Science with Different Size Telescope Apertures and Starshades

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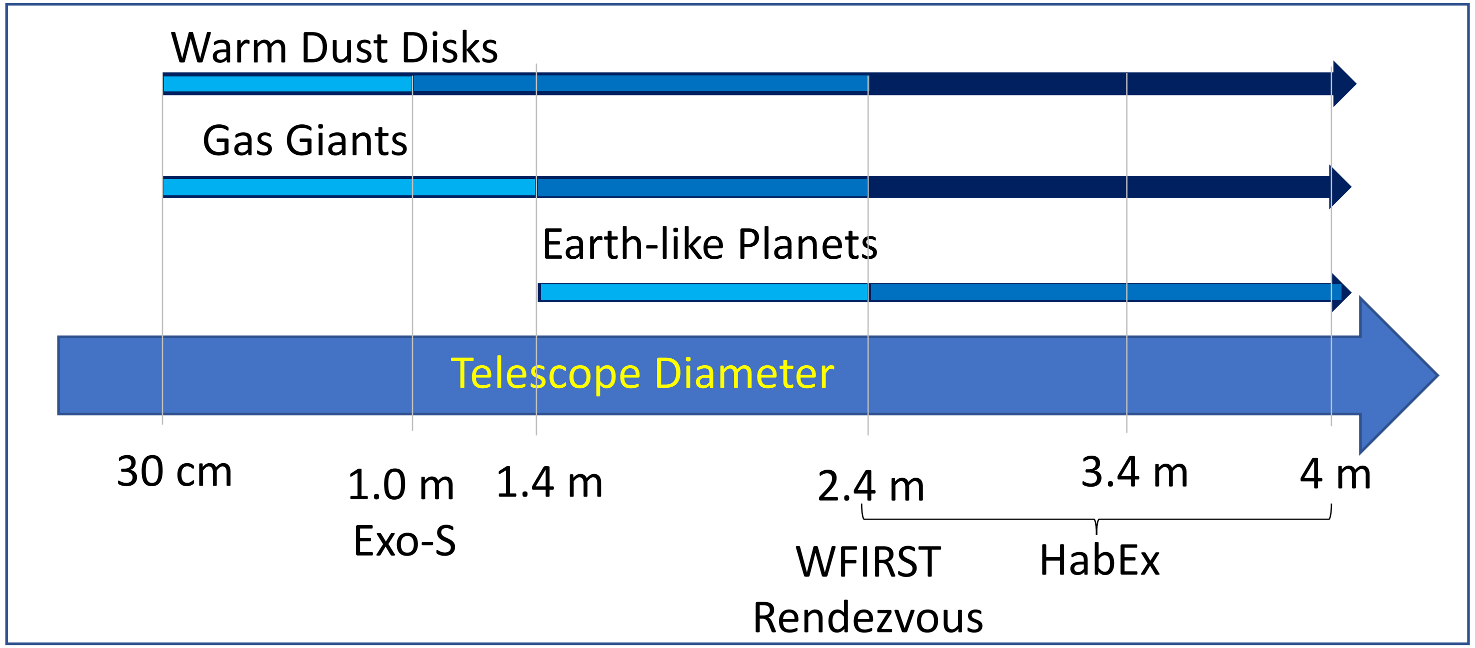
JPL

Science with Starshades



Detection, Characterization, Statistical (≳10)

Strashade Rendezvous Probe Science Objectives

Perform a "deep dive", an intense, long integration of the 10 nearest sunlike stars with highest imaging and spectral sensitivity and amenable to multiple visits to constrain orbits.

Habitability & Planetary Systems

Objective 1a: Habitability and Biosignature Gases. Determine whether super-Earth size or smaller exoplanets in the habitable zone exist around the nearest sunlike stars and have signatures of oxygen and water vapor in their atmospheres.

Objective 1b: The Nearest Solar System Analogs Detect and characterize planets orbiting the nearest sunlike stars

Exozodiacal Dust

Objective 2: Brightness of Zodiacal Dust Disks. Establish if the zodiacal cloud of our inner solar system is representative of the population of our nearest neighbor stars.

Planet Formation

Objective 3: Giant Planet Atmosphere Metallicity. Determine the metallicity of known cool giant planets to examine trends with planetary mass and orbital semi-major axis, and to determine if these trends are consistent with our solar system

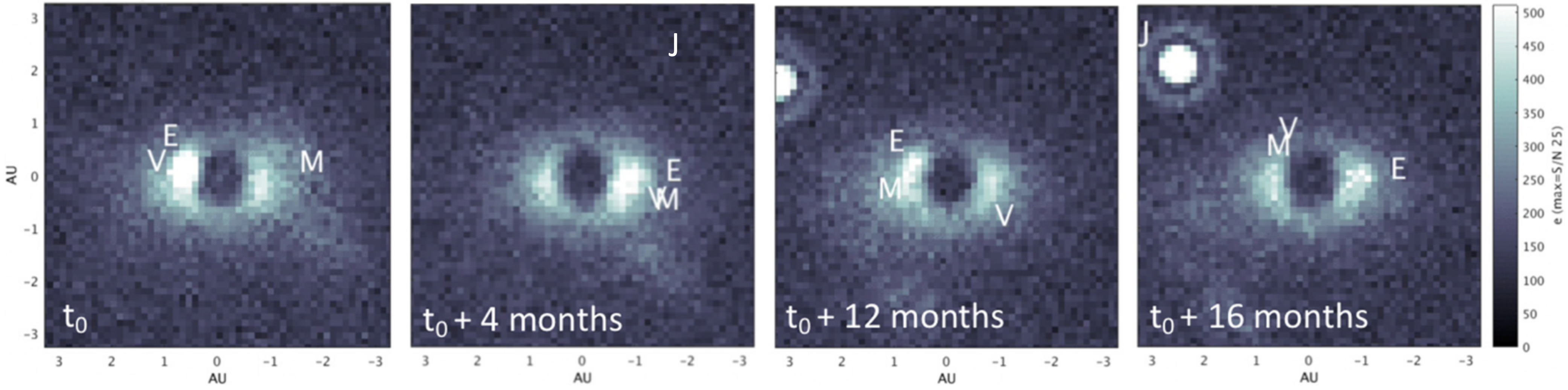
Habitability & Planetary System Architectures

Maintaining the sensitivity to discover and characterize Earth-like exoplanet candidates drives the observatory requirements.

The Deep Dive Approach

Initial Reconnaissance	First visit evaluates zodiacal dust brightness and detection of any exoplanets present.
Orbit Determination	Revisits to determine if planets are in the habitable zone of a star.
Spectral Characterization	Deep integration triggered by habitable zone exoplanet candidates. Any other planets in the field of view will also be spectroscopically characterized.

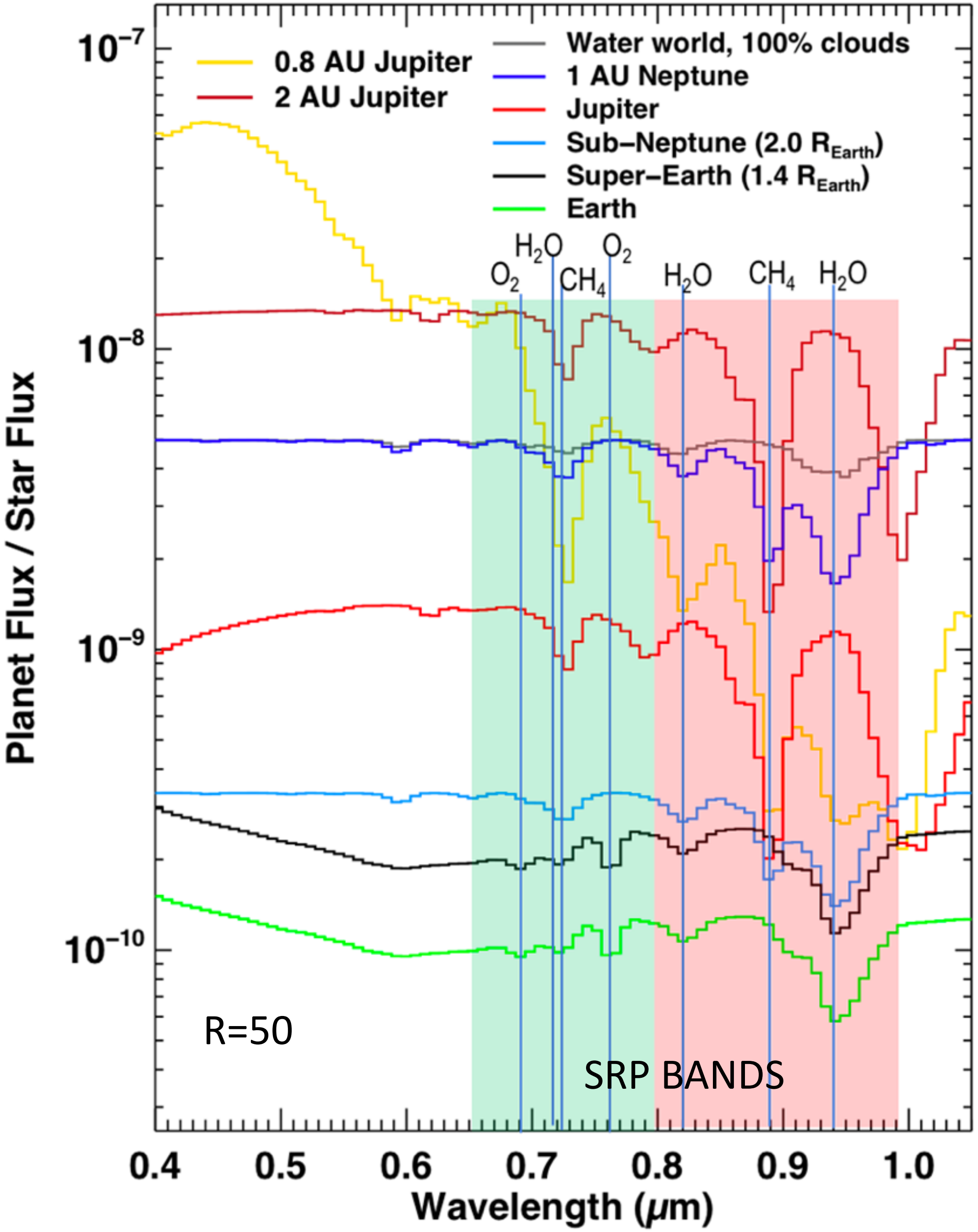
Simulated observations of the Solar System 10 pc away.



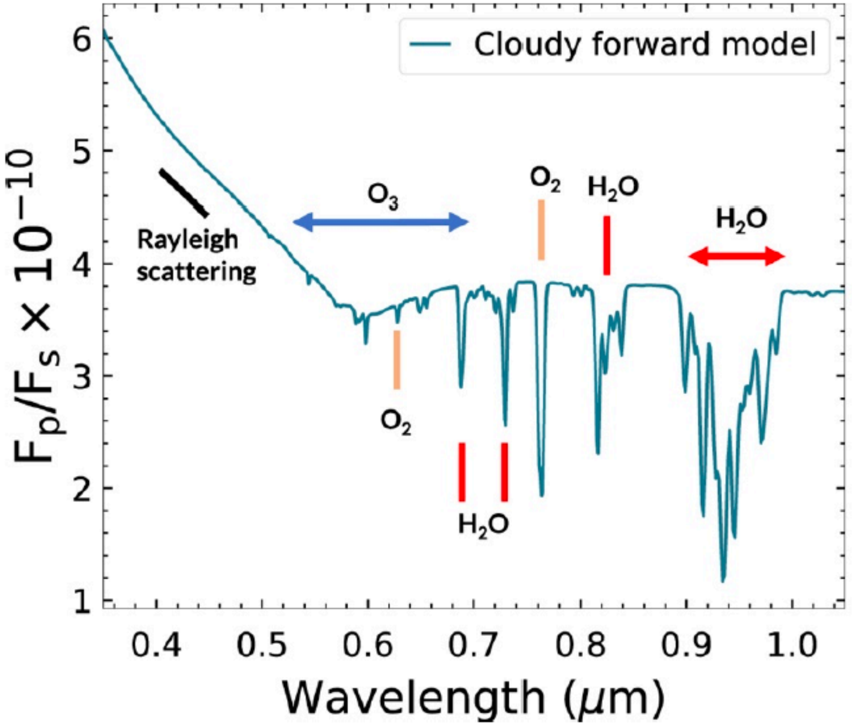
Planet Atmospheres

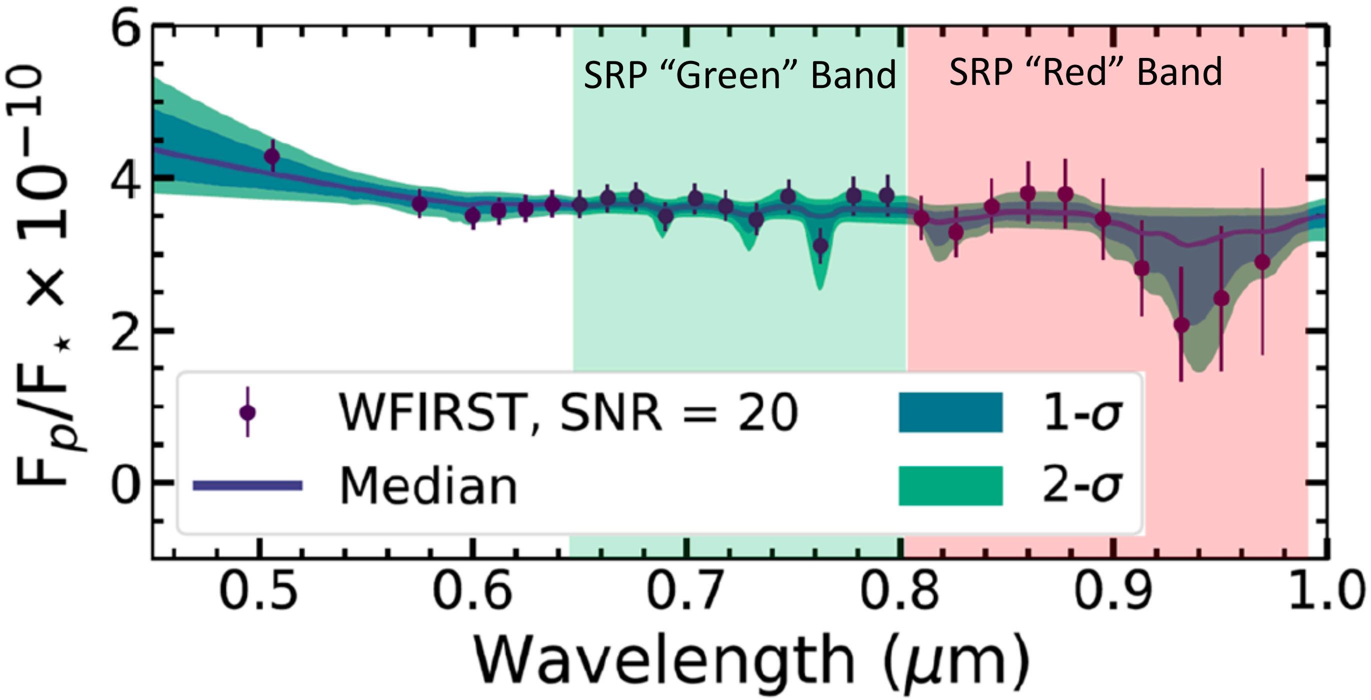
- Starshade + WFIRST-CGI has the capability to take spectral measurements of Exoplanet atmosphere.
- Requirements set using Earth as a model to enable the characterization of a wide class of planets.

Image Credit: Aki Roberge



Spectroscopic Characterization





- Study from Feng et al., 2018, determined that for WFIRST-CGI R=50, and sub-band SNR>20 is needed for weak detection of O_2 and H_2O features

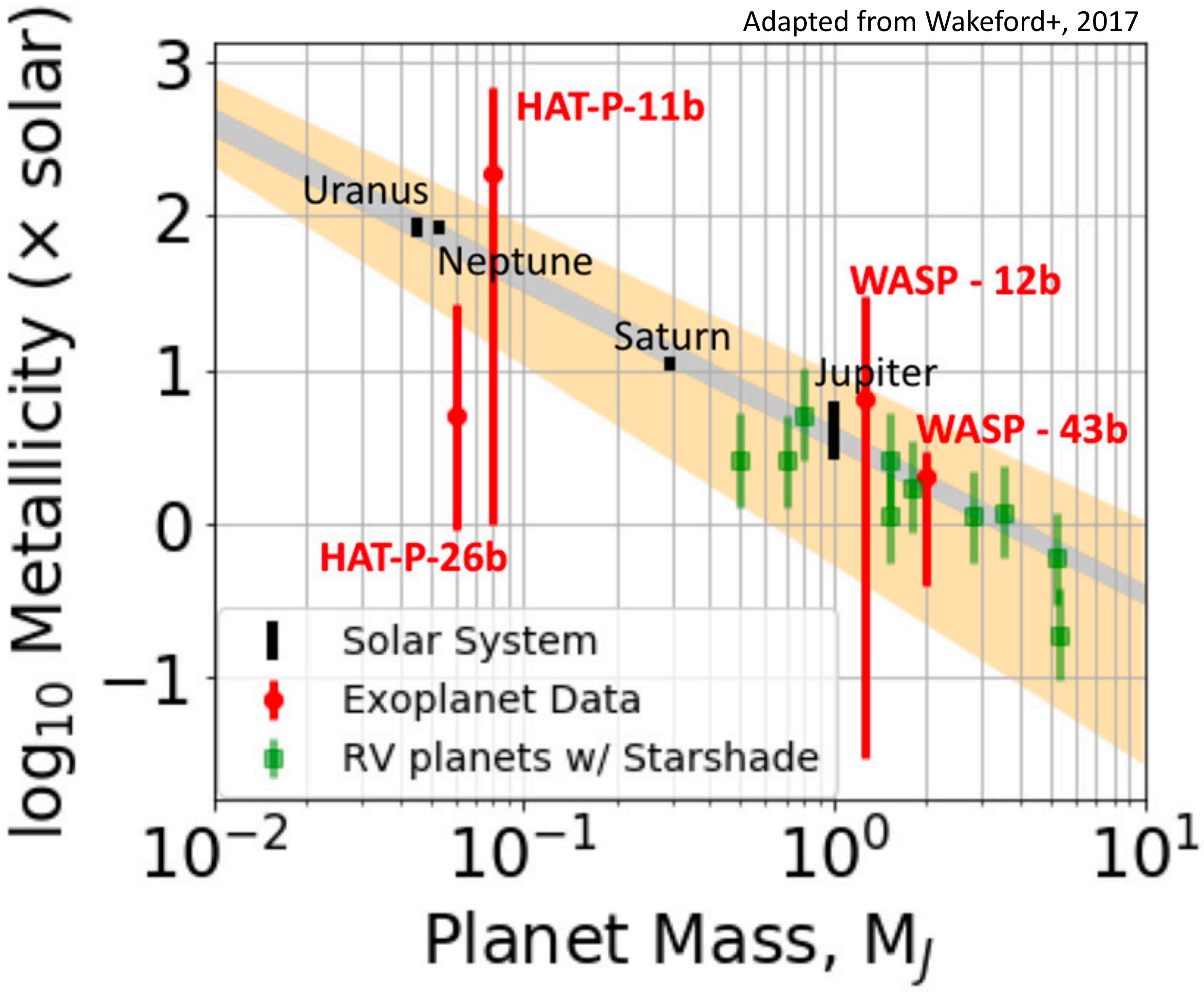
Metallicity of Known Extrasolar Planets

Objective is to test the correlation of metallicity in gas giant atmospheres with planet properties (mass and semi-major axis).

Solar system planets exhibit a strong correlation.

Transiting planet sample probes highly irradiated planets, starshade probes analogs of our own giant planets.

Adapted from Wakeford+, 2017

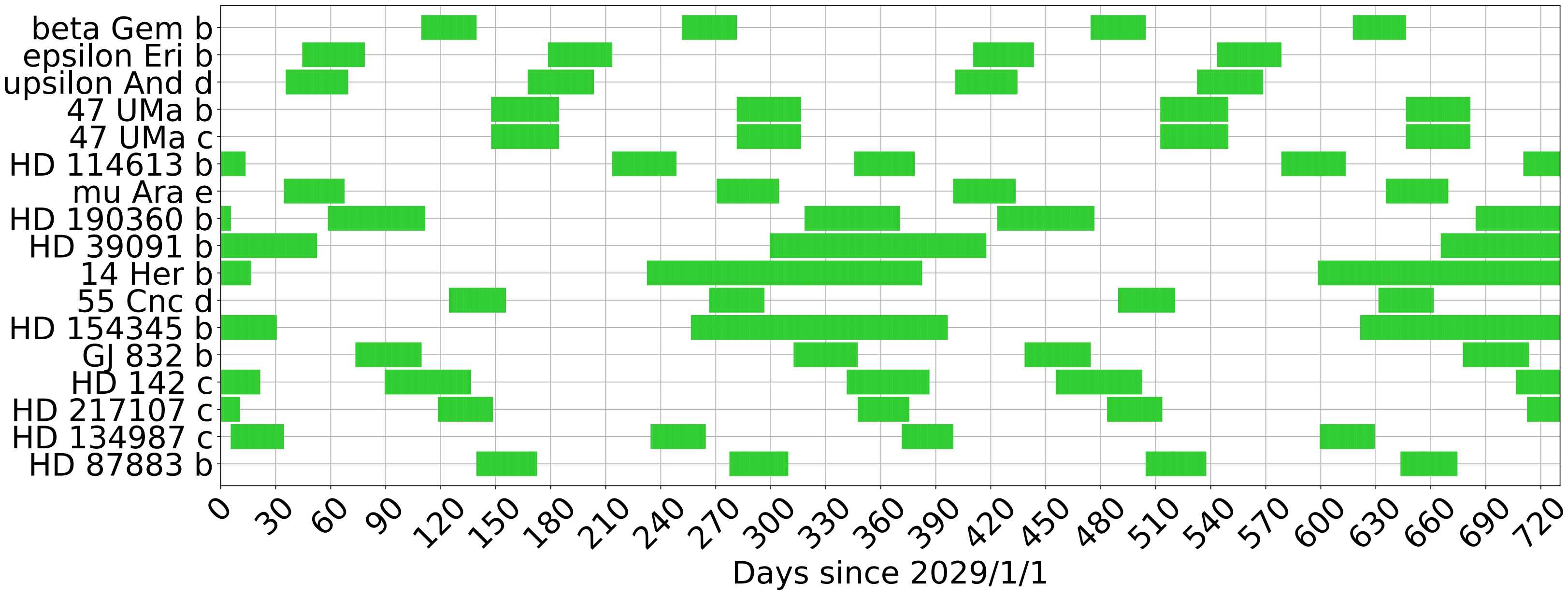


Metallicity of Known Extrasolar Planets

#	Target	Integration Time (days)		
		β=45°	β=90°	β=135°
1	beta Gem b	≤0.1	≤0.1	≤0.1
2	epsilon Eri b	≤0.1	0.25	4
3	upsilon And d	≤0.1	0.25	4
4	47 UMa b	≤0.1	0.4	6.3
5	47 UMa c	0.4	1.6	-
6	HD 114613 b	1.0	4.0	-
7	mu Ara e	1.6	6.3	-
8	HD 190360 b	1.6	6.3	-
9	HD 39091 b	2.5	10	-
10	14 Her b	2.5	10	-
11	55 Cnc d	4.0	16	-
12	HD 154345 b	6.3	25	-
13	GJ 832 b	10	-	-
14	HD 142 c	10	-	-
15	HD 217107 c	16	-	-
16	HD 134987 c	16	-	-
17	HD 87883 b	25	-	-

Indicates integration time is > 25 days

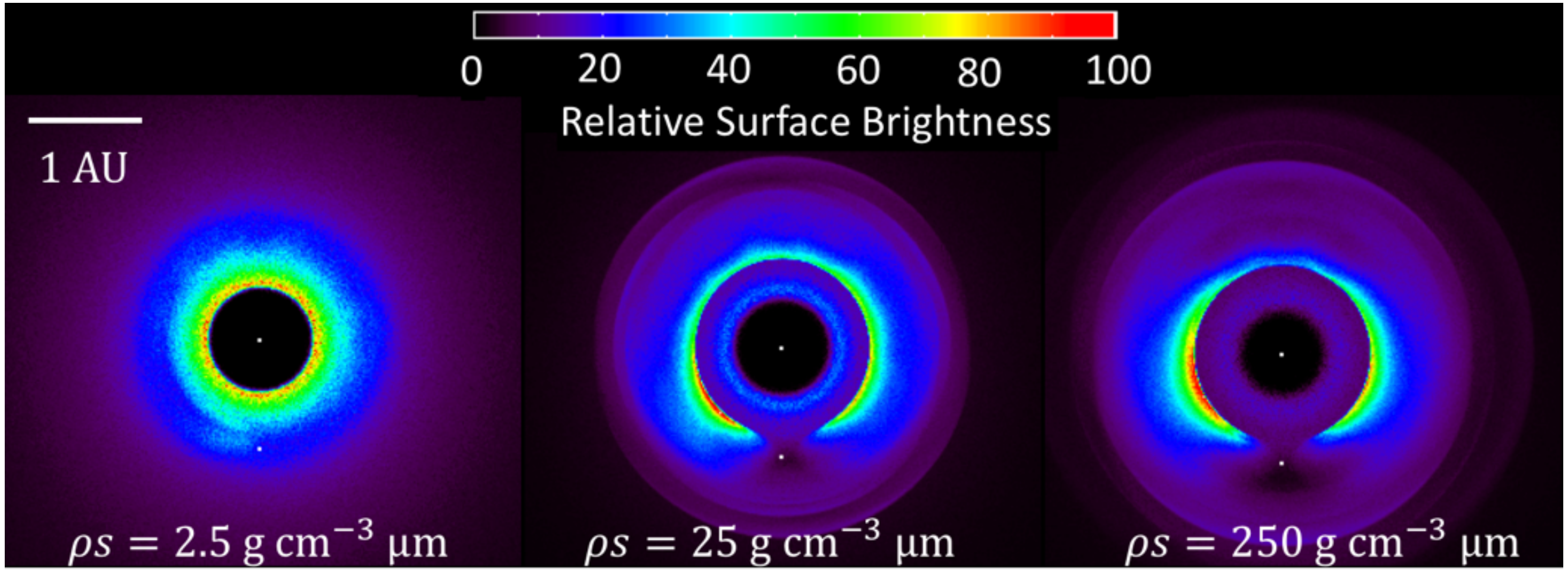
Observing Windows for Host Stars



- 17 candidate targets today with more expected by the time Starshade operates.
- WFIRST CGI expected to provide context images for these targets.

Exozodiacal Dust

- Main objective is to obtain 10 samples of exozodiacal dust disk brightness.
- Inform the HabEx deep dive and statistical distribution of warm dust disk brightness.
- Potentially observe the influence of planets in high dust environments.

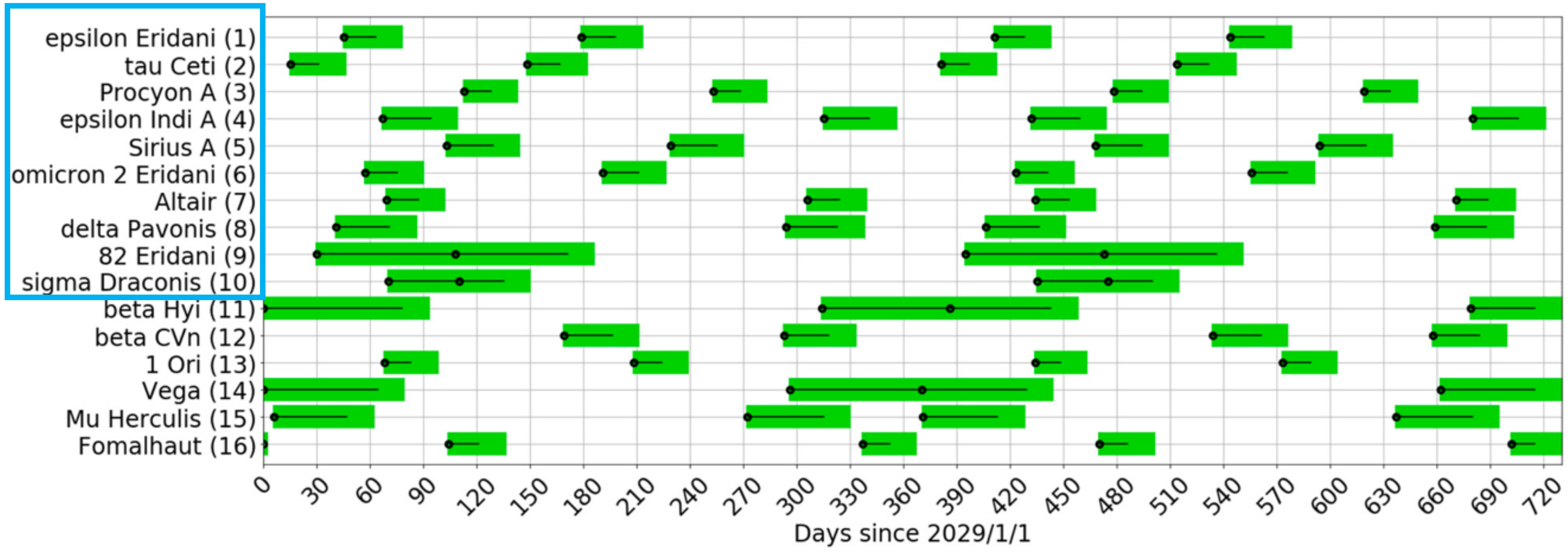


Simulation dust disk in the presence of a 5 M_E exoplanet with 1 AU orbit (Stark & Kuchner 2008). ρ is the dust density and s is the grain size.

Habitability Target Selection and Availability

	Common Name	Complete-ness
1	**epsilon Eridani**	**0.74**
2	**tau Ceti**	**0.71**
3	**Procyon A**	**0.69**
4	**epsilon Indi A**	**0.66**
5	**Sirius A**	**0.62**
6	**omicron 2 Eridani**	**0.67**
7	**Altair**	**0.55**
8	**delta Pavonis**	**0.64**
9	**82 Eridani**	**0.70**
10	**sigma Draconis**	**0.63**
11	beta Hyi	0.56
12	beta CVn	0.61
13	1 Ori	0.50
14	Vega	0.60
15	Mu Herculis	0.60
16	Fomalhaut	0.58

Top 10 targets



- Selected high completeness (>0.5) targets with no optical companions.
- Targets are distance range between 3 – 8 pc.
- Viewing windows determined by solar exclusion angles.
- Two ~30-day windows per year is typical.

Dividing the Objectives for Consideration of Different Telescope Apertures

	Warm Dust Disks	Gas Giants	Earth-like Planets
Detection	Determine if our Solar System's zodiacal dust disk brightness is typical (does the distribution of dust disk brightnesses enable or disable direct imaging of habitable zone exoplanets?)	Determine the masses of known gas giants (e.g. determine the orbit inclination to constrain the mass of RV observed planets).	Determine whether super-Earth size or smaller exoplanets exist in the habitable zone around the nearest sunlike stars.
Characterization	Constrain the presence of planets in bright warm dust disks via temporally varying morphological distortions.	Determine the atmospheric metallicity of known cool giant planets to examine trends with planetary mass and orbital semi-major axis, and to determine if these trends are consistent with our solar system.	Determine whether super-Earth size or smaller exoplanets in the habitable zone around the nearest sunlike stars have signatures of oxygen and water vapor in their atmospheres

Not considered (but should be): cold dust disks, Neptunes and sub-Neptunes, terrestrial planet atmosphere detection via Rayleigh scattering, terrestrial planet ozone.

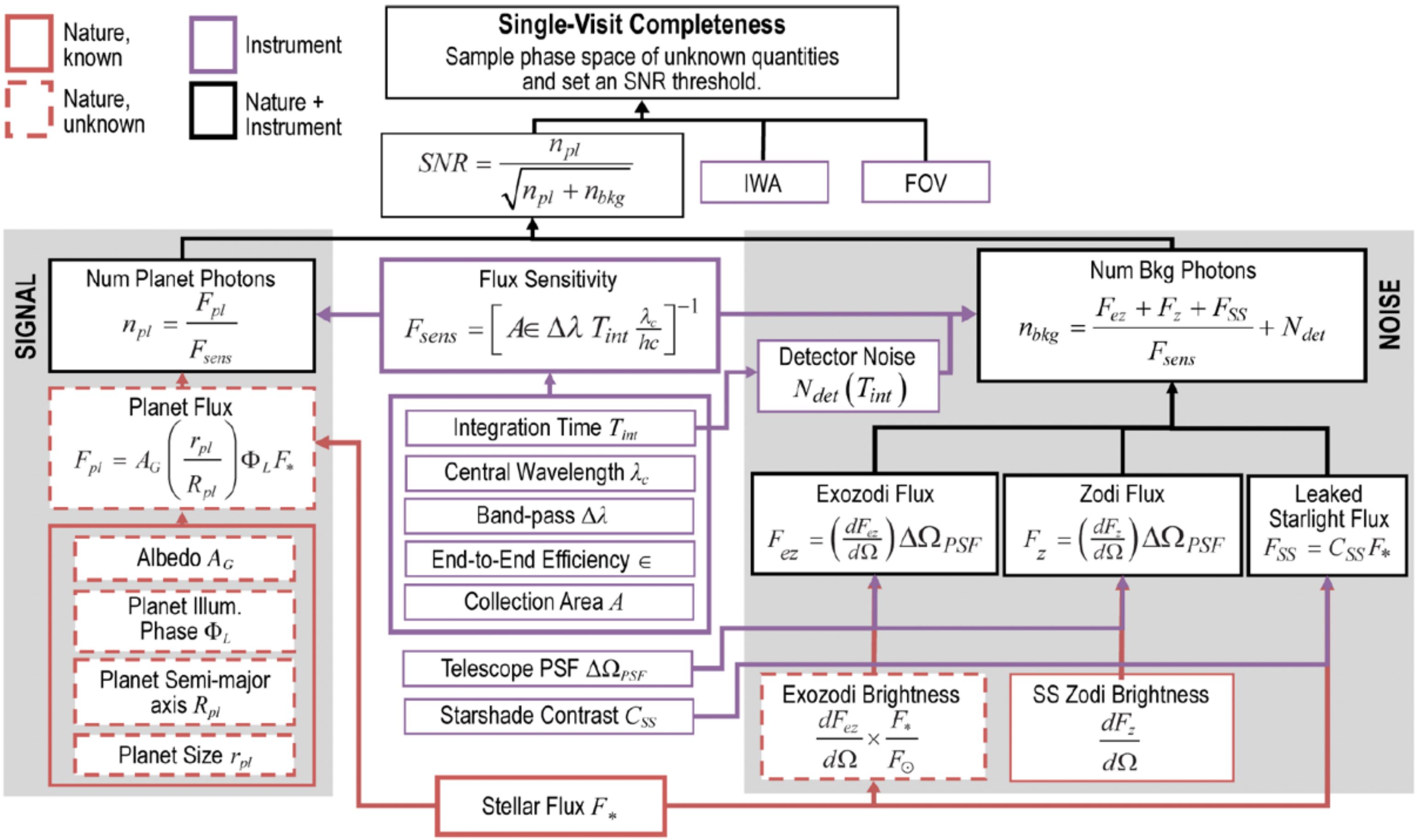
Assumptions

Telescope

- Diameter (D): variable
- PSF: 65 mas×(2.4 m / D)
- WFIRST-like detector efficiency.

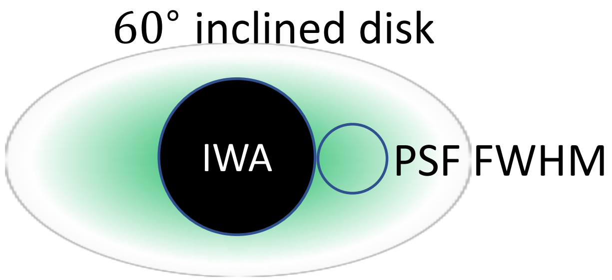
Starshade

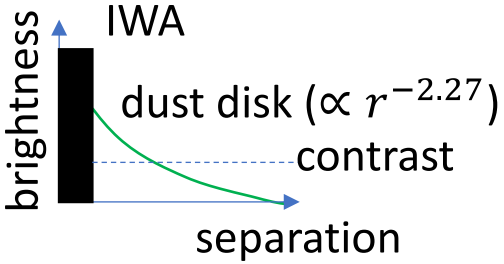
- IWA: S5 capability of 100 mas independent of the telescope aperture diameter.
- Instrument contrast: S5 capability of 10^{-10} or worse.



Warm Dust Disks (Detection)

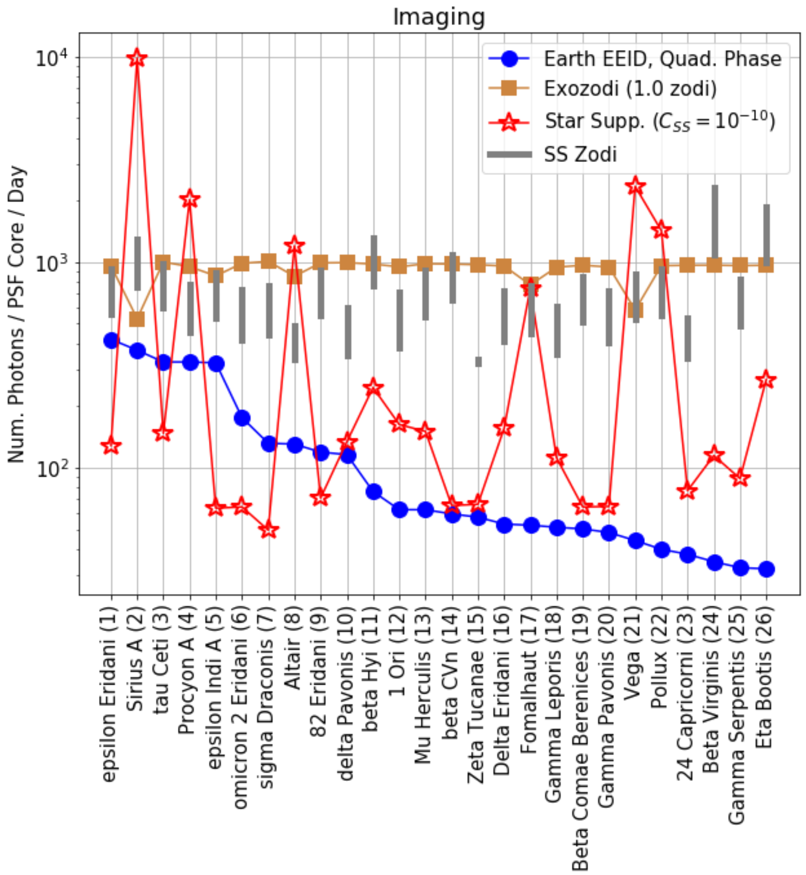
- Input parameters:
  - Apply solar system model of dust distribution
    - Brightness of 22 mag arcsec^{-2} at 1 AU.
    - Scale by star spectrum, luminosity and $1/r^{2.27}$ distance (ZODIPIC).
    - Apply zodiacal brightness scale (1 zodi for solar system, reference to 1.0 zodi expected median value based on LBTI results)
- Figure of Merit:
  - Estimate exozodiacal flux at a separation of IWA + PSF/2.
  - Compare with Starshade contrast (care needed when modelling smaller starshades since instrument contrast of 10^{-10} may not be achievable).
  - Detectable if SNR>7 (conservative since the brightness distribution may be captured over a field of view covering several PSFs).
- What combination of Starshade diameters and instrument contrasts enable detections (and for which nearby stars?).

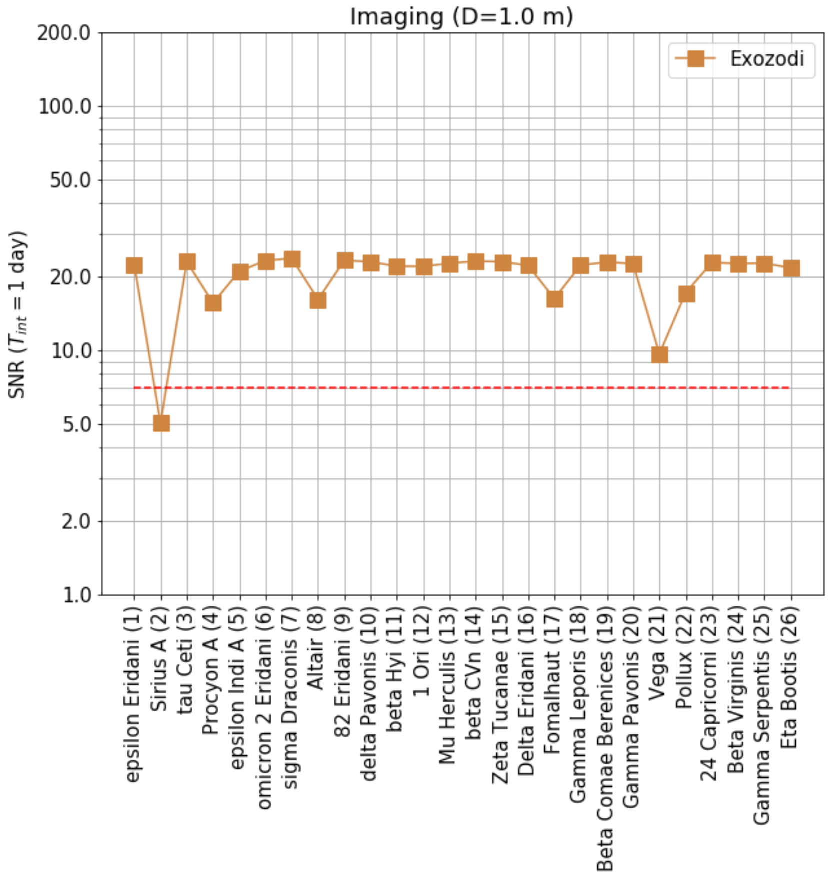




Warm Dust Disks (Detection) - Estimates

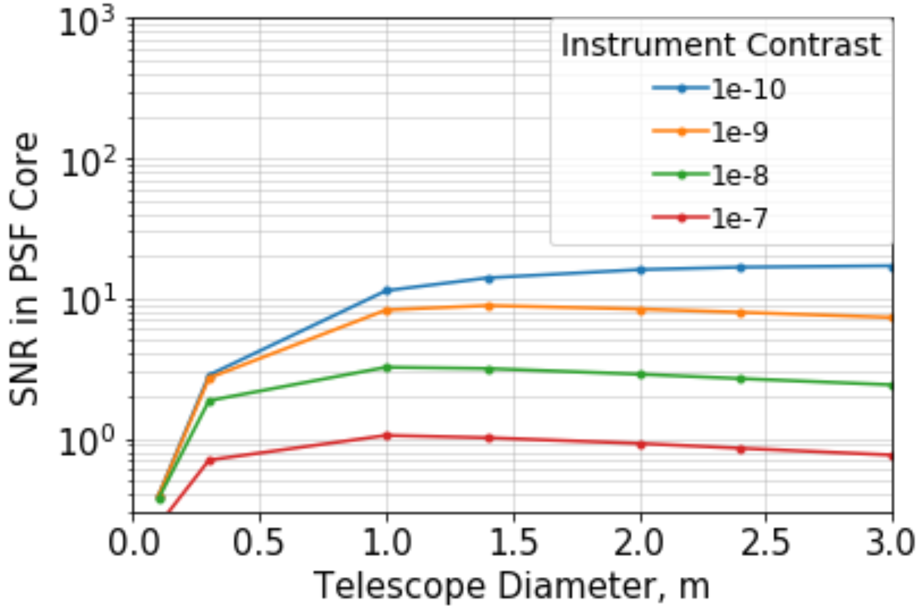
- The exozodi brightness at 1 zodi is comparable to solar system levels.
- The number of photons due to exozodi contained in the PSF is the signal. Zodi, starlight leakage, and detector noise contribute to the background.

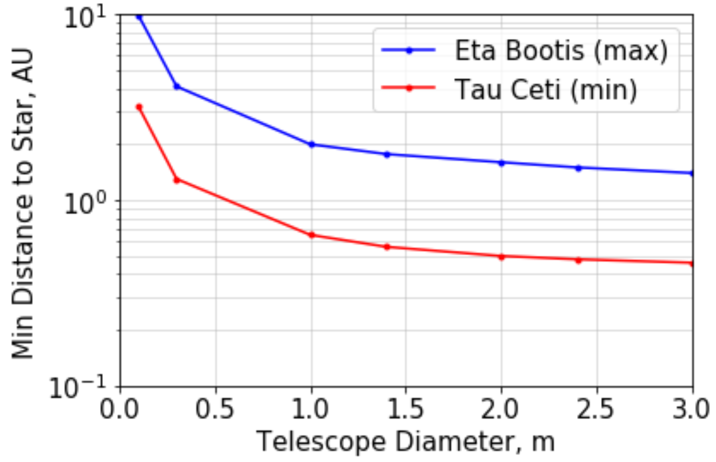


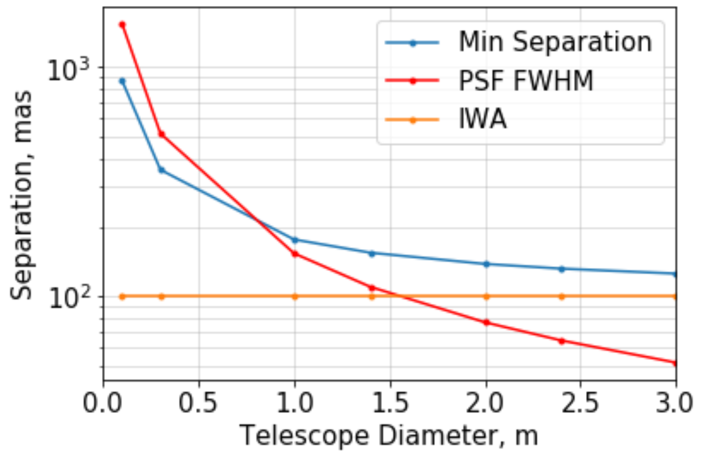


Warm Dust Disks (Detection) - Results

- High signal to noise ratios expected for small telescope diameters with order-of-magnitude tolerance for degradation of instrument contrast.
- Probing regions within 10 AU.

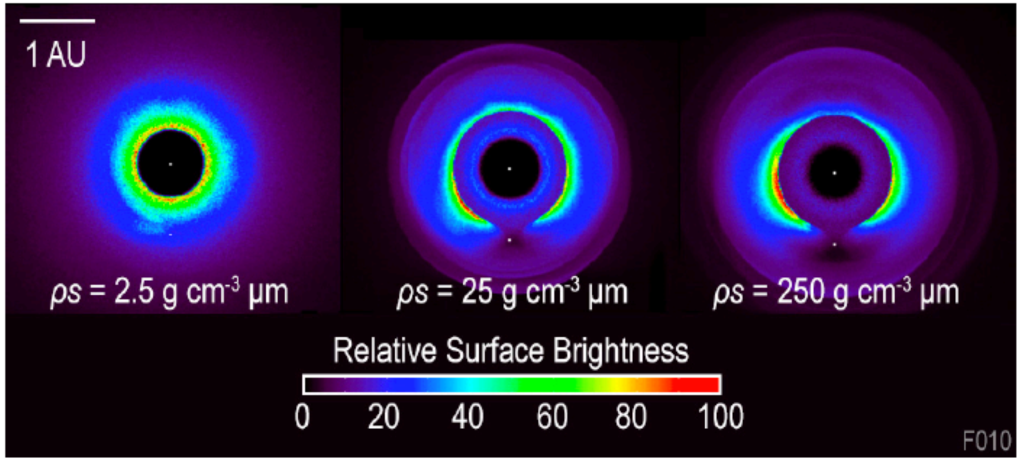






Warm Dust Disks (Characterization)

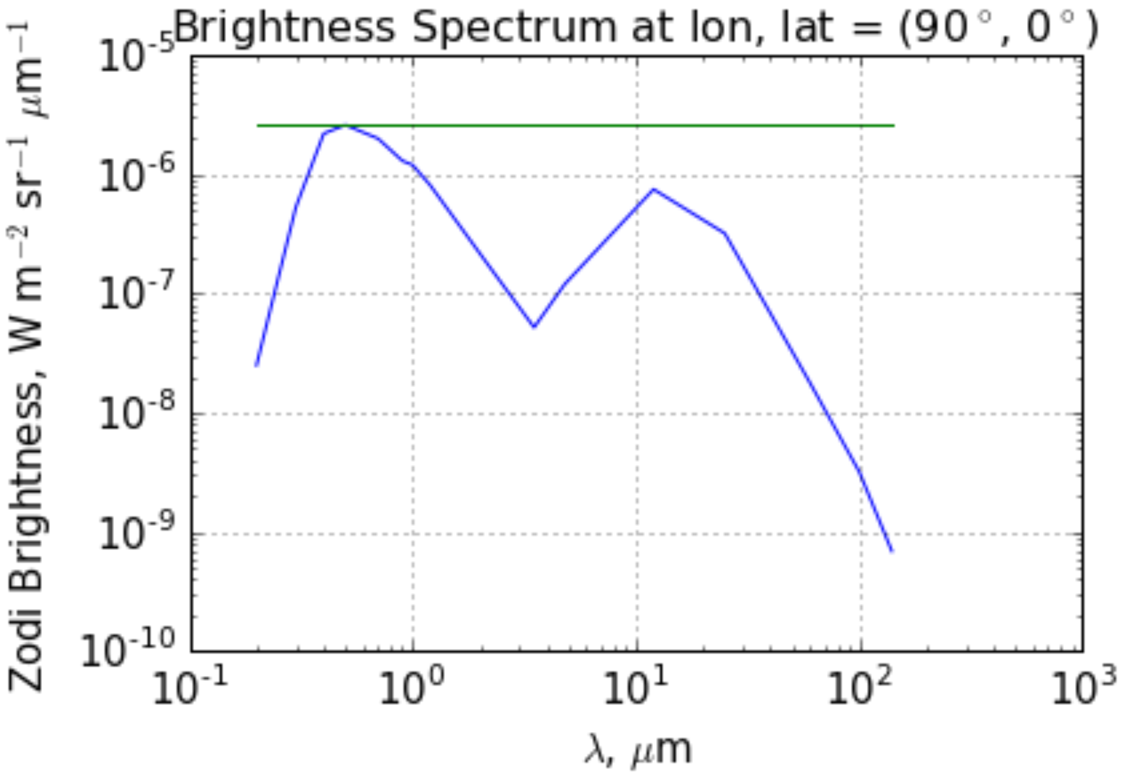
- Starshade Rendezvous Probe study required ≤ 0.5 AU resolution to identify bright regions in the nearest neighbor stars.
- This roughly corresponds to 100 mas PSF FWHM (2 m telescope) for the nearest stars.
- Mennesson et al. Astro2020 science white paper recommends 100 – 200 mas resolution (2.0 m - 1.0 m diameter telescope).
- There is a range of 4-10 zodi where these studies can be done, so prior measurements would be needed to make the mission efficient.



Stark & Kuchner, ApJ, 2008. 686(1): p. 637

Warm Dust Disks (Other Considerations)

- Is there a benefit to going to shorter wavelengths?
- Solar system zodiacal dust spectrum peaks at 500 nm.
- Benefits from optimizing for the shortest wavelength.



Gas Giants

- Input parameters:
  - Known RV gas giants [list from Bruce Macintosh].
  - Jovian radius, albedo 0.3
  - Variable illumination phase.
- Figure of merit
  - Likelihood of detection (how much of the illumination phase is detectable -> mass constraints. Use these planets on other stars?

Source: Starshade Probe Study Report

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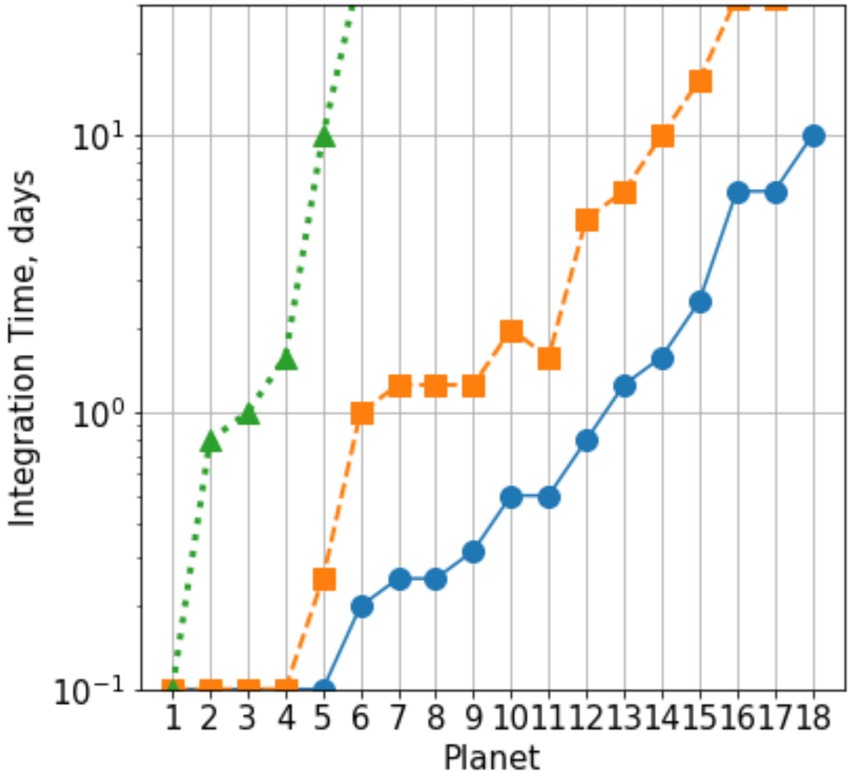
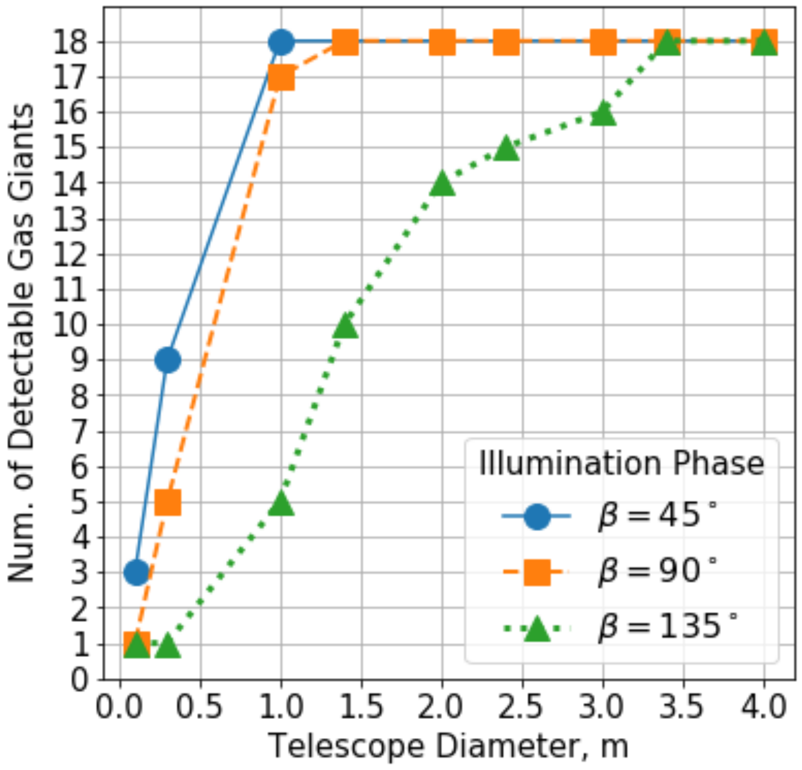
17	HD 87883 b	25	-	-

Gas Giants (Detection)

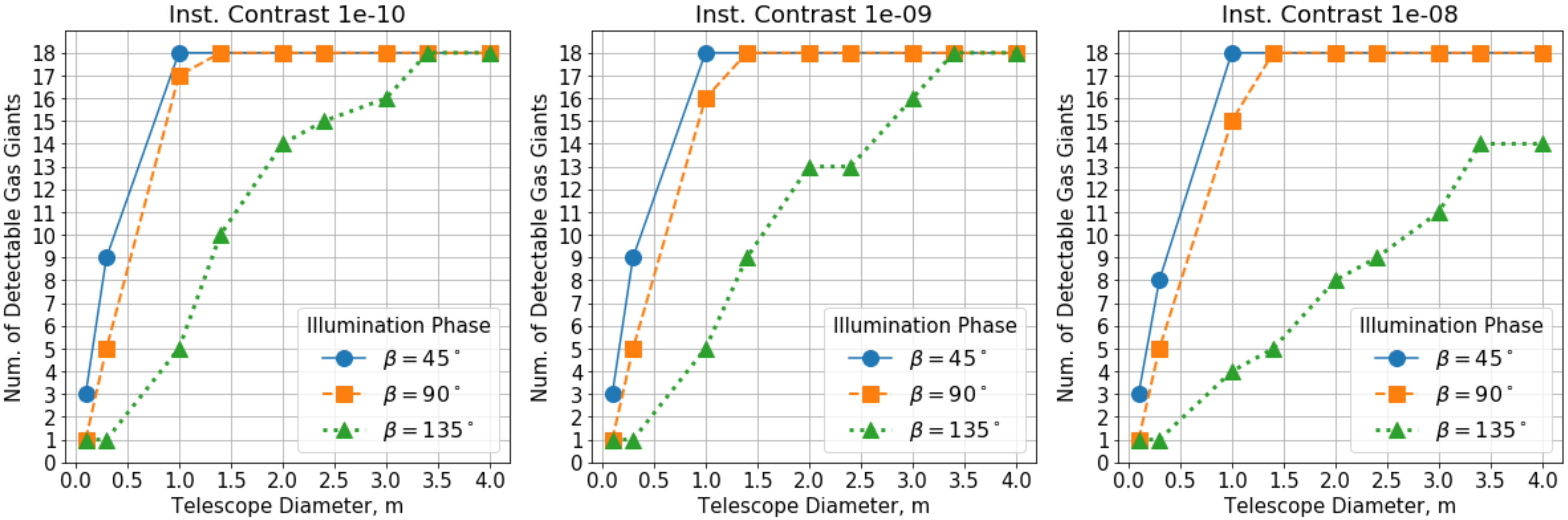
- Require SNR of at least 7 for a detection that is useable for astrometric estimates (orbit constraints).
- Allow up to 30 days of integration time.

Telescope Diameter = 1.0 m
Integration Time Required for Detection



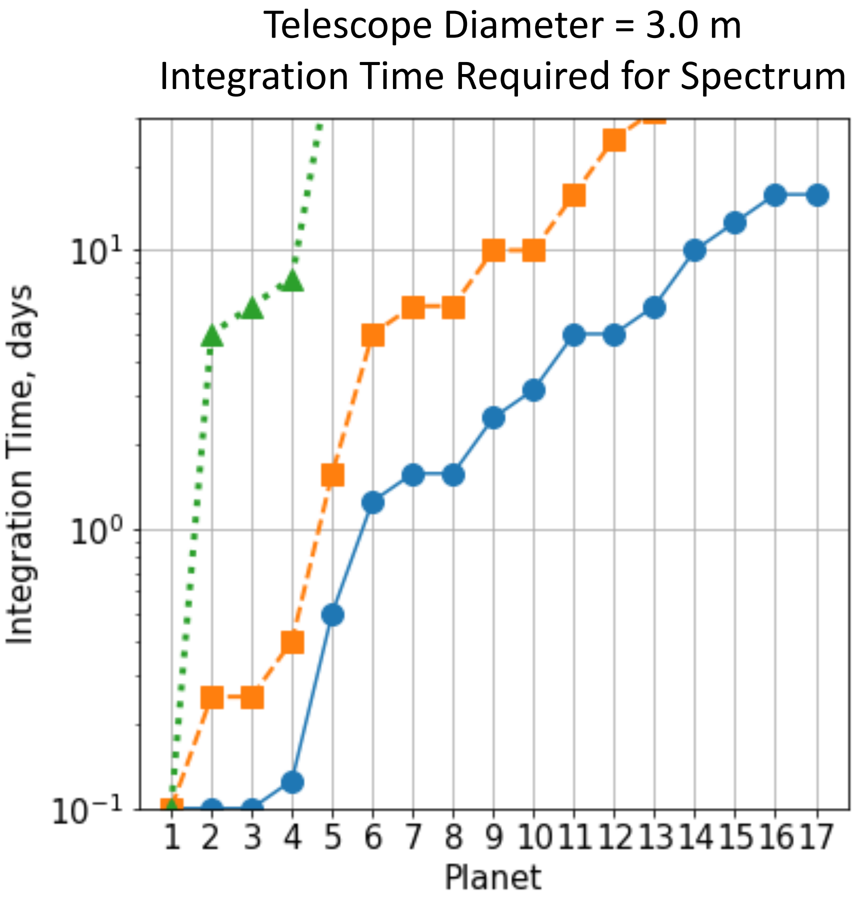


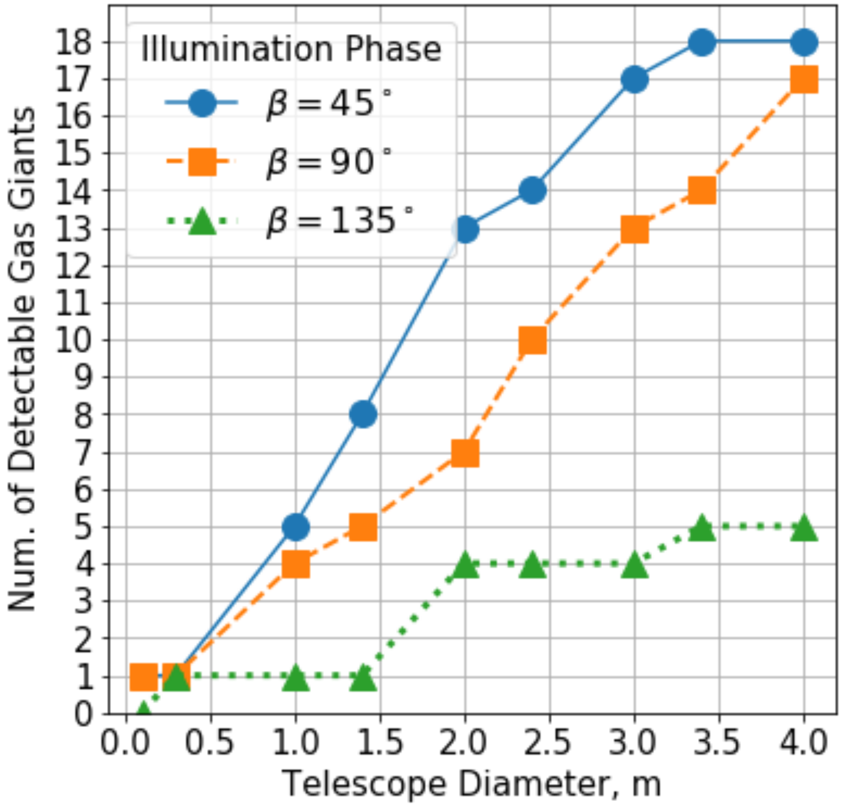
Gas Giant (Detection)



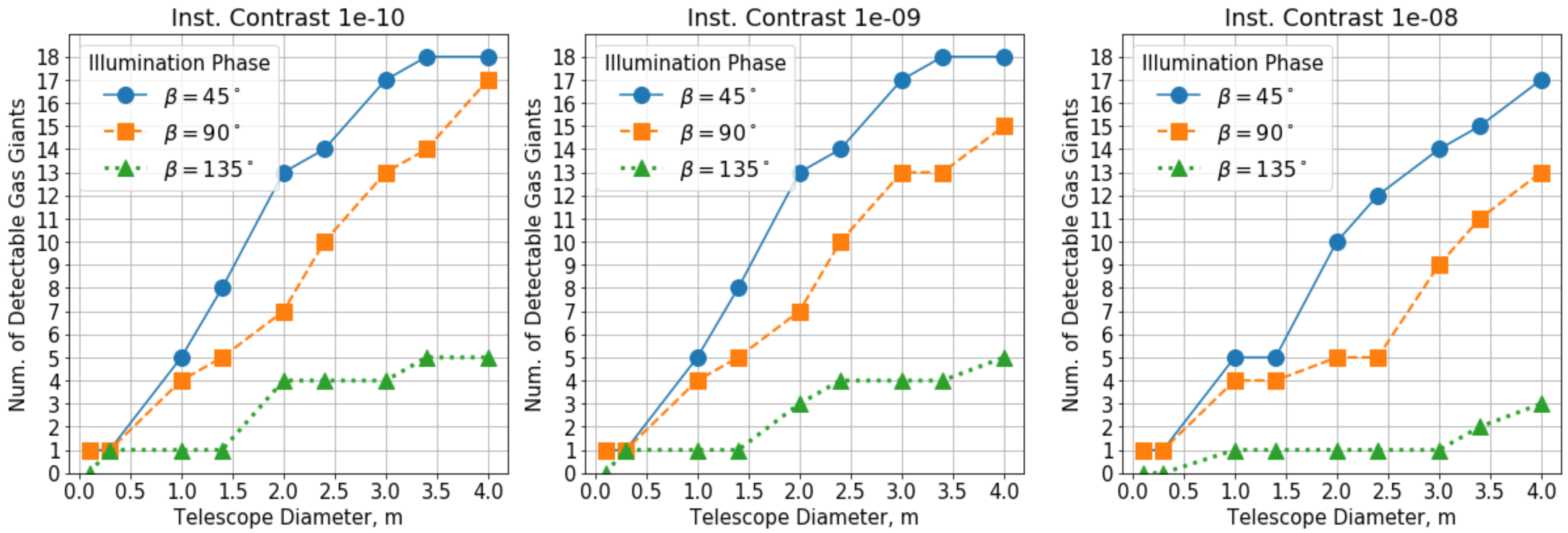
Gas Giants (Characterization)

- Require SNR of at least 15 for spectral characterization.
- Allow up to 30 days of integration time.





Gas Giant (Characterization)



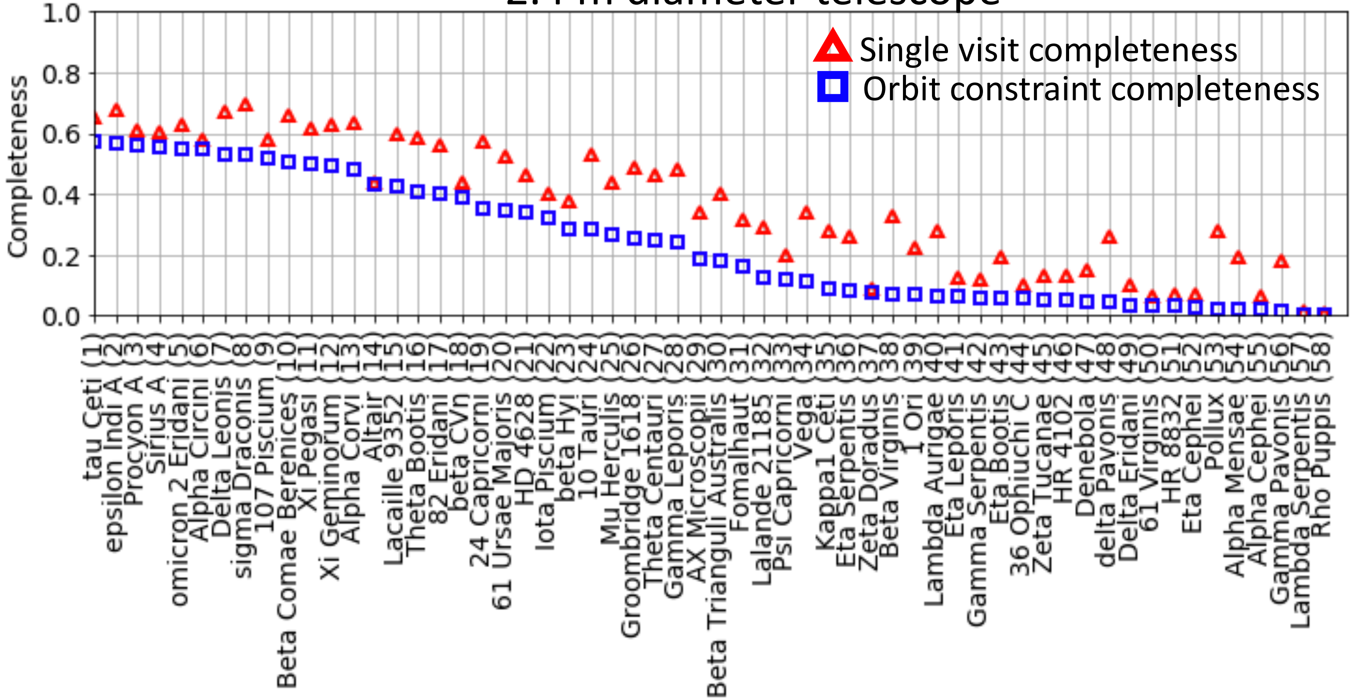
Earths

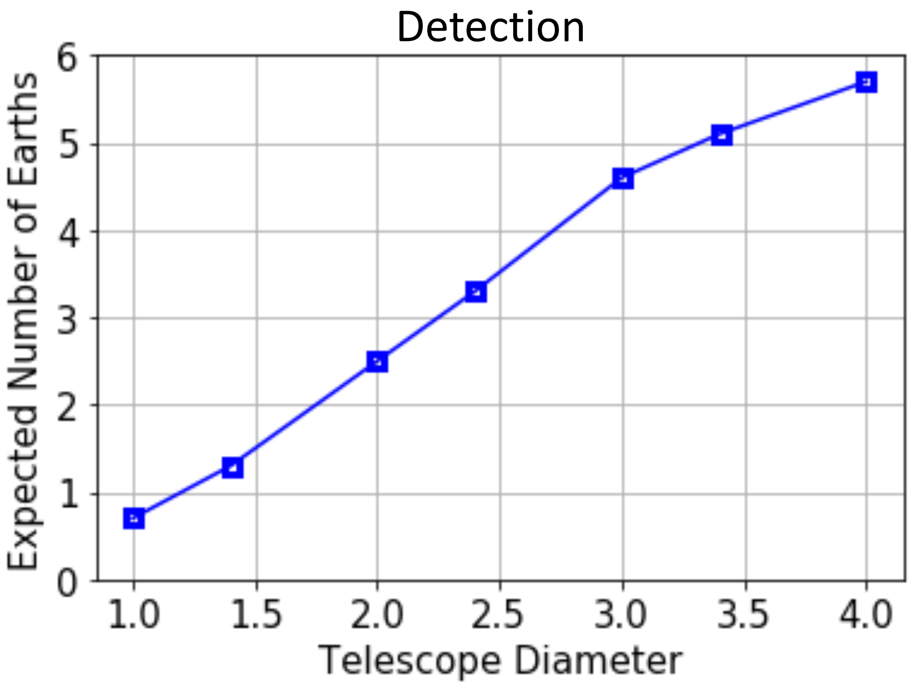
- Input parameters:
  - Using the same simulations for Starshade Rendezvous Probe study report.
- Figure of merit:
  - For how many systems could an Earth-like exoplanet be detected and have their orbits constrained to the habitable zone (requires 3 detections in 4 visits).
  - For how many systems could an Earth-like exoplanet be spectrally characterized.
  - Questions of fuel and retargeting are not yet addressed in detail.

Earths (Detection)

- Estimate the completeness (probability of success given variations in orbit and range of Earth-like planet size).
- Completeness is given for single visit and orbit constrain (3 detections in 4 visits).
- Detections assume 1-day integration time.
- Using $\eta_{Earth} = 0.24$, estimate the expected number of Earths detected.

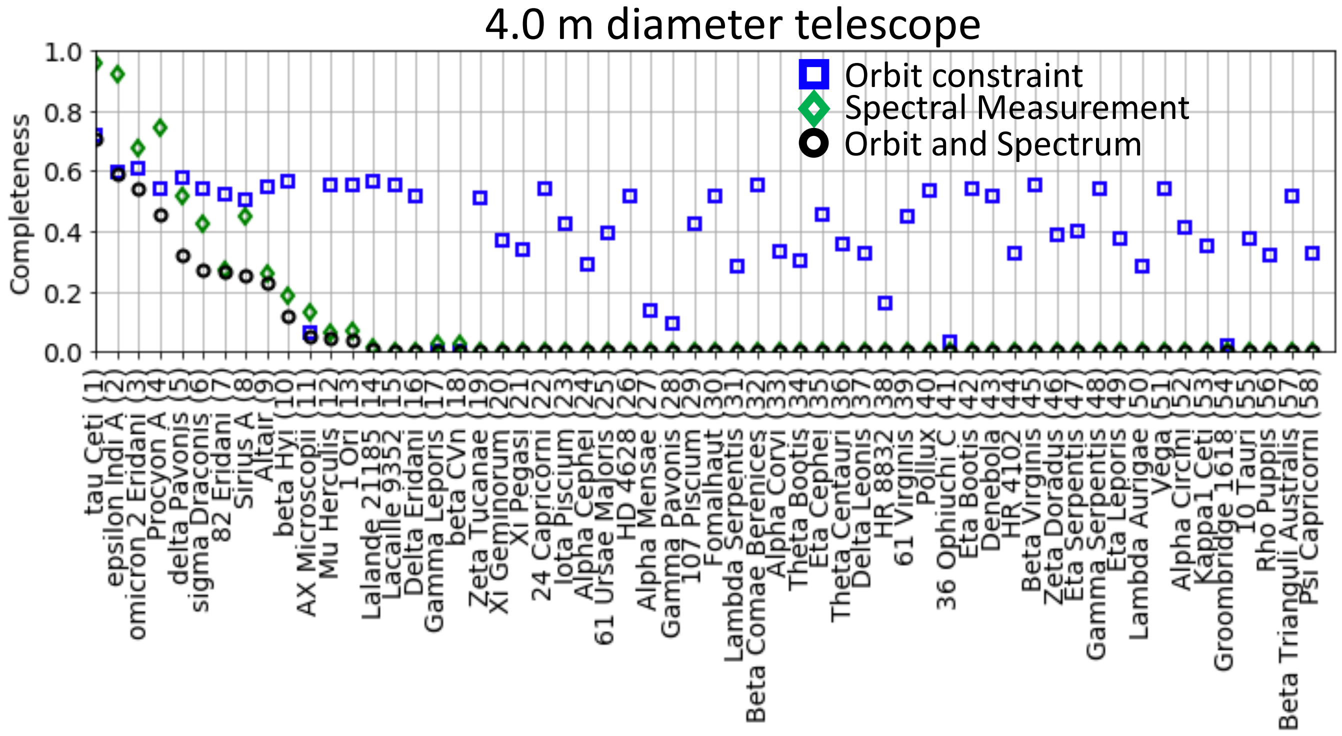
2.4 m diameter telescope

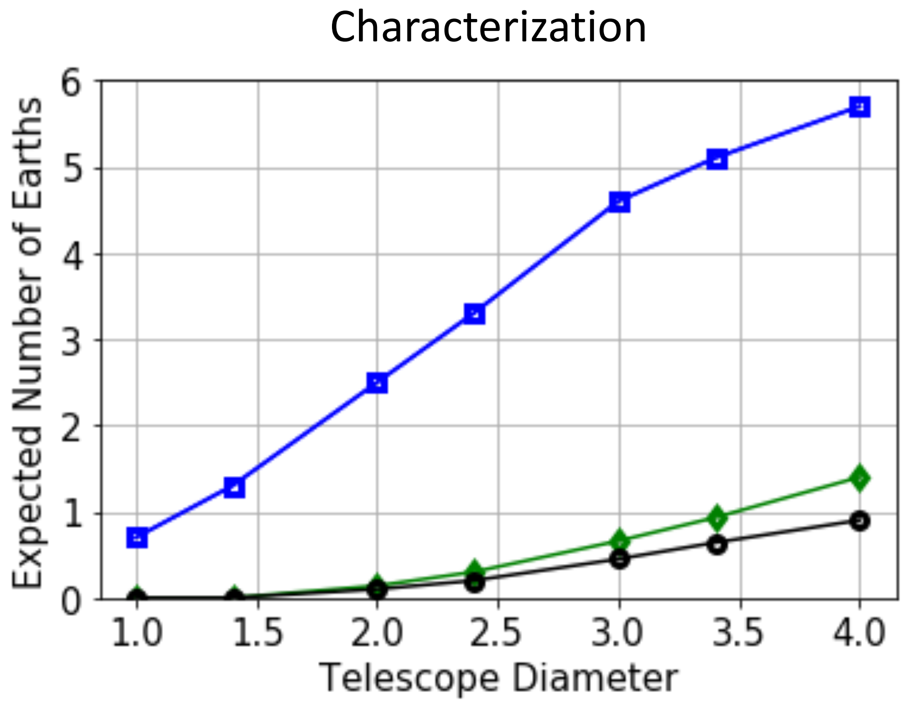




Earths (Characterization)

- Spectral measurement allows up to 25 days of integration time (typical observing window due to solar exclusion angles).
- Using $\eta_{Earth} = 0.24$, estimate the expected number of Earths detected.

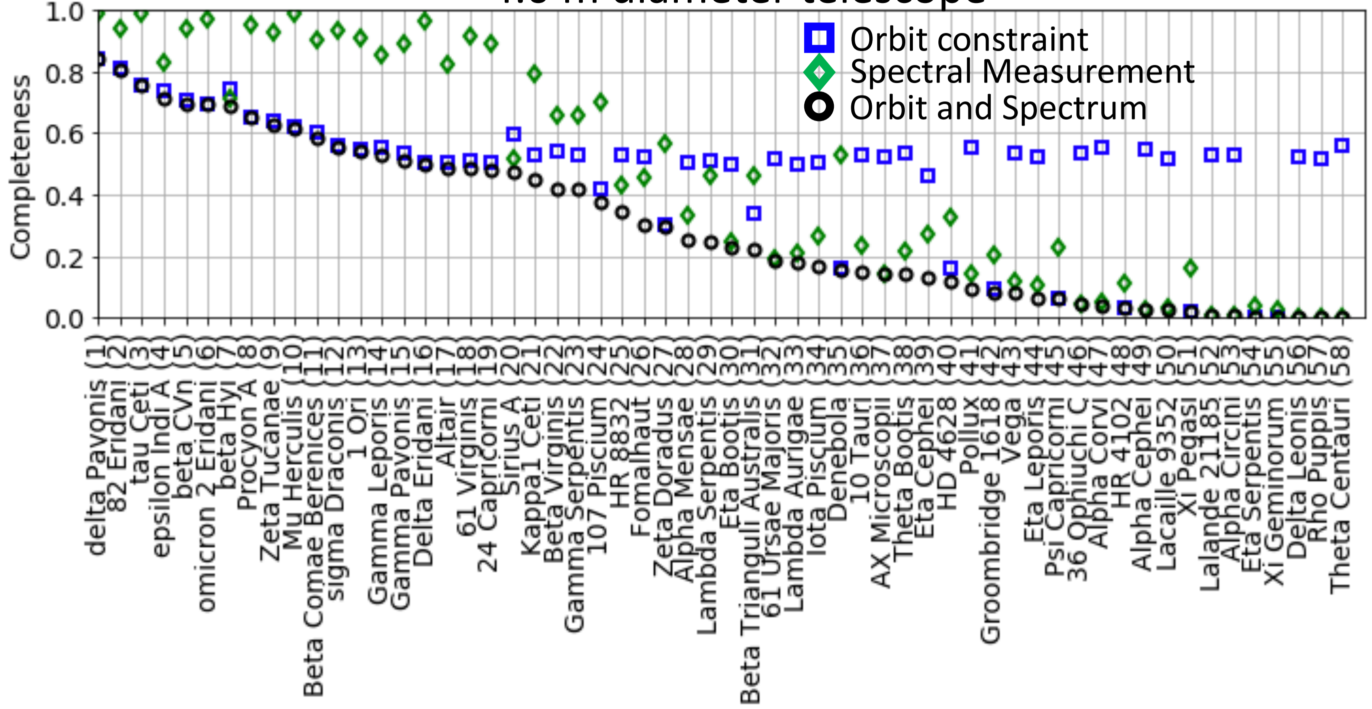




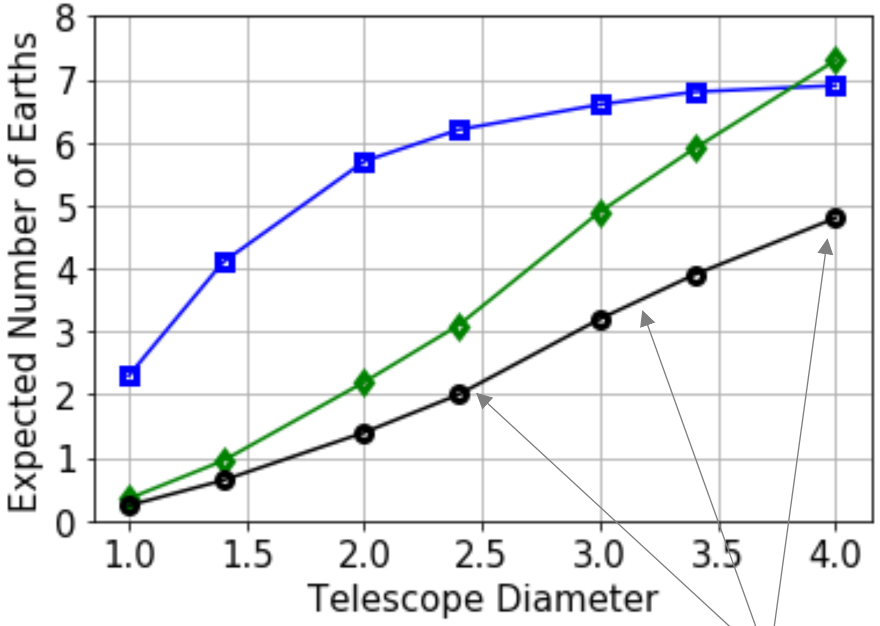
Earths (Characterization)

- The WFIRST CGI (at the time of the SRP study) had required end-to-end throughput values of 1.5% (spectral) and 2.6% imaging.
- HabEx is requiring an end-to-end throughput of at least 22%.
- Results below assume 20% e2e throughput for spectroscopy.

4.0 m diameter telescope

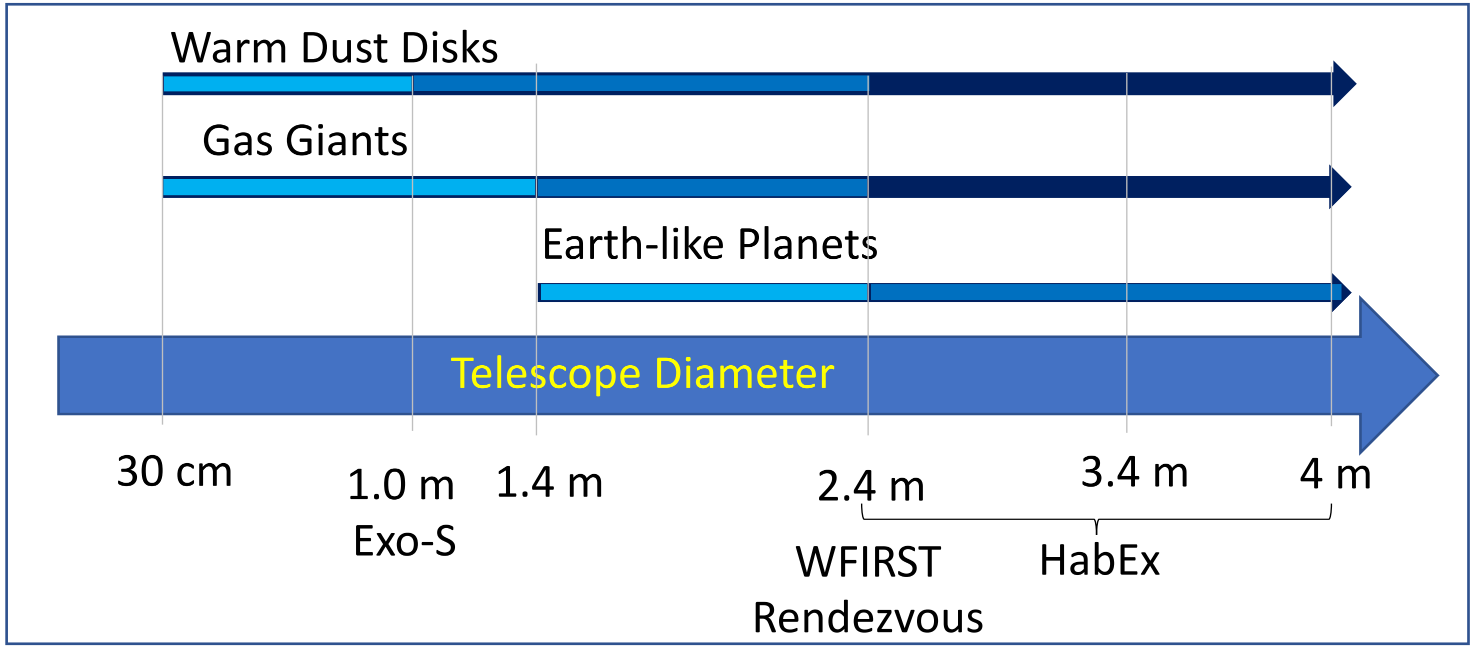


Characterization



Values consistent with HabEx predictions for Starshade-only option.

Science with Starshades



Detection, Characterization, Statistical (≳10)

BACKUP

Zodiacal Dust (Detection)