Disks, Exoplanet Characerization, and Exoplanet Demographics with the Roman Space Telescope

National Aeronautics and Space Administration

2021 Sagan Summer Workshop

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Nancy Grace Roman
"Mother of Hubble"

NANCY GRACE ROMAN SPACE TELESCOPE

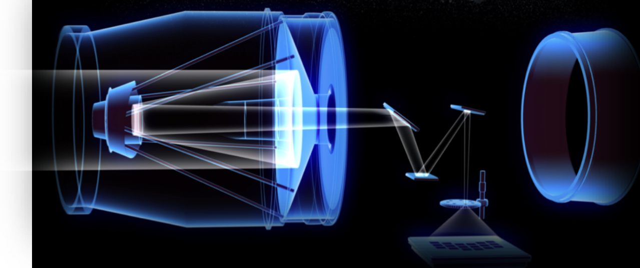
Roman Space Telescope

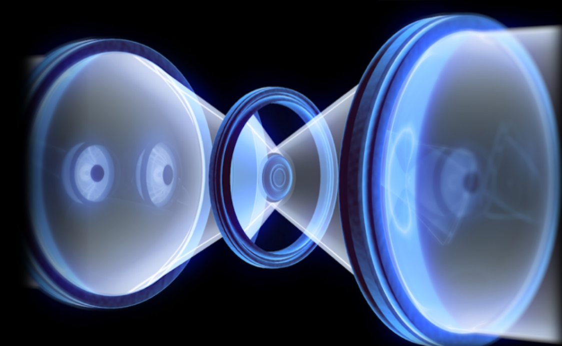
Properties	Current WFIRST
Eff. Aperture	2.28m
FOV	0.281 deg^2
Wavelengths	~0.5-2 μm (WFI)
FWHM@1μm	0.10”
Pixel Size	0.11”
Launch/Lifetime	2026/5 years
Orbit	L2

Wide-Field Instrument (WFI)
- Imaging & spectroscopy over 1000's sq deg.
- Monitoring of SN and microlensing fields
- ~0.5 – 2.0 micron bandpass
- 0.281 sq. deg. FoV (~100x HST ACS FoV)
- 18 H4RG detectors (288 Mpixels)
- 7 filter imaging, grism and prism spectroscopy

Coronagraph Instrument (CGI)
- Visible (545-865nm) imager
- Polarimeter and spectrograph
- 3 types of coronagraph masks

Observations
- Three core community surveys to address Astro2010 science goals
  - High latitude wide area survey
  - High latitude time domain survey
  - Galactic bulge time domain survey
- ~>25% of time will be devoted to General Astrophysics Surveys
- 3 months of coronagraph observations in first 18 months of the mission





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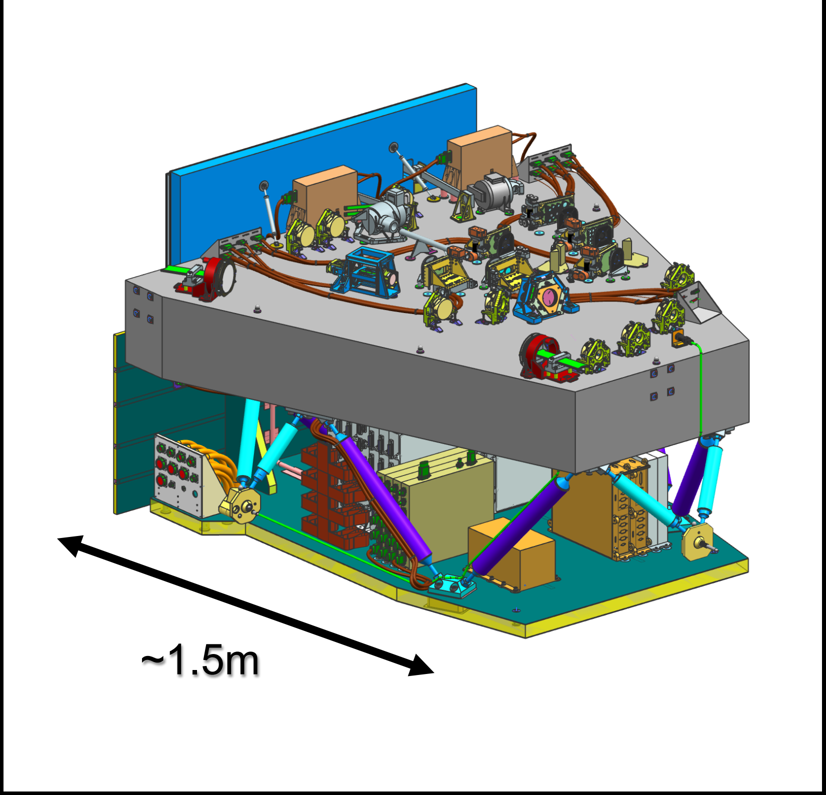
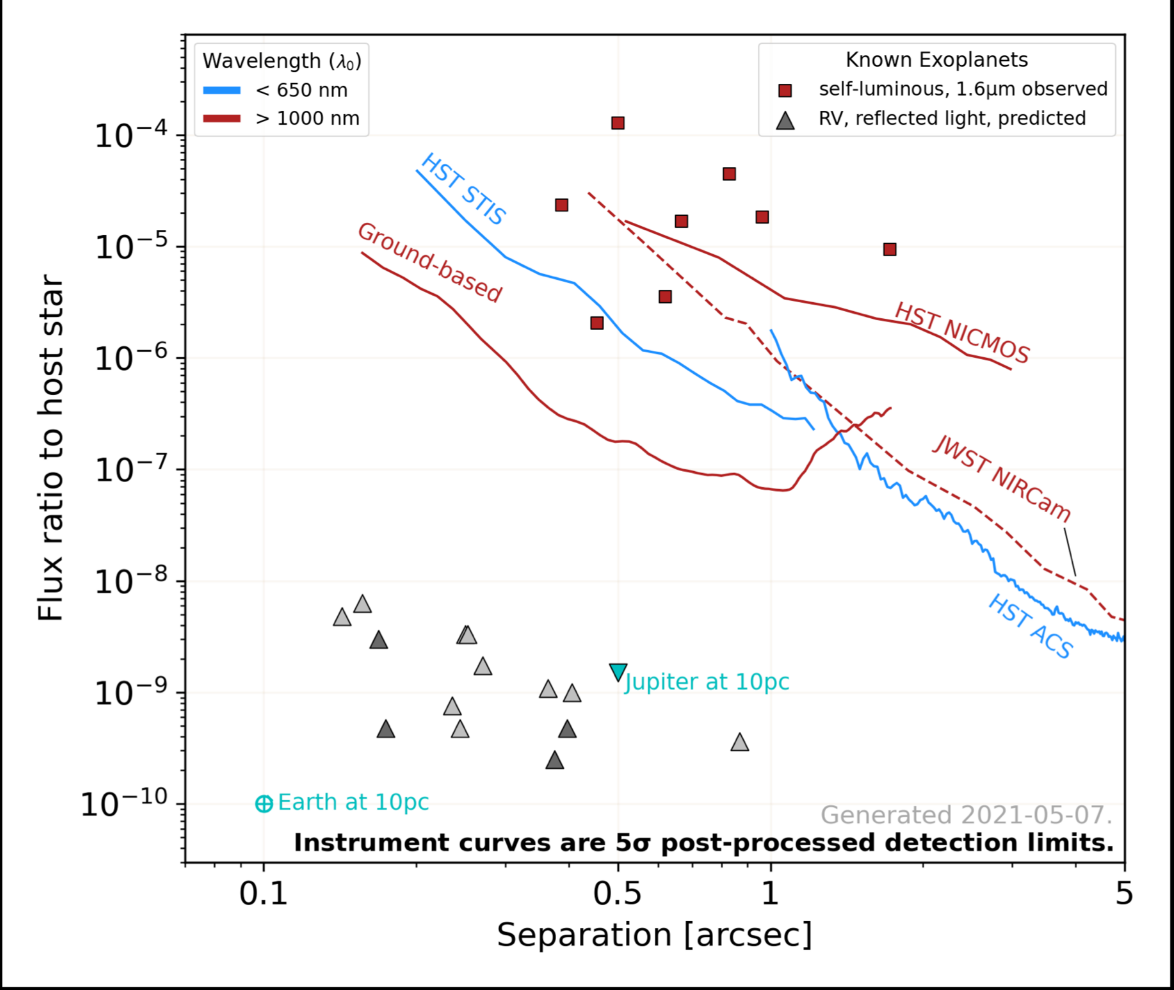
Disks and Direct Imaging of Exoplanets

Roman Coronagraph Instrument

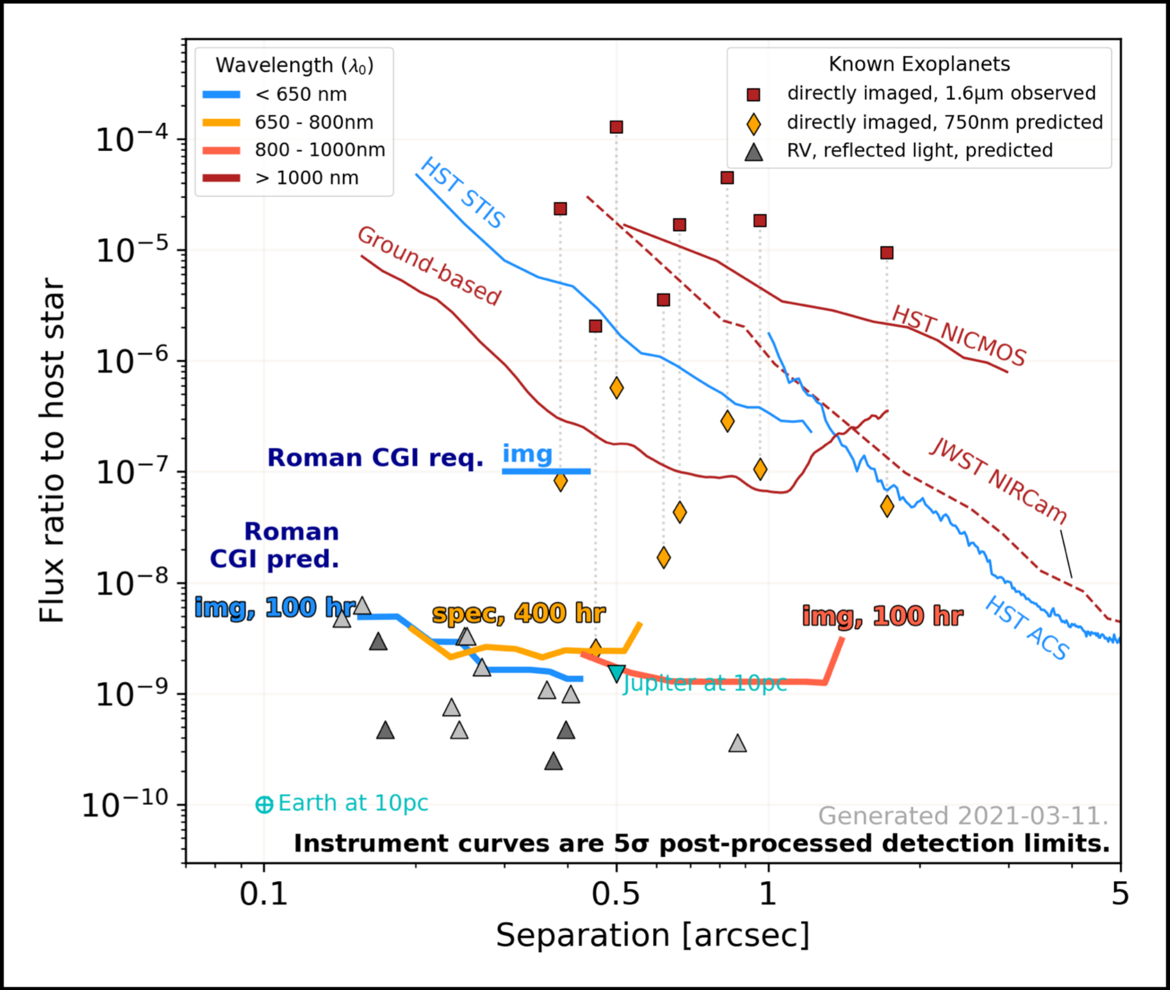
- A technology demonstration instrument on Roman
- The first space-based coronagraph with active wavefront control
- A visible light (545-865nm) imager, polarimeter and R~50 spectrograph
- A 100-1,000 times improvement in performance over current ground and space facilities
- Capable of exoplanetary system science



Bridging the Gap Between Massive, Self-Luminous Planets in the NIR and Reflected Light Planets in the Visible



Predicted Detection Limits are 100-1000x Better Than the Current State-of-the-Art



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

Primary Observing Modes

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

* Other filters and masks will be installed but will not be fully ground-tested and will not be guaranteed (eg: 660nm spectroscopy and ExEP-contributed coronagraph masks)

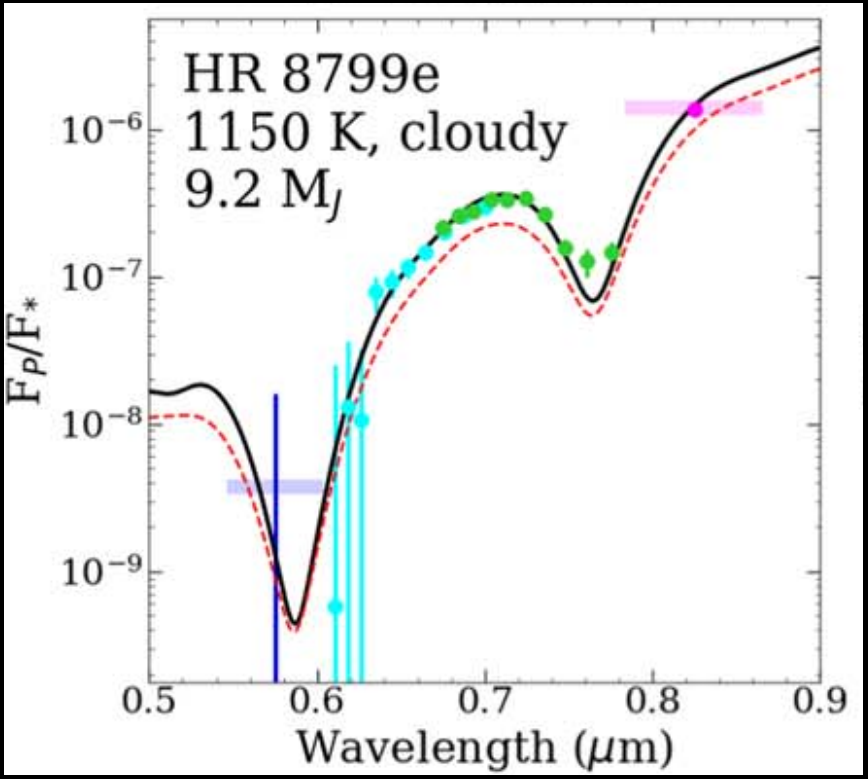
Complete list of filters available at https://roman.ipac.caltech.edu/sims/Param_db.html
Can't mix & match coronagraph mask w/ any filter; must be sub-band

Young, self-luminous massive planets

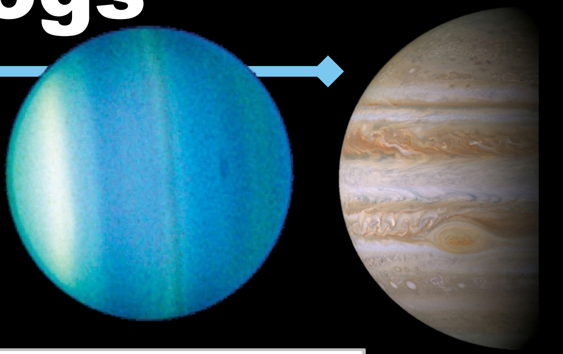
What are the cloud properties of young massive planets? How inflated are they? Are they metal rich?

- **CGI can:** Fill out SED with broadband photometry and spectroscopy
- **During Technology Demonstration Phase (TDP):** 1-2 systems
- **Beyond TDP:** Additional bandpasses and/or survey more known planets

Lacy & Burrows 2020



First reflected light images of mature Jupiter analogs



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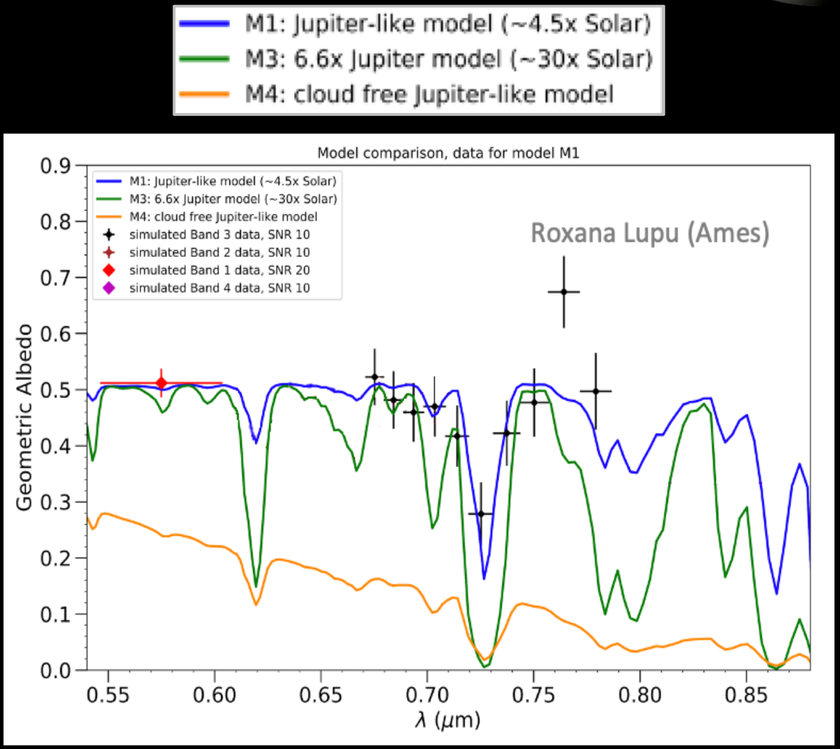

Natasha Batalha (UCSC)
Roxana Lupu (Ames)
Mark Marley (Ames

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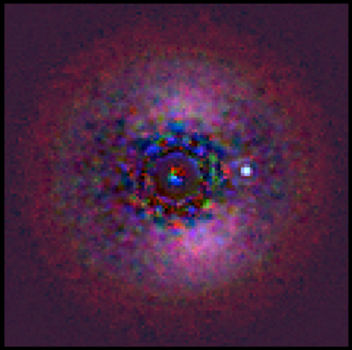
Characterization of a mature Jupiter analog

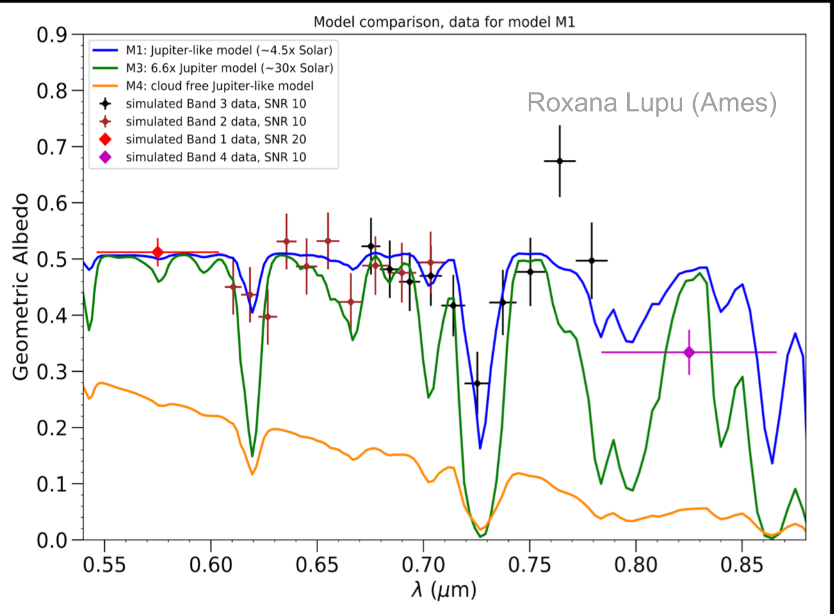
Increase confidence that we can detect molecular features in faint, high-contrast, reflected light spectra before we attempt exo-Earths

- 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



Preliminary imaging simulation
Sun-like star at 3 parsecs
Warm Jupiter at 2 AU

M. Rizzo / N. Zimmerman (NASA GSFC)



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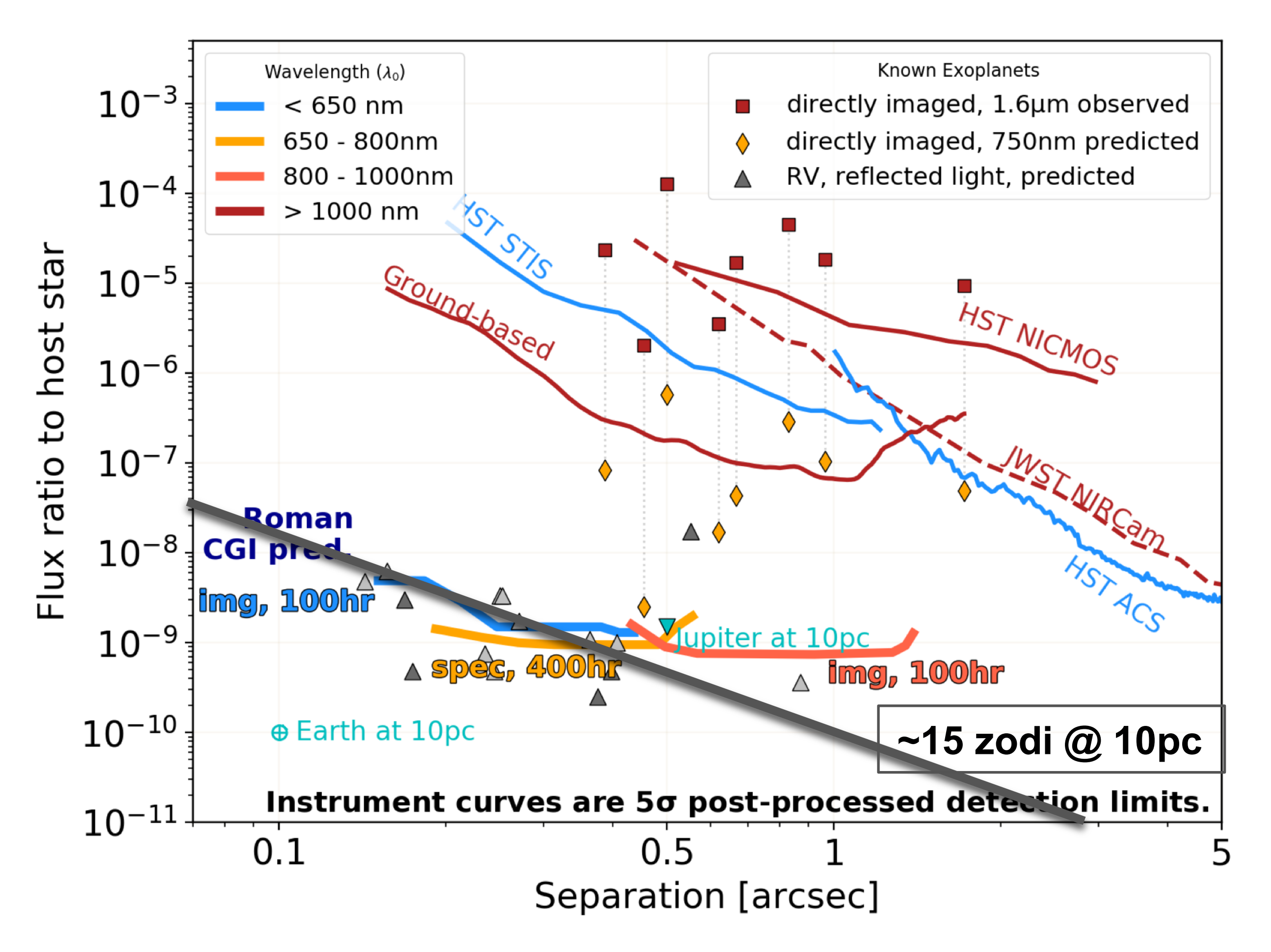
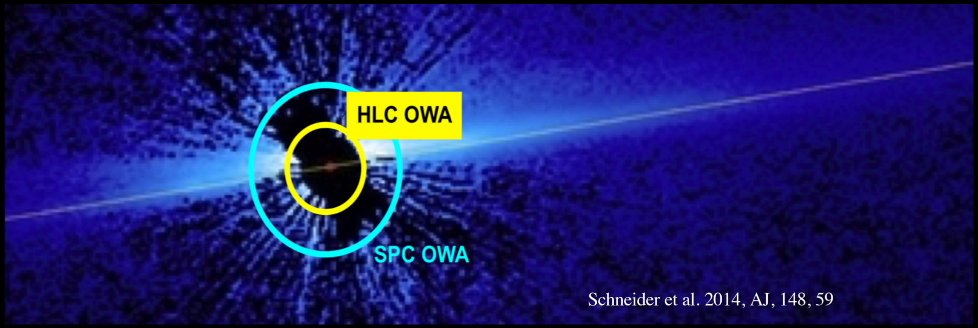
Roman can study tenuous debris and exozodi disks at solar system scales

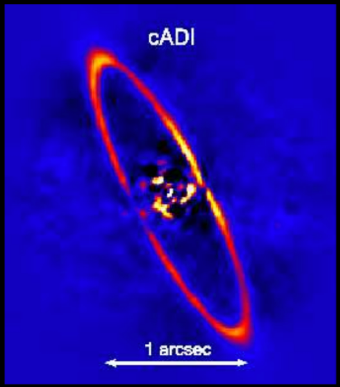


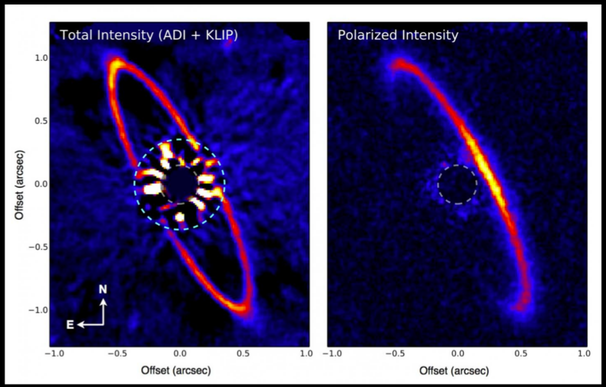
John Debes (STScI)
Ewan Douglas (UofAZ)
Bertrand Mennesson (JPL)
Bijan Nemati (UA Huntsville)

Imaging & Polarimetry of Known Cold Debris Disks

- **Q's**: Where does circumstellar material come from and how is it transported? What is the composition of dust in the inner regions of debris disks?
- **CGI can**: Map morphology and the degree of polarization.
- **During TDP:** 2-3 disks
- **Beyond TDP**: Additional disks with a variety of properties







Perrin+2015
Milli+2017

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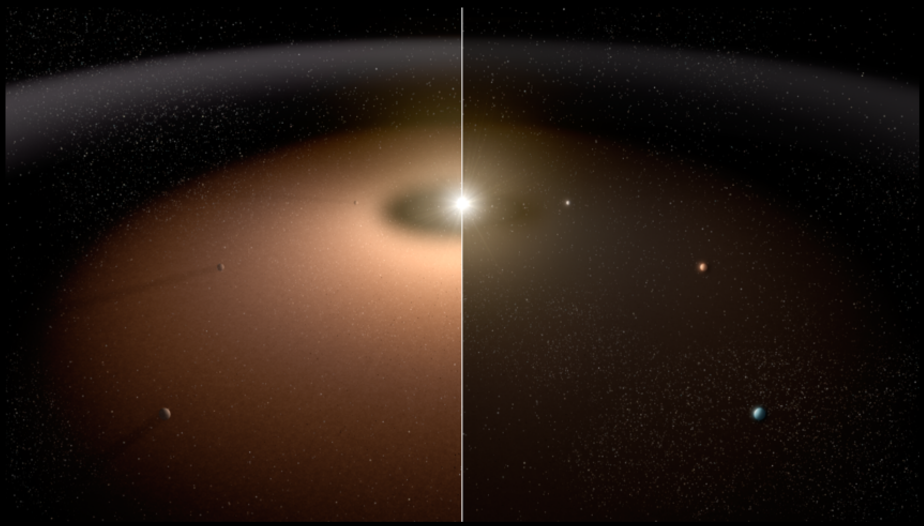
First visible light images of exozodiacal dust

- **Q**: How bright is exozodiacal dust in scattered light? Will it affect exo-Earth detection with future missions?
- **CGI can**: Probe low surface density disks in habitable zone of nearby stars. Complement LBTI mid-IR survey.
- **During TDP:** Opportunistic, as part of exoplanet observations.
- **Beyond TDP**: Survey best potential exo-Earth targets for future missions



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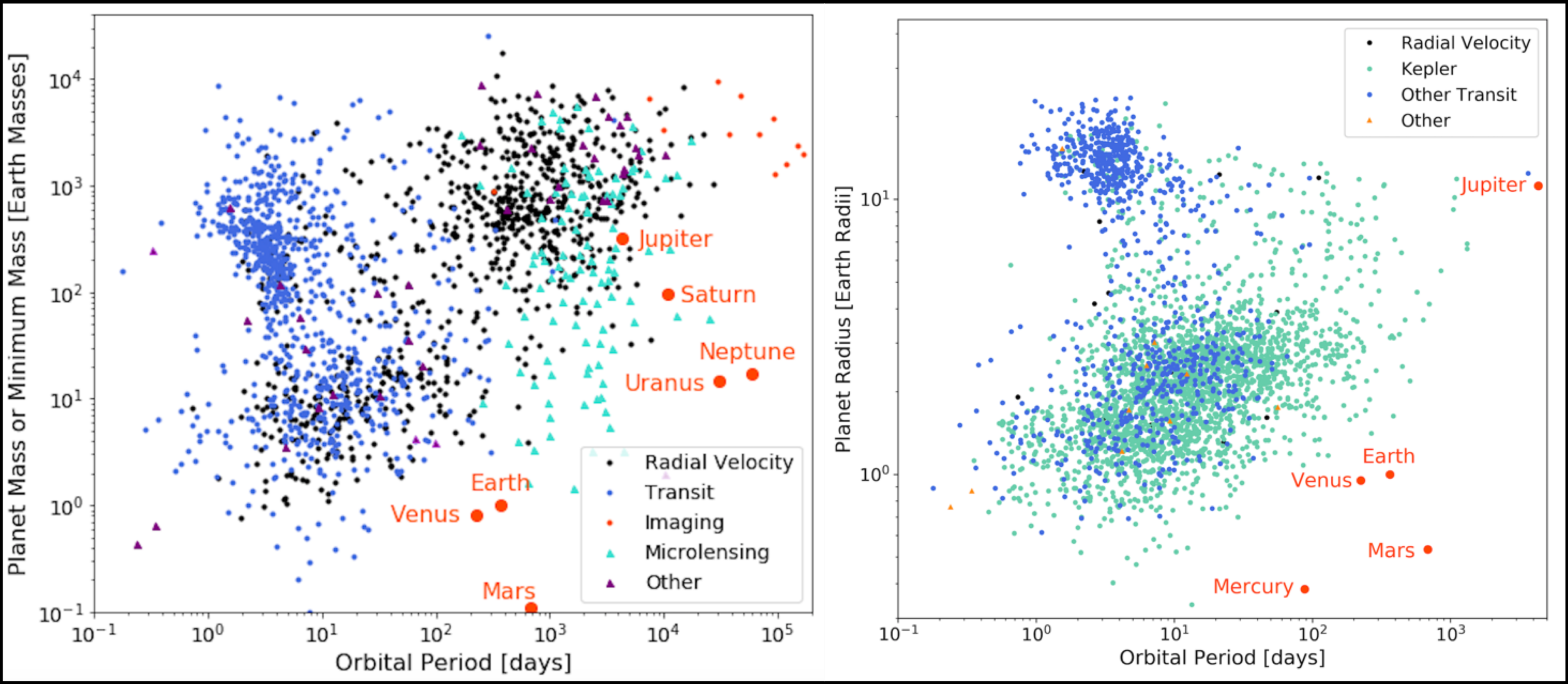
Exoplanet Demographics

Current Status of Exoplanet Demographics



(Courtesy of Jesse Christiansen based on data from NASA Exoplanet Archive)

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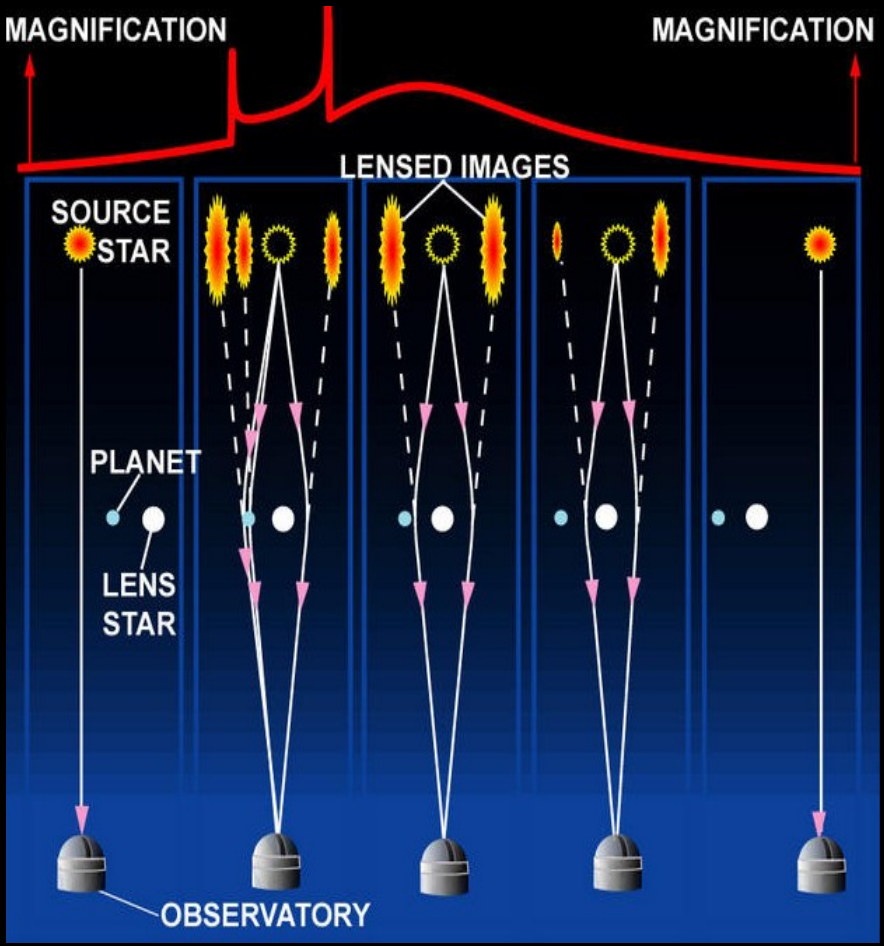
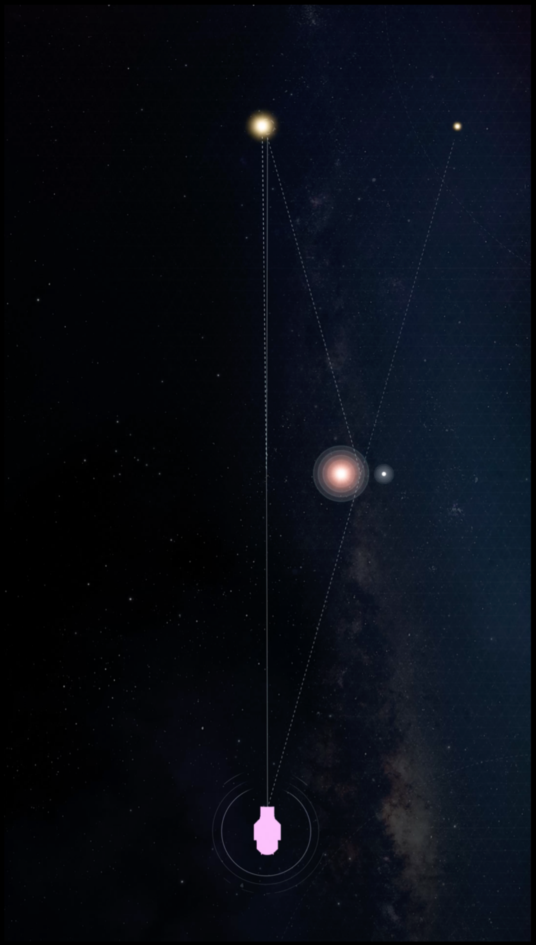
Microlensing.





Unique Sensitivity of Microlensing to Exoplanetary Systems.

- Planets beyond the snow line.
  - Most sensitive at ~few $\times$ a_{snow}
- ***Very*** low-mass planets.
  - >10% Mars.
- Long-period and free-floating planets.
  - 0.5 AU - ∞
- Wide range of host masses.
  - BD, $M<M_{Sun}$, remnants
  - Typically 0.5 M_{Sun}
- Planets throughout the Galaxy.
  - 1-8 kpc

A Complete Statistical Census of Exoplanets

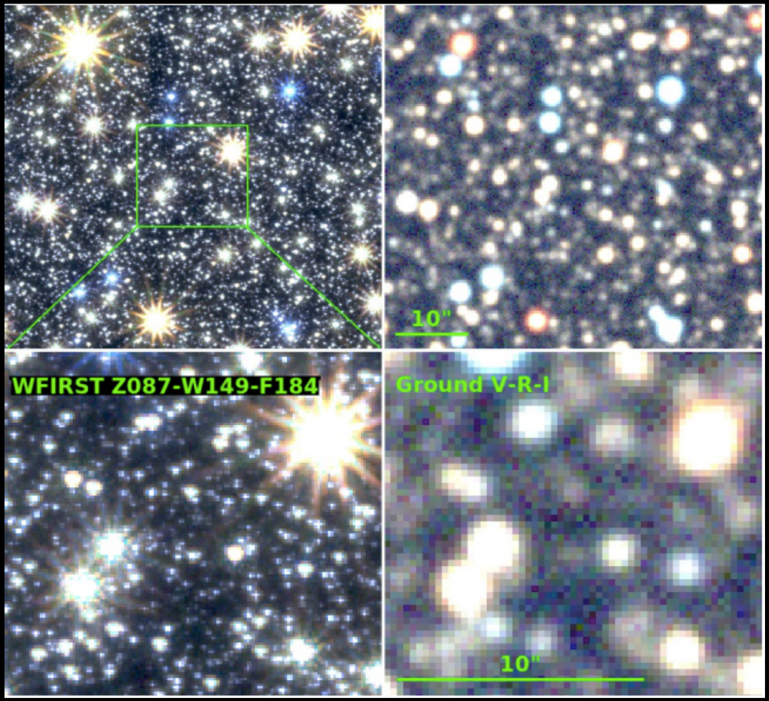
- Kepler provided the first large-scale demographic survey but was largely blind to planets with period less than ~1 year.
- A complete census provides the “ground truth” needed to understand planet formation and evolution.
- The outer parts of planetary systems are important:
  - Most giant planets likely formed beyond the snow line.
  - We would like to place our solar system in context.
  - Water for habitable planets likely delivered from beyond the snow line.
  - Understand the frequency of planet formation in different environments.

Requirements

- Monitor hundreds of millions of bulge stars continuously on a time scale of ~10 minutes.
  - Event rate ~10^{-5}/year/star.
  - Detection probability ~0.1-1%.
  - Shortest features are ~30 minutes.
- Relative photometry of a few %.
  - Deviations are few – 10%.
- Resolve main sequence source stars for smallest planets.
- Resolve unrelated stars for primary mass determinations.

Ground vs. Space

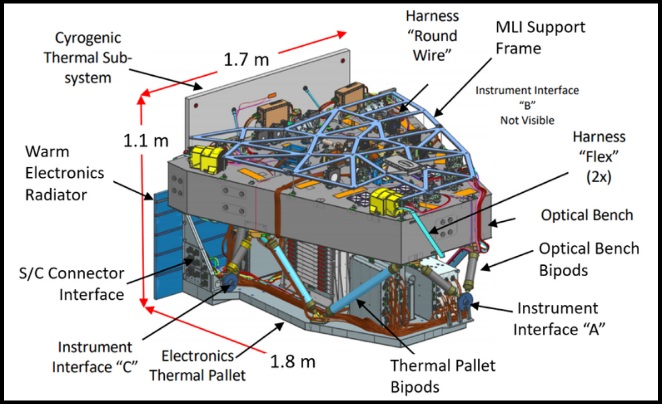
- Infrared.
  - More extincted fields.
  - Smaller sources.
- Resolution.
  - Low-magnification events.
  - Isolate light from the lens star.
- Visibility.
  - Complete coverage.
- Smaller systematics.
  - Better characterization.
  - Robust quantification of sensitivities.

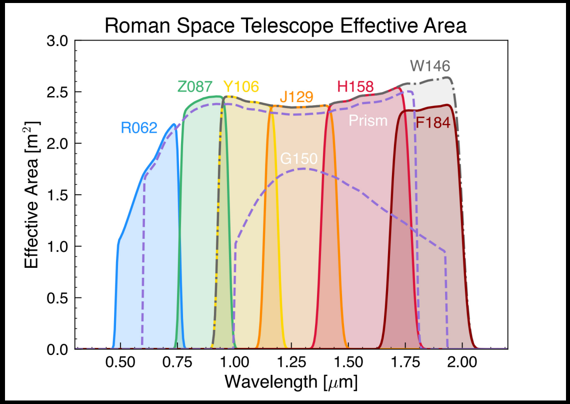


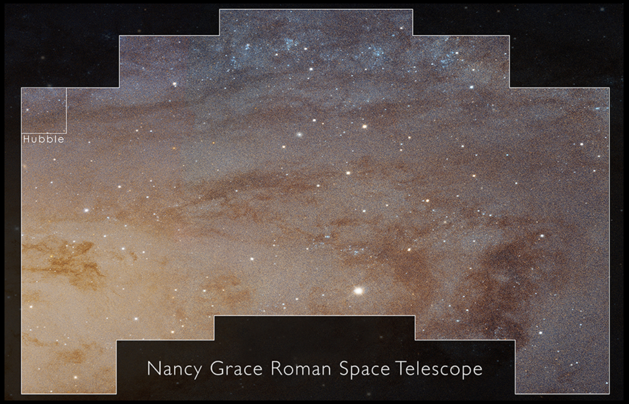
(Penny et al. 2019)

Science enabled from space: sub-Earth mass planets, habitable zone planets, free-floating Earth-mass planets, satellites, mass measurements (Bennett & Rhie 2002)

Wide-Field Instrument (WFI)

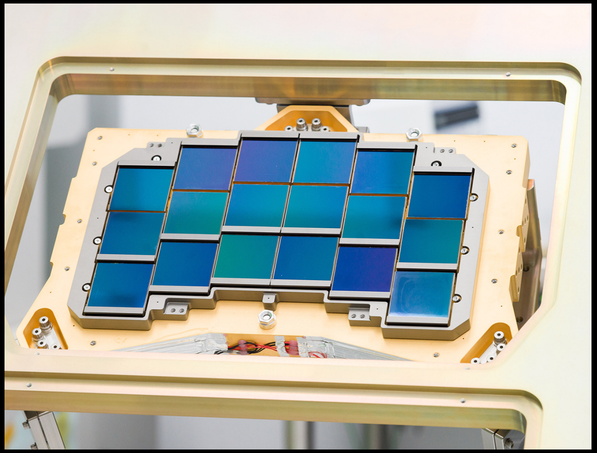




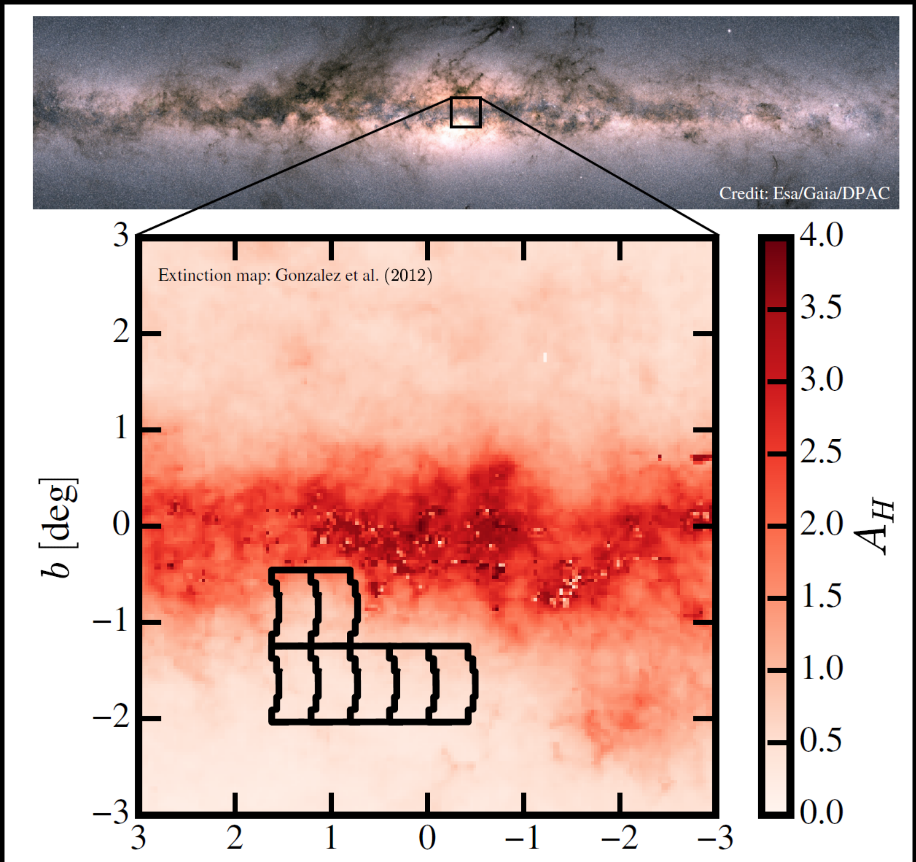


Roman Space Telescope Imaging Capabilities							
Telescope Aperture (2.4 meter)		Field of View (45′x23′; 0.28 sq deg)		Pixel Scale (0.11 arcsec)		Wavelength Range (0.5-2.0 μm)	
Filters	**R062**	**Z087**	**Y106**	**J129**	**H158**	**F184**	**W146**
Wavelength (μm)	0.48-0.76	0.76-0.98	0.93-1.19	1.13-1.45	1.38-1.77	1.68-2.00	0.93-2.00
Sensitivity (5σ AB mag in 1 hr)	28.5	28.2	28.1	28.0	28.0	27.5	28.3

Roman Space Telescope Spectroscopic Capabilities				
	Field of View (sq deg)	**Wavelength (μm)**	**Resolution**	**Sensitivity (AB mag) (10σ per pixel in 1hr)**
Grism	0.28 sq deg	1.00-1.93	435-865	20.5 at 1.5 μm
Prism	0.28 sq deg	0.75-1.8	70-170	23.5 at 1.5 μm



Roman Galactic Exoplanet Survey*



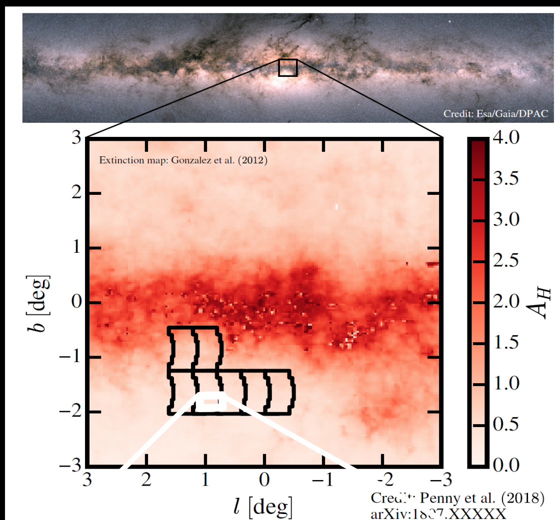
(Penny et al. 2019)

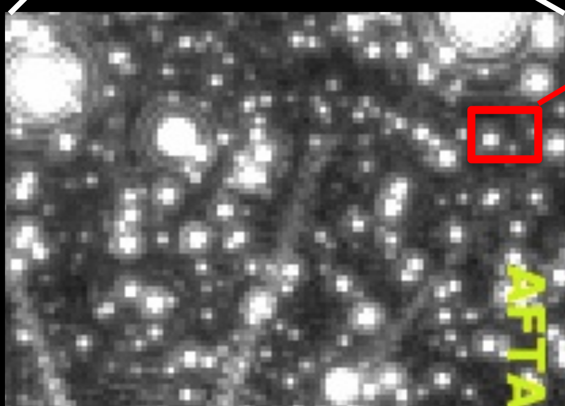
- 7 fields for a total of ~2 deg^2
- Wide $W149_{AB}$ (0.927-2 μm) filter**
- 15-minute cadence.
- ~50s exposures.
- Observations every 6 hours in alternating blue/red filters (e.g., F087, F184).
- 6 x 72-day seasons.
- ~41,000 exposures in $W149_{AB}$.
- ~432 total days spread over 5-year mission.

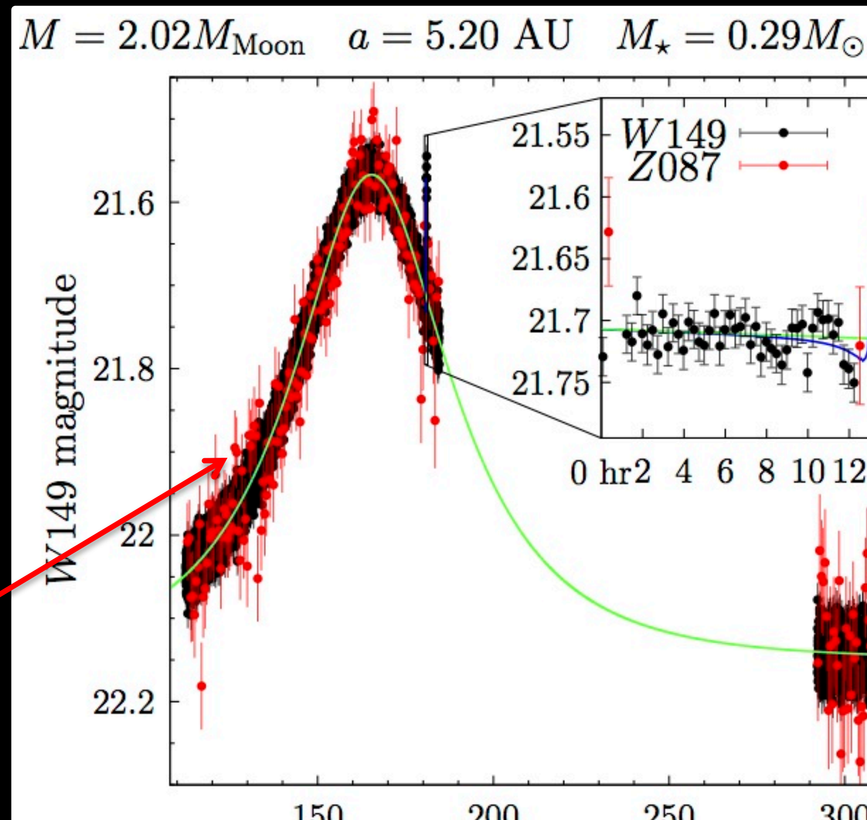
* Notional survey design required to achieve the science goals. The final design of the major surveys won't be finalized until much closer to launch, with input from the broader community.

** One photon per second for $W149_{AB}$ ~27.6

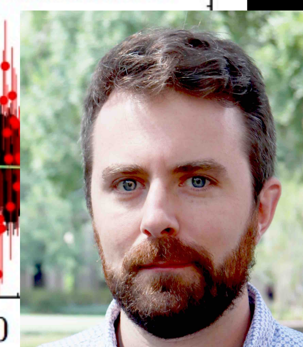
RGES Simulations





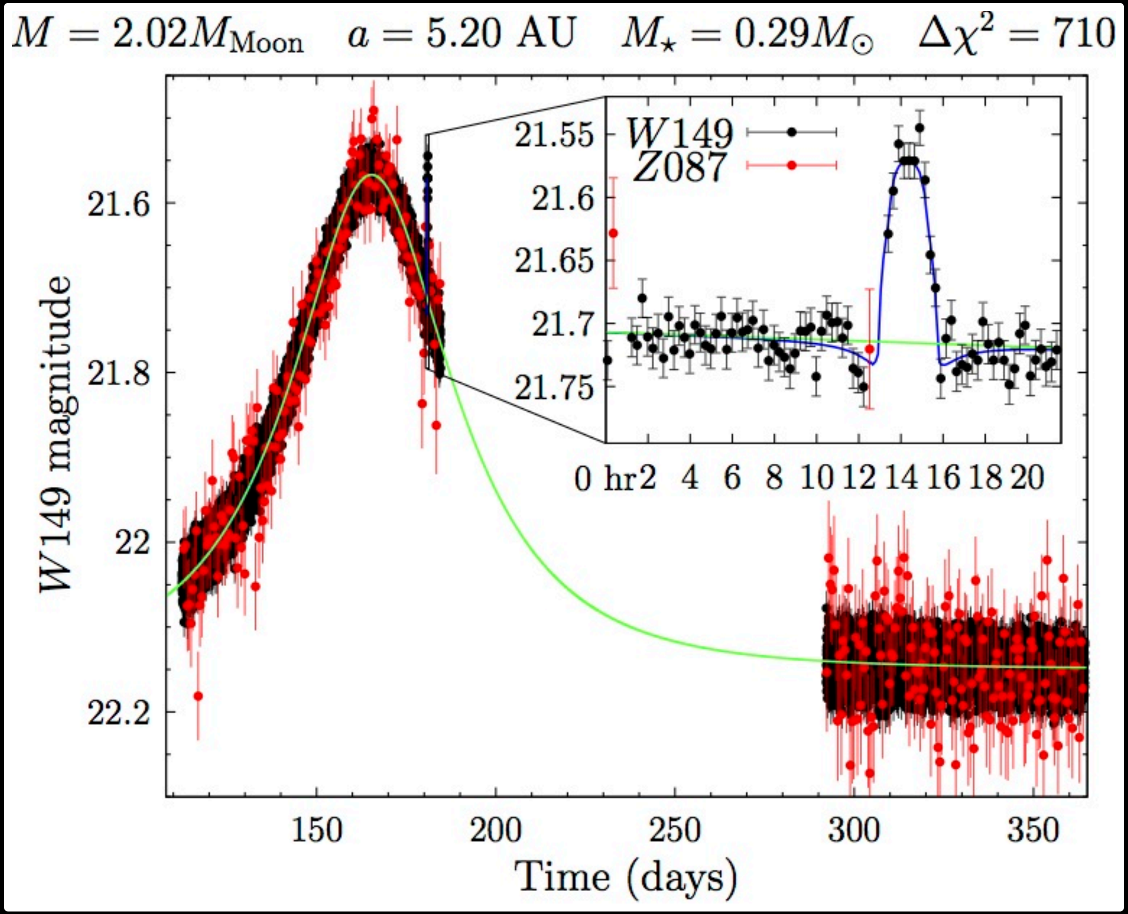


(Penny et al. 2019)



Matthew Penny

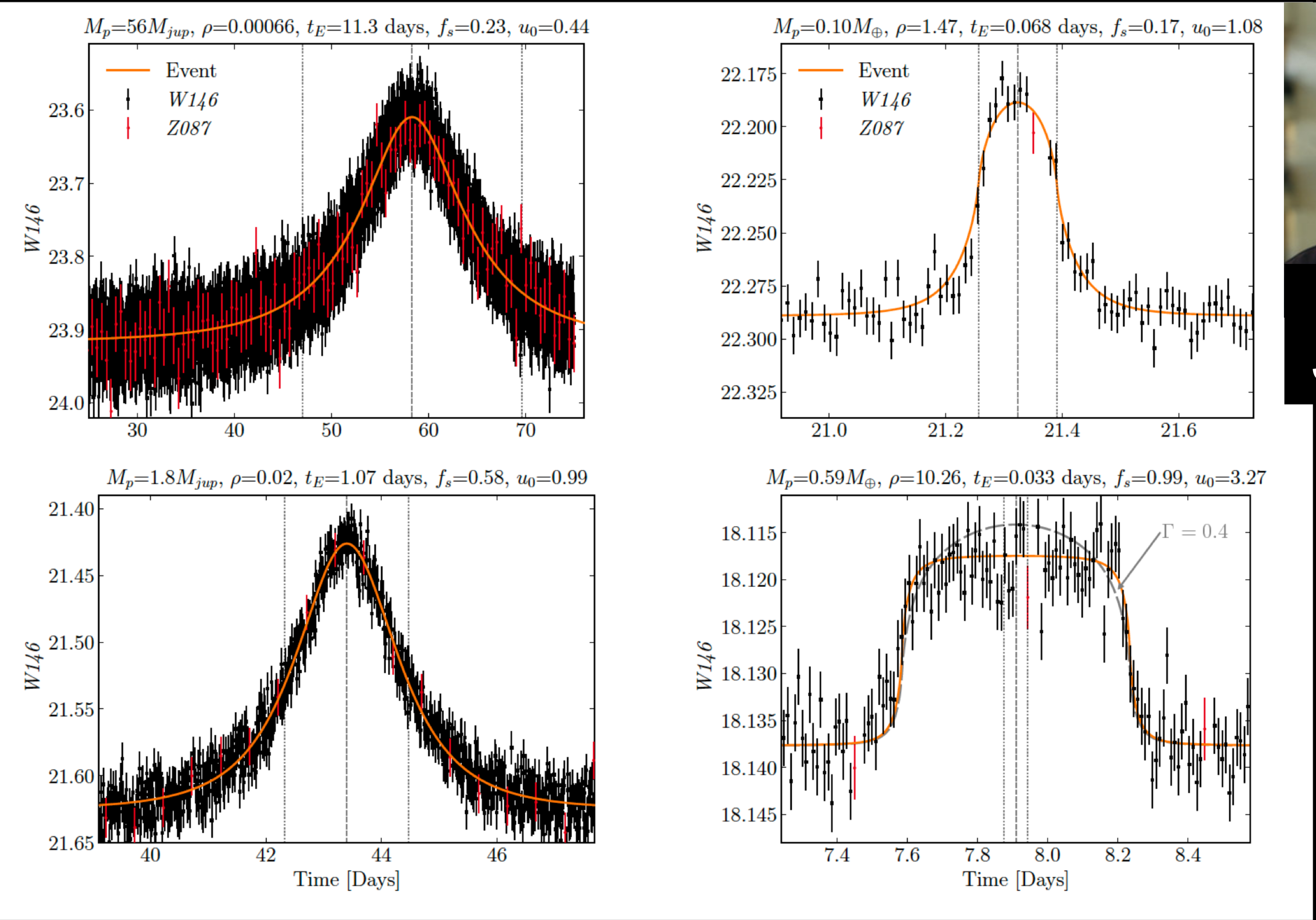
Sensitivity to Ganymede-mass Exoplanets



2 × Mass of the Moon @ 5.2 AU (~27 sigma)

(Penny et al. in 2019)

Also: Free Floating Planets!



Samson Johnson

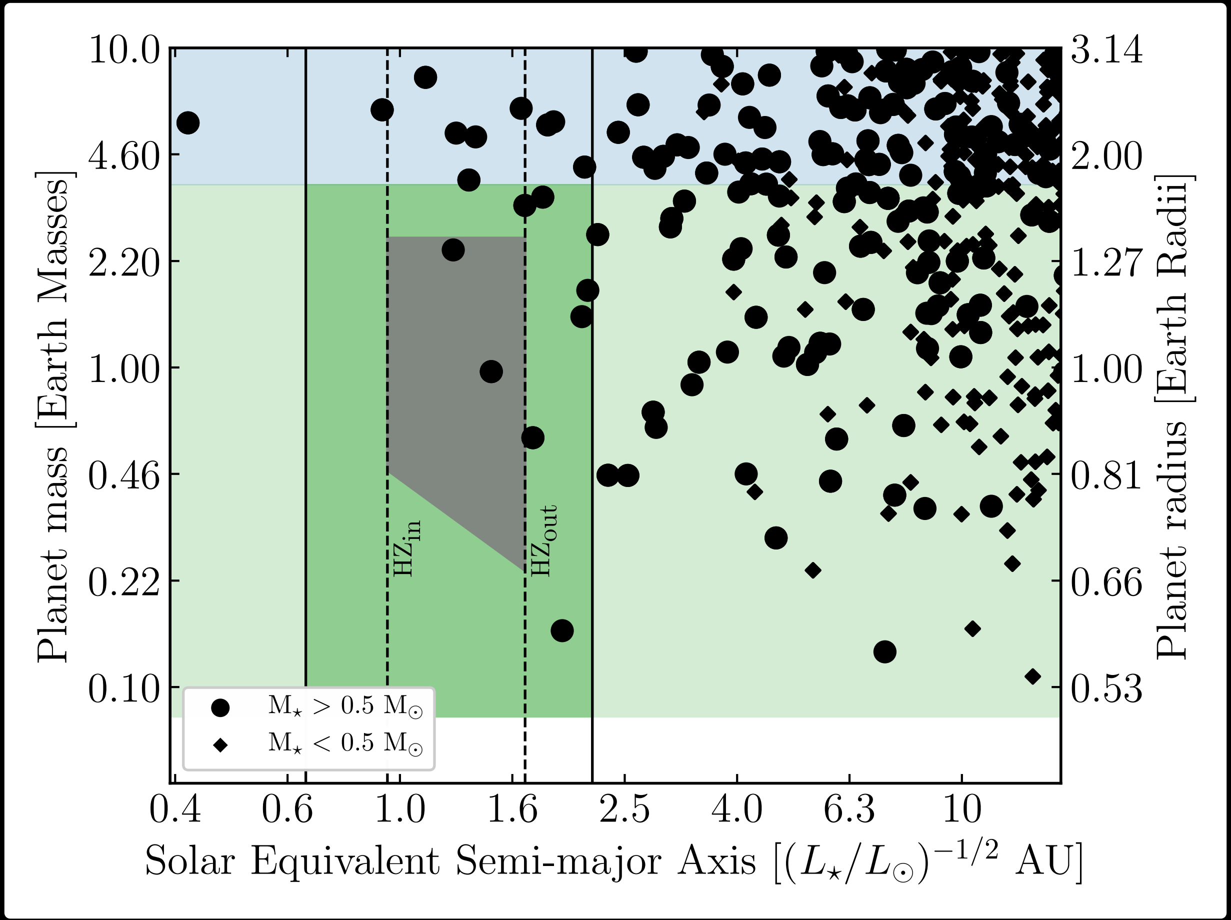
(Johnson et al. 2020)

Predictions for the Yield of FFPs

Mass ($M_\oplus$)	Mass Function: One-Per-Star	Log-Uniform	Fiducial
0.01	1.22	0.349	0.698
0.1	17.9	5.13	10.3
1	88.3	25.2	50.5
10	349	83.0	103.
100	1250	298	68.9
1000	4100	976	42.0
10000	13300	3170	25.4
Total	3750	897	249

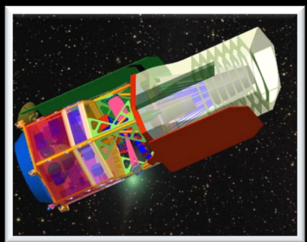
(Johnson et al. 2020)

Potentially Habitable Planets

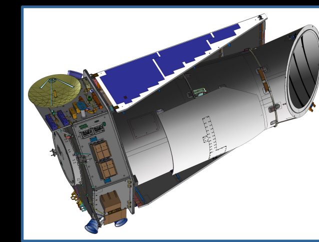


(Johnson et al., in prep.)

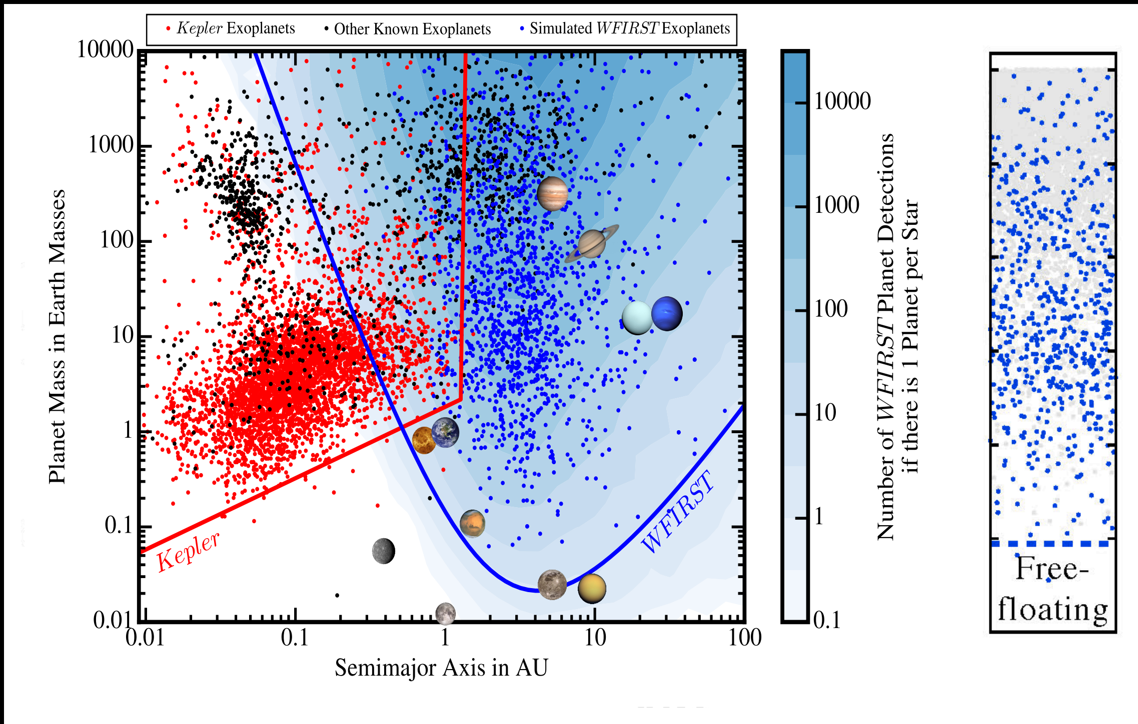
Exoplanet Demographics with *Roman*



Together, Kepler and *Roman* complete the statistical census of planetary systems in the Galaxy.

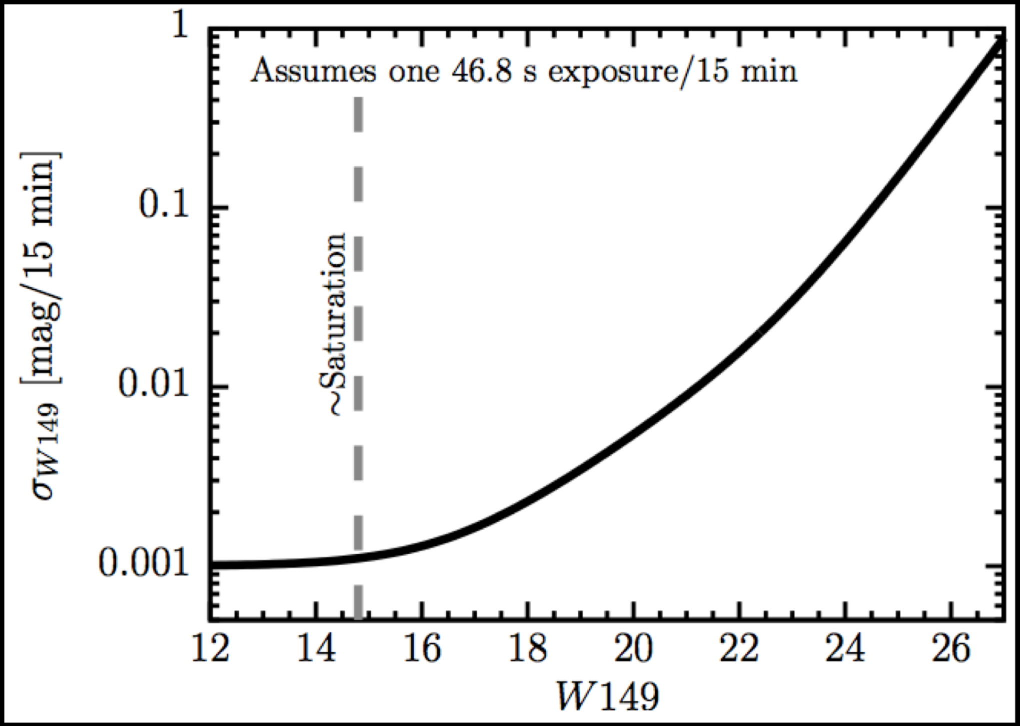


- ~1400 bound planet detections.
- Some sensitivity to "outer" habitable zone planets.
- Sensitive to analogs of all the solar systems planets except Mercury.
- Hundreds of free-floating planets (~60 with $M \leq M_{Earth}$).
- Characterize the majority of host systems.
- Galactic distribution of planets.
- Sensitive to lunar-mass satellites.
- 100,000 transiting planets.



(Penny et al. 2019)

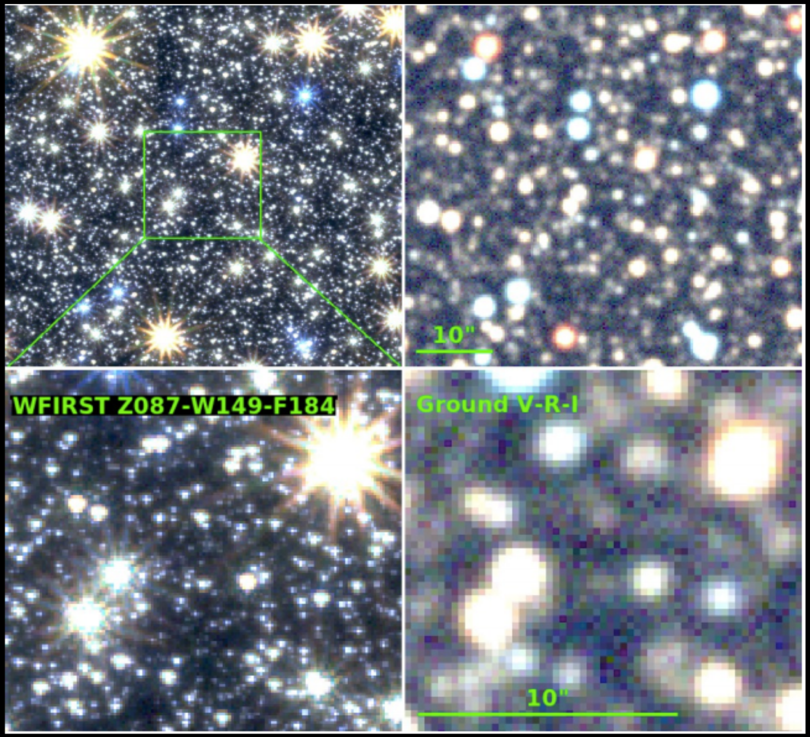
Statistical Power of the RGES Survey



Penny et al. 2019

- For a $W149_{AB}$~21.15 star:
  - Photon-noise relative photometric precision of σ~0.01 mag per exposure.
  - Total of ~10^9 photons over the survey.
  - Saturation @ $W149_{AB}$ ~14.8.
- Root N: $\sqrt{41{,}000}$ ~ 200

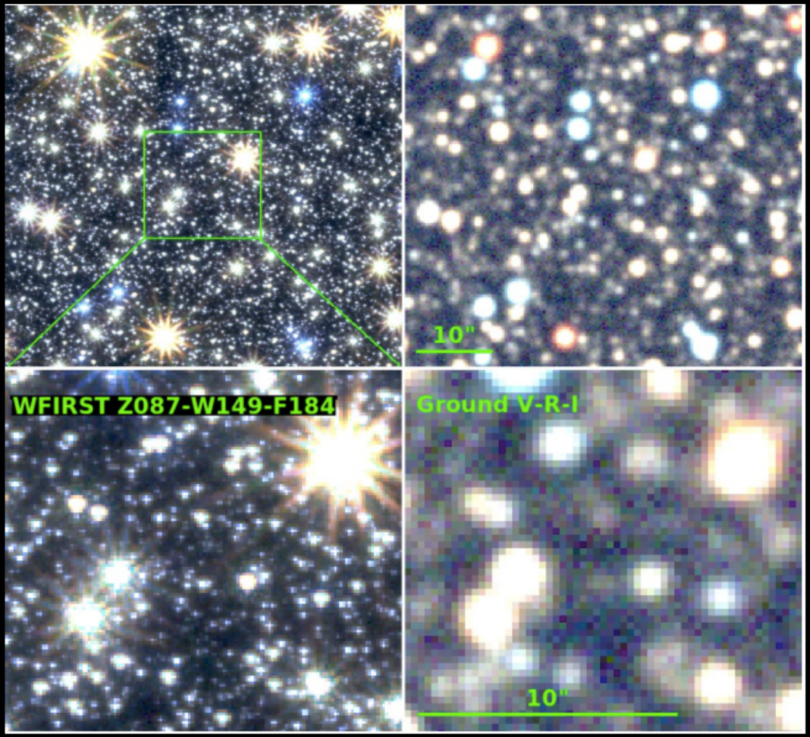
Number of Stars and Microlensing Events



Stars ($W149 < 15$)	$\sim 0.3 \times 10^6$
Stars ($W149 < 17$)	$\sim 1.4 \times 10^6$
Stars ($W149 < 19$)	$\sim 5.8 \times 10^6$
Stars ($W149 < 21$)	$\sim 38 \times 10^6$
Stars ($W149 < 23$)	$\sim 110 \times 10^6$
Stars ($W149 < 25$)	$\sim 240 \times 10^6$
Microlensing events $\lvert u_0 \rvert < 1$	$\sim 27,000$
Microlensing events $\lvert u_0 \rvert < 3$	$\sim 54,000$

Penny et al. 2019

Photometric and Astrometric Precision.
(Relative, Poisson Noise Only)



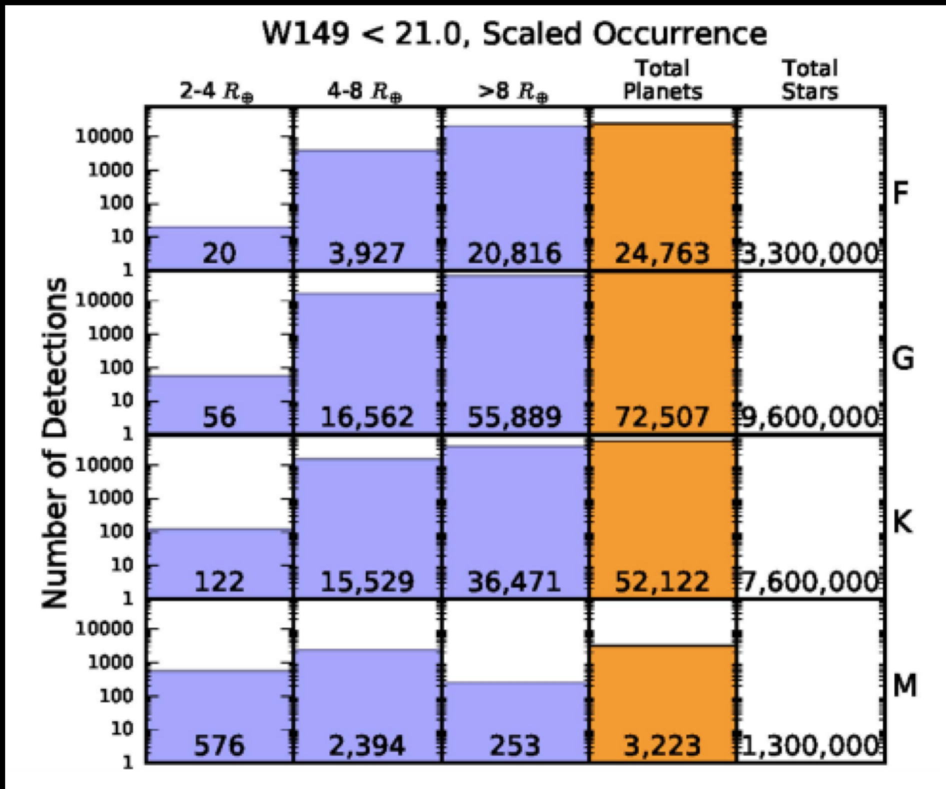
$W149_{AB}$	# of Stars	Relative photometric precision (per exp.)	Astrometric precision (per exp.)
19	6×10^6	~0.8%	~0.6 mas
21	40×10^6	~1%	~1.5 mas

Penny et al. 2019

“Auxiliary” Science with the *Roman* Galactic Exoplanet Survey

- Measurement of the mass function of condensed objects of 10 orders of magnitude, including remnants and binarity
- Detection of ~10^5 hot and warm Jupiters & Neptunes via transits (Montet+2017)
- Asteroseismology of ~10^6 bulge giants (Gould+2014b)
- Parallaxes and Proper Motions of ~$6x10^6$ Bulge and Disk Stars
- Detection of ~$5x10^3$ Trans-Neptunian Objects (Gould+2014a)
- Variable stars
- Much, much more..

~10^5 Transiting Planets!



Expected yield of transiting planets orbiting dwarfs with $W149_{AB}<21$ (Montet et al. 2017)

- WFIRST will detect ~10^5 transiting planets with radii down to ~$2R_\oplus$.
- Most host stars will have measured distances.
- Several thousand can be confirmed by the detection of their secondary eclipses.
- Some systems will have measured transiting timing variations.

Bennett & Rhie 2002
Montet et al. 2017

Summary: Directly-Imaged Planets and Disks with Roman

Roman Coronagraph instrument (CGI)

- Technology demonstration instrument: first active coronagraph in space
- Pathfinder for future reflected-light direct imaging missions to characterize Earth analogs (e.g., HabEx, LUVOIR)
- Also capable of novel exoplanet and disk science:
  - Imaging & spectroscopy of young planets in the optical
  - First reflected light images and spectroscopy of mature giant planets
  - Imaging and polarimetry of circumstellar debris and exozodiacal disks
- Get involved via the CGI Community Participation Program (CPP)!

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Summary: Demographics with Roman

- Microlensing is complementary to other exoplanet detection techniques. In particular, it is sensitive to
  - Cold planets beyond the "snow line"
  - Very low-mass planets with masses down to several lunar masses
  - Long period and free-floating planets
  - Planets orbiting stars throughout the Galaxy
- Realizing the full potential of microlensing requires going to space.
- Roman will complete the census begun by Kepler and will revolutionize our understanding of cold planets.
- Will enable qualitatively new, exciting science: sub-Earth-mass planets, free-floating planets, outer habitable zone planets, mass measurements.
- Enormous amount of 'auxiliary' science can be done with the RGES.
- Final survey design is not set, and we seek broad input from the community – you!