Roman coronagraph design

Axel Potier

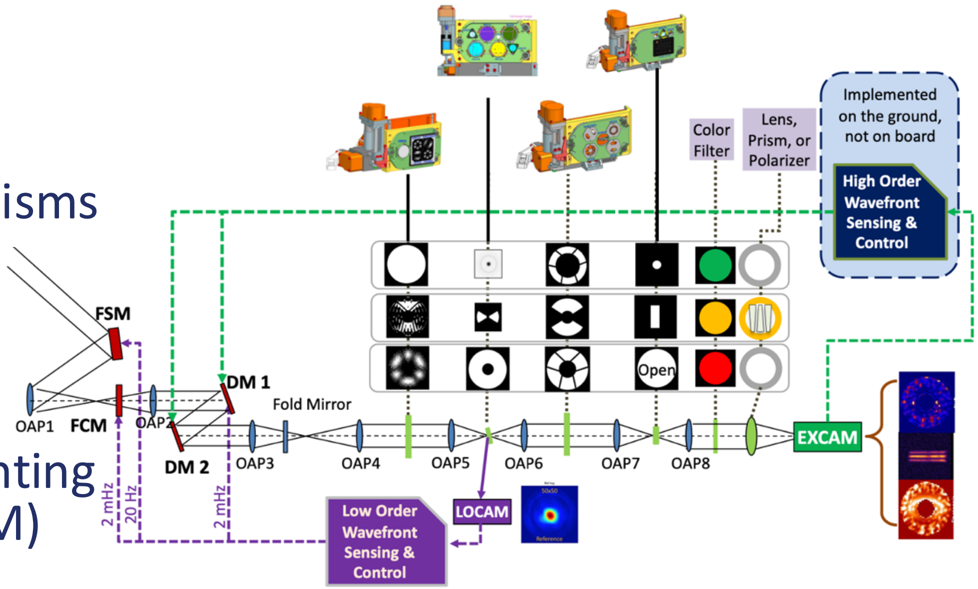
High-contrast imaging with Roman

Roman School, 2026

RST coronagraph instrument as a system

Complex instrument with many involved sub-systems:

- Coronagraphs
- Precision alignment mechanisms
- Large format deformable mirrors
- LOWFS and HOWFS
- Ultra-low-noise photon counting EMCCDs (LOCAM and EXCAM)
- Data processing

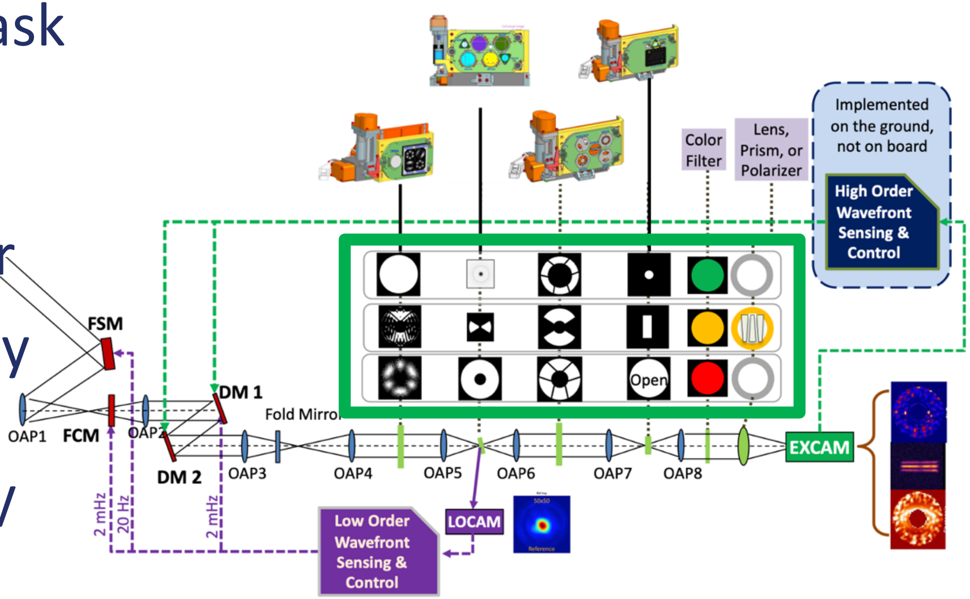


Mennession et al. (2022)

RST coronagraph configurations

Multiple coronagraphic mask configurations are needed for:

- Imaging close to the star
- Performing spectroscopy close to the star
- Imaging over a wide FoV (e.g. disks)



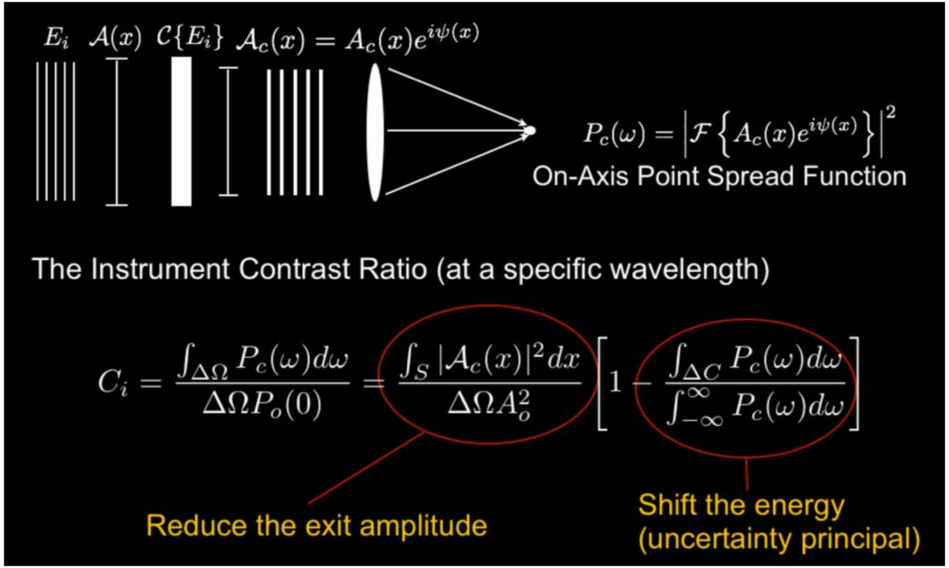
Mennession et al. (2022)

Coronagraph design metrics

- Contrast: the ratio of the halo at the planet location to the peak of the stellar PSF
- Inner working angle: The smallest angle on the sky at which the needed contrast is achieved
- Throughput: The ratio of the light in the planet PSF to the nominal telescope PSF after high-contrast is achieved
- Bandwidth: The wavelength range at which the high-contrast is achieved
- Sensitivity: The degree to which the contrast is degraded in the presence of aberrations

TTR5 definition: The Roman coronagraph shall be able to measure, with SNR ≥ 5, the brightness of an astrophysical point source located between 6 and 9 λ/D from an adjacent star with a VAB magnitude ≤ 5, with a flux ratio ≥1 × 10−7. The bandpass shall have a central wavelength ≤600 nm and a bandwidth ≥10%.

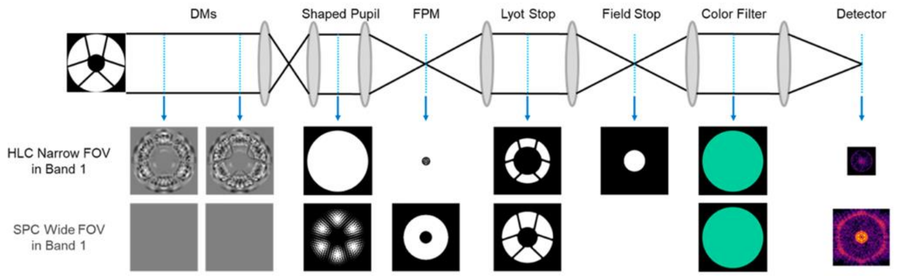
Coronagraph concept



Credits: J. Kasdin

- Three main coronagraph families:
  - Change amplitude – mainly focal planes
  - Reshape the PSF – mainly pupil plane
  - Hybrid – Combination of pupil and focal masks: HLC and SPLC
- Hybrid achieve higher performance in both IWA and throughput

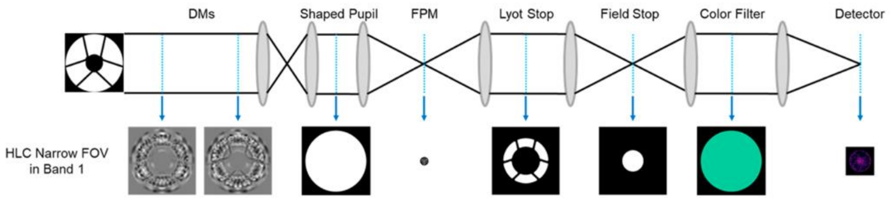
Roman coronagraph choices



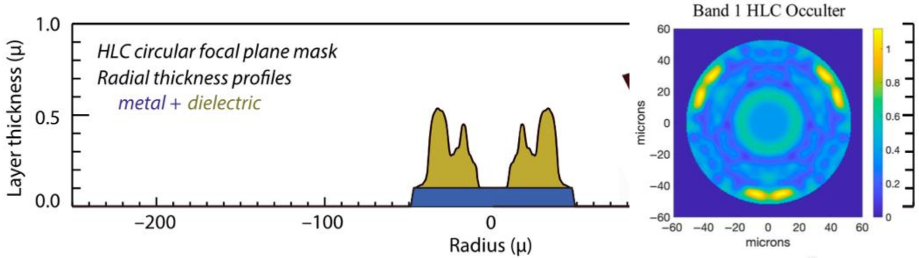
Cady et al. (2025)

- 6 masks originally proposed for design to meet TTR5
- Two flavors of hybrid coronagraphs selected:
    - Hybrid Lyot Coronagraph (HLC)
    - Shaped Pupil Lyot Coronagraph (SPLC)
- Similar architectures
- Complementary strengths and weaknesses

Hybrid Lyot Coronagraph: NFOV



Cady et al. (2025)

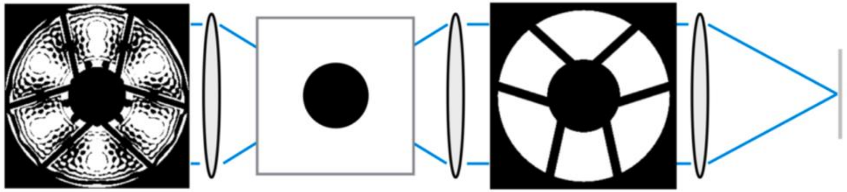


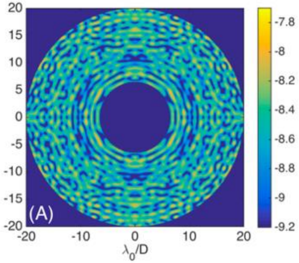
Trauger et al. (2016)

HLC is a hybrid between classical LC and phase mask coronagraph, with active control of wavefront phase and amplitude:

- Structured patterns on both DMs to help suppress strut diffraction
- Complex-valued focal-plane mask:
  - Metal dielectric rejects most of the starlight
  - Dielectric layer superimposed shapes the transmitted light to create destructive interferences
- Field stop required to handle large dynamic range on the camera
- Optimized for NFOV (3-9λ/D)at 575nm (10%)
- Small IWA, Good contrast, Moderate bandwidth, Moderate sensitivity to jitter, best expected yield

Shaped Pupil Lyot Coronagraph: WFOV

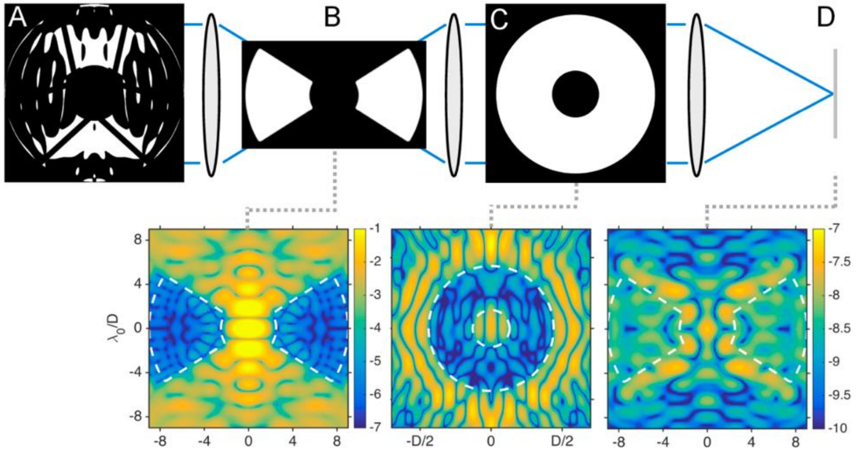




SPLC is a hybrid between classical LC and shaped pupil coronagraph:

- Binary-amplitude apodizer to reshape the PSF
- Classical focal-plane mask + Lyot Stop to block the starlight
- Field stop unnecessary
- Optimized for WFOV (6-20λ/D)at 575nm (10%) – capable of demonstrating TTR5
- Higher IWA, lower throughput w.r.t circular pupil (and HLC performance)
- Good contrast, High bandwidth, Low sensitivity to jitter

Shaped Pupil Lyot Coronagraph: NFOV



Zimmerman et al. (2016)

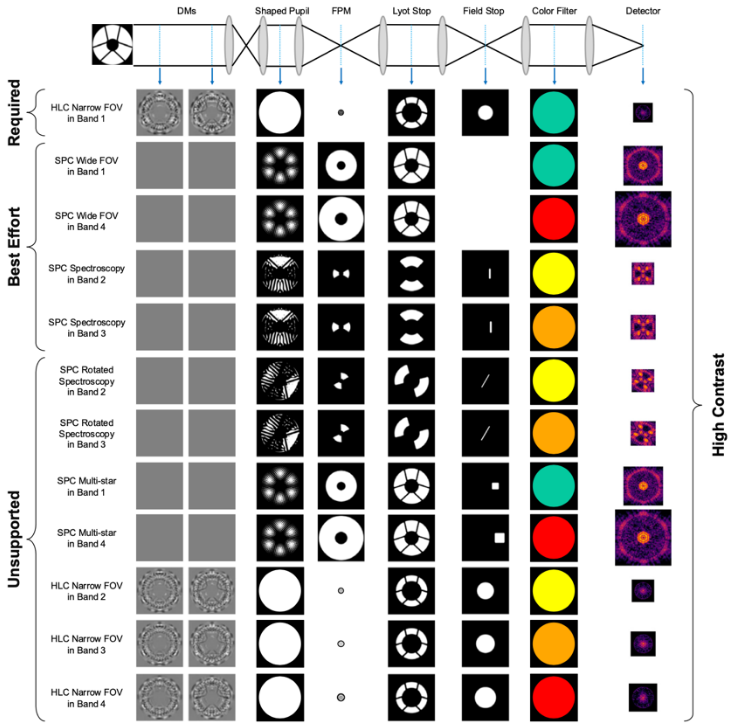
HLC is a hybrid between classical LC and shaped pupil coronagraph:

- Binary-amplitude apodizer to reshape the PSF into a « Boe tie »
- Optimized for NFOV (from $3\lambda/D$) at the expense of FoV (restric azimuthal span)
- Low sensitivity to jitter
- Quasi-achromatic
- Used for spectroscopy

All coronagraph configurations

Many additional modes:

- One required (supported) mode: HLC NFOV Band 1 – Tested in TVAC
- Best effort – Partially tested in TVAC, No guaranteed support on orbit
- Unsupported: not tested in TVAC



Riggs et al. (2025)

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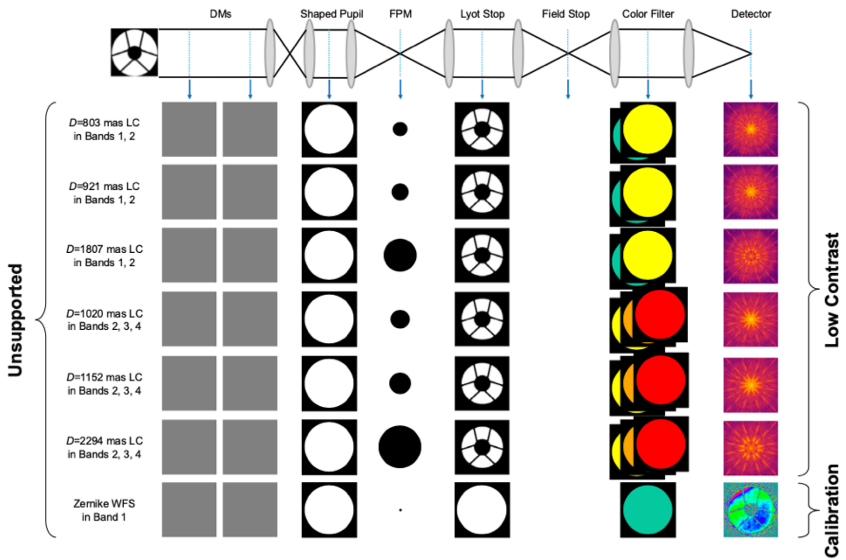

Riggs et al. (2025)

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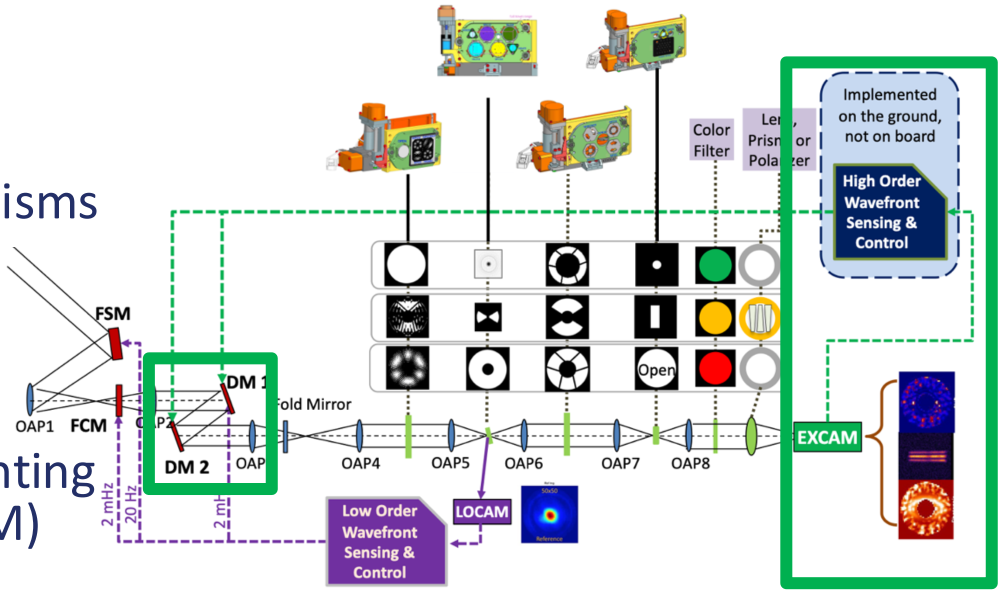
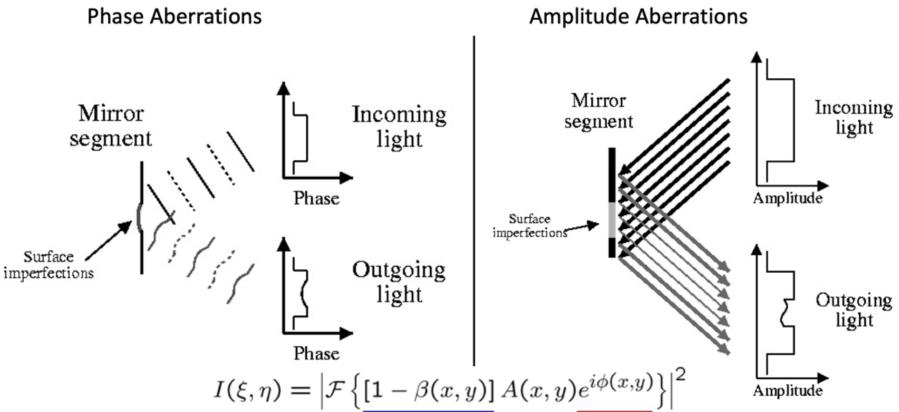


Mennession et al. (2022)

Correcting an abberated wavefront



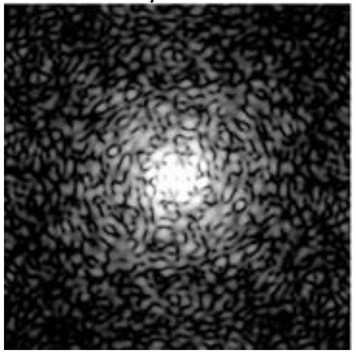
$$I(\xi,\eta) = \left|\mathcal{F}\left\{[1-\beta(x,y)]\,A(x,y)e^{i\phi(x,y)}\right\}\right|^2$$

Amplitude aberration — Phase aberration

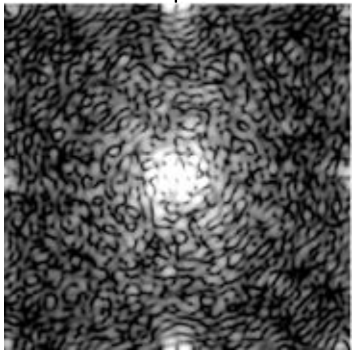
Amplitude errors cannot be corrected with a single DM.

Credits: Kasdin

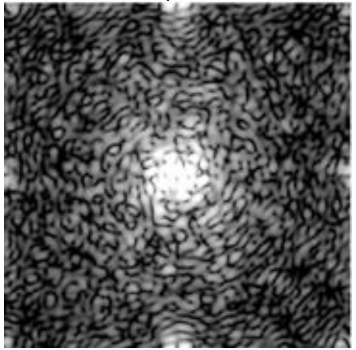
Phase only + 1DM + FDH



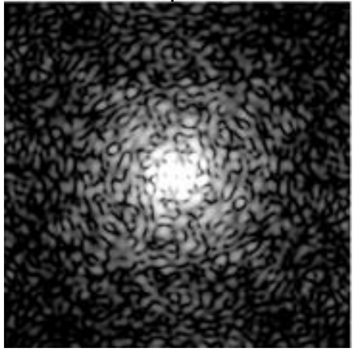
Phase and amp + 1DM + FDH



Phase and amp + 1DM + HDH

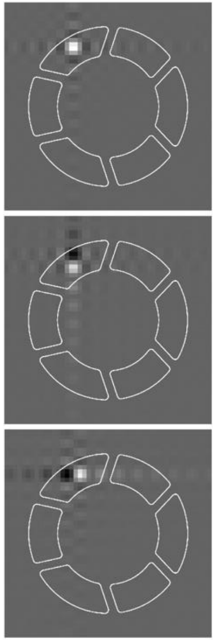


Phase and amp + 2DM + FDH



Use EXCAM as a wavefront sensor

Apply a set of diversities on the deformable mirror

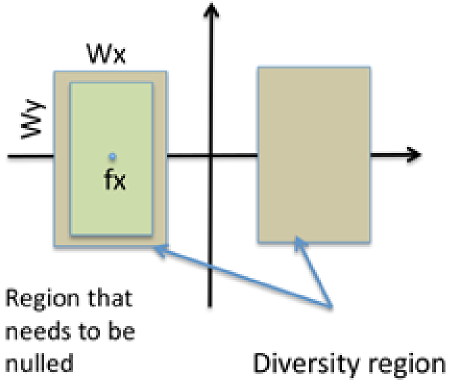


Cady et al. (2025)

Fourier Transform

Sinc function

It modulates the speckle intensity in the science image



Thomas et al. (2010)

Probe image difference are proportional to the focal plane e-field

$$J_{PW} = \min_F ||D - M \cdot F||^2$$

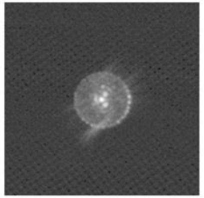
Linear model

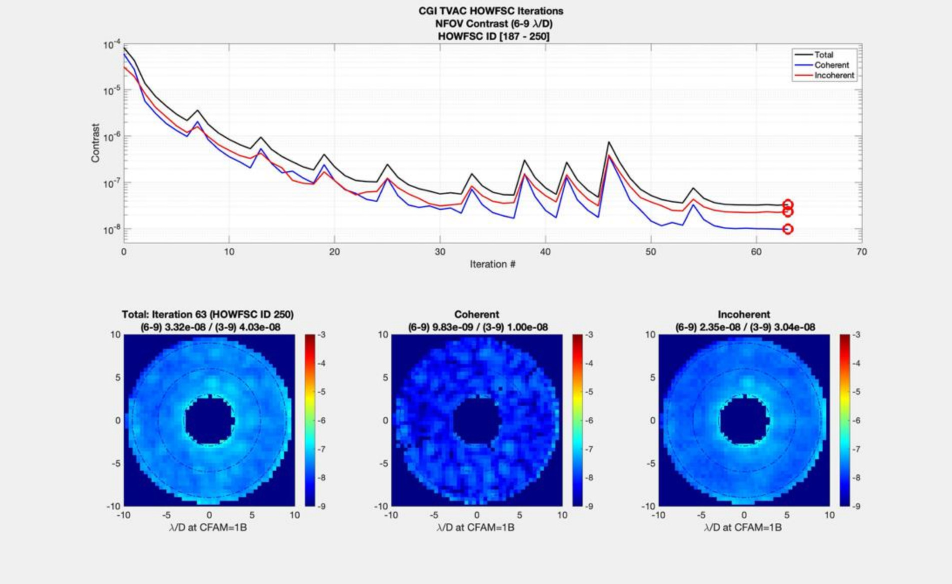
Image differences

Focal plane E-field

Active correction of optical aberration in TVAC/ HLC NFOV

- Requires many iterations (reducing duty cycle for science acquisition)
- Primary coronagraph mode (HLC NFOV) beats L1 requirement by at least 4x
- Not final performance: test time limited
- Unexpected light leak through a color filter: solved

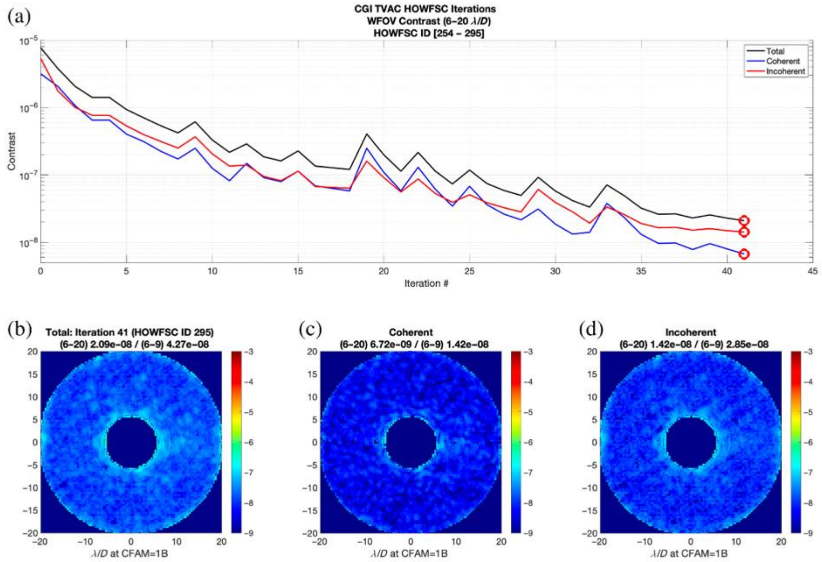




Cady et al. (2025)

Active correction of optical aberration in TVAC/ SPLC WFOV

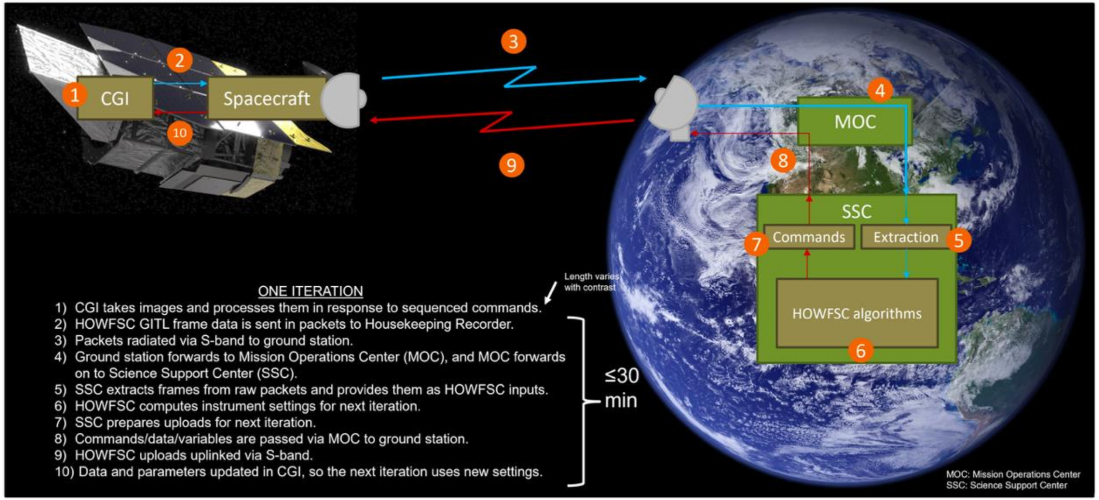
- Secondary coronagraph mode (SPLC WFOV at band 1) also beats L1 requirement
- Not final performance: test time limited
- Problem of Tip Tilt building in the instrument noticed and solved



Cady et al. (2025)

Active correction of optical aberration through GITL

- GITL: Ground In The Loop
- At each iteration:
  - Image data downlinked
  - DM and EXCAM settings uplinked
  - Takes ~30mn
- Eliminates the need for a second flight computer
- Offers the possibility of alternate DH digging and maintenance algorithm
- Data available <72h after operations



Cady et al. (2025)

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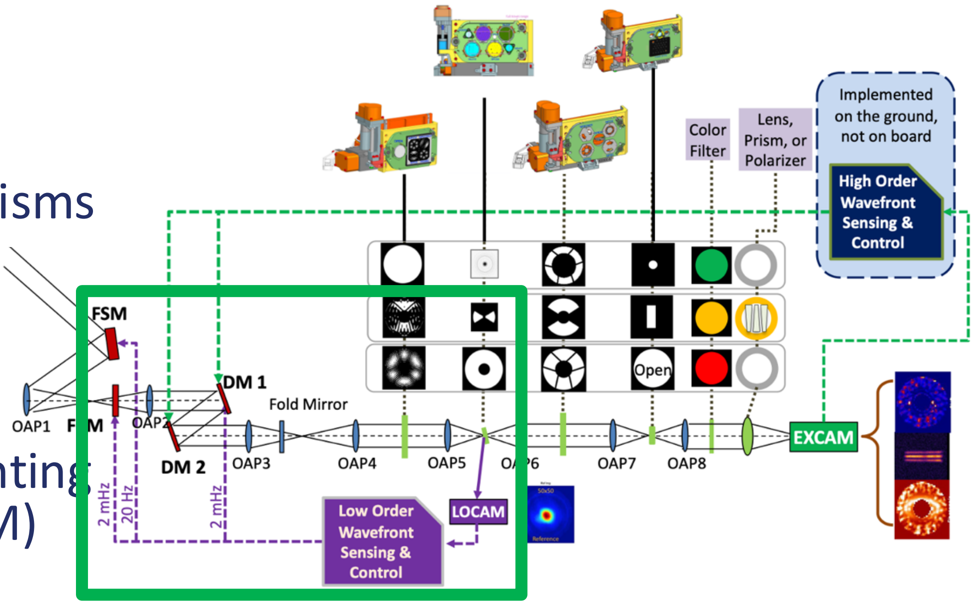
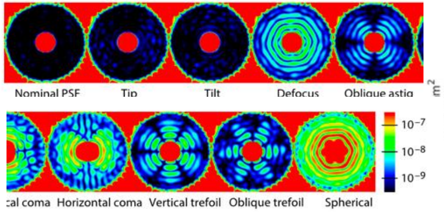


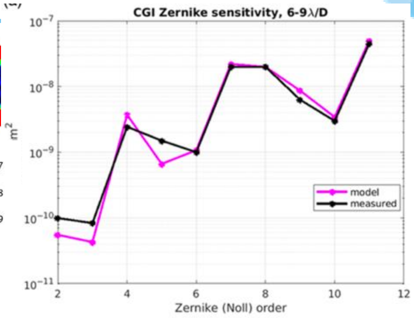
Mennession et al. (2022)

Dark Hole maintenance with LOWFS - model

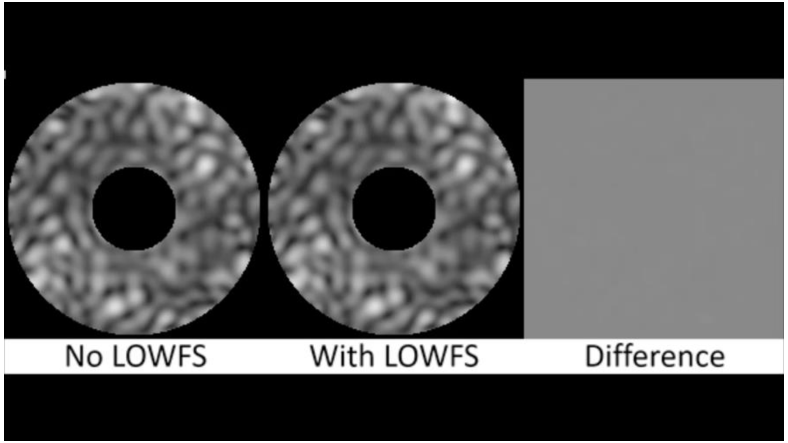
- Models show that both HLC and SPLC suffer from the first low order Zernikes
- After digging the DH:
  - thermal variation
  - vibration from reaction wheel
  - slew to/from target star

  will build low orders into the system
- Need for a LOWFS to sense and stabilize the wavefront in parallel to the observations





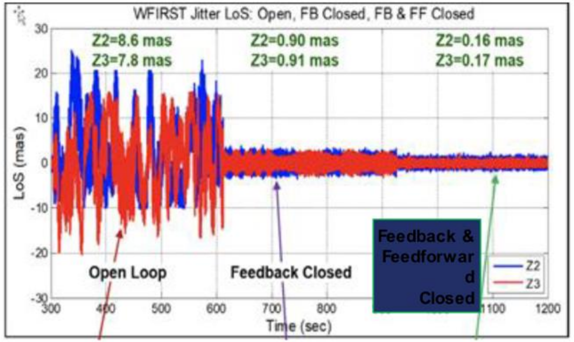
Zhou et al. (2025)



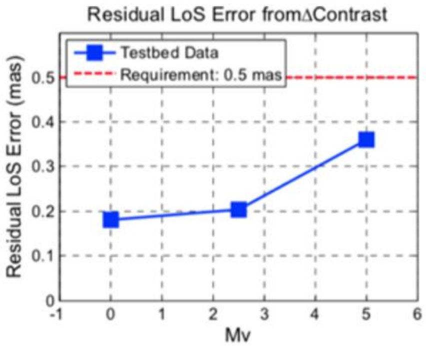
Krist et al. (2023)

Dark Hole maintenance with LOWFS - test

- LOWFS maintains star to focal plane mask alignment. Control TT to below 1mas
- Sets V<5 host star requirement
- Probably graceful degradation at V>5
- V~7 cutoff for coronagraphic target lists



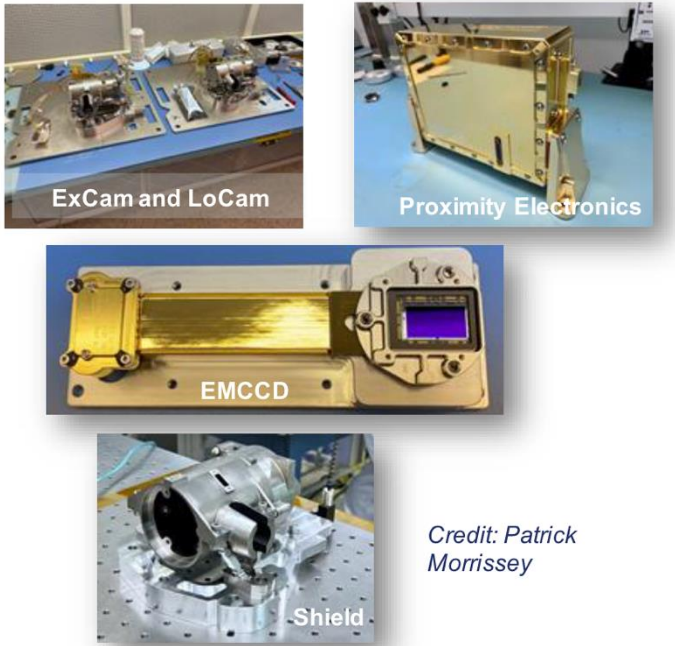
Shi+2019 lab demo: flight-like tip/tilt disturbances, bright "star."



Shi+2018 lab demo

Electron Multiplying CCDs count photons

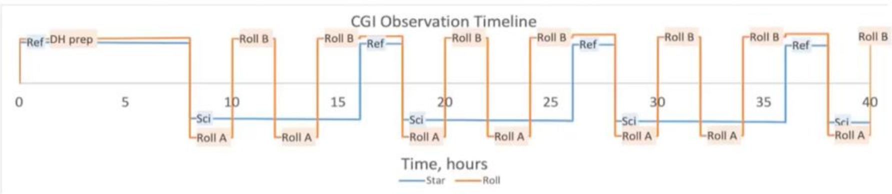
- Jupiter analogs V~27:
  - <1 planet photon/mn
- Teledyne e2V, two 1kx1K EMCCDs
  - EM = ultra low noise and no read noise
- Mind the cosmic rays!
- Two regimes:
  - Photon counting
  - Analogue

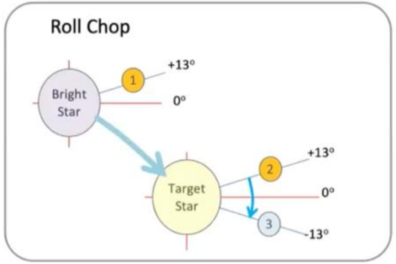


Credit: Patrick Morrissey

Postprocessing as an additional push in contrast

- After DH digging, combination of chop (RDI) and rolls (ADI)
- Target list of ref stars driven by coronagraph specifications
- Gain of ~>2
- See talk by Schuyler!





RDI and ADI enabled through a combination of rolling and chopping to a reference star for a PSF library.