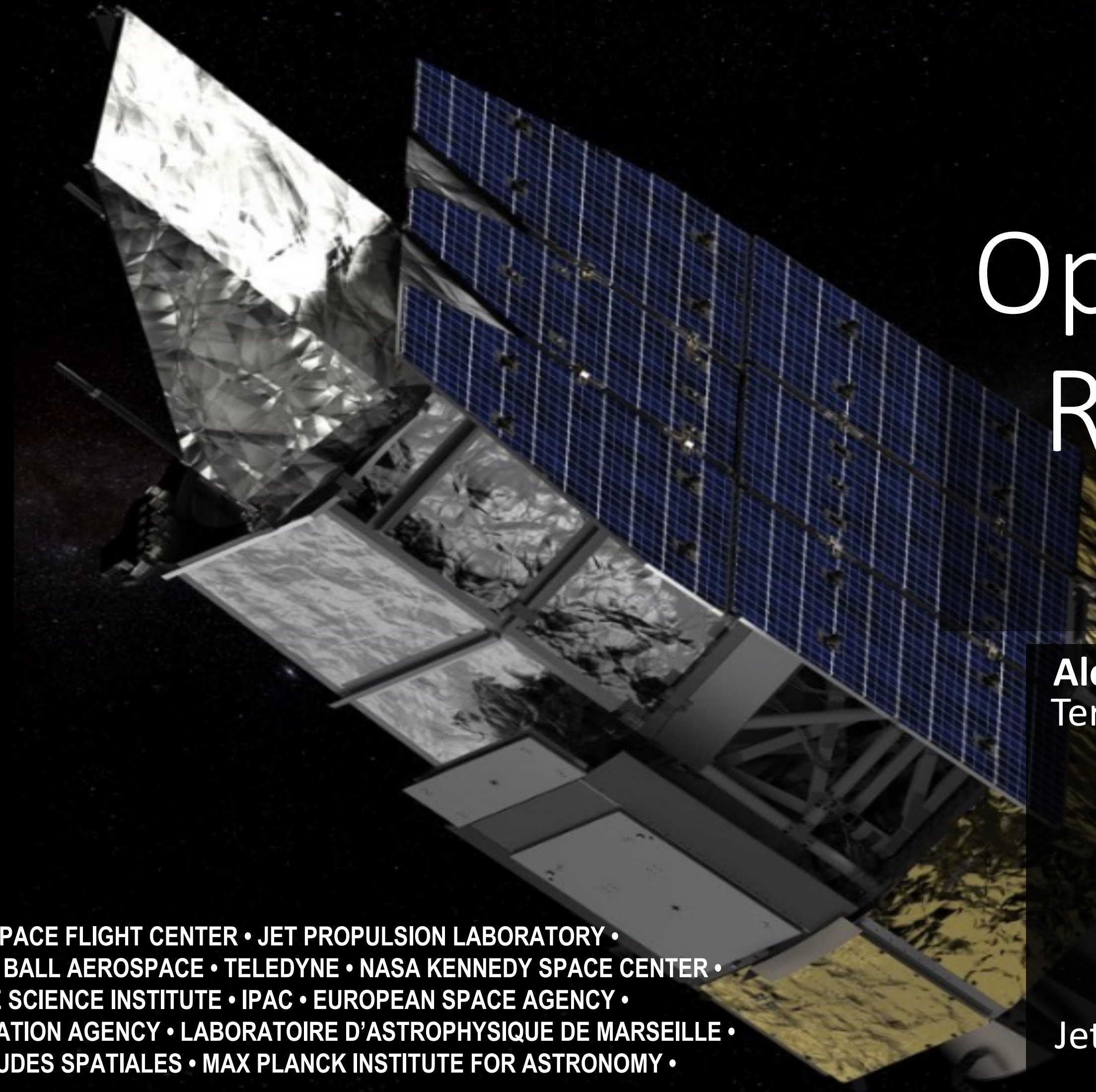

Upcoming Opportunities With the Roman Coronagraph Instrument

Alexandra Greenbaum, James Ingalls, Amelia Nash, Sarmen Ter-oganesyan Patrick Lowrance, Lee Armus, Rachel Akeson, & George Helou

Science Support Center at IPAC, California Institute of Technology

Marie Ygouf, Robert Zellem, Sergi Hildebrandt Rafels, Vanessa Bailey, Bertrand Mennesson, & Jason Rhodes

Jet Propulsion Laboratory, California Institute of Technology

• NASA GODDARD SPACE FLIGHT CENTER • JET PROPULSION LABORATORY •
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• SPACE TELESCOPE SCIENCE INSTITUTE • IPAC • EUROPEAN SPACE AGENCY •
• JAPAN AEROSPACE EXPLORATION AGENCY • LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE •
• CENTRE NATIONAL d'ÉTUDES SPATIALES • MAX PLANCK INSTITUTE FOR ASTRONOMY •

ipac

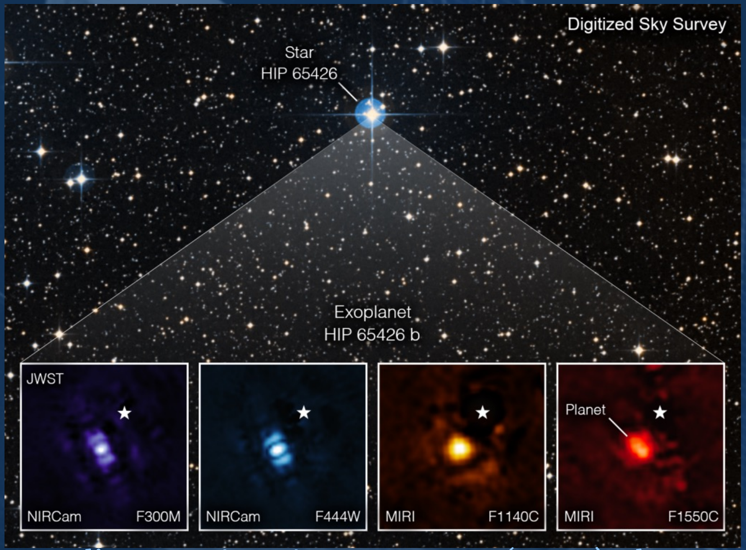
ROMAN SPACE TELESCOPE

ROMAN CORONAGRAPH

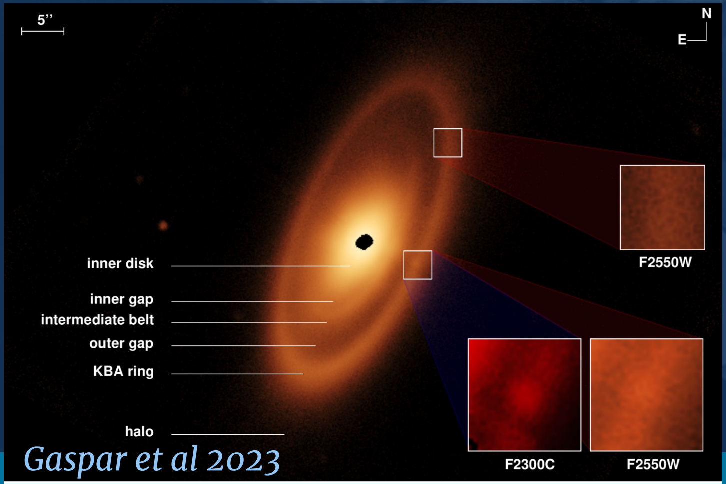
Outline

- Roman Coronagraph: Context & Overview of Key Technologies
- Observing Modes Available
- The Details: What/How/Who
  - Science Themes
  - Operations & Observing scenario
  - The Community Participation Program Structure & How to Get Involved

Circumstellar Environments from Space



Credit: NASA/ESA/CSA, A Carter (UCSC), the ERS 1386 team, and A. Pagan (STScI)

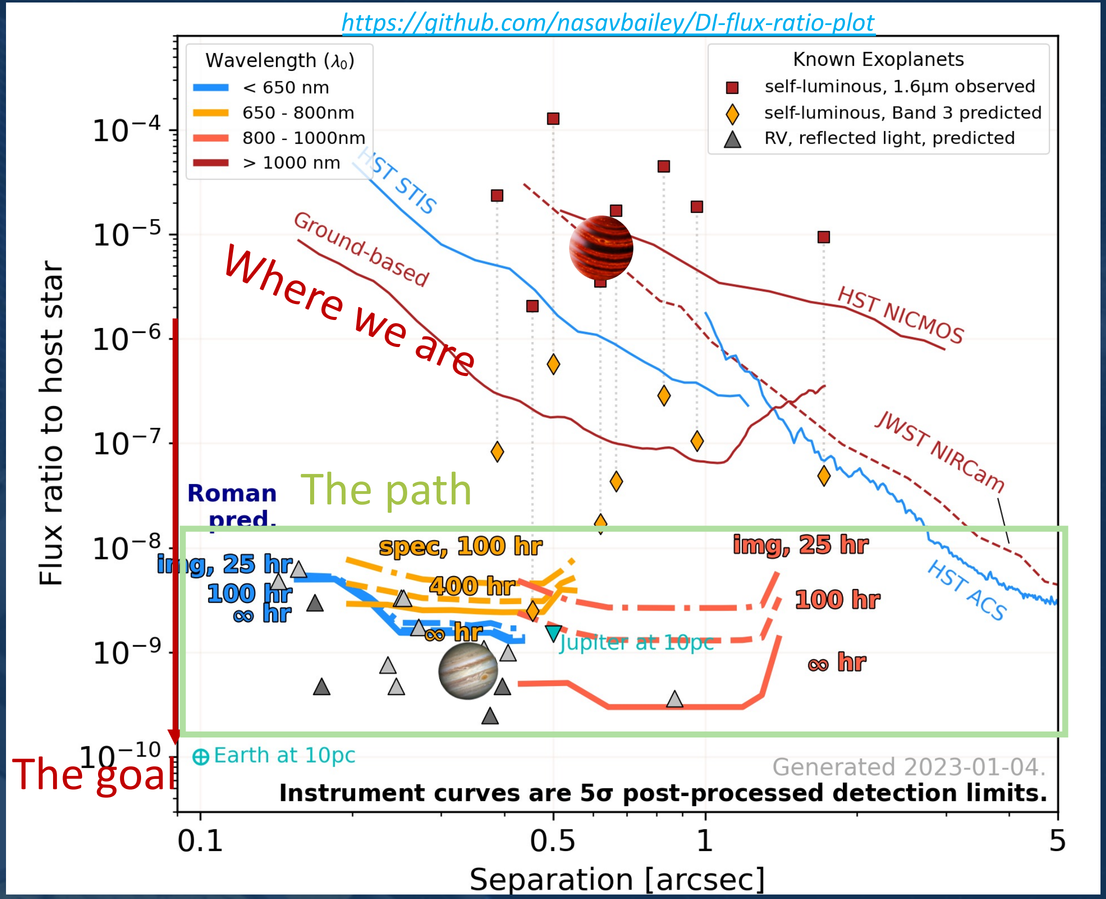


Gaspar et al 2023

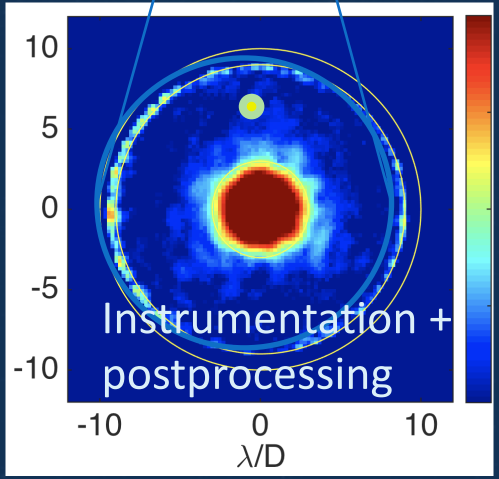
- Achieving unparalleled stability with JWST to image exoplanets and circumstellar environments in Near IR
- Excellent instrument model (always improving), wavefront control, knowledge of wavefront
- Favors giant, young, self-luminous planets, unprecedented view of disks in mid-IR
- No active wavefront control, high spatial frequencies cannot be corrected → limited contrast close to coronagraph

The Roman Coronagraph Instrument paves the way for imaging/spec of exo-earths

The Roman Coronagraph could take the first images of mature Jupiter analog **exoplanets** and circumstellar **disks** seen **in visible reflected starlight**



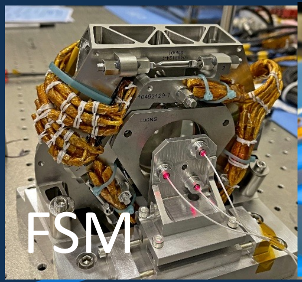
"RV" planets: planets already detected using the Radial Velocity technique and with minimum masses > 0.25 Jupiter mass

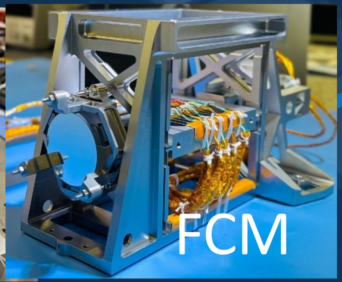


Critical Technologies

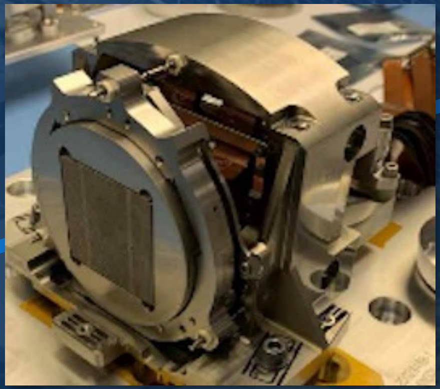
The Roman Coronagraph is an advanced technology demonstrator for NASA's future flagship mission that will directly image Earth-like exoplanets.

Ultra-Precise Wavefront Sensing & Control

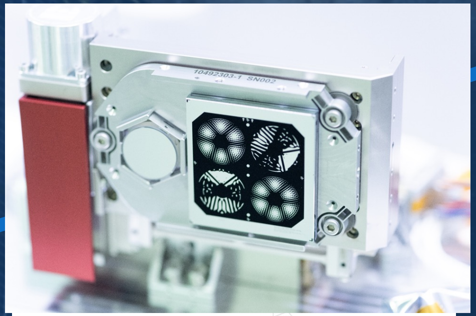


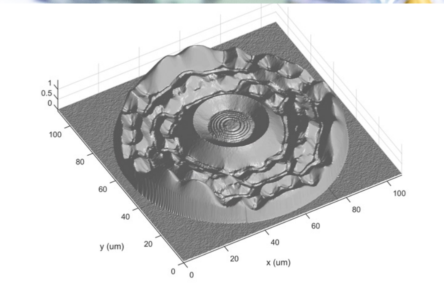


Large-format Deformable Mirrors

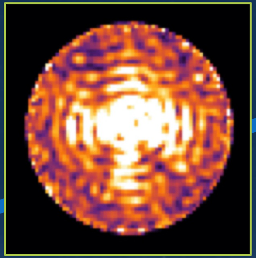


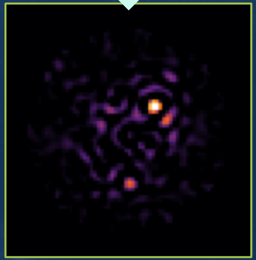
High-contrast Coronagraph Masks





Ultra-low noise photon-counting EMCCD Detectors





Data Post-Processing

The first space-based demo of tech needed to image and characterize rocky planets in the habitable zones of nearby stars.

Technology Demonstration Objectives

TTR5 requirement: 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%.

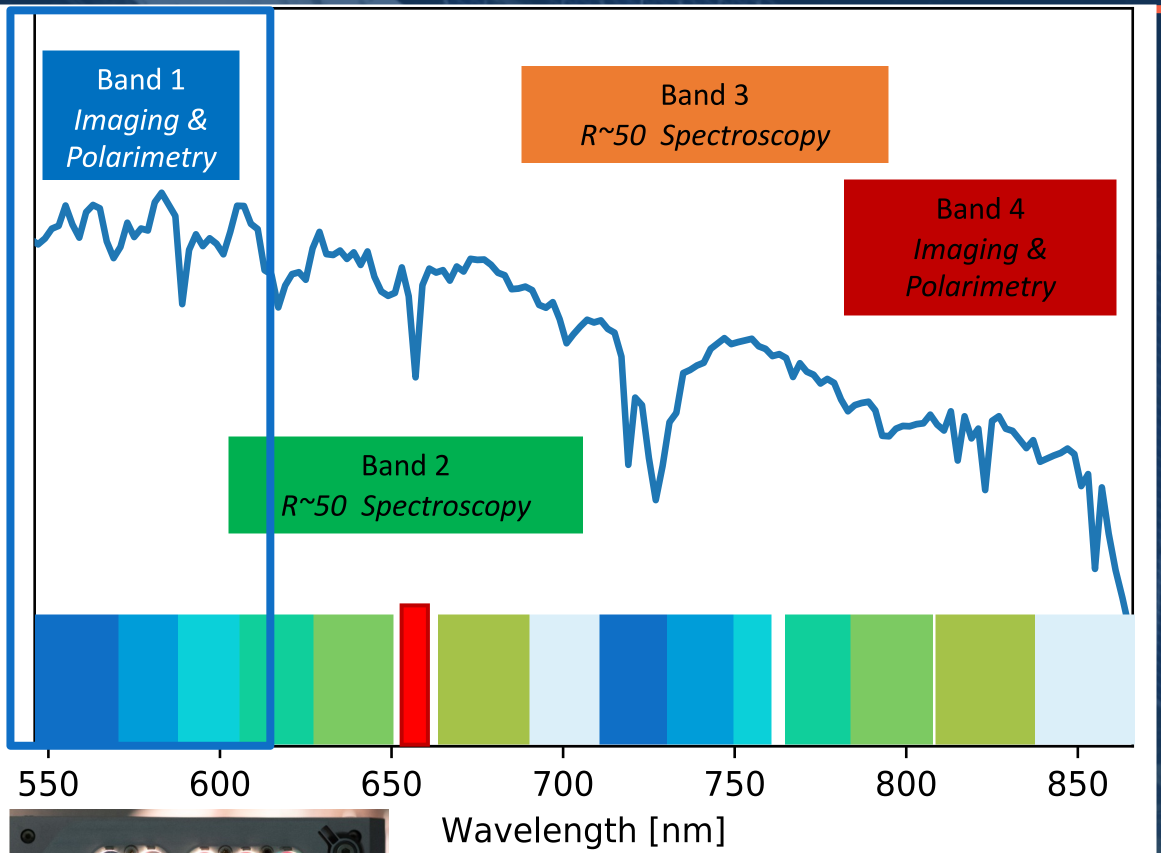
CGI Objectives & Goals

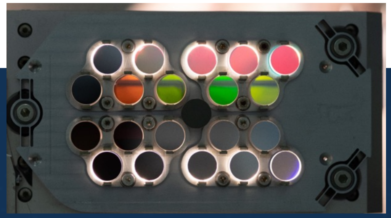
Objective	Operational Goal
Demonstrate active wavefront control	Detect a companion object to a star, on at least two stars
Demonstrate key coronagraph elements	Use coronagraph masks, low-order wavefront sensors, deformable mirrors, and low noise detectors
Demonstrate advanced coronagraph algorithms	Demonstrate modifying the wavefront sensing and control algorithms
Conduct high-contrast performance characterization	Characterize the integrated performance of the coronagraph and observatory as a function of time, wavelength, and polarization; use includes a revisit of the target and a repointing maneuver
Advance high-contrast data processing	Produce photometric, astrometric, and spectrographic measurements of at least one point source & at least one extended object.

Credit: Dominic Benford

- Learn throughout: design, model, build, test, use
- Falling below performance expectations, if we learn why, is still valuable for future missions
- The Roman coronagraph was designed to achieve even better contrasts up to 10^{-9}

Supported Instrument 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	-

One “official” mode will be fully tested prior to launch (Band 1) – Others modes (3, 4) are best effort

* 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.

Additional contributed modes not supported but could be available with extended operations

Complete list of filters available at https://roman.ipac.caltech.edu/sims/Param_db.html

Contributed modes include

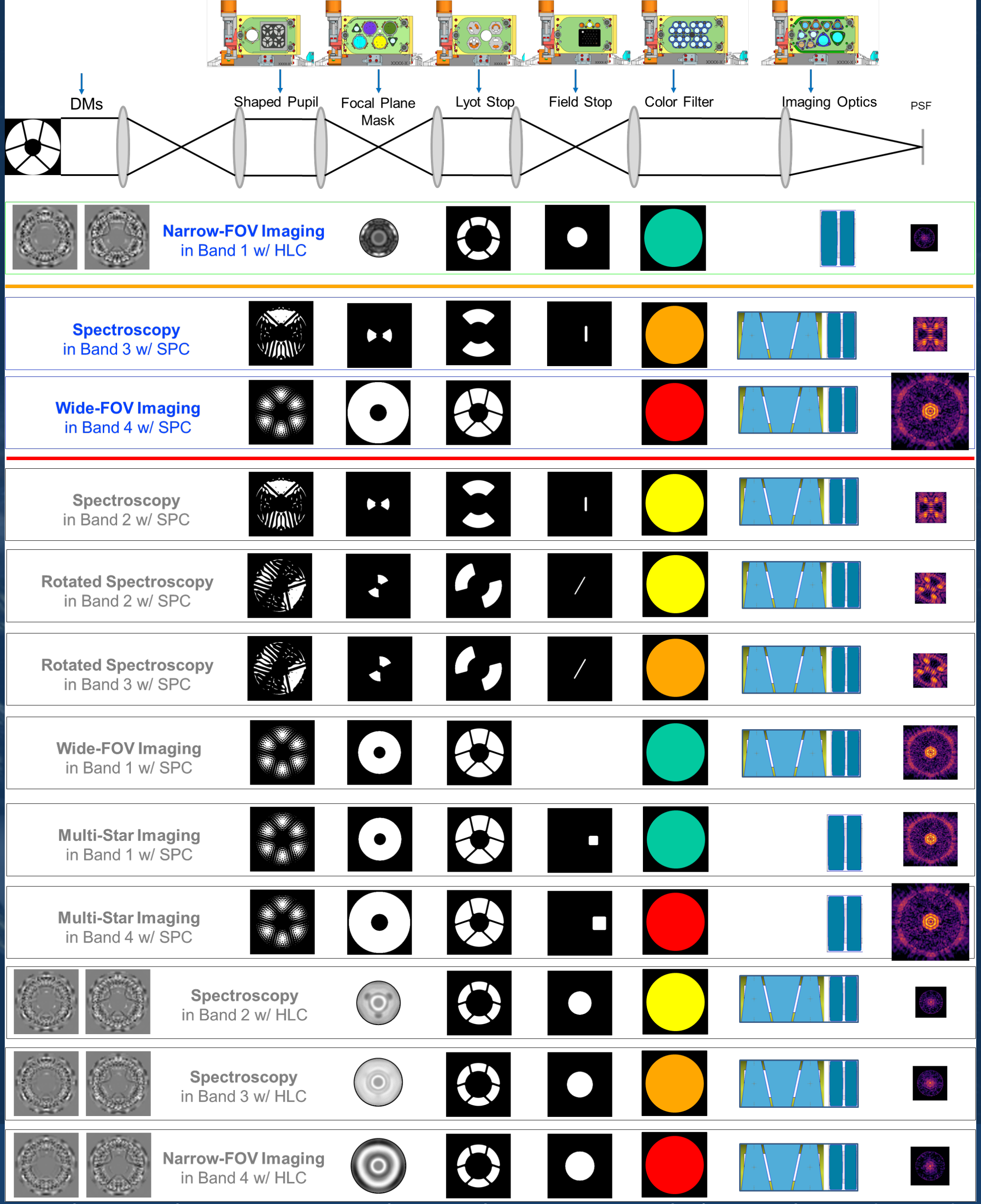
- **High order ZWFS**
- **Multi-star demo**

Further tech demonstration possible

- ***SPC & HLC orientations & filter combinations***
- *Classical Lyot coronagraphs*

** Are there additional on-orbit "tech" demos?*

https://lists.ipac.caltech.edu/mailman/listinfo/roman_announce



Not shown: low-contrast classical coronagraph 'contributed modes'

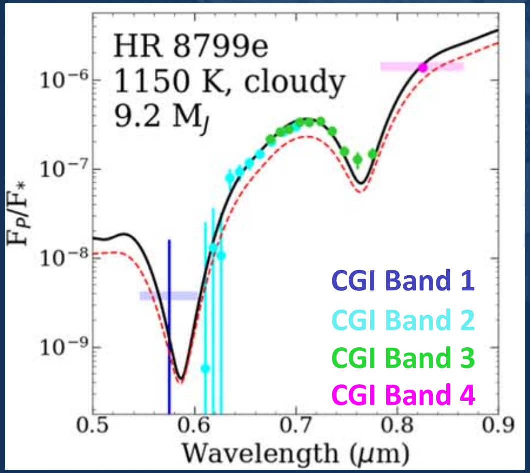
Exoplanet Science Themes

- **The Roman Coronagraph could take the first visible-light image and spectrum of a cool, Jupiter-like exoplanet**
  - Cool planets can be seen by their reflected visible light.
  - Visible wavelengths are sensitive to clouds and hazes

Roman/CGI

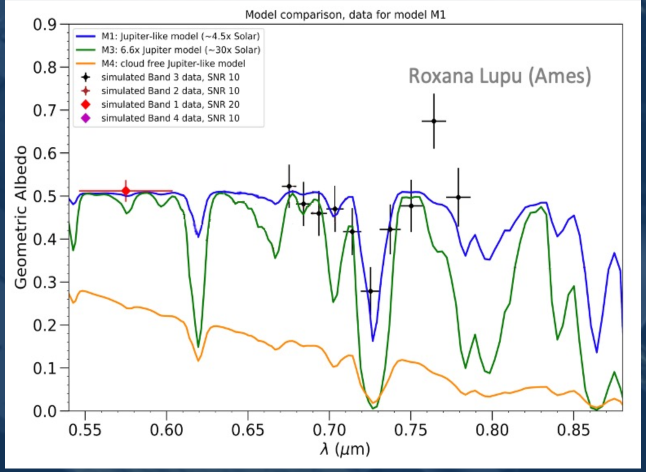
Visible and near-infrared wavelengths
Jupiter-like planets

Self-luminous, Young Super Jupiters: Atmospheric Properties



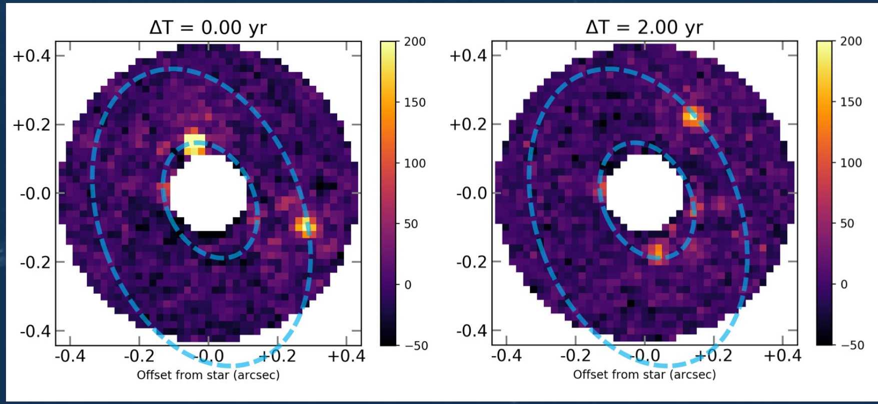
Lacy & Burrows (2020)

Mature Jupiter Analogues in Reflected Light: Atmospheric Properties



Natasha Batalha, Roxana Lupu, & Mark Marley (Ames)

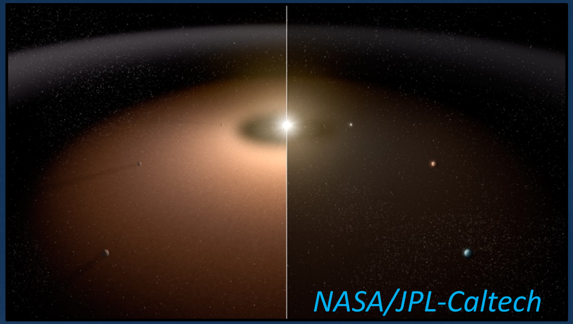
Orbital Solution and Mass Measurement

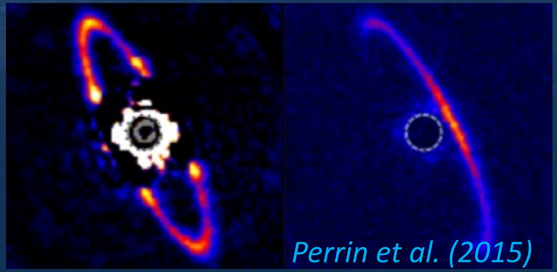


Neil Zimmermann (GSFC)

Disk Science Themes

- The Roman Coronagraph will probe the formation and evolution of extrasolar systems by observing three types of disks:
  - Exozodi disks (Douglas et al. 2022)
    - Colliding or evaporating asteroids and comets
    - Can potentially obscure small Earth-like planets from observation
  - Debris disks
    - Remains of planet formation + colliding or evaporating asteroids and comets
  - Protoplanetary & Transition disks (Stretch goal)
    - Newly-forming planetary systems


NASA/JPL-Caltech


Perrin et al. (2015)


ESO/A. Müller et al.

Credit: Rob Zellem

Roman Coronagraph Science Potential

- Science capability will depend on:
  - Coronagraph Performance
  - Time devoted to Coronagraph observations

	TTR5: 10^{-7}, 6-9 λ/D, Band 1	All modes, $3x\ 10^{-9}$ (optimistic)
Technology maturation	All key imaging technologies at TRL9	… + performance is approaching HWO needs in multiple areas + WFS & binary star tech demos **= strong supporting evidence for 2030 decadal HWO evaluation**
Jupiter analog spectra	No	A few*
Jupiter analog Images	No	**A handful***
Young giant planet spectra	No	**Yes***
Young giant planet images	No	**Yes***
Circumstellar disk images	Yes	**+ polarimetry + lower-mass disks + protoplanetary systems ****
Exo-Zodi Disks images	~5000 zodis	**~40 zodis *****

* Roman will likely be target-limited. Corollary: a modest extended operations period could observe all high-priority targets
** H-alpha imaging of transition (planet-forming) disks will depend on Coronagraph's faint star performance, which is TBD
*** ≥ 6x better than LBTI & first time in **HWO-like** visible wavelength. Potential for survey of prime HWO targets if Coronagraph operations extended

- The CPP will enable members of the community to engage in the technology demonstration phase.
  - If warranted by instrument performance, the CPP may perform science operations beyond the 18 month technology demonstration period.

Target list Objectives/Priorities

Tech demo phase (TDP)

- **Known self-luminous young planets**: observe at new wavelengths
- **Known RV planets**: Image for the first time in reflected visible light
- **Known debris disks**: imaging and polarimetry at new wavelengths and/or higher spatial resolution
- **Exozodi**: opportunistically during deep imaging of known RV systems
- **Calibrators**: single stars for PSF reference; photometric, spectroscopic, polarimetric, & astrometric standards

Post TDP

- All of the above, plus
  - Potential to observe protoplanetary disks
  - Search for new reflected light planets
  - Search for exozodi (future mission exo-Earth search targets prioritized)
- New science cases, including non-exoplanet?

Roman Coronagraph Tech Demo Operations

Instrument Operations:

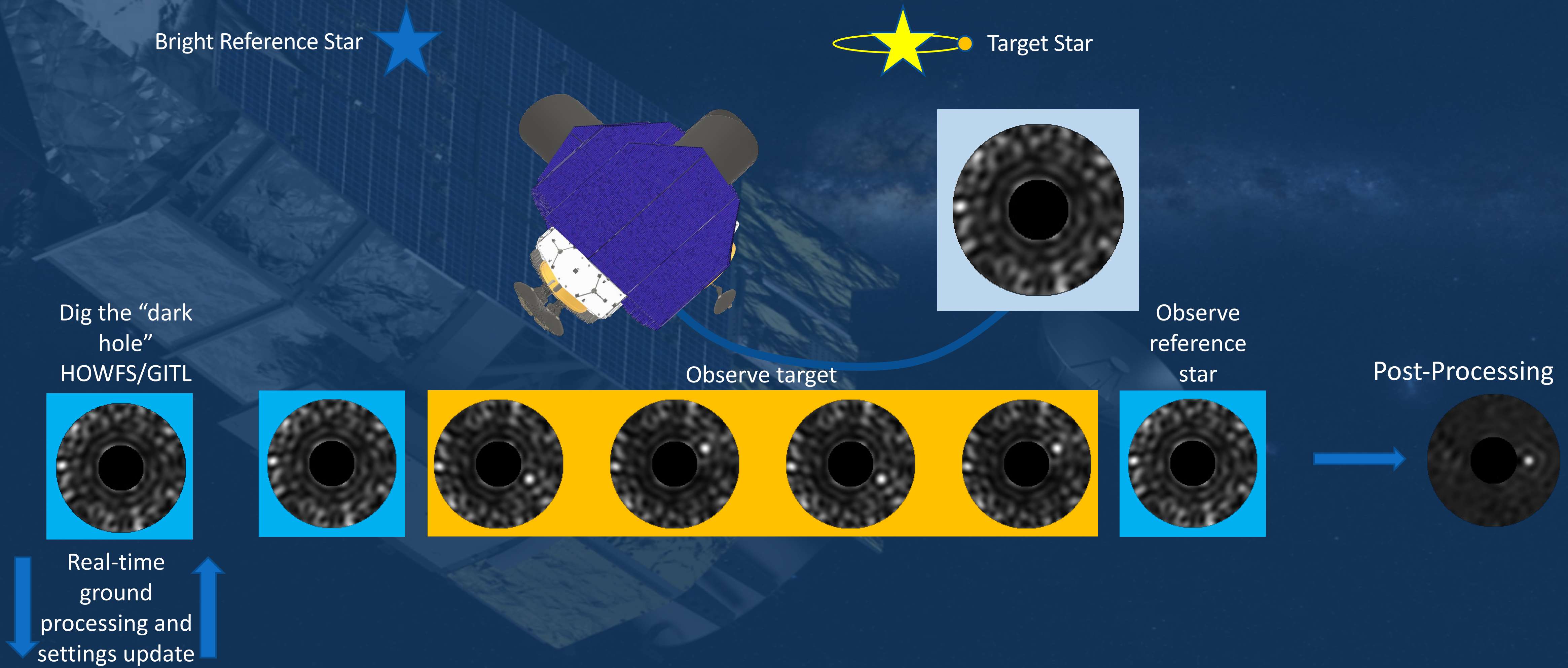
- Coronagraph Technology Center (CTC) at JPL
- The Science Support Center (SSC) at IPAC
- The Science Operations Center (SOC) at STScI
- The Mission Operations Center (MOC) at GSFC

The Community Participation Program (CPP) core team recently selected/assembled

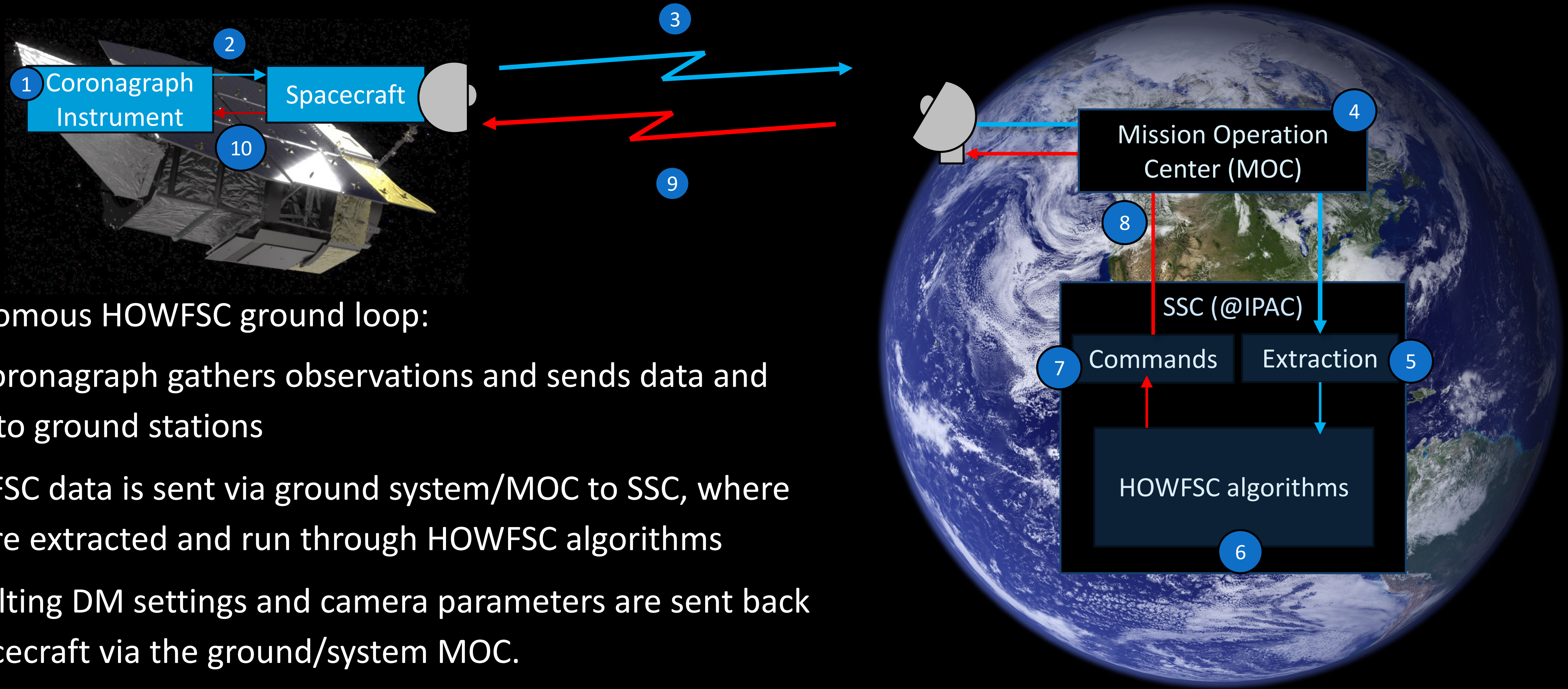
- 7 US members + 4 international partners
- Roman project points of contact

Detailed simulations, plan and carry out observations, coordinate data analysis, and more.

CGI Observing Scenario



High Order Wavefront Sensing and Control at Roman Science Support Center (SSC)



The autonomous HOWFSC ground loop:

1-3) The coronagraph gathers observations and sends data and telemetry to ground stations

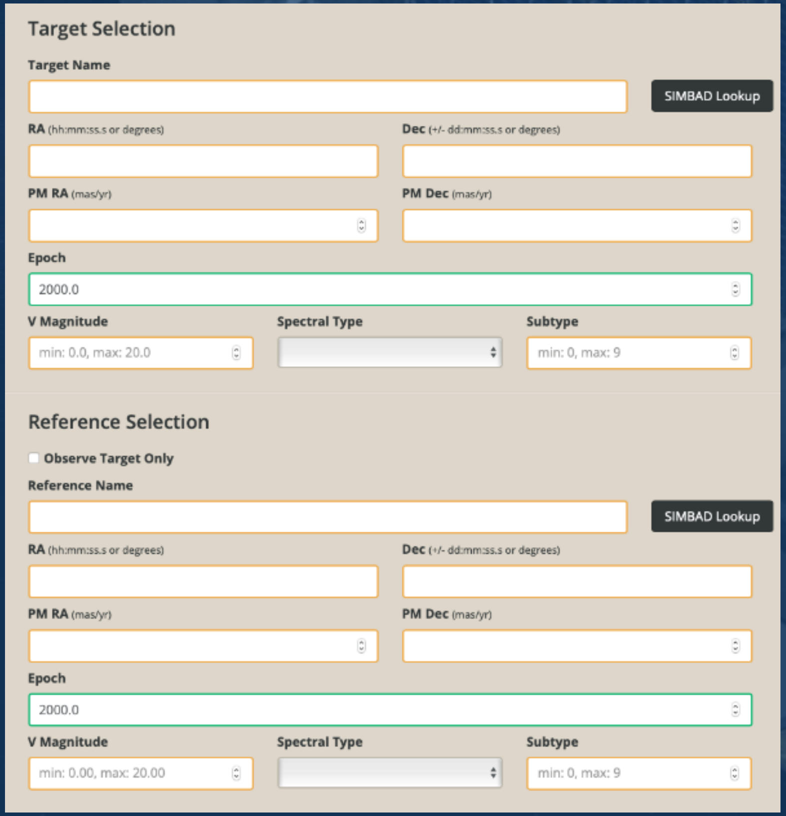
4-6) HOWFSC data is sent via ground system/MOC to SSC, where the data are extracted and run through HOWFSC algorithms

7-10) Resulting DM settings and camera parameters are sent back to the spacecraft via the ground/system MOC.

Operations at Roman SSC

Observation Design

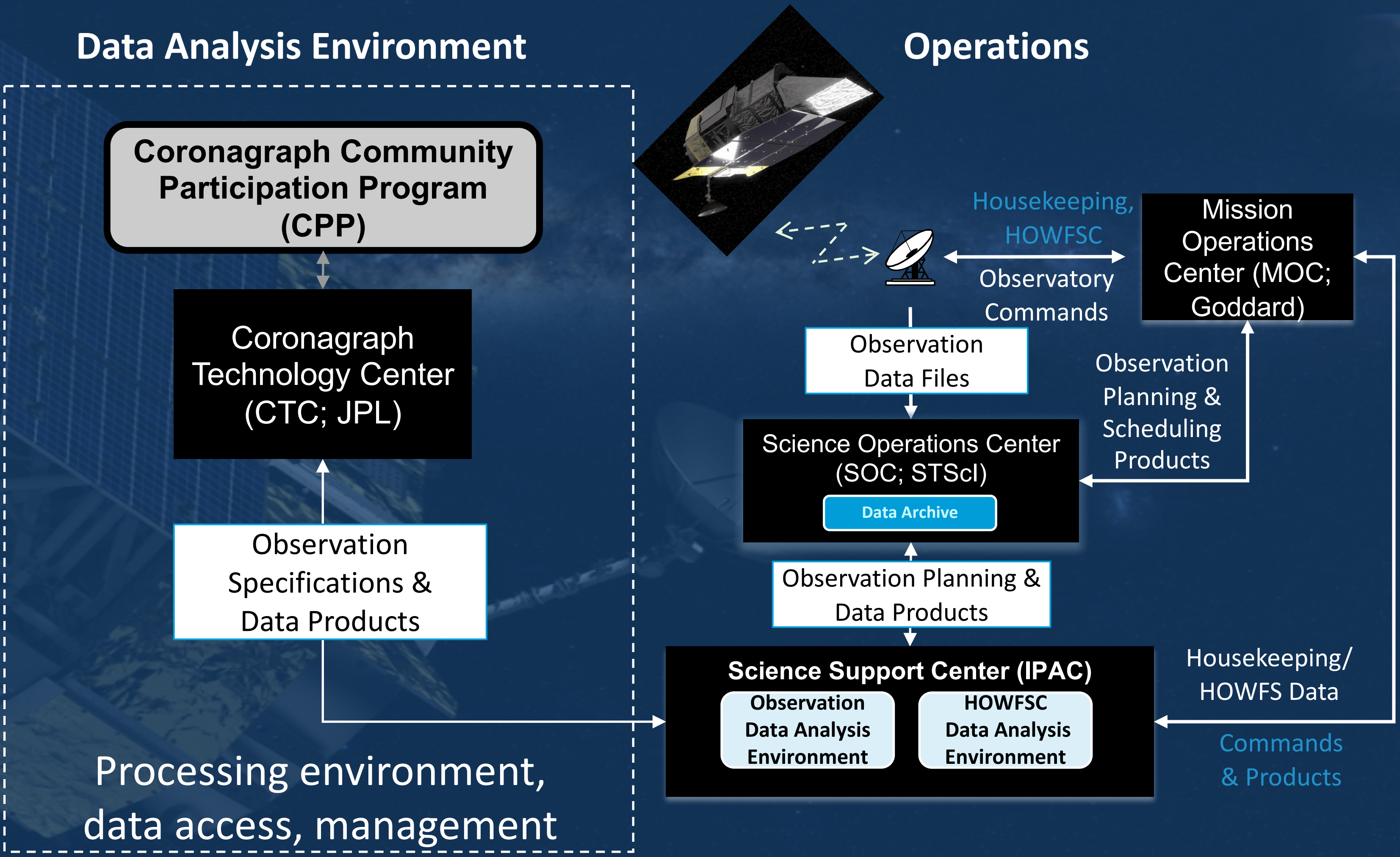
(Custom observation planning tool)



Web interface at SSC

Data Analysis Environment

Operations



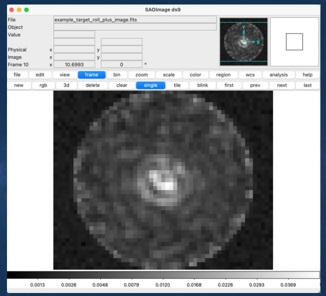
Data to be Produced During the Tech Demo

IPAC

Level 0 – S/C telemetry – retrieved by IPAC from Roman Archive

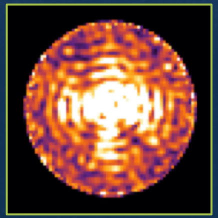
- All CGI health & status telemetry
- Standard image data, DM settings, HOWFSC data

1010101101010111000010



Level 1 – Generated by IPAC from subset of telemetry

- FITS images with programmatic & telemetry metadata
- Data Quality Assessment



CTC
+
CPP

Level 2 – Detector calibrations applied to data frames

Level 3 – Astrophysical units, WCS determined

Level 4 – PSF-subtracted combined images

**L1-L4 Data made public via Roman Archive

Timeline

Instrument Full Functional Tests complete!

Feb 2023: Instrument TVAC Tests

May 2024: Instrument delivery to GSFC

Late 2026: Launch

Commissioning Phase

→ 450 hr in first 90 days after launch

Coronagraph Instrument Technology Demonstration Phase (TDP)

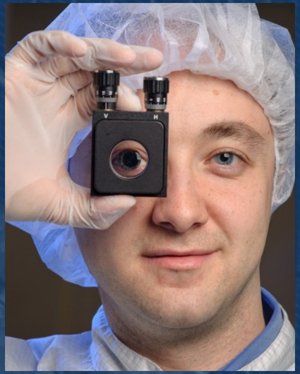
~2200 hr (3 months) baselined in next 1.5 years of mission

Roman Resources

https://roman.gsfc.nasa.gov/science/roses.html

ROMAN SPACE TELESCOPE

Coronagraph Community Participation Program PIs



Rus Belikov
Ames

Oliver Krause
MPIA

Max Millar-Blanchaer
UCSB

Naoshi Murakami
JAXA

Laurent Pueyo
STScI

Dmitry Savransky
Cornell
Inaugural co-chair

Ty Robinson
Univ of AZ

Arthur Vigan
CNES

Jason Wang
Northwestern

Schuyler Wolff
Univ of AZ

ESA TBA

https://lists.ipac.caltech.edu/mailman/listinfo/roman_announce

Community Participation Program Structure

Working Groups

Observation Planning (Lead: Schuyler Wolff)

- Target selection, target database, reference star identification, precursor observations
- Development and maintenance of the exposure time calculator & astrophysical modeling
- Observation planning for both primary and goal modes

Data Reduction and Simulation (Co-Leads: Jason Wang & Max Millar-Blancher)

- Development of the EXCAM observation data reduction pipeline
- Generation of image simulations and performance predictions
- Development of algorithms for data analysis and calibration

Hardware (Co-Leads: Dan Sirbu & Emil Por)

- Assist in CGI integration, testing, commissioning, and operations of the primary and goal observing modes
- Research high-order wavefront sensing and control algorithms

Community Participation Program Structure

Core team

All of the US team PIs, international team PIs, and Roman Project ex officio members.

Project Team

Members of the US and international partner teams who commit to supporting high-priority CPP activities

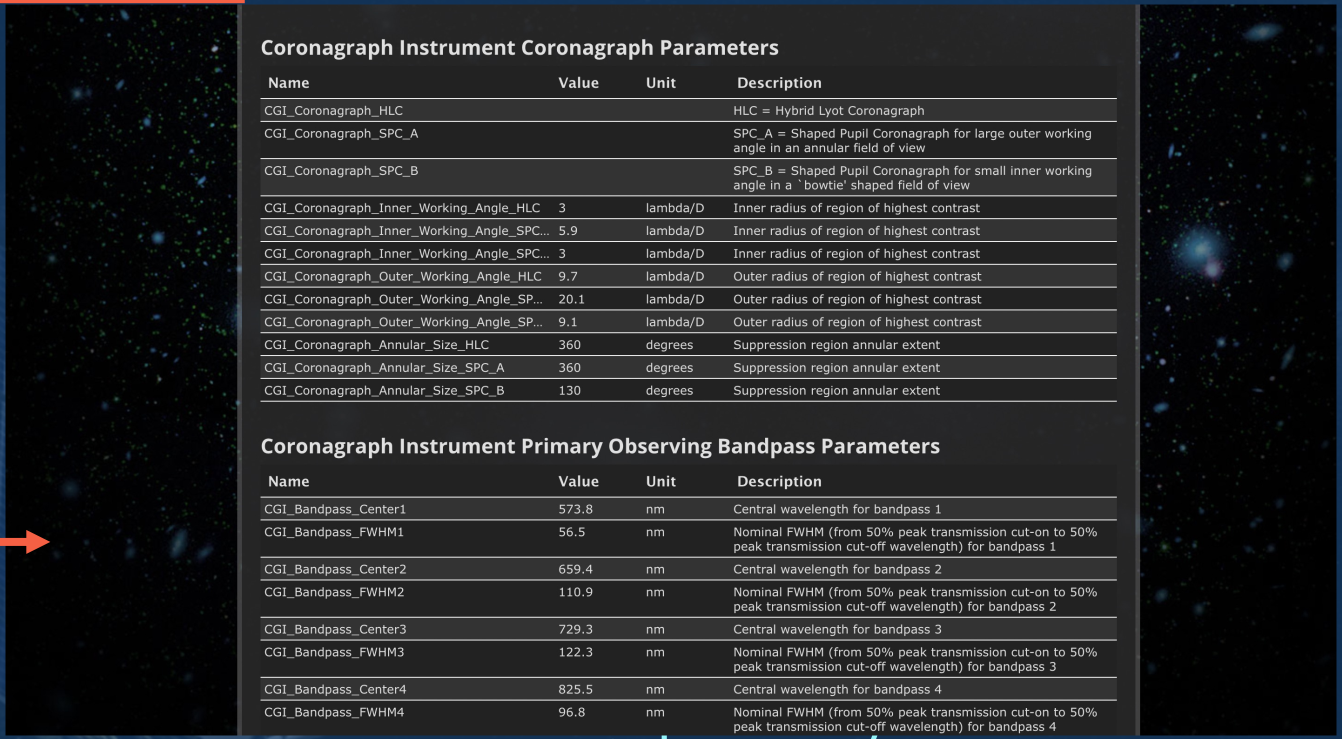
Community Team

All persons are welcome to participate in the work of the CPP as Community Team members.

Where to find more information

https://roman.gsfc.nasa.gov/
Mission/science overview, documents, media

https://roman.ipac.caltech.edu/
Instrument parameters, simulations, workshop materials



Coronagraph Instrument Coronagraph Parameters

Name	Value	Unit	Description
CGI_Coronagraph_HLC			HLC = Hybrid Lyot Coronagraph
CGI_Coronagraph_SPC_A			SPC_A = Shaped Pupil Coronagraph for large outer working angle in an annular field of view
CGI_Coronagraph_SPC_B			SPC_B = Shaped Pupil Coronagraph for small inner working angle in a `bowtie' shaped field of view
CGI_Coronagraph_Inner_Working_Angle_HLC	3	lambda/D	Inner radius of region of highest contrast
CGI_Coronagraph_Inner_Working_Angle_SPC...	5.9	lambda/D	Inner radius of region of highest contrast
CGI_Coronagraph_Inner_Working_Angle_SPC...	3	lambda/D	Inner radius of region of highest contrast
CGI_Coronagraph_Outer_Working_Angle_HLC	9.7	lambda/D	Outer radius of region of highest contrast
CGI_Coronagraph_Outer_Working_Angle_SP...	20.1	lambda/D	Outer radius of region of highest contrast
CGI_Coronagraph_Outer_Working_Angle_SP...	9.1	lambda/D	Outer radius of region of highest contrast
CGI_Coronagraph_Annular_Size_HLC	360	degrees	Suppression region annular extent
CGI_Coronagraph_Annular_Size_SPC_A	360	degrees	Suppression region annular extent
CGI_Coronagraph_Annular_Size_SPC_B	130	degrees	Suppression region annular extent

Coronagraph Instrument Primary Observing Bandpass Parameters

Name	Value	Unit	Description
CGI_Bandpass_Center1	573.8	nm	Central wavelength for bandpass 1
CGI_Bandpass_FWHM1	56.5	nm	Nominal FWHM (from 50% peak transmission cut-on to 50% peak transmission cut-off wavelength) for bandpass 1
CGI_Bandpass_Center2	659.4	nm	Central wavelength for bandpass 2
CGI_Bandpass_FWHM2	110.9	nm	Nominal FWHM (from 50% peak transmission cut-on to 50% peak transmission cut-off wavelength) for bandpass 2
CGI_Bandpass_Center3	729.3	nm	Central wavelength for bandpass 3
CGI_Bandpass_FWHM3	122.3	nm	Nominal FWHM (from 50% peak transmission cut-on to 50% peak transmission cut-off wavelength) for bandpass 3
CGI_Bandpass_Center4	825.5	nm	Central wavelength for bandpass 4
CGI_Bandpass_FWHM4	96.8	nm	Nominal FWHM (from 50% peak transmission cut-on to 50% peak transmission cut-off wavelength) for bandpass 4

https://www.jpl.nasa.gov/missions/the-nancy-grace-roman-space-telescope/
Instrument overview and capabilities

Sign up for the roman announcements mailing list and stay tuned!

Backup

Potential Target List

Potential Target List

Color coded by V-band magnitude (b/c only required to achieve optimal performance on V<5 stars)

Not set in stone! Will continue to add & update with inputs from current science teams & future "community participation" team

* = *tentatively* higher priority for Tech Demo Phase (TDP)

Known, Self Luminous

Probably observe 1-2 systems during TDP

	Name	V mag
	51 Eri	5.21
	HD 984	7.32
	HR 2562	6.10
*	HR 8799	5.95
	HD 95086	7.36
*	kap And	4.14
	beta Pic	3.86
	HD 206893	6.67
	HIP 65426	6.98

Selected on host star mag, projected separation, predicted fluxes from Lacy 2020 (+Lacy private communication)

Known RV, Reflected Light

Probably observe 1-2 systems during TDP

	Name	V mag
	14 Her	6.61
*	47 UMa	5.05
	HD 114613	4.85
	HD 134987	6.45
	HD 142	5.70
	HD 154345	6.76
	HD 160691	5.15
	HD 190360	5.73
	HD 192310	5.73
	HD 217107	6.16
*	HD 219134	5.57
	HD 39091	5.57
	tau Cet e	3.50
*	ups And d	4.10

From https://plandb.sioslab.com/ (mostly) NExScI orbits, masses + Batalha et al albedo models

Exozodi

Probably no dedicated exozodi search during TDP, unless opportunistic during point source search

	Name	V mag
	tau Ceti	3.50
*	eps Eri	3.82
	bet Vir	3.60
	Tet Boo	4.05
	lam Ser	4.42
	gam Ser	3.84
	72 Her	5.39
	Vega	0.00
	110 Her	4.19
	Sig Dra	4.68
*	Formalhaut	1.16

Work in progress. These are placeholders. Douglas et al. have submitted a paper that will refresh this top 10 list and describe the potential for a larger (~50 target) survey in support of future exo-Earth imaging missions. Combo of follow-up of 10um excesses and blind search.

Debris Disk

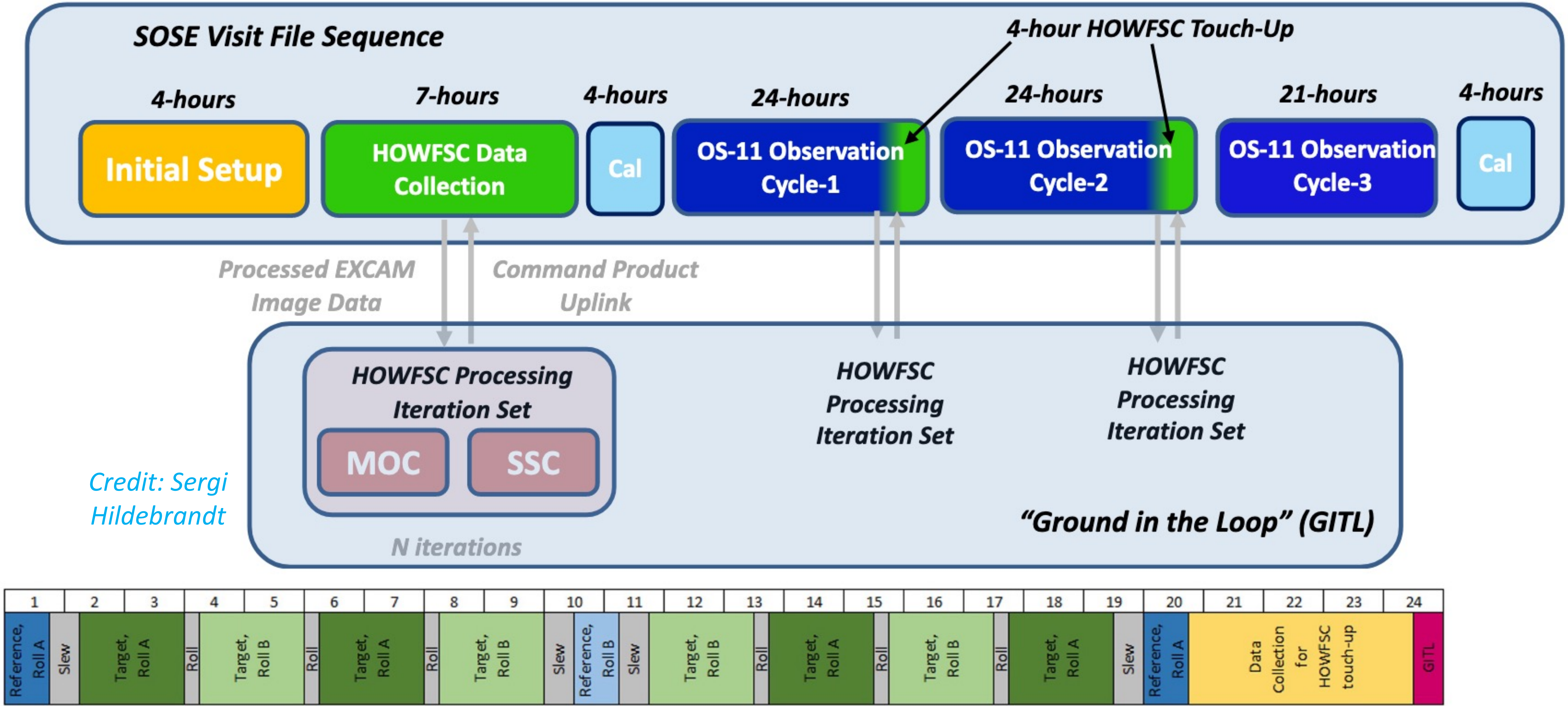
1-2 integrated light, 1-2 polarimetry during TDP

	Name	V mag
	49 Ceti	5.61
	beta UMa	2.37
	beta Leo	2.13
*	HD 139664	4.63
	eps Eri	3.82
	HD 172555	4.77
	HD 15115	6.80
	beta Pic	3.86
	eta Corvi	4.29
*	HR 4796	5.77

Work in progress. Will update & optimize as time goes on! Selected on star mag, known properties/limits from previous work. Combo of follow-up and blind search.

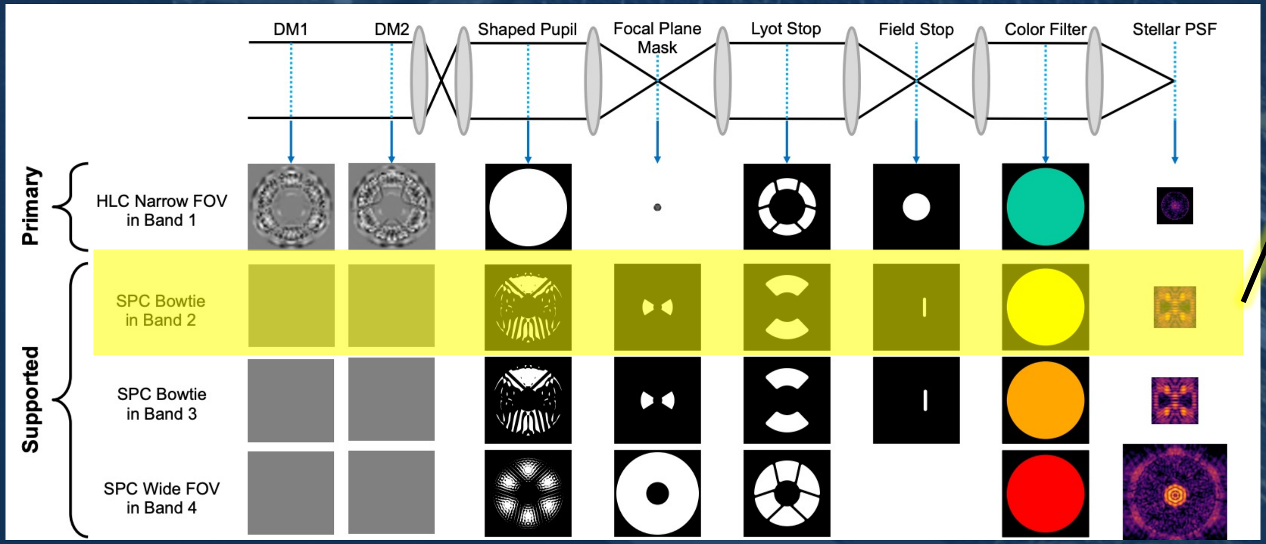
Roman Coronagraph Observing Sequence

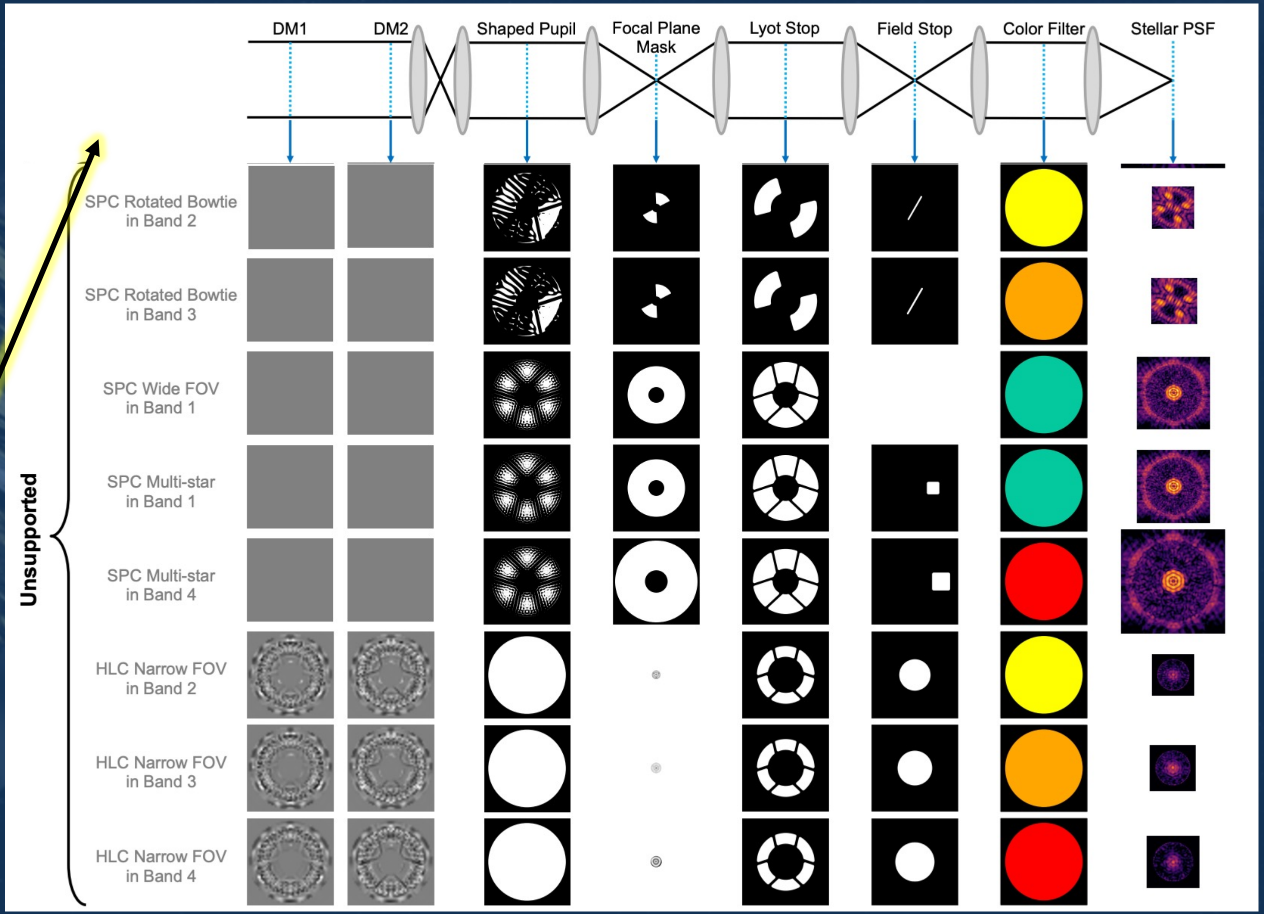
HOWFSC – High Order Wavefront Sensing Control, GITL – Ground In The Loop
SOSE – Science Observation Sequence Engine
MOC – Mission Operations Center, SSC – Software Support Center



Credit: Sergi Hildebrandt

Observing modes available





Riggs et al., 2021 SPIE

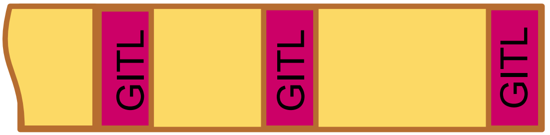
Some Roman & HWO+ common challenges

- Roman is a stepping stone to 10^{-10} contrast
  - Active control + novel coronagraph designs for “broadband” & small IWA
  - Understand stability (pointing jitter, low & high order WF)
- Efficient detection
  - Photon-counting detection
  - Low noise, High QE
- Capabilities: Imaging, Spectroscopy, & Polarimetry
- Commanding an instrument/telescope with active WF control at L2
- How can additional telemetry feed post-processing

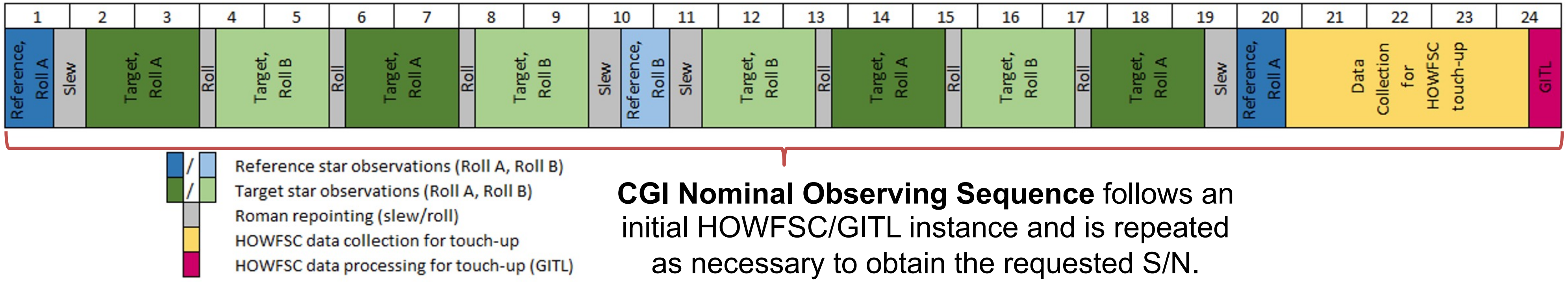
(How could a deep dive into the telemetry inform HWO technologies?)

HOWFSC Cadence

- High Order Wave Front Sensing and Control (HOWFSC)
  - 48x48 deformable mirror actuators to “dig a dark hole”
  - Iterative process (7-9 iterations for initial instance) optimizes actuator (and camera) settings
  - Used for initial dark hole (~7-30 hours) and touch-ups (~4 hours)
  - Approx. 24hr cadence between HOWFSC instances.
- The calculations needed to dig a dark hole are performed at the SSC using Ground In The Loop (GITL). The ground loop takes <30 minutes.



Initial HOWFSC Data Collection
(only a few iterations shown)



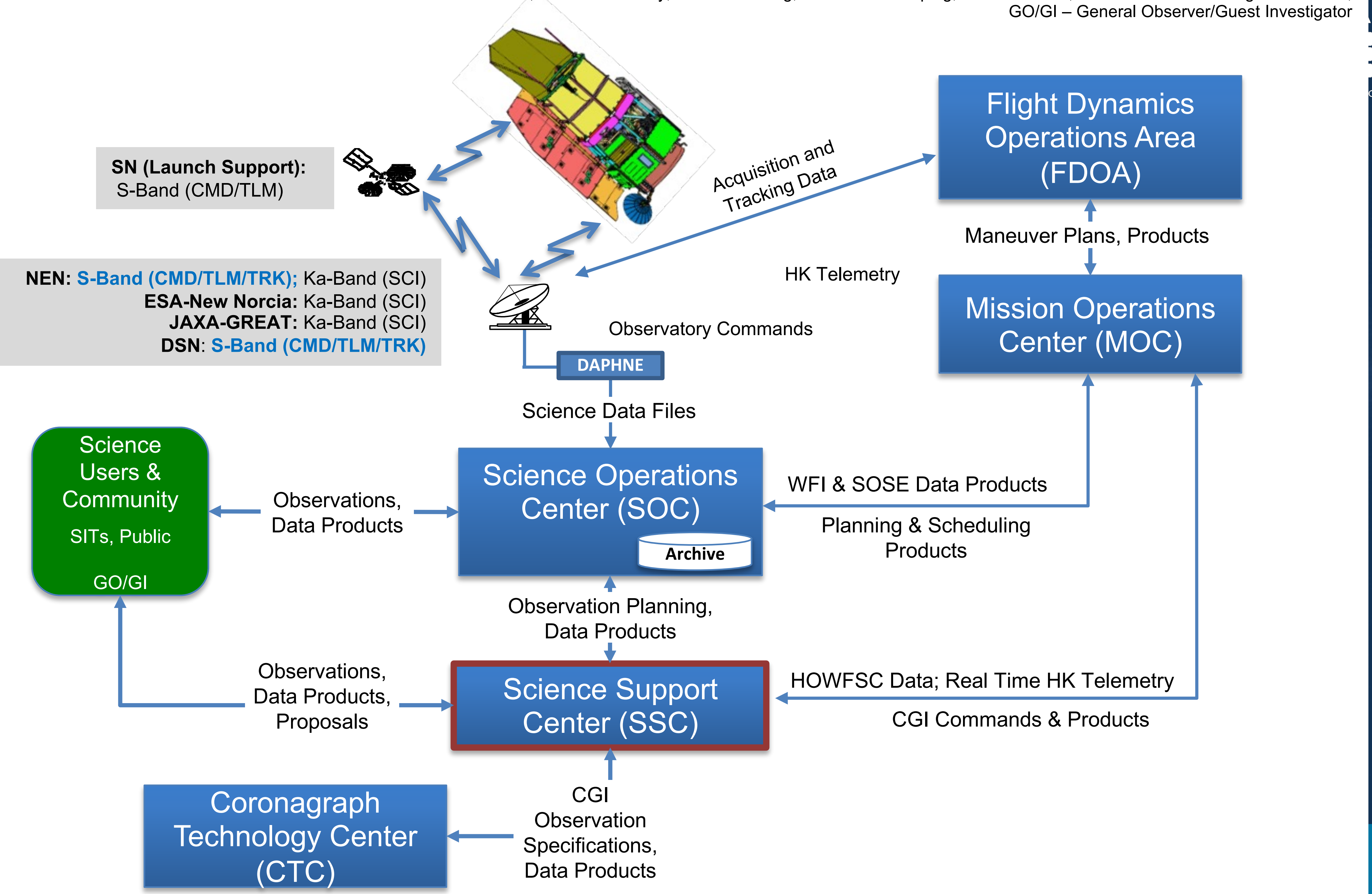
CGI Nominal Observing Sequence follows an initial HOWFSC/GITL instance and is repeated as necessary to obtain the requested S/N.

Data Volume

- L0-L1 processing to accommodate 0.9 Tb/24 hr
- Current best estimate (CBE): 0.43 Tb per 24h (5 megabits/s).
- SSC will store all L1-L4 data, HOWFSC data, and Housekeeping telemetry for the duration of the tech demo.

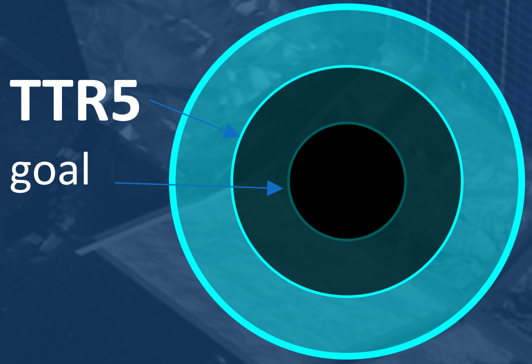
(CBE total storage volume: about 450 Tb (55 TB))

CMD – Command; TLM – Telemetry; TRK – Tracking; HK – Housekeeping; SCI – Science; SITs – Science Investigation Teams; GO/GI – General Observer/Guest Investigator

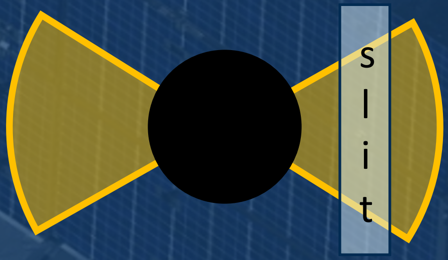


Req'd + Best Effort

Band 1
Imaging (& polarimetry)



Band 3
Slit spectroscopy



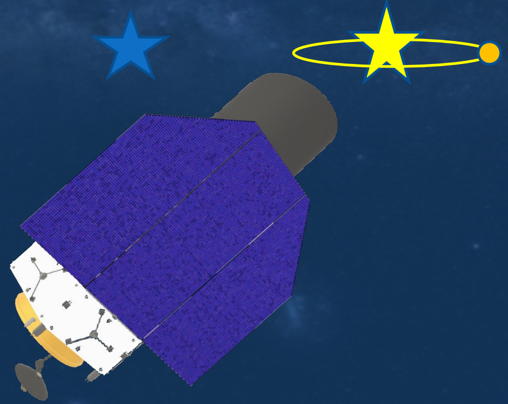
Band 4
Imaging (& polarimetry)

TTR5 band 1:	**0.6" - 0.9"**
HLC band 1 goal:	0.3" - 0.9"
SPC spec Band 3:	0.4" - 1.2"
SPC WFOV Band 4:	0.9" - 2.9"

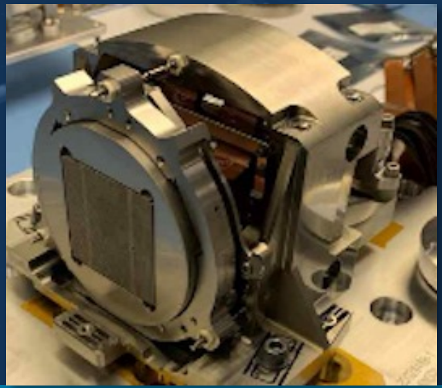
Band 1 = 575nm
Band 2 = 660nm
Band 3 = 730nm
Band 4 = 825nm

Lifetime studies

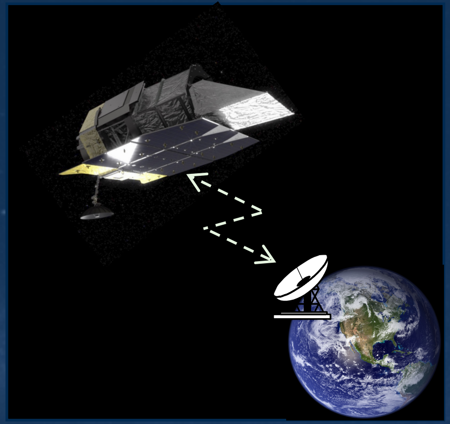
- Detector degradation & stability
- Necessary cadence of calibrations



- Main limiting sources of noise/systematics
- Wavefront stability
- Instrument model validation



Learning Opportunities in Operations



- High order wavefront sensing – “Ground in the Loop”
  - Not locked into WFS algorithm onboard
  - Assess on-board calibrations for HOWFSC loop
  - Respond to and troubleshoot any anomalies
  - Realtime operations & active control

- Explore challenges for observations (incl. calibrations)
  - Flat field sources: astrophysical or internal
  - Constraints from Roman/WFI that could be lifted for dedicated mission

Knowledge gained will carry forward to future missions