Apodized/Shaped Pupil Lyot Coronagraph designs for segmented apertures

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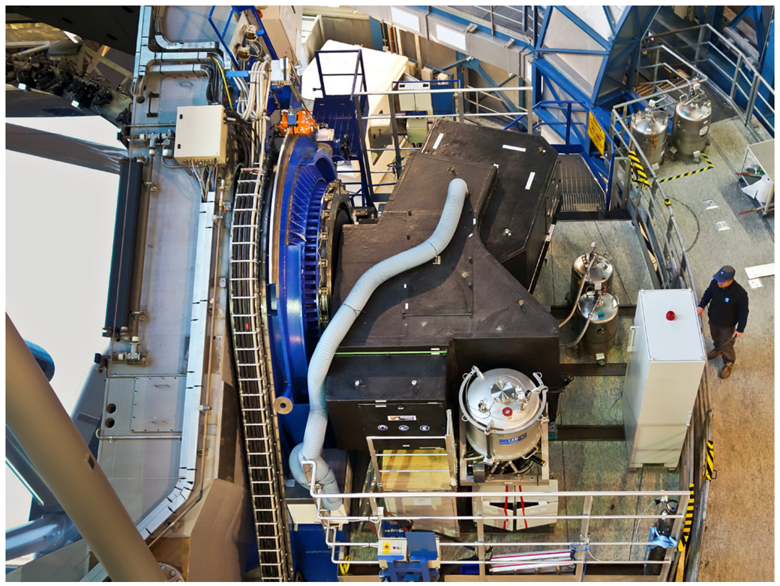
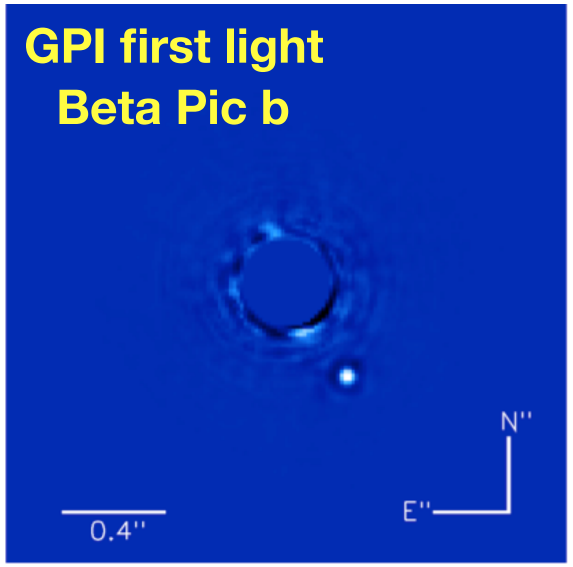
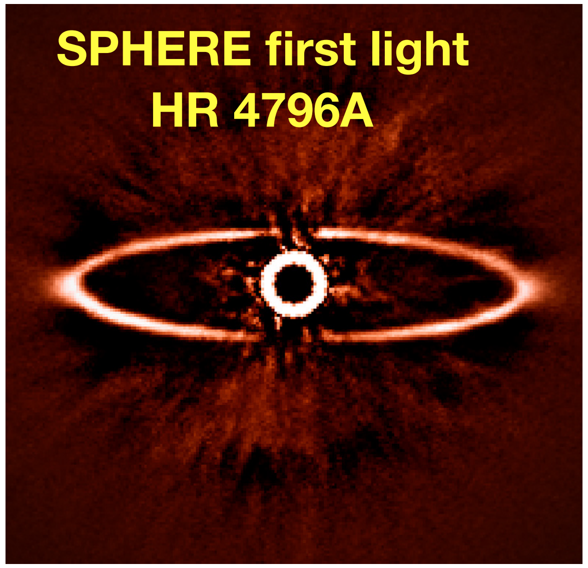
Context

GPI and VLT/SPHERE operating on sky



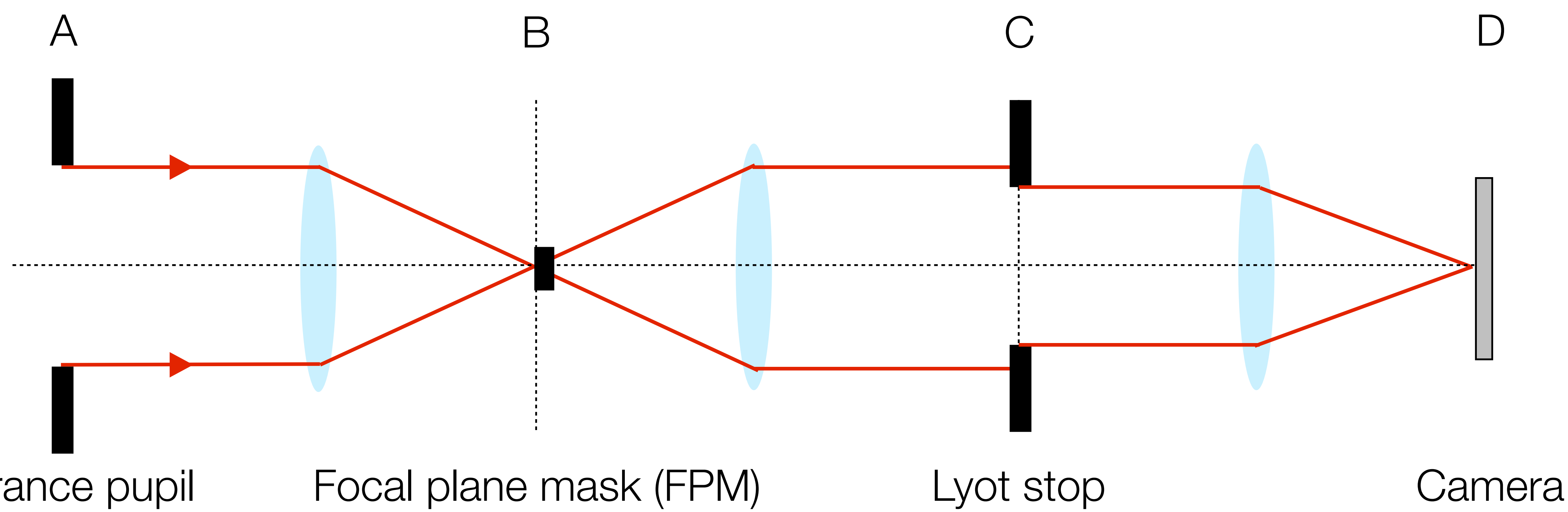




- Ground-based exoplanet imaging systems use Lyot coronagraphs to suppress diffracted starlight, after adaptive optics correction.
- P1640, GPI, and SPHERE all use an **Apodized Pupil Lyot Coronagraph** (**APLC**; Aime et al. 2002, Soummer et al. 2002-2011, Martinez et al. 2007-2010)

Macintosh et al. 2014,
ESO/Beuzit et al. 2014

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

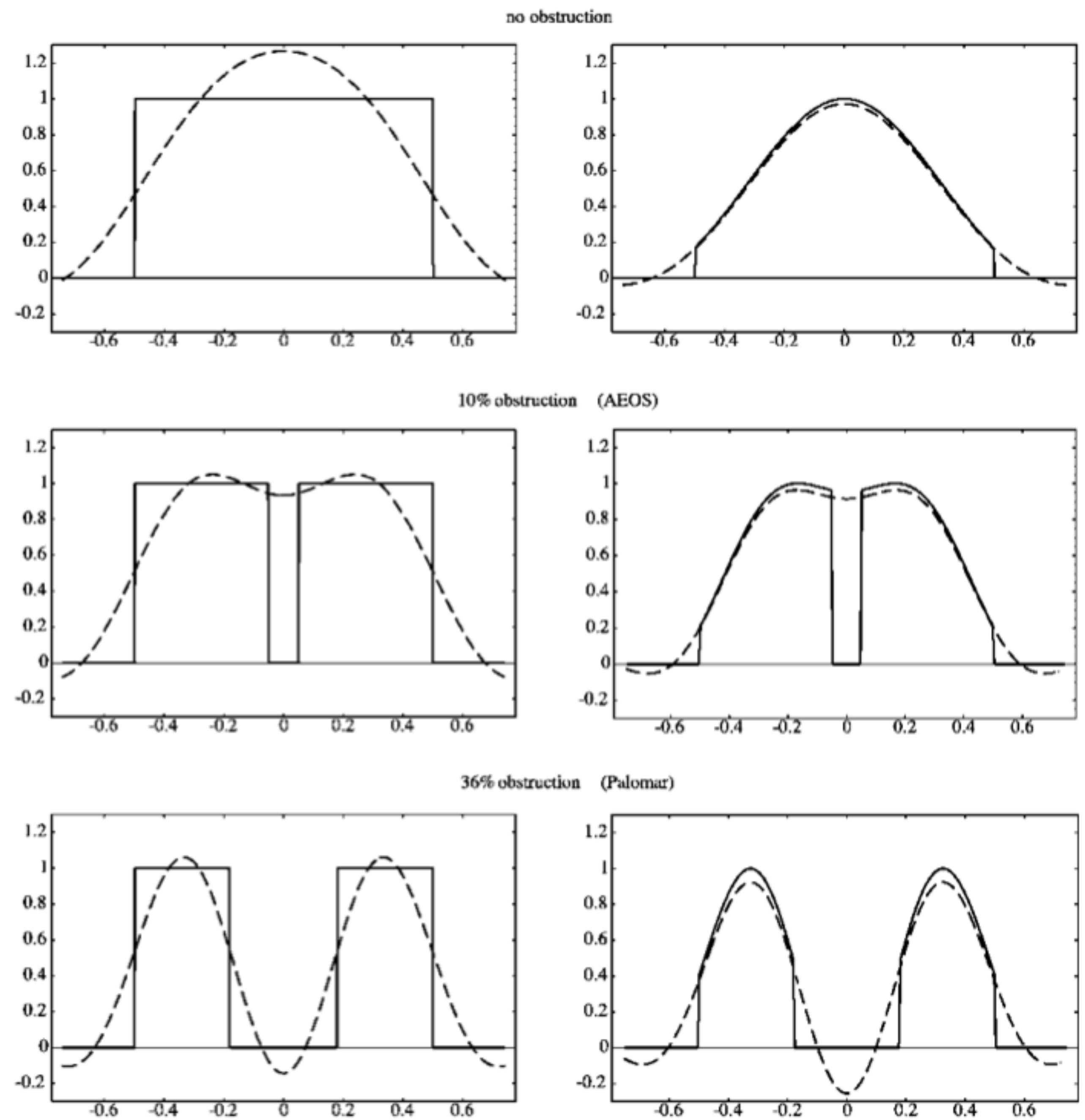
Prolate apodization

- Eigenvalue problem

$$\Psi_A(\mathbf{r}) = P(\mathbf{r})\Phi_0(\mathbf{r})$$

$$\Psi_C(\mathbf{r}) = (1 - \Lambda_0)\Phi_0(\mathbf{r})P(\mathbf{r})$$

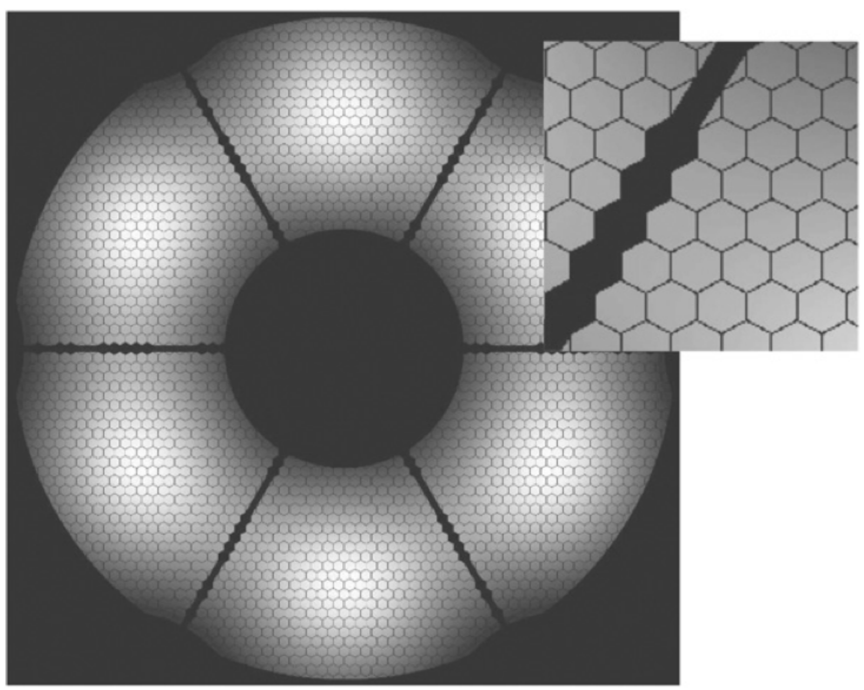
- No total extinction solution for APLC but...
- Prolate functions approach this perfect solution



Soummer et al. 2003, 2005

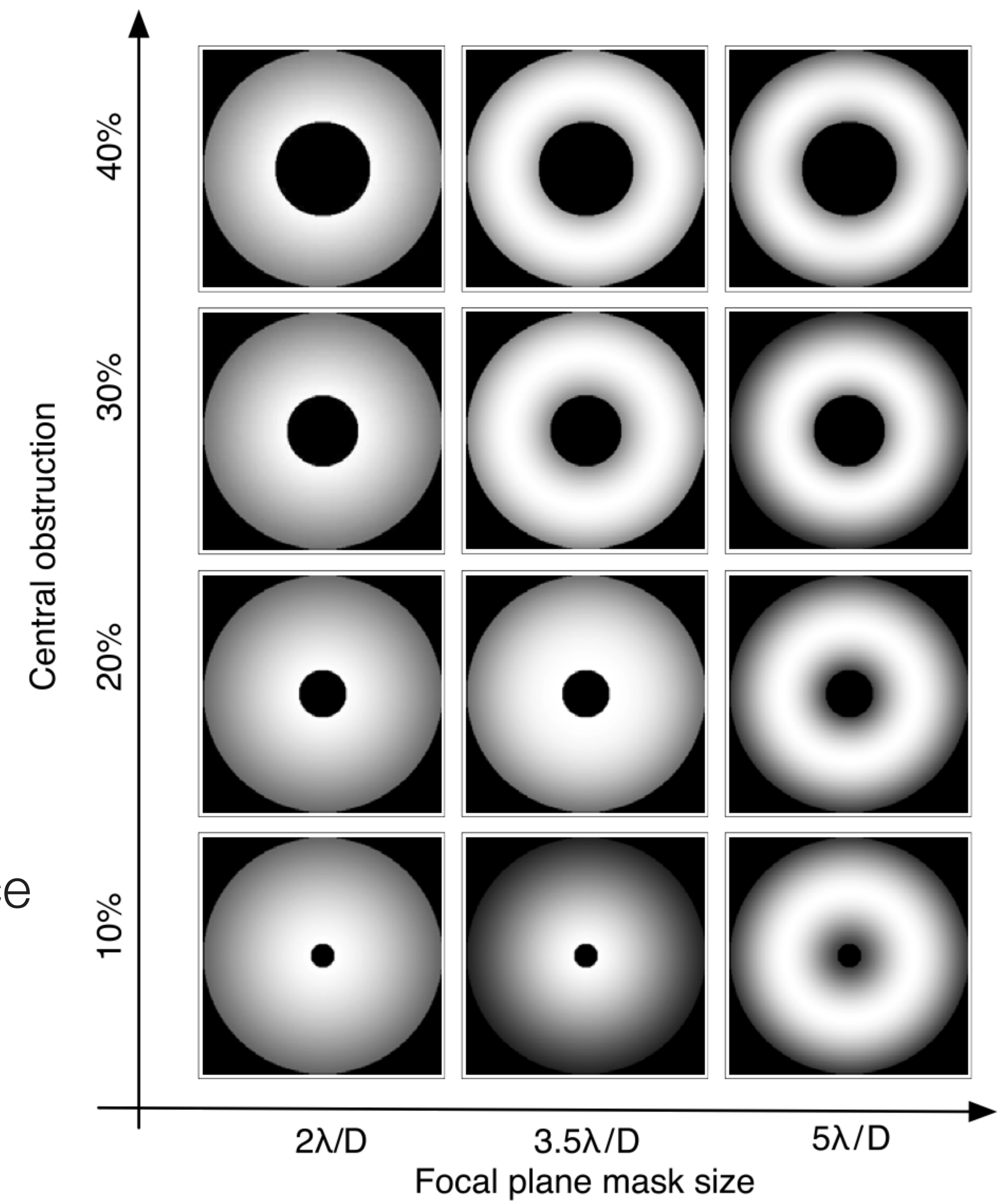
Solutions for arbitrary apertures

- Generalized prolate spheroidal apodizers exist for any aperture geometry and focal mask diameter



- Lyot stop geometry, same as entrance pupil

Martinez et al. 2007
Soummer et al. 2009
Sivaramakrishnan & Lloyd 2005



Shaped pupil

- Apodizer with binary-valued transmission
- Optimized via linear program to create a region of destructive interference in the image plane.

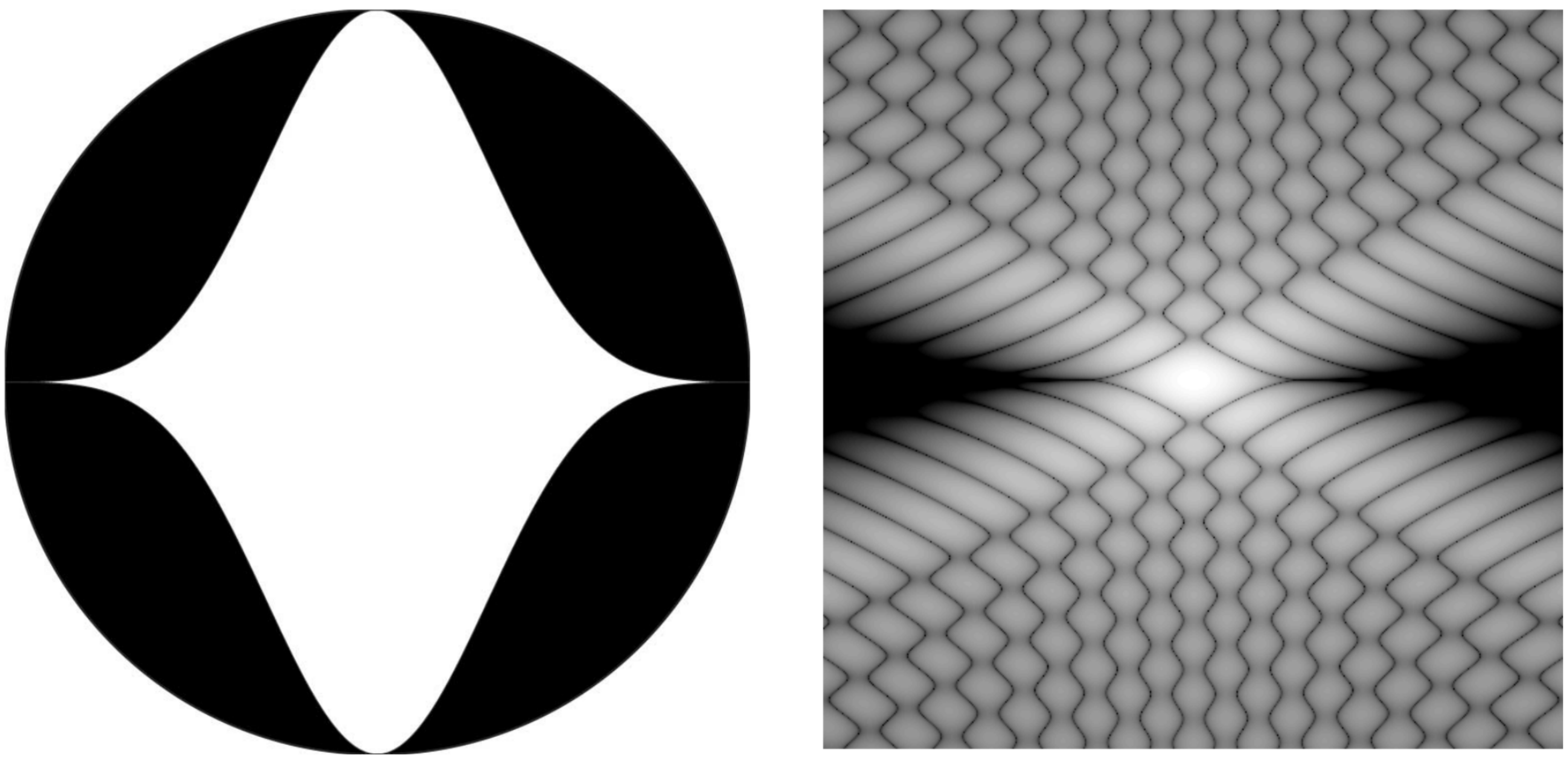
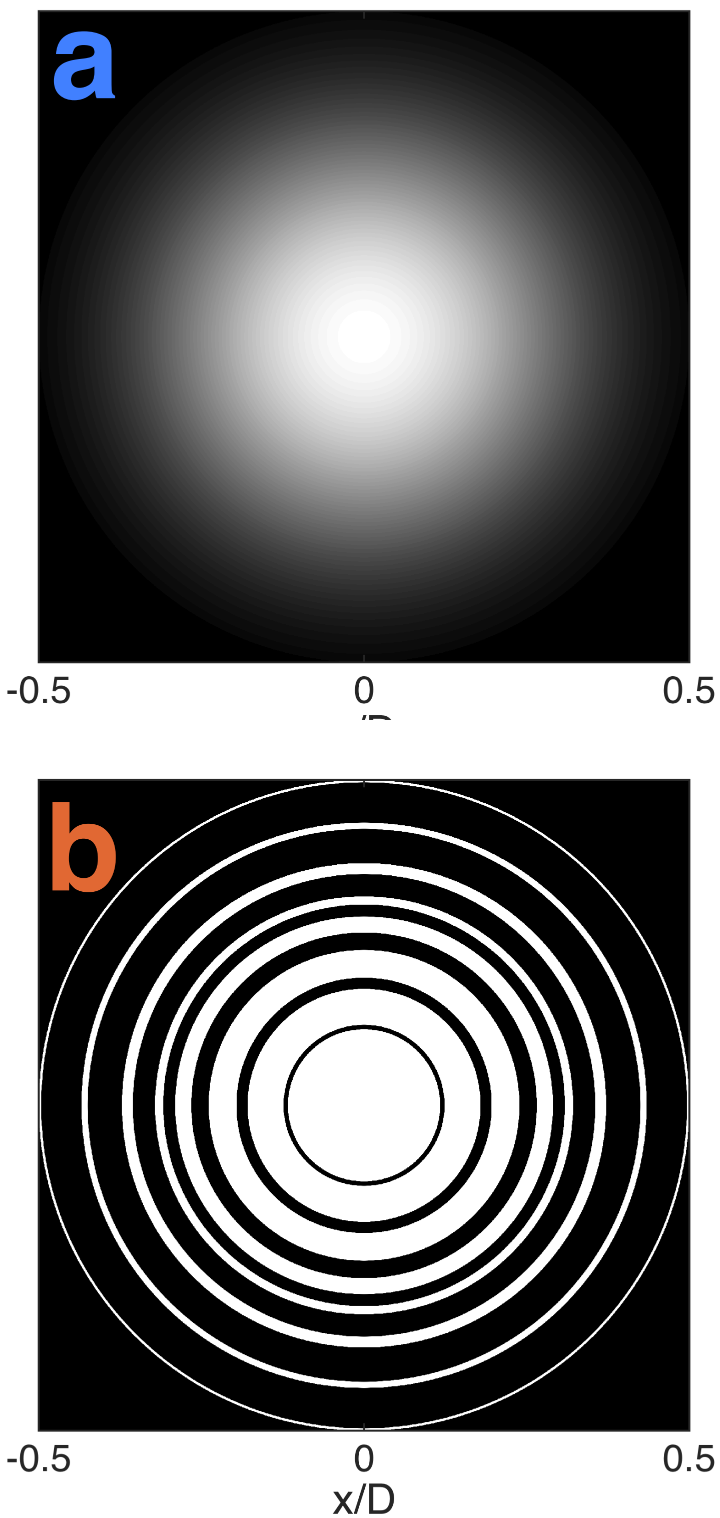


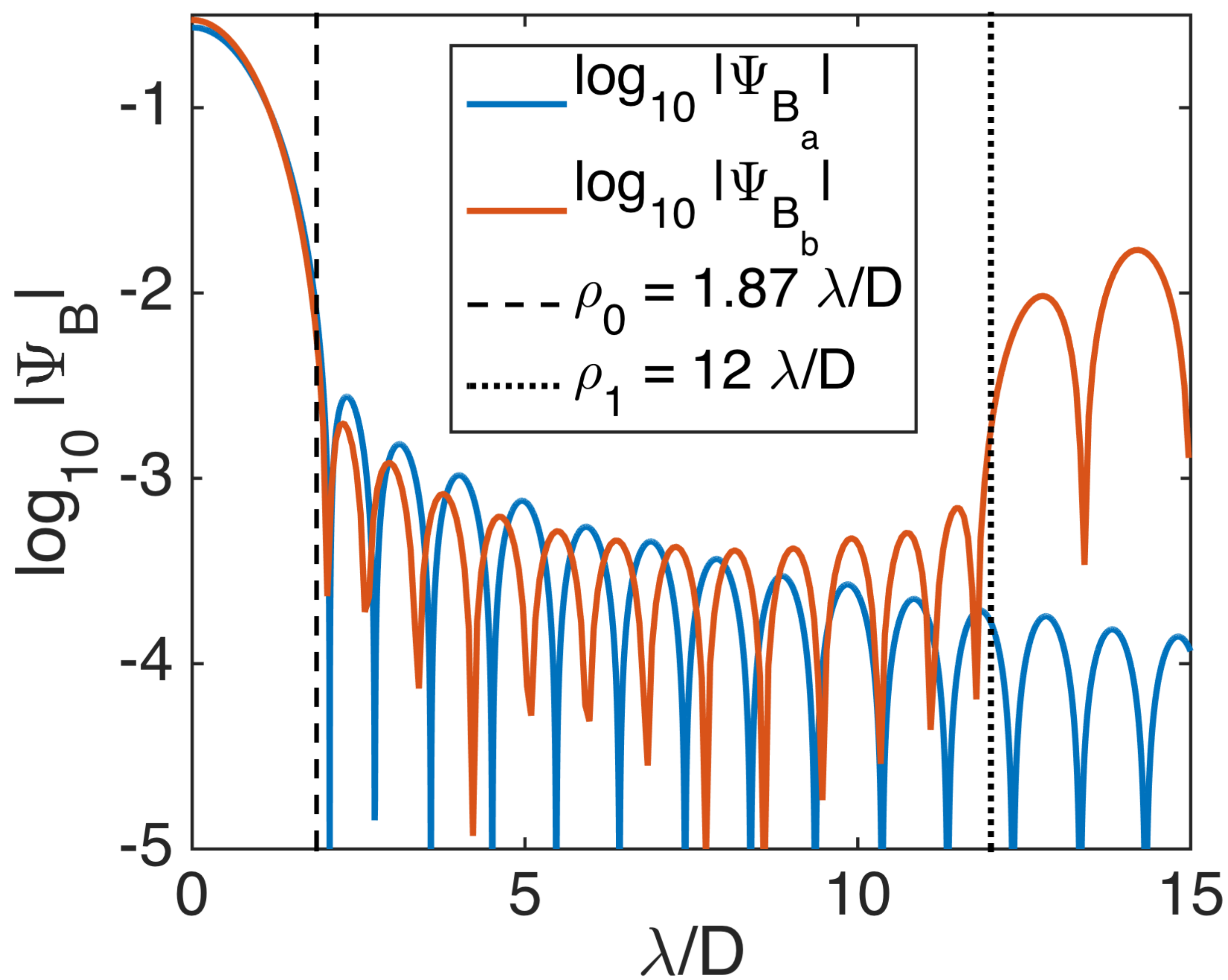
FIG. 5.—*Left*: Single prolate spheroidal wave function shaped-pupil aperture (Slepian 1965) inscribed in a circular aperture of unit area. *Right*: Corresponding PSF plotted on a logarithmic scale with black areas 10^{-10} below brightest. This mask has a single-exposure normalized discovery relative integration time of 4.6 with a small discovery space at the IWD.

Kasdin, Vanderbei, Spergel, Littman, ApJ 582,1147–1161 (2003)

Shaped pupil

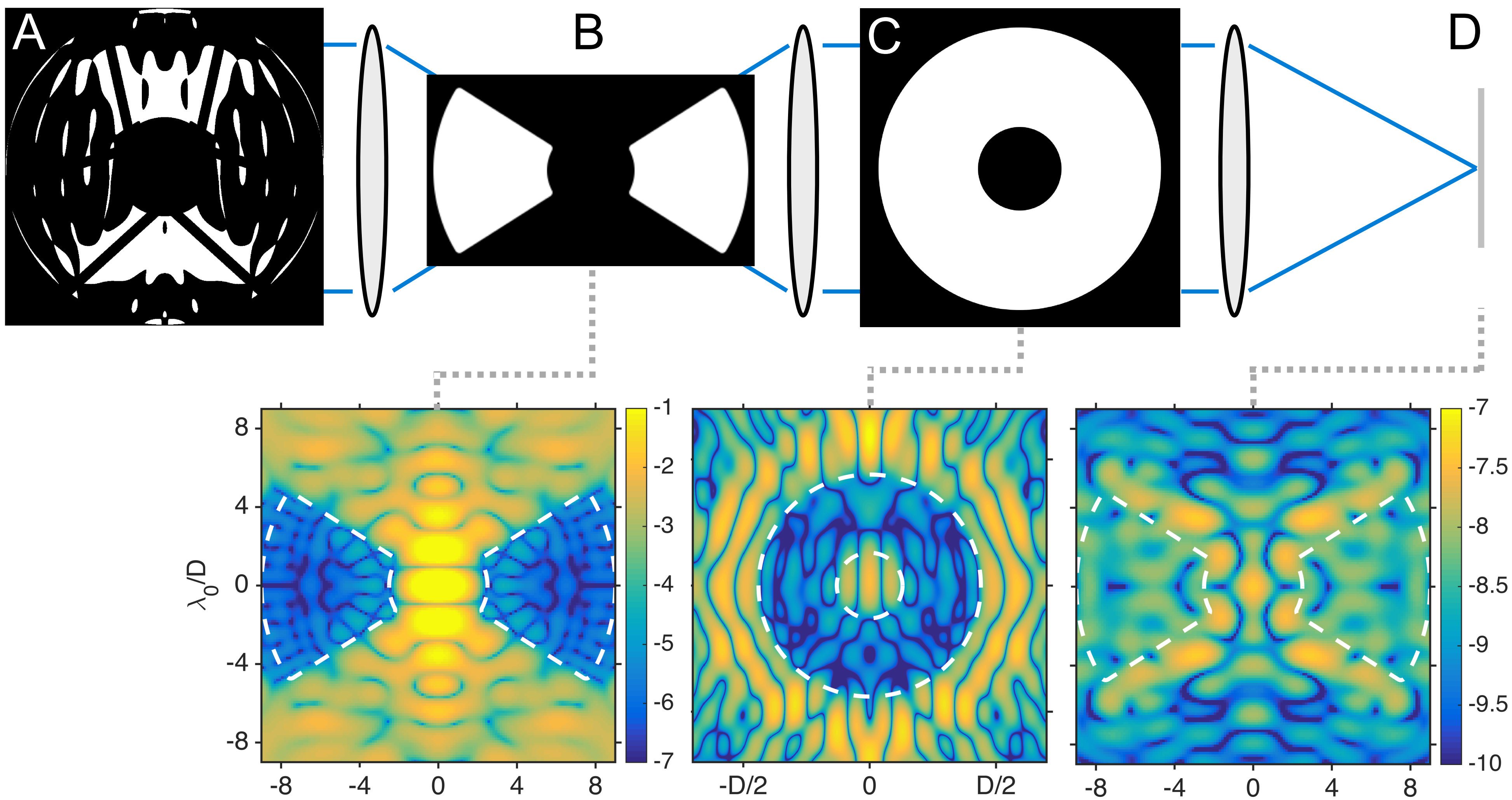


A shaped pupil can mimic the PSF of a graded prolate spheroidal apodizer



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

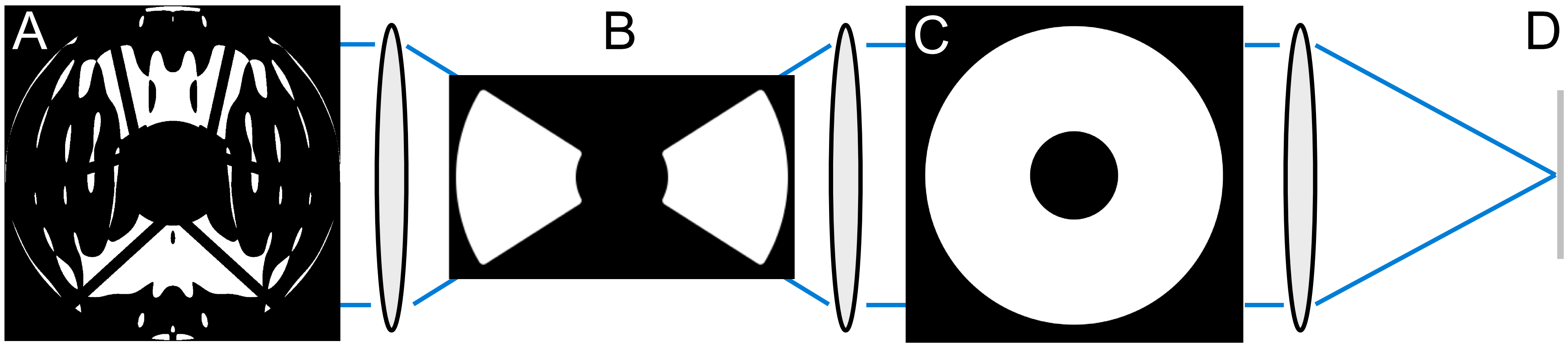
Shaped pupil Lyot coronagraph for WFIRST

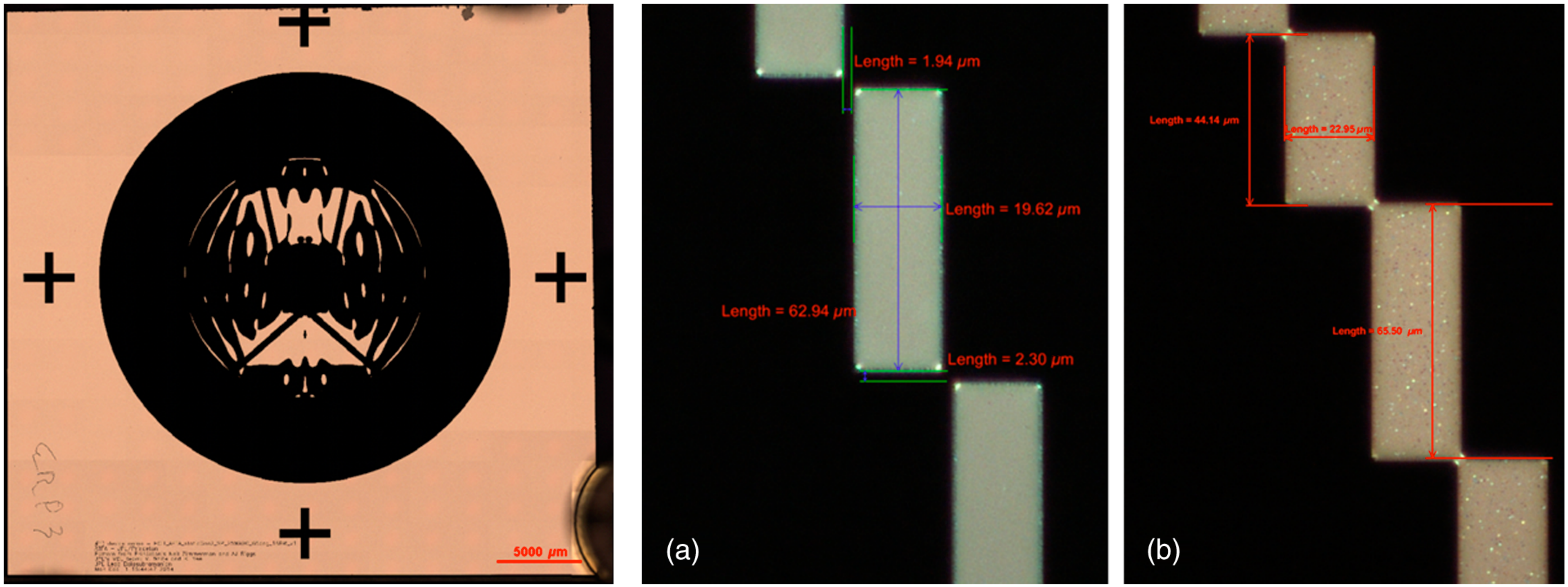


- Raw contrast ≤10^{-8} over an 18% bandwidth
- working angle **2.8 λ_0/D** — 9 λ_0/D
- 2 x 65 deg bowtie dark hole
- FWHM throughput 11%

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

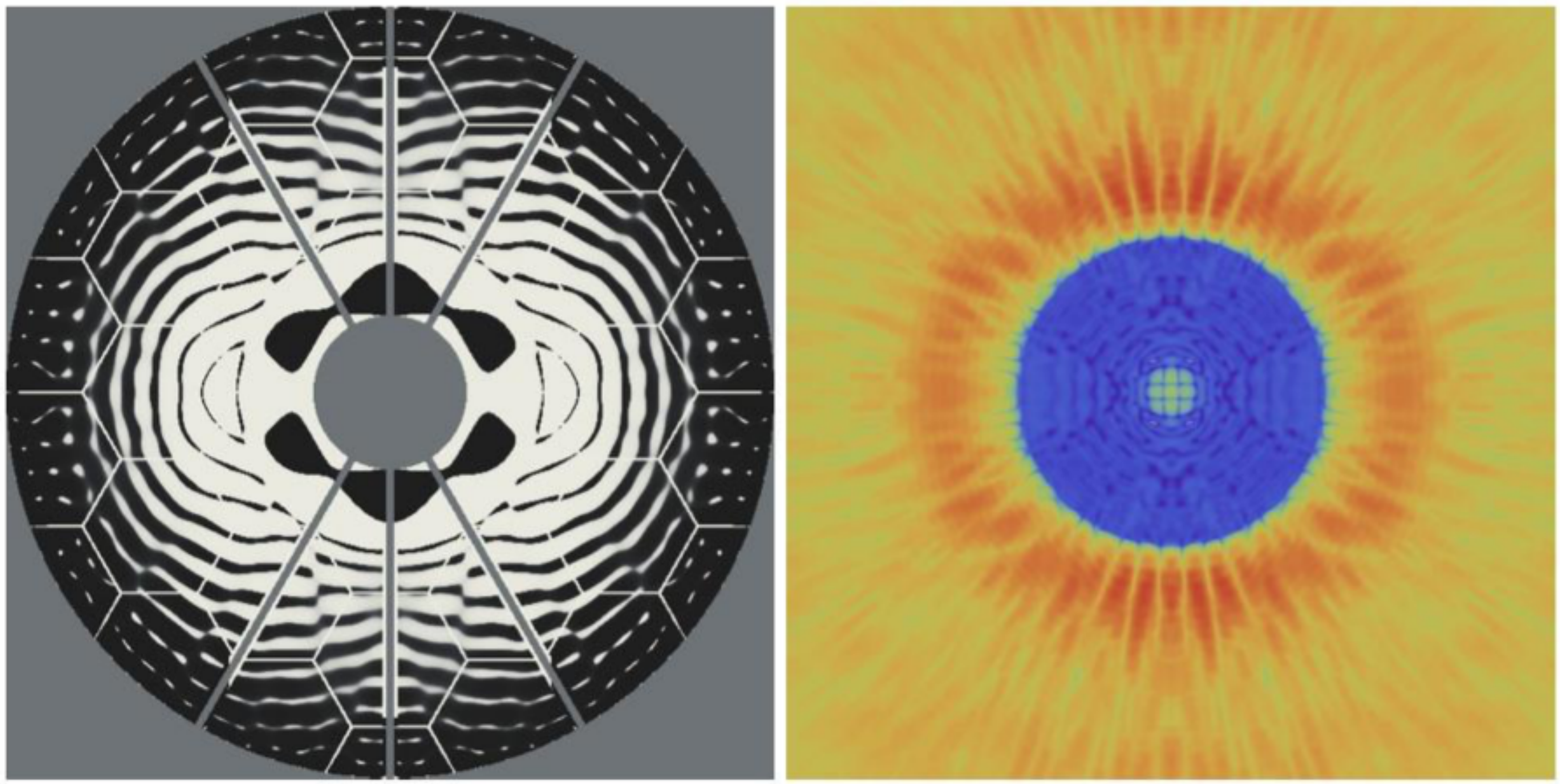
Shaped pupil Lyot coronagraph for WFIRST





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

Hybrid shaped pupil / APLC design approach

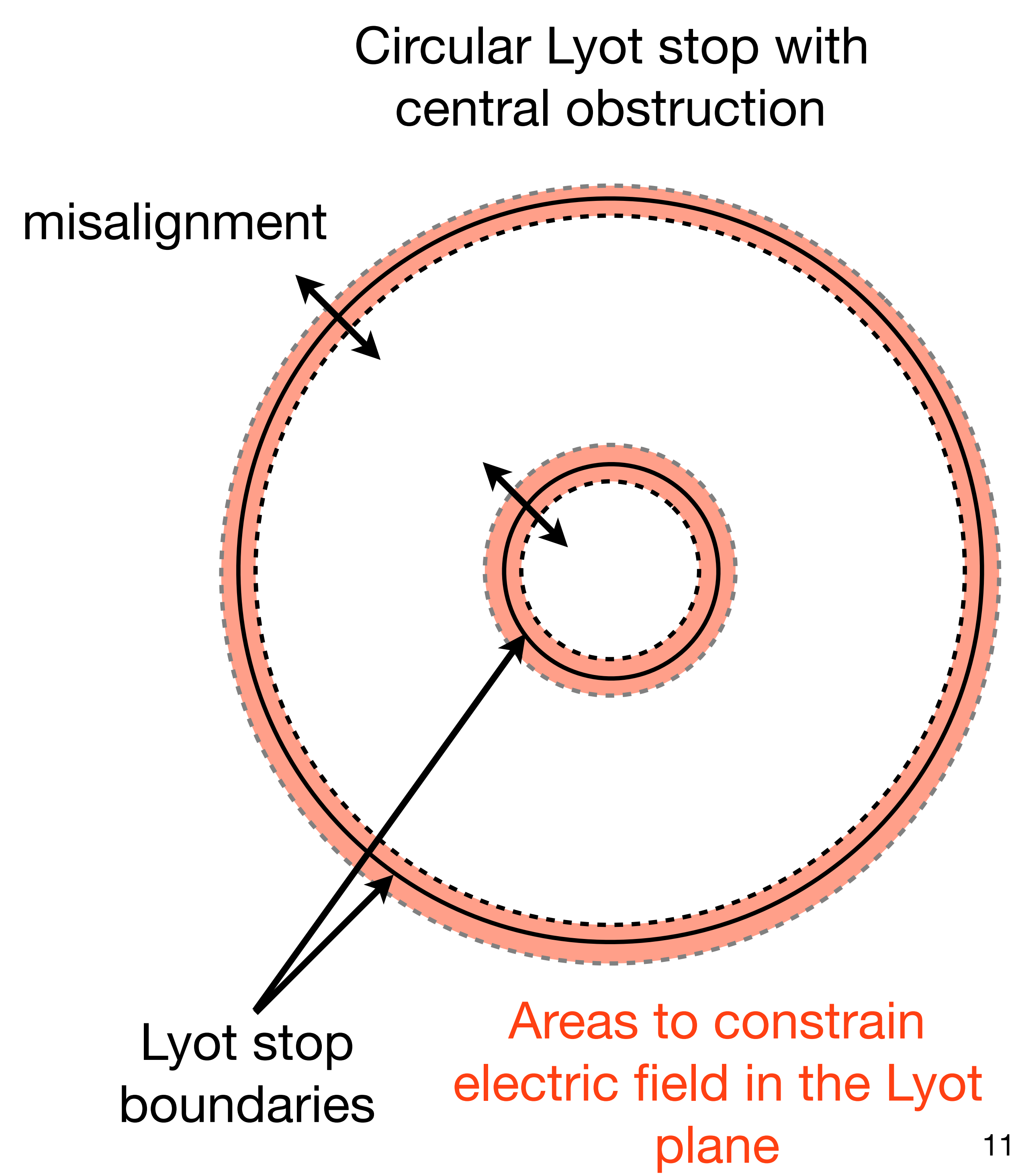


- Proof of concept for a segmented APLC design using a shaped pupil apodizer reaching 1E-10 contrast
- 10% bandwidth, Airy throughput 20%
- Built-in tolerance to pointing errors/stellar diameter

N'Diaye et al, ApJ 818, 163 (2016)

Recent APLC development: built-in robustness to Lyot stop misalignment and fabrication errors

Strategy: constrain the field amplitude in the Lyot plane around the stop edges



SCDA survey strategy

1. Build on 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. Surveying dependence of throughput and PSF shape on telescope aperture geometry, inner working angle, FPM mask size, Lyot stop dimensions, bandwidth

STScI

Hexagonal APLC design survey, April 2016

- 504 designs in total

- Fixed parameters: quarter-plane pupil symmetry, thin ‘X’-shaped secondary struts, 1E-10 contrast, outer working angle 10 λ/D

- Varied parameters:

1. Aperture segmentation: hex1, hex2, hex3, hex4
2. Focal plane mask (inner dark zone) radius:
   3, 4, 5 λ/D (2.5, 3.5, 4.5 λ/D)
3. LS inner diameter: 20, 25, 30% of pupil diameter
4. LS outer diameter: 70, 72, 74, 76, 78, 80, 82%
5. Bandwidth:10% and 15% (3 and 5 wavelengths)

Prepare a design survey test to run on NCCS Discover

In [26]:
```
survey_params = {'Pupil': { 'prim': ['hex1', 'hex2', 'hex3', 'hex4'],
                            'secobs': 'X', 'thick': '025',
                            'centobs': True, 'N': 125 },
                 'FPM': { 'rad': [3.0, 4.0, 5.0], 'M':60 },
                 'LS': { 'shape':'ann', 'obscure':0, 'aligntol':5, 'aligntolcon':3.,
                         'id':[20, 25, 30], 'od':[76, 78, 80, 82] },
                 'Image': { 'ida':-0.5, 'bw':0.15, 'Nlam':5}}
```

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Initiate a survey object with the above parameter combinations

In [37]:
```
hexap_survey = scda.DesignParamSurvey(scda.QuarterplaneAPLC, survey_params, fileorg=fileorg)
print("This survey has {0:d} design parameter combinations.".format(hexap_survey.N_combos))
print("{0:d} parameters are varied: {1}".format(len(hexap_survey.varied_param_index), hexap_survey.varied_param_index))
```

```
This survey has 144 design parameter combinations.
4 parameters are varied: (('Pupil', 'prim'), ('FPM', 'rad'), ('LS', 'id'), ('LS', 'od'))
```

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```

```
This survey has 144 design parameter combinations.
4 parameters are varied: (('Pupil', 'prim'), ('FPM', 'rad'), ('LS', 'id'), ('LS', 'od'))
```

Write the batch of AMPL files

In [35]:
```
hexap_survey.write_ampl_batch(override_infile_status=True, overwrite=True)
```

```
INFO:root:Wrote the batch of design survey AMPL programs into amplsrc
```

Write the batch of queue execution scripts

In [36]:
```
hexap_survey.write_exec_script_batch(overwrite=True, queue_spec='12h')
```

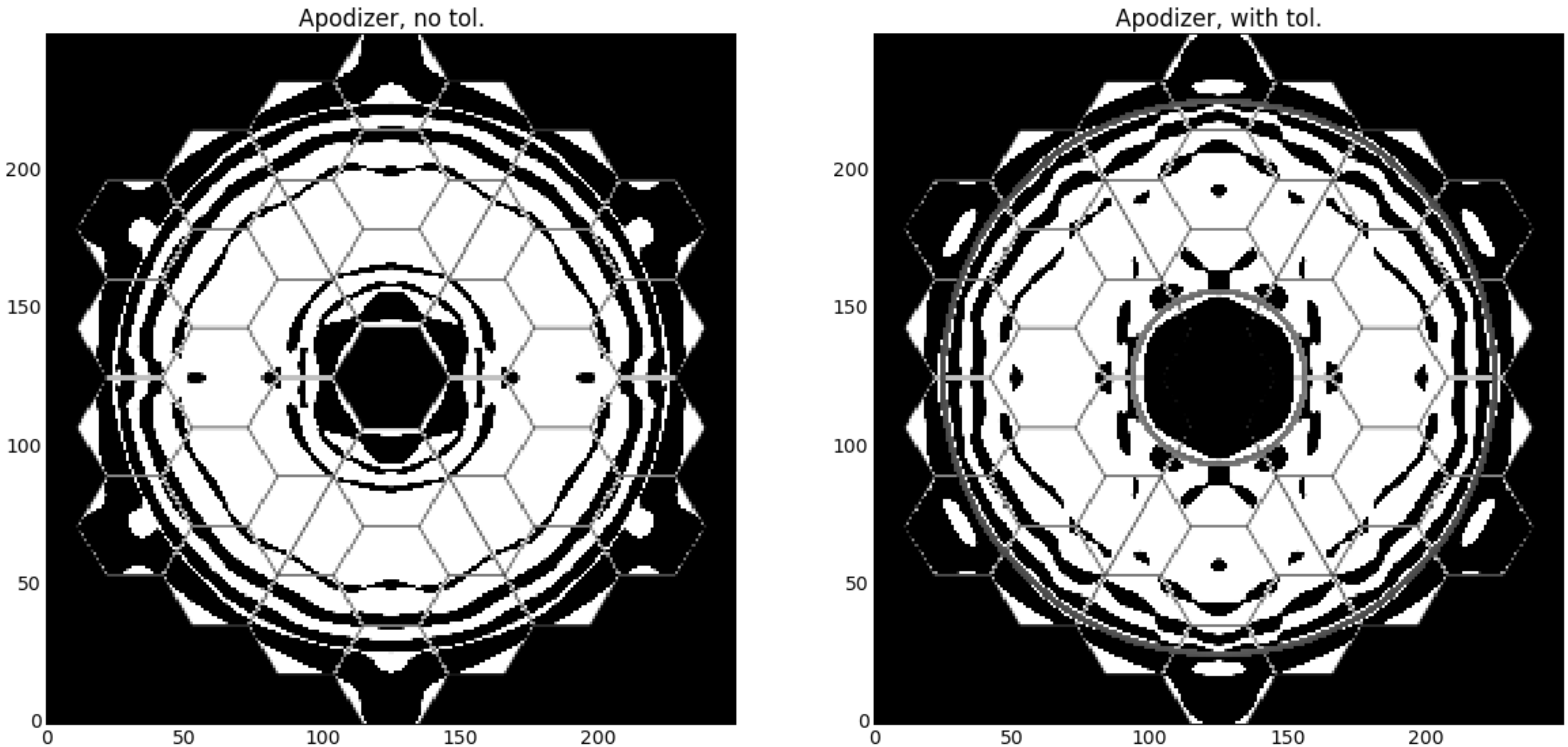
```
INFO:root:Wrote the batch of execution scripts into /astro/opticslab1/SCDA/Scripts/AMPL/nccs_april_survey01_15bw
```

Write tables summarizing the design survey configuration and status to a spreadsheet

In [38]:
```
hexap_survey.write_spreadsheet()
```

```
INFO:root:Wrote design survey spreadsheet to /astro/opticslab1/SCDA/Scripts/AMPL/nccs_april_survey01_15bw/scda_Quarte
rplaneAPLC_survey_ntz_2016-04-14.csv
```

Example design for Hex3 aperture
4 - 10 λ/D, 15% BW



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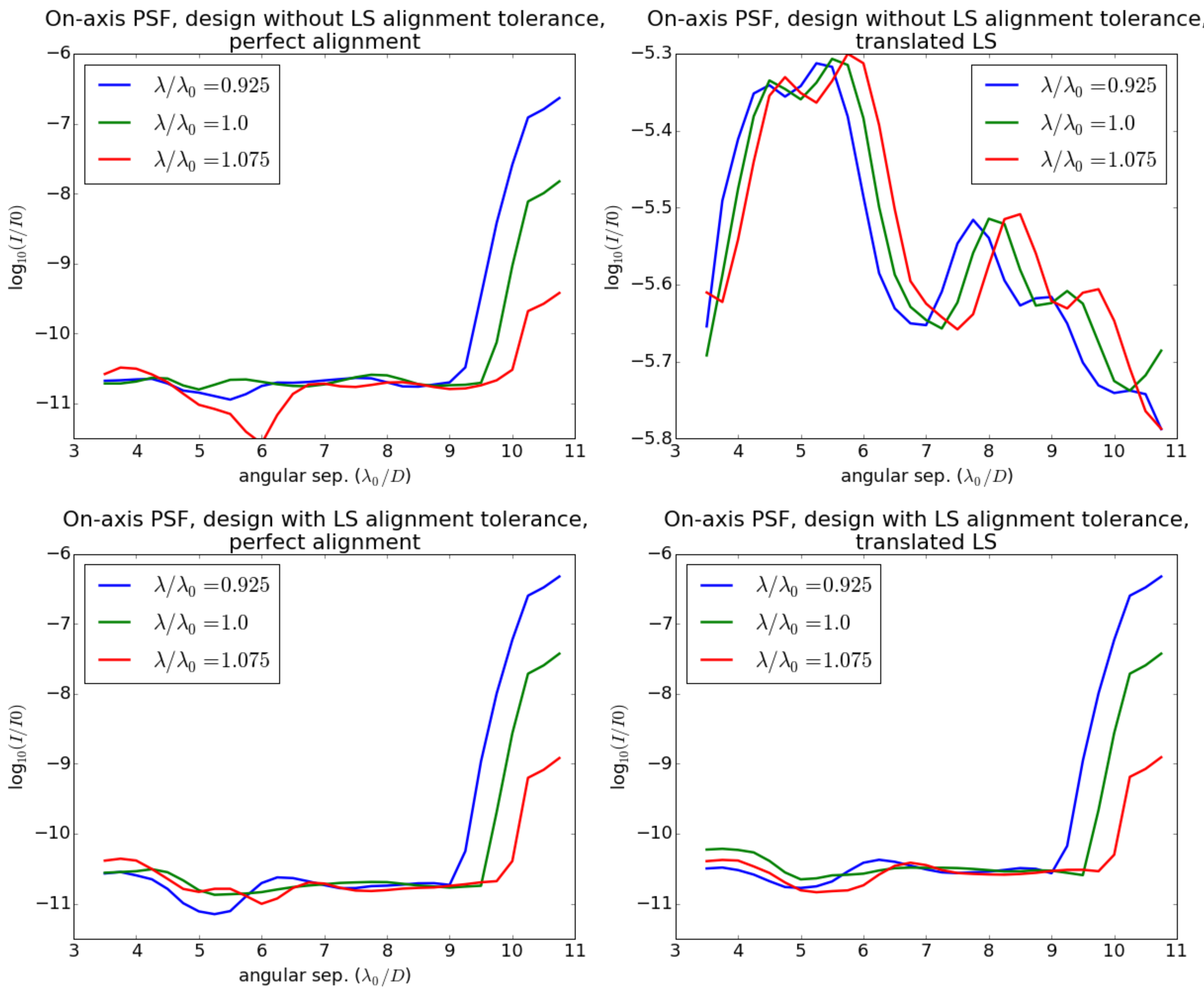


Hexagonal APLC survey results, 10% bandwidth

Provisional performance metric: “normalized throughput”

$$= \frac{\textbf{FWHM PSF throughput w.r.t. Telescope}}{\textbf{FWHM PSF area w.r.t. Telescope}}$$

Hexagonal APLC survey results, 10% bandwidth

Provisional performance metric: "normalized throughput"

$$= \frac{\textbf{FWHM PSF throughput w.r.t. Telescope}}{\textbf{FWHM PSF area w.r.t. Telescope}}$$

Aperture segmentation

FPM radius		hex1	hex2	hex3	hex4
	3 λ/D	8.9%	12.1%	11.4%	11.1%
	4 λ/D	29.4%	32.4%	33.6%	32.7%
	5 λ/D	35.0%	35.0%	34.0%	34.1%

Hexagonal APLC survey results, 15% bandwidth

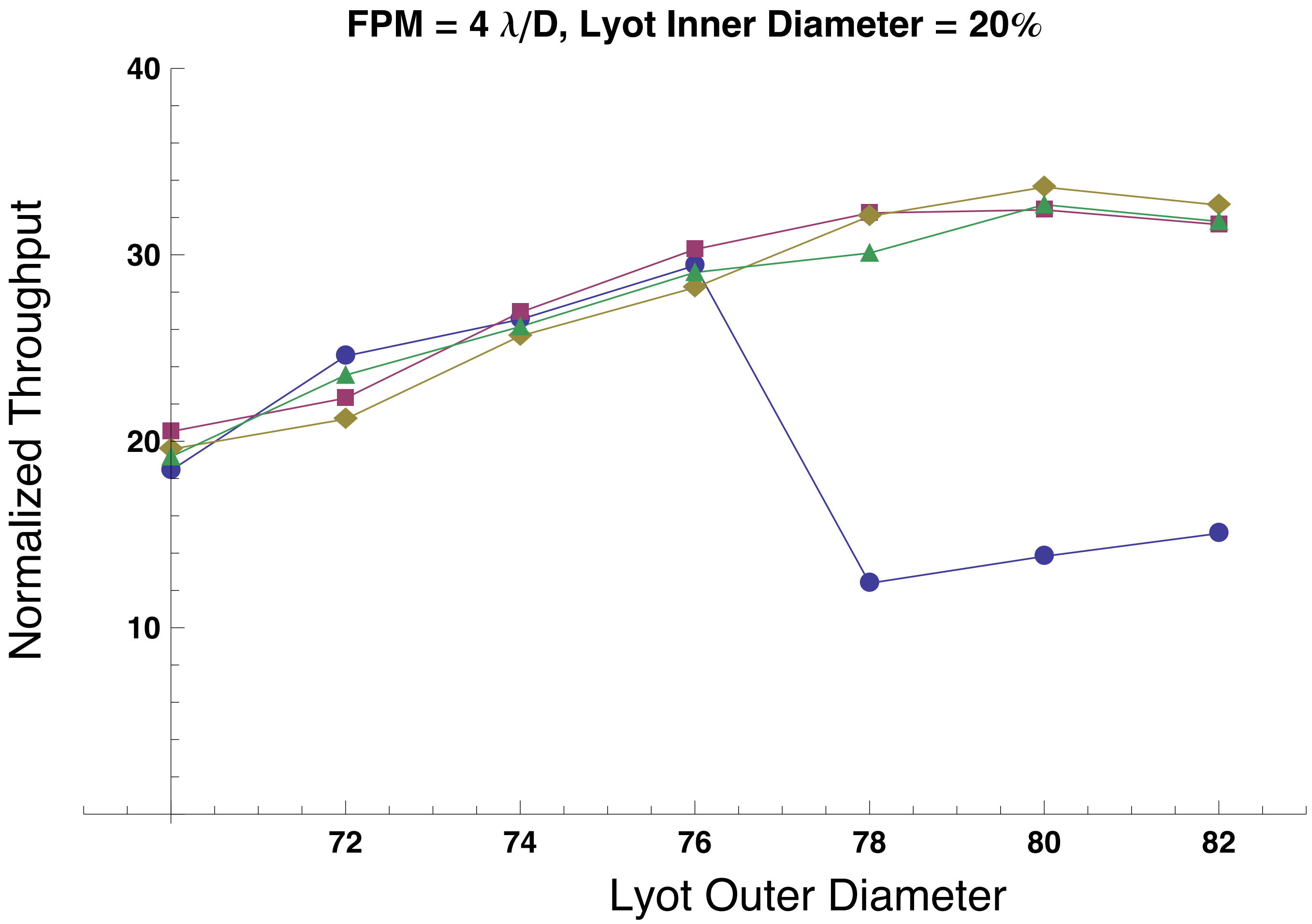
Provisional performance metric: "normalized throughput"

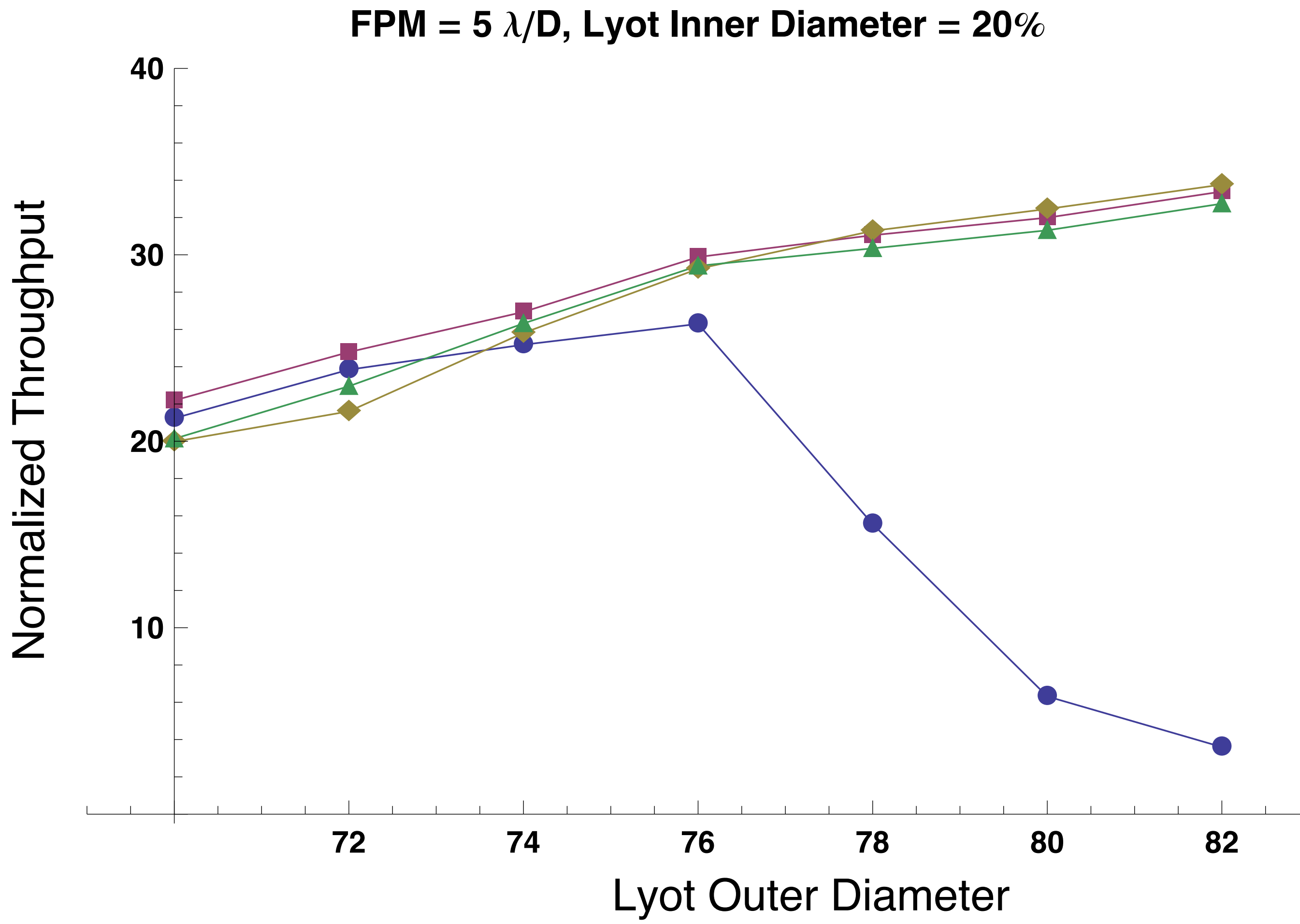
$$= \frac{\textbf{FWHM PSF throughput w.r.t. Telescope}}{\textbf{FWHM PSF area w.r.t. Telescope}}$$

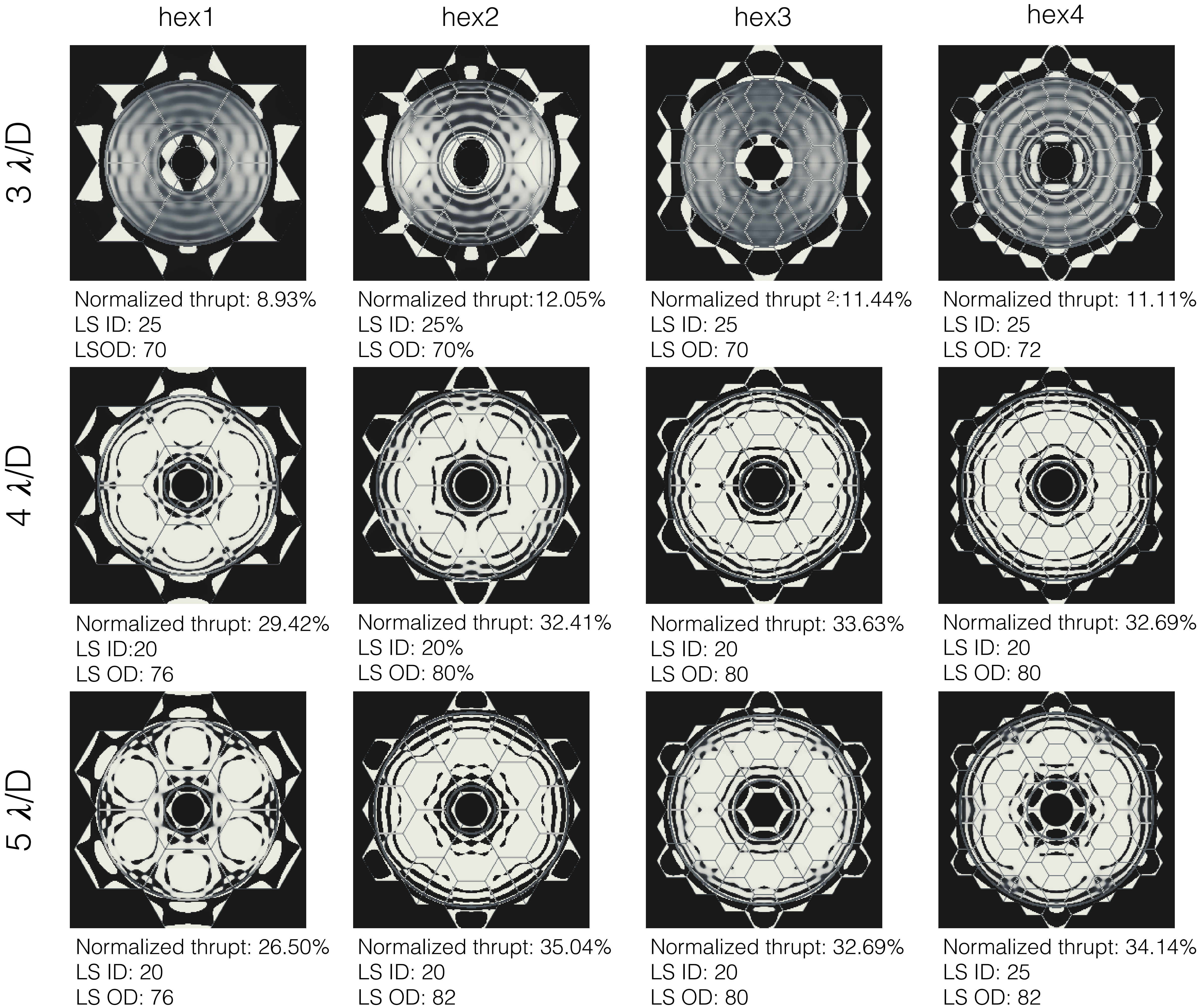
Aperture segmentation

FPM radius		hex1	hex2	hex3	hex4
	3 λ/D	1.1%	1.1%	0.7%	1.1%
	4 λ/D	18.7%	31.1%	31.1%	30.0%
	5 λ/D	25.8%	33.5%	33.4%	32.4%

Tuning the Lyot stop dimensions







hex1
hex2
hex3
hex4
3 λ/D
4 λ/D
5 λ/D
Normalized thrupt: 8.93%
LS ID: 25
LSOD: 70
Normalized thrupt:12.05%
LS ID: 25%
LS OD: 70%
Normalized thrupt [2]:11.44%
LS ID: 25
LS OD: 70
Normalized thrupt: 11.11%
LS ID: 25
LS OD: 72
Normalized thrupt: 29.42%
LS ID:20
LS OD: 76
Normalized thrupt: 32.41%
LS ID: 20%
LS OD: 80%
Normalized thrupt: 33.63%
LS ID: 20
LS OD: 80
Normalized thrupt: 32.69%
LS ID: 20
LS OD: 80
Normalized thrupt: 26.50%
LS ID: 20
LS OD: 76
Normalized thrupt: 35.04%
LS ID: 20
LS OD: 82
Normalized thrupt: 32.69%
LS ID: 20
LS OD: 80
Normalized thrupt: 34.14%
LS ID: 25
LS OD: 82

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

Next steps (May-June)

- Repeat hexagonal APLC survey with finer parameter sampling in promising regions (e.g., FPM radii between 3 and 4 λ/D).
- Apply error diffusion algorithms to convert select apodizer solutions to binary shaped pupils.
- Begin producing input products for scientific yield calculations.
- Continue work on the Lyot stop alignment/fab tolerance problem.
- Survey designs with diaphragm-type focal plane masks (WFIRST-like).