National Aeronautics and Space Administration

Roman Bulge Time Domain Survey:

Design, Requirements, and Data Products.

Roman Joint Survey Processing Splinter
AAS 239
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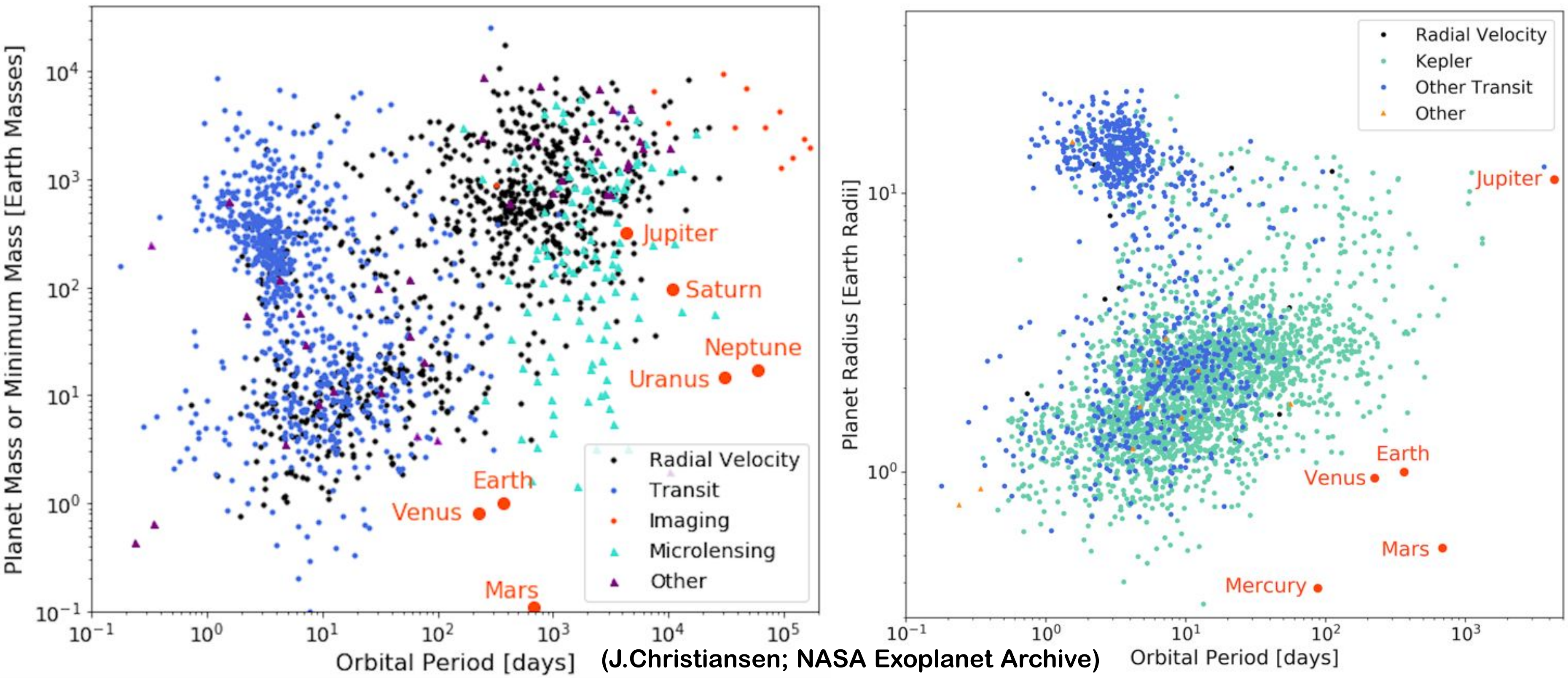
NANCY GRACE ROMAN SPACE TELESCOPE

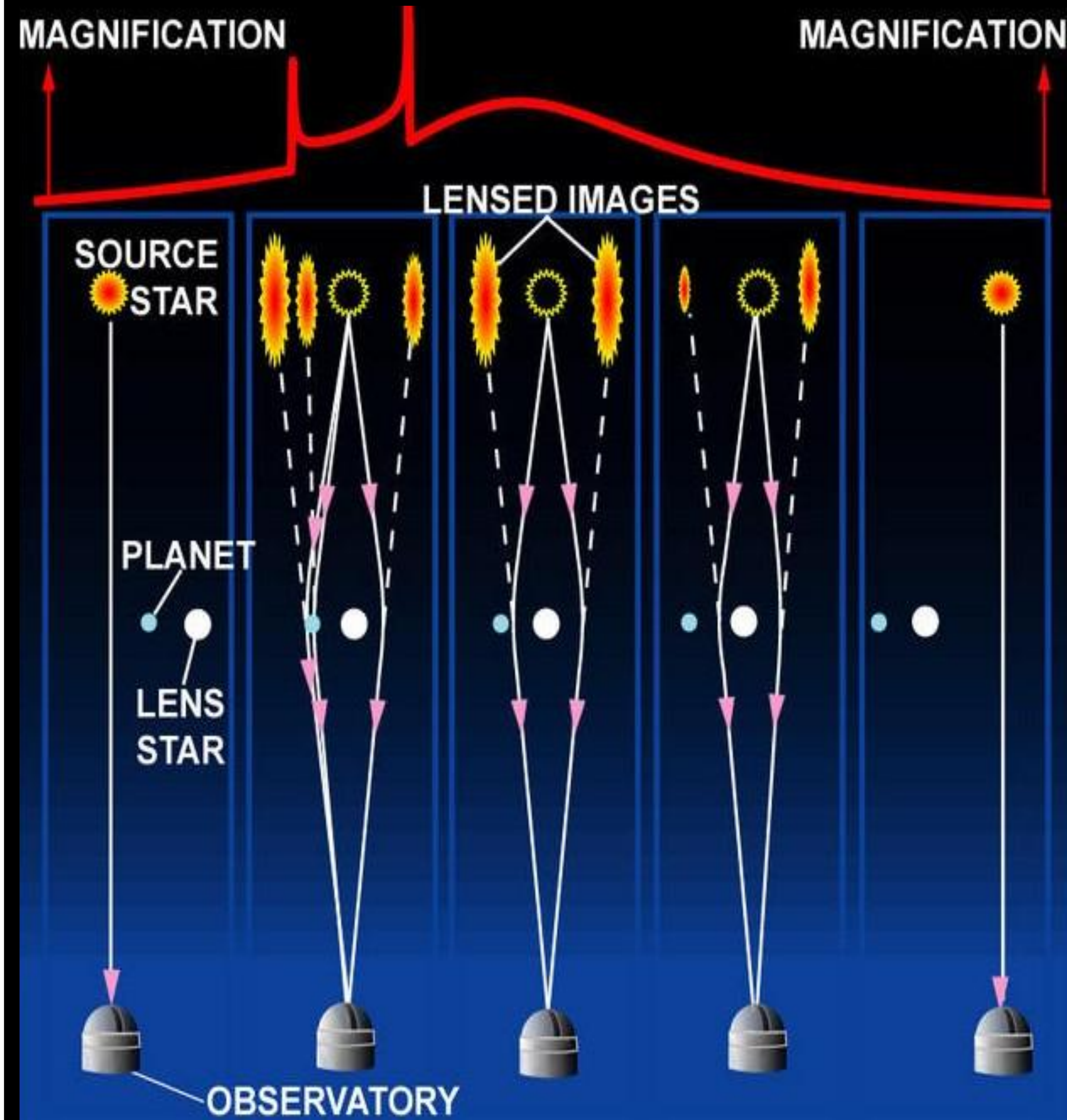
Current Status of Exoplanet Demographics



(J.Christiansen; NASA Exoplanet Archive)

Primary science goal of the RBTDS:
"Carry out a statistical census of planetary systems in the Galaxy, from the outer habitable zone to free floating planets, including analogs to all of the planets in our Solar System with the mass of Mars or greater."

Microlensing



Unique Sensitivity of Microlensing to Exoplanetary Systems

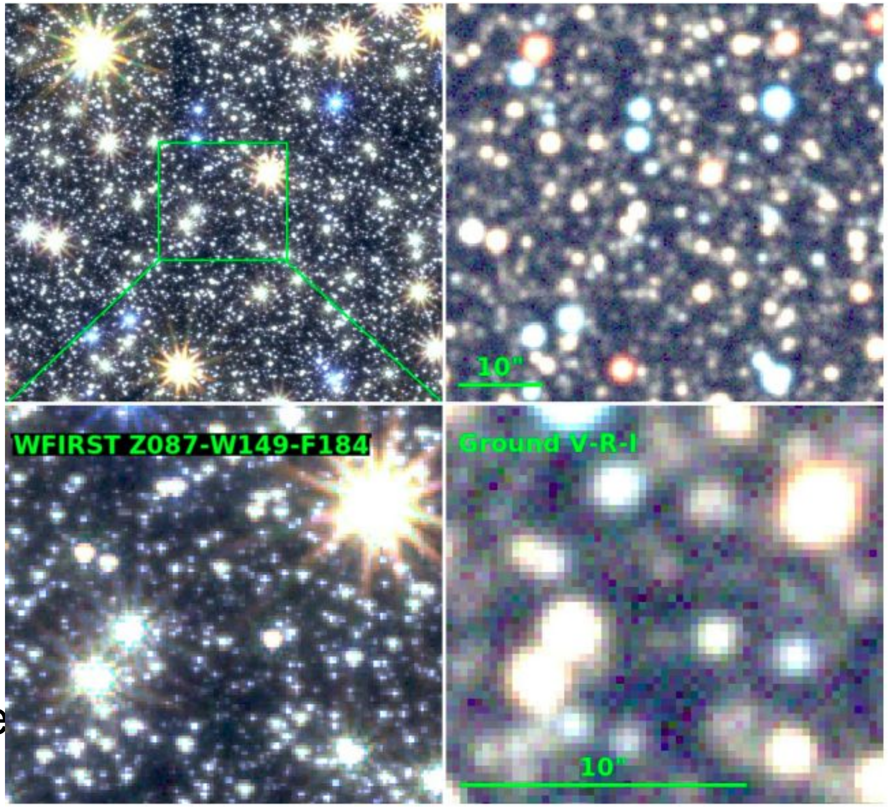
- Planets beyond the snow line.
  - Most sensitive at ~few × a_{snow}
- ***Very*** low-mass planets.
  - >10% Mars.
- Long-period and free-floating planets.
  - 0.5 AU - ∞
- Wide range of host masses.
  - BD, $M<M_{Sun}$, remnants
  - Typically 0.5 M_{Sun}
- Planets throughout the Galaxy.
  - 1-8 kpc

General 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.

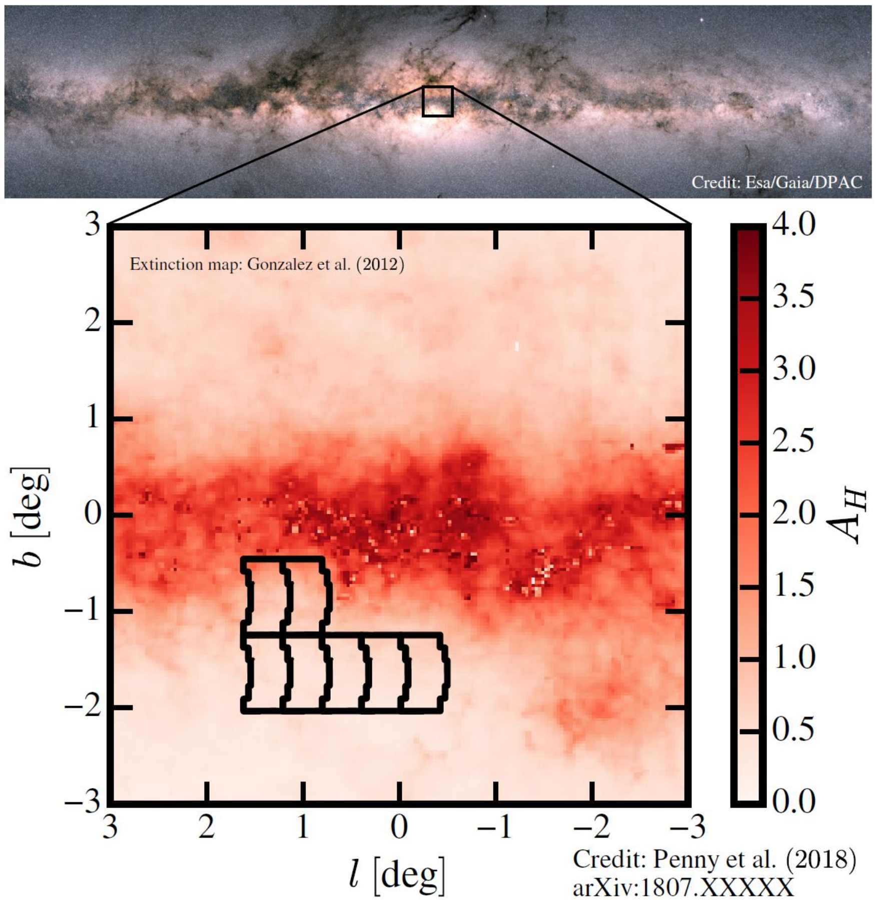
Ground vs. Space

- 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 sensitivitie



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

Roman Galactic Exoplanet Survey*



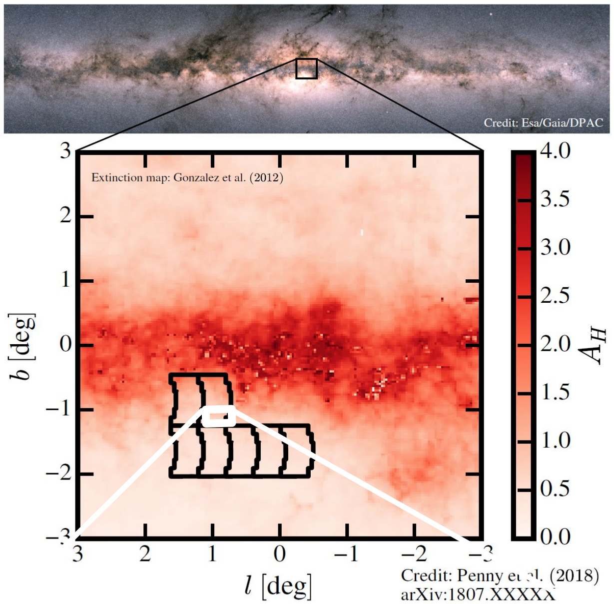
Penny et al. 2019

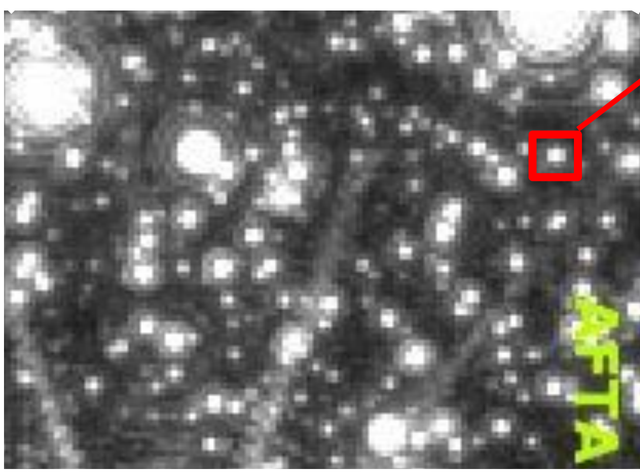
- 7 fields for a total of ~2 deg^2
- Wide $W149_{AB}$ (0.927-2 μm) filter**
- 15-minute cadence.
- ~50s exposures.
- Observations every 6 hours in alternating blue/red filters (e.g., F087, F184).
- 6 x 72-day seasons.
- ~41,000 exposures in $W149_{AB}$.
- ~432 total days spread over 5-year mission.

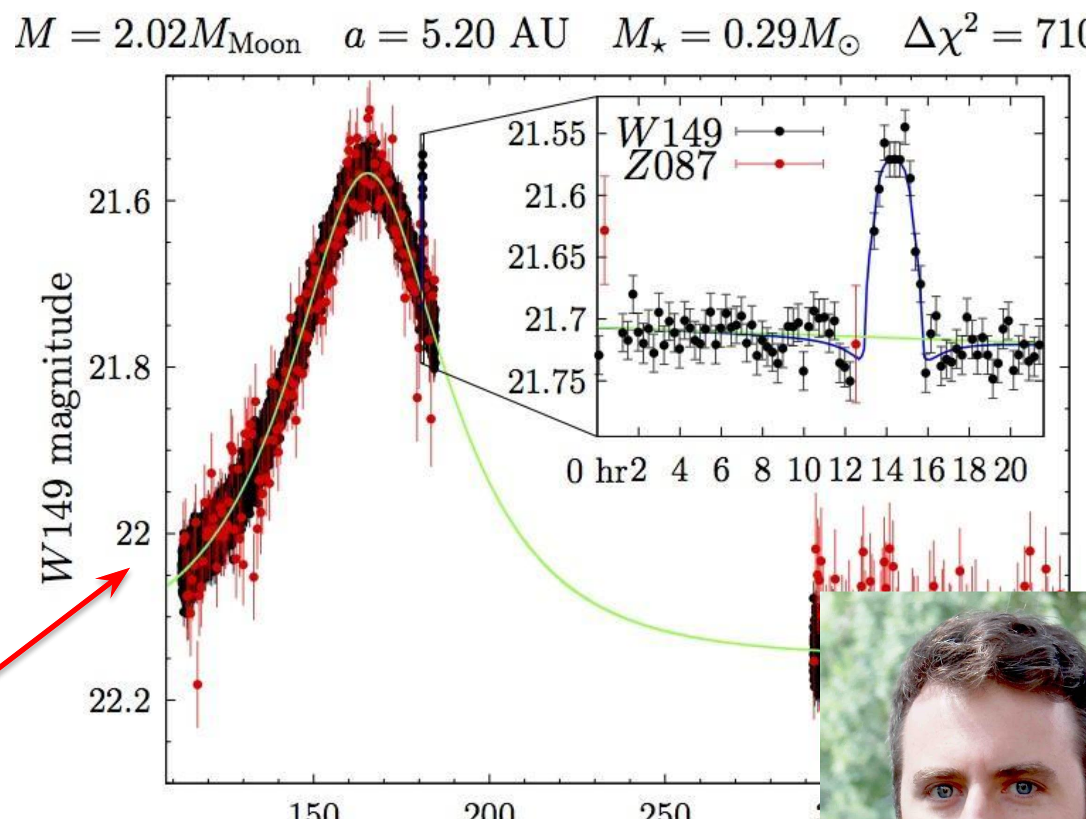
* Notional survey design required to achieve the science goals. The final design of the major surveys won't be finalized until much closer to launch, with input from the broader community.

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

RGES Simulations

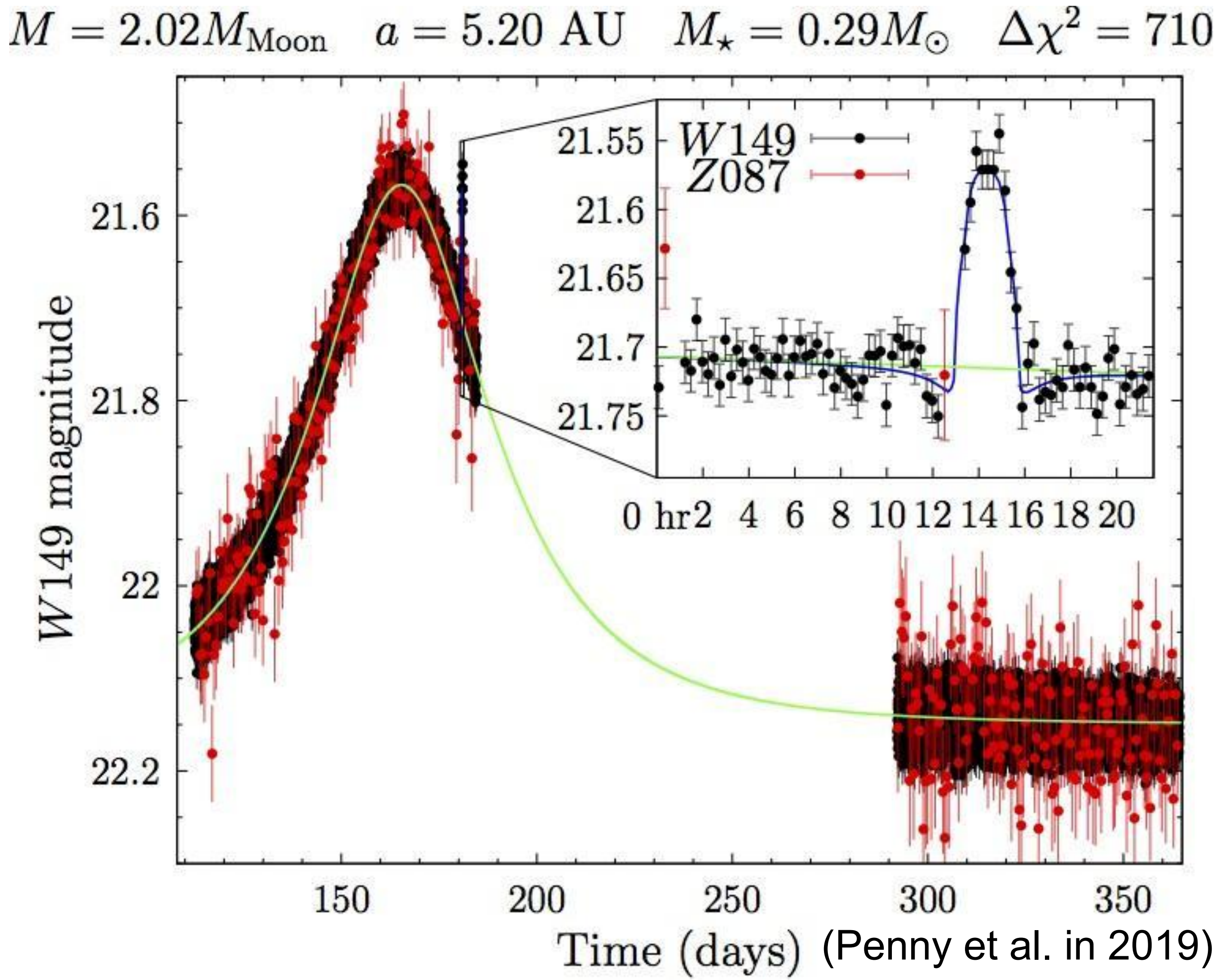






(Penny et al. 2019)

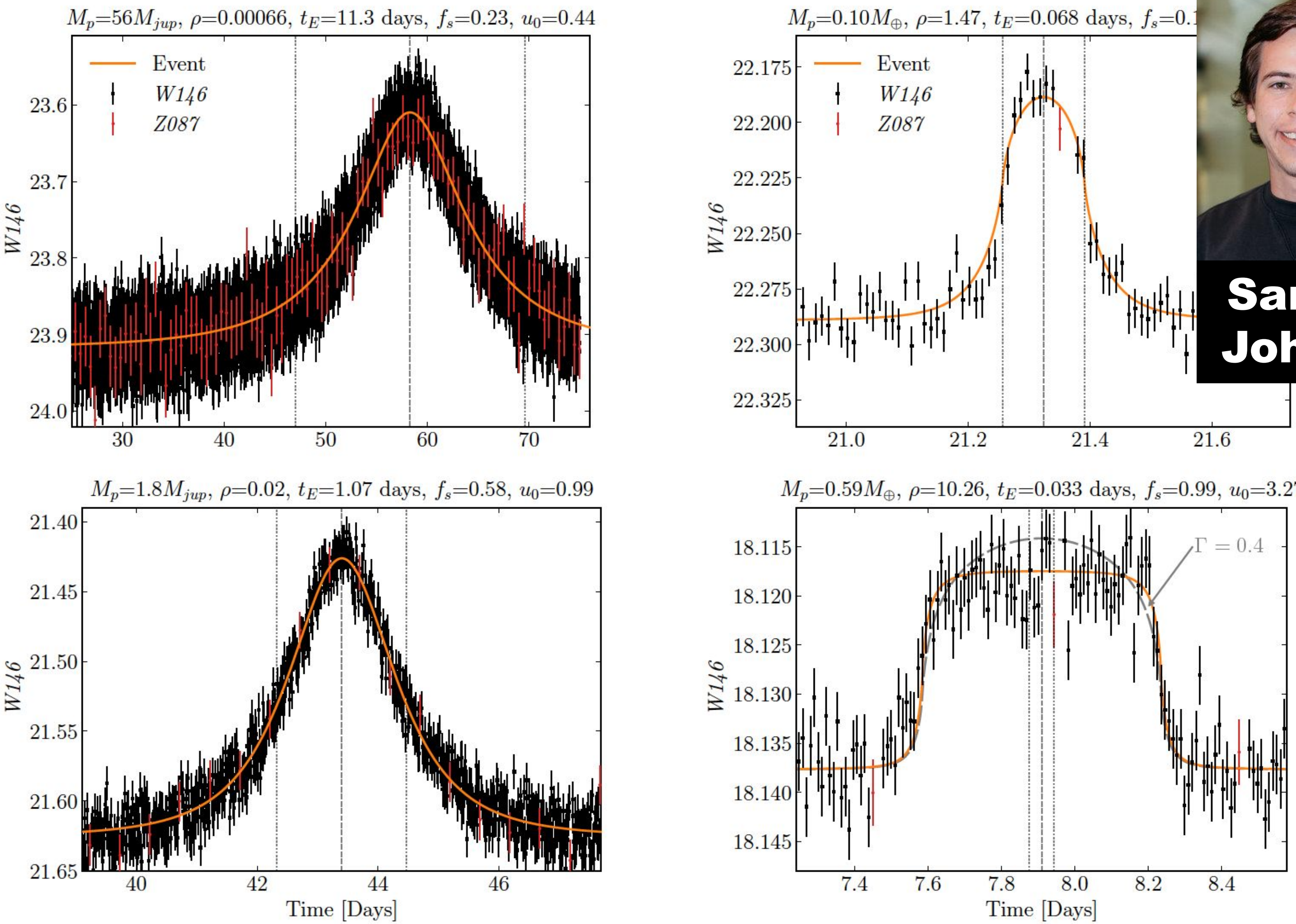
Matthew Penny



(Penny et al. in 2019)

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

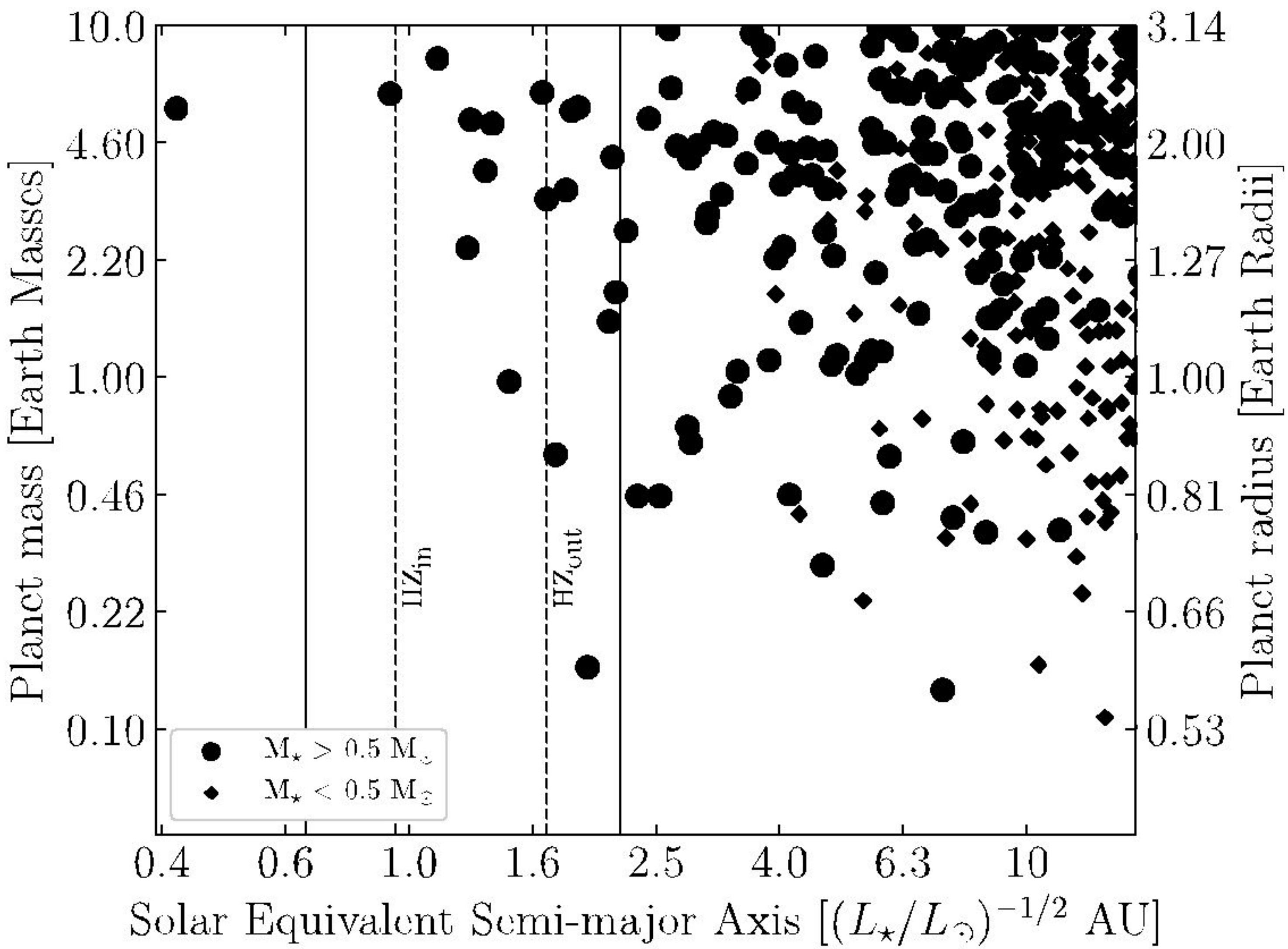
Free Floating Planets



Samson Johnson

(Johnson et al. 2020)

Potentially Habitable Planets.

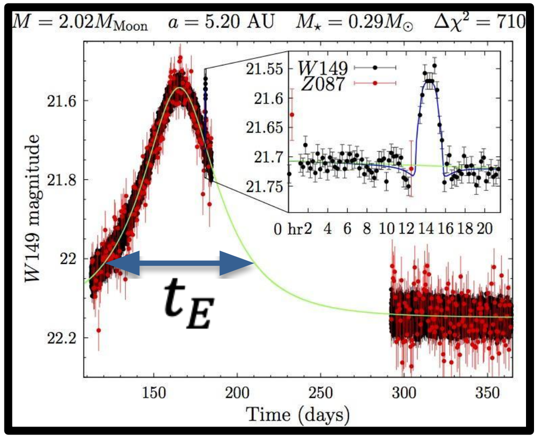


(Johnson et al. in prep.)

Planet and Star Mass Measurements

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

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

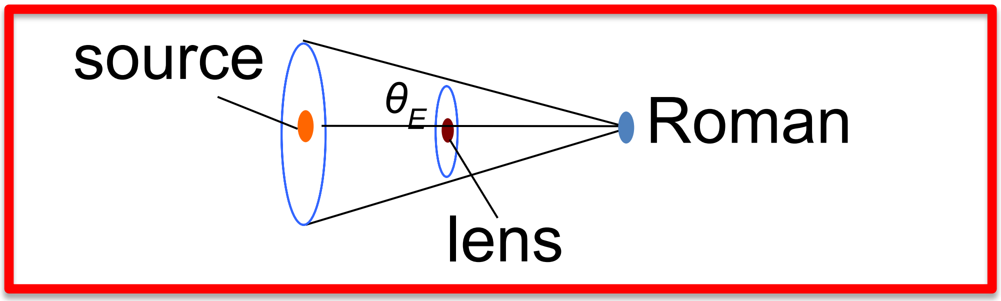


Planet and Star Mass Measurements

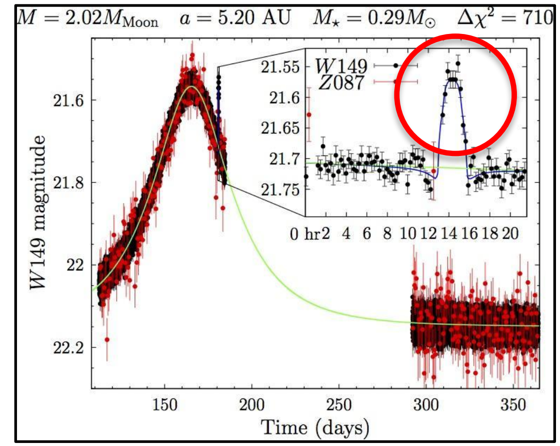
Angular Einstein Ring Radius: $\theta_E = f_1(M_L, D_L, D_S)$

Compare light curve features to ruler in source plane

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



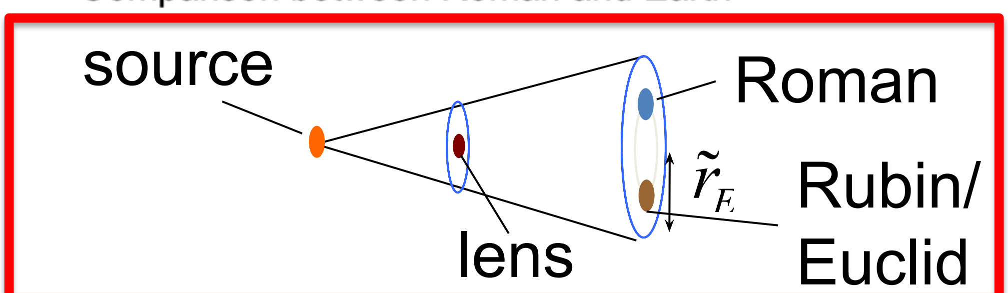
Finite Source Effects



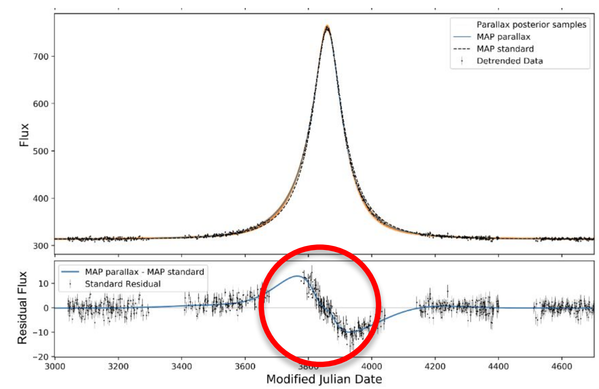
Microlensing Parallax: $\tilde{r}_E = f_2(M_L, D_L, D_S)$

Compare light curve features to ruler in observer plane

- Orbital Motion of Roman
- Comparison between Roman and Earth



Orbital Parallax

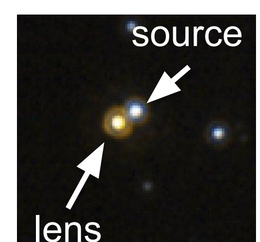


Lens Flux: $F_L = f_3(M_L, D_L, A_\lambda)$

Measure the flux from the lens

- Ground-based AO, HST

Lens flux
nd proper motion



Planet and Star Mass Measurements: Example

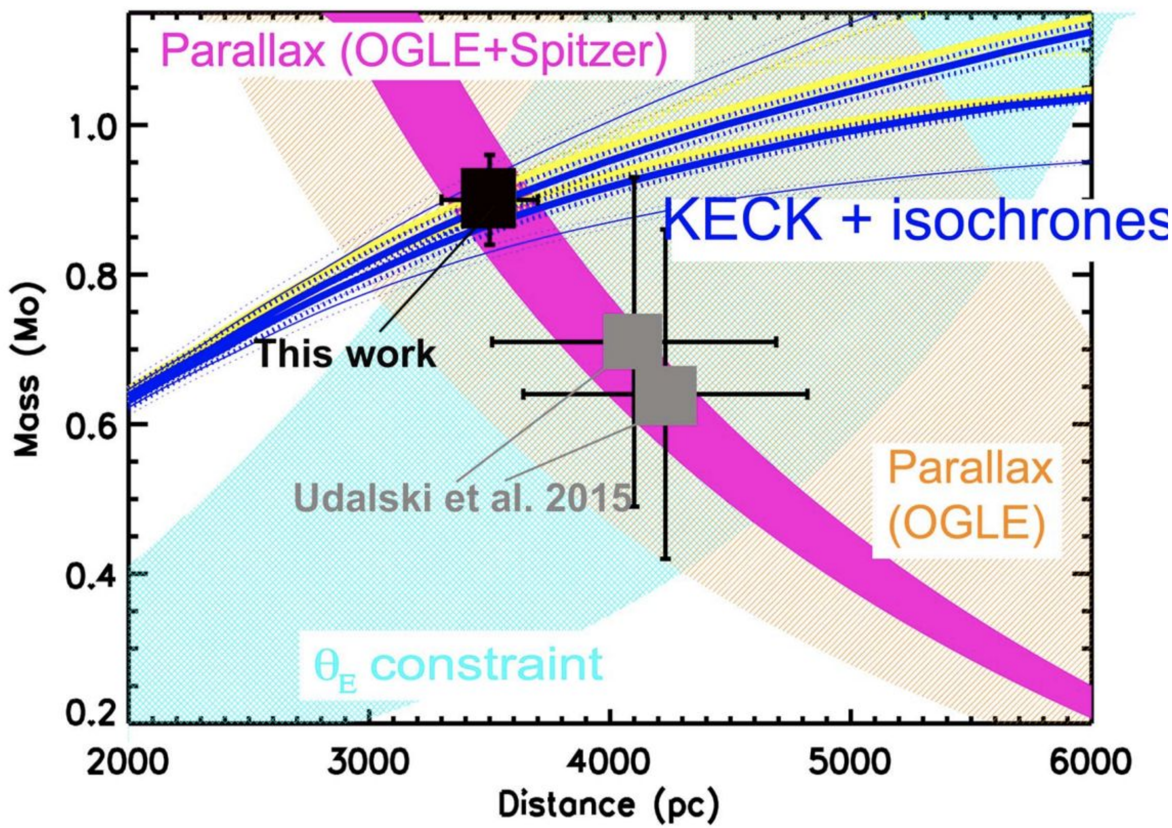
$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

+

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

⇓

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



(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:* $\theta_E = \mu_{rel}\, t_E$

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

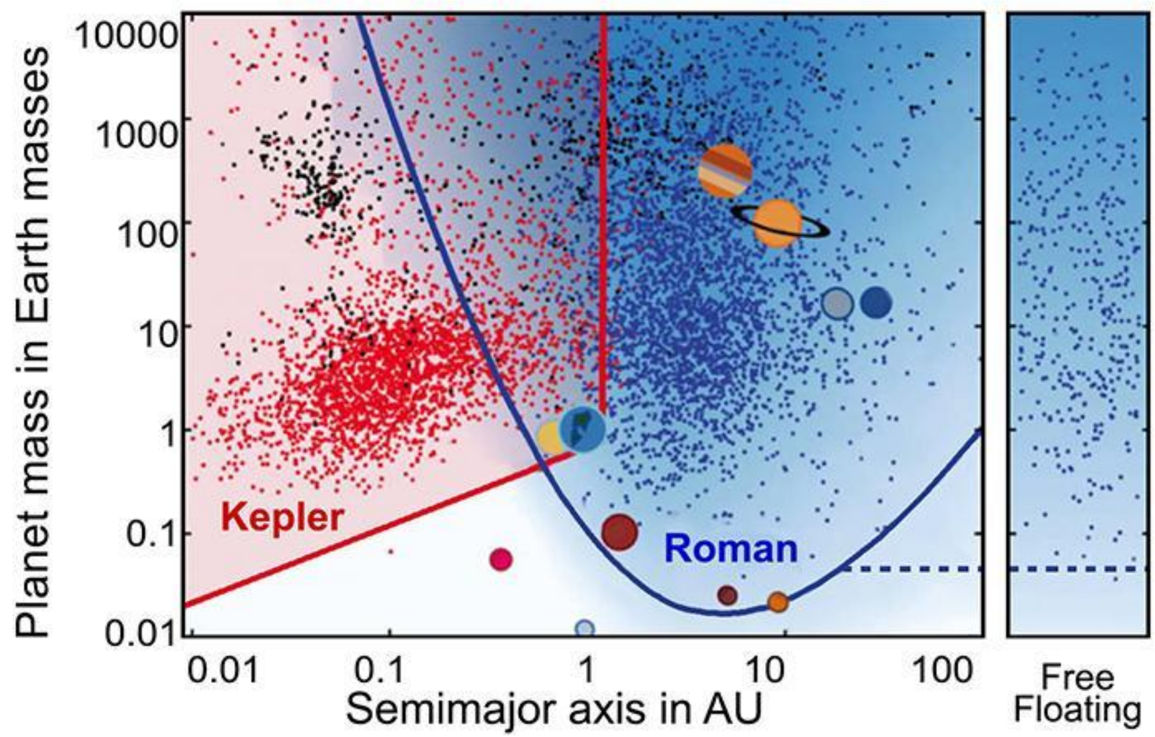
Measure the flux from the lens

- Ground-based AO, HST
- Roman!

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

Expected Demographic Results

- ~1400 bound planet detections.
- ~30 with mass $\leq 0.3 M_{Earth}$.
- Mass measurements for the majority of detected systems.
- Hundreds of free-floating planets (~60 with $M \leq M_{Earth}$).
- Some sensitivity to "outer" habitable zone planets



(Penny et al. 2019)

GBTDS Science Requirements

- EML 2.0.1: WFIRST shall be capable of measuring the mass function of exoplanets with masses in the range 1 M_{Earth} < m < 30 $M_{Jupiter}$ and orbital semi-major axes ≥ 1 AU to better than 15% per decade in mass.
- EML 2.0.2: WFIRST shall be capable of measuring the frequency of bound exoplanets with masses in the range 0.1 M_{Earth} < m < 0.3M_{Earth} to better than 25%
- EML 2.0.3: WFIRST 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.
- EML 2.0.4: WFIRST 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%.
- EML 2.0.5: WFIRST 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.

GBTDS Survey Requirements

- EML 2.3.2: WFIRST shall be capable of observing a total 585.4 square degree-days over the course of the mission, with relative photometric measurements in the primary microlensing filter that have a statistical S/N of ≥100 per exposure for a HAB=21.4 star, if it is allocated 6 seasons of observing time.
- EML 2.3.3: WFIRST shall be capable of providing raw microlensing images with relative photometric measurements in the primary microlensing filter having a statistical S/N of ≥100 per exposure for a HAB=21.4 star.
- EML 2.3.4: WFIRST shall be capable of providing raw images of the microlensing fields with a wide filter spanning λ ≈ 1 – 2 μm.
- EML 2.3.5: WFIRST shall be capable of providing a photometric sampling cadence of ≤15 minutes for each microlensing field, while simultaneously achieving the S/N specified in EML 2.3.3.
- EML 2.3.6: WFIRST shall be capable of providing microlensing raw images with an EE50 radius of the PSF in the wide filter <0.15”.

GBTDS Survey Requirements (cont'd)

- EML 2.3.9: WFIRST shall be capable of performing microlensing observations over seasons of at least 60 days. At least 36 days of each season should be on the opposition side of quadrature (line of sight at greater than 90 degrees from the Sun vector).
- EML 2.3.11: WFIRST shall be capable of periodically providing raw images of the microlensing fields in two R~4 filters; one with bandpass shortward of 1 μm and one with a bandpass longward of 1 μm.
- EML 2.3.12: WFIRST shall be capable of separating the first and last microlensing observing seasons by >4 years. In addition, the first two and last two seasons should occur during the same 12-month period.

GBTDS Data Product Requirements

- EML 2.1.1: WFIRST shall be capable of providing supersampled stacked images of the microlensing fields after every microlensing season.
- EML 2.1.2: WFIRST shall be capable of producing a catalog of each source in the microlensing fields containing positions, fluxes, with object-appropriate derived data.
- EML 2.1.3: WFIRST shall be capable of producing a catalog of each microlensing event in the microlensing fields containing positions, fluxes, object classification information with event-appropriate derived data.
- EML 2.1.5: WFIRST shall be capable of providing calibrated moment curves (photometry, position, ellipticity) for each microlensing event, on a daily basis.
- EML 2.1.6: WFIRST shall be capable of providing science data records with relative astrometric measurements having a systematic precision of ≤100 μas over each microlensing season, for sources imaged on the same detector in at least two passbands.

GBTDS Data Quality Requirements

- EML 2.2.3: WFIRST shall be capable of providing calibrated data records with relative astrometric measurements having a statistical precision of ≤1 mas per measurement for a star of H_{AB}=21.4 in at least two passbands.
- EML 2.2.4: WFIRST shall be capable of providing calibrated data records with the FWHM of each star measured in both axes, with a precision ≤1% per day for stars H_{AB}=21.4
- EML 2.2.5: WFIRST shall be capable of providing calibrated data records with the FWHM of each source measured in both axes of a H_{AB}=21.4 star to ≤0.2% for each observing season of the microlensing survey.
- EML 2.2.6: WFIRST shall be capable of providing calibrated data records with relative photometric measurements in the primary microlensing filter having a systematic precision of ≤0.1% over a season.
- EML 2.2.7: WFIRST shall be capable of providing calibrated data records with relative photometric measurements from separate seasons tied to ≤0.1% for any individual star.
- EML 2.2.8: WFIRST shall be capable of providing calibrated data records with absolute photometry calibrated in one or more of the standard filters to <3%.