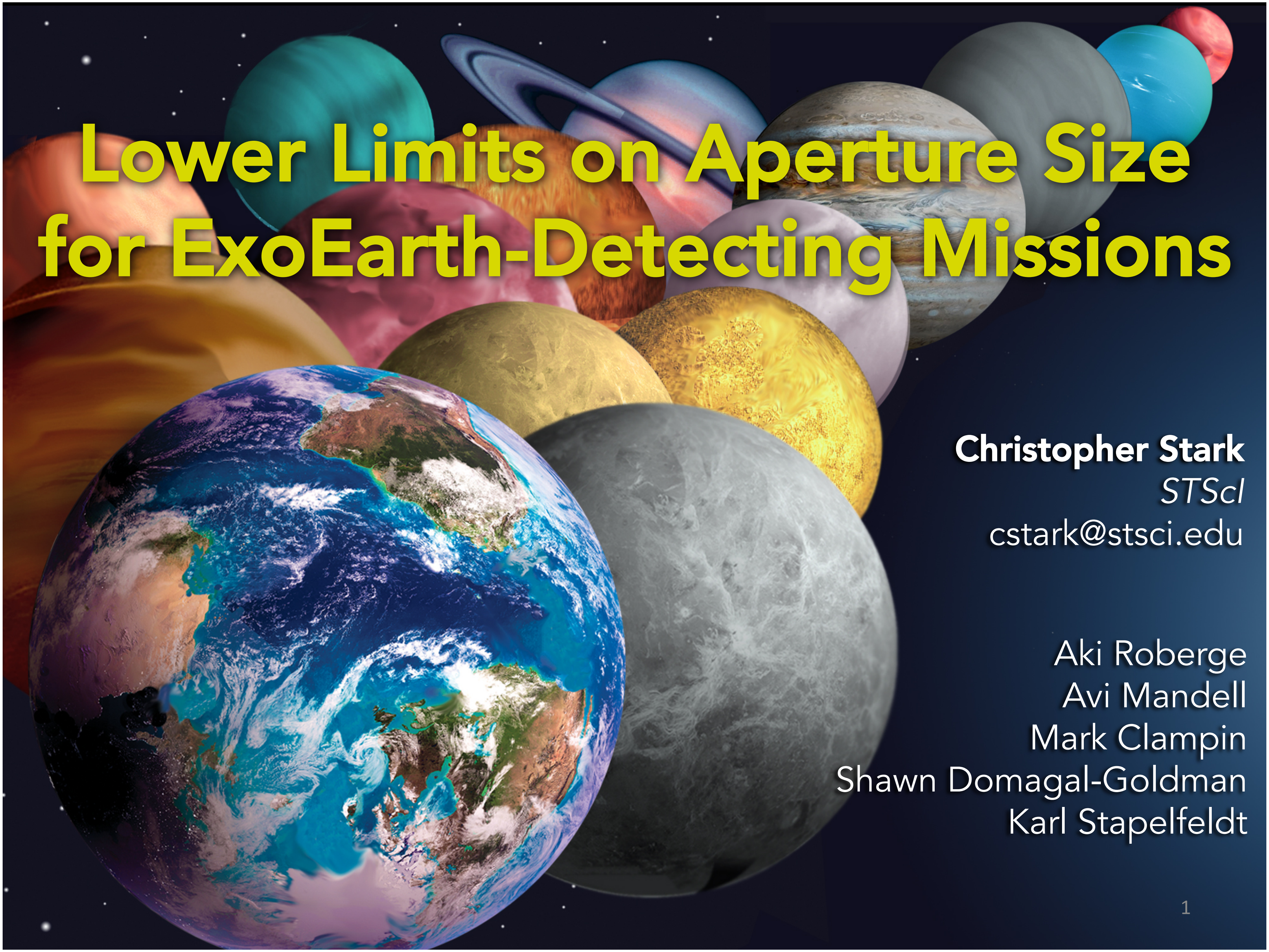

Lower Limits on Aperture Size for ExoEarth-Detecting Missions

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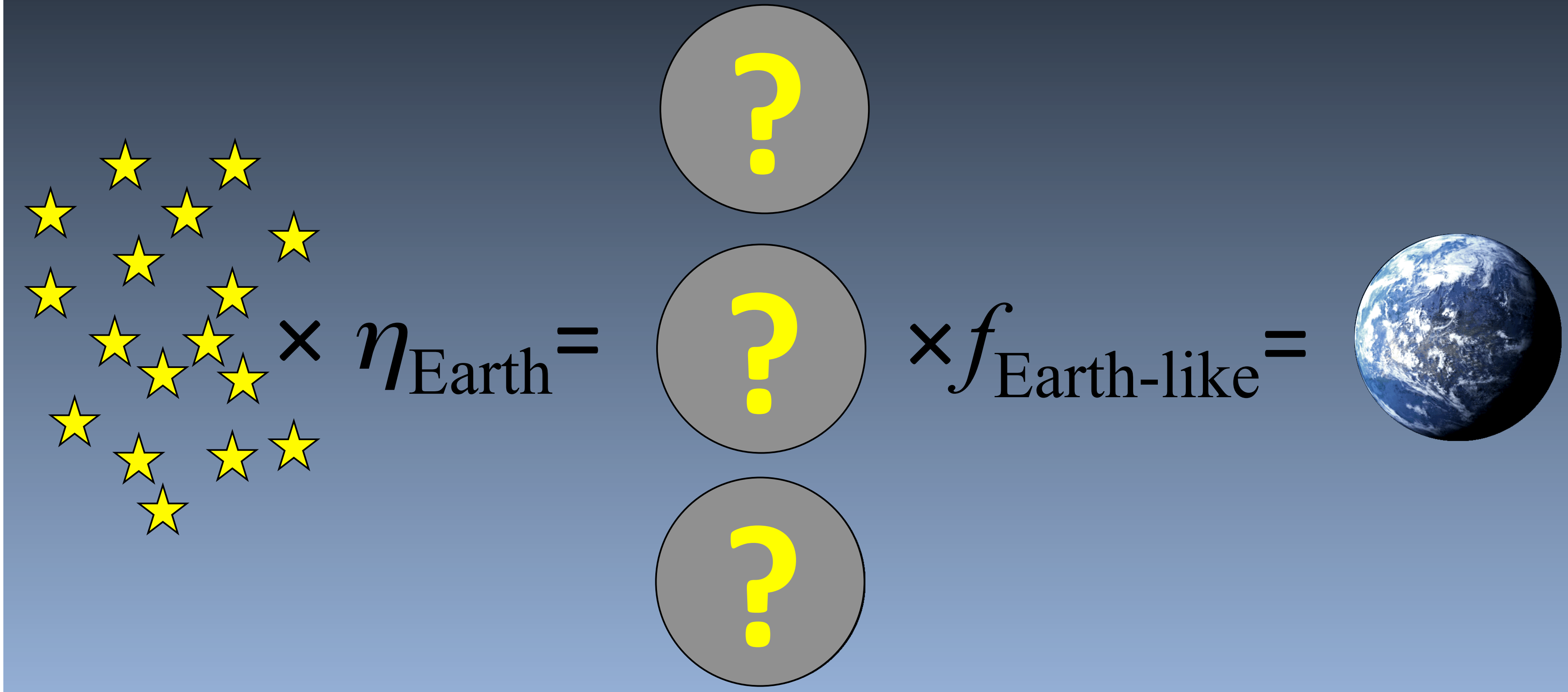
How Does One Choose a Yield Goal?



$$\times\ \eta_{\text{Earth}} = \; ? \; \times f_{\text{Earth-like}} =$$

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…

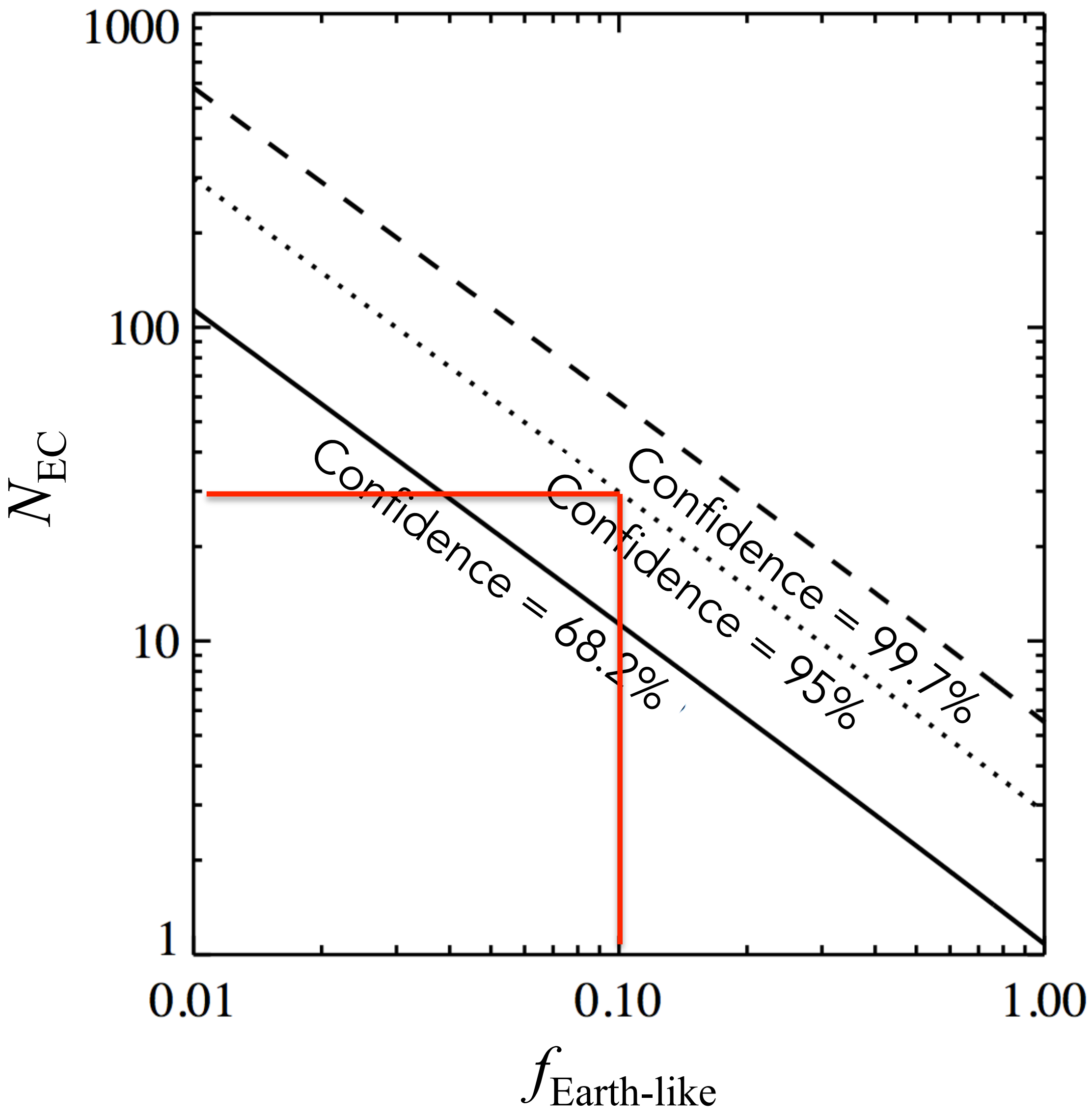
$$P(x, n, p) = \frac{n!}{x!(n-x)!} p^x \; (1-p)^{n-x}$$

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

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

How Does One Choose a Yield Goal?

Number of Candidates Needed to Guarantee ≥1 Earth-*like* Planet

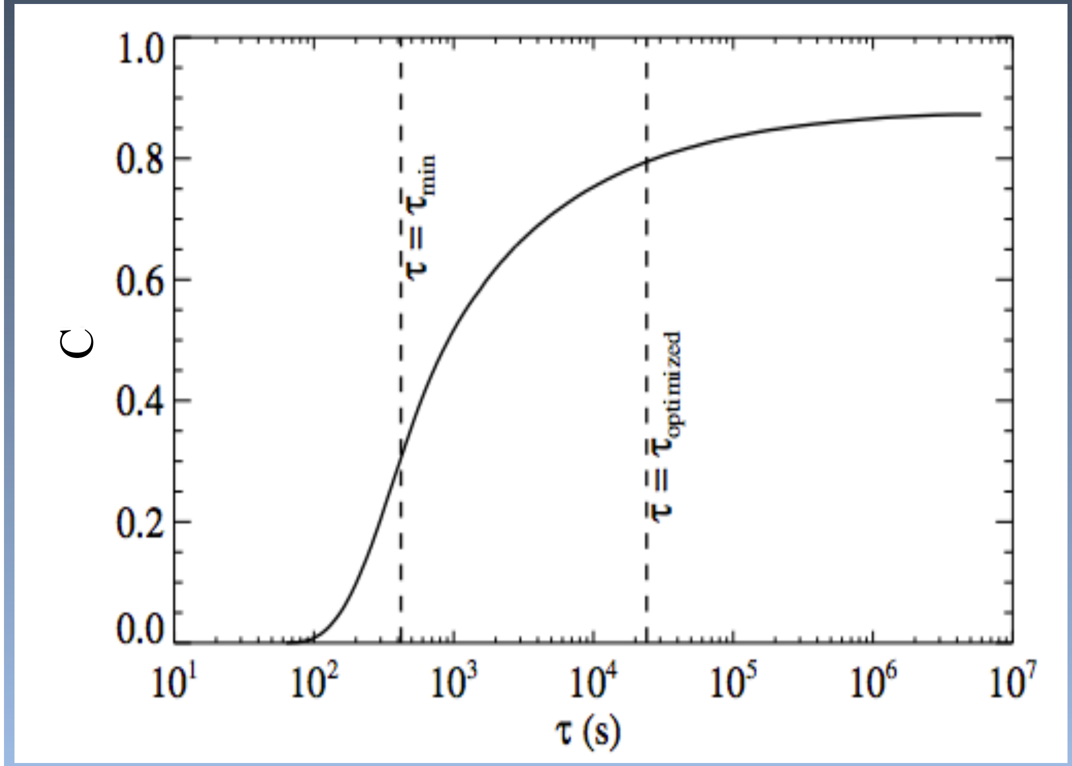


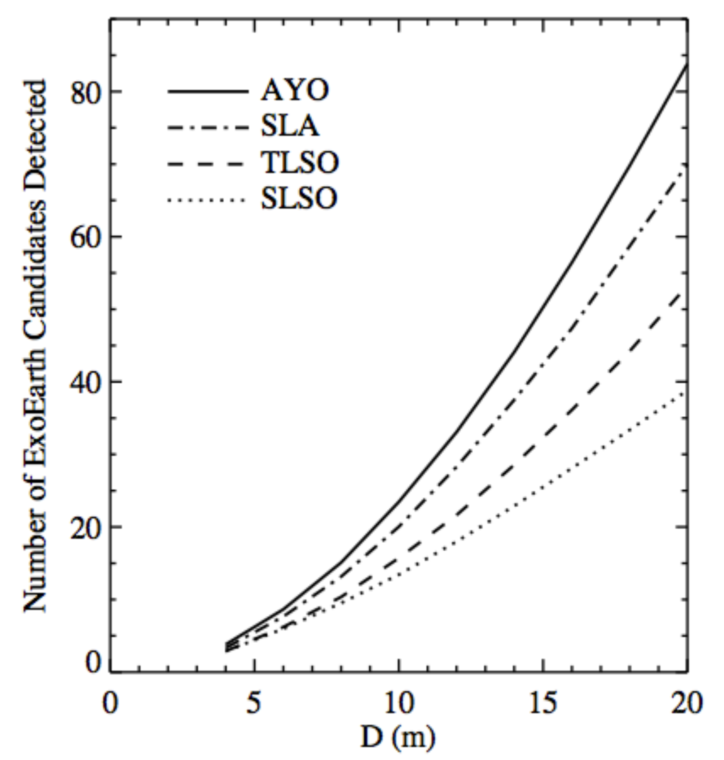
ExoEarth Yield Estimated via Completeness

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

Maximizing Yield by Optimizing Observations

Optimized Exposure Times

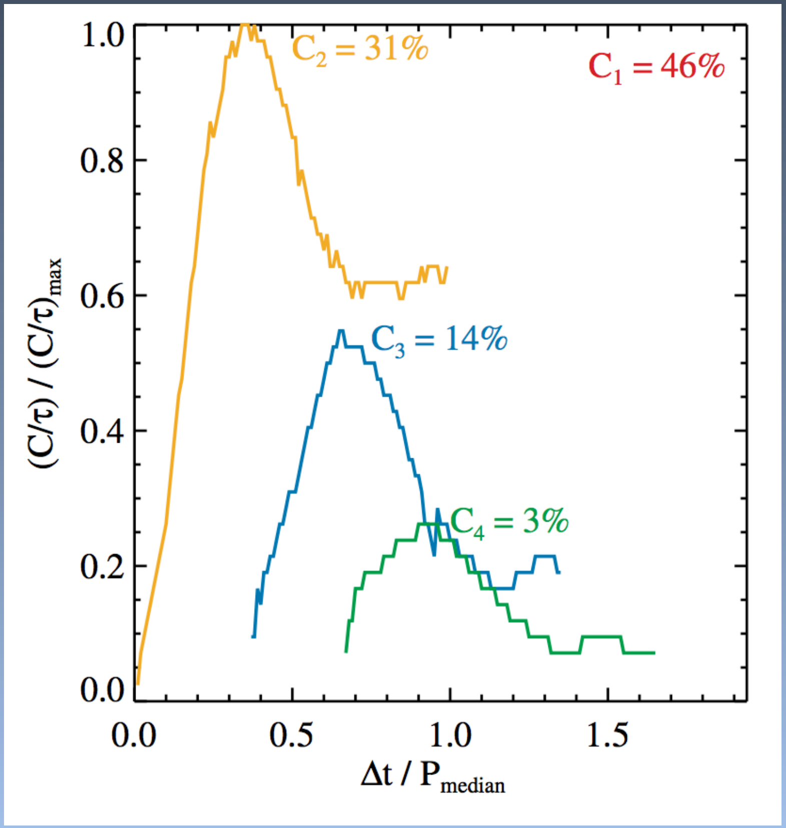


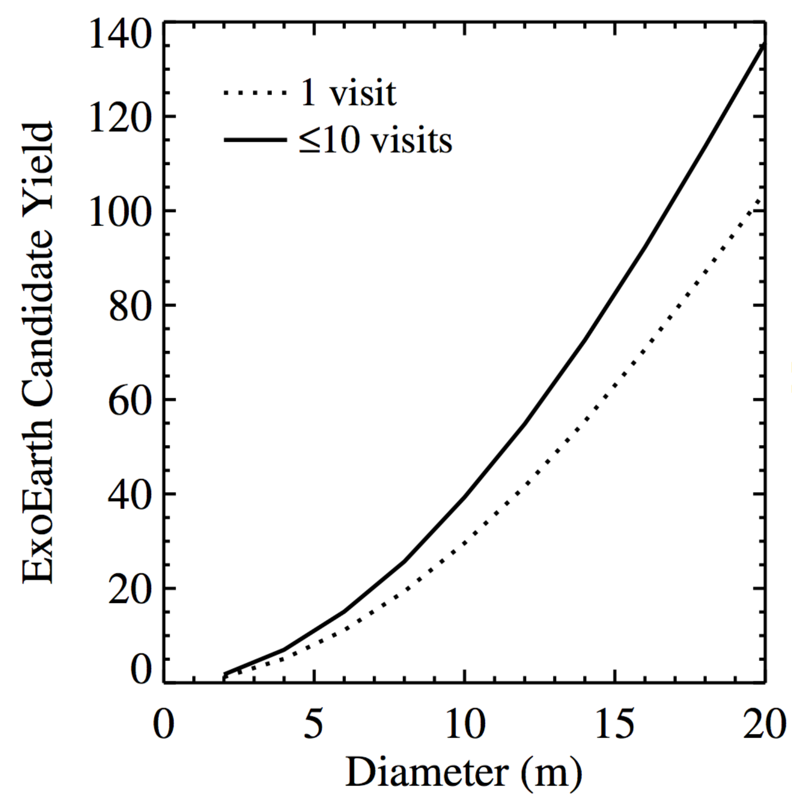


Optimizing exposure times can potentially double yield

Maximizing Yield by Optimizing Observations

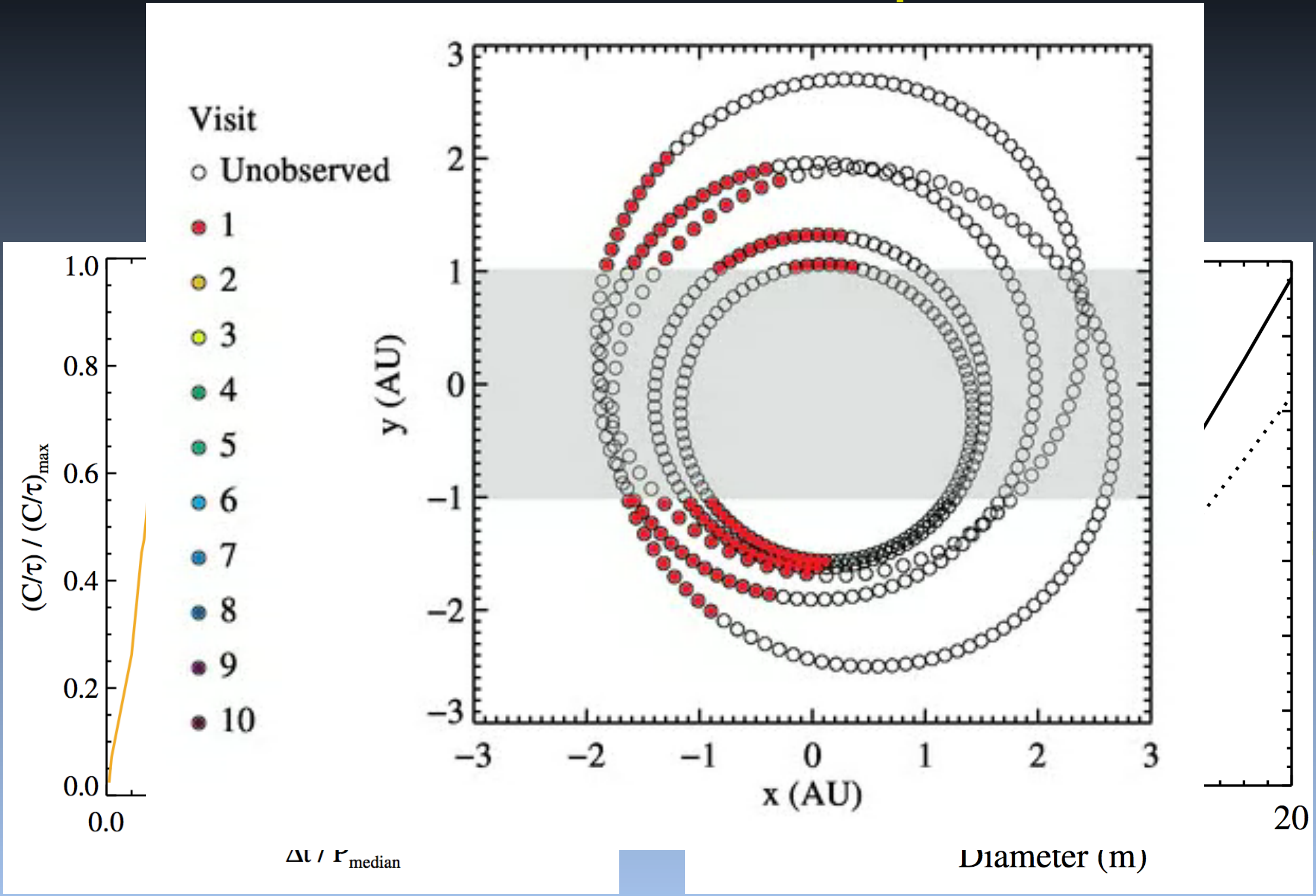
Optimized Revisits





Optimized revisits increase yield by additional 35-75%

Maximizing Yield by Optimizing



Optimized revisits increase yield by additional 35-75%

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

- $\eta_{Earth} = 0.1$
  - *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?

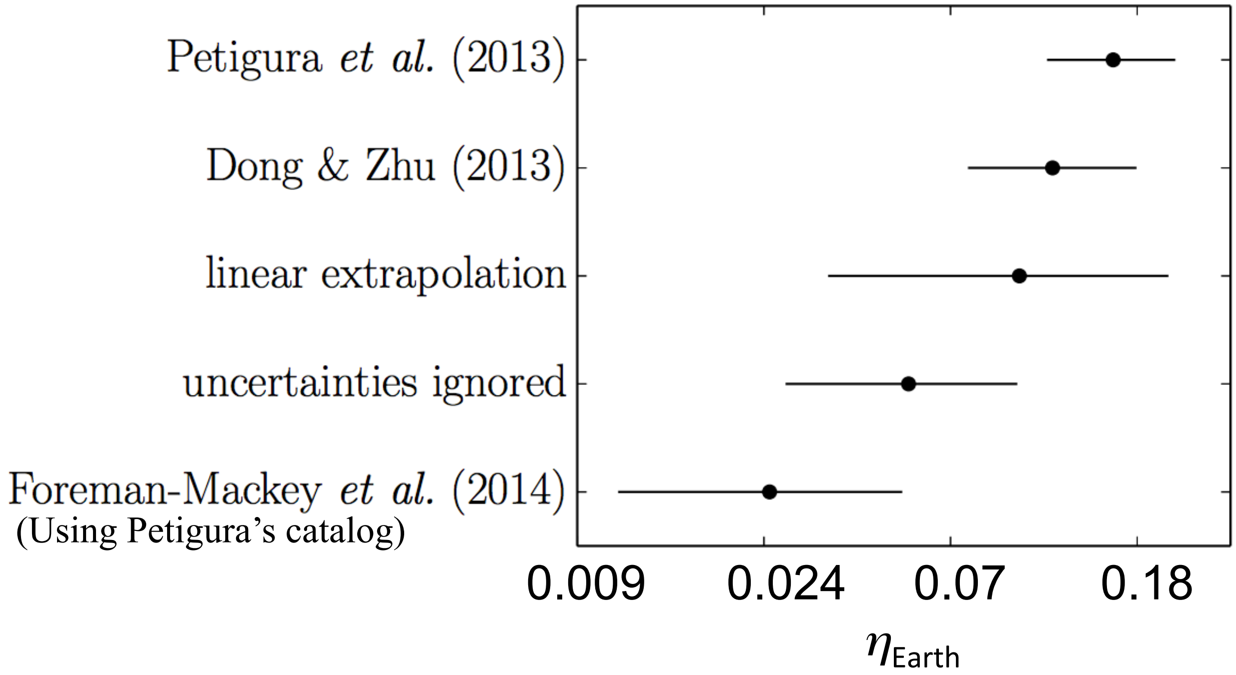


Fig 10 from Foreman-Mackey et al. (2014)

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

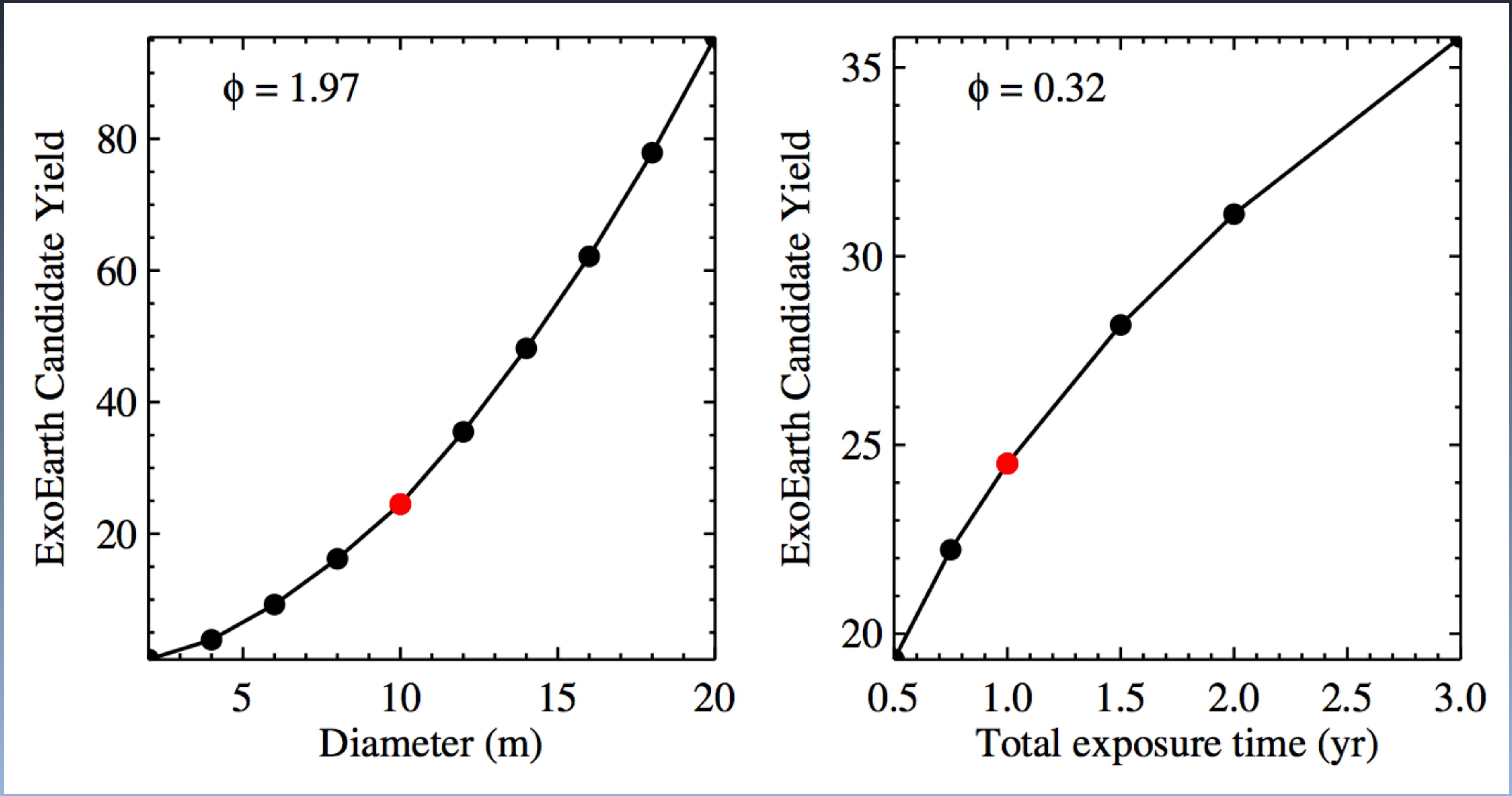
- $\Delta\lambda$ = 20%
- SNR = 7
- IWA = 3.6 λ/D
- Contrast, $\zeta = 10^{-10}$

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)

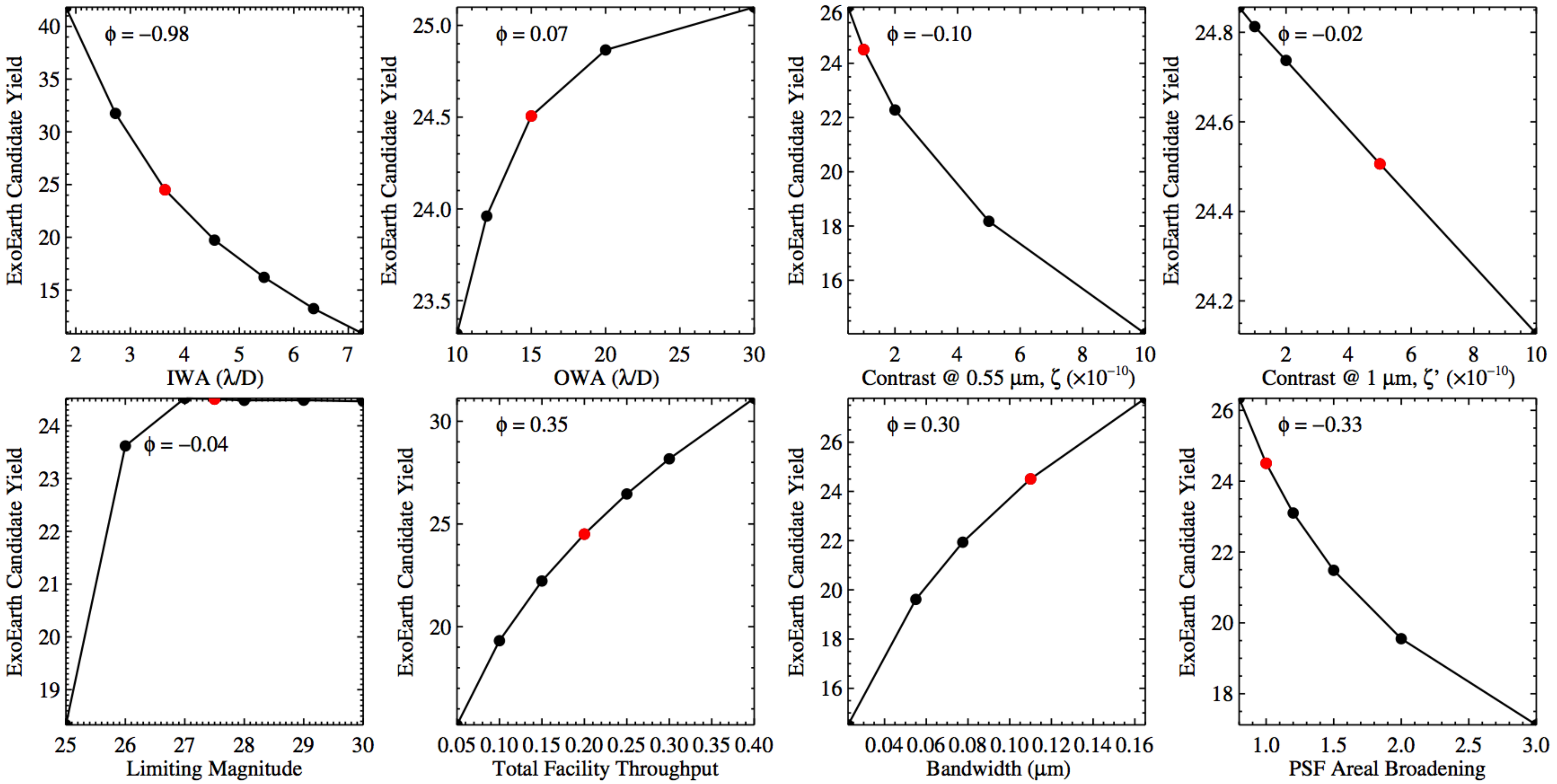
What Telescope/Instrument Parameters Matter?



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

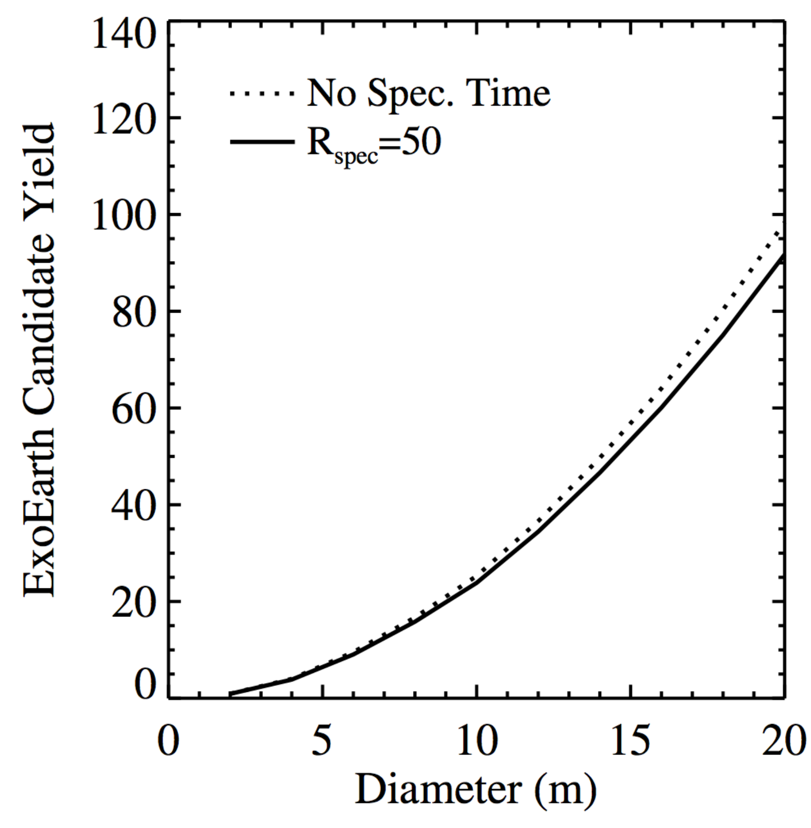
What Telescope/Instrument Parameters Matter?

Coronagraph Scaling Laws



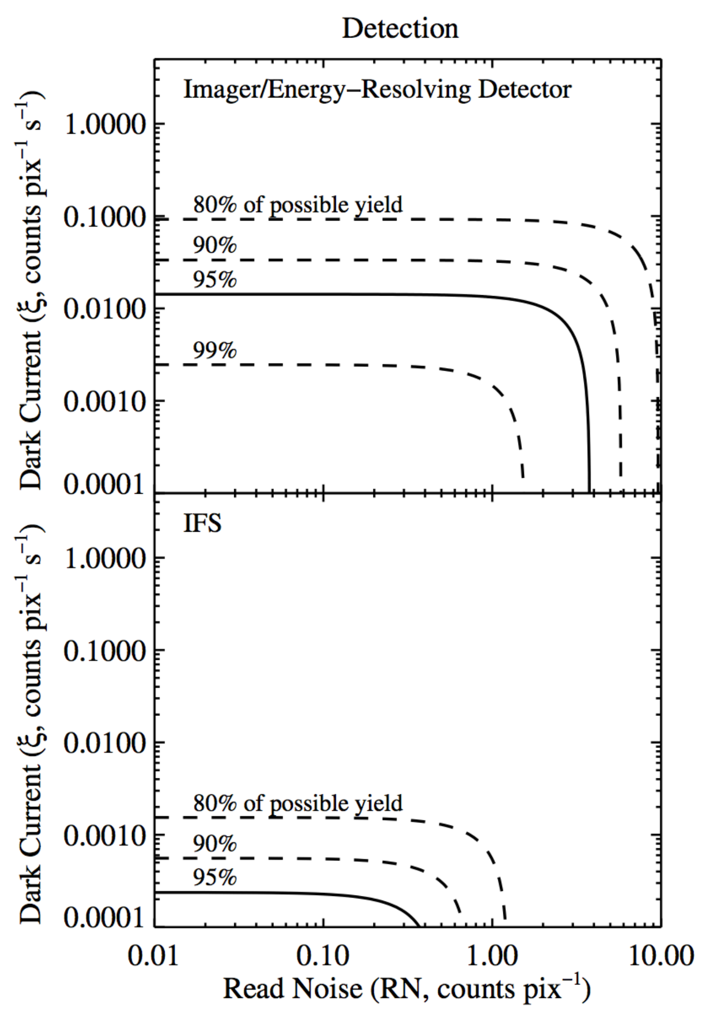
IWA matters more than contrast when treating both linearly. OWA doesn't matter much. Noise floors with Δmag > 26.5 are unnecessary.

Impact of Spectral Characterization Time



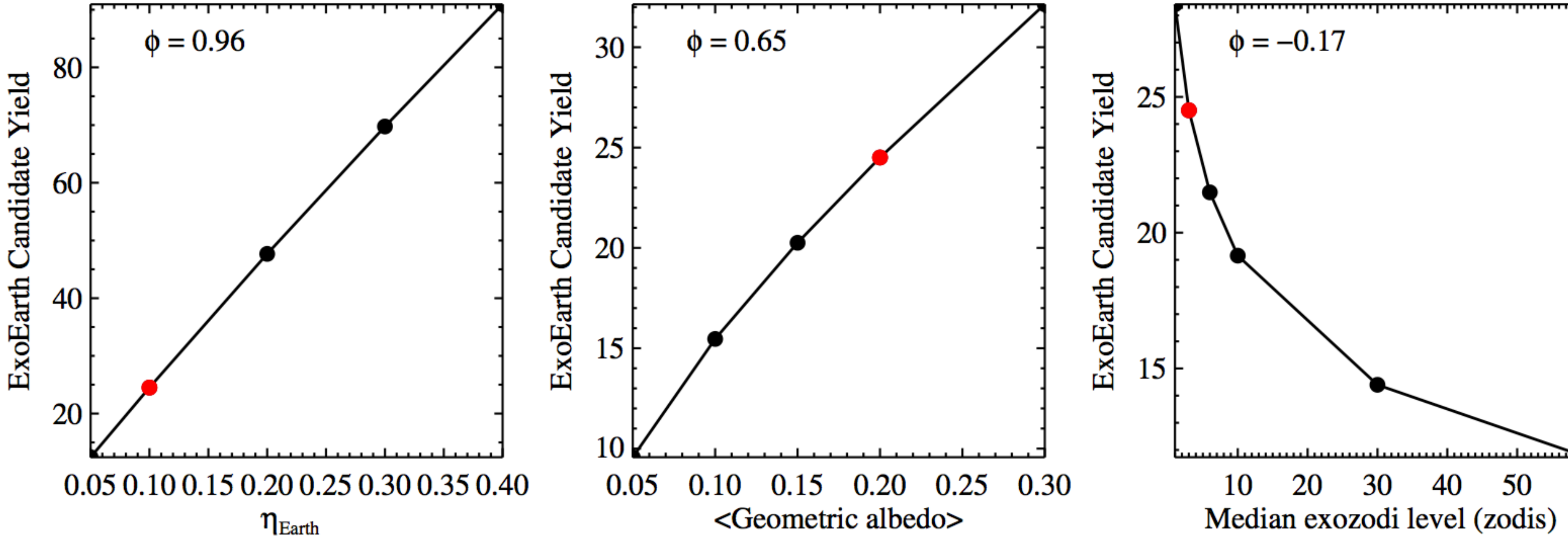
Assuming we can differentiate between exoEarth candidates and other objects, R=50 SNR=5 spectra do not greatly reduce yield

Impact of Detector Noise



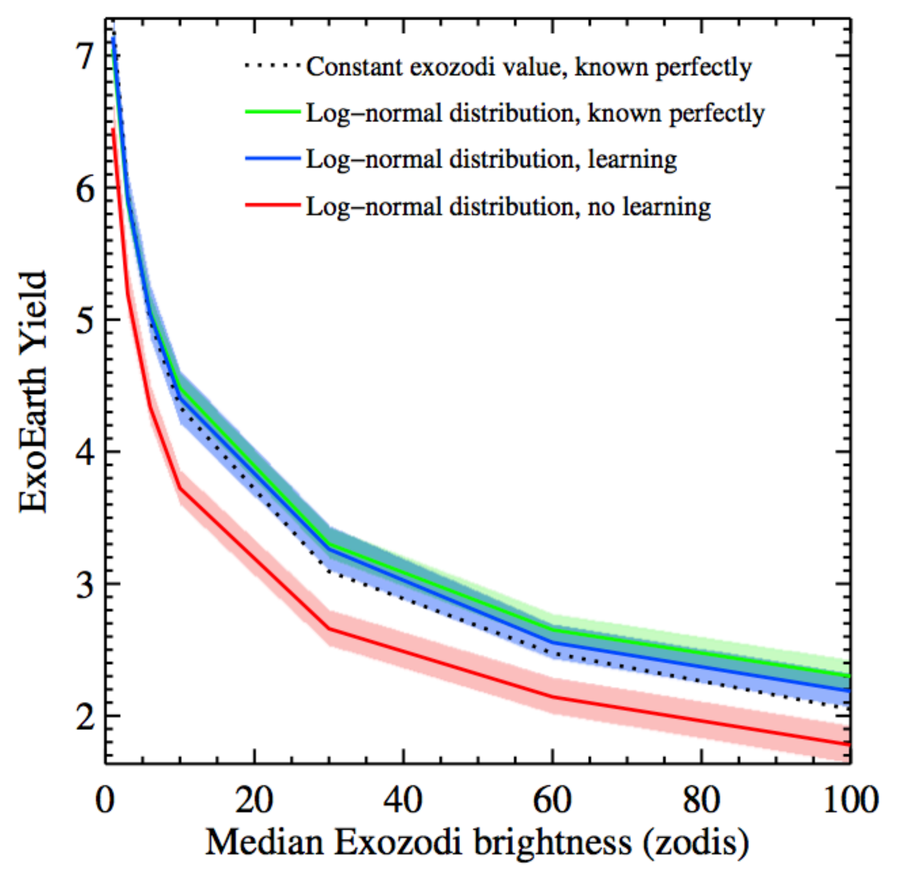
Traditional CCD in an IFS requires significant improvement to noise performance. Energy-resolving detectors relax these noise requirements.

What Astrophysical Parameters Matter?



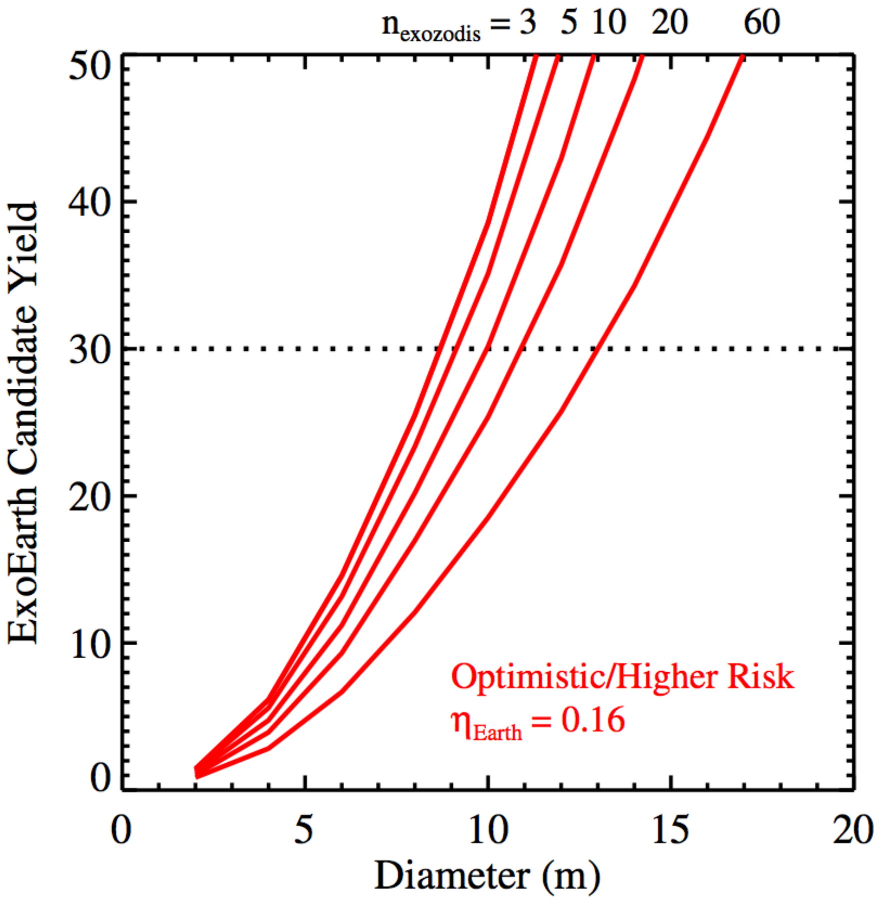
Non-linear dependence on $\eta_{\rm Earth}$ due to required spectral characterization. Weak dependence on exozodi level, but much room for improvement in exozodi level constraints.

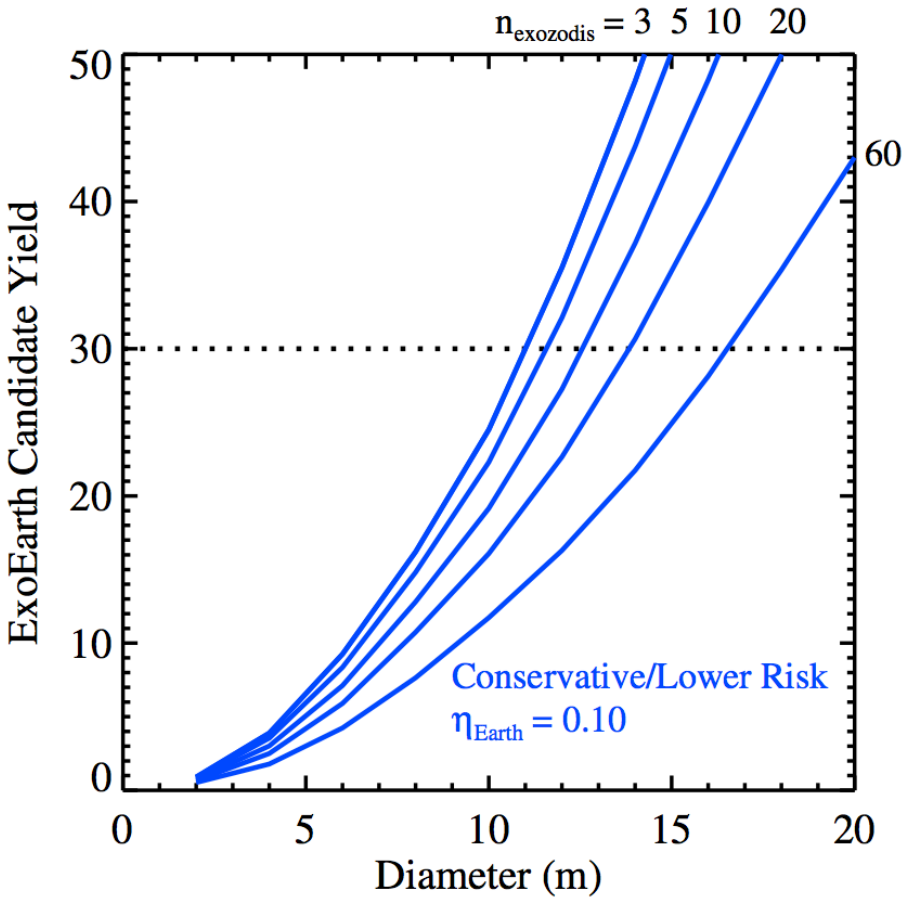
Impact of Exozodi Distribution



Knowing the median exozodi level should be adequate. If we learn individual exozodi levels on the fly, we should be able to avoid the negative impact of very dusty systems.

Lower Limits on Aperture Size





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

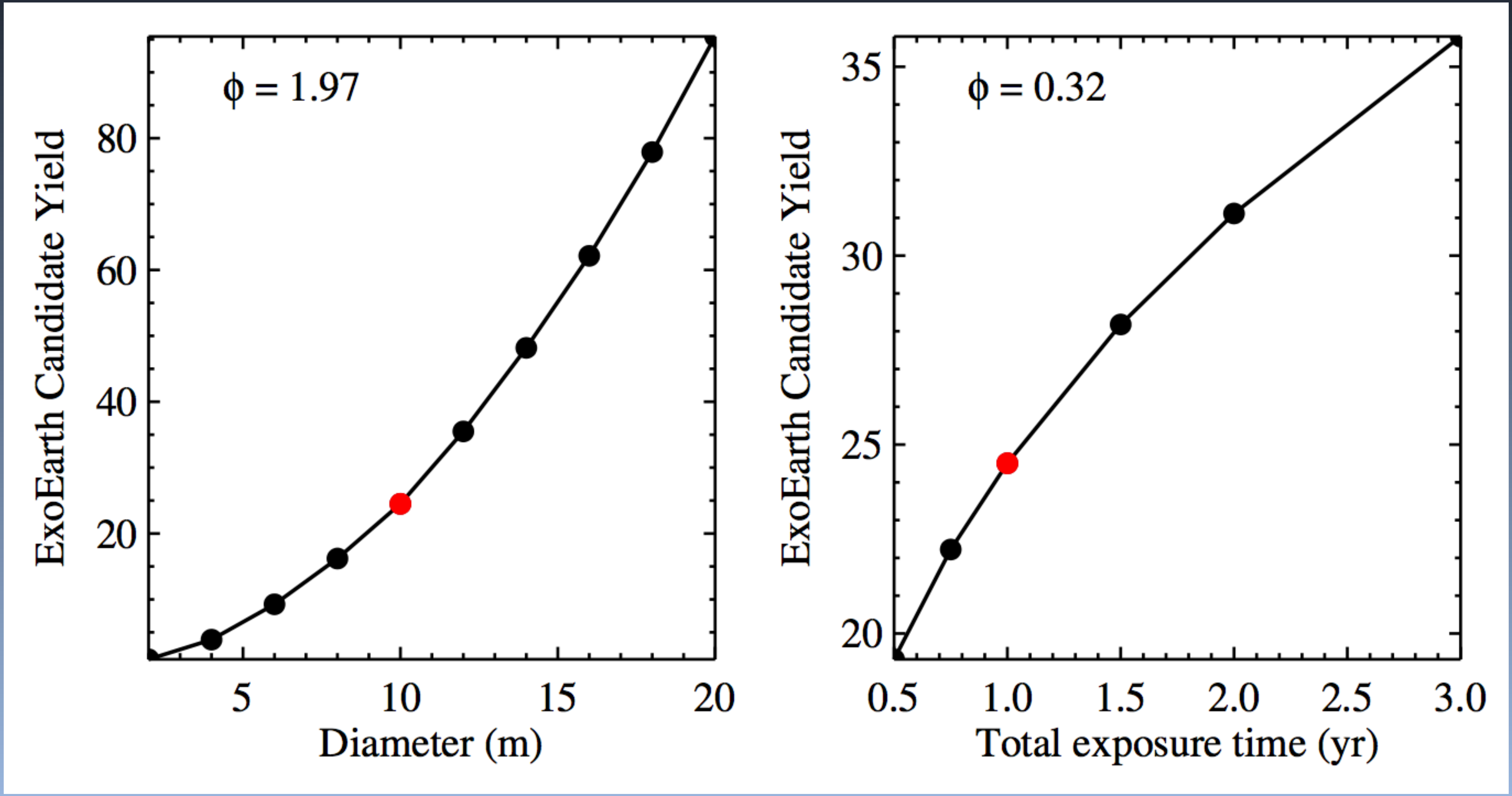
Baseline *Starshade* Mission Parameters

Detections @ 0.55 μm
- $\Delta\lambda$ = 40%
- SNR = 7
- IWA = 40 mas
- Contrast, $\zeta = 10^{-10}$

Characterization @ 1 μm
- R = 50
- SNR = 5
- IWA = 40 mas
- Contrast, $\zeta = 10^{-10}$

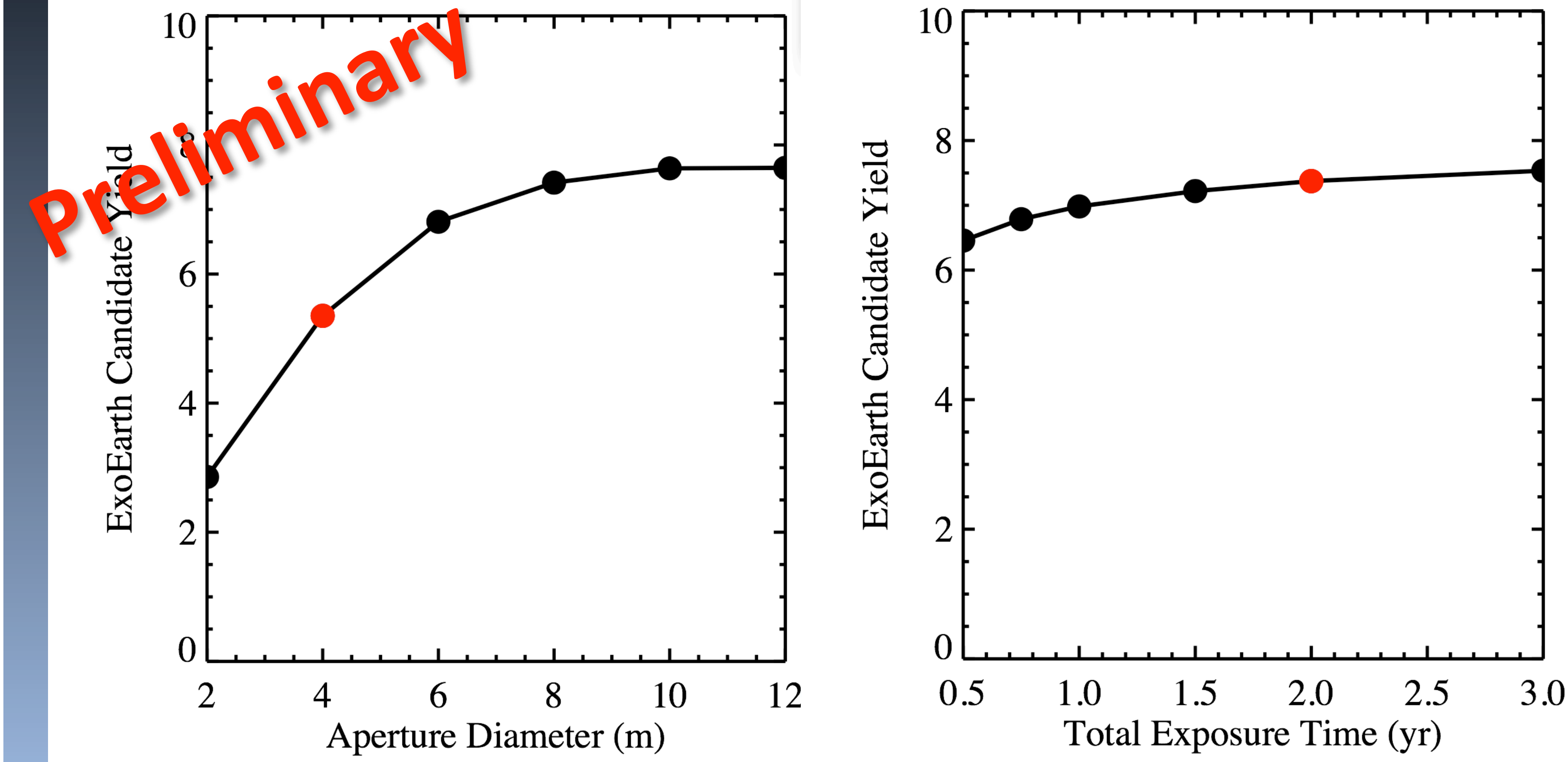
- throughput = 0.5
- Noise floor, $\Delta\mathrm{mag}_{\mathrm{floor}} = 27.5$
- OWA = infinite
- Diffraction-limited
- No detector noise
- 2 years of exposure time
- 0 year of overheads, 3 years of slewing
- 100 slews
- <5 visits per star, no optimization of revisit time
- Local zodi calculated at solar elongation of 60°
- Same astrophysical assumptions as coronagraph

Starshade Yields
For reference, recall the coronagraph…



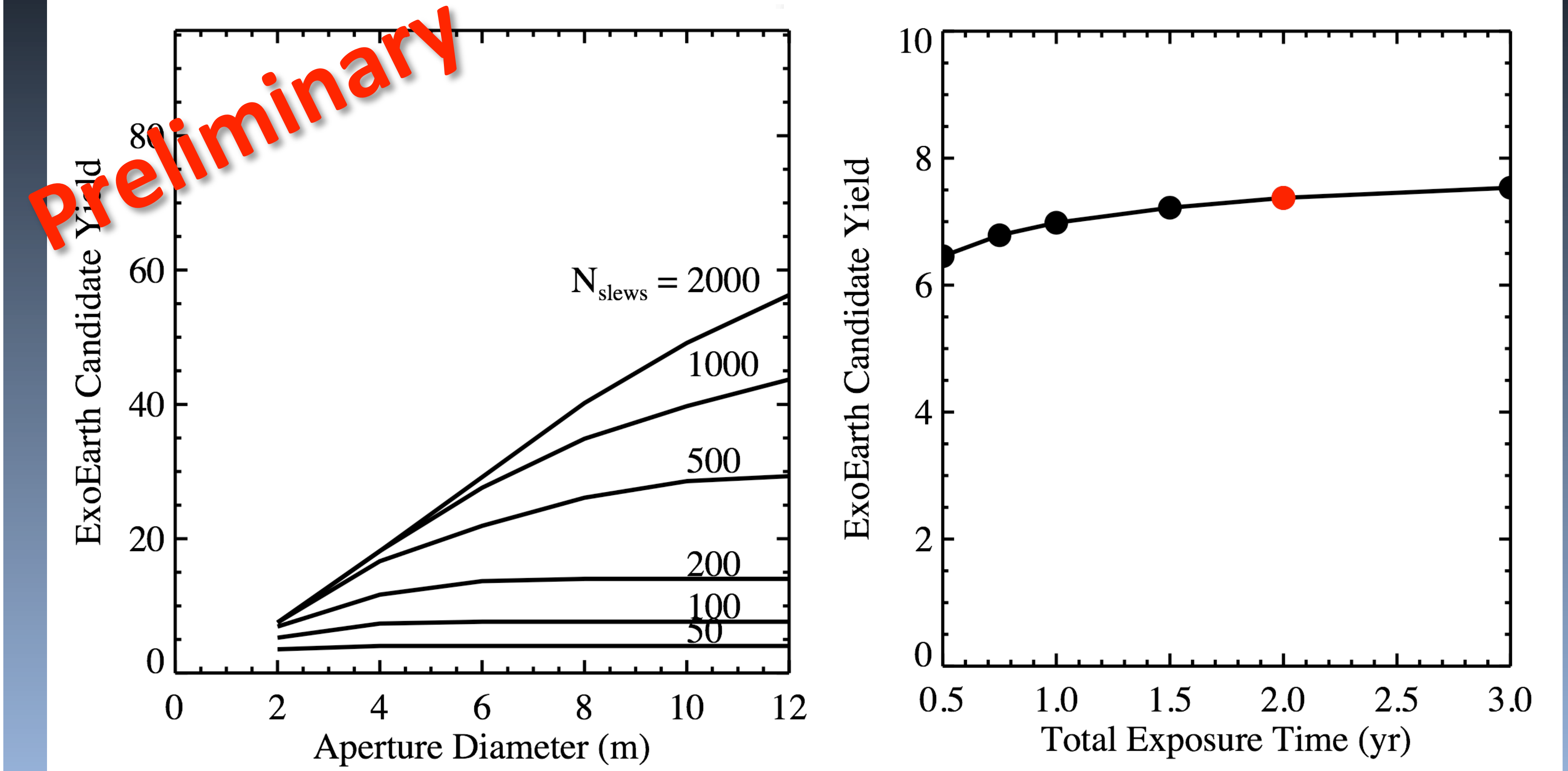
Above plots are for baseline coronagraph-based mission.

Starshade Yields
Scaling Relationships for a Starshade



Above plots are for baseline starshade-based mission.

Starshade Yields
Scaling Relationships for a Starshade



Baseline starshade mission is operating in slew-limited regime.

"Starshade Mode"

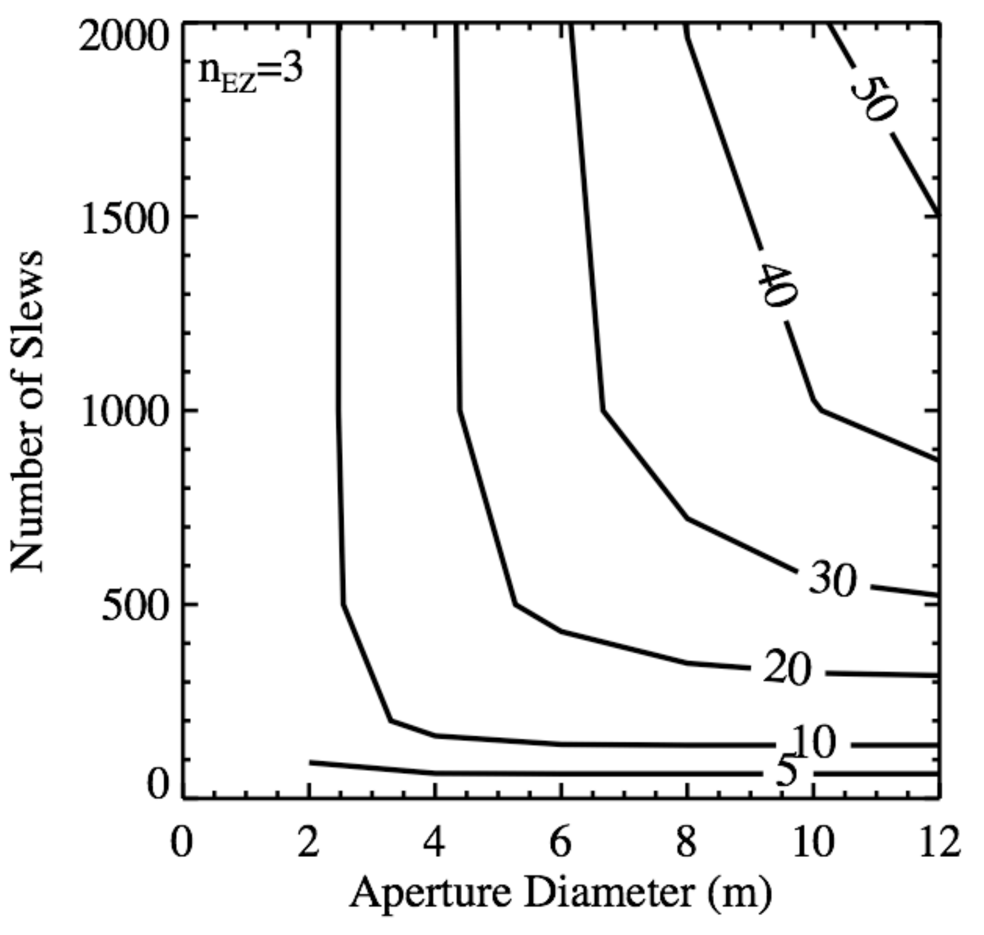
- Existing code valid in the time-limited regime, where observations are limited by a total allowable exposure time
    - Targets are prioritized & selected based on C/τ, the "benefit-to-cost" ratio

- 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*/fuel.

- 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/x, where the cost $x = \alpha\,(1/n_{\mathrm{slews}}) + (1-\alpha)\,(\tau/\tau_{\mathrm{tot}})$, and $0<\alpha<1$

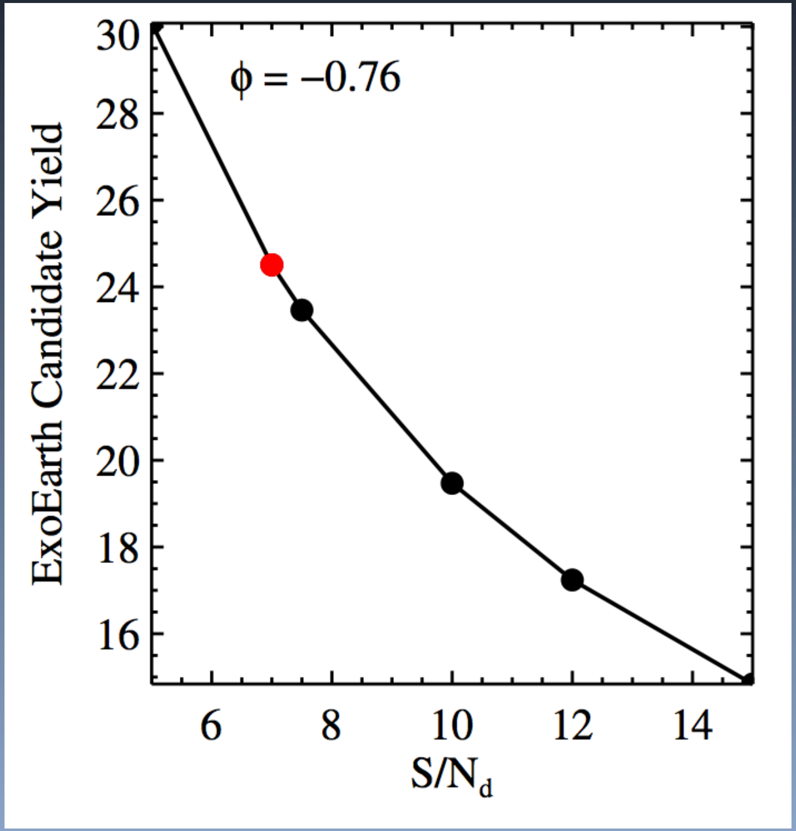
Yield Contour Plots for Starshades
IWA = 40 mas

Preliminary



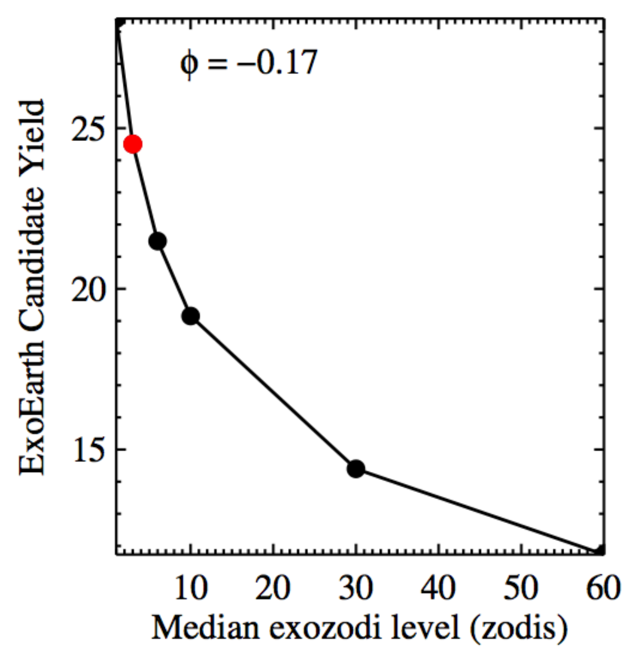
A yield of ~30 exoEarth candidates requires D ~ 7 m + ~900 slews

What Will Change These Results?
1. S/N Required for Detection



We should be able to better constrain this using the Haystacks results, instrument simulators, and existing image processing routines.

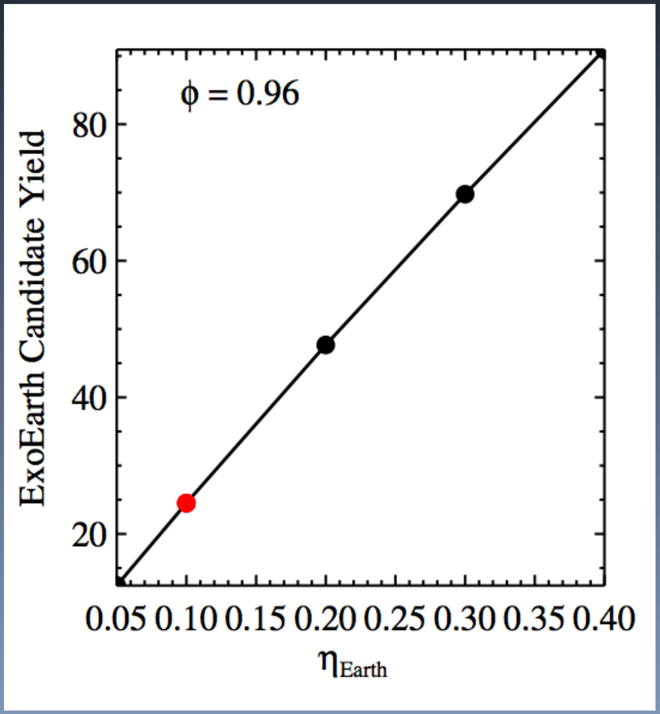
What Will Change These Results?
2. Exozodi Level



Expect a median exozodi level constraint from LBTI sometime in the next 2 – 3 years. Warning: LBTI measures thermal emission, not scattered light. Google "pseudo-zodi"

What Will Change These Results?

3. η_{Earth}



- Official Kepler result (probably ~1 year)
- Proposed SAG 13: standardize η_{Earth} def. & study differences between planet occurrence rate estimates (~1 year)
- Could be wildly uncertain
  - Burke et al. (2015): $0.01 < \eta_{\text{Earth}} < 2.0$ for G stars

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

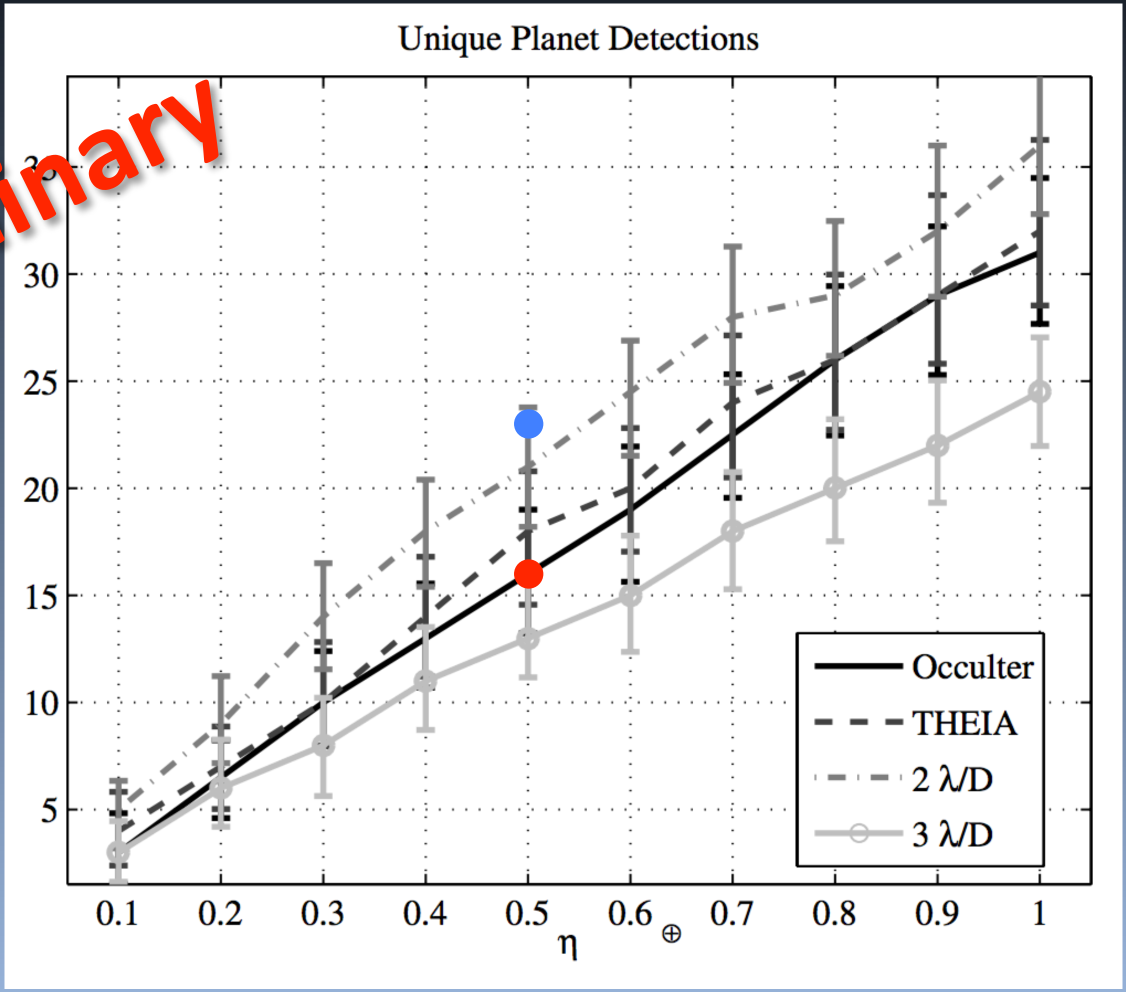
- Starshade yield maximized at the transition from slew- to time-limited regimes

- Designing a mission robust to $\eta_{\text{Earth}} = 0.1$ and $f_{\text{Earth-like}} = 0.1$ 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

Comparison to Previous Work



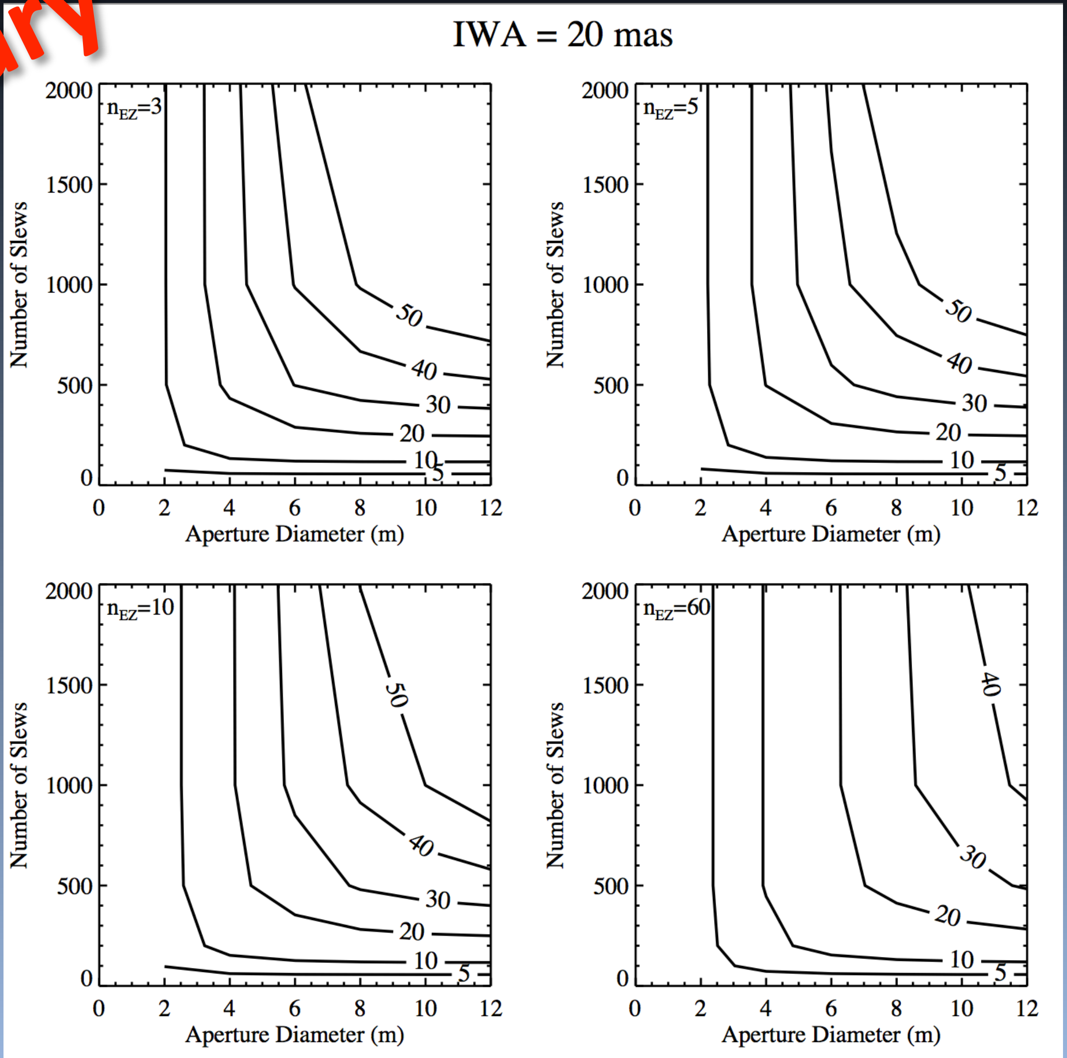
Preliminary

Fig 9 from Savransky et al. (2010)

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

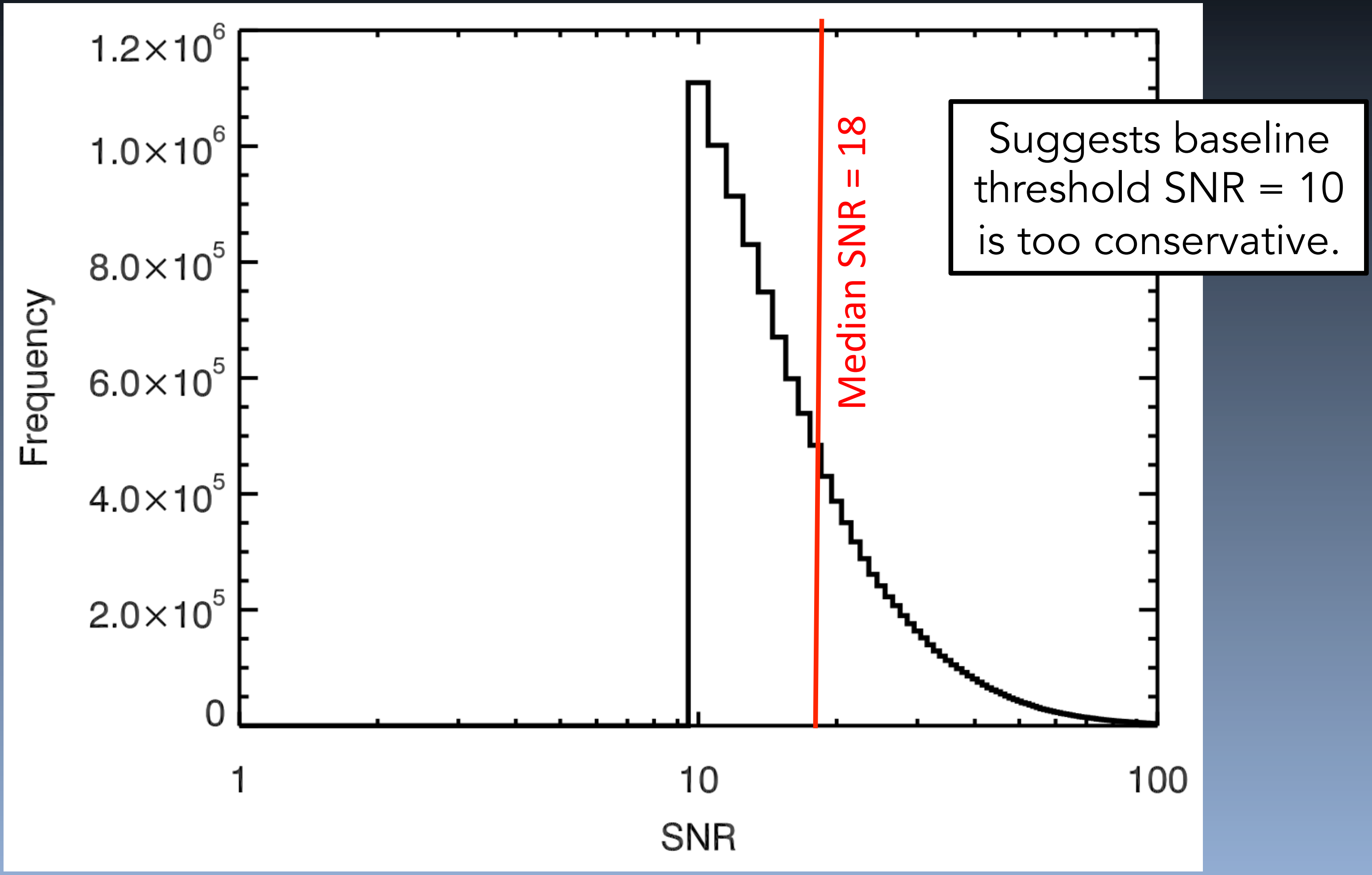
Yield Contour Plots for Starshades

Preliminary



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

What Telescope/Instrument Parameters Matter?



Suggests baseline threshold SNR = 10 is too conservative.

Summary

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