Observing with the Roman Coronagraph Instrument (CGI)

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(she/her/hers)
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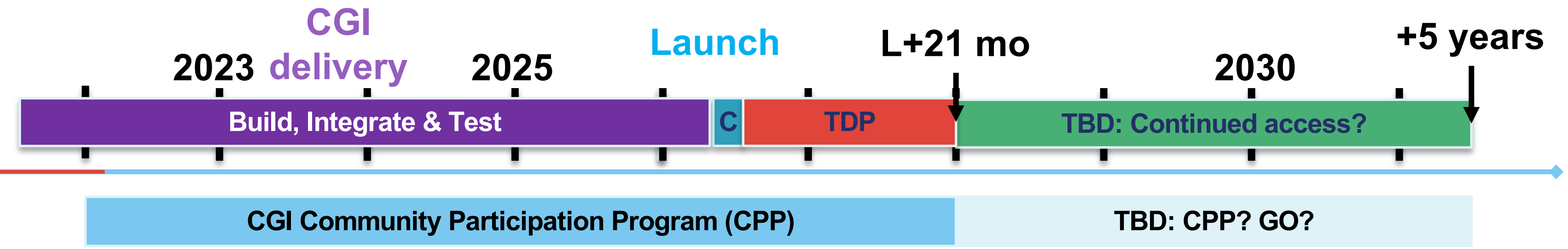
With support from many at the Jet Propulsion Laboratory, Goddard Space Flight Center, and the Science Investigation Teams



Apr 2021: Passed Instrument Critical Design Review

Late 2023: Instrument delivery to payload integration & test

~2026: Launch (new date pending official COVID relief decision)

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 follow-on**
    - 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

JPL "Coronagraph Technology Center" (CTC) responsibilities

- CTC to collaborate closely with CPP & IPAC Science Support Center (SSC) in any/all aspects
- Assist analysis of CGI integration and test data; assist test definition/execution where appropriate
- Top priority: Ensure Coronagraph Instrument (CGI) meets TTR5 requirement on sky (HLC+Band 1)
  - 2nd priority: also meet CGI "Objectives" and deprecated requirements (spec, pol, wide FOV, WFSC)
  - Best effort basis: push performance limits
- Target selection: Choose scientifically interesting targets for tech demo tests whenever possible
- Observation planning: high-contrast and calibration targets
- Data processing: analysis software development & prompt delivery to public archive
  - Up through PSF subtracted images, extracted spectra, etc., in astrophysical units ("Level 4" data products)
- Anomaly diagnosis and response
- Document on-sky performance

Supported Observing Modes

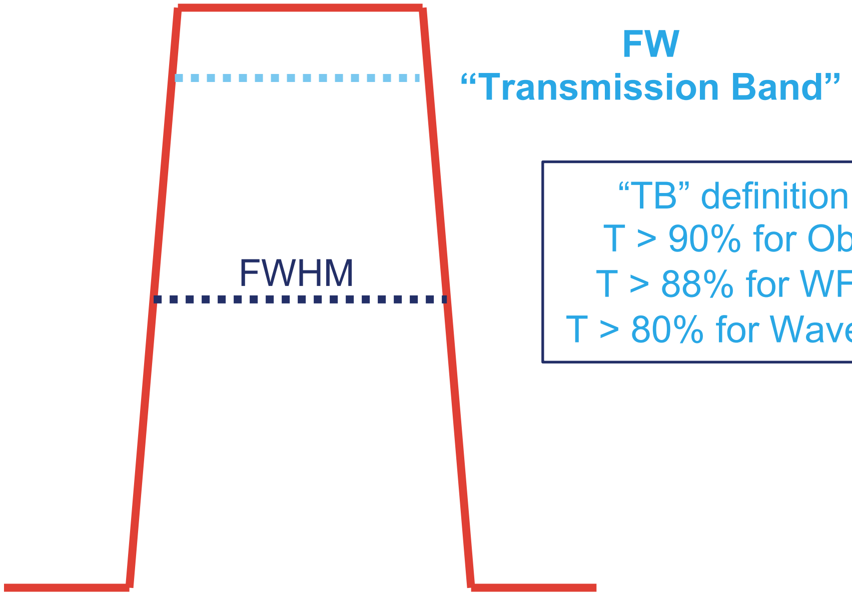
Band	λ_{center}	BW	Mode	FOV radius	FOV Coverage	Pol.	Coronagraph Mask Type	TTR5
1	575 nm	10%	Narrow FOV Imaging	0.14" – 0.45"	360°	Y	Hybrid Lyot	Y
2	660 nm*	15%	Slit + R~50 Prism Spectroscopy	0.18" – 0.55"	2 x 65°	-	Shaped Pupil	-
3	730 nm	15%	Slit + R~50 Prism Spectroscopy	0.18" – 0.55"	2 x 65°	-	Shaped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

* **660 nm spectroscopy** is the lowest priority for on-sky testing. If time is limited, this mode may not be exercised during the Technology Demonstration Phase.

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

Filter requirements (final specs will be released when vendor completes designs & prototypes)

name	λ_0 [nm]	FWHM [%]	FW Trans. Band [≥%] ***	Primary Purpose
1F (1) *	575	10.1%	8.0%	Obs
2F (2)	660	17.0%	15.2%	Obs
3F (3)	730	16.7%	15.1%	Obs
4F (4)	825	11.4%	9.9%	Obs
1A	555.8	3.5%	2.4%	WFS **
1B	575	3.3%	2.3%	WFS
1C	594.2	3.2%	2.2%	WFS
2A	615	3.6%	2.6%	WFS
2B	638	2.8%	1.9%	WFS
2C	656.3	1.0%	0.4%	Wavecal
3A	681	3.5%	2.6%	WFS
3B	704	3.4%	2.6%	WFS
3C	727	2.8%	2.0%	WFS
3G	752	3.3%	2.5%	WFS
3D	754	1.0%	0.5%	Wavecal
3E	777.5	3.5%	2.7%	WFS
4A	792	3.5%	2.8%	WFS
4B	825	3.6%	2.9%	WFS
4C	857	3.5%	2.8%	WFS



“TB” definition:
T > 90% for Obs
T > 88% for WFS
T > 80% for Wavecal

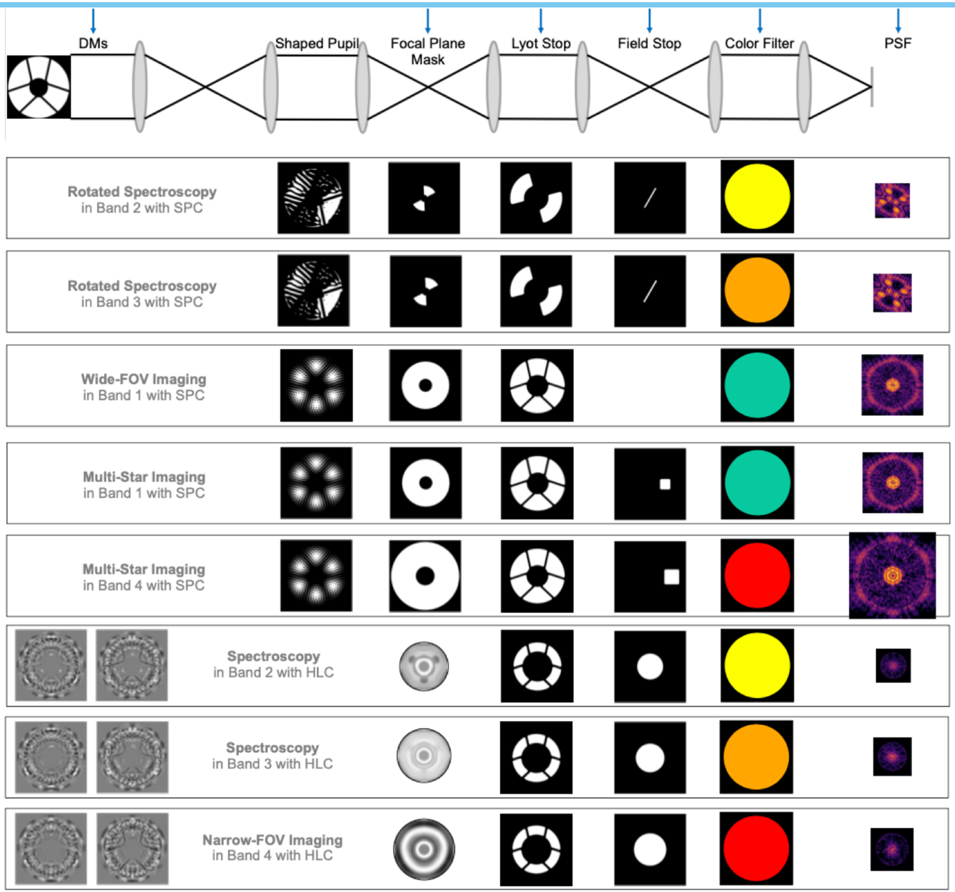
* Bands 1, 2, 3, 4 are shorthand for Band 1F, 2F, 3F, 4F
** WFS = High-order wavefront sensing
*** FWTB listed is minimum %; likely to be closer to FWHM value

https://roman.ipac.caltech.edu/sims/Param_db.html

Not all mask+filter combinations are valid

- High-Contrast masks are designed to operate at a specific wavelength (Band 1, 2, 3, or 4).
  - In principle, can be used with sub-bands of primary band (eg: SPC bowtie for Band 2 will also work for Band 2A, 2B, 2C, 3A, 3B, because they're all subsets of band 2).
- Combinations other than the 4 officially supported ones may not be commissioned for observations during the Tech Demo Phase

Unsupported mask configurations



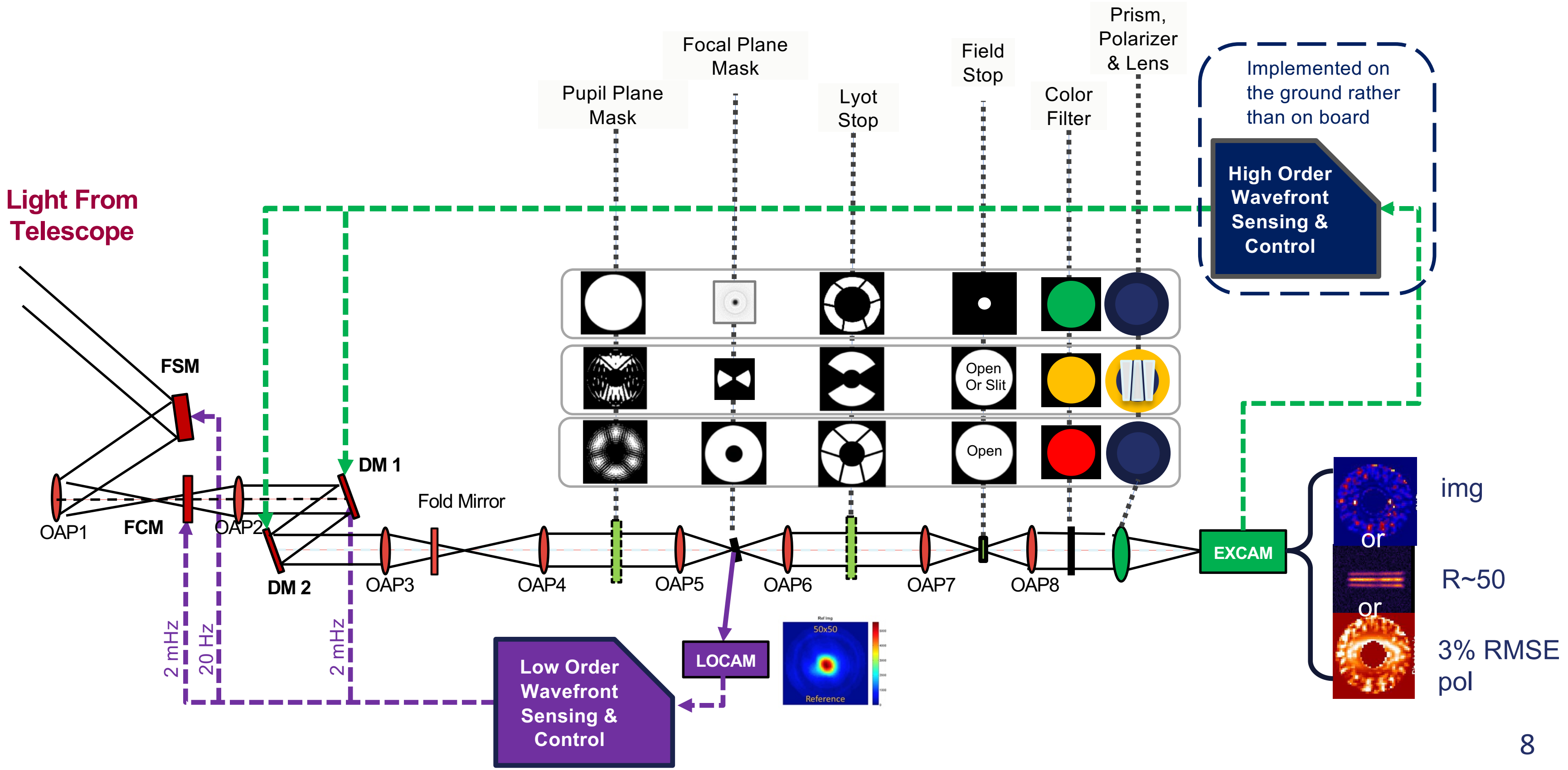
Additional masks contributed by NASA's Exoplanet Exploration Program to fill empty slots in mechanisms.

No funding for on-sky commissioning identified at this time. Analogous to HST/STIS Bar5.

Not shown: unsupported "low-contrast" classical Lyot spots (analogous to HST) for very wide FOV imaging (~1-3.5")

For complete list of masks see Riggs+ in prep; Bendek+ in prep to be in SPIE O&P 2021

Key technologies work together as a system to deliver high performance

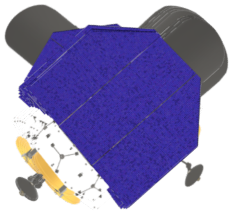


OAP = *Off-Axis Parabolic [Mirror]*

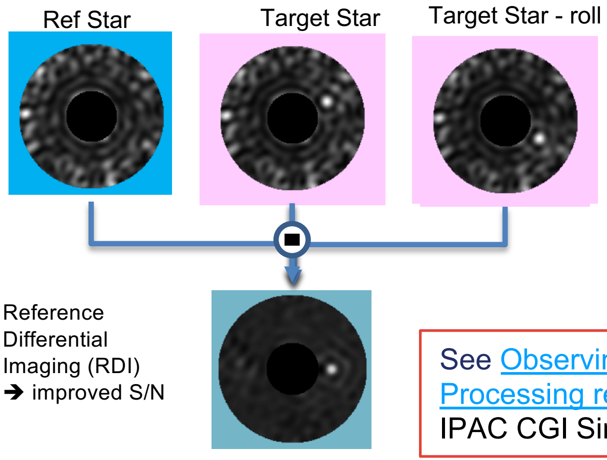
Nominal operations: target & reference star; PSF subtraction w/ reference differential Imaging

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



All stars must be **single**
Nothing equally bright within ~45";
increasingly stringent at smaller separations



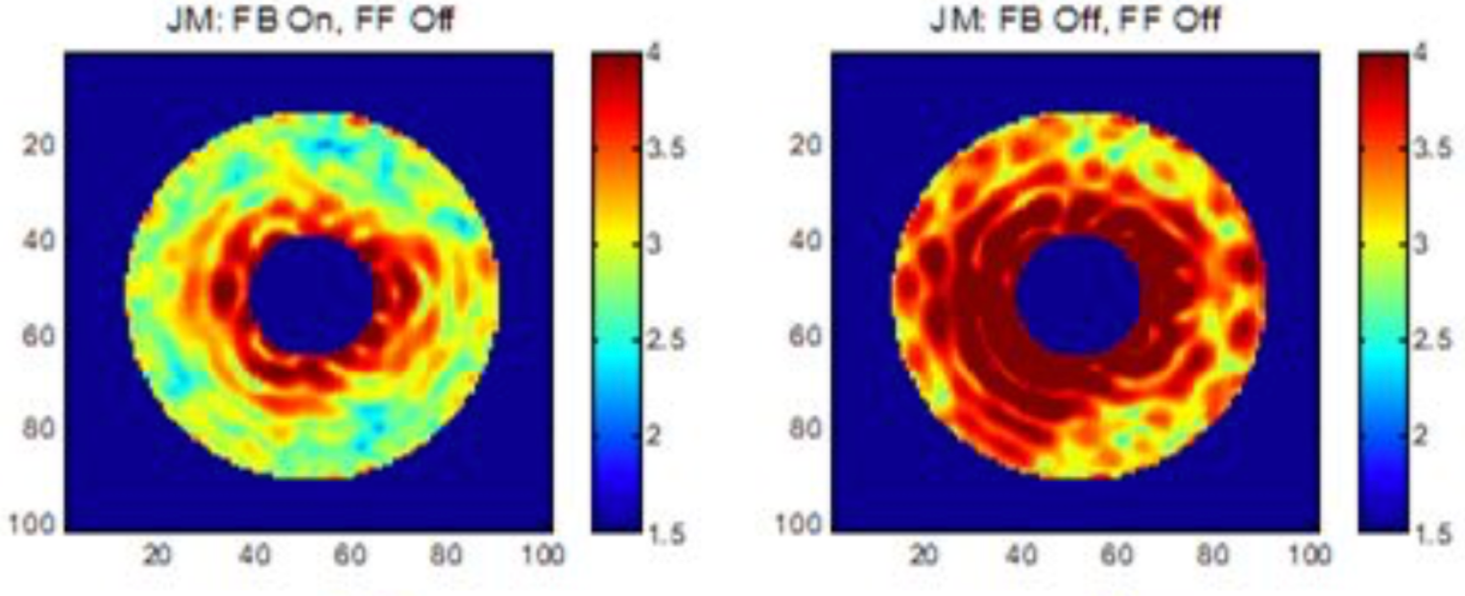
Reference Differential Imaging (RDI)
➔ improved S/N

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

See [Observing Scenario 9 Post-Processing report]() by Ygouf+ on IPAC CGI Sims page

Adapted from J. Krist

Residual tip/tilt jitter impacts contrast, sets V<5 host star requirement



Tip/tilt control on

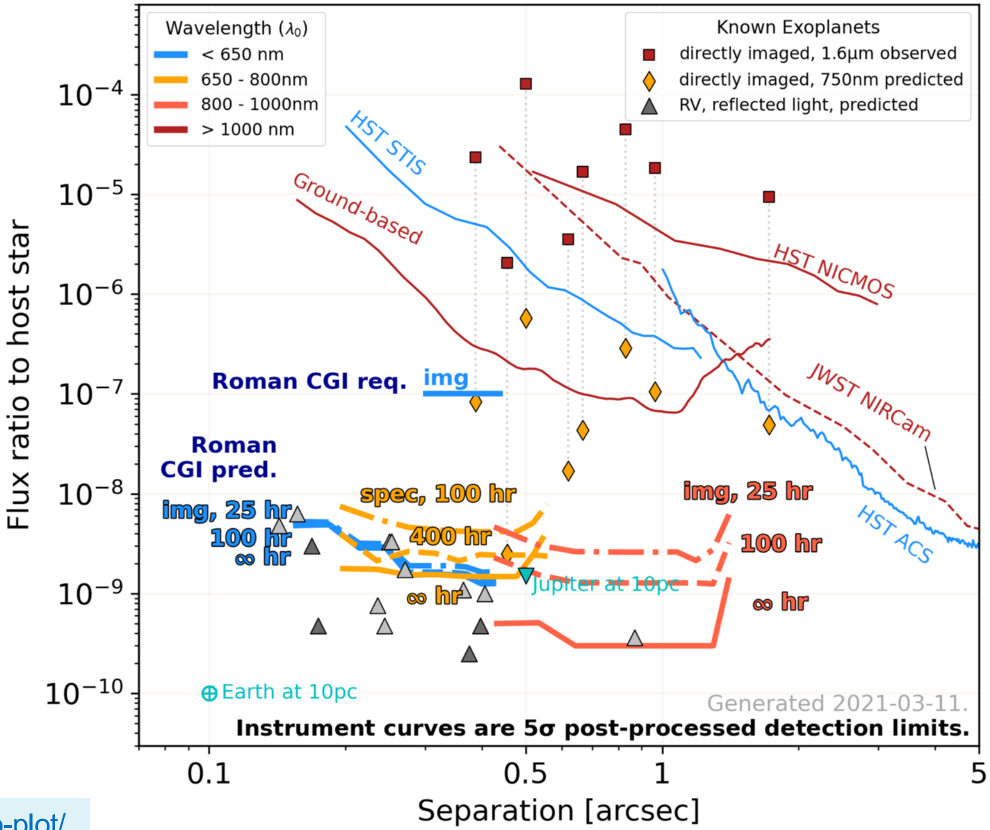
Tip/tilt control off

Shi, F., et al., SPIE, Vol 10698, p 106982O-5 2018 ; flight-like jitter tests on V=5 "star"
Note: feed-forward will NOT be implemented in flight (ie: tip/tilt control will be feedback only)

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.

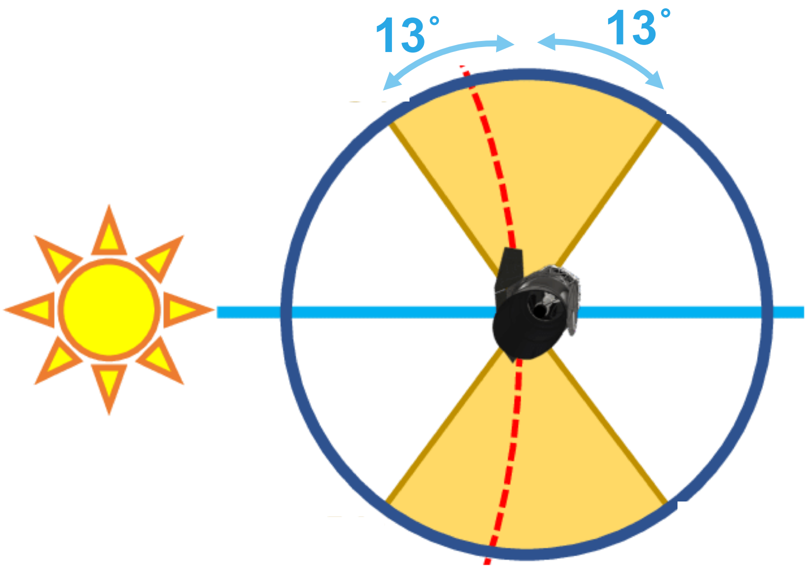
Most Model Uncertainty Factors set to ~1

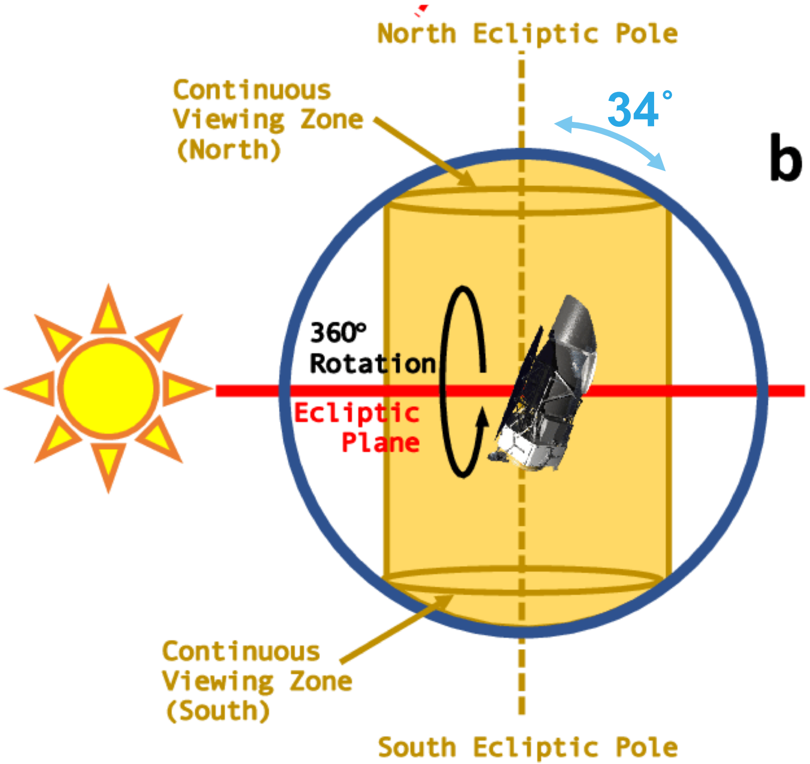


Brian Kern (JPL)
John Krist (JPL)
Bijan Nemati (UA Huntsville)
A.J. Riggs (JPL)
Hanying Zhou (JPL)
Sergi Hildebrandt-Rafels (JPL)

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

Pointing constraints:
±34˚ pitch, ±13˚ roll vs. sun



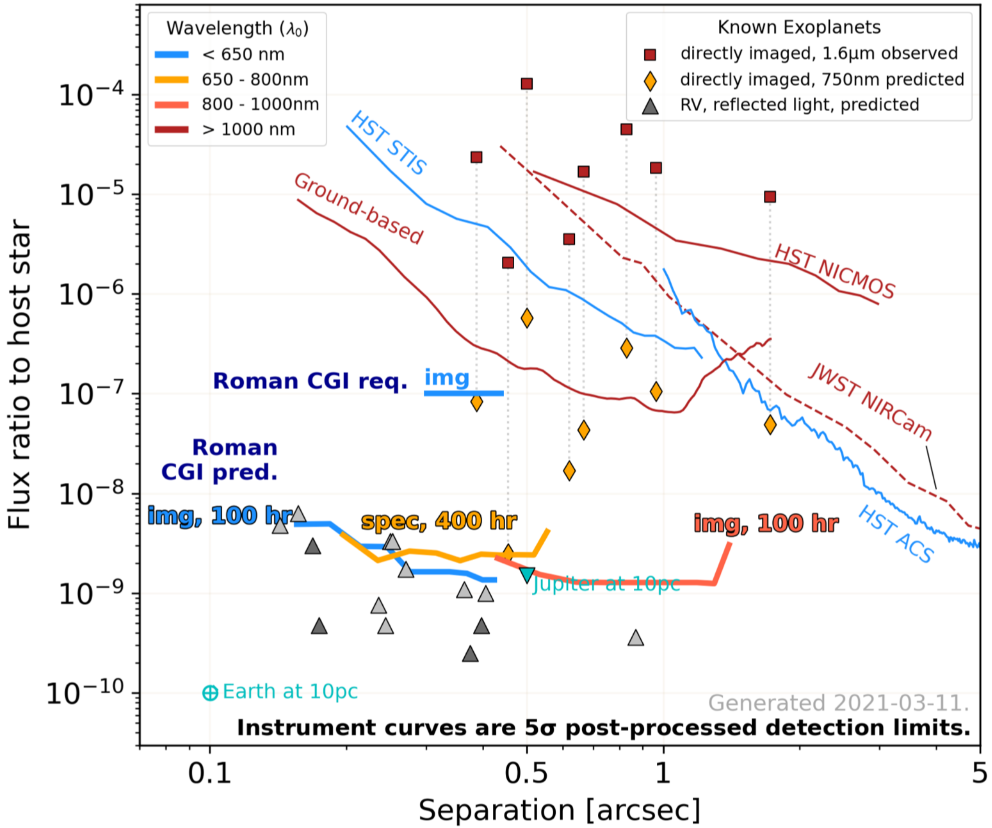


Potential Applications

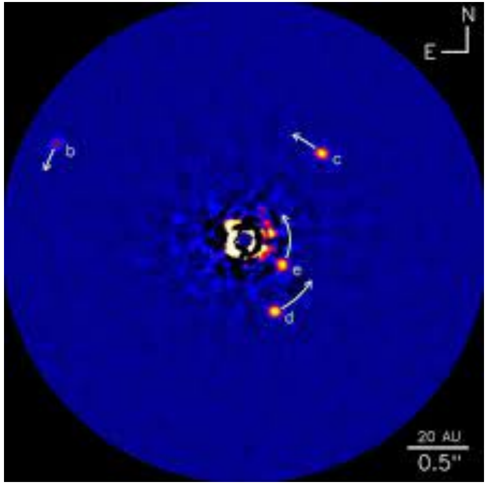
Target list is notional; will refine over time.

Observations ideally also enable verification of requirements/objectives (see Kasdin presentation for requirements text) or enhance performance characterization (ie: increase the value of the CGI technology demonstration).

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



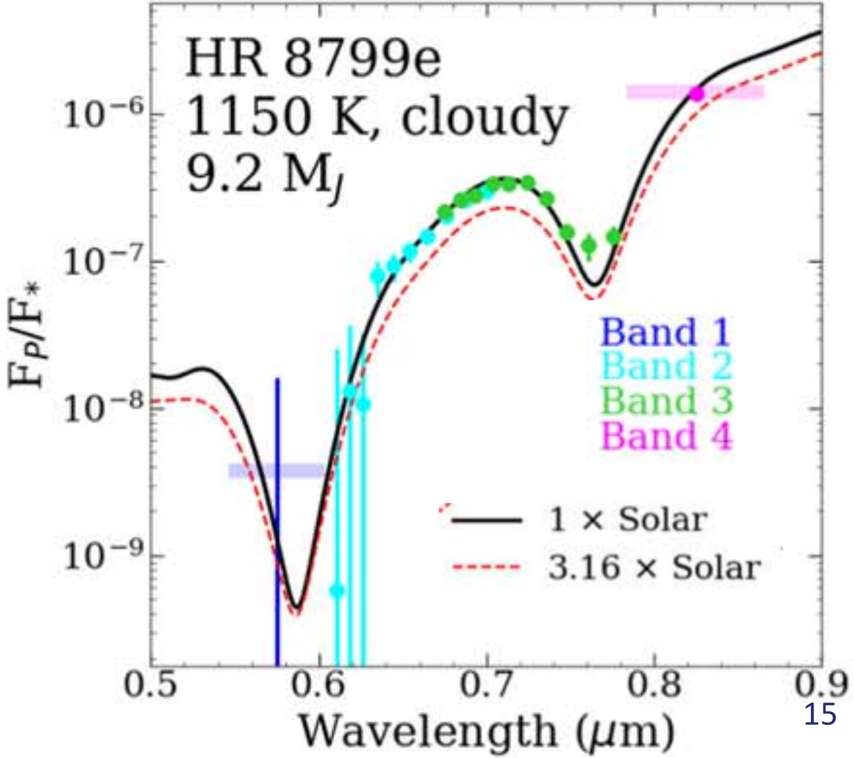
Lacy & Burrows, 2020, *ApJ*, 892, 151



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

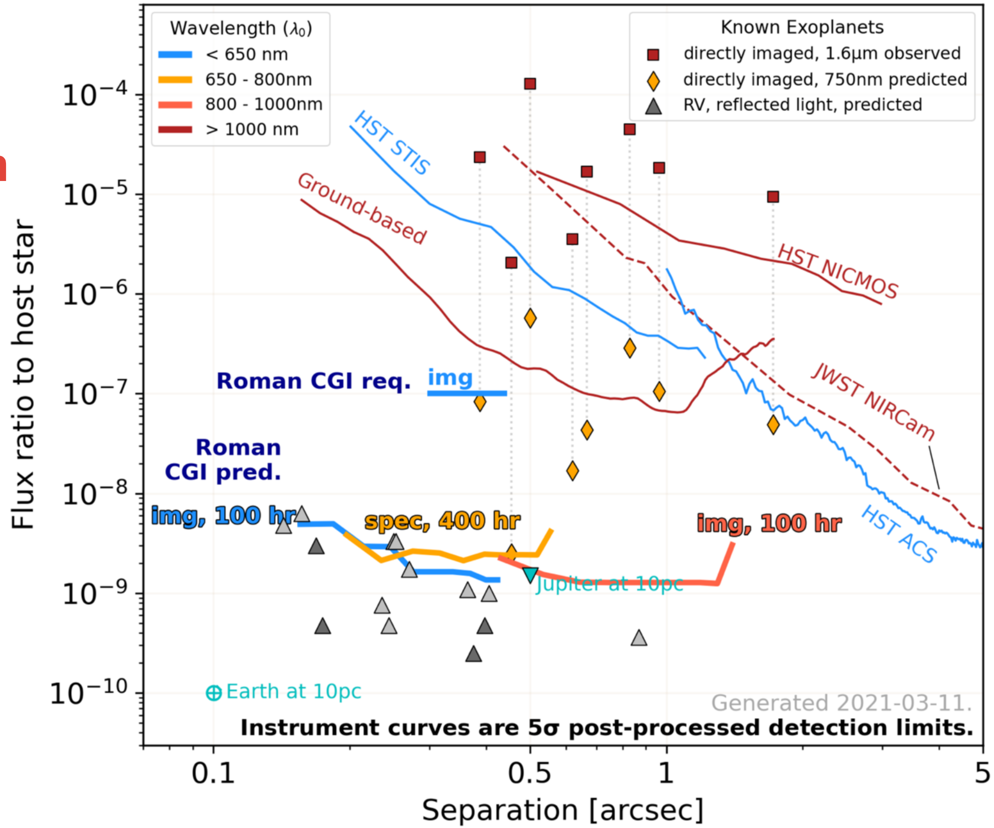
Lacy & Burrows, 2020, *ApJ*, 892, 151



Brianna Lacy (Princeton)

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

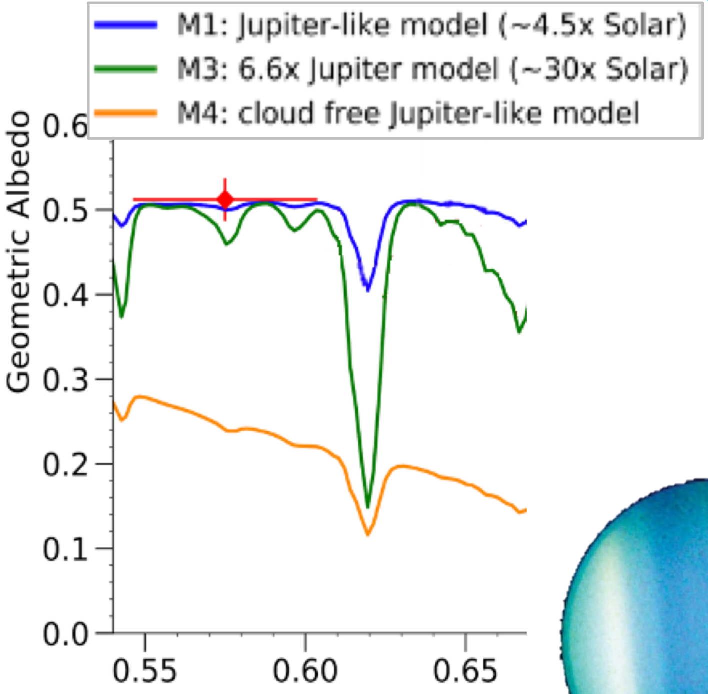
plandb.sioslab.com

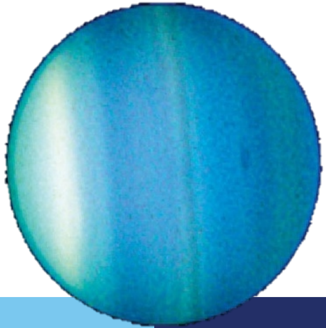


Natasha Batalha (Ames)
Nikole Lewis (Cornell)
Roxana Lupu (Ames)
Mark Marley (Univ. AZ)
Dmitry Savransky (Cornell)

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





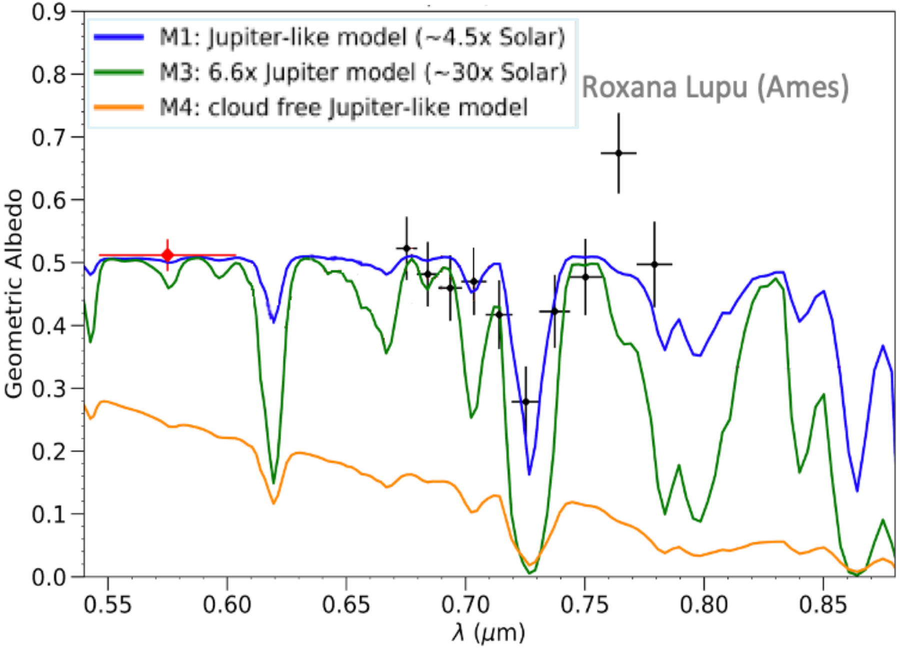
Batalha+, 2018, *AJ*, 156, 158
caveat: used older filter set

Natasha Batalha (UCSC)
Roxana Lupu (Ames)
Mark Marley (Univ. AZ)

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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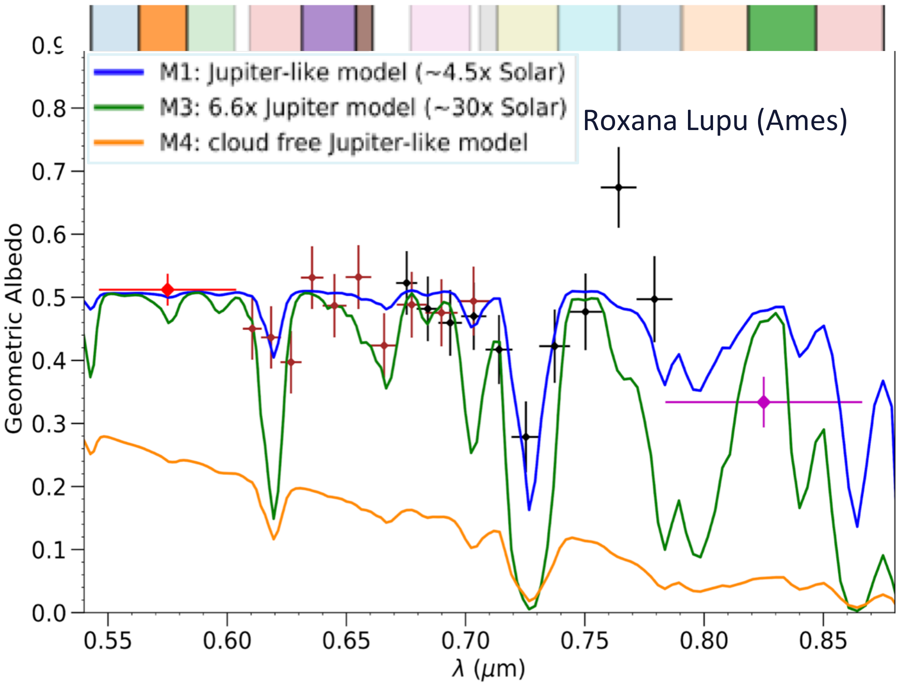
Characterization of a mature Jupiter analog

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
- During or beyond TDP
  - +1 planet
  - OR obtain narrowband photometry and/or 660nm spectroscopy of 1st planet.



Batalha+, 2018, *AJ*, 156, 158
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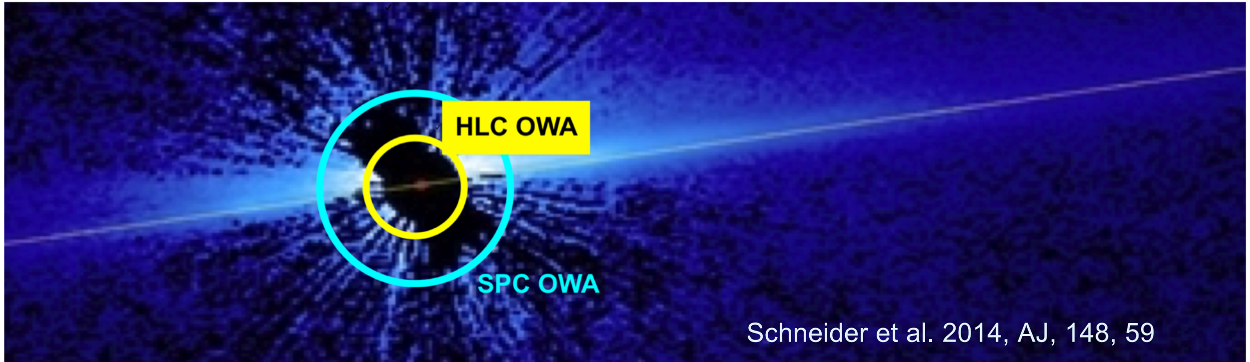
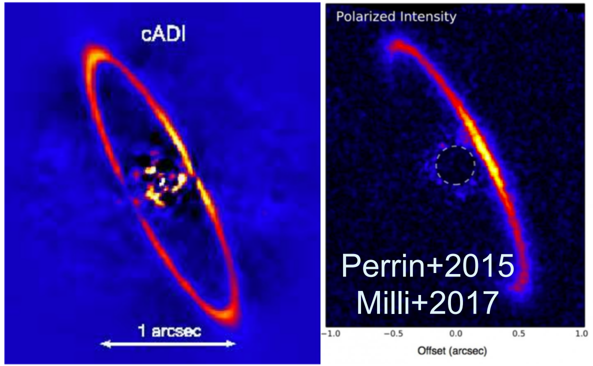
Imaging & Polarimetry of Known Cold Debris Disks

John Debes (STScI)
Ewan Douglas (Univ. AZ)
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 (±3% RMSE for brightest disks)
- During TDP: 2-3 disks



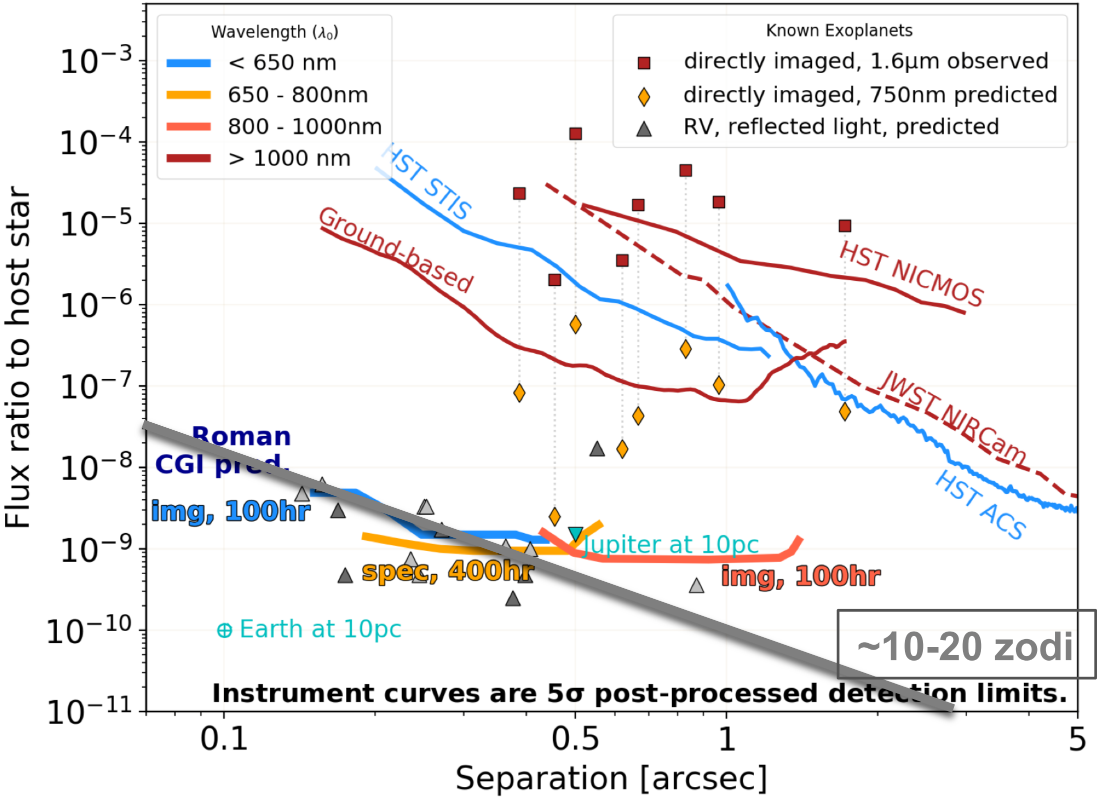
Schneider et al. 2014, AJ, 148, 59



Perrin+2015
Milli+2017

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

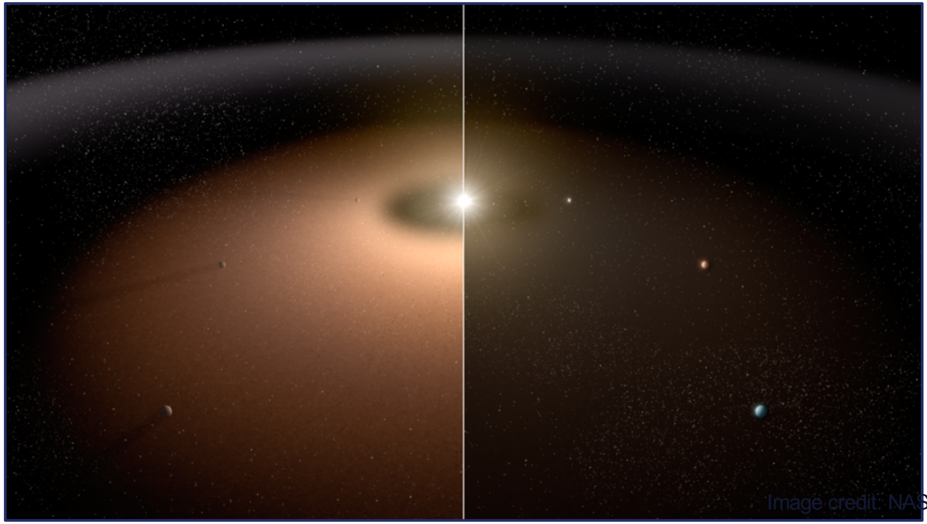
Douglas+, in prep



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.



Douglas+, in prep

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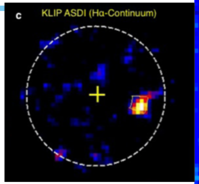
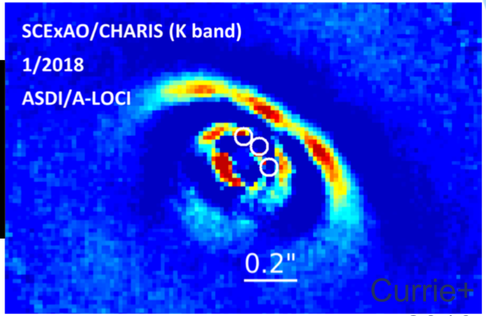
Ewan Douglas (UofAZ)
Bertrand Mennesson (JPL)
Bijan Nemati (UA Huntsville)

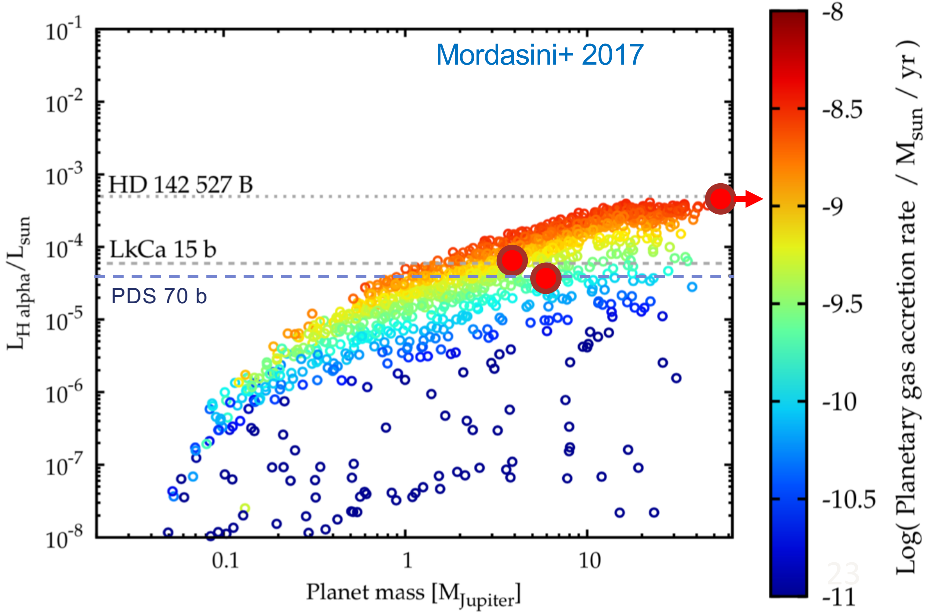
Protoplanetary systems

- 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 1?



Sallum+ 2015





Kate Follette (Amherst)
Ewan Douglas (Univ. AZ)

Resources

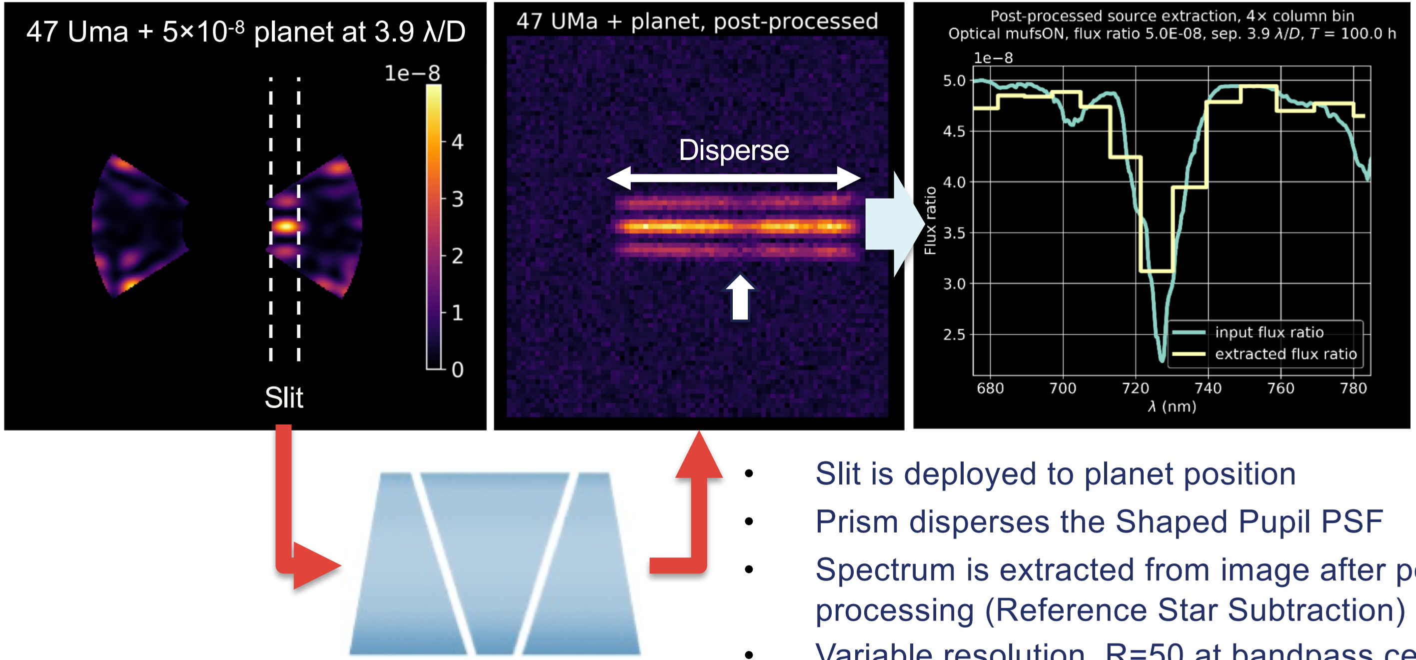
Vanessa Bailey vanessa.bailey@jpl.nasa.gov

- Roman IPAC website
  - Instrument parameters https://roman.ipac.caltech.edu/sims/Param_db.html
  - “Observing Scenario #N” Image simulations and reports https://roman.ipac.caltech.edu/sims/Coronagraph_public_images.html
    - Observing Scenario (OS) 9 is latest release; see “Observing Scenario 9 Post-Processing report” by Ygouf for more information & tutorial
    - OS11 expected later this year, incorporates ground-in-the-loop WFSC touchup cadence
  - Roman Virtual Lecture Series https://roman.ipac.caltech.edu/Lectures.html
- Simulated data processing tutorials (using OS6, but conceptually similar) https://www.exoplanetdatachallenge.com/
- CGISim and PROPER https://sourceforge.net/projects/cgisim/ Info session in late July; email Vanessa Bailey if interested.
- Performance predictions https://github.com/nasavbailey/DI-flux-ratio-plot/
- RV reflected light planet predictions https://plandb.sioslab.com/
- Dark Hole Algorithms Interest Group: neil.t.zimmerman@nasa.gov
- https://www.jpl.nasa.gov/missions/the-nancy-grace-roman-space-telescope
- https://roman.gsfc.nasa.gov/
- SPIE proceedings: 2018 Vol · 10698; 2019 Vol · 11117; 2020 Vol · 11443; 2021 in prep (Vol 11823)
  - Caveat: performance predictions have degraded over time; you should sanity check older papers’ conclusions against the latest contrast curves!

Questions?

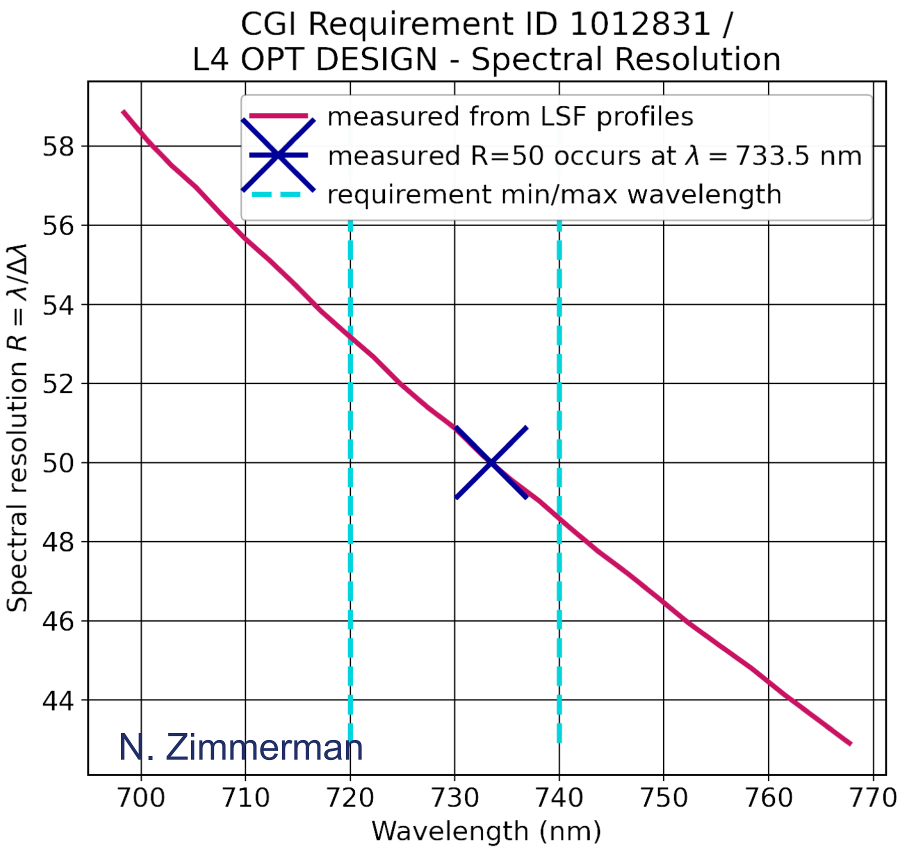
R~50 Spectroscopy w/ Slit Spectrograph (Band 3 or 2)

IFS -> Slit + Prism descope taken in 2019

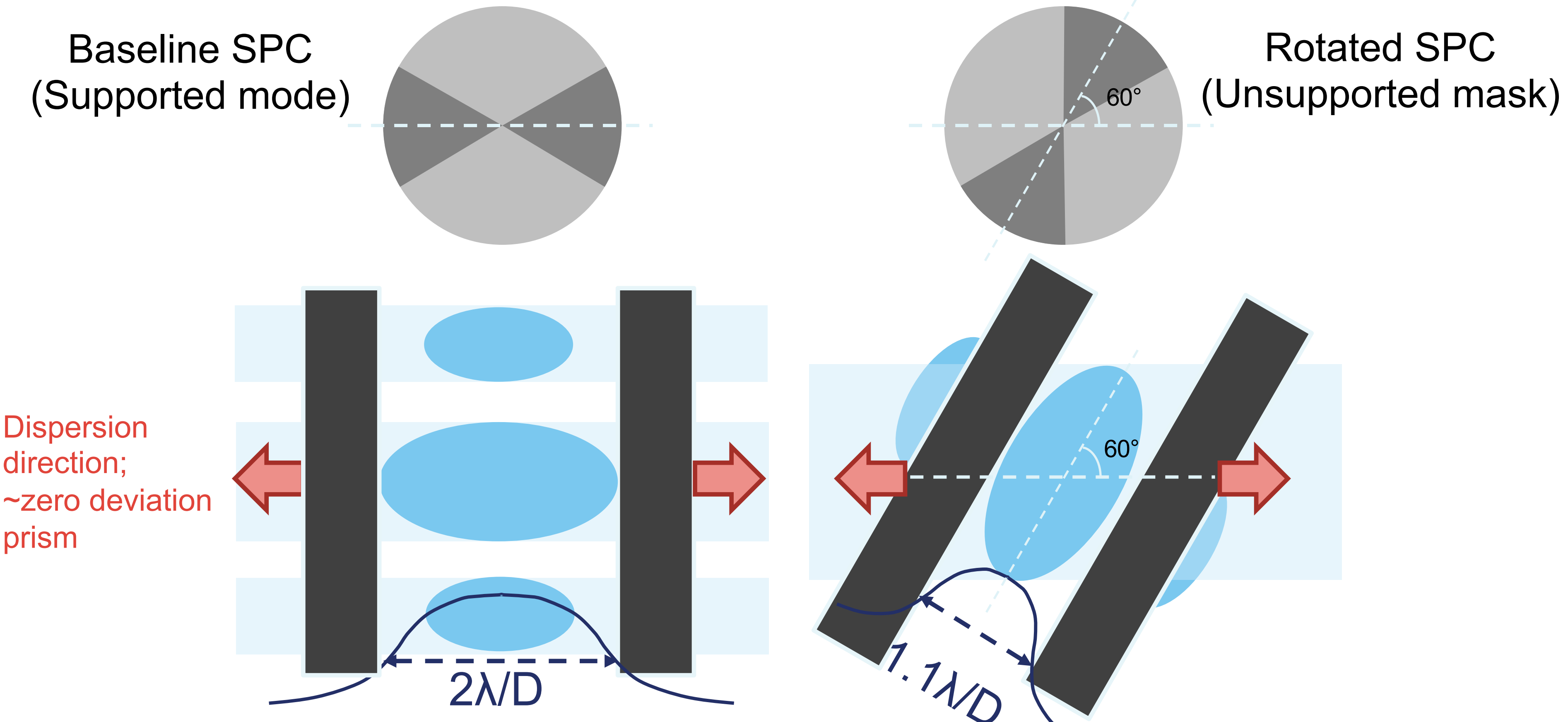


- Slit is deployed to planet position
- Prism disperses the Shaped Pupil PSF
- Spectrum is extracted from image after post-processing (Reference Star Subtraction)
- Variable resolution. R=50 at bandpass center, ±~10

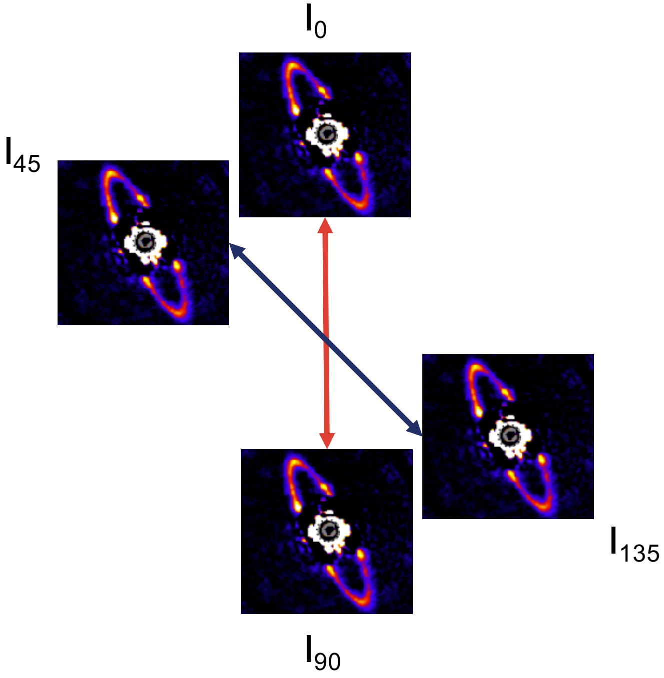
Band 3 Spectral Resolution



SPC “bowtie” slit orientations

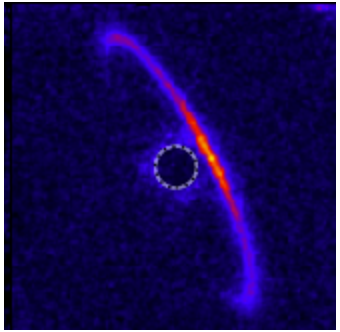


Wollaston Prism Polarimetry (Band 1 or 4 imaging)



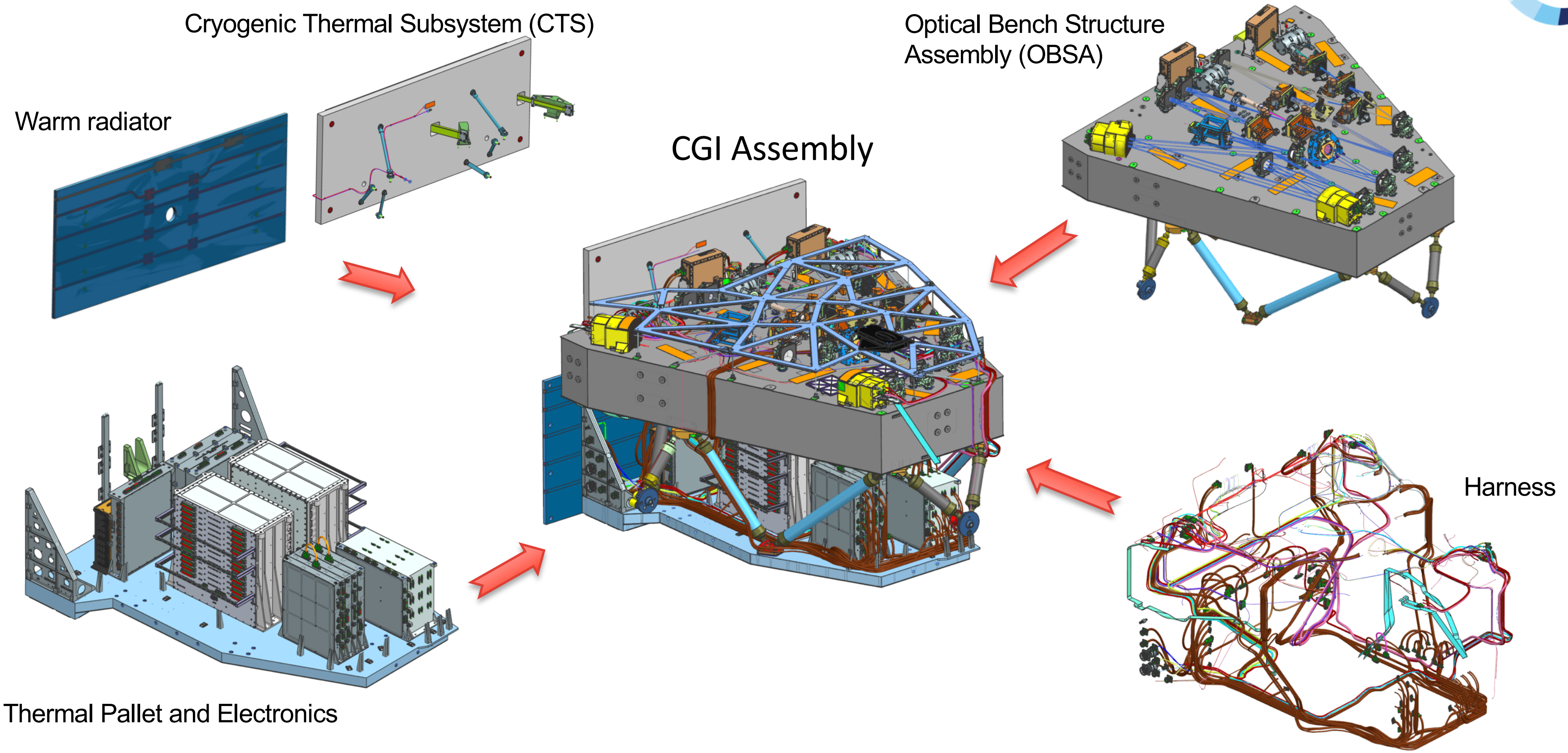
1 pair at a time
Pairs separated by 7.5" on chip

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



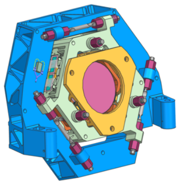
$$LPF = \text{sqrt}\ \{(I_0 - I_{90})^2 + \{(I_{45} - I_{135})^2\}\ /\ I_{tot}$$

CGI H/W Configuration Overview

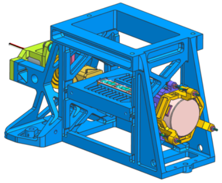


Light path (view in slideshow for animation)

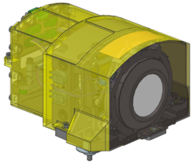
- Used in control loops
- Used in setting up modes



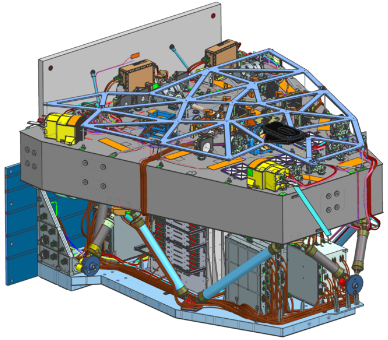
FSM: Fast Steering Mirror

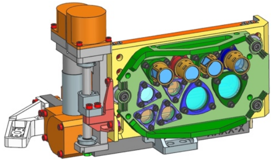


FCM: Focus Control Mirror

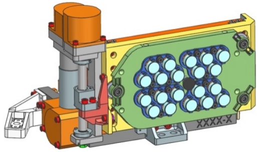


DM (2x): Deformable Mirror

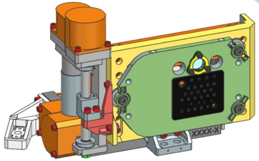




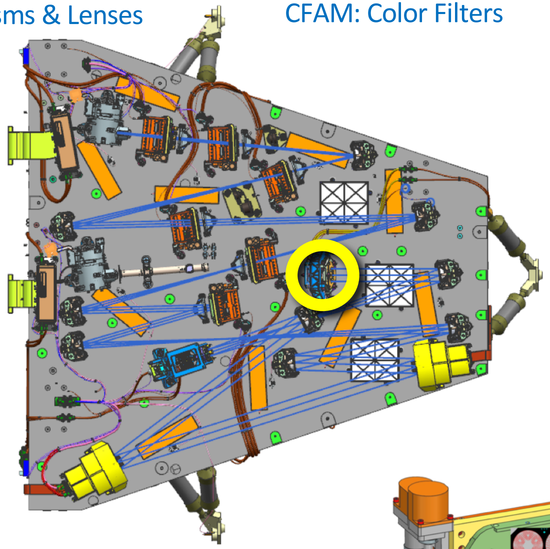
DPAM: Prisms & Lenses

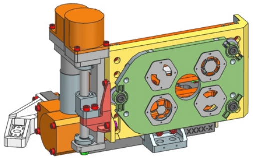


CFAM: Color Filters

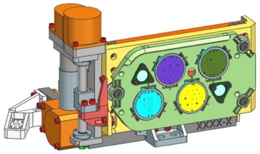


FSAM: Field Stops & Slits

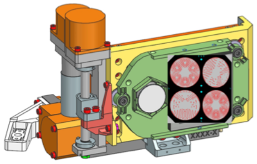




LSAM: Lyot Stops

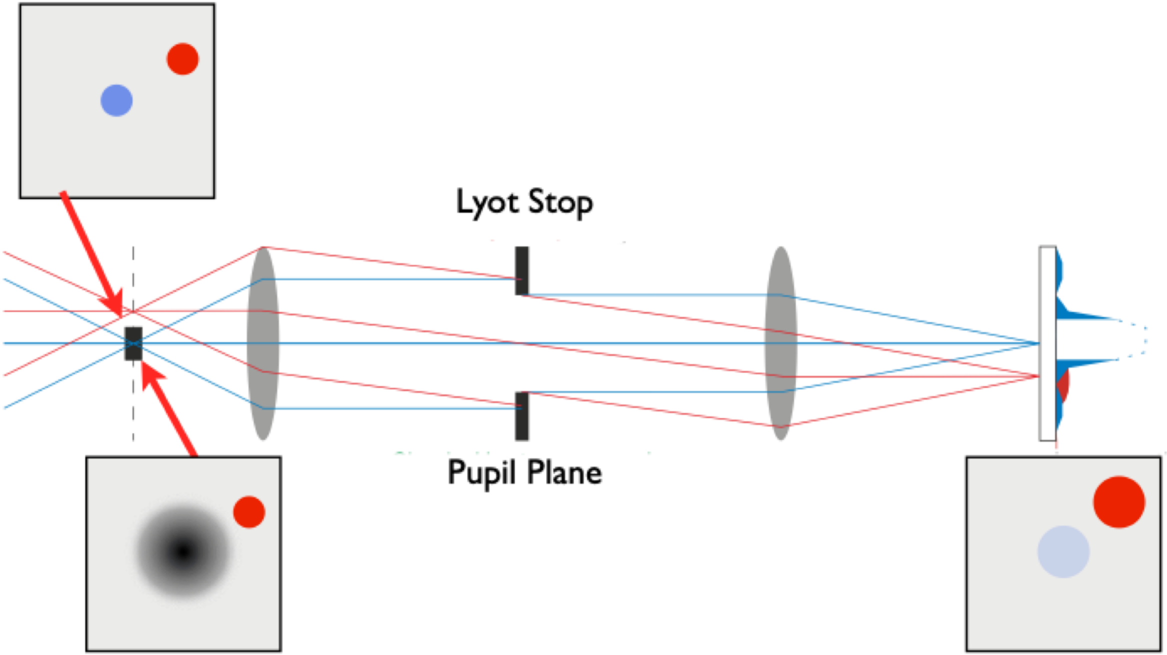


FPAM: Focal Plane Masks

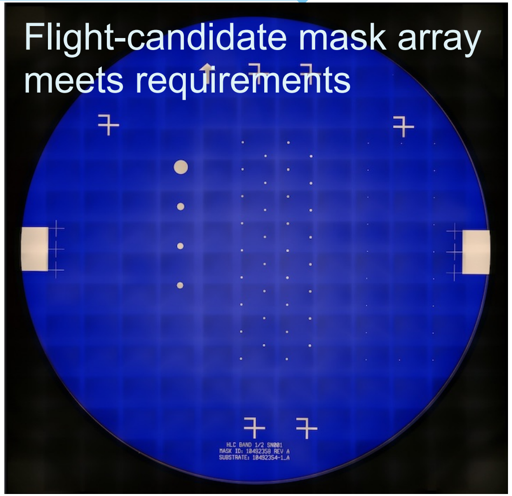


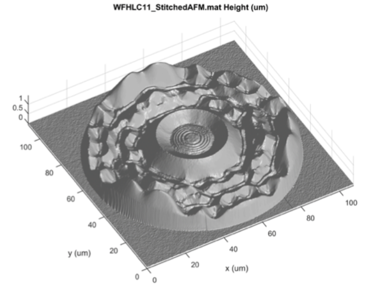
SPAM: Shaped Pupil Masks

(Hybrid) Lyot Coronagraph



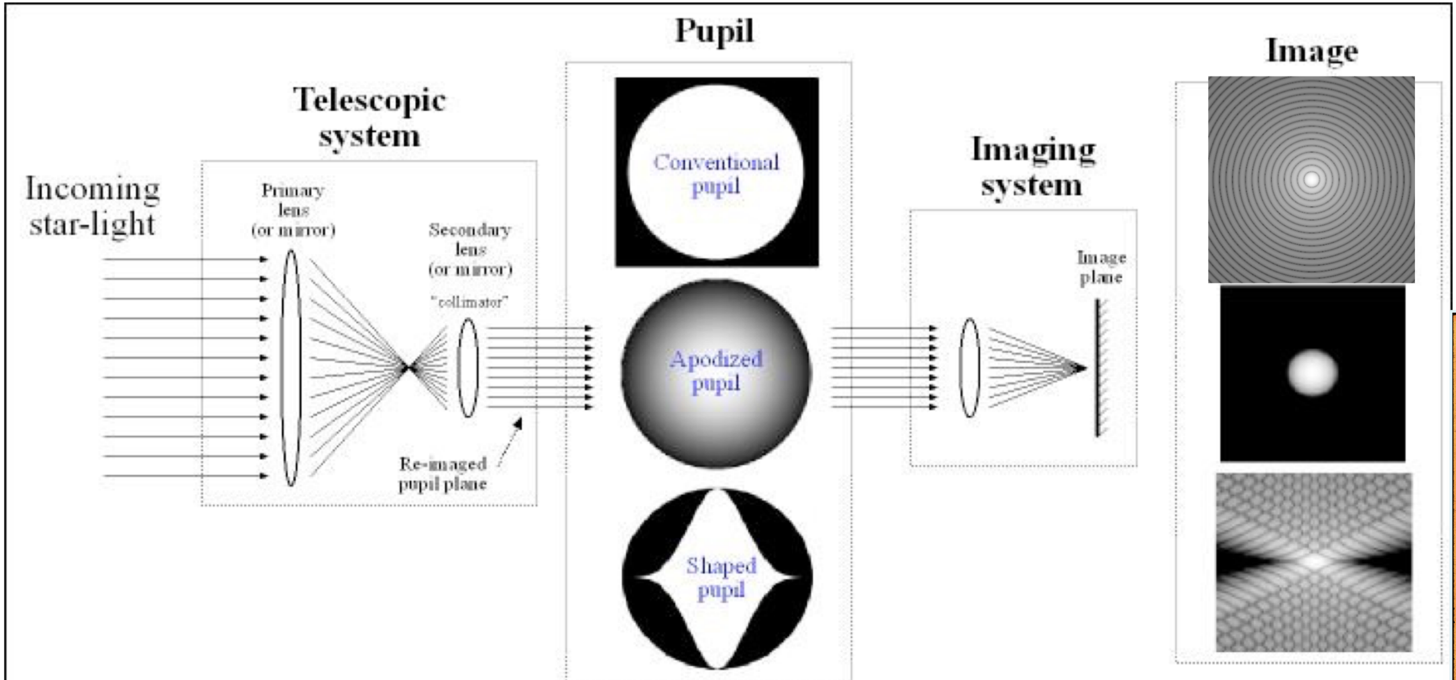
Credit: Matt Kenworthy, University of Leiden



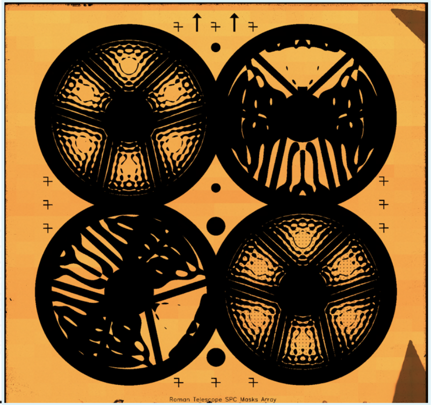


Balasubramanian+2019
Riggs+ in prep

Apodized and Shaped Pupil Coronagraph (SPC)



credit: Jeremy Kasdin



Change PSF to create high contrast at planet location.

Balasubramanian+2019
Riggs+ in prep