Coronagraphy
UVSTIG

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NHFP
NASA Hubble Fellowship Program

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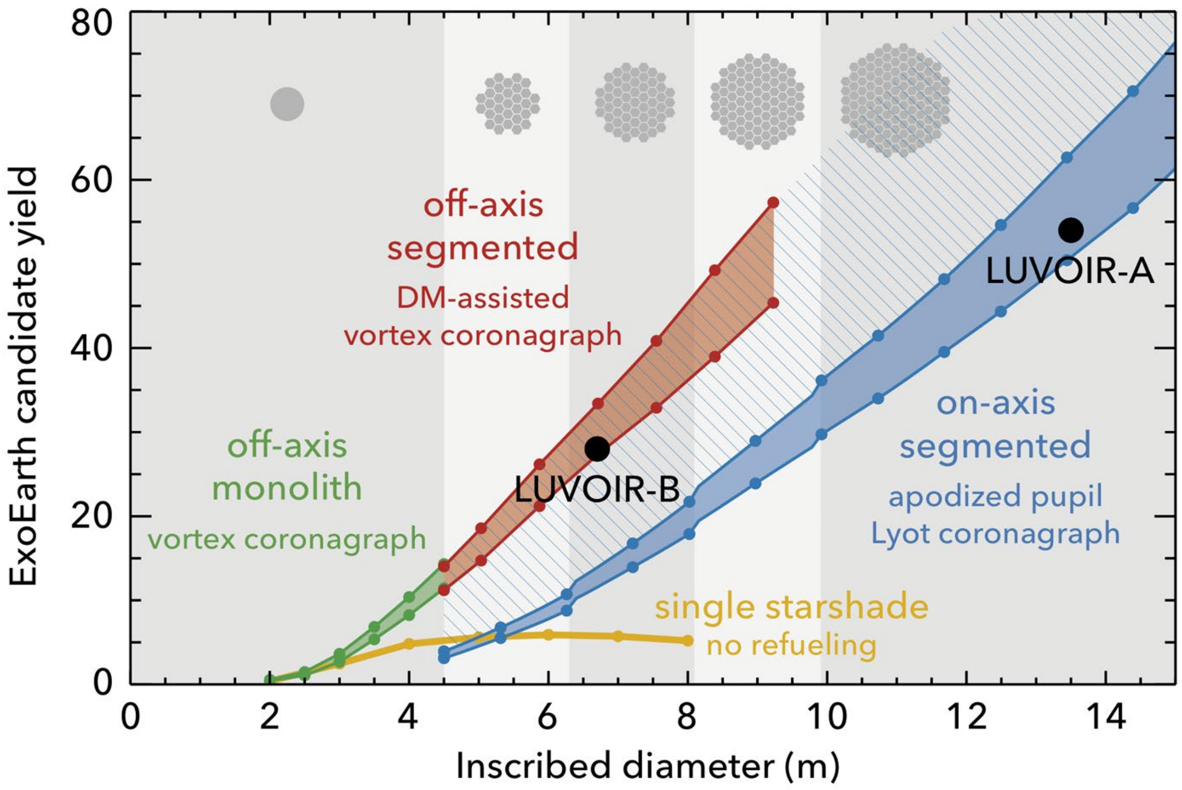
NASA

Exoplanet yield



LUVOIR-A report (2019), Fig. 1-7

HWO Starlight Suppression System **MUSTs**

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

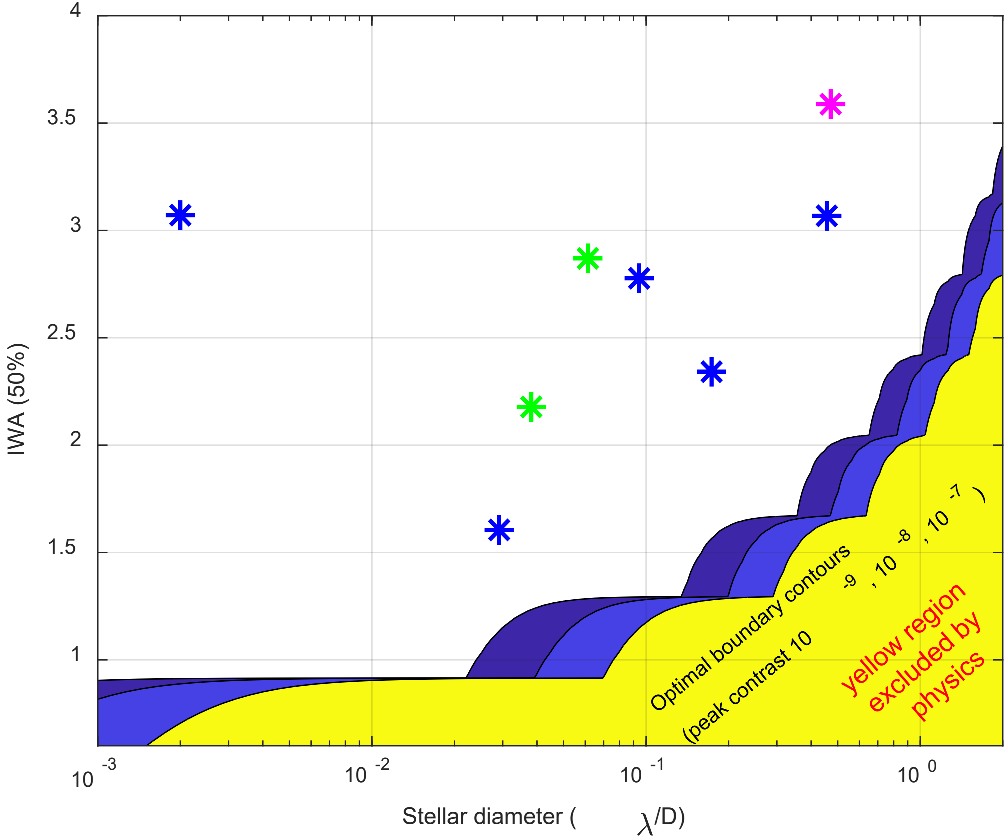
- Must reach a minimum point source detection limit **Δmag > 25 at < 70 mas** from FGK star
  - That's **2.1 λ/D** for λ=950 nm and D= 6m (4 λ/D at 500nm)
  - Requires raw contrast of a **few 10^{-10}** there, with "high" throughput & bandwidth >~ 20%.

- Must spectrally characterize detected exo-Earth candidates over a broad spectral range to
  - Search for Rayleigh scattering, water vapor and oxygen → **500-950 nm**
  - Search for low levels of oxygen → down to 250-300 nm
  - Search for methane and carbon dioxide → up to 1700 nm

Terminology and design metrics

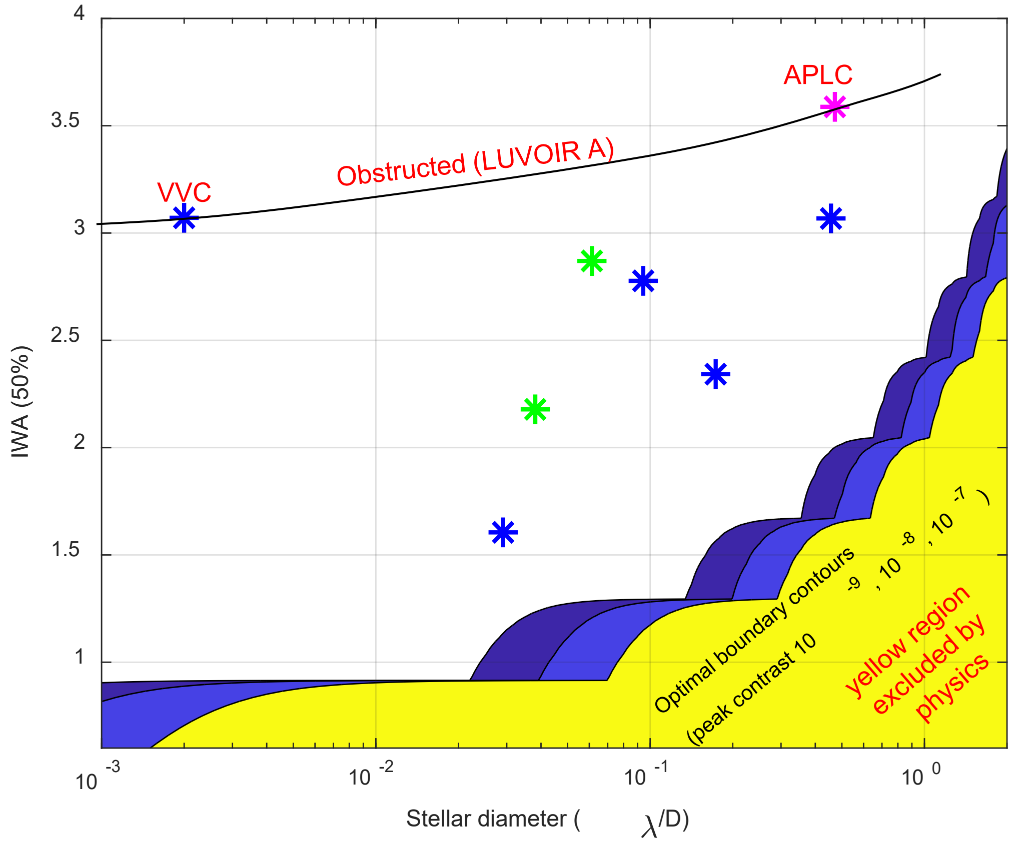
- Raw **contrast**
- Planet **throughput**
- **Inner** working angle
- **Field** of view
- Spectral **bandwidth**
- Robustness to **stellar diameter**
- Robustness to **low-order** aberrations
- Optical **complexity**
- Integration with **wavefront sensing**

Coronagraph performance



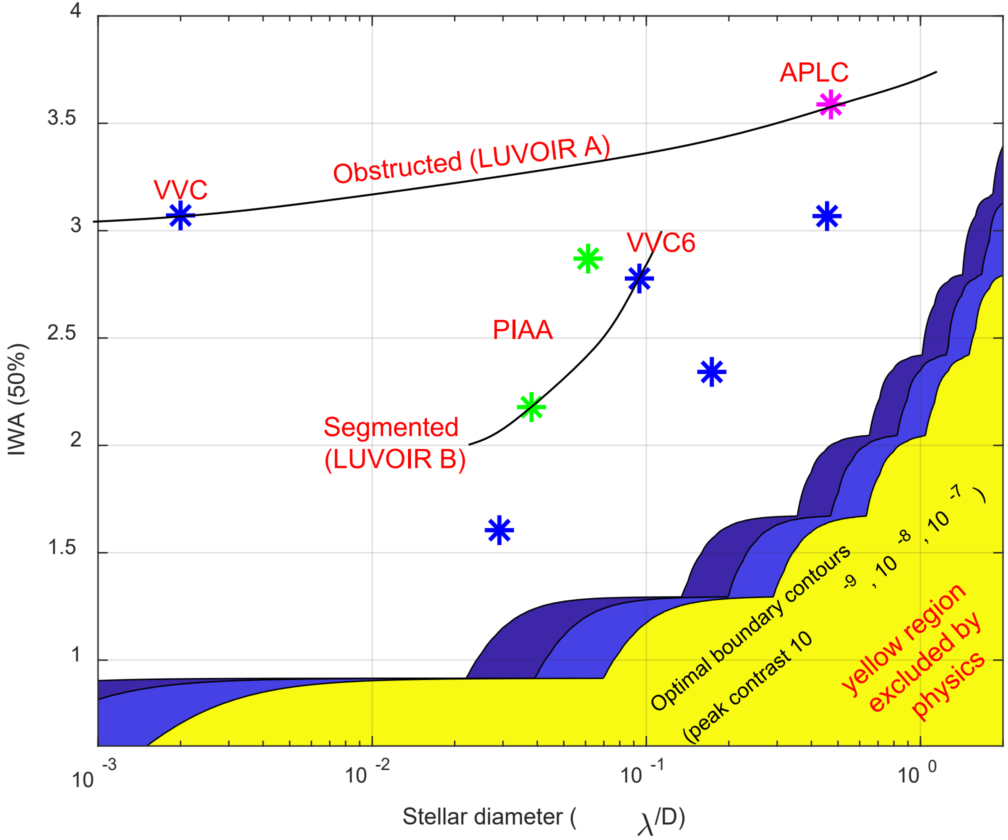
Belikov et al. 2019

Coronagraph performance



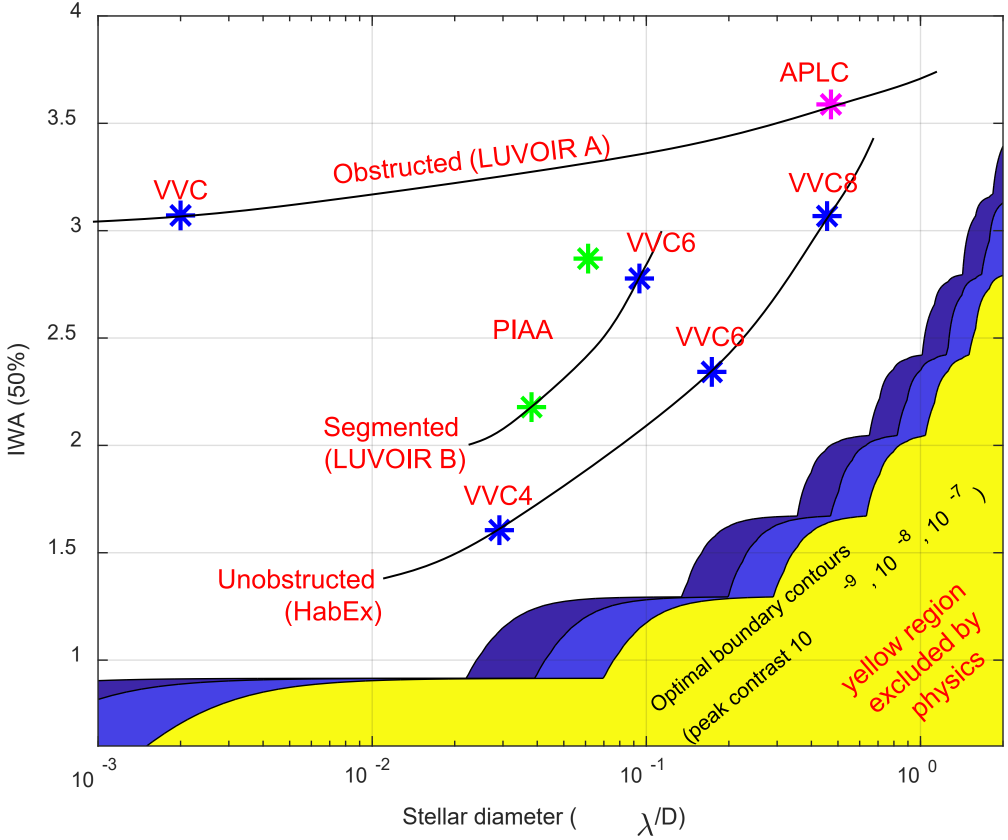
Belikov et al. 2019

Coronagraph performance



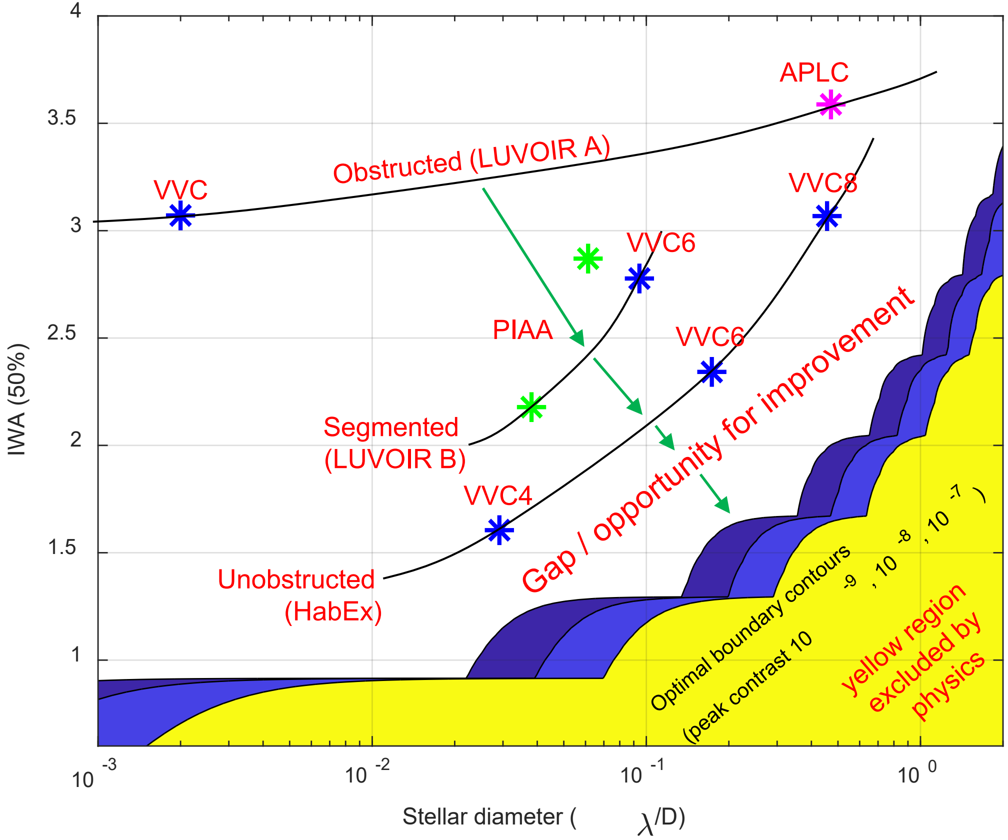
Belikov et al. 2019

Coronagraph performance



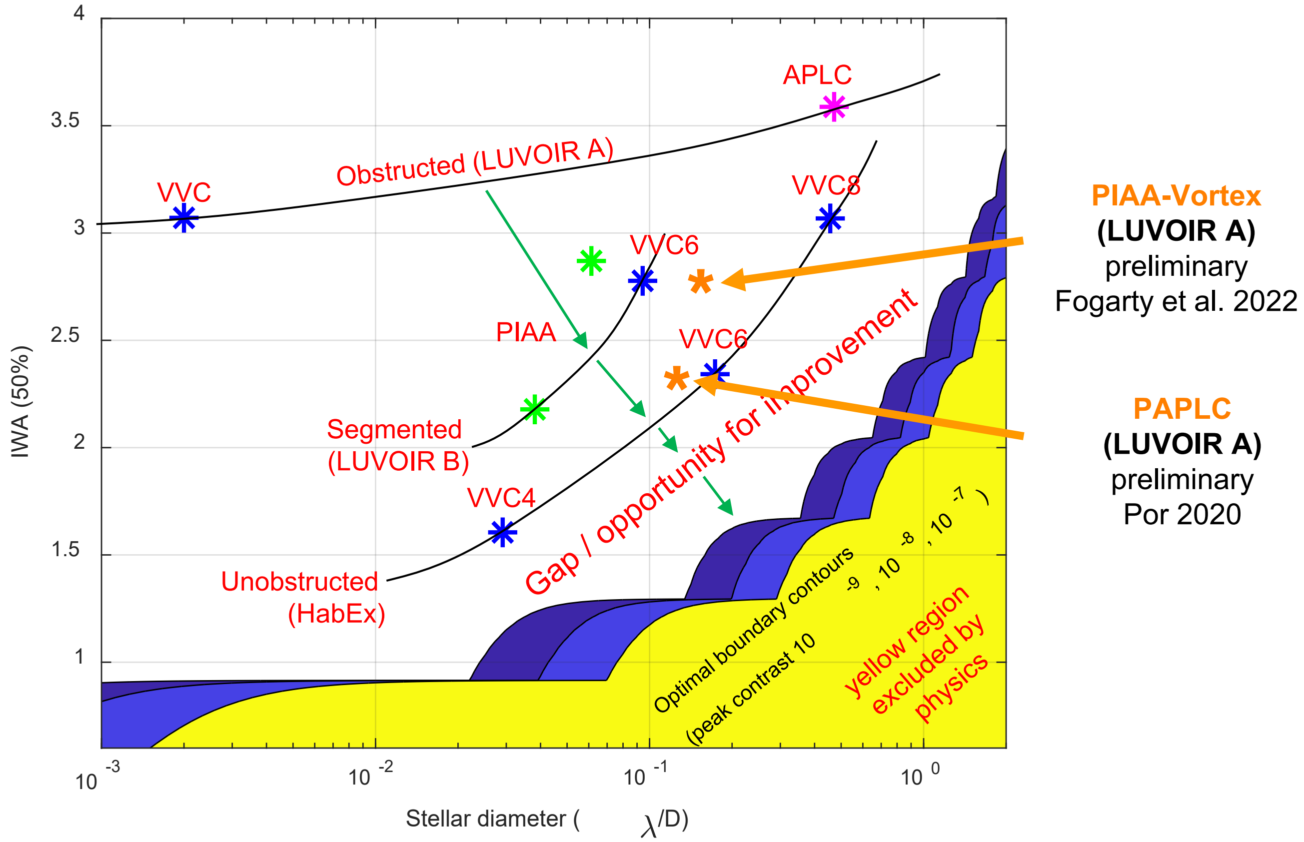
Belikov et al. 2019

Coronagraph performance



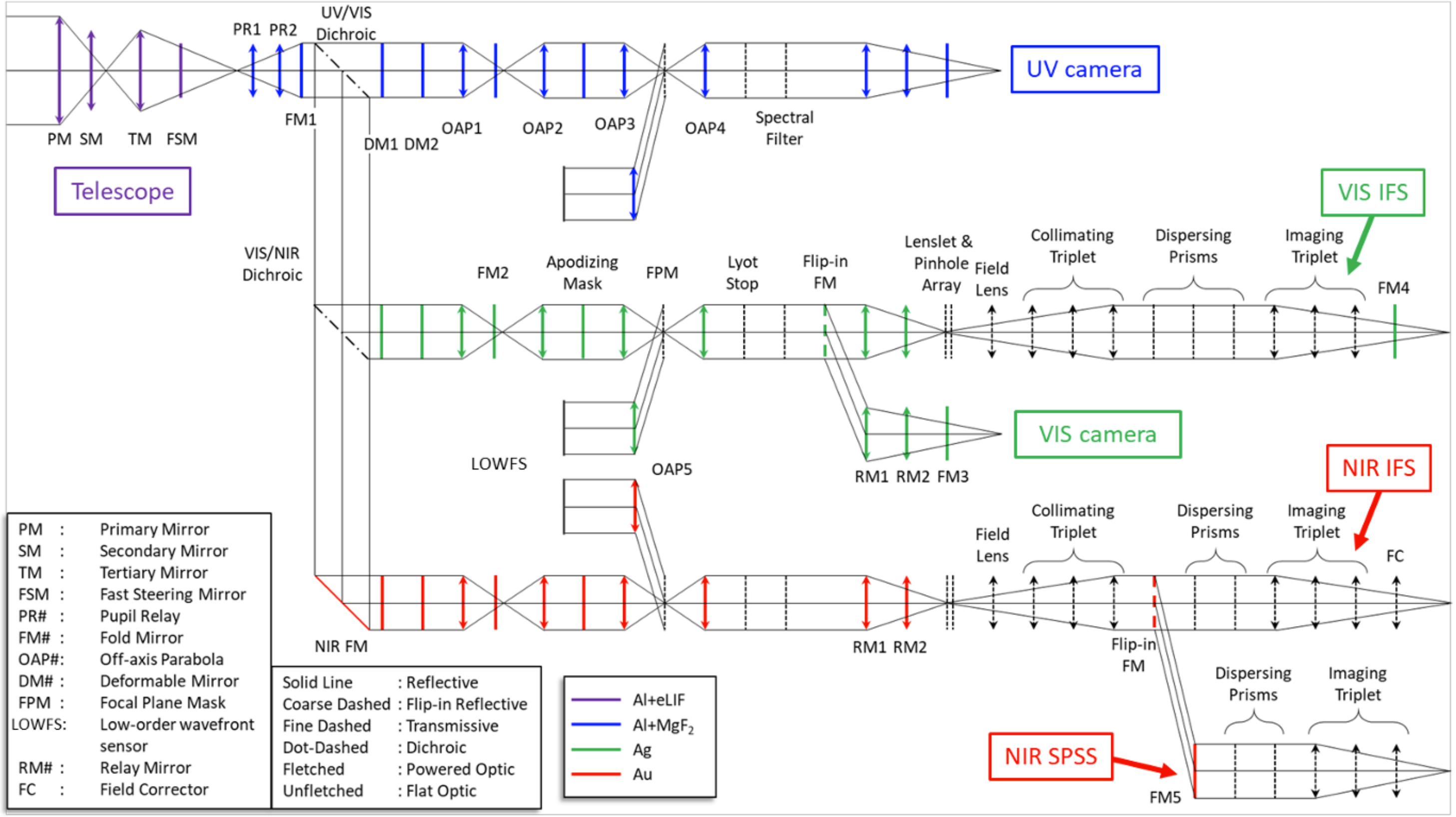
Belikov et al. 2019

Coronagraph performance



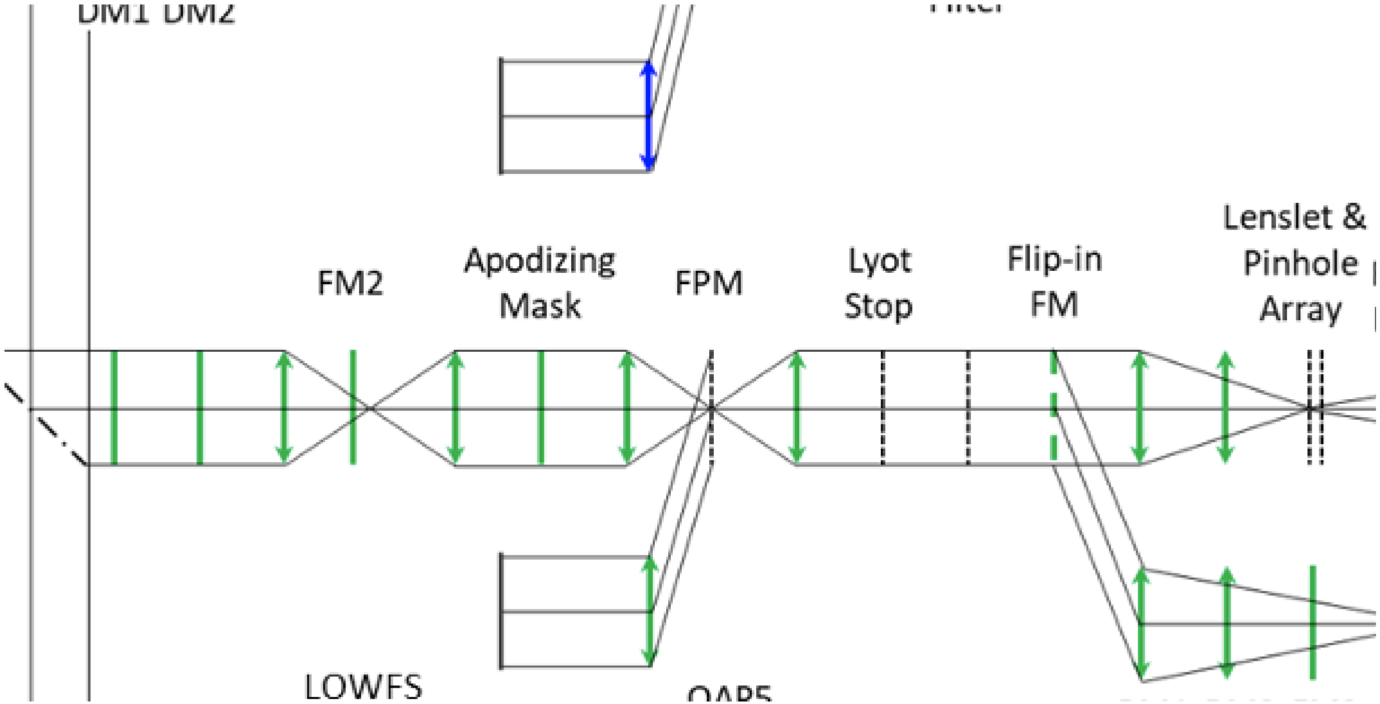
Belikov et al. 2019

Coronagraphic instrument layout



Corsetti et al. 2020

Coronagraphic instrument layout

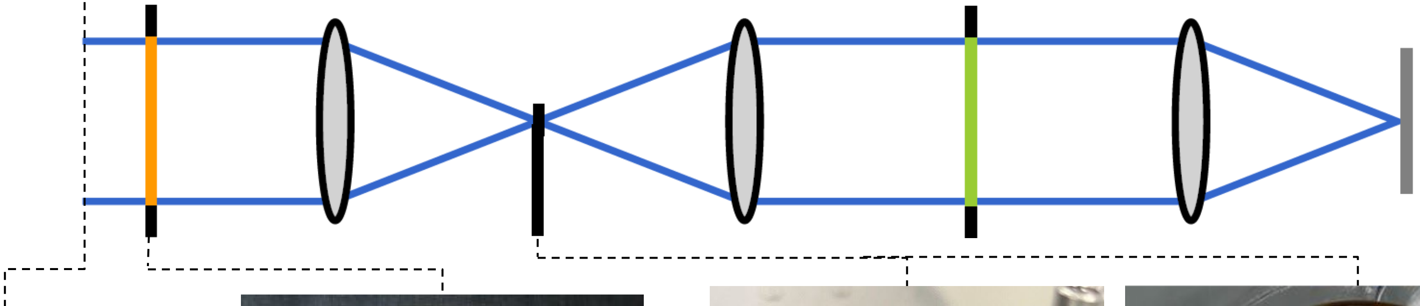


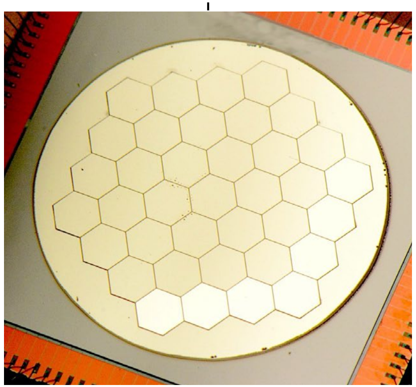
Corsetti et al. 2020

Coronagraphs current lab performance: segmented apertures

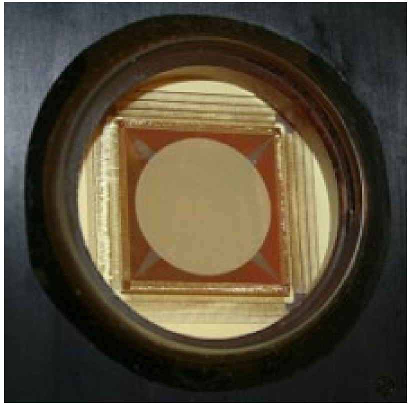
Phase
Apodized
Pupil
Lyot
Coronagraph

PAPLC coronagraph

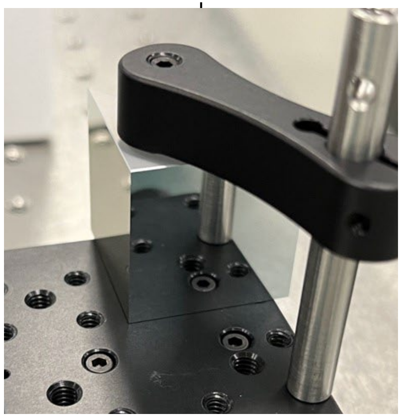




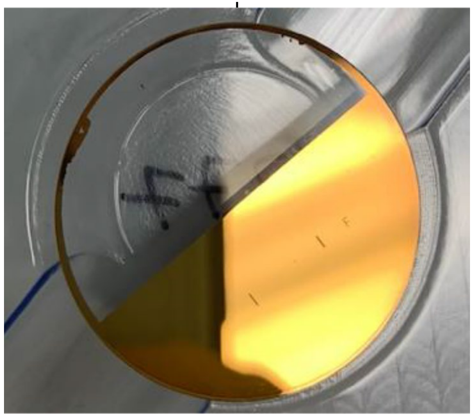
Segmented pupil
(DM by IrisAO)



Boston Micromachines
(2x 952 actuators)



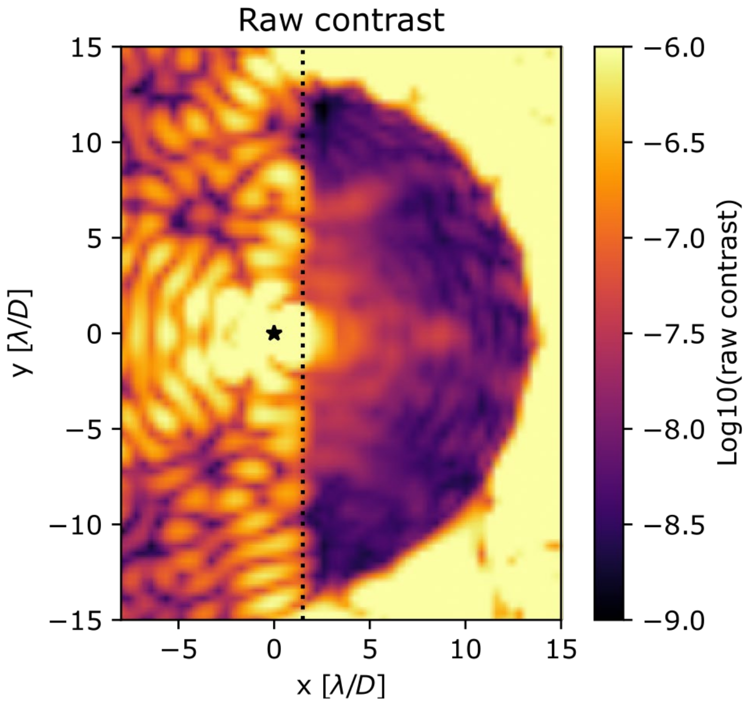
Thorlabs



University of Arizona
Nano Fabrication Center

Por et al. in prep.

PAPLC coronagraph



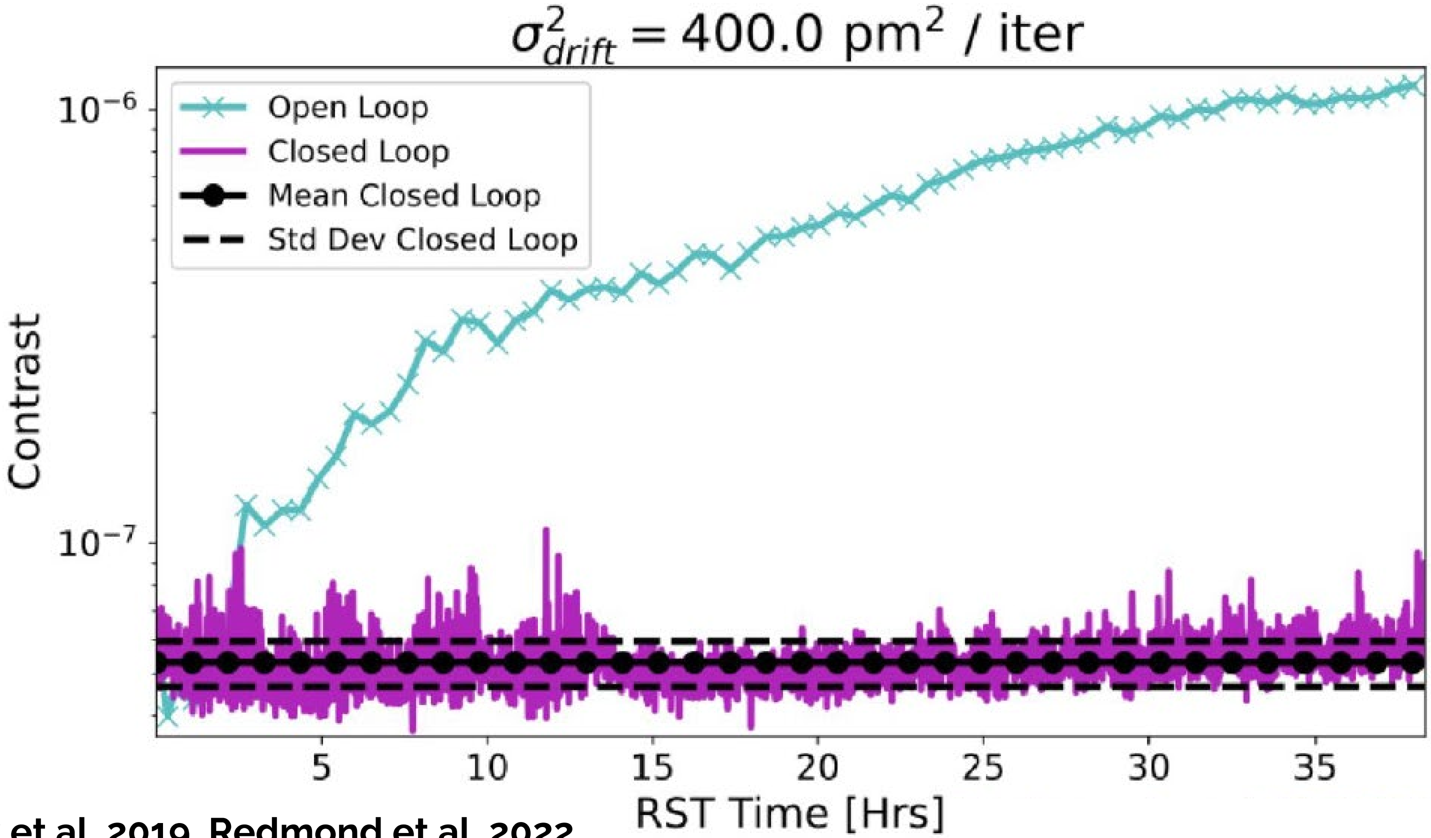
- Monochromatic at 638nm
- Unpolarized light
- Unobscured segmented aperture

↓

- 2×10^{-8} from 2 – 13 λ/D
- 8×10^{-9} from 4 – 13 λ/D

Por et al. in prep.

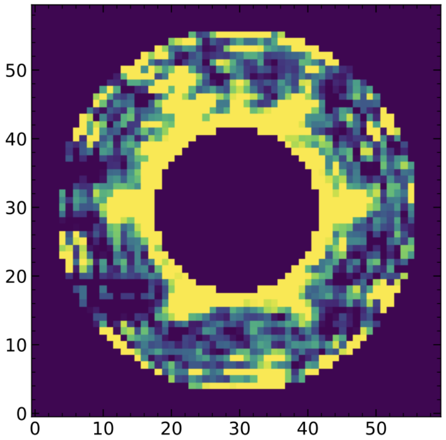
Maintaining the contrast



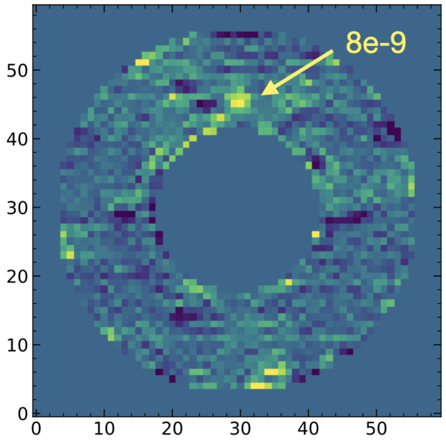
Pogorelyuk et al. 2019, Redmond et al. 2022

Differential imaging on HiCAT

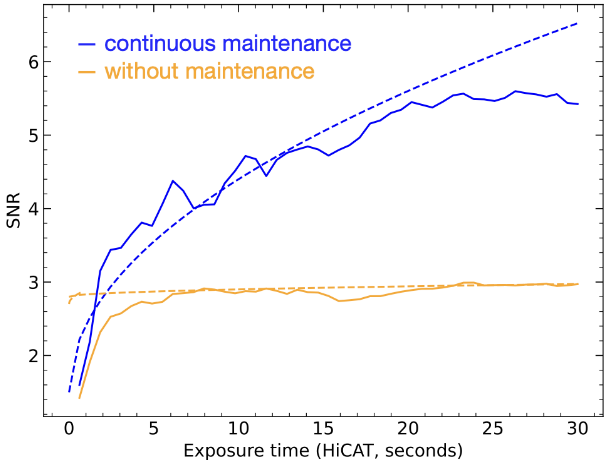
HiCAT Dark Hole long exposure



Differential imaging with reference from independent run



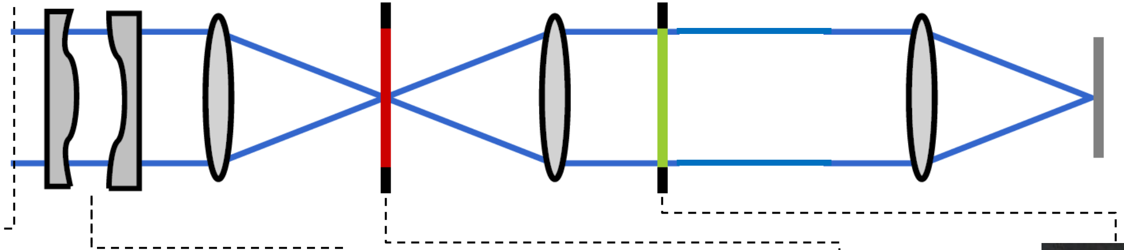
Synthetic Planet SNR vs. integration time

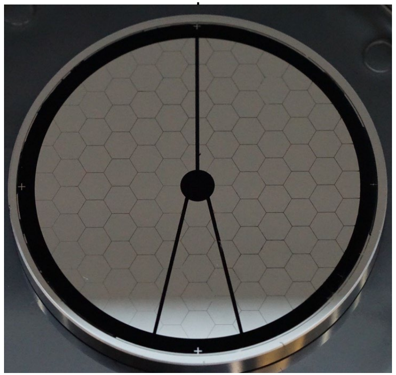


Data acquisition: Por; data processing: Pueyo

PIAACMC coronagraph

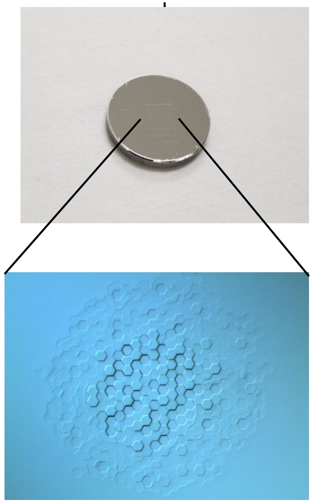
Phase
Induced
Amplitude
Apodization
Complex
Mask
Coronagraph





John Hagopian &
Eduardo Bendek

WFIRST PIAA Set assembly
(image by Camilo Mejia)



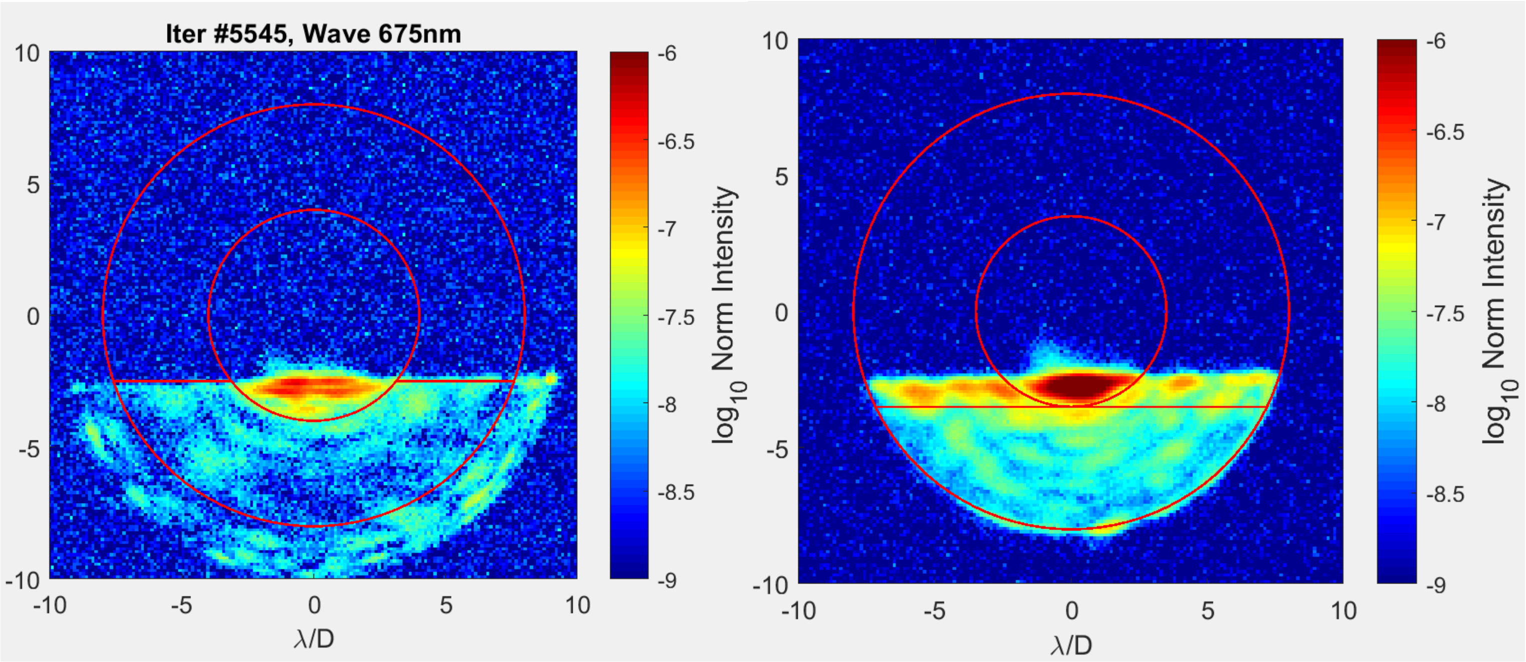
Dan Wilson

John Hagopian &
Eduardo Bendek

Belikov, Sirbu, Marx, et al. 2021

PIAACMC coronagraph

Monochromatic, 9×10^{-9}, 4 – 8 λ /D   10% broadband, 1.8×10^{-8}, 3.5 – 8 λ /D



Belikov, Sirbu, Marx, et al. 2021, vacuum testbed at HCIT operated by David Marx

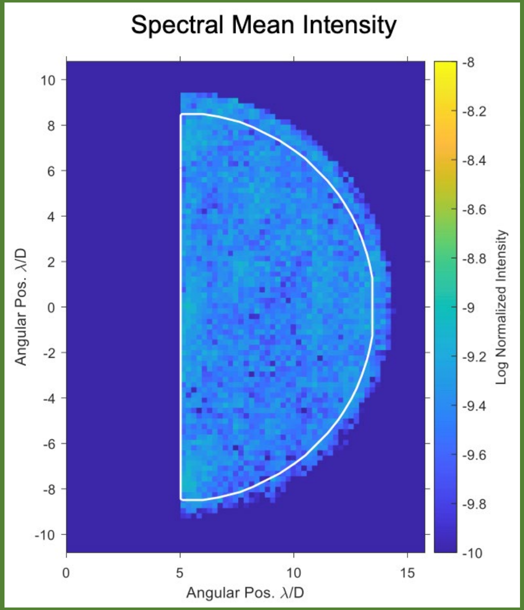
Coronagraphs current lab performance: monolithic apertures

Coronagraphs Current Lab Performance: unobscured aperture

Unobscured circular pupil with simple Lyot Coronagraph in vacuum:

4×10^{-10} contrast (1 polar), JPL HCIT Team – Decadal Survey Testbed (DST)

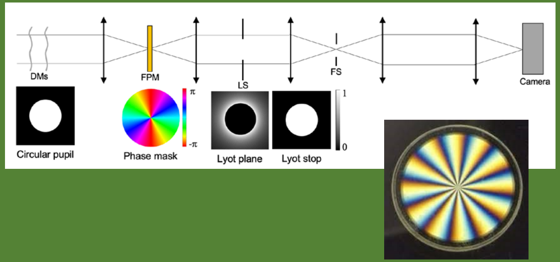
- Over 10% BW, averaging from 3-10 λ/D, 360° DH *(Seo, B.J. et al SPIE 2019)*
- Over 20% BW, from 5.5-13 λ/D, one-sided DH

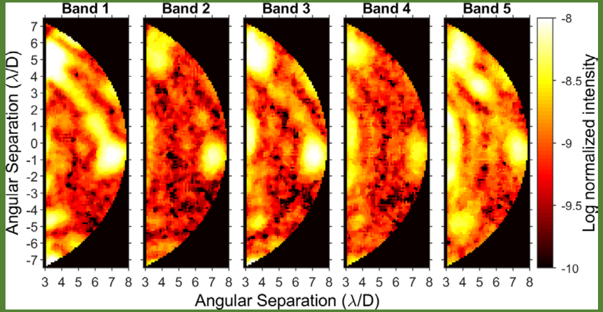


Unobscured circular pupil with Vector Vortex (VVC6) Coronagraph in vacuum:

JPL HCIT Team DST *(Ruane, G. et al. SPIE 2022)*:

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





Coronagraph Current Performance in the Lab (vs 2020)

Coronagraph Type	Classical Lyot	Vector Vortex charge 6	Phase Apodized Pupil Lyot Coronagraph	Phase Induced Amplitude Apodization Coronagraph
Aperture Type	**Circular unobscured (= off-axis Monolith)**		**Off-axis Segmented**	**Circular on-axis segmented**
Deformable Mirrors	2 AOX (each 48 x 48)	2 AOX (each 48 x 48)	2 BMC MEMs (each 952 actus)	1 BMC MEMs (952 actus)
Separation Range	5-13.5 λ/D (vs 3-10 l/D)	3-8 λ/D	2 – 13 λ/D	3.5 – 8 λ/D
Dark Hole Azimuthal Extent (deg)	180 (vs 360)	180	180	180
Mean Raw Contrast over Sep. Range	4×10^{-10} (idem)	5.9×10^{-9} (10^{-8})	2×10^{-8}	1.8×10^{-8}
Central wavelength (nm)	550	635	638	650
Spectral bandwidth	20% (10%)	20% (10%)	Monochromatic	10%
Number of polarizations	1	1	2	1
Off-axis Throughput	medium	high	high	high
Sensitivity to low order aberrations	medium	low	medium	medium
Facility	JPL HCIT Testbed	JPL HCIT Testbed	STScI HiCAT Testbed	JPL HCIT Testbed
Vacuum Operation	Y	Y	**N**	Y

Currently demonstrated static contrast performance degrades when moving to coronagraphs with higher throughput and lower sensitivity to aberrations, moving from monolithic to segmented apertures, and from off-axis to on-axis

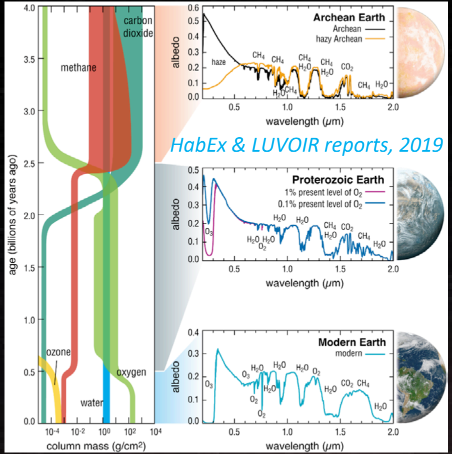
Near Term Priorities for Improving Coronagraph Technical Readiness toward HWO … and Informing Upcoming Trades

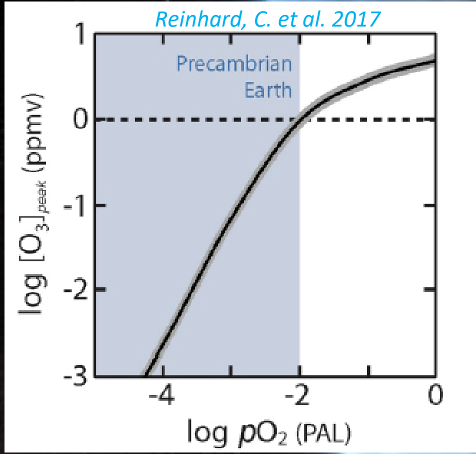
HWO required combination of contrast ($\sim 10^{-10}$), bandwidth (20%) and IWA (2-3 λ/D) not yet demonstrated

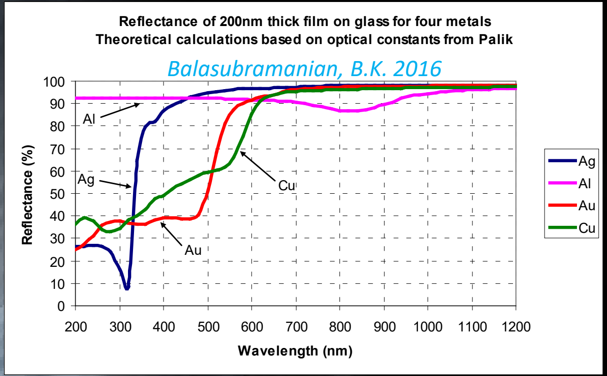
- Push in-vacuum static tests of simple Lyot coronagraphs on clear apertures to
  - Characterize and improve testbed environment ultimate limits using the simplest possible case
- Push in-vacuum static tests of more advanced coronagraphs (smaller IWA, better throughput and resilience to aberrations) on:
  - Clear and Segmented apertures
- Characterize performance in the presence of induced dynamic perturbations
  - Without correction: validate theoretical dependence to aberrations for different coronagraphs
  - With correction: test various WFSC systems to be used for dark hole optimization and maintenance
- Support industry partners in manufacturing high quality masks (e.g. VVC, APLC) and / or further develop in-house capabilities
- Conduct detailed optical simulations of static coronagraphic performance and expected yield in the UV, including realistic throughput losses and polarization effects

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*





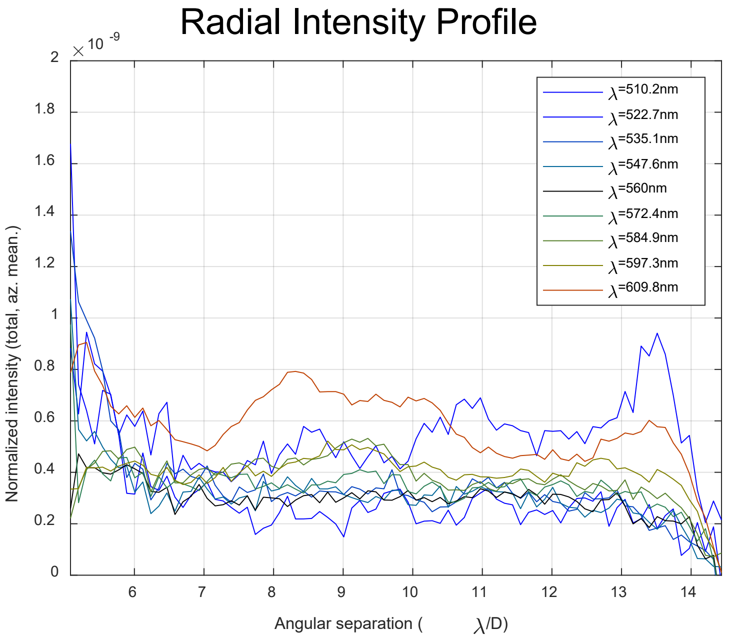


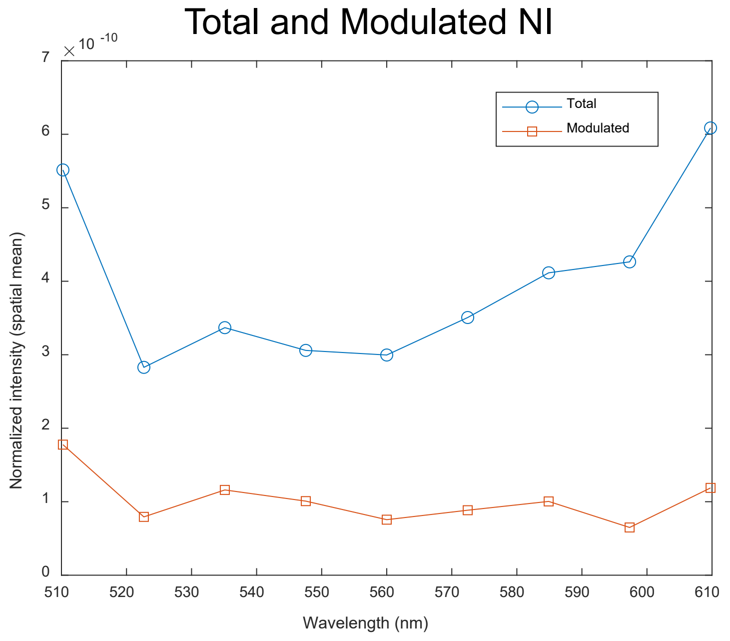
However

- 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"

Backup slides

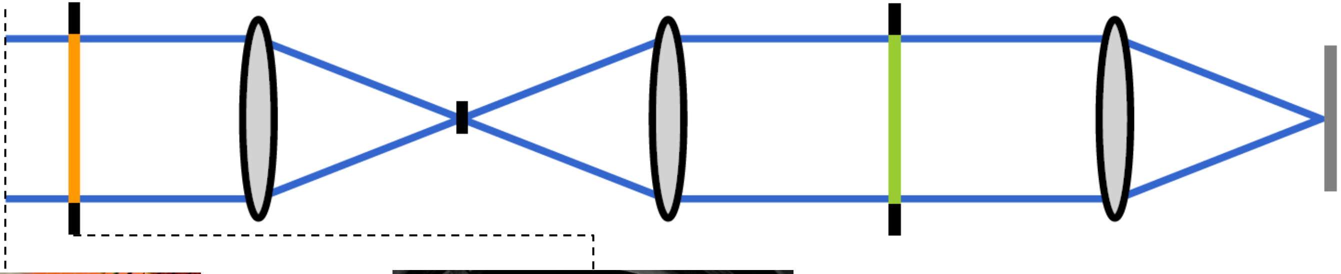
Wide-band contrast on the Decadal Survey Testbed (cont.)

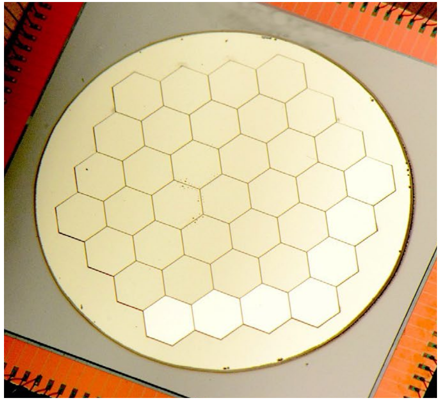




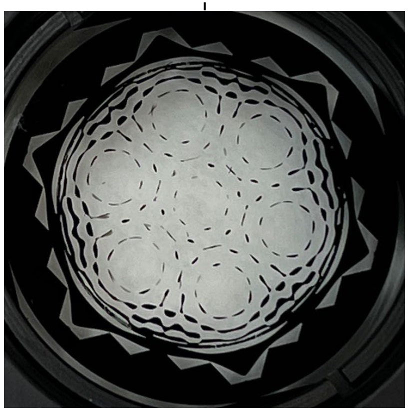
Apodized
Pupil
Lyot
Coronagraph

APLC coronagraph





Segmented pupil
(DM by IrisAO)



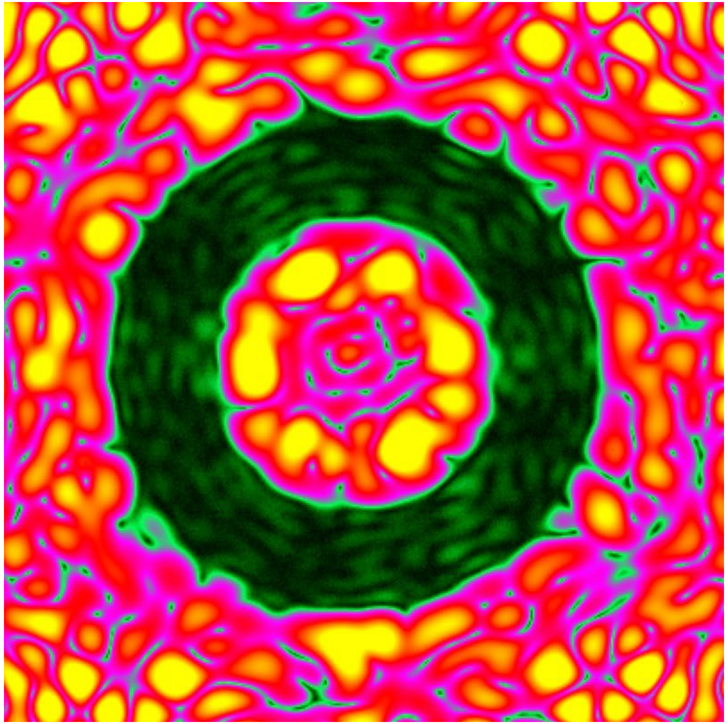
John Hagopian
(patterned carbon nanotubes
on silicon/glass)

Soummer et al. 2022

APLC coronagraph

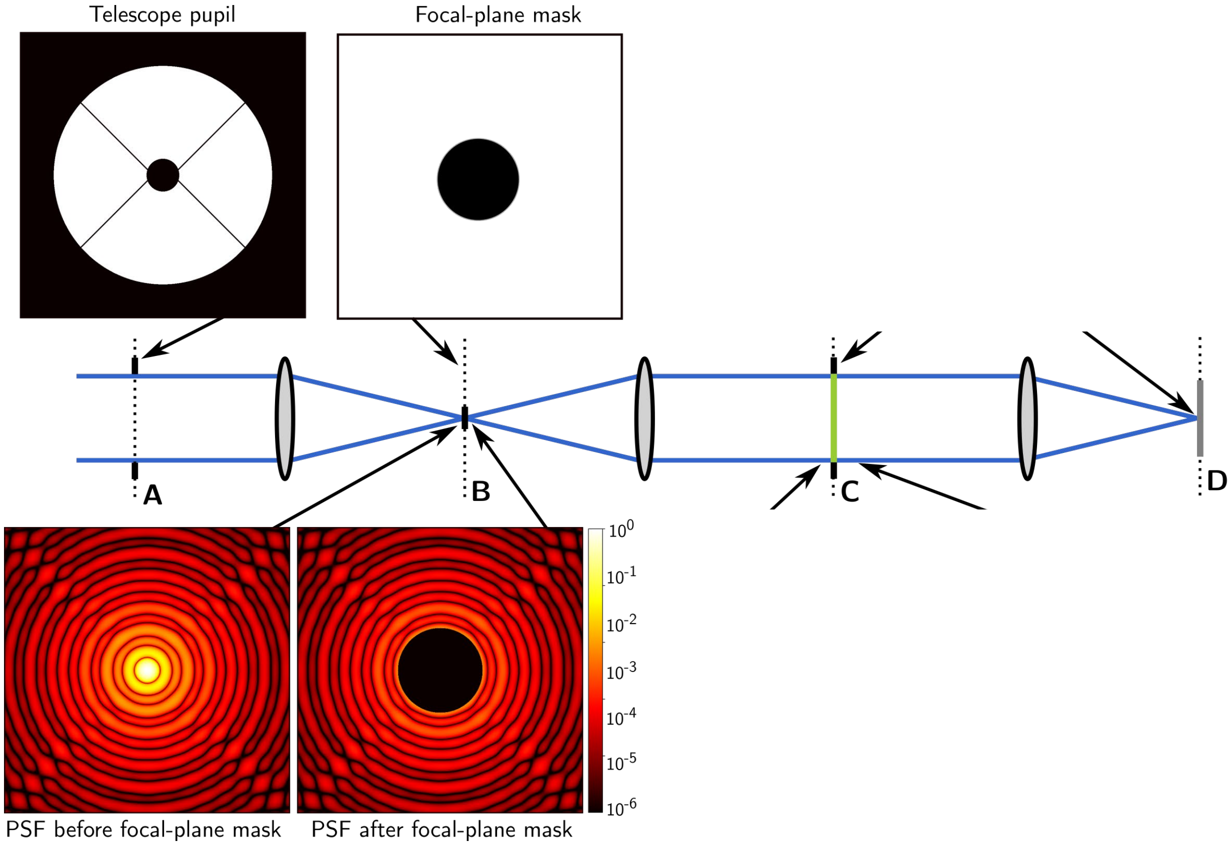
First transmissive APLC.
A very early test.

- Monochromatic at 638nm
- ~6-8×10-8 from 7 – 13 λ/D
- Limited by WFE on apodizer, calibration underway



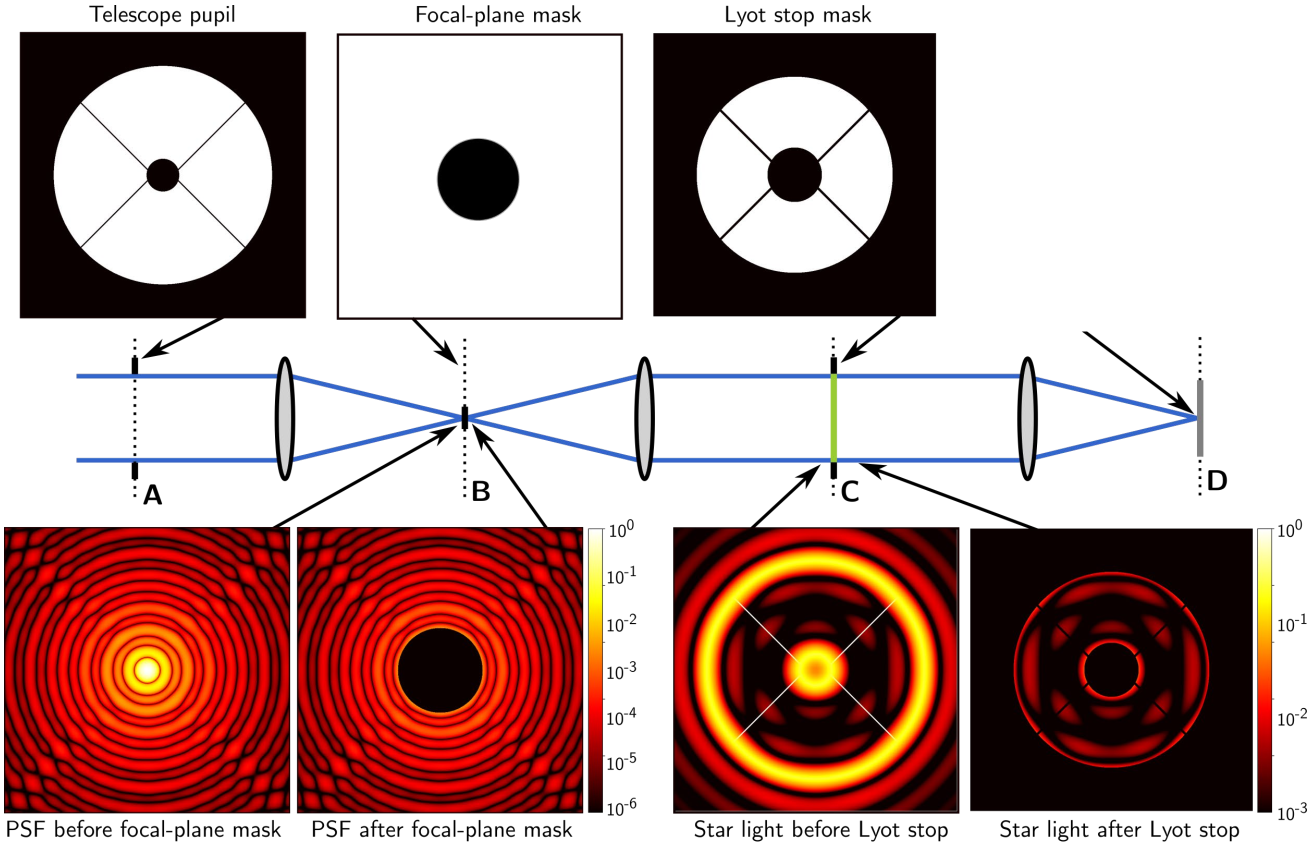
Soummer et al. 2022

Lyot-style coronagraph



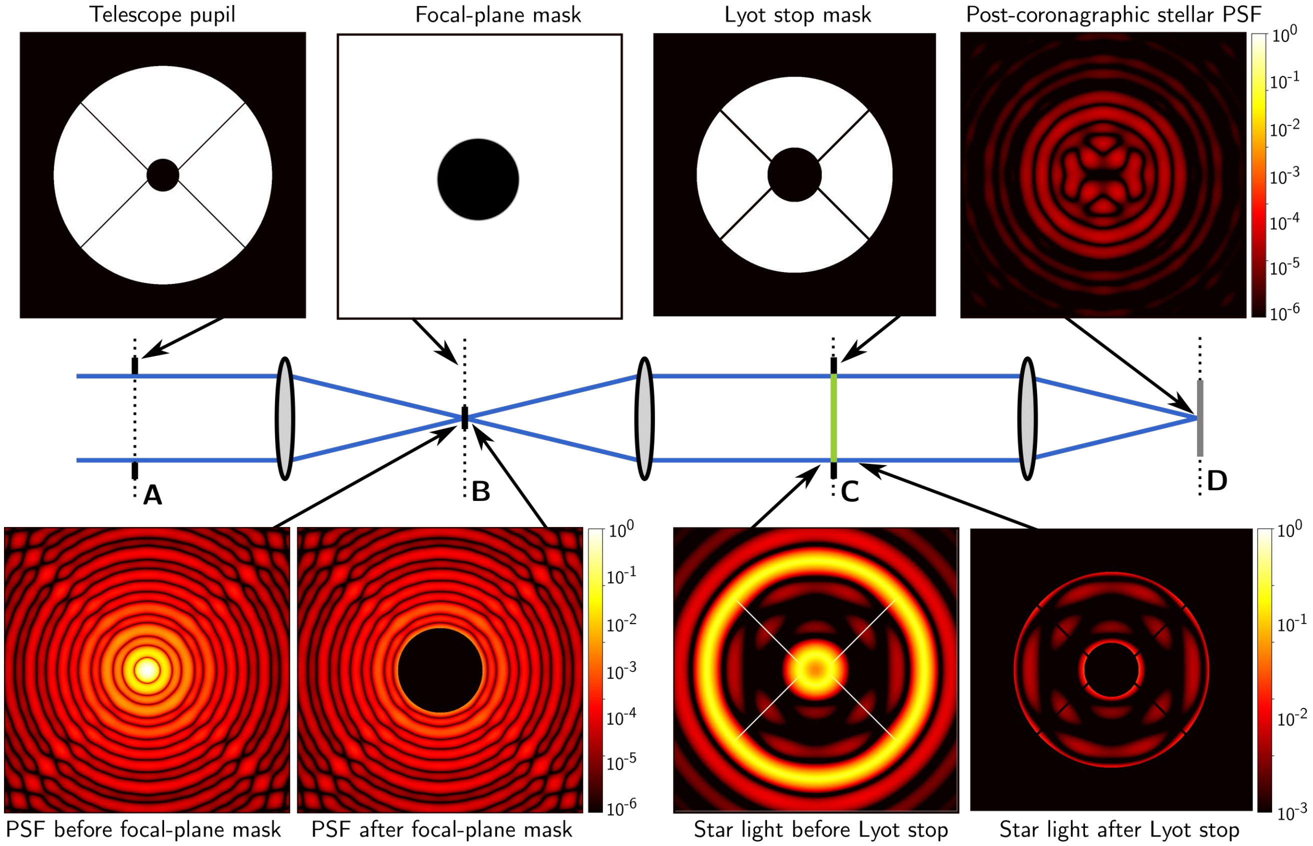
Lyot 1939, figure from Por (2020, thesis)

Lyot-style coronagraph

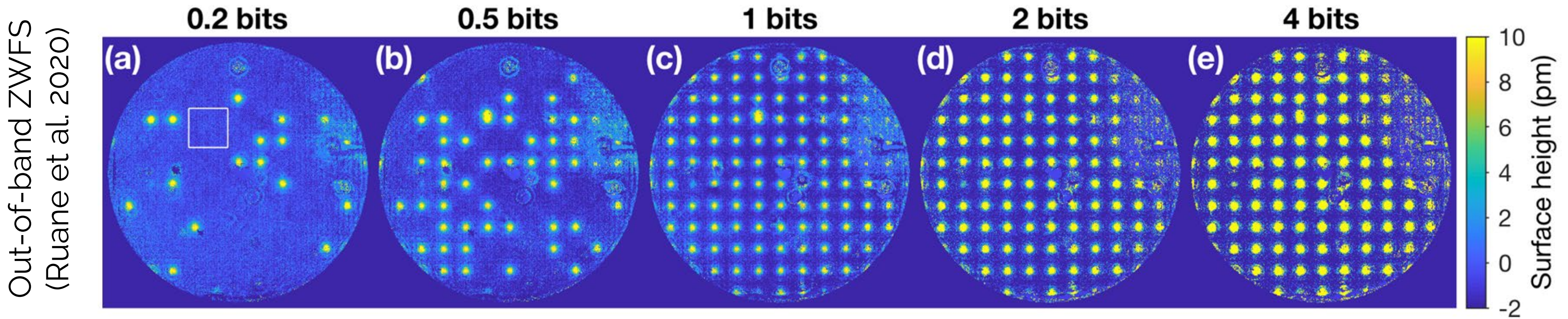


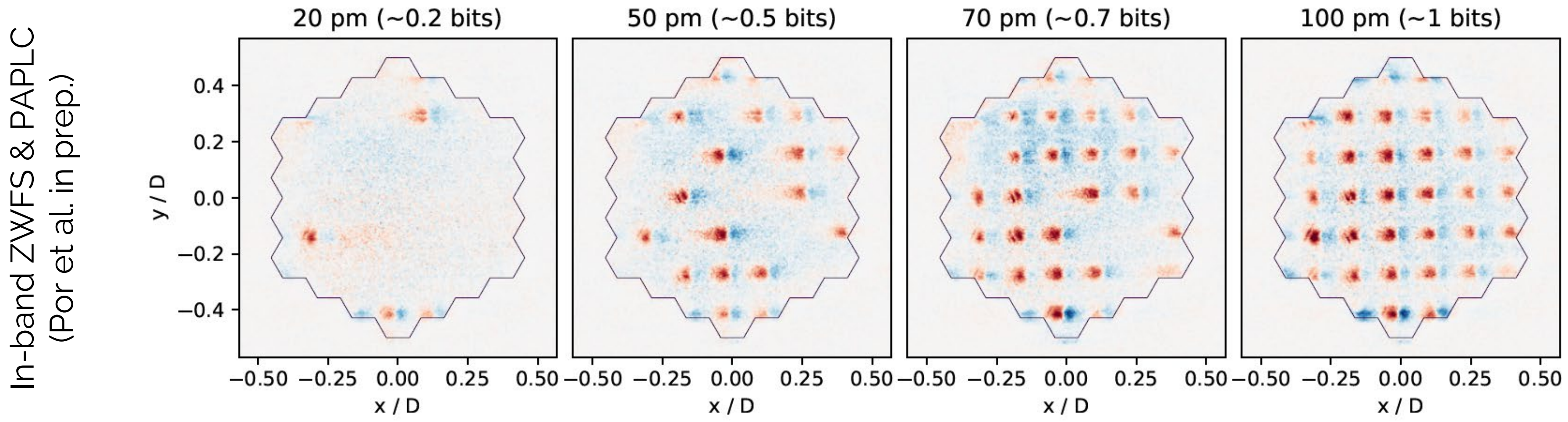
Lyot 1939, figure from Por (2020, thesis)

Lyot-style coronagraph

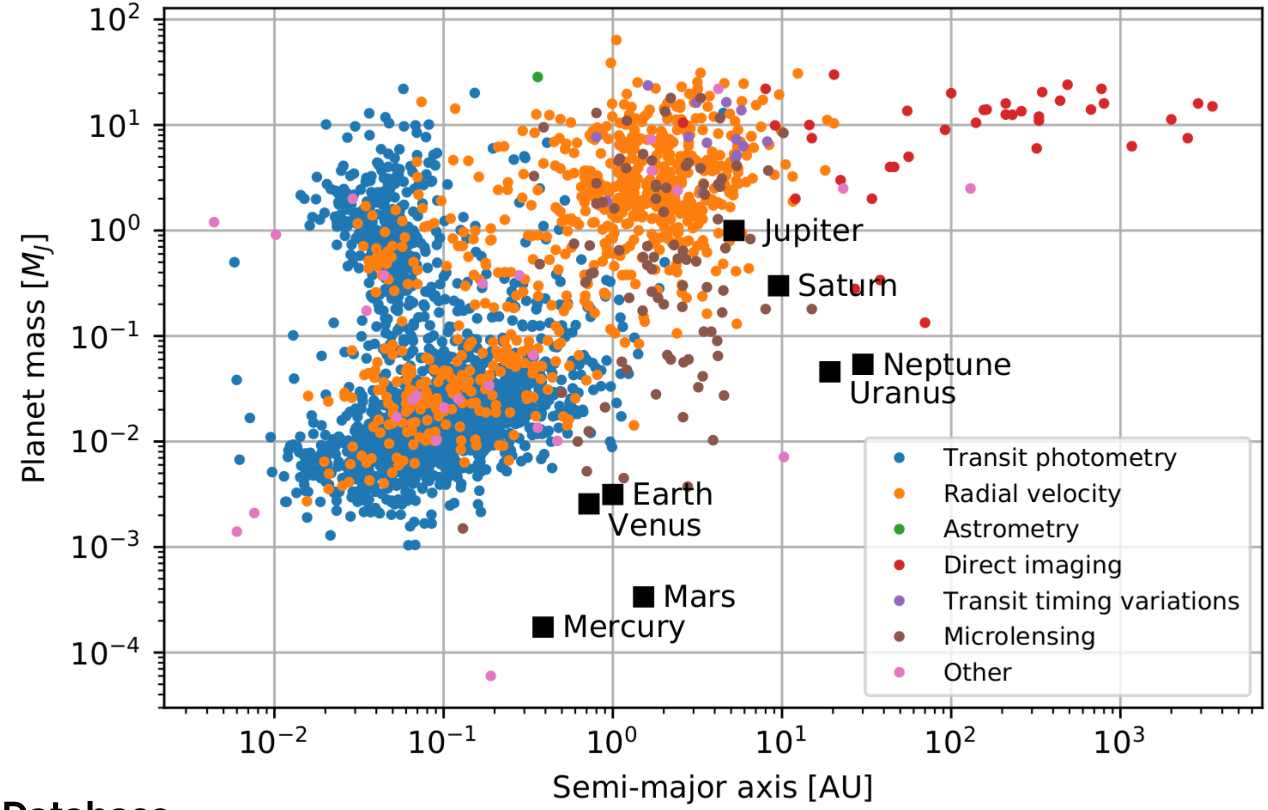


DM voltage discretization measured with ZWFS





Exoplanet detection methods



NASA Exoplanet Database