Starshade Characteristics and Performance

Stuart Shaklan
Jet Propulsion Laboratory, California Institute of Technology
August 3, 2016

Habex Concept STDT Meeting

© 2016 California Institute of Technology. Government sponsorship acknowledged.

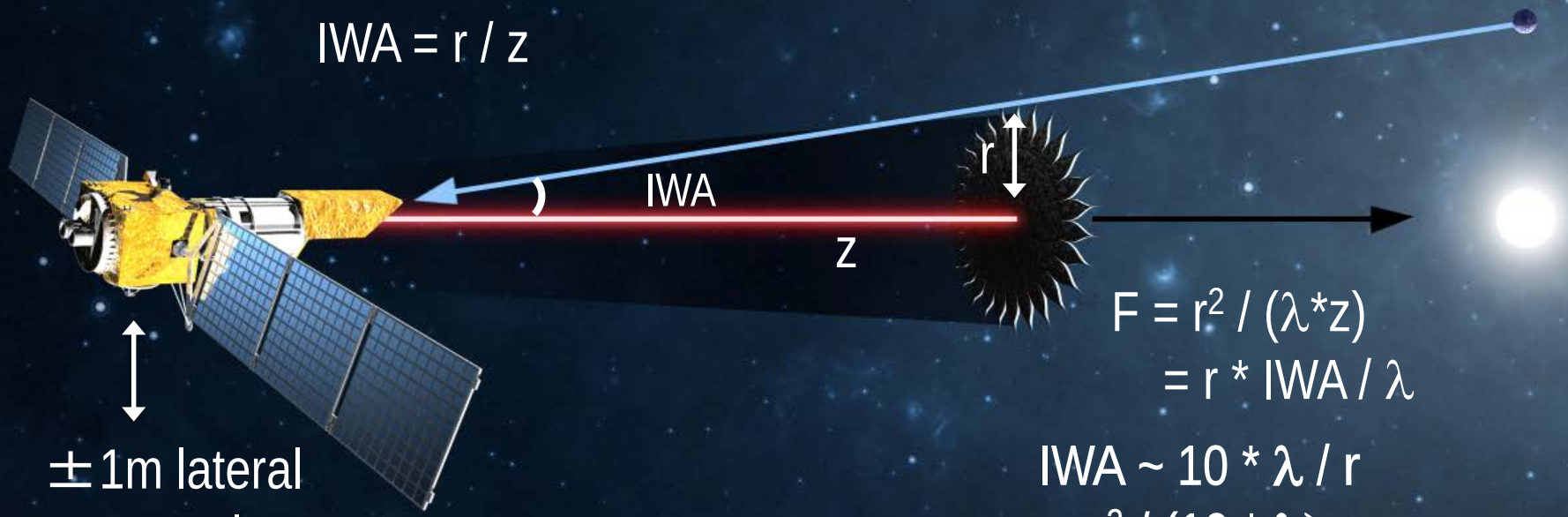
Overview

- Fresnel Number, IWA, wavelength dependence
- Bandwidth vs. IWA
  - What is the best bandwidth for discovery?
- Exo-earth discovery mission trade study (JPL)
- Exo-earth characterization and discovery trade study (Stark, STScI)

F = Fresnel Number ~10 for minimum starshade diameter, 30% bandpass, +/- 1 m lateral alignment tolerance

IWA = Inner Working Angle

IWA = r / z



$F = r^2 / (\lambda * z)$

$= r * IWA / \lambda$

$IWA \sim 10 * \lambda / r$

$z \sim r^2 / (10 * \lambda)$

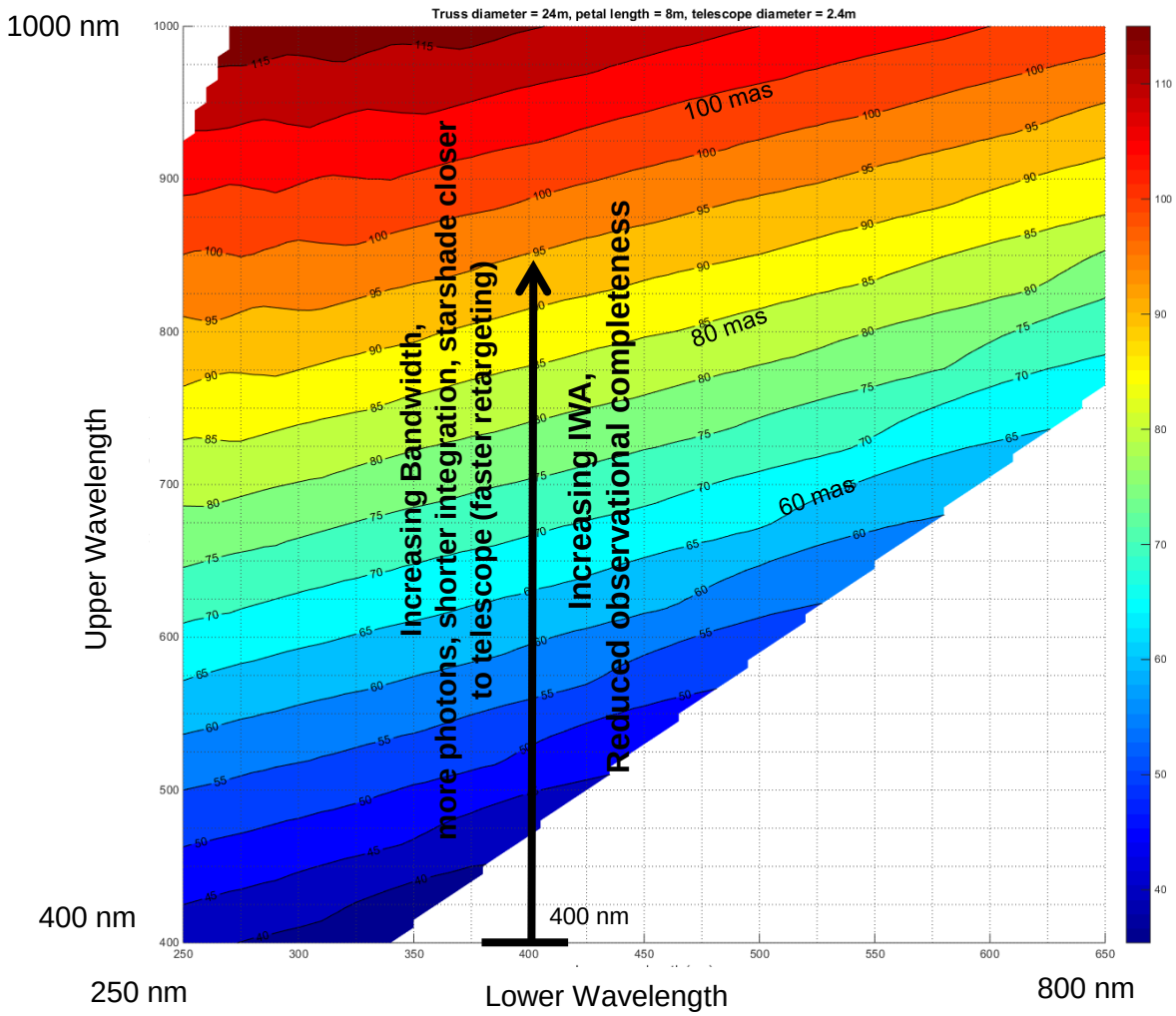
±1m lateral control

For a given starshade, we can move it closer (increase IWA, increase λ, characterize), or move it farther away (decrease IWA, decrease λ, discover).

Artist's concept of starshade mission.

Exo-Earth Detection Optimization

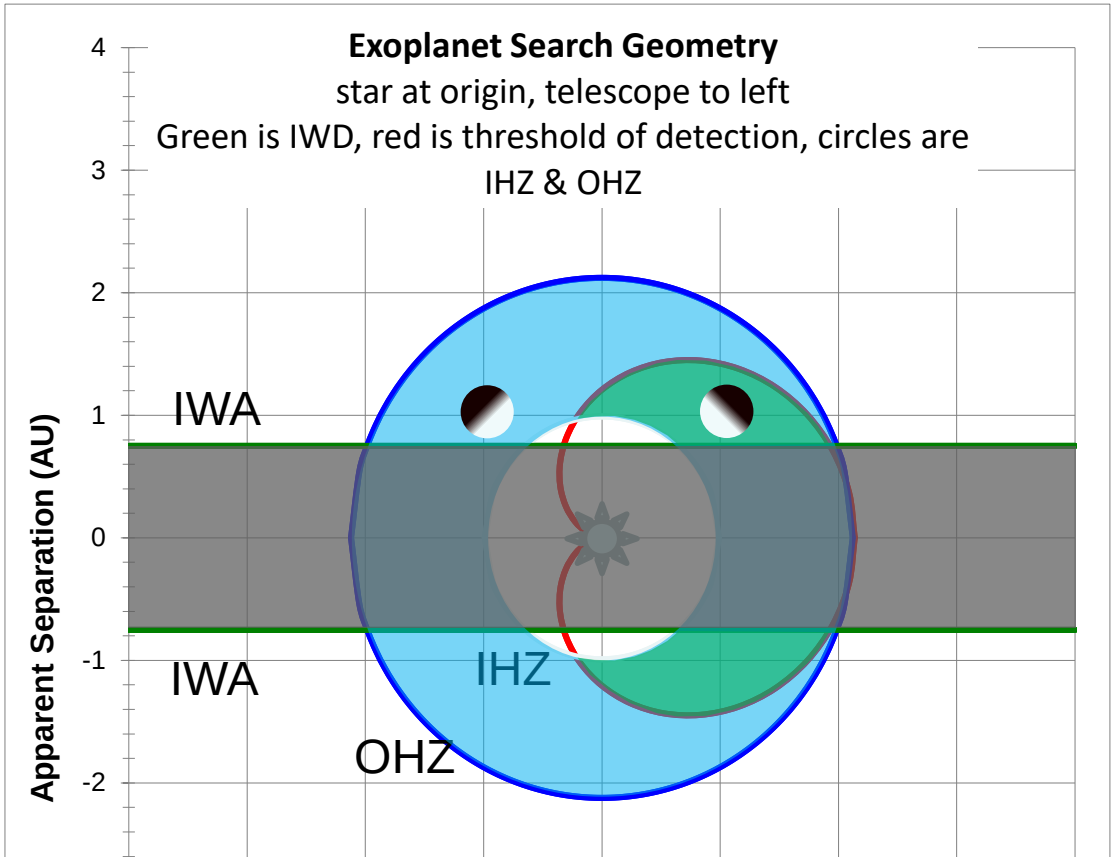
Contours of IWA for a 40 m starshade diameter



Observational Completeness

Obscurational and Photometric

To Starshade and Telescope



Completeness is the shaded green volume divided by shaded blue volume
= probability of seeing a planet if one is present

Cumulative completeness is the summed completeness for all stars observed
= expected number of planets observed if every star has one planet

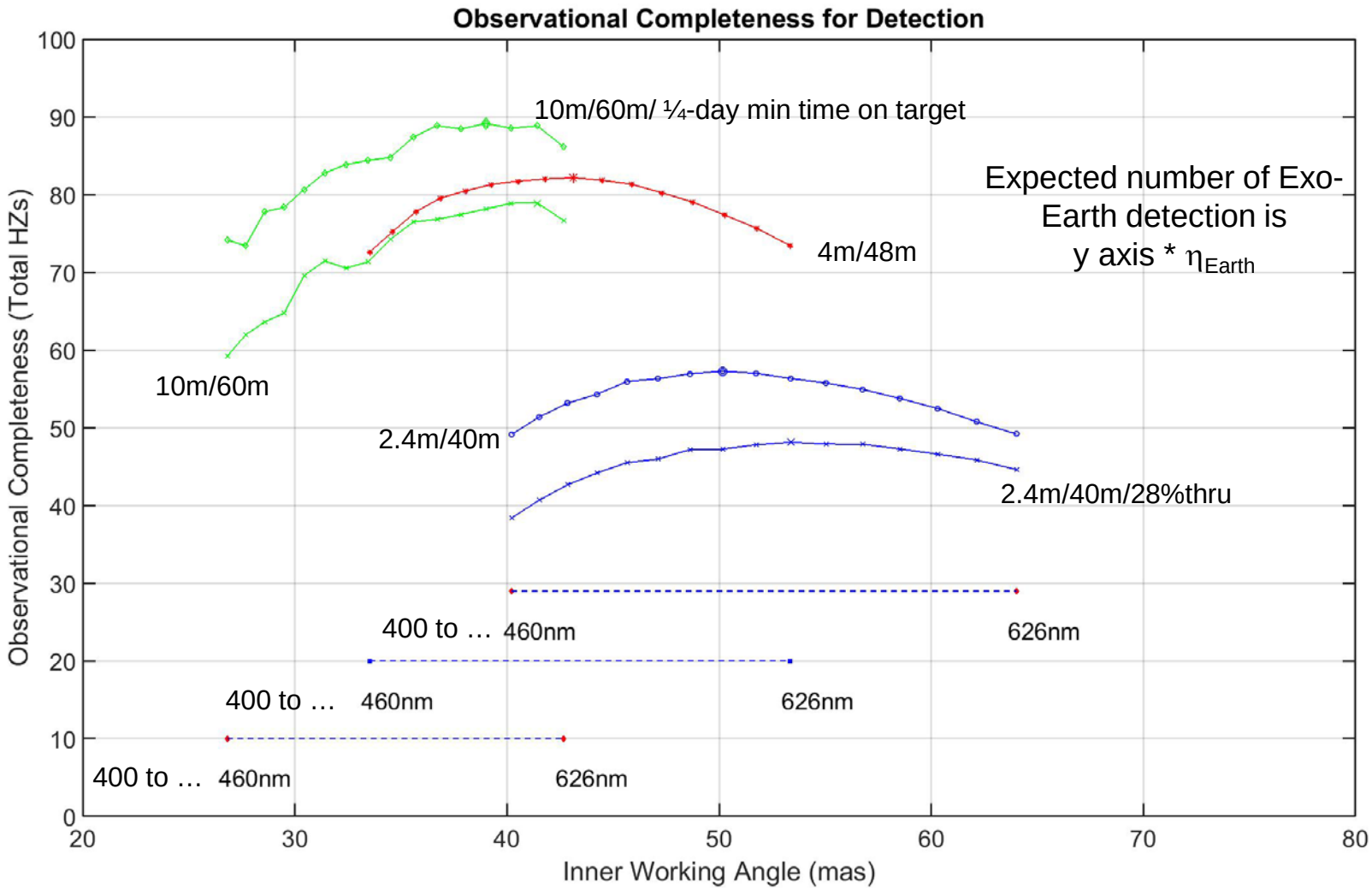
Exo-Earth Key Observational Parameter Trades

Do an exhaustive search over these quantities to maximize the number of Exo-Earth detections for a given period of observation (5 years), projected launch vehicle (Atlas 5), and starshade diameter / telescope pairing.

- Optical Bandwidth:
  - Smaller bandwidth reduces IWA, improving Completeness/Target
  - Reduced IWA moves starshade farther away, increasing slew time.
  - Smaller bandwidth increases integration time, reducing available slew time.
- Limiting Sensitivity:
  - Higher sensitivity increases Completeness/Target
  - Lower sensitivity decreases integration time leaving more time to slew.
- Completeness Threshold:
  - Too high and there are not enough stars.
  - Too low and the observational efficiency suffers.
- Maximum Integration Time per star:
  - Too low and there are not enough stars.
  - Too high and the observational efficiency suffers.
- *Limitations in our study*
  - Single visit completeness. With revisits can push observational completeness up ~25%
  - Assumes stars are equally spaced. DRM simulations confirm consistency with assumed number of targets.

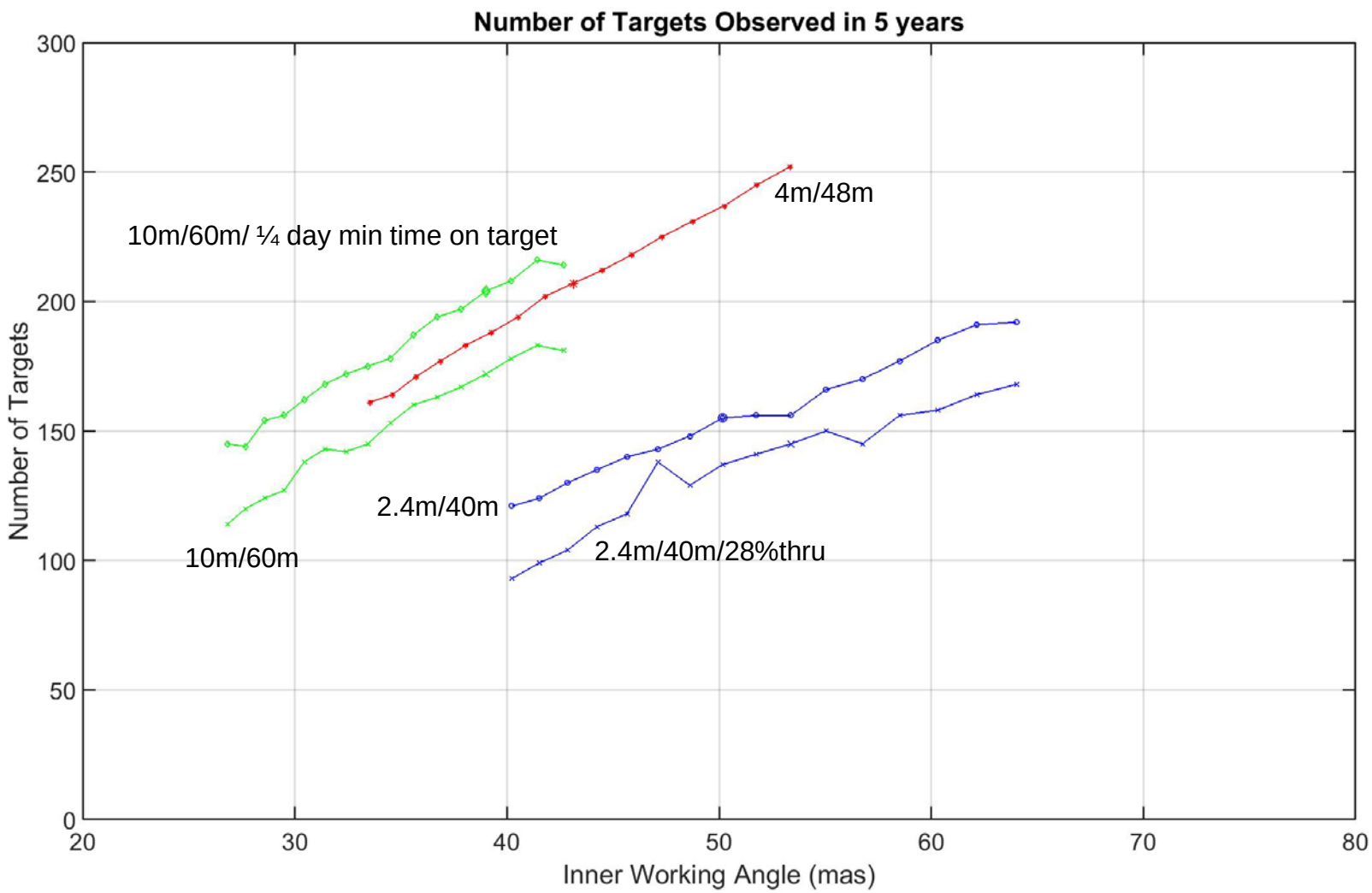
Comparative HZ Observational Completeness (JPL)

1-day min time on target assuming proposed ARRM Thrusters



Assumptions: optical throughput 46% unless otherwise stated. Minimum time on target = 1 day unless otherwise stated. QE = 0.8, read noise=2.8 e-, dark current=5.5e-4, read time=2000 s, Instrument contrast=1e-10, Sharpness=0.08, Total Zodis = 21.5 mag/sq. arcsec, SNR = 6, minimum wavelength 400 nm, maximum wavelength 460-626 nm, 5 yr mission.

Number of Targets Observed



Starshade Mission Concept Exo-Earth Detection Results

- WFIRST can be powerfully leveraged with a 40m starshade to find Exo-Earths.
  - Samples 48 cumulative HZs in 5 years using 25% of mission time (dark energy observations continue in parallel with starshade observations)
  - *It is an excellent precursor to a larger mission, e.g. HDST with a starshade*
- HABEX concept with a 48 m starshade samples 82 HZs in 5 years with minimal mission time.
- HDST concept with 2 60m starshades samples 134 HZs in 5 years with minimal mission time

Tel (m)	# Starshades	Thruput %	**Starshade (m)**	Bandwidth %	IWA (mas)	Total Int. Time (d)	# Targets	**Detection Cum. Compl. (HZ)**
10	**2**	46	**60**	32	36	320	320	**134**
10	1	46	**60**	42	41	54 (¼ day)	216	**89**
4	1	46	**48**	30	43	252	207	**82**
2.4	1	46	**40**	28	50	445	155	**57**
2.4	1	28	**40**	32	53	455	145	**48**

Wavelength band 400 nm - ~550 nm.
This band is useful for imaging surveys but not for characterization.

- Observational completeness for all planet types is much higher than Exo-Earth completeness shown in table

Table Assumptions: ARRM Thrusters, 1-Day min/target unless noted, QE = 0.8, Total Zodis = 21.5 mag/sq. arcsec, SNR = 6, minimum wavelength 400 nm. 5 yr mission.

Starshade Mission Concept Exo-Earth Characterization Results

- Characterization requires NIR wavelengths. Here we use 600-850 nm.
  - IWA increases in proportion to wavelength compared to the detection band.
  - R=70, SNR=10 per channel
- A 10 m telescope with a 60 m starshade characterizes nearly 70 HZs.
  - The completeness is still 50 HZs even when integration time is limited to 5 days per target.
- Smaller telescopes can't compete with the large aperture for characterization.

Tel (m)	Starshade (m)	IWA (mas)	Max Int. Time (d)	# Targets	Characteriz. Cum. Compl. (HZ)	Detection Cum. Compl. (HZ)
10	**60**	57	20	269	**69**	
4	**60**	57	20	61	**22**	
2.4	**60**	57	20	13	**6**	
10	**60**	57	20	269	**69**	**89**
4	**48**	71	20	55	**18**	**82**
2.4	**40**	85	20	11	**4**	**48**
10	**60**	57	10	227	**63**	
10	**60**	57	5	166	**50**	
10	**60**	57	1	55	**20**	

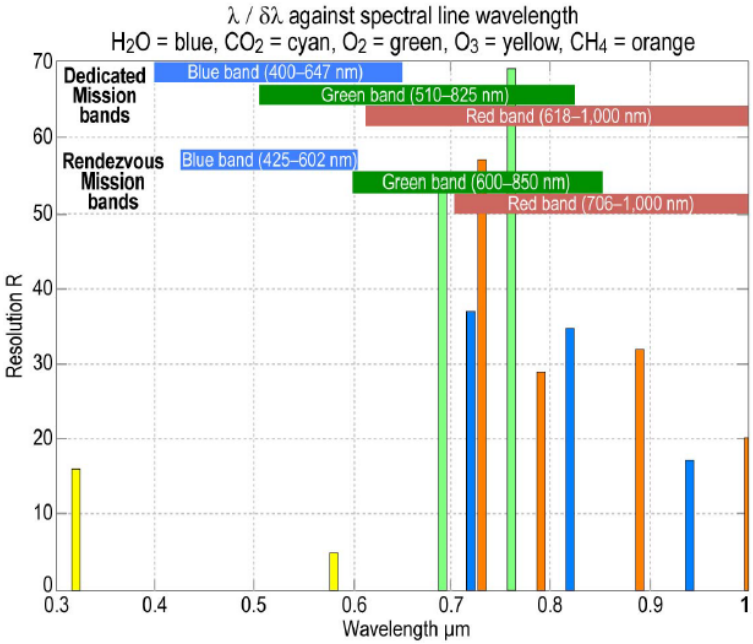


Table Assumptions: Optical throughput 46%, QE = 0.8, Total Zodis = 21.5 mag/sq. arcsec, Spectral resolution = 70, SNR = 10 per resolution element.

Stark et al (2016) Starshade Model Parameters

Table 2 Baseline mission parameters.

Parameter	Value	Description
D	4 m	Telescope diameter
I_{sk}	300 s	Specific impulse of stationkeeping propellant (chemical)
I_{slew}	3000 s	Specific impulse of slew propellant (electric)
ε_{sk}	0.8	Efficiency of stationkeeping fuel use
ε_{slew}	0.91[a,b]	Efficiency of slew fuel use
D_{ss}	61.7 m[b,c]	Diameter of starshade
m_{dry}	2742 kg[b,d]	Dry mass of starshade spacecraft including contingency
m_{tot}	9800 kg	Total initial mass of starshade spacecraft including fuel
$\mathcal{T}$	10 N[e]	Thrust
T	0.65	End-to-end facility throughput, excluding photometric aperture factor
X	0.7	Photometric aperture radius in λ/D

Delta IV heavy

[a]Optimized value chosen by code given high thrust assumption.
[b]Dependent quantity.
[c]Optimized for a given bandpass, IWA, contrast, and telescope diameter; see Sec. 2.5.
[d]See Sec. 2.5.
[e]Value chosen to ensure starshade operates far from thrust-limited regime.

Assumes 5 year mission

Table 2 (*Continued*).

Parameter	Value	Description
Υ	0.69	Fraction of Airy pattern contained within photometric aperture
Ω	$b\pi(X\lambda/D)^2$ radians[b]	Solid angle subtended by photometric aperture
b	1.0	Areal broadening of the planet's point spread function (PSF)
IWA	60 mas	Inner working angle
OWA	∞	Outer working angle
$\Delta\mathrm{mag}_{floor}$	2.5–2.5 $\log\zeta_d$[b]	Systematic noise floor (i.e., dimmest point source detectable at S/N)
λ_d	0.55 μm	Central wavelength for detection (V band)
$\Delta\lambda_d$	0.22 μm	Bandwidth for detection
S/N_d	7	Signal-to-noise ratio required for broadband detection of a planet
ζ_d	10^{-10}	Raw contrast level in detection region, relative to theoretical Airy pattern peak
$CR_{b,detector,d}$	0	Detector noise count rate for detection
λ_c	1.0 μm	Central wavelength for spectral characterization
R_c	50	Spectral resolving power required for spectral characterization
S/N_c	5	Signal-to-noise ratio per spectral resolution element required for spectral characterization
ζ_c	10^{-10}	Raw contrast level for spectral characterization, relative to theoretical Airy pattern peak
$CR_{b,detector,c}$	0	Detector noise count rate for spectral characterization

Projections for 4 m, 60 mas, 1e-10

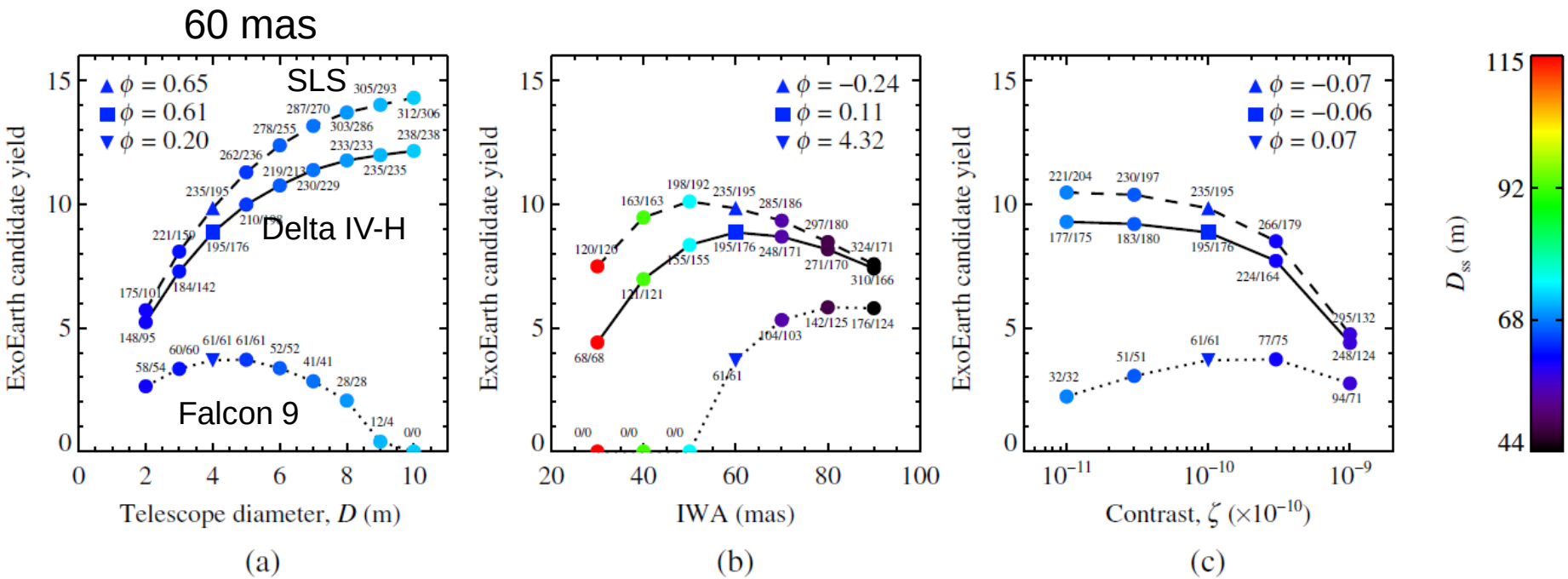


Fig. 7 ExoEarth candidate yield as a function of (a) telescope diameter, (b) IWA, and (c) contrast for the baseline mission assuming launch mass limits of 3600 (dotted line), 9800 (solid line), and 25,000 kg (dashed line). Color indicates starshade diameter and $n_{\text{slews}}/n_{\text{targets}}$ is listed next to each data point. The sensitivity of yield, ϕ, is given at the baseline parameter values of each curve.

Color of marker is starshade diameter.

Projections for 6 m, 50 mas, contrast 3e-10

50 mas

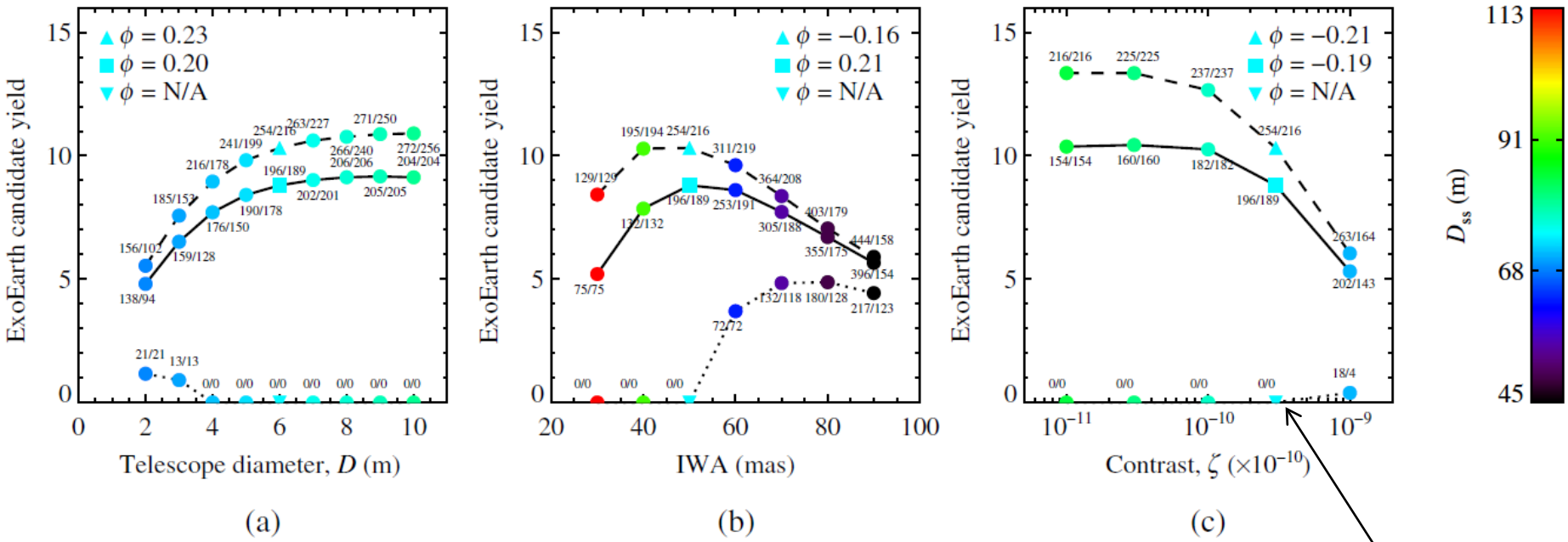


Fig. 8 Same as Fig. 7, but for values of $D = 6$ m, IWA = 50 mas, and $\zeta = 3 \times 10^{-10}$.

Not enough fuel to support the smaller working angle

Projection for Yield vs. Launch Mass

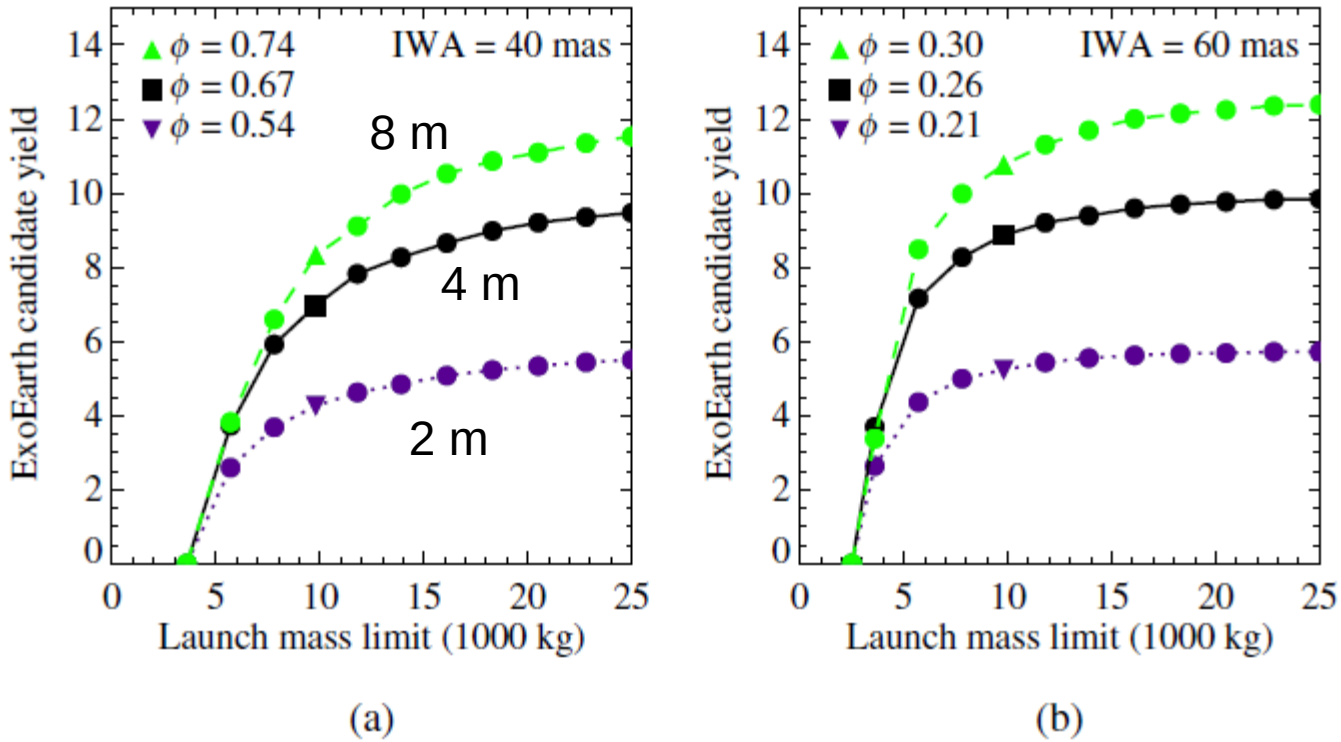


Fig. 10 ExoEarth candidate yield as a function of total launch mass. Lines correspond to telescope apertures of 2 (purple dotted), 4 (black solid), and 6 m (green dashed).

2-Starshade idea

- What if we had a Discovery starshade and a Characterization starshade.
- Discovery: 45 m, 40 mas at 500 nm
- Characterization 90 m, 40 mas at 1000 nm.

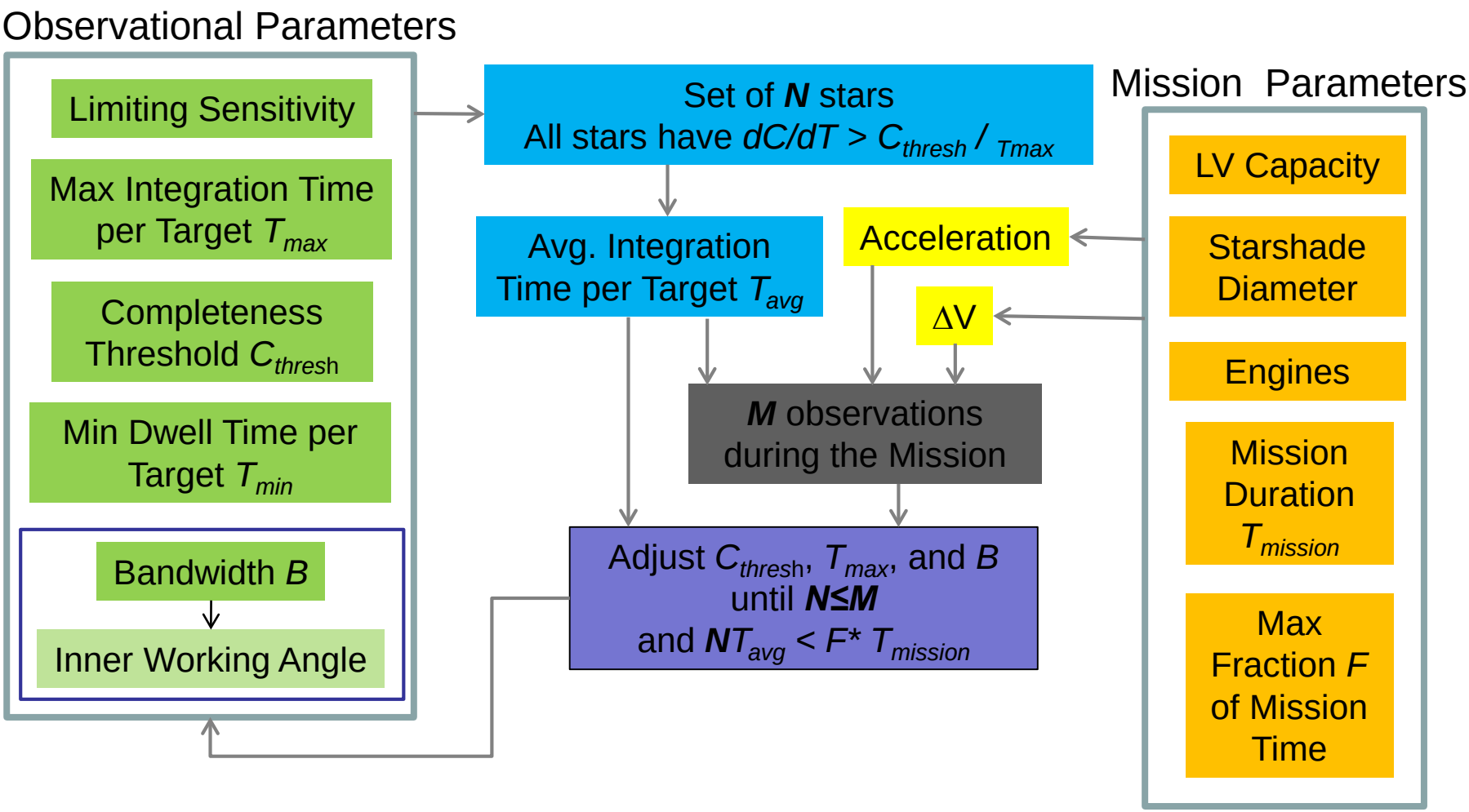
- The 45 m is agile and can point at hundreds of targets over 5 years.
- The 90 m hangs out in the same quadrant of the sky, within say 2 weeks of a newly discovered planet.

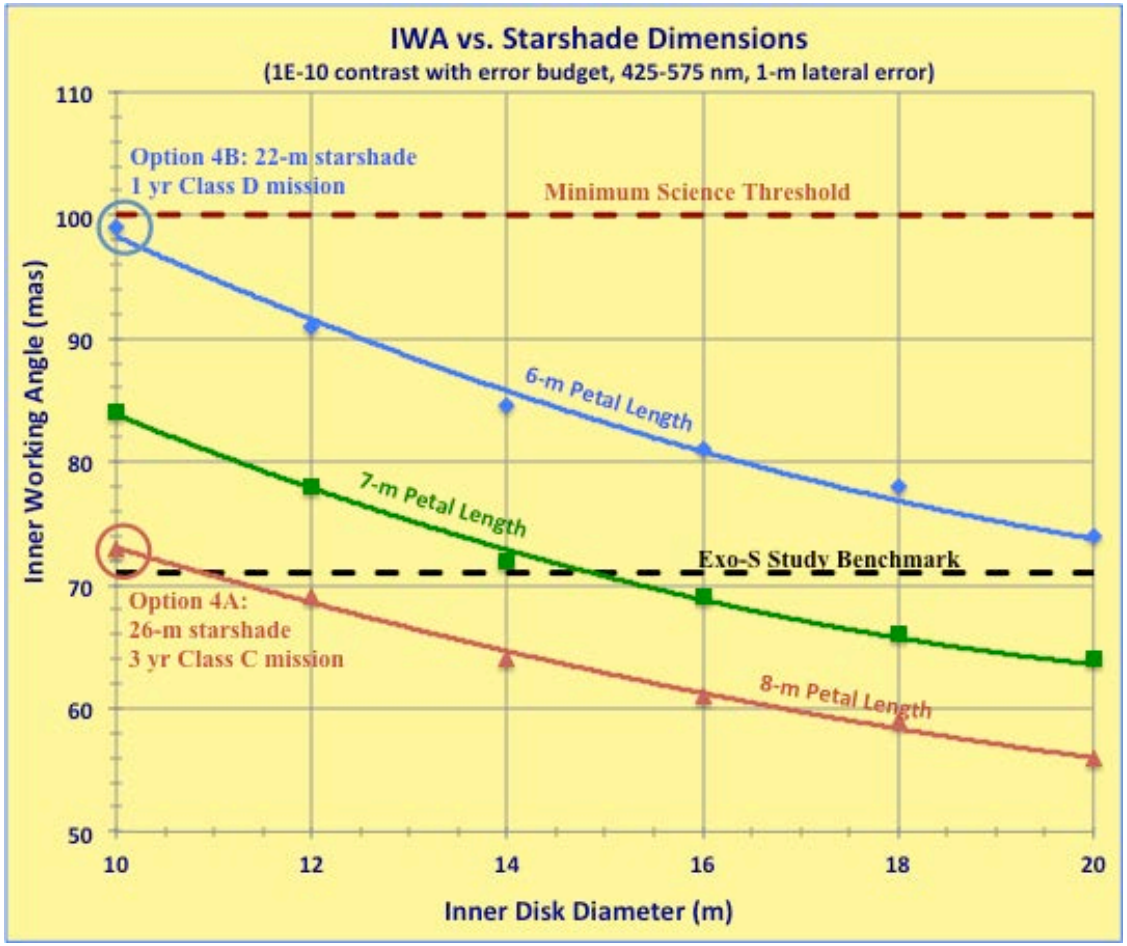
- It's not cheap, but it lets you characterize any Exo-Earth that you have discovered.

- Another thought, regarding coronagraphs:
- A coronagraph could take advantage of the proper motion of targets to look at the background objects around them in the months before and after a candidate planet is observed. This would greatly aid with disambiguating candidates from background targets. Small IWA not required, e.g. 4 lambda/D would be sufficient for this purpose.

BACKUP SLIDES

Maximizing Observational Completeness



Option 4 Definition

- Option 4A is a 26-m starshade concept with a 3 yr Class C Mission
- Option 4B is a 22-m starshade concept with a 2 yr Class D Mission
- The cost & schedule to TRL-6 is exactly the same for both options
  - A contingency schedule is shown, NOT as a separate option, but rather to demonstrate robustness