

# Focal Plane Wavefront Sensing and Control for Various Optical Systems

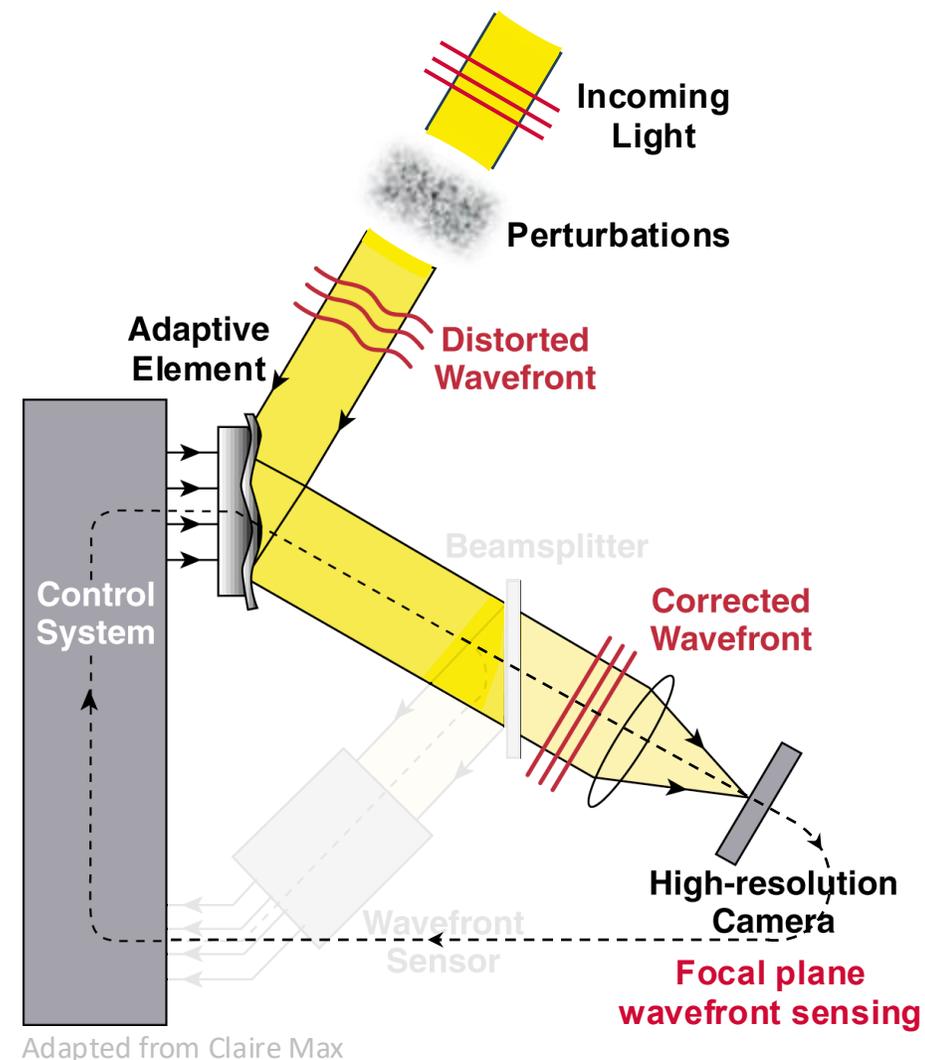
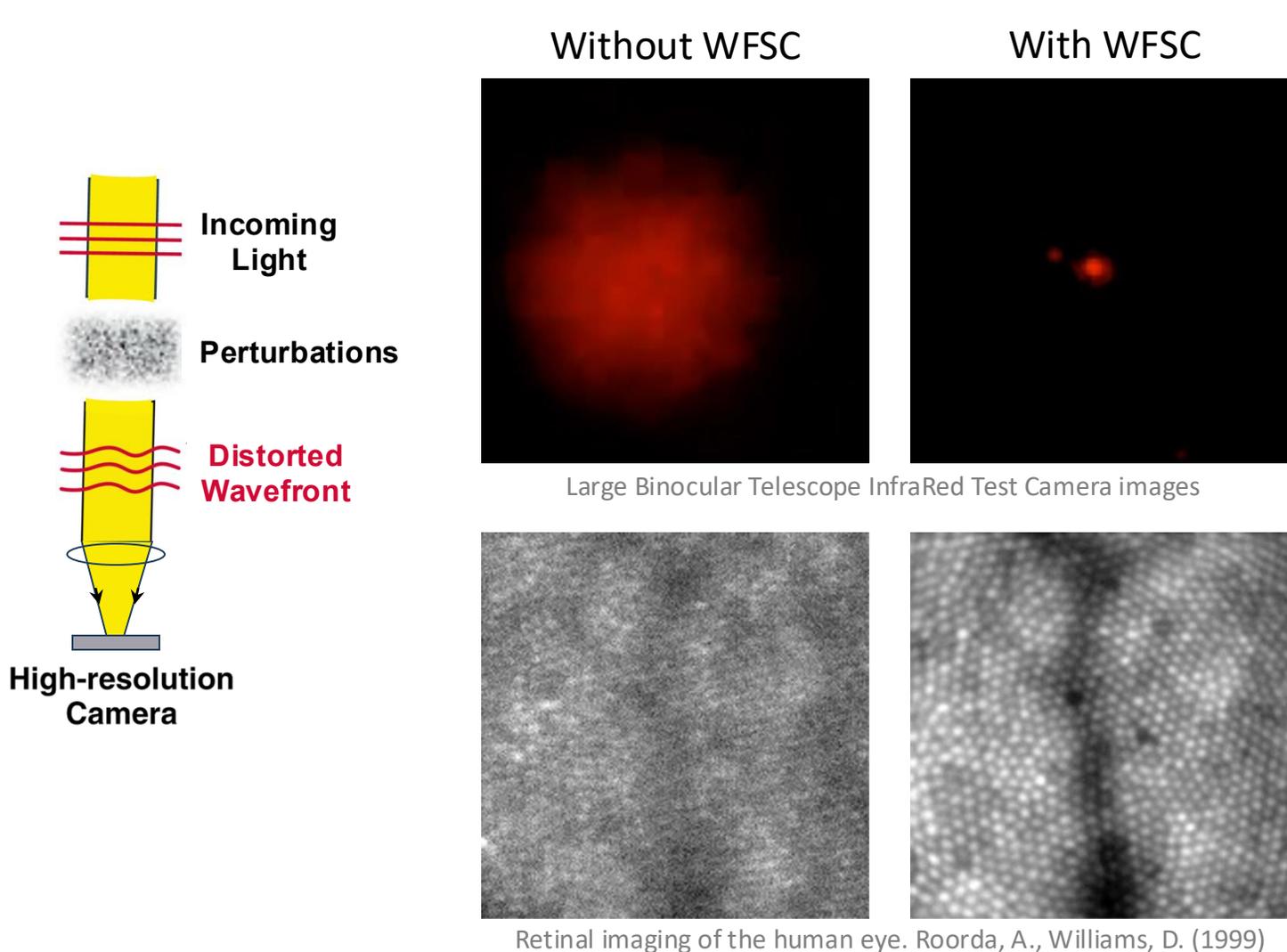
Duan Li

Committee: Dmitry Savransky, Douglas MacMartin, James Lloyd

Date: July 14, 2025

# Background

## Wavefront Sensing and Control (WFSC)



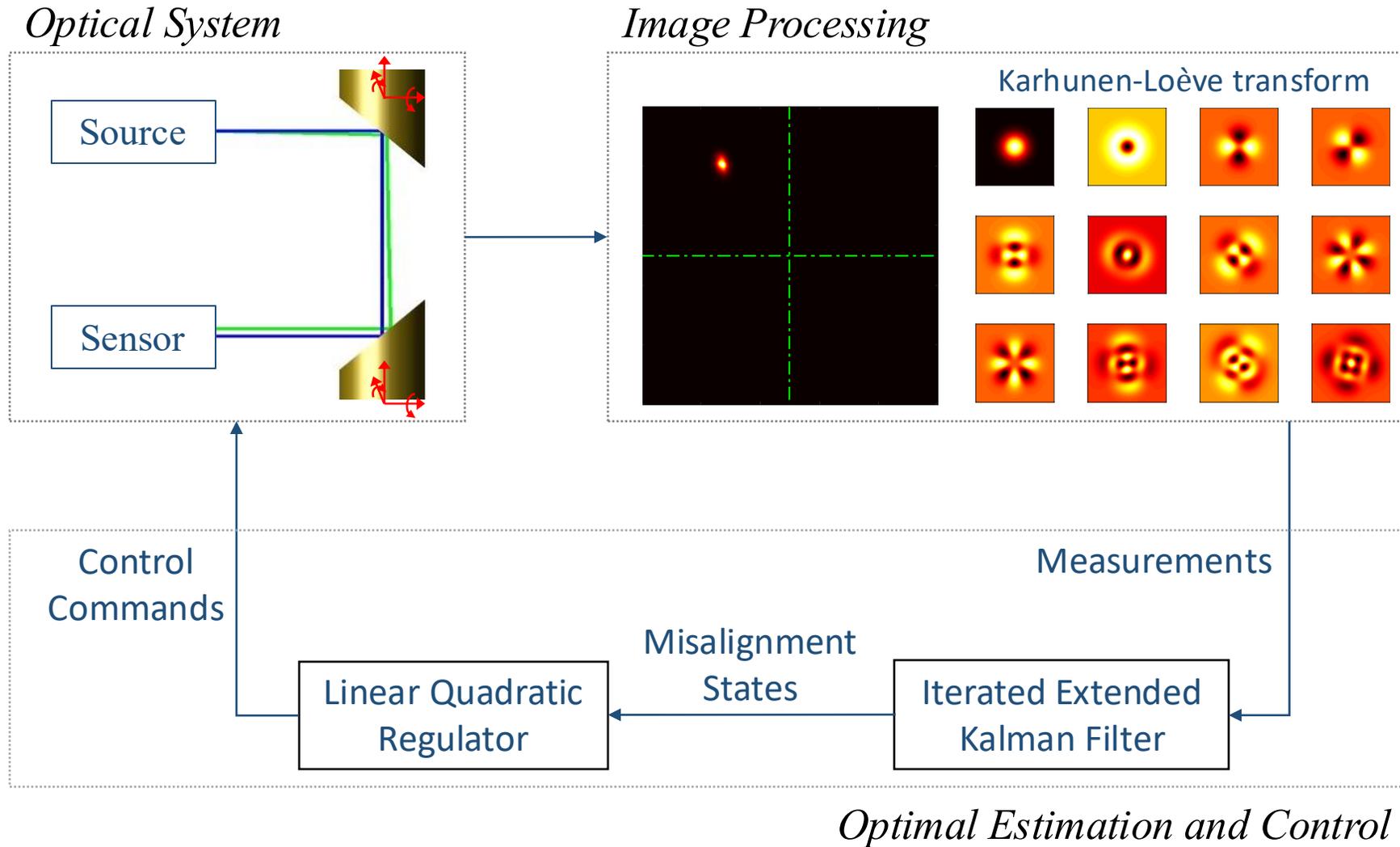
# Contributions

## Focal Plane Wavefront Sensing and Control

- Automated alignment of optical systems with off-axis aspherics
  - Li, D., Savransky, D. "Image plane wavefront sensing and Kalman filtering for automated alignment of off-axis aspherics." *JOSA A* (2023).
  - Li, D., Savransky, D. "Automated reflective optical system alignment: analysis and experiments." *SPIE* (2021).
  - Li, D., Savransky, D. "Automated reflective optical system alignment with focal plane sensing and Kalman filters." *SPIE* (2020).
- Gemini Planet Imager 2.0's Calibration System
  - Li, D., Savransky, D. "Focal Plane Wavefront Sensing and Control in the Gemini Planet Imager 2.0's calibration system" (To be submitted)
  - Li, D., Thompson, W., Savransky, D., & Marois, C. "Focal plane wavefront control for the Gemini Planet Imager 2.0 calibration system (CAL2)." *SPIE* (2023).

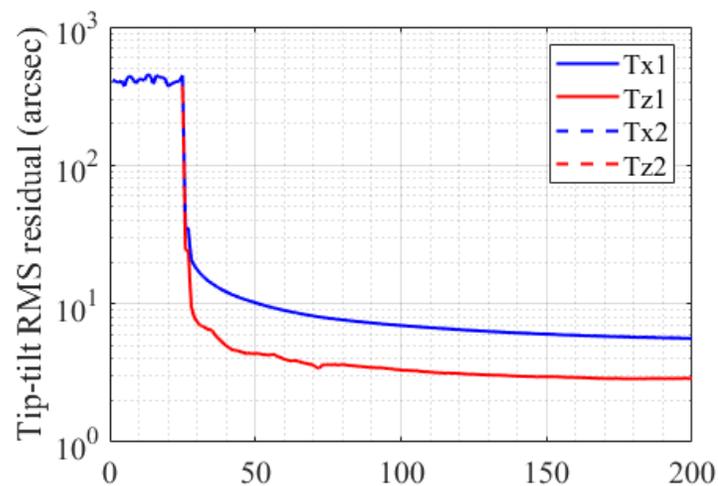
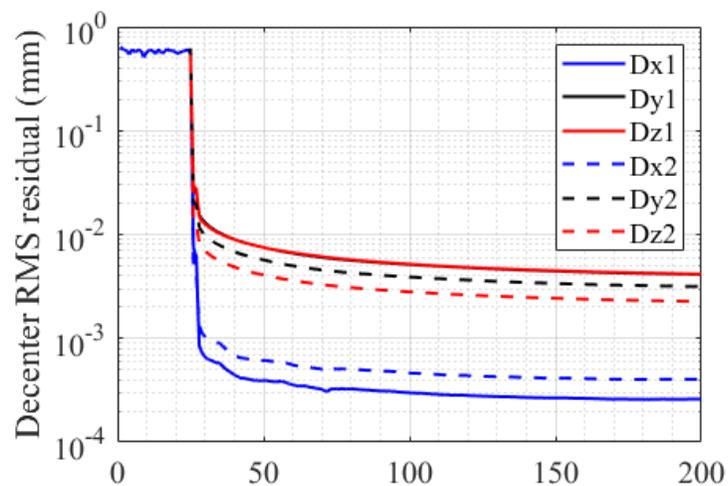
# Contributions

Automated Alignment of Off-axis Aspherics using Focal Plane Wavefront Sensing and Kalman Filtering



# Contributions

Automated Alignment of Off-axis Aspherics using Focal Plane Wavefront Sensing and Kalman Filtering



Linear misalignments

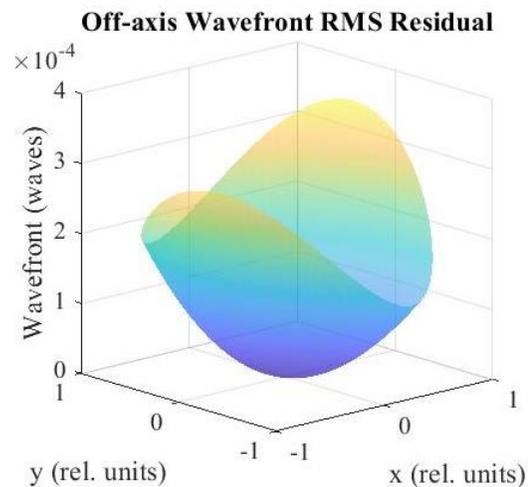
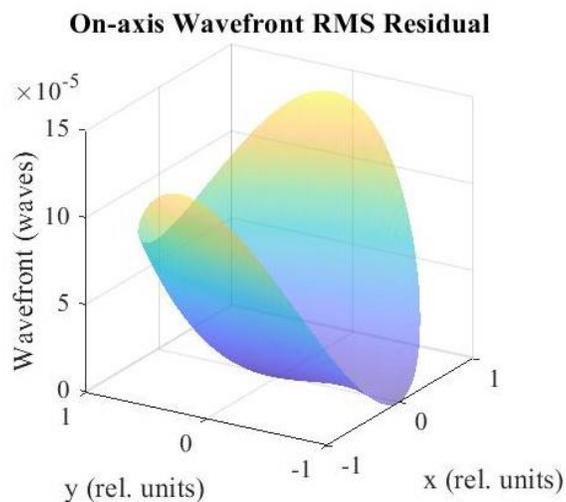
$$1 \text{ mm} \rightarrow < 5 \mu\text{m}$$

Angular misalignment

$$0.2^\circ \rightarrow < 6 \text{ arcsec}$$

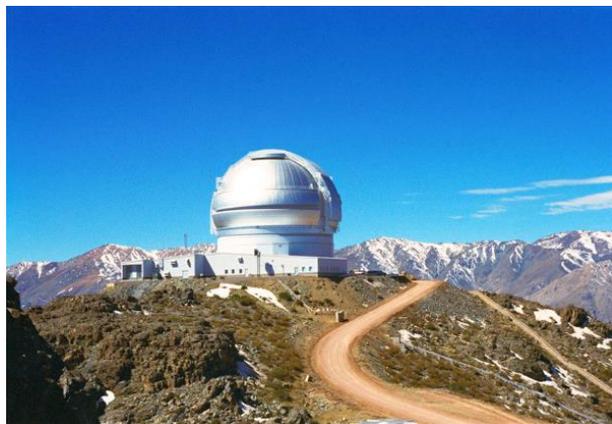
Wavefront error

$$6 \lambda \rightarrow < 0.0004 \lambda$$



# Contributions

## Focal Plane Wavefront Sensing and Control



- Gemini Planet Imager (GPI 2.0)'s Calibration System (CAL 2.0)
  - Li, D., Savransky, D. "Focal Plane Wavefront Sensing and Control in the Gemini Planet Imager 2.0's calibration system" (To be submitted)
  - Li, D., Thompson, W., Savransky, D., & Marois, C. "Focal plane wavefront control for the Gemini Planet Imager 2.0 calibration system (CAL2)." *SPIE* (2023).

# Contributions

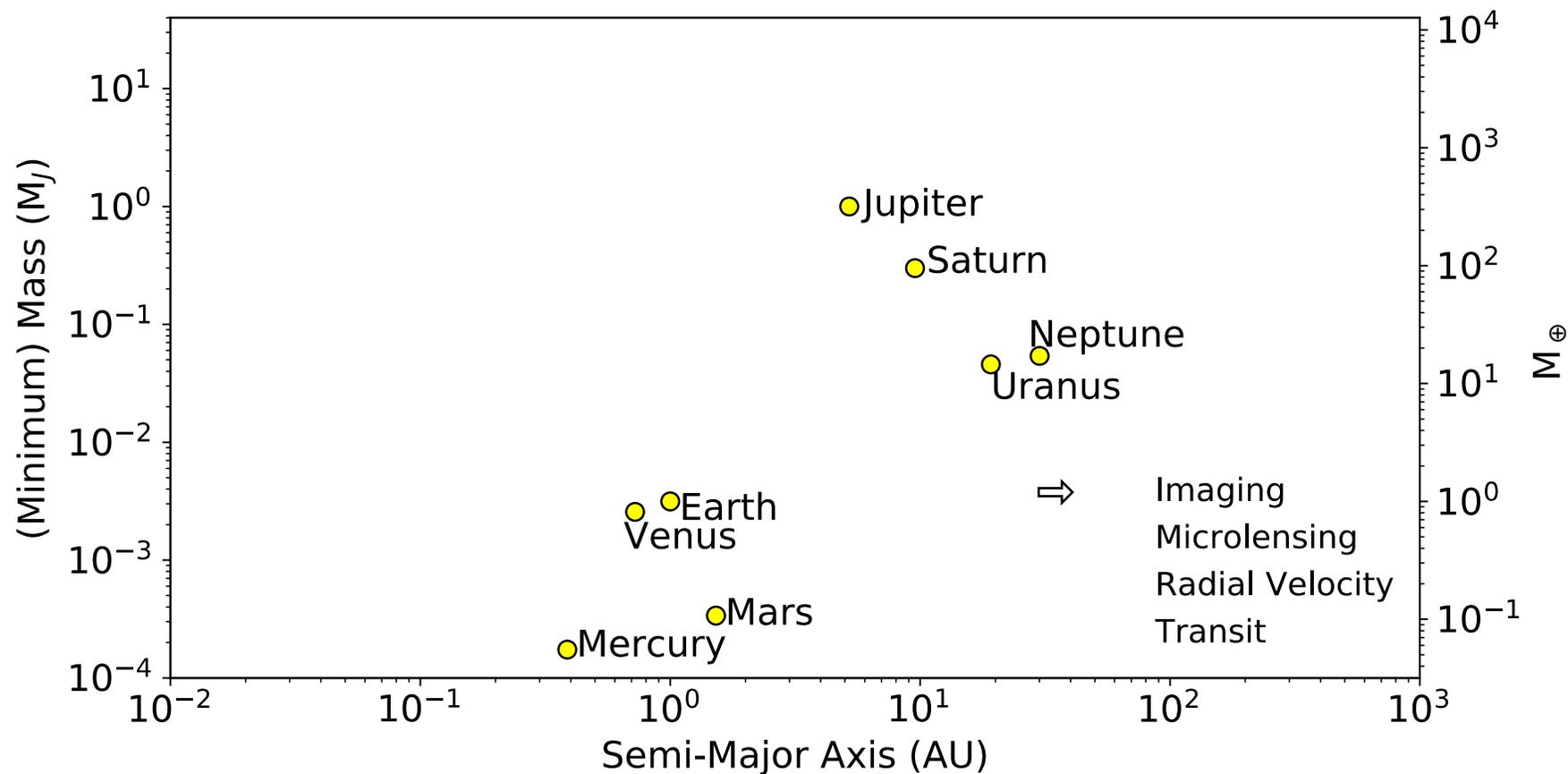
## Focal Plane Wavefront Control for the Gemini Planet Imager 2.0's Calibration System

Additionally...

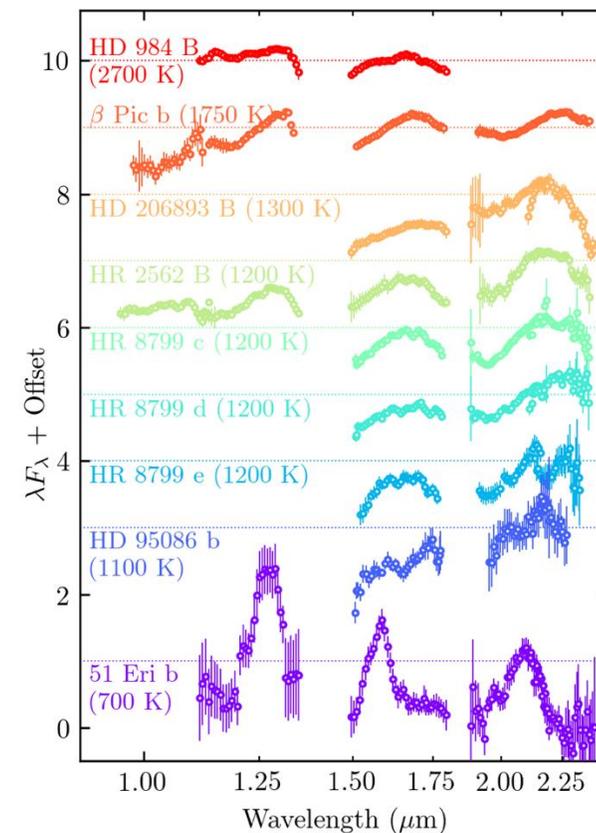
- First-author conference presentations
  - **Li, D.**, Thompson, W., Savransky, D., & Marois, C. (2023) *Speckle Nulling for High Contrast Imaging on a Self Coherent Camera*. American Astronomical Society.
  - **Li, D.** & Savransky, D. (2020) *Automated Reflective Optical System Alignment with Focal Plane Sensing and Optimal State Estimation*. OSA Imaging and Applied Optics Congress.
  - **Li, D.** & Savransky, D. (2019) *Automated Optical System Alignment with Focal Plane Sensing*. Emerging Researchers in Exoplanet Science.
- Co-authored conference publications
  - Nguyen, J. S., et al. (2024) *GPI 2.0: End-to-end simulations of the AO-coronagraph system*. SPIE.
  - Perera, S., et al. (2024) *GPI 2.0: Pre-integrated pyramid wavefront sensor results*. SPIE.
  - Marois, C., et al. (2024) *CAL2: Project update of the NRC Canada facility-class focal plane wavefront sensor for the Gemini Planet Imager 2 upgrade*. SPIE.
  - Do Ó, C. R., et al. (2024) *GPI 2.0: Exploring the impact of different readout modes on the wavefront sensor's EMCCD*. SPIE.
  - Perera, S., et al. (2023) *Upgrading the Gemini planet imager to GPI 2.0*. SPIE.
  - Do Ó, C. R., et al. (2022) *GPI 2.0: Performance evaluation of the wavefront sensor's EMCCD*. AO4ELT.
  - Perera, S., et al. (2022) *GPI 2.0: Pyramid wavefront sensor status*. SPIE.
  - Chilcote, J., et al. (2022) *GPI 2.0: Upgrade status of the Gemini Planet Imager*. SPIE.
  - Chilcote, J., et al. (2020) *GPI 2.0: Upgrading the Gemini Planet Imager*. SPIE.
  - Madurowicz, A., et al. (2020) *GPI 2.0 : Optimizing reconstructor performance in simulations and preliminary contrast estimates*. SPIE.

# Background

## Exoplanet Detection and Direct Imaging



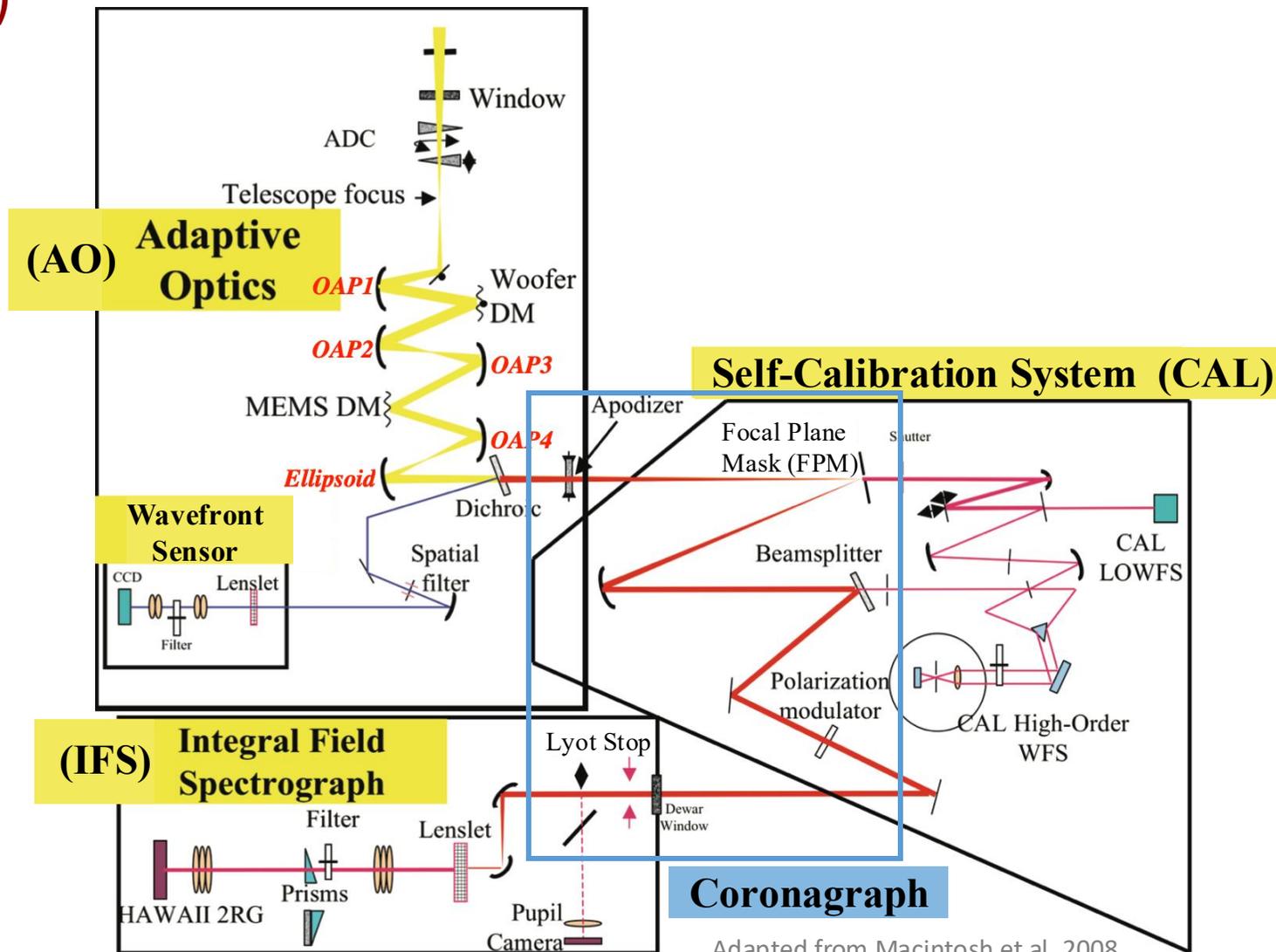
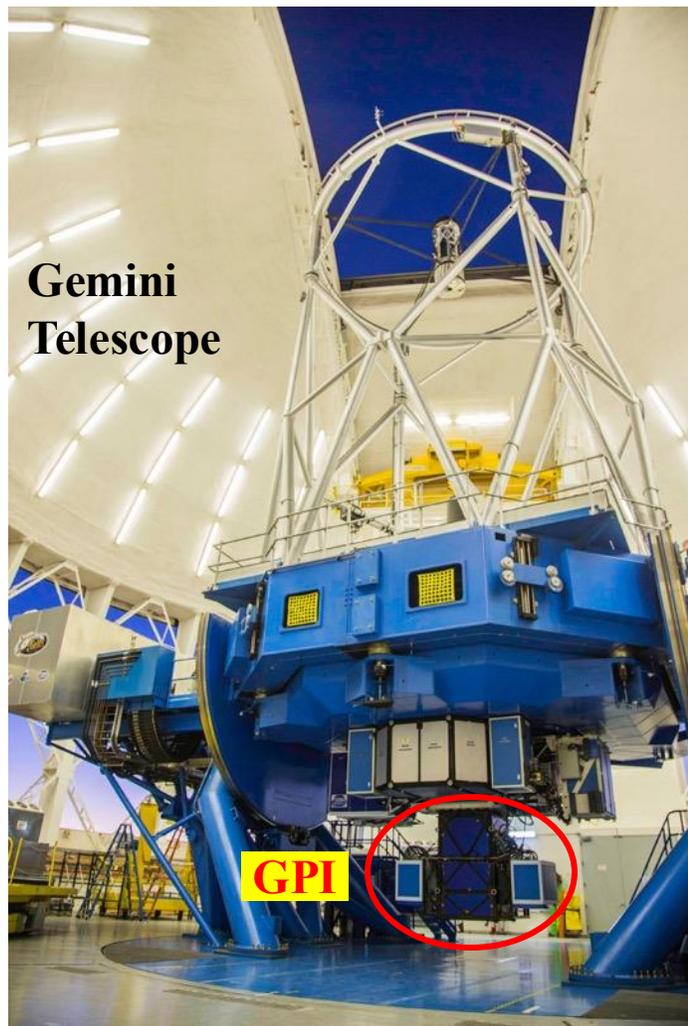
GPI Exoplanet Survey Spectral Library



<https://github.com/dsavransky/exoplanetarchivefigs>, Christiansen et al. 2025

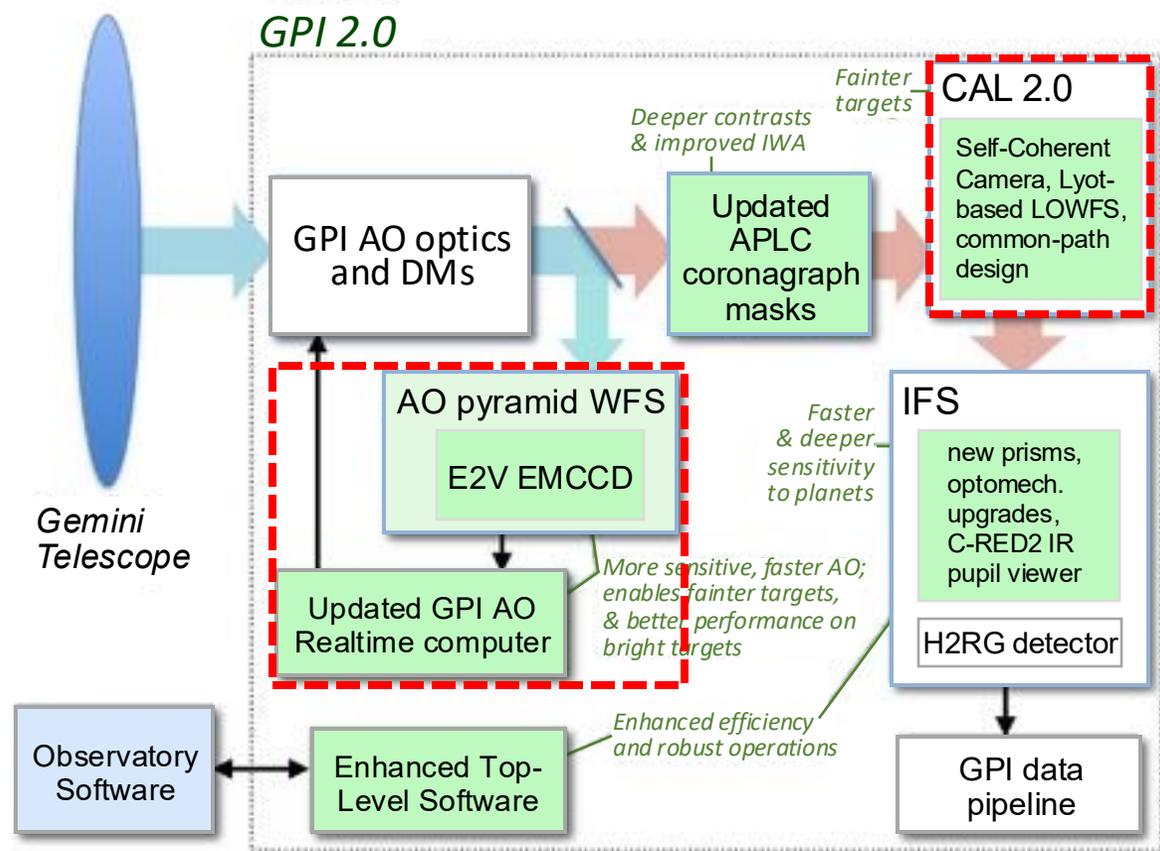
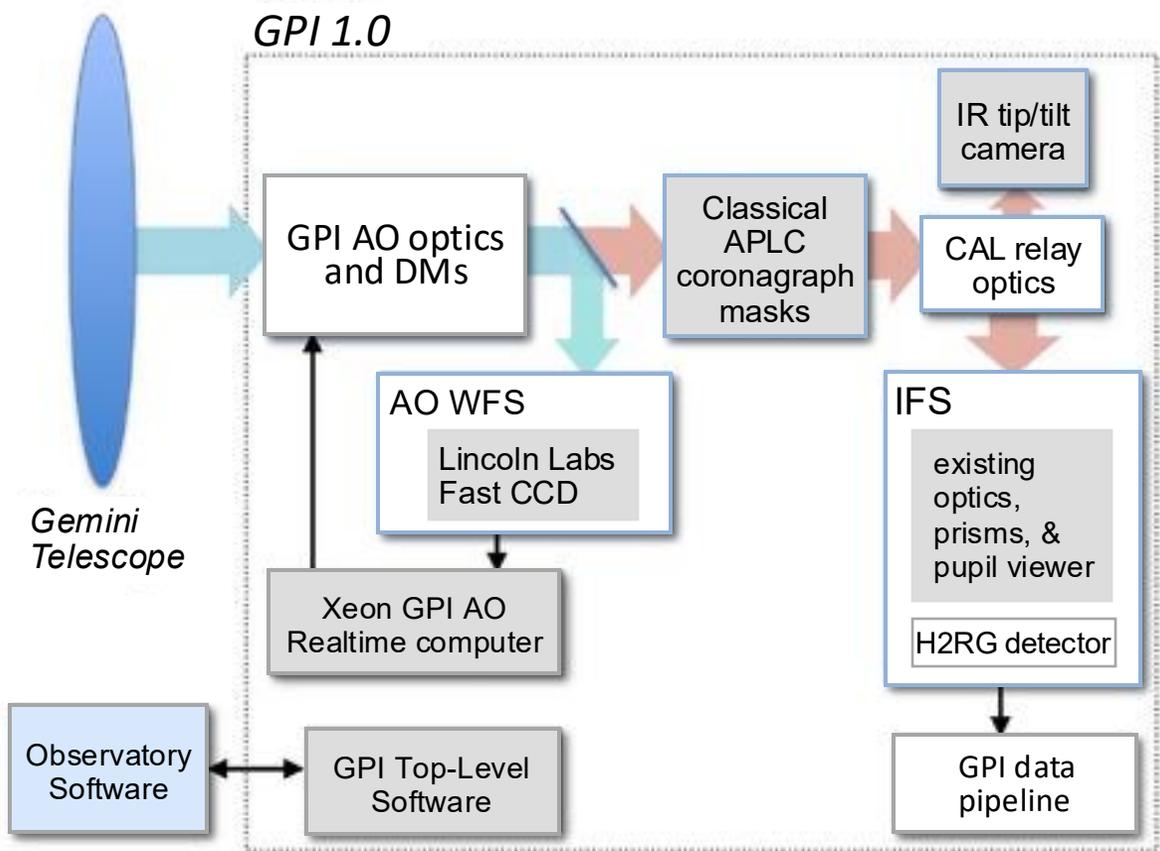
# Background

## Gemini Planet Imager (GPI)



# Background

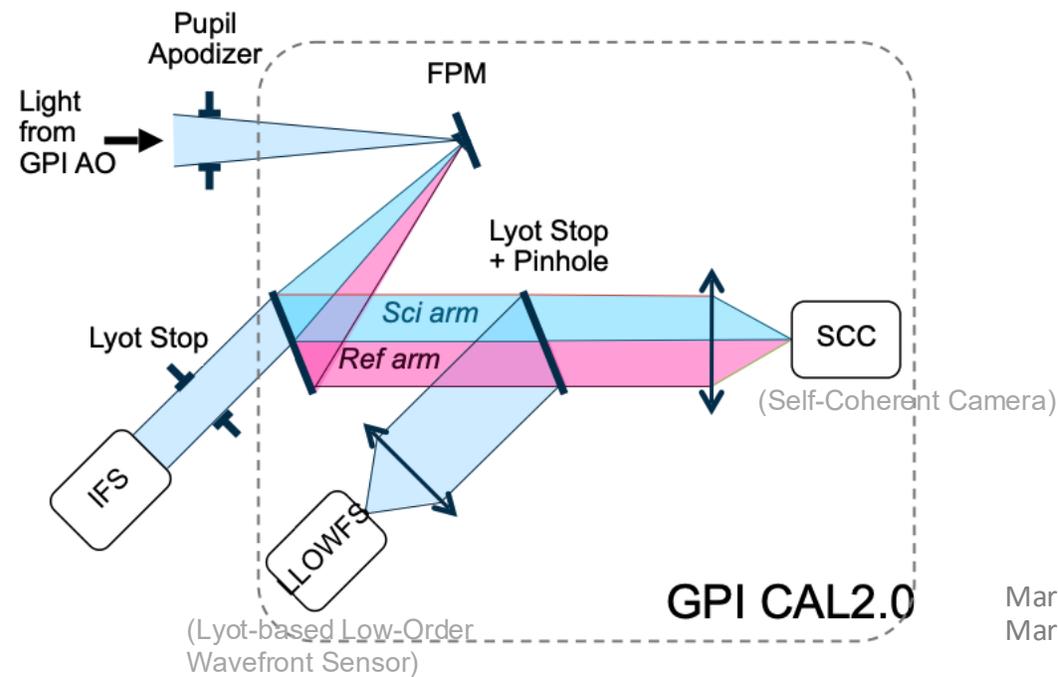
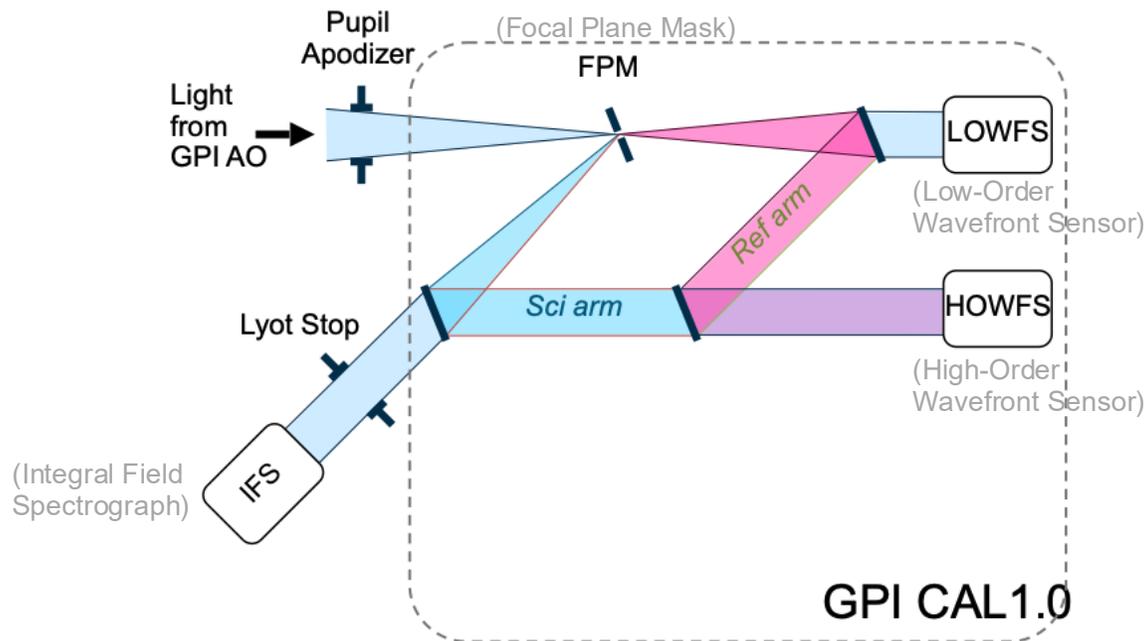
## Upgrade to GPI 2



Adapted from Chilcote et al. 2020

# Background

## Upgrade GPI calibration system to CAL 2



Marois et al. 2020,  
Marois et al. 2024

### Previous challenges:

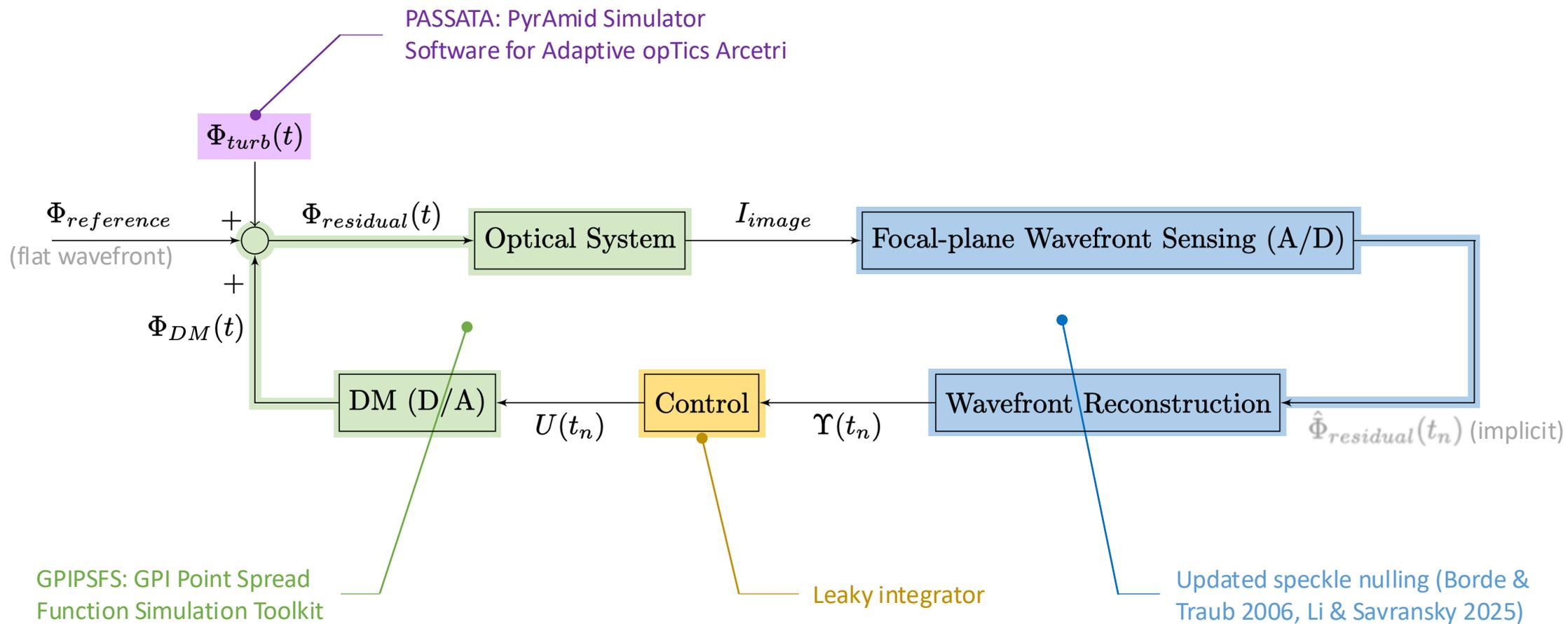
- Non-common path vibrations from dual-arm configuration
- Long integration time to achieve adequate SNR
- Unsuccessful on-sky performance

### Goal:

- Establish a reliable high-order wavefront sensing and control (WFSC) strategy
- Leveraging only SCC's intensity measurements
- Backup for the primary WFSC framework based on SCC's electric-field measurements

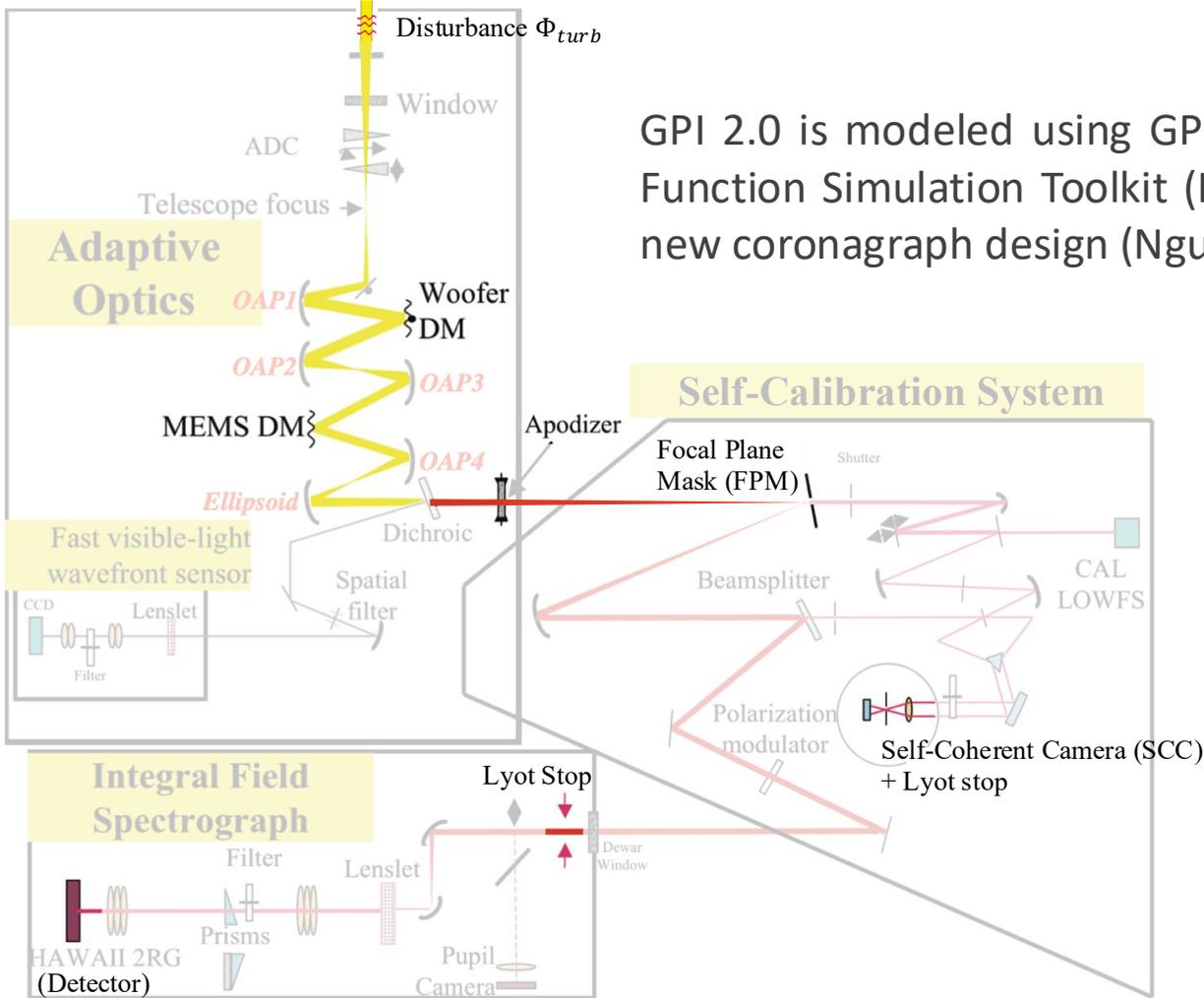
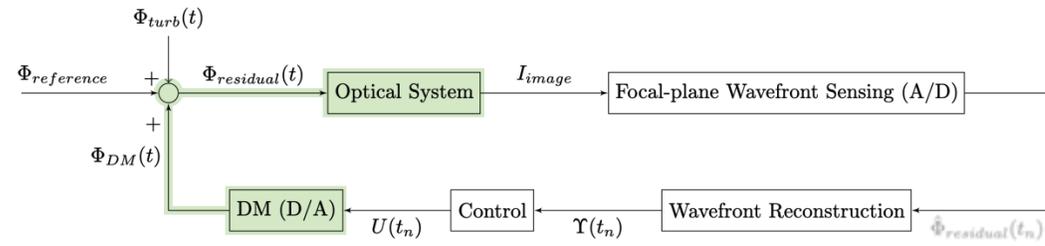
# Methodology

## End-to-end simulation

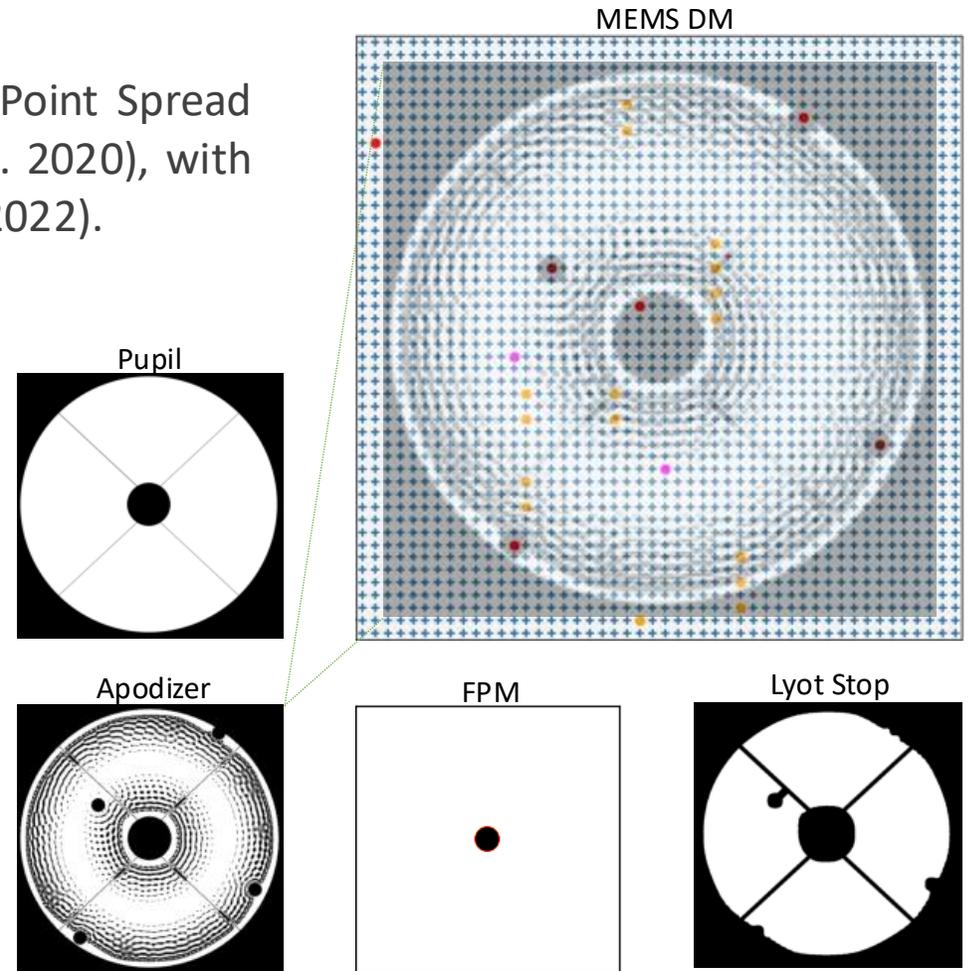


# Methodology

## Simulation of GPI

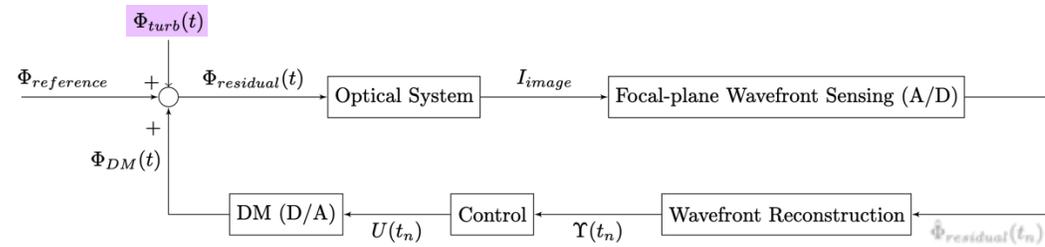


GPI 2.0 is modeled using GPIPFS: GPI Point Spread Function Simulation Toolkit (Perrin et al. 2020), with new coronagraph design (Nguyen et al. 2022).



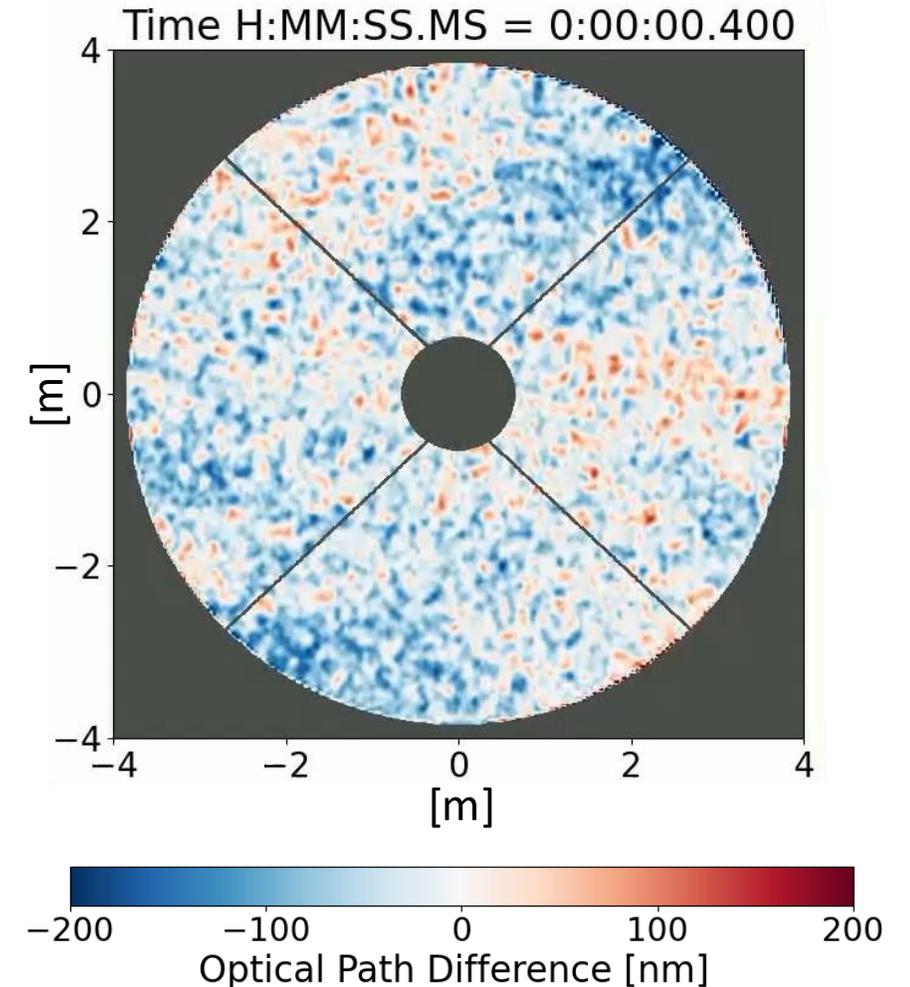
# Methodology

## Residual WF error



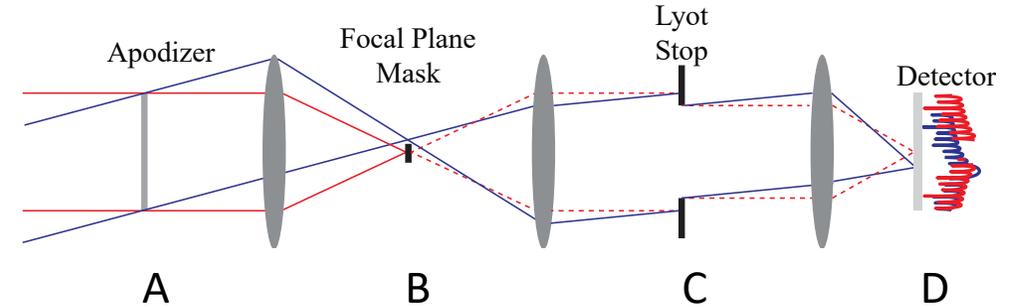
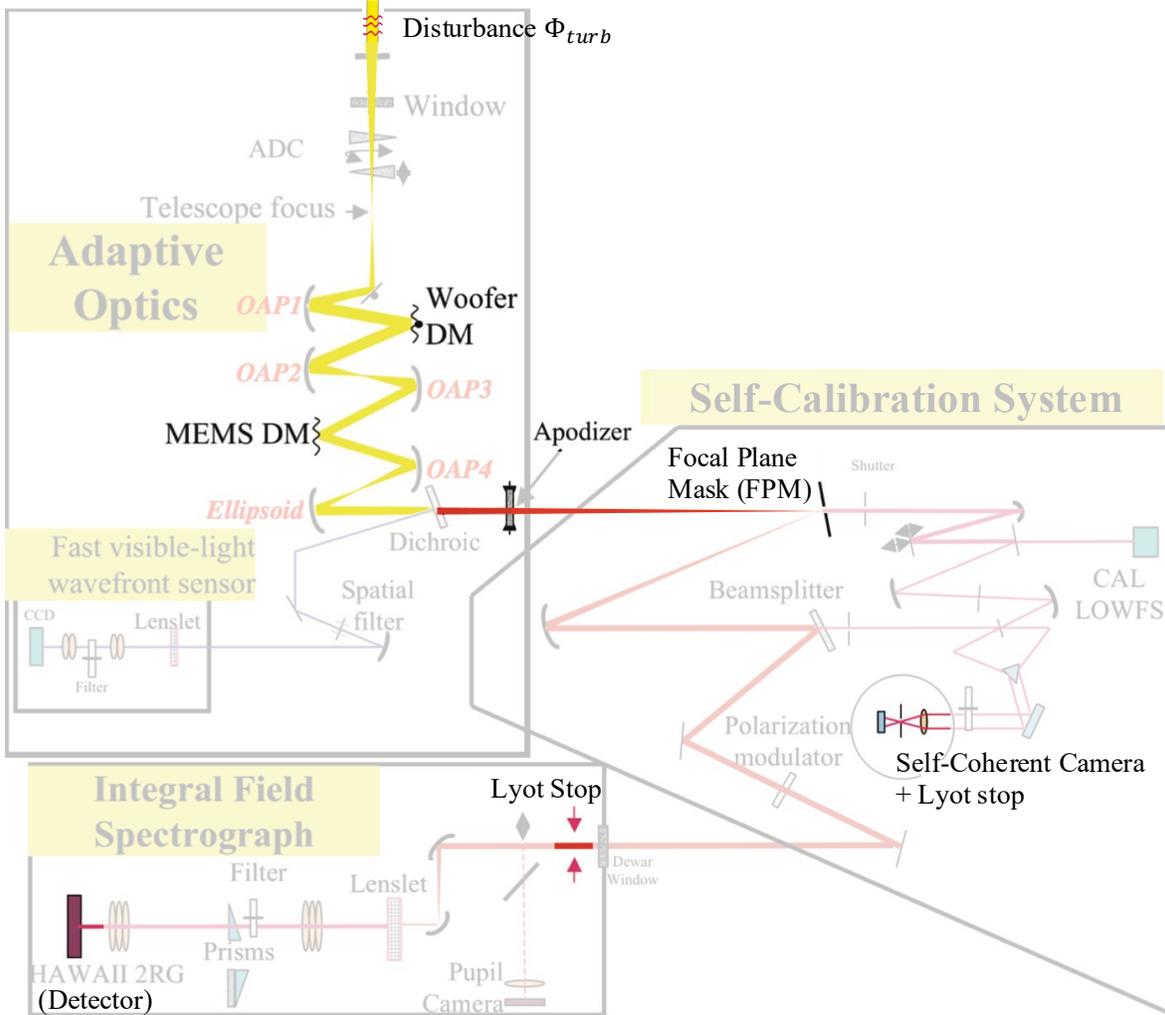
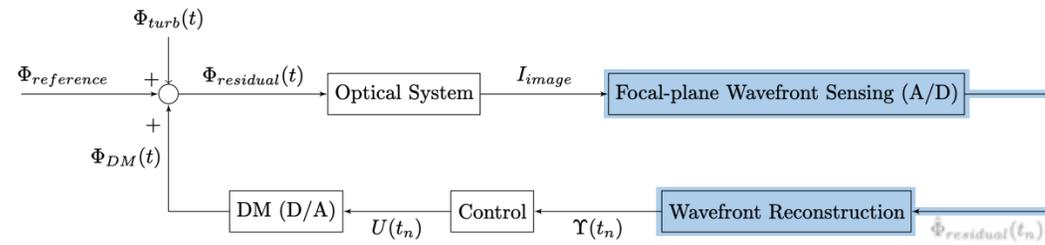
The residual WF error was generated by Jerome Maire using PASSATA: PyrAmid Simulator Software for Adaptive opTics Arcetri (Agapito et al. 2016).

- Natural on-axis 8-magnitude source
  - 7-layer atmosphere with 0.54" seeing
  - GPI 2 configs for pyramid WFS and CCD detector
  - DM capable to control 1603 Zernike modes
  - Real-time computer (slope computer + modal reconstructor + modal integrator controller)
  - Camera that computes H-band PSFs (imaging wavelength = 1650 nm)
  - Total simulation time: 10-sec with 1-msec time steps
- Input to our end-to-end simulation: 25 sample frames @ 1 frame every 4 msec during Time 0:00:00.400 - 0:00:00.500



# Methodology

## WF sensing & reconstruction



Scaling factor omitted in Fourier transforms

$$\Psi_A \propto \Phi_{turb} \Phi_{pupil} \Phi_{DM} \Phi_{apodizer}$$

$$\Psi_B \propto \mathcal{F}(\Psi_A) \Phi_{FPM}$$

$$\Psi_C \propto \mathcal{F}(\Psi_B) \Phi_{Lyot}$$

$$\Psi_D \propto \mathcal{F}(\Psi_C)$$

Electric field

Image intensity  $I \propto |\Psi_D|^2$

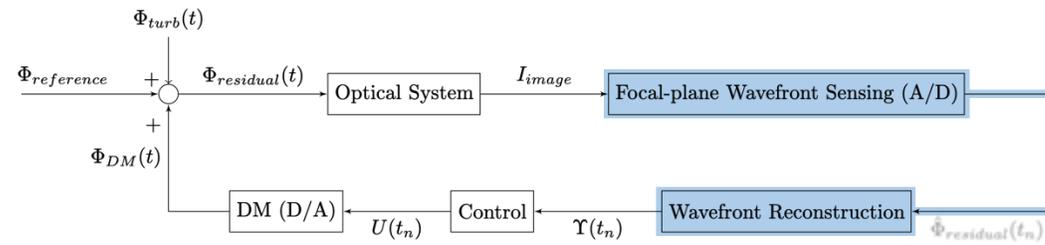
Theory based on Soummer et al. 2007

Convolution

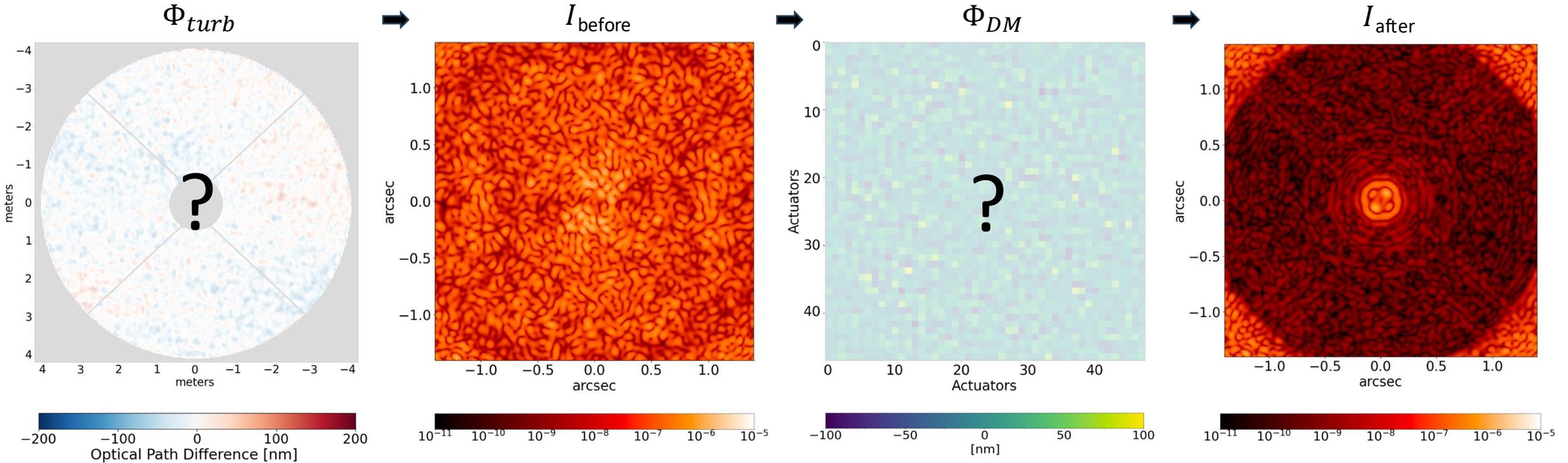
$$I \propto |[\mathcal{F}(\Phi_{turb} \Phi_{pupil} \Phi_{DM} \Phi_{apodizer}) \phi_{FPM}] \otimes \mathcal{F}(\phi_{Lyot})|^2$$

# Methodology

## WF sensing & reconstruction

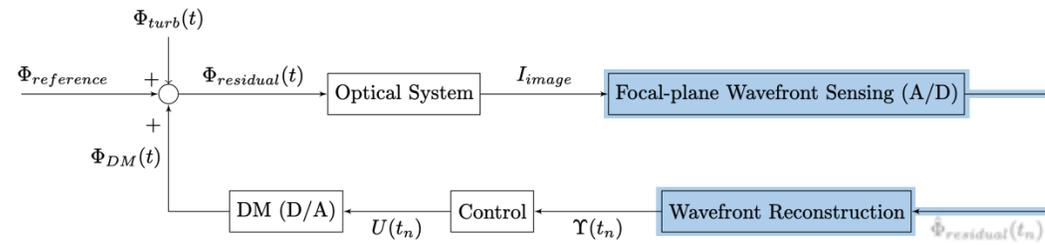


$$I \propto \left| [\mathcal{F}(\Phi_{turb} \Phi_{pupil} \Phi_{DM} \Phi_{apodizer}) \phi_{FPM}] \otimes \mathcal{F}(\phi_{Lyot}) \right|^2$$

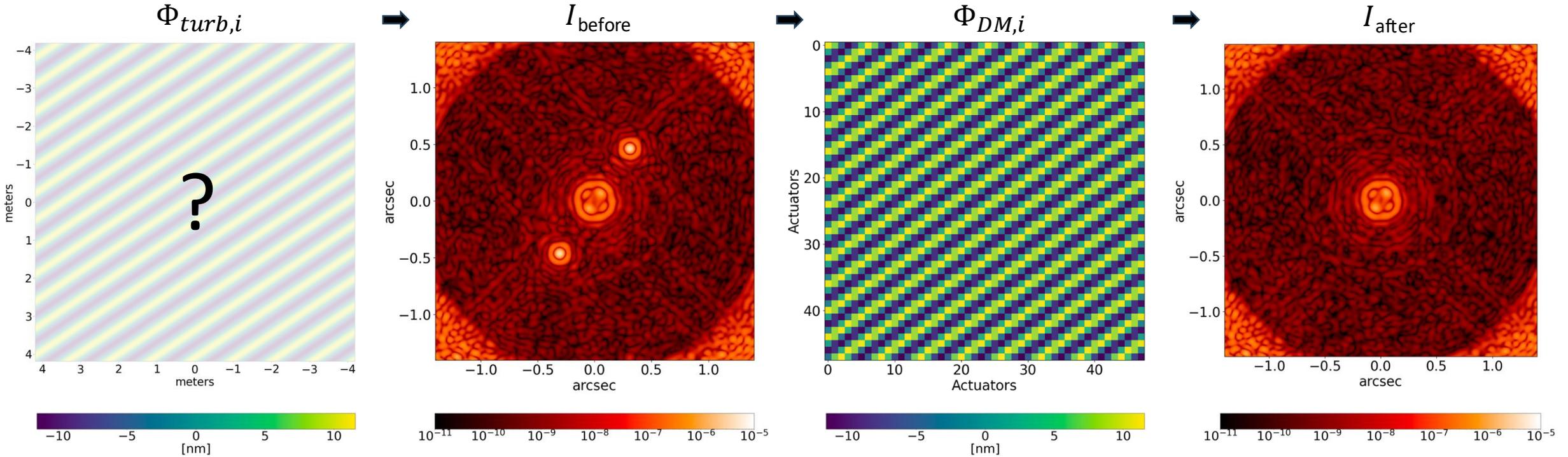


# Methodology

## WF sensing & reconstruction



$$I \propto \left| [\mathcal{F}(\Phi_{turb} \Phi_{pupil} \Phi_{DM} \Phi_{apodizer}) \phi_{FPM}] \otimes \mathcal{F}(\phi_{Lyot}) \right|^2$$

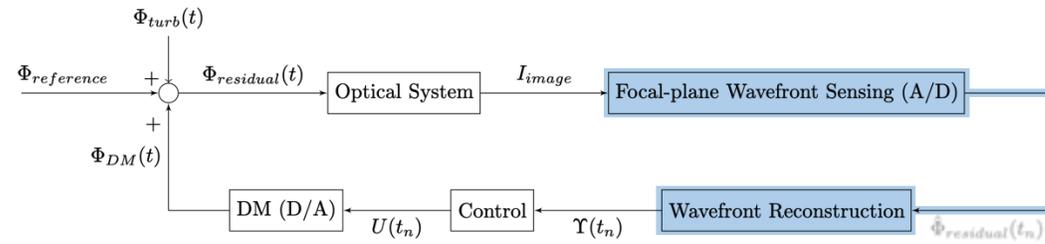


$$\begin{aligned} \Phi_{turb} &= \sum_i \Phi_{turb,i} \\ &= \sum_i B_i \sin(k_{x,i}x + k_{y,i}y + \eta_i) \end{aligned}$$

$$\begin{aligned} \Phi_{DM,ideal} &= \sum_i \hat{\Phi}_{turb,i} \\ &= -\sum_i \hat{B}_i \sin(\hat{k}_{x,i}x + \hat{k}_{y,i}y + \hat{\eta}_i) \end{aligned}$$

# Methodology

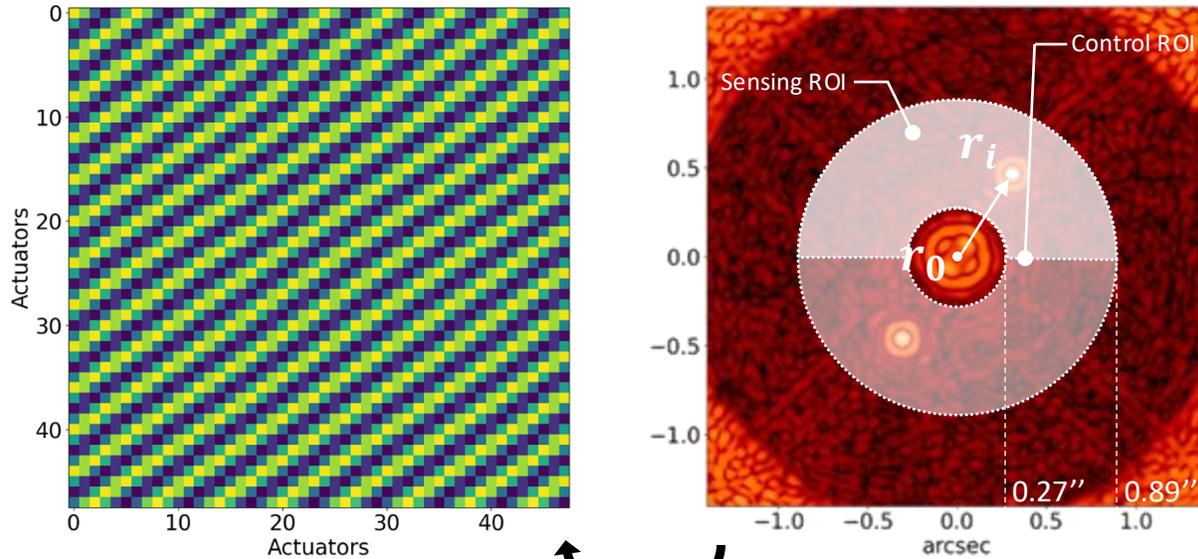
## WF sensing & reconstruction



$$\Phi_{turb} = 0$$

$$\Phi_{DM,i}$$

1-to-2 mapping



$$\hat{\Phi}_{DM} = \sum_i \hat{\Phi}_{DM,i} = -\sum_i \hat{B}_i \sin(\hat{k}_{x,i}x + \hat{k}_{y,i}y + \hat{\eta}_i)$$

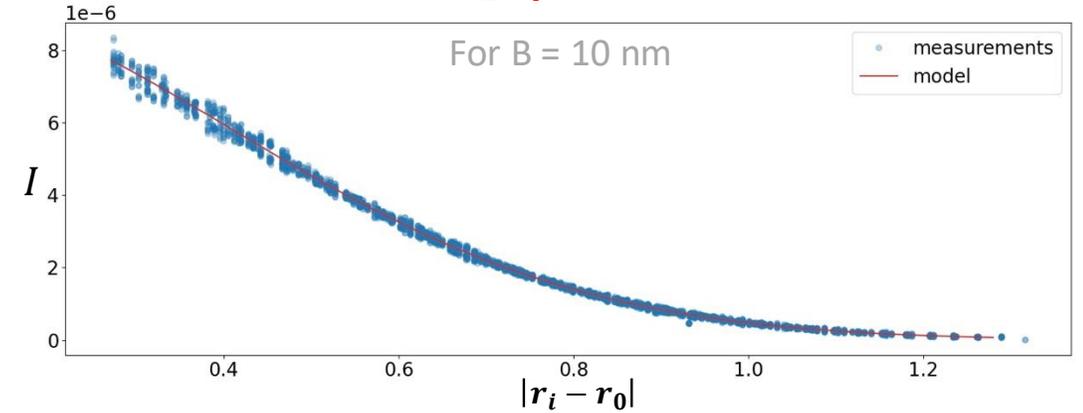
De-rotation between DM and sensor

Optical axis offset in image sensor plane

Scaling factor

$$\text{Speckle location } \mathbf{r}_i = \pm d \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} \begin{bmatrix} \hat{k}_{x,i} \\ \hat{k}_{y,i} \end{bmatrix} + \mathbf{r}_0$$

$$\text{Speckle intensity } I(\mathbf{r}_i) = c_1 \hat{B}_i^2 e^{c_2 |\mathbf{r}_i - \mathbf{r}_0|^2}$$



Destructive interference on residual intensity

$$\hat{\eta}_i = \arg \min_{\eta} I_{\text{after}}(\mathbf{r}_i)$$

$$\Phi_{DM,\text{trial}} = -\sum_i \hat{B}_i \sin(\hat{k}_{x,i}x + \hat{k}_{y,i}y + \eta_{\text{trial}})$$

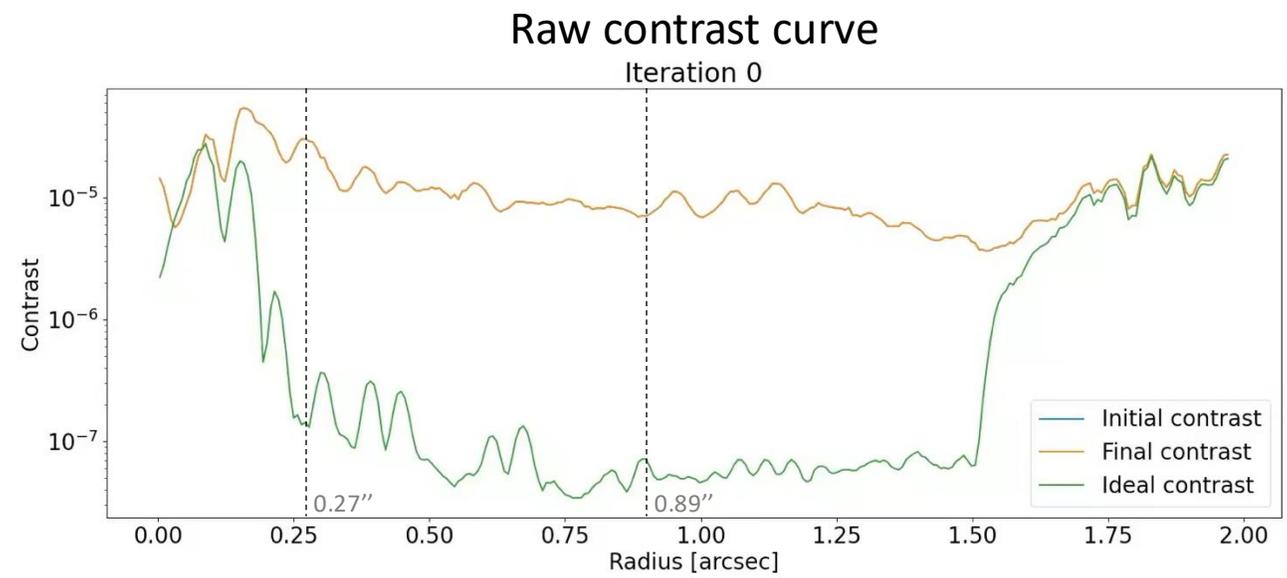
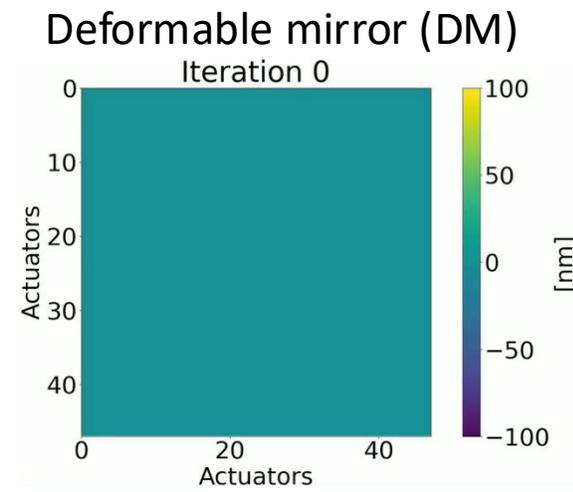
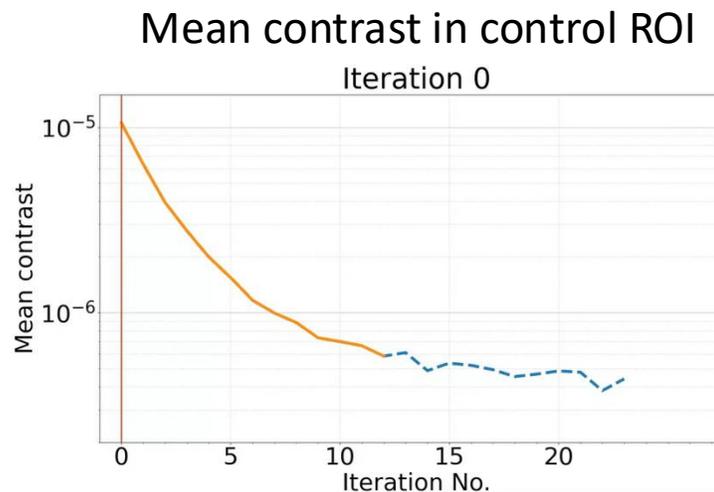
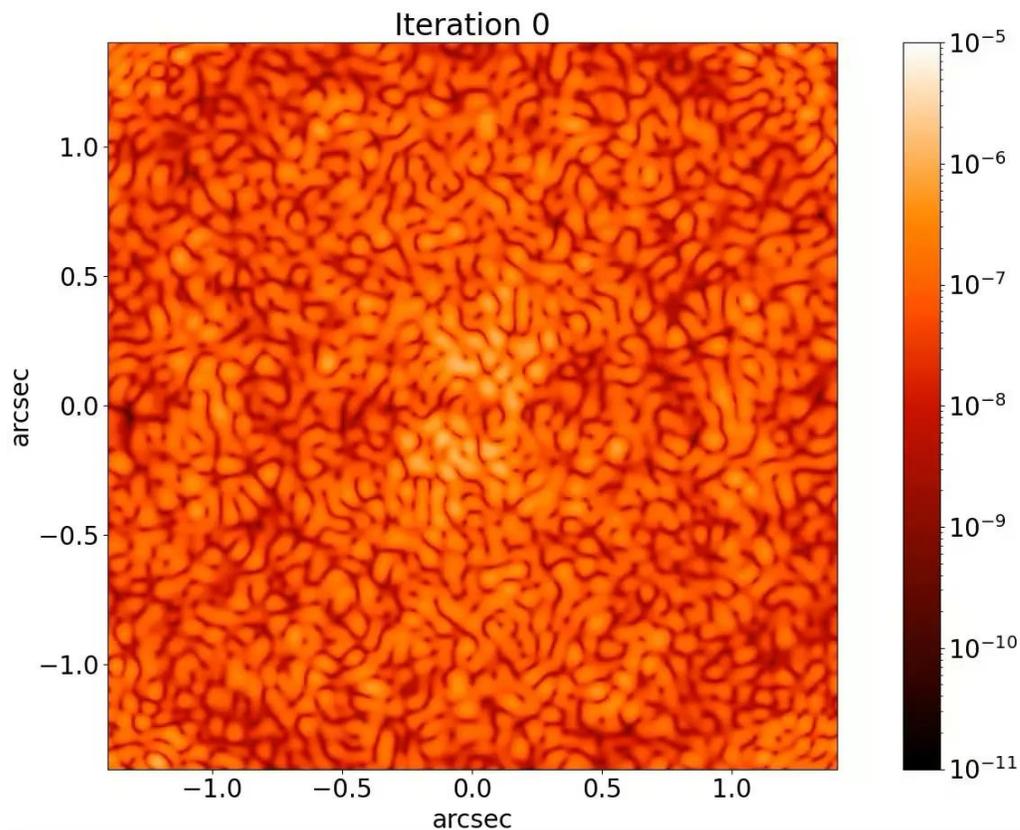
$$\eta_{\text{trial}} = 0, \frac{\pi}{4}, \frac{\pi}{2}, \dots, \frac{7\pi}{4}$$

# Results

## Contrast improvement

Wavelength =  $1.65 \mu\text{m}$

Point Spread Function (PSF)



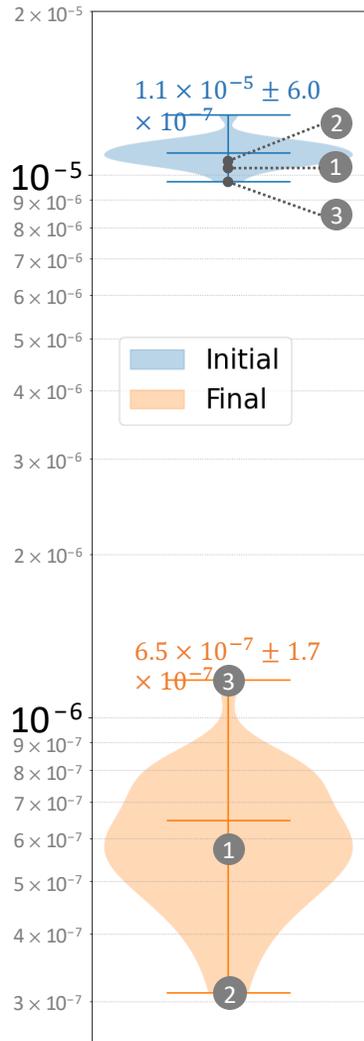
\*Showing results with input residual WF error at Time = 0:00:00.400

\*All contrast reported in this presentation is raw contrast.

# Results

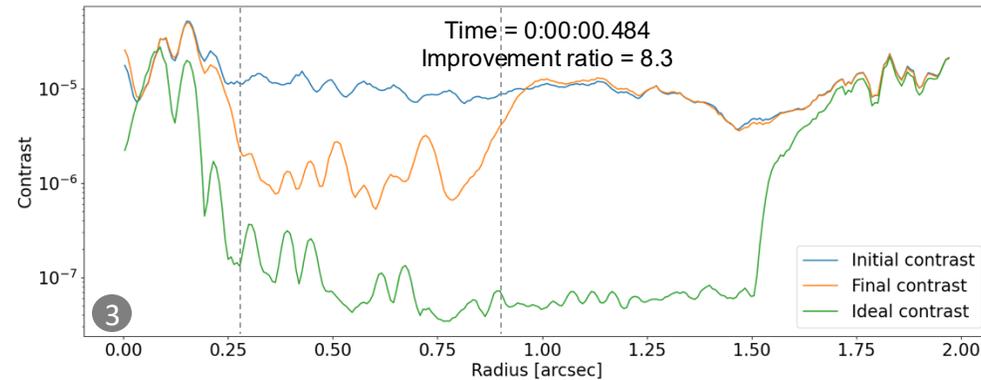
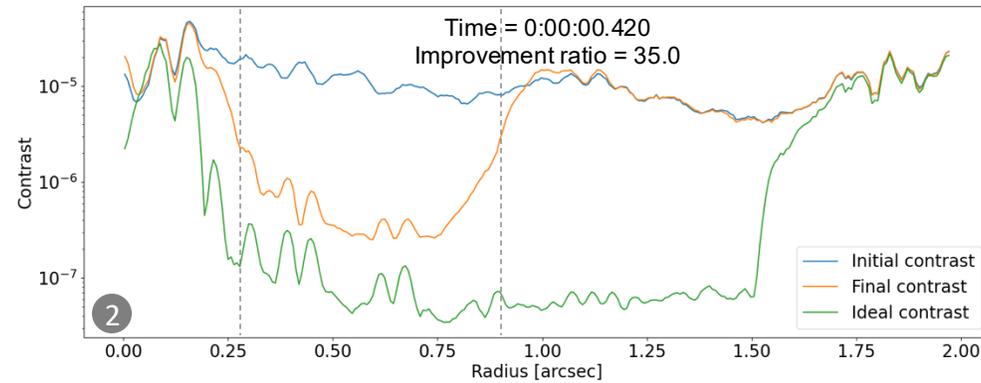
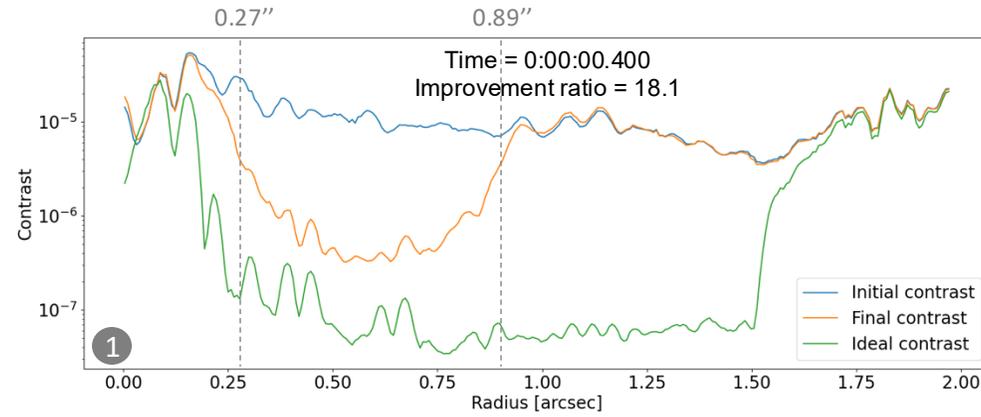
## Contrast improvement

Mean contrast in control region

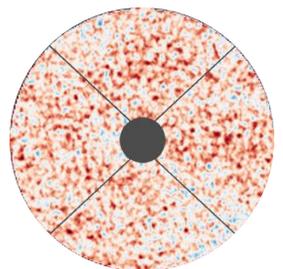
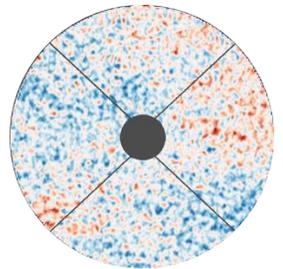
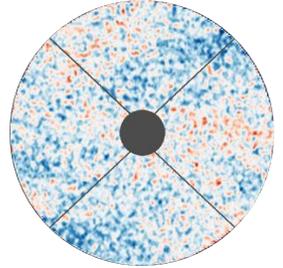


Contrast improvement ratio  
 =  $18.2 \pm 5.3$  for GPI 2  
 vs.  $5.3$  for GPI 1

\*Algorithm ends when there's no step improvement in mean contrast

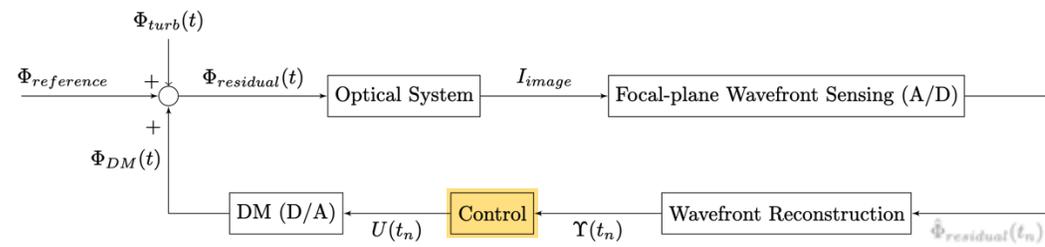


Input residual WF error



# Discussion

## Algorithm optimization – Control



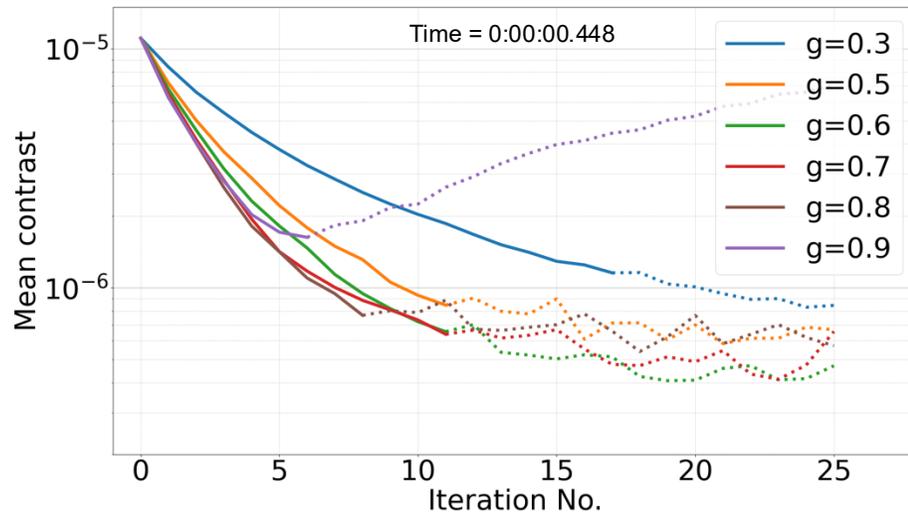
Leaky integrator

$$U(t_n) = f U(t_{n-1}) + g \Upsilon(t_n) \quad \frac{U(z)}{\Upsilon(z)} = \frac{g}{1 - fz^{-1}}$$

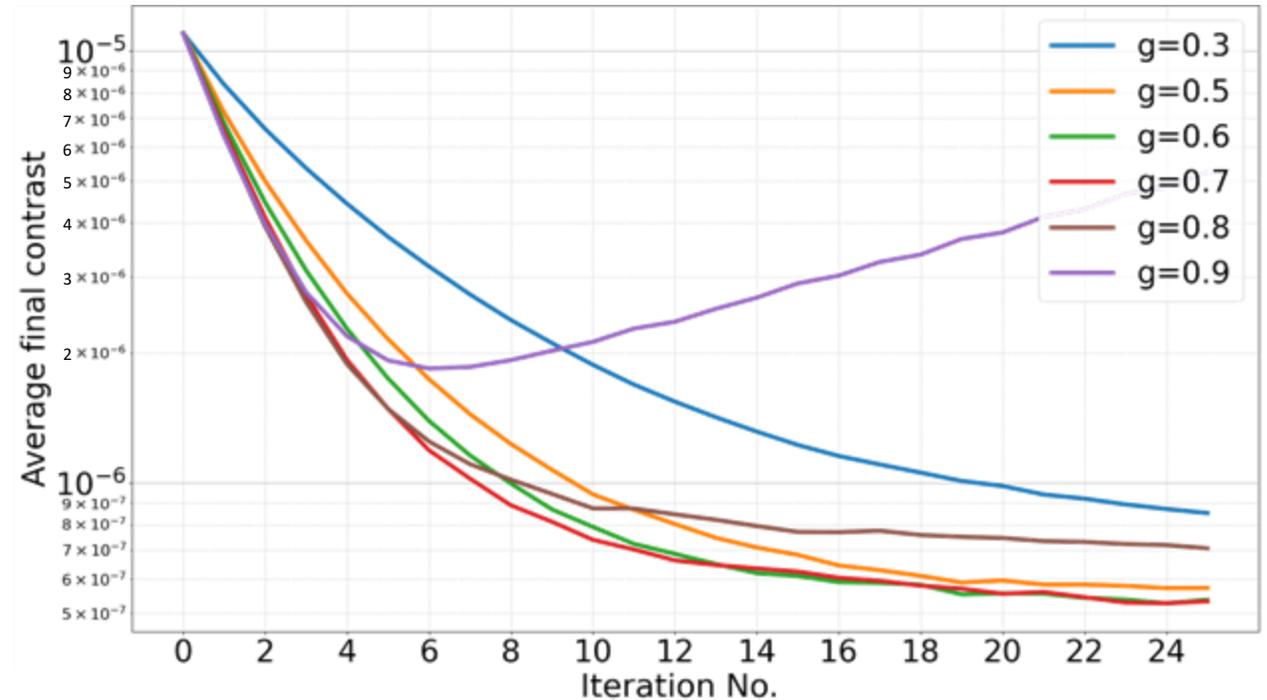
Leaky factor  $f = 0.999$  (legacy)

Integral gain  $g$  : optimized through simulation

Individual performance



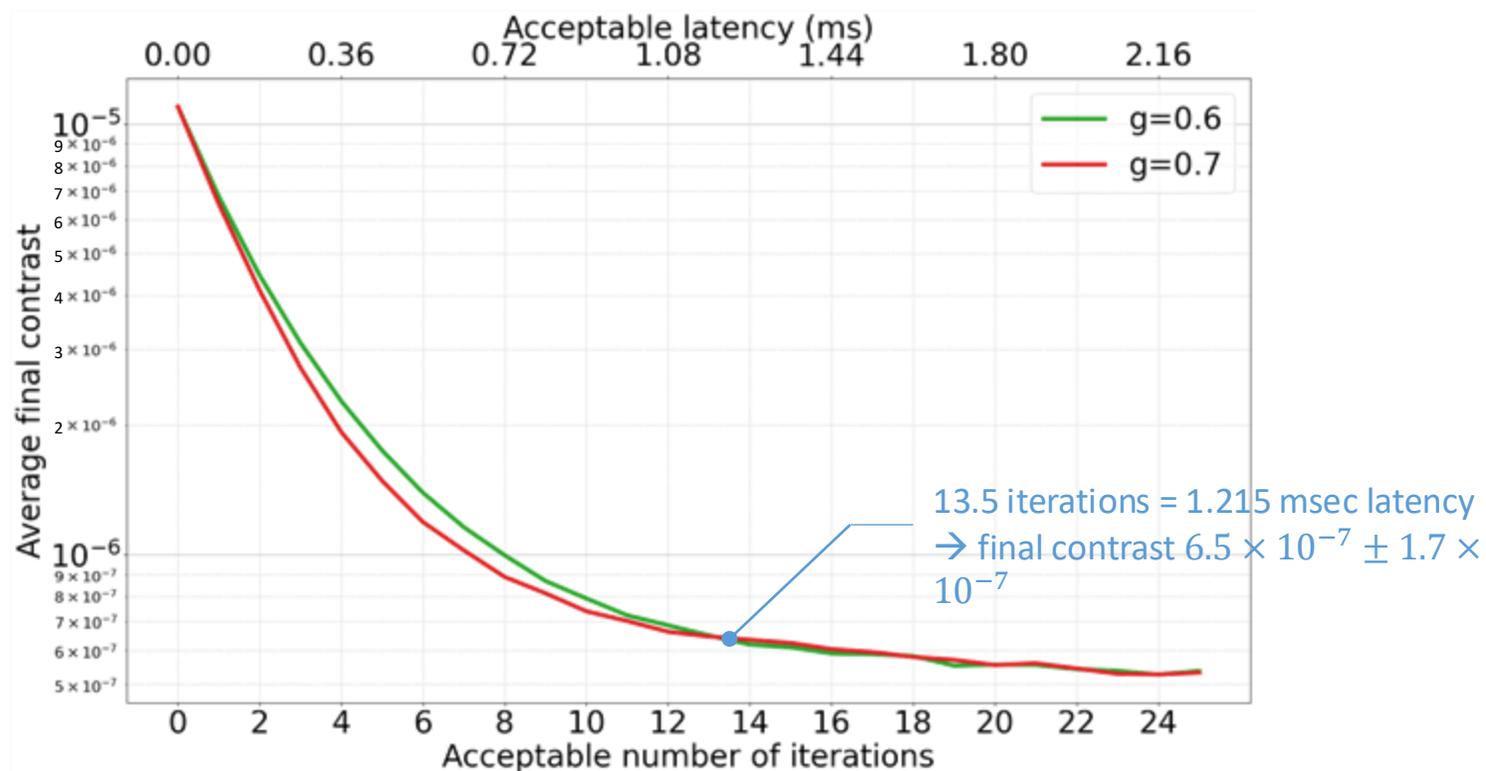
Average performance



# Discussion

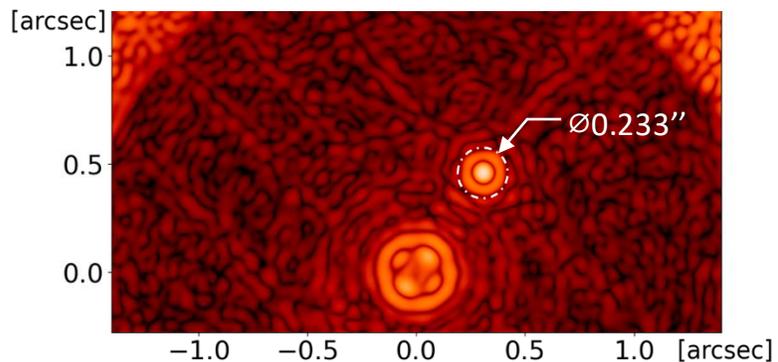
## Latency

- Current convergence criteria = no step improvement in mean contrast → Average 13.5 iterations to converge
- Algorithm requires 9 images per iterations; Self-Coherent Camera (SCC) integration + readout time  $\approx 10 \mu\text{sec}$
- In comparison, GPI 1 CAL camera's integration time  $\approx 30 \text{ sec}$
- Method removes the latency overhead of GPI 2 CAL 2's imaging system

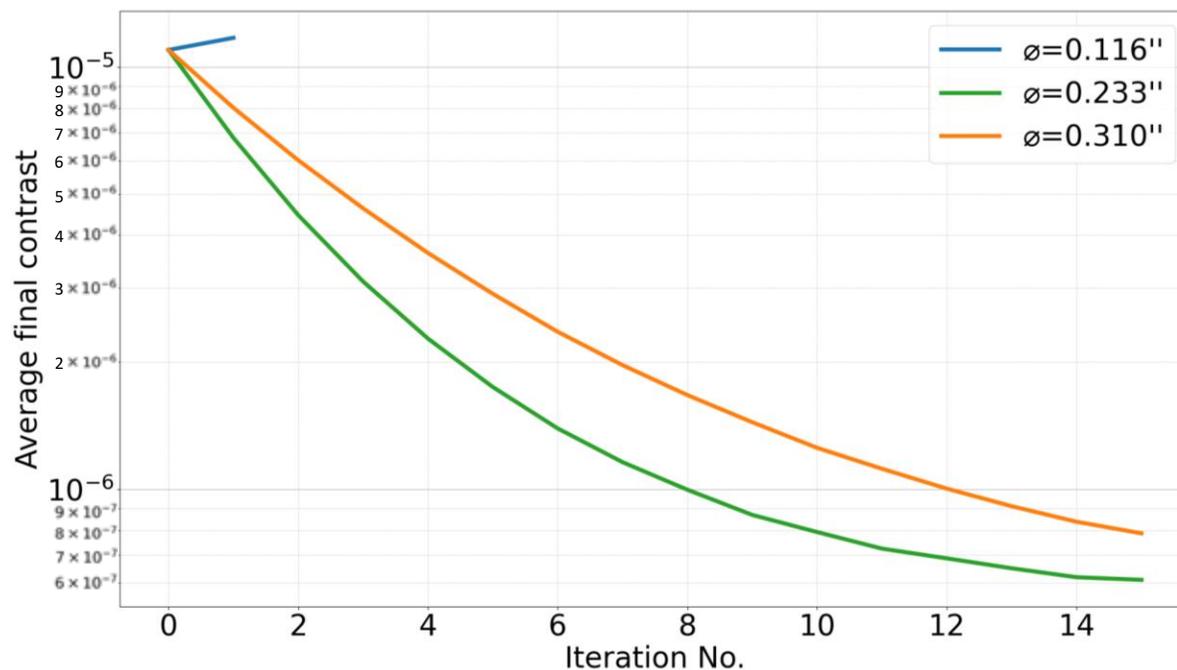
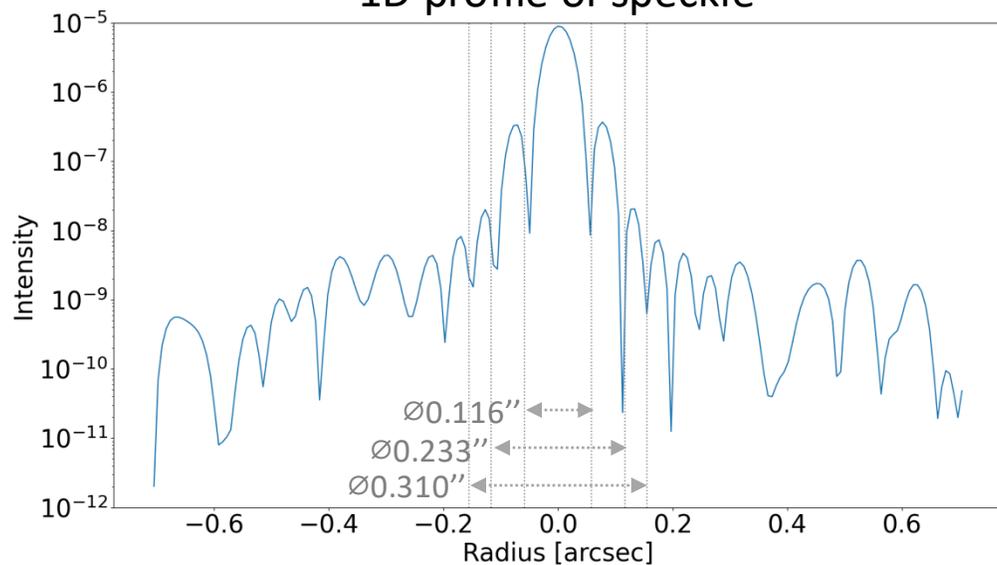


# Discussion

## Algorithm optimization – Crosstalk



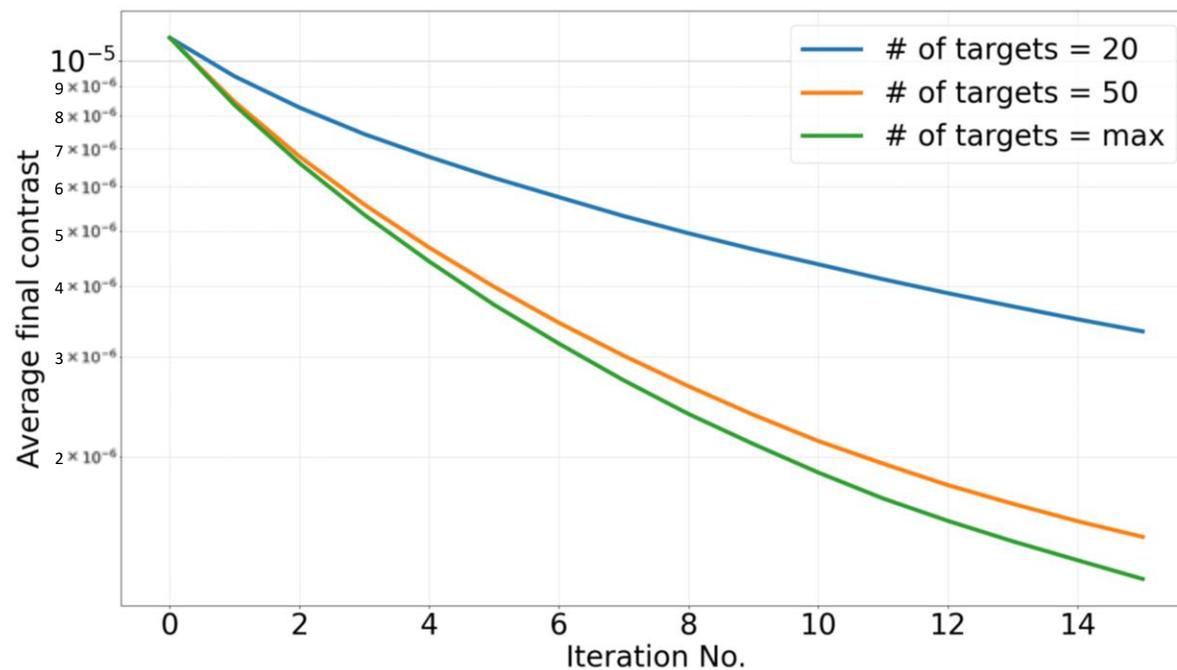
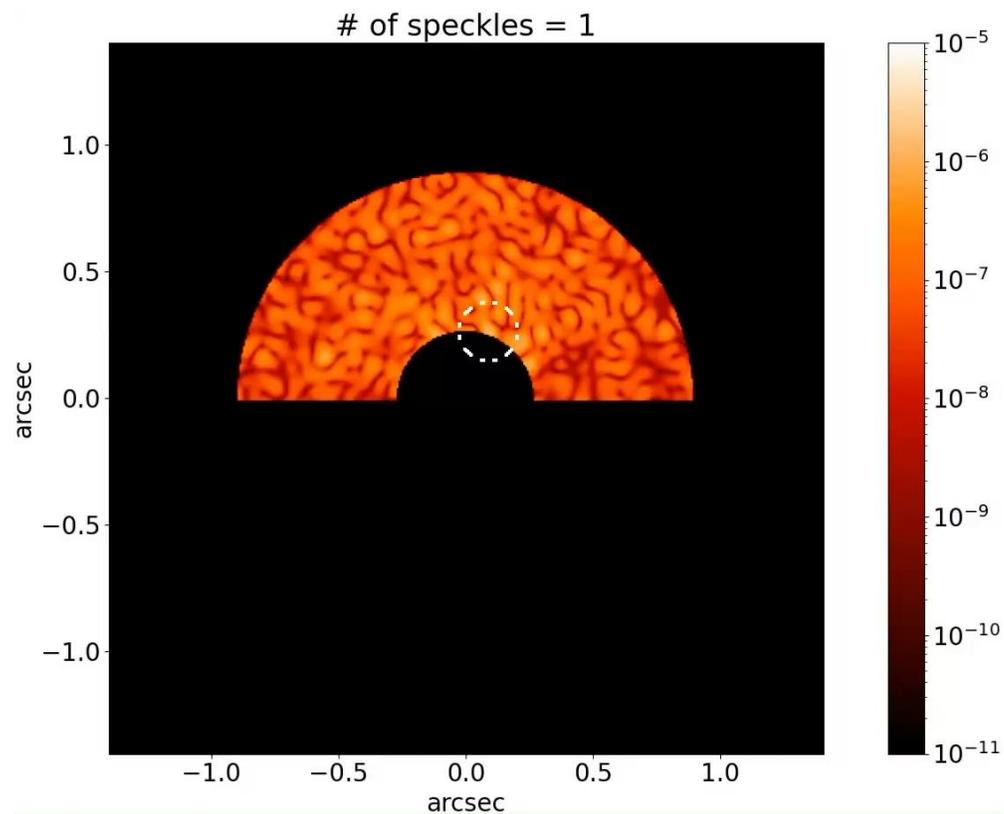
1D profile of speckle



Controlled variables: integral gain  $g=0.6$ , # of target speckles = max

# Discussion

## Algorithm optimization – Number of target speckles



Controlled variables: integral gain  $g=0.3$ , crosstalk mask  $\varnothing = 0.233''$

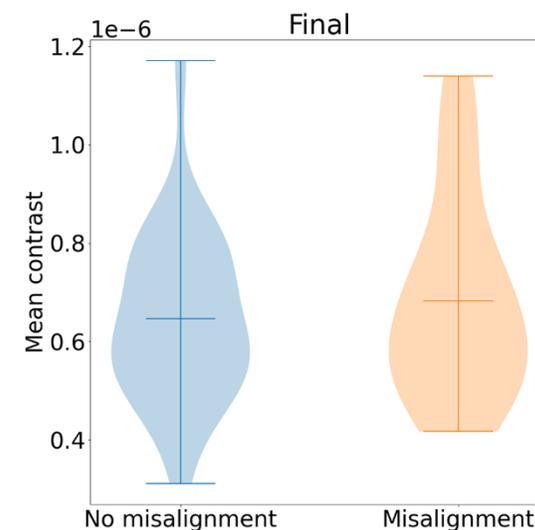
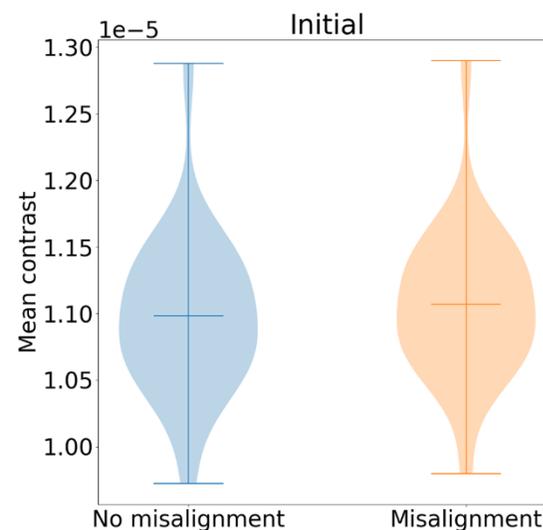
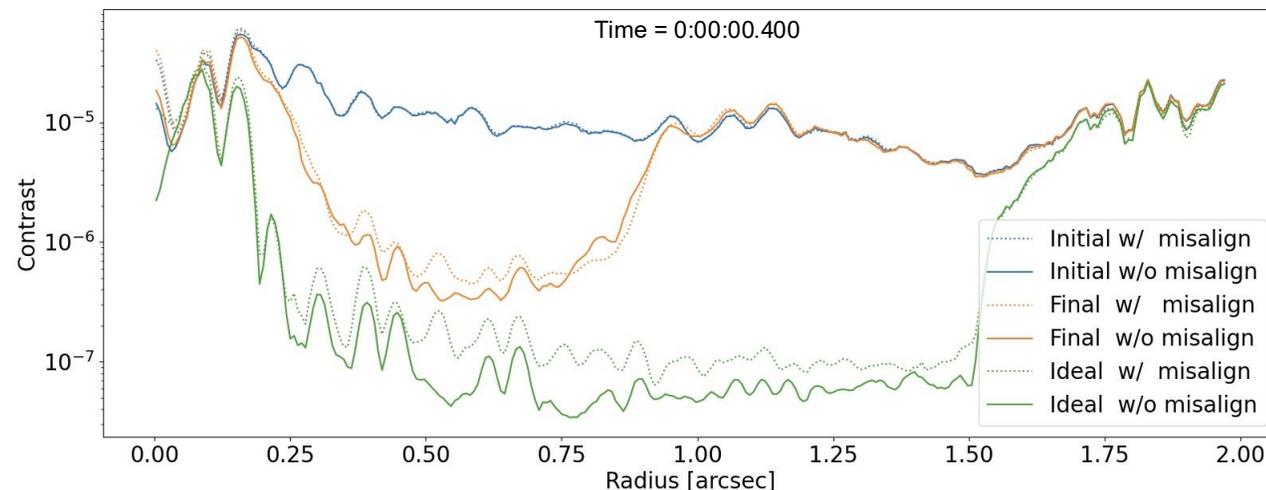
# Discussion

## Effect of misalignment

GPI estimated misalignment  $\leq 0.2\%$  (Savransky et al. 2013)

Conservative simulation: shift Apodizer and Lyot stop in opposite diagonal directions by 0.4% each

		Aligned	Misaligned
Mean contrast ( $\times 10^{-7}$ )	Ideal	0.86	1.76
	Initial	$110 \pm 6.0$	$111 \pm 5.7$
	Final	$6.5 \pm 1.7$	$6.8 \pm 2.0$
Contrast improve ratio	Avg. $\pm$ std.	$18.2 \pm 5.3$	$17.6 \pm 5.0$
	Max	35.0	26.9
	Min	8.3	8.6
Number of iterations		$13.5 \pm 1.9$	$13.0 \pm 1.9$



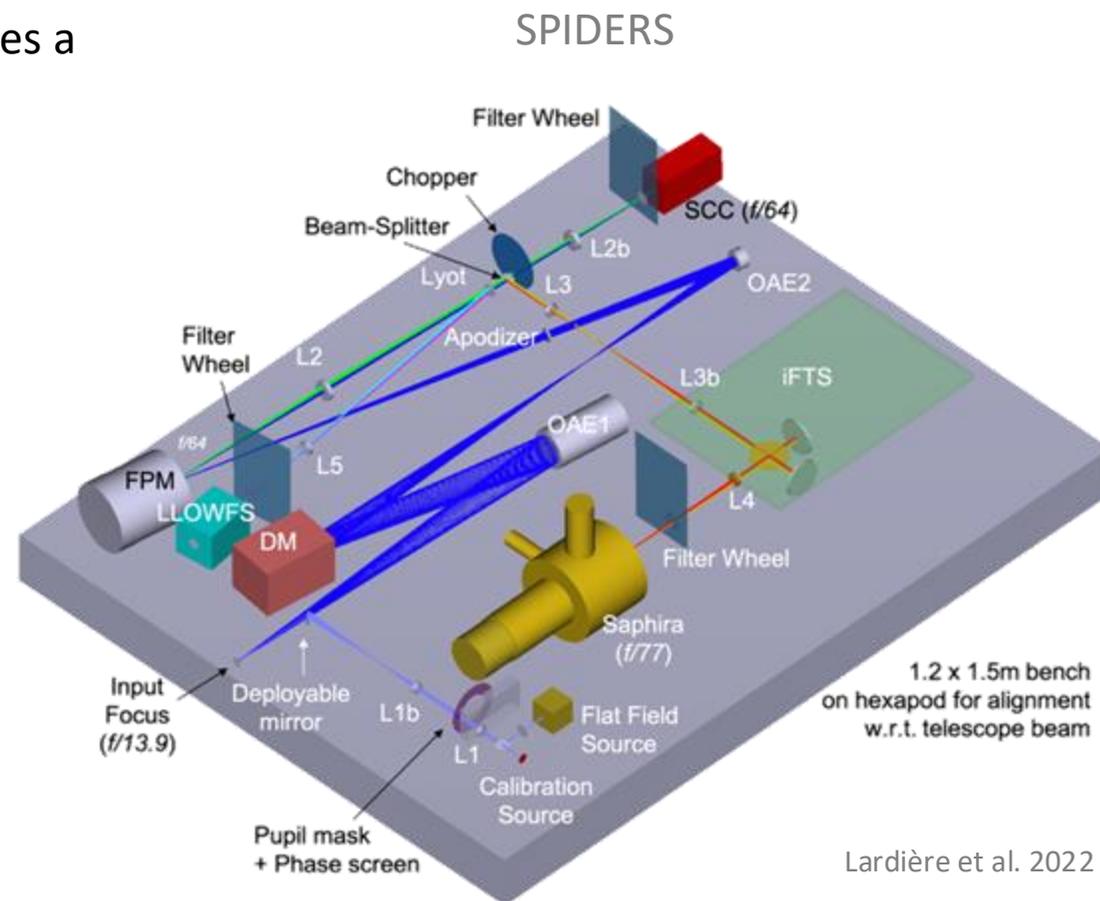
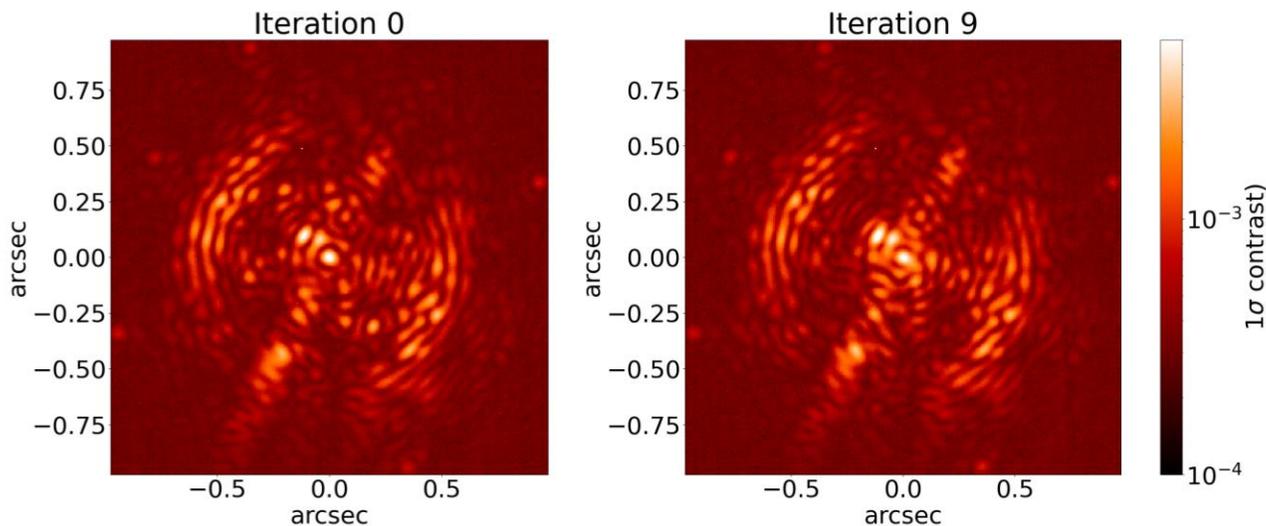
# Experiment

## Early work onsite

Early experiments were conducted on Subaru Pathfinder Instrument for Detecting Exoplanets & Retrieving Spectra (SPIDERS), which shares a similar architecture with CAL2.

### Limitations

- Insufficient crosstalk mask size
- Discrete Fourier modal control on DM (24 x 24 actuators)



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# Conclusion

## Achievements

- Focal-plane wavefront sensing and control method to mitigate AO residual wavefront errors
  - Relies solely on intensity measurements provided by the SCC
- Significant advancement compared to prior version on GPI 1
  - @ $\lambda = 1.65 \mu m$ , contrast improvement by a factor of  $18.2 \pm 5.3$  with 1.215 msec imaging latency
  - Final raw contrast  $6.5 \times 10^{-7} \pm 1.7 \times 10^{-7}$  within star-planet angular separations of [0.27,0.89] arcsec
- Robust fallback option for CAL2's primary high-order wavefront sensing and control system

## Existing error sources

- GPI 2.0 optical system modeling errors
  - GPIPFS using Fraunhofer diffraction
  - DM calibration error; approximating DM influence function as Gaussian
  - Interpolation error in phase estimation due to limited sampling
- Uncorrected amplitude aberration

## Future work

- Test and validate optimized algorithm on GPI 2.0 hardware
- Improve GPI 2.0 optical system modeling using Fresnel diffraction & simulate broadband performance
- Simulate the real-time impact of latency with quasi-static aberrations
- Implement alternative methods that potentially have lower latency, e.g. implicit Electric Field Conjugation (iEFC)

# Contributions

## Focal Plane Wavefront Sensing and Control for Various Optical Systems

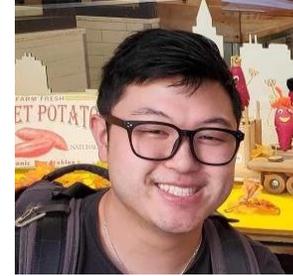
- Journals
  - **Li, D.** & Savransky, D. (2023) *Image plane wavefront sensing and Kalman filtering for automated alignment of off-axis aspherics*. JOSA A.
  - **Li, D.** & Savransky, D. "Focal Plane Wavefront Sensing and Control in the Gemini Planet Imager 2.0's calibration system" (To be submitted)
- First-author conference publications
  - **Li, D.**, Thompson, W., Savransky, D., & Marois, C. (2023) *Focal plane wavefront control for the Gemini Planet Imager 2.0 calibration system (CAL2)*. SPIE Astronomical Telescopes + Instrumentation.
  - **Li, D.** & Savransky, D. (2021) *Automated Reflective Optical System Alignment: Analysis and Experiments*. SPIE Optical Engineering + Applications.
  - **Li, D.** & Savransky, D. (2020) *Automated Reflective Optical System Alignment with Focal Plane Sensing and Kalman Filters*. SPIE Astronomical Telescopes + Instrumentation.

# Contributions

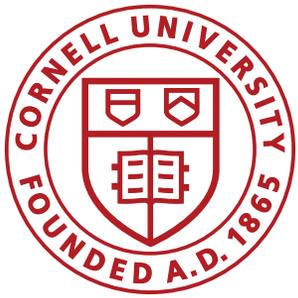
## Focal Plane Wavefront Sensing and Control for Various Optical Systems

- First-author conference presentations
  - **Li, D.**, Thompson, W., Savransky, D., & Marois, C. (2023) *Speckle Nulling for High Contrast Imaging on a Self Coherent Camera*. American Astronomical Society.
  - **Li, D.** & Savransky, D. (2020) *Automated Reflective Optical System Alignment with Focal Plane Sensing and Optimal State Estimation*. OSA Imaging and Applied Optics Congress.
  - **Li, D.** & Savransky, D. (2019) *Automated Optical System Alignment with Focal Plane Sensing*. Emerging Researchers in Exoplanet Science.
- Collaborative conference publications/presentations
  - Nguyen, J. S., et al. (2024) *GPI 2.0: End-to-end simulations of the AO-coronagraph system*. SPIE.
  - Perera, S., et al. (2024) *GPI 2.0: Pre-integrated pyramid wavefront sensor results*. SPIE.
  - Marois, C., et al. (2024) *CAL2: Project update of the NRC Canada facility-class focal plane wavefront sensor for the Gemini Planet Imager 2 upgrade*. SPIE.
  - Do Ó, C. R., et al. (2024) *GPI 2.0: Exploring the impact of different readout modes on the wavefront sensor's EMCCD*. SPIE.
  - Perera, S., et al. (2023) *Upgrading the Gemini planet imager to GPI 2.0*. SPIE.
  - Do Ó, C. R., et al. (2022) *GPI 2.0: Performance evaluation of the wavefront sensor's EMCCD*. AO4ELT.
  - Perera, S., et al. (2022) *GPI 2.0: Pyramid wavefront sensor status*. SPIE.
  - Chilcote, J., et al. (2022) *GPI 2.0: Upgrade status of the Gemini Planet Imager*. SPIE.
  - Chilcote, J., et al. (2020) *GPI 2.0: Upgrading the Gemini Planet Imager*. SPIE.
  - Madurowicz, A., et al. (2020) *GPI 2.0 : Optimizing reconstructor performance in simulations and preliminary contrast estimates*. SPIE.

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**Thank You!**

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