Coronagraphs, Occulters and Mission Scale

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NASA ExoPAG
January 7, 2012

Photo Courtesy of Robert Vanderbei

Scope:

A single future flagship UV/Vis telescope (4, 8, or 16 m) to do cosmic origins and exoplanet science.

What would the exoplanet “instrument” look like and how does it affect the telescope design and requirements?

Exoplanet Figures of Merit

- Feasibility
- Science
- Readiness
- Robustness (Risk)
- Cost (including launch)
- Impact on telescope design
- Impact on spacecraft

The best exoplanet instrument at a particular scale is still an open question requiring continued technology development and trades spanning the telescope, instruments, operations, and science.

April, 2011 COPAG:

SAG2: monolithic 4m aperture with internal coronagraph

SAG3: segmented 8m aperture with external occulter

This might very well be the opposite of the "best" solution!

Outline

- Comparison of approaches to planet characterization
- Impacts on Telescope
- Comparison of Science yield at different scales
- (Quick status of technology)

Important Questions

- What Exoplanet science can be done with 4, 8, or 16 m Telescope?
- What type of instrument does it require and how does the exoplanet instrument requirements affect telescope design and requirements?
- How does choice of telescope architecture affect the choice of exoplanet instrument and resulting science?
- How does the choice of exoplanet architecture (coronagraph or occulter) affect telescope design?
- Does an on-axis and/or segmented primary preclude terrestrial planet finding? Is it necessary?
- Is there a significant difference in technology readiness that could impact schedule and risk?

Coronagraphs

Good

- Agility allowing many observations and repeat visits.
- Single telescope to contain cost and programmatic challenges.
- End-to-end testing possible on the ground.

Not so Good

- Complex wavefront control system.
- Requires multiple narrow band channels (large volume and complexity).
- Limited spectral range.
- Limited outer working angle.
- High sensitivity to errors; requires very stable telescope.
- Requires off-axis telescope?
- Inner working angle and thus science yield strongly dependent on aperture.

Science yield driven primarily by achievable inner working angle.

External Occulters

Good

- Inner working angle independent of aperture size.
- No need for wavefront control; works with conventional telescope.
- Simultaneous wide-band spectra, including near-UV.
- No outer working angle; images entire system.

Not so Good

- Science performance limited by thrust and time to move across sky.
- Few repeat visits and orbits without single occulter.
- Requires two complex spacecraft and formation flying.
- No end-to-end testing on ground.
- Requires precise and stable starshade structure.
- Large occulters require separate launch vehicle, increasing cost.

Science yield driven primarily by time.

A Prototypical 4m Mission for Earthlike Planets (2009 ASMCS)

Why did we choose the THEIA architecture?

- Spectra across full band, including UV (250 - 1100 nm)
- Use of on-axis telescope (wide field astrophysics)
- Much relaxed stability requirements and smaller inner working angle compared to a coronagraph
- Instrument volume and packaging concerns
- Room for additional UV instruments (UVS and SFC)
- Best exoplanet science yield with available technology.

Note: At probe scale (1.5 - 2.5 m telescope), only way to get terrestrial planet science is an occulter (we've studied mission concepts).

Architectures on the Table (for 4, 8, or 16 m)

2, 3, or 4 lambda/D internal coronagraph

- Discovery in 110 nm band about 500 nm, spectra from 500 to 1000 nm
- Multiple bands covering wavelength and polarization
- Wavefront control with 2 DMs in each channel
- Static contrast of 5 x 10^{-12} mean and standard deviation required.

(Currently studying shaped pupils, PIAA, Lyot, & vortex)

Single distance occulter (SDO)

- Large occulter covering 250-1000 nm (50.2 m for 4m and 70.5 m for 8m)
- Separations of 70,400 km and 96,800 km
- 75 mas inner working angle (60 mas at 50% throughput)

Multiple distance occulter (MDO)

- Single occulter at 2 distances–250-700 & 700-1000 nm (40 m and 54 m)
- Separations of 55,000 km (35,000 km) and 74,800 km (52,360 km)
- 75 mas inner working angle (120 mas iwa)

Some thoughts toward a new architecture . . .

- Any new large UV/Vis telescope will almost certainly have a coronagraph
- It will also almost certainly have deformable mirrors and wavefront control
- But volume and cost is likely to limit the number of possible channels
- Occulters are great for getting spectra and for imaging entire systems, but the yield is limited and multiple visits (and thus orbits) are challenging
- Is there a way to increase robustness and reduce risk?

Independently using both a narrow band coronagraph (for discovery and orbits) and an occulter (for spectra) can leverage the advantages of each, thus reducing risk and increasing science.

New Hybrid Architecture (for 4, 8 m)

(See Savransky, Kasdin, Shaklan & Cady poster)

1. SDO with 4 m telescope and narrow band (100 nm) 3 or 4 l/D coronagraph
2. SDO with 8 m telescope and narrow band (100 nm) 3 or 4 l/D coronagraph
3. SDO for 4 m telescope (small shadow) with 8 m telescope (and aperture stop) and narrow band (100 nm) 3 or 4 l/D coronagraph

Limiting coronagraph to single channel reduces volume, mass and complexity from a full coronagraph, though the hybrid is more costly than occulter alone.

Note: The occulter and coronagraph are not used simultaneously; rather, each operates independently to perform separate tasks (detection and orbits vs. spectral characterization).

What does the comparison of science yield look like?

Monte-Carlo Mission Simulations

- System level analysis
- Starlight suppression is perfect
- Background limited (1.55 local zodi)
- 26 Delta-mag systematic limit
- 5 year mission life
- All results for Earth-twin populations on HZ orbits
- Targets chosen form stars within 30 parsec
- For given set of mission rules, shown to be close to optimal

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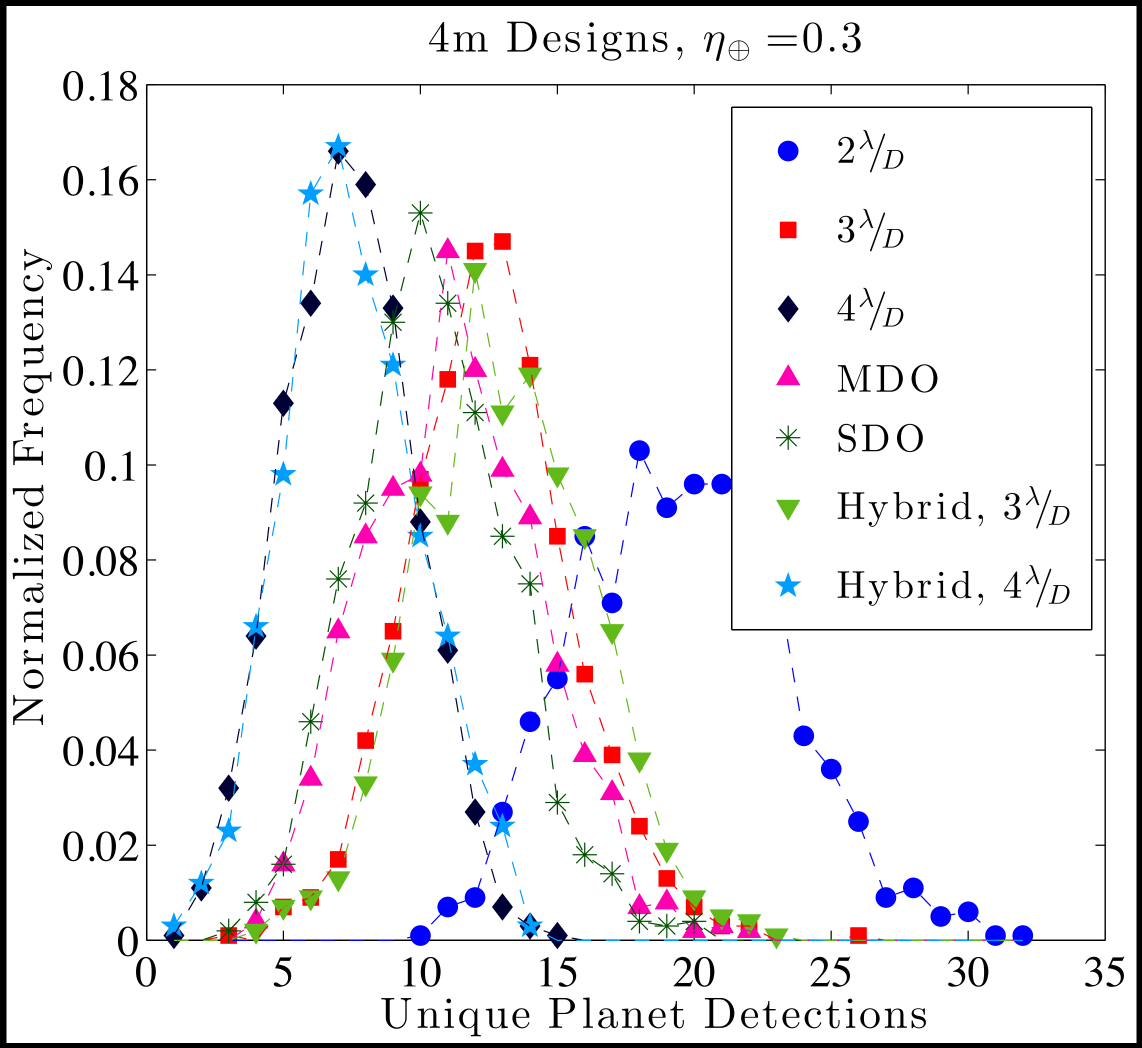
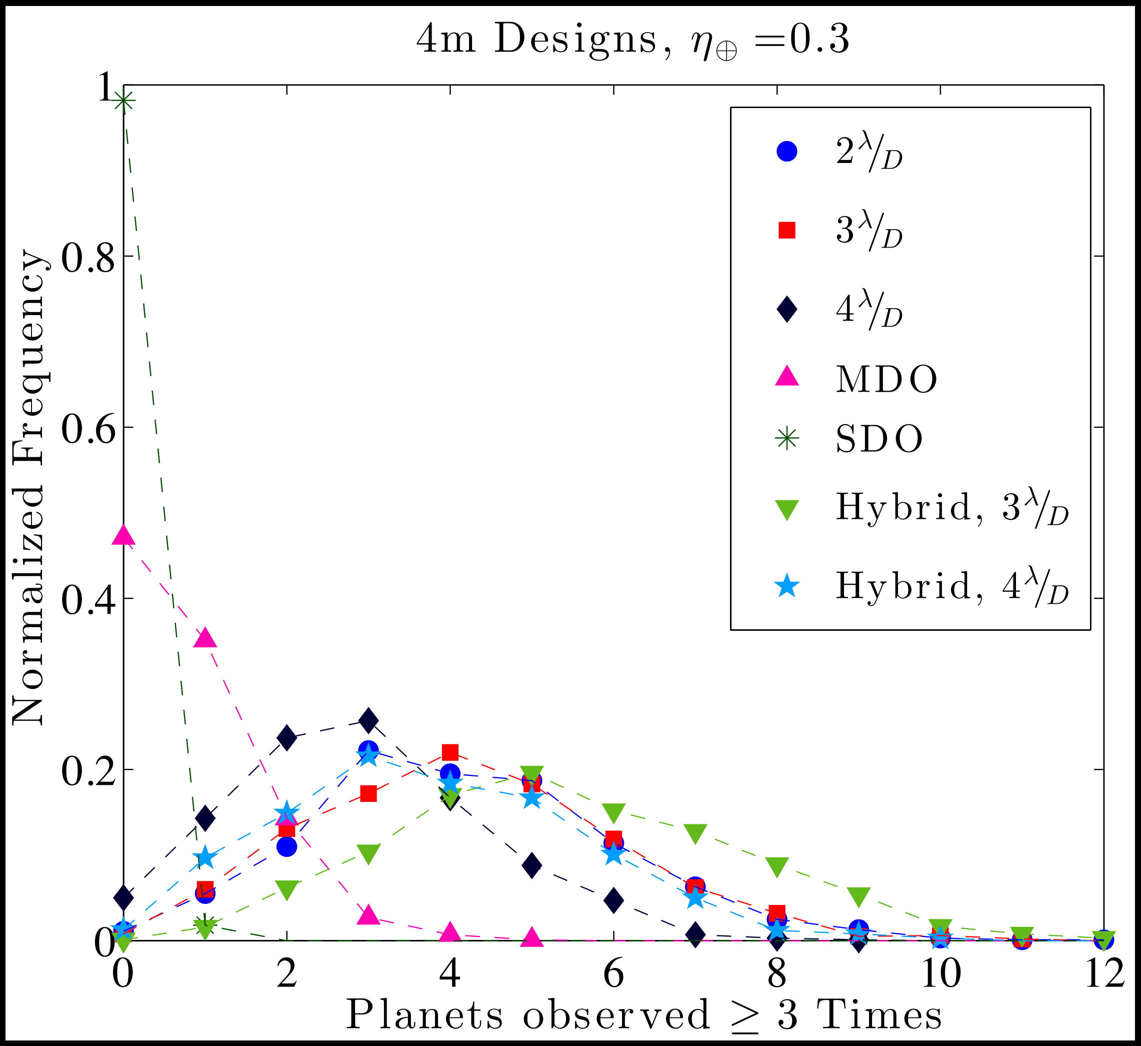
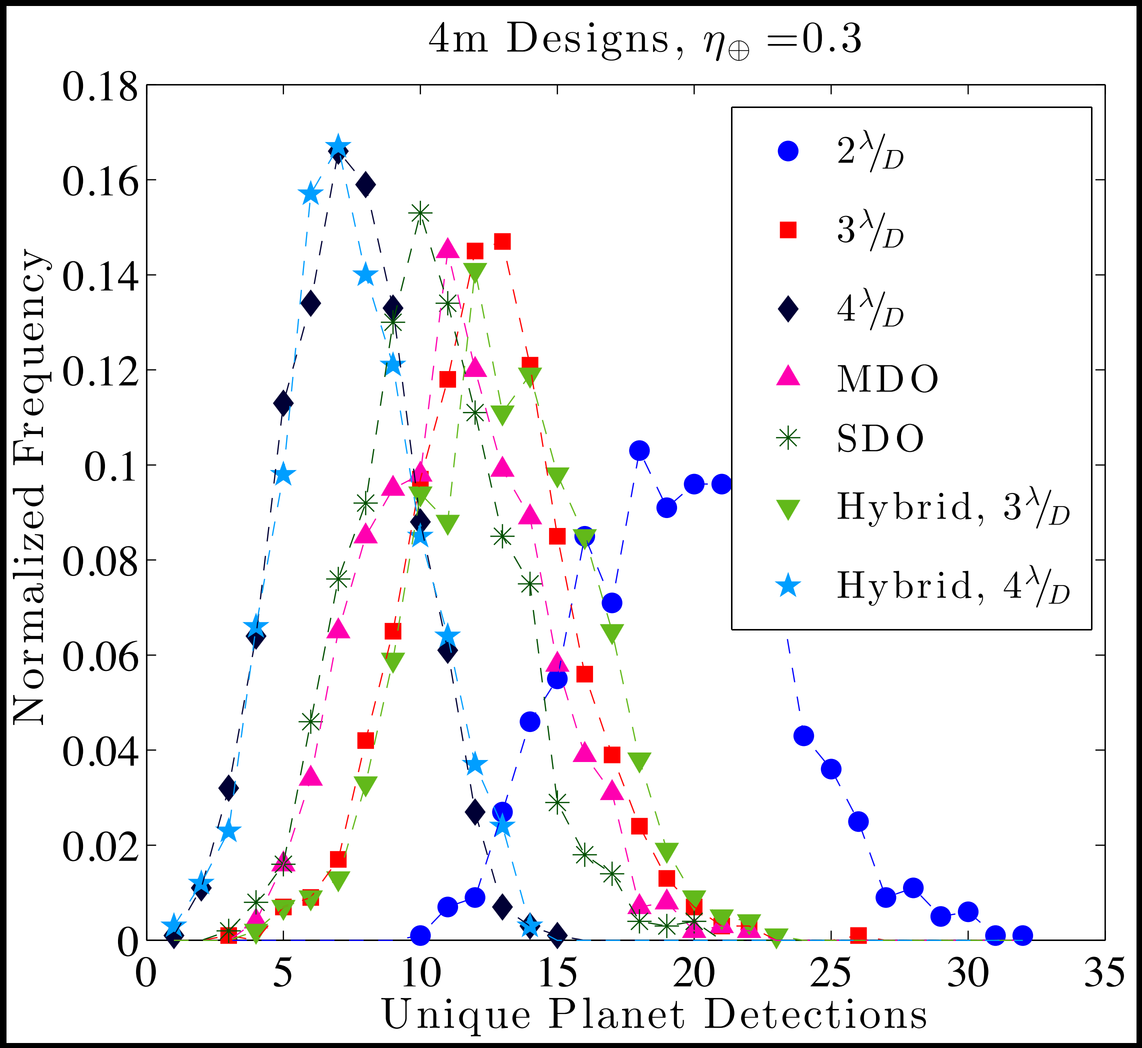
4 m telescope - Earth Detections (eta = 0.3)

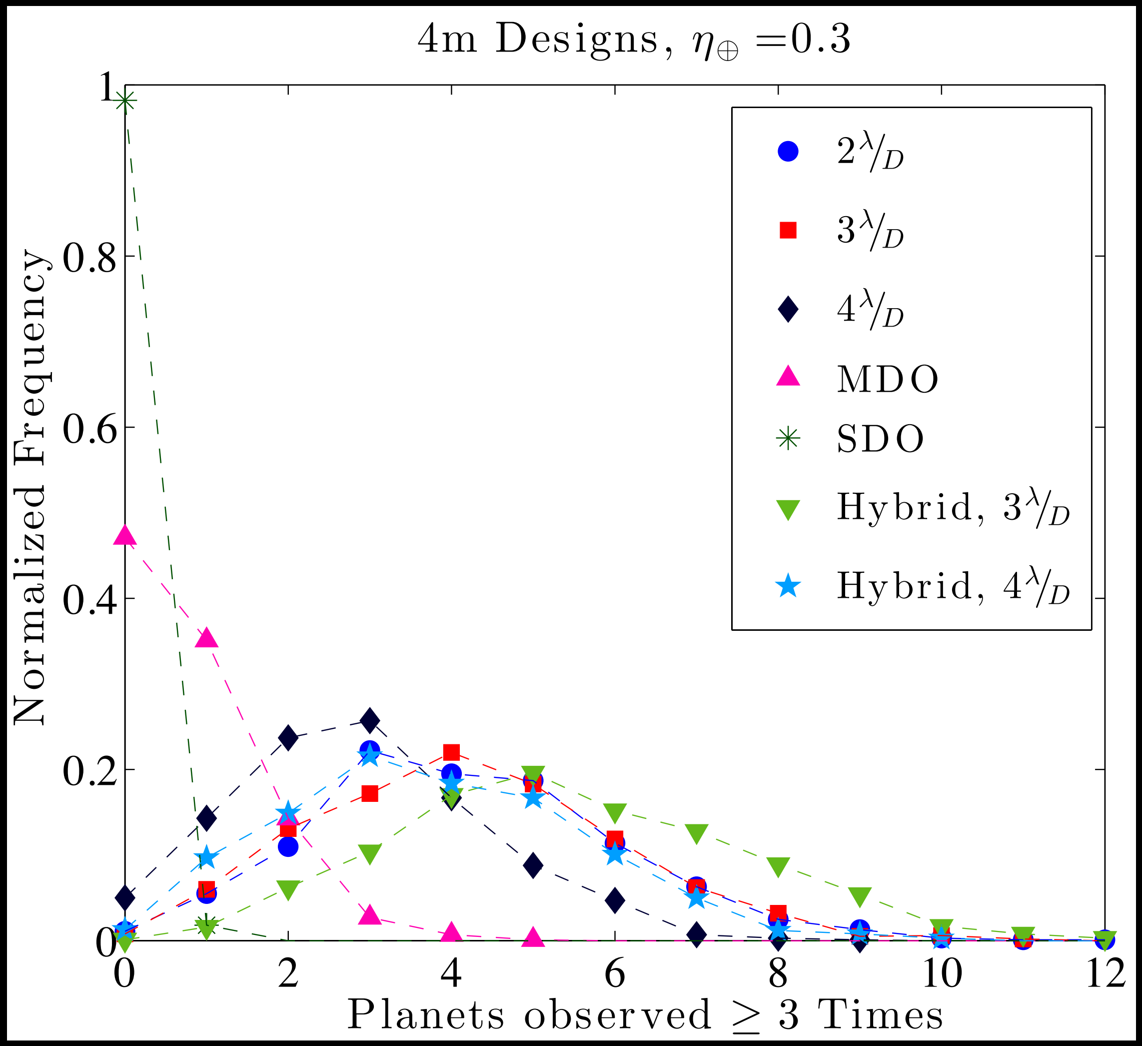




- 2 l/D coronagraph gets most detections but is extremely difficult.
- No difference between MDO and SDO. Repeat detections unlikely.
- Coronagraphs & Hybrids roughly the same repeat detections.
- 3 l/D and Hybrid have the same detections, including repeat detections.
- 4 l/D coronagraph has roughly half the number of detections of occulter
- Coronagraphs assumed 50% mission time and 24 hour setup time

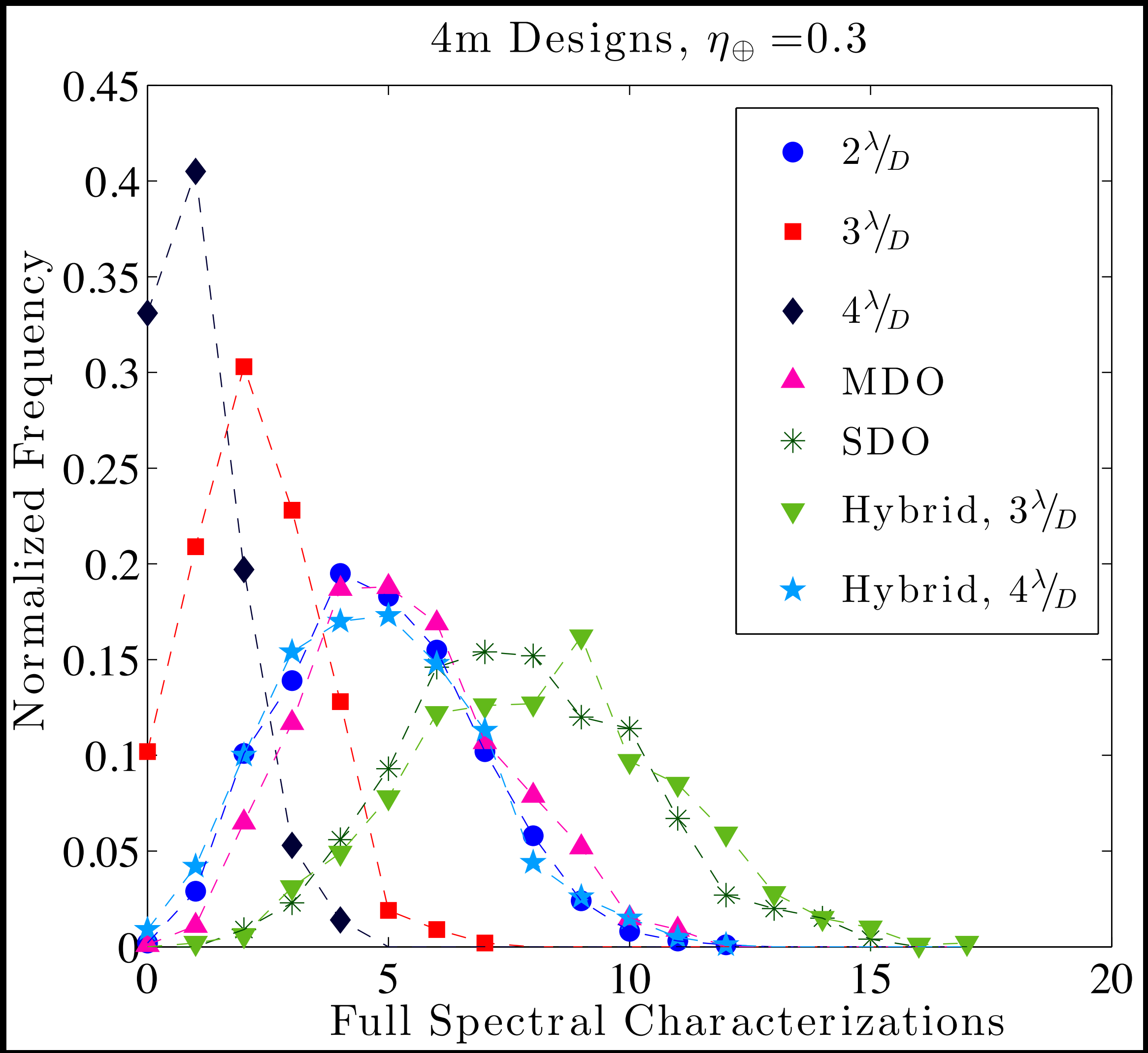
4 m telescope - Earth Detections (eta = 0.3)

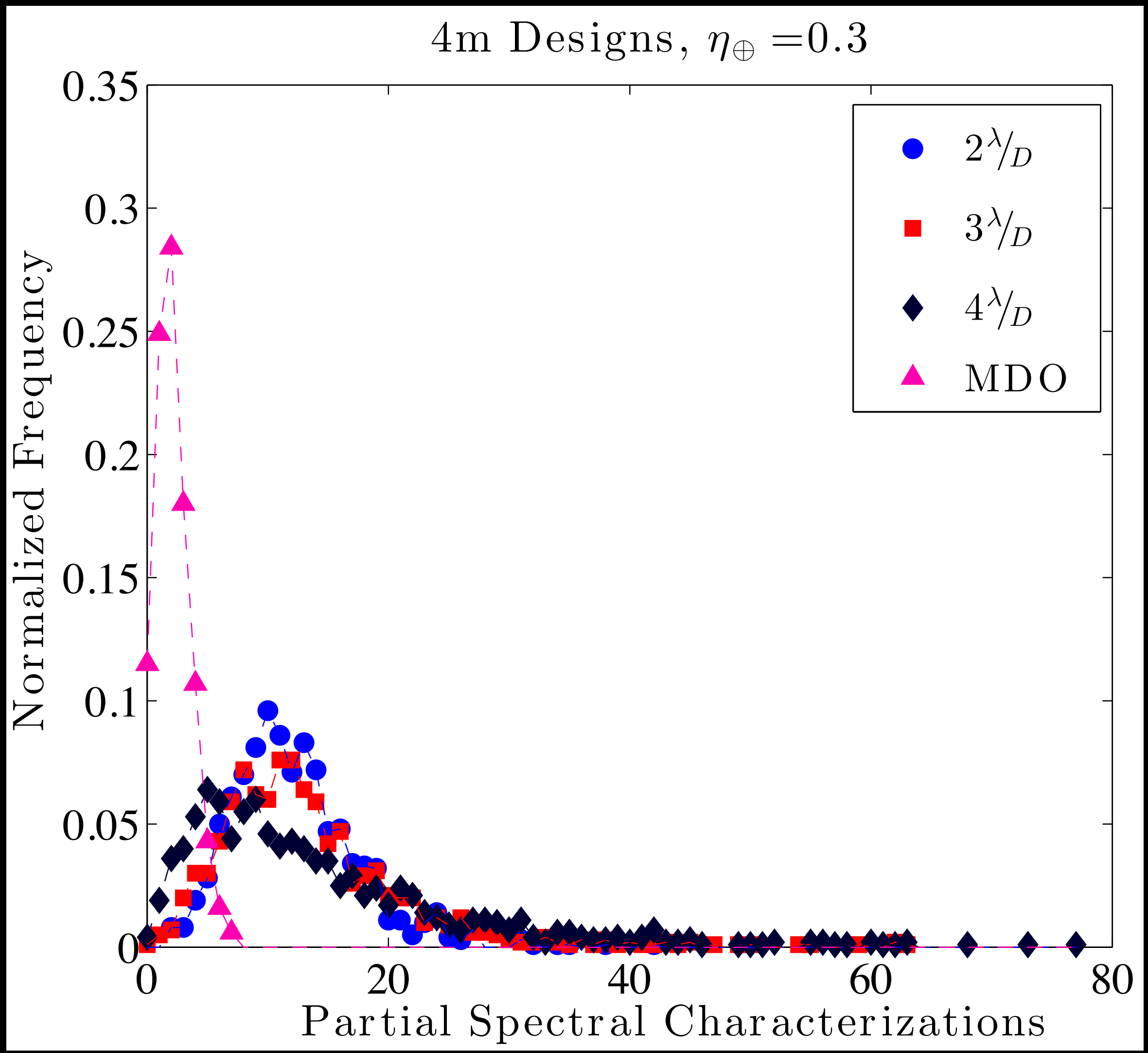




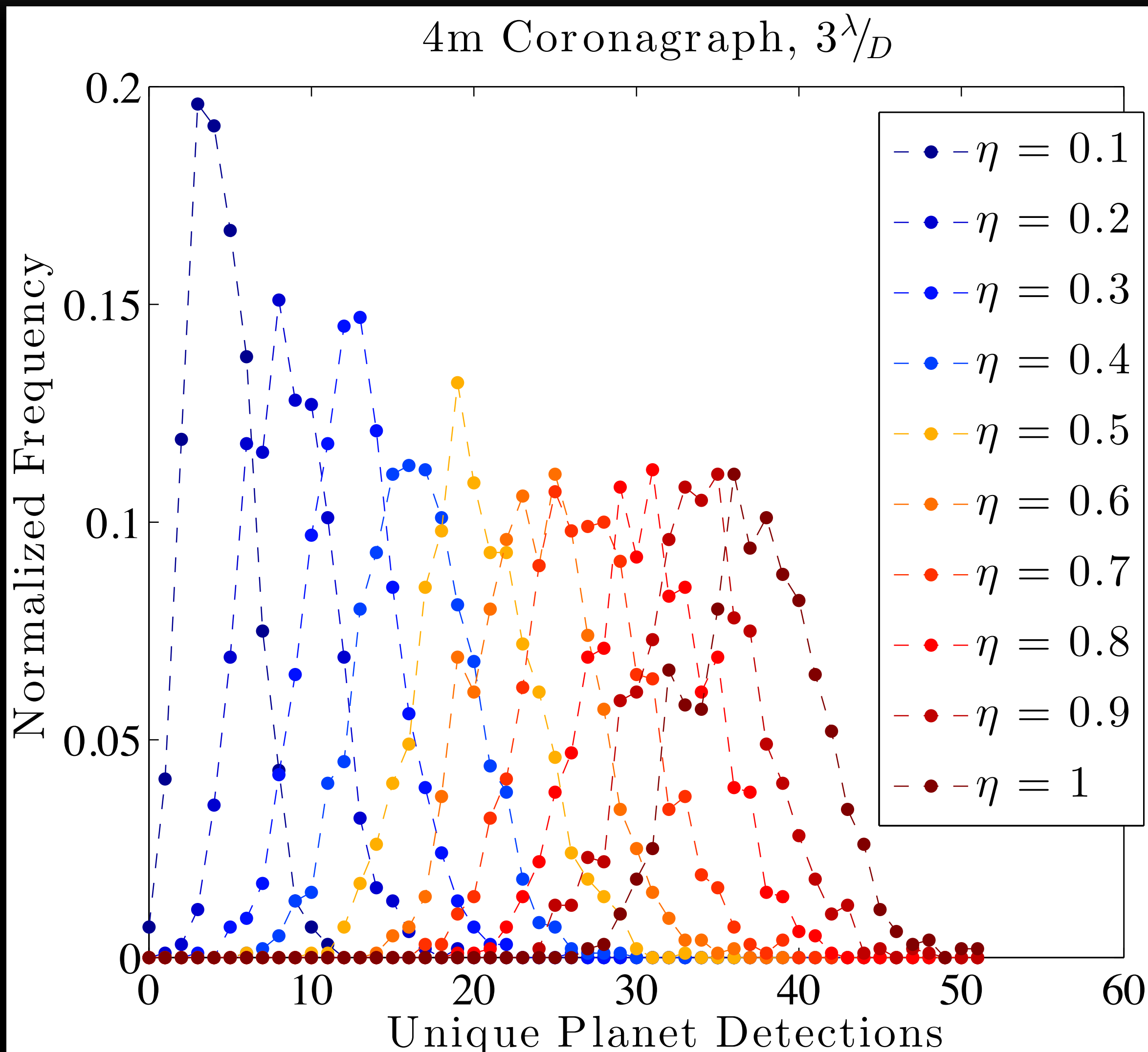
If you could make a 2 l/D coronagraph, clearly the most unique detections. 3 l/D and 4 l/D coronagraphs get same detections as hybrid by design. What about spectra . . .

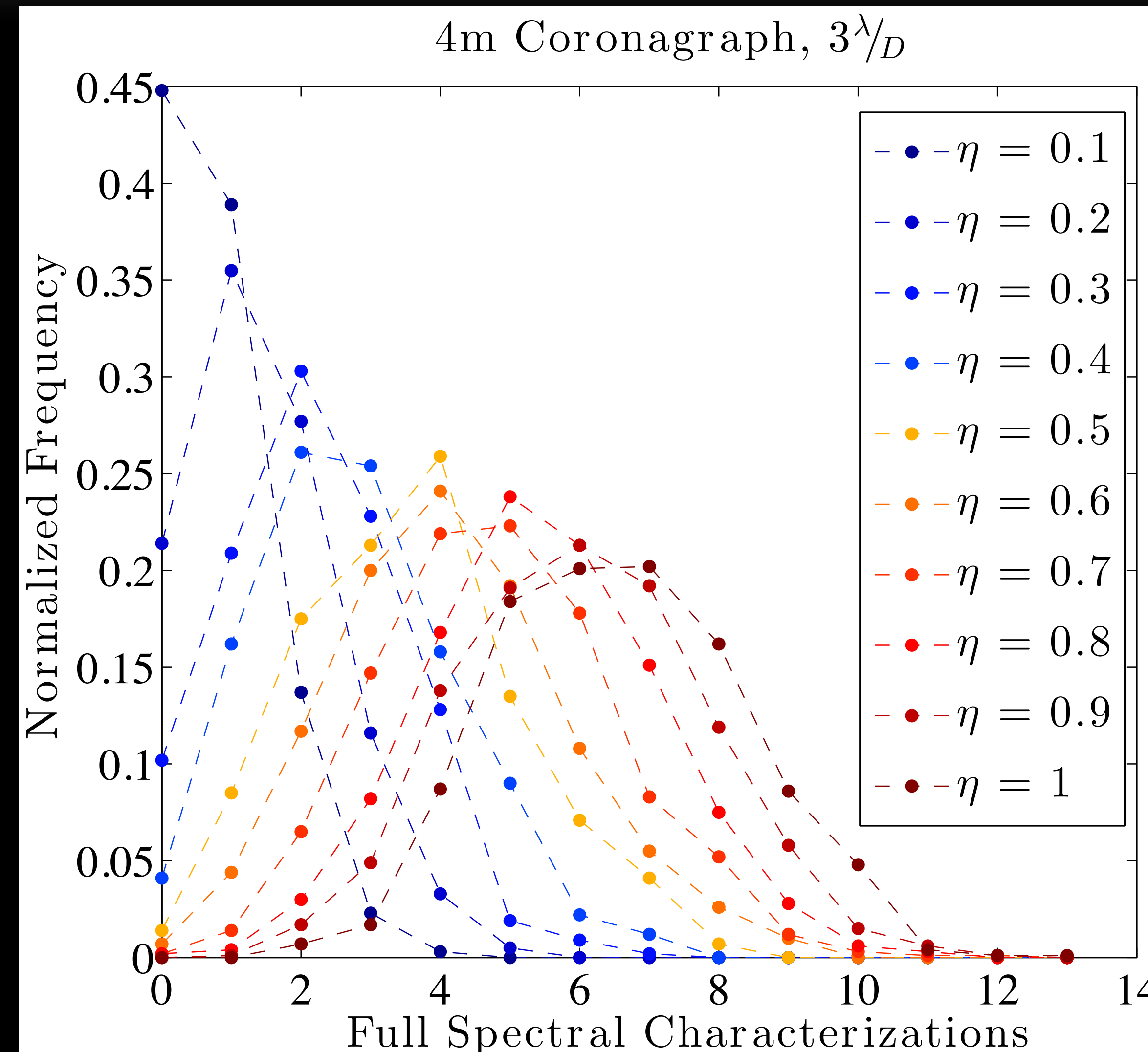
4 m telescope - Full and Partial Spectra



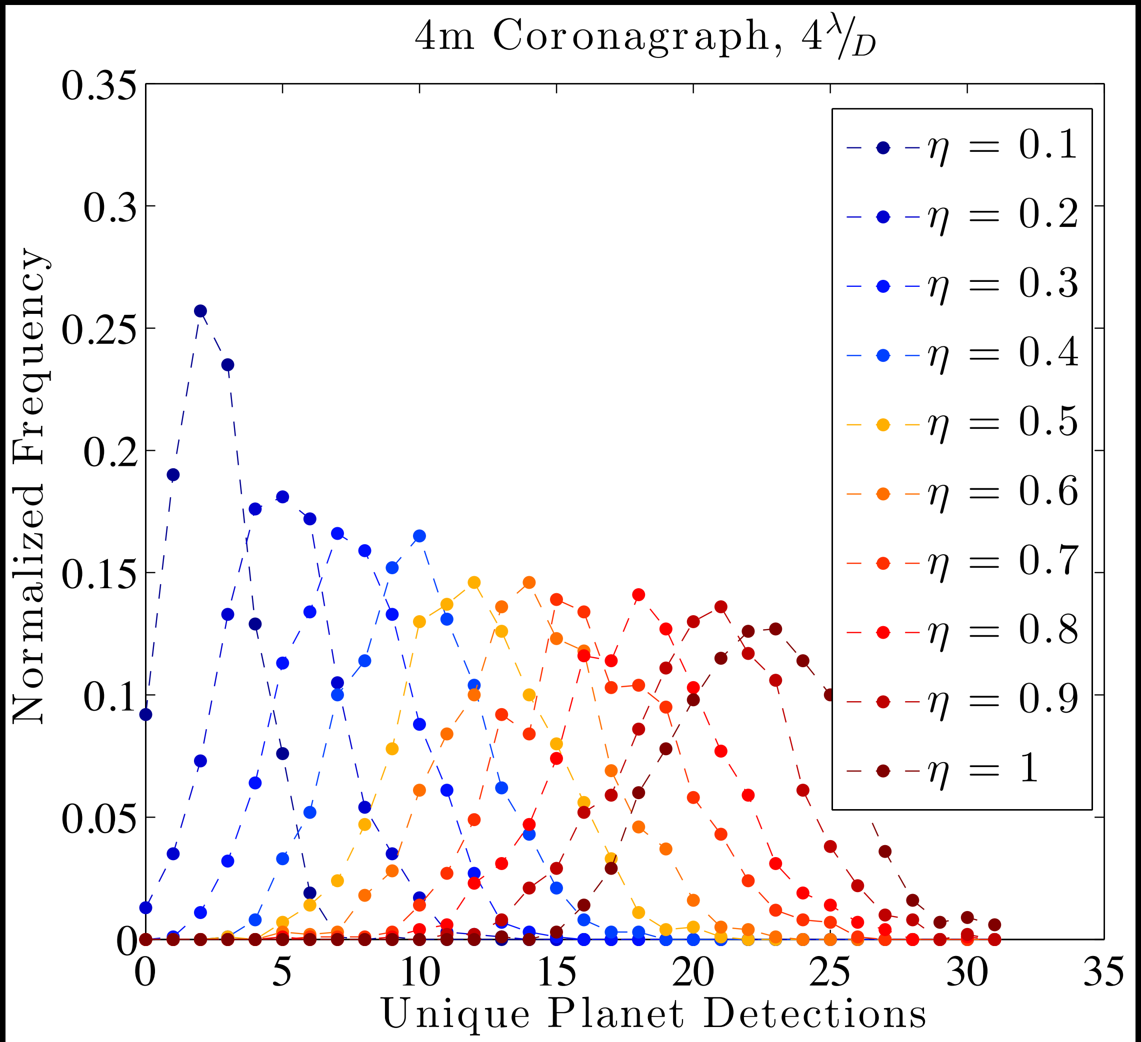


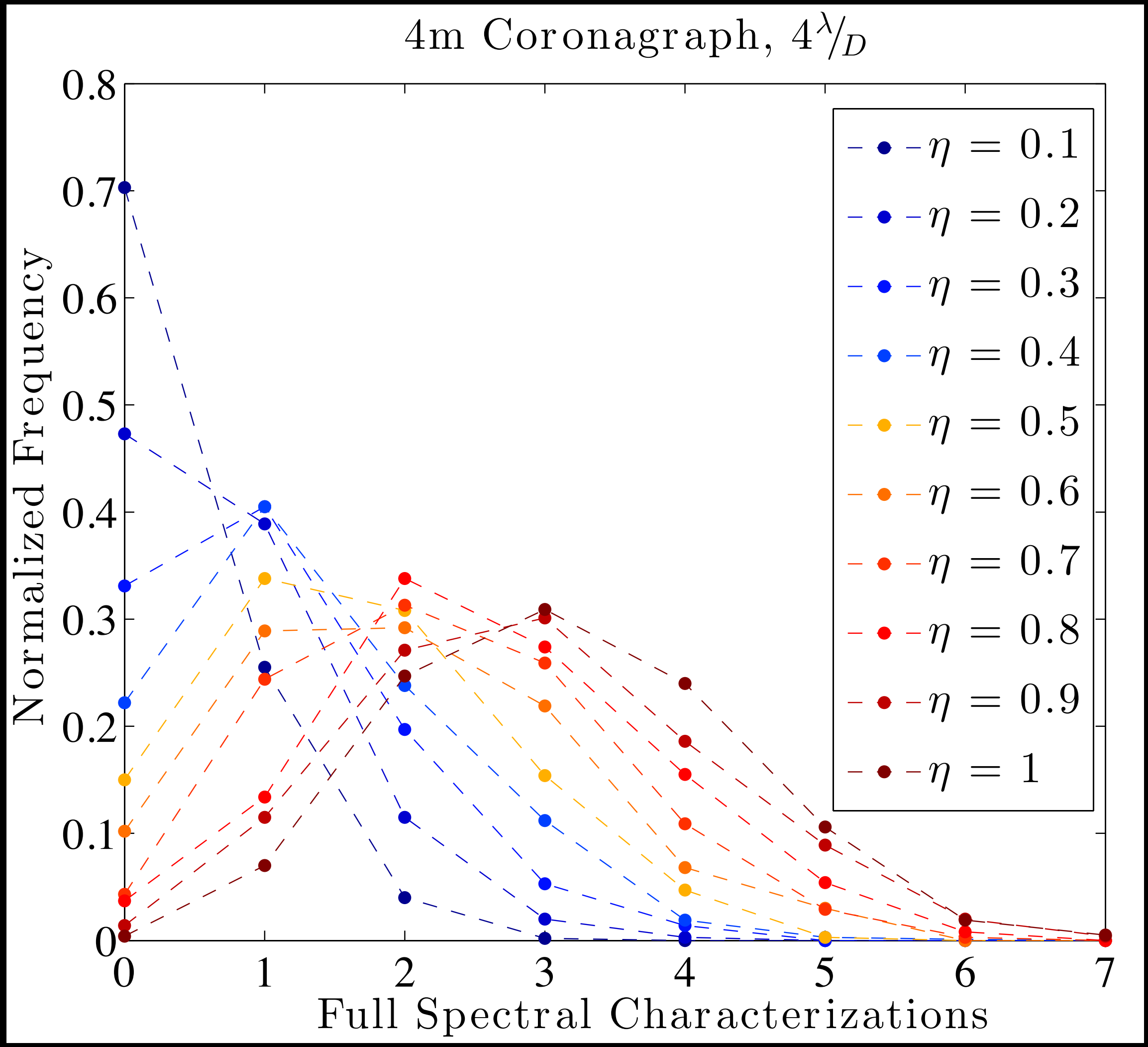
- SDO and 3 l/D Hybrid get most full spectra.
- 2 l/D coronograph, MDO and 4 l/D Hybrid same number of full spectra.
- 3 and 4 l/D corono have non-negligible probability of zero full planet spectra.
- Number of full spectra for coronagraph limited by red end (1000 nm)



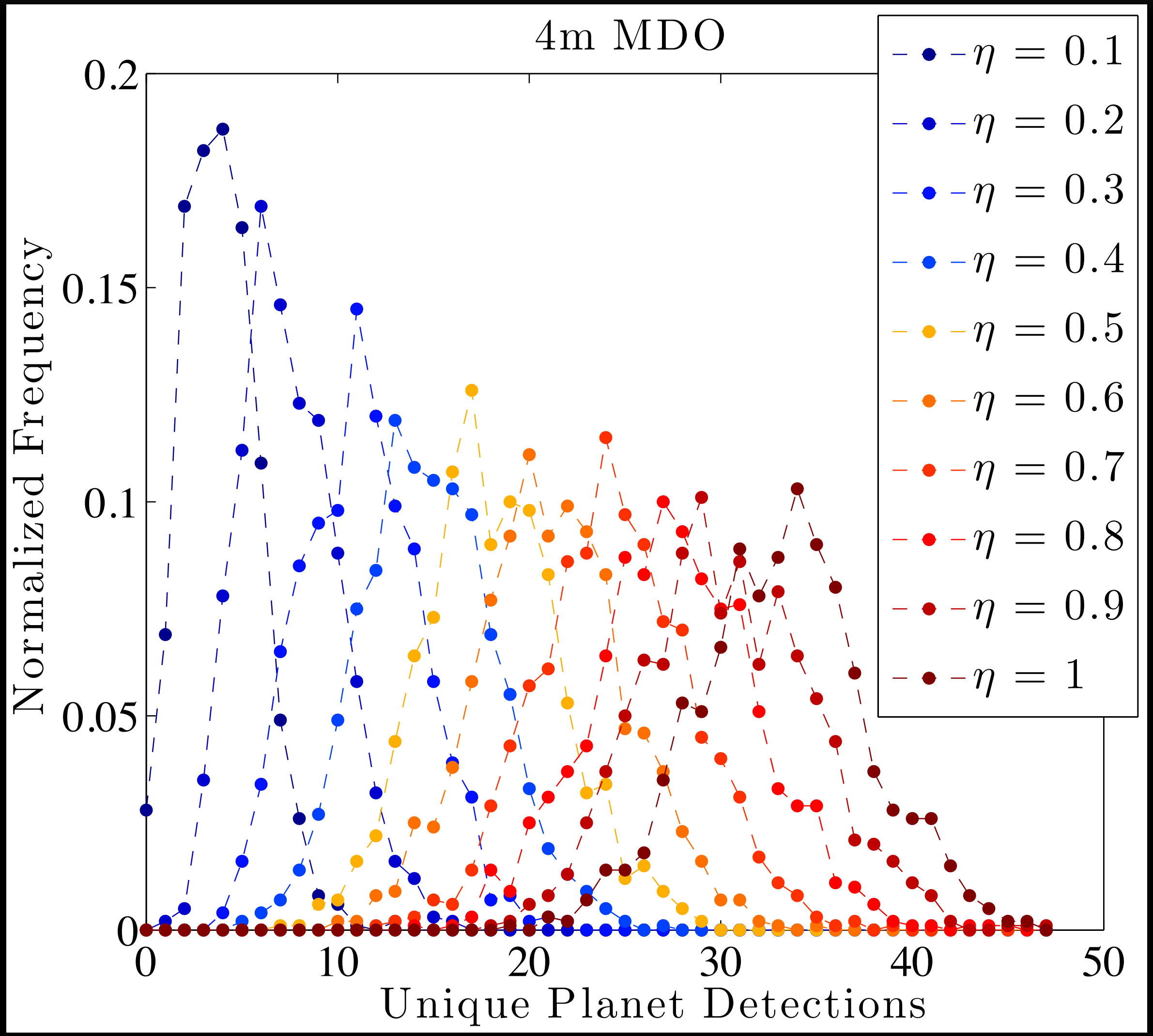


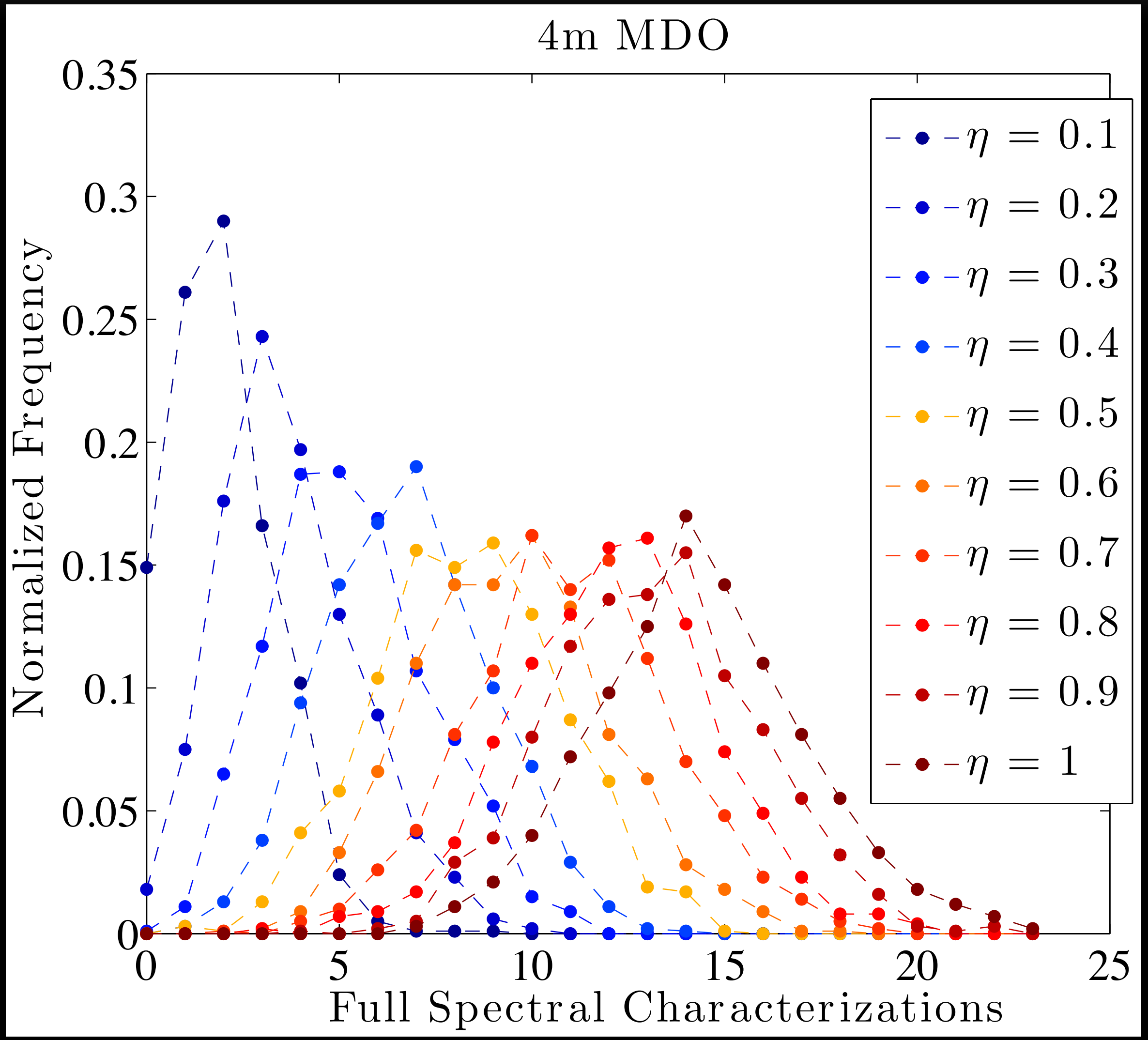
4 m telescope & 3 l/D Coronagraph



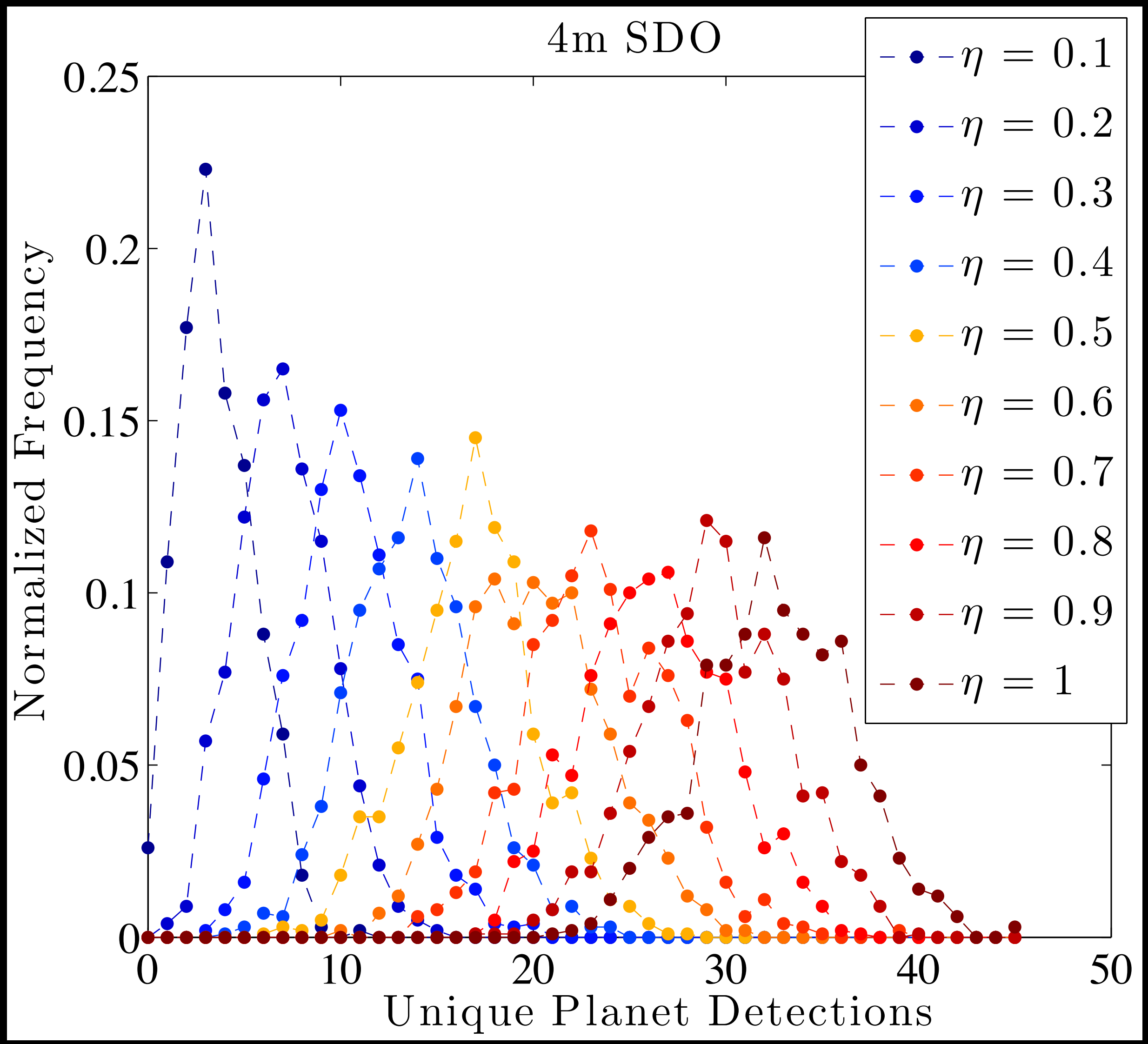


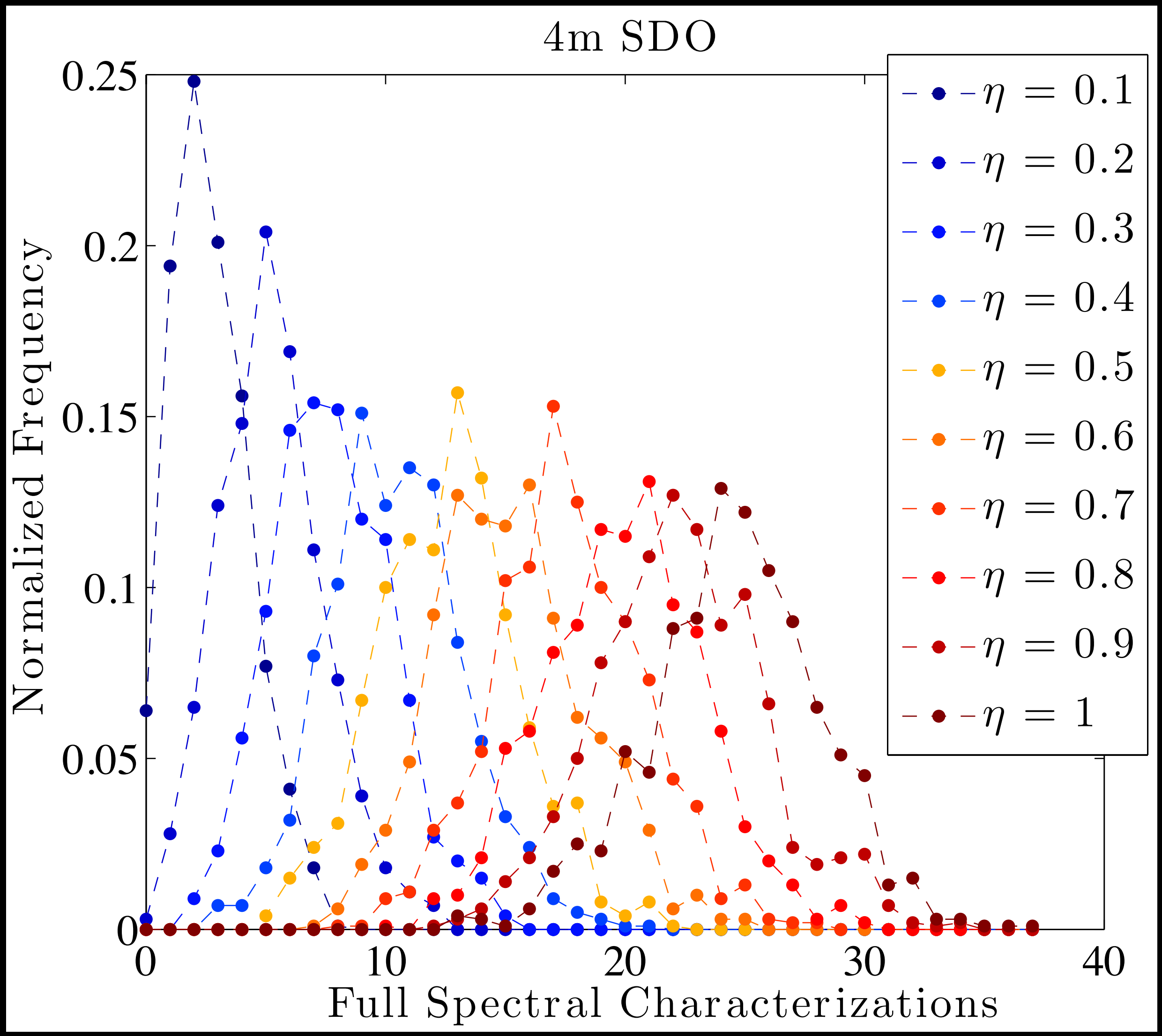
4 m telescope & 4 l/D Coronagraph



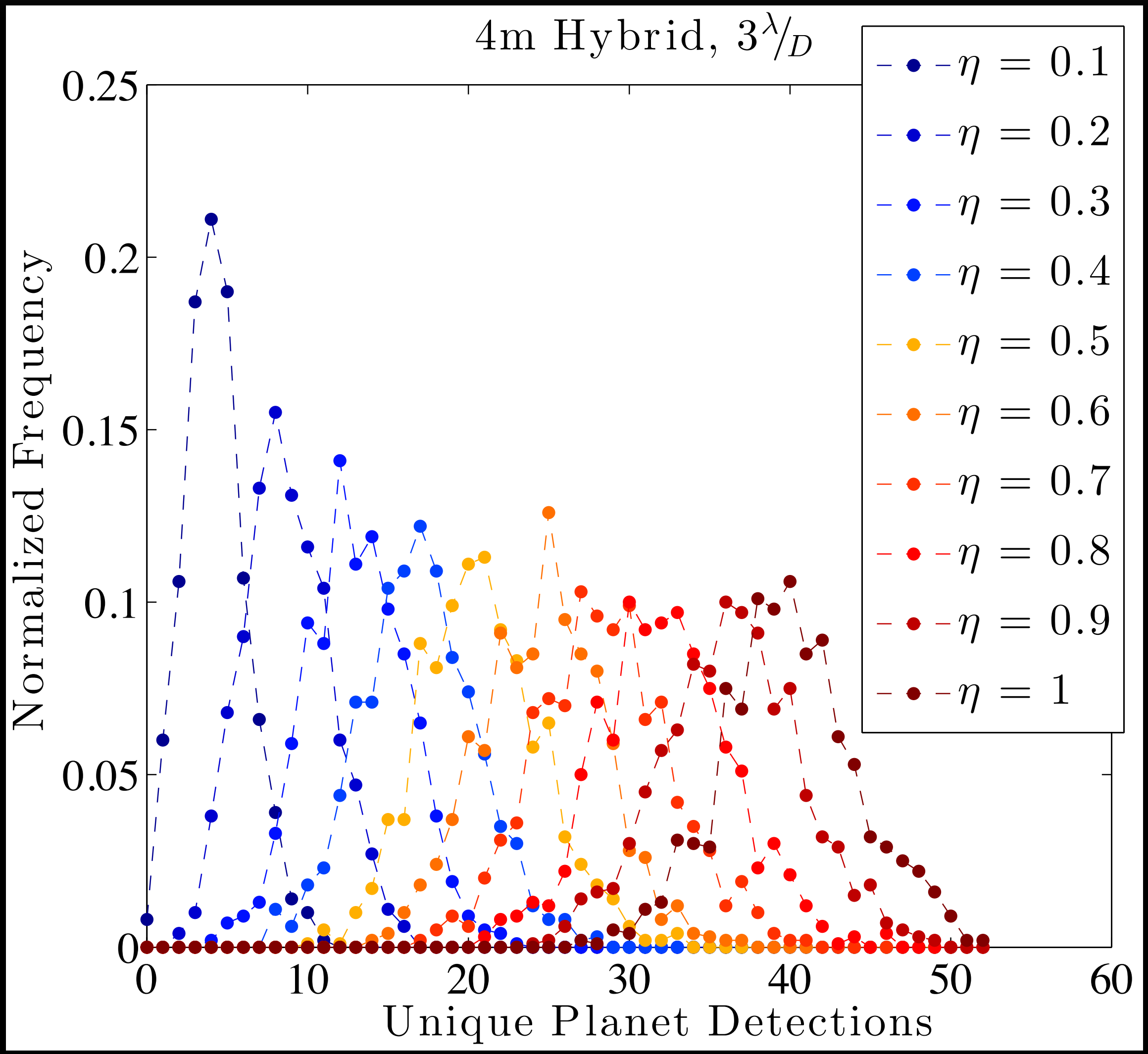


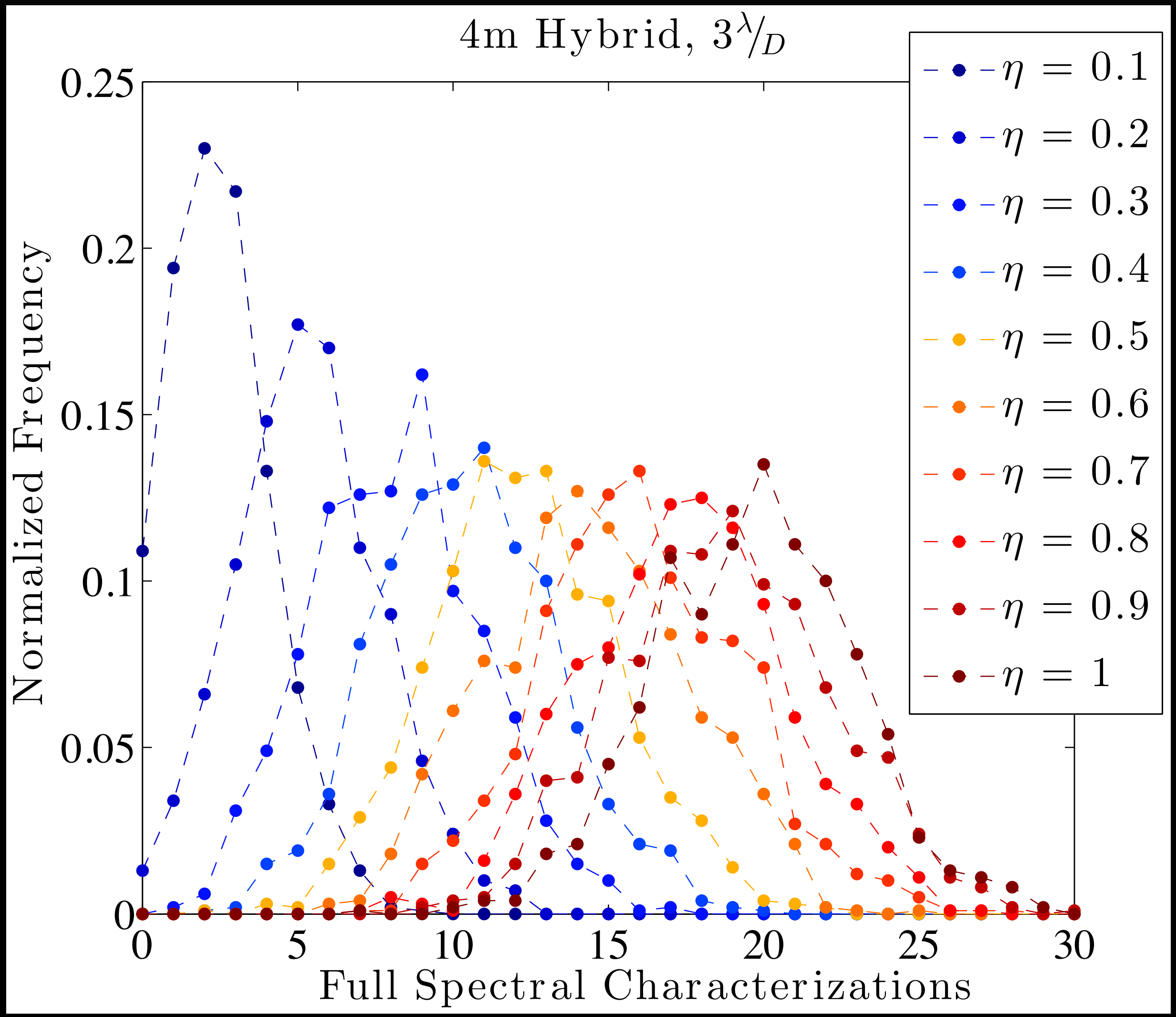
4 m telescope & Multi-distance Occulter



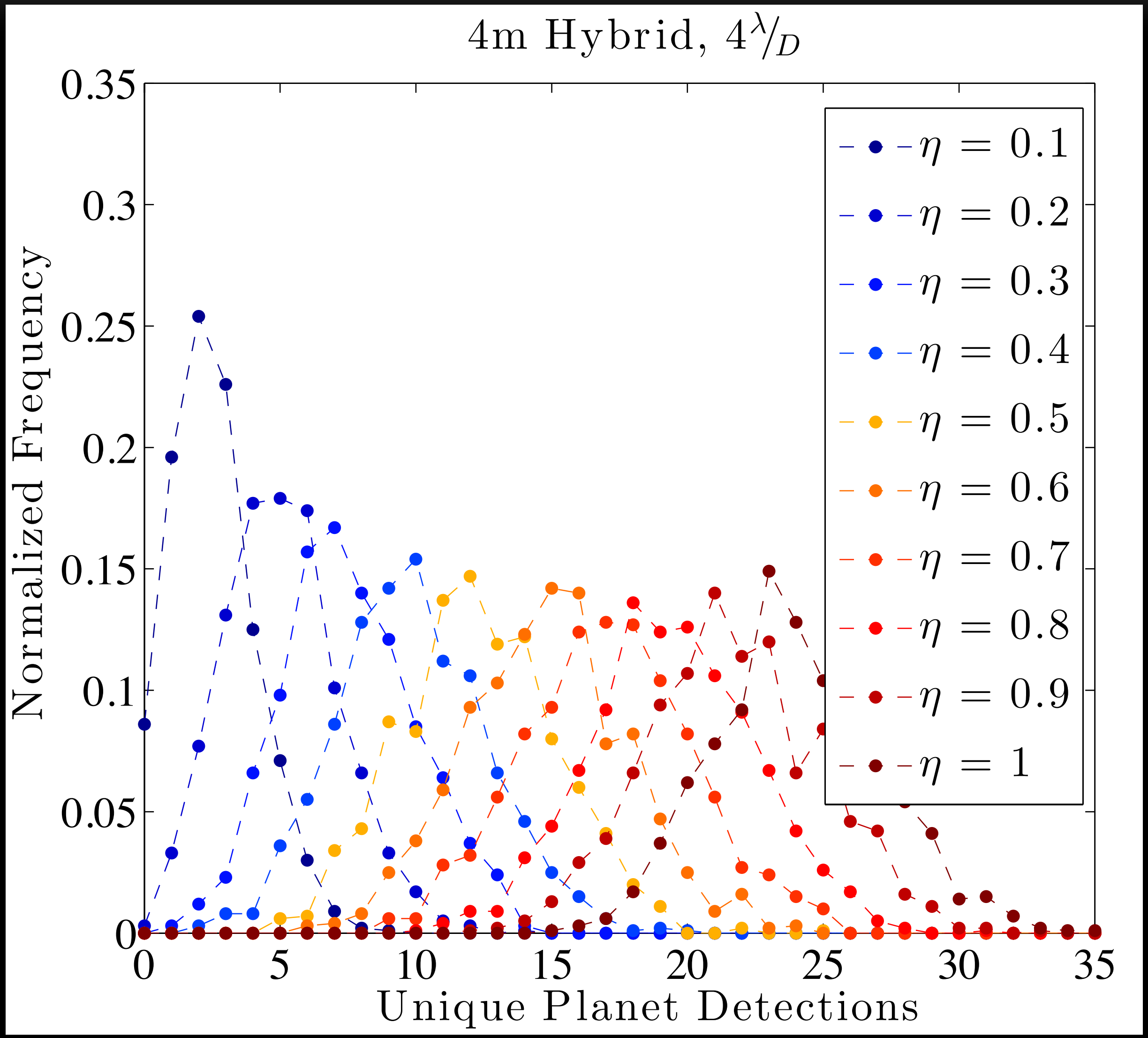


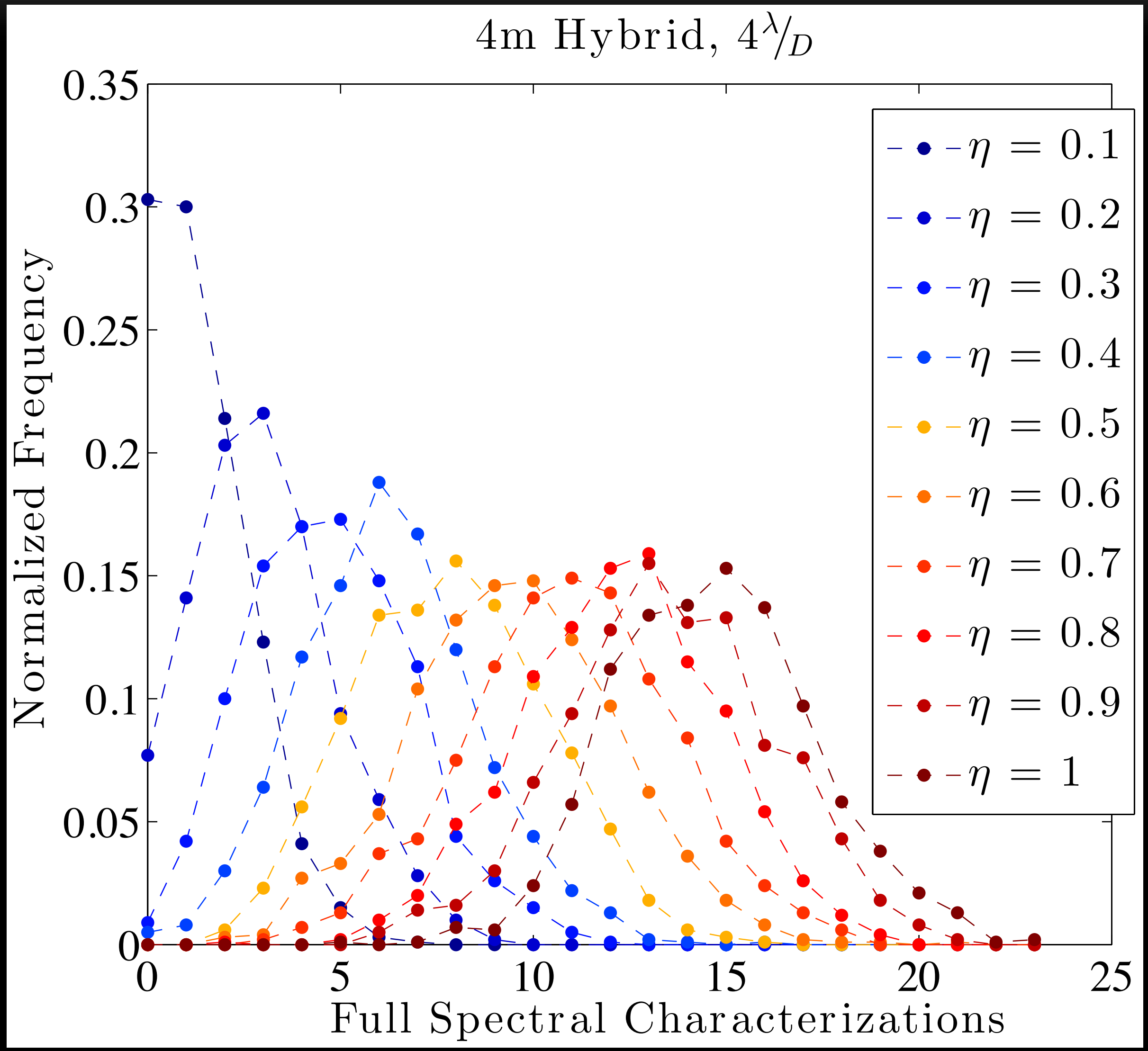
4 m telescope & Single Distance Occulter



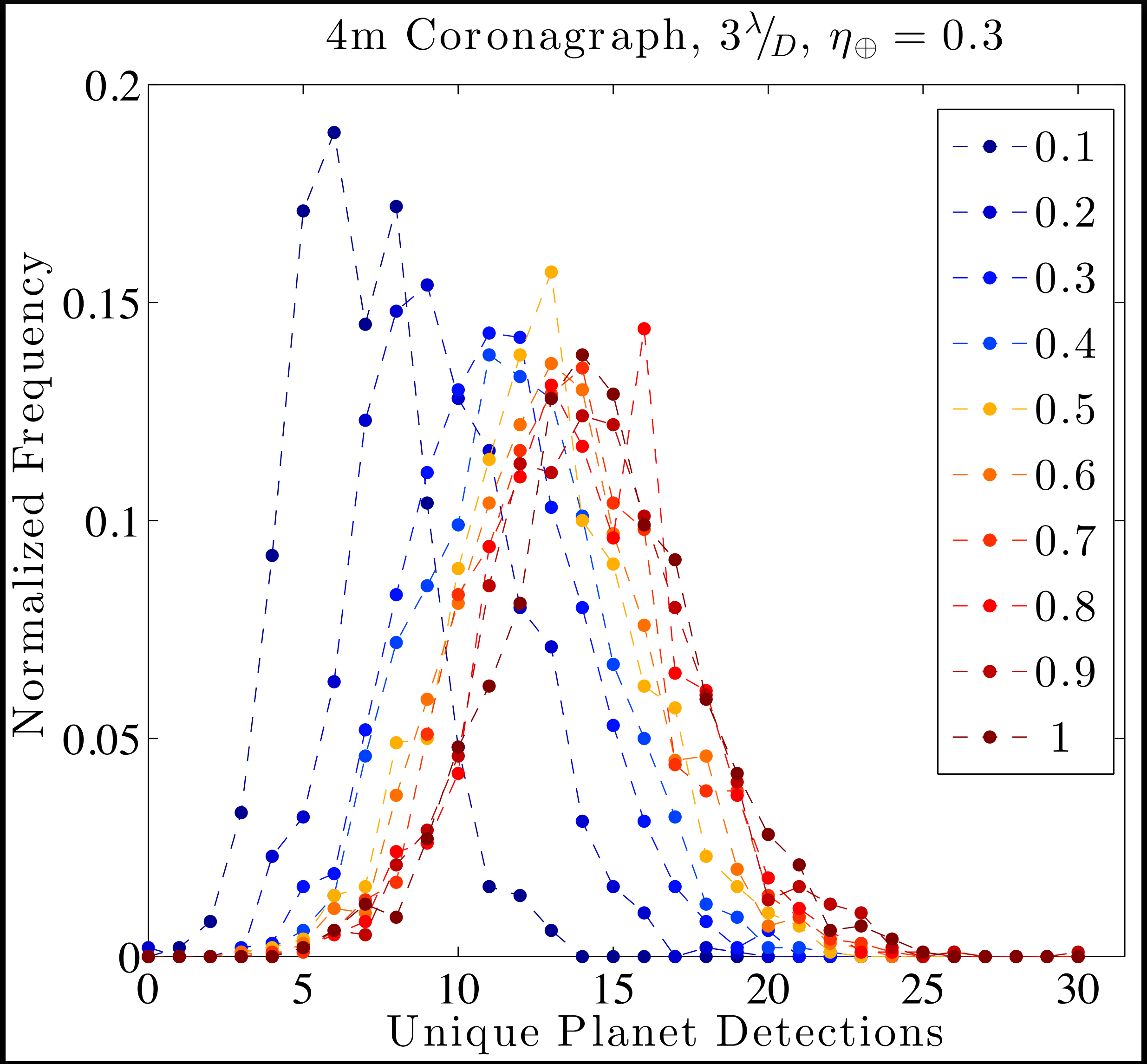


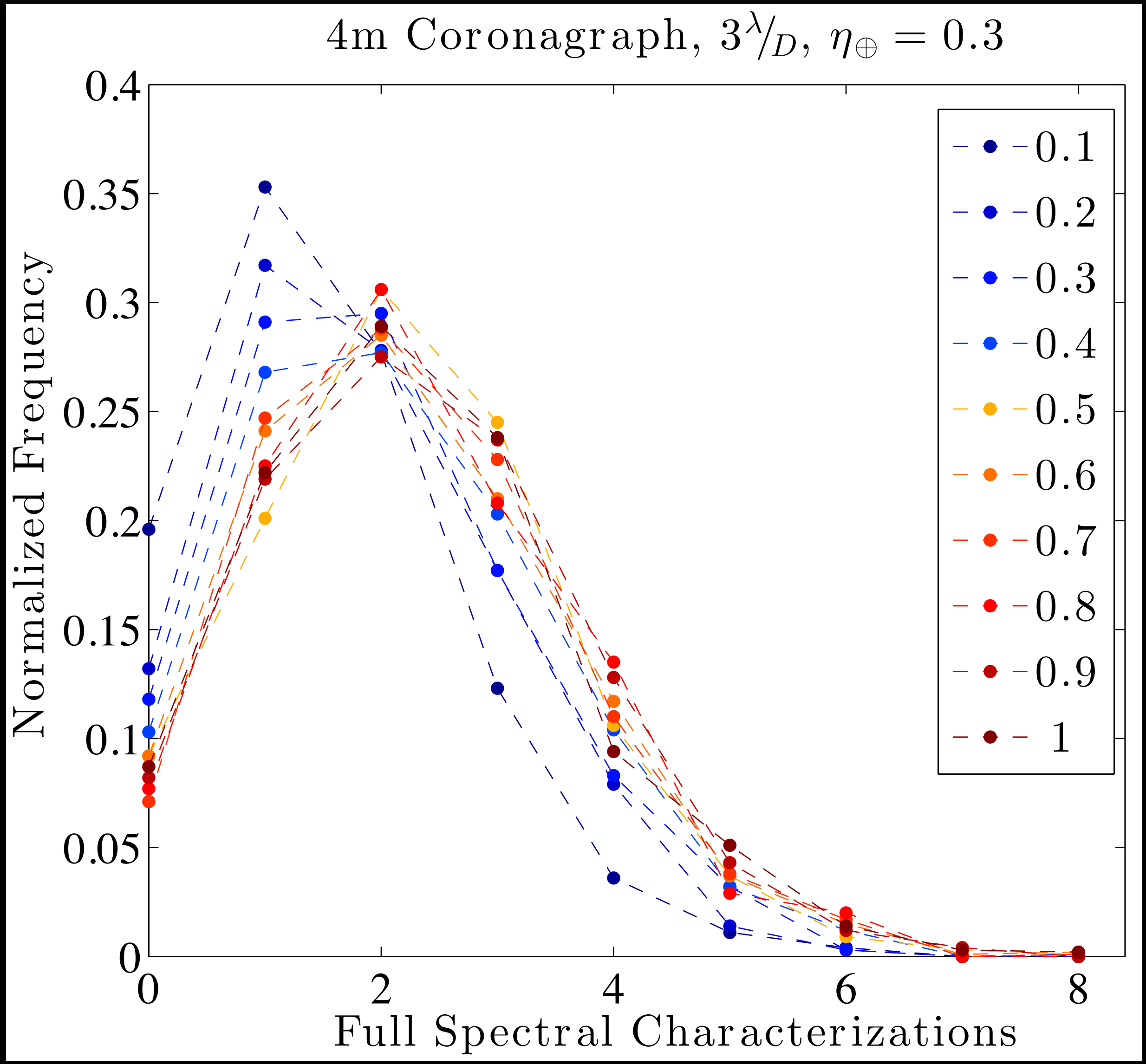
4 m telescope, SDO & 3 l/D Coronagraph





4 m telescope, SDO & 4 l/D Coronagraph





Coronagraph Science vs. Mission Fraction

What is impact on Telescope & Mission?

Coronagraphs

- Most require off-axis telescope (particularly at 2 l/D)
- Complex and large thermal control system (little room left).
- Single-digit picometer stability of primary and secondary
- sub-nanometer position stability (requires active isolation)
- Multiple channel wavefront control with 2 DMs results in large volume and mass
- No UV exoplanet science (too many bounces)
- At 4 m, exoplanet requirements drive the telescope design
- Requirements significantly relax for 8 m at 4 l/D

	2 l/D	3 l/D	4 l/D
Low Order Aberrations	1 pm	4 pm	400 pm
Secondary Motion	0.5 nm	2 nm	50 nm

Shaklan, et al., SPIE 8151-08, 2011

What is impact on Telescope & Mission?

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At 4m, exoplanet requirements drive the whole observatory: off-axis, thermal control, mass, volume, cost.

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Shaklan, et al., SPIE 8151-08, 2011

What is impact on Telescope & Mission?

Occulters

- No new requirements on telescope design or stability
- Additional camera for occulter position sensing
- Cost and complexity of additional spacecraft
- Simulations assumed solar electric propulsion though chemical is likely feasible.

Hybrids

- If operate at 4 l/D, TPF-C level stability requirements
- At 3 l/D, still very tight requirements (a few picometers)
- Significant change to Vis camera to include narrow channel coronagraph with wavefront control
- Thermal shroud around telescope and isothermal cavity for instrument still necessary.

4 m telescope - Observations & Conclusions

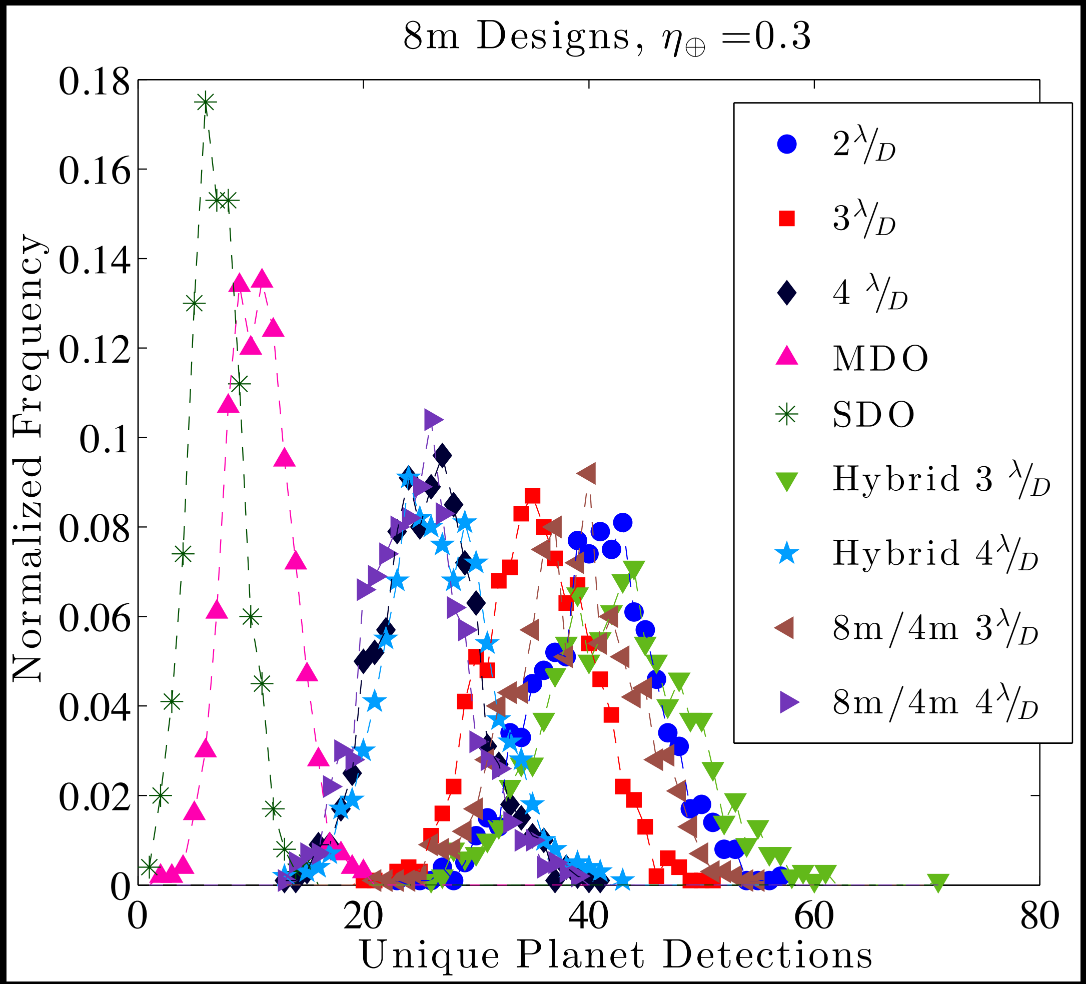
- If coronagraph alone, 2 l/D is best but still science at 3 and 4.
- For 2 and 3 l/D system, exoplanet instrument completely drives observatory requirements.
- At 2 l/D, stability requirements likely are unachievable and unverifiable.
- 2 and 3 l/D get small number of full spectra.
- Spectral performance essentially the same for occulter & hybrid.
- Only an occulter will get UV exoplanet science.
- A hybrid maintains larger number of detections (and repeat detections) with more full spectra, but at added cost and complexity.

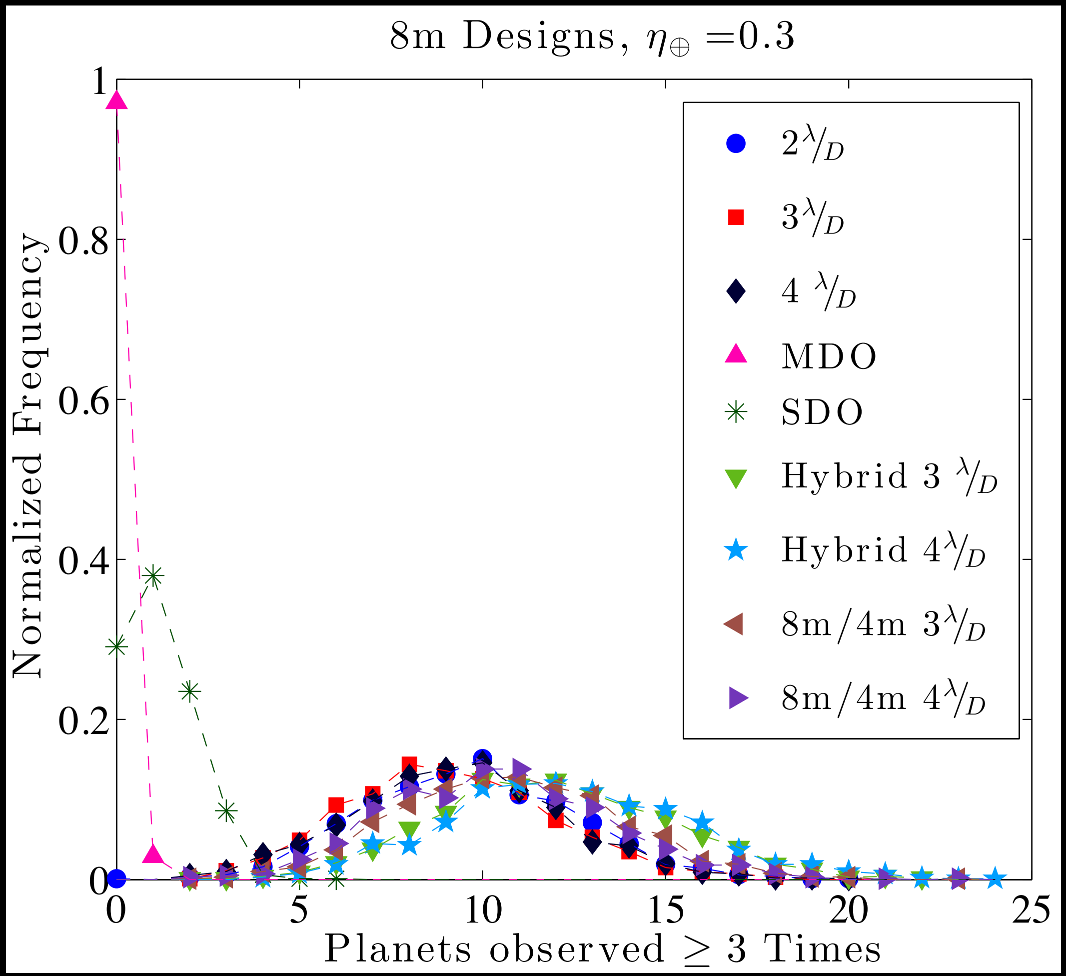
Best practical solution at this scale is the 4 l/D hybrid; most detections, repeat detections, and full spectra with minimal impact on telescope. Best solution with least impact on cost and complexity is occulter.

Note that 2 occulters would increase the number of detections with more repeat detections, though analysis hasn't been done.

What about an 8 m telescope. . .

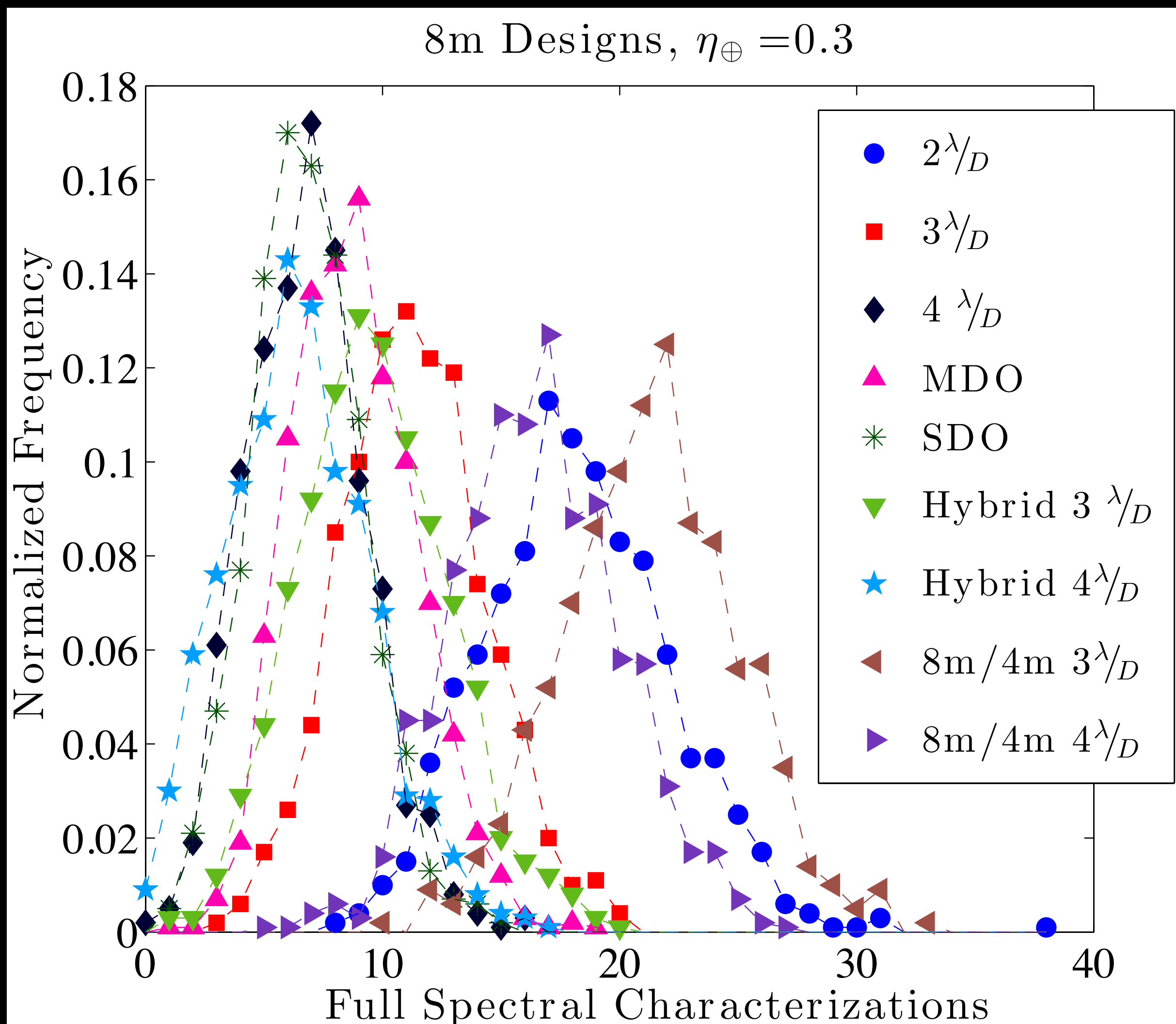
8 m telescope - Earth Detections (eta = 0.3)

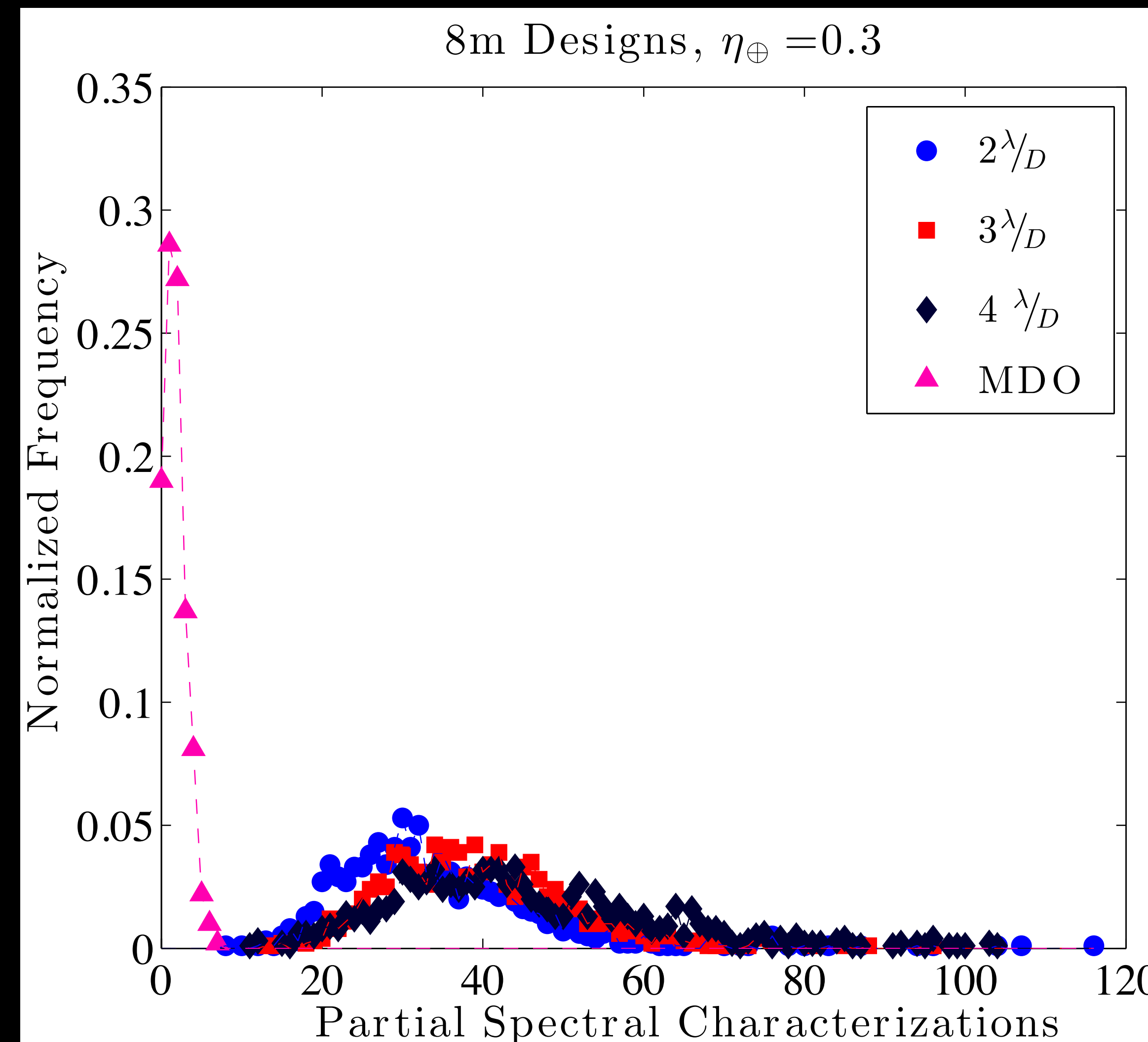




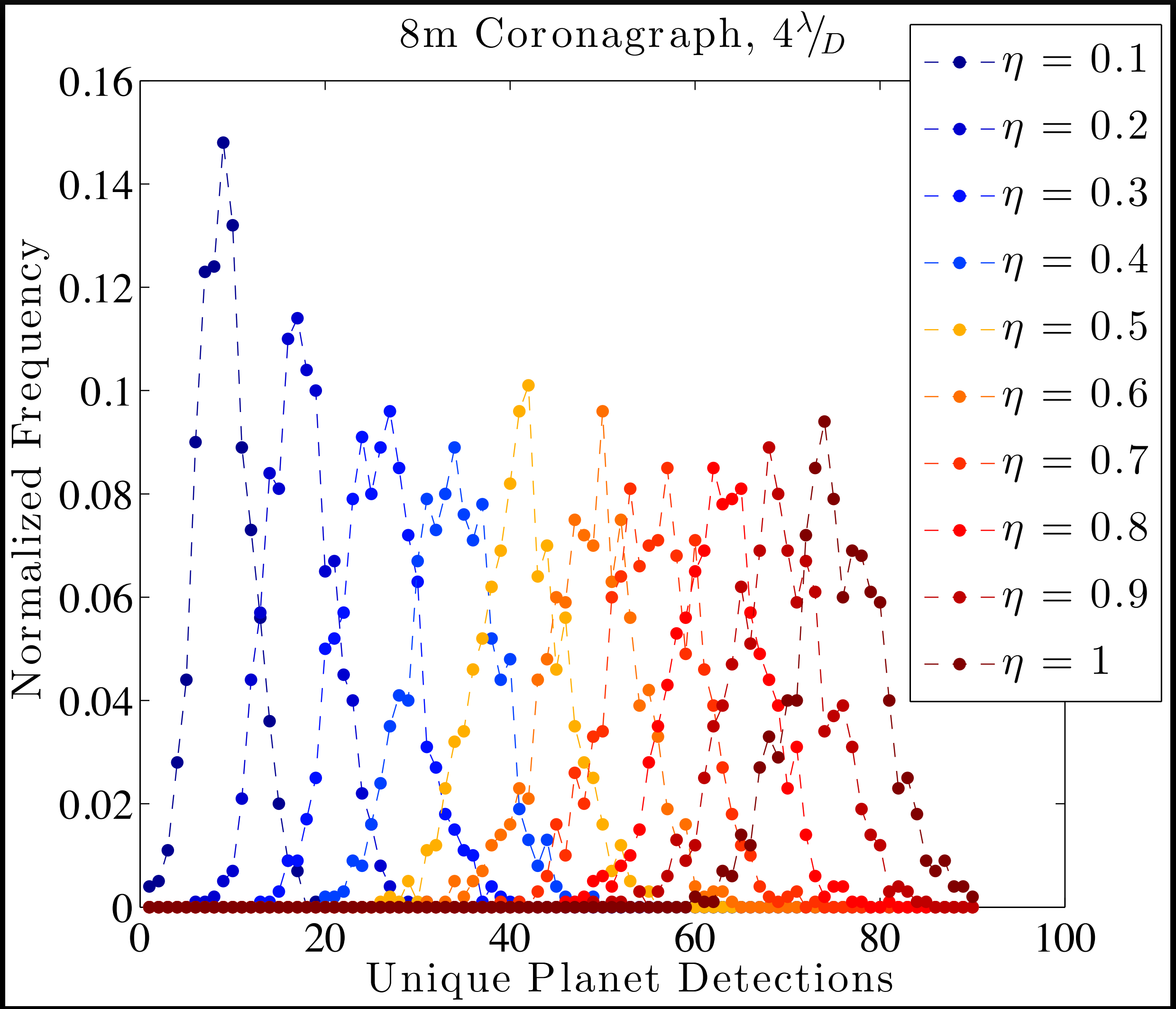
- 4 l/D coronagraph gets significant number of detections.
- Occulters have significantly fewer unique detections and no orbits.
- MDO & SDO same as for 4 m telescope unless improvement in thrust. (best solution is to fly smaller occulter from before and stop down telescope).
- 2, 3 l/D corongraphs & 3 l/d Hybrid roughly the same. 4 l/D coronagraph & Hybrid slightly lower yield.

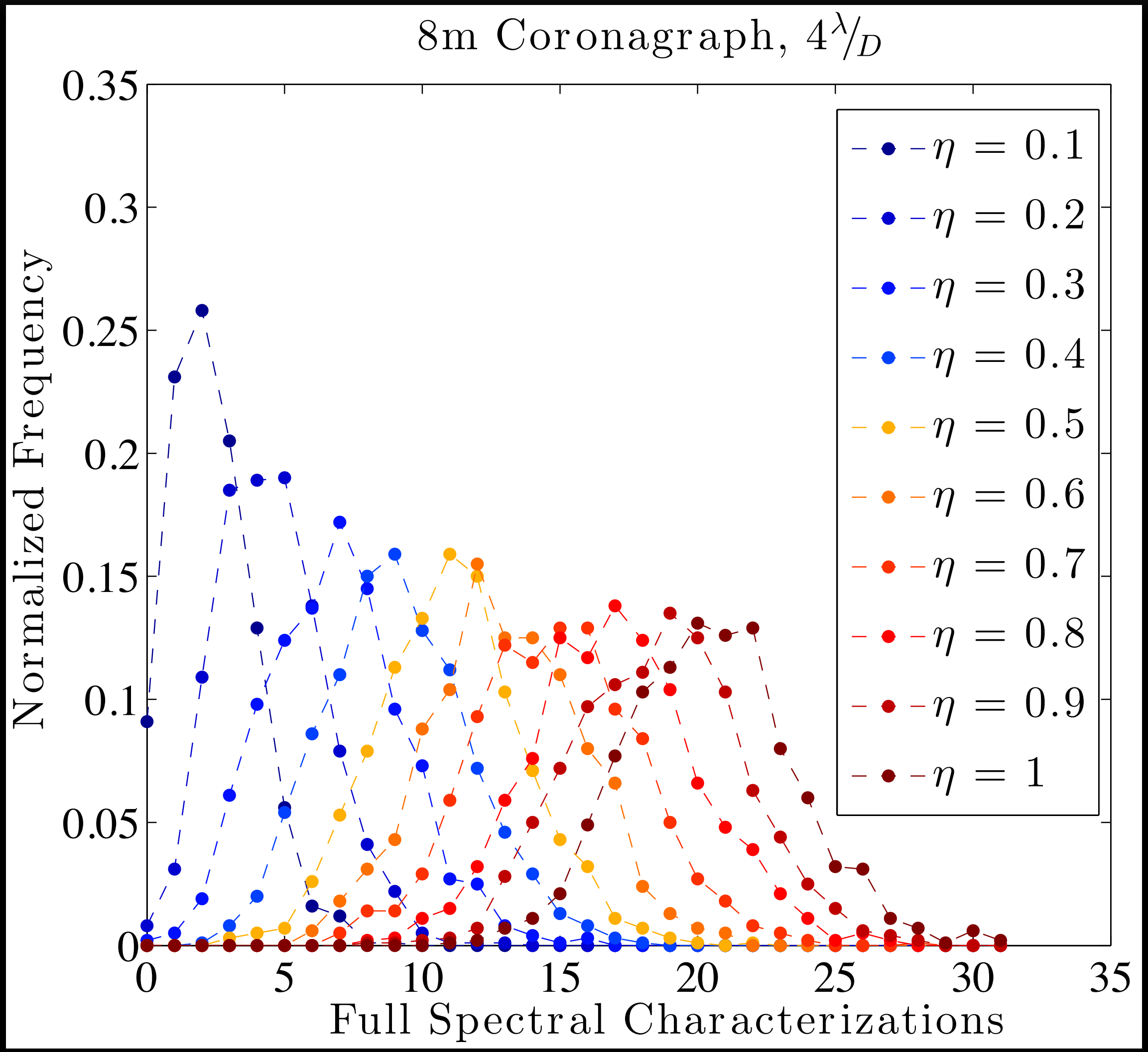
8 m telescope - Full Spectra



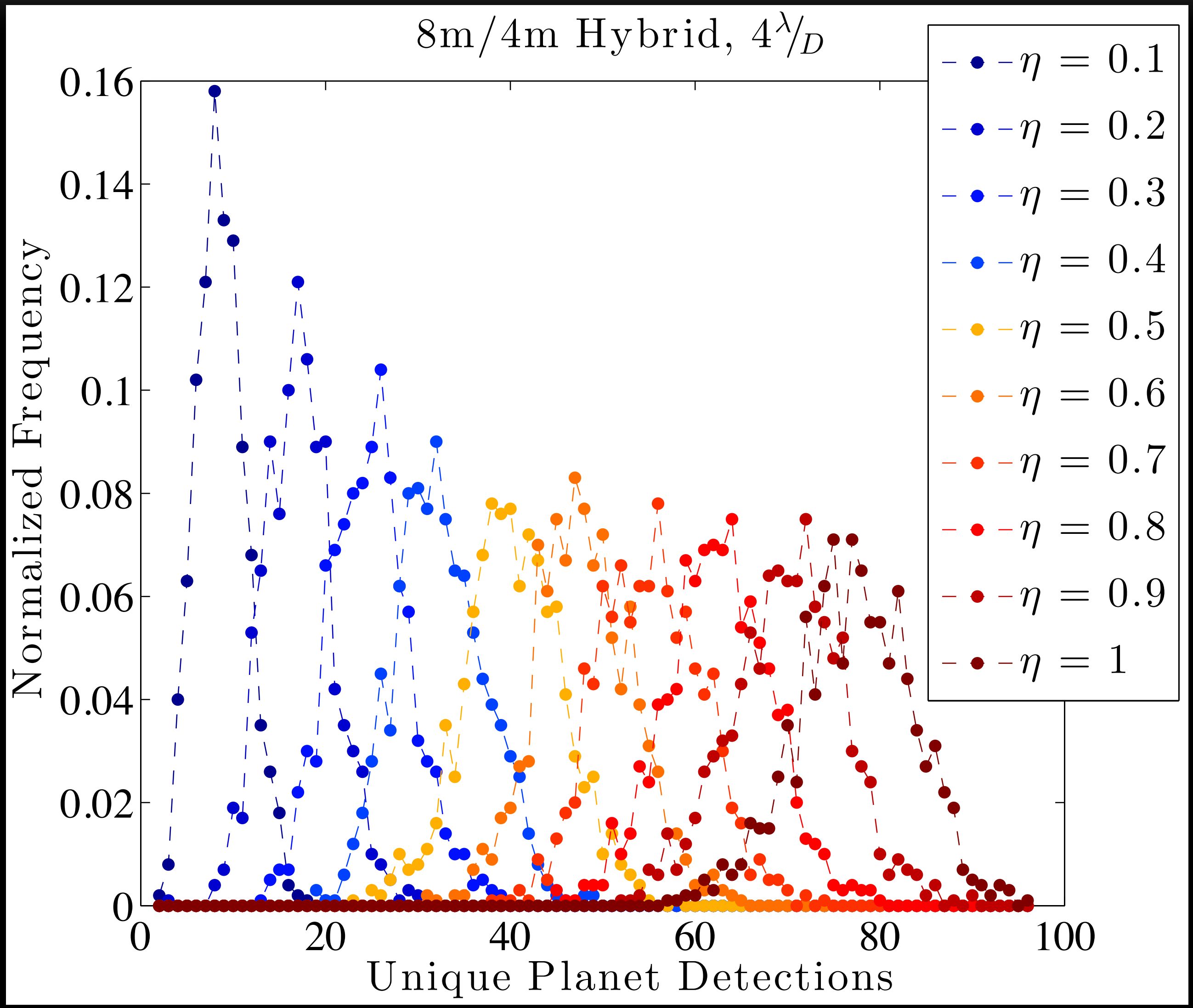


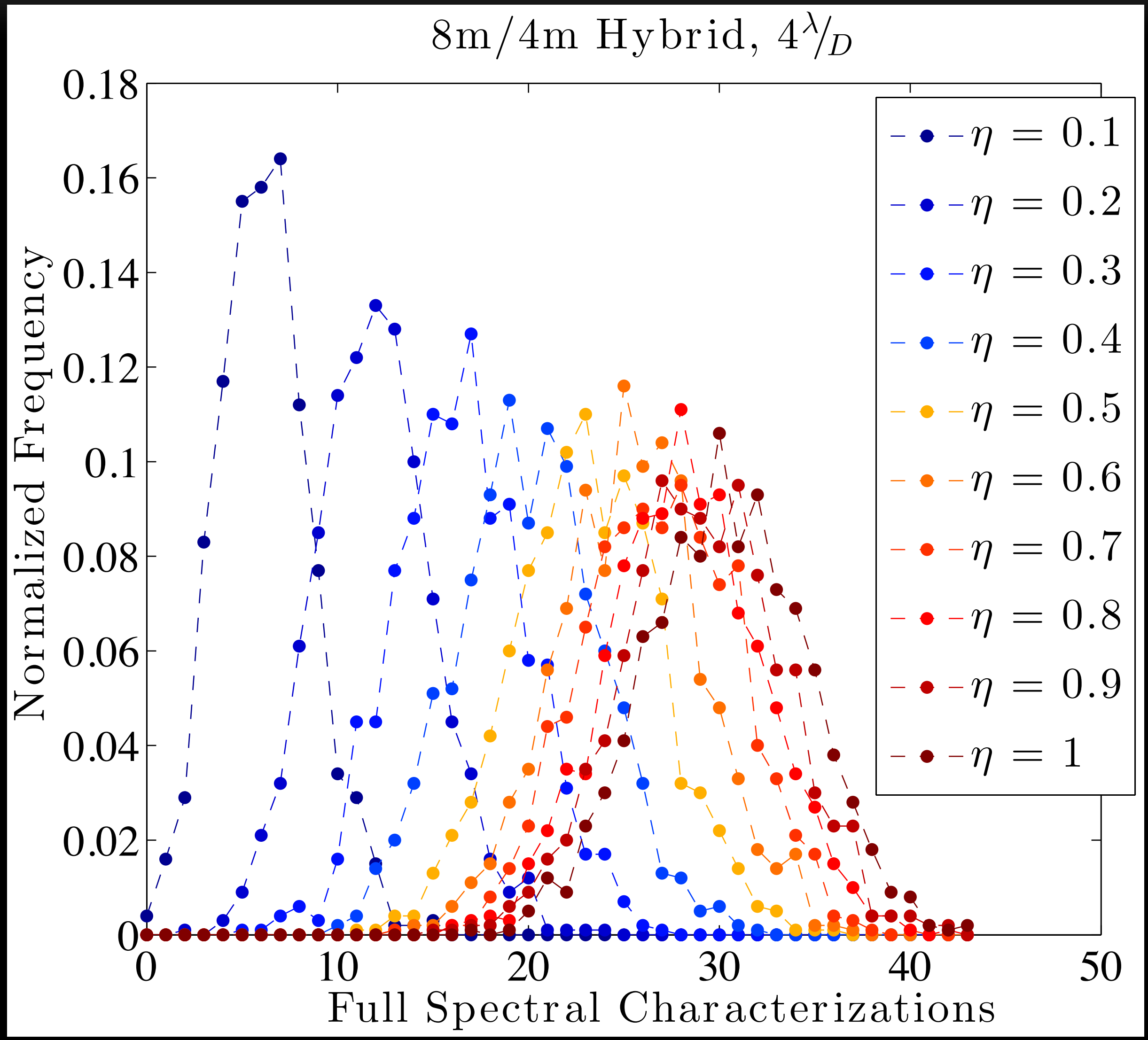
Hybrids with 3 or 4 l/D coronagraph have most full spectra, comparable with 2 l/D coronagraph alone.



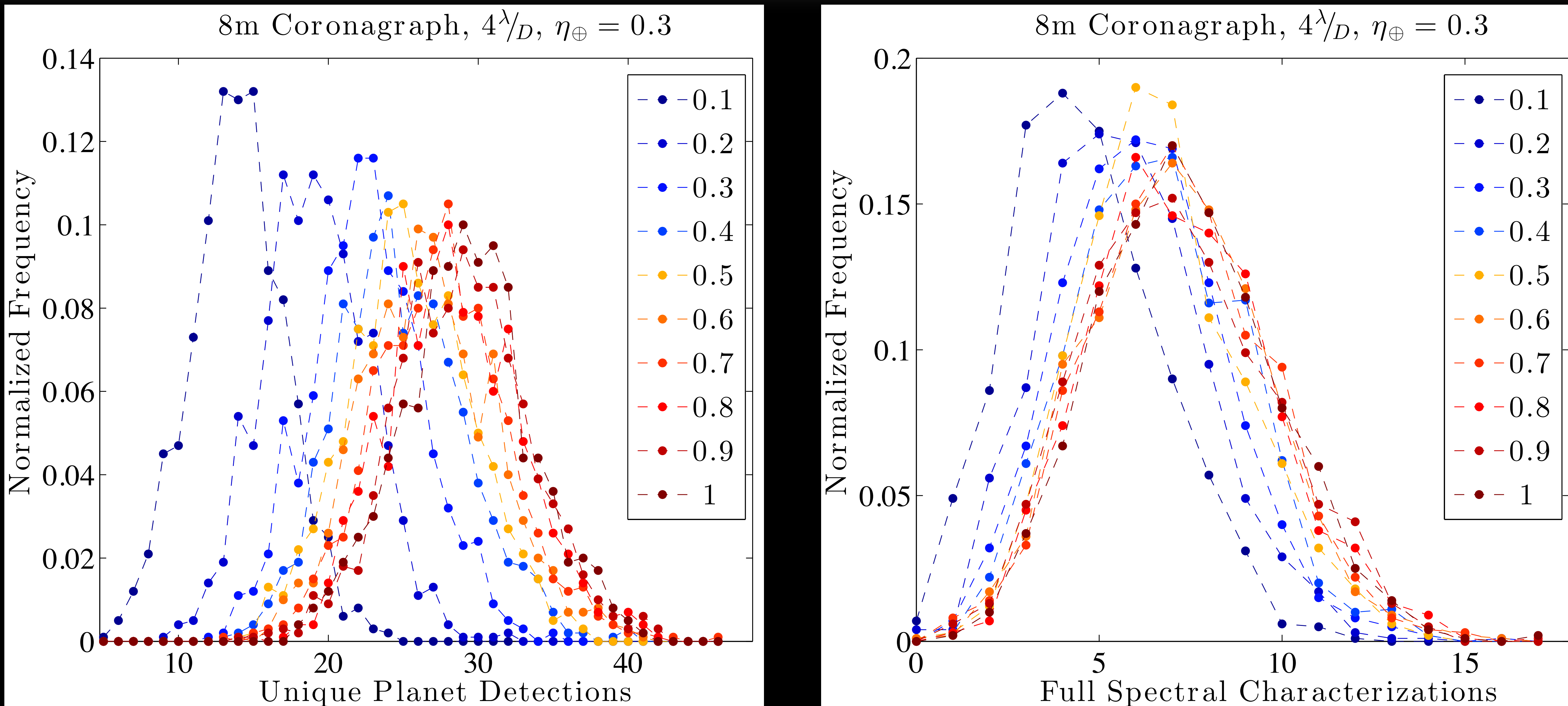


8 m telescope & 4 l/D Coronagraph





8 m telescope, 4 m SDO & 4 l/D Coronagraph



Coronagraph Science vs. Mission Fraction

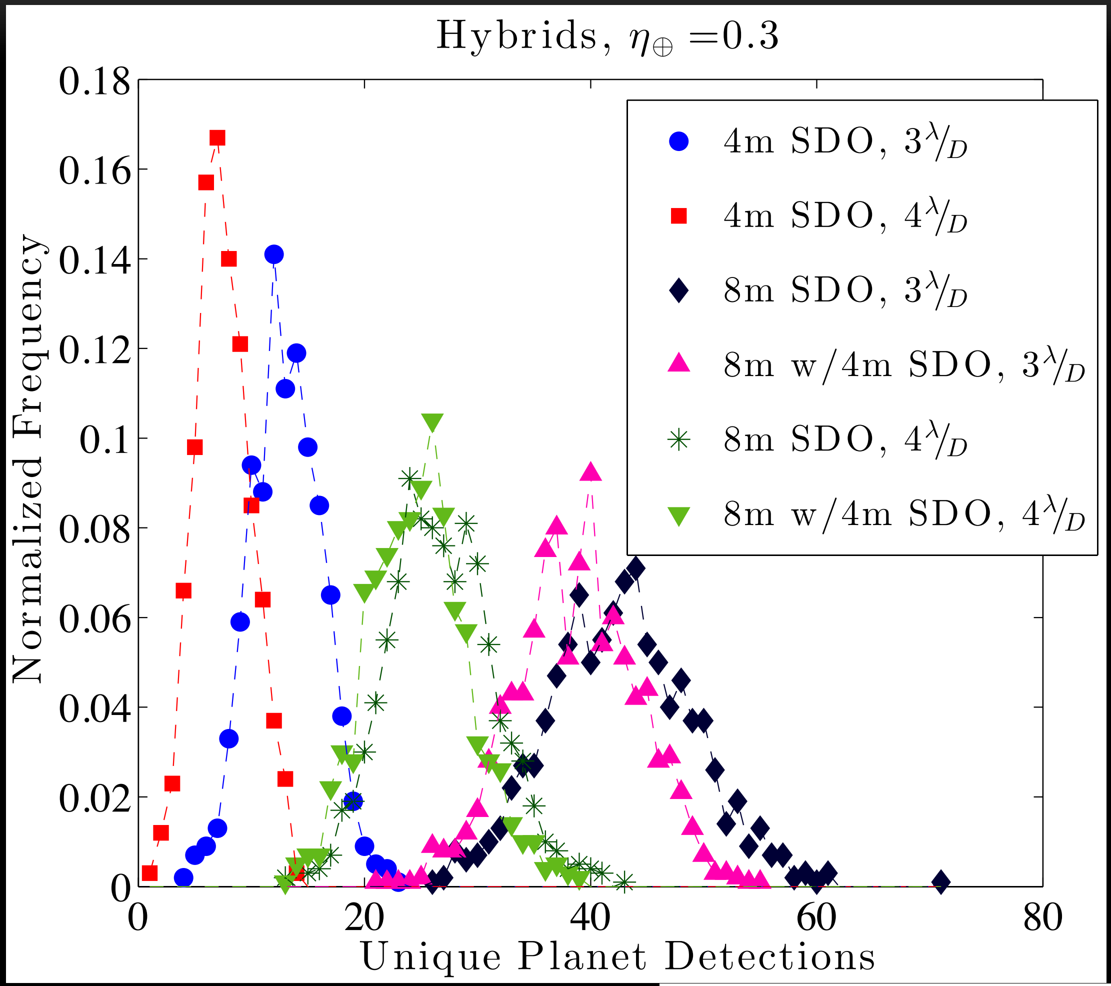
8 m telescope - Observations & Conclusions

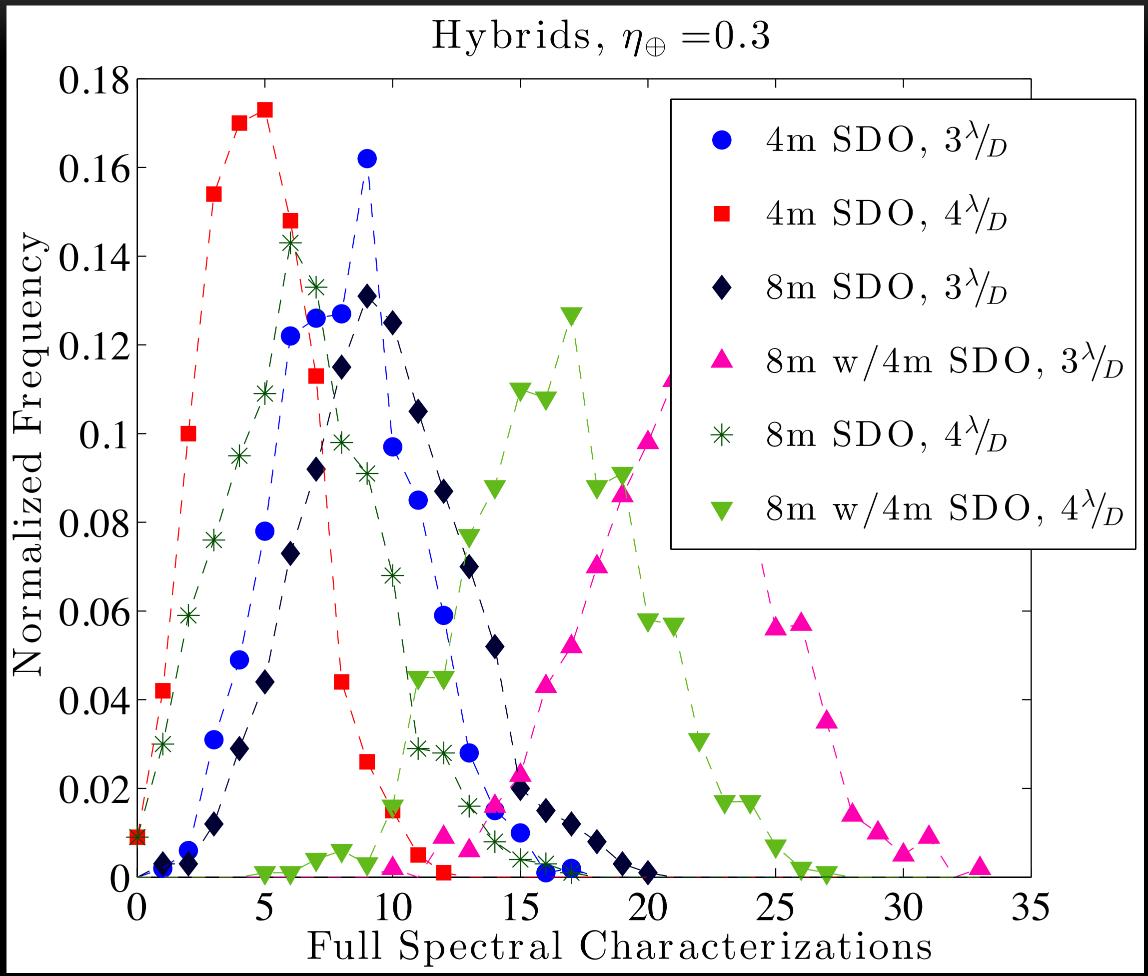
- If coronagraph alone, good science at 4 l/D (TPF-C).
- Similar challenges & requirements as 4 m to operate at 2 or 3 l/D (and perhaps harder to implement).
- SDO or MDO for 8 m provides no advantage over 4 m unless significant increase in thrust is possible.
- If coronagraph is impossible (on-axis), best solution is smaller occulter sized for 4 m telescope.
- Only an occulter will get UV exoplanet science.
- A hybrid recovers larger number of detections (and repeat detections) with more spectra than 4 l/D coronagraph.

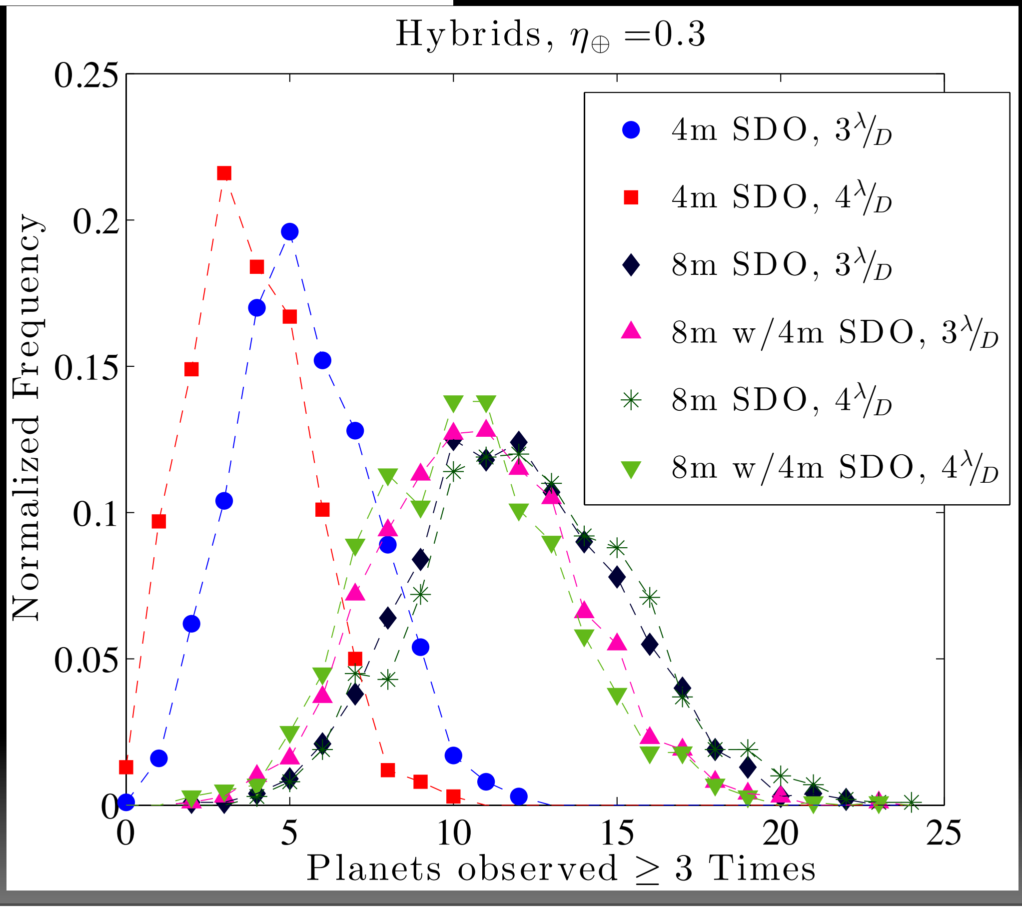
Best solution at this scale is a hybrid of 3 or 4 l/D coronagraph with occulter for 4 m telescope.

If too costly, then 4 l/D coronagraph is second best (though lose UV and some spectra).

If coronagraph is impossible, then single or multiple occulters is only choice (sized for 4 m telescope).


Hybrids, $\eta_\oplus$ =0.3
Normalized Frequency
Unique Planet Detections
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
20
40
60
80
4m SDO, $3\lambda/D$
4m SDO, $4\lambda/D$
8m SDO, $3\lambda/D$
8m w/4m SDO, $3\lambda/D$
8m SDO, $4\lambda/D$
8m w/4m SDO, $4\lambda/D$


Hybrids, $\eta_\oplus$ =0.3
Normalized Frequency
Full Spectral Characterizations
0.18
0.16
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0
5
10
15
20
25
30
35
4m SDO, $3\lambda/D$
4m SDO, $4\lambda/D$
8m SDO, $3\lambda/D$
8m w/4m SDO, $3\lambda/D$
8m SDO, $4\lambda/D$
8m w/4m SDO, $4\lambda/D$


Hybrids, $\eta_\oplus$ =0.3
Normalized Frequency
Planets observed $\geq$ 3 Times
0.25
0.2
0.15
0.1
0.05
0
0
5
10
15
20
25
4m SDO, $3\lambda/D$
4m SDO, $4\lambda/D$
8m SDO, $3\lambda/D$
8m w/4m SDO, $3\lambda/D$
8m SDO, $4\lambda/D$
8m w/4m SDO, $4\lambda/D$

Next Steps

- Analyze performance of multiple occulter missions for comparison. What is comparison of cost and operational complexity?
- Examine sensitivity of telescopes with other coronagraphs (PIAA, shaped pupils, vortex)
- Perform sensitivity studies of 8 m designs and hybrids (update to TPF-C)
- Continue the important TDEM studies to demonstrate feasibility!

Verification and Validation

Occulters

- Lab experiment to verify optical performance and analysis (currently at 4×10^{-10} monochromatic).
- Edge shape and deployment metrology to verify shape and positioning
- Analysis to confirm that measured shape meets suppression requirement.
- Thermal and Dynamic analysis for requirements.
- Thermal vacuum testing with laser metrology to confirm thermal deformations and model (not a technology issue).

Coronagraphs

- Vacuum bench experiments to confirm static corrected contrast (currently at 5×10^{-10} in 10% band).
- Analysis to confirm telescope stability meets suppression requirement.
- Thermal and Dynamic analysis for requirements.
- Thermal vacuum testing to confirm thermal deformations and model.

Coronagraph for on-axis, segmented Telescope?

All of the previous coronagraphs require an off-axis, monolithic telescope.

Many believe an on-axis telescope is preferable at 8 m (though TPF-C was an 8 m, off-axis monolith). Such a telescope would probably also include a segmented primary.

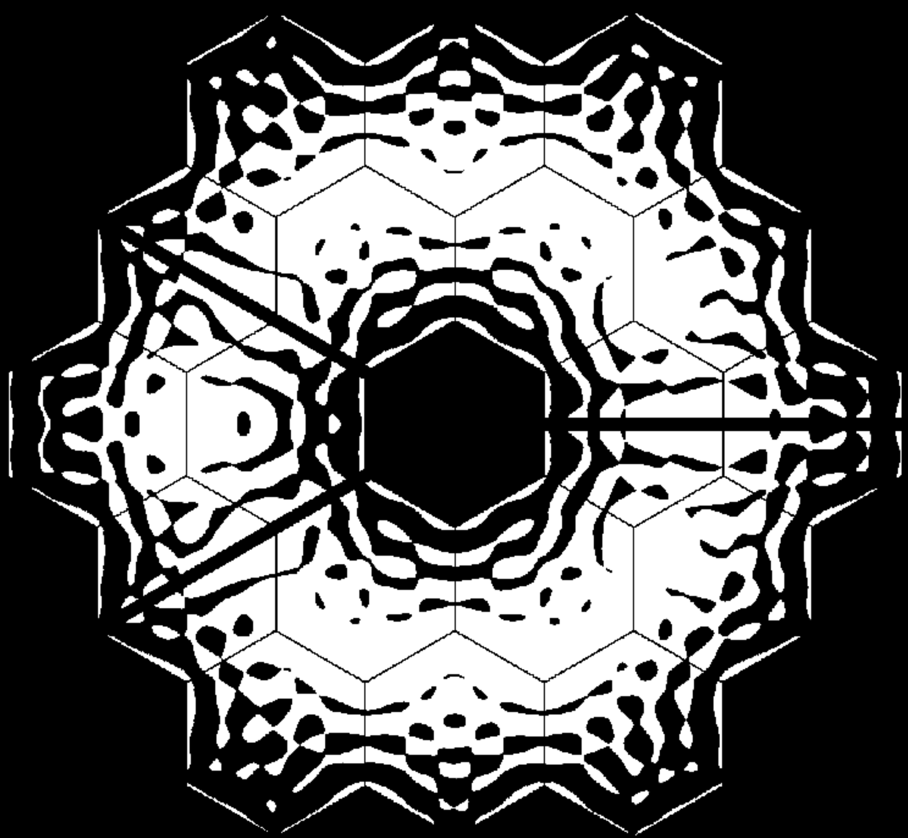
Recent results at Princeton in 2D optimization have pointed to the real possibility of on-axis and segmented telescopes with shaped pupil coronagraphs.

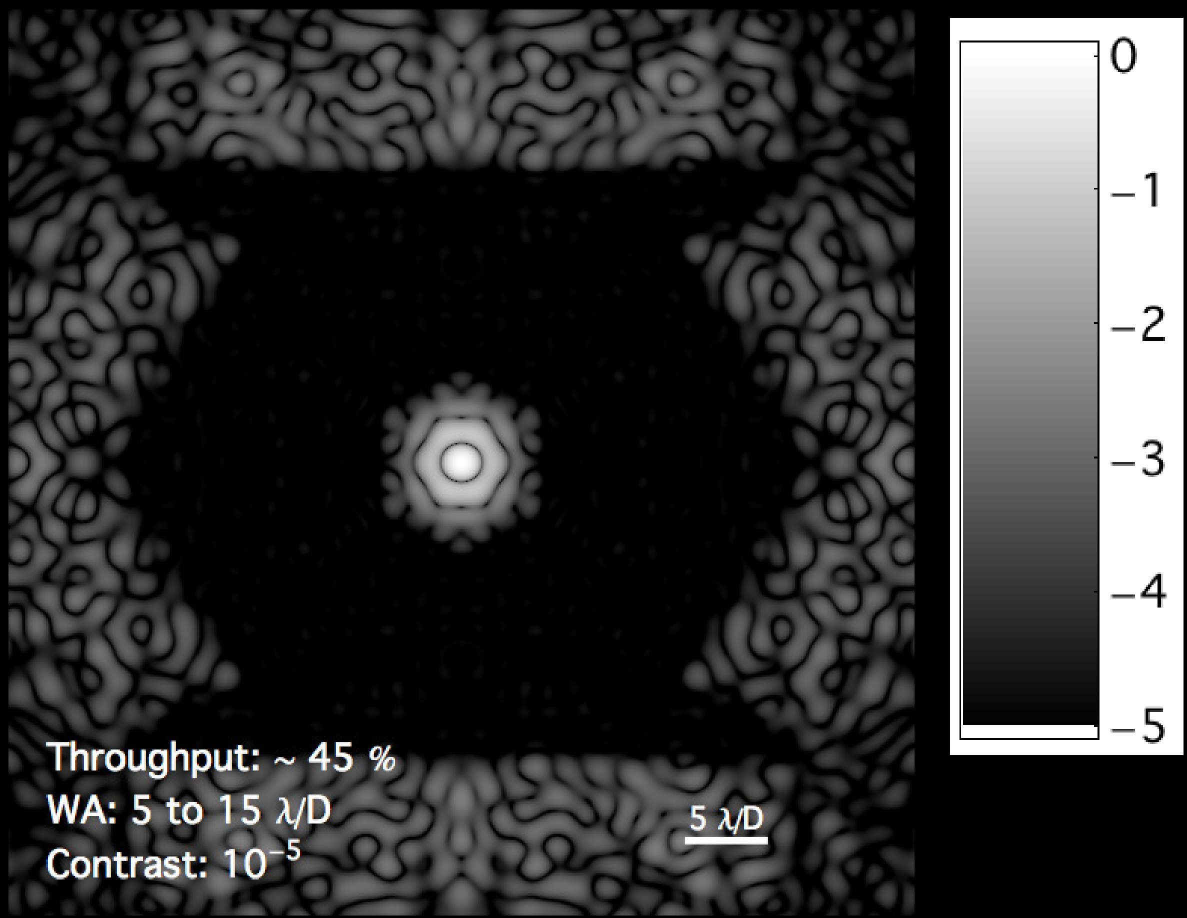
A recently awarded TDEM under PI Rémi Soummer will study on-axis and segmented coronagraphs.

We should not rule out the possibility of a coronagraph for an on-axis and/or segemented telescope!

Segmented Mirror – JWST

Carlotti, Vanderbei, Kasdin, Optics Express, Dec. 2011





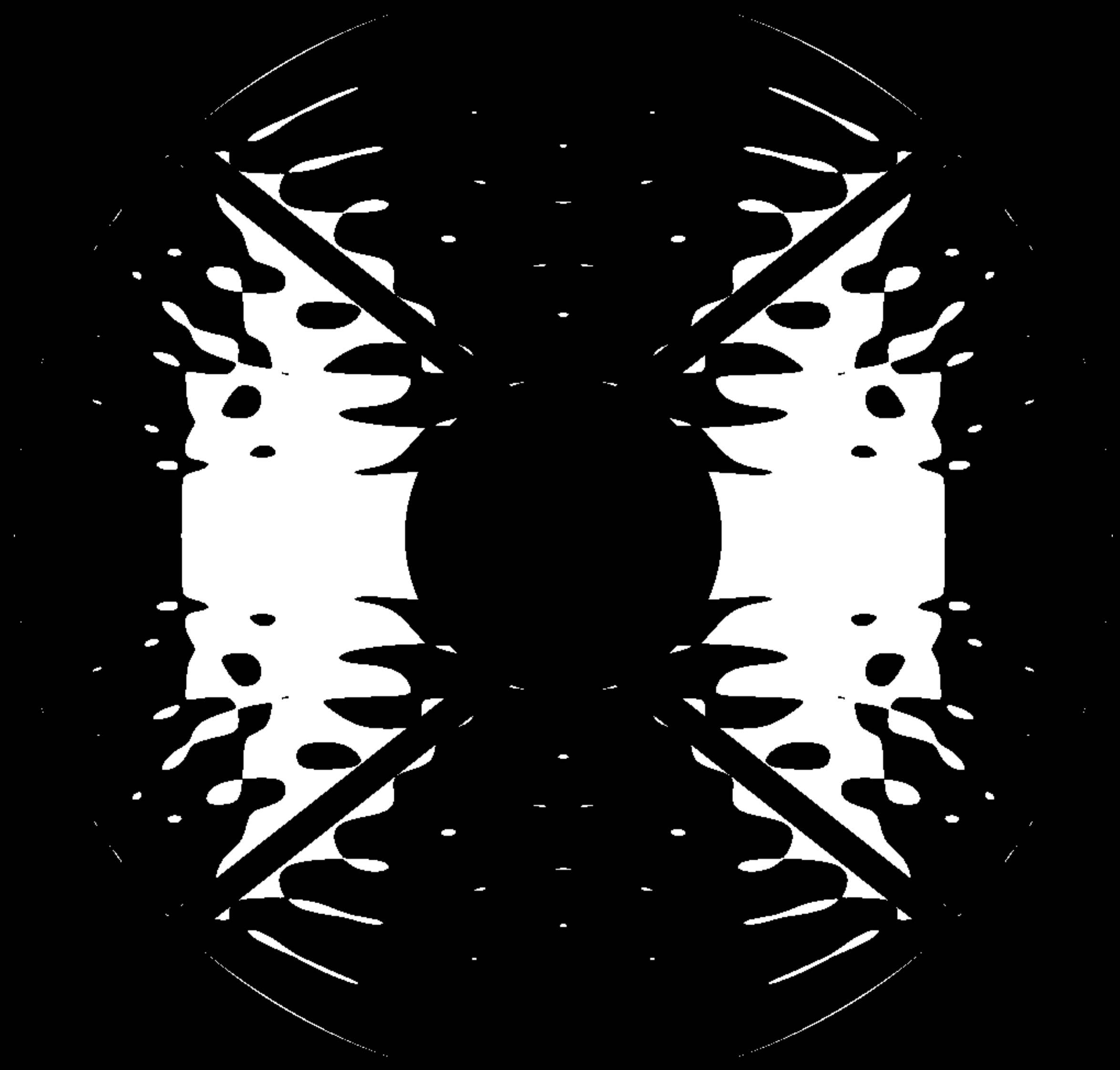
JWST

45% Throughput

5 to 15 lambda/D

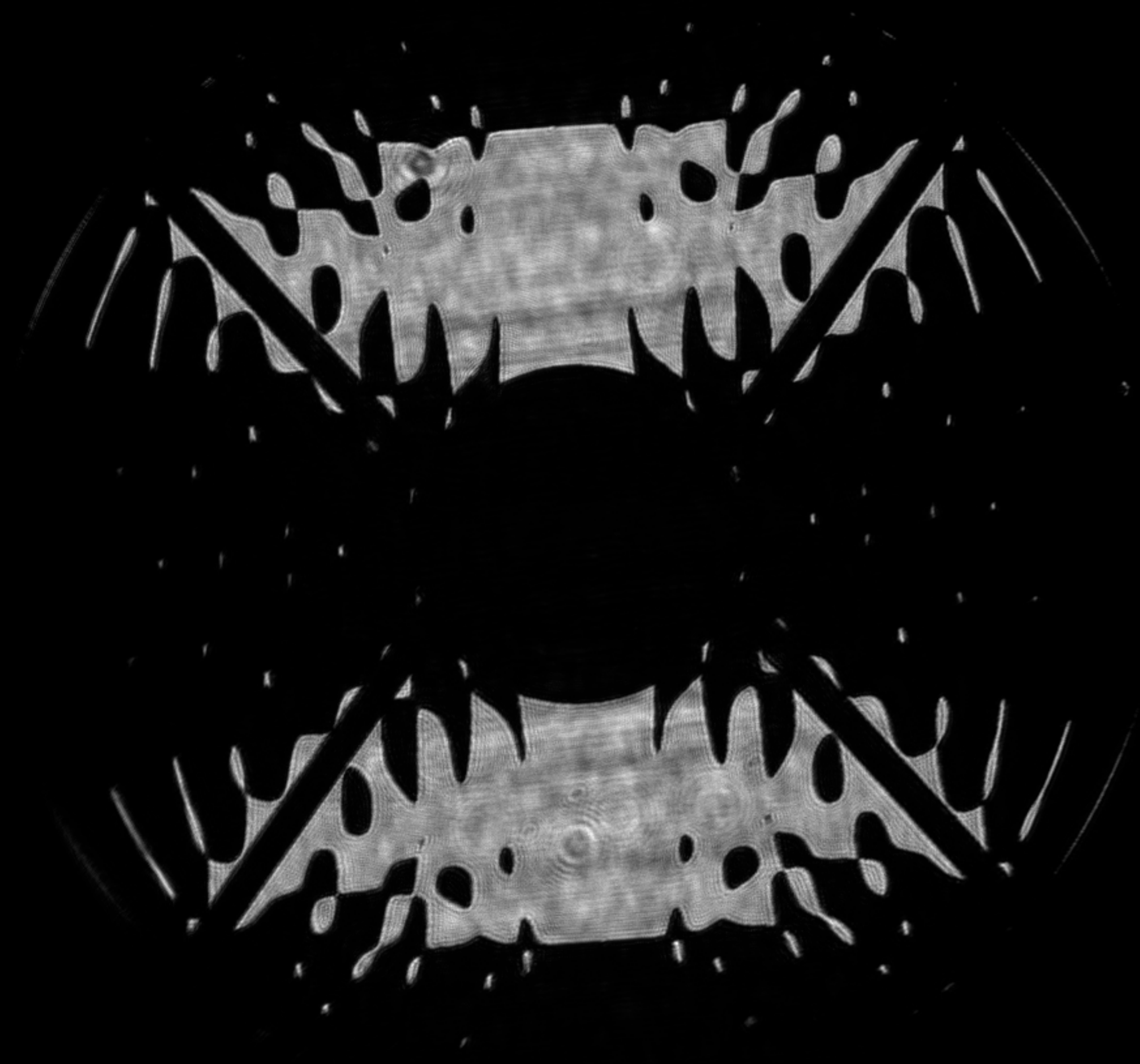
10^{-5} Contrast

First Lab Results–A Mask for Subaru



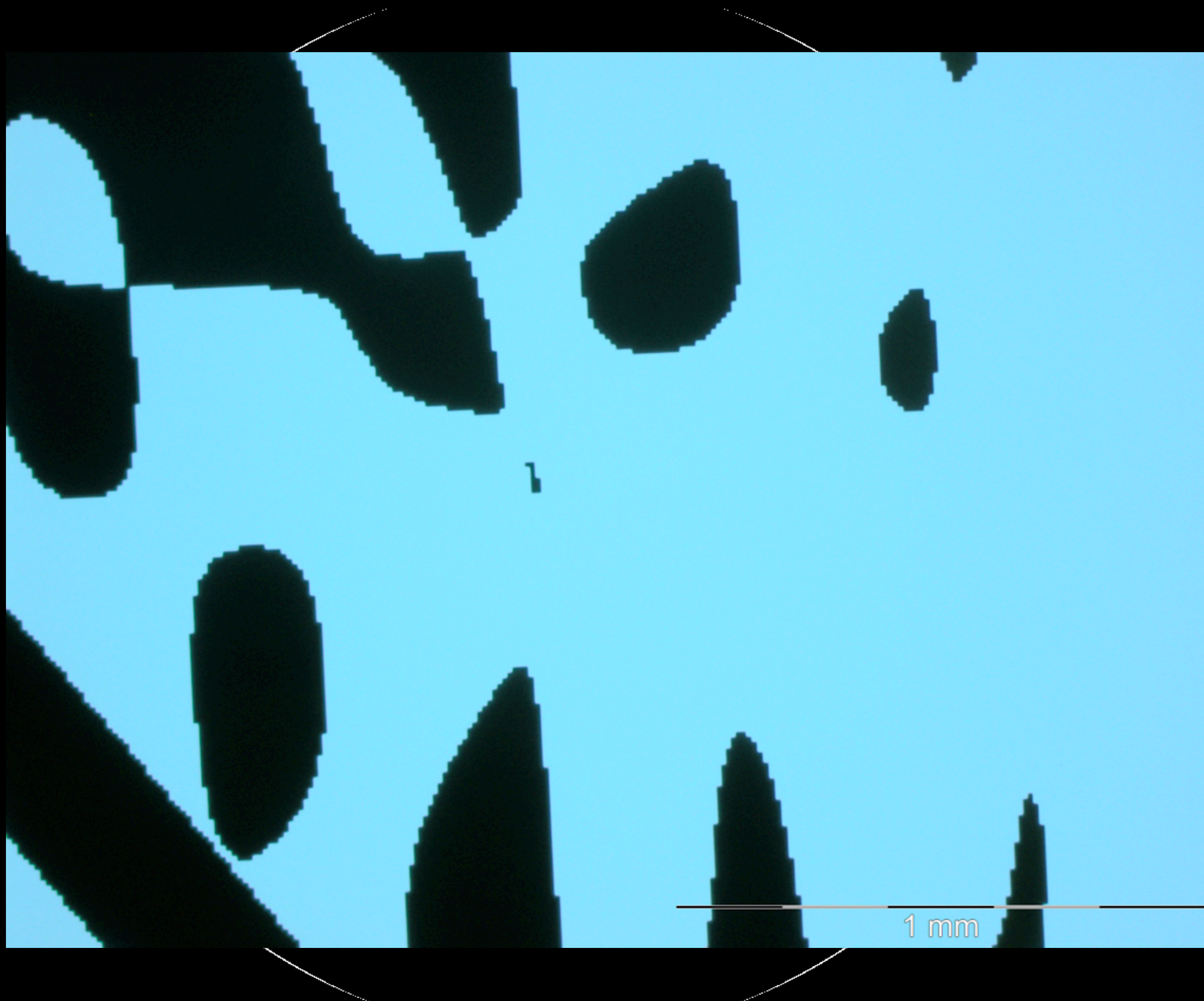
Numerically Designed Mask

10^{-7} Contrast, 25% throughput
dark hole from 3 to 16 lambda/D

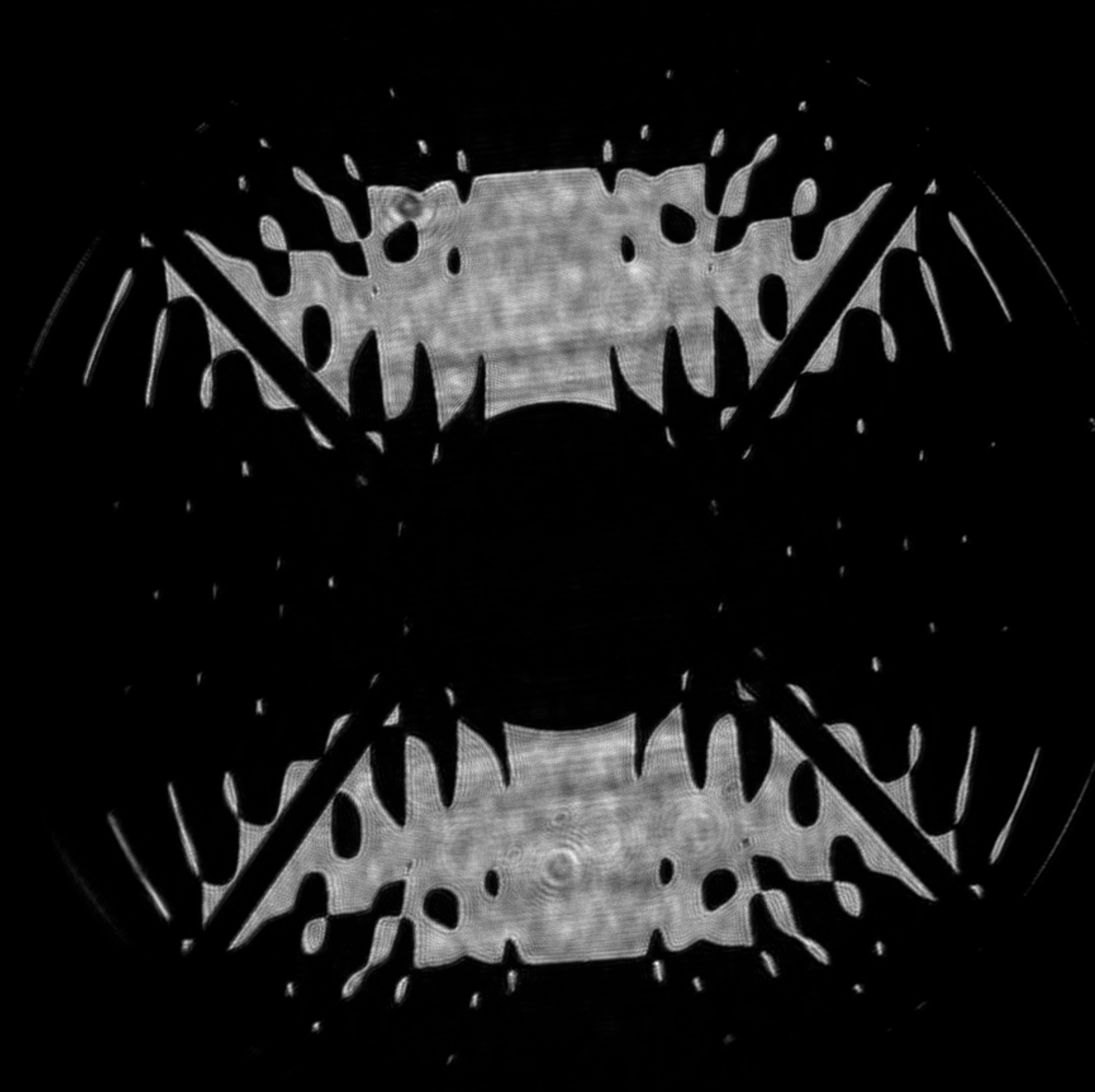


Experimental Pupil Image

First Lab Results–A Mask for Subaru



Microscope Image



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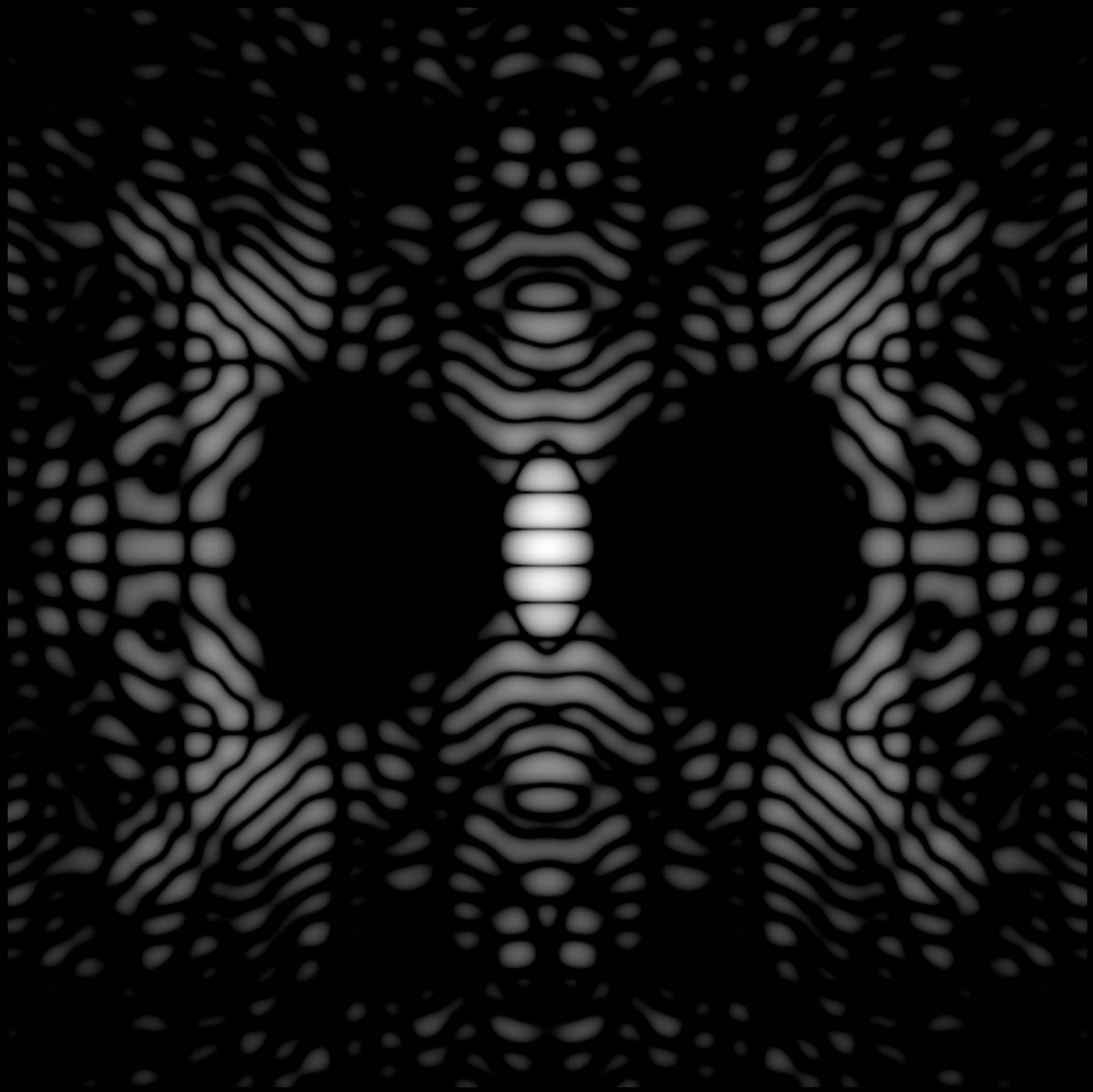
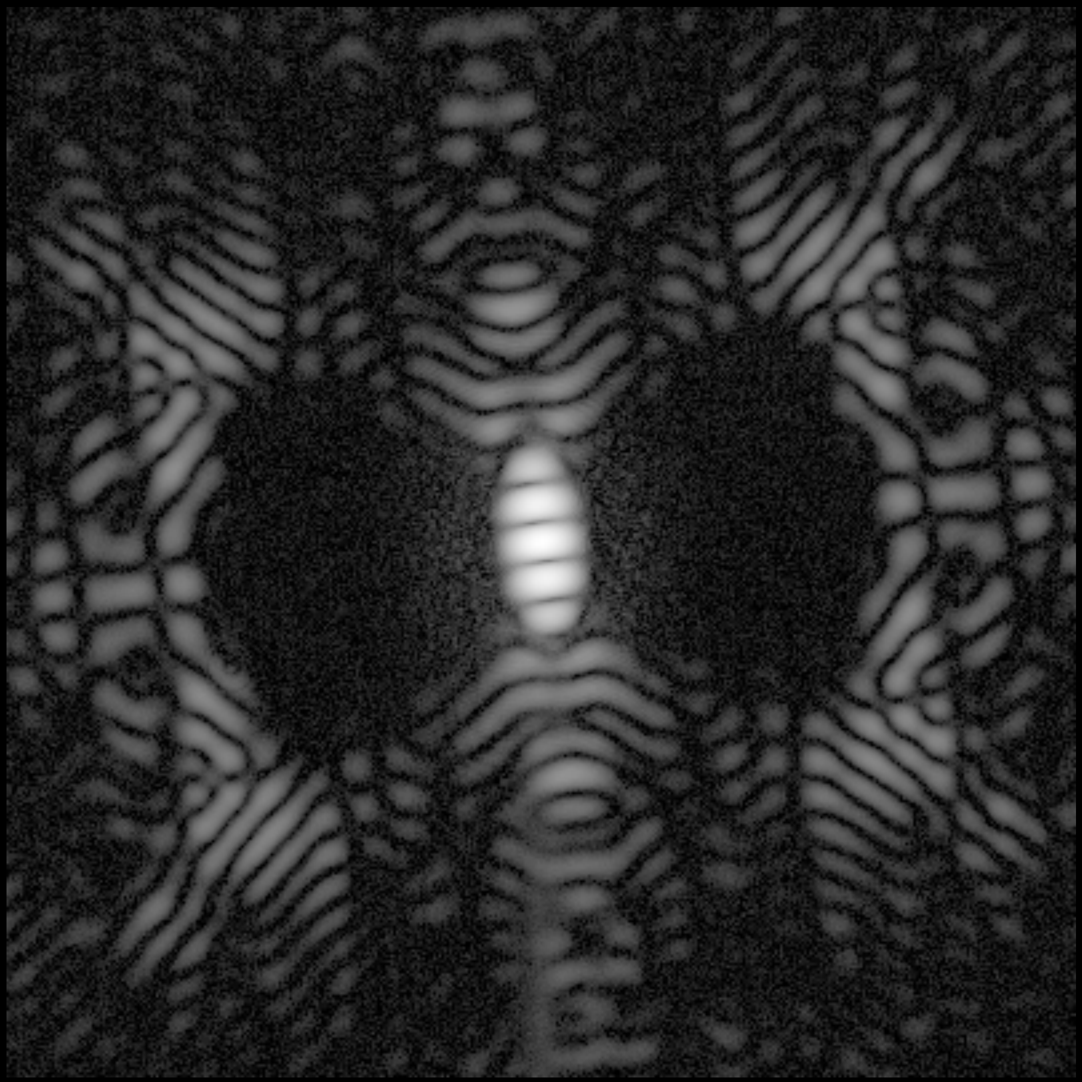


Theoretical PSF



Experimental PSF

10^{-7} dark hole
3-16 lambda/D

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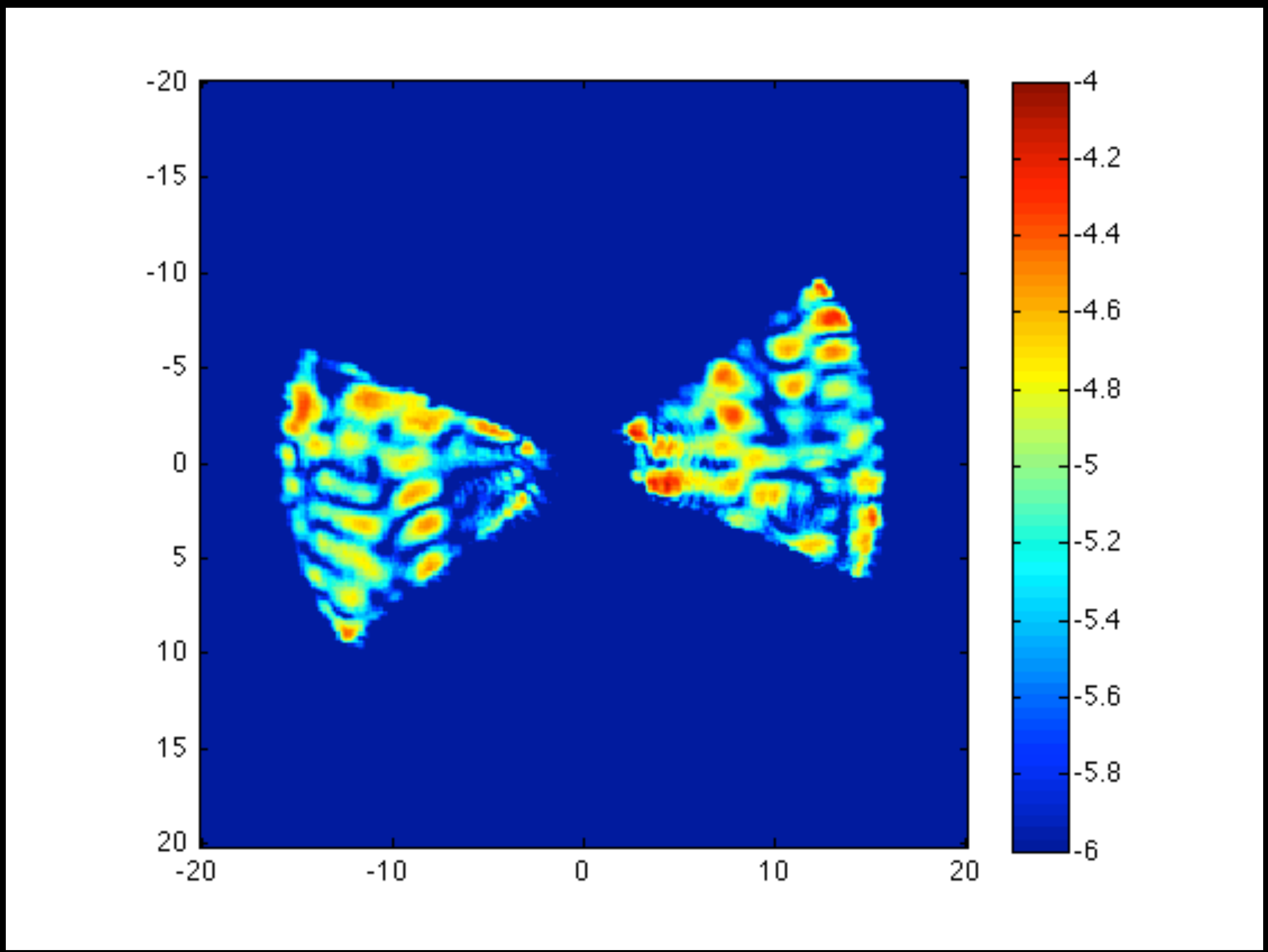

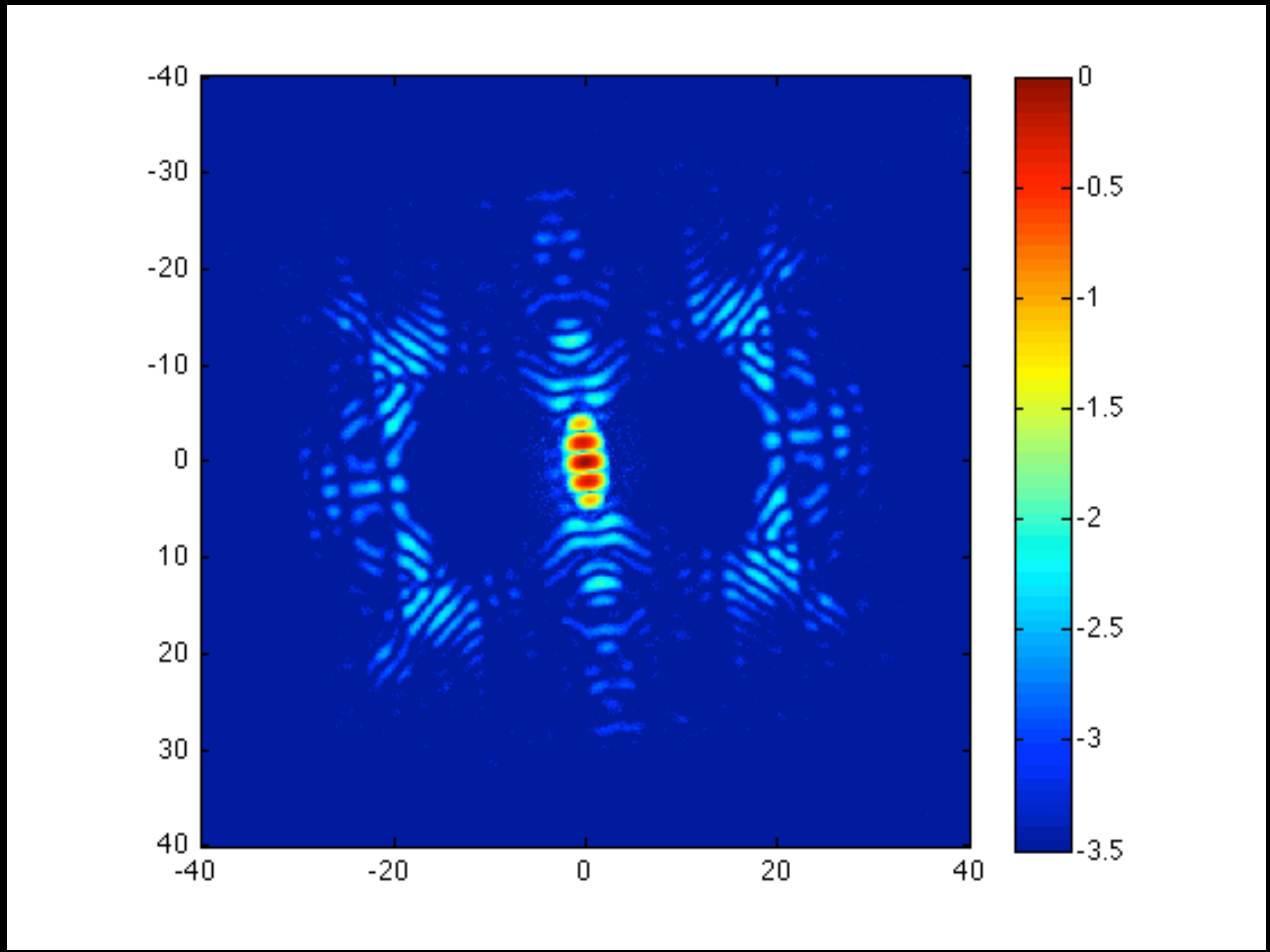

Average Contrast 10^{-5}