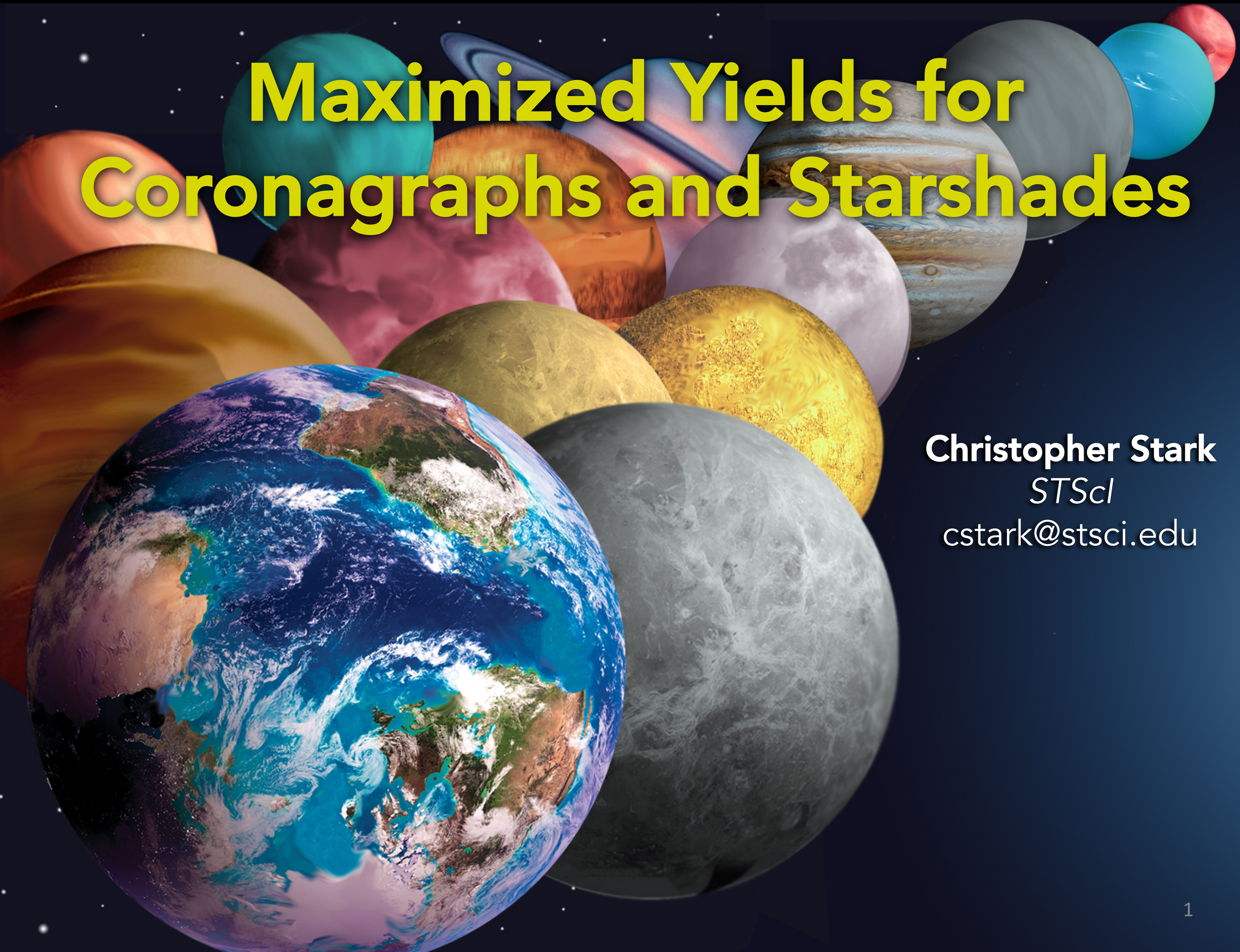
Maximized Yields for Coronagraphs and Starshades



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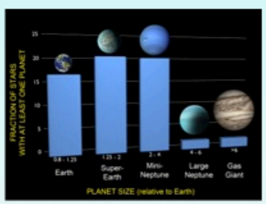
Calculating Yield with a DRM Code

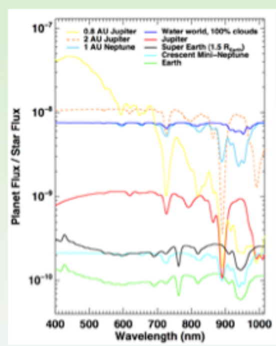
Astrophysical Constraints

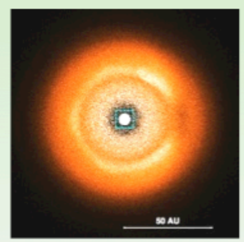
- η_{Earth}
- $\eta_{exozodi}$
- Planet sizes
- Albedos
- Phase functions



Observational Requirements

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



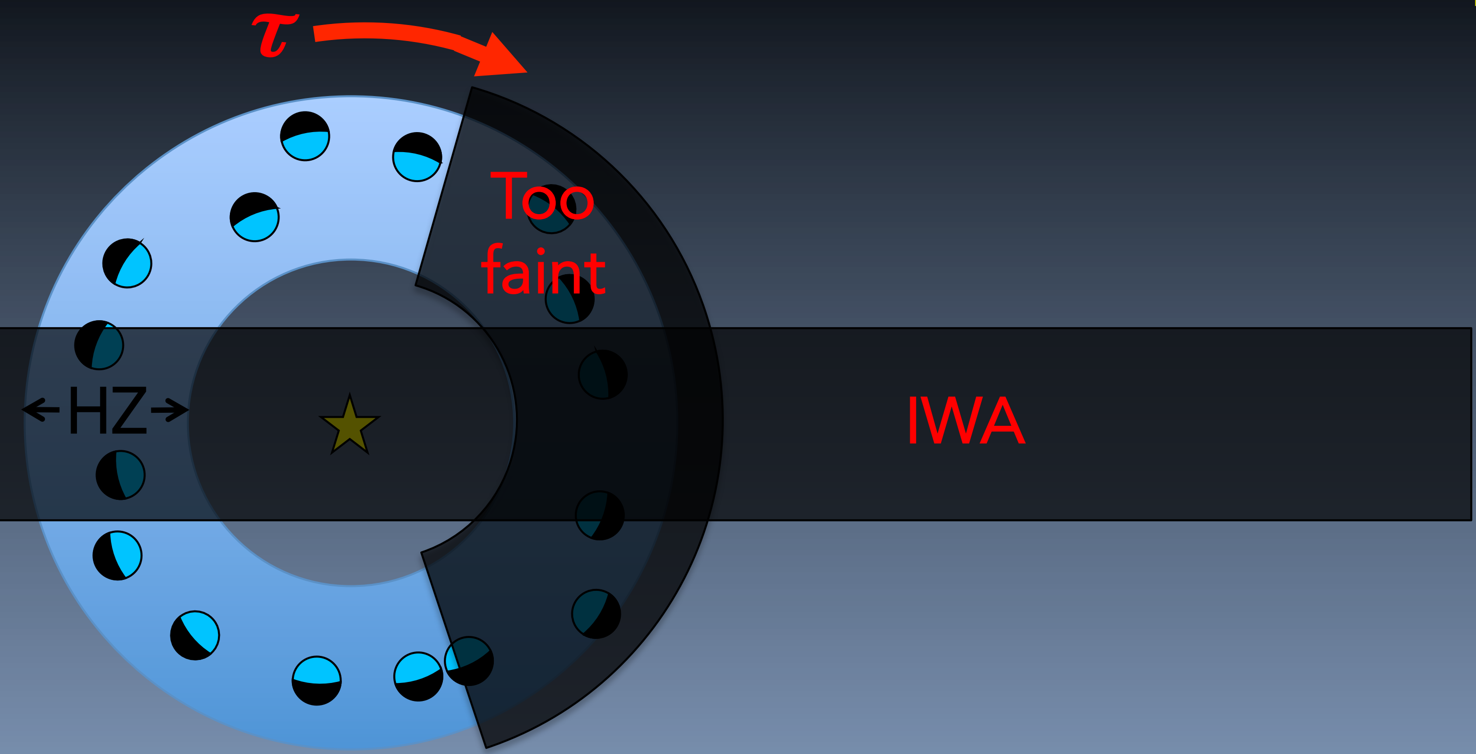


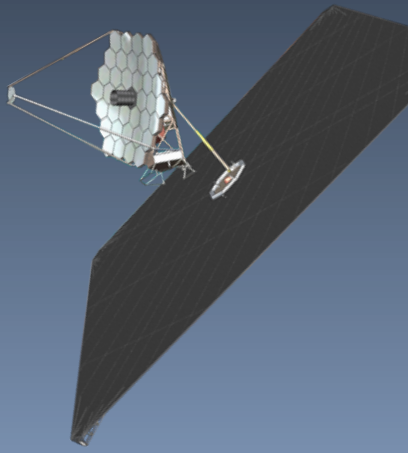
Technical Requirements

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

DRM

ExoEarth Yield Estimated via Completeness

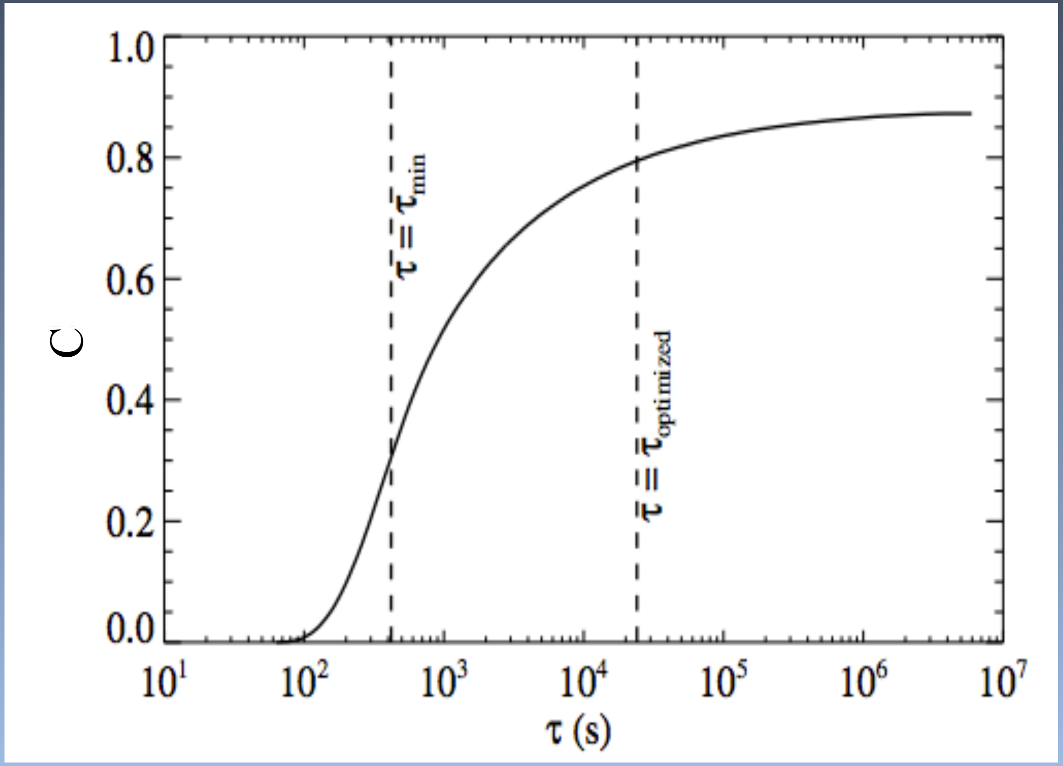


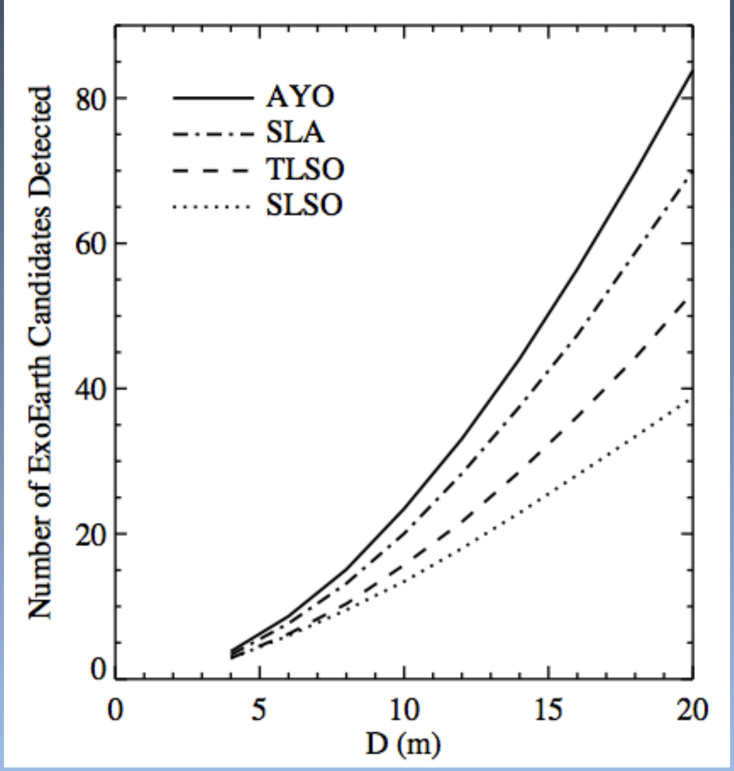


- Completeness, C = the chance of observing a given planet around a given star if that planet exists (Brown 2004)
- Yield = $\eta_{\mathrm{Earth}} \Sigma C$
- Calculated via a Monte Carlo simulation with synthetic planets

Maximizing Yield by Optimizing Observations

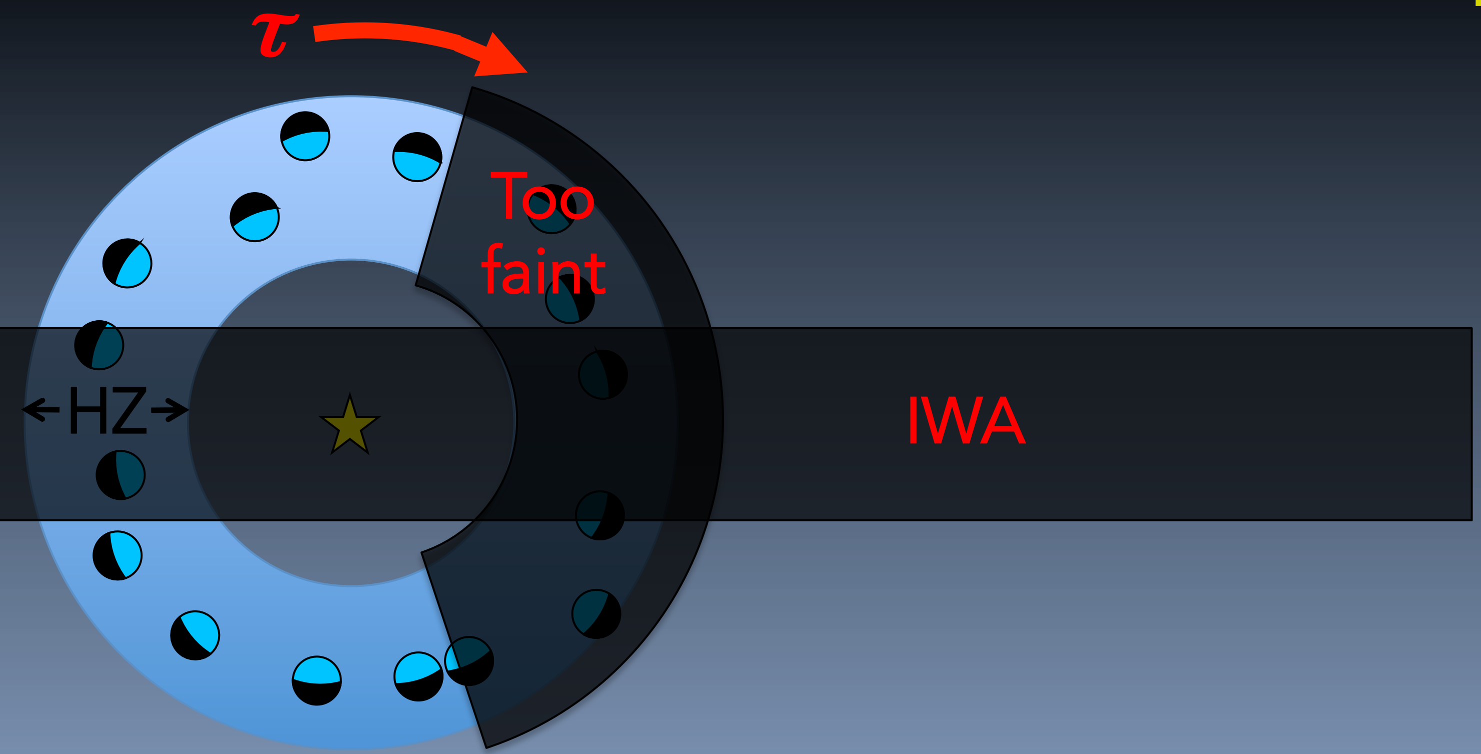
Optimized Exposure Times

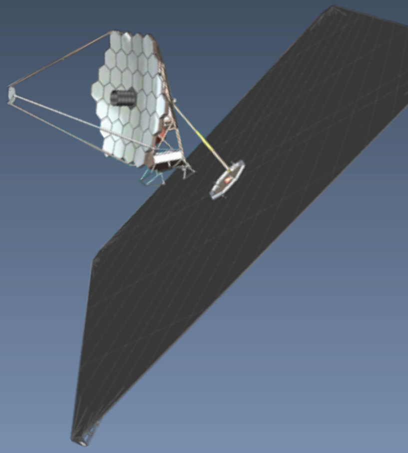




Optimizing exposure times can potentially double yield

ExoEarth Yield Estimated via Completeness

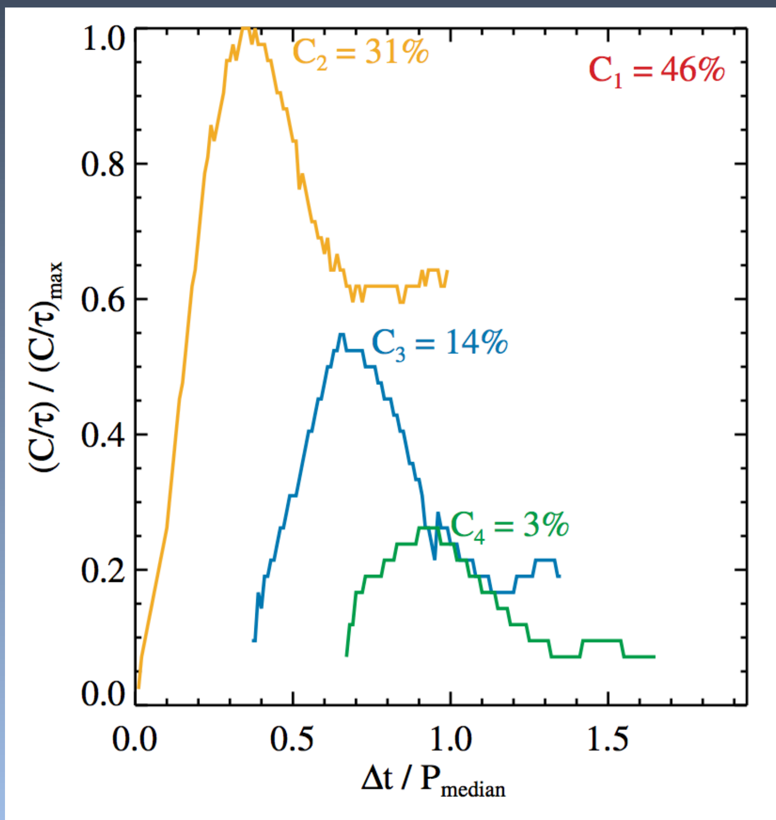


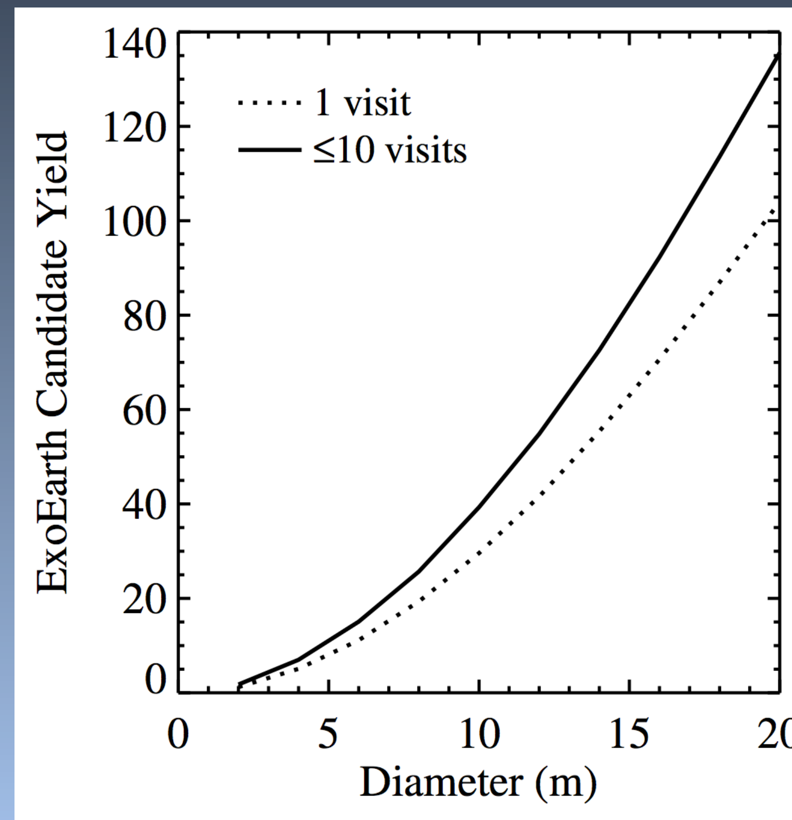


- Revisiting same star multiple times can increase total completeness
- Can optimize number of visits and delay time between visits

Maximizing Yield by Optimizing Revisits

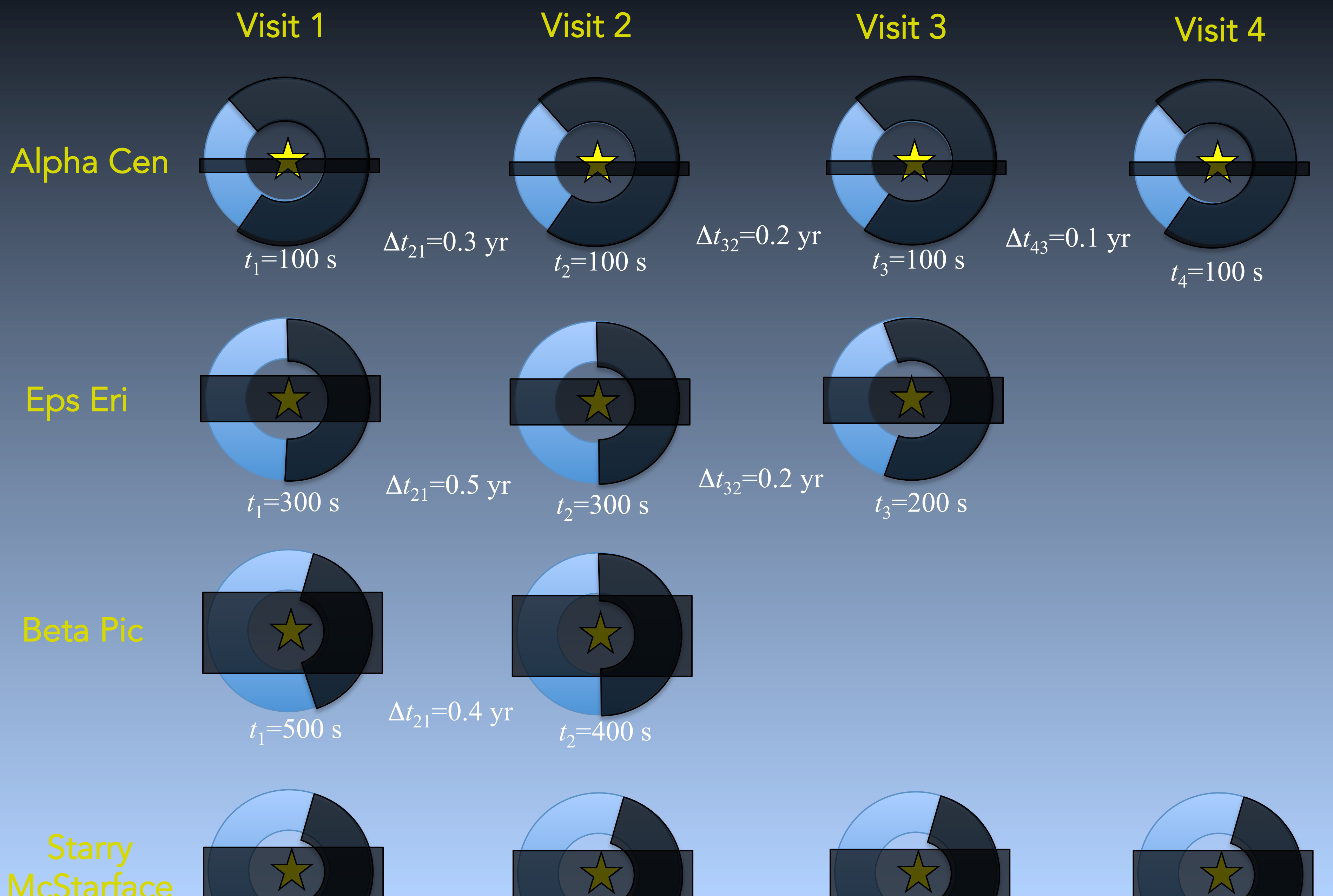
Optimized Revisits





Optimized revisits increase yield by additional 35-75%

Result: A Static Optimized Observation Plan



Astrophysical Assumptions in Yield Models

Occurrence rate of Earth-sized planets in the habitable zone of Sun-like stars

η_{Earth} = 0.1

(Published estimates of η_{Earth} range from ~0.03 – 1.0)

Habitable Zone

0.75 – 1.77 AU for Sun-like star

(Somewhat wide/optimistic)

Planet characteristics

Earth twins on circular orbits

Amount of "exozodiacal" dust obscuring the planet

n_{exozodis} = 3 × our own zodiacal dust

(Best-case future upper limit from LBTI observations)

Baseline Coronagraph Mission Parameters

2 Coronagraphs:

Detection Coronagraph

Designed for fast searches

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

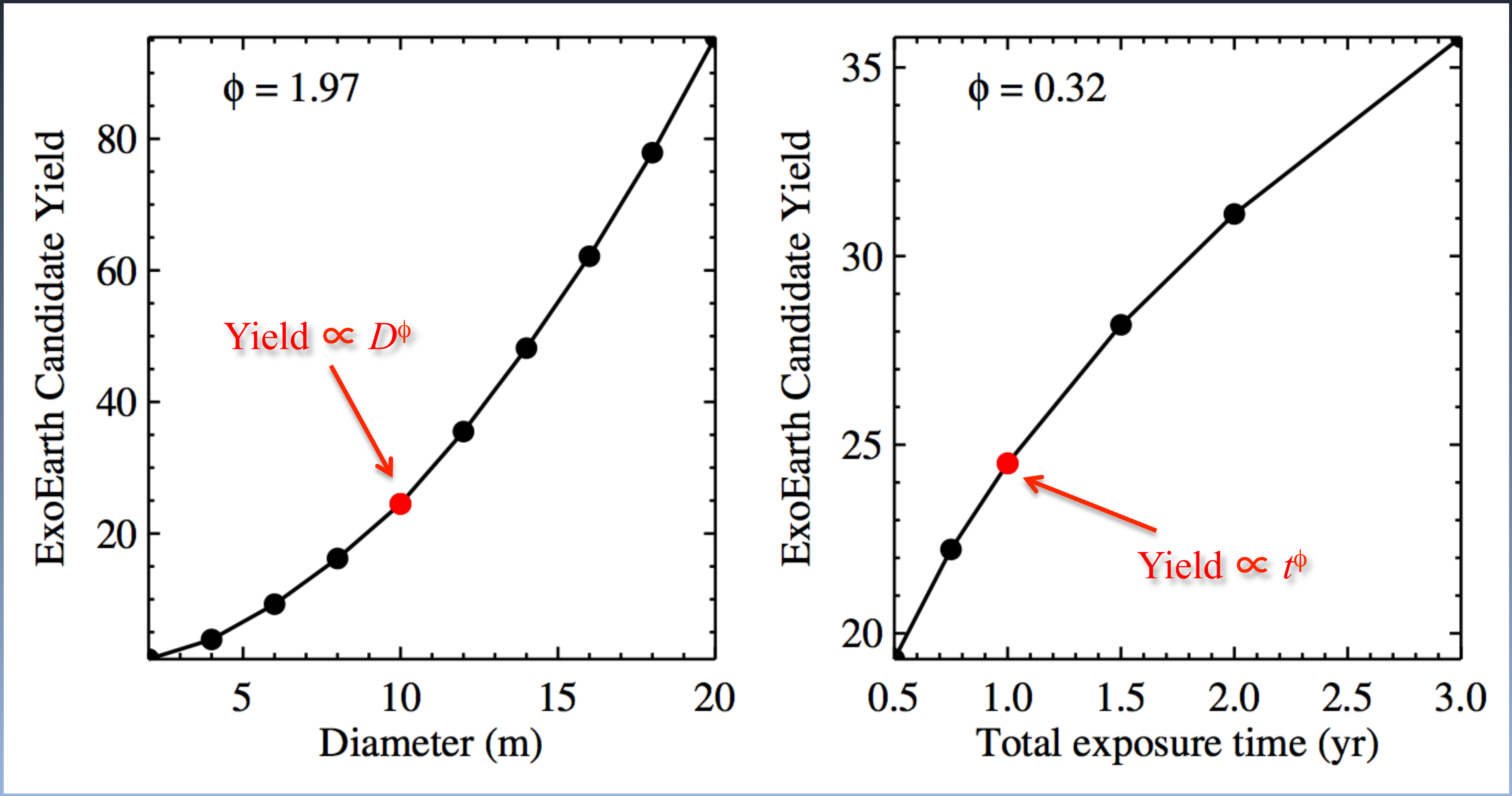
Characterization Coronagraph

Designed to detect water

λ = 1.0 μm
Spectral Res. = 50
SNR = 5
IWA = 2.0 λ/D
Contrast, $\zeta = 5\times10^{-10}$

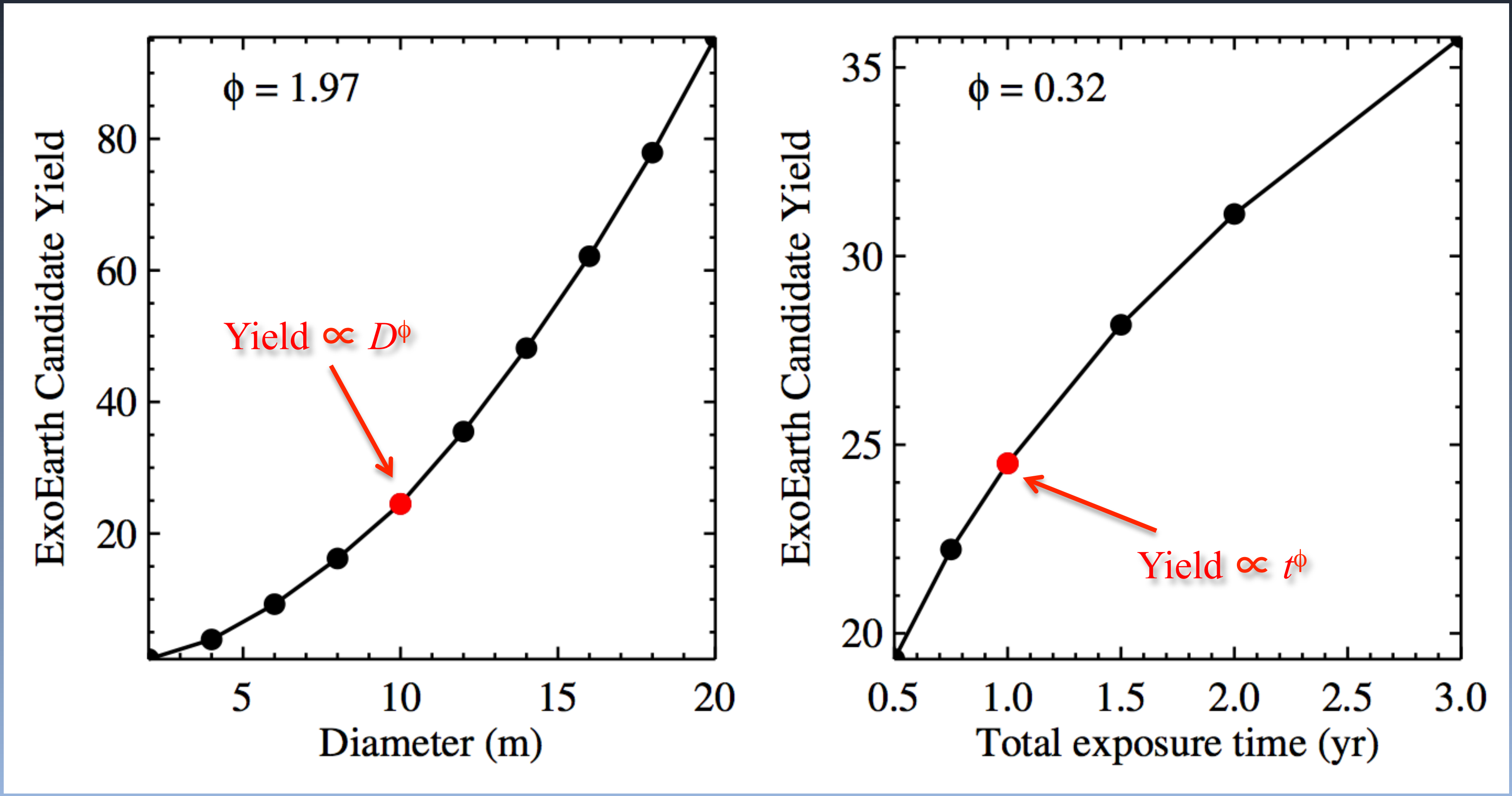
- End-to-end throughput = 0.2
- Noise floor, $\Delta\text{mag}_{\text{floor}} = 27.5$
- OWA = 15 λ/D
- Diffraction-limited Airy pattern PSF
- No detector noise
- 1 year of total exposure time
- 1 additional year of total overheads
- Up to 10 visits allowed to each star

What Telescope/Instrument Parameters Matter?



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

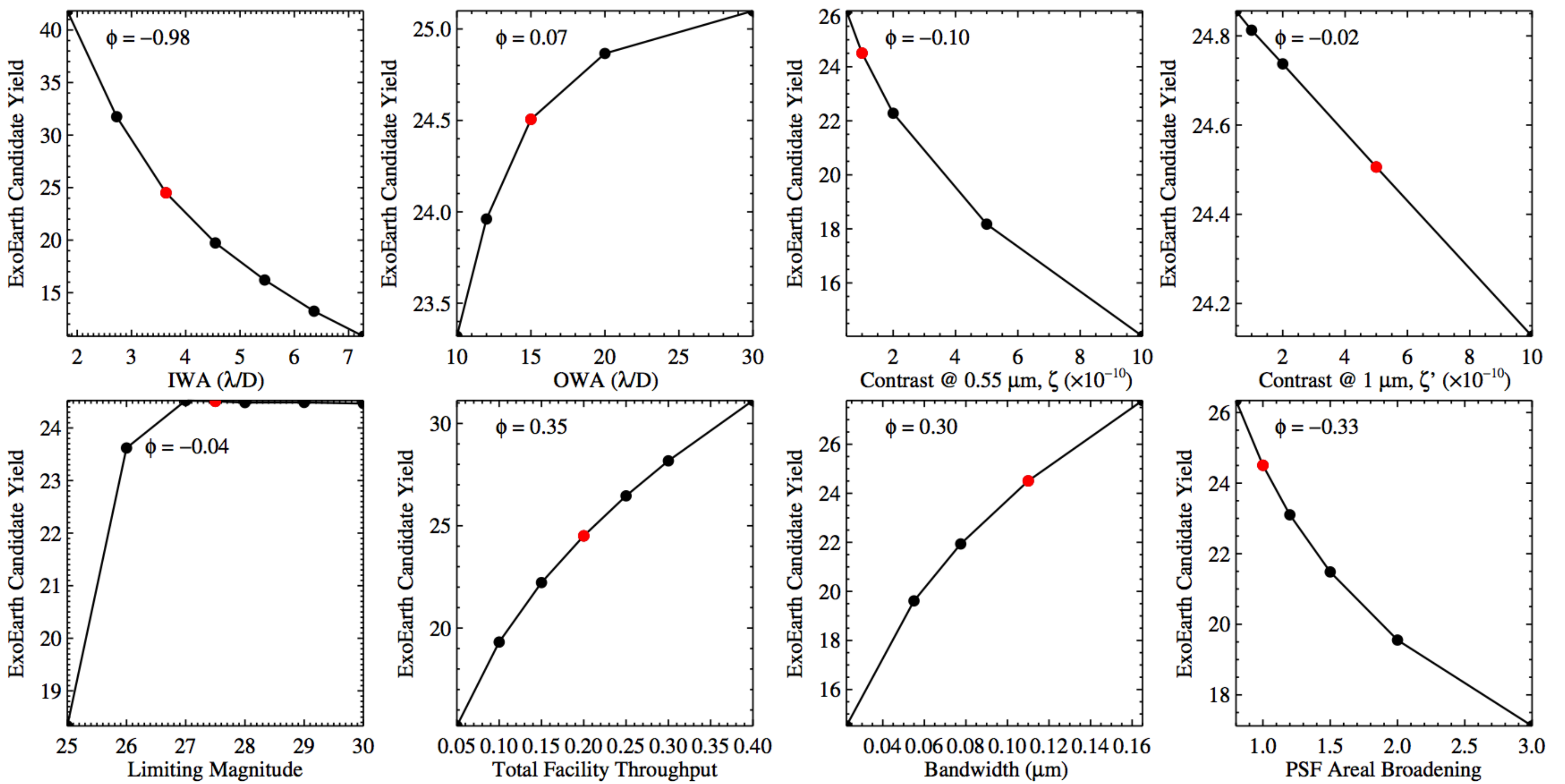
What Telescope/Instrument Parameters Matter?



D^2 dependence: roughly equal contributions from collecting area, IWA, and PSF solid angle.

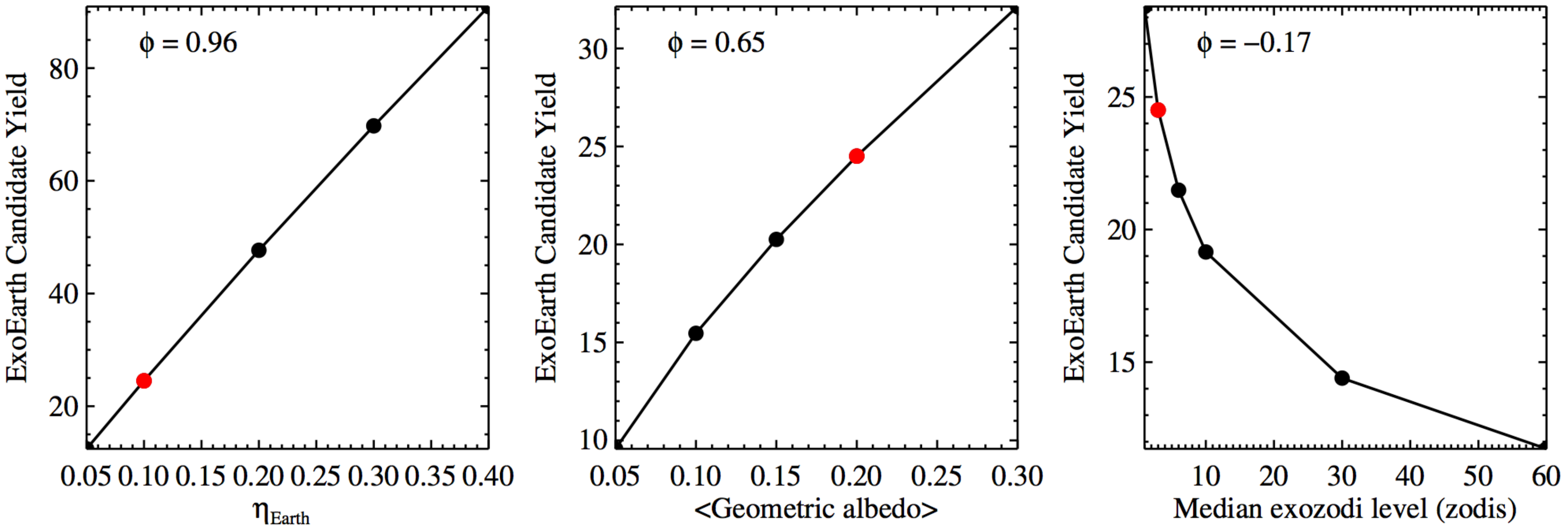
What Telescope/Instrument Parameters Matter?

Coronagraph Scaling Relationships



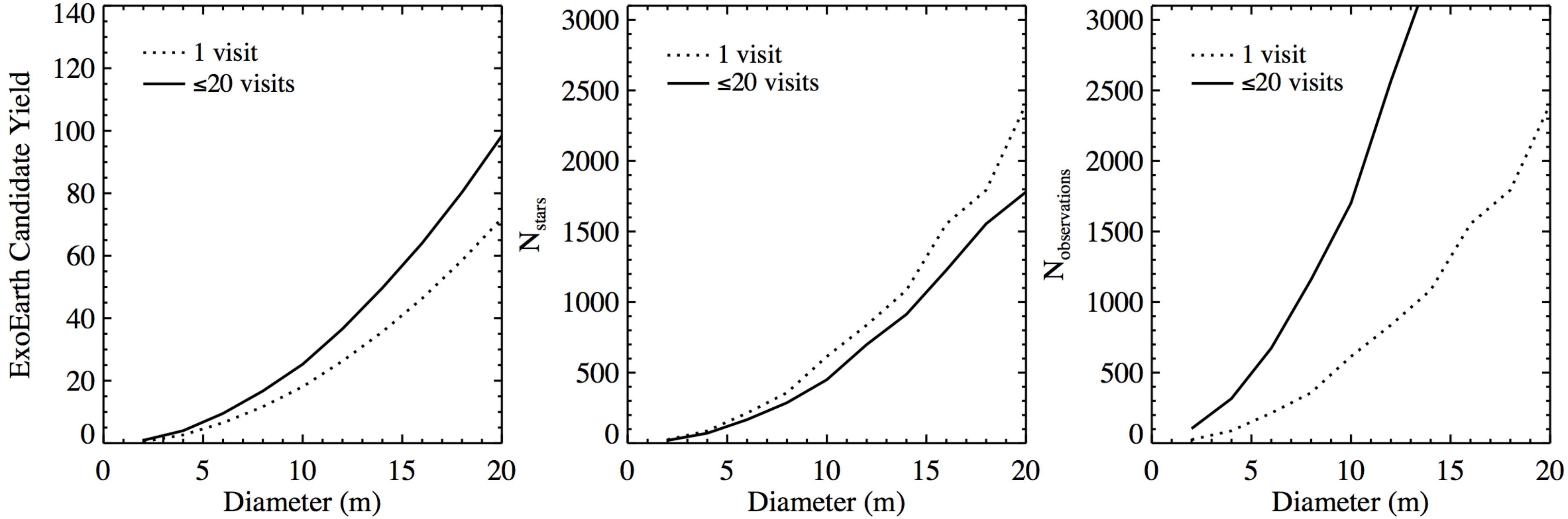
IWA matters more than contrast when treating both linearly. OWA doesn't matter much. Noise floors with Δmag > 26.5 are unnecessary.

Impact of Astrophysical Assumptions



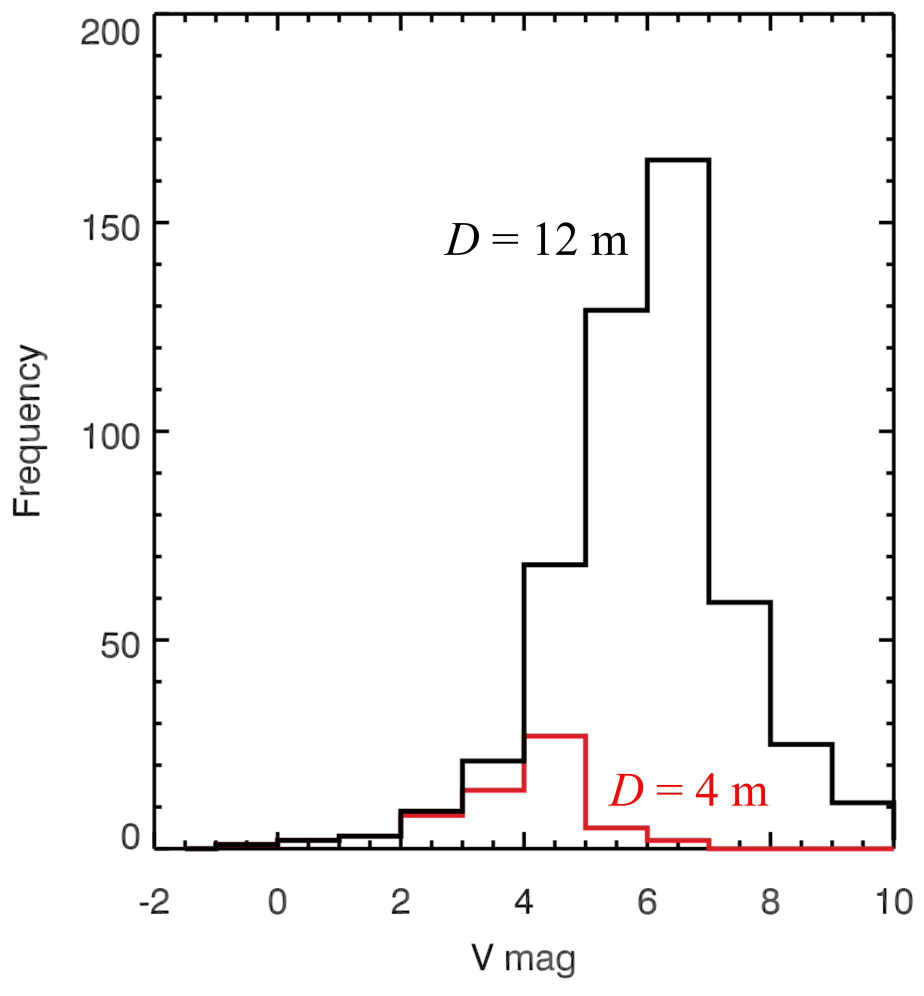
Coronagraphs yield linearly proportional to η_{Earth}.
Moderately strong dependence on exoEarth albedo.
Weak dependence on exozodi level.

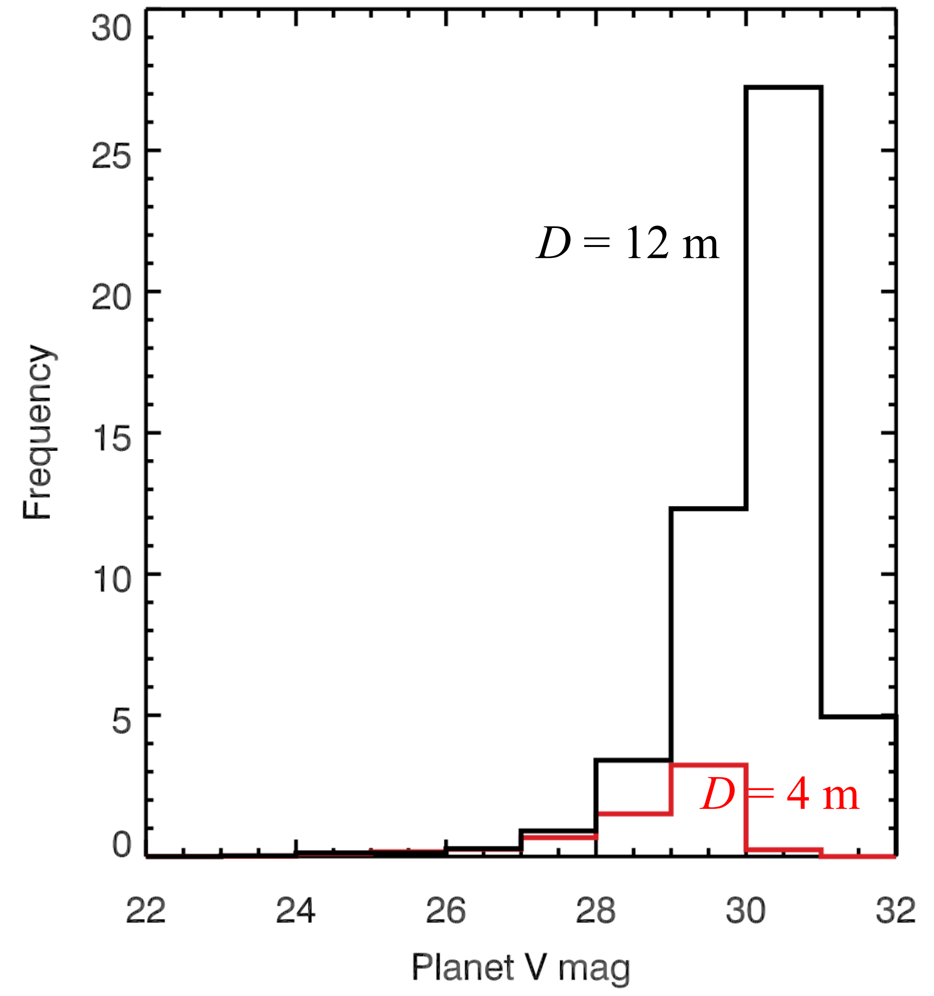
Details of an Optimized Observation Plan: Number of Stars & Number of Observations



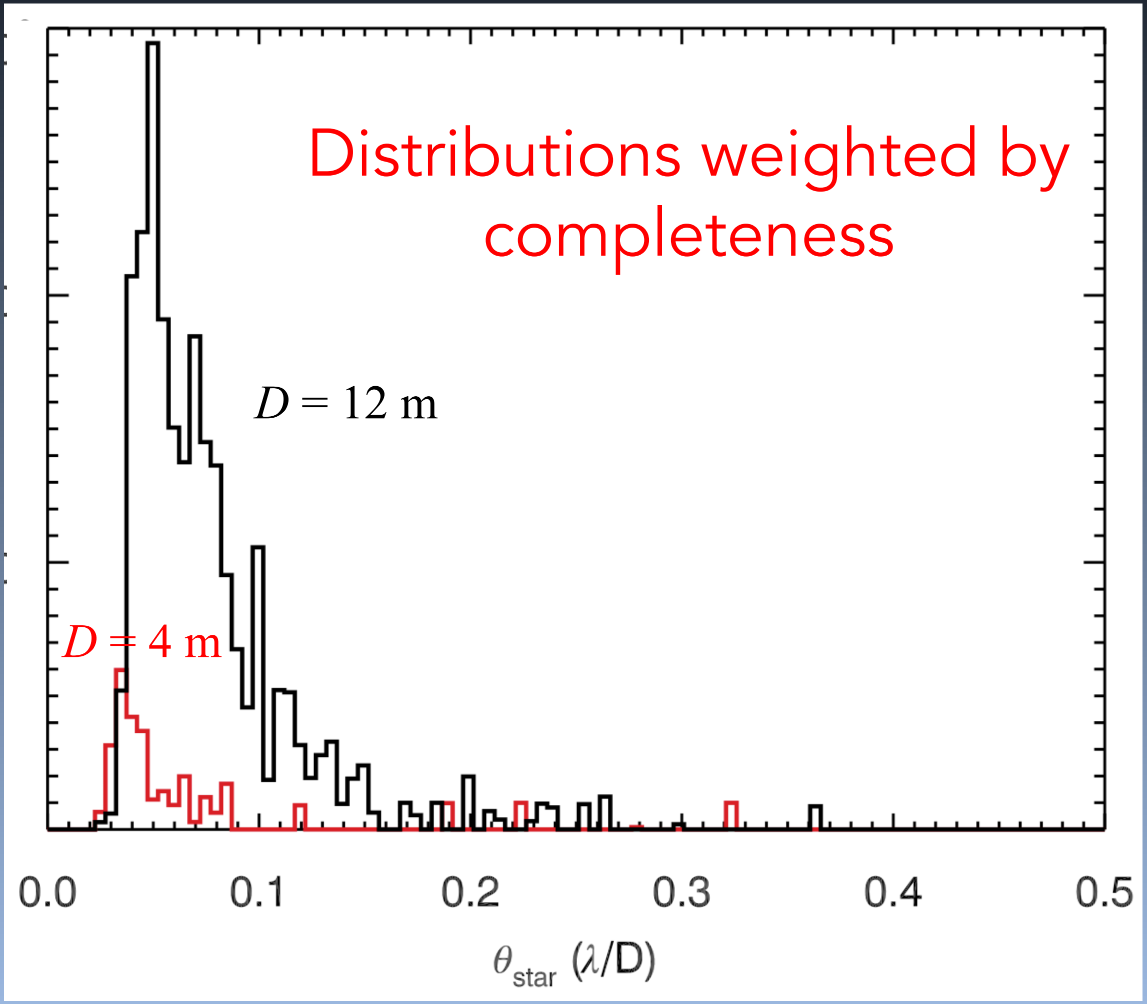
Optimization results in hundreds of stars and thousands of observations—code is skimming off gibbous phase planets. Don't worry! The # of observations can be greatly reduced with only small impact on yield. Overheads will ultimately limit # of observations.

Details of an Optimized Observation Plan: Stellar and Planet V_{mag} distribution





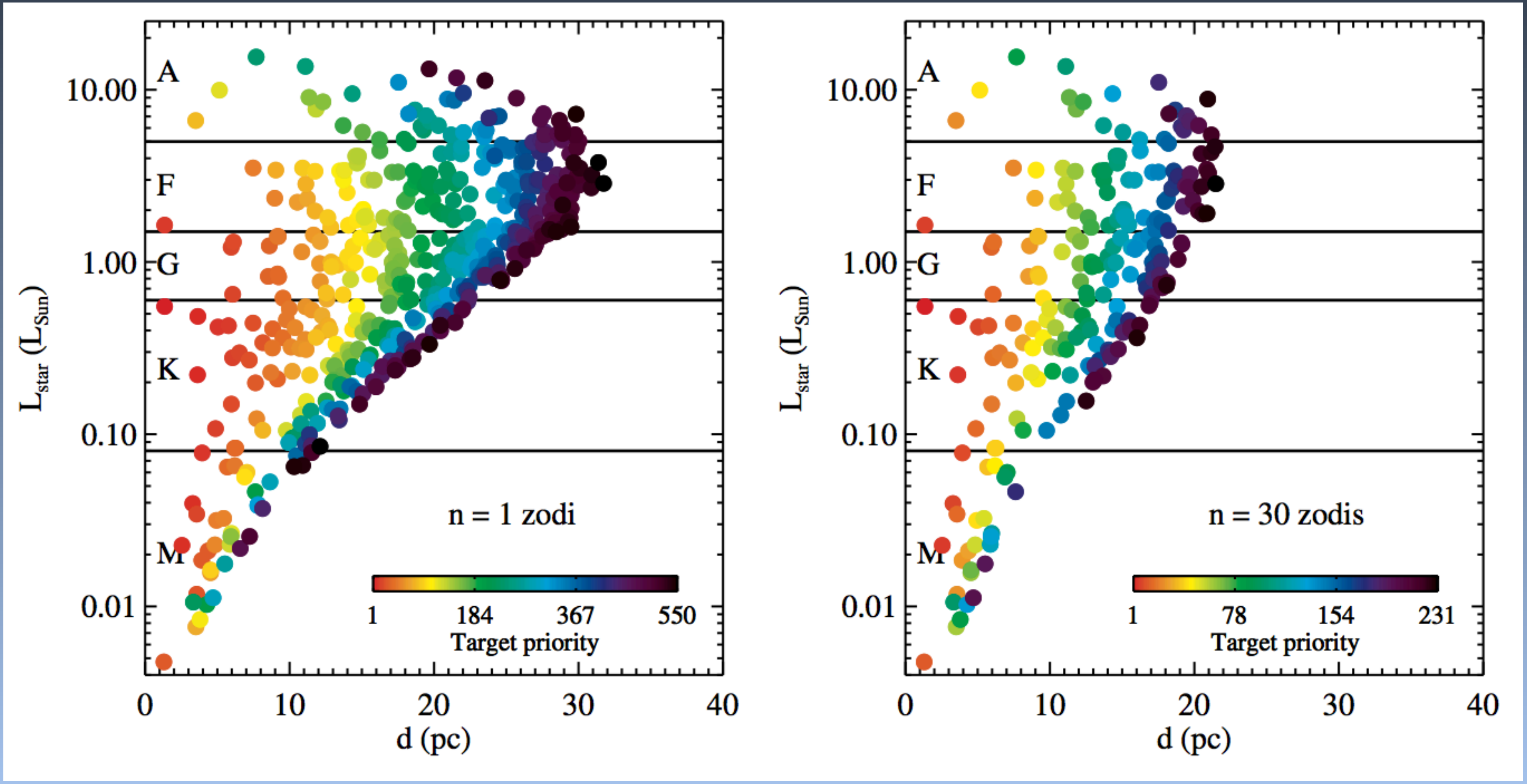
Details of an Optimized Observation Plan: Stellar Angular Diameter Distribution



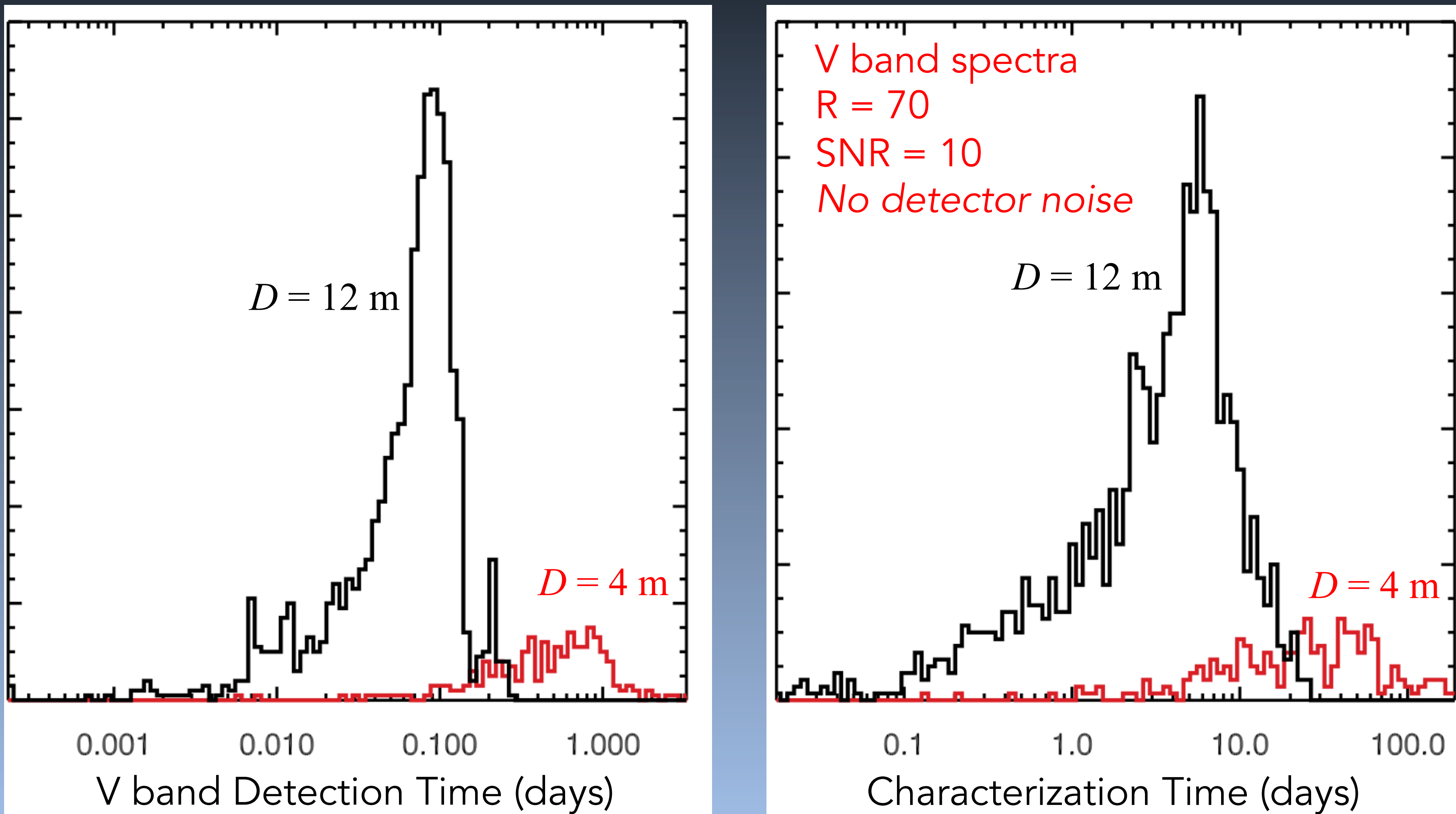
Peak of distribution not linearly proportional to *D*.
Larger apertures access smaller stars.

Details of an Optimized Observation Plan: Stellar Type and Distance Distribution

$D = 8$ m

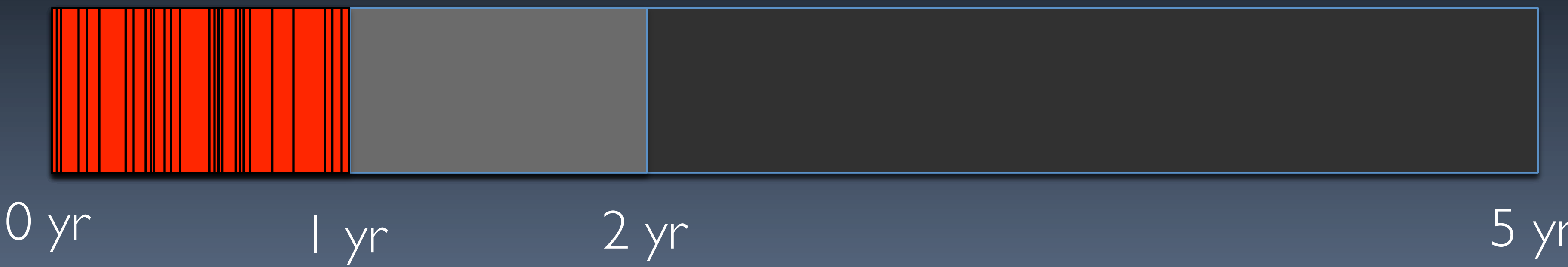


Details of an Optimized Observation Plan: Detection & Characterization Time Distribution

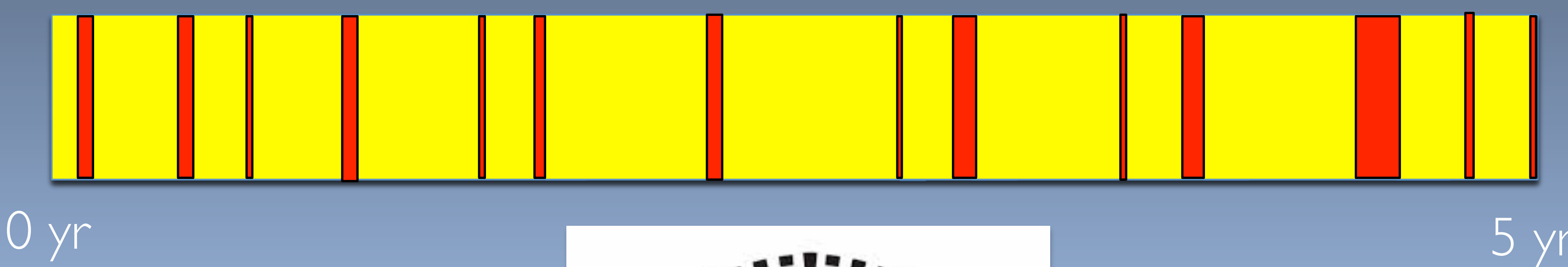


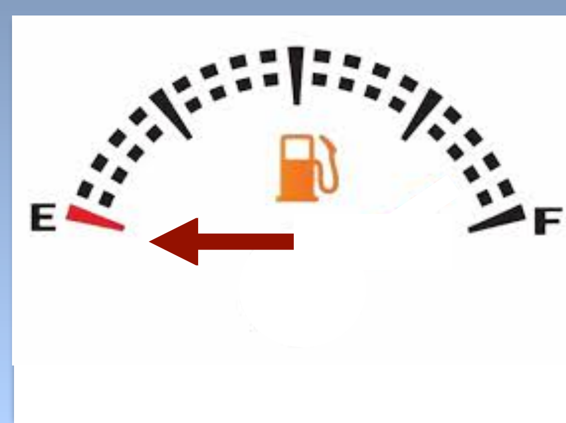
Optimizing Starshades: Balancing Time with Fuel

Coronagraph Optimization: Simple Time Budgeting

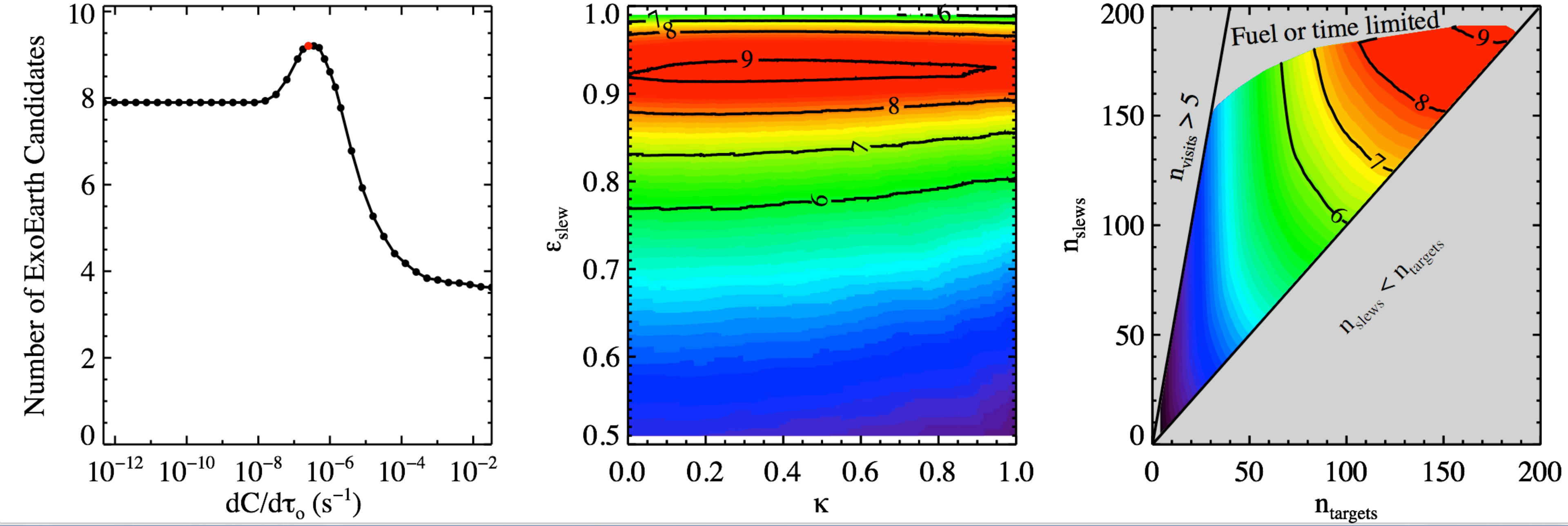


Starshade Optimization: Exposure Time & Fuel Are Connected





Optimizing Starshades: Balancing Time with Fuel



We search the 5-dimensional parameter space controlling starshade yield to maximize yield

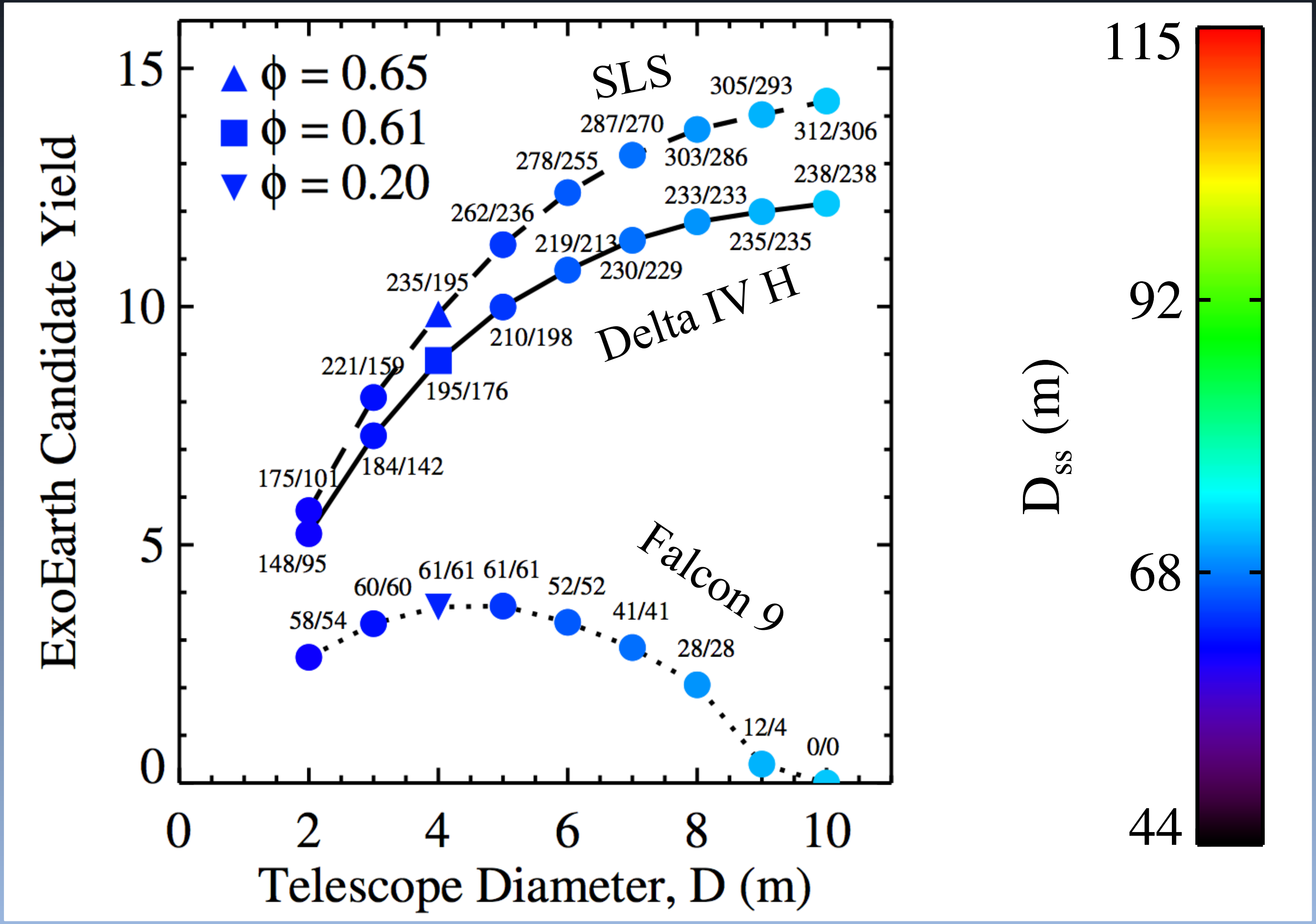
Baseline Starshade Mission Parameters

1 starshade

Detection Bandpass	Characterization Bandpass
$\lambda = 0.55\ \mu m$	$\lambda = 1.0\ \mu m$
$\Delta\lambda = 40\%$	Spectral Res. = 50
SNR = 7	SNR = 5
IWA = 60 mas	IWA = 60 mas
Contrast, $\zeta = 10^{-10}$	Contrast, $\zeta = 10^{-10}$

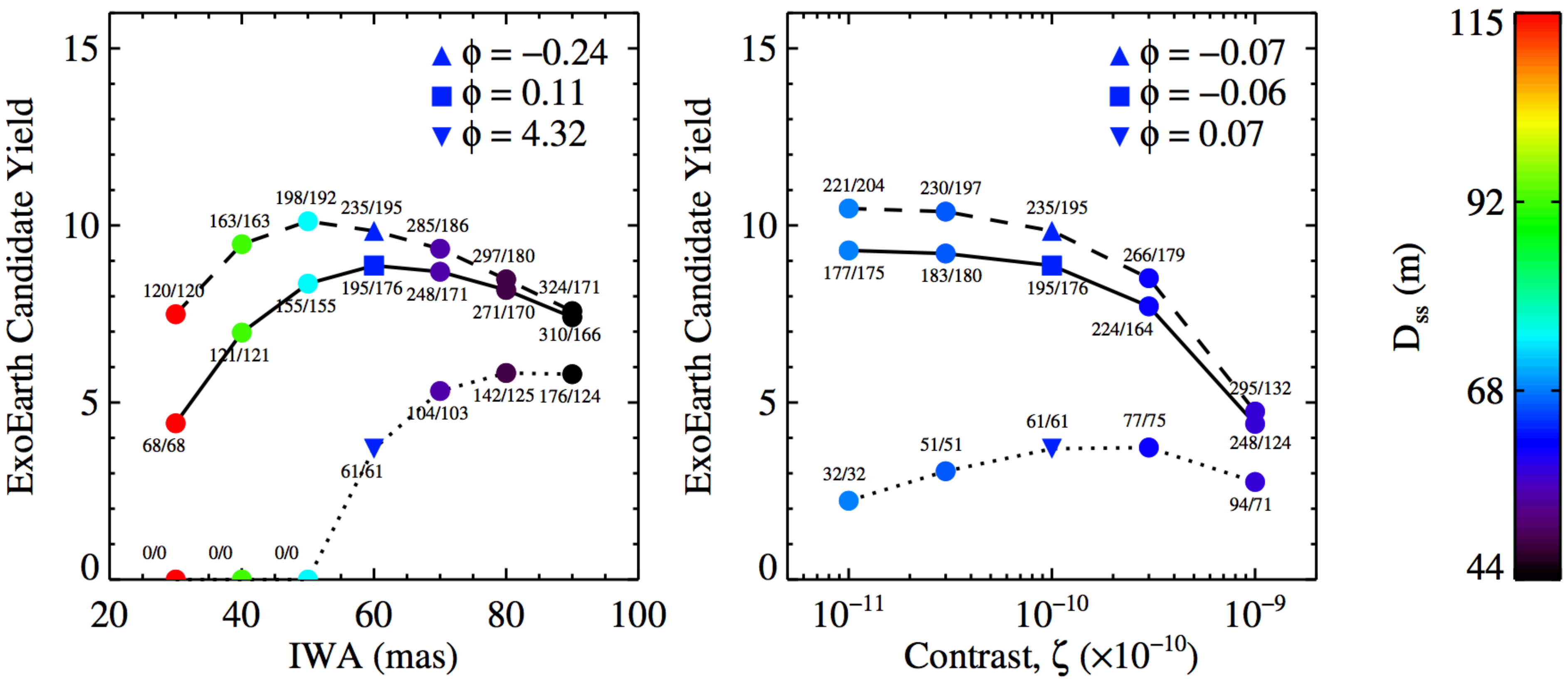
- End-to-end throughput = 0.65
- Noise floor, $\Delta mag_{floor} = 27.5$
- OWA = Infinite
- Diffraction-limited Airy pattern PSF
- No detector noise
- 5 yr mission: **Optimized exposure/slew time balance, no overheads**
- **<5 visits per star, no optimization of revisit time**
- **I_{slew} = 3000 s, I_{sk} = 300 s, Thrust = 10 N (!)**
- **Delta IV Heavy payload limit of 9800 kg to S-E L2**
- **Optimized starshade design from Eric Cady**

Maximized Yields for Starshades



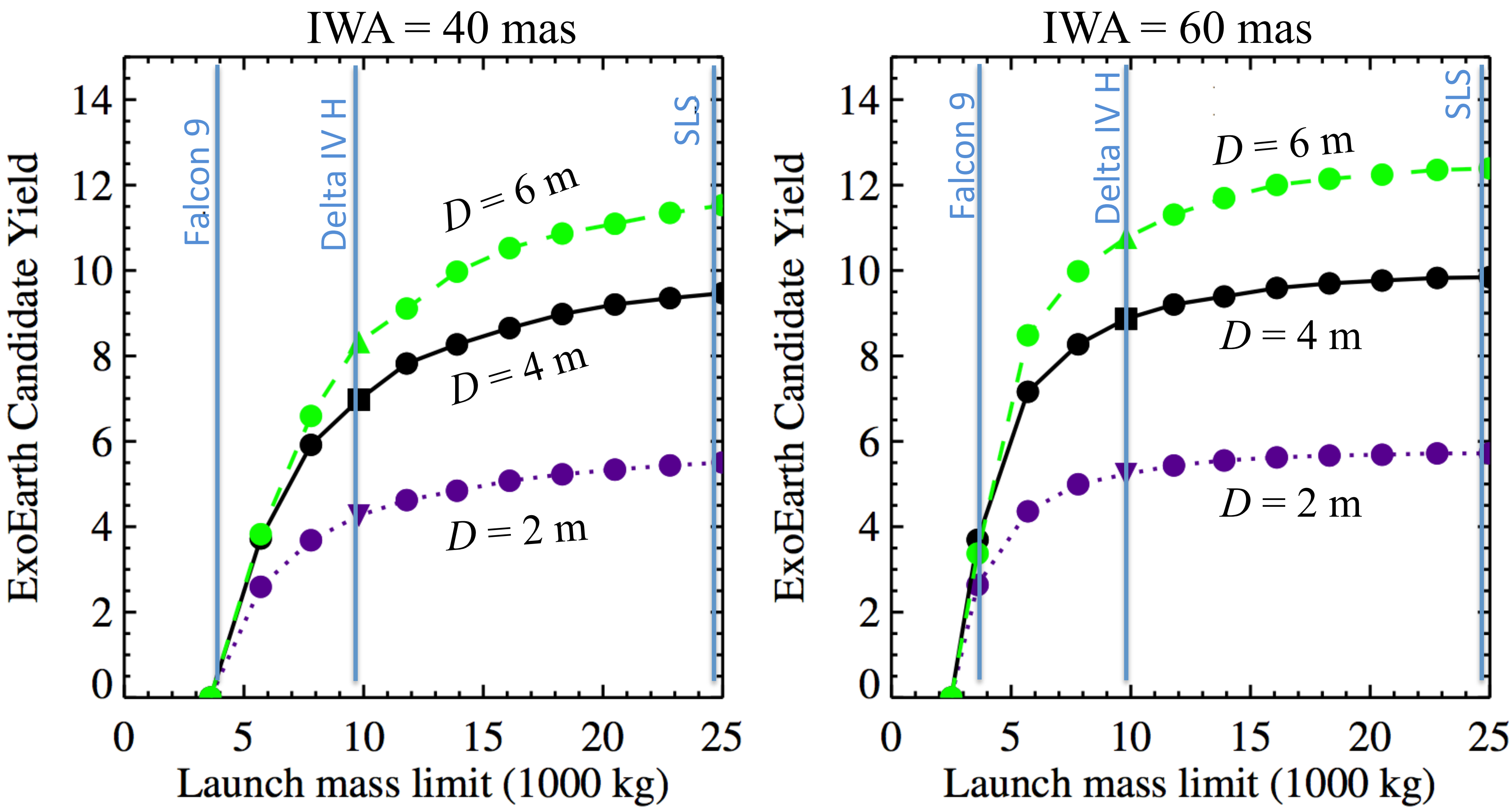
Yield is moderately sensitive to aperture size and turns over at large *D*; an optimum aperture size exists.

Yield vs Instrument Optical Parameters



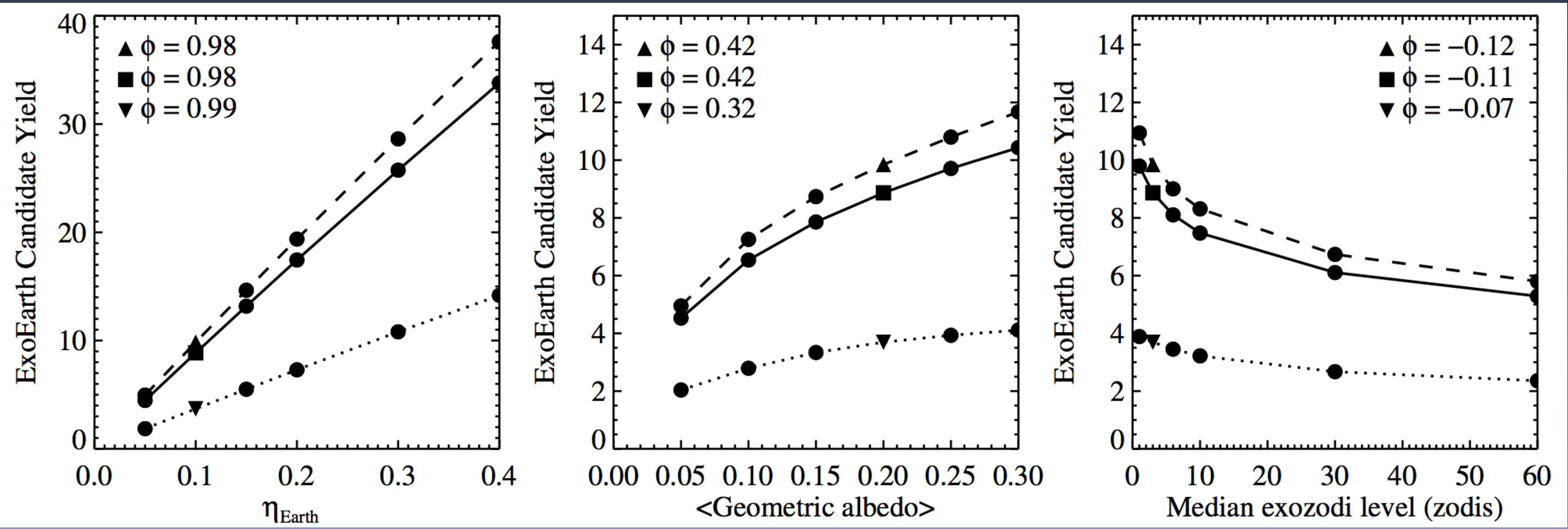
Small IWA = fuel hungry; Large IWA = planets unobservable.
An optimum IWA exists.

Yield vs Launch Mass



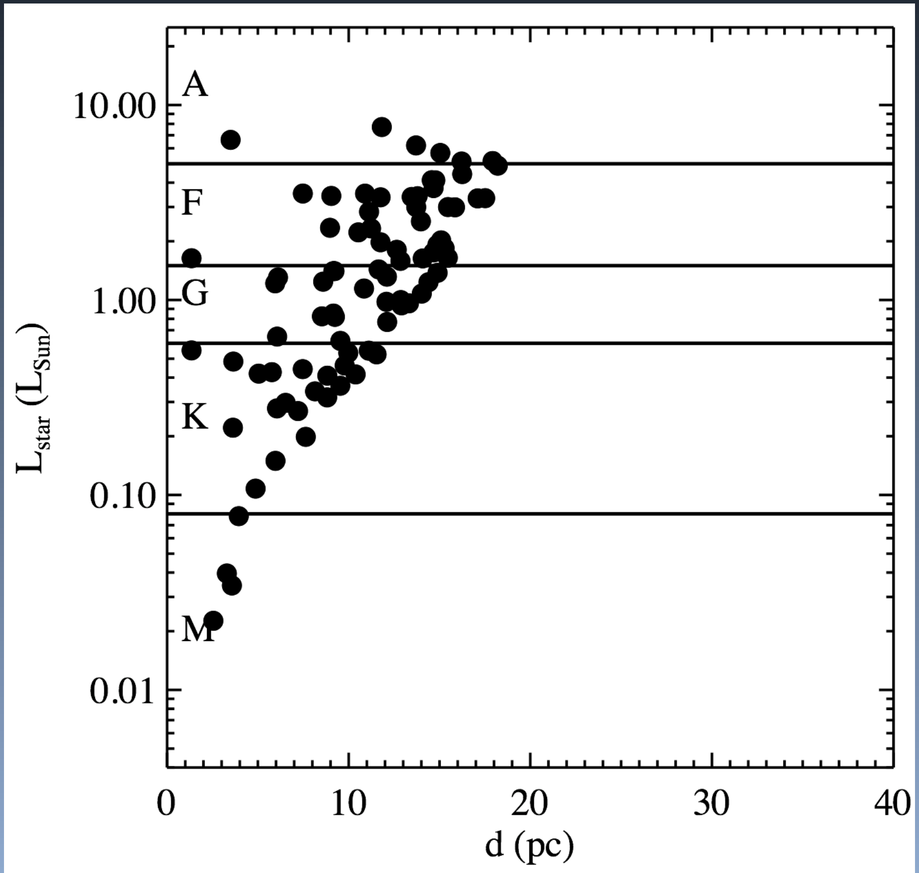
Starshade performance highly dependent on launch mass budget, i.e. fuel mass.

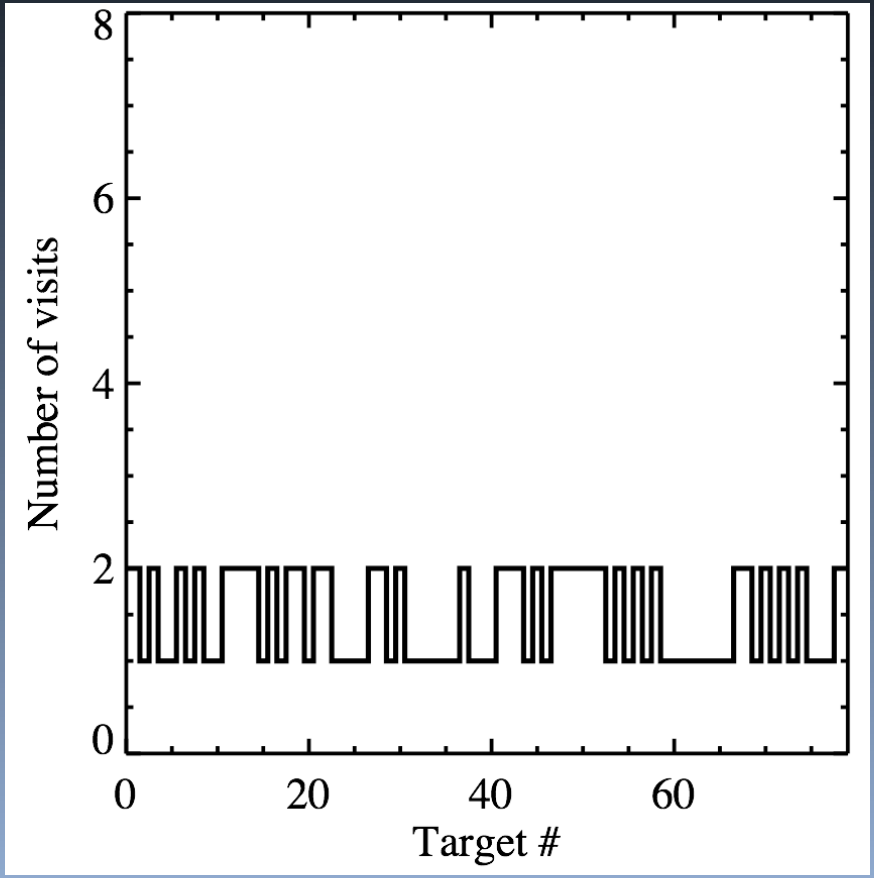
Impact of Astrophysical Assumptions



Compared to coronagraph, starshade yield more robust to astrophysical sources of photometric noise! This is because yield is partially limited by fuel.

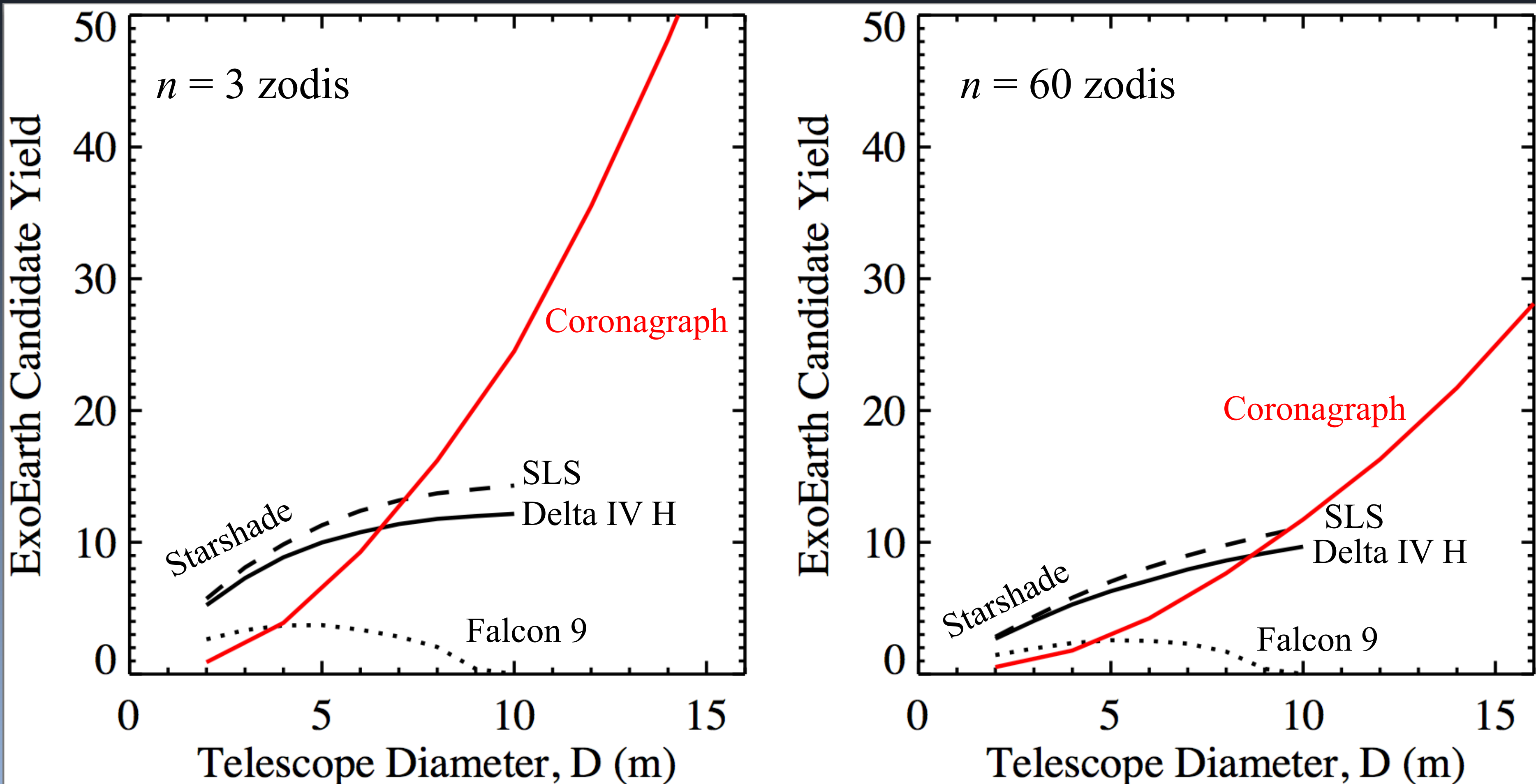
Details of an Optimized Observation Plan: Spectral Type & Visit Distribution





Starshade optimization chooses similar targets to coronagraphs, but observes them more deeply and only a couple of times.

Direct Comparison of Baseline Coronagraph & Baseline Starshade Yields



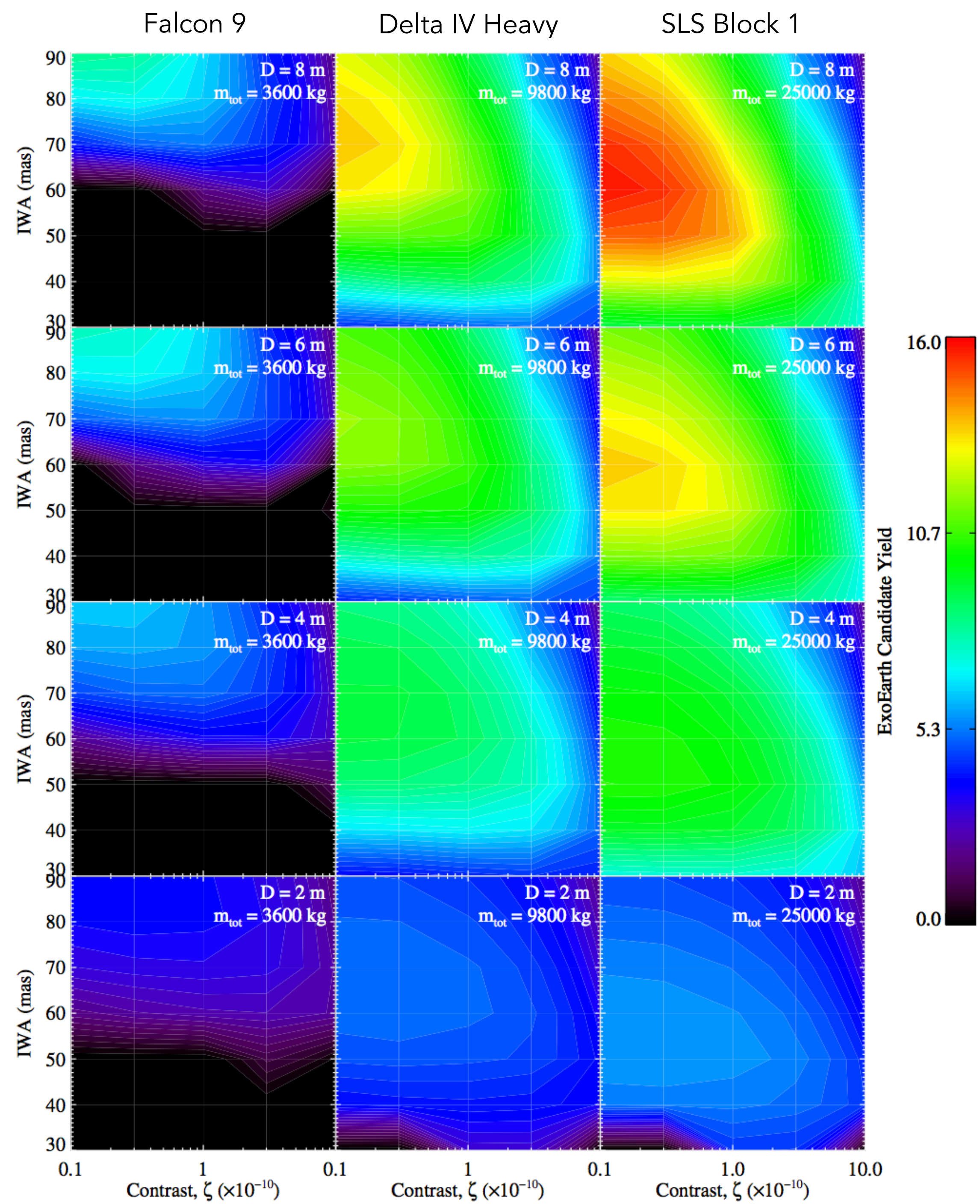
Assumes identical astrophysical assumptions, science goals, and observational "rules."

Need to examine the impact of the rules.

Future Work

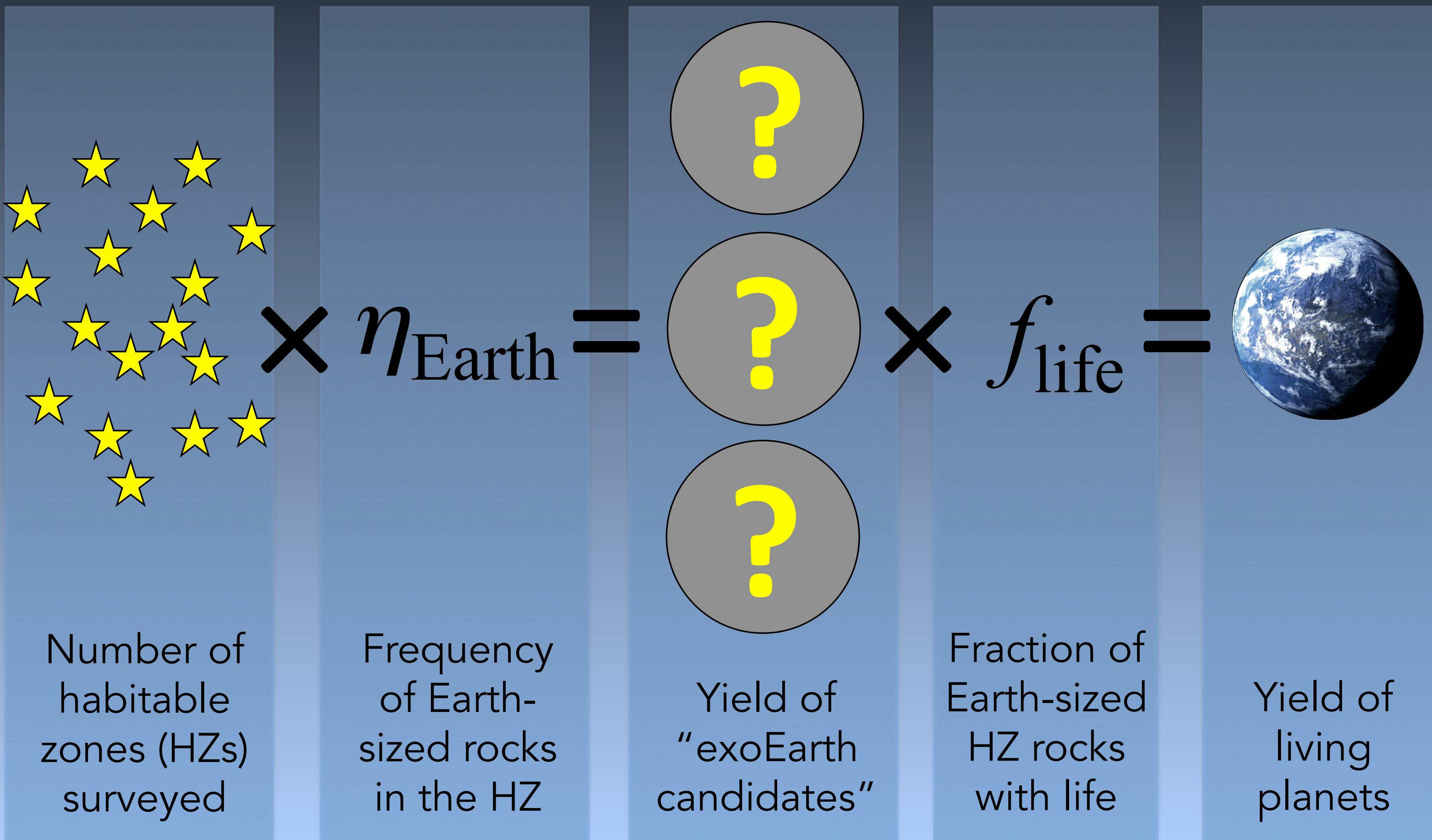
- Run yield calculations for actual coronagraph designs:
  www.starkspace.com/yield_standards.pdf
- Compare coronagraph & starshade yields for a variety of astrophysical scenarios, science goals, and observational approaches
- Produce a code capable of dynamic observation plans (learns as the mission progresses)
- Support Exoplanets Standards Team analysis of decadal studies

Backup Slides



Falcon 9
Delta IV Heavy
SLS Block 1
D = 8 m
m_tot = 3600 kg
m_tot = 9800 kg
m_tot = 25000 kg
D = 6 m
D = 4 m
D = 2 m
IWA (mas)
Contrast, ζ (×10^-10)
ExoEarth Candidate Yield
16.0
10.7
5.3
0.0

Choosing a Powerful Null Result in the Search for Life



How Does One Choose a Yield Goal?

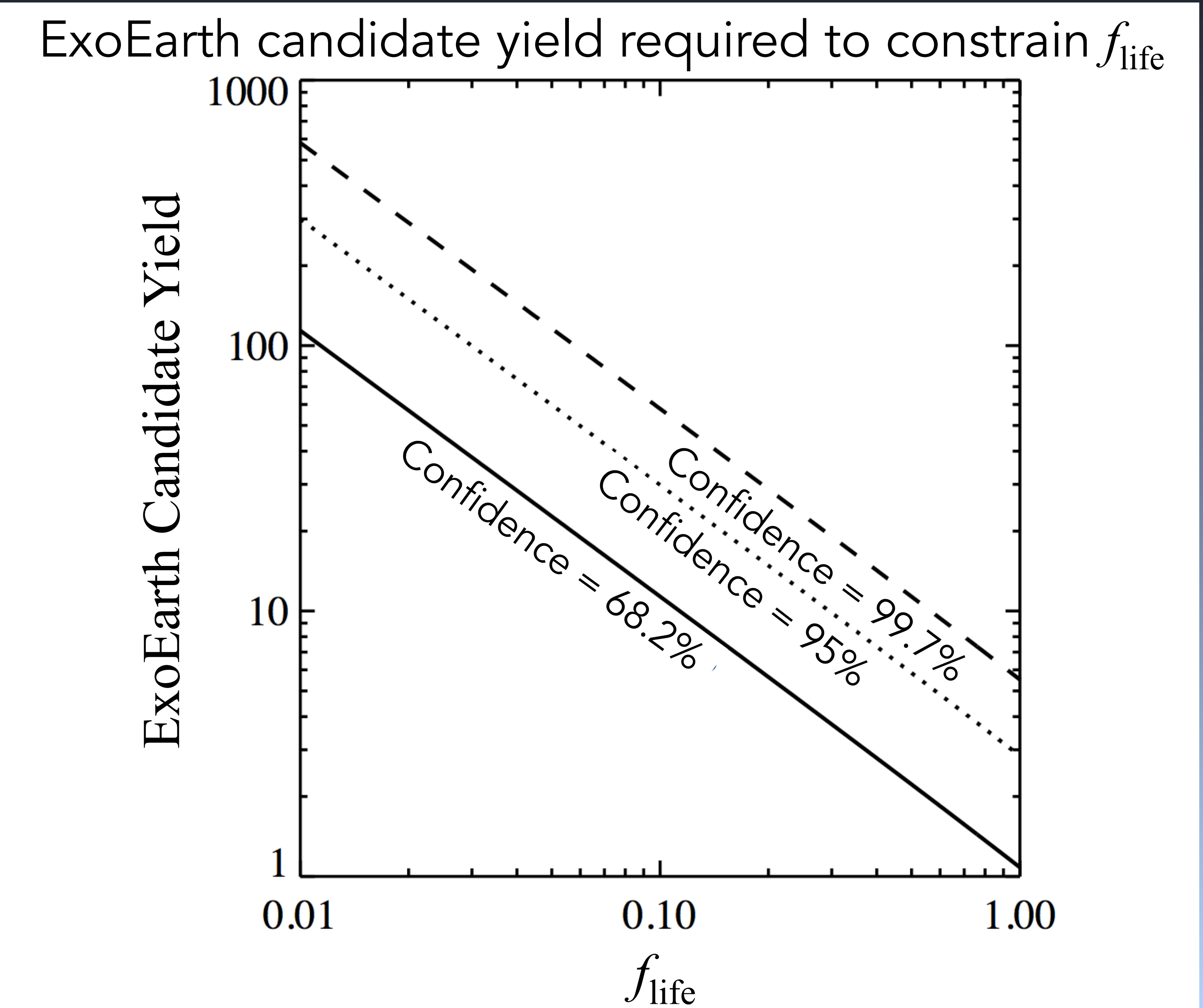
Must rely on blind selection counting. The probability P of x successes out of n tries, each with probability p of success, is given by the binomial distribution function…

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

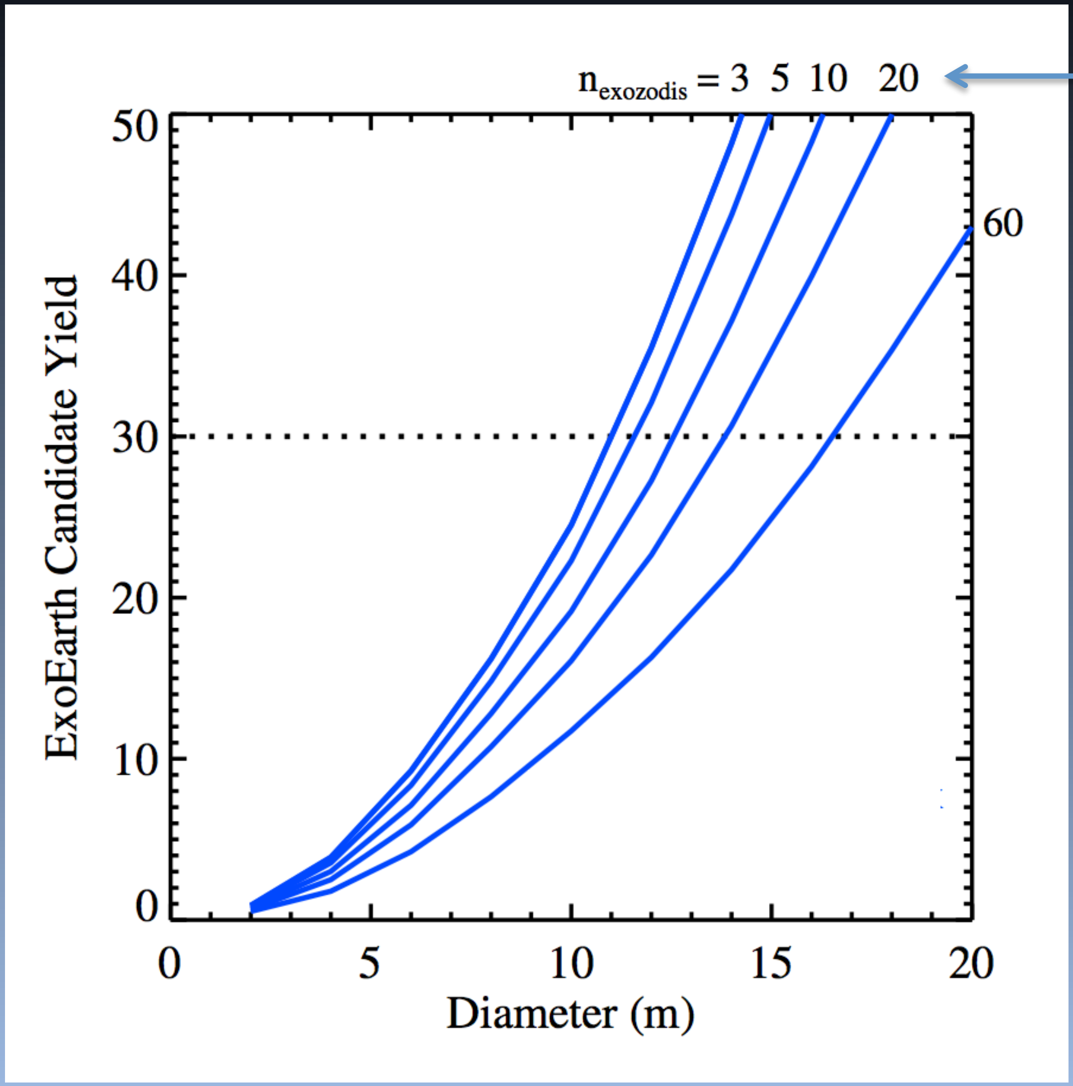
To guarantee at least 1 Earth-*like* planet at confidence level C

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

Choosing a Powerful Null Result in the Search for Life



Lower Limits on Aperture Size

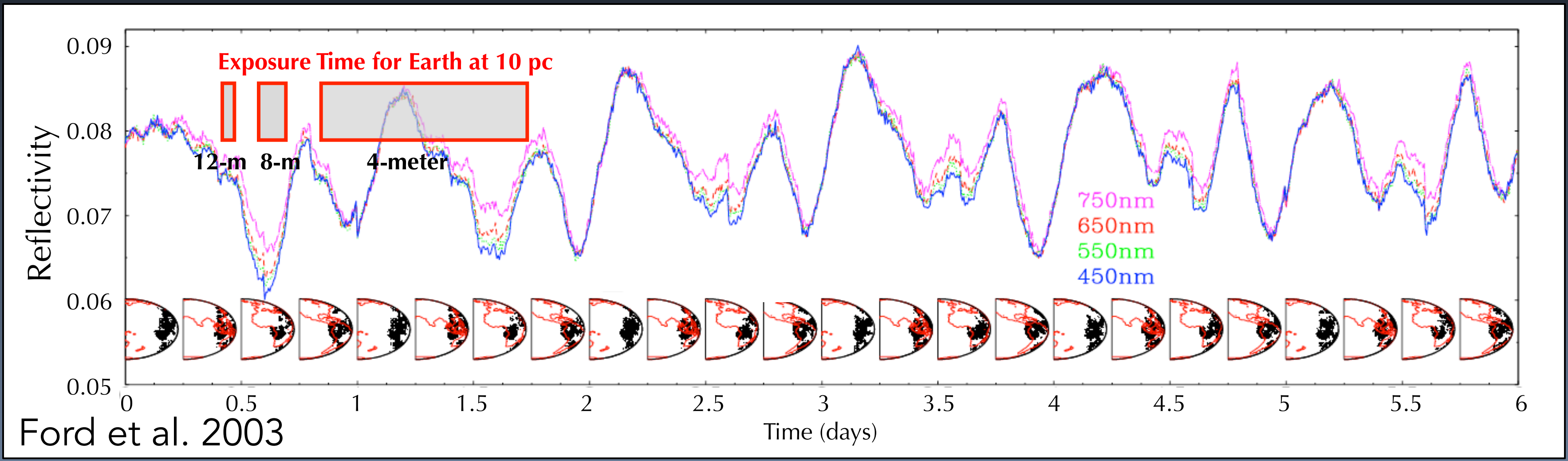


Amount of exozodiacal dust (× solar zodiacal amount)

If $\eta_{\text{Earth}} = 0.1$, detecting >30 exoEarth candidates requires $D \gtrsim 11$ m.

Larger Apertures Can Improve Characterization

Measuring rotational period and mapping planet



Ford et al. 2003

Require S/N~20 (5% photometry) to detect ~20% variations in reflectivity.

Reconstruction of Earth's land:sea ratio from disk-averaged time-resolved EPOXI observations.