Optimized Coronagraph Design for Segmented Aperture Telescopes

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Workshop on Technology for Direct Detection and Characterization of Exoplanets

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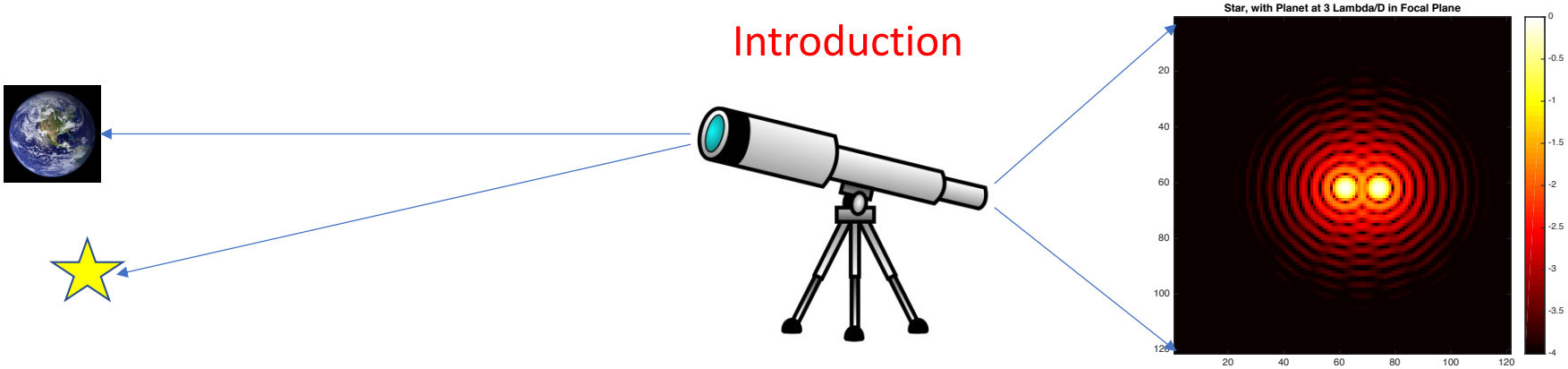
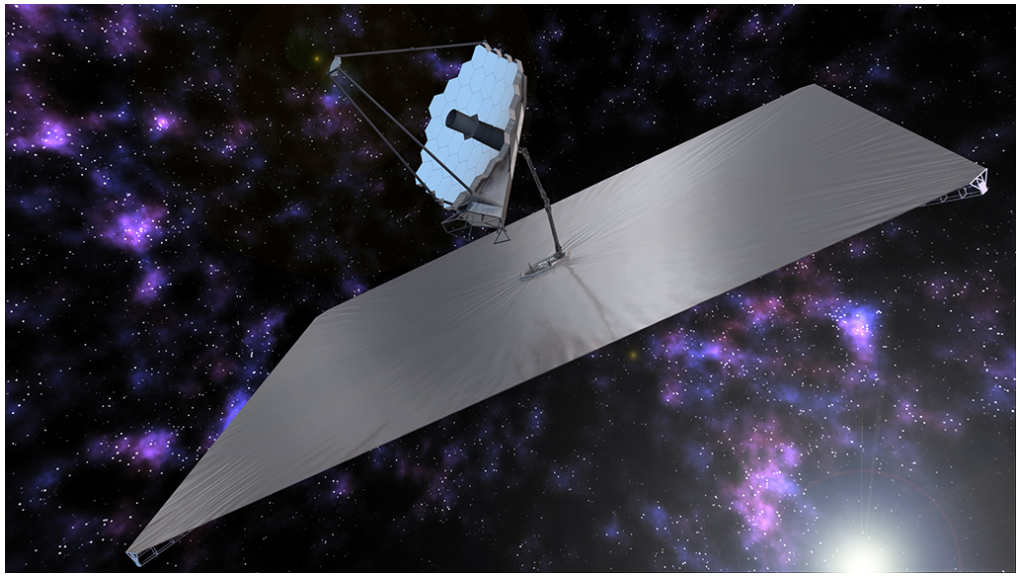
Introduction



- Goal: Directly Image Earth-like planets in the habitable zone (0.7 to 1.5 AU from host star)
- "Back of the envelope" (see C. Stark et al, ApJ, 795, Nov. 2014 for detailed study)
  - Hipparcus catalog gives 5449 stars with d < 50 pc – *can we find exo-Earth's?*
  - Angular separation of a planet at 1 AU, star between 10-50 pc, is 0.1 to .02 arcsec respectively
  - A star 10, 30, 50 pc away requires a telescope diameter of 3.4, 10, 17 meters for the planet (at 1 AU) to be resolved at $3\ \lambda/D$ away from star.
  - For comparison, Hubble's primary is 2.4 meters…
- A star is 10 ***billion times brighter*** than a planet!
- Direct Imaging of Exoplanets in the habitable zone therefore requires
  - Large Apertures (to collect enough light)
  - High-contrast imaging
- *Can we design "ideal" coronagraphs for direct imaging of exoplanets in the habitable zone?*

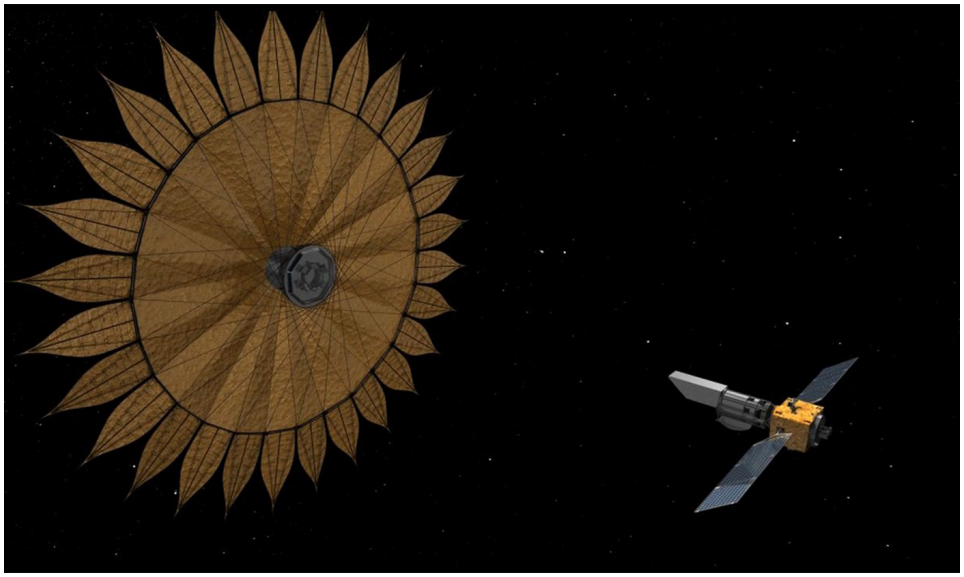
Looking To the Future: Direct Imaging of Exoplanets in the Habitable Zone

Exoplanet Imaging is a Key Science Driver for Two (of Four) Large Mission Concept Studies for the 2020 Decadal Review.



Large UV/Optical/Infrared Surveyor (LUVOIR)

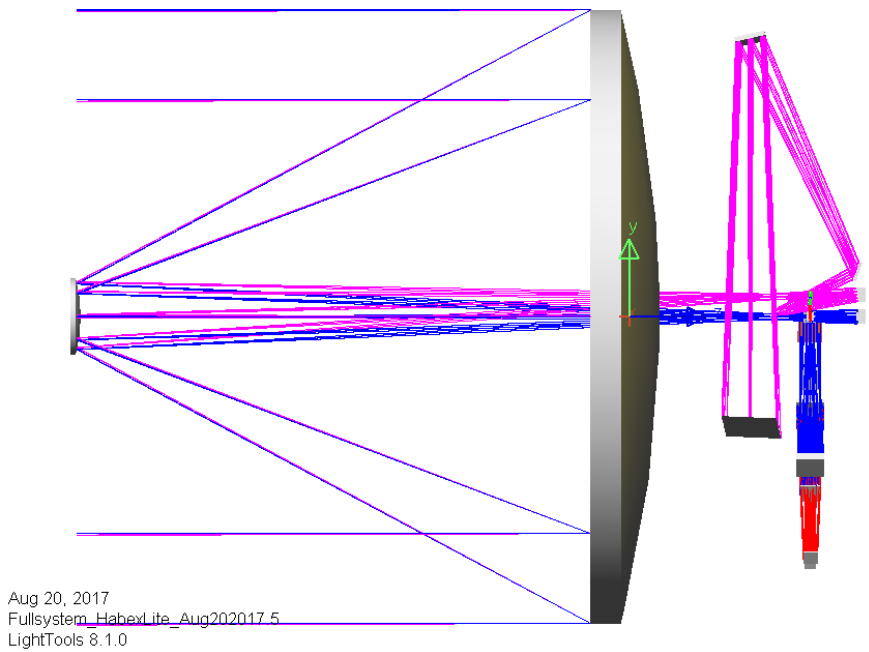
- 15 meter(!) segmented on-axis telescope
- High-contrast imaging with a coronagraph

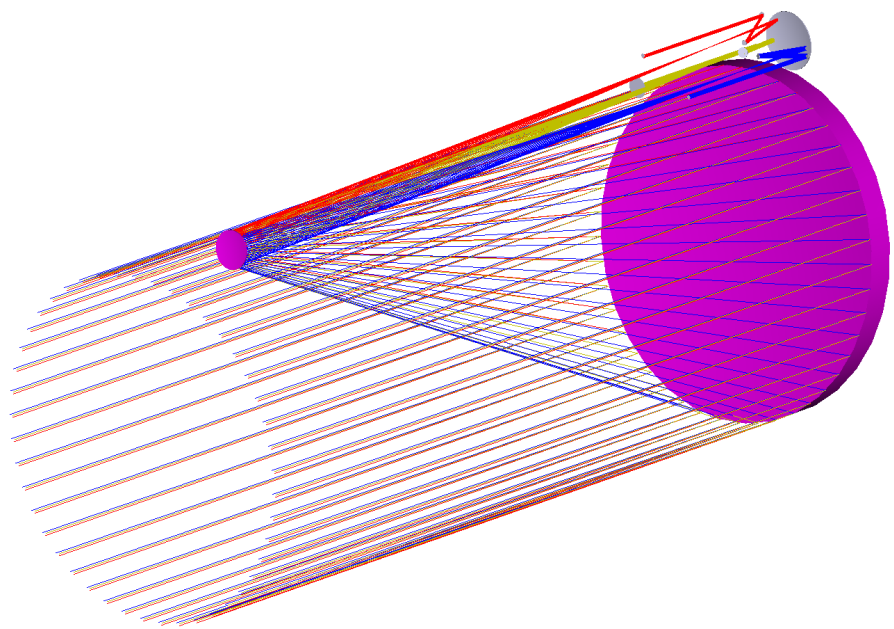


Habitable Exoplanet Imaging Mission (HabEx)

- 4-6.5 meter (possibly segmented) off-axis telescope
- High-contrast imaging with a starshade (studying the inclusion of a coronagraph as well)

Two Designs for Large Aperture Space Telescopes





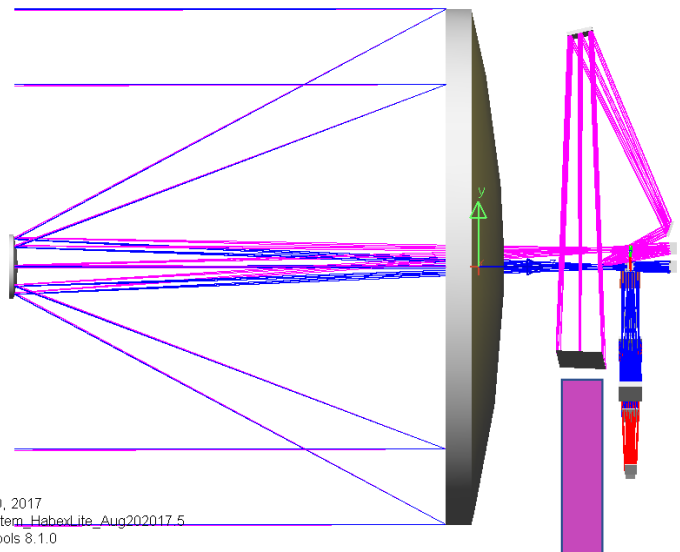
On-Axis Telescope

- Allows for larger primary mirror (greater area to collect more light)
- Secondary mirror and structural supports obscure the primary (as seen by science instruments)

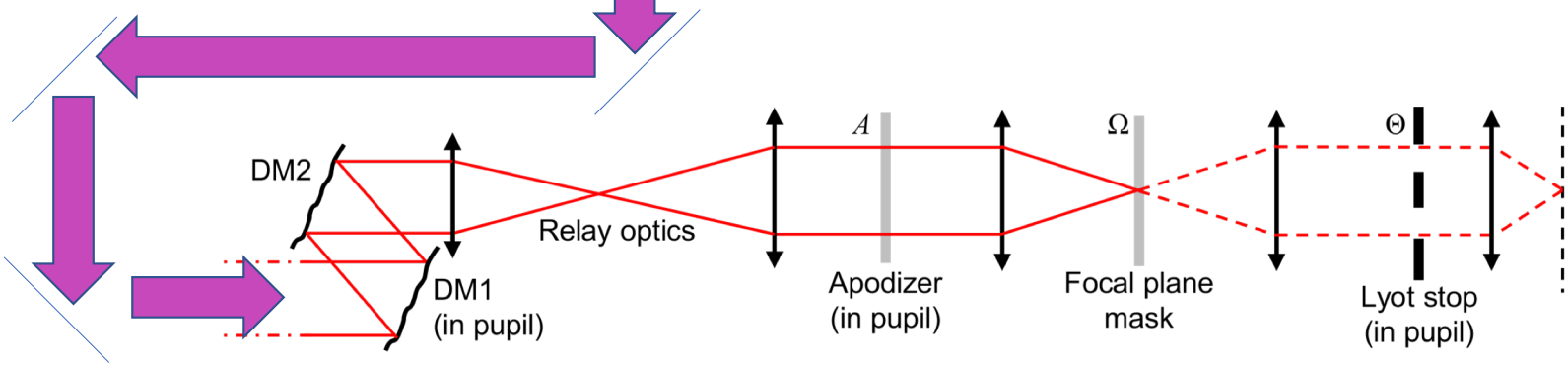
Off-Axis Telescope

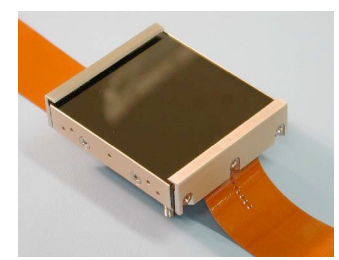
- Smaller primary mirror
- Secondary mirror and structural supports *do NOT* obscure the primary (as seen by science instruments)

A Photon's "Roller-Coaster Ride": From the Primary to Science Focal Plane

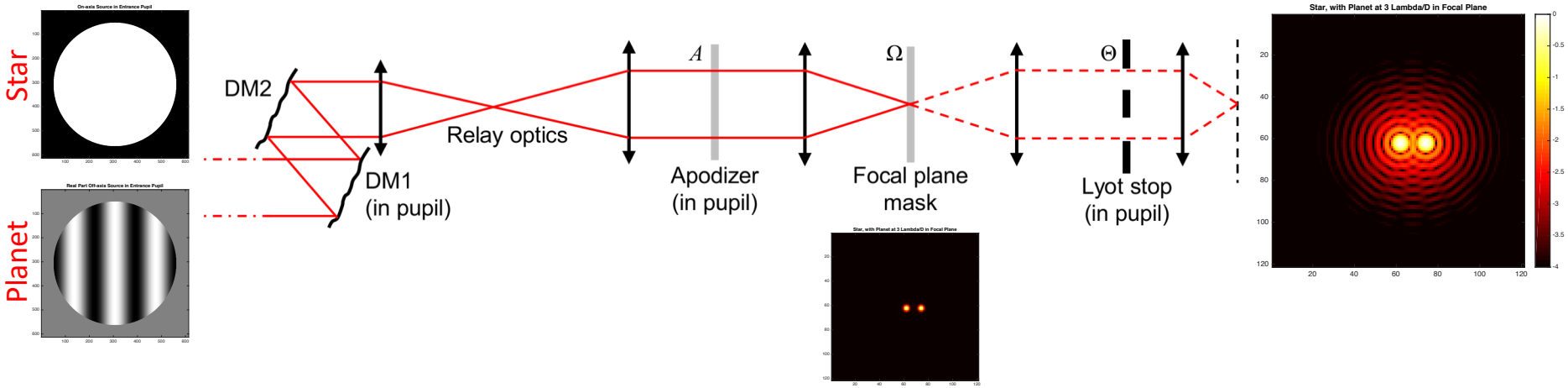


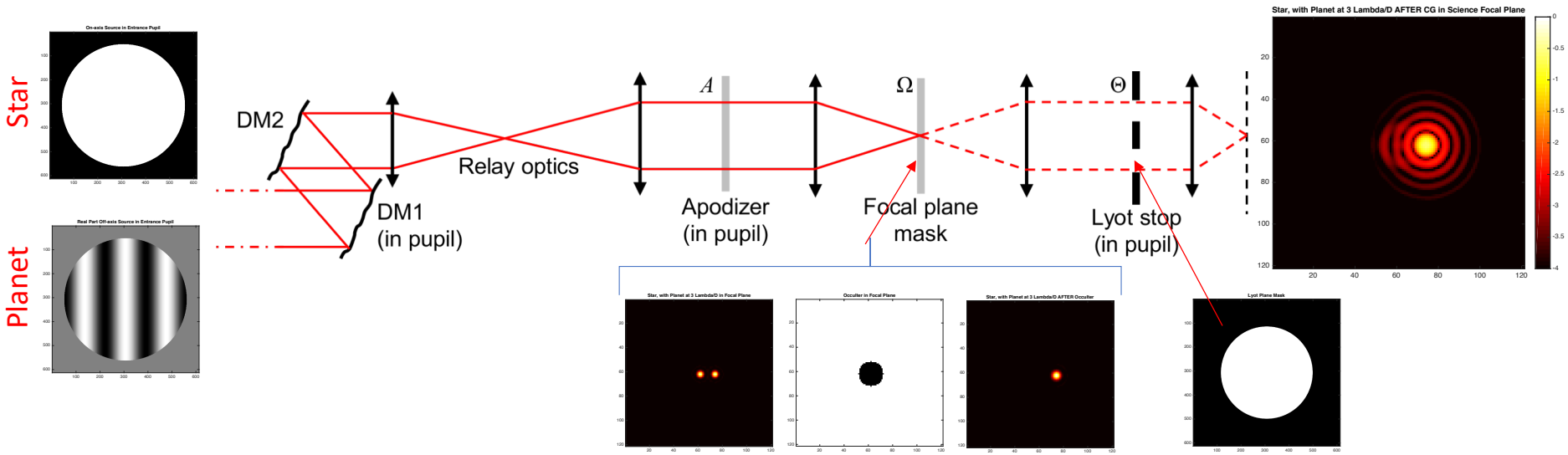
- Primary Mirror receives plane-parallel wavefront (star at "infinity")
- Curved surface of primary directs light to the secondary mirror
- Secondary reflects light back towards additional optics (flat mirrors, etc) to bring beams into various science instruments
- Our coronagraph entrance "sees" a re-imaged pupil plane conjugate to the telescope primary
- *Inside the coronagraph instrument, various optical elements work to suppress the starlight and let planet light through…*



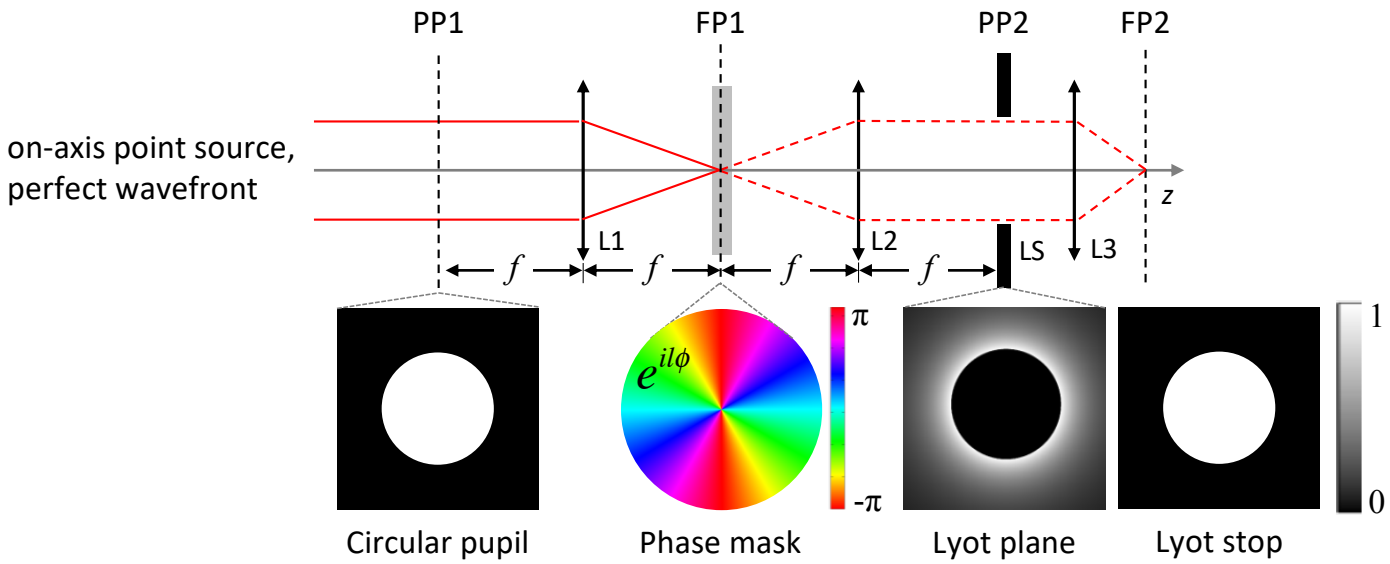


How Does a Coronagraph Suppress Starlight?





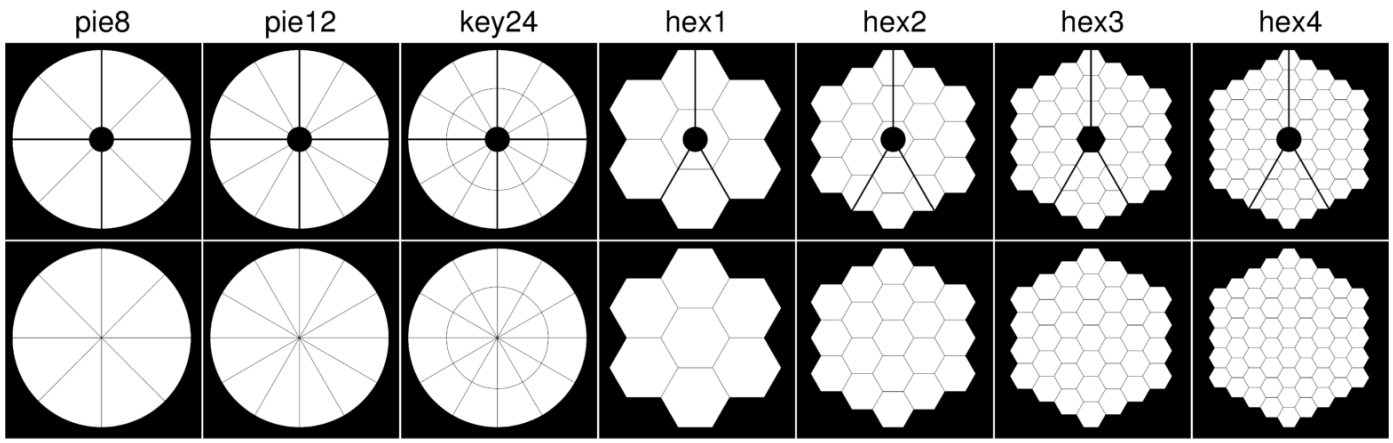
Vortex coronagraph for unobscured telescopes



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

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

Can we take advantage of these benefits on segmented apertures?

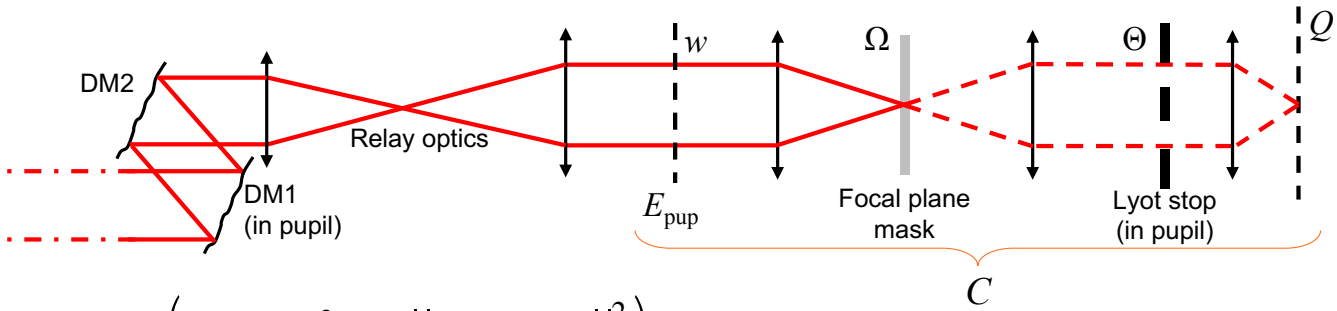


Example apertures used in the Segmented Coronagraph Design and Analysis (SCDA) study supported by the Exoplanet Exploration Program (ExEP)

- Siegler, N. and Shaklan, S., “Segmented Coronagraph Design and Analysis Task Description." Available at http://exep.jpl.nasa.gov/files/exep/SCDA_Summary.pdf (2016).

- Feinberg, L., Hull, T., and Knight, J., “Apertures for Segmented Coronagraph Design and Analysis.” Available at http://exep.jpl.nasa.gov/files/exep/SCDAApertureDocument0504161.pdf (2016)

Coronagraph Design Optimization: Beam Shaping and/or Apodization



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

Algorithm:

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

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

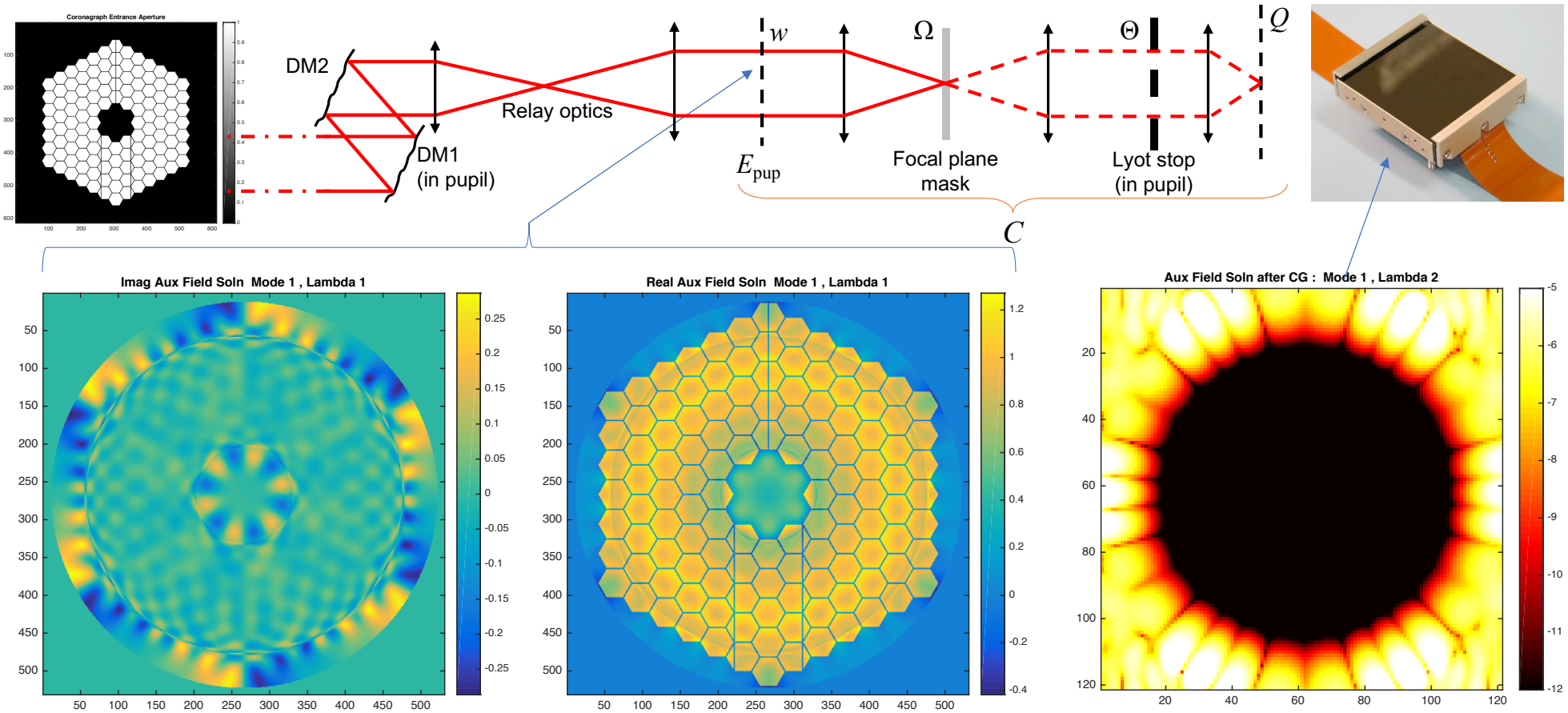
2. Determine the DM surfaces and/or apodization that achieve the best match between true E_{pup} and the target ideal field w.

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

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

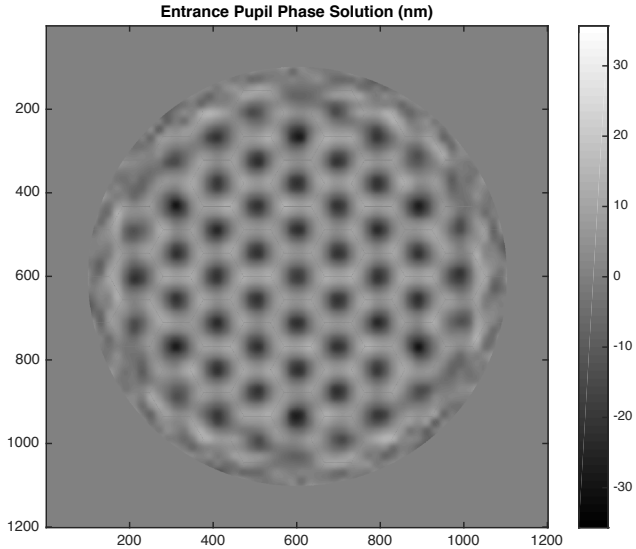
Detailed formulation of the algorithm:
J. Jewell et al, Proc. SPIE 10400, 10400H (2017).

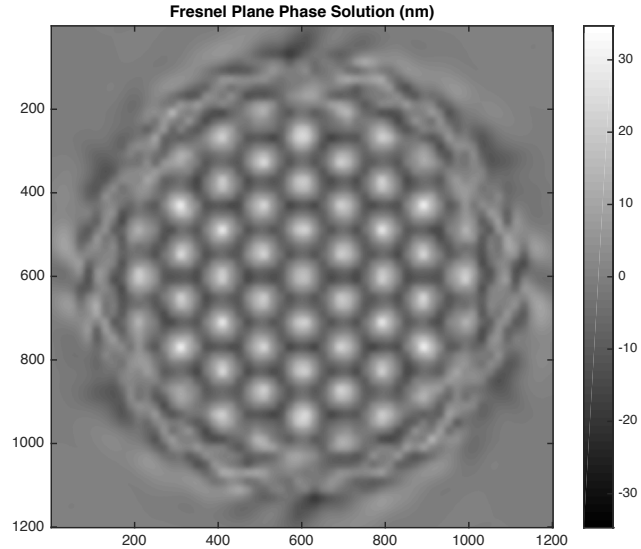
Example Target Conjugate Plane Electric Field: LUVOIR Aperture with a Charge 6 Vortex Focal Plane Mask

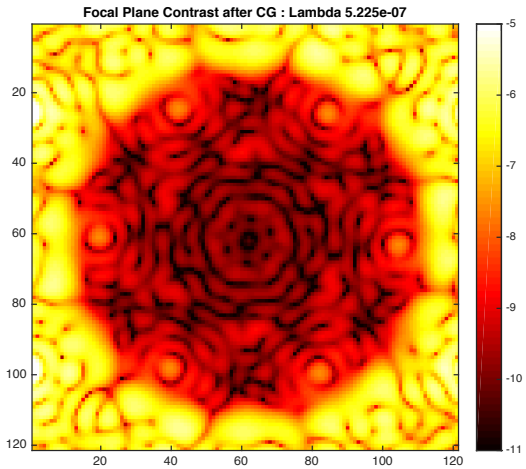


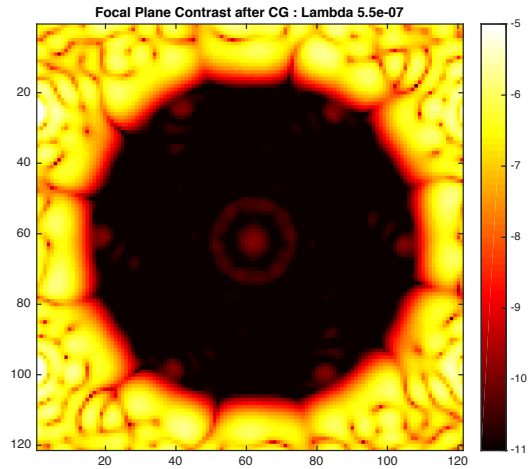
The target (conjugate plane) E-field for the on-axis source has $\lim_{b\to 0}\|QCW\|^2 = 0$ *energy where planets live!*

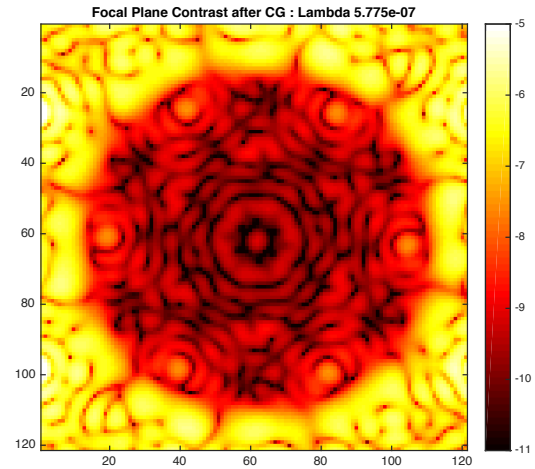
SCDA Hex Unobscured Aperture – DM Solutions





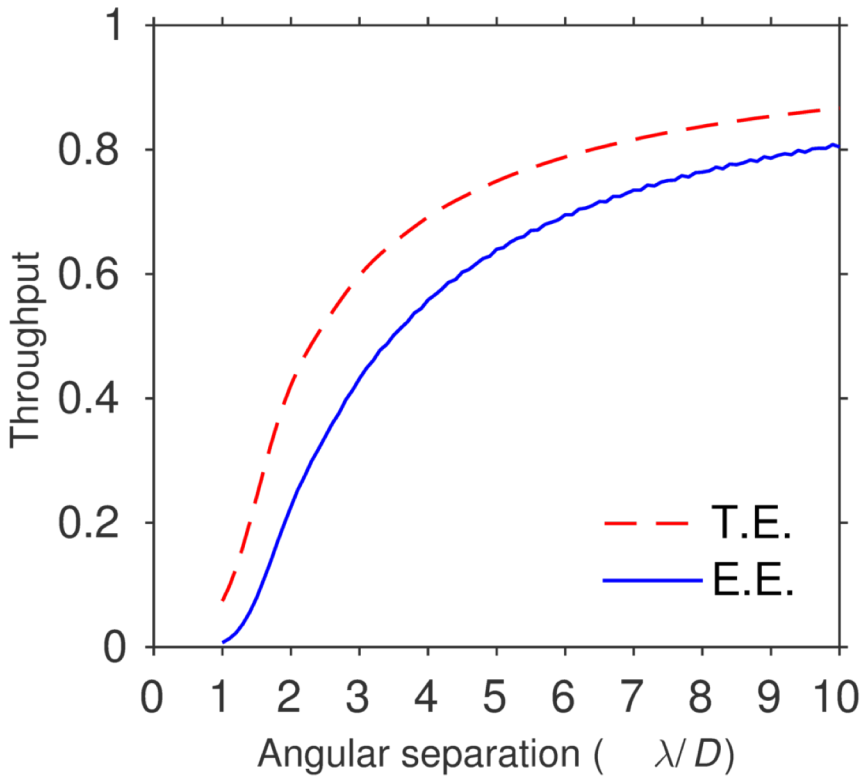


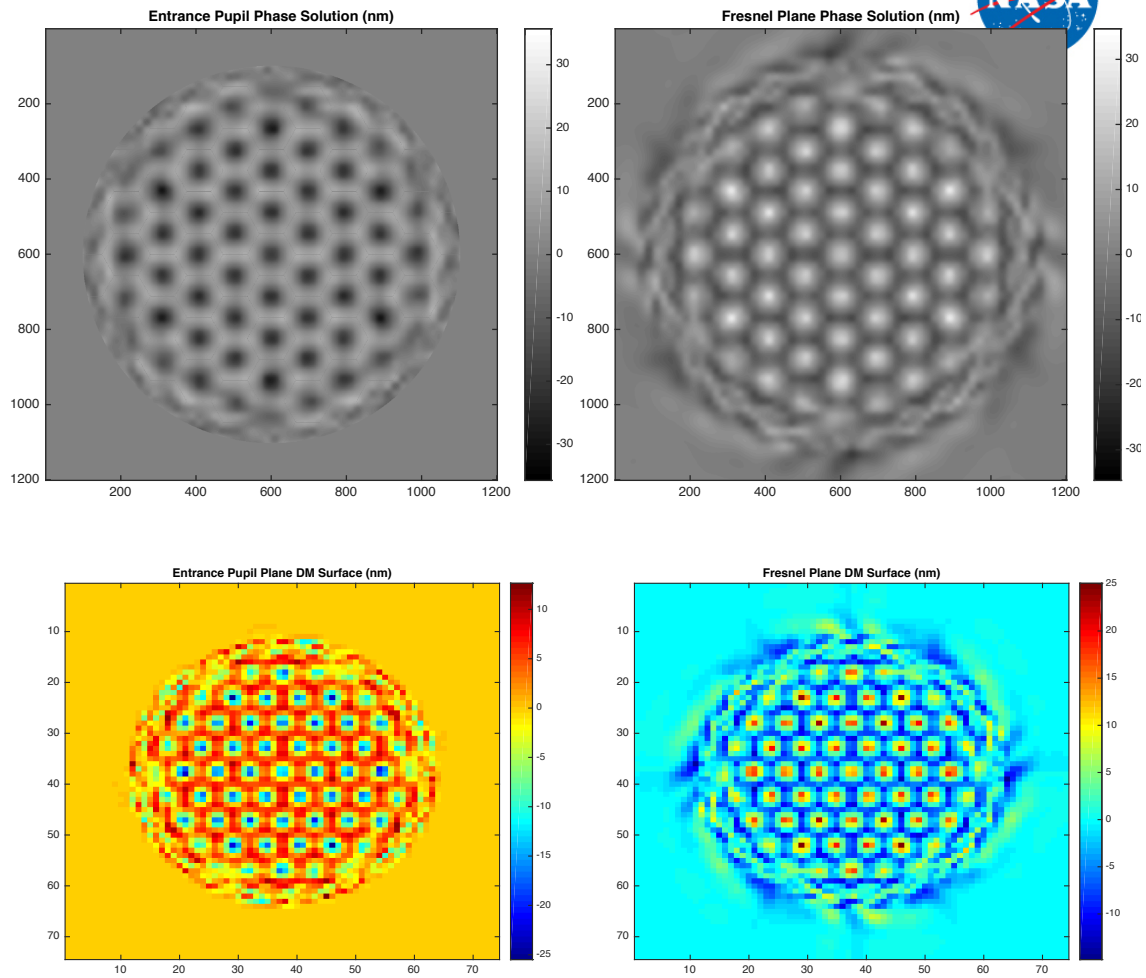




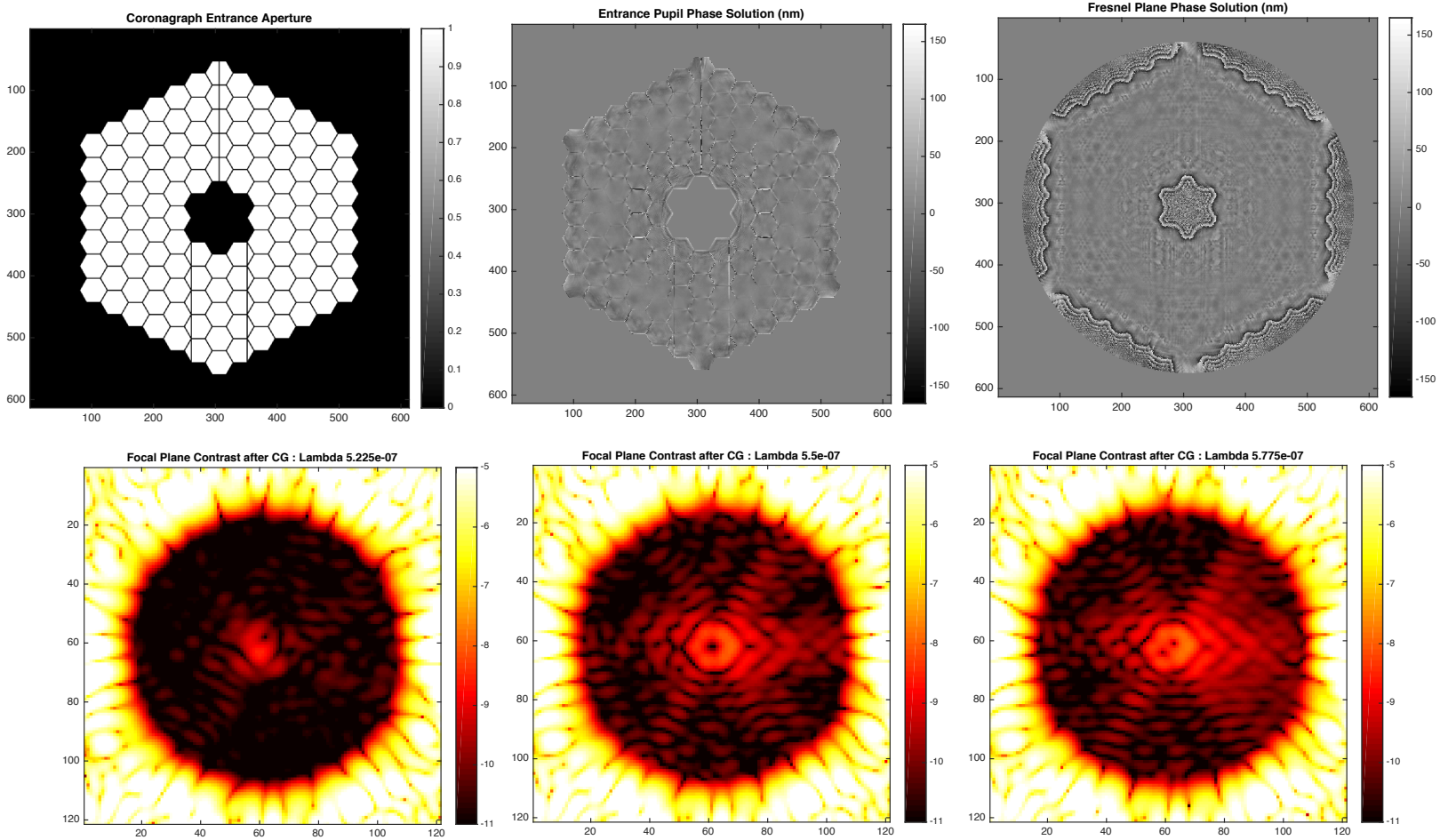
SCDA Hex Unobscured Aperture – DM Solutions

- Charge 6 vortex in focal plane, circular Lyot stop (outer radius 0.99 of entrance pupil)
- 10% Band (550 nm center wavelength)
- 74 x 74 DM array (actuator pitch 400e-6 meters)
- *Solution achieves 2.8e-10 broadband contrast*

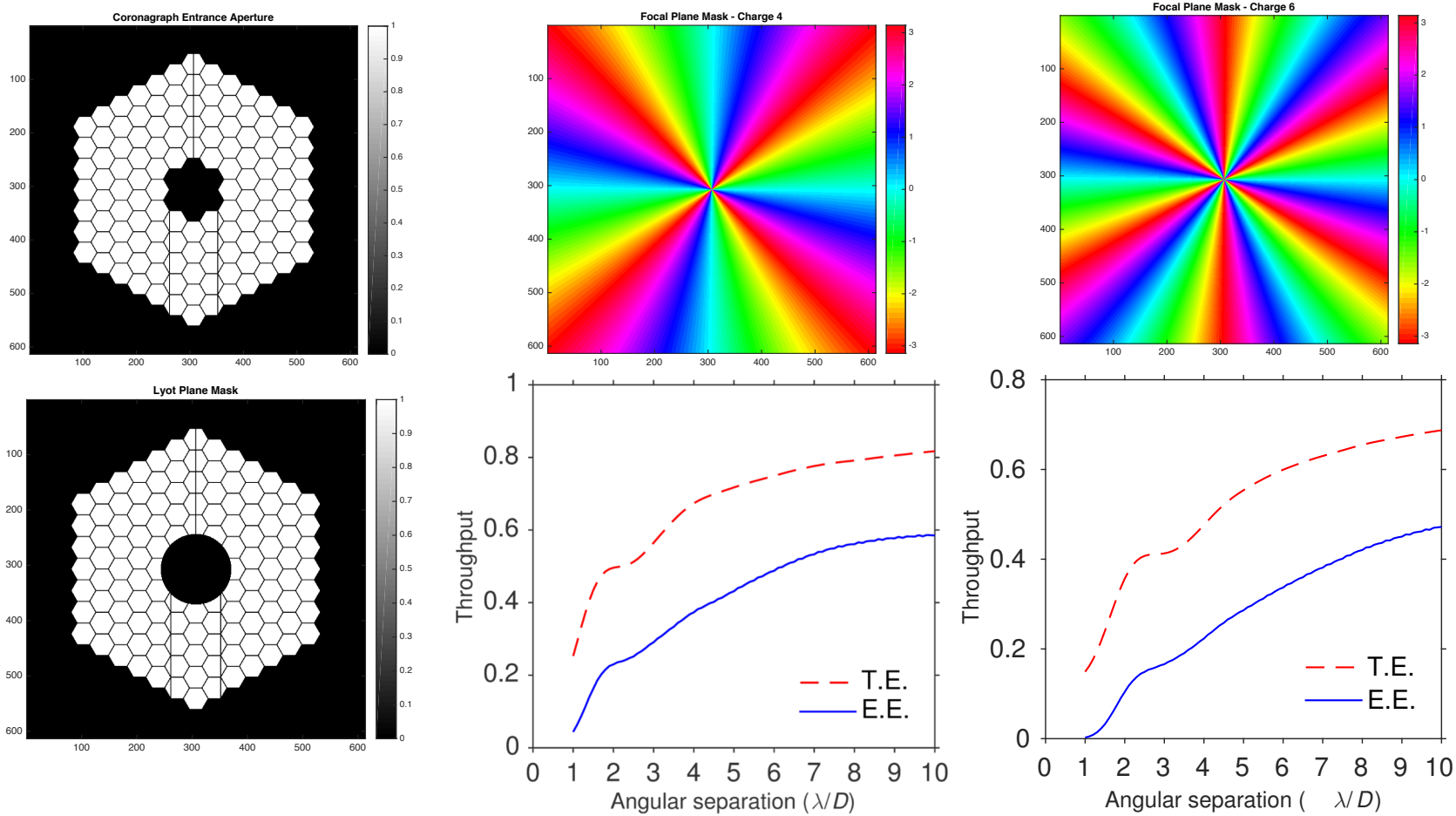




Application to the LUVOIR 'A' Architecture – Charge 6 Vortex with (Pixel) DM1 and DM2 Phase, 10% Band (550 nm) Science Focal Plane Dark Holes



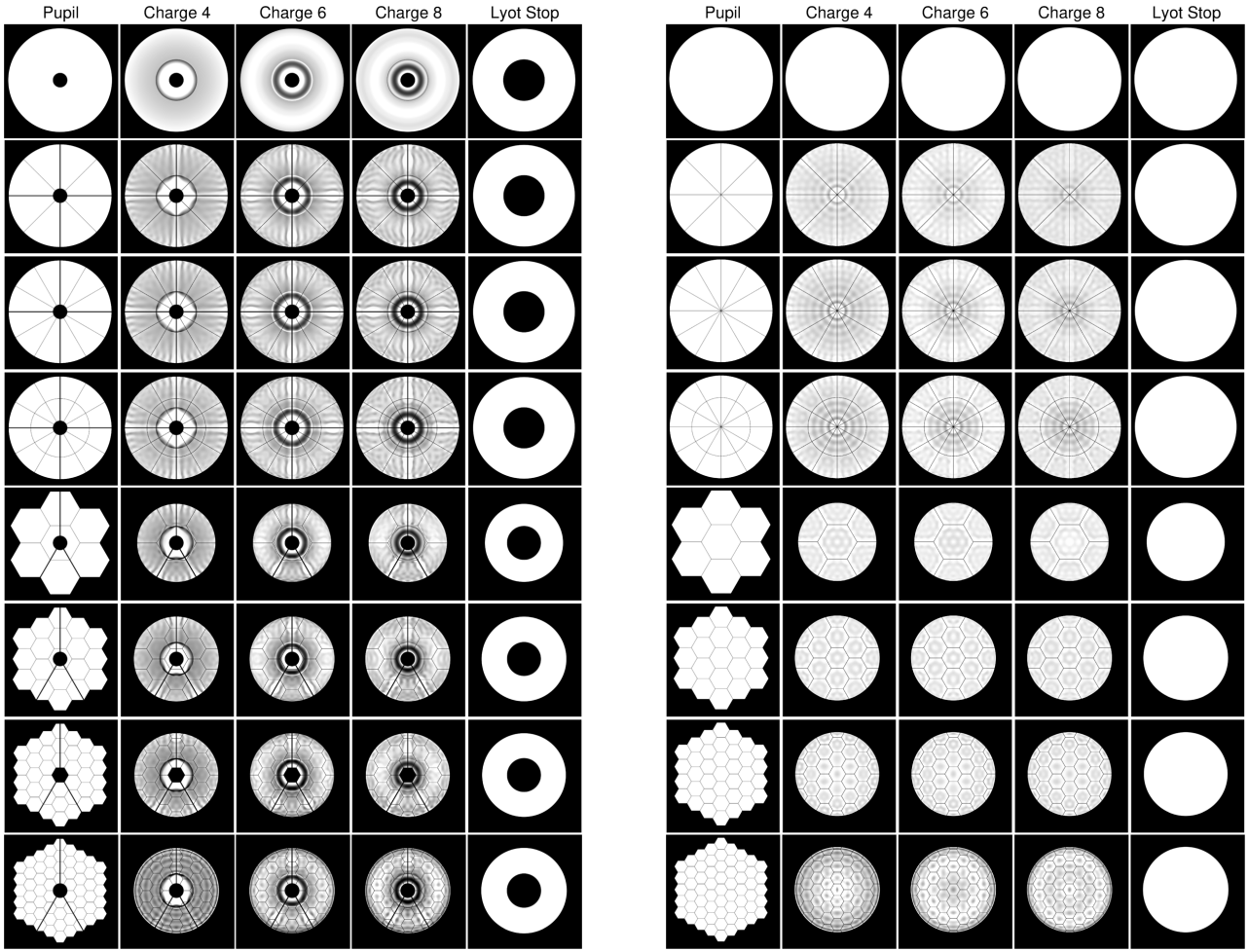
LUVOIR Aperture – Vortex Charge 4 and 6 Throughput Comparisons



These solutions are optimized for a point source and will not work with a finite stellar disc!!

Work in progress – generalization of AFO for robustness…

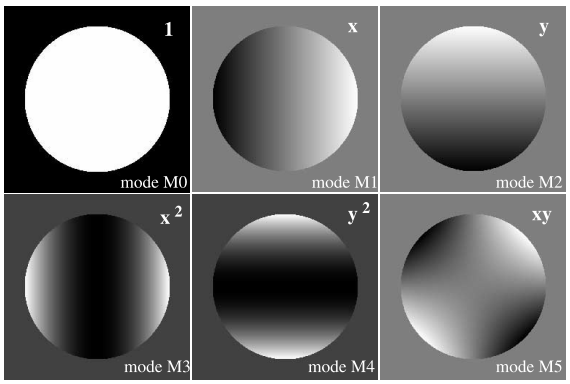
A family portrait of apodizer designs



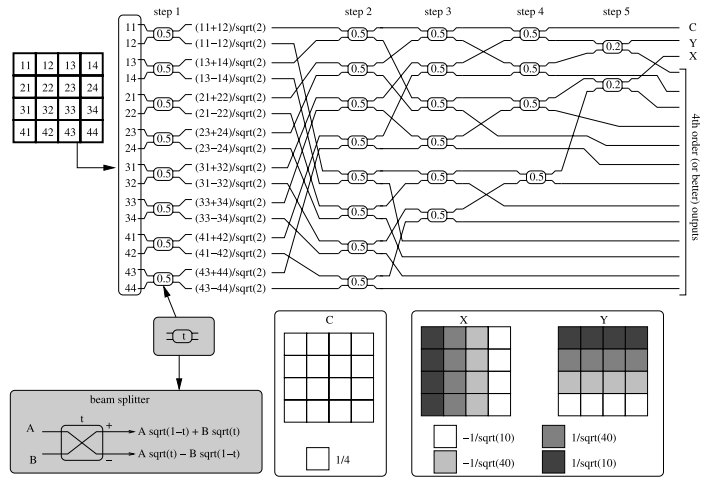
Ruane, G., Jewell, J., Mawet, D., Pueyo, L., and Shaklan, S., Proc. SPIE 9912, 9912L (2016)

Can We Improve Coronagraph Design for Segmented Apertures?

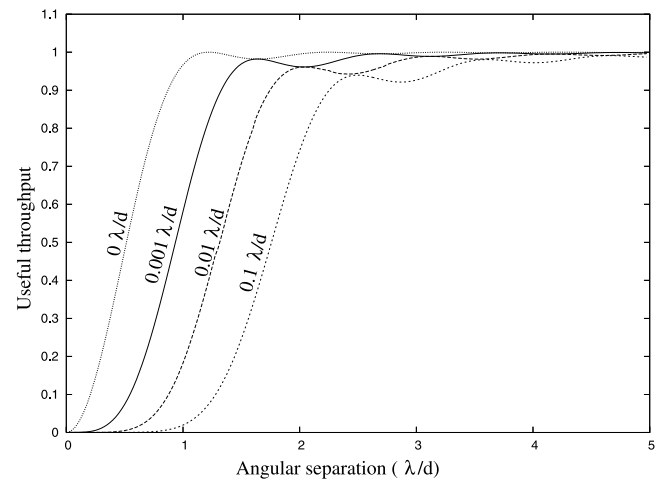
Credit: O. Guyon, *"Theoretical Limits on Extrasolar Terrestrial Planet Detection with Coronagraphs"*, ApJS, **167,** Nov. 2006



Orthogonal Stellar Disc Modes



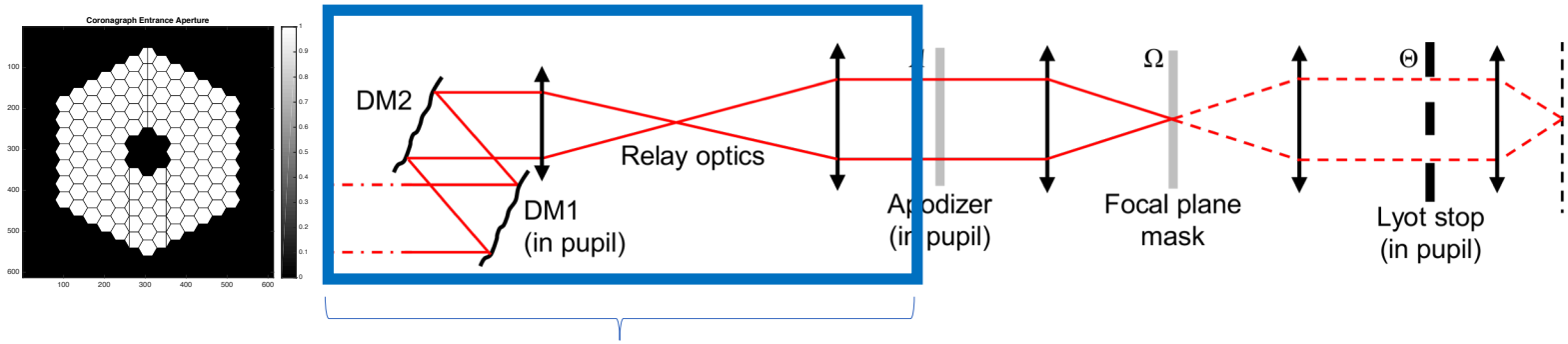
Beam Splitter Concept for Ideal Coronagraphy (perfect suppression for square aperture shown…)



Throughput for ideal coronagraph: perfect stellar disc suppression!!

$$C_{\text{Ideal}} = I - \sum_{\text{S.D. Modes } k} |X_k\rangle\langle X_k|$$

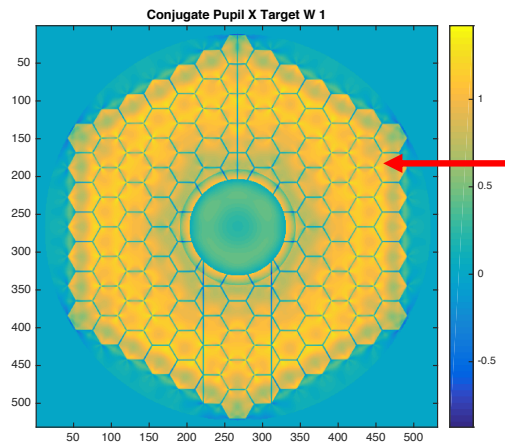
Ideal Coronagraphs for Centrally-Obscured Segmented Apertures

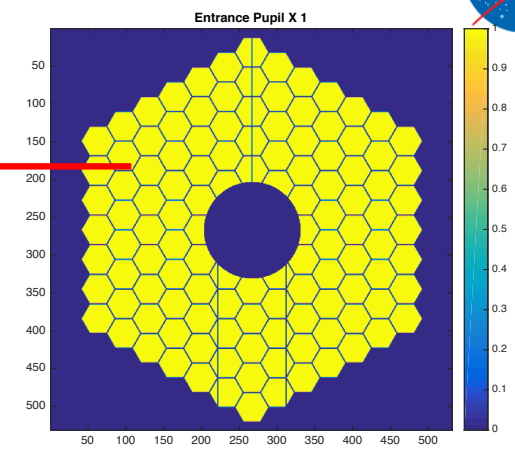


Replace with "Ideal Unitary Operator"

- Generalize Guyon et al, 2006 "Theoretical Ideal Coronagraphs" to explore simulation of a coronagraph built with standard focal plane mask and Lyot stop, but "ideal" block box unitary operator (instead of DM's)
- Why?
  - Guide to technology development
  - Allows "best case" sensitivity analysis, and can generalize to add robustness
  - Can compare DM or Apodization components with "upstream" theoretical ideal performance (for fixed downstream coronagraph focal and Lyot plane masks)

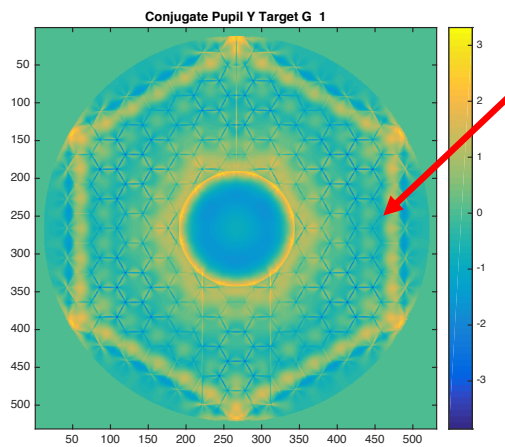
Mode Decomposition and Unitary Operator for On-Axis Source

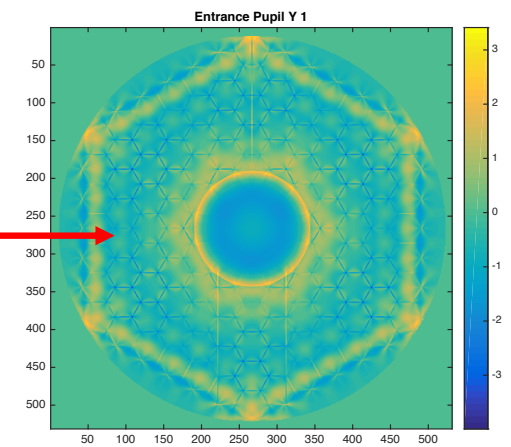




$$\xi_j|W_j\rangle \equiv \left(I - \sum_k |g_k\rangle\langle g_k|\right)|X_j\rangle$$

$$\omega_j|G_j\rangle \equiv \left(\sum_k |g_k\rangle\langle g_k|X_j\rangle\right)$$





$$|\hat{Y}_j\rangle = \xi_j^*|G_j\rangle - \omega_j^*|W_j\rangle$$

$$U_1 = |W_1\rangle\langle\hat{X}_1| \oplus |G_1\rangle\langle\hat{Y}_1| \oplus (I - |W_1\rangle\langle W_1| - |G_1\rangle\langle G_1|)$$

Unitary Operator for K Modes to be Suppressed

$$U_1 = |W_1\rangle\langle\hat{X}_1| \oplus |G_1\rangle\langle\hat{Y}_1| \oplus (I - |W_1\rangle\langle W_1| - |G_1\rangle\langle G_1|)$$

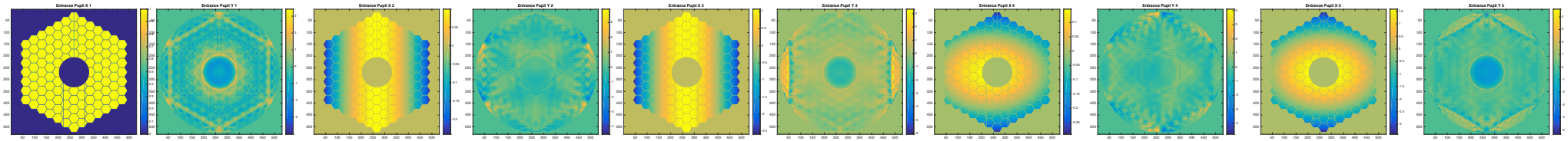
$$\begin{aligned} U_1|X_1\rangle &= \beta_1|W_1\rangle \\ U_1|X_2\rangle &= |G_1\rangle\langle Y_1|X_2\rangle \oplus (|X_2\rangle - |W_1\rangle\langle W_1|X_2\rangle - |G_1\rangle\langle G_1|X_2\rangle) \\ &= \alpha_2|G_2\rangle + \beta_2|W_2\rangle \end{aligned}$$

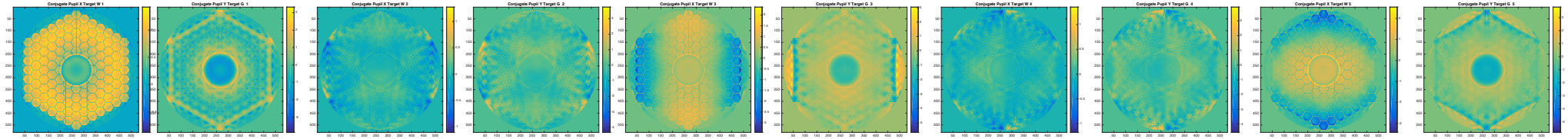
$$U_2 = |W_2\rangle\langle\hat{X}_{12}| \oplus |G_2\rangle\langle\hat{Y}_{12}| \oplus (I - |W_2\rangle\langle W_2| - |G_2\rangle\langle G_2|)$$

$$\boxed{\text{Unitary Operator for } K \text{ Suppressed Modes} = \prod_{1:K} U_k}$$

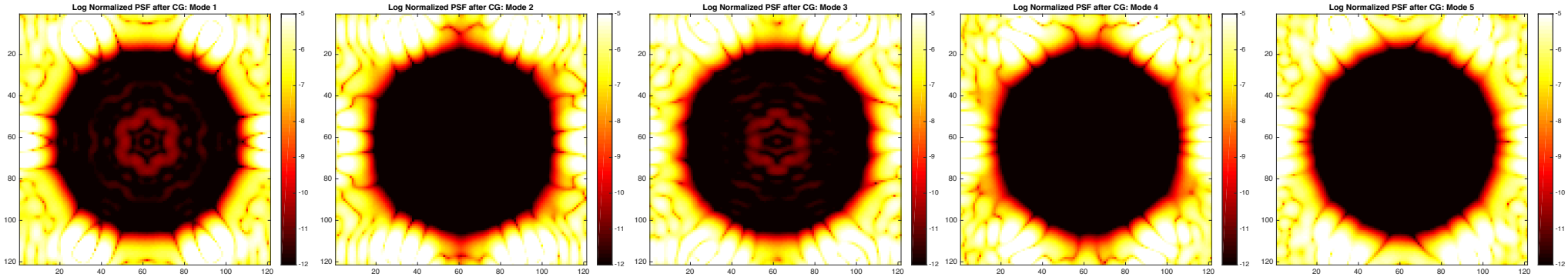
Unitary Operator: Entrance to Conjugate Pupil Plane “Input/Output” Eigenmode Decomposition

X1 Y1 X2 Y2 X3 Y3 X4 Y4 X5 Y5

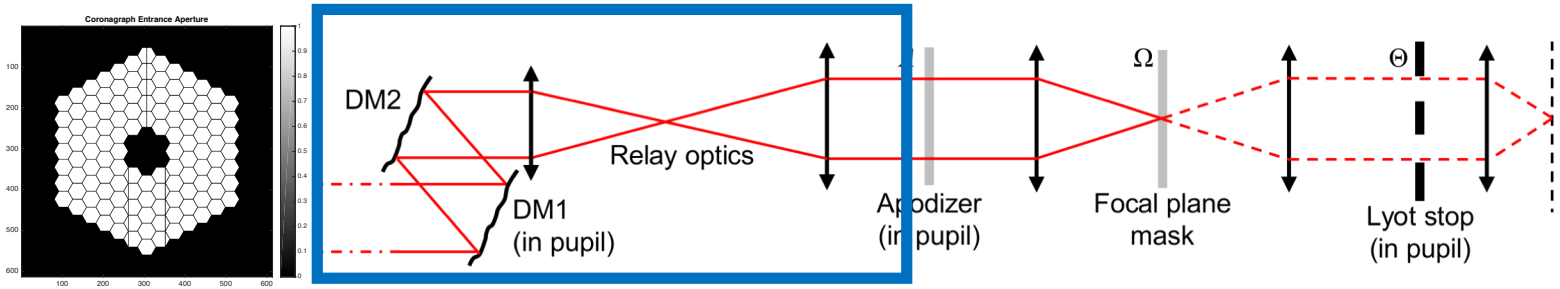


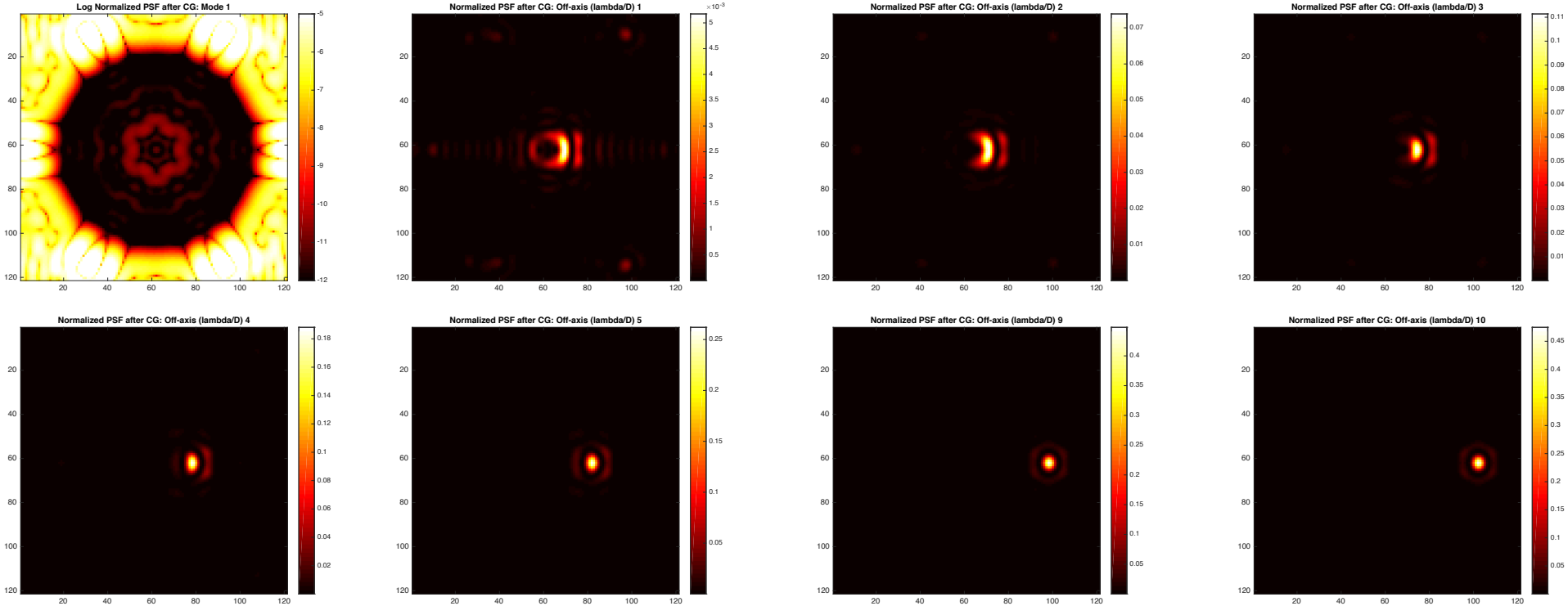


W1 G1 W2 G2 W3 G3 W4 G4 W5 G5

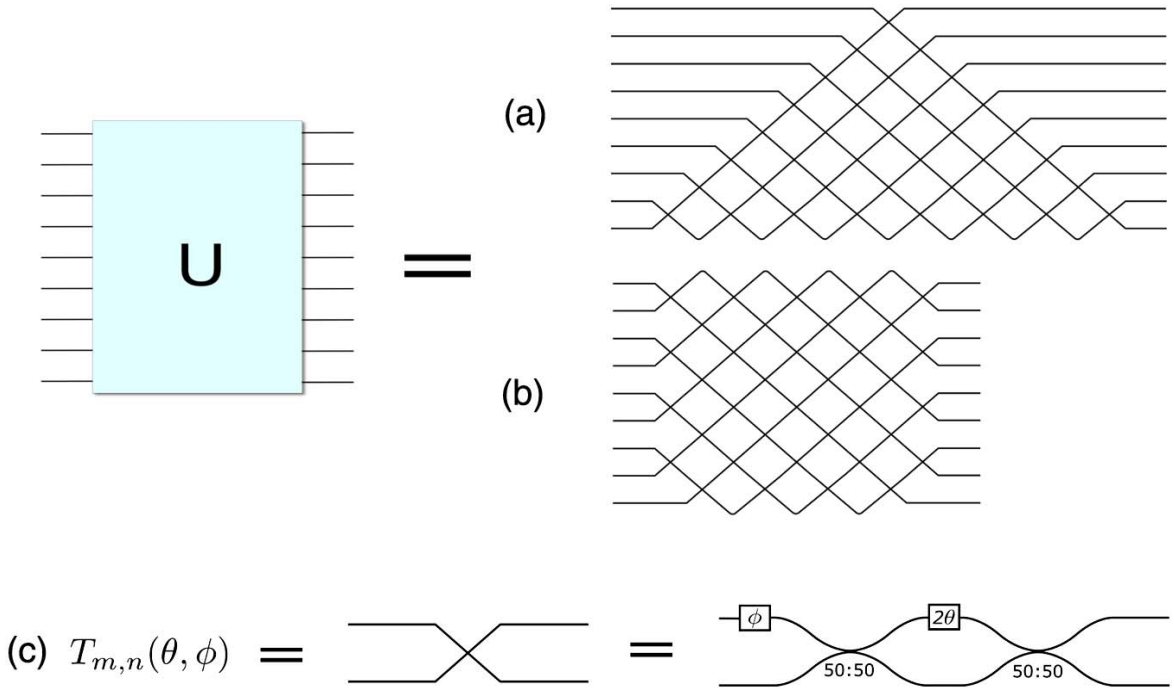


Ideal Coronagraph: LUVOIR ‘A’ Aperture, Null Stellar Disc



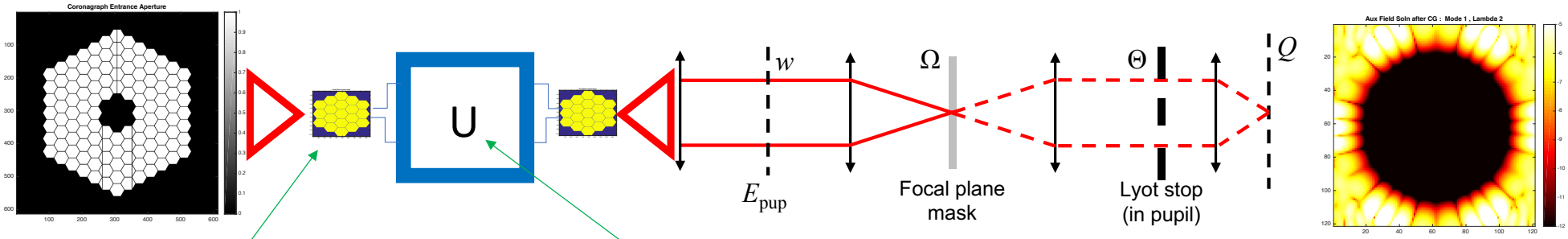


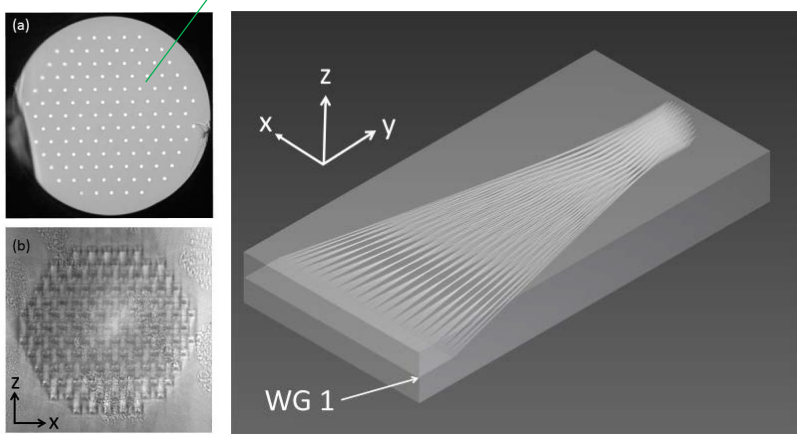
How Can We Implement General Optical Unitary Operators?

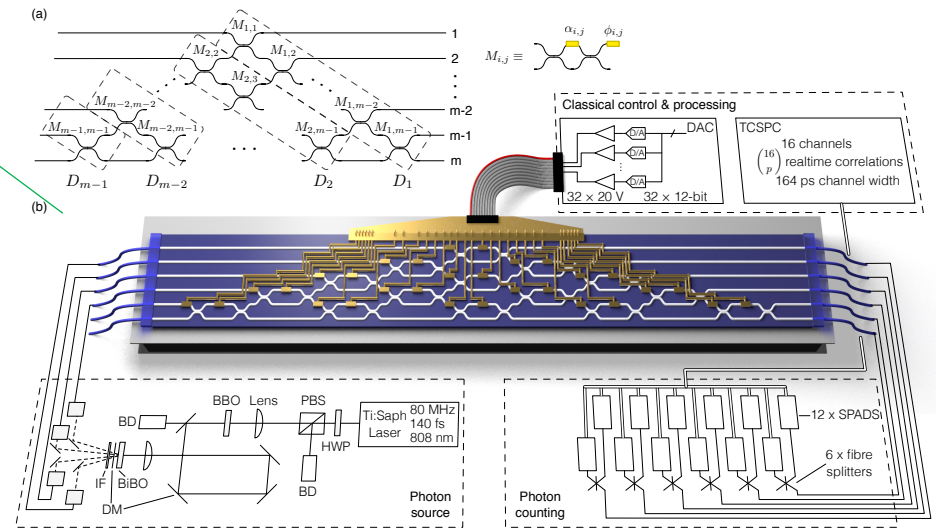


- (Figure: W. Clements et al, *"Optimal Design for Universal Linear Multiport Interferometers"*, Optica, **3**, 2016)
- ***Any NxN unitary operator can be implemented with N(N-1)/2 2x2 operators, each with 2 Mach-Zehnder (50:50) beam splitters and phase shifters!*** (Reck et al, "Experimental Realization of Any Discrete Unitary Operator", Physical Review Letters, **73**(1), 1994).

Hardware Implmentation: Photonic Lantern SMF Out, Into Optical Chip



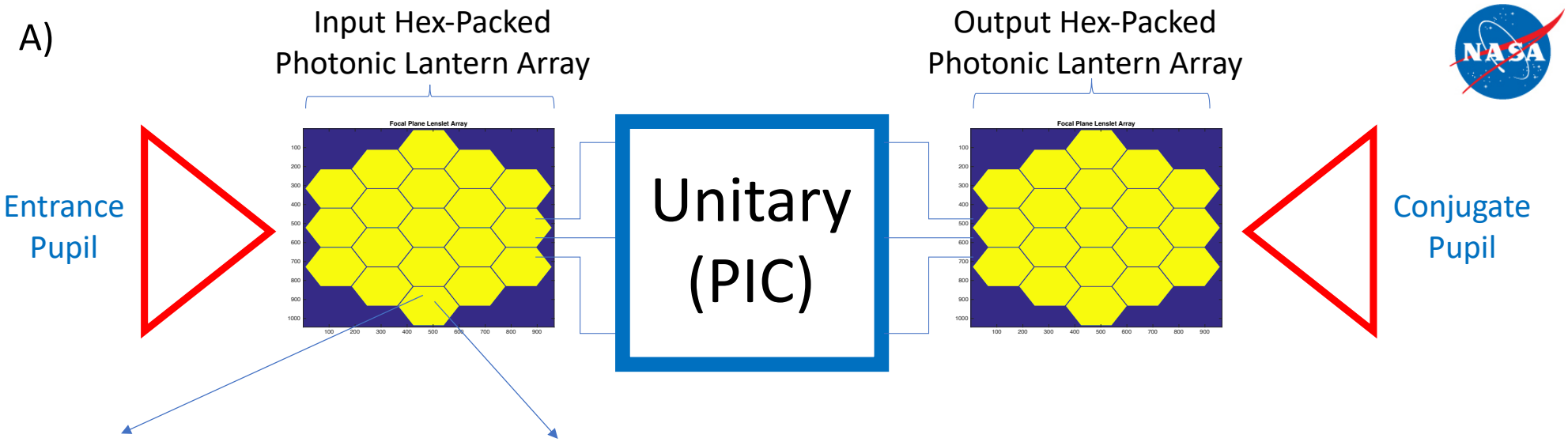




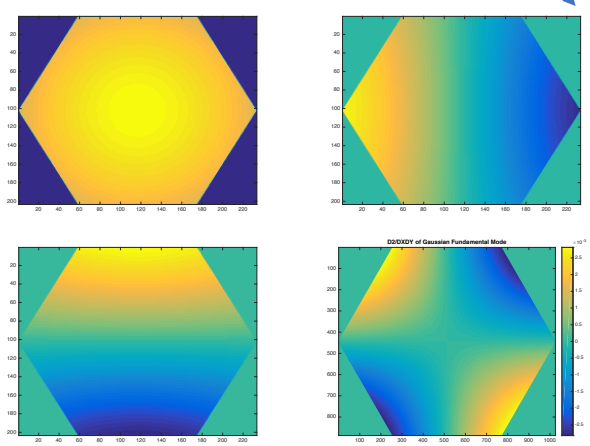
121 MCF to Fan-Out Device (3D Laser Inscription):
Ref. R. Thomson, Proc SPIE, 977400, 13 Feb. 2016

Ref. J. Carolan et al, “Universal Linear Optics”, Science, **349**, 2015.

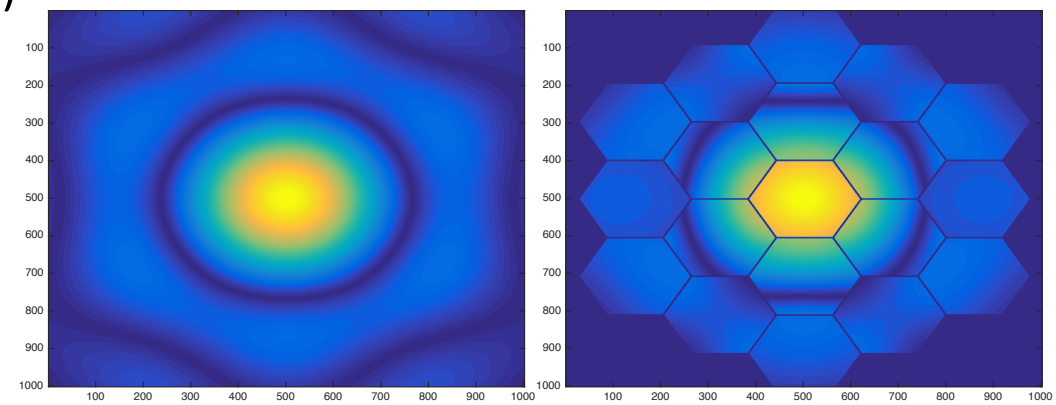
A)



B)

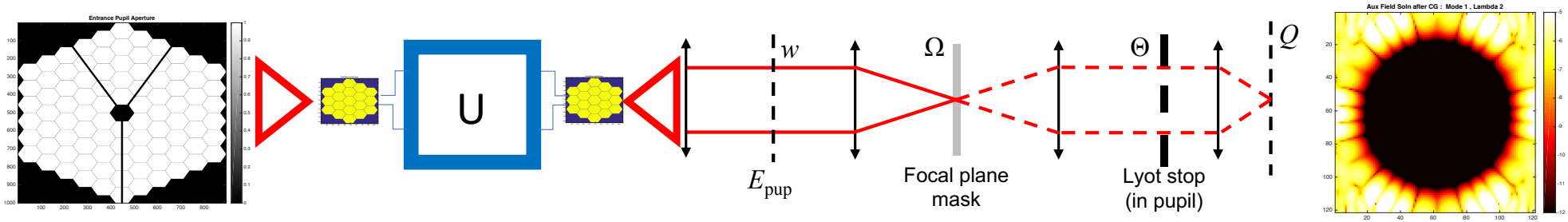


C)

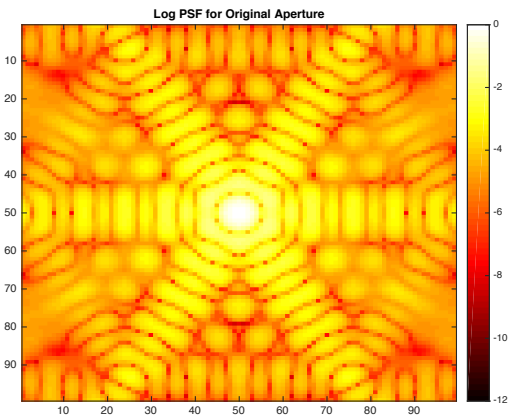


Photonic Lantern Gauss-Hermite Modes

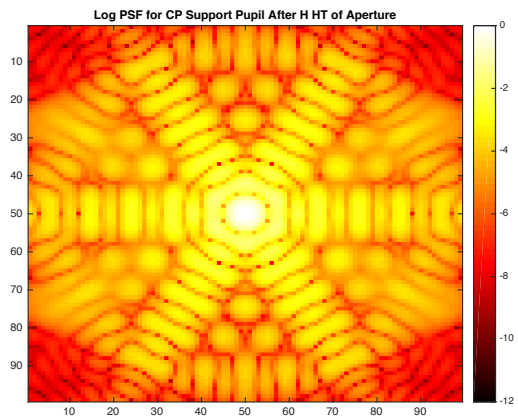
”Nearly Lossless” Compression of Modes : Entrance Pupil to Focal Plane

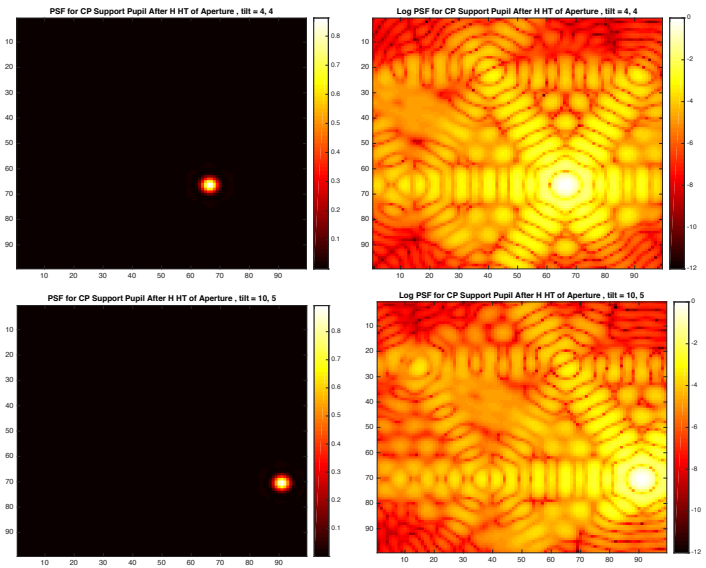


Log PSF of FFT Aperture



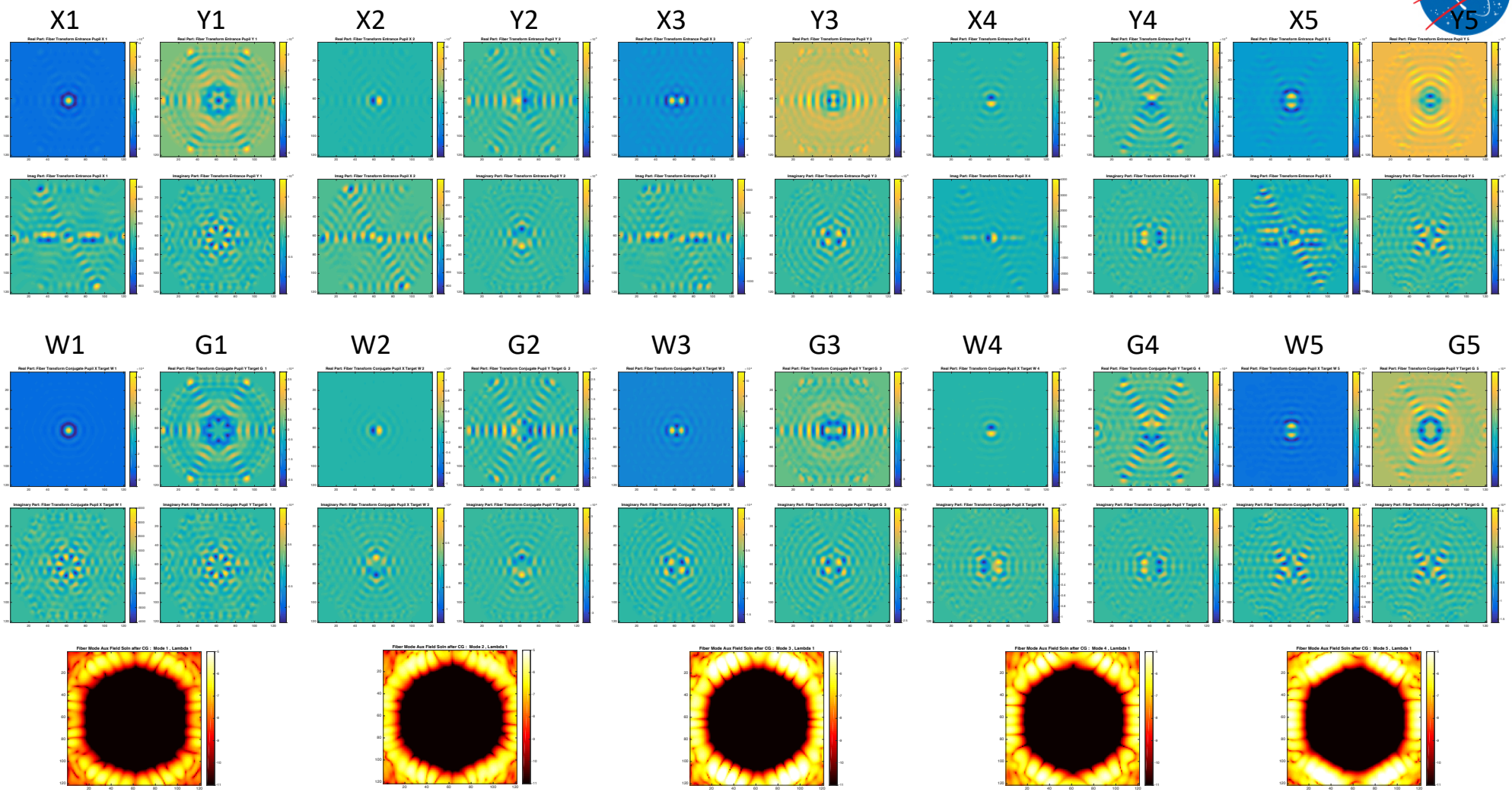
Log PSF After Lantern Array



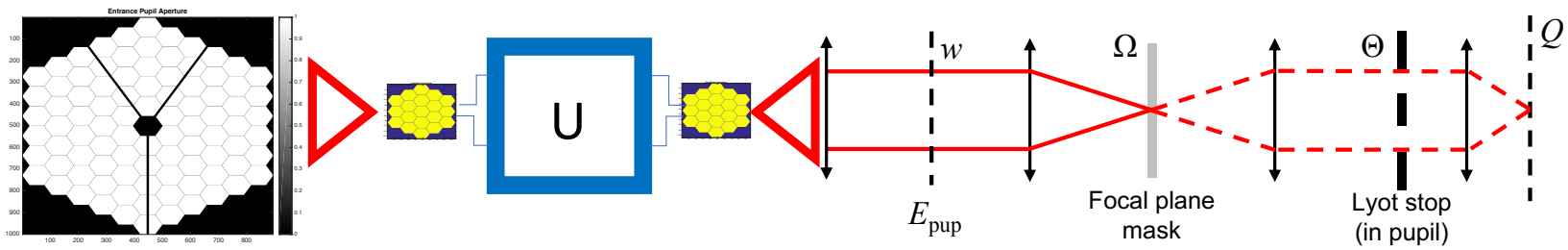


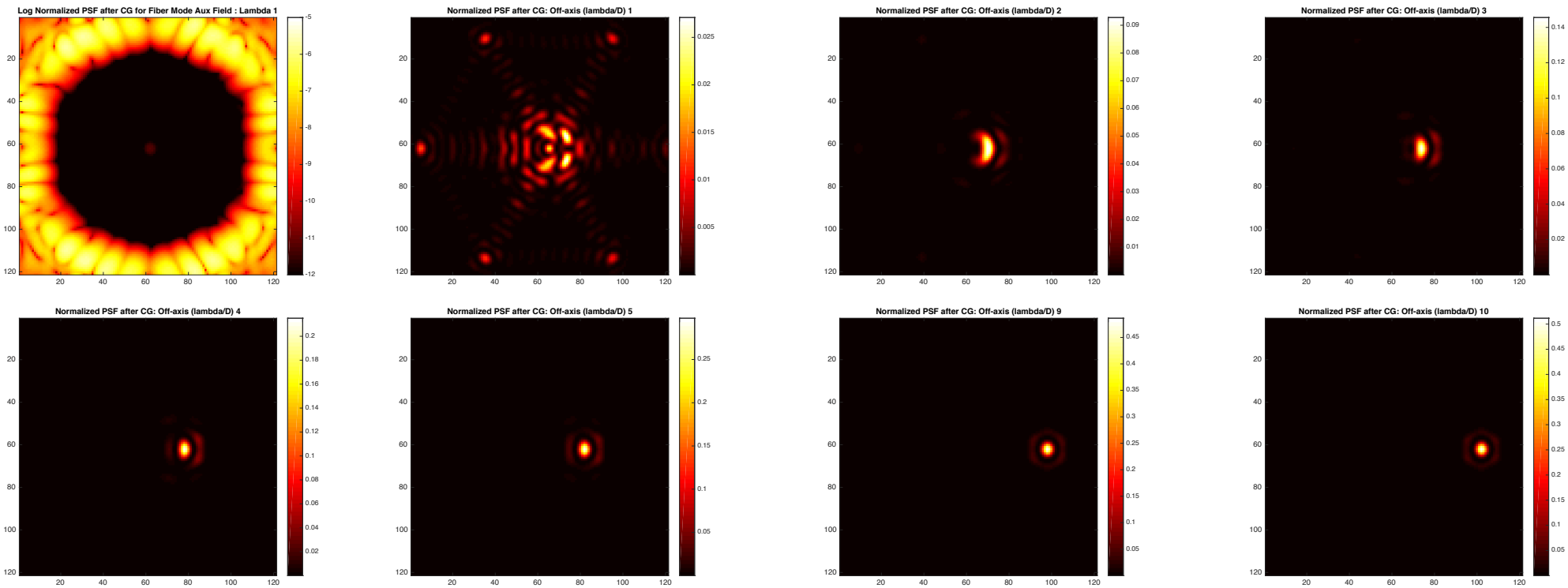
- Comparison of PSF of aperture and after the Lantern array, with the PIC set to the “Identity”.
- PSF core’s out to the design OWA retained with 90% of the light (can be increased with more lantern modes)

Unitary Operator: Lantern ”Coefficient Basis” Eigenmode Decomposition

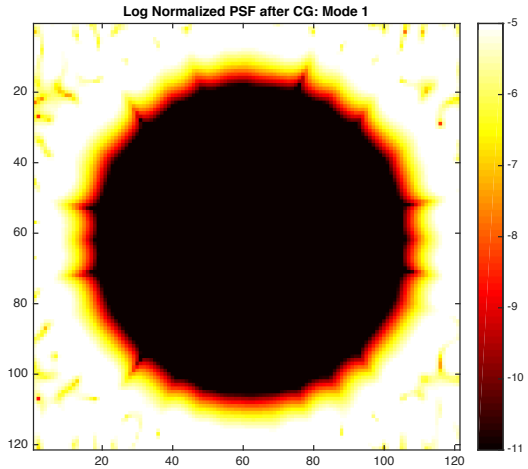


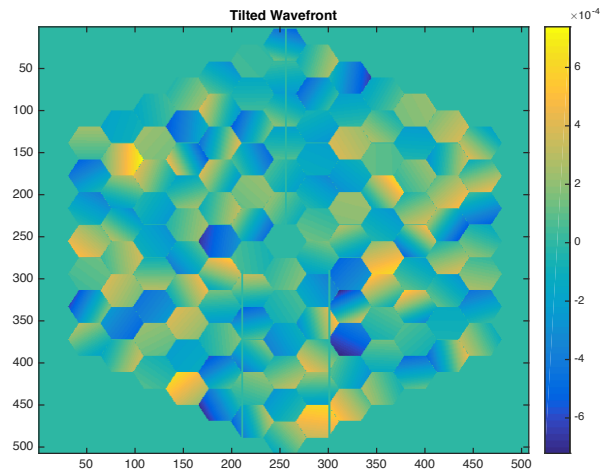
”Nearly Lossless” Compression of Modes : Entrance Pupil to Focal Plane

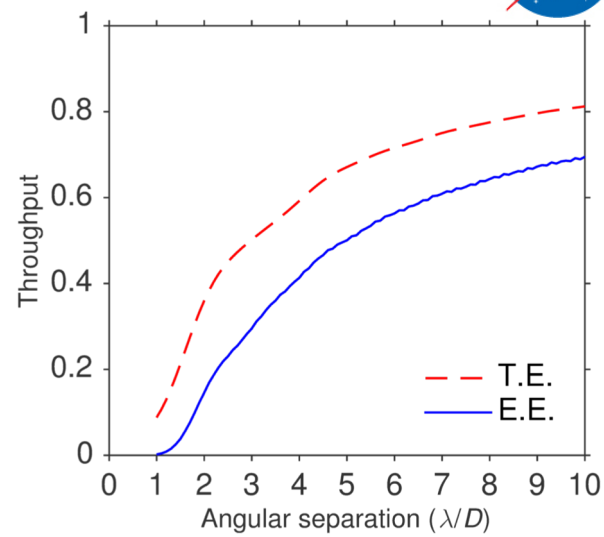


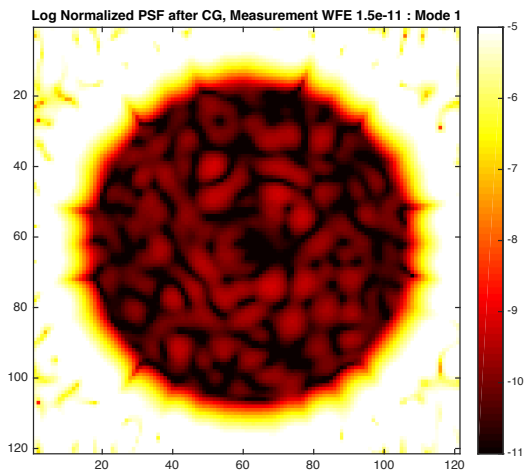


Segment RB Sensitivity: 10 nm Segment RB, 15 pm WFS Measurement Error









- Upper Left – Stellar Disc Modes Completely Suppressed for RB segment errors IF perfectly measured
- Center – 15 pm (per segment RB d.o.f) WFS measurement error
- Bottom Left – Contrast degradation (< 1.0e-10)
- Upper Right – Throughput

Summary

- "Auxiliary Field Optimization" (AFO) algorithm for coronagraph design for segmented aperture space telescopes, with applications to LUVOIR and HabEx
  - Algorithm Details:
    J. Jewell, G. Ruane, S. Shaklan, D. Mawet, D. Redding, Proc. SPIE, 10400, 10400H, 2017.
  - Apodization solutions (Segmented Coronagraph Design & Analysis catalog):
    G. Ruane, J. Jewell, D. Mawet, L. Pueyo, S. Shaklan, Proc. SPIE, 9912, 9912L, 2016.
  - Apodization solutions with detailed performance and sensitivity analysis:
    G. Ruane, D. Mawet, J. Jewell, S. Shaklan, Proc. SPIE, 10400, 10400J, 2017.
    G. Ruane, D. Mawet, B. Mennesson, J. Jewell, S. Shaklan, arXiv:1803.03909(accepted for publication, JATIS, 2018)
- General "null space" suppression (i.e. finite stellar disc)
  - *Unsolved Problem* (for central obscuration apertures) - achieving "ideal coronagraph" throughput limits with broadband suppression of stellar disc modes
  - *New Result* - Analytic unitary operators for any aperture and downstream coronagraph
  - *New Path for Technology Development* - explore advances in photonics and Photonic Integrated Chip technology for high-contrast imaging
- *What will state-of-the-art segmented aperture telescope and high-contrast imaging instrument designs look like after the next 10 years of development??*

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