Spatial Linear Dark Field Control: Maintaining high-contrast imaging capabilities on an extreme AO system

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Laboratoire D' Astrophysique
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Presentation Overview

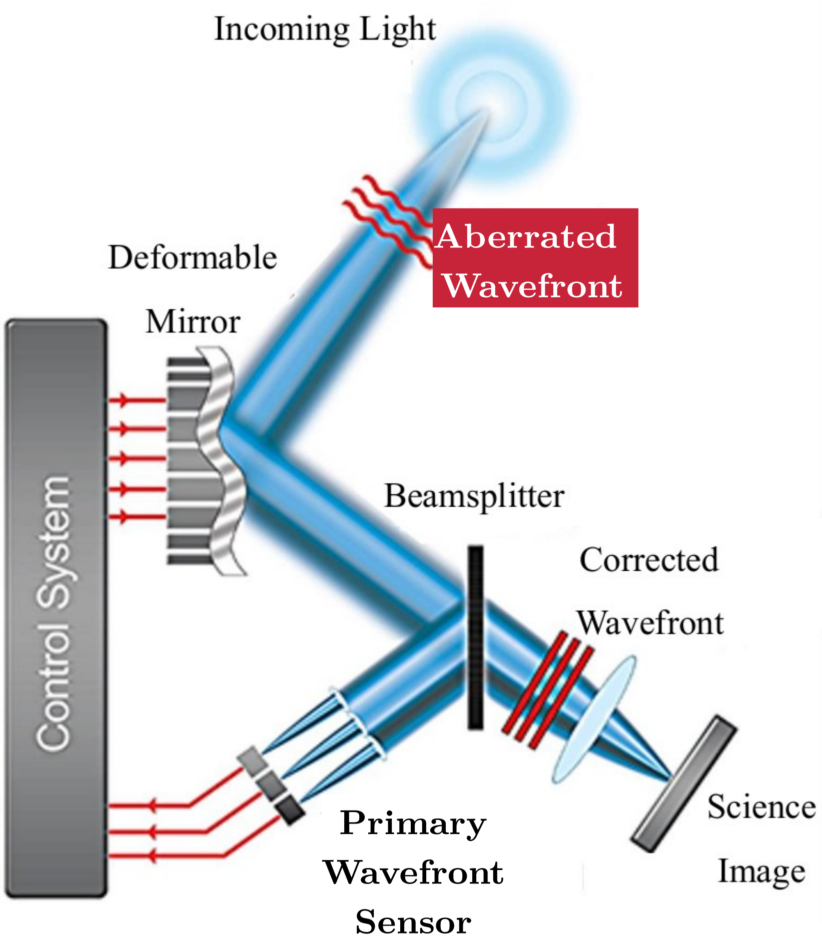
- **Background**
    - Focal plane wavefront sensing
    - Coronagraphy with a vector apodizing phase plate (vAPP)
- **Linear dark field control (LDFC)**
    - Theory
    - Operation
- **Results on the Subaru Coronagraphic Extreme AO instrument (SCExAO)**

Background

What is focal plane wavefront sensing?
Why do we use it?
How is it implemented with a vAPP coronagraph?

Focal Plane Wavefront Sensing

Standard Closed-Loop Adaptive Optics System



Aberrated Wavefront

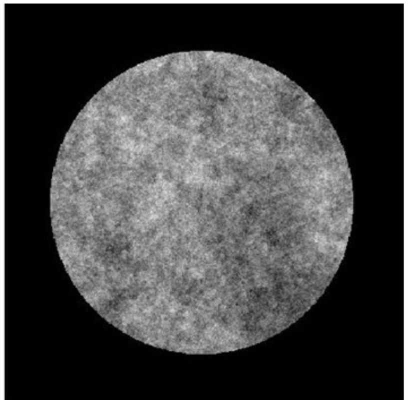
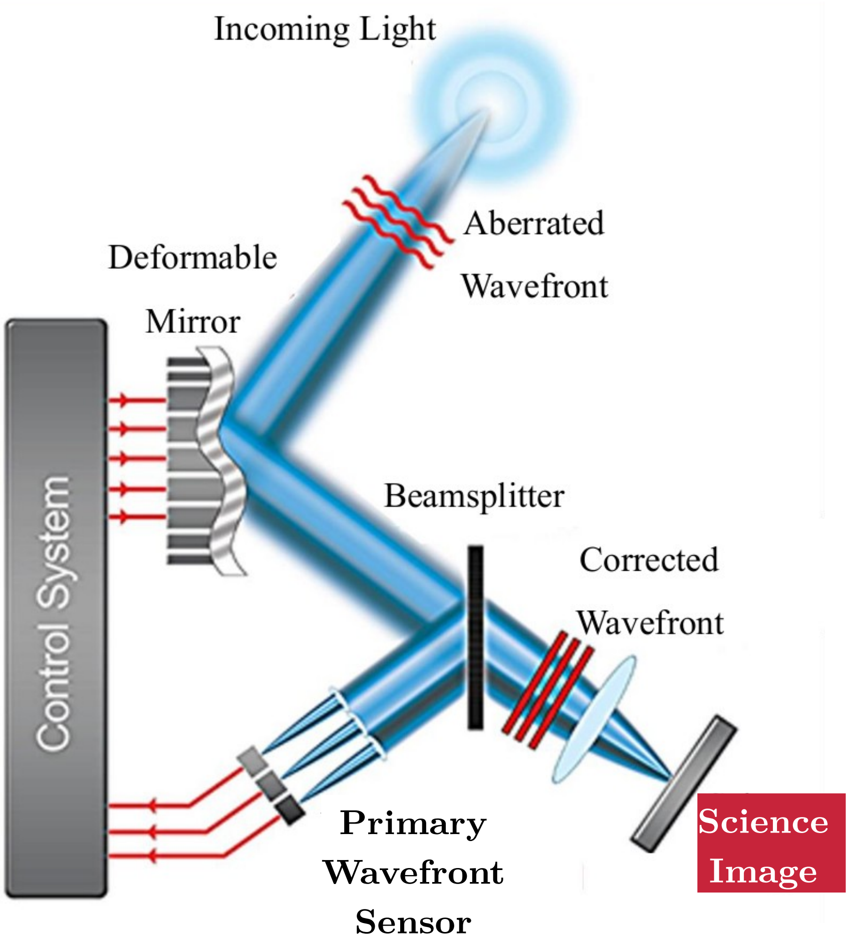


Diagram credit: BMC

Focal Plane Wavefront Sensing

Standard Closed-Loop Adaptive Optics System



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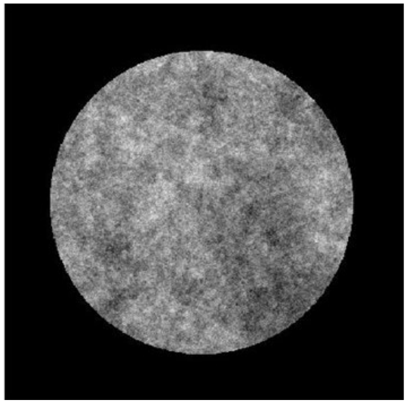
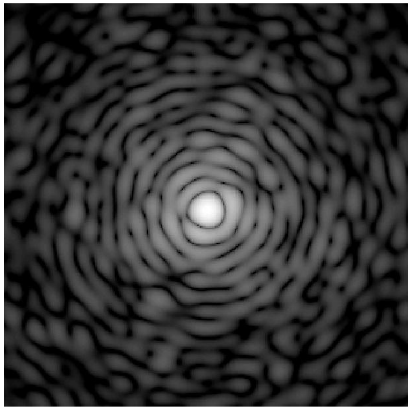


Science Image



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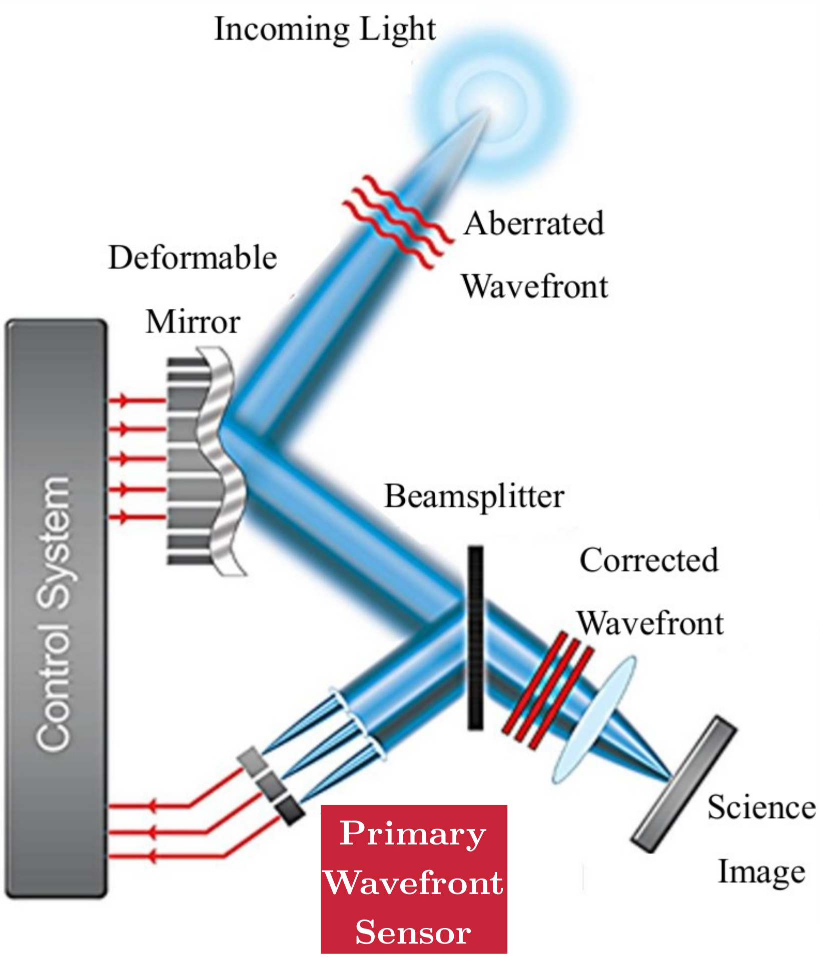
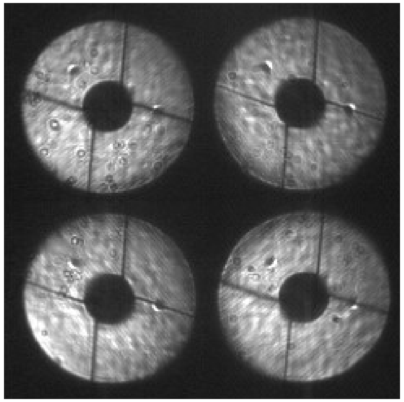
Focal Plane Wavefront Sensing

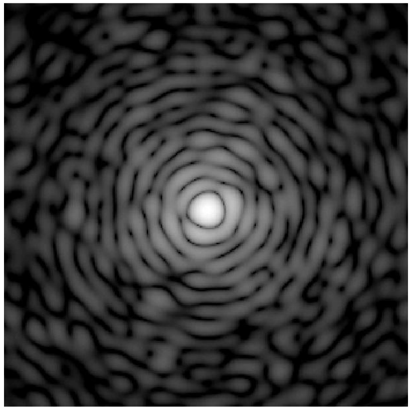
Standard Closed-Loop Adaptive Optics System



Primary Wavefront Sensor: Pyramid



Science Image



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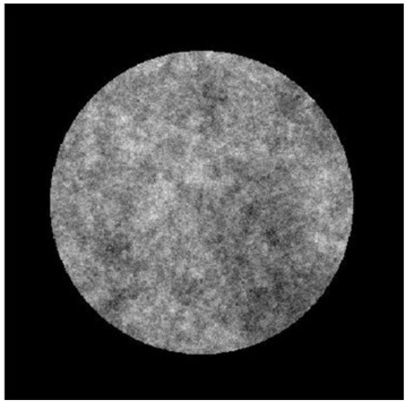

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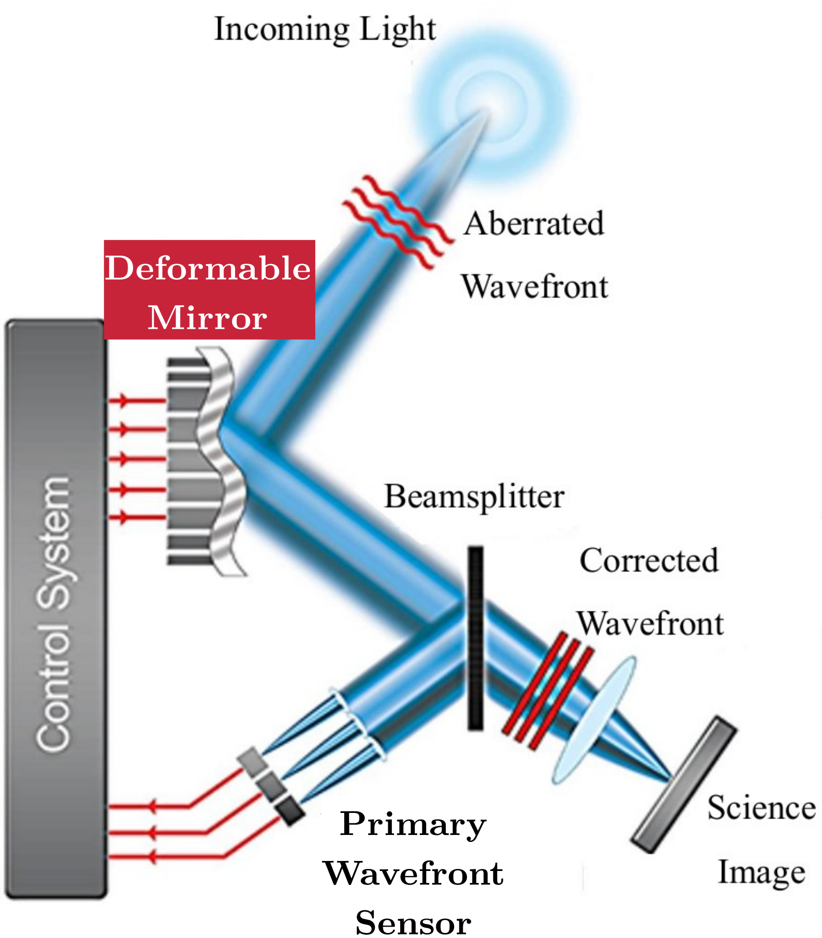
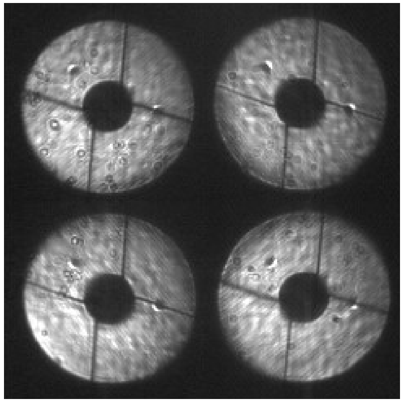
Focal Plane Wavefront Sensing

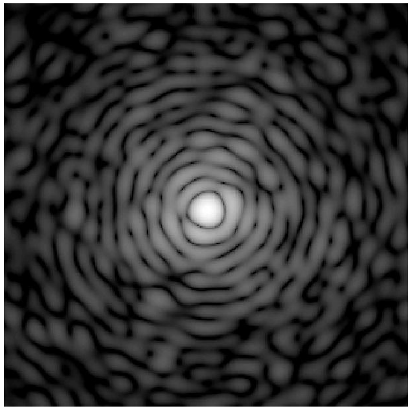
Standard Closed-Loop Adaptive Optics System



Primary Wavefront Sensor: Pyramid



Science Image



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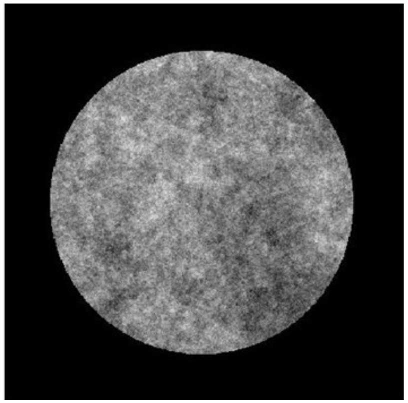
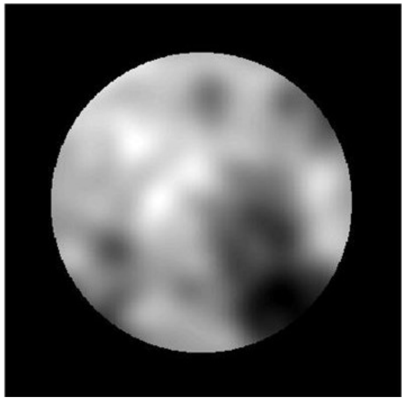


Deformable Mirror: Correction



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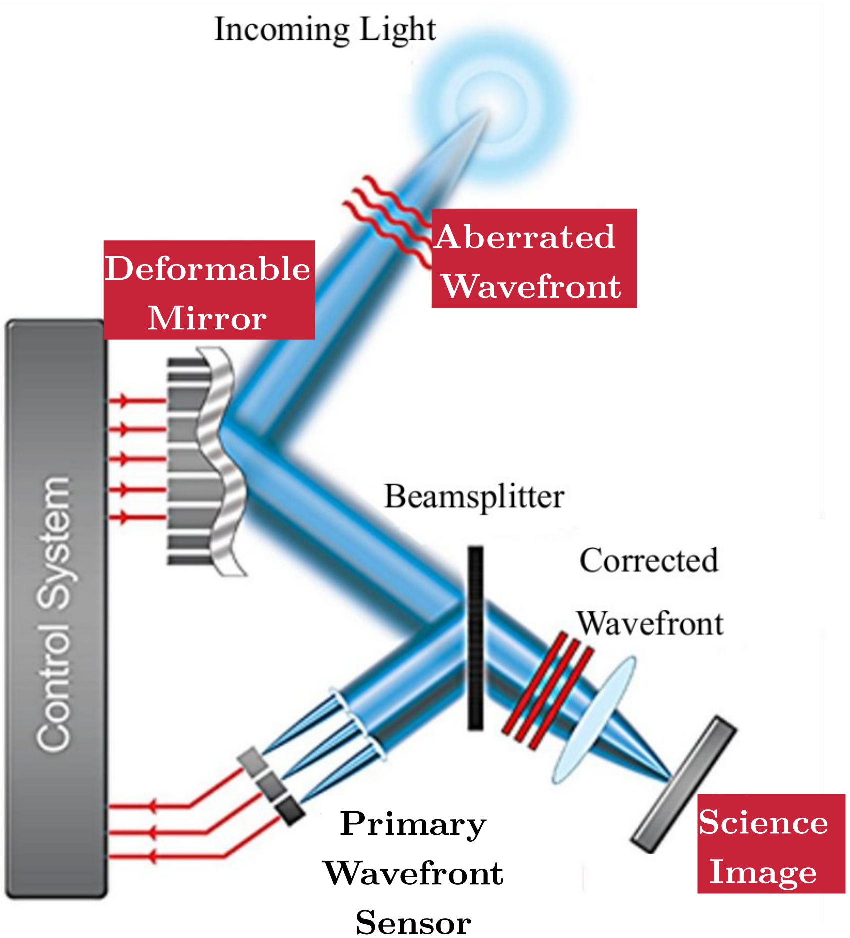
Focal Plane Wavefront Sensing

Standard Closed-Loop Adaptive Optics System



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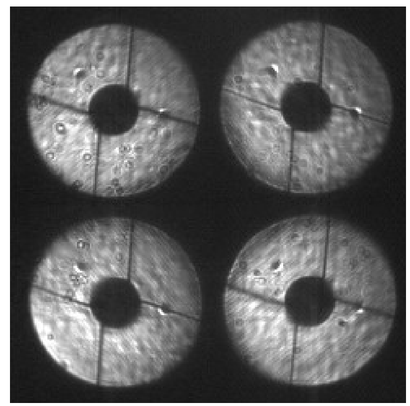
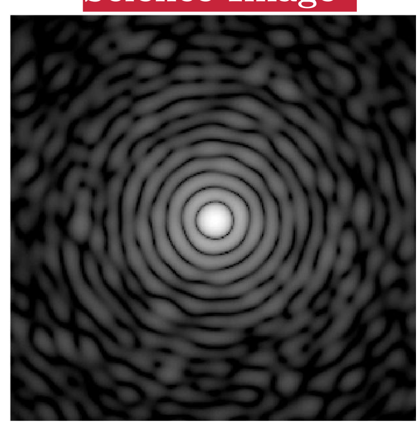
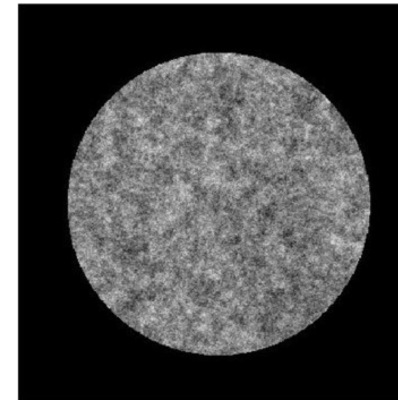


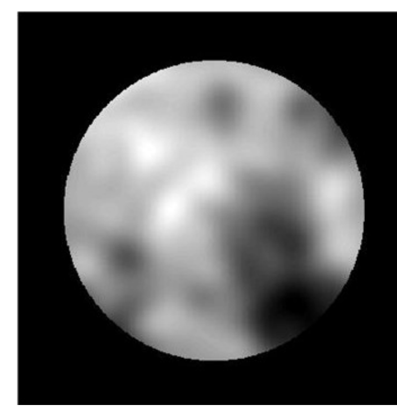
Science Image



Aberrated Wavefront + Correction

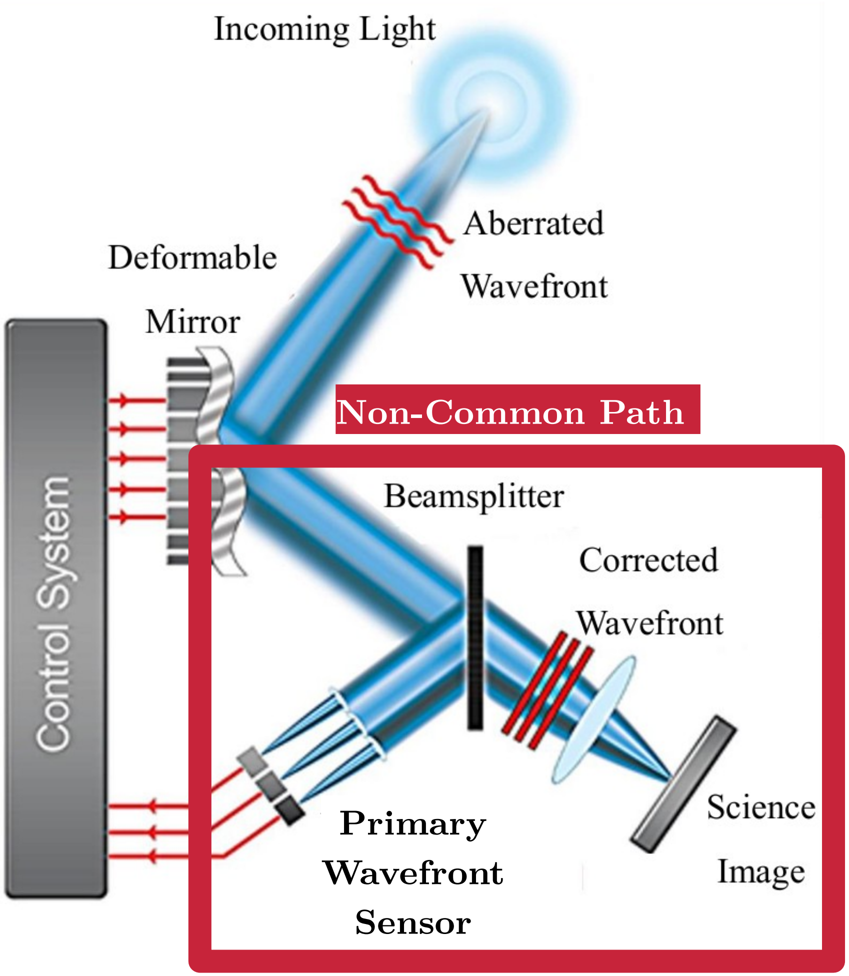


Deformable Mirror: Correction



Focal Plane Wavefront Sensing

Standard Closed-Loop Adaptive Optics System



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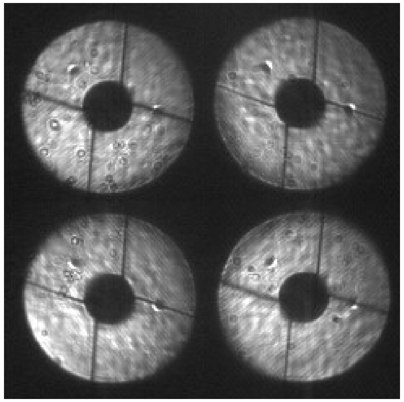
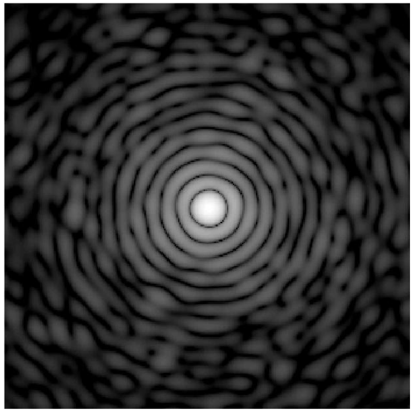


Science Image



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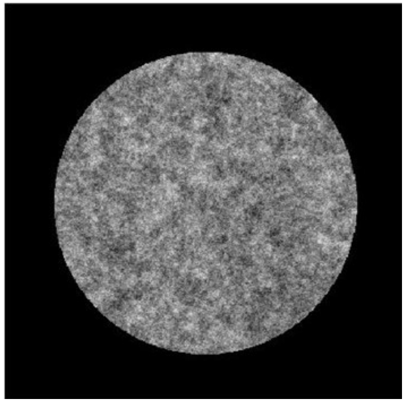

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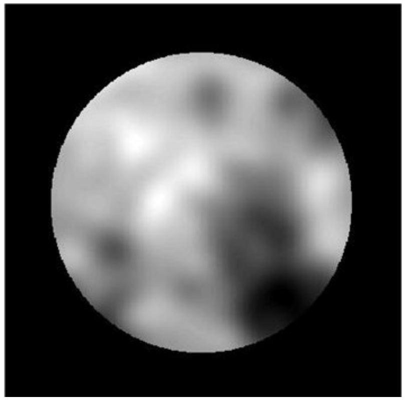
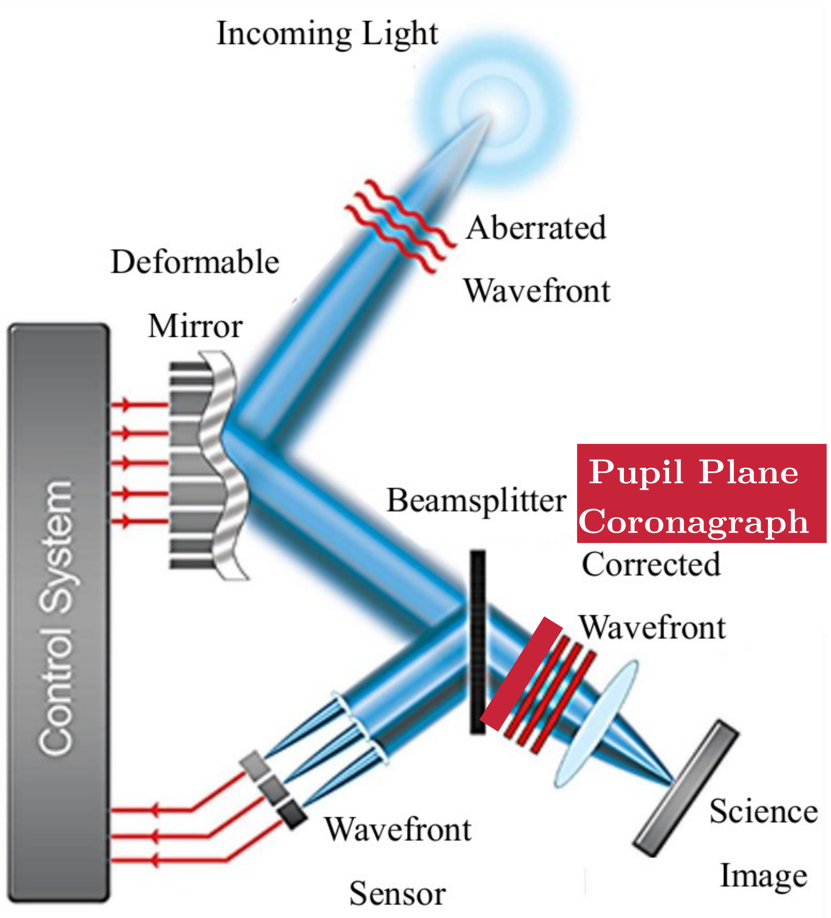


Vector Apodizing Phase Plate

Standard Closed-Loop Adaptive Optics System



Pupil Plane Coronagraph

Science Image

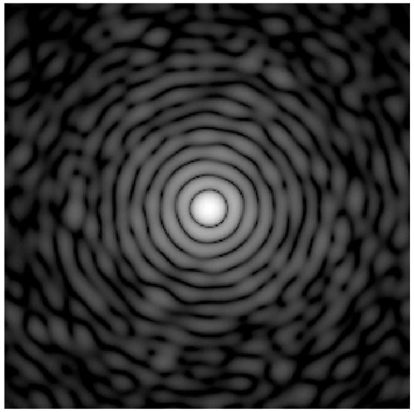
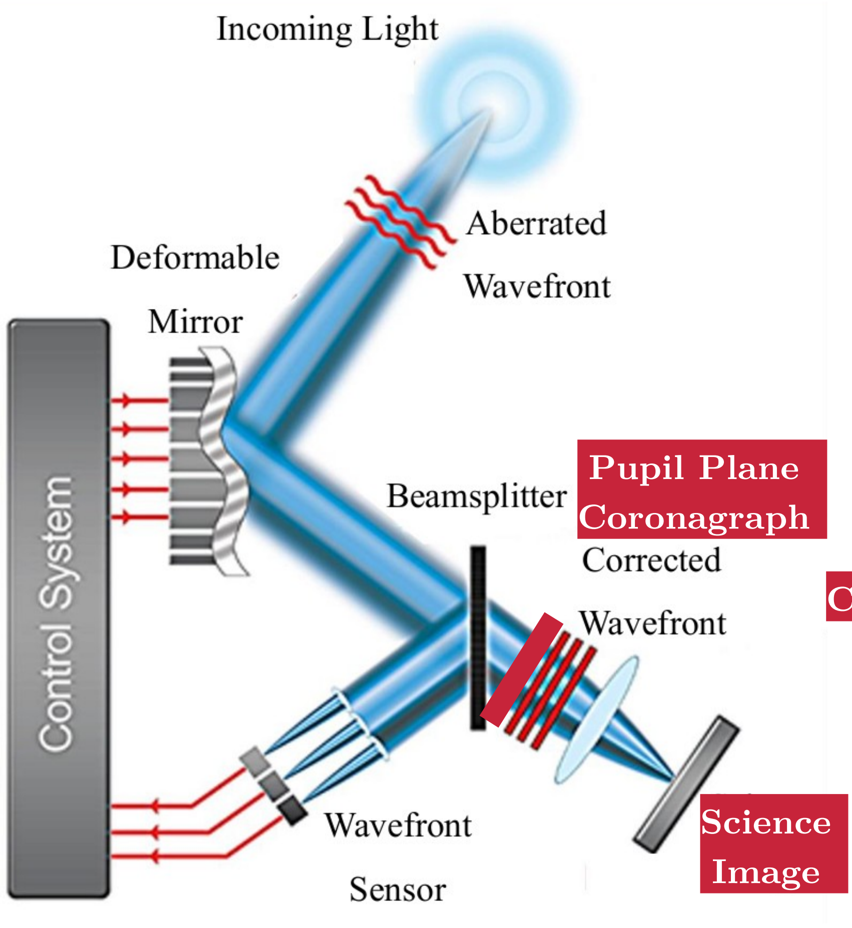


Diagram credit: BMC

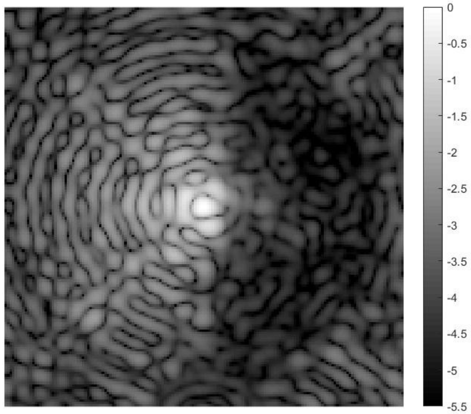
Vector Apodizing Phase Plate

Standard Closed-Loop Adaptive Optics System



Pupil Plane Coronagraph

Coronagraphic Science Image

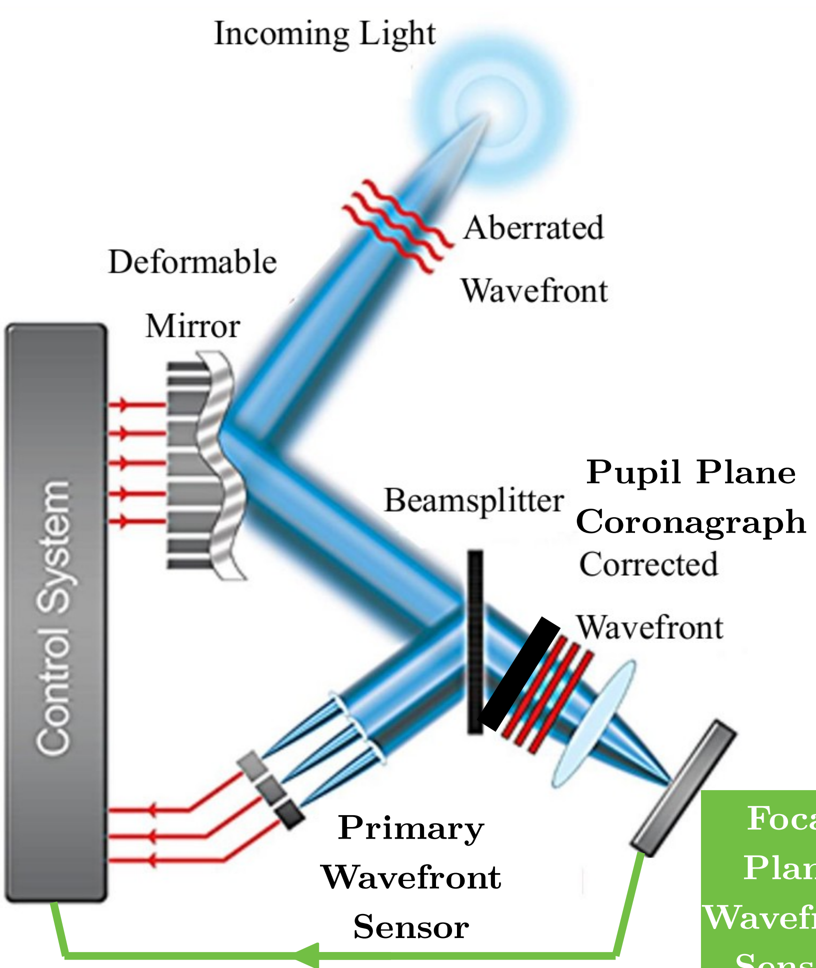


Problem: Quasi-static speckles due to non-common path errors degrade the deep contrast within the dark hole

Diagram credit: BMC

Vector Apodizing Phase Plate

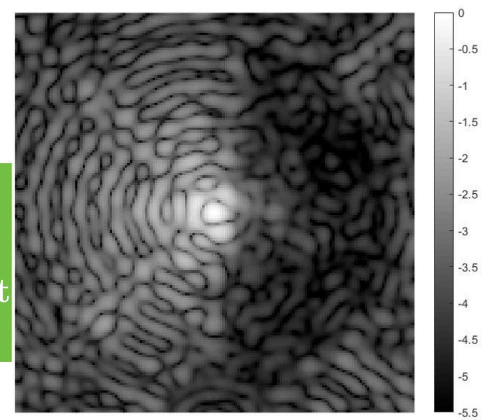
Standard Closed-Loop Adaptive Optics System



Pupil Plane Coronagraph

Secondary Wavefront Sensor: Coronagraphic Science Image

Focal Plane Wavefront Sensor



Solution: Use the science image as a secondary wavefront sensor which is fully common path and can sense non-common path aberrations and maintain deep contrast in the dark hole

Diagram credit: BMC

Vector Apodizing Phase Plate

Standard Closed-Loop Adaptive Optics System

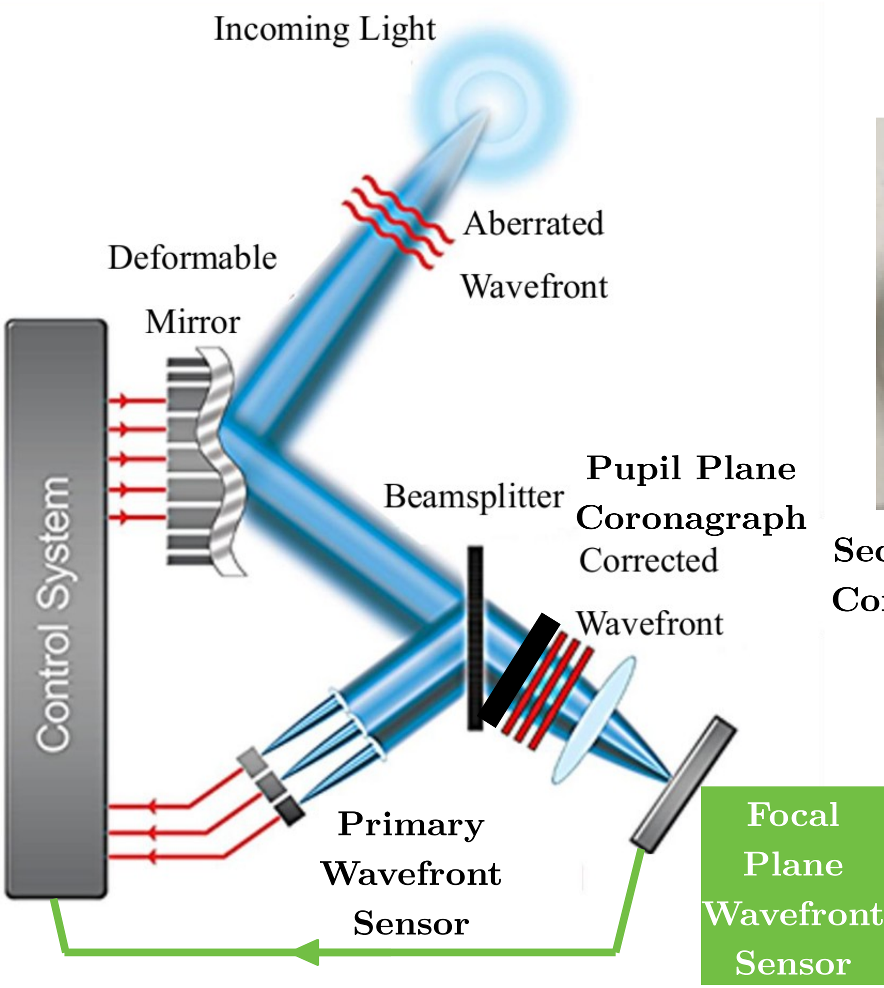
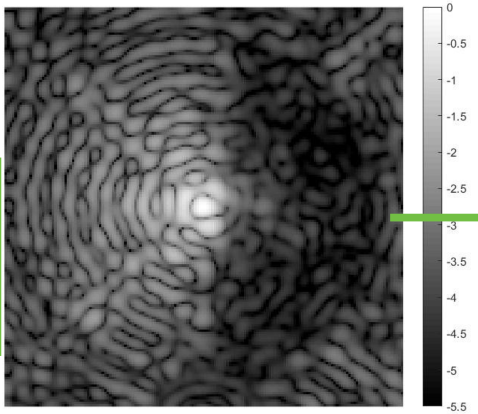


Diagram credit: BMC

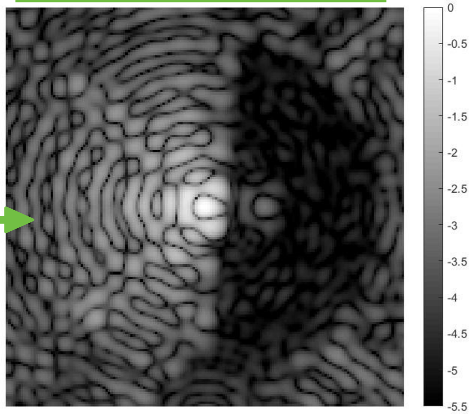
Pupil Plane Coronagraph

Solution: Use the science image as a secondary wavefront sensor which is fully common path and can sense non-common path aberrations and maintain deep contrast in the dark hole

Secondary Wavefront Sensor: Coronagraphic Science Image

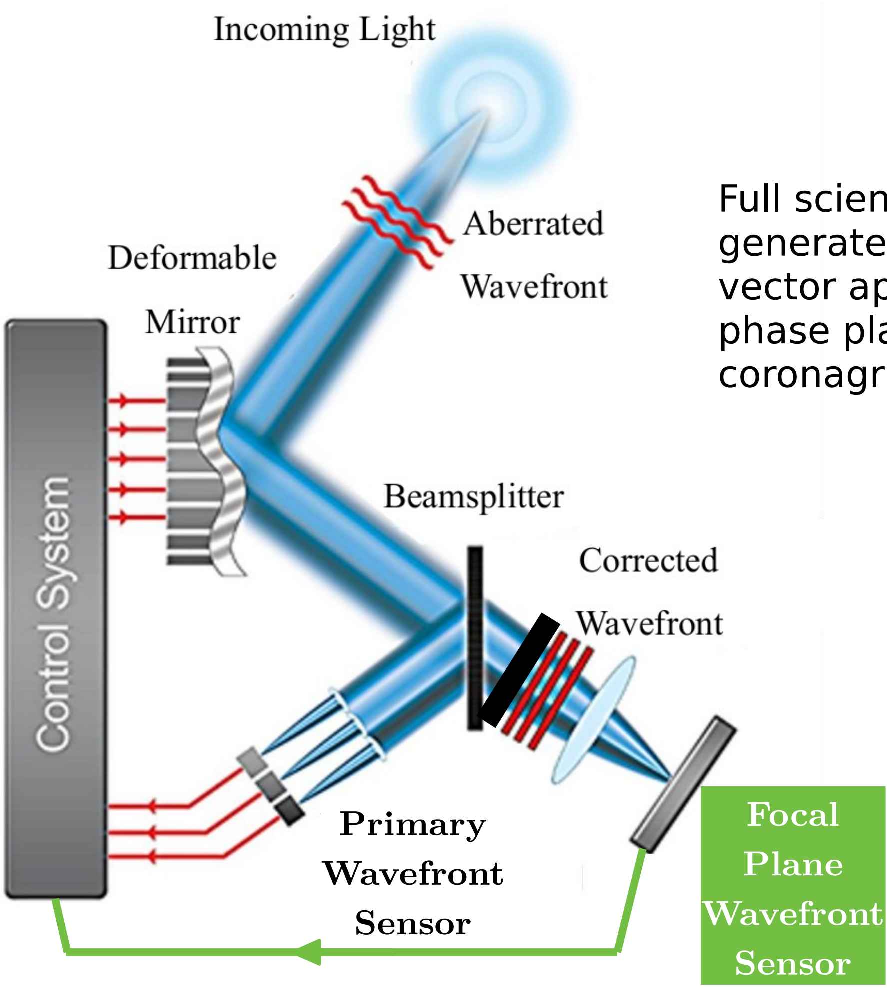


Science Image with NCPA Correction



Vector Apodizing Phase Plate

Standard Closed-Loop Adaptive Optics System



Full science image generated by a vector apodizing phase plate coronagraph

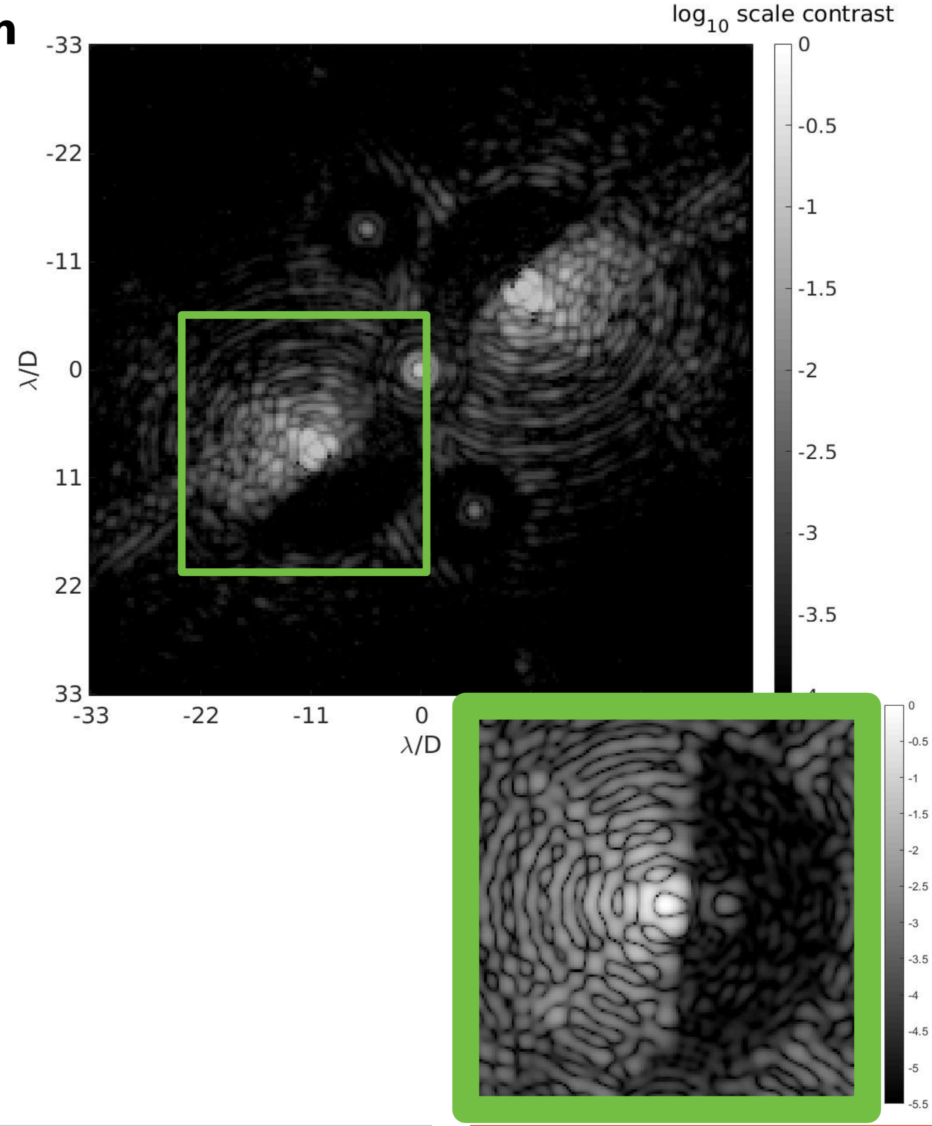
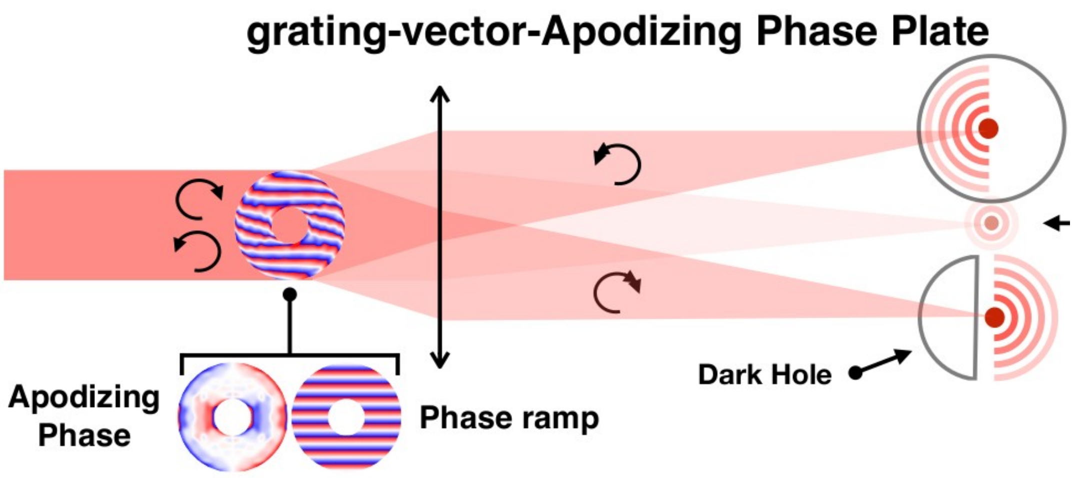
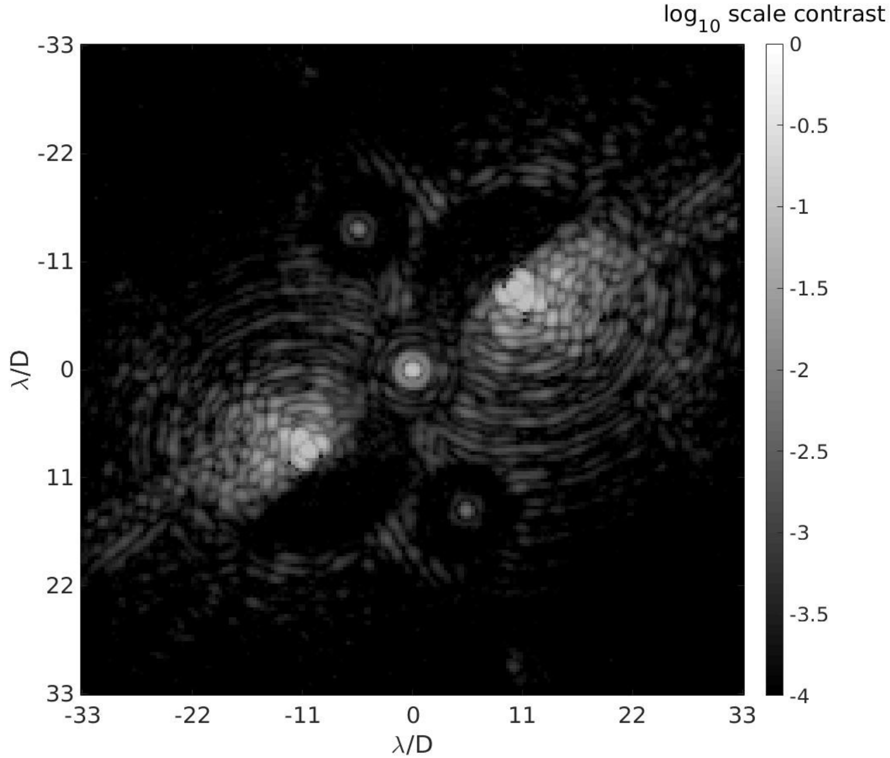


Diagram credit: BMC

Vector Apodizing Phase Plate





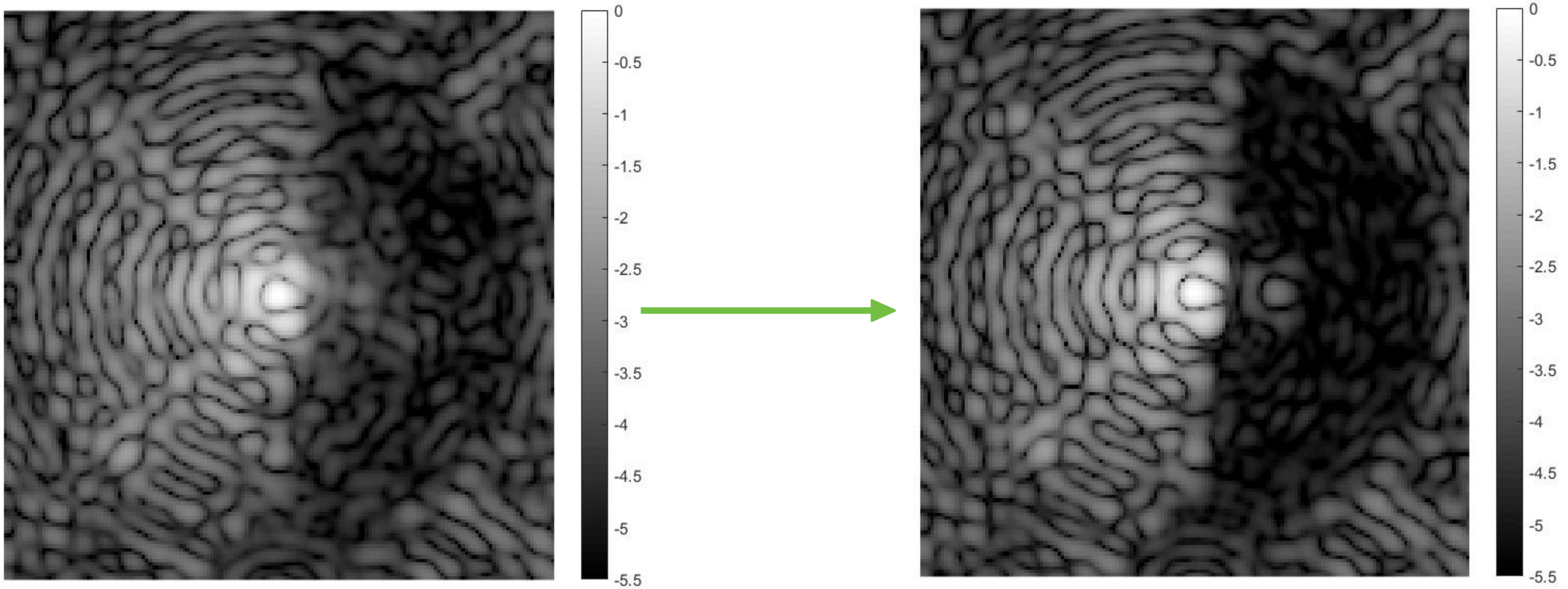
Half-wave retarder pupil plane optic with a spatially varying fast-axis orientation. The varying fast-axis orientation induces a geometric phase on the circular polarization states, each of which receives the opposite phase. This creates two coronagraphic PSFs with dark holes on opposite sides. The two PSFs are separated by adding a ramp function to the phase pattern. (Bos et al 2019) (Image courtesy of D. Doelman)

Linear Dark Field Control

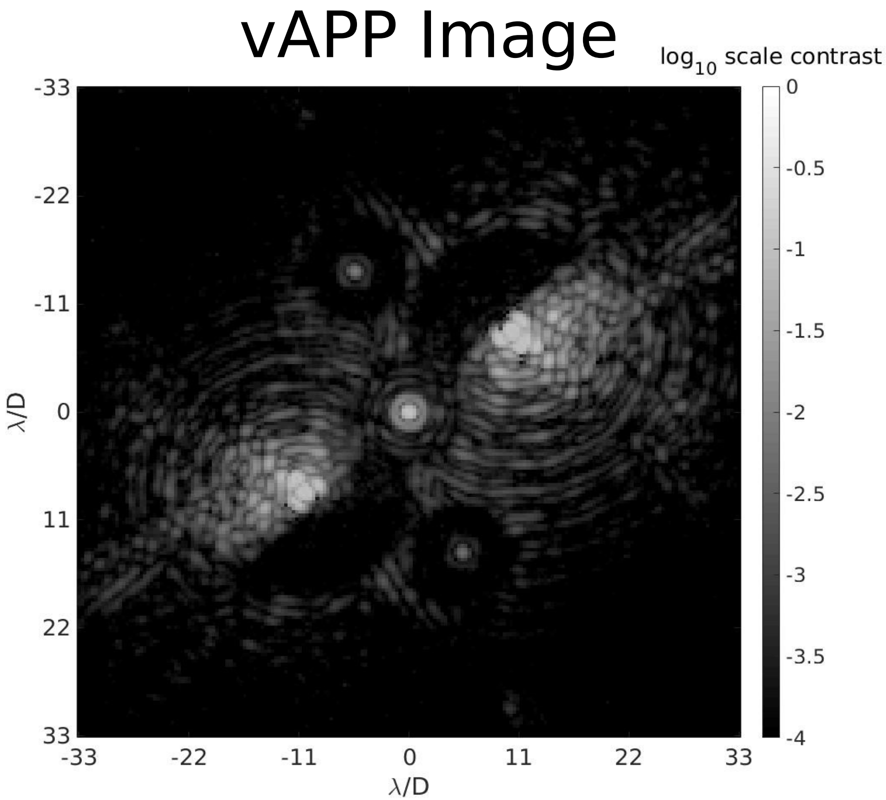
How does it work?
How do we implement it with a vAPP?

Linear Dark Field Control

Purpose:
To sense and correct high-order, non-common path aberrations that degrade the deep contrast within the dark hole



Linear Dark Field Control



Linear Dark Field Control

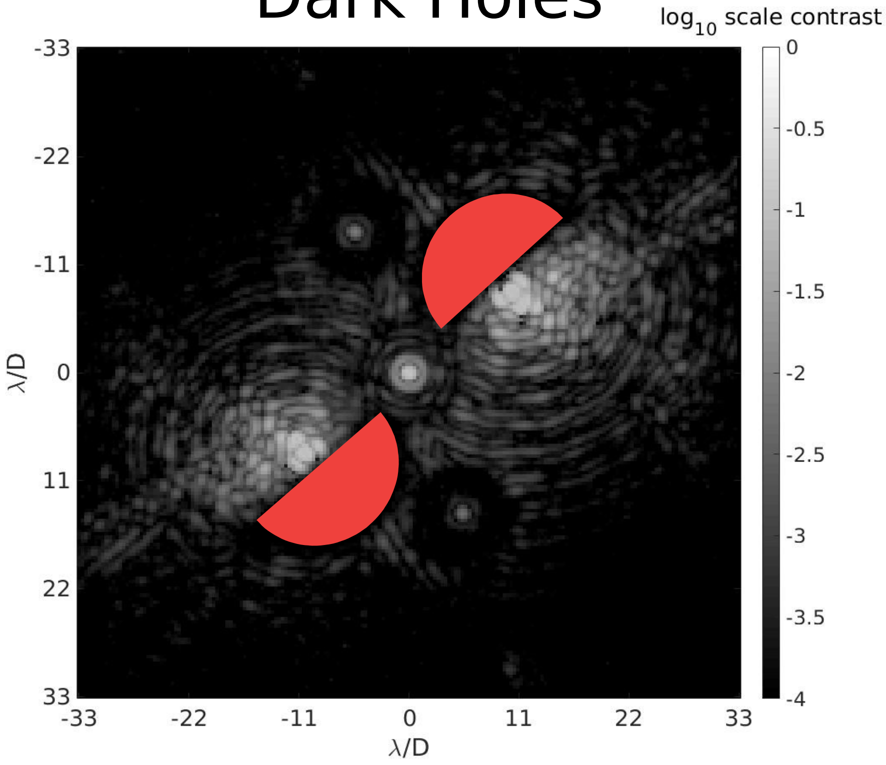
(Miller et al 2017)

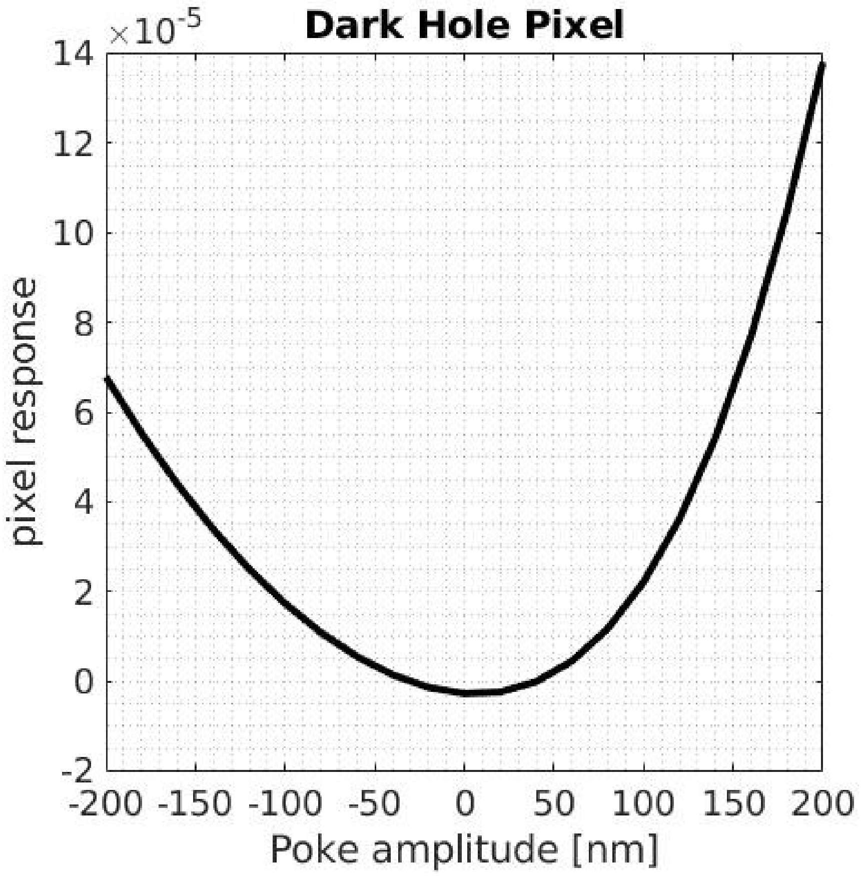
Dark Hole Response in Intensity to Pupil Plane Poke: **Quadratic**

$$E_t \approx E_0 + E_{DM}$$

$$I_t = |E_t|^2 \qquad I_t \approx |E_0|^2 + |E_{DM}|^2 + 2\langle E_0, E_{DM}\rangle$$

Dark Holes





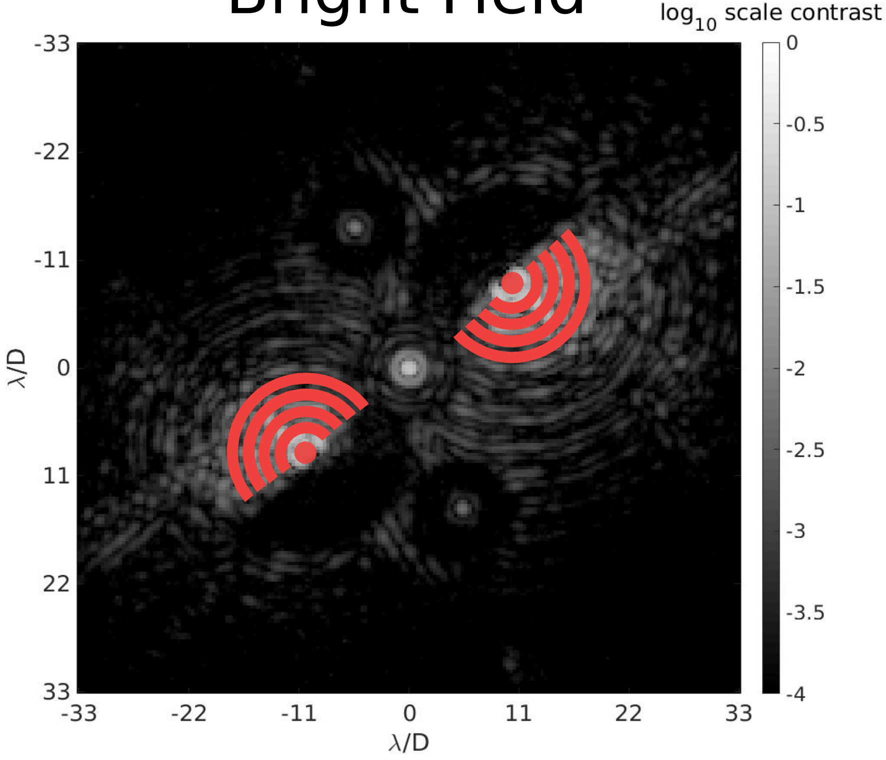
Linear Dark Field Control

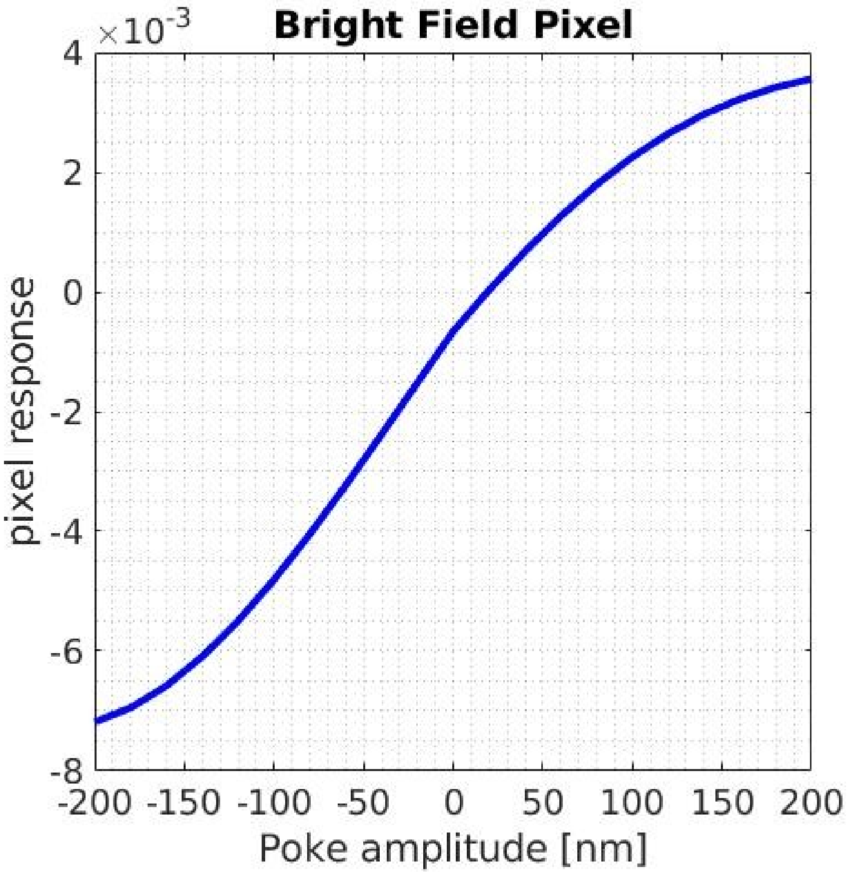
(Miller et al 2017)

Bright Field Response in Intensity to Pupil Plane Poke: **Linear**

$$|E_0|^2 \gg |E_{DM}|^2$$
$$I_t \approx 2\langle E_0, E_{DM}\rangle + |E_0|^2$$
$$\Delta I_t = I_t - I_{ref} \approx 2\langle E_0, E_{DM}\rangle$$

Bright Field

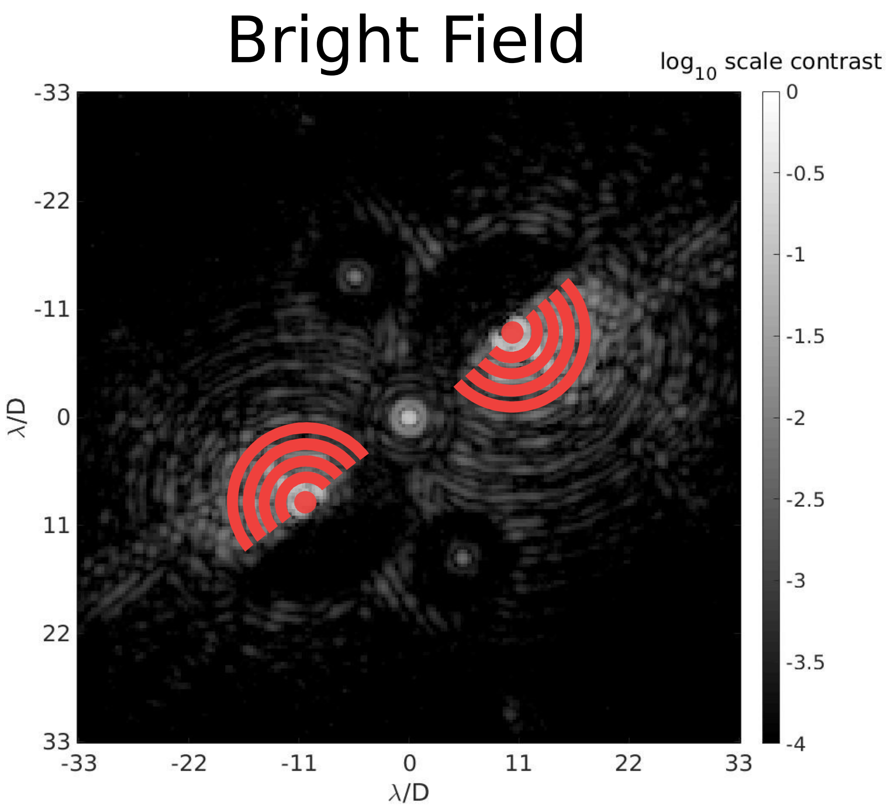




Linear Dark Field Control

(Miller et al 2017)

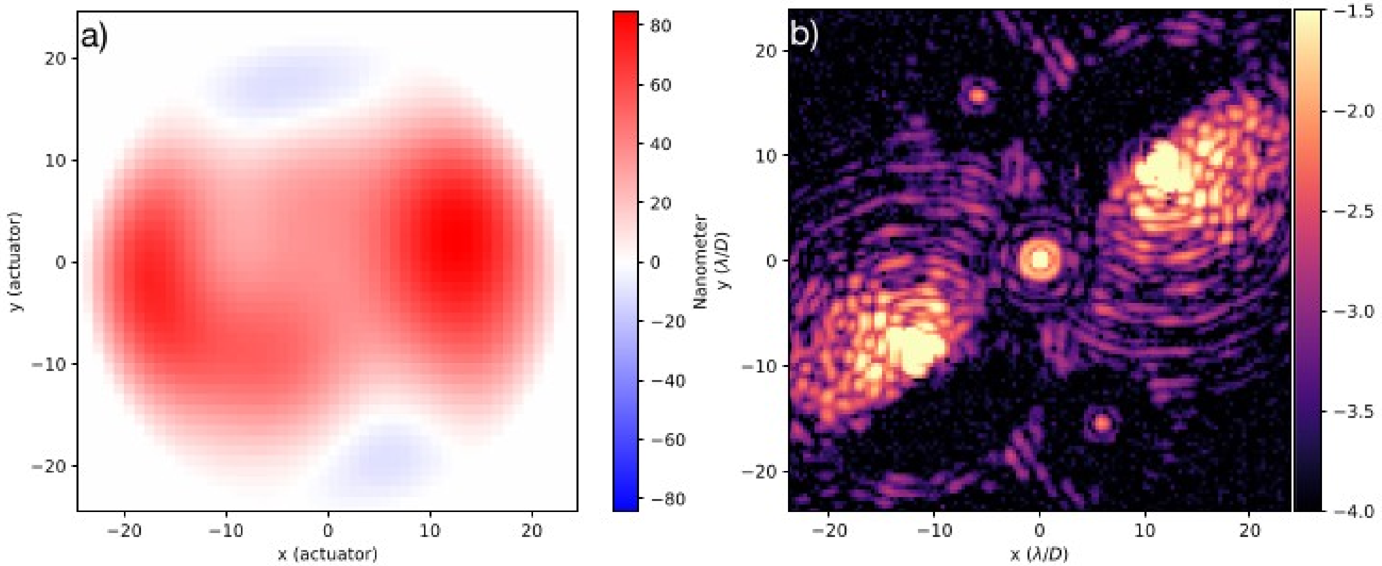
Bright Field Response in Intensity to Pupil Plane Poke: **Linear**



Operation:
Uses the bright field opposite the dark hole to measure fluctuations in intensity with respect to an **ideal reference image** and derive an estimate of the wavefront aberration

Linear Dark Field Control

Deriving a reference image



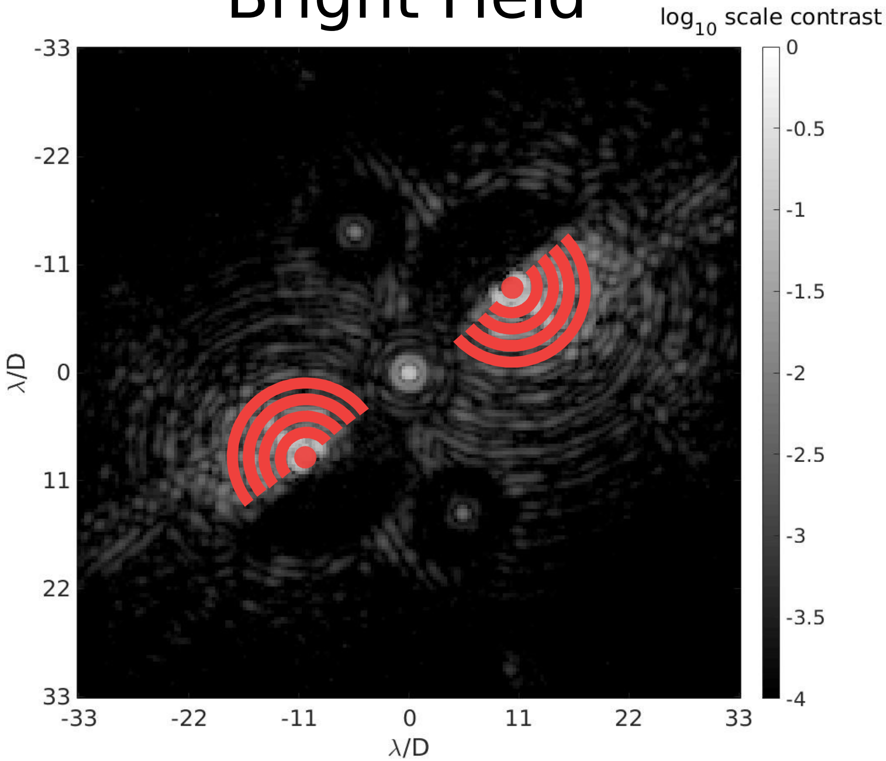
Results of the non-linear WFS algorithm (Bos et al 2019) used to remove static, low-order instrumental NCPA and derive a clean reference image for LDFC

(Miller et al 2020, In-prep)

Linear Dark Field Control

Building the
control matrix

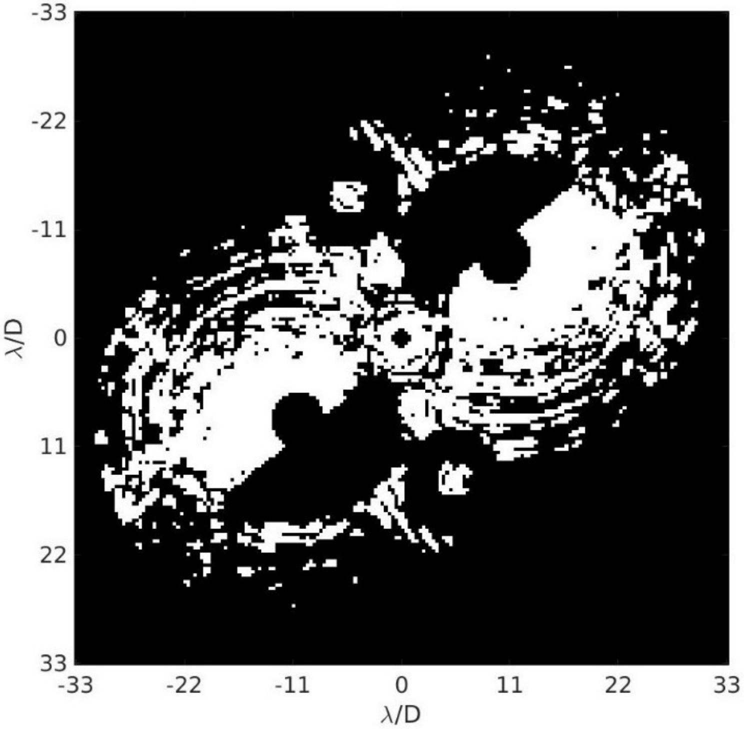
Bright Field



Linear Dark Field Control

Building the control matrix

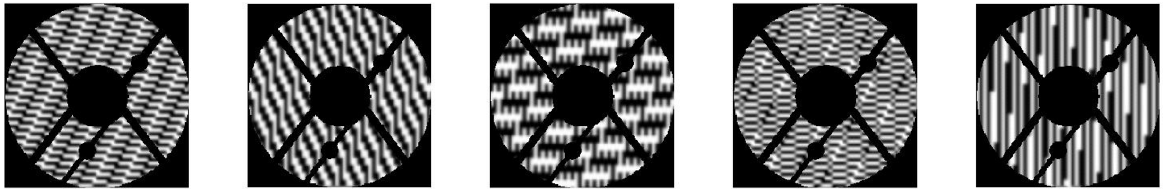
Bright Field



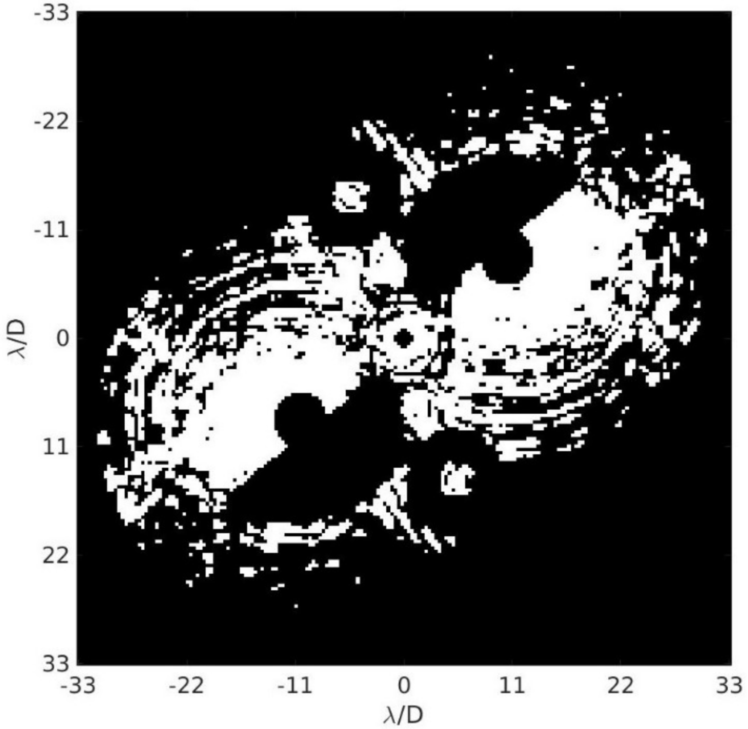
Linear Dark Field Control

Building the control matrix

Apply Hadamard modes in pupil



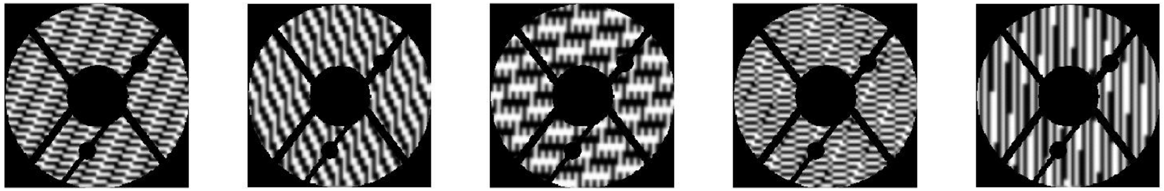
Bright Field



Linear Dark Field Control

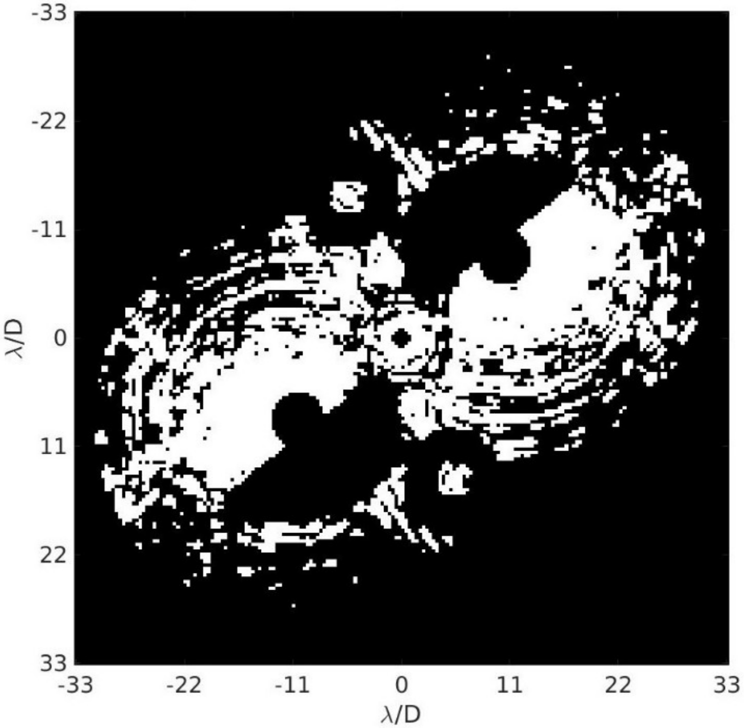
Building the control matrix

Apply Hadamard modes in pupil



SVD {bright field response}

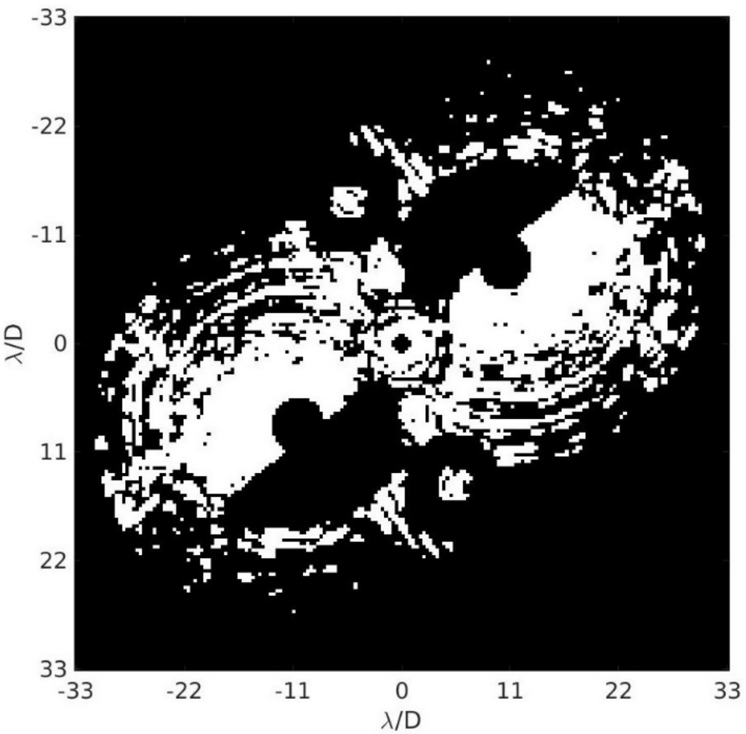
Bright Field



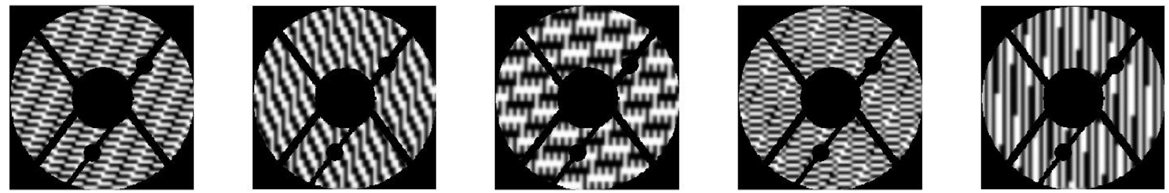
Linear Dark Field Control

Building the control matrix

Bright Field

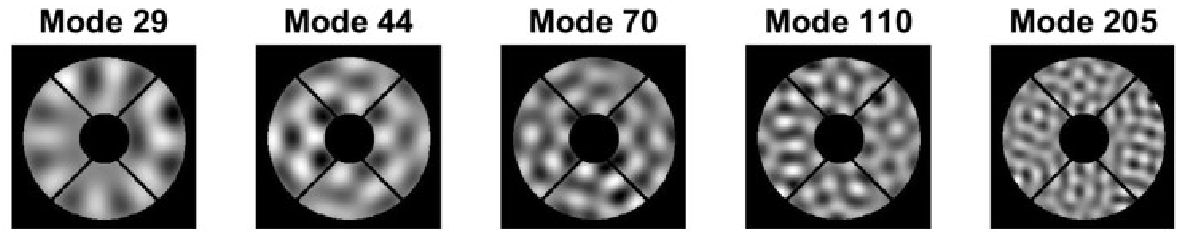


Apply Hadamard modes in pupil



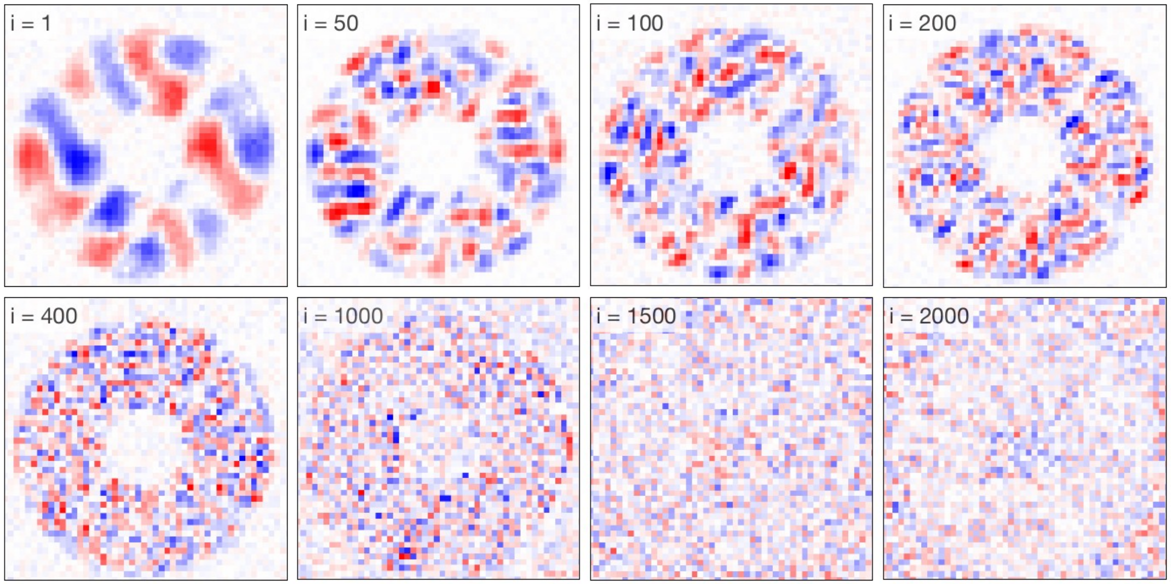
SVD {bright field response}

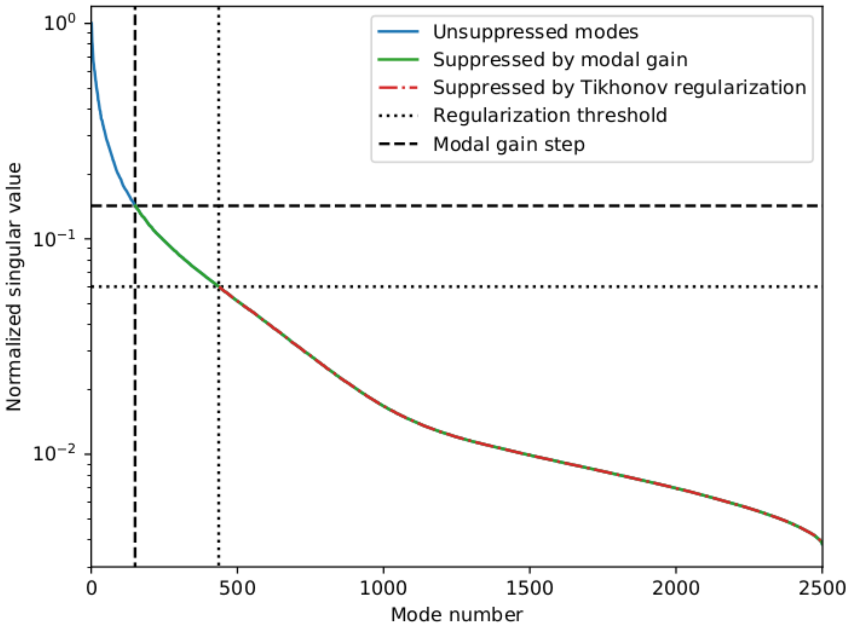
Eigenmodes



Linear Dark Field Control

Selecting Eigenmodes





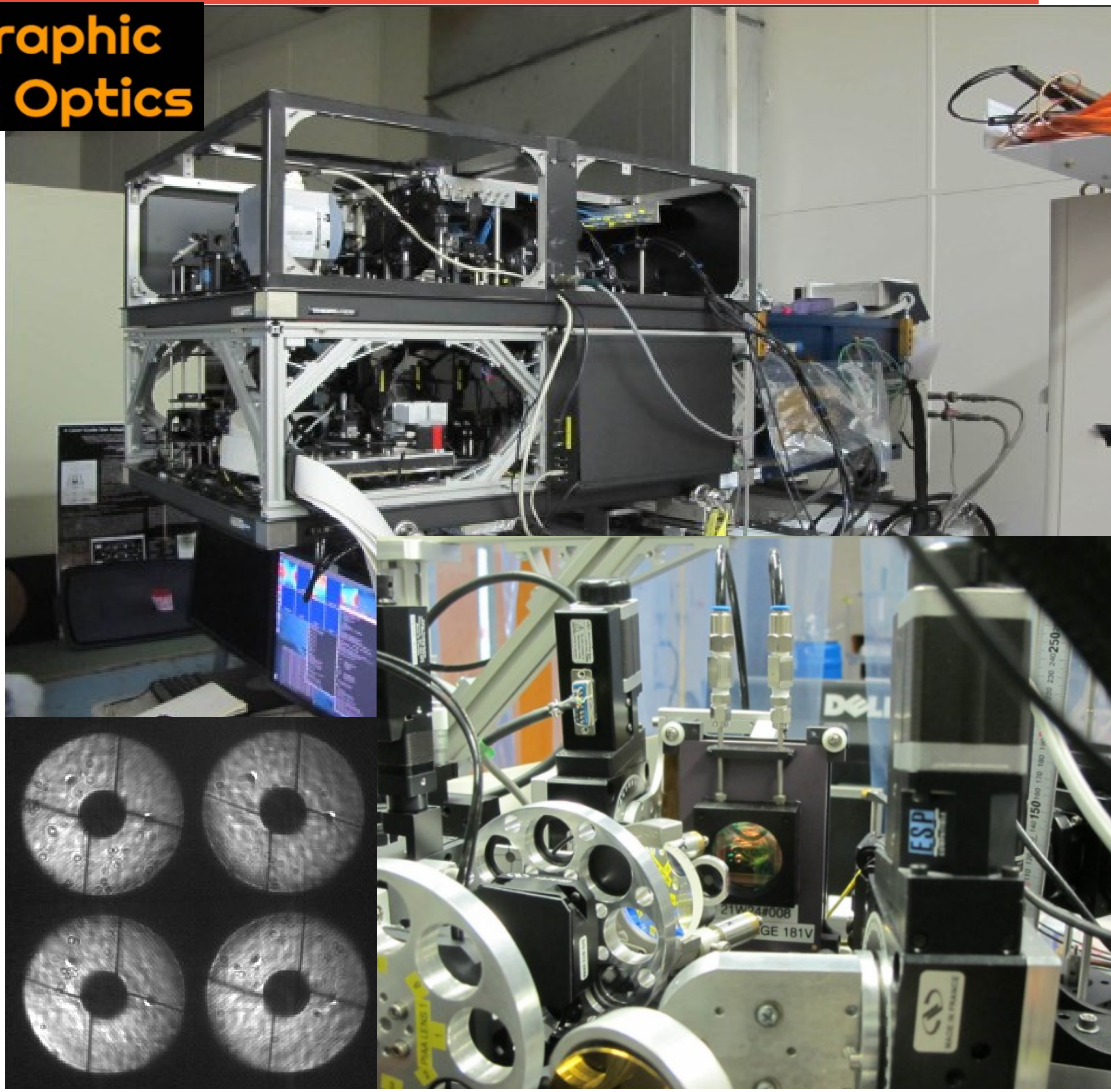
Modal selection process: Suppressing noisy modes with Tikhonov regularization in the derivation of the control matrix and applying modal gain to give greater weight to less noisy modes

(Miller et al 2020, In-prep)

LDFC with a vAPP on SCExAO

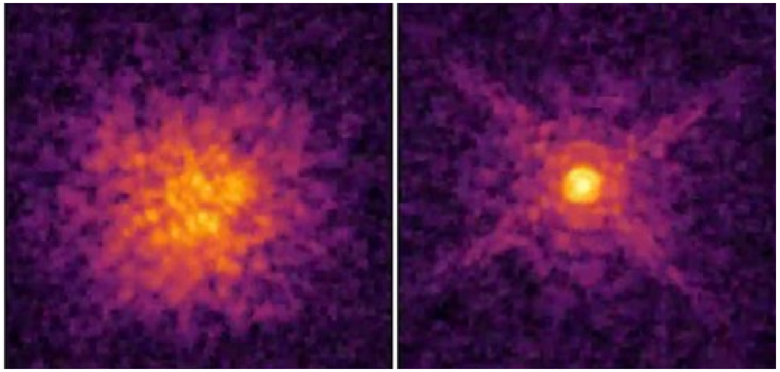
LDFC with a vAPP on SCExAO

SCExAO Subaru Coronagraphic Extreme Adaptive Optics



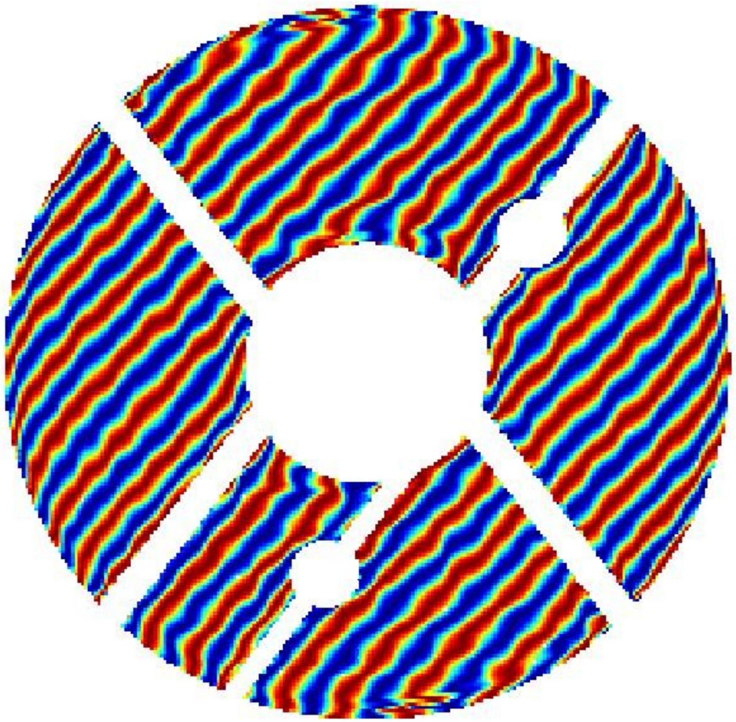
Extreme AO system
on 8.2m Subaru Telescope

Primary AO: Pyramid WFS running @ ~3.5 kHz
Deformable mirror: BMC 2K
Coronagraph: vector apodizing phase plate (among others)

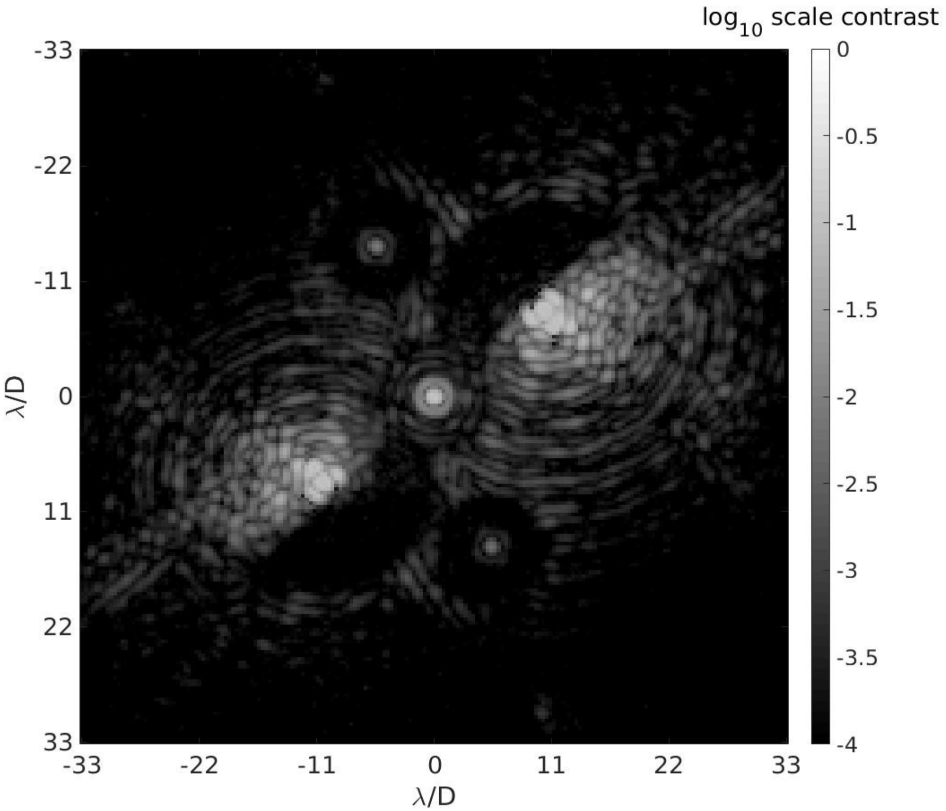


LDFC with a vAPP on SCExAO

Pupil plane vAPP



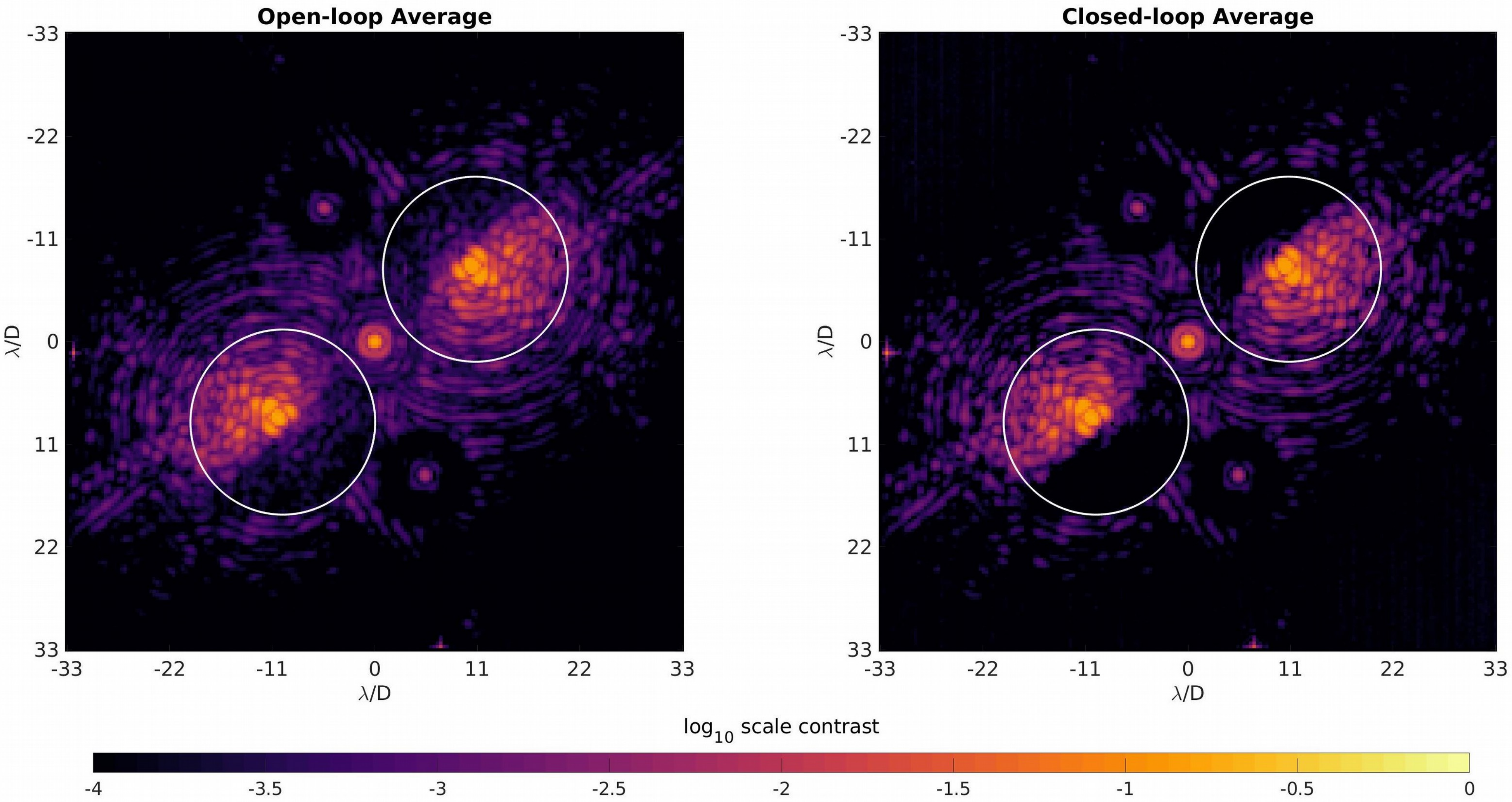
Focal plane image



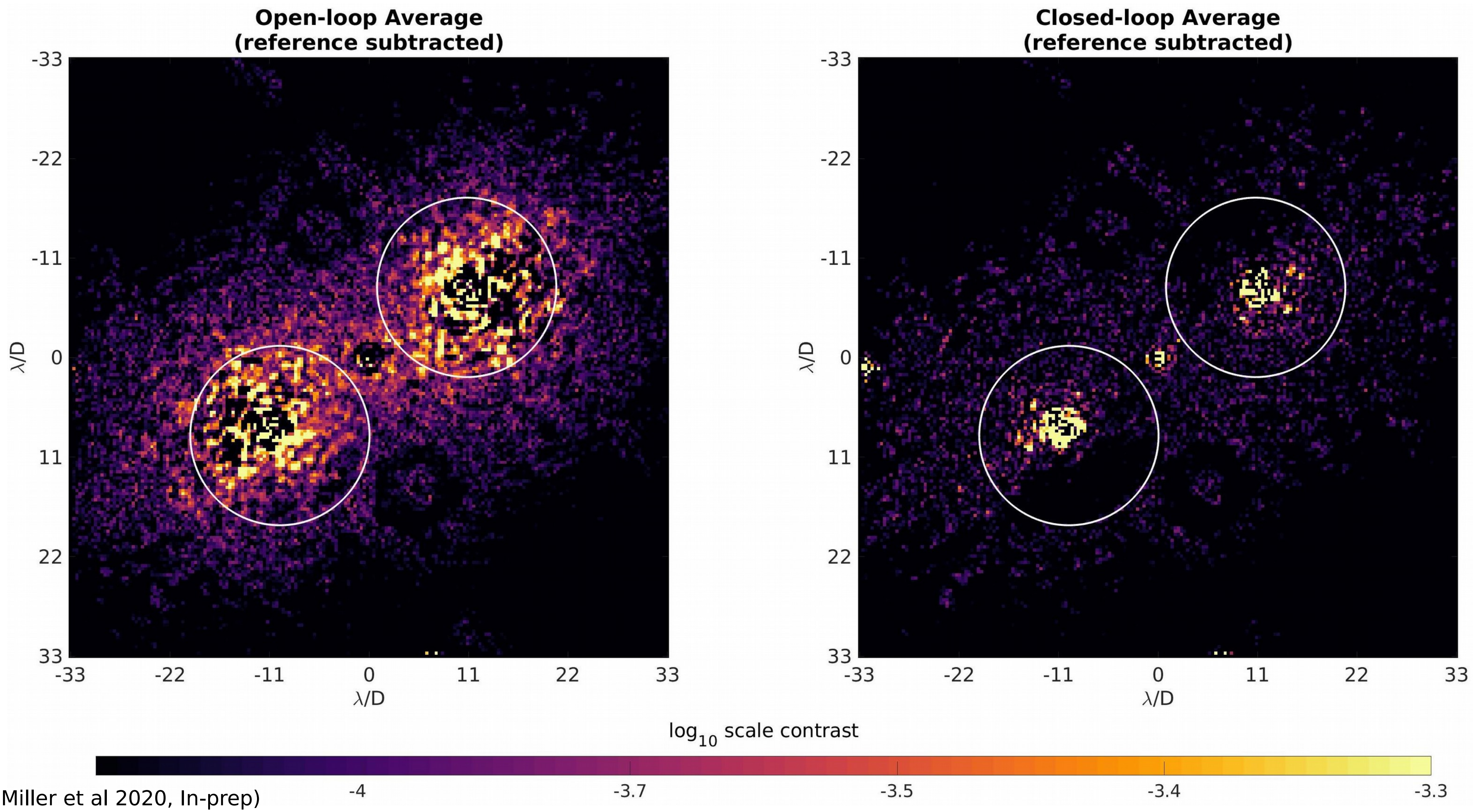
(Bos et al 2019)

LDFC with a vAPP on SCExAO

(Miller et al 2020, In-prep)

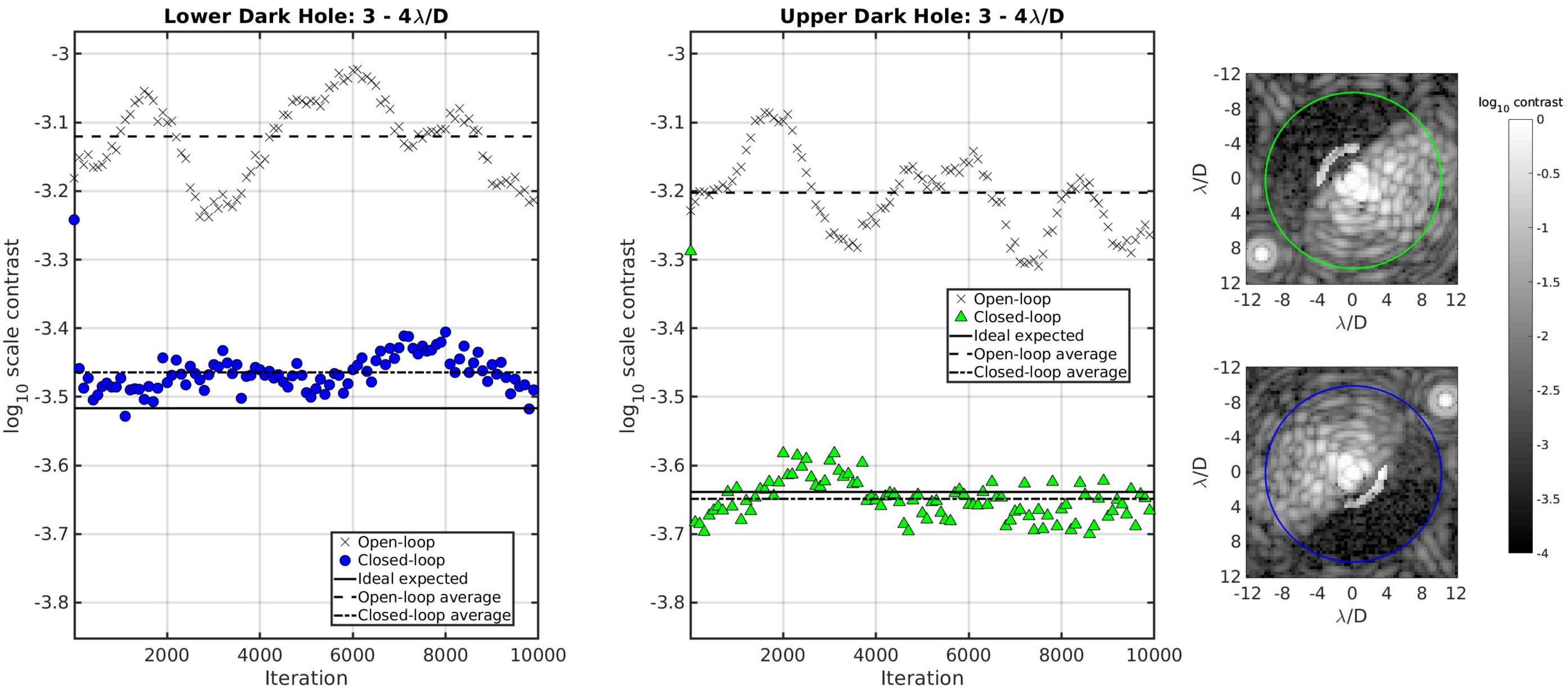


LDFC with a vAPP on SCExAO



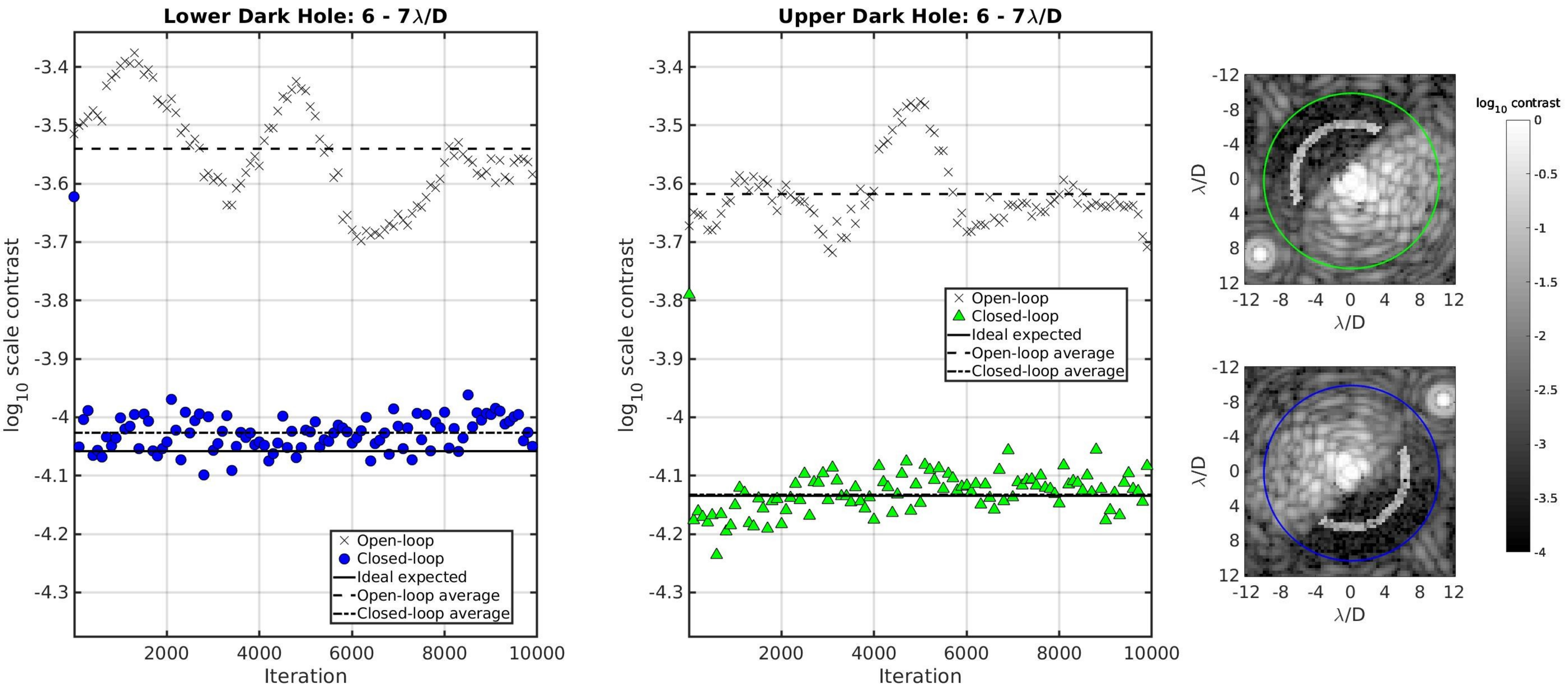
(Miller et al 2020, In-prep)

LDFC with a vAPP on SCExAO



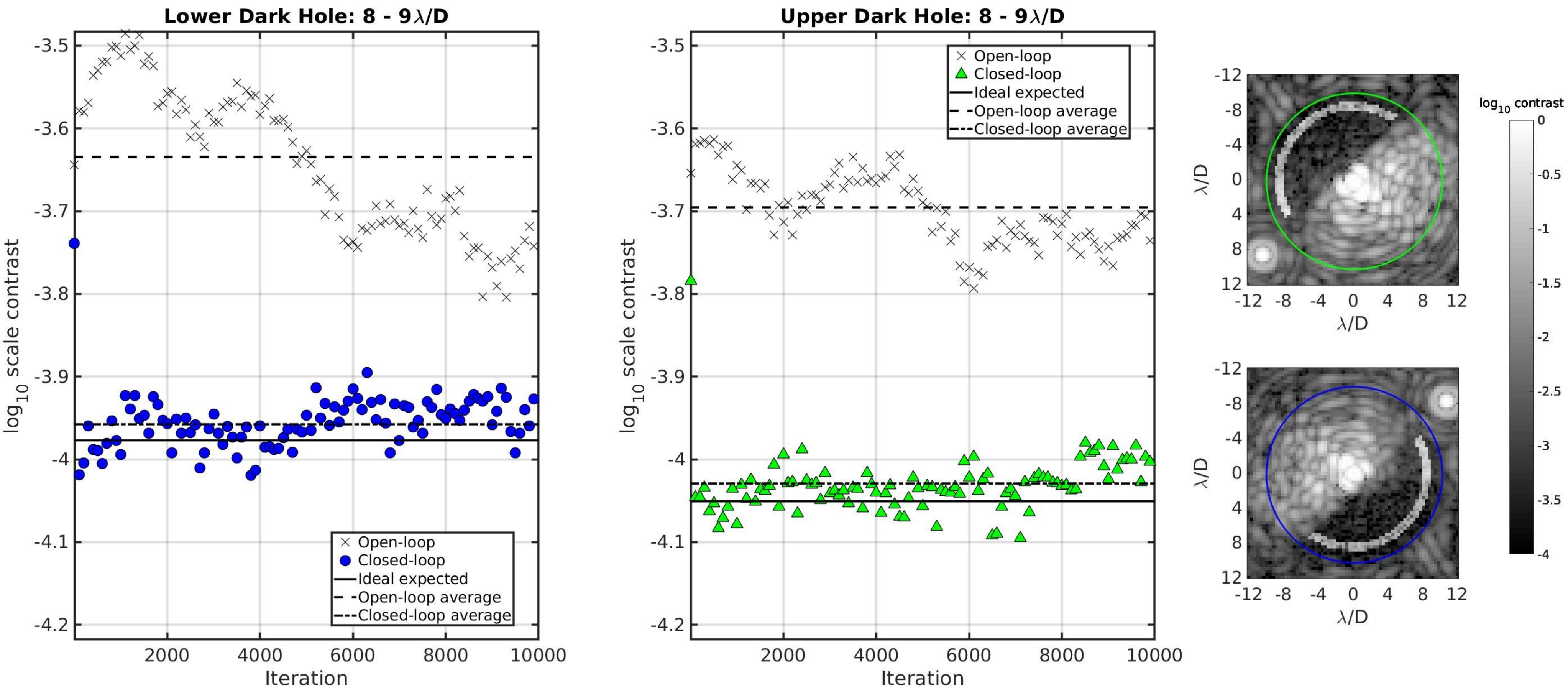
(Miller et al 2020, In-prep)

LDFC with a vAPP on SCExAO



(Miller et al 2020, In-prep)

LDFC with a vAPP on SCExAO



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Upcoming Results

Papers

Spatial linear dark field control on Subaru/SCExAO: Maintaining high contrast with a vAPP coronagraph
Miller & Bos et al, Submitted

First on-sky demonstration of spatial linear dark field control with the vector apodizing phase plate at Subaru/SCExAO
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Talks

On-sky results of focal-plane wavfront sensing and control with the asymmetric pupil vector-apodizing phase plate coronagraph
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