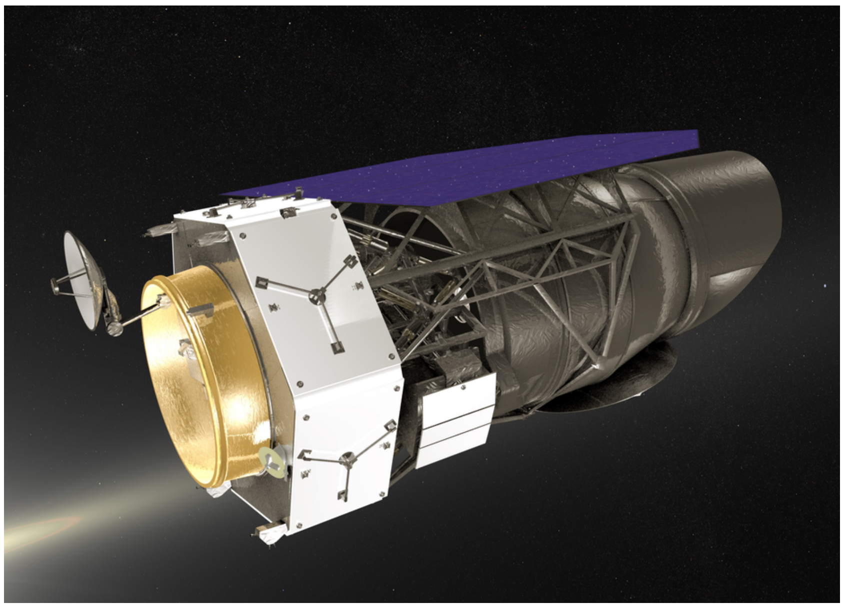
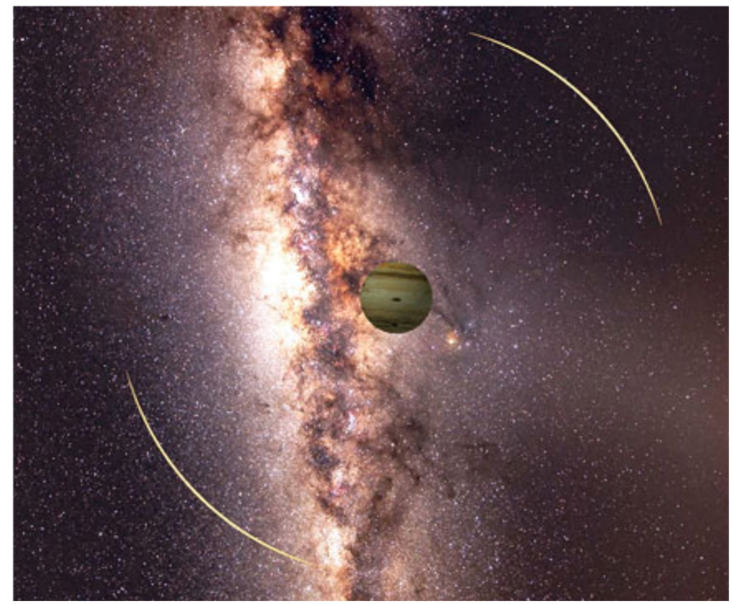
Overview of the WFIRST Microlensing Survey





Matthew Penny
Sagan Fellow, Ohio State University

Sagan Summer Workshop, August 2017

Overview

- Microlensing Surveys Order of Magnitude
- The WFIRST microlensing survey
- Overview of WFIRST Microlensing Science
- Areas you can Contribute

Back of the Envelope Survey

- Goal: Detect ~100 Earths

Back of the Envelope Survey

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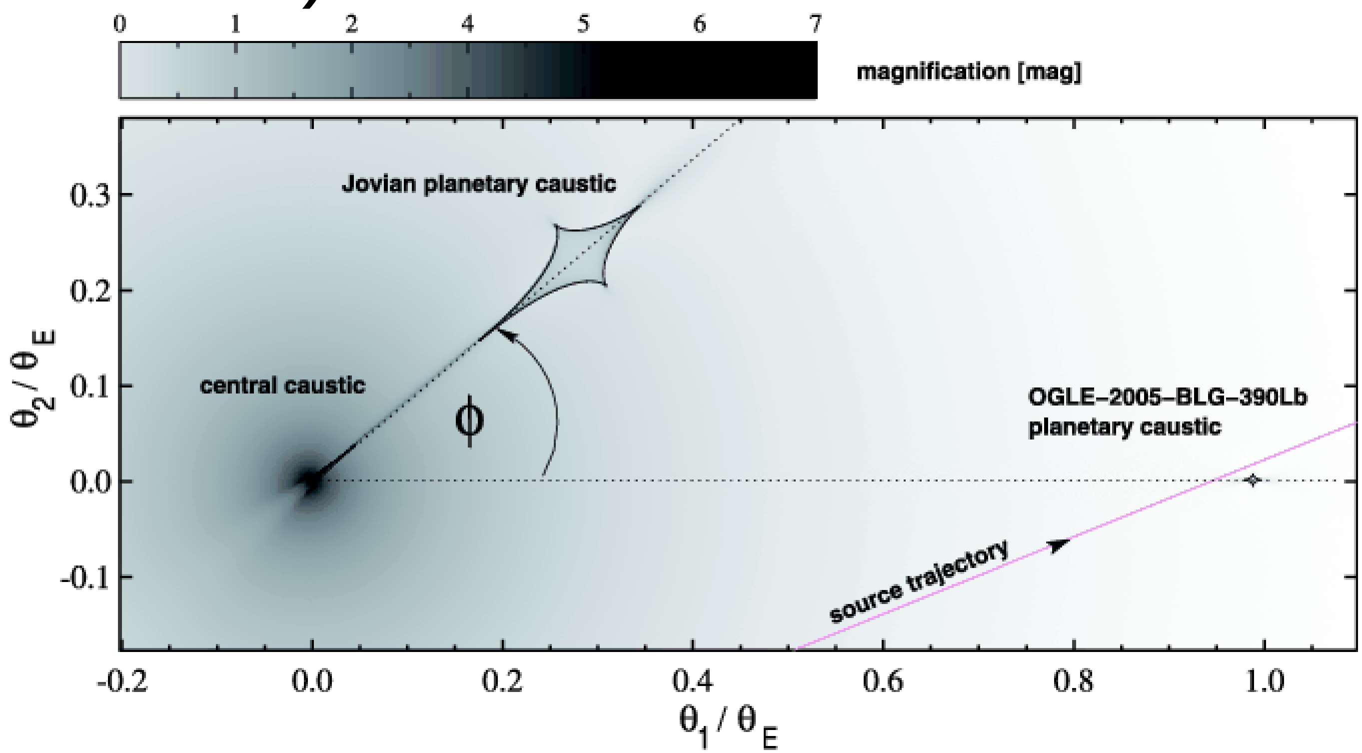
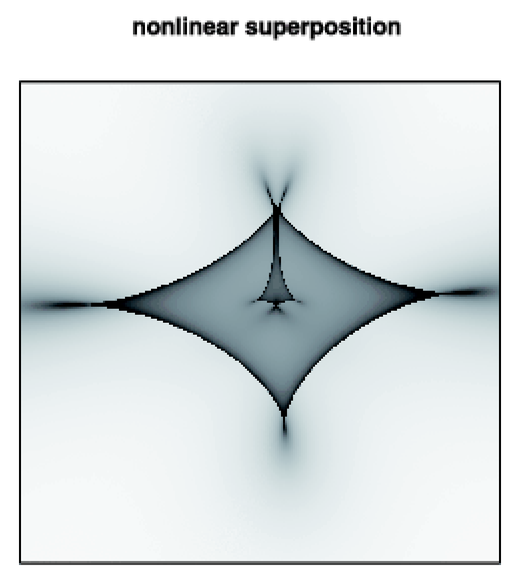
- Detection Efficiency: 0.01* (Bennett & Rhie 1998) *with continuous observations



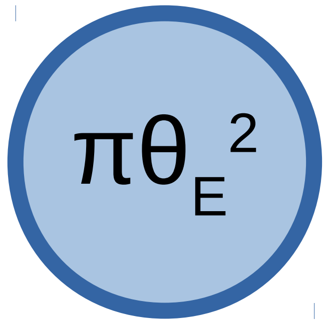


Kubas et al (2008)

Back of the Envelope Survey

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

Optical Depth



Optical Depth $\tau(D_s)$

= fraction of sky covered by Einstein rings

~ Number of intervening stars/deg^2 x $\pi\theta_E^2$

~ 10^8 μas^2 / deg^2 ~ 10^2 / 3600^2 ~ few x 10^6

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

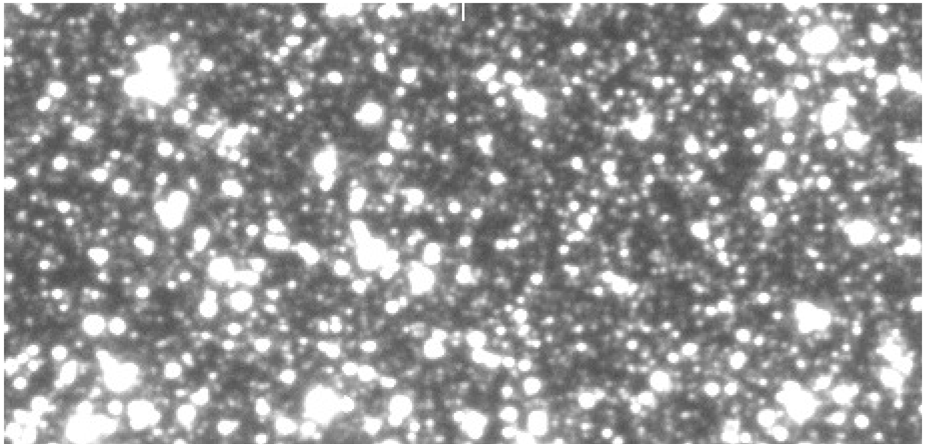
Event rate per star ~ few x 10^{-5}

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



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

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Jupiter	0.001					2.3	1.7	1.1
Neptune	3×10^{-5}					0.4	0.3	0.2 days
Earth	3×10^{-6}					3.0	2.2	1.4 hours
Mars	3×10^{-7}					0.9	0.7	0.5 hours

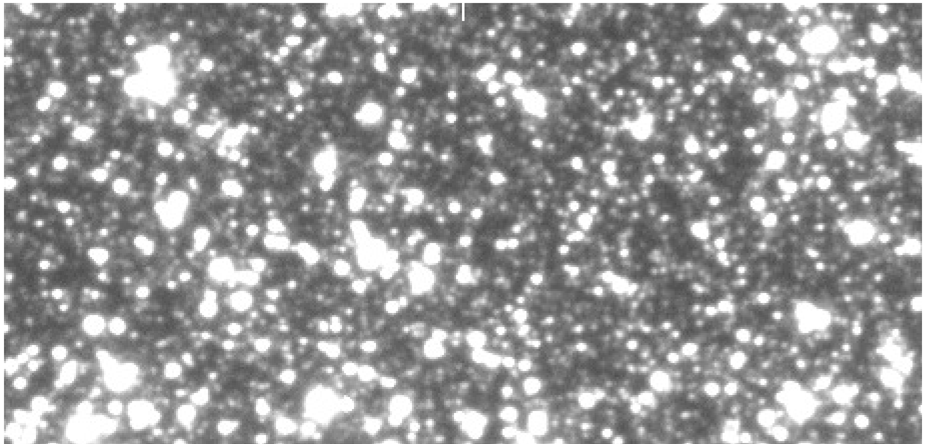
Back of the Envelope Survey

- 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

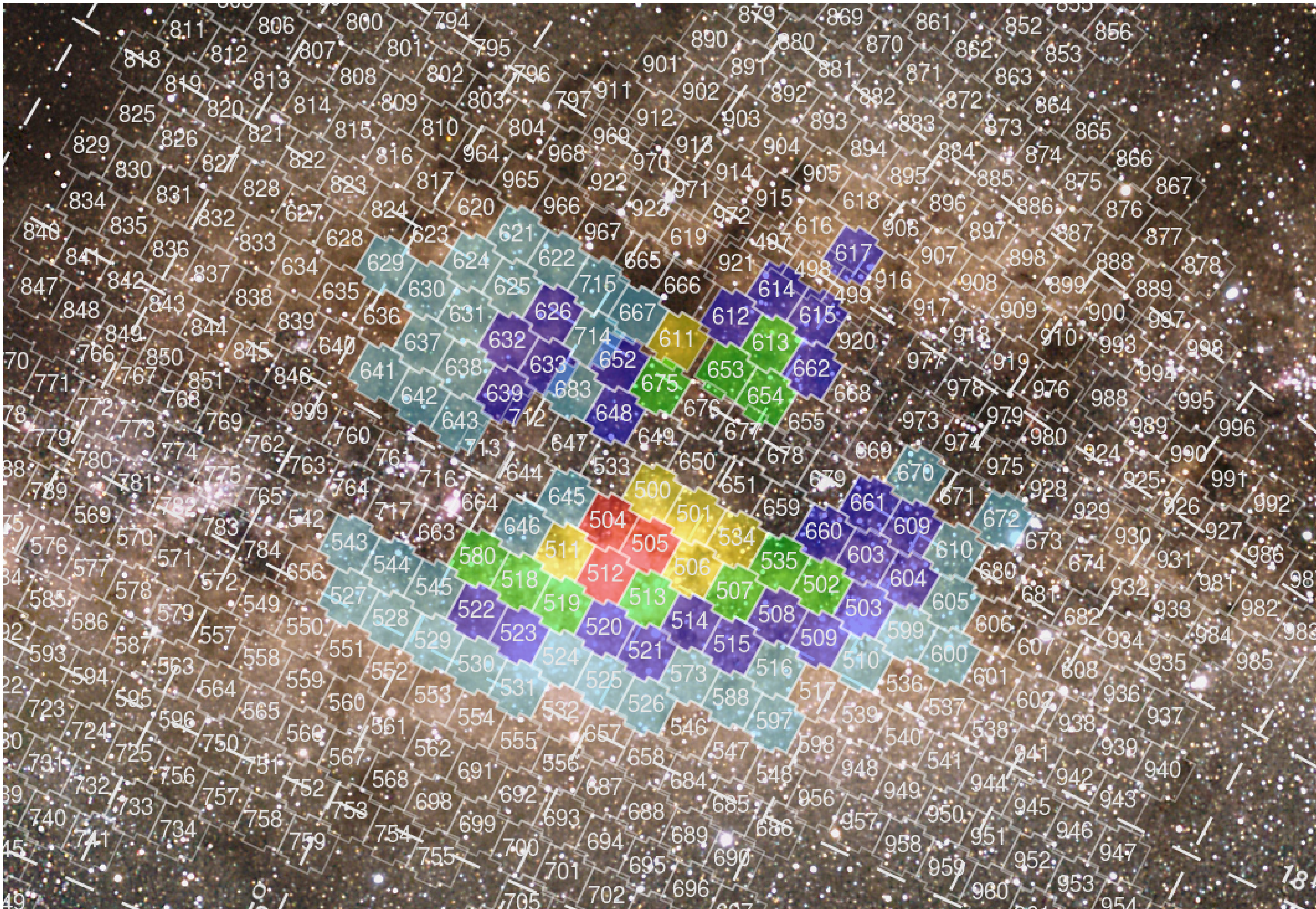
Back of the Envelope Survey

- 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

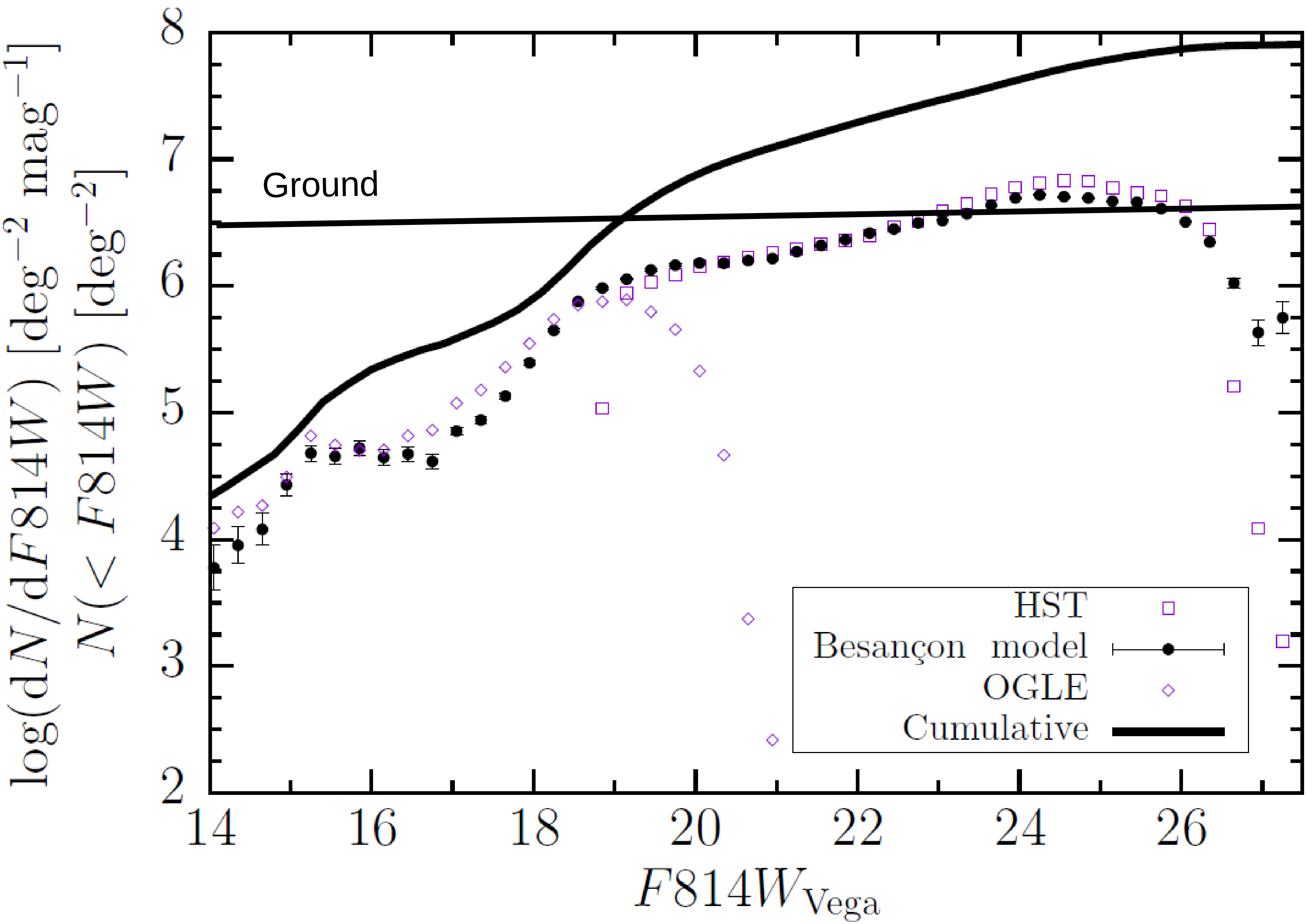


Limitations of the Ground

- 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 3/18 x 6/10 x 100 = 10
  - But, calculation was likely optimistic

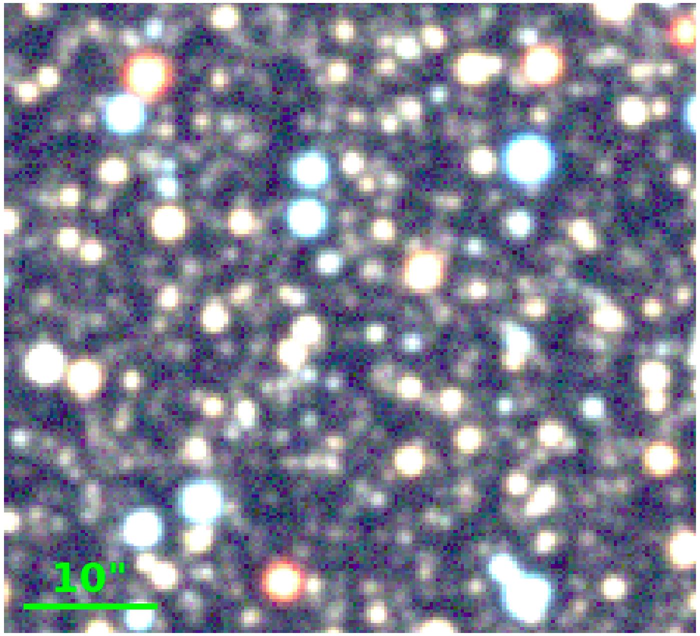
- KMTNet increases area (12 vs 4 deg^2) and time coverage (3 vs 1 site)
  - Expect ~20 Earths in 10 years under same assumptions

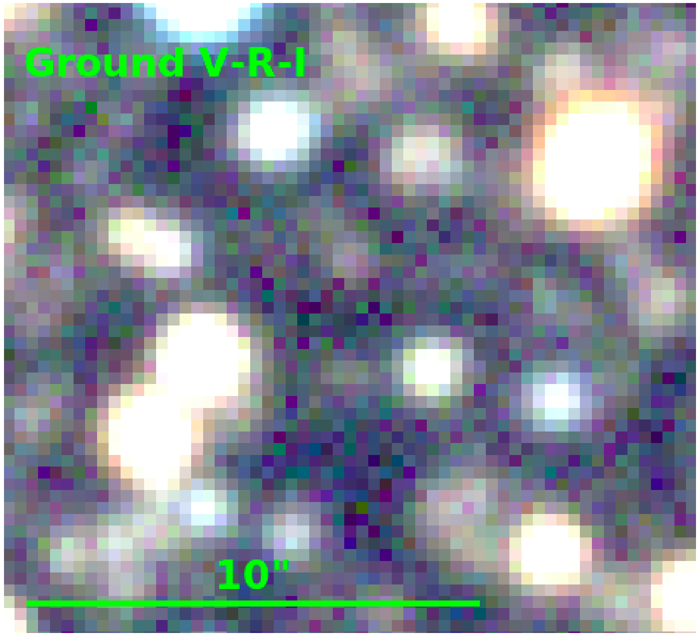
Stellar Density



Crowded Fields

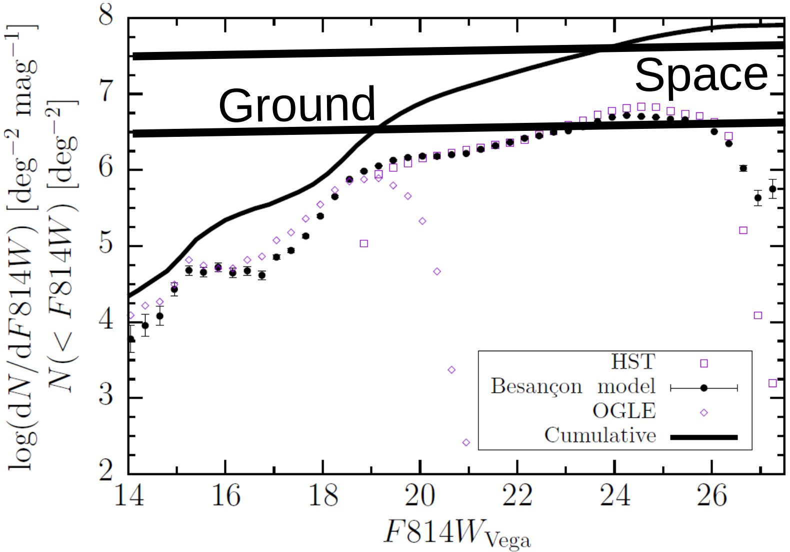
- Ground:
  - ~1" seeing
  - ~1 $arcsec^2$ seeing disk
  - 5 million $stars/deg^2$
  - = 0.4 $stars/arcsec^2$



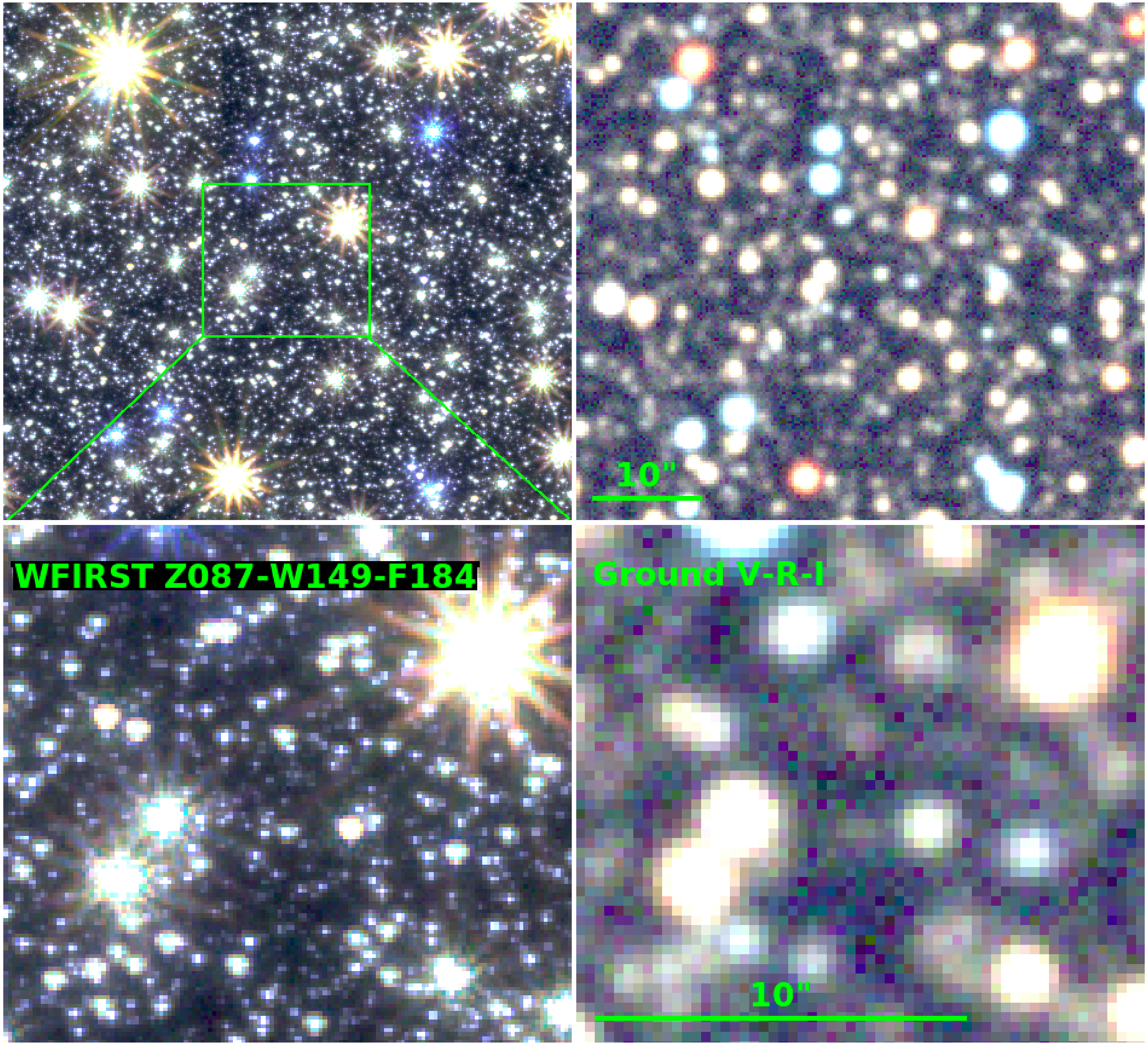


Crowded Fields

- Space:
  - 1m telescope @ 1um
  - ~0.25” FWHM
  - ~1/16 arcsec² disk
  - 80 million stars/deg²
  - = 6 stars/arcsec²



Crowded Fields



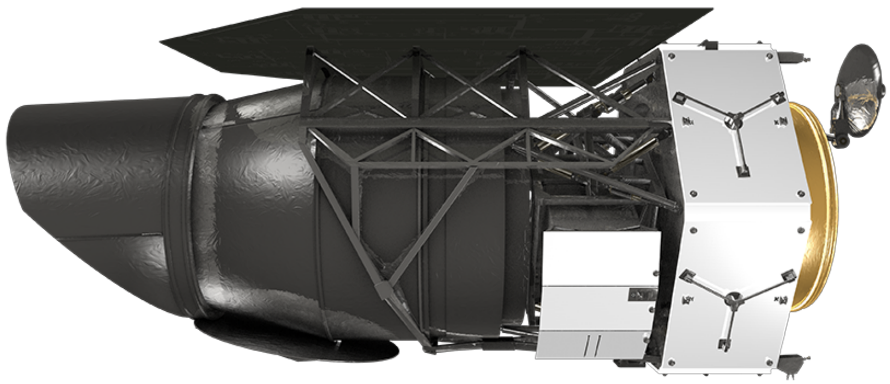
Space-based survey

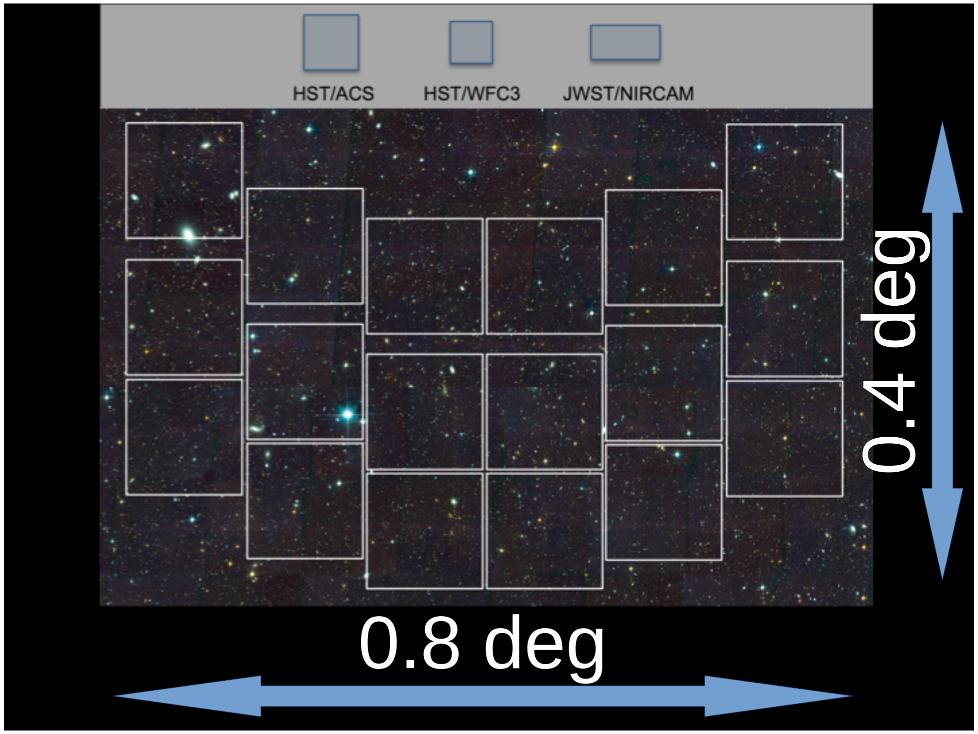
- >= 1 m telescope
- 200 million stars → ~2.5 deg^2
- 15 minute cadence, ~2 min/field
- → 0.36 deg^2 Field of View
- 1 year survey (total time)

- 200 million stars → 10000 events → 100 Earths

WFIRST

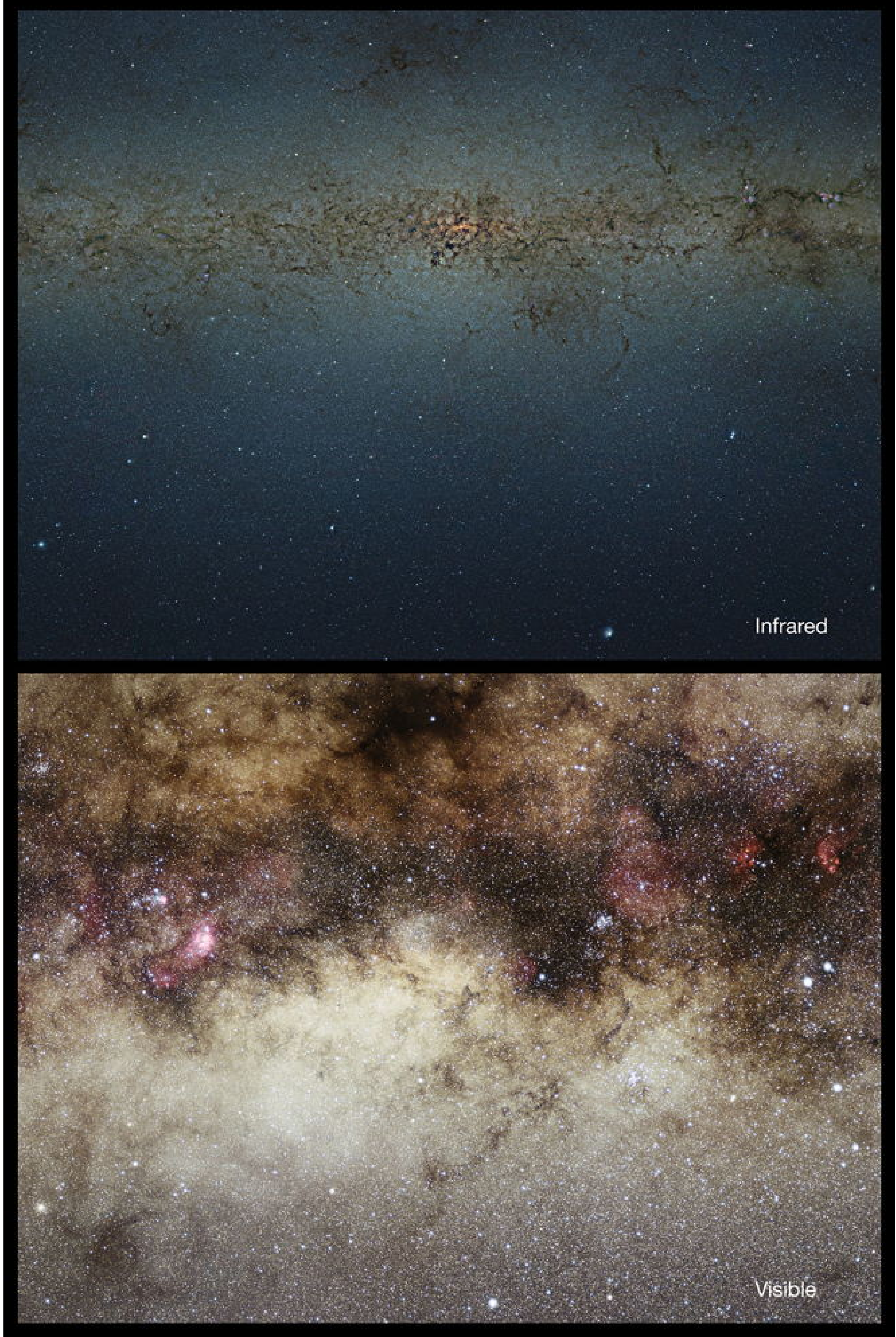
- 2.4 m mirror
- 0.9-2.0 um IR detectors
- 18 4k x 4k H4RGs
- 0.28 deg² FoV
- 0.16" FWHM
- 5 year mission,
  ~1 year microlensing





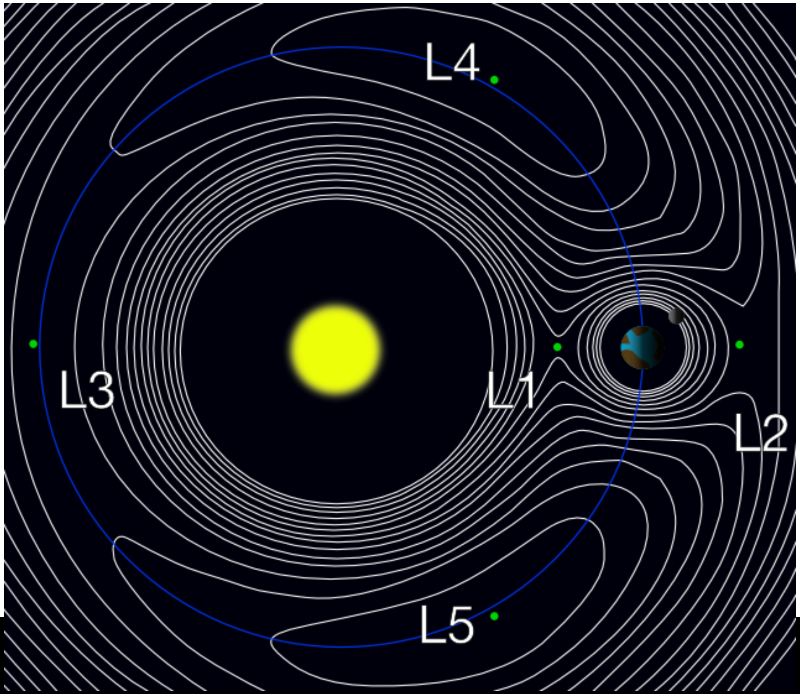
Why Infrared?

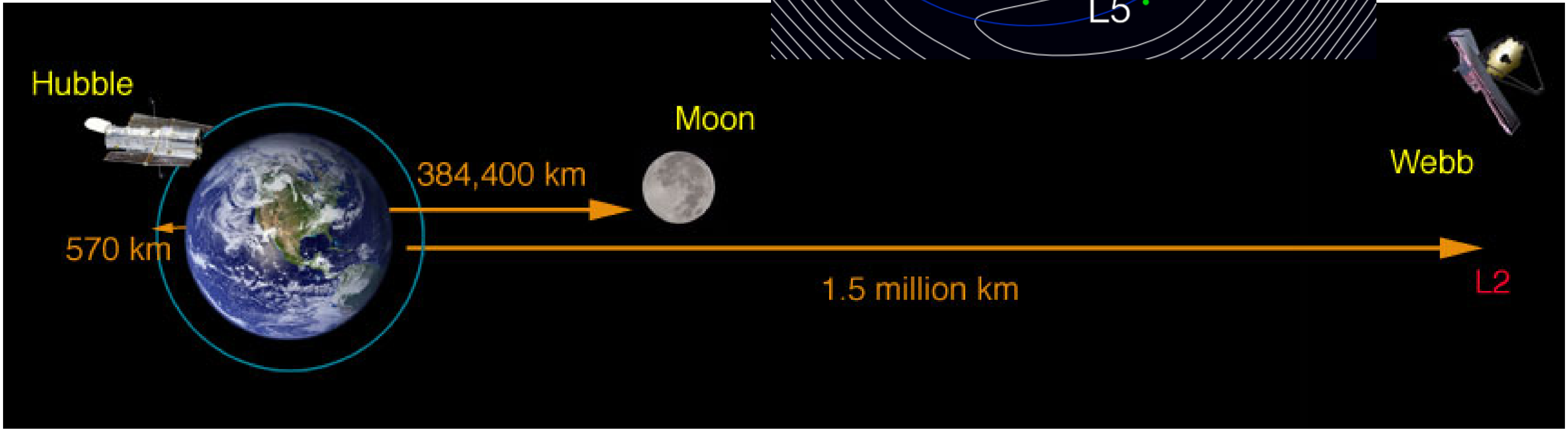
- Lots of dust in the Galactic plane
- Low IR background from space
- Can get away with bigger pixels



WFIRST's Orbit

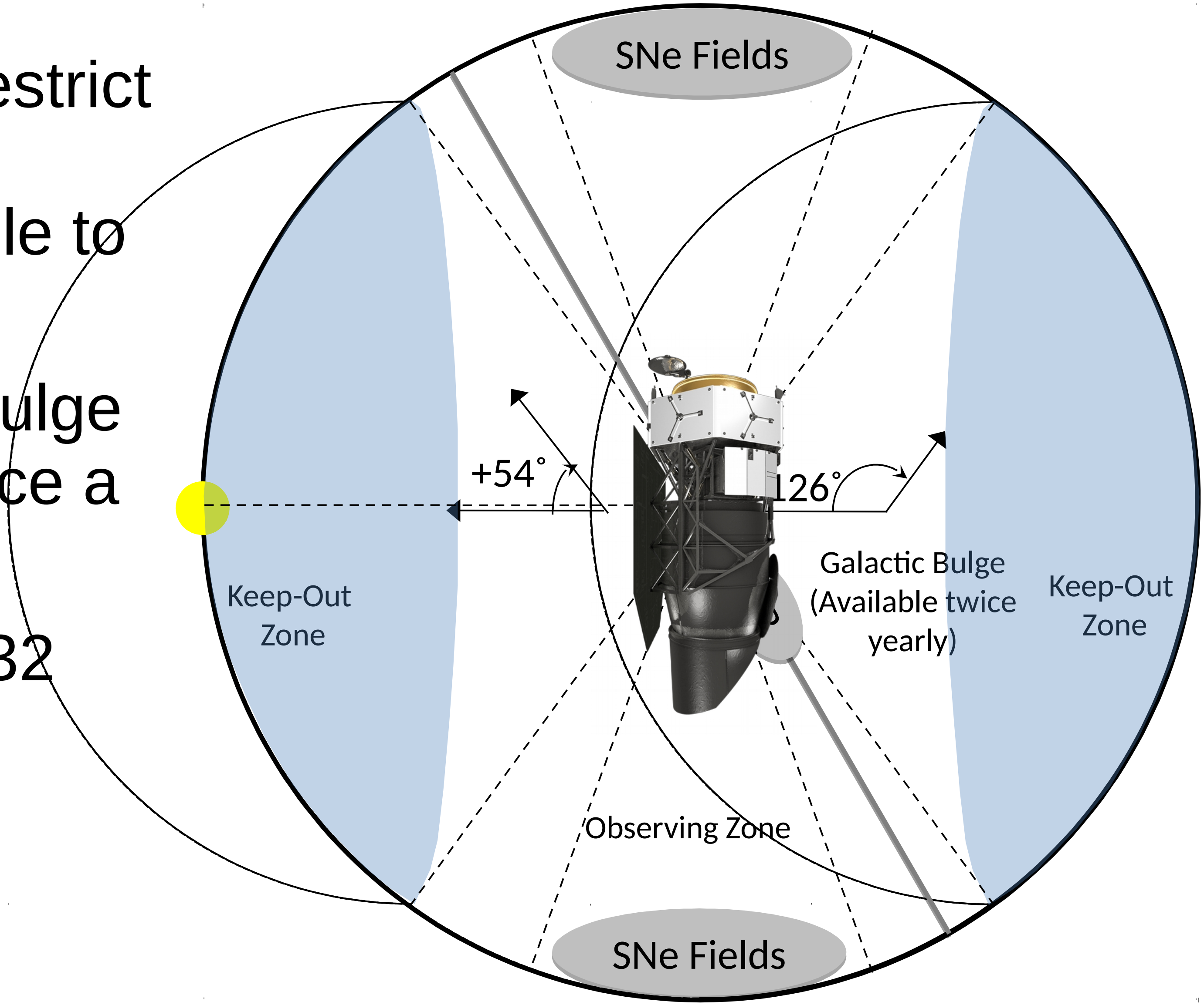
- L2 orbit
- Thermally stable environment
- But lower data rates



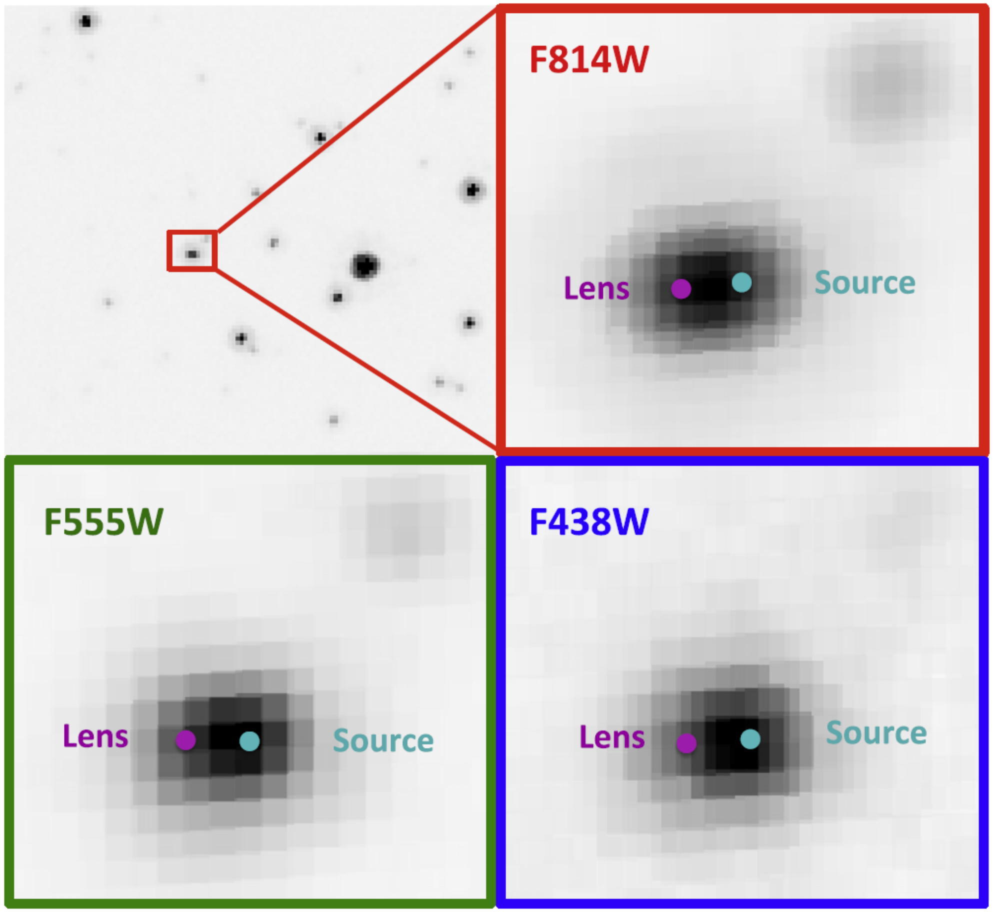


WFIRST's Seasons

- 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 =



WFIRST Microlensing Masses

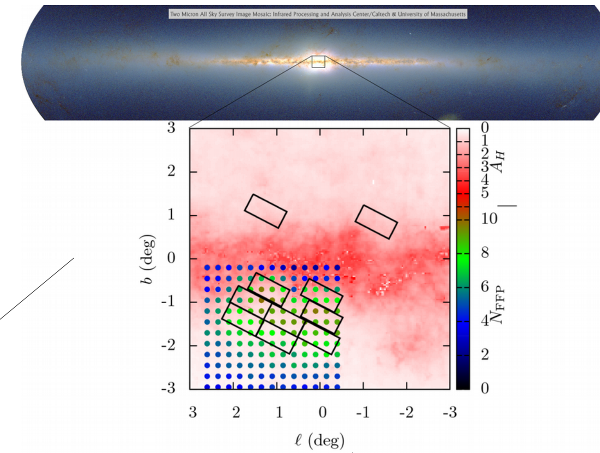


e.g., OGLE-2005-BLG-169 (Gould+06)
HST imaging in 2011 (Bennett+15)

- 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

Estimating the number of detections

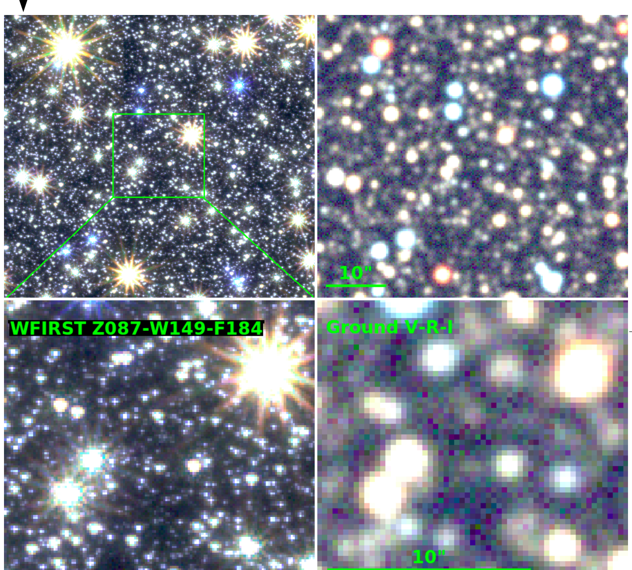
Normalize to event rates



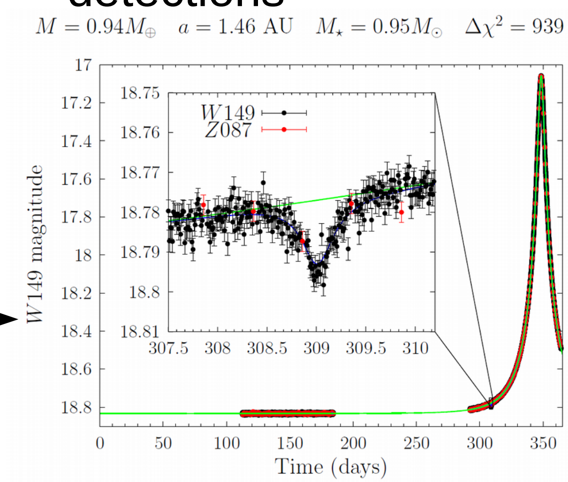
Draw source, lens, Generate images

Number of detections

Count up detections



Generate lightcurves, Do photometry



Penny et al. (2013, 2017 in prep)

Caveats

- Current best estimates of WFIRST yields are a factor of a 2-3 lower than the Spergel et al. (2015) report, due to:
  - Improved estimates of corrections to Galactic model
  - Reduced slew performance for the current observatory design (10 → 8 fields)
  - Some other factors
- Observatory design only recently fixed for WIETR* and SRD reviews, and will begin to change once more after these. Design Reference Mission still under development

  *WIETR = WFIRST Independent External Technical/Management/Cost Review

WFIRST Yields

Bound Planets

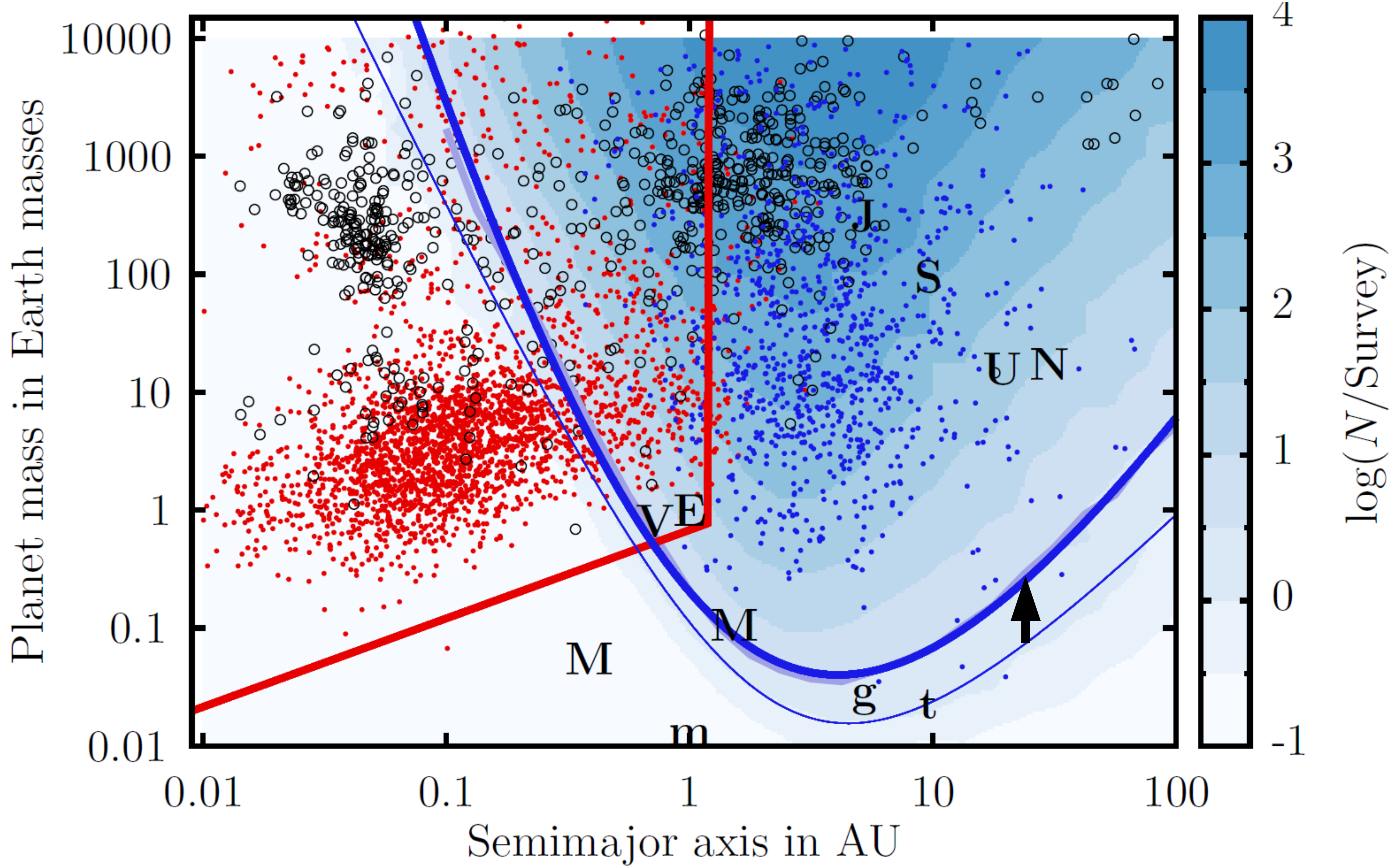
Mass (Mearth)	1/star	Cassan+ 2012
0.1	6.6	14
1	58	120
10	293	363
100	1189	275
1000	3470	149
10000	7540	60

Free-floating Planets

Mass (Mearth)	1/star	Cassan+ 2012
0.1	3.0	6.2
1	16	32
10	60	75
100	216	50
1000	708	31
10000	2290	18

Deltas

Still out of date, but reasonably indicates the order of magnitude of the changes



The WFIRST microlensing survey: What do we learn?

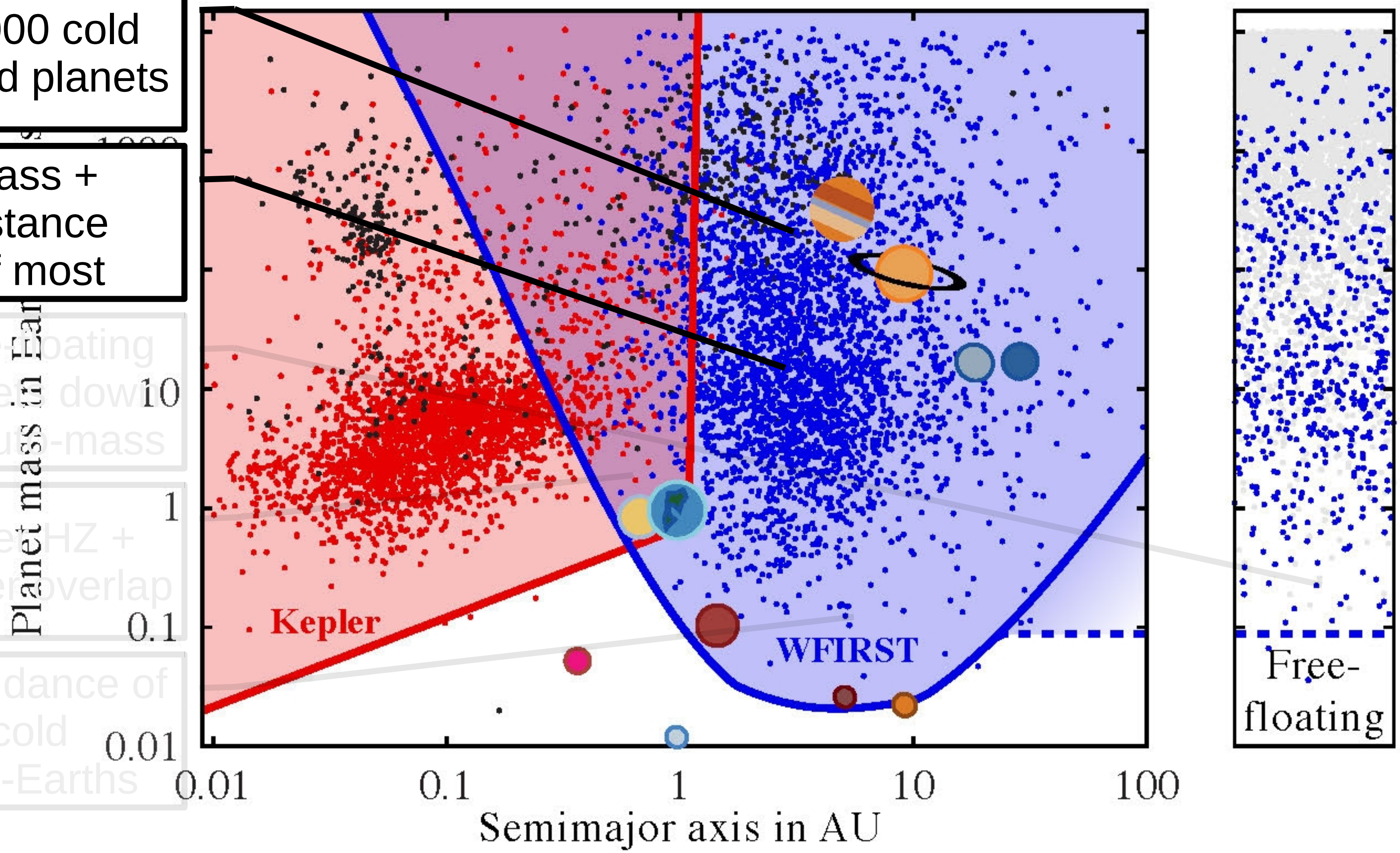
~1000 cold bound planets

Mass + distance of most

Free-floating planets down to Pluto-mass

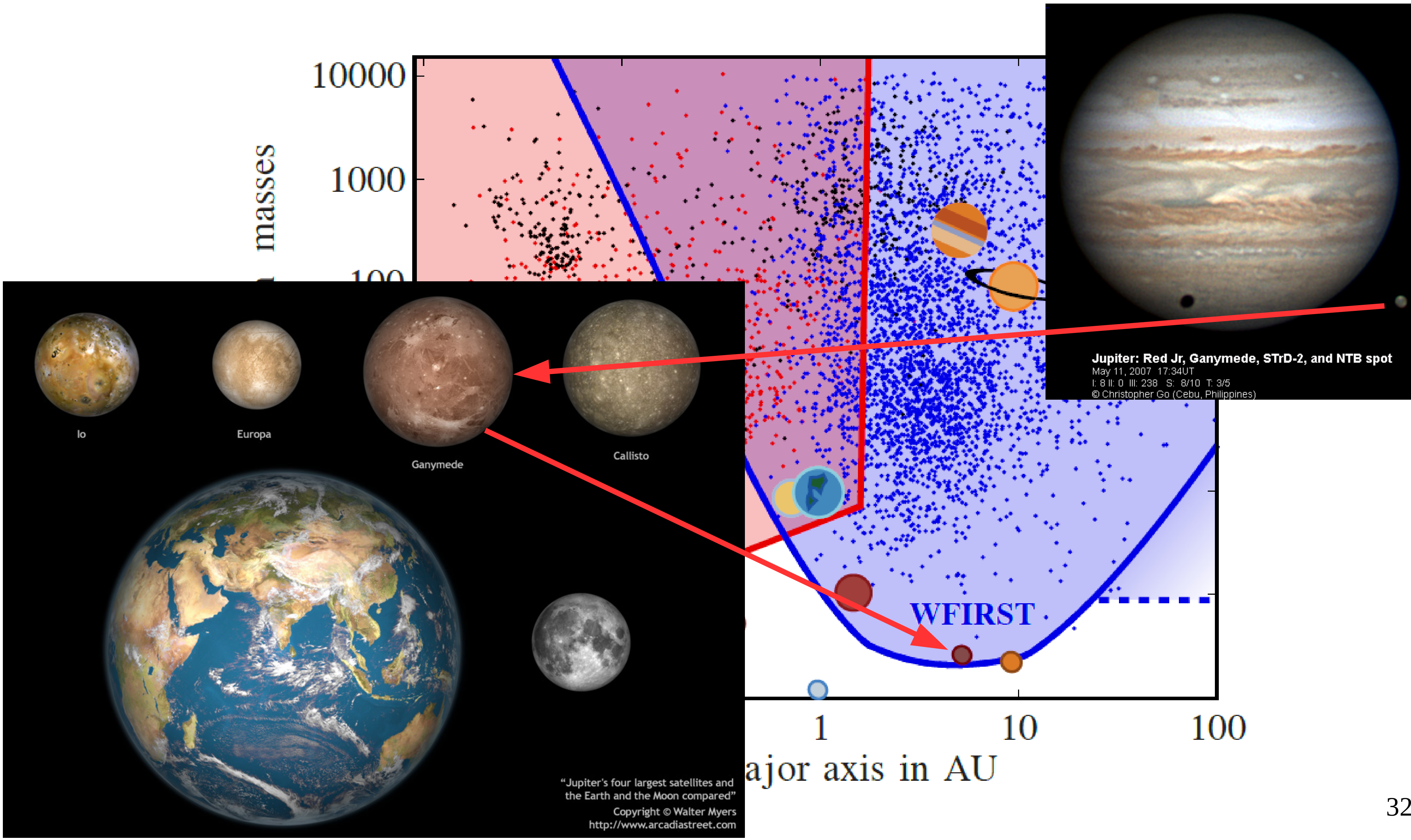
Outer HZ + Kepler overlap

Abundance of cold sub-Earths



Spergel et al. (2015), Penny et al. 2017 (in prep)

Really low-mass planets



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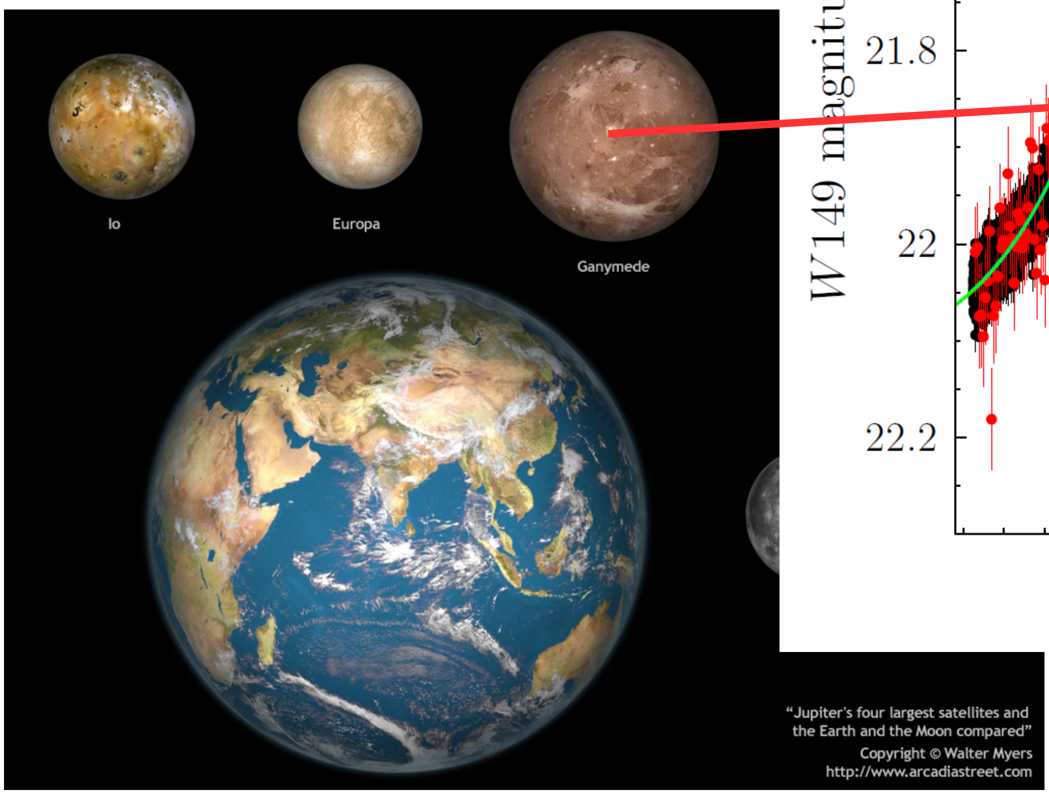

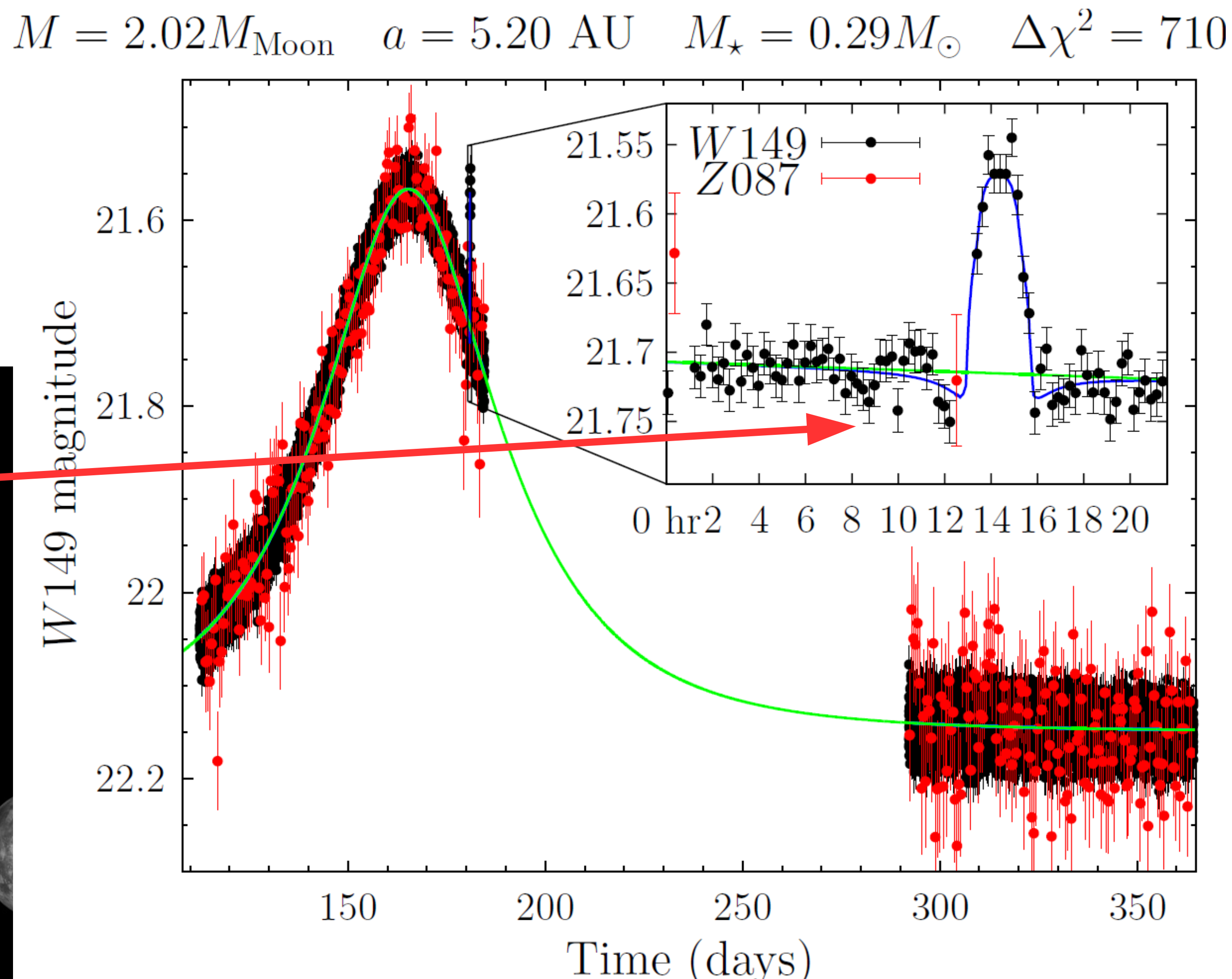

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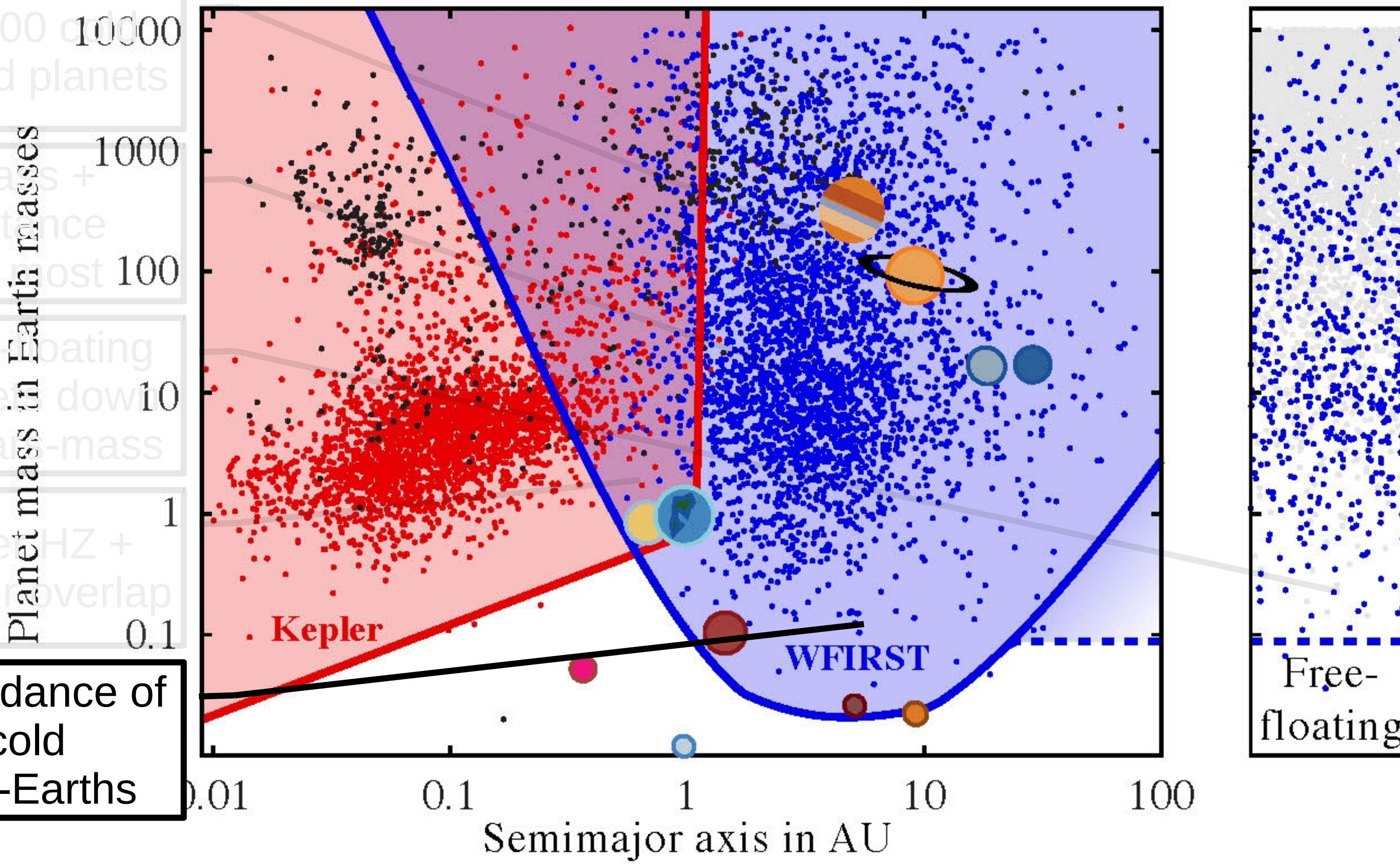
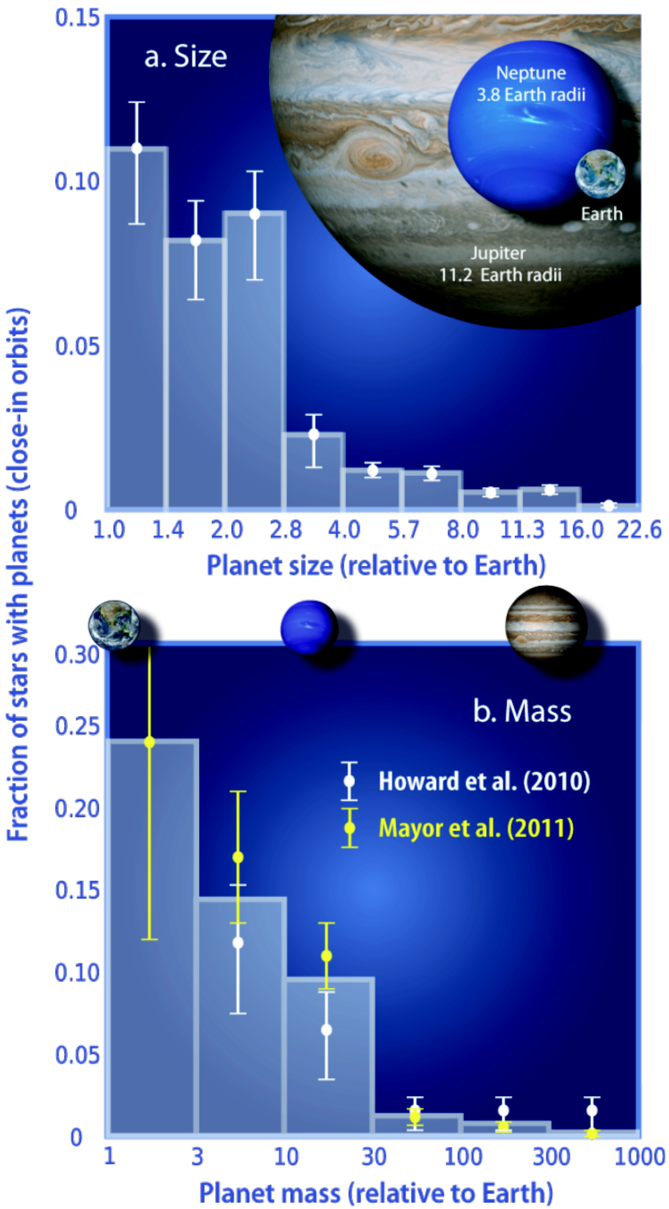


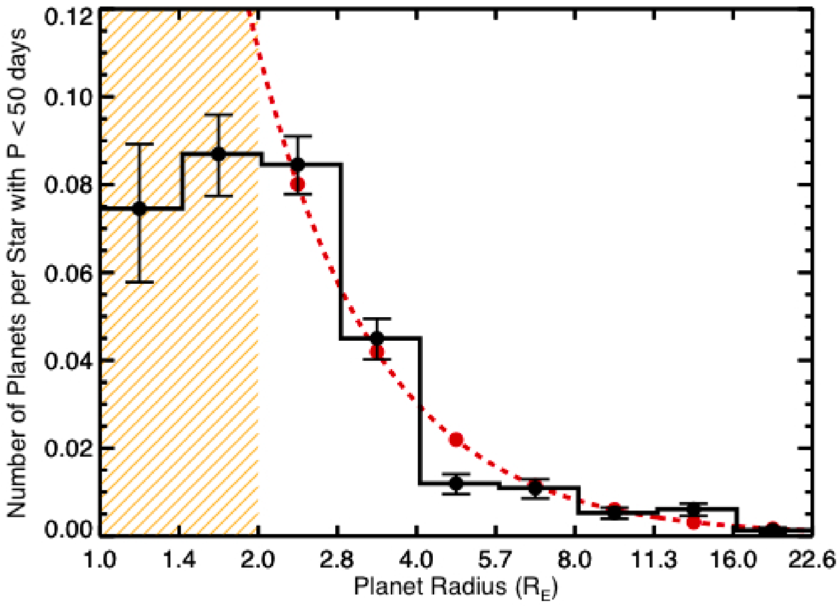
Spergel et al. (2015), Penny et al. 2017 (in prep)

Failed Cores?

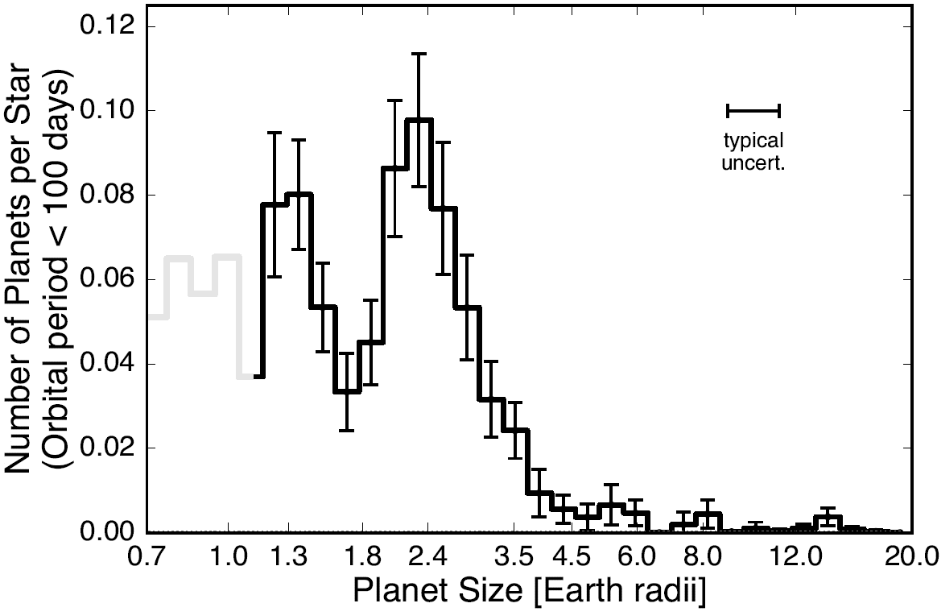
- Only a sub-dominant fraction of systems have gas giant planets
- A Larger Fraction host super-Earths/mini-Neptunes, but only ~1/2
- Planet formation is ubiquitous, so could the remainder of systems be teeming with planetary cores that failed to grow?



WFIRST's Mass Measurements Will Help Immensely



Howard+2011



Fulton+2017

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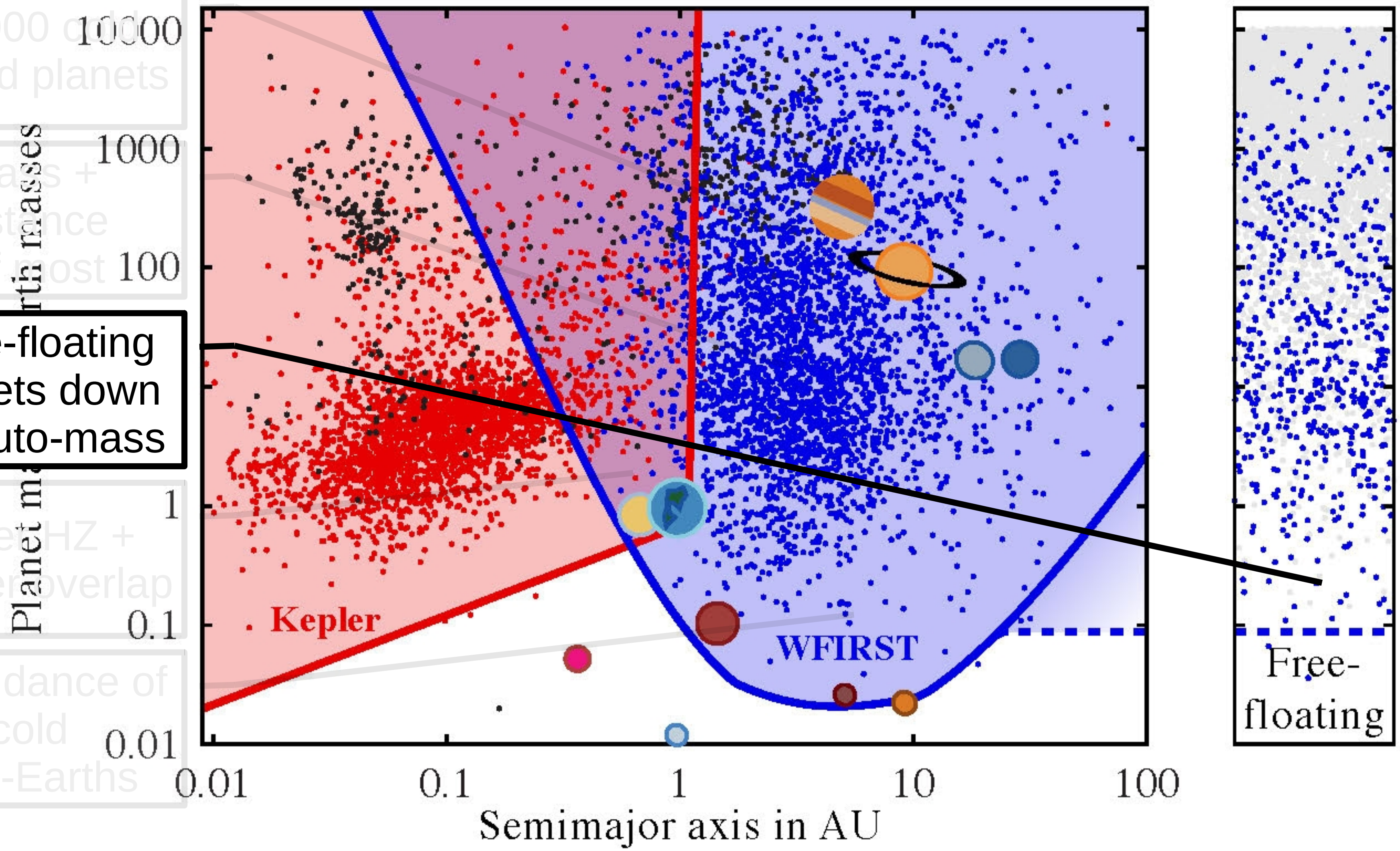
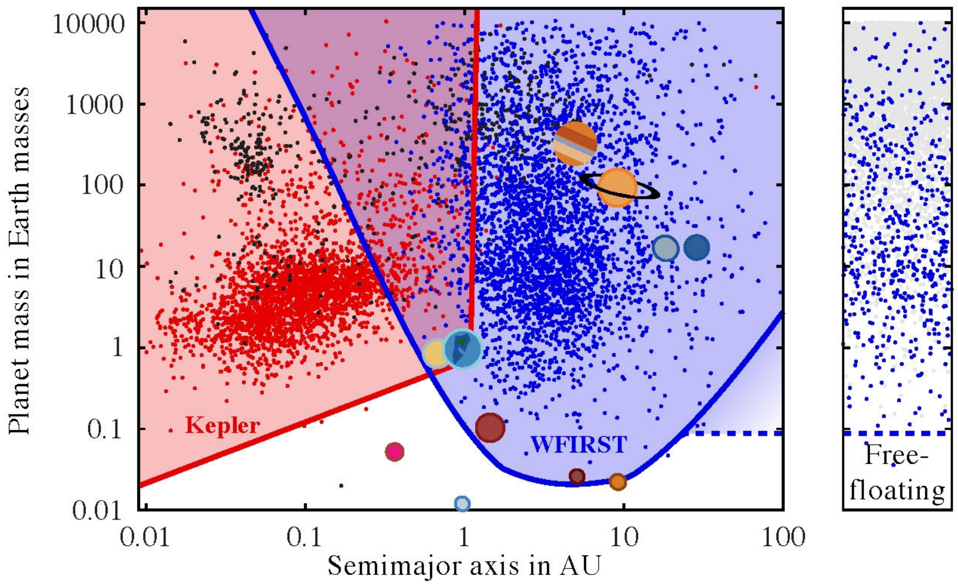
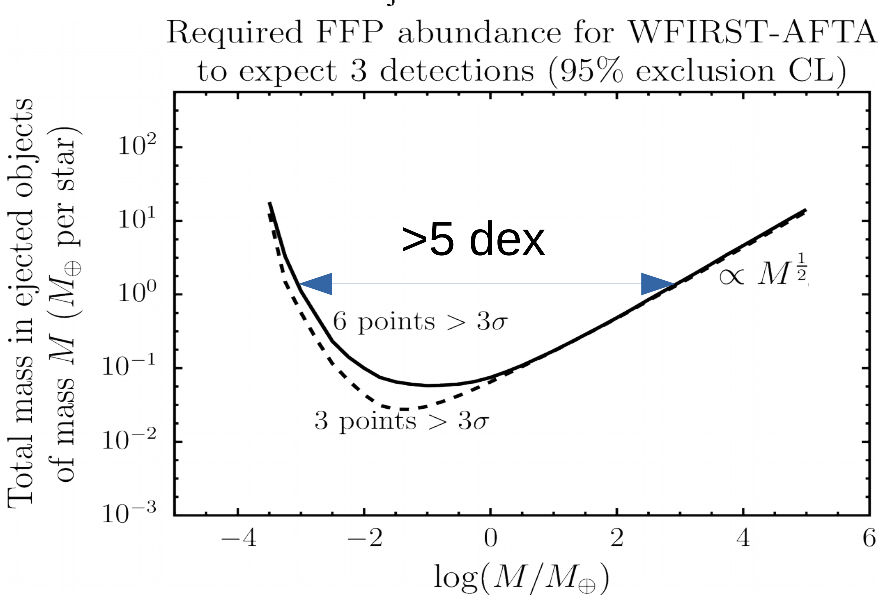


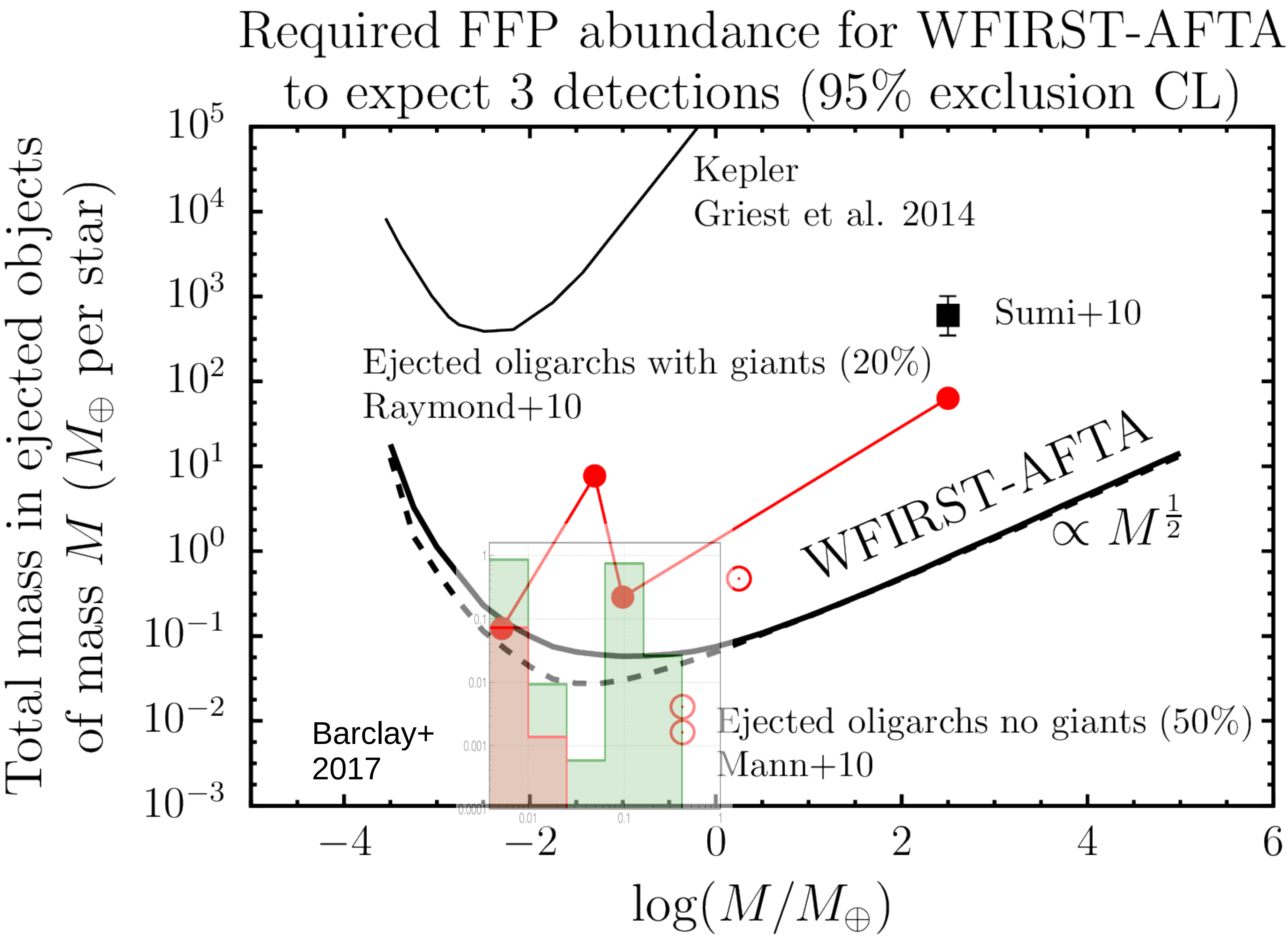
Spergel et al. (2015), Penny et al. 2017 (in prep)

WFIRST will Measure How Ejected Mass is Partitioned





- Ejected objects
- Exo-Kuiper belts and Exo-Oort clouds
- Possible to separate these populations statistically by searching for light from a putative host



Required FFP abundance for WFIRST-AFTA
to expect 3 detections (95% exclusion CL)
Total mass in ejected objects
of mass M ($M_\oplus$ per star)
$\log(M/M_\oplus)$
Kepler
Griest et al. 2014
Sumi+10
Ejected oligarchs with giants (20%)
Raymond+10
WFIRST-AFTA
$\propto M^{\frac{1}{2}}$
Ejected oligarchs no giants (50%)
Mann+10
Barclay+
2017

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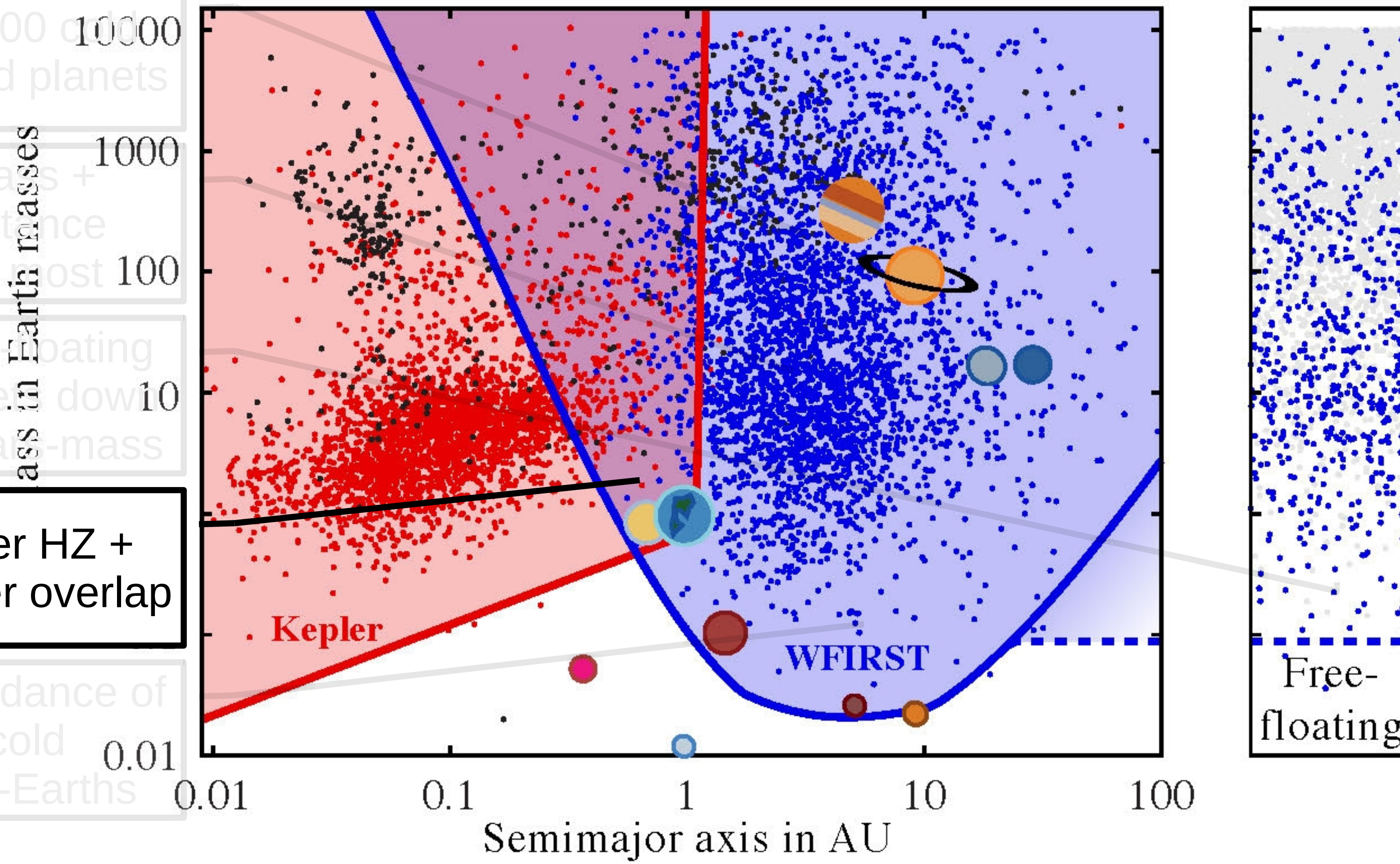
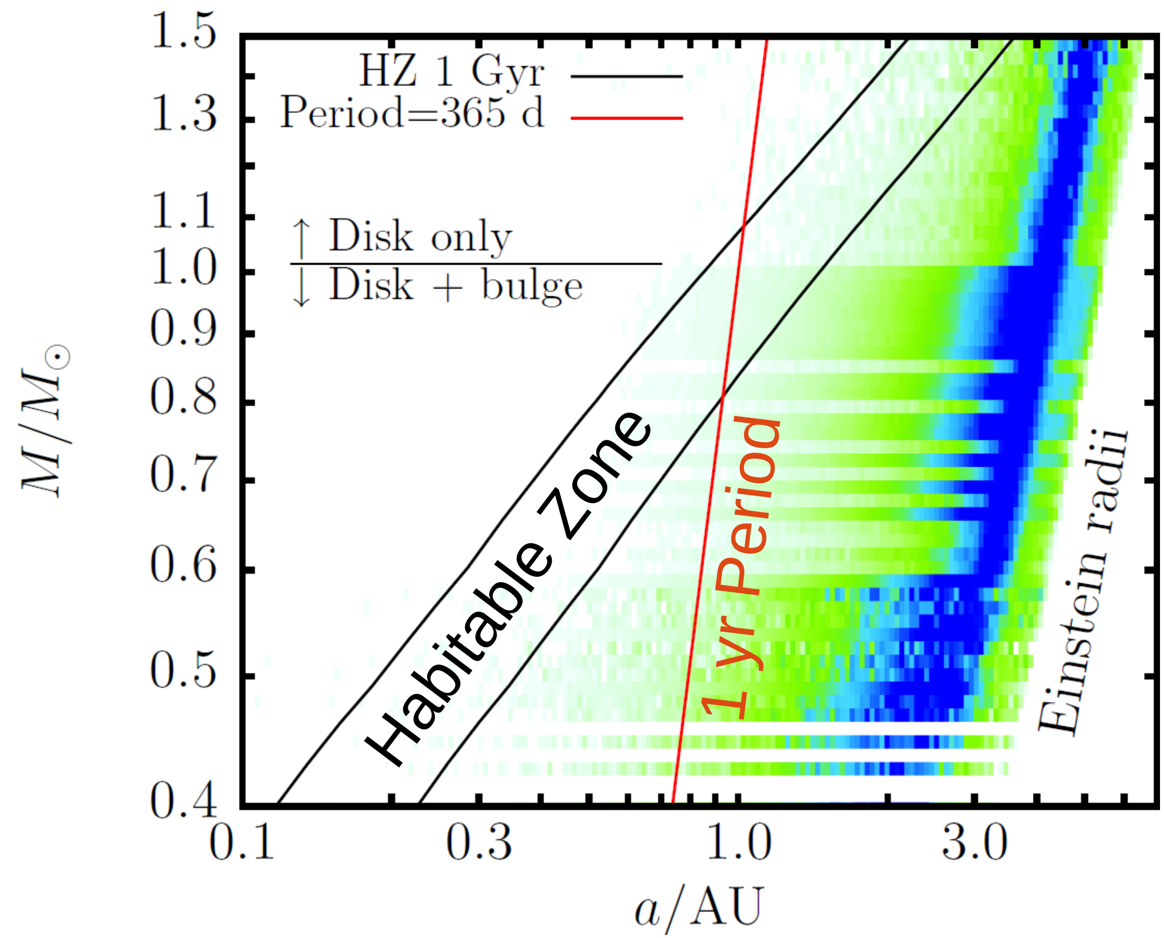


Spergel et al. (2015), Penny et al. 2017 (in prep)

Microlensing in the Habitable Zone

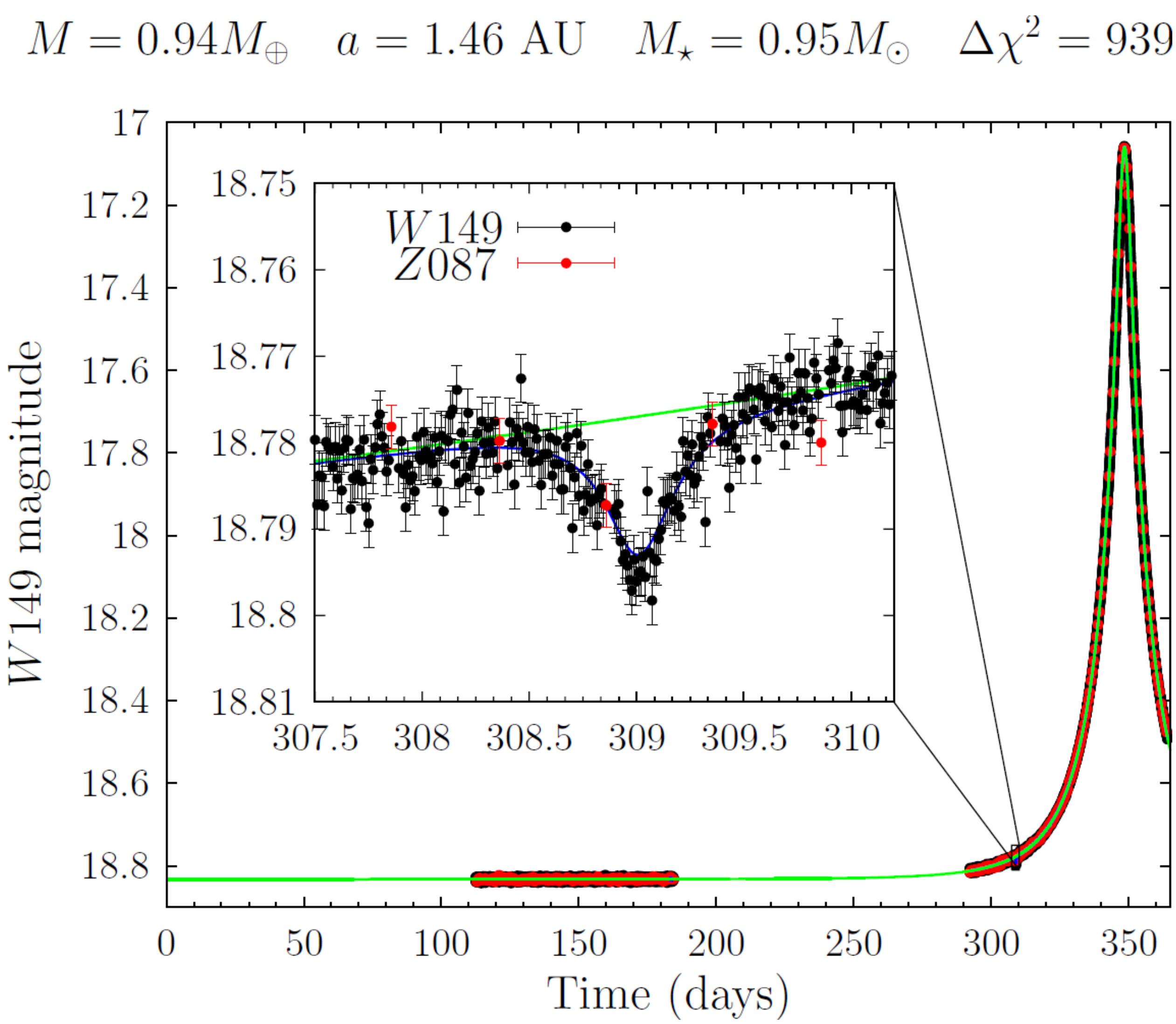
- Transits most sensitive to HZ of low-mass hosts
- Microlensing most sensitive to HZ of high-mass hosts

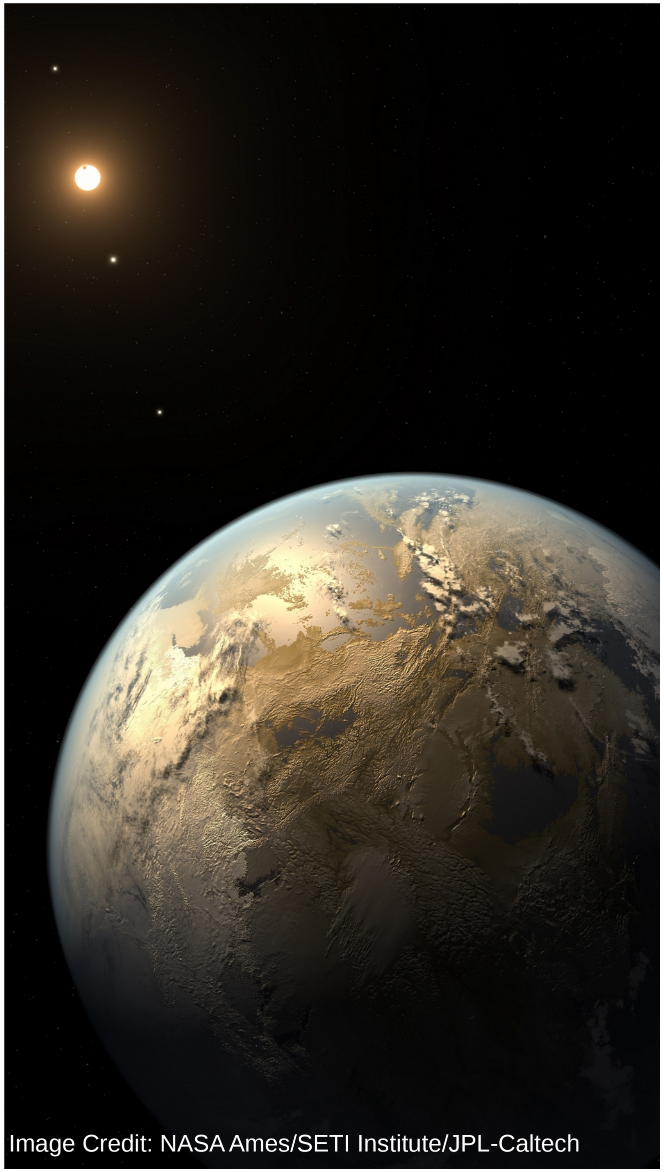
  -but how sensitive?



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

Habitable Zone planets

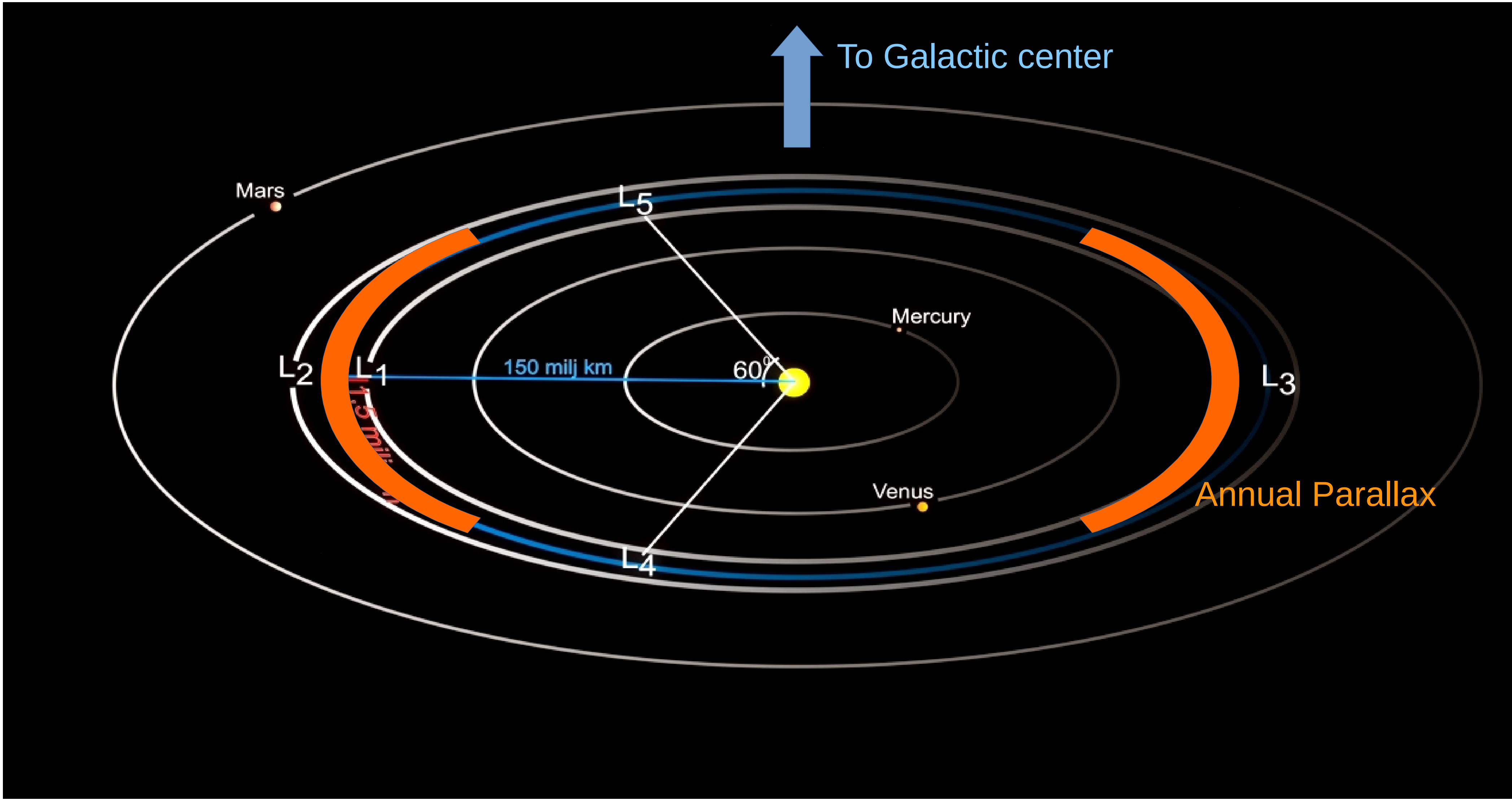




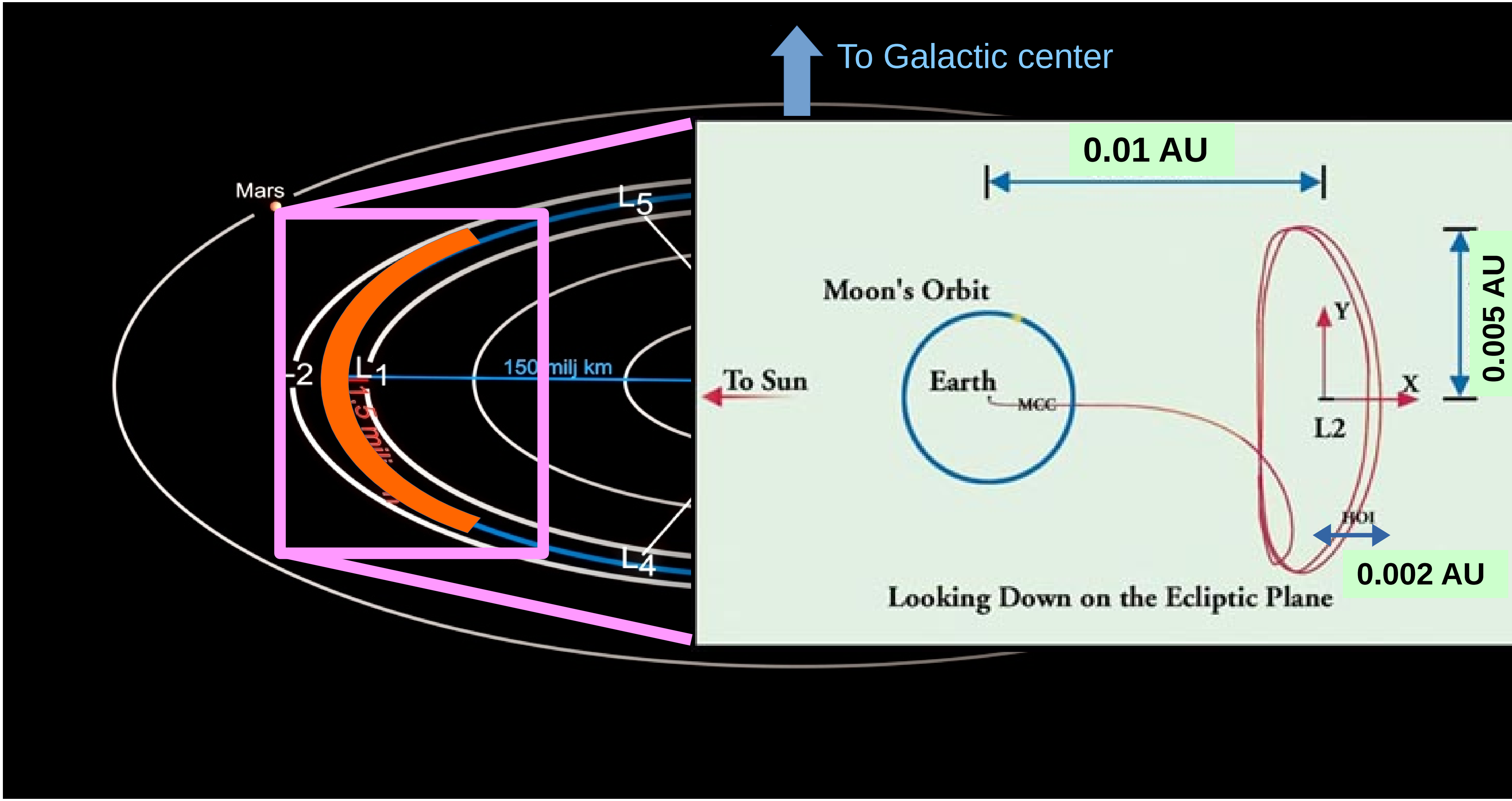
Potential WFIRST Projects
[speak with MP, Scott Gaudi, Dave Bennett, +]

- We have not fully explored what parallax information we can get from WFIRST (+others) [Jennifer Yee]
- Trade-off between depth and resolution with respect to AO vs WFIRST mass measurements [JP Beaulieu, Calen Henderson]
- Improving galactic model inputs, understand the uncertainties
- Multiple planet systems
- Planets in binary systems
- Exomoons
- UKIRT IR Microlensing survey [Yossi Shvartzvald]
- Astrometric Microlensing [Lukasz Wyrzykowski, Kailash Sahu]
- Understanding WFIRST systematics [Sebastiano Calchi Novati, Sean Carey]
- Non microlensing science with survey [Dan Huber, Ben Montet]

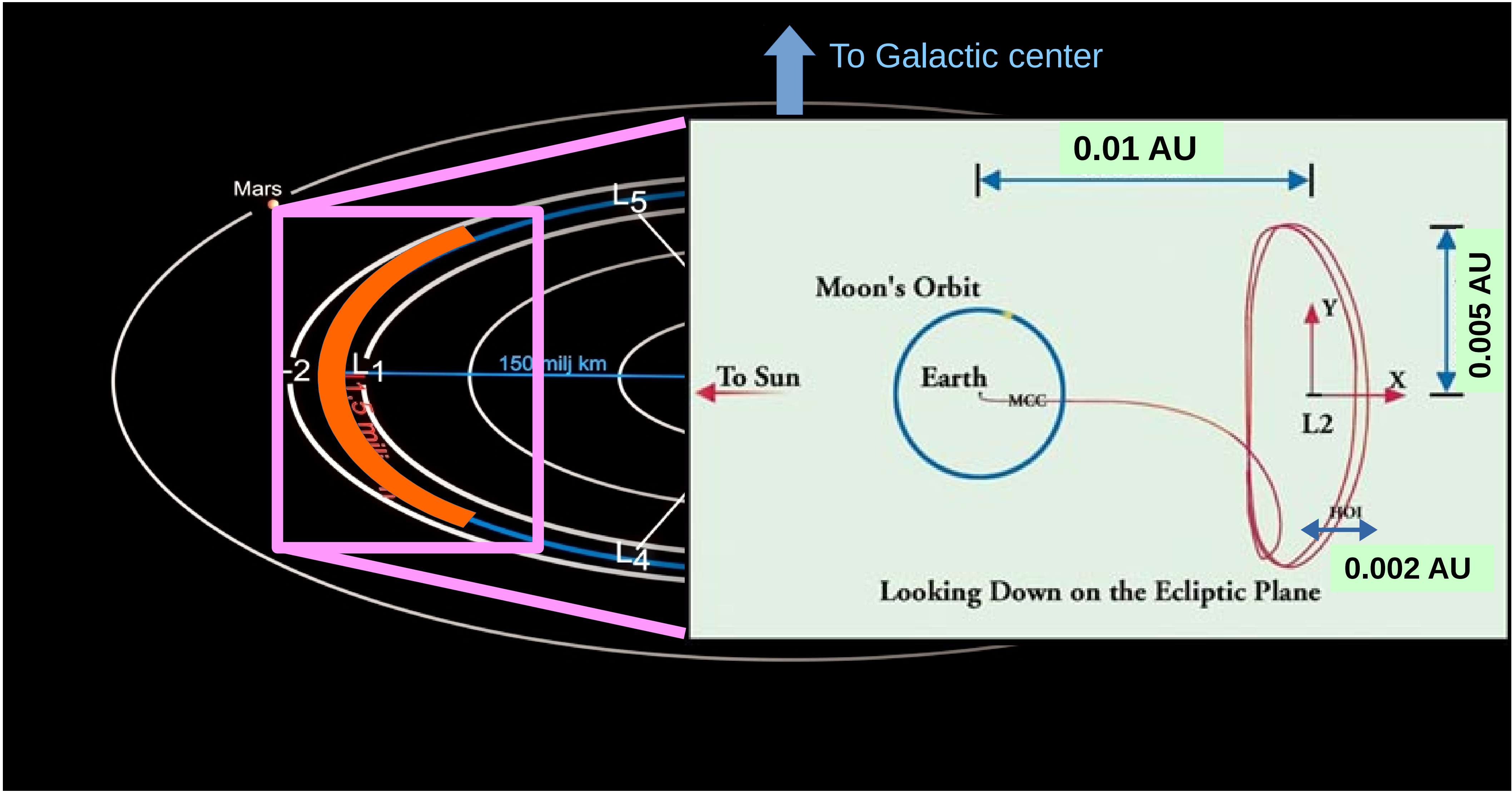
WFIRST Parallax Opportunities



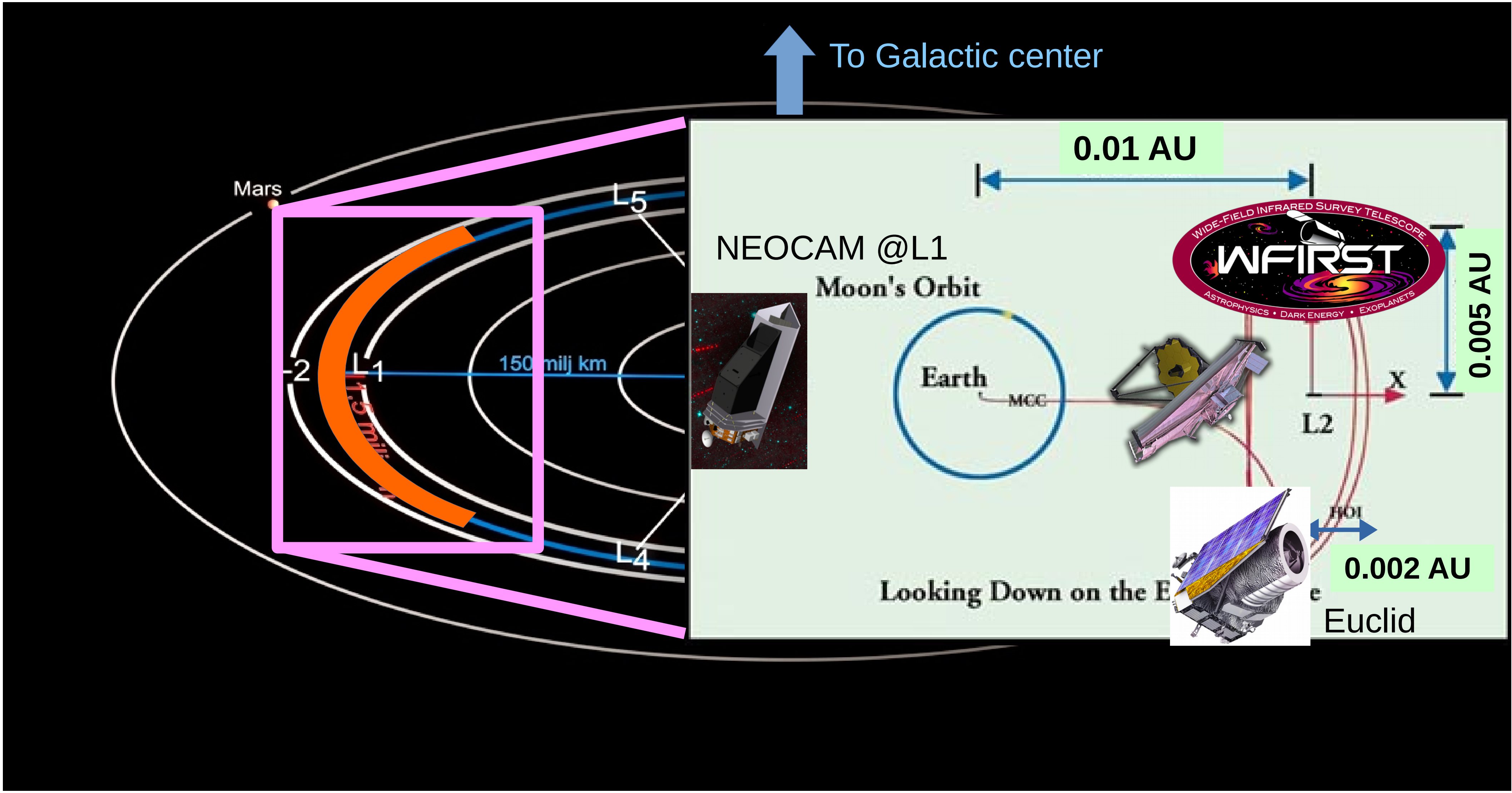
WFIRST Parallax Opportunities



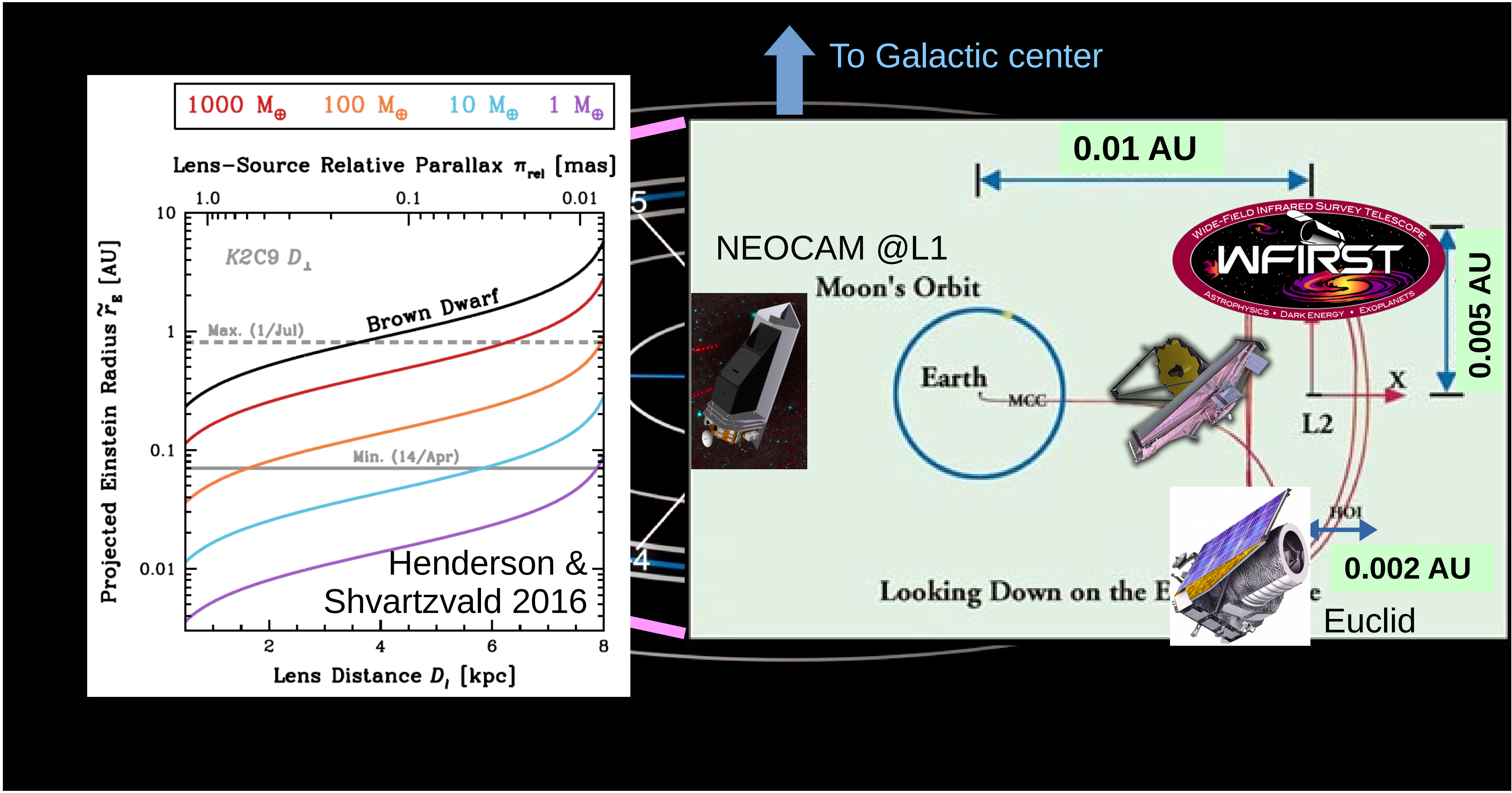
WFIRST Parallax Opportunities



WFIRST Parallax Opportunities



WFIRST Parallax Opportunities



Non WFIRST Projects [US-based attendees to speak to]

- KMTNet data releases (2015 available, more on its way) [Jennifer Yee]
- K2 C9 data reduction very close to ready [MP, Dave Bennett] + lots of ground-based data [MP, Etienne Bachelet, Rachel Street]
- LSST microlensing [Rachel Street, MP]
- Gaia microlensing [Lukasz Wyrzykowski, Katarzyna Kruszyńska]
- Also, ZTF, PanSTARRS, ASAS-SN, EvryScope, ...
- Spitzer Microlensing [Jennifer Yee, Yossi Shvartzvald, Sebastiano Calchi Novati]
- Parallax survey interpretation, meta analysis
- ...

Think Small?

- Lots of robotic ".50-.50" telescopes
  - LCOGT, DEMONEXT
- A new era for follow-up?
  - OGLE, MOA Surveys covering a wider area than ever
  - Networks of follow-up telescopes (LCOGT, PROMPT/SkyNet, SONG, TESS-FUN…)
  - Easier than ever to conduct follow-up planet searches