Apodization Methods for Vortex Coronagraphs on Segmented Aperture Space Telescopes

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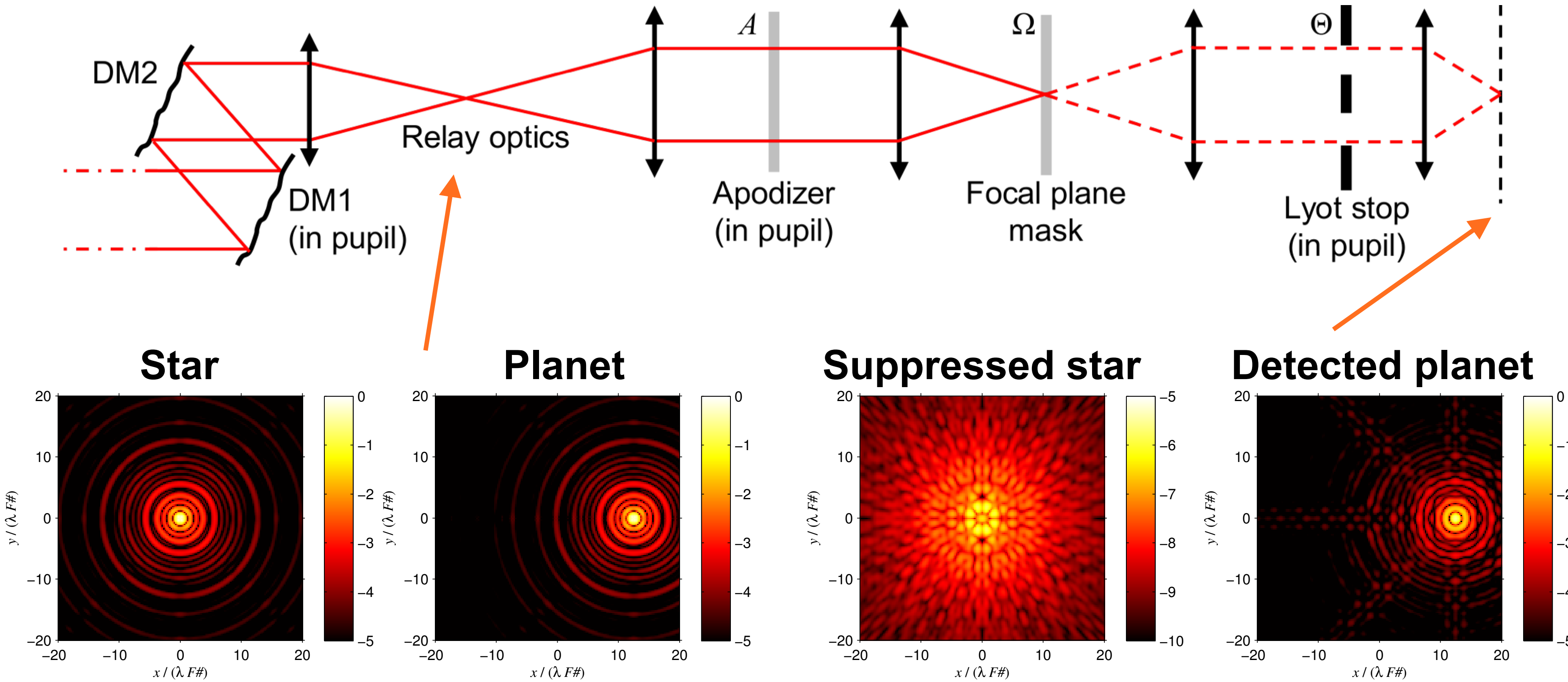
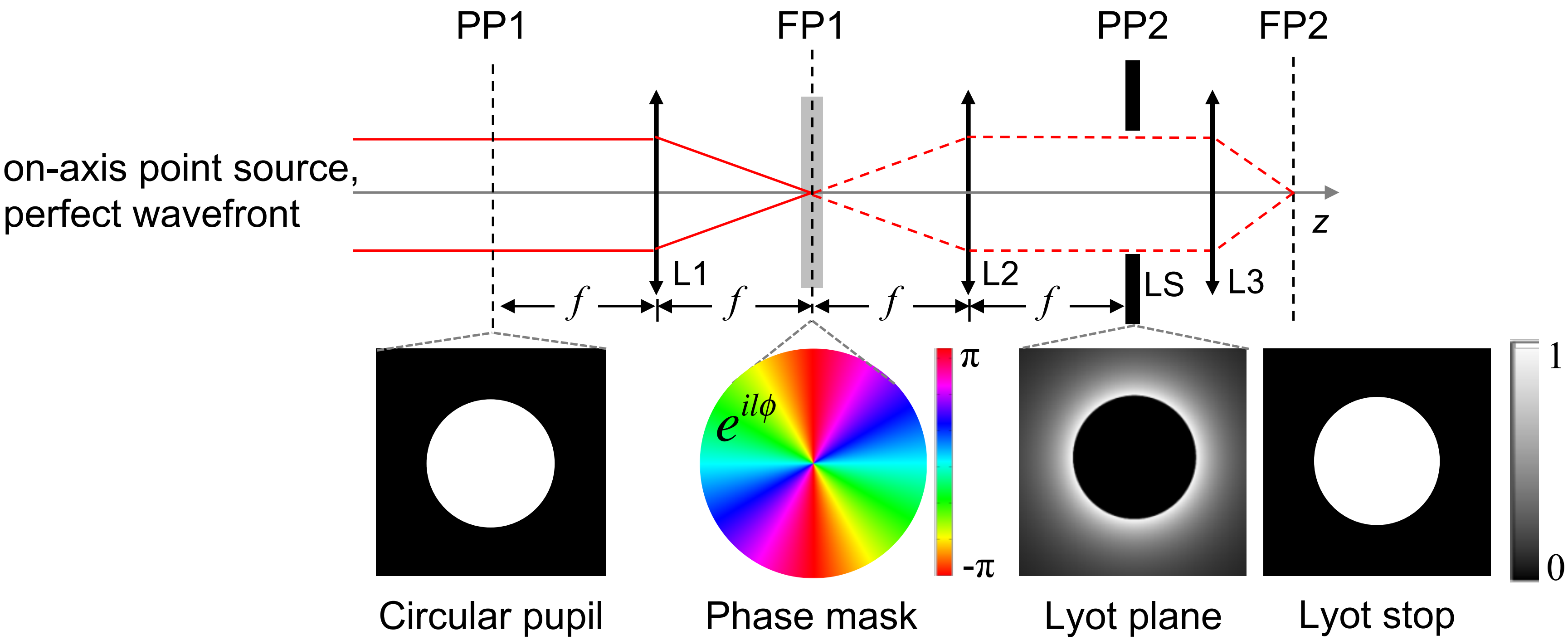
Three-mask coronagraph concept



Coronagraphs are designed to:

1. **Passively suppress starlight**
2. **Maximize signal from planets**

Vortex coronagraph for unobscured telescopes

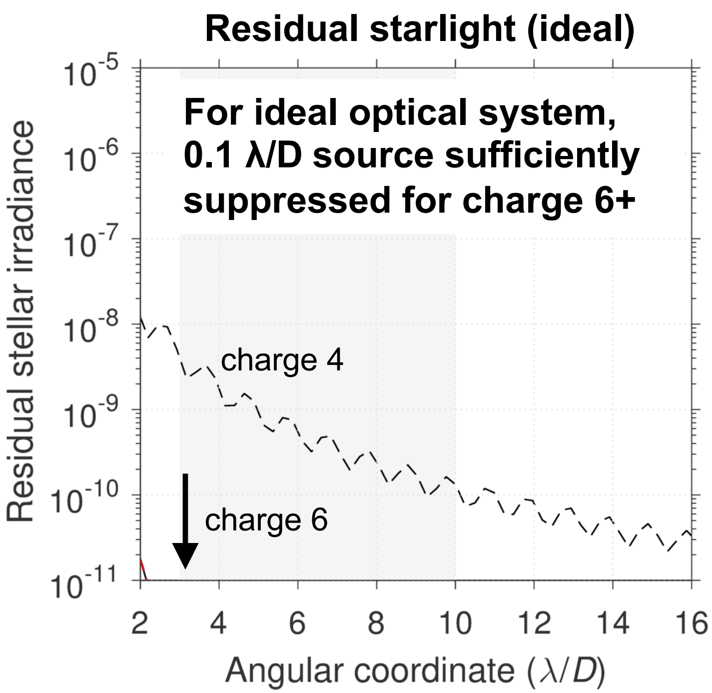


Light from point source rejected by Lyot stop for even (nonzero) charges.

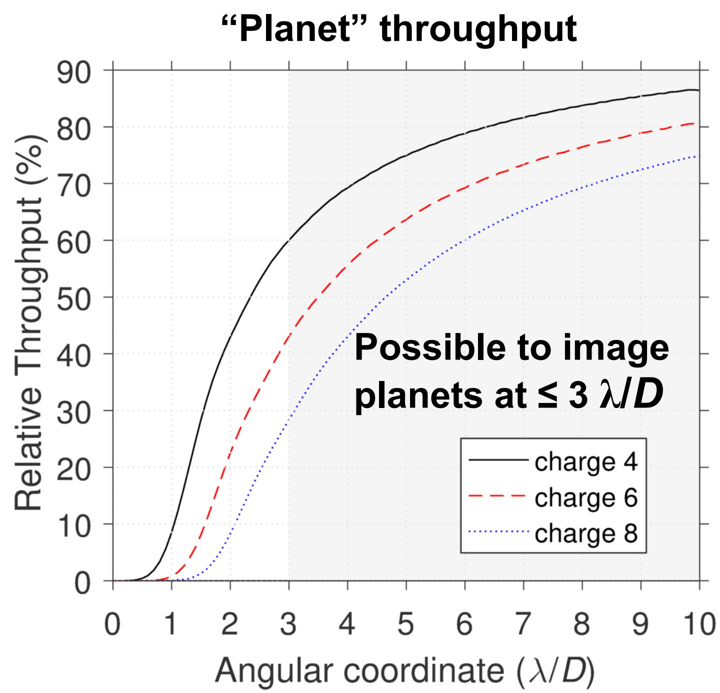
Mawet et al., *ApJ* **633** 1191 (2005)

Performance with *unobscured* telescopes

1. Insensitivity to finite size of star (and jitter).
2. High throughput at small angular separations.



Stellar irradiance is azimuthally averaged and normalized to the peak of the telescope PSF.



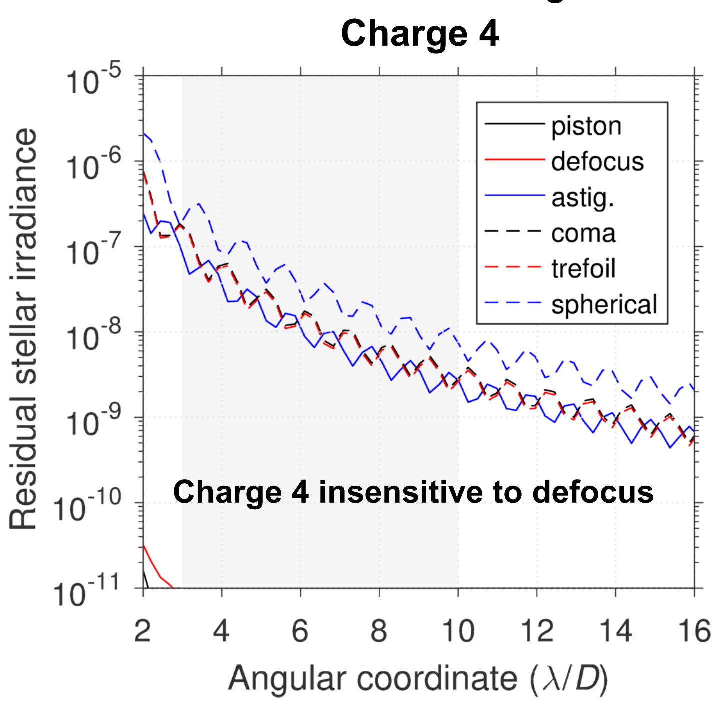
Throughput is defined as energy within 0.7 λ/D of the source position, normalized to that of the telescope.

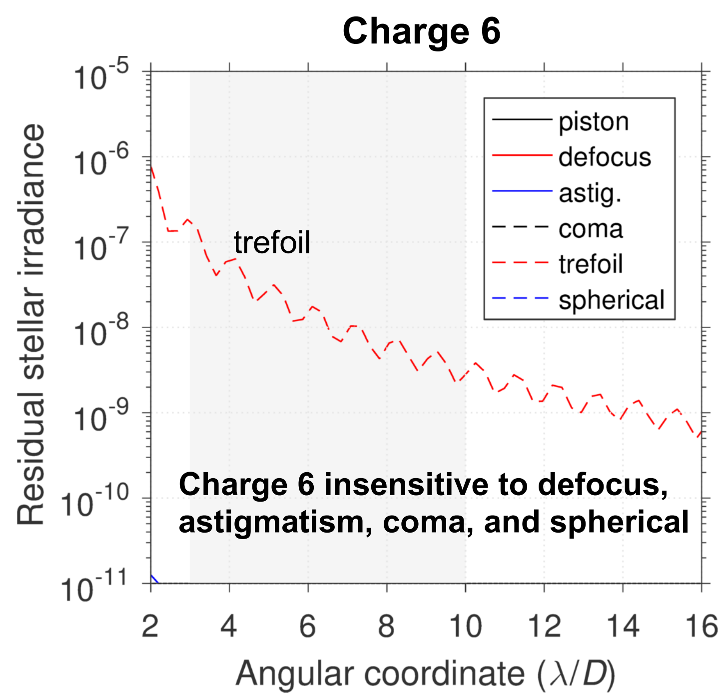
Mawet et al., *Proc. SPIE* 773914 (2010)

Performance with *unobscured* telescopes

3. Insensitivity to low order aberrations.

Residual starlight with λ/1000 rms wavefront error





Stellar irradiance is azimuthally averaged and normalized to the peak of the telescope PSF.

Mawet et al., *Proc. SPIE* 773914 (2010)

Zernike mode selection rules

For small phase aberration

i.e. $\Phi \ll 1$ rad

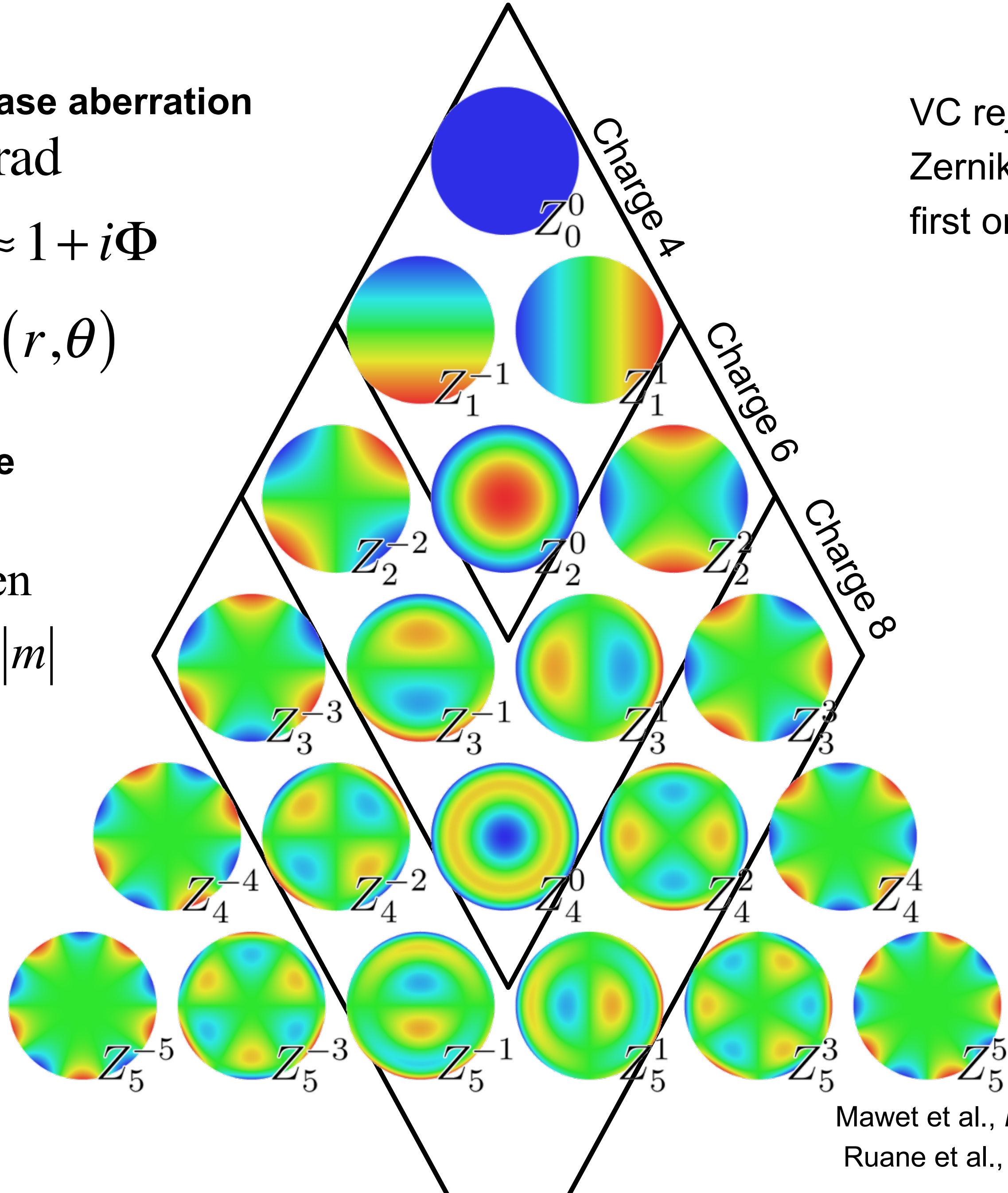
$$\exp(i\Phi) \approx 1 + i\Phi$$

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

Zernike mode is rejected if:

l is even

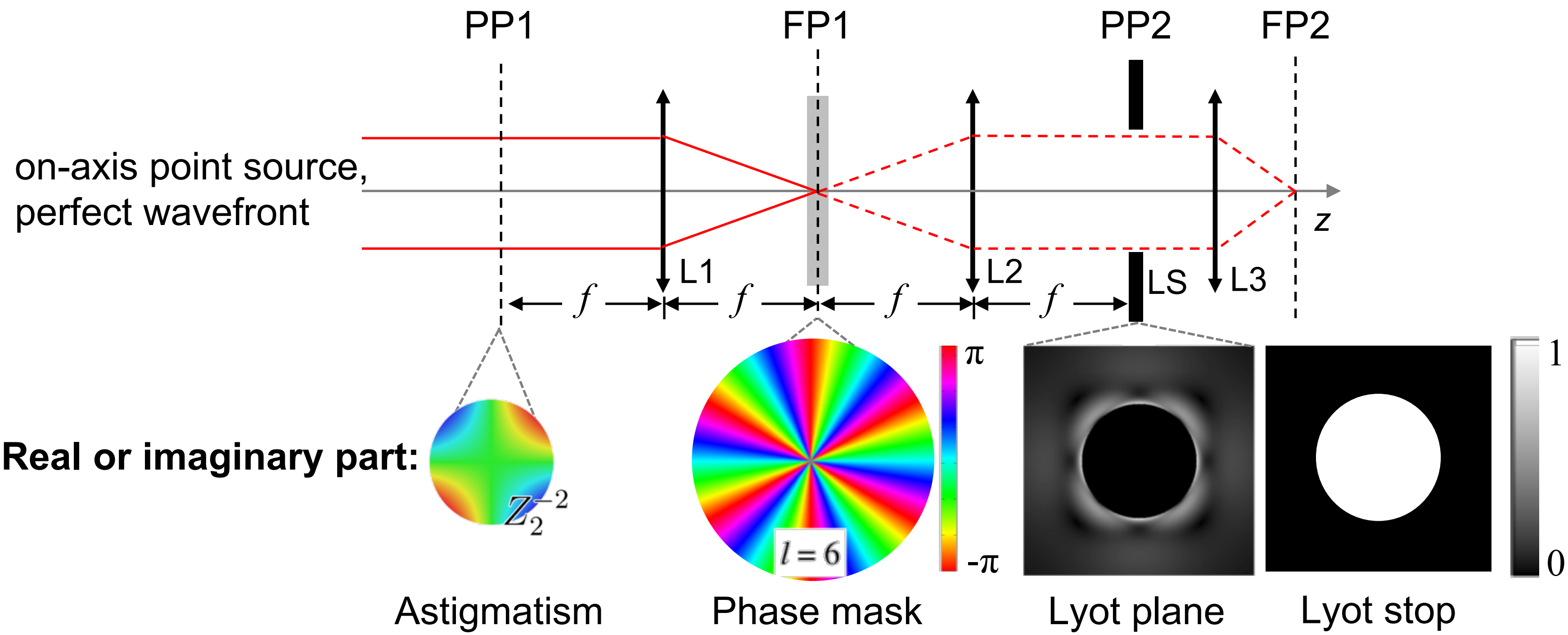
$|l| > n + |m|$



VC rejects $(l/2)^2$ Zernike modes to first order

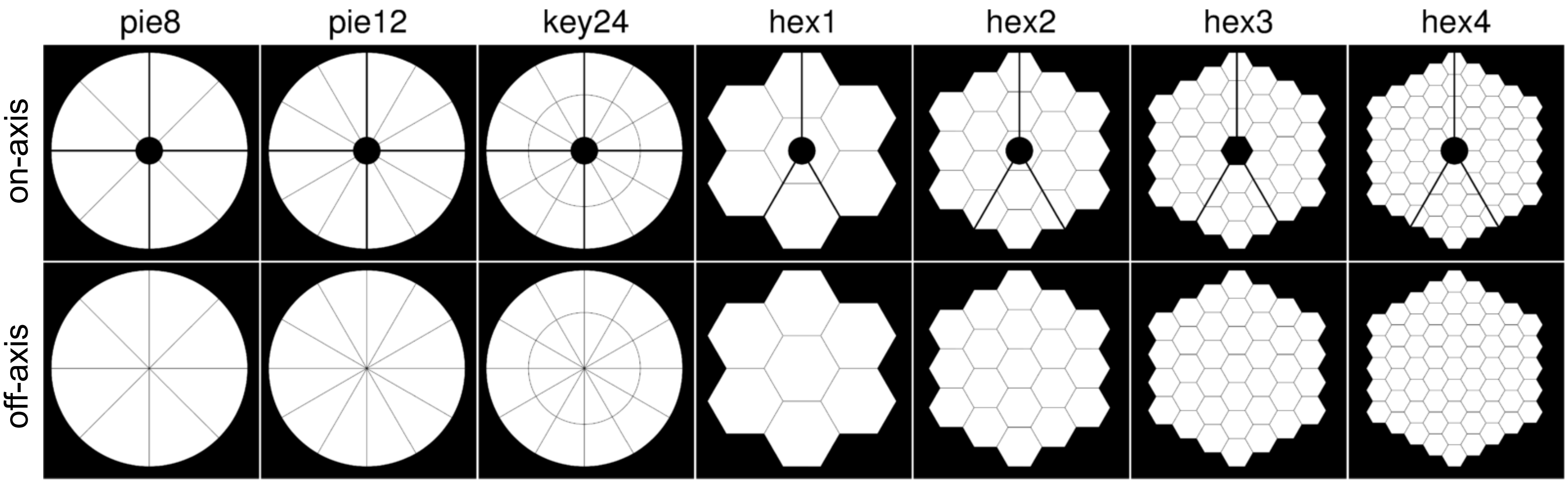
Mawet et al., *Proc. SPIE* 773914 (2010)
Ruane et al., *Proc. SPIE* 96051I (2015)

e.g. Charge 6 rejects astigmatism



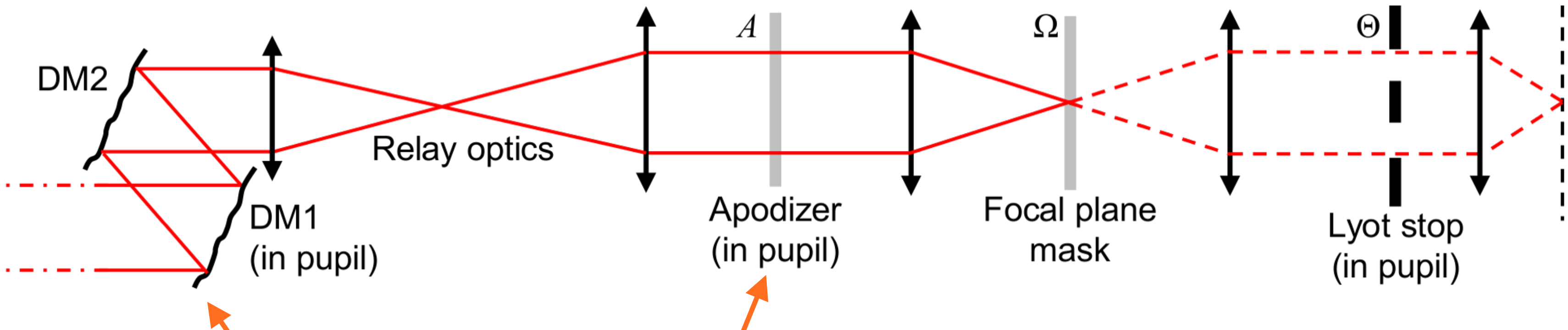
Mawet et al., *Proc. SPIE* 773914 (2010)
Ruane et al., *Proc. SPIE* 96051I (2015)

Can we take advantage of these benefits on segmented apertures?



SCDA study, led by Stuart Shaklan (JPL), supported by the Exoplanet Exploration Program (ExEP).

Apodization approaches

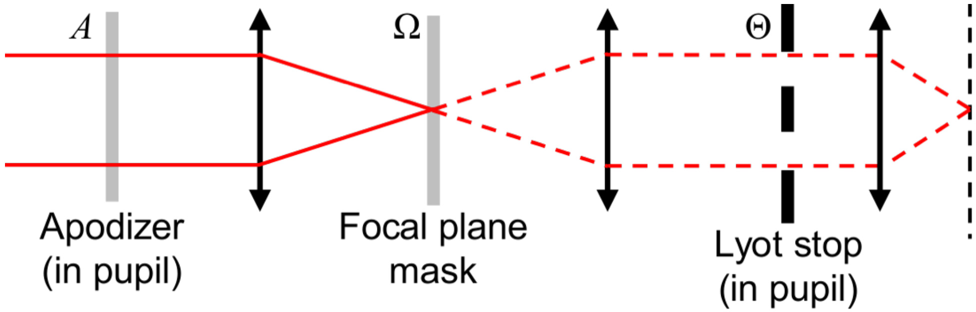


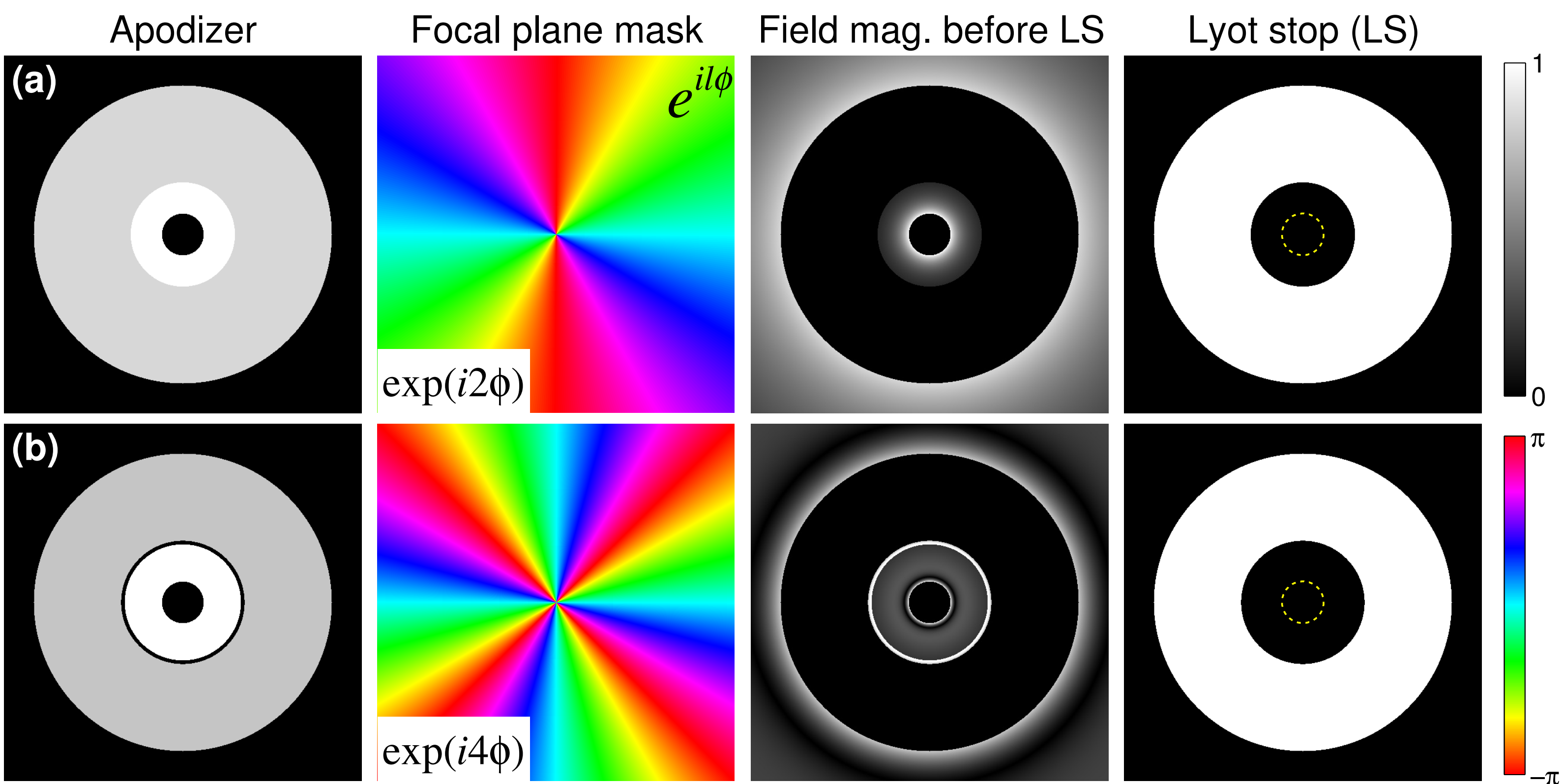
Option #1: Apodizing pupil mask (e.g. Shaped pupil, APLC, APP, etc.)

Option #2: Beam shaping with DMs (e.g. WFIRST Lyot coronagraph)

Grayscale apodized vortex coronagraph

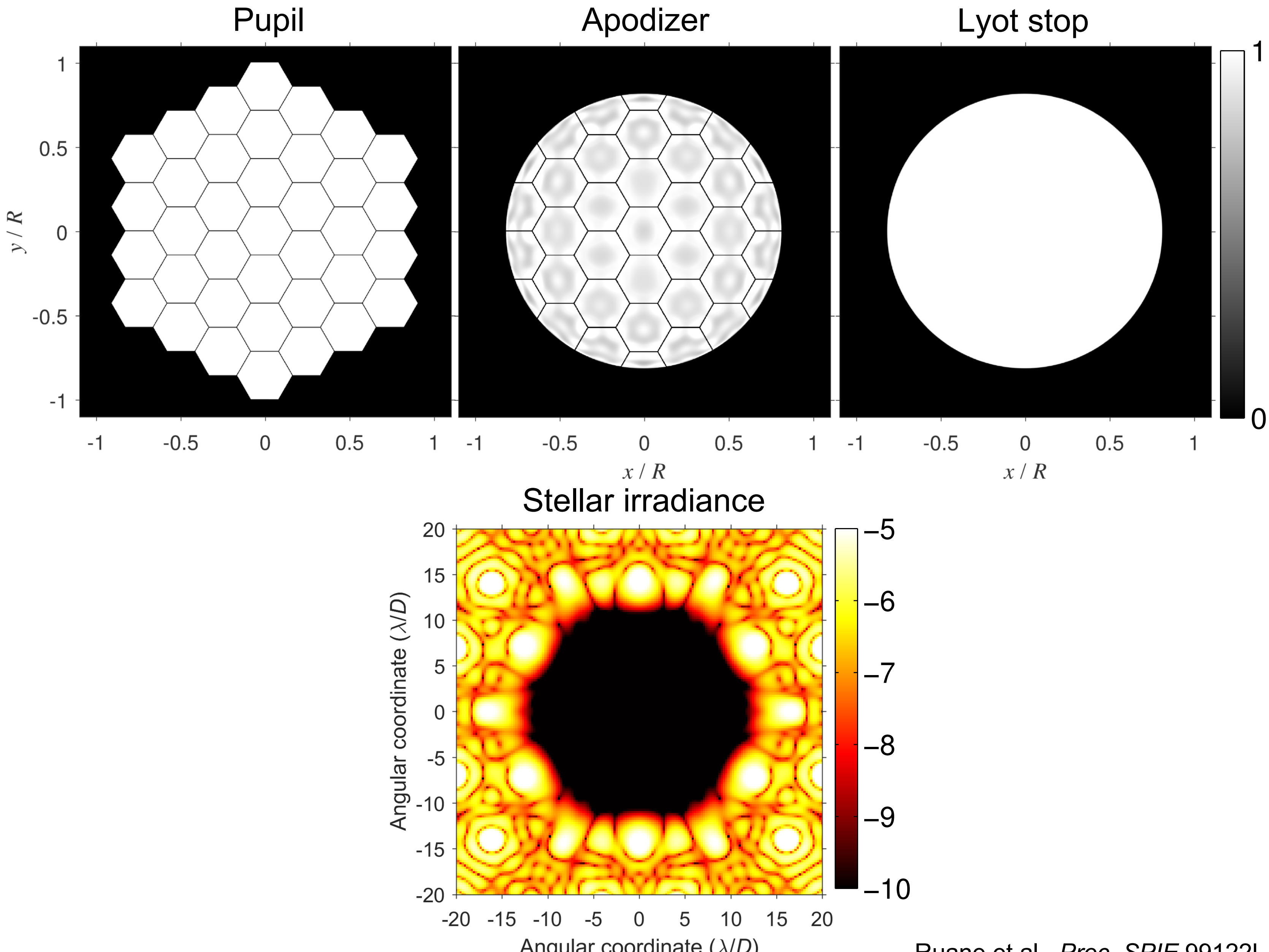
on-axis point source,
perfect wavefront





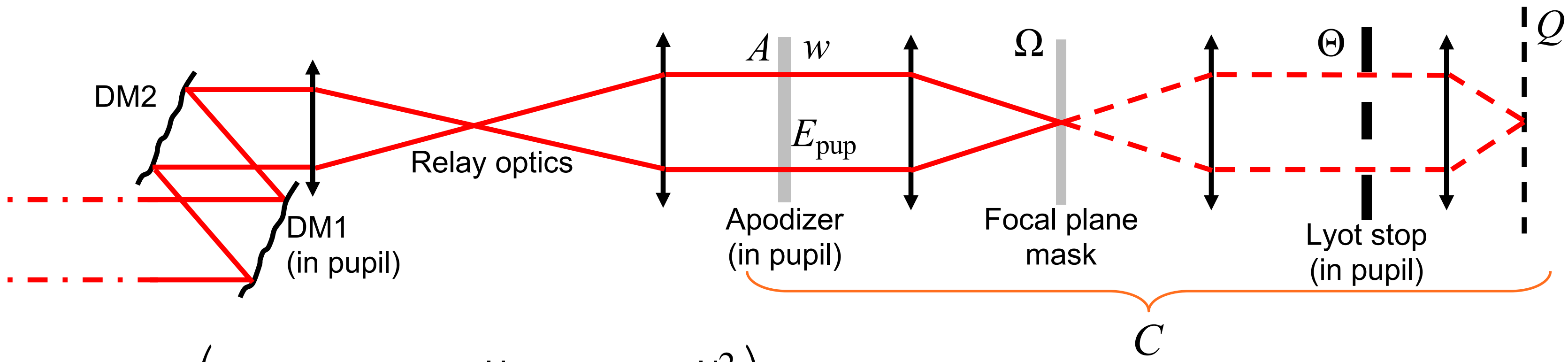
Mawet et al., *ApJS* **209** 7 (2013)

Grayscale apodized vortex coronagraph



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

Auxiliary field optimization: gray-scale apodizers



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

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 $A = |w|$:

$$0 \le A \le 1$$

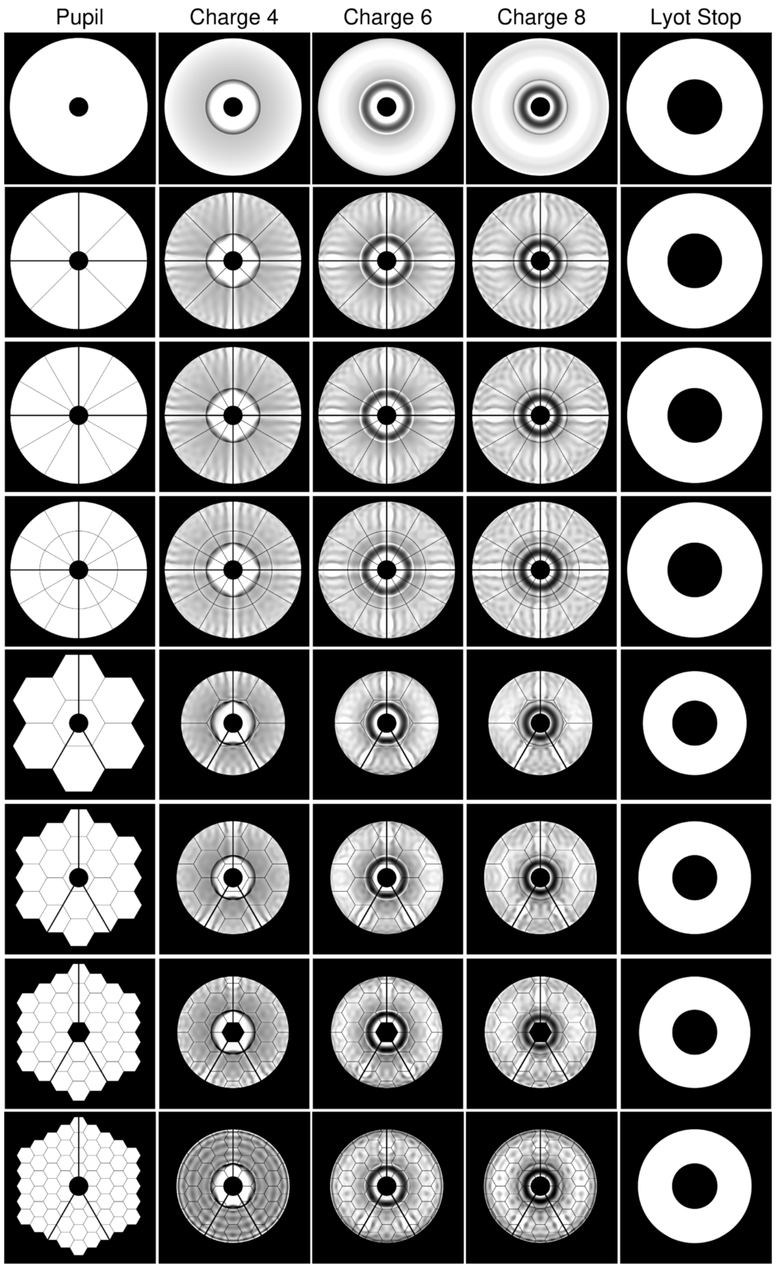
$$\text{supp}\left\{A\right\} = \text{supp}\left\{P\right\}$$

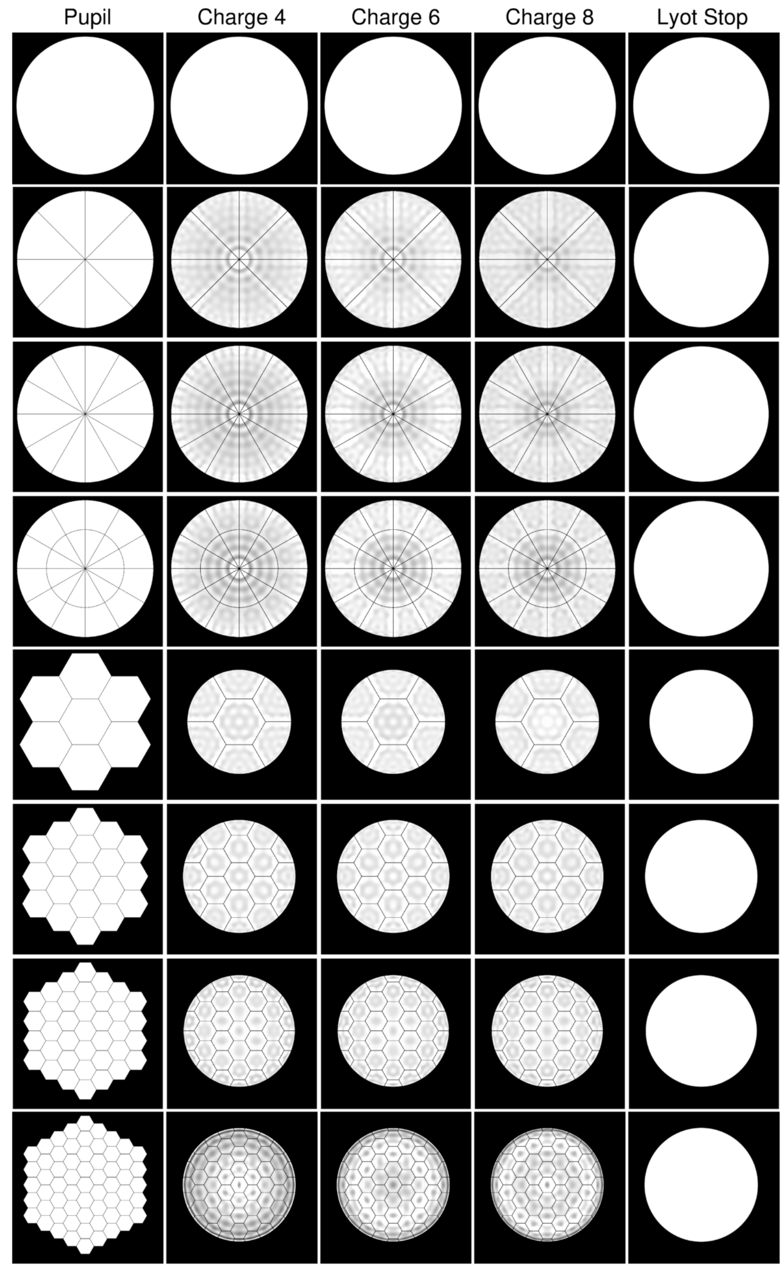
3. Set $E_{\text{pup}} = PA$, and repeat

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 optimization algorithm developed by Jeff Jewell, JPL

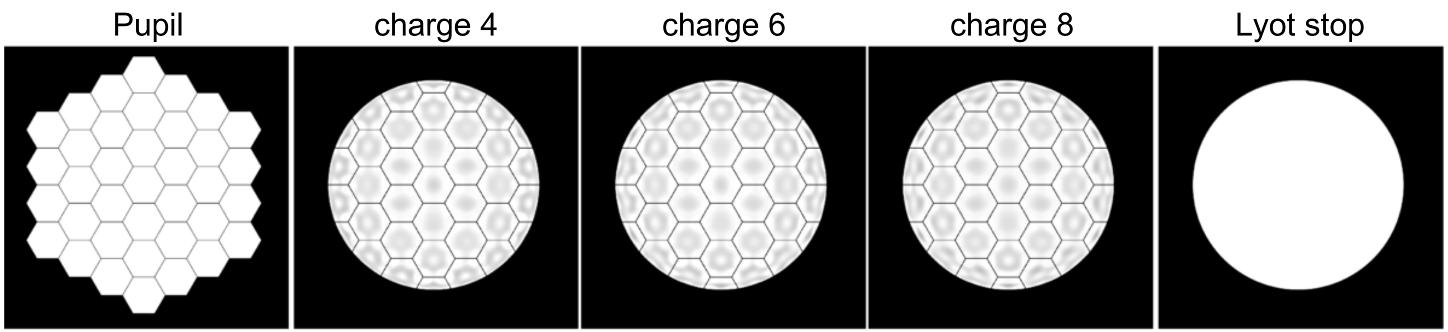
A family portrait of apodizer designs



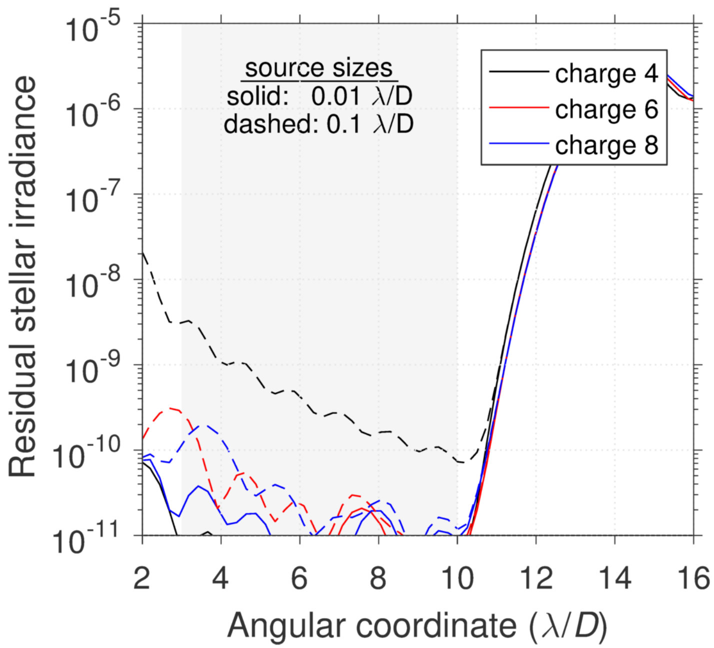


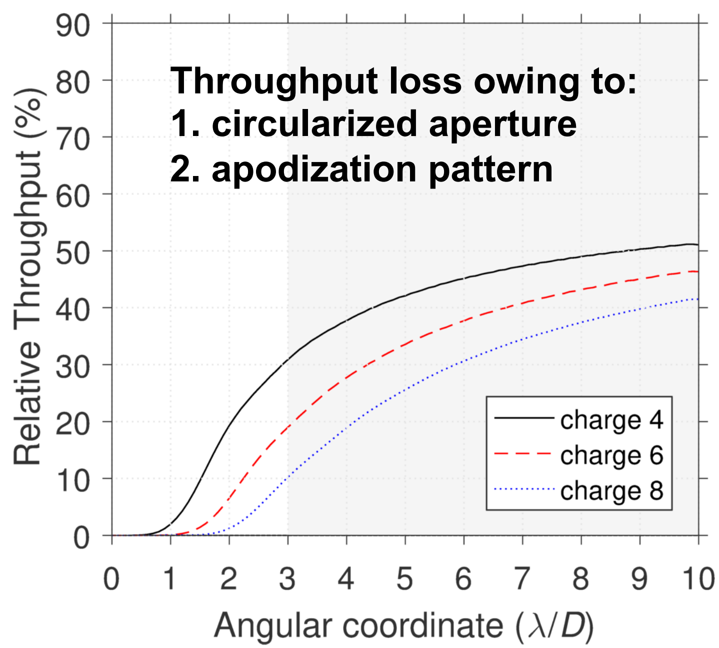
Performance for off-axis segmented telescopes

hex3: 3-ring hexagonally segmented primary (37 segments)



1. Insensitivity to finite size of star and jitter maintained.
2. Apodizer introduces a throughput loss.





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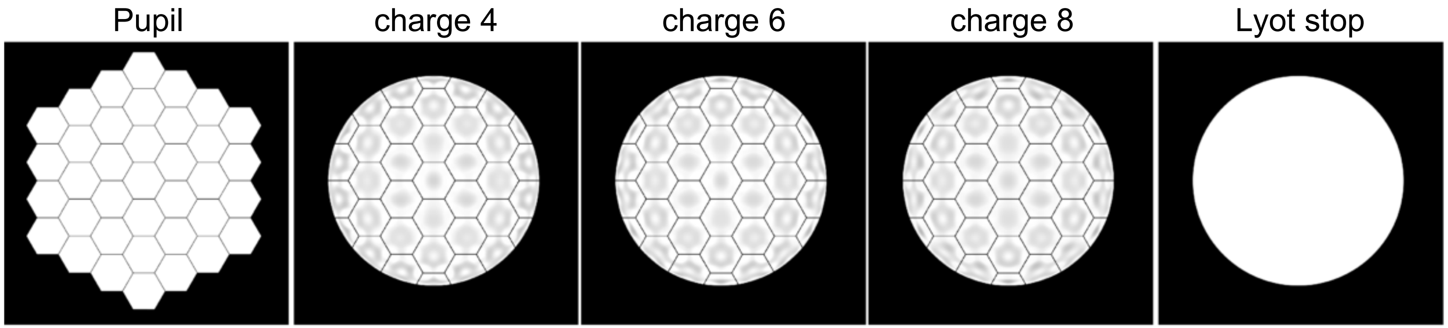
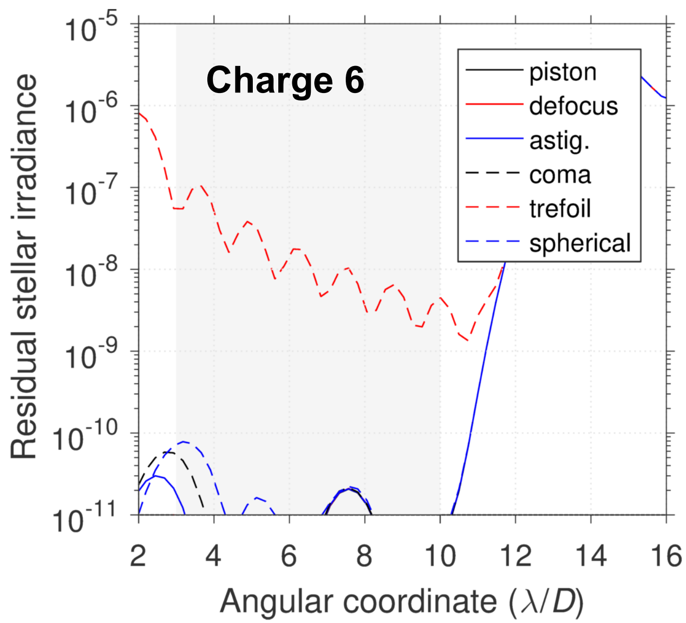


3. Insensitivity to Zernike aberrations maintained.

Residual starlight with λ/1000 rms wavefront error



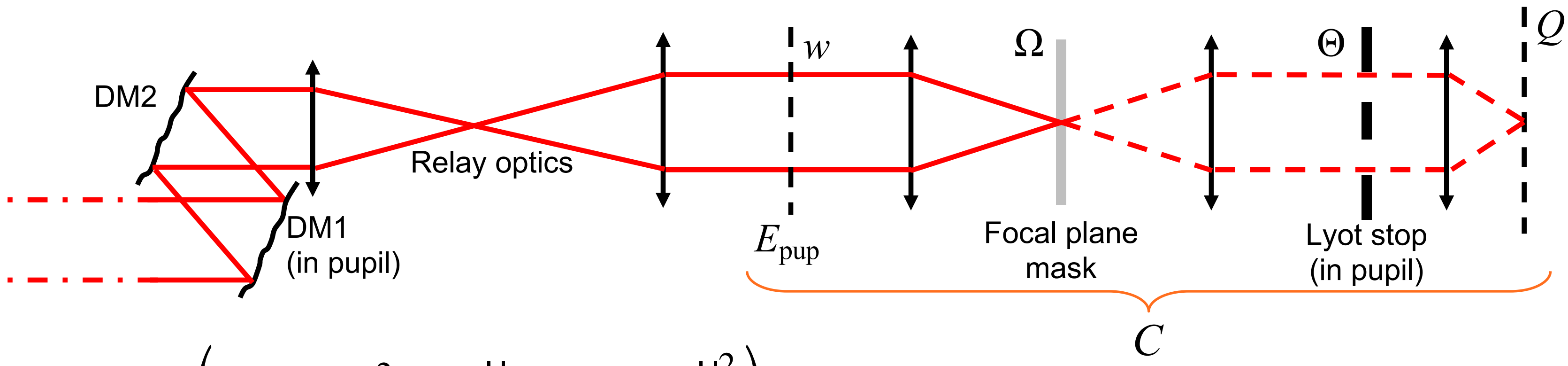
Improving designs for on-axis telescopes

- **Compounding issues with current on-axis designs:**
  1. Decreased throughput.
  2. More sensitivity to the finite size of the star.
  3. Large *D* means *λ*/*D* is smaller with respect to the star.

- **Updating optimization procedure to combat these effects.**

- **Several approaches have yet to be considered:**
  - Gray-scale apodizers with updated metrics
  - Lyot stop optimization
  - Focal plane mask optimization
  - Beam shaping with DMs
  - Multiplexed sub-apertures

Auxiliary field optimization: beam shaping



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

C – coronagraph propagation operator
Q – dark hole region
w – "auxiliary" field
b – regularization parameter
E_{pup} – current pupil field

Algorithm:

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

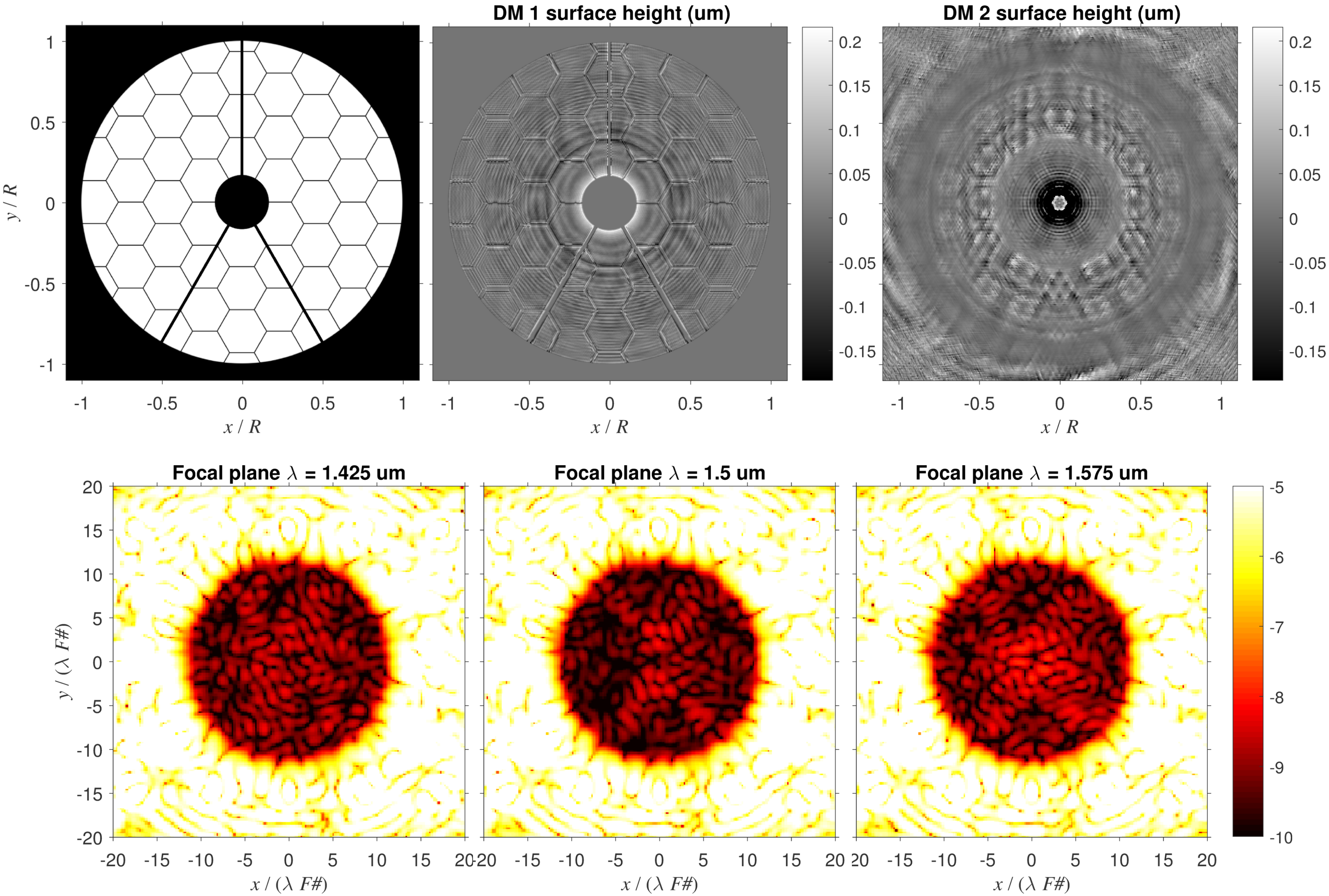
$$w = \left(bI + C^{\dagger}QC\right)^{-1} bE_{\text{pup}}$$

2. Determine the DM surfaces that achieve the best match between E_{pup} and the target field w.

3. Repeat steps 1 and 2 until sufficient starlight suppression is obtained.

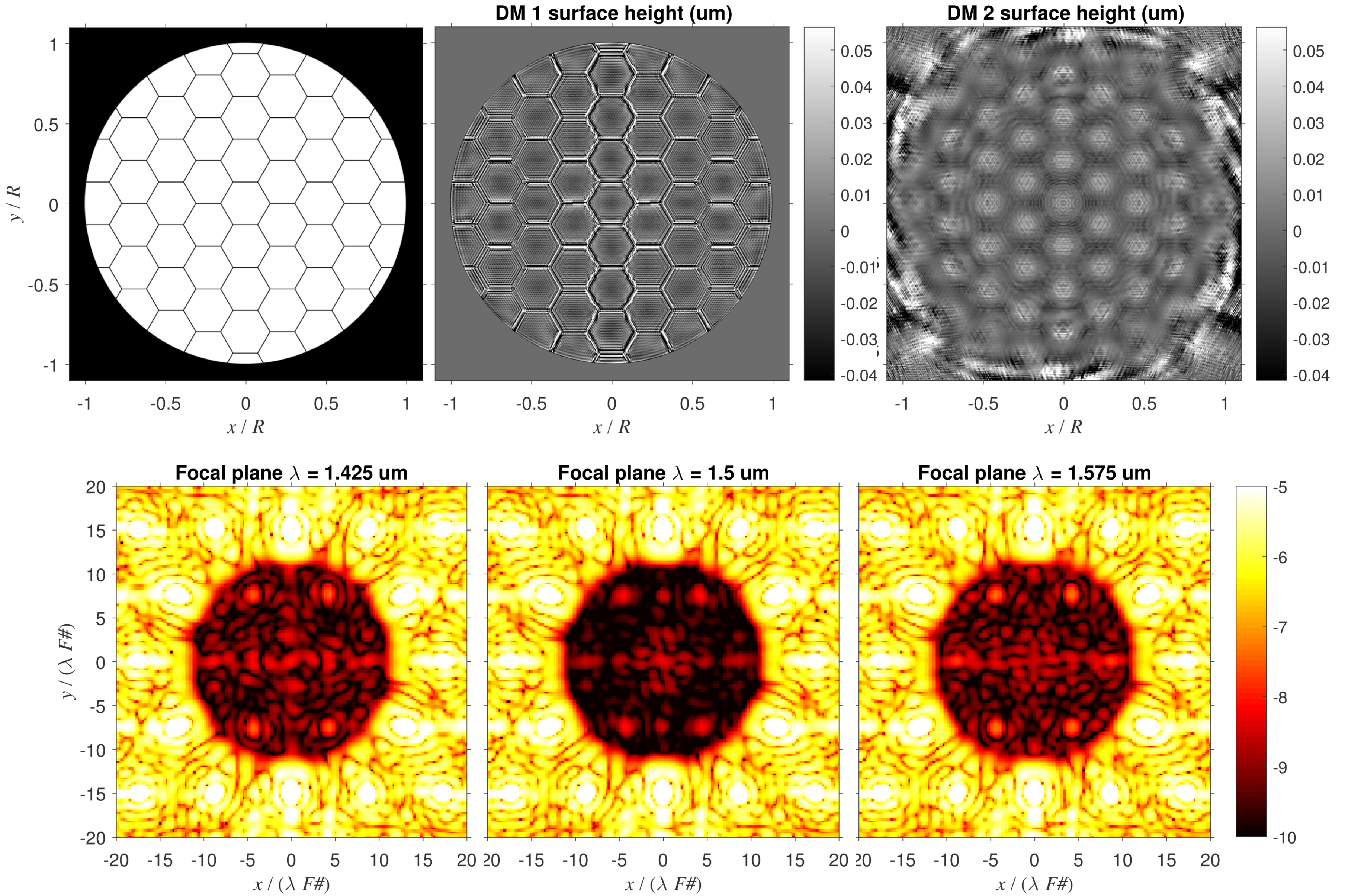
Aux. field optimization algorithm developed by Jeff Jewell, JPL

Beam shaping with central obscuration



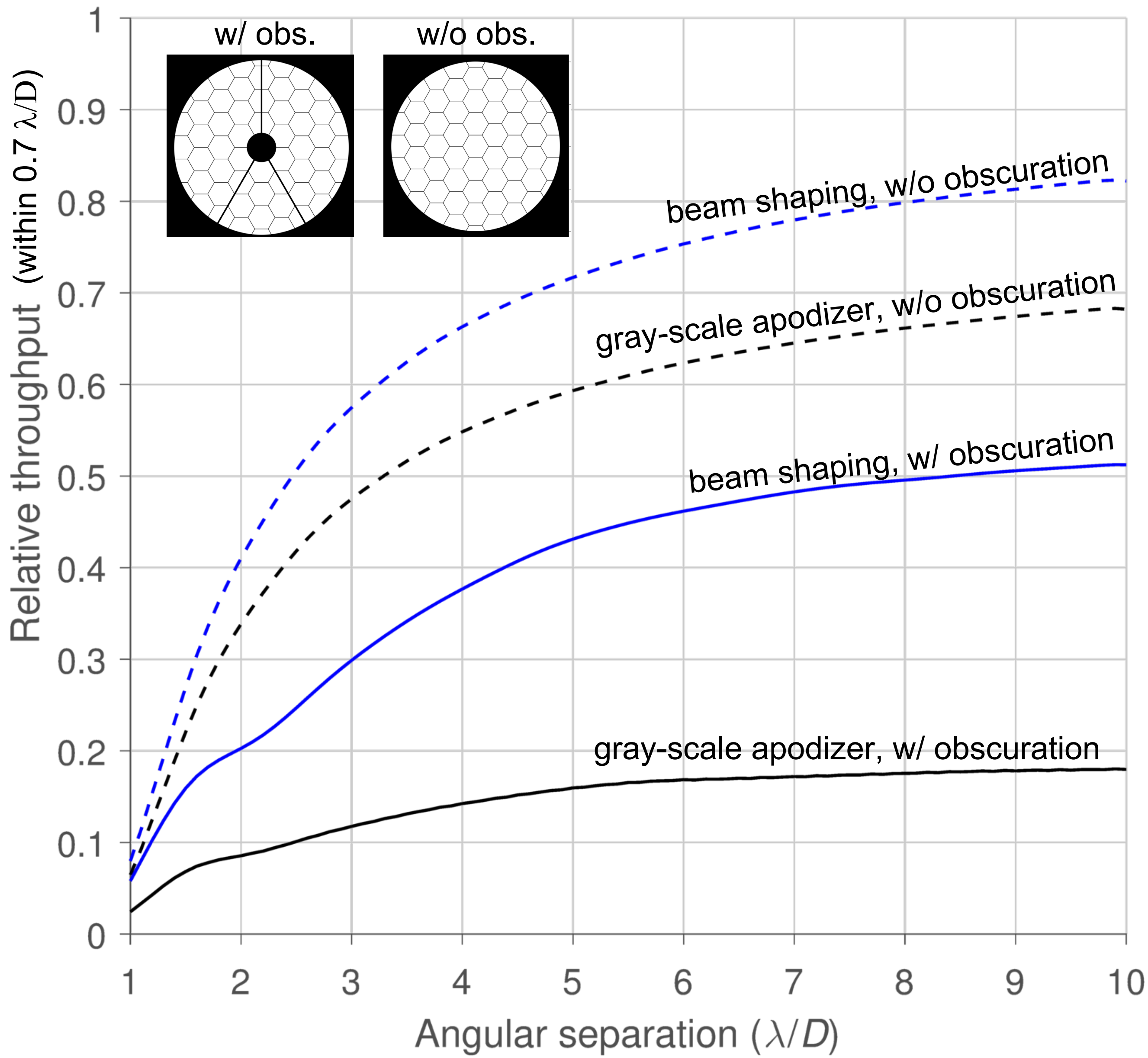
Solution obtained via “Auxiliary Field Optimization” (Jewell et al., in prep.)

Beam shaping without central obscuration



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

Throughput comparison



Summary

- **Current vortex coronagraph designs perform well with an off-axis telescope (even if segmented).**
- **Designs for on-axis telescopes are currently limited by sensitivity to finite size of stars.**
- **Optimization approach to be tailored to the finite size of stars, especially for large on-axis telescopes.**
- **Apodization by means of beam shaping with deformable mirrors is a pathway to higher throughput.**

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*G. Ruane is an NSF Postdoctoral Fellow.