NANCY GRACE ROMAN SPACE TELESCOPE

Vanessa Bailey

Jet Propulsion Laboratory, California Institute of Technology

Starlight Suppression Workshop
Aug 8, 2023

JPL sidewalk art day 2018

Nancy Grace Roman was NASA's first Chief Astronomer

appointed 1959

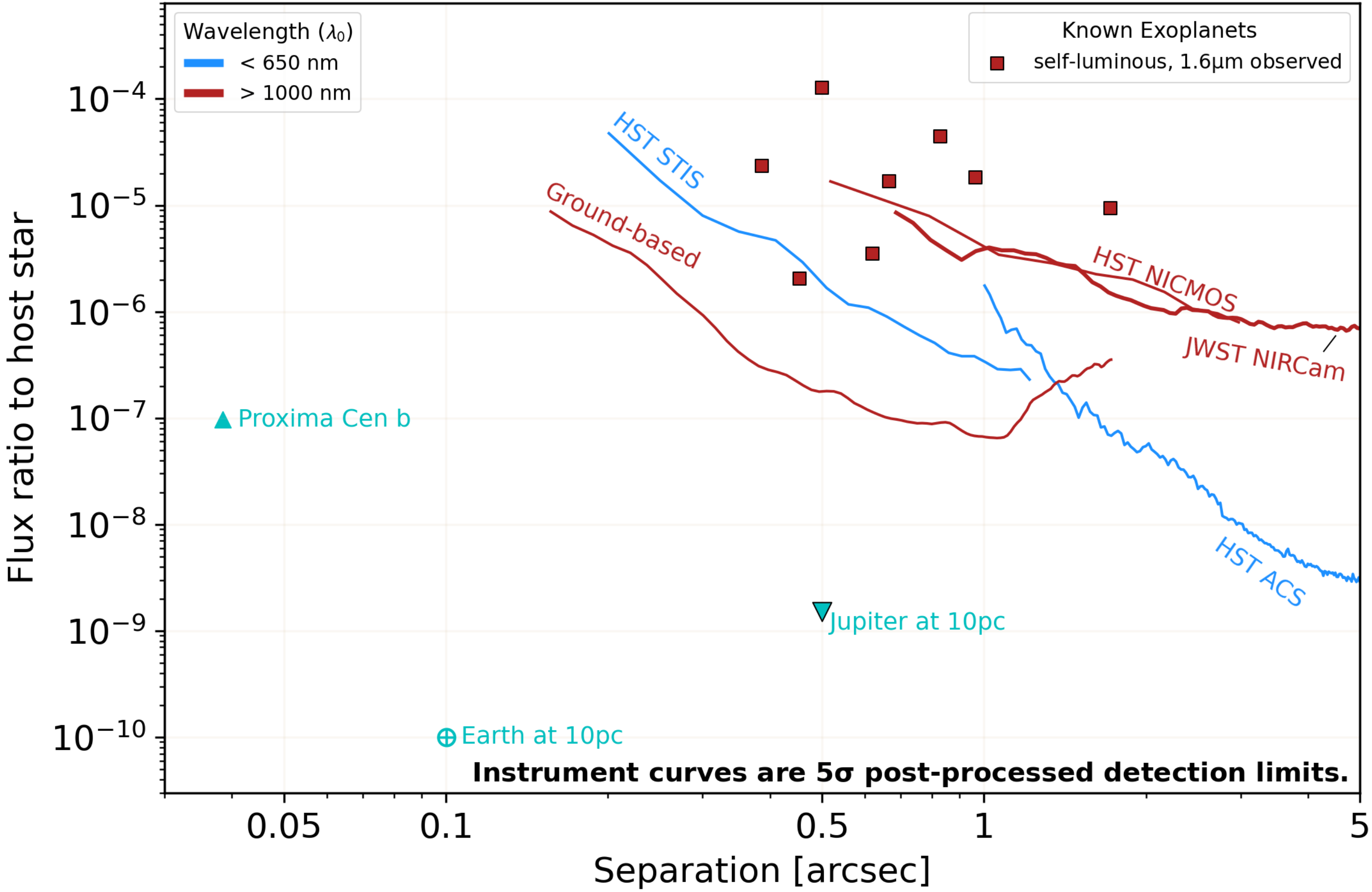
1959 October THE ASTRONOMICAL JOURNAL

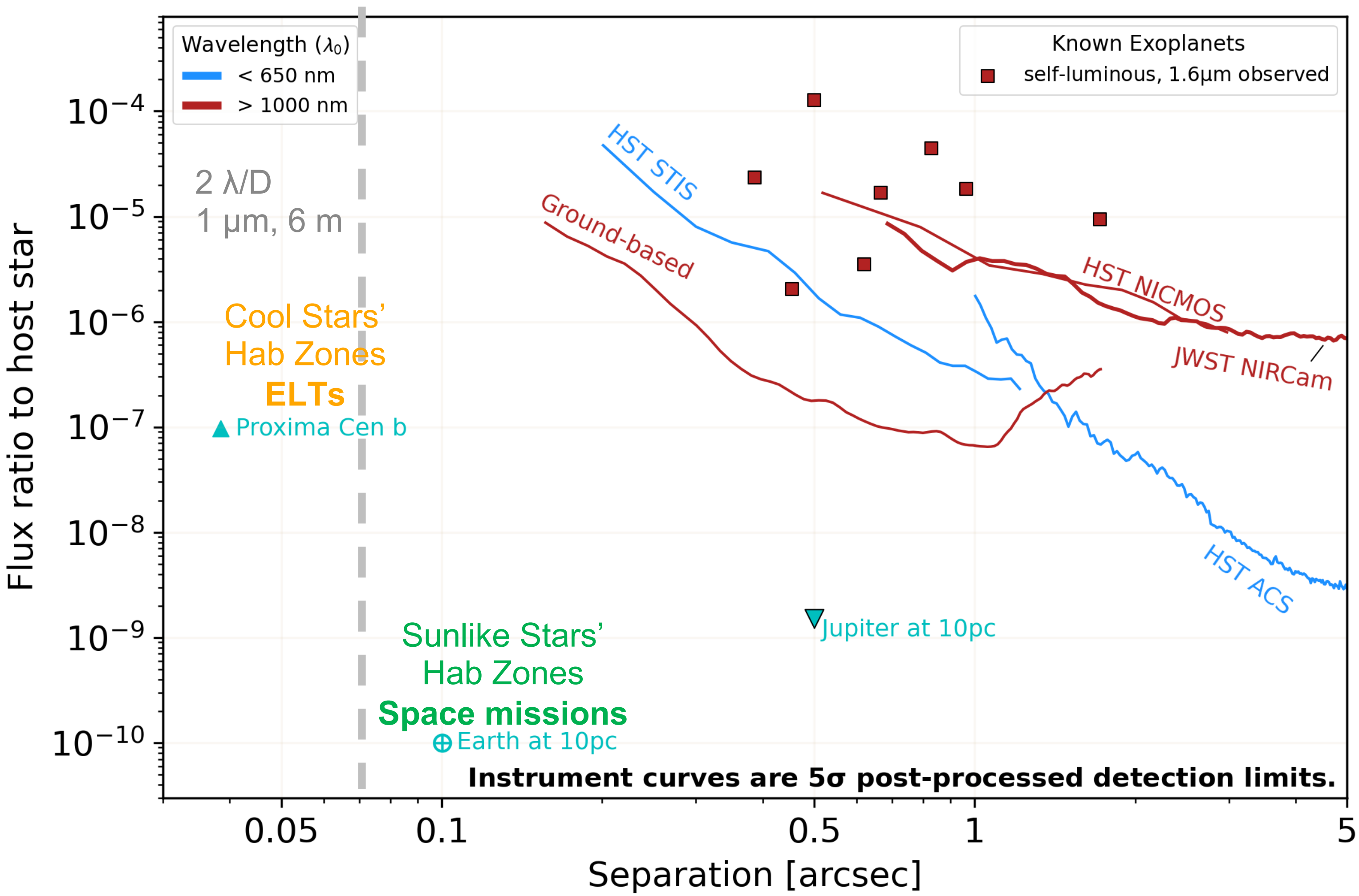
Roman, Nancy Grace. *Planets of other suns.*

As seen from the distance of Alpha Centauri, Jupiter, at its maximum apparent separation from the sun, $3''.94$, would be a star of $23^{m}.4$ (assuming that its phase function is that of Venus); it would brighten to a maximum of $22^{m}.0$ at exterior conjunction. For Venus, Earth, Saturn, the maximum brightnesses and separations are, respectively: $22^{m}.5$ and $0''.55$, $23^{m}.4$ and $0''.76$, and $22^{m}.7$ and $7''.23$ (with the rings at moderate inclination).

Thus, a similar planetary system around Alpha Centauri would be within the reach of our largest telescopes and our current photoelectric techniques if our terrestrial atmosphere did not limit our resolution. At a separation of more than $2''$, it does not seem to be a serious problem to get rid of the light of the primary in the absence of an atmosphere.

Image credit: NASA, ESA link


Wavelength (λ0)
< 650 nm
> 1000 nm
Known Exoplanets
self-luminous, 1.6μm observed
Flux ratio to host star
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-10
HST STIS
Ground-based
HST NICMOS
JWST NIRCam
HST ACS
Proxima Cen b
Jupiter at 10pc
Earth at 10pc
Instrument curves are 5σ post-processed detection limits.
0.05
0.1
0.5
1
5
Separation [arcsec]


Wavelength (λ_0)
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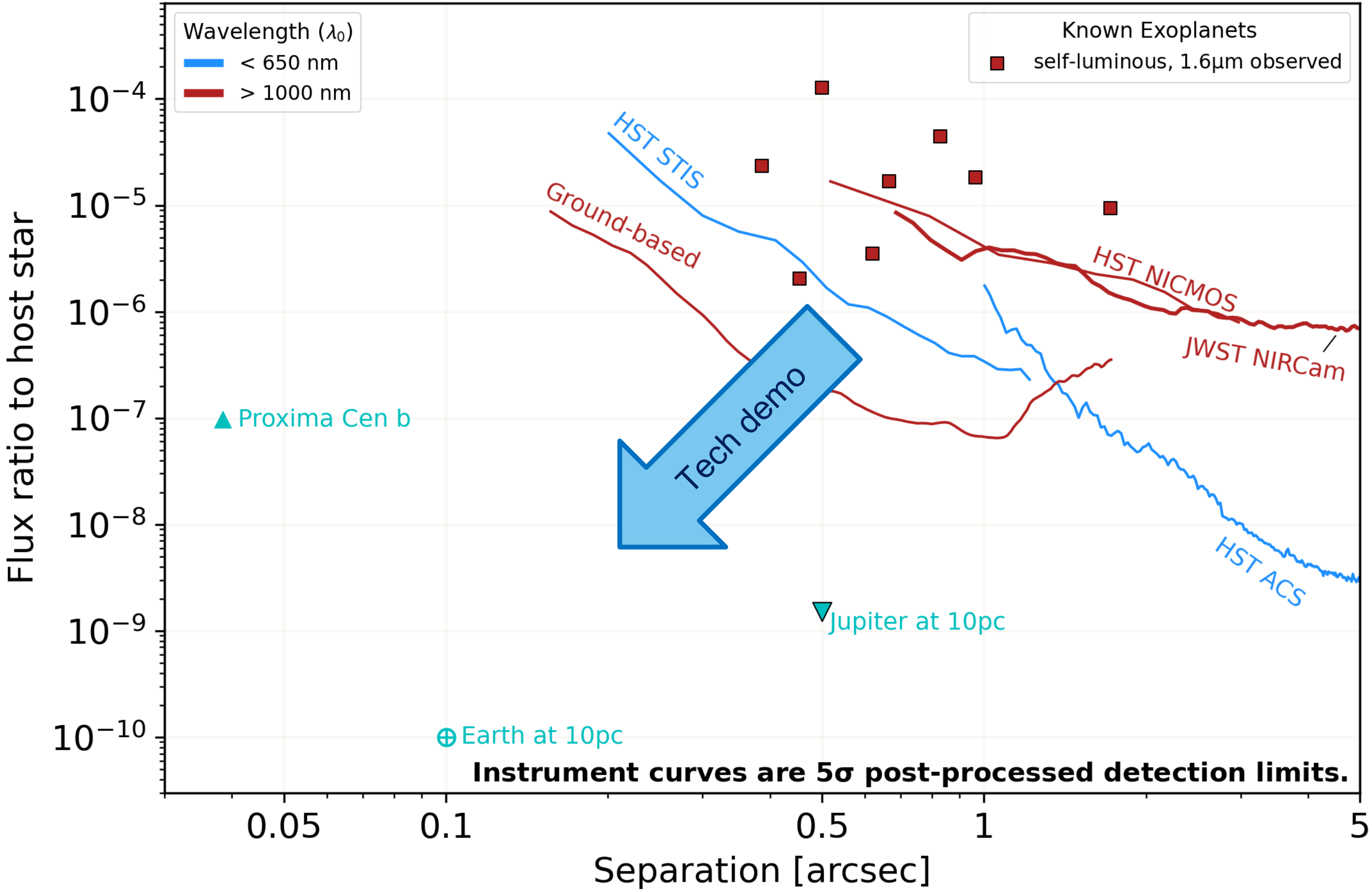
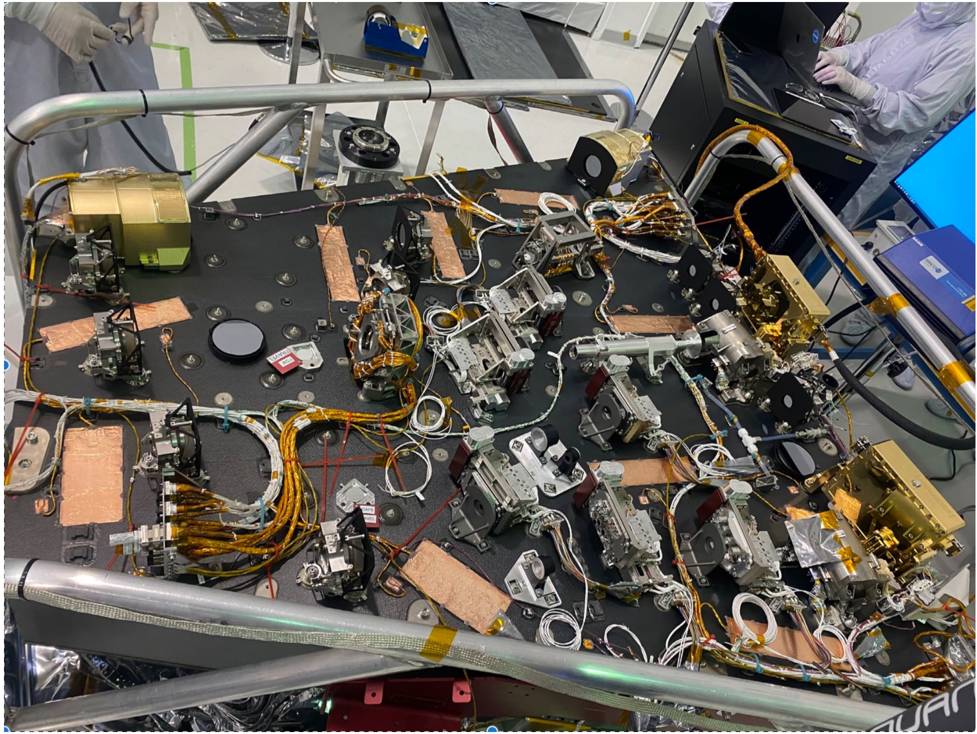
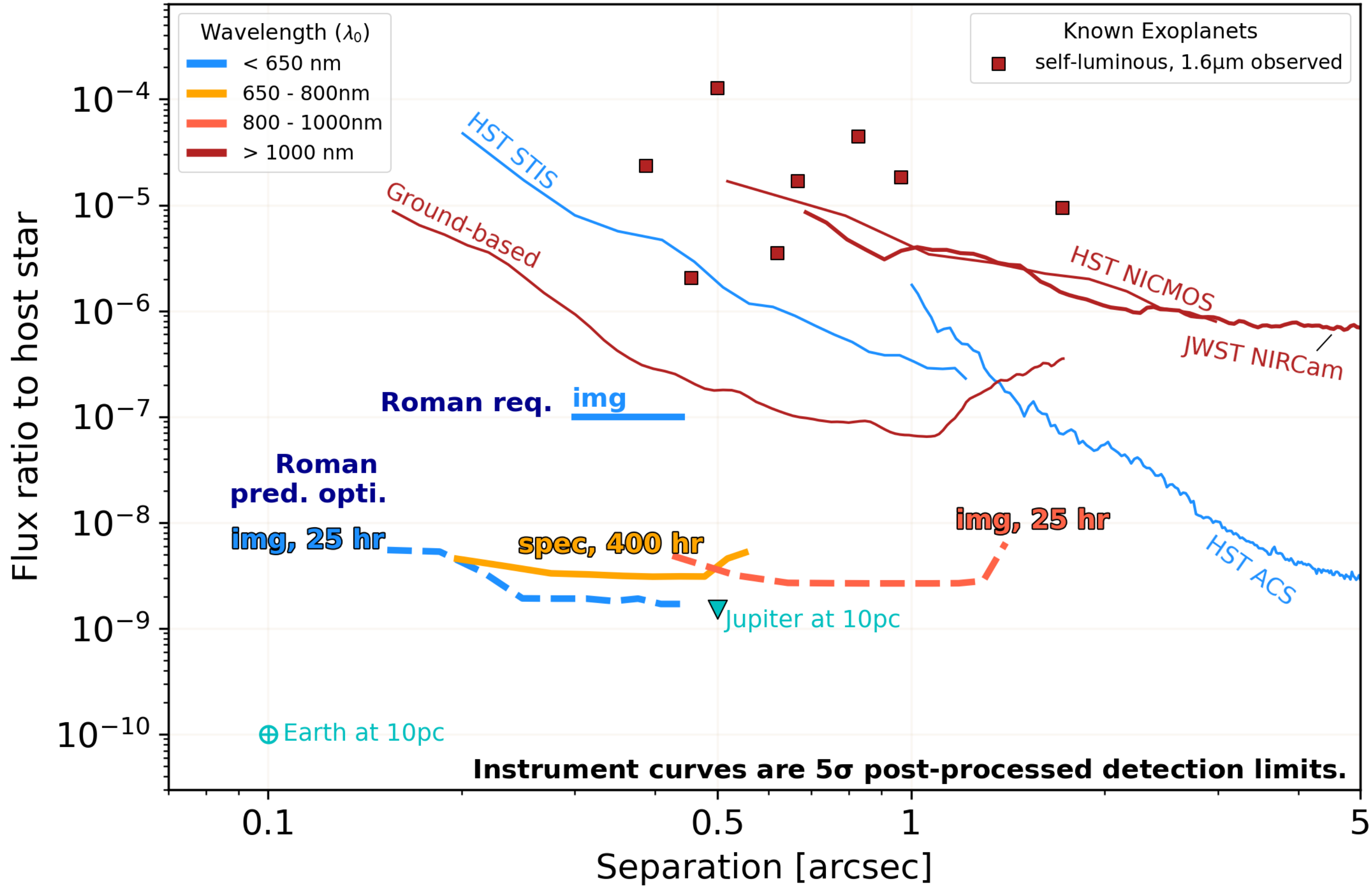
> 1000 nm
Known Exoplanets
self-luminous, 1.6μm observed
2 λ/D
1 μm, 6 m
Cool Stars' Hab Zones
ELTs
Proxima Cen b
HST STIS
Ground-based
HST NICMOS
JWST NIRCam
HST ACS
Jupiter at 10pc
Sunlike Stars' Hab Zones
Space missions
Earth at 10pc
Instrument curves are 5σ post-processed detection limits.
Flux ratio to host star
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.05
0.1
0.5
1
5
Separation [arcsec]

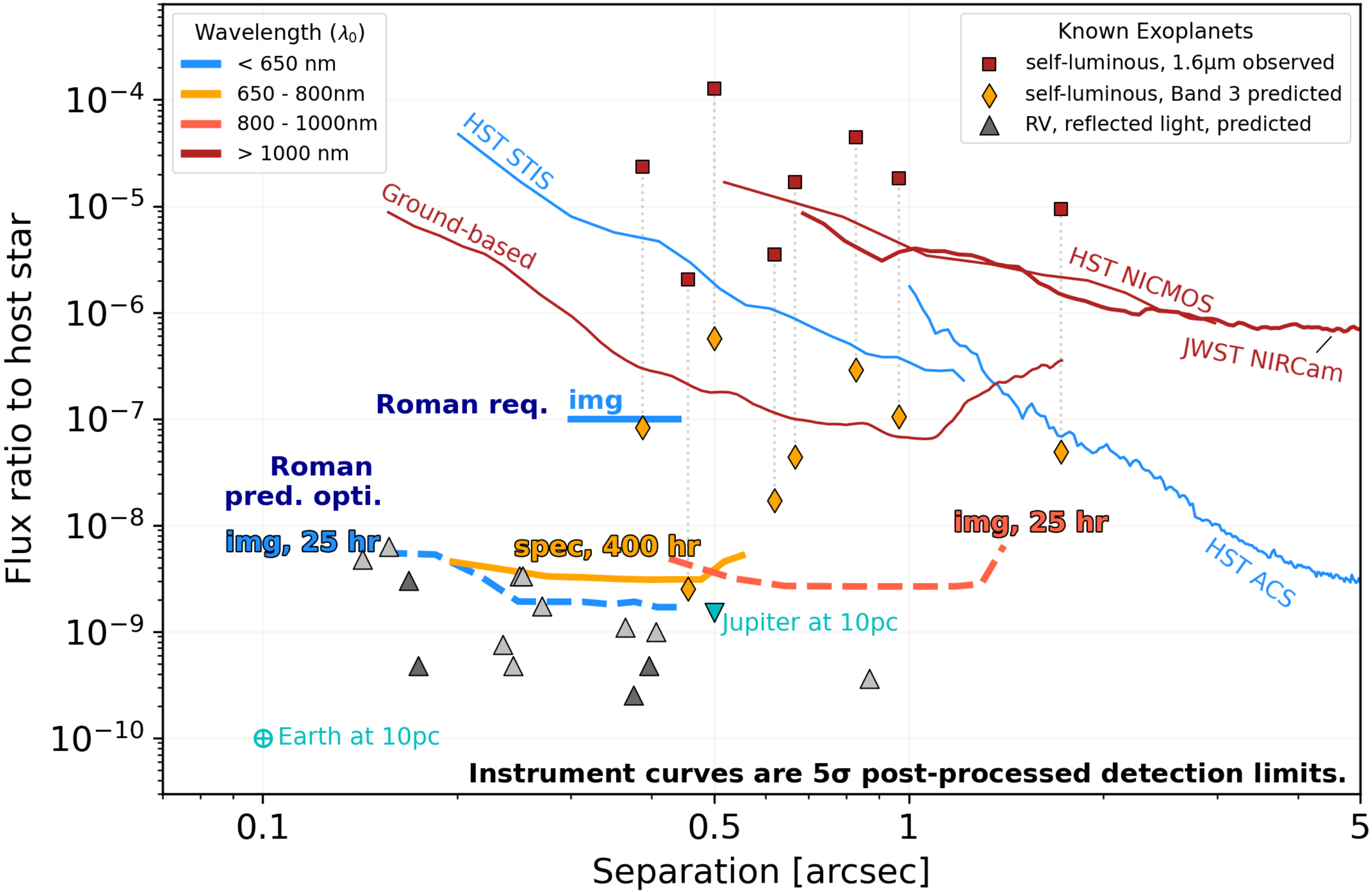

Wavelength (λ_0)
< 650 nm
> 1000 nm
Known Exoplanets
self-luminous, 1.6µm observed
HST STIS
Ground-based
HST NICMOS
JWST NIRCam
HST ACS
Tech demo
Proxima Cen b
Jupiter at 10pc
Earth at 10pc
Instrument curves are 5σ post-processed detection limits.
Flux ratio to host star
Separation [arcsec]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.05
0.1
0.5
1
5

Roman Coronagraph paves the way for HWO

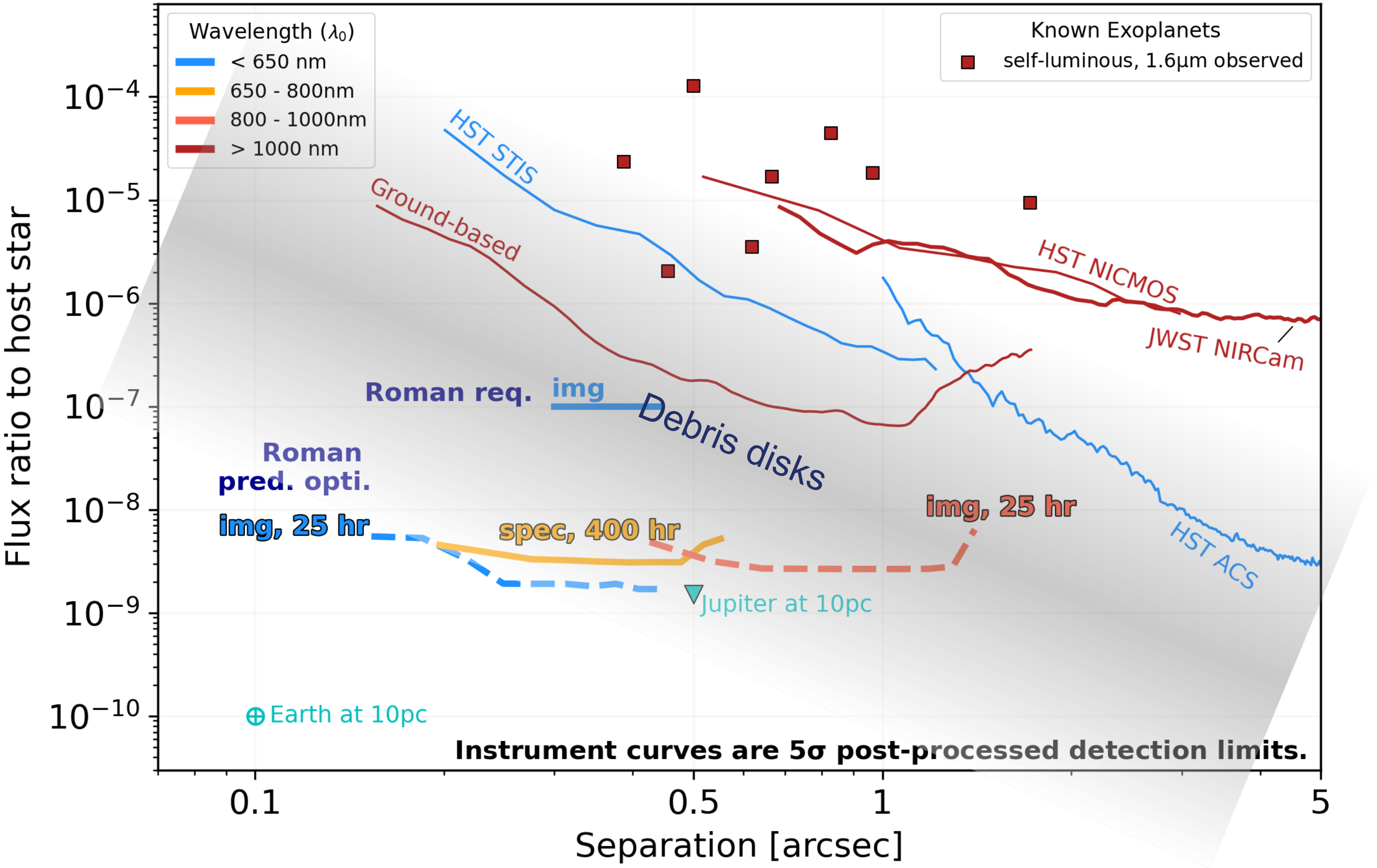
- the first space-based coronagraph with active wavefront control
- a visible light "technology demonstration" instrument
  - "easy" requirement: 10^{-7} detection limit
  - Ambitious goals: few 10^{-9}
- a risk mitigation for HWO
- a potential testbed for HWO *(if resources)*
- Delivering May 2024
- Launching no later than May 2027



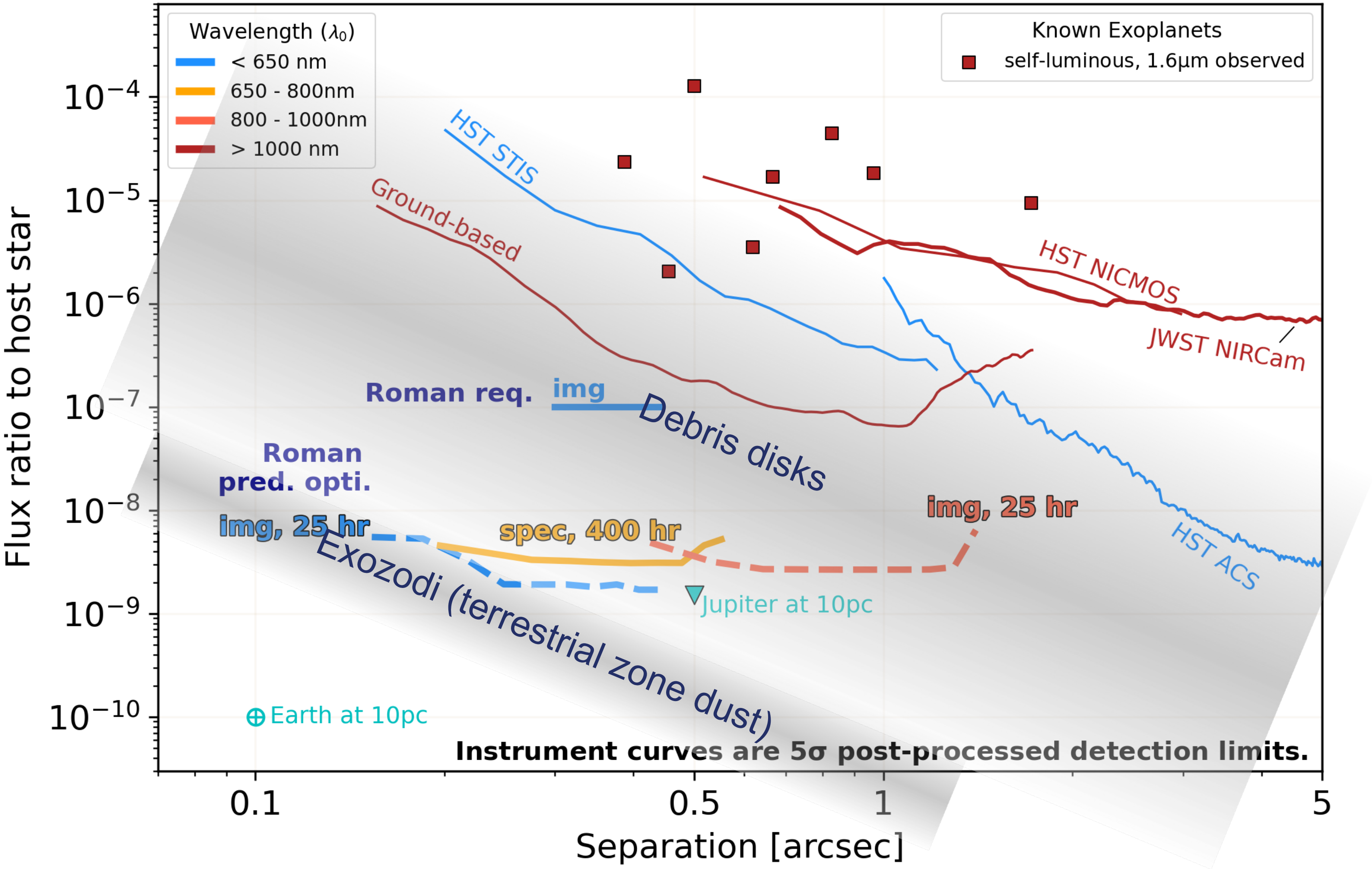

Wavelength (λ_0)
< 650 nm
650 - 800nm
800 - 1000nm
> 1000 nm
Known Exoplanets
self-luminous, 1.6μm observed
HST STIS
Ground-based
HST NICMOS
JWST NIRCam
HST ACS
Roman req.
img
Roman
pred. opti.
img, 25 hr
spec, 400 hr
img, 25 hr
Jupiter at 10pc
Earth at 10pc
Instrument curves are 5σ post-processed detection limits.
Flux ratio to host star
Separation [arcsec]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.1
0.5
1
5



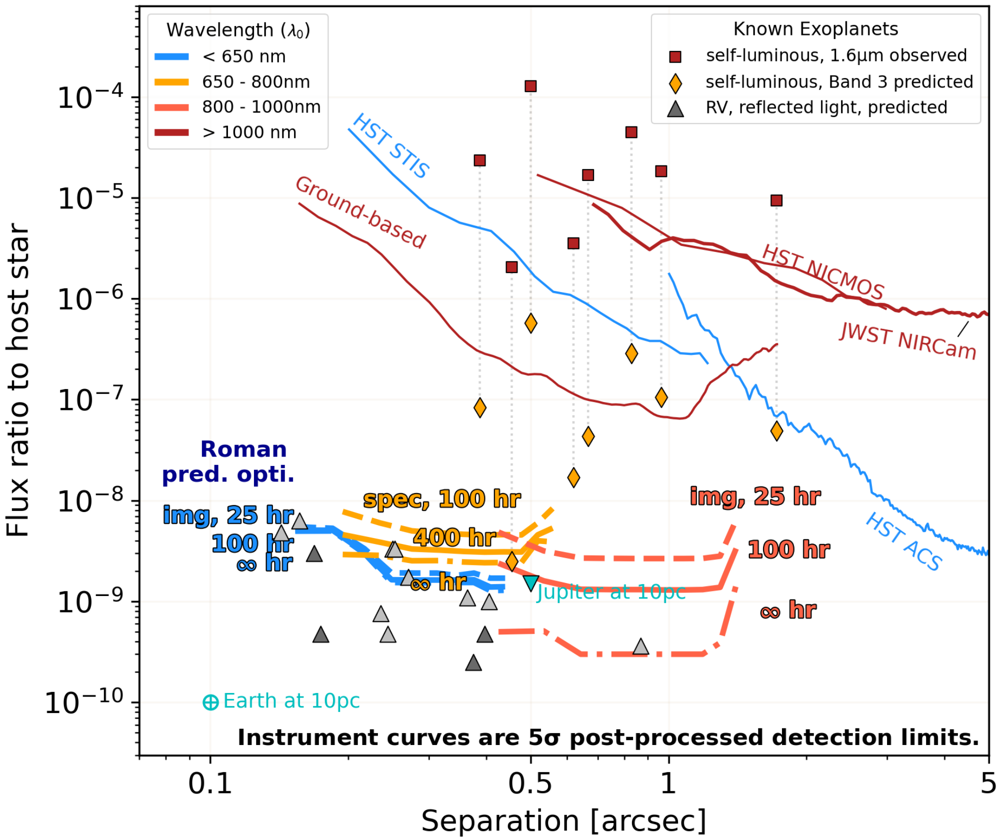
Wavelength (λ_0)
< 650 nm
650 - 800nm
800 - 1000nm
> 1000 nm
Known Exoplanets
self-luminous, 1.6μm observed
self-luminous, Band 3 predicted
RV, reflected light, predicted
HST STIS
Ground-based
HST NICMOS
JWST NIRCam
HST ACS
Roman req. img
Roman pred. opti.
img, 25 hr
spec, 400 hr
img, 25 hr
Jupiter at 10pc
Earth at 10pc
Instrument curves are 5σ post-processed detection limits.
Flux ratio to host star
Separation [arcsec]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.1
0.5
1
5



Wavelength (λ_0)
< 650 nm
650 - 800nm
800 - 1000nm
> 1000 nm
Known Exoplanets
self-luminous, 1.6μm observed
HST STIS
Ground-based
HST NICMOS
JWST NIRCam
Roman req.
img
Debris disks
Roman
pred. opti.
img, 25 hr
spec, 400 hr
img, 25 hr
HST ACS
Jupiter at 10pc
Earth at 10pc
Instrument curves are 5σ post-processed detection limits.
Flux ratio to host star
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0.1
0.5
1
5
Separation [arcsec]


Wavelength (λ_0)
< 650 nm
650 - 800nm
800 - 1000nm
> 1000 nm
Known Exoplanets
self-luminous, 1.6μm observed
HST STIS
Ground-based
HST NICMOS
JWST NIRCam
HST ACS
Roman req.
img
Debris disks
Roman
pred. opti.
img, 25 hr
spec, 400 hr
img, 25 hr
Exozodi (terrestrial zone dust)
Jupiter at 10pc
Earth at 10pc
Instrument curves are 5σ post-processed detection limits.
Flux ratio to host star
Separation [arcsec]

Strongly speckle-limited at shortest wavelength



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

Exoplanet Exposure Time Calculator
https://roman.ipac.caltech.edu/sims/ETC.html
Built on EXOSIMS

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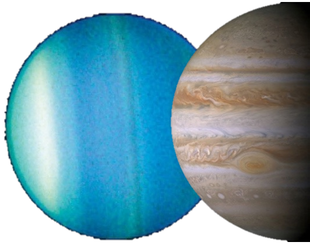
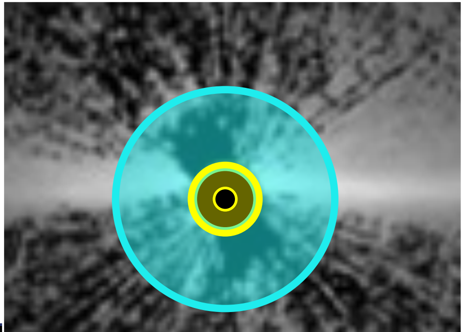
Ewan Douglas
Brianna Lacy
Nikole Lewis
Dean Keithly
Brian Kern
John Krist

Bijan Nemati
Dmitry Savransky
Leah Sheldon
Corey Spohn
Sergi Hildebrandt Rafels
A.J. Riggs
Hanying Zhou

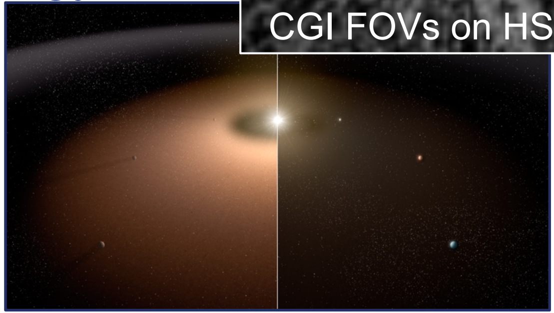
With “goal” capabilities: exciting exoplanetary system science

- After demonstrating our Level 1 requirement…
- Known, self-luminous planets at visible wavelengths
  - (eg: Lacy & Burrows 2020)
- Potential for first images and spectrum of true Jupiter analog
  - Known RV planet
  - (eg: Batalha+2018, Saxena+2021)
- Low surface brightness disks, improved morphology
  - (eg: Mennesson+2018)
- Potential for first visible light images of exozodi
  - (Douglas+2022)



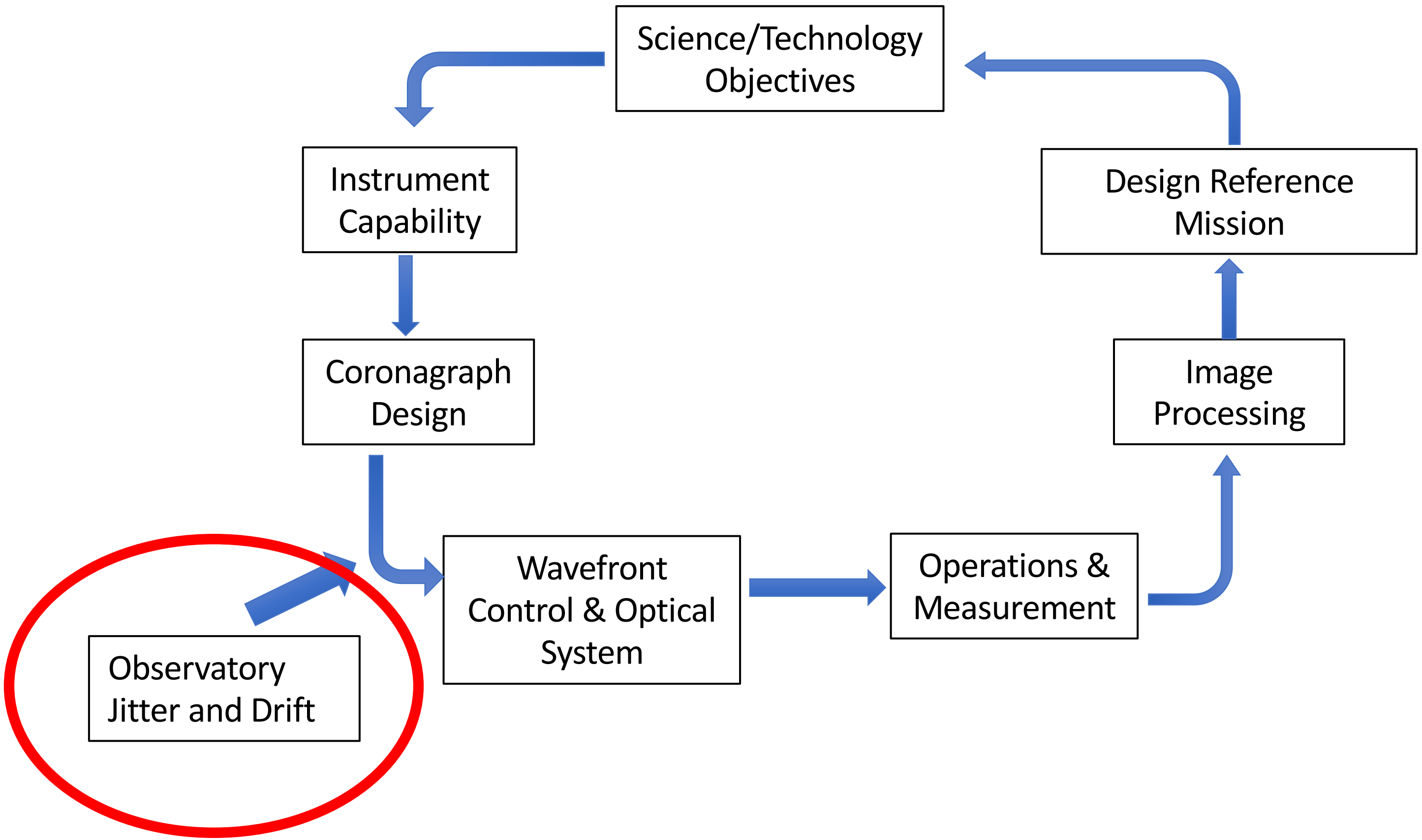


CGI FOVs on HST image



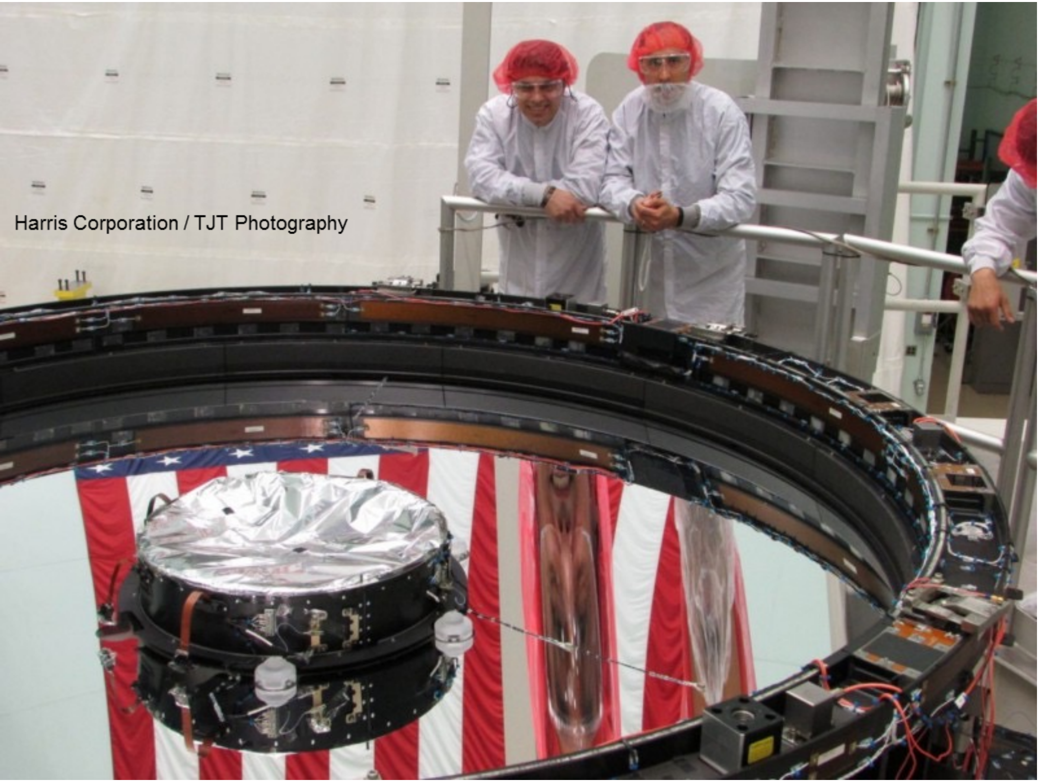
How do we do it? Key technologies

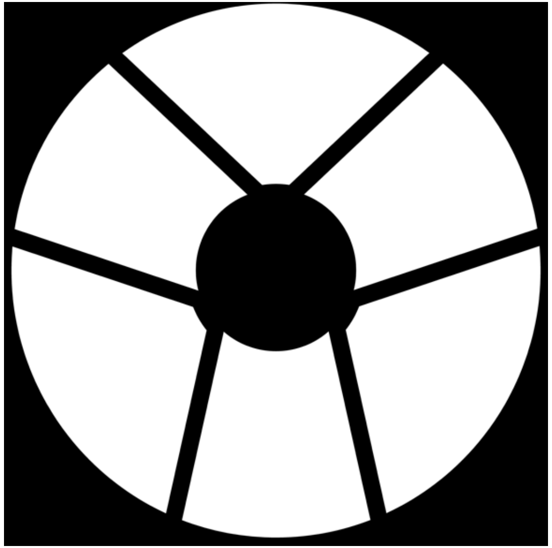
- High actuator-count deformable mirrors
  - Exquisite thermal control (10mK stability)
- Optimized coronagraph masks
- Photon-counting Electron-Multiplying CCDs
- Iterative system-level performance modeling throughout the design process (see Krist's & Liu's talks)
  - Operations tailored based on results

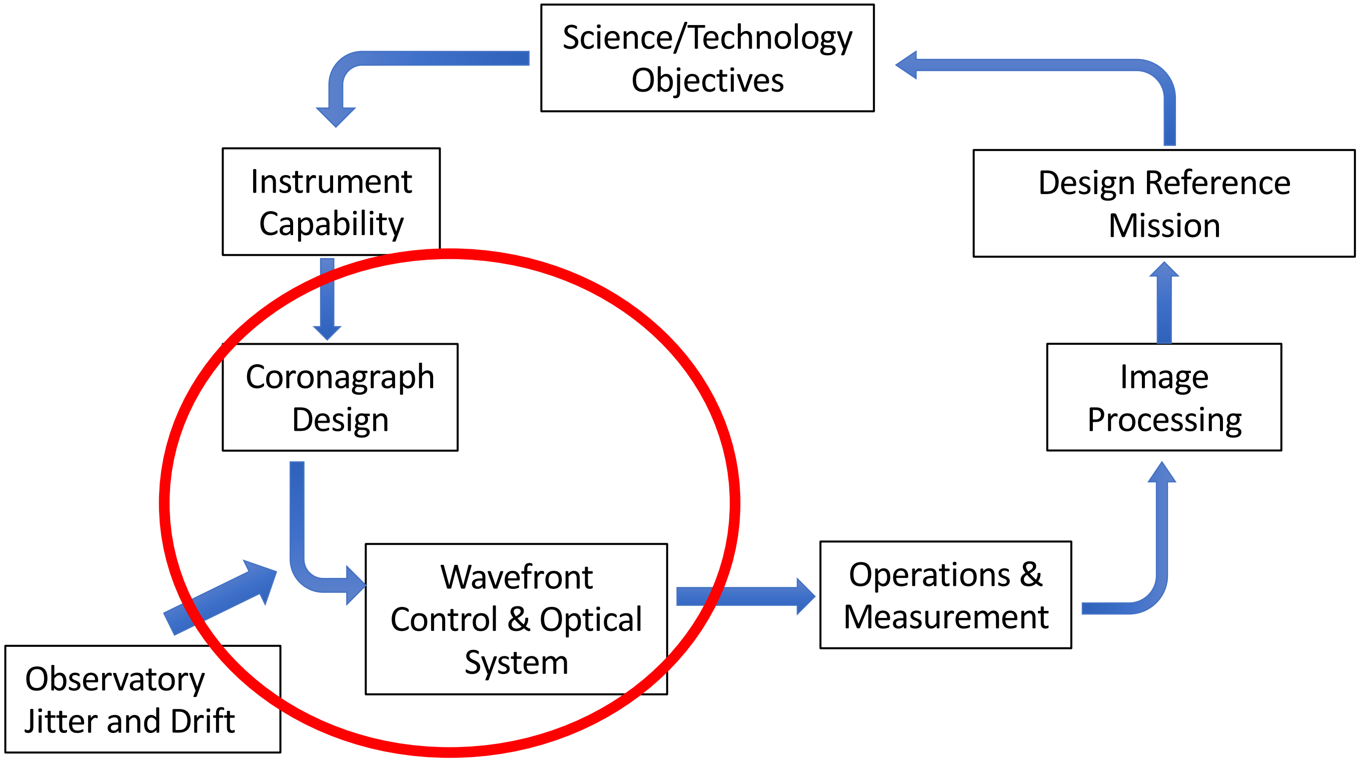

Science/Technology Objectives
Instrument Capability
Coronagraph Design
Wavefront Control & Optical System
Operations & Measurement
Image Processing
Design Reference Mission
Observatory Jitter and Drift

Roman uses a donated 2.4m telescope. Lesson: design instrument + observatory *system*

ROMAN SPACE TELESCOPE

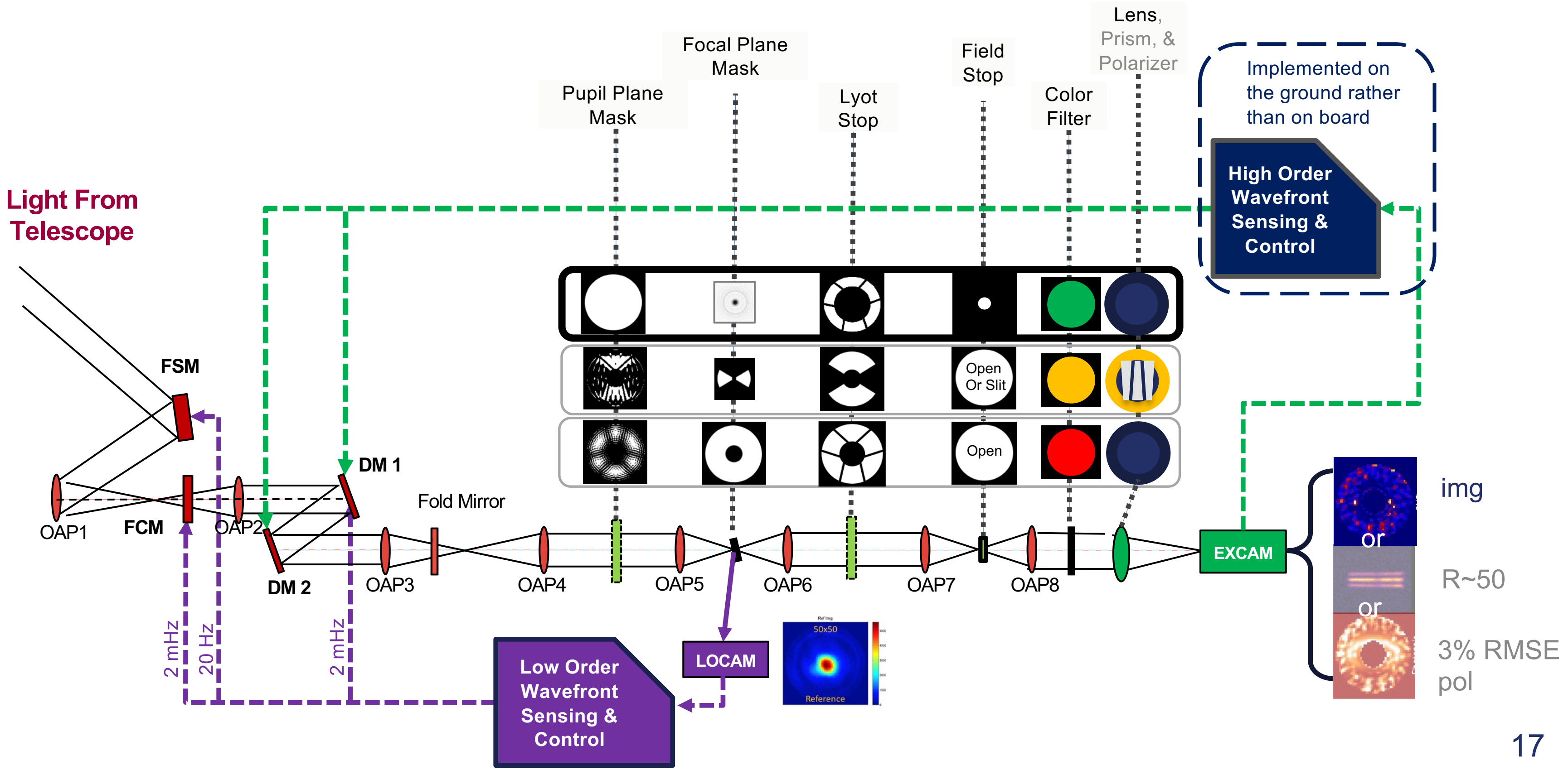






Science/Technology Objectives
Instrument Capability
Design Reference Mission
Coronagraph Design
Image Processing
Wavefront Control & Optical System
Operations & Measurement
Observatory Jitter and Drift

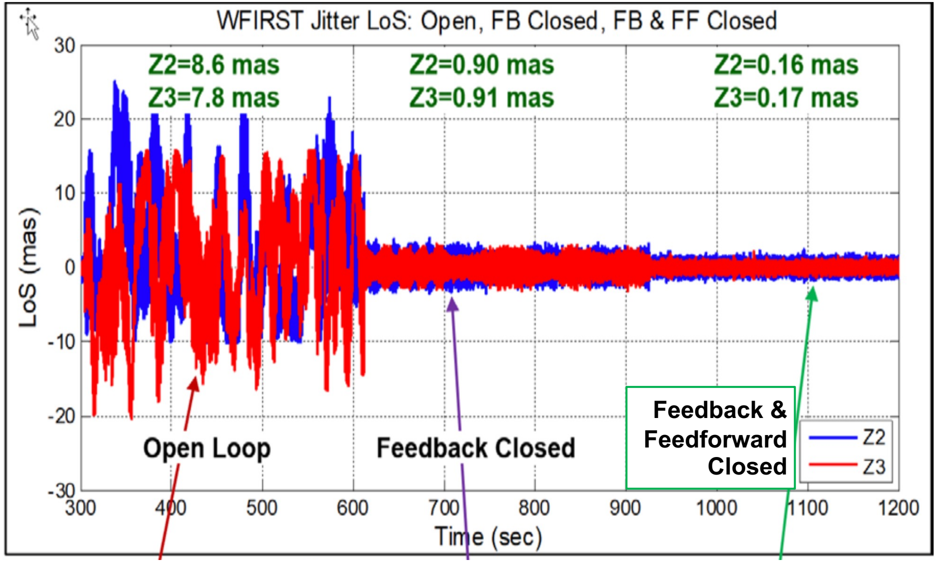
First telescope with active wavefront sensing and control for high-contrast optimization



OAP = *Off-Axis Parabolic [Mirror]*

CGI jitter & low order control is already in family with HWO

Unlike HST & JWST fine guidance sensors, Roman Coronagraph uses starlight rejected from focal plane mask => minimize non-common path errors



Shi+2019 lab demo: flight-like tip/tilt disturbances, **bright** “star.”

<u>Jitter</u>:

- CGI lab: ~0.35mas RMS on V=5 star
- HabEx/LUVOIR B: ≤0.3mas

<u>Low order:</u>

Challenging Roman pupil => trade low-order sensitivity for overall throughput

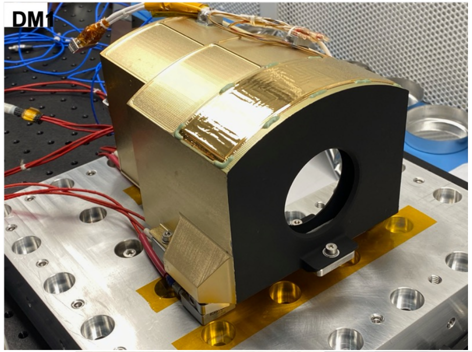
- CGI lab: ~10pm RMS
- HabEx/LUVOIR B: <100pm

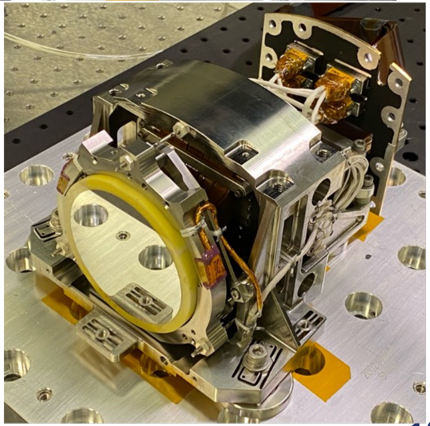
(Mennesson+2020)

HWO will need better DMs

- Actuators: 48X48 vs. 64x64 or even 96x96
- Stroke resolution: 7.5pm vs <2pm
  - Due to drive electronics: add more bits!
  - JPL HCIT has 20bit demo w/ <1pm resolution
- Stability is crucial (PSF subtraction)
  - Temperature sensitivity
    - CGI: <10mK temperature control
  - Actuator creep after “large” move
    - Xinetics need days-weeks to settle
- Lesson: low-order tolerances on DM ***static*** aberrations can be relaxed
  - Compensate for *static* focus/astig… with internal optics (eg: OAPs, fold mirrors)

DM1 (with thermal cover on)

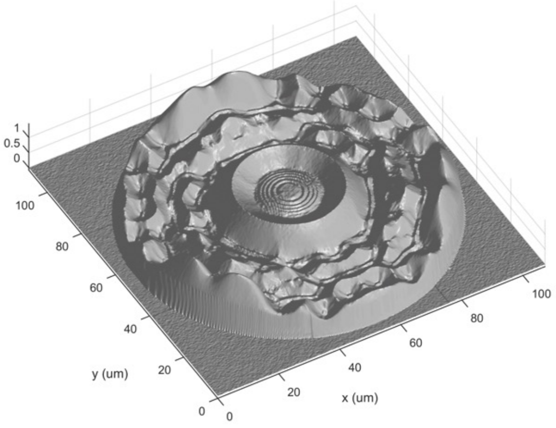


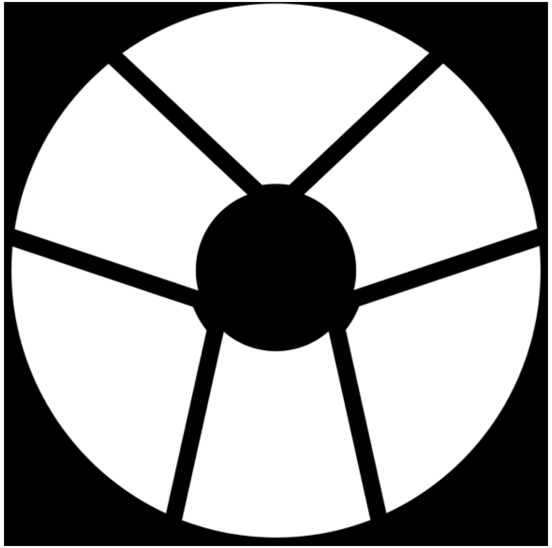


DM2 (thermal cover off)

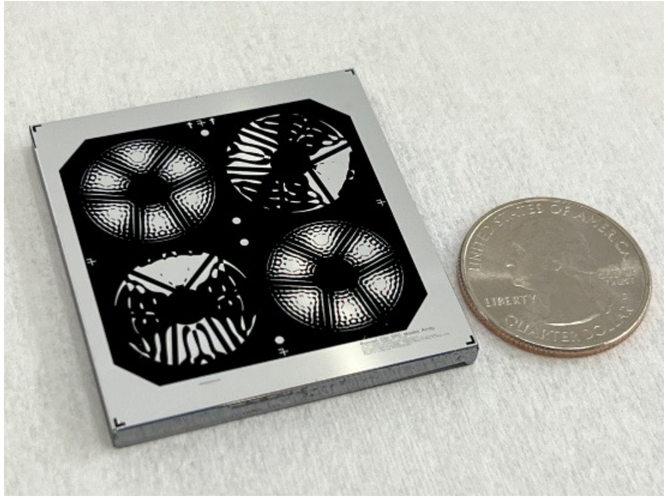
Roman's pupil is more challenging than HWO's

HLC masks





SPC masks



Wish list:

- minimize pupil magnification and rotation uncertainties for any mask that depends on pupil plane
- Deliver DMs before masks: mitigate bad actuators

Balasubramanian+2019
Riggs+ 2021, 2022
Gersh-Range+2022

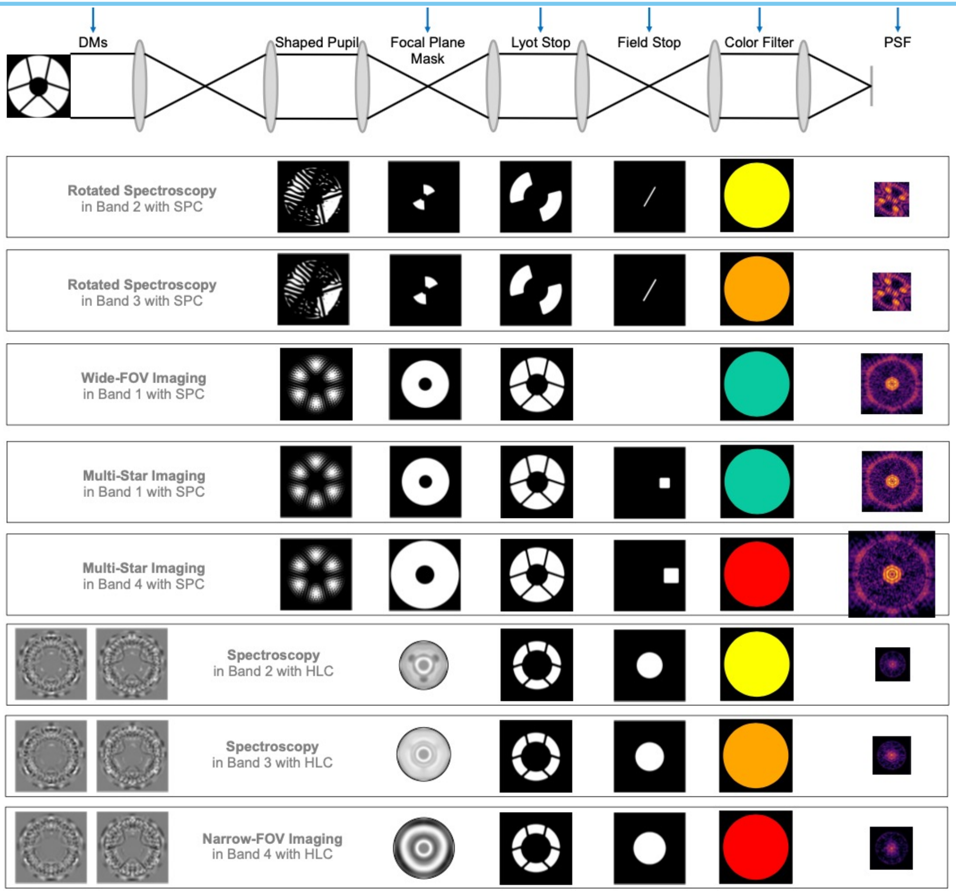
Roman has only 1 fully supported mode, but will fly additional “goal mode” hardware

Band	λ_{center}	BW	Mode	FOV radius	FOV Coverage	Pol?	Coronagraph Mask Type	Support
1	**575 nm**	**10%**	**Narrow FOV Imaging**	**0.14” – 0.45”**	**360°**	**Y ****	**Hybrid Lyot**	**Req’d**
2	**660 nm**	17%	Slit + R~50 Prism Spectroscopy	0.17” – 0.52”	2 x 65°	-	Shaped Pupil	Best Effort
3	**730 nm**	17%	Slit + R~50 Prism Spectroscopy	0.18” – 0.55”	2 x 65°	-	Shaped Pupil	Best Effort
4	**825 nm**	11%	“Wide” FOV Imaging	0.45” – 1.4”	360°	Y	Shaped Pupil	Best Effort

“Best effort” modes will not be end-to-end performance tested prior to delivery & do not have guaranteed support on-orbit. They have been tested at component and assembly levels.

** Polarimetry in Band 1 is ‘best effort’

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.

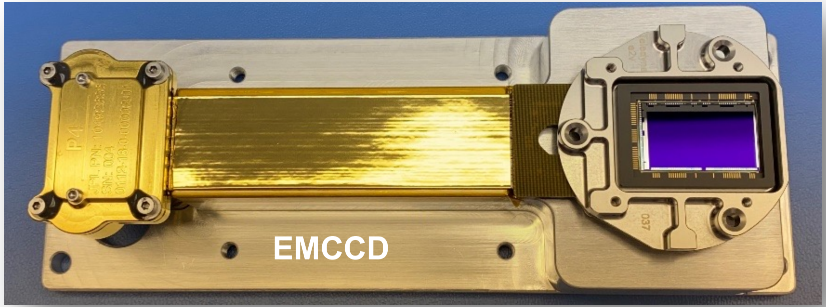
Not shown: unsupported "low-contrast" classical Lyot spots (analogous to HST) for very wide FOV imaging (~1-3.5")

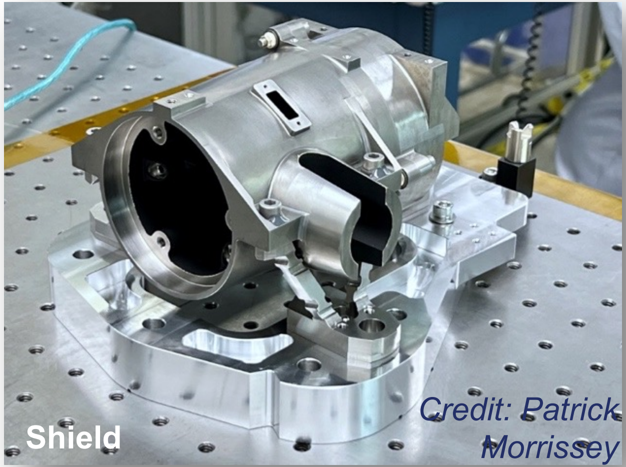
For complete list of masks see [Riggs+ SPIE O&P 2021]

Morrissey+2023

Electron-Multiplying CCDs Count Photons

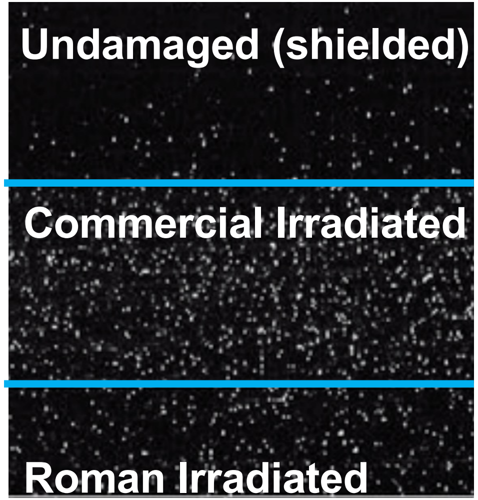
- EM => negligible read noise
  - Teledyne e2v
- Science camera: photon-counting
  - Jupiter analogs V ~ 27
  - < 1 planet γ / pix / minute
- High dynamic range also needed!
  - Calibration, acquisition, initializing dark hole, …
  - up to ~10^8 brighter than DH
- Low-order WFS camera
  - 1kHz framerate => nearly photon-counting



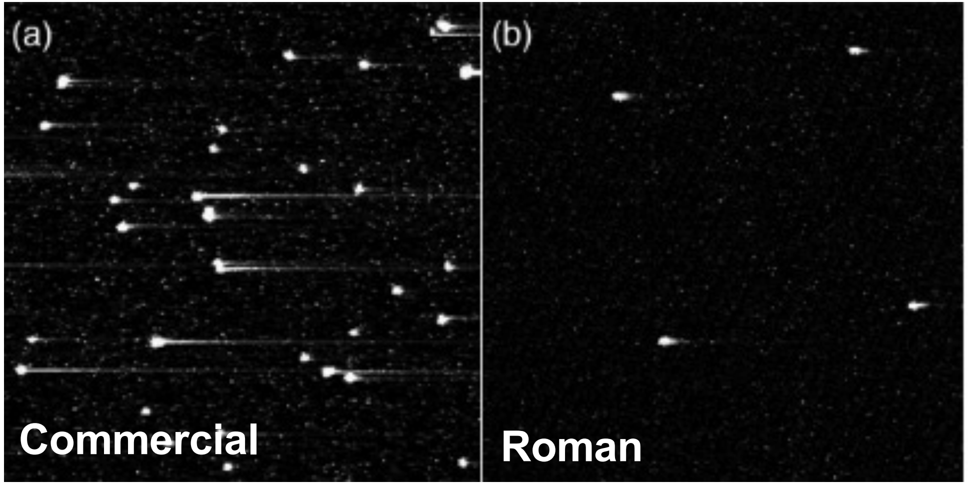


EMCCD: improved effective QE by **up to 3x**, but still room for improvement for HWO

- Radiation-induced charge traps capture electrons in **CCDs**
  - Effect is strongest when photon-counting
  - Not life-limiting for Roman
  - Roman reduced ~5x vs commercial, but didn't explore all optimization options. Room for improvement for HWO



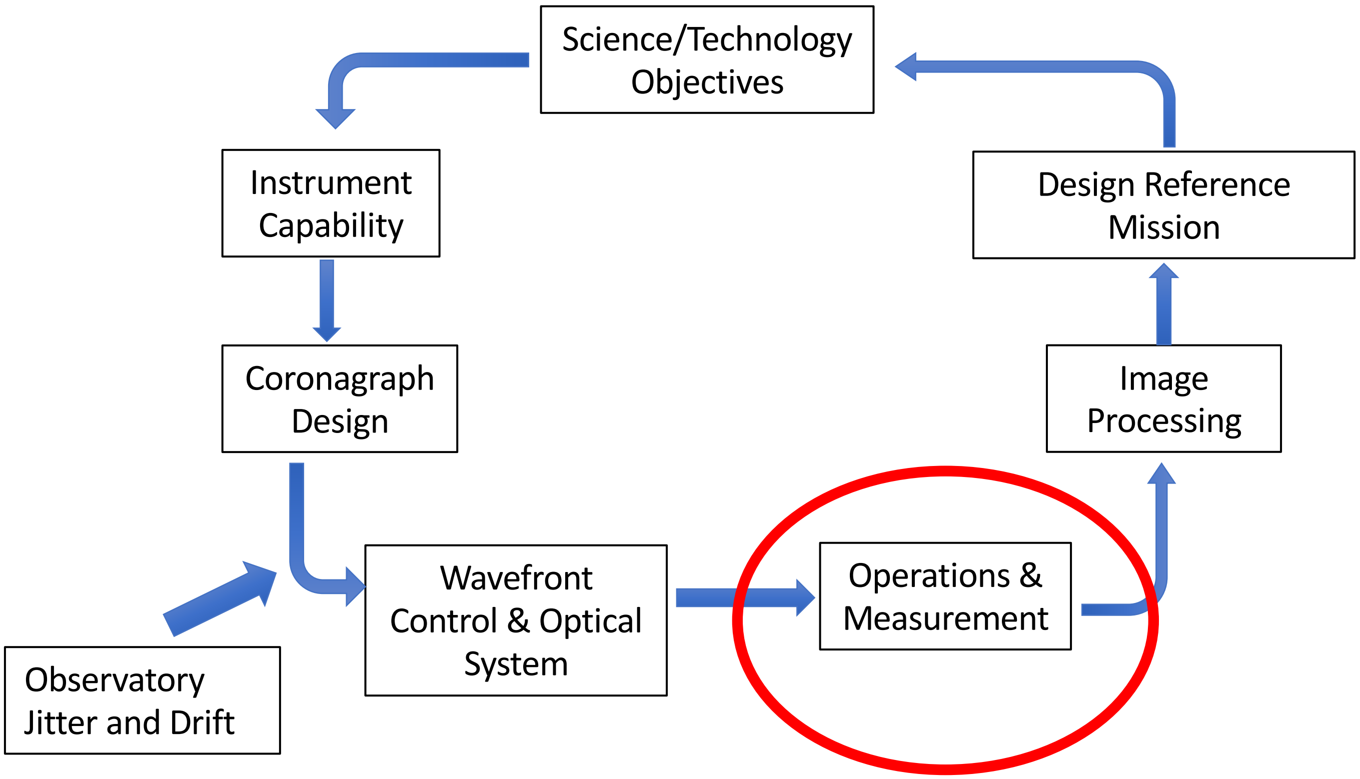
- EMCCDs: cosmic ray tails can cover appreciable portion of image
  - New readout 'overspill' in mitigates



Morrissey+2023

Other EMCCD concerns: aging & clock-induced charge

- **Aging of EM gain register :**
  - Charge out = photoelectrons **x** EM gain
  - Aging = higher voltage needed to achieve same EM gain
  - Depends on cumulative charge out over lifetime & on EM gain
    - Higher gain = faster aging, even for same charge out
  - Roman Science camera: very low flux. Not an issue
  - Roman LOWFS camera: moderate gain, higher flux.
    - Roman 5 year life tests @ gain=1500 show modest aging, but at a level that that can be completely compensated by increased EM gain voltage. Not an issue
  - HWO can minimize aging by enabling lower gain operations
    - eg: lower read noise & bias drift (Brandon Dube's poster)
- **Clock induced charge:**
  - CIC has a short burn-in period but then stabilizes
    - => select flight detector after burn-in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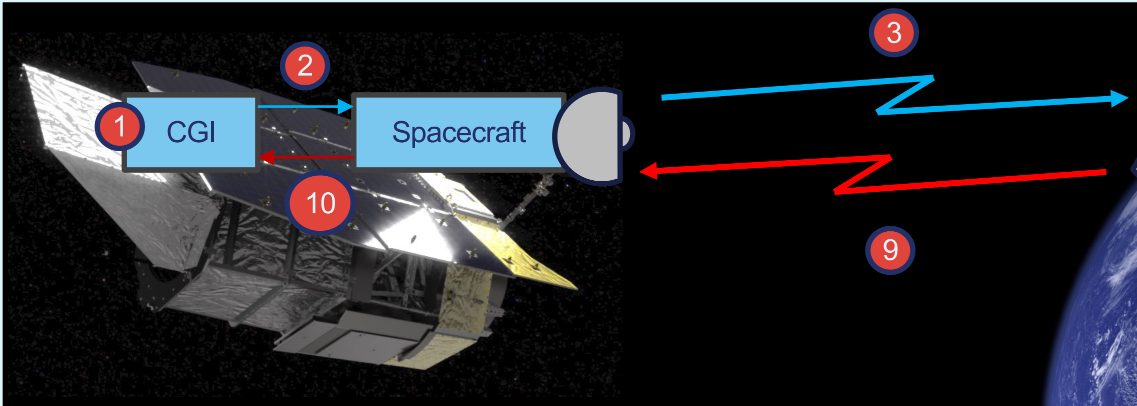
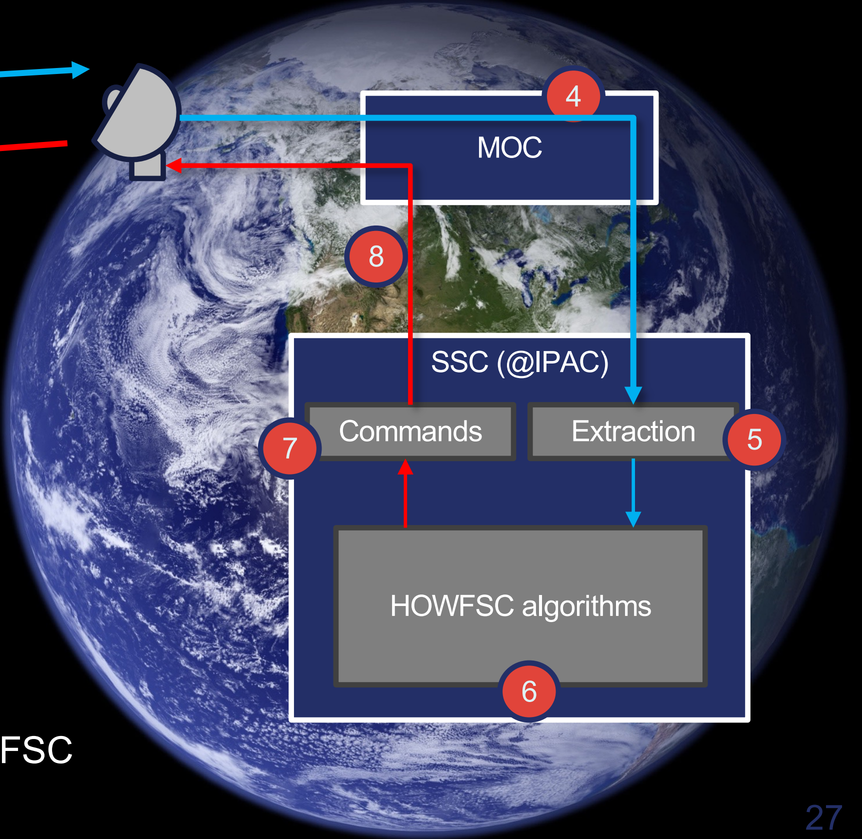
HOWFSC Operates “Ground In the Loop” (GITL)





Pros:

More powerful computers

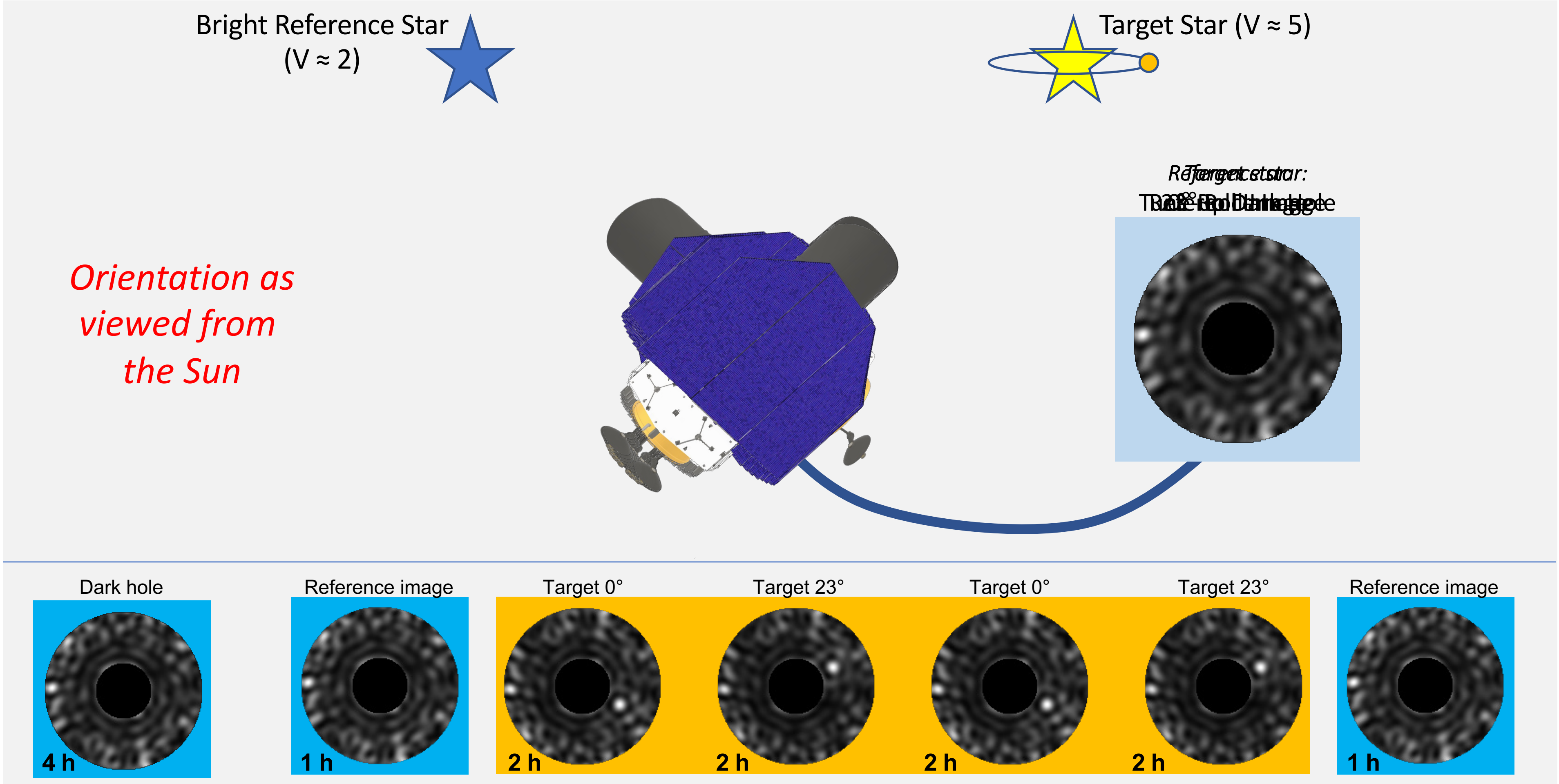
Can *in principle* accept contributed new algorithms later. (Testing support resources TBD)

Cons:

Requires ground station contact => no continuous HOWFSC

Slide credit: John Krist

CGI Observing Scenario



Knowledge Sharing from Roman to HWO

- ExEP is funding Roman Coronagraph personnel to document, beyond what is captured in formal NASA Lessons Learned process. **Work in progress…full report coming later**
- A few examples:
  - Novel payloads should use extra margins beyond current NASA Flight Project Practices and Design Principles (volume, mass, power, etc.) to avoid painful descopes later in life
  - Select launch vehicle early: mirror diameter, launch vibration environment
  - Keep key trades open as long as possible (eg: DM and mask types)
  - Each channel (imager, IFS) must have built-in high-order wavefront sensing capabilities with high dynamic range
    - Non-common-path errors between channels are too large to assume one may be used to precondition for the other
  - Wish: Build a full instrument engineering model instrument, not only at the sub-element level to shake out issues.
  - Consider investing effort to qualify automotive-grade off the shelf parts when lead times on already-qualified parts are long
  - …

Resources

Vanessa Bailey vanessa.bailey@jpl.nasa.gov

- https://roman.gsfc.nasa.gov/science/roses.html
- Roman IPAC website https://roman.ipac.caltech.edu/
  - Instrument parameters https://roman.ipac.caltech.edu/sims/Param_db.html
  - "Observing Scenario" Image simulations and reports https://roman.ipac.caltech.edu/sims/Coronagraph_public_images.html
  - Recordings & slides from 2-day Coronagraph information session
    - https://roman.ipac.caltech.edu/mtgs/Roman_CGI_workshop.html
  - Roman Virtual Lecture Series https://roman.ipac.caltech.edu/Lectures.html
  - …and more!

Summary

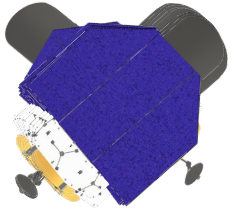
- Roman Coronagraph is a tech demo for HWO
  - Matures precursor technologies
    - Still work to go for HWO
  - Demonstrates *system* in flight
    - Reduces technology & model validation risks
  - *Potential* to increase value to HWO by going beyond requirements
    - Goal observing modes & add'l tech demonstrations *if resources*

backup

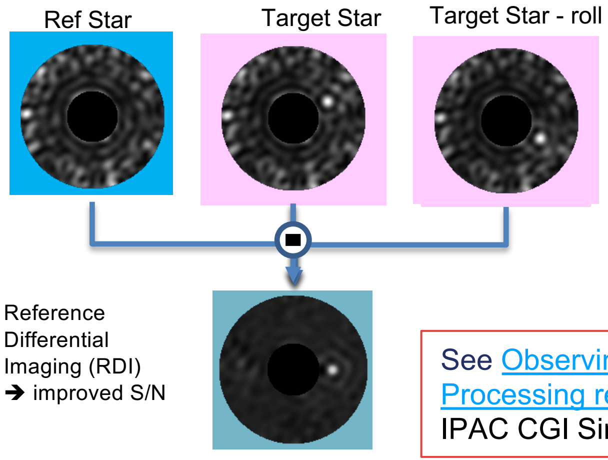
Nominal operations: target & reference star; PSF subtraction w/ reference differential Imaging

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



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

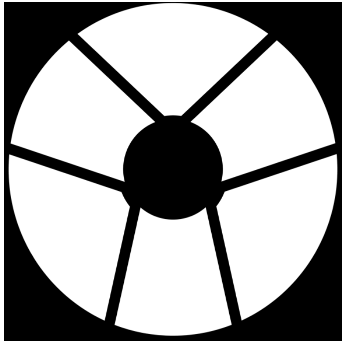
Adapted from J. Krist

Parameter	CGI vs. Future Missions (FM) with unobscured apertures: HabEx & LUVOIR B
10σ Flux Ratio Detectable at 3 λ/D	10^{-8} vs 10^{-10} Roman Space telescope Pupil is challenging
Wavefront error sources	Comparable Phase & "new physics" (amplitude and polarization)
Pointing Jitter Control	Comparable CGI lab: ~ 0.35 mas rms V=5 star, CBE = 0.49 mas rms FM: 0.3mas NTE*
Low-order Control	~ 100x better than required for HabEx better than LUVOIR needs Complex Roman Space Telescope pupil: trading low-order sensitivity for overall throughput
High-order drift	Comparable (~5pm) CGI: 1σ prediction** FM: NTE*
# of DMs	Same (2)
DM Stroke Resolution	~4X worse (7.5pm vs 2pm) Engineering problem, not physics problem
DM Actuator Count	48x48 vs 64x64
EMCCD	Comparable at V-band Bit better: dark current, clock-induced charge Bit worse: QE at UV/red at 5 years (rad hard)

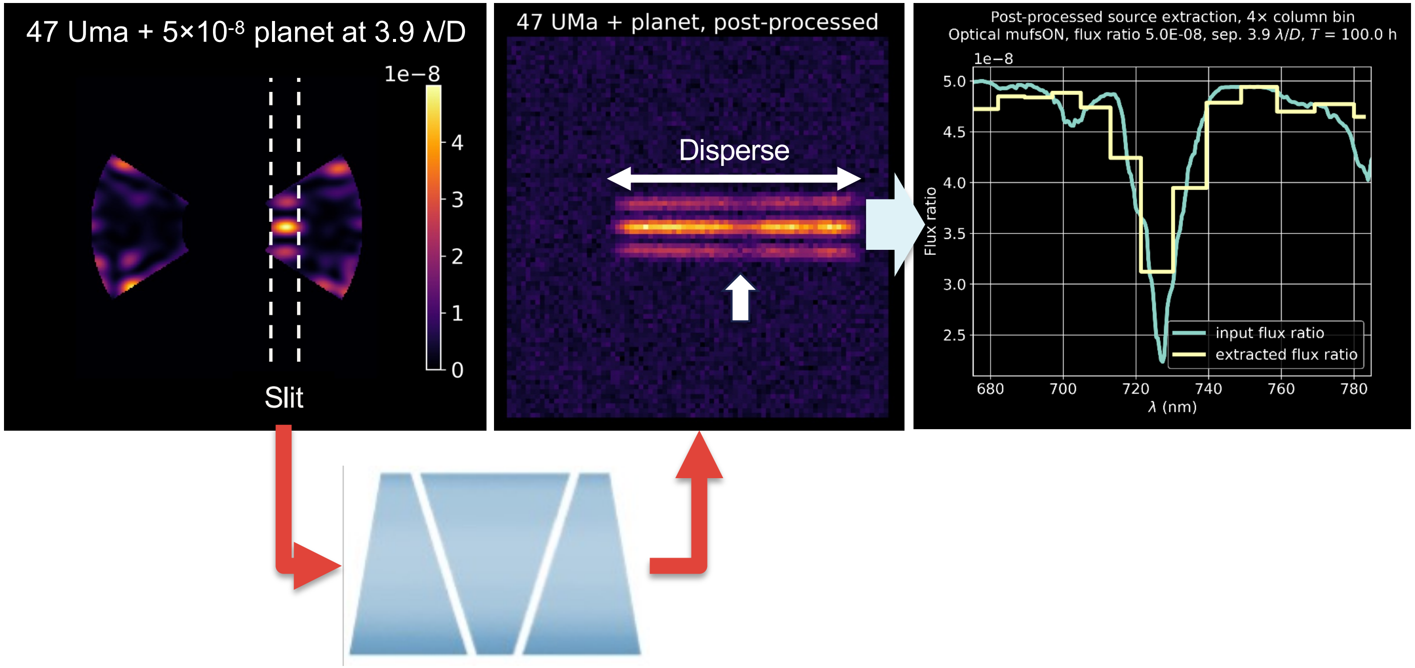
Mennesson+2020

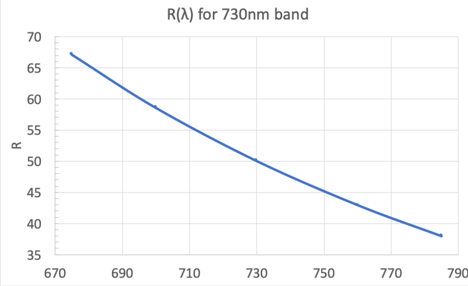
Point source-to-star Flux Ratio detectable by Roman coronagraph far from HabEx/LUVOIR

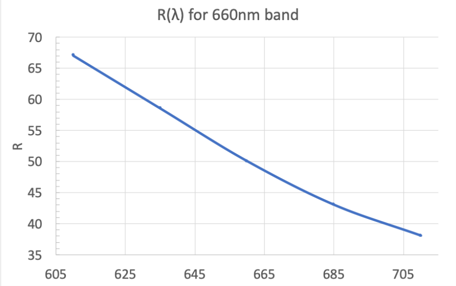
…but Roman Coronagraph components and subsystems performance are highly comparable!



Goal: Low-res Spectroscopy w/ Slit Spectrograph (R 35 – 70 in Band 3 or 2)

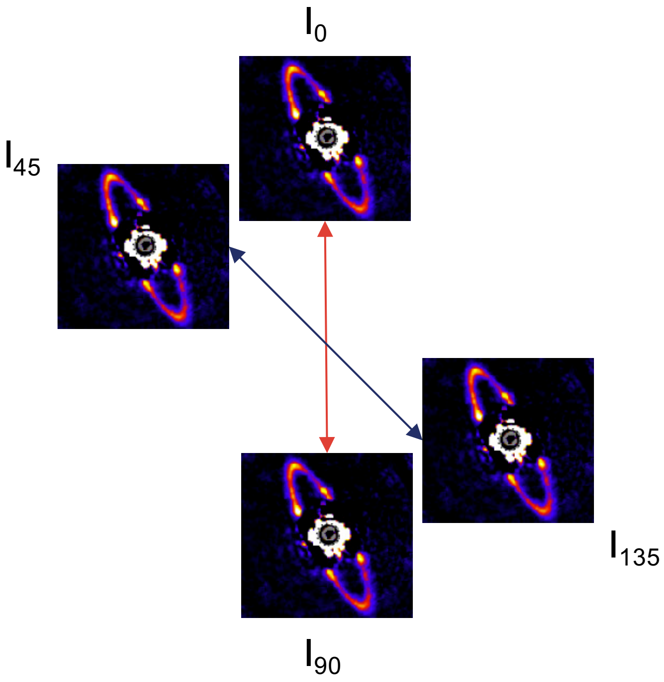




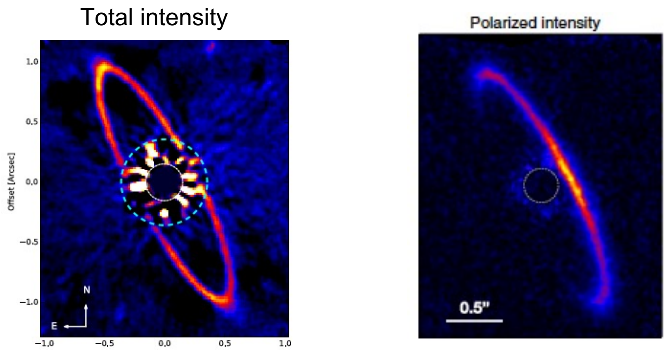


Figures Courtesy: N. Zimmerman and T. Groff (GSFC)

Goal: 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*

Current CBE is 1.6% (limited by detector effects)

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

Images from Perrin+2015