A possible Exozodi survey of HWO targets with the Roman Coronagraph

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"Shifting Landscapes in Astrophysics – New Frontiers to Explore with Roman"

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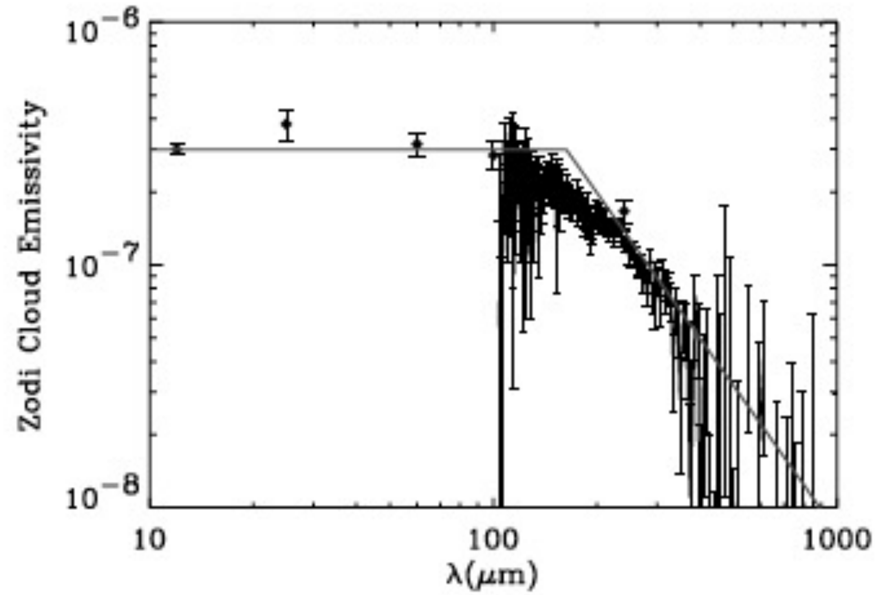
Solar Zodiacal Light

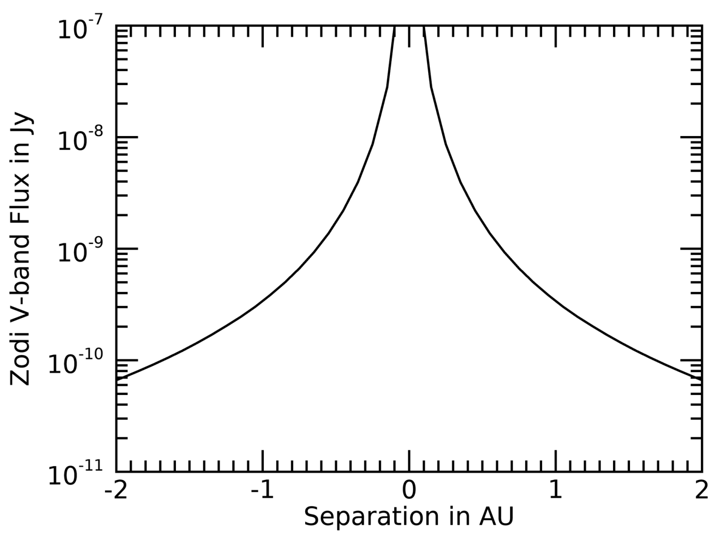
- Warm circum-solar dust located within the asteroid belt, from <0.1 AU to ~3.3 AU
- Optically thin cloud of small (1-100 μm) dust grains created from asteroid collisions, comets evaporation and disruption
- Temperature and density profiles measured by COBE/DIRBE (Kelsall et al. 1998):
  - Tdust ~ 286 K $(r/1AU)^{-0.467}$
  - Optical depth ~ 10^{-7} $(r/1AU)^{-1.34}$
- Total mass equivalent to asteroid of 10 miles radius or a few 10^{-9} Earth mass
- But *total* flux > 100 times the Earth at both visible and mid-infrared wavelengths
- Solar zodi surface brightness at 1 AU is ~ 23 mag/arcsec^2 at V band
  - Varying with ecliptic latitude (23.4 looking at poles, 22.5 in the plane)



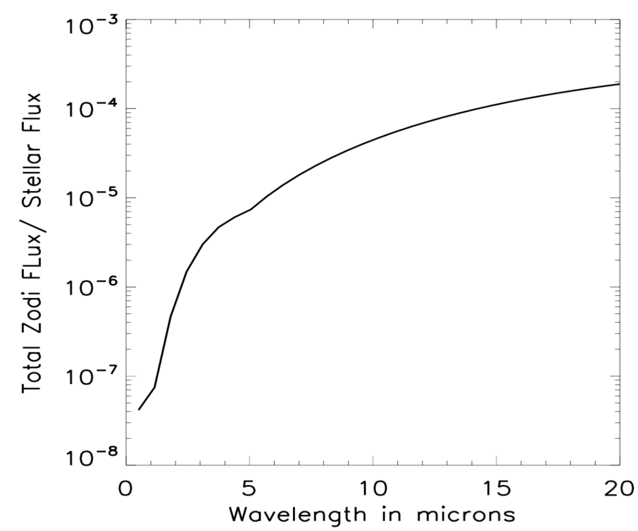
COBE/DIRBE NIR to FIR data
Fixsen & Dwek 2002

”1 zodi” worth of Exo-zodiacal dust

- Stars will have the equivalent of the solar zodi → exo-zodiacal dust
- Exo-zodi level of ”1 zodi” means the exozodi dust density spatial profile, size distribution and albedo are strictly identical to solar system
  - With density profile rescaled by sqrt(L*/Lsun) to preserve solar dust density at **EEID**
  - V band apparent surface brightness is ~22 mag/arcsec^2 at EEID (e.g., Stark et al. 2014)



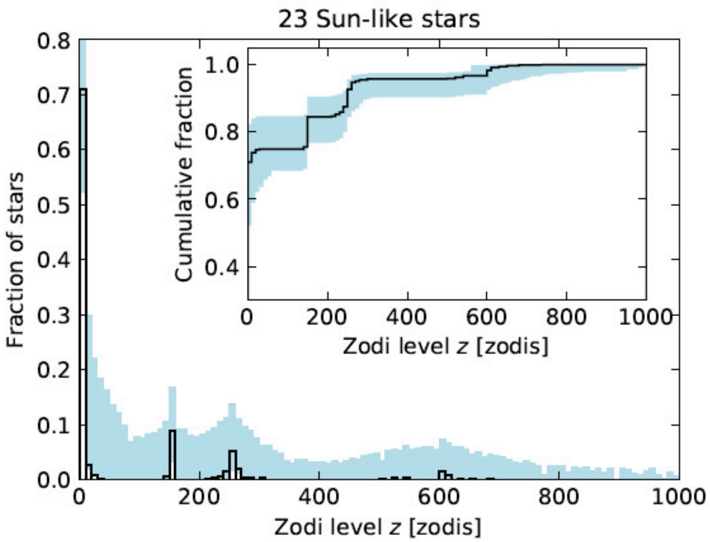
1 Zodi worth of exozodi flux as seen from 10 pc



Total exozodi flux vs wavelength, assuming “1 Zodi”

Current Knowledge of Exozodi Levels and Representation in Yield Estimates

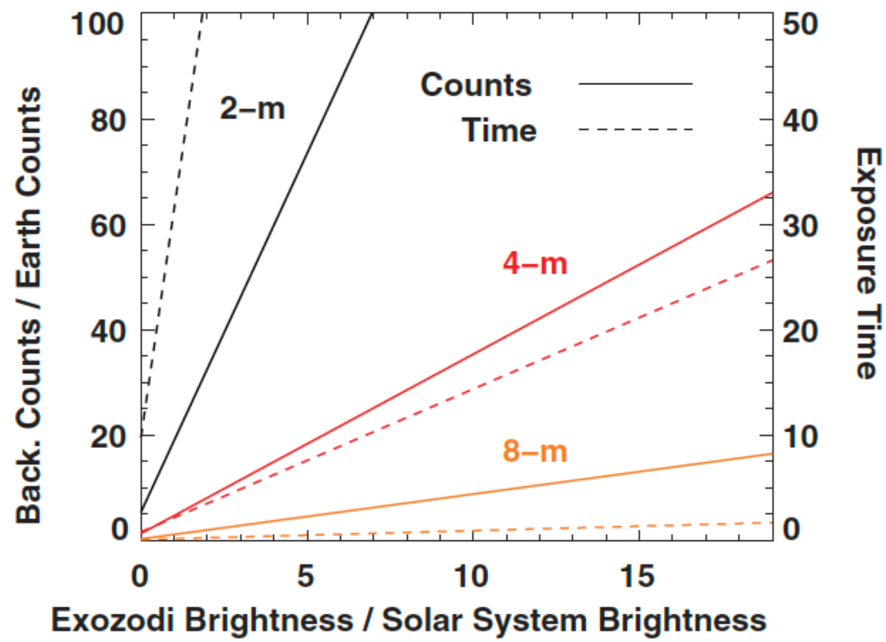
- Best measurements to date come from LBTI Exozodi Survey around 11 μm
- 23 sunlike stars observed, typical 1σ uncertainty per star ~ 50 zodis
- Statistical analysis suggest stars come in 2 flavors: < 30 zodis (most) and > 100 zodis
- Median Exozodi Level = 3^{+6}_{-2} zodis, with 95% confidence upper limit of 27 zodis



LBTI survey results
Ertel et al. 2020

Exozodi dust per resel will likely be brighter than an Earth-like planet at vis/nir wavelengths

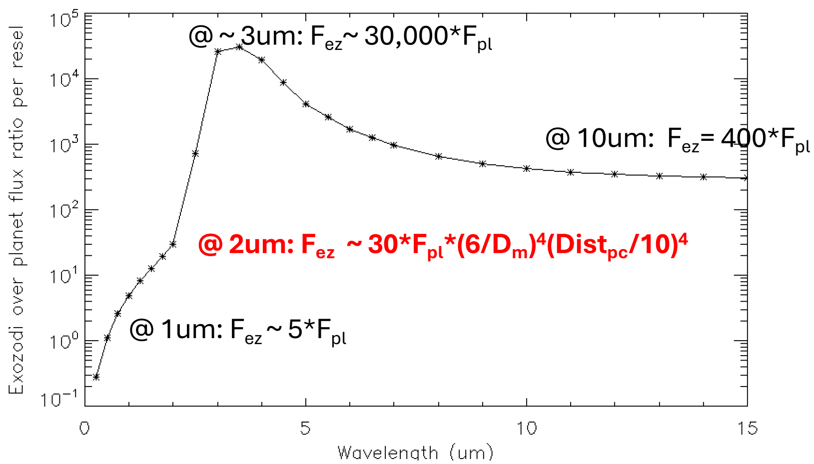
- Already a problem identified for observations with TPF-I (Mennesson et al. 1997) and then TPF-C / HWO (Roberge et al. 2012, V band , 10 pc):

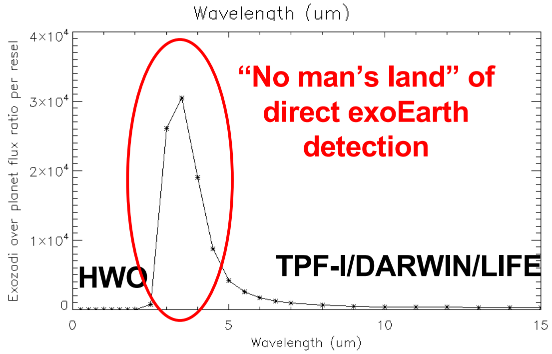


from Roberge et al. 2012

Exozodi dust *per resel* will likely be brighter than Earth-like planet at VIS/NIR wavelengths

- Worse issue as wavelength increases (Mennesson et al. 2024)





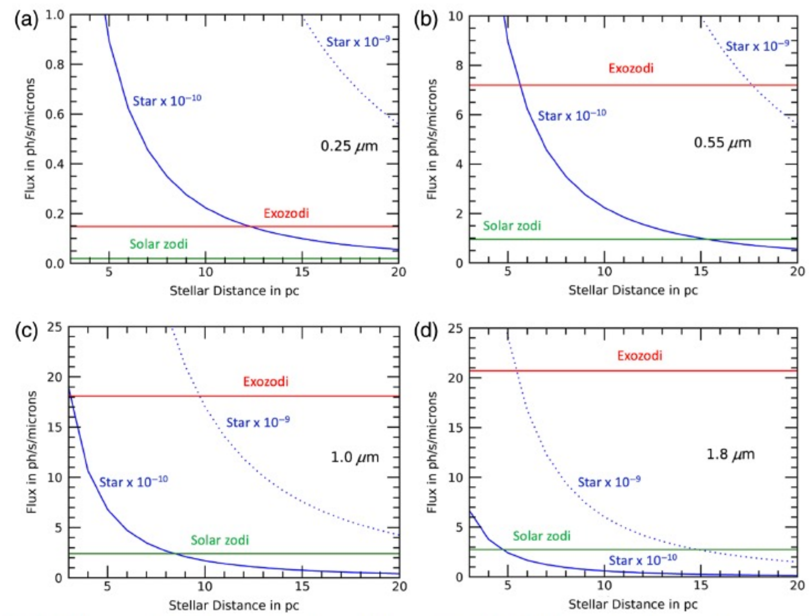
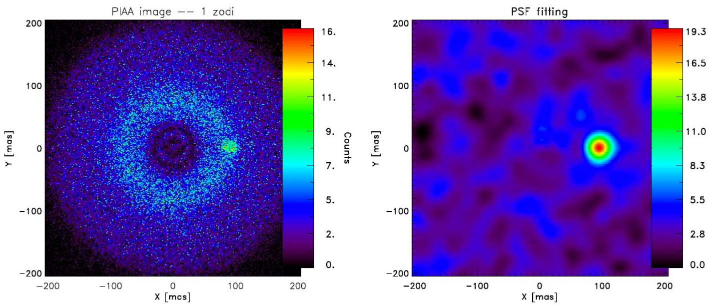


Fig. 23 Astrophysical fluxes detected at 1 AU from a Sun-like (G2V) star, in a photometric region of radius $0.7\lambda/D$, as a function of stellar distance. The four panels correspond to wavelengths of (a) 0.25, (b) 0.55, (c) 1.0, and (d) 1.8 μm (note the different y-axis ranges). All cases assume a $D = 6$ m telescope with a starlight suppression system with unit end-to-end transmission (including detector) efficiency and an off-axis PSF described by a perfect Airy pattern (i.e., with a core throughput of 0.68 within the photometric region). The starlight suppression RC at 1AU is set to either 10^{-10} (plain blue curve) or 10^{-9} (dotted blue curve). The blue curves also correspond to the flux from an exoplanet with a planet-to-star flux ratio of 10^{-10} (an exo-Earth at quadrature) or 10^{-9}. The exozodi level is set to three zodis in all cases.

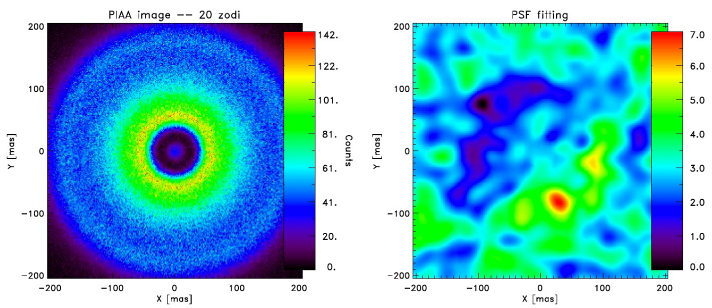
Limitations and Future Work

- LBTI measures a total mid-infrared (~11 um) excess integrated over a few 100 mas (weak spatial info)
- <u>A solar zodi like model is assumed </u>to convert excess to exozodi brightness, scaling up from “1 zodi” density at 1 AU (or EEID)
- Converting to exozodi level at visible wavelengths also depends on exozodi dust model (albedo, grain size and spatial distributions)
- There is evidence, from joint MIR and NIR interferometric measurements that some stars have exozodi dust very different from solar (e.g. hot dust phenomenon, Absil et al. 2006 & 2009, Ertel et al. 2014, Mennesson et al. 2011)
- Yield simulations assume smooth exozodi signals that <u>only add photon noise</u>
  - Need to include the effect of any bright resonant dust clumps that may mimic planets and hamper their detection

Simulations of V-band coronagraphic observations of a Sun/Earth twin at 10 pc with a 4m telescope (Defrere et al. 2012)



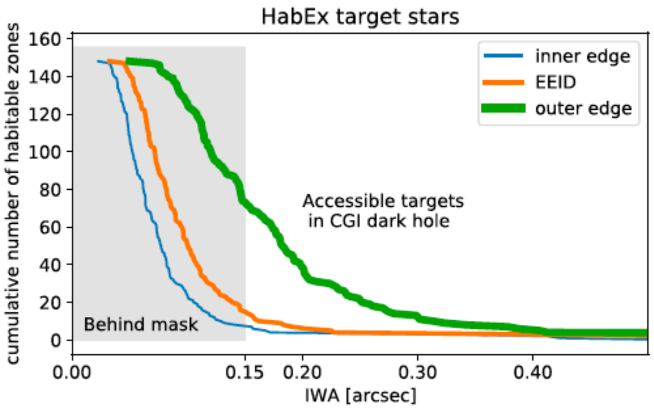
1 “zodi” case: exo-Earth is retrieved

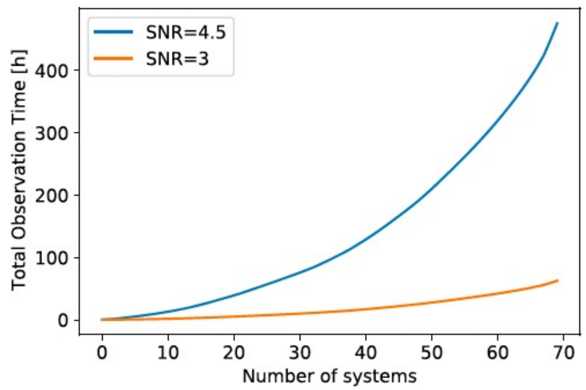


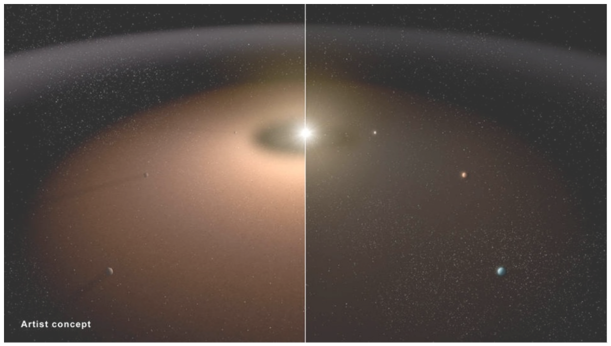
20 “zodis” case : bright dust clump is retrieved instead of planet

A Roman coronagraph survey of Exozodi dust around HWO targets?

- The Roman Coronagraph could conduct a visible survey of HZ exozodi dust around 70 HWO targets down to 10-100 zodis sensitivity (5σ) in < 1 month depending on in-flight performance



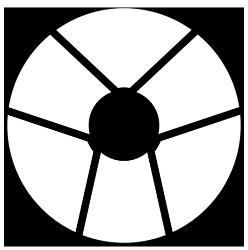


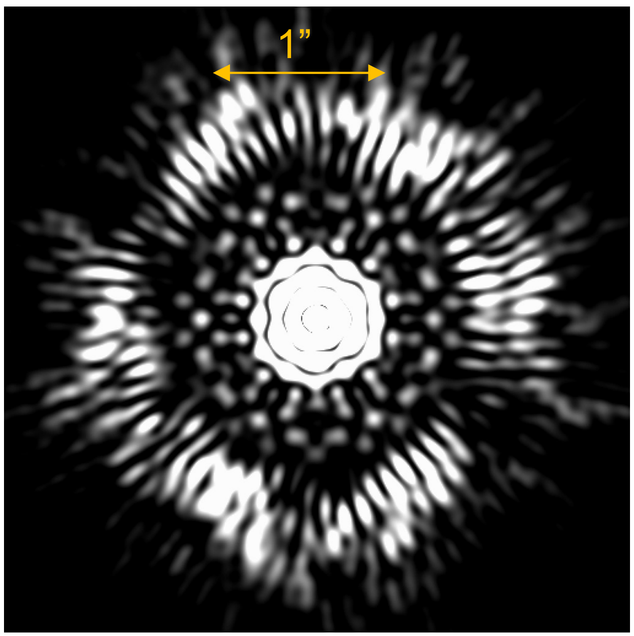


Douglas et al. 2022, Mennesson et al. 2018 & 2019

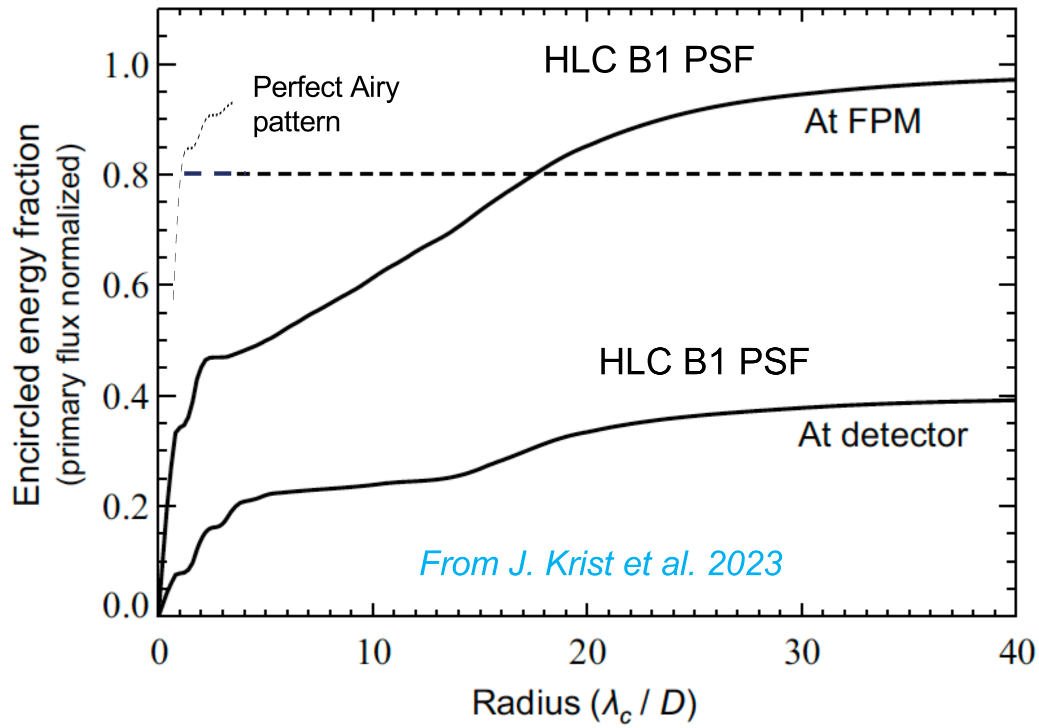
Off-axis Coronagraphic PSF is significantly extended

$$\eta_p(x, y) = \eta_{\rm occ}(x, y).\eta_{\rm PSF}(x, y)$$

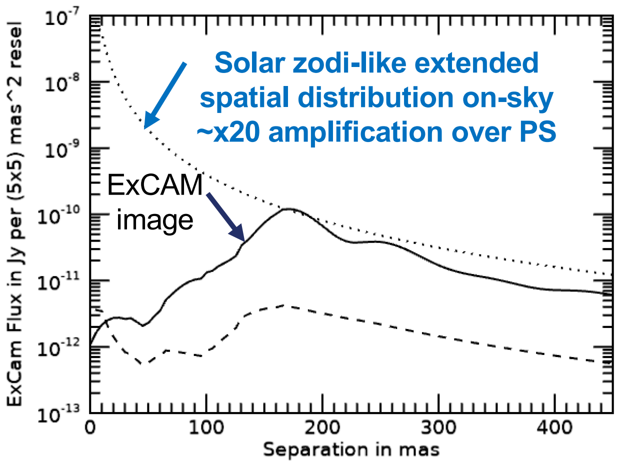


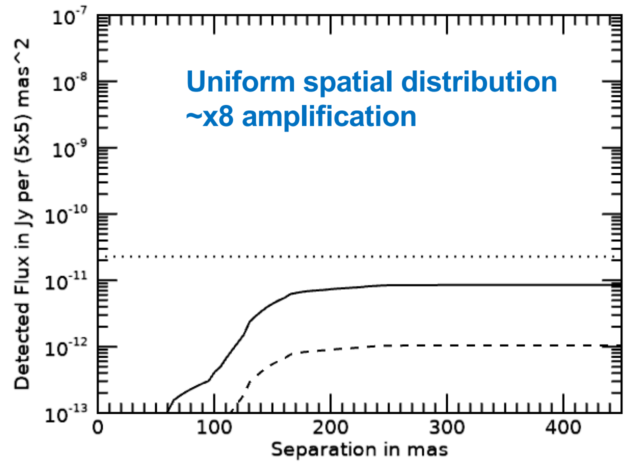


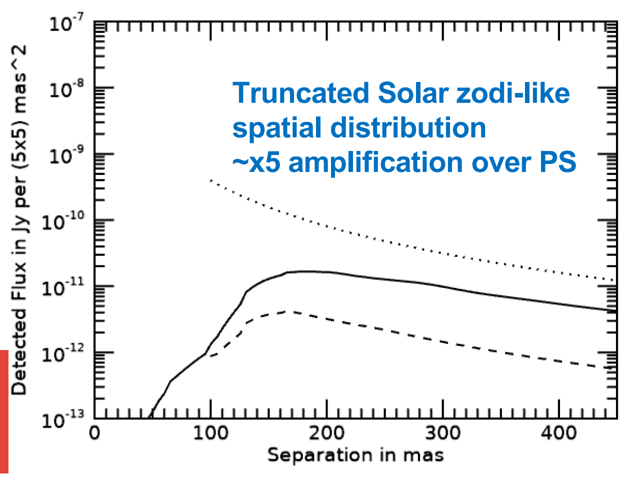
HLC B1 PSF (with no field stop, source at center of B1 DH)

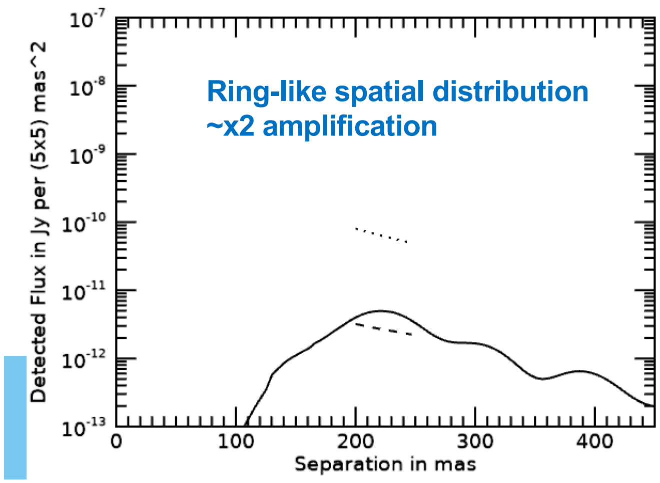


Not Optimized for Planets – But OK for Disks









---------------- On-sky Disk Flux
———— Detected Disk Flux
- - - - - - - - - Detected Point Source Flux

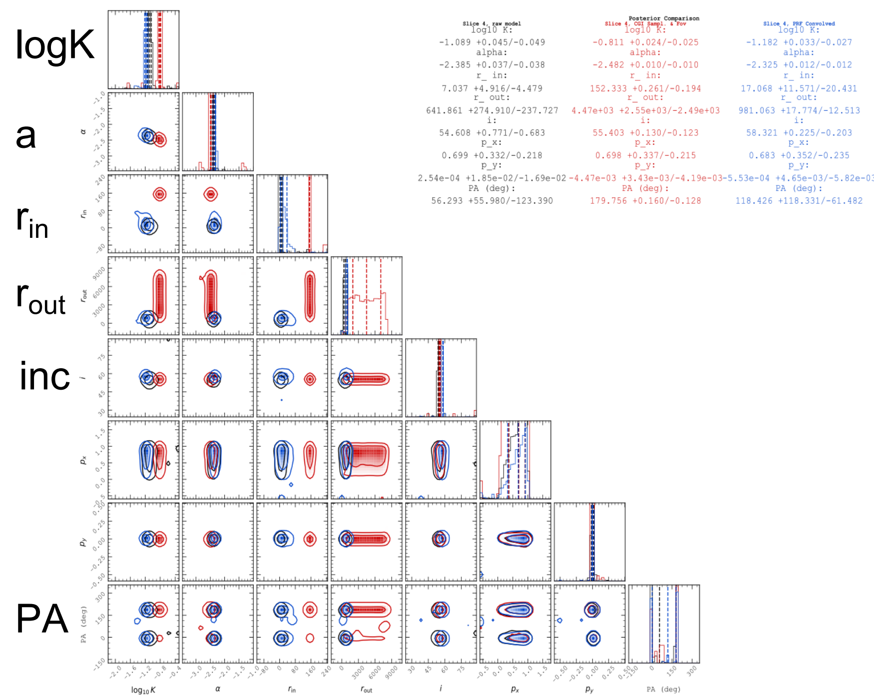
- **Disks flux amplified wrt Point Source flux**
- **Amplification factor depends on source BD**
- **Forward modeling needed to assess where the flux is coming from**

Some examples of physical info that might be retrieved

- Varying, inc, PA, r_{in}, r_{out}, SB(EEID), power law in the input on-sky SB(r)
  (cgirtr.pro)

- Full convolution to generate fake EXCAM *noiseless* images

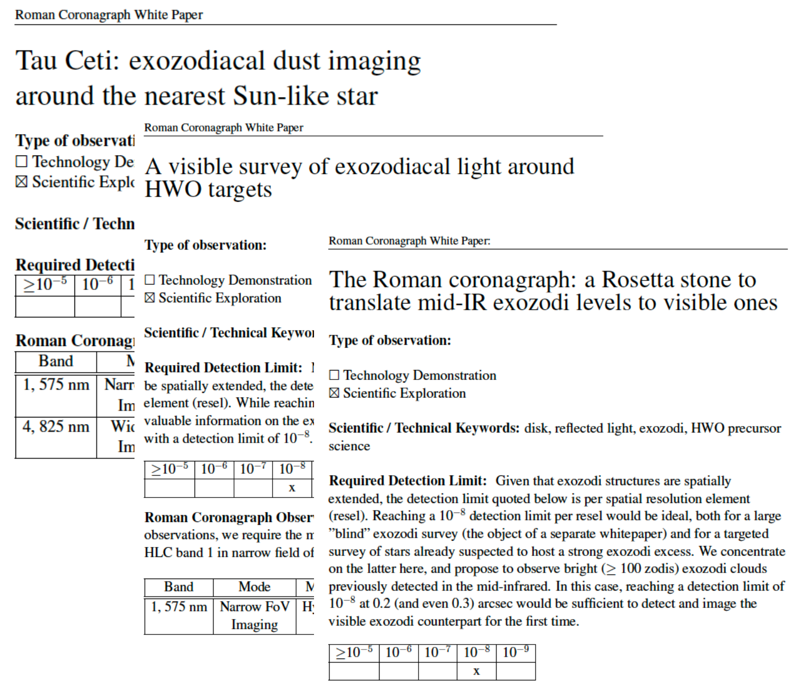
- MCMC exercise (Llopp-Sayson) with simple geometric model shows good retrieval of overall params except for r_{in} < 100 mas (IWA=150 mas)



The exozodi pilot survey stars

- Inspired by 3 exozodi whitepapers submitted in 2025:
- Assessing instrument capablities via a pilot exozodi survey of 7 diverse science targets:
  - Eps Eri, τ ceti, β Vir, 72 Her, δ Uma, β Leo, β Uma
  - Both solar and A type stars
  - With and without previous exozodi detection with LBTI/HOSTS
  - 150 mas exozodi SB predicted from 15 to >18 Vmag/arcsec^2
- Observed nominally between Jan and July 2027, Program ”D1”, 3 campaigns (4,6,7)
- Goal is to motivate a possible broader (~ 1 month?) exozodi survey of HWO sunlike target stars

From 2025 WP Call:



Roman Coronagraph White Paper

Tau Ceti: exozodiacal dust imaging around the nearest Sun-like star

Roman Coronagraph White Paper

A visible survey of exozodiacal light around HWO targets

Roman Coronagraph White Paper:

The Roman coronagraph: a Rosetta stone to translate mid-IR exozodi levels to visible ones

Type of observation:

☐ Technology Demonstration
☒ Scientific Exploration

Scientific / Technical Keywords: disk, reflected light, exozodi, HWO precursor science

Required Detection Limit: Given that exozodi structures are spatially extended, the detection limit quoted below is per spatial resolution element (resel). Reaching a 10^{-8} detection limit per resel would be ideal, both for a large "blind" exozodi survey (the object of a separate whitepaper) and for a targeted survey of stars already suspected to host a strong exozodi excess. We concentrate on the latter here, and propose to observe bright ($\geq$ 100 zodis) exozodi clouds previously detected in the mid-infrared. In this case, reaching a detection limit of 10^{-8} at 0.2 (and even 0.3) arcsec would be sufficient to detect and image the visible exozodi counterpart for the first time.

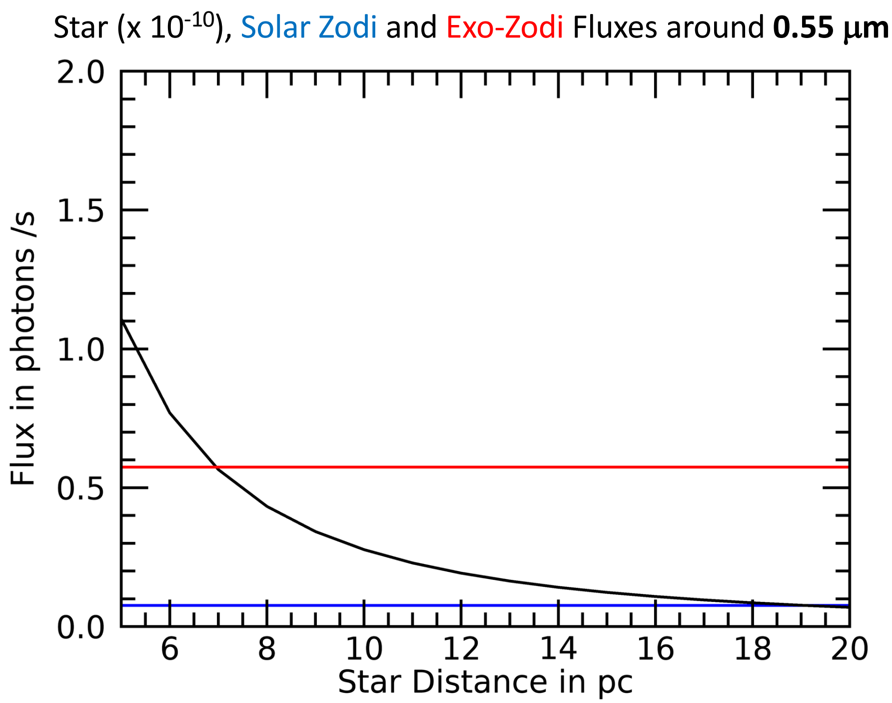
$\geq 10^{-5}$	10^{-6}	10^{-7}	10^{-8}	10^{-9}
			x	

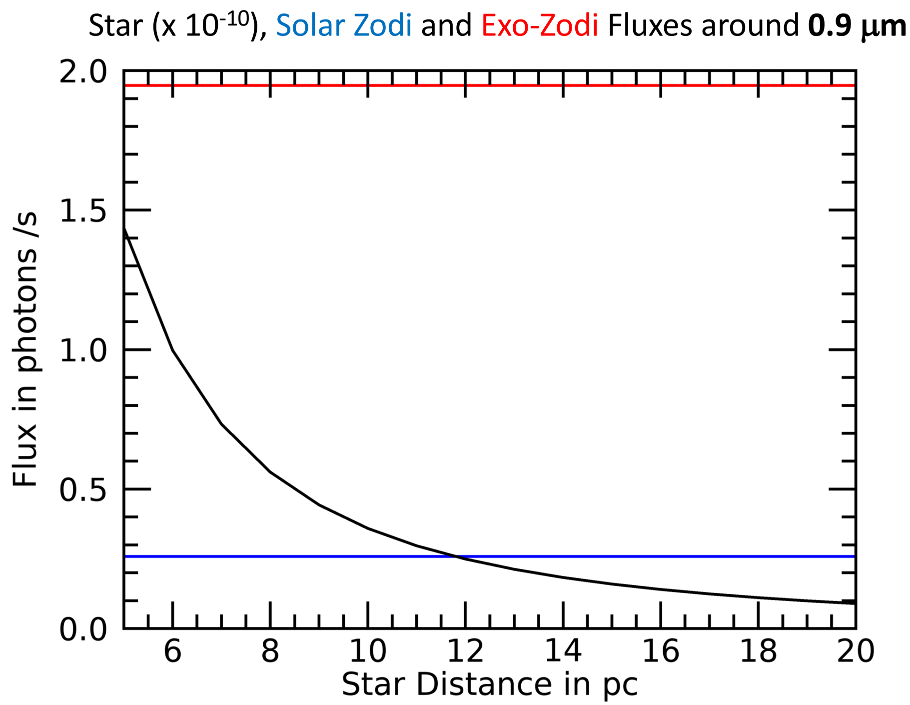
Summary

- Exozodi at few solar level will dominate over exo-Earth flux per resel at vis/nir wavelengths
- Exozodi has been measured by LBTI/HOSTS around 11 um, deriving a typical median level around 3 zodis, but with ~150 zodis 3-sigma uncertainty for individual sunlike stars
- Exozodi has never been measured at the < 1000 solar zodis level at visible/near IR wavelengths!
- RCI is designed to detect and resolve exozodi structures for the 1st time at optical wavelengths at the 10-100 solar zodis level, as supported by initial MCMC forward modeling of simulated EXCAM data
- A pilot exozodi survey will be conducted during the observing phase, including 7 stars in the 1st 6 months.
- Designed to inform and motivate a broader exozodi survey of dozens of HWO targets after 18 months of Roman operations

Back-up

Impact as a function of stellar distance (G2V star)





Fluxes detected per solid angle $(\lambda/D)^2$ over a 20% spectral bandwidth assuming a 6m telescope with unit optical transmission and QE. Exozodi level assumed to be “3 zodis", flux computed at 1AU from the star. Starlight assumed to be rejected by 10^{10} at that location.

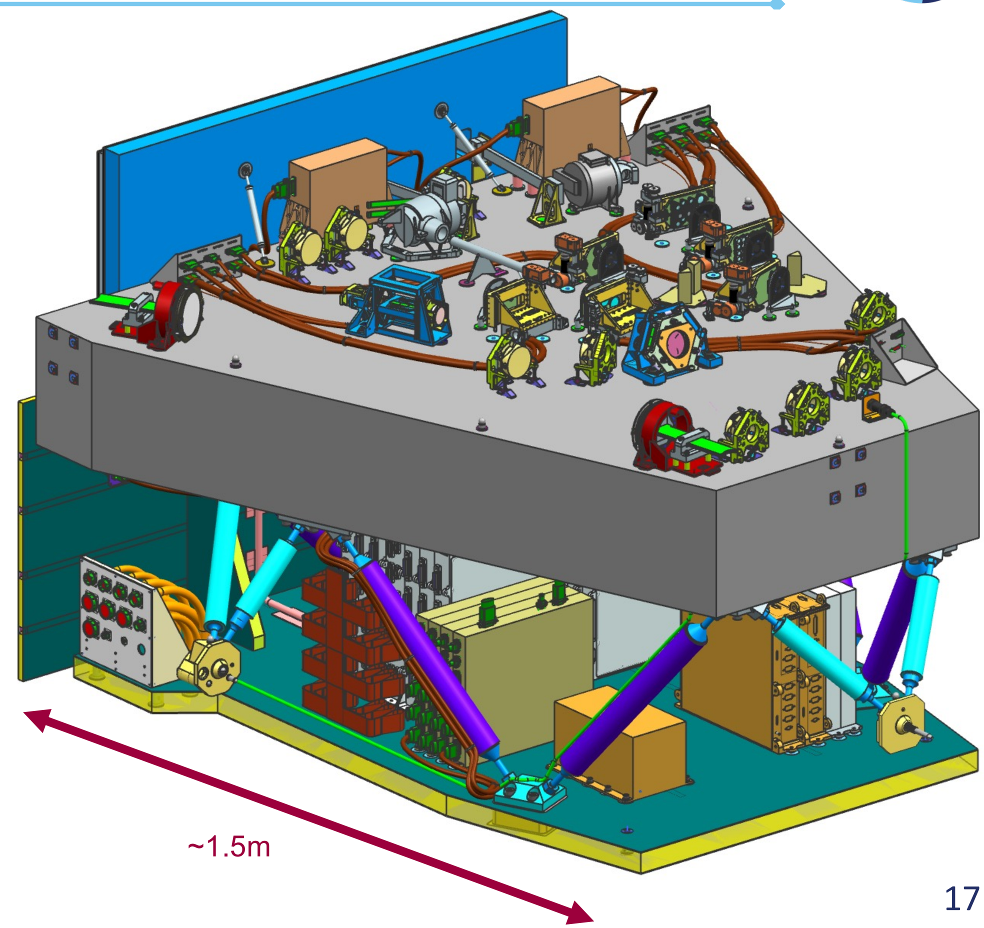
- At the current best estimate of typical exozodi level (3 zodis), exozodi signal dominates over residual starlight level
  - Even more so at longer wavelengths

Outline

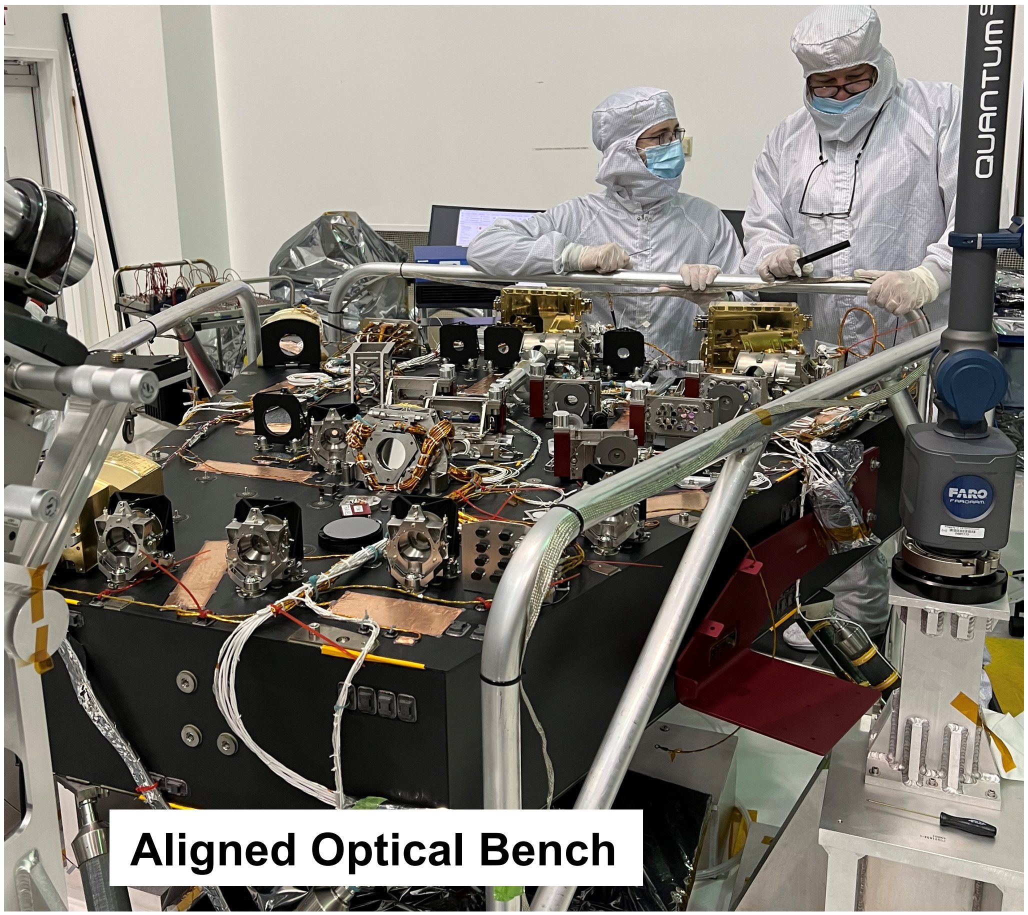
- The Roman Coronagraph in a Nutshell
- Observing Modes
- I&T Lab Results and Expected in-Flight Performance
- Potential Science Observations
- Disks vs Planets
- Community Participation

Roman Coronagraph is a stepping stone toward Habitable Worlds Observatory

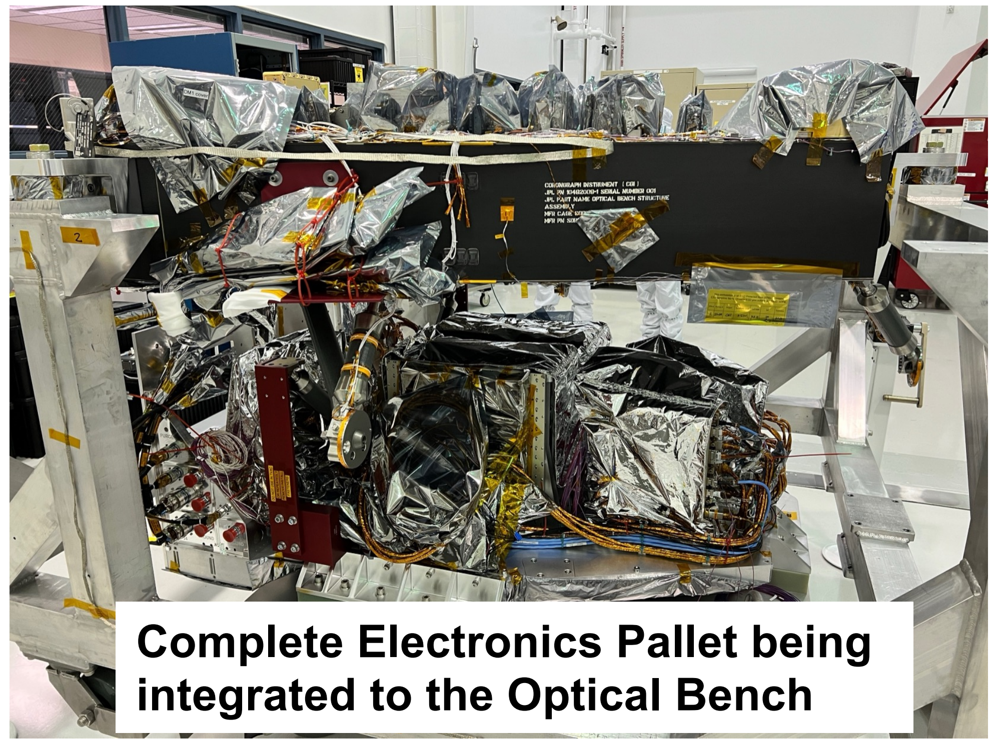
- A visible-light, high-contrast "**technology demonstration**" instrument for HWO
  - first space-based coronagraph with active wavefront control
  - requirement: 10^{-7} flux ratio 5σ detection limit in a single photometric band
    - Designed to outperform requirement
  - Predicted performance ≥4x beyond req
    - Based on end2end TVAC performance testing



Coronagraph Instrument during I&T (JPL 2023-2024)

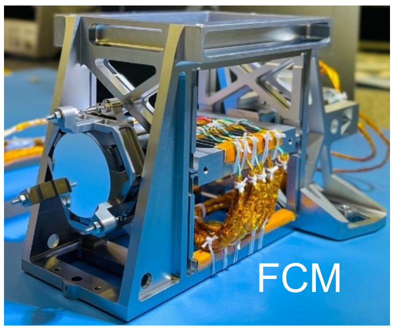


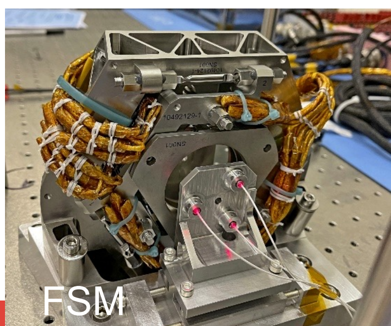
Aligned Optical Bench


Complete Electronics Pallet being integrated to the Optical Bench

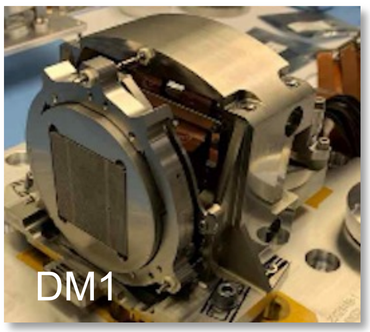
The Roman Coronagraph will Demonstrate Key Technologies for HWO

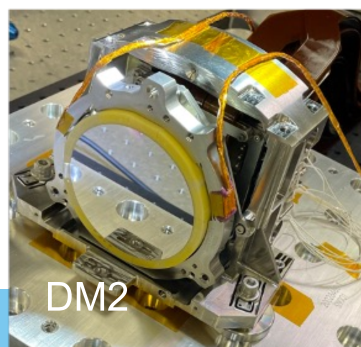
Ultra-Precise (LO/HO) Wavefront Sensing & Control



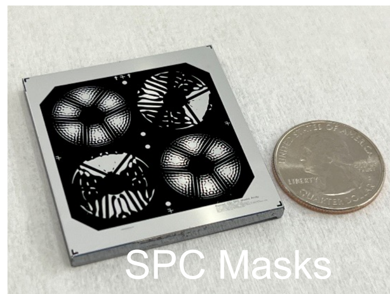


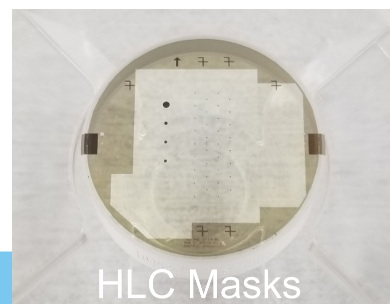
Large-format Deformable Mirrors



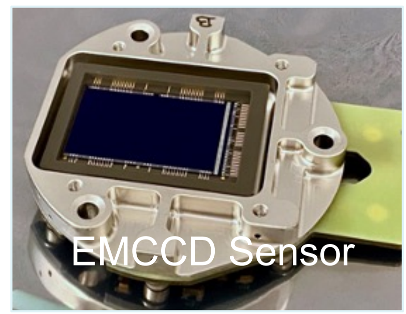


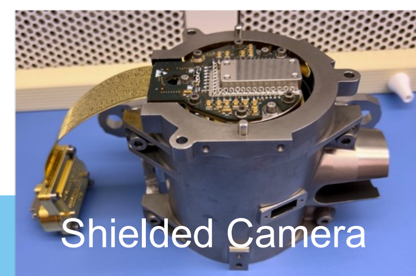
High-contrast Coronagraph Masks



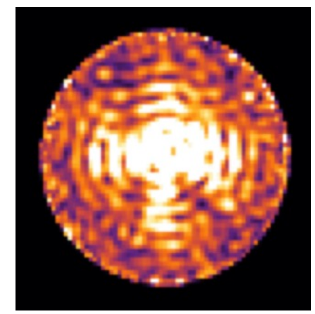


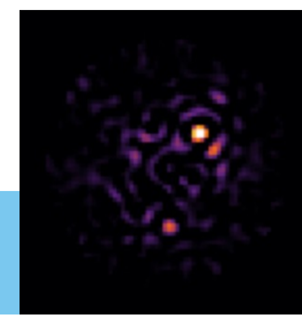
Ultra-low-noise Photon-counting EMCCDs



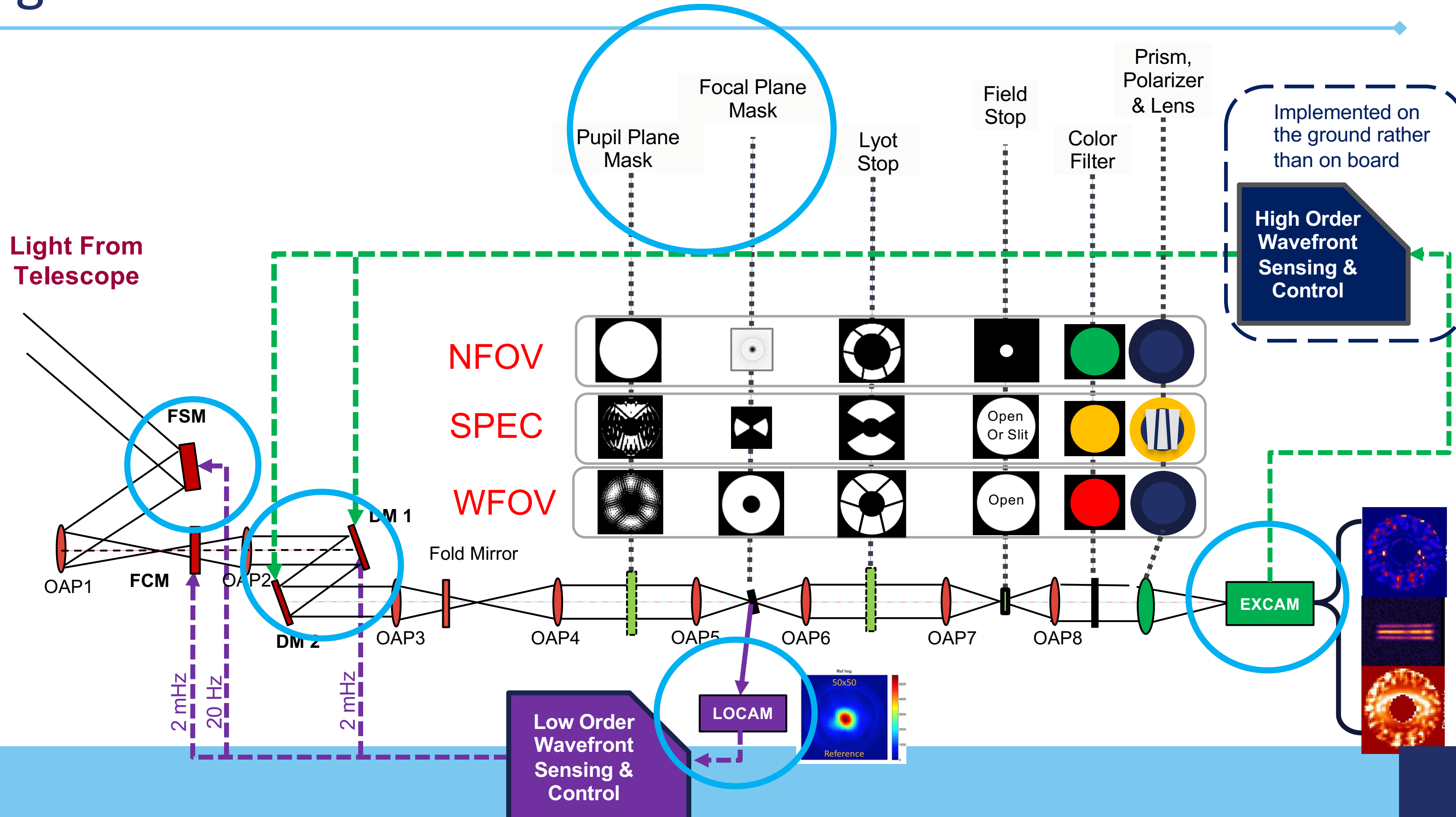


Data Post-Processing





Key Technologies Work Together as a System to Deliver High Performance



OAP = Off-Axis Parabolic

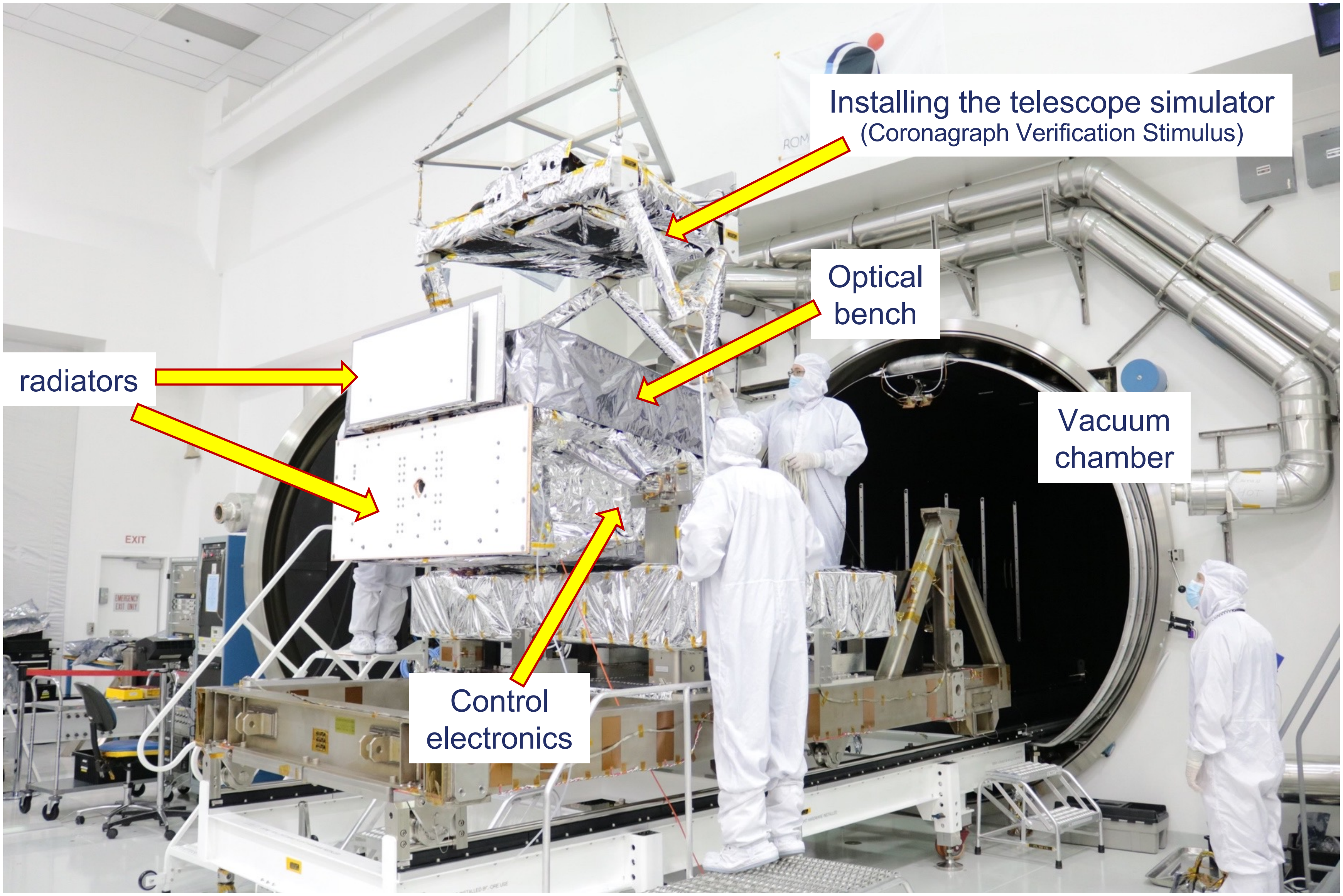
Observing Modes: 1 fully supported mode + 3 “best effort” & “unsupported” modes

λ_{center}	Mode	Approx. FOV radius	FOV Coverage	Support
575 nm	**NFOV:** Narrow FOV Imaging	**0.15” – 0.45”**	**360°**	**Required (full support)**
730 nm, 660 nm	**SPEC**: Slit + R~50 Prism Spectroscopy	0.2” – 0.55”	slit	Best Effort
575 nm, 825 nm	**WFOV**: “Wide” FOV Imaging	0.3” – 1.4”	360°	Best Effort
575 nm, 825 nm	Imaging Polarimetry (WPs)	0.15” – 1.4”	360°	Best Effort
any	Other coronagraph mask combinations	0.15” – 1.4”	various	Unsupported
any	Other technology demonstrations: binary star, transmissive Zernike wavefront sensor, alternative wavefront sensing algorithms	various	various	Unsupported

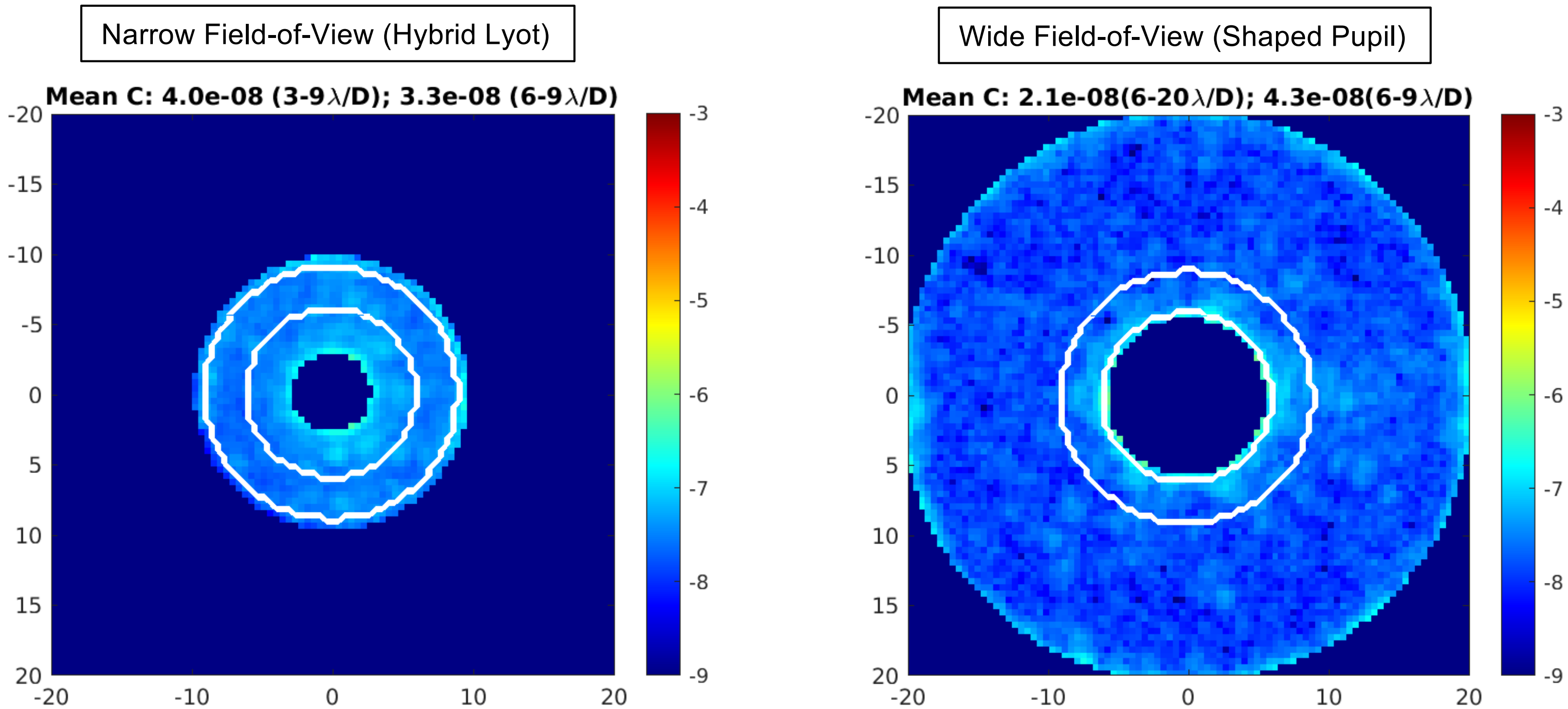
Best effort: partially tested in TVAC; no guaranteed support on-orbit.
Unsupported not tested in TVAC; no guaranteed support on-orbit

Contributed by ExEP: 575nm “Wide” FOV mask & all “unsupported” masks

February – April 2024 : Thermal Vacuum (TVAC) Performance testing


Installing the telescope simulator
(Coronagraph Verification Stimulus)
Optical bench
radiators
Vacuum chamber
Control electronics
EXIT

Starlight Suppression: Raw Broadband Contrast Results (10% BW around 575 nm)

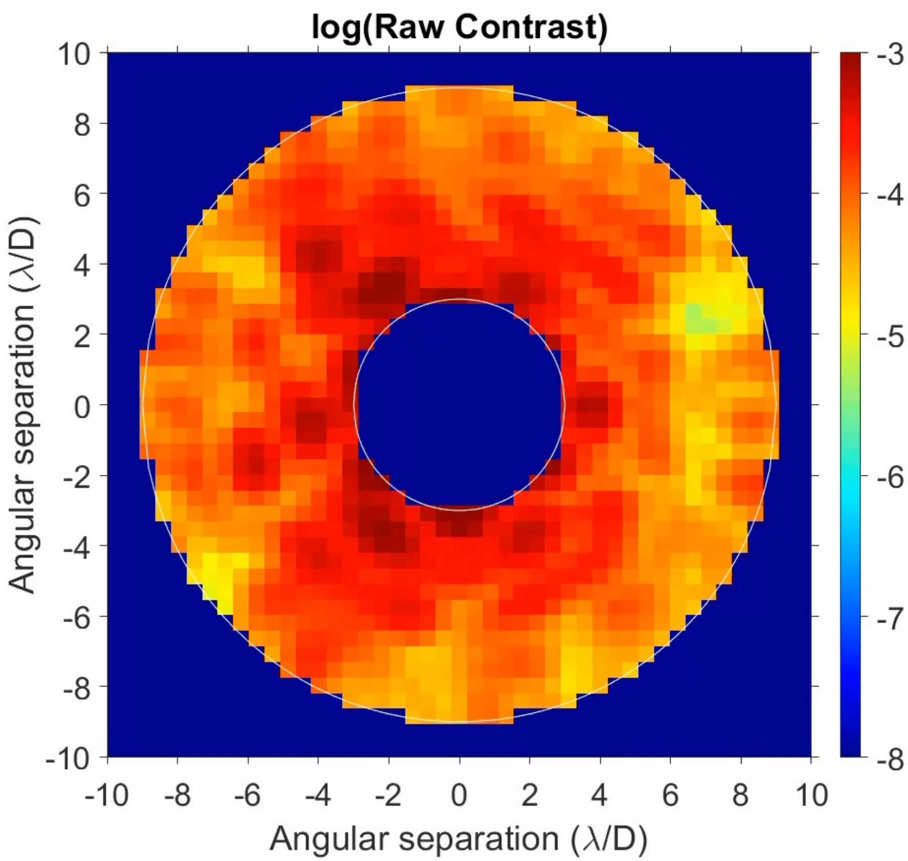


- ~30 shifts of dark hole digging during TVAC: team working 24 hours or 3 shifts a day, 7 days a week
- Contrast not at a hard physical limit: Stopped after meeting requirements with margin and running out of allocated time

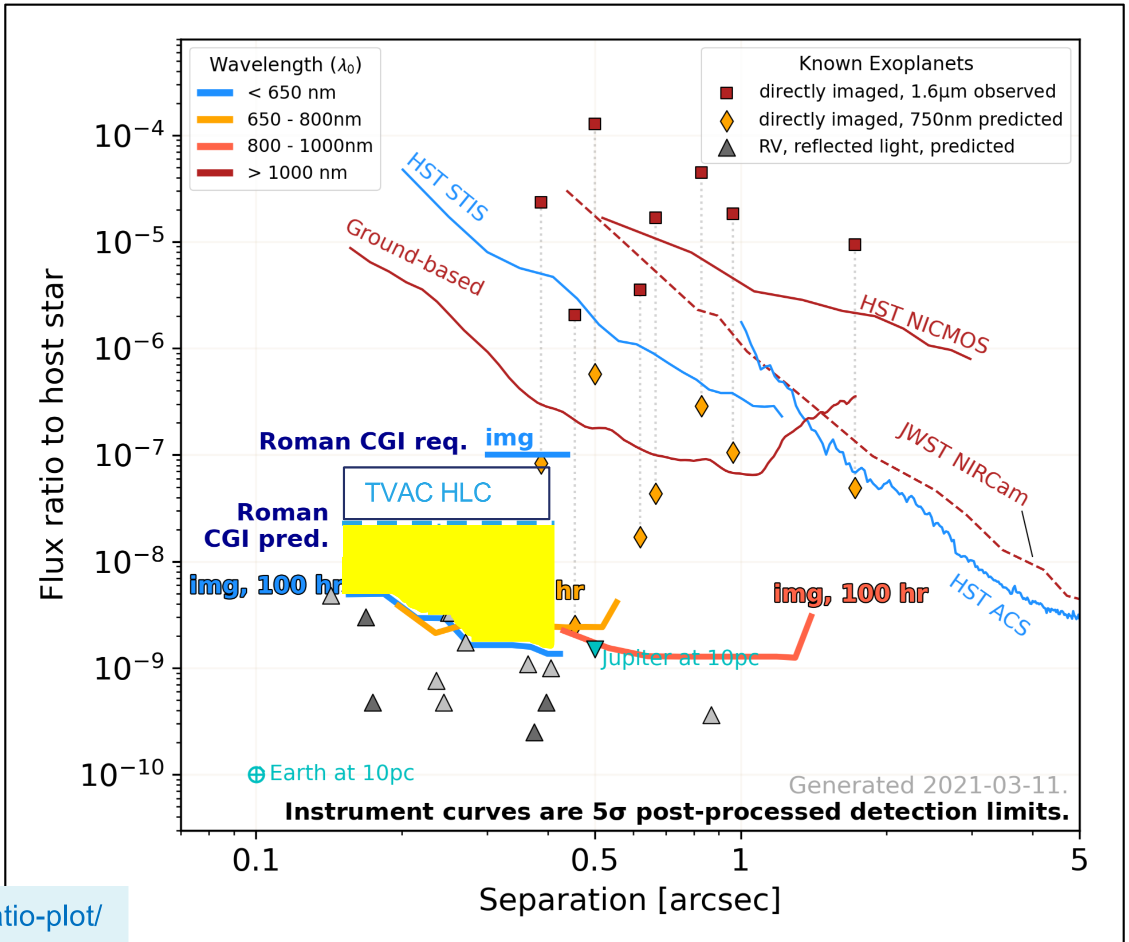
While the requirement called out 6-9 λ/D annulus, high contrast was demonstrated in 3-9 λ/D and 6-20 λ/D for exoplanet and disk science tech demonstrations, respectively

Primary coronagraph mode ("HLC") beats L1 requirement by at least 4x

- Starlight suppression via high order wavefront sensing & control (HOWFSC)
  - Aka: "digging the dark hole"
- Test time-limited
  - not fundamentally performance-limited
- **Credit: Eric Cady** (lead), Byoung-Joon Seo, A. J. Riggs, Brian Kern, David Marx, Fang Shi, Hanying Zhou, John Krist, Garreth Ruane

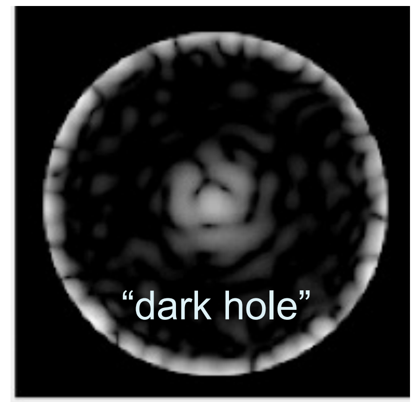


Predicted Detection Limit is 100-1000x Better than State-of-the-Art



Based on lab demonstrations as inputs to high-fidelity, end-to-end thermal, mechanical, optical models.

NASA terminology: MUF=1 predictions



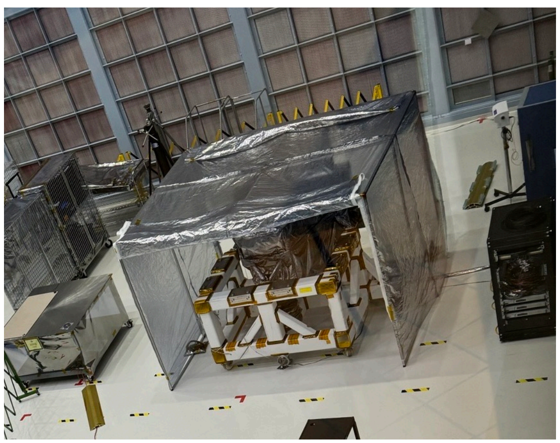
Brian Kern (JPL)
John Krist (JPL)
Bijan Nemati (Tellus1)
A.J. Riggs (JPL)
Hanying Zhou (JPL)
Sergi Hildebrandt-Rafels (JPL)

github.com/nasavbailey/DI-flux-ratio-plot/

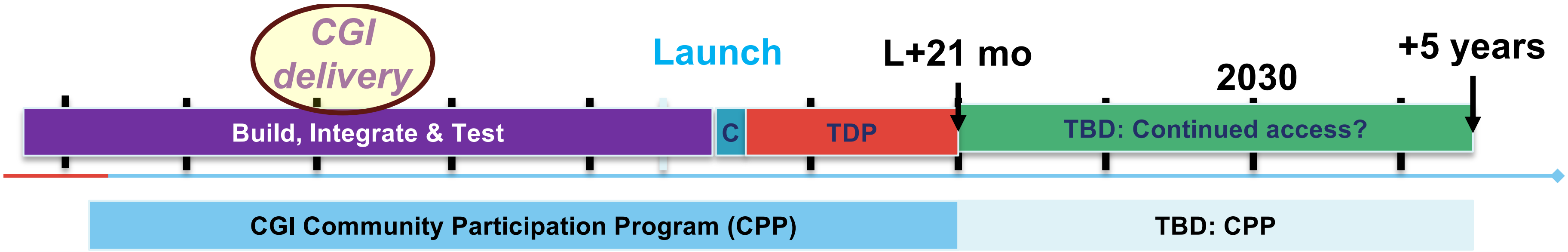
Delivery to NASA Goddard on May 19 2024

NASA JPL, Pasadena, California

NASA Goddard, Greenbelt, Maryland



Coronagraph Instrument arrived at GSFC on May 19, 2024



- May 2024: Instrument delivery to payload integration & test at GSFC
- Launch before May 2027 - SpaceX Falcon Heavy
- Commissioning Phase: 450 hr in first 90 days after launch
- Coronagraph Instrument Technology Demonstration Phase (TDP):

If TDP successful, potential follow-on observations

Observations Guiding Principles

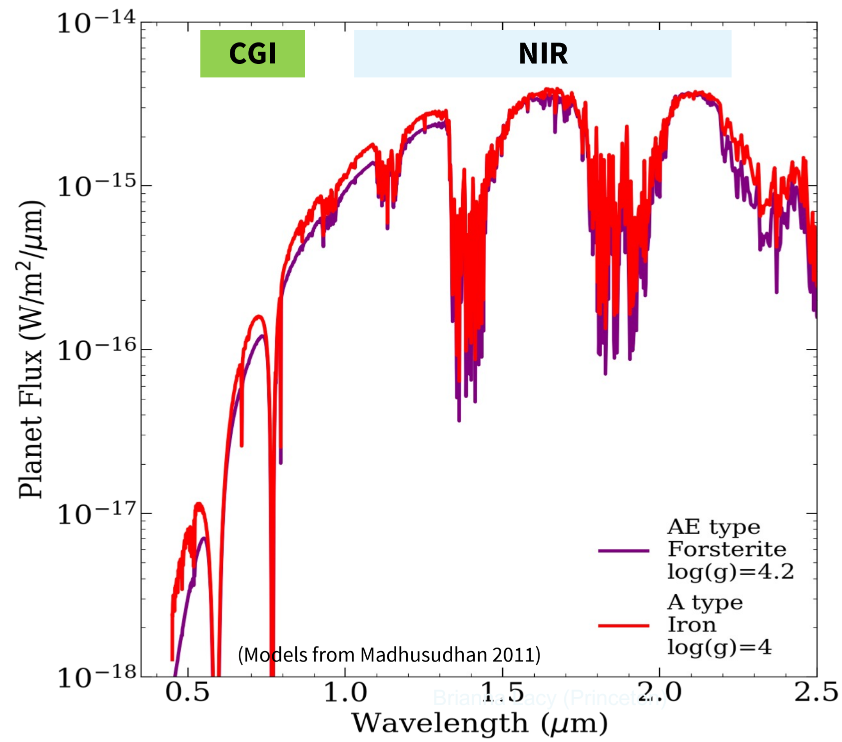
- Baseline: 2200hr (90 days) during first 18mo of Mission
- Top priority: achieve L1 Technology Requirement (“TTR5”)
  - L1 would constitute a successful technology demonstration for HWO
- Then, *as time/resources allow*, push performance limits
  - Baseline resources are not sufficient to support all “best-effort” and “unsupported” mode tests
  - Guiding principle for decision-making: Maximize long-term value to science community & Habitable Worlds Observatory
- Use scientifically-interesting targets whenever possible

Potential Observations of Scientifically Interesting Targets

- Self luminous planet image and spectra
- Reflected light planet image and spectrum
- Bright debris disk polarimetry
- Faint debris disk detection

Young, self-luminous massive planets: Roman coronagraph complements ground-based NIR

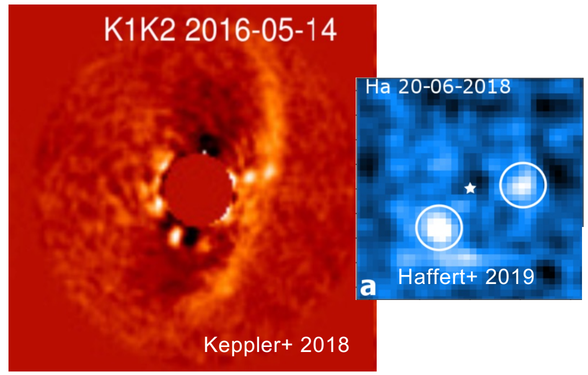
- **Q:** What are the cloud properties of young massive planets? How inflated are they? Are they metal rich? (e.g., Na and K searches)
- **CGI can:** Fill out SED with broadband photometry and spectroscopy
- **During TDP:** 1-2 systems
- **Beyond TDP:** Additional bandpasses and/or survey more known planets

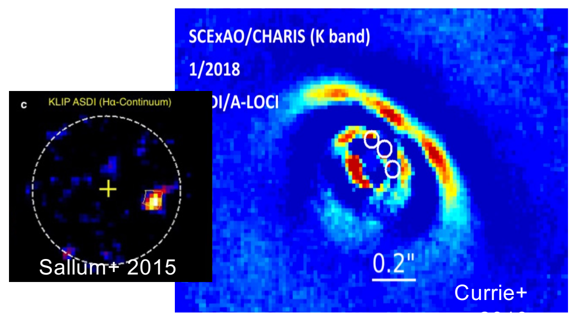


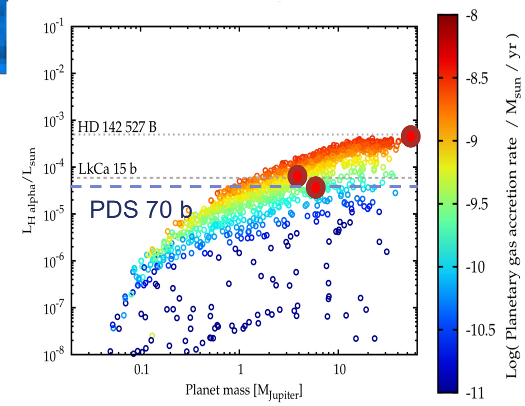
A = Clouds extending all through the entire atmosphere with particle number density scaling with gas
AE = Clouds have scale height 1/2 of the gas, so still extend up into atmosphere, but not as much as A type

H-alpha Imaging of Protoplanetary systems

- **Q:** What are the accretion properties of low-mass planets in formation (test model predictions)? How can we distinguish protoplanets vs. disk structures?
- **CGI Can**: Measure H-alpha at high contrast
- **Caveat***: Roman coronagraph will not achieve optimal contrast on faint (V > 6) host stars. Performance modeling TBD.*
- **During TDP:** *Perhaps* a test observation
- **Beyond TDP**: Observe transition disks with gaps in CGI FOV







First reflected light images of a mature Jupiter analog

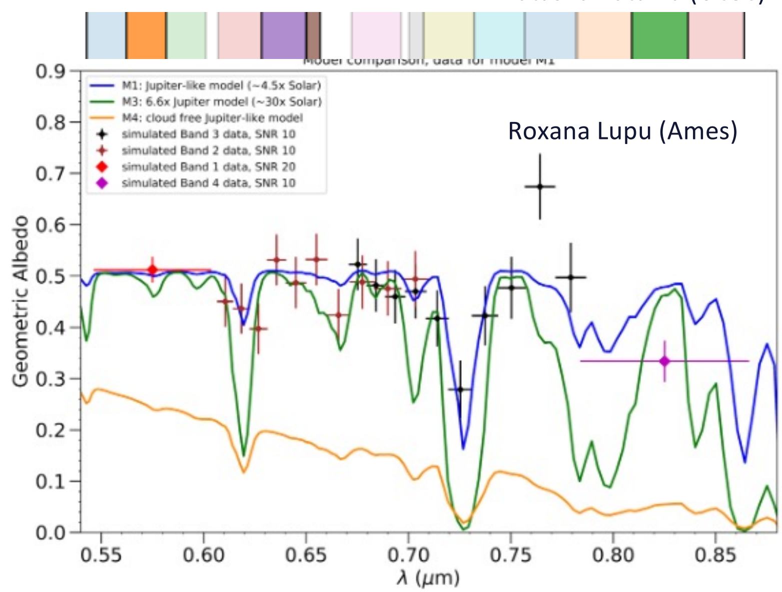
- **Q**: Are cold Jupiter analogs cloudy or clear?
- **CGI can:** Measure albedo at short wavelengths;
- **Q**: What are the masses of known RV giant planets?
- **CGI can**: Constrain inclination with 2-3 imaging epochs
- **During TDP:** 1-2 planets
- **Beyond TDP:** Additional narrowbands and/or survey more known planets

Spectral Characterization of a mature Jupiter analog

Increase confidence that we can detect molecular features in faint, high-contrast, reflected light spectra before we attempt exo-Earths

- **Q**: Are Jupiter analogs metal rich?
- **CGI can**: Coarsely constrain metallicity (5x vs. 30x Solar) if cloudy (high albedo)
- **During TDP:** 1 planet with 730nm spectroscopy
- **Beyond TDP**:
  - +1 planet
  - *OR* improve SNR of 1st planet
  - *OR* obtain narrowband photometry or 660nm spectroscopy of 1st planet.

Natasha Batalha (UCSC)



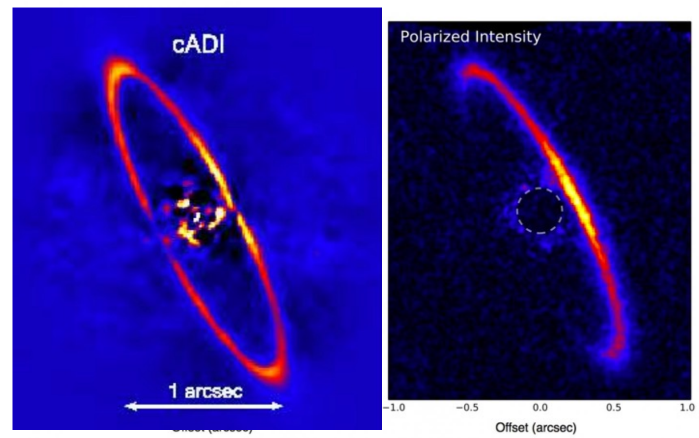
660nm spectroscopy is an unofficial observing mode

Known Cold Debris Disks Imaging in Total Intensity

- **Q**: Where does circumstellar material come from and how is it structured at low dust density levels where transport phenomena dominate over collisions?
- **CGI can**: Map morphology and scattered light flux of faint disks at smaller working angles than HST
- **During TDP:** 2-3 disks
- **Beyond TDP**: Additional disks with a variety of properties

Known Cold Debris Disks Polarimetric Imaging

- **Q**: What is the composition of planetary dust in the inner regions of debris disks?
- **CGI can:** Map color, degree of forward scattering, and the degree of polarization.
- **During TDP:** 1-2 disks
- **Beyond TDP:** Additional disks with a variety of properties



HR 4796A ring: Perrin+2015, Milli+2017, Anche+ 2023

Engaging the community in observation planning and preparation

- Community Participation Program (**CPP**)
  - External researchers from US & int'l partners (CNES, ESA, JAXA, MPIA)
  - Not only end users; also develop infrastructure (data pipeline, observation planning tools, etc)
  - Observation planning is a joint exercise between the instrument team and the CPP
  - Selected CPP proposals and PIs:

1. Coronagraph Instrument testing and performance evaluation in single- and binary star modes, *Rus Belikov, NASA Ames*
2. Calibrating Roman's Coronagraphic Imaging and Polarimetry Modes, *Max Millar-Blanchaer, UCSB*
3. Data driven investigations of the Coronagraph Instrument as a starlight suppression yardstick, *Laurent Pueyo, STScI*
4. Roman's Giants: Jovian Exoplanet Modeling and RCI Detectability, *Tyler Robinson, Univ. of Arizona*
5. Target Selection and Observation Modeling Tools for Coronagraph Tech Demo and Beyond, *Dmitry Savranski , Cornell Univ.*
6. Imaging and Characterizing Exoplanets with the Roman Coronagraph and Open-Source Tools, *Jason Wang, Northwestern Univ.*
7. Circumstellar Dust with the Roman Coronagraph, *Schuyler Wolff, Univ. of Arizona*

Engaging the community in observation planning and preparation (see https://roman.gsfc.nasa.gov/science/Roman_teamlist_cpp.html)

- Selected CPP proposals and PIs (2022 & 2024)

1. Coronagraph Instrument testing and performance evaluation in single- and binary star modes, *Rus Belikov, NASA Ames*
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7. Circumstellar Dust with the Roman Coronagraph, *Schuyler Wolff, Univ. of Arizona*
8. Unveiling the architecture of planetary systems through total and polarized intensity observations with the Roman Coronagraph, *Ramya Anche, Univ. of Arizona*
9. Modeling, Simulation, and Data Analysis Software Development for the Roman Coronagraph Instrument, *Jessica Gersh-Range, DM telescopes LLC*
10. Enabling Maximum Technical and Science Return of the Roman-Coronagraph with Precursor Observations and Simulations, *Justin Hom, Univ. of Arizona*
11. Maximizing the lessons to be learned from the Roman coronagraph, *Bruce Macintosh, University of Santa Cruz, CA*

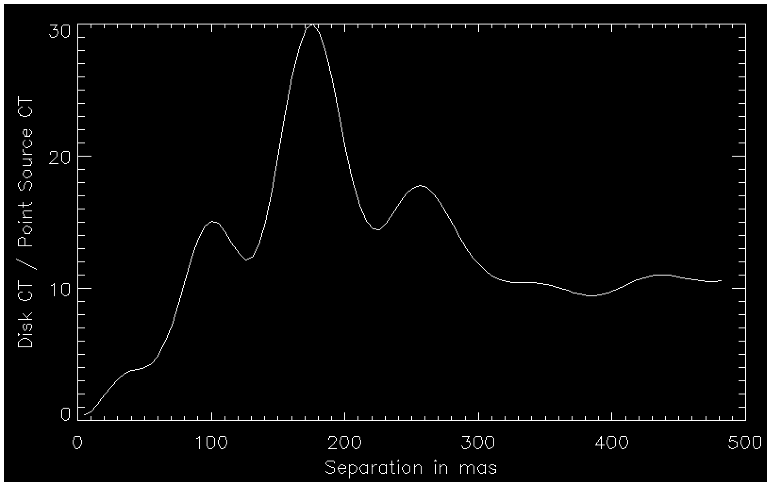
Summary

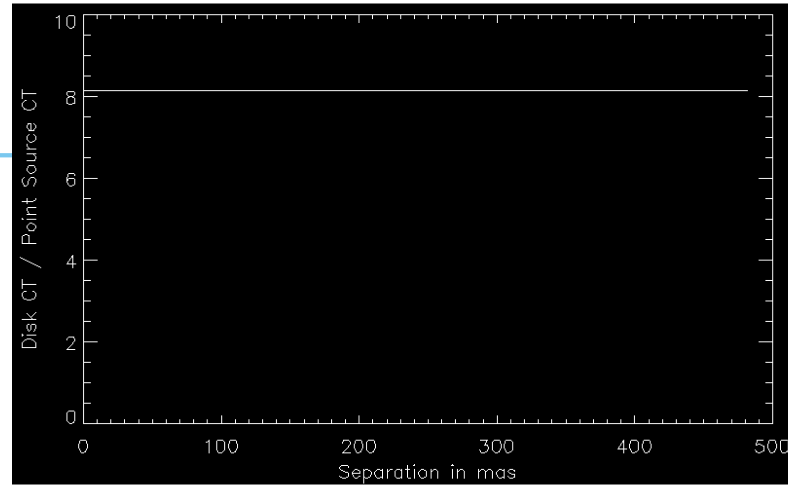
- Coronagraph matured multiple key technologies to lay the foundation for HWO
- Coronagraph was delivered to GSFC in May 2024
- TVAC testing demonstrated performance >4x beyond requirement
- Outlook improving for *some* use of "best effort" modes on sky
  - Some pre-delivery TVAC testing + FY24/25 budget overguide
- Community Participation Program (CPP) science team supports observation preparation, including broader community engagement
- CPP informed and solicited feedback from the community on target selection and worthy scientific and technical observations
- Will be more sensitive to faint extended disks than mature exoplanets
- *Full observational potential will go beyond what we can imagine today*

and will be for you to realize

Like to Know More about the Roman Coronagraph?

- Nancy Grace Roman Space Telescope at GSFC: https://roman.gsfc.nasa.gov
- Nancy Grace Roman Space Telescope at JPL:
  - https://www.jpl.nasa.gov/missions/the-nancy-grace-roman-space-telescope
- Nancy Grace Roman Space Telescope at IPAC https://roman.ipac.caltech.edu and https://roman.ipac.caltech.edu/sims/Coronagraph_public_images.html#CGI_OS11_report
- Nancy Grace Roman Space Telescope at STScI: https://www.stsci.edu/roman/
- Roman Coronagraph Test Results Info Session held at Caltech/IPAC on Aug 26-27 2024: https://conference.ipac.caltech.edu/romancgi24/
- Roman CPP website: https://www.romancoronagraph.space


Disk CT / Point Source CT
Separation in mas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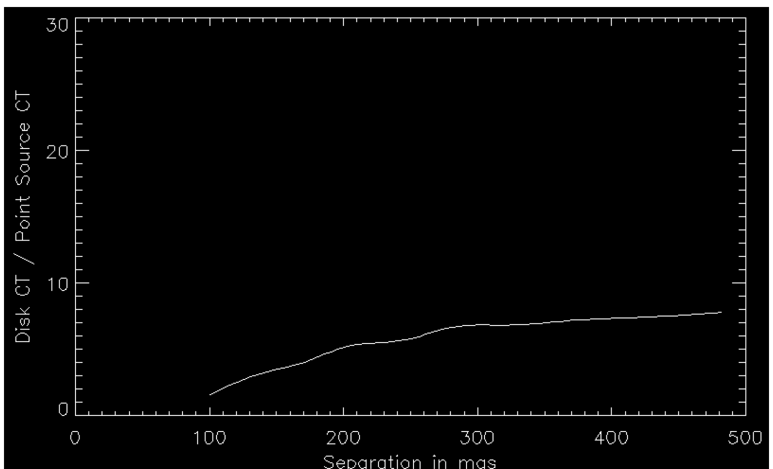
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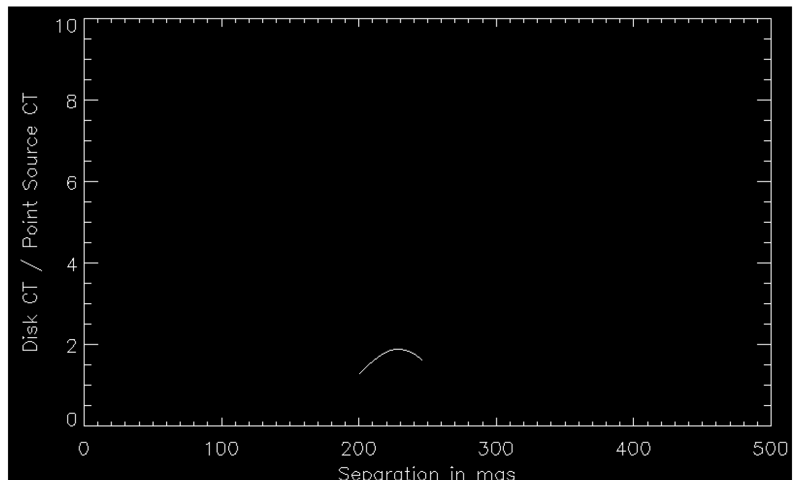
Disk CT / Point Source CT
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Coronagraph Mask Configurations: Tested vs. Launched

Coronagraph includes significant capability beyond what was tested during I&T to verify requirements

These modes can be commissioned in orbit if time and resources allow

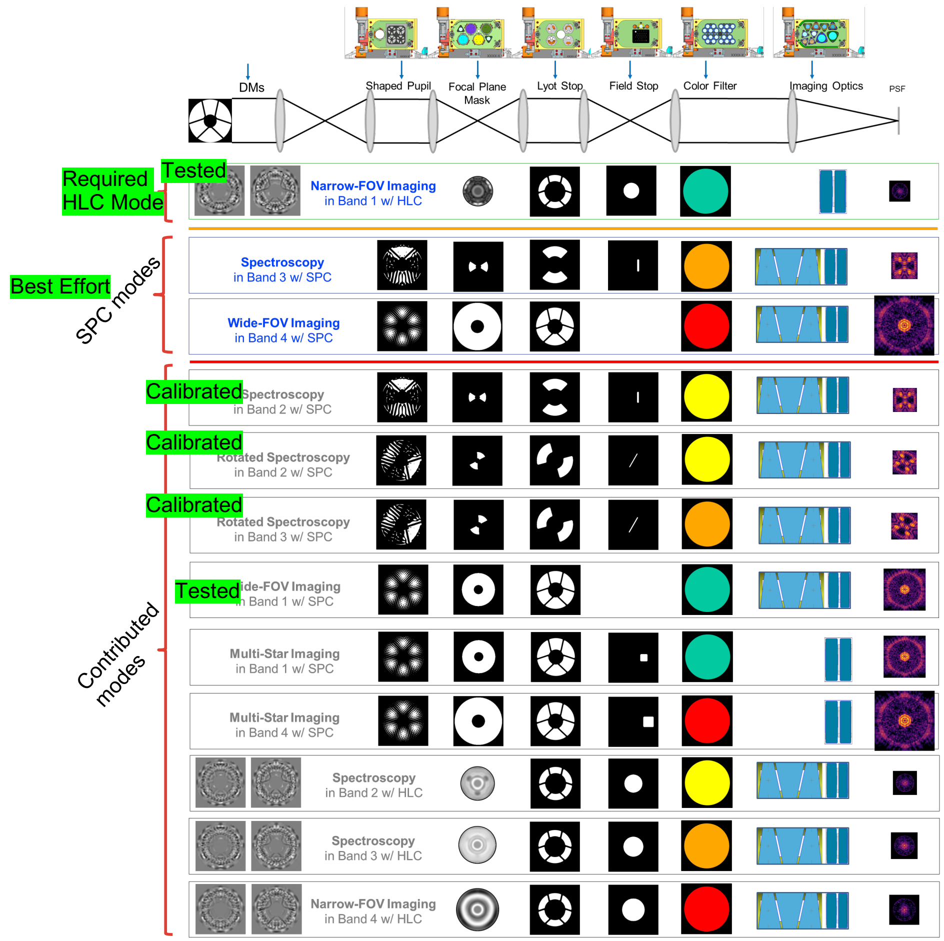
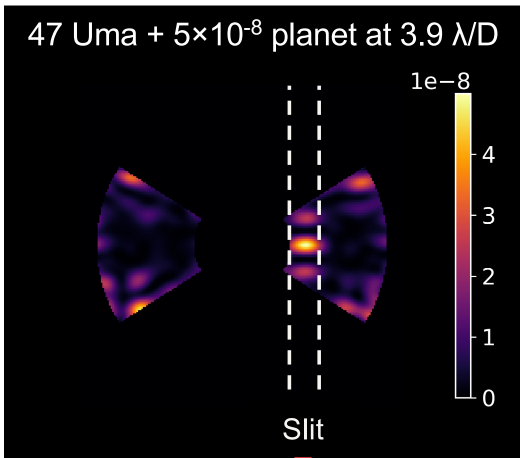
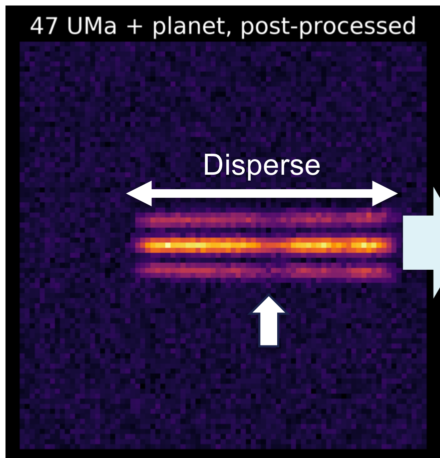


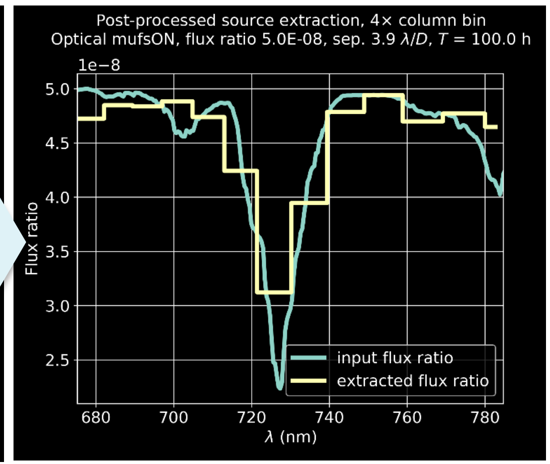
Fig. from Riggs et al, 2021, Vol. 11823, pp. 611-633 SPIE

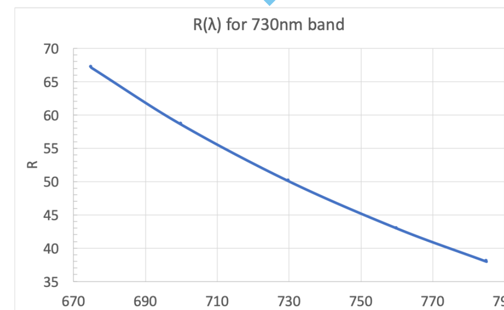
R~50 Spectroscopy w/ Slit Spectrograph (Band 3 or 2)

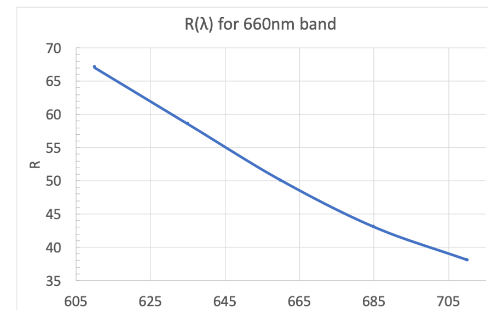
Simulated Performance











- Slit is deployed to planet position
- Prism disperses the Shaped Pupil PSF
- Spectrum is extracted from image after post-processing (Reference Star Subtraction)

Figures Courtesy: N. Zimmerman and T. Groff (GSFC)