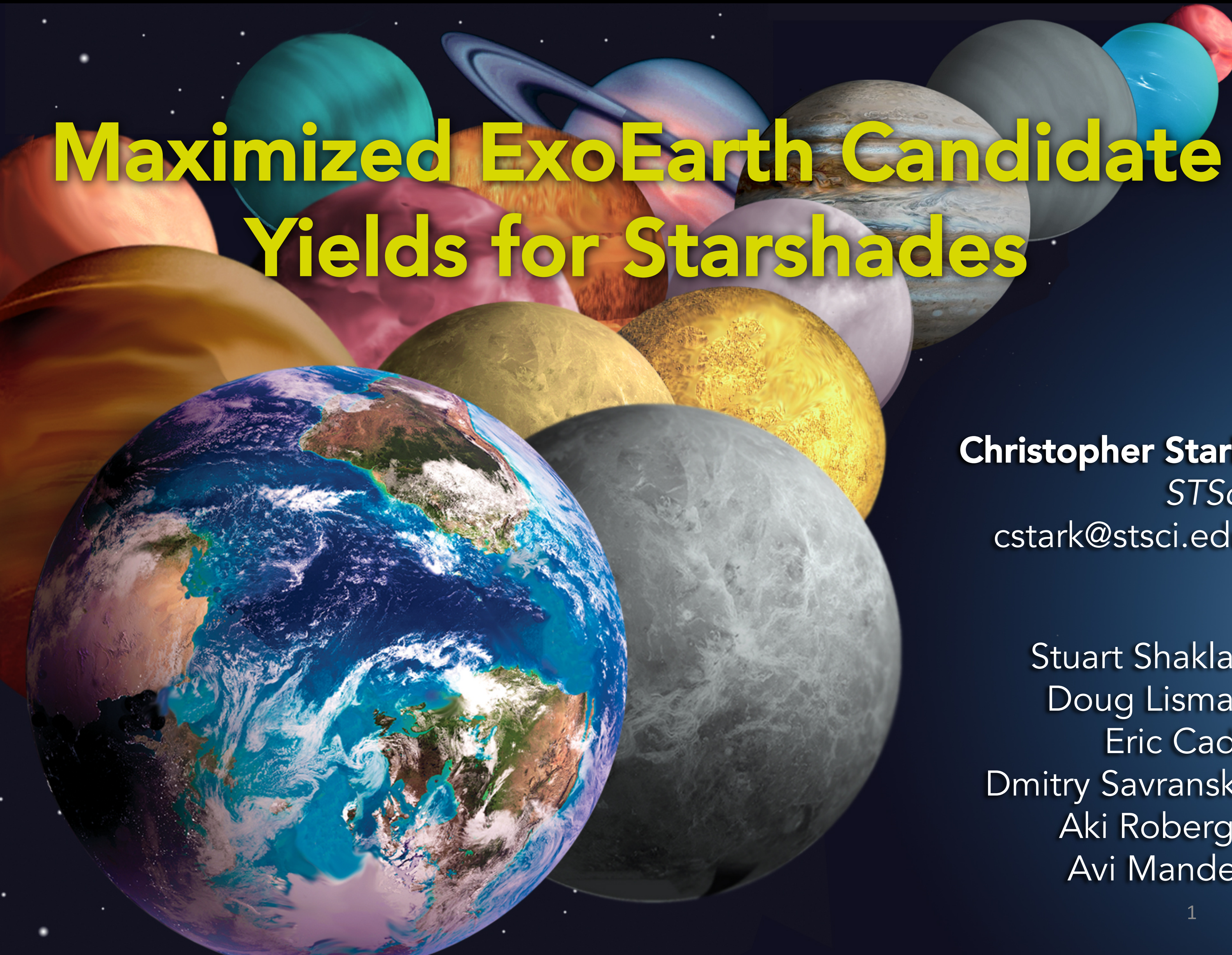

Maximized ExoEarth Candidate Yields for Starshades

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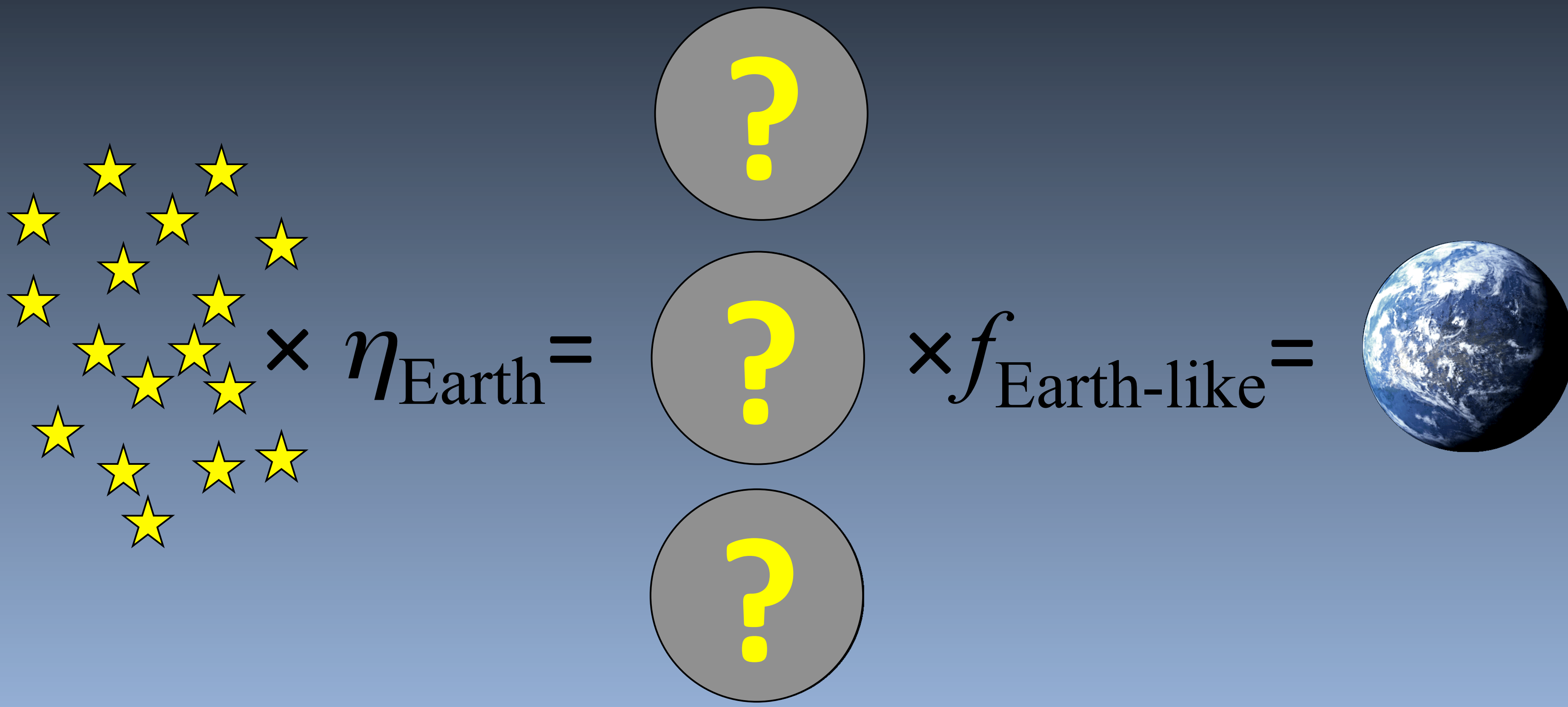
Avi Mandell

How Does One Choose a Yield Goal?

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

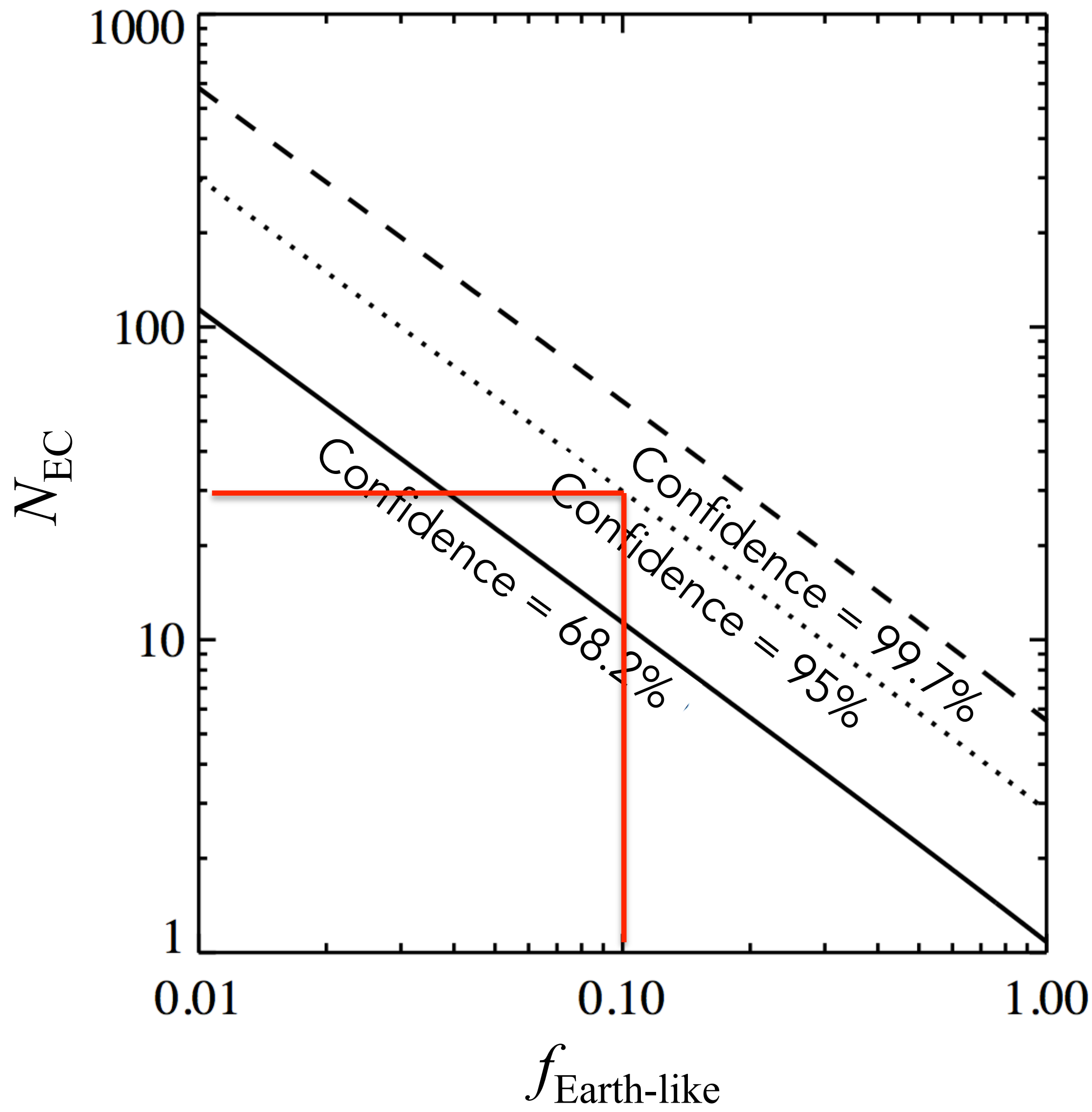
How Does One Choose a Yield Goal?



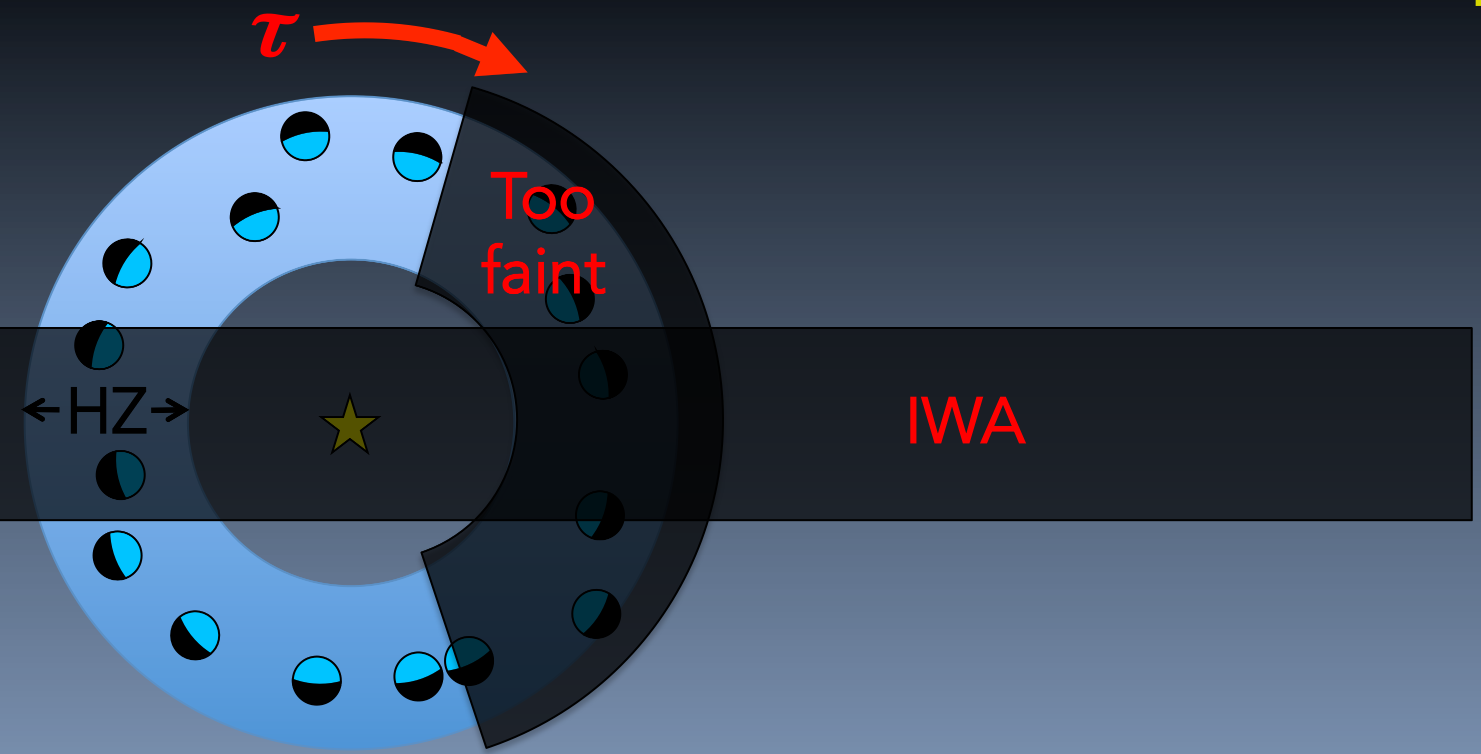
η_{Earth} does not express the number of Earth-*like* planets per star.

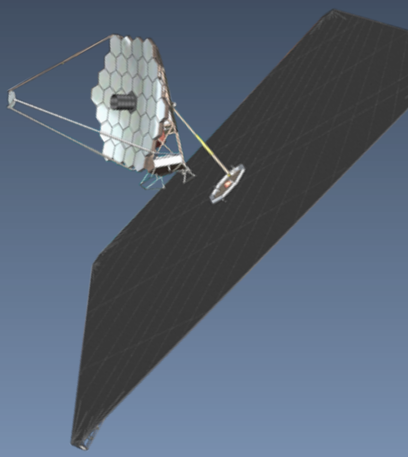
How Does One Choose a Yield Goal?

Number of Candidates Needed to:
Guarantee ≥1 Earth-*like* planet **OR** Constrain $f_{\text{Earth-like}}$



ExoEarth Yield Estimated via Completeness

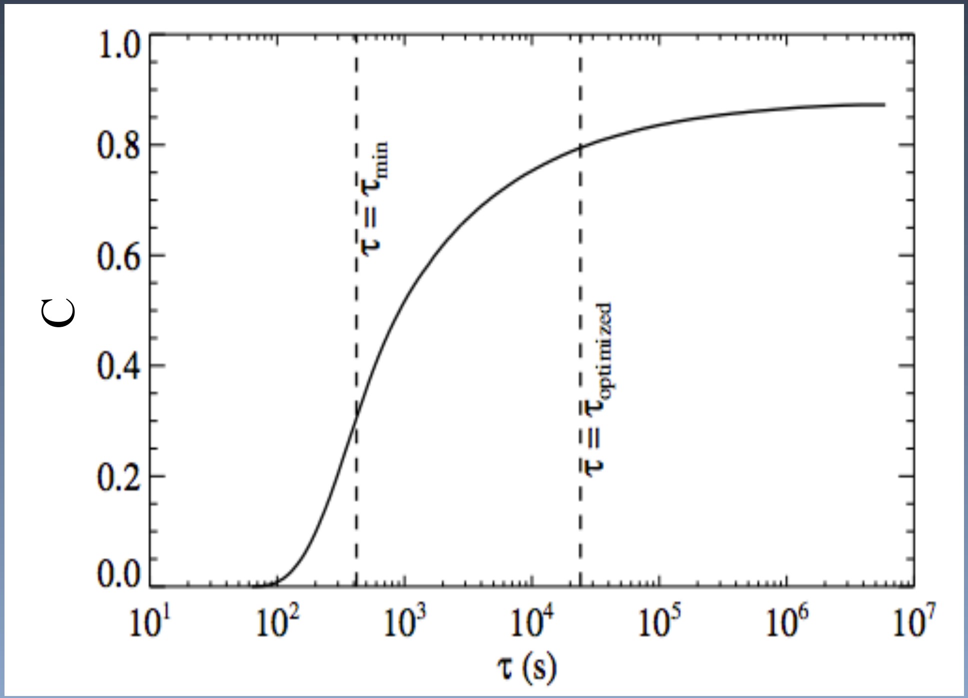




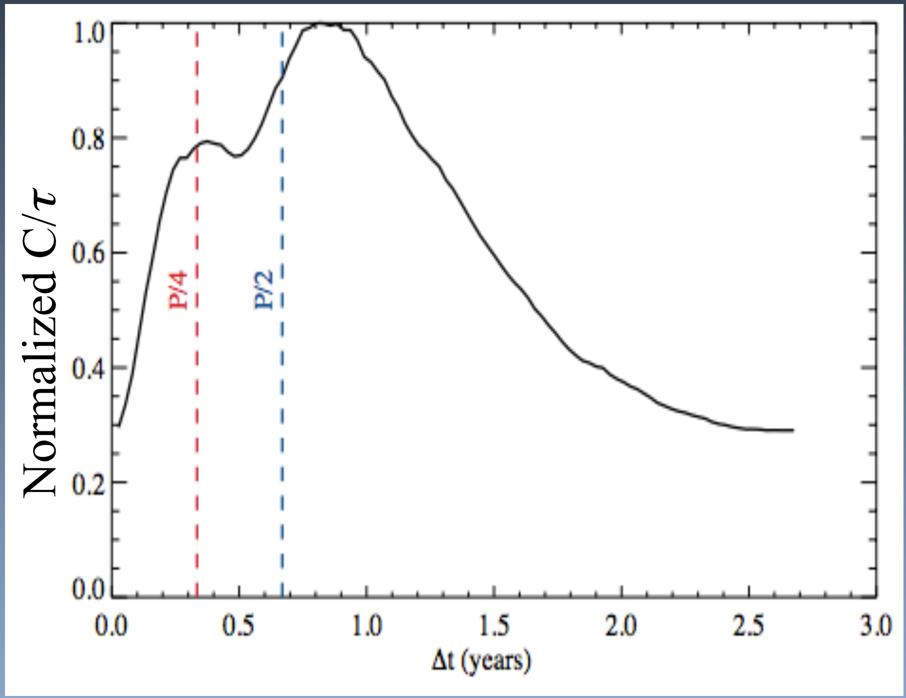
- Completeness, C = the chance of observing a given planet around a given star if that planet exists (Brown 2004)
- Yield = $\eta_{\mathrm{Earth}} \Sigma C$
- Calculated via a Monte Carlo simulation with synthetic planets
- Can revisit same star multiple times to increase total completeness

Maximizing Yield by Optimizing Observations for a Coronagraph

Optimize Exposure Time

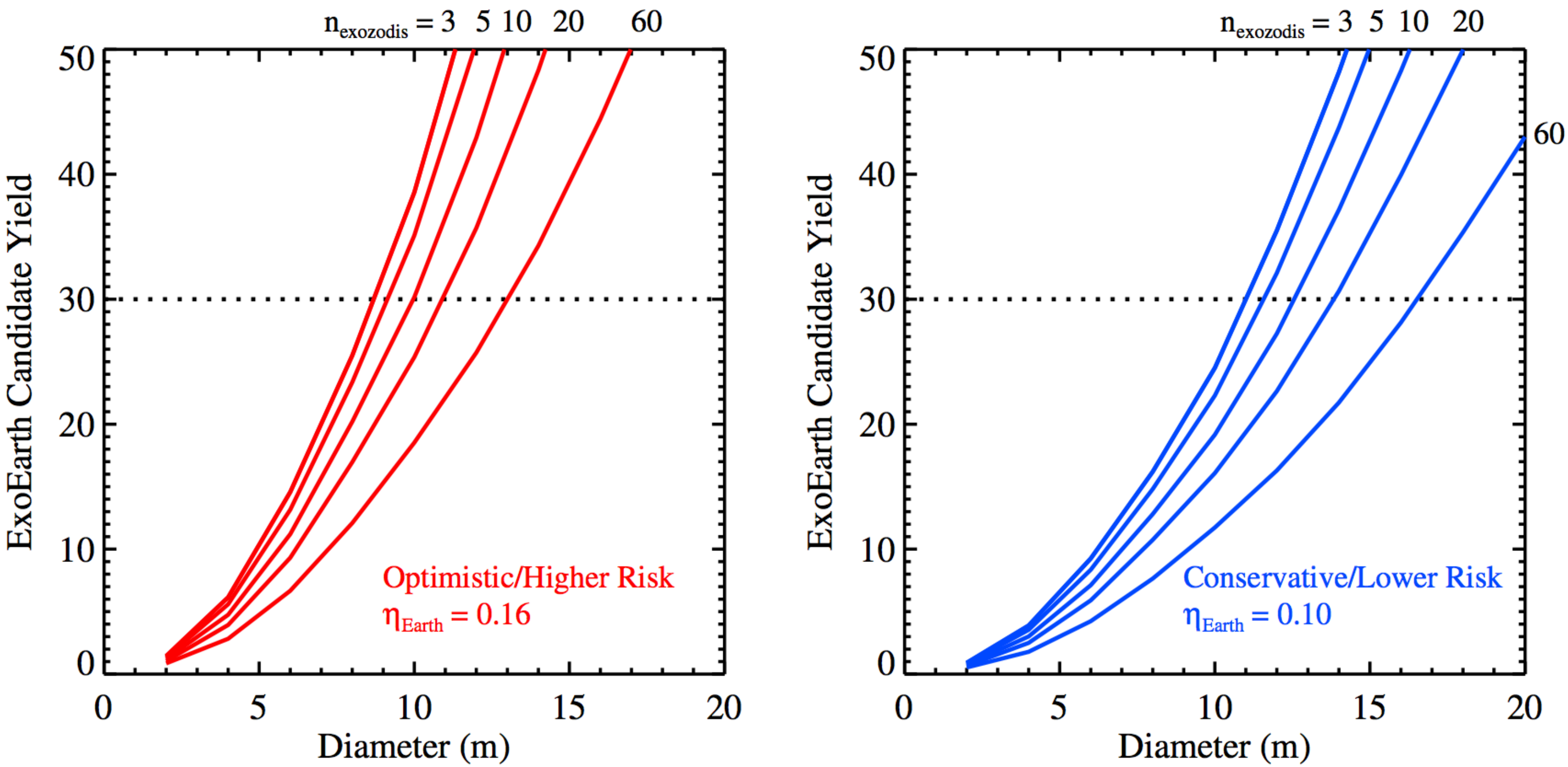


Optimize Revisit Delay Time



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. Factor of ~3 increase in yield compared to old single visit completeness.

Maximized Yields for a Coronagraph



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

Starshade Optimization

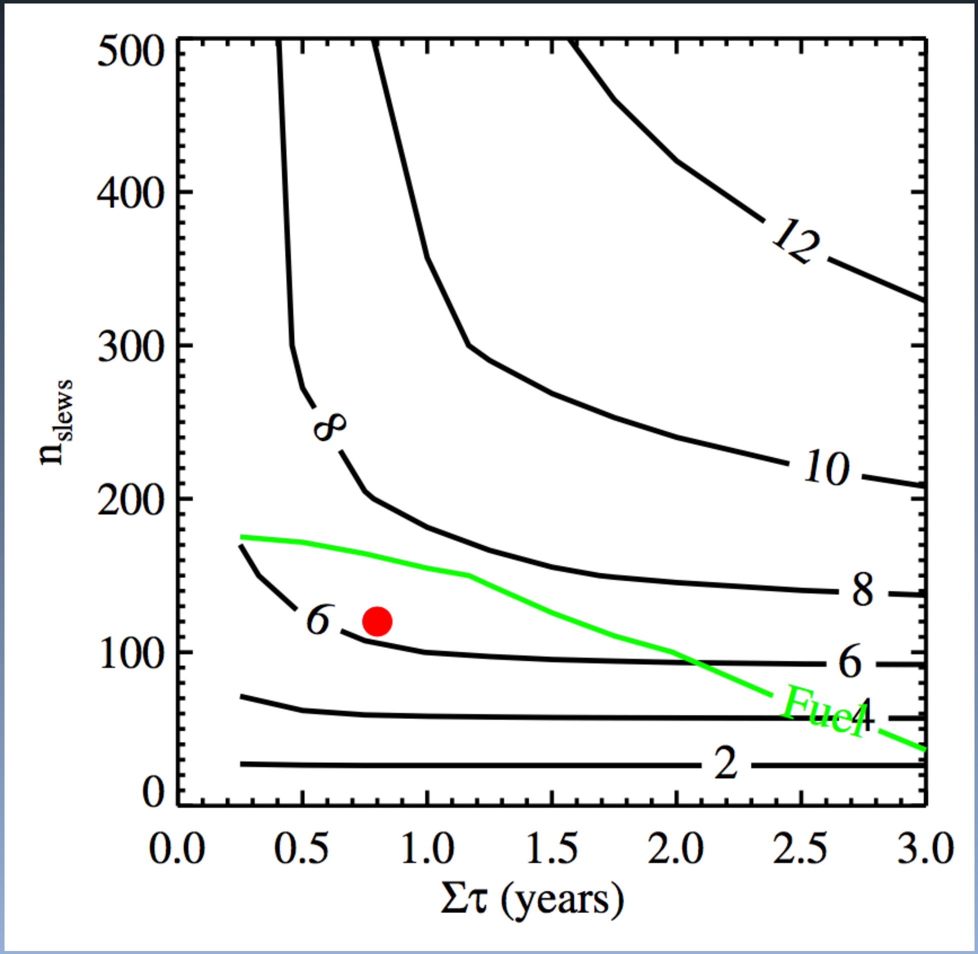
- Existing code valid in the time-limited regime, where observations are limited by a total allowable exposure time
  - Targets are prioritized & selected based on C/τ, the "benefit-to-cost" ratio

- 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.

- How to find this solution? Prioritize by C/x, where the cost $x = \alpha\,(1/n_{slews}) + (1-\alpha)\,(\tau/\tau_{tot})$, and $0<\alpha<1$

Yield Contour Plots for Baseline Starshade

D = 4 m, IWA = 60 mas



Starshades can operate in slew- or time-limited regimes. Optimal solution requires balancing n_{slews} and t via fuel use expression.

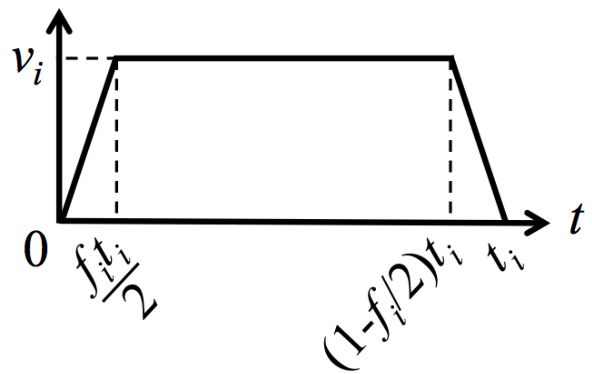
Starshade Fuel Use Calculation

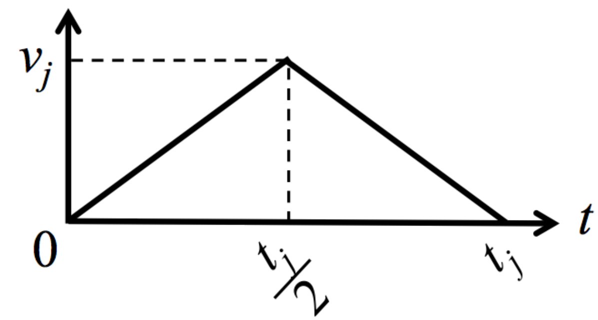
$$\ln \frac{m + dm}{m} = \frac{\Delta v_{\mathrm{slew}}}{g\, I_{\mathrm{slew}}} + \frac{\Delta v_{\mathrm{sk}}}{g\, I_{\mathrm{sk}}}$$

$$\frac{\Delta v_{i,\mathrm{sk}}}{g\, I_{\mathrm{sk}}} \approx \frac{\Delta a_{\mathrm{transverse}} \tau_i}{g\, I_{\mathrm{sk}}\, \epsilon_{\mathrm{sk}}}$$

Starshade Fuel Use Calculation

$$\ln \frac{m+dm}{m} = \frac{\Delta v_{\rm slew}}{g\, I_{\rm slew}} + \frac{\Delta v_{\rm sk}}{g\, I_{\rm sk}}$$





$$s_i = \frac{1}{2} a_i \left(\frac{t_i f_i}{2}\right)^2 + v_i t_i (1 - f_i) + \frac{1}{2} a_i \left(\frac{t_i f_i}{2}\right)^2$$

$$\langle v \rangle_i = v_i \left(1 - \frac{f_i}{2}\right)$$

$$t_i = \sqrt{\frac{2 m_i s_i}{\mathcal{T}\,(f - f^2/2)}}$$

$$\frac{\Delta v_{i,\rm slew}}{g\, I_{\rm slew}} = \frac{2 s_i}{g I_{\rm slew} \epsilon_{\rm slew} t_i}$$

$$s = 2z \sin \sqrt{\frac{\pi}{n_{\rm targets}}}$$

Starshade Optimization

- Have derived scaling relationships to estimate mission-long fuel use

- Fuel use agrees with Savransky et al. (2010) to within 4% on average

- Simultaneously optimizing star selection, exposure time, visits to each star, number of stars, slew efficiency, exposure-slew time balance

- A single yield estimate runs in ~few minutes on a single processor

Comparison to Previous Work

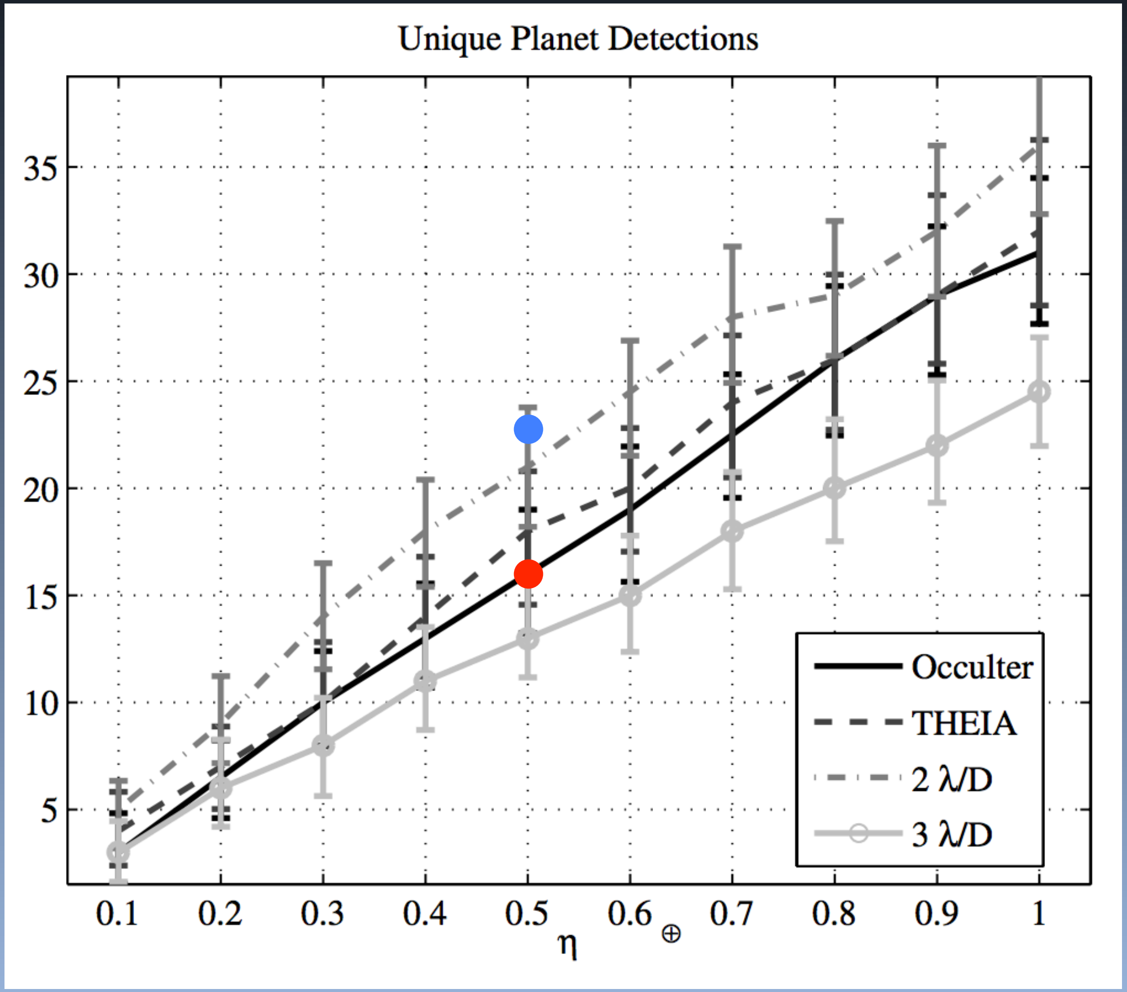
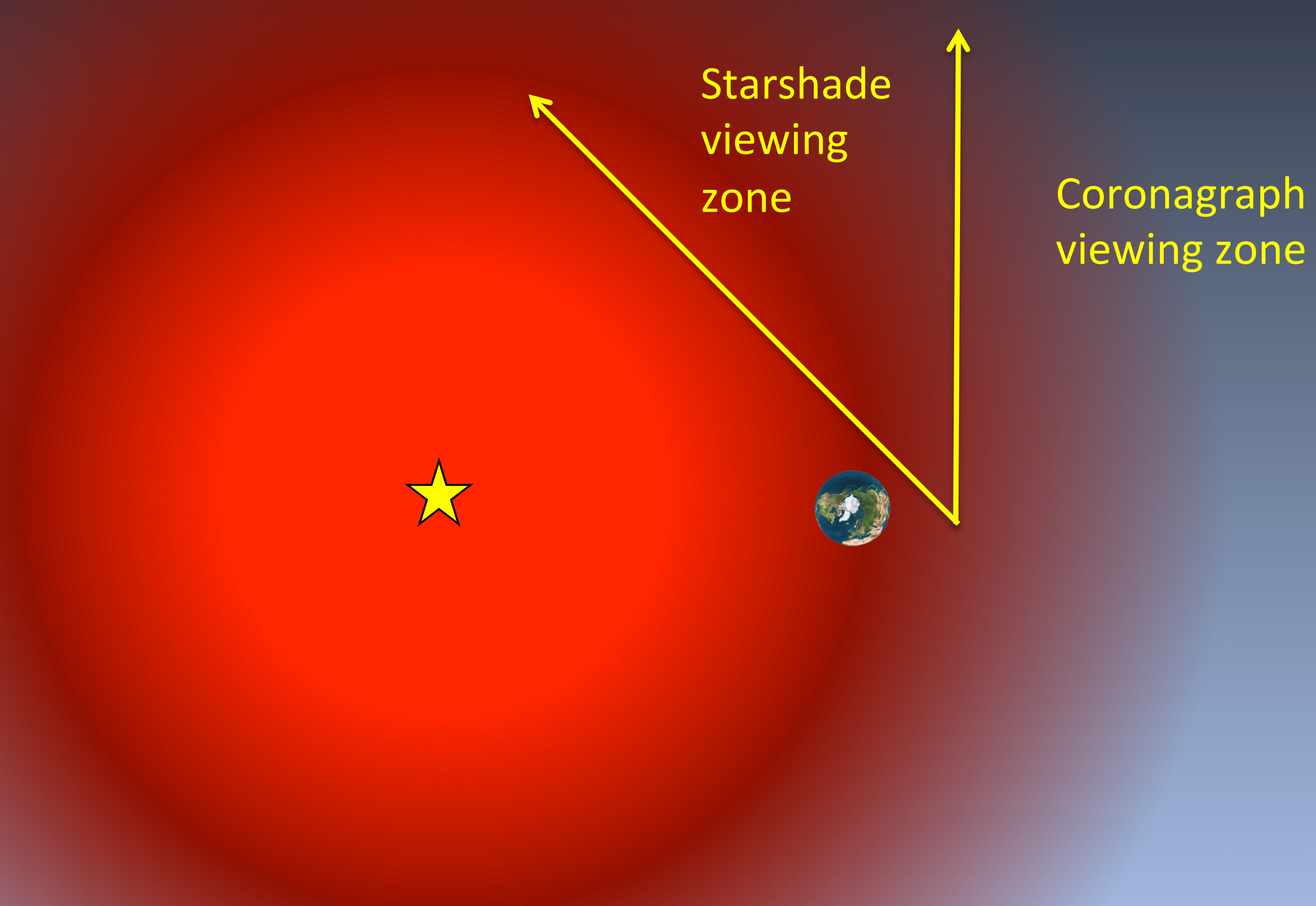


Fig 9 from Savransky et al. (2010)

35% greater yield than Savransky et al. (2010).

Baseline Astrophysical Parameters

- Same astrophysical assumptions as coronagraph
- **Zodiacal light calculated at solar elongation of 60°**



Starshades observe at smaller solar elgonations, where the zodiacal cloud is brighter.

Baseline Astrophysical Parameters

- Same astrophysical assumptions as coronagraph
- Zodiacal light calculated at solar elongation of 60°

$\beta°$ / $\lambda - \lambda_\odot$	0	5	10	15	20	25	30	45	60	75
0				3140	1610	985	640	275	150	100
5				2940	1540	945	625	271	150	100
10			4740	2470	1370	865	590	264	148	100
15	11500	6780	3440	1860	1110	755	525	251	146	100
20	6400	4480	2410	1410	910	635	454	237	141	99
25	3840	2830	1730	1100	749	545	410	223	136	97
30	2480	1870	1220	845	615	467	365	207	131	95
35	1650	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	320	193	125	93
40	1180	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	282	179	120	92
45	910	730	555	442	356	292	250	166	116	90
60	505	442	352	292	243	209	183	134	104	86
75	338	317	269	227	196	172	151	116	93	82
90	259	251	225	193	166	147	132	104	86	79
105	212	210	197	170	150	133	119	96	82	77
120	188	186	177	154	138	125	113	90	77	74
135	179	178	166	147	134	122	110	90	77	73

~10x average zodi brightness

Table 17 from Leinert et al. (1998)

Starshades observe at smaller solar elgonations, where the zodiacal cloud is brighter.

Baseline Starshade Mission Parameters

Detections @ 0.55 μm
- $\Delta\lambda$ = 40%
- SNR = 7
- IWA = 60 mas
- Contrast, $\zeta = 10^{-10}$

Characterization @ 1 μm
- R = 50
- SNR = 5
- IWA = 60 mas
- Contrast, $\zeta = 10^{-10}$

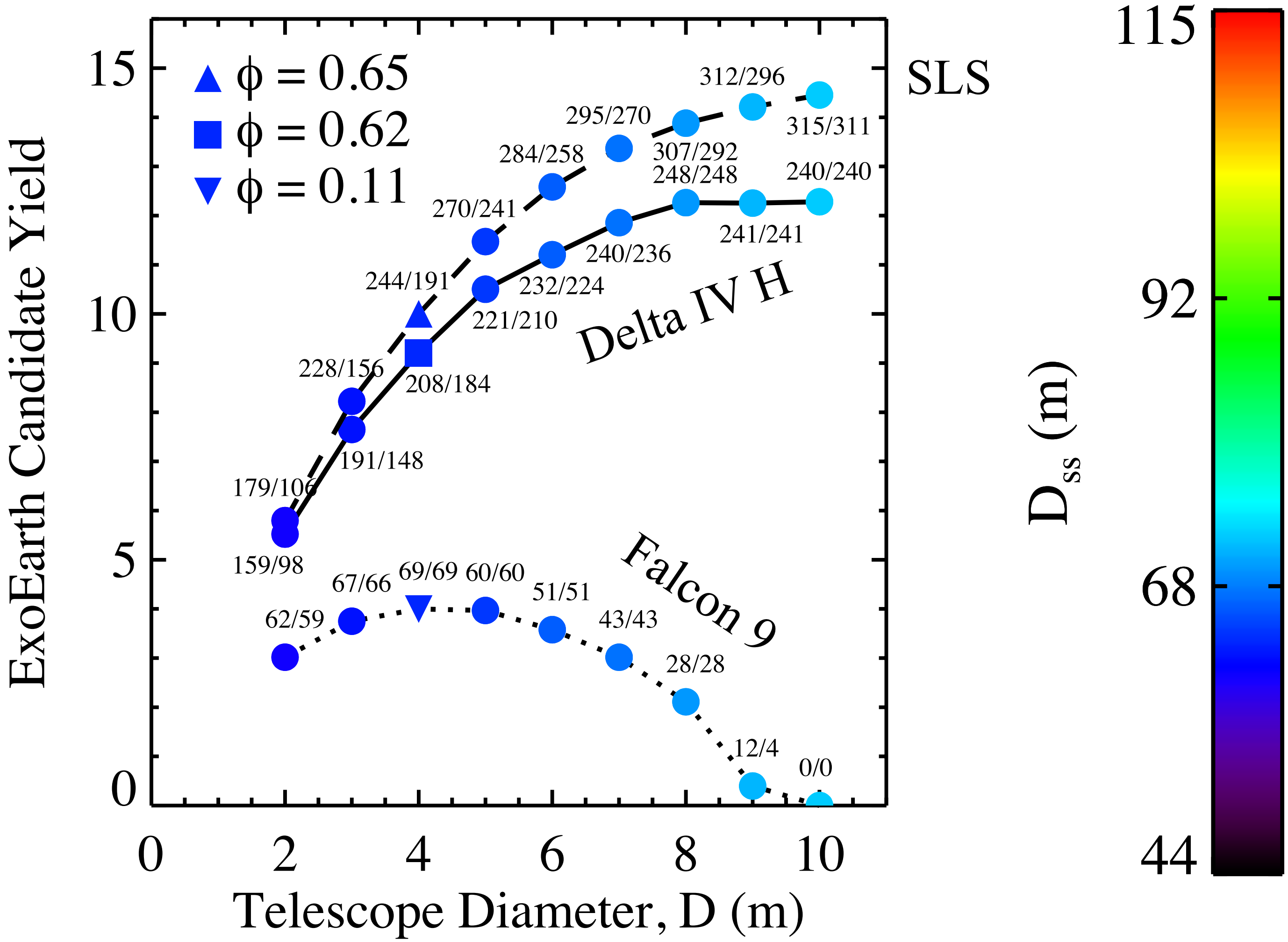
- throughput = 0.65
- Noise floor, $\Delta mag_{floor} = 27.5$
- OWA = infinite
- Diffraction-limited Airy pattern PSF
- No detector noise
- Optimized exposure time/slew time balance
- 0 year of overheads
- <5 visits per star, no optimization of revisit time
- I_{slew} = 3000 s, I_{sk} = 300 s
- Thrust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

Maximized Yields for Starshades

$$\phi(x_0) = \frac{\Delta N_{EC}}{\Delta x}\frac{x_0}{N_{EC}}$$

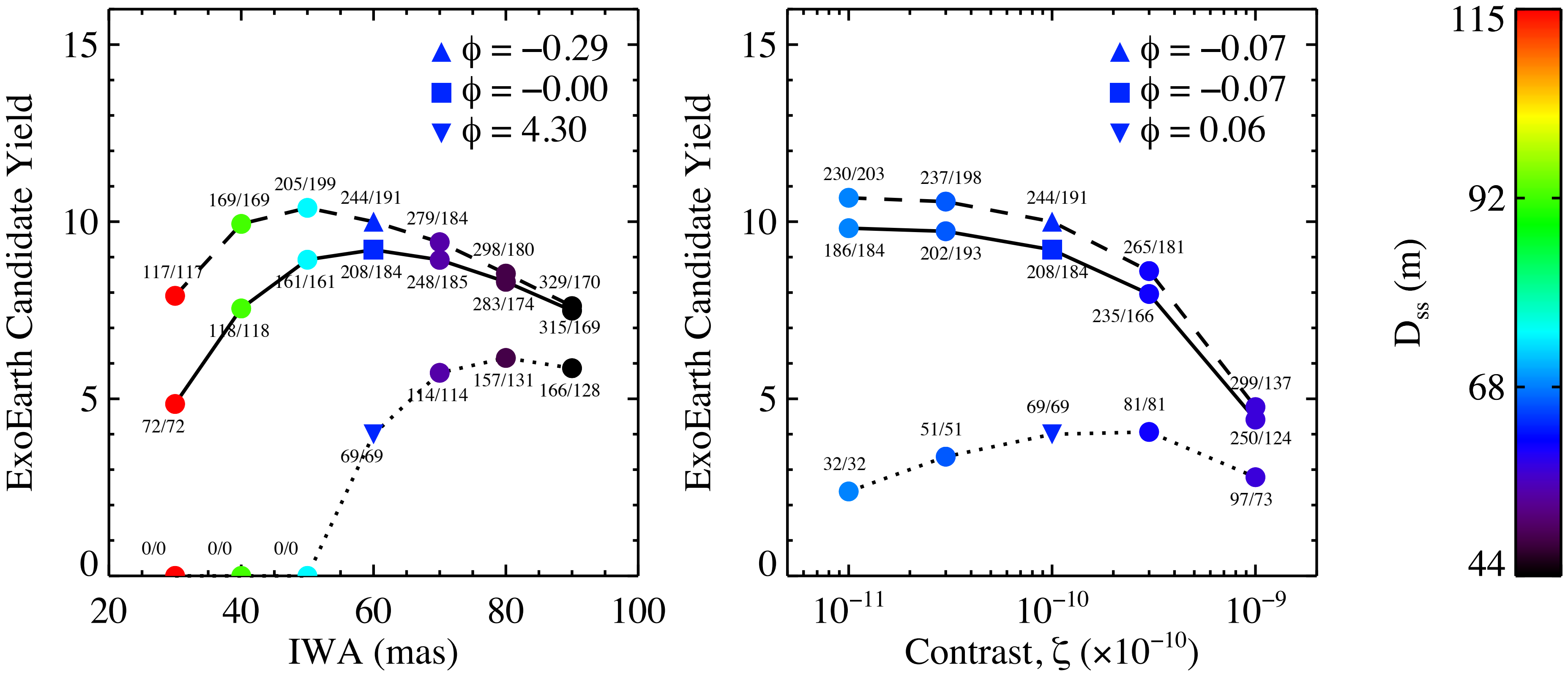
Near $x = x_0$,

$$N_{EC} \propto x^{\phi(x_0)}$$



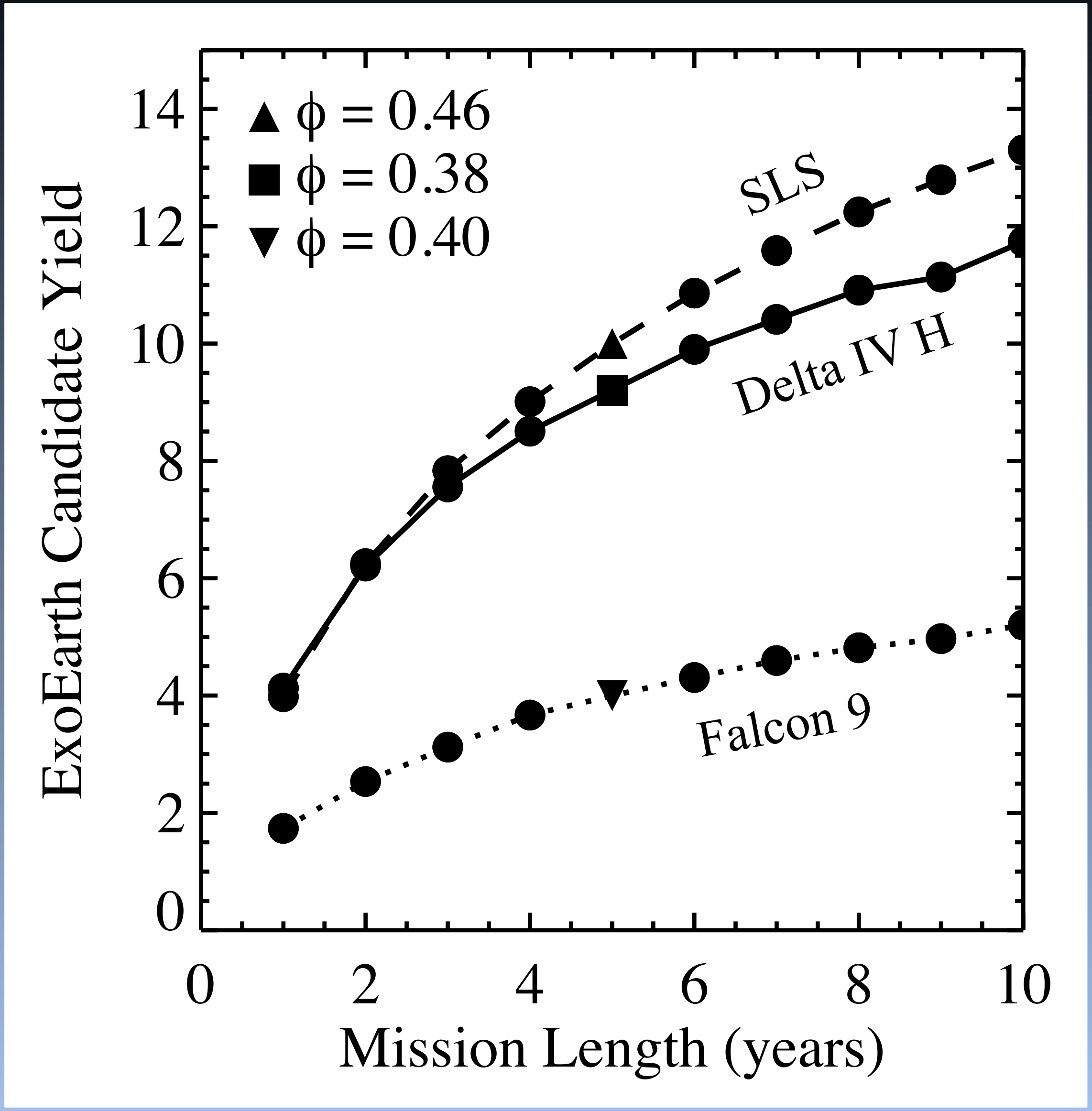
Yield is moderately sensitive to aperture size and turns over at large *D*; an optimum aperture size exists.

Yield vs Instrument Optical Parameters



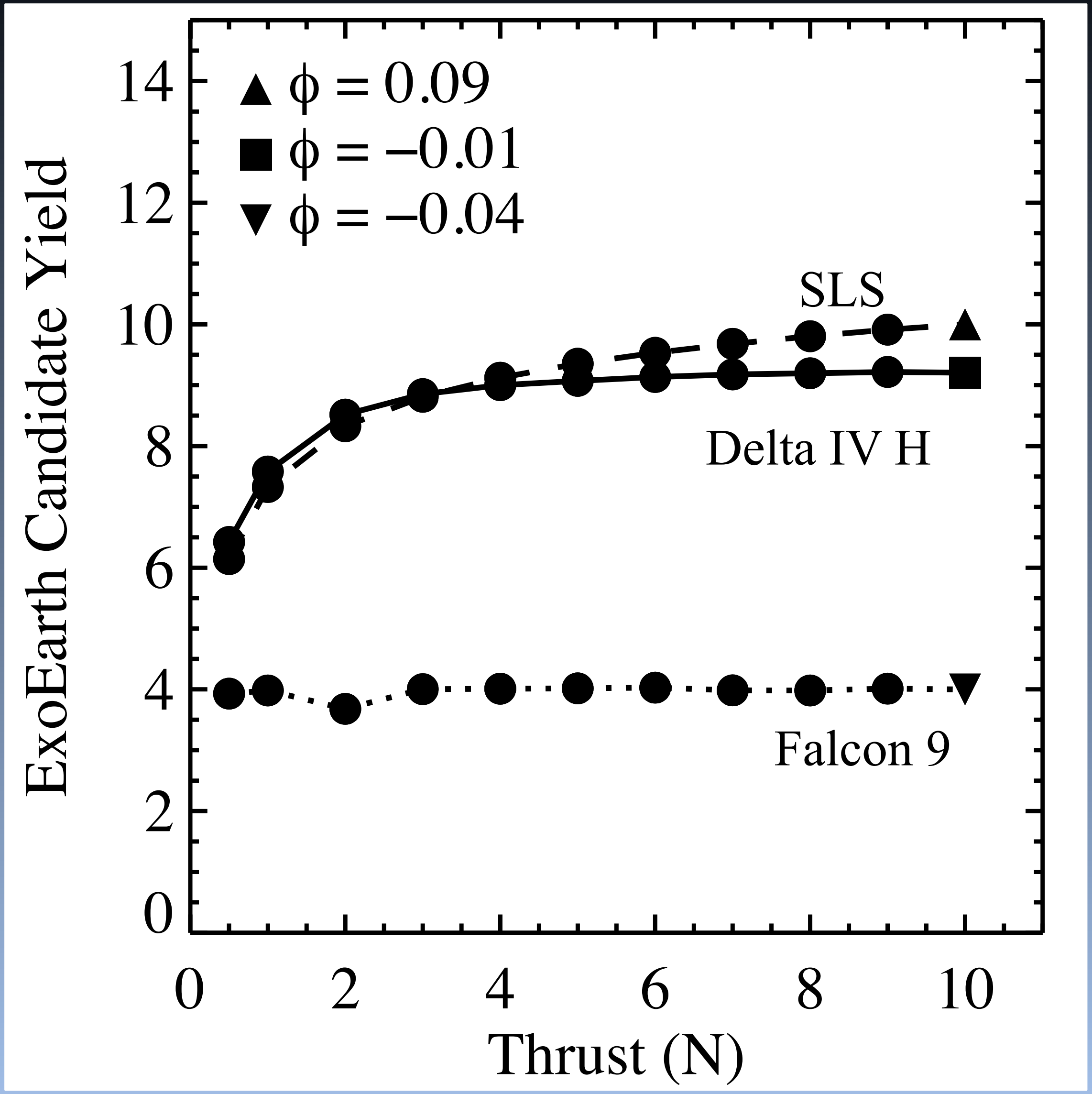
Small IWA = fuel hungry; Large IWA = poor HZ completeness.
An optimum IWA exists.

Yield vs Mission Lifetime



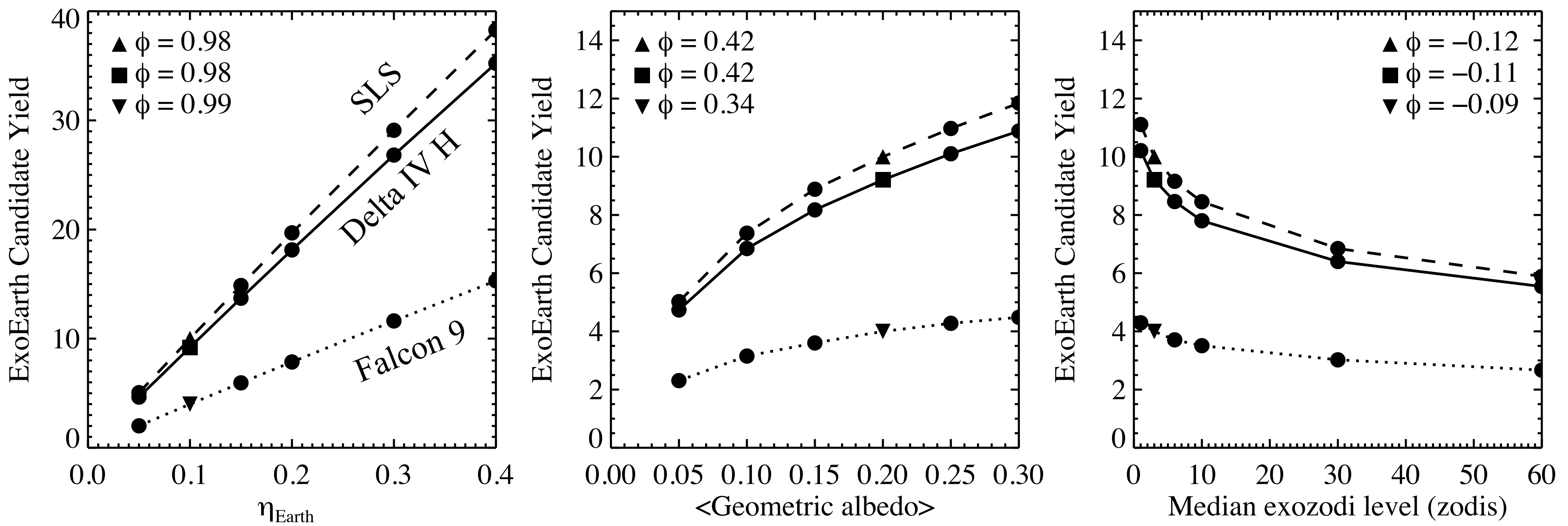
On par with coronagraph yield sensitivity

Yield vs Thrust



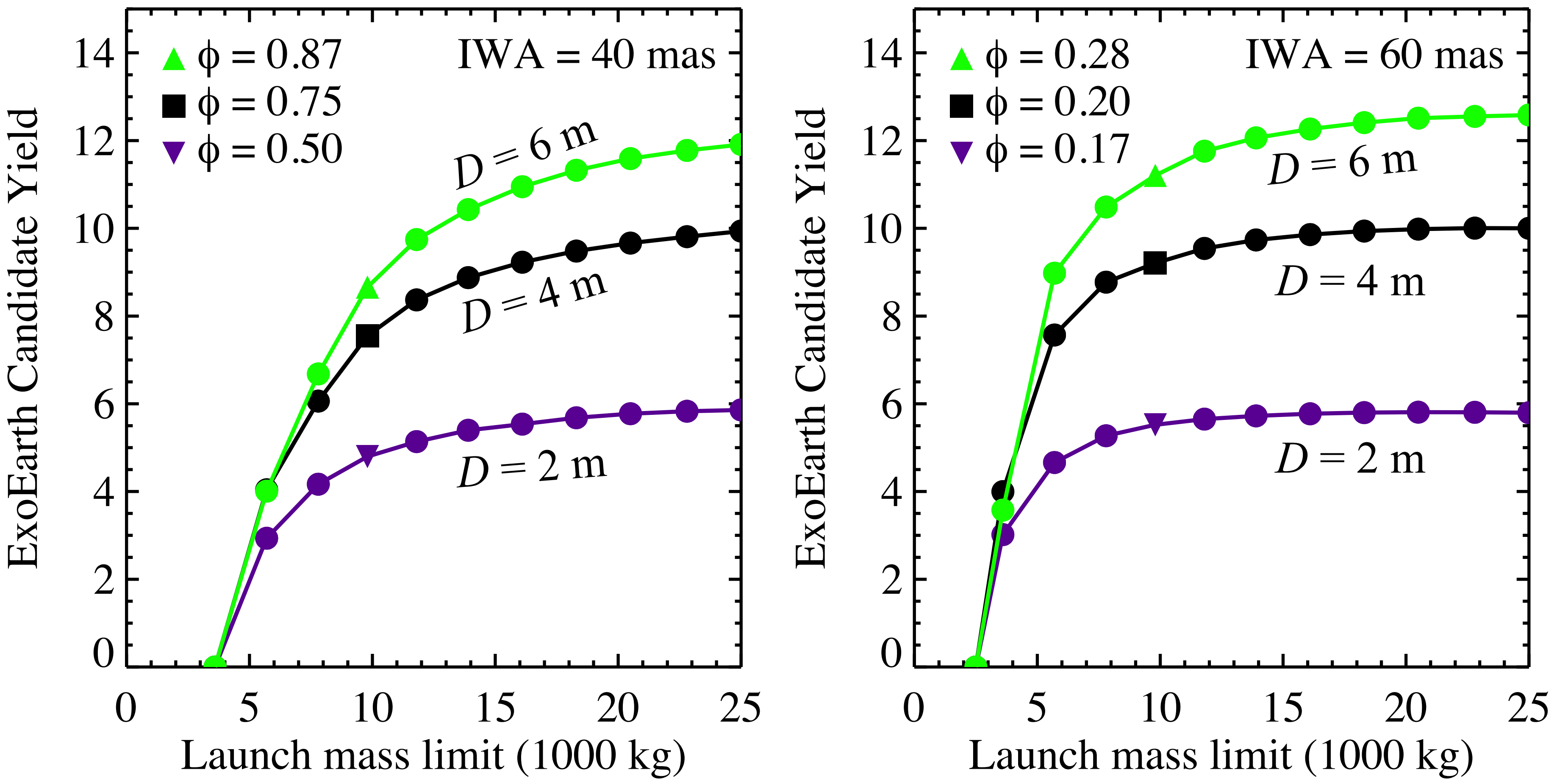
All Falcon 9 scenarios not thrust-limited. Delta IV not thrust-limited for thrust > 2 N, SLS not thrust-limited for thrust > 5 N.

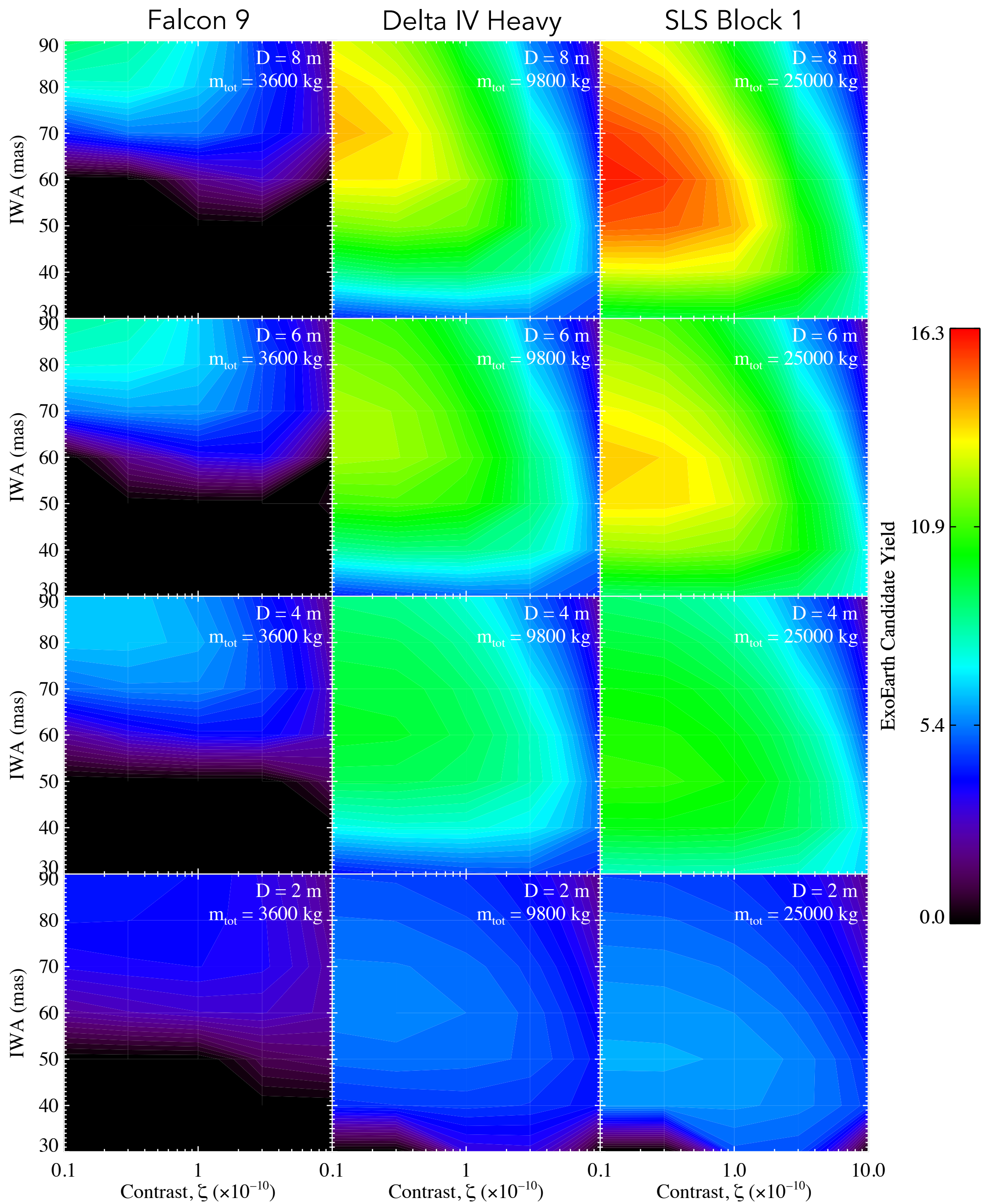
Yield vs Astrophysical Parameters



Starshades are more robust to astrophysical sources of photometric noise!

Yield vs Launch Mass





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, ξ (×10^{-10})
ExoEarth Candidate Yield
16.3
10.9
5.4
0.0

Summary

- Starshade DRM calculates fuel use on the fly using scaling relationships; fuel mass calculations agree with Savransky et al. (2010) to within 4% on average
    - Starshade yield maximized by balancing slew time & exposure time
    - Optimizes observation plan and assumes targets are schedulable

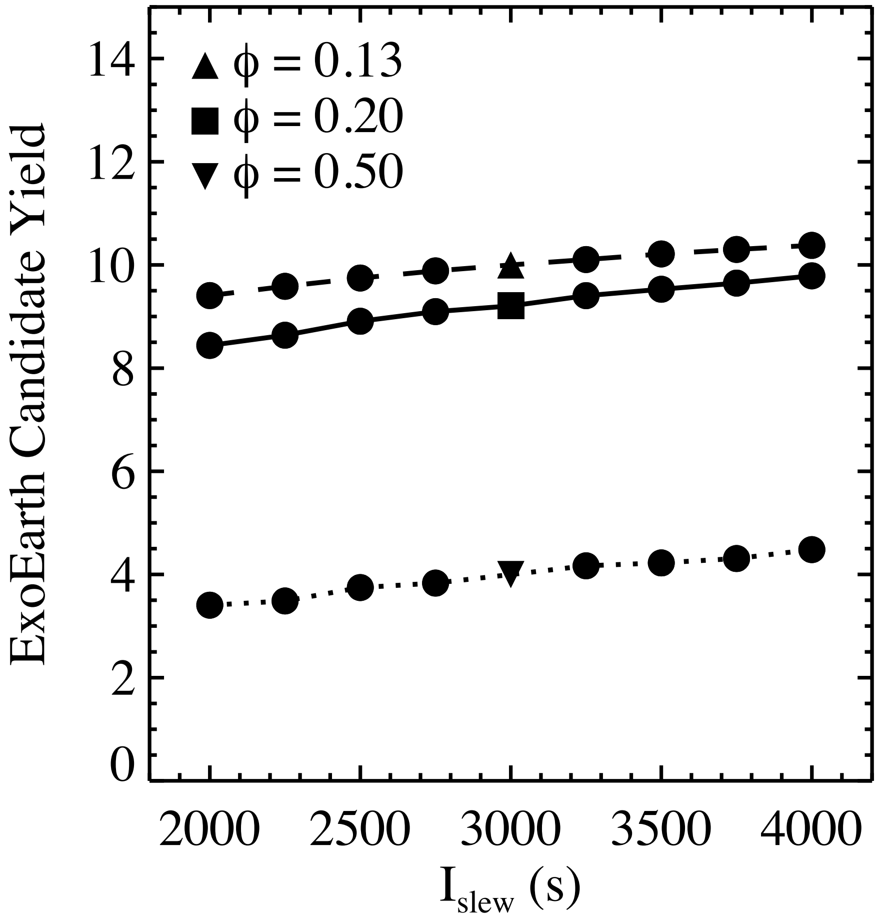
- Starshades operate between fuel and time-limited regimes. As a result, starshades can be less sensitive to astrophysical sources of photometric noise.

- The maximum yield obtained in our calculations was ~16, which required the full launch mass of the SLS Block 1, a ~7 m aperture, and a ~70 m starshade. Assuming $\eta_{\rm Earth} = 0.1$, we are unable to find a set of parameters for a starshade mission that results in several dozen exoEarth candidates. If $\eta_{\rm Earth} \gtrsim 0.4$, a 4 m aperture with a single starshade may be able to achieve a yield of several dozen exoEarth candidates.

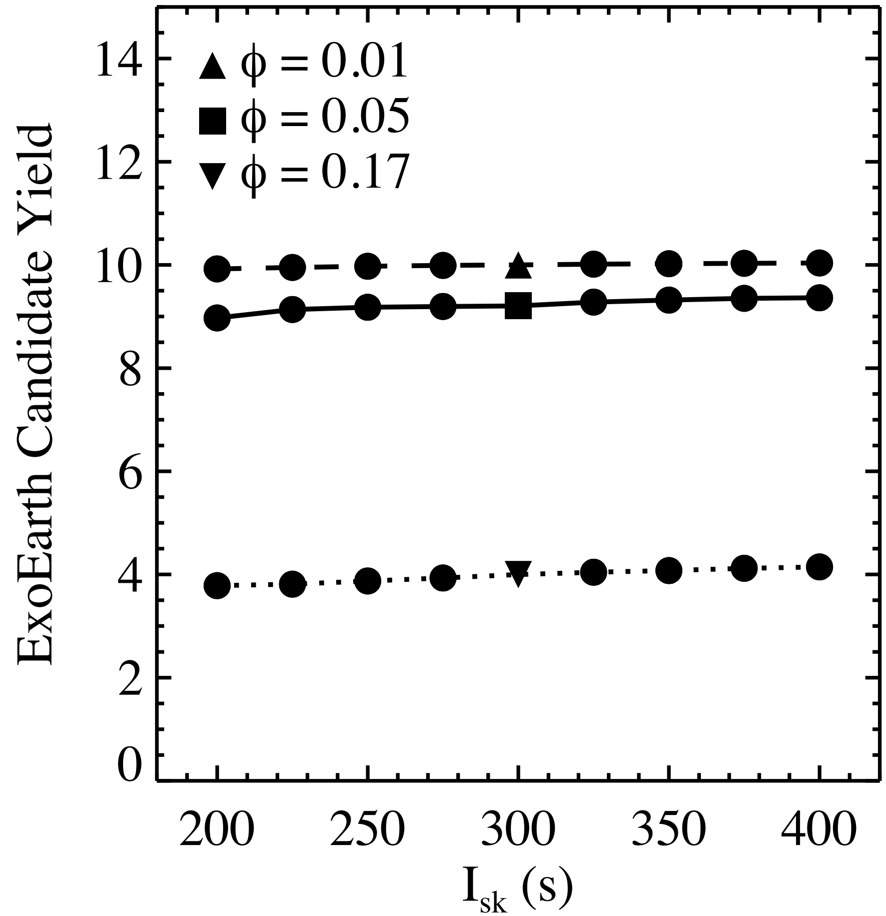
- Multiple starshades will be considered in future work

Backup Slides

Yield vs I_{sp}

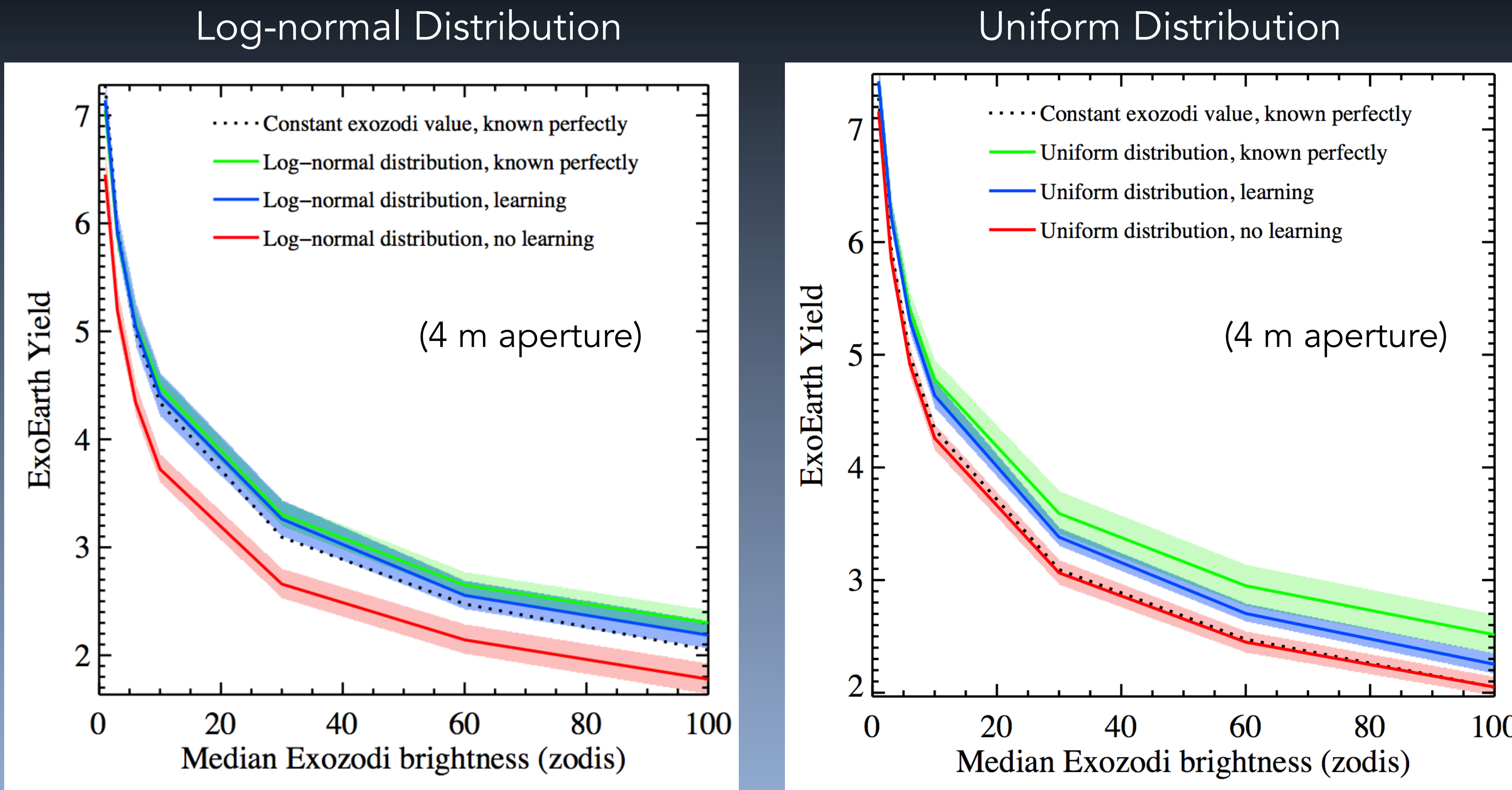


▲ ϕ = 0.13
■ ϕ = 0.20
▼ ϕ = 0.50
ExoEarth Candidate Yield
0
2
4
6
8
10
12
14
2000
2500
3000
3500
4000
I_slew (s)



▲ ϕ = 0.01
■ ϕ = 0.05
▼ ϕ = 0.17
ExoEarth Candidate Yield
0
2
4
6
8
10
12
14
200
250
300
350
400
I_sk (s)

Does a Distribution of Exozodi Affect the Results?



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

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…

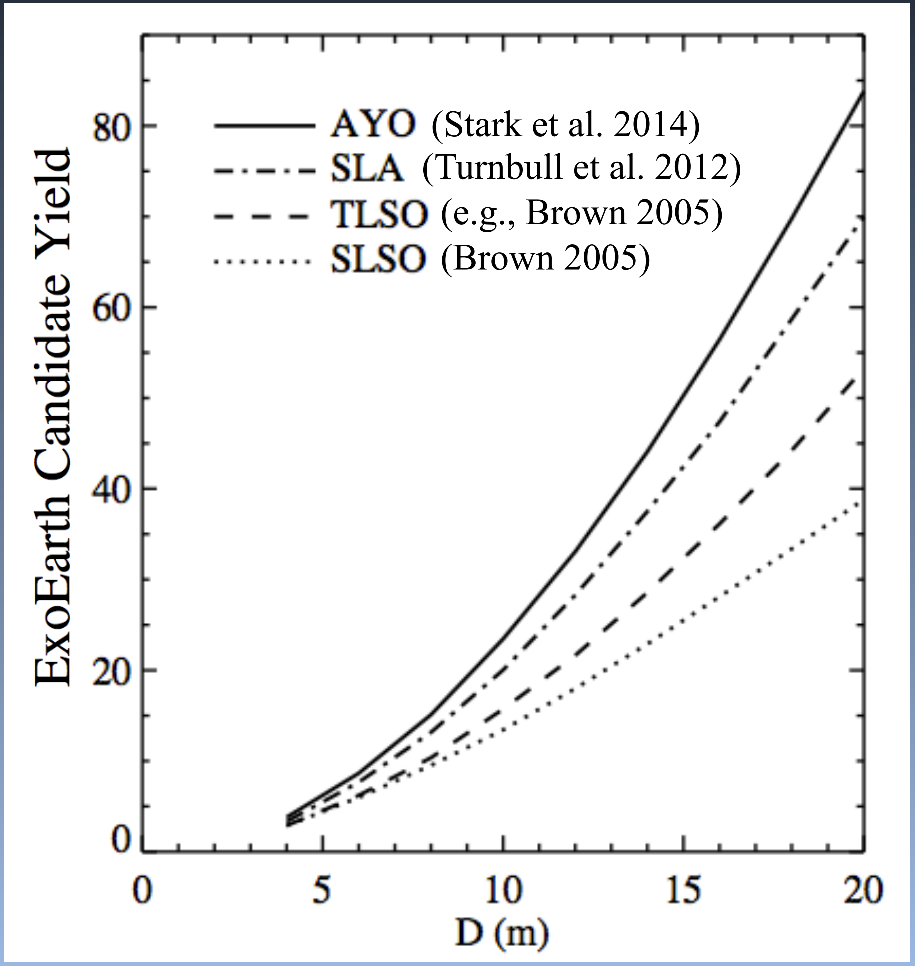
$$P\left(x, n, p\right) = \frac{n!}{x!(n-x)!}\, p^x \,\left(1-p\right)^{n-x}$$

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

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

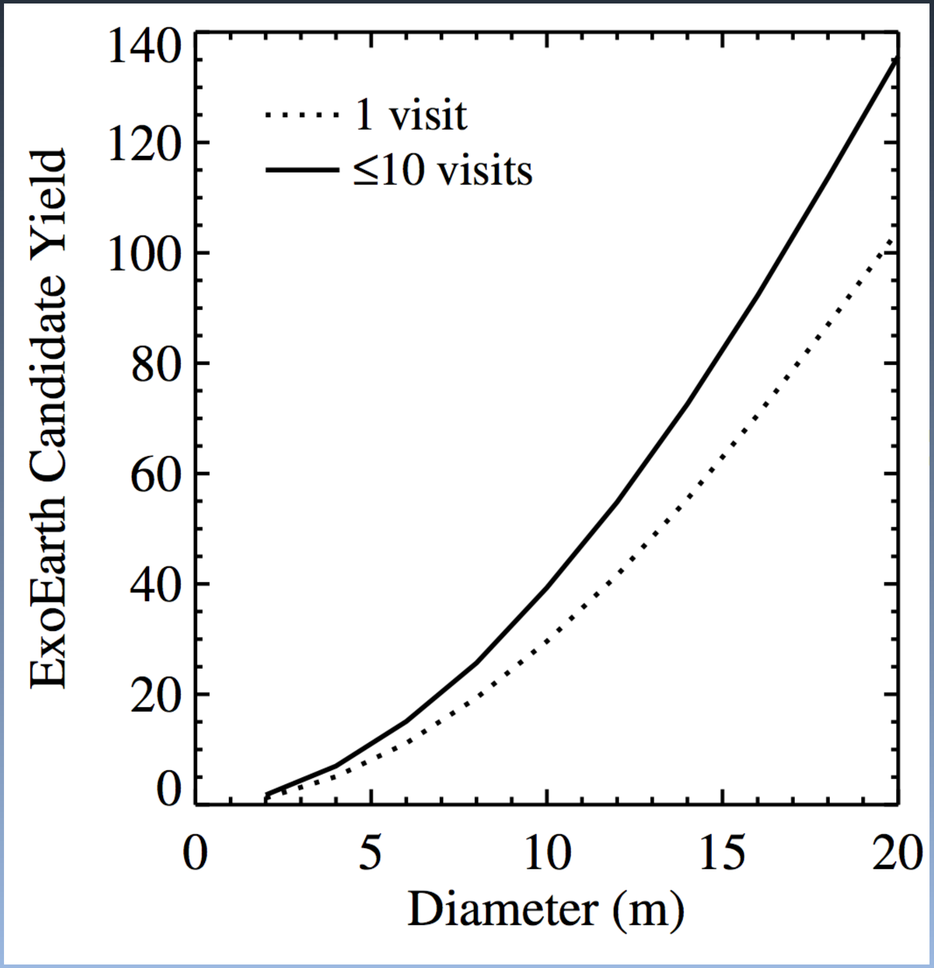
The Impact of Optimization on Yield

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

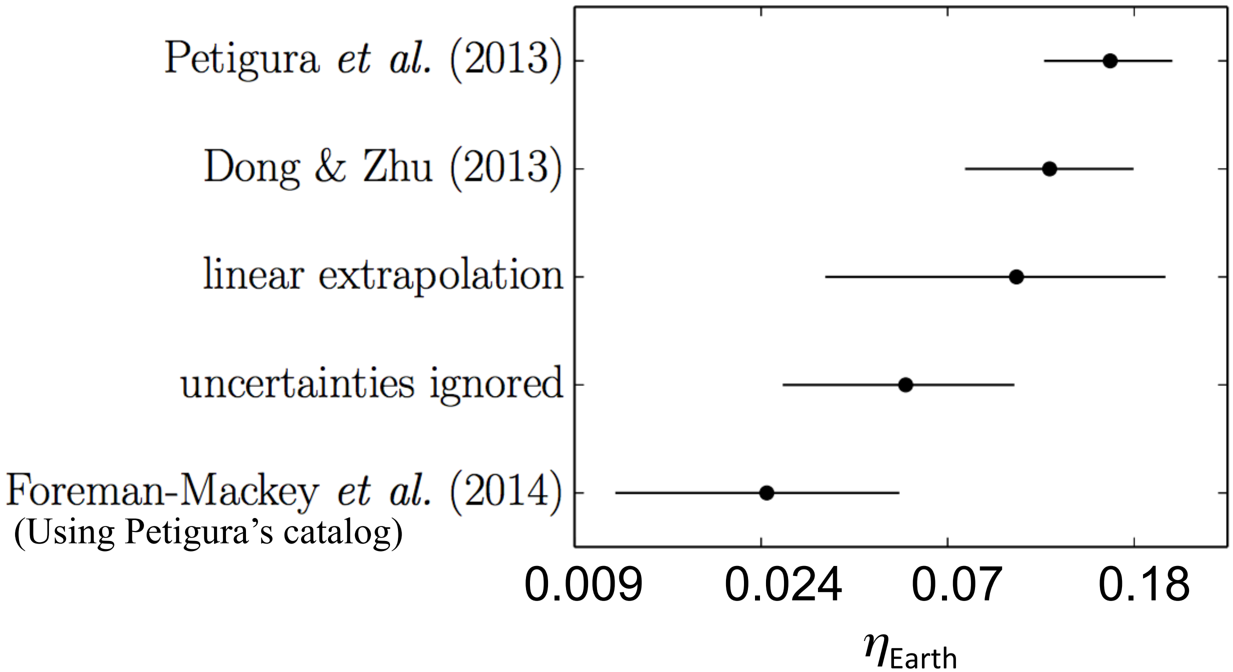


Fig 10 from Foreman-Mackey et al. (2014)

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

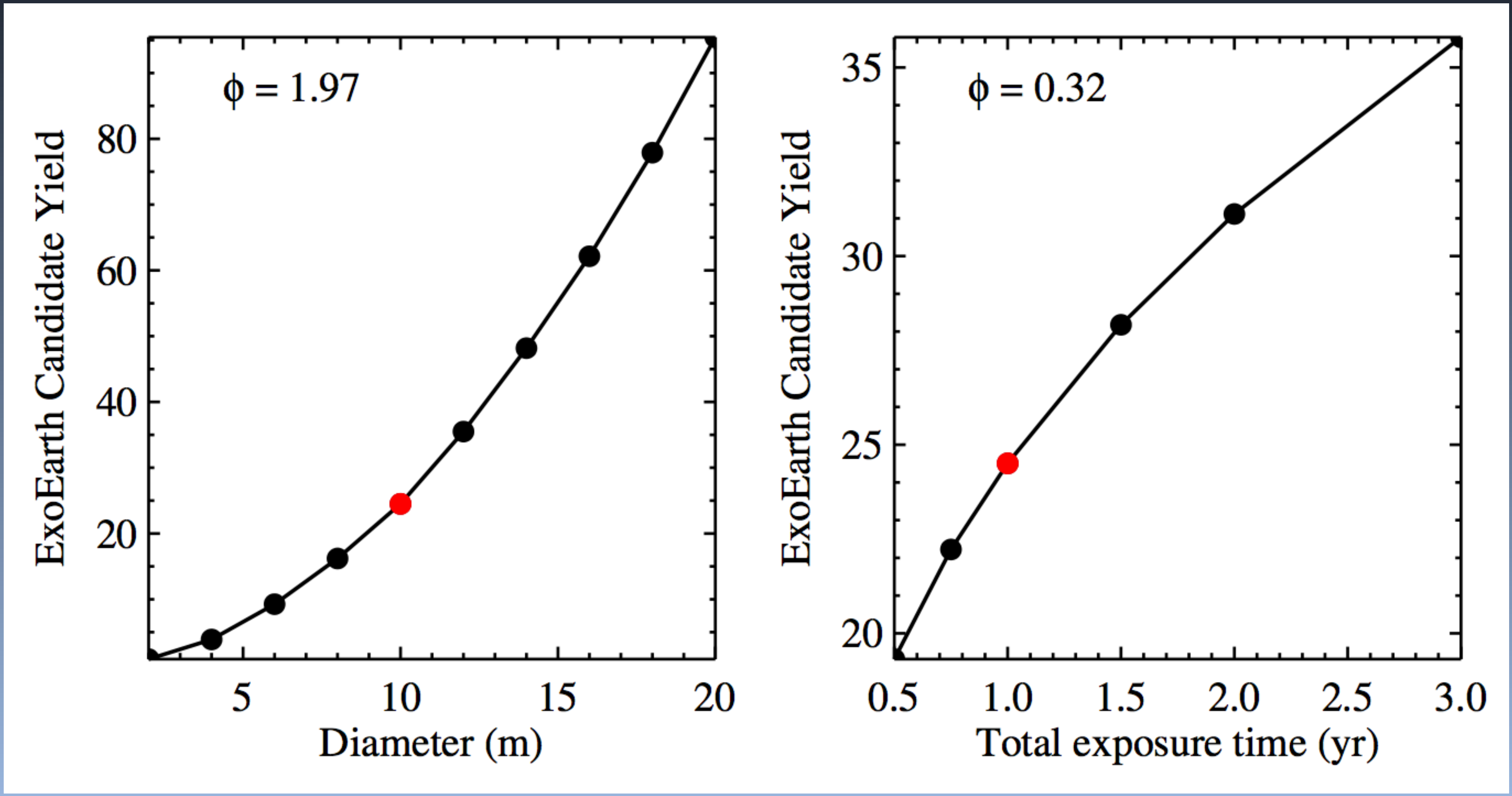
- $\Delta\lambda$ = 20%
- SNR = 7
- IWA = 3.6 λ/D
- Contrast, $\zeta = 10^{-10}$

Characterization @ 1 μm

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

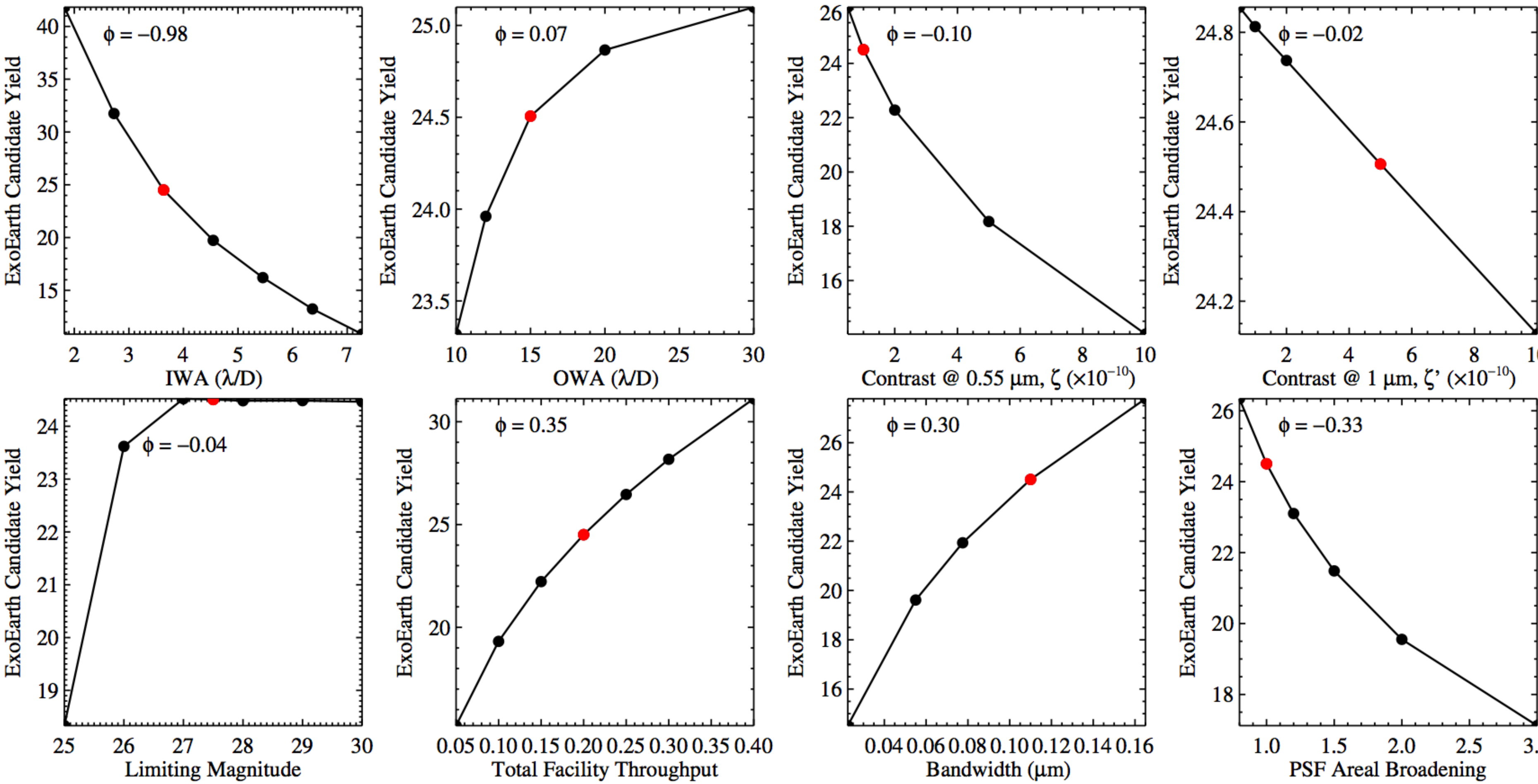
- throughput = 0.2
- Noise floor, $\Delta\mathrm{mag}_{\mathrm{floor}} = 27.5$
- OWA = 15 λ/D
- Diffraction-limited Airy pattern PSF
- No detector noise
- 1 year of observation time
- 1 year of overheads
- Up to 10 visits per star
- η_{Earth} = 0.1
- Habitable Zone def: OKHZ
- Earth-twins with A_G =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

What Telescope/Instrument Parameters Matter?



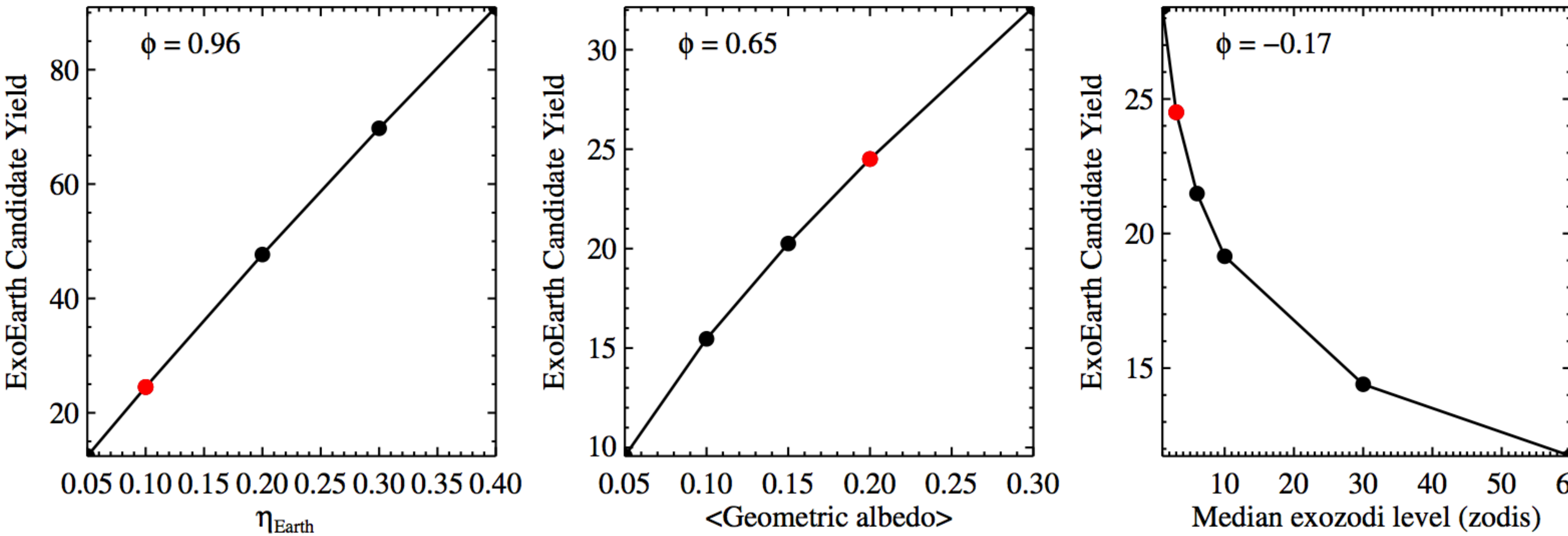
Yield most strongly depends on aperture.
Moderately weak exposure time dependence.

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.

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.