Coronagraph Testbed Results

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Image credit: Mark Garlick, space-art.co.uk

Outline

- HWO Starlight Suppression MUSTs
- Coronagraphs "Static" Polychromatic Contrast Performance in the lab under vacuum (plain & segmented apertures)
- Contrast Stabilization on segmented apertures (in air)
- Overall State of Affairs
- Near Term Priorities for Improving Coronagraph Technical Readiness for HWO

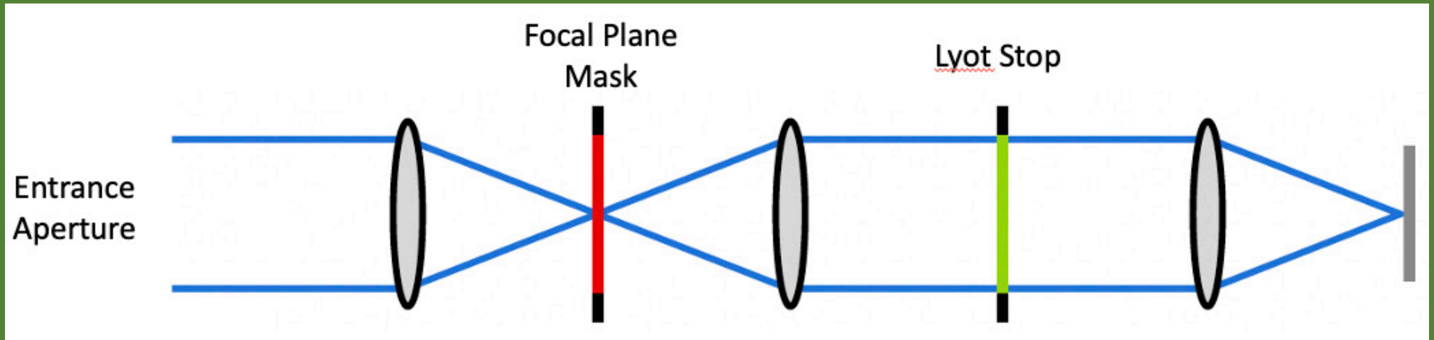
HWO Starlight Suppression System MUSTs

Detailed requirements yet to be derived. From previous studies and Astro2020 language:

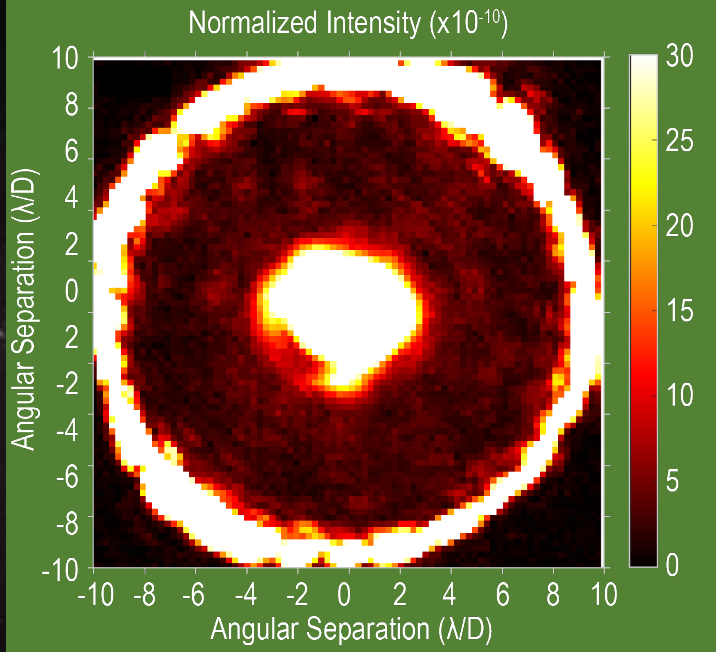
- Must reach a minimum point source detection limit Δmag ~ 25 at ~ 70 mas from FGK stars
  - That is 2 λ/D for λ=1 um and D= 6m (4 λ/D at 0.5 um)
  - Requires in-flight raw contrast < 10^{-9} there (a few 10^{-10}?) , with "high" off-axis throughput, high stability and a bandwidth >~ 20% per channel
  - Requires detectability of planets at or below speckles level → contrast stability *and /or* data post-processing must reduce starlight residuals down to <~ 10^{-11} level (1σ)
- Must spectrally characterize exo-Earth candidates over broad λ range to
  - Search for Rayleigh scattering, methane (high [ ]), water vapor and oxygen → 450-950 nm
  - Search for low levels of oxygen via O_3→ down to 250 nm
  - Search for methane (low [ ]) and carbon dioxide → up to 1800 nm

Coronagraphs Current Lab Performance: off-axis monolith (I)

Unobscured circular pupil with simple Lyot Coronagraph in vacuum: 4×10^{-10} contrast (1 polar), JPL HCIT Team – Decadal Survey Testbed (DST)



- Over 10% BW, averaging from 3-10 λ/D, 360° DH

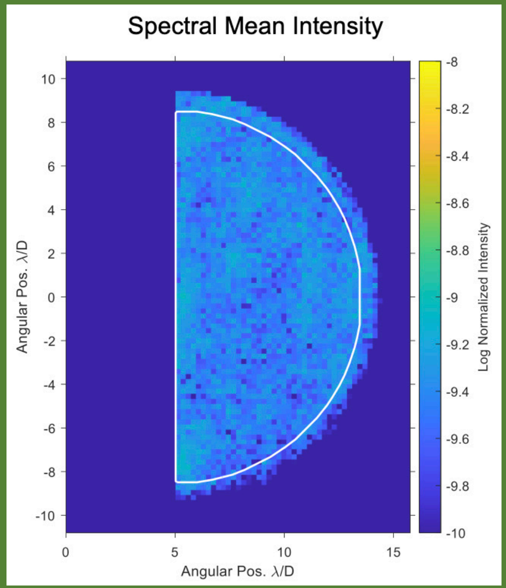


Performance limitations:

Contrast, 3.82E-10 Total		Measured	Model/Indirect Expectation	Morphology
Modulated 1.81E-10	LSB effect of DM actuators	8.78E-11	~1E-10	Specklish
	Chromatic Control Residual	9.32E-11	~4E-11	Specklish
Unmodulated 2.01E-10	Occulter Ghost (+Chromatic Residual)	1.01E-10	~1E-10	Patterned March with wavelength
	Testbed LoS Jitter impact	4.19E-11	< 1E-11	Centered
	Unknown	5.04E-11	N/A	Diffused

Seo, B.J. et al SPIE 2019

- Over 20% BW, averaging from 5.5-13 λ/D, one-sided DH

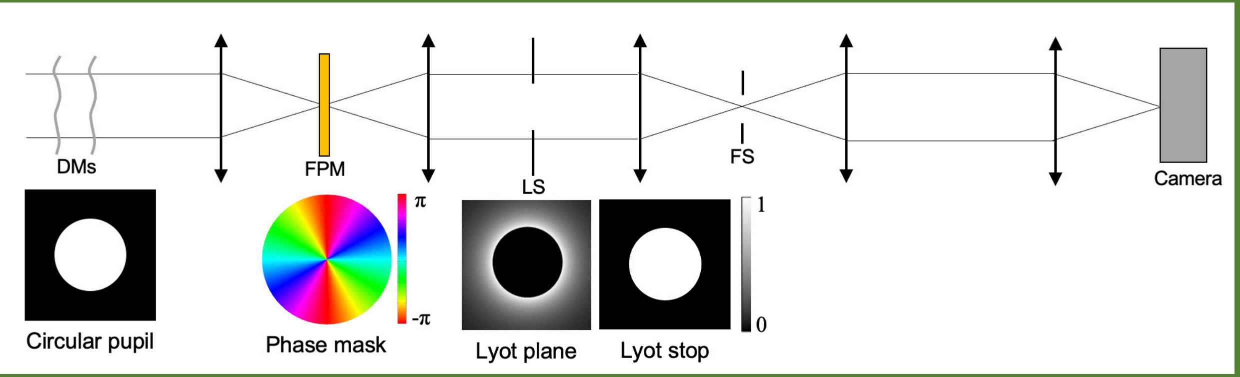


Allan, G. et al. 2022 in prep

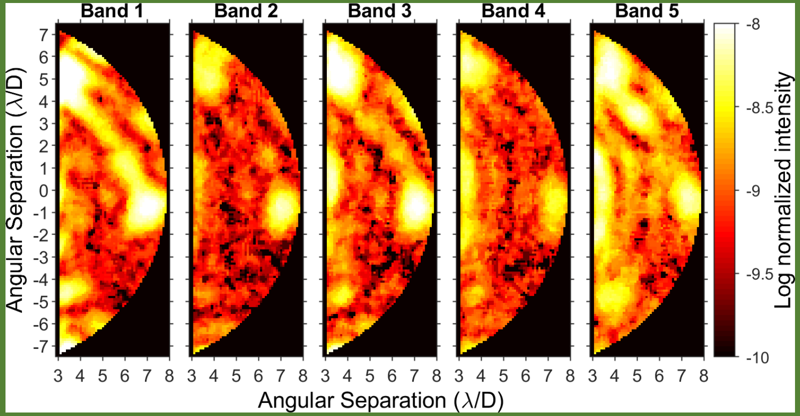
Coronagraphs Current Lab Performance: off-axis monolith (II)

Unobscured circular pupil with Vector Vortex Coronagraph (VVC4) in vacuum: **HCIT/DST Team**

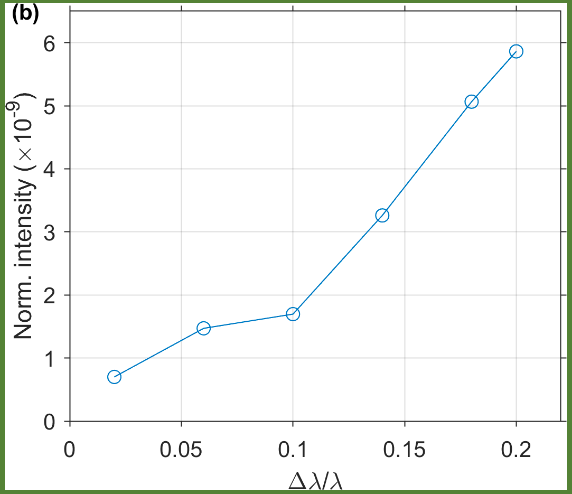
VVC4 offers Smaller IWA, higher throughput and resilience to aberrations than CLC



- 1.6 x 10 9 contrast over 10% BW, averaging from 3-8 λ/D, one-sided DH, 1 polar
- 5.9 x 10 9 contrast over 20% BW, averaging from 3-8 λ/D, one-sided DH, 1 polar



Performance limited by residual mask imperfections and chromatic retardance

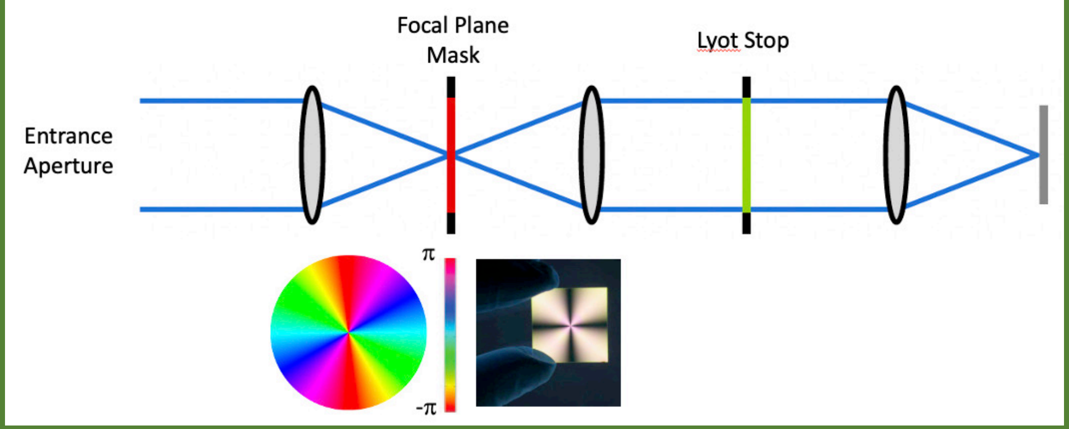


Ruane, G. et al. SPIE 2022

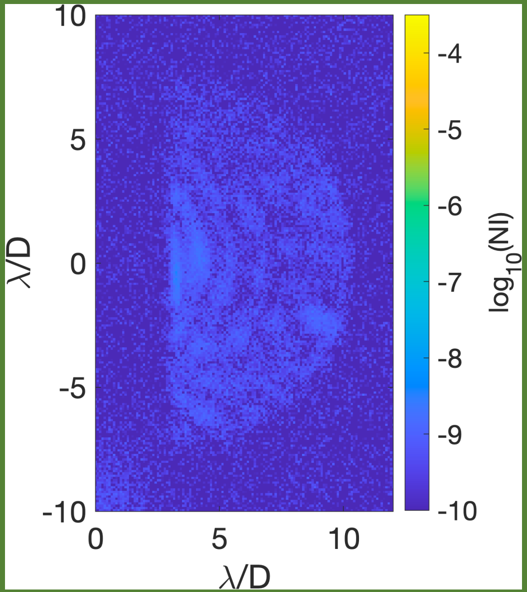
Coronagraphs Current Lab Performance: off-axis segmented

Segmented Mask with no central obscuration Vector Vortex Charge 4 (VVC4) in vacuum: **HCIT**

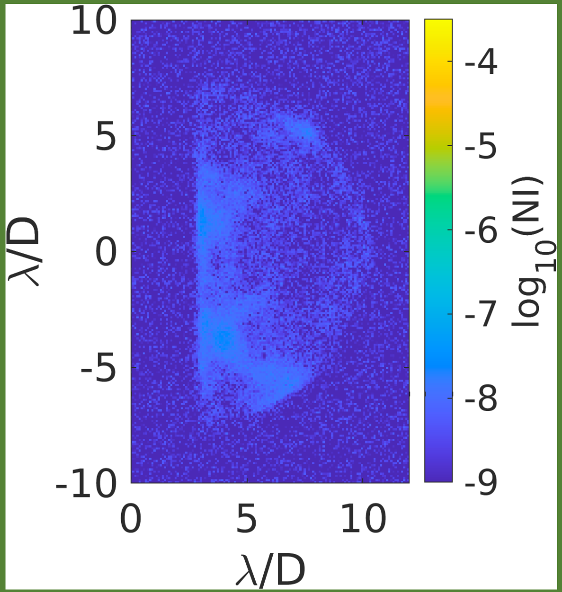
Segmented aperture mask



- 3.6 x 10 ^{10} monochromatic contrast averaging from 3-10 λ/D:



4.7 x 10 ^{9} 10% bandwidth contrast averaging from 3-10 λ/D:

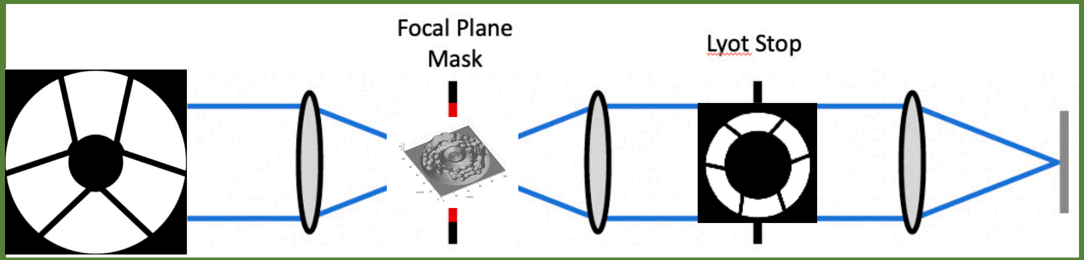


one-sided DH, unpolarized light

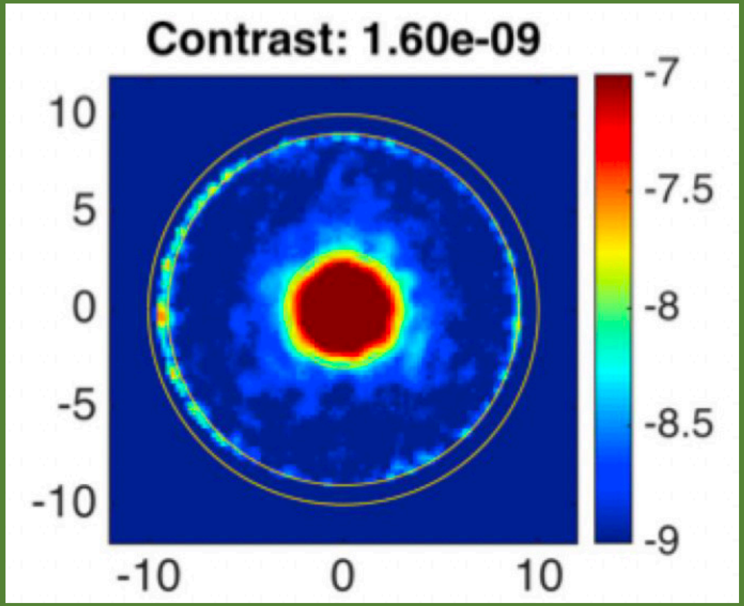
Riggs, A.J. et al. SPIE 2022

Coronagraphs Current Lab Performance: on-axis heavily obscured monolith: Roman CGI in HCIT

Hybrid Lyot coronagraph (HLC)

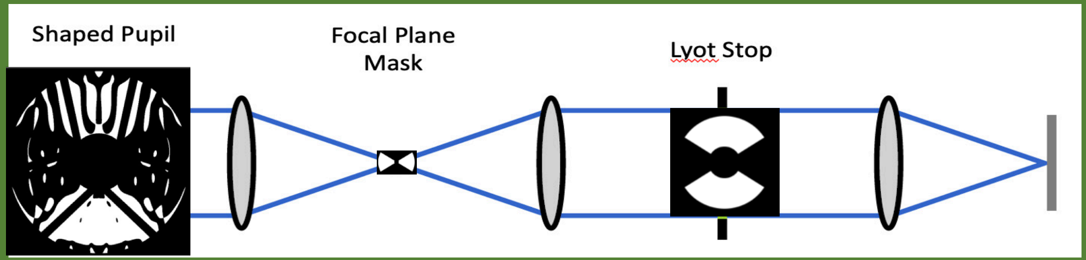


1.6 x 10^{9} 10% bandwidth contrast averaging from 3-10 λ/D with 2 polars

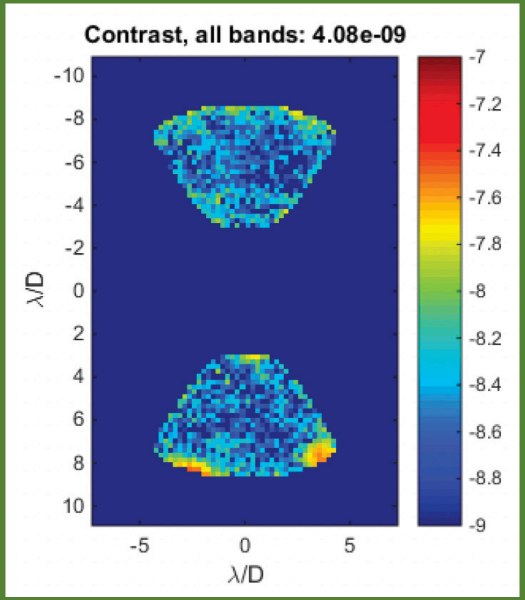


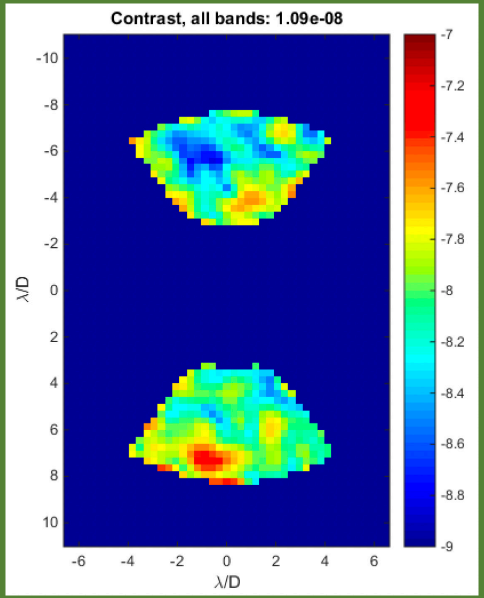
Seo, B.-J. et al. 2017

Shaped Pupil Coronagraph (spectro bow-tie mode)



4.1 x 10^{9} 10% BW contrast and 1.1 x 10^{8} 18% BW contrast averaging from 3-10 λ/D with 2 polars

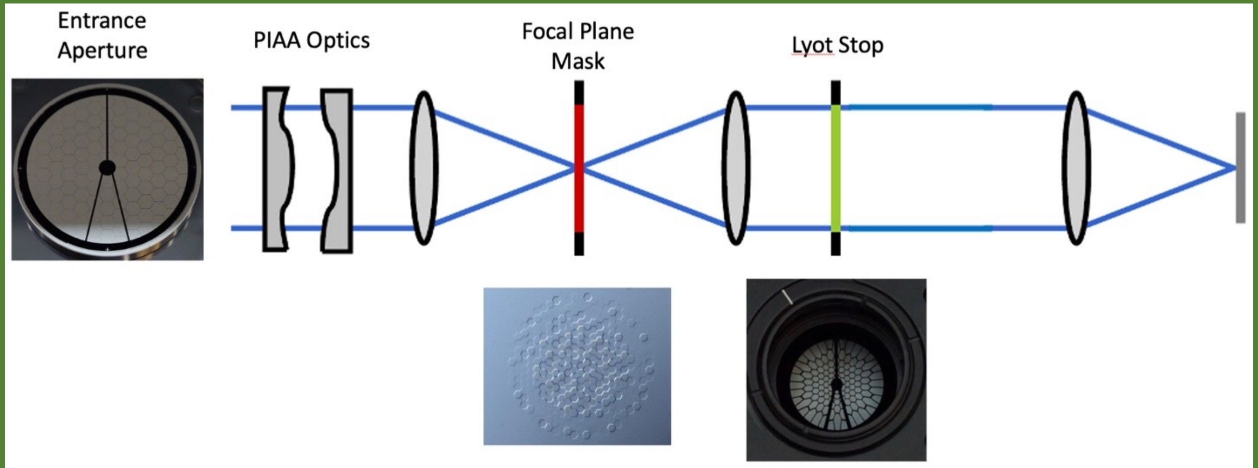




Cady, E. et al. 2017

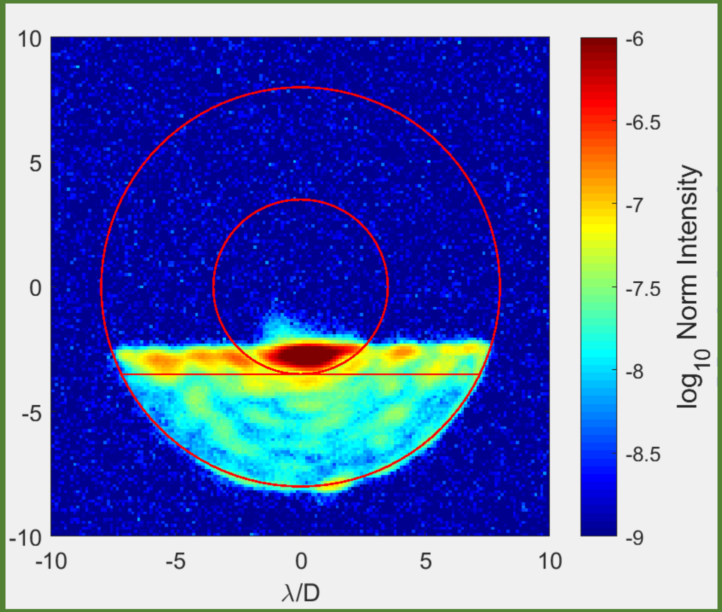
Coronagraphs Current Lab Performance: on-axis segmented

Segmented Pupil: 120 hexagons, central obscuration and spiders - Phase Induced Amplitude Apodization Complex-value Mask Coronagraph (PIACMC) in vacuum: **HCIT Testbed**



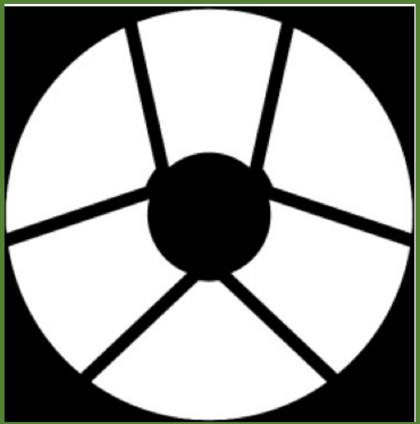
- 1.9×10^{8} 10% bandwidth contrast averaging from 3.5-8 λ/D, one-sided DH, polarized light

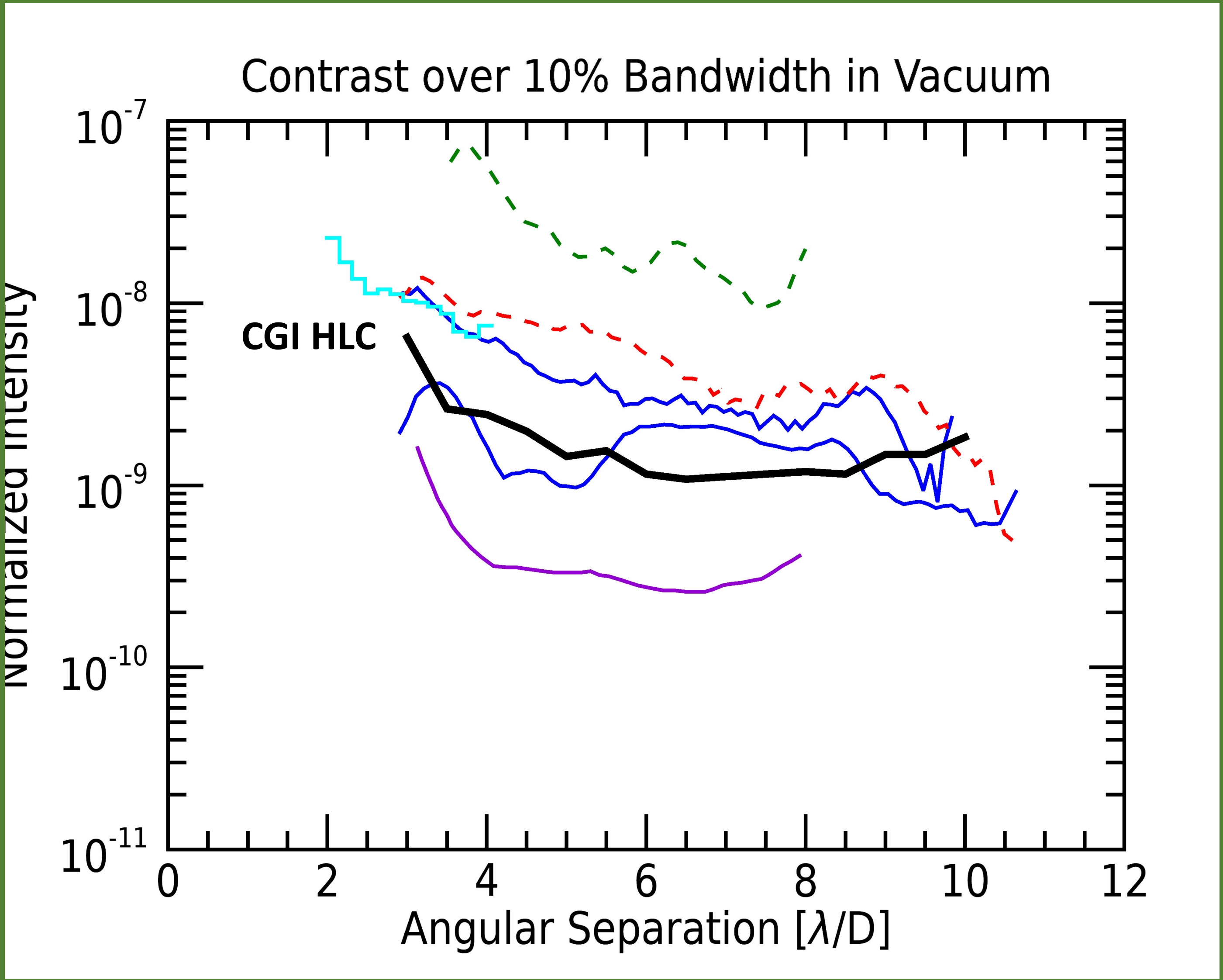
Performance limited by coherent chromatic effects - which should be correctable according to wavefront control simulations



Belikov, Sirbu, Marx et al. 2021

Coronagraphs Current Lab Performance: Summary



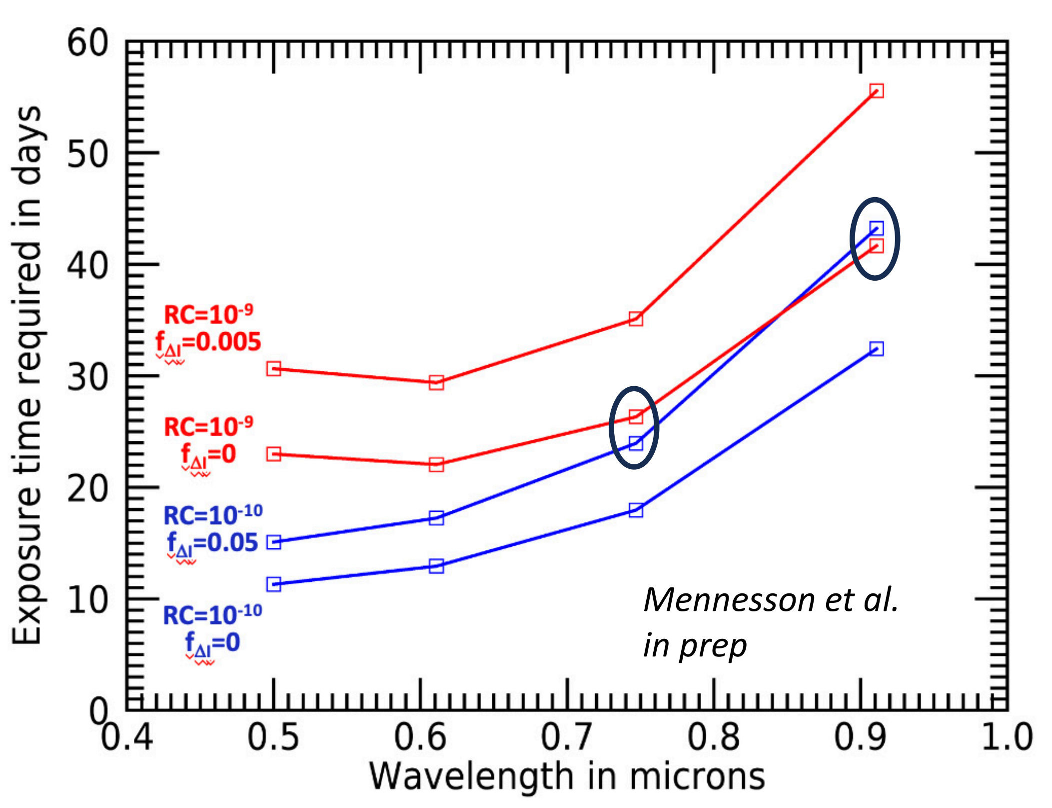


Coronagraph Static Performance in vacuum

Coronagraph Type	HWO goal	Classical Lyot	Vector Vortex charge 4	Vector Vortex charge 4	CGI HLC CGI SPC	Phase Induced Amplitude Apodization Complex Mask Coronagraph
Aperture Type	**Segmented**	**Circular unobscured (off-axis monolith)**		**Circular off-axis static segmented mask**	**Circular on-axis heavily obscured monolith**	**Circular on-axis static segmented mask**
Deformable Mirrors	2x 96 x 96	2 AOX each 48 x 48 act	2 AOX each 48 x 48 act	1 BMC MEMs (2k act)	2 AOX each 48 x 48 act	1 BMC MEMs 1k act
Separation Range	3-45 λ/D	3-10 λ/D *(5-13.5 λ/D)*	3-8 λ/D	3-10 λ/D	3-9 λ/D	3.5 – 8 λ/D
Dark Hole Azimuthal Extent (deg)	360	360 (180)	180	180	360 2x65	180
Mean Raw Contrast over Sep. Range	**few x 10^{-10}**	**4 x 10^{-10}** ***(idem)***	**1.6 x 10^{-9}** ***(5.9 x 10^{-9})***	**4.7 x 10^{-9}**	**1.6 x 10^{-9}** ***4.1 x 10^{-9} (1.1 x 10^{-8})***	**1.9 x 10^{-8}**
Central wavelength (nm)	TBD	550	635	635	550	650
Spectral bandwidth	20%	10% *(20%)*	10% *(20%)*	10%	10% *10% (18%)*	10%
Number of polarizations	2	1	1	1	2	1
Core throughput at 3λ/D	high	medium-low	high	high	low	high
Sensitivity to low order aberrations	low	medium	low	low	medium	medium
Facility and Testbed		JPL HCIT-2 DST	JPL HCIT-2 DST	JPL HCIT-2 DST	JPL HCIT	JPL HCIT-2
Vacuum Operation		Y	Y	Y	Y	Y

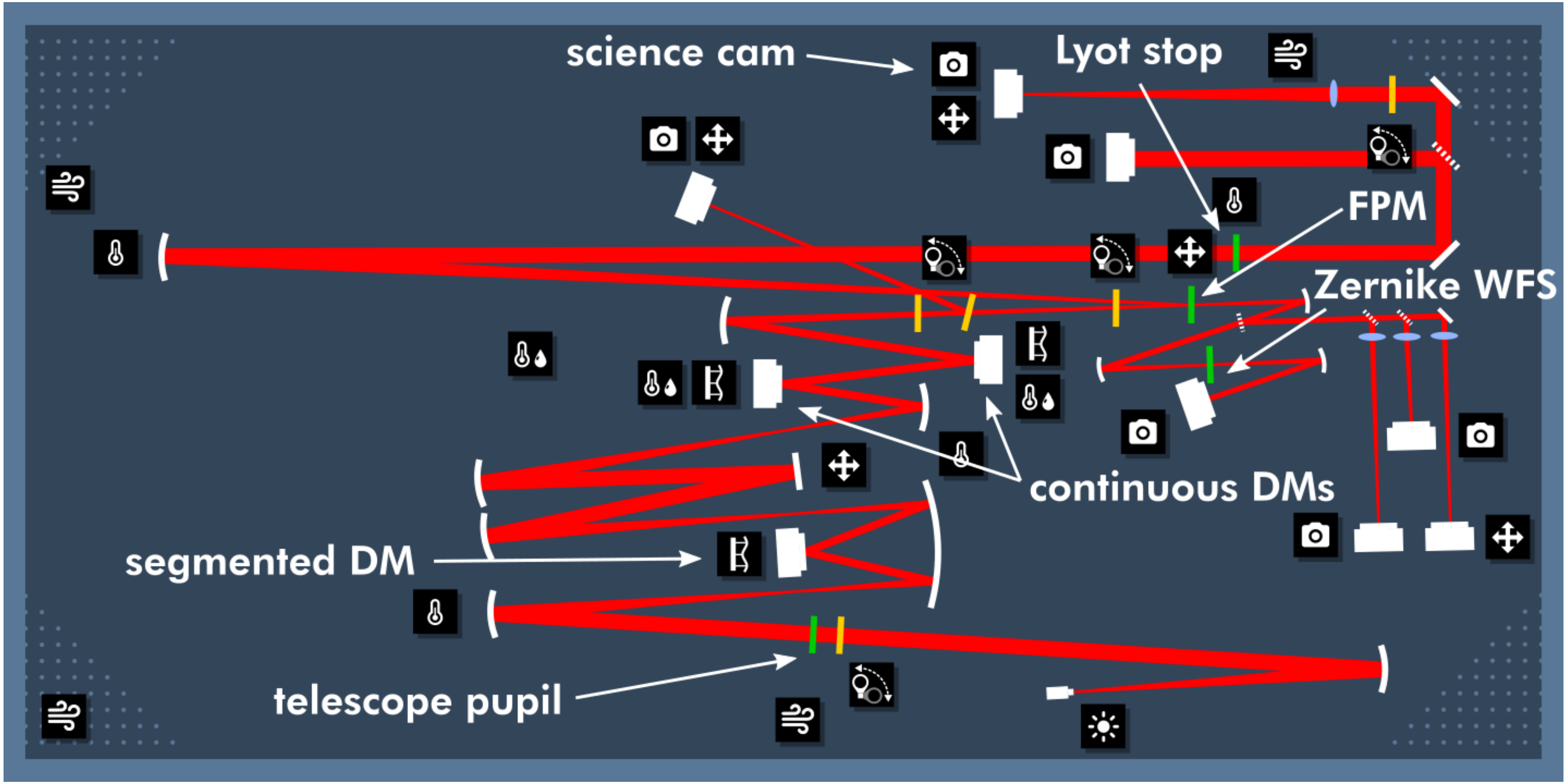
Triple trade: mean contrast vs contrast stability vs post-processing effectiveness

Parameter	Value
Stellar type	Solar twin
Stellar distance	12 pc
Planet type	Earth twin
Planet semi major axis	1 AU
Planet illumination phase and flux ratio	Quadrature; resulting in 10^{-10} planet-to-star flux ratio
Solar zodiacal light surface brightness at planet location	23 Vmag/arcsec^2
Exozodiacal light surface brightness at planet location	22 Vmag/arcsec^2 for a 1 zodi solar analog
Exozodi Level	3 zodis
Telescope diameter	6m
Central obscuration	None
Central wavelengths	0.5 µm, 0.61 µm , 0.74 µm, 0.91µm
Spectral resolution	70
End to end optical throughput (excluding all starlight suppression masks and detector quantum efficiency)	0.3
Radius of photometric aperture	0.7 λ/D (centered at planet location)
Core throughput at planet location within photometric aperture	Coronagraph dependent 0.36 at 3λ/D for VVC4
Raw contrast at planet location	10^{-10} or 10^{-9}
Differential imaging suppression effectiveness ($f_{\Delta I}$)	Varied between 0 and 0.05 (0 = shot noise limit)
Detector quantum efficiency (QE)	0.9
Detector noise	0
Number of polarizations instantaneously observed	2
Spectrocopic Signal to noise (on continuum)	10

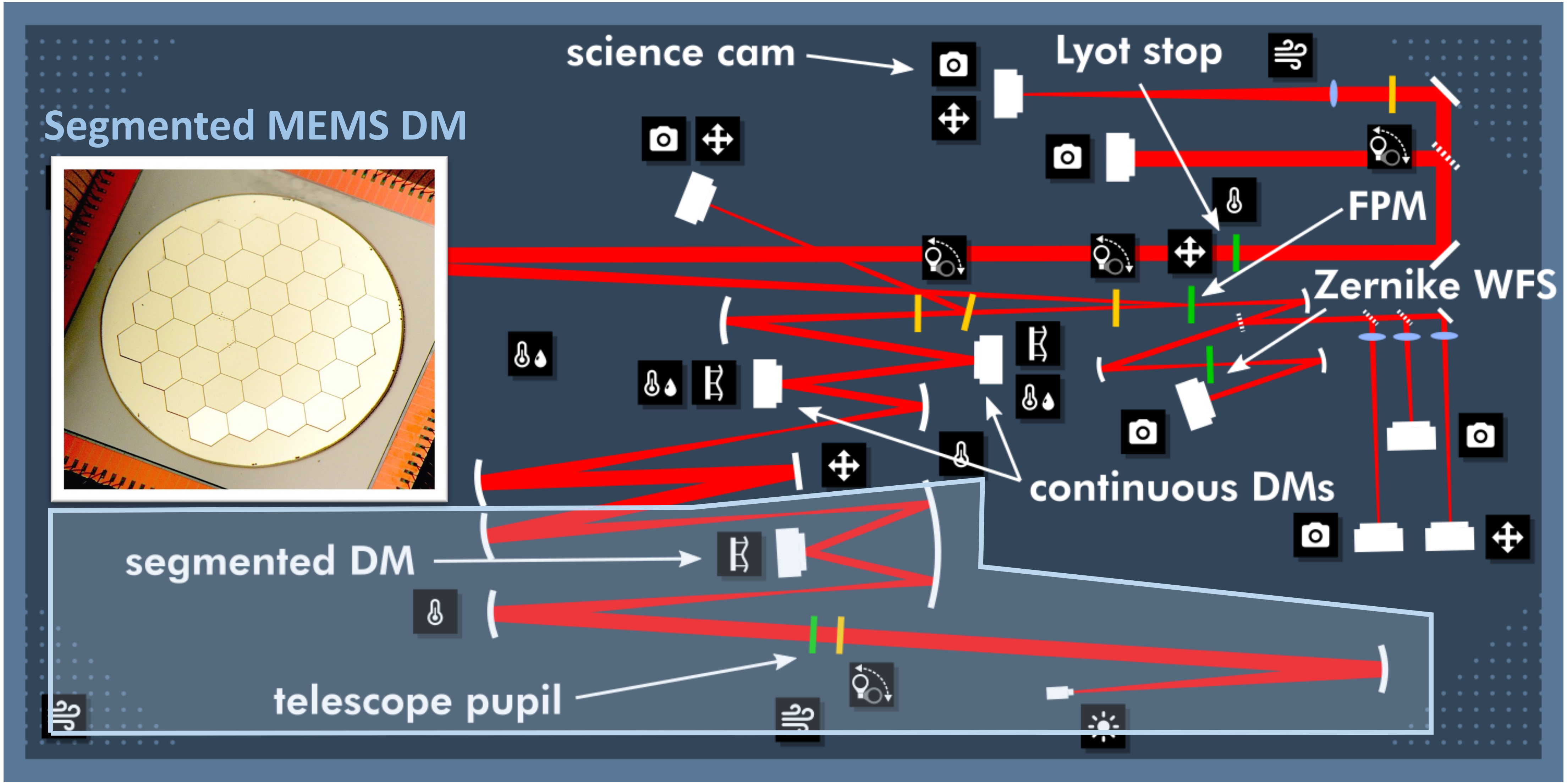


- To characterize exo-Earths at 10^{-9} instrumental contrast rather than 10^{-10}, better contrast stability and/or better data post-processing is required
- However, raw contrast degradation not only increases stellar shot noise. It also degrades contrast stability at a given perturbation level → better WF stability and / or post-processing required to work at 10^{-9} contrast

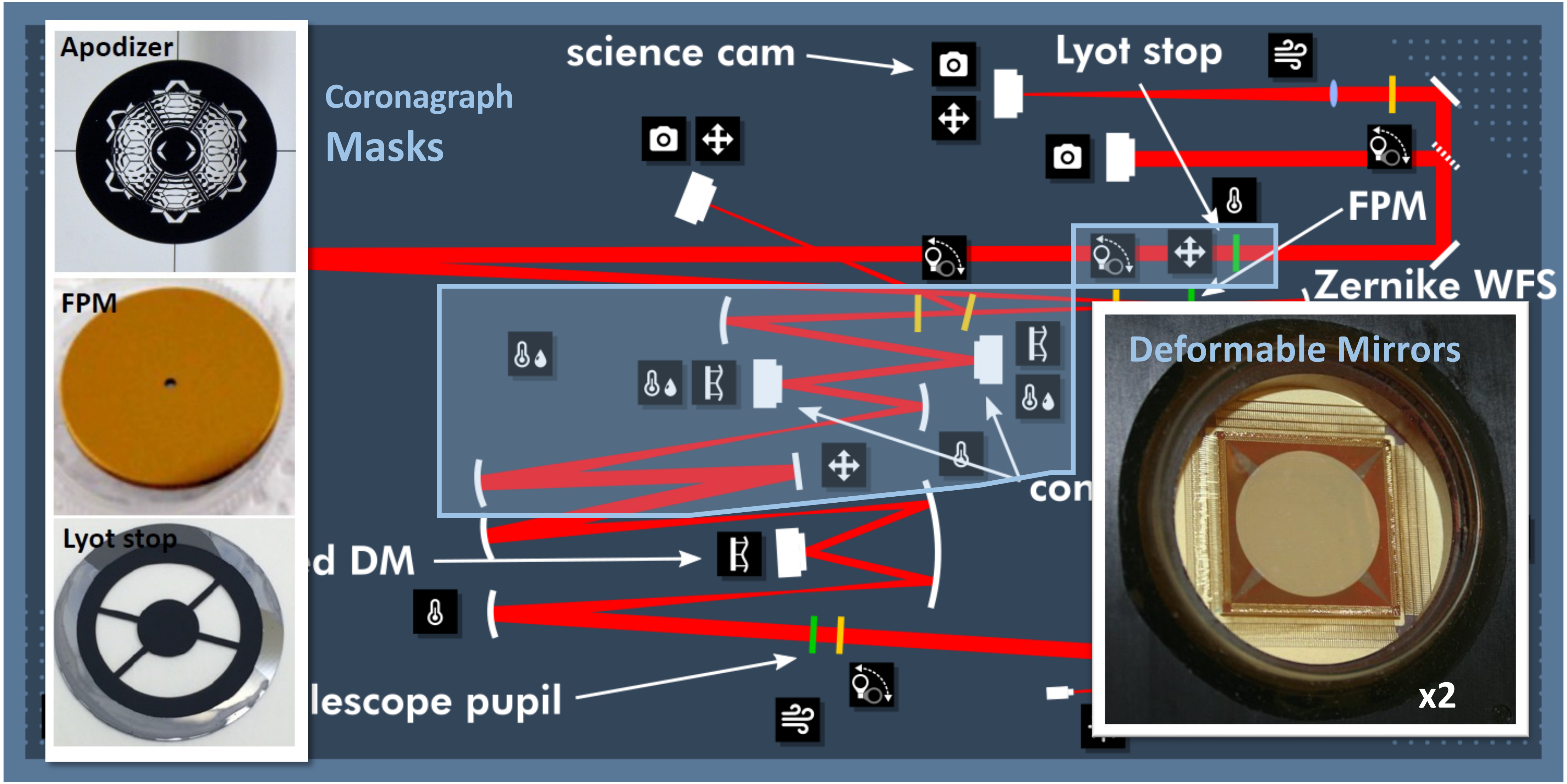
Preparing for a highly complex observatory needs integrated full-system demonstrations



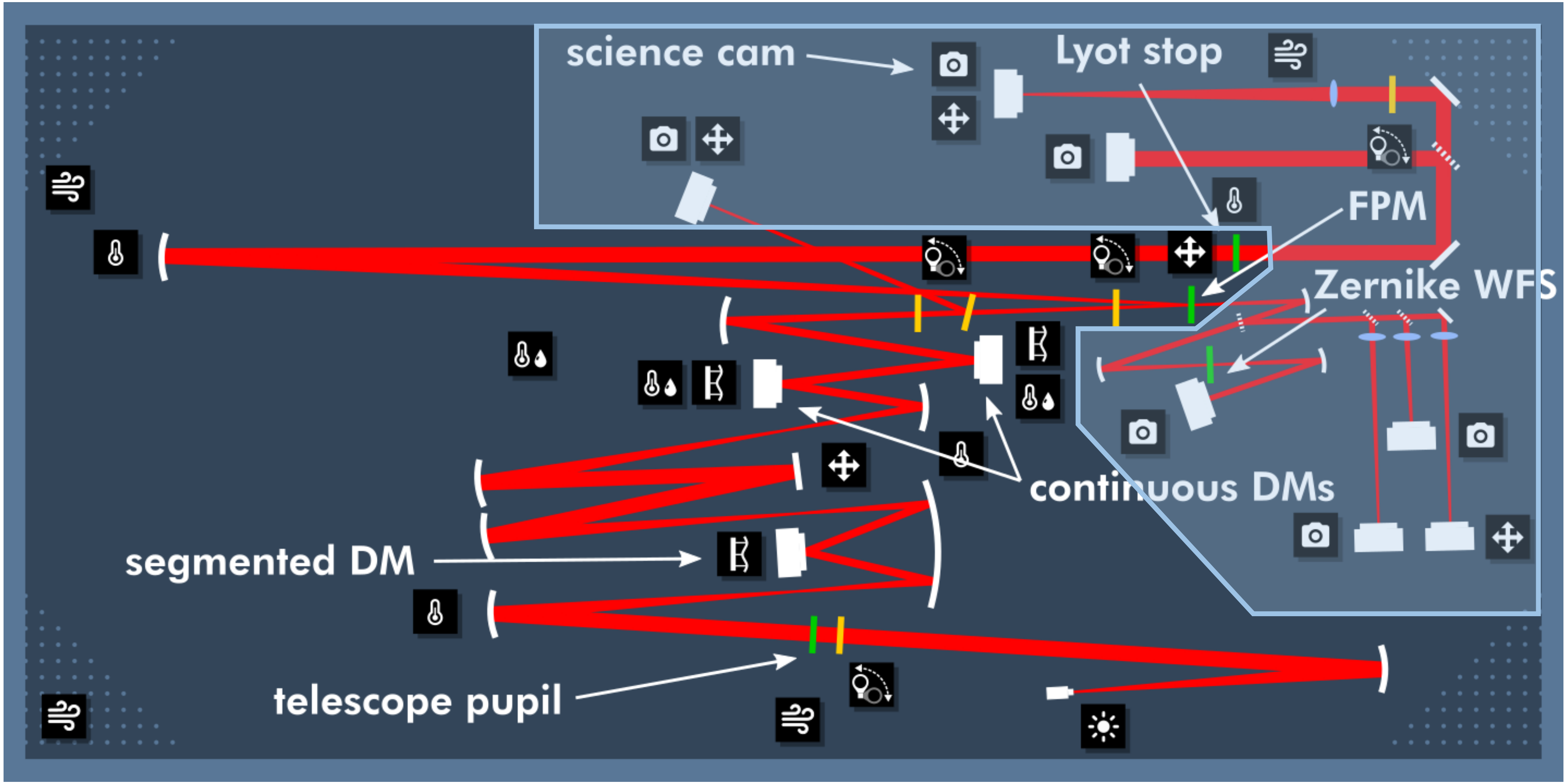
Segmented telescope simulator



Starlight suppression and wavefront control



Science channel & wavefront metrology

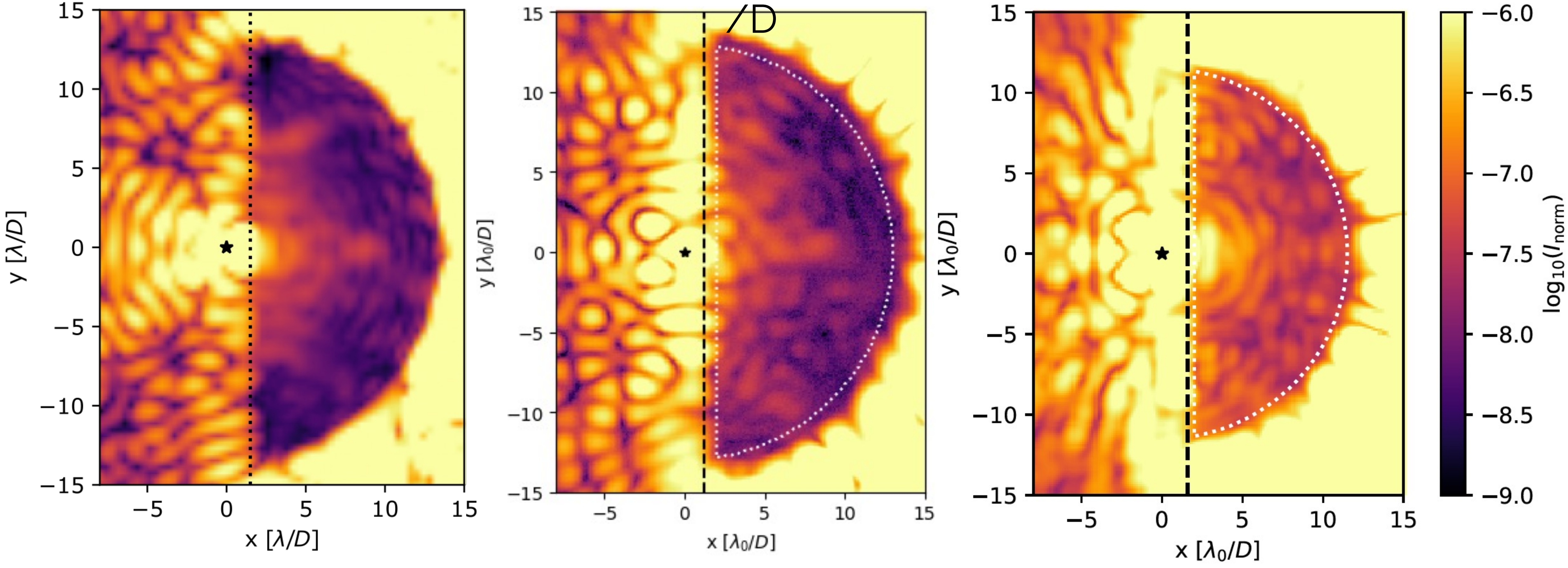


PAPLC coronagraph in broadband

monochromatic
2×10^{-8}, 2 – 13 λ /D

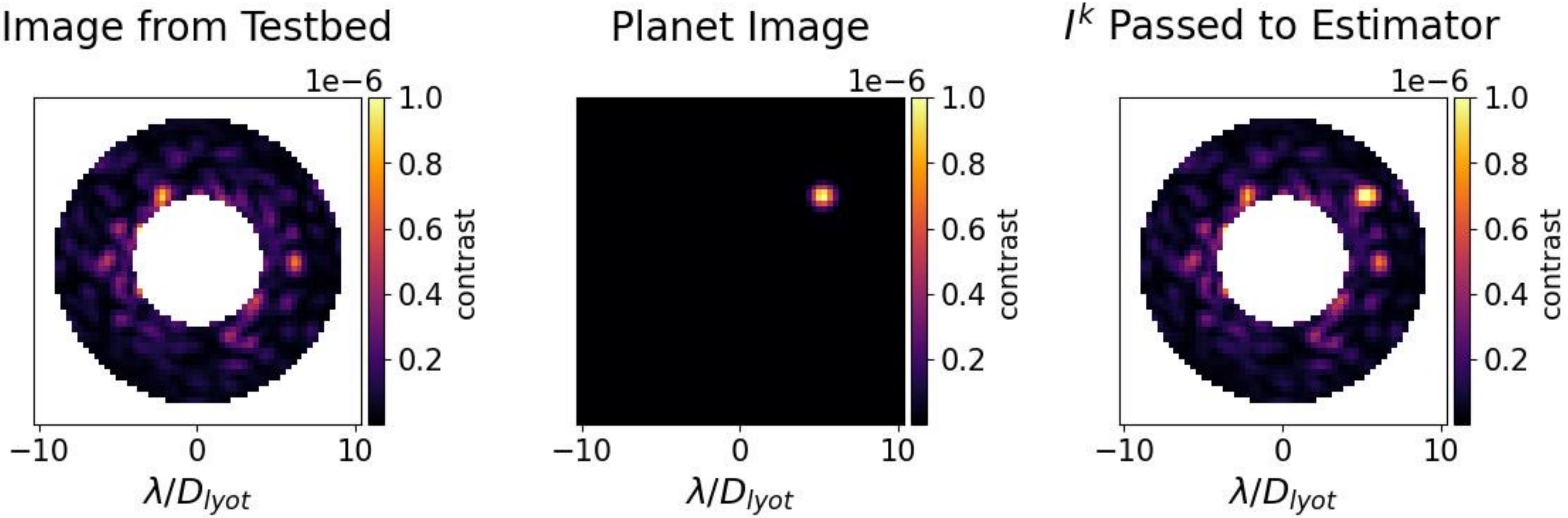
9% broadband
4.2×10^{-8}, 2 – 13 λ /D

25% broadband
9.5×10^{-8}, 2 – 12 λ /D



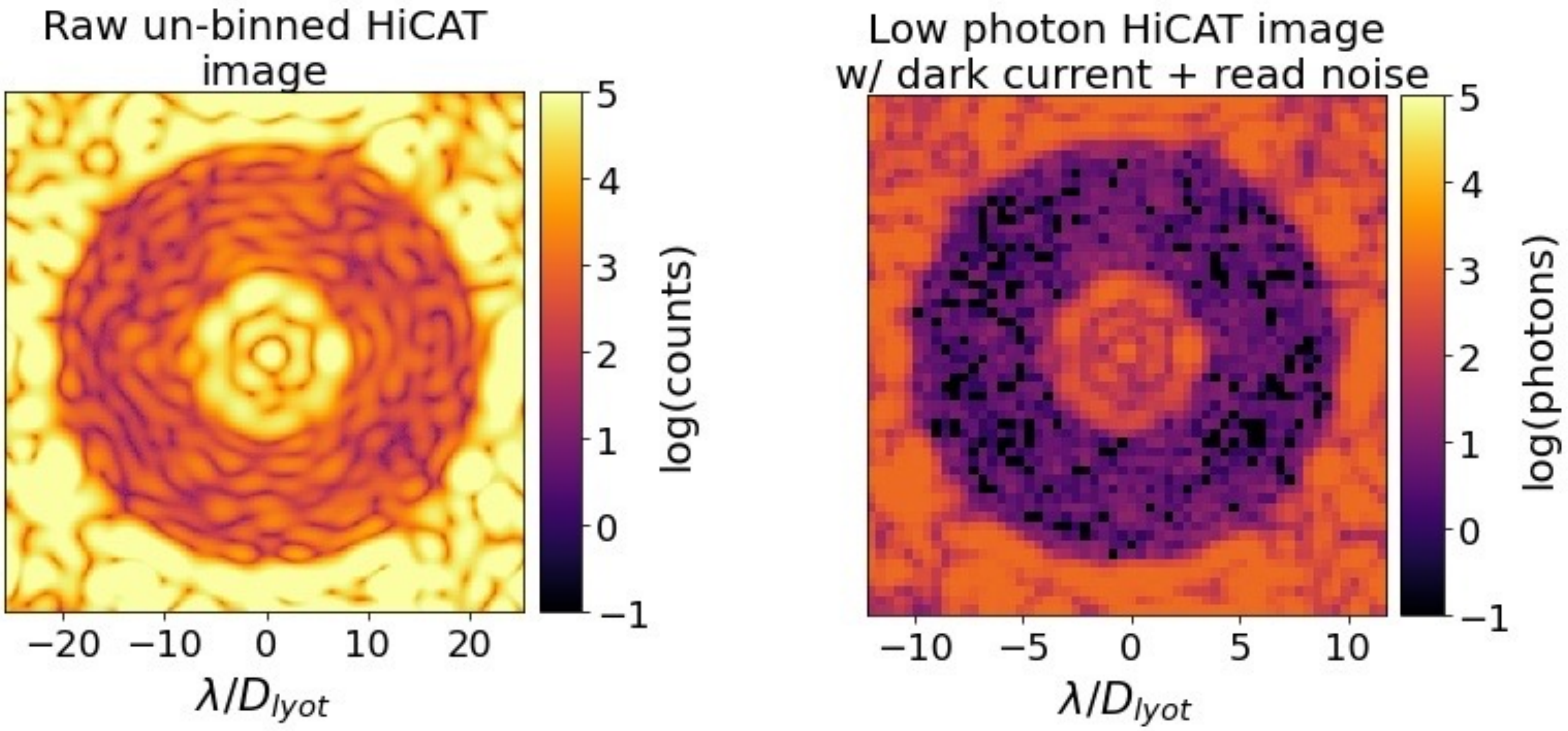
Por et al. (in prep.)

Adding incoherent planet light



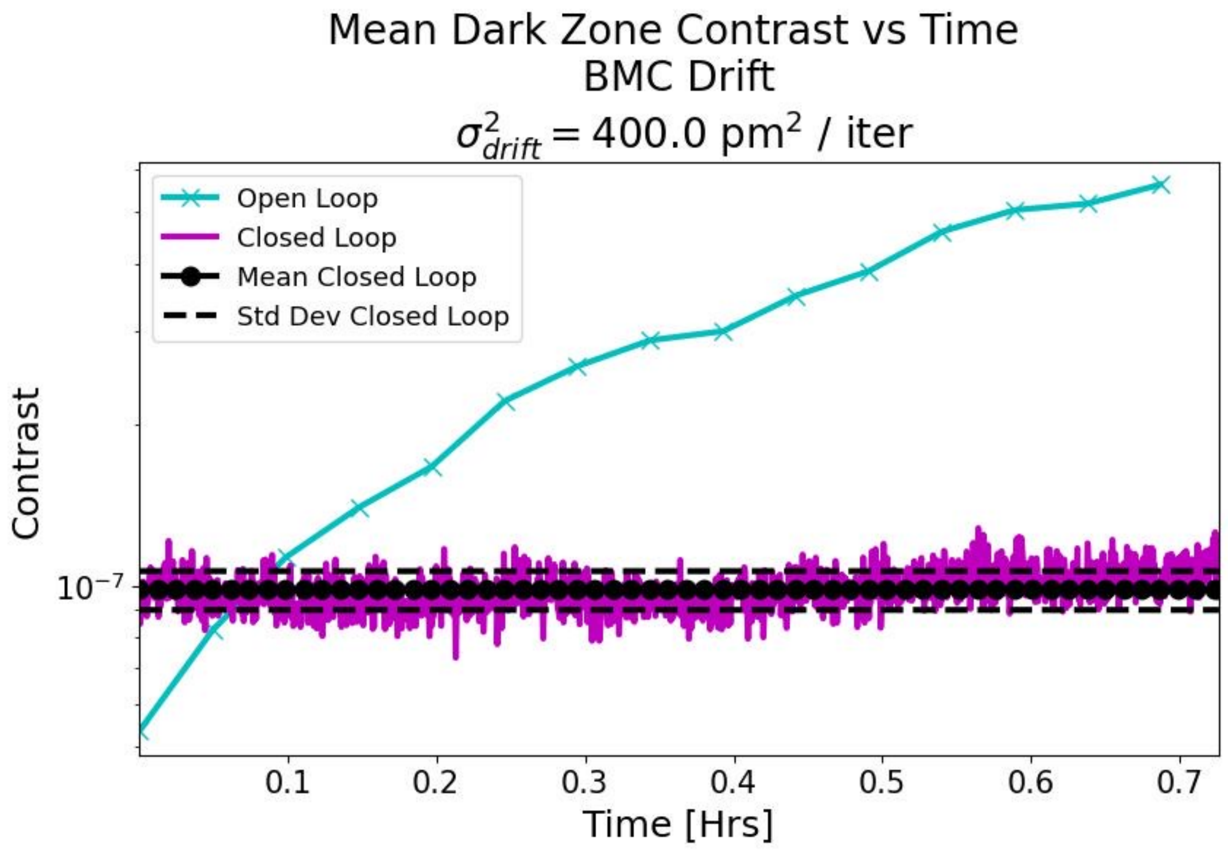
Redmond et al. (in prep.)

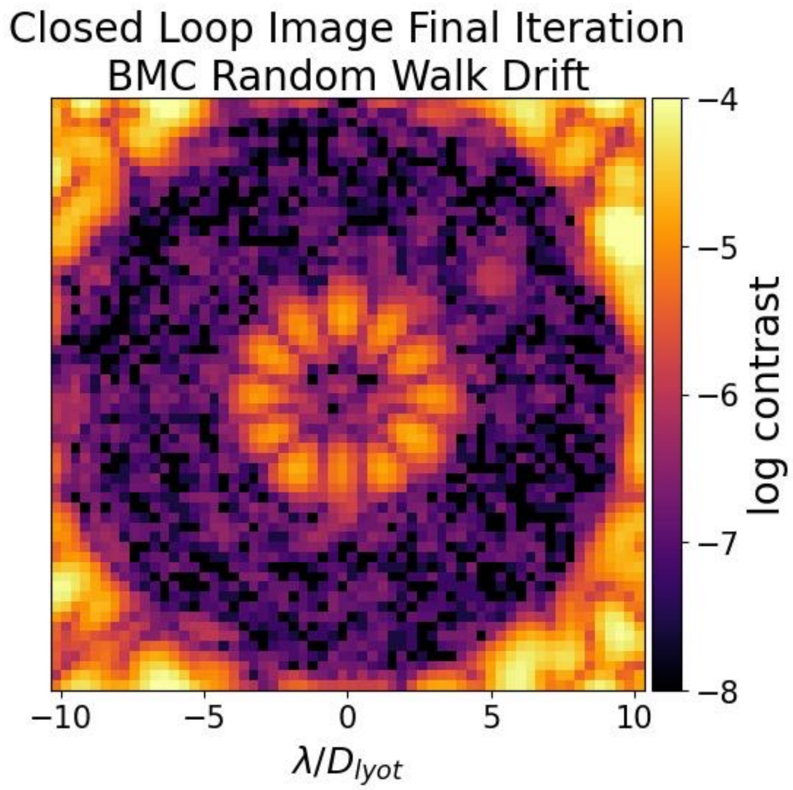
Emulated low-photon images



Redmond et al. (in prep.)

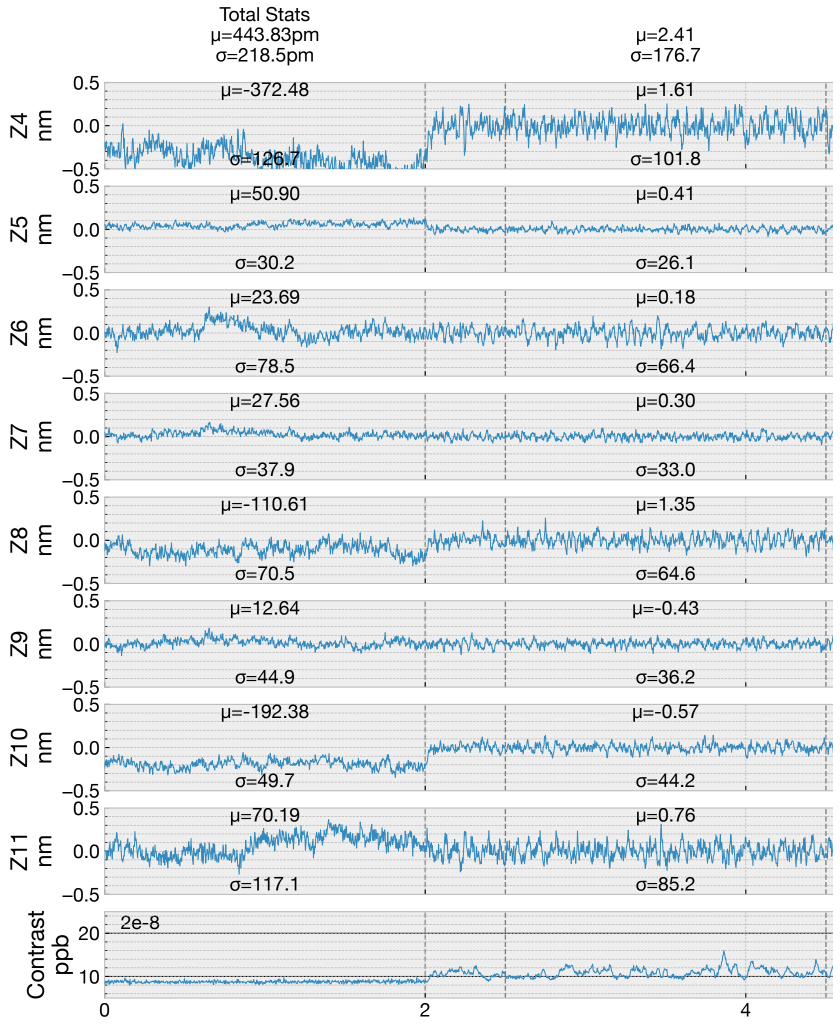
Stabilize the contrast with LOWFS and other control loops





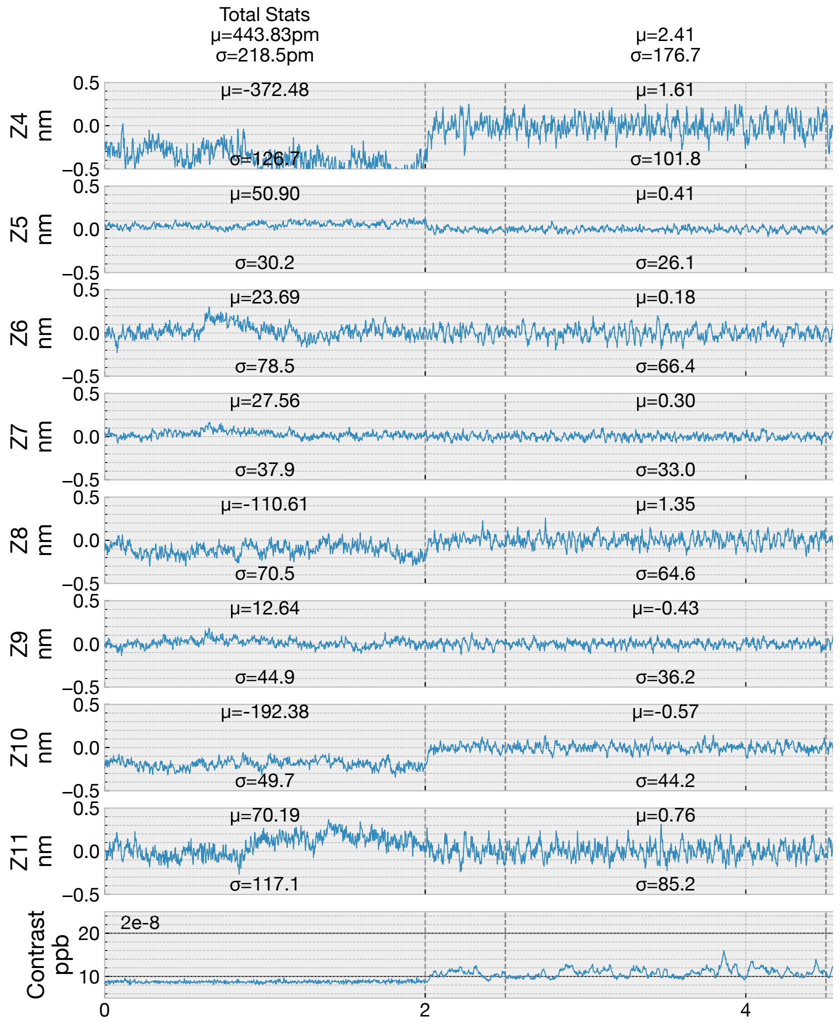
Redmond et al. (in prep.)

Stabilize the contrast with LOWFS and other control loops

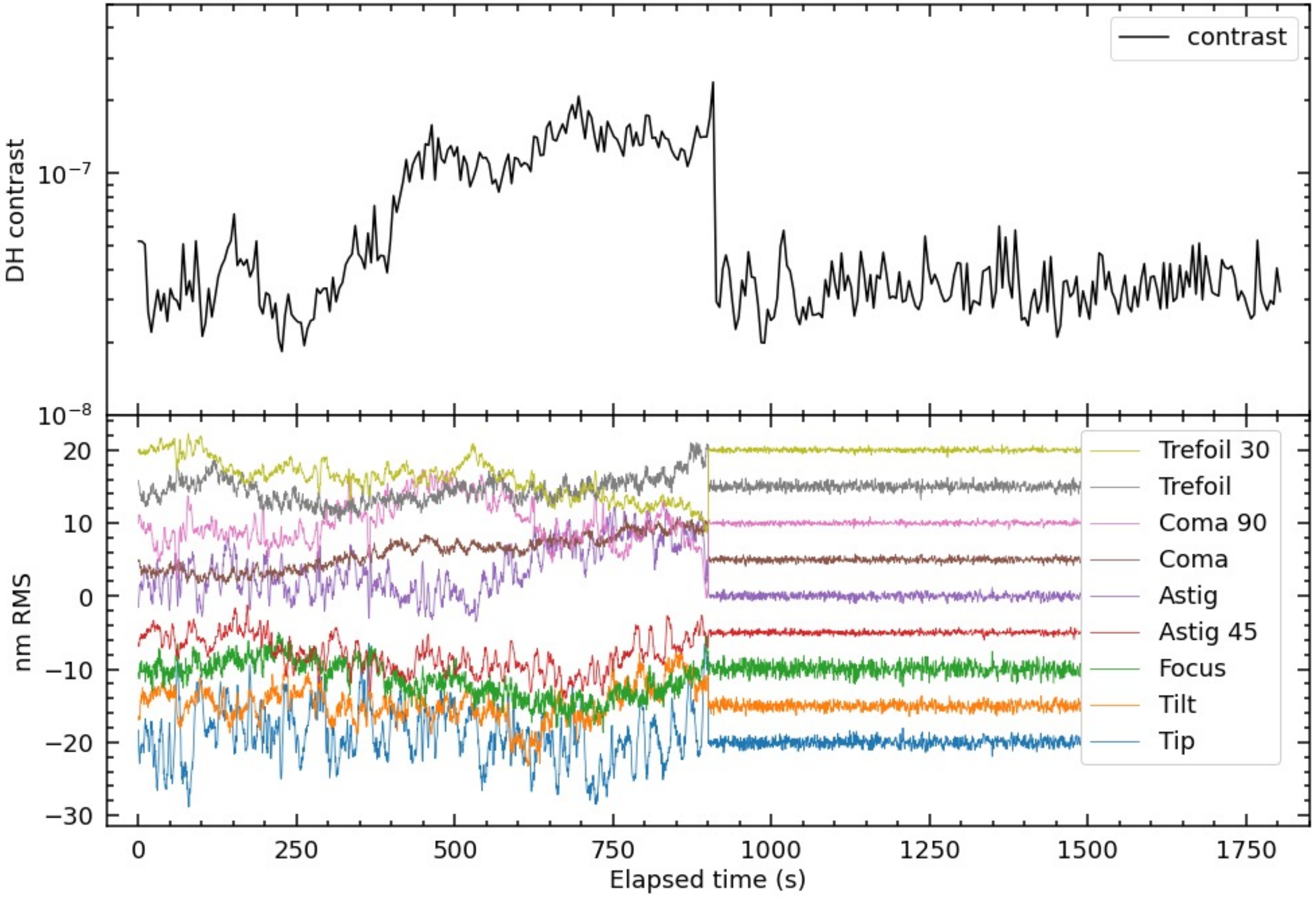


Dube et al. (in prep.)

Stabilize the contrast with LOWFS and other control loops

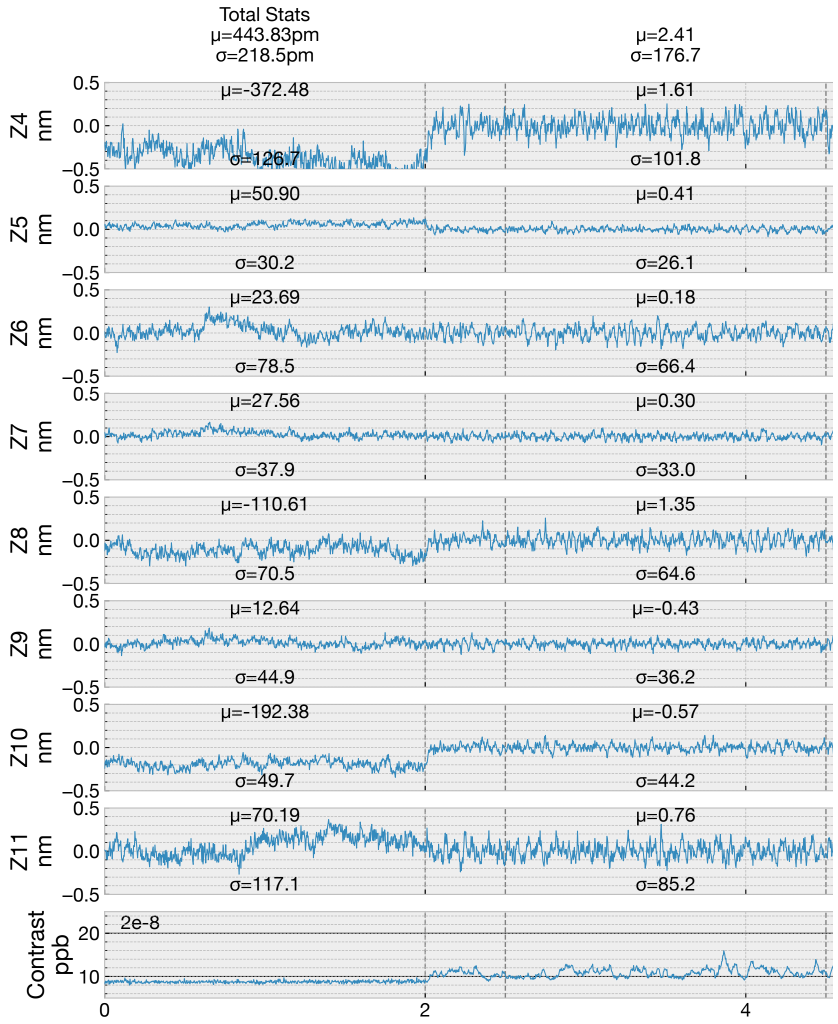


Dube et al. (in prep.)

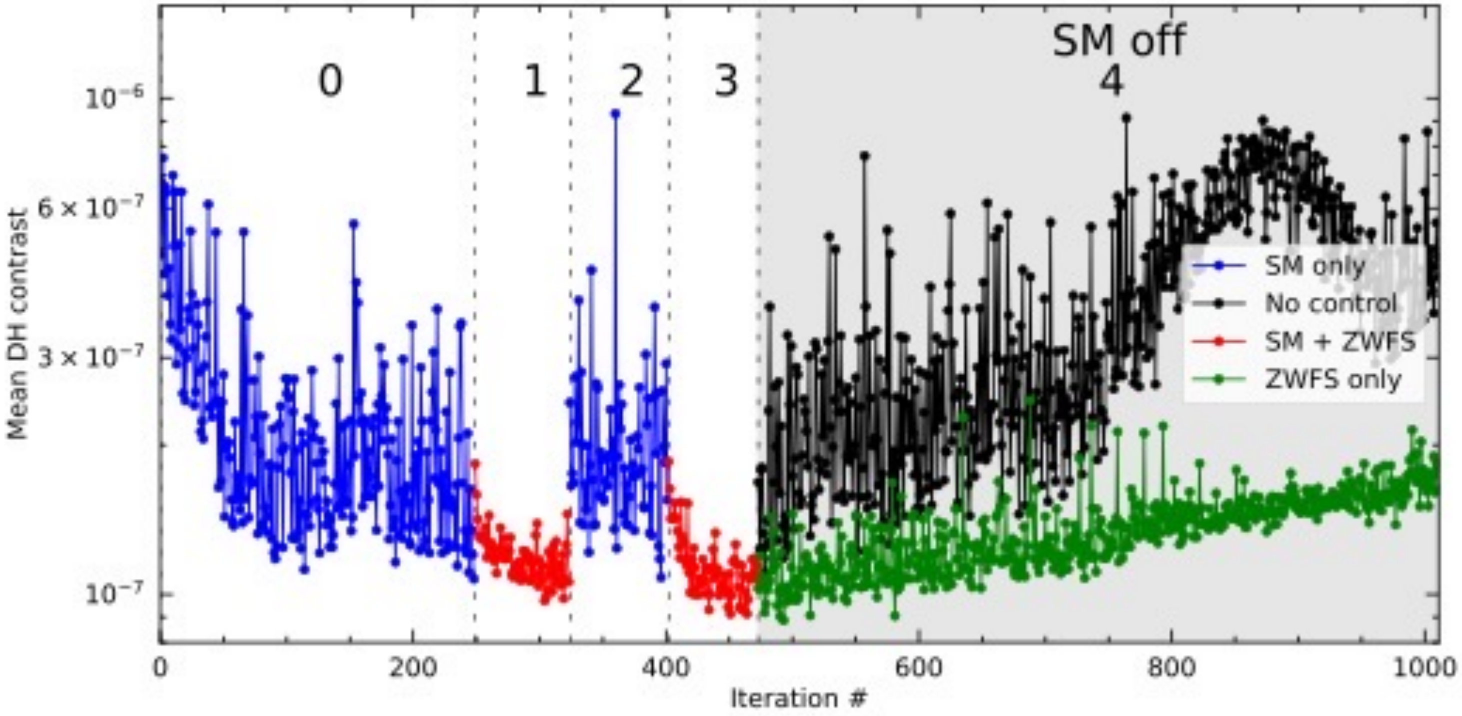


Pourcelot et al. 2023

Stabilize the contrast with LOWFS and other control loops

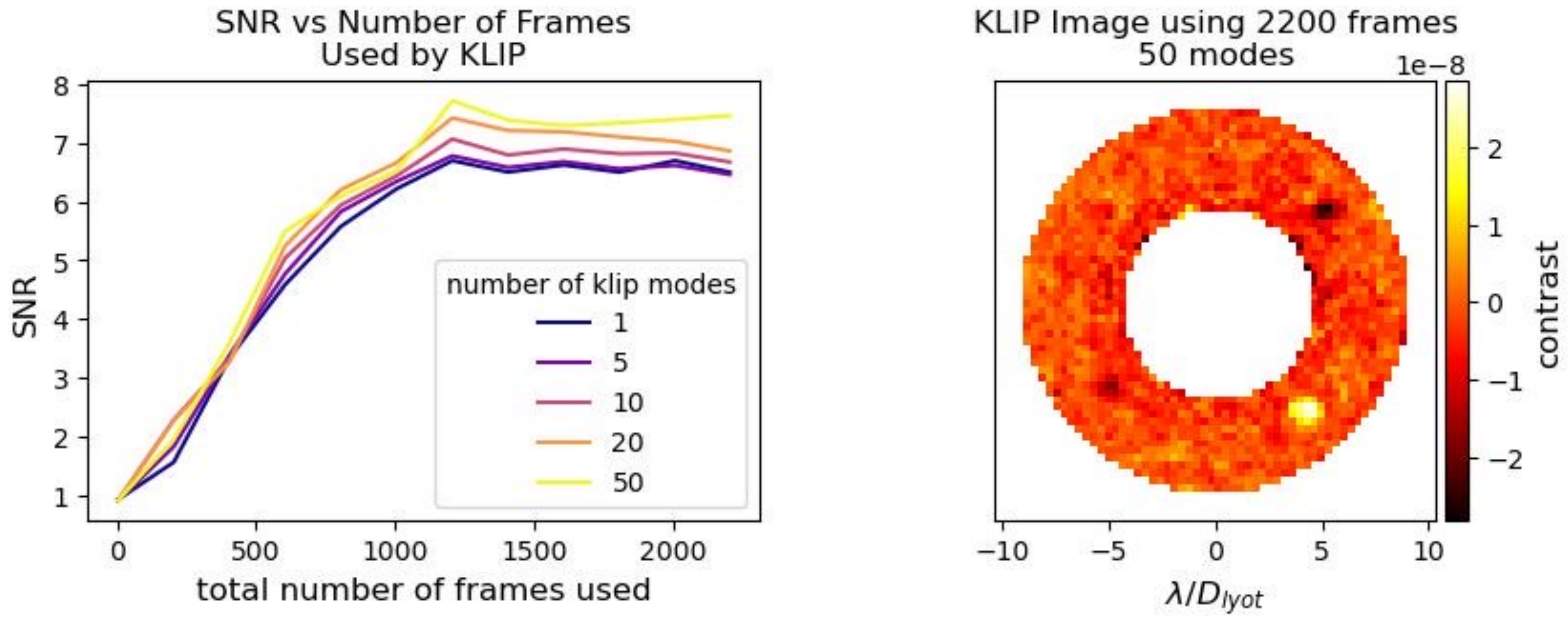


Dube et al. (in prep.)



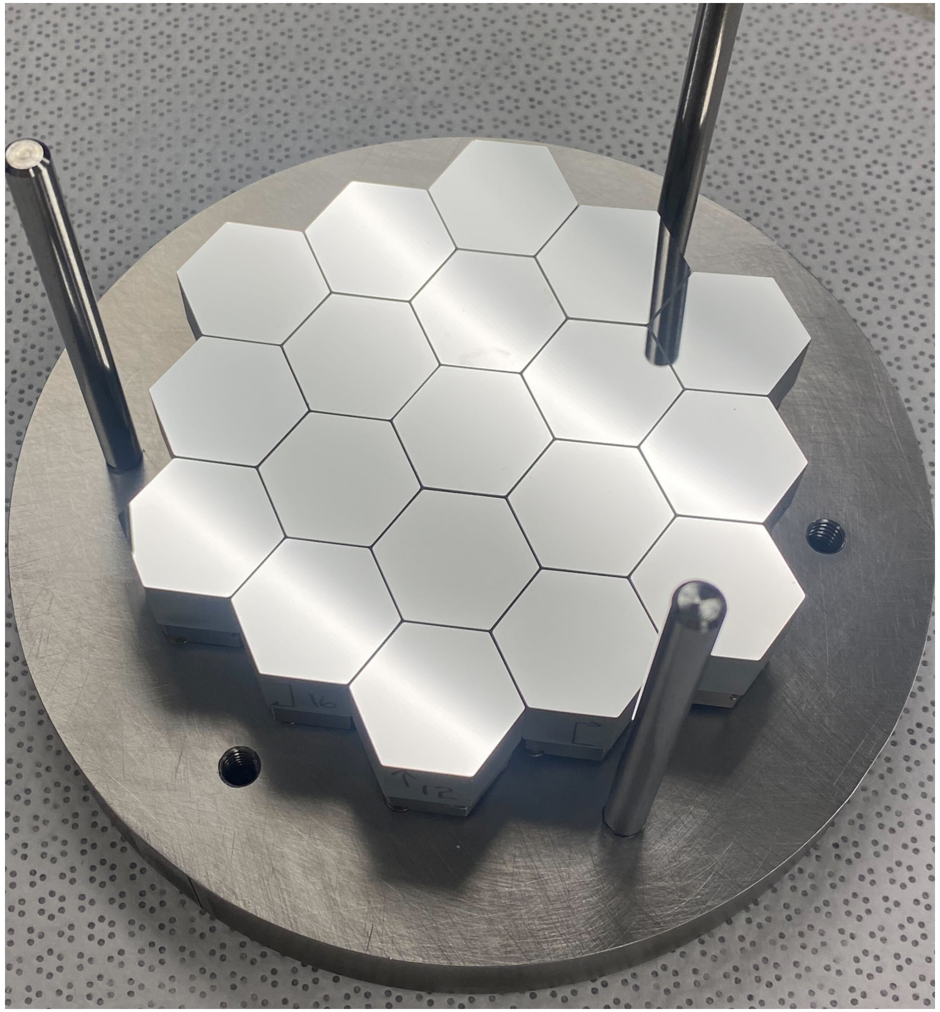
Pourcelot et al. 2023

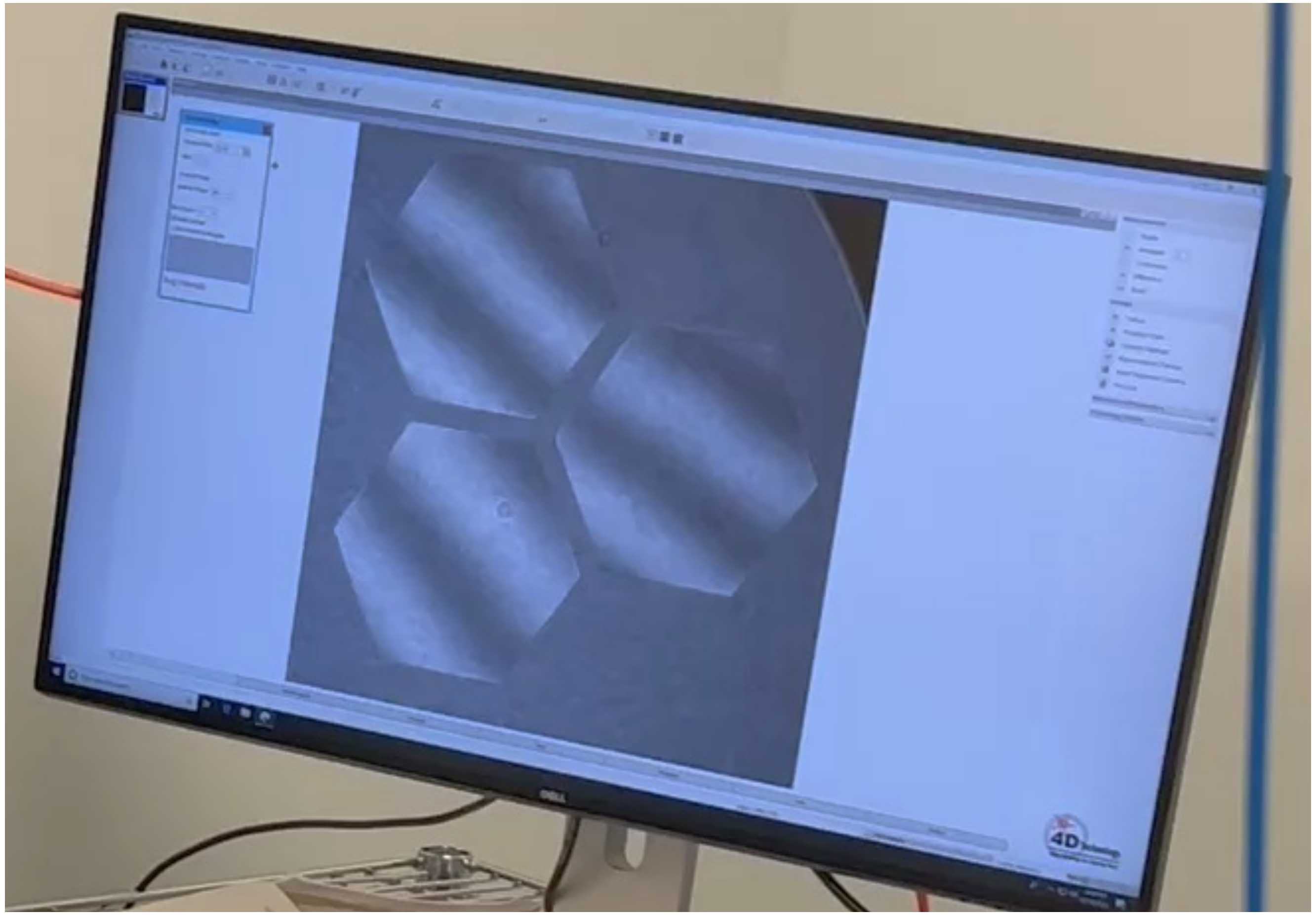
Perform data reduction on testbed data



Redmond et al. (in prep.)

Improved segmented telescope simulators





Latest 19 segment F/4 parabolic prototype (primary mirror for ASSIST funded for vacuum tests)

Overall State of Affairs

- HWO-required combination of contrast, bandwidth, IWA (and OWA) not yet demonstrated
  - Current best performance is 4×10^{-10} at > $3\lambda/D$ (10% BW) or > $5\lambda/D$ (20% BW) with ***classical Lyot Coronagraph on clear aperture***

- Current best contrast performance is on clear apertures. Worsens when using:
  - Coronagraph with smaller IWA, higher throughput and better resilience to low-order aberrations (e.g. VVC4)
  - Segmented aperture
  - Centrally obscured aperture, whether monolithic (CGI) or segmented (PIAACMC)

- Sequential observations or parallel coronagraph channels required to cover large spectral BW (and possibly both polars)

- All lab experiments are visible. High contrast UV coronagraphy likely more challenging (throughput and contrast issues)

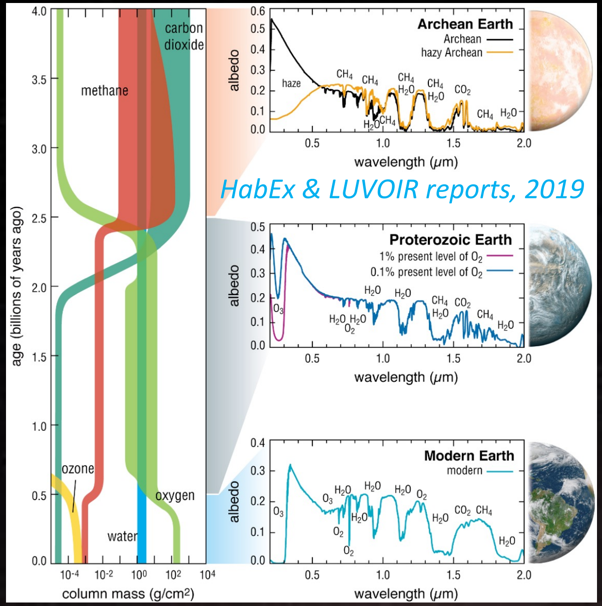
Some Near-Term Priorities for Improving Coronagraphs Technical Readiness toward HWO and Informing Upcoming Trades

- Push in-vacuum ***static*** contrast tests of simple Lyot coronagraphs on clear apertures to
  - Characterize and improve testbed environment ultimate limits using the simplest possible case
- Push in-vacuum ***static*** contrast tests of advanced coronagraphs (smaller IWA, better throughput and resilience to aberrations) on:
  - Clear apertures (diagnosis)
  - Segmented apertures (HWO baseline)
- Push in-vacuum ***dynamic*** contrast tests in the presence of induced perturbations
  - Without correction: validate theoretical contrast dependence to aberrations for different coronagraphs
  - With correction: test various WFSC systems for DH optimization, DH maintenance, and post-processing
- Key Technical Investments applicable to 3 points above: see Garreth Ruane's talk tomorrow
- Focus and sustain community efforts on 1-2 nominal apertures, with "bounding" WF stability cases ("the CGI effect")
  - Balance future efforts on established coronagraphs while testing smart new ideas (CDS activity, Belikov and Stark)
- Conduct optical simulations of UV coronagraphic performance and science yield with
  - Realistic end-to-end throughput from UV coronagraph beam train. Polarization cross-talk effects

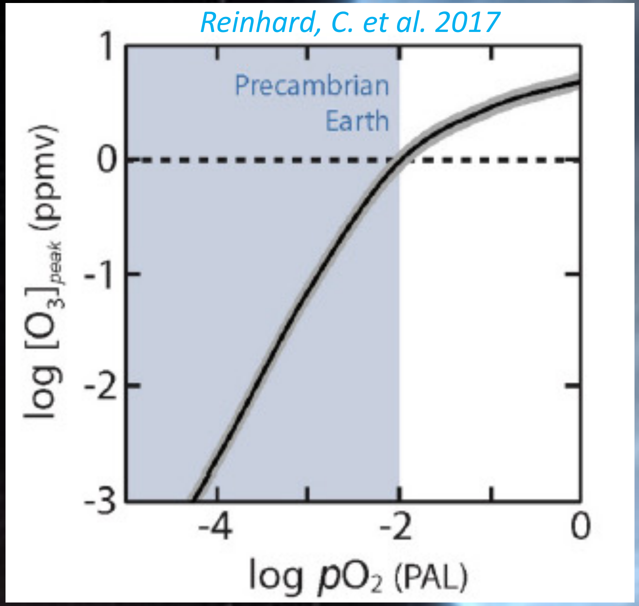
Back-up

Benefits and Challenges of UV Coronagraphy

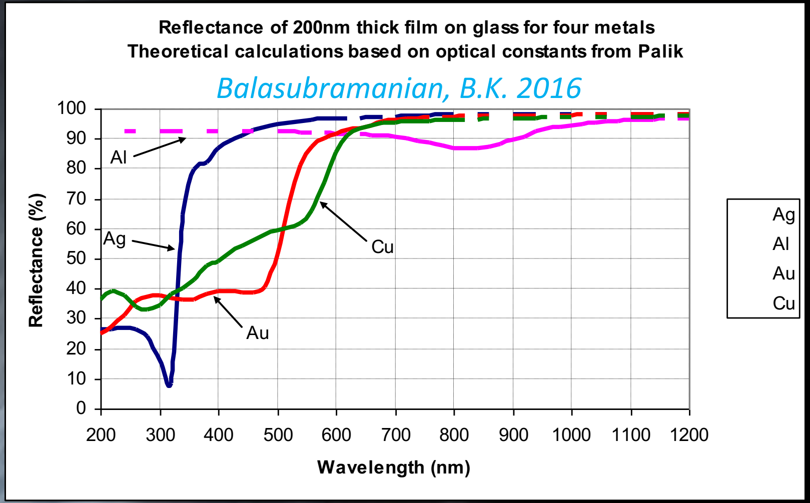
- "The most sensitive indicator of atmospheric O_2 is the UV O_3 (Hartley-Huggins) band, which would have created a measurable impact on Earth's spectrum for ~50% of its history to date, versus ~10% for O2". *Schwieterman, E. et al. 2019*



HabEx & LUVOIR reports, 2019



Reinhard, C. et al. 2017



Balasubramanian, B.K. 2016

However

- Planets are much fainter in the UV
- UV Throughput is low UV reflectivity per surface is no better than 92% (for bare Al) and coronagraphs need many optics (15 on CGI)
- WFC reqts scale as λ
- Birefringence is generally higher in the UV, inducing incoherent "polarization aberrations"