New Concepts in Wavefront Sensing for High-Contrast Imaging

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NASA Exoplanet Exploration Program / JPL:

Workshop on Advanced Wavefront Sensing for Coronagraphs

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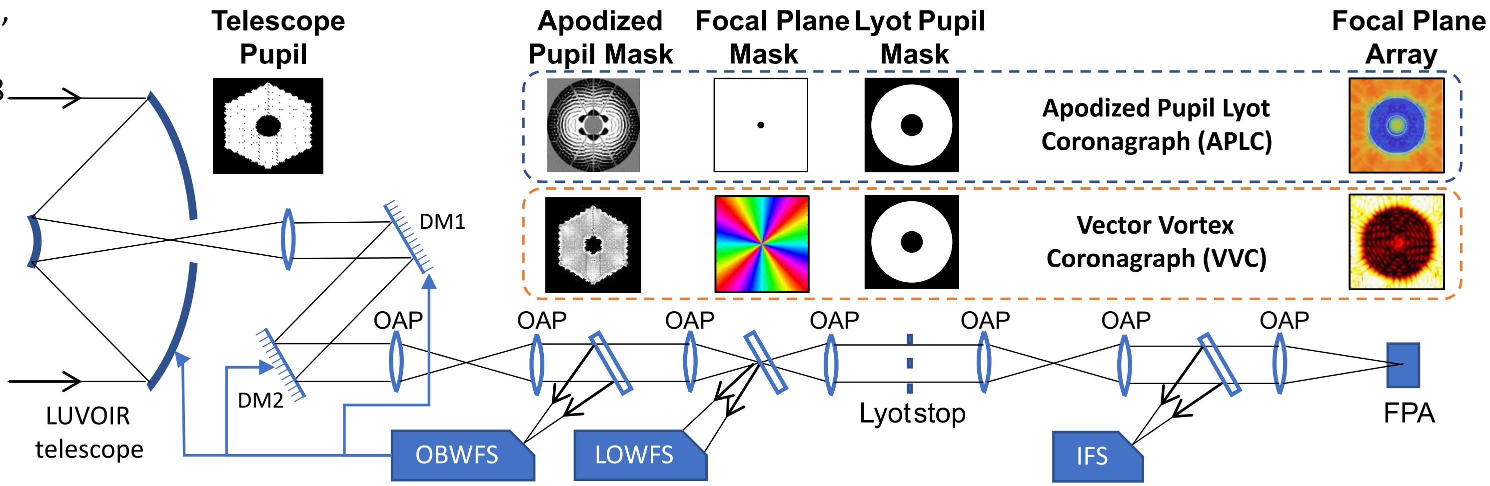
Jet Propulsion Laboratory
California Institute of Technology

Overview: WFS for Segmented Aperture Coronagraphs

Figure: D. Moore, D. Redding; SPIE 10698, July 2018

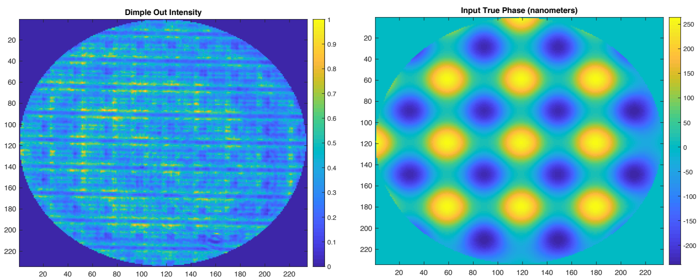


- Picometer-level accurate Wavefront Sensing (WFS) required for coronagraph 10^{-10} contrast
- WFS sensitivity sets closed-loop stability constraints
- This talk:
  - Nonlinear reconstruction algorithms and WFS dynamic range
  - Simulations of ZWFS-driven dark hole acquisition (including DM monitoring)
  - Achromatic WFS with geometric phase metasurface or liquid crystal polymers
  - Integrated WFS and Coronagraph architectures
  - Photonics for Focal Plane-WFS (calibrate non-common path error with direct measurement)
- Summary

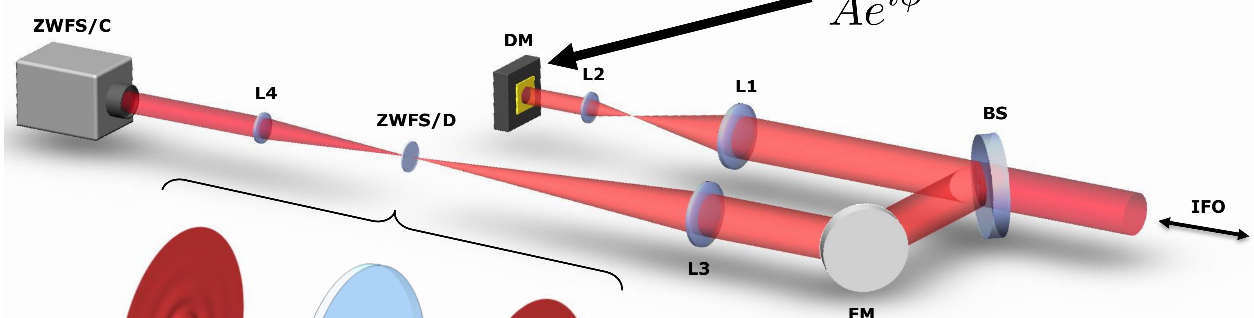
Review of ZWFS and Some Notation

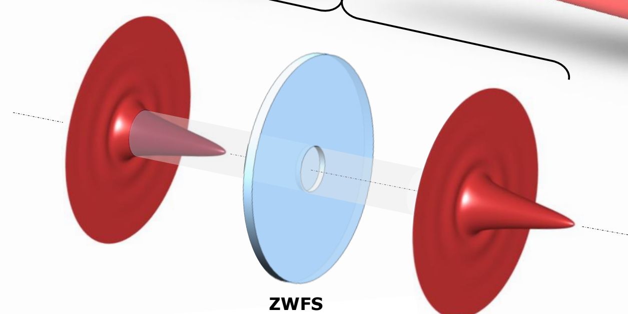
$$
\begin{aligned}
Y_{\pm} &= Ae^{i\phi} - (1 \mp i)F^{\dagger}RFAe^{i\phi} \\
B &= F^{\dagger}RFAe^{i\phi} \\
&\equiv |B|e^{i\beta} \\
B_0 &\equiv F^{\dagger}RFA
\end{aligned}
$$

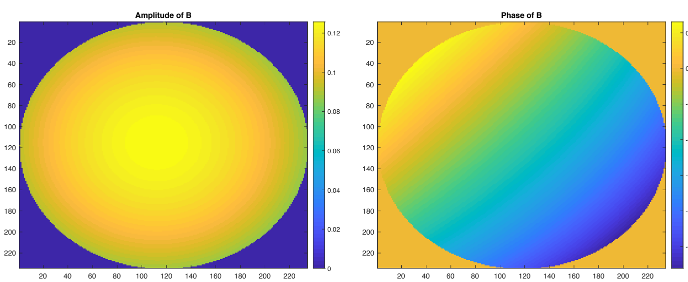
Input Amplitude (left) and Phase(right)



$Ae^{i\phi}$





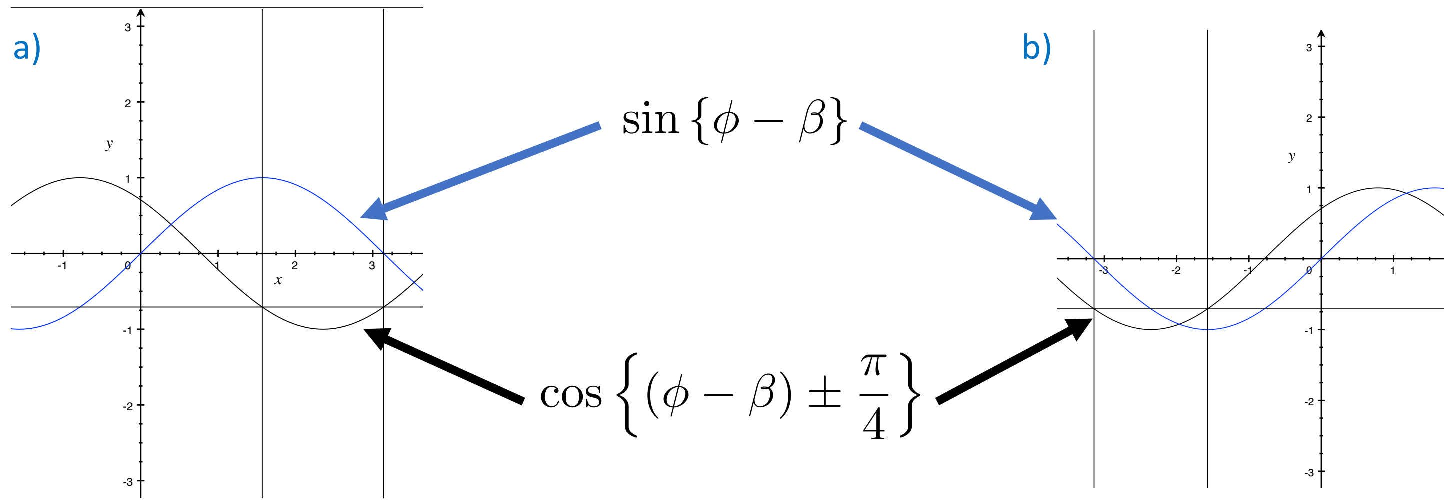


$Be^{i\beta}$

- (Left) Low-pass reference beam amplitude
- (Right) Low-pass reference beam phase

Figure: J. Steeves, et al., *"Picometer Wavefront Sensing via the Phase-Contrast Technique"*, to be submitted

Two Dimples, with Perfect Knowledge of the Low-Pass Reference: *Exact Analytic Phase Reconstruction*



$$
\begin{array}{llllllll}
\text{a) IF} & \frac{I_+ - I_-}{4|B||A|} \geq 0 & \text{IF} & \left[(-1)\left[\frac{I_+ - |A|^2 - 2|B|^2}{2\sqrt{2}\ |B||A|}\right] \geq -\frac{1}{\sqrt{2}}\right] & \rightarrow & \phi - \beta = \cos^{-1}\{\cdot\} - \frac{\pi}{4} \\
 & & \text{ELSE} & \left[(-1)\left[\frac{I_+ - |A|^2 - 2|B|^2}{2\sqrt{2}\ |B||A|}\right] < -\frac{1}{\sqrt{2}}\right] & \rightarrow & \phi - \beta = \pi - \sin^{-1}\{\cdot\} \\
\text{b) IF} & \frac{I_+ - I_-}{4|B||A|} < 0 & \text{IF} & (-1)\left[\frac{I_- - |A|^2 - 2|B|^2}{2\sqrt{2}\ |B||A|}\right] \geq -\frac{1}{\sqrt{2}} & \rightarrow & \phi - \beta = -\cos^{-1}\{\cdot\} + \frac{\pi}{4} \\
 & & \text{ELSE} & (-1)\left[\frac{I_- - |A|^2 - 2|B|^2}{2\sqrt{2}\ |B||A|}\right] < -\frac{1}{\sqrt{2}} & \rightarrow & \phi - \beta = -\pi - \sin^{-1}\{\cdot\}
\end{array}
$$

"Intensity Error:"

$$\mathcal{E}_\pm(p;\phi) = I_\pm(p) - \left|\sum_{p'} \mathcal{L}_\pm(p,p')A(p')e^{i\phi(p')}\right|^2$$

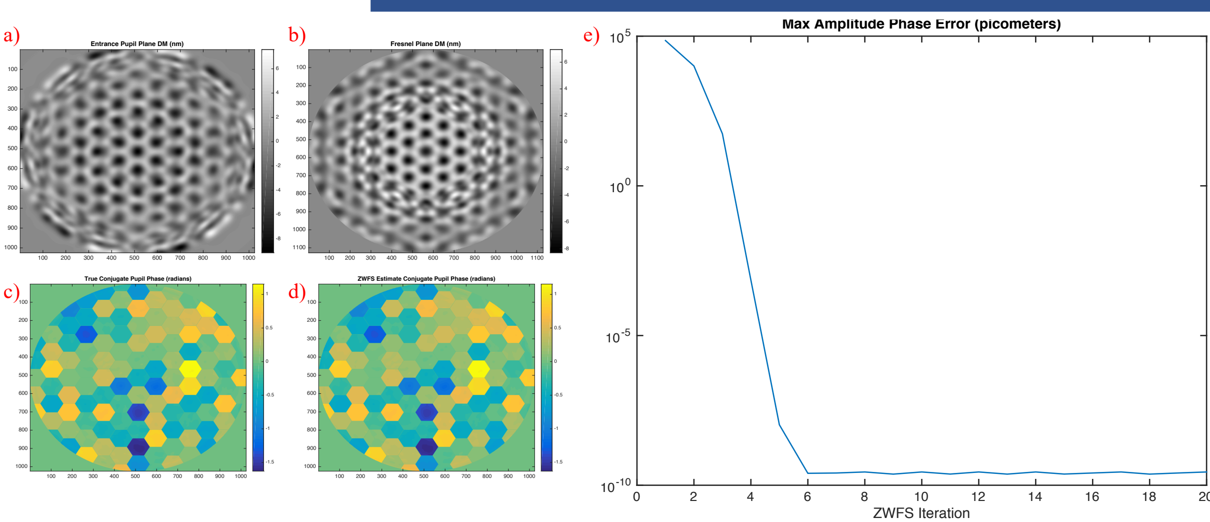
NL-WFS Reconstruction Algorithm

(builds on NL-ZWFS in Moore, Redding, SPIE 10698, July 2018)

$$\mathcal{E}_\pm(p;\phi+\nu\gamma) = (1-\nu)\mathcal{E}_\pm(p;\phi) + \nu^2\mathcal{E}^{(2)}(\phi;\gamma) + \nu\left[\mathcal{E}_\pm(p;\phi) - 2\mathrm{Re}\left\{Y^*(\phi)\mathcal{L}_\pm Ae^{i\phi}(i\gamma)\right\}\right]$$

"Step size" ν in "direction" $\gamma(p)$

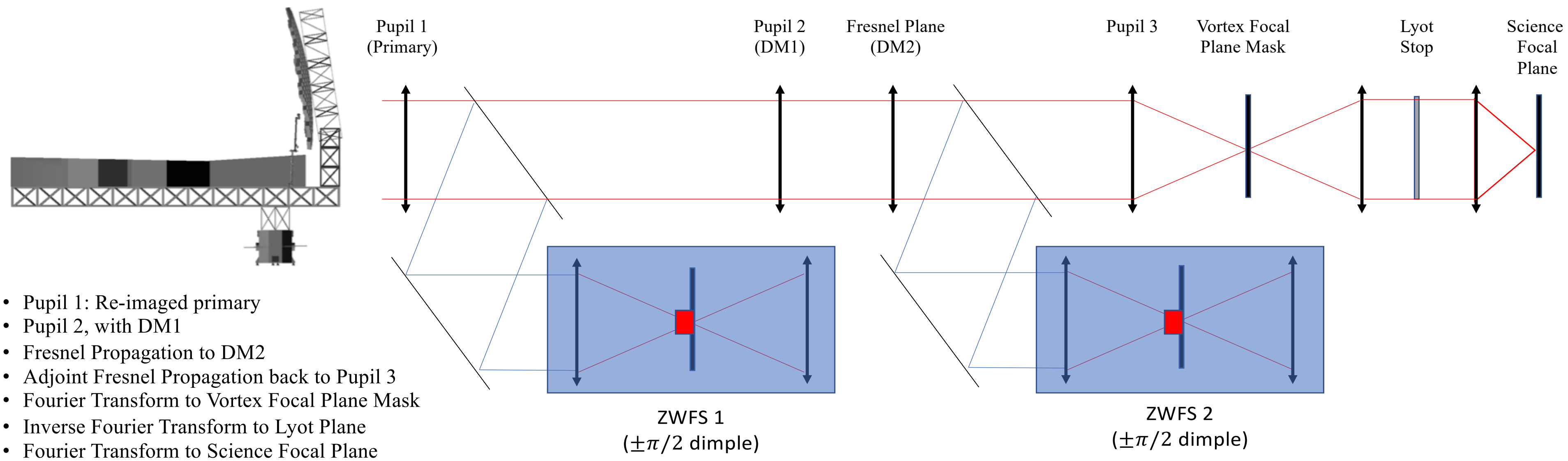
$$\boxed{\begin{aligned}\|\mathcal{E}_\pm(p;\phi+\nu\gamma)\| &\le (1-\nu)\,\|\mathcal{E}_\pm(p;\phi)\| + \nu\left(\nu\left\|\mathcal{E}^{(2)}(\phi;\gamma)\right\|\right)\\ &< \|\mathcal{E}_\pm(p;\phi)\|\end{aligned}}$$



ZWFS Accuracy for Conjugate Pupil Fields

- a) DM1, b) DM2 beam-shaping solutions for a charge 6 vortex (Peak to Valley 40 nm at 600 nm)
- c) Phase in 'Pupil 3' downstream of DM's, with 100 nanometer (Peak to Valley) primary mirror segment piston errors
- d) NL-ZWFS phase reconstruction (building on Moore and Redding, 2018 [1]) after 20 iterations.
- e) Error vs. iteration of the Nonlinear ZWFS.
- *Neglecting photon noise, the NL-ZWFS algorithm can reconstruct the amplitude and phase at each pixel to machine precision.*

Architecture with Multiple ZWFS for DM State Estimation



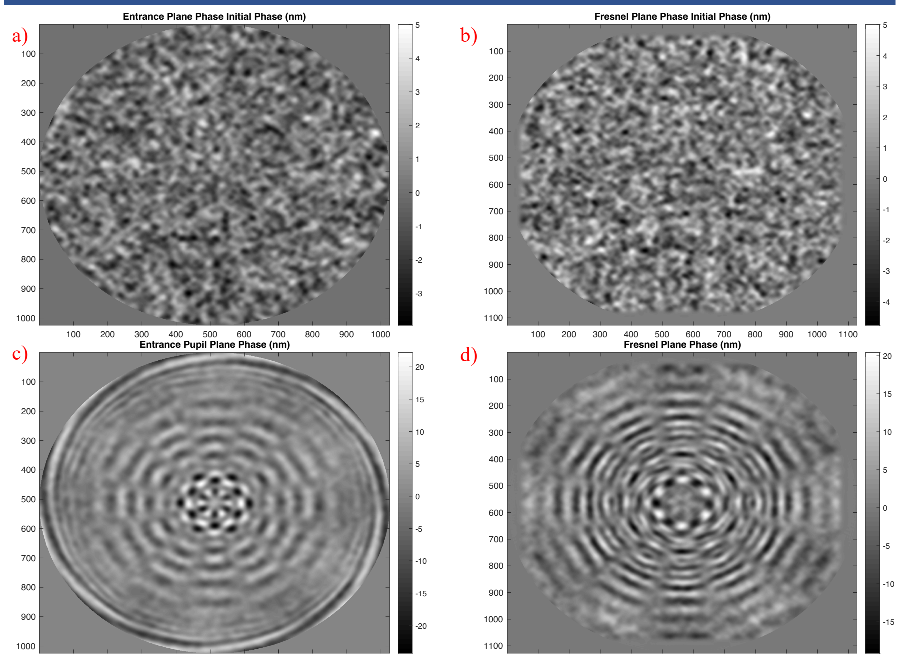
- Pupil 1: Re-imaged primary
- Pupil 2, with DM1
- Fresnel Propagation to DM2
- Adjoint Fresnel Propagation back to Pupil 3
- Fourier Transform to Vortex Focal Plane Mask
- Inverse Fourier Transform to Lyot Plane
- Fourier Transform to Science Focal Plane

Dark Hole Acquisition with Entrance and Conjugate Pupil ZWFS

Step 1. $|X_{\pm}\rangle$ Probe fields in 'Pupil 1', *measured by ZWFS1*
$|Y_{\pm}\rangle$ Probe fields in 'Pupil 3', *measured by ZWFS2*

Step 2. DM State Estimate : $(\hat{\Gamma}, \hat{\Phi}) \;=\; \min \left\| |Y_{\pm}\rangle - P^{\dagger} e^{i\Gamma} P e^{i\Phi} |X_{\pm}\rangle \right\|$

Step 3. Dark Hole Correction: $-|E_{\text{focal plane}}\rangle \;=\; J[\hat{\Gamma}, \hat{\Phi}](\delta\Gamma, \delta\Phi)$

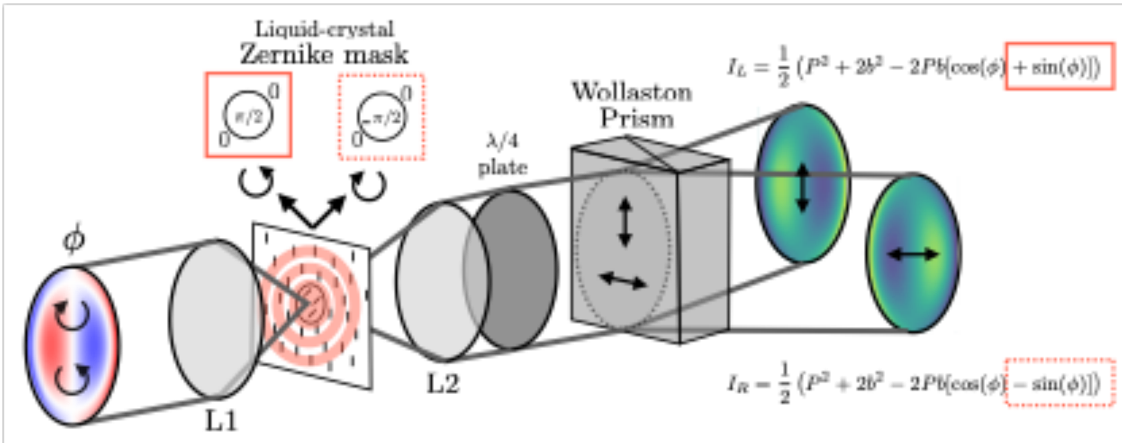


Dark Hole Acquisition with ZWFS Inferred DM States

- Acquiring a "dark hole", and subsequent closed-loop control, requires knowledge of the DM states
- The DM states represent one of the most uncertain model elements in the coronagraph (i.e. knowledge of influence functions, errors in linear superposition, etc)
- We explore the ability to infer the DM states with 'Pupil 1' and 'Pupil 3' measurements provided by ZWFS1 and ZWFS2
- *Measurement sequence:* 1) Generate piston primary mirror "probe" fields in 'Pupil 1', and measure before and after DM's with ZWFS1 and ZWFS2, 2) Nonlinear iterative (Newton) method to estimate the DM states *(pixel-based, independent of influence functions),* 3) DM state estimates are used in the control Jacobian to improve the dark hole.
- (a-b): Initial (and unknown) DM states, with 5 nm (rms) DM actuator heights. The initial states were inferred with ZWFS measurements to initialize the Jacobian.
- (c-d): DM solutions computed using the ZWFS estimated DM states at each iteration. These solutions achieve 3e-11 normalized intensity (single wavelength here due to computational expense – ongoing work to generalize to broadband on a cluster architecture)
- Ongoing work – fully Bayesian approach including ZWFS detector noise, and Bayes optimal closed-loop control
- *This architecture has the potential for continuous dark hole closed-loop control while taking science data!!*

Vector Zernike Wavefront Sensor: Simultaneous $\pm\pi/2$ Measurements

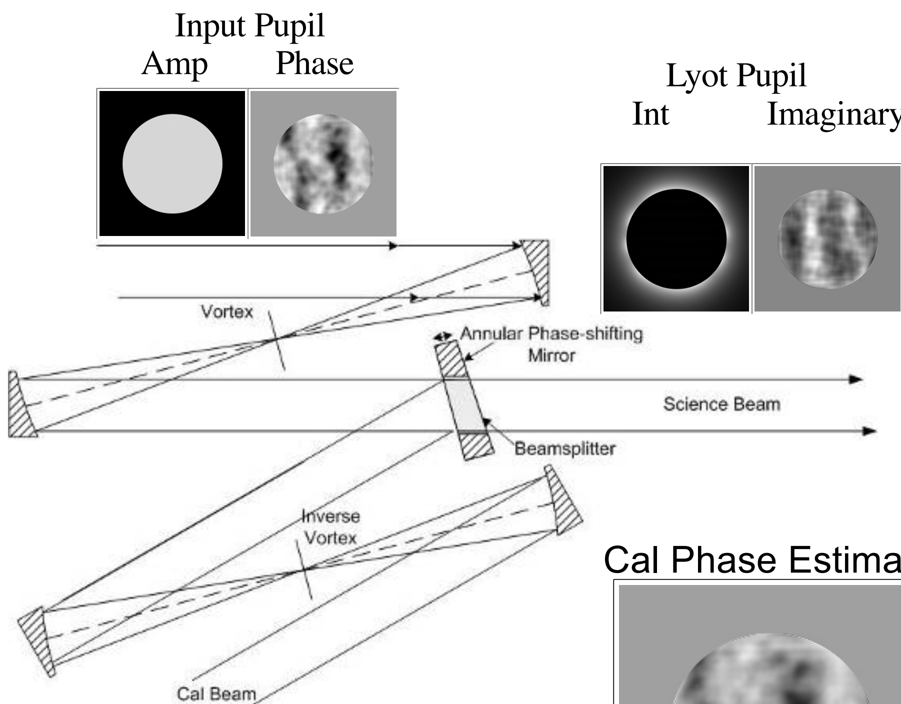
Figure Credit: D. Doelman et al, Optics Letters, vol 44, Jan. 2019



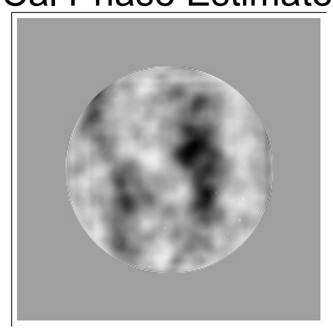
- vector Zernike Wavefront Sensor – imparts geometric (achromatic) $\pm\pi/2$ phase to PSF core, serving as the “piston” reference beam for in-line interferometric intensity measurements.
- The TWO split polarization beams allow full $\pm\pi$ wavefront dynamic range
- “Size chromaticity” of the PSF (see Doelman et al for a discussion of this point)
- *Can we find a solution to achromatic wavefront sensing?*
  - *Improved efficiency – shorter integration times to achieve accurate wavefront sensing*
  - *Could directly translate into relaxed segmented primary stability requirements*

GPI V2.0

Original Double Vortex Wavefront Sensor Concept – Introduced by J. Kent Wallace, GPI Fall Retreat, Nov. 2009!! (original slide shown here, courtesy J. Kent Wallace)



Cal Phase Estimate

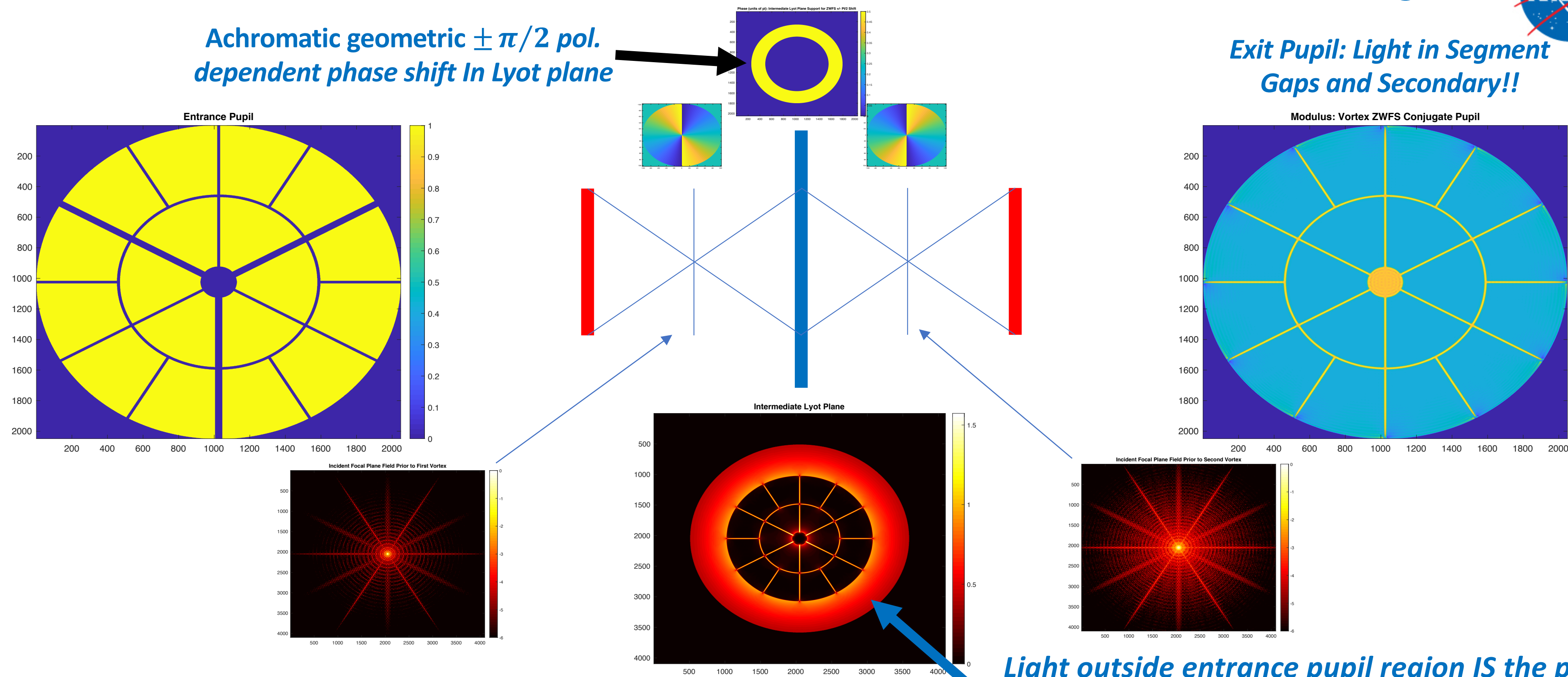


- Can we make the above "achromatic"?
- What is the optimal way to split off light for wavefront sensing, with minimal impact to planet light throughput?

Metasurface Extension of the DV-WFS: "Achromatic" Wavefront Sensing!

Achromatic geometric $\pm\pi/2$ pol. dependent phase shift In Lyot plane

Exit Pupil: Light in Segment Gaps and Secondary!!



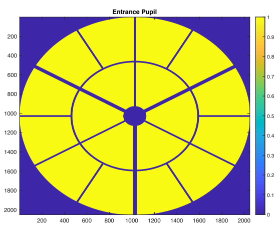
Light outside entrance pupil region IS the pupil 'piston' mode and serves as the WFS reference beam. We use a metasurface to impart a geometric phase of +/- PI/2 to this light!

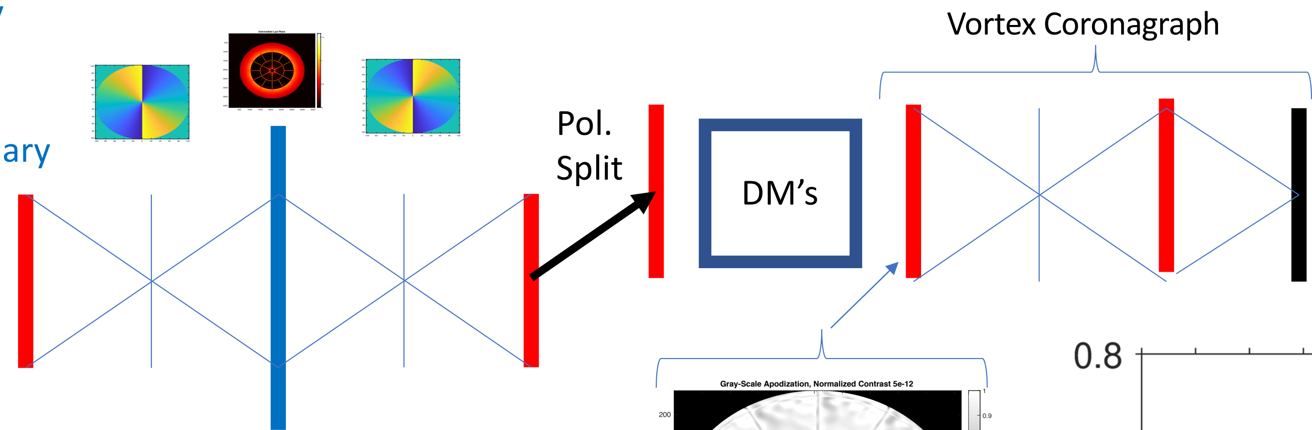
Jewell, Wallace, et al. in prep.

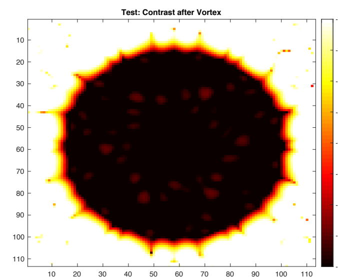
Integrated DV-WFS and Metasurface CG

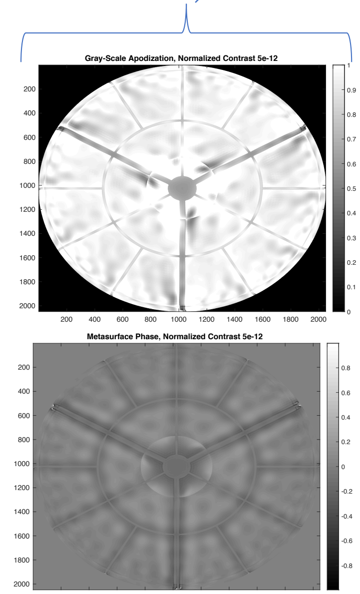
Example Seg. Aperture:

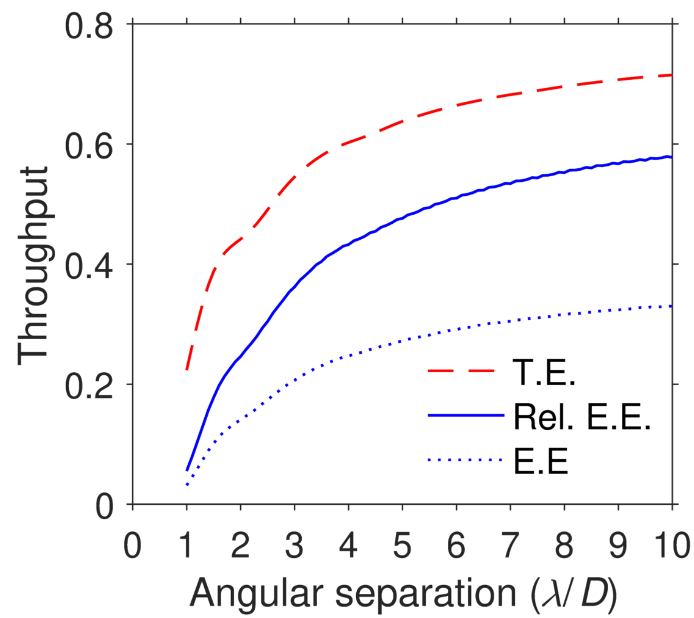
- 6 meter primary
- 120 mm struts
- 50 mm seg gaps
- .6 meter secondary







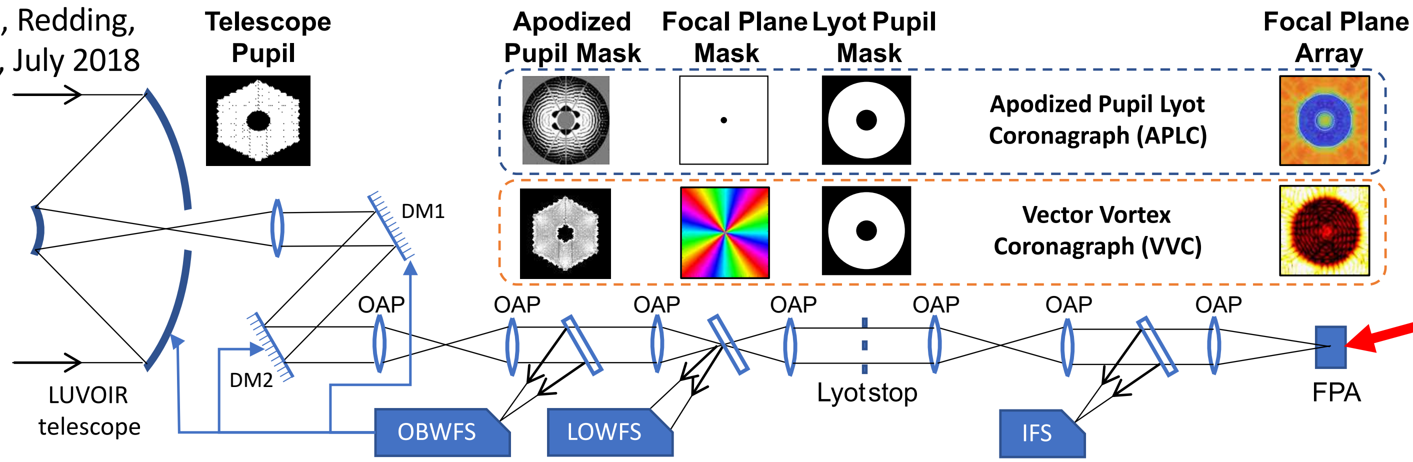




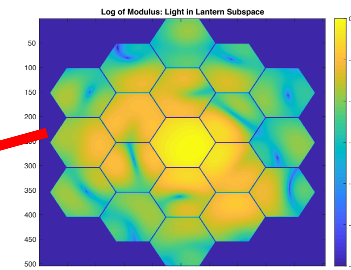
- *One (of two) polarization branch shown above*
- Apodization and phase (geometric,"achromatic") mask in conjugate pupil, downstream of DM's (optimized with "Auxiliary Field" approach, Jewell et al, Proc. SPIE 10400,10400H,2017))
- Wavefront sensing with in-band light, picked off the apodization mask in reflection (either the $+\pi/2$ or $-\pi/2$ in each polarization channel)
- Solution above with 5e-12 normalized intensity (relative to final vortex FPM removed)
- (Jewell et al, in prep.)

Direct Calibration with Focal Plane WFS (Prior to Dark Hole Acquisition)

Fig: Moore, Redding, SPIE 10698, July 2018

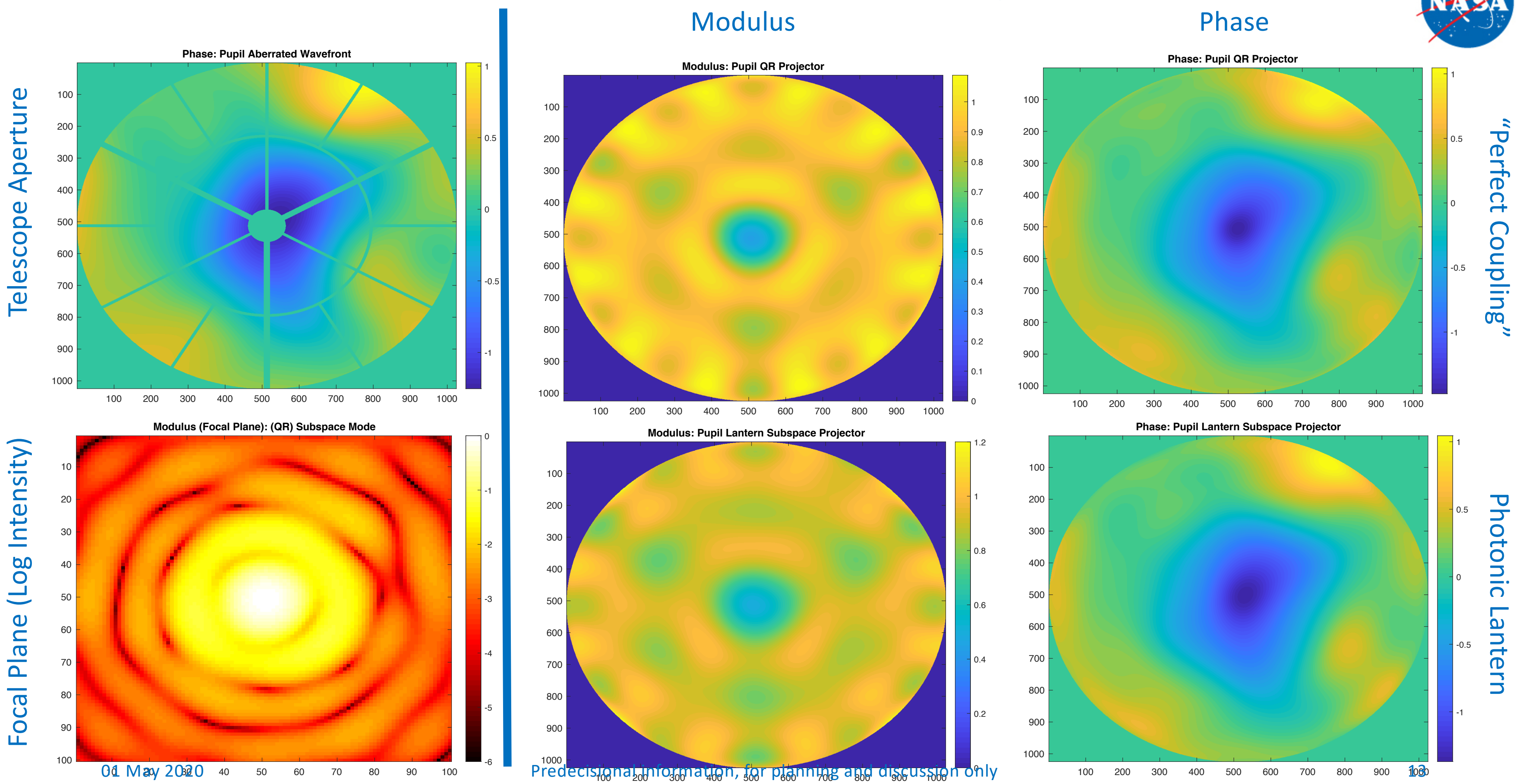


Photonic Focal Plane Wavefront Sensing!

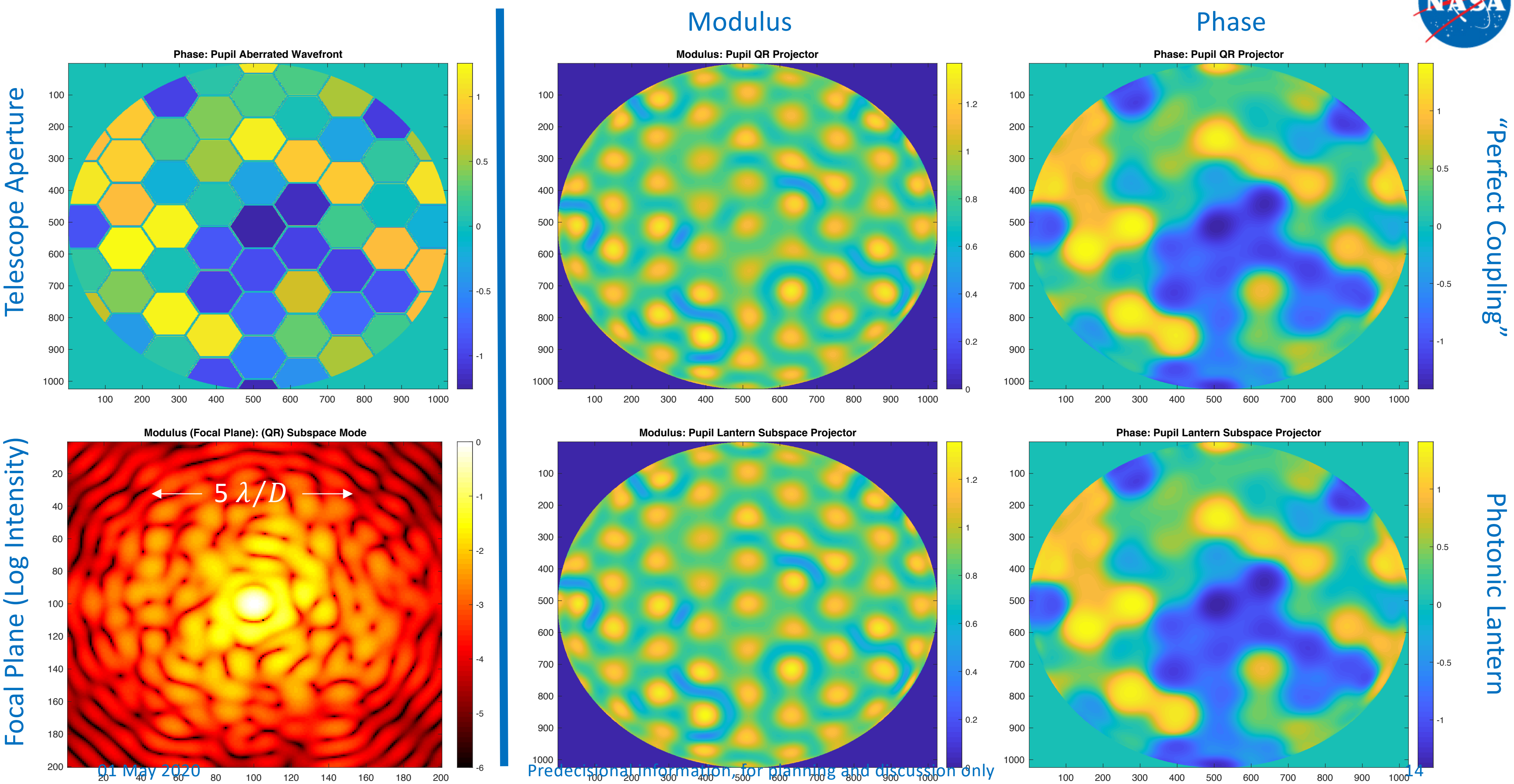


- *We are working at JPL on advanced photonic approaches to focal plane wavefront sensing for coronagraph applications (Jewell et al, in preparation)*
- Represents another example of *photonic technology* assimilation into coronagraphs (and other instruments):
  - *All-photonic (lantern) focal plane wavefront sensor* (Neural Network wavefront reconstruction) (B.R.M. Norris et al, arXiv:2003.05158, 11 Mar 2020)
  - *Lenslet-fed single-mode fiber focal plane array "SCAR Coronagraph"* (Por, E.H.; Haffert, S.Y, arXiv:1803.10691 and Haffert, S.Y. et al, arXiv 1803.10693):
  - *Vortex Fiber Nuller* (Ruane, G; et al., ApJ, 867,143): Vortex nulling on single-mode fiber
  - *Integrated photonic spectrographs* (Jovanovic et al, Astro2020 APC white paper, arXiv 1907.07742v2)

DM (100 nm @ 600 nm) Aberrations: 2-Ring FPWFS Subspace



LUVOIR B Piston (100 nm @ 600 nm) Aberrations: FPWFS Subspace



Summary

- Wavefront Sensing with simultaneous $\pm\,^{\pi}/_{2}$ provides $\pm\pi$ phase reconstruction
  - Novel vector ZWFS (Doelman et al, 2019)
  - Achromatic Double Vortex WFS
- Simulations with WFS capability both upstream and downstream of DM's provide accurate (enough) closed-loop control Jacobian measurements
  - Simultaneous Primary Mirror closed loop control
  - DM state estimation for accurate commanding while acquiring the dark hole
  - Can we be more aggressive in Dark Hole acquisition with advanced WFS? More time for science!
- Calibration of closed-loop control enabled with Focal Plane WFS
  - Before Dark Hole is acquired, can calibrate non-common path errors with simultaneous ZWFS and FP-WFS measurements
  - Advanced applications of photonics enable FP-WFS
- *What will state-of-the-art segmented aperture telescope and high-contrast imaging designs look like after the next 5-10 years of development??*

Background on Meta-surfaces:

Sub-wavelength structures allow local (at each pixel) any 2x2 symmetric Jones matrix operation n the incoming polarization vector!!

Local (Pixel) Meta-surface degrees of freedom

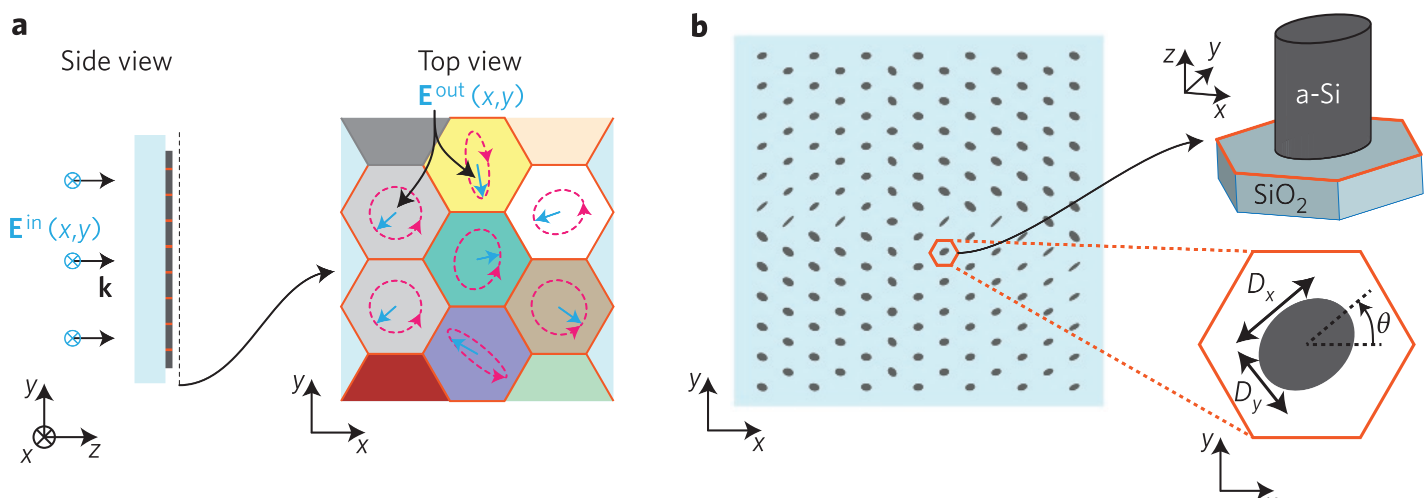


Figure Credit: Arbabi et al, Nature Nanotechnology, August 2015

Jones Matrix in the Linear Polarization Basis:

Controlled by pillar orientation (achromatic – controls geometric phase)

$$U = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix} \underbrace{\begin{bmatrix} e^{i\phi_x} & 0 \\ 0 & e^{i\phi_y} \end{bmatrix}} \overbrace{\begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix}}$$

Controlled by pillar DX and DY (chromatic – controls propagation phase)

Polarization basis states and transformations (quarter wave plates)

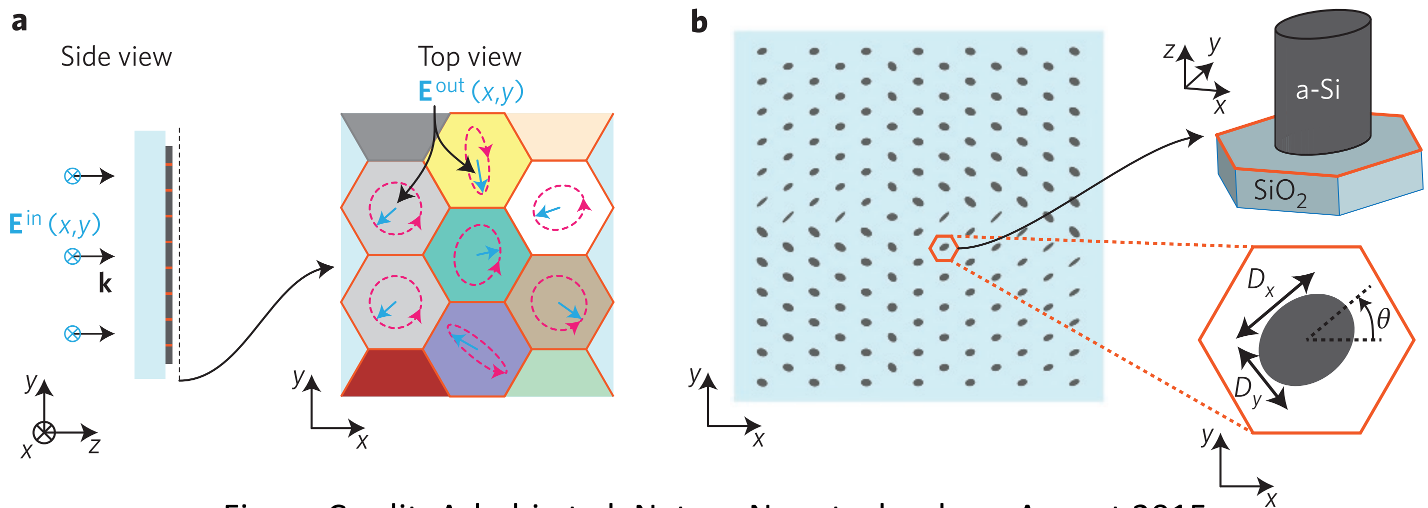


Figure Credit: Arbabi et al, Nature Nanotechnology, August 2015

Right, Left CP Basis:

$$|R\rangle = \frac{1}{\sqrt{2}}\left(|X\rangle - i|Y\rangle\right)$$

$$|L\rangle = \frac{1}{\sqrt{2}}\left(|X\rangle + i|Y\rangle\right)$$

Quarter Wave Plate:

$$U = |R\rangle\langle X| + |L\rangle\langle Y|$$

QWP Jones Matrix Elements in XY-Basis

$$U = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ -i & i \end{bmatrix}$$

Geometric Phase

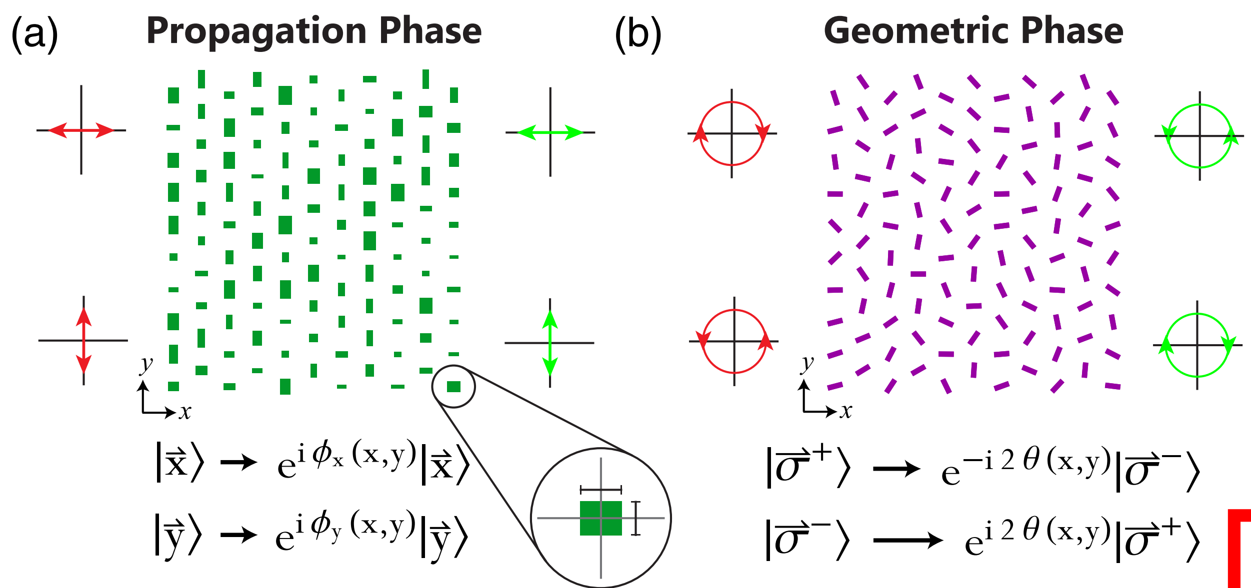


Figure: Mueller et al, PRL, 118,2017)

$$\boxed{|\phi_x - \phi_y| = \pi}$$

"Geometric Phase" Unitary:

$$\boxed{U = e^{i\phi}|L\rangle\langle R| + e^{-i\phi}|R\rangle\langle L|}$$

Unitary Matrix Elements in LP Basis:

$$U = e^{i\phi_x}\begin{bmatrix}\cos(\theta) & -\sin(\theta)\\ \sin(\theta) & \cos(\theta)\end{bmatrix}\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}\begin{bmatrix}\cos(\theta) & \sin(\theta)\\ -\sin(\theta) & \cos(\theta)\end{bmatrix}$$

$$= e^{i\phi_x}\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}R(2\theta)$$