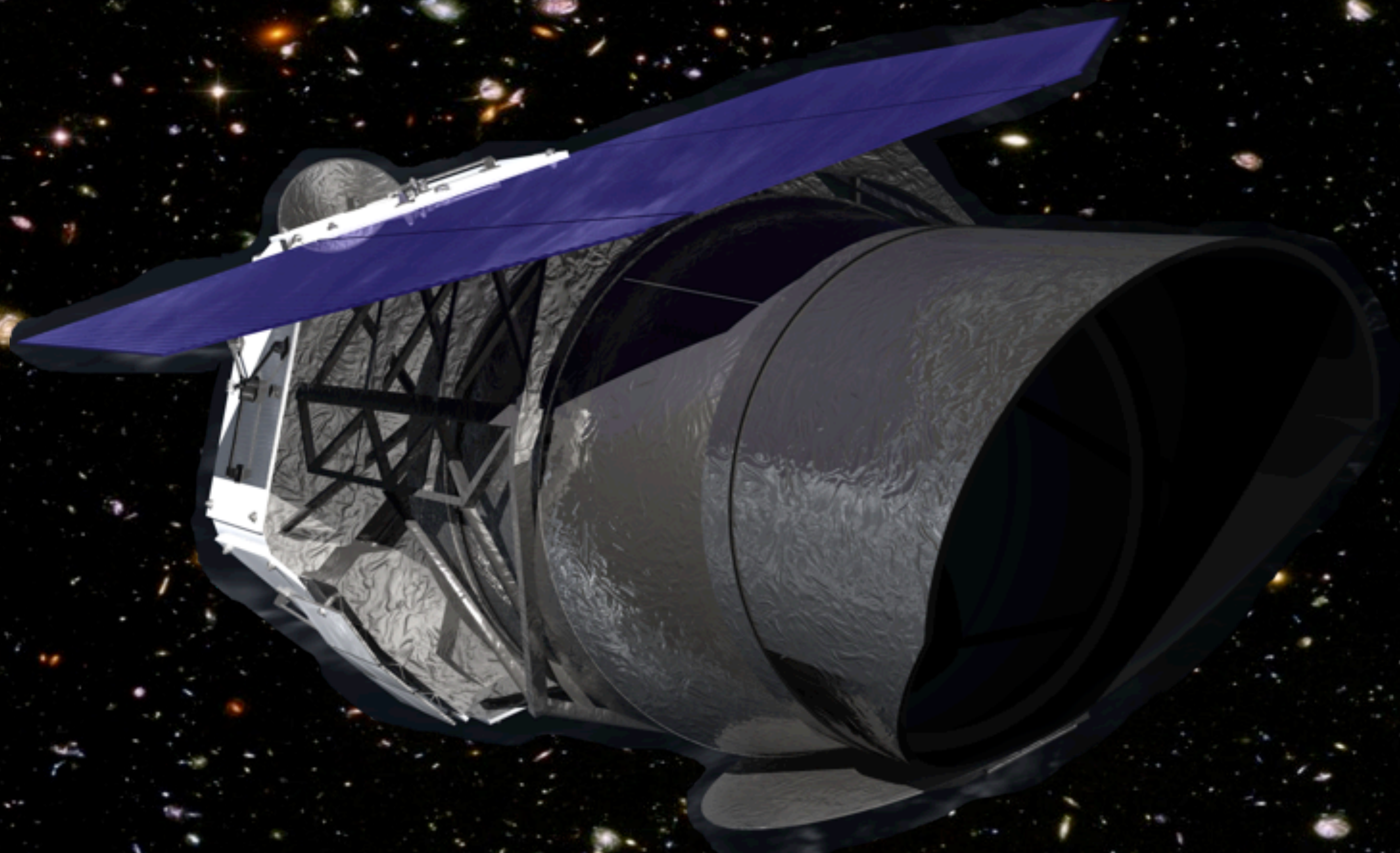

The Coronagraph Instrument on WFIRST

N. Jeremy Kasdin/Princeton University
CGI Adjutant Scientist

The Science/Technology Teams

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Tyler Robinson
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Vanessa Bailey
Tiffany Meshkat
Neil Zimmerman
AJ Riggs
Eric Cady
Tyler Groff

Adjutant scientist: Jeremy Kasdin

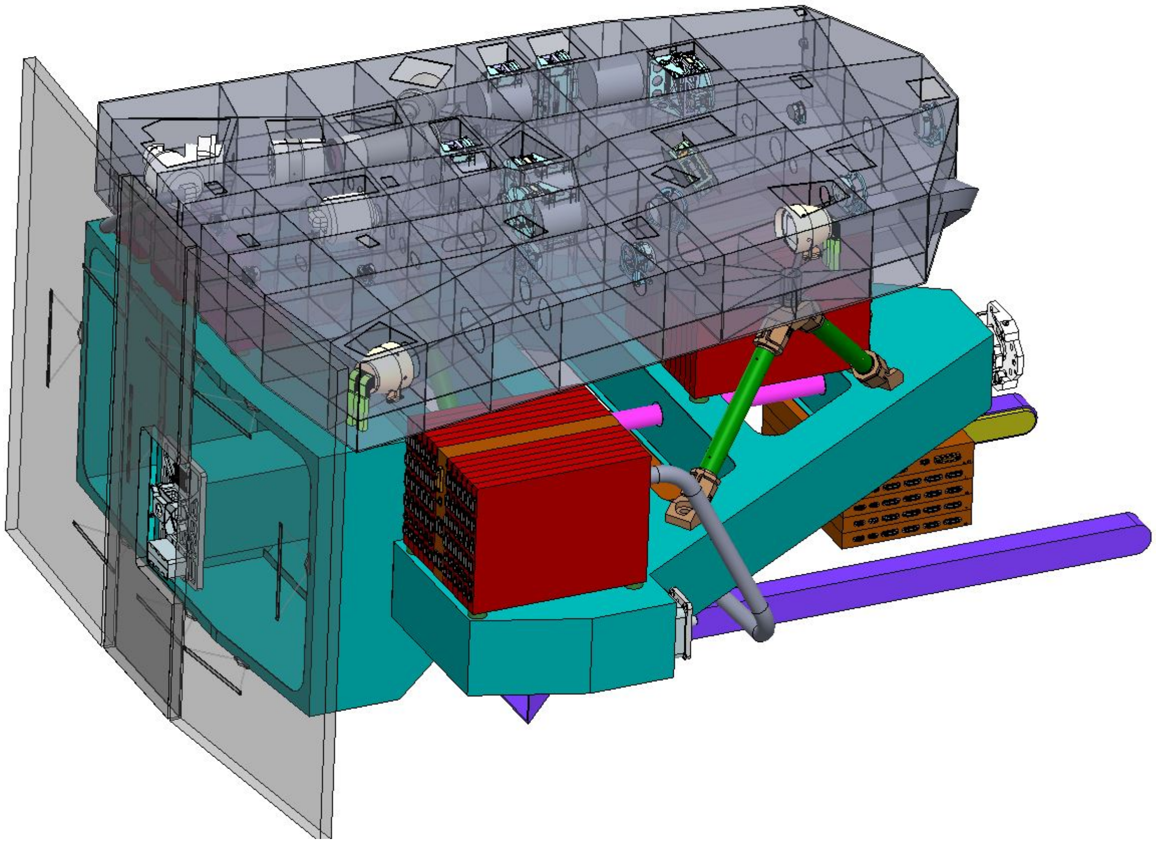
Post-WIETR CGI Status

- The Coronagraph Instrument is a technology demonstration only
- Requirements established using standard engineering practice
- If successful, ”Participating Science Program” following tech demo
- Design should support possible starshade (pending Decadal recommendation)

<u>Notional CGI Program</u>

- 3 months of technology demonstration observing in year 1 of WFIRST mission
- If meet success criteria, 1.5 year Participating Science Program
- If successful, follow-on 2.5 year science program

The Coronagraph Instrument (CGI)



- 2 Coronagraphs (SPLC & HLC)
- 2 Deformable Mirrors
- Low-Order Wavefront Sensing & Control
- Wide-band Imaging Camera
- Integral Field Spectrograph (R = 50)
- Photon-Counting EMCCD camera

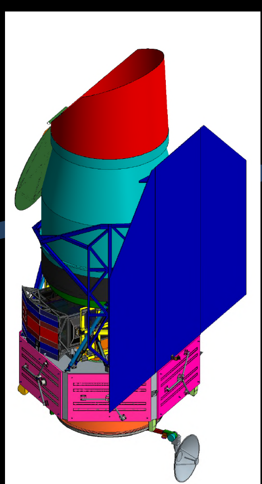
International Contributions

- Polarizers
- Polarization module
- Wheel mechanisms
- EMCCD camera
- Precision optics

The WFIRST CGI as a Technology Pathfinder

CGI is a direct predecessor to potential future flagship direct imaging missions aimed at *Earth-like* exoplanets (HabEx and LUVOIR)

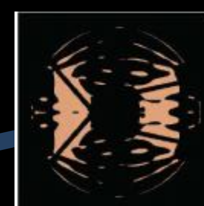
Ultra-stable Space Telescope & Observatory

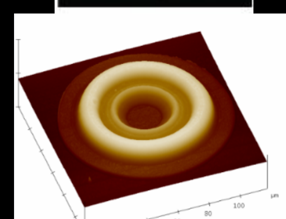


Autonomous Ultra-Precise Wavefront Sensing & Control System

First Use of Deformable Mirrors in Space

High Contrast Coronagraph Masks





Ultra-low noise photon counting Visible Detectors

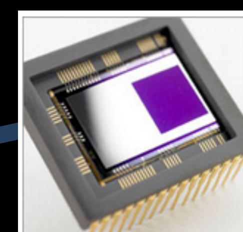
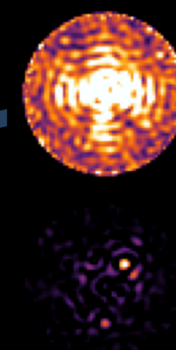


Image Processing at Unprecedented Contrast Levels



CGI will premiere in space many key technologies required for the characterization of rocky planets in the Habitable Zone, significantly reducing the risk and cost of future possible missions such as HabEx and LUVOIR

Technology Objectives

- **Coronagraph with Active Wavefront Control**
  - The CGI will demonstrate coronagraphy in space with an obscured aperture and active wavefront control to lay the foundation for the coronagraphs that will be needed for future missions capable of detecting and characterizing Earthlike planets.

- **Coronagraph Elements**
  - The CGI will advance the engineering and technical readiness of key coronagraph elements needed for future missions capable of detecting and characterizing Earthlike planets. These elements include coronagraph mask design and mask manufacture, low-order wavefront sensors, high actuator count deformable mirrors, low noise detectors, and integral field spectrographs.

- **Advanced Coronagraph Algorithms**
  - The CGI will support development and in-flight demonstration of new wavefront sensing and control algorithms and other software elements that could enhance the capability or simplify the architecture of future missions.

Technology Objectives, cont.

➢ High Contrast Performance Characterization

- WFIRST will perform measurements that characterize the integrated performance of the coronagraph and observatory, including error sources such as wavefront error, wavefront stability, and temporal jitter as functions of time, wavelength, and polarization.

➢ High-Contrast Data Processing

- The CGI will demonstrate the application of advanced data processing and analysis techniques required to identify, spectrally characterize and distinguish astronomical sources in the presence of instrumental and astrophysical background noise in a previously unexplored contrast regime.

Baseline Technology Requirements

Broadband High-Contrast Imaging WFIRST shall be able to measure, after post-processing, the brightness of an astrophysical point source located between 0.23″ and 0.40″ from an adjacent star with a V magnitude as dim as 5, with a flux ratio down to $5 \cdot 10^{-8}$ in a 10% bandwidth with an SNR=10 or better.

High-Contrast Imaging Spectroscopy WFIRST shall be able to measure, after post-processing, the spectrum of an astrophysical point source located between 0.30″ and 0.45″ from an adjacent star with a V magnitude as dim as 5, with a flux ratio down to $5 \cdot 10^{-8}$ over an 18% bandwidth at R=50 with an SNR=10 per spectral resolution element.

High-Contrast Extended Source Imaging and Polarimetry WFIRST shall be able to map the extended surface brightness from 0.25″ to 0.95″ around a host star with V magnitude as dim as 5, at a sensitivity at or below 17 mag/arcsec^2 with an SNR of at least 10, and be able to map a linear polarization with a polarization fraction ≥0.3 with a systematic uncertainty of less than 0.03

Engineering Data Collection and Performance Characterization WFIRST shall be able to conduct operations and download data from the CGI and other observatory sensors that monitor spacecraft and payload thermal and dynamic disturbances.

Technology Success Criteria

- The coronagraph shall be used to observe at least three stars during at least two different epochs, and at least one known debris disk, detecting a companion exoplanet.
- The CGI shall be used to conduct operations and perform in-flight measurements of the CGI in the presence of flight error sources including WFE, WF stability, polarization, and jitter.

Rewrites of the baseline requirements and success criteria is a work in progress targeting the Systems Requirements Review in late February.

Exoplanet & Disk Direct Imaging Science Goal

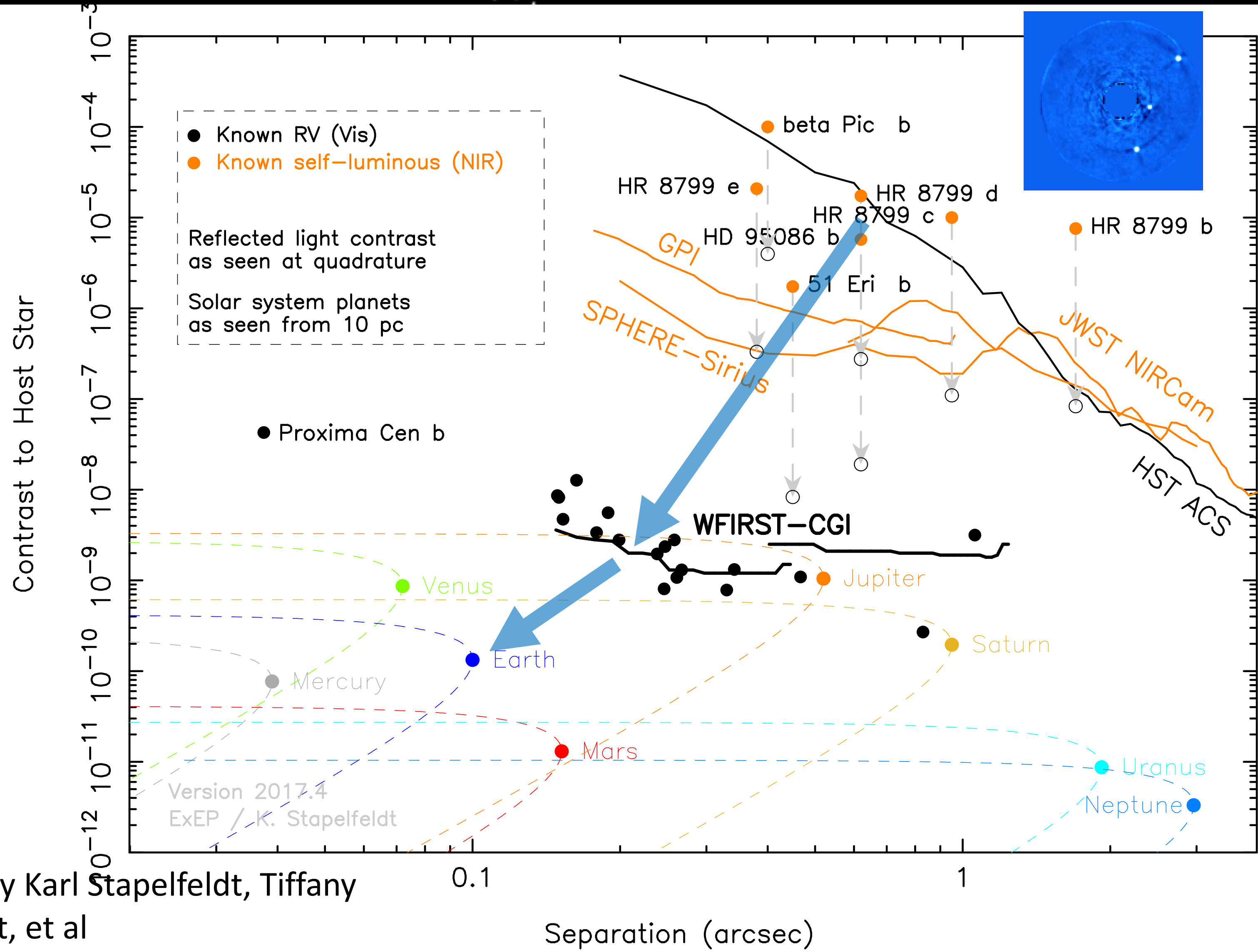
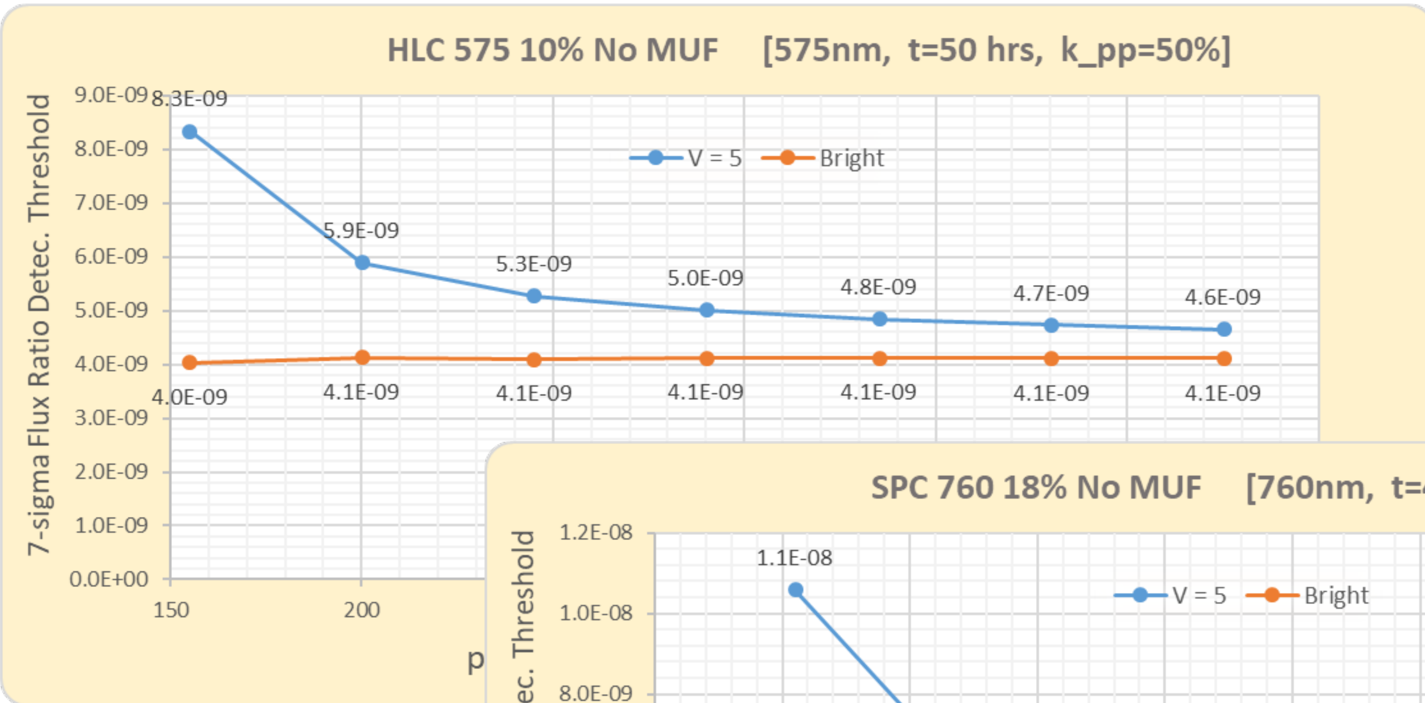
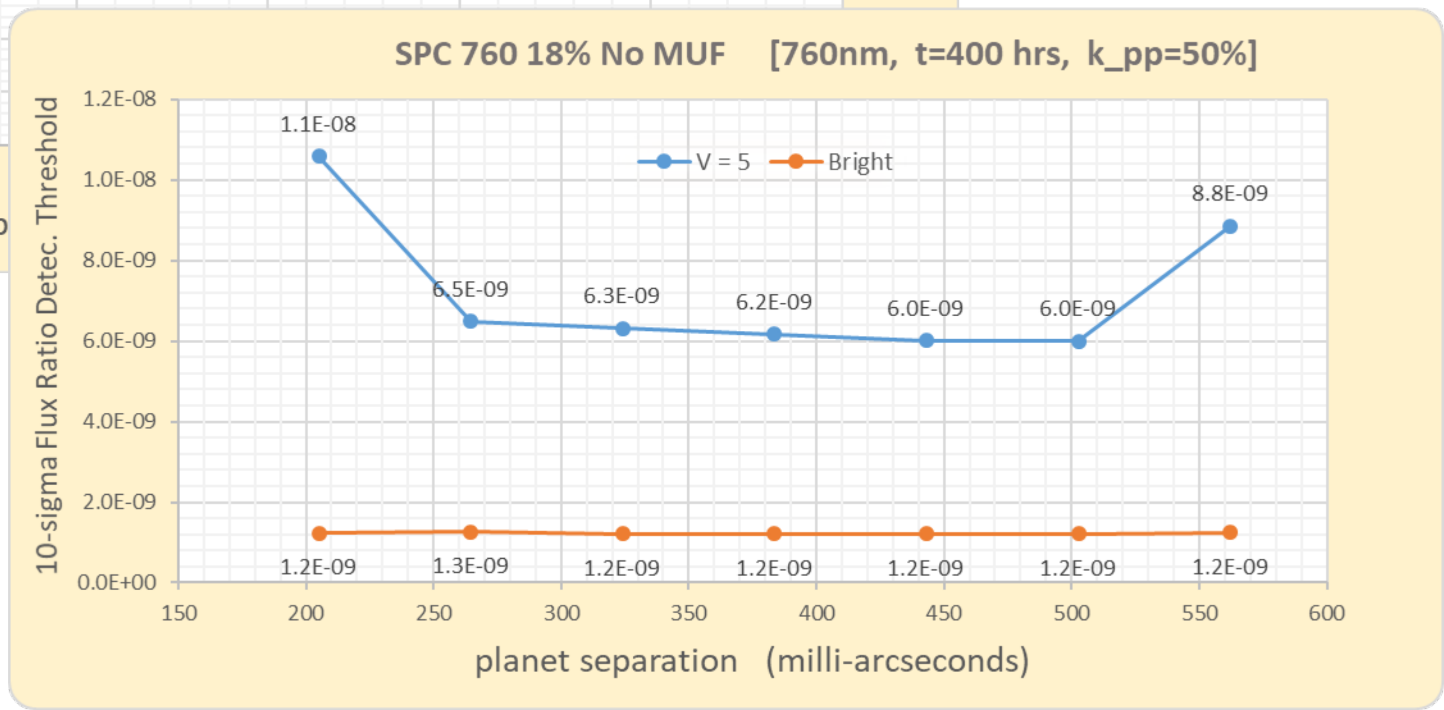


Figure by Karl Stapelfeldt, Tiffany Meshkat, et al

Current Tentative Performance Estimate





Participating Science Program Potential Objectives

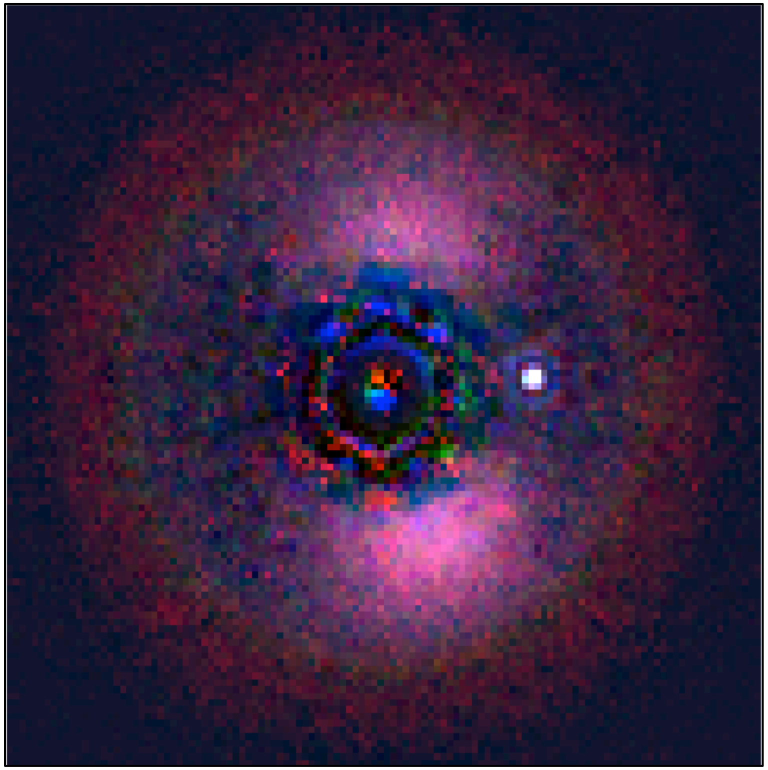
Imaging Photometry of Giant Planets (Imager)
- Rayleigh Scattering
- Methane and Water detection
- Methane Continuum
- Clouds

Narrow-band Spectroscopy of RV Planets (IFS)
- Measure Methane Abundance
- Clues to metallicity and formation mechanism

Giant planet discovery

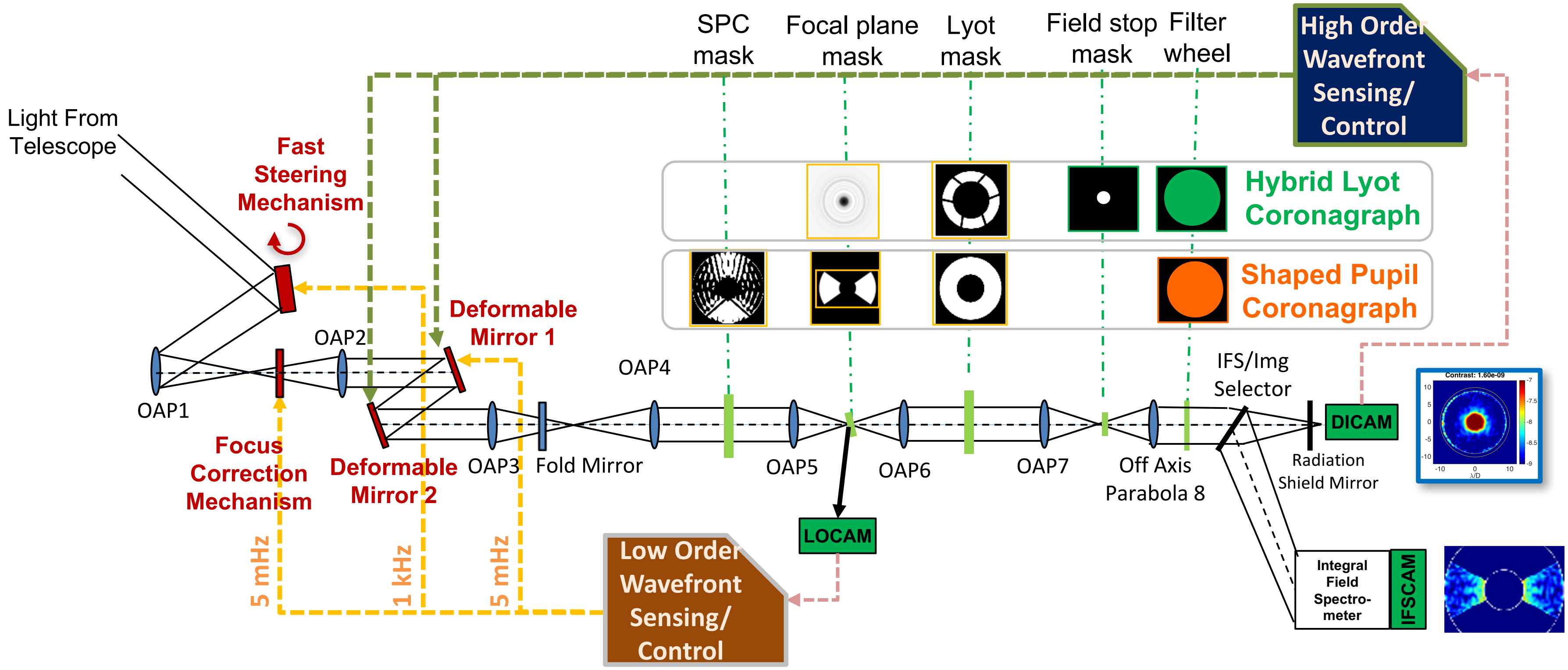
Exozodiacal Disk Imaging
- Complementary to LBTI
- Resonant clumps

Visible light imaging of inner debris disks
- Wide field and Polarization



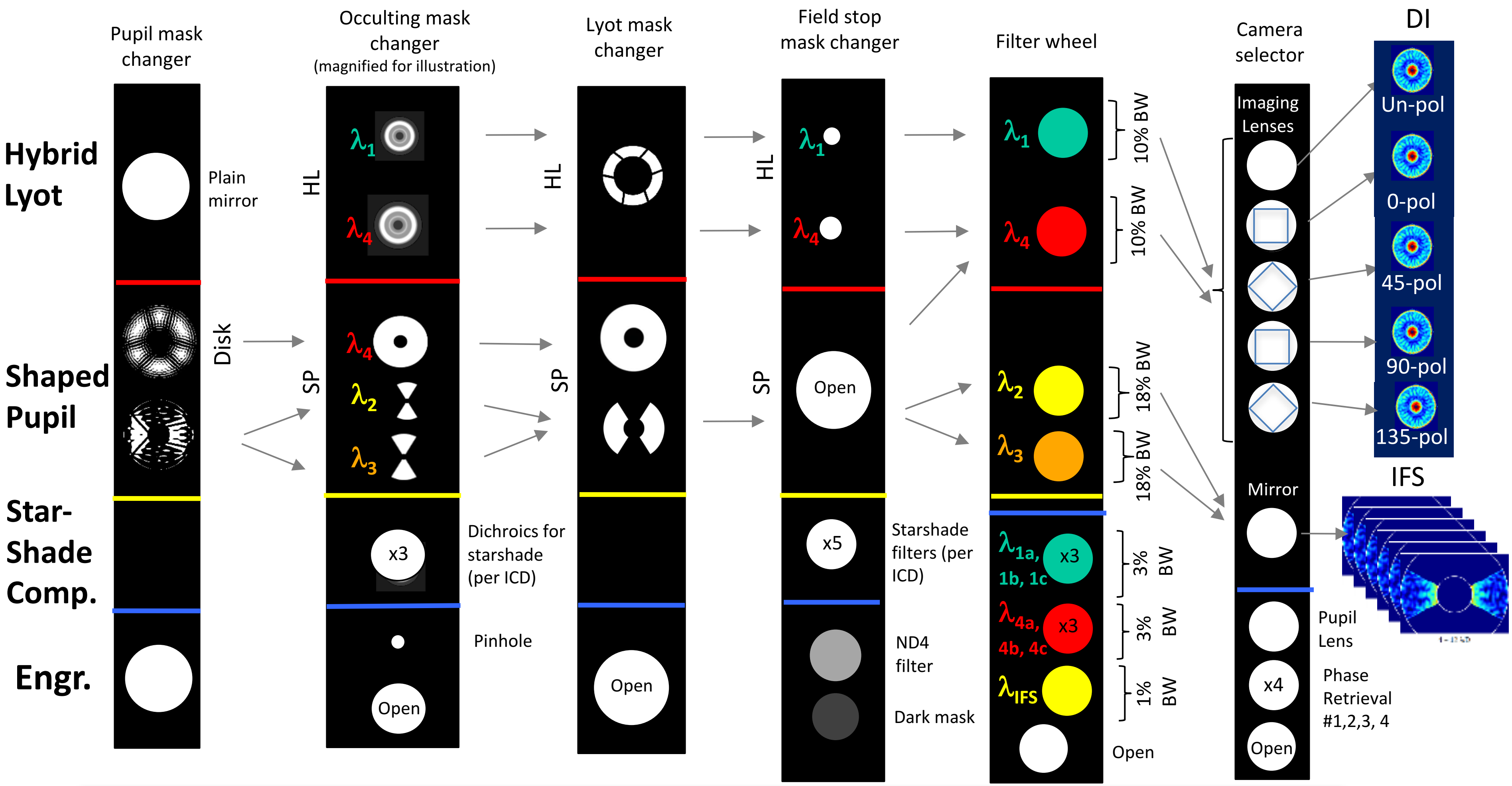
Credit: M. Rizzo, N. Zimmerman, A. Roberge (NASA GSFC), E. Douglas (MIT), L. Pueyo (STScI)

CGI Architecture



- Little has changed in CGI architecture over past year
- Some modes removed and some modes not tested to meet new cost goals

CGI Baseline



λ_1=575 nm, 10% (annular, 3-9 λ/D)
λ_2=660 nm, 18% (bow-tie / IFS, 3-9 λ/D)
λ_3=760 nm, 18% (bow-tie / IFS, 3-9 λ/D)
λ_4=825 nm, 10% (annular, 3-19 λ/D)

CGI Modes Table

CGI Filters	λ_{center} (nm)	BW	Channel	Masks	Working Angle	Can use w/ linear polarizers	Starlight Suppression Region	Tested before launch?
1	575	10%	Imager	HLC	3-9 λ/D	Y	360°	Y
2	660	18%	IFS	SPC	3-9 λ/D		130°	
2	660	18%	Imager	SPC	3-9 λ/D	Y	130°	
3	760	18%	IFS	SPC	3-9 λ/D		130°	Y
3	760	18%	Imager	SPC	3-9 λ/D	Y	130°	
4	825	10%	Imager	HLC	3-9 λ/D	Y	360°	
4	825	10%	IFS	HLC	3-9 λ/D		360°	
4	825	10%	Imager	SPC disk	6.5-20 λ/D	Y	360°	Y

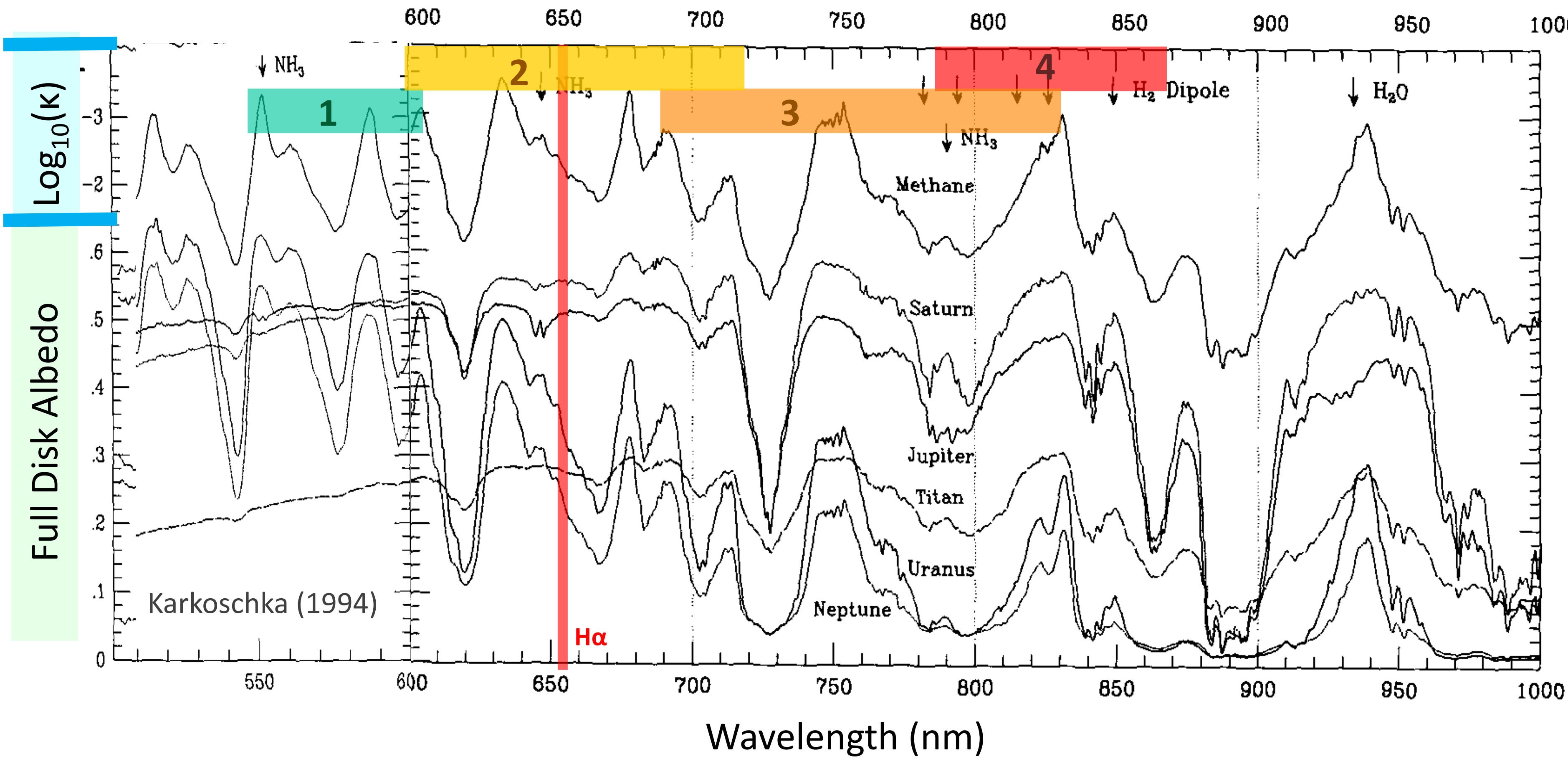
λ_1=575 nm, 10% (annular, 3-9 λ/D)

λ_2=660 nm, 18% (bow-tie / IFS, 3-9 λ/D)

λ_3=760 nm, 18% (bow-tie / IFS, 3-9 λ/D)

λ_4=825 nm, 10% (annular, 3-19 λ/D)

CGI Science Filters



λ_1=575 nm, 10% (annular, 3-9 λ/D)

λ_2=660 nm, 18% (bow-tie / IFS, 3-9 λ/D)

λ_3=760 nm, 18% (bow-tie / IFS, 3-9 λ/D)

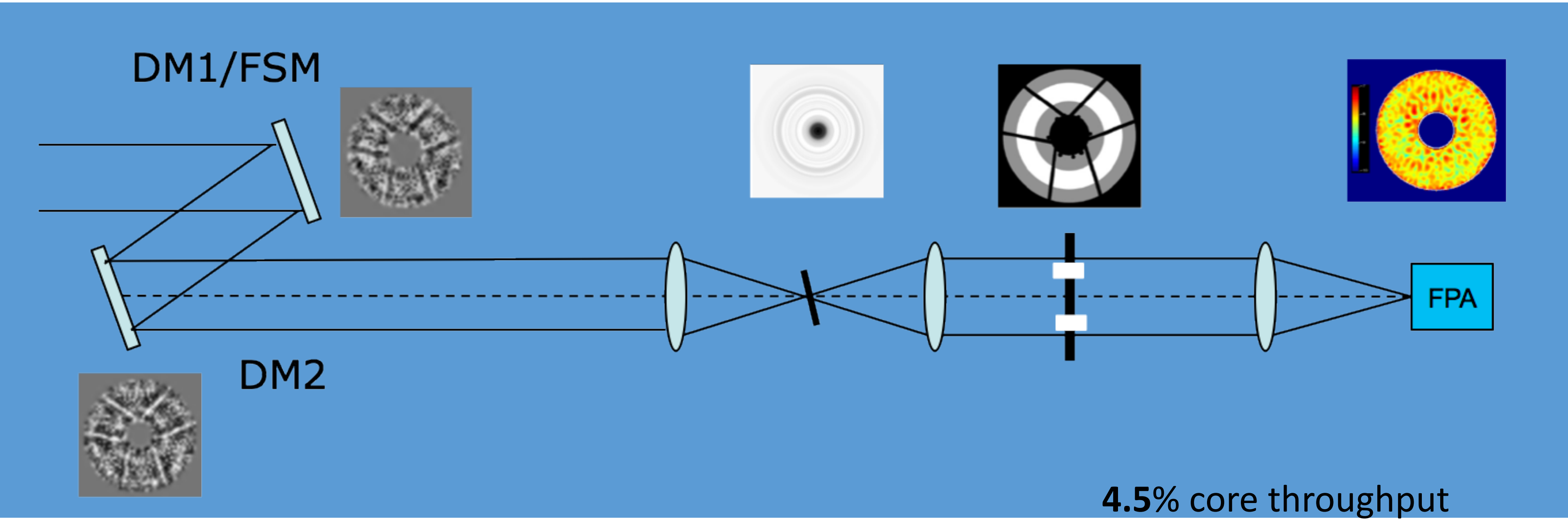
λ_4=825 nm, 10% (annular, 3-19 λ/D)

Starshade Filter List

Starshade Science Bands

λ (nm)	BW	Δλ	λ_{min} (nm)	λ_{max} (nm)
488.5	26.0%	127	425	552
707.5	26.1%	185	615	800
728	19.8%	144	656	800
884.5	26.1%	231	769	1000
910	19.8%	180	820	1000

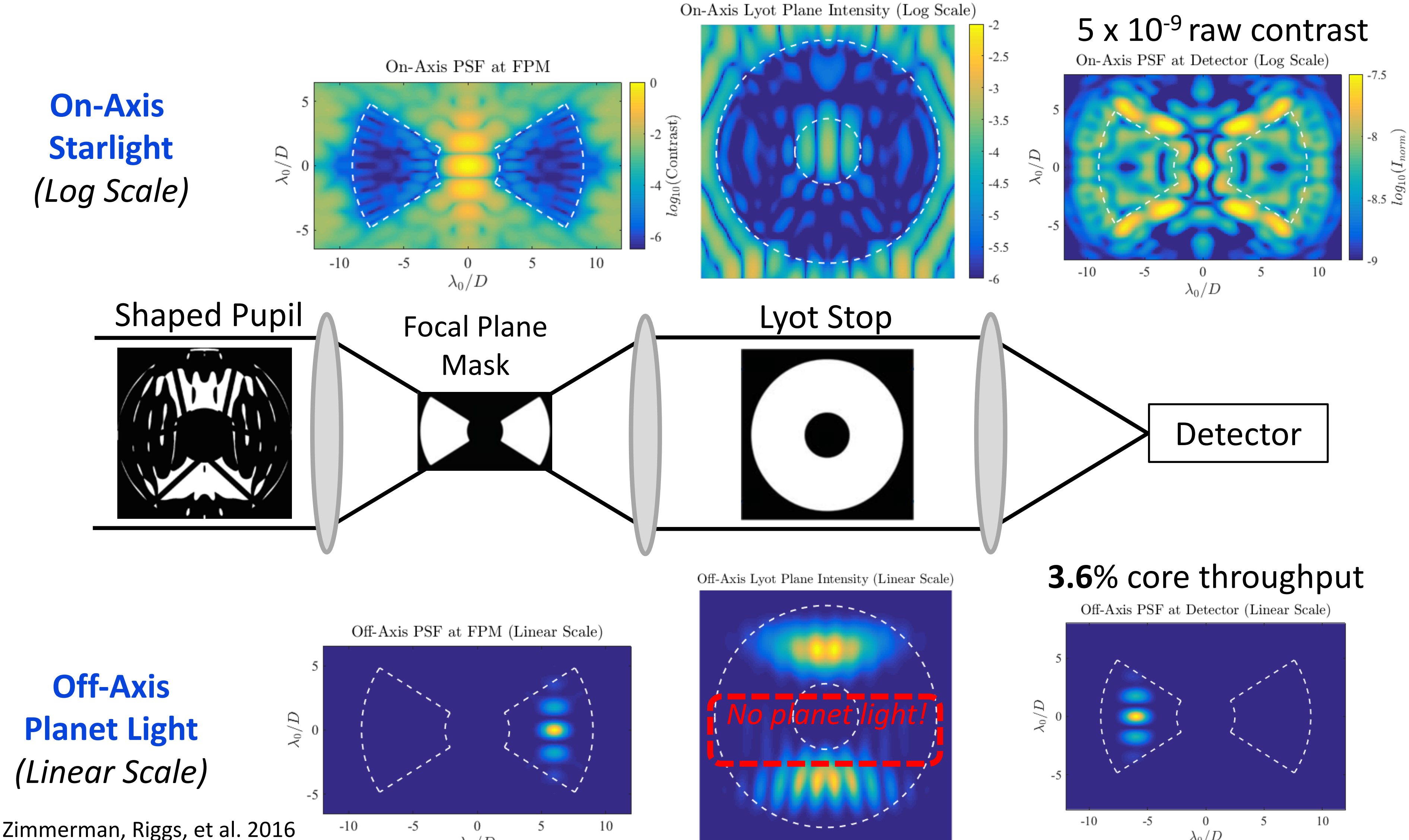
HLC Coronagraph for Photometry



- Higher performance over 10% bands
- Filters matched to continuum and methane bands
- Full dark hole
- Selectable polarizers

WFIRST
Wide-Field Infrared Survey Telescope
Dark Energy • Exoplanets • Astrophysics

SPC-IFS Design 2015-2016

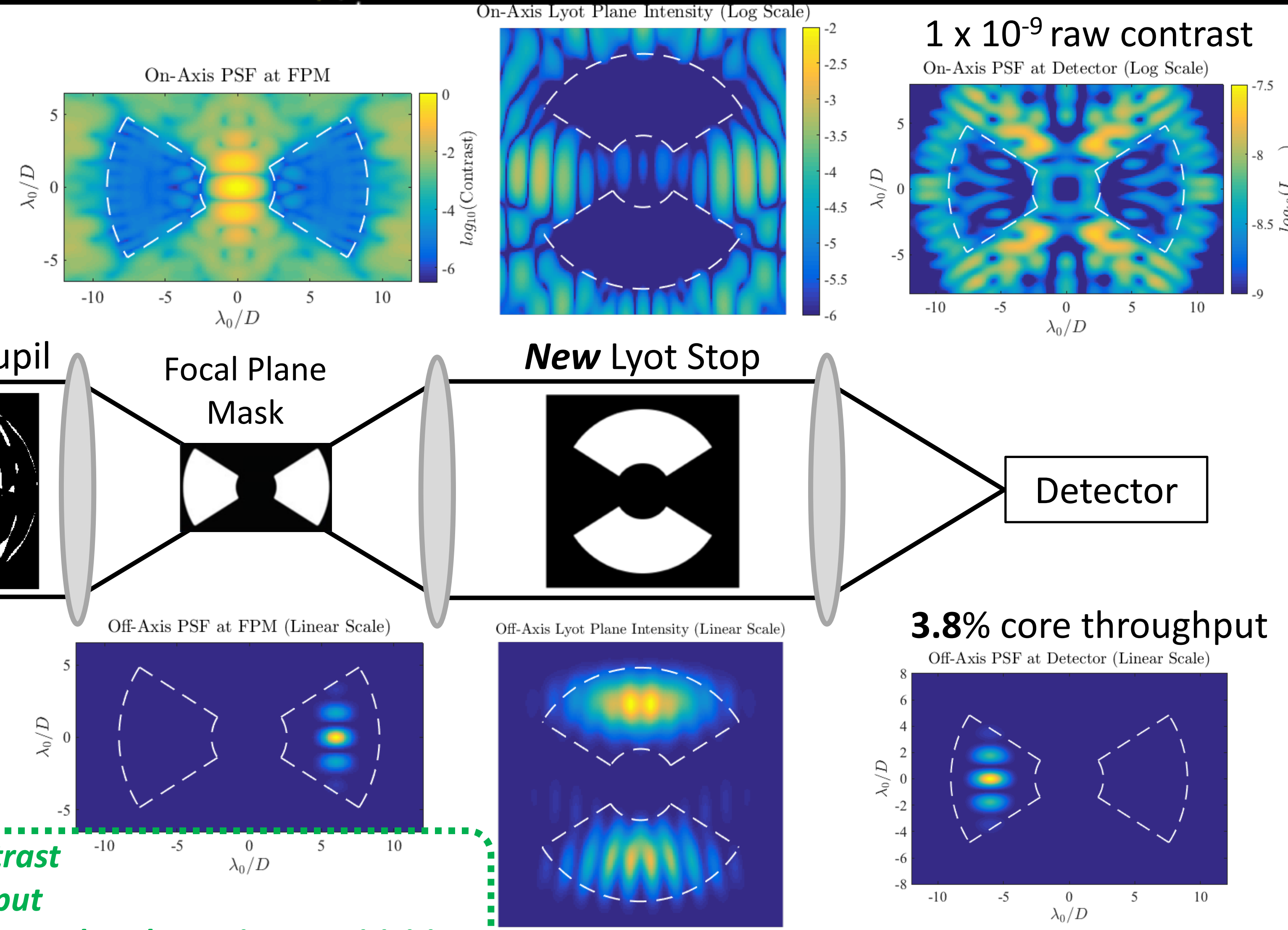


Zimmerman, Riggs, et al. 2016

SPC-IFS Design (June 2017)

On-Axis Starlight
(Log Scale)

1 x 10^{-9} raw contrast

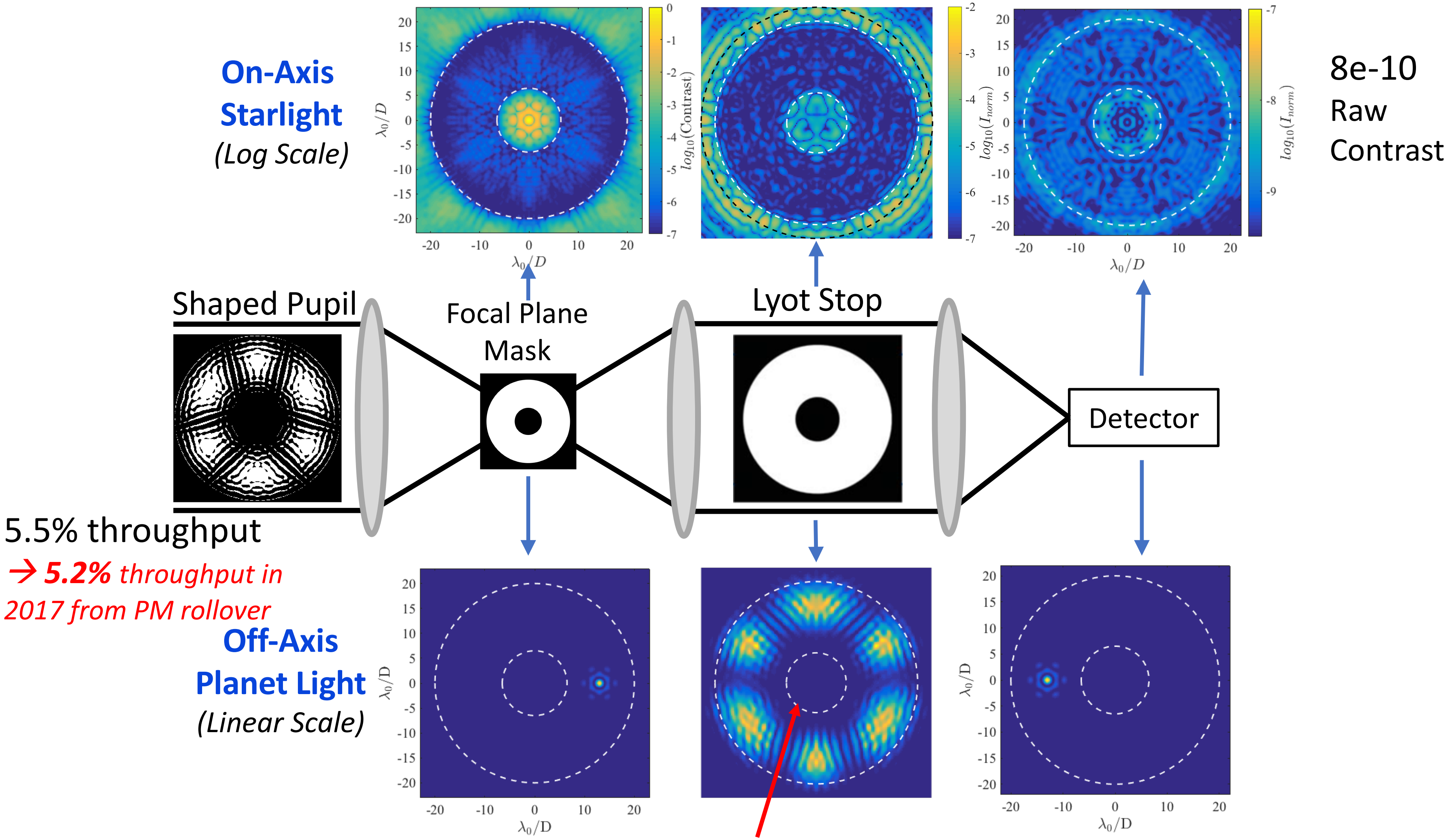


3.8% core throughput

Off-Axis Planet Light
(Linear Scale)

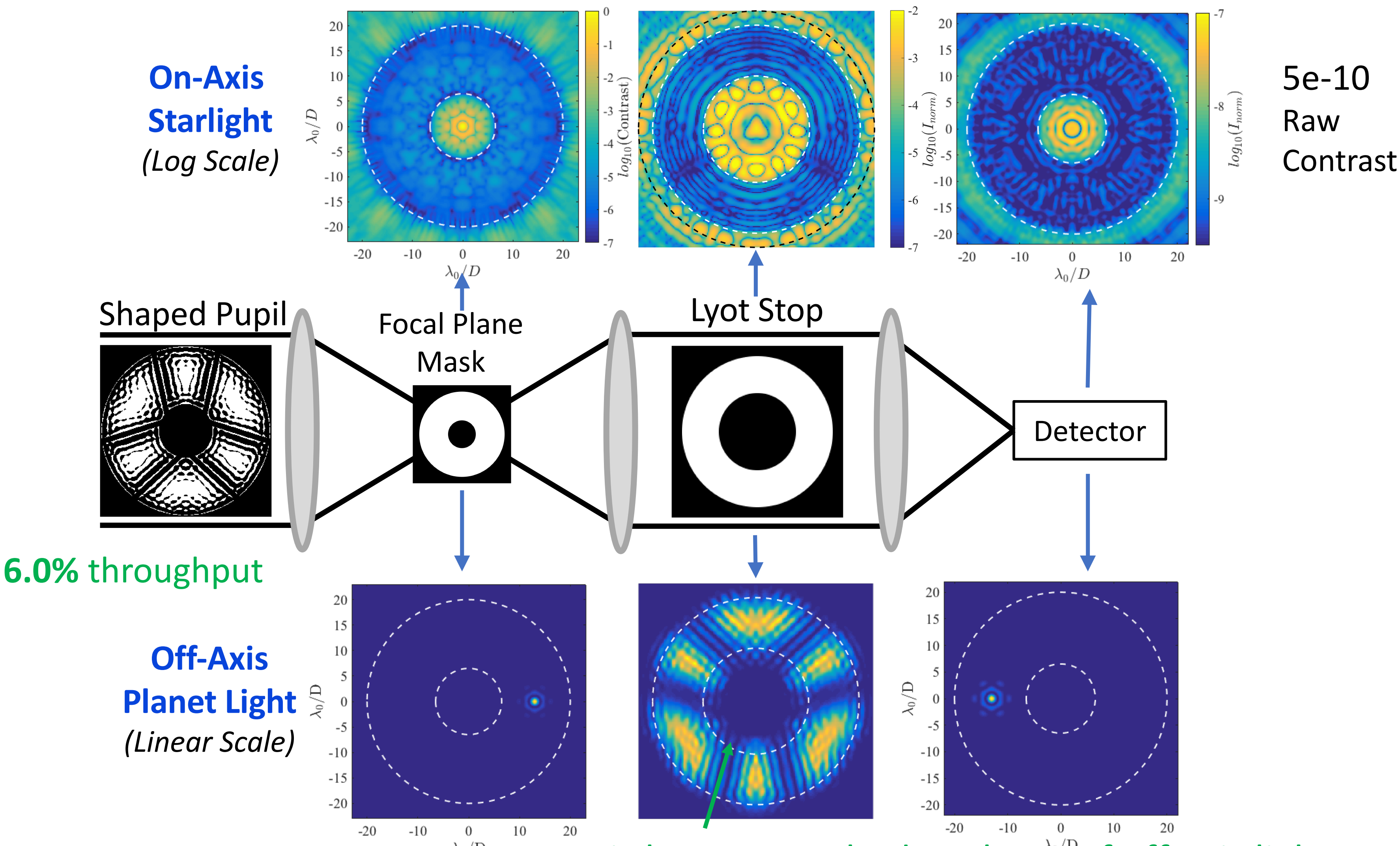
- ***Better raw contrast***
- ***Better throughput***
- ***Same/Better low-order aberration sensitivities***

SPC Disk Design (2015-2016)
6.5-20 l/D, 8e-10 contrast



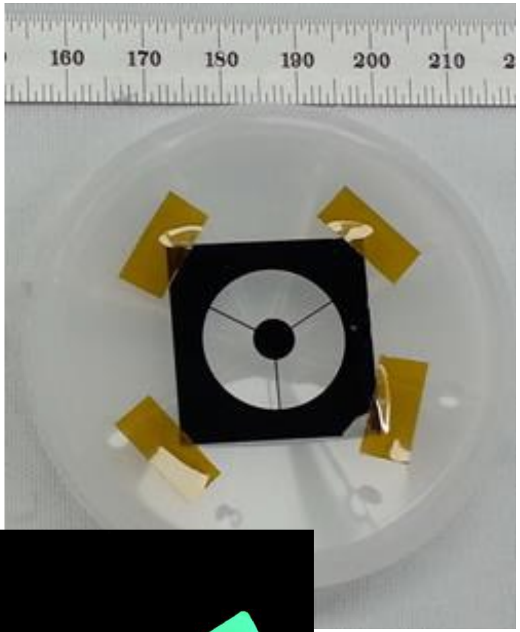
Lyot stop inner diameter is unnecessarily small → worse performance

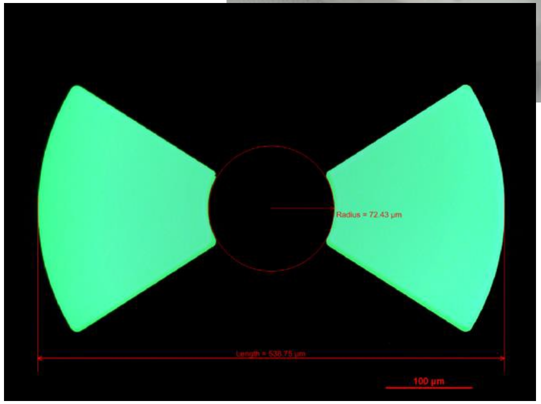
SPC Disk Design (2017)
5.2-20 l/D, 5e-10 contrast



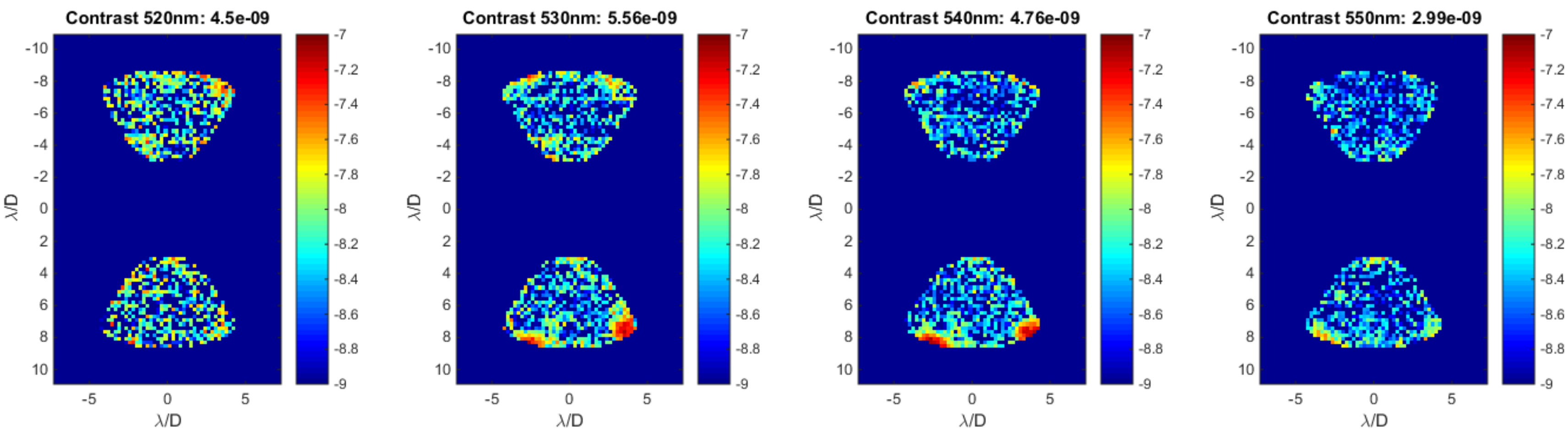
Lyot stop is better matched to shape of off-axis light

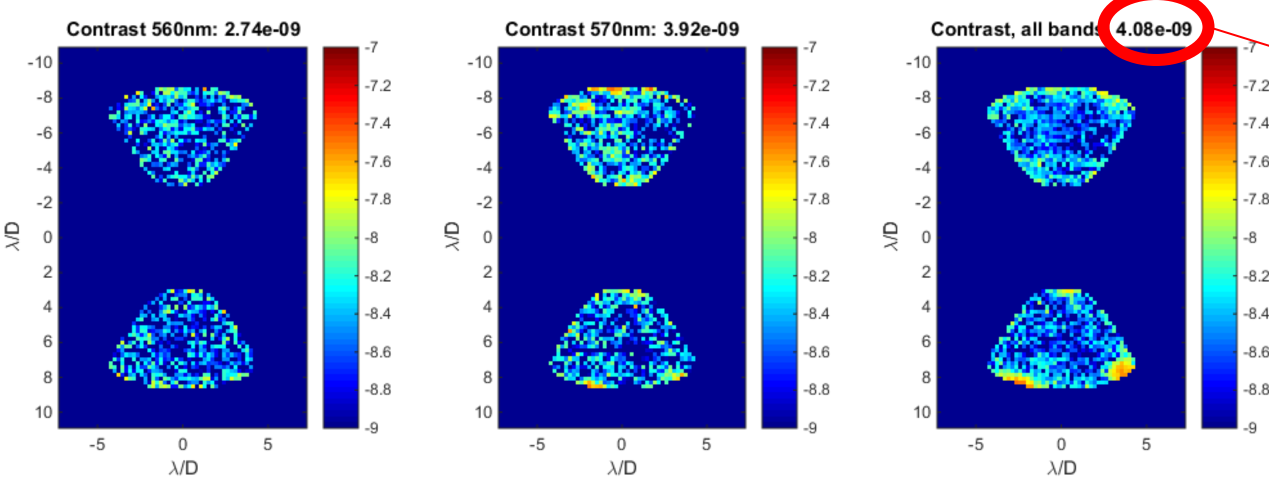
Shaped Pupil Masks





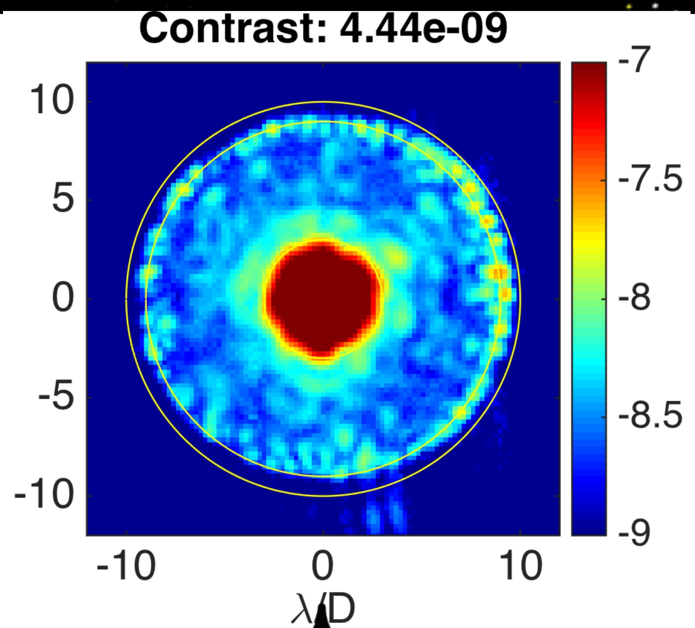
Static Testbed Results

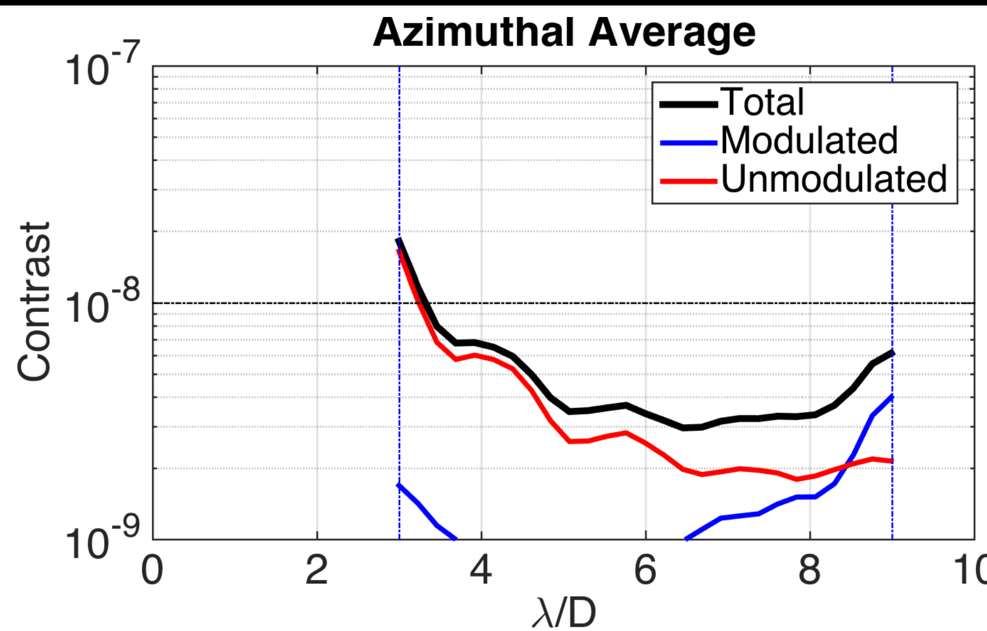


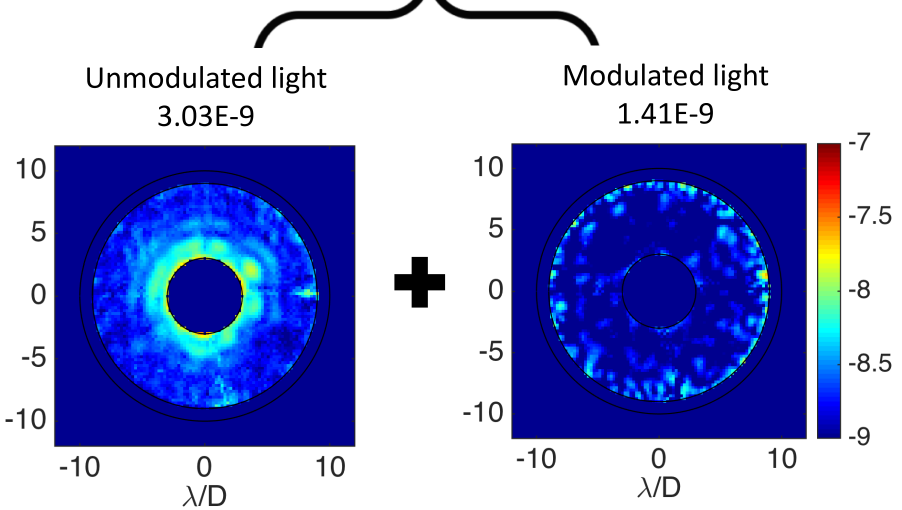


Best 10% static SPC contrast: 4.08e-9

HLC DynamicTestbed Result

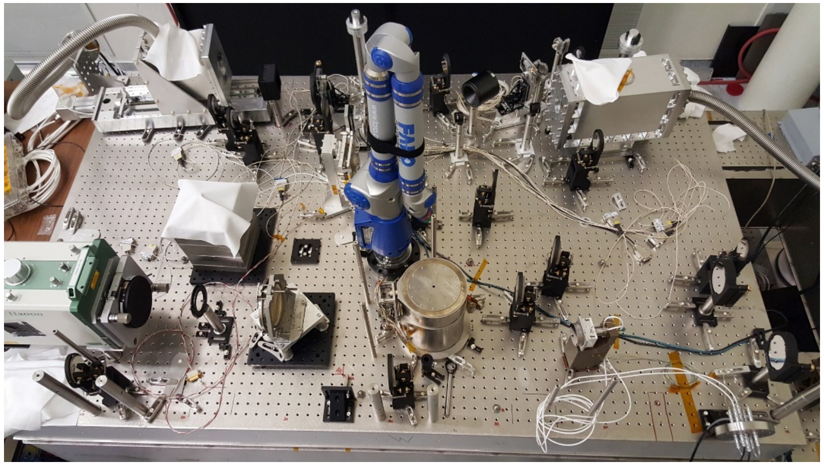


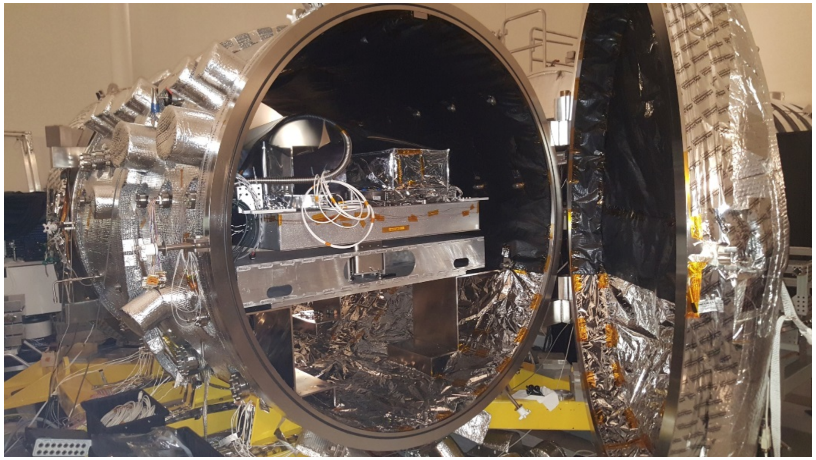


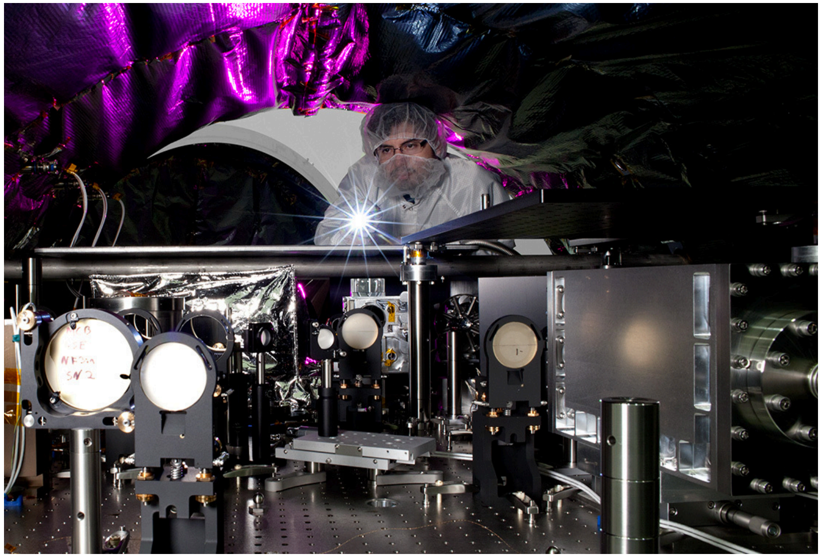


- **Contrast consisted of two terms:**
  - **Unmodulated light dominated by the LoS Jitter.**
  - **Modulated light dominated by calibration error.**

OMC Dynamic Testbed







Summary

- WFIRST will carry the first active coronagraph in space
  - Combines multiple technologies and modes
  - Demonstrates new technology in space critical to future missions
- Coronagraph has potential for a participating science program bearing on the questions of planetary system formation
  - Spectroscopy of a small number of known RV planets
  - Photometry of additional systems
  - Discovery of unknown lower-mass planets, potential targets for future missions
  - Characterization of zodiacal dust and debris disks
- Progress in the design and in the laboratory is on schedule and achieving significant successes.