Roman Coronagraph Instrument

Vanessa Bailey – Jet Propulsion Laboratory, California Institute of Technology

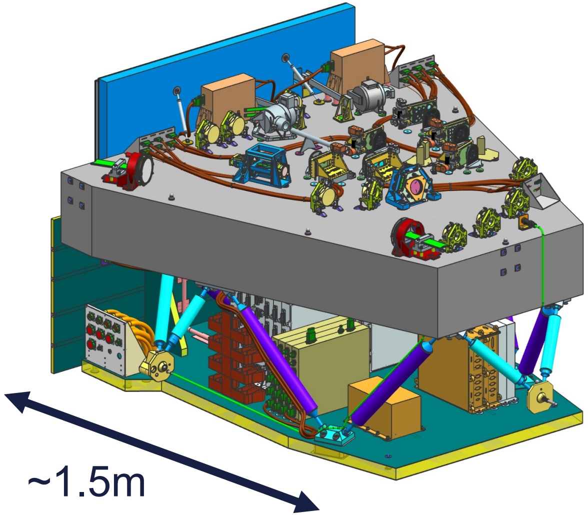
Many slides borrowed from prior talks, incl. from Dominic Benford, Jeremy Kasdin, Eric Cady, Bertrand Mennesson, …

Topics

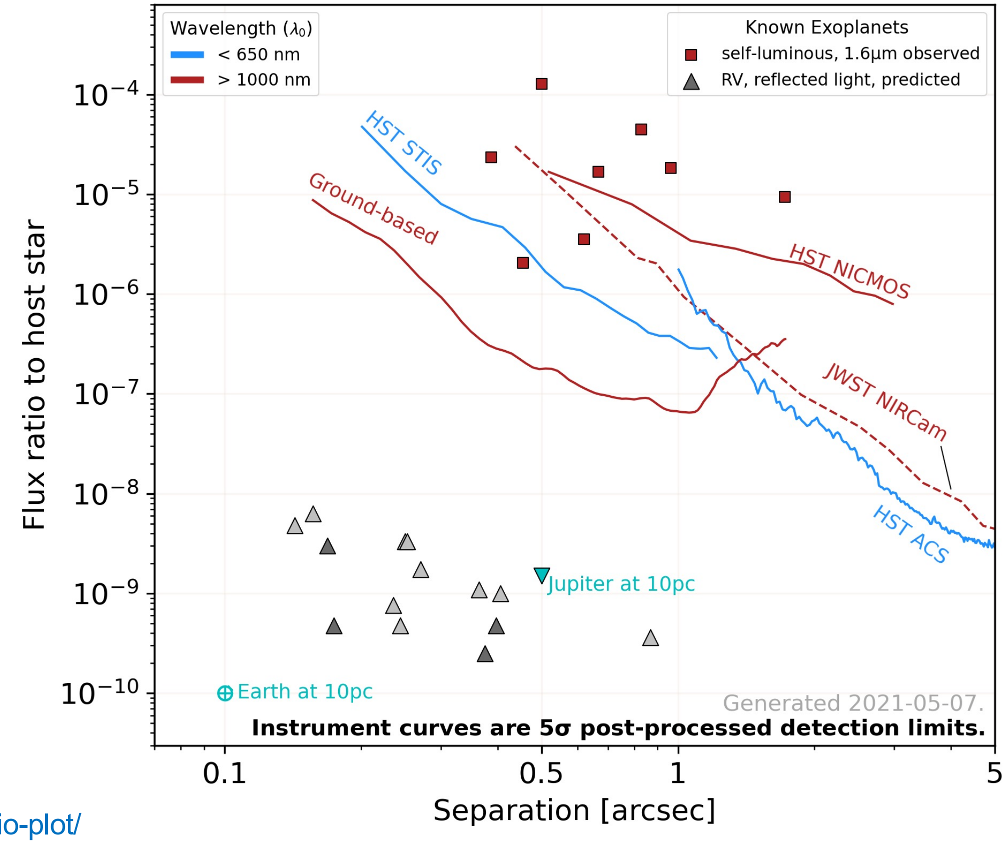
- Overview – tech demo, key technologies, modes
- Operations & performance predictions
- Potential science applications

Coronagraph Instrument paves the way for future 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



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



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

Tech Demo Purpose & Constraints

- Pave the way for future exo-Earth imaging missions
- **System-level** demonstration, on orbit
  - Component testing alone is not sufficient
- Learn throughout: design, model, build, test, use
  - allowed to incorporate improved technological advances beyond PDR
- Cannot drive mission requirements or schedule
  - Will be flown with best possible performance given cost and schedule constraints
  - Has no mission success criteria, but does have PLRA Objectives
  - No Threshold Science Req't, only one Threshold Technology Req't (TTR5)
- Required & funded lifetime (launch + 21mo) < Mission duration

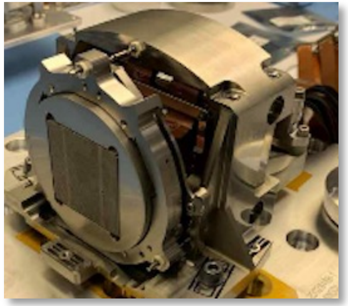
PLRA Objectives for Coronagraph Instrument

- 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

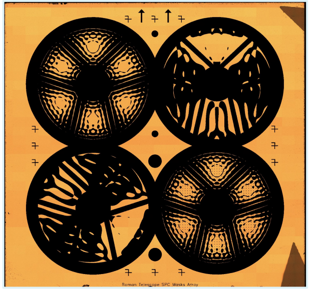
CGI will demonstrate key technologies for future missions

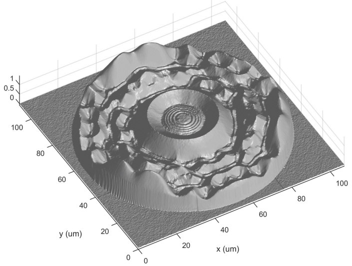
Proc. SPIE volume 11443

Large-format Deformable Mirrors



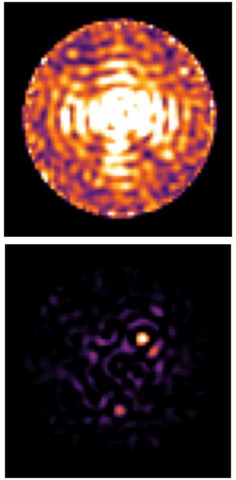
High-contrast Coronagraph Masks



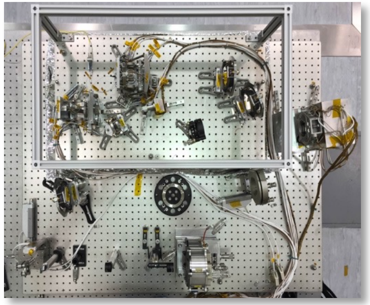


Ultra-low-noise Photon-counting EMCCDs

Data Post-Processing

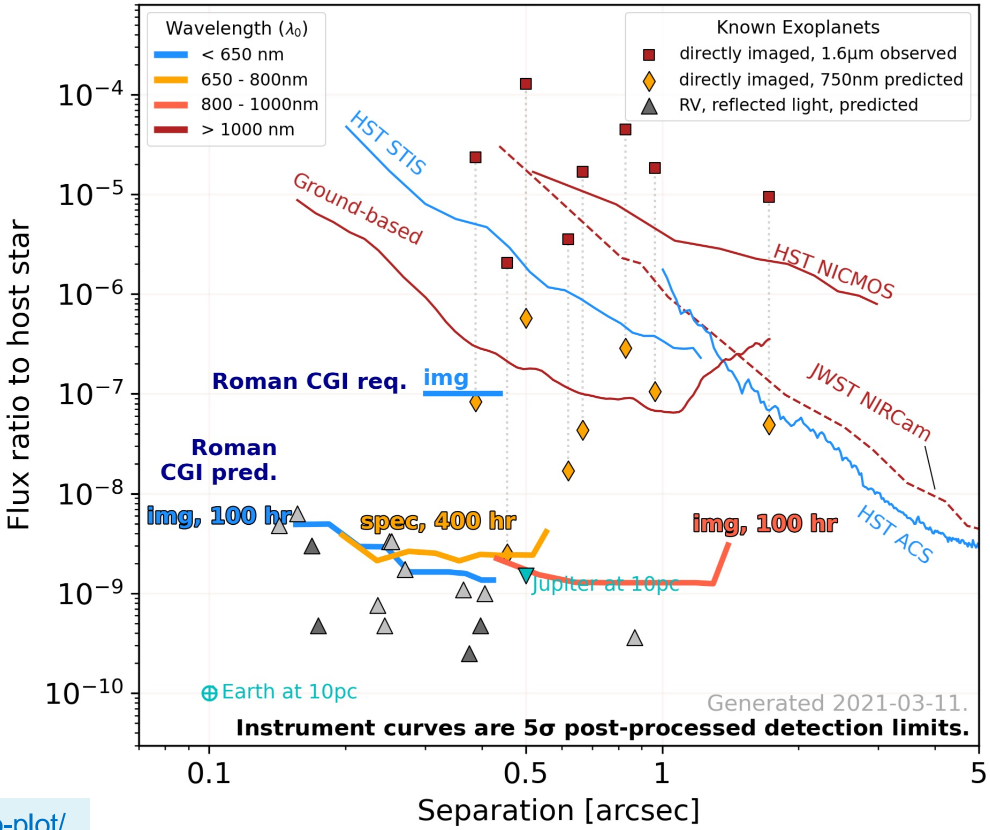


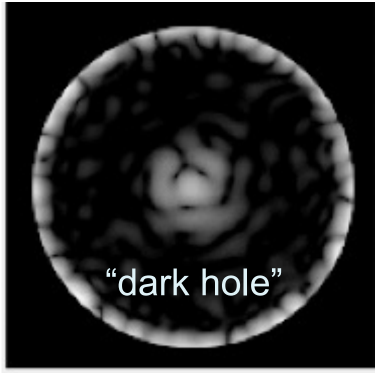
Ultra-Precise Wavefront Sensing & Control (now Ground-In-The-Loop)



All hardware now at TRL ≥ 6

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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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 $V_{AB} \leq 5$, flux ratio ≥ 10^{-7}; bandpass shall have a central wavelength ≤ 600 nm and a bandwidth ≥ 10%.

- Despite removing all but TTR5, HQ directed us 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.

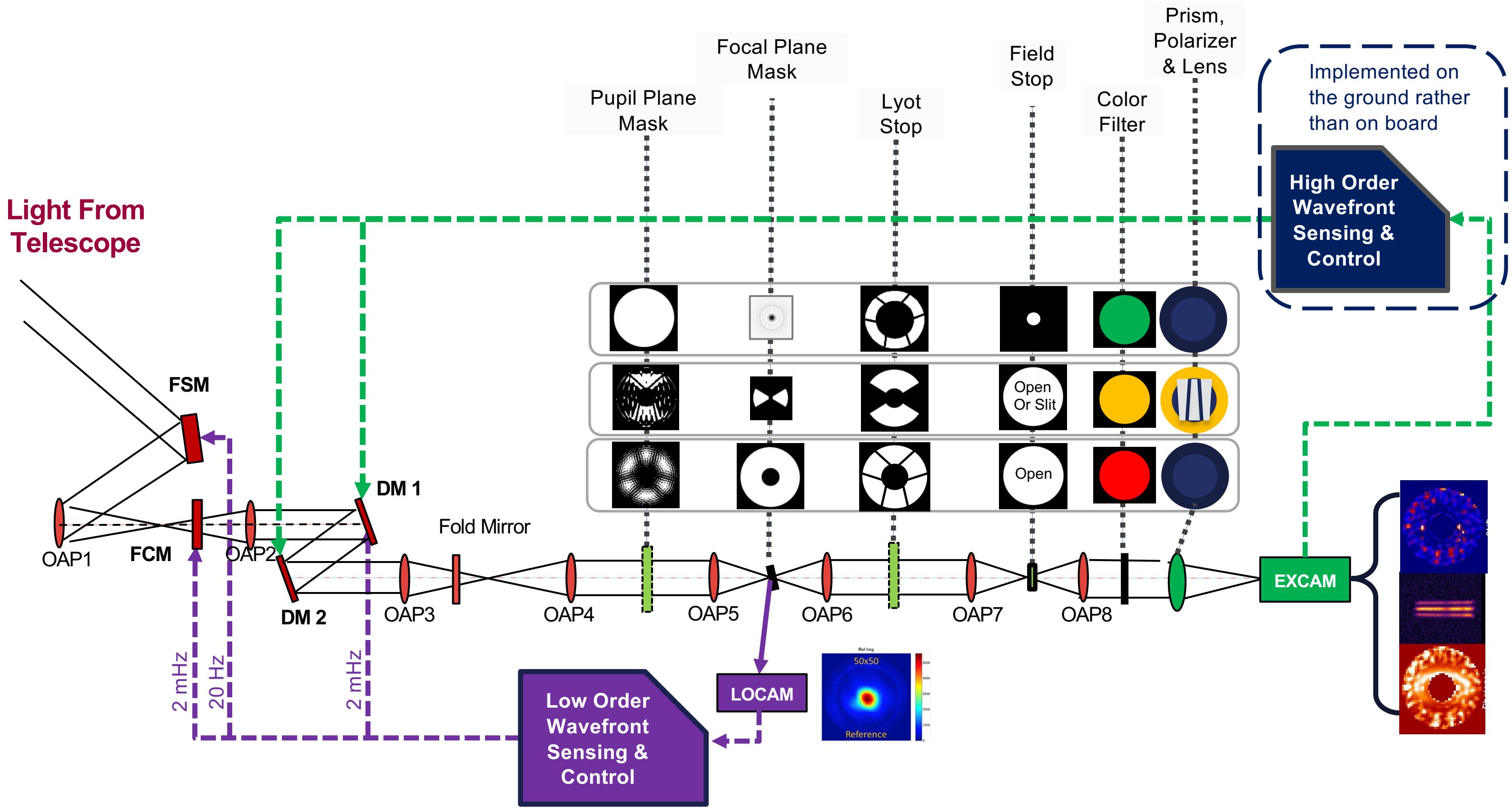
Primary Observing Modes

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

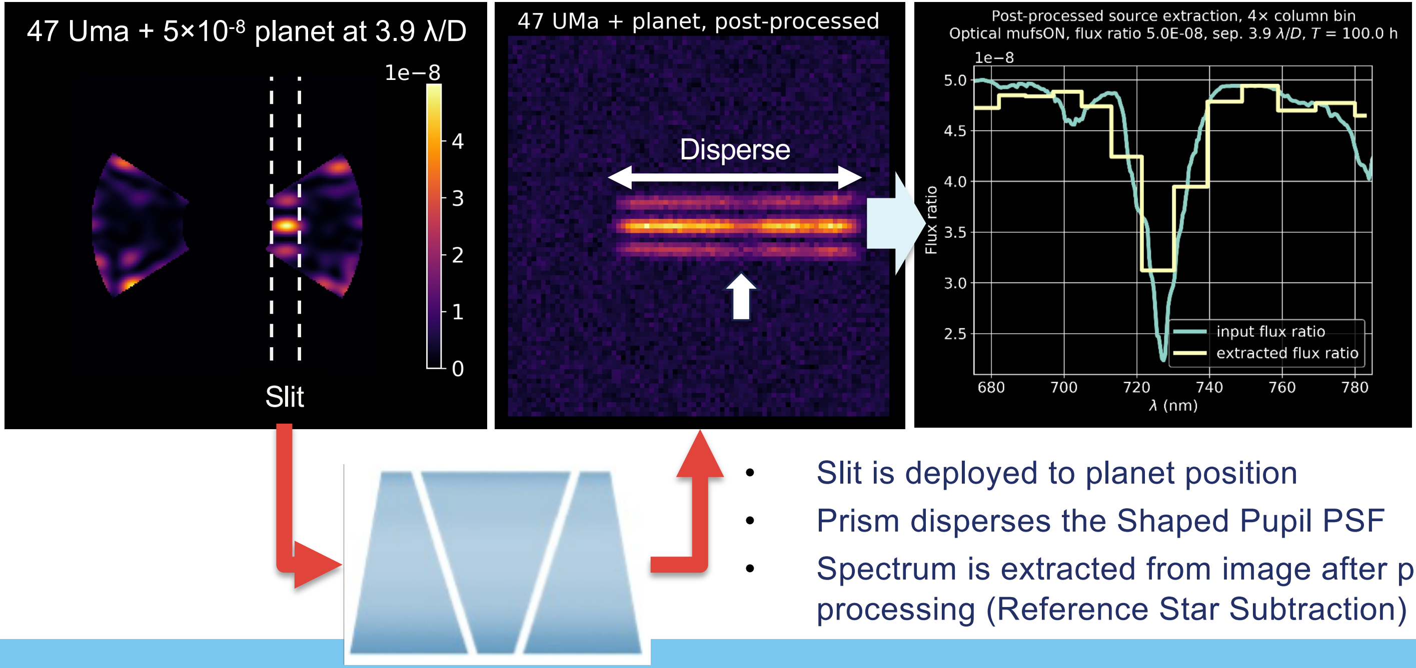
Key technologies work together as a system to deliver high performance



OAP = Off-Axis Parabolic [Mirror]

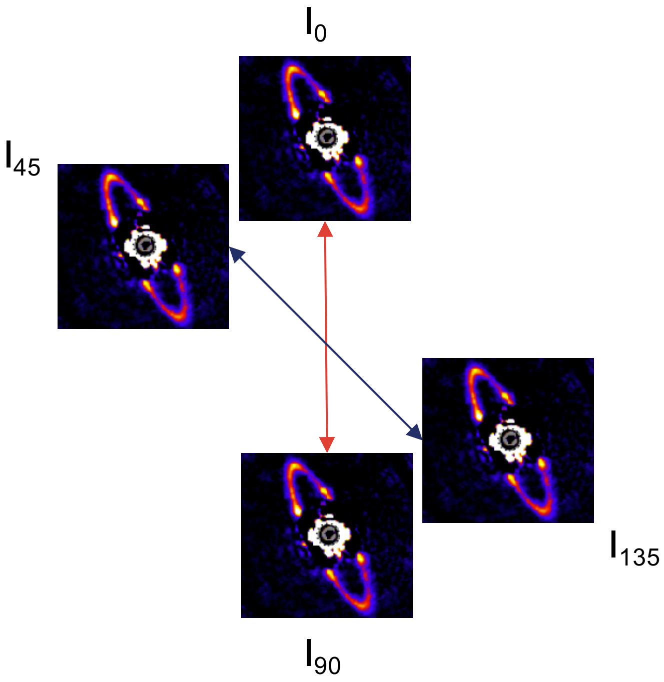
R~50 Spectroscopy w/ Slit Spectrograph (Band 3 or 2)

Simulated Performance



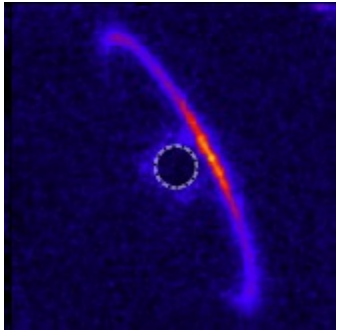
- Slit is deployed to planet position
- Prism disperses the Shaped Pupil PSF
- Spectrum is extracted from image after post-processing (Reference Star Subtraction)

Wollaston Prism Polarimetry (Band 1 or 4 imaging)



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

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

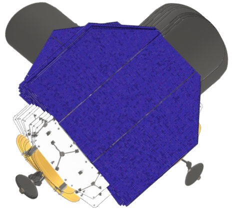


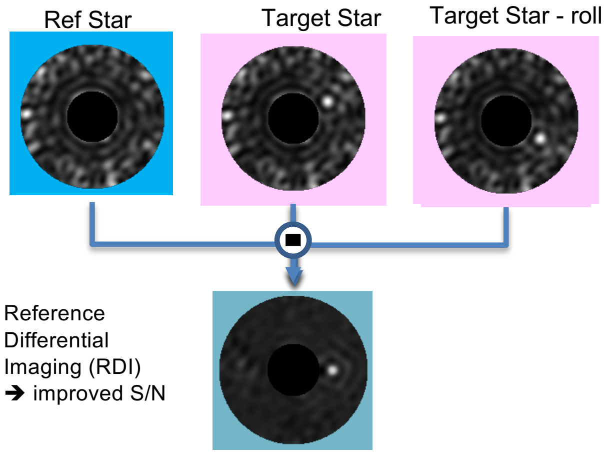
$$LPF = \mathrm{sqrt}\,\{(I_0 - I_{90})^2 + \{(I_{45} - I_{135})^2\} \;/\; I_{tot}$$

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

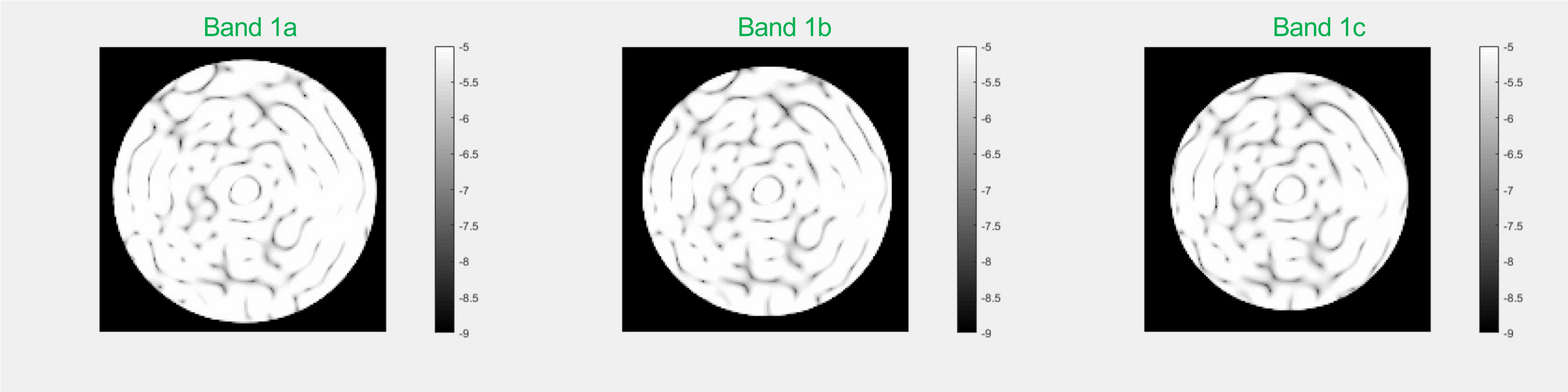
What is High-Order Wavefront Sensing and Control (HOWFSC)?

HOWFSC “digs the dark hole” by cycling through iterations of:

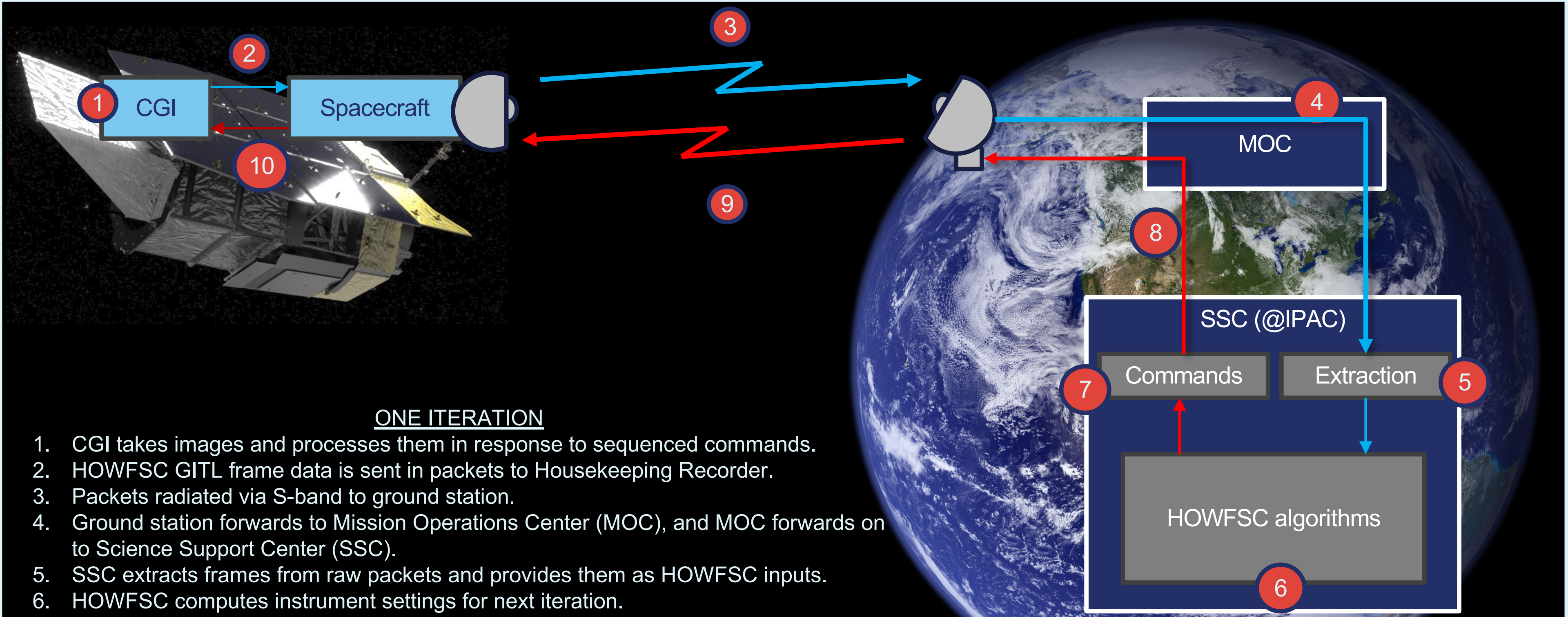
Wavefront sensing at primary camera EXCam ("focal plane wavefront sensing")

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)



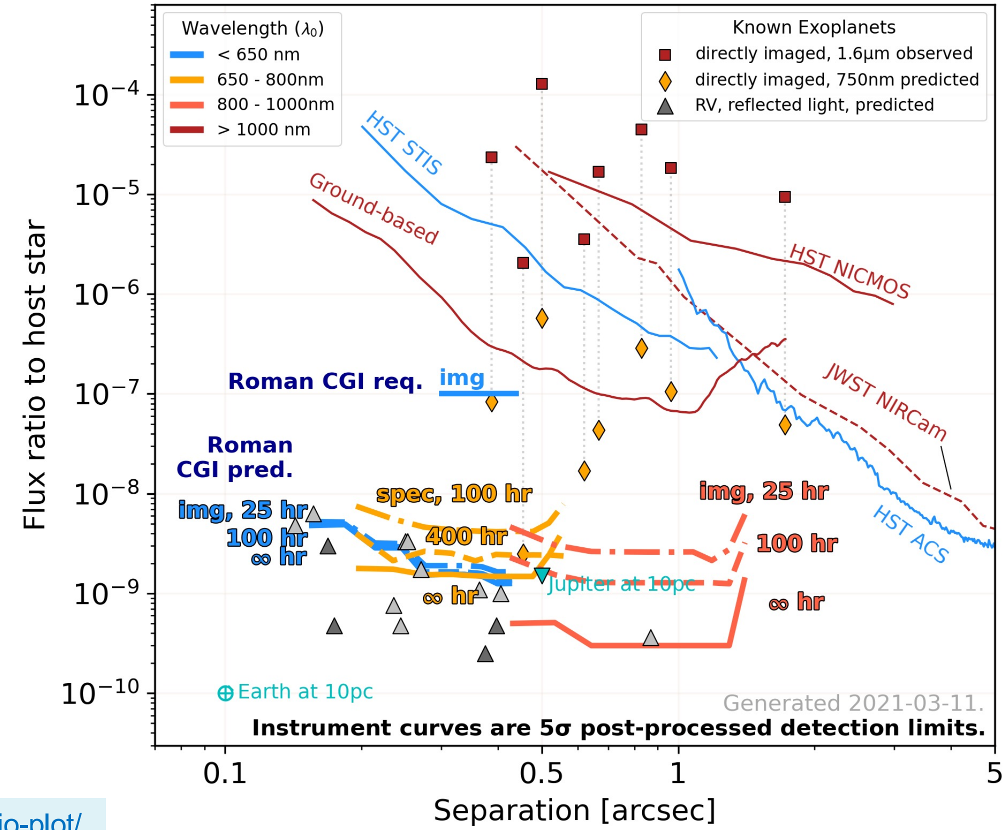
ONE ITERATION

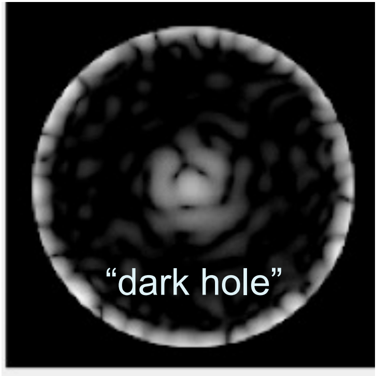
1. CGI takes images and processes them in response to sequenced commands.
2. HOWFSC GITL frame data is sent in packets to Housekeeping Recorder.
3. Packets radiated via S-band to ground station.
4. Ground station forwards to Mission Operations Center (MOC), and MOC forwards on to Science Support Center (SSC).
5. SSC extracts frames from raw packets and provides them as HOWFSC inputs.
6. HOWFSC computes instrument settings for next iteration.
7. SSC prepares uploads for next iteration.
8. Commands/data/variables are passed via MOC to ground station.
9. HOWFSC uploads uplinked via S-band.
10. Data and parameters updated in CGI, so the next iteration uses new settings.

Predicted detection limits are strongly speckle-limited at shorter wavelengths

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

NASA terminology: MUF=1 predictions





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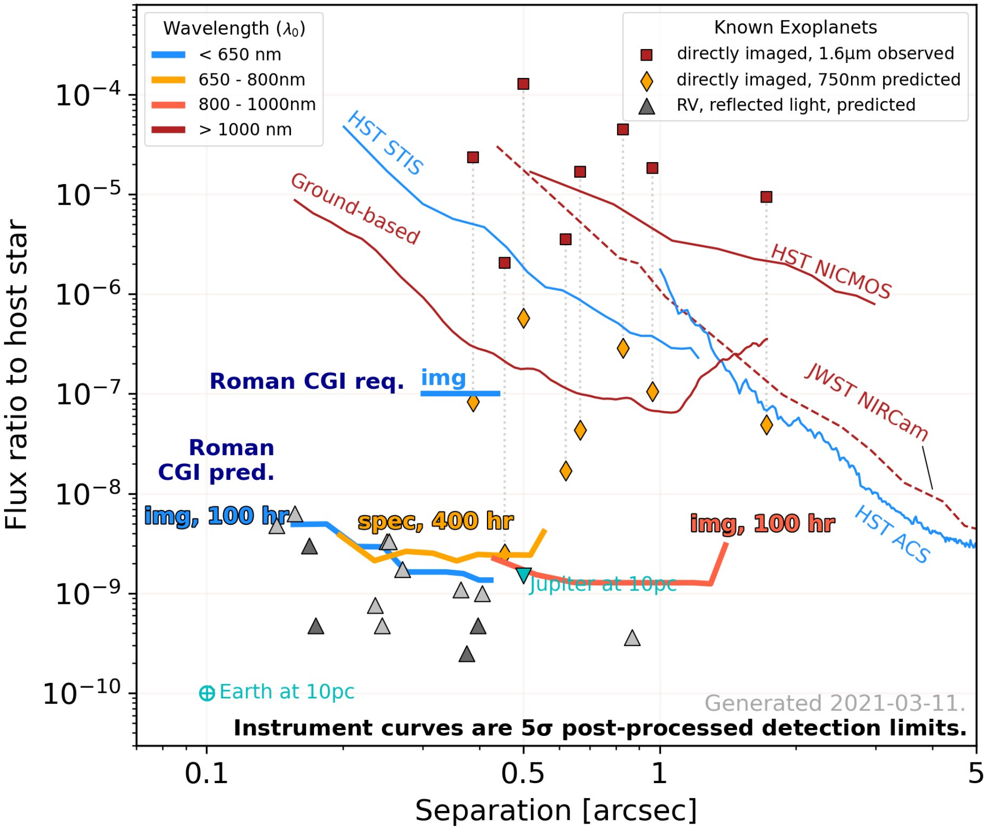
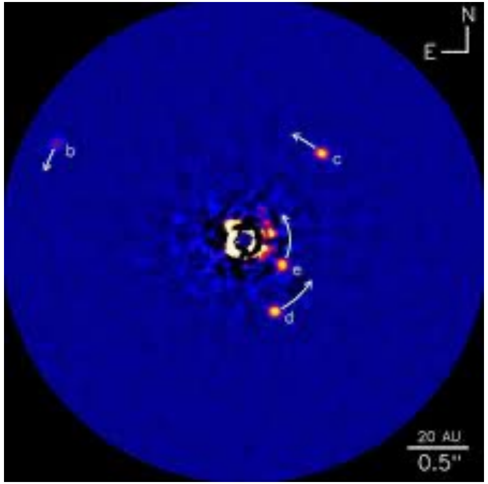
github.com/nasavbailey/DI-flux-ratio-plot/

CGI can study young, self-luminous planets at new wavelengths

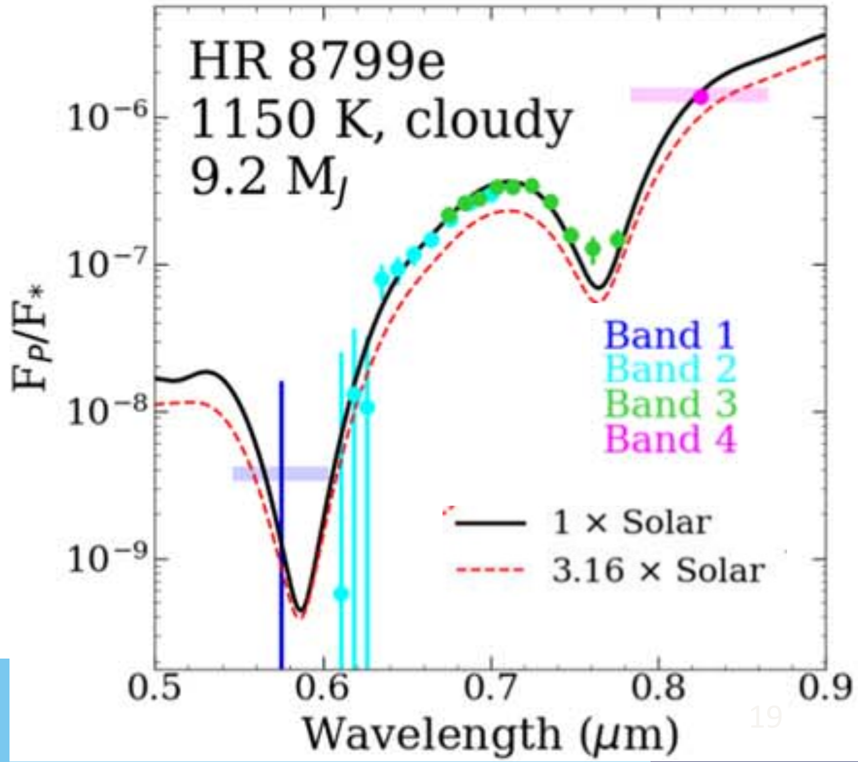




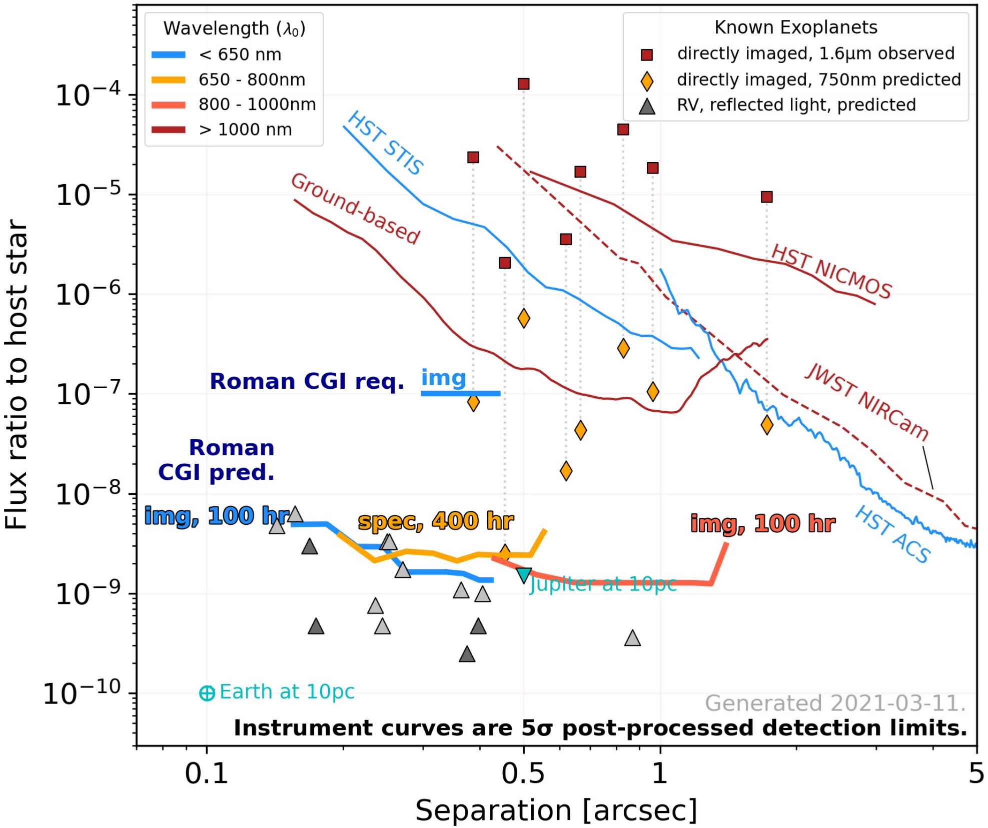
Young, self-luminous massive planets: CGI complements ground-based NIR

- **Q:** What are the cloud properties of young massive planets? How inflated are they? Are they metal rich?
- **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

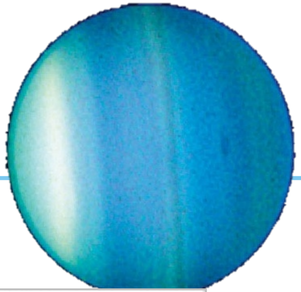
Lacy & Burrows 2020

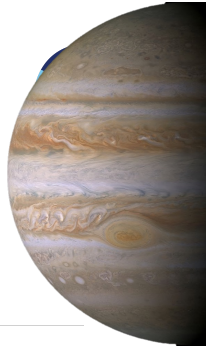


CGI can take the first reflected light images of true Jupiter analogs

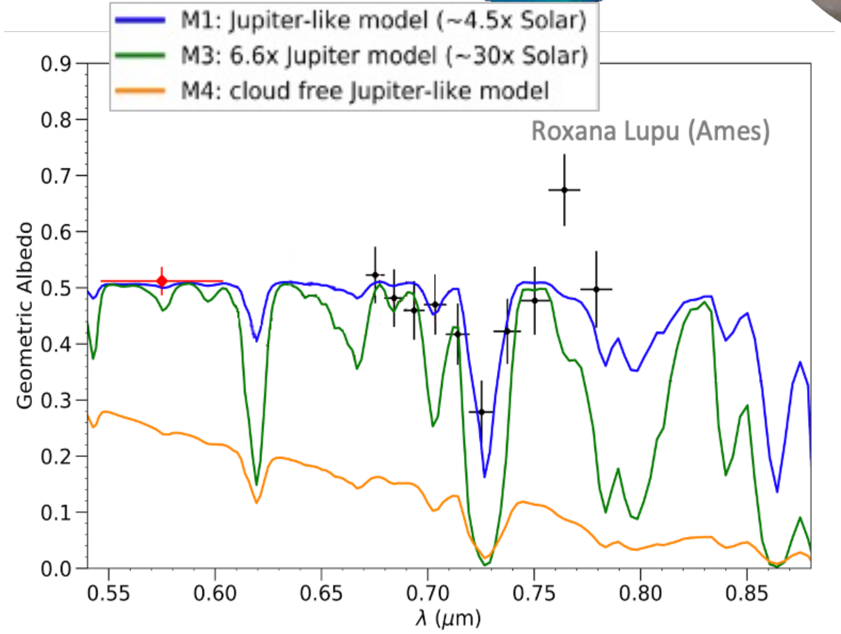


First reflected light images of a mature Jupiter analog





- **Q**: Are cold Jupiter analogs cloudy or clear?
- **CGI can**: Measure albedo at short wavelengths
- **During TDP**: 1-2 (known RV) planets
- **Beyond TDP**: Additional narrowbands and/or survey more known planets

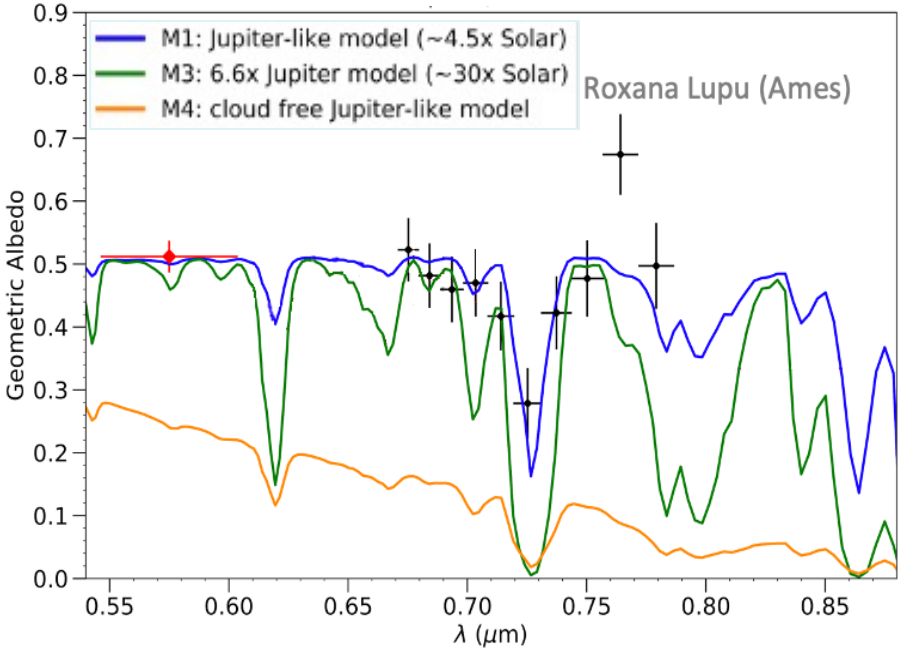


Natasha Batalha (UCSC)
Roxana Lupu (Ames)
Mark Marley (Ames)

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



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Characterization of a mature Jupiter analog

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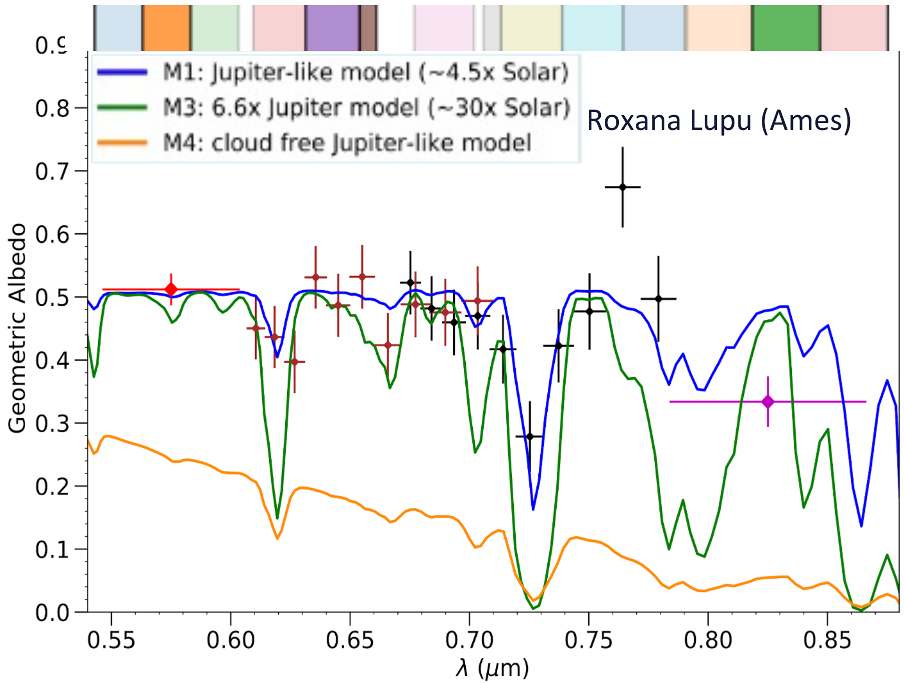
- **Q**: Are Jupiter analogs metal rich?
- **CGI can**: Coarsely constrain metallicity (5x vs. 30x Solar) if cloudy (high albedo)
- **During TDP:** 1 planet with 730nm spectroscopy
- **Beyond TDP**:
  - +1 planet
  - *OR* obtain narrowband photometry and/or 660nm spectroscopy of 1st planet.

Batalha, et al 2018

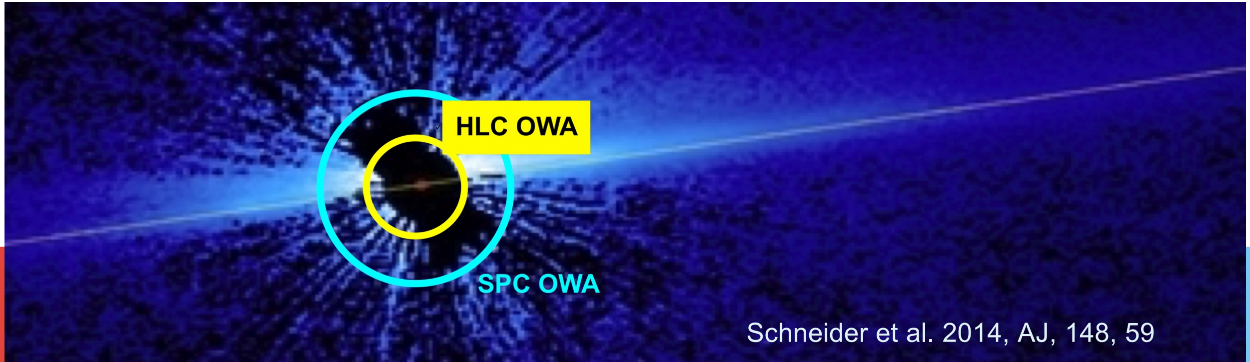


Roxana Lupu (Ames)

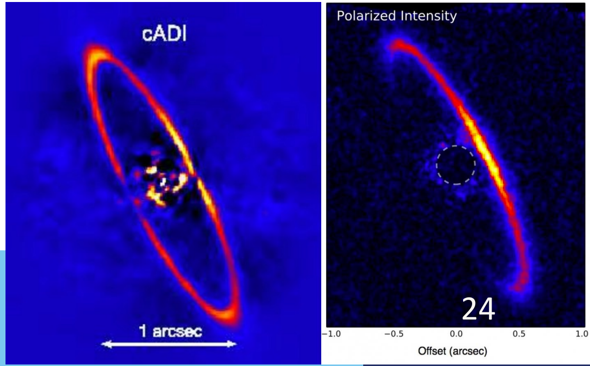
Imaging & Polarimetry of Known Cold Debris Disks

John Debes (STScI)
Ewan Douglas (UofAZ)
Bertrand Mennesson (JPL)

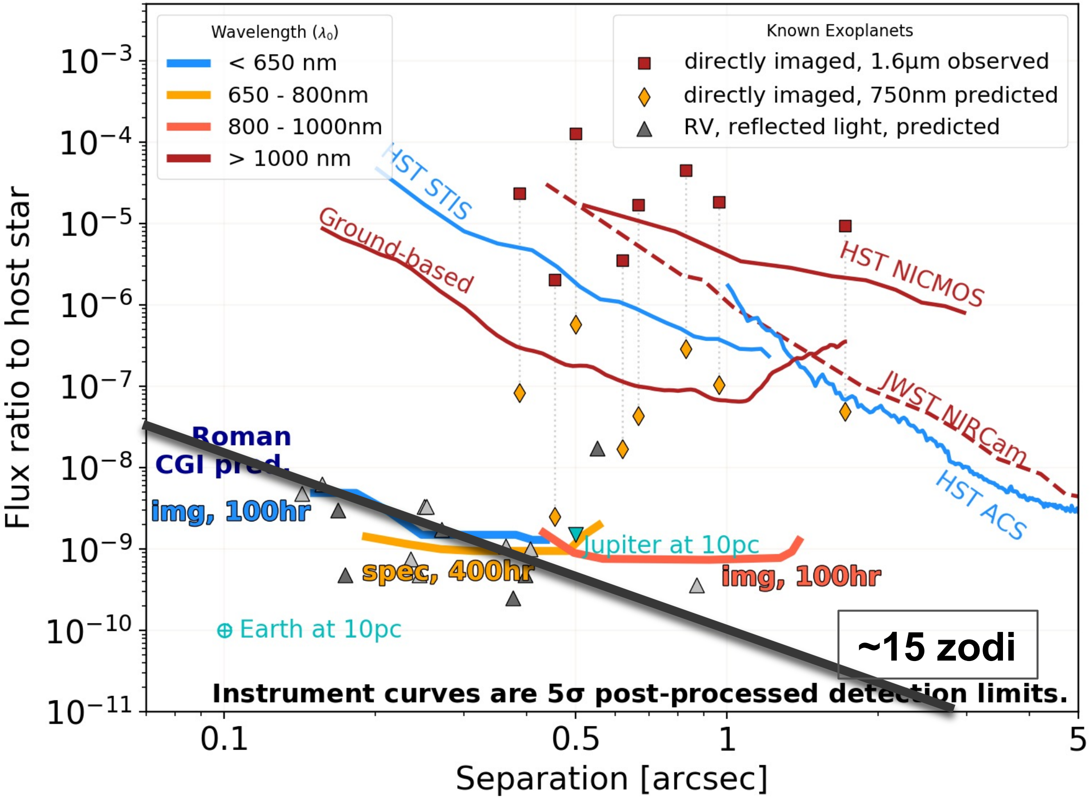
- **Q's**: Where does circumstellar material come from and how is it transported? What is the composition of dust in the inner regions of debris disks?
- **CGI can**: Map morphology and the degree of polarization.
- **During TDP:** 2-3 disks
- **Beyond TDP**: Additional disks with a variety of properties



Perrin+2015
Milli+2017



CGI can study tenuous debris and exozodi disks at solar system scales



John Debes (STScI)
Ewan Douglas (UofAZ)
Bertrand Mennesson (JPL)
Bijan Nemati (UA Huntsville)

First visible light images of exozodiacal dust

- **Q**: How bright is exozodiacal dust in scattered light? Will it affect exo-Earth detection with future missions?
- **CGI can**: Probe low surface density disks in habitable zone of nearby stars. Complement LBTI mid-IR survey.
- **During TDP:** Opportunistic, as part of exoplanet observations.
- **Beyond TDP**: Survey best potential exo-Earth targets for future missions

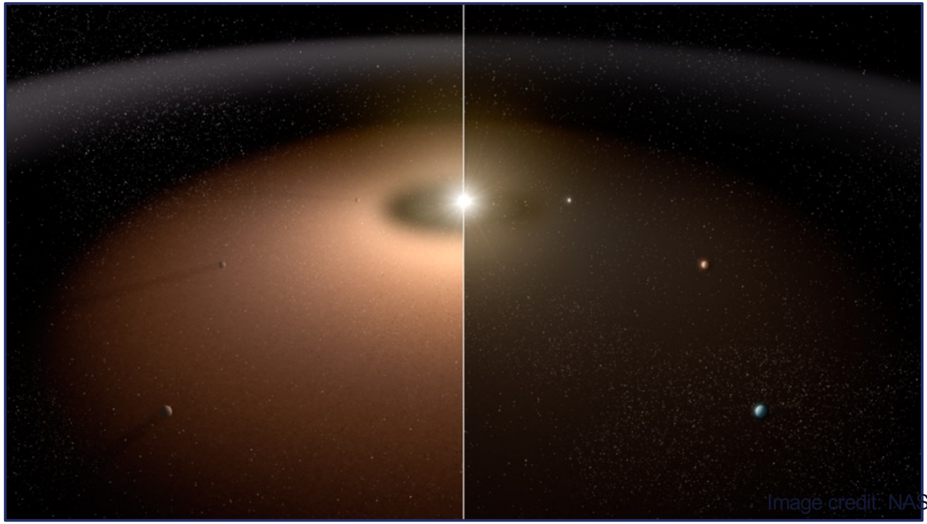
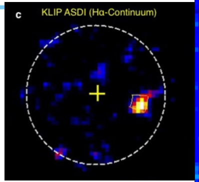


Image credit: NASA

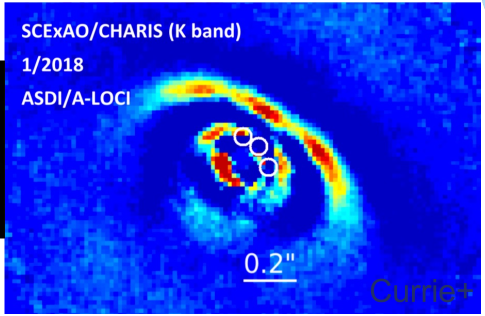
John Debes (STScI)
Ewan Douglas (UofAZ)
Bertrand Mennesson (JPL)
Bijan Nemati (UA Huntsville)

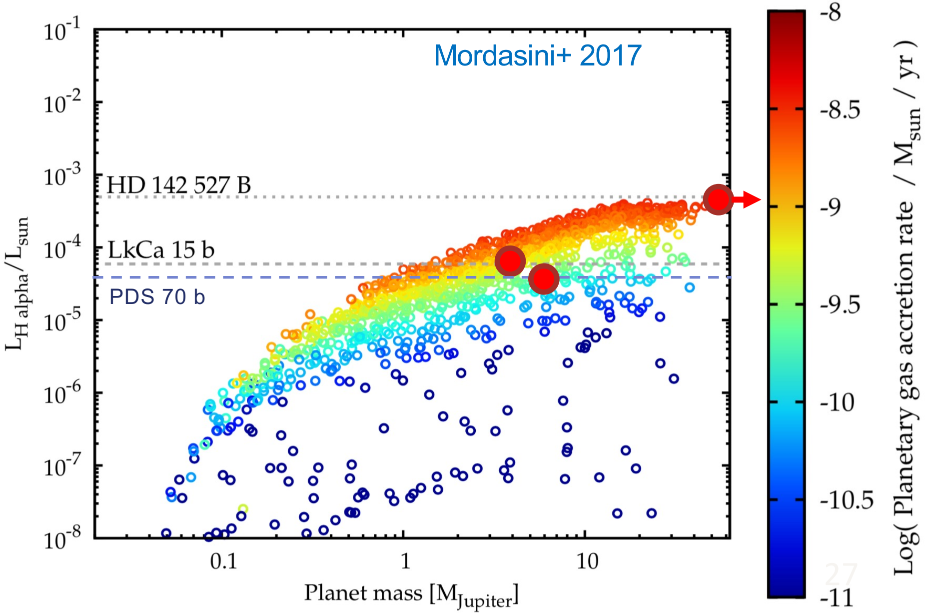
Protoplanetary systems

- **Q's:** What are the accretion properties of low-mass planets in formation? How can we distinguish protoplanets vs. disk structures?
- **CGI Can**: Measure Hα at high contrast
  - Caveat: CGI will not achieve optimal performance on faint host stars. Performance TBD, but may be $10^{-6} – 10^{-7}$
- **During TDP:** *Perhaps* a test observation
- **Beyond TDP**: Observe transition disks with gaps in CGI FOV

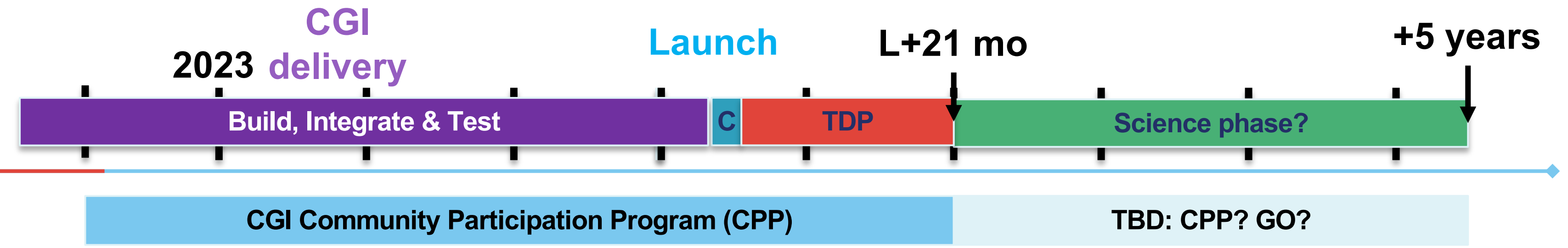


Sallum+ 2015





Kate Follette (Amherst)
Ewan Douglas (UofAZ)



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)

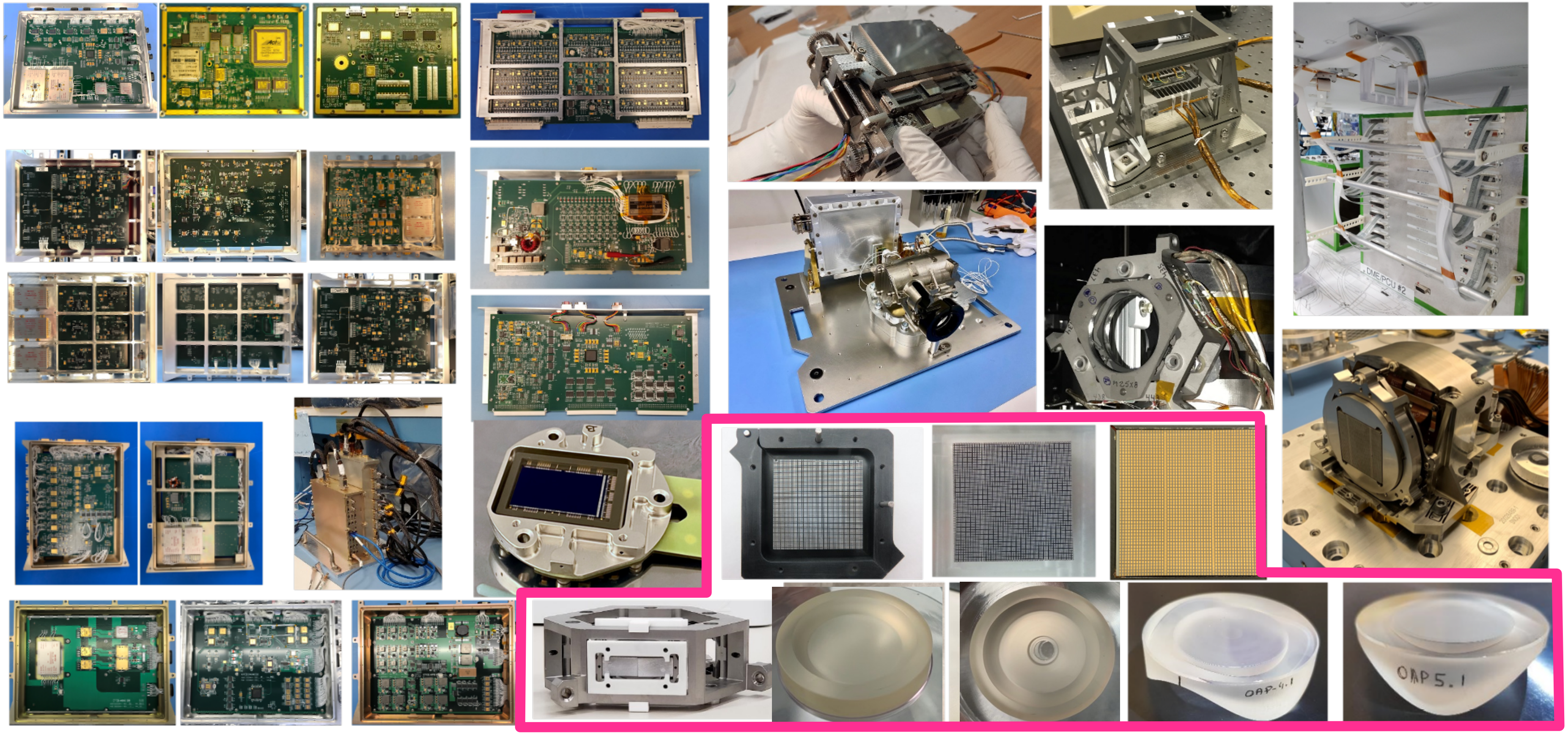
~2200 hr (3 months) baselined in next 1.5 years of mission

- **If TDP successful, potential add'l science phase**
  - OOM 10% (TBD!) 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

CGI Community Participation Program (CPP)

- Community teams, with members from US and all partner agencies.
- Work with CTC+PS in tech-demo preparation and operations. Add value by complementing the expertise of JPL and SSC Project staff.
  - Potential examples: Target/observation preparatory work; image simulations; data analysis tools; wavefront sensing and control strategies; …
  - Definitive list of need areas will be released in ROSES call
- Only a small number expected to be selected initially, depending on available funding.
  - Funded by Roman Project, not by CGI
- TBD:
  - Do all members stay from 2022 through Phase E, or are there refresh points? Depends on task phasing.
  - Individuals or small groups?

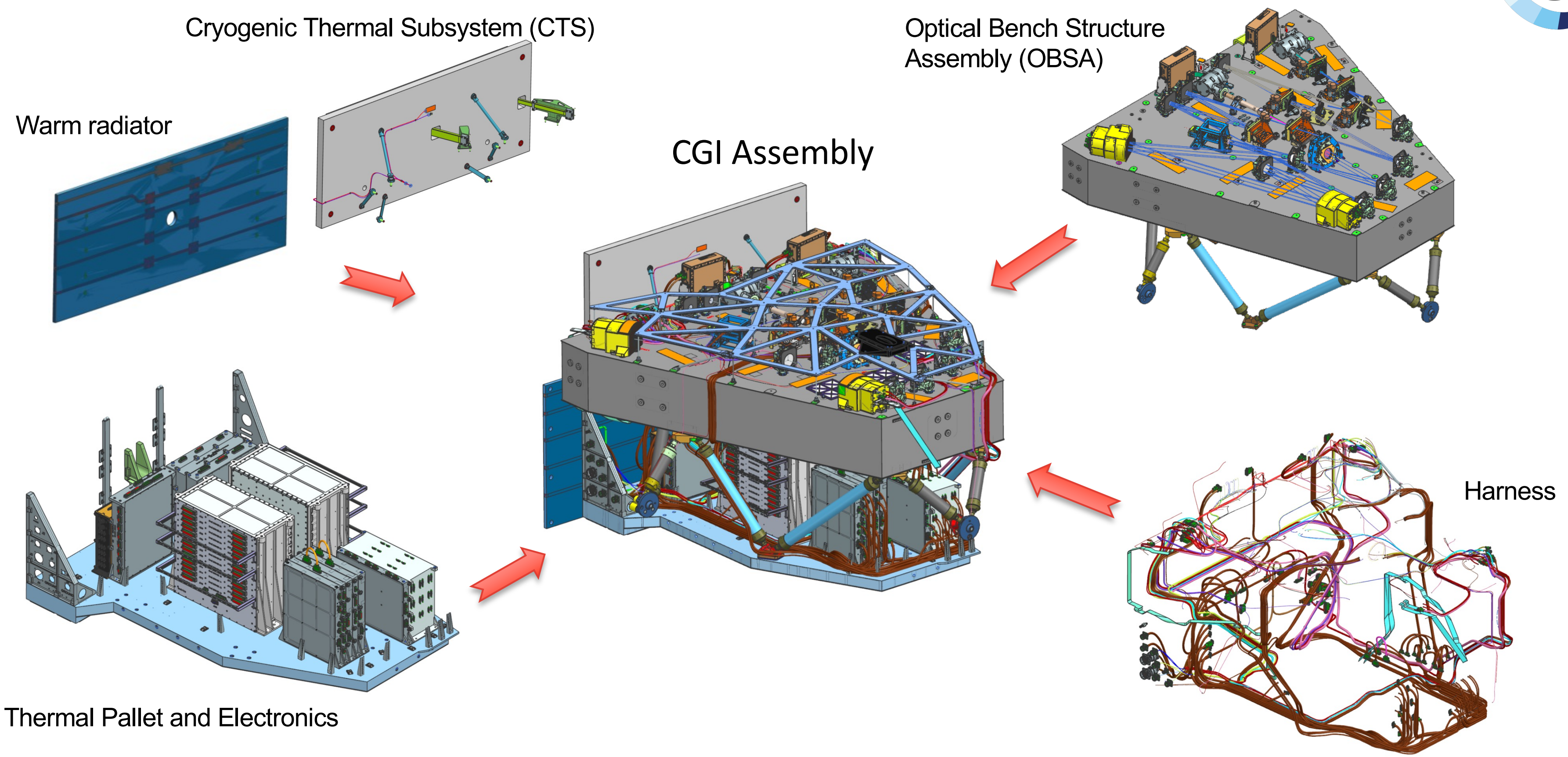
Coronagraph Instrument – Engineering Development Units and Flight Hardware



Summary

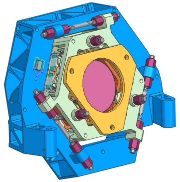
- **CGI is a technology demonstrator**
  - first "active" coronagraph in space
  - Important pathfinder for future missions to study exo-Earths
- **CGI is capable of interesting exoplanetary system science**
  - Imaging & spectroscopy of young planets
  - First reflected light imaging and spectroscopy of mature Jupiter analogs
  - Imaging and polarimetry of circumstellar disks, including exozodi
- **Get involved**
  - CGI data challenges **exoplanetdatachallenge.com**
  - Instrument parameters and simulations **roman.ipac.caltech.edu**
  - RV planet simulated photometry & observability **plandb.sioslab.com**
  - **Community Participation Program**

CGI H/W Configuration Overview

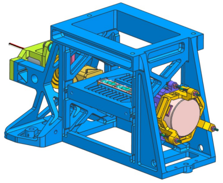


Light path (view in slideshow for animation)

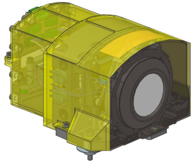
- Used in control loops
- Used in setting up modes



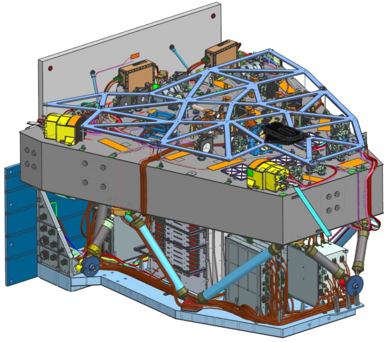
FSM: Fast Steering Mirror

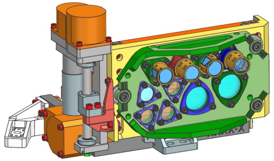


FCM: Focus Control Mirror

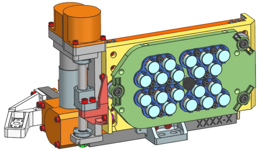


DM (2x): Deformable Mirror

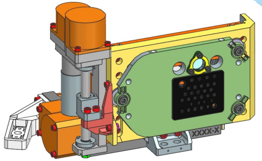




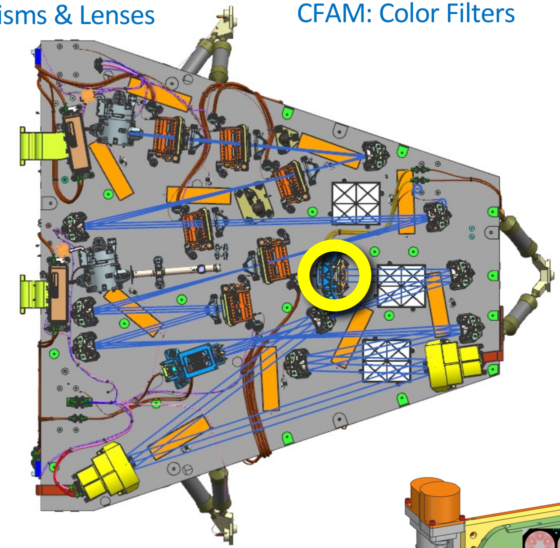
DPAM: Prisms & Lenses

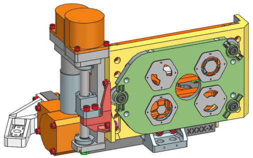


CFAM: Color Filters

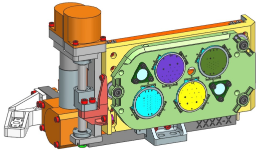


FSAM: Field Stops & Slits

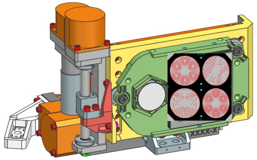




LSAM: Lyot Stops



FPAM: Focal Plane Masks



SPAM: Shaped Pupil Masks