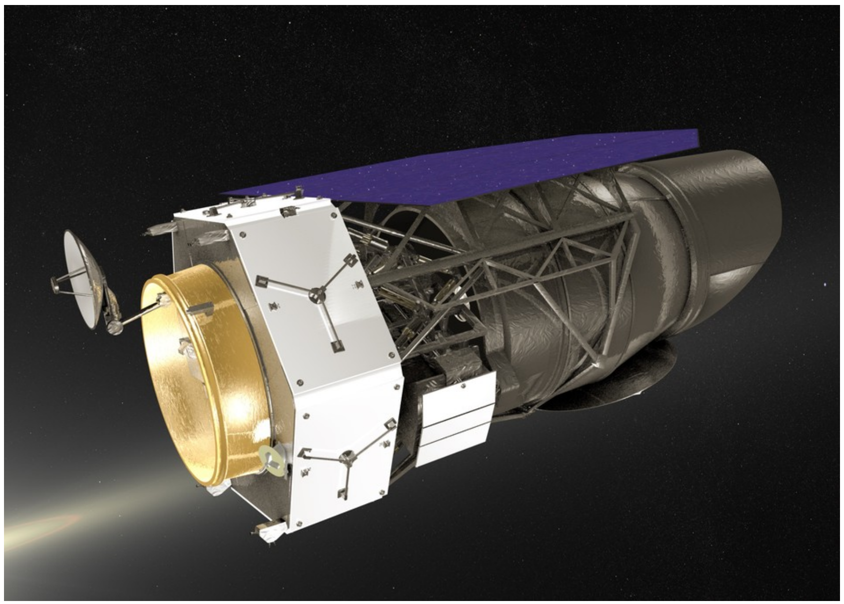
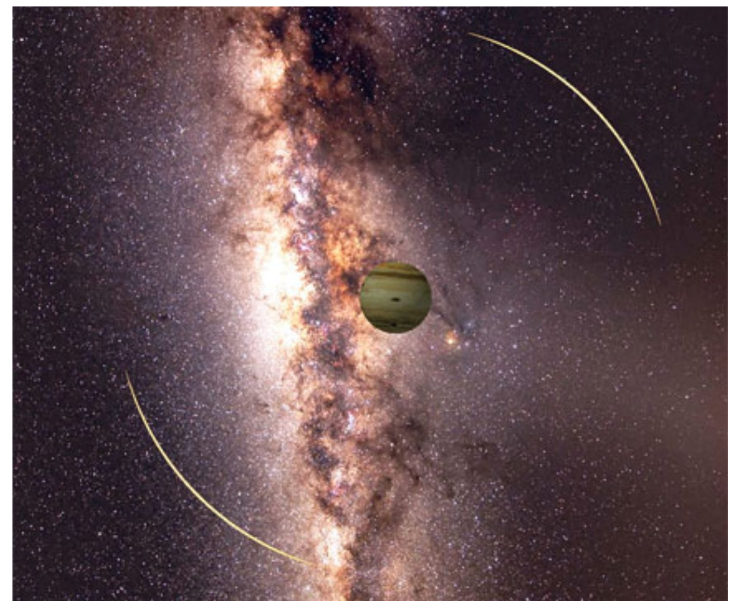
Design of the Roman Galactic Exoplanet Survey (RGES)





Matthew Penny
Louisiana State University

RSIG, January 2021

Overview

- RGES Survey Requirements & Motivation
- Microlensing Surveys Order of Magnitude

- More in depth version of this talk at: https://www.youtube.com/watch?v=5dn7QEviU74&list=PLIbTYGsIVYthWRS14eCEK8SK9IOTcaYsf&index=15

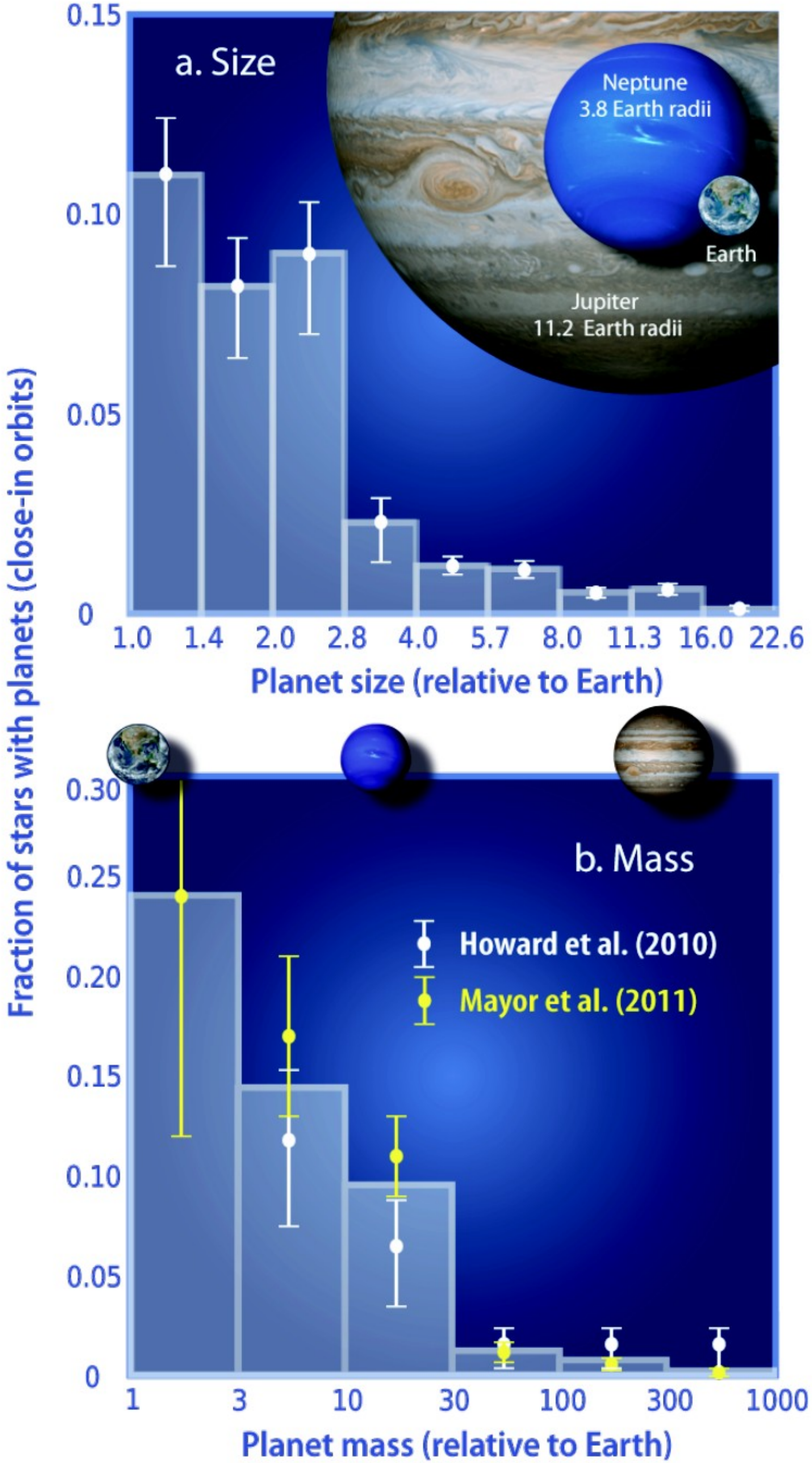
RGES
Science requirements.

1. Measure the mass function of cold exoplanets with masses > 1 M_{Earth} and semimajor axes ≥ 1 AU to better than ~ 10% per decade*.
2. Measure the frequency of Mars–mass embryos to ~ 15%*.
3. Measure the frequency of free floating planetary–mass objects in the Galaxy over nearly six orders of magnitude in mass. If there is one M_{Earth} free–floating planet per star, measure this frequency to ~ 20%.
4. Estimate the mass and distance to the host stars and planets to better than ~ 20% for the majority of the detected systems.
5. Estimate η_{Earth} via extrapolation from larger and longer–period planets.

*Assumes a fiducial mass function.

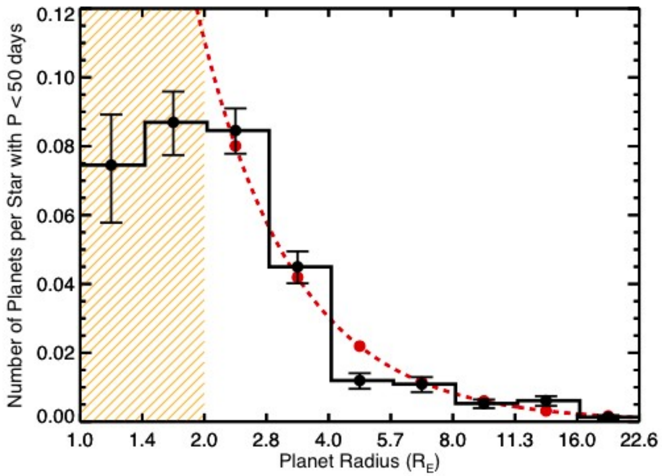
Failed Cores?

- Only a sub-dominant fraction of systems have gas giant planets
- A Larger Fraction host super-Earths/mini-Neptunes, but only ~1/2
- Planet formation is ubiquitous, so could the remainder of systems be teeming with planetary cores that failed to grow?



Roman’s Mass Measurements

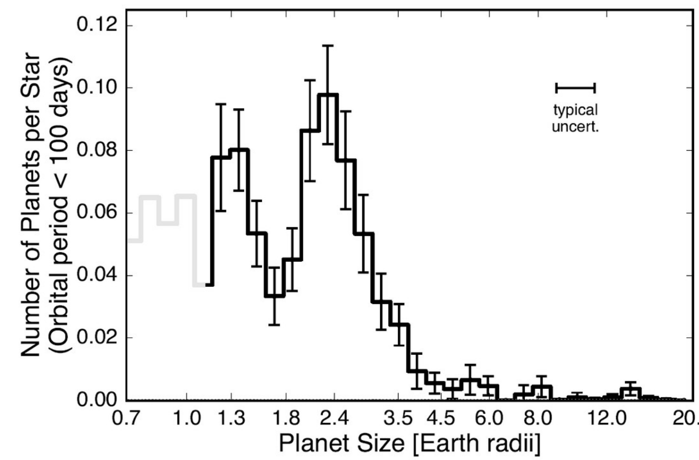
Combination of large numbers of detections, plus accurate physical parameters can yield spectacular clarity

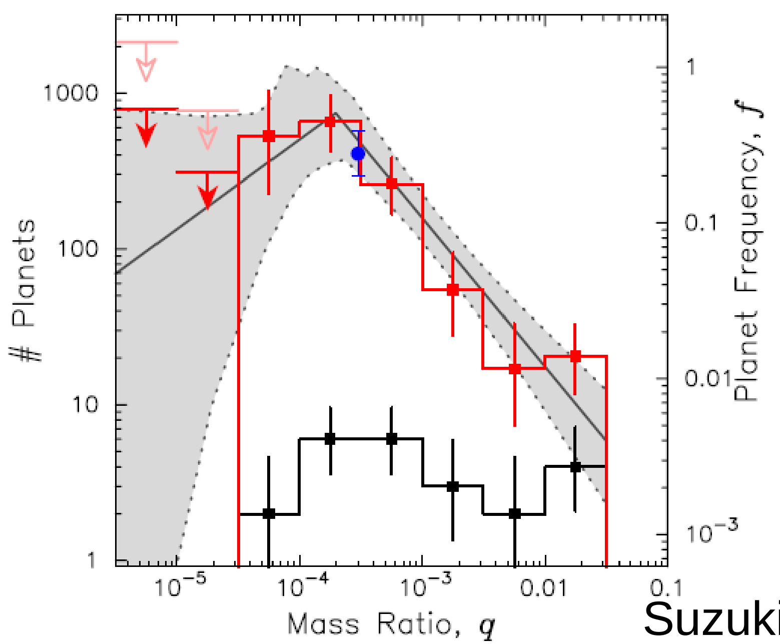


Howard+2011

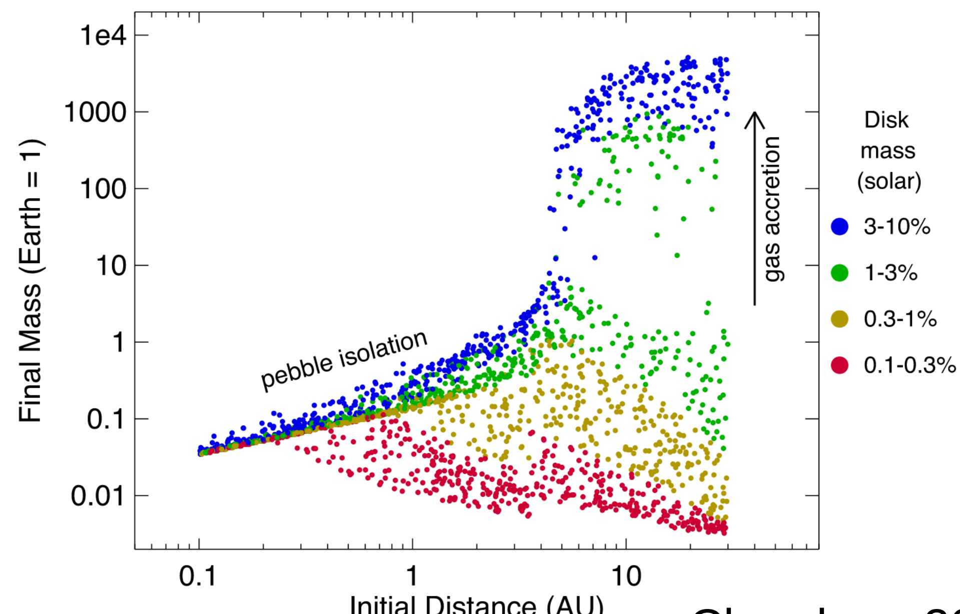
High-accuracy R_* →

Fulton+2017



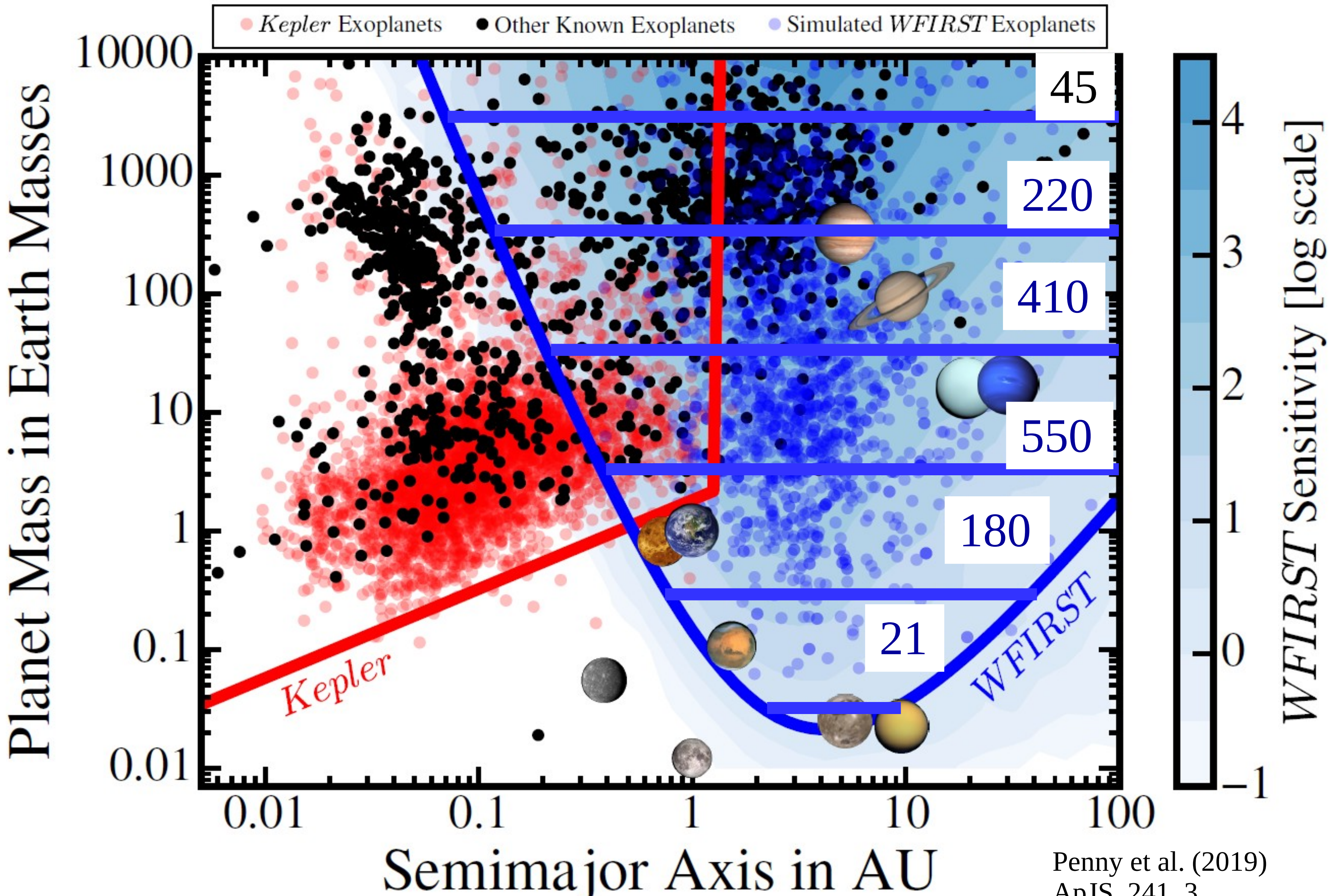


Suzuki+2016



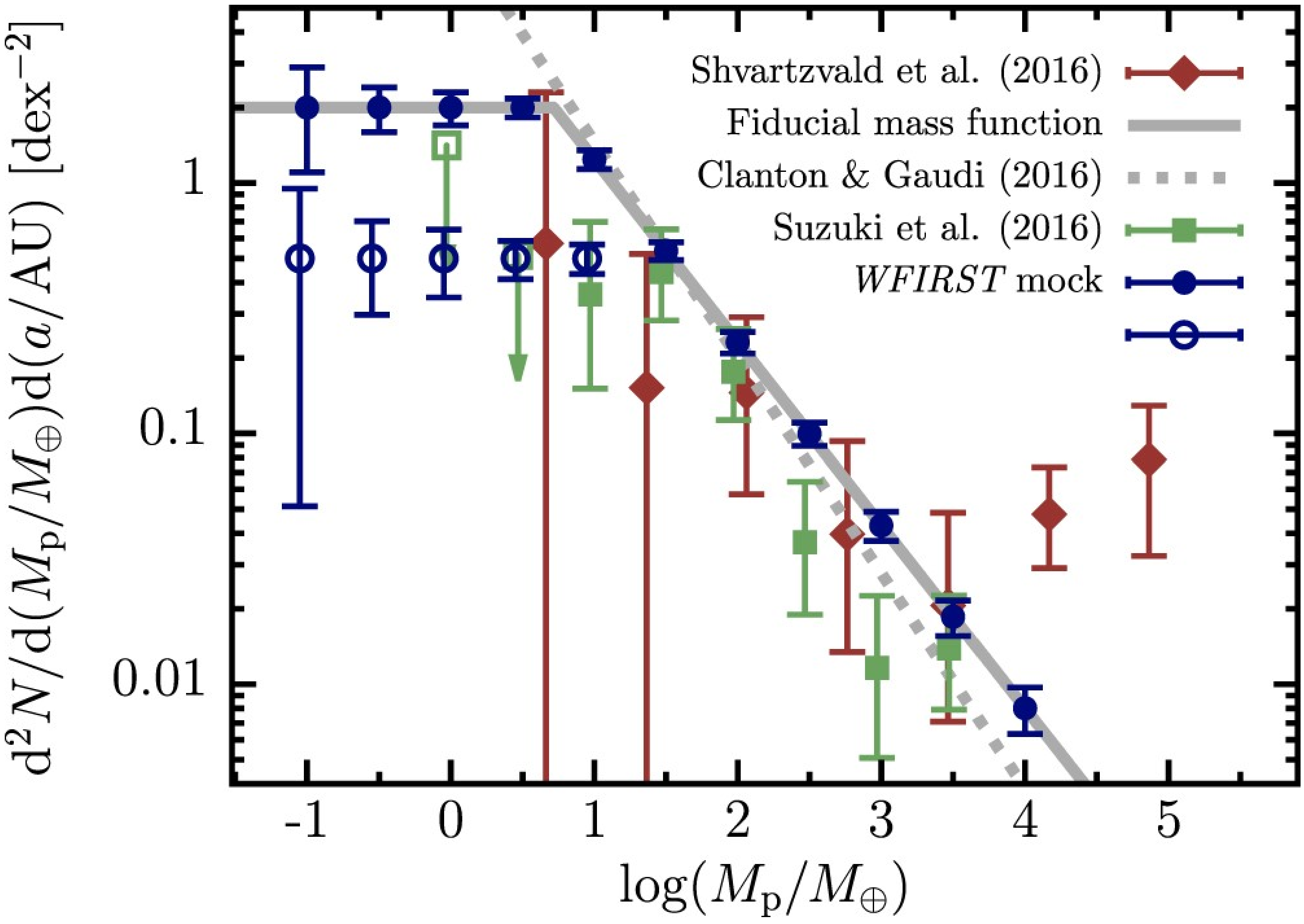
Chambers 2018

Completing the Census of Exoplanets



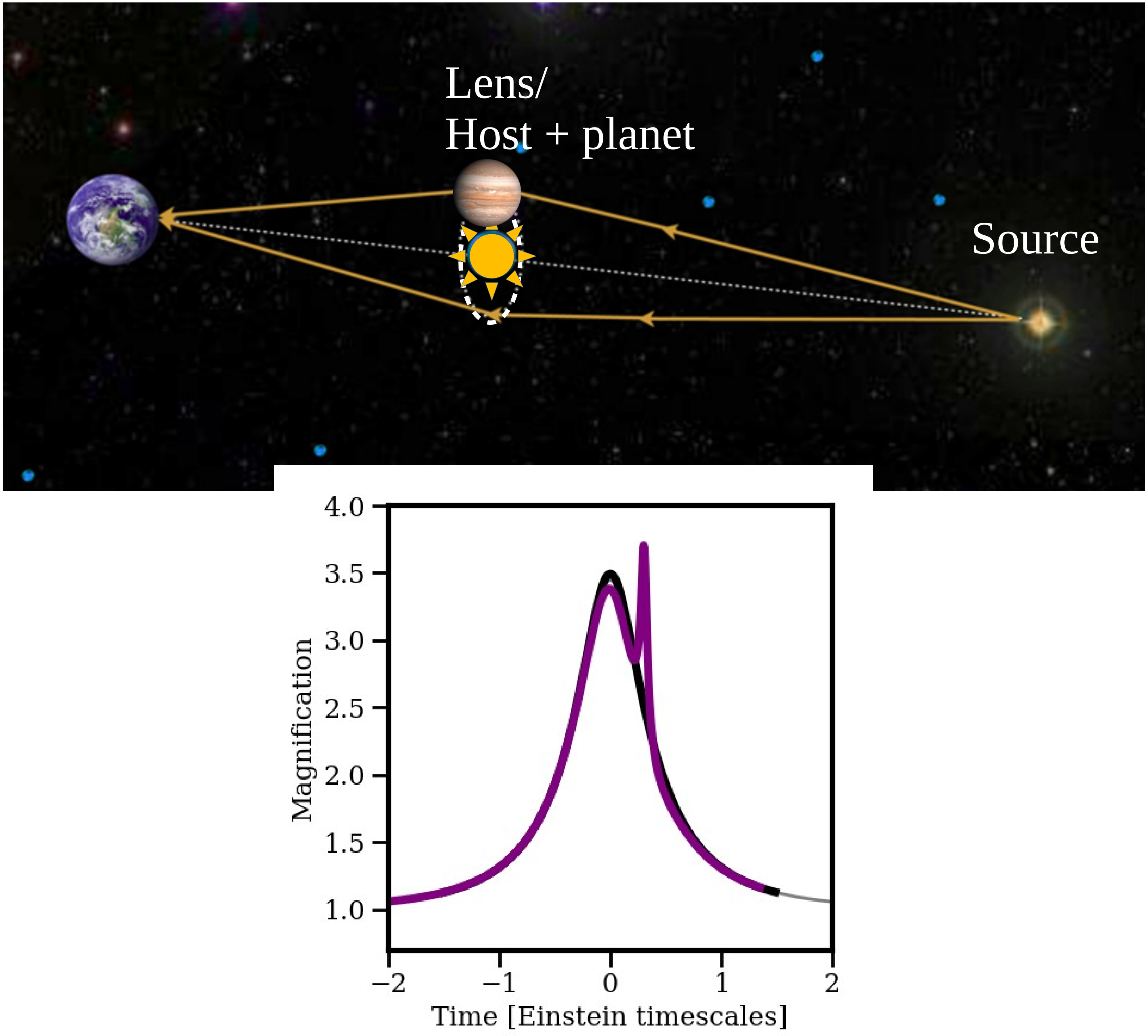
Penny et al. (2019)
ApJS, 241, 3

Predicted *Roman* Mass Function



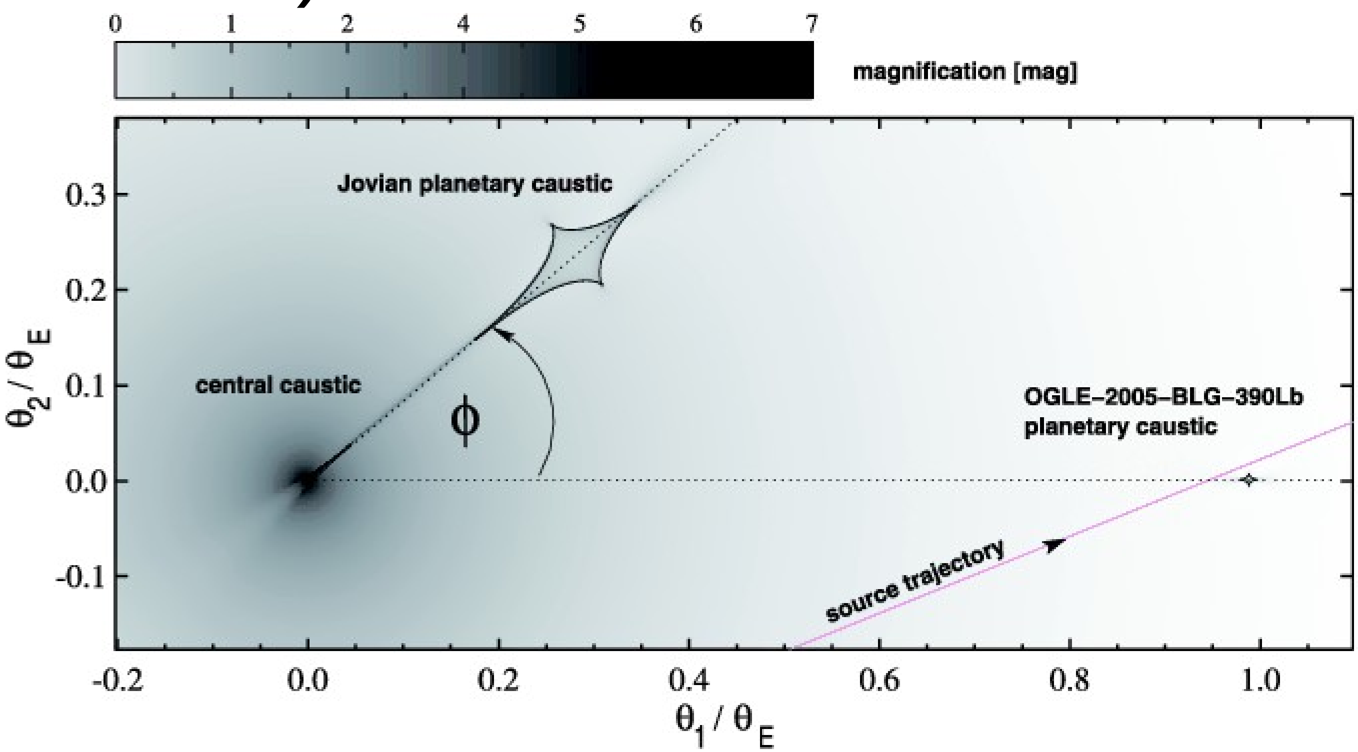
Back of the Envelope Survey

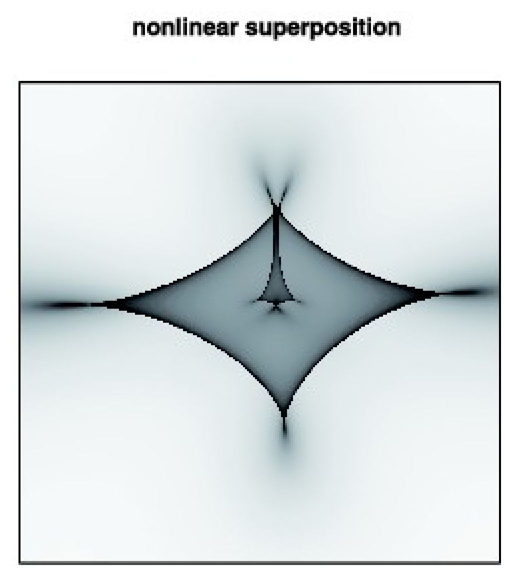
- Goal: 10% precision requires detecting ~100 Earths


Lens/
Host + planet
Source
4.0
3.5
3.0
2.5
2.0
1.5
1.0
Magnification
−2
−1
0
1
2
Time [Einstein timescales]

Back of the Envelope Survey

- Goal: Detect ~100 Earths
- Detection Efficiency: 0.01* (Bennett & Rhie 1998) *with continuous observations





Kubas et al (2008)

Back of the Envelope Survey

- Goal: Detect ~100 Earths
- Detection Efficiency: 0.01 (Bennett & Rhie 1996)
  - → ~10,000 microlensing events
- Event rates:

Event Rate

Event rate Γ

= Area swept out by all Einstein rings per year x Source stars per deg^2

~ mas x 5 mas / year x (10^8 lenses) x (10^6-10^8 sources / $deg^{2)}$ ~ 40-4000 / deg^2 /year

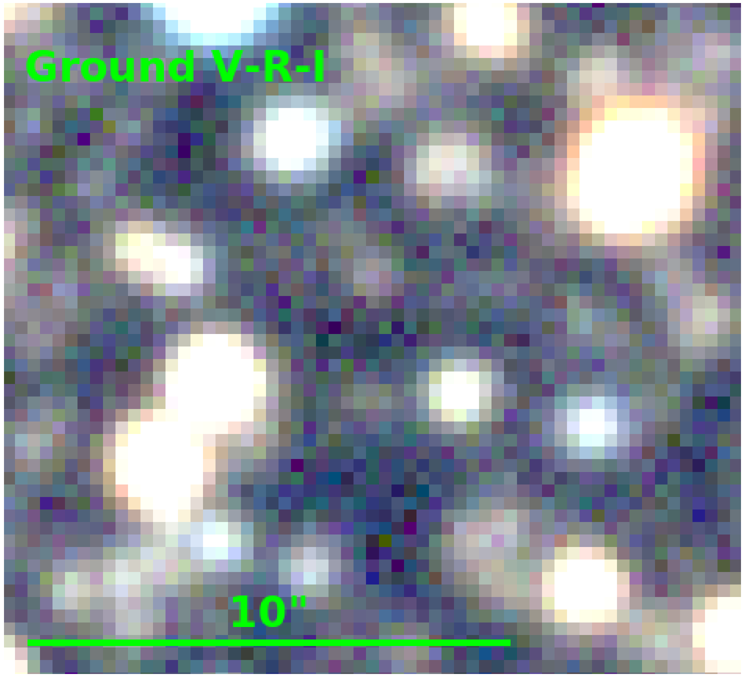
Event rate per star ~ few x 10^{-5}

Back of the Envelope Survey

- Goal: Detect ~100 Earths
- Detection Efficiency: 0.01 (Bennett & Rhie 1996)
  - → ~10,000 microlensing events
- Event rates: 5×10^{-5} per star per year
  - → Monitor 200 million star years

Back of the Envelope Survey

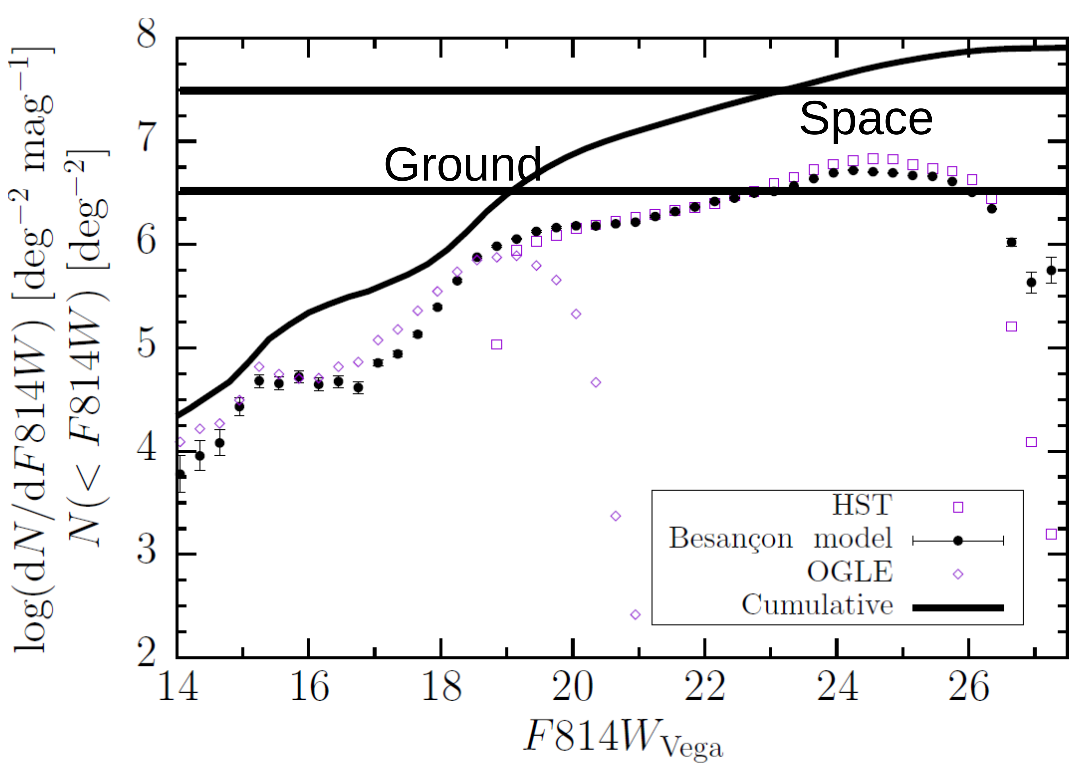
- 200 million star years
  - Ground based imaging (e.g., OGLE)
    - 5 million stars / deg^2 (detected)
    - 1.4 deg^2 imager
    - 28 fields for 1 year, 3 fields for 10 years
      - For *continuous observations* (24 hrs/day, 365 days/year)
    - 500 fields for 1 year, 18 fields for 10 years
      - ~Accounting for seasons and night/day cycles

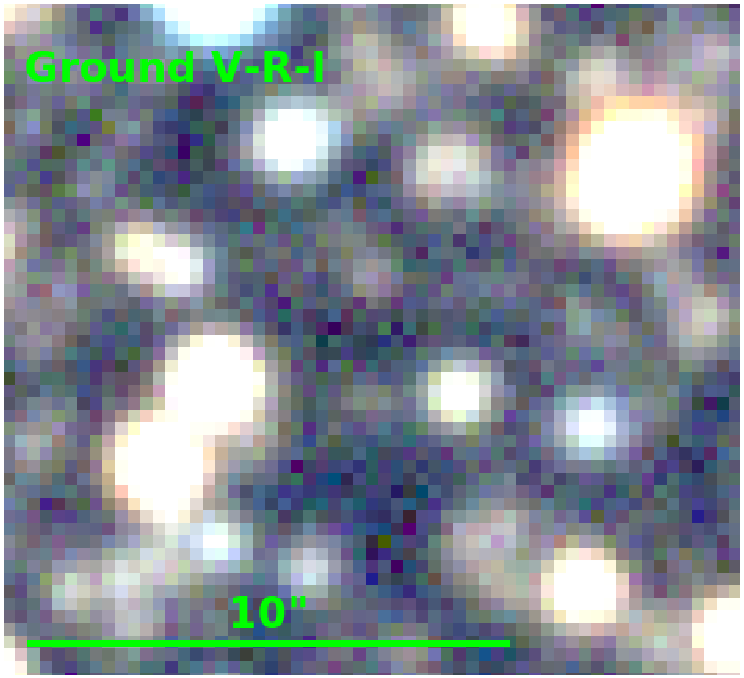


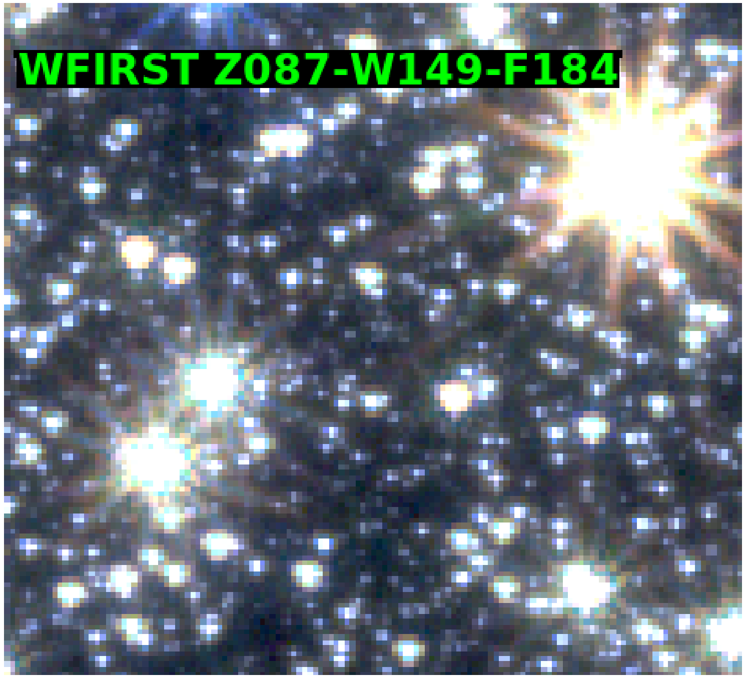
Space-based survey

- 2.4m telescope @ 1.5 um
- ~0.15” FWHM
- ~1/50 arcsec² disk
- ~100m stars/deg²= 6 /arcsec²

➔ Need ~2 deg² years







Back of the Envelope Survey

- Observational Timescales:
  - Planets around stars

Lens Type	M_ℓ [$M_\odot$]	D_ℓ [kpc]						
		1.0	2.0	3.0	4.0	5.0	6.0	7.0
Black hole	10					225.5	168.1	110.1
G Dwarf	1					71.3	**53.2**	34.8
M Dwarf	0.3					39.1	**29.1**	19.1
M Dwarf	0.1					22.6	16.8	11.0
Brown Dwarf	0.01					7.1	5.3	3.5
Jupiter	0.001					2.3	1.7	1.1

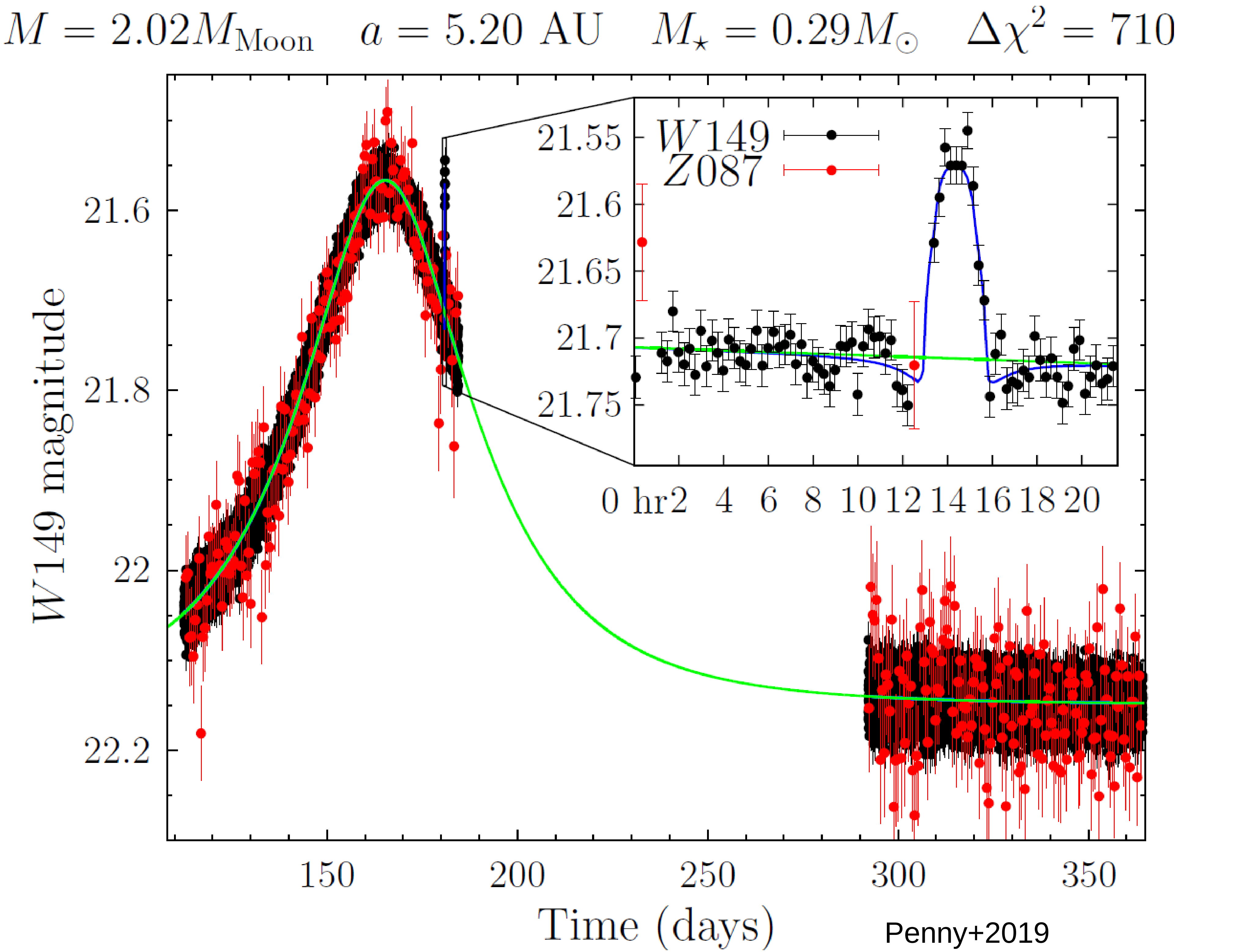
Neptune	$3x10^{-5}$	0.4	0.3	0.2 days
Earth	$3x10^{-6}$	3.0	2.2	1.4 hours
Mars	$3x10^{-7}$	0.9	0.7	0.5 hours

Back of the Envelope Survey

- Observational Timescales:
  - Source diameter crossing time

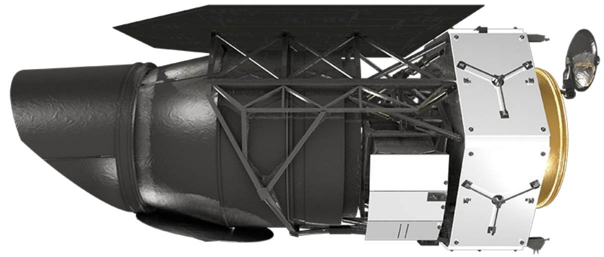
Radius (R_{sun})	Diameter crossing time (hours)
10 (Red giant)	22
1 (G dwarf)	2.2
0.3 (M dwarf)	0.7

- Need <~15 minute cadence



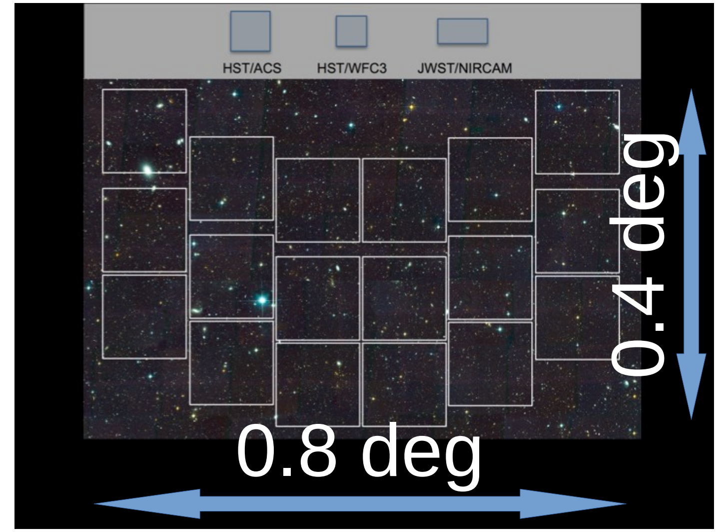
$M = 2.02 M_{\rm Moon}$ $a = 5.20$ AU $M_\star = 0.29 M_\odot$ $\Delta\chi^2 = 710$
W149 magnitude
Time (days)
W149
Z087
0 hr 2 4 6 8 10 12 14 16 18 20
Penny+2019

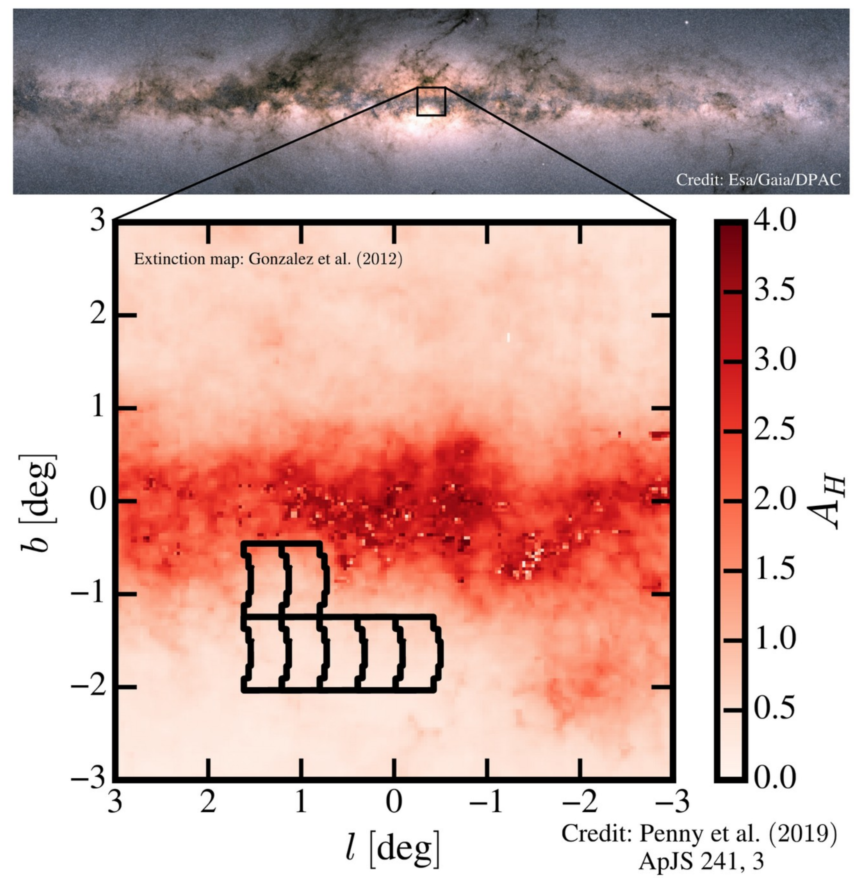
Roman RGES



- 2.4 m mirror
- 0.9-2.4 um IR detectors
- 18 4k x 4k H4RGs
- 0.28 deg^2 FoV
- 7-9 fields (2-2.6 deg^2)
- 15 min cadence
- 0.16" FWHM, 0.11" pix
- 5 year mission,

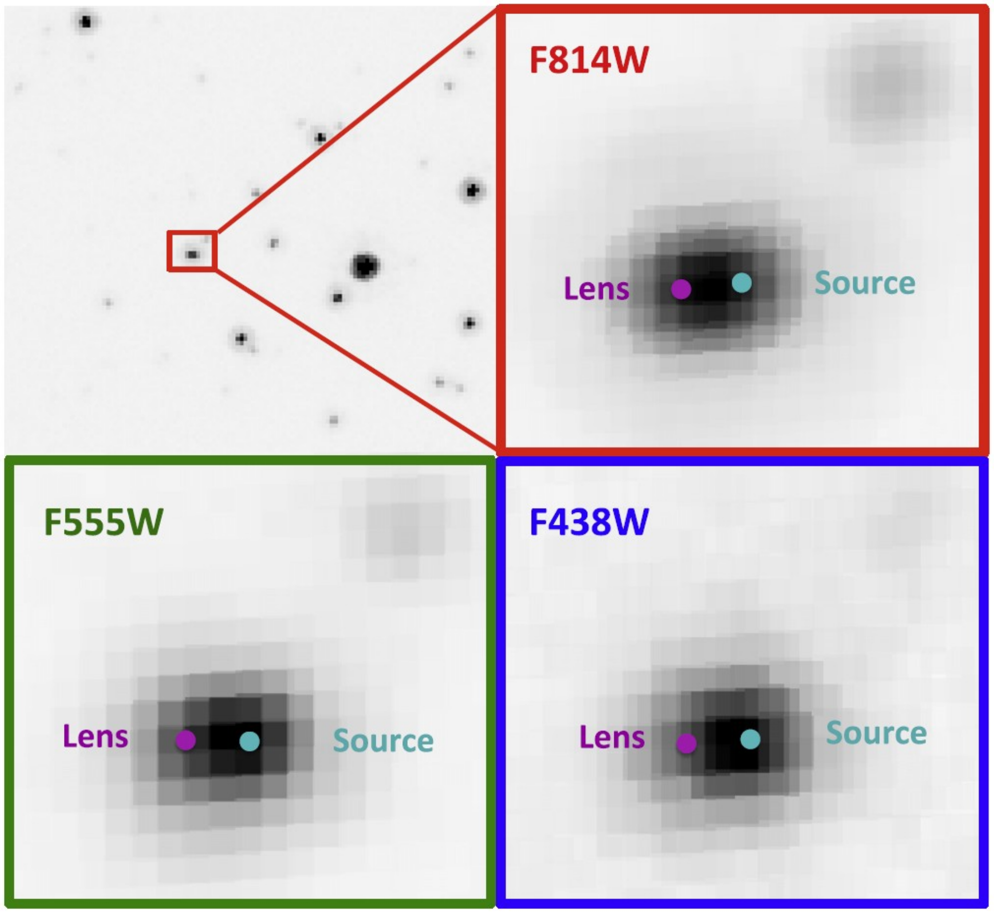
  ~1 year microlensing





WFIRST Microlensing Masses

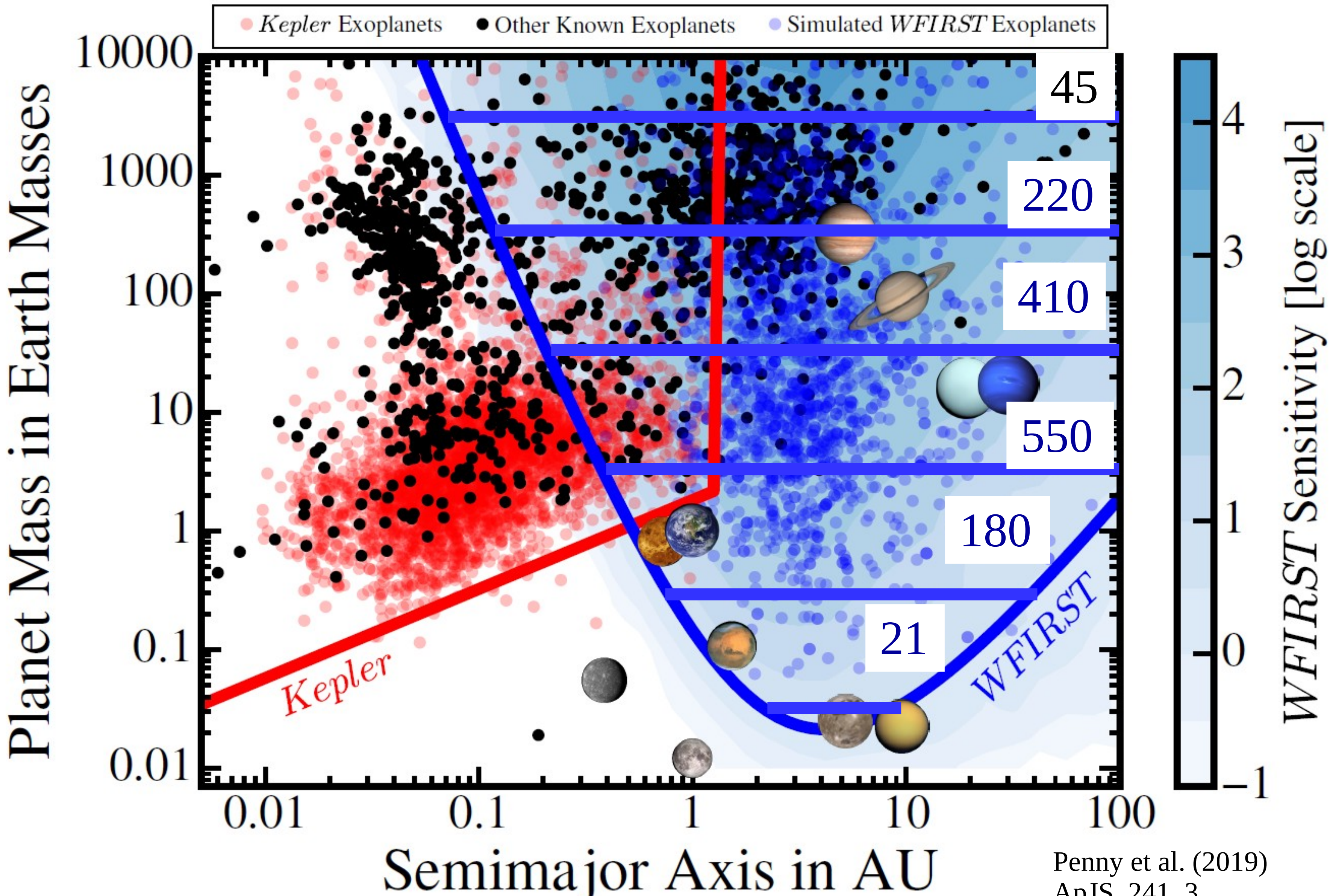
Bennett, Anderson & Gaudi (2007)



e.g., OGLE-2005-BLG-169 (Gould+06)
HST imaging in 2011 (Bennett+15)

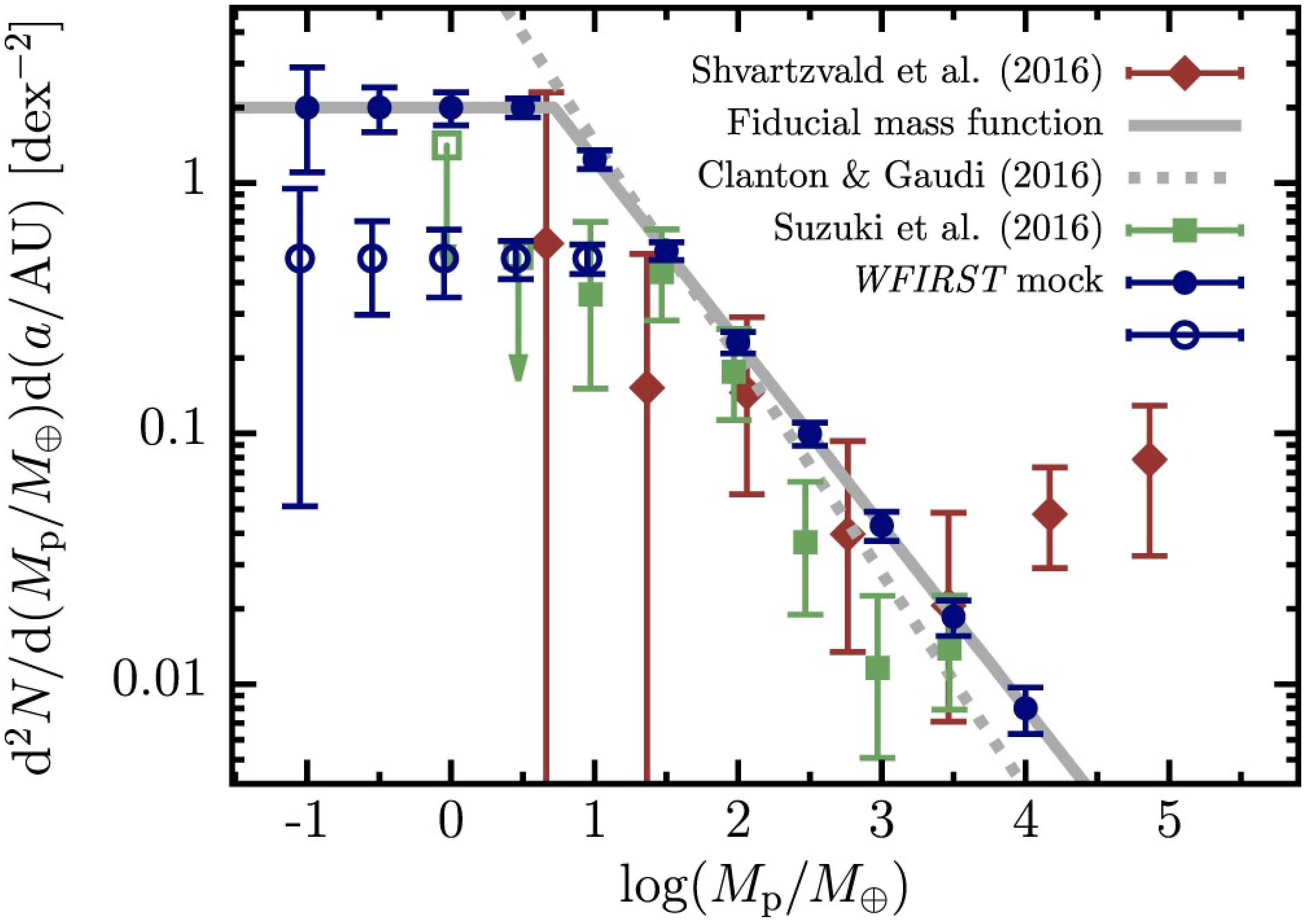
- After a few years, lens and source star may separate enough to be partially resolved
- Measurements of the lens-source separation and lens flux can be used to solve for the mass and distance to the lens
- Assumes no luminous companions or interloping stars
- Roman requires 20% masses for >50% of events
- **Need observations over maximum (~5 year) baseline**

Roman: ~1400 cold exoplanets



Penny et al. (2019)
ApJS, 241, 3

Predicted *Roman* Mass Function

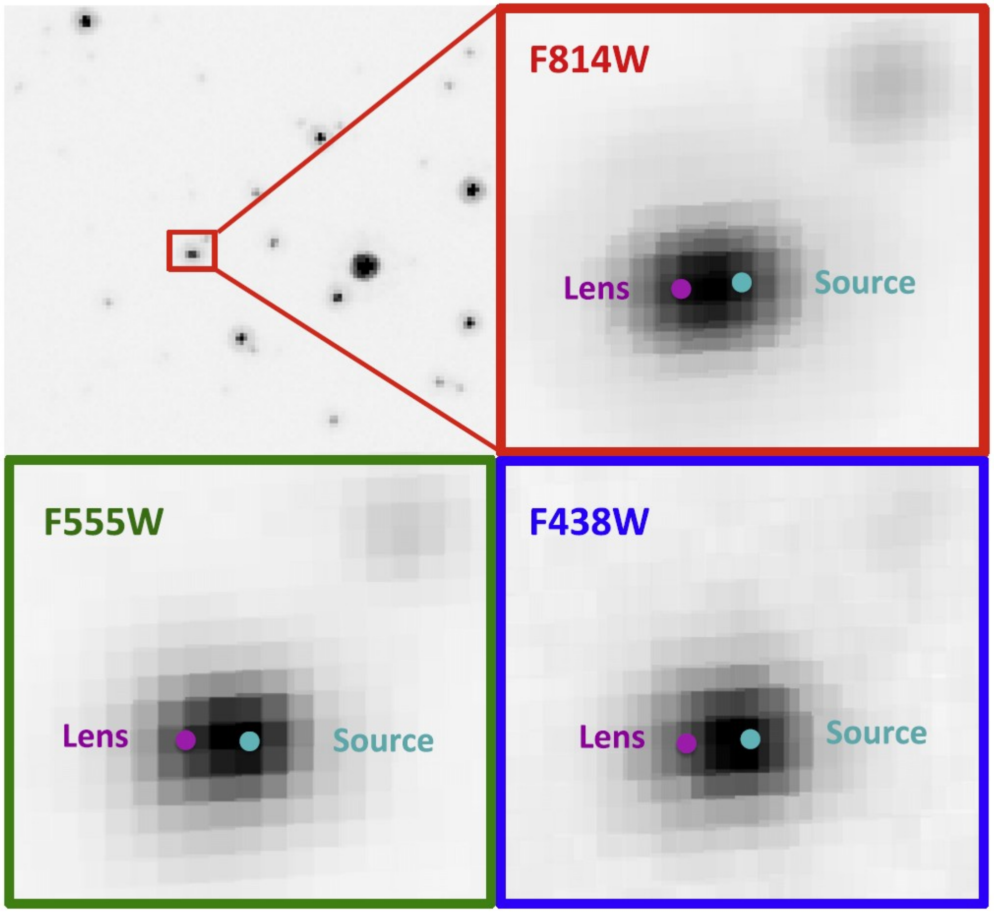


Conclusions

- RGES survey designed to collect large statistical sample of cold exoplanets, comparable to Kepler. This is needed to detect fine features in the cold exoplanet mass function that could be signatures of planet formation.
- Survey design driven by requirements to detect and characterize short duration planetary anomalies that occur unpredictably (cadence), the maximum microlensing event rate in the Galaxy (duration), and the need to watch lens and source separate over time (baseline).

Backup slides

WFIRST Microlensing Masses



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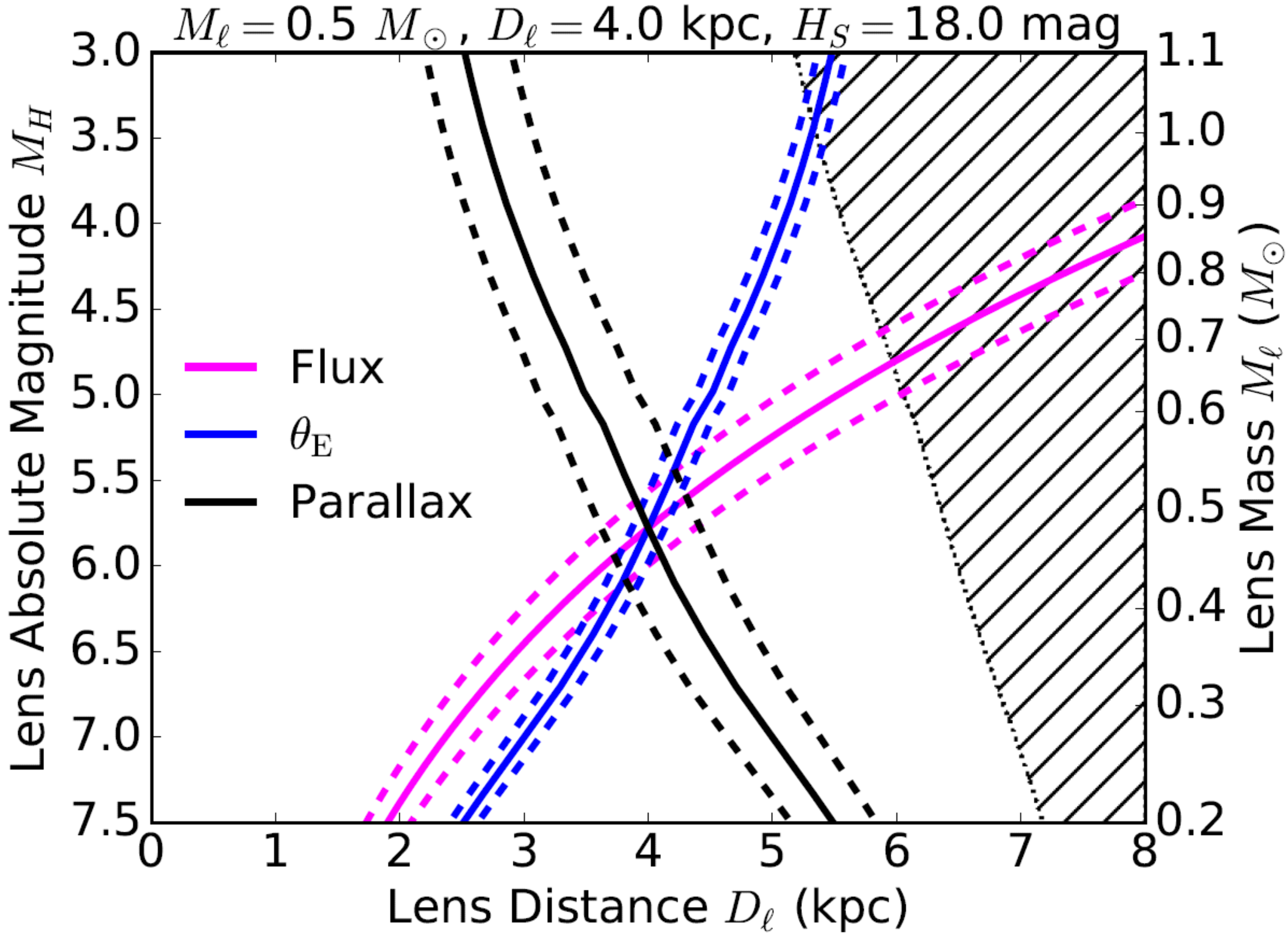
- Measurements of the lens-source separation and lens flux can be used to solve for the mass and distance to the lens
- Assumes no luminous companions or interloping stars
- Roman requires 20% masses for >50% of events

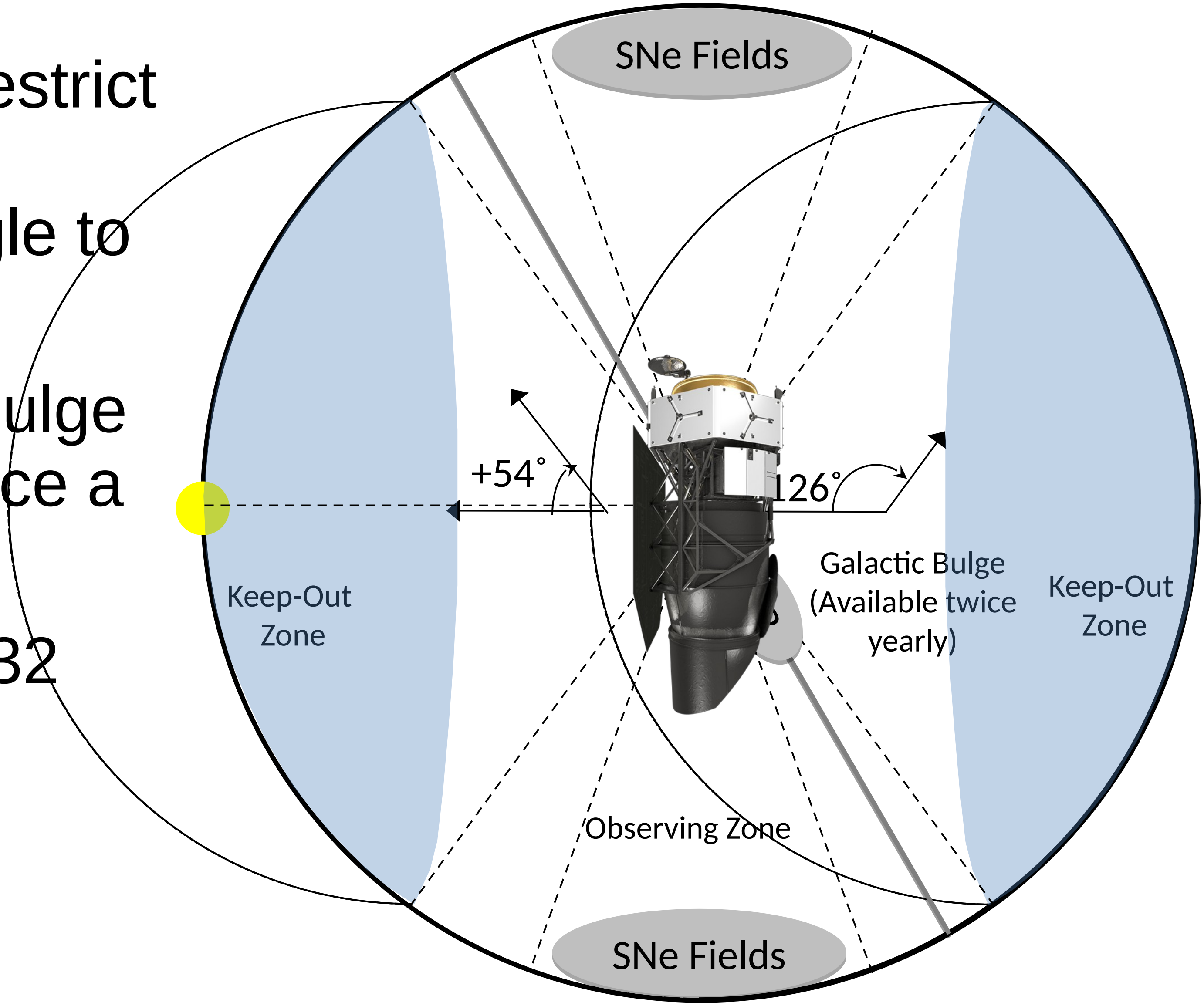
Essential Reading: Bennett, Anderson & Gaudi (2007)

Flux + θ_E or π_E



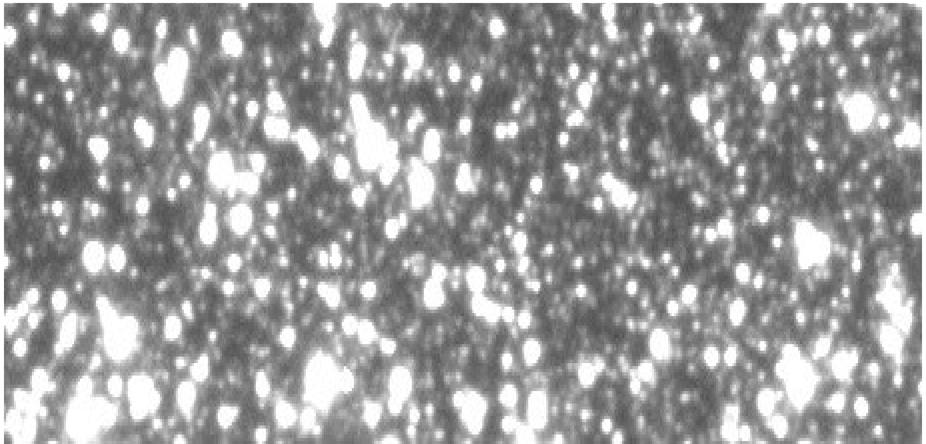
WFIRST's Seasons

- Solar panels restrict range of Sun-spacecraft angle to ~72 deg range
- Can observe bulge for 72 days twice a year
- 6x72 days = 432 days =



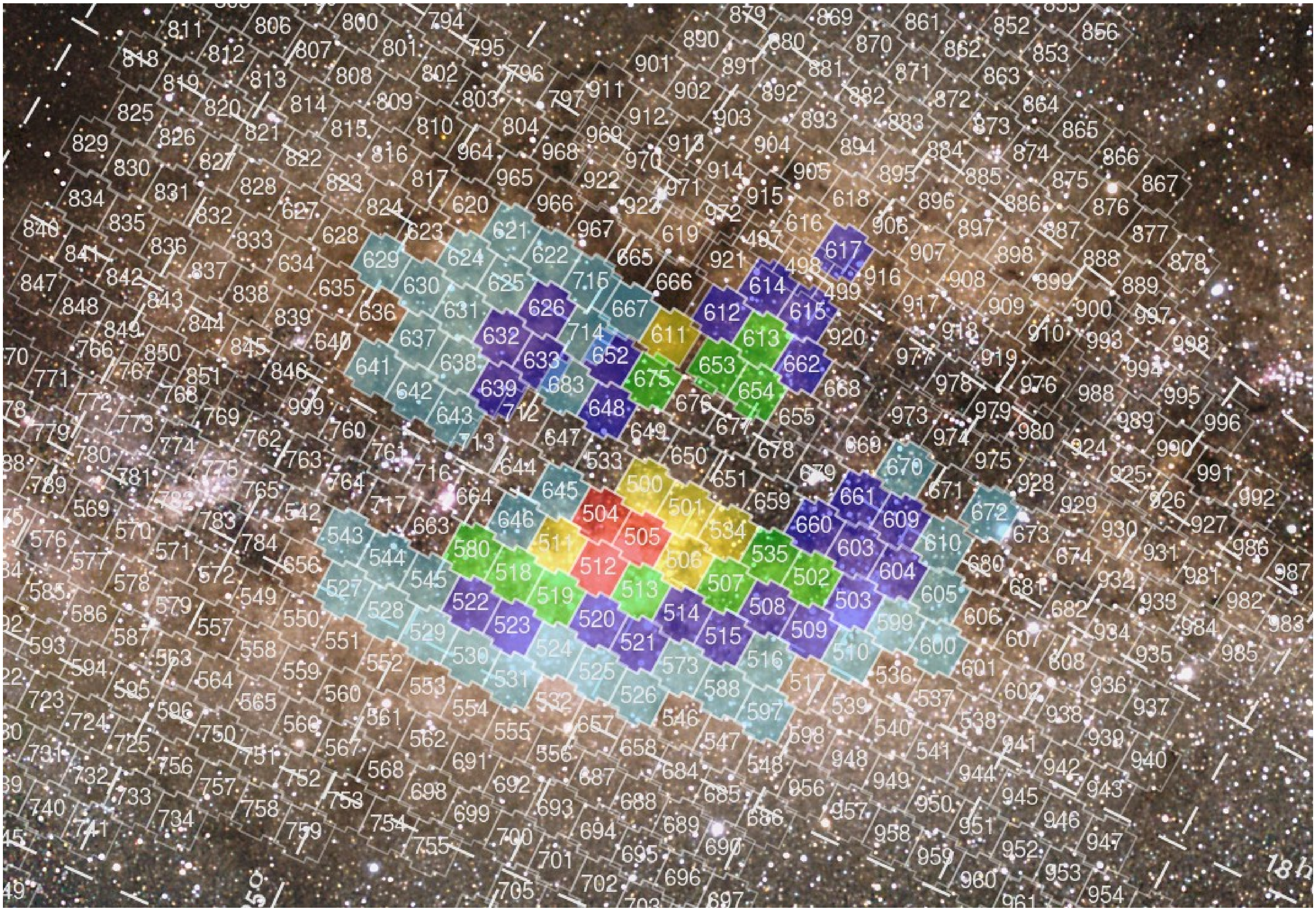
Back of the Envelope Survey

- 200 million star years
  - Ground based imaging (e.g., OGLE)
    - 5 million stars / deg^2 (detected)
    - 1.4 deg^2 imager
    - 15 minute cadence (~2 minutes for exposure + overhead)
    - Need 500 fields for 1 year, 18 fields for 10 years
    - Max 7 fields at necessary cadence



OGLE-IV fields

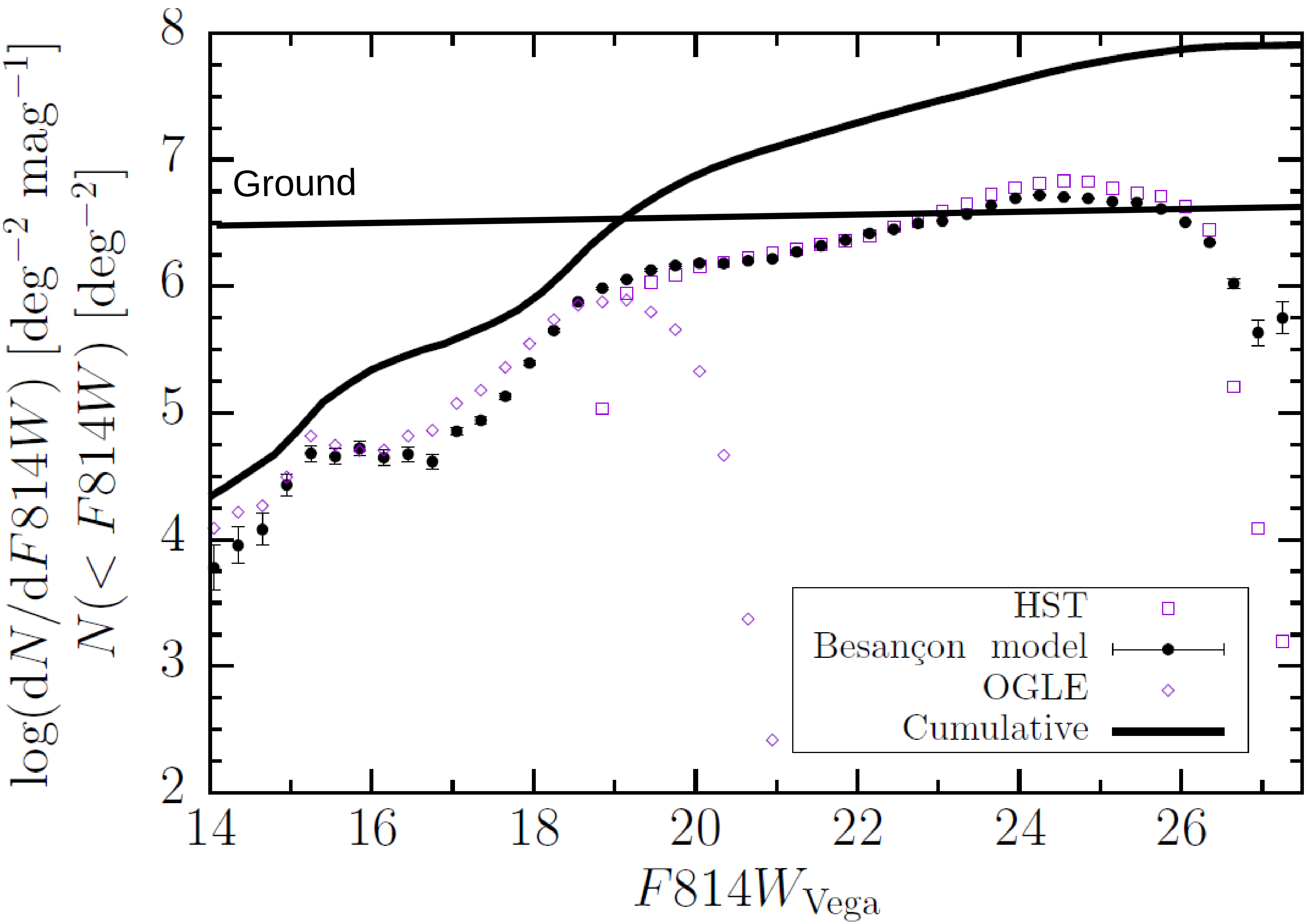
Credit: K. Ulaczyk, J. Skowron



Limitations of the Ground

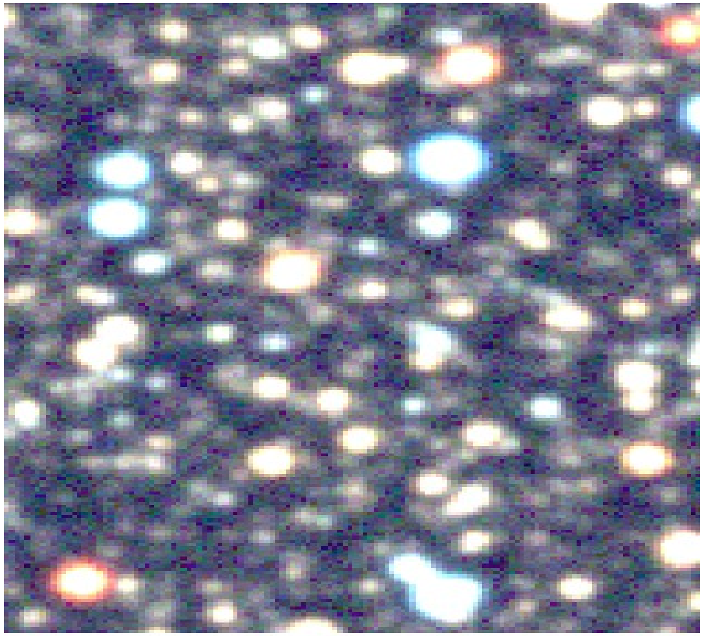
- Mass ratio of Earth (for 0.3 Msun) = 10^{-5}
- OGLE-IV running 6 years, no planets with mass ratio less than few~10^{-5}
- Expected: 4 deg^2 x 6 years → 6 Earths
  - But, calculation was likely optimistic
- KMTNet increases area (12 vs 4 deg^2) and time coverage (3 vs 1 site)
  - Expect ~20 Earths in 10 years under same assumptions

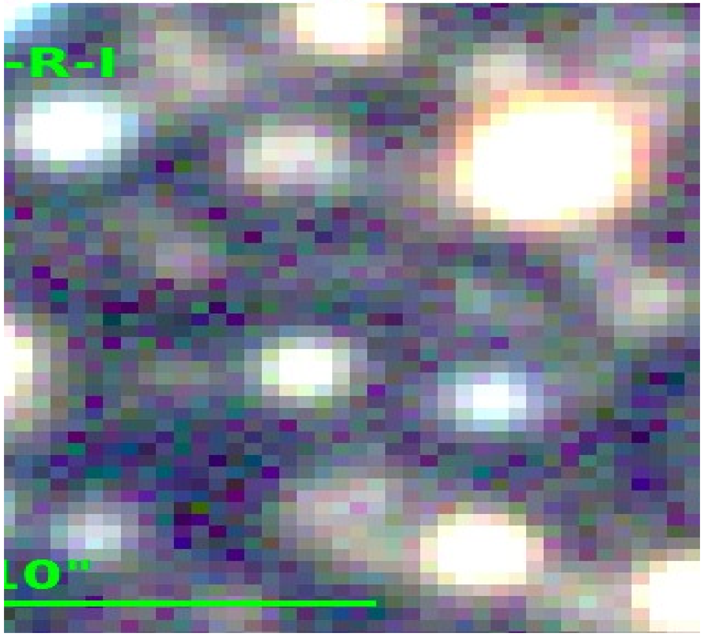
Stellar Density



Crowded Fields

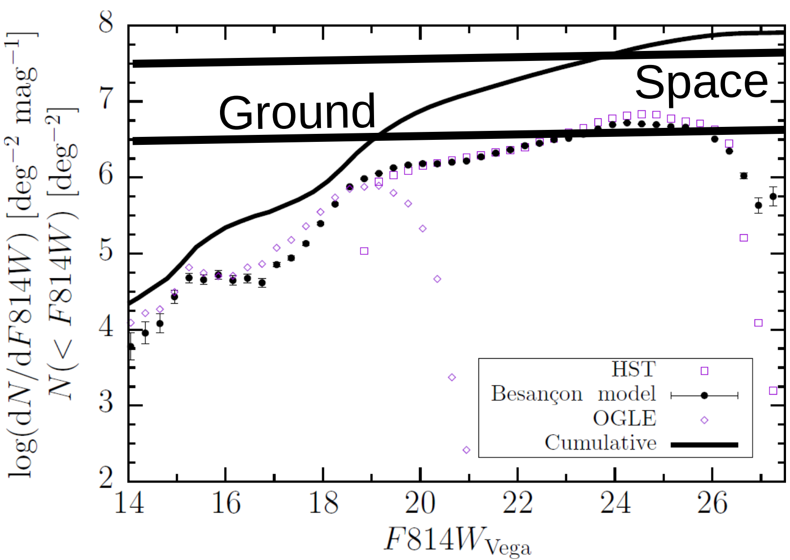
- Ground:
  - ~1" seeing
  - ~1 arcsec^2 seeing disk
  - 5 million stars/deg^2
  - = 0.4 stars/arcsec^2

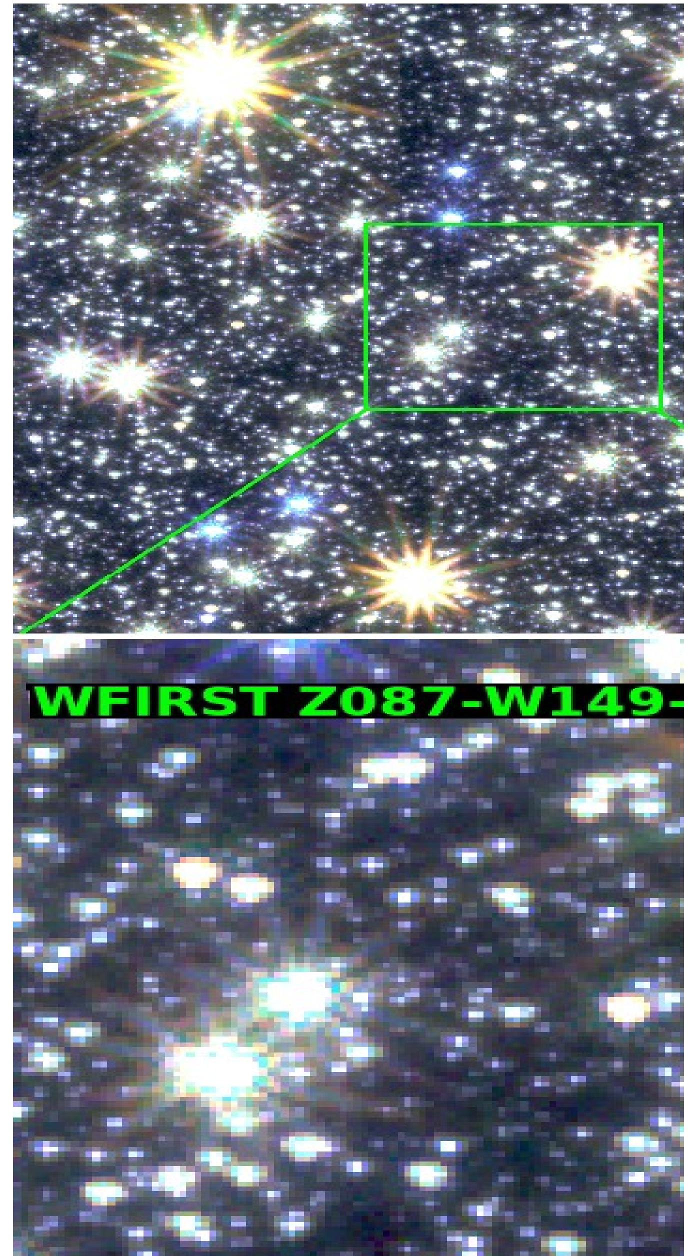




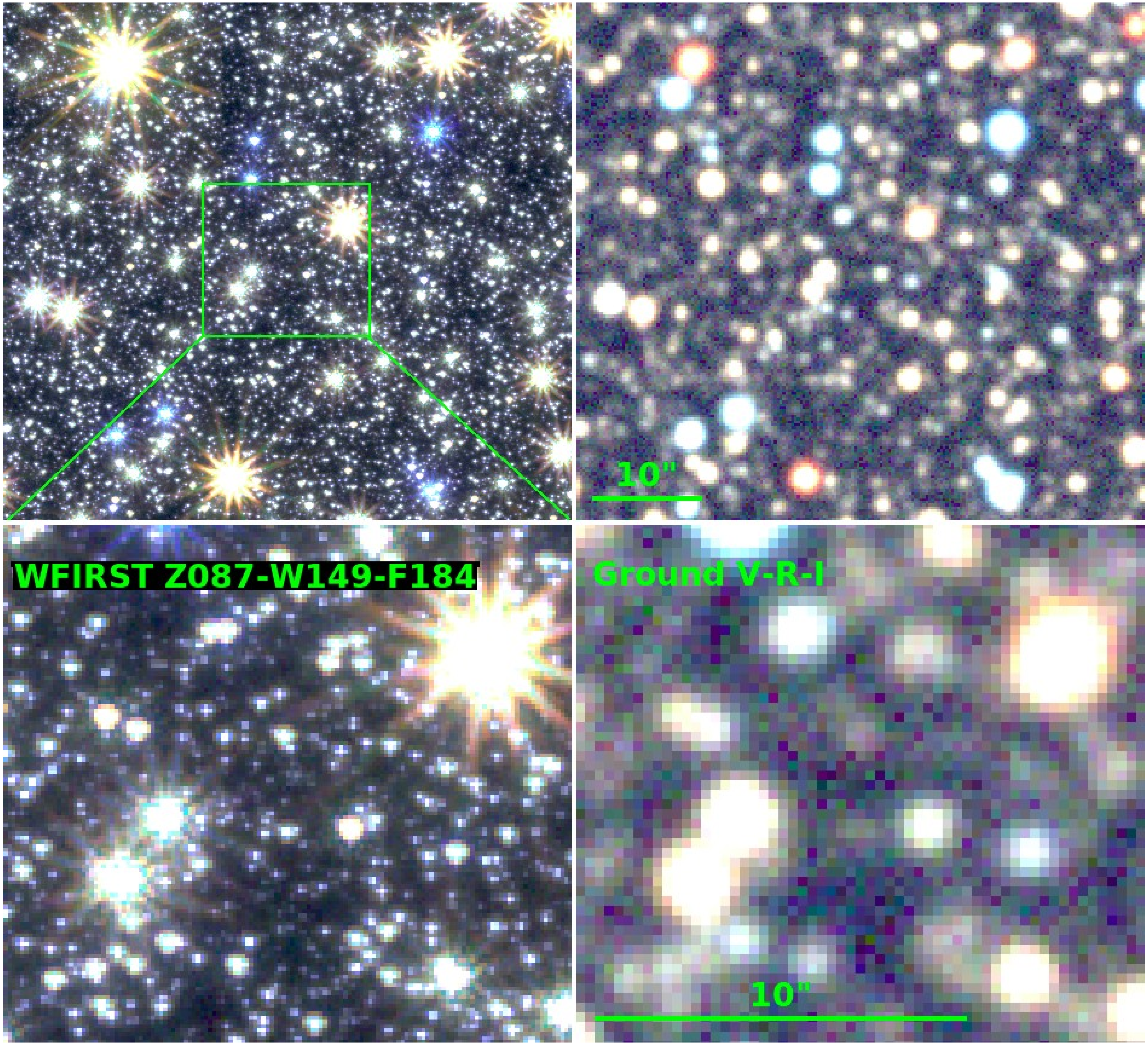
Crowded Fields

- Space:
  - 1m telescope @ 1um
  - ~0.25” FWHM
  - ~1/16 arcsec^2 disk
  - 80 million stars/deg^2
  - = 6 stars/arcsec^2





Crowded Fields



Space-based survey

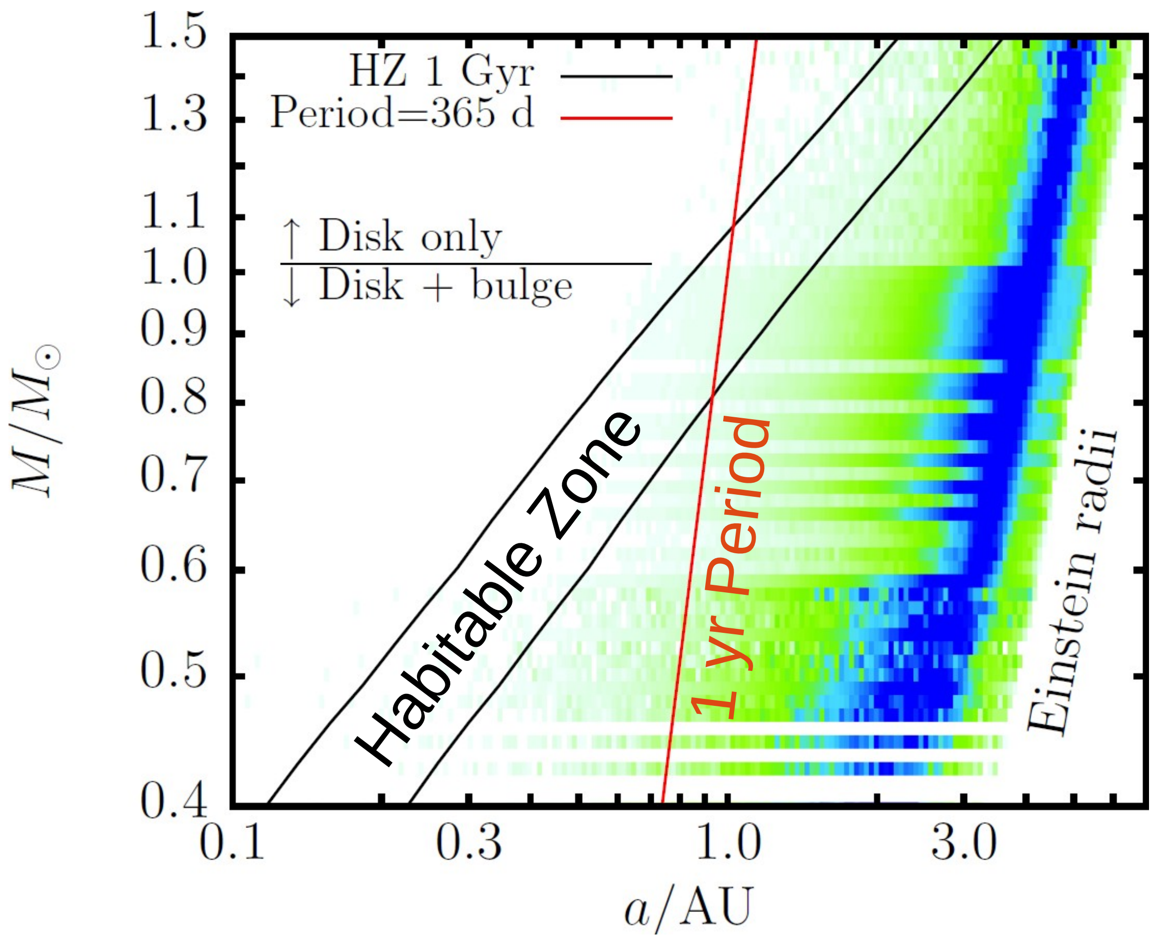
- >= 1 m telescope
- 200 million stars → ~2.5 deg^2
- 15 minute cadence, ~2 min/field
- → 0.36 deg^2 Field of View
- 1 year survey (total time)

- 200 million stars → 10000 events → 100 Earths

Microlensing in the Habitable Zone

- Transits most sensitive to HZ of low-mass hosts
- Microlensing most sensitive to HZ of high-mass hosts

  -but how sensitive?



$$\frac{a_{\rm HZ}}{r_{\rm E}} \simeq 0.3 \begin{cases} M^{1.5} & M \lesssim 1 M_\odot \\ M^{1.75} & M \gtrsim 1 M_\odot \end{cases}$$

Habitable Zone planets