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Apodized/Shaped Pupil Lyot Coronagraph designs for segmented apertures

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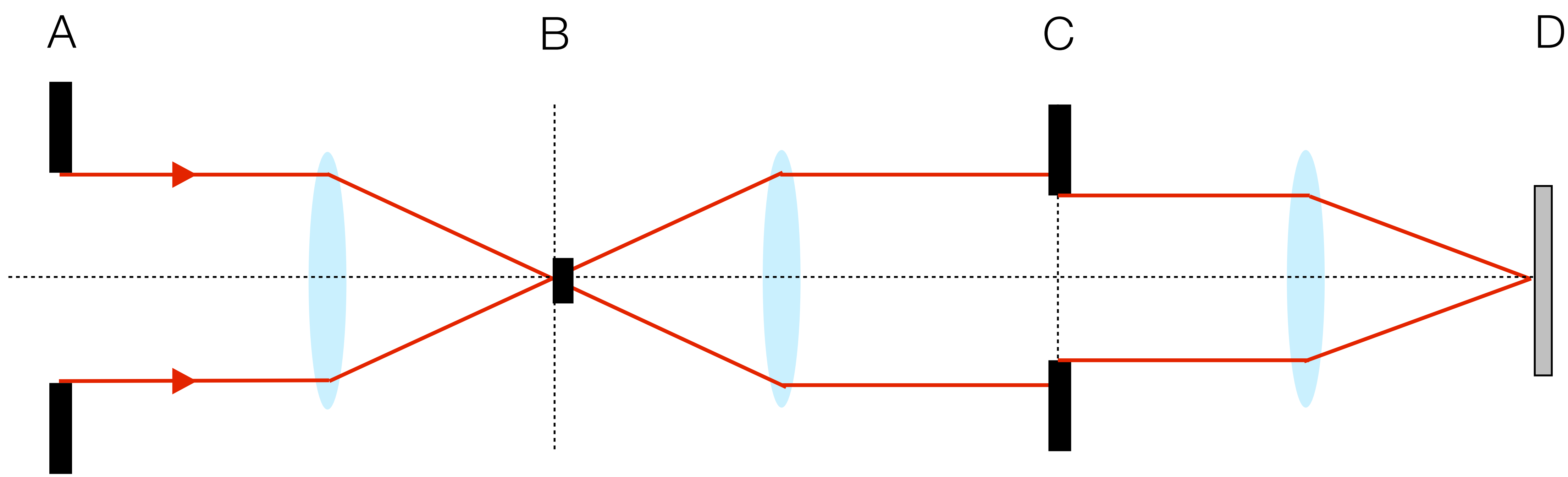
Lyot coronagraph: formalism



Lyot plane field amplitude

$$\Psi_C(\mathbf{r}) = \Psi_A(\mathbf{r}) - \left(\Psi_A(\mathbf{r}) * \widehat{M}(\mathbf{r})\right) P(\mathbf{r})$$

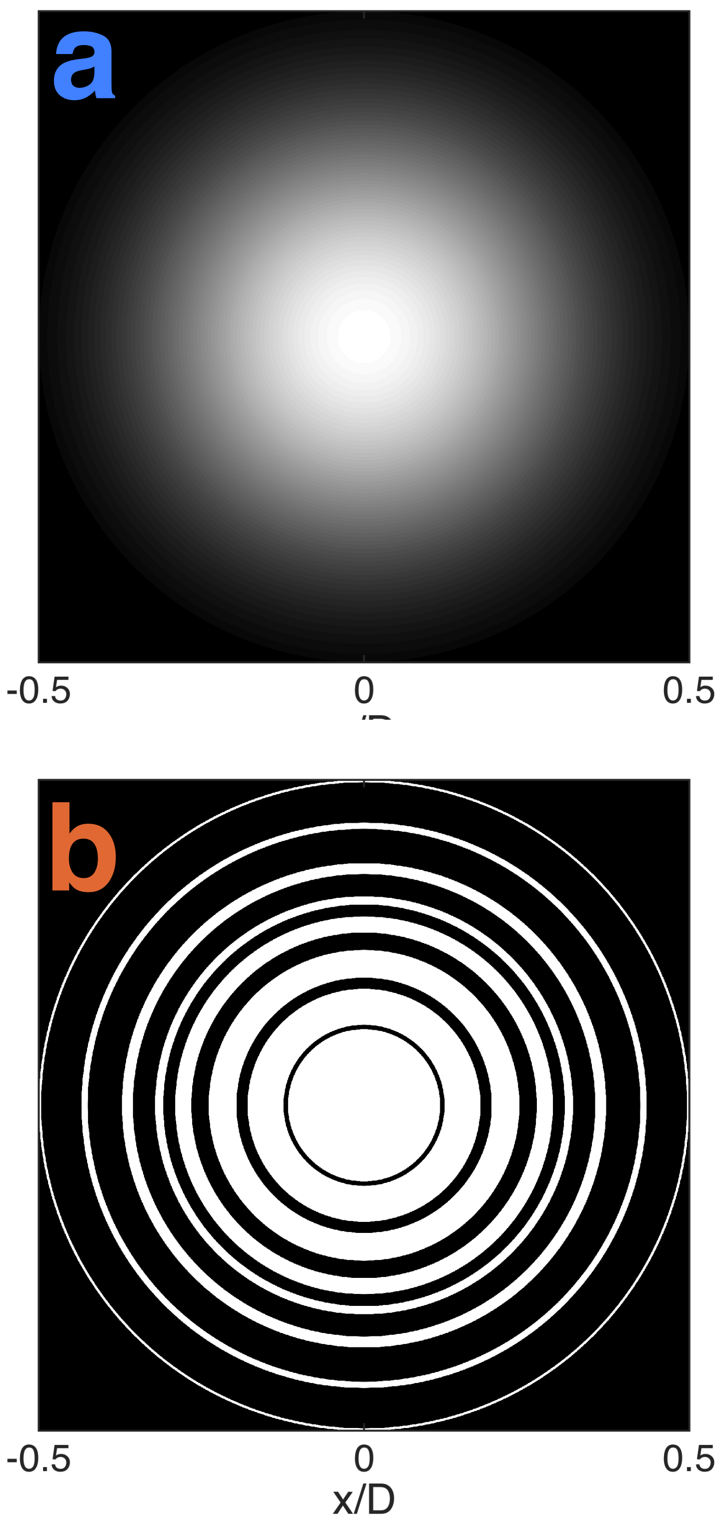
Pupil amplitude

Diffracted wave by the mask

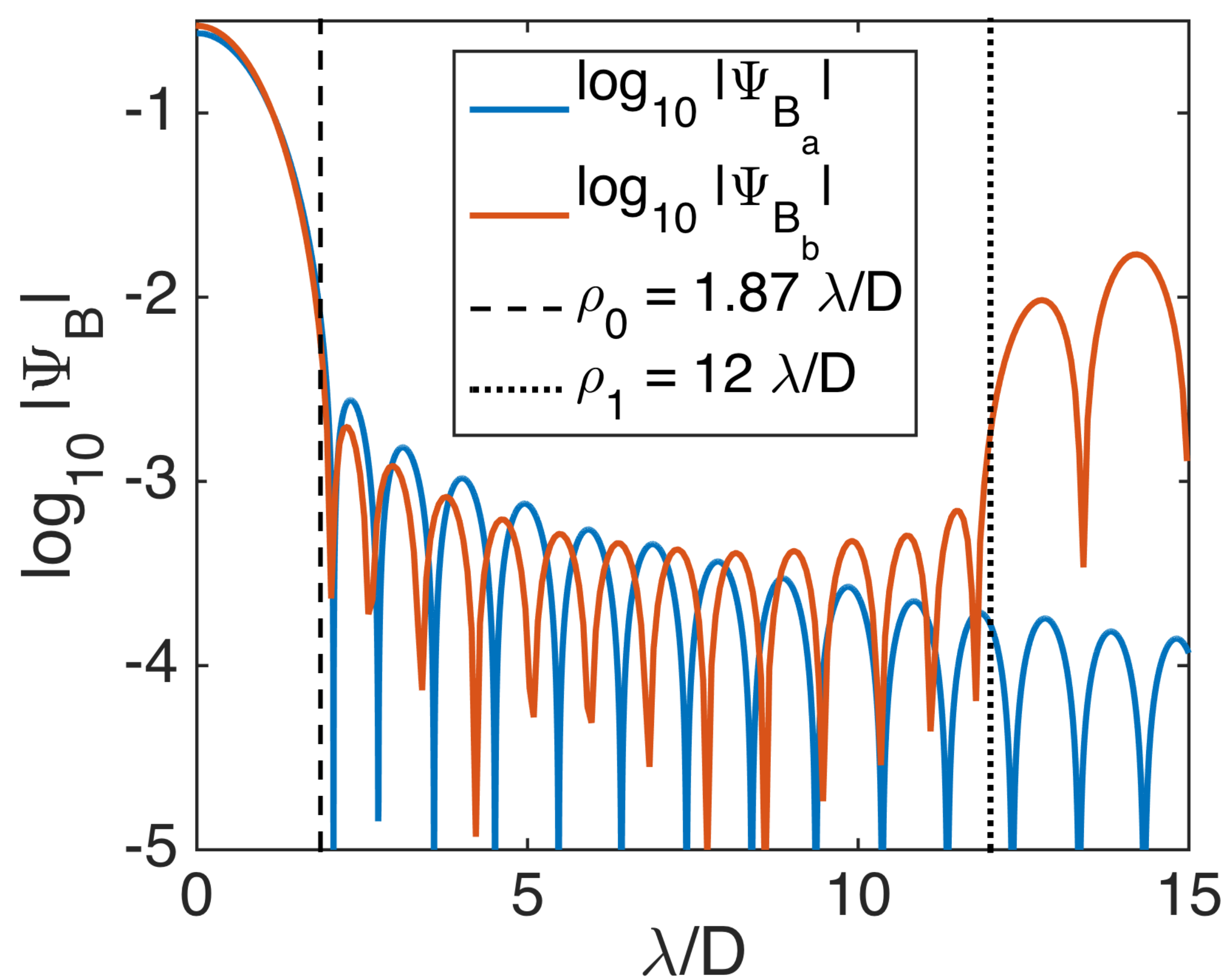
Perfect on-axis star image cancellation if both terms match.
How to match them?

Sivaramakrishnan et al. 2001

Shaped pupil

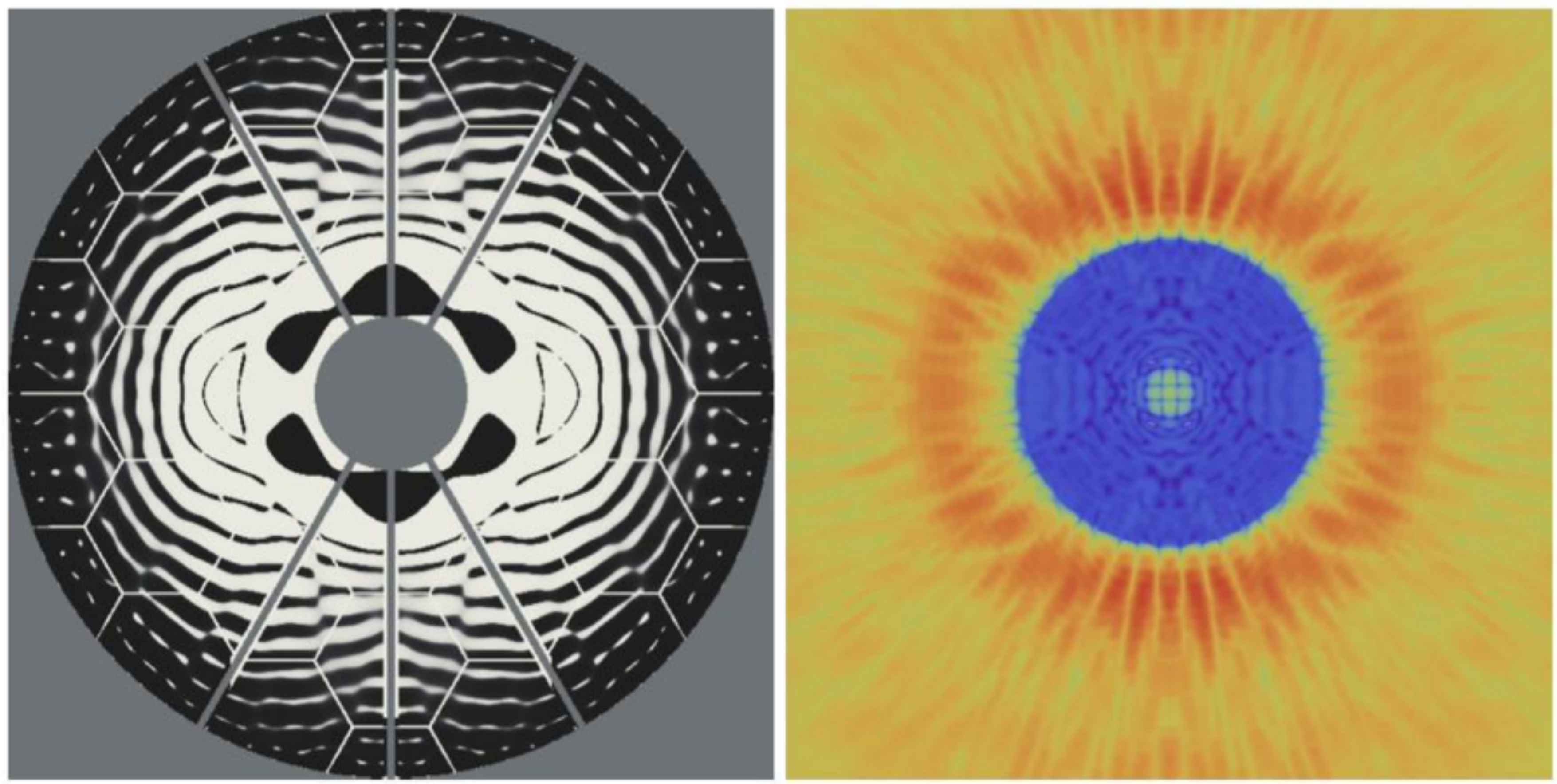


A shaped pupil can mimic the PSF of a graded prolate spheroidal apodizer



Zimmerman et al., J. Astron. Telesc. Instrum. Syst. 2(1), 011012 (2016)

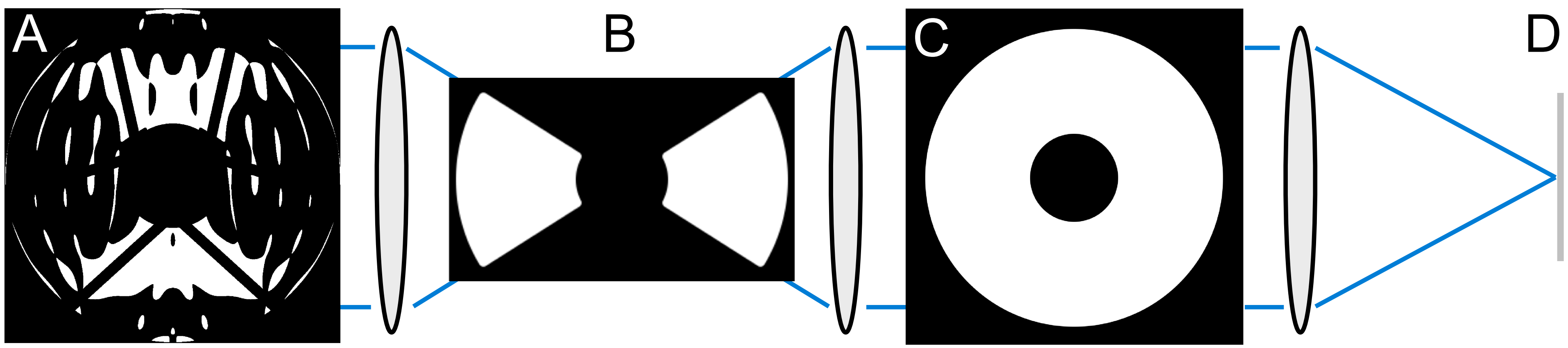
Hybrid shaped pupil / APLC design approach

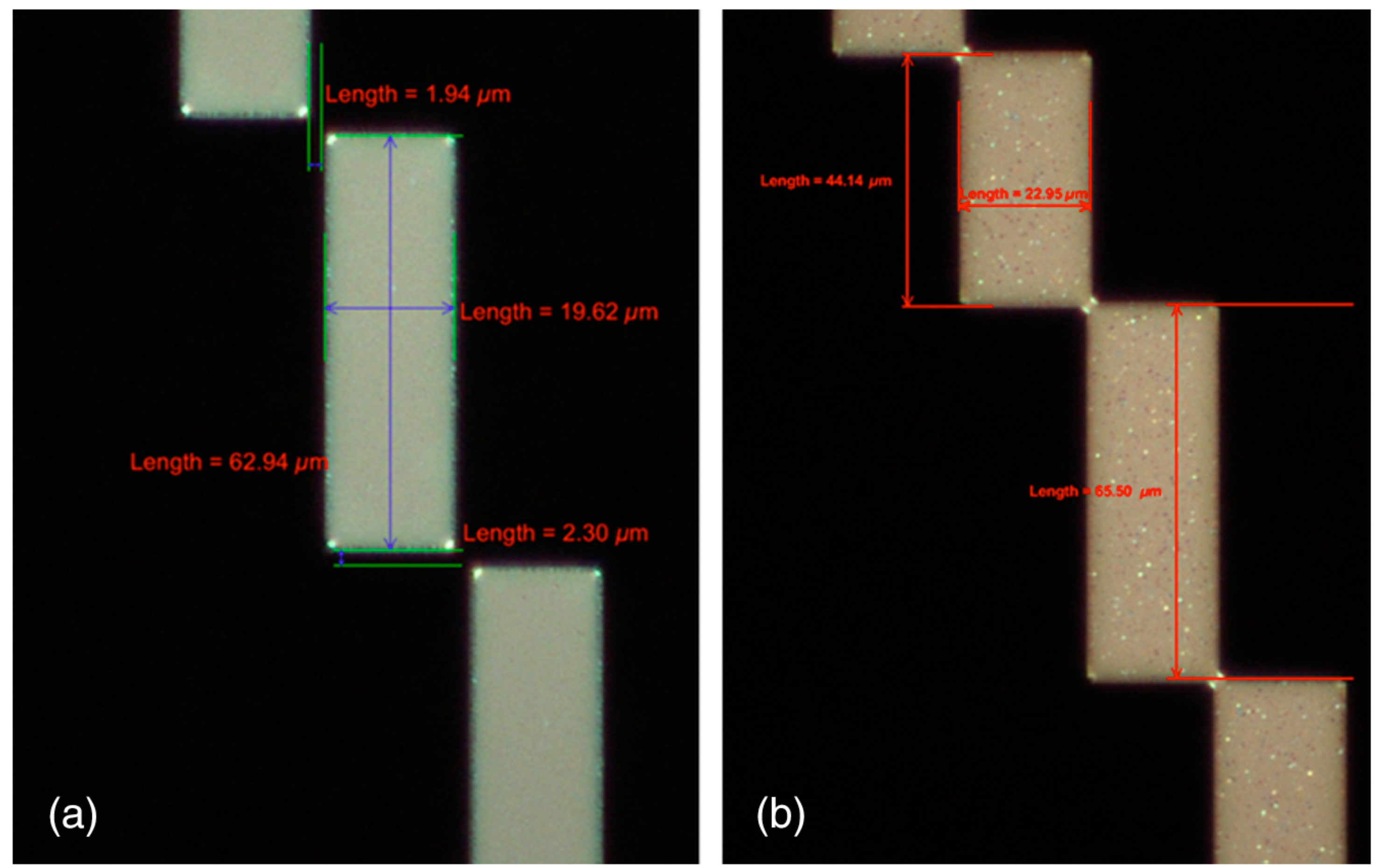


- Proof of concept for a segmented APLC design using a shaped pupil apodizer reaching 1E-10 contrast
- 10% bandwidth, Airy throughput 20%
- Built-in tolerance to pointing errors/stellar diameter

N’Diaye et al, ApJ 818, 163 (2016)

Shaped pupil Lyot coronagraph for WFIRST





Balasubramian et al., J. Astron. Telesc. Instrum. Syst. 2(1), 011005 (2015)

Design survey strategy

1. Build toolkit on top of existing optimization code (linear programs in AMPL+Gurobi)

2. Automate the creation, execution, and harvesting of optimizations.

3. Test many parameter combinations by running on NASA's *NCCS Discover* supercomputer

4. Standard PSF products (including finite star response and off-axis PSFs) fed to Stark DRM code for yield evaluation

Summary of design surveys

- April 2016: 504 designs, hexagonal apertures only
- August 2016: 3100 designs, all apertures

- Fixed parameters: 1E-10 contrast, quarter-plane pupil symmetry, thin (2.5 cm) secondary struts, outer working angle 10 λ/D

- Varied parameters:

1. Aperture segmentation
2. Focal plane mask radius (2.5–4.0 λ/D)
3. Lyot stop inner and outer diameter
4. Bandwidth: 10% and 15%

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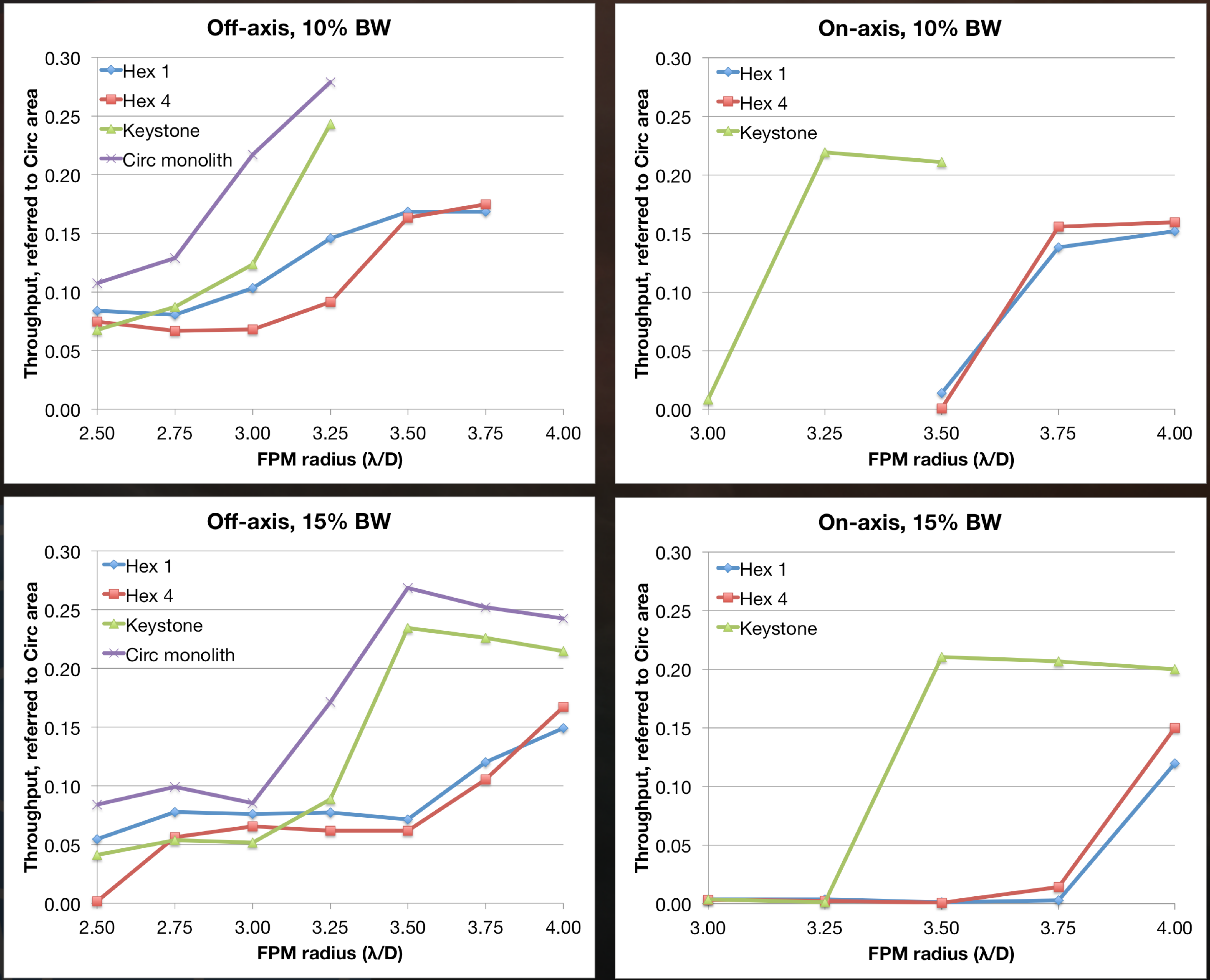
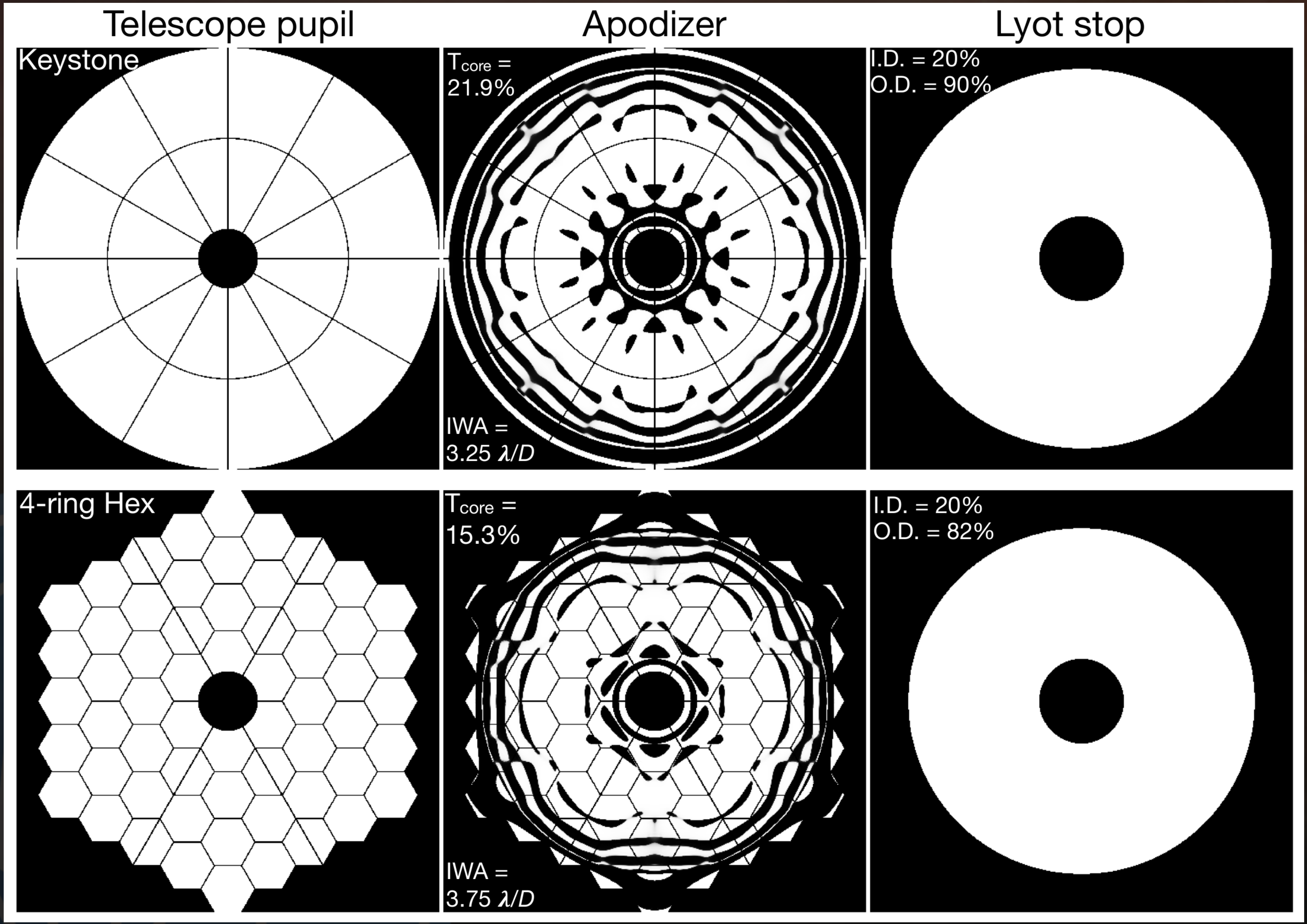
- Nov 2016: Deep surveys on select apertures over FPM size, Lyot stop dimensions, and contrast level

August survey results: Throughput vs IWA



August survey results: Max yield designs



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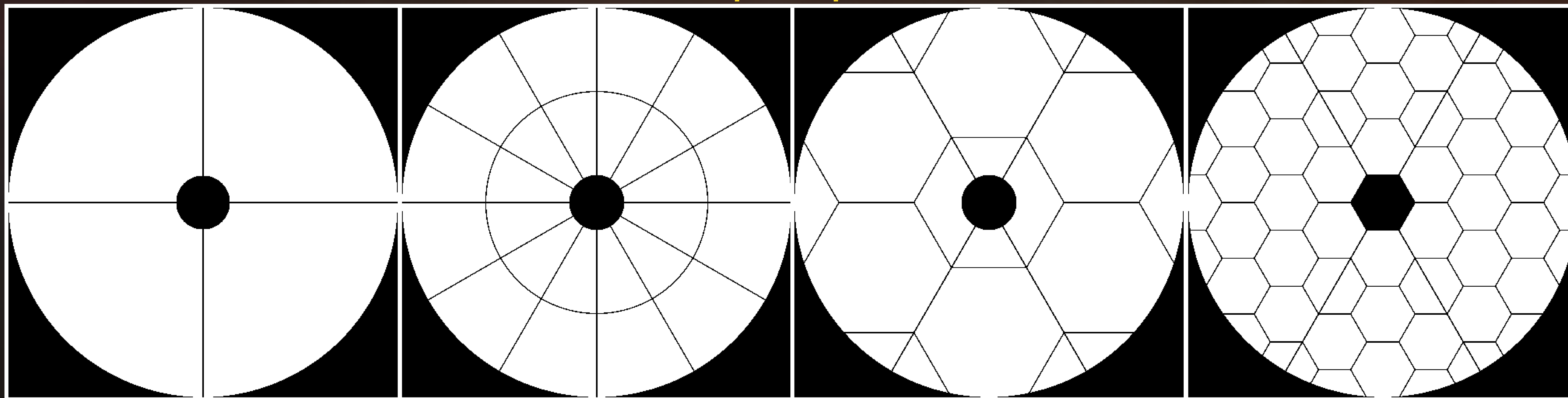
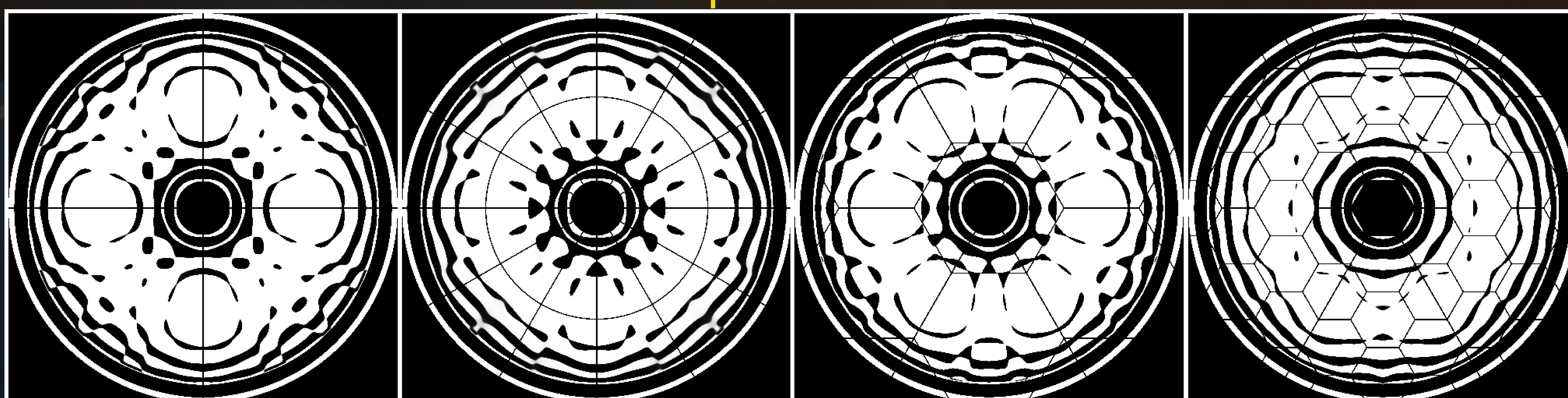
Aperture modification: hexagonal segments with “filled in” perimeter

Telescope apertures

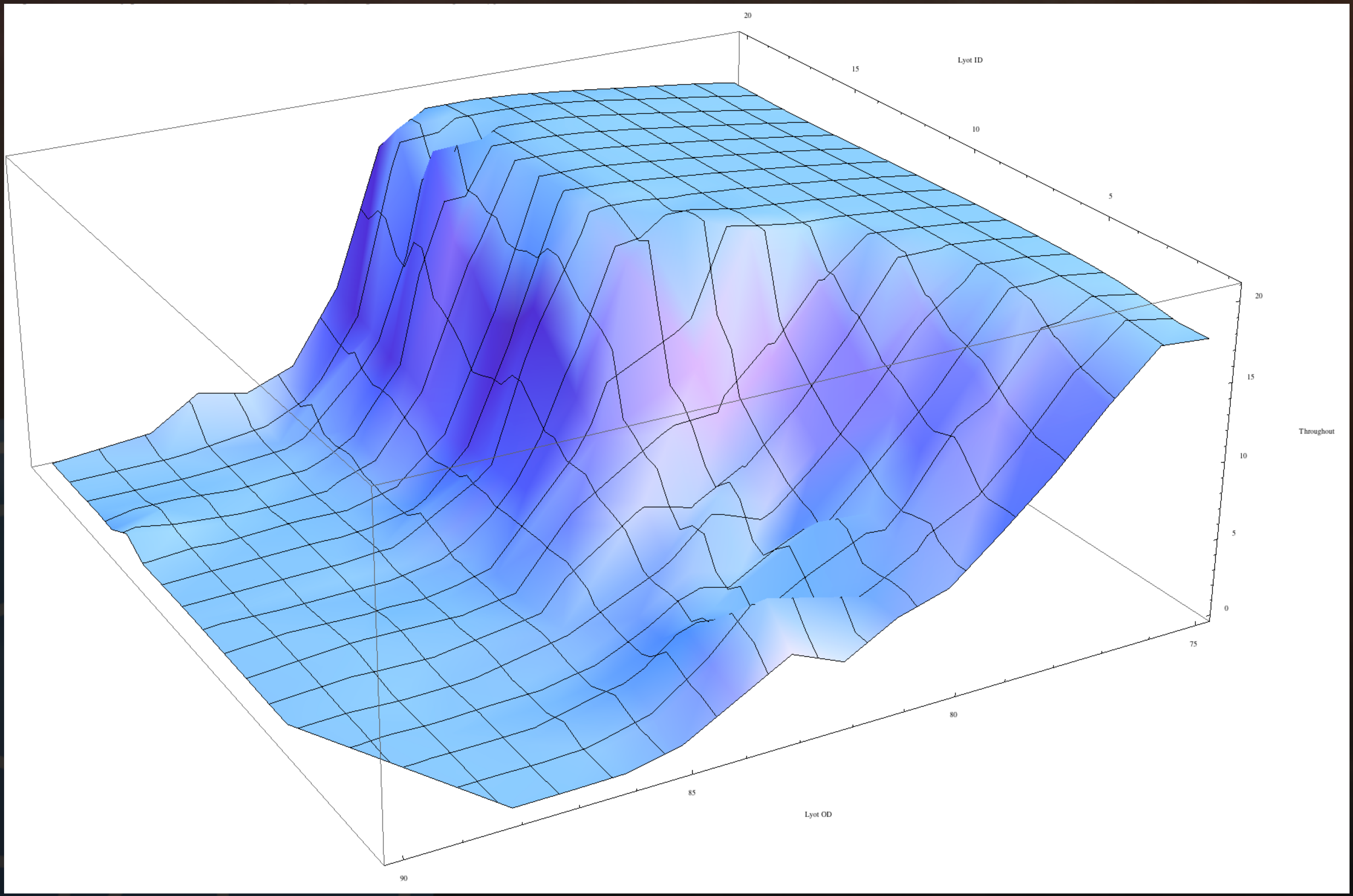


Apodizers



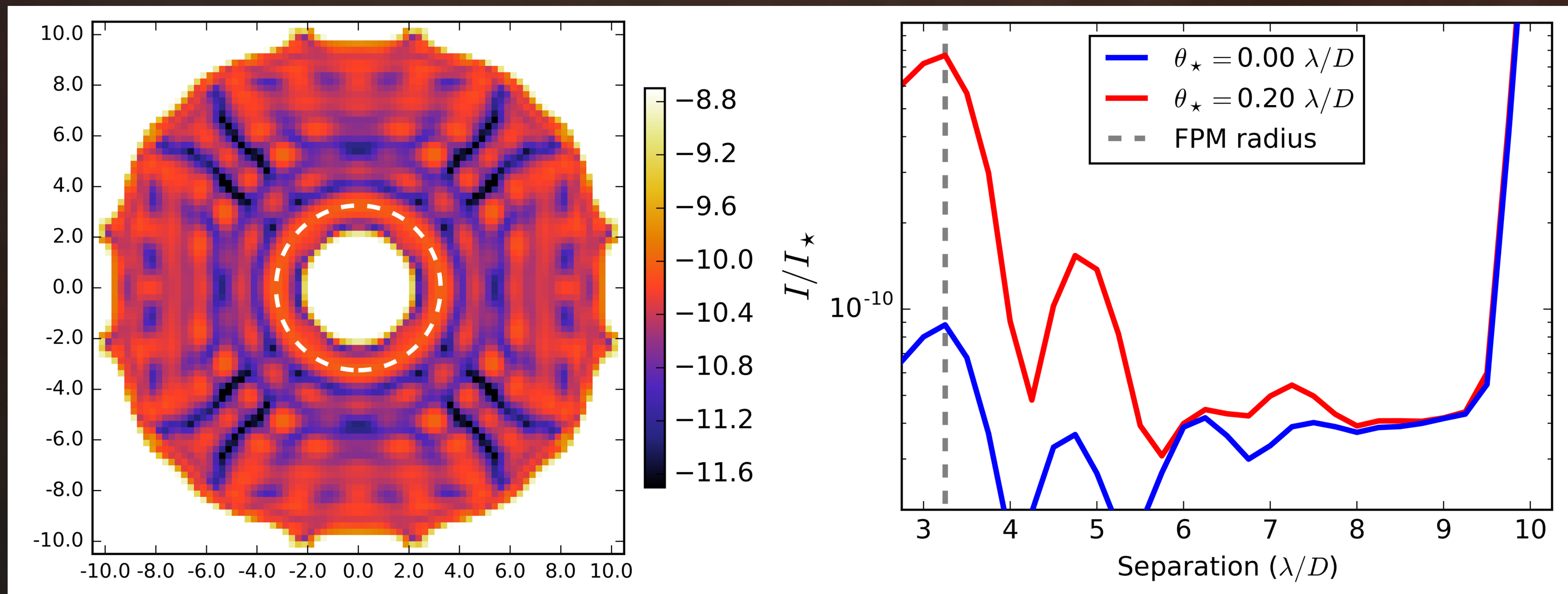
$T_{0.7/circ}$ = 23.6% | $T_{0.7/circ}$ = 21.8% | $T_{0.7/circ}$ = 23.6% | $T_{0.7/circ}$ = 22.0%

Deep parameter survey example: Lyot stop inner and outer diameter

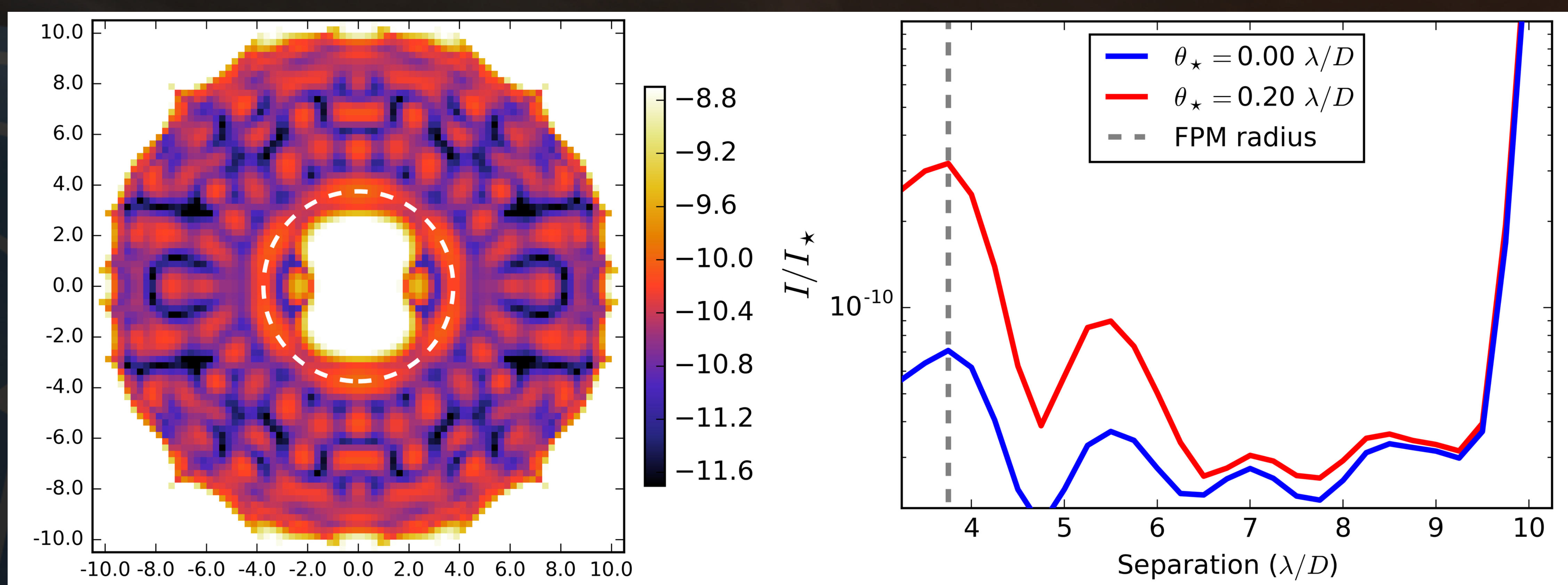


Star diameter robustness
0.2 λ/D ~ 2 mas for D=12 m @ V band

Obscured Keystone design



Obscured Hex 4 design



Alignment/fabrication robustness: Design strategies

1. Reticulated Lyot stop to block re-imaged aperture discontinuities

2. Optimize the apodizer for multiple, misaligned stops

3. Use deformable mirrors to compensate

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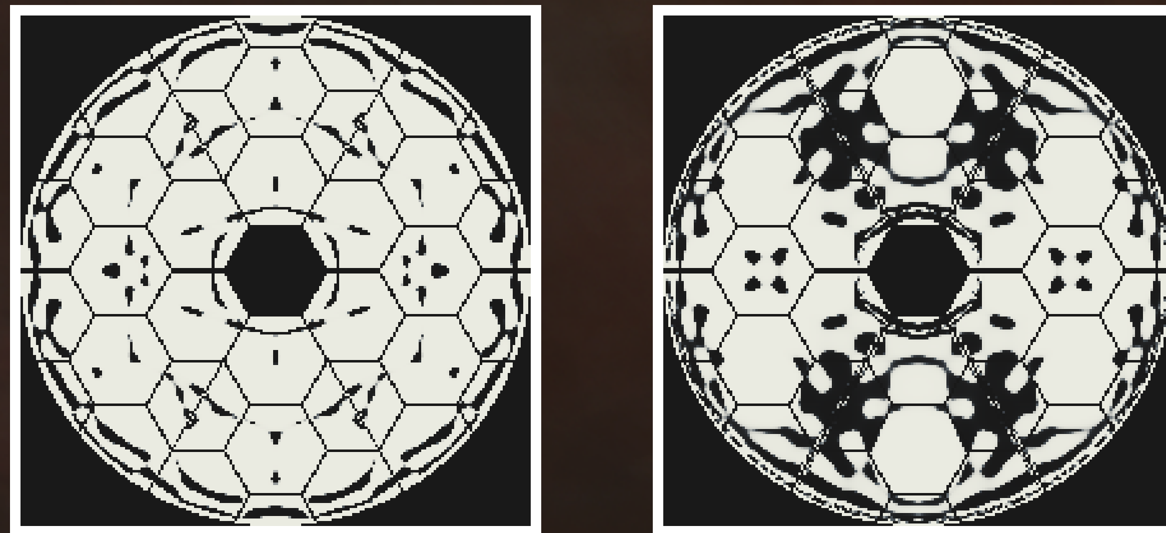
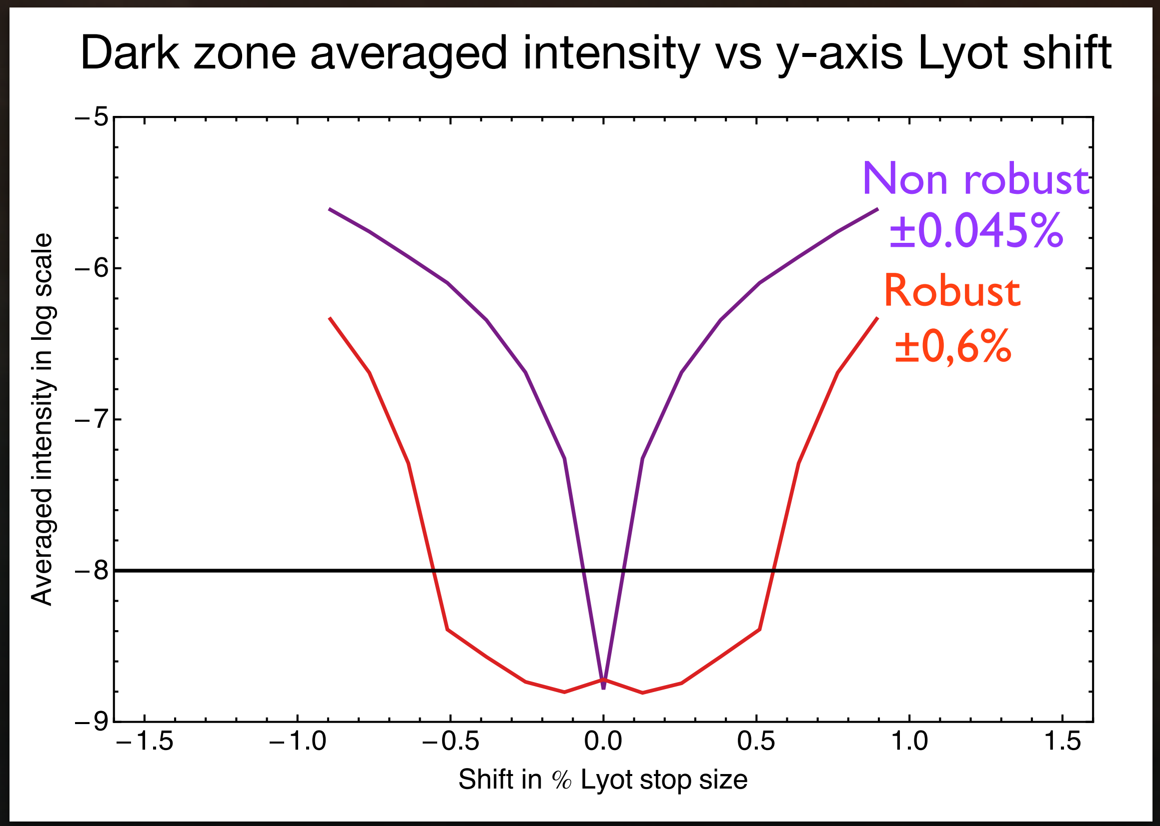
Alignment/fabrication robustness
"Misaligned" apodizer optimization

SP for APLC with 4.3λ/D radius FPM to produce a 10^8 contrast dark zone between 6-10 λ/D

Non robust   Robust

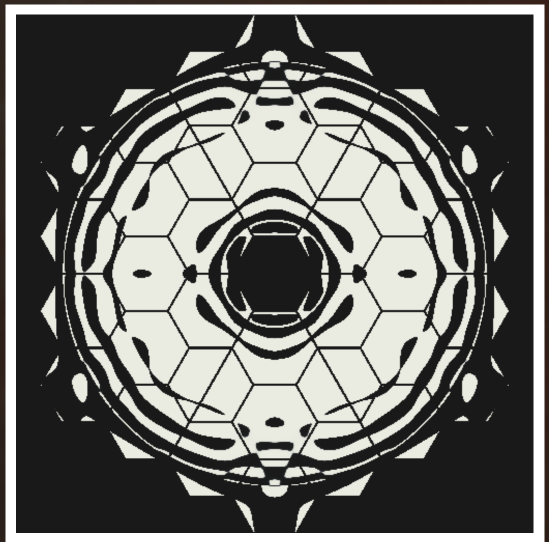




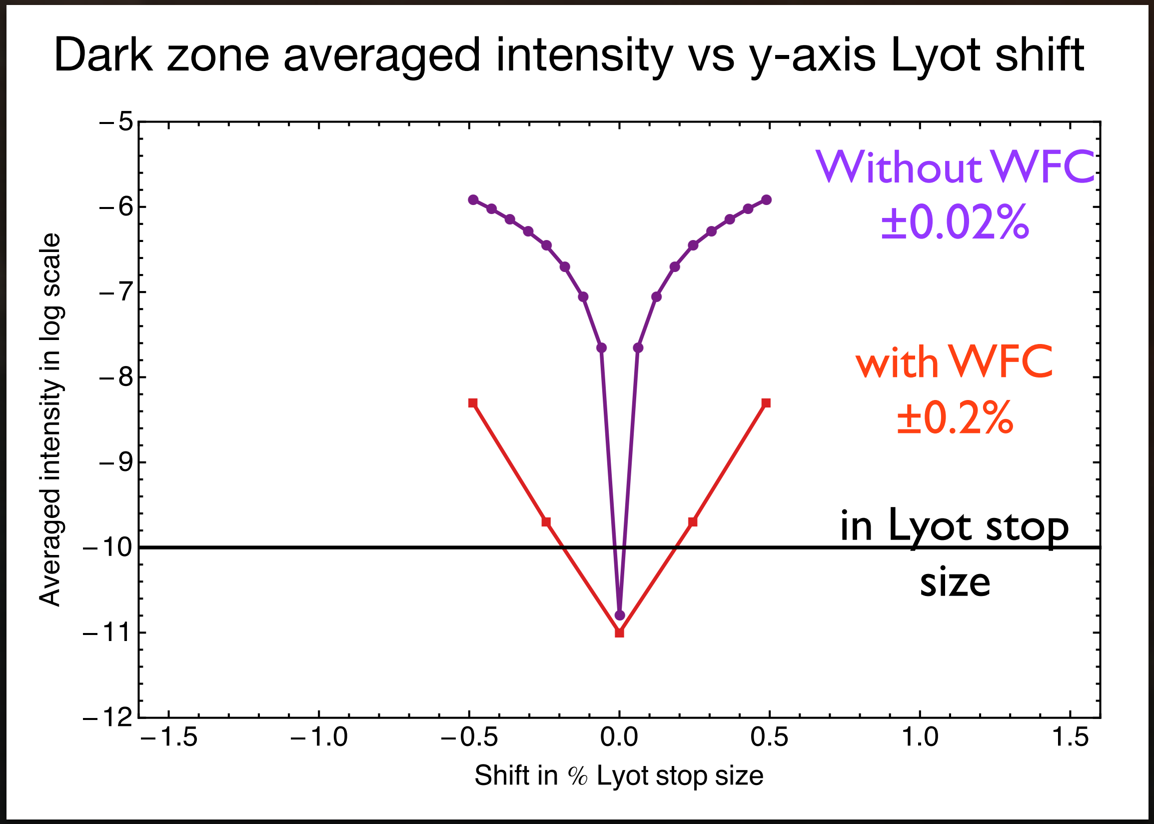
- Development of robust designs to produce dark zone for multiple, translated versions of the Lyot stop simultaneously
- First results: increase in alignment tolerance by ~10 for 10^8 contrast design
- Next step: find robust solutions with 10^{10} contrast

Alignment/fabrication robustness DM compensation

SP for APLC with 4λ/D radius FPM to produce a 10^{10} contrast dark zone between 3.5-10λ/D



- Combination of non robust APLC/SP design with Stroke Minimization algorithm as WFC (Pueyo et al. 2009, Mazoyer et al. 2016) - code provided by J. Mazoyer
- Assumptions: 2 32x32 Boston DMs with 9.6mm size, z=300mm device separation, 10 nm rms wavefront errors.
- Results: increase in robustness by ~10 for 10^{10} contrast design over 10% bandpass
- Next steps: combine WFC with alignment-robust design at 10^{10} contrast



Early conclusions from the April 2016 hexagonal APLC design survey

- When we push the bandwidth and inner working angle, the 2-, 3-, and 4-ring hexagonal segmentations perform better than the 1-ring segmentation.

- Once the Lyot stop is tuned, similar performance (within few %) for the 2, 3, and 4-ring hexagonal segmentation patterns.

- Sharp jump in throughput (~ 3x) as the focal plane mask radius is increased from 3 λ/D to 4 λ/D

Summary

- We have developed a design toolkit to traverse the large parameter space of segmented APLC solutions, and estimate their Exo-Earth yields via the Stark DRM.

- The perimeter shape of the primary mirror dominates APLC performance differences across the SCDA apertures. APLC performance is only weakly effected by the specific segmentation pattern within the pupil.

- We have identified several strategies to handle the challenge of alignment robustness. Further investigations are needed to advance these methods and find the most efficient balance in terms of throughput.