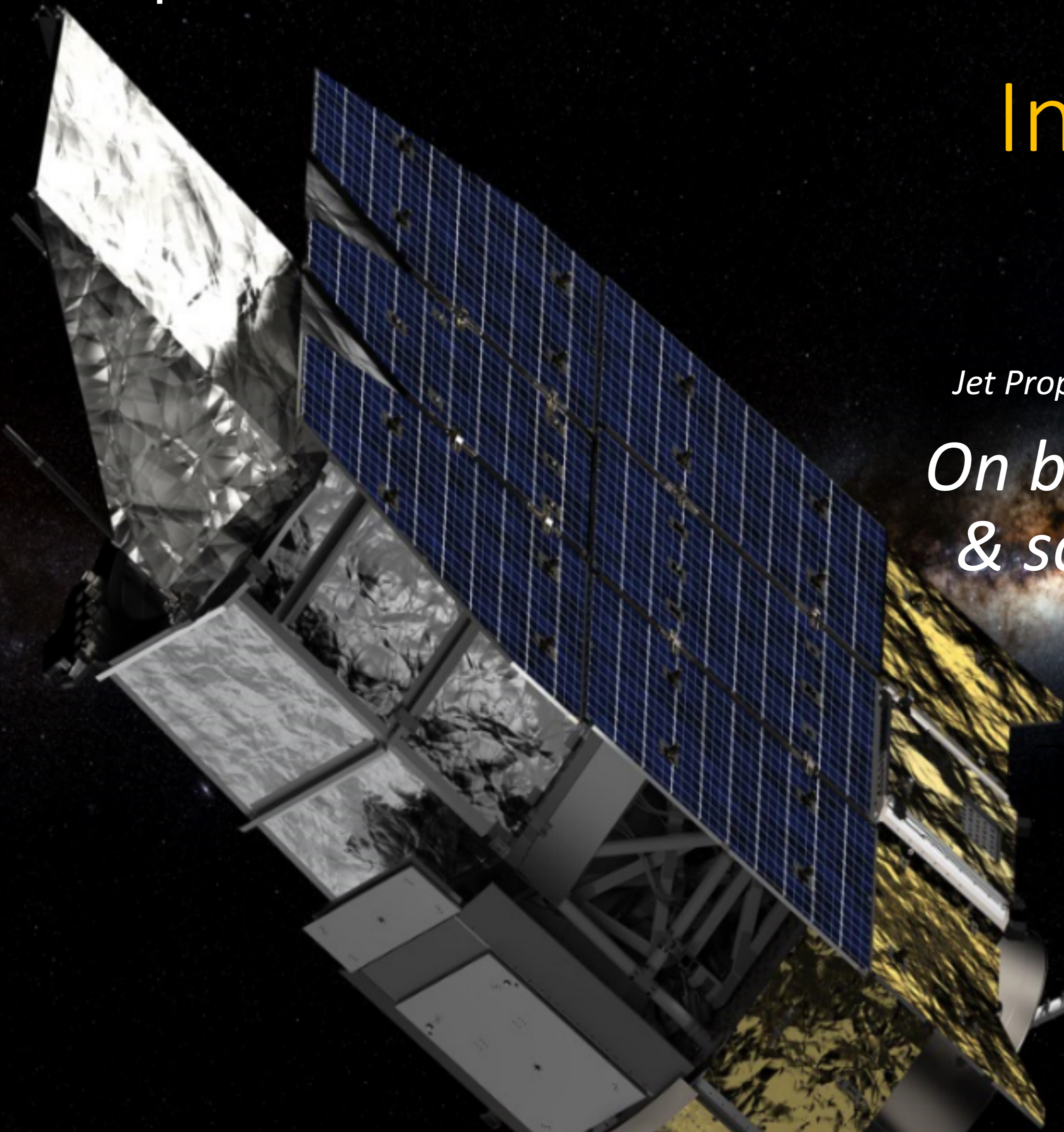
Roman Space Telescope



Coronagraph Instrument Update

Bertrand Mennesson

Jet Propulsion Laboratory, California Institute of Technology

On behalf of the CGI instrument & science investigation teams

ExoPAG Meeting #22
June 18, 2020

• NASA GODDARD SPACE FLIGHT CENTER • JET PROPULSION LABORATORY •
• L3HARRIS TECHNOLOGIES • BALL AEROSPACE • TELEDYNE • NASA KENNEDY SPACE CENTER •
• SPACE TELESCOPE SCIENCE INSTITUTE • INFRARED PROCESSING AND ANALYSIS CENTER •
• EUROPEAN SPACE AGENCY • JAPAN AEROSPACE EXPLORATION AGENCY •
• CENTRE NATIONAL d'ÉTUDES SPATIALES • MAX PLANCK INSTITUTE FOR ASTRONOMY •

Outline

- Overview of CGI
- Status of key technologies and path to delivery
- Comparison of capabilities to future mission needs
- Potential Science
- Community Participation

CGI is step on the path toward biomarkers on an Earth-like planet

- Exoplanet Science Strategy recommendations:
  - NASA should lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars.
  - NASA should launch WFIRST [now Roman] to … demonstrate the technique of coronagraphic spectroscopy on exoplanet targets.

"The most effective way to do it, is to do it."

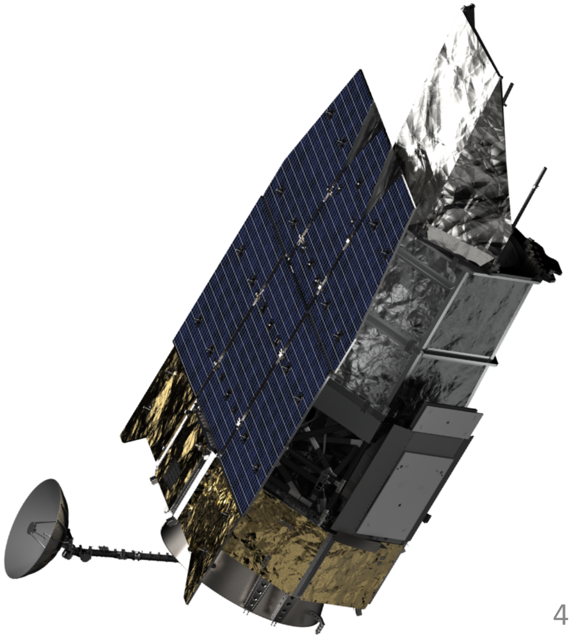
– Amelia Earhart

- System-level demonstration, on orbit

Roman Space Telescope

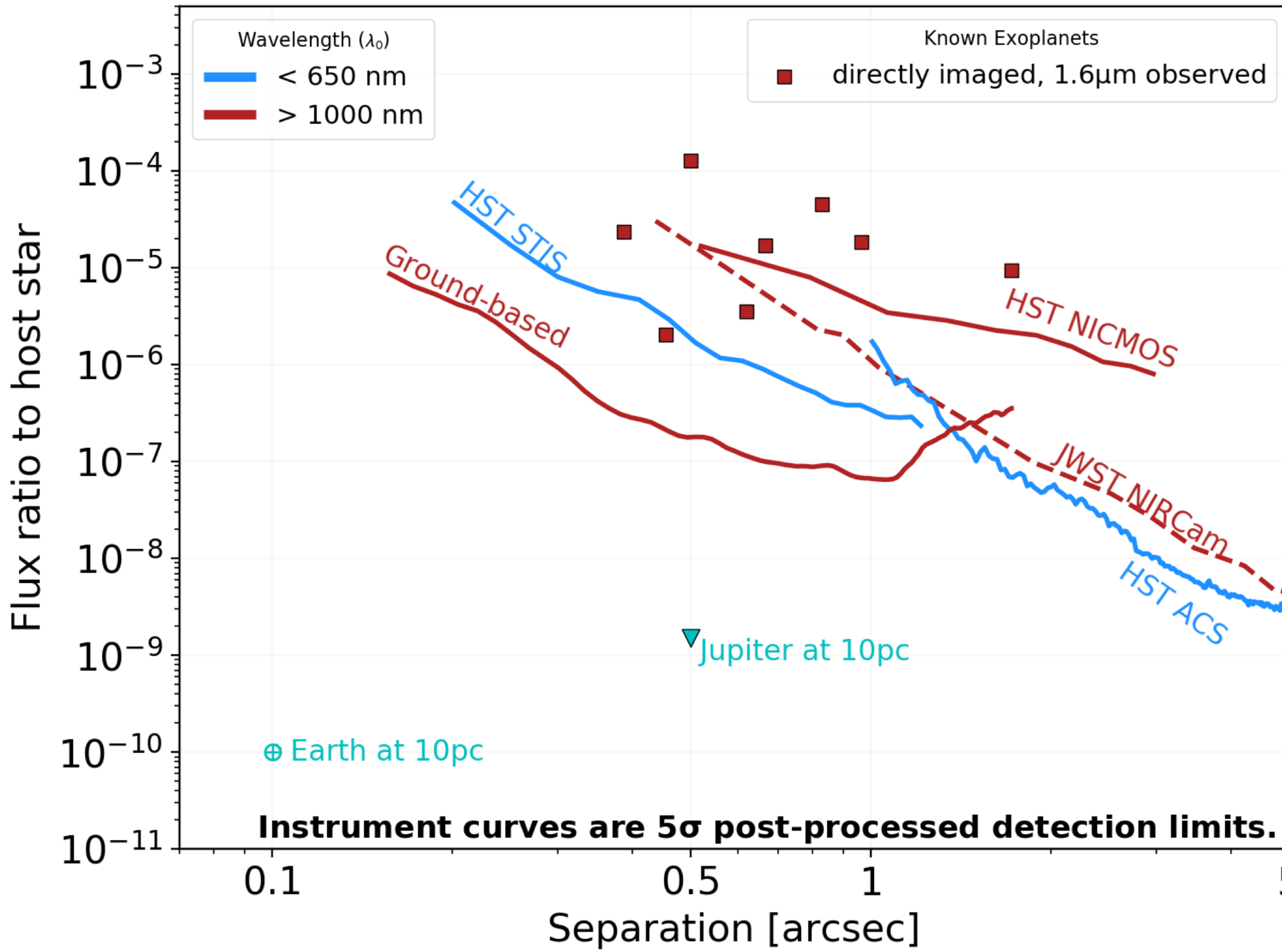
CGI paves the way for future direct imaging missions

- CGI is:
  - a technology demonstration instrument on the Roman Space Telescope
  - the first space-based coronagraph with active wavefront control
  - a visible light (545-865nm) imager, polarimeter and R~50 spectrograph
  - a 1,000 times improvement in contrast performance over current space facilities



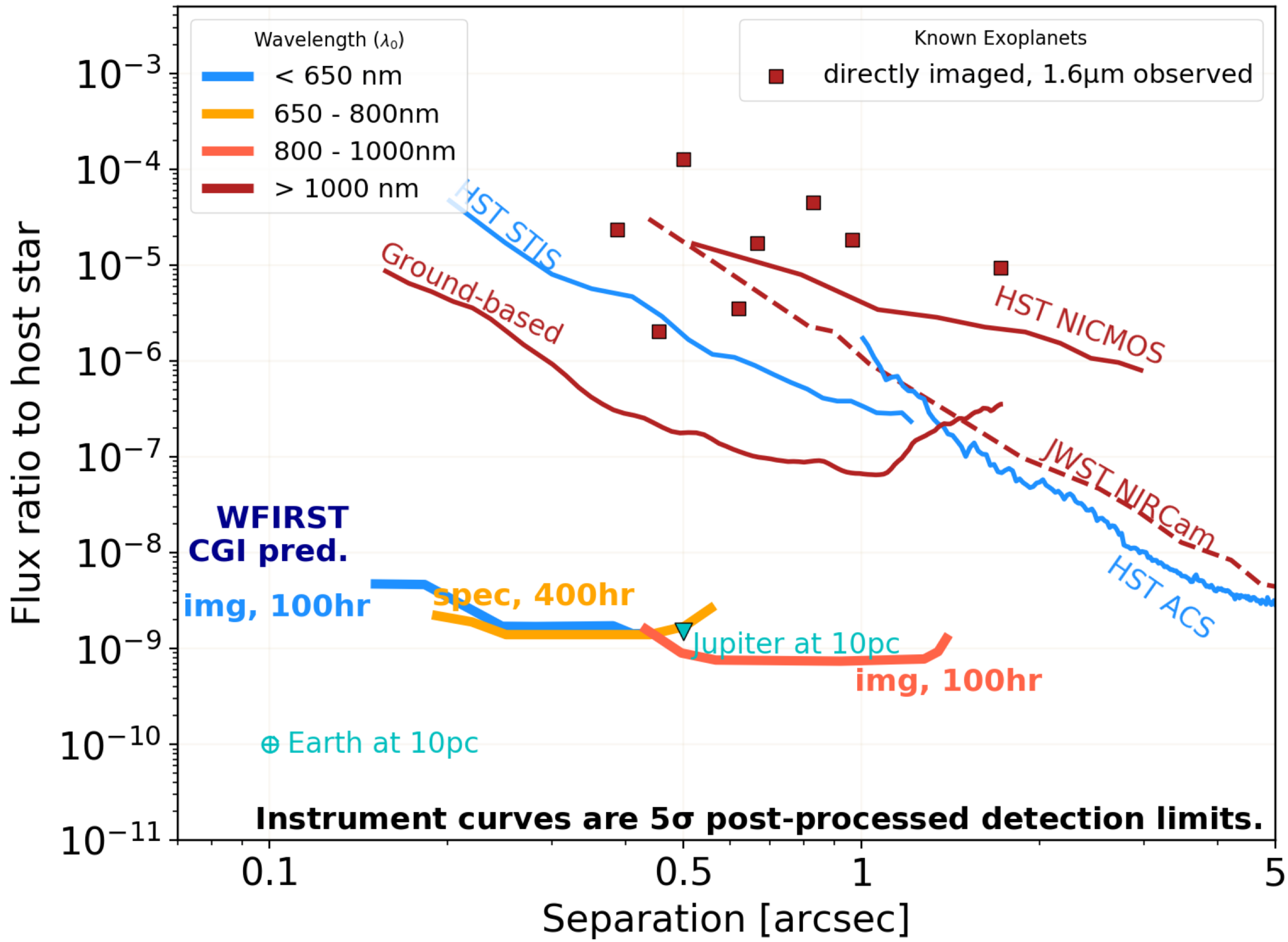
Roman Space Telescope

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



Roman Space Telescope

CGI's predicted performance is 100-1000x better than State-of-the-Art



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

NASA terminology: MUF=1 predictions

Primary Observing Modes

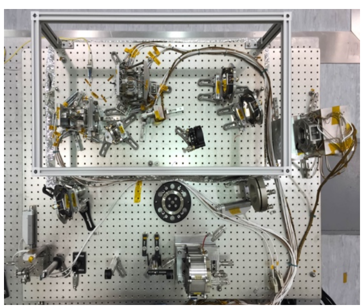
CGI has three baseline modes:

	λ_{center}	BW	Mode	FOV radius	Polarimetry
1	575 nm	10%	Narrow field Imaging	0.14” – 0.45”	Y
2	730 nm	15%	Slit + R~50 Prism Spectroscopy	0.18” – 0.55”	-
3	825 nm	10%	“Wide” field Imaging	0.45” – 1.4”	Y

Roman
Space
Telescope

CGI will demonstrate key technologies for future missions

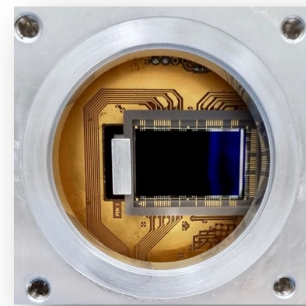
Ultra-Precise Wavefront Sensing & Control



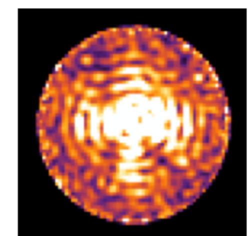
Large-format Deformable Mirrors

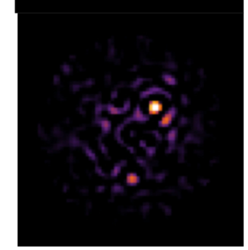
High-contrast Coronagraph Masks

Ultra-low-noise photon counting visible detectors



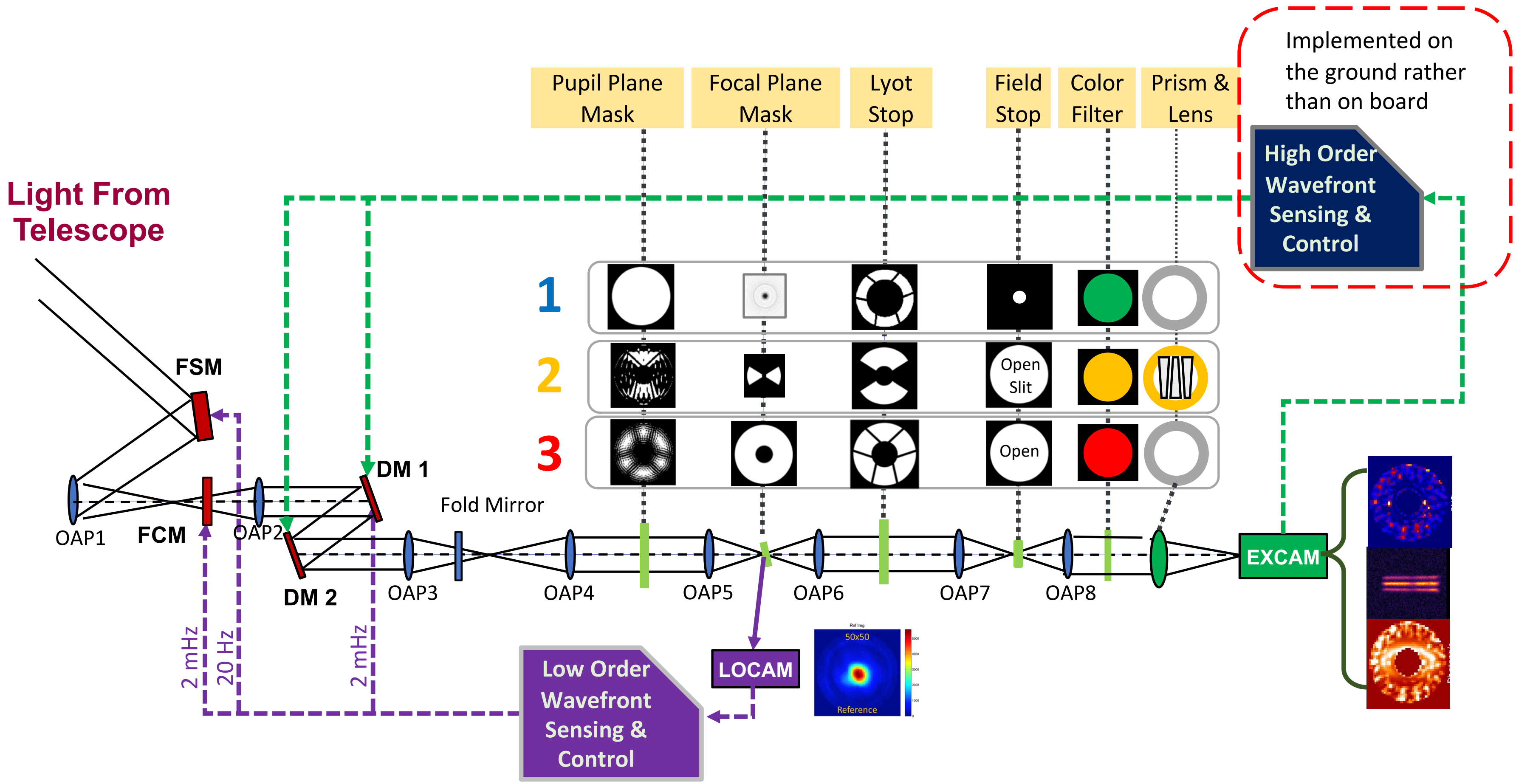
Photon-Counting High-Contrast Data Processing





Roman Space Telescope

Key technologies work together as a system to deliver high performance

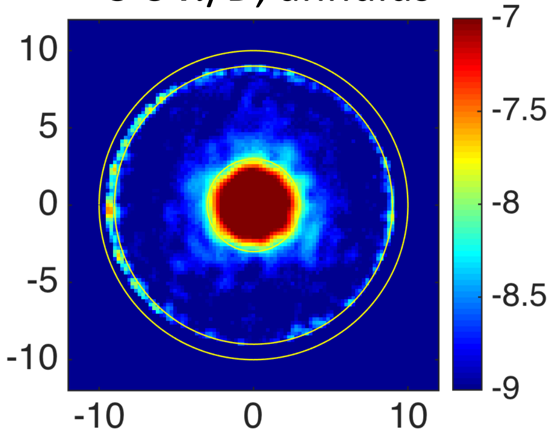


OAP = Off-Axis Parabolic [Mirror]

All CGI coronagraph designs have achieved high contrast in the JPL testbed

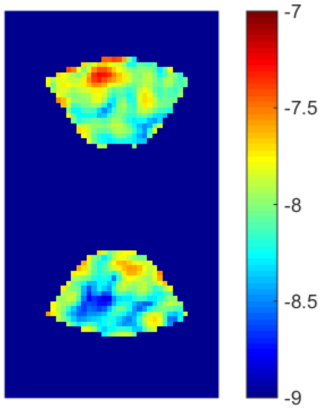
(results as of Sept 2019 PDR)

Hybrid Lyot Coronagraph
Narrow-FOV Imaging
575 nm, 10% BW
3-9 λ/D, annulus



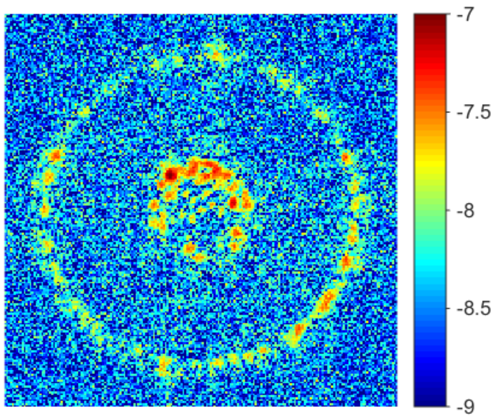
1.6e-9 raw contrast
550 nm, 10% BW

"Bowtie" Shaped Pupil Coronagraph
Spectroscopy
730 nm, 15% BW
3-9 λ/D, Bowtie



1.0e-8 raw contrast
760 nm, 18% BW

"Wide" Shaped Pupil Coronagraph
Wide-FOV Imaging
825 nm, 10% BW
6.5-20 λ/D, annulus



4.3e-9 raw contrast
565 nm, 10%

CGI predicted performance compares favorably to future missions' requirements

Parameter	**CGI vs. Future missions** *unobscured aperture: HabEx & LUVOIR B*
5σ Flux ratio at 3 λ/D (6 λ/D)	**$5 \cdot 10^{-9}$ ($2 \cdot 10^{-9}$) * vs. $5 \cdot 10^{-11}$ **** Roman Space Telescope pupil is challenging

* model, typically without Model Uncertainty Factors (MUFs)

** NTE = not-to-exceed = requirement on max tolerable.

Roman Space Telescope

CGI predicted performance compares favorably to future missions' requirements

Part 1

Parameter	**CGI vs. Future missions** ***unobscured aperture: HabEx & LUVOIR B***
EMCCD	**Comparable at V-band** Bit better: dark current, clock-induced-charge Bit worse: QE at UV/red at 5 years (rad hard)
Pointing jitter control	**Comparable** CGI lab: ~0.35mas RMS V=5 star, FM: 0.3mas RMS
Low order control (Z4-Z11)	**A few to ~10x better** ~10pm RMS * vs ~100pm NTE ** Challenging WFIRST pupil: trade low-order sensitivity for overall throughput

* model, typically without Model Uncertainty Factors (MUFs)

** NTE = not-to-exceed = requirement on max tolerable.

Roman Space Telescope

CGI predicted performance compares favorably to future missions' requirements

Part 2

Parameter	CGI vs. Future missions *unobscured aperture: HabEx & LUVOIR B*
Wavefront error sources	**Comparable** Phase & "new physics" (amplitude & polarization)
High order drift (≥Z12)	**Comparable (~5pm)** CGI: 1σ prediction*, FM: NTE**
# of DMs	**Same (2)**
DM actuator count	**48x48 vs 64x64**
DM stroke resolution	**~4x worse (7.5pm vs 2pm)** Engineering problem, not physics problem

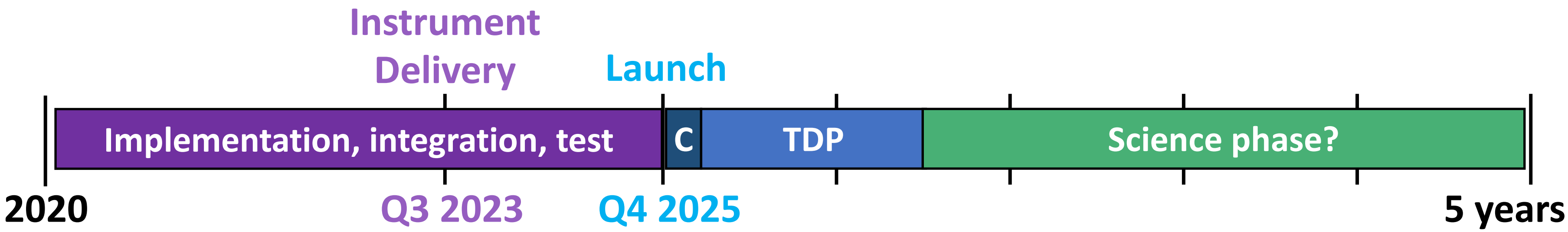
* model, typically without Model Uncertainty Factors (MUFs)

** NTE = not-to-exceed = requirement on max tolerable.

Critical to validate end-to-end system on sky, especially interaction with telescope

Roman Space Telescope

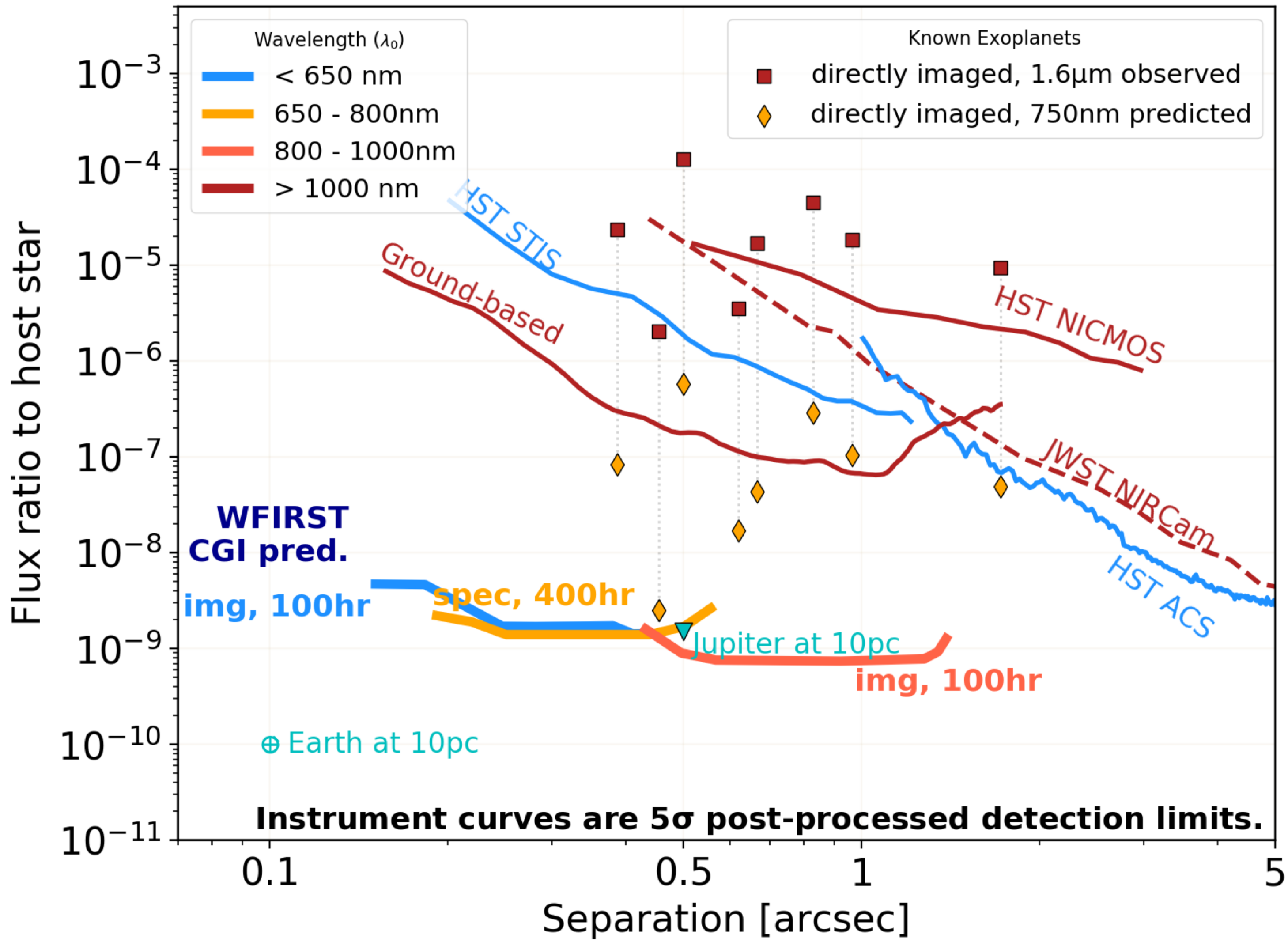
Path to Delivery and Observations



- **Feb 2020: Entered implementation phase (Phase C)**
- **Q3 2023: Instrument delivery to payload integration & test**
- **Q4 2025: Launch**
- **Commissioning Phase**
  - 450 hr in first 90 days after launch
- **Technology Demonstration Phase (TDP)**
  - **~2200 hr (3 months) baselined** in first 1.5 years of mission
- **If TDP successful, potential science phase**
  - 10-25% of remainder of 5 year mission
  - Support community engagement with *extended* Participating Scientist Program (PSP) and/or GO (with additional tools)
  - Requires additional resources post tech-demo
  - Starshade rendezvous, if selected

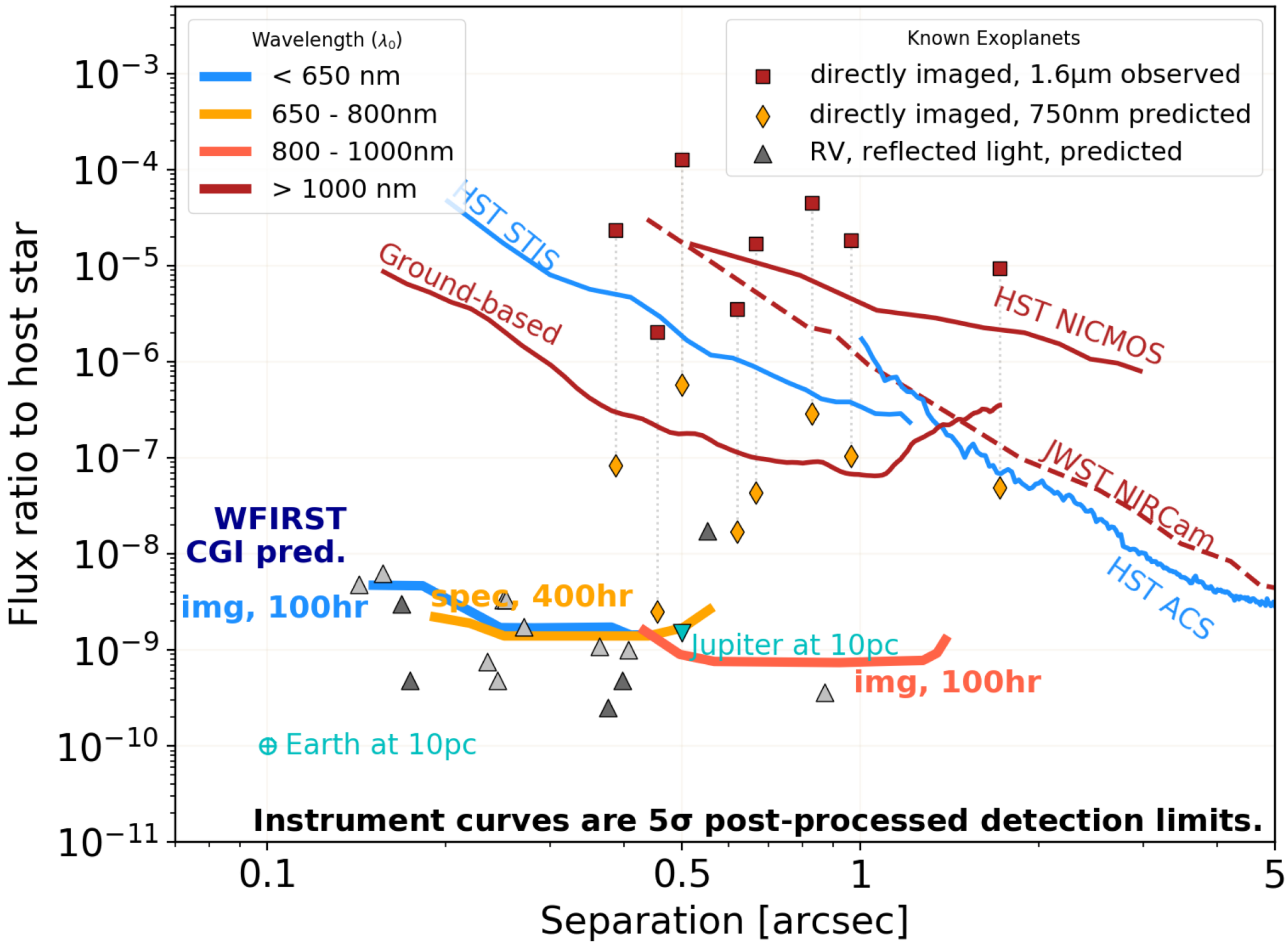
Roman Space Telescope

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



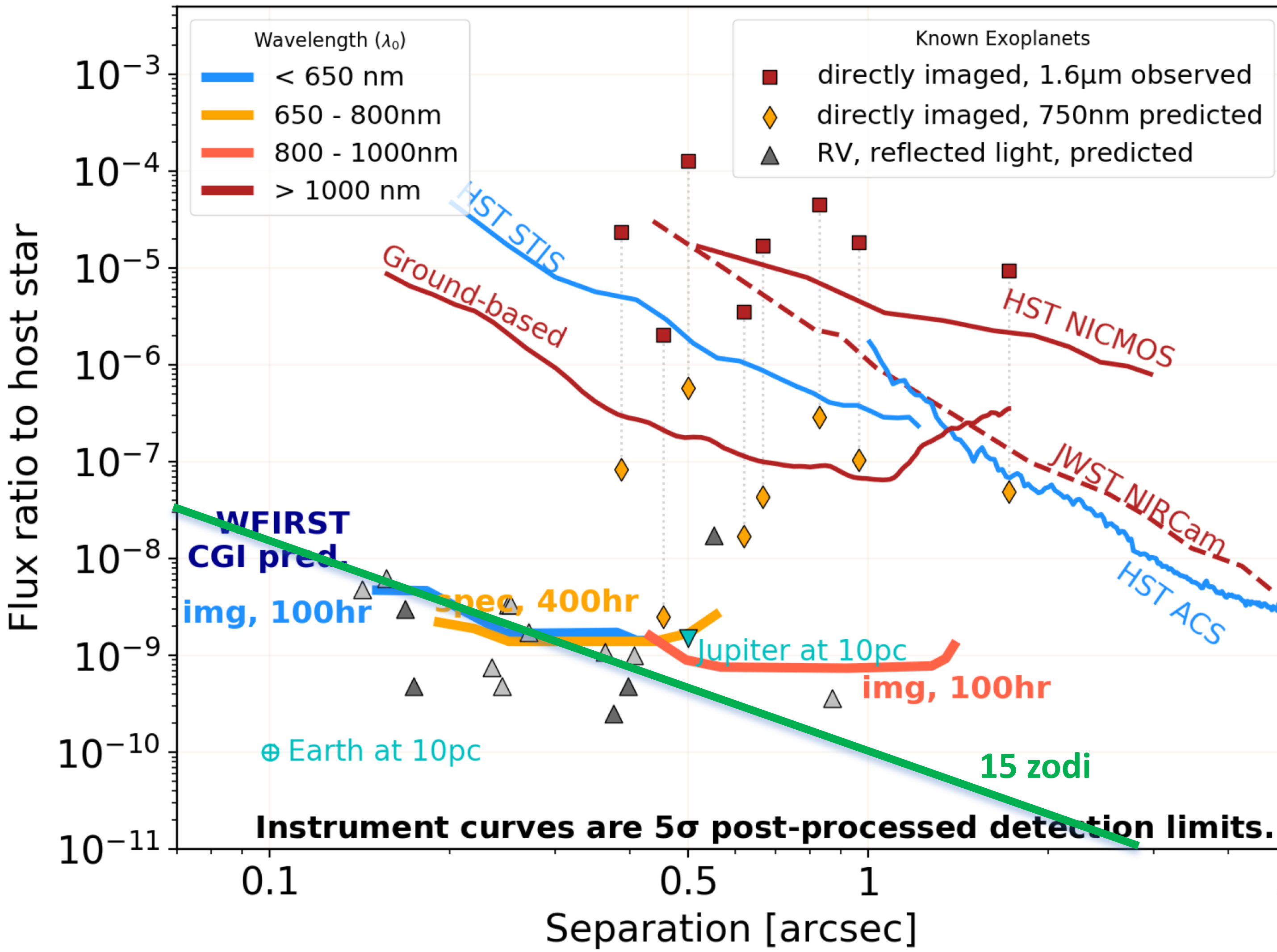
Roman Space Telescope

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



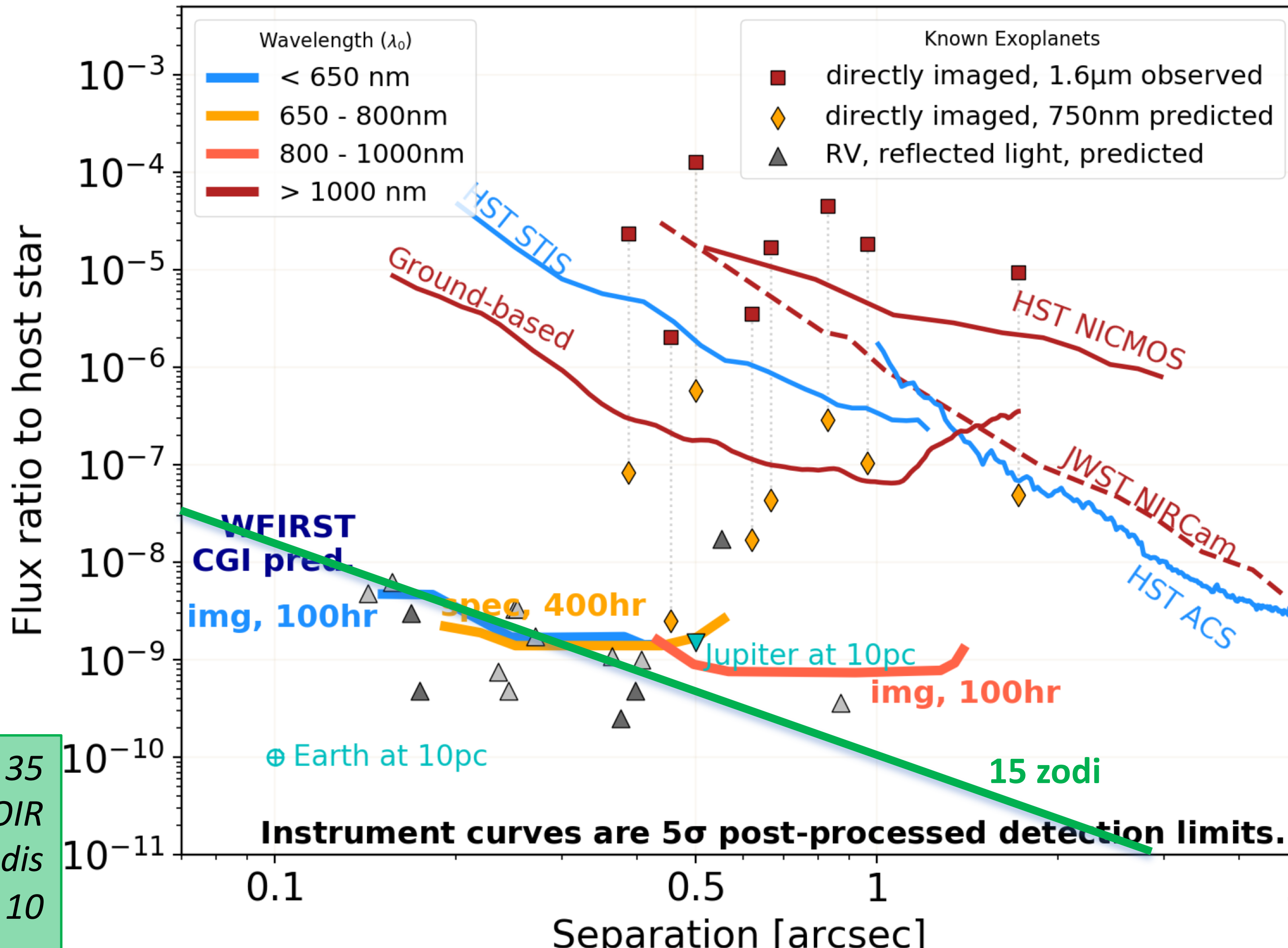
Roman Space Telescope

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



Roman Space Telescope

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



Could reach the best 35 (75) HabEx & LUVOIR targets HZ with 15 zodis sensitivity per resel in 10 (~30) days

Opportunities for community involvement: Participating Scientist Program (PSP)

- Current SITs disbanded mid 2021
- CGI SITs will not be recompeted
- PSP instead, likely competeted through a future ROSES call in early FY 21
- PSP task list and exact modalities currently being defined by HQ / Project
  - Community support group to maximize lessons learned from Tech Demo, and potential science if CGI obs extended post TDP

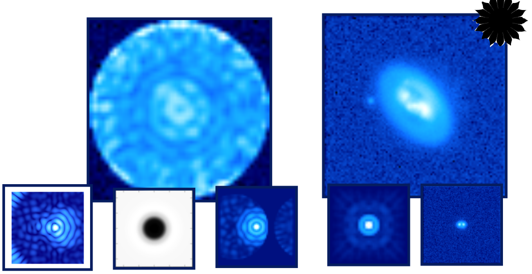
The 2019-2020 Roman (CGI) Exoplanet Imaging Data Challenge

Aims to get the community acquainted with CGI data's **new contrast regime** and astrophysics that will be enabled: **giant planets in reflected light** (*contact Julien Girard: jgirard@stsci.edu*)

DATA

6 imaging epochs throughout the mission

Realistic simulations:OS6 Speckle field time series, detector model, background contamination sources, exozodiacal light



Hybrid Lyot C.

4 epochs, 2 rolls

+ Reference star
+ Calibrations

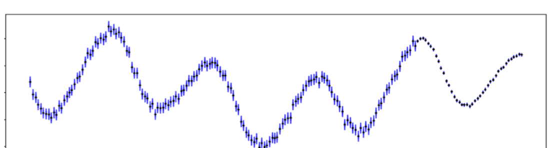
&

Star Shade

2 epochs

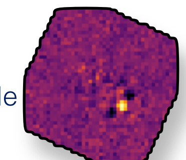
+ Calibrations

15 years of precursor RV data



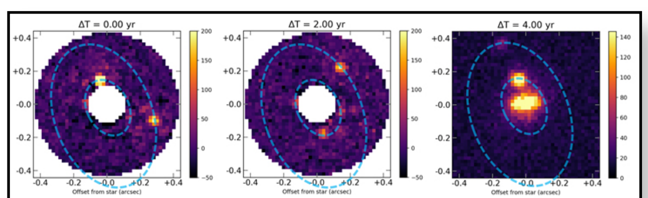
CHALLENGE

1. **Extract & identify point sources** in 4 HLC **epochs**, disentangle from background sources, provide **census and rough astrometry**

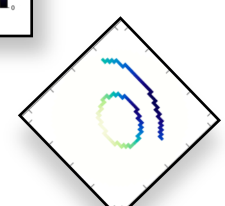


2. **Compute orbital parameters** & masses with those **4 epochs**, use **priors from RV data**

3. **Refine orbital parameters & masses** using additional **2 SS epochs**, all the information available



4. For a given planet, measure the **phase curve** assuming it is Lambertian, provide **radius & albedo** given mass-radius relationship



www.exoplanetdatachallenge.com

TRAINING

4 Tutorial "hack" events

STScI SPACE TELESCOPE SCIENCE INSTITUTE

Take-way messages – Questions?

- First space-based coronagraph with active wavefront control
- Meaningful technology demonstrator
  - Lab & models are compelling, but need system-level on-sky test
  - Comparable to future missions' needs:
    - low order control, high-order stability, "new physics," EMCCD noise
  - Improvement over SOTA, but more work needed:
    - high order wavefront control, DMs, EMCCD lifetime & UV/red sensitivity
- Capable of interesting science
  - Jupiter analogs in reflected light; young exoplanets at new λ
  - Tenuous debris/exozodi disks; perhaps protoplanetary systems
- Approved to begin implementation with a plan to stay on time and on budget with expected instrument delivery for payload I&T in Q3 2023

Back-ups

Implications of Tech Demo Designation

- CGI has technology, not science, requirements
  - Will still make scientifically compelling obs during TD phase
  - If TD phase successful, CGI likely to be used for science obs

Take-away messages - Questions?

Status of key technologies

All will be TRL6 by November

Comparison of capabilities to future mission needs

Many key areas are "in family"

Potential Science

Tech Demo with no science requirements does not mean no science

Path to delivery

On schedule, on budget

Community Participation

PSP ROSES call, on-going data challenge

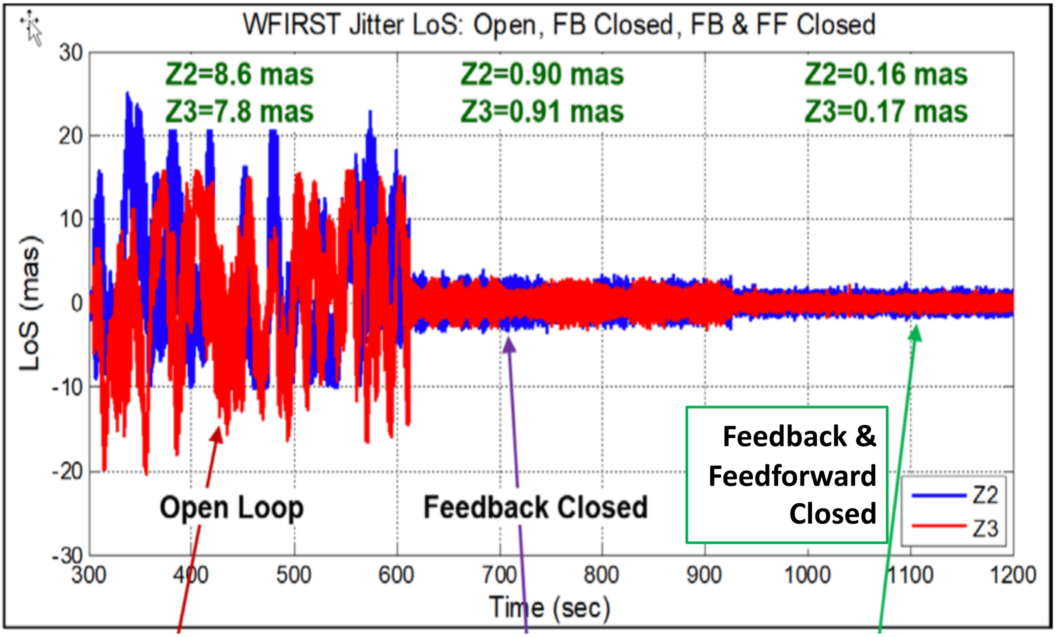
Implications of Tech Demo Designation

- CGI cannot drive mission cost or schedule
  - CGI may not be on the critical path
  - CGI is cost capped
    - No access to NASA or WFIRST Project reserves
  - CGI may not drive observatory design
  - CGI is now Class D
- CGI has technology, not science, requirements
  - Will still make scientifically compelling obs during TD phase
  - If TD phase successful, CGI likely to be used for science obs

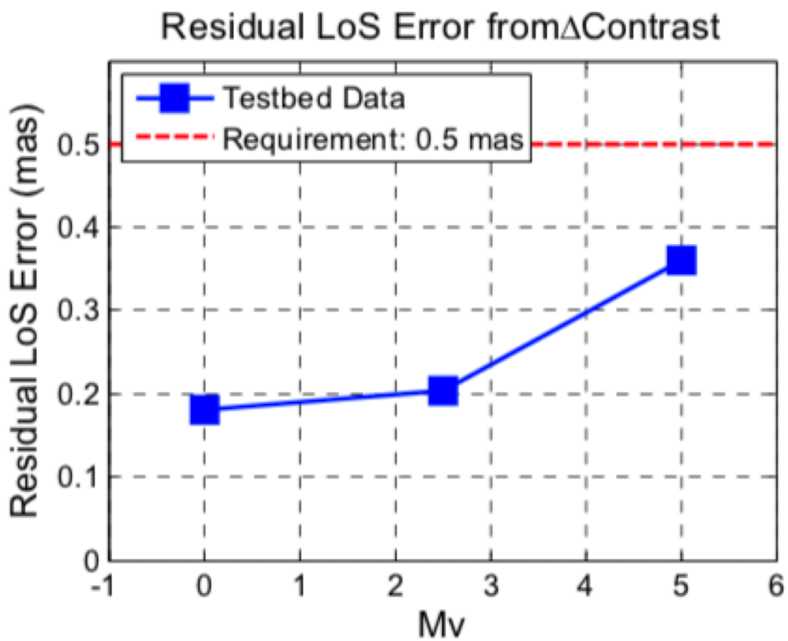
Roman Space Telescope

CGI Low-Order Wavefront Sensor: 1st (in space) to use science light for control

Unlike HST & JWST fine guidance sensors, CGI LOWFS is designed to minimize non-common path errors & operate in low-photon regime.



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

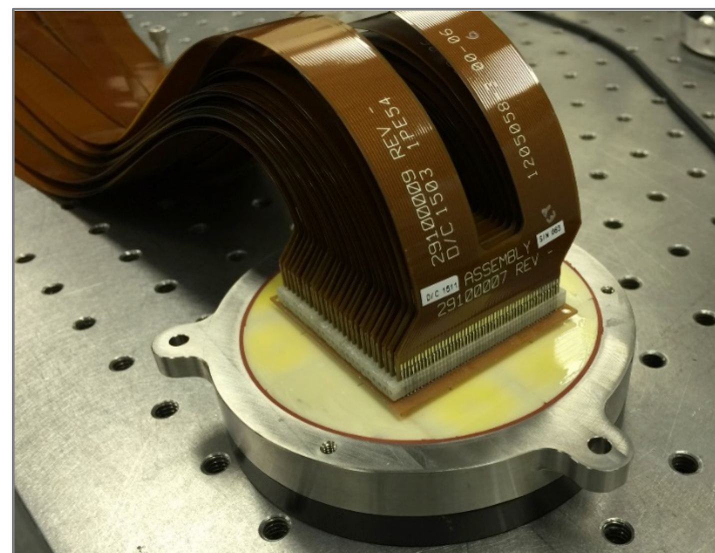


Shi+2018 lab demo

Roman Space Telescope

CGI is maturing high-actuator-count DMs for space applications

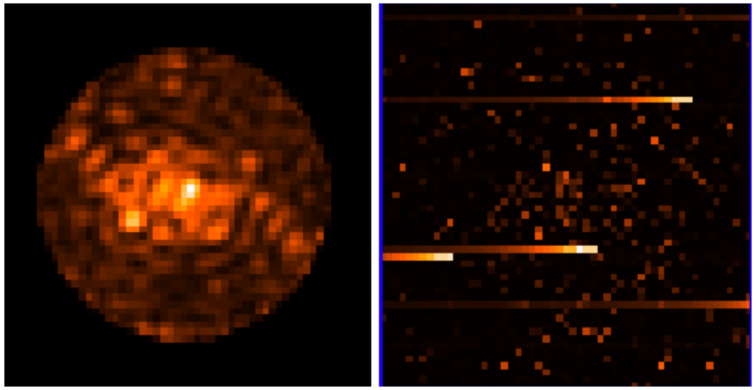
- CGI uses Northrop Grumman Xinetics Deformable Mirrors
  - 48X48 PMN (lead magnesium niobate) electro-strictive ceramics actuators
- Xinetics has strong **lab** heritage:
  - >10 years without failures
  - 4 x 10^{-10} contrast in testbed
- CGI is maturing to flight-ready:
  - Flight interconnect will be demonstrated to survive flight environment by November, 2020



Roman Space Telescope

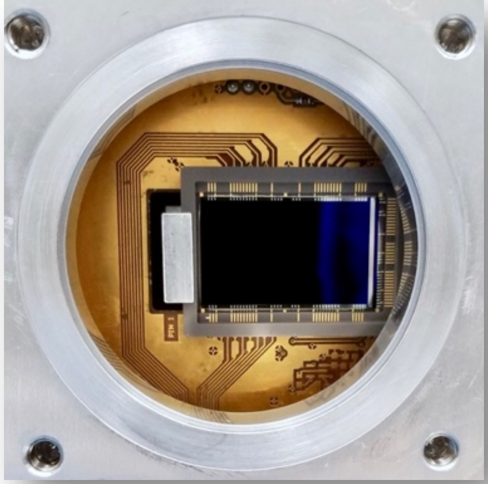
CGI is maturing photon-counting EMCCDs for space applications

Simulated images
John Krist (JPL)



- Low-flux images:
  - EXCAM: Jupiter analogs < 1 photon/min
  - LOCAM: 1kHz framerate
- EM => ~ no read noise
  - First space-qualified photon-counting EMCCD
- Tech & data processing development
  - mitigation and characterization of charge traps from radiation damage
  - Mitigation of cosmic ray effects (overspill)

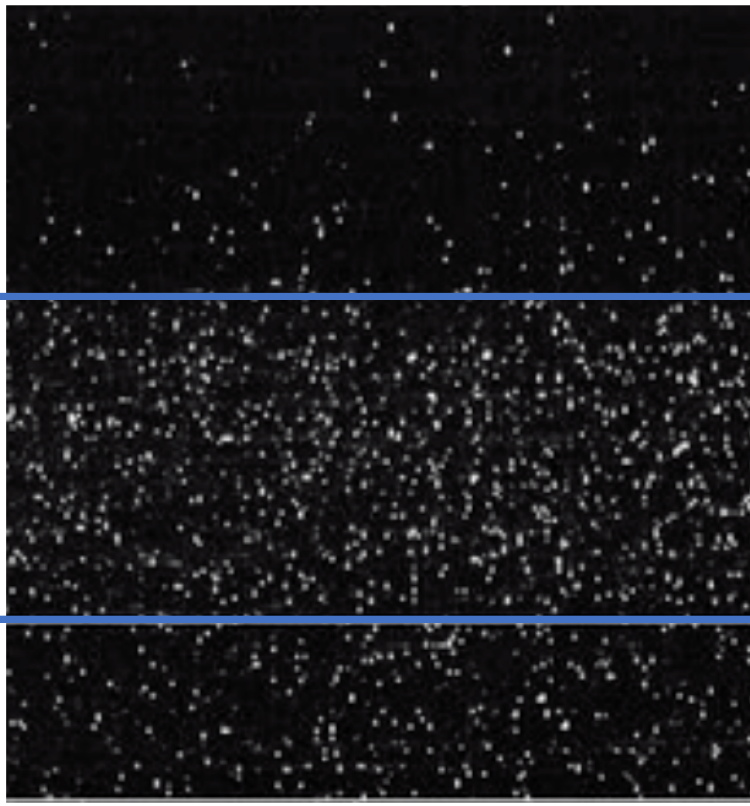
Patrick Morrissey (JPL)



Roman Space Telescope

"notch" channels reduce effects of radiation damage up to ~5x

Patrick Morrissey (JPL)



Undamaged (shielded) region

commercial design: irradiated

CGI "notch" design: irradiated

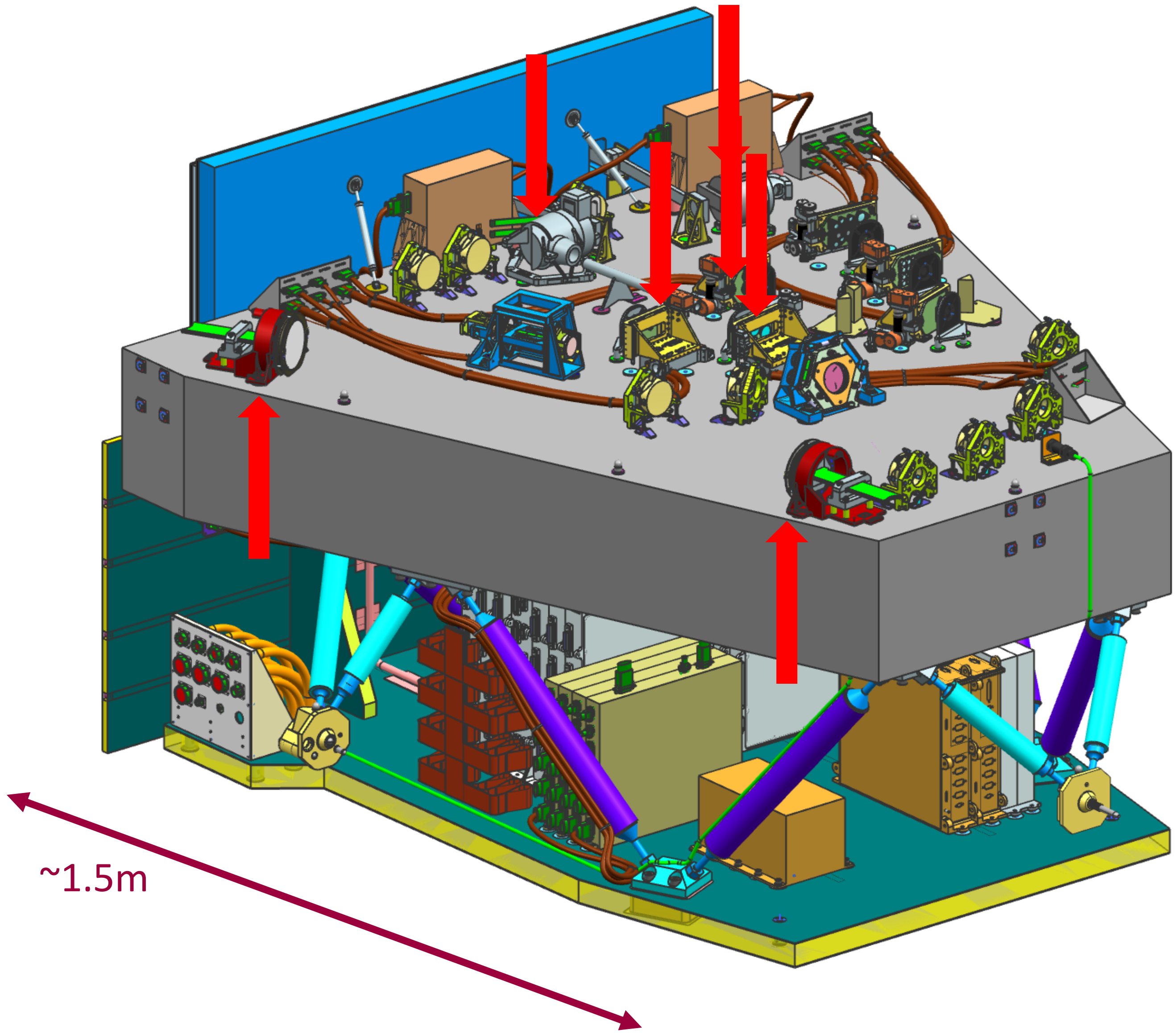
CBE effective QE @ 5 years ~ 50%

Plan to deliver a capable instrument on time and on budget

- Increased performance margin by removing L1 Baseline requirements, leaving only L1 Threshold requirement
  - 1·10-7 flux ratio, 6 - 9 λ/D, λ ≤ 600 nm, bandwidth ≥ 10%, V≤5 star
- **CGI design has not changed as a result of L1 relaxation**
  - Re-design to Threshold would hurt both cost & schedule
- Improved cost & schedule robustness by identifying "off-ramps" and descopes that could be triggered if problems arise
  - May trade performance/risk for cost/schedule.
  - Assess with performance modeling tools.
- Granted CGI Project sole decision authority, unless the L1 threshold requirement is at risk
  - Key decisions advised by stakeholders

Roman Space Telescope

Key technologies work together as a system to deliver high performance



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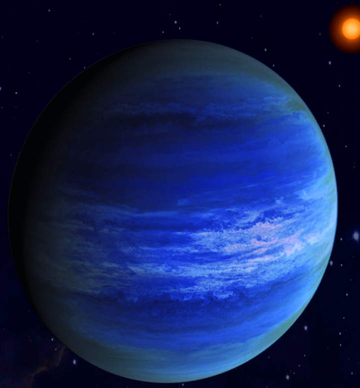
THE 2019-2020 ROMAN (CGI)

EXOPLANET IMAGING

DATA CHALLENGE

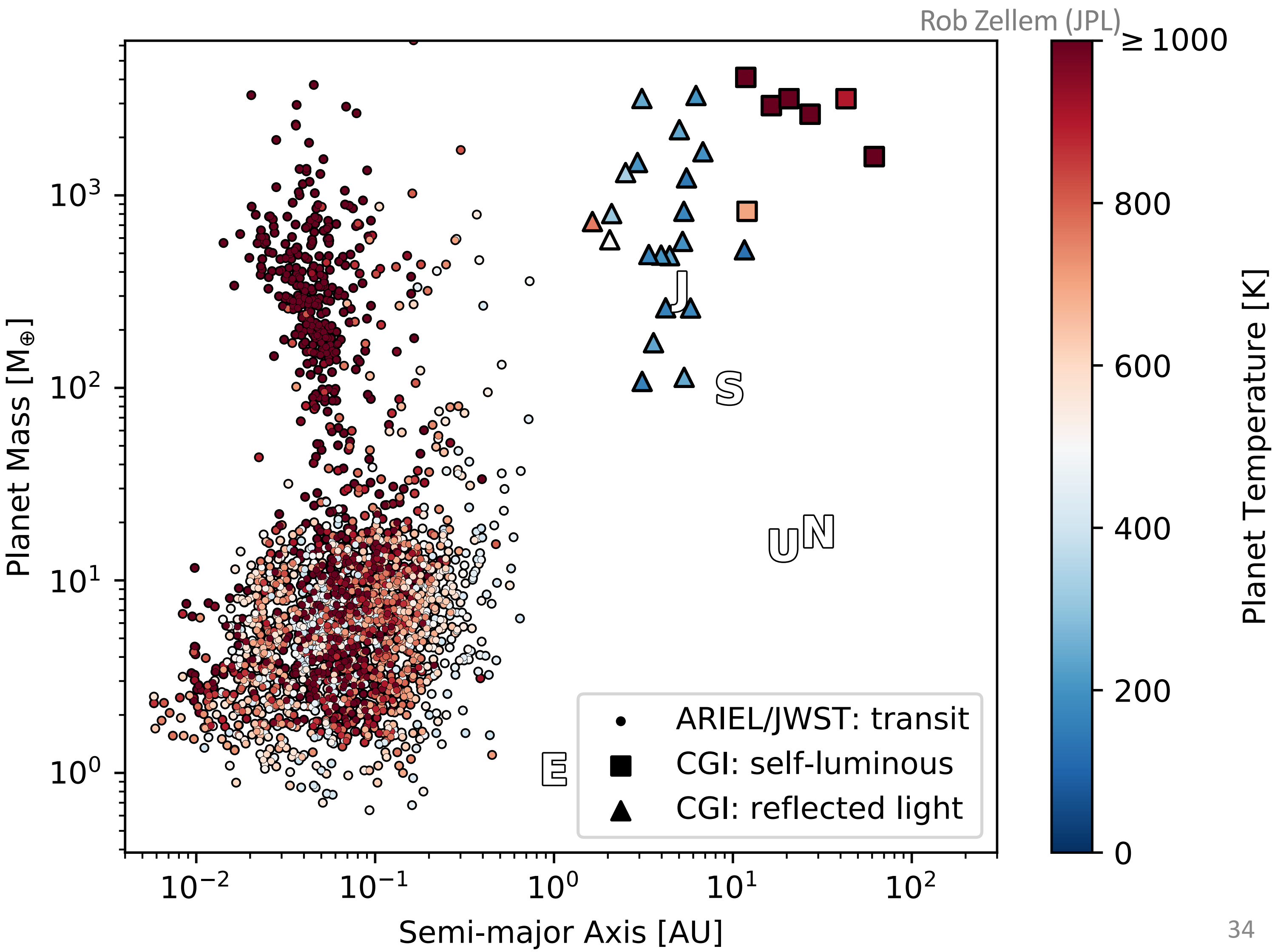
Julien Girard (STScI)
Junellie Gonzalez-Quiles (GSFC)
Sergi Hildebrandt (JPL)
Stephen Kane (UCR)
Davy Kirkpatrick (IPAC)
Zhexing Li (UCR)
Avi Mandell (GSFC)
Tiffany Meshkat (IPAC)
Chris Stark (STScI)
Maggie Turnbull (SETI)
Neil Zimmerman (GSFC)



October 20th 2019 - June 20th 2020

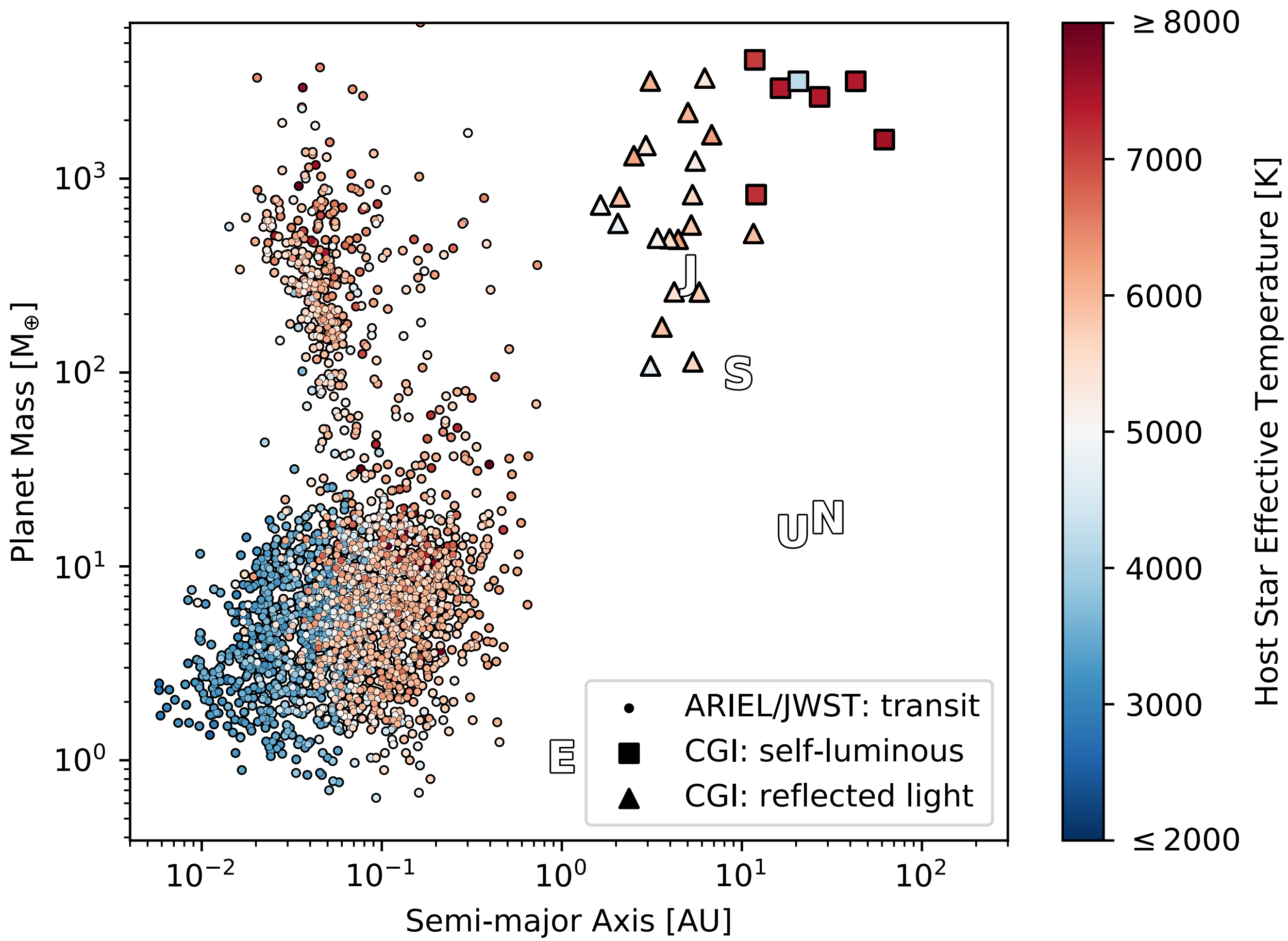
Intro backups

Transit spectroscopy probes a different class of planets



Note:
most CGI mature planets will only have photometry

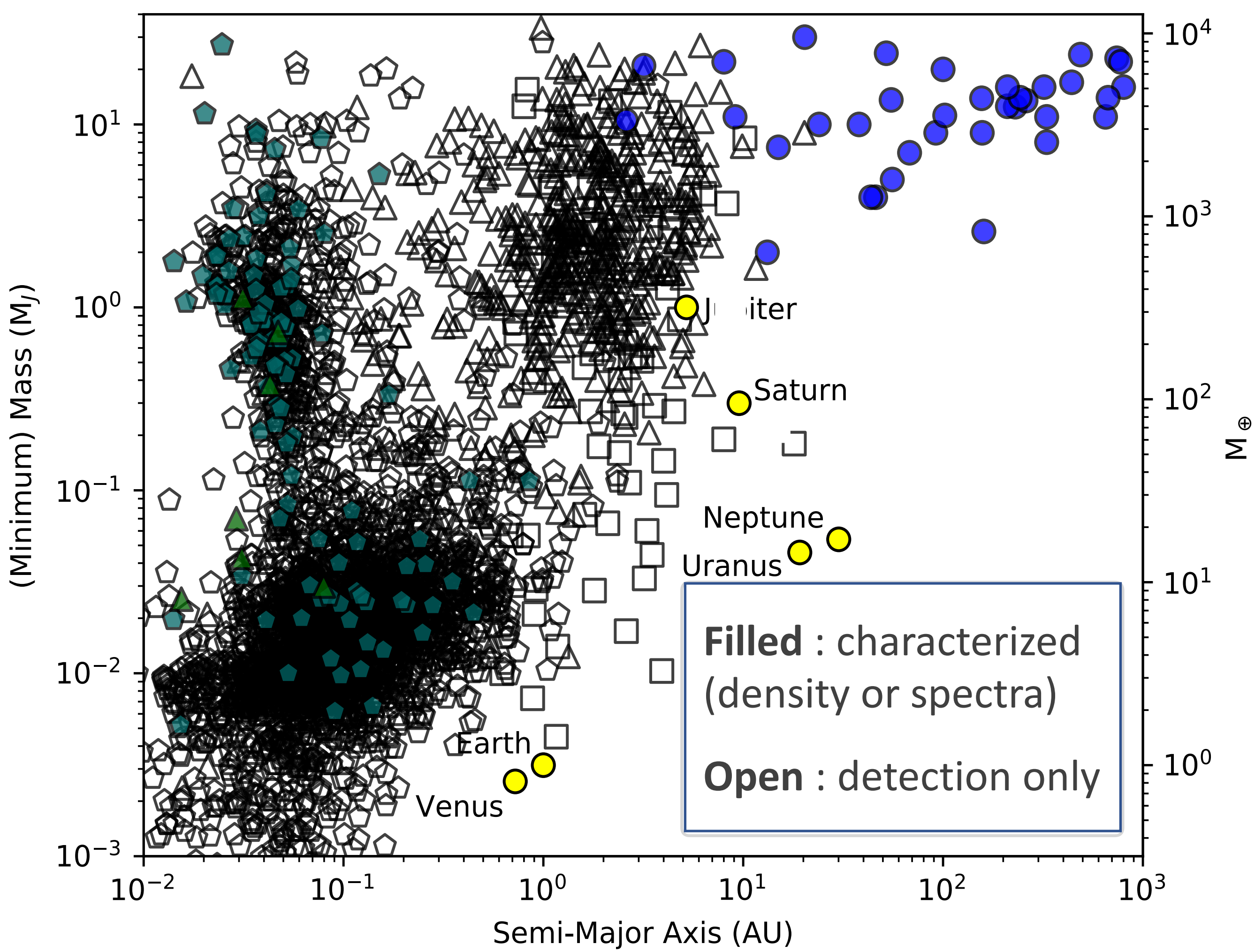
Transit spectroscopy probes different class of planets



Note: some CGI planets will have photometry only

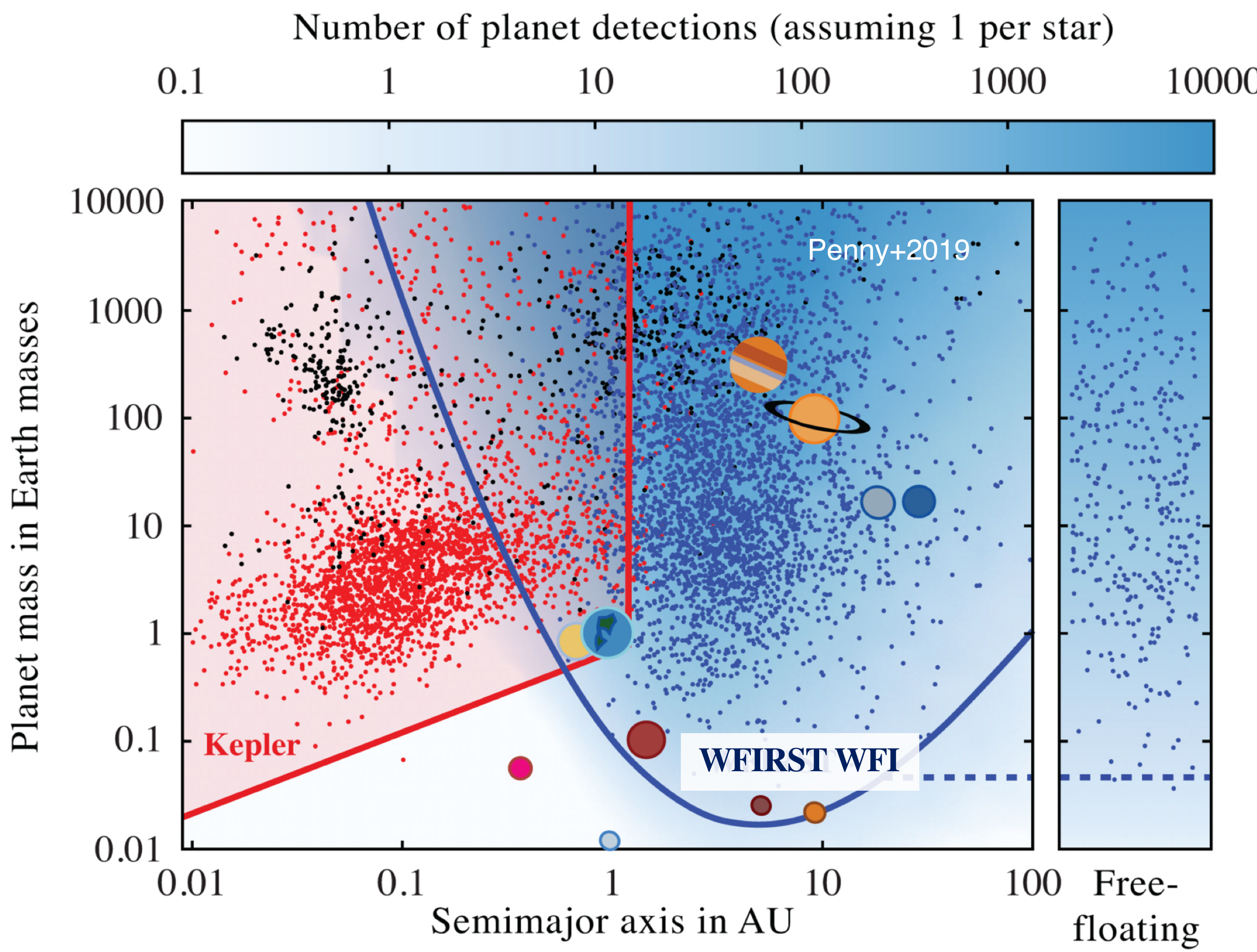
Roman Space Telescope

Only a small fraction of known exoplanets have been characterized



Roman Space Telescope

WFIRST *Wide Field Instrument* microlensing will discover 1000s of planets, but they cannot be characterized



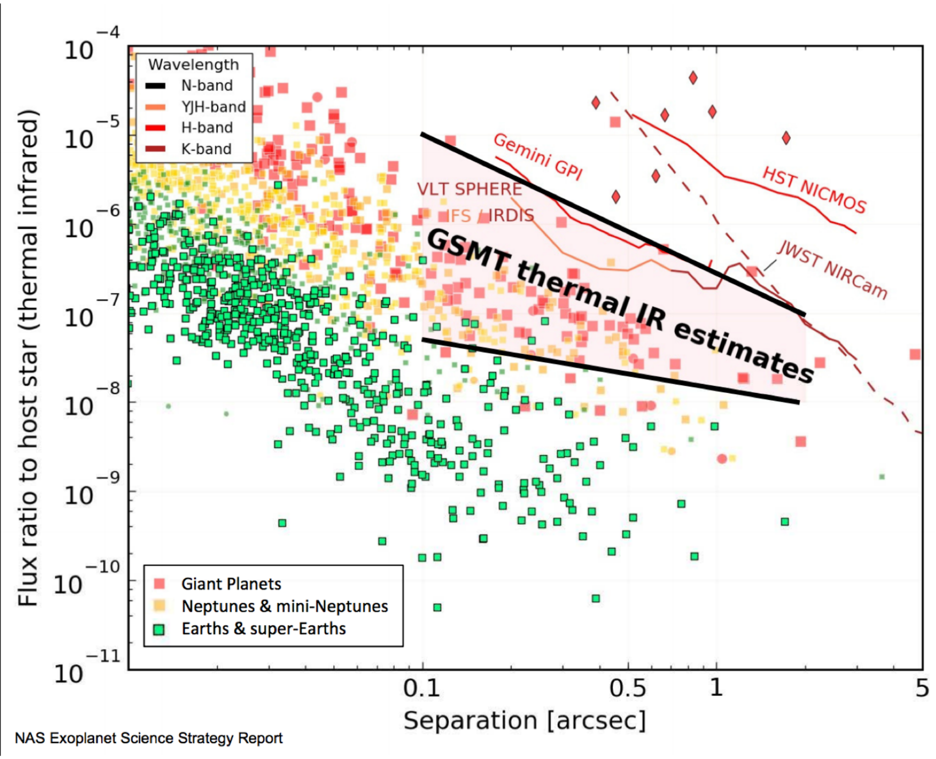
Roman Space Telescope

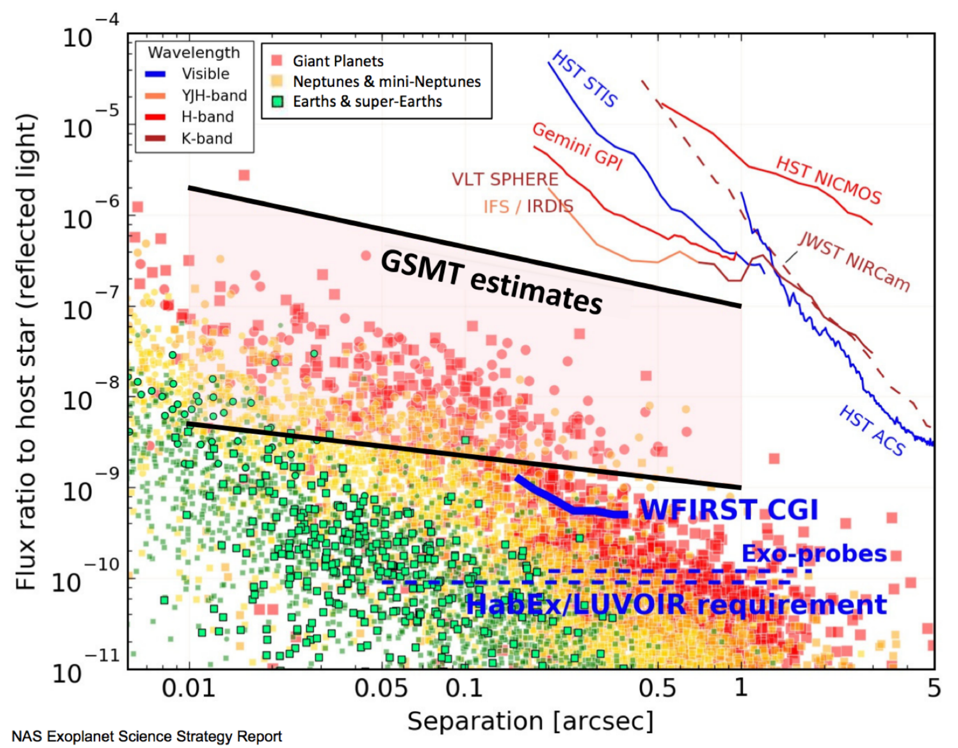
ELTs and space missions are complementary

- CGI: Jupiter analogs around Sun-like stars
  - Visible, modest working angle, intermediate flux ratio
- ELTs: small, temperate planets around cool stars
  - Infrared, small working angle, shallower flux ratio
- Future space missions: Earth analogs around Sun-like stars
  - UV (ozone) and visible, intermediate working angle, deepest flux ratio

Roman Space Telescope

Synergies between Ground and Space (NAS ESS report)

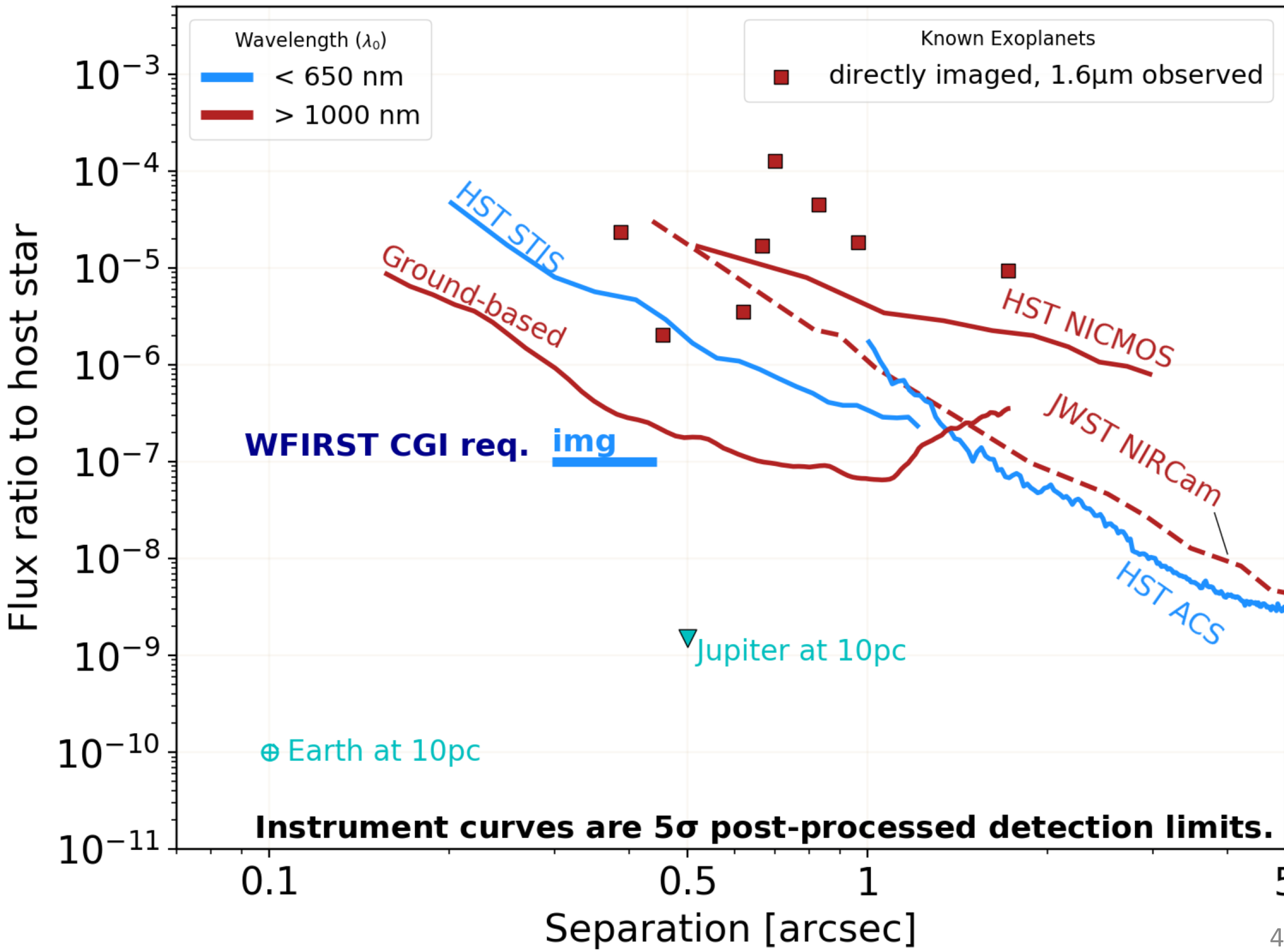




Technology / Instrument

Roman Space Telescope

CGI minimum performance requirement

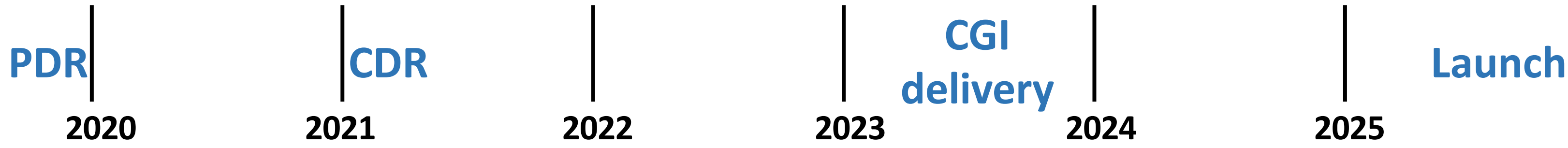


L1 Threshold requirement

(trigger cancellation review if do not meet)

Roman Space Telescope

Timeline: pre-launch



- Preliminary Design Review (Q3/Q4 2019)
- Critical Design Review (Q1 2021)
- Deliver CGI for Payload I&T (Q3 2023)
- Launch (Q4 2025)

Potential enhancements

- Improve confidence in **instrument lifetime** with additional component testing and ground support equipment

Roman Space Telescope

CGI Observing Modes

λ_{center} (nm)	BW	Mode	FOV radius	Polarimetry?
575	10%	Imager	0.14" – 0.45"	Y
730	15%	Slit + R~50 Prism	0.18" – 0.55"	-
825	10%	Imager	0.45" – 1.4"	Y

Three modes will be fully tested prior to launch.

630	15%	Slit + R~50 Prism	0.17" – 0.5"	Y
Hα	1%	Imager	0.17" – 0.5"	Y
575	10%	Imager	0.35" - 1"	Y
825	10%	Imager	0.2" - 0.65"	Y

Additional narrow *sub-bands* (2.5-3.5%) installed

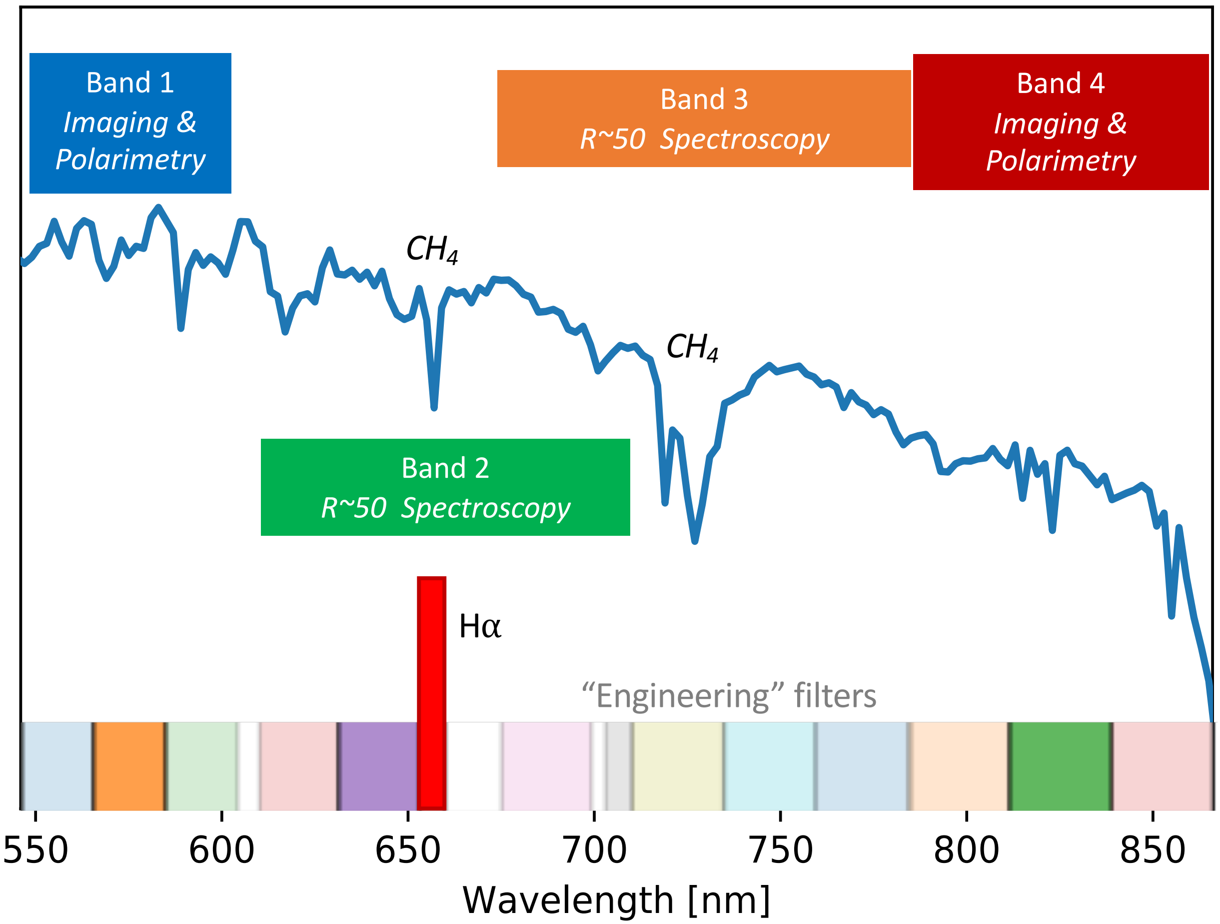
Additional modes installed but not fully tested before launch

Potential enhancement

more pre-flight testing

Roman Space Telescope

WFIRST CGI Passbands



Three official modes will be fully tested prior to launch.

Additional modes will be installed but not fully tested before launch

<u>Potential enhancement</u>
Add'l unofficial mode combinations and/or more pre-flight testing

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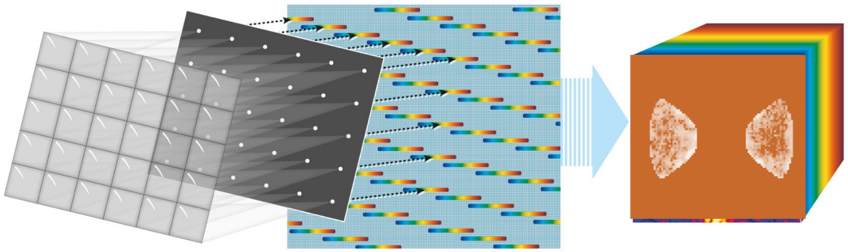
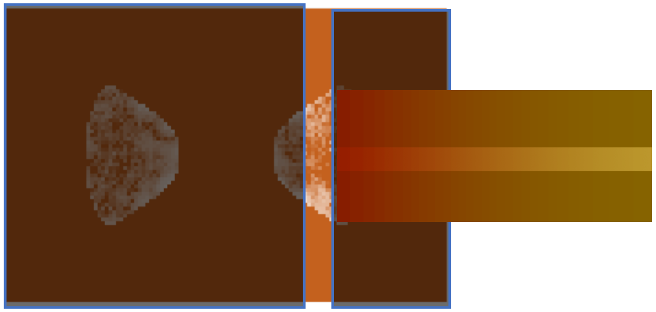
2019 spectroscopy change: IFS => slit+prism

Tyler Groff (GSFC)
Neil Zimmerman (GSFC)

- **IFS**: R=50. Sampled across FOV.
- **Slit**: R~35-70. Sampled in slit only.
  - Fewer optics => higher throughput



- **CGI science capabilities largely unchanged**
  - Exoplanets: comparable
    - Not expecting to observe multi-planet systems
  - Disks: Not planned
    - More time consuming, but was never planned, because no spectral features of interest.
  - Operations: Increased alignment/calibration complexity, but solvable



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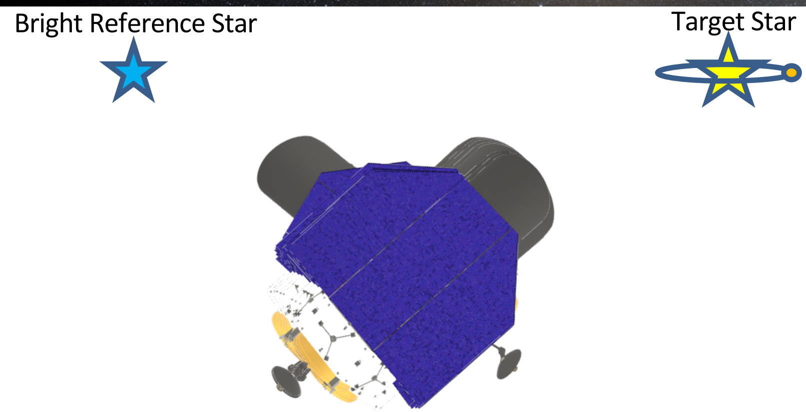
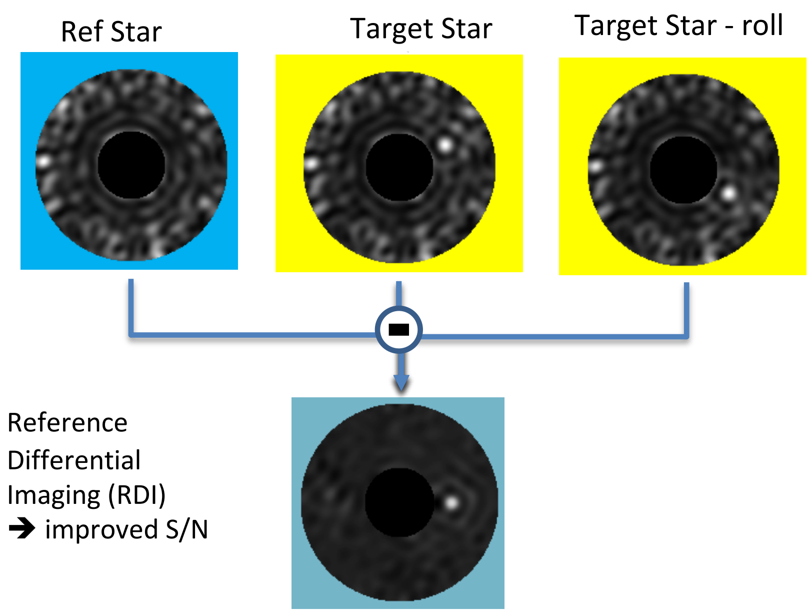
EMCCD Degradation

- **Concern: How much does detector performance degrade due to radiation damage over the 5 year mission?**
- Custom chip design significantly mitigates radiation susceptibility vs. commercial version.
  - Performance is being validated in lab with radiation source.
- Detector performance is more important when sensitivity is photon- or detector noise-limited vs speckle-limited (ie: spectroscopy).
  - For spectroscopy mode, expect only a small (<10% *relative* decrease) in effective quantum efficiency between 0yrs and 5yrs.
    - assumes long (~120s) exposure times, consistent with spec observations. During long exposures, dark current helps to fill traps, reducing their effect.
  - The relative reduction in QE would be larger when shorter exposures are used (ie: in speckle-limited imaging mode). But in this case, detector noise and traps are not the limiting factor.
  - Dark current could increase by ~3x over 5yr. (still <5 e-/px/hr)

For more details, see Patrick Morrissey's 2019 SPIE presentation: https://www.spiedigitallibrary.org/conference-proceedings-of-spie/11117/111170J/Flight-photon-counting-EMCCDs-for-the-WFIRST-coronagraph-Conference-Presentation/10.1117/12.2529758.full

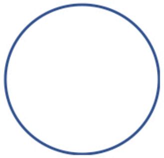
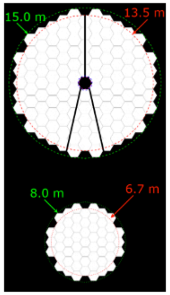
L1 Requirements Demonstration – Operations Optimization





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

CGI vs FMs (1)

Top Level Characteristics	CGI (CBEs)	CGI (Design Specifications)	HabEx Requirements	LUVOIR A/B Requirements
IWA (in lambda/D)	3 (HLC at 575 nm; SPC at 730 nm)	4 (HLC at 575 nm; SPC at 730 nm)	3.1 (at 500 nm)	3.5 (at 500 nm)
Flux Ratio Detection Limit at IWA	10-8 (10σ)	5 x 10^-8 (10σ)	10^-10 (10σ)	10^-10 (10σ)
Spectral Bandwidth	10% (HLC) - 15% (SPC)	10% (HLC) - 15% (SPC)	20%	20%
Spectral Resolution	50 (SPC)	50 (SPC)	70	140 (VIS IFS); 70 (NIR IFS); 200 (NIR Single Point Source)
Multiplanet Spectroscopy Capability	No	No	Yes	Yes
Polarimetric Capability	Yes, 4 linear states, 2 at a time	Yes	Yes	Yes
Entrance Pupil				
Aperture type	on axis 2.4m monolith with 6 struts	on axis 2.4m monolith with 6 struts	off-axis 4m monolith	A: on-axis segmented with 13.5 m inscribed diameter; B: off-axis segmented with 6.7 m inscribed diameter
Relative central Obscuration (linear in %)	28%	28%	0	A: 8% ; B: 0
F/#	1.3	1.3	2.5	A: 1.3; B: 2.73

CGI vs FMs (2)

Lower Level Characteristics	CGI (CBEs)	CGI (Design Specifications)	HabEx Requirements	LUVOIR Requirements
Wavefront Sensing and Control			Assumes VVC6	LUVOIR A: APLC; LUVOIR B: VVC6
Low Order Wavefront Sensing and Control	Yes (up to Z11)	Yes (up to Z11)	Yes	Yes
Pointing jitter after correction (mas rms per axis)	0.35 for V=5 (0.2 for V<3)	< 0.5 (HLC) ; < 2 (SPC)	< 0.3	< 0.3
Residual Defocus (pm of Z4) drift after correction	3 (temporal rms from OS9)	< 15 (HLC) ; < 88 (SPC)	< 1315	A: < 130, B: ?
Residual Astigmatism (pm of Z5 & Z6) drift after correction	3 temporal rms from OS9)	< 47 (HLC) ; < 223 (SPC)	< 157	A: < 200, B: ?
Residual Coma (pm of Z7 & Z8) drift after correction	2 (temporal rms from OS9)	< 4 (HLC) ; < 29 (SPC)	< 94	A: < 10, B: ?
Residual Trefoil (pm of Z9 & Z10) drift after correction	2 (temporal rms from OS9)	< 13 (HLC) ; < 112 (SPC)	< ?	A: < 20, B: ?
Residual Spherical (pm of Z11) drift after correction	2 (temporal rms from OS9)	< 2 (HLC) ; < 11 (SPC)	< 76	A: < 10, B: ?
Higher order wavefront drift in pm after any correction (weighted rss sum above Z11 over science exposure)	5 (temporal rms from OS9)	< 50	< 5	< 5
Laser Metrology	No	No	Yes (M1-M2-M3)	Yes (6 per M1 segments (?)-M2-M3)
Deformable Mirrors (DM)				
Number of actuators	48 x 48	48 x 48	64 x 64	A: 128 x 128, B: 64 x 64
Number of DMs per coronagraph channel	2	2	2	2
DM stroke range (µm)	> 0.5	> 0.5	> 0.5	> 0.5
DM stroke resolution (pm)	7.5	< 15	2.5	1.9
DM2 lateral displacement relative to DM1 (x,y) in nm	?	< 100	?	?
Low Flux Detection				
Photon counting	Y	Y	Y	Y
Detected point source flux (e-/s) per PSF core for broad-band imaging	0.14 (HLC around 575 nm)	0.14 (HLC around 575 nm)	0.01	0.06 (A)
Detected point source flux (e-/s) per PSF core and spectral bin for spectroscopy	0.027 (SPC around 730 nm)	0.027 (SPC around 730 nm)	0.0004	0.0008 (A)
Detector Format	1024 x 1024 (imaging and spectroscopy)	1024 x 1024 (imaging and spectroscopy)	1024 x 1024 (imaging); 2048 x 2048 (IFS)	1024 x 1024 (imaging); 4096 x 4096 (IFS)
dQE at 550nm	0.50	> 0.47	> 0.56	0.72 (CBE)
Read-out-noise (amplified read noise divided by gain in e- rms/ pix /read)	0.015	< 0.02	< 0.1	0 (CBE)
Dark Current (e-/pix/s)	1.3x 10-4	< 5.2 x 10-4	< 4 x 10-4 (CBE: 3 x 10-5)	3 x 10-5 (CBE)
Clock-induced Charge (e-/pix/read)	5.00E-03	< 0.01	< 6 x 10-2 (CBE: 1.3 x 10-3)	1.3 x 10-3 (CBE)
Lifetime at specified detector parameters	5 years	> 21 months	> 5 years	> 5 years
Opto-Mechanical Alignments				
Precision Mechanisms: focal or pupil plane masks positioning accuracy (µm)	Derek ?	< 2		LUVOIR A: Remi
Precision Mechanisms: pupil plane masks clocking accuracy (arcsec)	N/A	N/A		
Pupil clocking error (coronagraph FSM vs telescope, in mrad)	AJ	< 4 mrad	N/A	LUVOIR A: Remi
Pupil Magnification error a coronagraph level	1.25%, AJ	< 1.5%, AJ	N/A	LUVOIR A: Remi

Science Summary Slides

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Potential CGI Exoplanet Science Contribution

Question	WFIRST can	During Tech. Demo Phase	Additional Science Phase (may not do all cases)
What are the cloud properties of young massive planets? How inflated are these planets?	Fill out SEDs with photometry and spectroscopy at ≥600nm	1-2 test cases	Additional filters and/or more known planets
Are cold Jupiter analogs cloudy or clear?	Measure albedo at short wavelengths	1-2 planets	Additional filters and/or up to ~10 more planets
Are Jupiter analogs metal rich?	Distinguish 5x vs 30x Solar CH_4	1 planet * 730nm spec. only	+1 planet *OR* improve 1st planet w/ 660nm spec or better SNR in 730 spec.
Are there Neptune-like planets orbiting nearby stars?	Survey nearby systems, informed by Gaia & RV	No	5-10 best systems

** Clear atmosphere planets may be too dim for spectroscopy*

Potential CGI Disk Science Contributions

Question	WFIRST can	During Tech. Demo Phase	Additional Science Phase (may not do all cases)
Where does circumstellar material come from and how is it transported?	Map morphology of disks in the transport dominated density regime.	2-3 disks	Additional disks with a variety of properties
What is the composition of planetary dust in the inner regions of debris disks?	Map color, degree of forward scattering, and the degree of polarization.	1-2 disks	Additional disks with a variety of properties
How bright is exozodiacal dust in scattered light? Will it affect exo-Earth detection with future missions?	Probe low surface density disks in habitable zone of nearby stars	Opportunistic (as part of known exoplanet observation)	Survey best 25-50 potential exo-Earth targets for future missions
What are the accretion properties of low-mass planets in formation?	Measure H-alpha at high contrast	0 – 1 test observations	Observe transition disks with gaps in CGI FOV

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Science Yield vs Instrument Performance

	10^{-9}	*$3x\ 10^{-9}$*	*10^{-8}*	*10^{-7}*
Jupiter analog spectra	Some	A few	No	No
Jupiter analog Images	Yes	Yes	Possibly	No
Young GP optical spectra	Yes	Yes	Yes	Few
Young GP optical images	Yes	Yes	Yes	Some
Exo-Zodi Disks optical images	~2 zodi	~5 zodi	~15 zodi	~100 zodi

Exoplanet backups

Today

≥ 1 um

Self-luminous, hot, super-Jupiters

WFIRST/CGI

550 – 880 nm

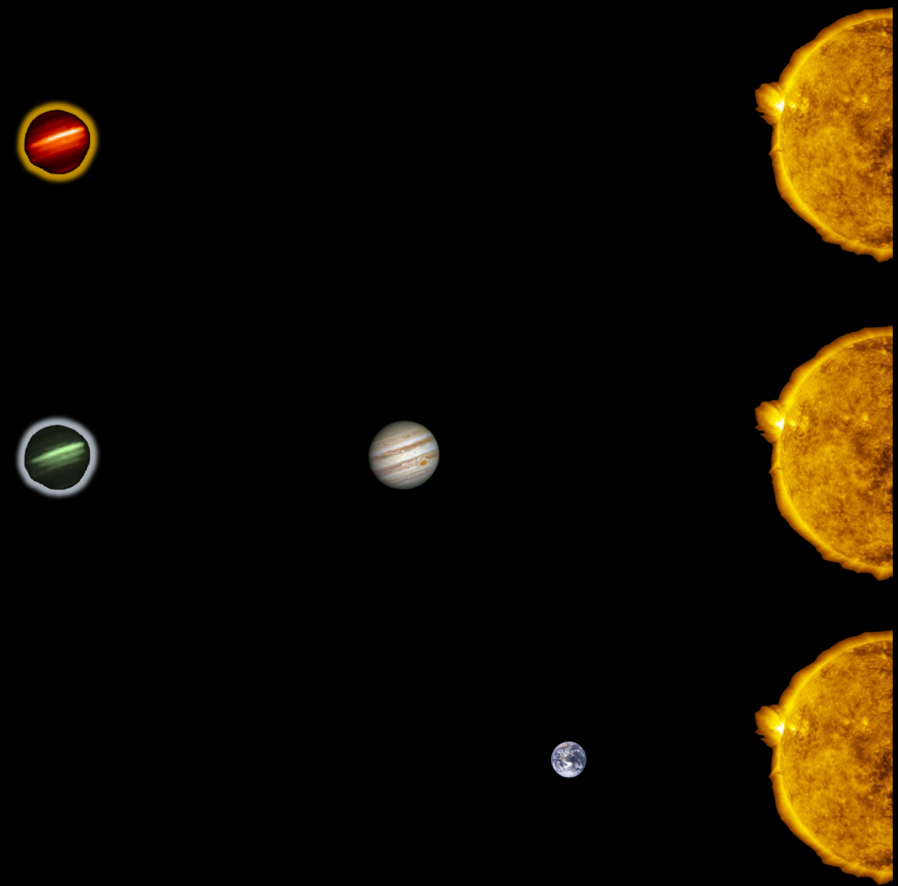
Reflected light Jupiter analogs

Self-luminous planets in visible light

Future Missions

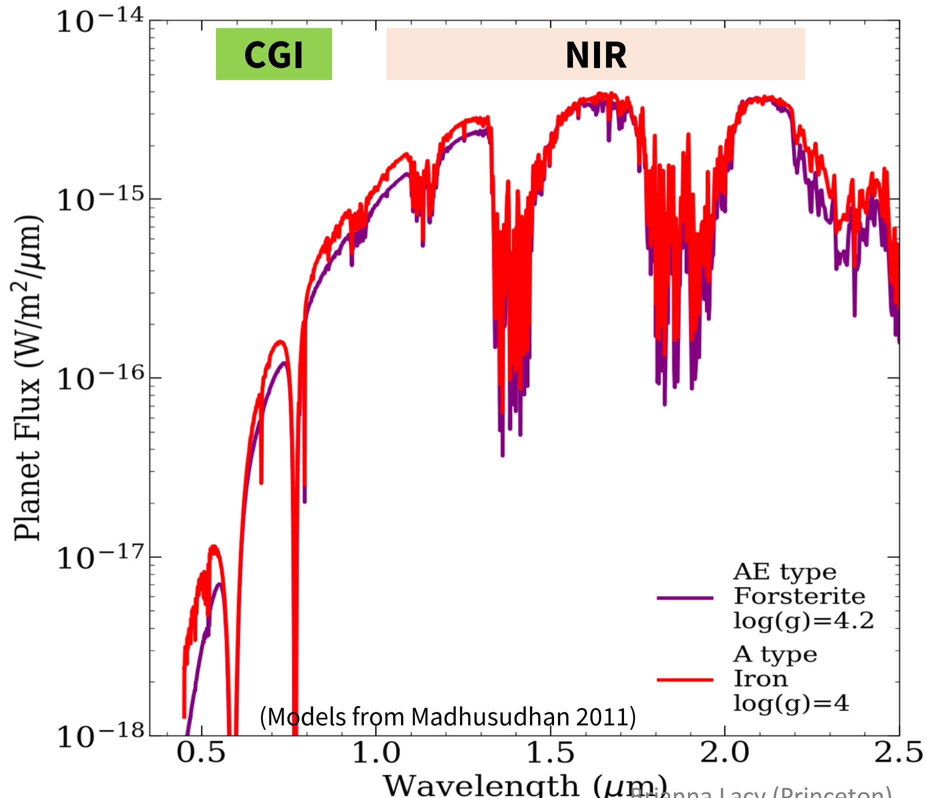
0.3 – 1 um

Earth-like, potentially habitable, planets



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



Brianna Lacy (Princeton)

A = Clouds extending all through the entire atmosphere with particle number density scaling with gas
AE = Clouds have scale height 1/2 of the gas, so still extend up into atmosphere, but not as much as A type

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First reflected light images of a mature Jupiter analog

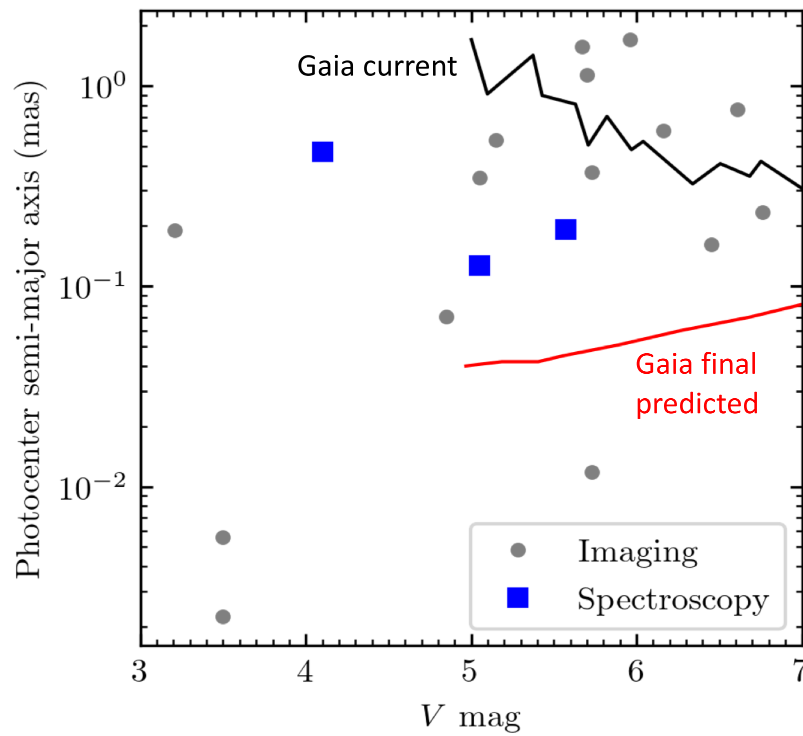
Rob De Rosa (Stanford)
Julien Girard (STScI)
Stephen Kane (UCR)
Eric Nielsen (Stanford)
Maggie Turnbull (SETI)
Neil Zimmerman (GSFC)
…

- limited observing time

  ⇒ target known RV Jupiter analogs

- **Q**: What is the mass of the planet?
- **CGI can**:
  - constrain inclination with 2-3 imaging epochs
  - combine with Gaia for better constraints

Astrometric signal for CGI RV targets



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 planets
- **Beyond TDP:** Additional narrowbands and/or survey more known planets

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

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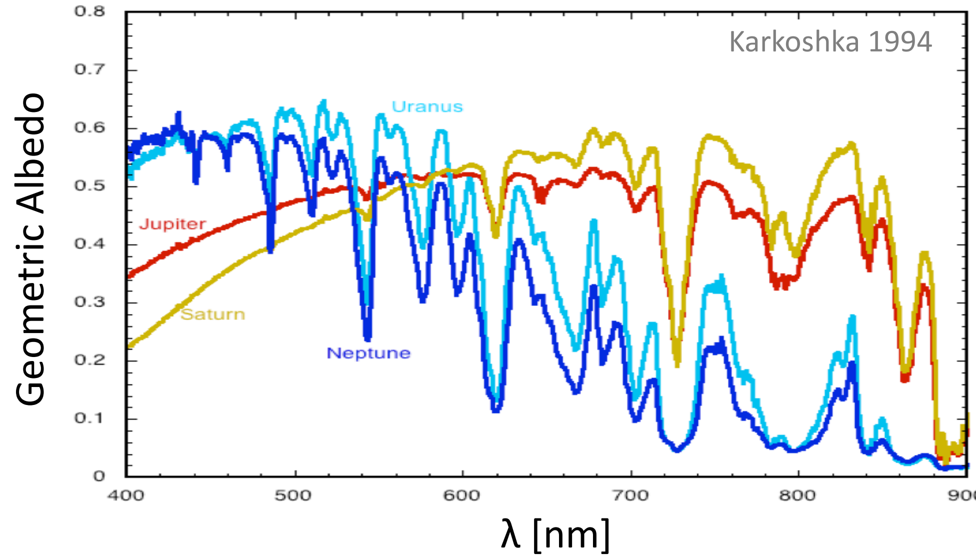
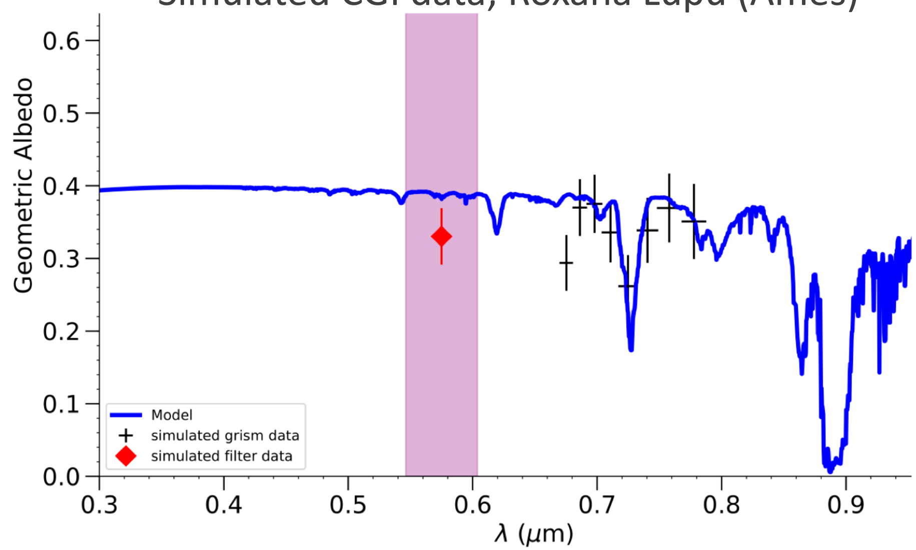
Characterization of a mature Jupiter analog

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



Simulated CGI data; Roxana Lupu (Ames)



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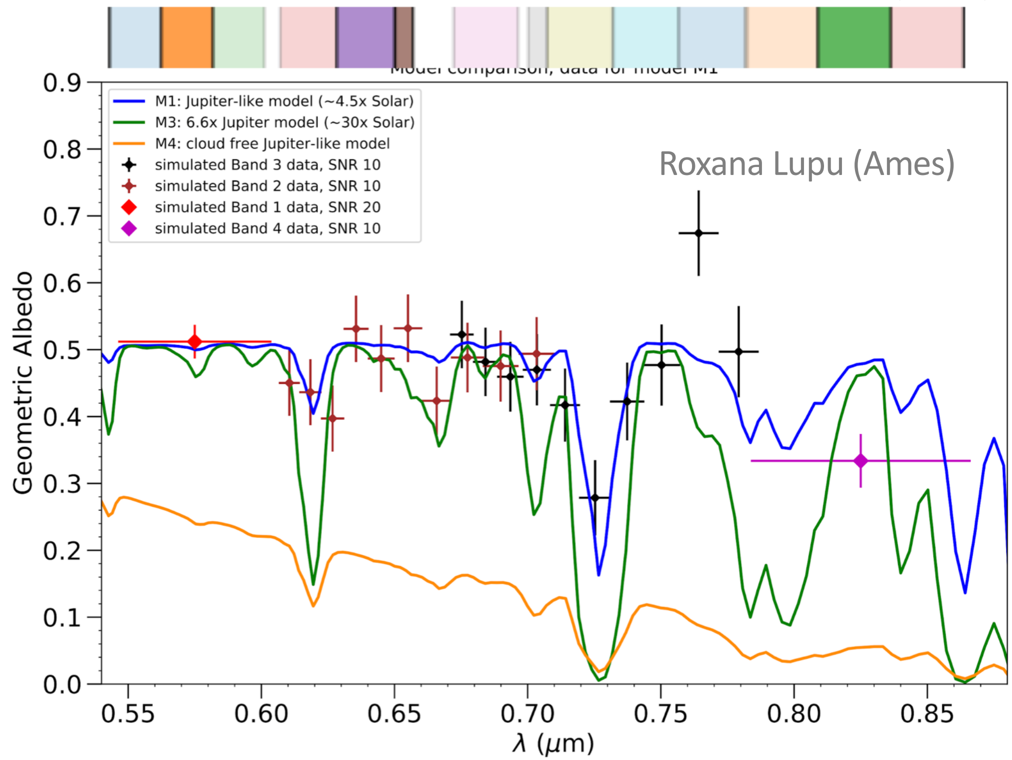
Characterization of a mature Jupiter analog

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
- **Beyond TDP**:
  - +1 planet
  - *OR* improve SNR of 1st planet
  - *OR* obtain narrowband photometry or 660nm spectroscopy of 1st planet.

Natasha Batalha (UCSC)



Caveat! 660nm spectroscopy and 825nm narrow field imaging are NOT officially supported observing modes

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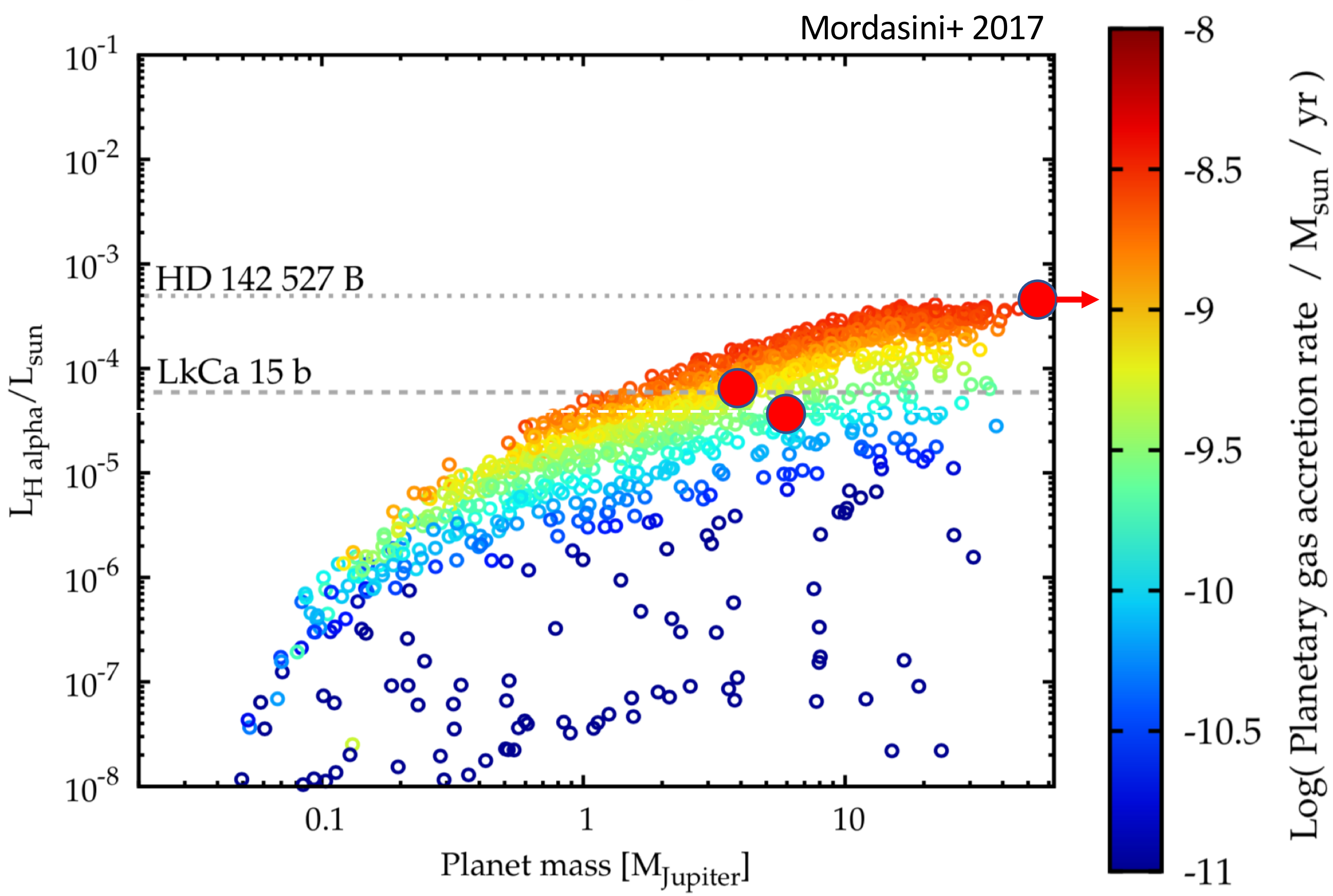
H-alpha Imaging of Protoplanets

High-contrast H-alpha measurements will test these predicted core accretion luminosities.



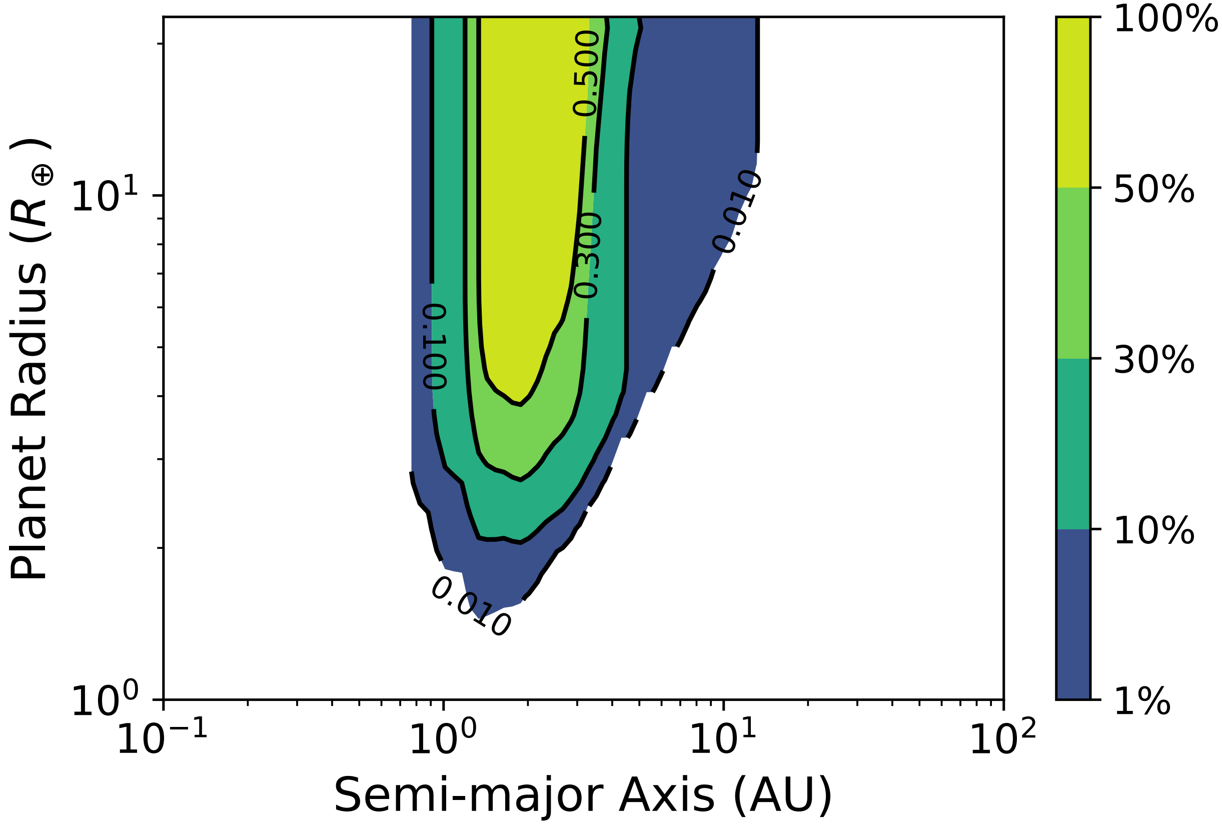
Beyond TDP: Search for small planets

Dmitry Savransky (Cornell)

CGI completeness for 10 best targets

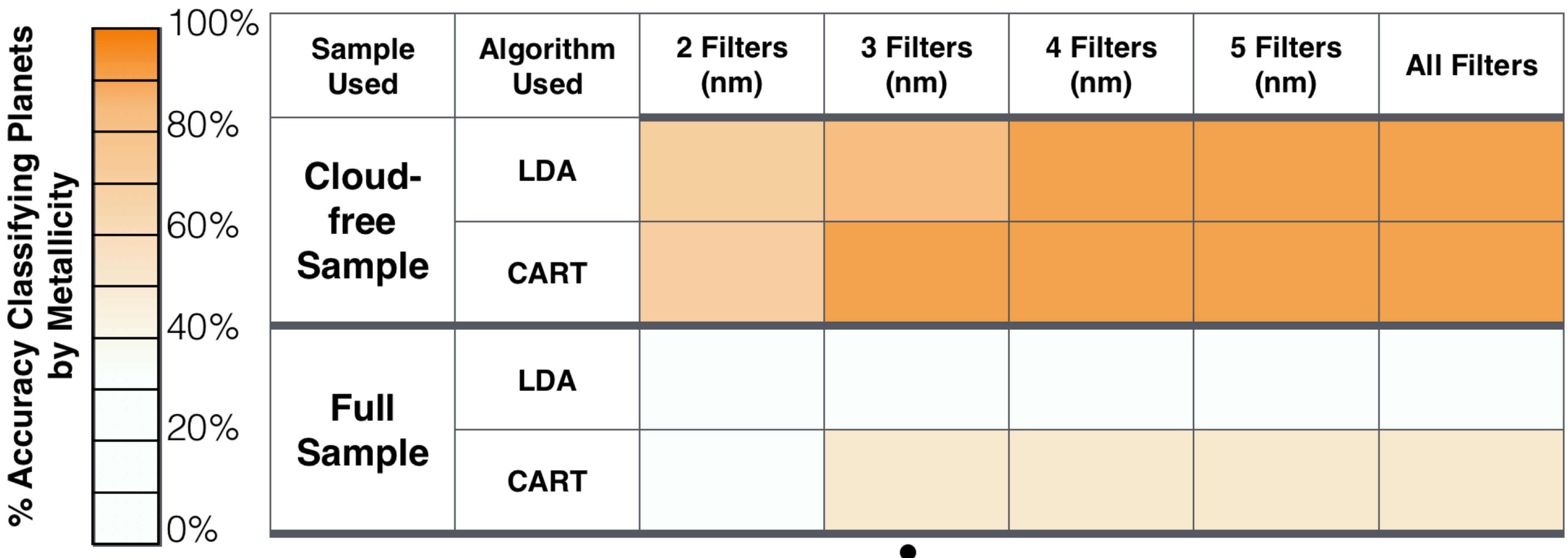
- ~100hr imaging per target

Informed by Gaia and RV limits



Beyond TDP: Multi-band photometric survey of reflected light planets. **Metallicity?**

Natasha Batalha (UCSC)



Addition of 3rd filter gives largest gain in success rate for classification

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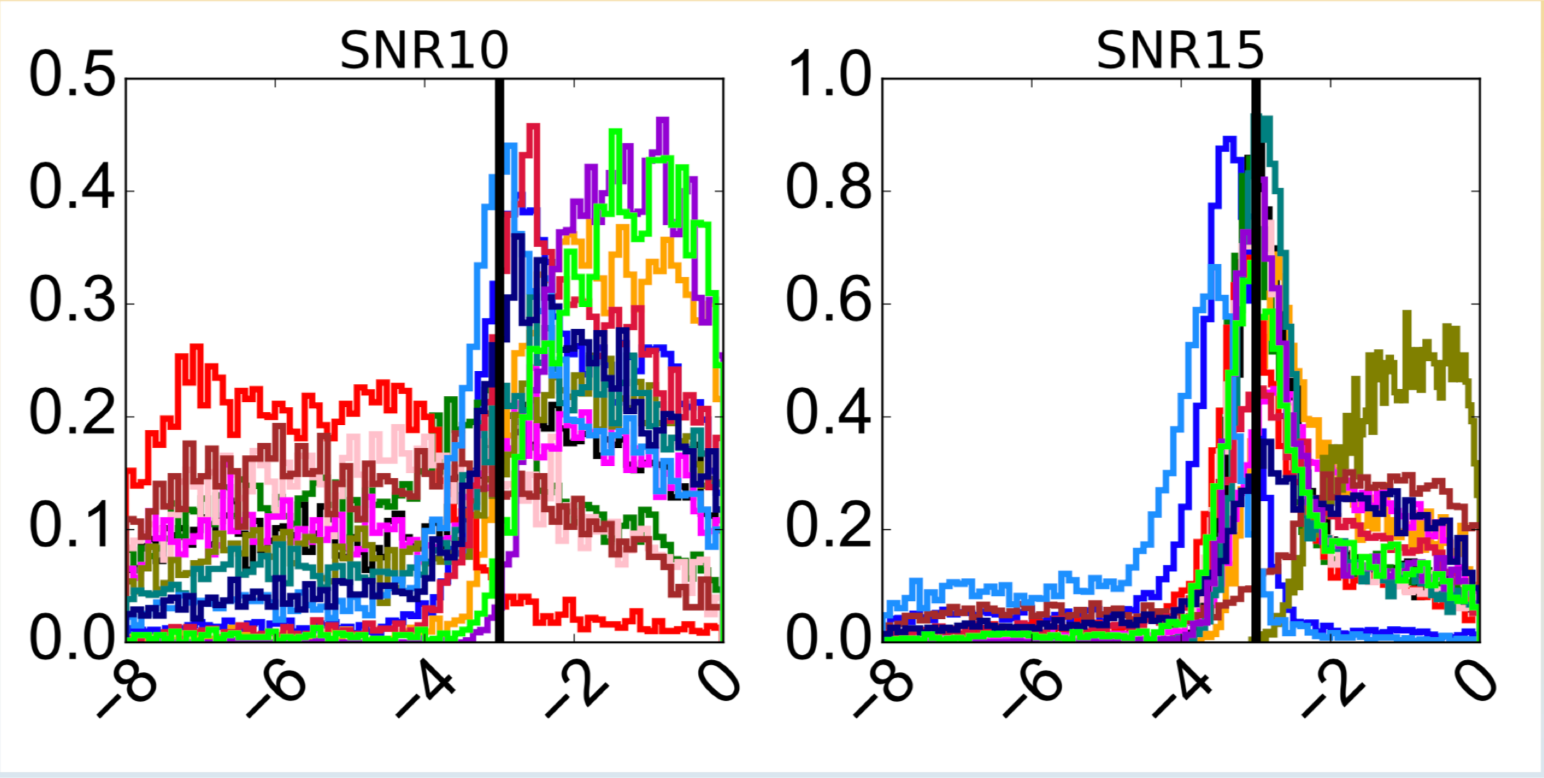
Beyond TDP: improve SNR of reflected light planet spectrum for CH_4 abundance

Roxana Lupu (Ames)

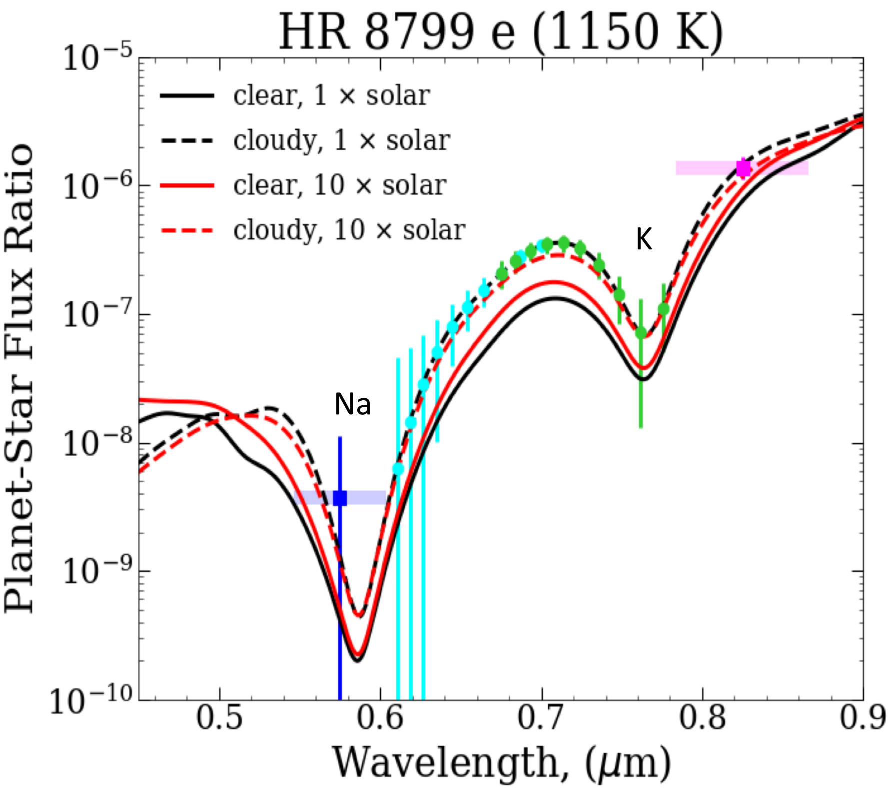
Additional 500-1000hr



Beyond TDP: Na and K in self-luminous planets

Brianna Lacy

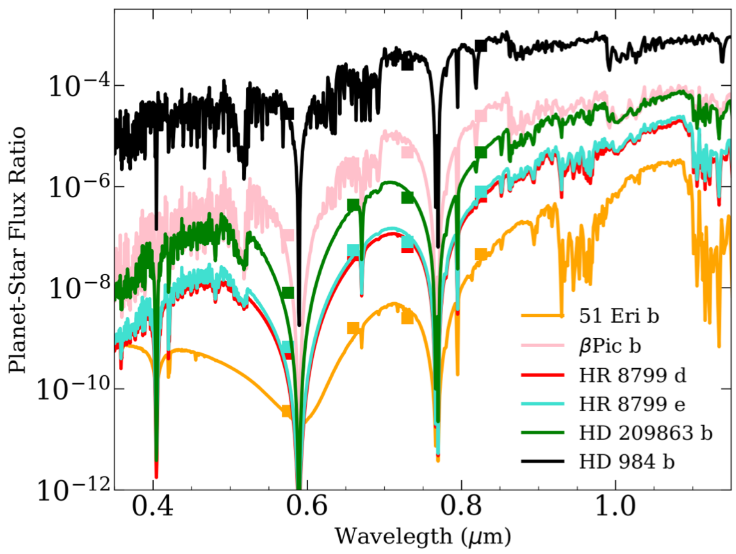
- Detect Na and K
- combine with NIR to help constrain:
  - the species, spatial extent, and particles sizes of condensates
  - the planet's effective temperature, surface gravity, and radius
  - the atmospheric metallicity



Self-luminous planet flux ratio in CGI bandpasses

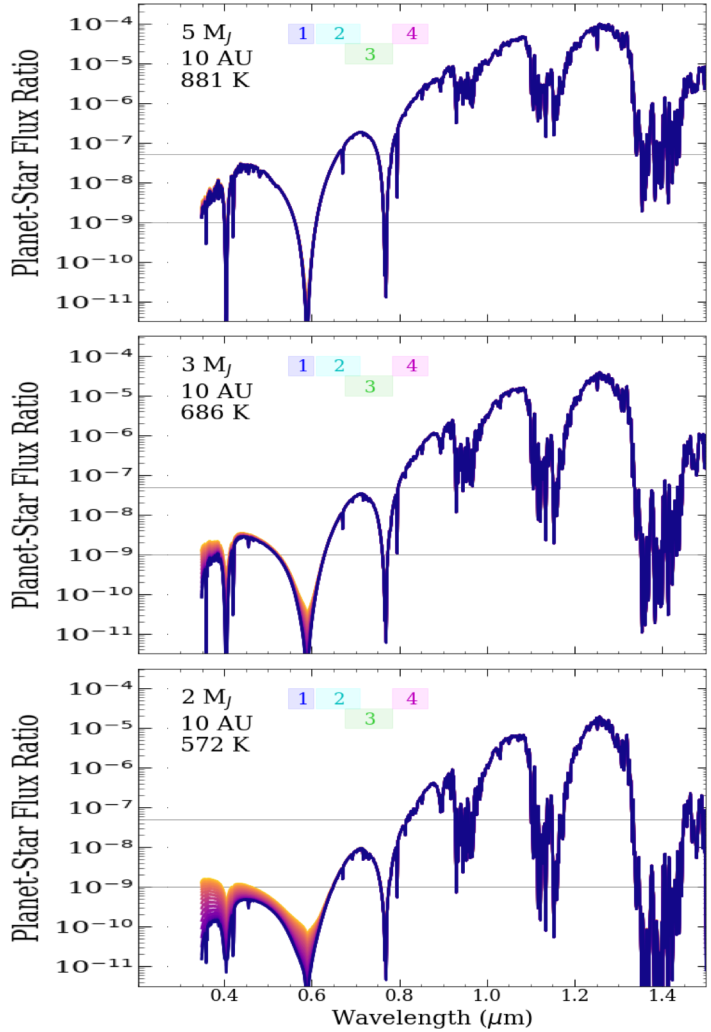
Brianna Lacy (Princeton)

Object	Band 1	Band 2	Band 3	Band 4
51 Eri b	3.7E-11	1.6E-09	2.5E-09	4.6E-08
*Beta Pic b	1.1E-07	2.9E-06	4.7E-06	2.5E-05
HR 8799 d	5E-10	4.4E-08	6.4E-08	6.3E-07
HR 8799 e (cloudy)	6.8E-10 (2.7E-09)	5.6E-08 (1.6E-07)	8.1E-08 (2.1E-07)	7.9E-07 (1.4E-06)
HD 206893	7.9E-9	4.4E-07	6.1E-07	4.7E-06
HD 984 b	2.7E-05	1.4E-04	2.6E-04	6.1E-04



Brianna Lacy (Princeton)

Reflected light is negligible for self-luminous planets



Larger mass + Warmer

Lower mass + Cooler

Colors in the plot indicate phase angle.

CGI-Gaia synergies

Rob De Rosa (Stanford)

- CGI-Gaia synergies:
  - Prior to launch:
    - Constraints on inclination -> better constraint on mass (i.e. differentiate planet/BD) to refine target selection for reference mission.
  - During demonstration phase:
    - Help reduce inclination degeneracy with a single epoch of CGI relative astrometry to further constrain mass. Most useful for observations near line of nodes where single CGI epoch tells you nothing about inclination (see work by Eric Nielsen).
  - Potential GO program:
    - Identify promising blind search targets based on astrometric signature of massive orbiting companion (joint RV+astrometry constraints on mass/sma of companion).

Gaia constraints on CGI targets

Neil Zimmerman (GSFC)
Rob De Rosa (Stanford/ESO)

- Most CGI known-RV planet targets have expected astrometric amplitudes (semi-major axis) of 200 microarcsec (μas), with several as greater than 500 μas
  - Easily detectable with Gaia's predicted snapshot precision of 50--80 μas for V=5--7 stars.
- CGI's formal requirements are for V<5 stars, but Gaia's final capabilities on V<5 stars are not yet well understood.
  - There have been efforts to develop specific data processing strategies for recovering the photocenters of bright stars (Sahlmann, et al, 2016); however the implementation of such methods in the final Gaia data release is not guaranteed.
  - CGI's technology demonstration would greatly benefit from stronger collaboration with the Gaia Data Processing and Analysis Consortium's (DPAC) in this area.

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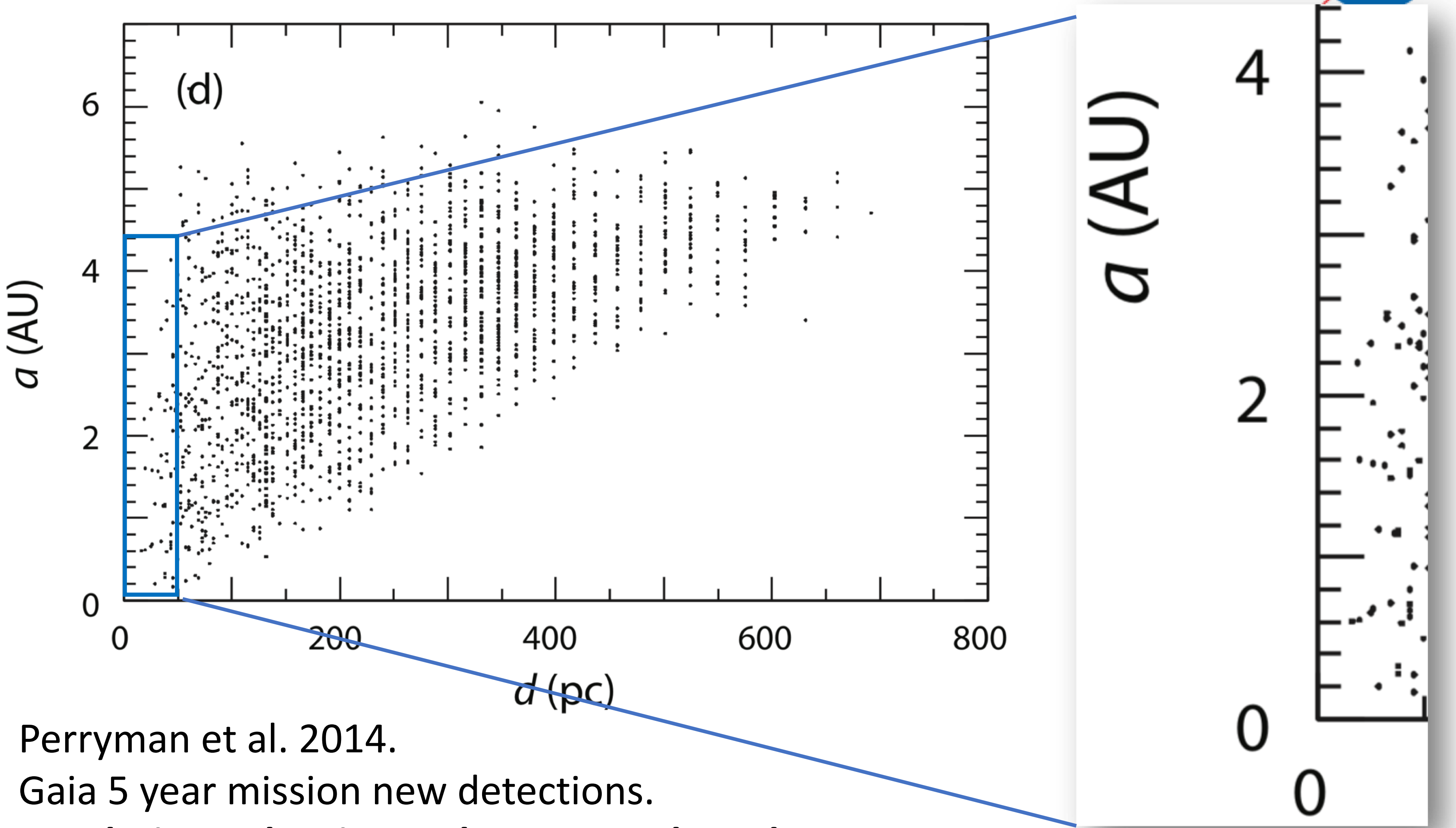

Perryman et al. 2014.

Gaia 5 year mission new detections.

For clarity, only 1 in 10 planets are plotted.

RV precursors aid exoplanet target selection

Stephen Kane (UCR)

- RV precursor work needed to:
  - Refine ephemerides for CGI RV planets
    - Needs: 1-2 nights per year for next several years
  - Survey nearby stars discover more RV planets
    - Would need: ~2 weeks on NEID per year until launch
    - Also aids future missions
- Automated Planet Finder now underway
- Potential NASA resources:
  - Keck, NEID time & Key Projects
  - southern facilities (MINERVA, CHIRON)

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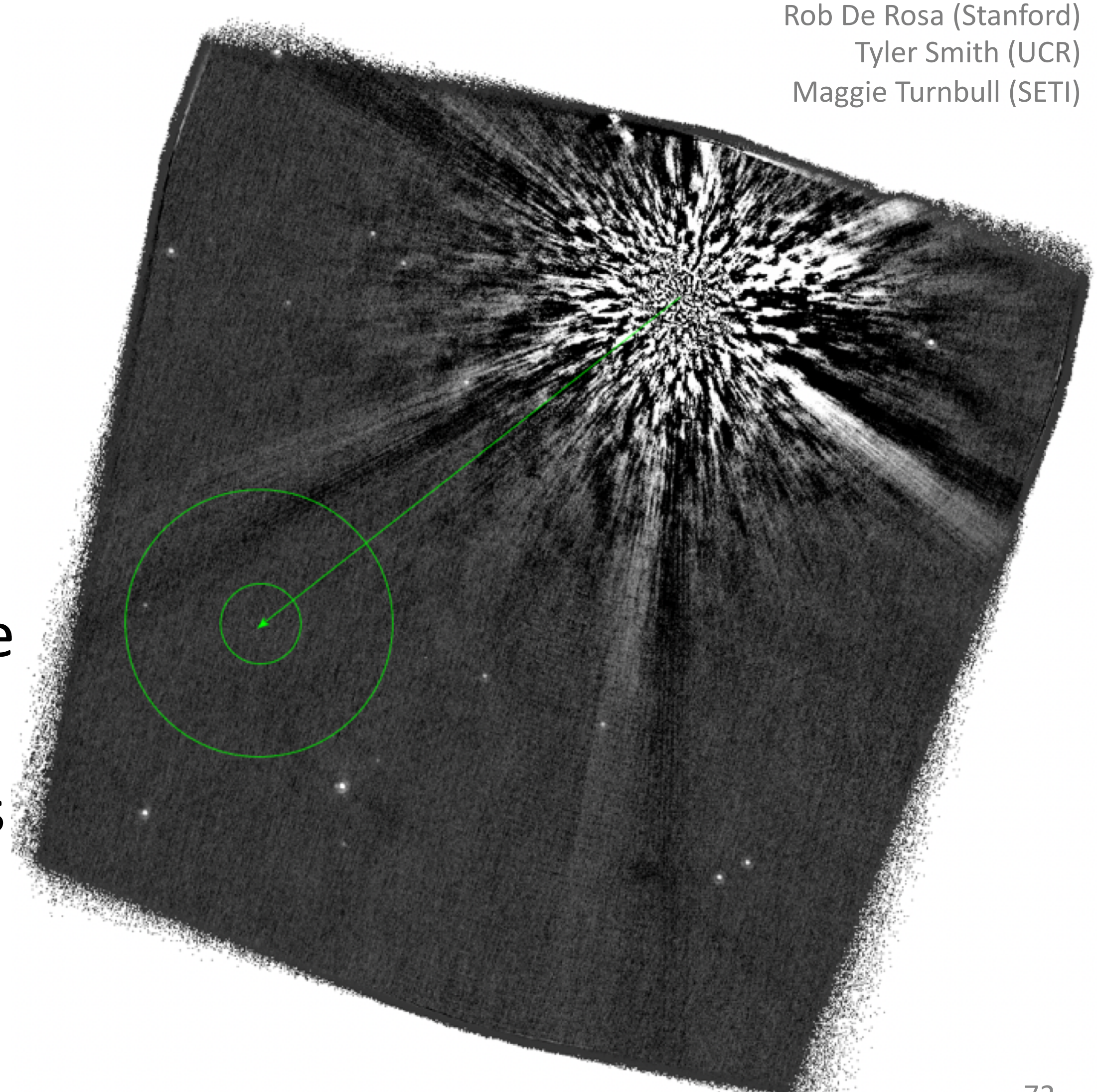
Imaging precursors aid exoplanet target selection

Vanessa Bailey (JPL)
Misty Craycraft (STScI)
Rob De Rosa (Stanford)
Tyler Smith (UCR)
Maggie Turnbull (SETI)

- CGI target stars near the Galactic Plane could be contaminated by background stars
- Keck/NIRC2 precursor imaging of high-priority, high-proper motion CGI targets is mostly complete
- Required future work: survey CGI reference stars for binary companions

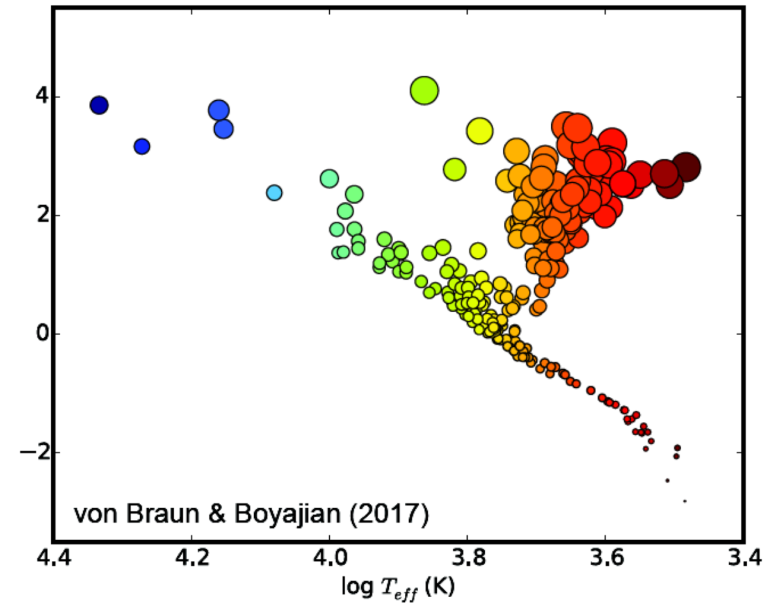


Ground-based optical interferometry to measure fundamental stellar parameters of CGI targets

Neil Zimmerman

- Georgia State University's CHARA Array has measured the precise radii of numerous exoplanet host stars, including ~1/3 of the 20 best CGI targets.

- An observing campaign to complete such measurements on all top-priority targets would add value to CGI in two ways:
  - For RV planet targets, the uncertainty in the mass of the star can be a significant contribution to the error in the semi-major axis of the planet's orbit. An independent estimate of the stellar mass can refine the global fit of the orbit parameters (e.g., von Braun, et al. 2012) and thereby assist in predicting the observability as a function of time.
  - If CGI acquires reflected-light photometry and spectroscopy of a planet, more precise knowledge of the stellar radiation incident on the planet and of the system age can inform atmosphere modeling efforts, and the retrieval of specific parameters such as CH4 abundance (Batalha, et al., 2019).



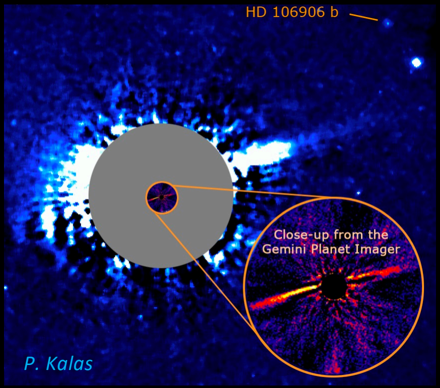
Empirical H-R diagram constructed using direct measurements of stellar radii (von Braun & Boyajian, 2017).

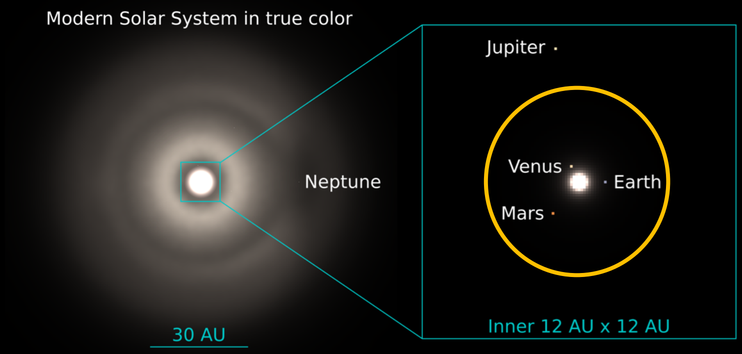
Disk backups

Environment Matters

- Protoplanetary & Transition disks
  - Newly-forming planetary systems
- Debris disks
  - Remains of planet formation
  - Colliding or evaporating minor planetary bodies
- Exozodi disks
  - Can potentially shroud planets from observations

ESO/A. Müller et al.



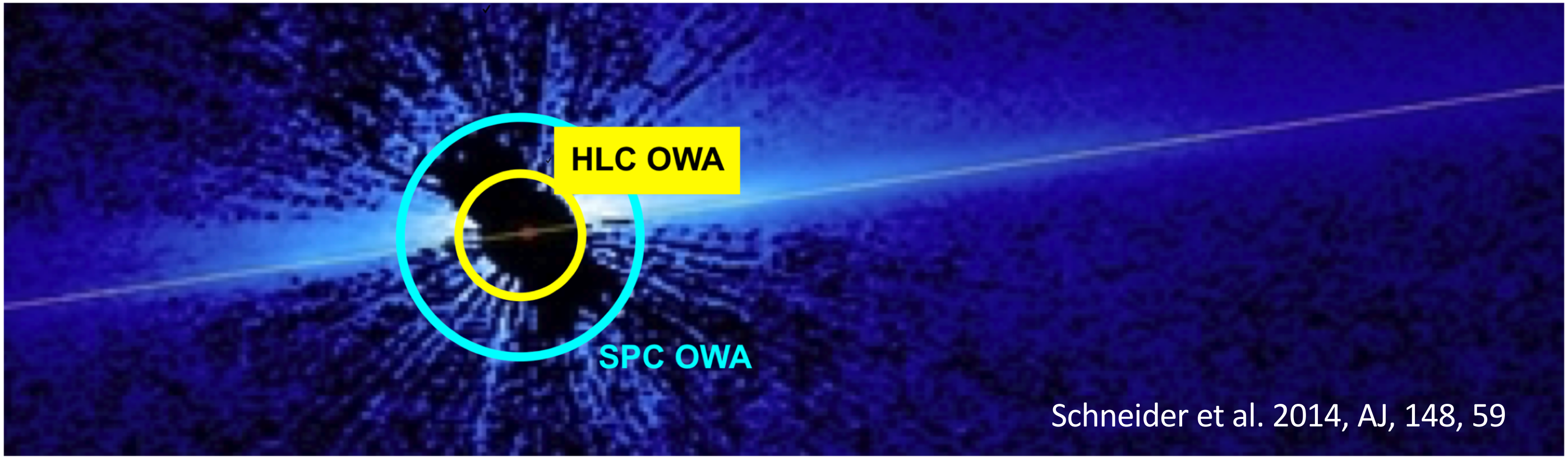


Credit: A. Roberge & the Haystacks team

Known Cold Debris Disks

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

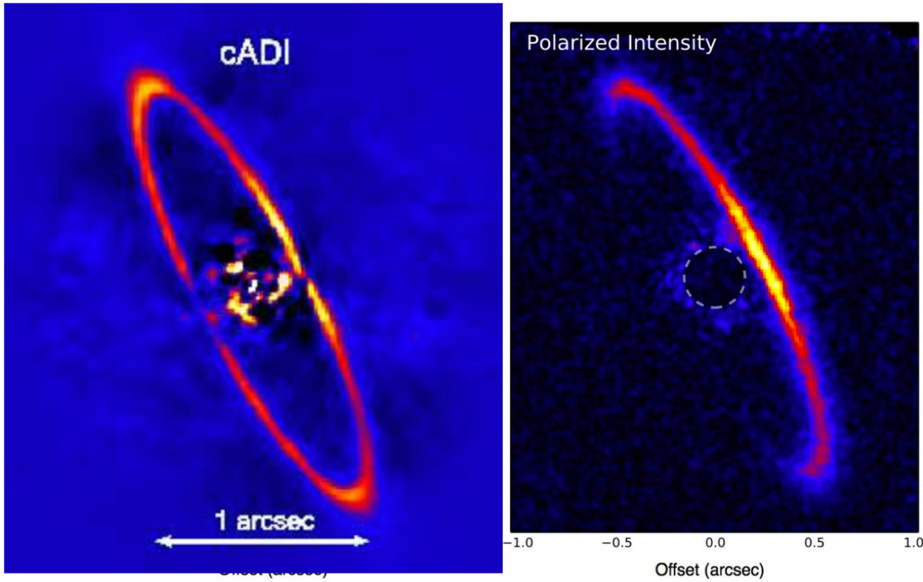
- **Q**: Where does circumstellar material come from and how is it transported?
- **CGI can**: Map morphology and scattered light flux of faint disks at smaller working angles than HST
- **During TDP:** 2-3 disks
- **Beyond TDP**: Additional disks with a variety of properties



Known Cold Debris Disks

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

- **Q**: What is the composition of planetary dust in the inner regions of debris disks?
- **CGI can:** Map color, degree of forward scattering, and the degree of polarization.
- **During TDP:** 1-2 disks
- **Beyond TDP:** Additional disks with a variety of properties



Perrin+2015
Milli+2017

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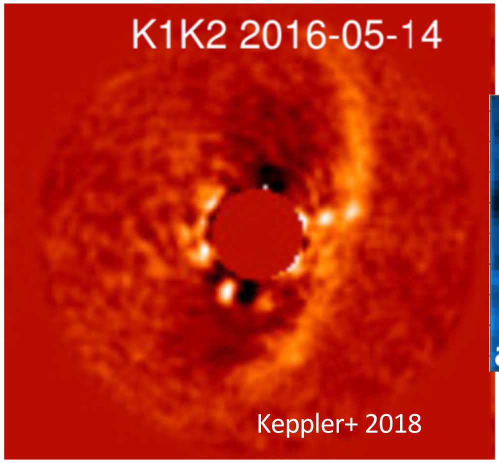
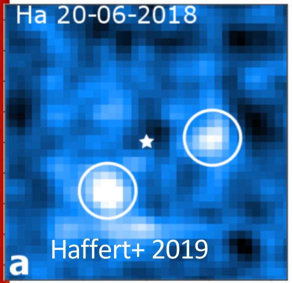
Protoplanetary systems

Kate Follette (Amherst)
Ewan Douglas (UofAZ)

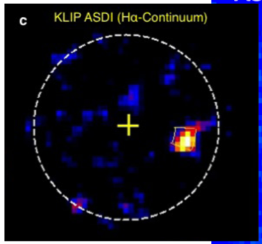
- **Q:** What are the accretion properties of low-mass planets in formation? How can we distinguish protoplanets vs. disk structures?
- **CGI Can**: Measure H-alpha at high contrast
  - Caveat: CGI will not achieve optimal performance on faint host stars. Performance modeling TBD.
- **During TDP:** *Perhaps* a test observation
- **Beyond TDP**: Observe transition disks with gaps in CGI FOV



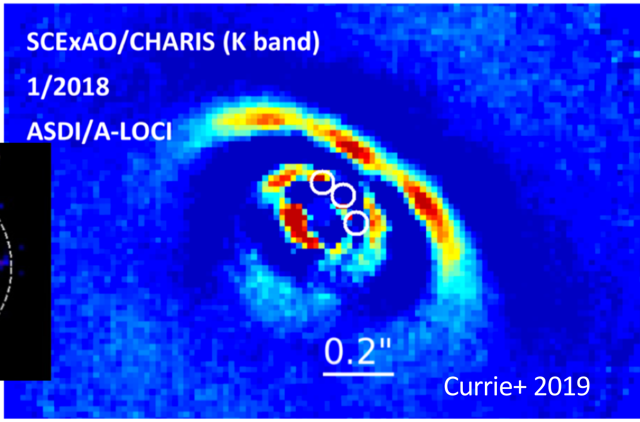
Keppler+ 2018



Haffert+ 2019



Sallum+ 2015



Currie+ 2019

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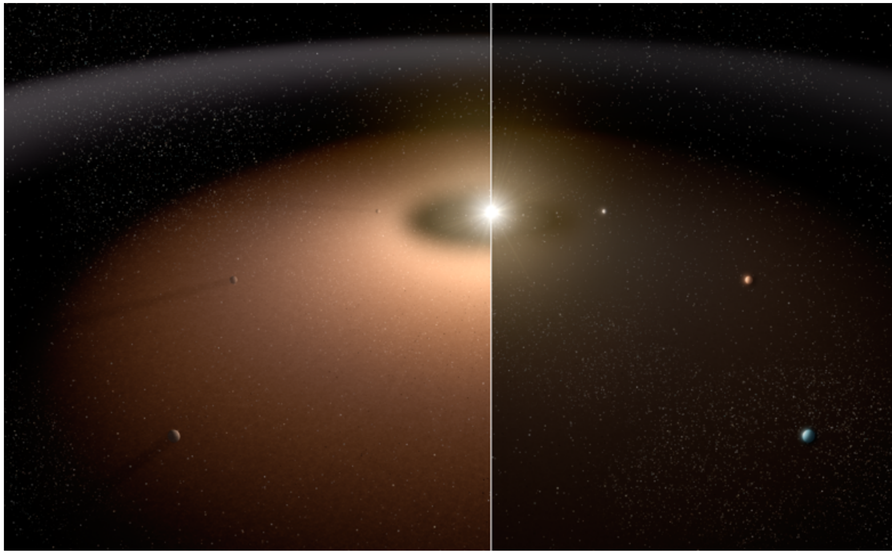
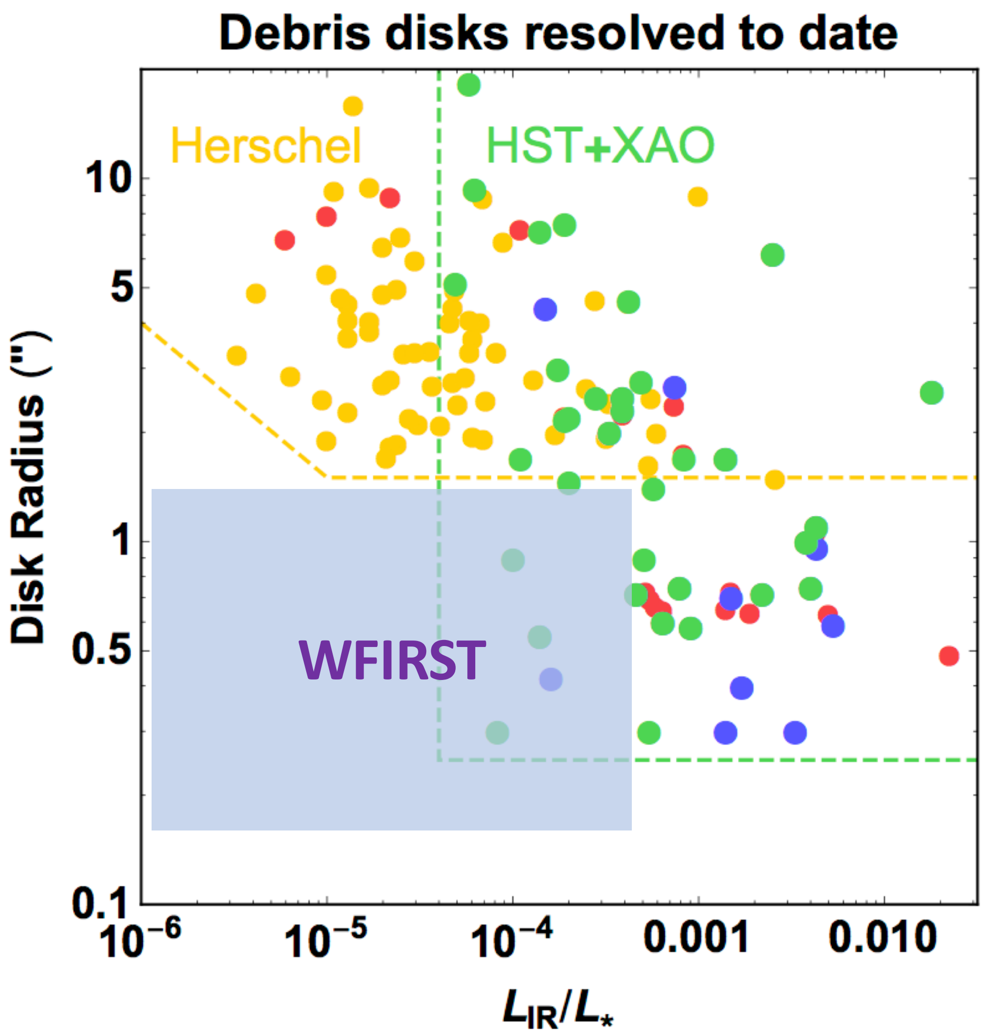
First visible light images of exozodiacal dust

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

- **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
- **During TDP:** *Opportunistic*, as part of exoplanet observations
- **Beyond TDP**: Survey best 25-50 potential exo-Earth targets for future missions



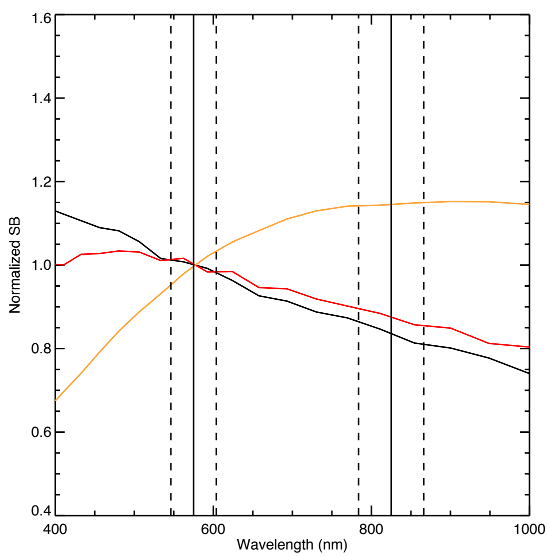


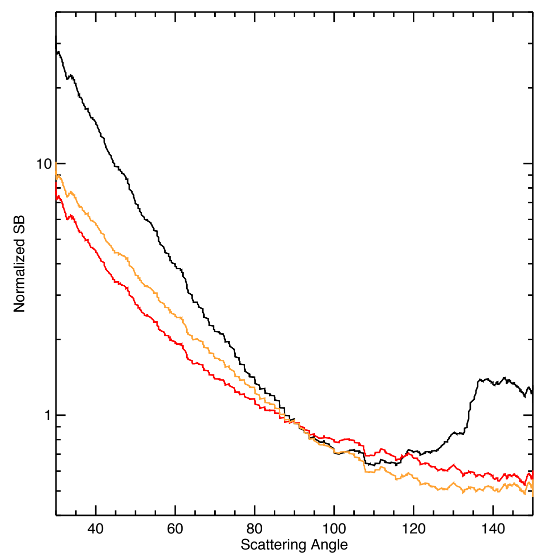
Debes et al. 2019, BAAS, 51, 566

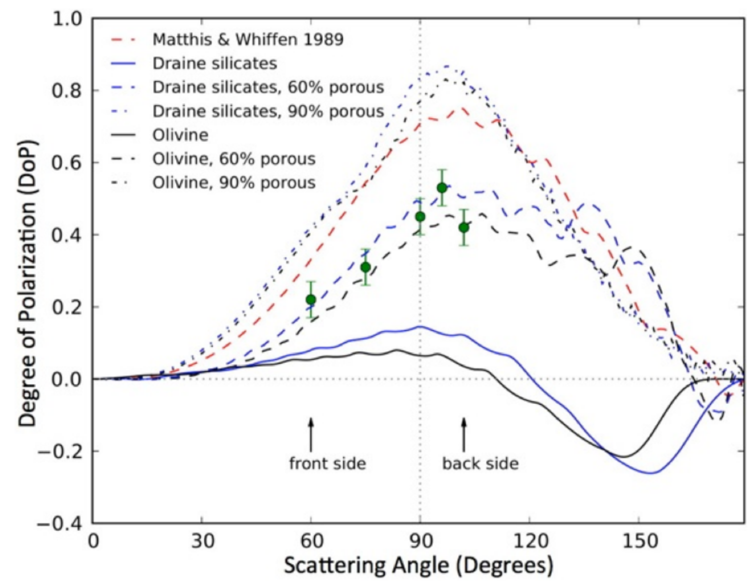
Dust Composition

- Combination of scattering efficiency, forward scattering, and polarization fraction (DOP) can constrain compositions

Water ice, organics, silicates







Testbed Objectives through CGI Lifecycle

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Now

Stage I

- CGI model validation
- Mitigation of top CGI risks approved by the project.

2/2021 Begin of delivery of EDUs

Stage II

- Verify CGI operation using EDUs, FPGAs and flight software (Risk #62)
- Dry run CGI TVAC test operation. Also test CVS.

8/2022 Begin of CGI TVAC test

Stage III

- Continue debugging late software, firmware issues
- Resolve performance issues identified during II&T. Root cause analysis on PFRs.
- **Prepare/check TVAC2 procedures while CGI is going through TVAC1**

8/2023 CGI Delivery to GSFC

Stage IV

- Model validation in support of closing L2 MRD (Mission Req. Doc.) requirements
- Troubleshooting payload AI&T issues (e.g. pupil alignment)

- Late FSW patches/ Closing late PFRs
- **Dry run in-orbit commissioning procedures**
- **Work with IPAC to generate data for their pipeline.**
- Train new flight operators, if needed

8/2025 WFIRST Launch

Stage V

- Validating command sequences
- Troubleshooting performance issues that emerge during CGI commissioning and tech demo
- **Validating new algorithms and other FSW updates**

- **Acronyms**
- CVS: CGI Verification Stimulus (GSE unit for OTA simulator during CGI test)
- PFR: Problem Fault Report
- FSW: Flight Software

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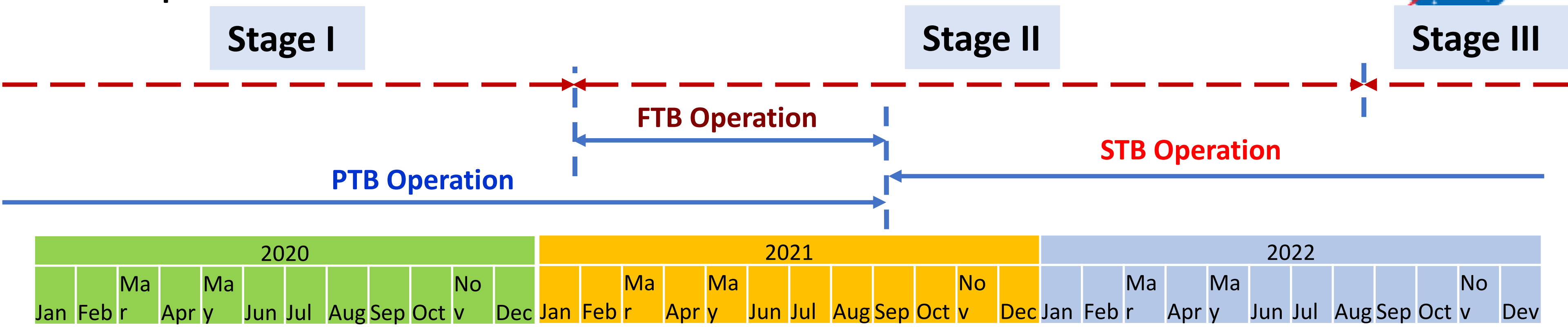
CGI Testbeds



- **Performance Testbed (PTB)**
  - The testbed since 2016. (Other names of OMC, MCB, and Technology Testbed)
  - Has no EDUs but the flight-like optical layouts, masks, and mechanisms.
  - Used for coronagraphic performance & model validation
- **Functional Testbed (FTB):**
  - Populated with available EDUs on a Table near PTB but not in vacuum. (aka Table-top testbed)
  - No optical stimulus, no indication of optical performance
  - Only for FSW & EDU Avionics development and troubleshooting
  - Run by I&T. FSW and Avionics as the primary user early on, used for operations later
- **System Testbed (STB) = PTB + FTB**
  - PTB receives all the EDUs from FTB and undergoes a limited optical reconfiguration to become the CGI Systems Testbed.
  - STB is a single flight-like CGI testbed afterward.
  - STB performs meaningful CGI system-level tests prior to flight II&T, during II&T, after CGI delivery, and during on-orbit commissioning and tech demo

CGI vs FM **requirements**

Parameter	**CGI vs. Future missions** ***unobscured aperture: HabEx & LUVOIR B***
5σ Flux ratio at 3 λ/D (6 λ/D)	**n/a (~10^{-7}) vs. 5·10^{-11} **** L1 Threshold Requirement

** NTE = not-to-exceed = requirement on max tolerable.

Future missions working group: Bertrand Mennesson, Laurent Pueyo, Matt Bolcar, Chris Stark, Stefan Martin, Aki Roberge

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CGI vs FM **requirements**

Part 1

Parameter	**CGI vs. Future missions** ***unobscured aperture: HabEx & LUVOIR B***
Pointing jitter control	**Slightly worse** CGI: ~0.5mas RMS V=5 star, FM: 0.3mas NTE**
Low order control (Z4-Z11)	**~10x better** (~100pm RMS) ~100pm RMS * vs ~1nm NTE **
EMCCD	**Comparable**: dark current, clock-induced-charge **Worse**: QE at UV/red. 21mo lifetime req.

** NTE = not-to-exceed = requirement on max tolerable.

Future missions working group: Bertrand Mennesson, Laurent Pueyo, Matt Bolcar, Chris Stark, Stefan Martin, Aki Roberge

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CGI vs FM **requirements**

Part 2

Parameter	CGI vs. Future missions ***unobscured aperture: HabEx & LUVOIR B***
Wavefront error sources	**Comparable?** Can't probe "new physics" (amplitude & polarization) as well at 10^{-7}
High order drift (≥Z12)	**10x Worse** CGI: 50pm NTE**, FM: 5pm NTE**
# of DMs	**Same (2)**
DM stroke resolution	**~8x worse (15pm vs 2pm)** Engineering problem, not physics problem
DM actuator count	**48x48 vs 64x64**

* model, typically without Model Uncertainty Factors (MUFs)

** NTE = not-to-exceed = requirement on max tolerable.

Future missions working group: Bertrand Mennesson, Laurent Pueyo, Matt Bolcar, Chris Stark, Stefan Martin, Aki Roberge

International Contributions

WFIRST Program Level Requirements Appendix (PLRA), *2020-01-30*

International partners may[b] participate in the project by providing the following contributions:

JAXA	Coordinated, contemporaneous ground-based observations on Subaru Ground station for telemetry and tracking Polarization optics for the CGI Microlensing data from the MOA project Access to microlensing data from and observations with PRIME
MPIA	Precision mechanisms for the CGI
ESA	Batteries Star trackers Electron Multiplying Charge-Coupled Device (EMCCD) detectors for the CGI Ground station for telemetry and tracking
CNES	Superpolished optics for the CGI Grism data processing Coronagraph starlight suppression algorithms

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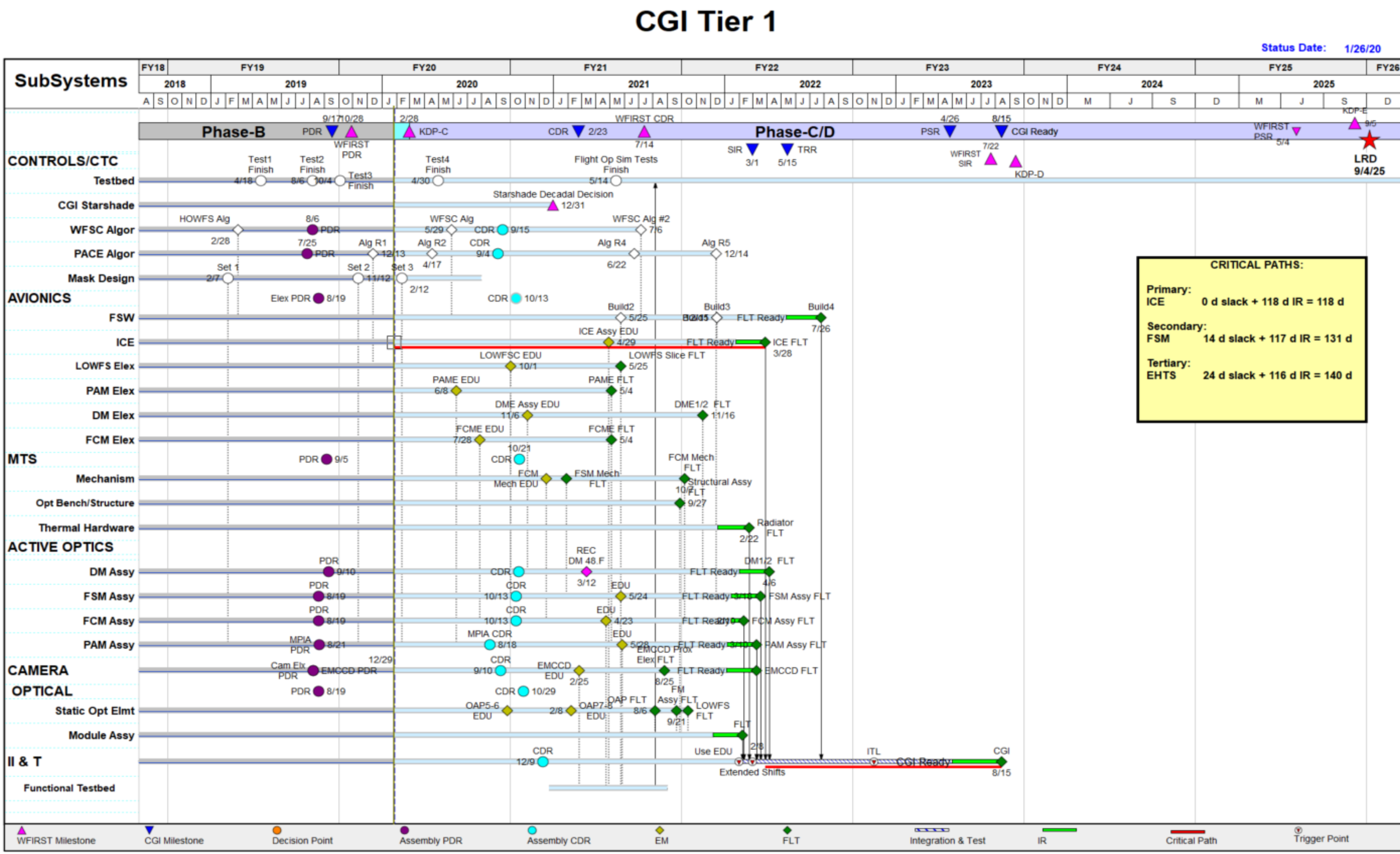
CGI TIER 1 Summary Schedule



Preliminary Disposition of Tiger Team Recommendations

		Disposition				
#	Recommendation	WFIRST Project	CGI	Preliminary Consensus	descope now or offramp later?	HQ included in decision?
1	When faced with decisions, choose the side of simplest design or test that meets threshold, not the side of deeper contrast.	Yes	Yes	Yes	offramp	No
2	Carry an incompressible test list that has only one mode (direct imaging) with test of function and model correlations.	Yes	Yes	Yes	offramp	No
3	The WFIRST Level 2's state CGI has a 5.25 year life; this needs to be corrected to be consistent with the anticipated tech demo duration.	Consider	Yes	Yes	now	Yes
4	HQ should clarify the timeline and hours available for tech demo completion in WFIRST mission, consistent with Class C reliability.	Consider	Yes	Yes	same scope	Yes
5	Do all High Order Wave Front Sensing and Control (HOWFSC) calculations on the ground.	Consider	Yes	Yes	now	No
6	Consider moving other processes such as phase retrieval and calibrations to ground	Consider	Yes	Yes	now	No
7	Consider moving the MPIA/JPL interface. Specifically, have MPIA (with their industrial partner) deliver both PAM and PAME.	No	No	No	same scope	No
8	If EDU schedule impacts FLT deliveries, be prepared to overlap the EDU and FLT	Yes	Yes	Yes	offramp	No
9	The Mechanical WBS integrates and tests the FSM and FCM mechanisms and delivers in-place to the Adaptive Optics WBS which adds the flat mirrors and does more tests. Look for savings by integrating/merging the testing in the two WBS elements.	Yes	Yes	Yes	same scope	No
10	The EDU and FLT EMCCD detectors come from the same lot. Get EDU earlier with minimal screening.	Yes	Yes	Yes	offramp	No
11	Relaxing the star magnitude (Mv=4 or brighter… Level 1 says Mv=5), identify suitable brighter science targets, and for purely technical experiments consider possibility of even brighter targets and brighter reference stars. Potential gains will likely be mode-dependent.	Yes	Consider	Consider	now	Yes
12	Increasing number of DM opens/shorts that can be tolerated (beyond 5/6 offramp already taken). Because impact depend on how they are distributed, run the models when the DMs get connectorized	Consider	Consider	Consider	offramp	No
13	Relaxing DM precision and stability. 15-bit DAC linearity performance (without hardware change) is consistent with DM electronics stability of 1 mV (from 0.5mV). [CGI has adopted this already].	Yes	Yes	Yes	now	No
14	Relaxing filter specs - 1% wide filters with high optical density could be relaxed…drives procurement.	Yes	Yes	Yes	now	No
15	That timing/efficiency should not drive anything. WFIRST should be asked to give CGI the time that is needed. Use efficiency metrics to see if relief is worthwhile. Chopping cadence to reference can be optimized. CONOPS is a useful knob to buy back performance	Consider	Consider	Consider	same scope	No
16	Have fallback hardware options wherever possible for both flight and EDUs.	Yes	Yes	Yes	offramp	No
17	Safe to mate EGSE alternatives for any avionics that drive EDUs.	Yes	Yes	Yes	offramp	No
18	Buy additional EDUs to add schedule robustness	Yes	Consider		offramp	No
19	In case of a late EDU element, use existing testbed element for testing (project has adopted this offramp)	Yes	Yes	Yes	offramp	No

Moving forward: balancing performance with constraints

- L1 - Threshold Technology Requirement:
  - "TTR5: WFIRST shall be able to measure (using CGI), with SNR ≥ 5, the brightness of an astrophysical point source located between 6 and 9 λ/D from an adjacent star with a VAB magnitude ≤ 5, with a flux ratio ≥ 1·10^-7; the bandpass shall have a central wavelength ≤ 600 nm and a bandwidth ≥ 10%."
- CGI design is not changing as a result of L1 relaxation
  - Re-design to Threshold would hurt both cost & schedule
- However, if required to stay "in the box," CGI will accept as-built performance and/or additional risk
  - Key decisions advised by stakeholders

CGI plan to stay off the critical path

- 0th line of defense - accept as-built performance
  - If schedule and/or cost margin are not available, demonstrated performance will be accepted
  - Use CGI integrated modeling & performance budget to assess impact
- 1st line of defense – aggressive schedule management
  - Instituted off-ramps with schedule work arounds to be used if necessary
- 2nd line of defense - adequate schedule reserve
  - Increased funded schedule reserve during II&T by postponing some verification by test to post launch (eg. stability tests)
- 3rd line of defense – rescope II&T test program to the Incompressible Test List that covers only one mode (L1 Threshold requirement)

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Consequence of Class D: allowed to trade cost/schedule for risk

- Tailoring currently in progress.
- Example: electronics parts:
  - Many parts already in procurement => no benefit to reducing quality
  - May reduce some screening or conduct in parallel if schedule driver
- Example: simplify process and oversight
  - Drawing quality and review
  - Lower level sign-off for documents, reviews, etc.

Accepted Tiger Team Recommendation: HOWFS Ground-in-the-Loop

- Offload computations to ground (at IPAC/SSC)
  - Downlink images, uplink DM commands
  - Significant schedule risk reduction for CGI (avionics/FSW)
  - Consistent with the current WFIRST ground systems architecture
  - Existing CGI HOWFS/C timing requirements can be met with margin using S-band up/down link
    - Data volume, ground station coverage, and down/uplink rates
- Will bring to PDR maturity for WFIRST Ground Systems PDR in July 2020

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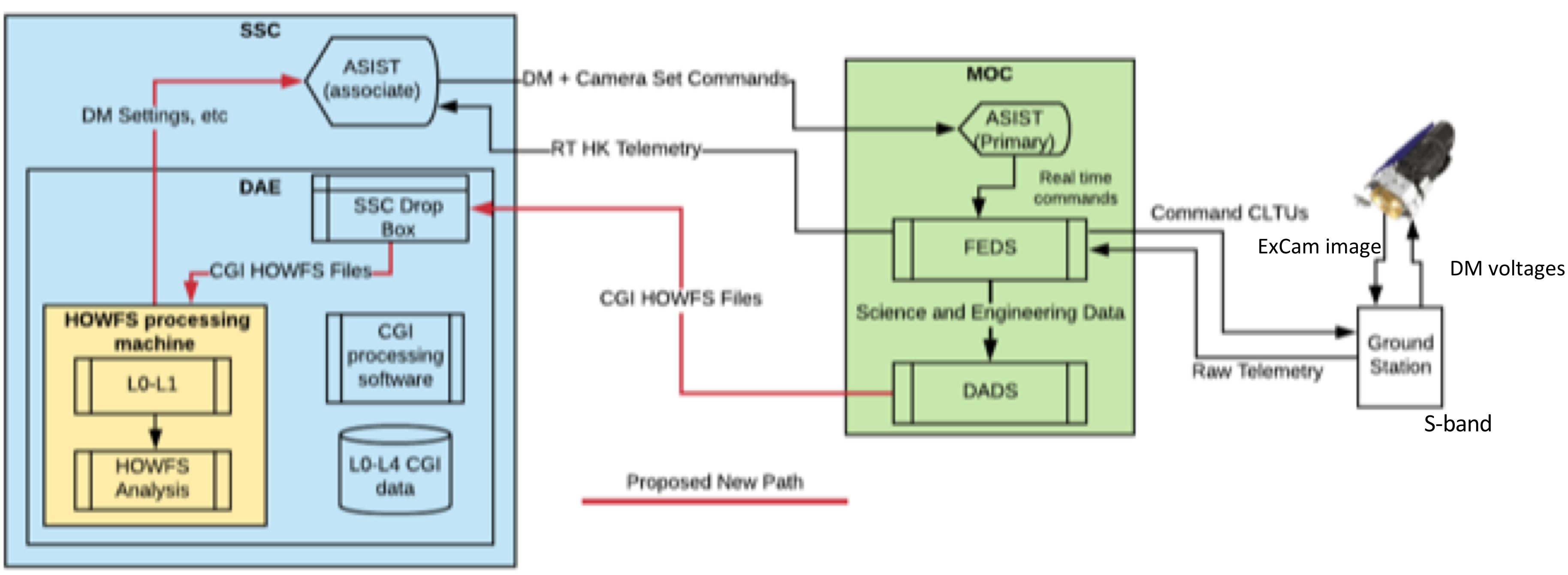
Data Flow for HOWFS Ground-in-the-Loop



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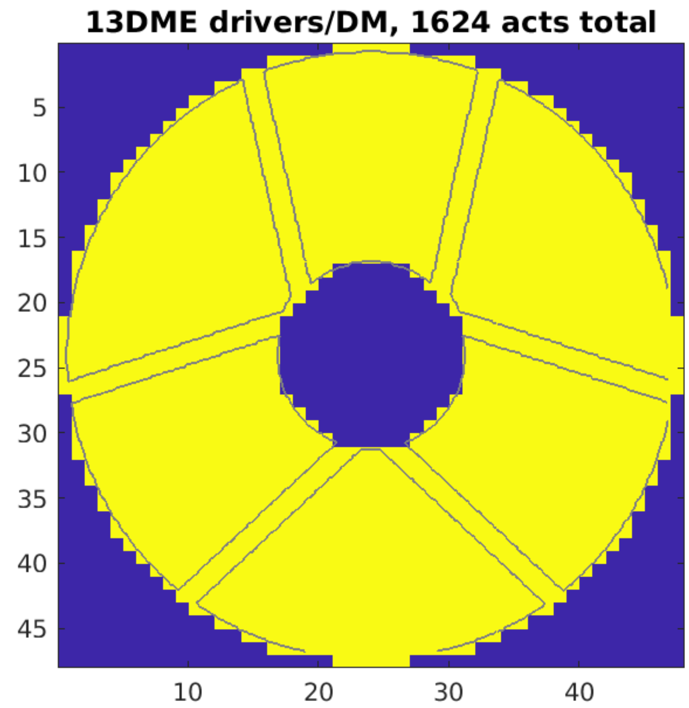
Design change example: Do not drive unilluminated actuators

- Number of driver boards per DM : 16->13
- Reduces mass, power, cost, schedule for minimal performance risk



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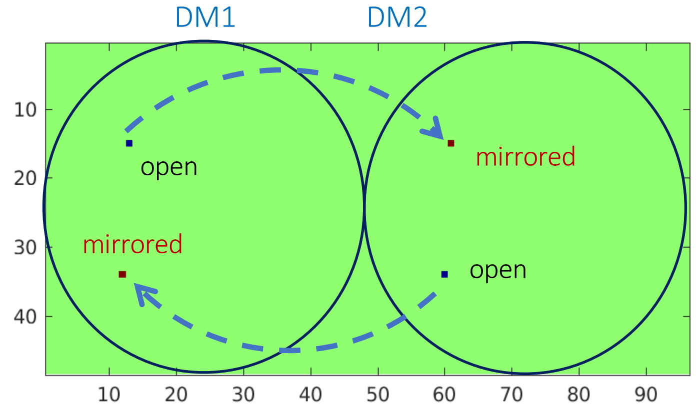
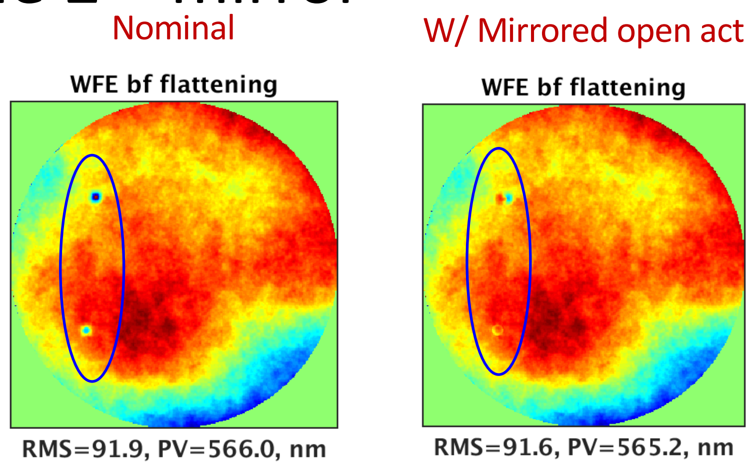
Accepted offramp example: accept up to 5 bad actuators per DM

Hanying Zhou, JPL

- Open actuators on one mirror can be mitigated using the corresponding actuator on the 2nd mirror





- New acceptance criteria are based on integrated modeling
  - HLC & SPC bowtie (spectroscopy) minimally impacted
  - SPC wide FOV raw contrast may degrade up to ~4x, depending on exact distribution of bad actuators.
- Trades schedule robustness for modest performance risk