Don’t Heckle My Speckle: A Coronagraph Design Study for the SEAL testbed

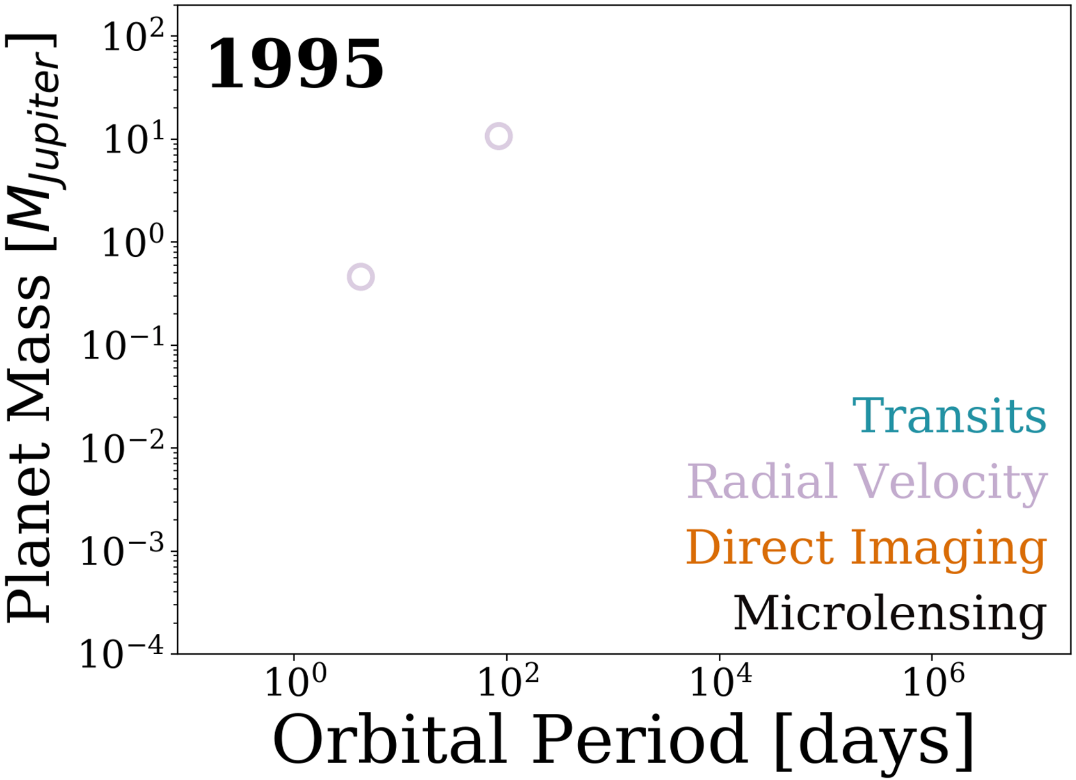
Jules Fowler . ExoExplorer Seminar Series . 5/14/21

Talk Outline

- Extreme Adaptive Optics
- SEAL testbed
- Optics refresher
- Coronagraphy primer
- Simulations
- Current state of the coronagraph design
- Next steps

Direct Imaging and Extreme Adaptive Optics

Directly Imaged Planets are Few and Far Between



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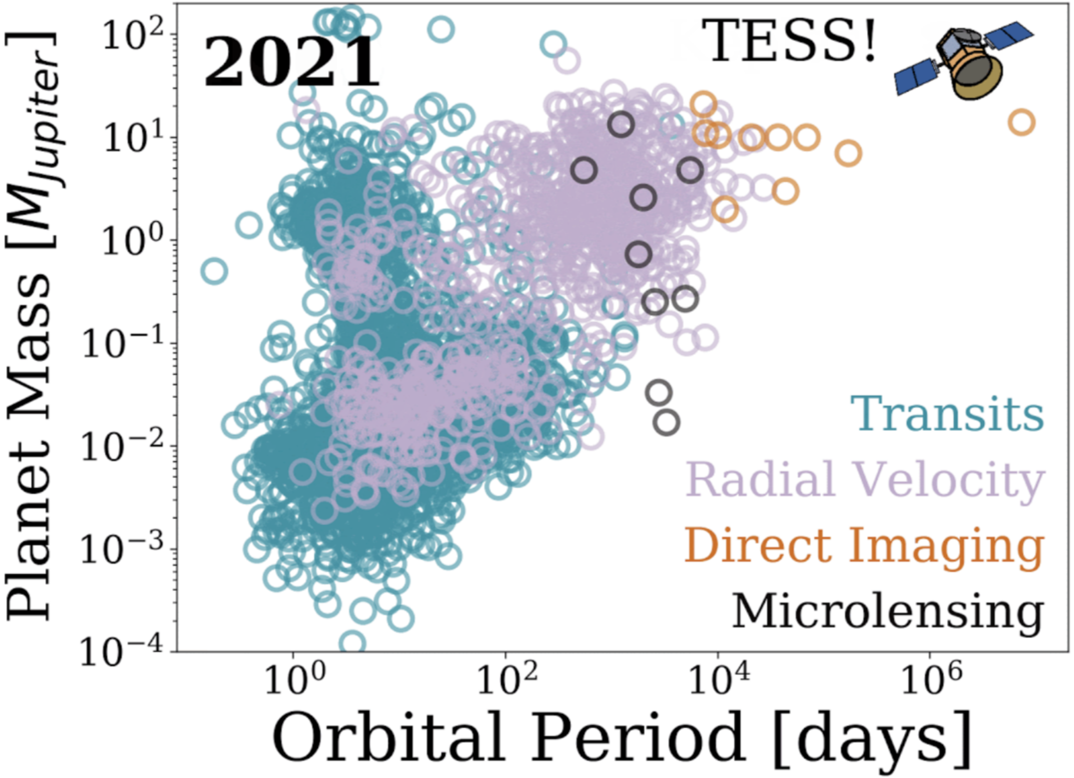
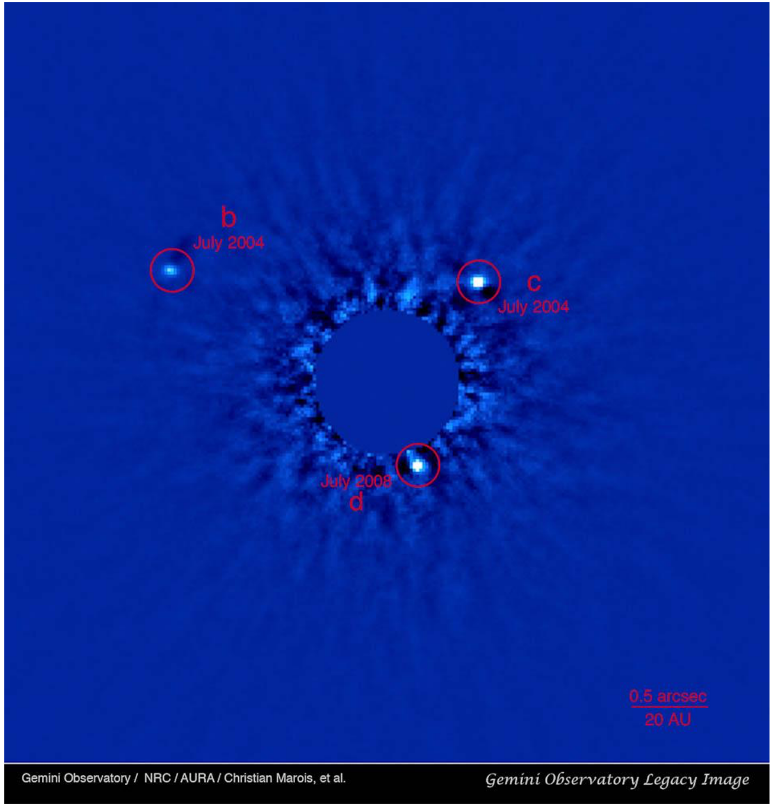
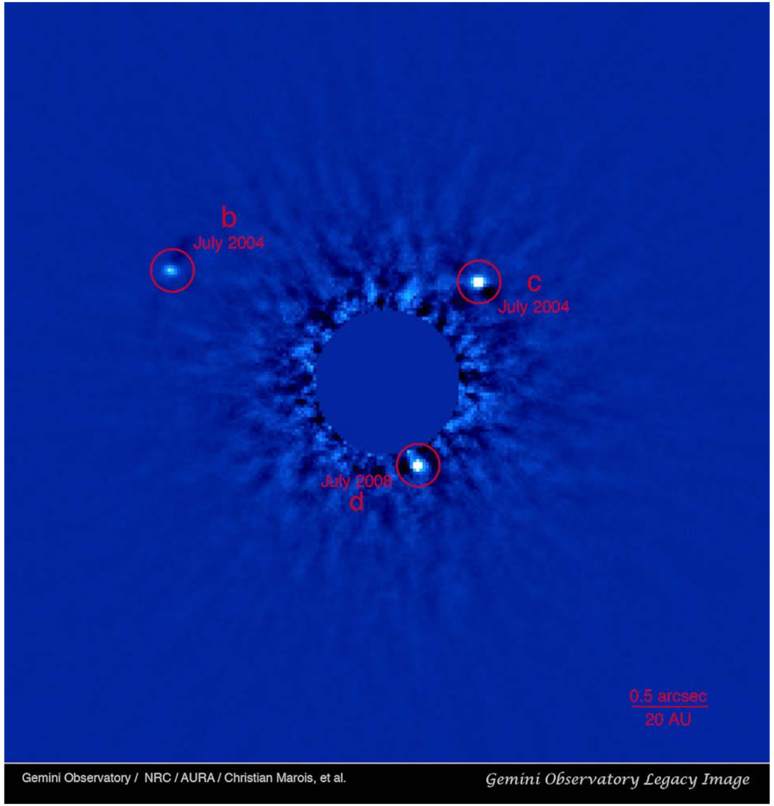


Direct Imaging Resolves the Light of a Planet

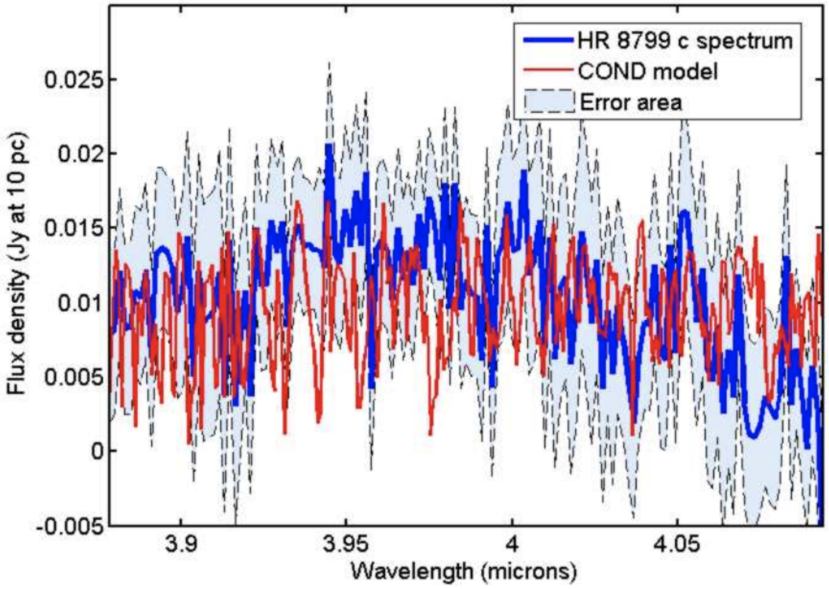


HR8799 Planetary System

Direct Imaging Unlocks Exoplanet Characterization

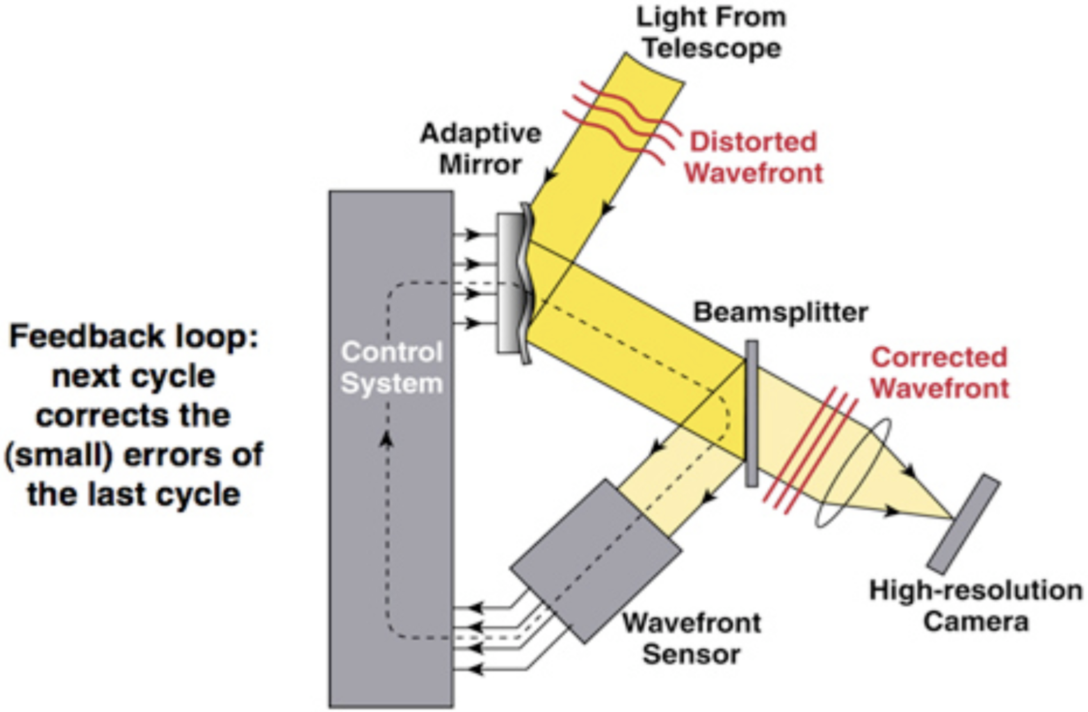


HR8799 Planetary System



(Janson, 2010)

Ground-based Imaging Requires Adaptive Optics



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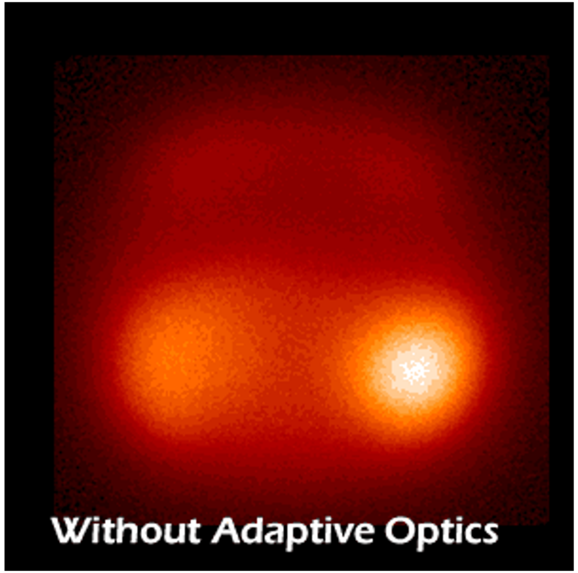
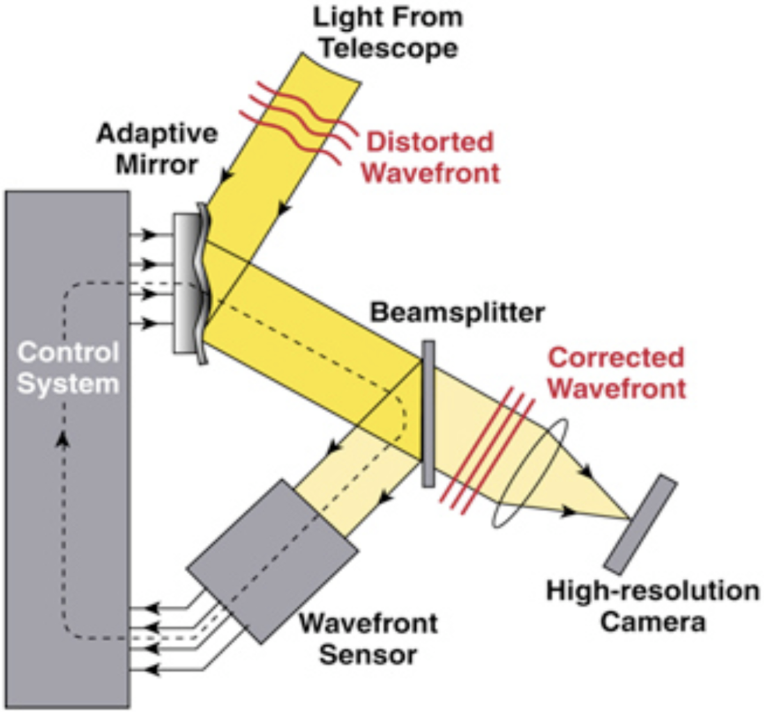
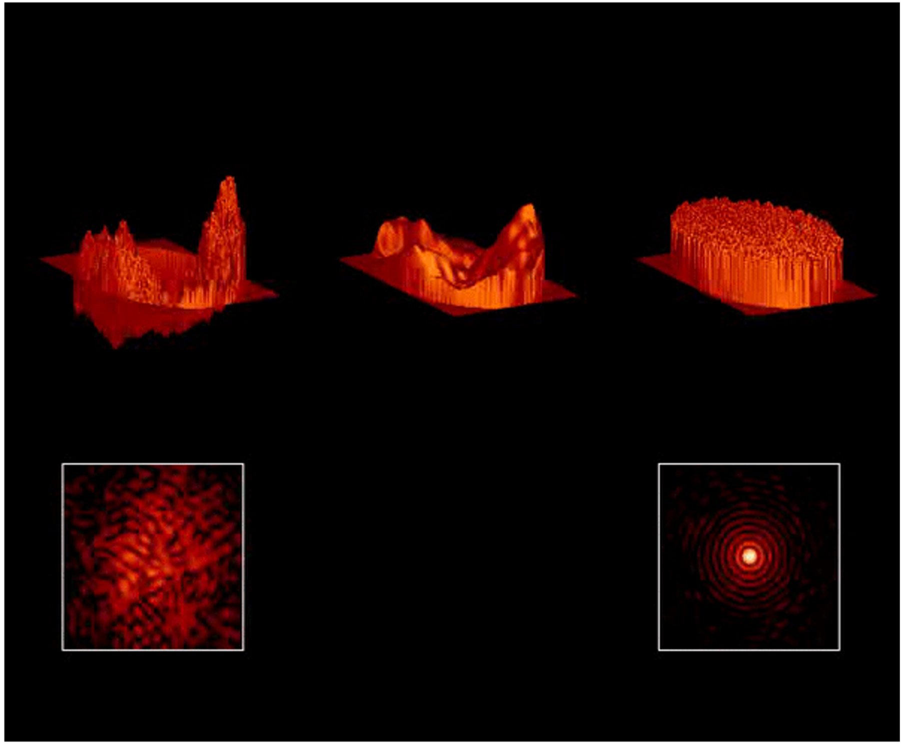


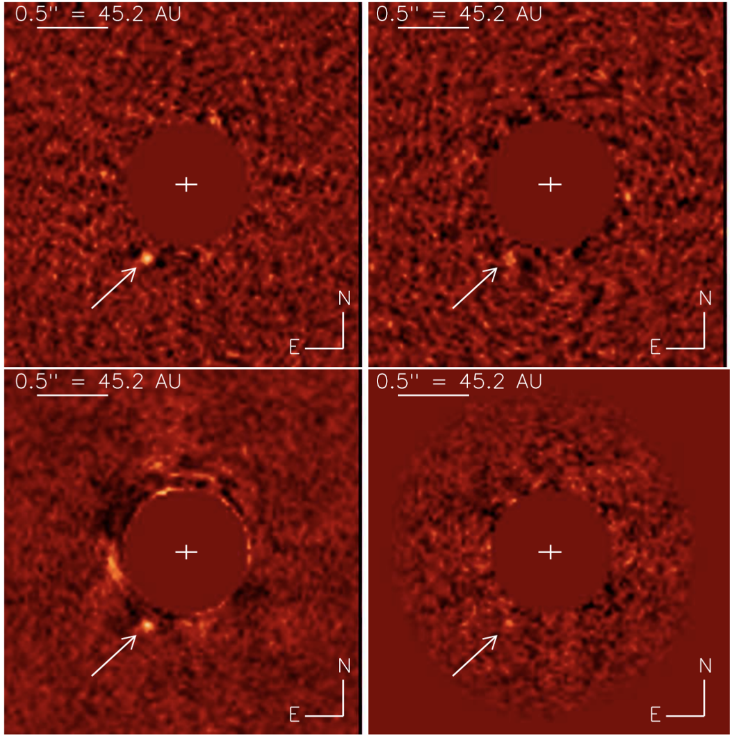
Feedback loop: next cycle corrects the (small) errors of the last cycle



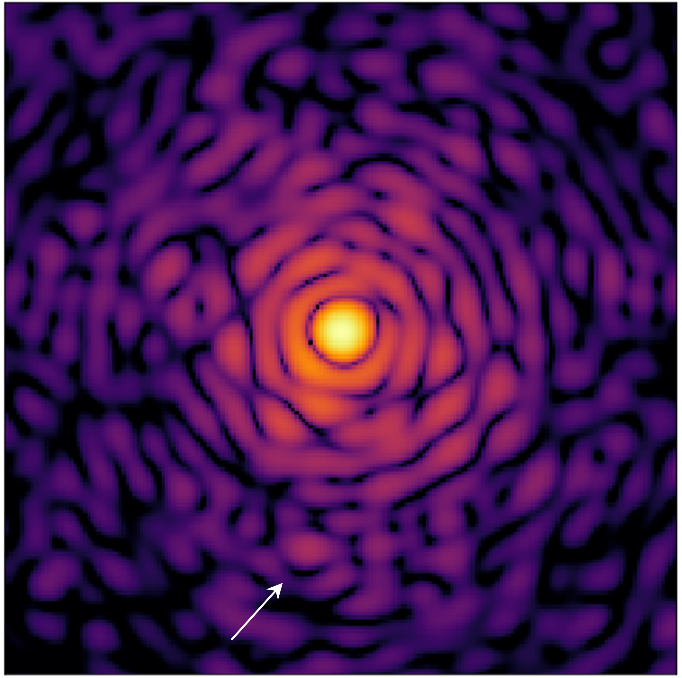
Ground-based High Contrast Imaging Requires **EXTREME** Adaptive Optics



HD 95086b and a Speckle are Hard to Distinguish



(Rameau, 2013)

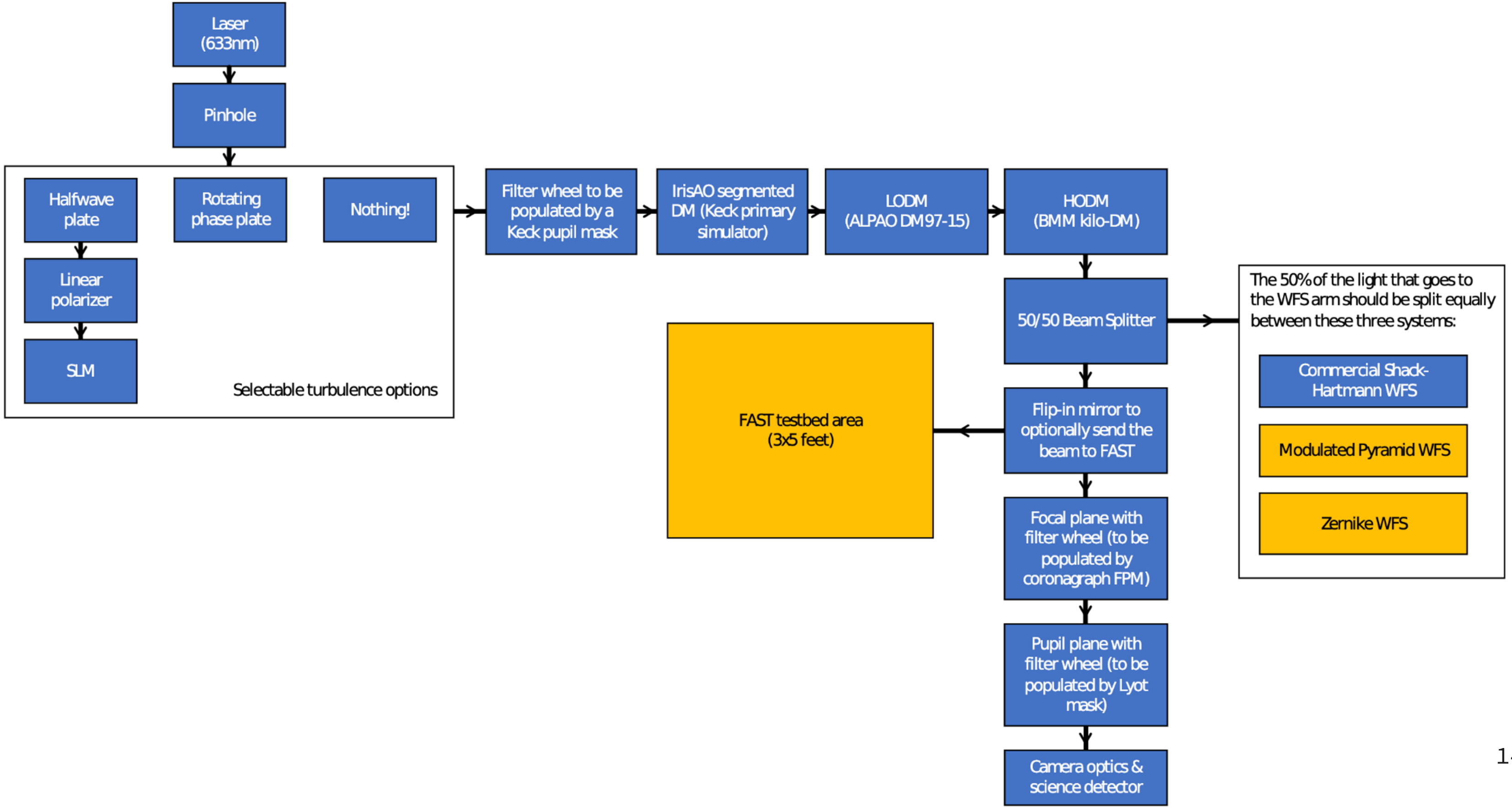


The Santa Cruz Extreme AO Laboratory (SEAL)

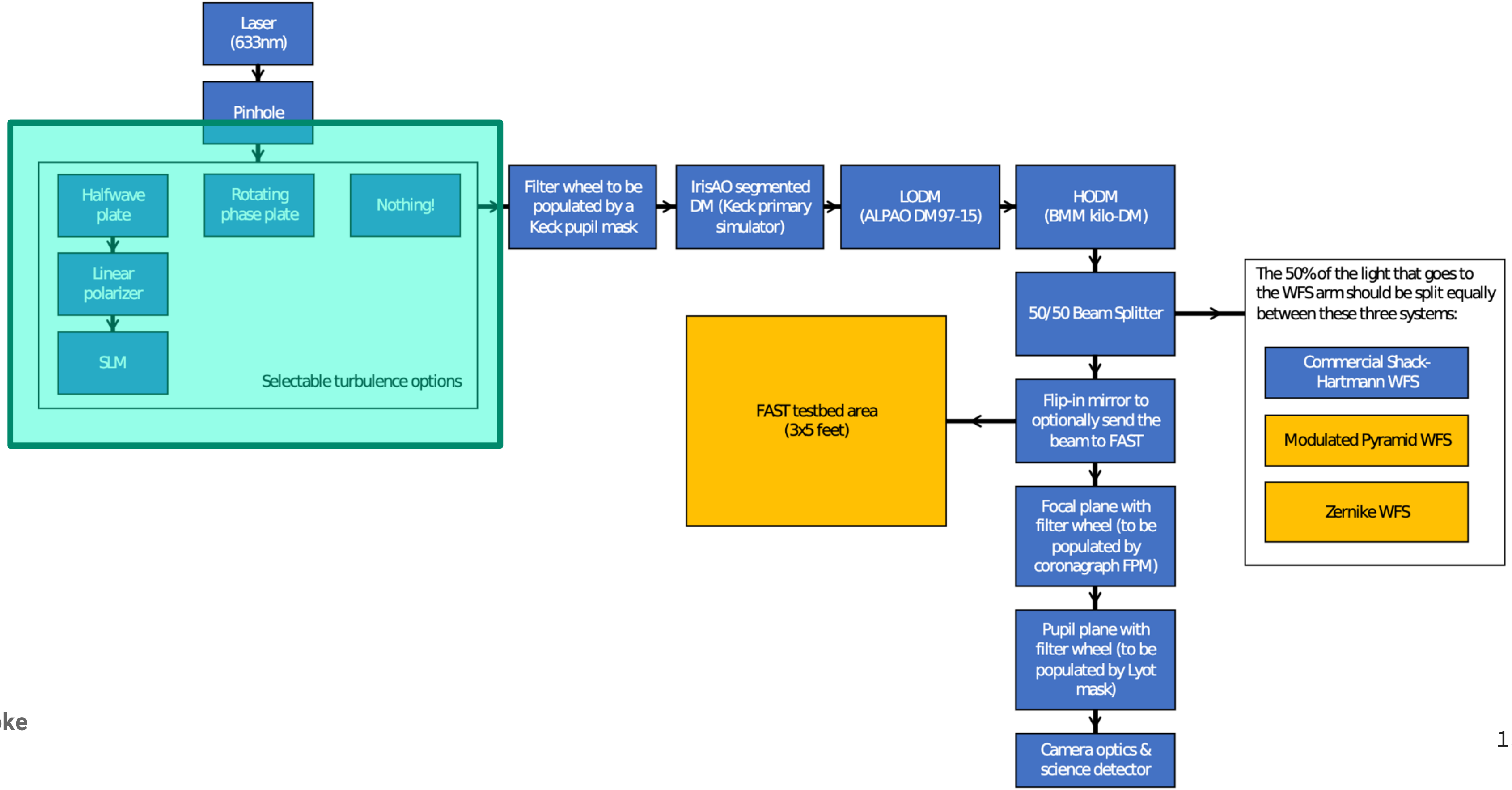
SEAL Tests Novel Wavefront Sensing, Wavefront Control, and Coronagraphy in Synergy with Keck

- Part of the UCSC Lab for Adaptive Optics
- PI: Rebecca Jensen-Clem
- Supported by Renate Kupke, Daren Dillon, and Sylvain Cetre
- Predictive wavefront control (Maaike Van Kooten)
- Focal plane wavefront sensing (Benjamin Gerard)
- Pyramid wavefront sensing (Dominic Sanchez)
- Zernike wavefront sensing(Maaike Van Kooten, soon to be Maissa Salama, and Jules Fowler)
- **Coronagraph Design (Jules Fowler)**

SEAL Includes ...

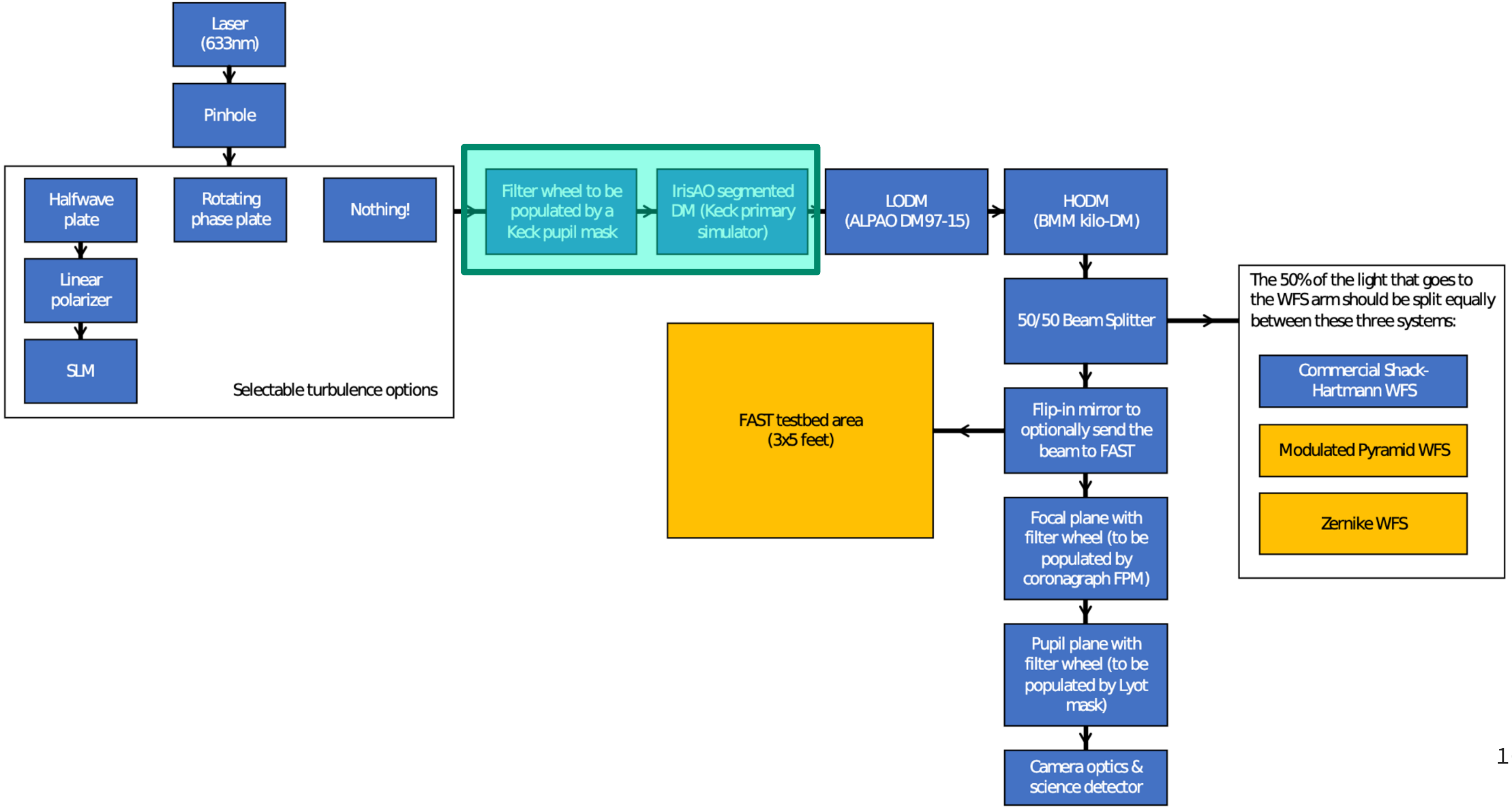


SEAL Includes Atmospheric Turbulence Generation



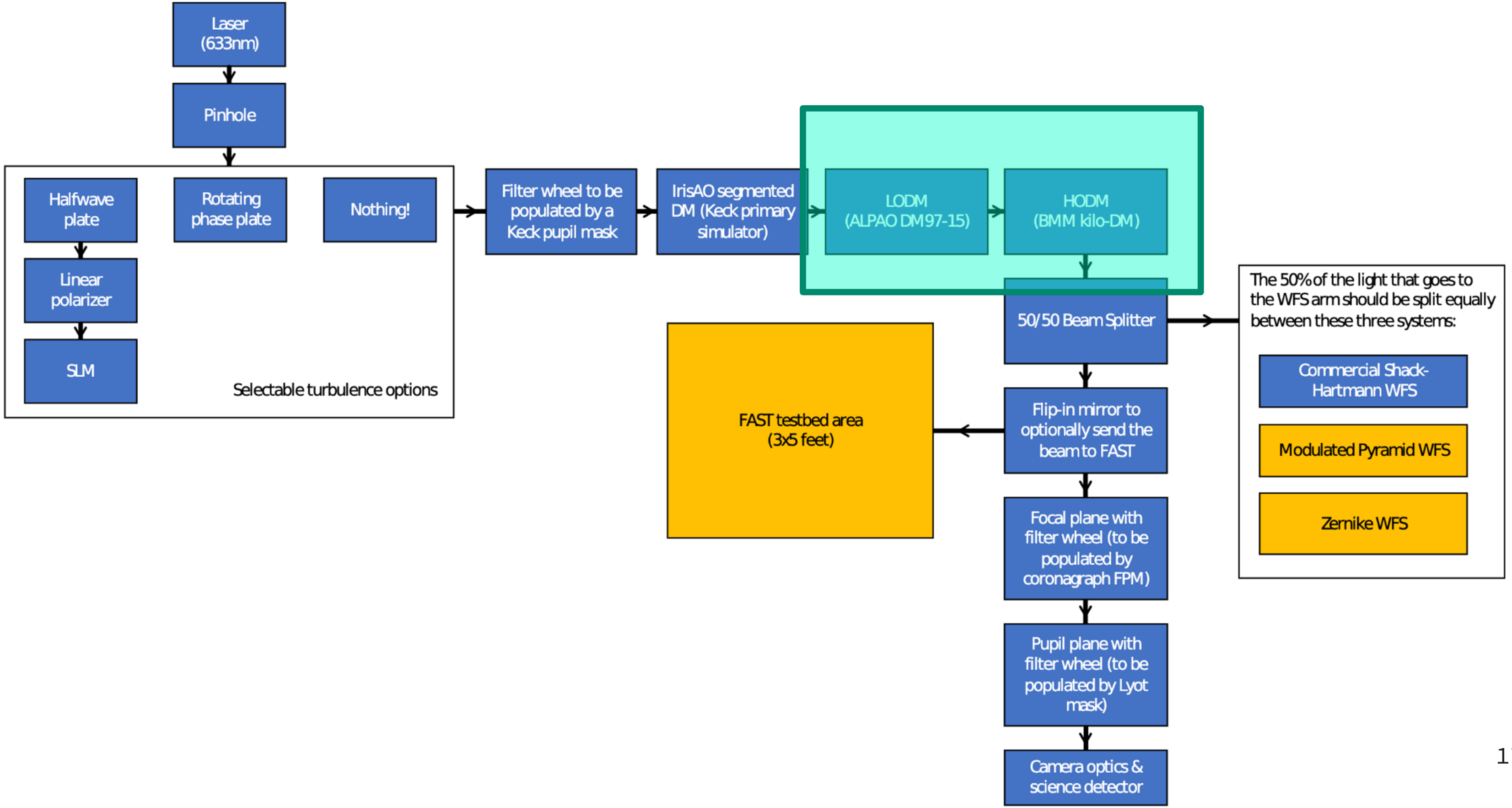
Renate Kupke

SEAL Includes Keck-like Pupil Shaping

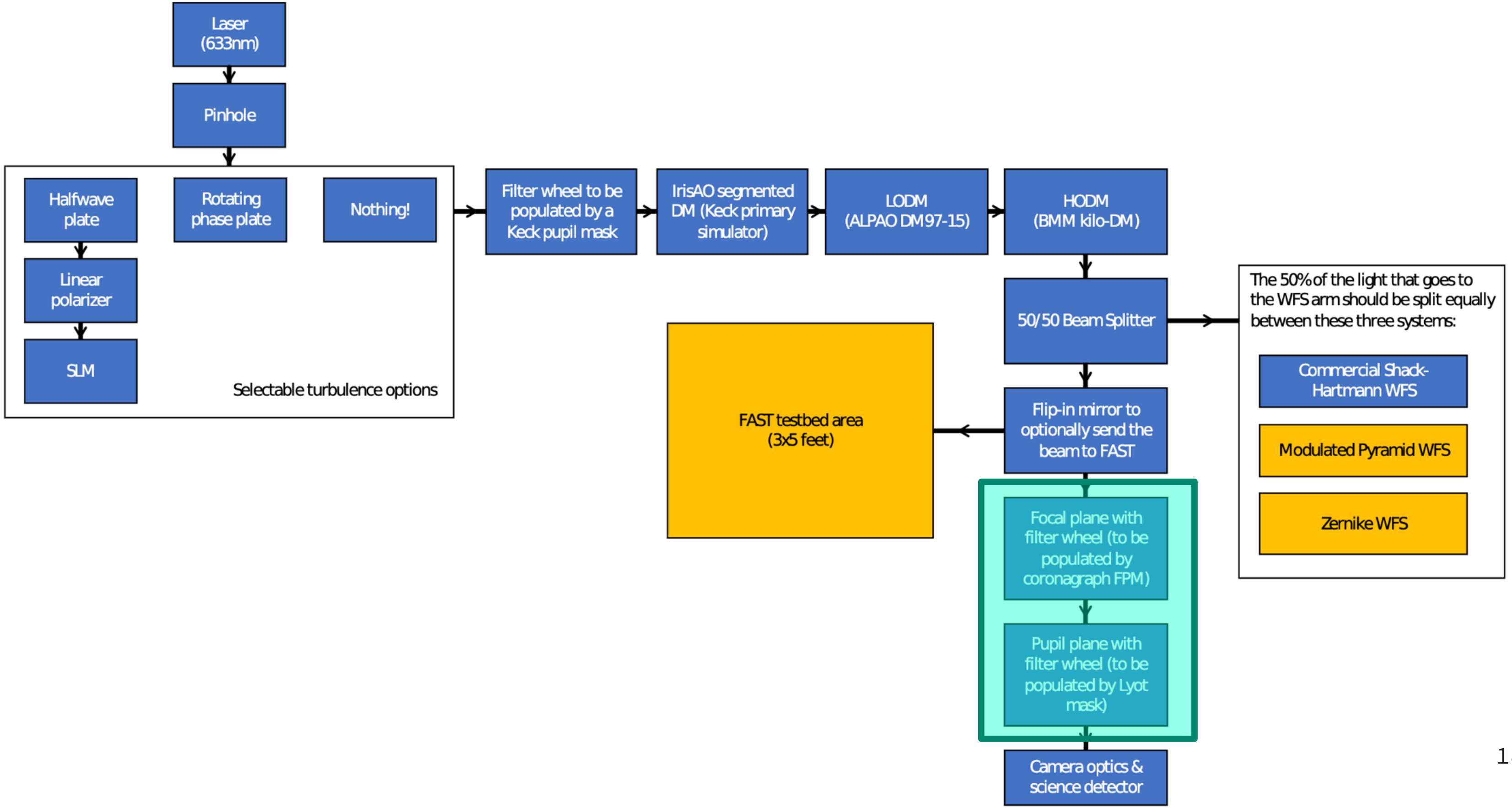


Renate Kupke

SEAL Includes High/Low Order Deformable Mirrors



SEAL Includes This Very Coronagraph!

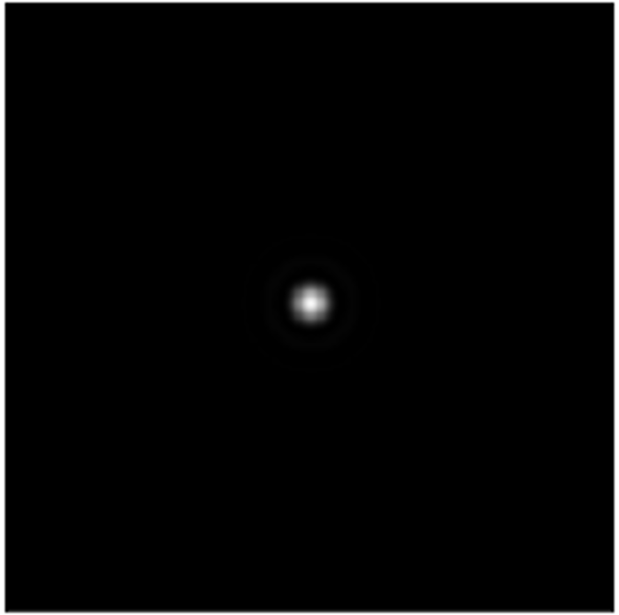


Renate Kupke

Everything You Wanted to Forget About Optics

Pupil and Focal Images are a Fourier Transform Apart

Focal Plane



$\leftarrow \mathcal{F}(f(x,y))$

$\mathcal{F}^{-1}(F(\theta_x,\theta_y))\rightarrow$

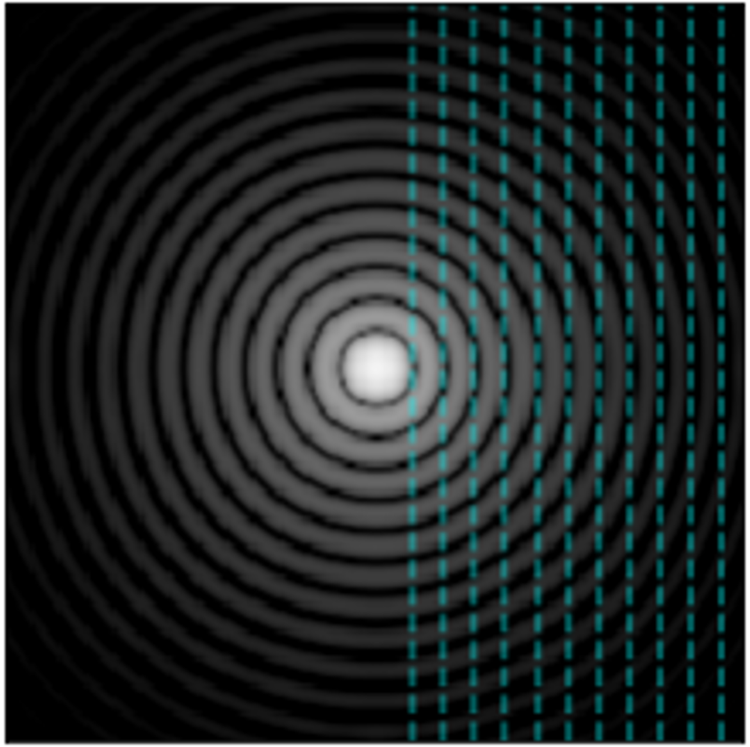
Pupil Plane

Natural Units Intuitively Describe the Focal Plane

Diffraction Limited Resolution of a Telescope System:

$$\theta = \lambda/D$$

Airy Rings at 1λ/D intervals

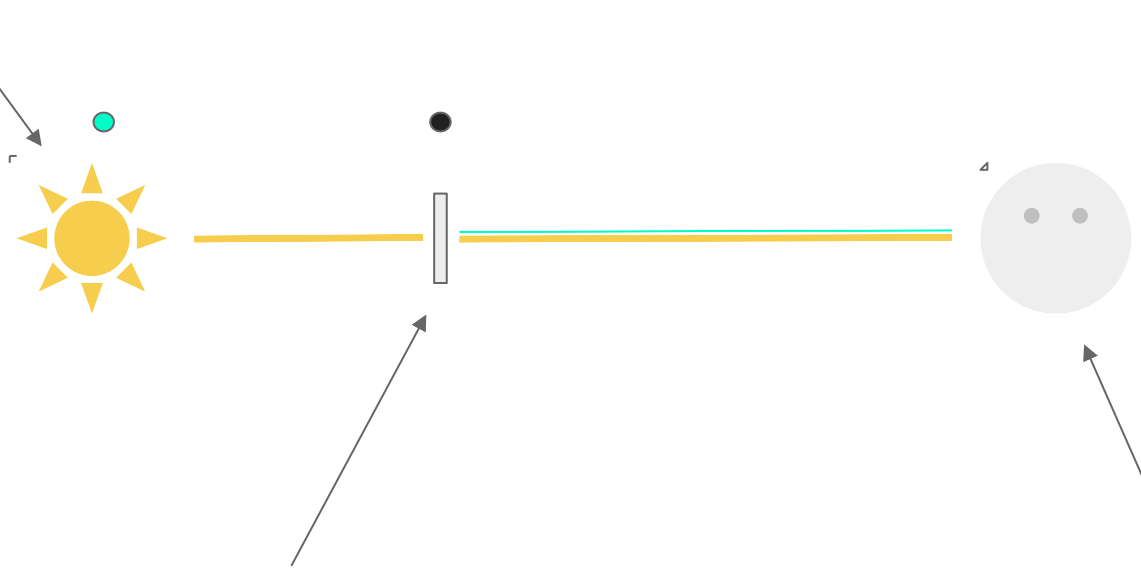


Coronagraphy Basics

Starlight Is Suppressed by a Coronagraph

Starlight Is Suppressed by a Coronagraph

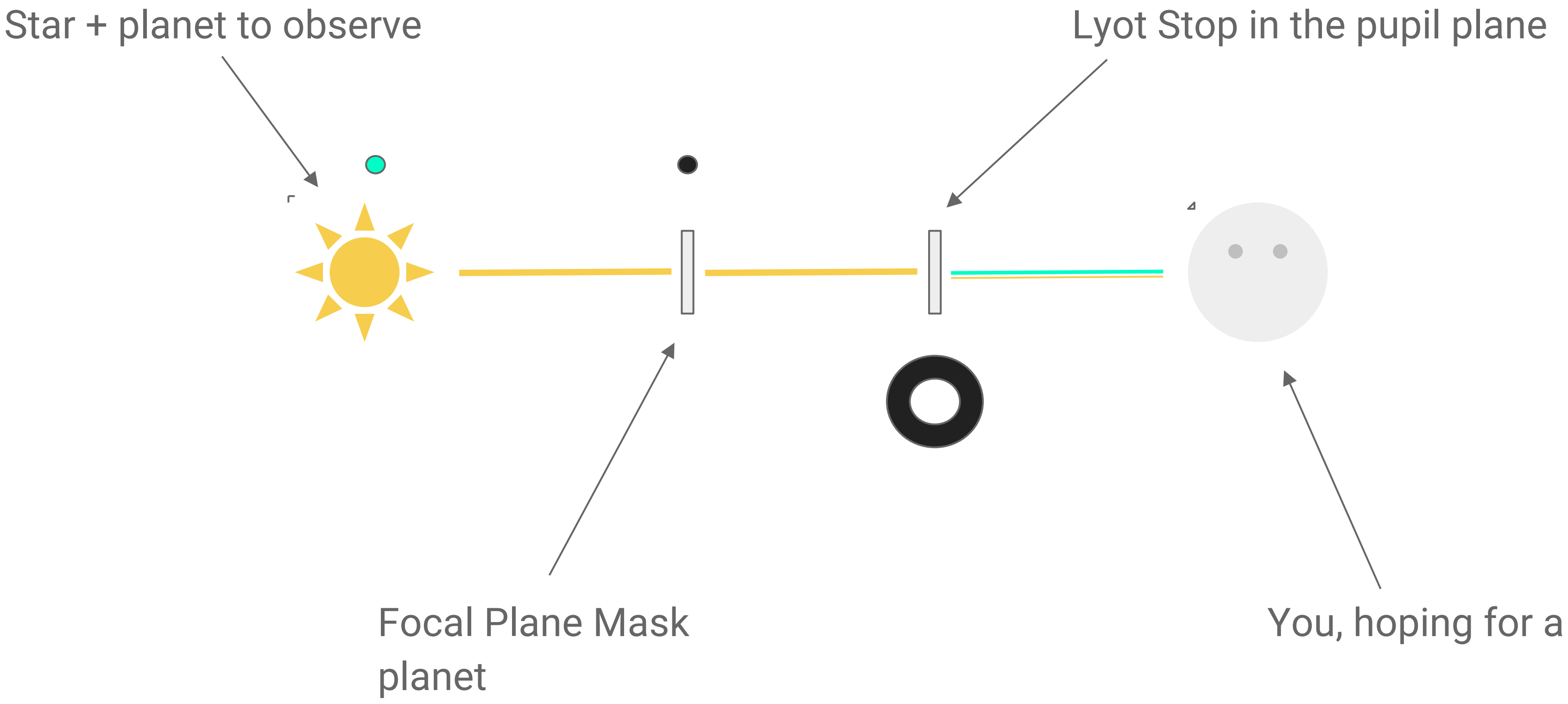
Star + planet to observe



Focal Plane Mask

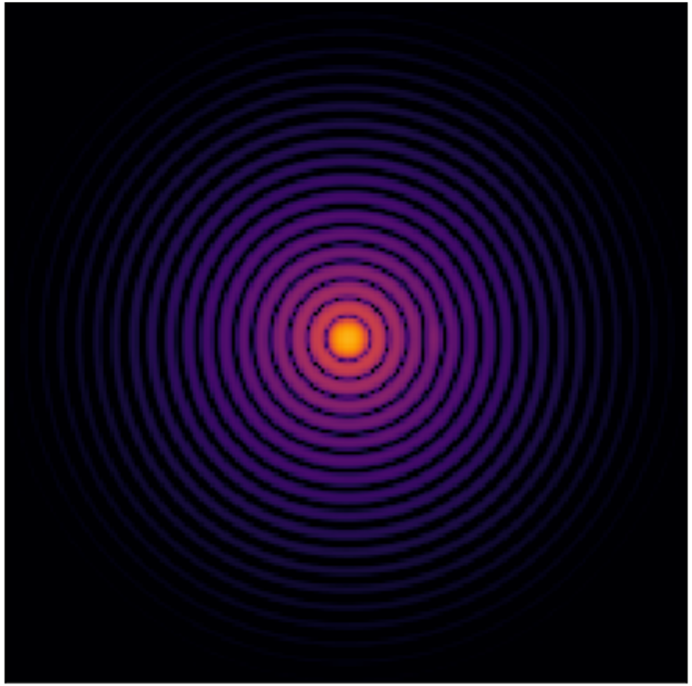
You, hoping for a planet

Starlight Is Suppressed by a Coronagraph

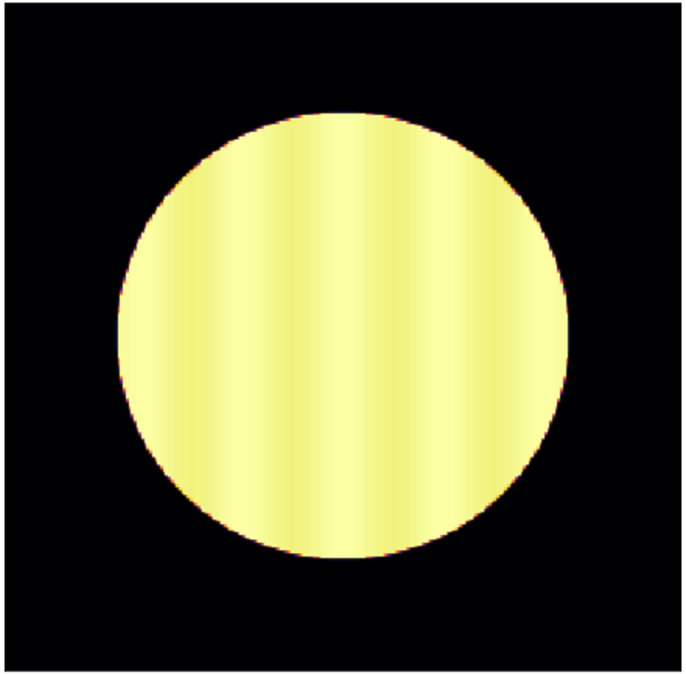


Only Starlight is Visible, Despite an Injected Companion

Focal Plane

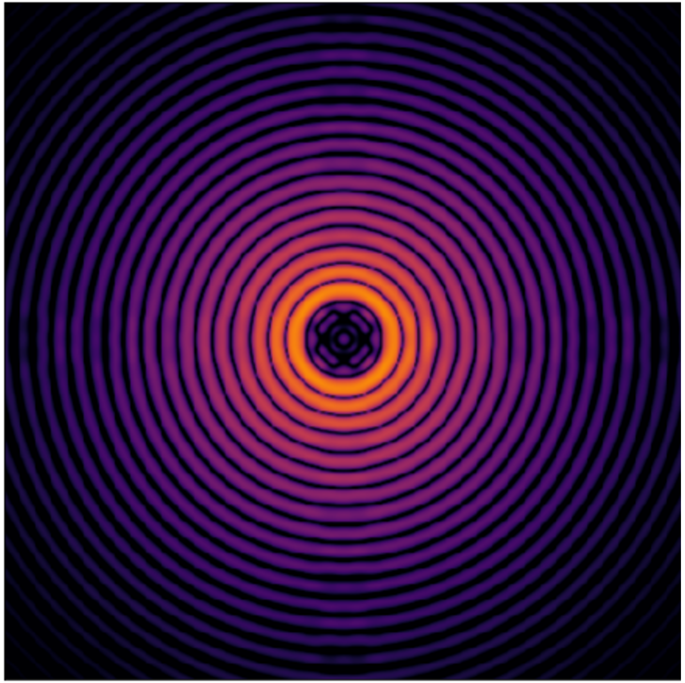


Pupil Plane

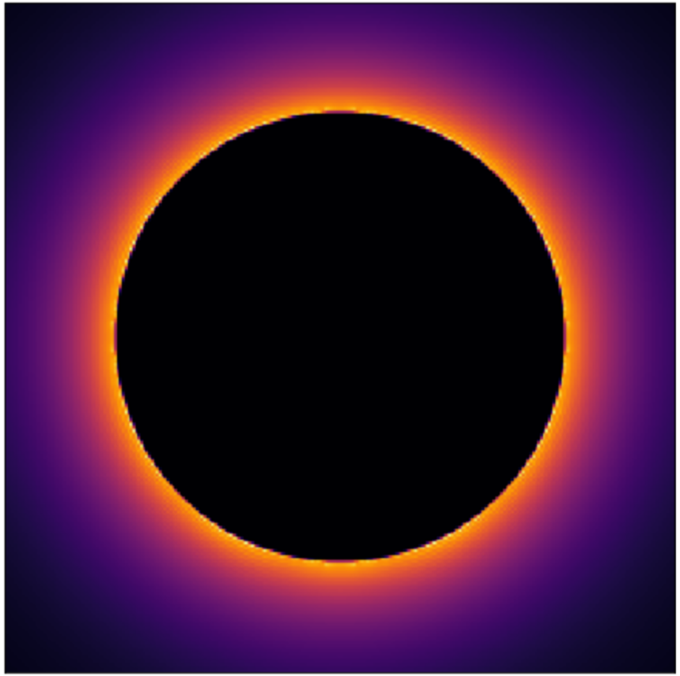


Starlight is Diffracted to the Edge of the Aperture

Focal Plane

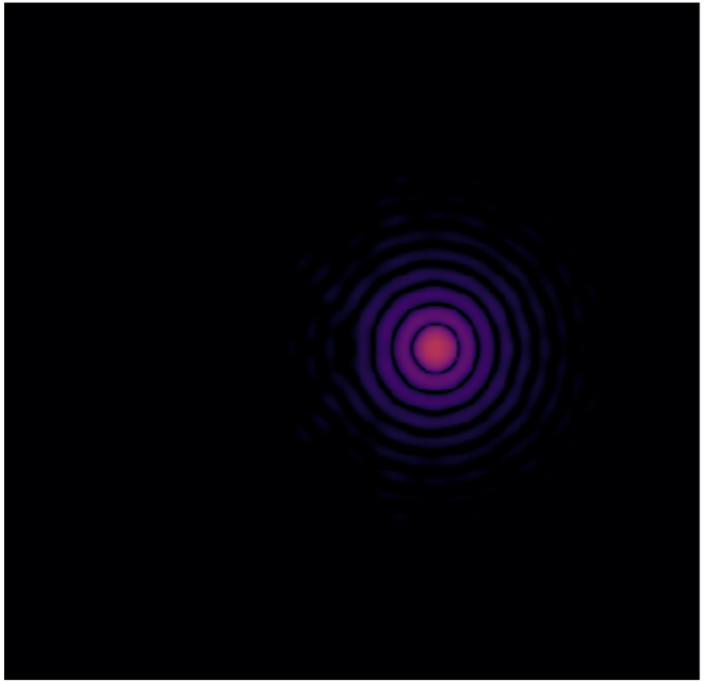


Pupil Plane

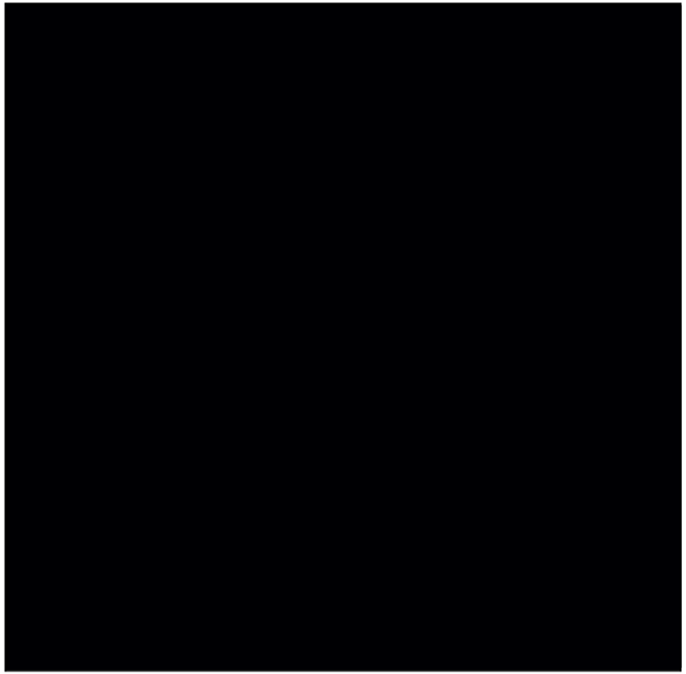


The Planet Appears!

Focal Plane



Pupil Plane



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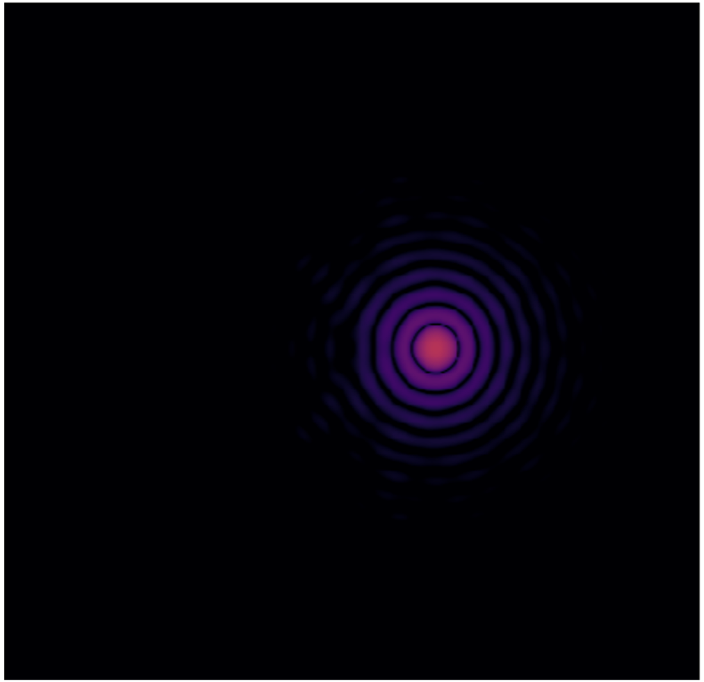
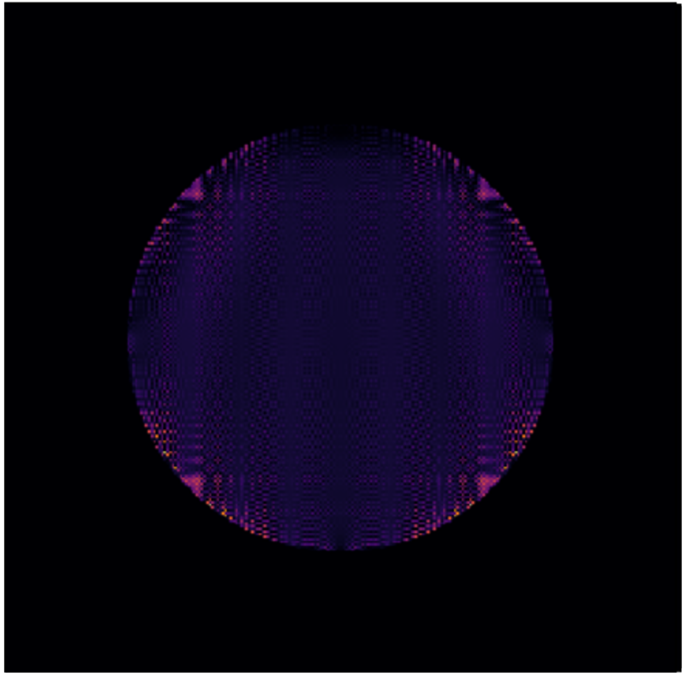
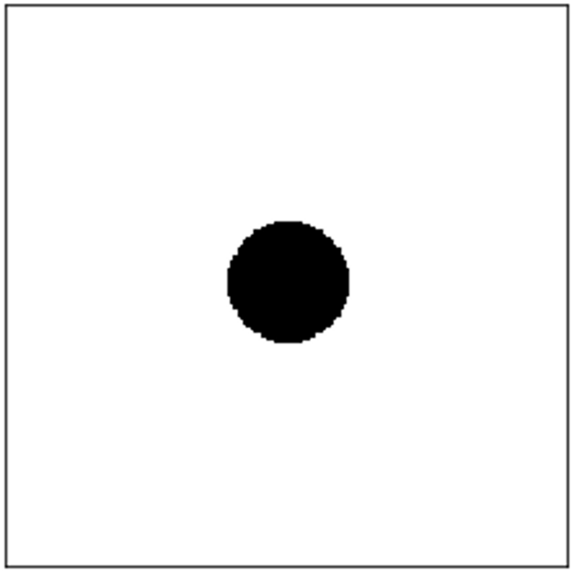


Pupil Plane

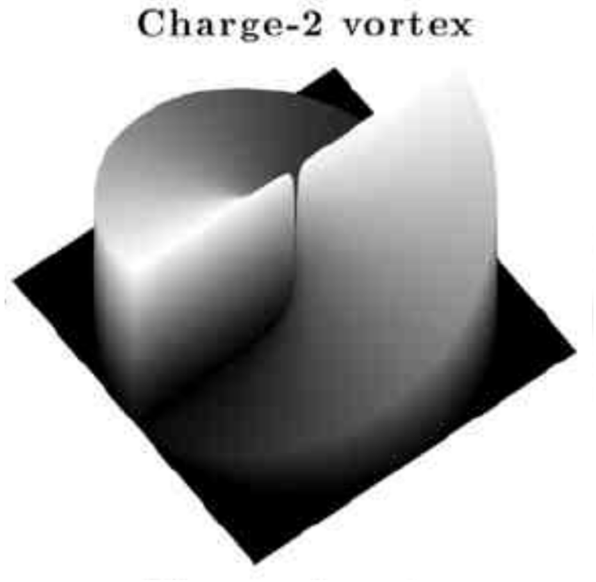


Focal Plane Masks Vary for Classical Lyot and Vortex Coronagraphy

Classic Focal Plane Mask



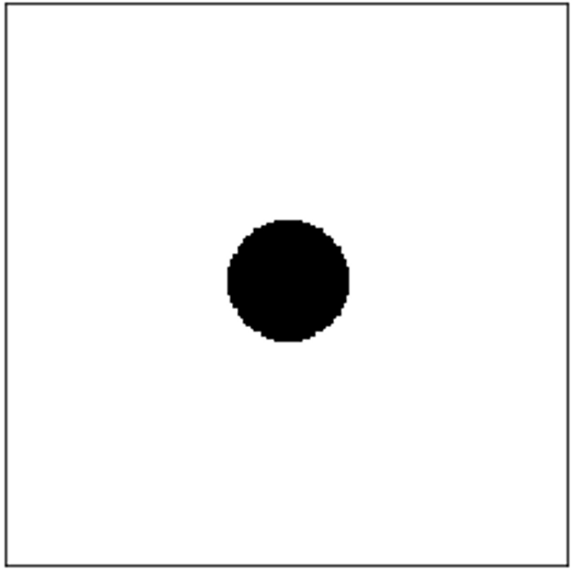
Vortex Focal Plane Mask



(Delacroix, 2014)

Focal Plane Masks Vary for Classical Lyot and Vortex Coronagraphy

Classic Focal Plane Mask



Vortex Focal Plane Mask

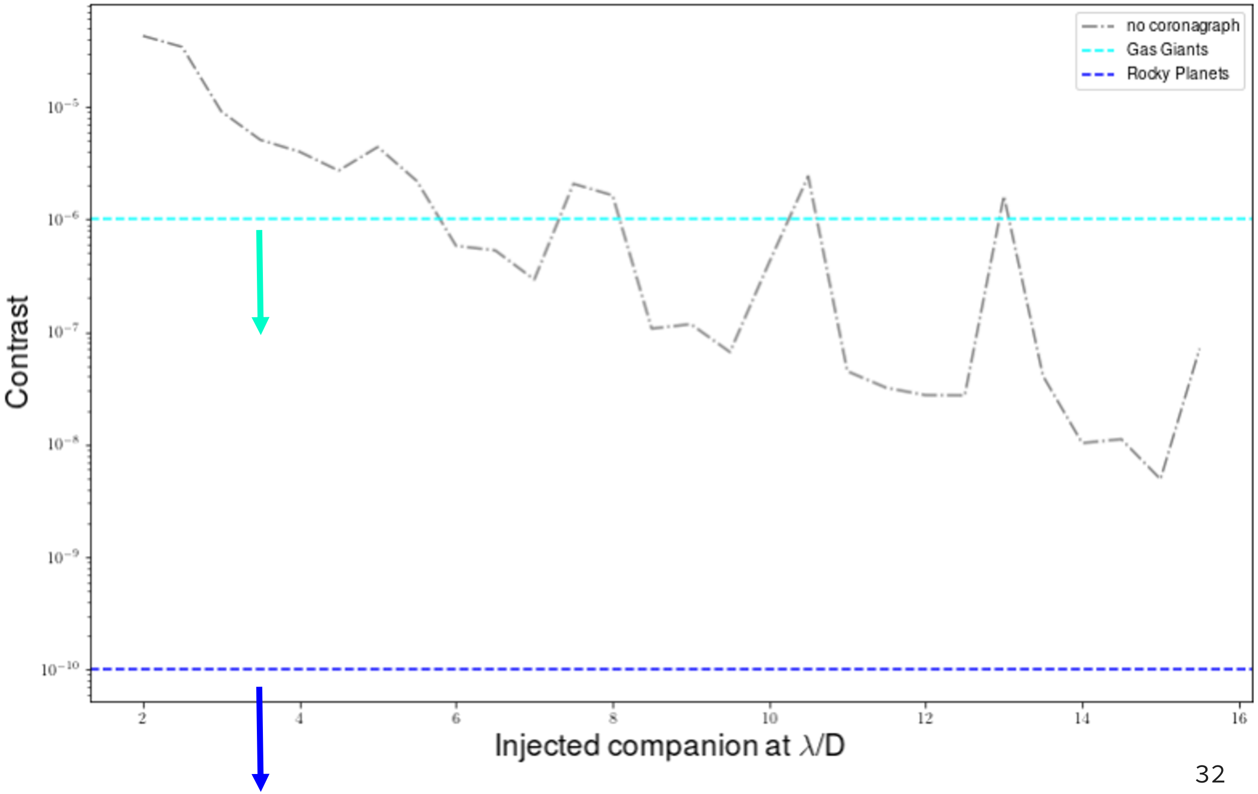
(MarbulaOne, 2020)

Contrast Curves Across the Image Plane are a Coronagraph Performance Metric

Contrast normalized by throughput

- Jensen-Clem 2018

$$\text{contrast} = \left(\frac{\text{factor} \times \text{noise}}{\text{stellar aperture photometry}}\right) \times \left(\frac{1}{\text{throughput}}\right)$$



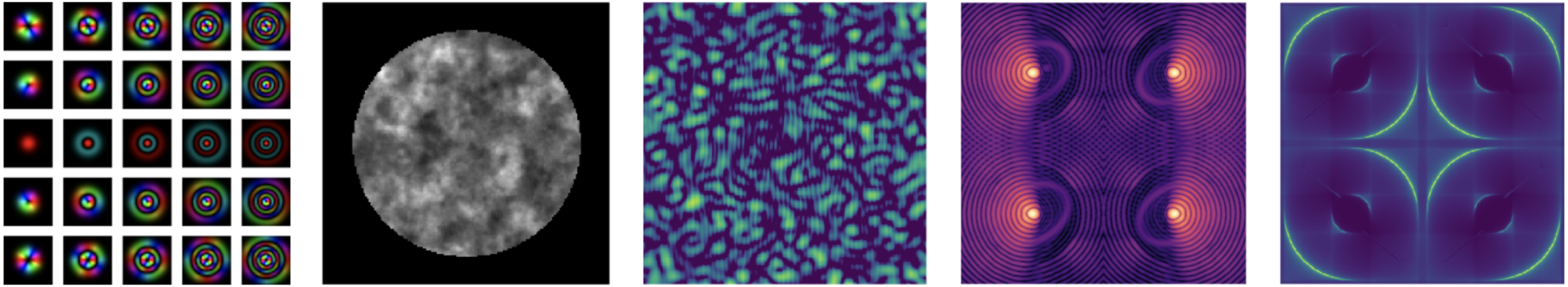
Simulating a Coronagraph with HCIPy

High Contrast Imaging for Python

github.com/ehpor/hcipy

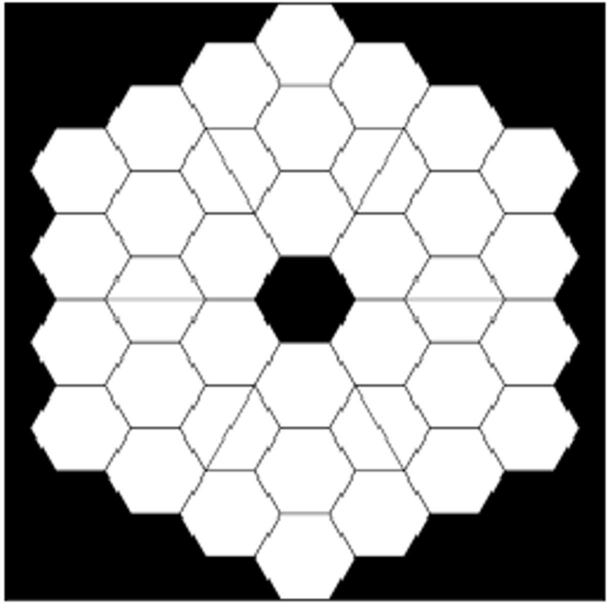
pypi v0.4.0 | build passing | coverage 79% | docs latest build | license MIT

HCIPy: High Contrast Imaging for Python

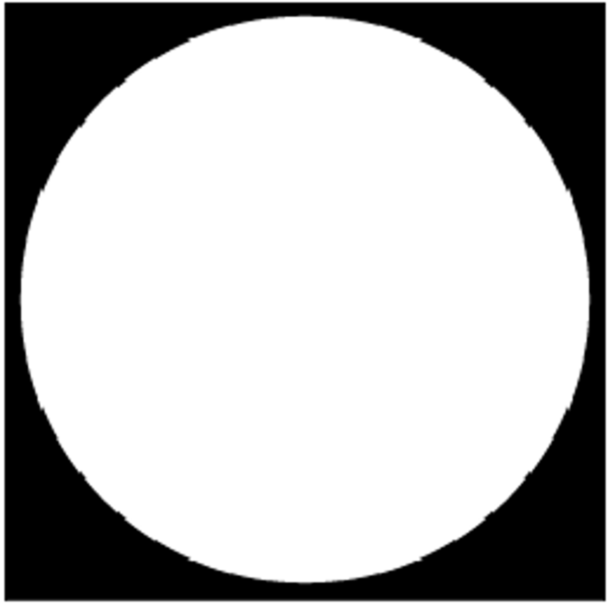


Our Simulations Use a Circular Aperture

Keck Aperture



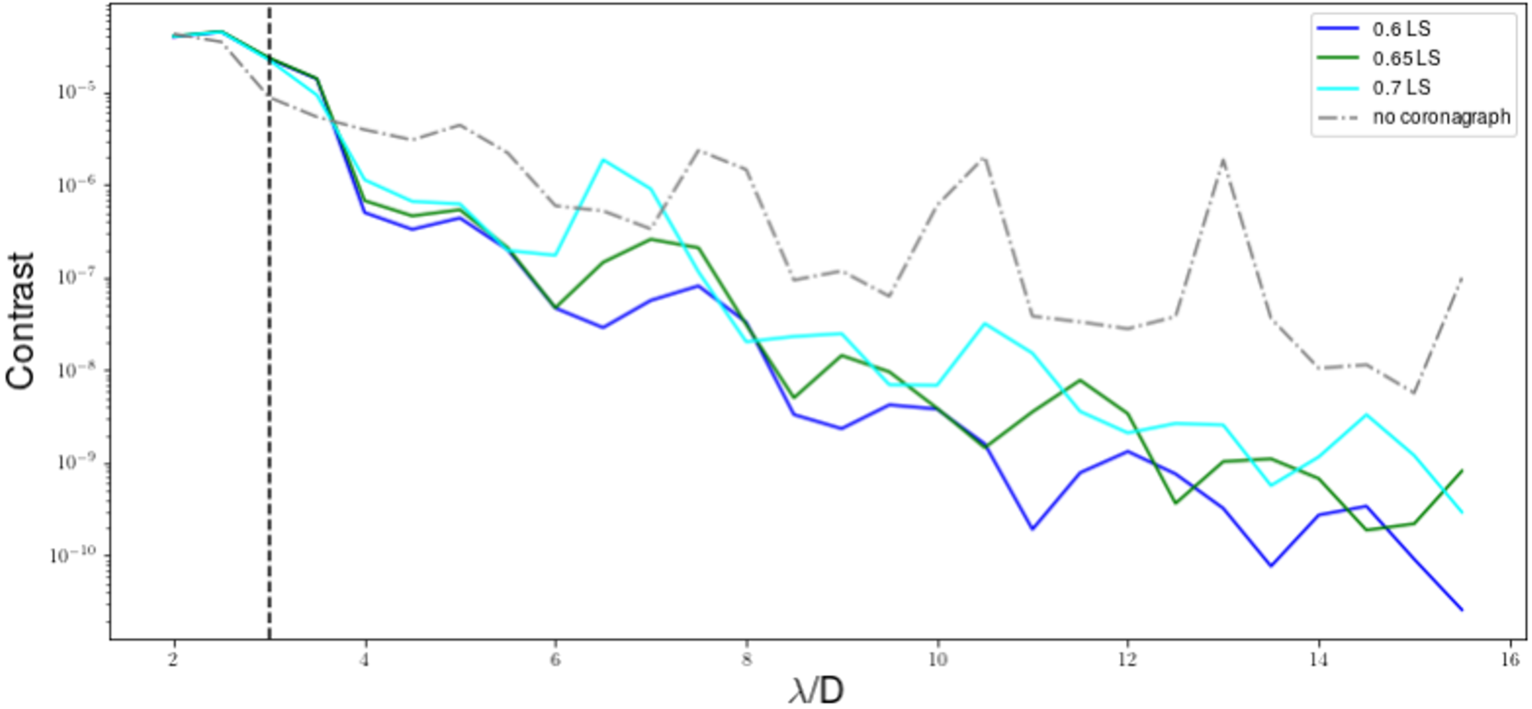
Circular Aperture



Designing a B- Lyot Coronagraph

$D_{LS}/D_{aperture} < 1 - 1/D_{FPM}$: $D_{FPM} = 3 \Rightarrow D_{LS} < 0.67$

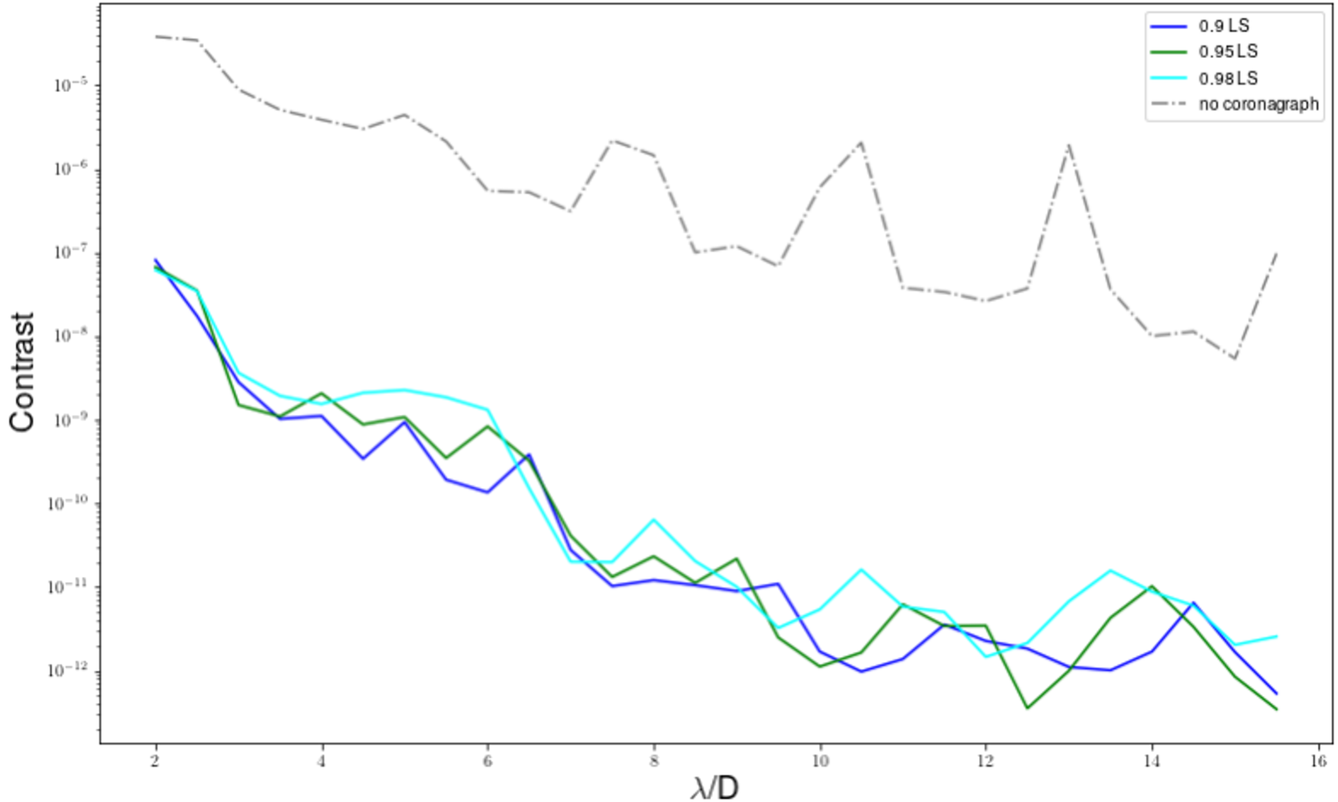
- Sivaramakrishnan, 2001



Designing an A+ Vortex Coronagraph

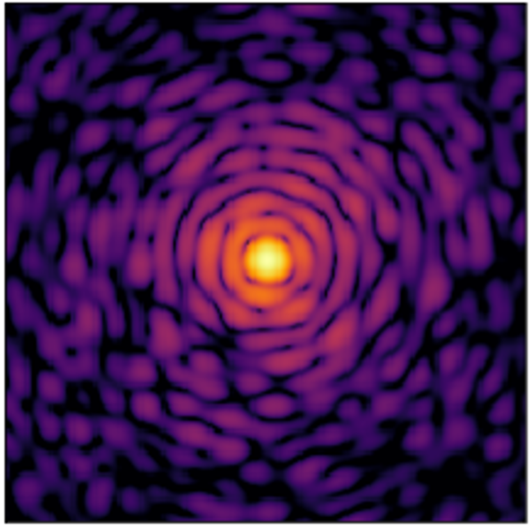
We expect to see no contrast difference past a certain threshold (~0.98).

- Ruane, 2018

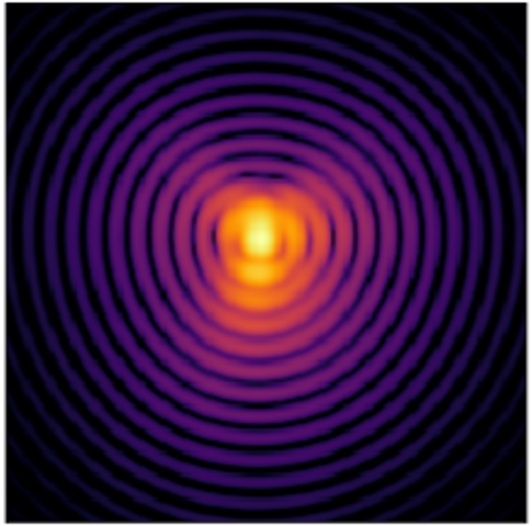


Wavefront Error from Imperfect Optics Creates Speckles

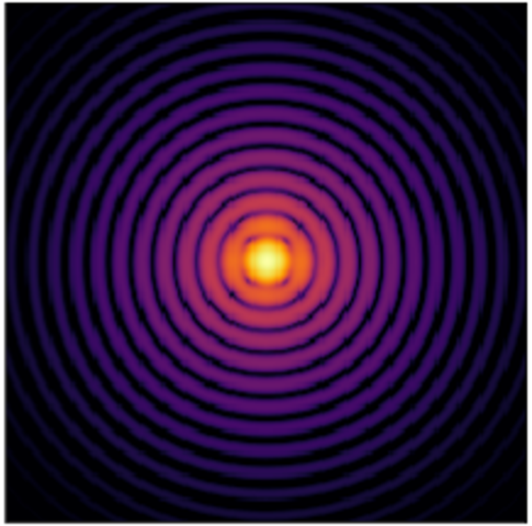
High Order WFE



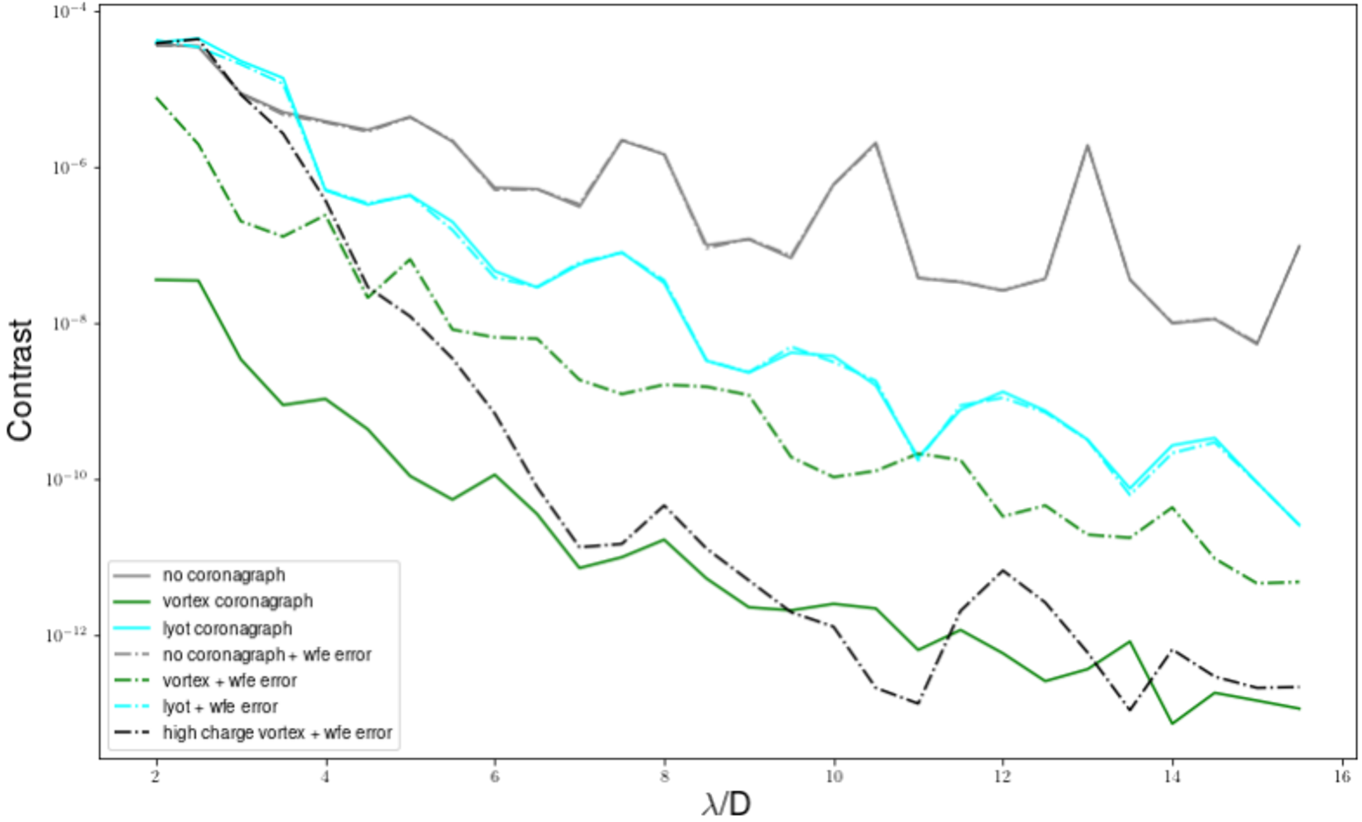
Low Order WFE



Realistic WFE

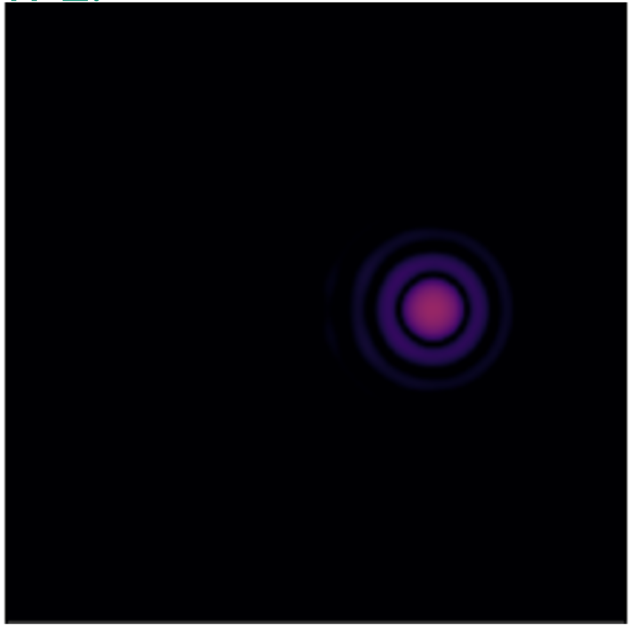


Wavefront Error Impacts Contrast, Especially for the (low charge) Vortex

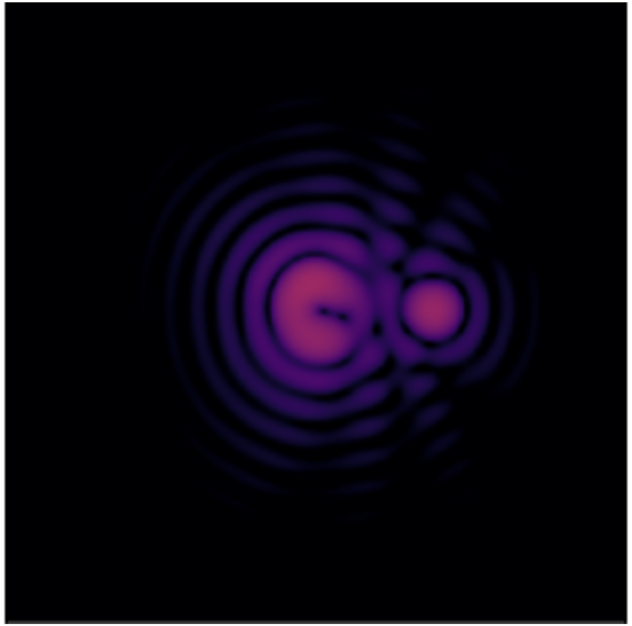


Wavefront Error from Impacts the Final Coronagraphic Image

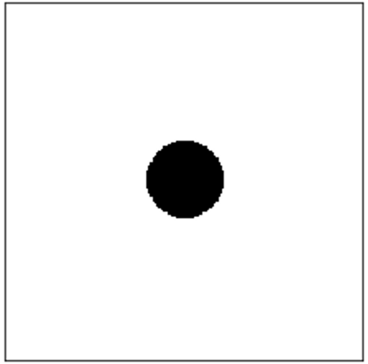
Perfect vortex:

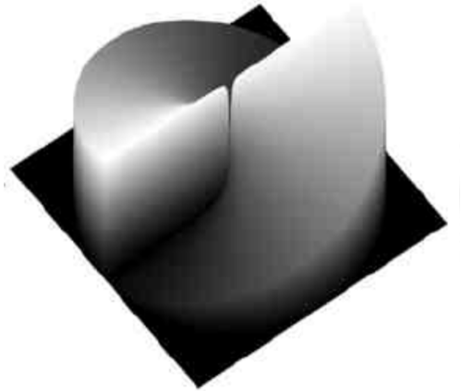


Vortex with WFE:



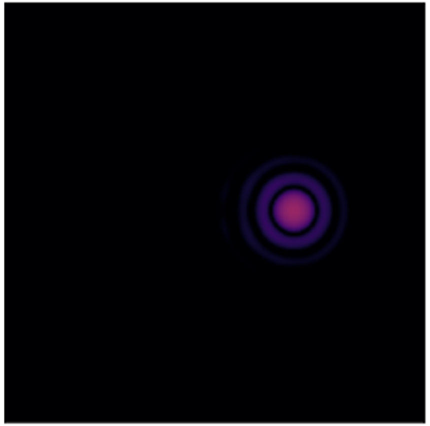
Typical Vortex Masks are Imperfect



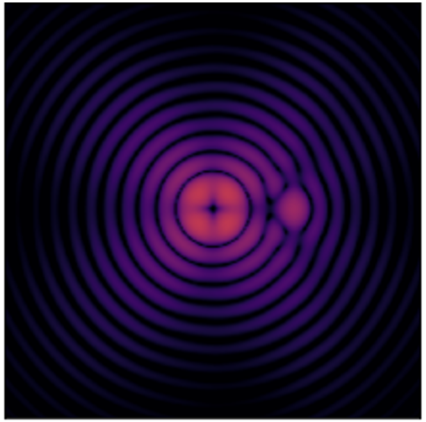


⇒

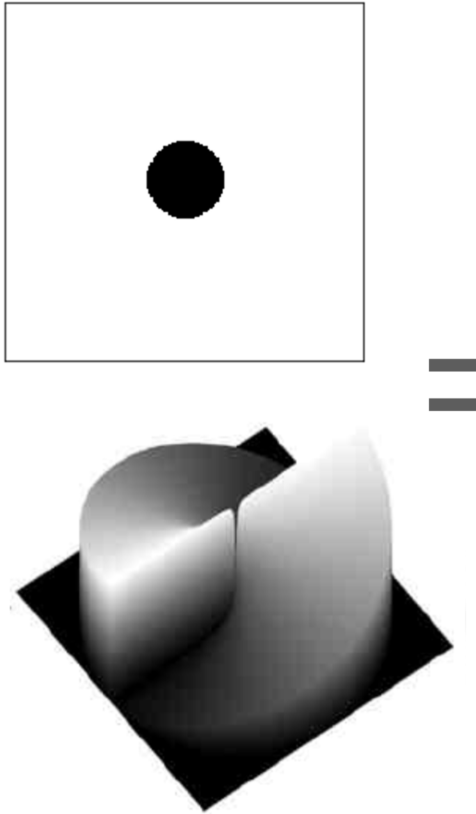
perfect vortex:

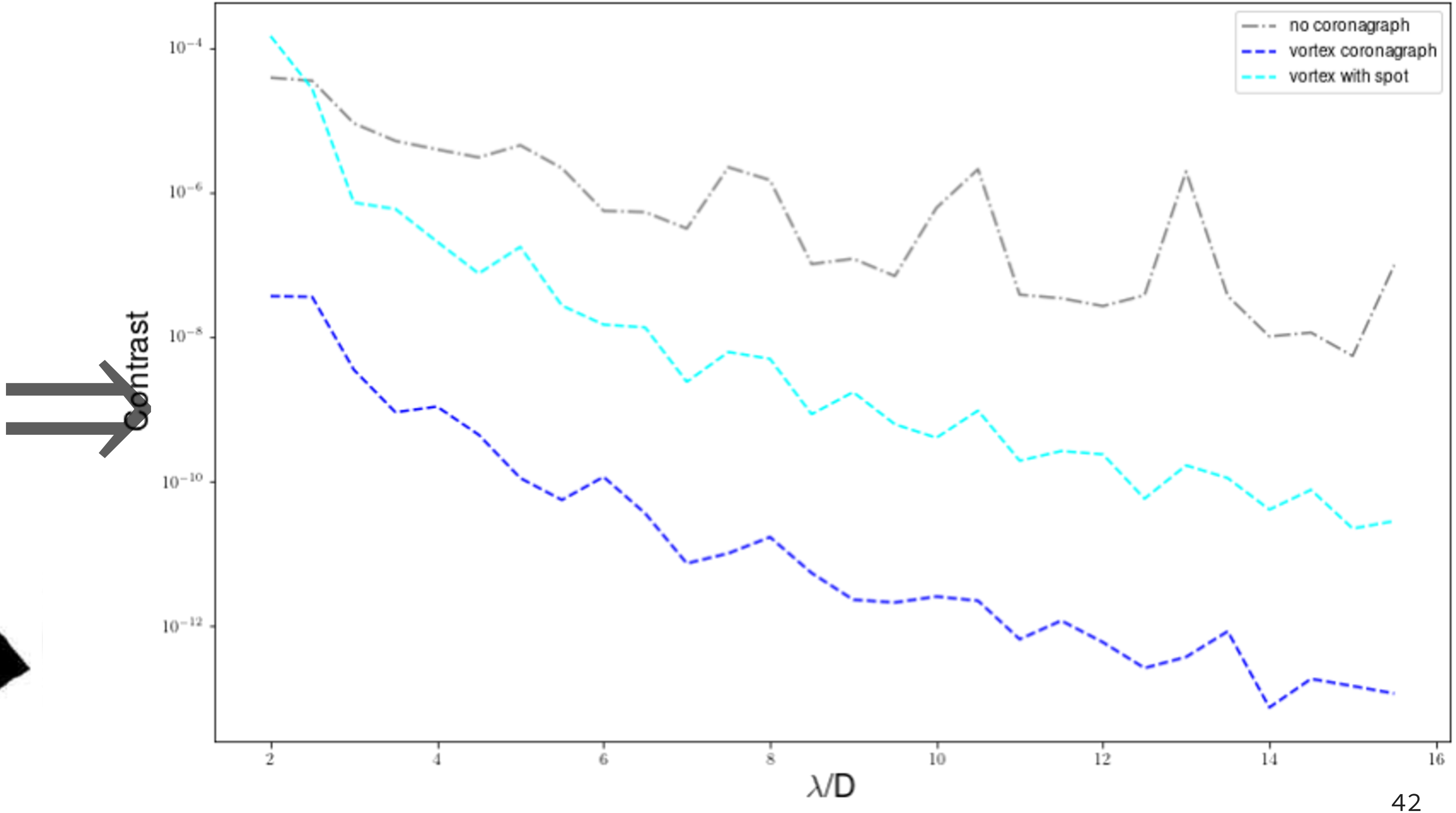


vortex + spot:

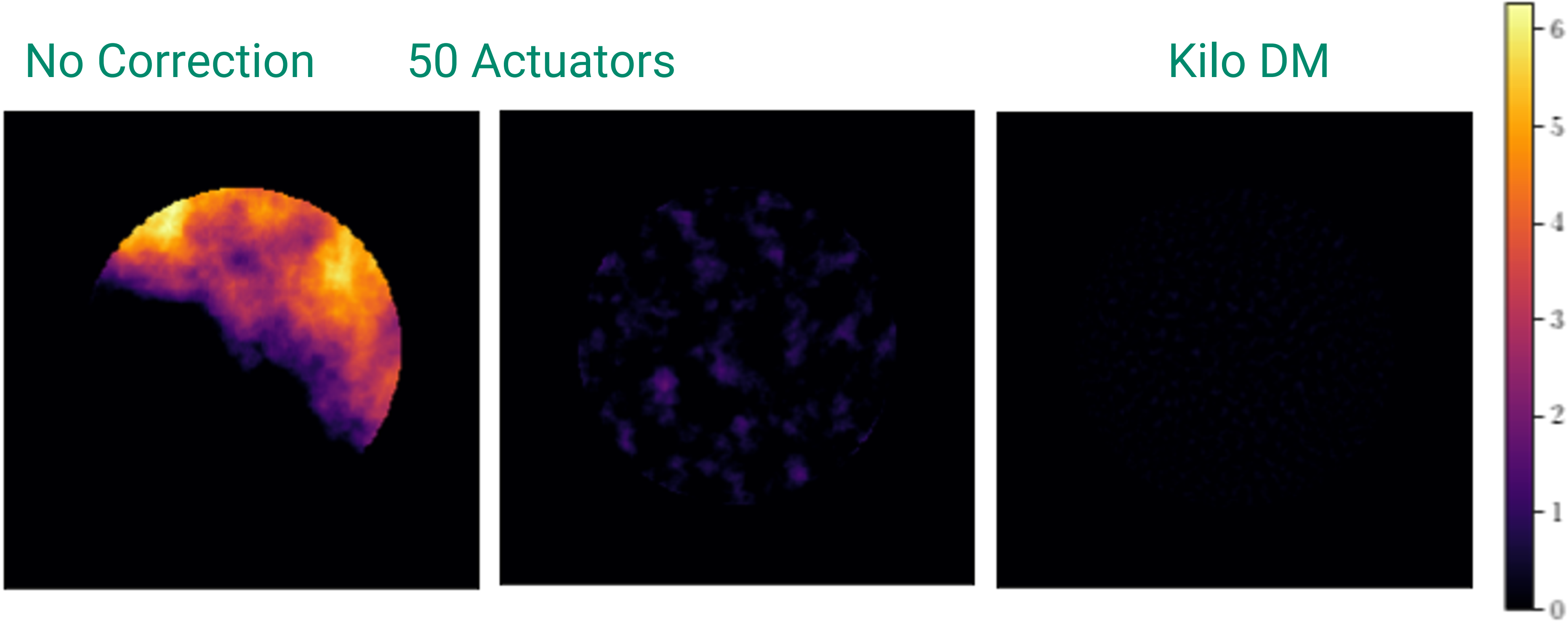


Imperfect Vortex Masks Impact Contrast



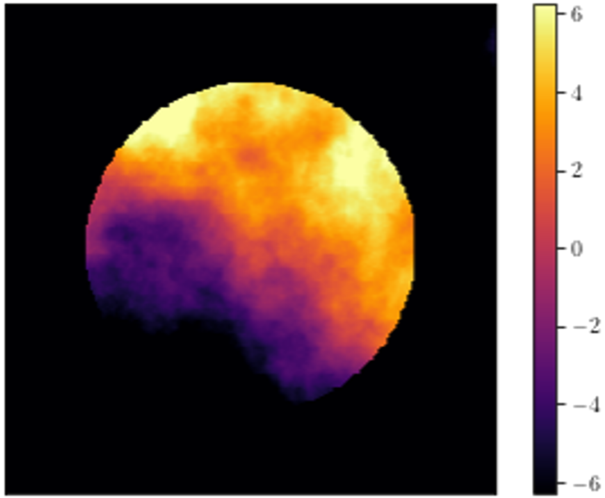


Atmosphere Imparts Phase Errors But Can be Corrected with Deformable Mirrors

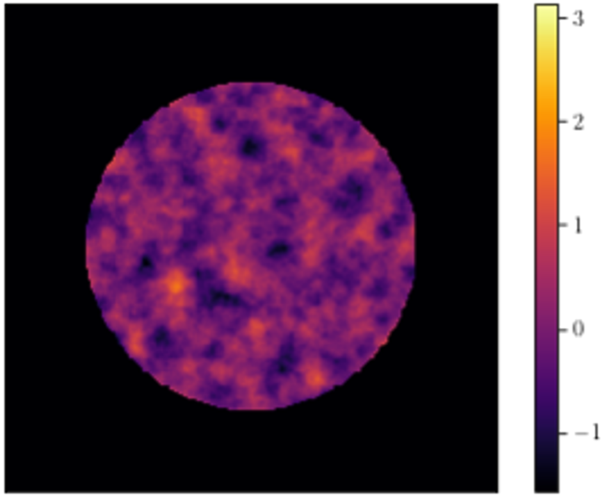


Atmosphere Imparts Phase Errors But Can be Corrected with Deformable Mirrors

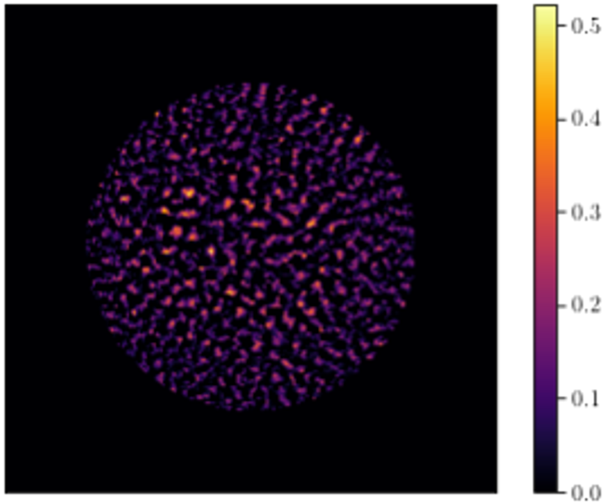
No Correction



50 Actuators



Kilo DM

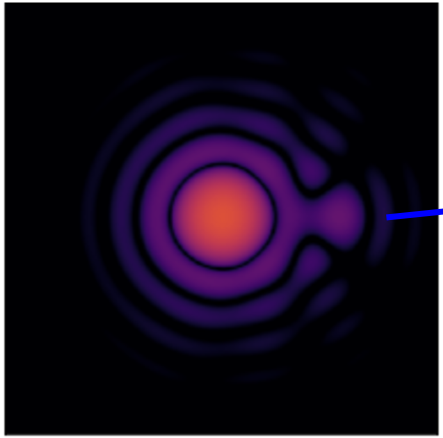


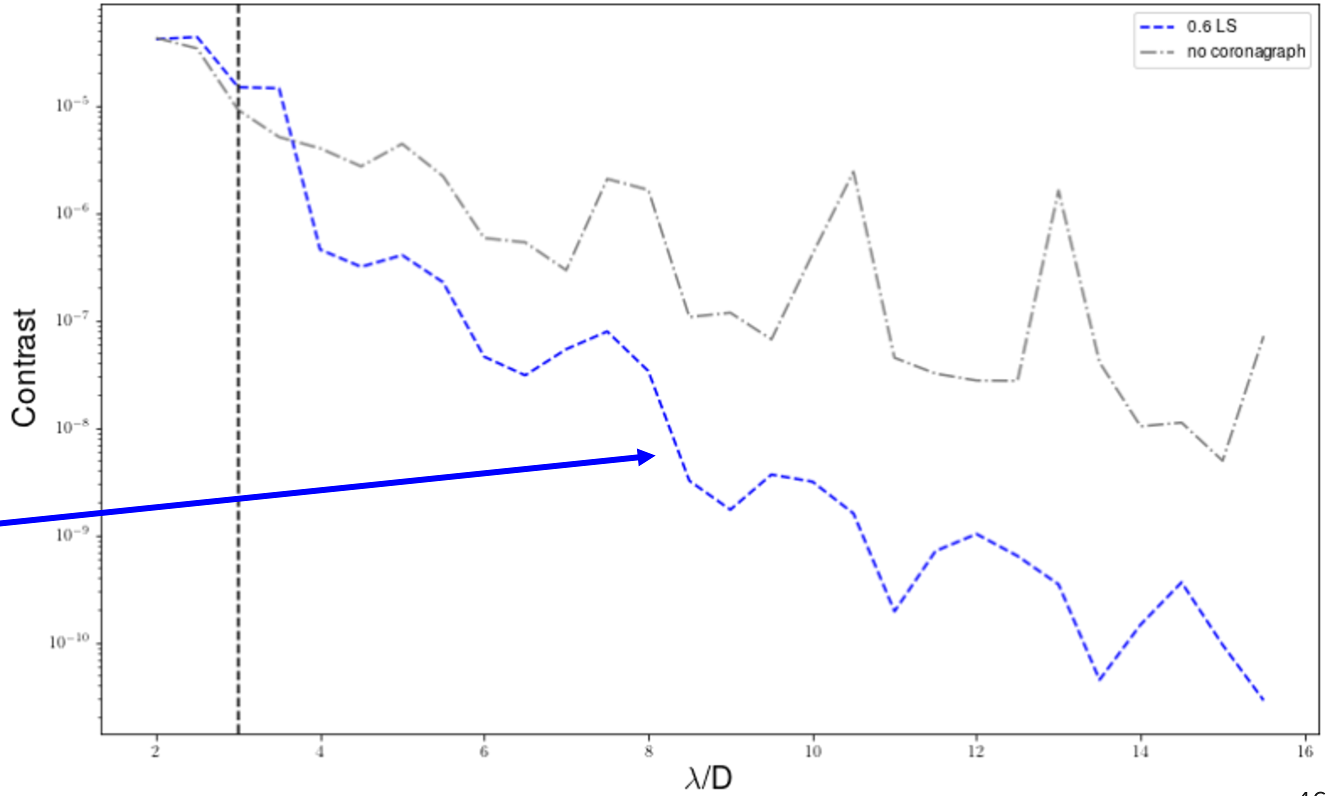
Current State of the Design

Large FPM Allows for Larg(er) Lyot Stop

FPM: 3λ/D

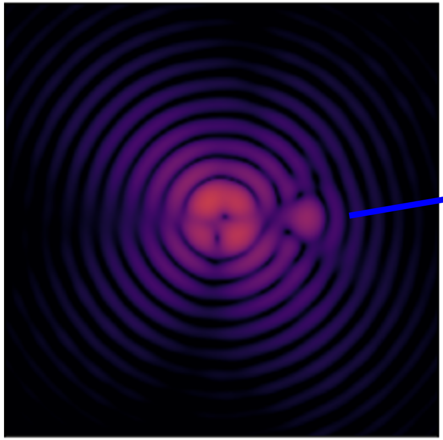
LS: 0.6

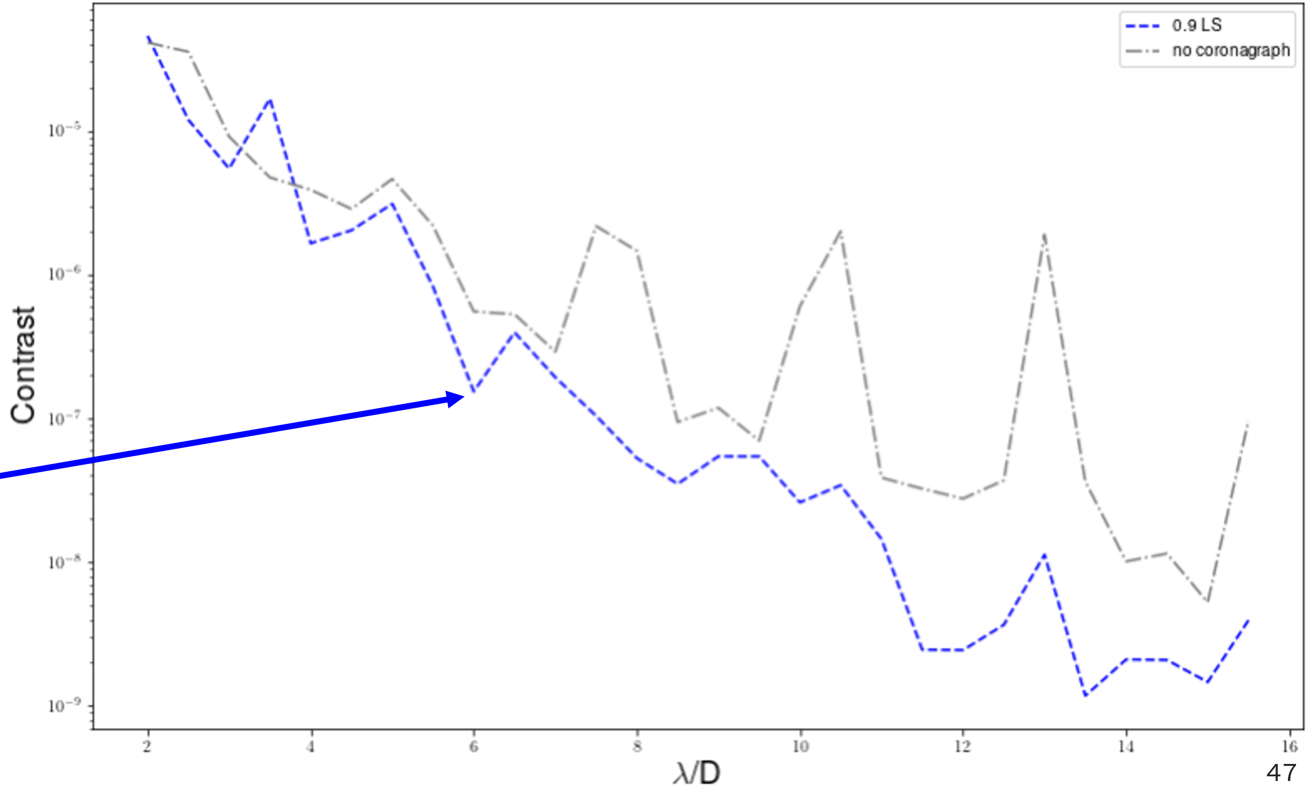




Optimal Vortex Will be Difficult to Integrate and Align: Lyot Stop 0.98 → 0.9

LS: 0.9

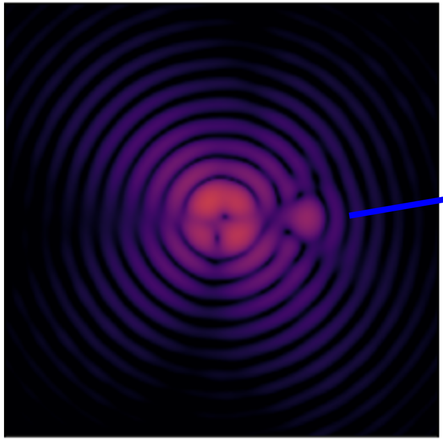


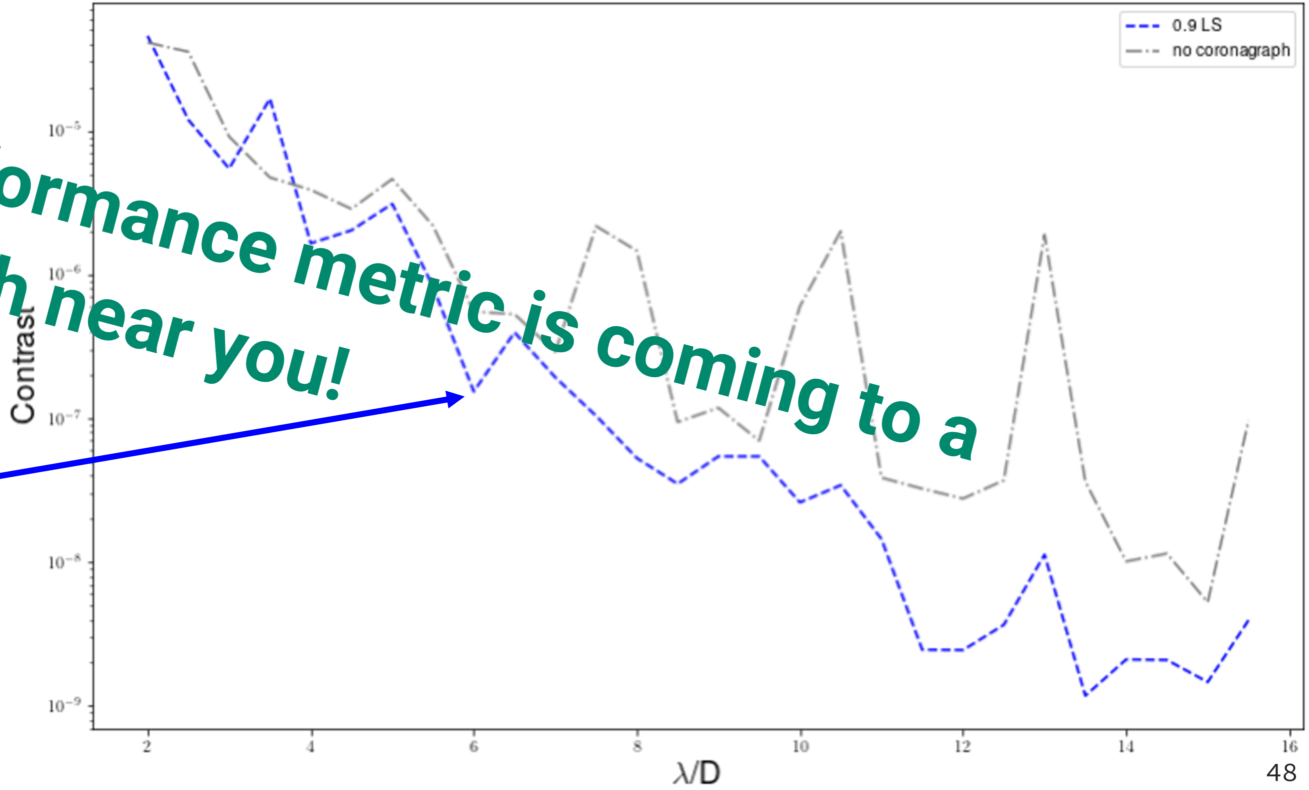


Optimal Vortex Will be Difficult to Integrate and Align: Lyot Stop 0.98 → 0.9

A new performance metric is coming to a coronagraph near you!

LS: 0.9





Next Steps

- Incorporate cost function to minimize exposure time as secondary metric
- Model and design additional elements, including a pupil mask optimized for Keck-like apertures and an apodizing phase pattern we could apply with Deformable Mirrors
- Simulate and design a preliminary Lyot Coronagraph for the Thirty Meter Telescope (TMT)
- Use our setup to compare predictive wavefront control methods side-by-side

Acknowledgements

Many thanks to ExEP and the ExoExplorers program,the UCSC Lab for Adaptive Optics, Becky Jensen-Clem, Maaike Van Kooten, Ben Gerard, Anand Sivaramakrishnan, Gary Ruane, Renate Kupke, and Daren Dillon, and the other grads at UCSC.

In Conclusion

- Lyot Coronagraphs: stand up well to system errors but rule out close in companions.
- Vortex Coronagraphs: on paper offer stunning performance but don't hold up as well to practical systems.
- Other coronagraphic elements and algorithms will be vital for high contrast, and practical integration will bring other affects we haven't yet thought to model.

- Feel free to contact me with any further questions (or heckling):

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