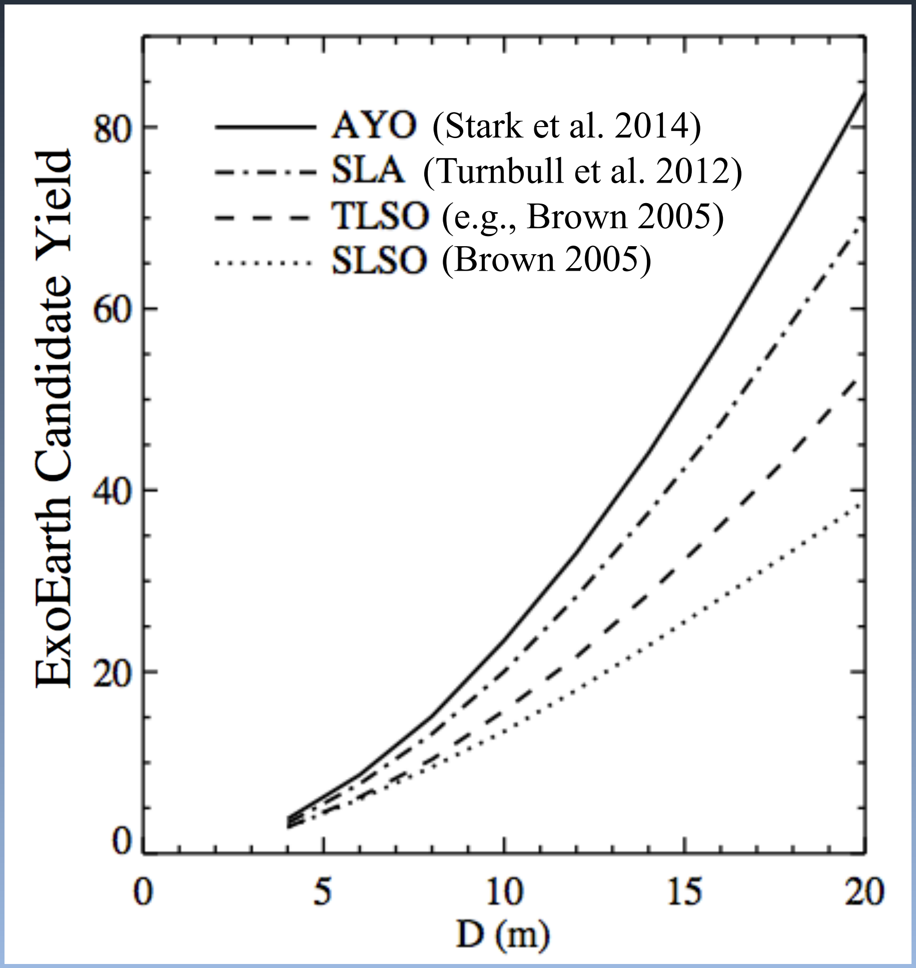
Optimize Revisit Delay Time



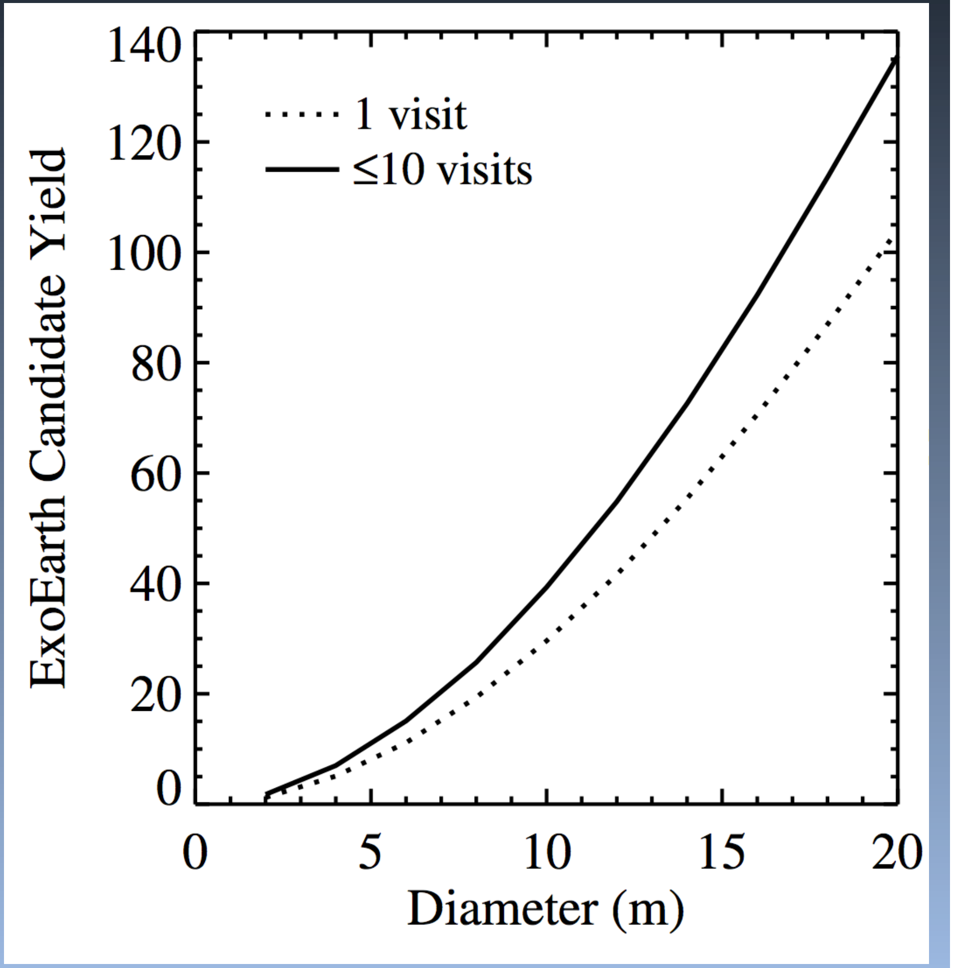
We simultaneously optimize the exposure time of every observation, the number of visits to each star, the delay time between visits, and the stars selected for observation.

The Impact of Optimization on Yield

Single Visit Optimization vs. Previous Methods



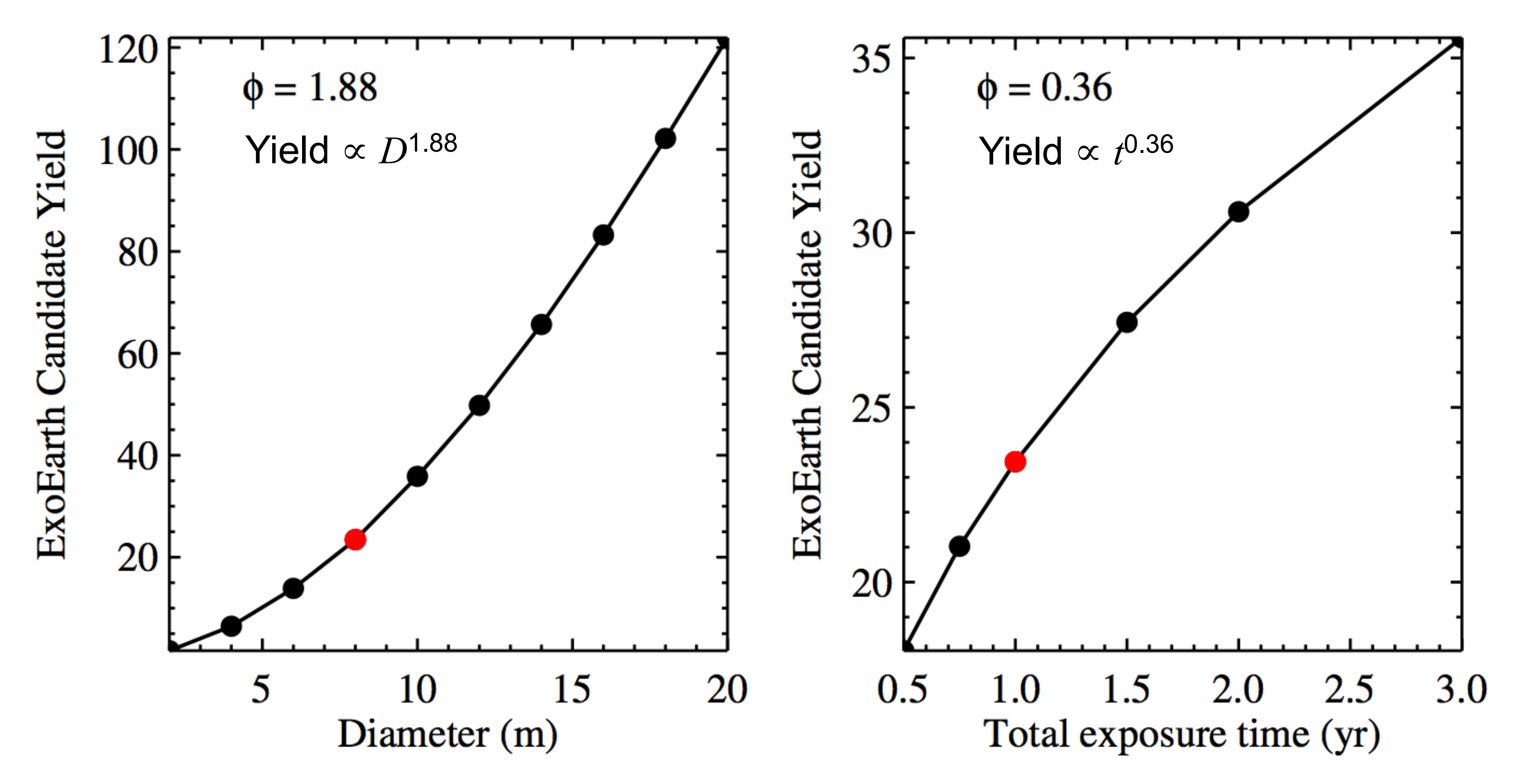
Single Visit Optimization vs. Multi-visit Optimization



Optimizing exposure times can potentially double yield

Optimized revisits increase yield by additional ~40%

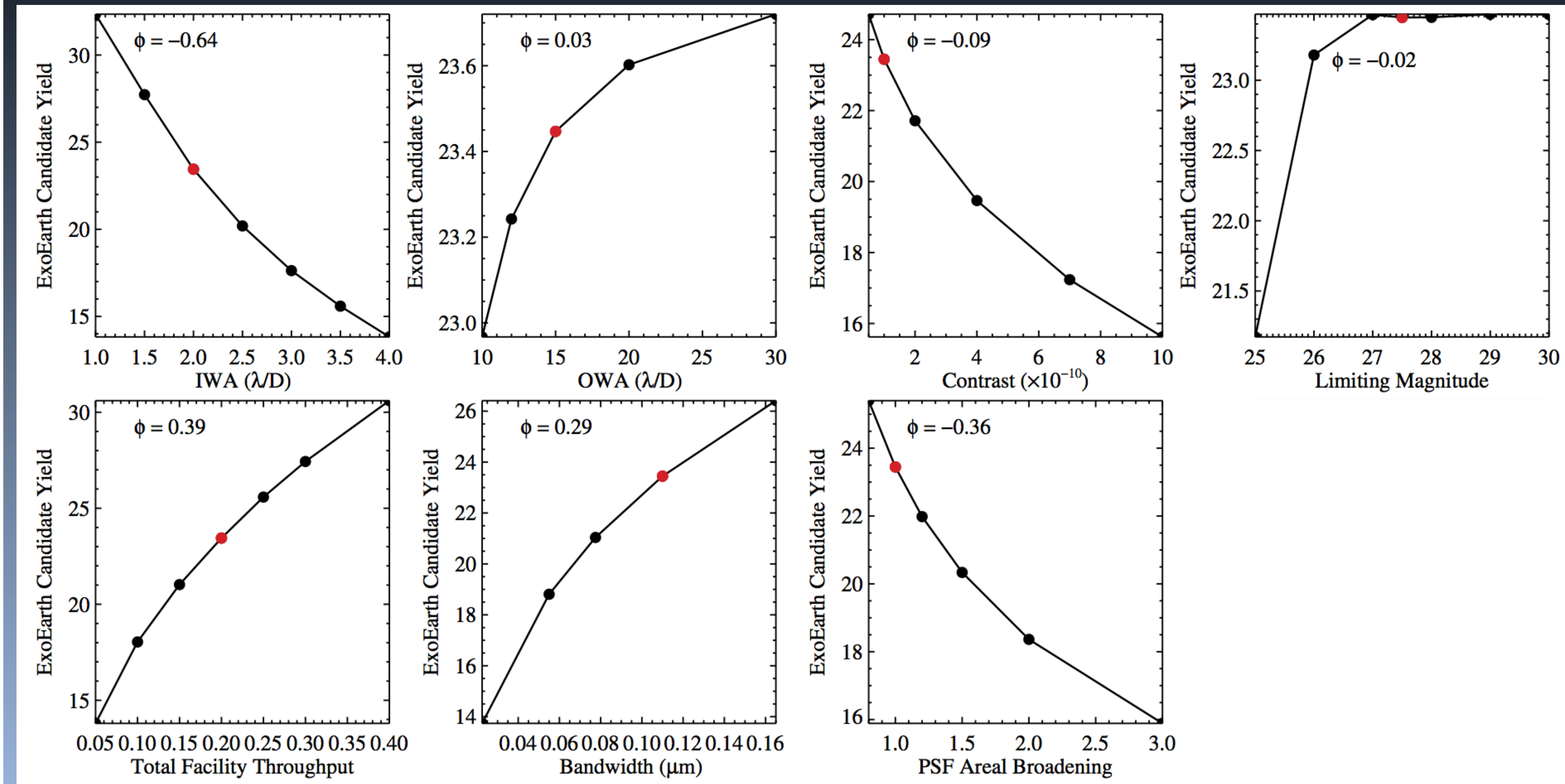
What Telescope/Instrument Parameters Matter?



Yield most strongly depends on aperture.
Moderately weak total exposure time dependence.

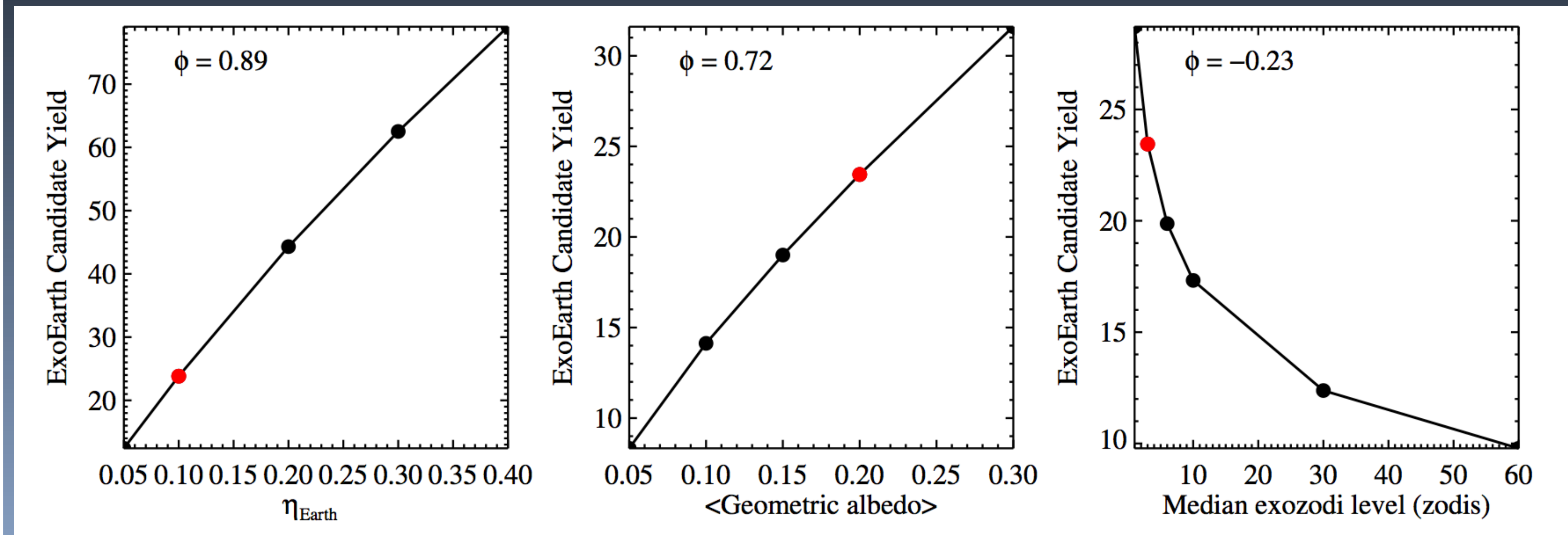
What Telescope/Instrument Parameters Matter?

Coronagraph Scaling Laws



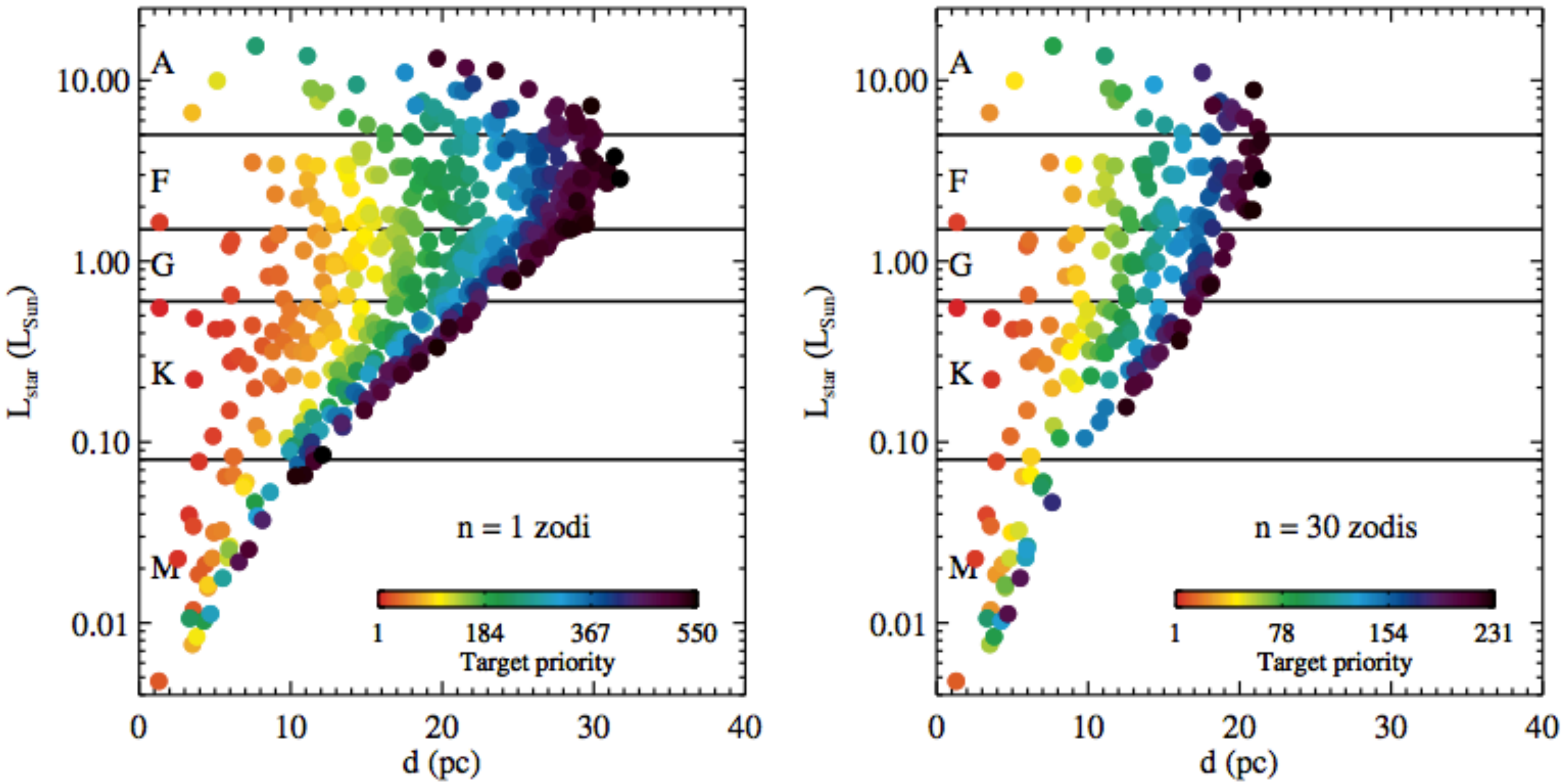
IWA matters more than contrast when treating both linearly. OWA doesn't matter. Noise floors with Δmag > 26.5 are unnecessary.

What Astrophysical Parameters Matter?



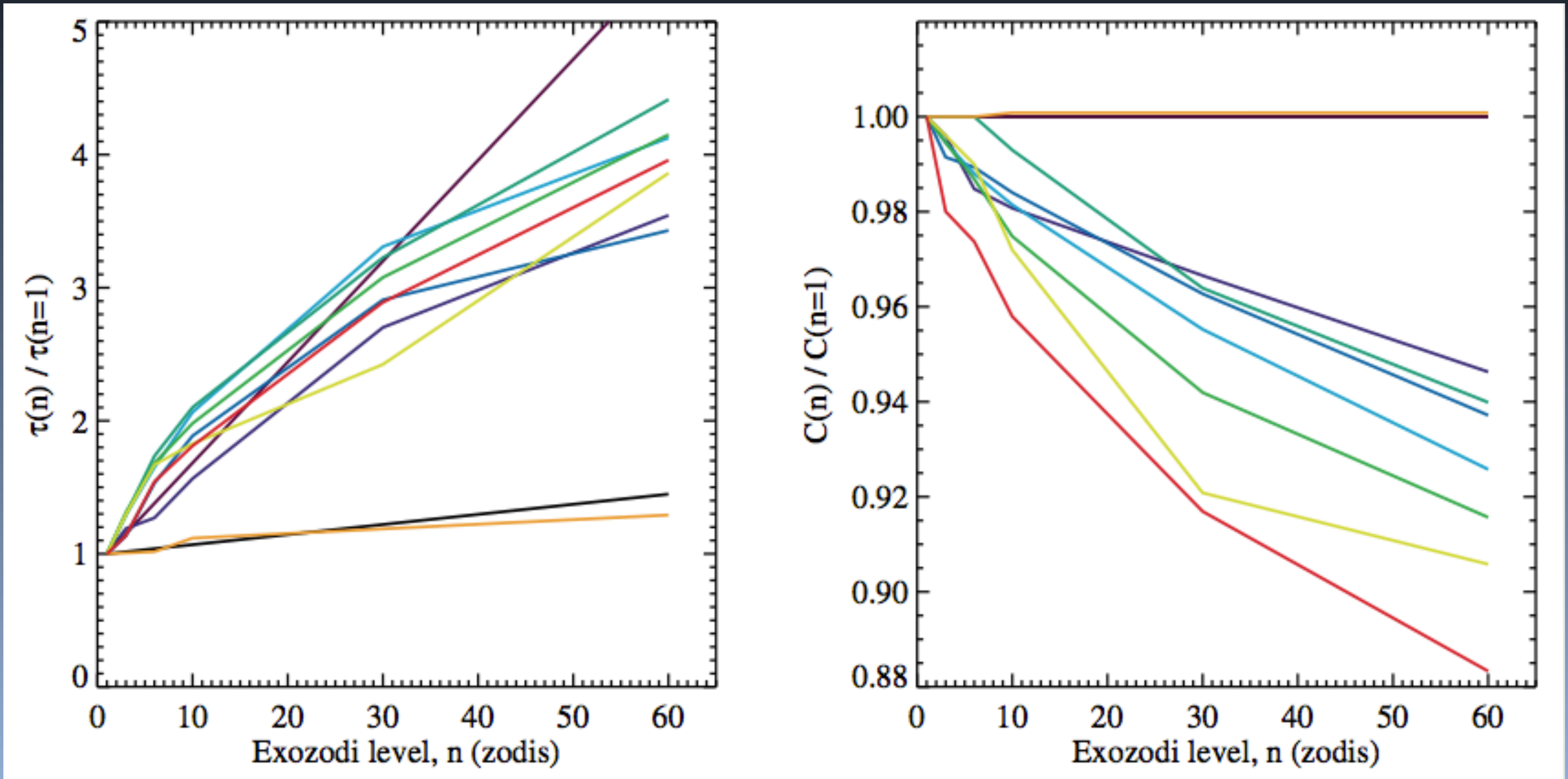
Non-linear dependence on η_{Earth} due to required spectral characterization. Weak dependence on exozodi level, but much room for improvement in exozodi level constraints.

Why is the Exozodi Dependence so Weak?



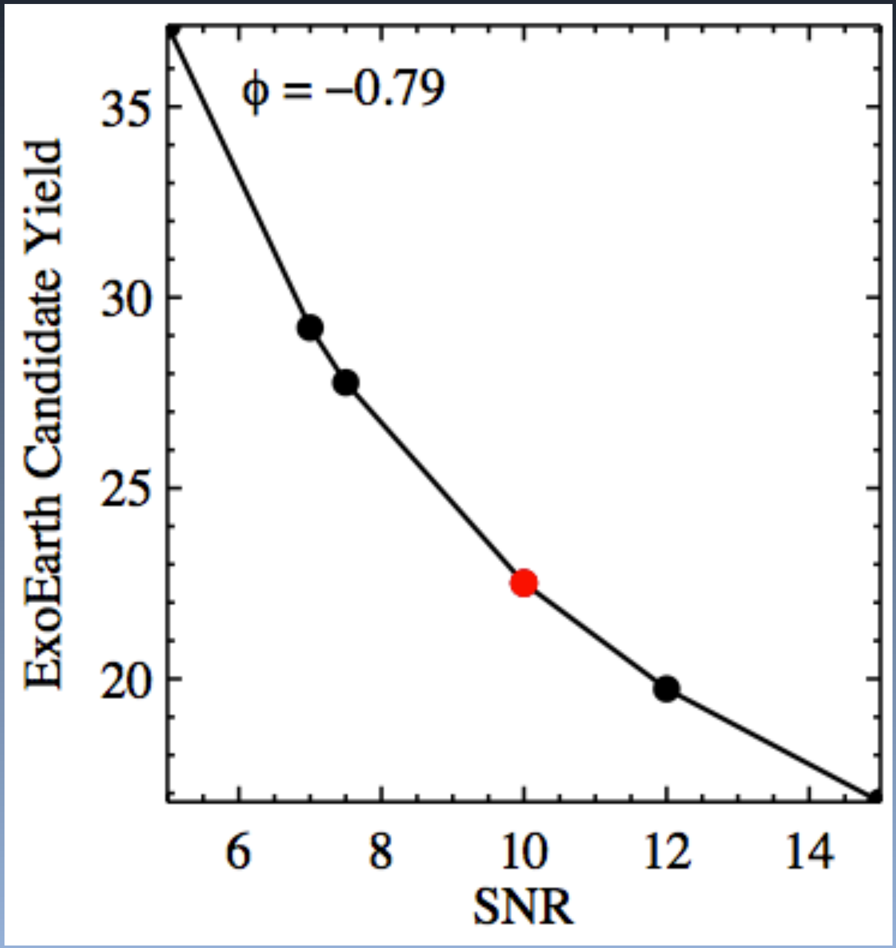
1. Increasing exozodi naturally removes the *worst* targets

Why is the Exozodi Dependence so Weak?



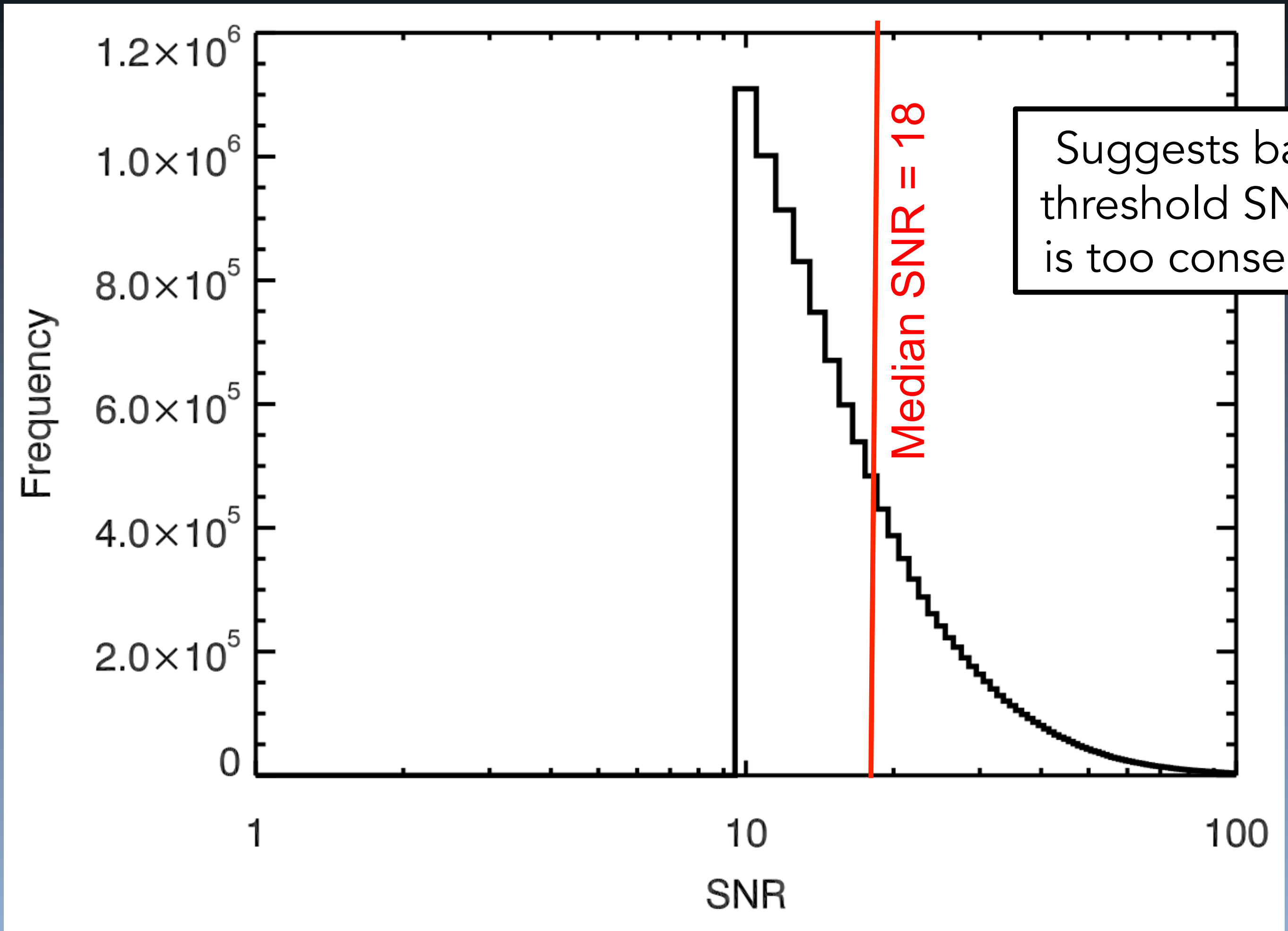
2. AYO sacrifices exposure time and completeness on individual stars to observe *more* stars, which maximizes yield

What Telescope/Instrument Parameters Matter?



Yield is a strong function of detection threshold SNR.
What is the correct SNR?

What Telescope/Instrument Parameters Matter?

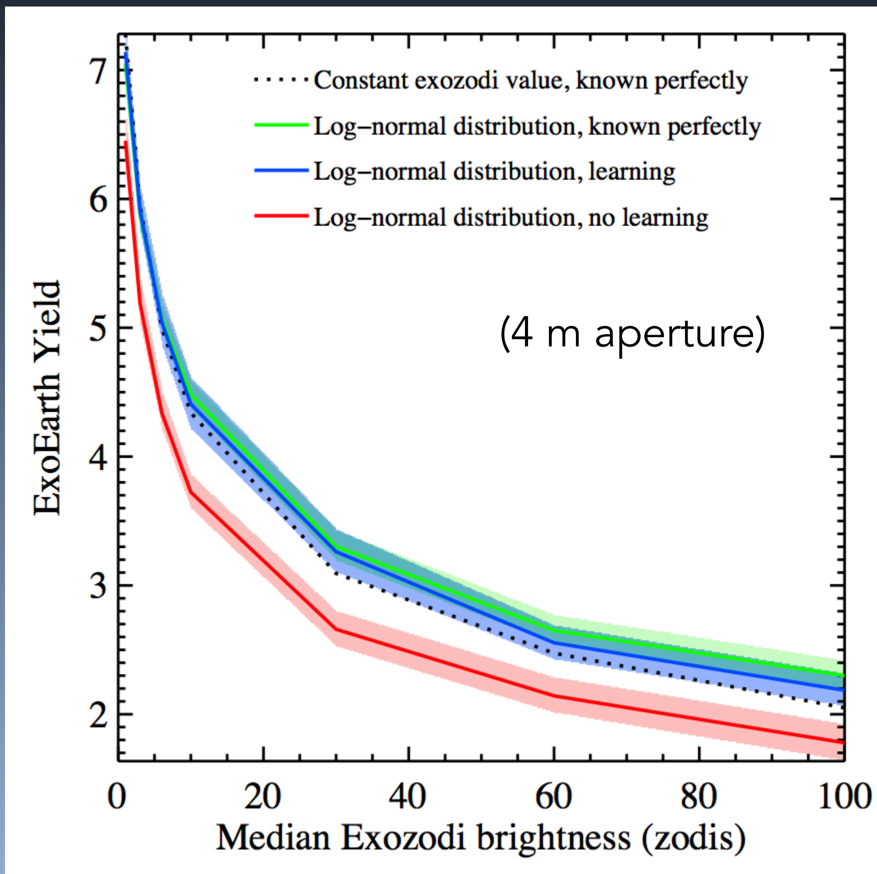


Suggests baseline threshold SNR = 10 is too conservative.

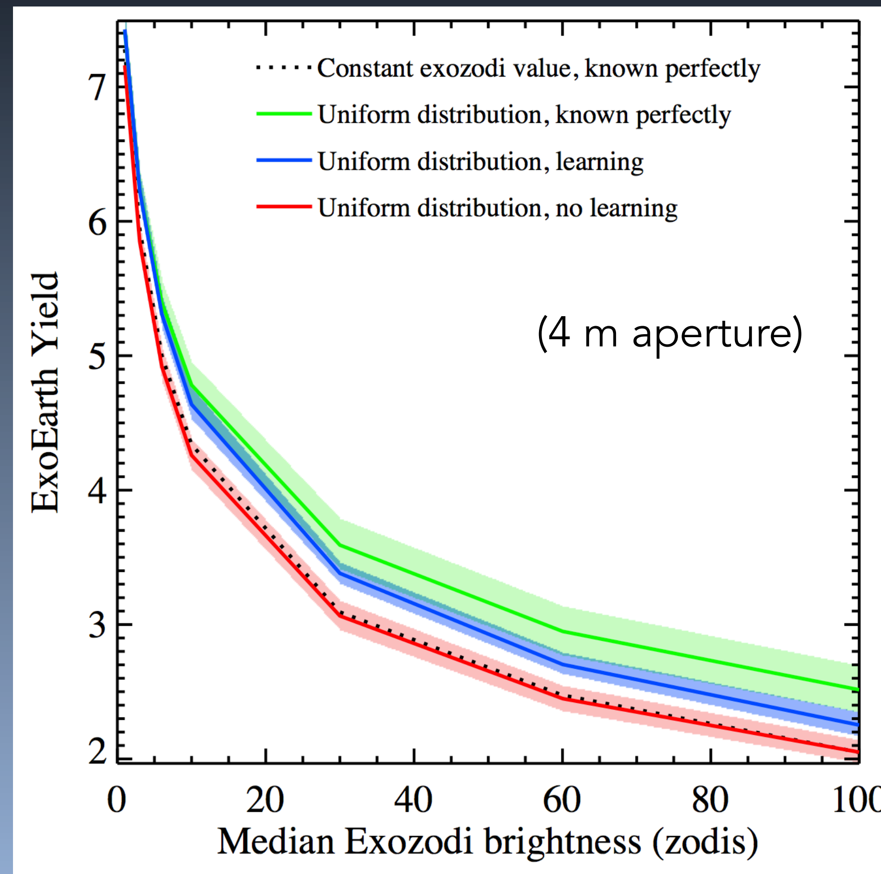
Many exoEarth candidates will be observed at higher SNR by chance. We will get ~50% of water detections for *free* if detected with IFU.

Does a Distribution of Exozodi Affect the Results?

Log-normal Distribution



Uniform Distribution



Distribution does not greatly impact yield. We can adapt observations to avoid the negative impacts of the distribution.

Baseline Mission Parameters

Detections @ 0.55 μm

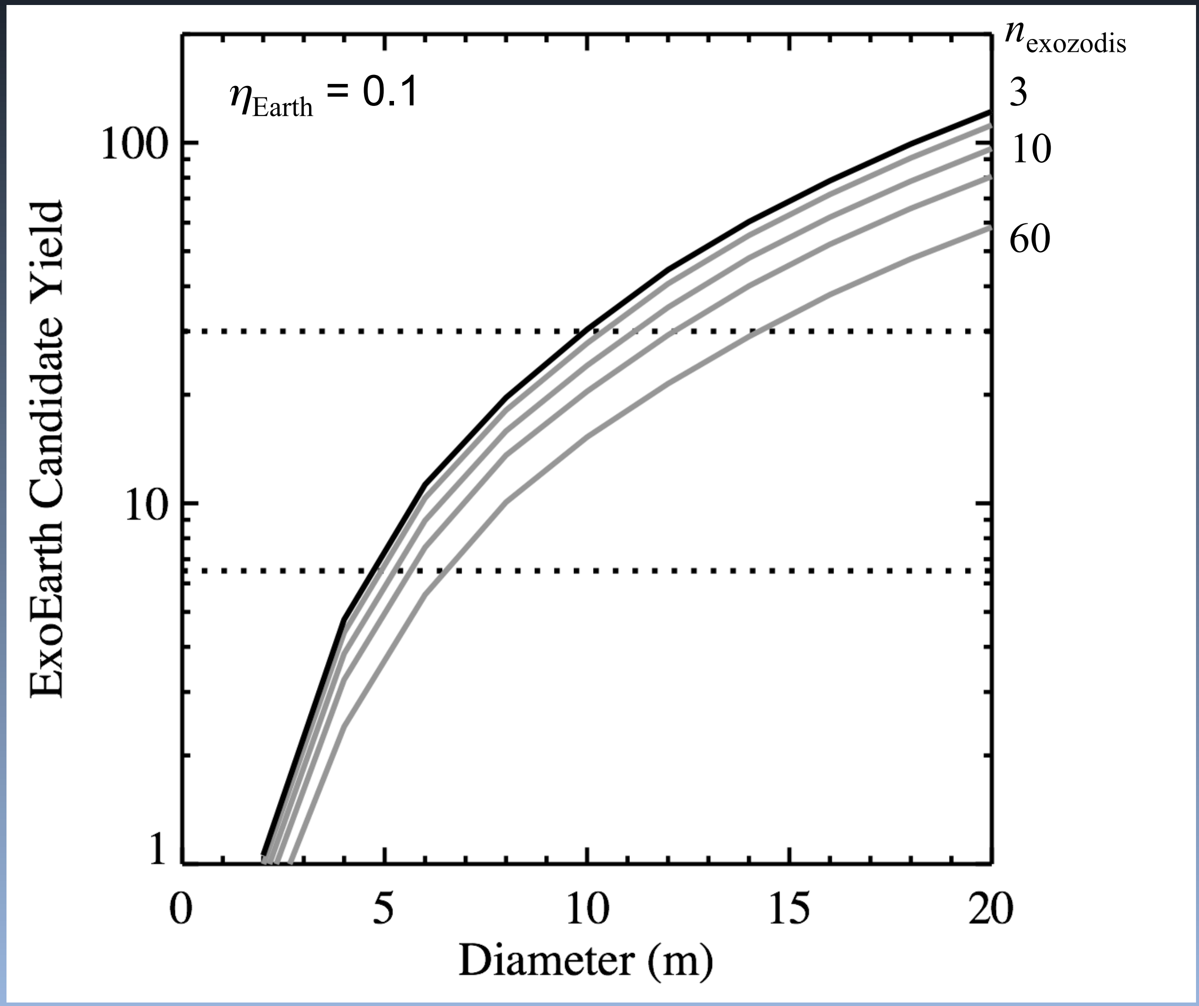
- $\Delta\lambda$ = 0.11 mm
- SNR = 7
- IWA = 3.6 λ/D
- Contrast, $\zeta = 10^{-10}$

Characterization @ 1 μm

- R = 50
- SNR = 5
- IWA = 2 λ/D
- Contrast, $\zeta = 10^{-9}$

- throughput = 0.2
- Noise floor, $\Delta\text{mag}_{\text{floor}} = 26.5$
- OWA = 128 λ/D
- Diffraction-limited
- No detector noise
- 2 years of observation time
- No overheads
- Up to 10 visits per star
- η_{Earth} = 0.1
- n_{exozodis} = 3
- Habitable Zone def: OKHZ
- A_G = 0.2

Yield vs. Aperture for a Coronagraph



To detect & characterize 6-7 ECs, you need ≥ 5 m.
To detect & characterize 30 ECs, you need ≥ 10 m.

Summary

- Yield goals < 6-7 ExoEarth Candidates are not robust to probabilistic uncertainties.
- ExoEarth Candidate yield most sensitive to aperture size (scales roughly as $\sim D^{1.9}$)
- Systematic noise floors with Δmag_{floor} > 26.5 not required
- Weak dependence on many mission parameters due to selection effect & optimization
- To determine whether a planet is Earth-like, we must observe out to 1 μm
- Designing a mission robust to η_{Earth} = 0.1 and $f_{Earth\text{-}like}$ = 0.1 requires 30 exoEarth candidates to ensure a 95% chance of detecting & characterizing ≥1 Earth-like planet. This requires segmented apertures ≥10 m.