Lower Limits on Aperture Size for ExoEarth-Detecting Missions

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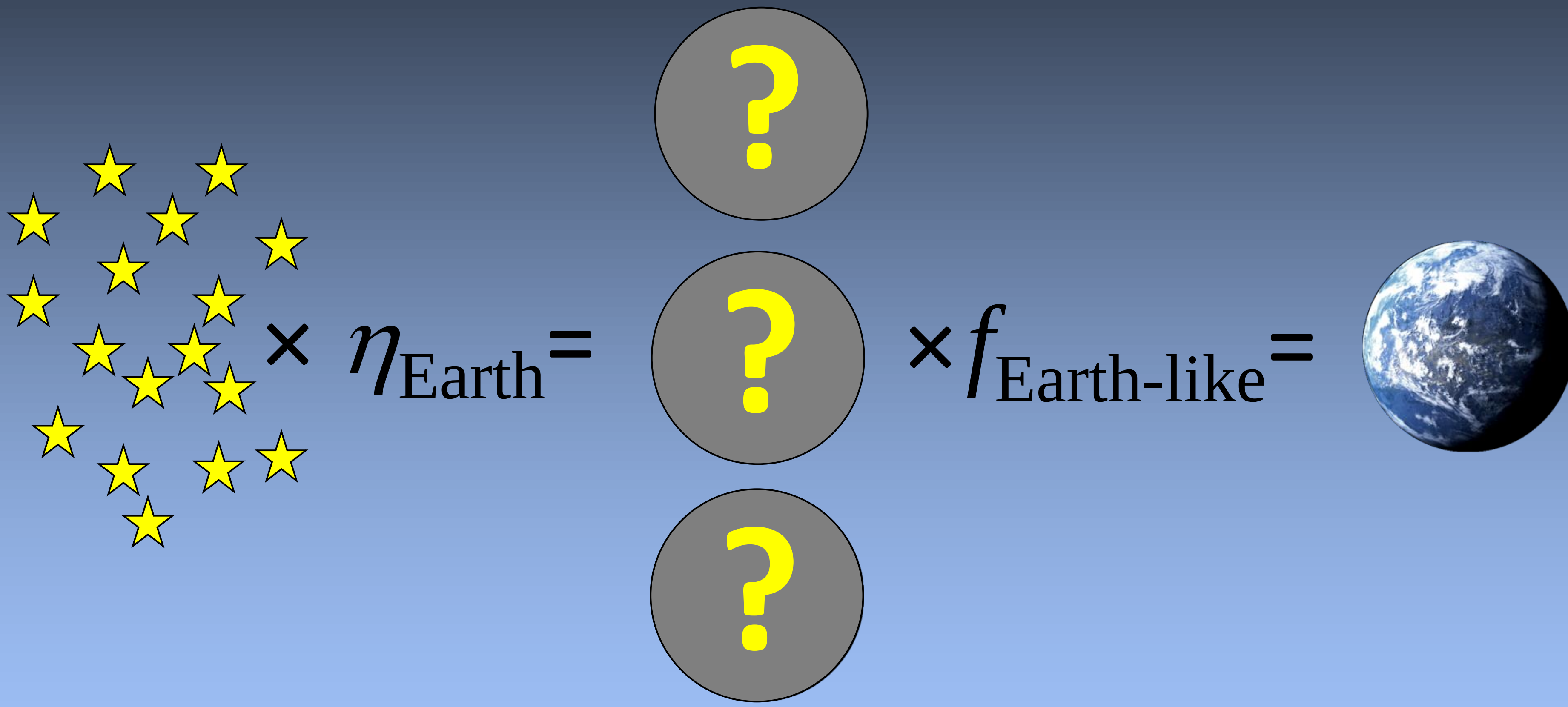
How Does One Choose a Yield Goal?



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

How Does One Choose a Yield Goal?

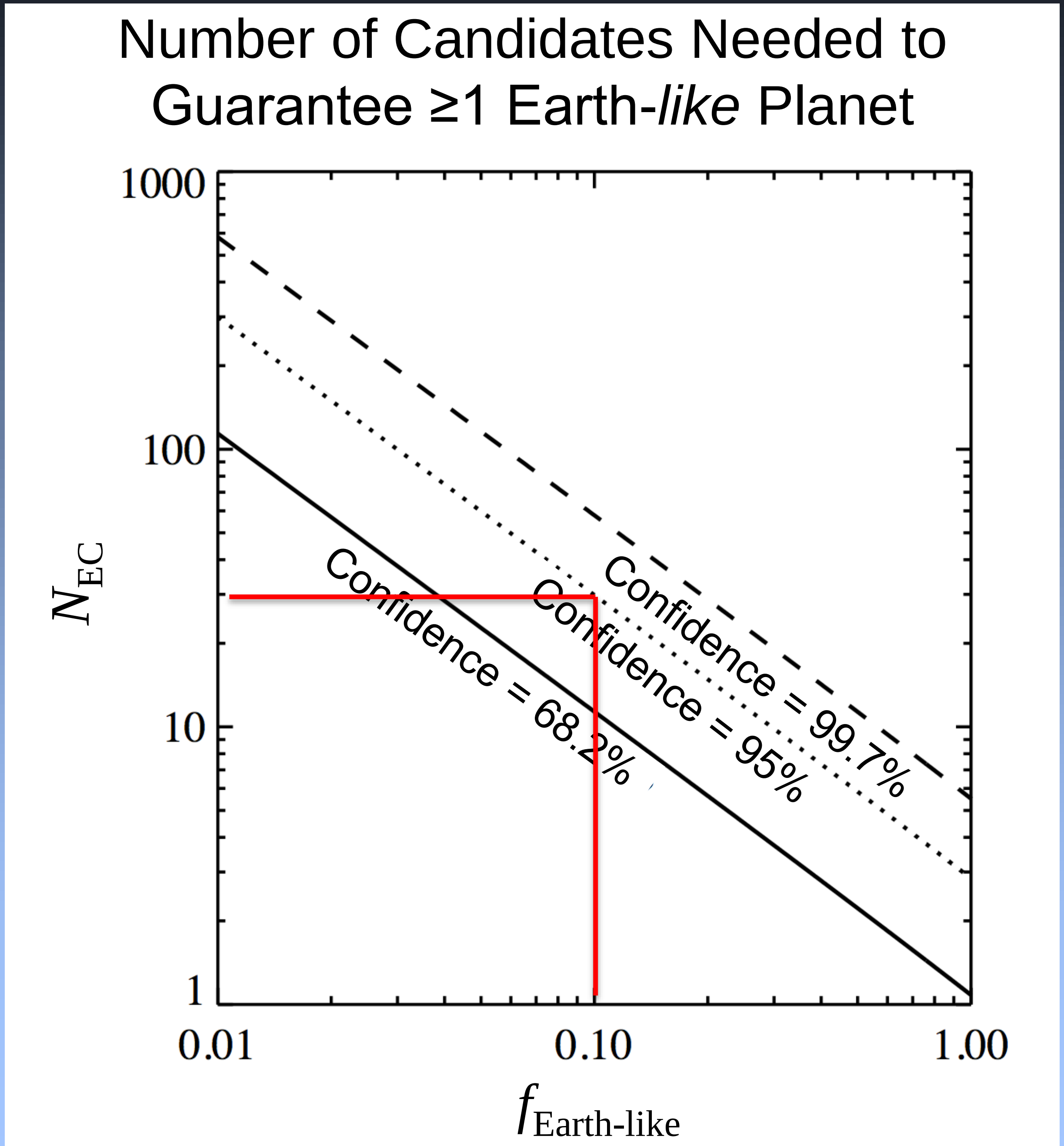
Must rely on blind selection counting. The probability P of x successes out of n tries, each with probability p of success, is given by the binomial distribution function…

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

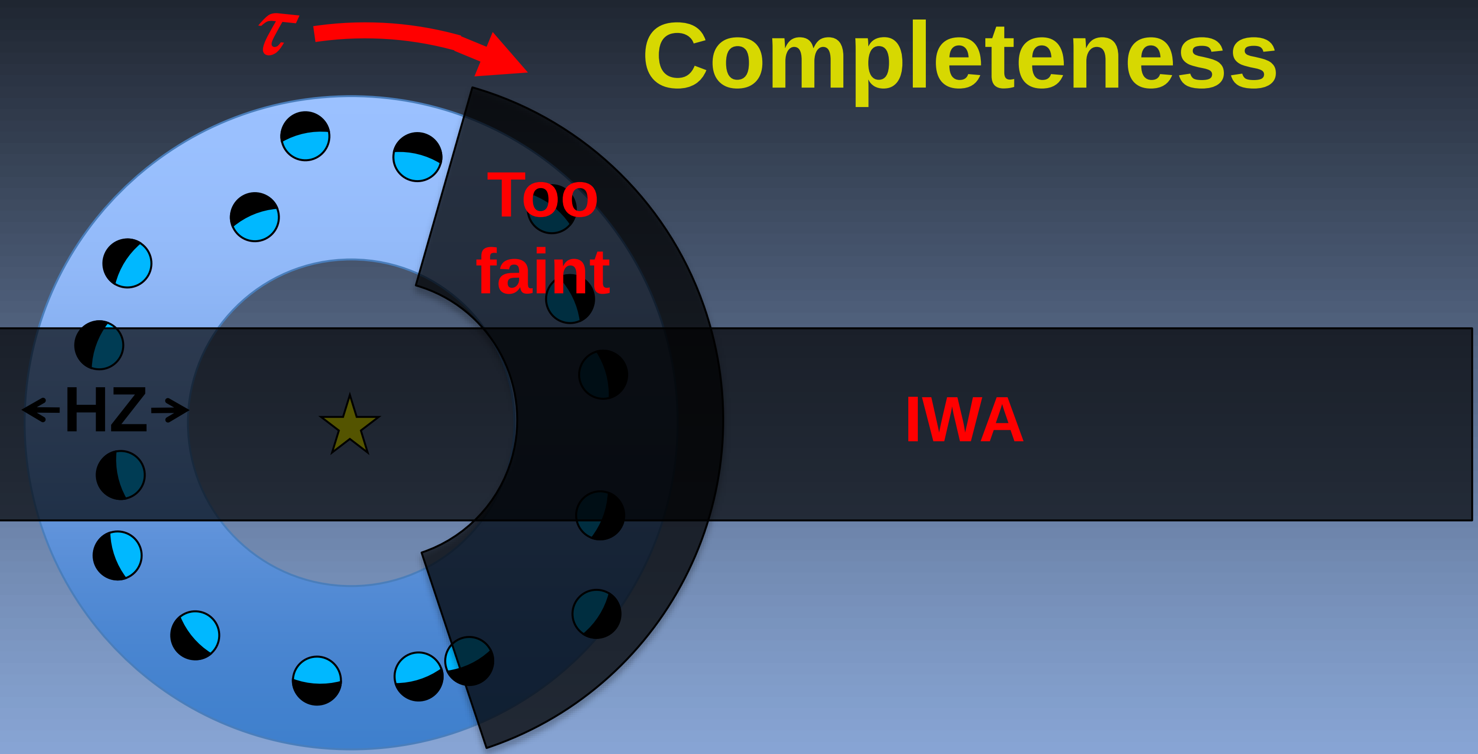
To guarantee at least 1 Earth-*like* planet at confidence level *C*

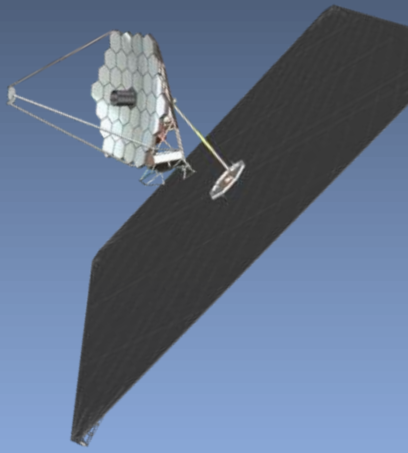
$$N_{\mathrm{EC}} = \eta_{\oplus} \frac{\log(1-C)}{\log(1-\eta_{\oplus} f_{\text{Earth-like}})}$$

How Does One Choose a Yield Goal?



ExoEarth Yield Estimated via Completeness

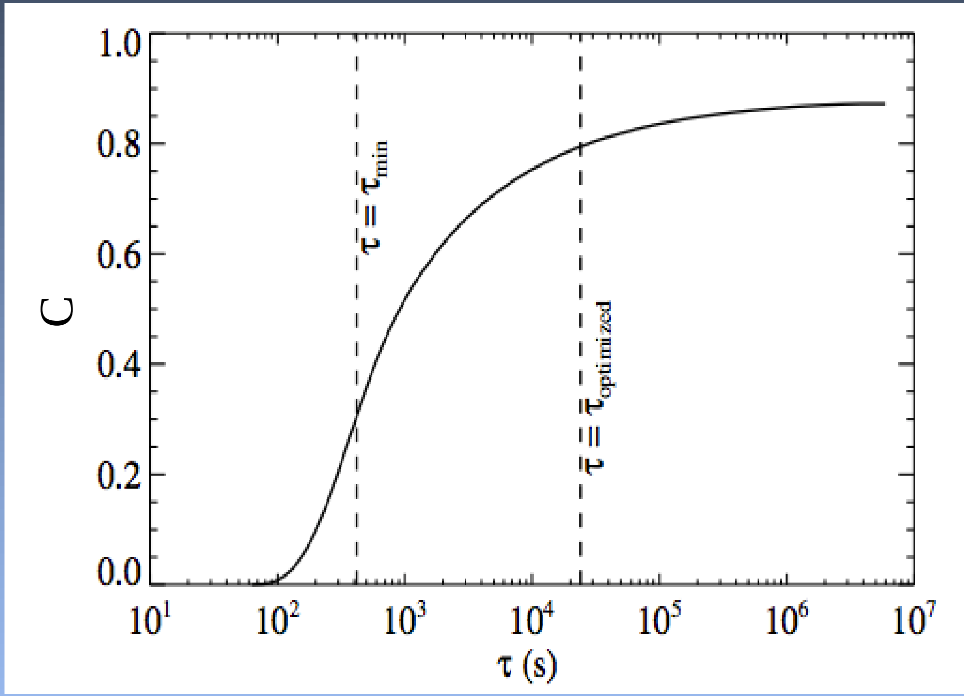




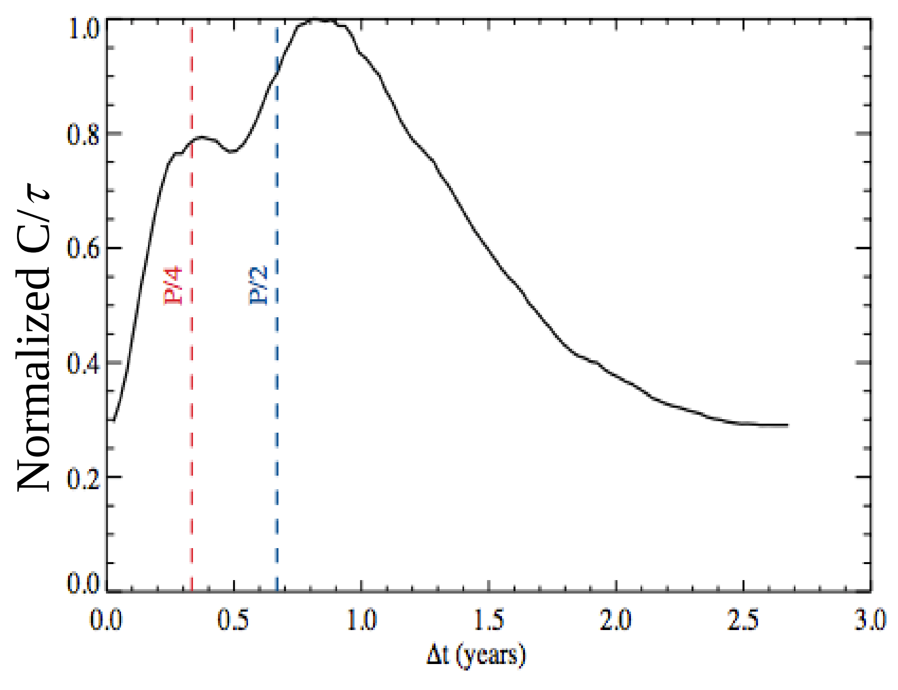
- Completeness, C = the chance of observing a given planet around a given star if that planet exists (Brown 2004)
- Yield = $\eta_{\mathrm{Earth}} \Sigma$ C
- Calculated via a Monte Carlo simulation with synthetic planets
- Can revisit same star multiple times to increase total completeness

Maximizing Yield by Optimizing Observations

Optimize Exposure Time



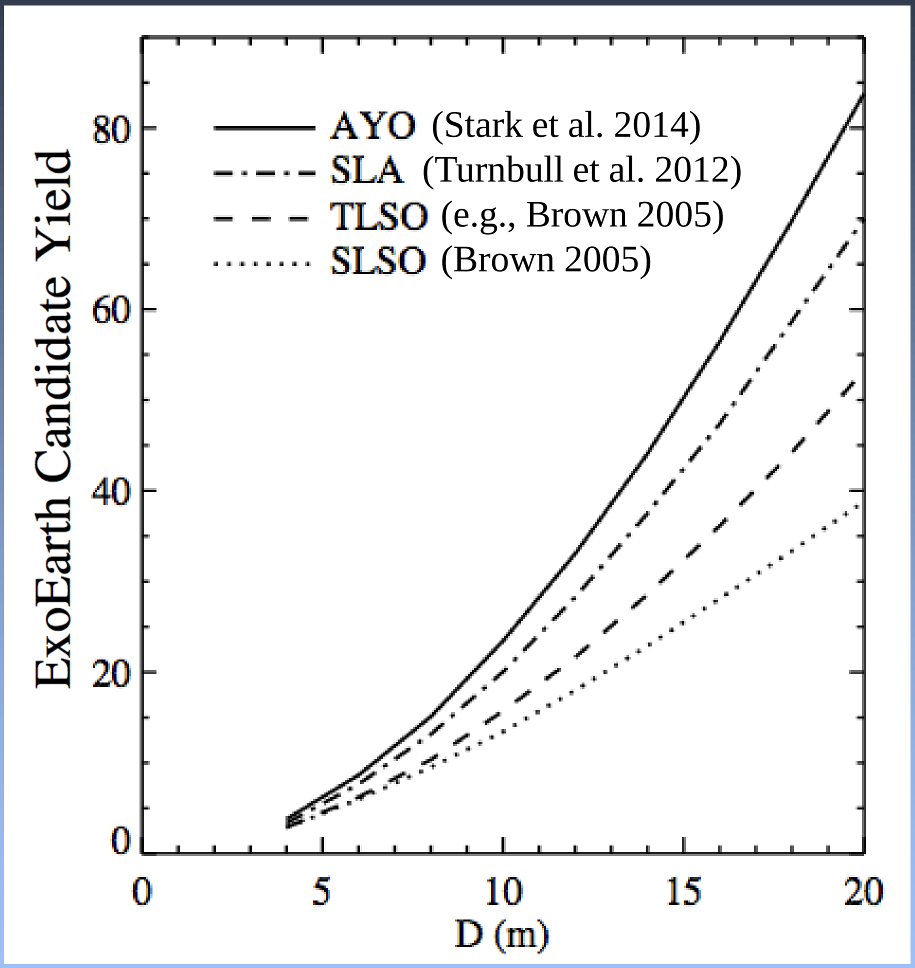
Optimize Revisit Delay Time



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.

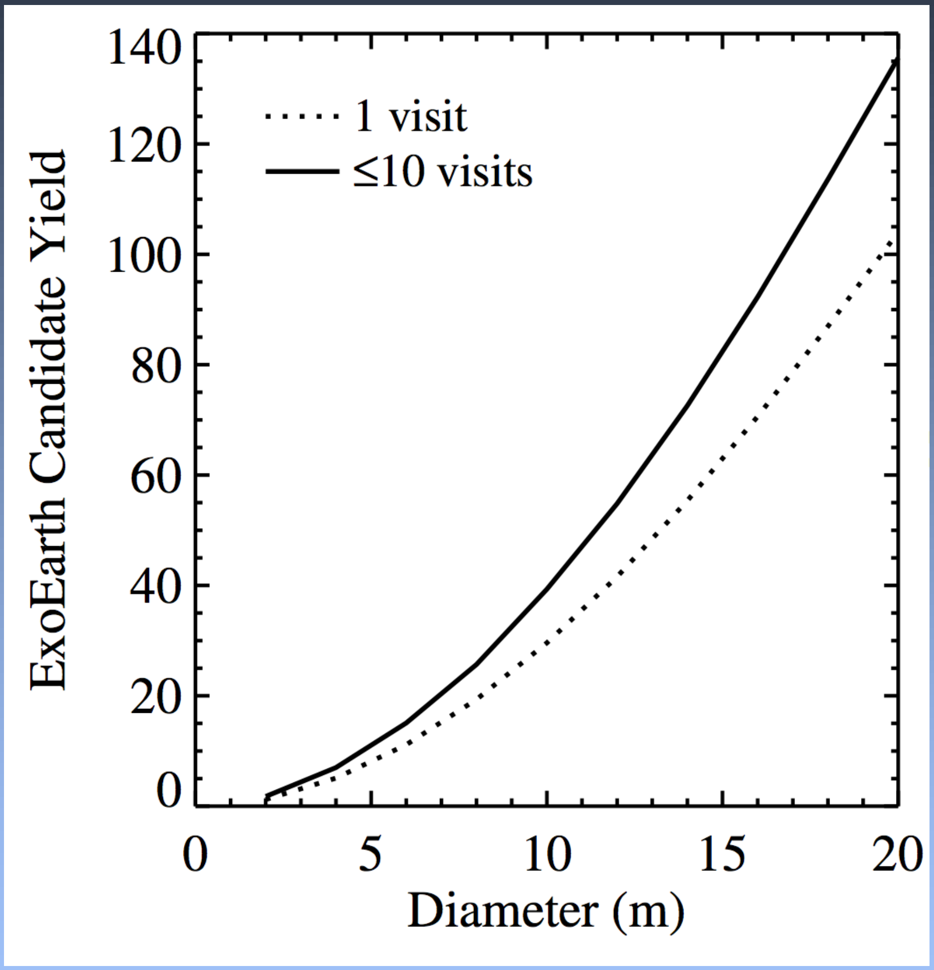
The Impact of Optimization on Yield

Single Visit Optimization vs.
Previous Methods



Optimizing exposure times can potentially double yield

Single Visit Optimization vs.
Multi-visit Optimization



Optimized revisits increase yield by additional ~40%

Current Astrophysical Assumptions

- Earth twin: R_p = 1 R_{Earth}, A_G = 0.2
  - *Robinson et al. (2010)*
- Optimistic Habitable Zone definition
  - *Kopparapu et al. (2013)*
  - 0.75 – 1.77 AU for Sun-like star
- Circular orbits
  - *Kane et al. (2012)*
- $n_{exozodis}$ = 3 zodis for all stars
  - 1 zodi = 22 mag arcsec^{-2}
  - Guess at best-case future performance of LBTI
- η_{Earth} = 0.1
  - *Petigura et al. (2013); Silburt et al. (2014)*
  - For 0.66 < R_p < 1.5 R_{Earth} & the OKHZ, $\eta_{Earth} = 0.16 \pm 0.06$

What Value of η_{Earth} Should We Use?

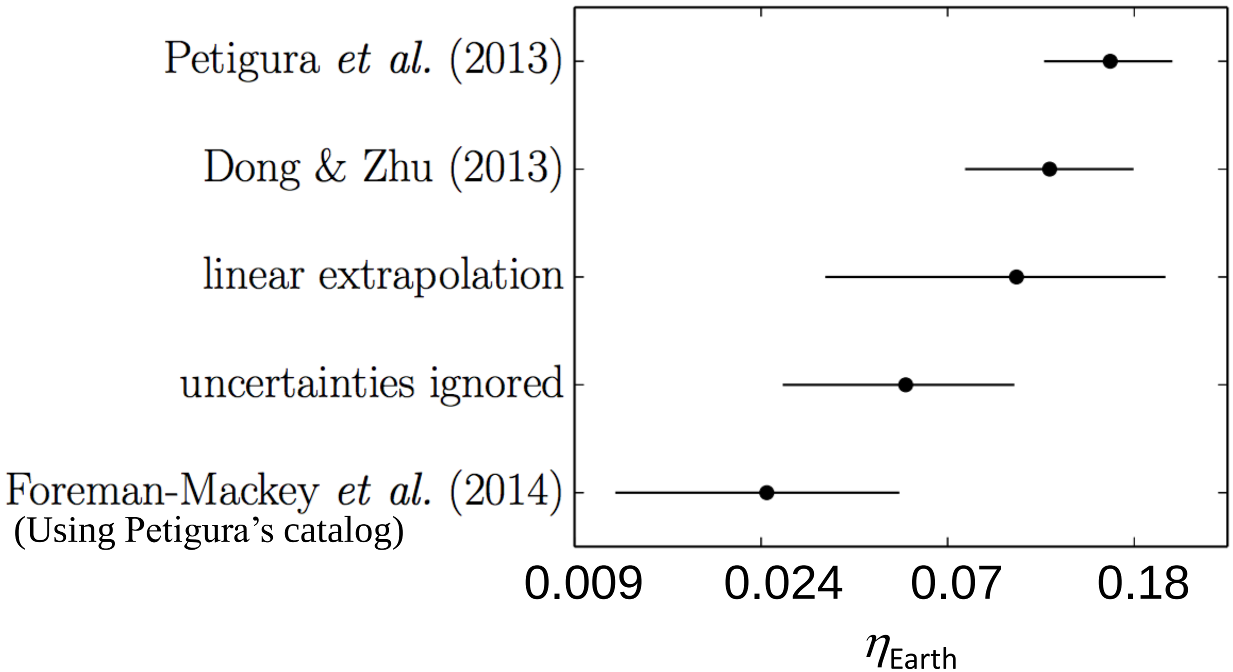


Fig 10 from Foreman-Mackey et al. (2014)

From the 3 most recent published estimates of η_{Earth}, I am choosing the most optimistic estimate.

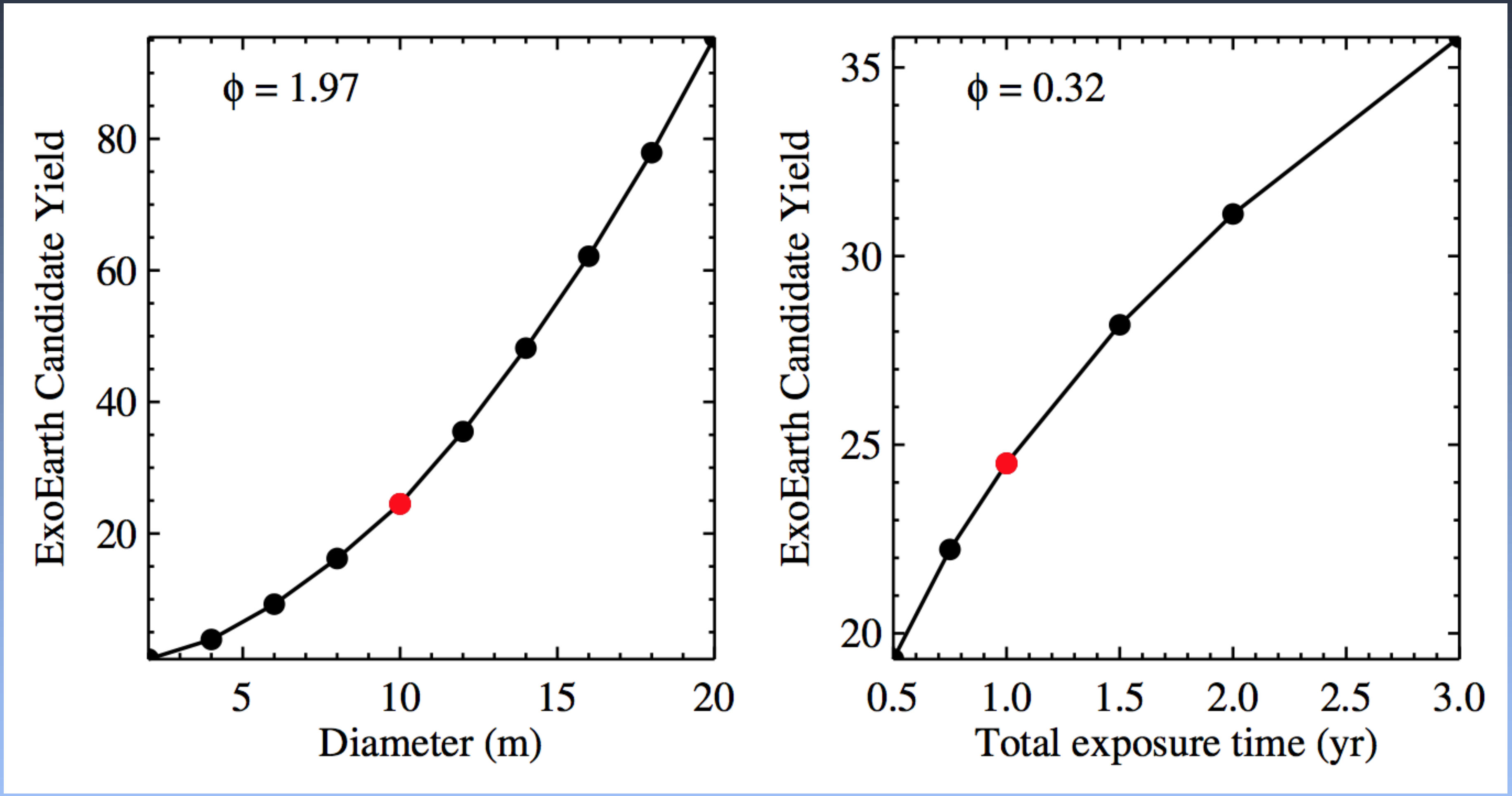
Baseline *Coronagraph* Mission Parameters

Detections @ 0.55 μm
- $\Delta\lambda$ = 20%
- SNR = 7
- IWA = 3.6 λ/D
- Contrast, $\zeta = 10^{-10}$

Characterization @ 1 μm
- R = 50
- SNR = 5
- IWA = 2 λ/D
- Contrast, $\zeta = 5\times10^{-10}$

- throughput = 0.2
- Noise floor, $\Delta\mathrm{mag}_{\mathrm{floor}} = 27.5$
- OWA = 15 λ/D
- Diffraction-limited Airy pattern PSF
- No detector noise
- 1 year of observation time
- 1 year of overheads
- Up to 10 visits per star
- η_{Earth} = 0.1
- Habitable Zone def: OKHZ
- Earth-twins with A_G = 0.2 (Earth's albedo)

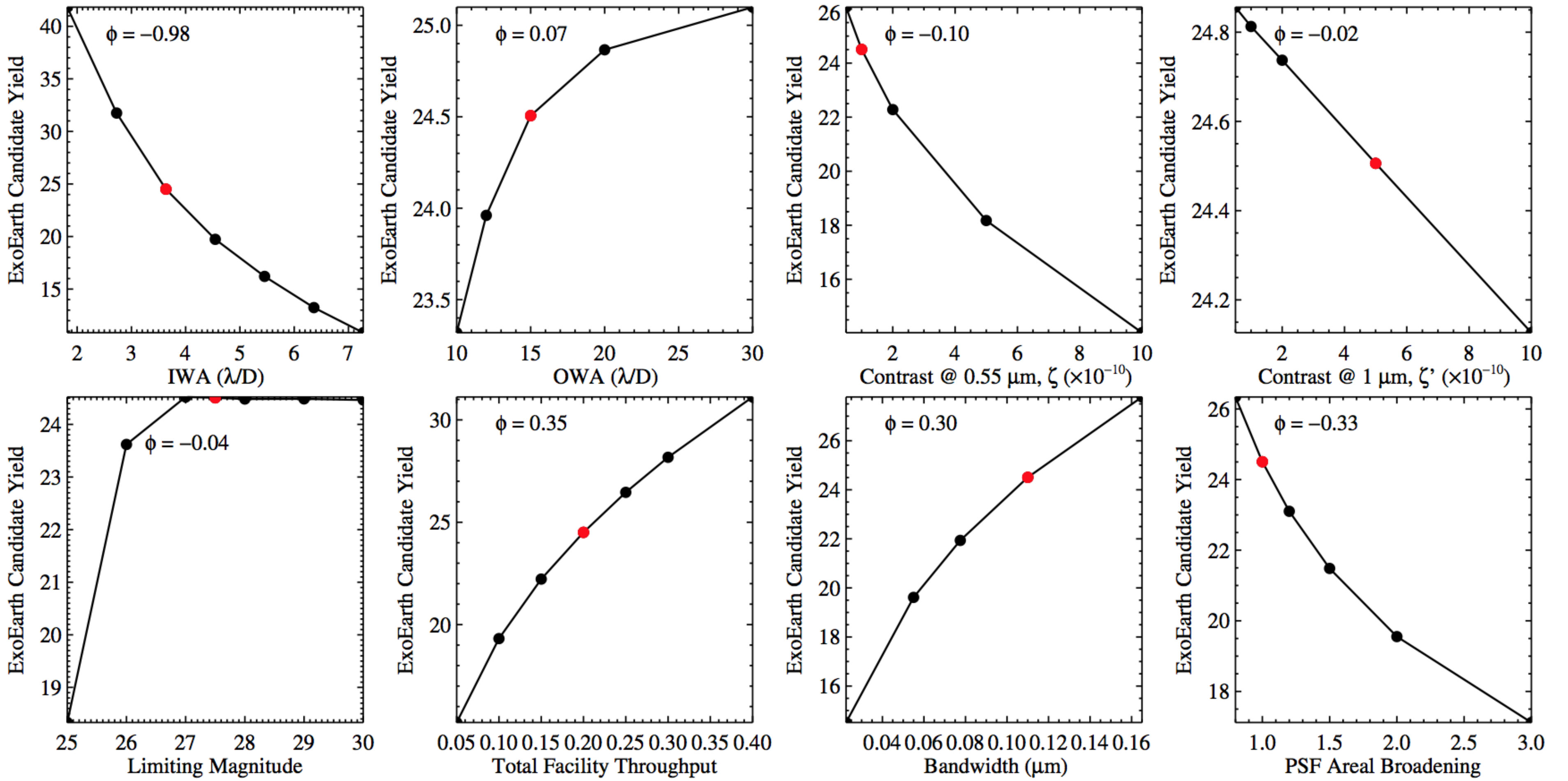
What Telescope/Instrument Parameters Matter?



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

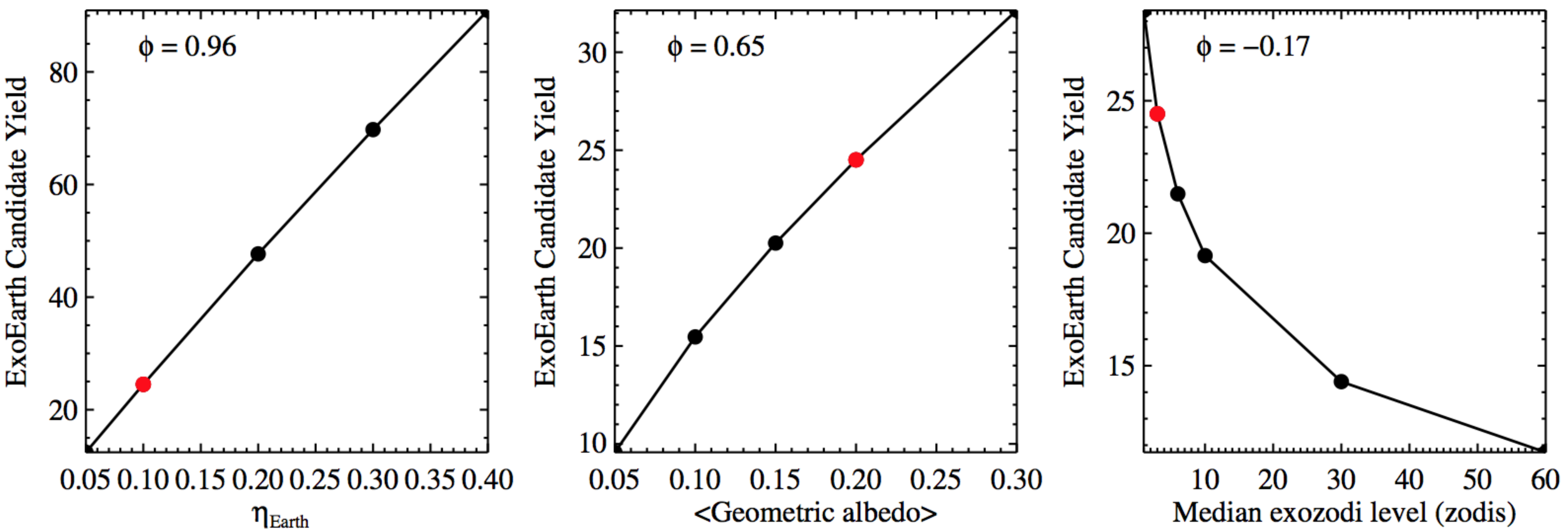
What Telescope/Instrument Parameters Matter?

Coronagraph Scaling Laws



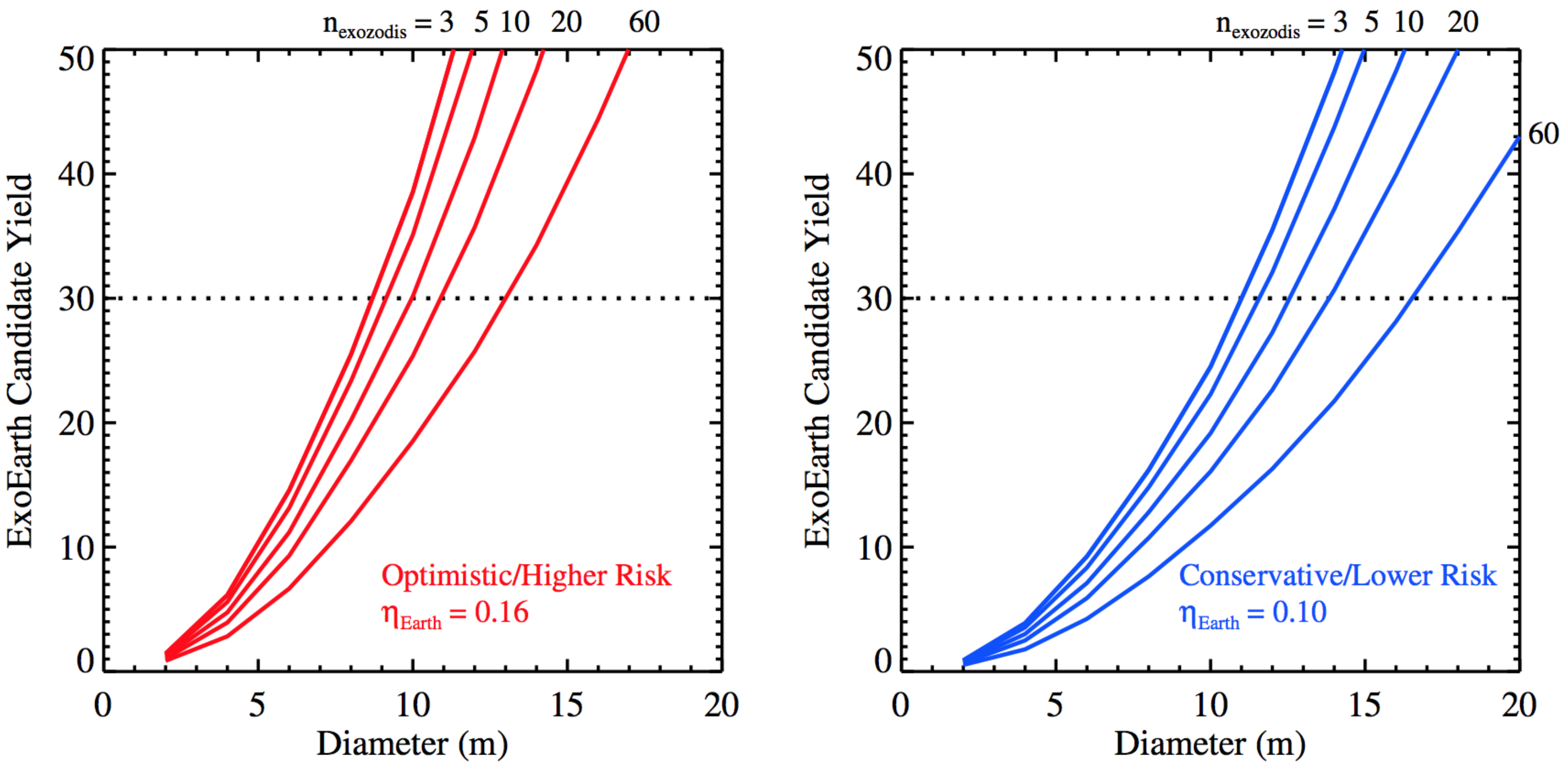
IWA matters more than contrast when treating both linearly. OWA doesn't matter much. Noise floors with Δmag > 26.5 are unnecessary.

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.

Lower Limits on Aperture Size



In a very optimistic scenario, detecting >30 exoEarth candidates requires D > 8.5 m.

"Starshade Mode"

- Existing code valid in the time-limited regime, where observations are limited by a total allowable exposure time
    - Targets are prioritized & selected based on C/τ, the "benefit-to-cost" ratio (C/τ^1)

- Starshades are also limited by fuel, i.e. a given # of slews
    - In the slew-limited regime, we don't care about a target's τ. We should prioritize by C only (C/τ^0).

- Starshade yield is maximized at the *transition* from time-limited to slew-limited regimes, i.e. when all slews and exposure time is used.
    - How to find this solution? Prioritize by C/τ^α, where $0<\alpha<1$

Comparison to Previous Work

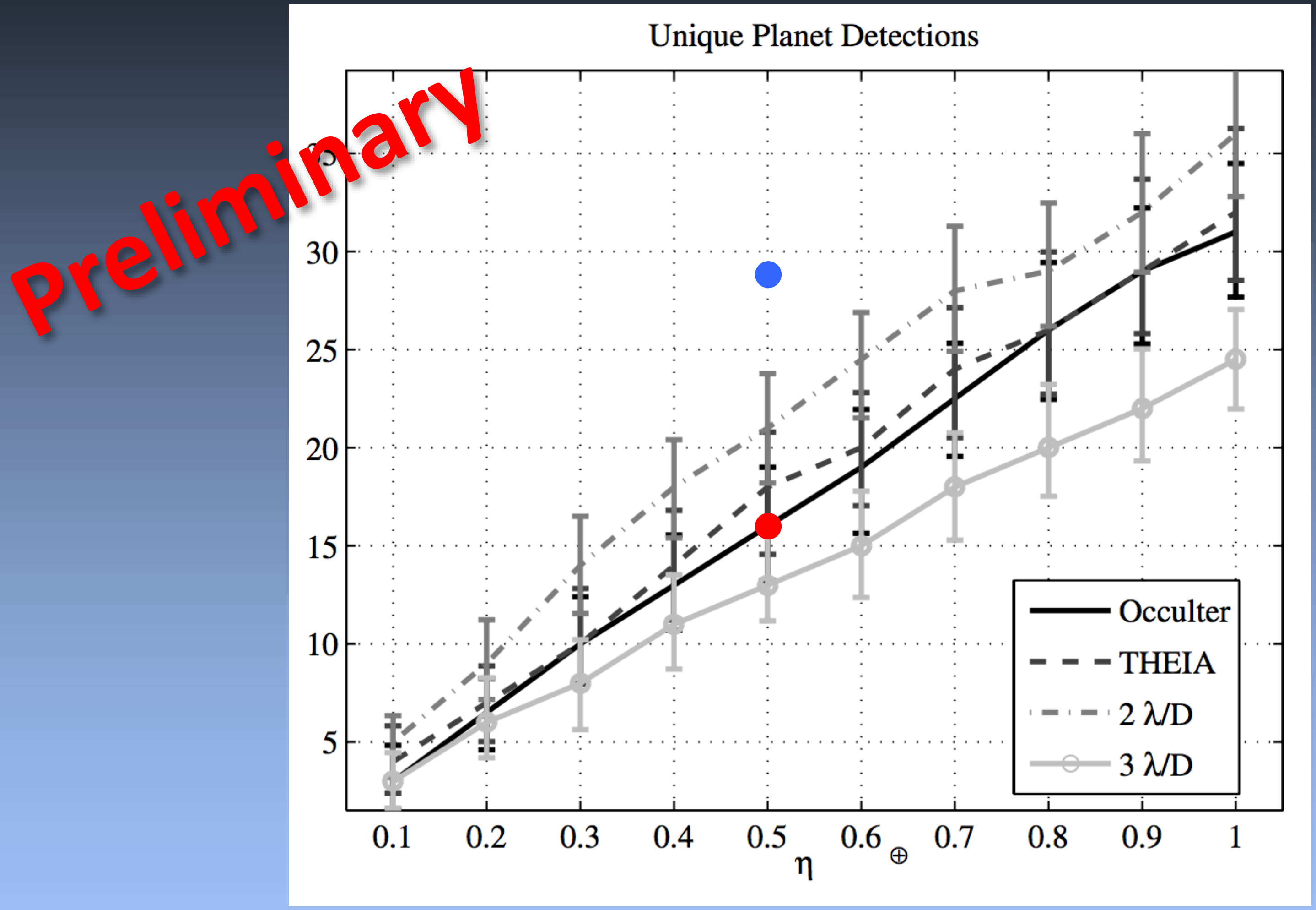


Fig 9 from Savransky et al. (2010)

Roughly double the yield from Savransky et al. (2010), but this needs to be revisited

Baseline *Starshade* Mission Parameters

Detections @ 0.55 μm

- **Δλ = 40%**
- SNR = 7
- **IWA = 40 mas**
- Contrast, $\zeta = 10^{-10}$

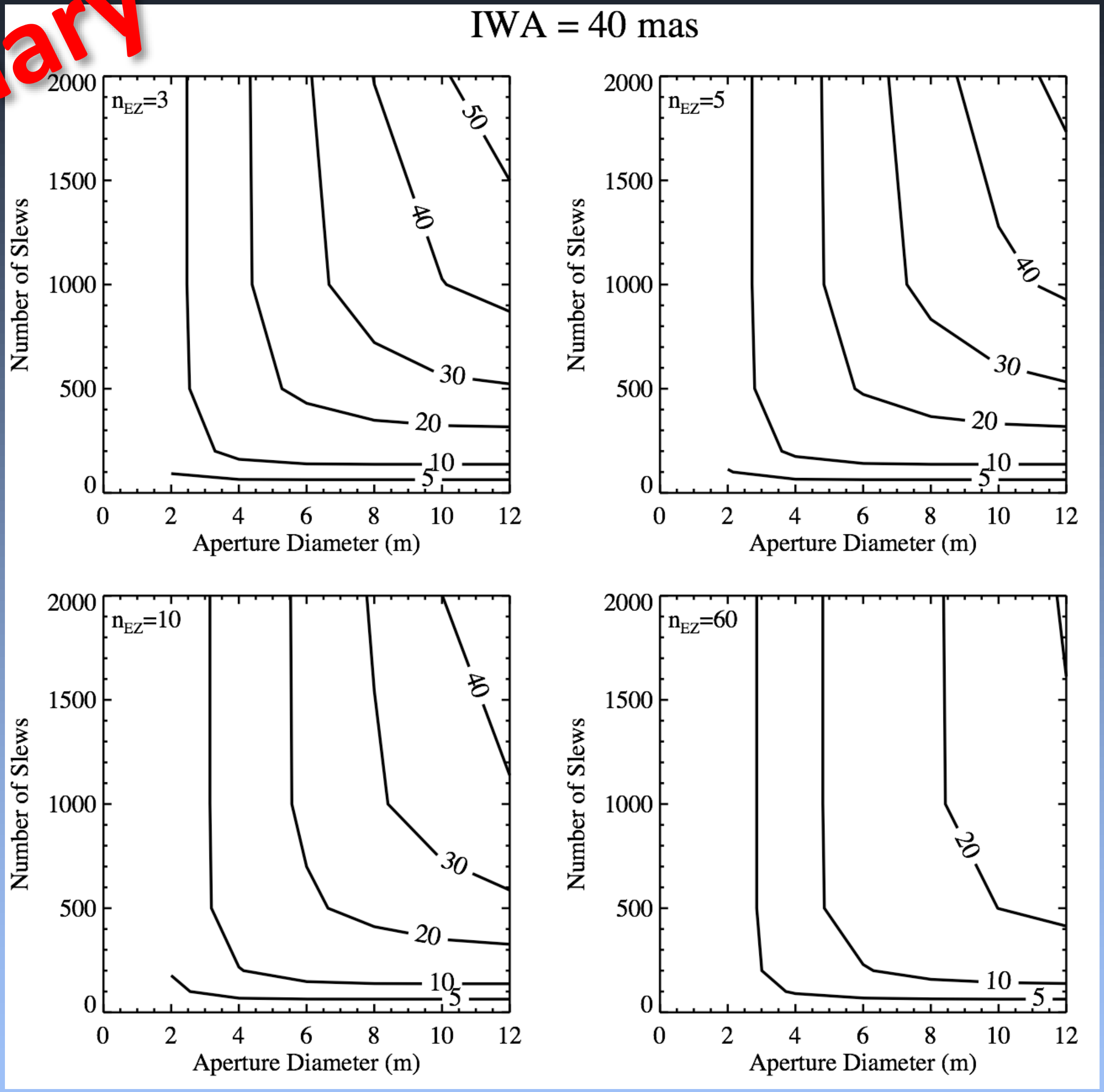
Characterization @ 1 μm

- R = 50
- SNR = 5
- **IWA = 40 mas**
- **Contrast, $\zeta = 10^{-10}$**

- **throughput = 0.5**
- Noise floor, $\Delta mag_{floor} = 27.5$
- **OWA = infinite**
- Diffraction-limited
- No detector noise
- **2 years of exposure time**
- **0 year of overheads, 3 years of slewing**
- **<5 visits per star, no optimization of revisit time**
- η_{Earth} = 0.1
- Habitable Zone def: OKHZ
- Earth-twins with A_G = 0.2 (Earth's albedo)
- 3 zodis of exozodi

Yield Contour Plots for Starshades

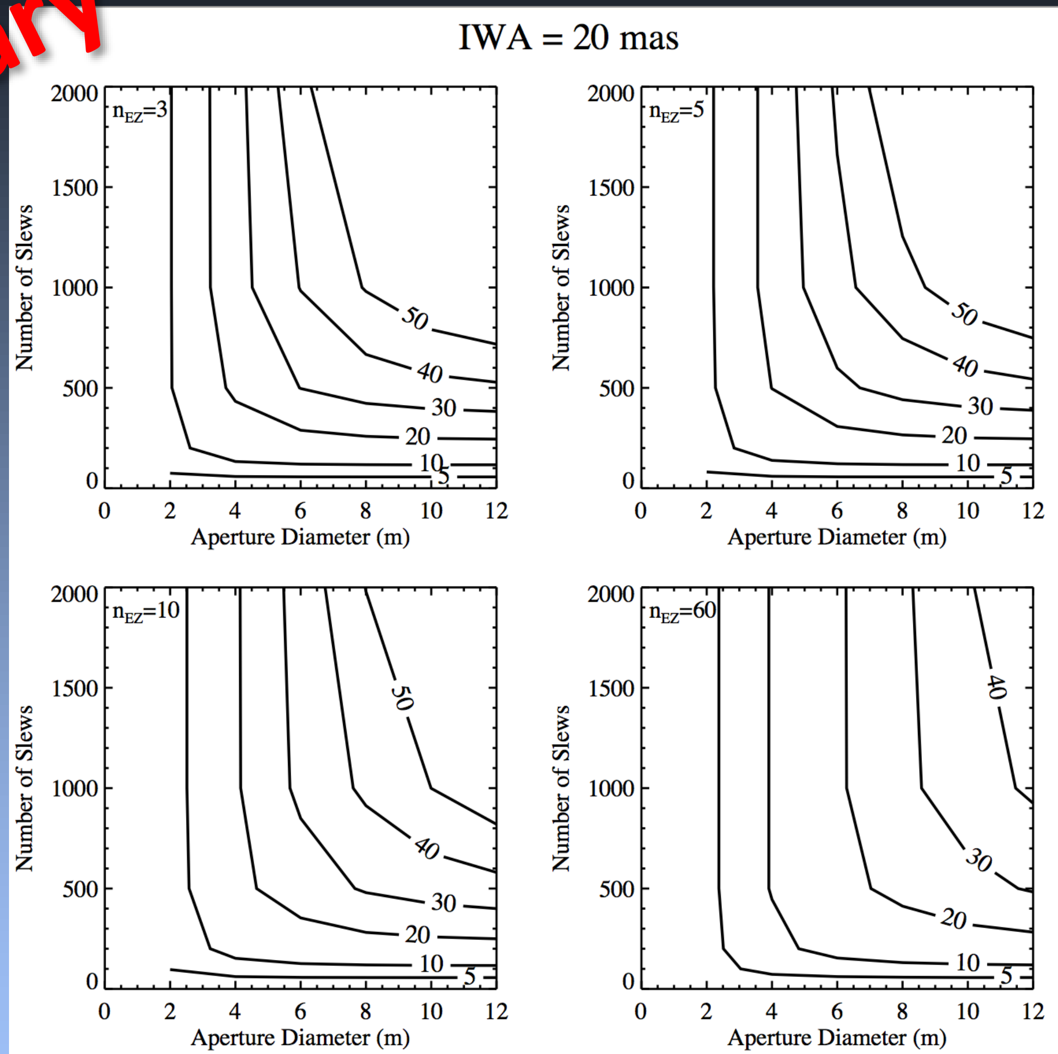
Preliminary



A yield of ~30 exoEarth candidates requires D ~ 7 m + ~900 slews

Yield Contour Plots for Starshades

Preliminary



A smaller IWA ~20 mas can reduce the requirements to ~6 m aperture + ~500 slews

Summary

• DRM includes optimized revisits, spectral characterization time, detector noise, multi-wavelength capability, “starshade mode”; maximizes yield.

• Yield dependencies for coronagraph:
  • Strong: D, η_{Earth}, planet albedo
  • Moderately strong: IWA
  • Moderately weak: mission lifetime, throughput, PSF broadening
  • Weak: bandwidth, median exozodi level, contrast, OWA

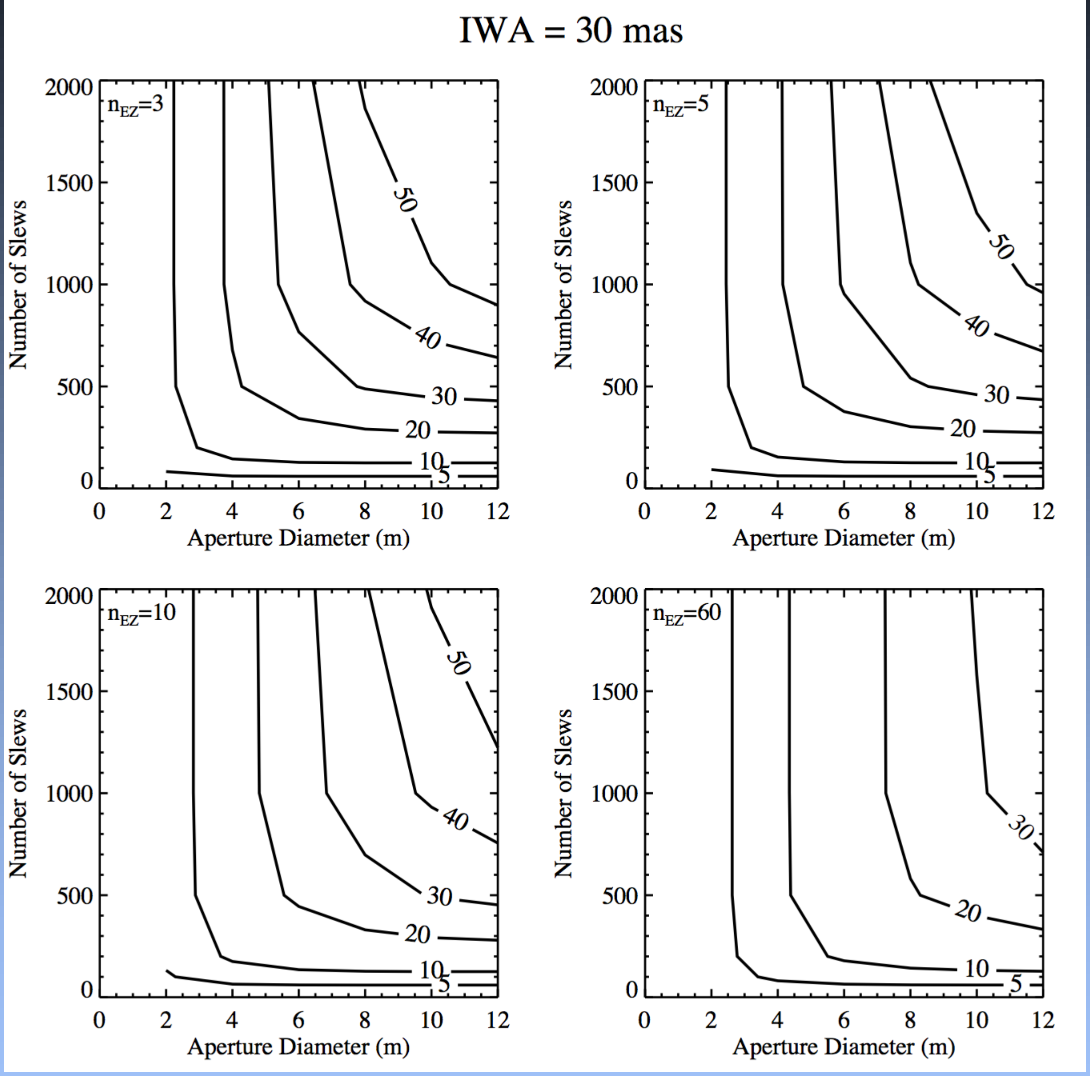
• Starshade yield maximized at the transition from slew- to time-limited regimes

• Designing a mission robust to η_{Earth} = 0.1 and $f_{\mathrm{Earth\text{-}like}}$ = 0.1 requires 30 exoEarth candidates to ensure a 95% chance of detecting ≥1 Earth-like planet.
  • For a coronagraph-based mission, this requires apertures >8.5 m.
    • If LBTI constrains median exozodi level to ≤3 zodis, uncertainty in η_{Earth} could cause required D to span 8 m mark

  • For a starshade-based mission, preliminary results suggest this requires apertures >6 m and >500 observations. Likely requires refueling

Backup Slides

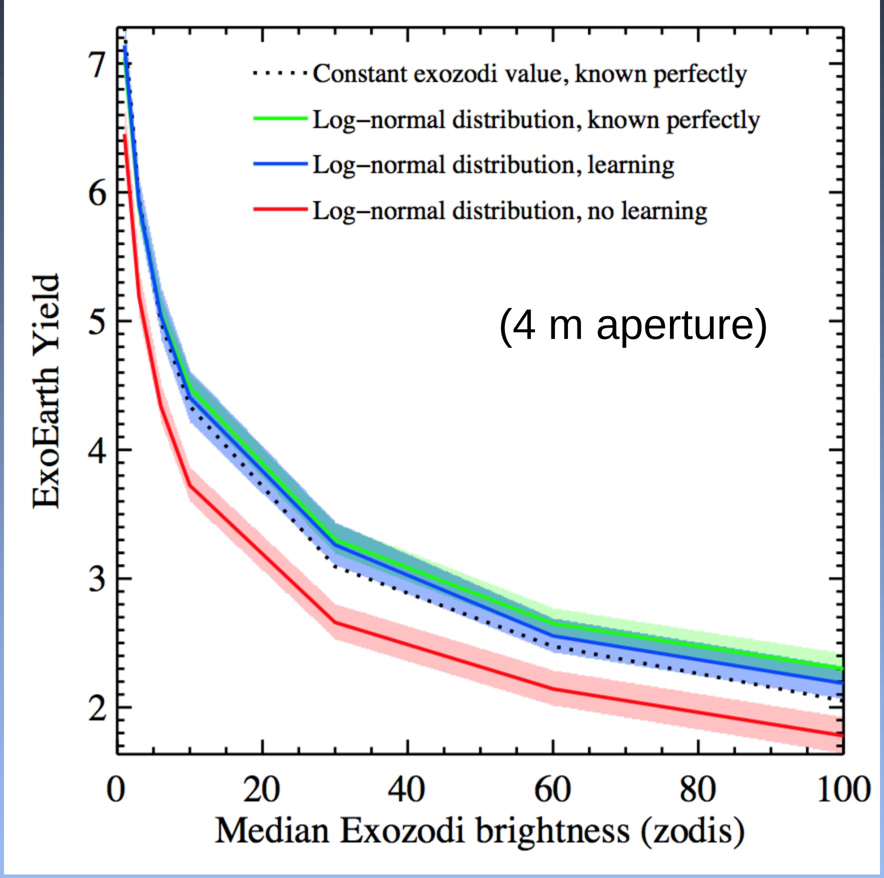
Starshades



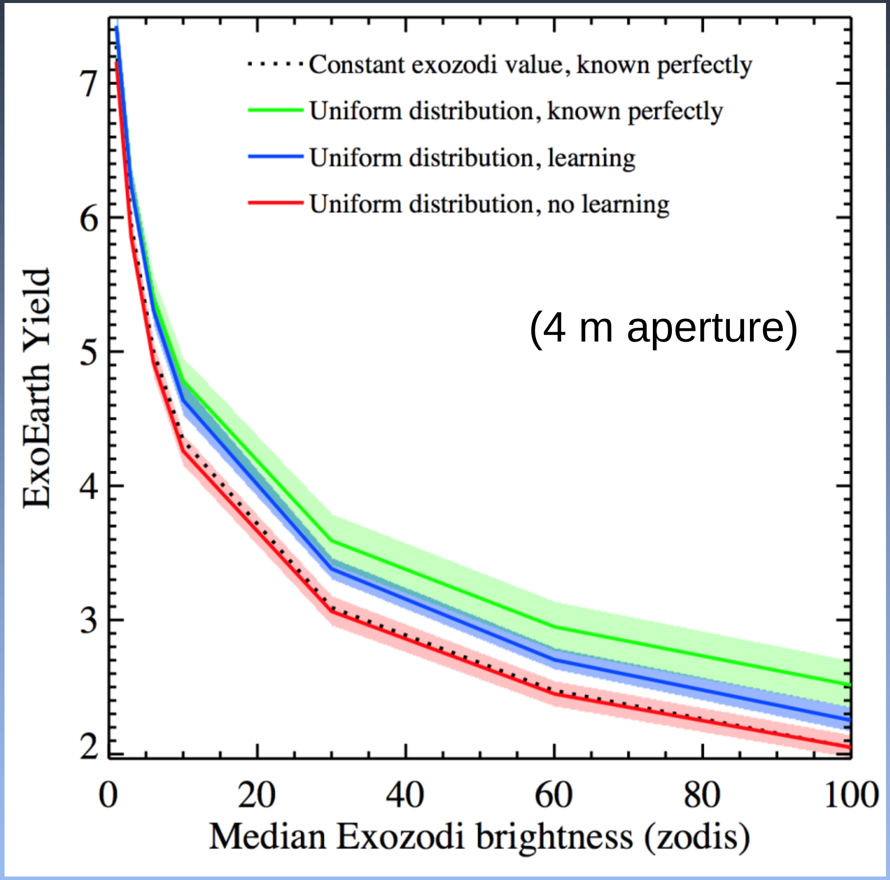
Blah

Does a Distribution of Exozodi Affect the Results?

Log-normal Distribution

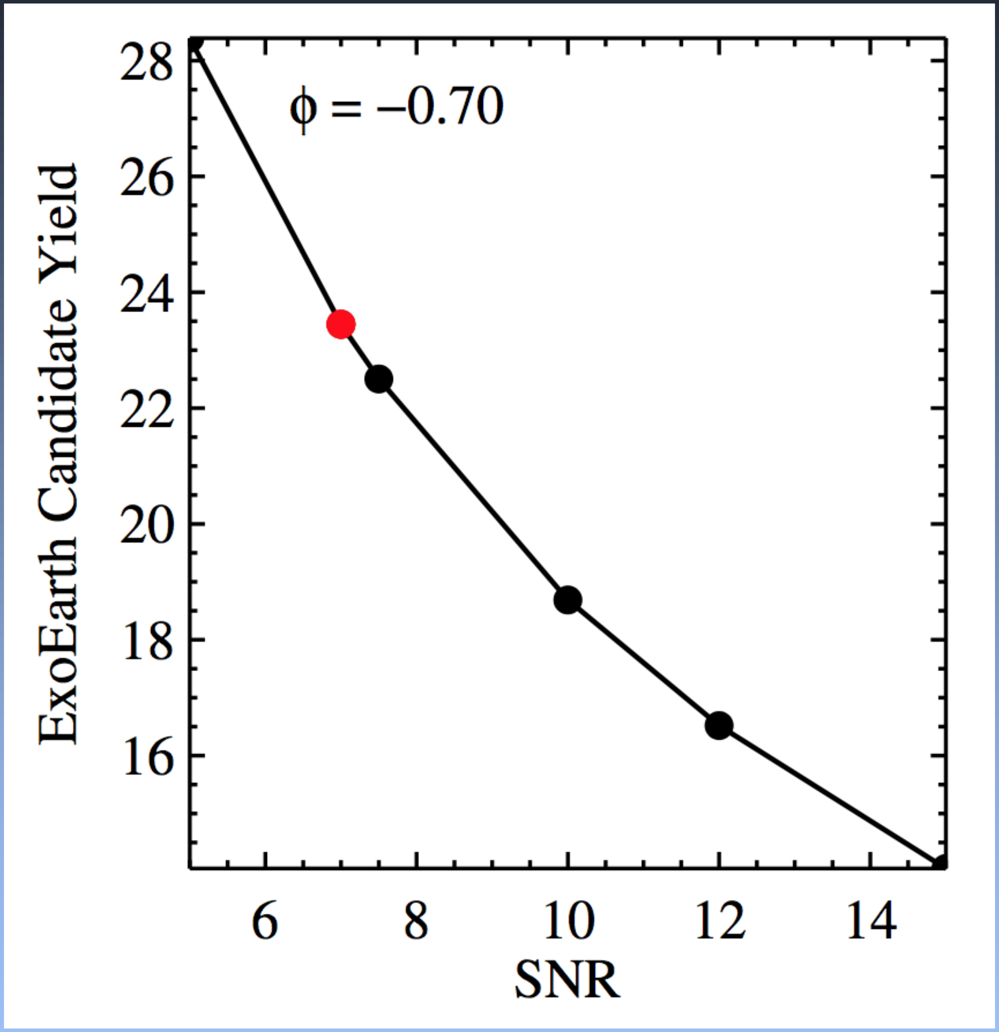


Uniform Distribution



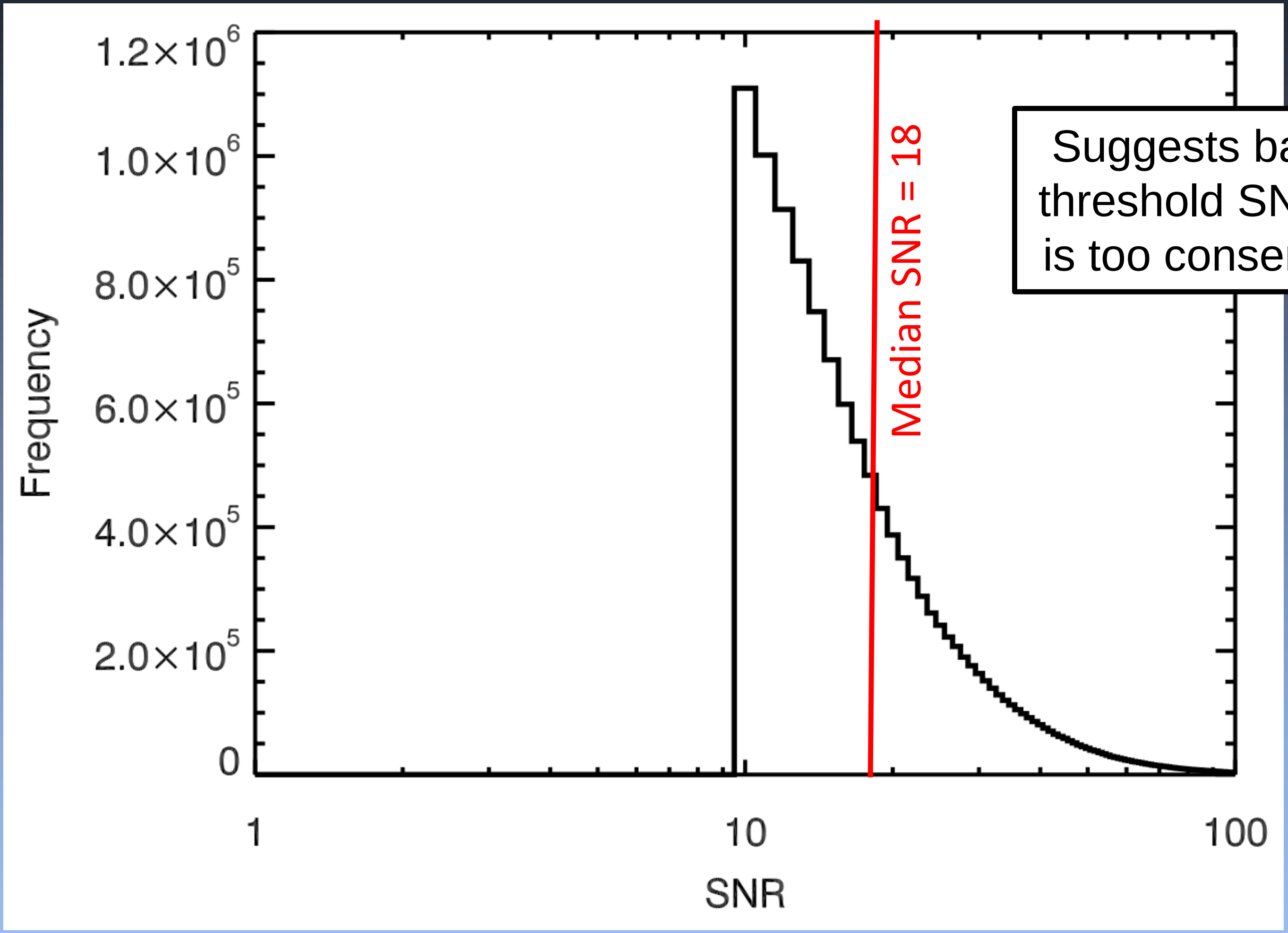
Distribution does not greatly impact yield. We can adapt observations to avoid the negative impacts of the distribution.

What Telescope/Instrument Parameters Matter?



Yield is a strong function of detection threshold SNR.

What Telescope/Instrument Parameters Matter?



Suggests baseline threshold SNR = 10 is too conservative.

Summary

In order of importance: D, SNR, IWA, bandwidth/throughput, contrast