Segmented mirror coronagraph study update

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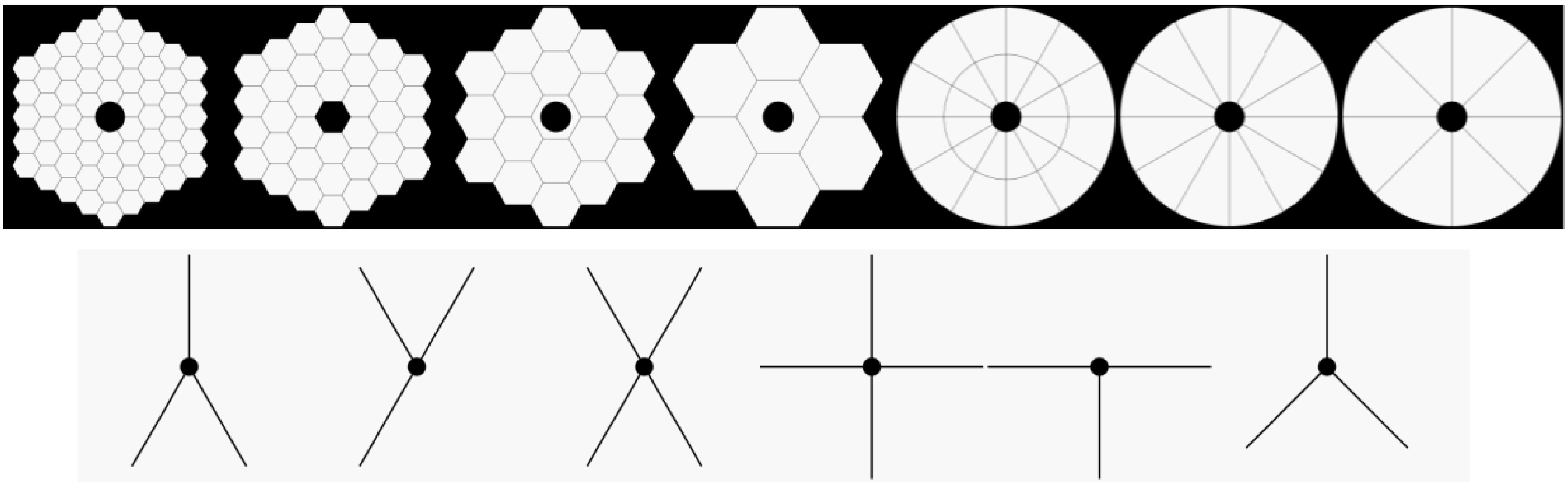
on behalf of Stuart Shaklan (PI), Jet Propulsion Laboratory, California Institute of Technology

AND

Caltech/JPL team: **G. Ruane, J. Jewell**, S. Shaklan, D. Mawet
STScI/Princeton team: **Neil T. Zimmerman, Mamadou N'Diaye, Kathryn St. Laurent**, Rémi Soummer, Christopher Stark, Laurent Pueyo, Anand Sivaramakrishnan, Marshall Perrin, Robert Vanderbei, Jessica Gersh-Range, Jeremy Kasdin
Arizona/AMES/JPL team: **O Guyon, J. Codona**, R. Belikov, B. Kern

HabEx STDT, JPL, 08-03-2016

Apertures for Segmented Coronagraph Design and Analysis (SCDA)



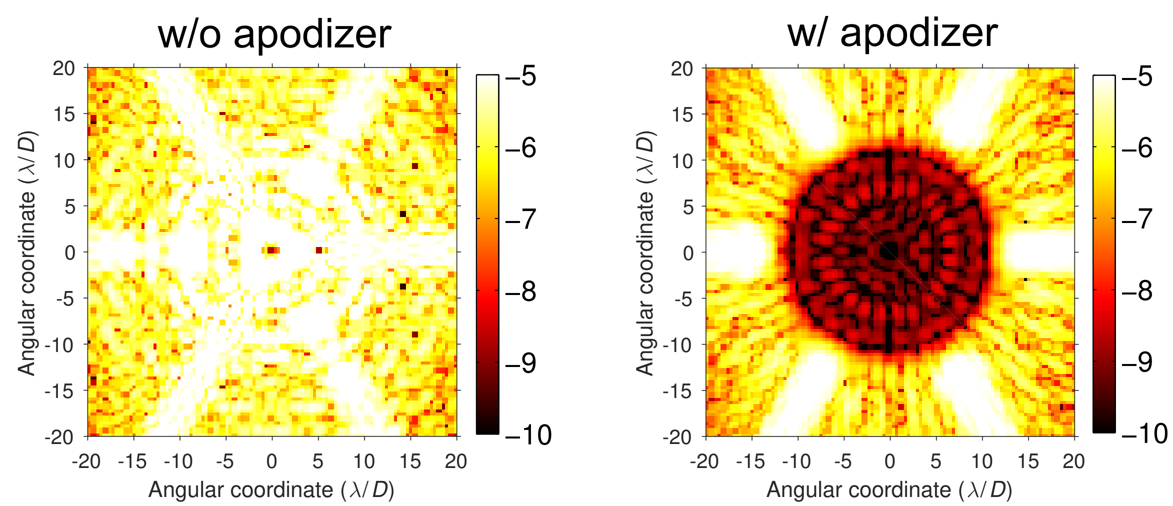
L. Feinberg, T. Hull, J. Scott Knight, J. Krist, P. Lightsey, G. Matthews, P. Stahl, and S. Shaklan

Relative challenges of designs under consideration

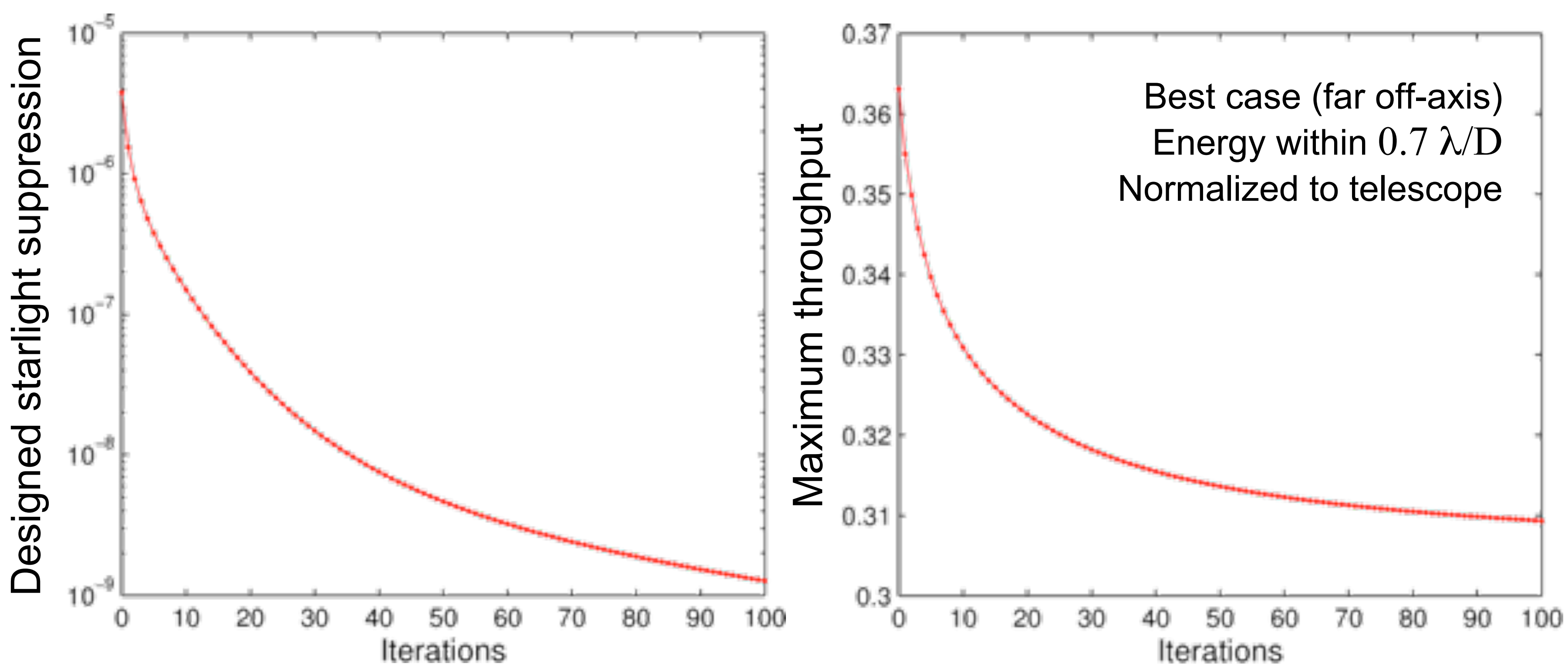
	APERTURES						
	4 ring	3 ring	2 ring	1 ring	Keystone 24	Pie wedge 12	Pie wedge 8
Segment Shape	Hex	Hex	Hex	Hex	Keystone	Pie wedge	Pie wedge
Max Segm. Dimension	1.54 m	1.98 m	2.77 m	4.62 m	2.5 m x 3.14 m	5 m x 3.14 m	5 m x 4.71 m
Segments							
Backplane							
Stability							
Launch Configuration							
SM Support							
Overall Ranking							

Throughput vs starlight suppression

G. Ruane et al. 2016, in prep

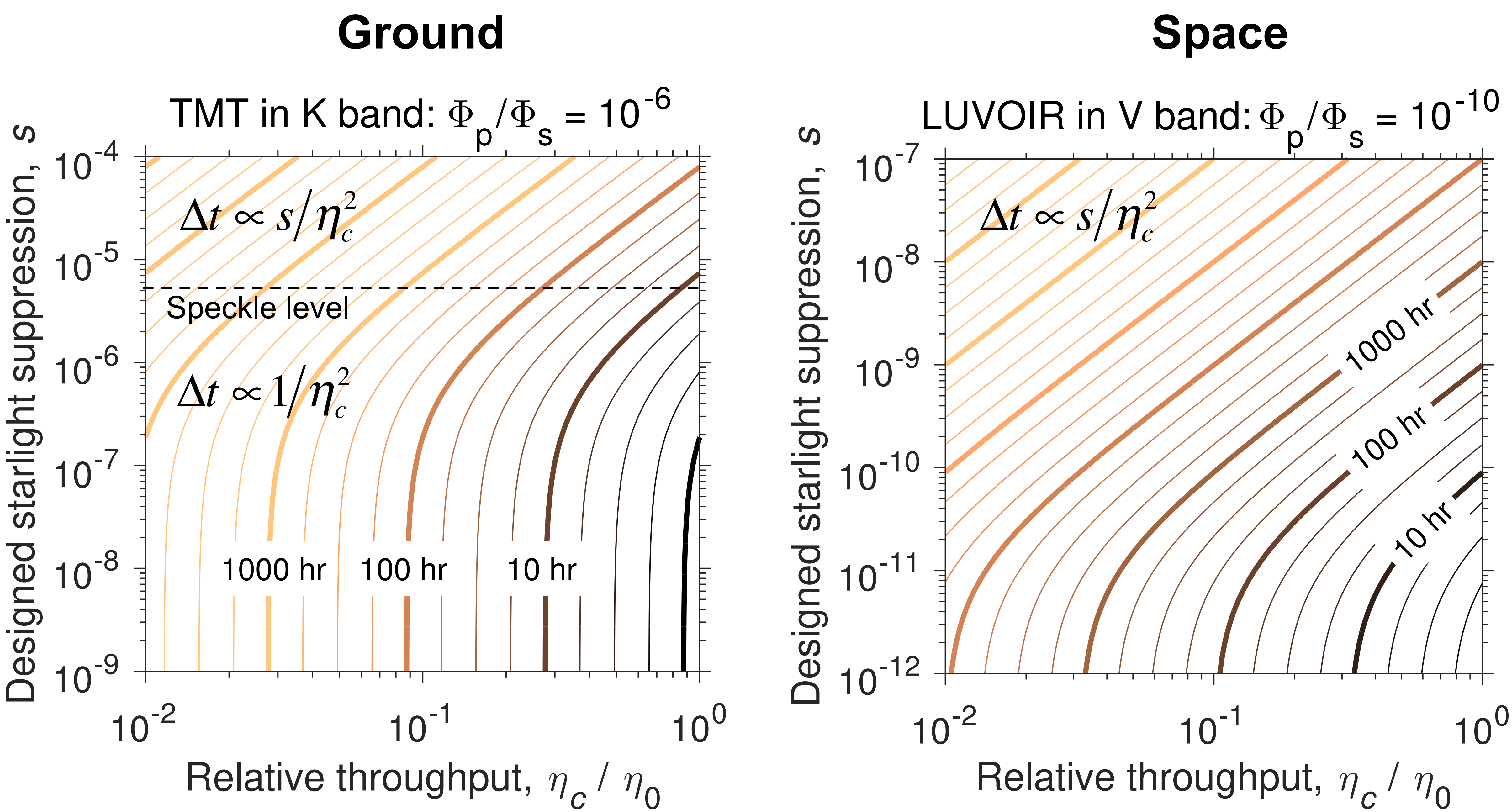


How much throughput should be sacrificed for starlight suppression?

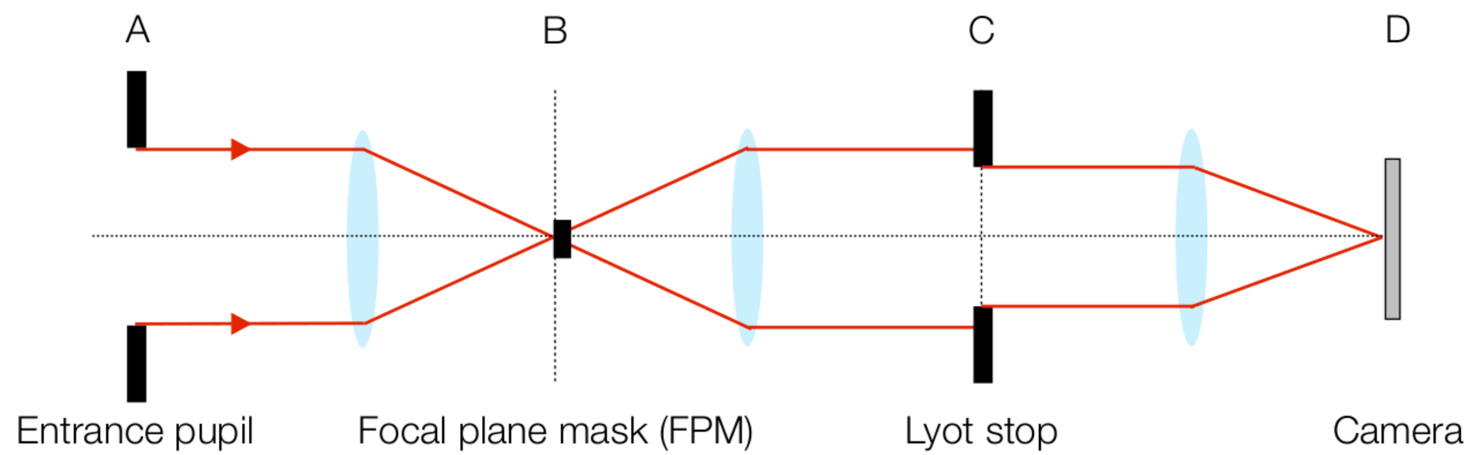


Relevant metric: integration time

G. Ruane et al. 2016, in prep



Team STScI/Princeton: Apodized/shaped pupil Lyot coronagraph



Lyot plane field amplitude

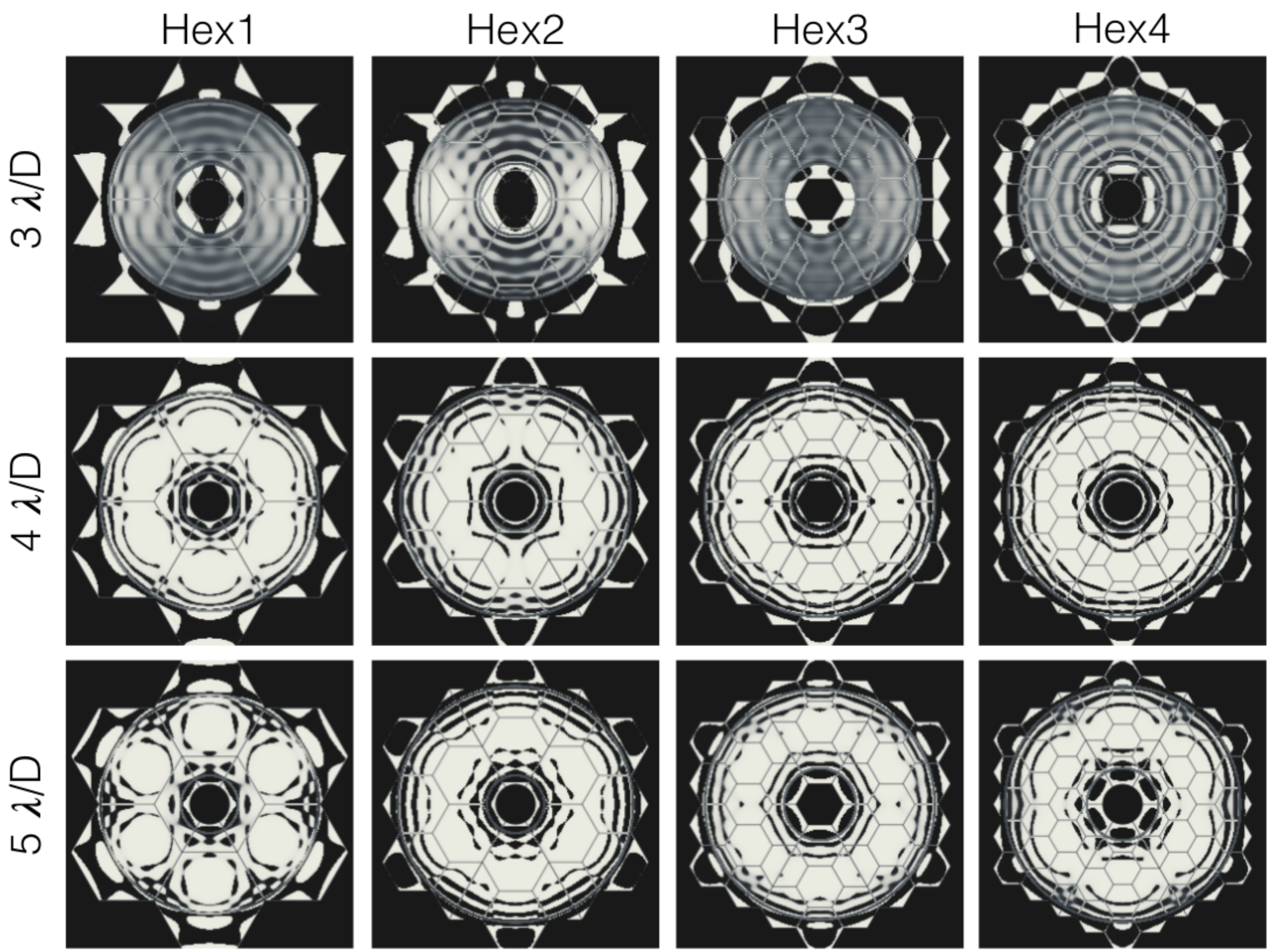
$$\Psi_C(\mathbf{r}) = \Psi_A(\mathbf{r}) - \left(\Psi_A(\mathbf{r}) * \widehat{M}(\mathbf{r})\right) P(\mathbf{r})$$

Pupil amplitude

Diffracted wave by the mask

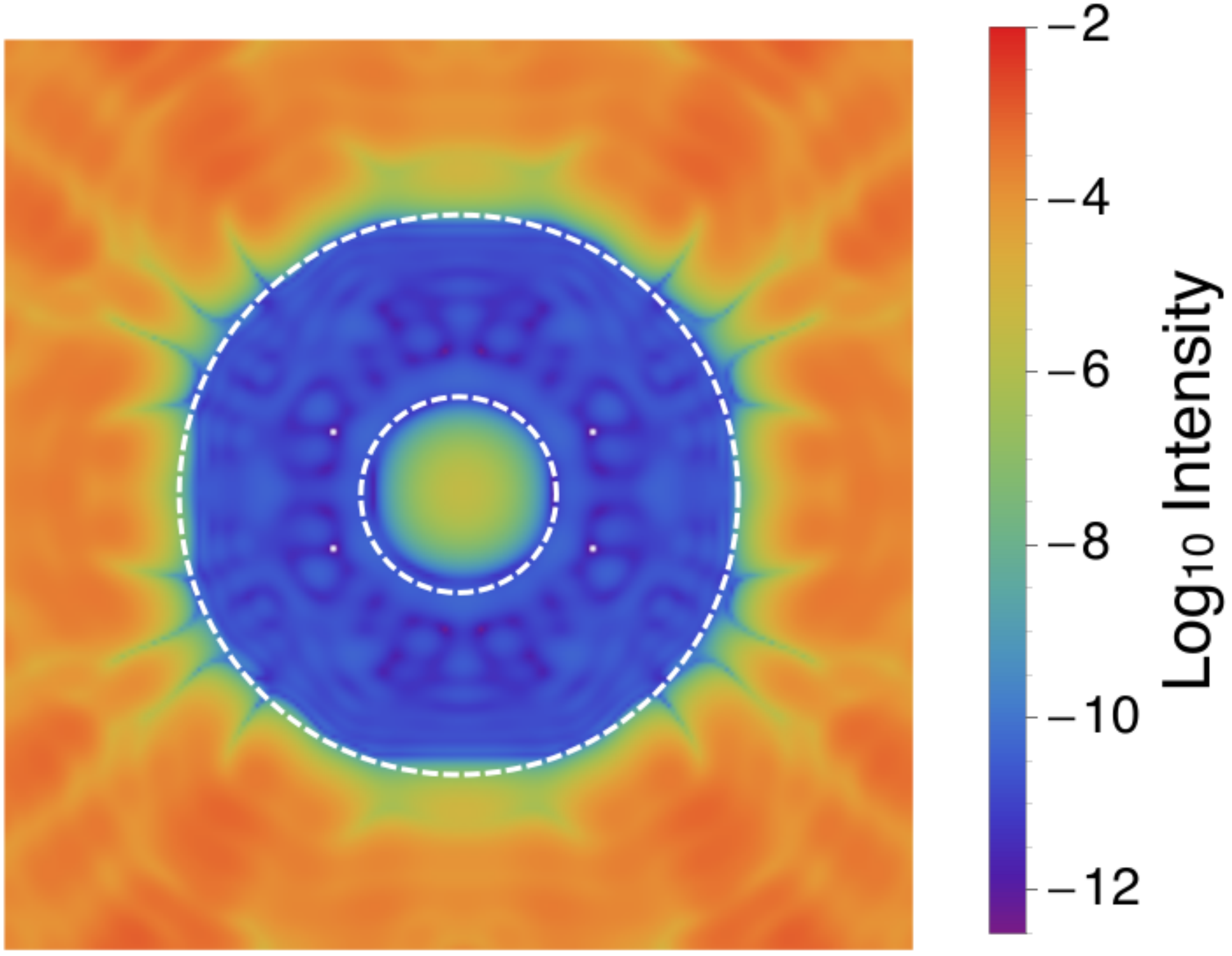
- Space Telescope Science Institute: Neil T. Zimmerman, Mamadou N'Diaye, Kathryn St. Laurent, Rémi Soummer, Christopher Stark, Laurent Pueyo, Anand Sivaramakrishnan, Marshall Perrin
- Princeton University: Robert Vanderbei, Jessica Gersh-Range, Jeremy Kasdin

APLC designs



Brute force optimization

APLC raw contrast



APLC throughput

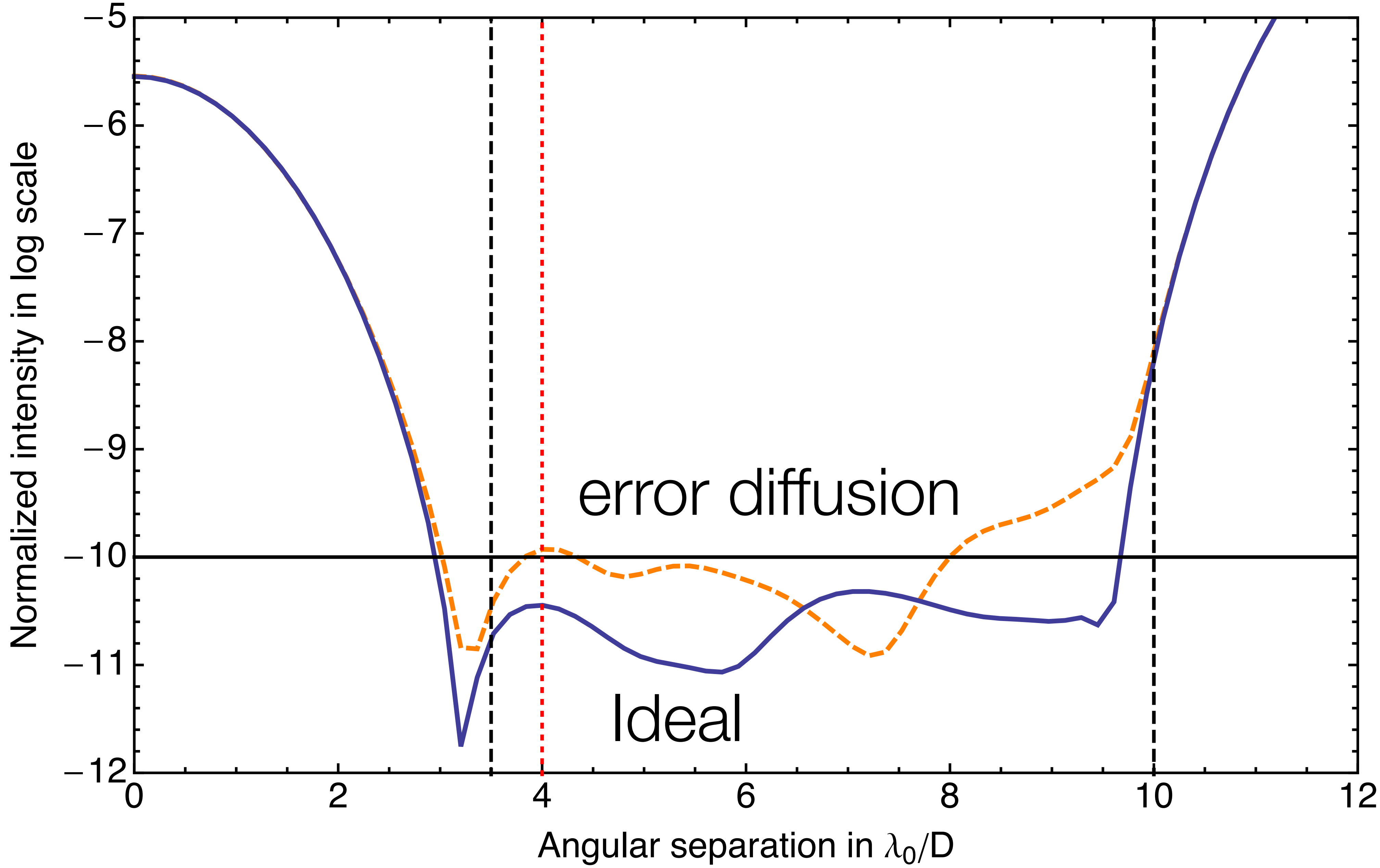
10% BW

FPM rad.	Telescope aperture							
	Hex1		Hex2		Hex3		Hex4	
(λ_0/D)	core	rel.	core	rel.	core	rel.	core	rel.
3.0	7.7%	17.6%	7.8%	17.6%	7.0%	16.0%	6.4%	14.6%
4.0	17.9%	40.9%	18.9%	42.7%	19.2%	44.0%	19.0%	43.2%
5.0	16.2%	37.1%	18.6%	42.1%	18.0%	41.4%	18.1%	41.1%

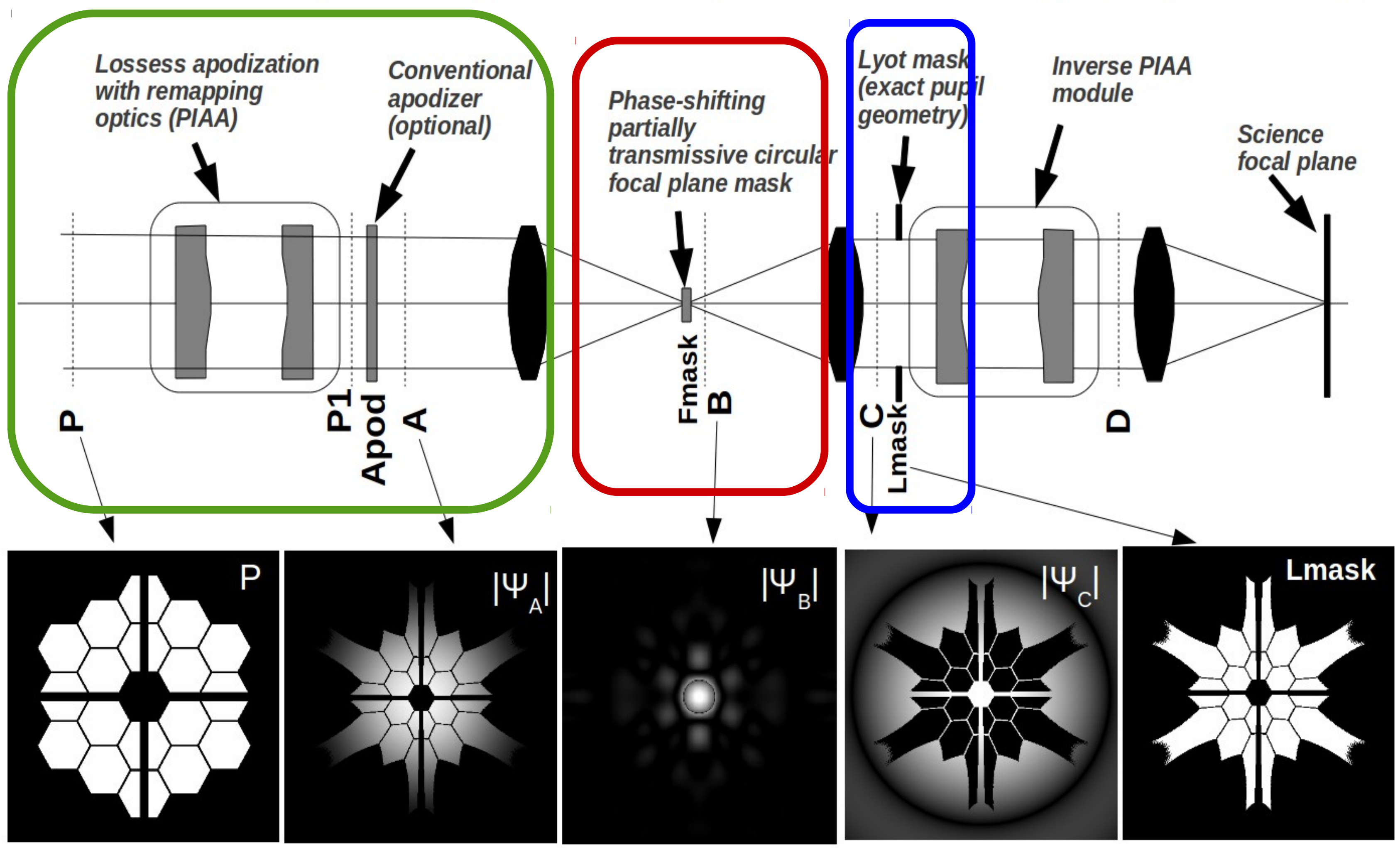
15% BW

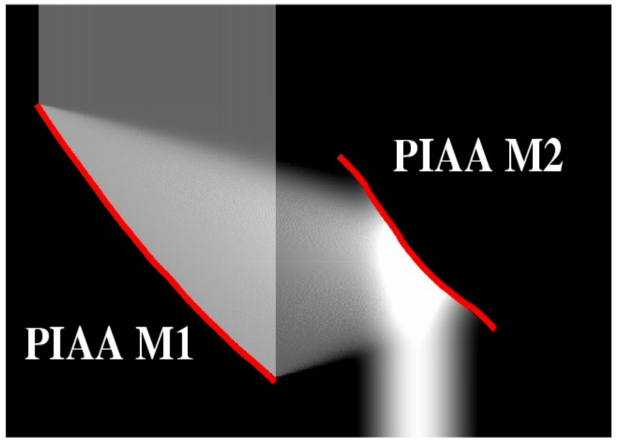
FPM rad.	Telescope aperture							
	Hex1		Hex2		Hex3		Hex4	
(λ_0/D)	core	rel.	core	rel.	core	rel.	core	rel.
3.0	7.3%	16.6%	7.5%	17.2%	8.0%	18.5%	8.0%	18.1%
4.0	12.5%	28.4%	18.1%	41.3%	18.0%	41.7%	17.7%	40.3%
5.0	15.6%	35.4%	18.3%	41.9%	17.9%	41.4%	18.0%	40.7%

Apodizer manufacturing challenges



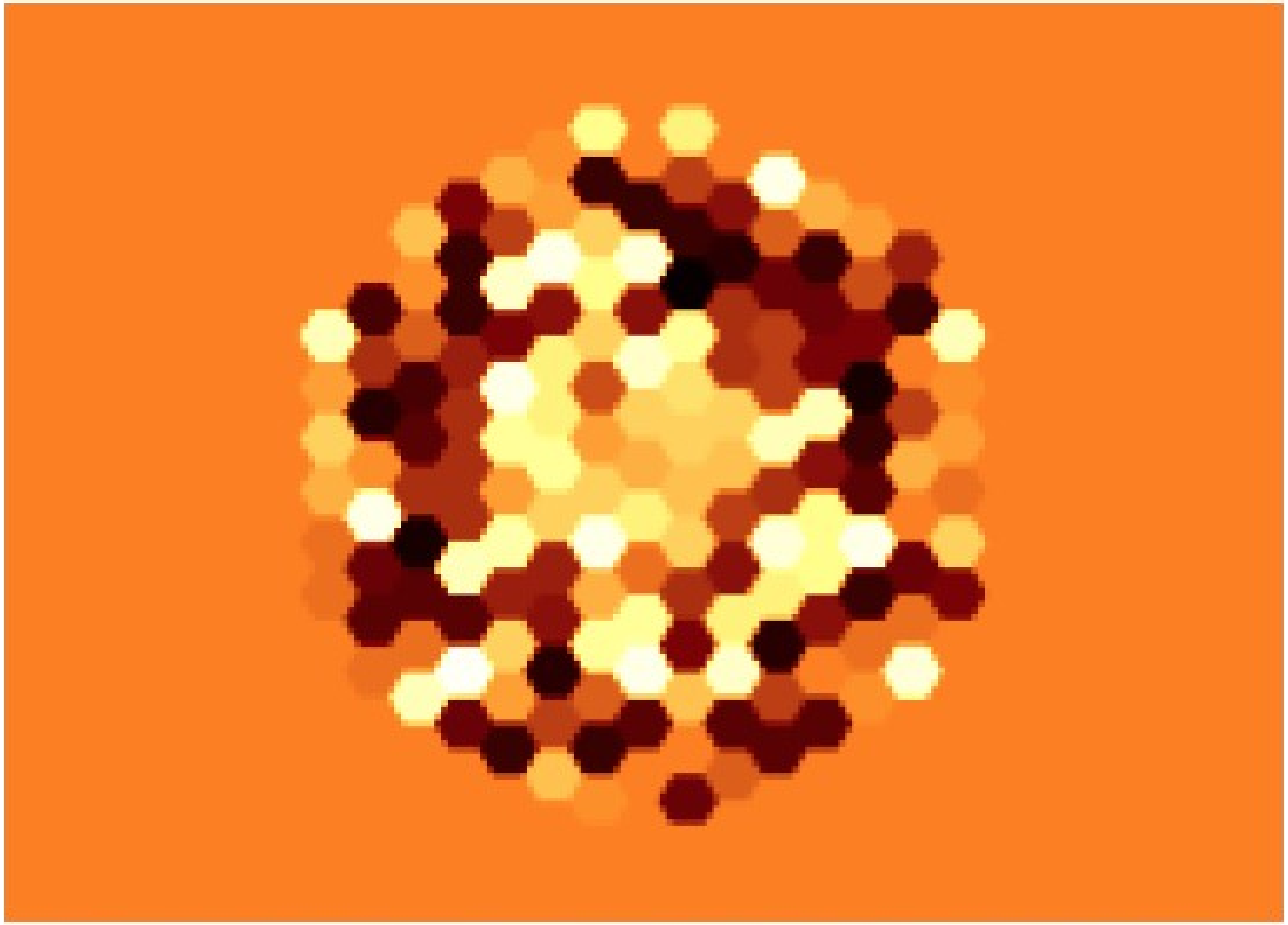
Team UoA/AMES/JPL:
Phase Induced Amplitude Apodized Complex Mask Coronagraph





- University of Arizona/AMES/JPL: O. Guyon, J. Codona, R. Belikov, B. Kern

~~Complex~~ Phase Mask Coronagraph: mask design

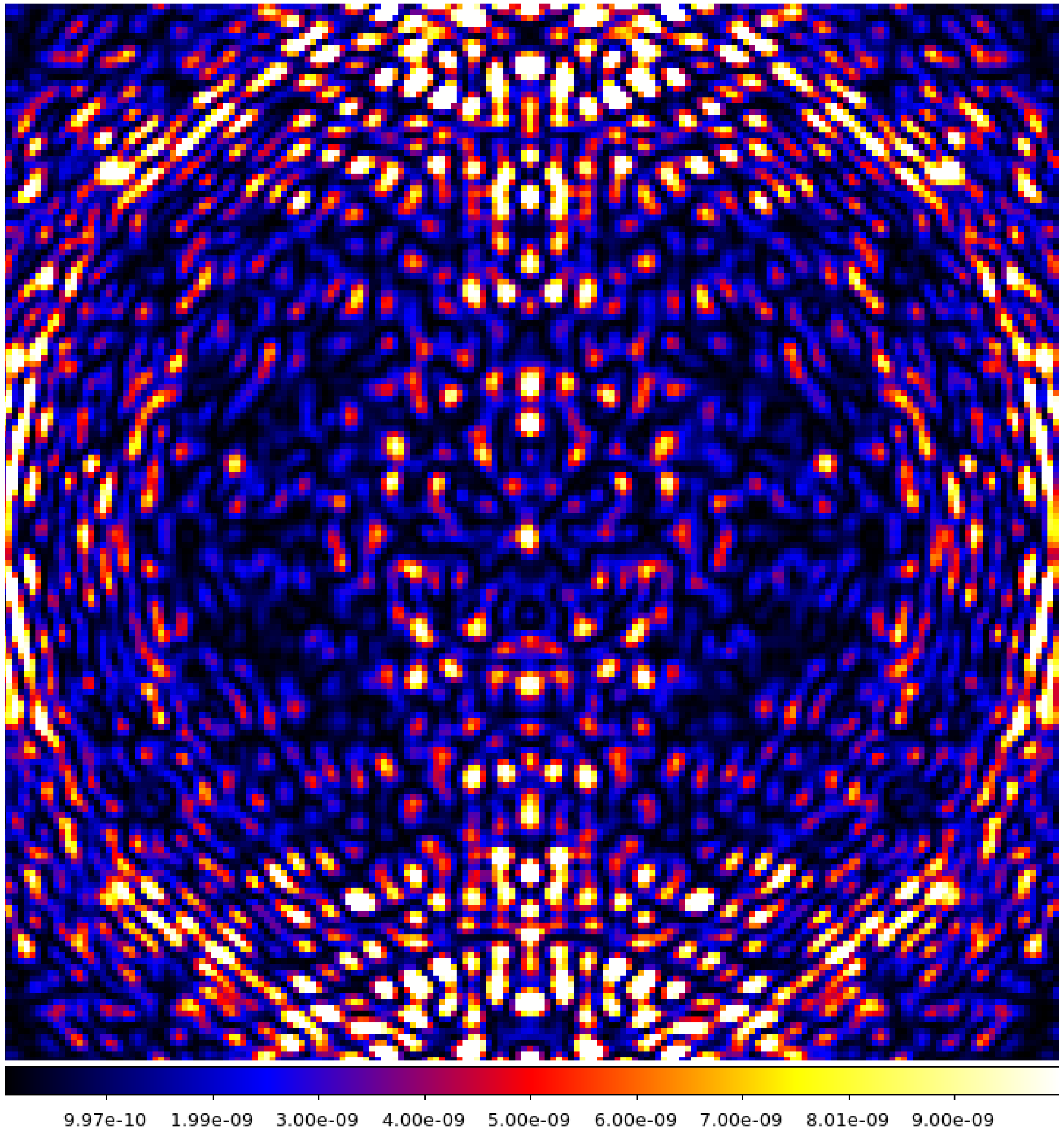


~1 wave PTP, d ~ 3 λ/D

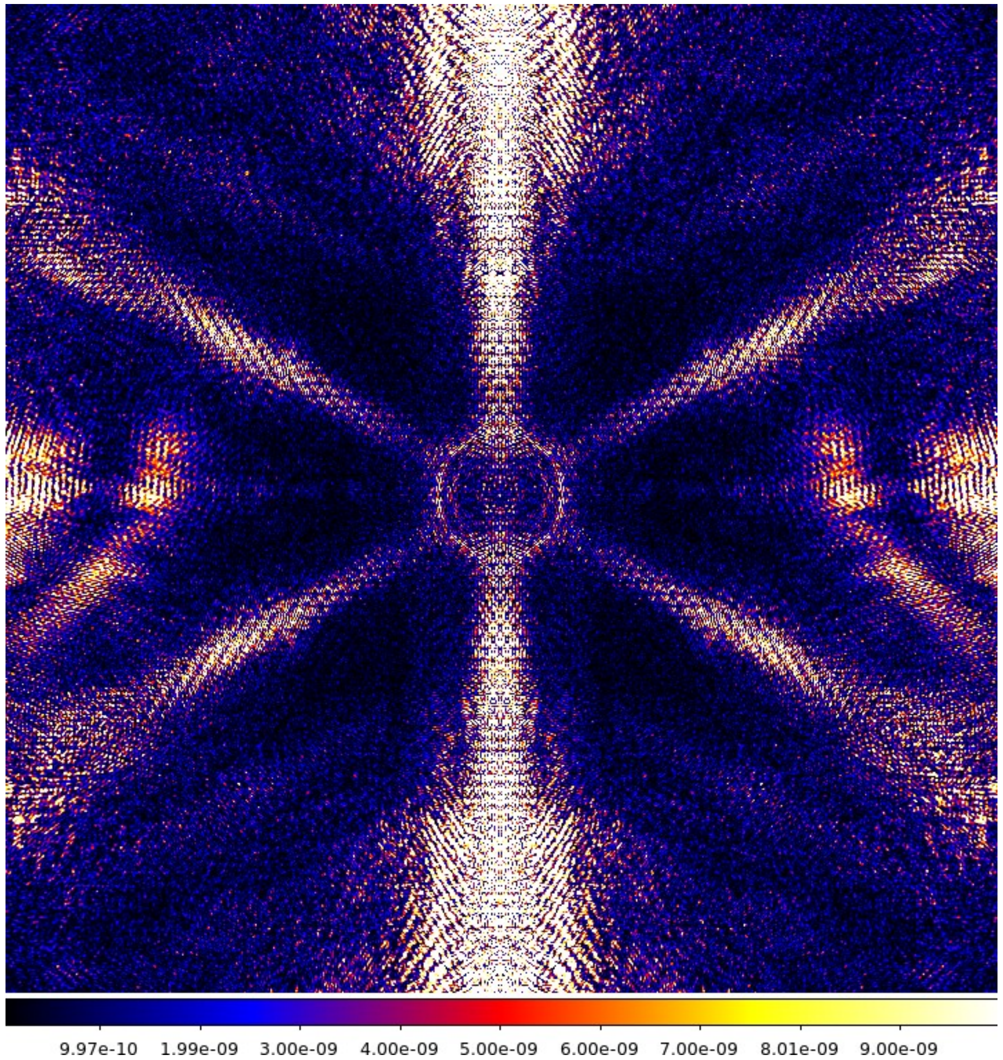
Current PSF contrast (point source, monochromatic)

contrast : 2.8e-9 average in 1.5-8 l/D zone
… currently optimizing PIAA shape to improve

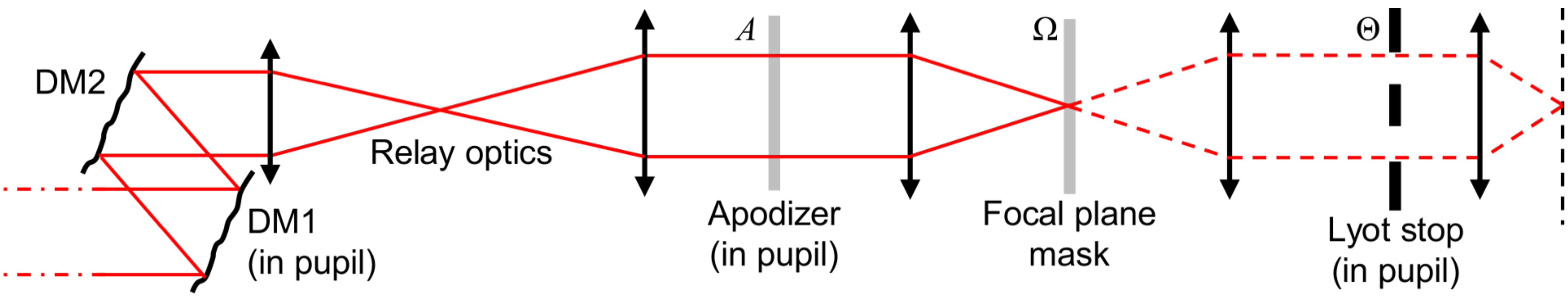
10% BW(*)



wide view:
0.17% of starlight scattered by high spatial frequency noise



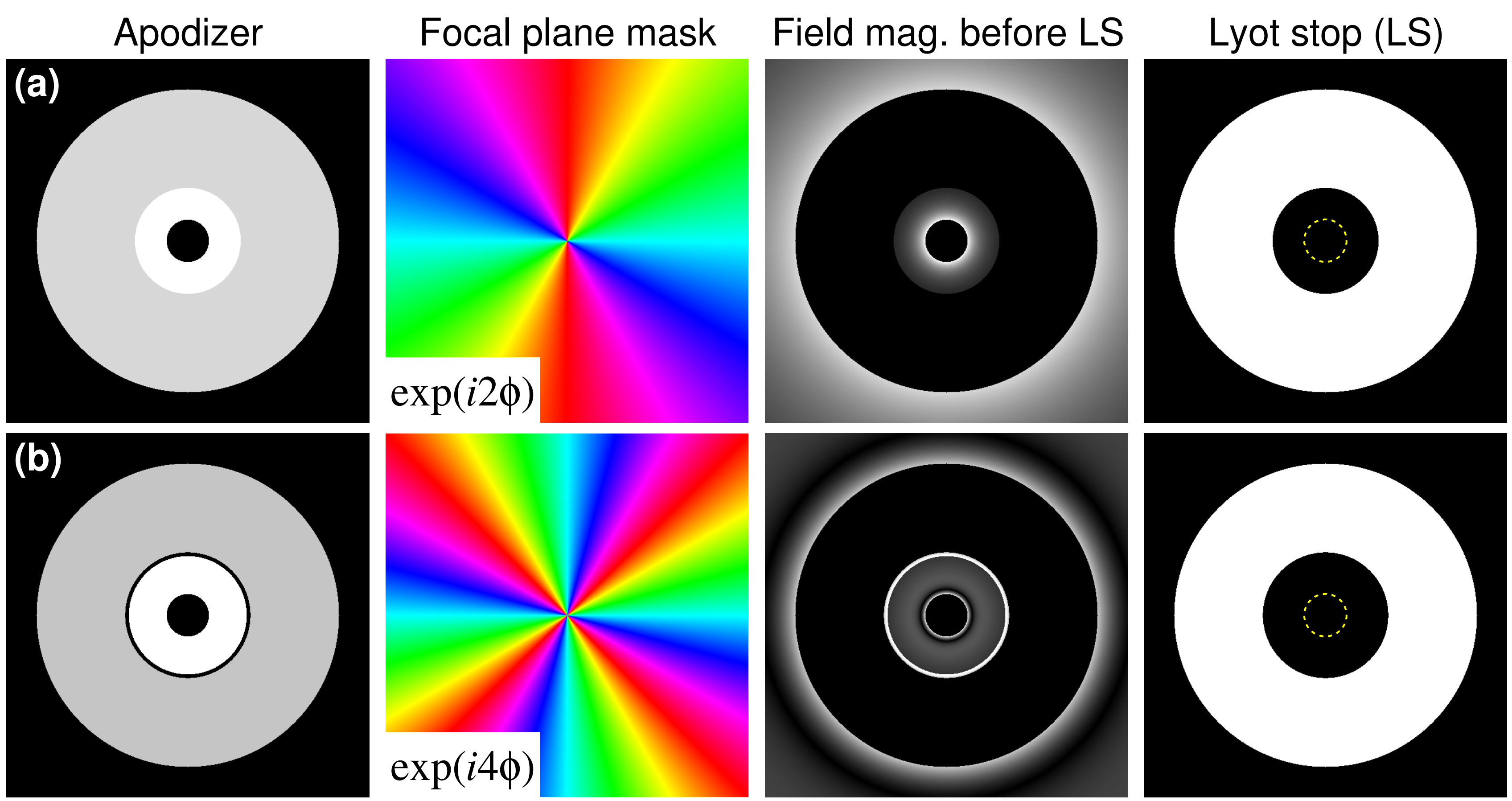
Team Caltech/JPL:
Apodized vortex (and HLC)



- Caltech: **Garreth Ruane**, Dimitri Mawet
- JPL: Jeff Jewell, Stuart Shaklan

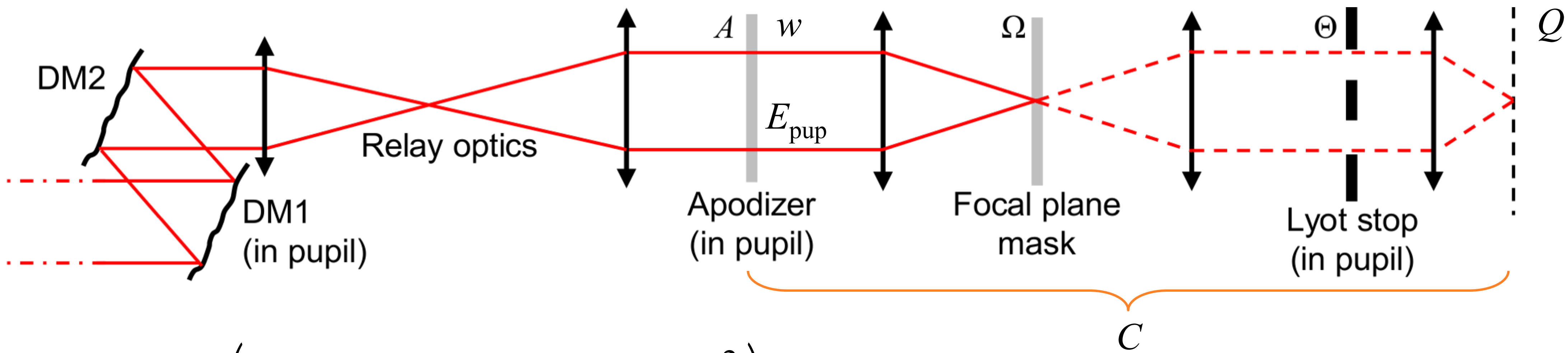
Apodized vortex design

- Start with ring-apodized vortex (RAVC) analytical solution (Mawet et al. 2013)



- Finish off with a new, game-changing method invented by Jeff Jewell (JPL): *Auxiliary Field Conjugation*

Optimization procedure



$$\min_{w}\left(\left\|QCw\right\|^2 + b\left\|w - E_{pup}\right\|^2\right)$$

Algorithm: 1. Solve for pupil field that will create the specified dark hole:

$$w = \left(bI + C^{\dagger}QC\right)^{-1} bE_{pup}$$

2. Apply constraints set by optical system to $A = |w|$:

$$0 \leq A \leq 1$$

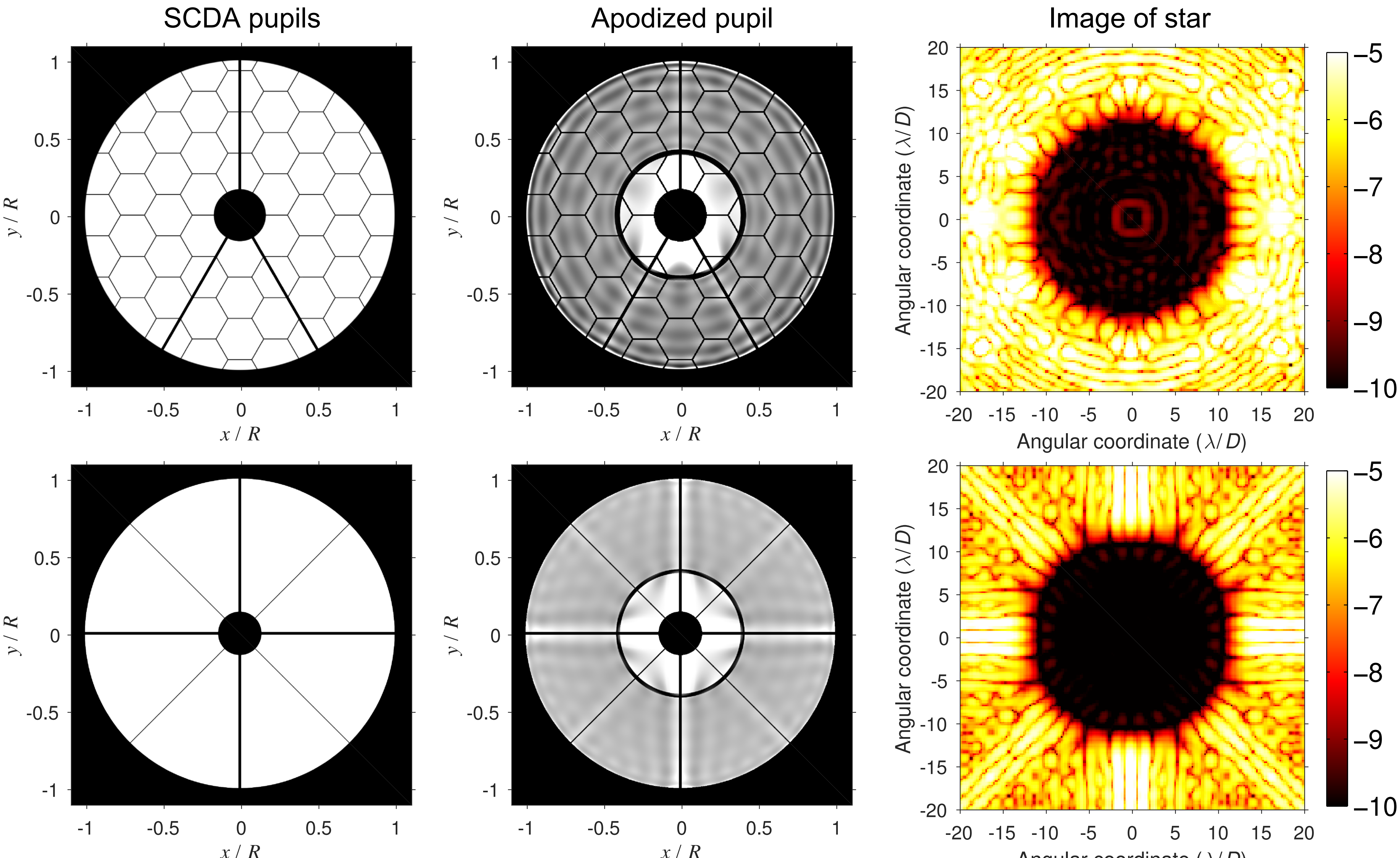
$$\mathrm{supp}\{A\} = \mathrm{supp}\{P\}$$

3. Set $E_{pup} = PA$, and repeat

C – coronagraph propagation operator
Q – dark hole region
w – auxiliary field
b – regularization parameter
E_{pup} – current pupil field
A – gray-scale apodizer
P – original pupil field

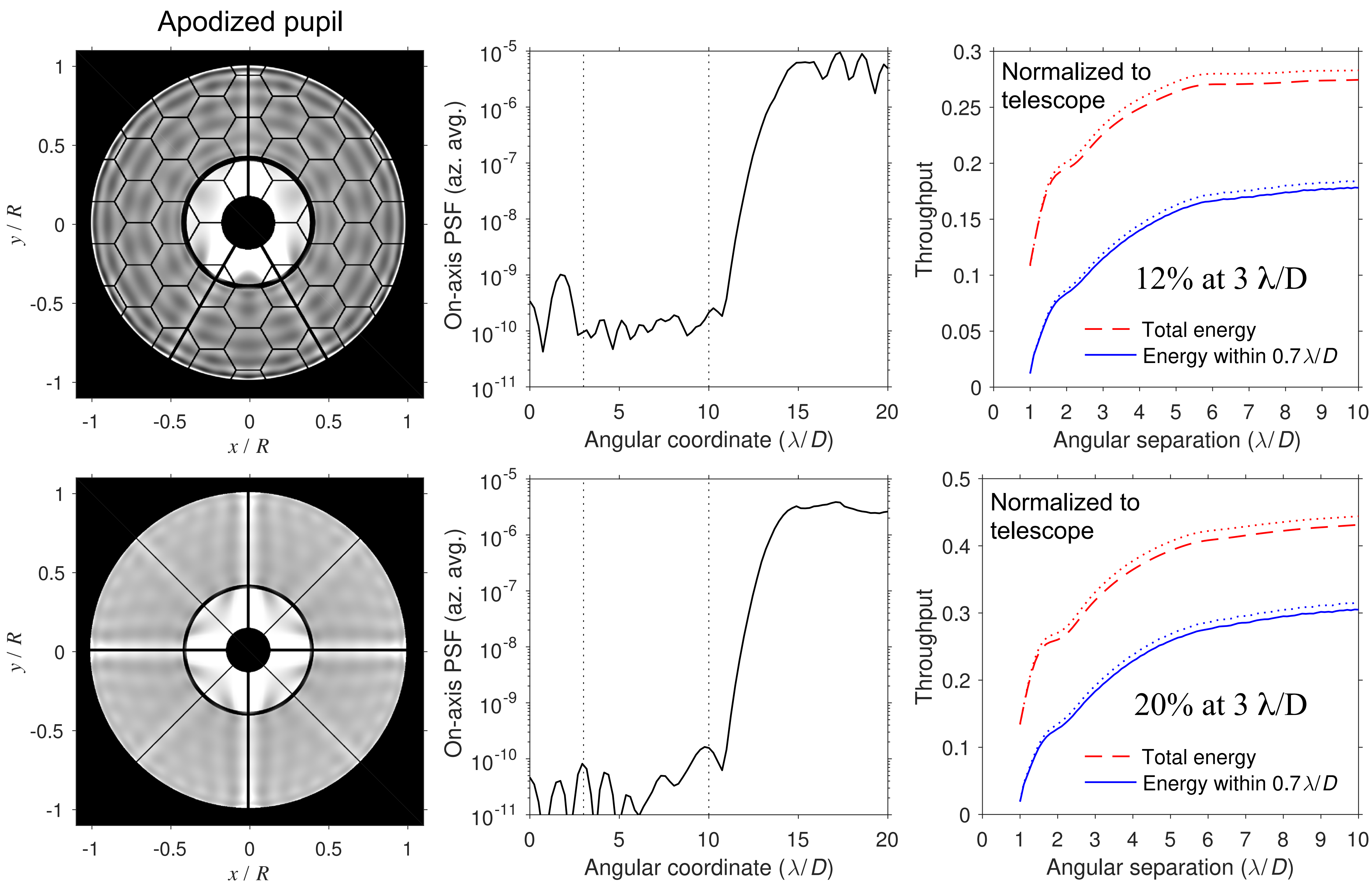
Aux. field conjugation algorithm developed by Jeff Jewell, JPL

Apodized vortex solutions for SCDA pupils



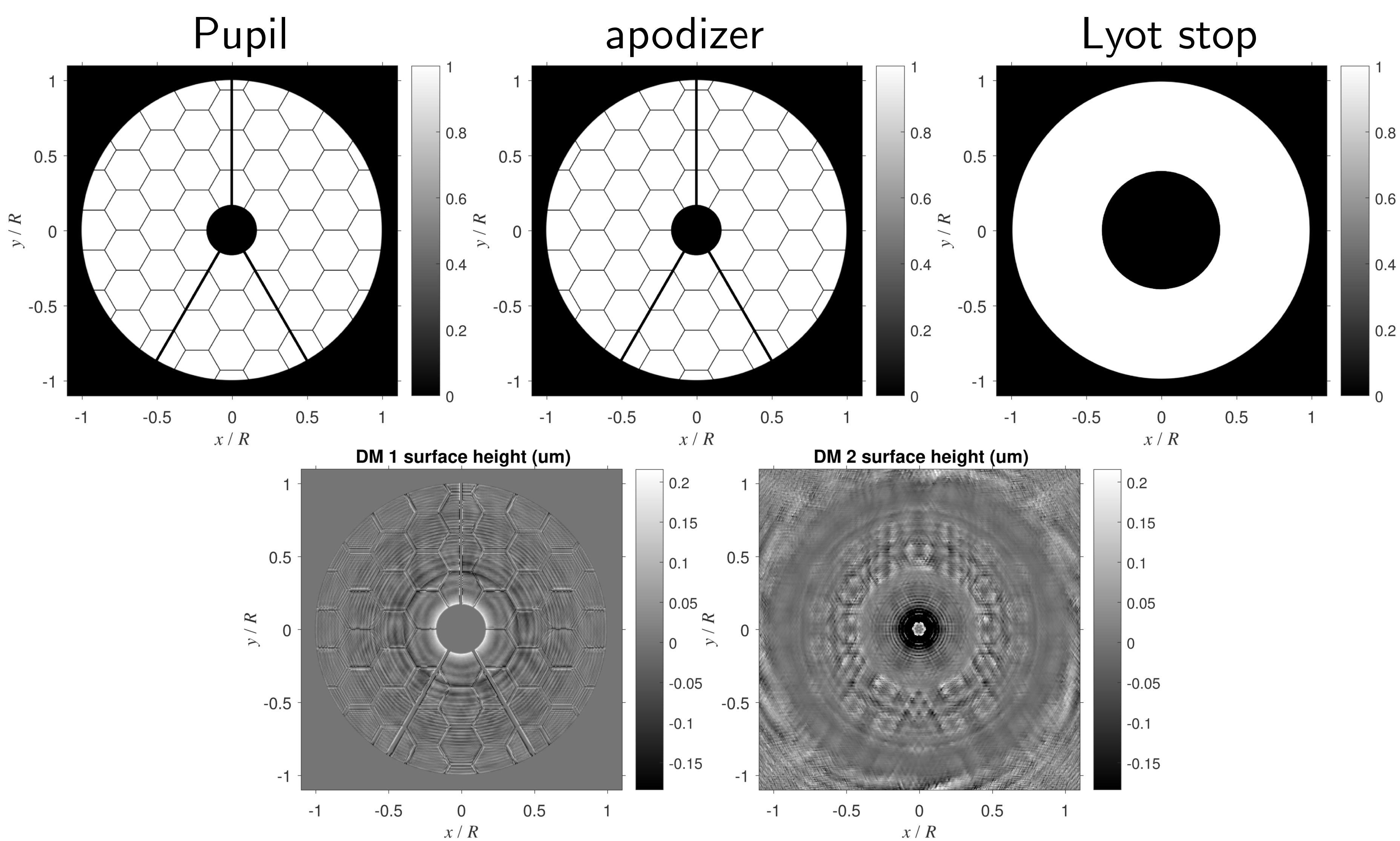
Solutions are wavelength independent!

Apodized vortex solutions for SCDA pupils



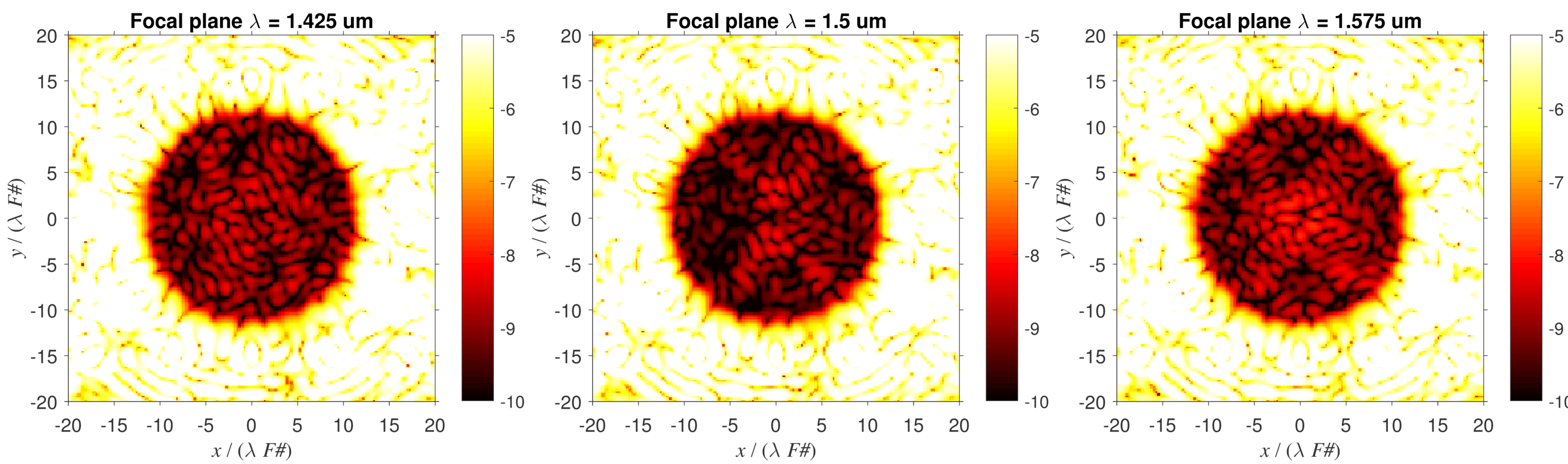
Using the DMs to generate phase-induced apodization of spiders

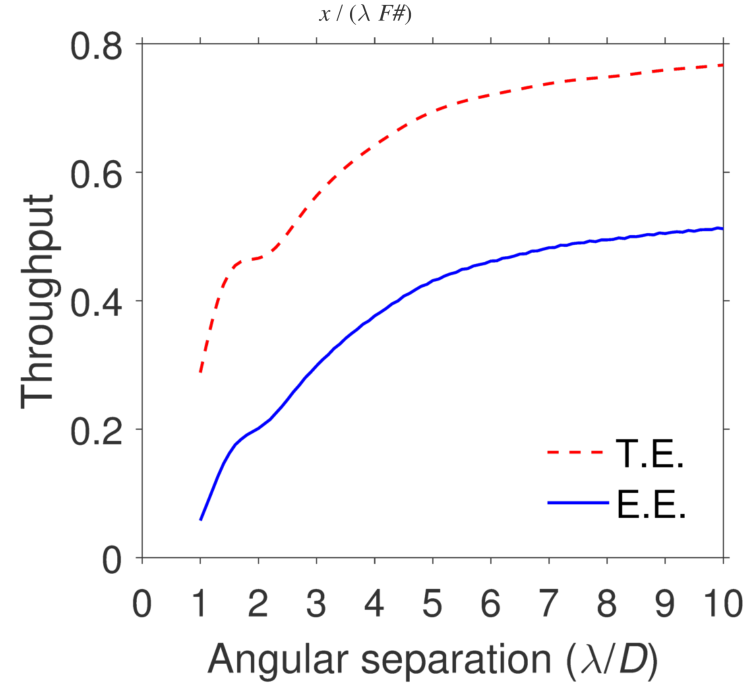
Clippedhex4 w/ 10cm spiders, VC4 (no apod.), Dark hole: 3-10 λ/D annulus, $z = 300$mm, F = 56, 10% bandwidth (3λ's), 500 iterations



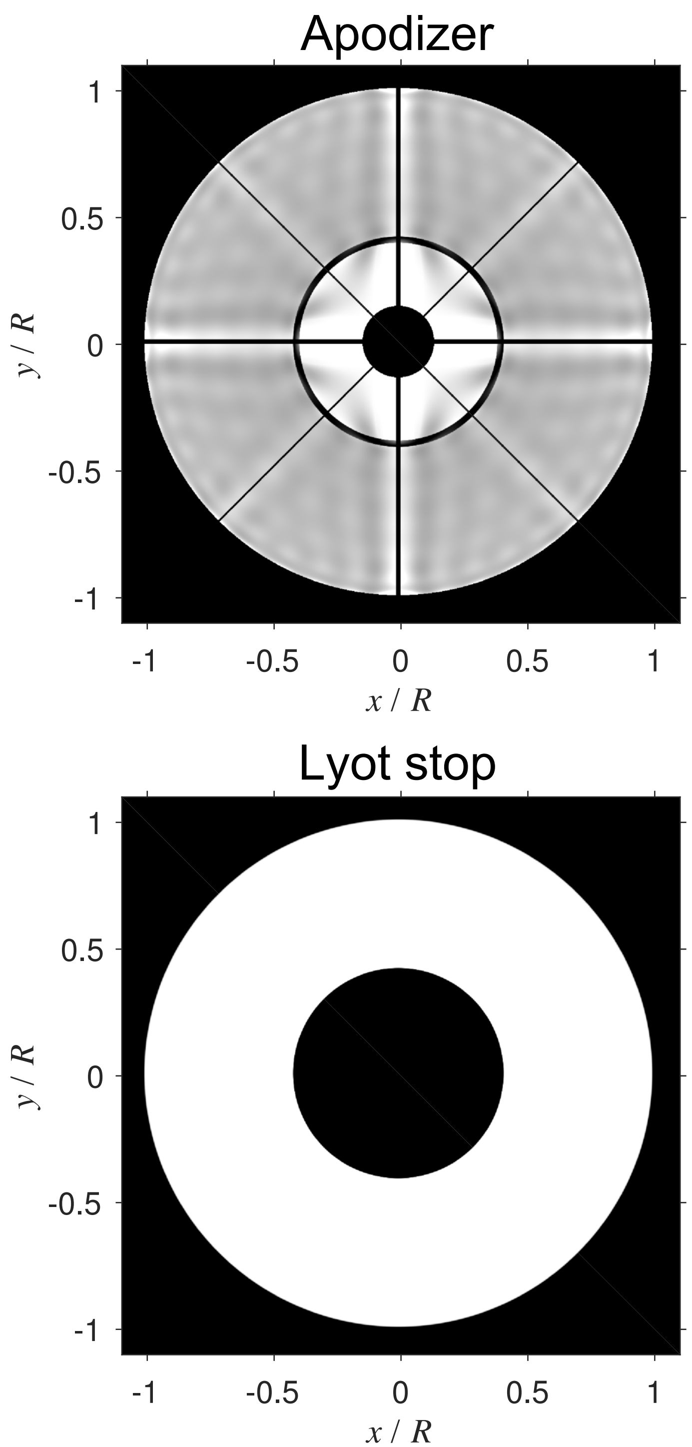
Doubles throughput

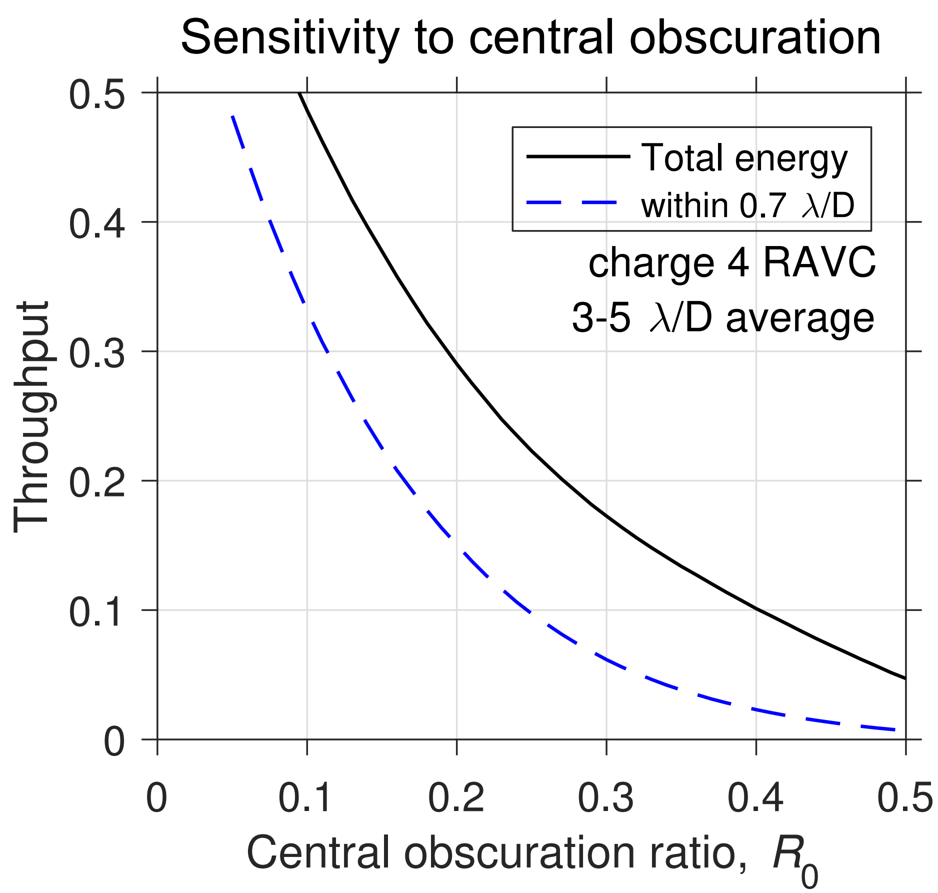
Clippedhex4 w/ 10cm spiders, VC4 (no apod.), Dark hole: 3-10 λ/D annulus, $z = 300$mm, F $= 56$, 10% bandwidth (3λ's), 500 iterations





Central obscuration limits the throughput

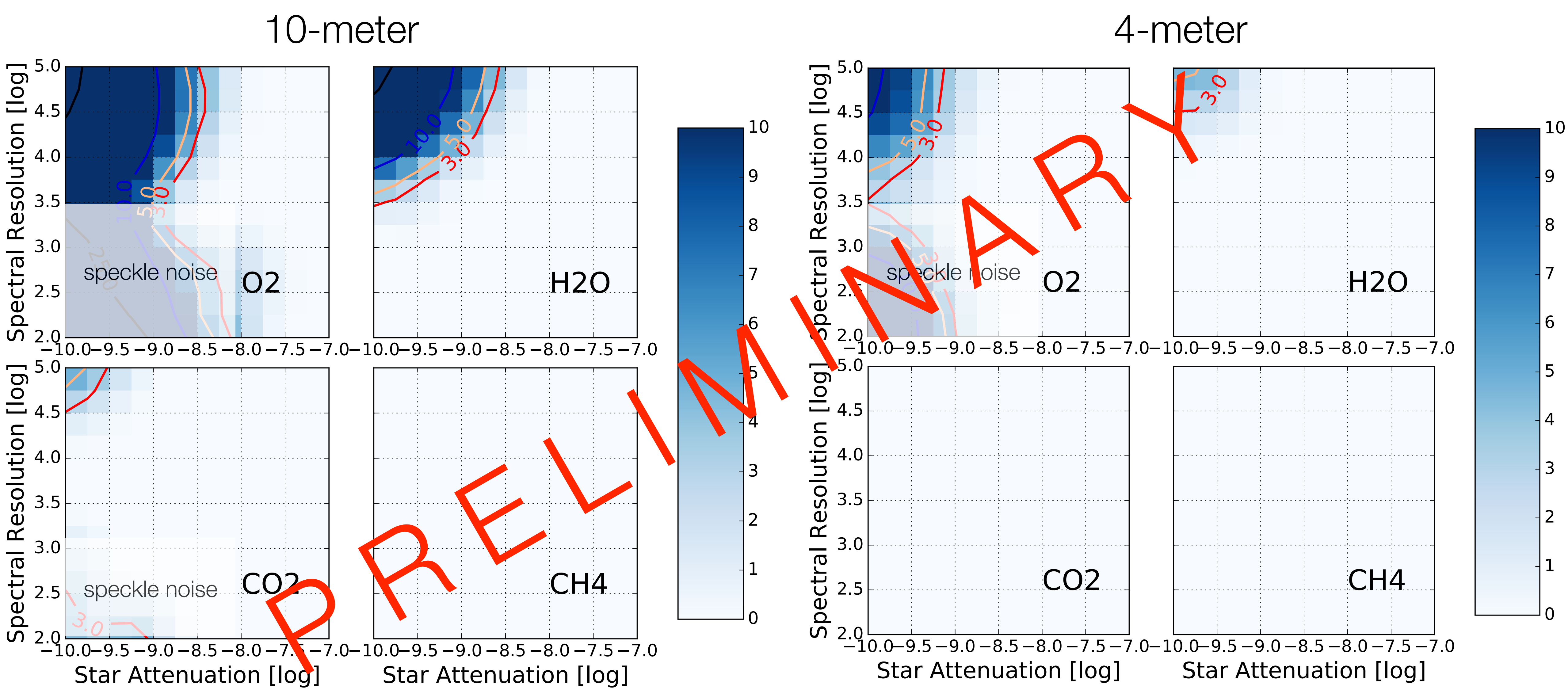




Unobscured, segmented telescopes

Scientific motivation for larger apertures

Wang, Mawet, Ruane, Hu, Benneke 2016, in preparation

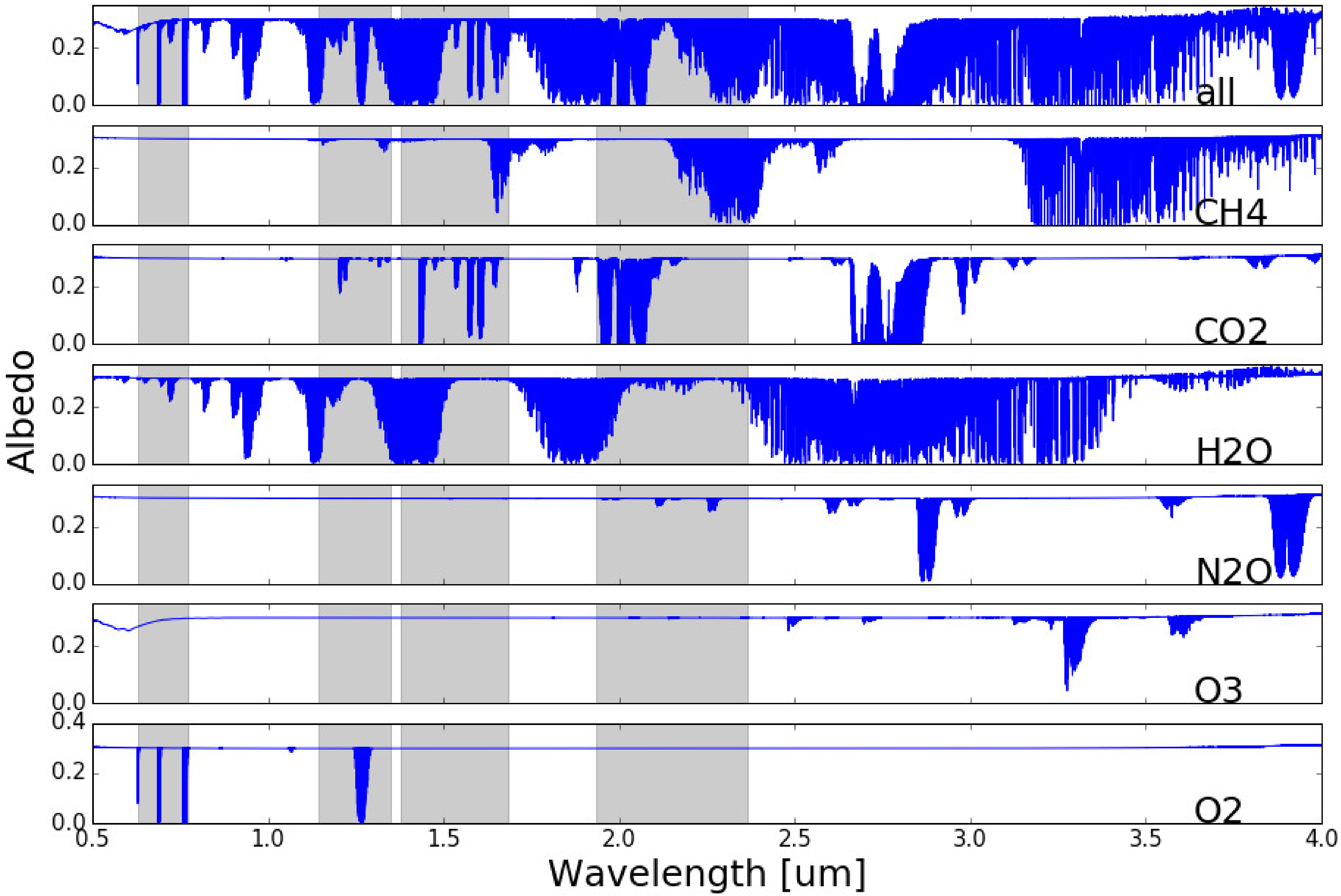


SNR in the spectral resolution vs starlight attenuation space (tint = 100 hr)

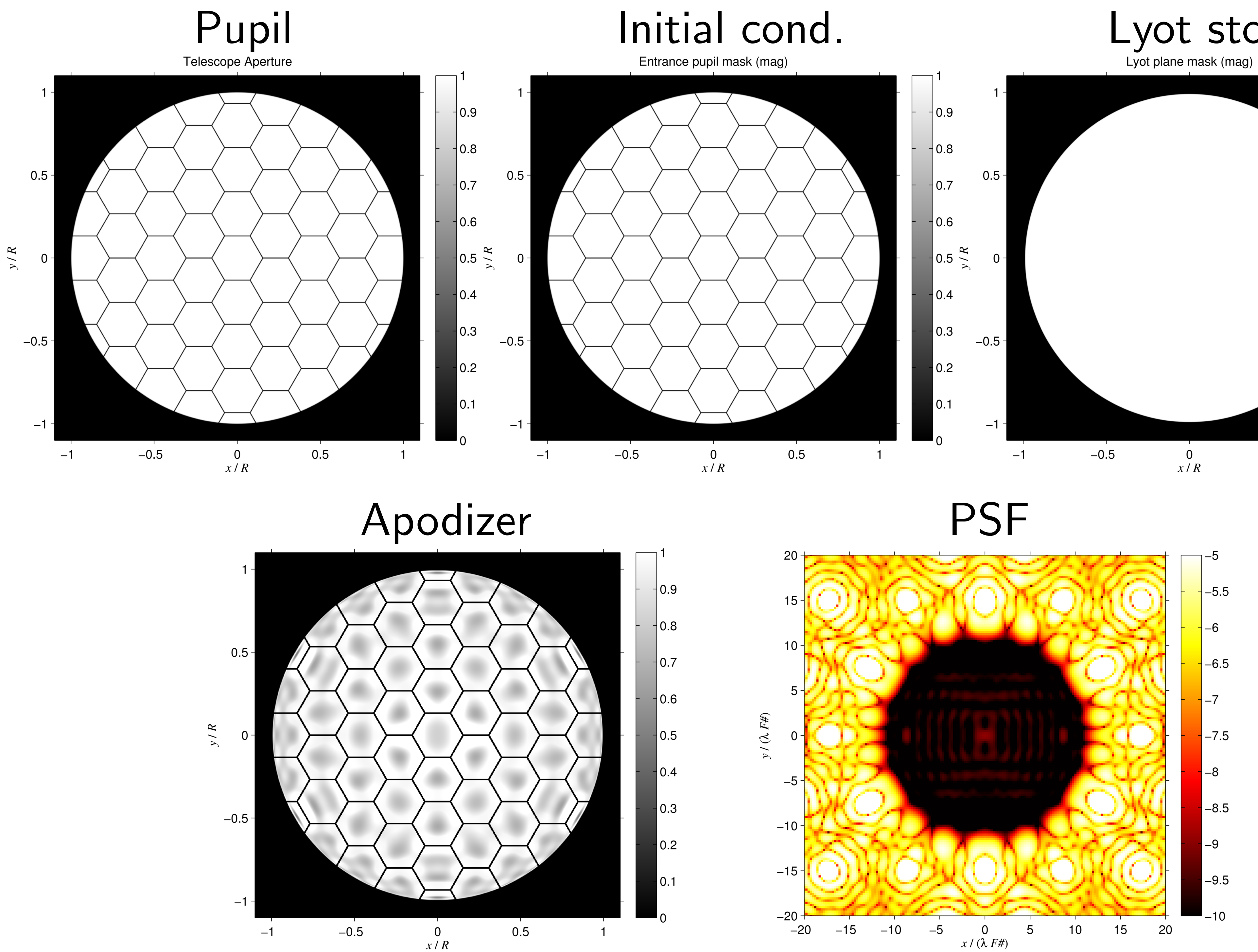
- Impact on telescope architecture: relax contrast requirements, thus stability
- Impact on instrument architecture: IFS or imager + classical high-R spectrograph

Scientific motivation for larger apertures

Wang, Mawet, Ruane, Hu, Benneke 2016, in preparation

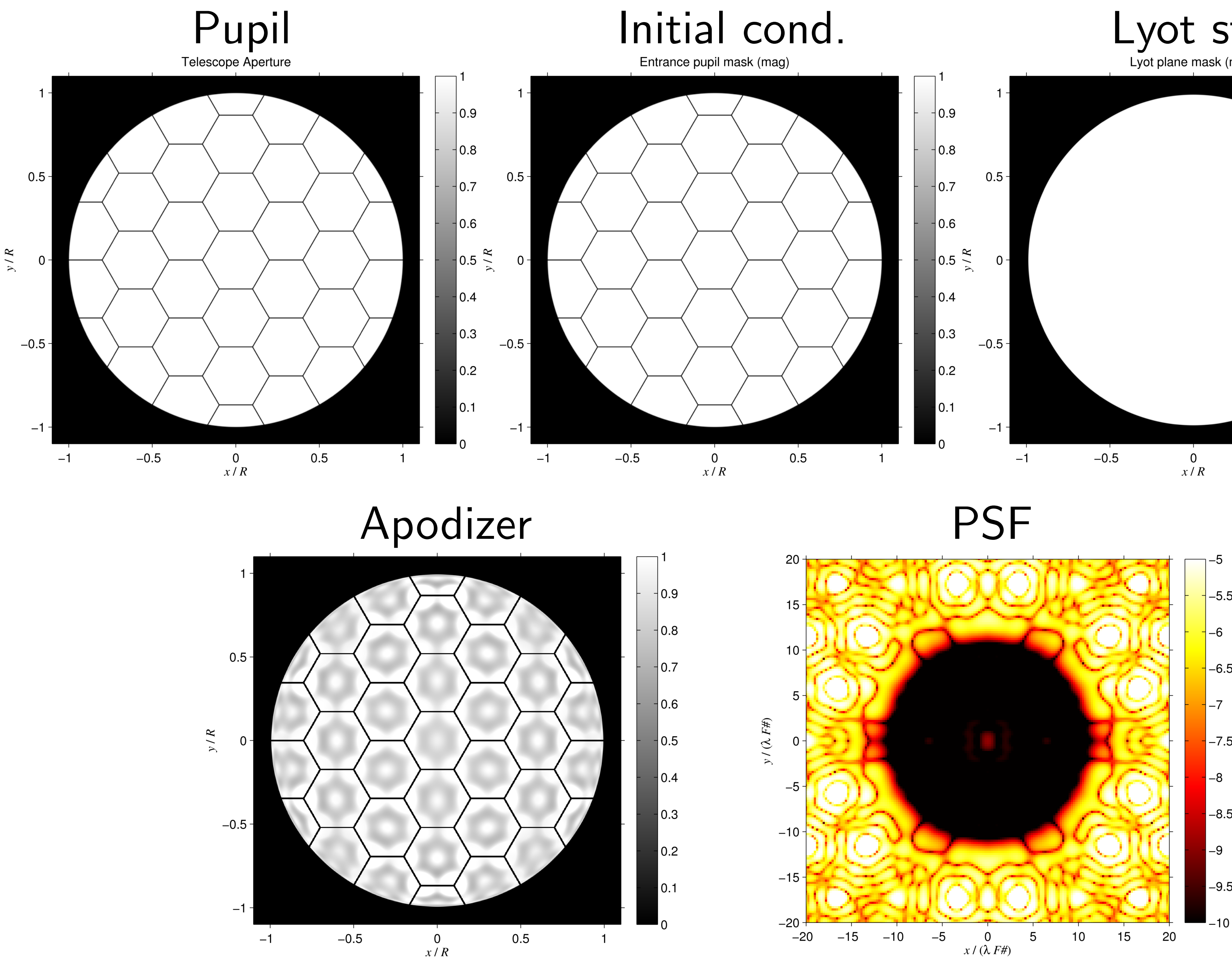


Clippedhex4 w/o central obscuration



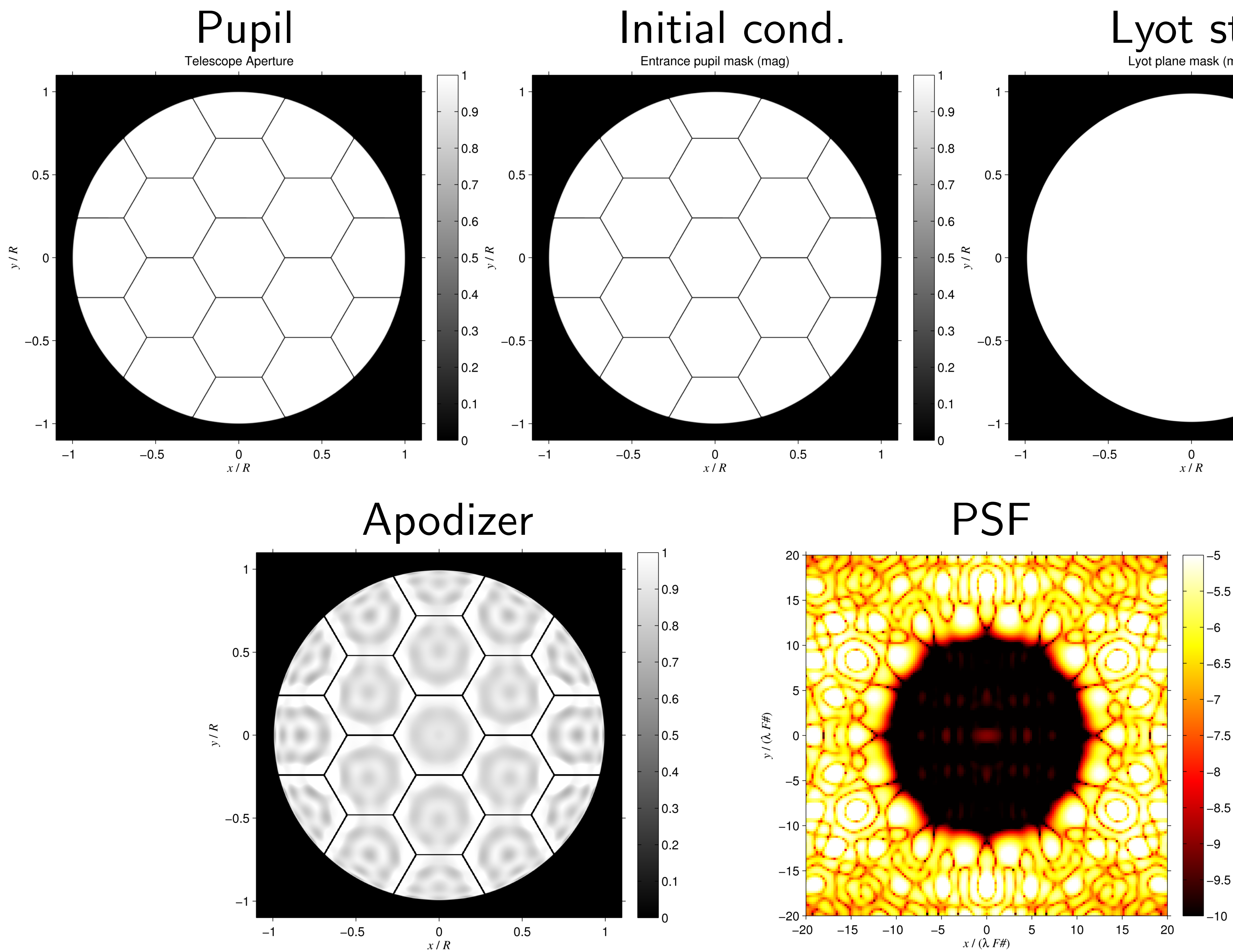
Max. throughput = 76% (PSF core relative to telescope).

Clippedhex3 w/o central obscuration



Max. throughput = 76% (PSF core relative to telescope).

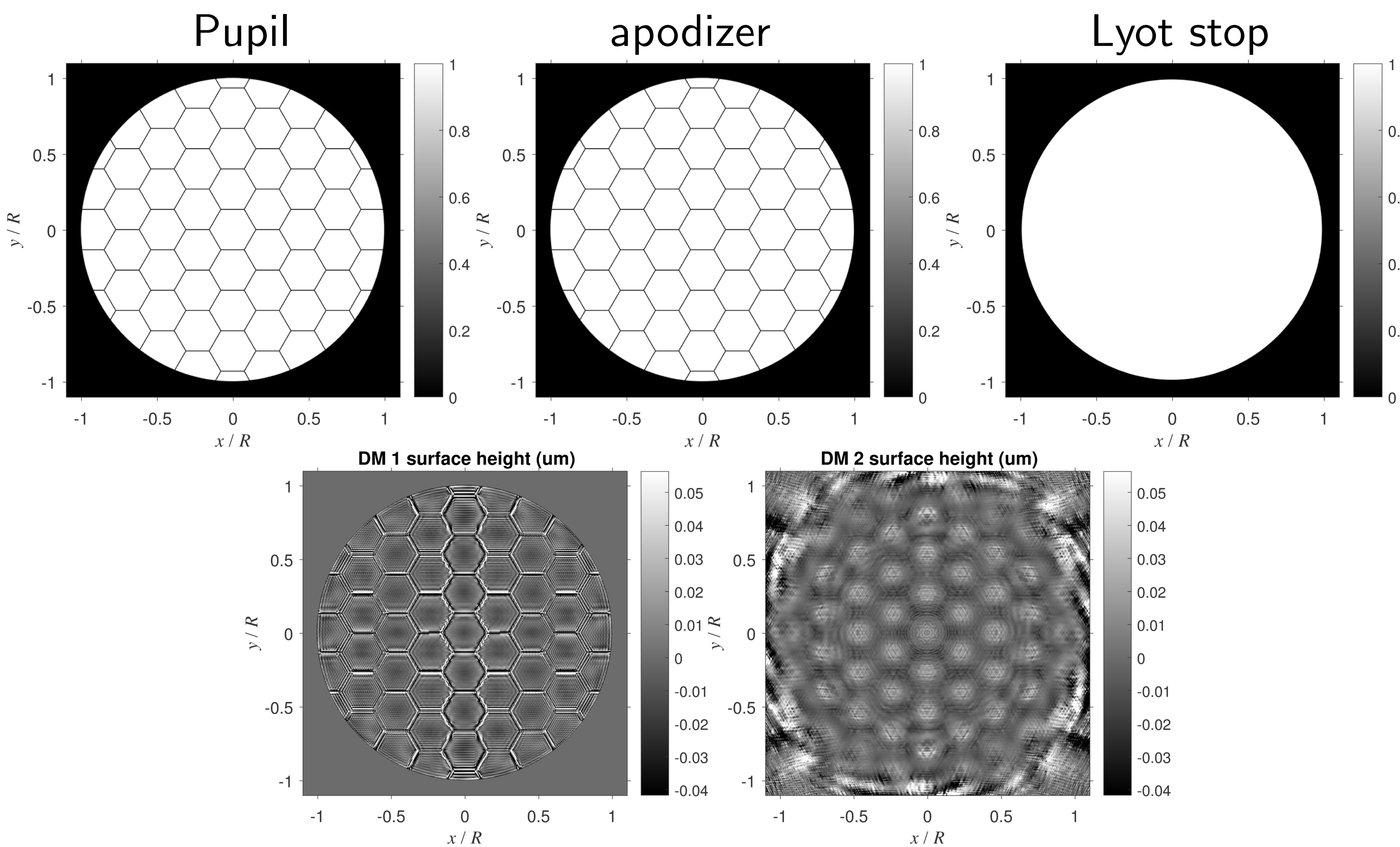
Clippedhex2 w/o central obscuration



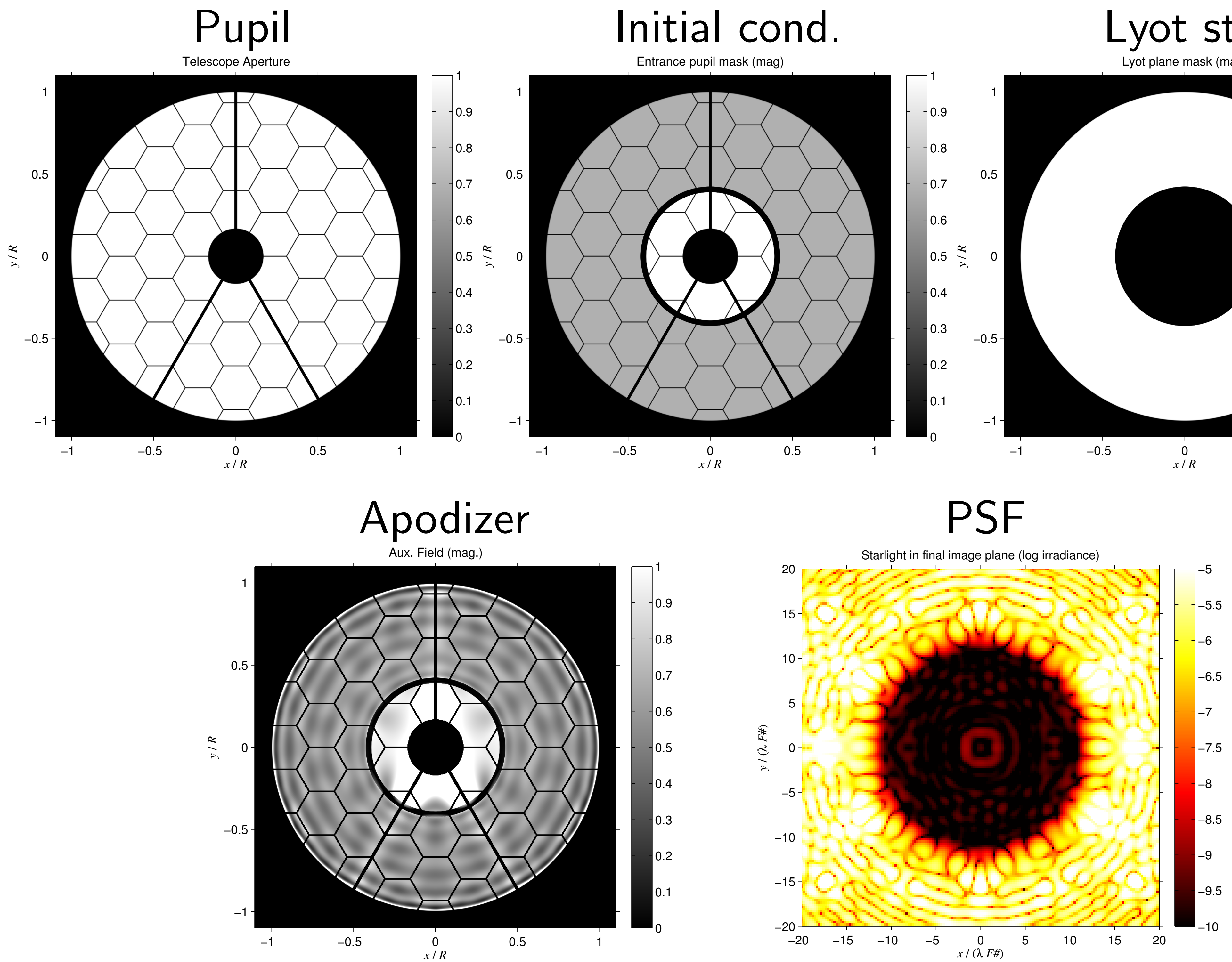
Max. throughput = 78% (PSF core relative to telescope).

Using the DMs to generate phase-induced apodization of segment gaps

- Gain additional ~5-10% in throughput, approach lossless coronagraph (>80% throughput)



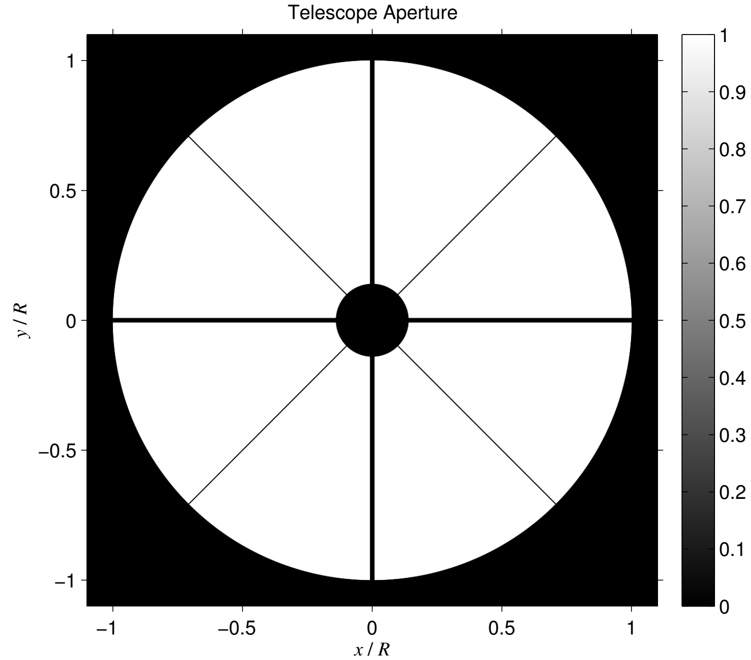
Clippedhex4 w/ central obscuration and ring apodizer (for comparison)



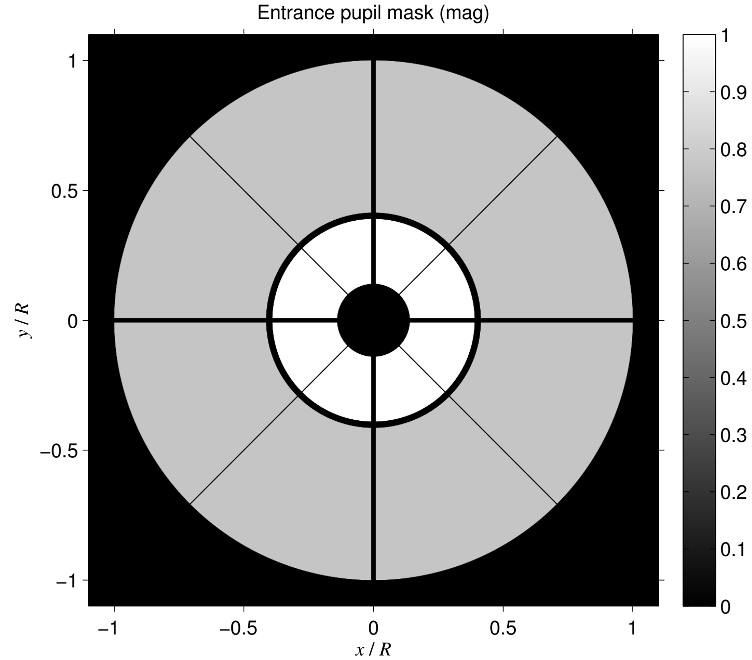
Max. throughput = 21% (PSF core relative to telescope).

Piewedge8 w/ central obscuration and ring apodizer (for comparison)

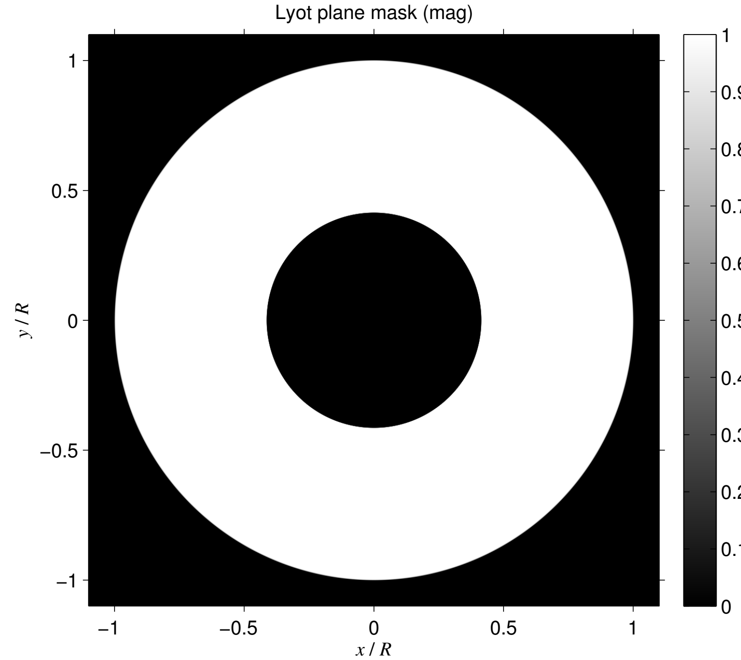
Pupil



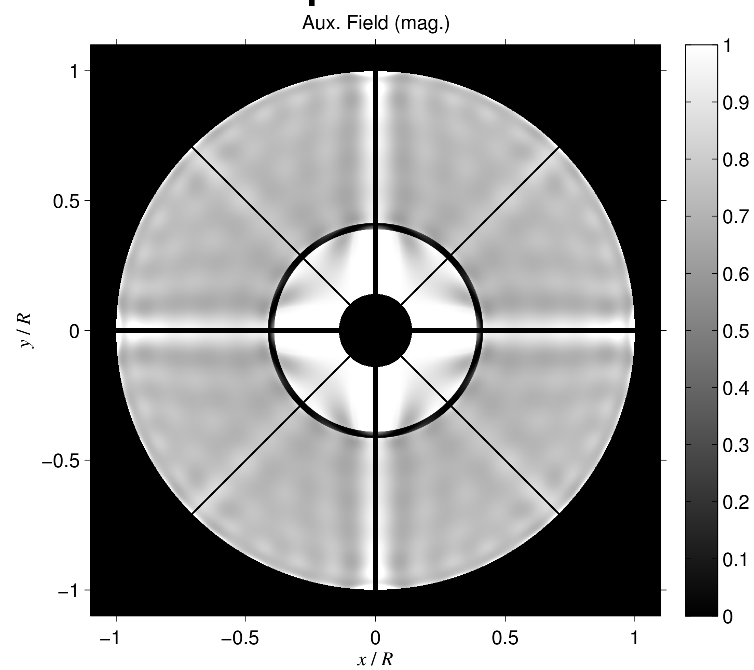
Initial cond.



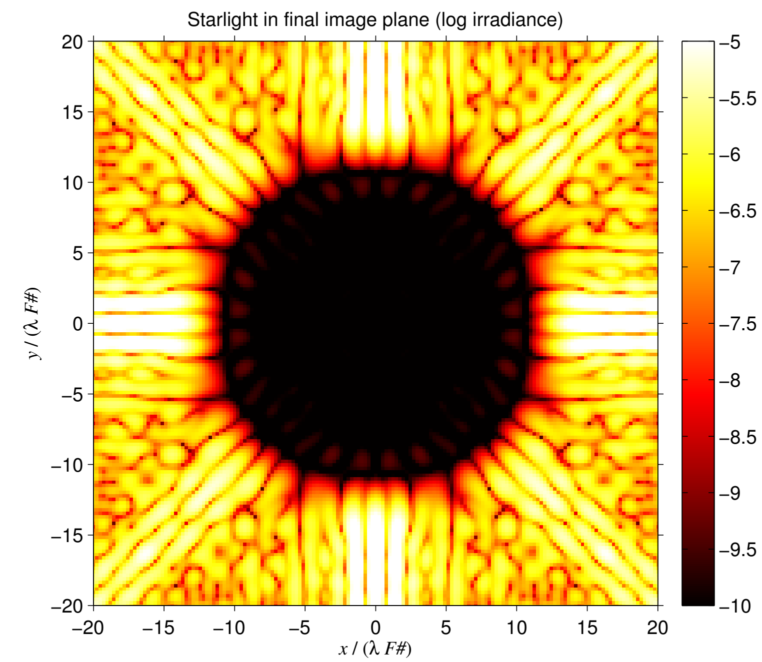
Lyot stop



Apodizer

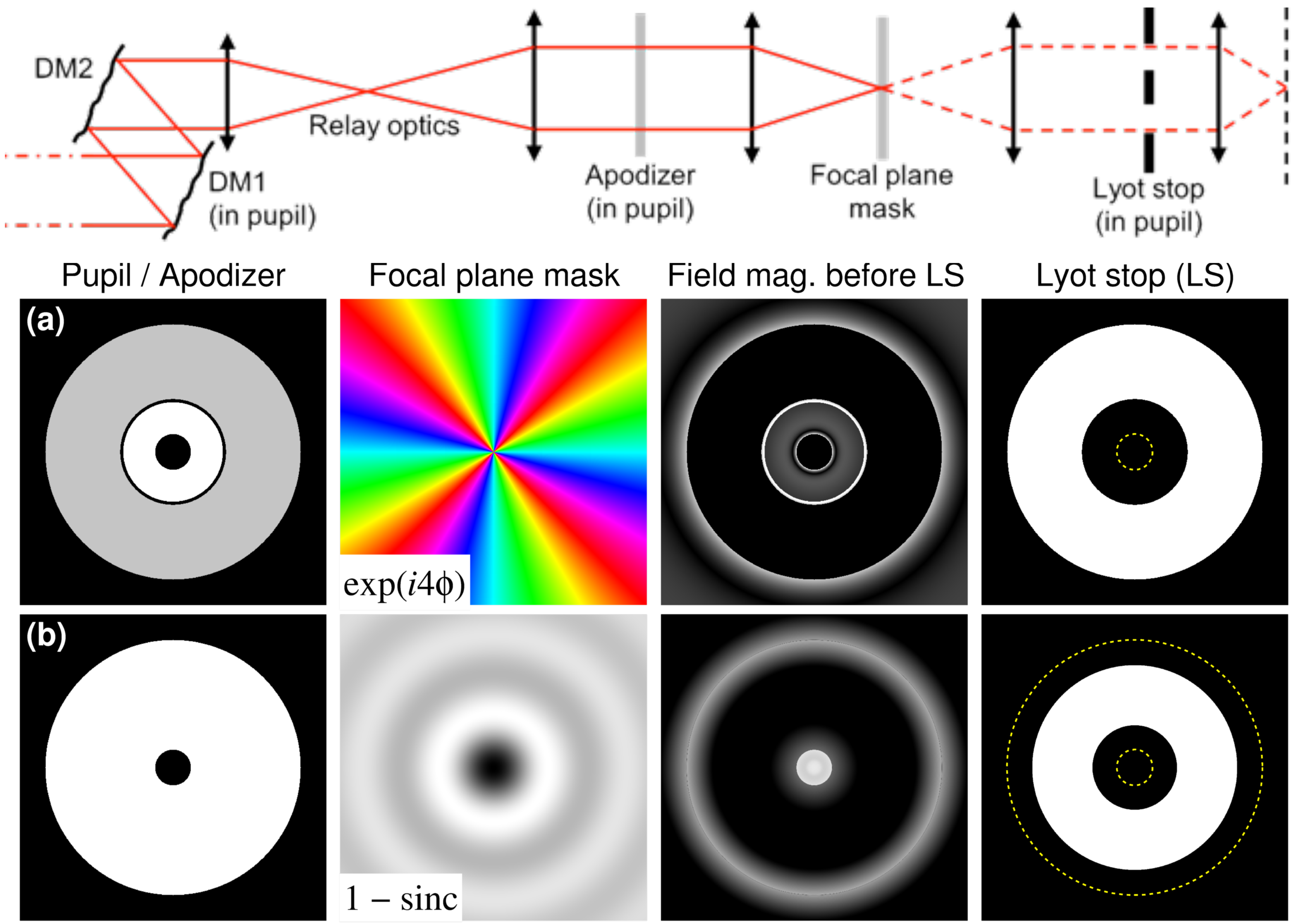


PSF

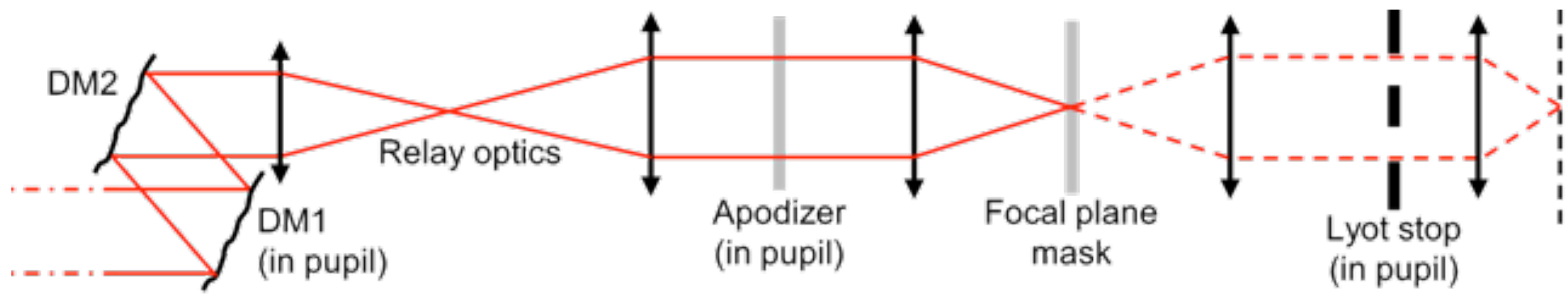


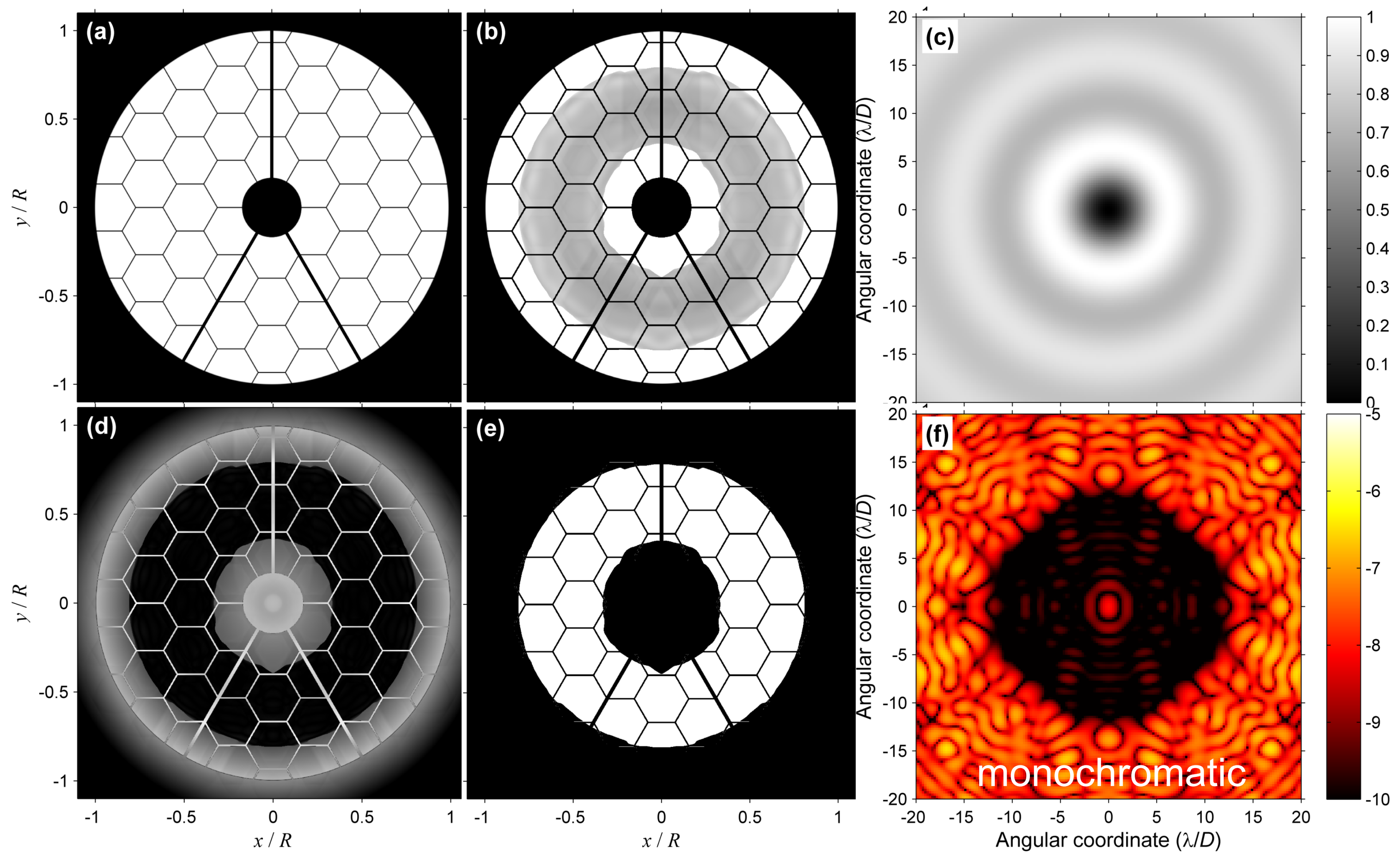
Max. throughput = 37% (PSF core relative to telescope).

Band-limited coronagraphs: work in progress



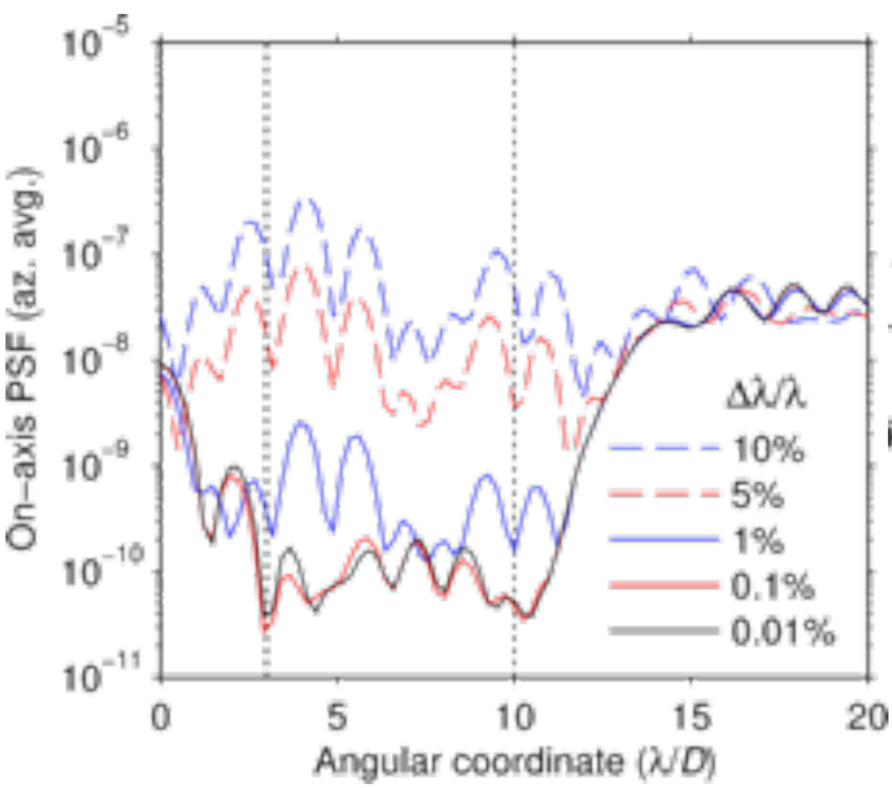
Band-limited coronagraphs: work in progress

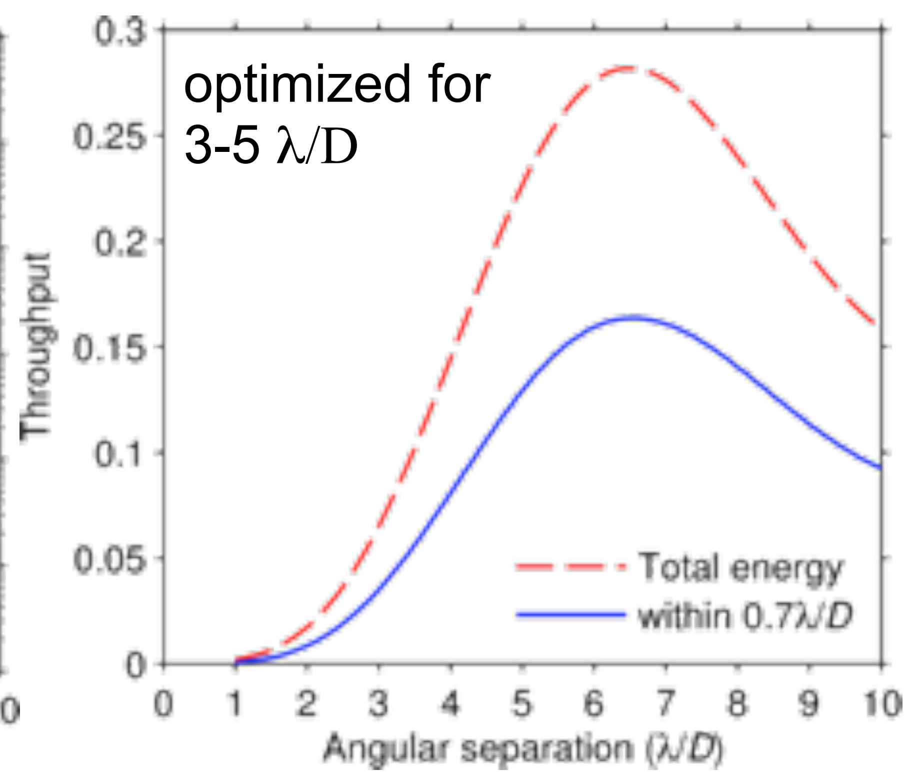


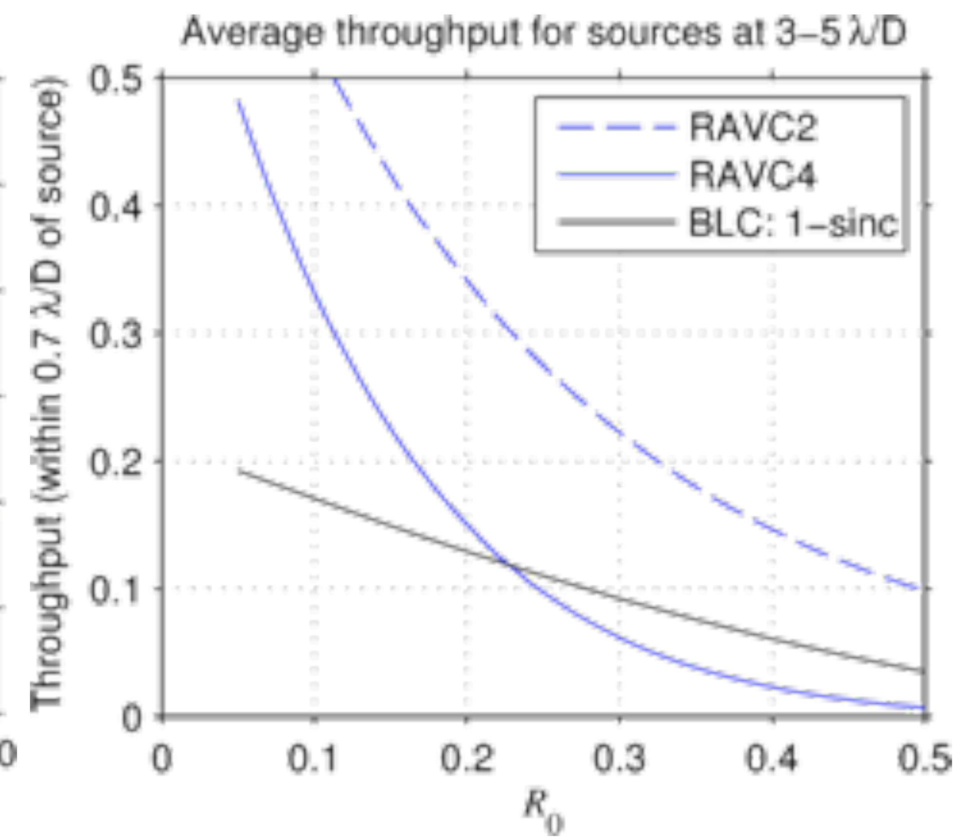


Band-limited coronagraphs: work in progress

Dark hole degrades with bandwidth







Conclusions relevant to HabEx

- There are high-contrast coronagraph solutions for obscured, segmented telescopes
- Throughput is key, more important than starlight suppression
- Unobscured, segmented apertures are coronagraph friendly and much higher throughput (factor ~2 to 4)

  => up to factor 10 in integration time

TBD

- Consolidate unobscured segmented coronagraph designs (APLC, PIAACMC)
- Sensitivity to segment phasing and gap sizes and shapes?
- Tolerancing to alignment
- Manufacturing errors of apodizers and focal plane masks