# Exoplanet Yields: An Example of Optimized Science Simulation

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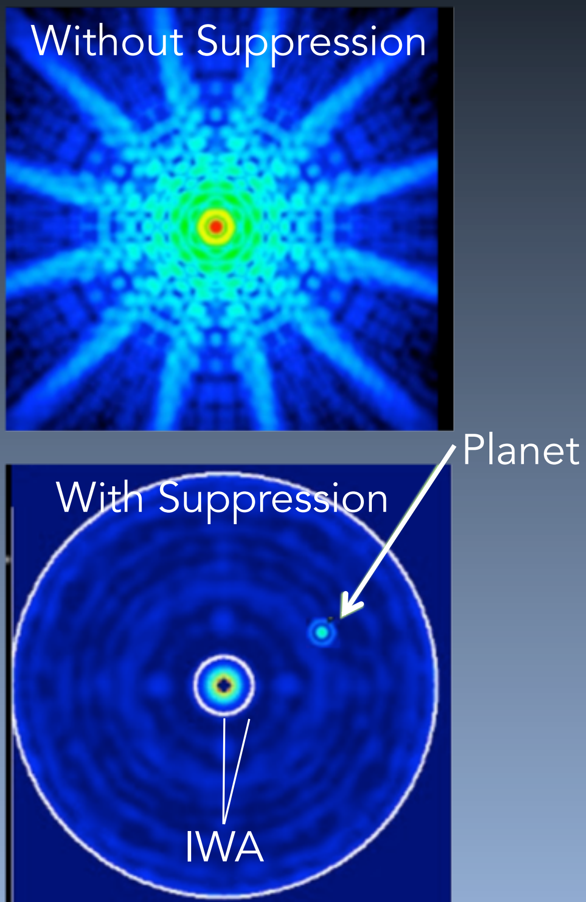
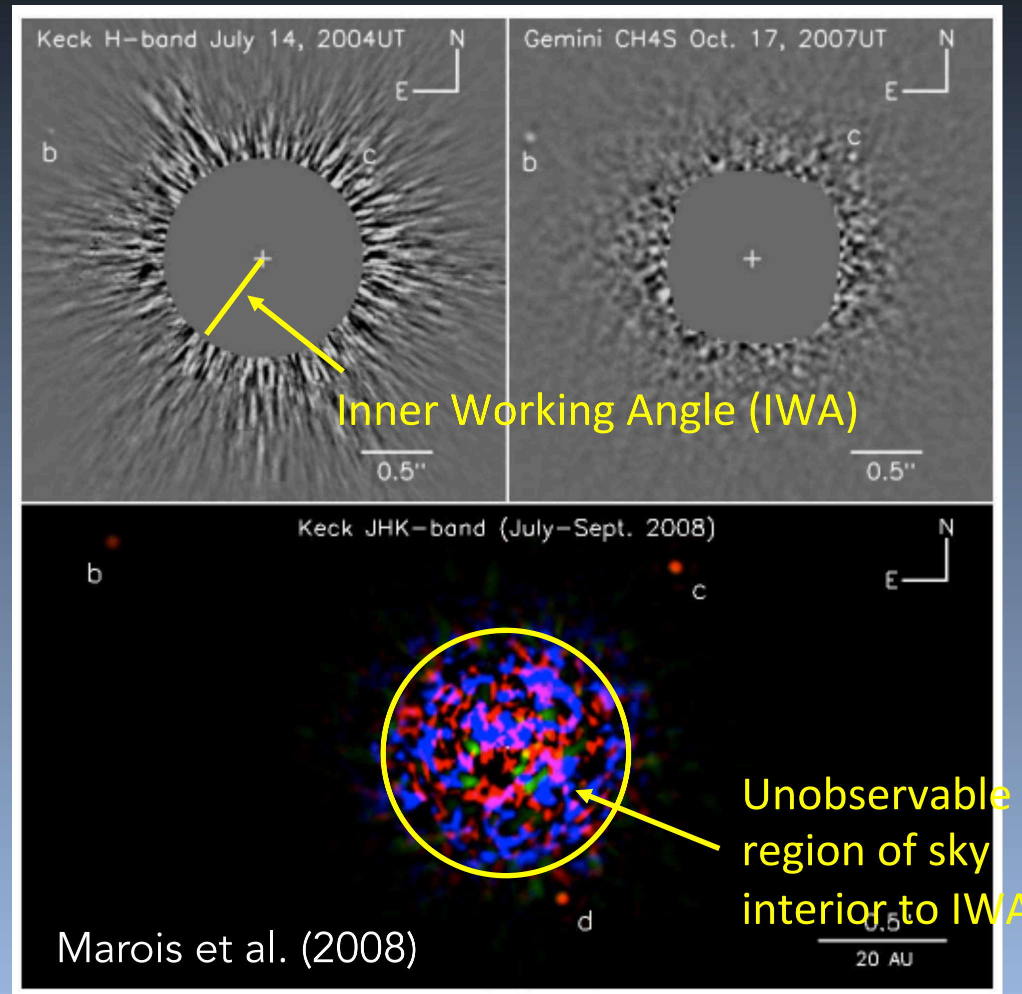
1. Pick a science goal
2. Simulate mission and determine what it takes

# Observing Exoplanets & Inner Working Angle

## Model



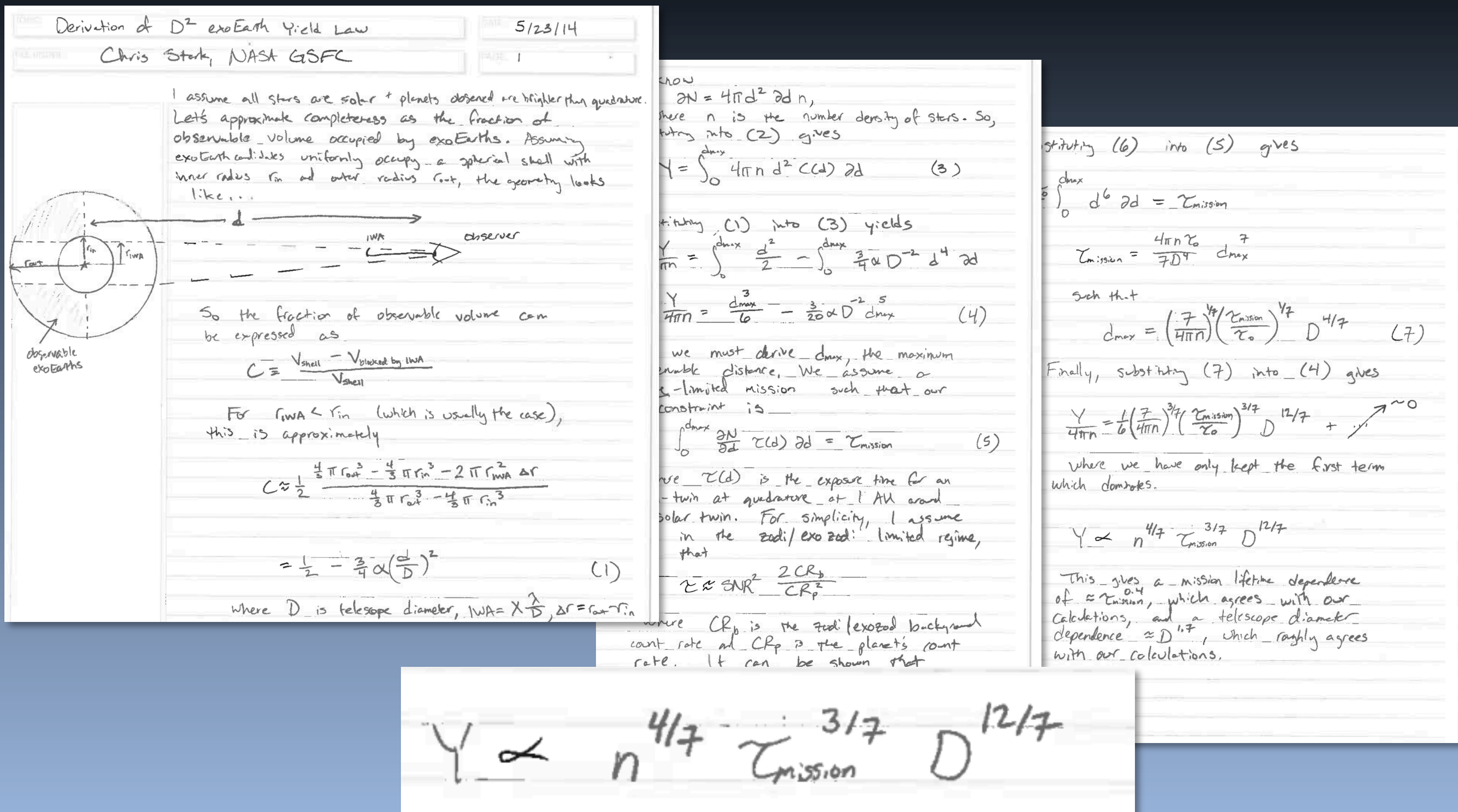

## Actual Observations




Coronagraph IWA ∝ $\lambda/D$.

Max distance ~ 1 AU / IWA, so should yield go as $D^3$?

# The Limiting Resource



Derivation of $D^2$ exoEarth Yield Law — 5/23/14

Chris Stark, NASA GSFC — 1

I assume all stars are solar + planets observed are brighter than quadrature. Let's approximate completeness as the fraction of observable volume occupied by exoEarths. Assuming exoEarth candidates uniformly occupy a spherical shell with inner radius $r_{in}$ and outer radius $r_{out}$, the geometry looks like...



So the fraction of observable volume can be expressed as

$$C \equiv \frac{V_{shell} - V_{blocked\ by\ IWA}}{V_{shell}}$$

For $r_{IWA} < r_{in}$ (which is usually the case), this is approximately

$$C \approx \frac{1}{2}\,\frac{\frac{4}{3}\pi r_{out}^3 - \frac{4}{3}\pi r_{in}^3 - 2\pi r_{IWA}^2 \Delta r}{\frac{4}{3}\pi r_{out}^3 - \frac{4}{3}\pi r_{in}^3}$$

$$= \frac{1}{2} - \frac{3}{4}\alpha\left(\frac{d}{D}\right)^2 \qquad (1)$$

where $D$ is telescope diameter, $IWA = X\frac{\lambda}{D}$, $\Delta r = r_{out} - r_{in}$

…now

$$\partial N = 4\pi d^2 \partial d\, n,$$

…here $n$ is the number density of stars. So, …tuting into (2) gives

$$Y = \int_0^{d_{max}} 4\pi n\, d^2 C(d)\, \partial d \qquad (3)$$

…tituting (1) into (3) yields

$$\frac{Y}{\pi n} = \int_0^{d_{max}} \frac{d^2}{2} - \int_0^{d_{max}} \frac{3}{4}\alpha D^{-2} d^4\, \partial d$$

$$\frac{Y}{4\pi n} = \frac{d_{max}^3}{6} - \frac{3}{20}\alpha D^{-2} d_{max}^5 \qquad (4)$$

…we must derive $d_{max}$, the maximum …vable distance. We assume a …-limited mission such that our constraint is

$$\int_0^{d_{max}} \frac{\partial N}{\partial d}\tau(d)\, \partial d = \tau_{mission} \qquad (5)$$

…re $\tau(d)$ is the exposure time for an …-twin at quadrature at 1 AU around …solar twin. For simplicity, I assume …in the zodi/exozodi limited regime, …that

$$\tau \approx SNR^2 \frac{2 CR_b}{CR_p^2}$$

…where $CR_b$ is the zodi/exozodi background count rate and $CR_p$ is the planet's count rate. It can be shown that

…stituting (6) into (5) gives

$$\ldots \int_0^{d_{max}} d^6\, \partial d = \tau_{mission}$$

$$\tau_{mission} = \frac{4\pi n \tau_0}{7 D^4} d_{max}^7$$

Such that

$$d_{max} = \left(\frac{7}{4\pi n}\right)^{1/7}\left(\frac{\tau_{mission}}{\tau_0}\right)^{1/7} D^{4/7} \qquad (7)$$

Finally, substituting (7) into (4) gives

$$\frac{Y}{4\pi n} = \frac{1}{6}\left(\frac{7}{4\pi n}\right)^{3/7}\left(\frac{\tau_{mission}}{\tau_0}\right)^{3/7} D^{12/7} + \ldots \sim 0$$

where we have only kept the first term which dominates.

$$Y \propto n^{4/7}\, \tau_{mission}^{3/7}\, D^{12/7}$$

This gives a mission lifetime dependence of $\approx \tau_{mission}^{0.4}$, which agrees with our calculations, and a telescope diameter dependence $\approx D^{1.7}$, which roughly agrees with our calculations.

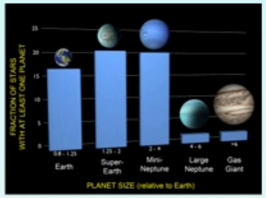
$$Y \propto n^{4/7}\, \tau_{mission}^{3/7}\, D^{12/7}$$

To correctly estimate science yield, one must understand the limiting resource.

# Calculating Yield with a DRM Code

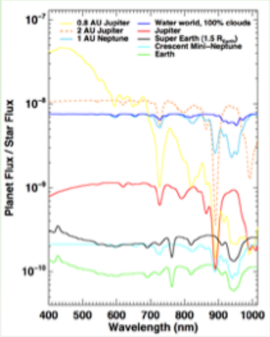
## Astrophysical Constraints

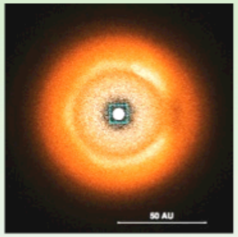
- $\eta_{Earth}$
- $\eta_{exozodi}$
- Planet sizes
- Albedos
- Phase functions




## Observational Requirements

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



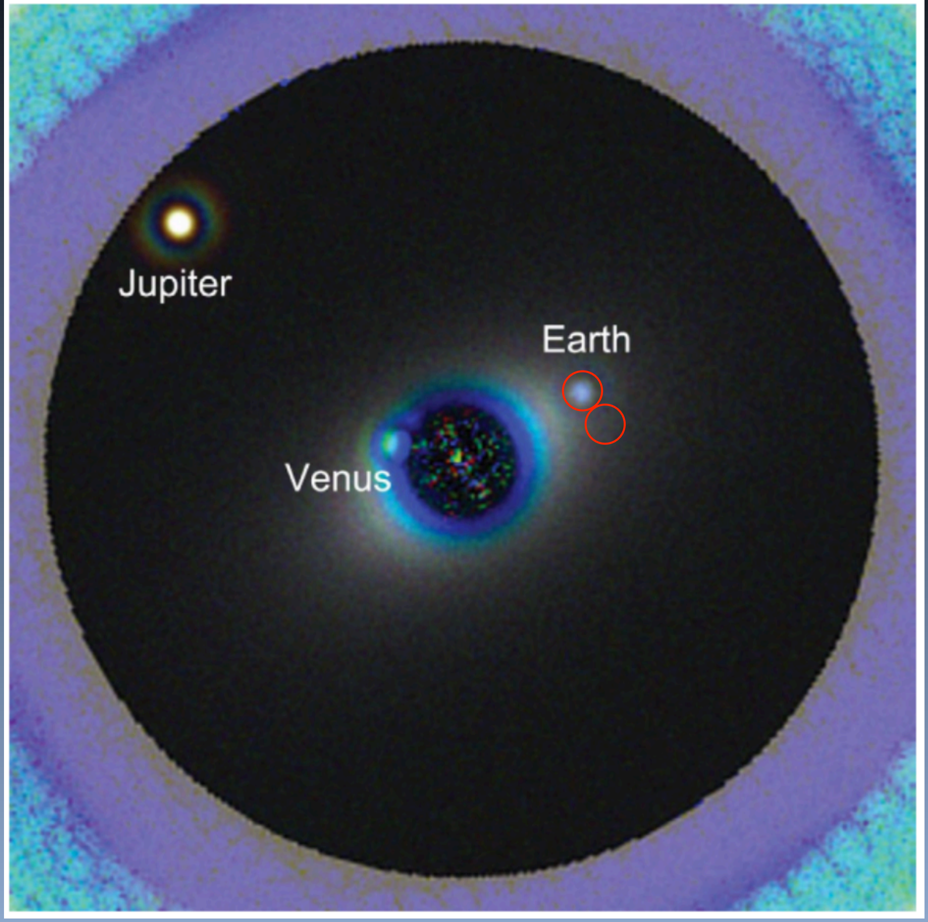




## Technical Requirements

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

DRM

# Observing an Exoplanetary Scene




L. Pueyo & M. N'Diaye

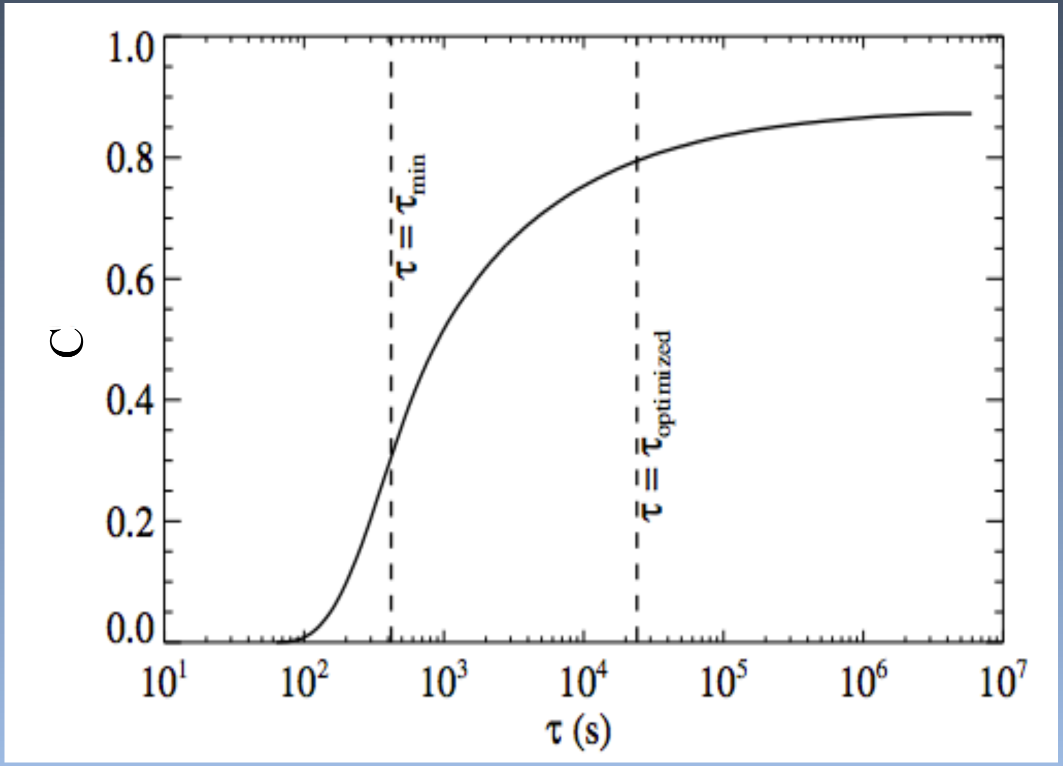
$$\tau = (\mathrm{S/N})^2 \left( \frac{\mathrm{CR_p} + 2\,\mathrm{CR_b}}{\mathrm{CR_p}^2} \right)$$

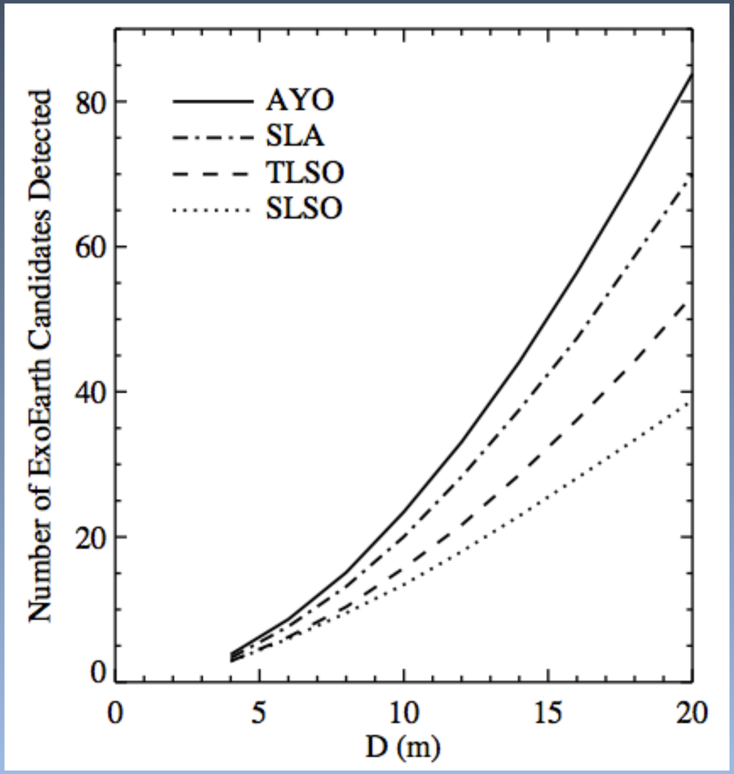
# ExoEarth Yield Estimated via Completeness


- 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

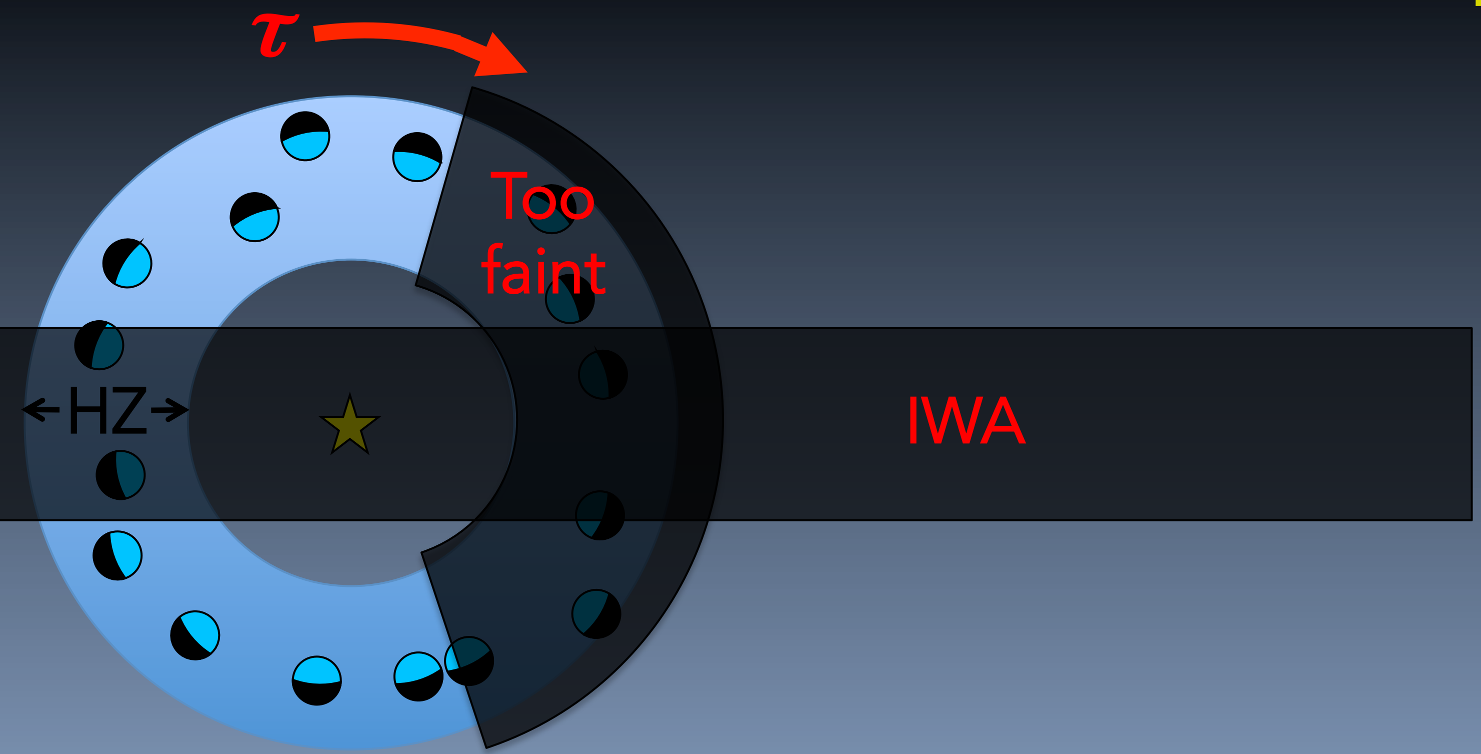
## Optimized Exposure Times

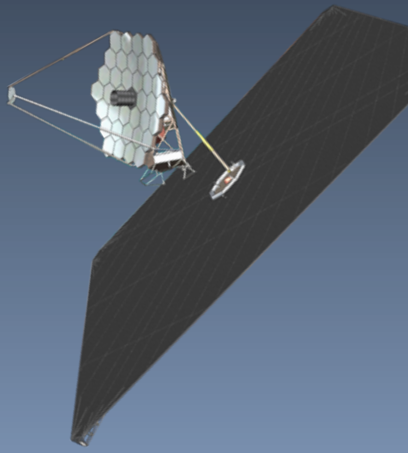



Optimizing exposure times can potentially double yield

# ExoEarth Yield Estimated via Completeness

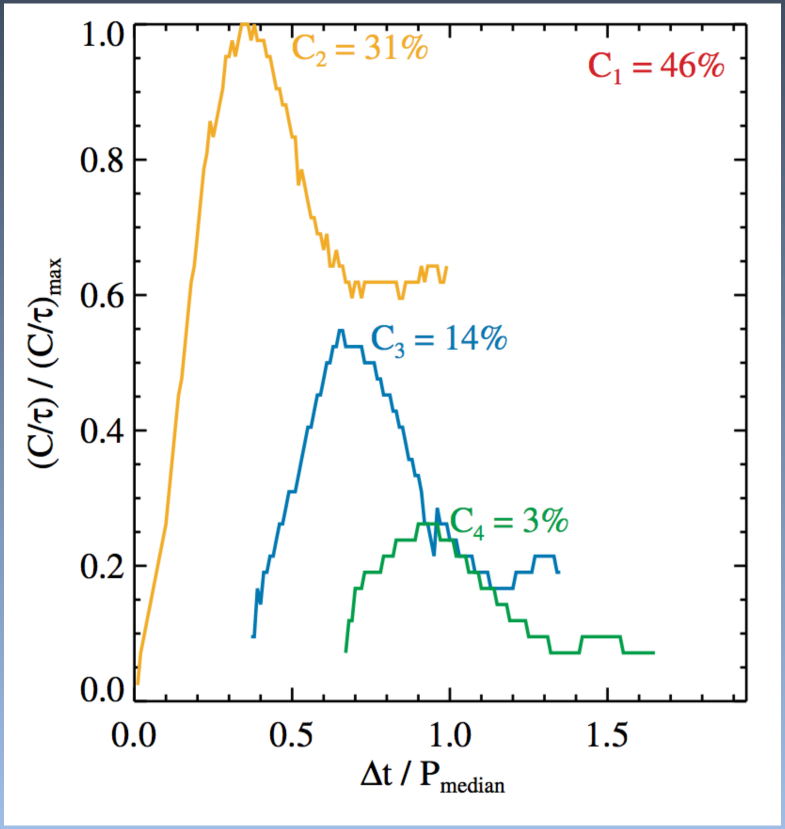


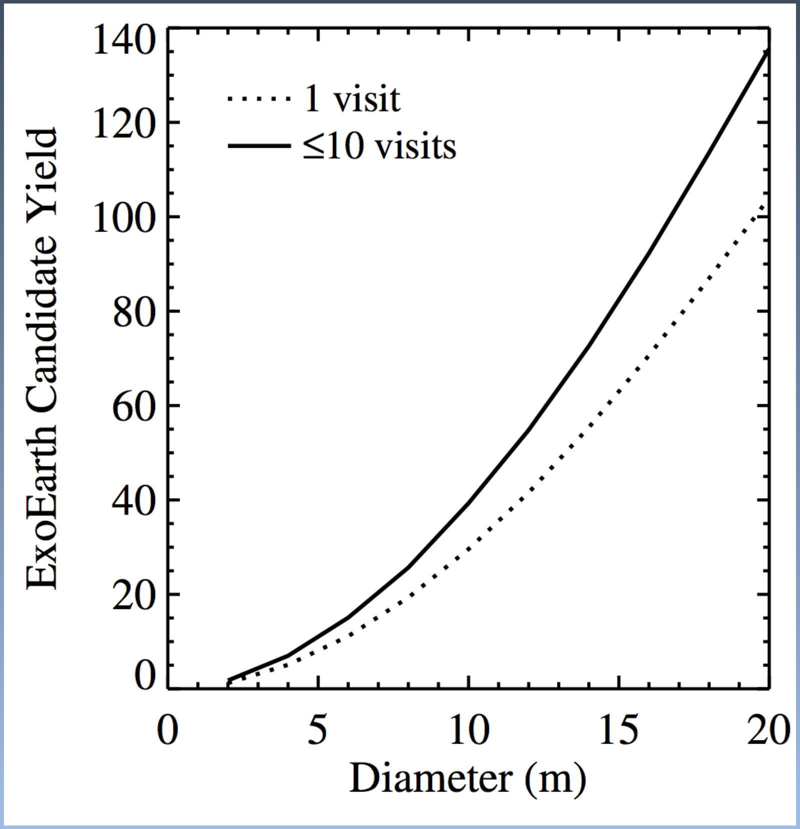



- Revisiting same star multiple times can increase total completeness
- Can optimize number of visits and delay time between visits

# Maximizing Yield by Optimizing Observations

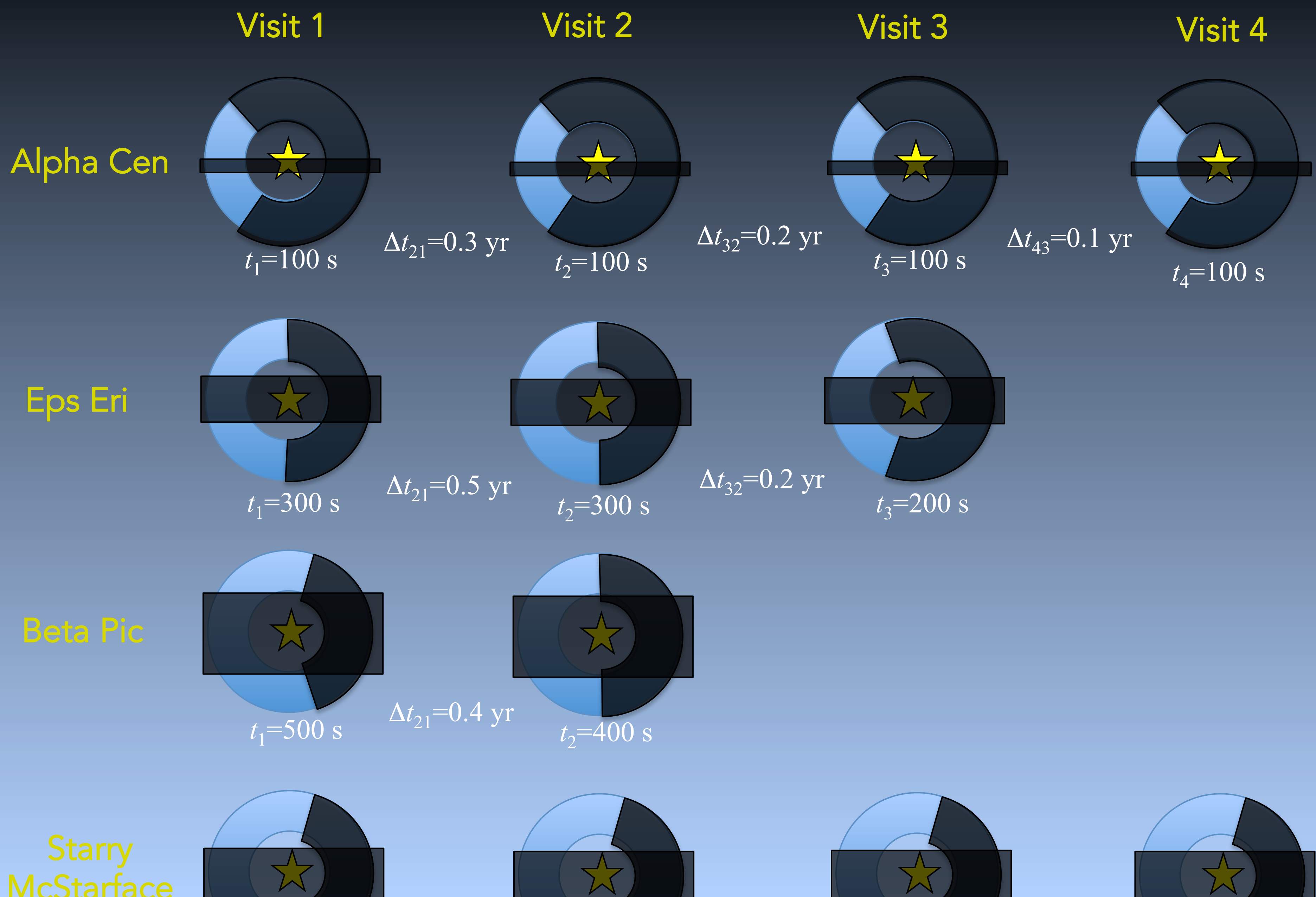
## Optimized Revisits



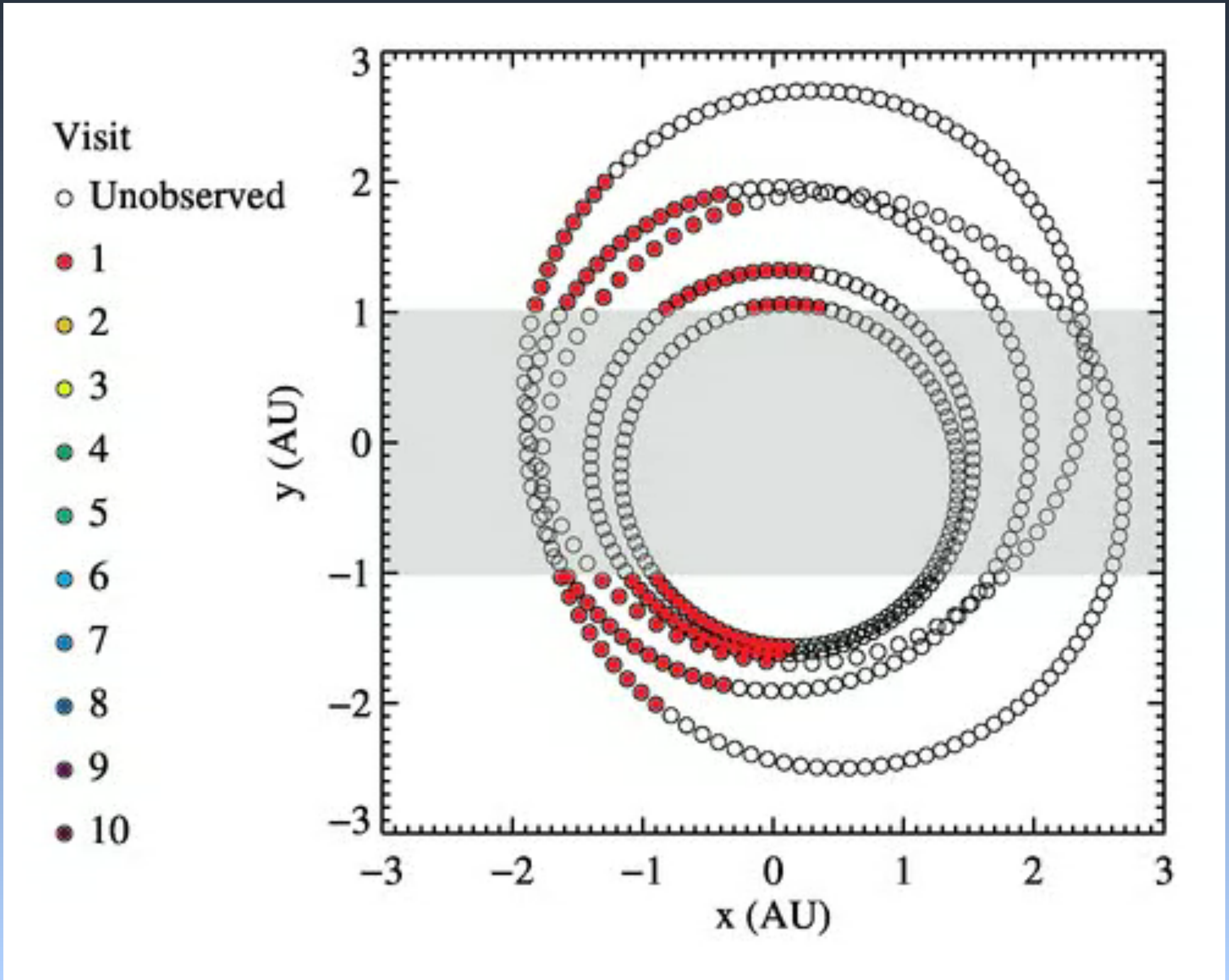




Optimized revisits increase yield by additional 35-75%

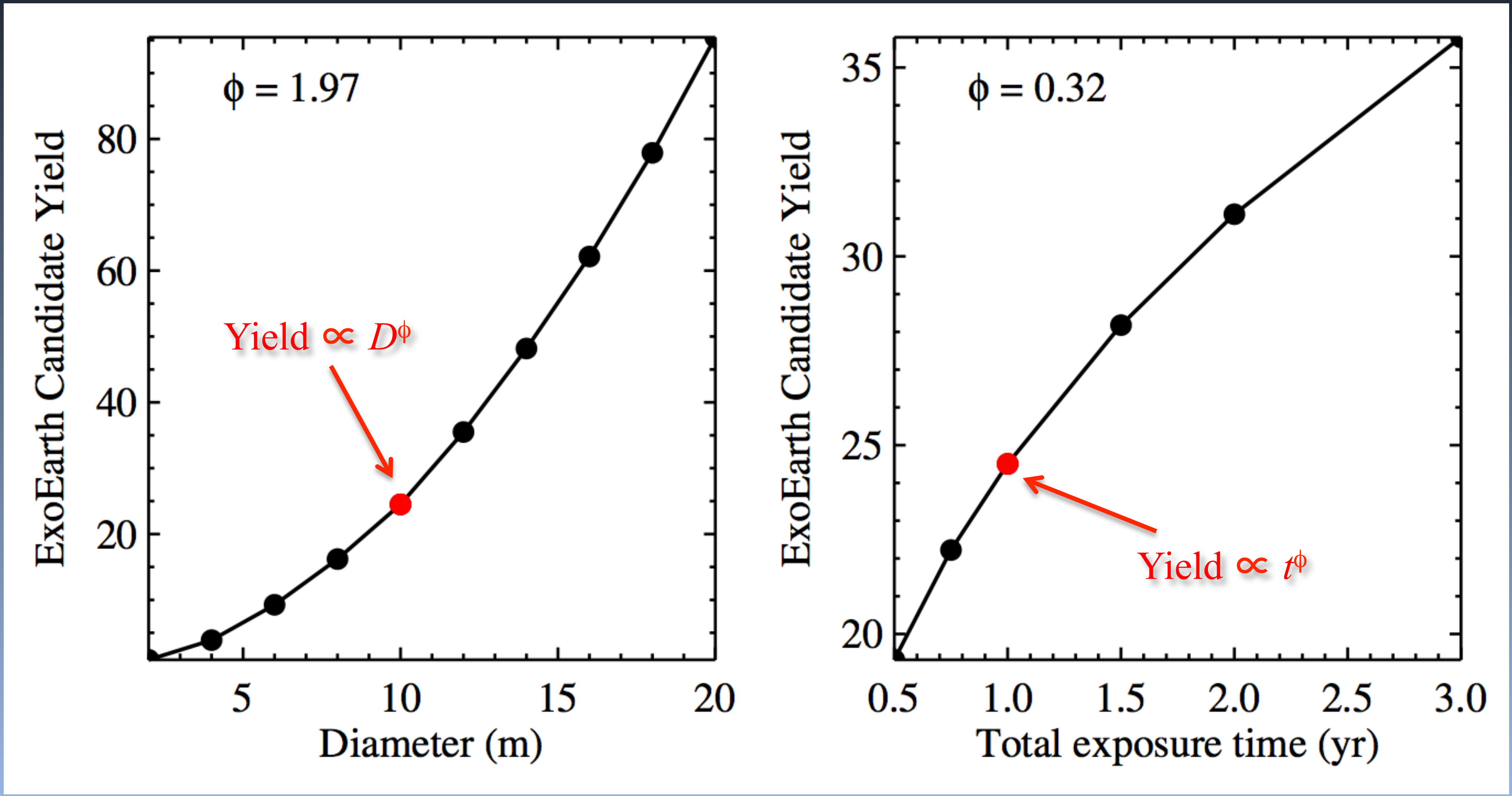
# Result: A Static Optimized Observation Plan



# Maximizing Yield by Optimizing Observations



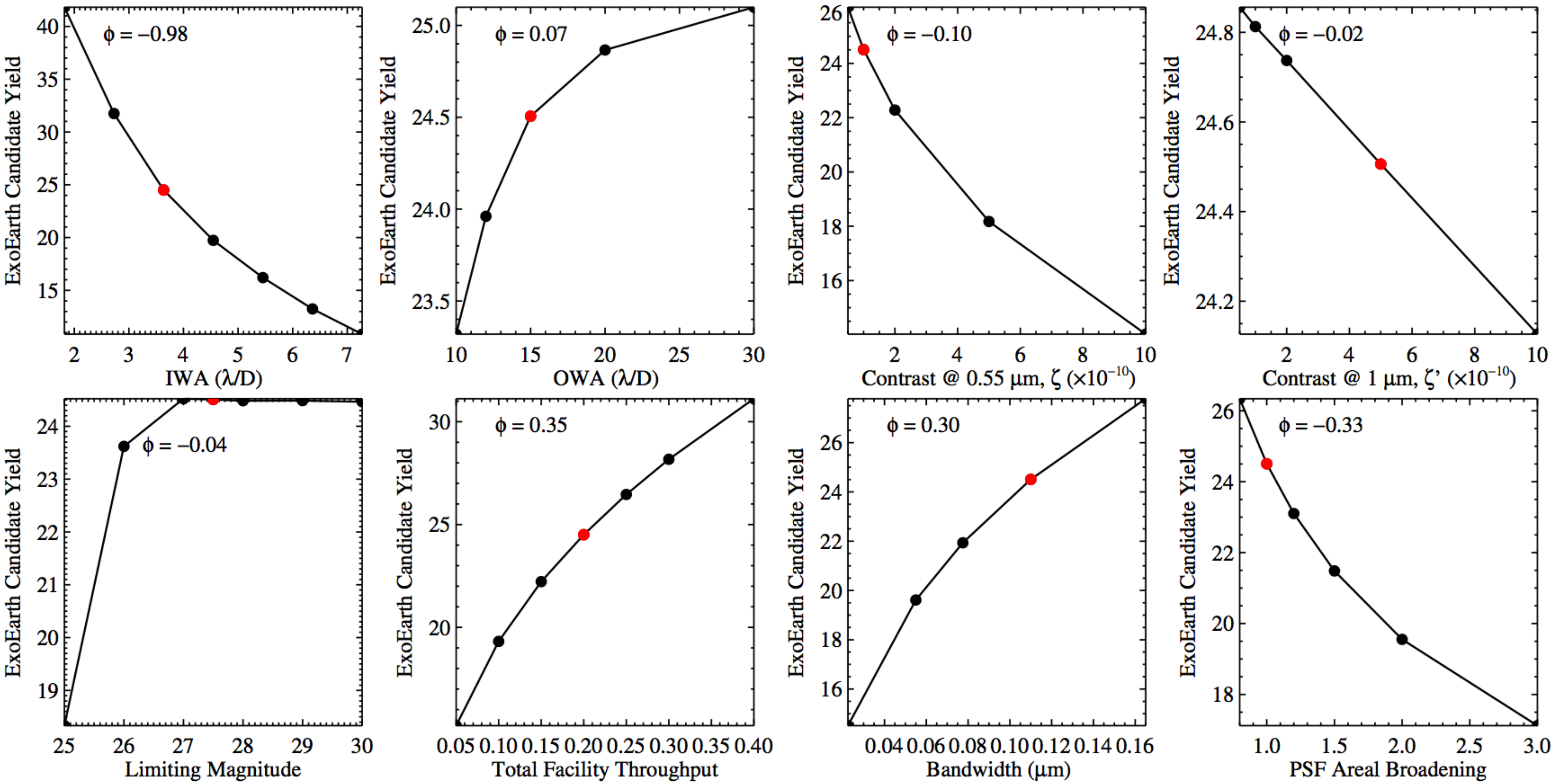
# What Telescope/Instrument Parameters Matter?




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

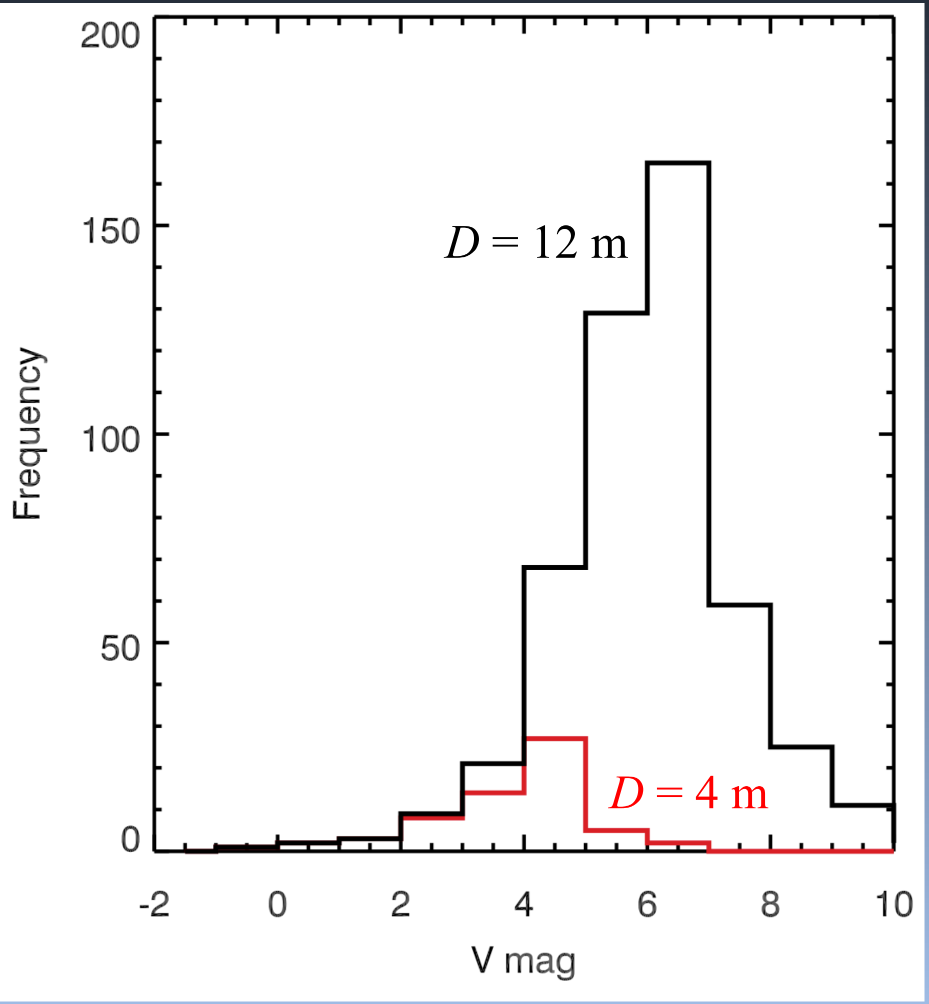
# What Telescope/Instrument Parameters Matter?

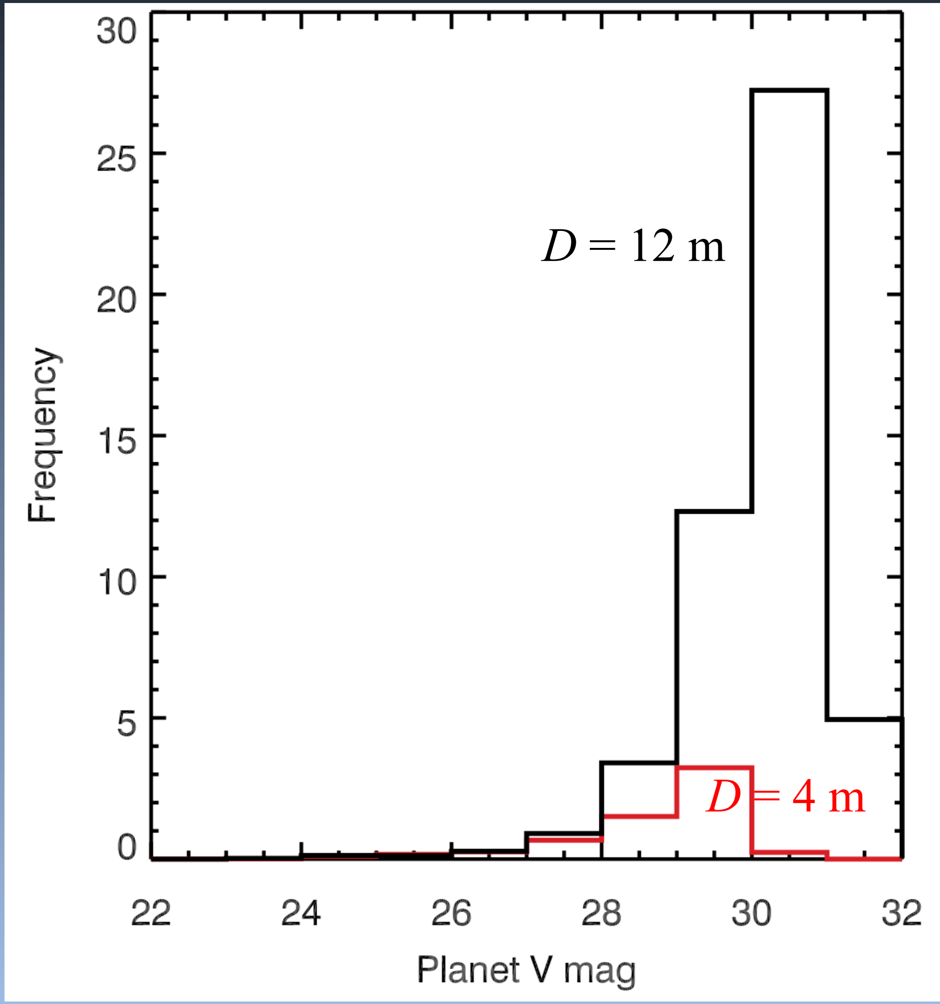
## Coronagraph Scaling Laws



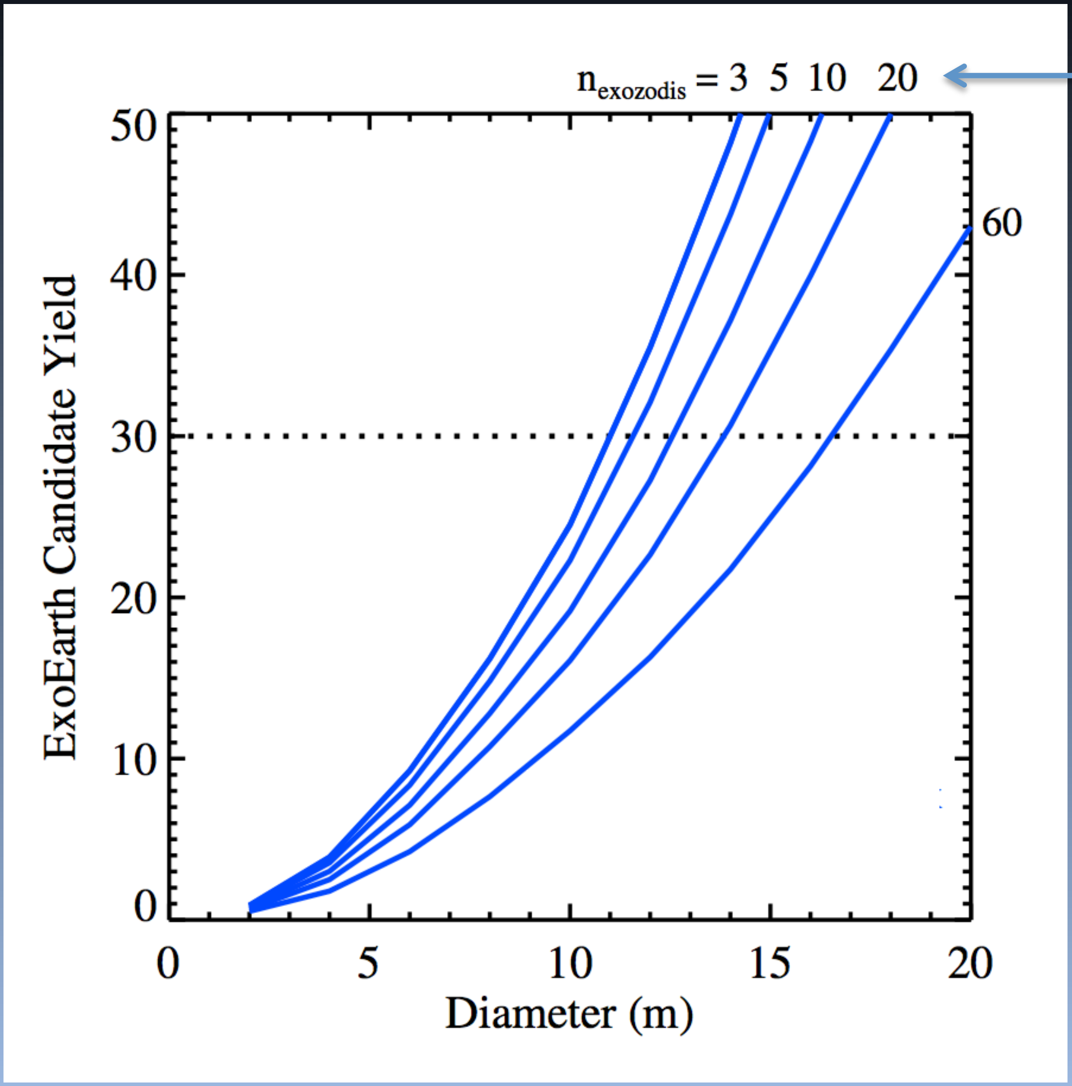

IWA matters more than contrast when treating both linearly. OWA doesn't matter much. Noise floors with Δmag > 26.5 are unnecessary.

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



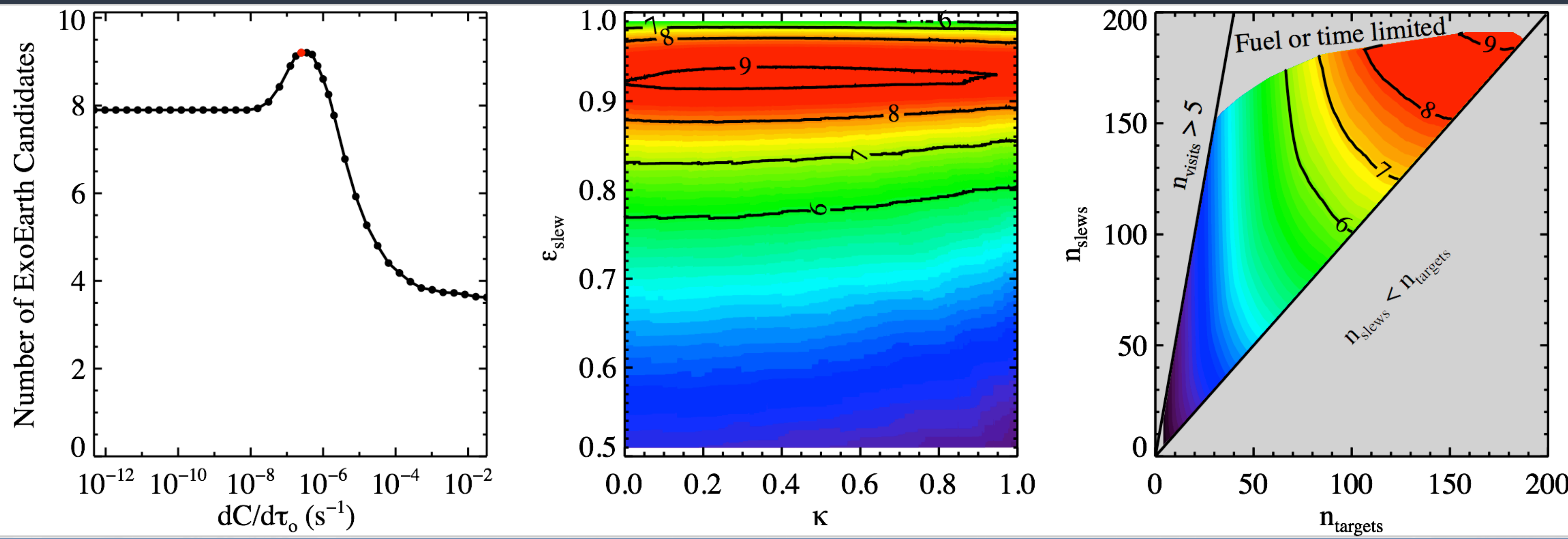
# Lower Limits on Aperture Size




Amount of exozodiacal dust (× solar zodiacal amount)

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

# Optimizing Starshades: Balancing Time with Fuel



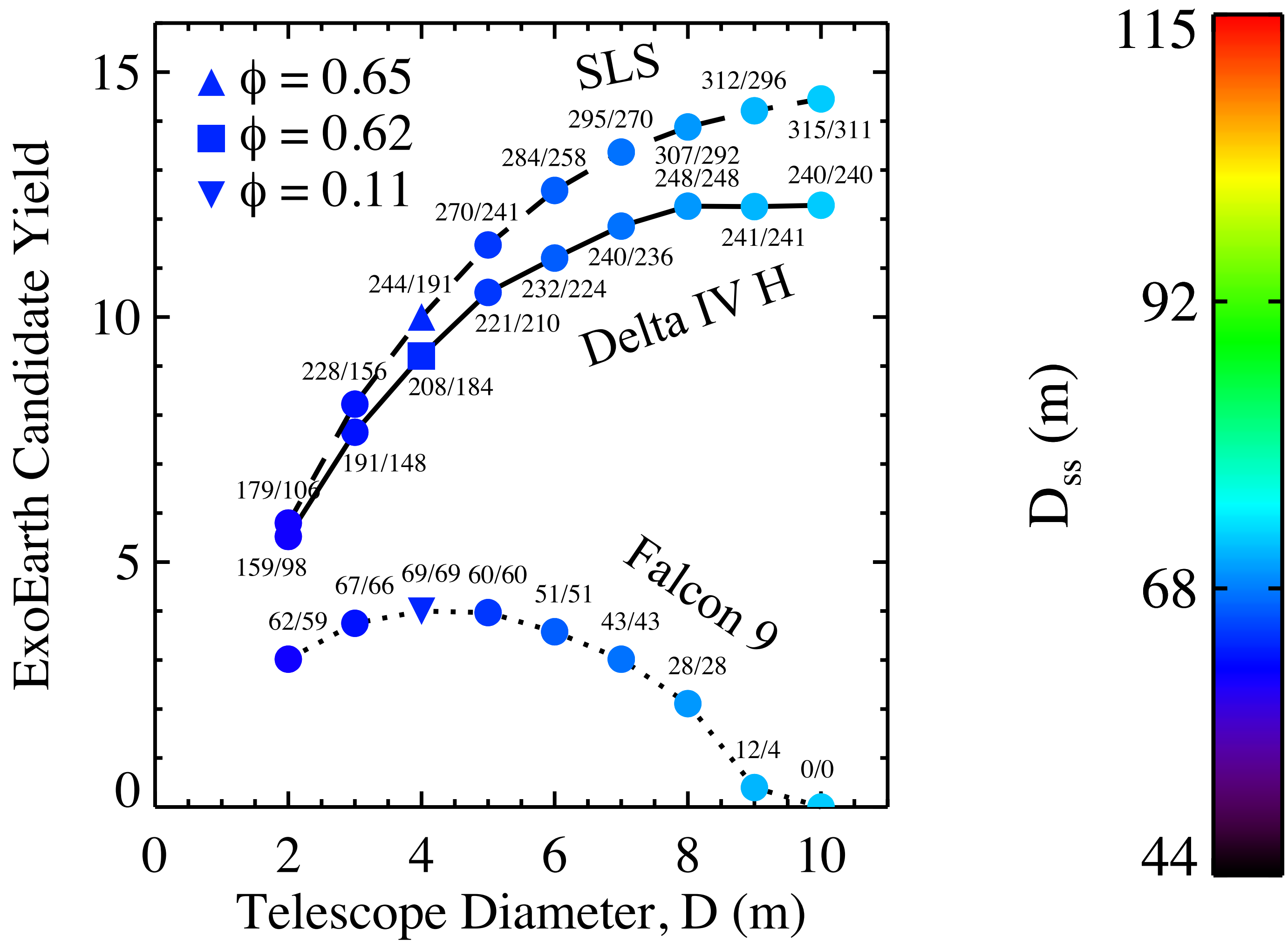

We search the 5-dimensional parameter space controlling starshade yield to maximize yield

# Maximized Yields for Starshades

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

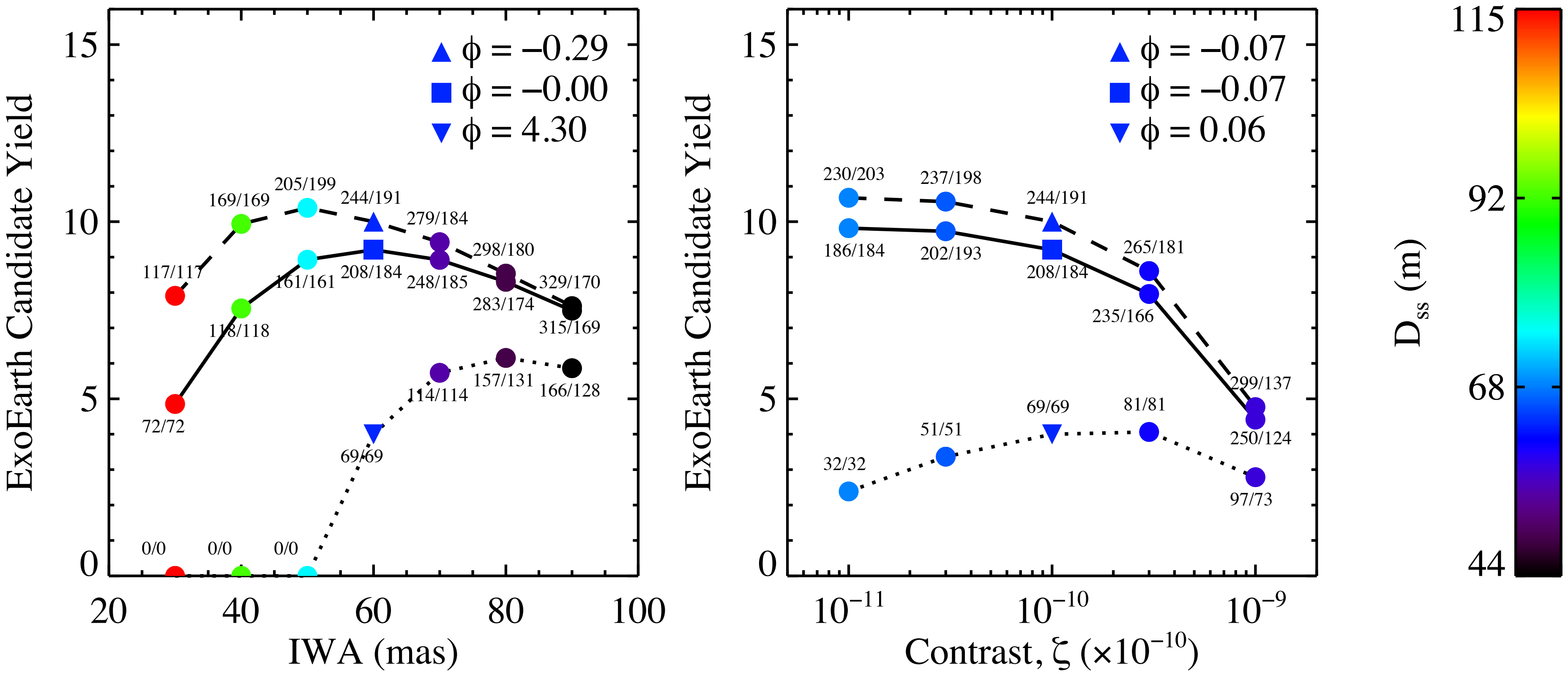
Near $x = x_0$,

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



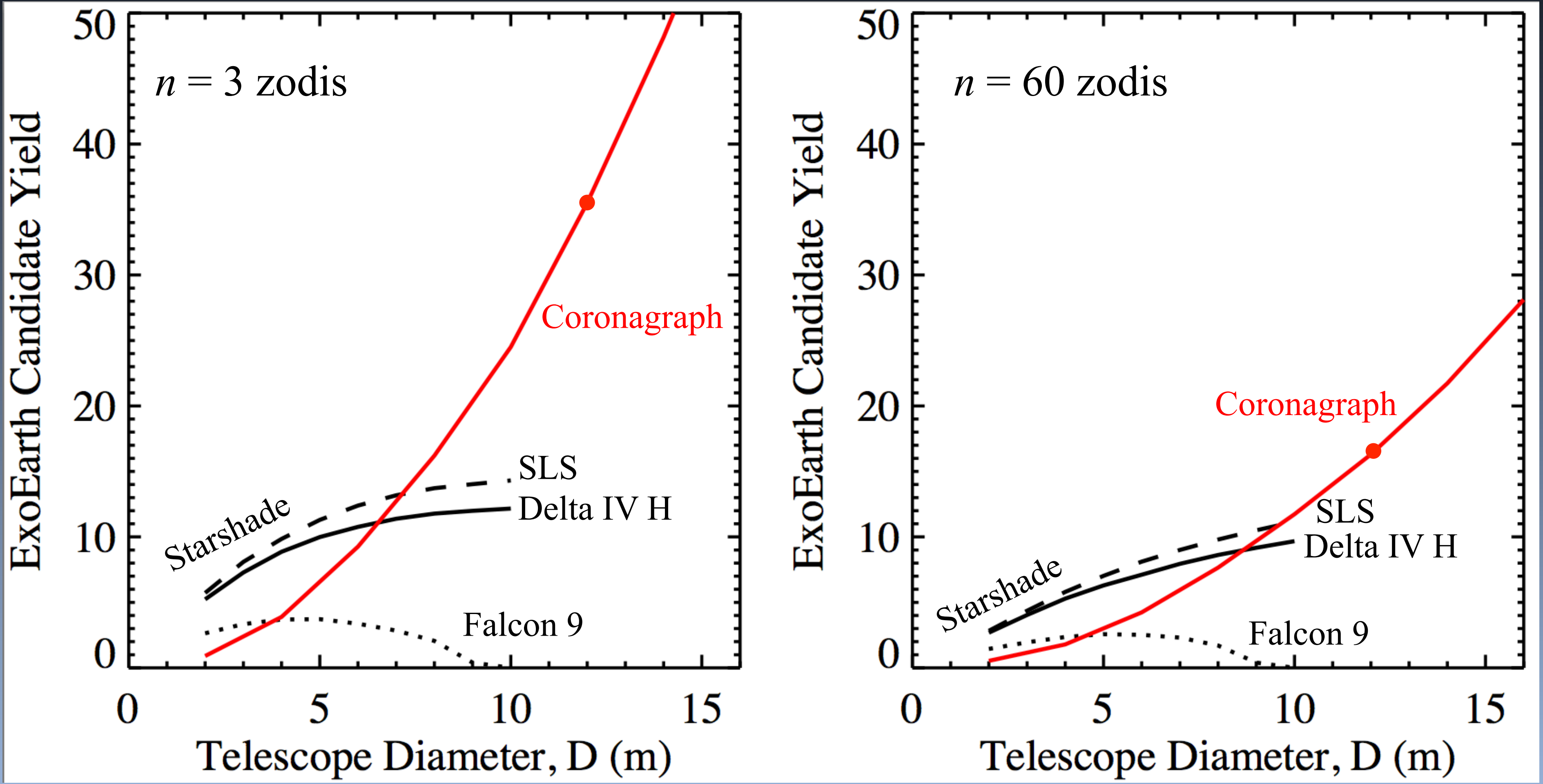

Yield is moderately sensitive to aperture size and turns over at large *D*; an optimum aperture size exists.

# Yield vs Instrument Optical Parameters




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

# 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.***