Hybrid Schemes for Space-based Planet-Finding

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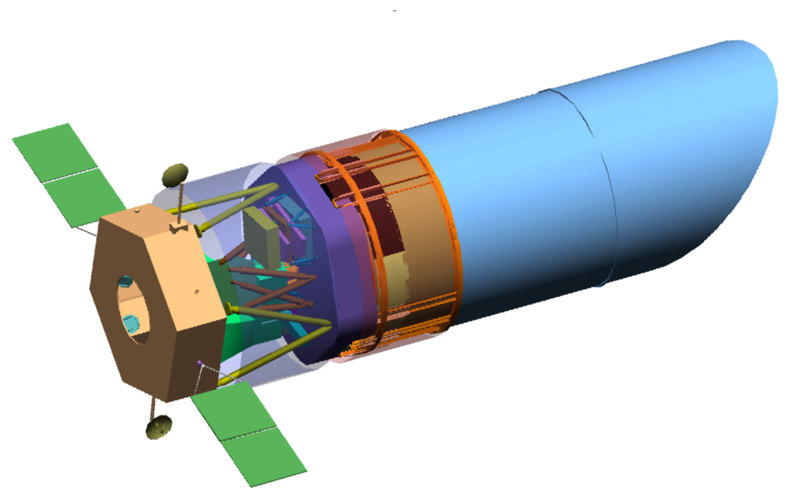
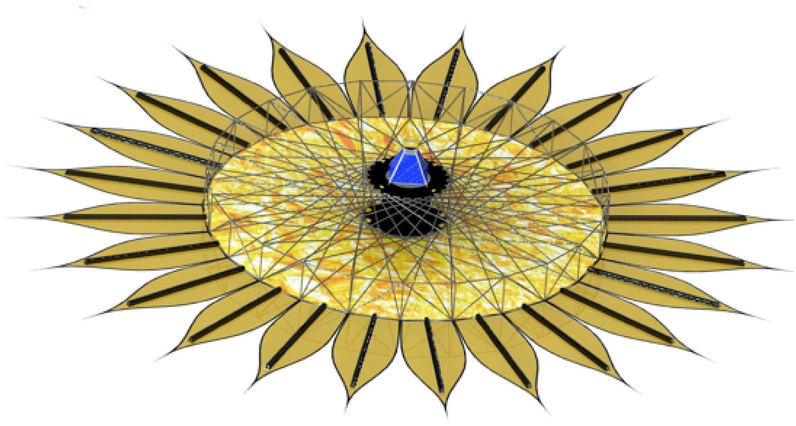
Abstract

We present a new class of space-based exoplanet observatories incorporating both internal coronagraphs and external occulters. Occulters work well over broad wavelength bands and have wavelength independent inner working angles (IWA), but spend much of the mission time switching between targets, and thus produce fewer total detections. Coronagraphs have single-digit picometer stability requirements to achieve low IWAs, but take very little time to switch between targets. As their IWAs are wavelength dependent, coronagraphs produce proportionately fewer full spectra of the planets they detect. Using a higher IWA, narrow band coronagraph for planet discovery with an occulter for spectral characterizations produces comparable or even improved science yields with greatly relaxed engineering requirements. Of particular interest is a hybrid scheme involving an 8 m telescope with an occulter designed for a 4 m aperture, which is shown to outperform both the standalone occulter and 2 λ/D coronagraph.

Observatory Design





Telescope

- 4 or 8 m diameter circular aperture
- Sunshield permitting observations with sun within 45° of line of sight
- UV/visible wavelength sensitivity

Starshade

- Designed to produce shadow over 4 or 8 m telescope aperture [Cady, 2010]
- Geometric IWA of 75 mas
- Solar-electric propulsion for retargeting and chemical propulsion for stationkeeping

Designs

- Coronagraph - High throughput, pupil mapping system with IWA of 2, 3 or 4 λ/D [Guyon, 2003]
- SDO - Occulter covers the whole wavelength range at one separation distance
- MDO - Occulter covers the wavelength range using multiple separation distances, which allows for smaller starshade, but increases the geometric IWA for longer wavelengths
- Hybrid - Planetary detection with internal coronagraph, spectral characterization with external starshade. Can use starshade designed for 4 m telescope with a stopped-down 8 m telescope

All simulations were performed with software described in Savransky et al. [2010]. All hybrid designs use SDOs.

Planetary Populations

Earth Twins

- Planets with mass, radius, and average albedo of the Earth
- Habitable Zone (HZ) orbits
  - Semi-major axis sampled log-uniformly from $a \in [0.7, 1.5]$ AU
  - Eccentricity sampled uniformly from $e \in [0, 0.35]$
- All orbit orientations are isotropically distributed with respect to the observer
- Occurrence of planets is determined via universal rate parameter η

Giants

- Mass and semi-major axis distributions extrapolated from known exoplanet populations
  - Mass sample from power law $dN/dM \propto M^{-1.31}$ [Cumming et al., 2008]
  - Semi-major axis sampled from power law $dN/da \propto a^{-0.62}$ [Nielsen et al., 2008]
- Eccentricity sampled from Rayleigh distribution suggested by formation models and observations [Juric and Tremaine, 2008]
- Radii derived from masses via lookup tables from Fortney et al. [2007]

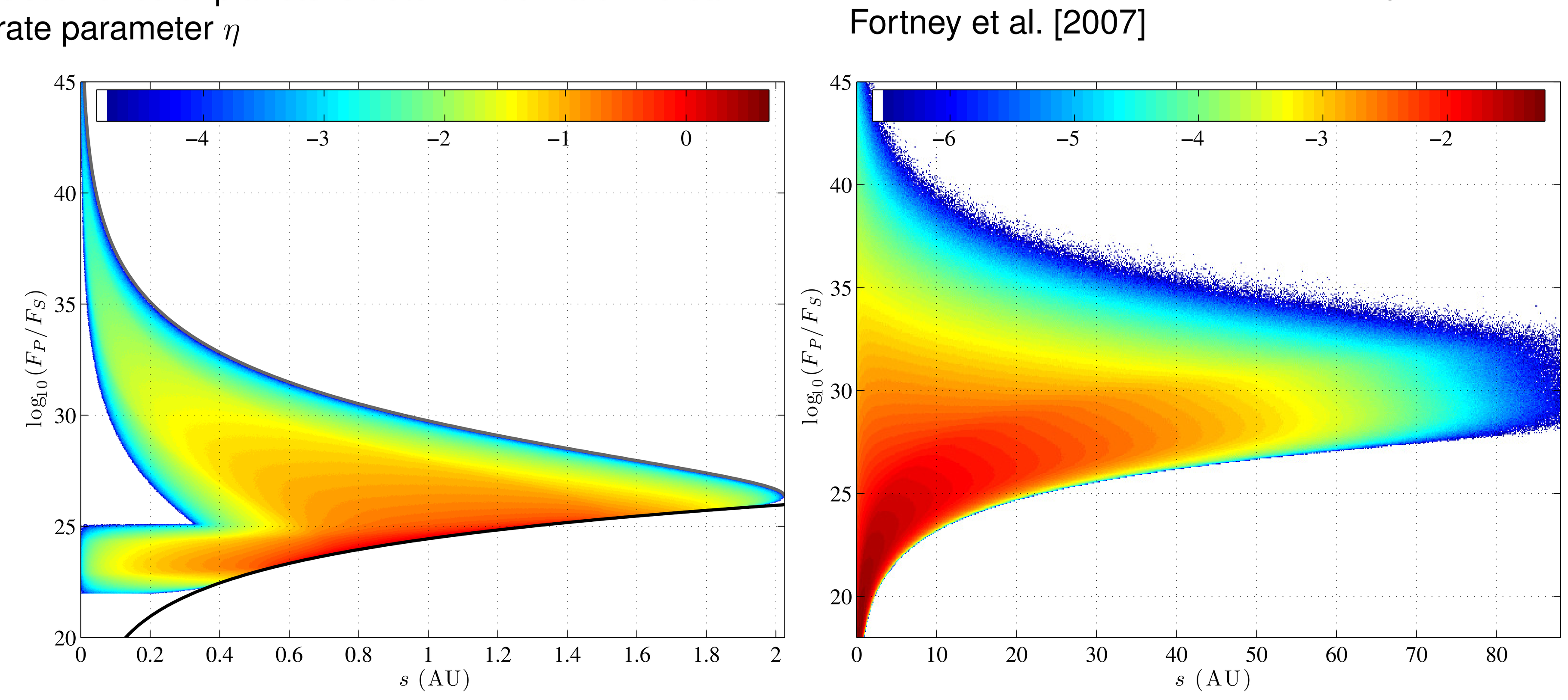


Figure: Probability of detection as a function of apparent separation and brightness for Earth twins (*left*) and giants (*right*). Color scale is logarithmic. [Brown, 2005, Savransky et al., 2010]

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Effects of η

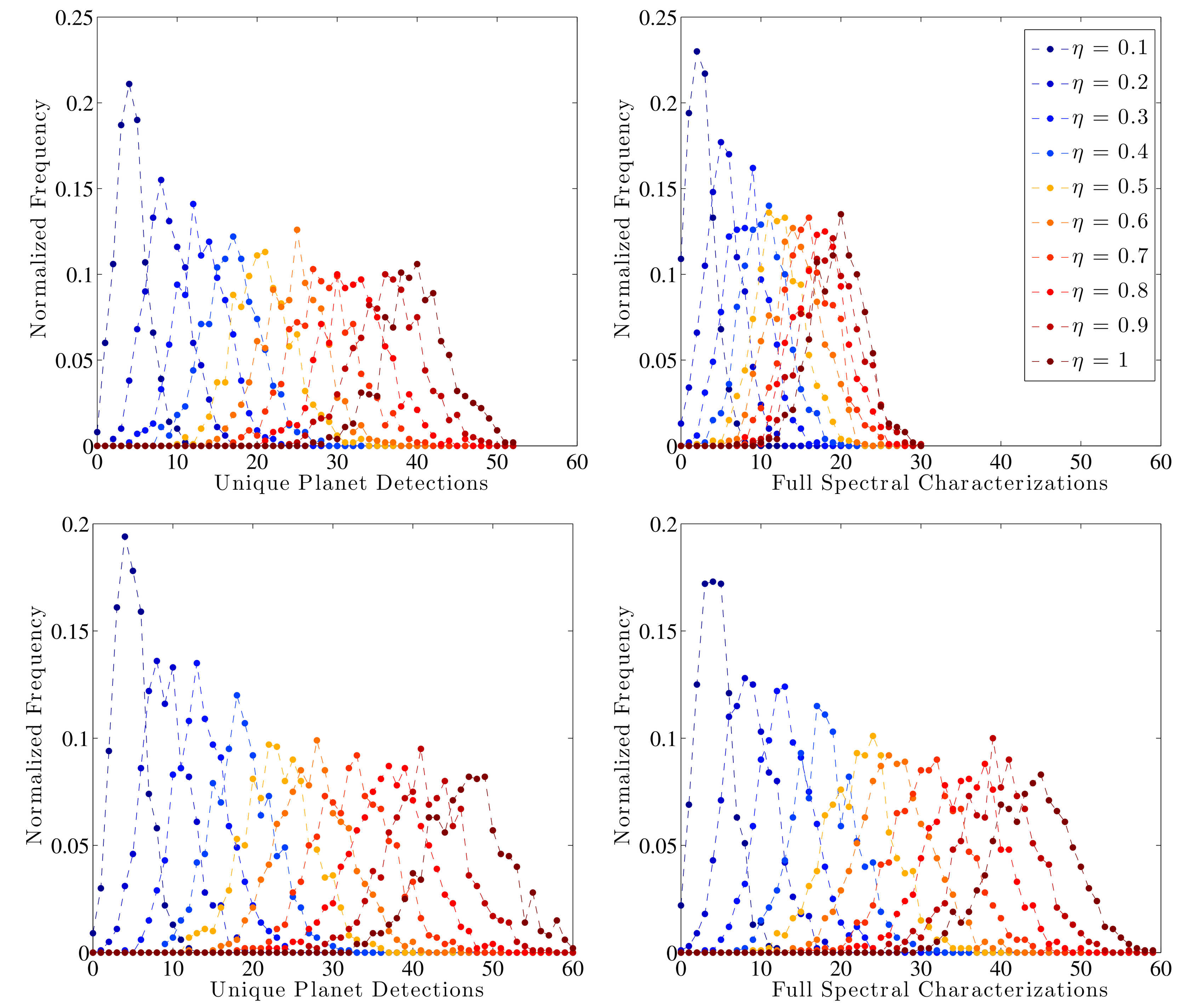

Figure: Probability of unique detections (*left*) and spectral characterizations (*right*) with varying η for hybrid design with 4 m telescope aperture, SDO, and 3 λ/D coronagraph. Earth-twin population (*top row*) and Giant population (*bottom row*).

Significant probability of zero detections/characterizations only for $\eta \leq 0.1$

Comparison of Designs

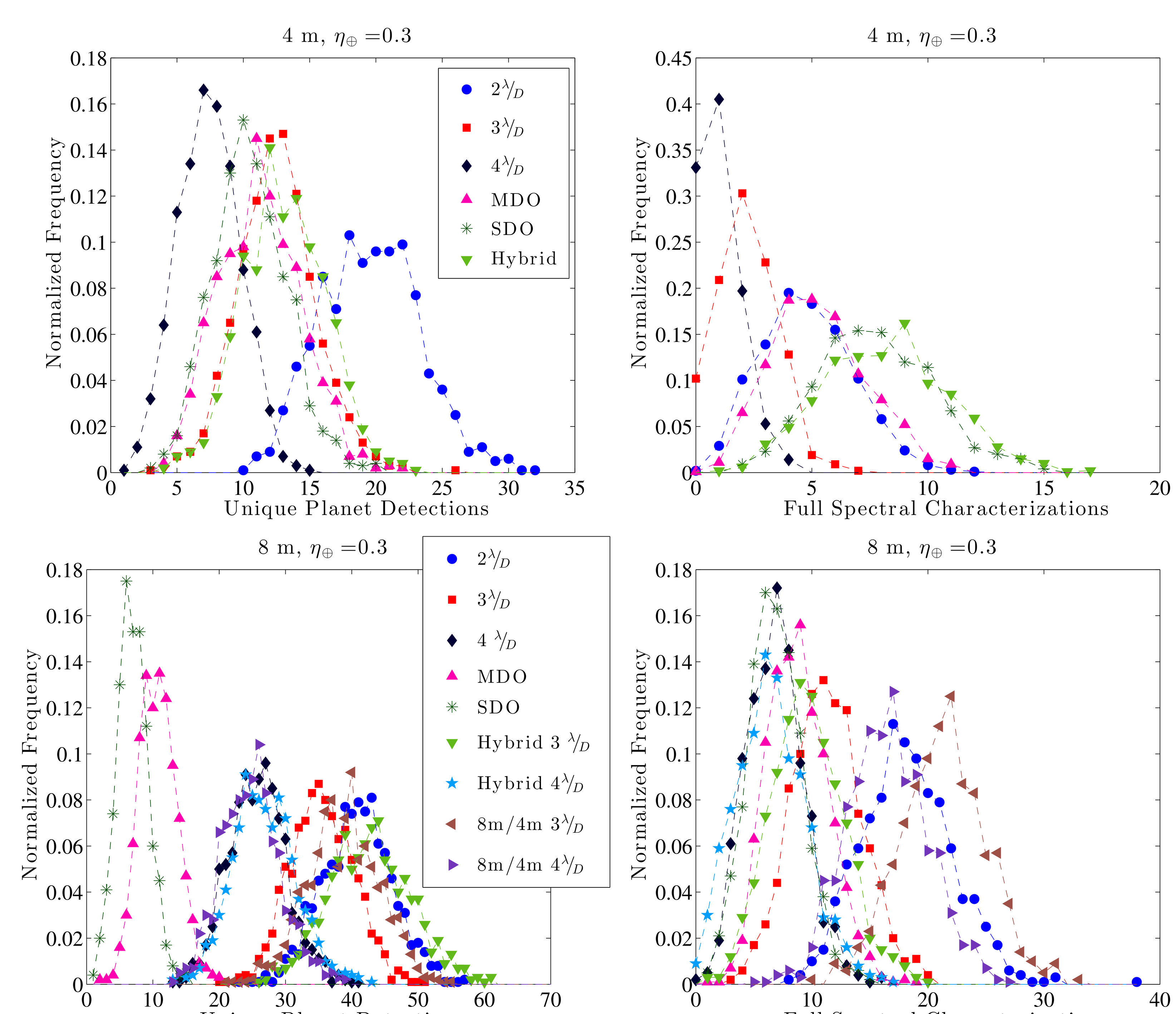

Figure: Probability of unique detections (*left*) and spectral characterizations (*right*) for various designs with a 4 m telescope (*top row*) and 8 m telescope (*bottom row*). Earth-twin population with $\eta = 0.3$. Designs marked 8m/4m refer to hybrid designs using an 8 m telescope and an occulter designed for a 4 m aperture. Note that the x scale for the 8 m plots is twice that of the 4 m plots.

- **At 4 m, a hybrid using a 3 λ/D coronagraph outperforms a 2 λ/D coronagraph in terms of full spectra.**
- **At 8 m, a hybrid using a 3 λ/D coronagraph and a starshade designed for a 4 m telescope matches a 2 λ/D coronagraph in unique detections and gets more full spectra.**

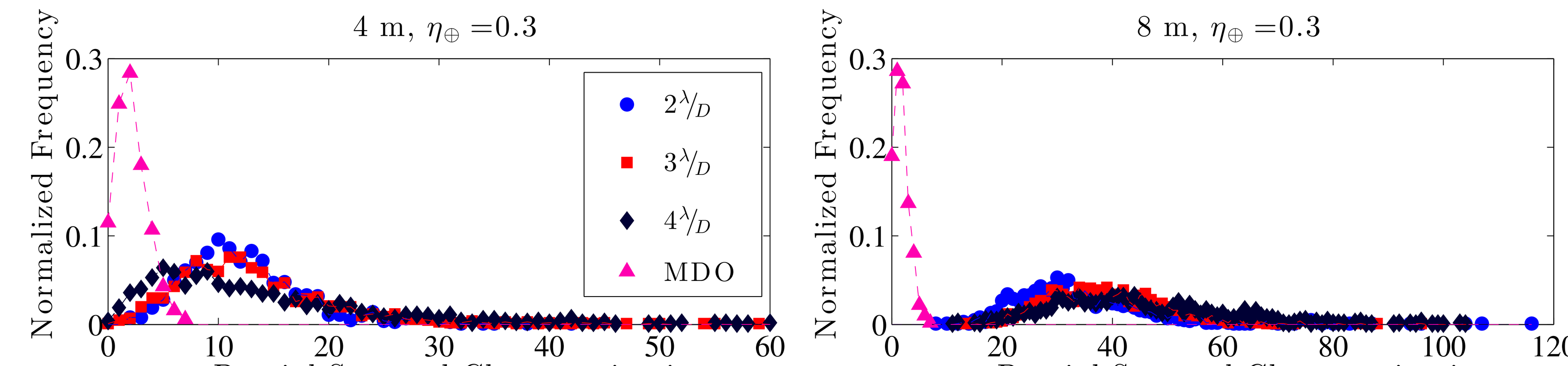

Figure: Probability of partial spectra for 4 m designs (*left*) and 8 m designs (*right*). Earth-twin population with $\eta = 0.3$. MDOs get partial spectra when they can only characterize at one separation, coronagraphs get partial spectra due to wavelength-dependent IWA.

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