

Roman Galactic Bulge Time Domain Survey: Motivation, Science Requirements, Survey Optimization and Requirements, Descope, and Auxiliary Science

Committee on Astronomy and Astrophysics

March 17, 2022

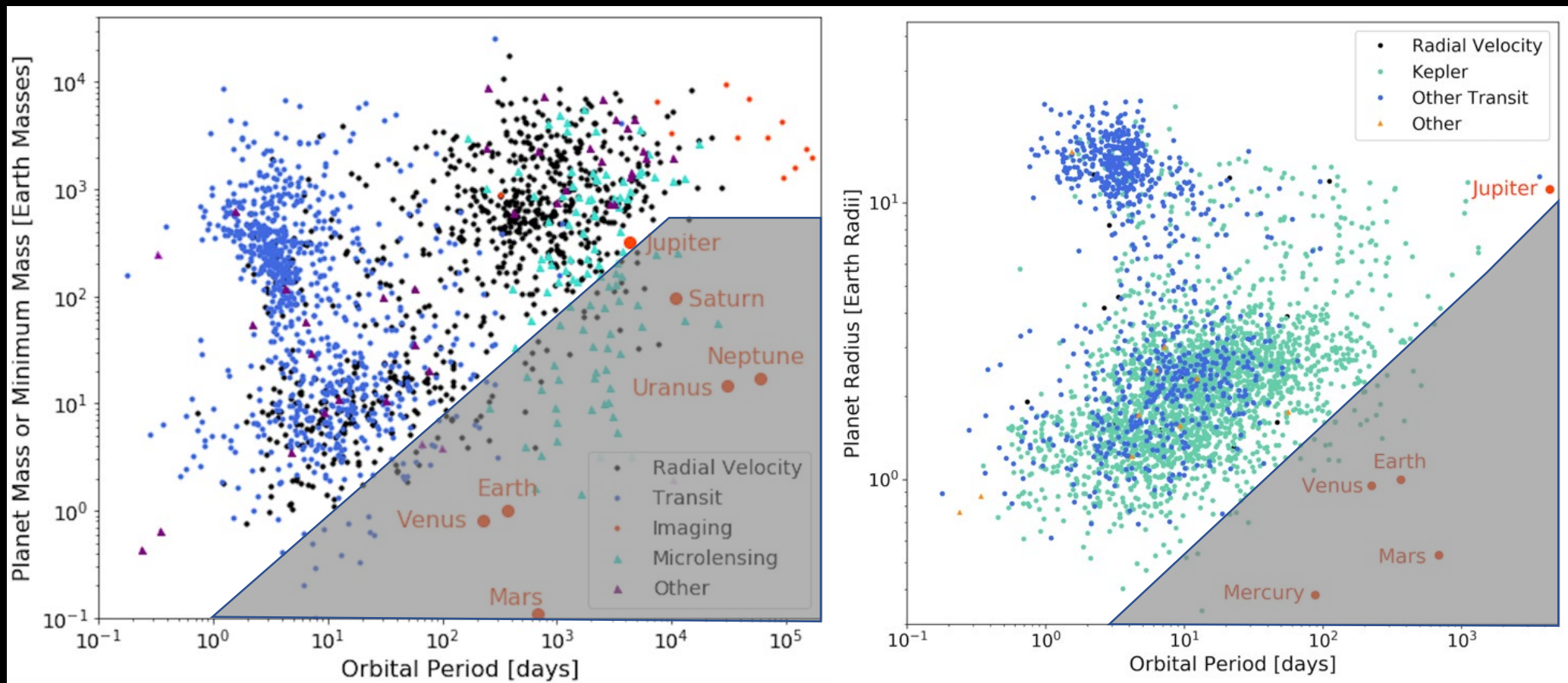
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On behalf of Microlensing SIT

National Aeronautics and
Space Administration



Current Status of Exoplanet Demographics



Why do we want to complete the census of exoplanets by surveying the cold, low-mass regions of planetary systems?

- Planet formation is thought to be more efficient beyond the snow line, the region in the protoplanetary disk where solid water ice is stable.
 - May be where most giant planets form
- Need to survey over a broad mass range to understand planet formation
 - How do planets grow from embryos to giant planets?
 - Are ice giants just failed gas giants?
 - Do the cold regions of planetary systems mostly contain failed giant systems, multiple giant planets, or lonely gas giants?
- The region beyond the snow line may be source of water for potentially habitable planets



Methods of Detecting Exoplanets

Radial Velocity



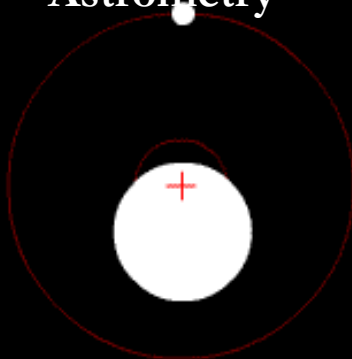
Transits



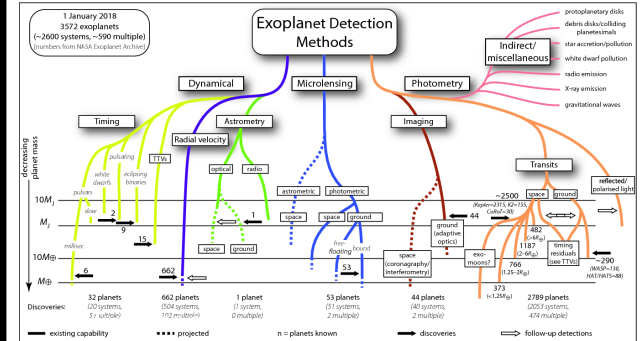
Microlensing



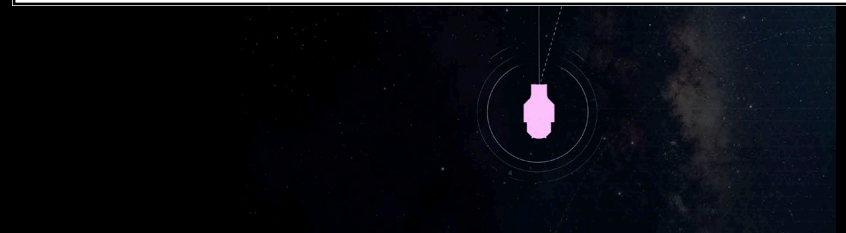
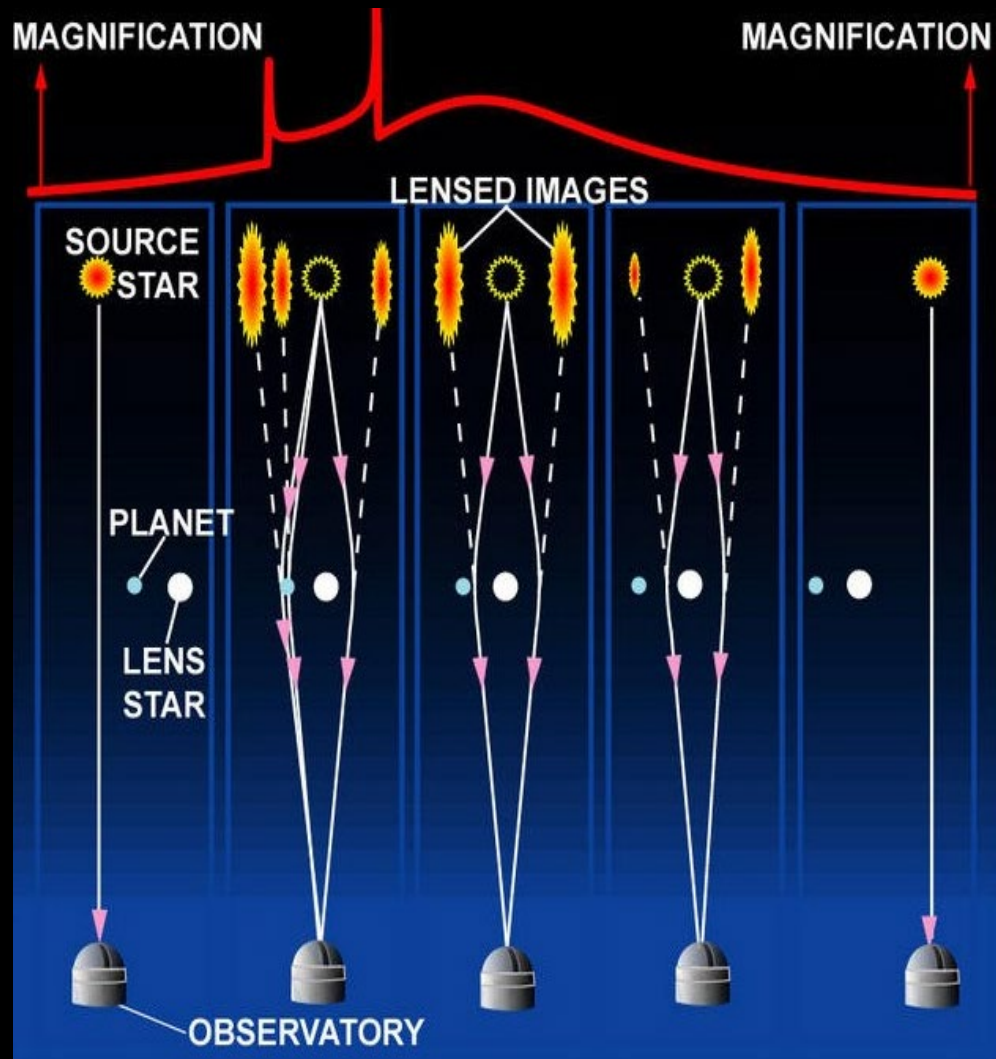
Astrometry



Everything Else



Microlensing



Unique Sensitivity of Microlensing to Exoplanetary Systems.

- Planets beyond the snow line.
 - Most sensitive at $\sim \text{few} \times a_{\text{snow}}$
- *Very* low-mass planets
 - $>10\%$ Mars.
- Long-period planets
 - Including ice giant analogs
- Wide range of host masses
 - **Not just M dwarfs!**
 - Brown dwarfs, $M < M_{\text{Sun}}$, remnants
 - Typical mass $\sim 0.5 M_{\text{Sun}}$
 - 1-8 kpc
- Free-floating planets
- Giant moons
 - Earth/moon analogs
- Multi-planet systems
 - Analogs of our giant planet system
- Wide circumbinary planets
- Outer habitable zone planets
- Planets throughout the Galaxy.
 - 1-8 kpc
 - Bulge and disk populations
 - Planet frequency versus $[\text{Fe}/\text{H}]$ and $[\alpha/\text{Fe}]$



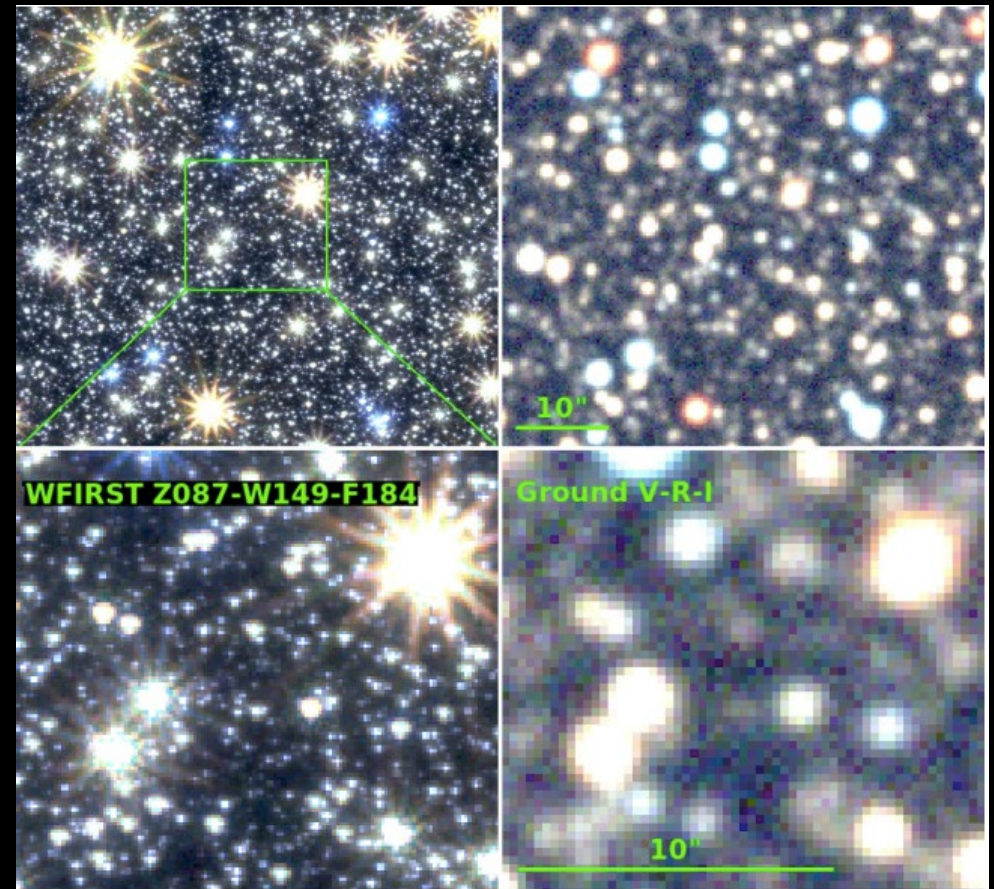
Requirements to detect and measure masses of order ~ 100 Earth-mass planets

- Monitor ~ 100 s of millions of bulge stars continuously on a time scale of ~ 10 minutes for a $\sim$ year
 - Microlensing event rate toward central bulge $\sim \text{few} \times 10^{-5} / \text{year} / \text{star}$
 - Detection probability $\sim 1\%$.
 - 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 lens flux measurements.
- Longest possible time baseline for proper motion measurements.



A space telescope is required

- Infrared
 - More extincted, higher event rate fields
 - Smaller sources
- Resolution
 - Low-magnification events
 - Isolate light from the lens star
- Visibility
 - Complete coverage of planetary perturbations
- Smaller systematics
 - Better characterization
 - Robust quantification of sensitivities



(Penny et al. 2019)

Science enabled from space: sub-Earth mass planets, outer habitable zone planets, free-floating Earth-mass planets, mass measurements.



Requirements to complete the exoplanet census

- Large ($\gtrsim 1\text{m}$) space-based ($\lesssim 0.3$ arcsec resolution), near-IR telescope with relatively large field-of-view, capable of ~continuous observations at relatively rapid cadence ($\lesssim 15\text{m}$) for long periods of time ($\gtrsim \text{year}$) over long time baselines ($\gtrsim 5$ years)
- e.g., The Roman Space Telescope or something very similar
- This science cannot be done:
 - from the ground
 - with a substantially shorter survey
 - with Euclid
 - in any other way
- Corollary: This science
 - is as relevant and important as it was when Astro2010 was released
 - will remain relevant until something like Roman is done



Science Requirements

- Roman shall be capable of measuring the mass function of exoplanets with masses in the range $1 M_{\text{Earth}} < m < 30 M_{\text{Jupiter}}$ and orbital semi-major axes $\geq 1 \text{ AU}$ to better than 15% per decade in mass.
- Roman shall be capable of measuring the frequency of bound exoplanets with masses in the range $0.1 M_{\text{Earth}} < m < 0.3 M_{\text{Earth}}$ to better than 25%
- Roman shall be capable of determining the masses of, and distances to, host stars of 40% of the detected planets with a precision of 20% or better.
- Roman shall be capable of measuring the frequency of free floating planetary-mass objects in the Galaxy from Mars to 10 Jupiter masses in mass. If there is one M_{Earth} free-floating planet per star, measure this frequency to better than 25%.
- Roman shall be capable of estimating η_{Earth} (defined as the frequency of planets orbiting FGK stars with mass ratio and estimated projected semimajor axis within 20% of the Earth-Sun system) to a precision of 0.2 dex via extrapolation from larger and longer-period planets.



Survey Design and Optimization: Free and Fixed Survey Parameters

Fixed Parameters

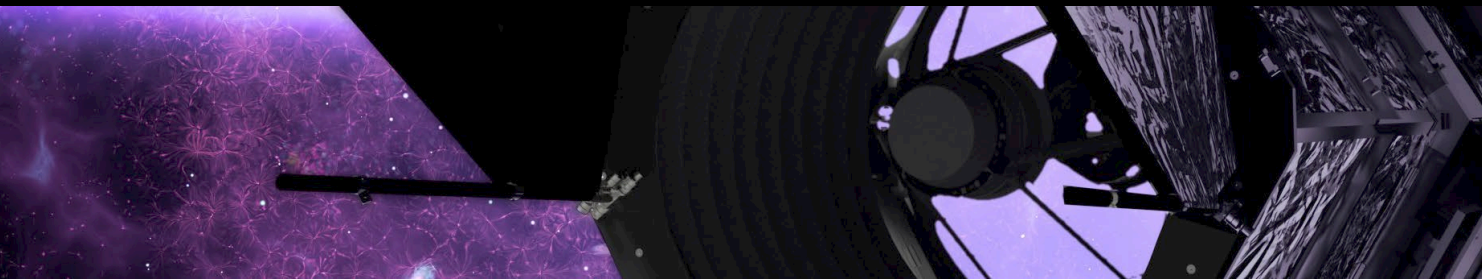
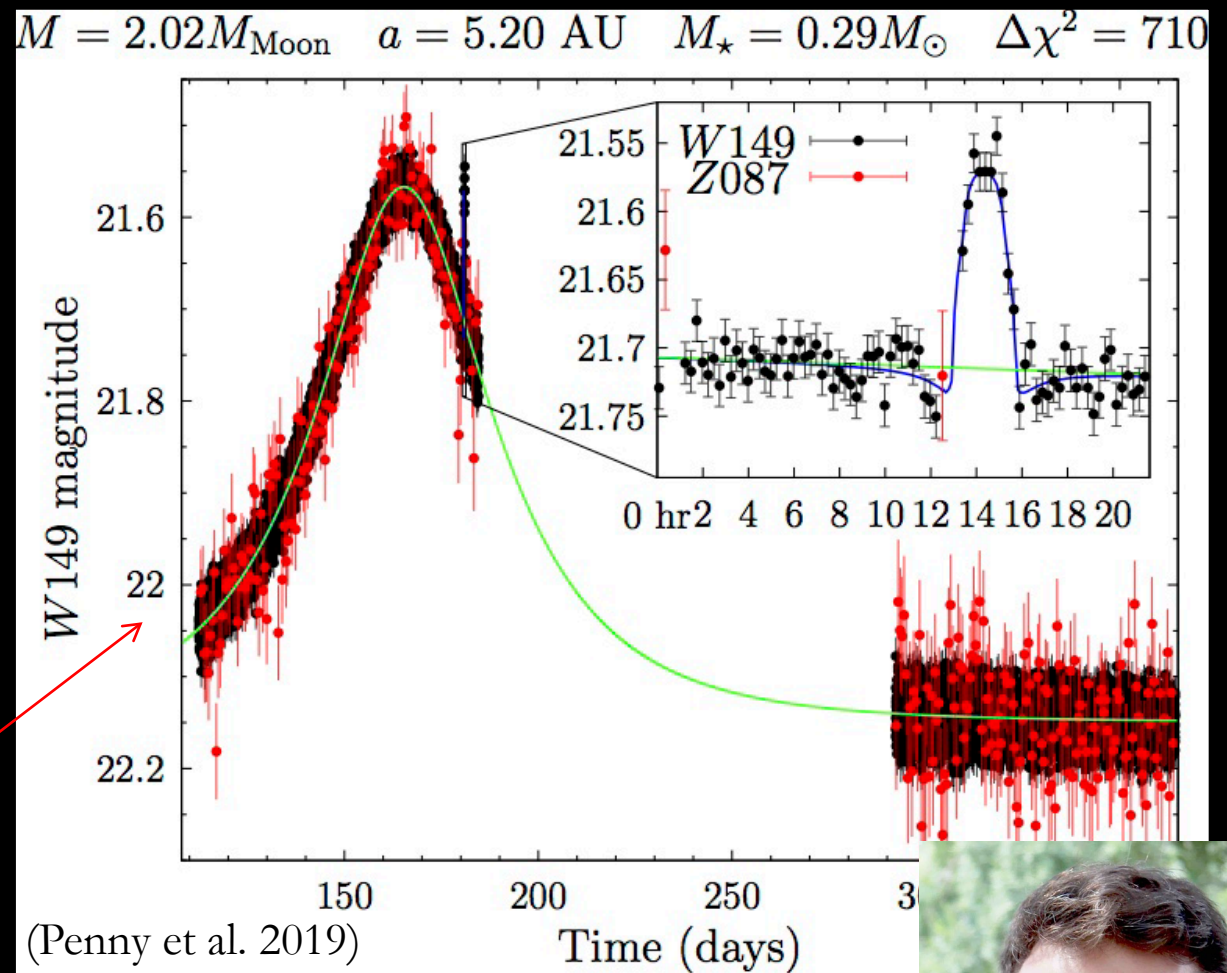
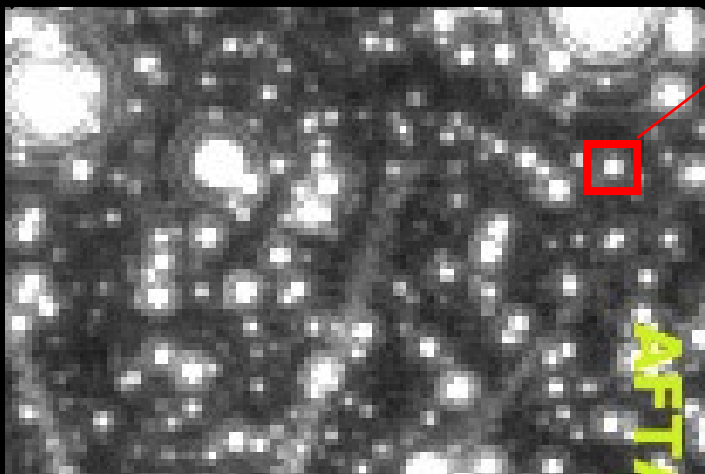
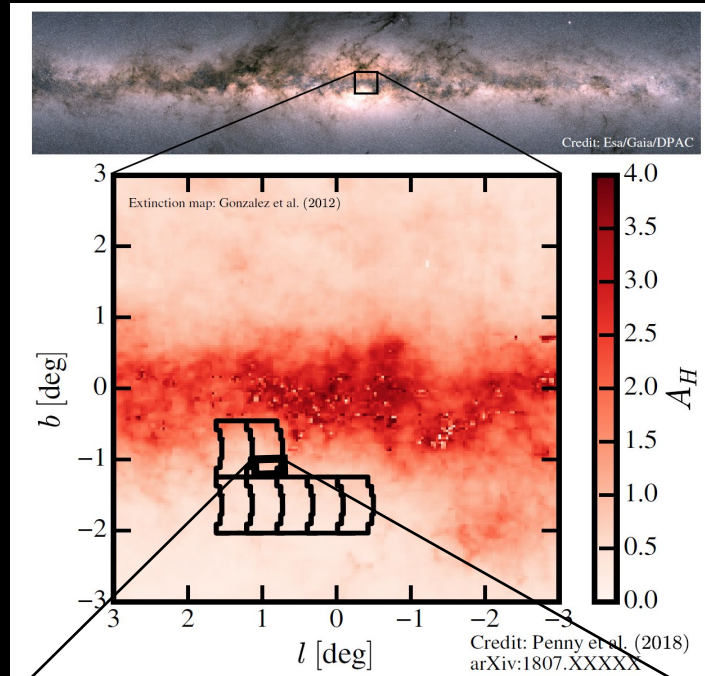
- Duration of a 'bulge season'
 - Set by field of regard
- Slew & Settle time
- Detector size
- Pixel size
- Field of View
- Non-microlensing filters
- Etc.

Free Parameters

- Photometric Resolution shortest features { • **Microlensing filter**
- Optimized for yield { • **Cadence of primary filter**
- Set by optimization Set by science requirements { • **Number of fields**
- Set by optimization Set by science requirements { • **Field location**
- Set by optimization Set by science requirements { • *Exposure time*
- Set by optimization Set by science requirements { • **Total survey time**
- Optimized for planet mass measurements { • **Choice of bulge seasons**
- Optimized for planet mass measurements { • **Cadence of secondary filters**

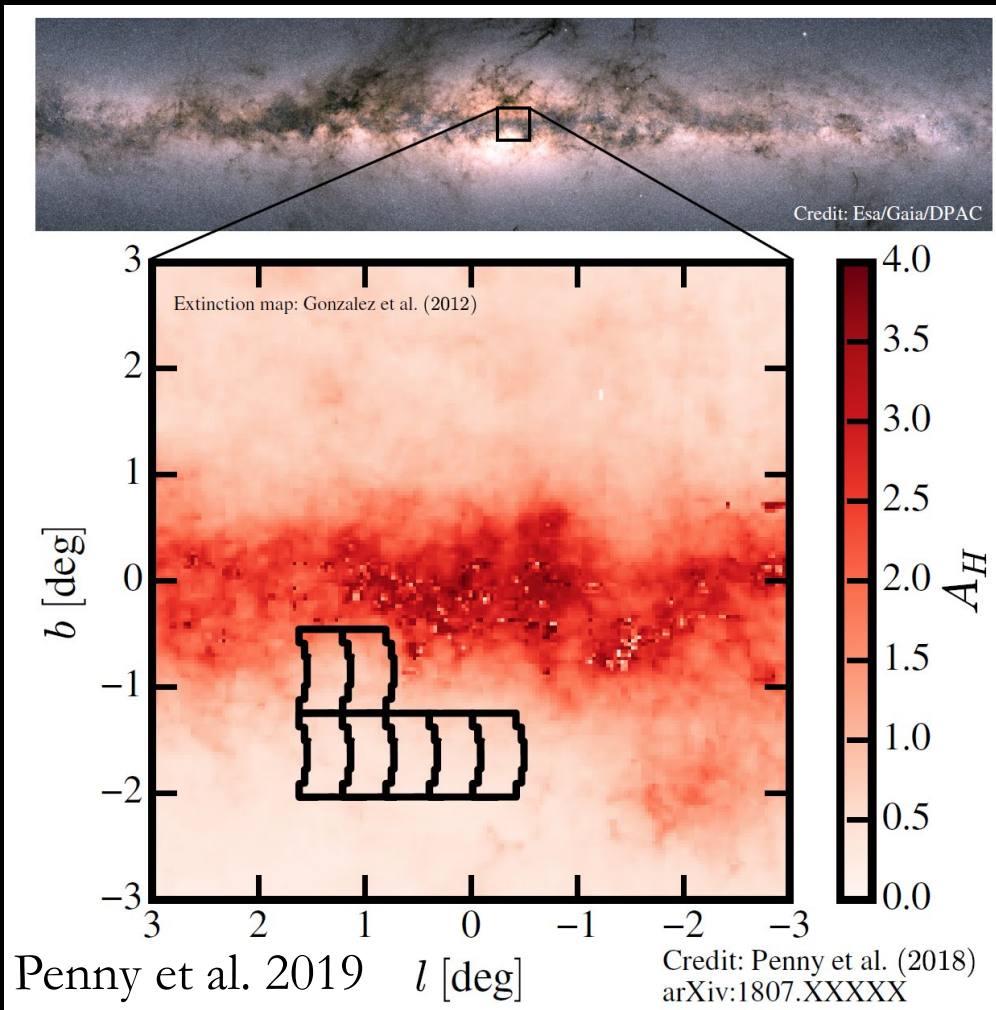


Simulations



Matthew
Penny

Notional Parameters for the Roman GBTDS



- 7 fields for a total of $\sim 2 \text{ deg}^2$
- Wide F146_{AB} (0.93-2 μm) filter**.
- 15-minute cadence.
- $\sim 50\text{s}$ exposures.
- Observations every 6 hours in alternating filters (e.g., F087, F219), 2 x 450 total obs.
- 6 x 72-day seasons.
- $\sim 41,000$ exposures in W149_{AB}.
- ~ 432 total days spread over 5-year mission.

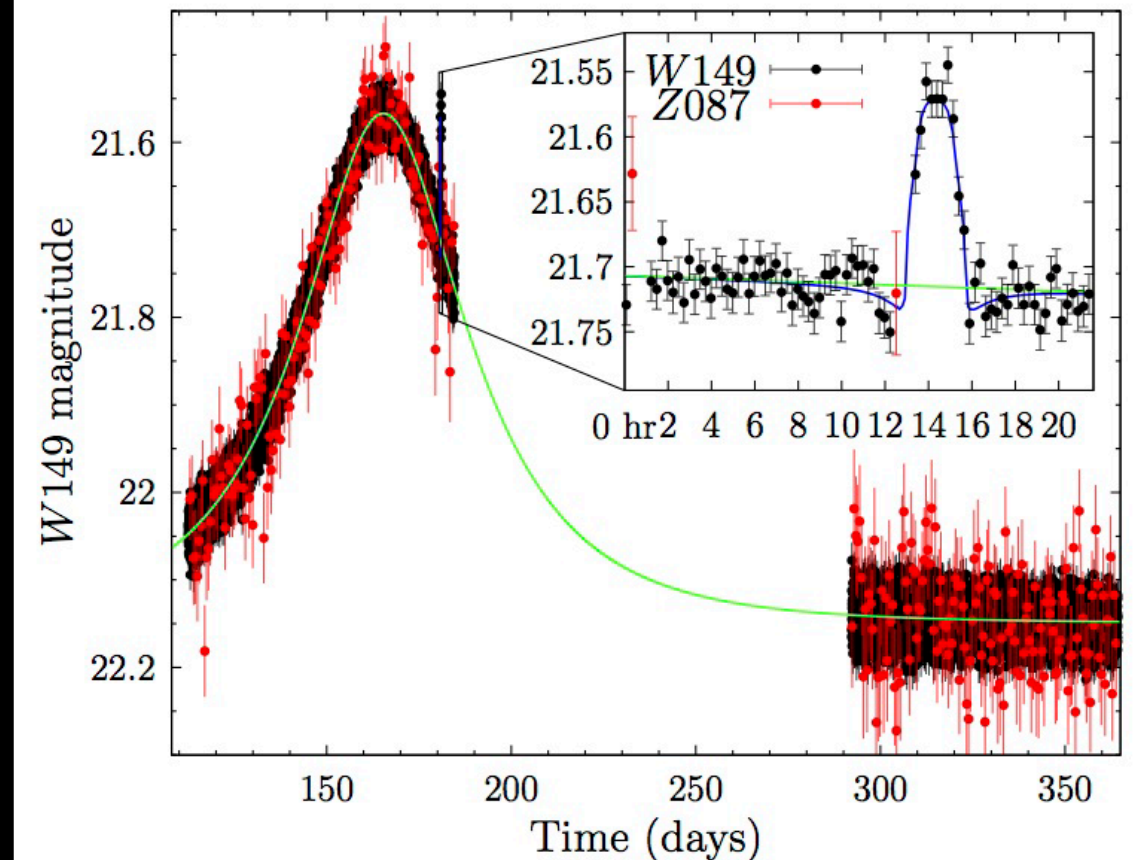
*Notional time allocation; exact survey strategy to be determined based on broad community input.

**One photon per second for F146_{AB} ~ 27.6



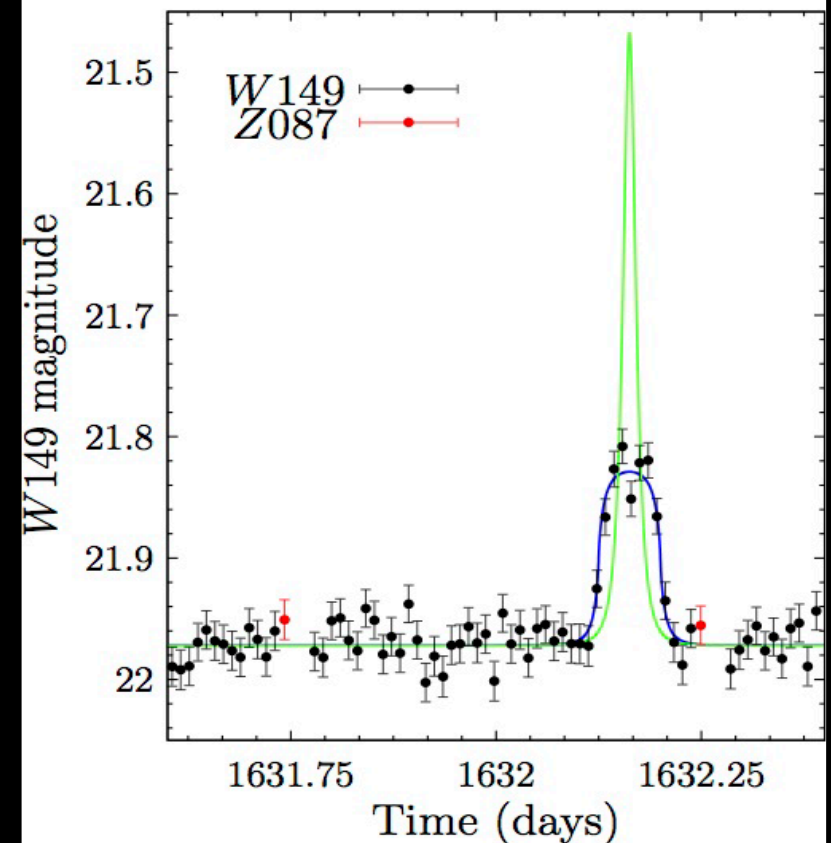
Example Planet Detections

$M = 2.02M_{\text{Moon}}$ $a = 5.20 \text{ AU}$ $M_{\star} = 0.29M_{\odot}$ $\Delta\chi^2 = 710$



$2 \times \text{Mass of the Moon @ } 5.2 \text{ AU}$
(~ 27 sigma)

$M = 0.1M_{\oplus}$ $\Delta\chi^2 = 552$



Free floating Mars
(~ 23 sigma)

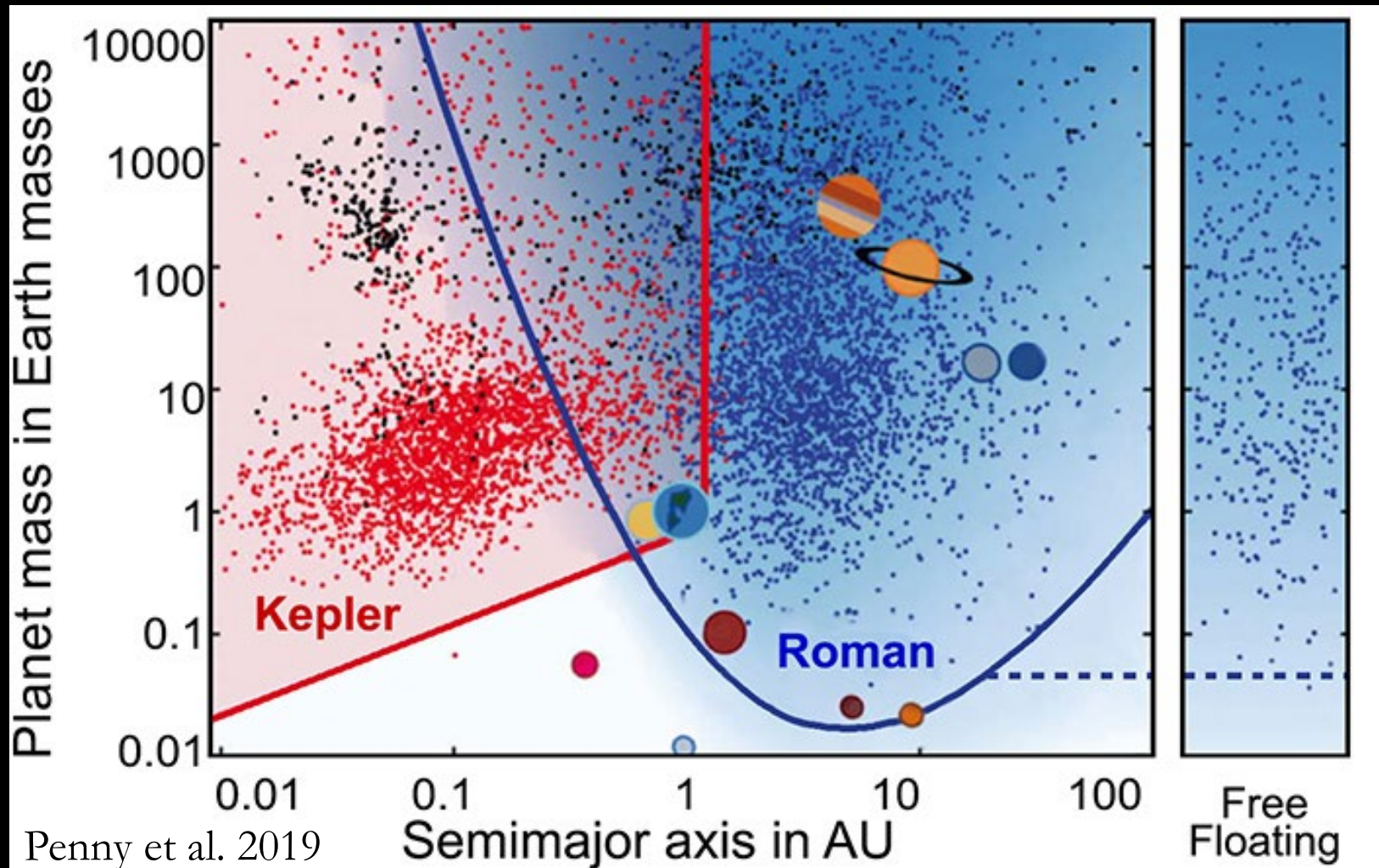
Yields for Notional Survey Design

$M/M_{\oplus}$ Duration	0.1 -0.3	1	10	100	1000	3000- 10000	Total	Free- Floating Earths
432 days (Uncertainty)	20 (22%)	181 (7%)	545 (4%)	412 (5%)	224 (7%)	91 (10%)	1474	23 (21%)
0.8×432 days (Uncertainty)	16 (25%)	144 (8%)	436 (5%)	330 (6%)	179 (7%)	73 (12%)	1179	19 (23%)

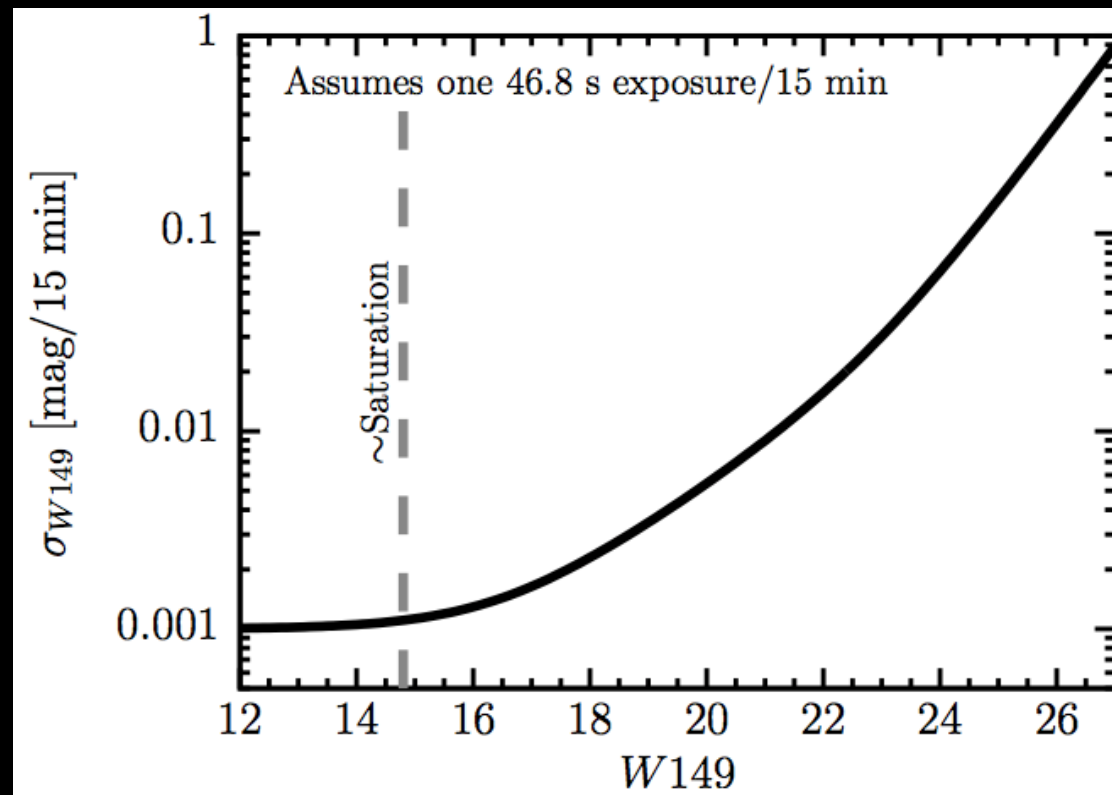
- To first order, yields scale linearly with total survey duration
- The notional survey design (used in the DRM) meets the science requirements with 20% margin.



A Complete Statistical Census of Exoplanets (a.k.a. the “Penny Plot”)



Statistical Power of the RGBTDS



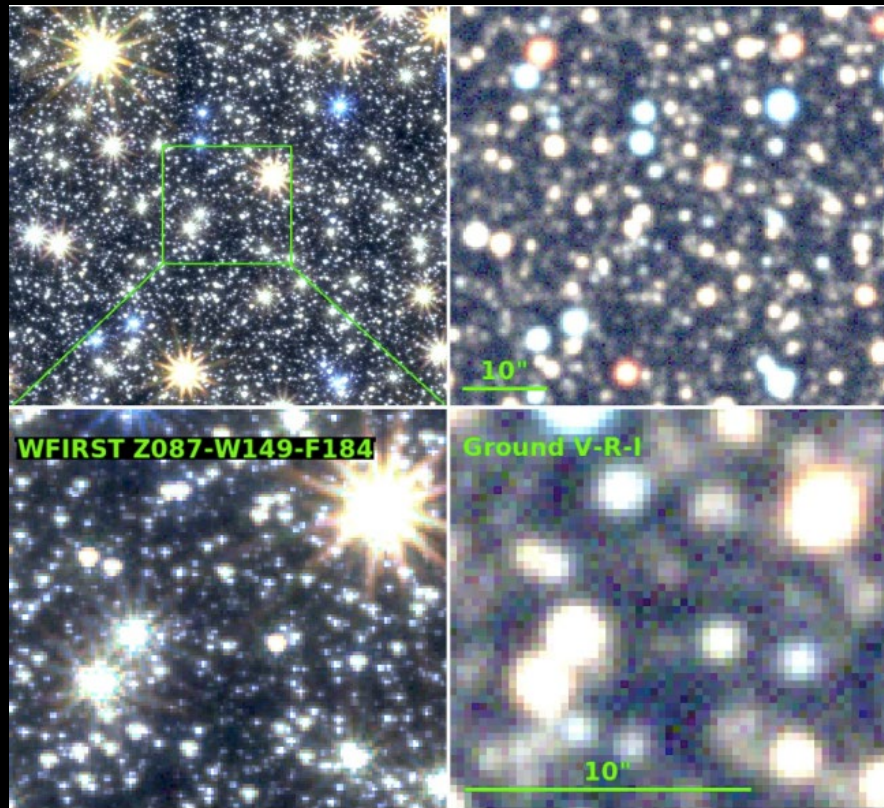
For a $F146_{AB} \sim 21.15$ star:

- Photon-noise relative photometric precision of $\sigma \sim 0.01$ mag per exposure.
- Total of $\sim 10^9$ photons over the survey.
- Saturation @ $F146_{AB} \sim 14.8$.
- Root N: $\sqrt[2]{41,000} \sim 200$.

Penny et al. 2019



Number of Sources and Microlensing Events



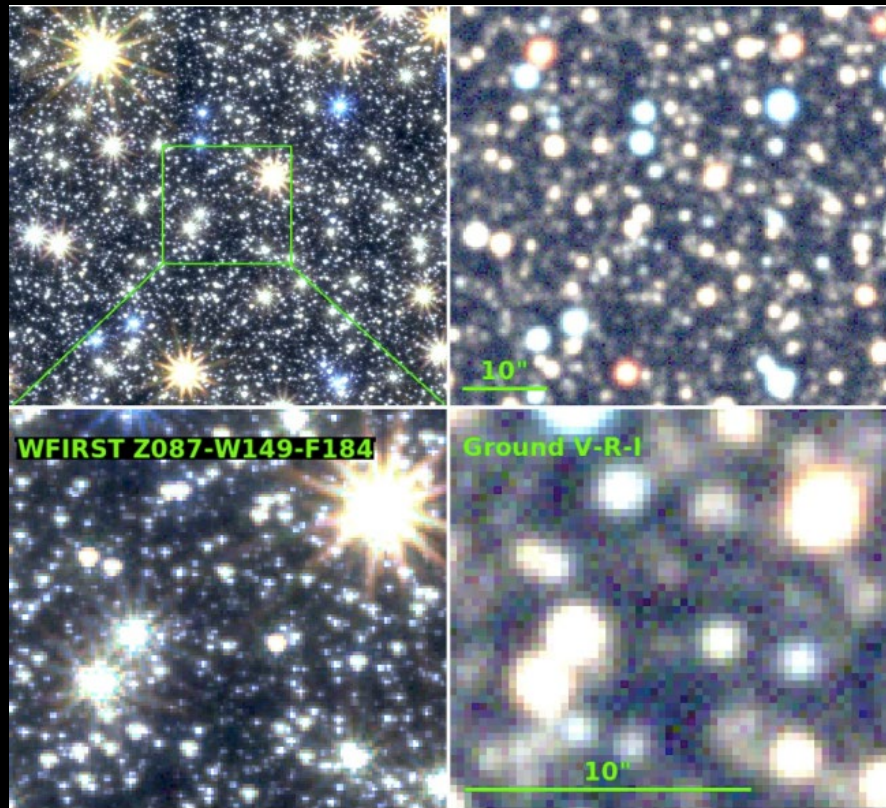
Stars ($W149 < 15$)	$\sim 0.3 \times 10^6$
Stars ($W149 < 17$)	$\sim 1.4 \times 10^6$
Stars ($W149 < 19$)	$\sim 5.8 \times 10^6$
Stars ($W149 < 21$)	$\sim 38 \times 10^6$
Stars ($W149 < 23$)	$\sim 110 \times 10^6$
Stars ($W149 < 25$)	$\sim 240 \times 10^6$
Microlensing events $ u_0 < 1$	$\sim 27,000$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

Penny et al. 2019



Photometric and Astrometric Precision

(Relative, Poisson Noise Only)



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

Penny et al. 2019



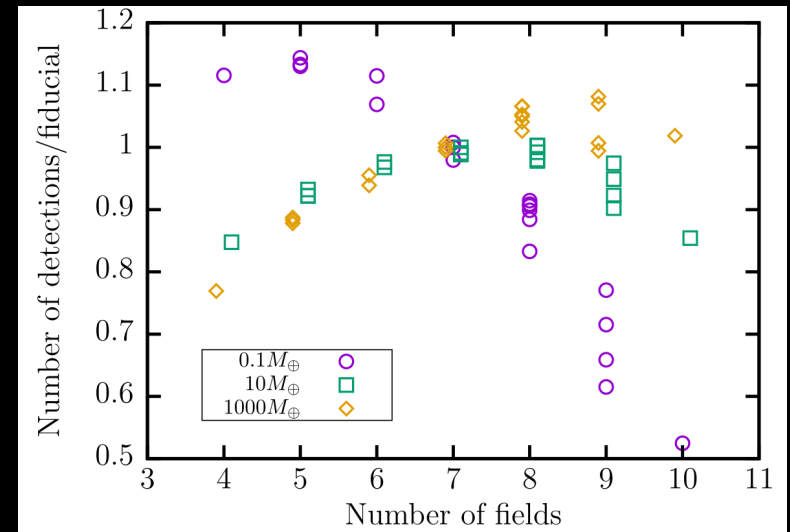
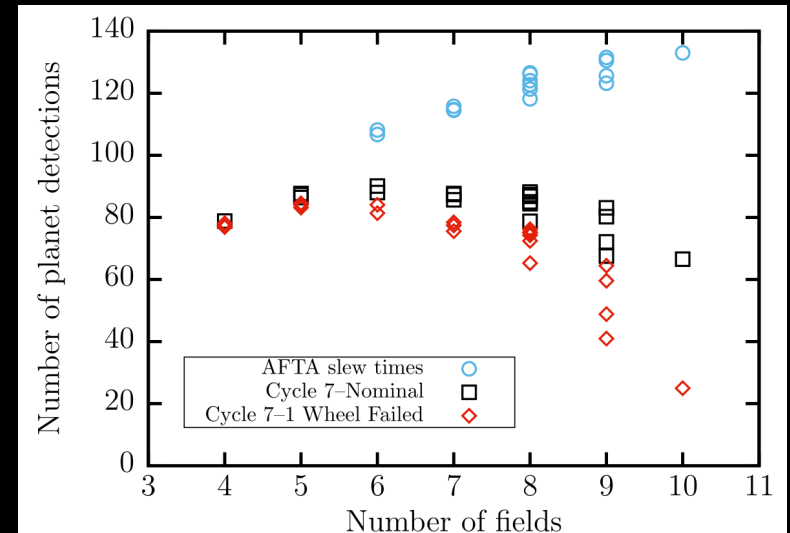
Additional Science Enabled by the RGBTDS

- Measurement of the Compact Object Mass Function over ~ 10 Orders of Magnitude
 - Mass, distance, and transverse velocity measurements for hundreds of isolated black holes (Gould 2000, Lam et al. 2020)
- Detection of $\sim 10^5$ Transiting Planets (Monet et al. 2017)
- Astroseismology of $\sim 10^6$ Bulge Giants (Gould et al. 2015)
- Resolved Stellar Populations and Galactic Structure
- Parallaxes and Proper Motions of $\sim 6 \times 10^6$ Bulge and Disk Stars
- Detection of $\sim 5 \times 10^3$ Trans-Neptunian Objects (Gould 2015)
- More...



Survey Optimization

- The notional survey is optimized for the yield per unit time of Earth-mass planets
- Precise choice of field location is a second-order effect
- The maximum is soft, and thus there is some margin to account for increases in the slew and settle times
- Shorter slew and settle times would allow for similar yields with less total observing time
- It is possible to increase the yield of lower-mass planets by decreasing the number of fields at the expense of the yield of higher-mass planets



Penny et al. 2019



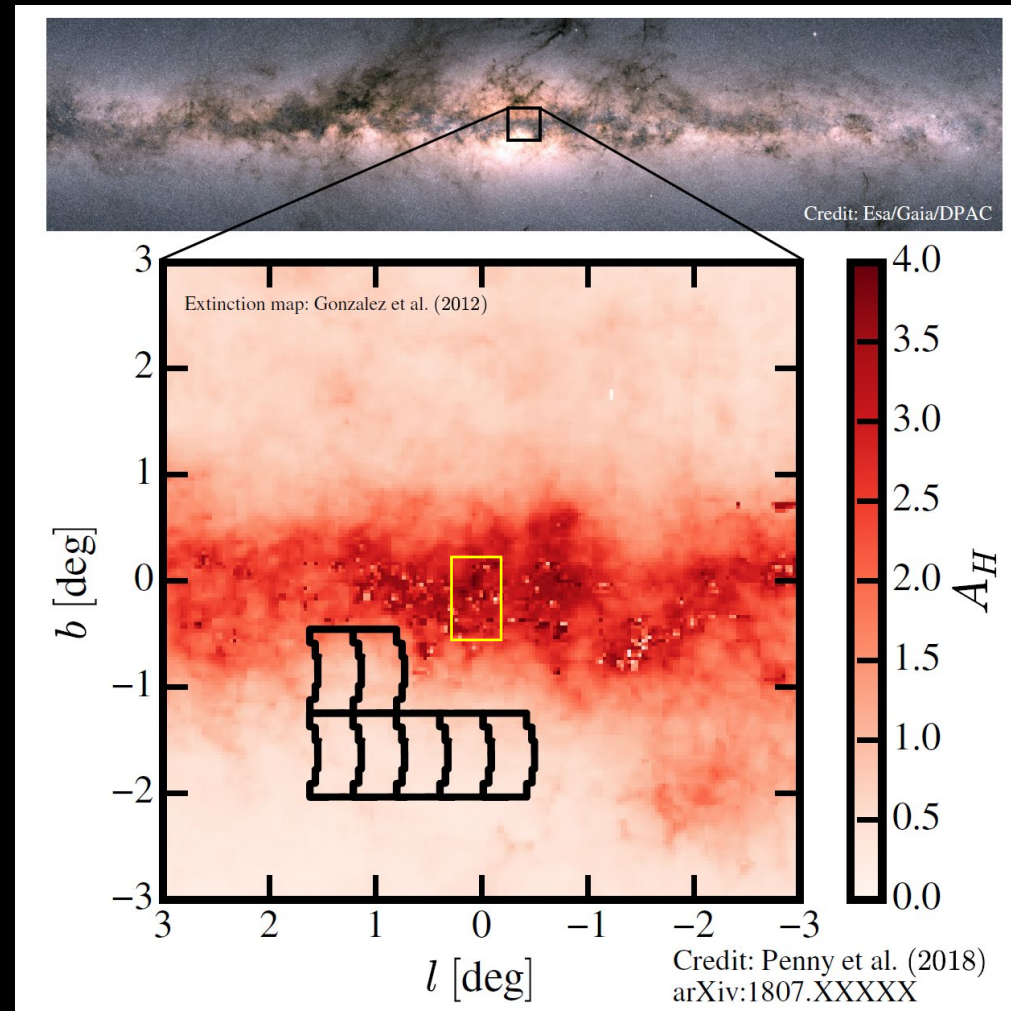
'Tweaks' of the Survey.

Many ways in which the survey strategy can be 'tweaked' to yield additional science without significantly impacting the requirements of the microlensing survey.

To first order, $\text{Yield} \propto \text{Total Time}$

For example:

- Periodic observations of the GC.
- Periodic observations of the survey fields in all filters.
- Periodic observations of a much larger survey area (more isolated BHs!)
- Others?



Extensions of the Survey?

There are many possible extensions to the RGBTDS that may yield additional science, e.g., during an extended mission.

- Extending the survey for N additional seasons
- Very high cadence observations of a smaller area
- Lower-cadence observations of a larger area
- High-cadence observations in alternate filters
- Surveying Northern Galactic fields
- High cadence observations of the GC



Summary, Part 1

- Completing the statistical census of exoplanets requires a large survey for low-mass cold and free-floating planets.
- Microlensing is the only technique capable of performing this survey
- A microlensing survey has been prioritized by the exoplanet community (NAS ESS Report)
- A microlensing survey has been prioritized by the astronomical community (New Worlds, New Horizons)
 - The Astro2020 DS explicitly called for a large (~ 500 day) survey
 - This priority has been reaffirmed many times
- It is not possible to realize this science any other way (e.g., from the ground or with a substantially shorter survey)



Summary, Part 2

- This science is as relevant and important as it was when Astro2010 was released and will remain so until something like Roman is done
- There is very little room for additional optimization
- Roman is *not* HST or JWST
 - It is optimized to be a survey machine
 - This is Roman's unique capability
 - Surveys by their very nature require large amounts of time
- It is very unlikely that any large ($\gtrsim$ year) surveys would be competitively selected by a TAC
- An enormous amount of additional science will be enabled by the GBTDS.
- All of the science that is enabled by the RGBTDS should be considered when determining the time allocation for Roman



Backup Slides



Statement of Task

- “Experience with both the Hubble Space Telescope and the Chandra X-ray Observatory has demonstrated that peer reviews do not do a good job of comparing small programs to large programs.”
- “For both Hubble and Chandra, time is explicitly set aside for, and competed, to enable large programs.”



A microlensing survey has been prioritized by the exoplanet community

- Because microlensing is sensitive to planets of all masses having orbits larger than about half of Earth's, WFIRST would be able to complement and complete the statistical task underway with Kepler, resulting in an unbiased survey of the properties of distant planetary systems. The result from this survey will constrain theoretical models of the formation of planetary systems, enabling extrapolation of current understanding to systems that will still remain below the threshold of detectability.
- Recommendations for New Space Activities—Large Projects Priority 1 (Large, Space). Wide-Field Infrared Survey Telescope (WFIRST) “WFIRST will carry out a powerful extrasolar planet search by monitoring a large sample of stars in the central bulge of the Milky Way for small deviations in brightness due to microlensing by intervening solar systems. This census, combined with that made by the Kepler mission, will determine how common Earth-like planets are over a wide range of orbital parameters.”

- National Academies of Science Exoplanet Science Strategy Report



A microlensing survey has been prioritized by the astronomical community

- **Finding:** A microlensing survey would complement the statistical surveys of exoplanets begun by transits and radial velocities by searching for planets with separations of greater than 1 AU (including free-floating planets) and planets with masses greater than that of Earth. A wide-field, NIR, space-based mission is needed to provide a similar sample size of planets as found by Kepler.
- **Recommendation:** NASA should launch WFIRST to conduct its microlensing survey of distant planets and to demonstrate the technique of coronagraphic spectroscopy on exoplanet targets.

- New Worlds, New Horizons



Decadal Survey Guidance.

New Worlds, New Horizons

- Main Report, p. 16:
 - "An equally important outcome will be to open up a new frontier of exoplanet studies by monitoring a large sample of stars in the central bulge of the Milky Way for changes in brightness due to microlensing by intervening solar systems. This census, combined with that made by the Kepler mission, will determine how common Earth-like planets are over a wide range of orbital parameters.
- Main Report, p. 192
 - "To complete the planetary census, it will be necessary to use techniques that are sensitive to Earth-mass planets on large orbits. One such technique is called gravitational microlensing, whereby the presence of planets is inferred through the tiny deflections that they impose on passing light rays from background stars. A survey for such events is one of the two main tasks of the proposed WFIRST satellite."
- EOS panel report, p. 27d0
 - "In the optimistic scenario that every star has an Earth-like planet (fraction of stars hosting an Earth $\eta_{\text{Earth}} = 1$), a 500-day microlensing campaign (spread over the first 5 years of the mission) would find ~ 200 Earth-mass planets (and many thousands of larger planets)."
- EOS panel report, p. 274
 - "As a straw-man example for the first 5 years of a 10-year mission, the panel imagines 2+ years dedicated to the cosmic-acceleration program. These observations will provide more than 8,000 deg² for the BAO survey (grism) and 4,000 deg² for the weak lensing (single-band imaging) survey (about half of the JDEM/ Omega program) and will produce a large multiband galaxy survey for public archives. Dedicated microlensing campaigns of 100 days duration in each of the 5 years could accumulate a significant sample, even within the first few years of the mission."



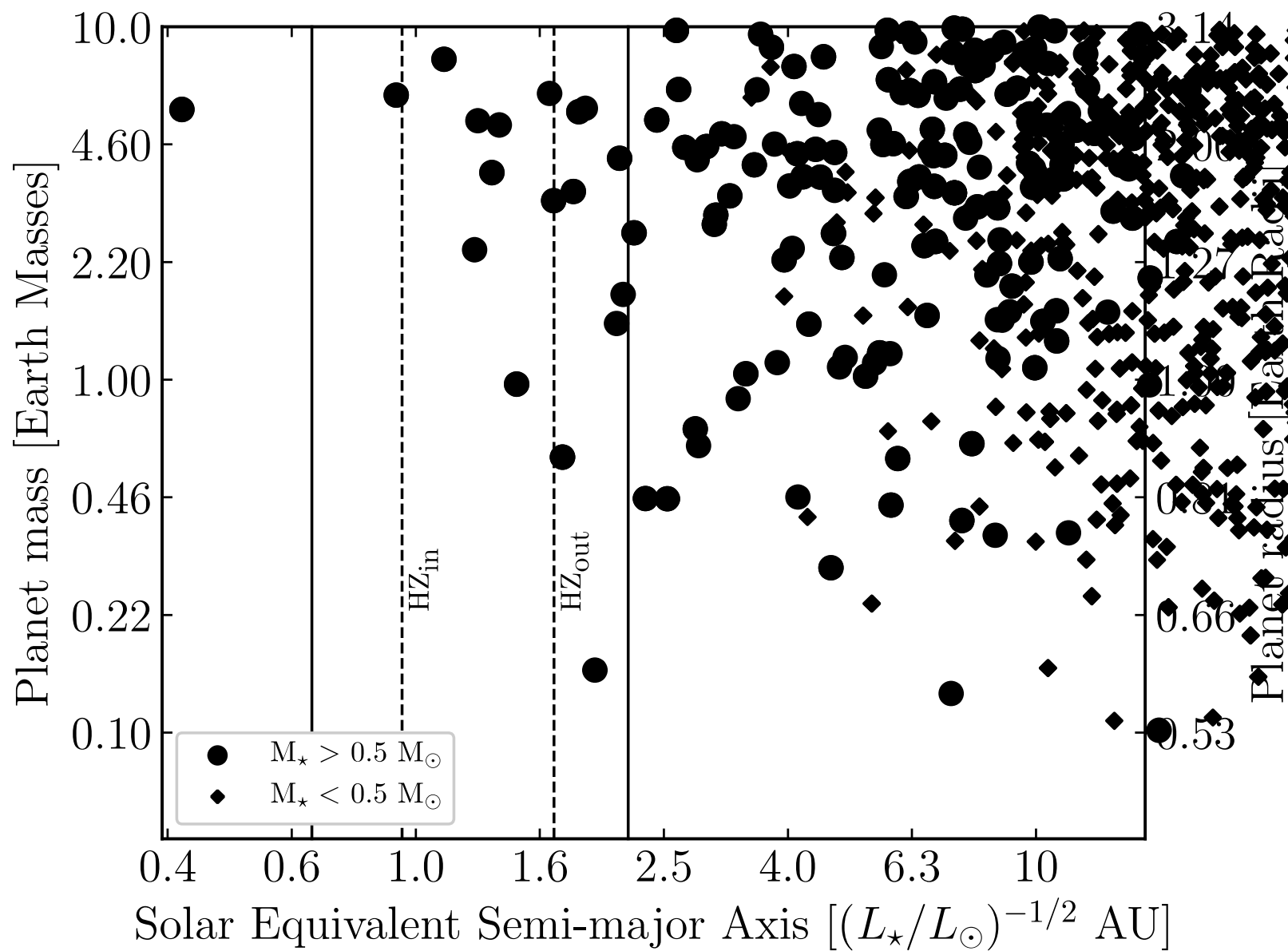
Decadal Survey Guidance.

New Worlds, New Horizons

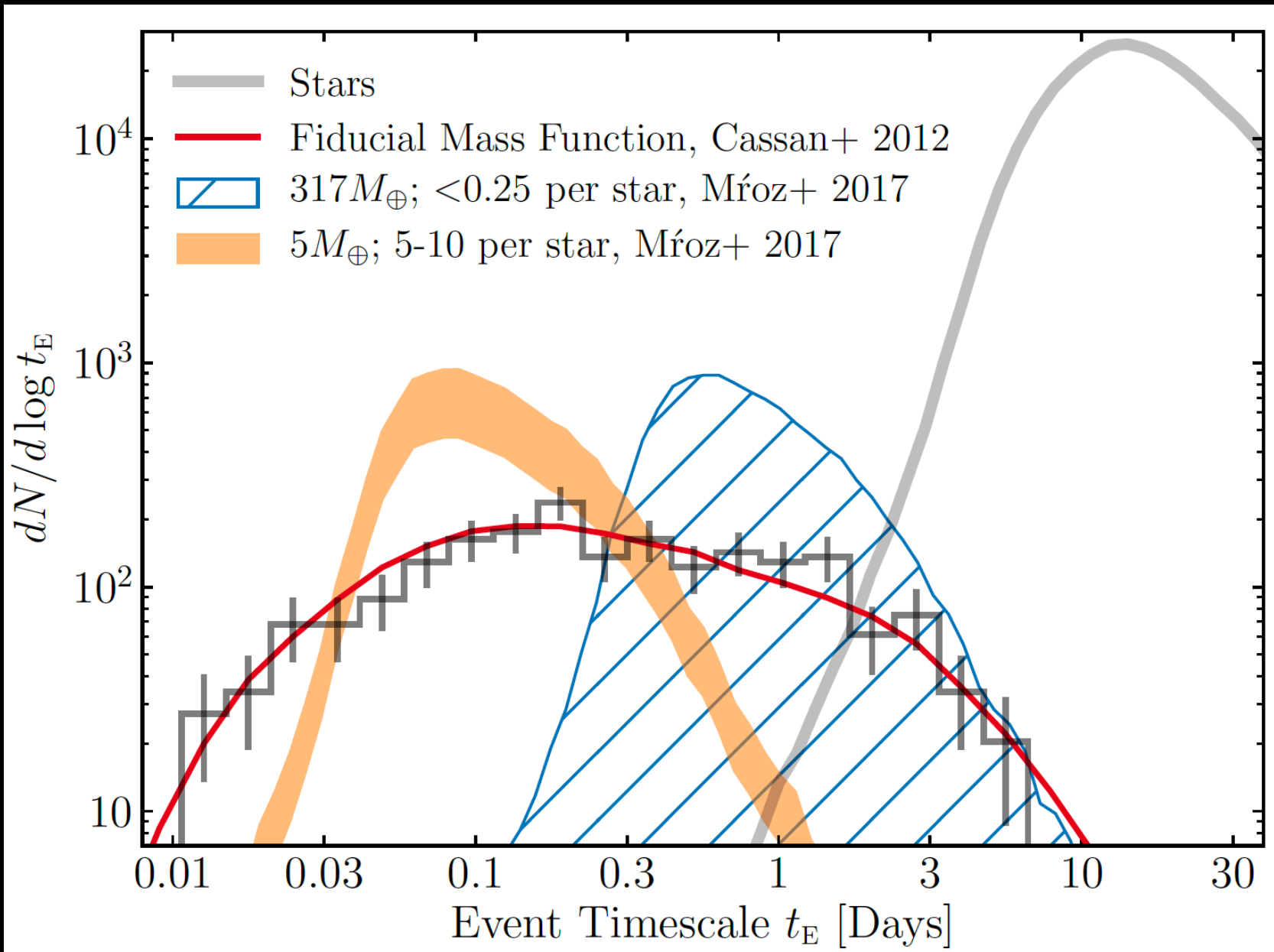
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- EOS panel report, p. 270
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Potentially Habitable Planets

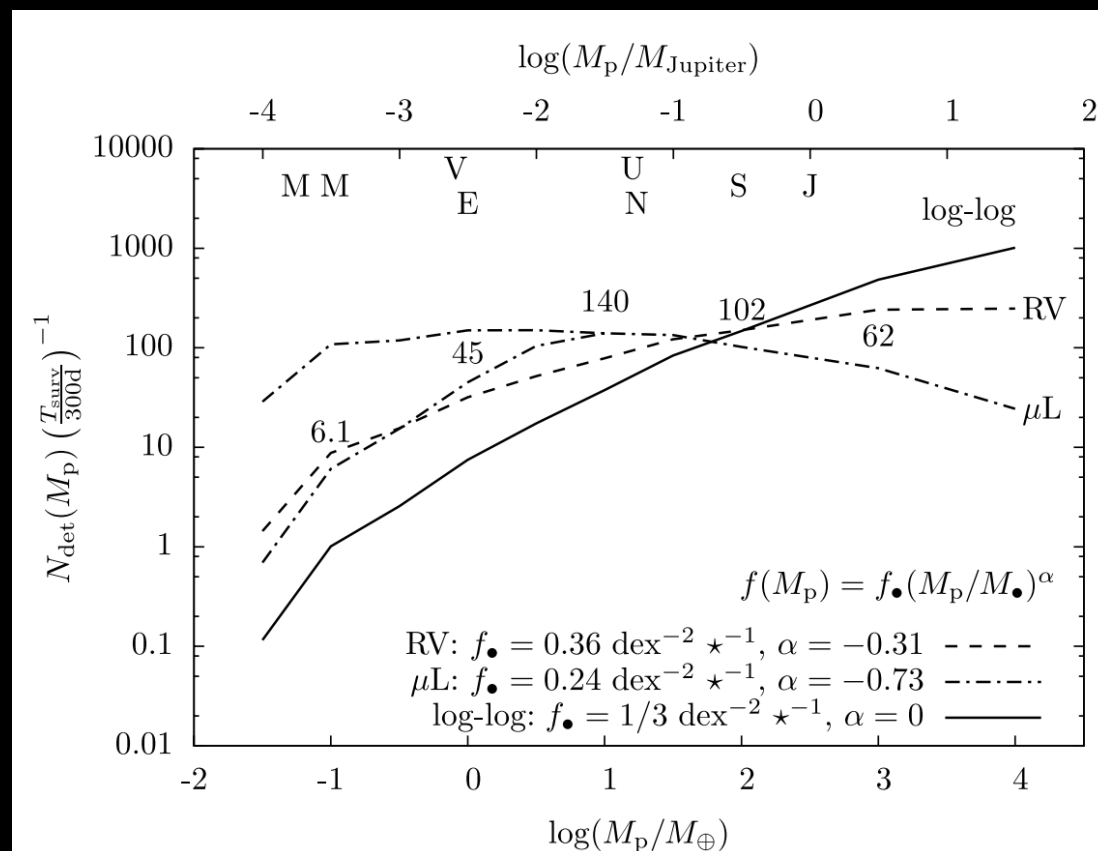


Predictions for the Yield of FFPs.



Euclid Yields

- There are currently no plans to do a microlensing survey with Euclid
- The yields for Euclid assuming the same total survey time are 36%-45% smaller than Roman, and are preferentially smaller for the lowest-mass planets



Penny et al. 2013

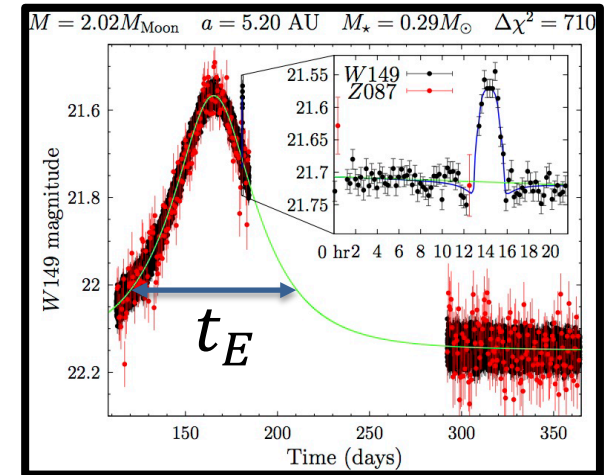


Planet and Star Mass Measurements

The one physical observable that is generally measured in microlensing events is the Einstein timescale:

$$t_E = \frac{\theta_E}{\mu_{rel}}, \text{ where}$$

$$\theta_E = \sqrt{\kappa M_L \pi_{rel}}; \quad \pi_{rel} = \pi_L - \pi_S; \quad \mu_{rel} = \mu_S - \mu_L$$



Thus, the timescale is a degenerate function of mass and distance to the lens, as well as the relatively lens-source proper motion:

$$t_E = f(M_L, D_L, \mu_{rel})$$

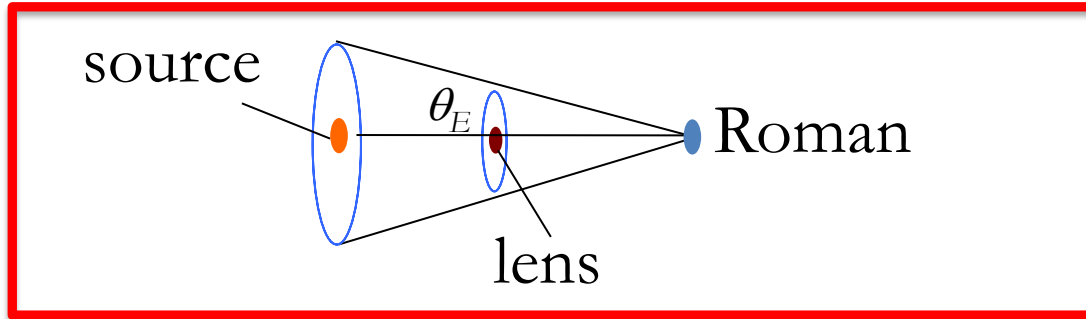
As well as the distance to the source, which can typically be assumed to be in the Galactic bulge.

Planet and Star Mass Measurements

Angular Einstein Ring Radius: $\theta_E = f_1(M_L, D_L, D_S)$

Compare light curve features to ruler in source plane

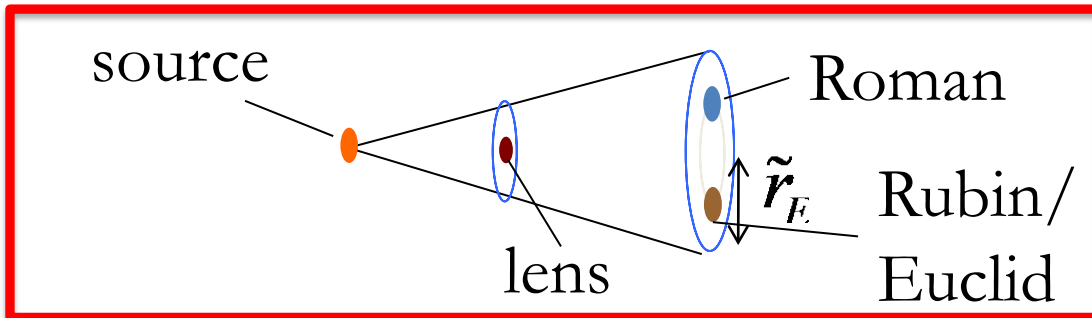
- *Finite source size:* $\theta_E = \theta_* / \rho_*$
- *Source proper motion:* $\theta_E = \mu_{\text{rel}} t_E$



Microlensing Parallax: $\tilde{r}_E = f_2(M_L, D_L, D_S)$

Compare light curve features to ruler in observer plane

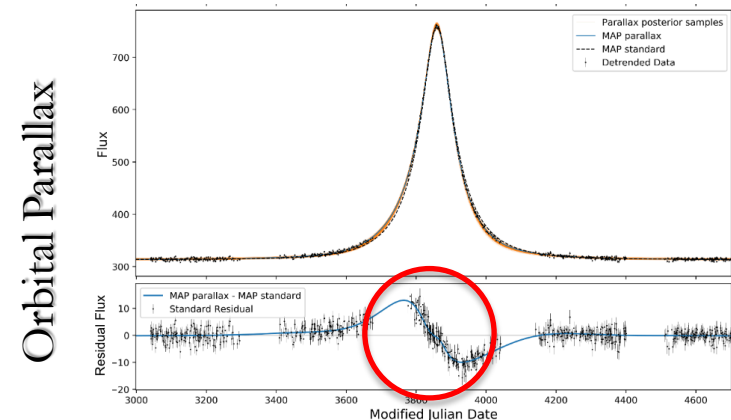
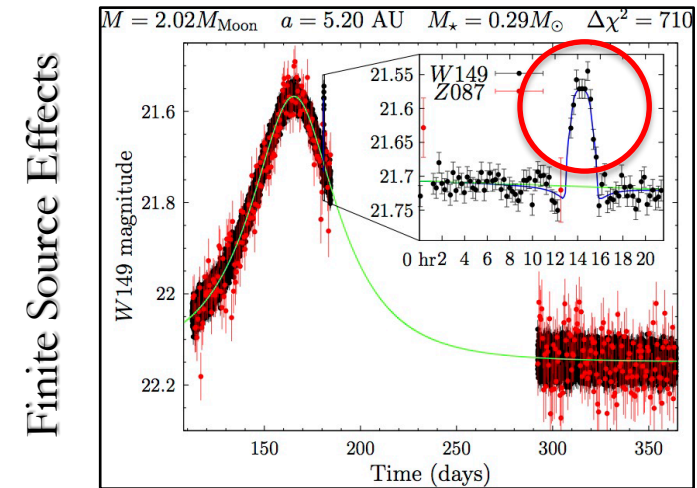
- Orbital Motion of Roman
- Comparison between Roman and Earth



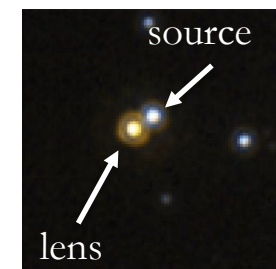
Lens Flux: $F_L = f_3(M_L, D_L, A_\lambda)$

Measure the flux from the lens

- Ground-based AO, HST
- Roman!



Lens flux
and proper motion



Planet and Star Mass Measurements: Example

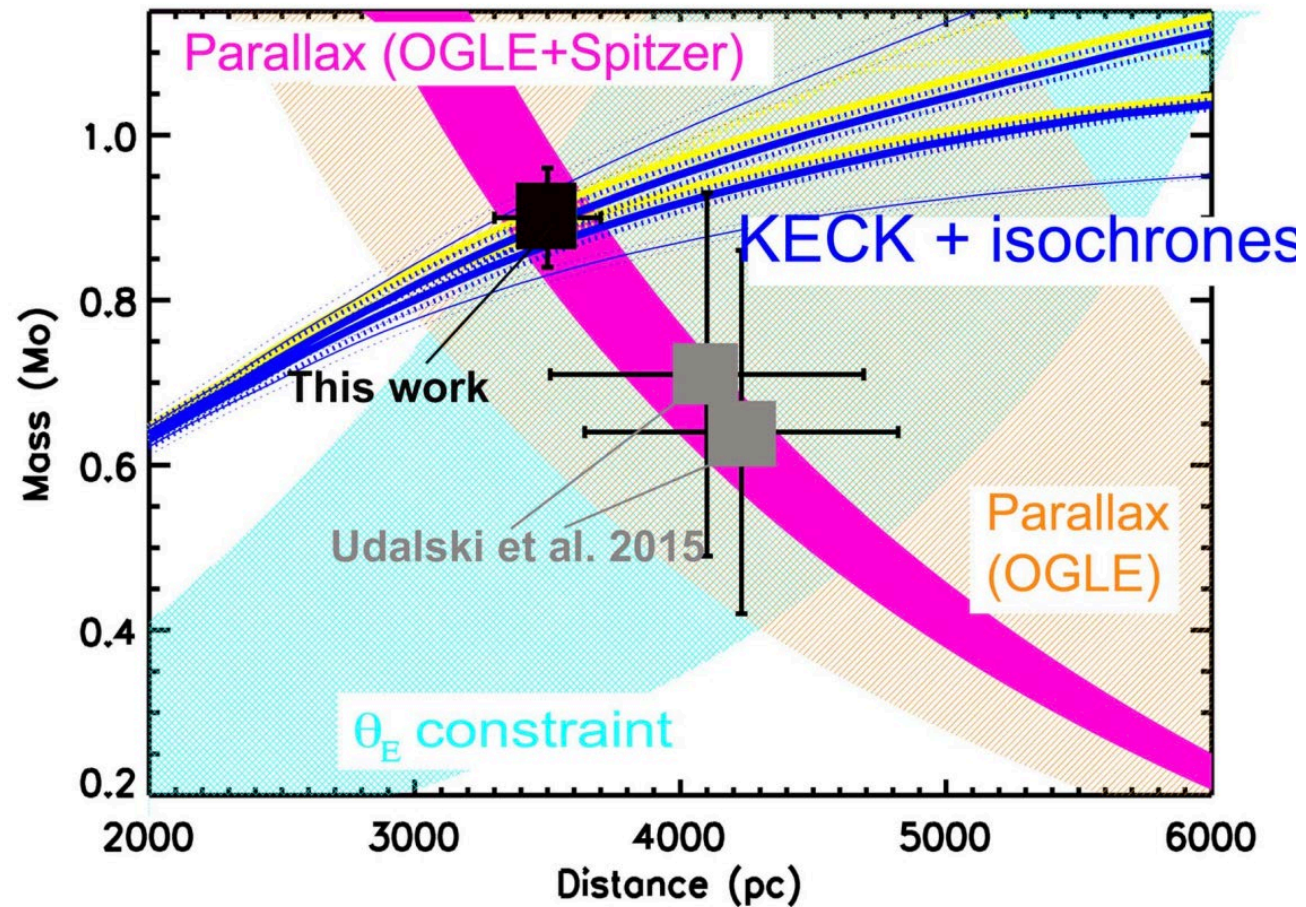
$$M_L = \frac{c^2}{4G} \theta_E^2 \frac{D_S D_L}{D_S - D_L}$$



$$M_L = \frac{c^2}{4G} \tilde{r}_E^2 \frac{D_S - D_L}{D_S D_L}$$



$$M_L = \frac{c^2}{4G} \tilde{r}_E \theta_E$$



(Beaulieu et al. 2018)

Planet and Star Mass Measurements

Angular Einstein Ring Radius: $\theta_E = f_1(M_L, D_L, D_S)$

Compare light curve features to ruler in source plane

- *Finite source size:* $\theta_E = \theta_* / \rho_*$
- *Source proper motion:* $\theta_E = \mu_{\text{rel}} t_E$



Places requirements on the primary and secondary filters, as well as the angular resolution and time baseline.

Microlensing Parallax: $\tilde{r}_E = f_2(M_L, D_L, D_S)$

Compare light curve features to ruler in observer plane

- Orbital Motion of Roman
- Comparison between Roman and Earth



Places requirements on the length of the seasons + motivates ground-based imaging

Lens Flux: $F_L = f_3(M_L, D_L, A_\lambda)$

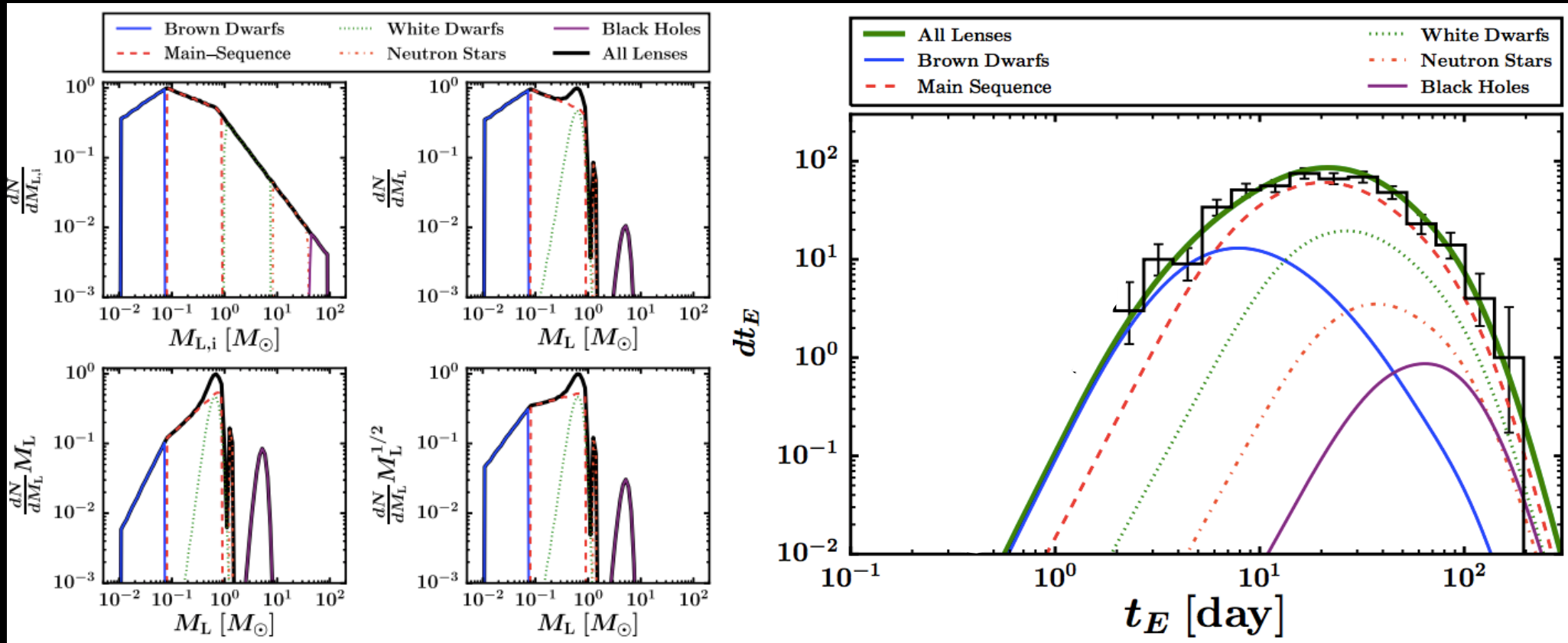
Measure the flux from the lens

- Ground-based AO, HST
- Roman!



Places requirements on the angular resolution and time baseline of the survey

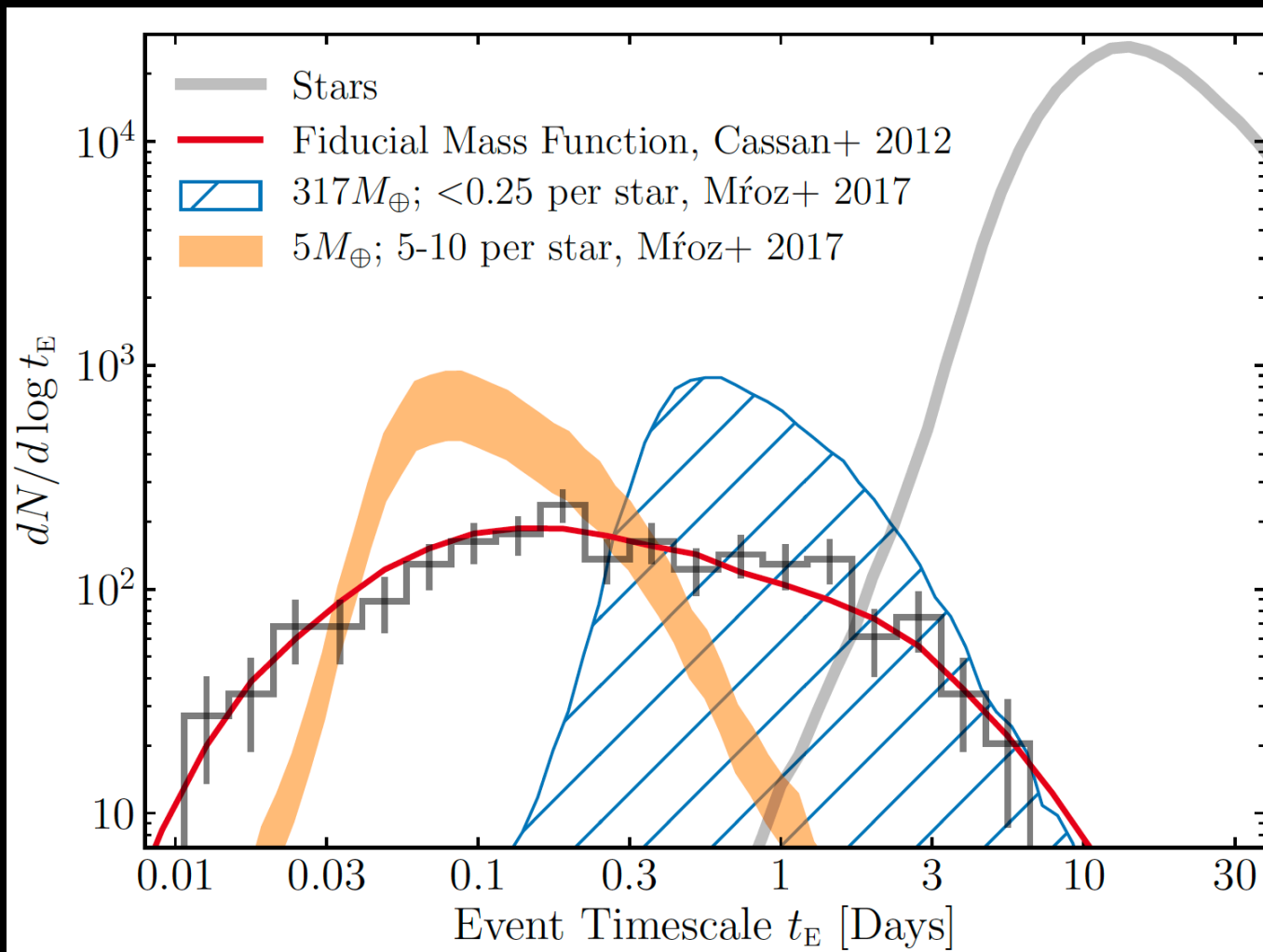
Probe the Compact Object Mass Function from $\sim 30 M_{\odot}$...



Clanton & Gaudi 2017



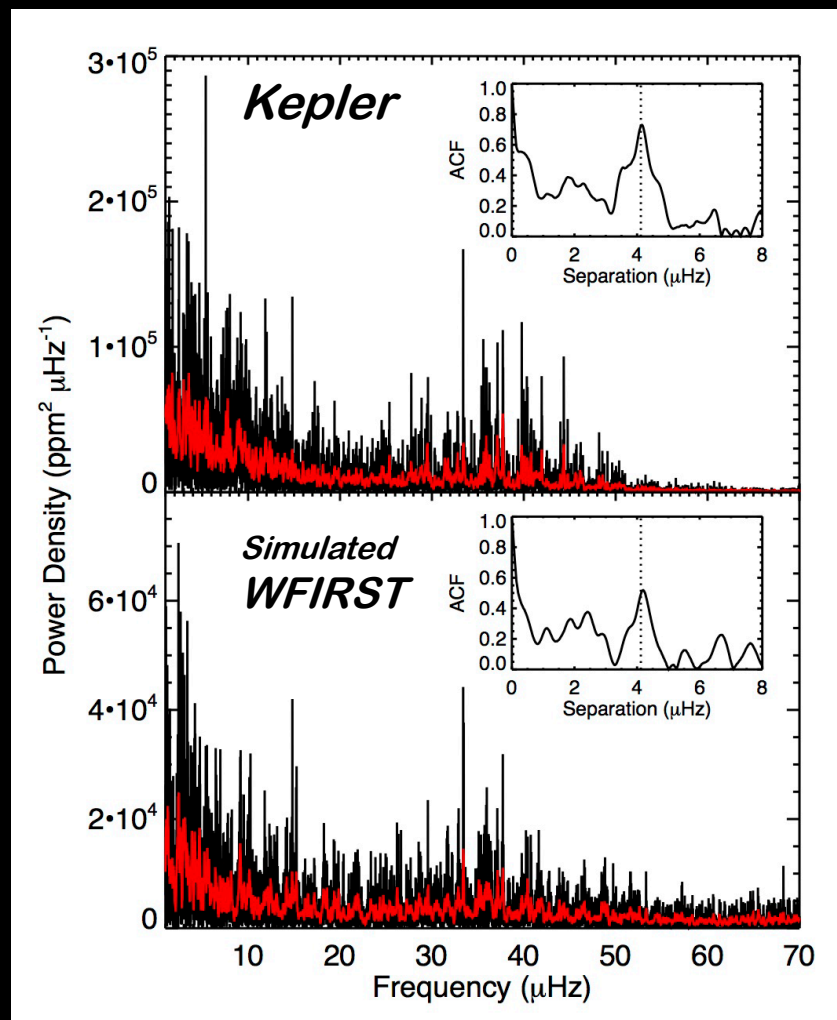
...to Free-Floating Planets!



(Johnson et al. 2020)



Asteroseismology of $\sim 10^6$ giants

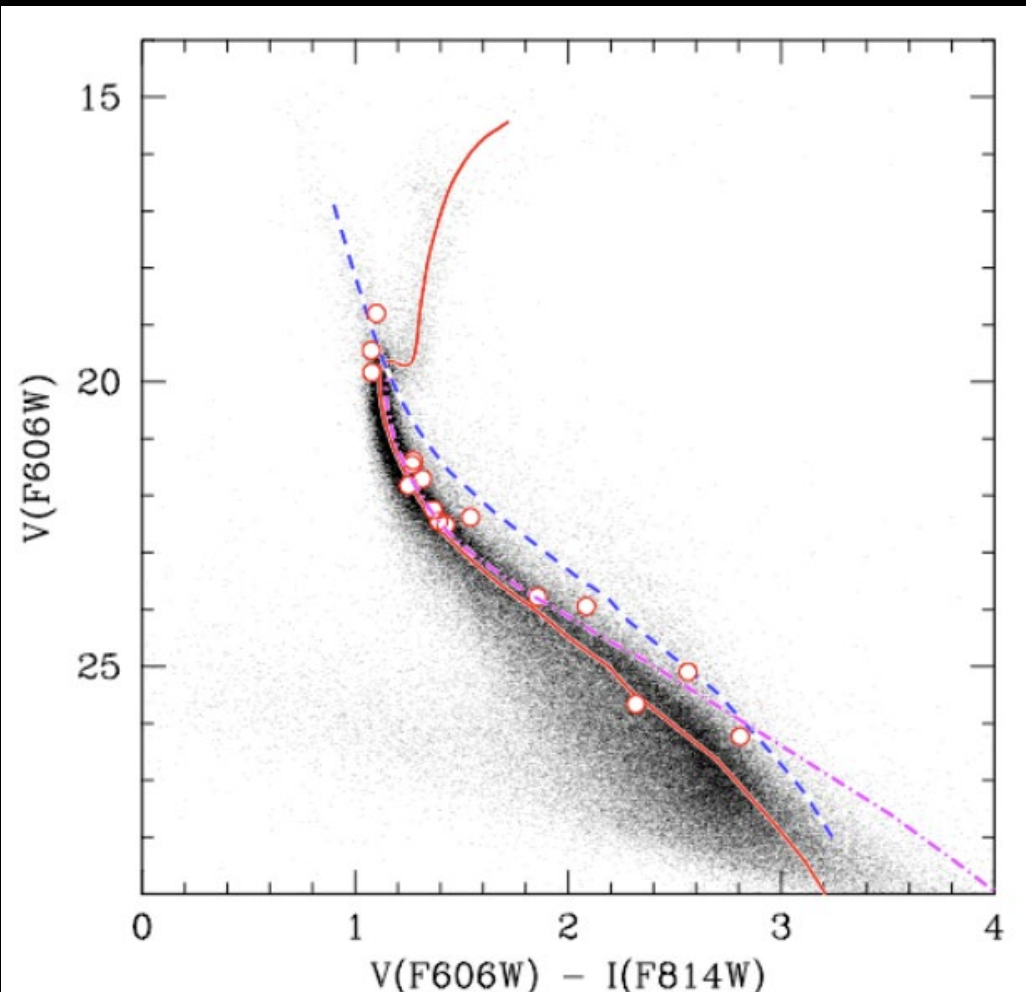


Gould et al. 2015

- Roman will be able to measure $\nu_{\max}$ and $\Delta\nu$ for the $\sim 10^6$ $H_{\text{AB}} < 14$ red giant stars in the survey fields.
- Only measure $\nu_{\max}$ for fainter stars.
- Will also be able to measure precise ($\sim 0.3\%$) distances to these stars via parallax (if photon-noise limited).



Resolved Stellar Populations



- Roman will obtain one of the deepest fields ever taken.
 - $\sim 2 \times 10^6$ s in F146.
 - $\sim 3 \times 10^5$ s in F087.
- Compare to the SWEEPS 9×10^4 s in F606W (V) and F814W (I).

Sahu et al. 2006

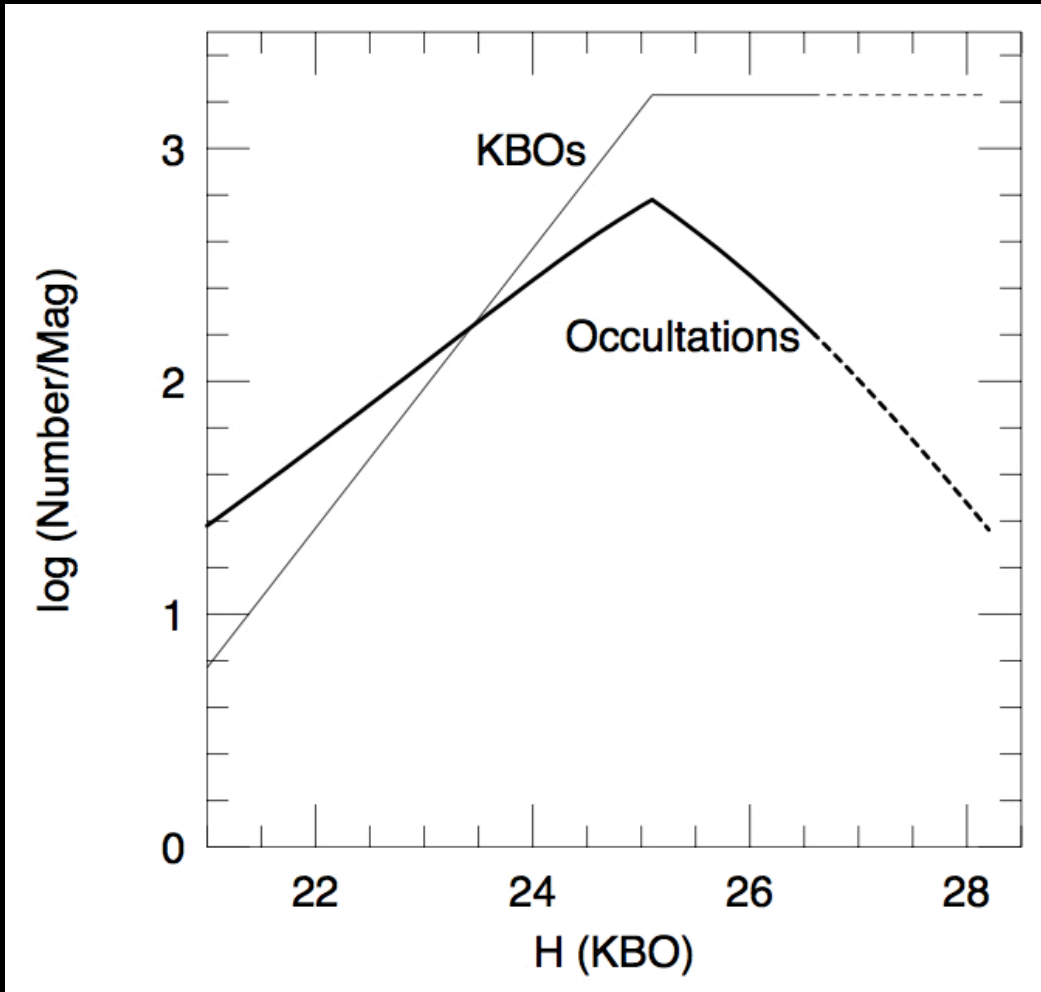


Galactic Structure

- Photon noise-limited parallaxes of $<10\%$ and proper motion measurements of 0.3% (0.01 mas/yr) for $\sim 4 \times 10^6$ bulge and disk stars with $F146_{\text{AB}} < 21$.
- Deep multicolor photometry in a least one narrower bluer filter (e.g., F087) and one narrower red filter (e.g., F213) for these stars.
- Shallow photometry in all filters.
- With this dataset, it will be possible to:
 - Estimate T_{eff} , $[M/H]$, Age, Luminosity, and A_H for all these stars.
 - Probe the disk and Galactic bulge mass and velocity distribution (including Galactic bar structure).
 - Probe the metallicity and age distribution of the disk and bulge.
 - Create an exquisite extinction map in the survey area.



Solar System Science

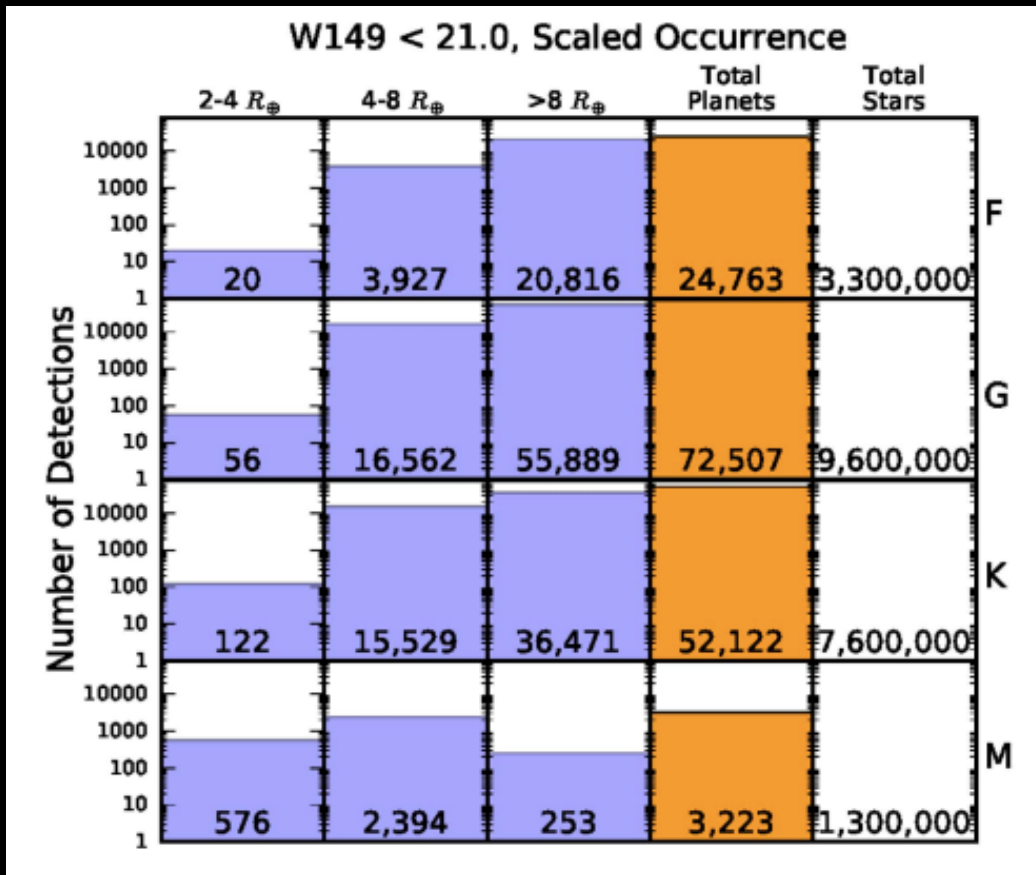


- Roman will detect ~ 5000 TNOs down to $F146_{AB} < 30$ (corresponding to $D \sim 10$ km) of 17 deg^2 .
 - Substantially below the collisional break.
- Orbital elements will be determined to a few %, allowing for dynamical classification.
- ~ 1000 of these will occult stars, and several dozen will occult more than one star.

Gould 2014



10⁵ Transiting Planets



- Roman will detect $\sim 10^5$ transiting planets with radii down to $\sim 2R_{\oplus}$.
- 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.

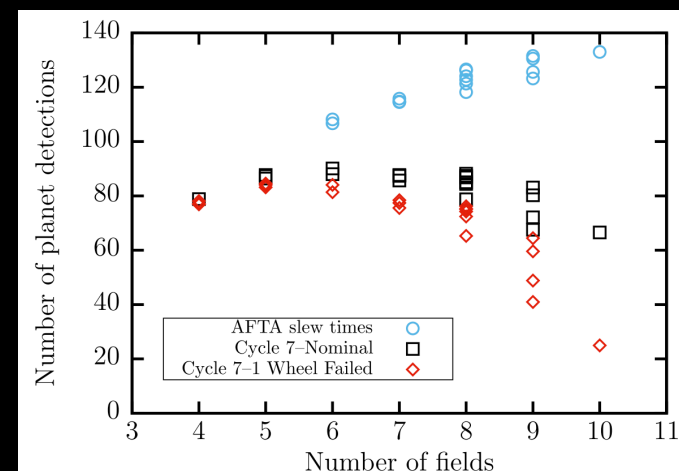
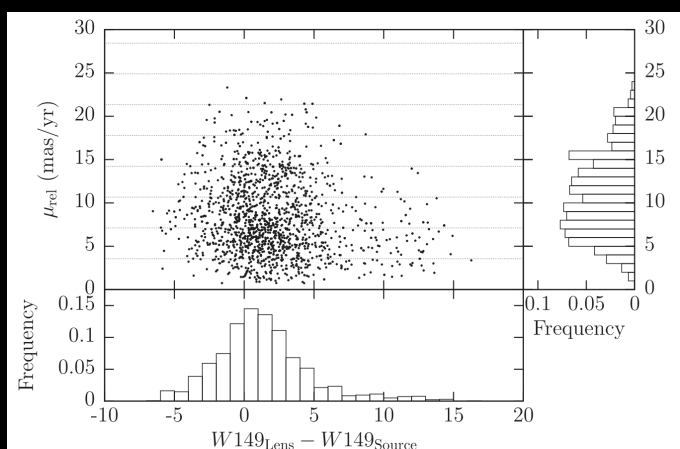
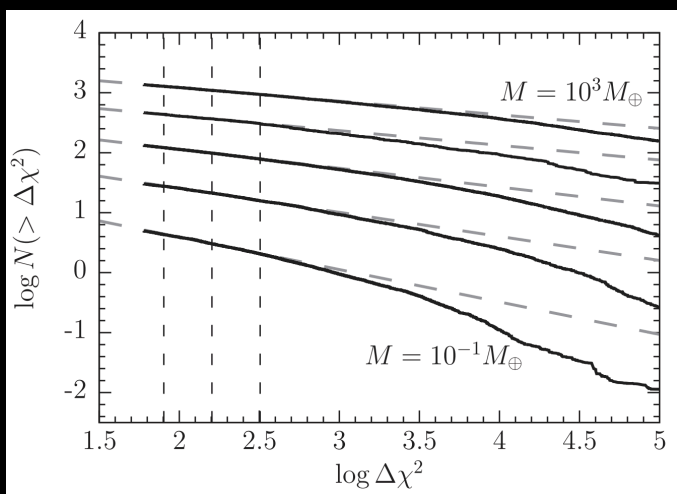
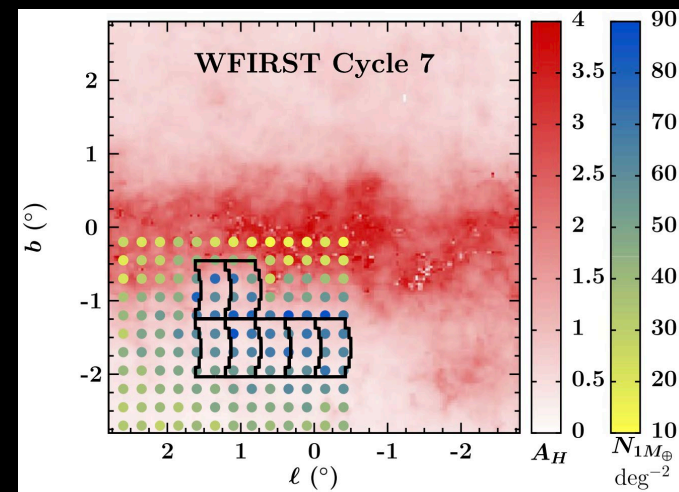
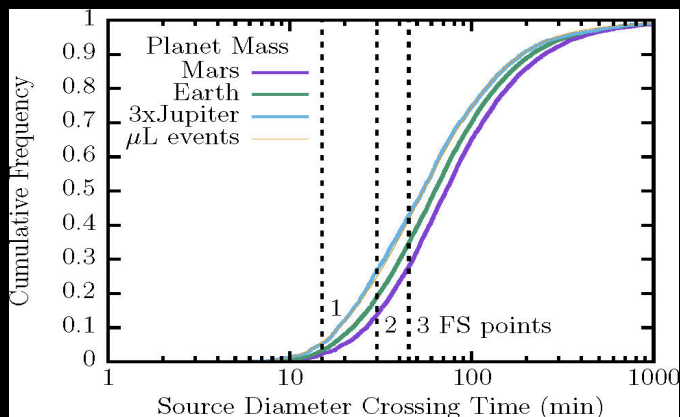
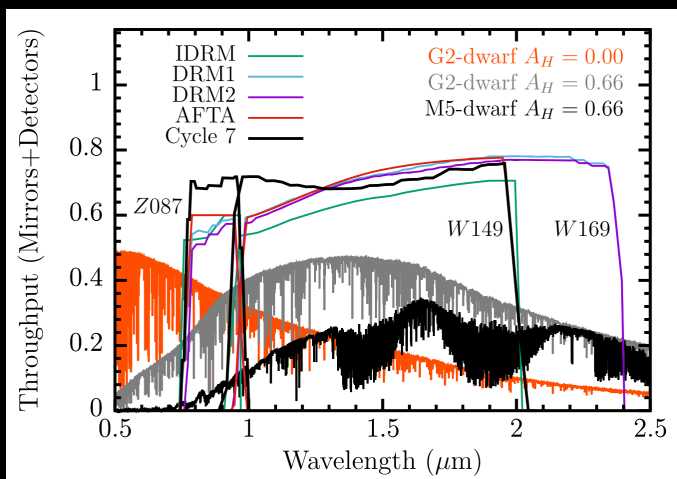
Bennett & Rhie 2002

Montet et al. 2017

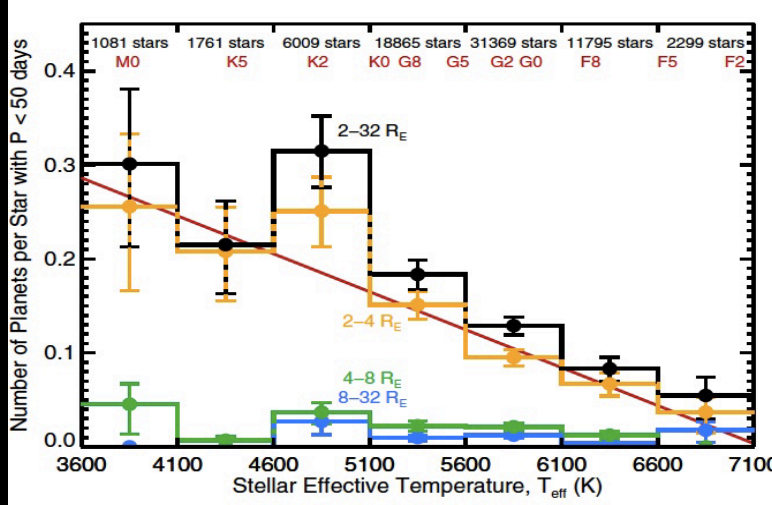
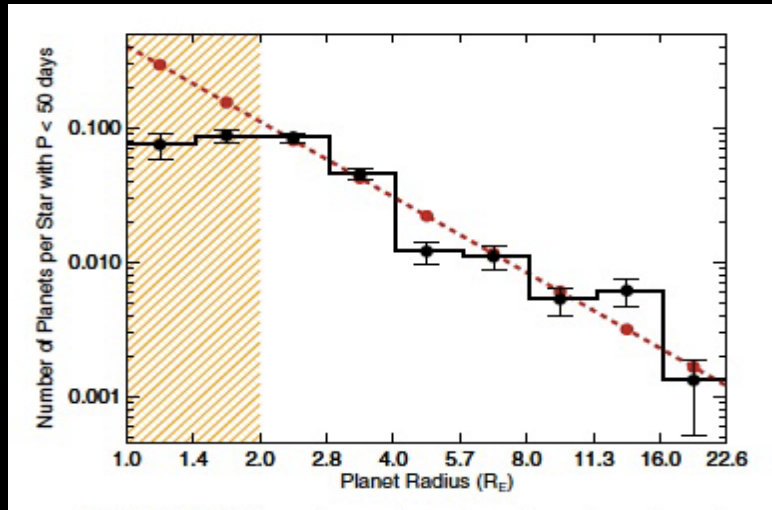
Expected yield of transiting planets orbiting dwarfs with $W149_{AB} < 21$ (Montet et al. 2017)



Survey Design



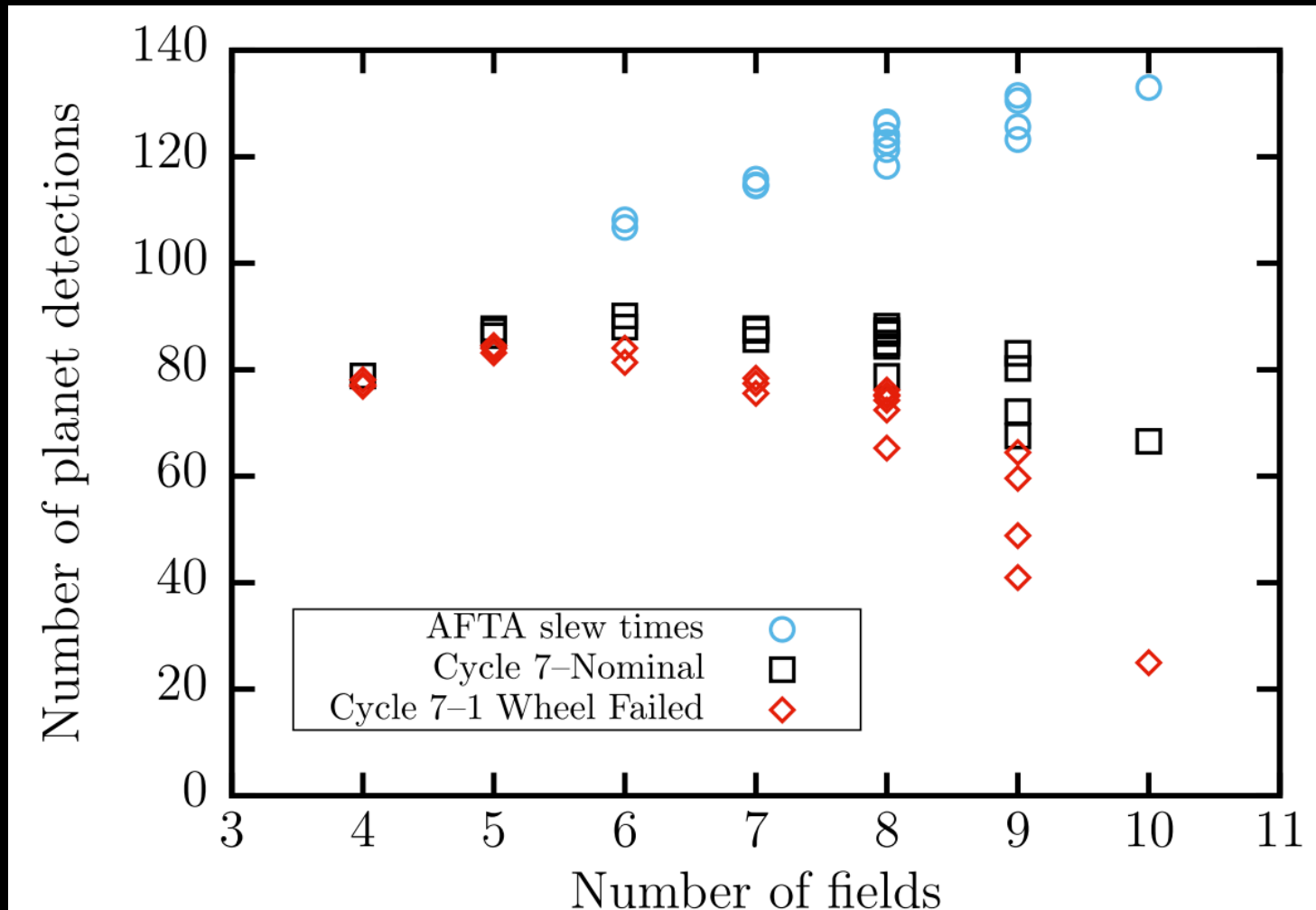
Justification for Required Yield



- A large (≥ 1000) yield is needed to precisely resolve planet distribution functions
- Example: Howard et al. 2012 analyzed 1235 candidate planets from Kepler
- Even with ~ 1200 planets, it is difficult to discern features in the planet distribution functions, particularly if one subdivides the sample.



Optimizing the Number of Fields



Optimizing the Number of Fields

