Coronagraph design considerations

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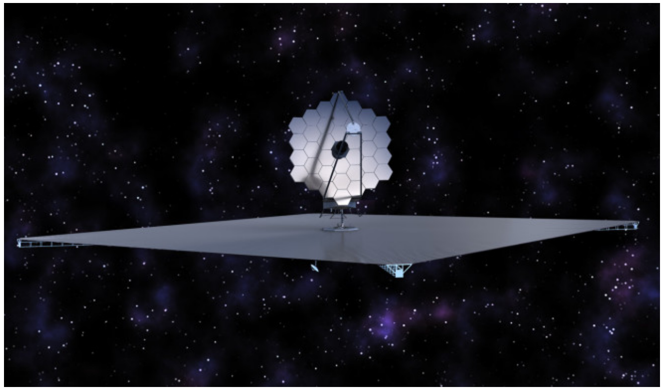
High contrast imaging with large aperture telescopes

Science driver: direct characterization in the habitable zone (HZ)

Thirty Meter Telescope (TMT)

HZ around cool stars
- Modest contrast
- Small inner working angle

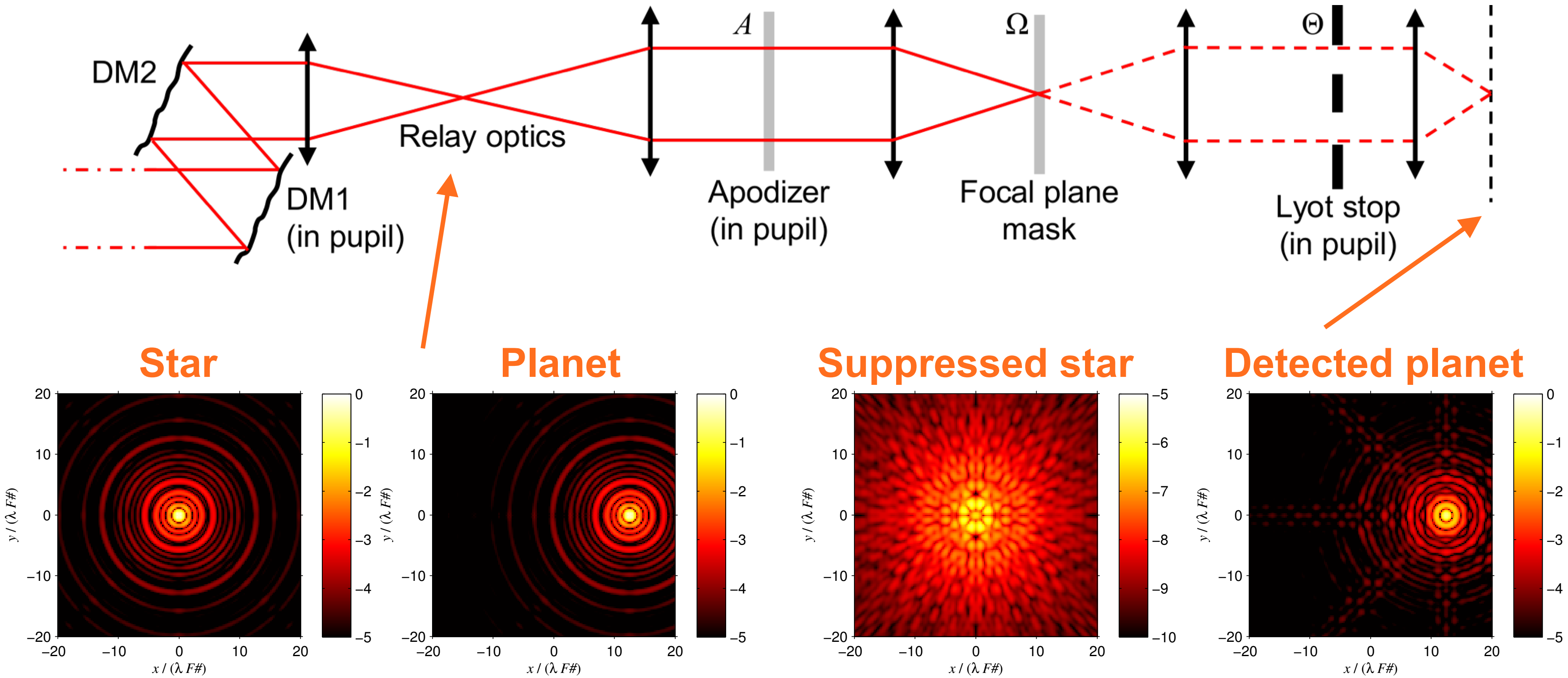
Future space telescopes (4-16 m)



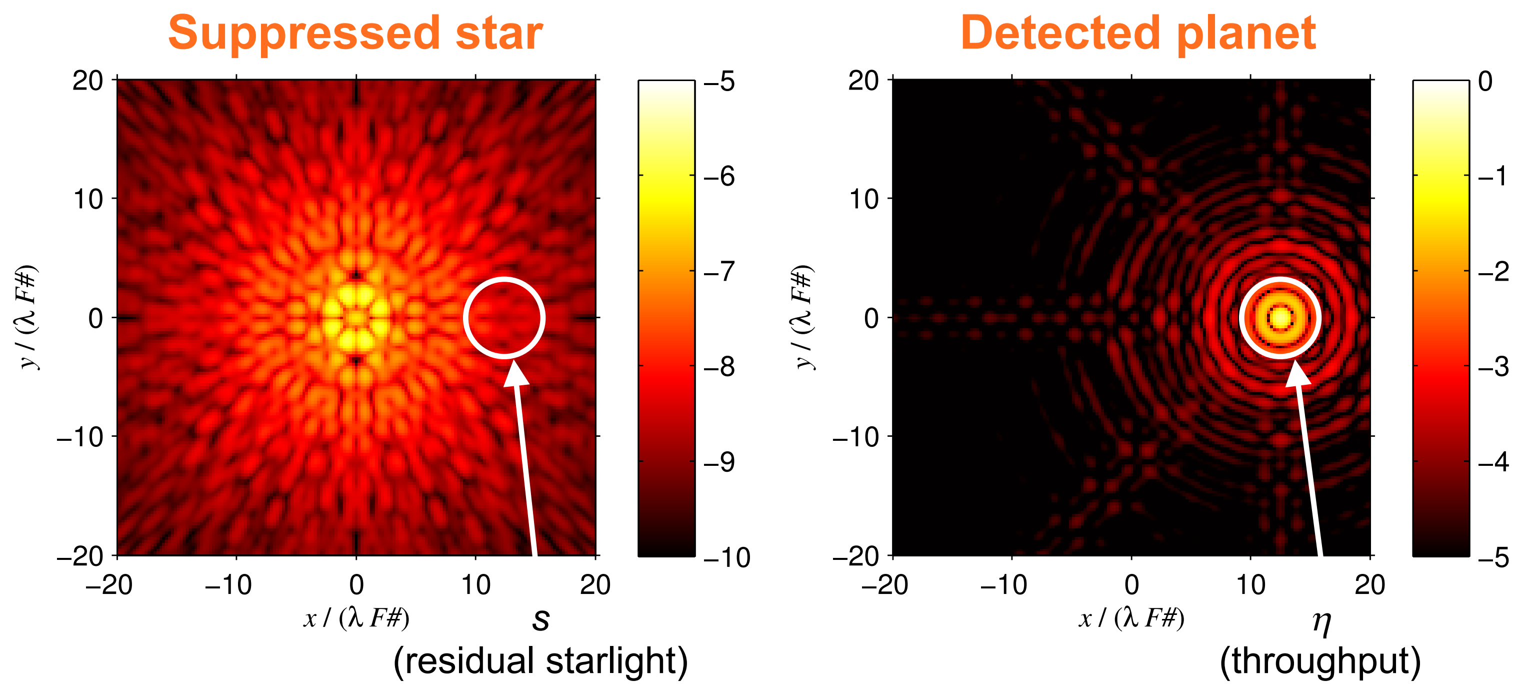
HZ around solar-type stars
- Extremely high contrast
- Modest inner working angle

Technology needs: Wavefront control + efficient coronagraphs

Three-mask coronagraph concept



Three-mask coronagraph concept



Coronagraph throughput (η): Fraction of total planet energy counted as signal.

Suppression factor (s): Fraction of stellar energy that is measured along with the signal.

Signal-to-noise for planet imaging

Spectral irradiance at a position in the final image plane:

$$\hat{\Phi} = \eta_c \Phi_p + s\Phi_{\text{star}} + \Phi_b + \hat{\Phi}_{\text{spk}}$$ (photons/sec/wavelength/area)

Signal-to-noise ratio for planet observation:

$$\text{planet signal} = \eta_c T q A \Delta t \Delta\lambda \Phi_p$$

$$SNR = \frac{\eta_c T q A \Delta t \Delta\lambda \Phi_p}{\sqrt{\sigma^2_{\text{phot}} + \sigma^2_{\text{det}} + \sigma^2_{\text{spk}}}}$$

Noise terms:

$$\sigma^2_{\text{phot}} = T q A \Delta t \Delta\lambda \hat{\Phi}$$

$$\sigma^2_{\text{det}} = i_{\text{dark}} \Delta t + \sigma^2_{\text{read}}$$

$$\sigma^2_{\text{spk}} = ?$$

Contribution of speckle noise

e.g. Soummer et al. (2007), for speckles lifetime with lifetime τ:

$$\sigma_{\mathrm{spk}}^{2} = \Delta t \left(TqA\right)^{2} \left(\tau \hat{\Phi}_{\mathrm{spk}}^{2} + 2\tau s \Phi_{\mathrm{star}} \hat{\Phi}_{\mathrm{spk}}\right)$$

Integration time relationships

Integration time to reach SNR threshold Γ:

$$\Delta t = \Gamma^2 \left(\Delta t_{\text{shot}} + \Delta t_{\text{det}} + \Delta t_{\text{spk}} \right)$$

Stellar photon noise limited regime:

$$\Delta t_{\text{phot}} \approx \frac{1}{\left(\eta_c \Phi_p\right)^2} \frac{s\Phi_{\text{star}}}{TqA\Delta\lambda} \propto \boxed{s/\eta_c^2}$$

"Pinned" speckle limited regime:

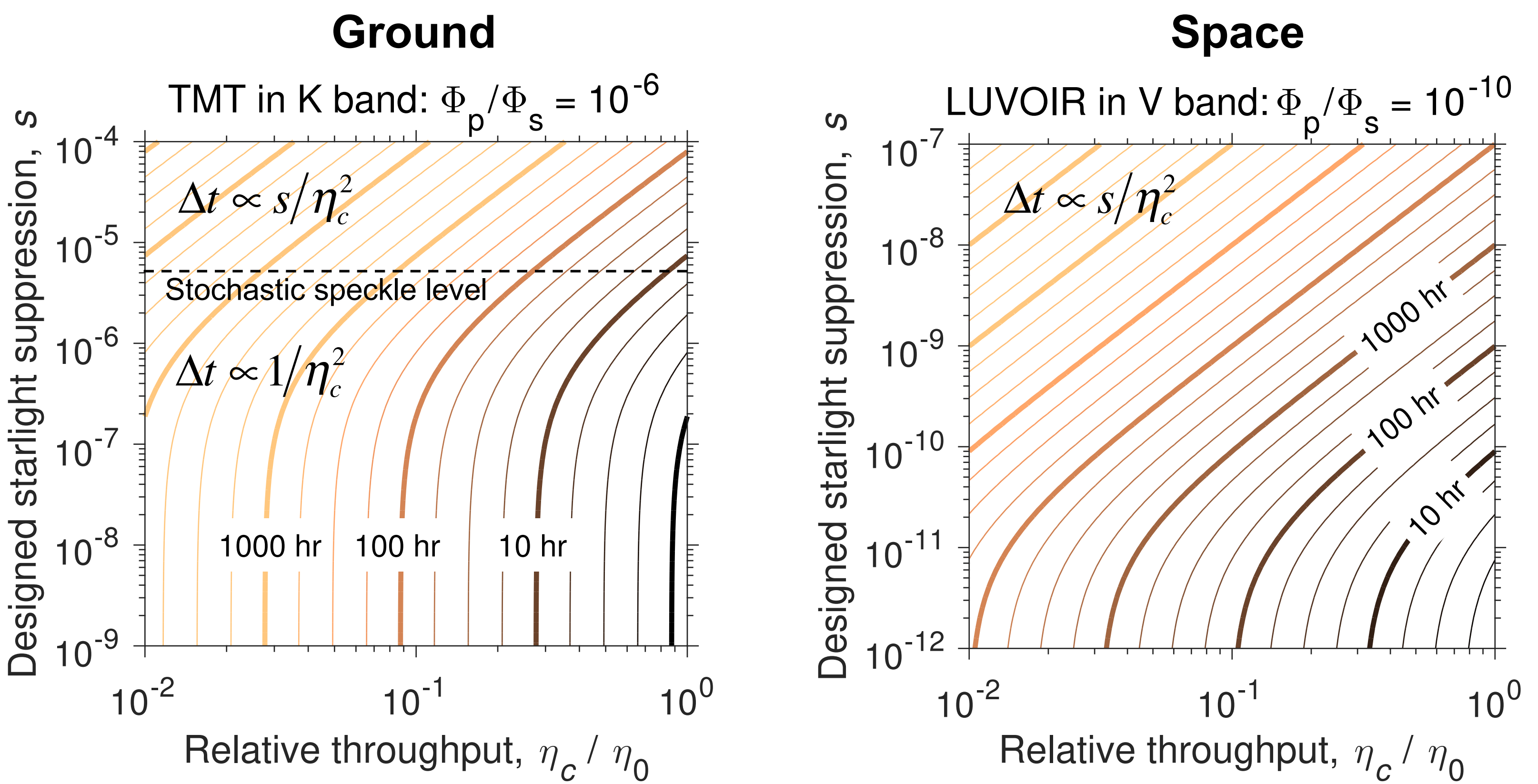
$$\Delta t_{\text{spk}} = \frac{\tau}{\left(\eta_c \Phi_p\right)^2} \left(\hat{\Phi}_{\text{spk}}^2 + 2s\Phi_{\text{star}}\hat{\Phi}_{\text{spk}} \right) \propto \boxed{s/\eta_c^2}$$

If any other noise term dominates (stochastic speckles, detector noise, thermal background, exozodi, etc):

$$\Delta t \propto \boxed{1/\eta_c^2}$$

Towards a coronagraph optimization metric:

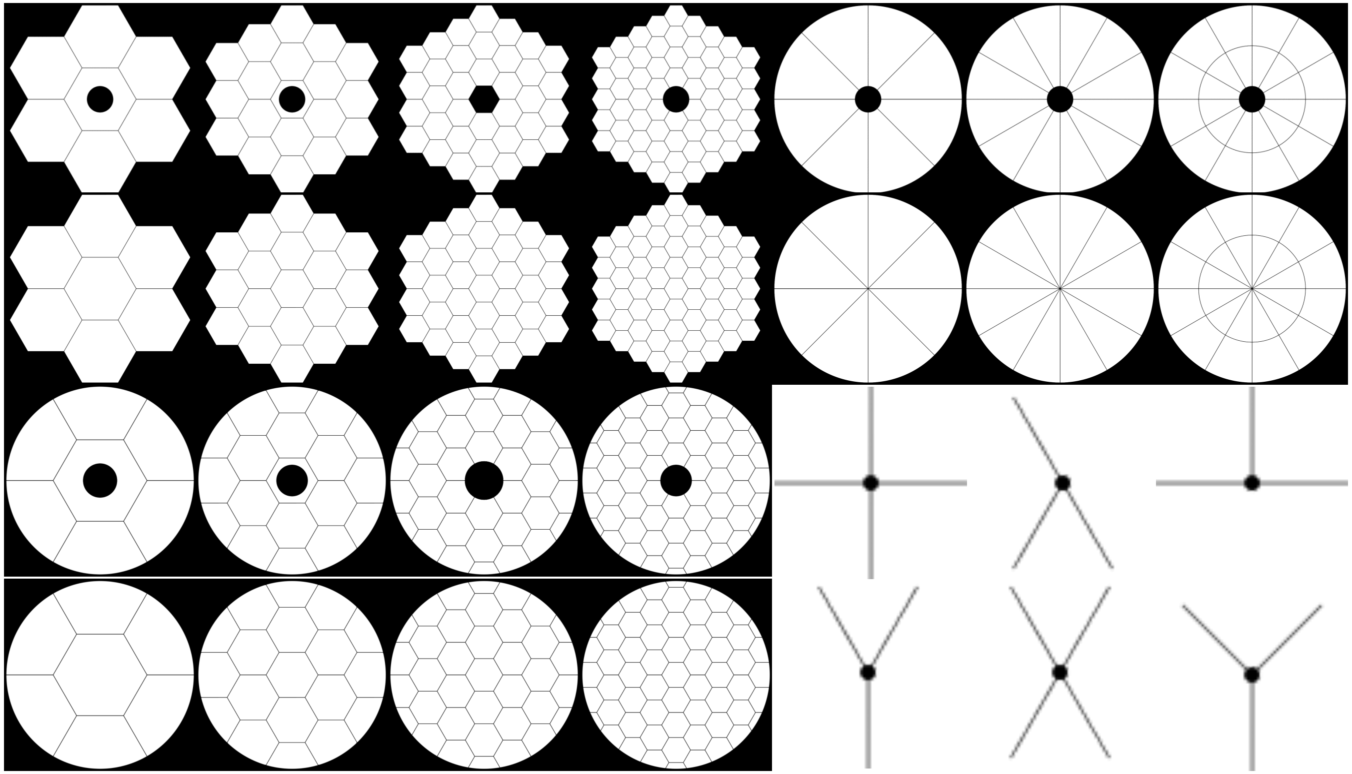
minimization of integration time



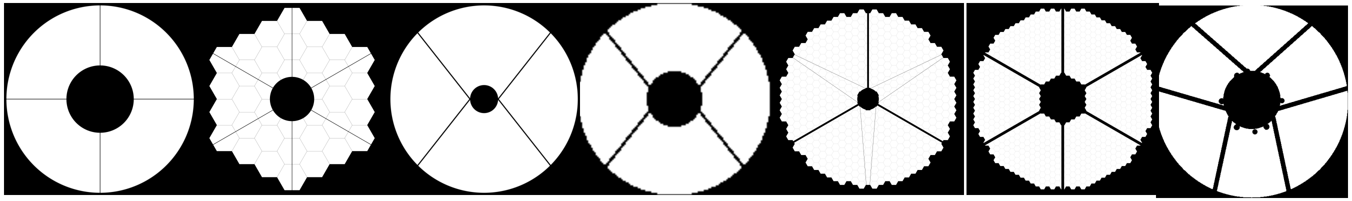
Ruane et al., *Proc. SPIE* 99122L (2016)

A family portrait of aperture designs

Segmented Coronagraph Design and Analysis (SCDA)

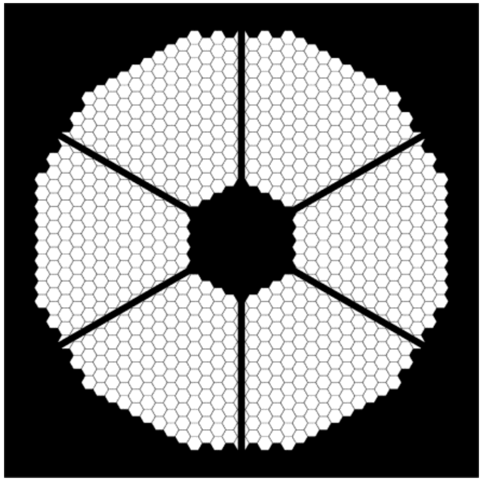


Other relevant examples

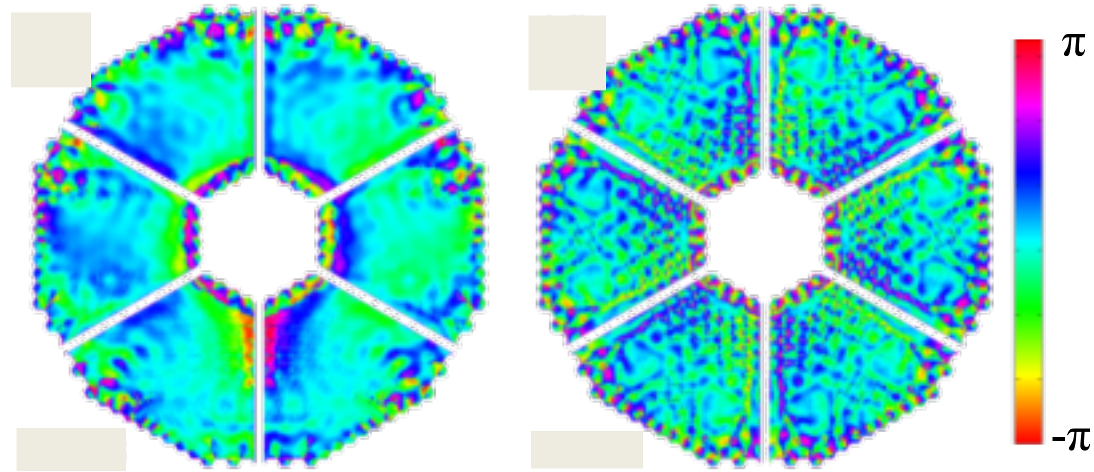


Lyot stop phase mask

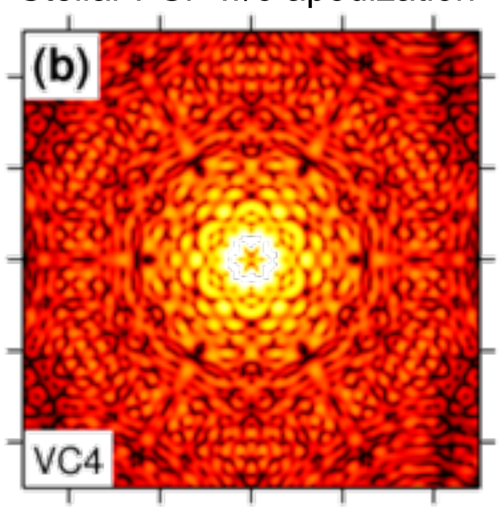
Entrance pupil (E-ELT)



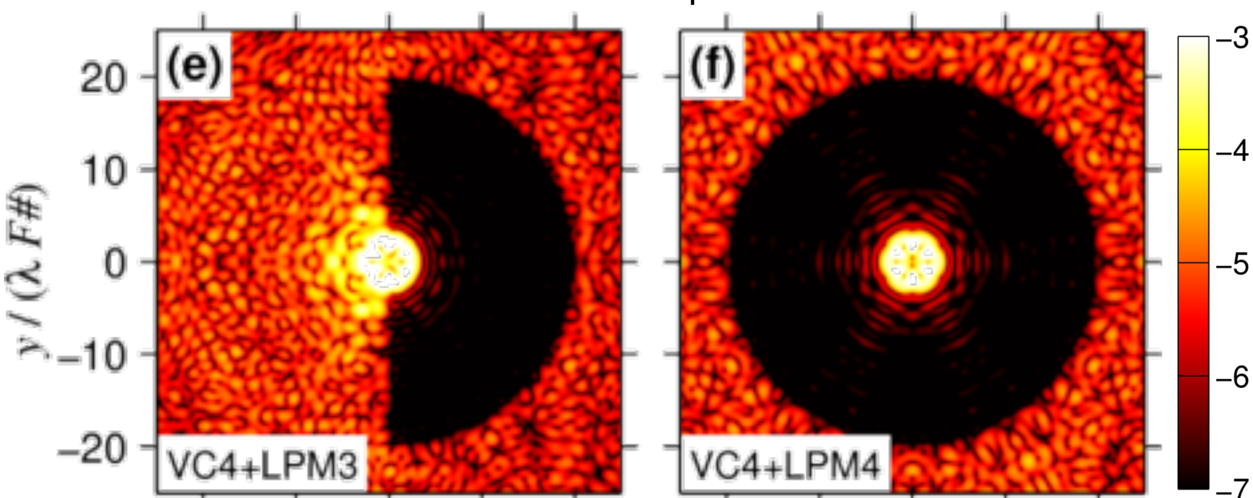
Phase masks for Lyot Stop



Stellar PSF w/o apodization



Stellar PSF w/ apodization

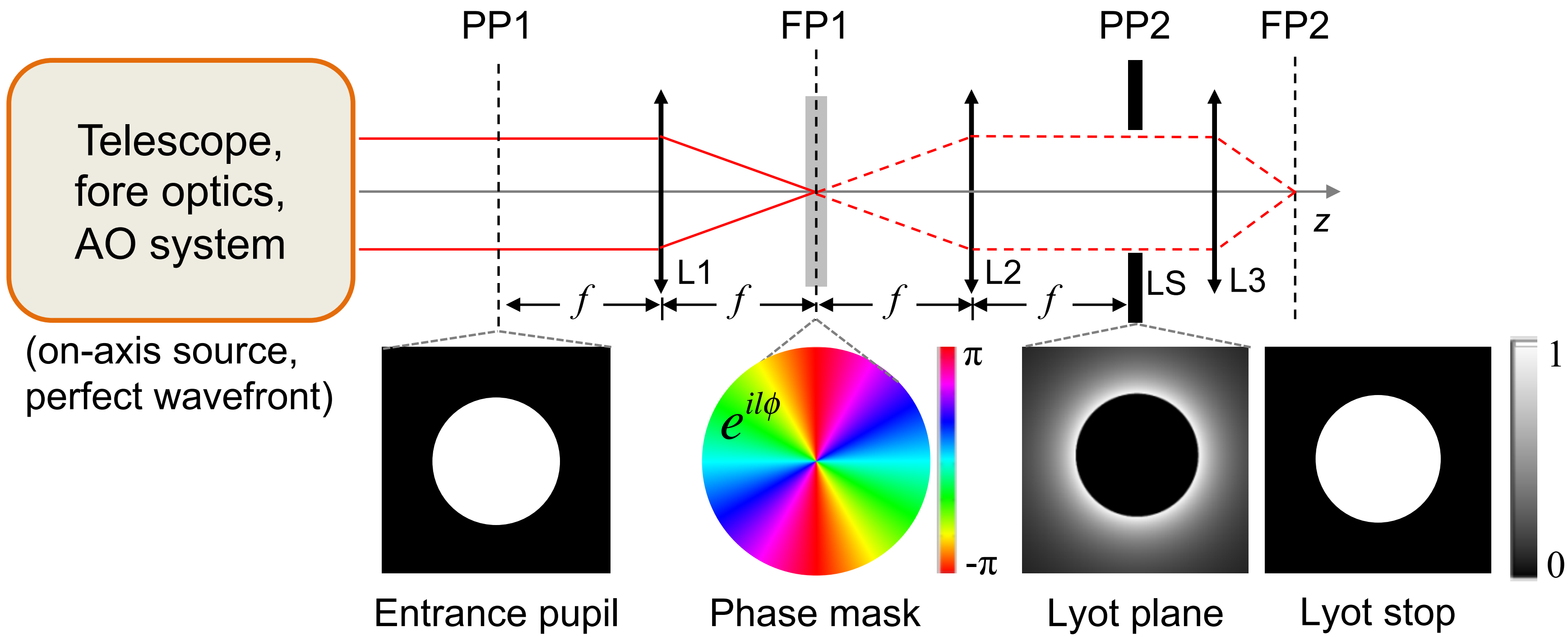


~50% throughput

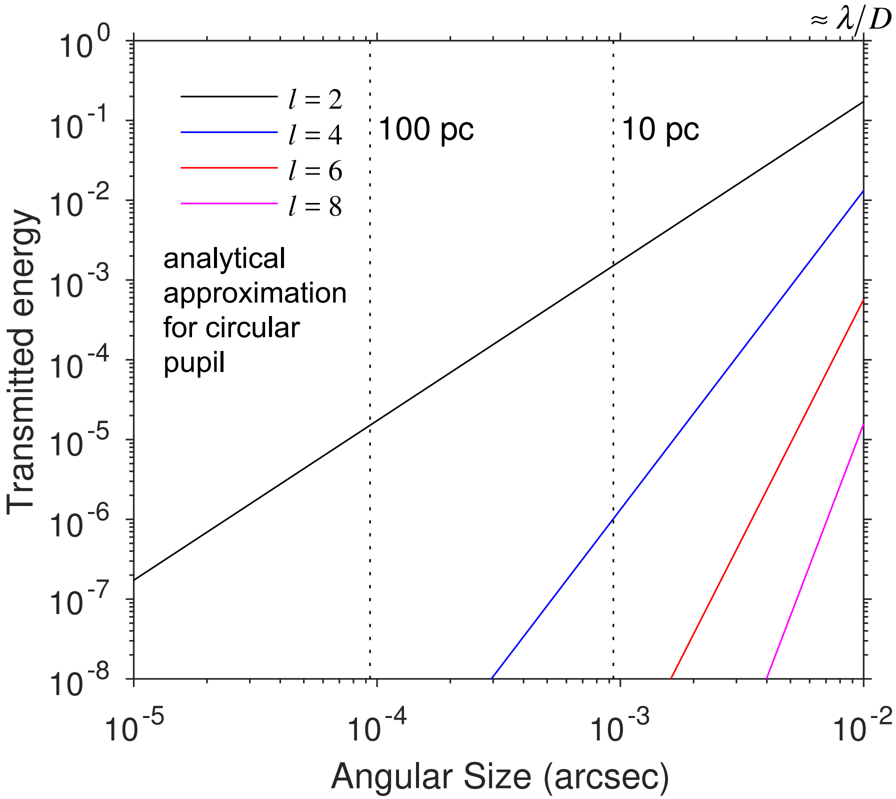
~30% throughput

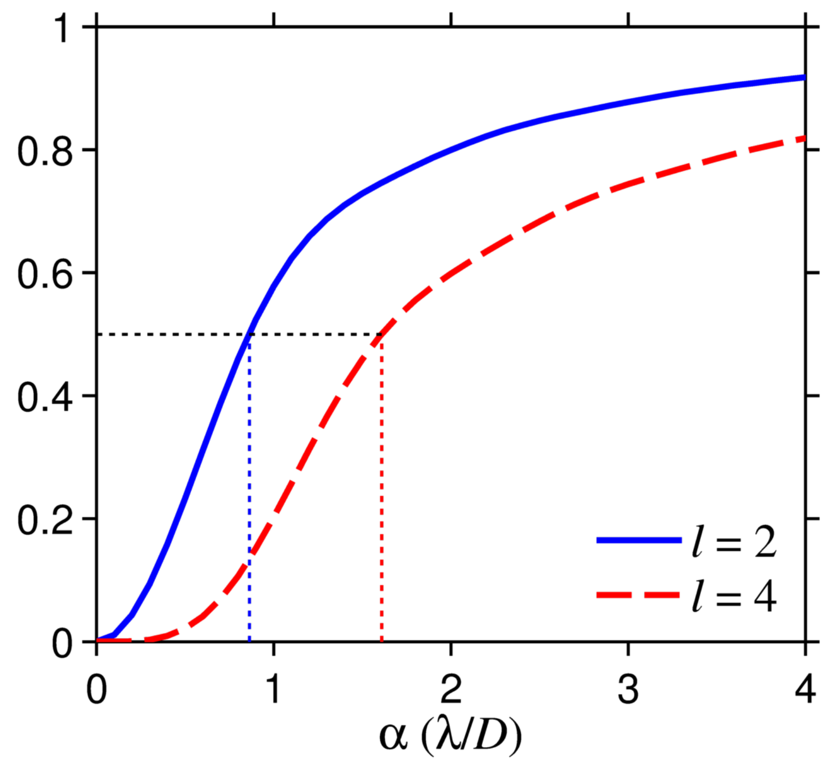
Ruane et al., *A&A* 583, A81 (2015)
Ruane et al., *Proc. SPIE* 96051I (2015)

Vortex coronagraph



Sensitivity to stellar size





Fraction of energy transmitted through the Lyot stop assuming a 12 m diameter aperture and λ = 550 nm.

Guyon et al., *ApJS* **161** 81 (2006)
Jenkins, *MNRAS* **384** 515 (2008)
Mawet et al., *Proc. SPIE* 773914 (2010)

Sensitivity to low order aberrations

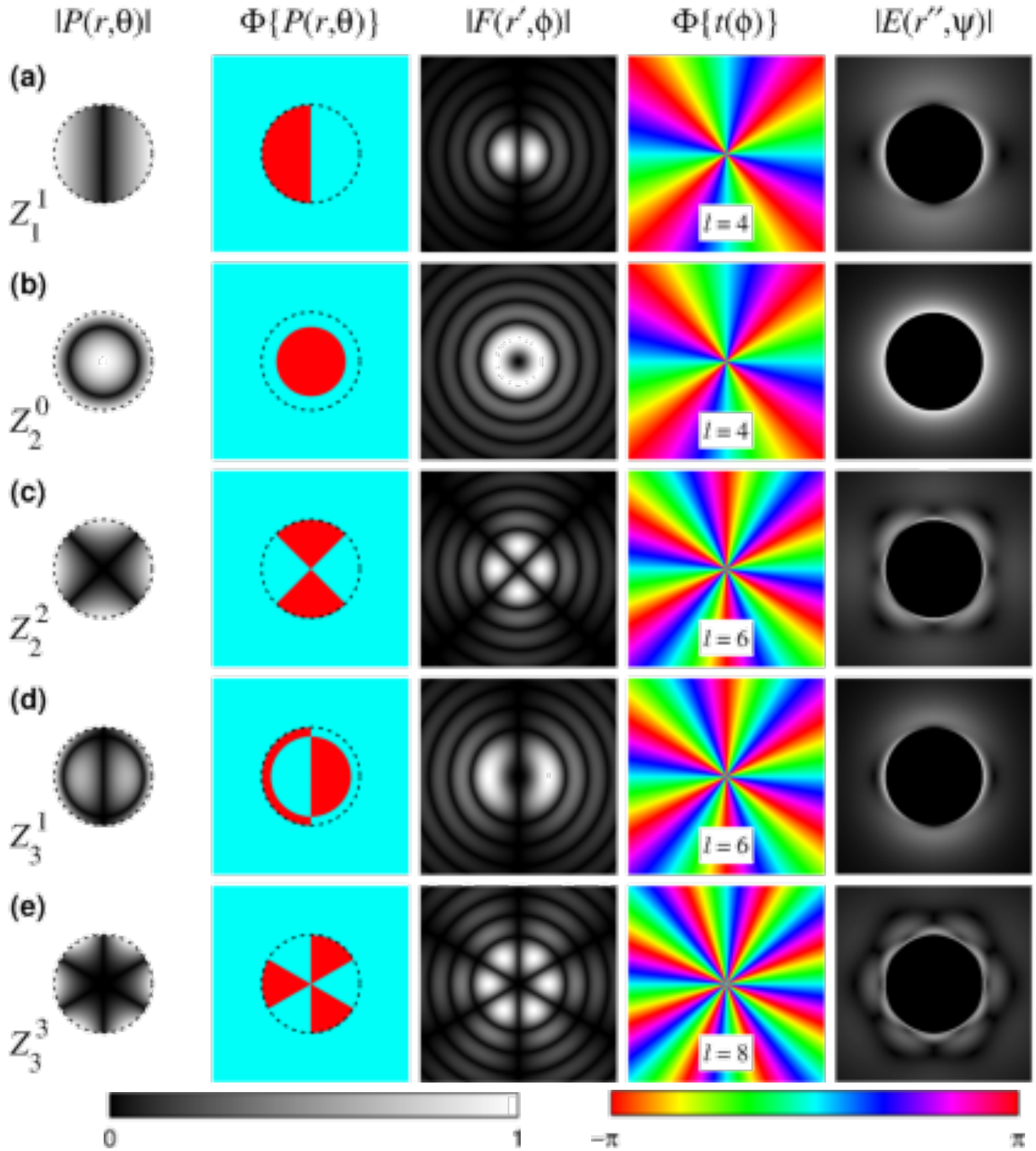
$$\exp(i\Phi) \approx 1 + i\Phi$$

$$\Phi = Z_n^m(r,\theta)$$

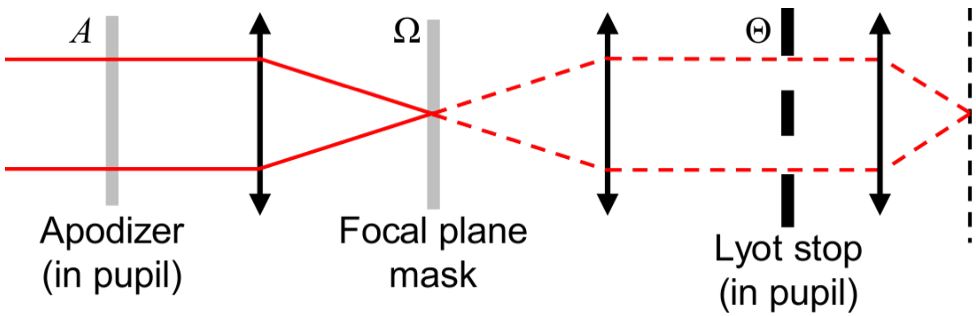
Conditions for rejection:

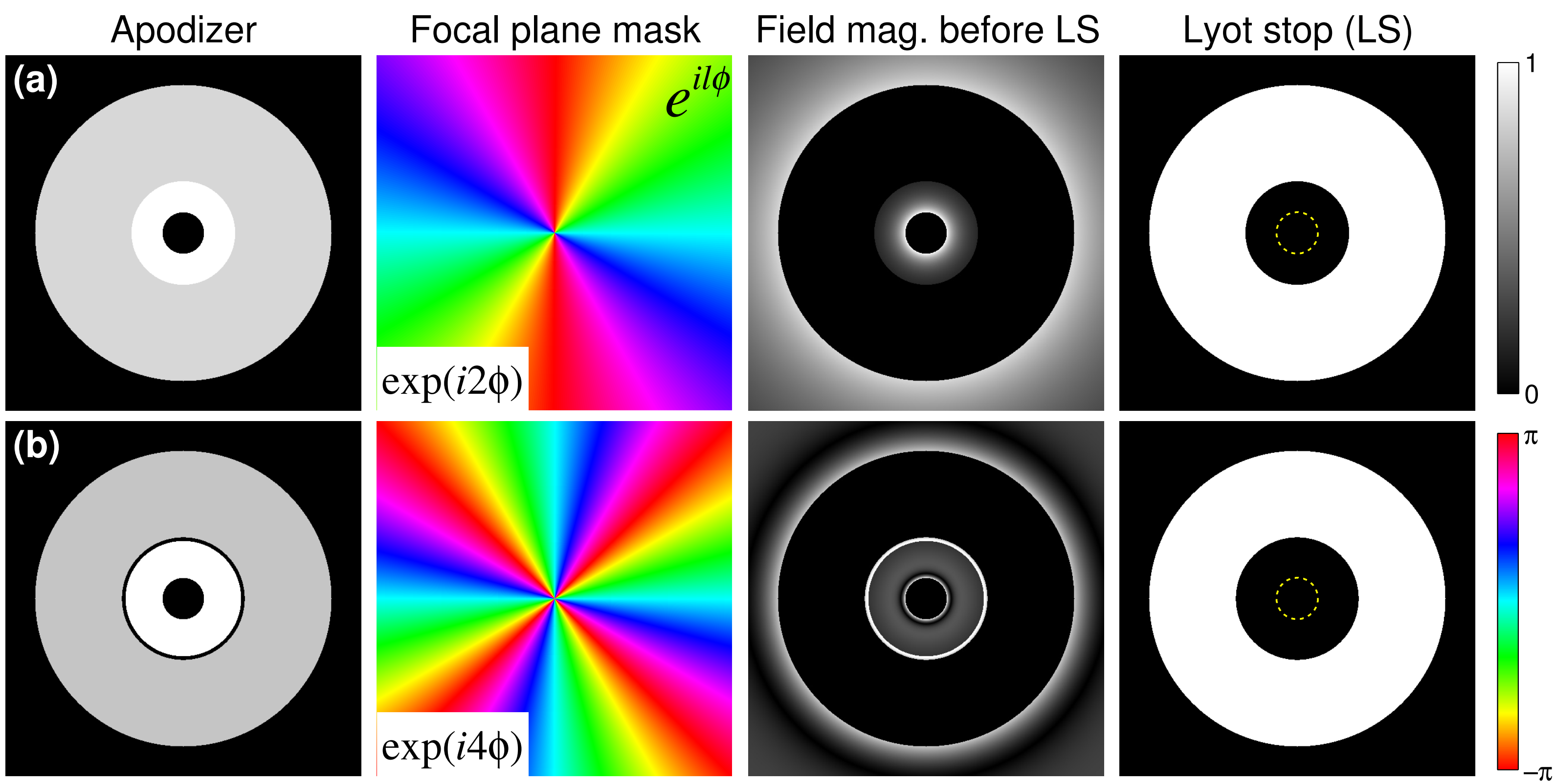
l is even

$$|l| > n + |m|$$



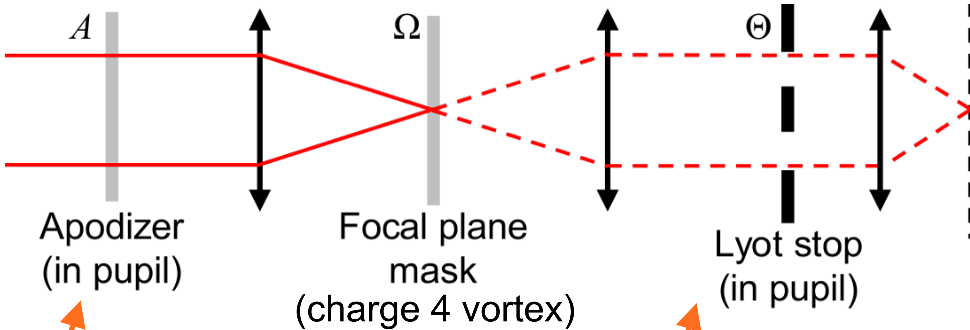
Input pupil apodization

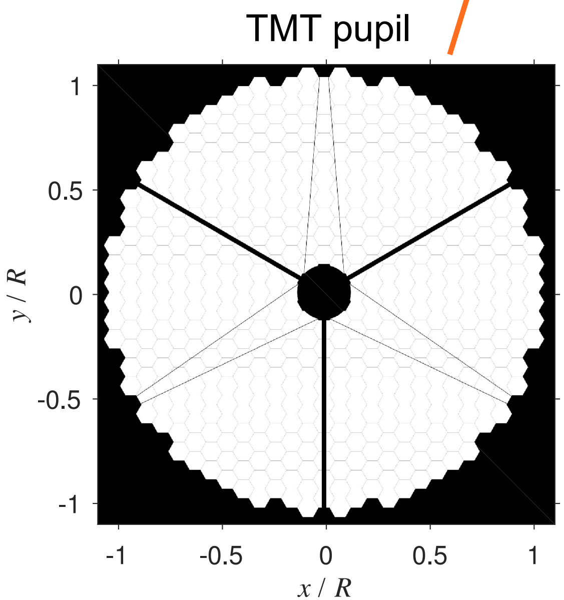


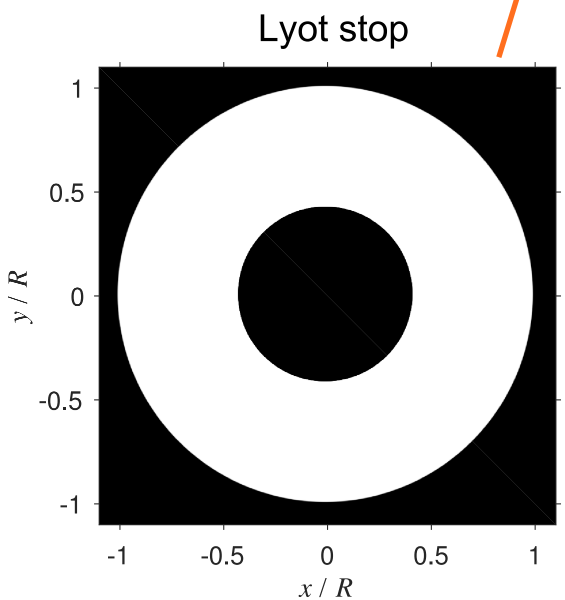


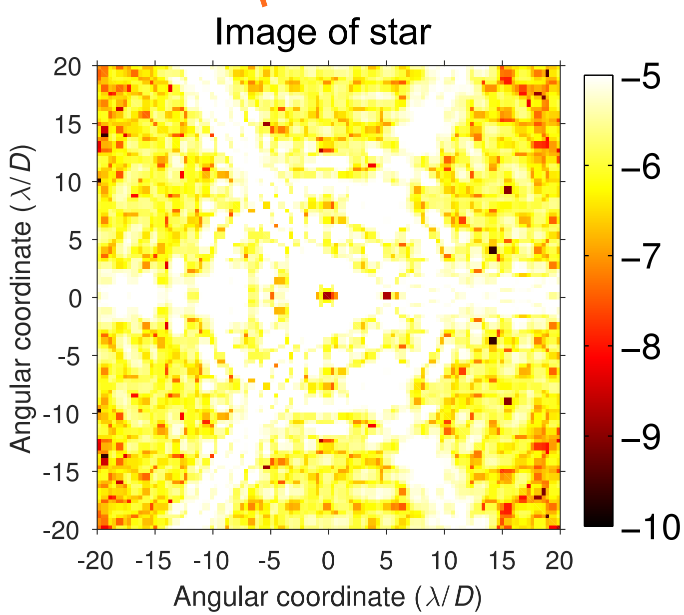
Mawet et al., *ApJS* **209** 7 (2013)

Apodized vortex coronagraph design for TMT



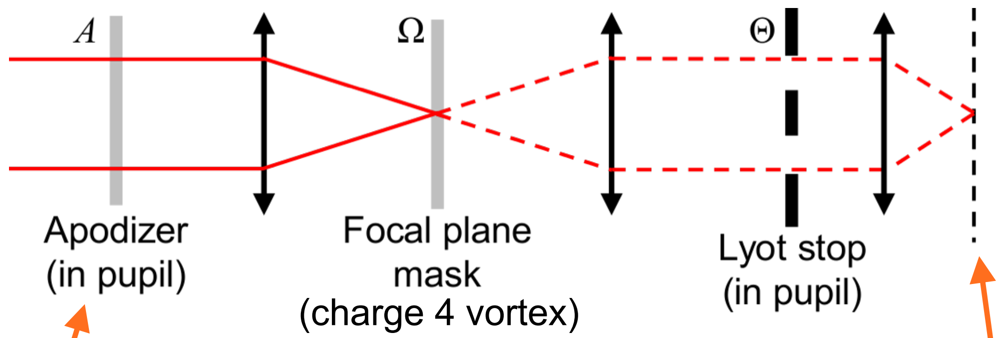




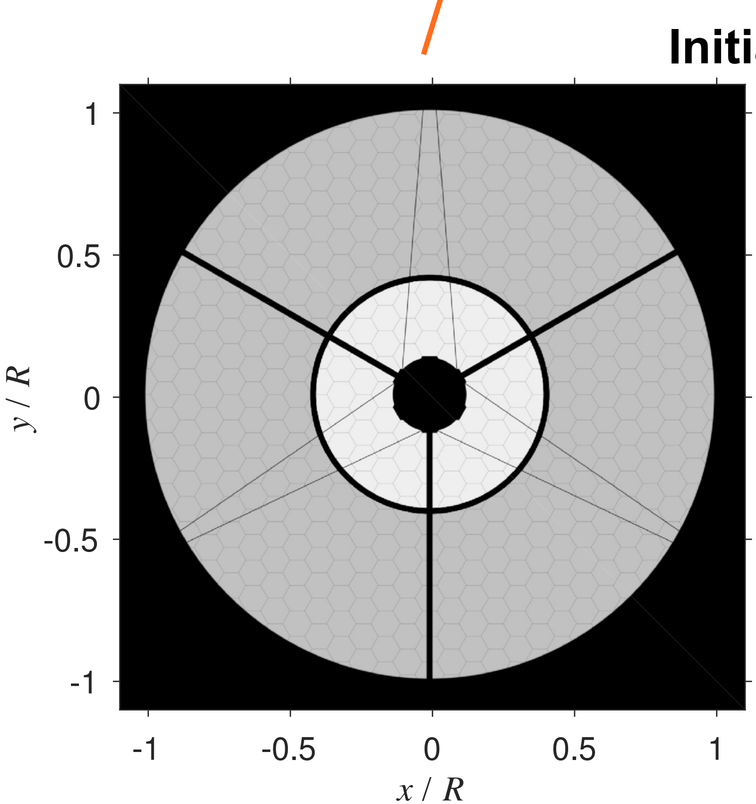


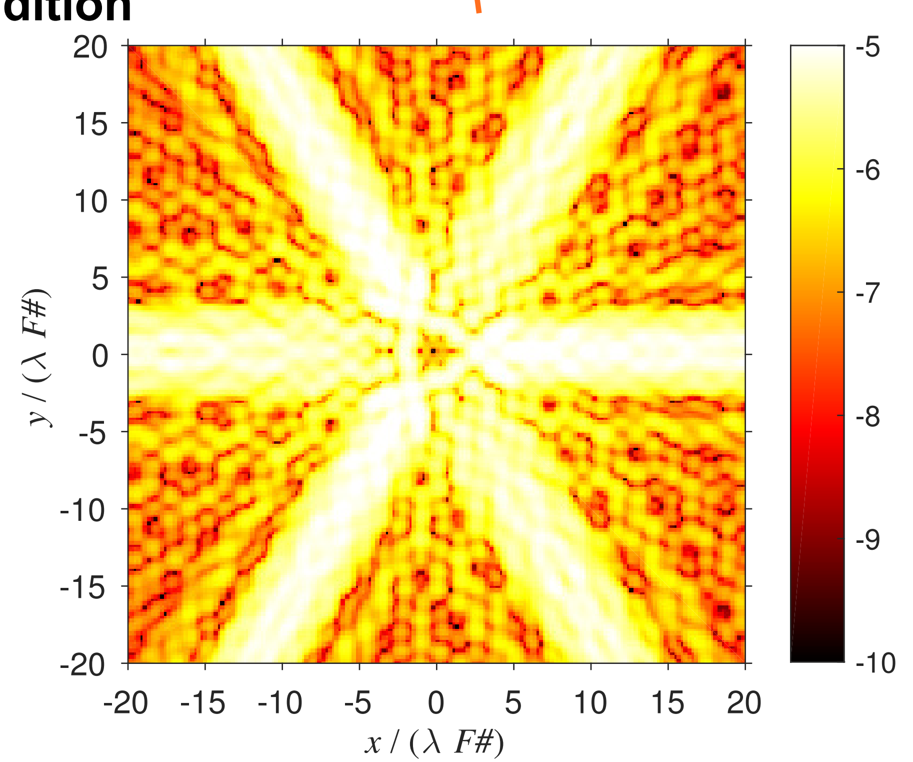
No aberrations or WFE included.

Apodized vortex coronagraph design for TMT

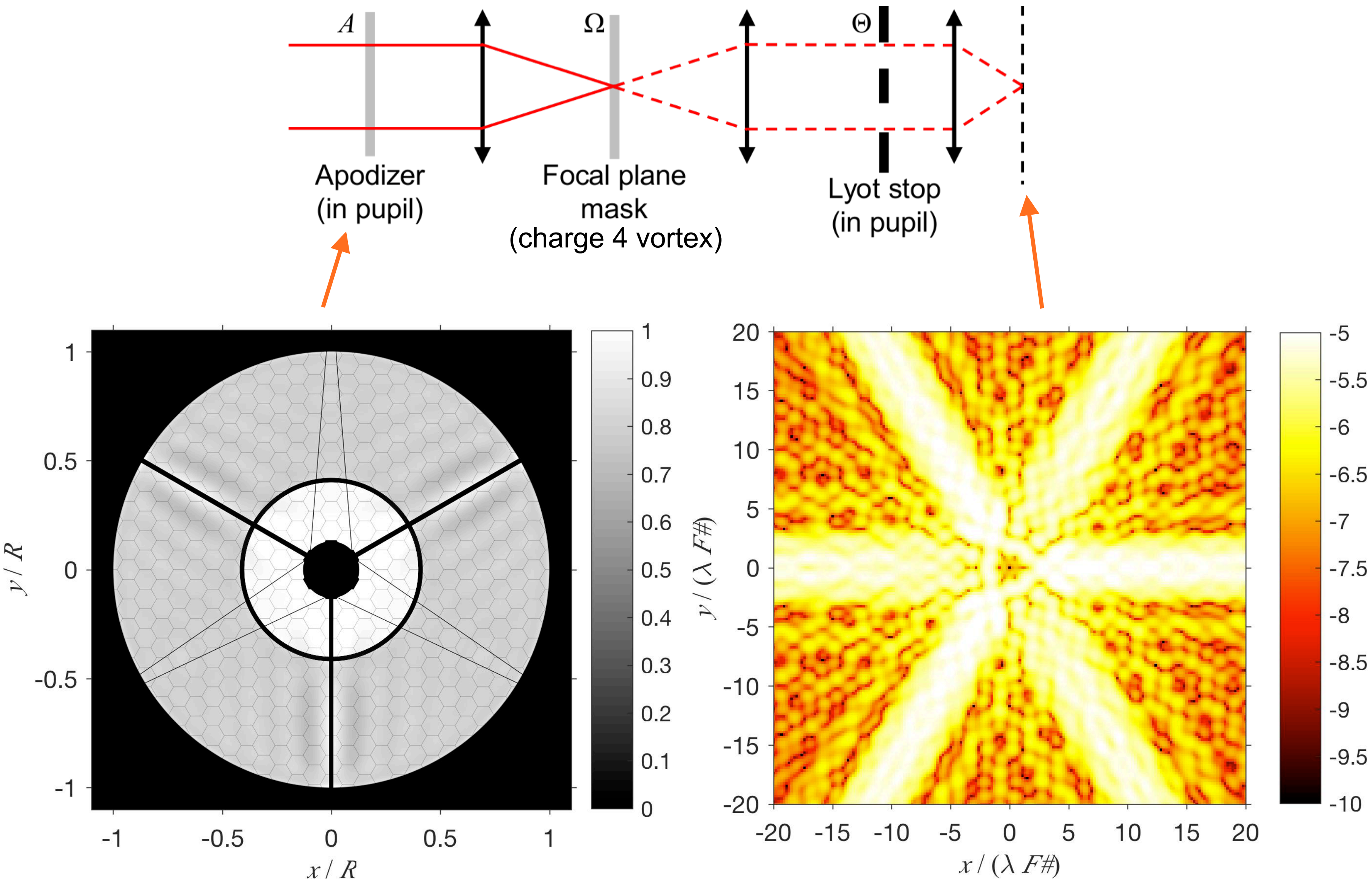


Initial condition



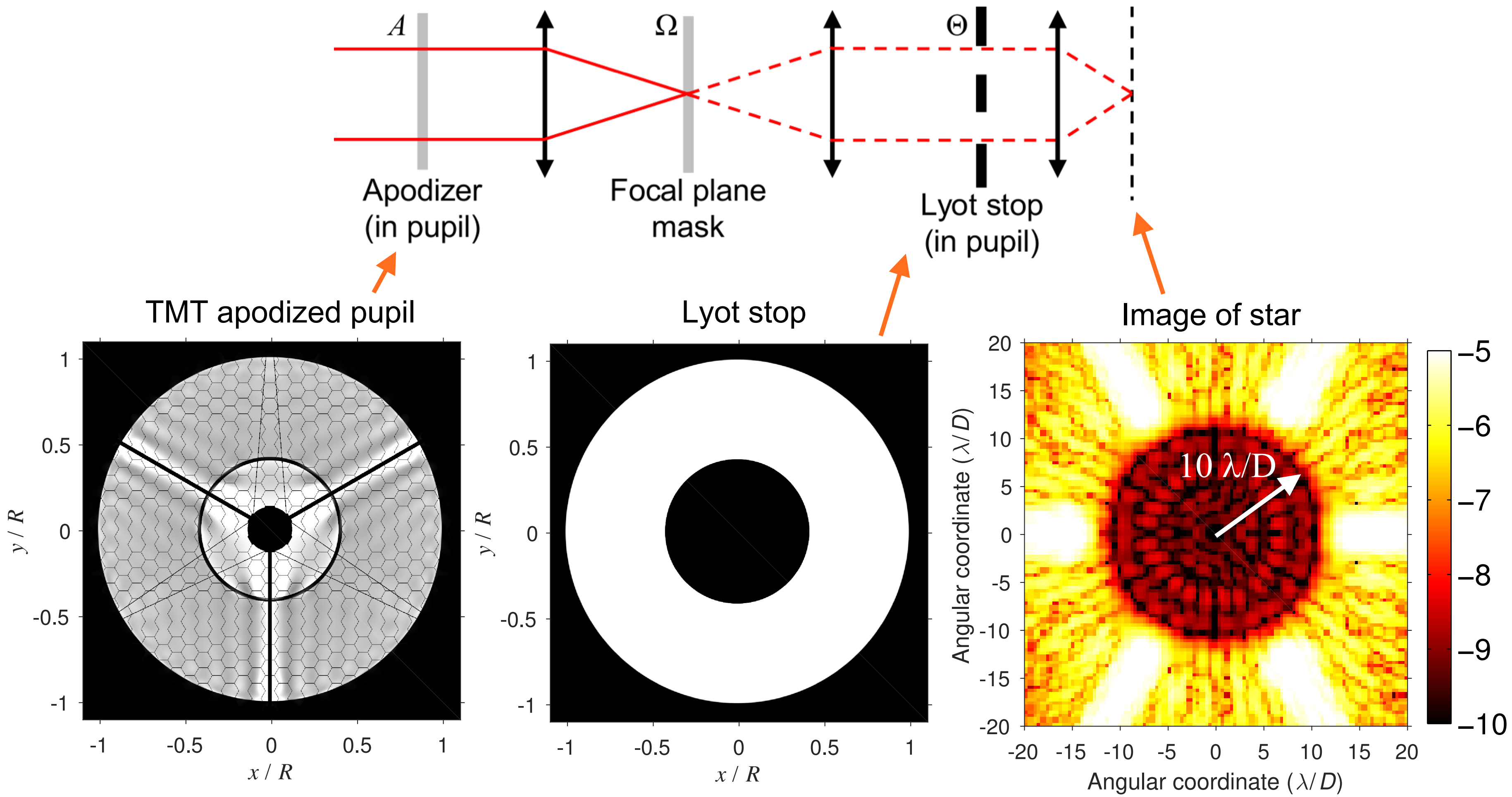


Apodized vortex coronagraph design for TMT



Solution obtained via “Auxiliary Field Conjugation” (Jewell et al., in prep.)

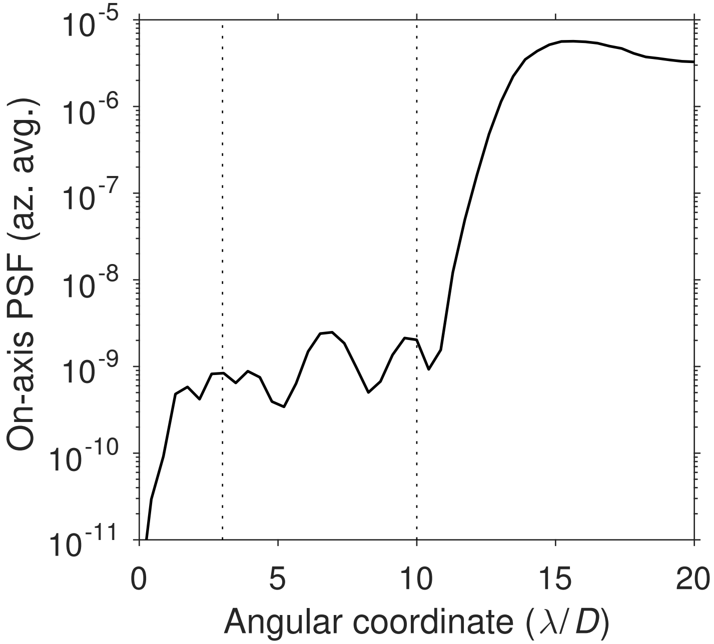
Apodized vortex coronagraph design for TMT



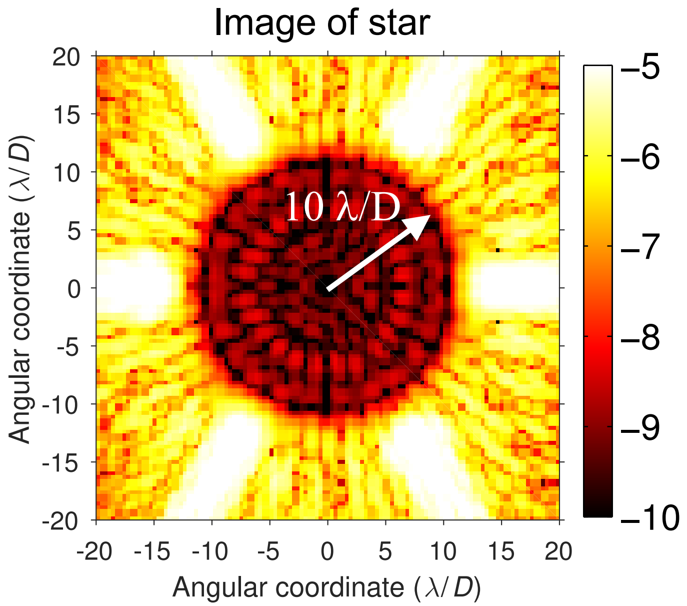
Solution obtained via “Auxiliary Field Conjugation” (Jewell et al., in prep.)

Apodized vortex coronagraph design for TMT

A TMT solution

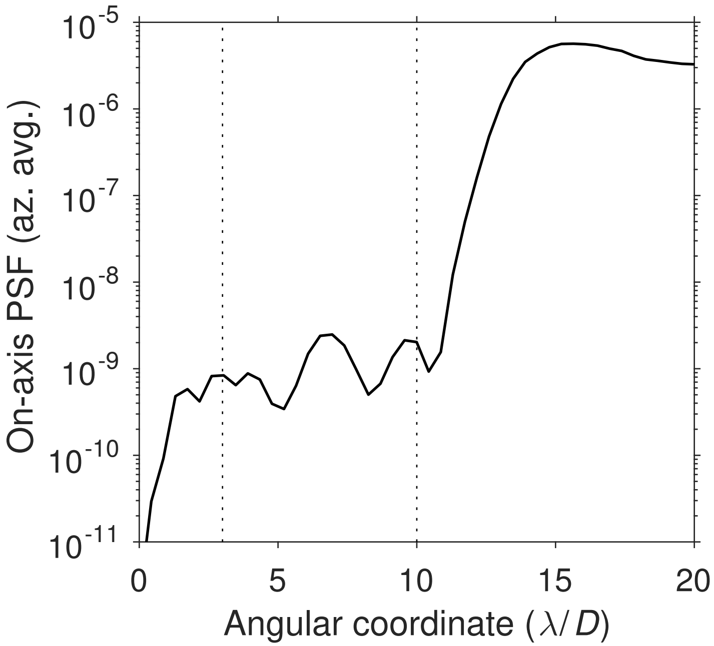


Design starlight suppression: $s \sim 10^{-9}$



Apodized vortex coronagraph design for TMT

A TMT solution



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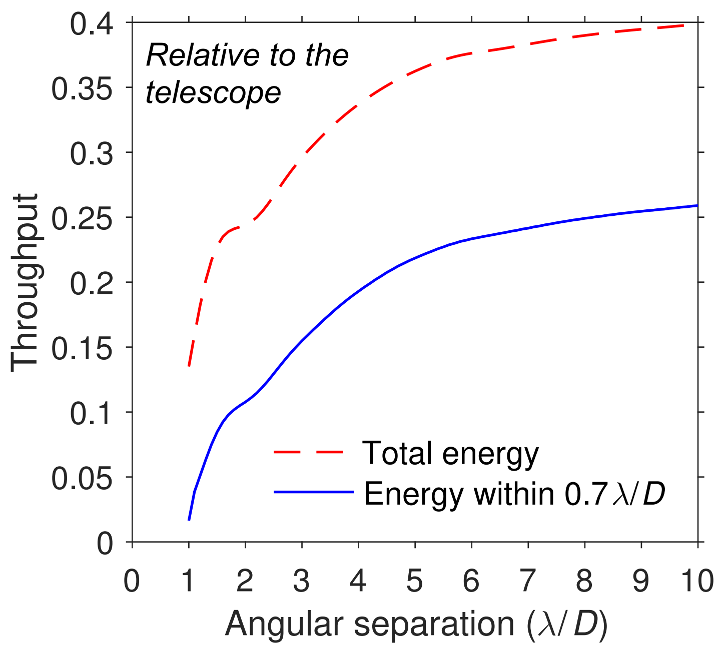
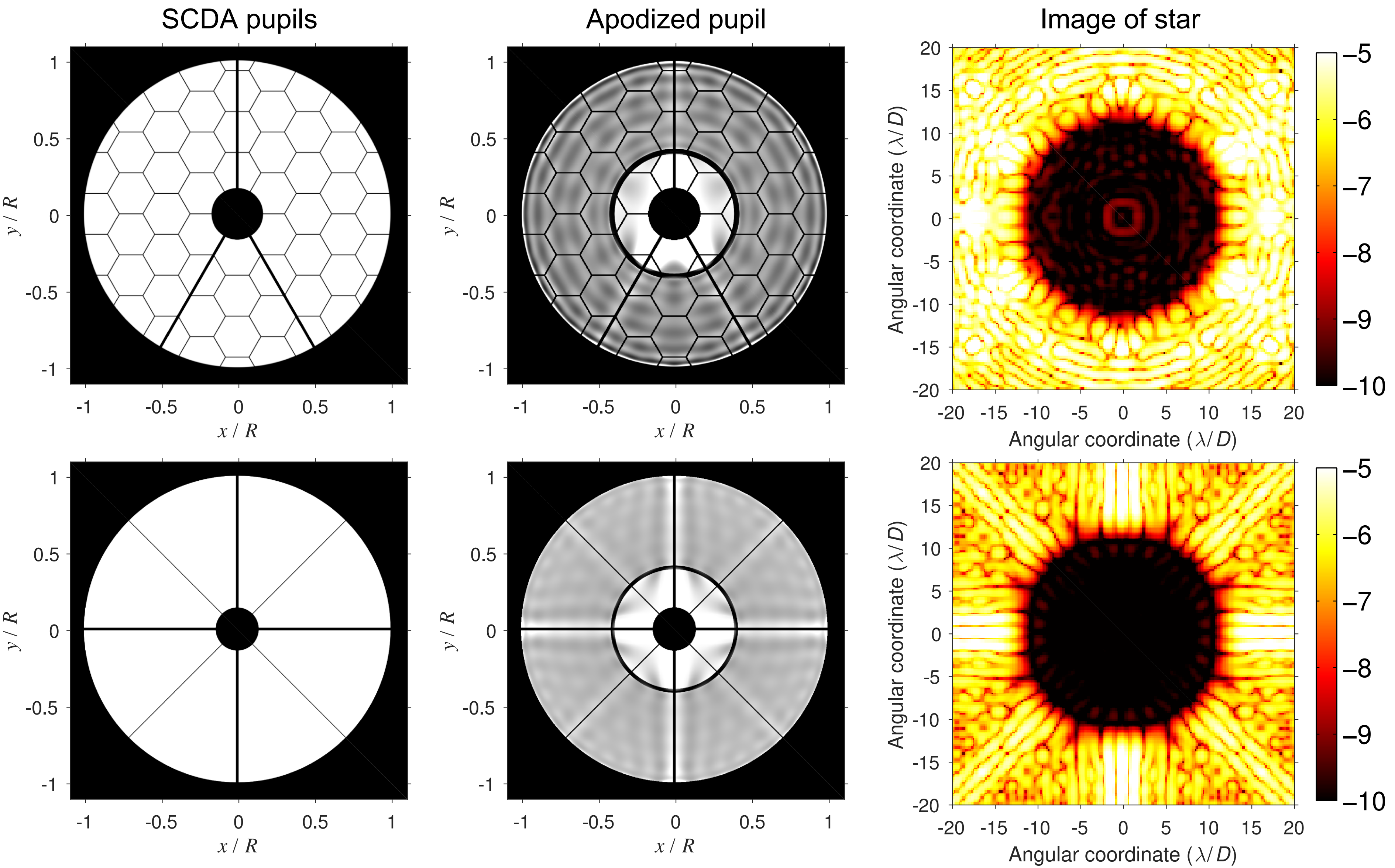


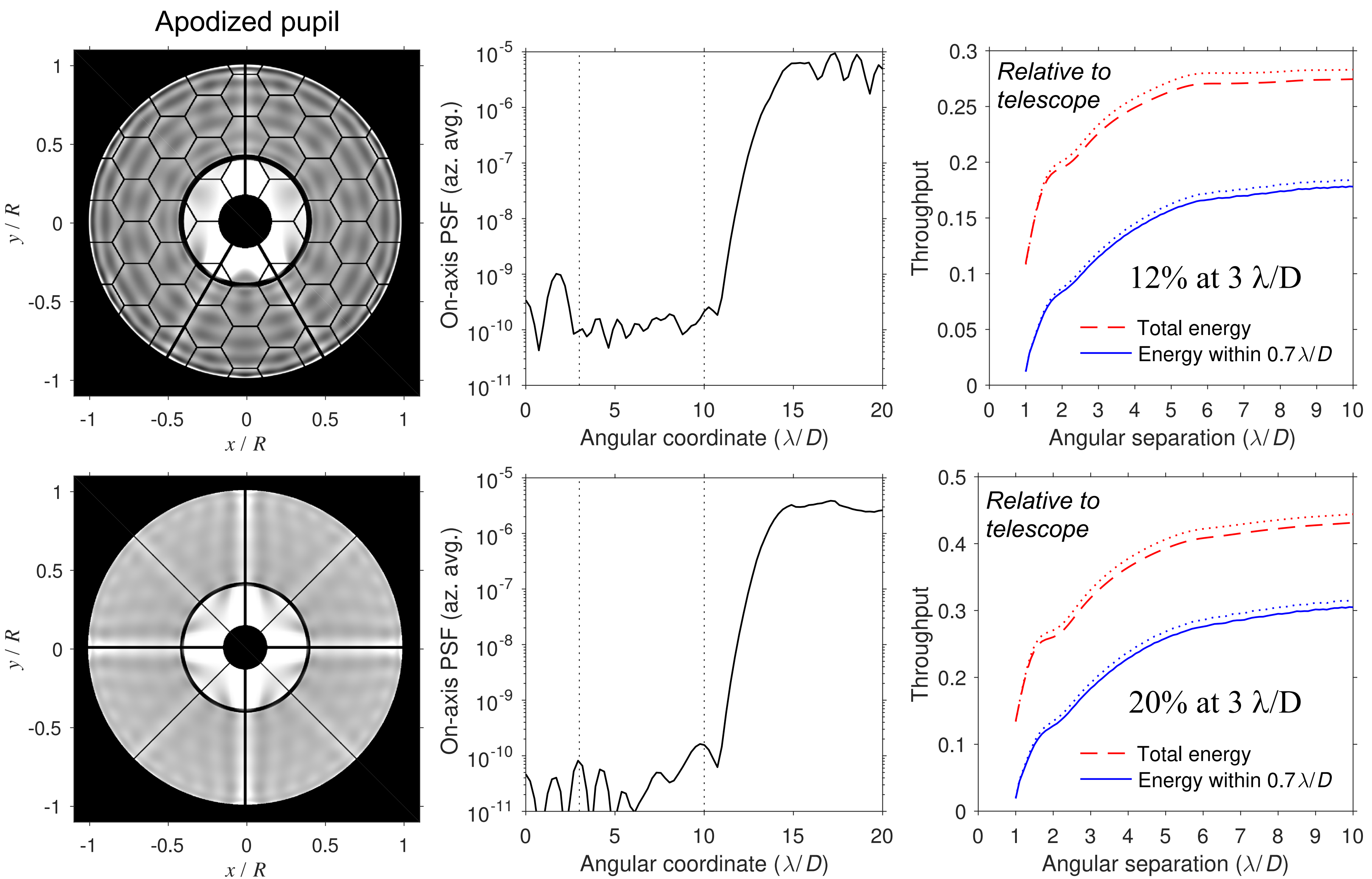
Throughput: $\eta_c > 15\%$ for angular separations $>3\ \lambda/D$

Apodized vortex coronagraph designs for space telescopes

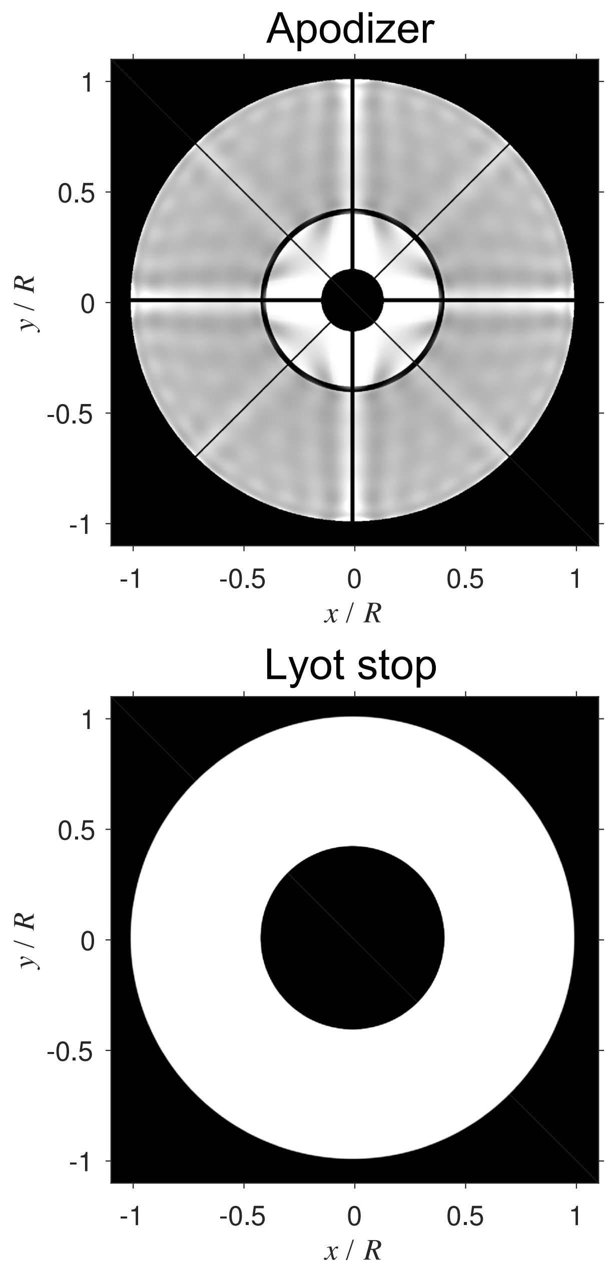


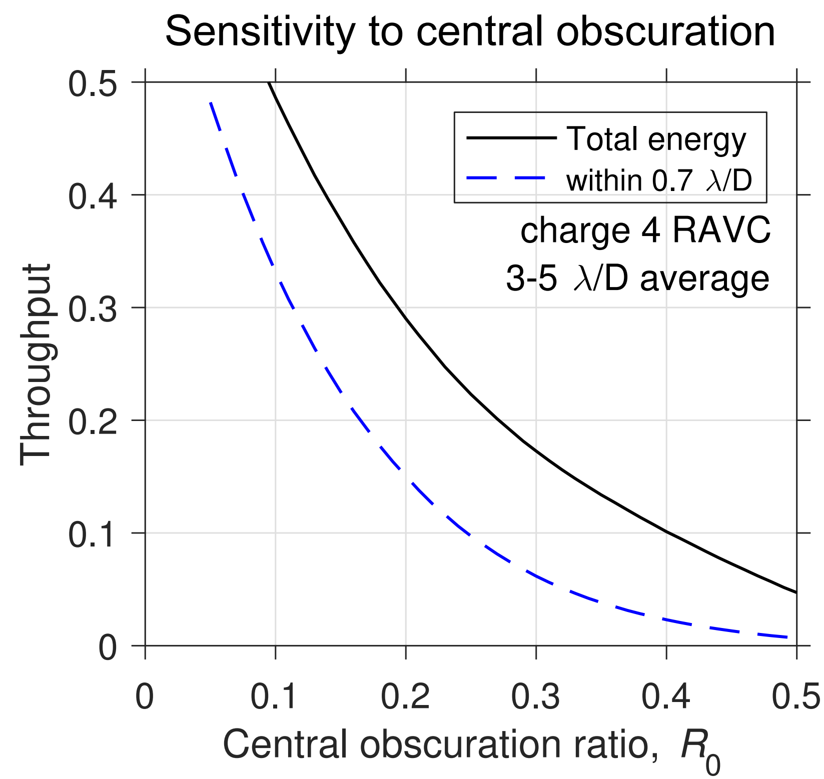
Solutions are wavelength independent!

Apodized vortex coronagraph designs for space telescopes

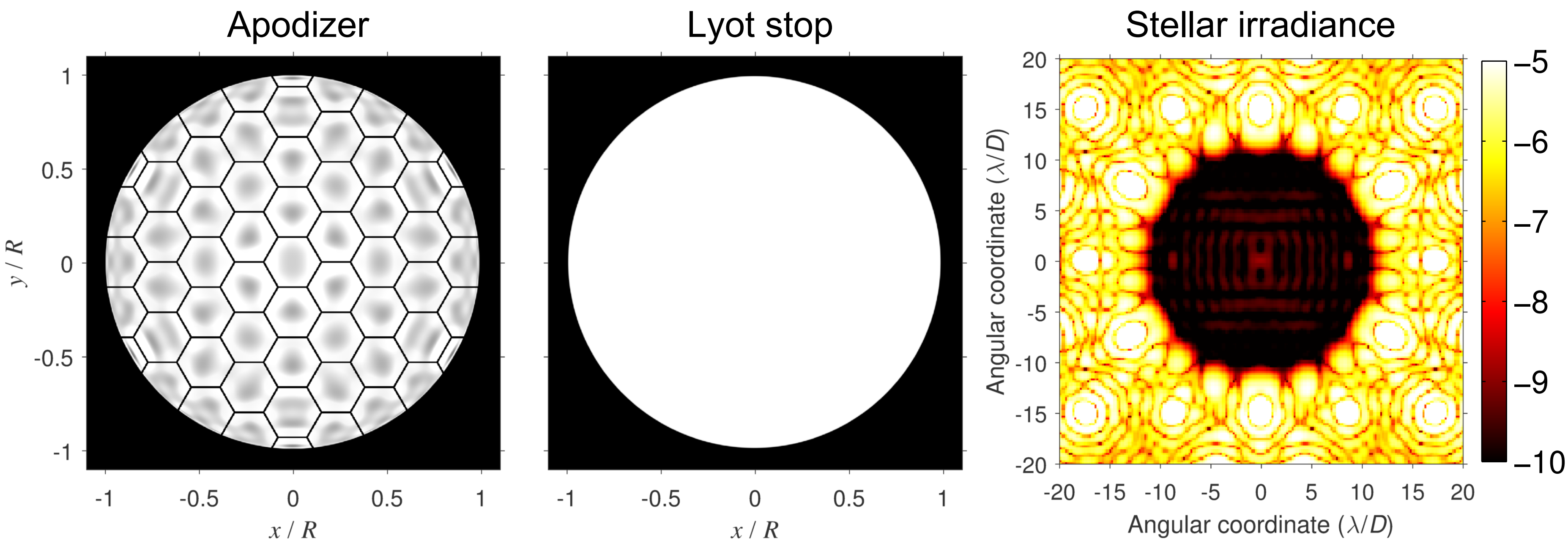


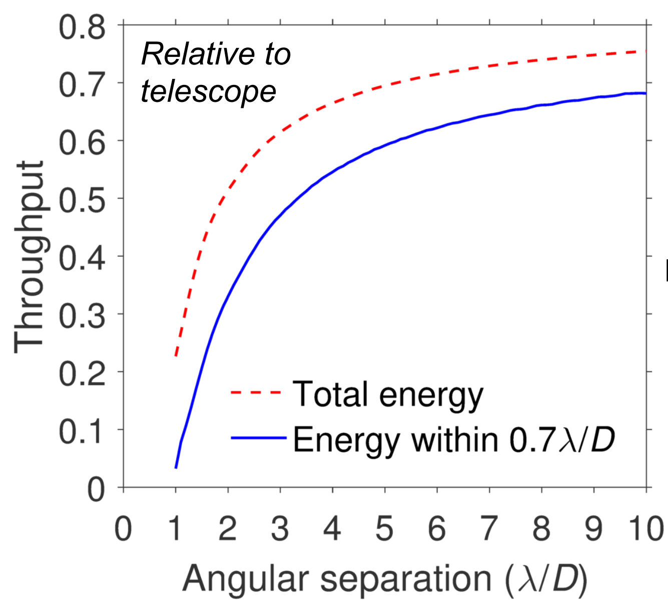
Central obscuration limits the throughput





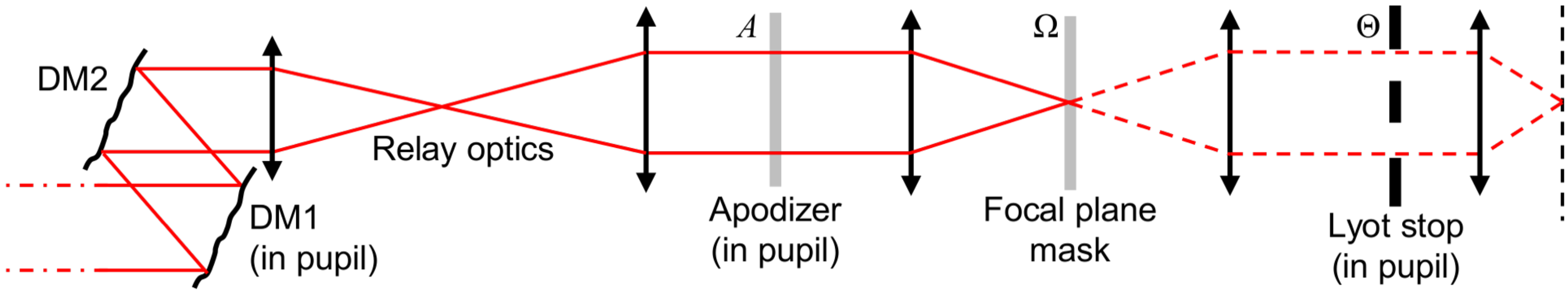
Throughput is much better with unobscured apertures



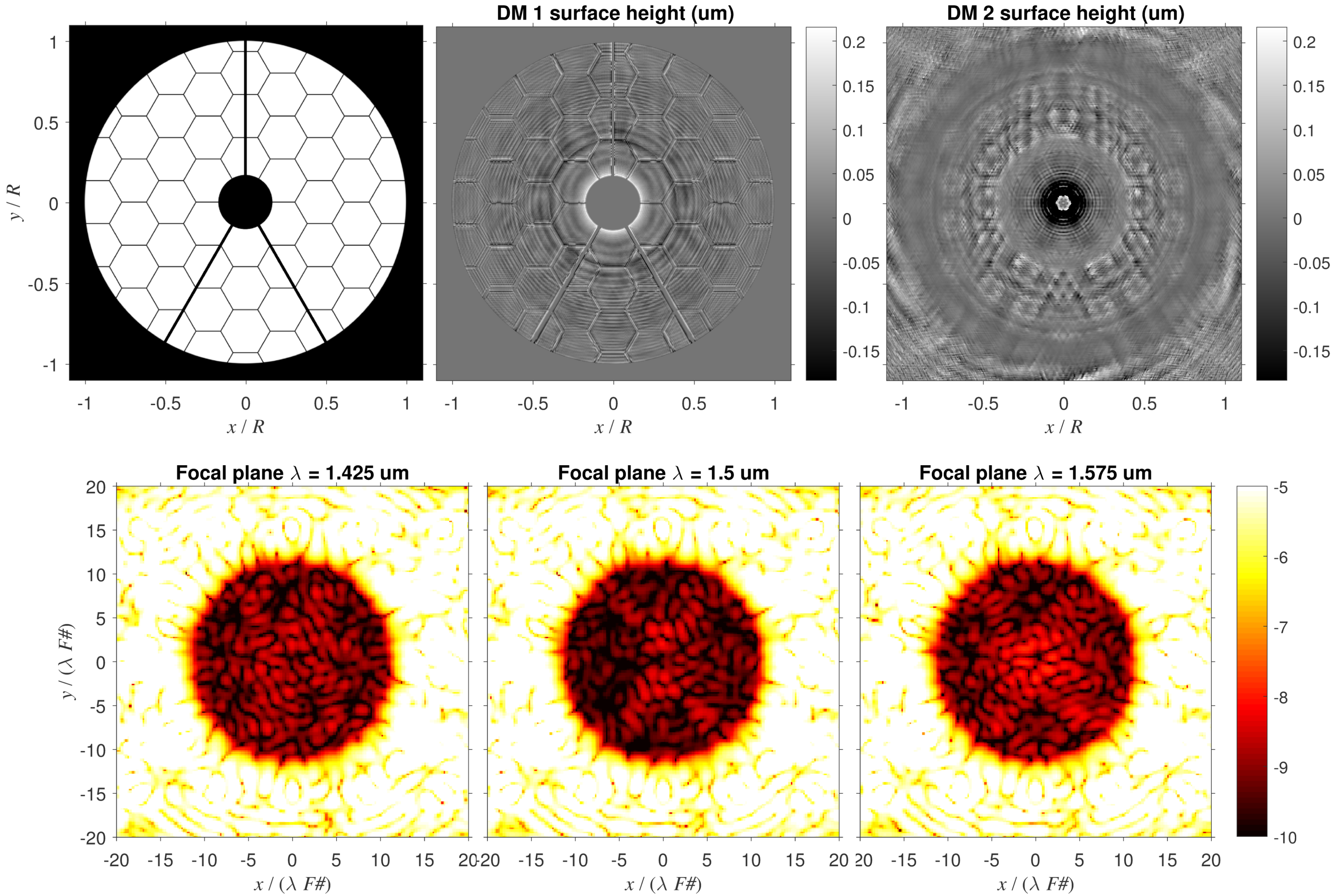


Vortex coronagraph is 3.5 times more efficient without obscuration!

Beam shaping used in lieu of an apodizer can improve throughput

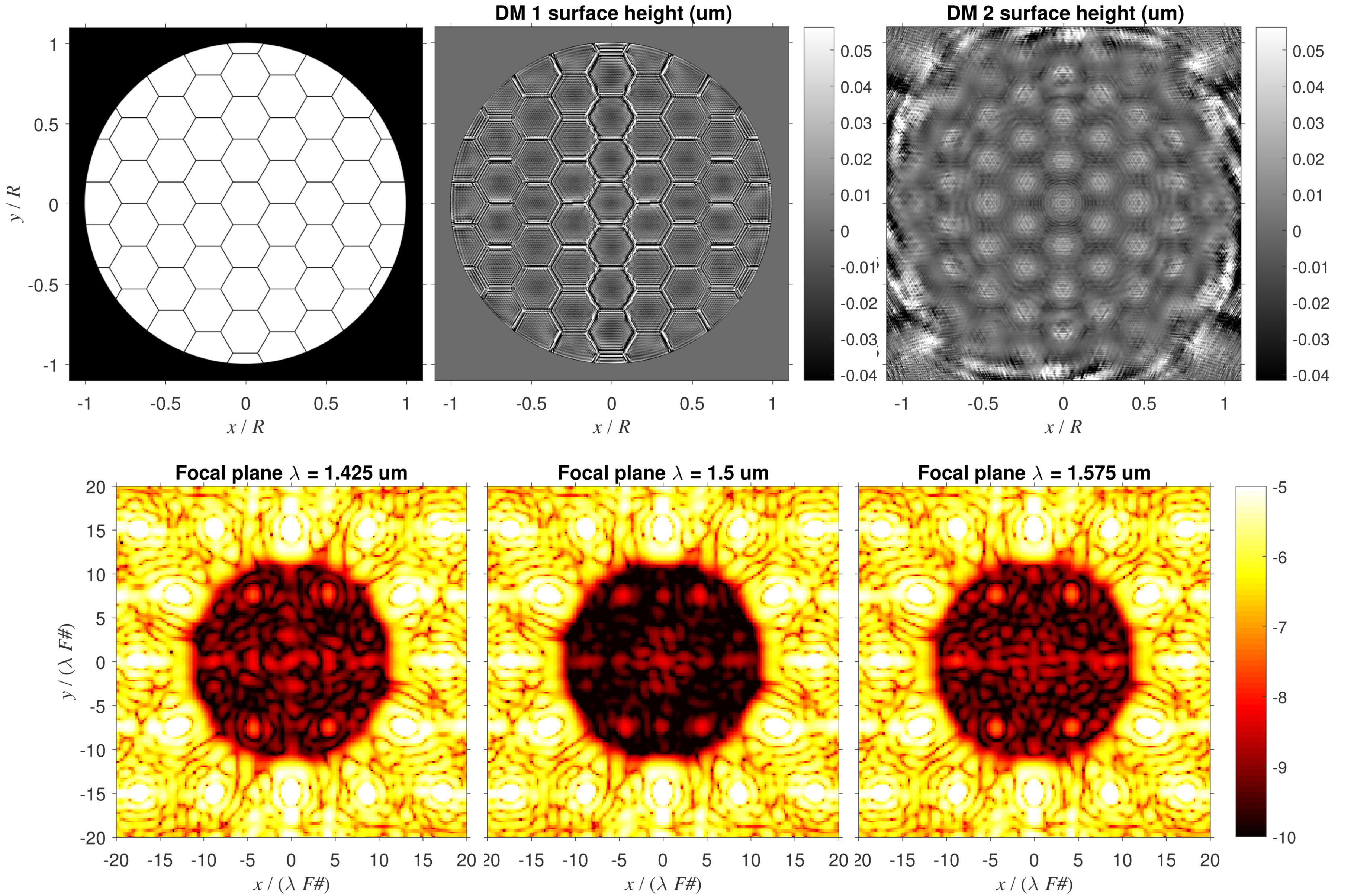


Beam shaping with central obscuration



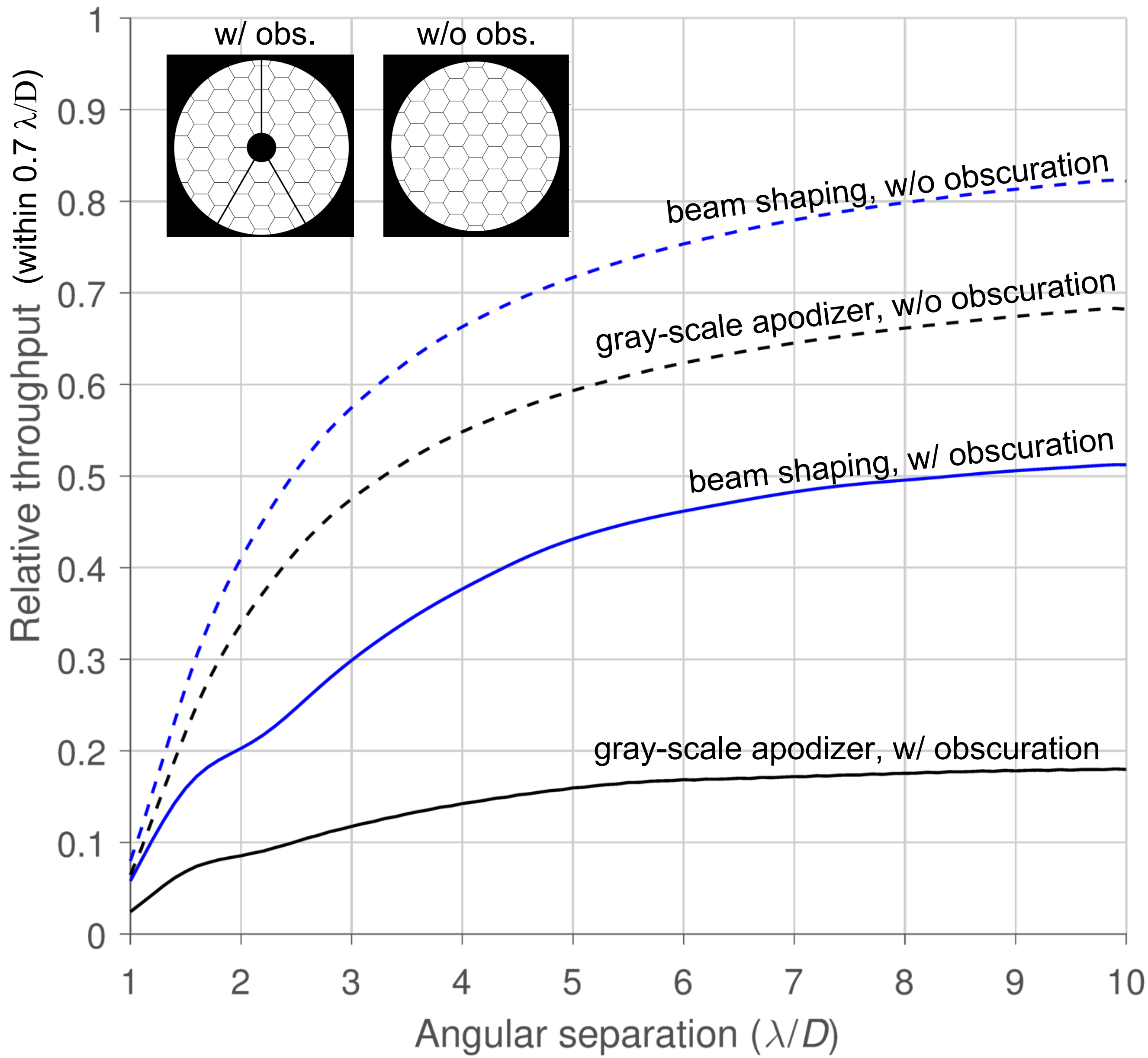
Solution obtained via "Auxiliary Field Conjugation" (Jewell et al., in prep.)

Beam shaping without central obscuration



Solution obtained via “Auxiliary Field Conjugation” (Jewell et al., in prep.)

Throughput comparison



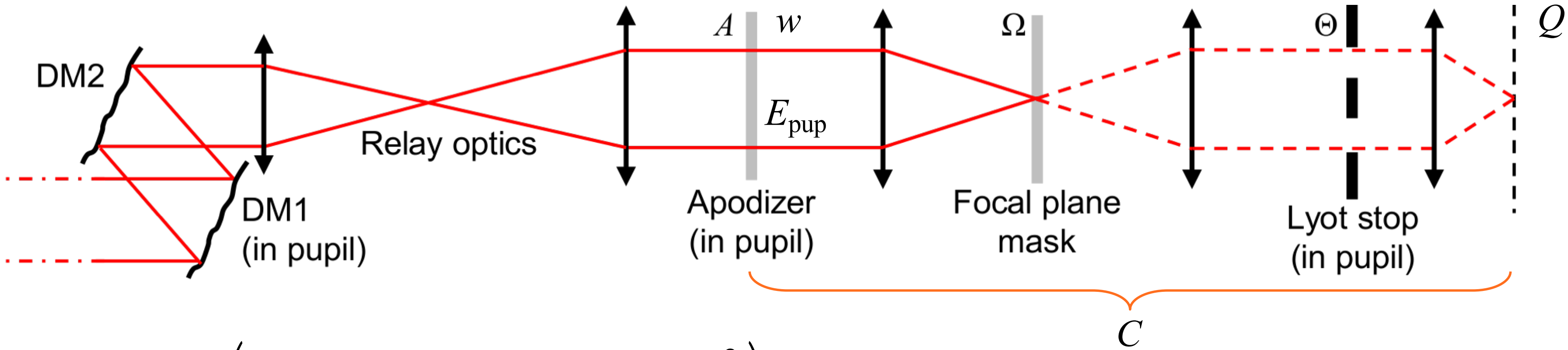
Summary

- **Many possible designs for telescopes and coronagraphs.**
- **Two mask options:** ampl./phase Lyot masks, modified FPM.
- **Three mask options:** optimized gray-scale apodizers.
- **Wavefront control "tricks":** beam shaping in lieu of (or in addition to) gray-scale apodizers.
- **Throughput most sensitive to central obscuration.**
- **Very important to understand performance metrics!!!**

This work is supported by the Exoplanet Exploration Program (ExEP), Jet Propulsion Laboratory, under contract to NASA.

Extra slides

Optimization procedure



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

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

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

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

$$0 \le A \le 1$$

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

3. Set $E_{\text{pup}} = PA$, 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