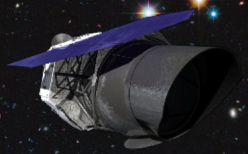


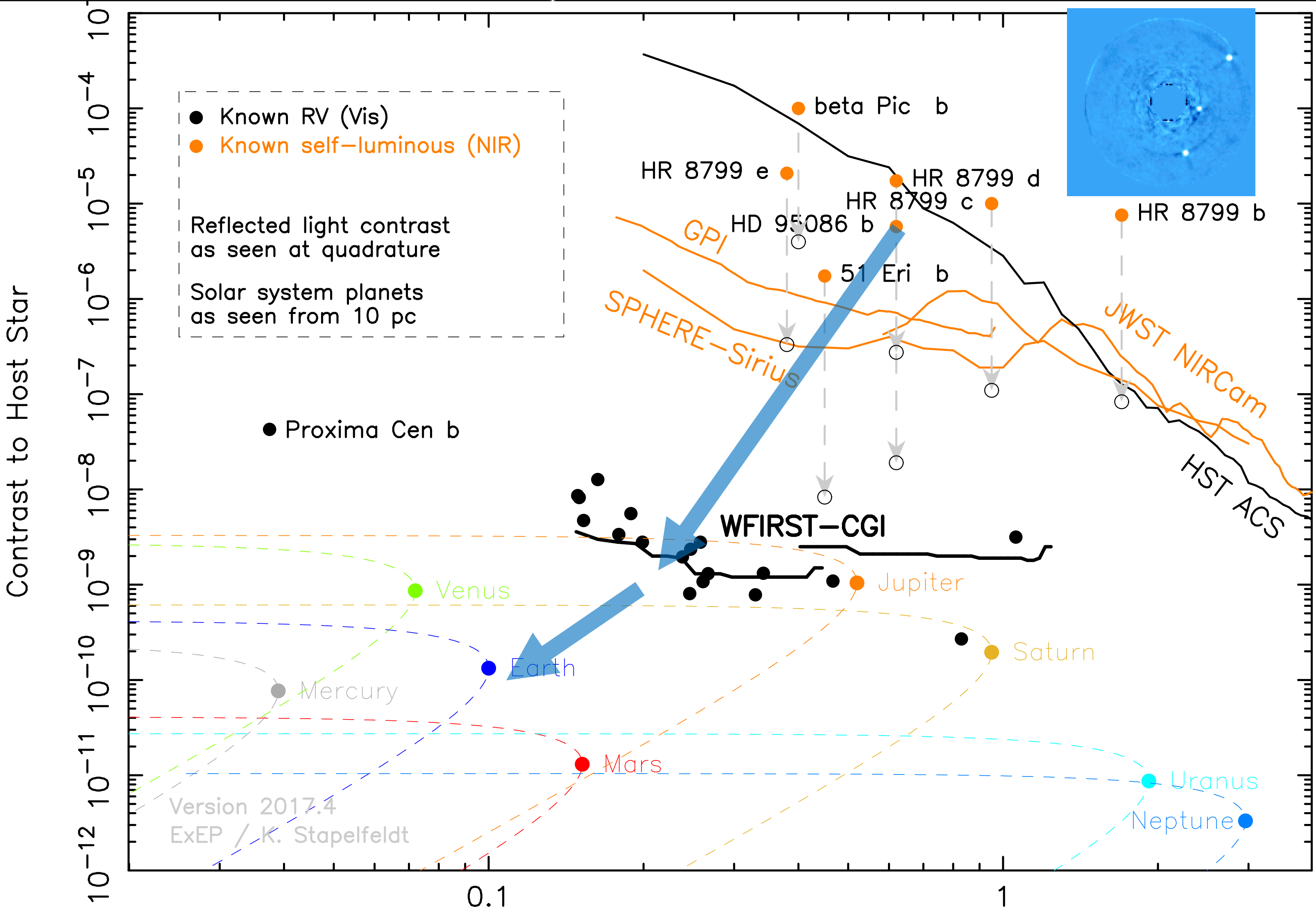
WFIRST CORONAGRAPH INSTRUMENT

Science with the Roman Coronagraph

Bruce Macintosh (Stanford)
Nikole Lewis (STScI), Ewan Douglas (UArizona), Kerri Cahoy (MIT), John Debes (STScI), Roxana Lupu (Ames), Mark Marley (UArizona), Eric Nielsen (NMSU), Laurent Pueyo (STScI), a host of amazing students, postdocs, and collaborators (including many from the Turnbull SIT, JPL and GSFC).

WFIRST
WIDE-FIELD INFRARED SURVEY TELESCOPE
DARK ENERGY • EXOPLANETS • ASTROPHYSICS

Exoplanet & Disk Direct Imaging

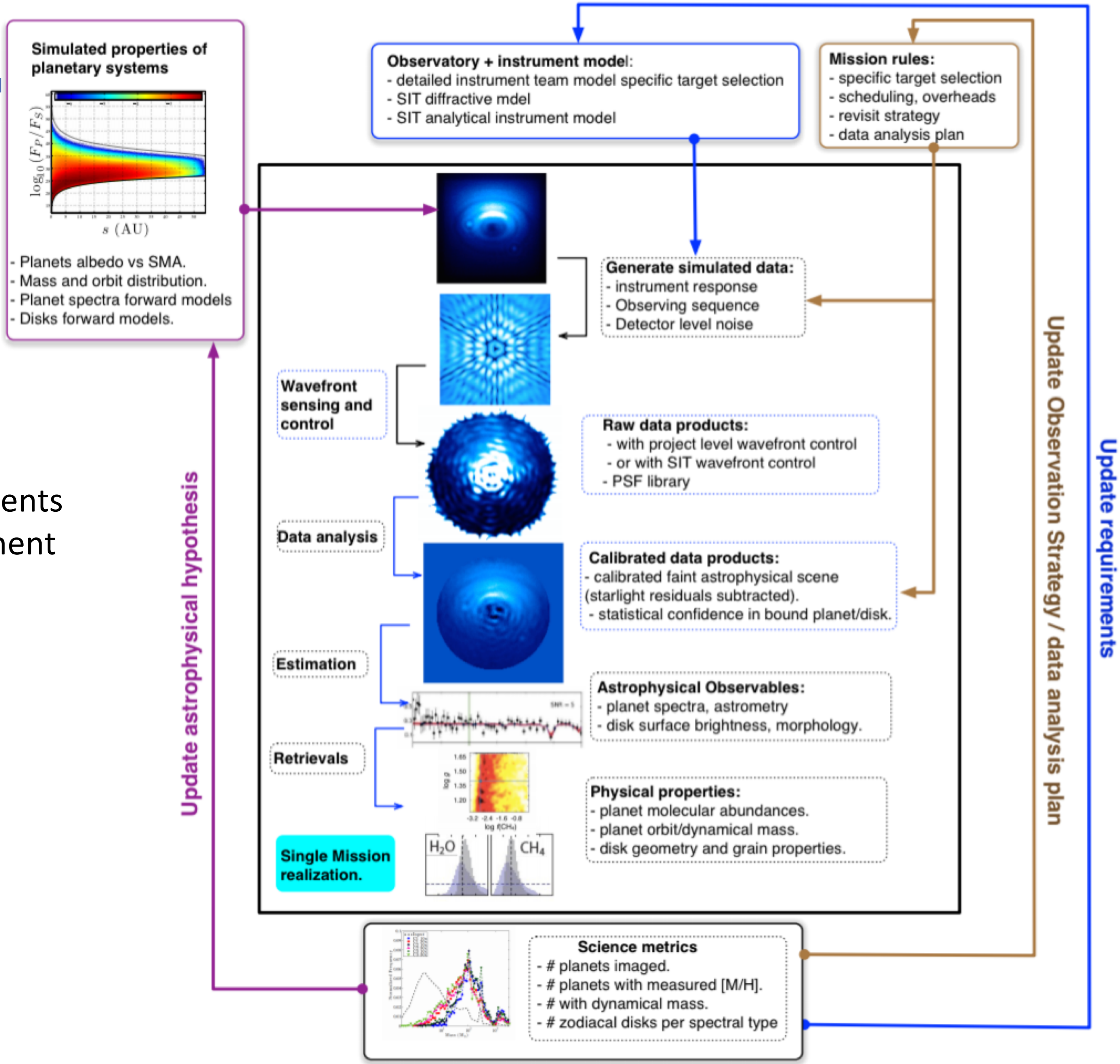


Early science reach - Figure by Karl Staplefeldt, Tiffany Meshkant, et al

Science Objectives

- Exoplanet Direct Imaging Characterization
  - WFIRST will study the composition and bulk properties of giant planets via multi-band photometry and spectroscopy of features such as methane, to constrain their atmospheric metallicity, to determine the diversity of properties dependent on mass and orbital parameters, and to constrain their formation mechanisms.
- Exoplanet Direct Imaging Discovery
  - WFIRST will contribute to the census of known planets around nearby stars by searching for previously undetected new planets.
- Exozodiacal Dust Direct Imaging
  - WFIRST will explore the occurrence of exozodiacal and circumstellar dust around nearby stars, resolve the disk internal structures, and constrain their microphysical properties by measuring scattered light and mapping the surface brightness, photometric color, and linear Stokes polarization.
- Protoplanetary Disk Imaging
  - WFIRST will characterize protoplanetary disk structure and potential self-luminous or accreting planets around nearby young stars.

Requirements Development approach



ROMAN CORONAGRAPH

What we learned in the early days

- A coronagraph operating at 10^{-9} contrast with good throughput could spectroscopically characterize 5-20 RV-detected giant planets
  - These planets are at temperatures inaccessible to JWST
- ”Fresh” RV orbits would allow determination of optimal time to observe
- Spectroscopy (R>50) of mature planets in reflected light at good SNR (10-20) could meaningfully measure carbon abundance
- Image processing techniques developed by ground-based coronagraphs could mitigate speckle noise in well-behaved space coronagraphs
- Sensitivity for extended sources / disks was transformative compared to ground-based
- Learned how to develop requirements flowdown for high-performance coronagraph missions

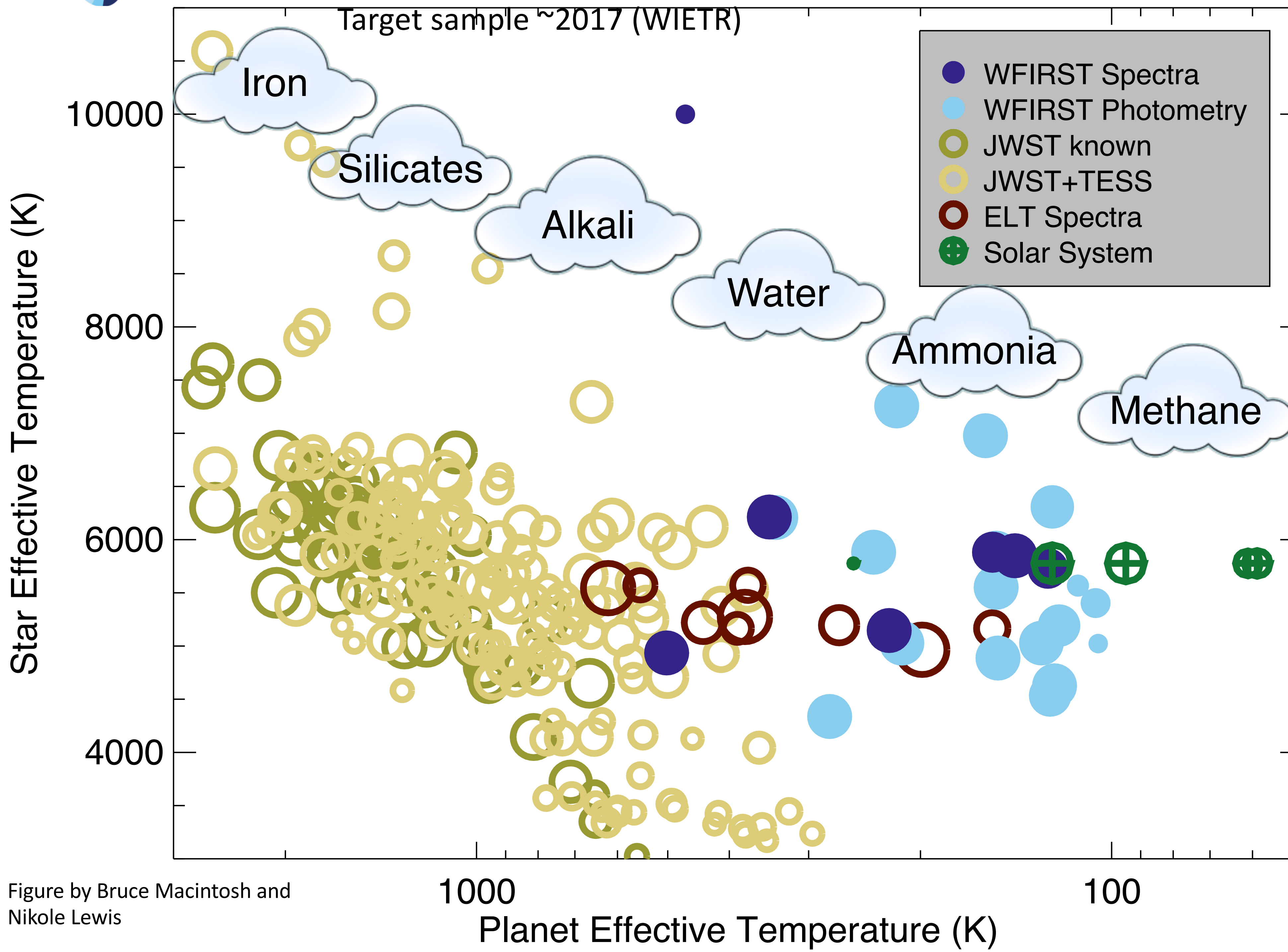
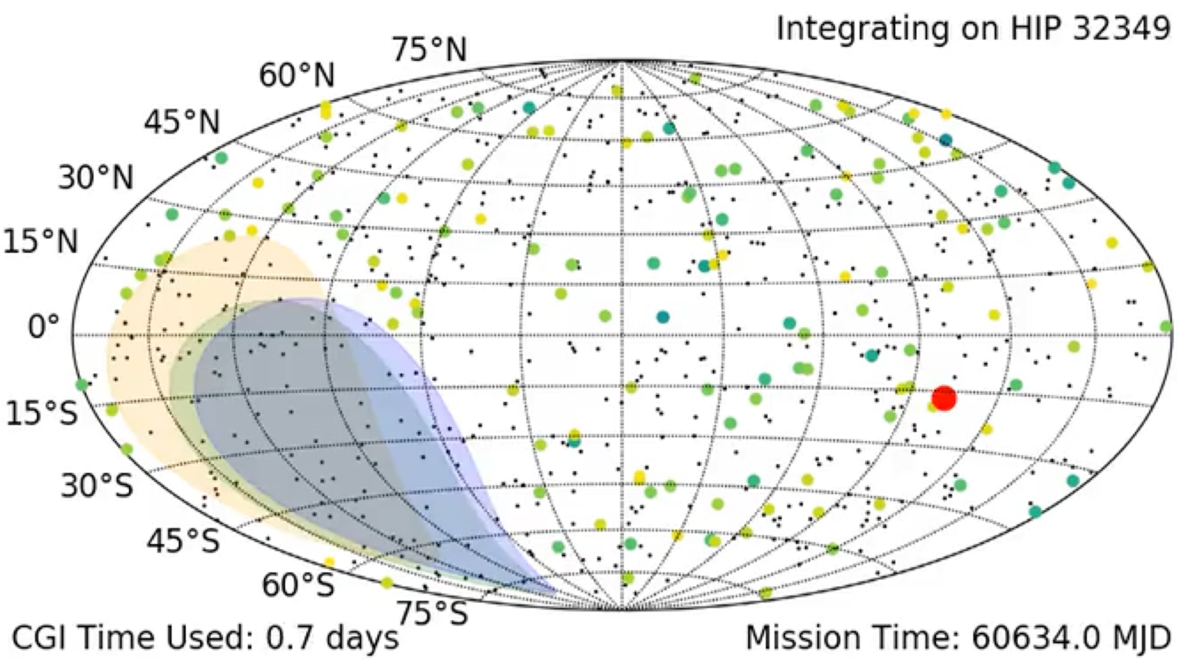


Figure by Bruce Macintosh and Nikole Lewis

Blind Search Analysis Strategy 1: Full Mission Simulation



- Red spot is current target
- Blue spots are observed targets
- Colored spots are currently selectable targets with colorscale representing time allocated
- Teardrops are Sun/Earth/Moon keepouts

See: Savransky and Garrett (2015), Delacroix et al. (2016), Keithly et al. (2019)

https://github.com/dsavransky/EXOSIMS http://ascl.net/1706.010

Science objective flow from early SIT

PLRA Objective 2.1.5: WFIRST will study the composition and bulk properties of giant planets via multi-band photometry and spectroscopy of features such as methane, to constrain their atmospheric metallicity, to determine the diversity of properties dependent on mass and orbital parameters, and to constrain their formation mechanisms.

SIT scientific analysis: methane fraction recovery

L2: WFIRST CGI shall be able to measure exoplanet spectra with R = 50 or greater spectral resolution, with a wavelength accuracy of 5 nm or smaller, and achieve an SNR of 10 or greater for a spectral resolution element in the IFS1 and IFS2 bands, assuming a scattered light background equal to the solar zodiacal dust, and an exoplanet-star flux ratio of 7e-9 at a separation of 0.3 arcsec from a V=5 mag star with a stellar radius of 0.4 milliarcseconds, in less than 240 hours of integration time per band on the target.

Project&SIT exposure time calculations and observational sims

L3 hardware requirements

Early CGI L2 Science Requirements Document

ID	Short Name	Text	
CGI-2.1	Photometry filters	WFIRST CGI shall be able to make photometric measurements with both the hybrid Lyot coronagraph and shaped pupil coronagraph in each of the bands as defined by wavelength range in the CGI Science Filter Table over a spectral range from 480 nm to 970 nm.	
CGI-2.2	Photometric characterization of known RV planets	WFIRST CGI shall be able to measure the brightness in Filter 2 of an exoplanet with an SNR of 10 or greater within 10 hours of integration time on the target, assuming an exozodial scattered light background equal to the solar zodiacal dust, and an exoplanet-star flux ratio of 8e-9 at a separation of 0.2 arcsec from a V=5 mag star with a stellar radius of 0.3 masec.	✓ driving
CGI-2.3	Detection of new planets	WFIRST CGI shall be able to a detect a new exoplanet with a false positive rate below 10% per target at a detection threshold of 50% for an exoplanet flux ratio of 2e-9 at an angular separation of 0.15 arcsec around a star of V=4 mag or brighter, assuming an exozodial scattered light background equal to the solar zodiacal dust, in an integration time of 24 hours on the target.	
CGI-2.5	High contrast spectra	WFIRST CGI shall be able to measure exoplanet spectra with R = 50 or greater spectral resolution, with a wavelength accuracy of 5 nm or smaller, and achieve an SNR of 10 or greater for a spectral resolution element in the IFS1 and IFS2 bands, assuming a scattered light background equal to the solar zodiacal dust, and an exoplanet-star flux ratio of 7e-9 at a separation of 0.3 arcsec from a V=5 mag star with a stellar radius of 0.4 milliarcseconds, in less than 240 hours of integration time per band on the target.	✓ driving
CGI-2.6	Surface brightness mapping of inner circumstellar dust	WFIRST CGI shall be able to map the distribution of circumstellar dust by measuring the scattered light surface brightness around a V=5 mag host star with a sensitivity at or below 19 mag/arcsec^2 from a separation of 0.15 arcsec to 0.95 arcsec, in Filter 2 with an SNR of 3 or greater per spatial resolution element in less than 24 hours of integration time on the target in each angular separation range.	
CGI-2.7	Detection of dust at wide separations	WFIRST CGI shall be able to make coronagraphic observations of circumstellar disks from a separation of 0.9 arcsec to 3.0 arcsec in Filter 2 with a raw star resolution element flux ratio dominated by the shape and surface quality of optical elements upstream of the CGI.	
CGI-2.8	Distinguishing astrophysical false positives	WFIRST CGI shall be able to distinguish between an exoplanet and an astrophysical background object with 90% confidence in three or fewer observations for stars within 15 parsecs with SNR greater than 6 per measurement.	
CGI-2.9	Polarization of disks	WFIRST CGI shall be able to discriminate between dust grain compositions by mapping the linear polarization of a circumstellar debris disk that has a polarization fraction greater or equal to 0.3 with an uncertainty of less than 0.03 in Filters 2 and 8.	
CGI-2.10	Orbital parameter accuracy	WFIRST CGI shall be able to measure the orbital semi-major axis to an uncertainty of plus or minus 10%, the eccentricity to an uncertainty of less than plus or minus 0.1, and the inclination to an uncertainty of less than plus or minus 17 degrees for exoplanets imaged at separations between 0.2 arcsec and 0.9 arcsec with orbital periods of less than 10 years.	
CGI-2.11	Exoplanet astrometric accuracy	WFIRST CGI shall be able to measure the relative astrometry between an exoplanet and its host star, in photometric images, from separations of 0.2 arcsec to 0.95 arcsec, with an accuracy of 5 milliarcsec or less, assuming SNR of 10 or greater, including systematic errors, for the duration of the mission. Knowledge of the star-planet position angle shall be obtained from concurrent imaging with other WFIRST sensors.	
CGI-2.12	Observations of young planets orbiting distant young stars	WFIRST CGI shall be able to measure H-Alpha and continuum emission from protoplanetary systems at an SNR of 5 or greater and a flux ratio of 2e-5 at 0.15 arcsec to 0.25 arcsec and 5e-6 outside of 0.25 arcsec, for a system with R = 14.2, V=15.1, I=13.1 or brighter stars in less than 240 hours of integration time.	
CGI-2.13	WFS telemetry	WFIRST CGI shall be able to record and transmit wavefront control system telemetry in parallel with science data, including raw wavefront sensor measurements and commanded deformable mirror actuator values.	
CGI-2.14	Orbital parameter accuracy for new detections	WFIRST CGI shall be able to measure the orbital semi-major axis to an uncertainty of less than plus or minus 20% and the eccentricity to an uncertainty of less than plus or minus 0.3 for exoplanets without previous orbital constraints that are imaged at separations between 0.2 arcsec and 0.9 arcsec with orbital periods of less than 5 years.	

see also https://arxiv.org/pdf/1807.05422.pdf

ROMAN CORONAGRAPH

But we also learned…

- JWST will characterize dozens of close-in giant planets
- Photometric characterization, or even a single methane band, would not provide strong physical constraints on RV planet properties or origins
- Measuring orbital inclinations is easy but not exciting
- Exposure times were very long for spectroscopy
- Discovering a significant number of new planets would be hard unless sensitivity reached "super-Earth" planets
- Telescope issues impose complexities on design
  - Large secondary mirror
  - Image jitter (though LOWFS controls this well)
- "Set and forget" observation scenarios make performance very sensitive to telescope stability
- Photometric observations of known young planets would also not be transformative

Where are we now?

- CGI *formal* performance requirements have been significantly relaxed
- CGI's *predicted* performance will still be by far the most powerful coronagraph every pointed at a star

- This can still be scientifically extremely important
  - Visible-light spectroscopy of young planets previously only seen in the near-IR
    - Can we measure metallicity? Gravity?
  - Photometry (+spectroscopy?) of mature RV planets to measure cloud properties
  - Detection of visible light from zodiacal disks will be incredibly valuable in conjunction with LBTI data
  - First reconnaissance of the environment of nearby sunlike stars

Bruce's thoughts about the CPP

- The CPP will have to figure out how to maximize science impact within the constraints of the mission and CGI
- This will require being not just supporting scientists, but advocates at all levels
- If CGI performs as predicted, observations in year 3-5 (GO, or some other mechanism) could be incredibly scientifically valuable
  - CPP is going to have to lead the fight to make that happen
- **You – the future CPP members - are our best chance to learn how to do science with a high-performance active coronagraph**

Conclusions

- Requirements flow down process enhanced current-best-estimate performance and suggest possible science
- Tools were developed and are available to inform future missions and potential guest observer campaigns

- Summary of SIT efforts (public datasets, code repositories, and ADS abstracts library): https://romancgi.sioslab.com/

Original Coronagraph Science Teams

SIT

PI: Maggie Turnbull

Aki Roberge

David Ciardi

Renyu Hu

Hannah Jang-Condell

Stephen Kane

Nikku Madhusudhan

Avi Mandell

Michael McElwain

Laurent Puyeo

Stuart Shaklan

William Sparks

Chris Stark

Maxime Rizzo

SIT

PI: Bruce Macintosh

Nikole Lewis

Adam Burrows

Kerri Cahoy

Ewan Douglas

John Debes

Roxana Lupu

Jonathan Fortney

Eric Nielsen

Katherine Follettte

Tom Greene

Mark Marley

Caroline Morley

Marshall Perrin

Tyler Robinson

Dmitry Savransky

Laurent Puyeo

Adjutant scientist:
Jeremy Kasdin