Roman Coronagraph Instrument

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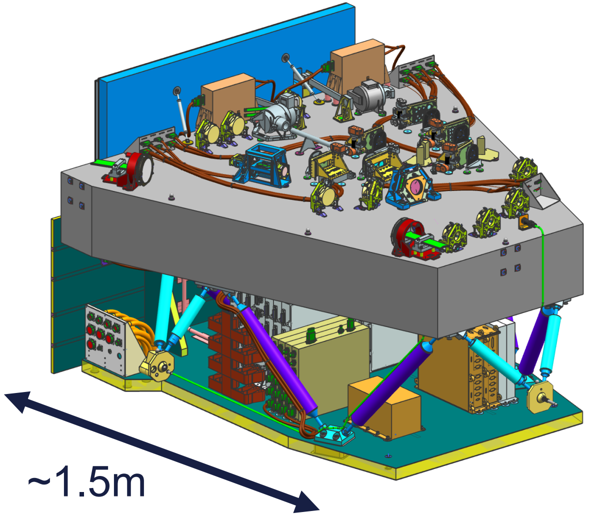
Support from many at the Jet Propulsion Laboratory, Goddard Space Flight Center, and the Science Teams led by Bruce Macintosh and Maggie Turnbull

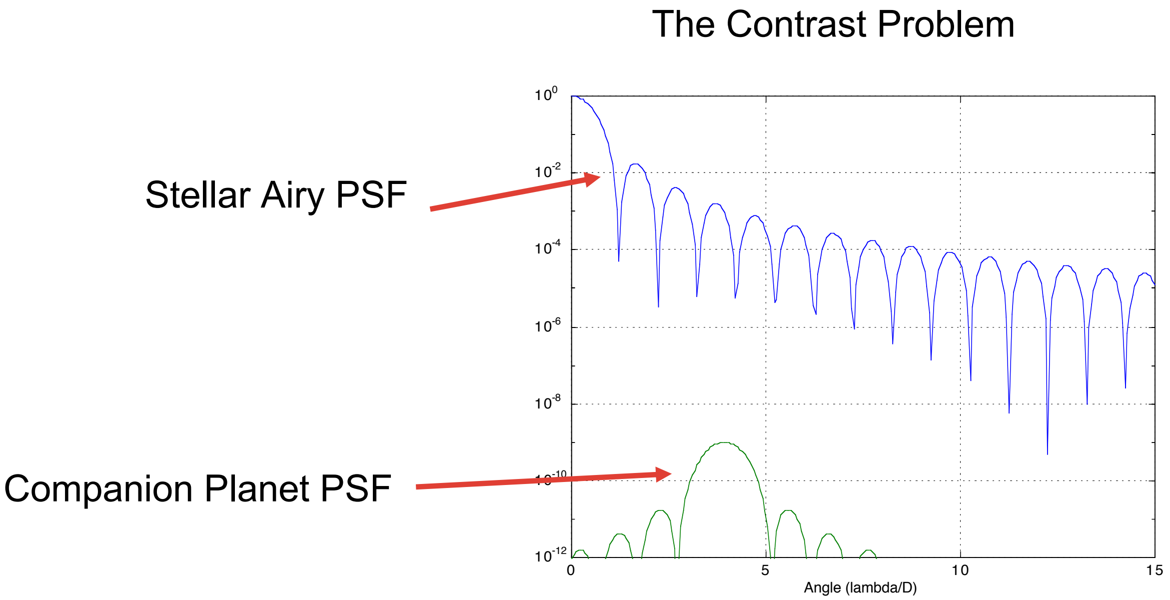
The Roman Coronagraph Instrument paves the way for future exoplanet direct imaging missions

- Coronagraph Instrument is:
  - a technology demonstration instrument on Roman
  - the first space-based coronagraph with active wavefront control
  - a visible light (545-865nm) imager, polarimeter and R~50 spectrograph
  - a 100-1,000 times improvement in performance over current ground and space facilities
  - Capable of exoplanetary system science
  - passed Instrument CDR

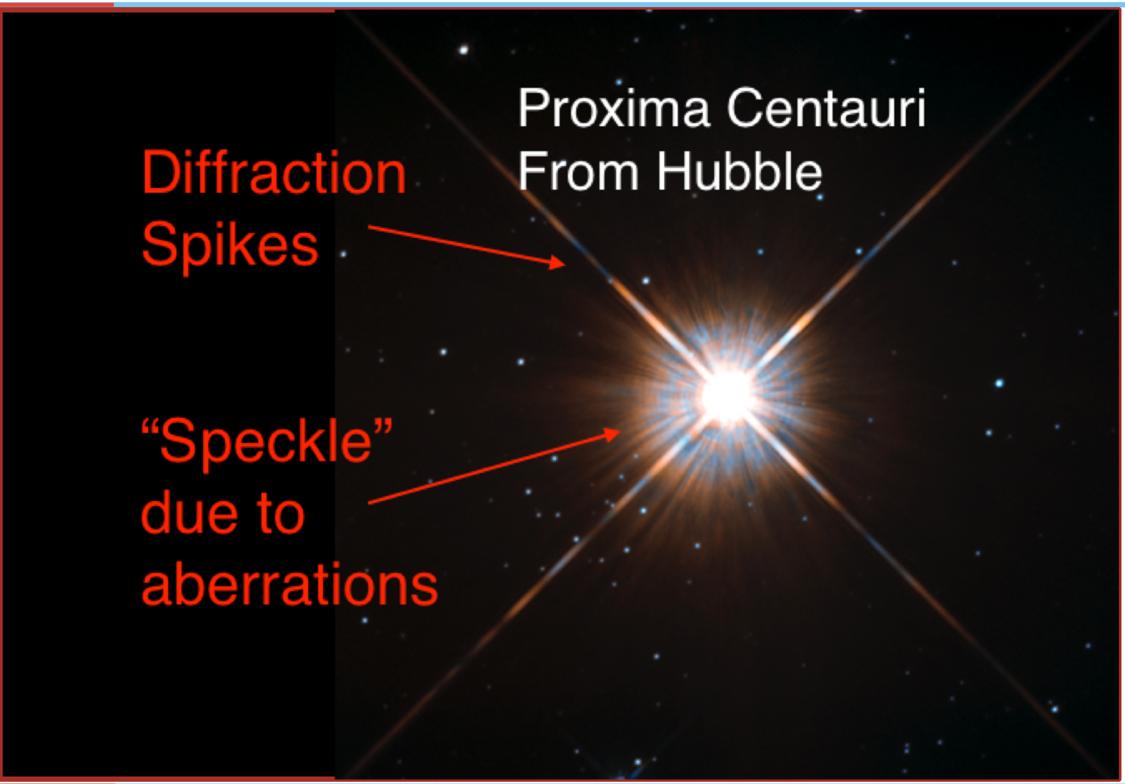


What is coronagraphy or high-contrast imaging?

Planets are hidden behind the diffracted and scattered light of the parent star.

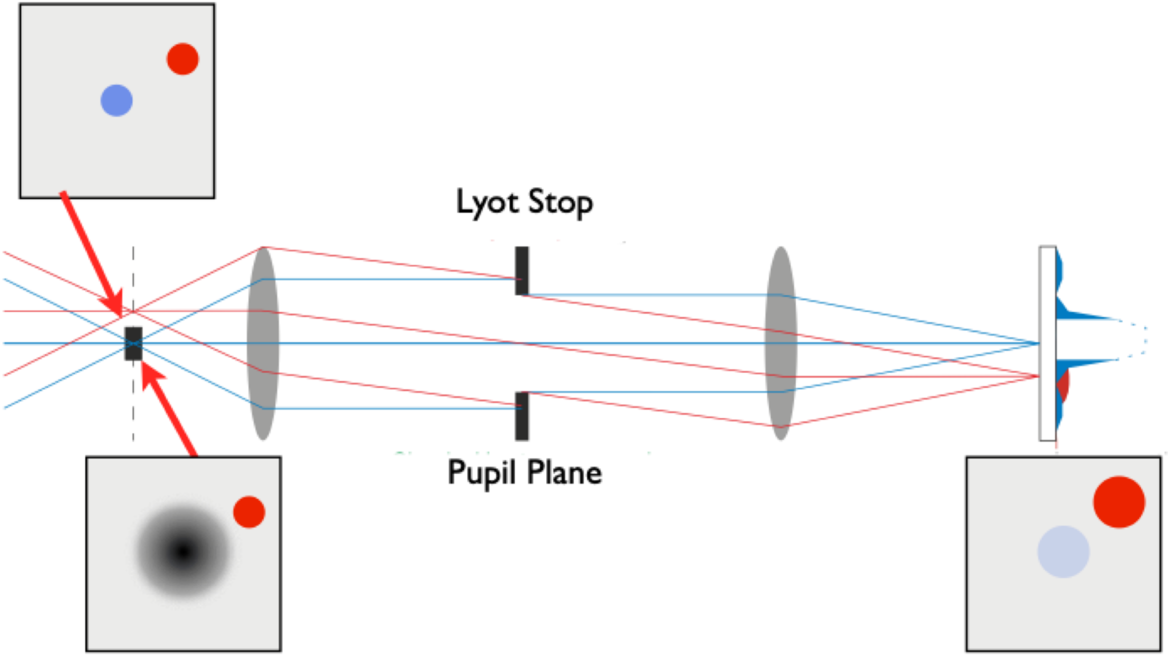


What is coronagraphy and high-contrast imaging?



A coronagraph uses specialized optics, masks, and stops to control diffraction and create high contrast and wavefront control with deformable mirrors (similar to adaptive optics) to correct aberrations that produce speckles.

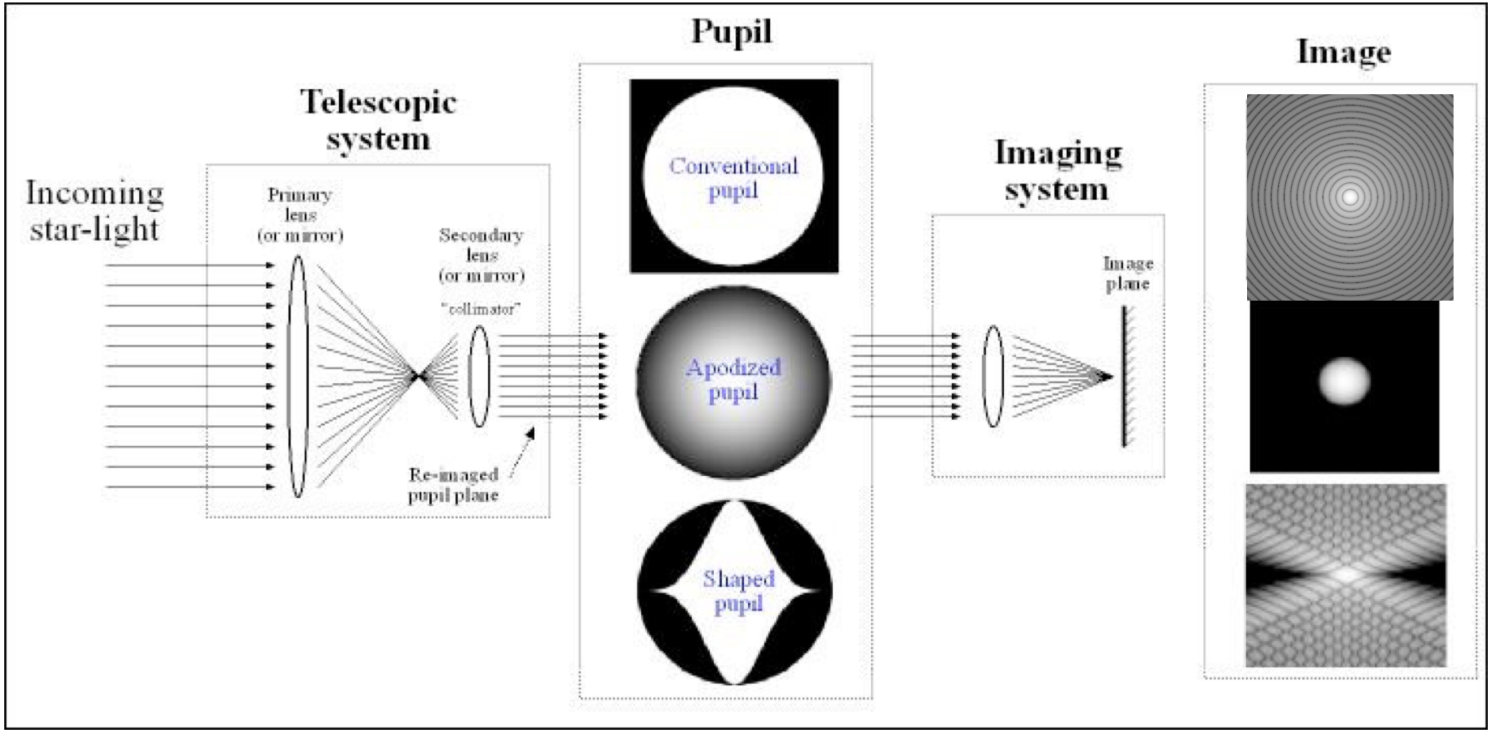
A Lyot Type Coronagraph



Removes diffracted starlight while letting some of planet light pass

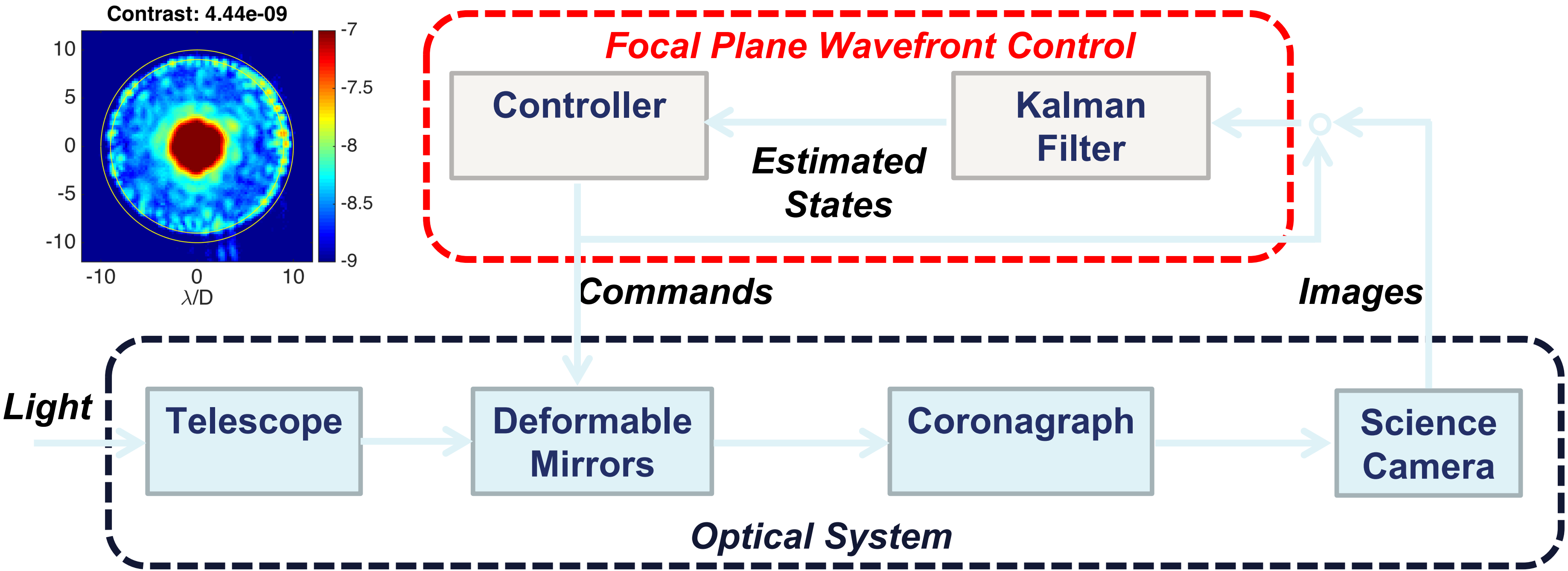
from Matt Kenworthy, University of Leiden

Apodized and Shaped Pupil Coronagraph

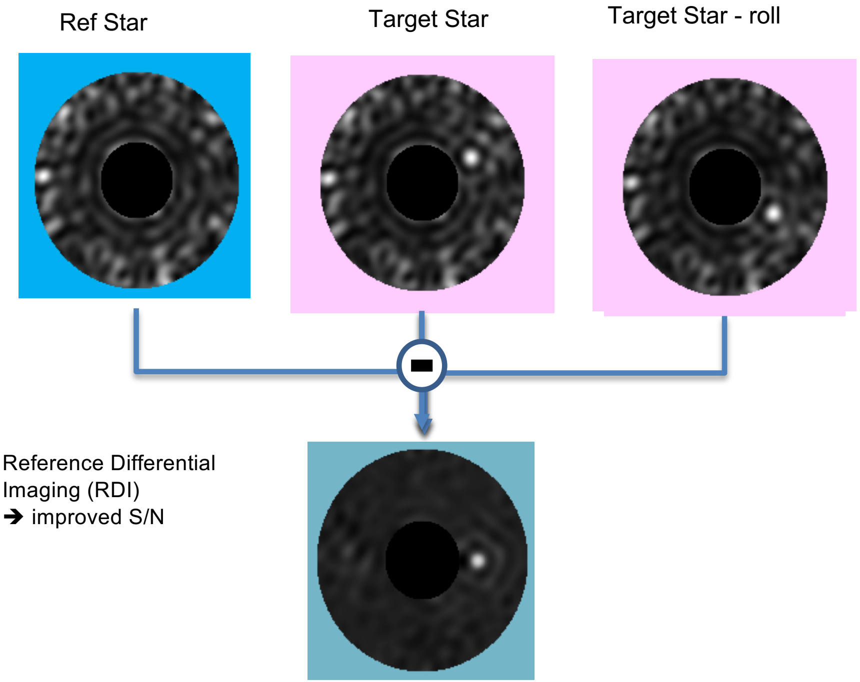


Change PSF to create high contrast at planet location.

Wavefront Sensing and Control



Differential Imaging - Postprocessing

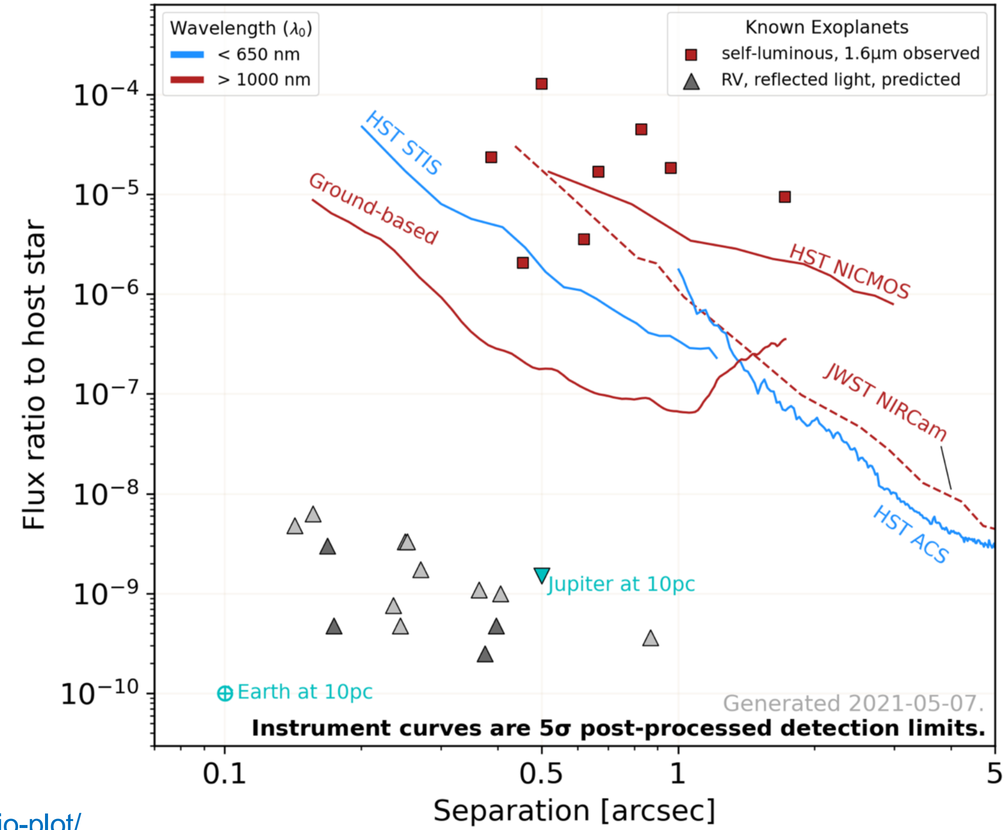


Reference Differential
Imaging (RDI)
➔ improved S/N

Technology Objectives for Coronagraph Instrument

- Demonstrate Coronagraphy with Active Wavefront Control
- Advance Engineering & Readiness of Coronagraph Elements
- Development and Demonstration of Advanced Coronagraph Algorithms
- Collect Data to Enable Integrated Observatory Performance Characterization
- Demonstration of Advanced High-Contrast Data Processing

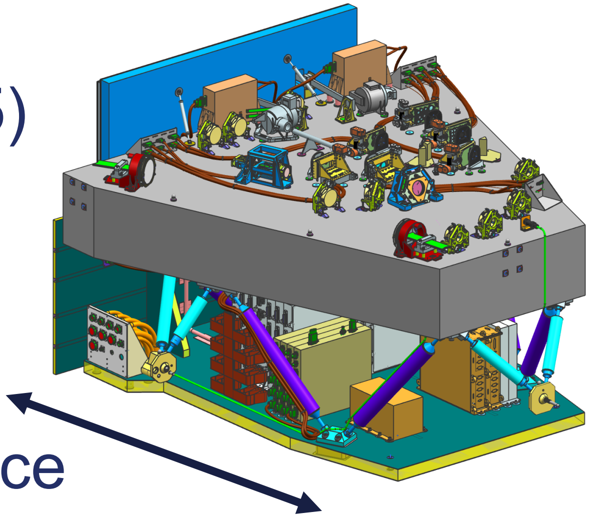
Goal: bridge gap between massive self-luminous planets (IR) and reflected light exo-Earths (visible)



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

Original Baseline Technology Requirements (BTRs)

- Broadband High-Contrast Imaging (BTR5)
- High-Contrast Spectroscopy (BTR6)
- High-Contrast Extended Source Imaging (BTR7)
- Broadband High-Contrast Extended Source imaging and Polarimetry (BTR8)



After PDR, NASA HQ directed team to move to only Threshold Technology Requirements but retain PDR design.

Threshold Technology Requirement #5 (TTR5)

- **TTR5:** Roman shall be able to measure brightness of an astrophysical point source w/ SNR ≥ 5 located 6 – 9 λ/D from an adjacent star with V_{AB} ≤ 5, flux ratio ≥ 10^{-7}; bandpass shall have a central wavelength ≤ 600 nm and a bandwidth ≥ 10%.

- Despite removing all but TTR5, HQ directed the team to keep original design
- TTR5 will be verified before instrument delivery with end-to-end performance testing.
  - The optics for the other observing modes will be fully aligned but not end-to-end performance-tested before delivery.

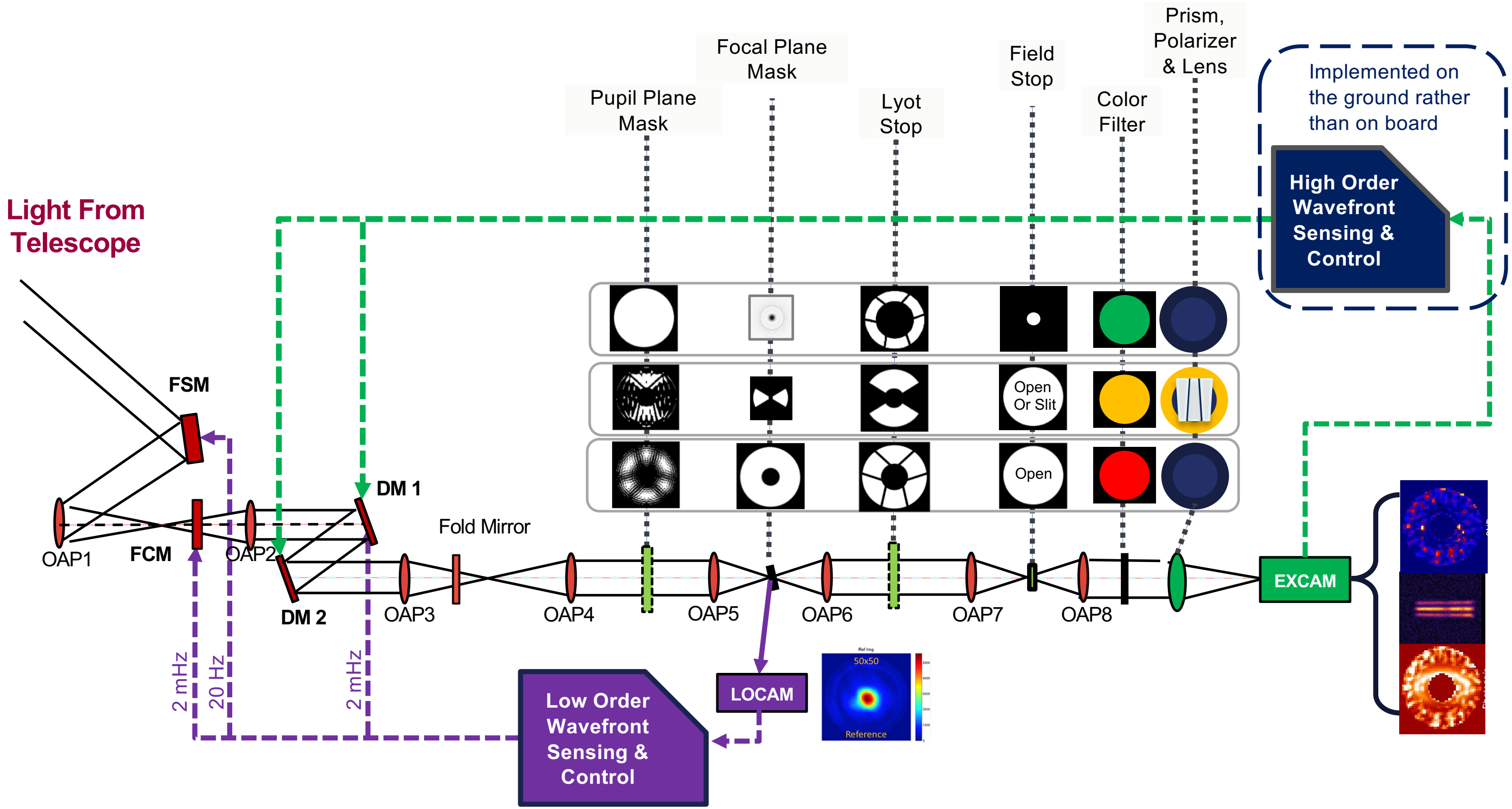
Primary Observing Modes

Band	λ_{center}	BW	Mode	FOV radius	FOV Coverage	Pol.	Coronagraph Mask Type	TTR5
1	**575 nm**	**10%**	**Narrow FOV Imaging**	**0.14" – 0.45"**	**360°**	**Y**	**Hybrid Lyot**	**Y**
2	660nm*	15%	Slit + R~50 Prism Spectroscopy	0.18" – 0.55"	2 x 65°	-	Shaped Pupil	-
3	730 nm	15%	Slit + R~50 Prism Spectroscopy	0.18" – 0.55"	2 x 65°	-	Shaped Pupil	-
4	825 nm	10%	"Wide" FOV Imaging	0.45" – 1.4"	360°	Y	Shaped Pupil	-

* Other filters and masks will be installed but will not be fully ground-tested and will not be guaranteed (eg: 660nm spectroscopy and ExEP-contributed coronagraph masks)

Complete list of filters available at https://roman.ipac.caltech.edu/sims/Param_db.html
Can't mix & match coronagraph mask w/ any filter; must be sub-band

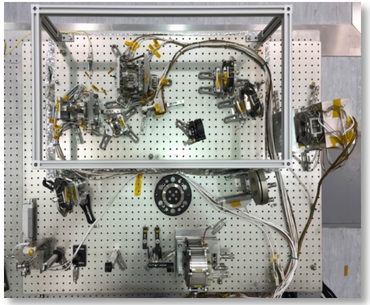
Key technologies work together as a system to deliver high performance



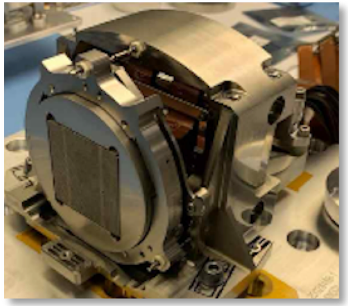
OAP = Off-Axis Parabolic [Mirror]

CGI will demonstrate key technologies for future missions

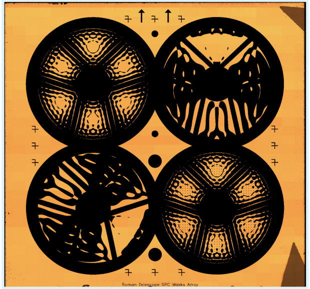
Ultra-Precise Wavefront Sensing & Control (now Ground-In-The-Loop)

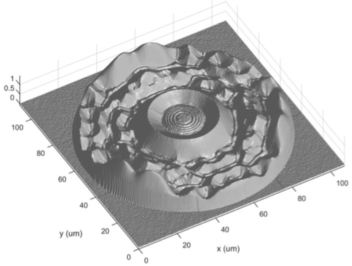


Large-format Deformable Mirrors

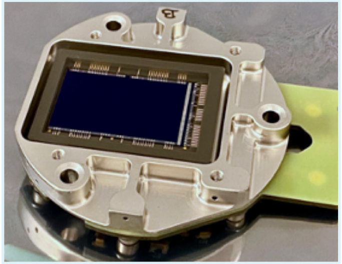


High-contrast Coronagraph Masks

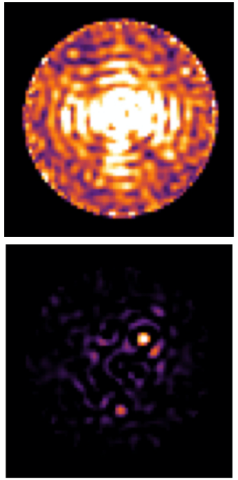




Ultra-low-noise Photon-counting EMCCDs



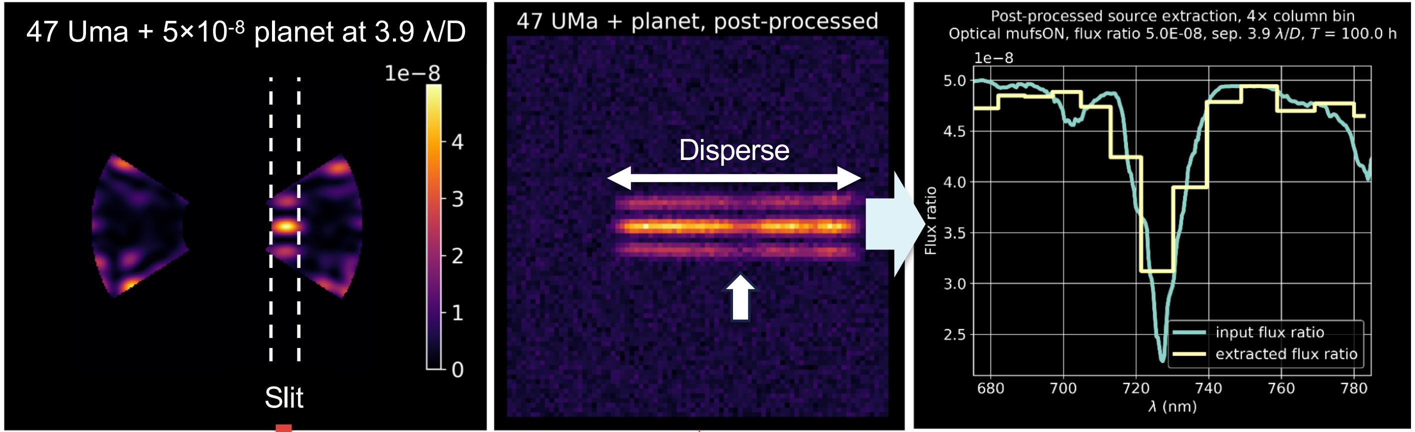
Data Post-Processing



All hardware now at TRL ≥ 6

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

Simulated Performance

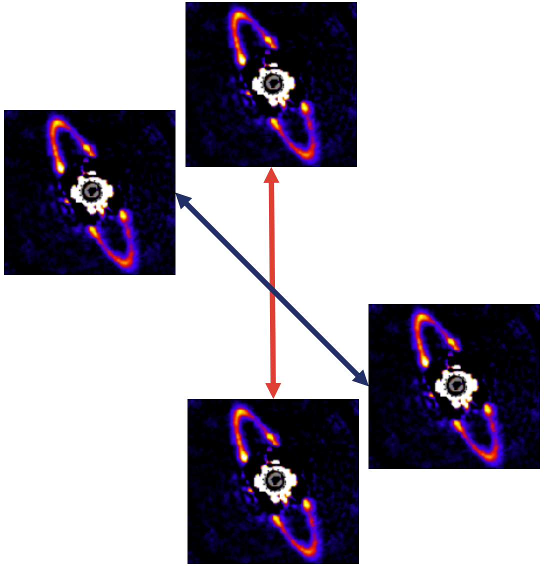


- Slit is deployed to planet position
- Prism disperses the Shaped Pupil PSF
- Spectrum is extracted from image after post-processing (Reference Star Subtraction)

Wollaston Prism Polarimetry (Band 1 or 4 imaging)

I_0

I_{45}

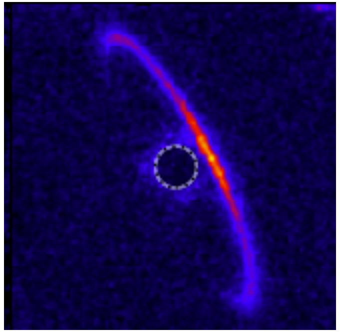


I_{135}

I_{90}

1 pair at a time
Pairs separated by 7.5” on chip

Linear polarized fraction (LPF) goal:
RMSE < 3% *per resel*

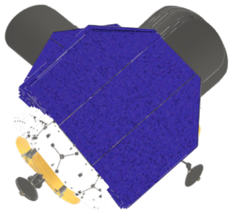


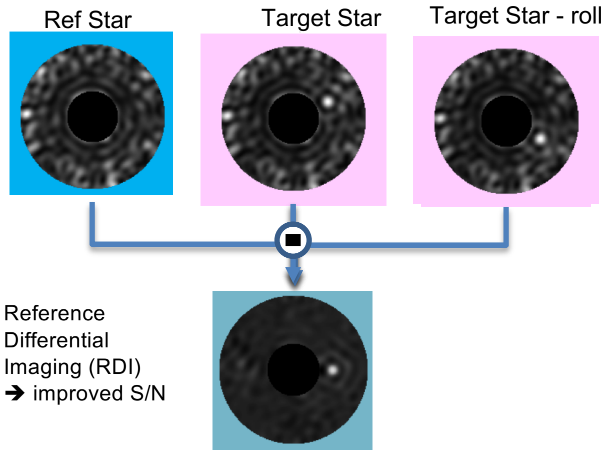
$LPF = \text{sqrt} \{(I_0 - I_{90})^2 + \{(I_{45} - I_{135})^2\} \; / \; I_{tot}$

Nominal operations: target & reference star

Reference Star
V < 3
<~ 1 mas angular diameter
Hot O/B
WFSC & PSF reference

Target Star
V < 5 (maybe V<6-7; TBD)
< 2 mas strongly preferred
Typically Solar-type





Target vs Reference should have small delta (spacecraft) pitch for better thermal stability

Adapted from J. Krist

Need both active wavefront control and optimized in-orbit operations to meet L1 requirements

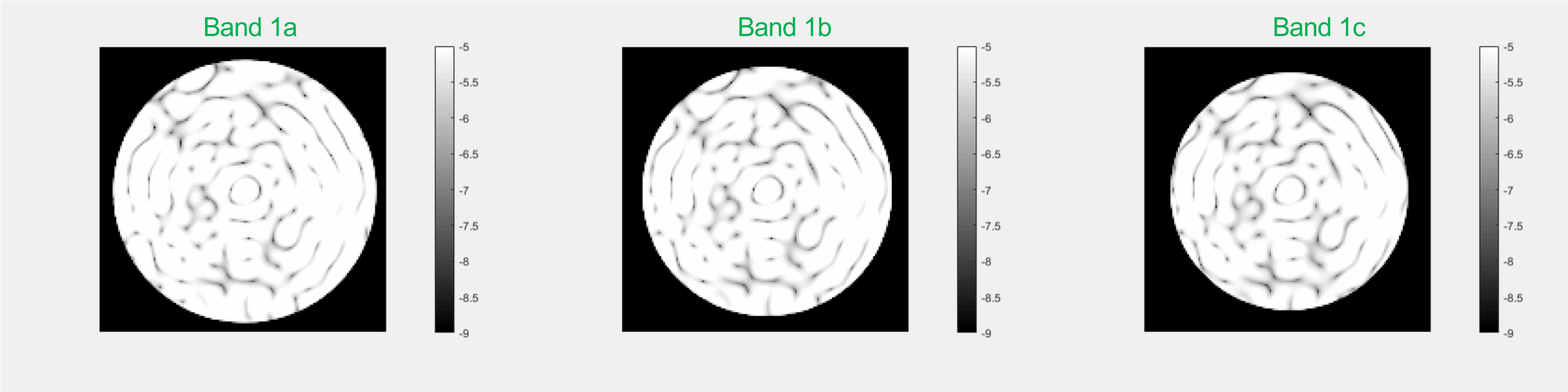
What is High-Order Wavefront Sensing and Control (HOWFSC)?

HOWFSC "digs the dark hole" by cycling through iterations of:

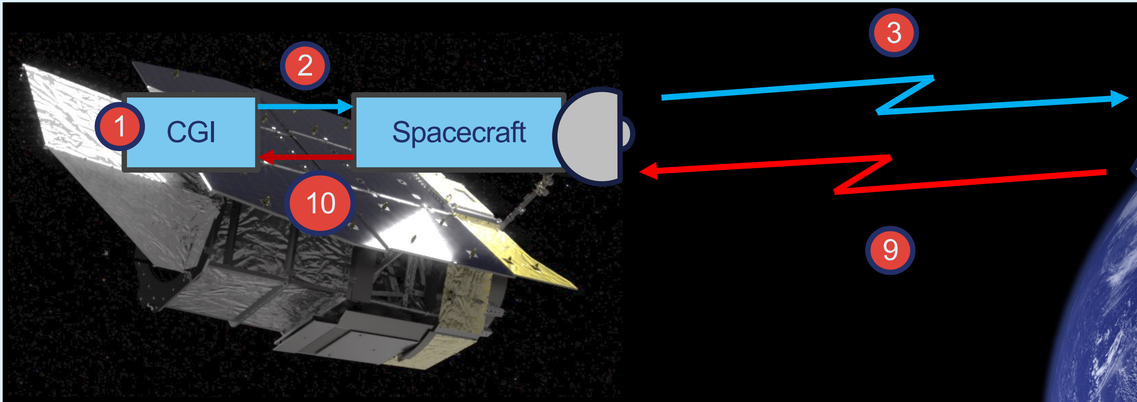
Wavefront sensing at primary camera EXCam ("focal plane wavefront sensing")

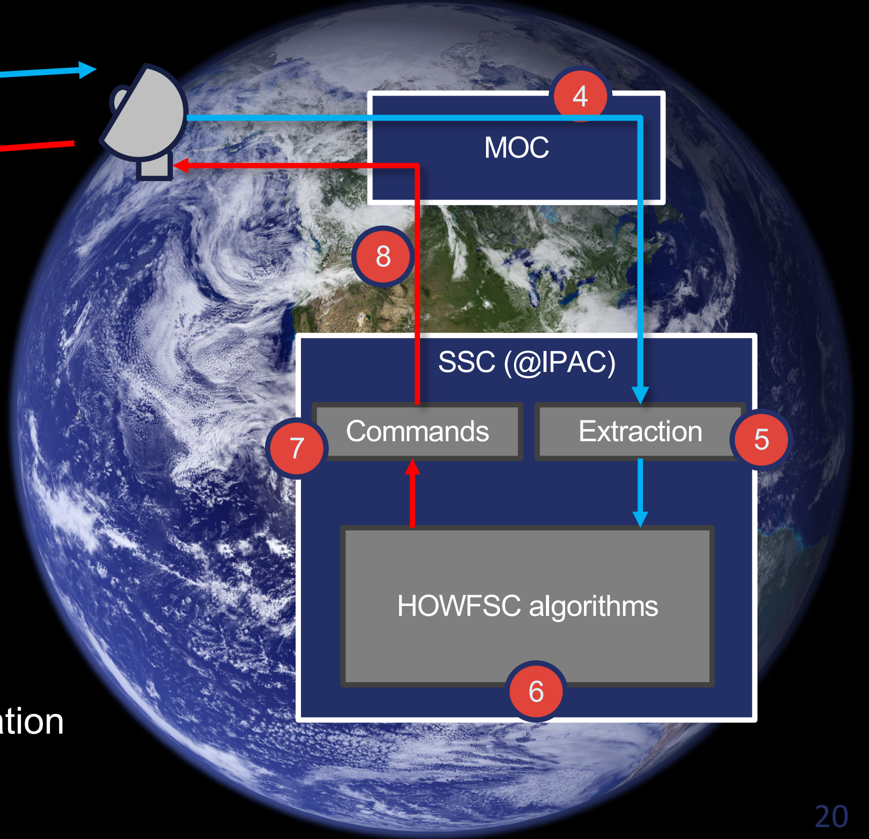
Wavefront control, by using a model to solve for the next set of DM settings

These cycles are repeated to reduce the residual starlight level and permit the detection of faint astrophysical signals in the vicinity of the star.



HOWFS Operates "Ground In the Loop" (GITL)





Roman Coronagraph Dark Hole Algorithms Interest Group

Neil Zimmerman neil.t.zimmerman@nasa.gov

Computation offloaded to ground

~Daily contacts; Small number of iterations per contact

10s of minutes / iteration due to comm's bandwidth

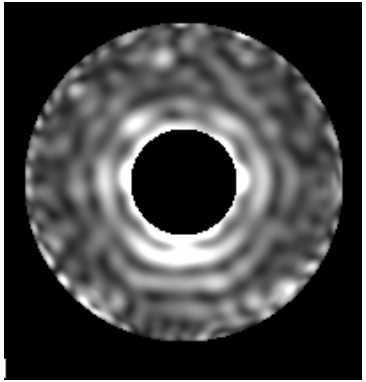
Potential for contributed HOWFSC algorithms. Testing/validation support TBD

Observing Scenarios (OS#)

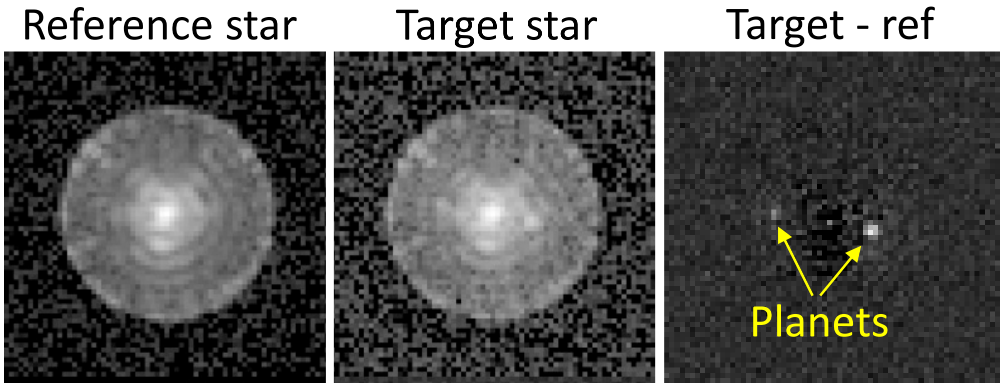
- Observing scenario includes slews to/from target & reference stars
- Thermal (solar incidence) and structural finite element modeling
- Dynamic modeling (vibration from reaction wheels)
- Low-order wavefront sensing & correction modeling
- Optical diffraction modeling produces speckle field time series

OS9 Speckle Field Time Series

(includes model uncertainty factors)



Summed Images



Simulations are available from:

https://roman.ipac.caltech.edu

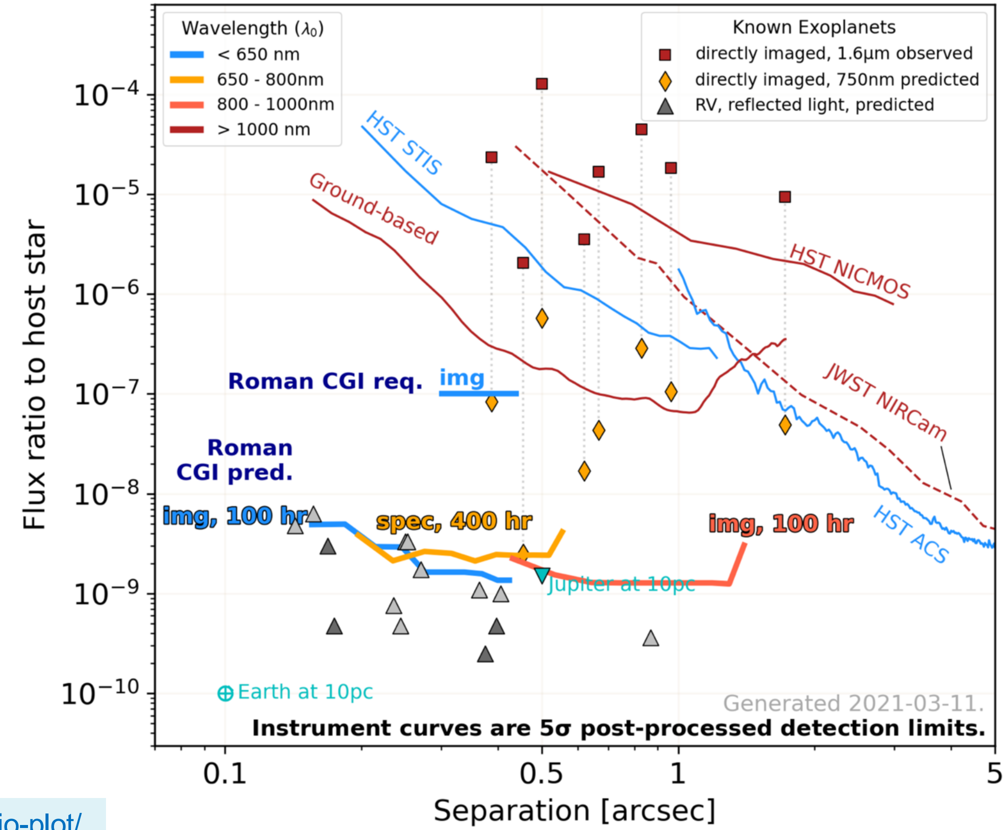
OS9 is the latest scenario

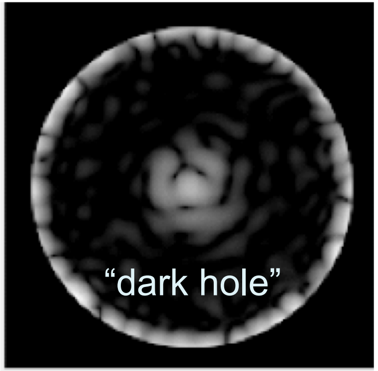
OS11 due later this year, will incorporate ground-in-the-loop

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 (UA Huntsville)
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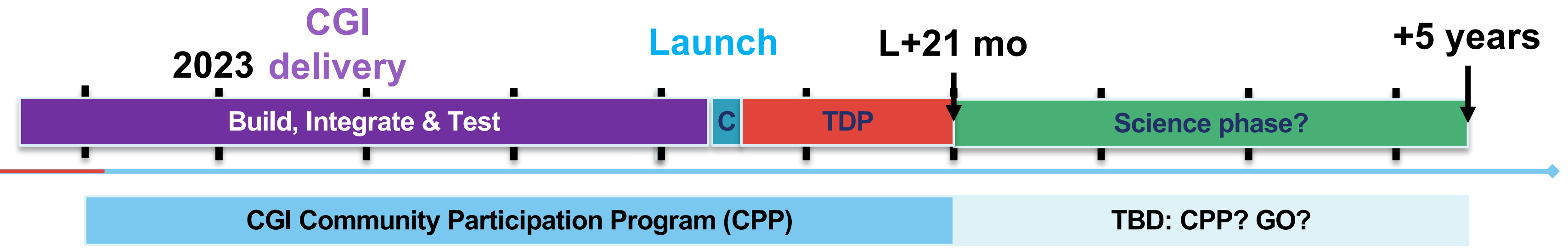
Hanying Zhou (JPL)
Sergi Hildebrandt-Rafels (JPL)

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



Apr 2021: Passed Instrument Critical Design Review

~2023: Instrument delivery to payload integration & test

~2026: Launch

Commissioning Phase

450 hr in first 90 days after launch

Coronagraph Instrument Technology Demonstration Phase (TDP)

~2200 hr (3 months) baselined in next 1.5 years of mission

- **If TDP successful, potential add'l science phase**
  - 10-25% of remainder of 5 year mission
  - Commission unofficial observing modes (add'l mask+filter combo's)
  - Support community engagement in science and technology
  - Not guaranteed: would require additional resources
  - Starshade rendezvous, if selected

Backup Slides

Original Baseline Requirements - 1

BTR5: (Broadband High-Contrast Imaging) WFIRST shall be able to measure, with SNR ≥ 10, the brightness of an astrophysical point source located between 4 and 7.5 lambda/D from an occulted star of V_{AB} magnitude ≤ 5, for a source with a flux ratio as faint as $5 \cdot 10^{-8}$ and a bandpass with a central wavelength ≤ 600nm and a bandwidth ≥ 10%.

BTR6: (High-Contrast Spectroscopy) WFIRST shall be able to measure, with average SNR per spectral resolution element ≥ 10, a spectrum of an astrophysical point source located between 4 and 7.5 lambda/D from an occulted star with V_{AB} magnitude ≤ 5, for a source with a flux ratio as faint as $5 \cdot 10^{-8}$, a bandpass with a central wavelength ≤ 750nm and a bandwidth ≥ 15%, and a spectral resolution R ≥ 50 at the bandpass central wavelength.

Original Baseline Requirements - 2

BTR7: : (High-Contrast Extended Source Imaging) WFIRST shall be able to map, with SNR ≥ 10, an extended source located between 8 and 18 lambda/D from an occulted star with V_{AB} magnitude ≤ 5, for an integrated surface brightness per resolution element sensitivity equivalent to a source-to-star flux ratio as faint as $5 \cdot 10^{-8}$ in a bandpass with a central wavelength ≤ 850 nm and a bandwidth ≥ 10%.

BTR8: (Broadband High-Contrast Extended Source Polarimetry) WFIRST shall be able to map, with a systematic uncertainty (rmse) ≤ 0.03, the linear polarization fraction of an extended source adjacent to an occulted star with V_{AB} magnitude ≤ 5, for regions with linear polarization fractions between 0.2 and 0.4, in a bandpass with a central wavelength ≤ 850 nm and a bandwidth ≥ 10%.