Vortex coronagraphs for segmented aperture space telescopes

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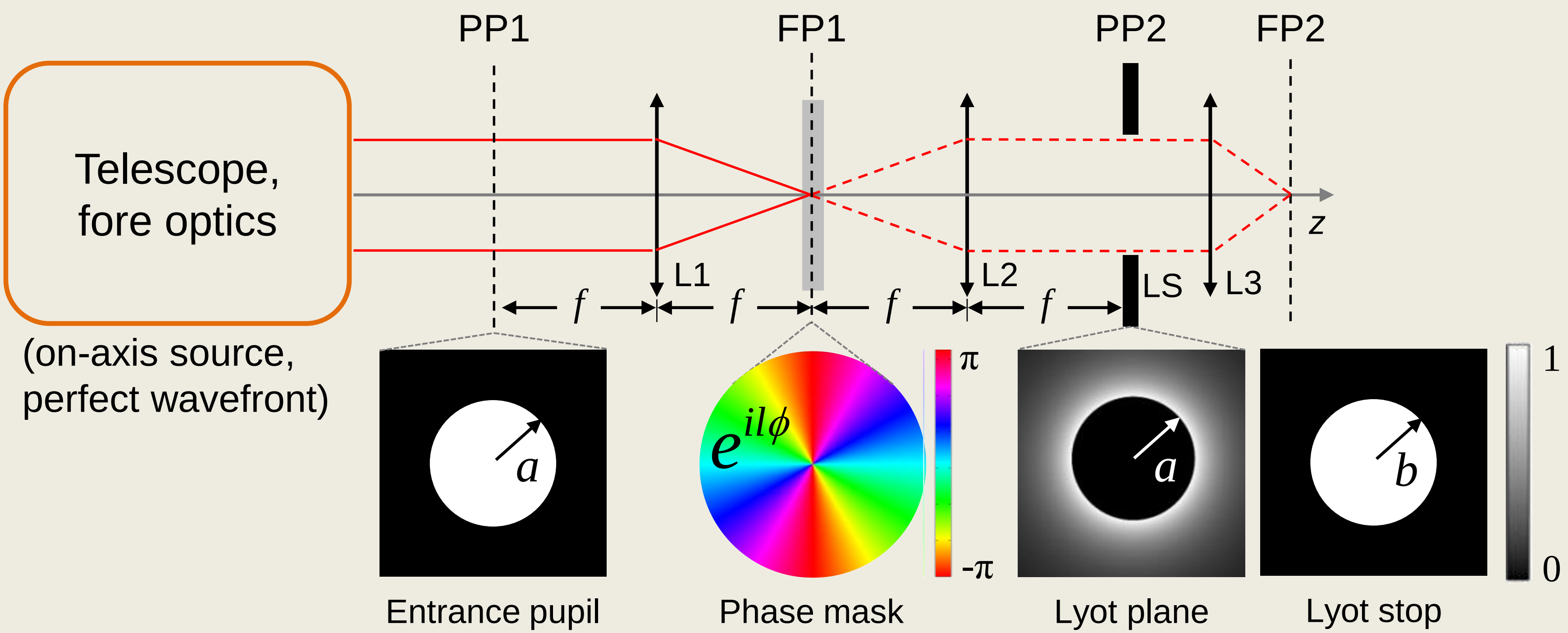
Caltech NASA

Outline of talk

1. Background on vortex coronagraphs
2. Optimization of coronagraphic masks
3. Wavefront control with aperture discontinuities
4. Outlook for future work

1. Background

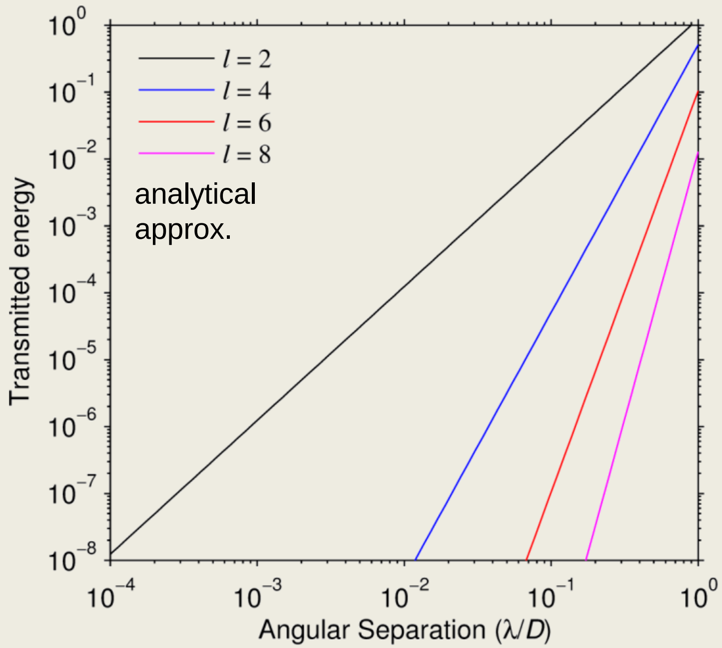
The vortex coronagraph



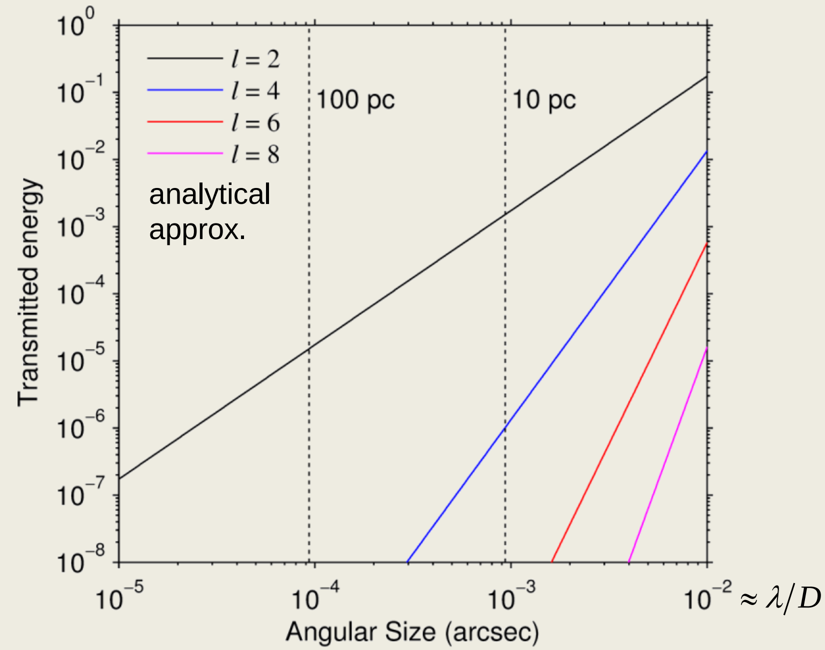
Focal plane vortex phase mask provides theoretically perfect starlight cancellation for an unobstructed, circular pupil and $l = 2, 4, 6, \ldots$

Mawet et al., *ApJ* **633** 1191 (2005)
Foo et al., *Opt. Lett.* **30,** 3308 (2005)

Sensitivity to tip-tilt and finite sources



Fraction of energy transmitted through the Lyot stop for an off-axis point source.



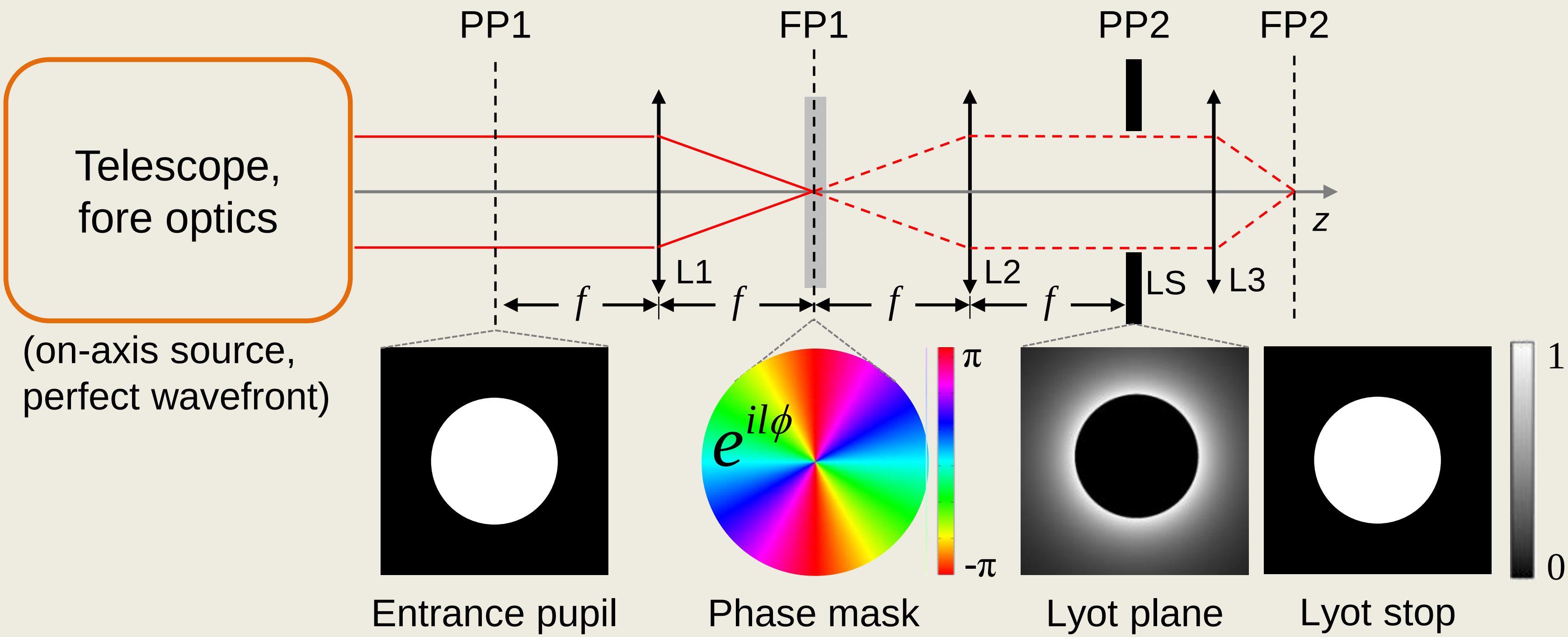
Fraction of energy transmitted through the Lyot stop assuming a 12 m diameter aperture and λ = 550 nm.

Dashed lines indicate the size of a sun-like star at 10 and 100 pc.

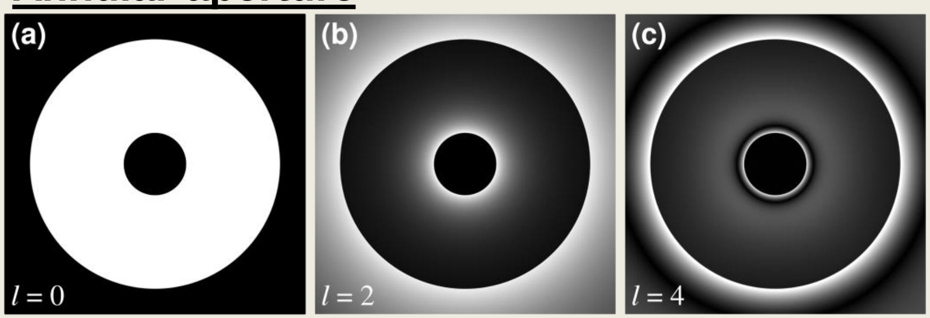
Need at least charge 4 for a 12 m space telescope

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

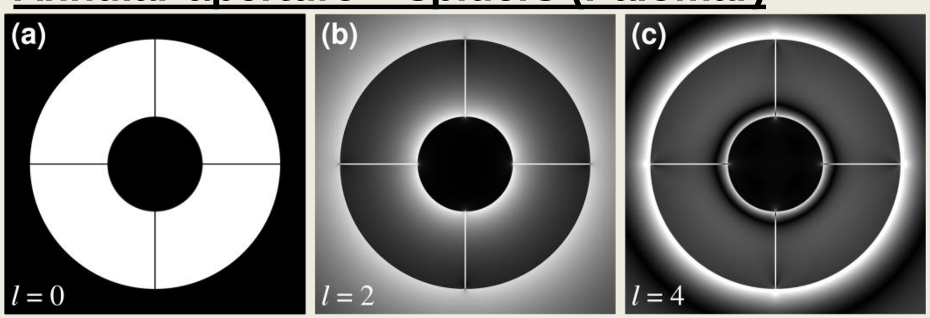
Sensitivity to aperture shape



Annular aperture

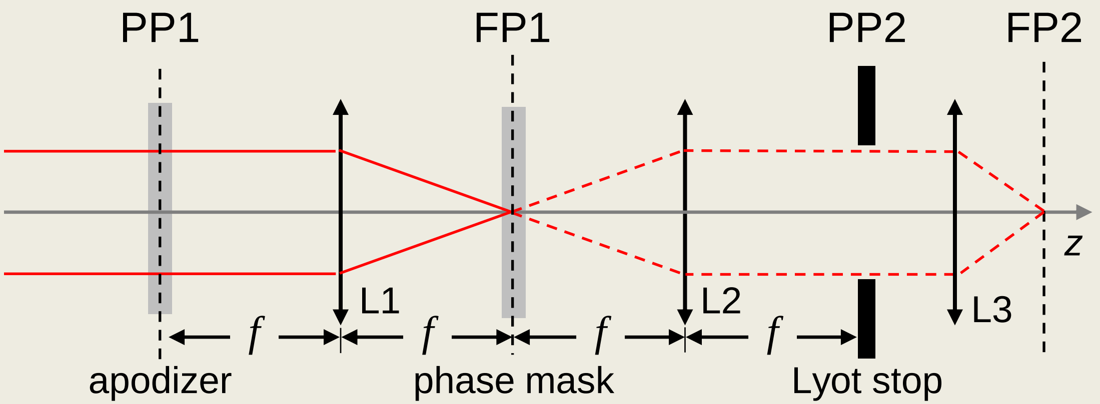


Annular aperture + spiders (Palomar)

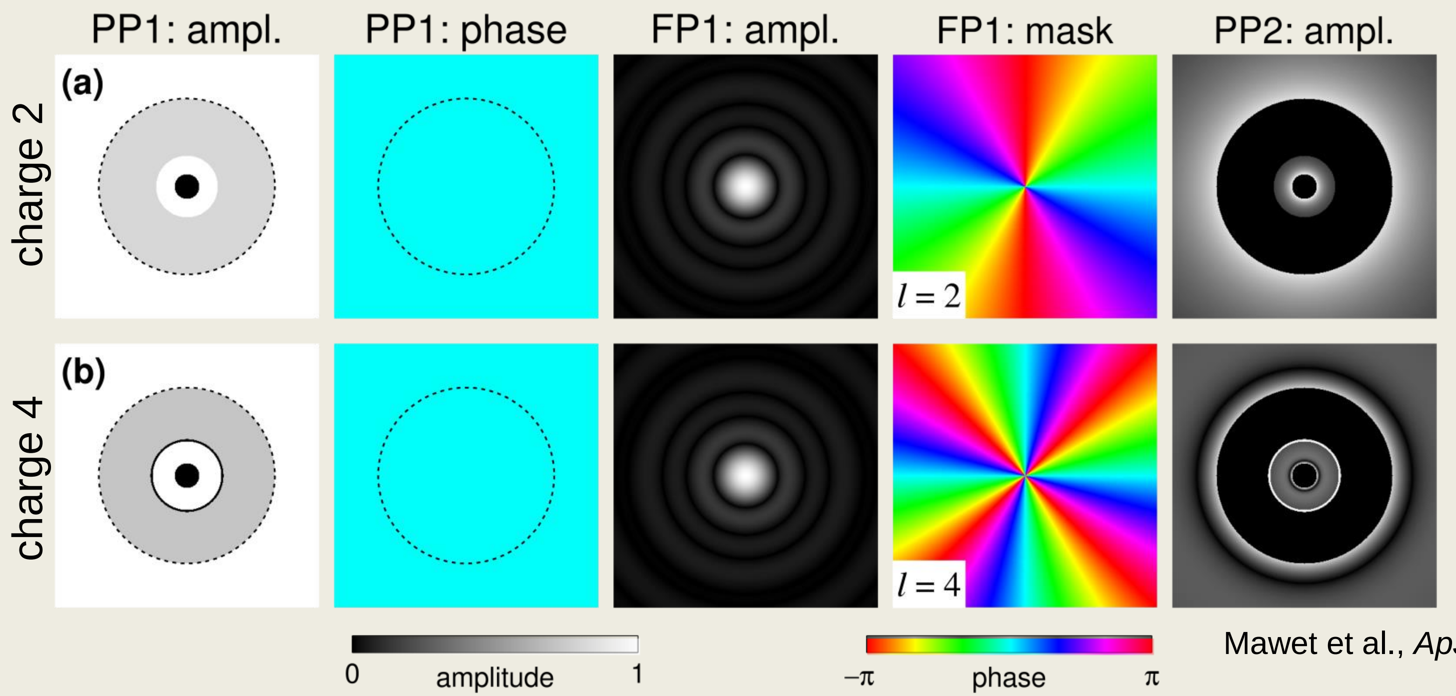


Need advanced designs for segmented aperture space telescopes

Apodized vortex coronagraphs

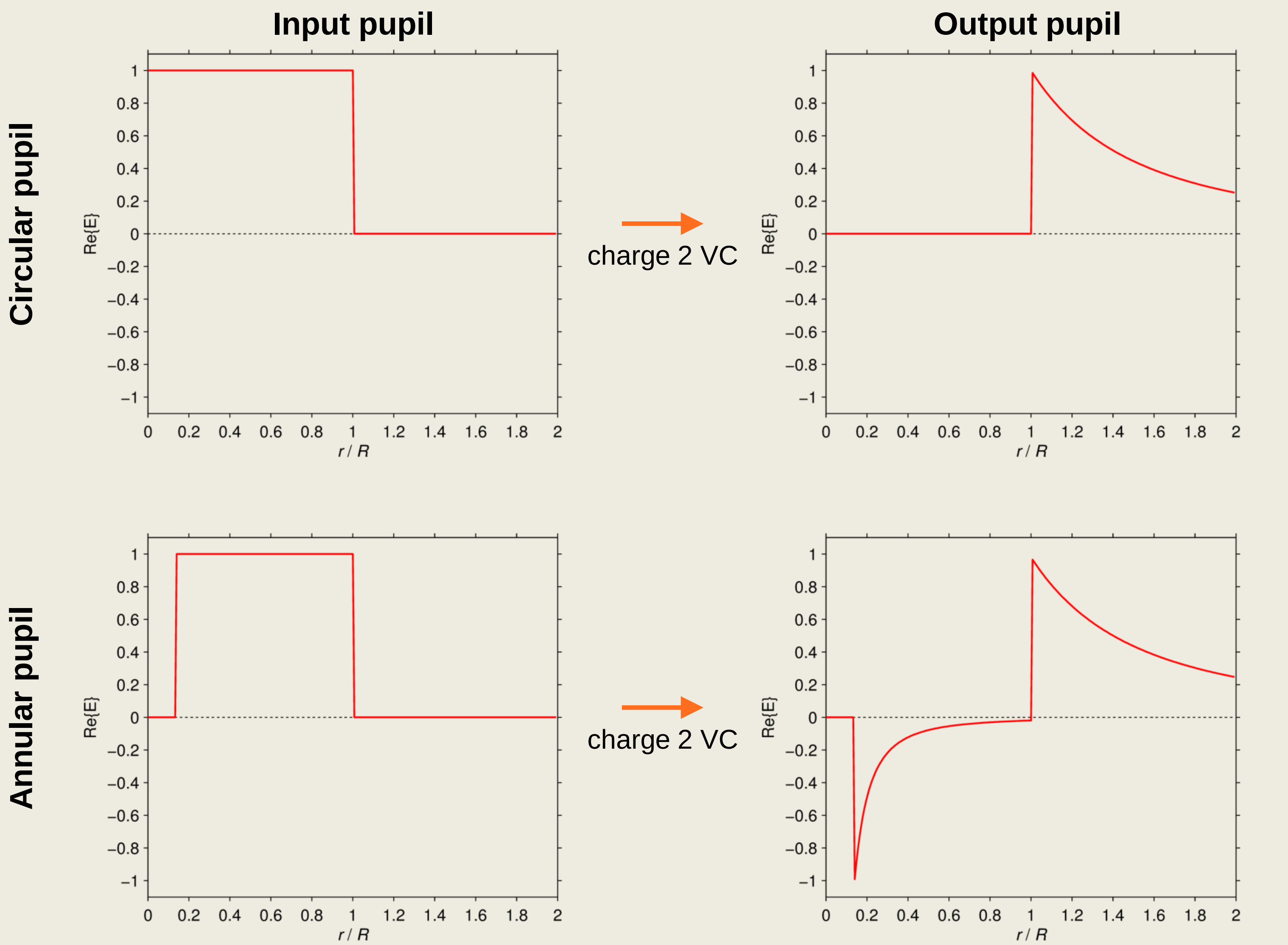


Ring apodizers



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

Starlight cancellation with a ring apodizer



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

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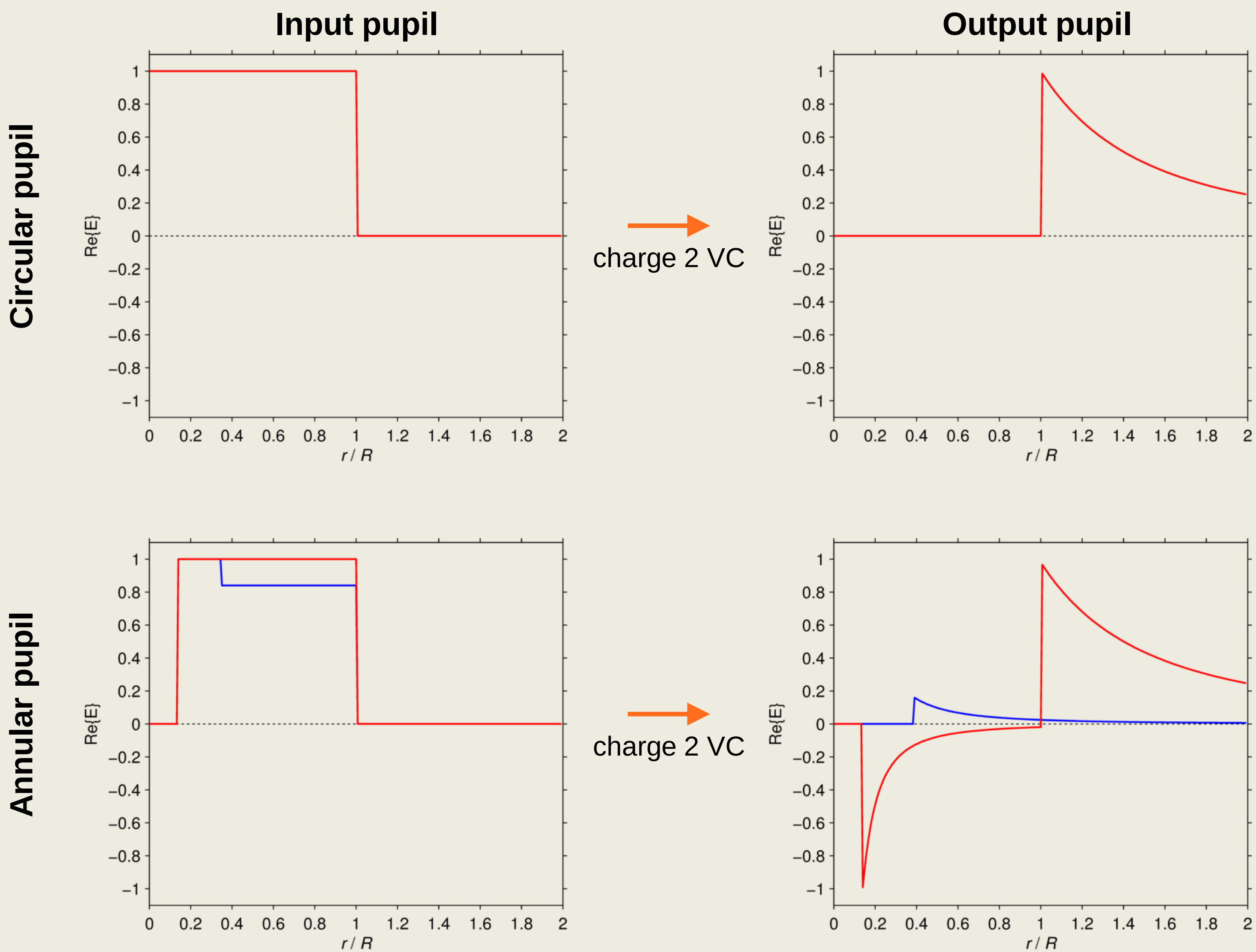
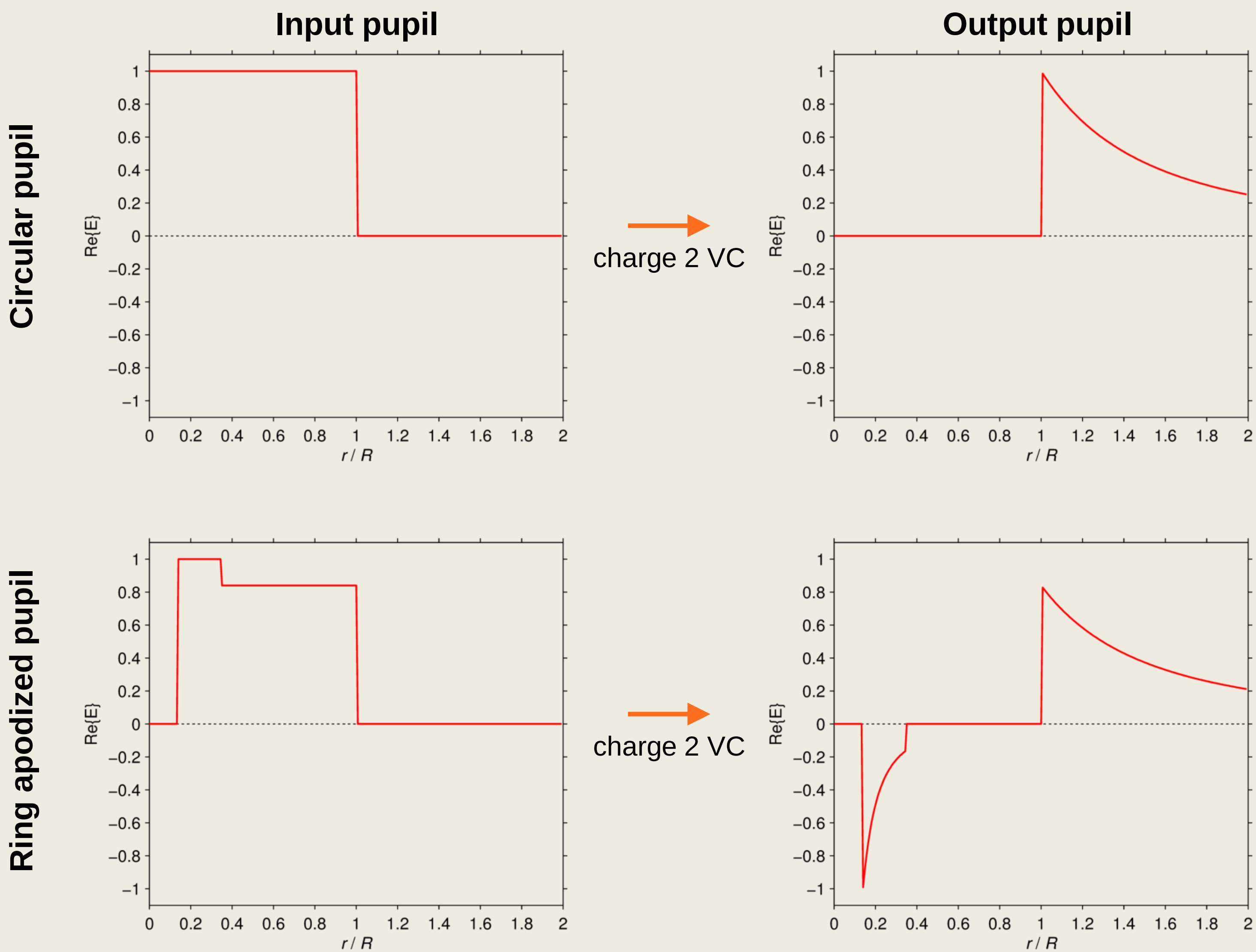


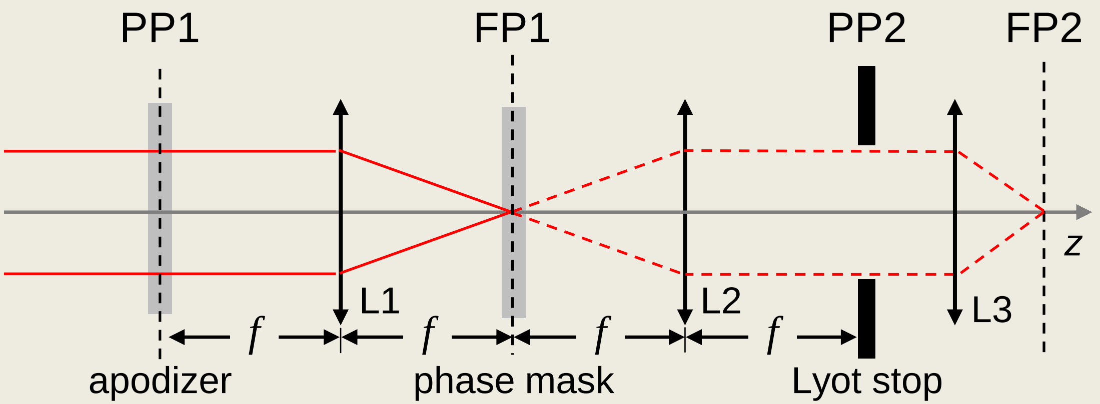
Mawet et al., *ApJS* **209** 7 (2013)

Starlight cancellation with a ring apodizer

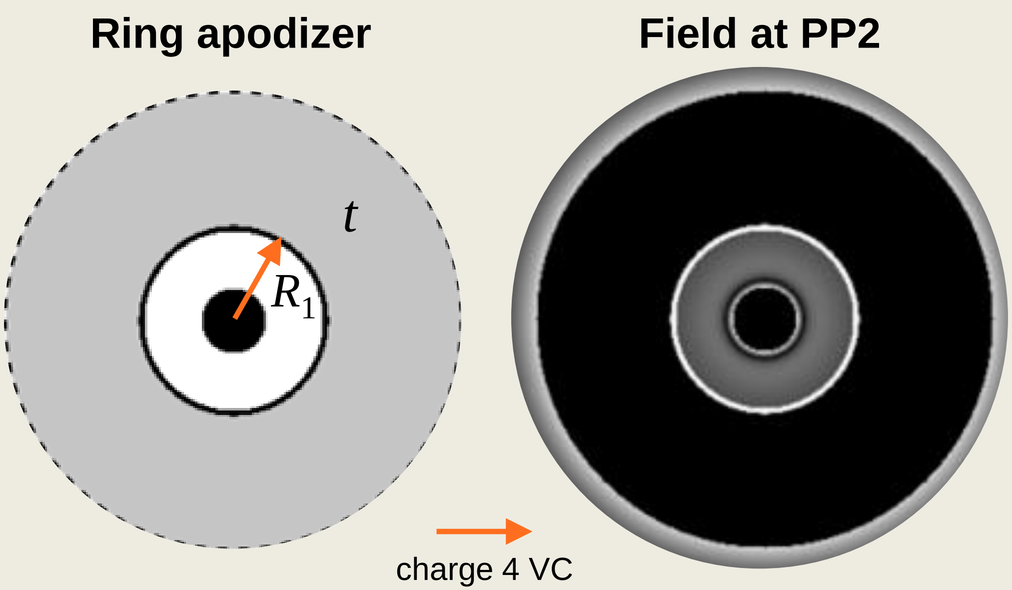


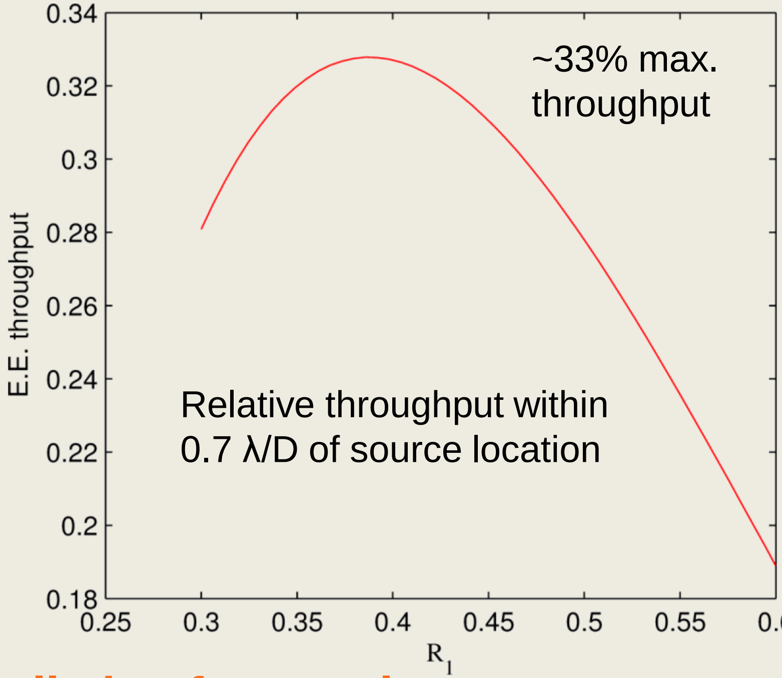
Mawet et al., *ApJS* **209** 7 (2013)

Apodizer optimization



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

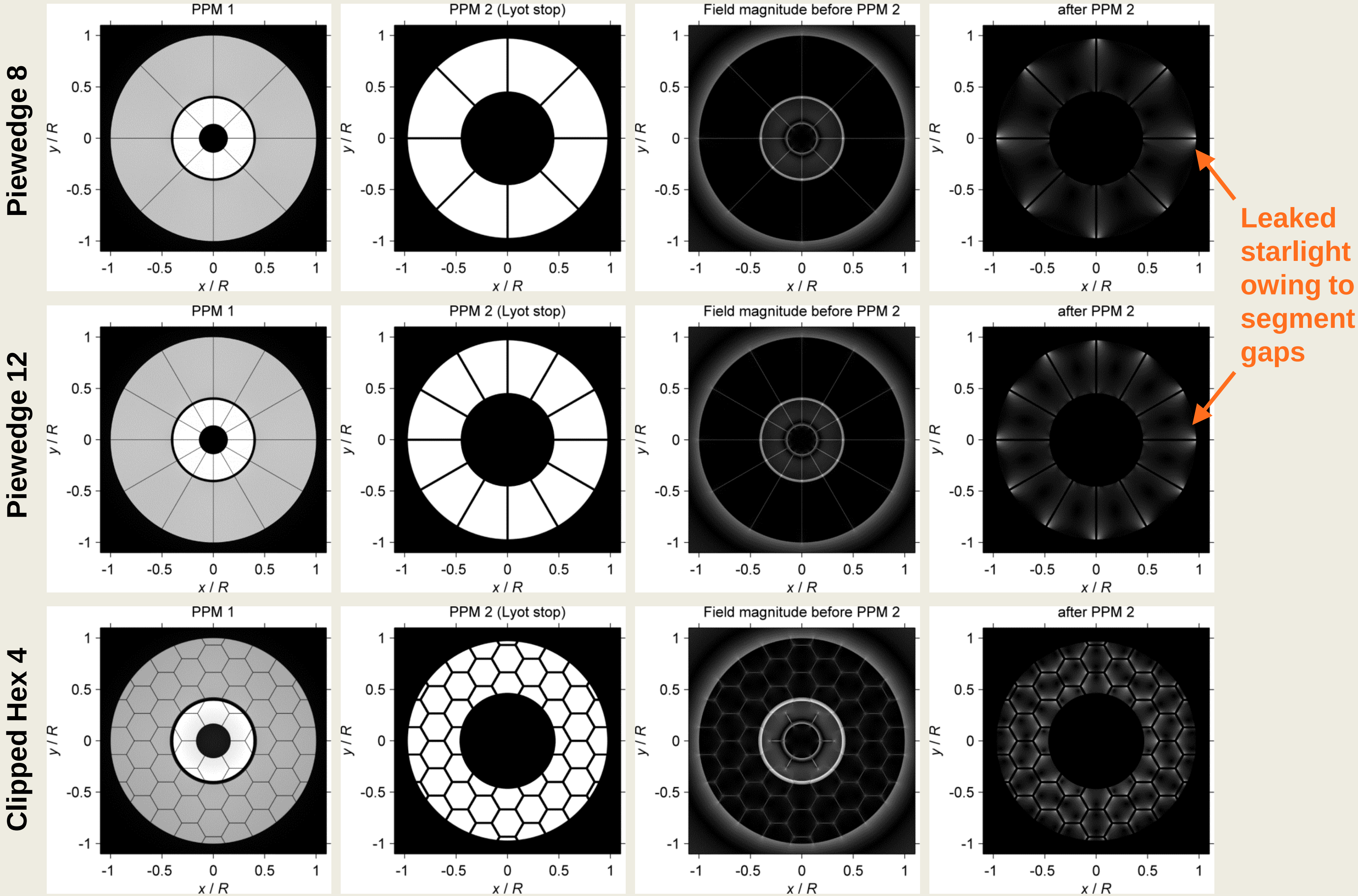




Yields theoretically perfect starlight cancellation for annular aperture

Apodized VC performance with segmented apertures

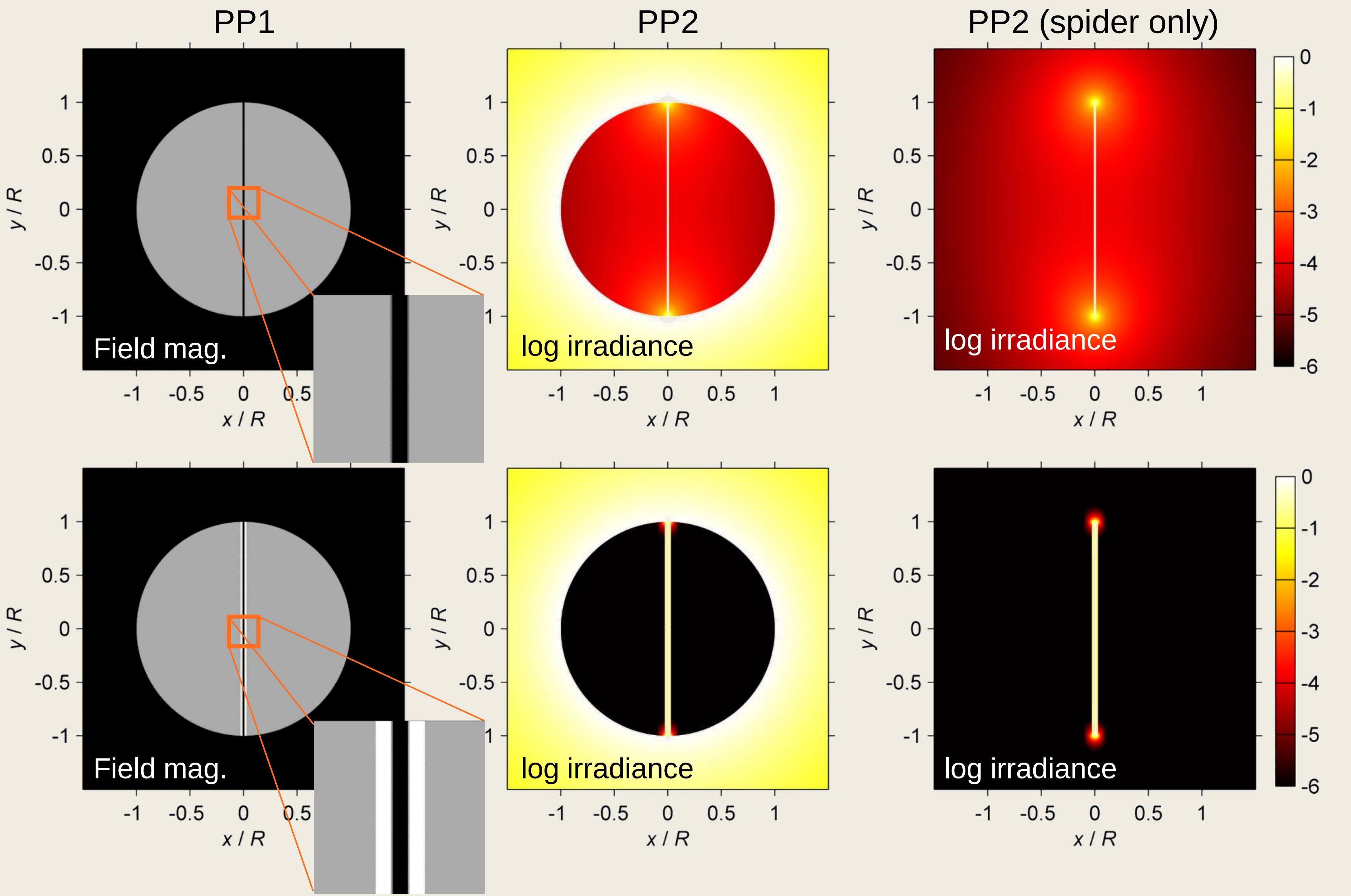
Analytically-inspired, ring-apodized VC (RAVC) with charge 4



2. Optimizing the masks

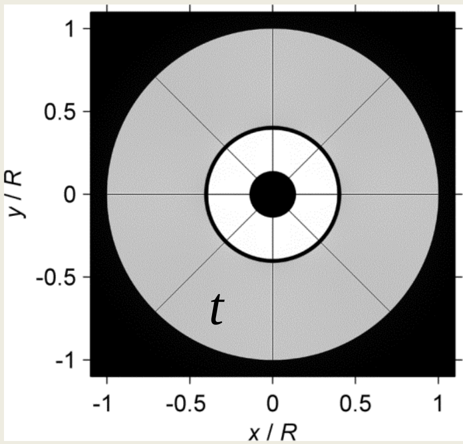
Option I: Optimizing the apodizer

Unity padding of aperture discontinuities

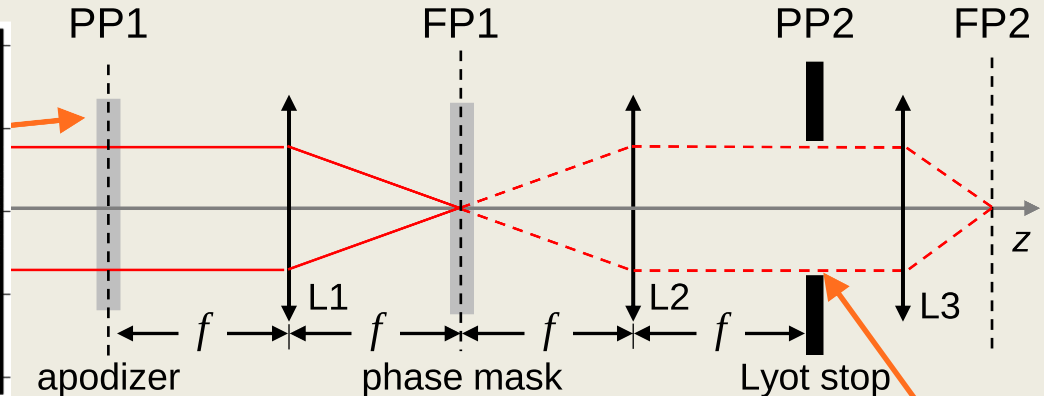


Option I: Optimizing the apodizer and Lyot stop

Apodizer

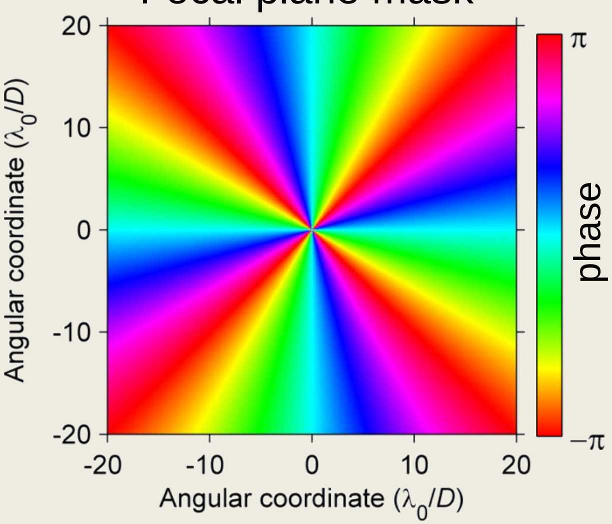


Unity padded, $t = 0.77$, $R_1 = 0.4R$

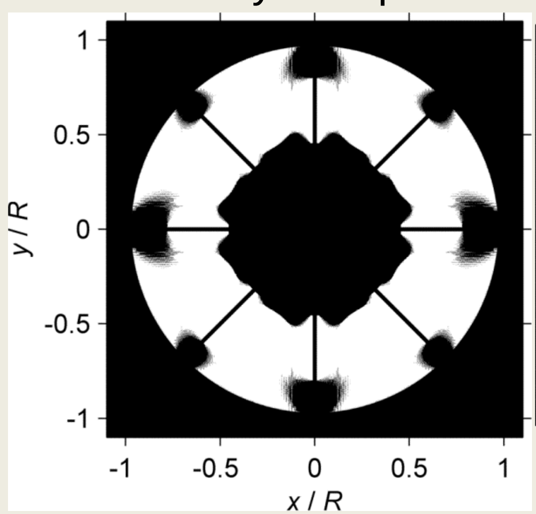


- Pupil plane: 1000 samples per D
- Focal plane: 8 samples per λ_0/D
- FPM is median filtered (3×3 samples)

Focal plane mask

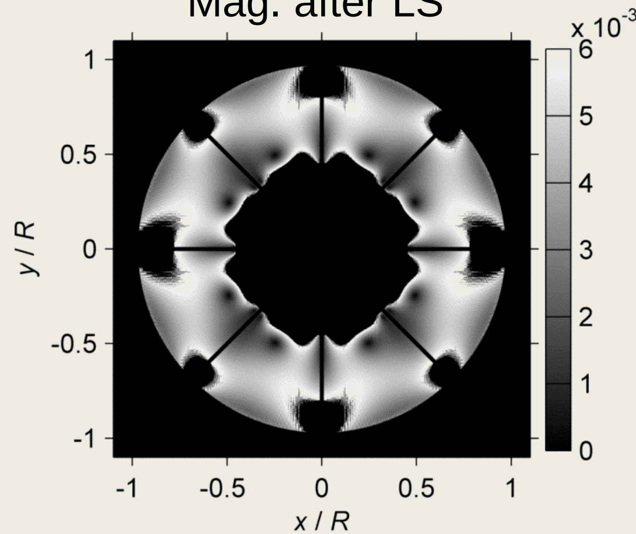


Lyot stop

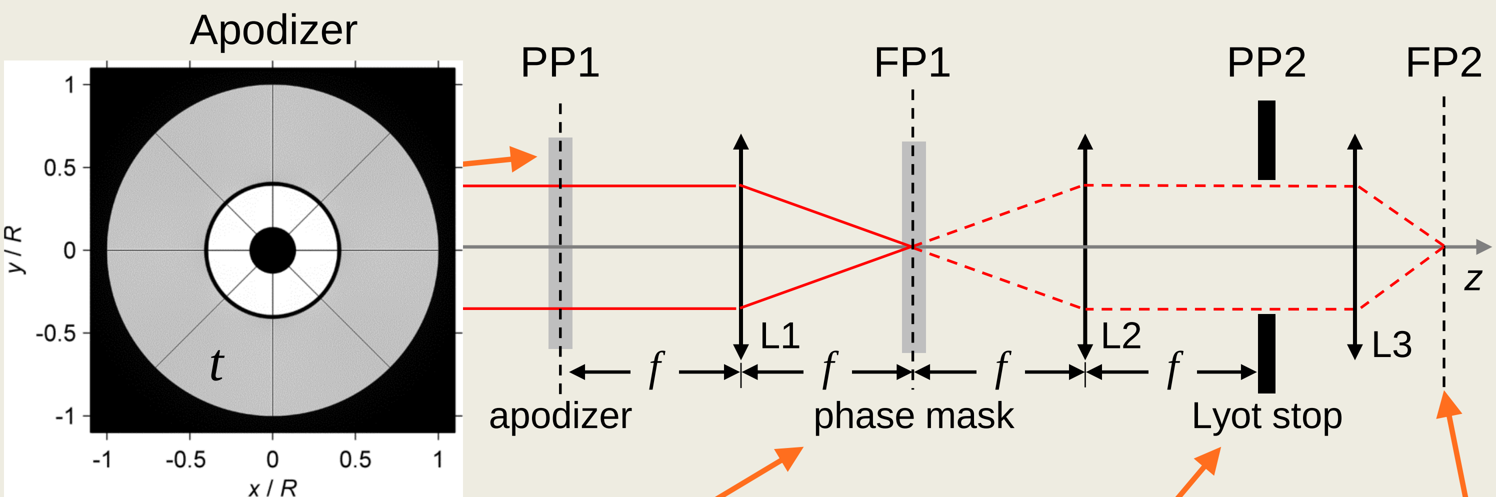


Determined via irradiance thresholding

Mag. after LS

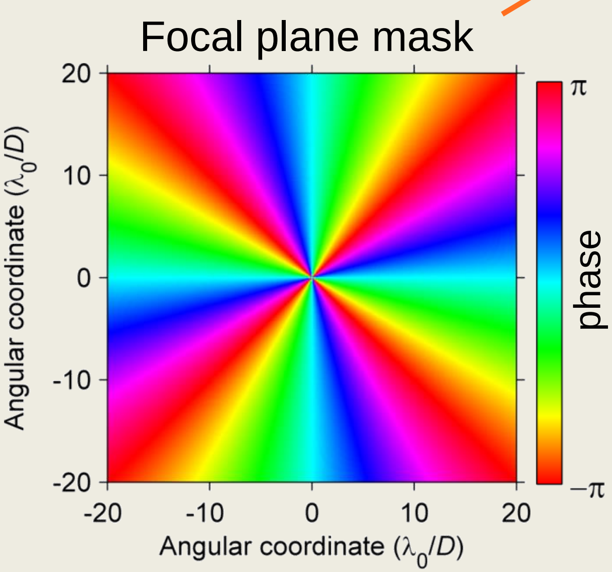


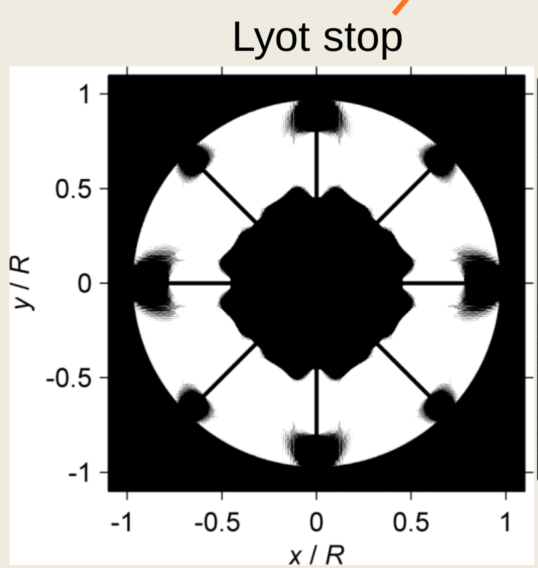
Option I: Optimizing the apodizer and Lyot stop



Unity padded, t = 0.77, R_1=0.4R

- Pupil plane: 1000 samples per D
- Focal plane: 8 samples per λ_0/D
- FPM is median filtered (3×3 samples)





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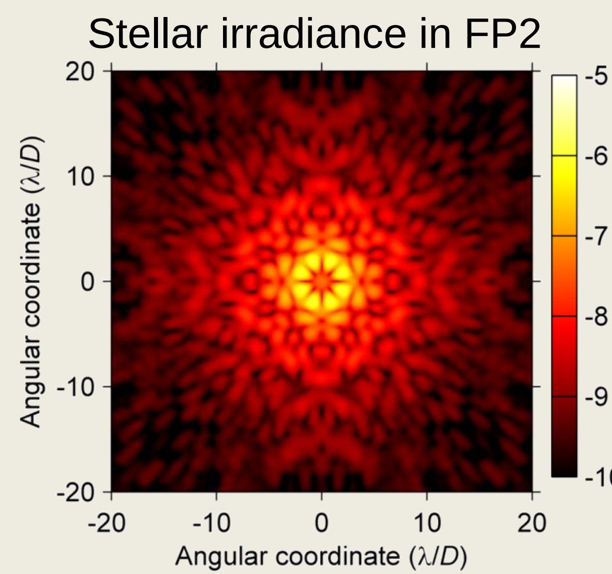
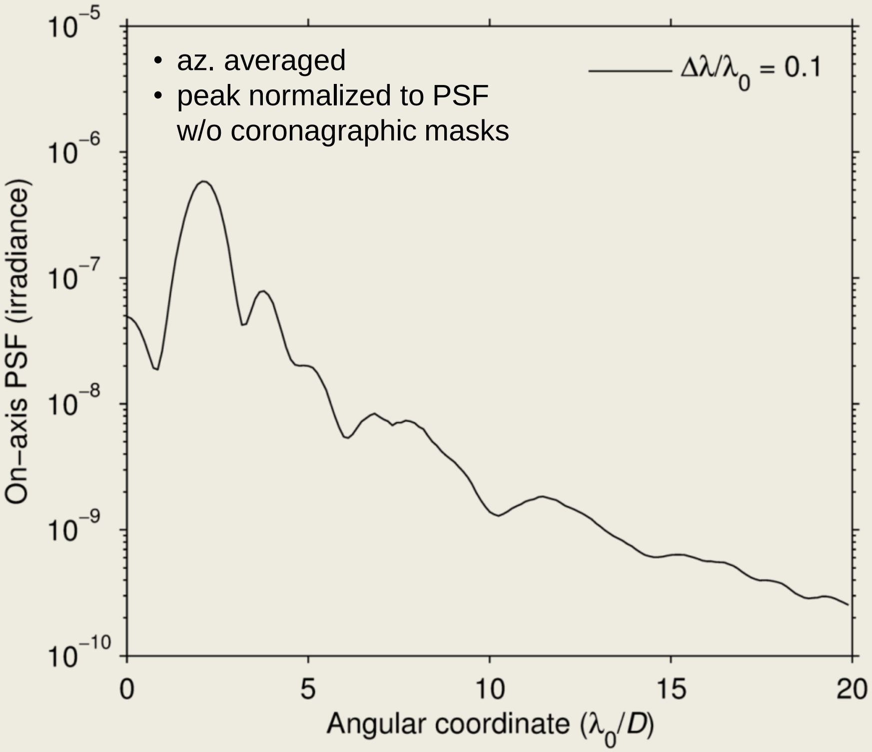
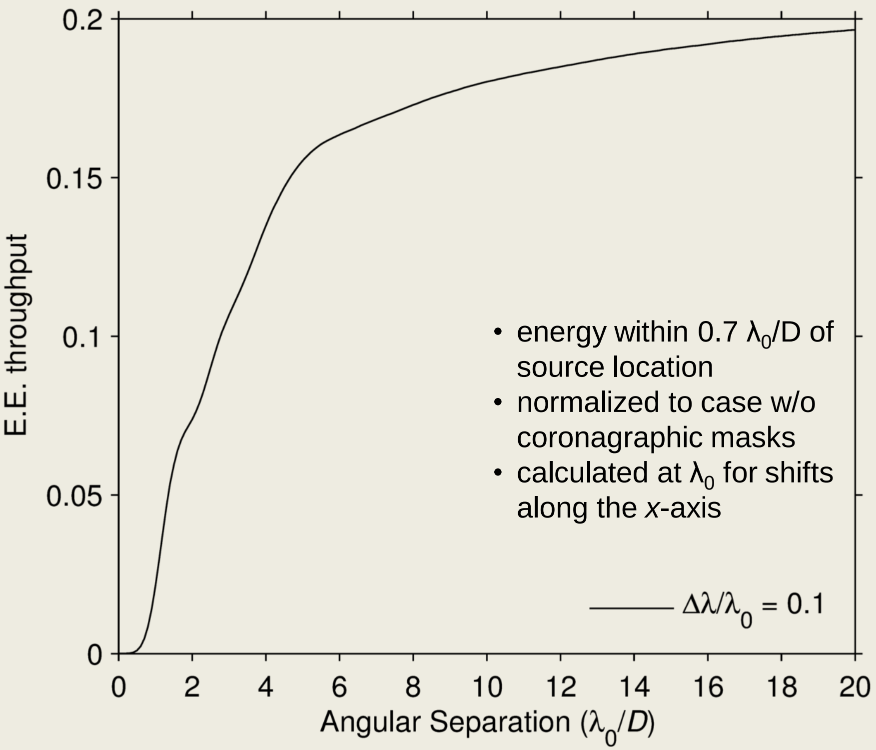


Option I: Optimizing the apodizer and Lyot stop



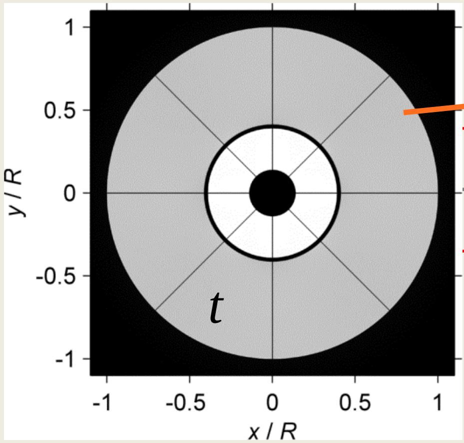


$<10^{-7}$ stellar irradiance for angular separations >3 λ_0/D

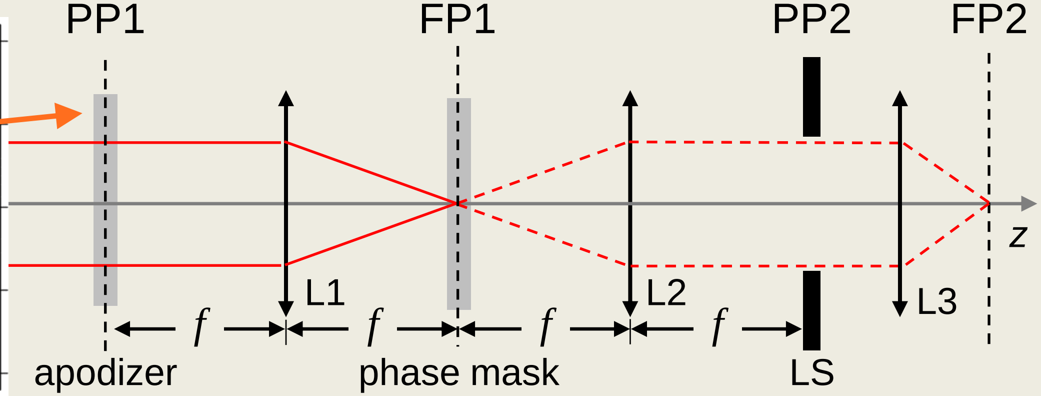
>10% encircled energy throughput for angular separations >3 λ_0/D (w.r.t the telescope)

Option II: Optimizing the focal plane mask

Apodizer

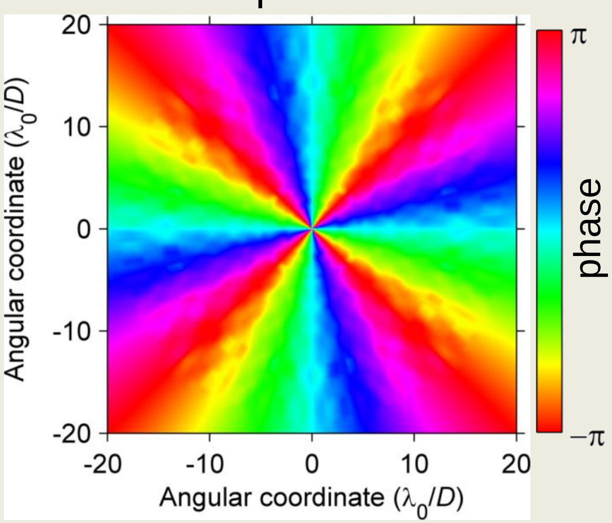


Ring only, $t = 0.77$, $R_1 = 0.4R$

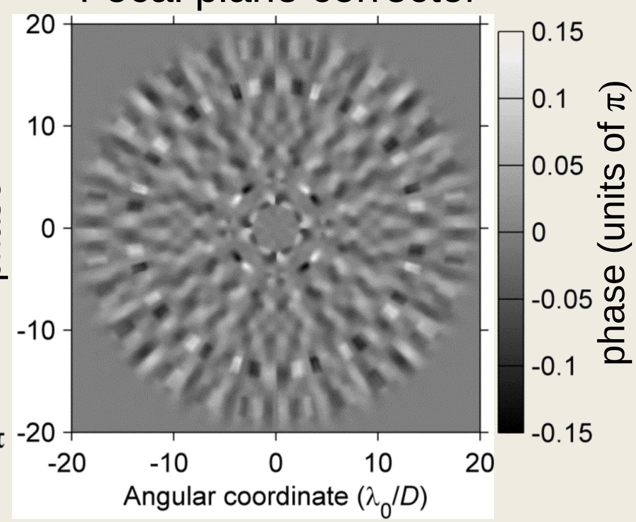


- Optimized for 10% passband
- ~30% max. E.E. throughput
- Pupil plane: 1000 samples per D
- Focal plane: 8 samples per λ_0/D
- FPM is median filtered (3×3 samples)

Focal plane mask



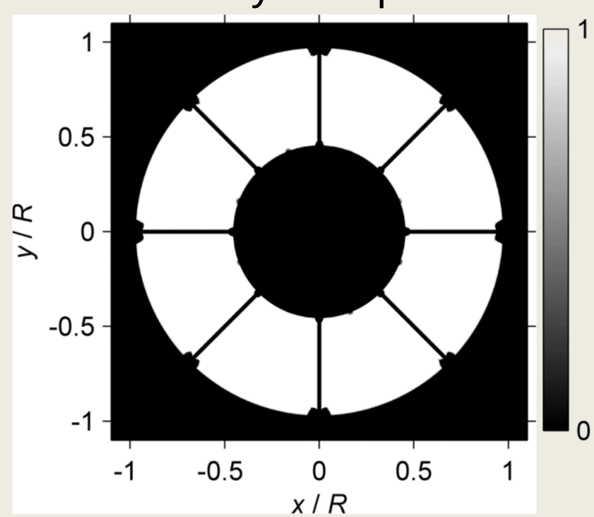
Focal plane corrector



P-V = 0.28 π

radius = 20 λ_0/D

Lyot stop



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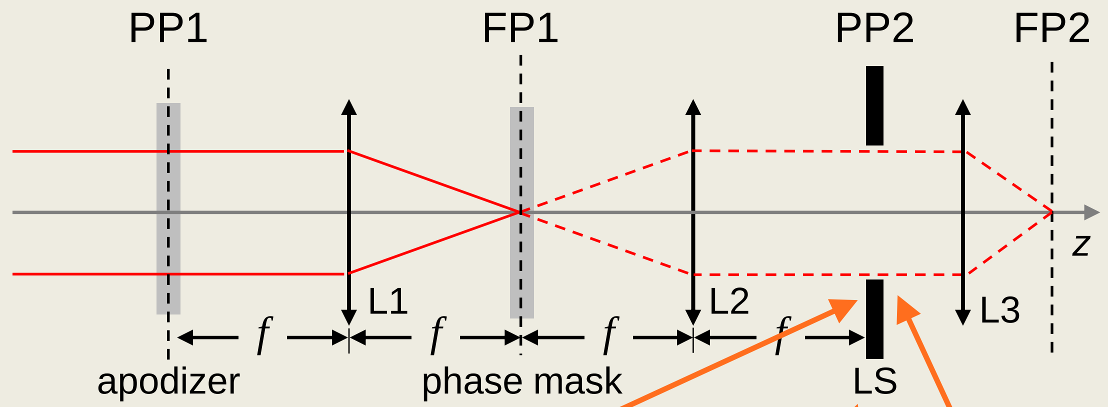
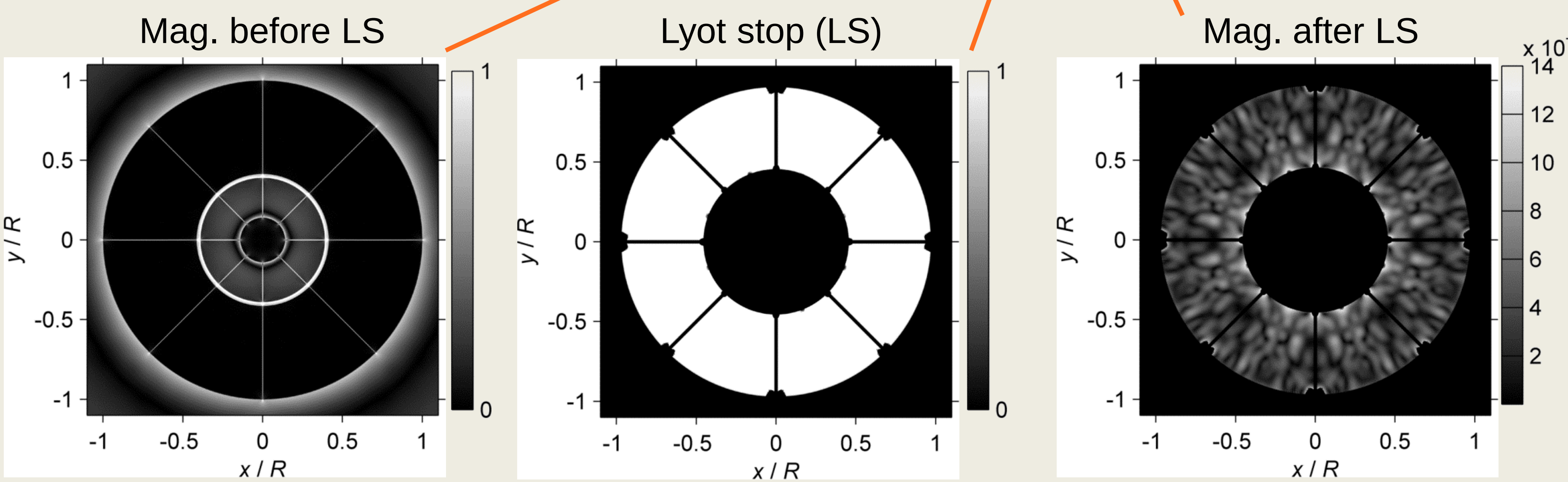
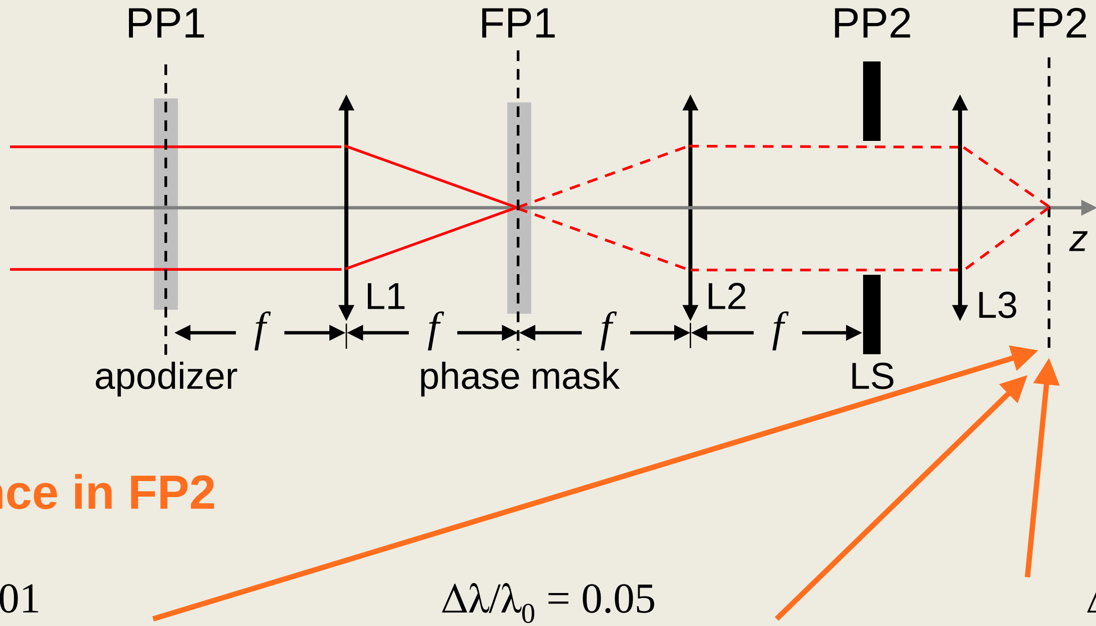


Field in PP2 (at λ_0)

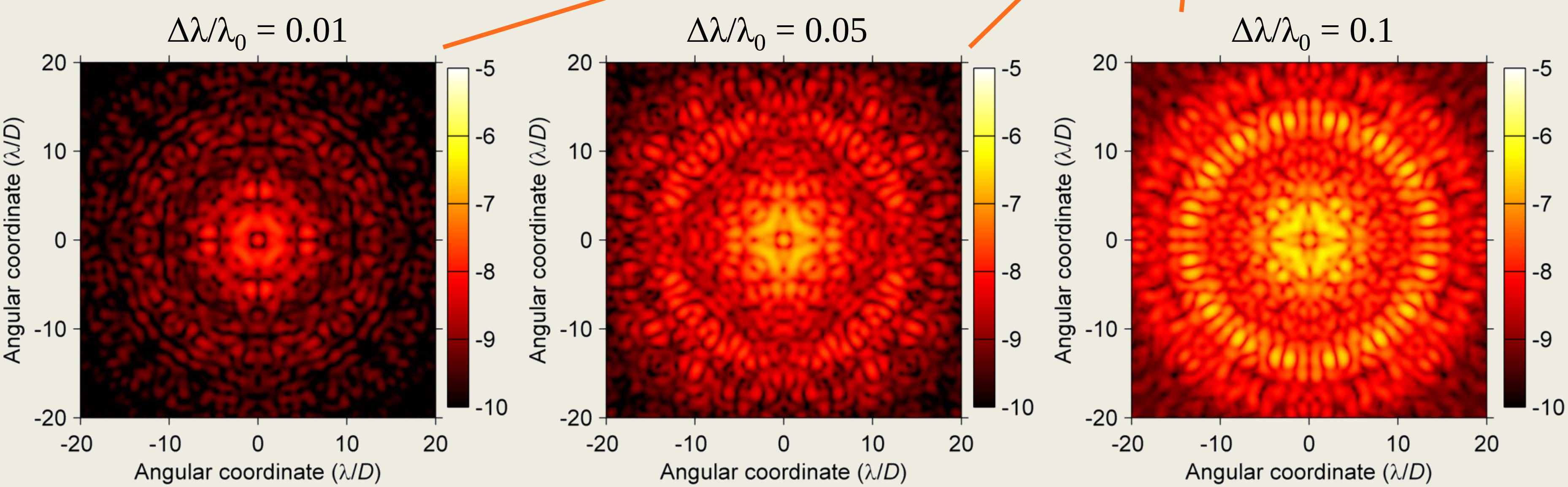


leaked energy fraction at λ_0 = 1.3×10^{-4}

Option II: Optimizing the focal plane mask



Stellar irradiance in FP2



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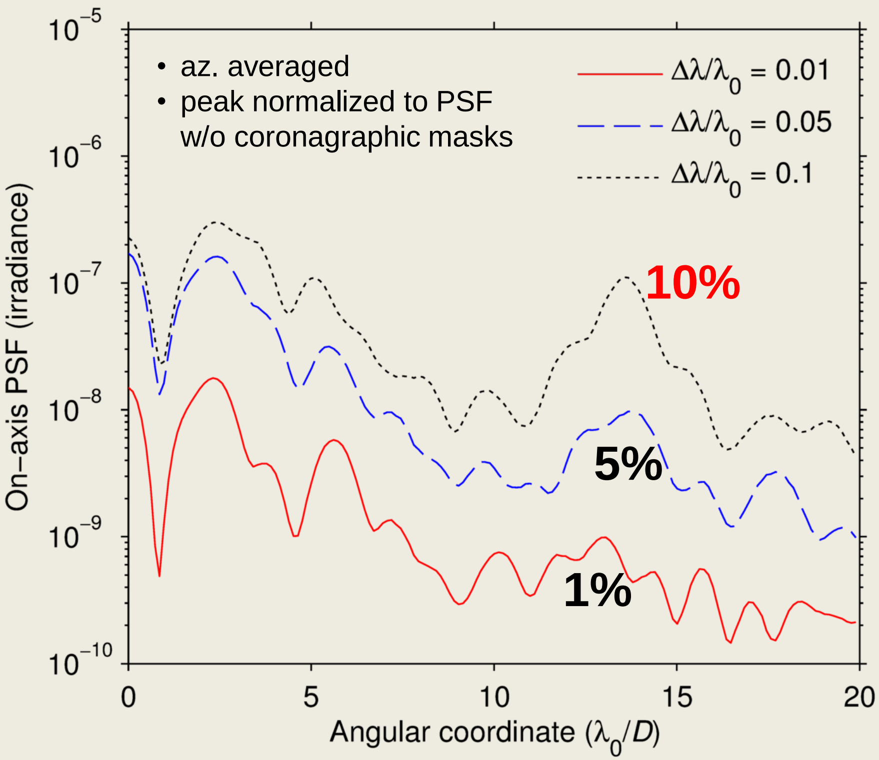
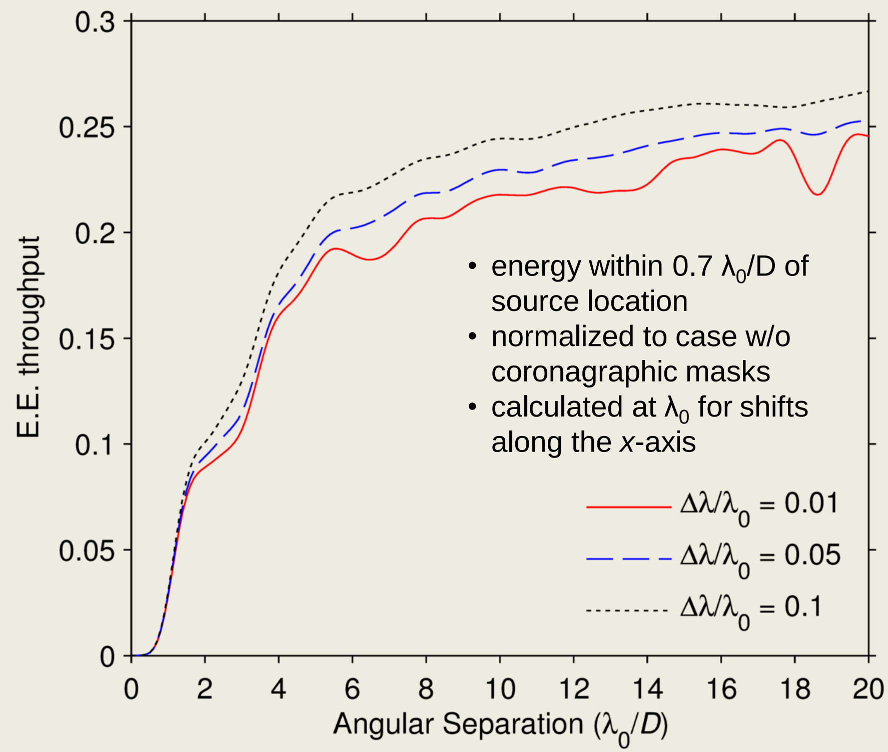




>10% encircled energy throughput for angular separations >3 λ_0/D (w.r.t the telescope)

Optimizing the *sensitivity* to planets

In photon-noise limited regime:

$$\text{SNR} \sim \frac{\text{planet energy}}{\sqrt{\text{star energy} + \text{noise terms}}} \approx \frac{\text{planet energy}}{\sqrt{\text{star energy}}}$$

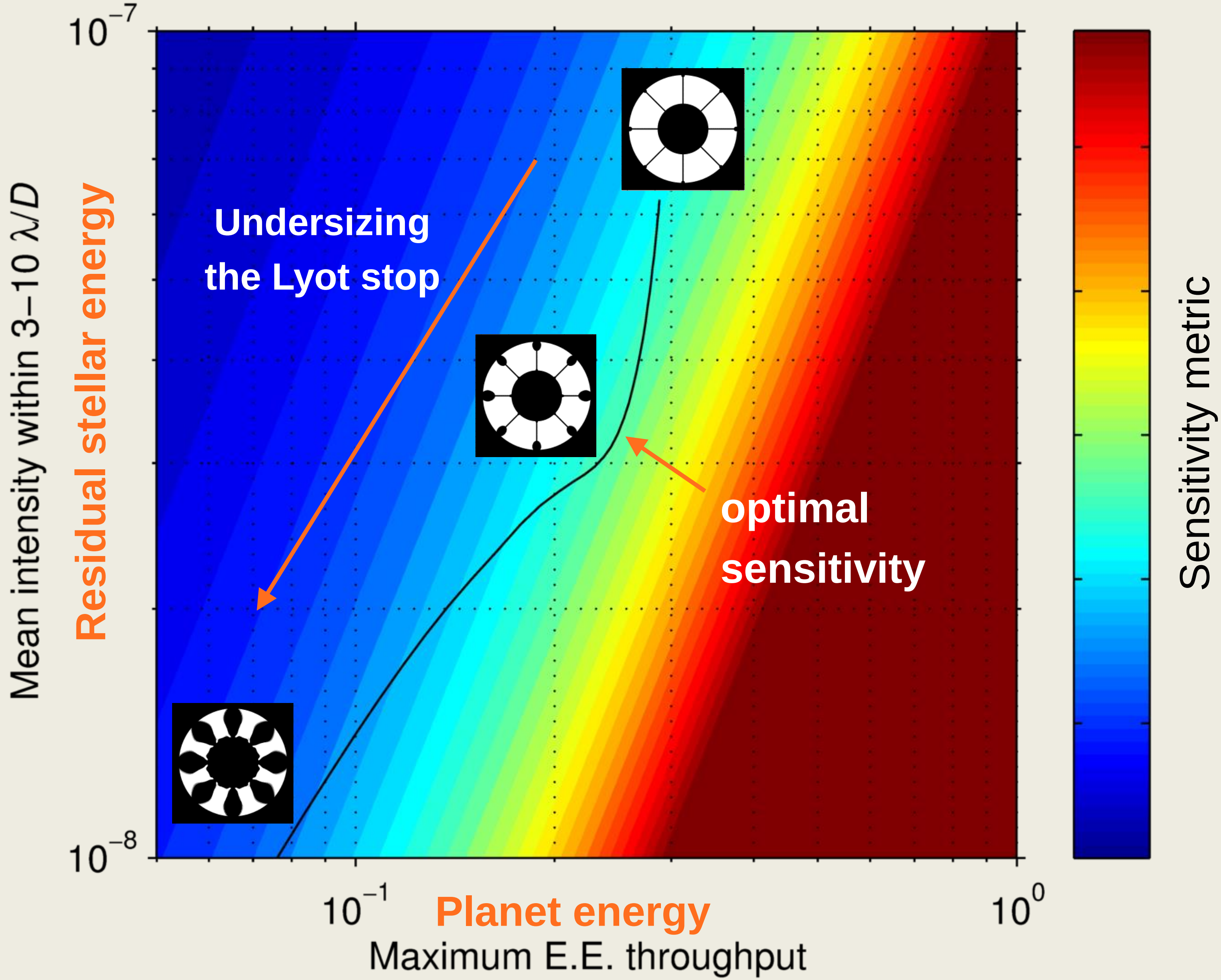
$$\text{sensitivity metric} = \frac{\eta \times B}{\sqrt{s \times B}} = \eta\sqrt{\frac{B}{s}}$$

η – Max. encircled energy throughput (within 0.7 λ_0/D of source position, normalized to telescope throughput)

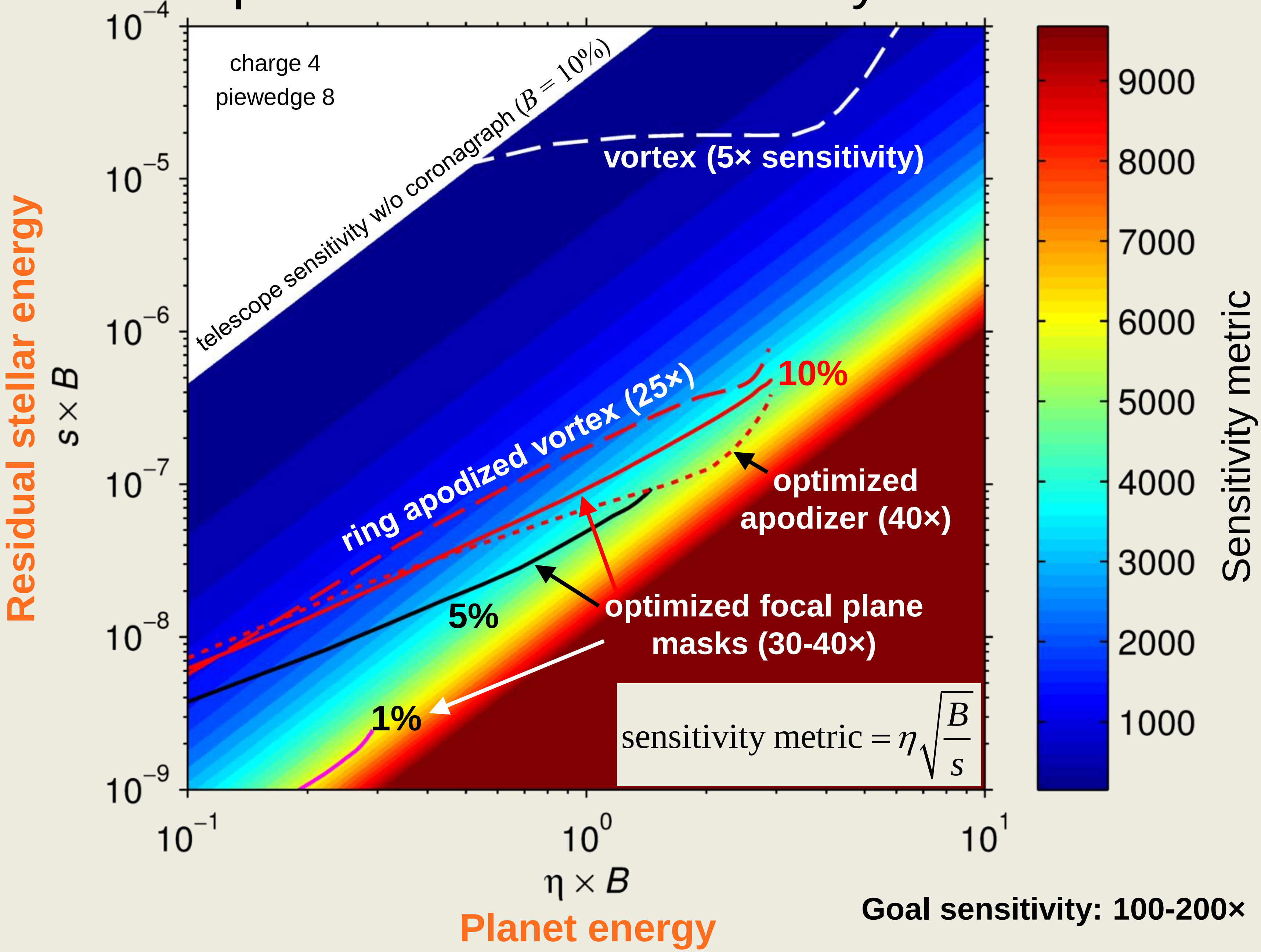
s – Residual stellar energy in the image plane (averaged over 3-10 λ_0/D annulus and passband)

B – Percent bandwidth $B = \Delta\lambda/\lambda_0 \times 100$

For example: optimizing the Lyot stop



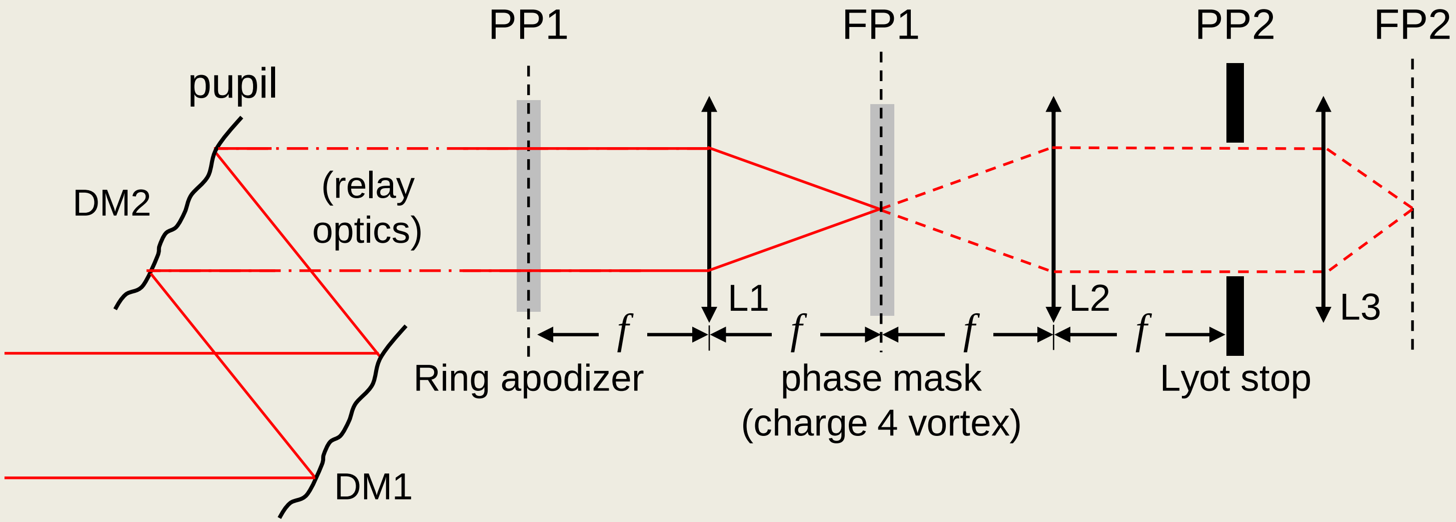
Optimization via a sensitivity metric

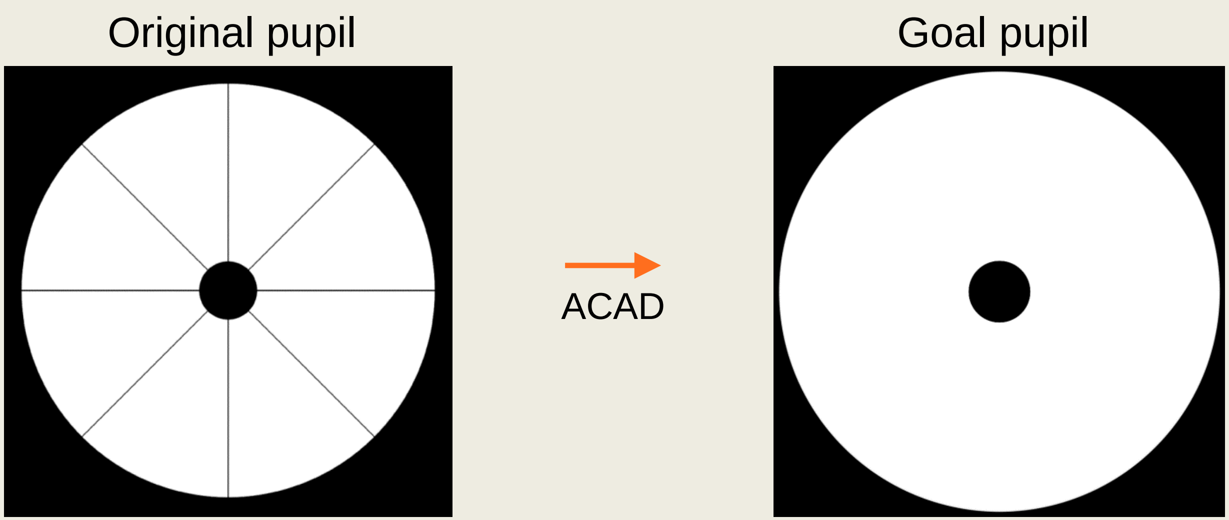


Goal sensitivity: 100-200×

3. Wavefront control for segmented apertures

Active Compensation of Aperture Discontinuities (ACAD)





Pueyo & Norman, *ApJ* **769** 102 (2013)
Mazoyer et al., *Proc. SPIE* 96050M (2015)

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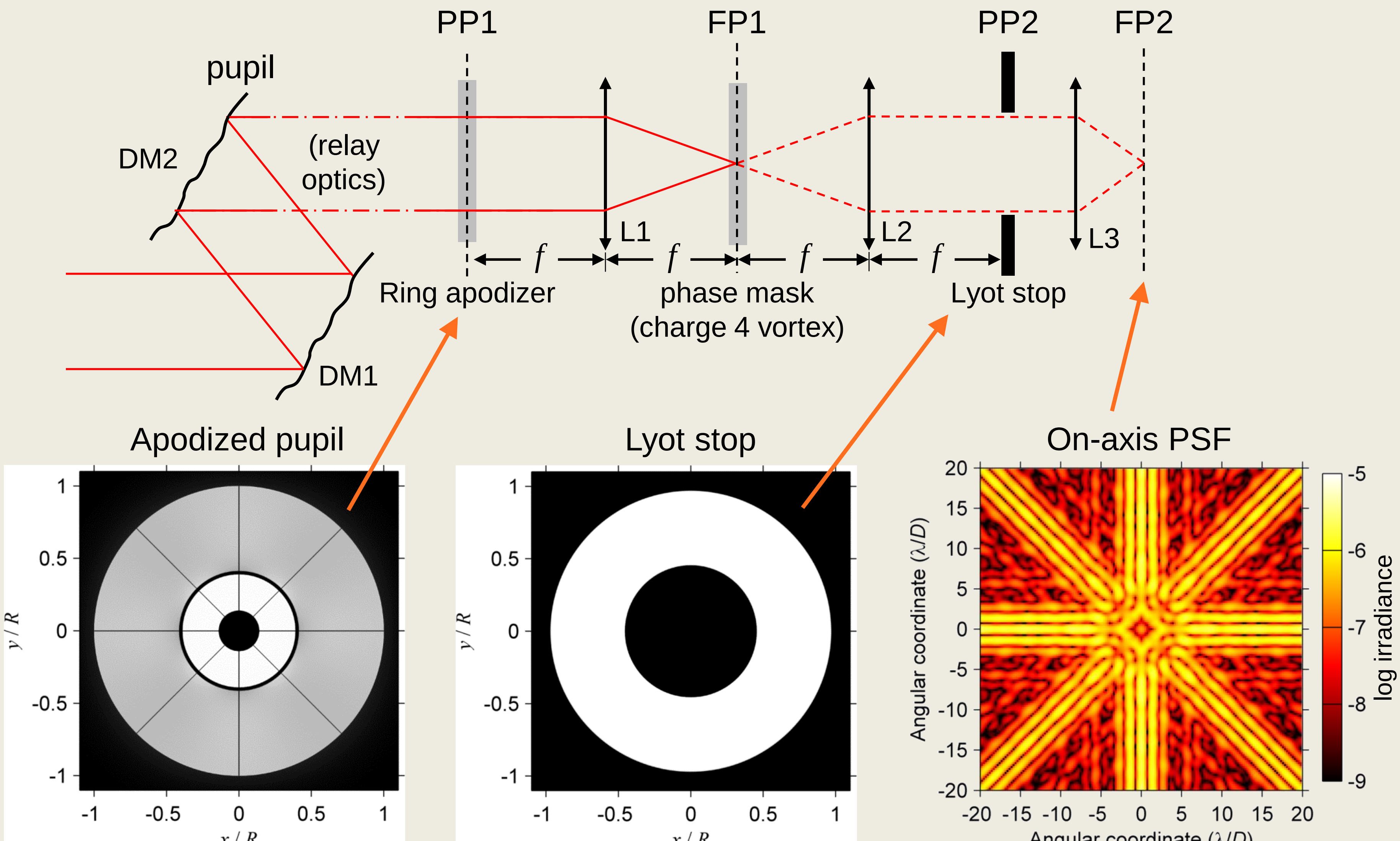

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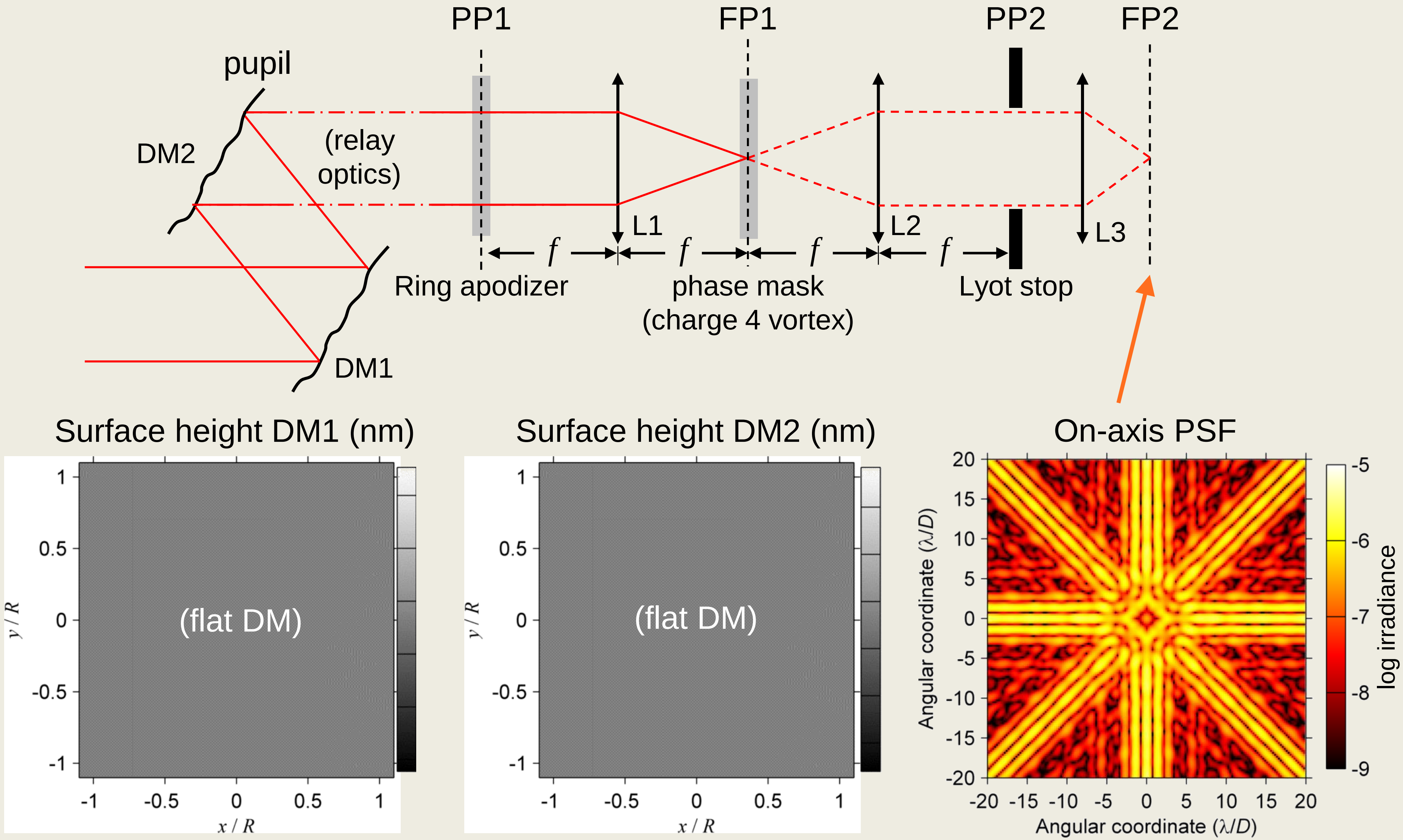

(Located in pupil)

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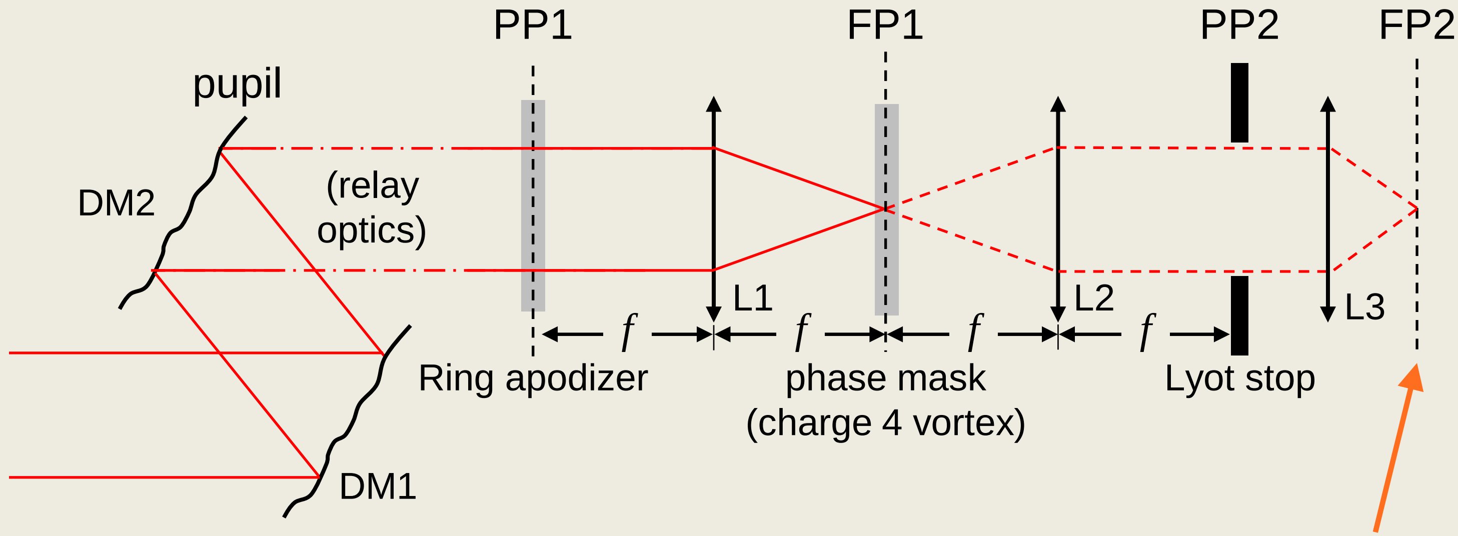
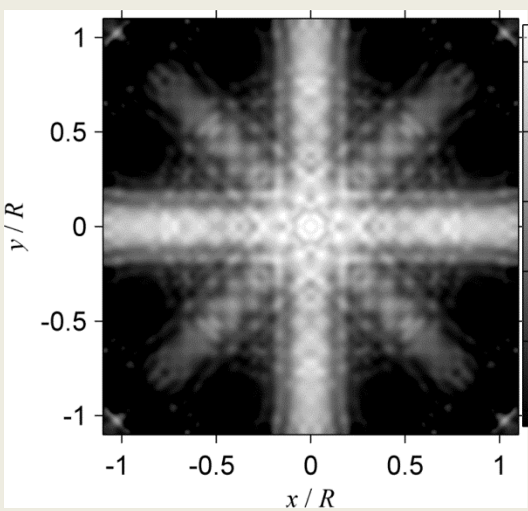
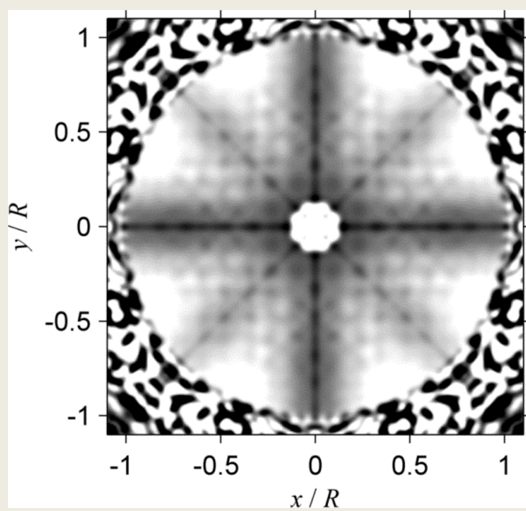


Surface height DM1 (nm)

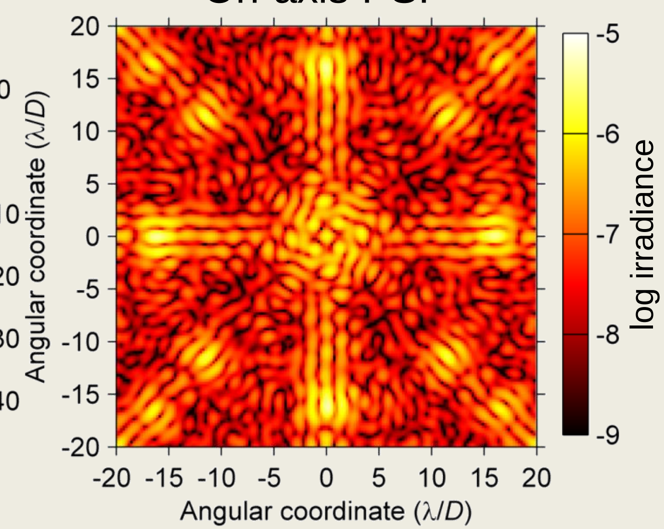


Surface height DM2 (nm)



(Located in pupil)

On-axis PSF



λ = 500 nm

N_{act} = 64

Pueyo & Norman, *ApJ* **769** 102 (2013)
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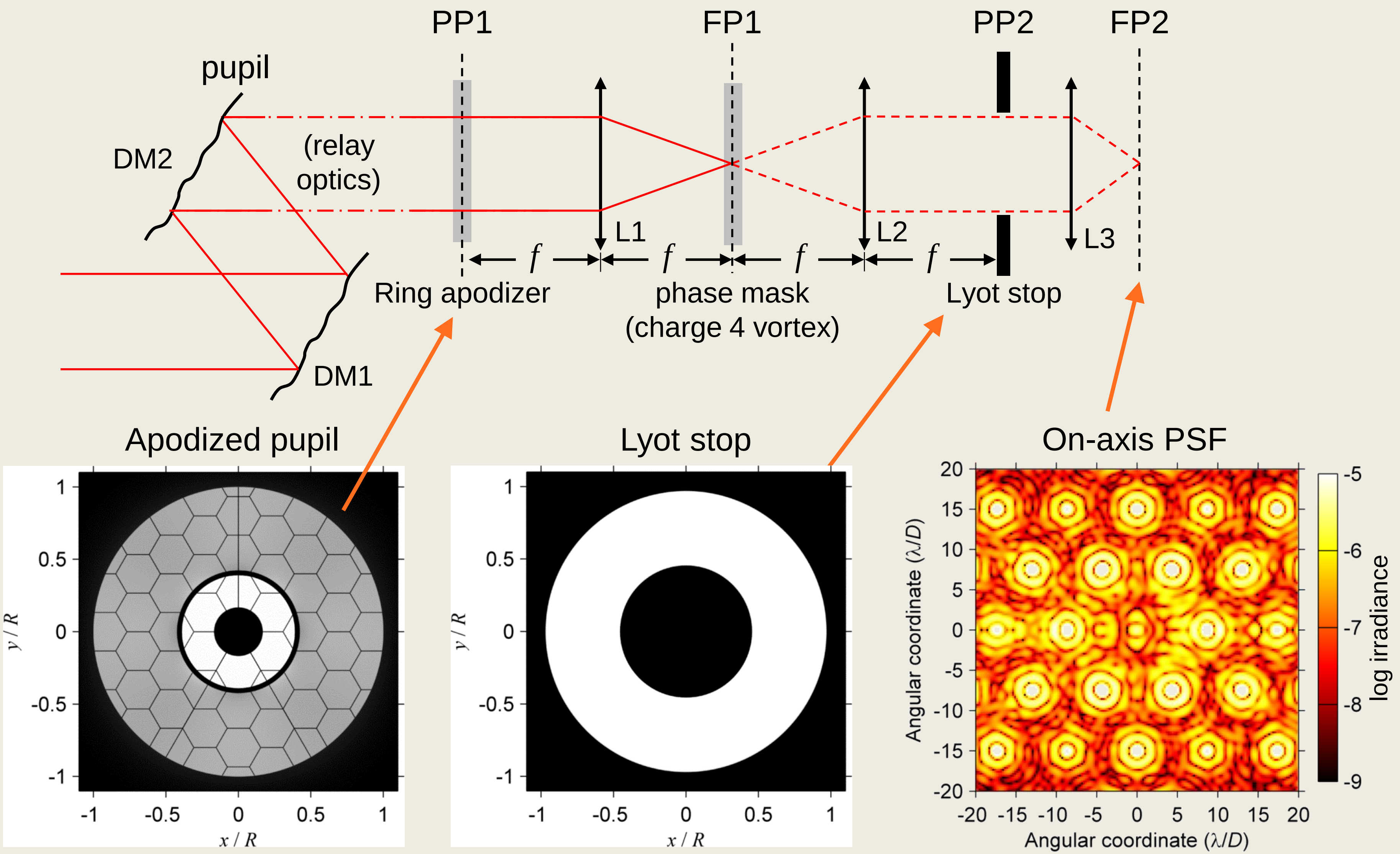
Active Compensation of Aperture Discontinuities (ACAD)



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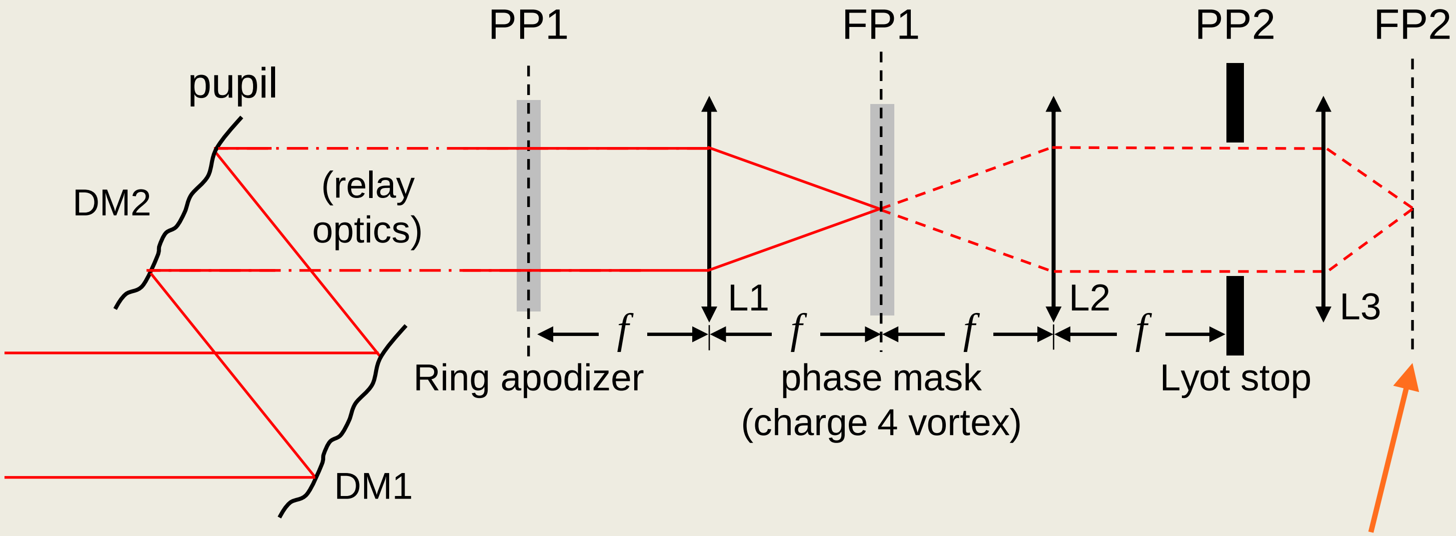

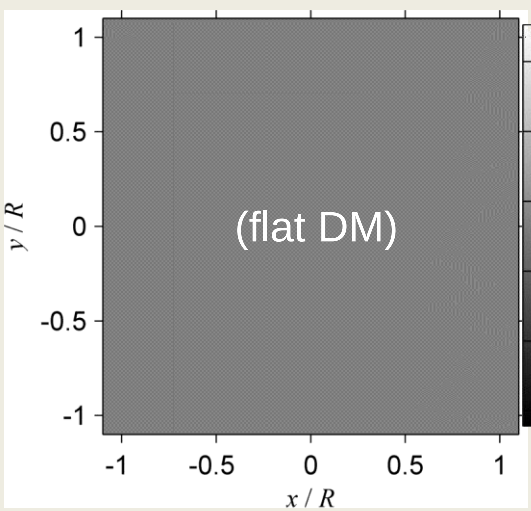

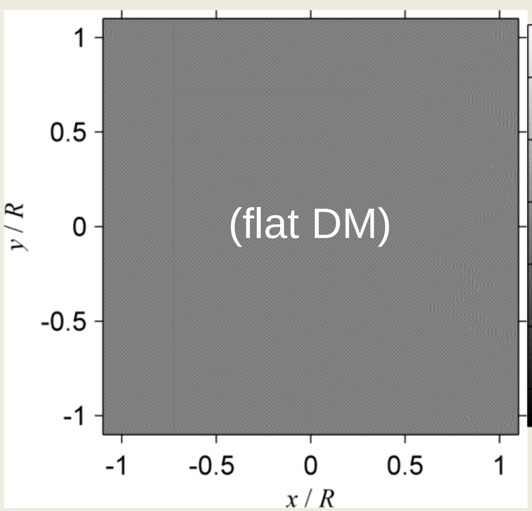

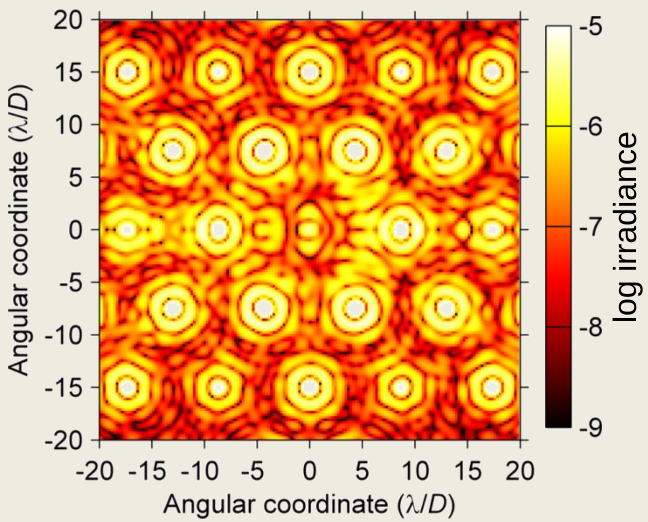

(Located in pupil)

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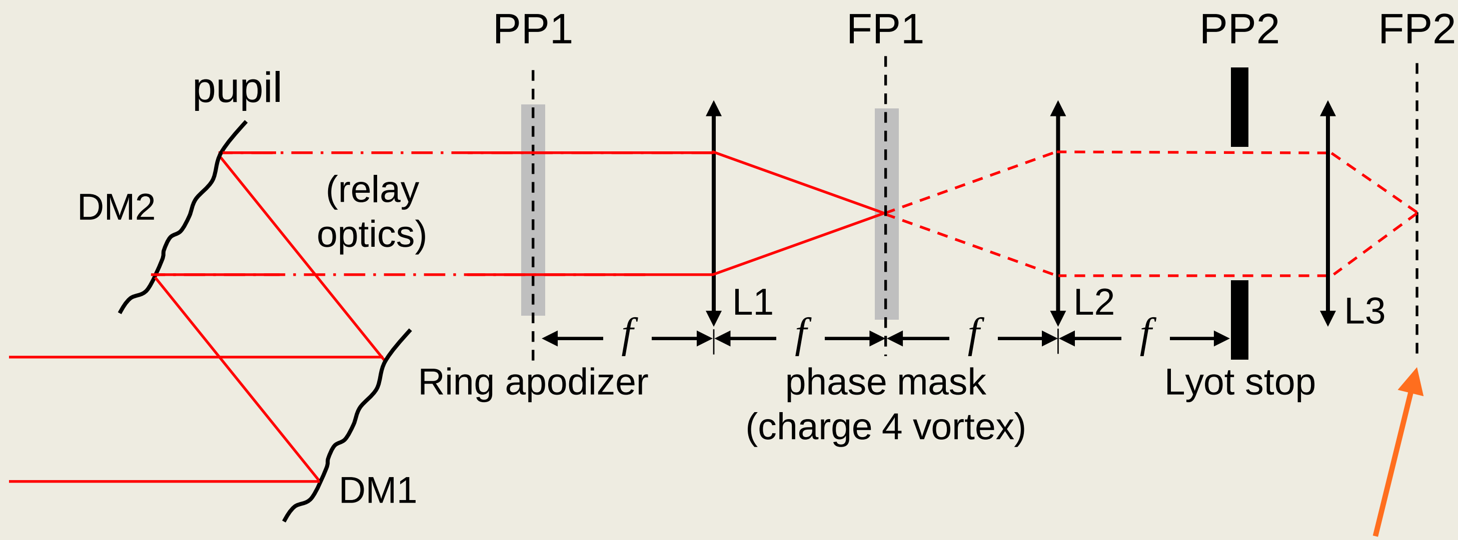
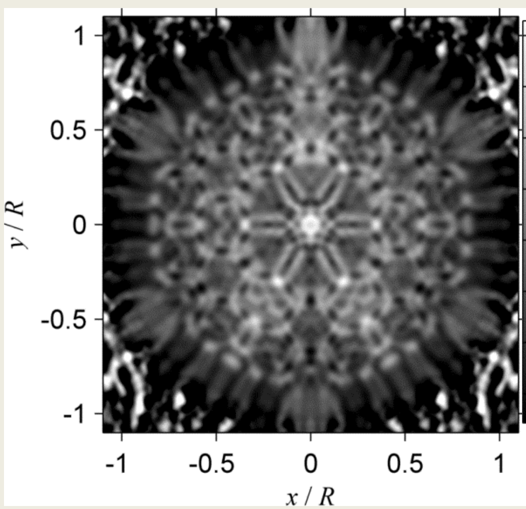
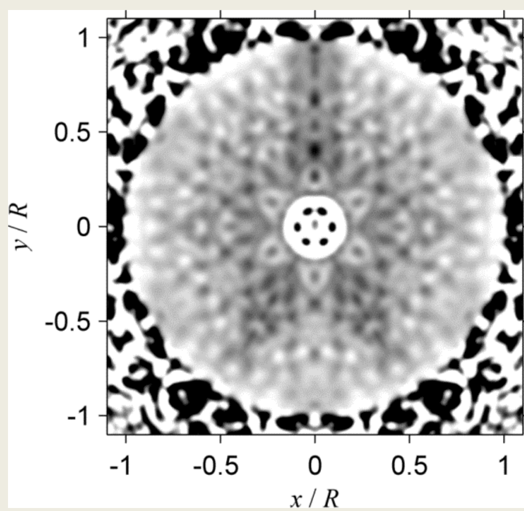


Surface height DM1 (nm)

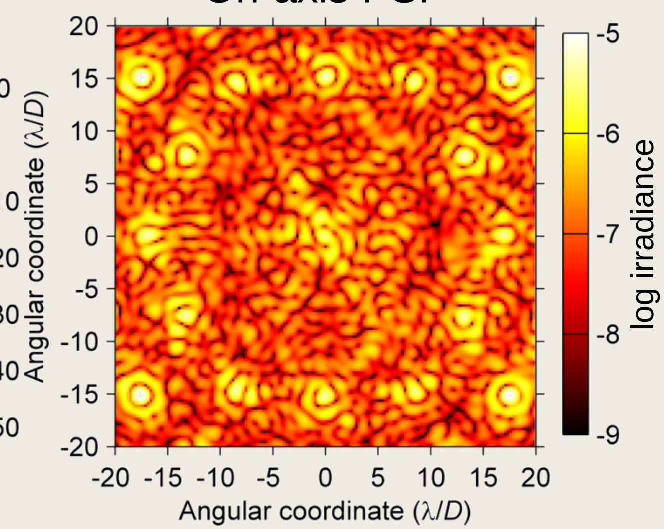


Surface height DM2 (nm)



(Located in pupil)

On-axis PSF



$\lambda = 500$ nm
$N_{act} = 64$

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Mazoyer et al., *Proc. SPIE* 96050M (2015)

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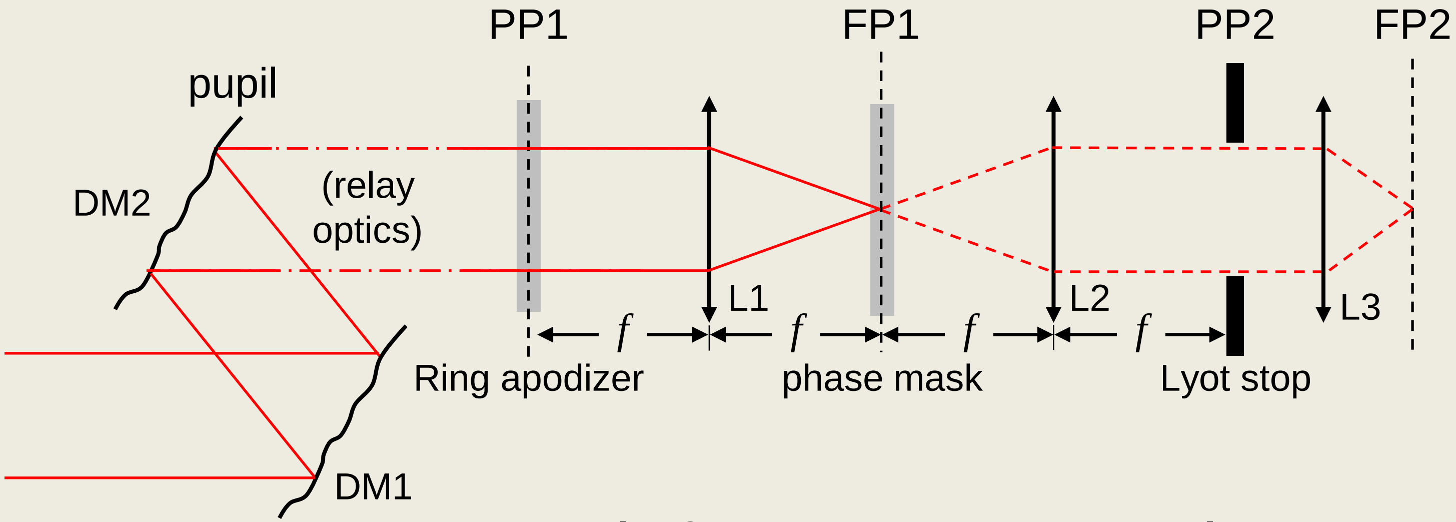
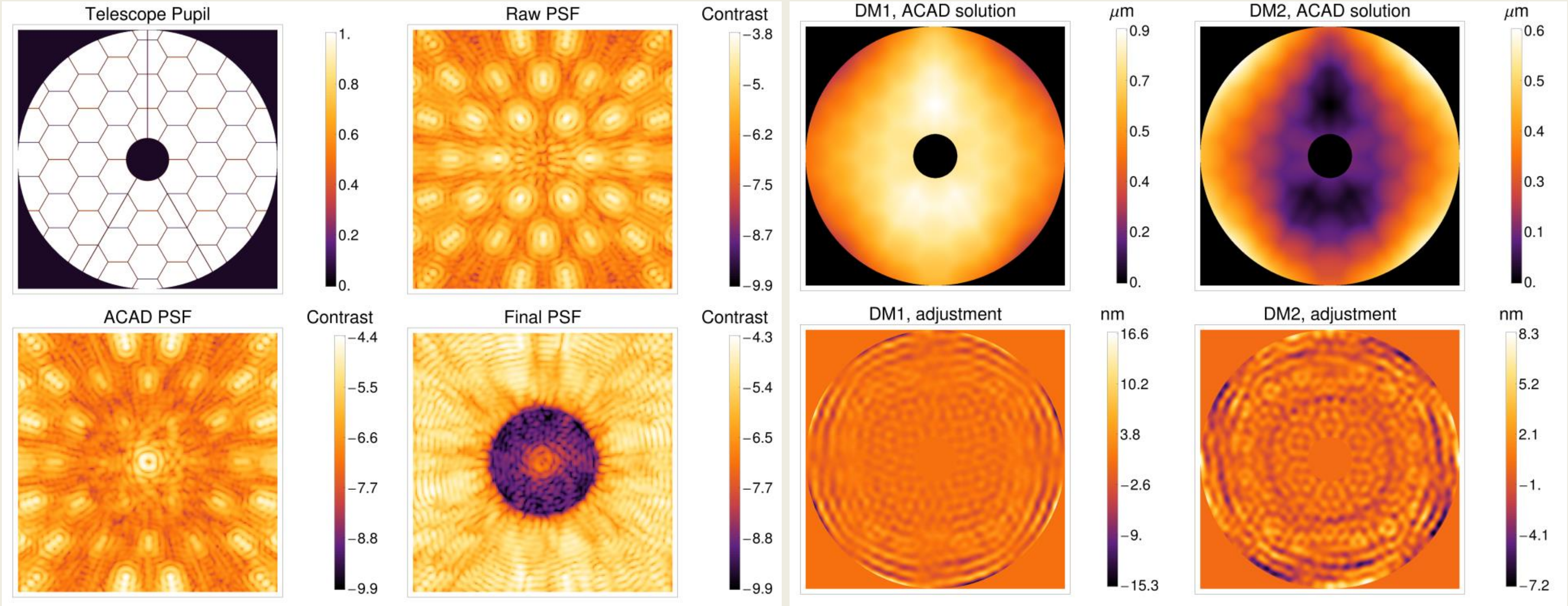


ACAD results from Mazoyer, Pueyo, et al.



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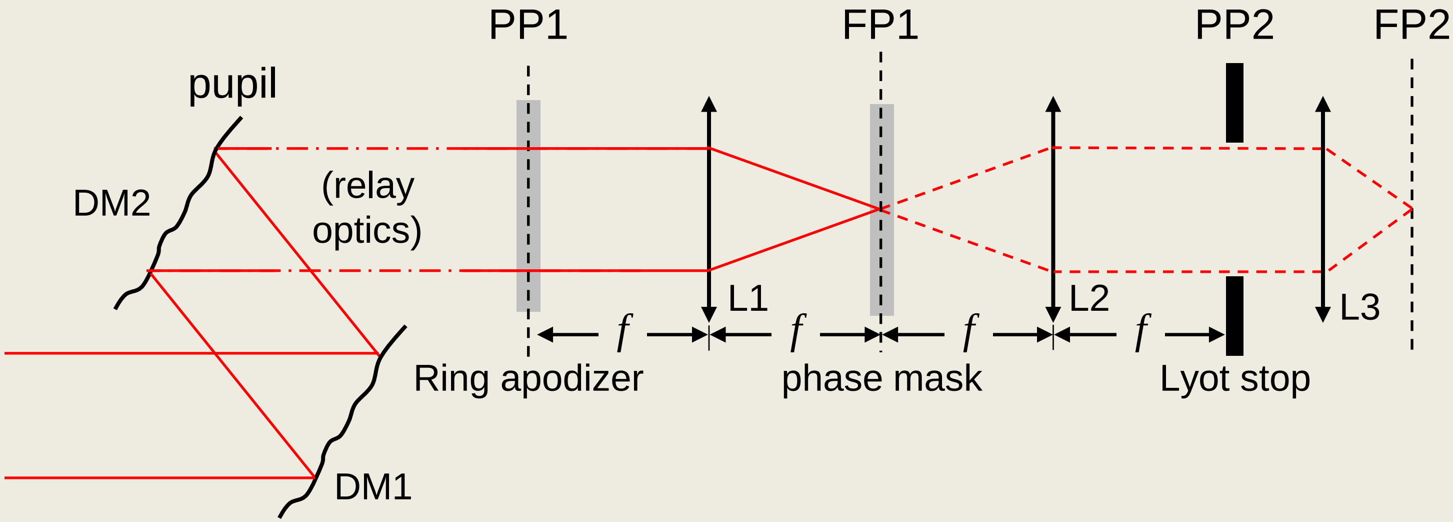
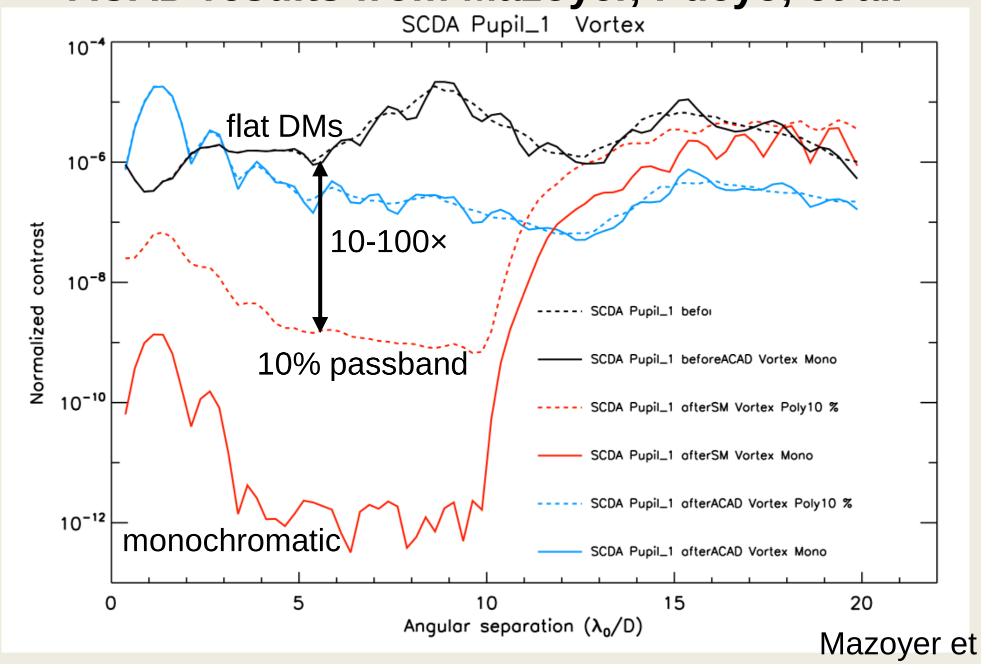
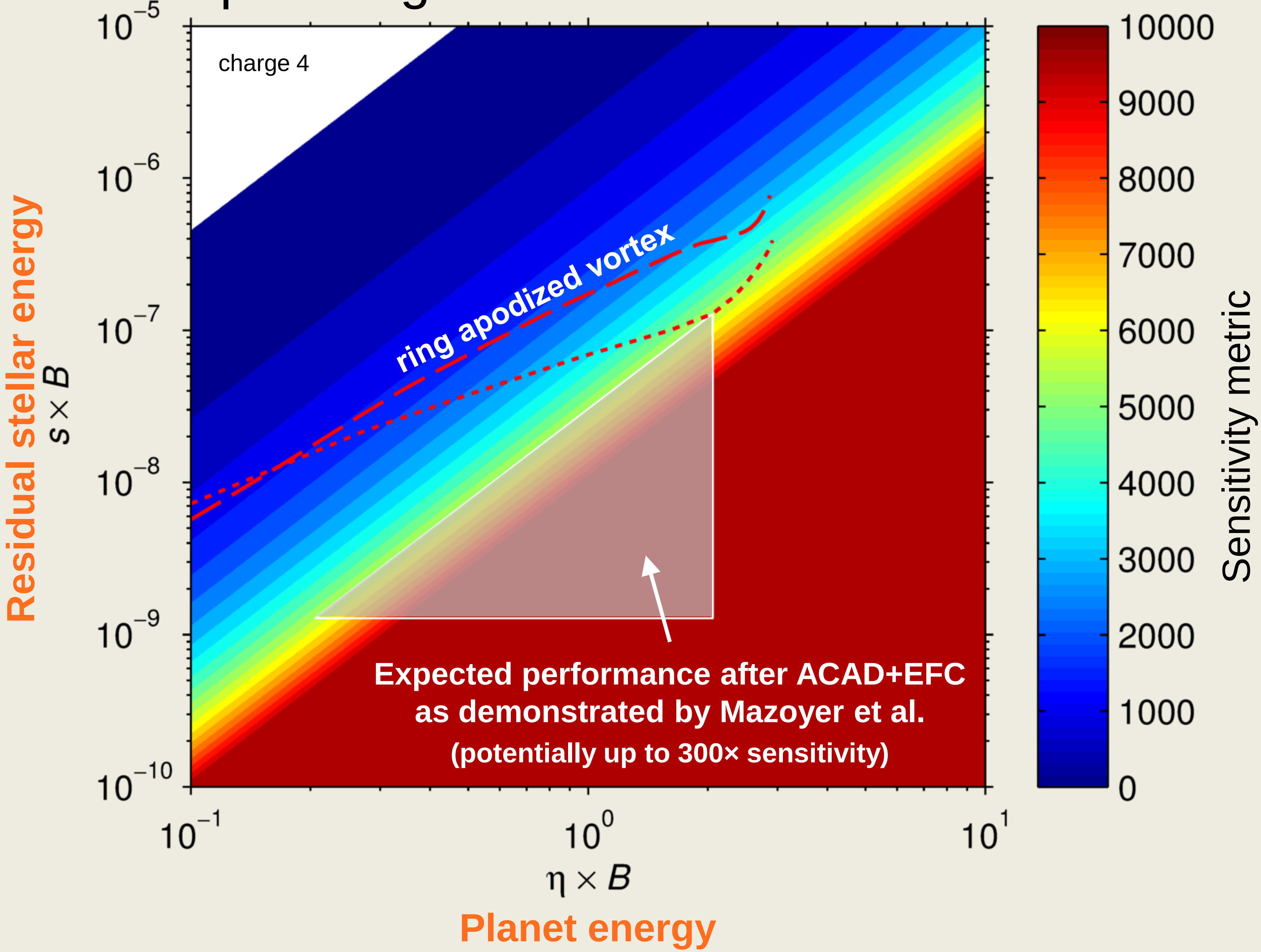


ACAD results from Mazoyer, Pueyo, et al.



Mazoyer et al., *Proc. SPIE* 96050M (2015)

Expected gains with wavefront control



Outlook for future work

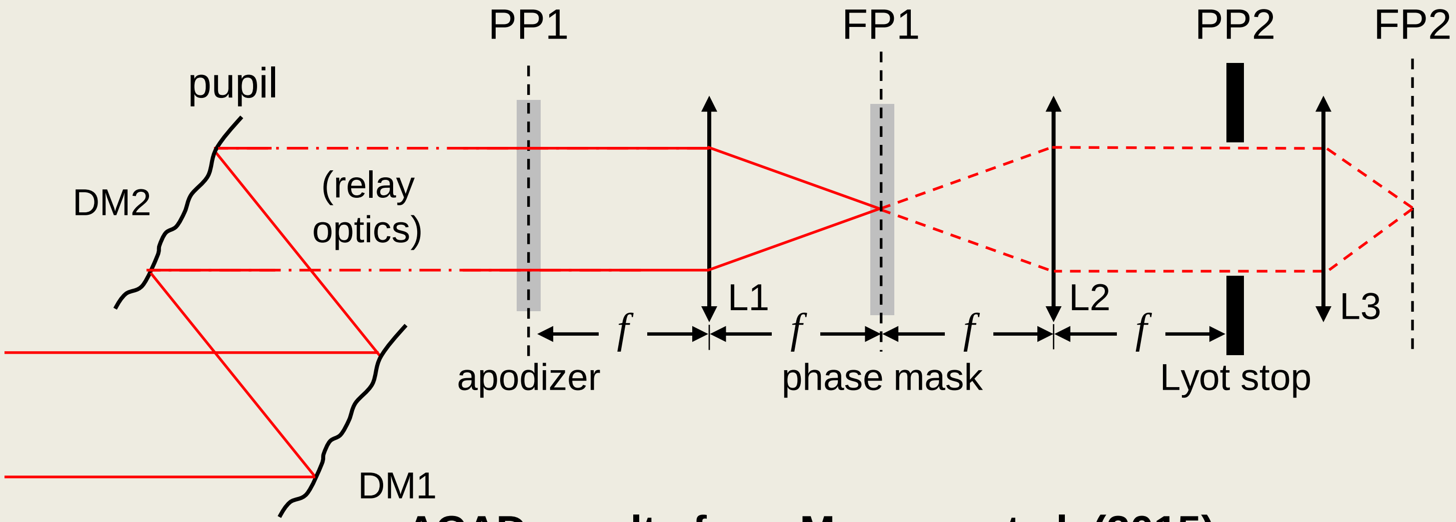
1. **Develop numerical optimization of grayscale apodizers for VCs.**

2. **Optimize broadband performance of wavefront control algorithms for VCs on segmented apertures.**

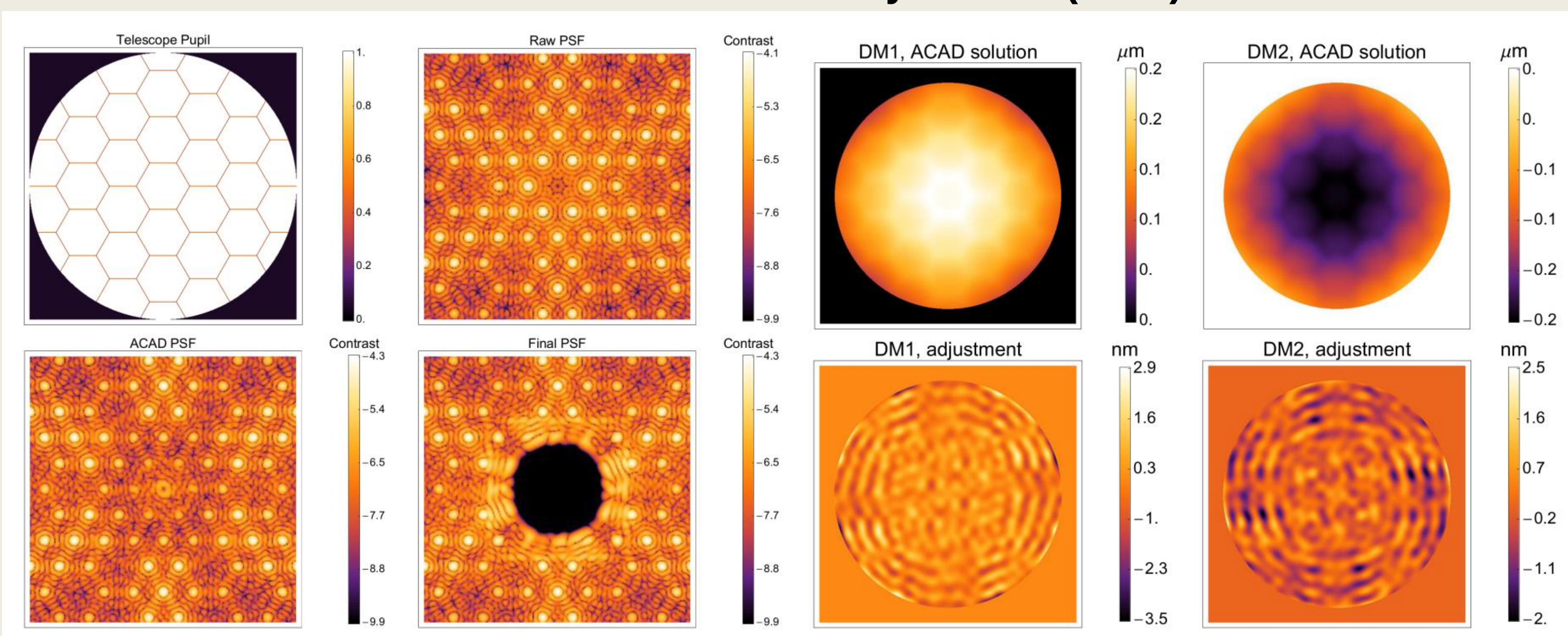
3. **Investigate potential performance gains by combining wavefront control and optimized coronagraphic masks.**

Extra slides

Active Compensation of Aperture Discontinuities (ACAD)

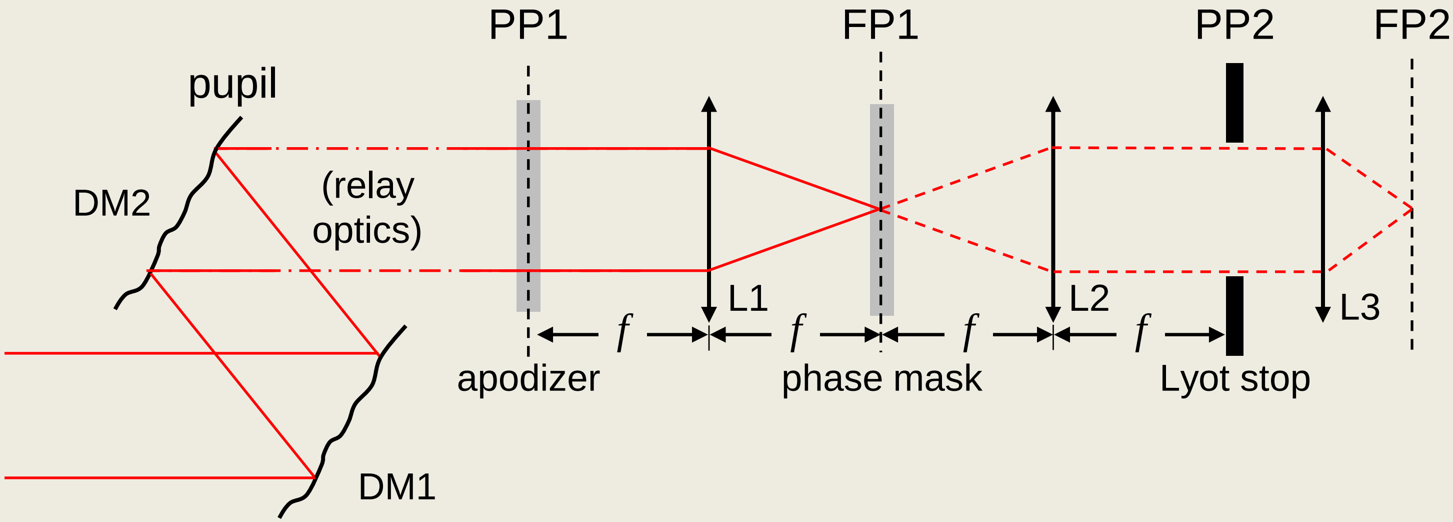


ACAD results from Mazoyer et al. (2015)

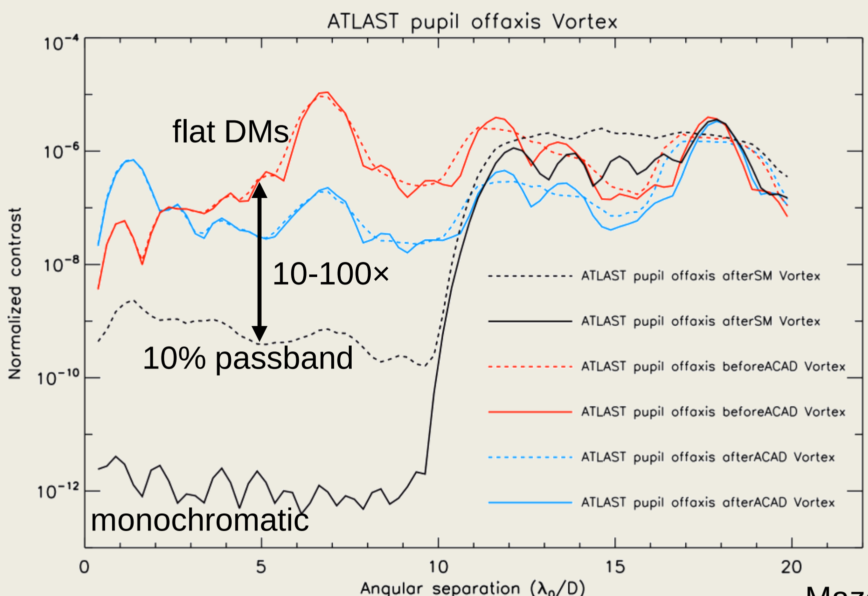


Mazoyer et al., *Proc. SPIE* 96050M (2015)

Active Compensation of Aperture Discontinuities (ACAD)



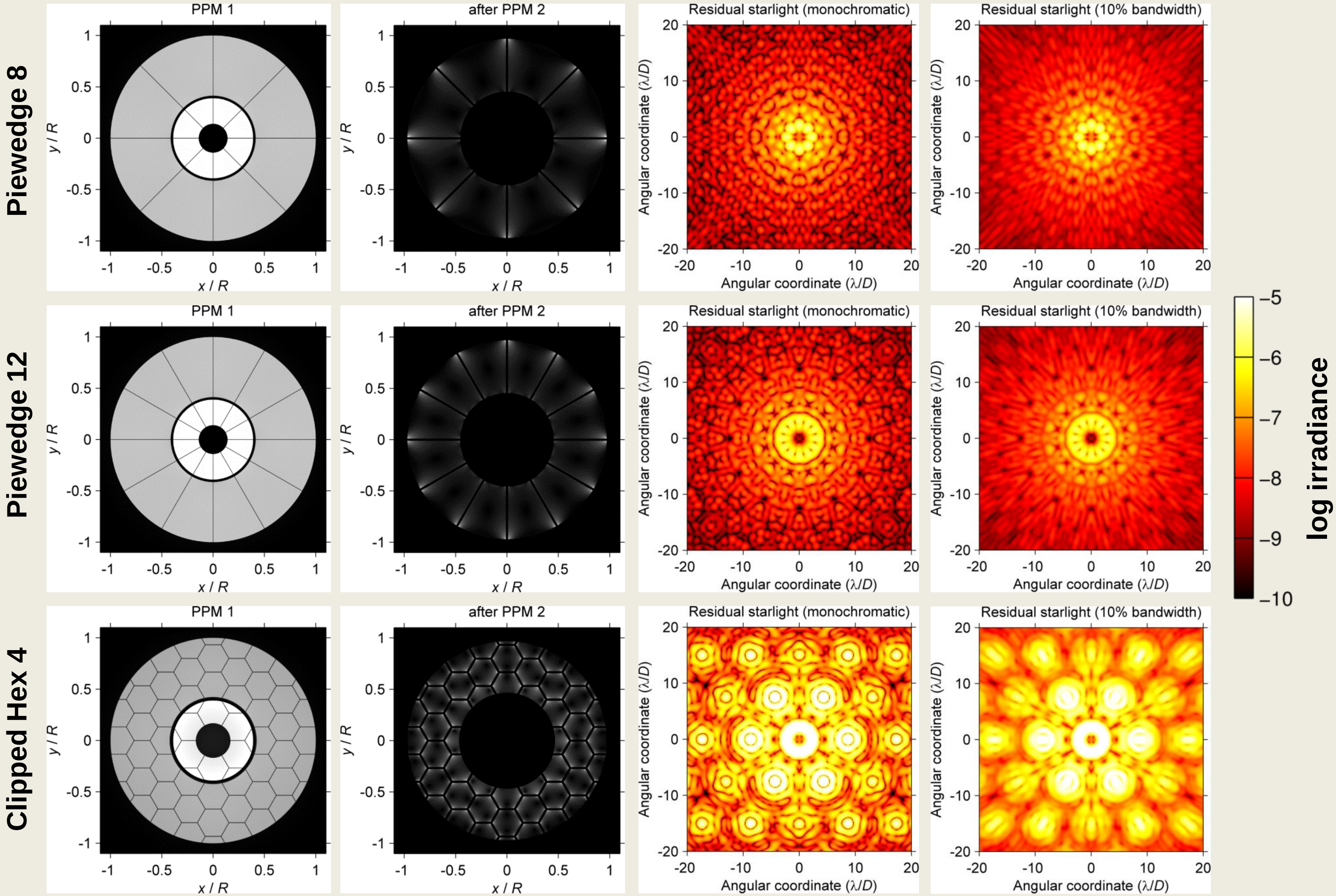
ACAD results from Mazoyer et al. (2015)



Mazoyer et al., *Proc. SPIE* 96050M (2015)

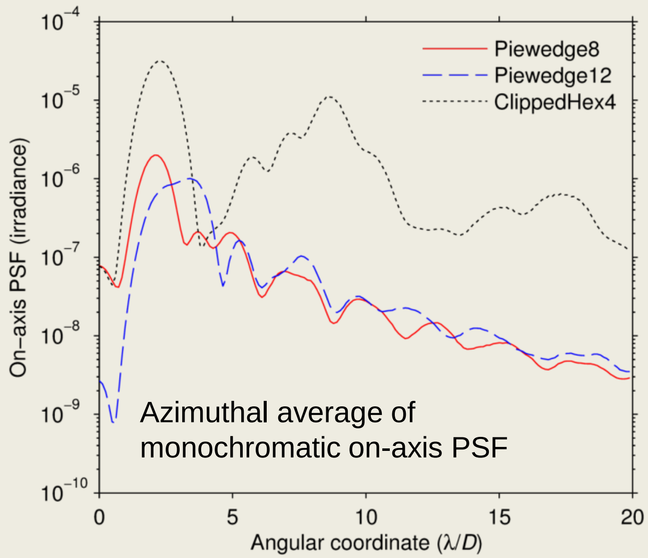
Apodized VC performance with segmented apertures

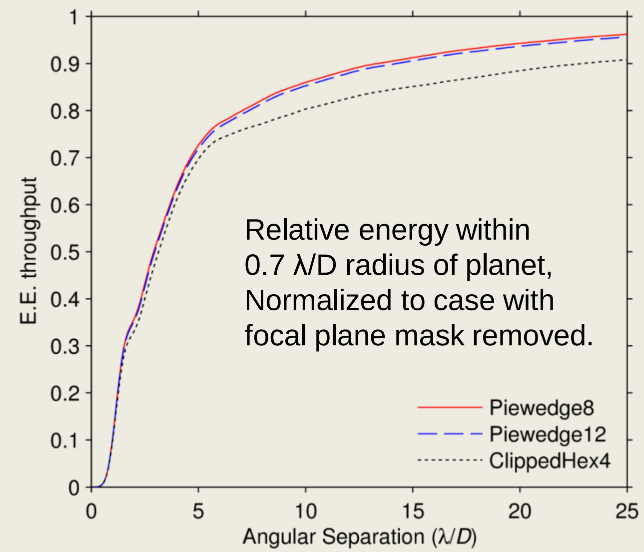
Analytically-inspired, ring-apodized VC (RAVC) with charge 4

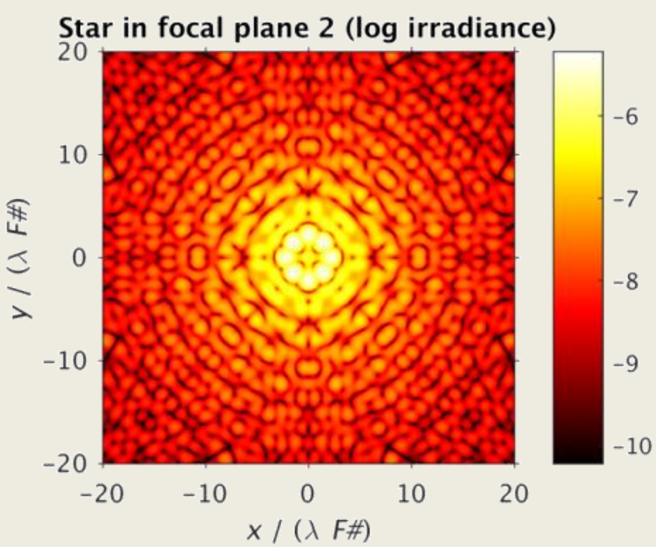


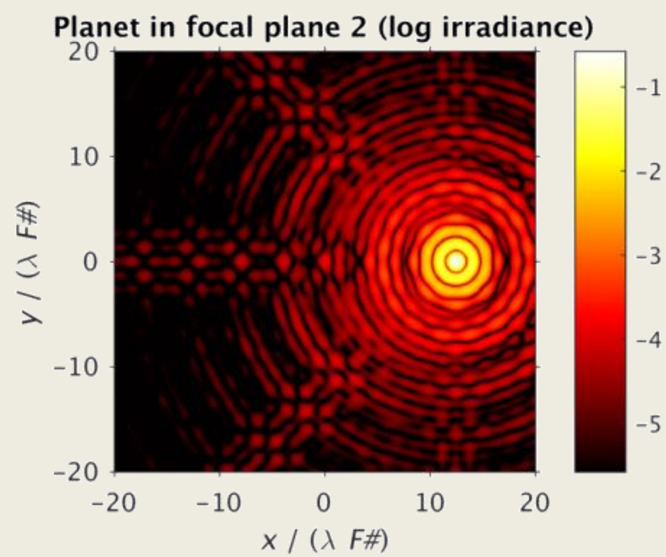
Apodized VC performance with segmented apertures

Analytically-inspired, ring-apodized VC (RAVC) with charge 4

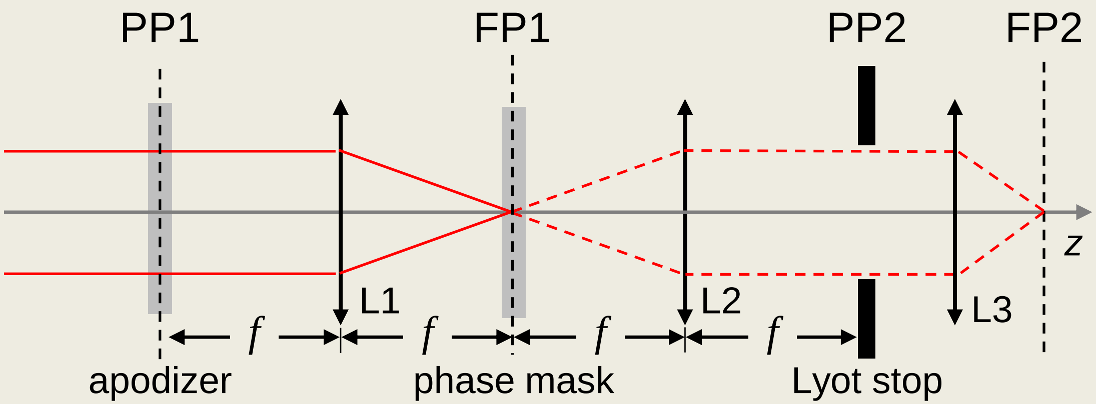






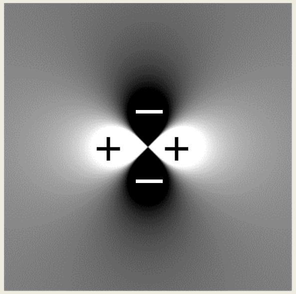


Option I: Optimizing the apodizer

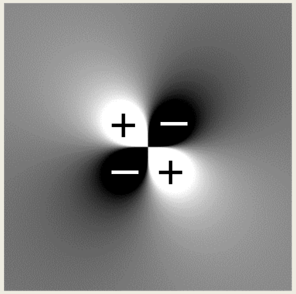


$$VC_l\left\{P(x,y)\right\} = P(x,y) * FT^{-1}\left[e^{il\phi}\right]$$

$$FT^{-1}\left[e^{il\phi}\right] = \frac{1}{r^2} e^{il\theta}$$



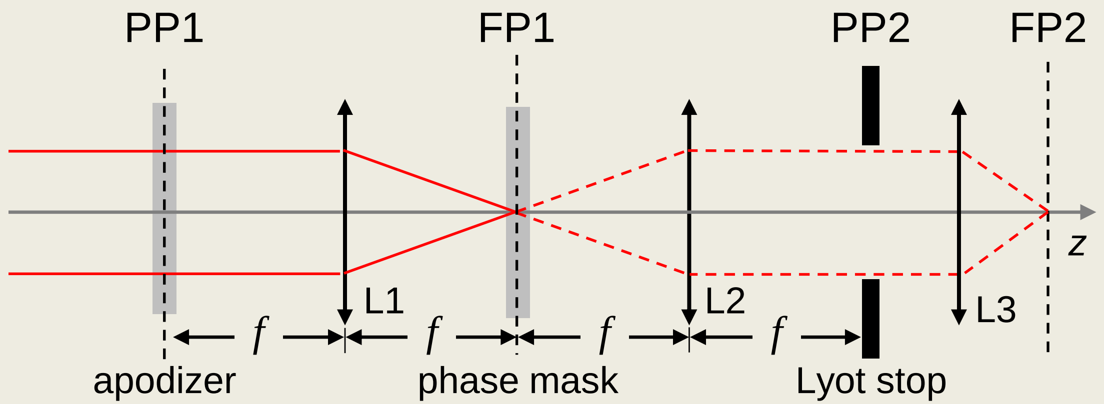
real part



imag. part

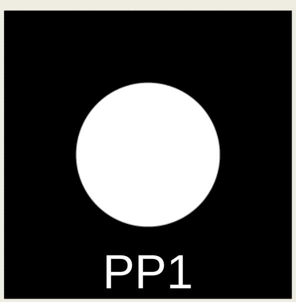
Swartzlander, *J. Opt. A* **11** 094022 (2009)

Option I: Optimizing the apodizer

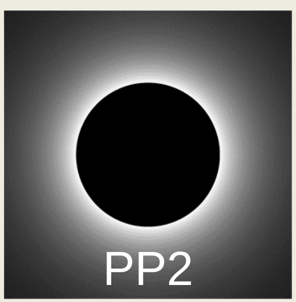


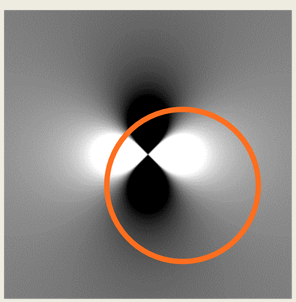
$$VC_l\left\{P(x,y)\right\} = P(x,y) * FT^{-1}\left[e^{il\phi}\right]$$

Convolution with a circular pupil

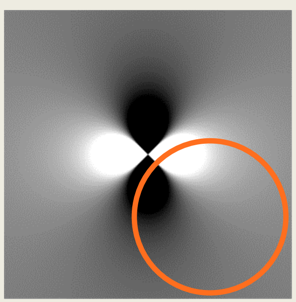


$$* \frac{1}{r^2} e^{i2\theta} =$$





zero
(inside)

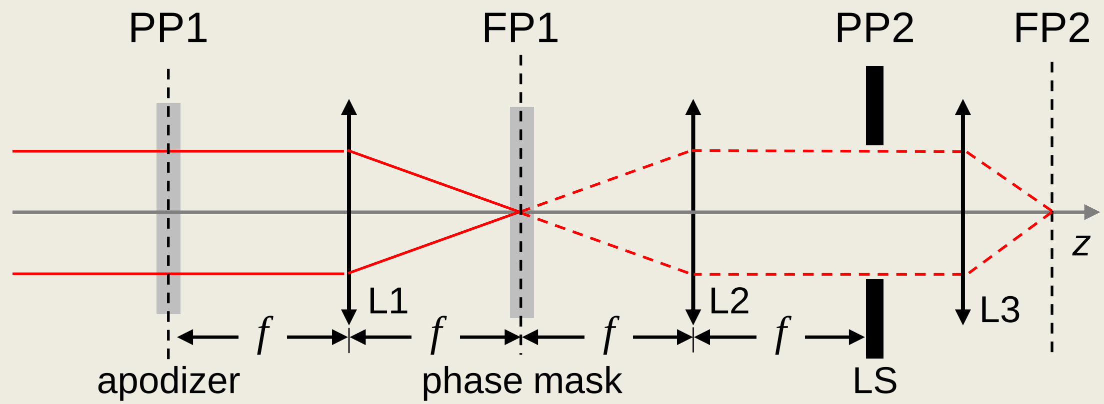


non-zero
(outside)

Occurs for nonzero even values of l

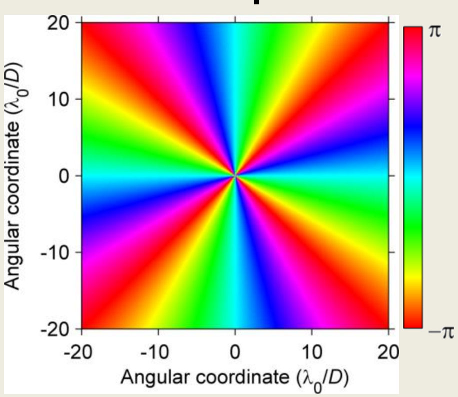
Swartzlander, *J. Opt. A* **11** 094022 (2009)

Option II: Optimizing the focal plane mask



Broadband FPM optimization process

1. Initial phase



(charge 4 vortex)

2. Solve for new phase at each λ

$$\Phi_1(\lambda_1)$$
$$\Phi_2(\lambda_2)$$
$$\vdots$$
$$\Phi_i(\lambda_i)$$
$$\vdots$$
$$\Phi_N(\lambda_N)$$

3. Take weighted average of solutions

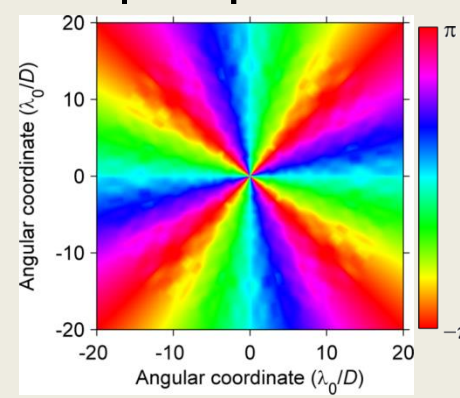
Achromatic (e.g. liquid crystal):

$$\Phi = \sum_i c_i \Phi_i(\lambda_i)$$
$$M = \exp(i\Phi)$$

Dielectric material:

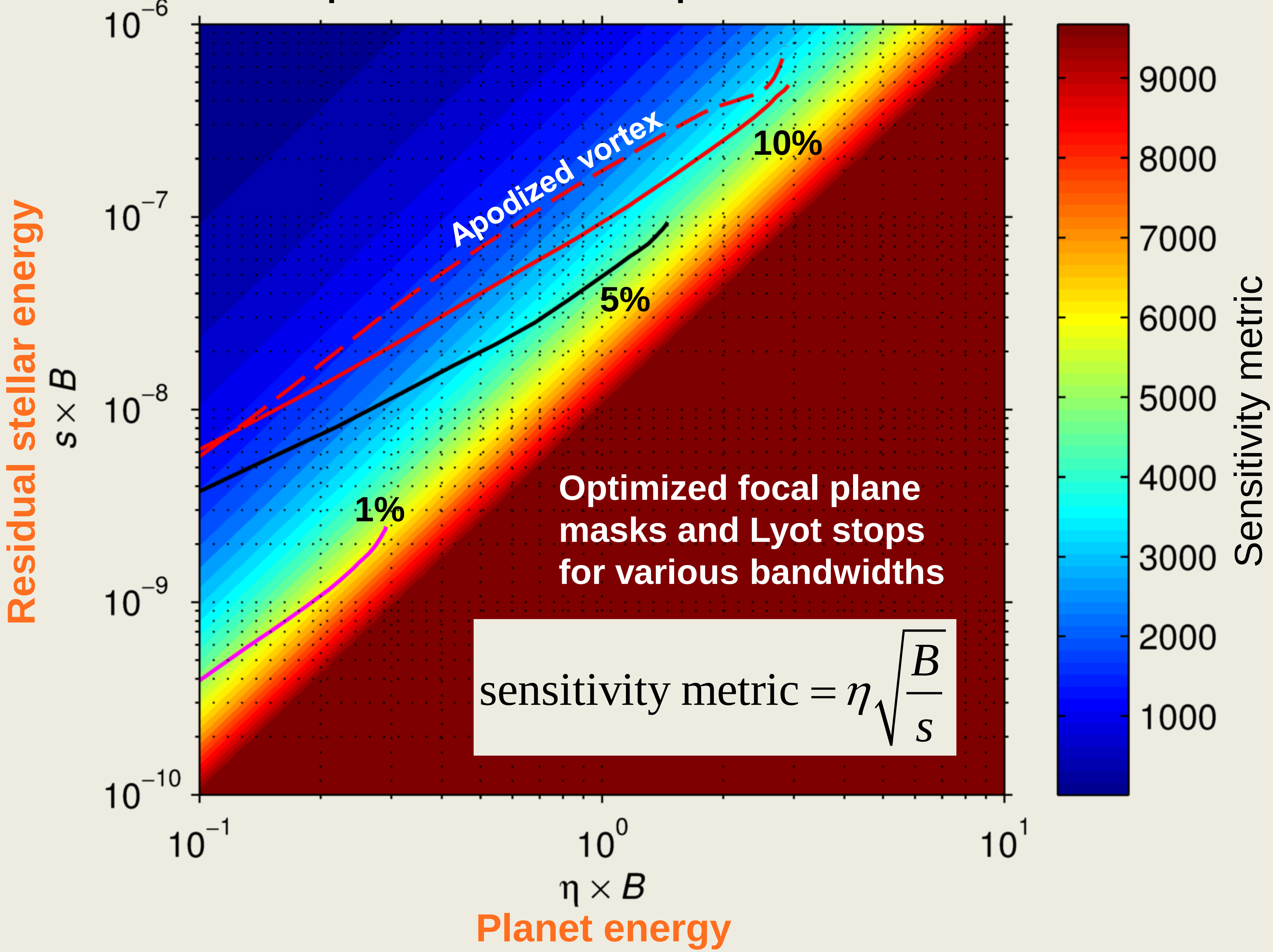
$$h = \sum_i \frac{c_i \lambda_i}{n(\lambda_i)} \Phi_i(\lambda_i)$$
$$M = \exp\left(i \frac{2\pi}{\lambda} n(\lambda) h \right)$$

4. Update phase mask

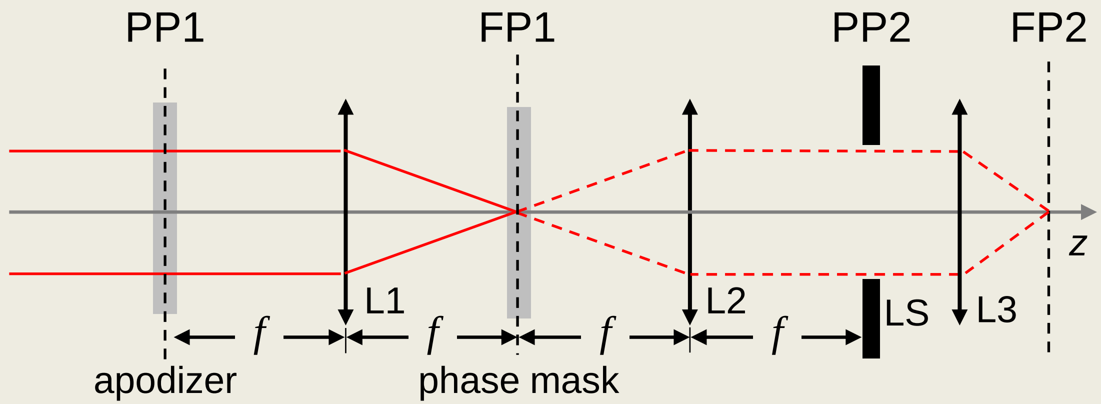


5. Repeat steps 2 - 4

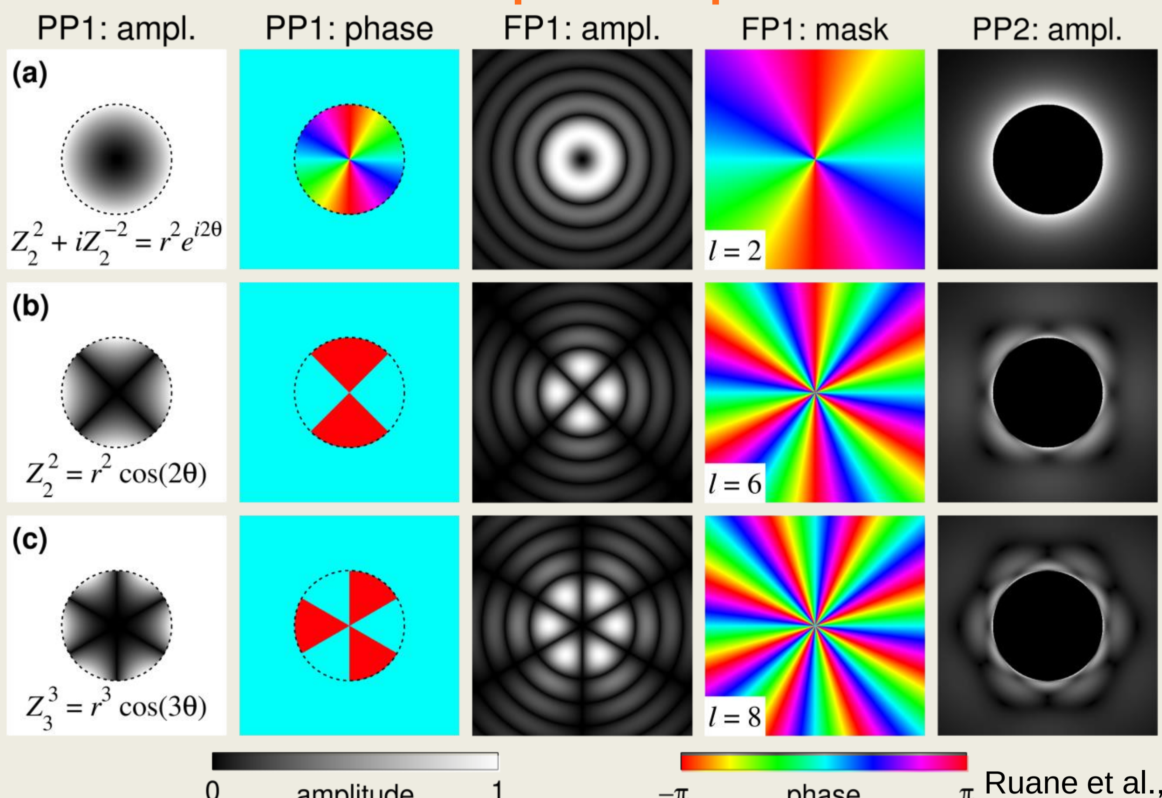
Optimized focal plane masks



Alternate apodization schemes



Zernike amplitude apodizers



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

<u>rules</u>

l is even

$$P = \sum a_{nm} Z_n^m(\rho, \theta)$$

$$|l| > \max\{n + |m|\}$$

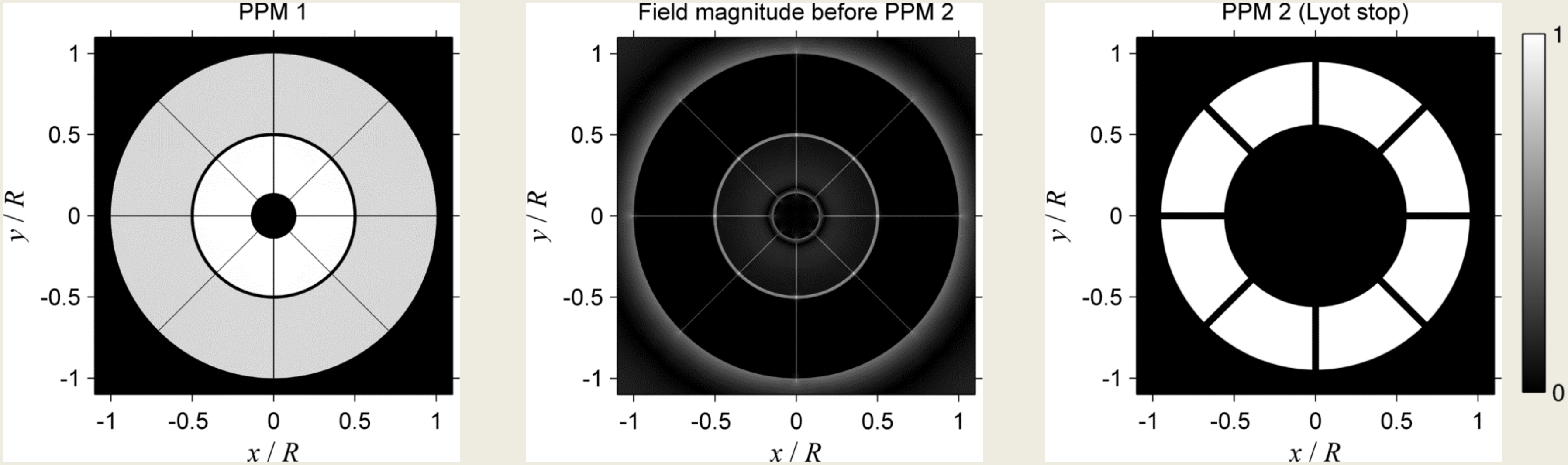
$$\text{or } P = \sum b_m r^{|m|} e^{im\theta}$$

$$\text{sgn}(l) = \text{sgn}(m)$$

Monochromatic focal plane mask optimization

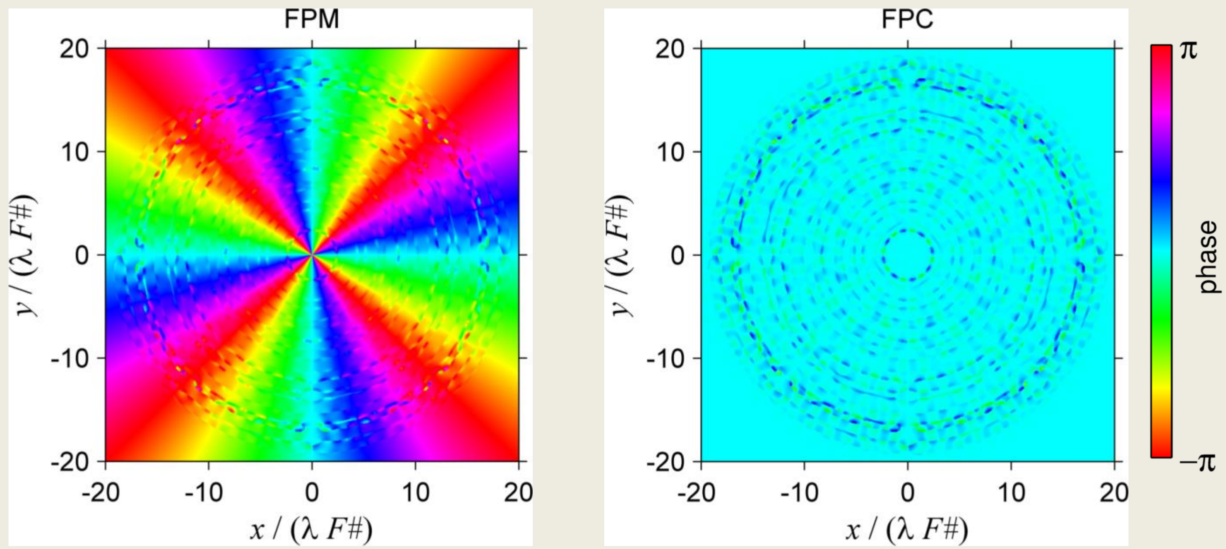
RAVC4 w/ focal plane corrector (FPC)

Ruane et al., *Optica* **2**, 147 (2015)
Ruane et al., *Proc. SPIE* **9605** 1I (2015)



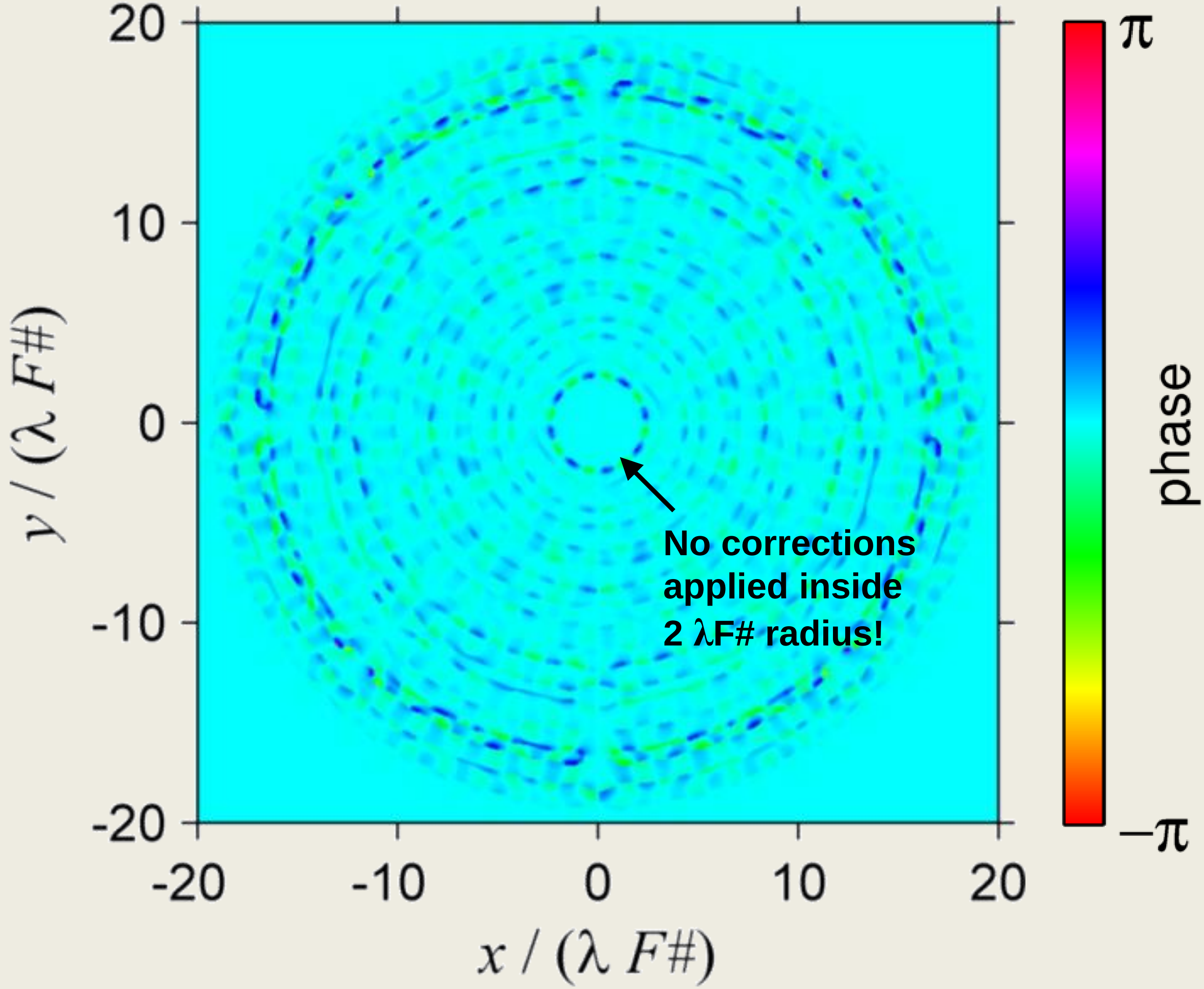
Focal plane mask (FPM)

Focal plane corrector (FPC)



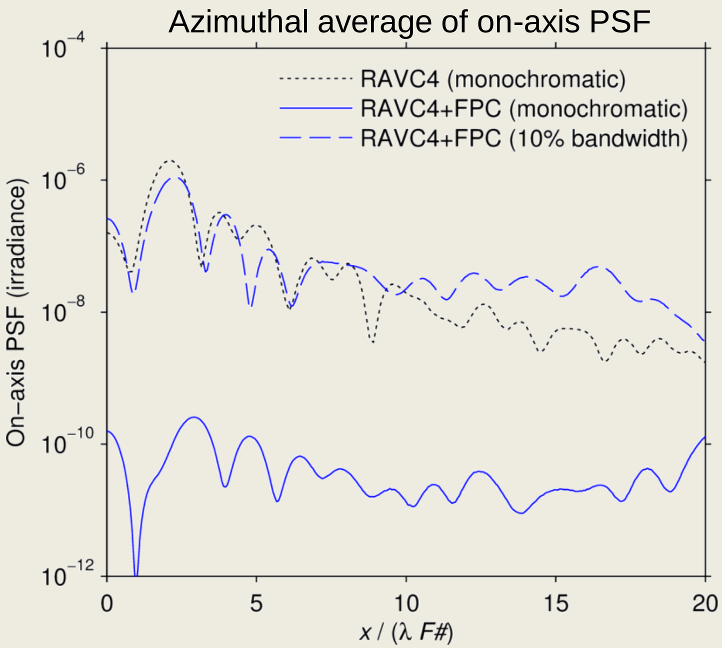
The focal plane mask (FPM) is numerically optimized to improve starlight suppression at a single wavelength.

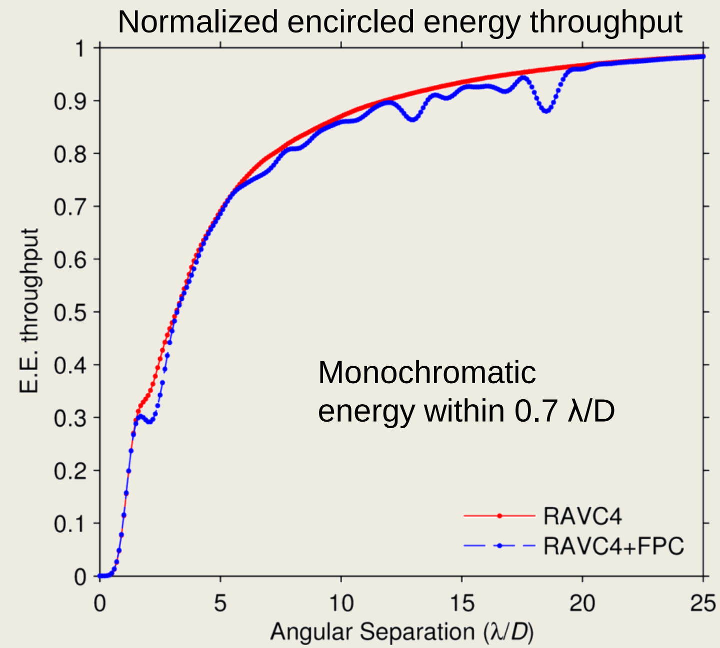
Monochromatic focal plane mask optimization

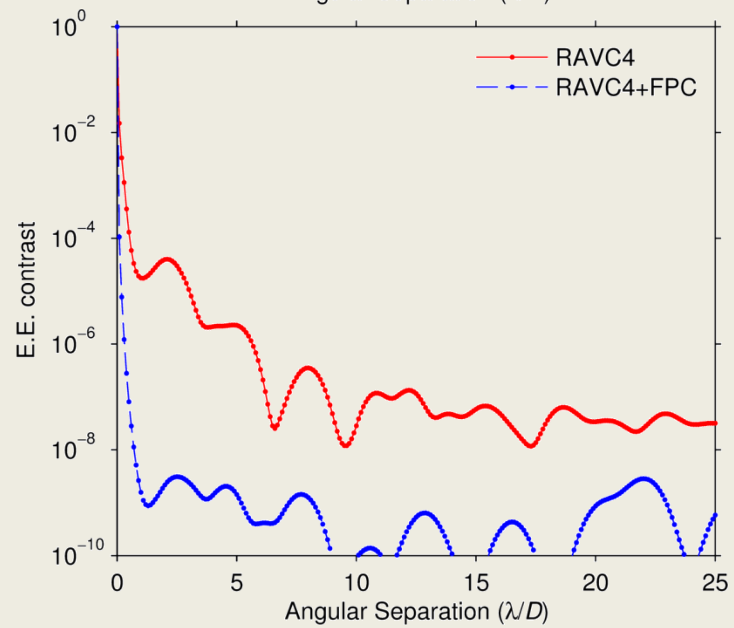


Phase corrections needed for monochromatic suppression.
This will inform the basis used for broadband optimization.

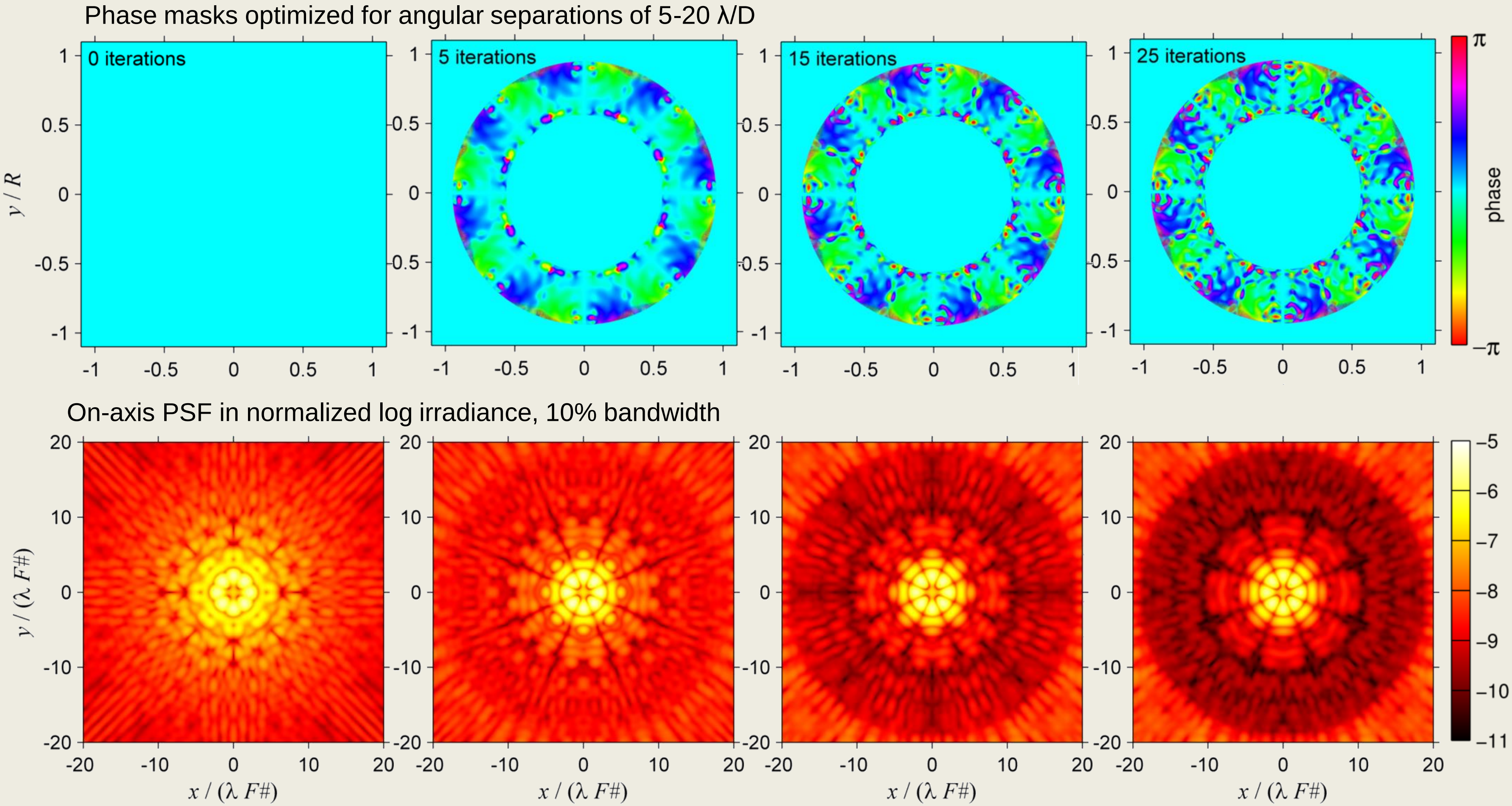
Monochromatic focal plane mask optimization





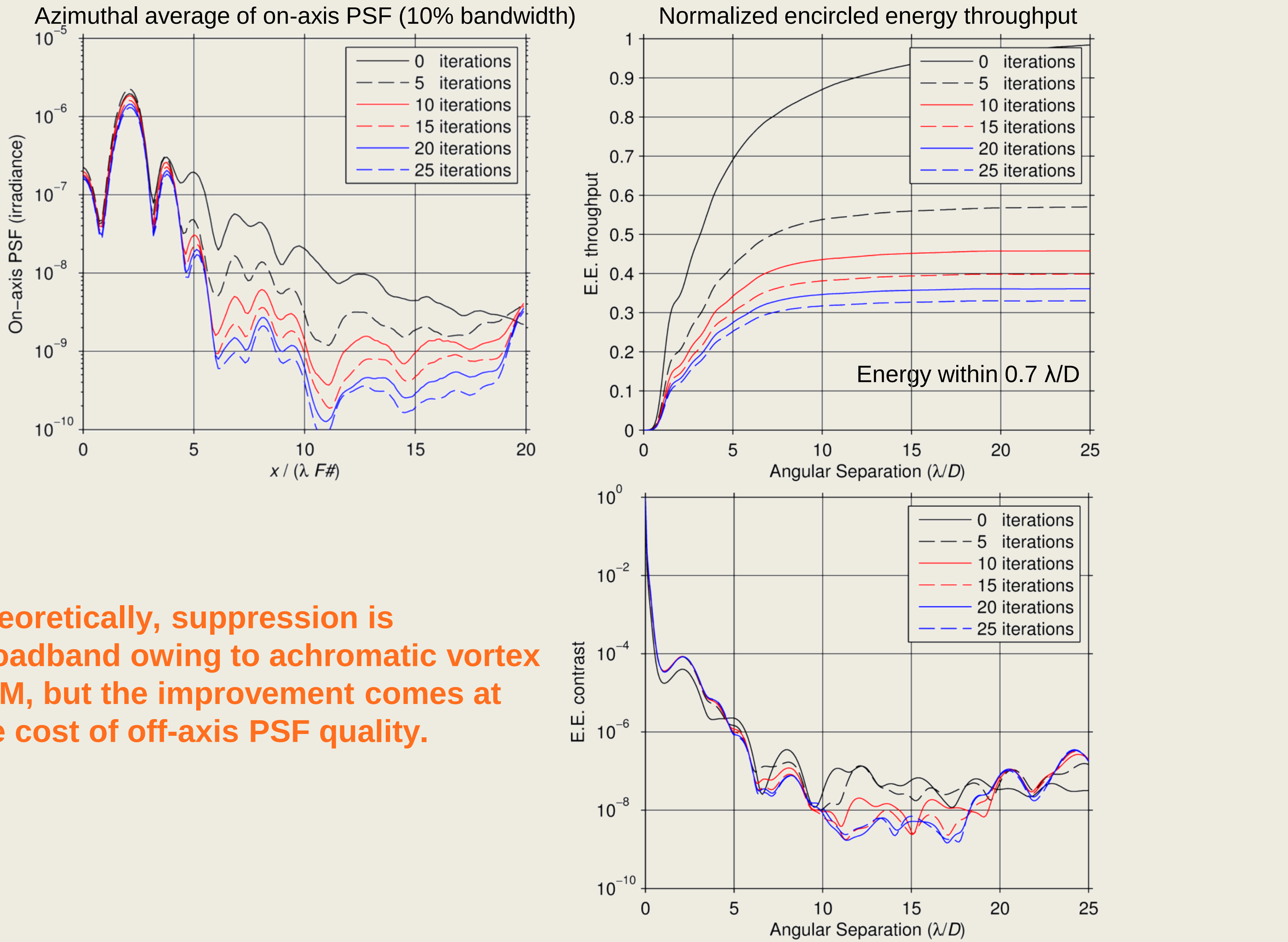


Phase-shifting Lyot plane masks for RAVC4



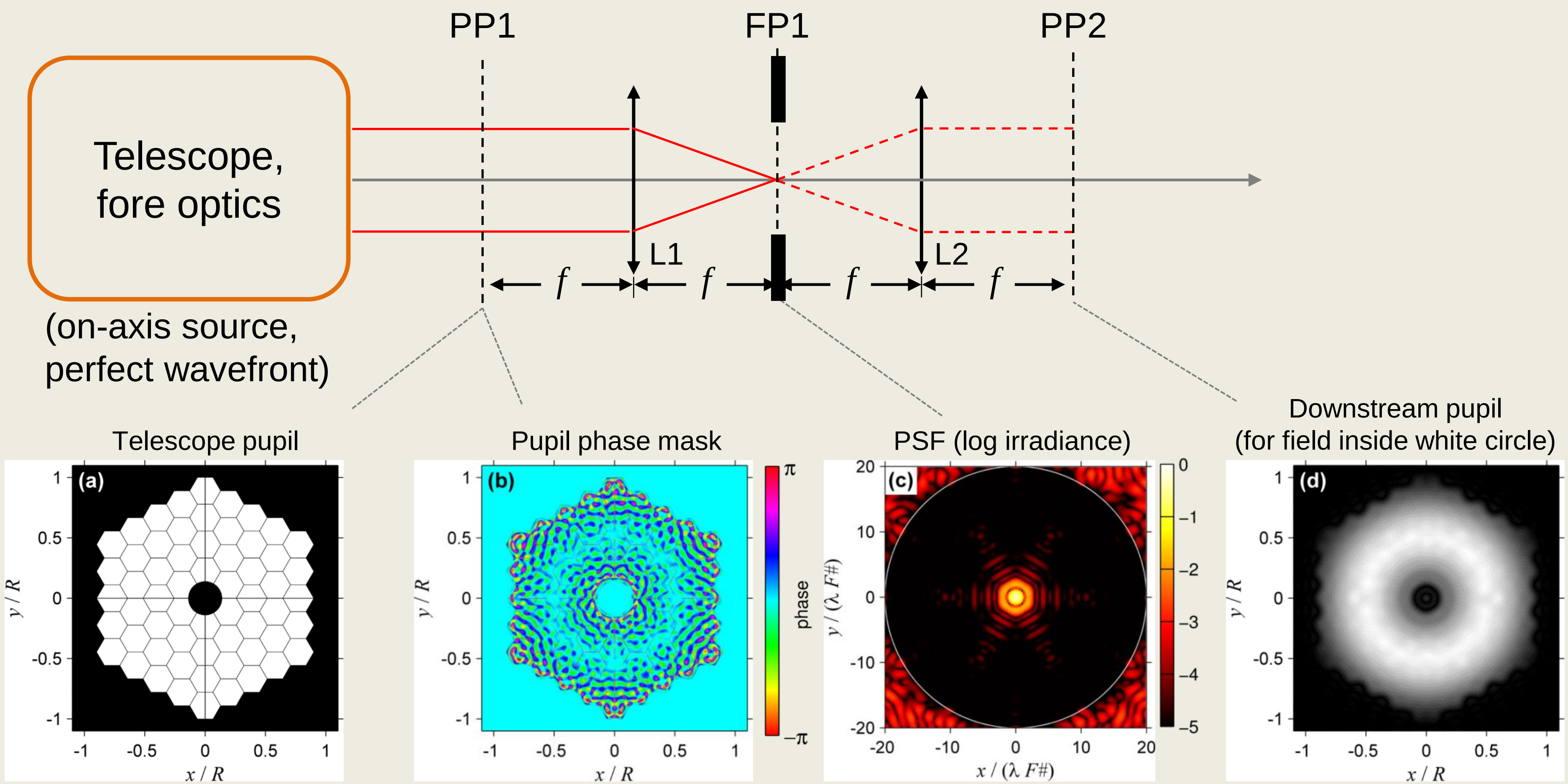
Optimized LPMs for the VC improve the suppression over a substantial spectral bandwidth (achromatic phase shifts assumed)

Phase-shifting Lyot plane masks for RAVC4



Theoretically, suppression is broadband owing to achromatic vortex FPM, but the improvement comes at the cost of off-axis PSF quality.

Phase masks designed for apodization

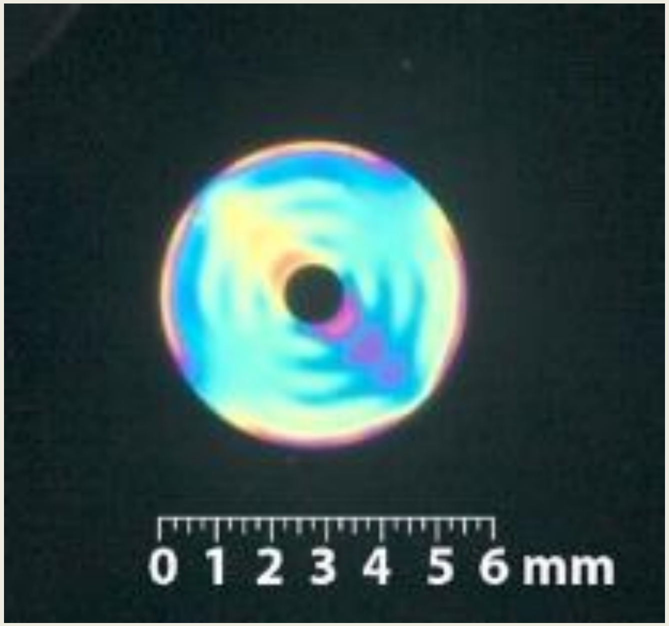


E.E. throughput = ~0.5

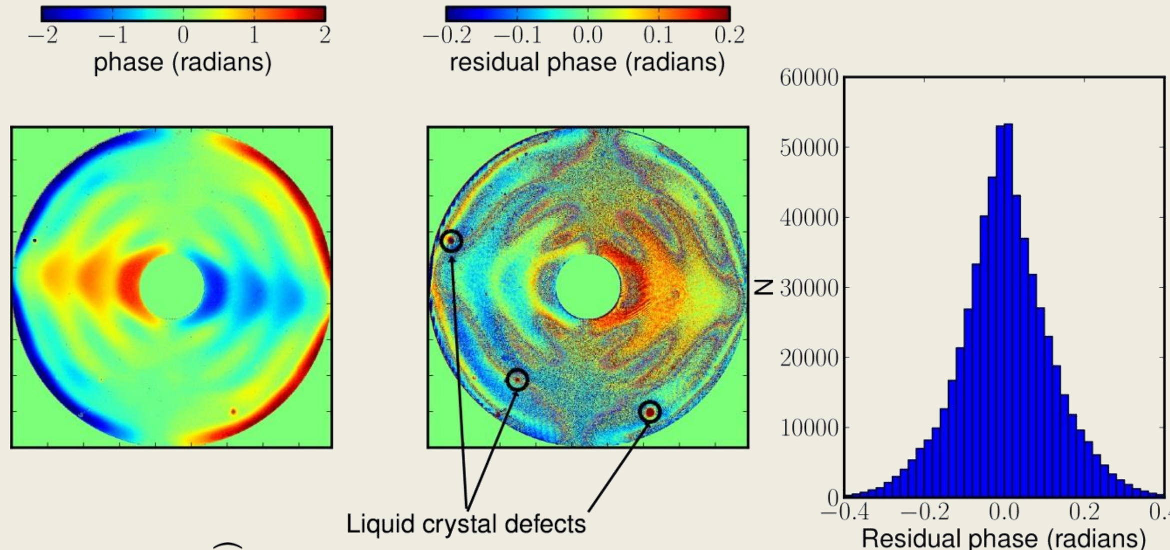
Phase masks may be used to apodize segmented aperture telescopes, effectively erase aperture discontinuities, and maintain high throughput (e.g. w.r.t. shaped pupils).

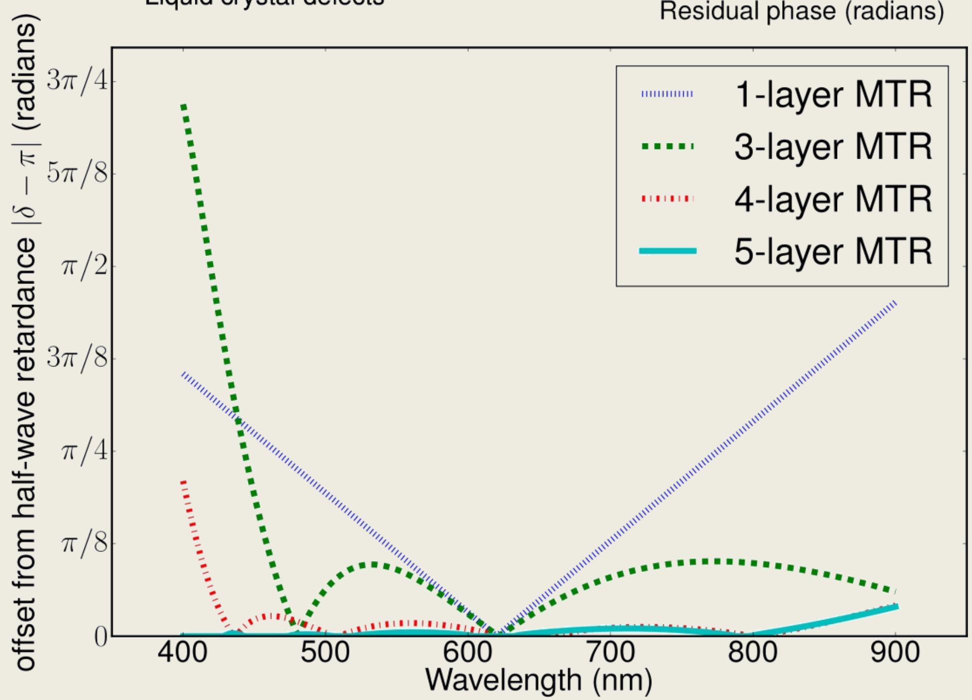
Achromatic phase mask technologies

Vector phase masks
photo-aligned liquid crystal



Vector phase mask imaged through crossed polarizers

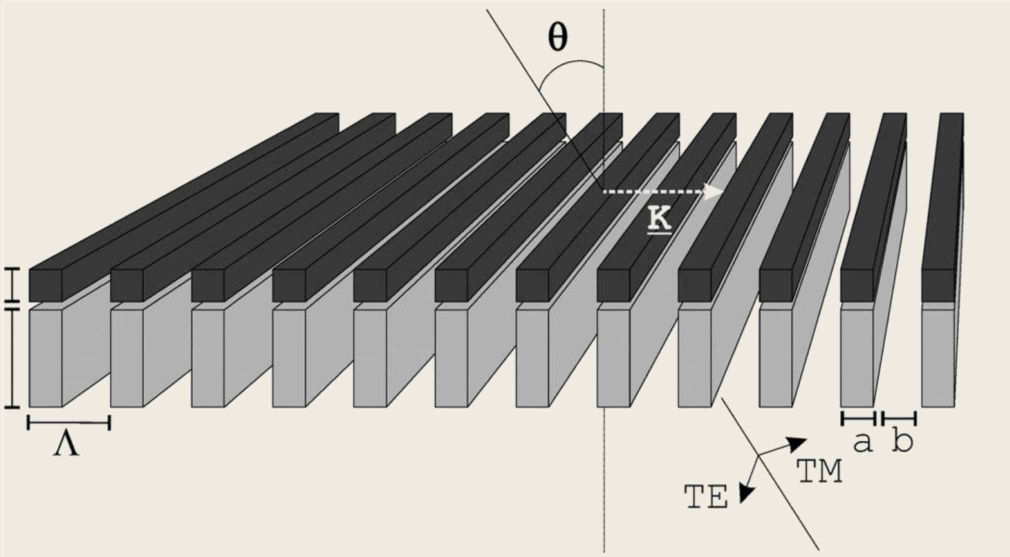




Otten et al., *Opt. Express* 22, 30287 (2014)
Miskiewicz and Escuti, *Opt. Express* 22, 12691 (2014)
Komanduri et al. *Opt. Express* 21, 404 (2013)

Achromatic phase mask technologies

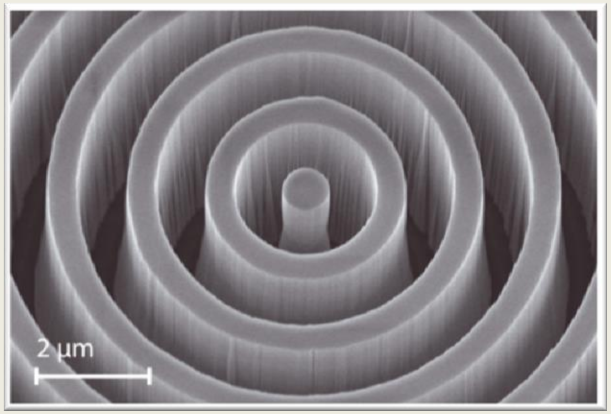
Vector phase masks
subwavelength gratings



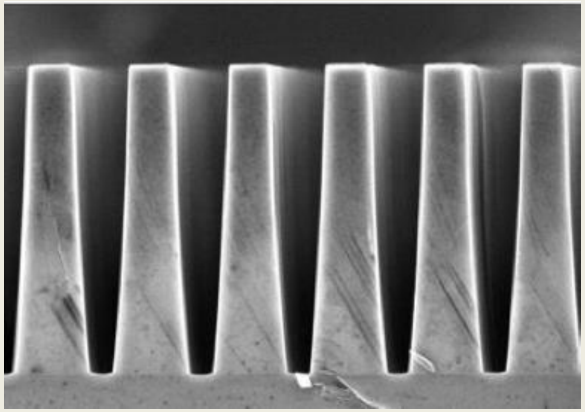
Phase shift depends on direction of grating.

Annular groove phase masks (AGPM)

L band (Sep 2012)



1.4 µm period



4.7 µm depth

Delacroix et al., *A&A* 553, A98 (2013)
Mawet et al., *Appl. Opt.* 44, 7313 (2005)
Bomzon et al., *Opt. Lett.* 26, 1424 (2001)