Detecting and Characterizing Exoplanetary Systems using Astrometry with the Nancy Grace Roman Space Telescope

2022 Sagan Exoplanet Summer Hybrid Workshop
Exoplanet Science in the Gaia Era
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National Aeronautics and Space Administration

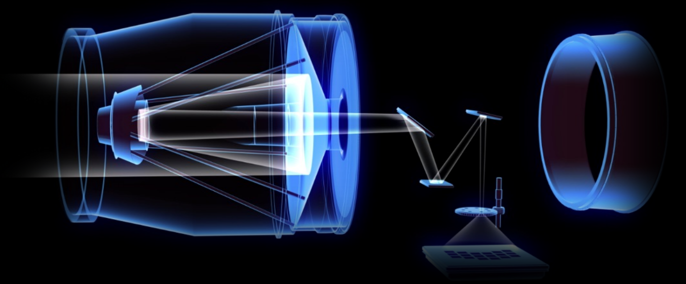
Roman Observatory and Instrument Properties, and Expected Astrometric Performance

Summary of Roman Properties

Properties	Roman
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	202/5 years
Orbit	L2

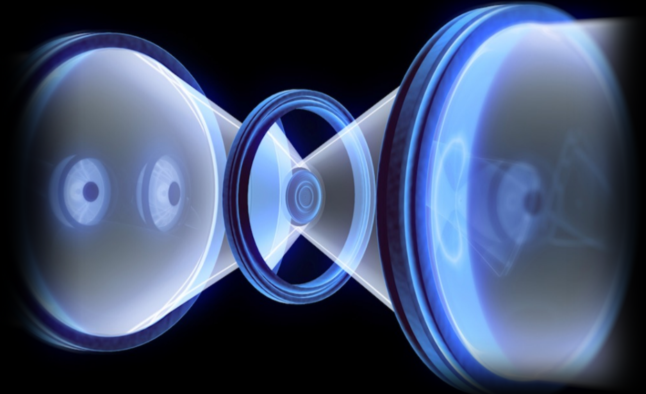
Wide-Field Instrument (WFI)

- ~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) high-contrast imager
- Polarimeter and spectrograph
- 3 types of coronagraph masks

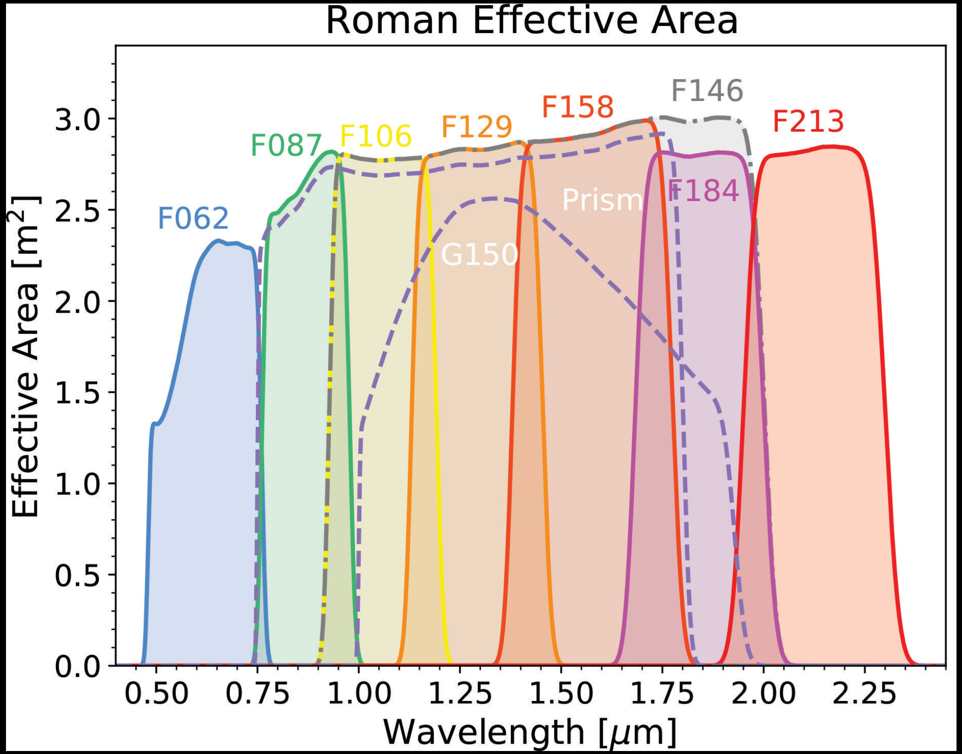


Surveys and Observations

- HLS: Imaging & spectroscopy over 1000's sq deg
- SNe & μL: Repeated monitoring of smaller areas
- Coronagraph: tech demo observations

Wide Field Imaging Filters and Dispersers

- Seven ~standard imaging filters
- Wide F146 filter used for the μL survey (~1-2 μm)
- Grism (1.0 – 1.93 μm, R~600)
- Prism (0.75 –1.80 μm, R~100)



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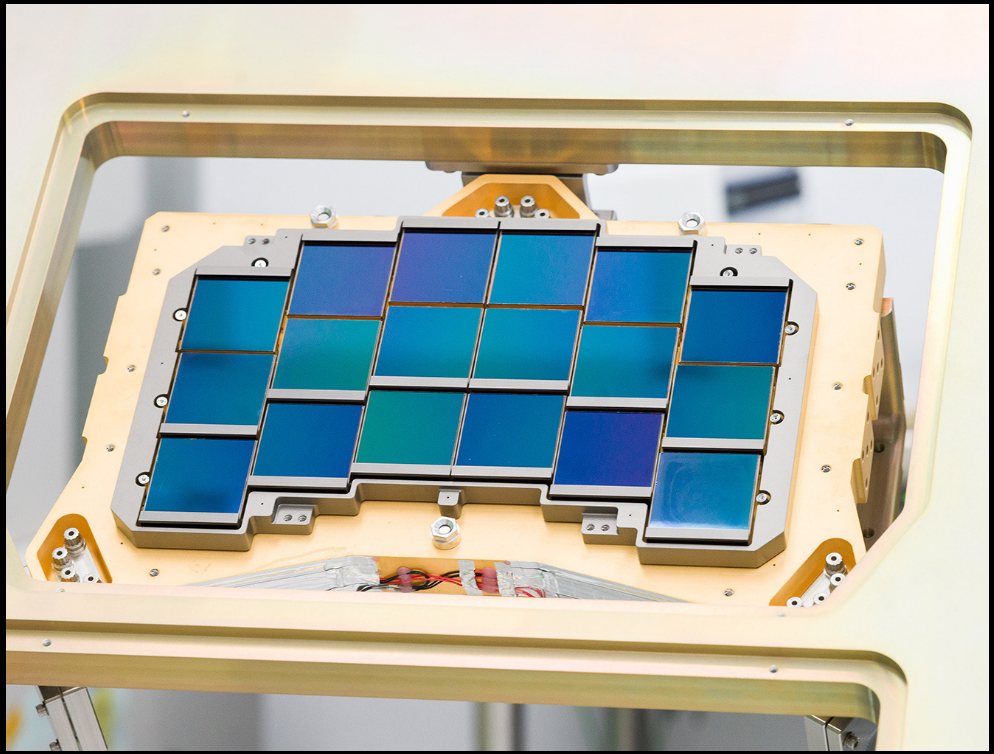
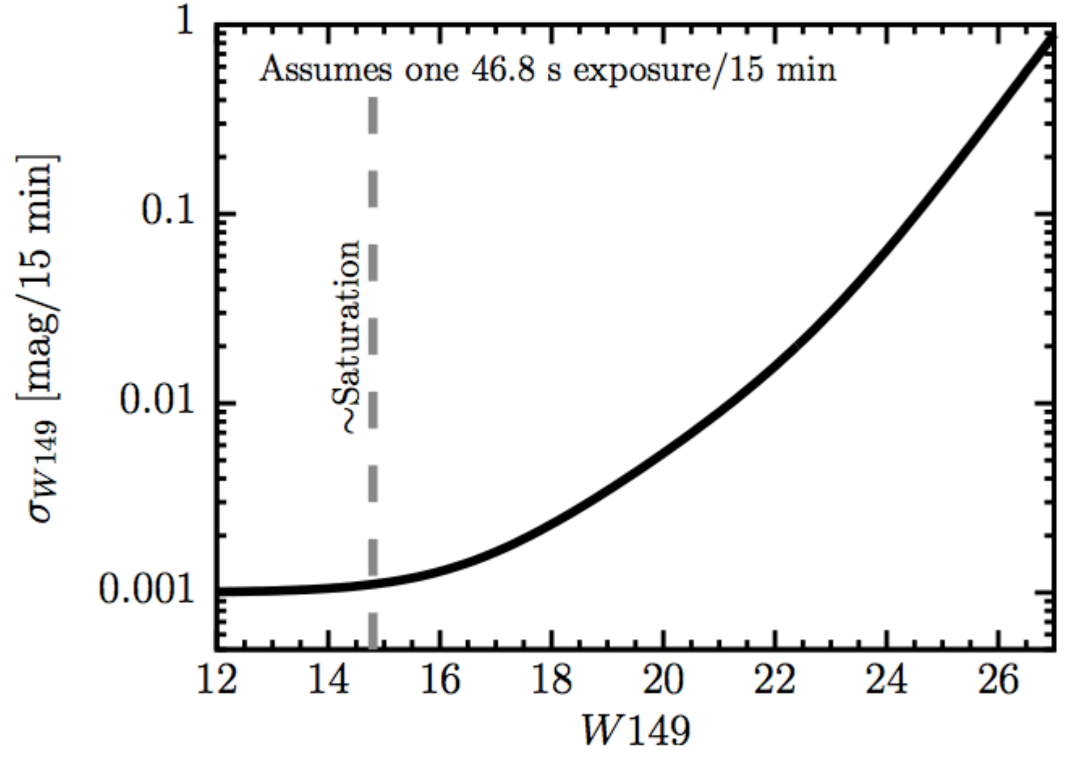
~100 Times the Field-of-View Of Hubble



Photometric and Astrometric Precision



- For a $F146_{AB}$~21.15 star, σ_{phot}~1% per ~50s exposure
- σ_{ast}~FWHM/SNR

  ~FWHM×σ_{phot}~0.1" ×0.01

  ~1 mas per exposure
- In principle, can be improved using $\sqrt{N}$, drift scanning, diffraction spikes
- Generally requires exquisite detector characterization for $\sigma_{\mathrm{ast}} \ll$ mas

Expected Astrometric Performance

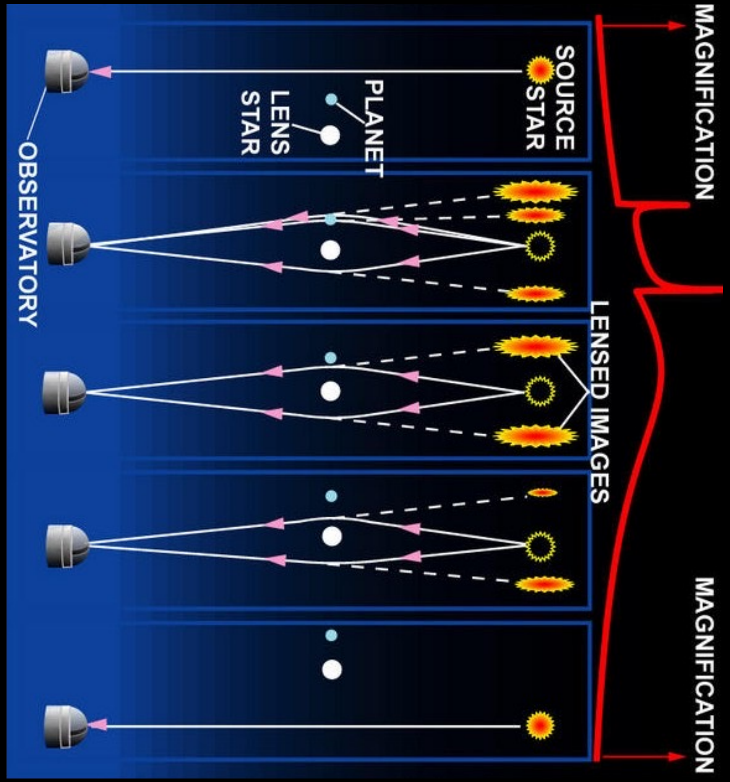
Context	Estimated performance
Single-exposure precision	0.01 px; 1.1 mas
Typical guest-observer program (100 exposures of one field)	0.1 mas
Absolute astrometry accuracy	0.1 mas
Relative proper motions derived from High-Latitude Survey	25 μas yr^{-1}
Relative astrometry, Exoplanet MicroLensing Survey (per image)	1 mas
Relative astrometry, Exoplanet MicroLensing Survey (full survey)	3–10 μas
Spatial scanning, single scan	10 μas
Spatial scanning, multiple exposures	1 μas
Centering on diffraction spikes	10 μas

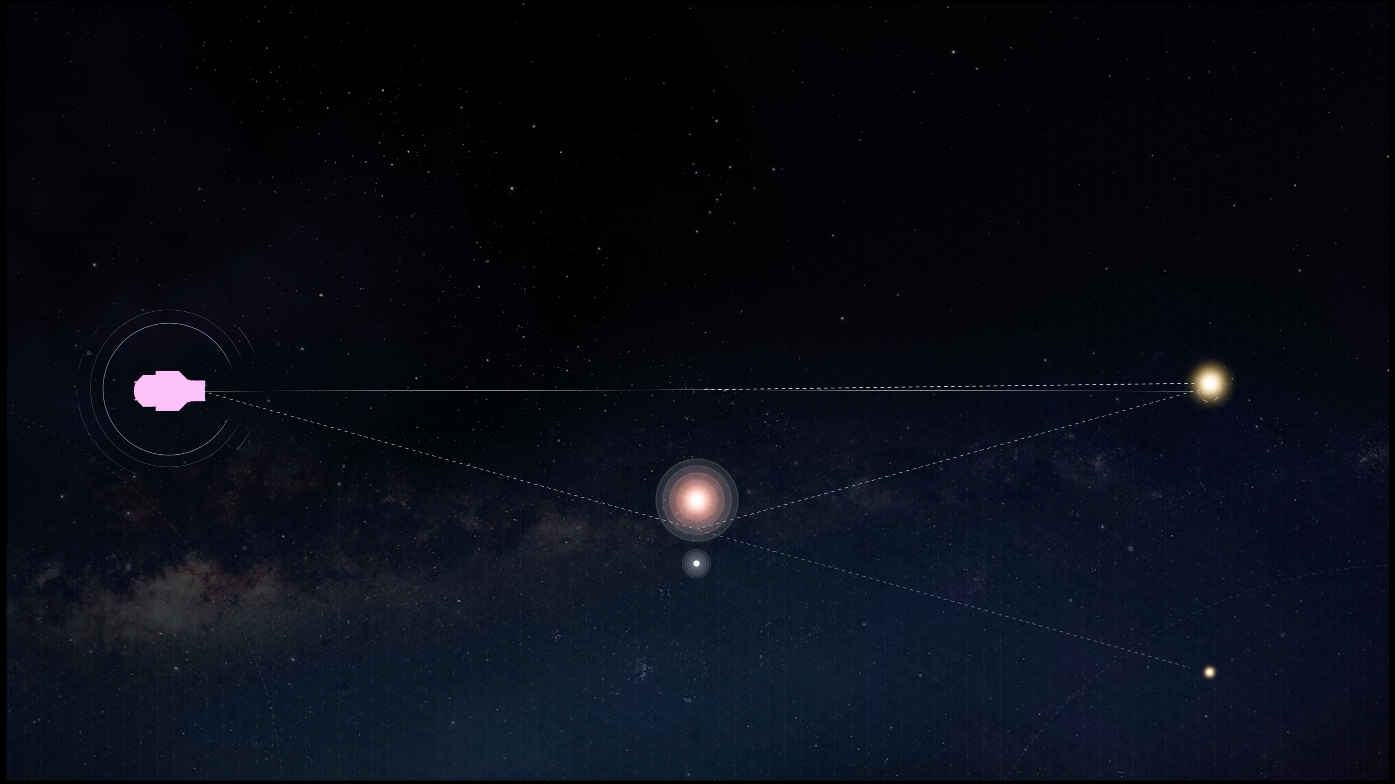
Sanderson et al. 2019

Exoplanet Applications of Precise Astrometry with Roman

The Roman Galactic Bulge Time Doman Survey (RGBTDS)

Detection of Extrasolar Planets with Microlensing

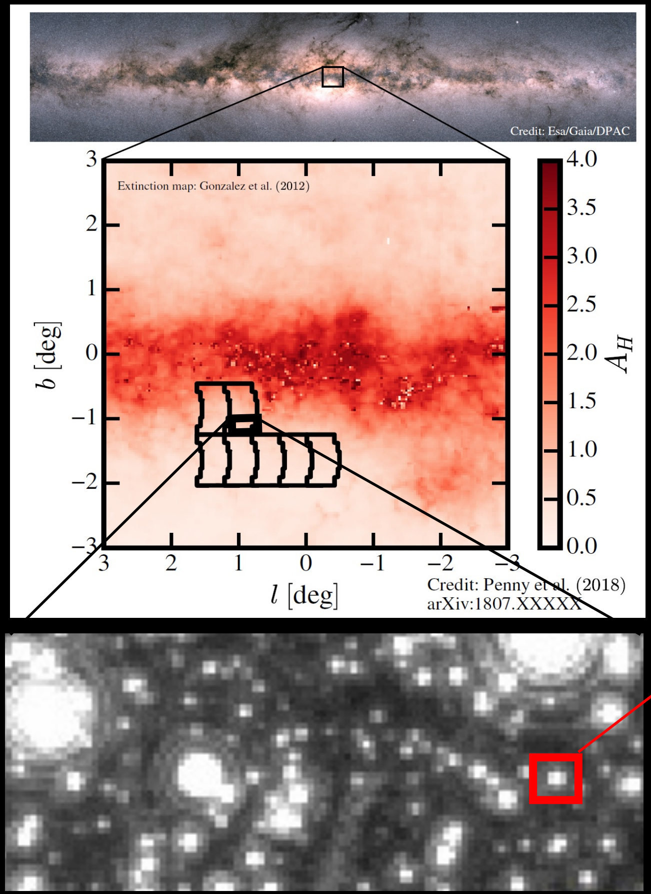


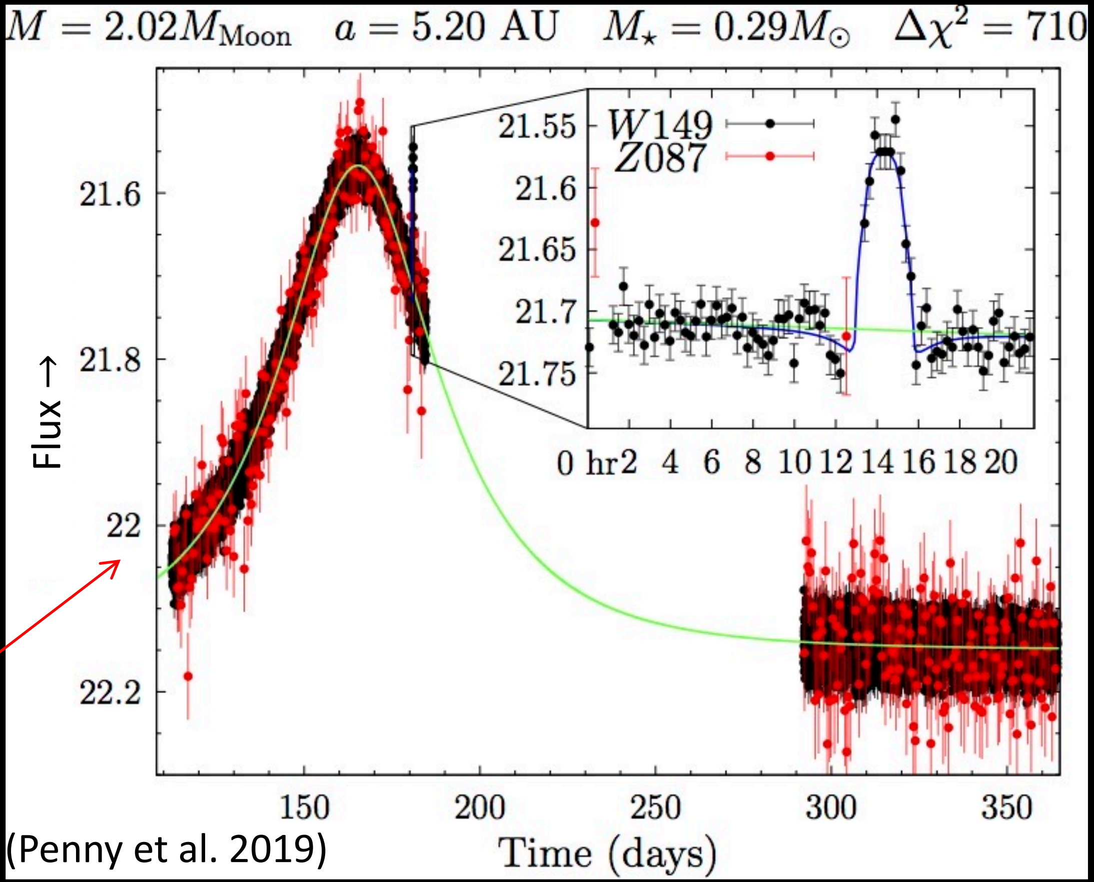


Unique Sensitivity of Microlensing to Exoplanetary Systems

- Planets beyond the snow line.
  - Most sensitive at ~few × 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
- Solar System analogs
- Moons of giant and terrestrial planets

A Microlensing Exoplanet Survey with Roman





Simulation software written by:

Matthew Penny (LSU)

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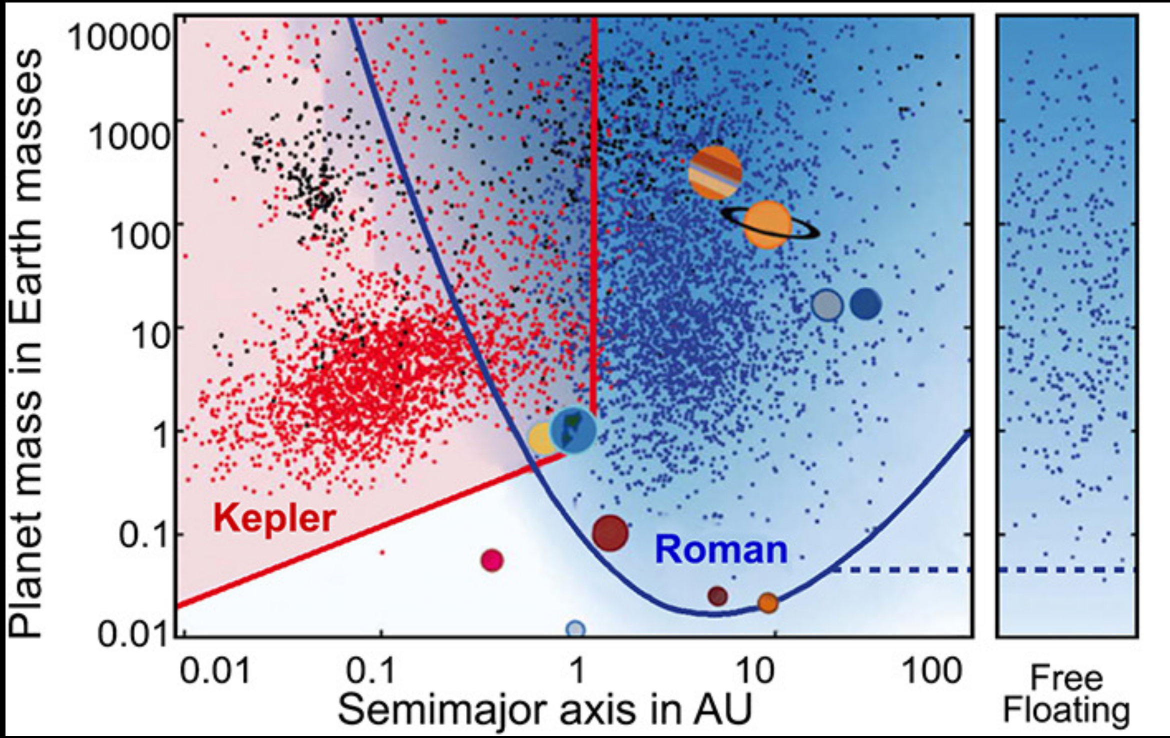
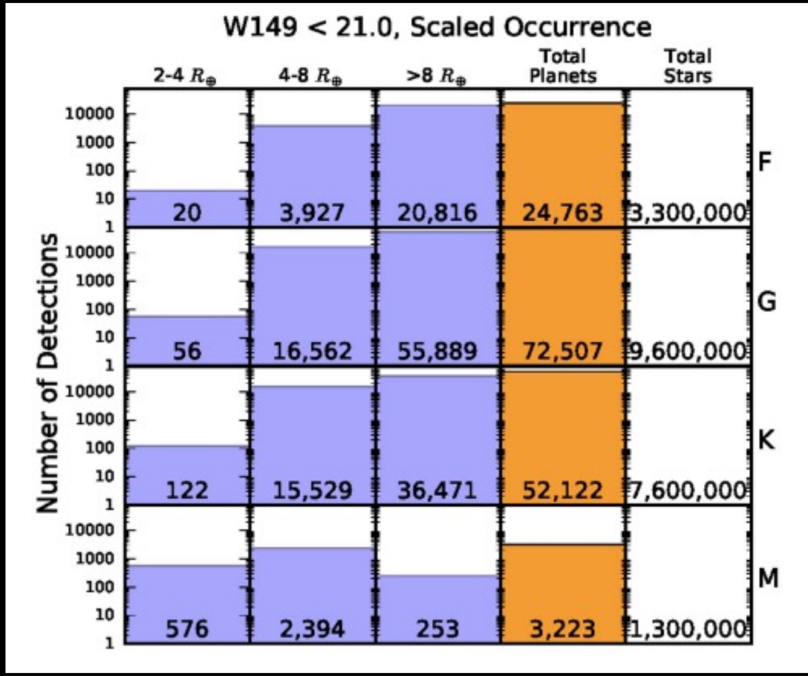
0.1% of the survey area

Roman will complete the statistical census of exoplanets



$M/M_\oplus$ Duration	0.1 -0.3	1	10	100	1000	3000 - 1000 0	Total
Bound Planets	20	181	545	412	224	91	1474
Free Floating Planets	10	51	103	69	42	25	249

Also, ~10^5 Transiting Planets!



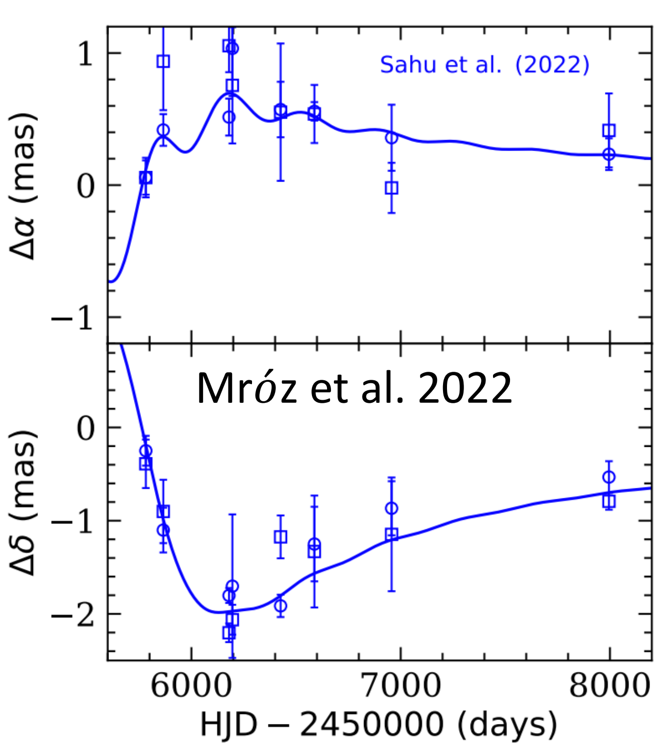
Expected yield of transiting planets orbiting dwarfs with $W149_{AB}<21$

Montet et al. 2017 studied the prospects for detecting transiting planets with Roman's GBTDS:

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

How Roman's precise astrometry will help exoplanets

- Roman will measure parallaxes to the source stars of a planetary microlensing events, helping to constrain the parameters of the host stars and planets.
- Roman will measure the astrometric microlensing deflection that accompanies photometric microlensing events, enabling the mass measurement of host stars and planets.
- Roman will measure parallaxes to the host stars of the transiting planets detected during the RGBTDS, thereby helping to eliminate false positives and constrain the system properties.



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Astrometric Detection of Exoplanets with Roman

Astrometric Detection of Exoplanets

- This approximate $^S/_N$ assumes N uniform-sampled 2D astrometric measurements each with precision σ along each axis,.
- The astrometric signal of planets with periods longer than the duration of the survey T are very hard to detect
- They appear as linear 'trends', which cannot be distinguished from the host star proper motion.

$$^S/_N = \begin{cases} \sqrt{N} F(i,e,\omega) \dfrac{\alpha_0}{\sigma} \ \text{if}\ P \lesssim T \\ 0 \ \text{if}\ P \gtrsim T \end{cases},$$

where $\alpha_0 \equiv \left(\frac{a}{d}\right)\left(\frac{m_p}{M_*}\right)$ is the astrometric signal for a circular, face-on orbit, and

$$F(i,e,\omega) = \sqrt{\frac{1}{2}(1+\cos^2 i)\left[1 - e^2\left[3 - \left(\frac{2}{1+\cos^2 i} - 1\right)\right]\cos^2\omega\right]}$$

accounts for the effects of inclination i, eccentricity e, and longitude of periastron ω, and is generally of order unity.

Astrometric Detection of Exoplanets

$$S/N \simeq 20F\left(\frac{N}{50}\right)^{1/2}\left(\frac{\sigma}{10\mu\text{as}}\right)\left(\frac{P}{10\text{yr}}\right)^{2/3}\left(\frac{m_p}{10M_\oplus}\right)\left(\frac{M_*}{M_\odot}\right)^{-2/3} \text{ if } P \lesssim T$$

- A planet with $P = 10\text{yr}$ and m_p =10 $M_\oplus$ can be detected with $S/N \simeq 20$ (σ_{m_p}~5%) with N=50 (2D) astrometric measurements each with precision $\sigma = 10\ \mu\text{as}$ along each axis.
- Highly simplified treatment but provides a rough sense of the number and quality of the astrometric measurements needed.

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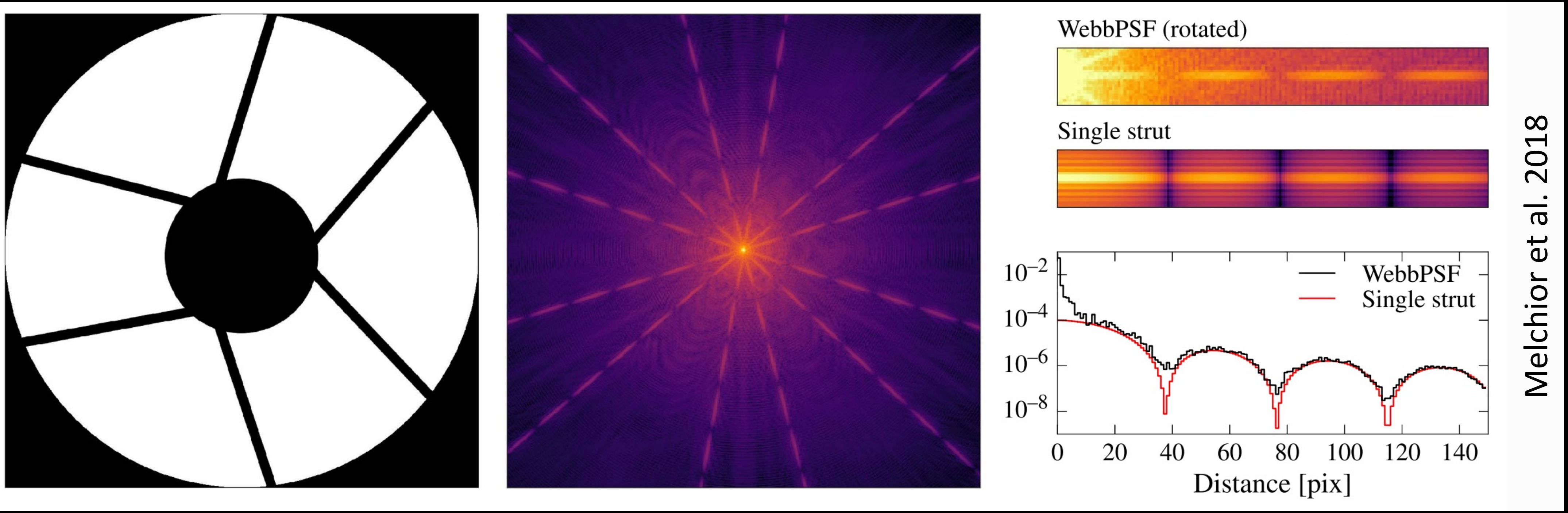
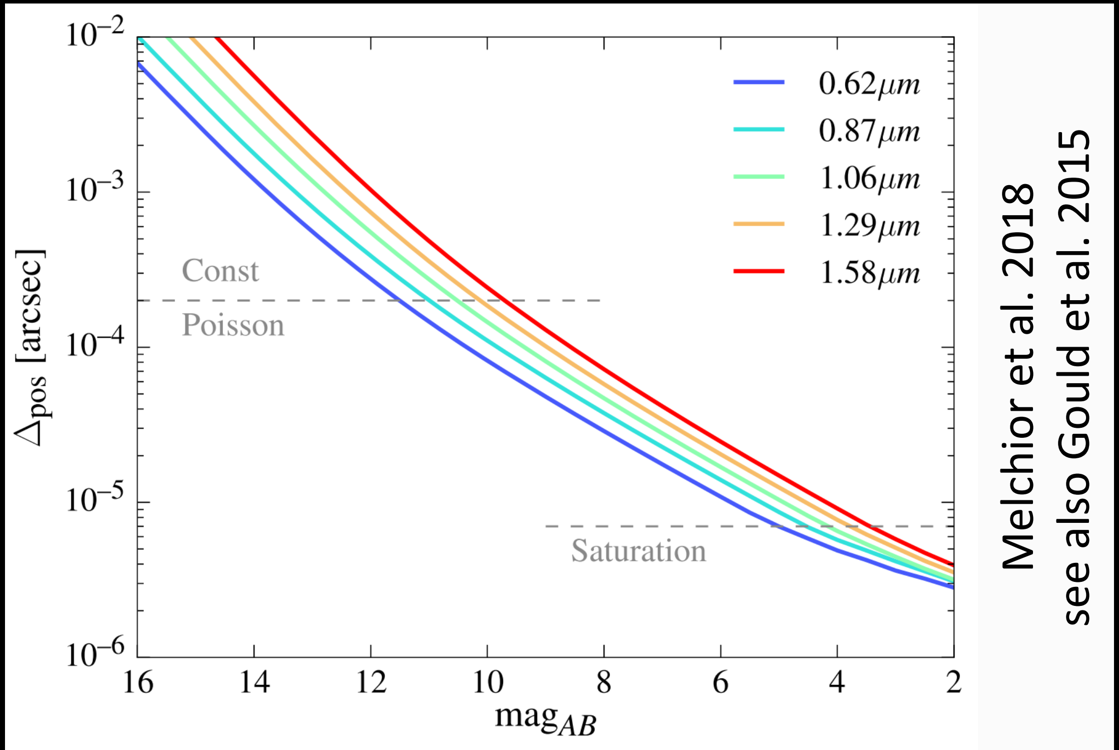
High-precision Astrometry with Roman – Centroiding Diffraction Spikes



Melchior et al. 2018

High-precision Astrometry with Roman – Centroiding Diffraction Spikes

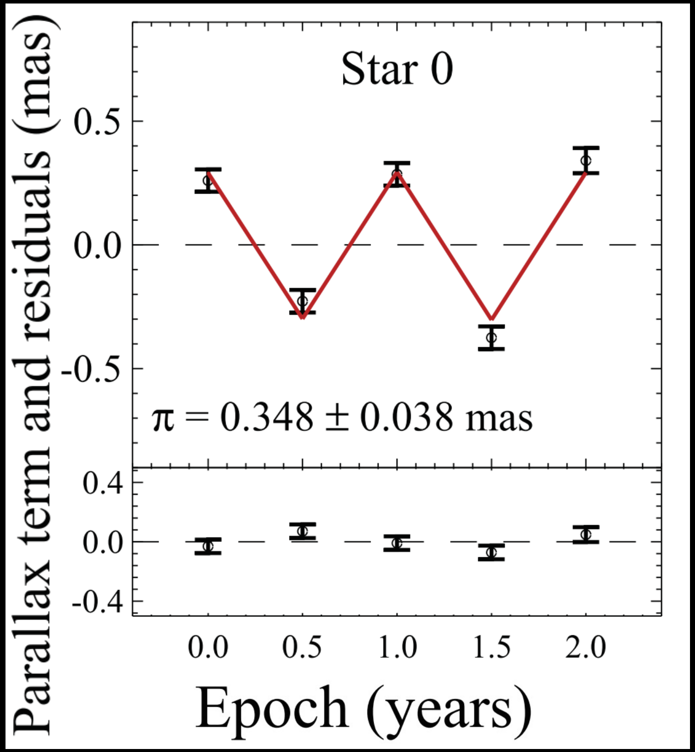
- Can achieve $\sigma \sim 10\ \mu as$ astrometric precision (1D) in a single 100s exposure of a $R_{AB} \sim 6$ star.
- This corresponds to 10^{-4} of a pixel → need exquisite control of systematics.



Melchior et al. 2018
see also Gould et al. 2015

High-precision Astrometry with Roman – Spatial Scanning

- Spatial Scanning distributes the flux over many pixels, increasing the signal and suppressing systematics
- Parallaxes accurate to ~40 μas have been measured with HST on V~10 stars (Reiss et al. 2015, Casertano et al. 2016)
- Expect to better with Roman because of larger detector and non-destructive reads
- Brighter stars, up to H_{AB}~4
- Expect a measurement precision (1D) of ~10 μas with Roman (Sanderson et al. 2019)



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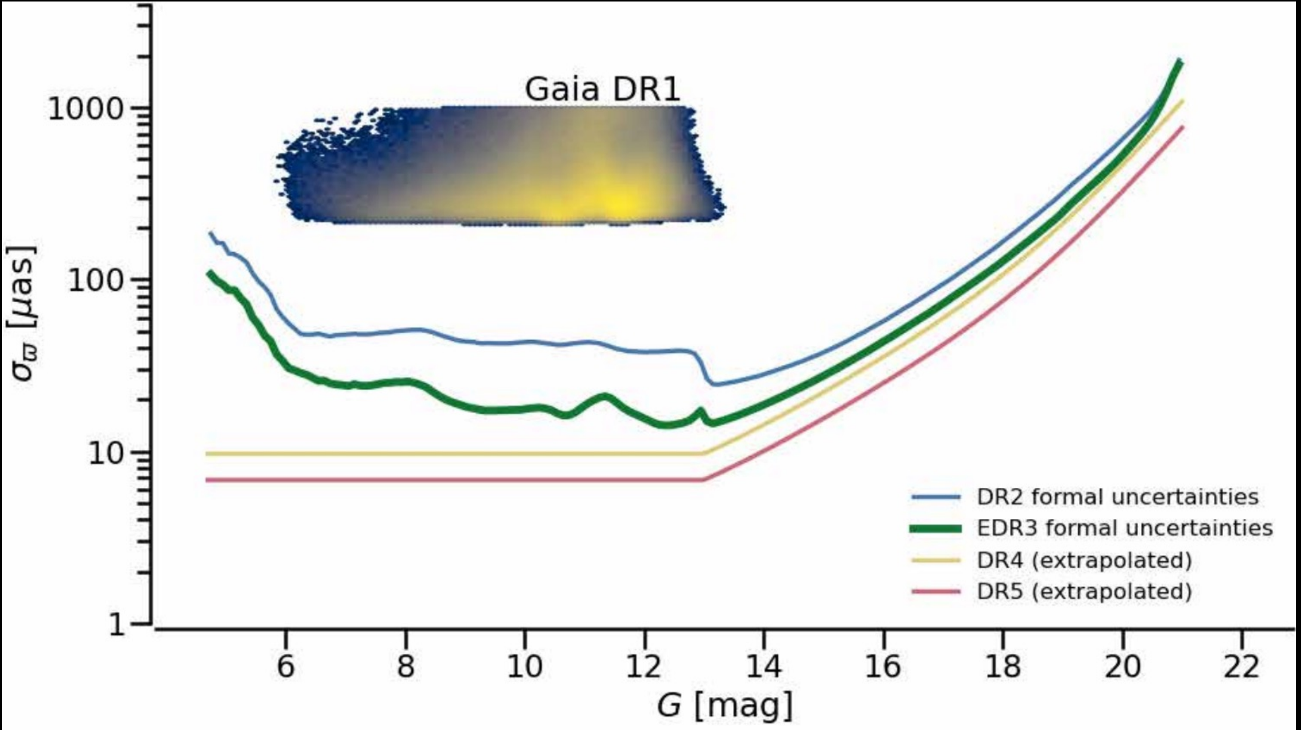
High-precision Astrometry with Roman – Combining with Gaia to Increase the Baseline

- Gaia is predicted to have a final parallax precision of σ_{ϖ}~10 μas for $G \lesssim 13$ stars.
- This roughly corresponds to $S/_N \sim \frac{\alpha_0}{\sigma_{\varpi}}$,
  or
  $$S/_N \sim \left(\frac{P}{10\text{yr}}\right)^{2/3} \left(\frac{m_p}{10M_{\oplus}}\right) \left(\frac{M_*}{M_{\odot}}\right)^{-2/3}$$



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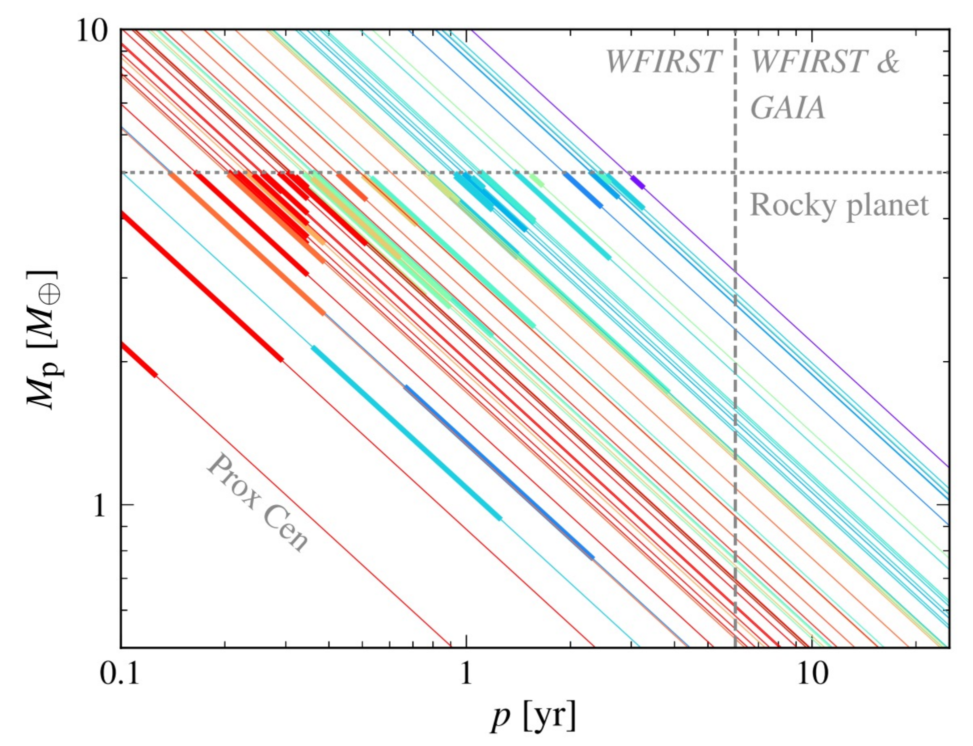
Roman's sensitivity to exoplanets orbiting nearby stars

- Roman will be sensitive to super-Earths in the habitable zones of a handful of nearby stars
- The best targets are nearby M dwarfs
- A survey of the 10 best targets requires ~10 days of observing time



Summary

- Roman will have a single-measurement astrometric precision of ~1 mas using traditional imaging
- With spatial scanning or by centroiding diffraction spikes, it may be possible to achieve precisions of ~10 μas.
- Precise astrometry can be used to measure the parallaxes of the source stars and the masses of the host stars of the ~1000 microlensing events detected in the Roman Galactic Bulge Time Domain survey
- A dedicated 10-day survey using spatial scanning or by centroiding diffraction spikes could detect rocky super Earths in the habitable zones of roughly a dozen nearby stars