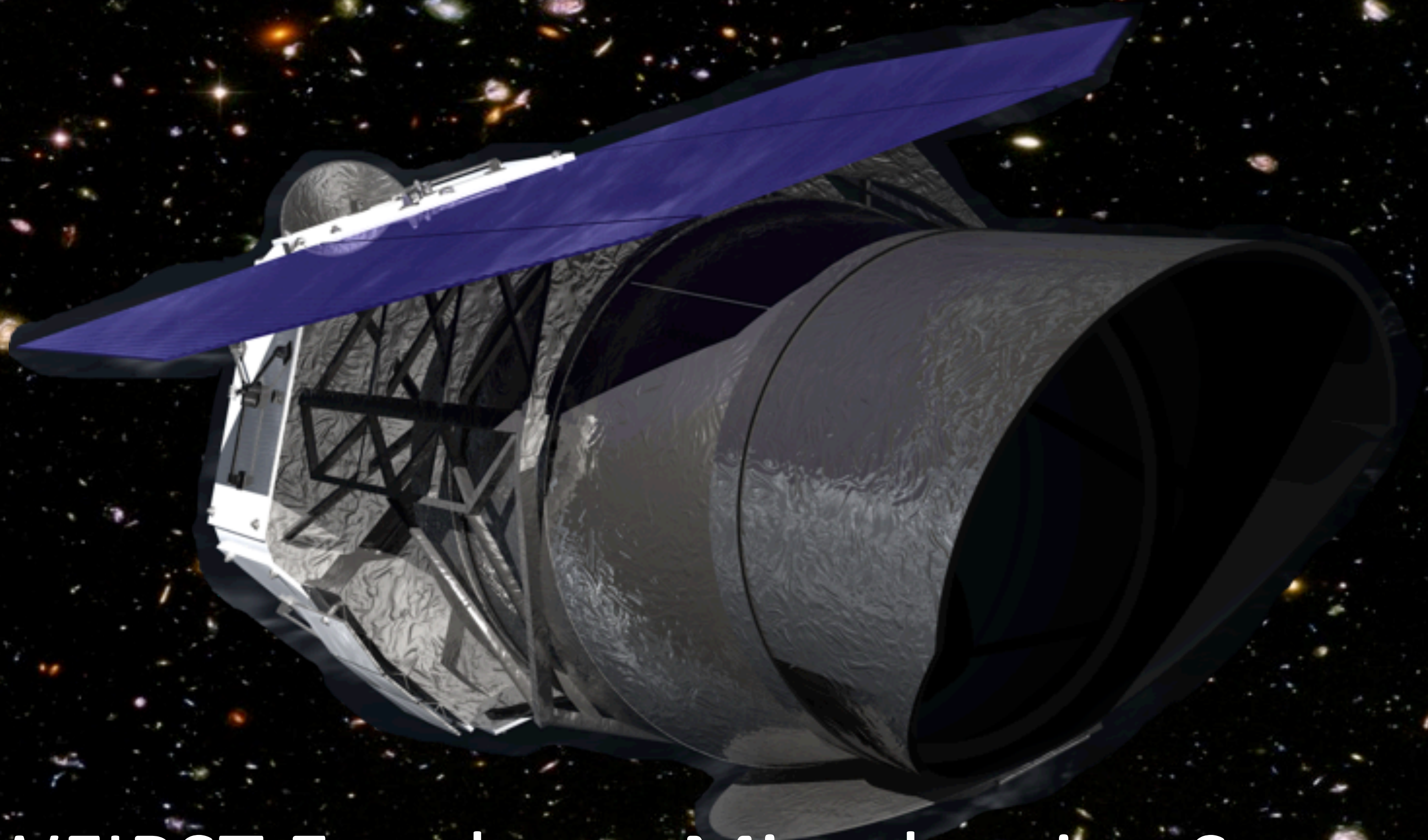


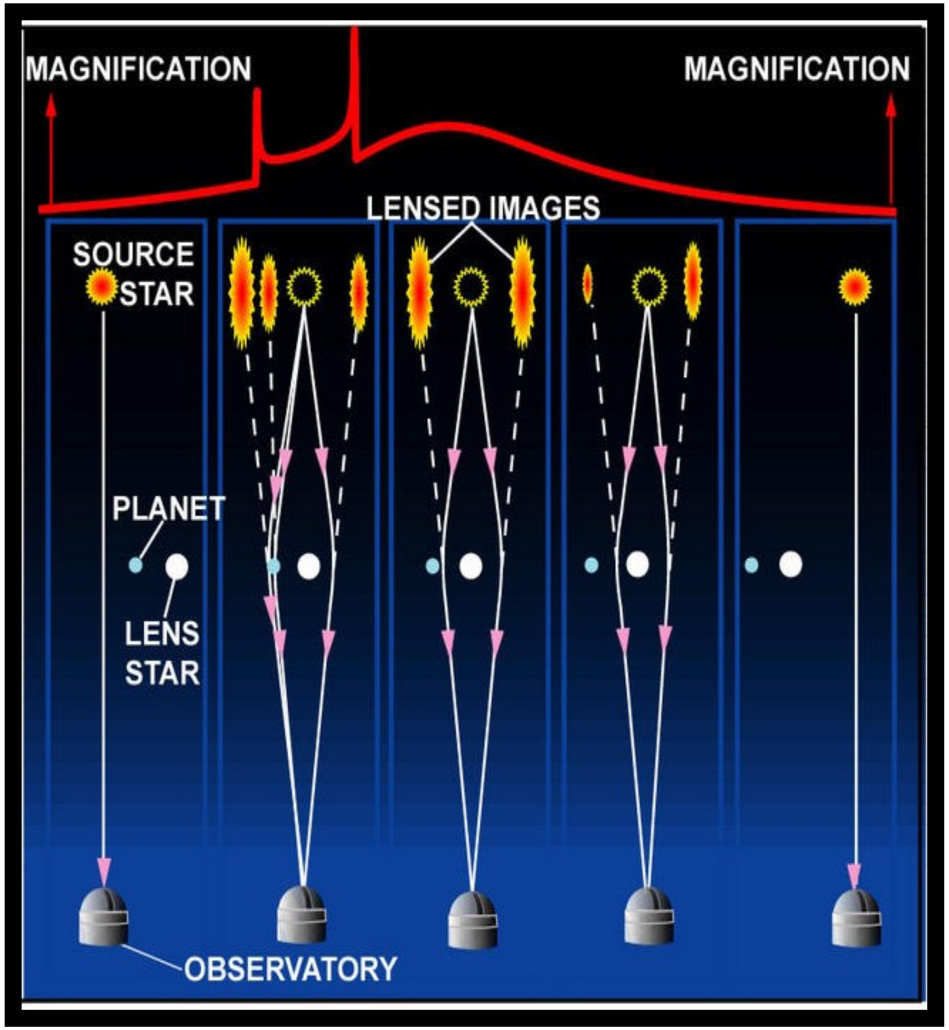
WFIRST Exoplanet Microlensing Survey

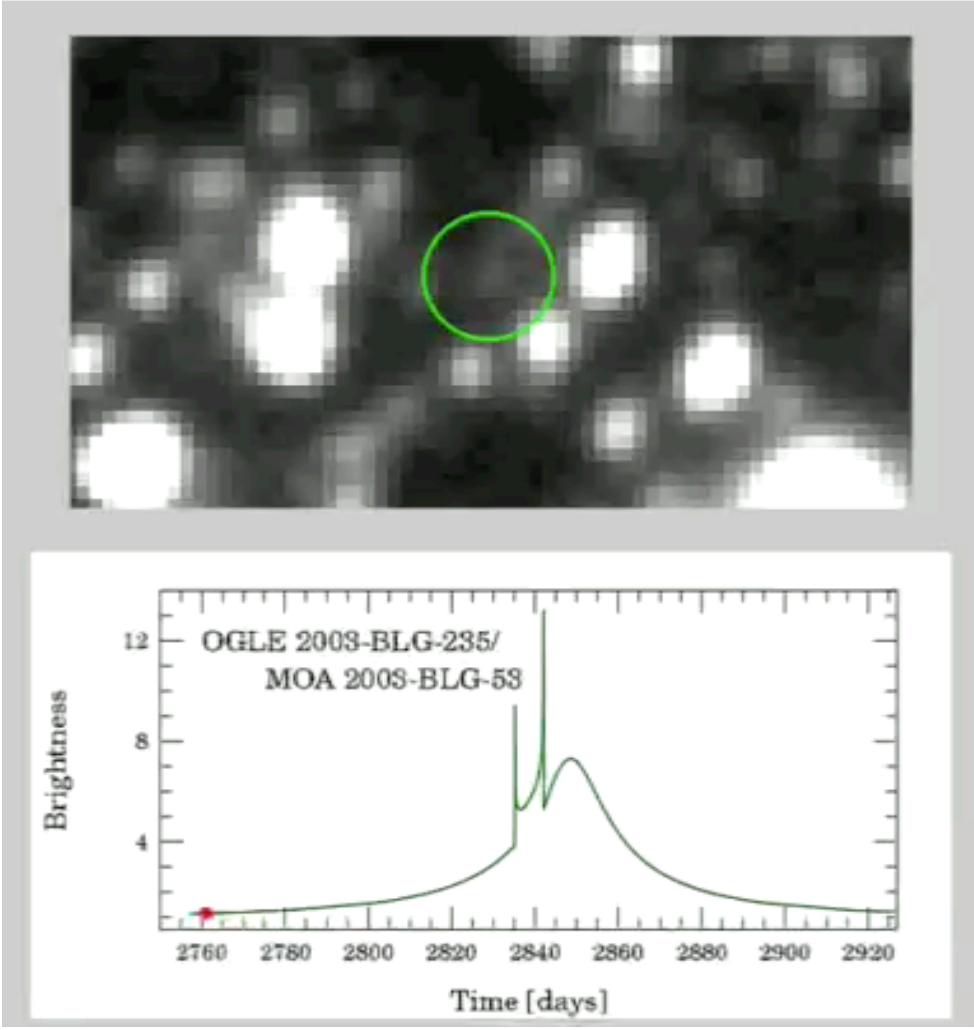
with Subaru Mass measurements

David Bennett

NASA Goddard Space Flight Center

Microlensing



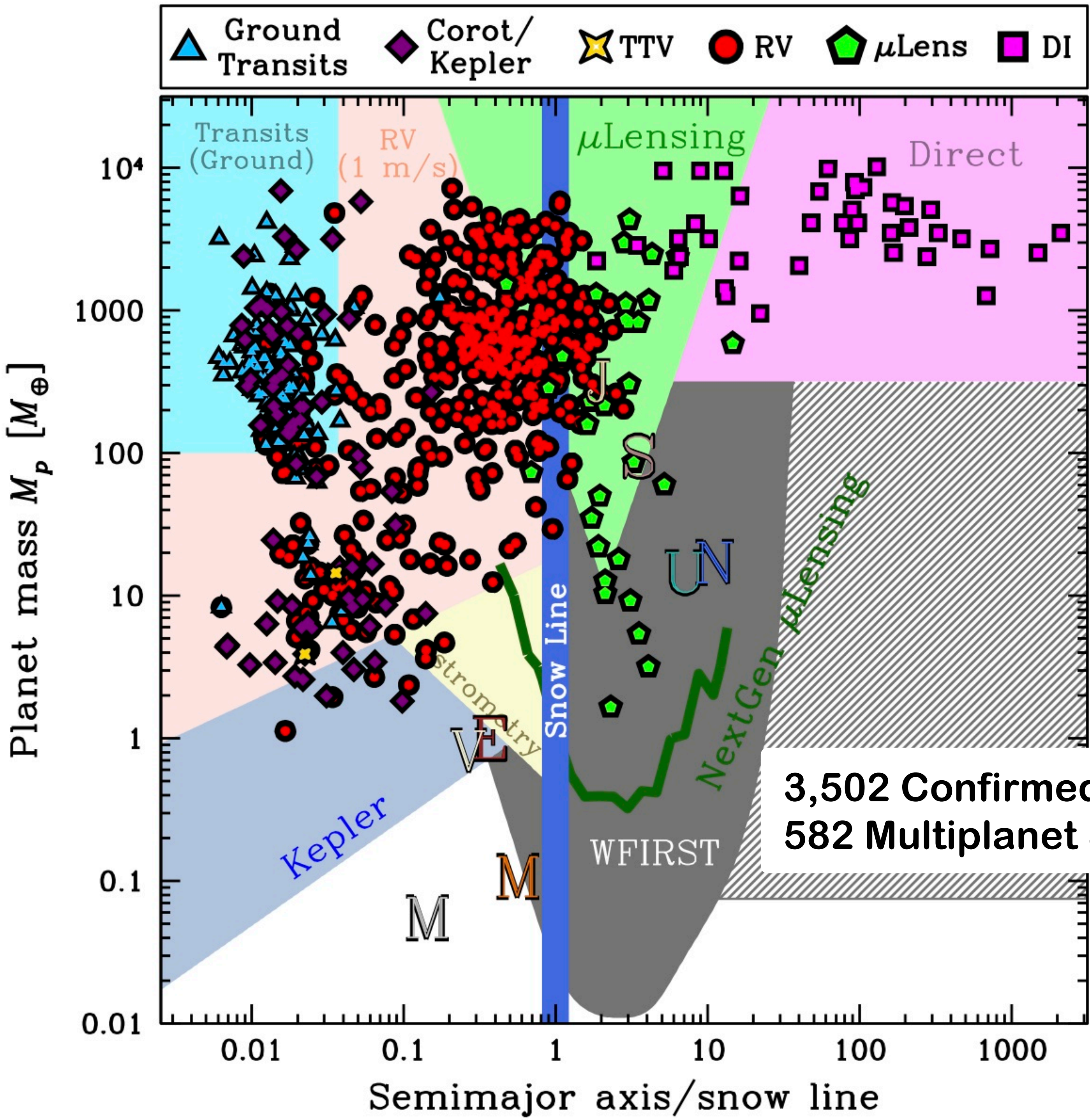


(Bond et al. 2004)

WIDE-FIELD INFRARED SURVEY TELESCOPE

WFIRST

DARK ENERGY • EXOPLANETS • ASTROPHYSICS



3,502 Confirmed Planets
582 Multiplanet Systems

Why is Exoplanet Demographics Important?

- Planet formation theory is difficult
  - Theory follows observation
- The exoplanet mass and separation function may have the physics of planet formation imprinted on it.
- The exoplanet distribution function depends on at least 4 parameters (planet mass and semi-major axis, stellar mass, stellar metallicity), and the mass/radius relation depends on these parameters.
- It probably depends on many more (binarity, birth environment, age, etc.)
- Planet migration may erase much of initial condition info.
- We must piece together this distribution from many disparate detection methods with different detection biases

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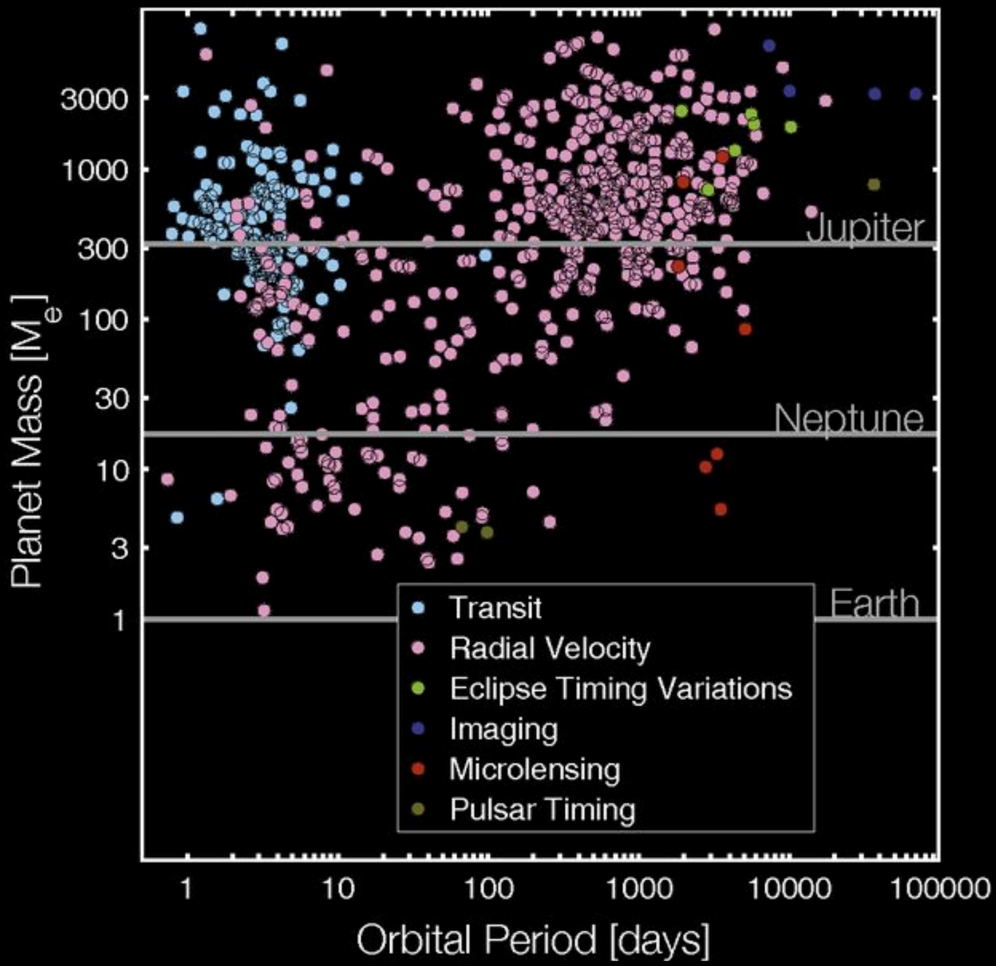
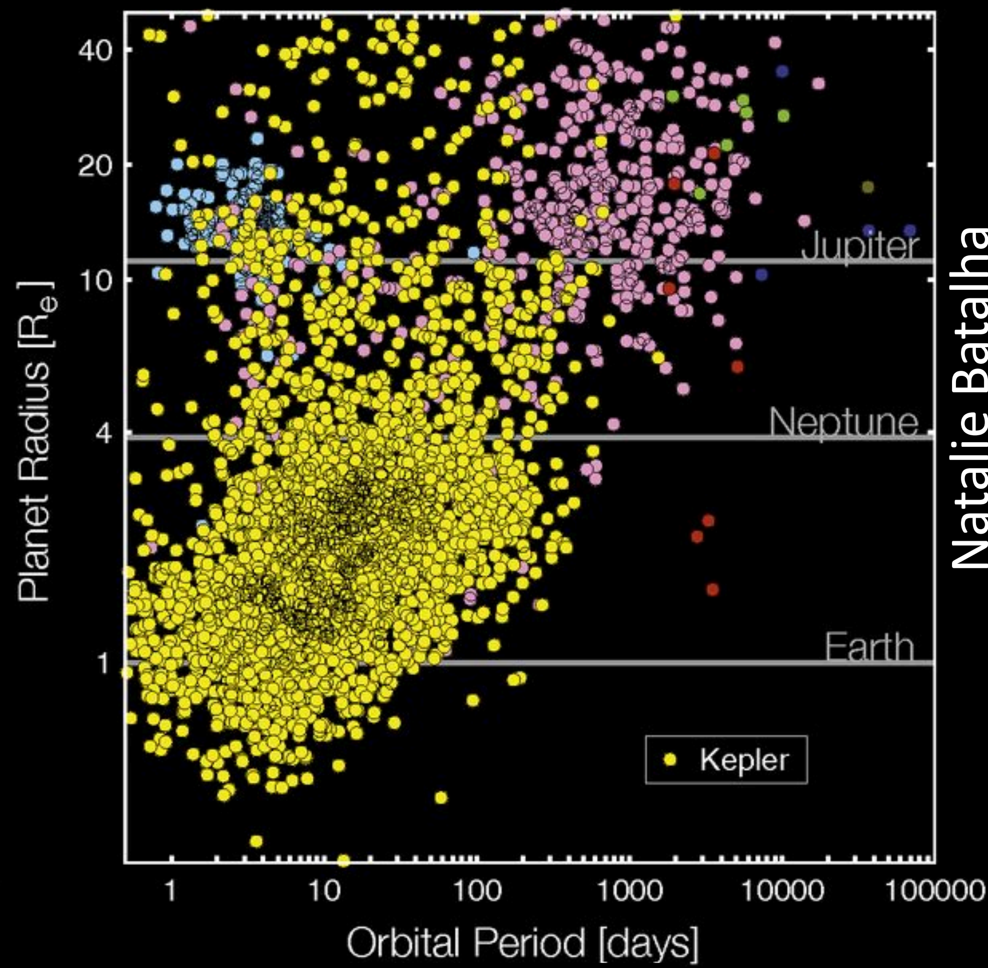
Kepler!





Natalie Batalha

~3502 Confirmed Planets

~4496 Kepler Candidates

WFIRST
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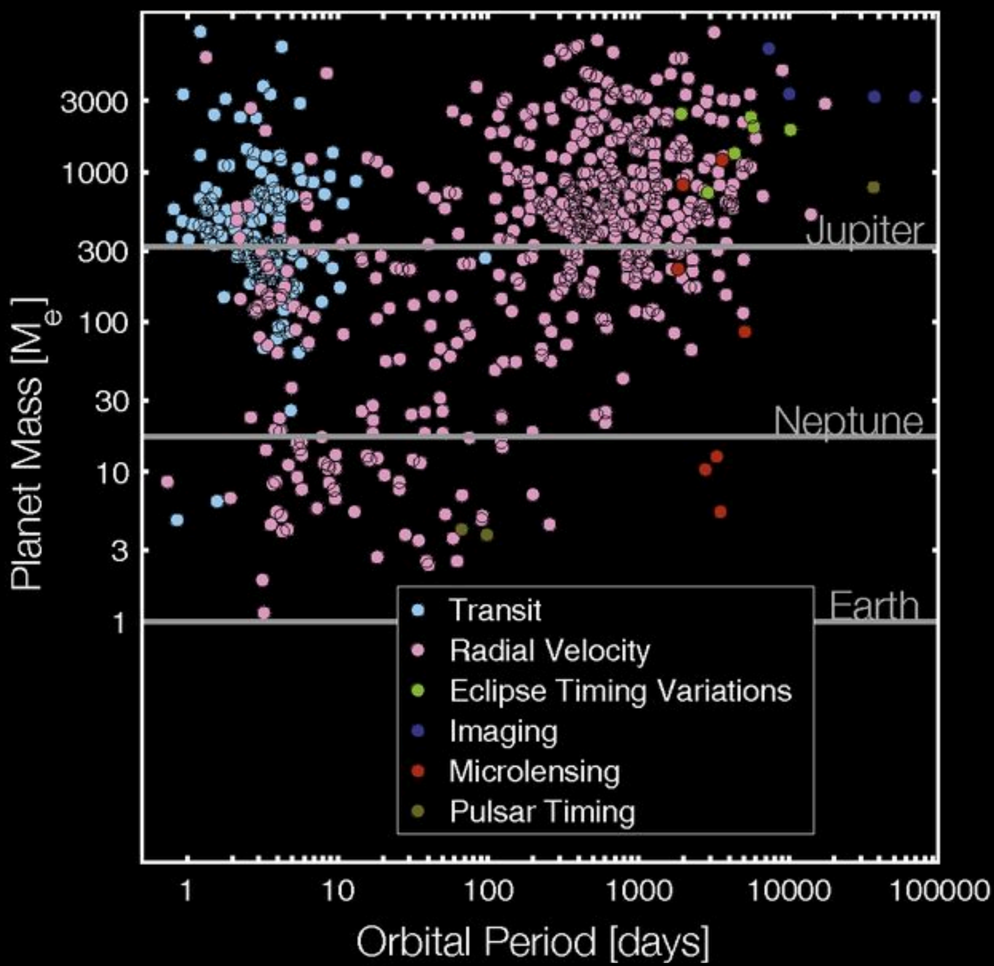
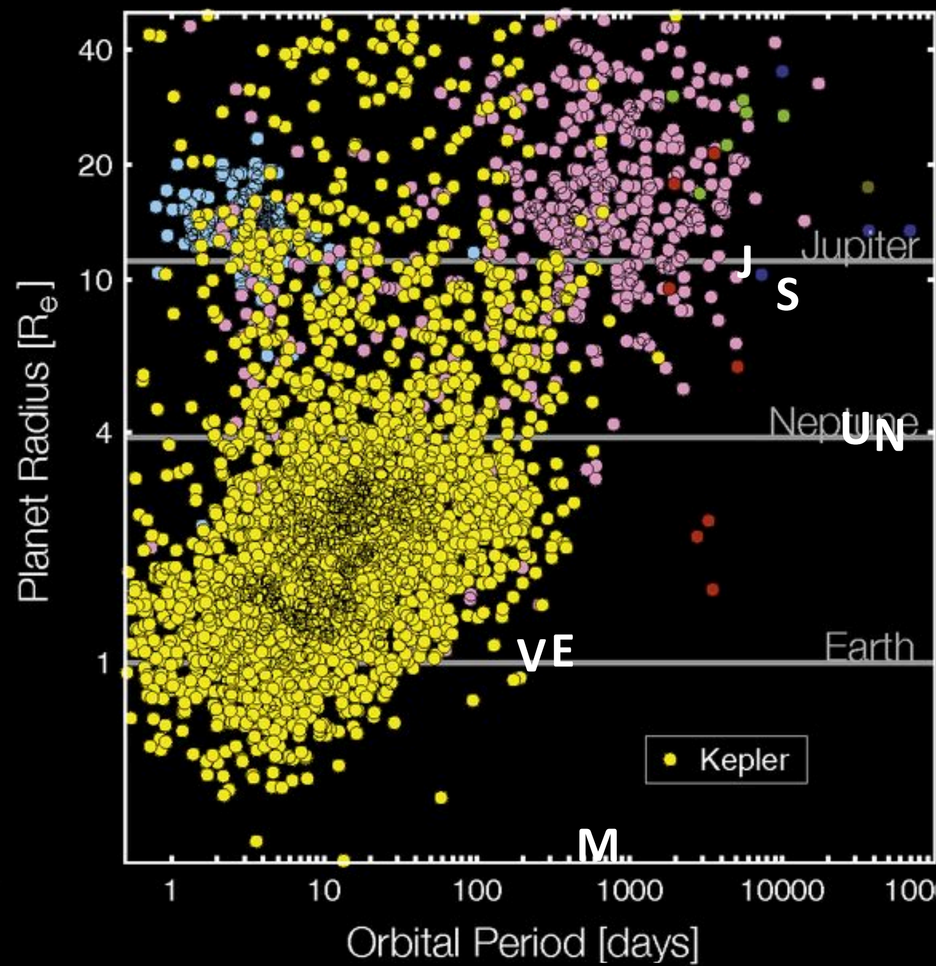
DARK ENERGY • EXOPLANETS • ASTROPHYSICS

Kepler ☹

few solar system analog planets

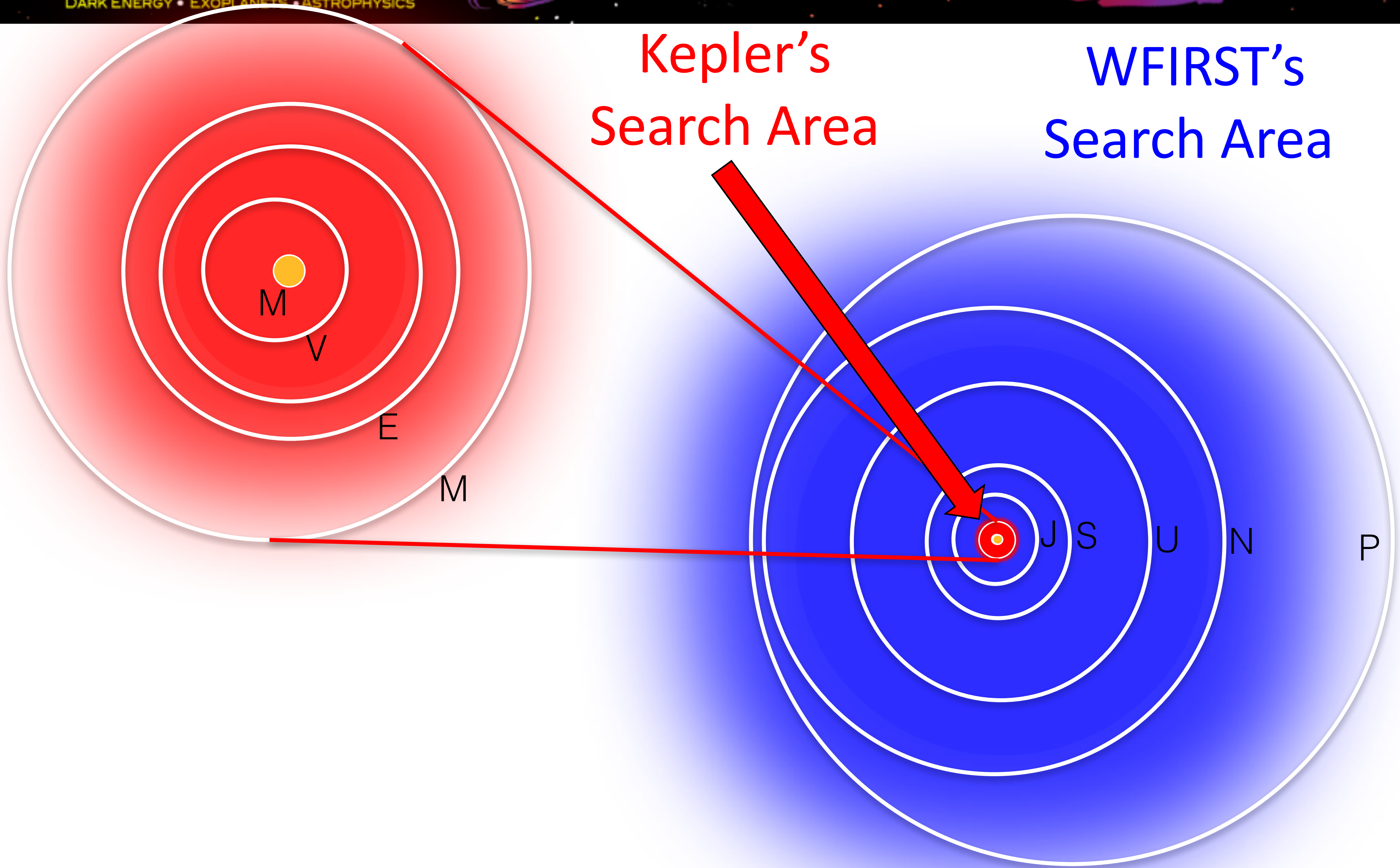




Natalie Batalha

~3502 Confirmed Planets

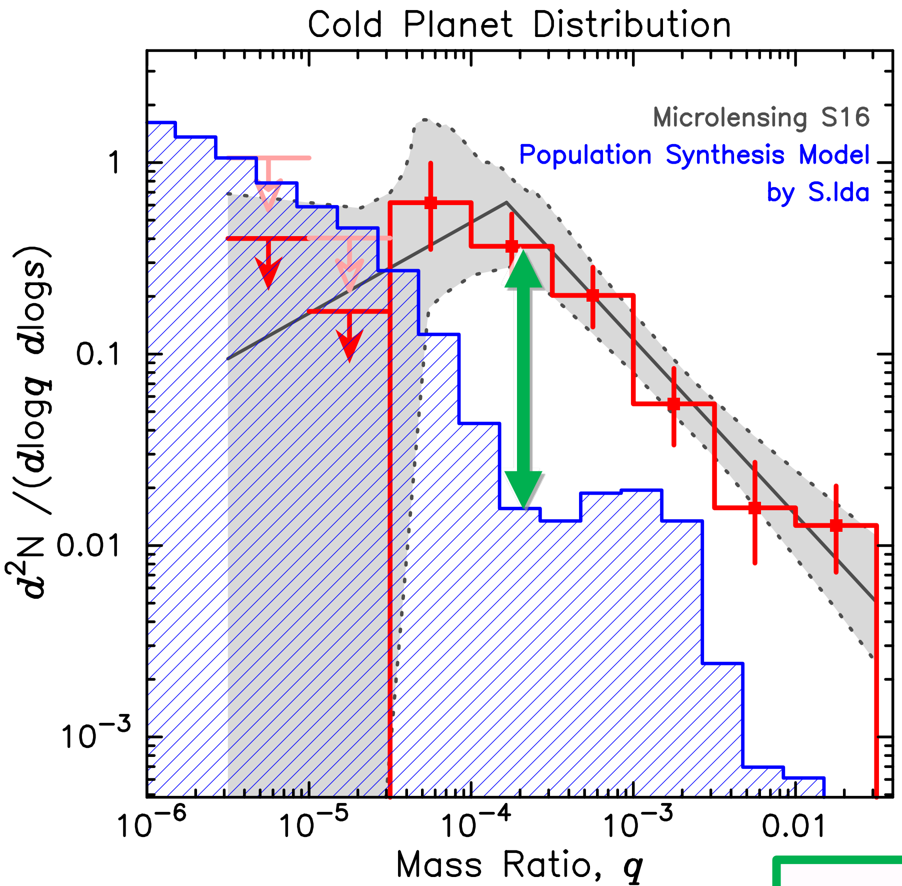
~4496 Kepler Candidates


Kepler's
Search Area
WFIRST's
Search Area
M
V
E
M
J
S
U
N
P

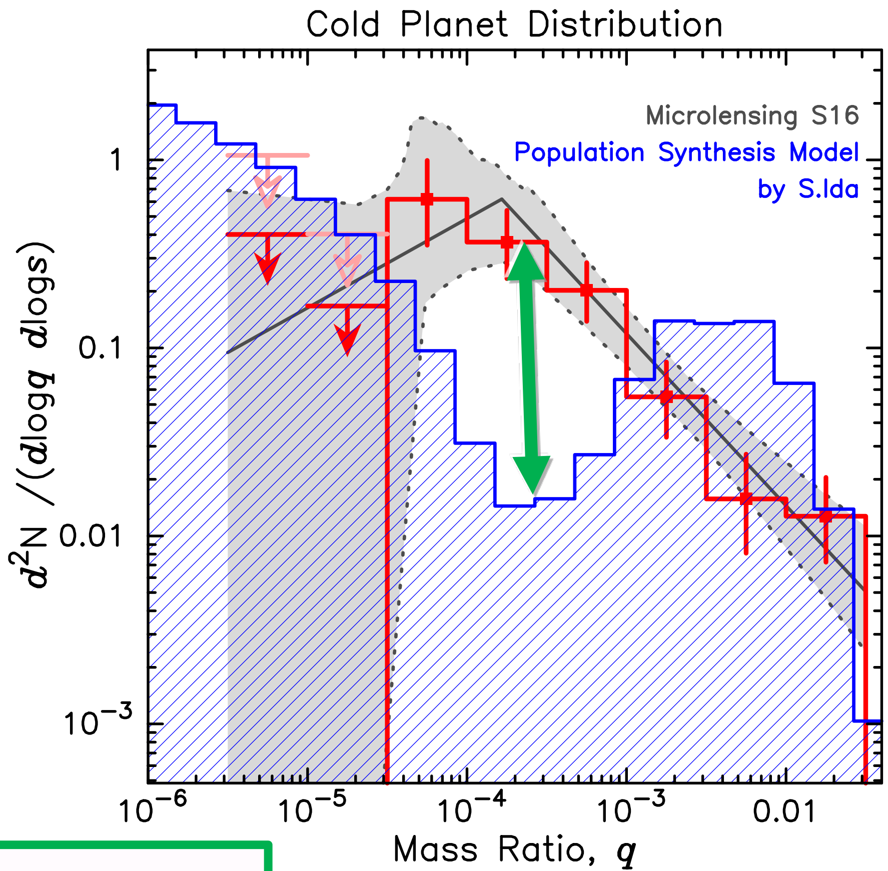
Why complete the census?

- A complete census is likely needed to understand planet formation and evolution.
  - Most giant planets likely formed beyond the snow line.
  - Place our solar system in context.
  - Water for habitable planets likely delivered from beyond the snow line.
  - Understand the frequency of planet formation in different environments.
- Kepler's final estimate of η_{Earth} is likely to have a substantial uncertainty.
- Our understanding of planetary habitability is primitive

Current Results vs. Population Synthesis



"standard migration"

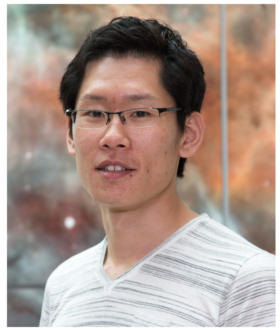


no migration

Factor of 25 discrepancy!

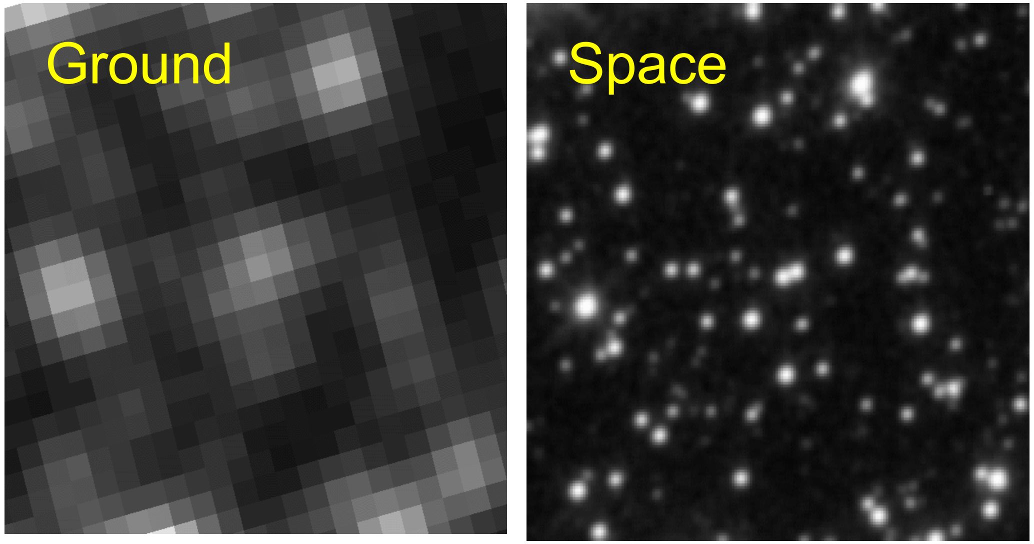
Turning off migration improves the cold planet distribution, but does not generate enough planets at $q \sim 2\text{-}5 \times 10^{-4}$, or about 50 $M_\oplus$

(Bern group results are similar) (Suzuki+18)



Ground vs. Space

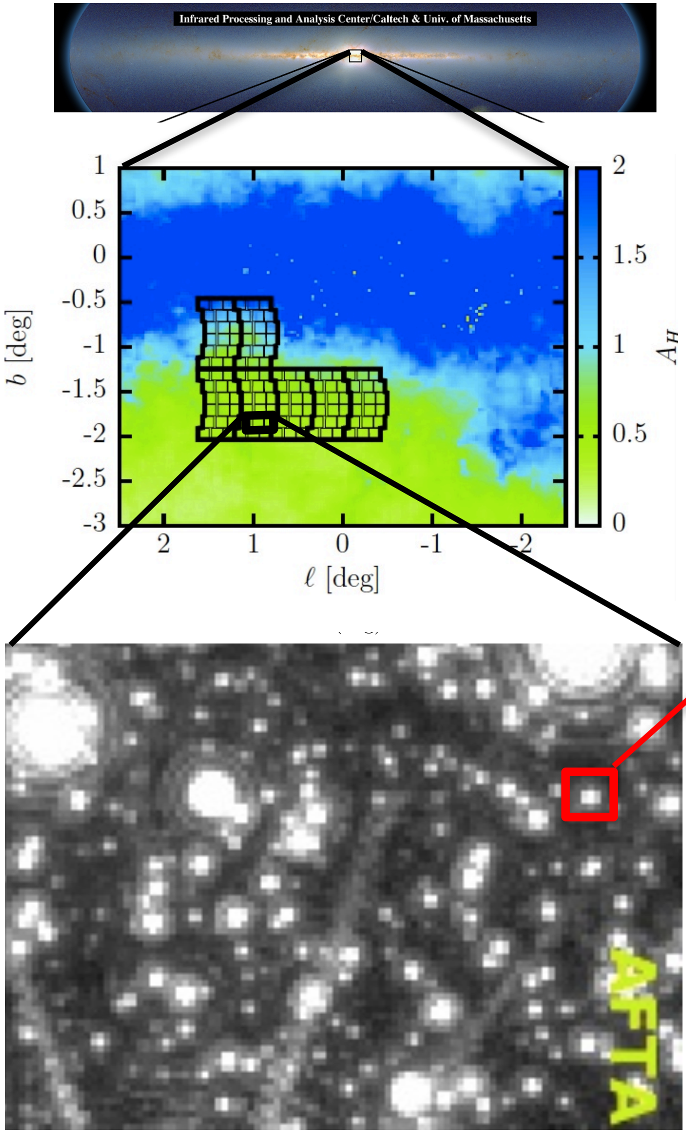
- Infrared.
  - More extincted fields.
  - Smaller sources.
- Resolution.
  - Low-magnification events.
  - Isolate light from the lens star.
- Visibility.
  - Complete coverage.
- Smaller systematics.
  - Better characterization.
  - Robust quantification of sensitivities.

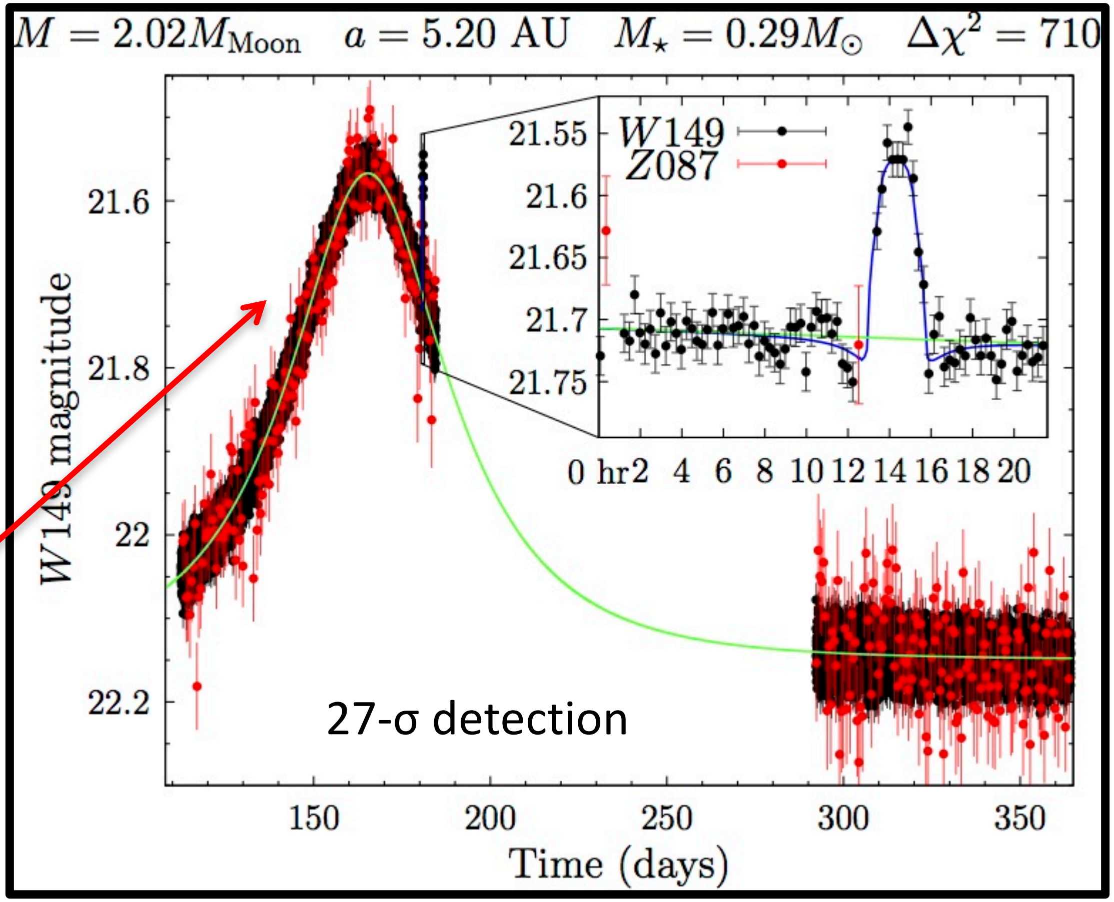


The field of microlensing event MACHO 96-BLG-5 (Bennett & Rhie 2002)

Science enabled from space: completing the census beyond the snow-line, sub-Earth mass planets, habitable zone planets, free-floating Earth-mass planets, routine mass measurements.

WFIRST μLensing Survey Simulations

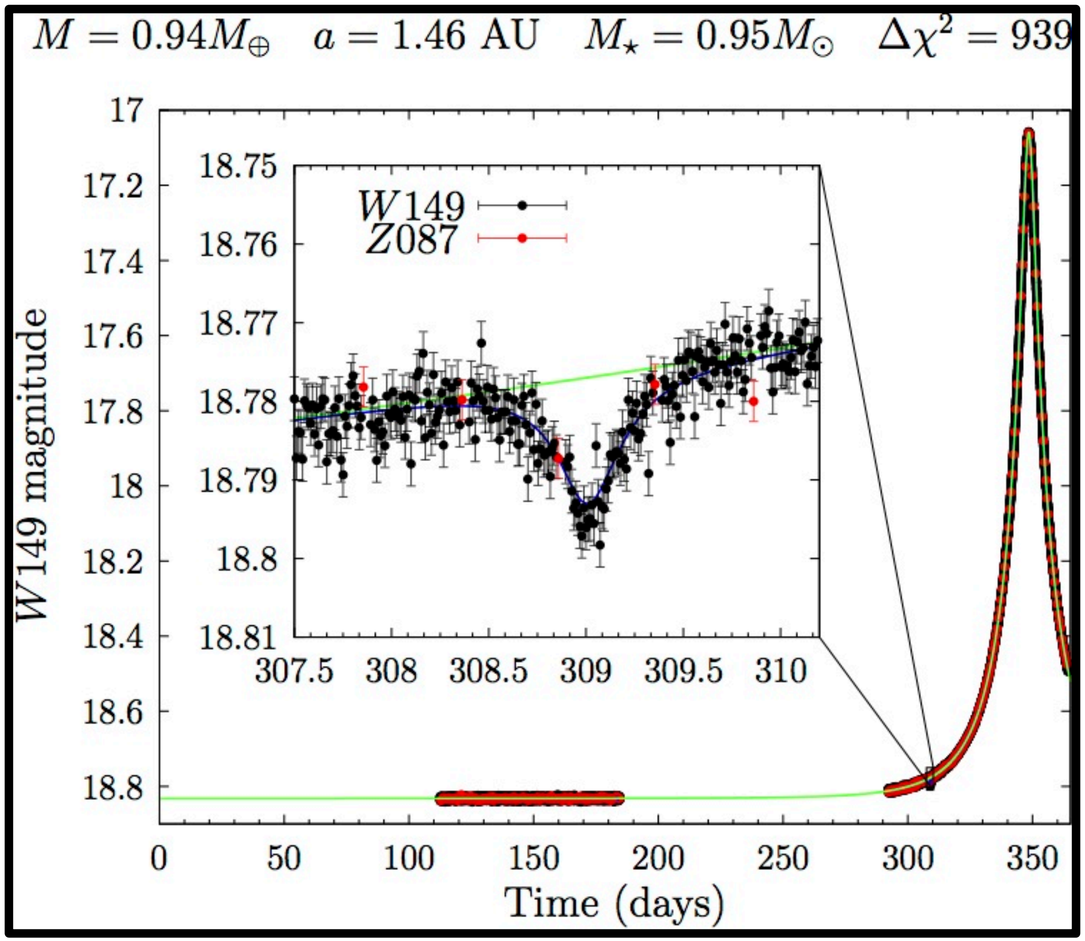




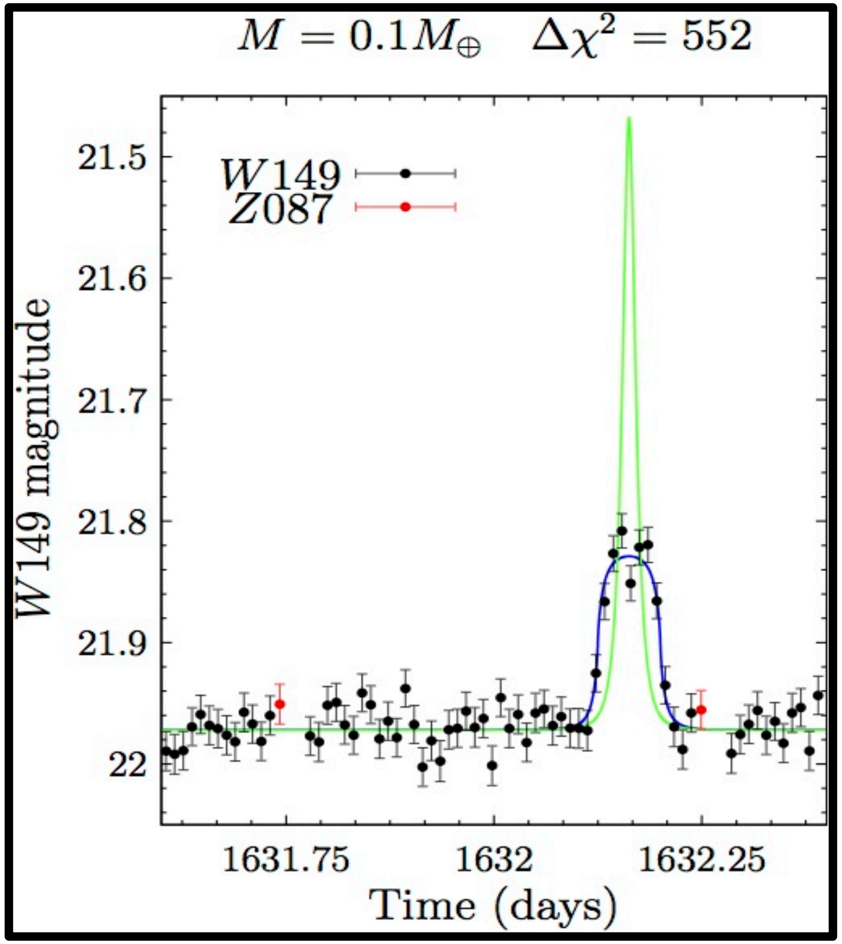
(Penny et al., in prep)

Example Discoveries.

High precision photometry on short timescales enables detection of weaker signals: smaller planets, HZ planets



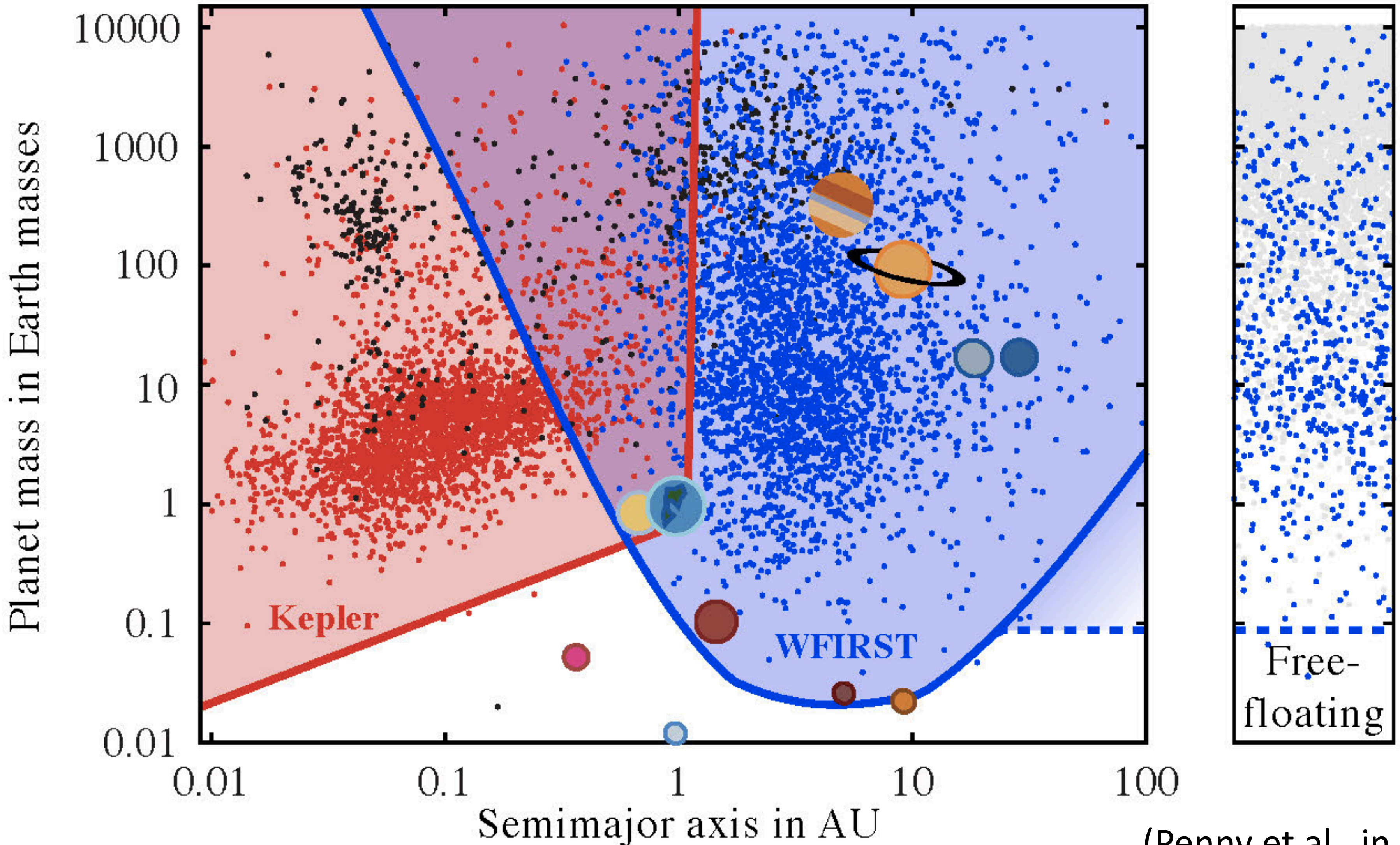
31-σ detection



(Penny et al., in prep)

23-σ detection

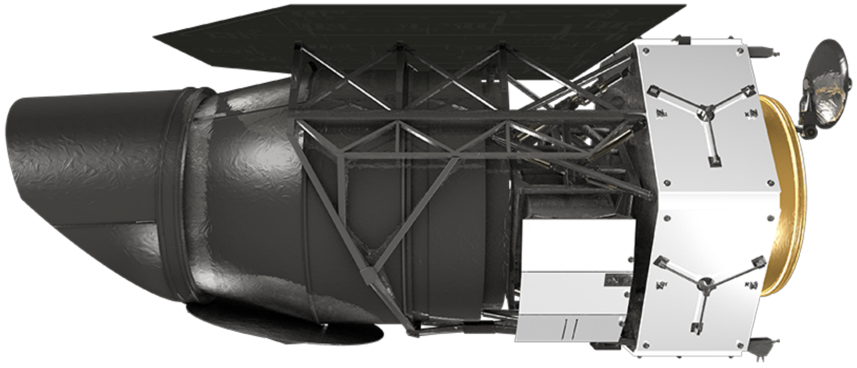
Completing the Census ("Penny Plot")

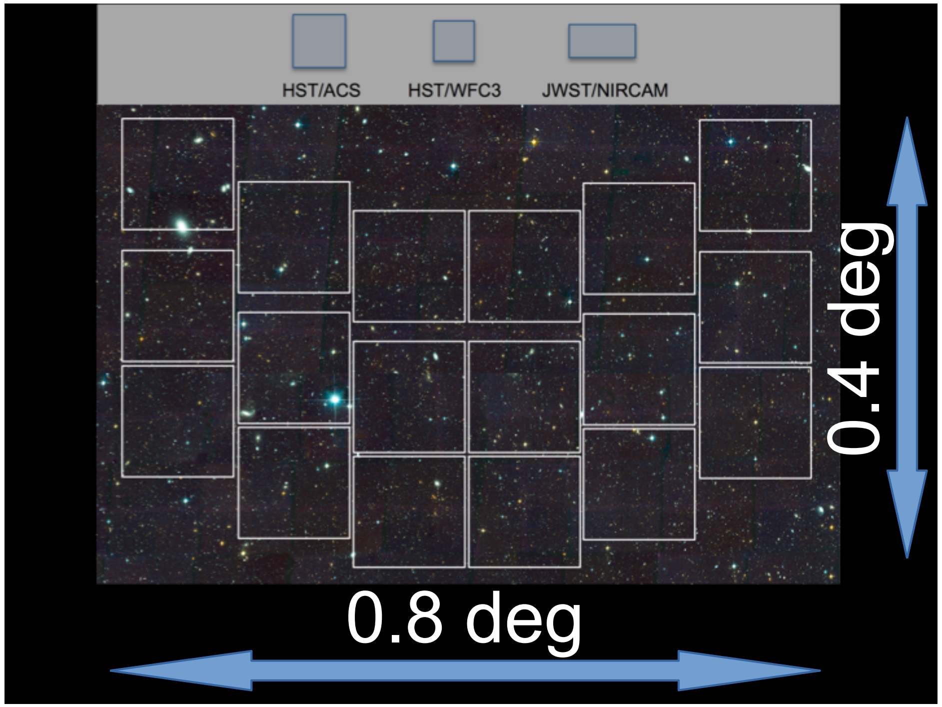


(Penny et al., in prep)

WFIRST

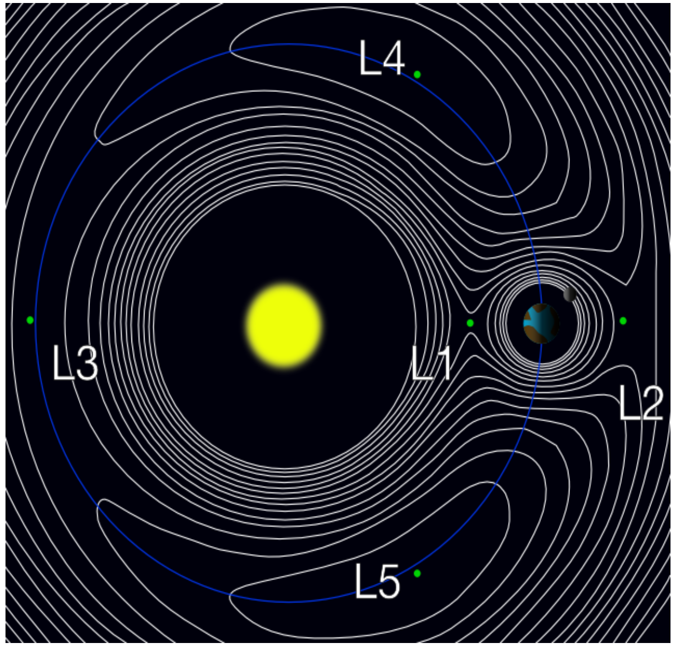
- 2.4 m mirror
- 0.9-2.0 um IR detectors
- 18 4k x 4k H4RGs
- 0.28 deg^2 FoV
- 0.16” FWHM, 0.11” pix
- 5 year mission,
- ~1.2 year microlensing
- cycle over 6 fields every 15 minutes

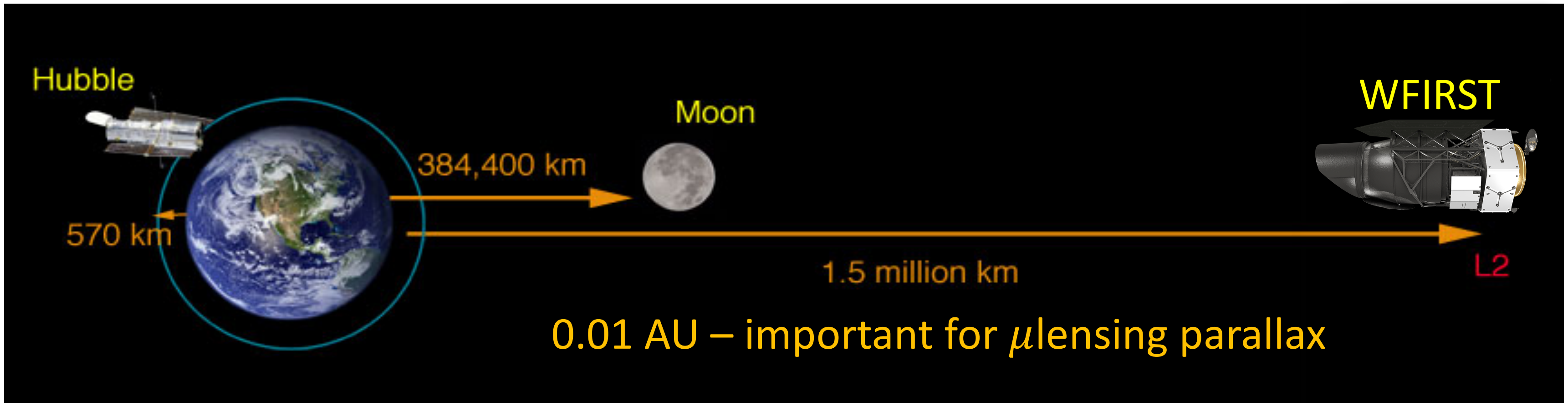




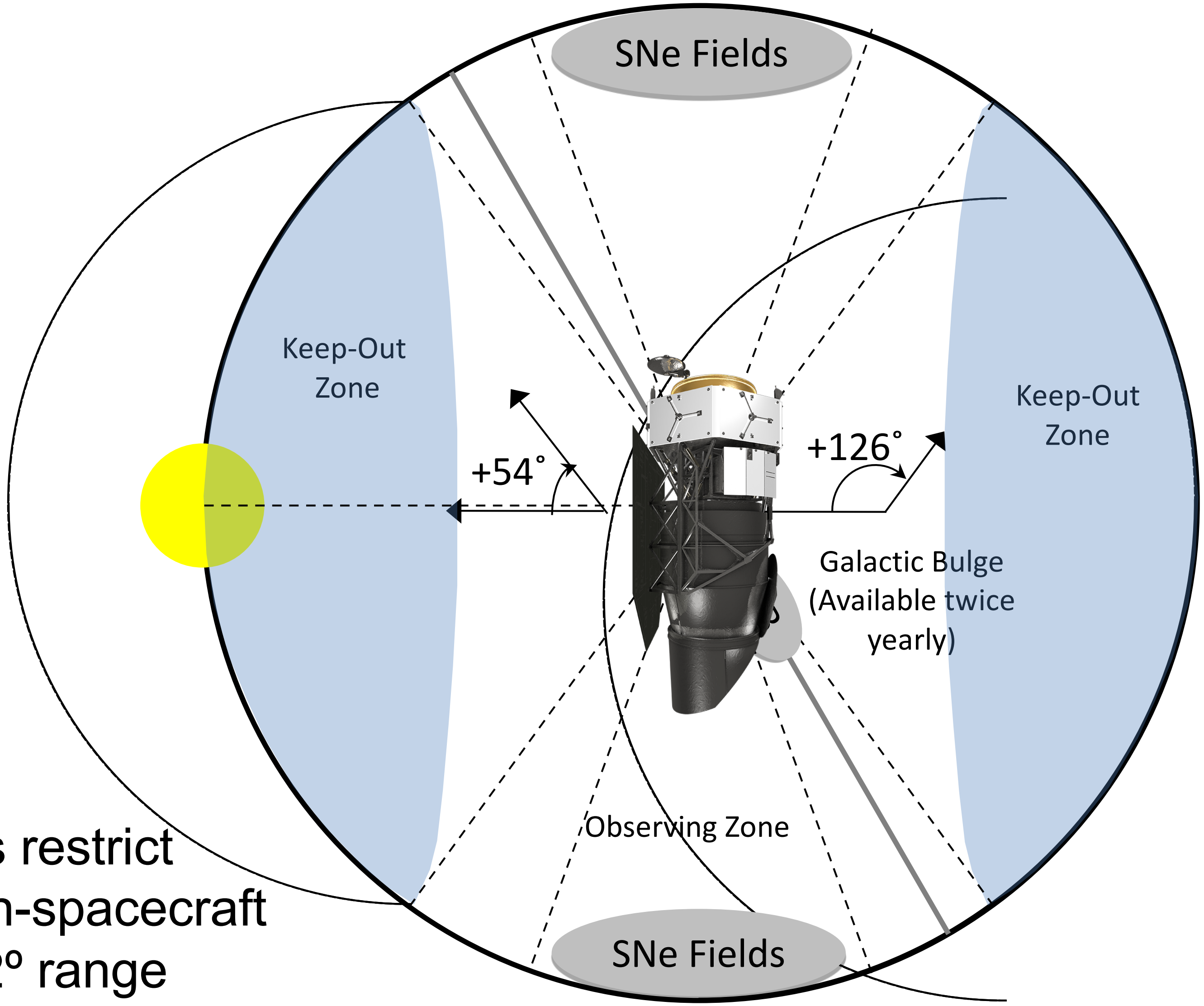
WFIRST's Orbit

- L2 orbit
- Thermally stable
- environment
- But lower data rates
- Planetary microlensing parallax





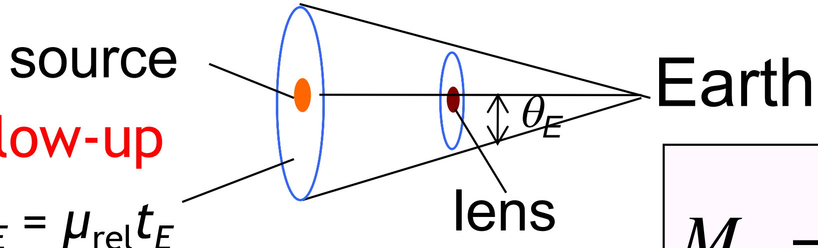
WFIRST's μLensing Seasons



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

Optimal time for microlensing parallax observations: acceleration is ⊥ line-of-sight

2 (of 3) Mass-Distance Relations



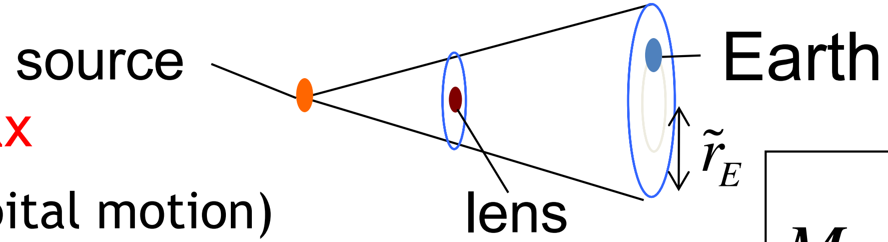
- μ_{rel} - finite source or follow-up

  Angular Einstein radius $\theta_E = \mu_{rel} t_E$

  $\mu_{rel} = \theta_* / t_*$ θ_* = source star angular radius

  D_L and D_S are the lens and source distances

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



- Microlensing Parallax

  (Effect of Earth's orbital motion)

  Einstein radius projected to observer, $\tilde{r}_E$

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

OR

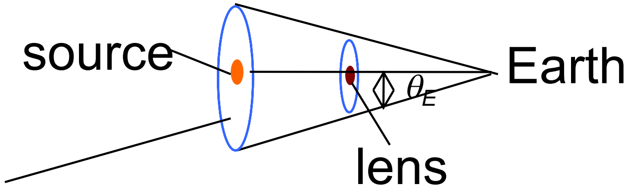
- One of above +

  Lens brightness & color(AO,HST)

  mass-distance relation → D_L

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

Any 2 of 3 Mass-Distance Relations Give Mass and Distance



- **Finite source effect or lens-source proper motion:**

  Angular Einstein radius $\theta_E = \theta_* t_E / t_*$

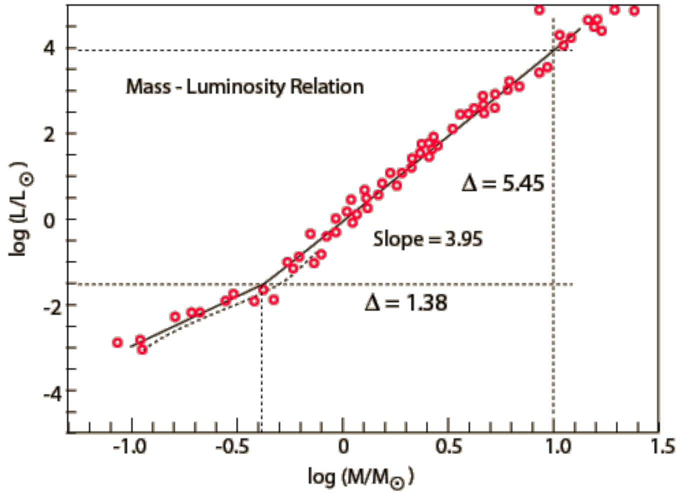
  θ_* = source star angular radius

  D_L and D_S are the lens and source distances

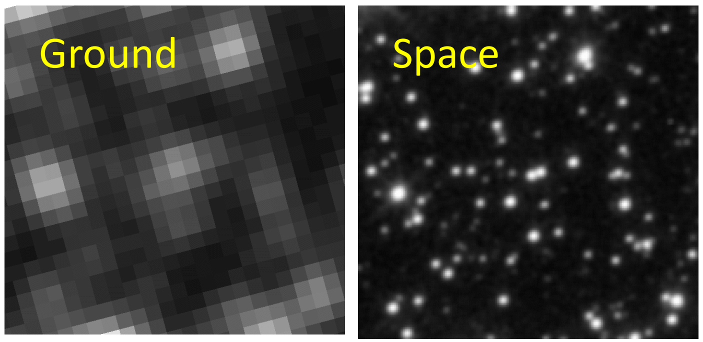
$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

- **Lens brightness from high resolution image used in Mass- Luminosity relation**

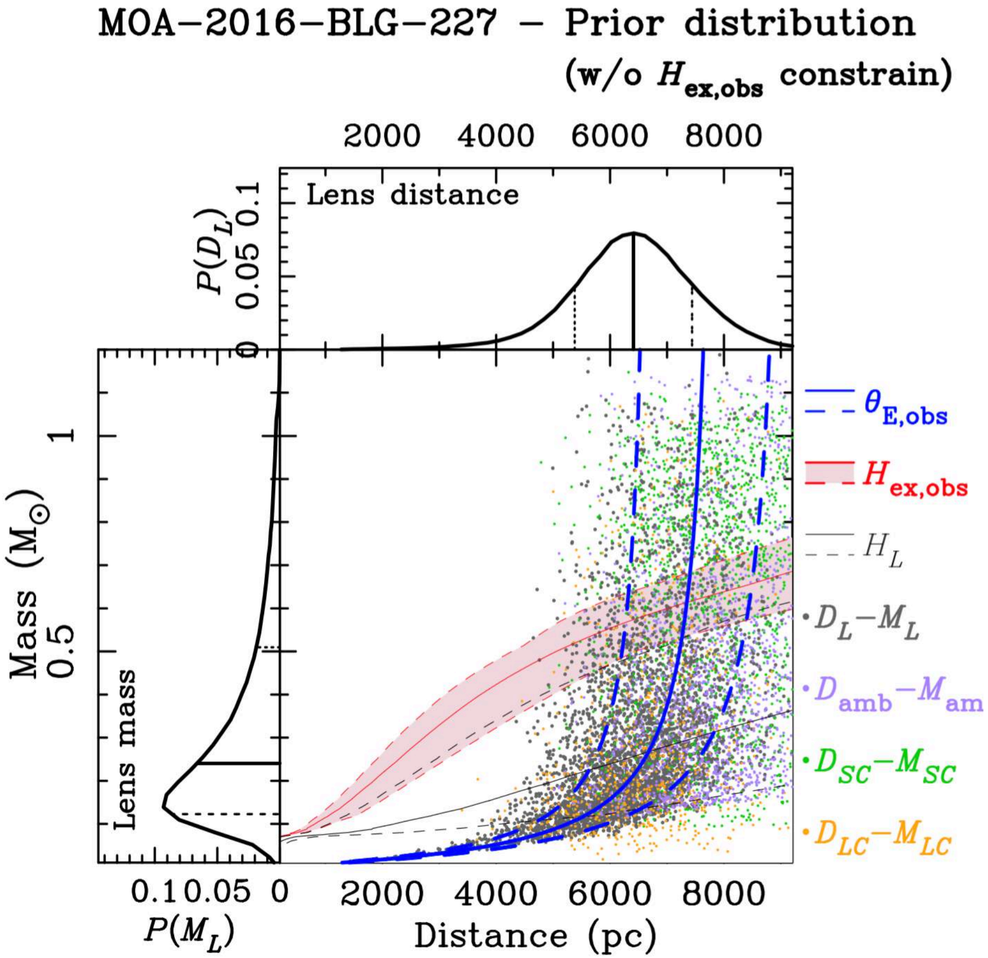
  mass-distance relation ➔ D_L , M_L

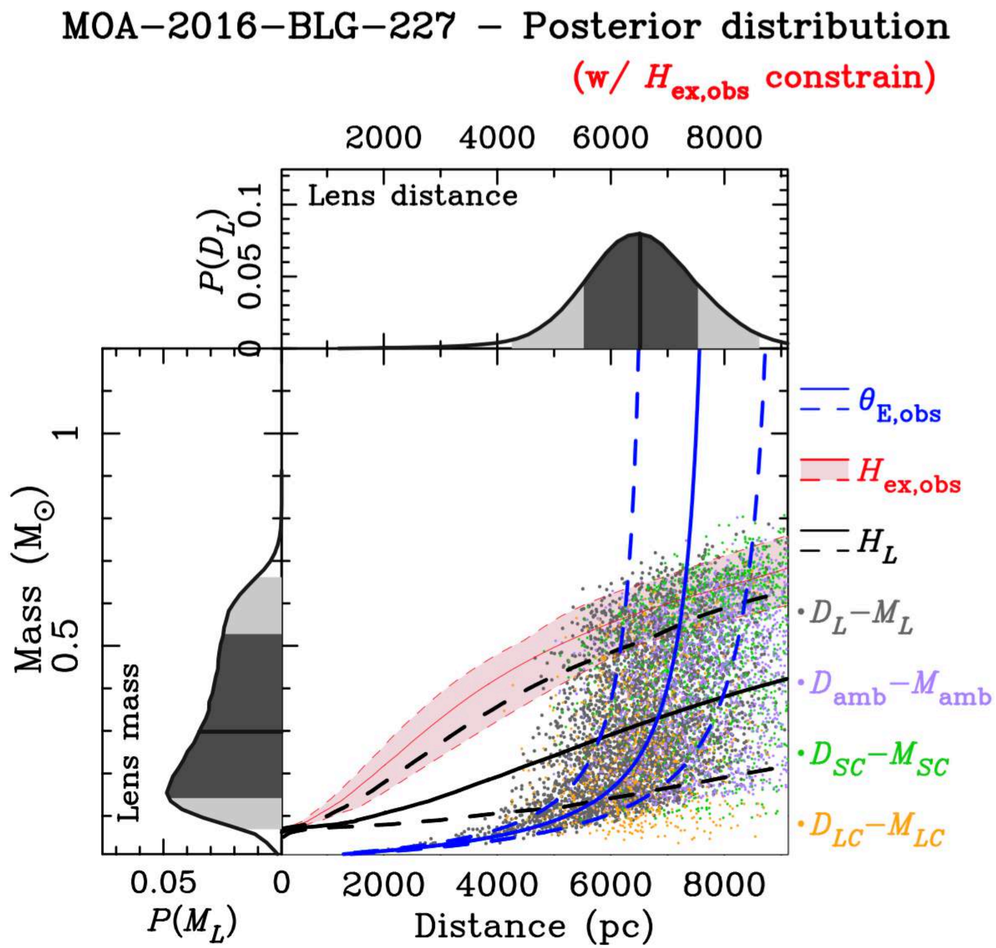


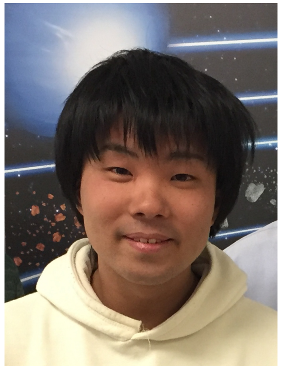
- Lens-source relative proper motion is key to lens star identification
- Independent measurement in every passband
- Seeing limited image don't help



Bayesian Analysis of Excess Flux





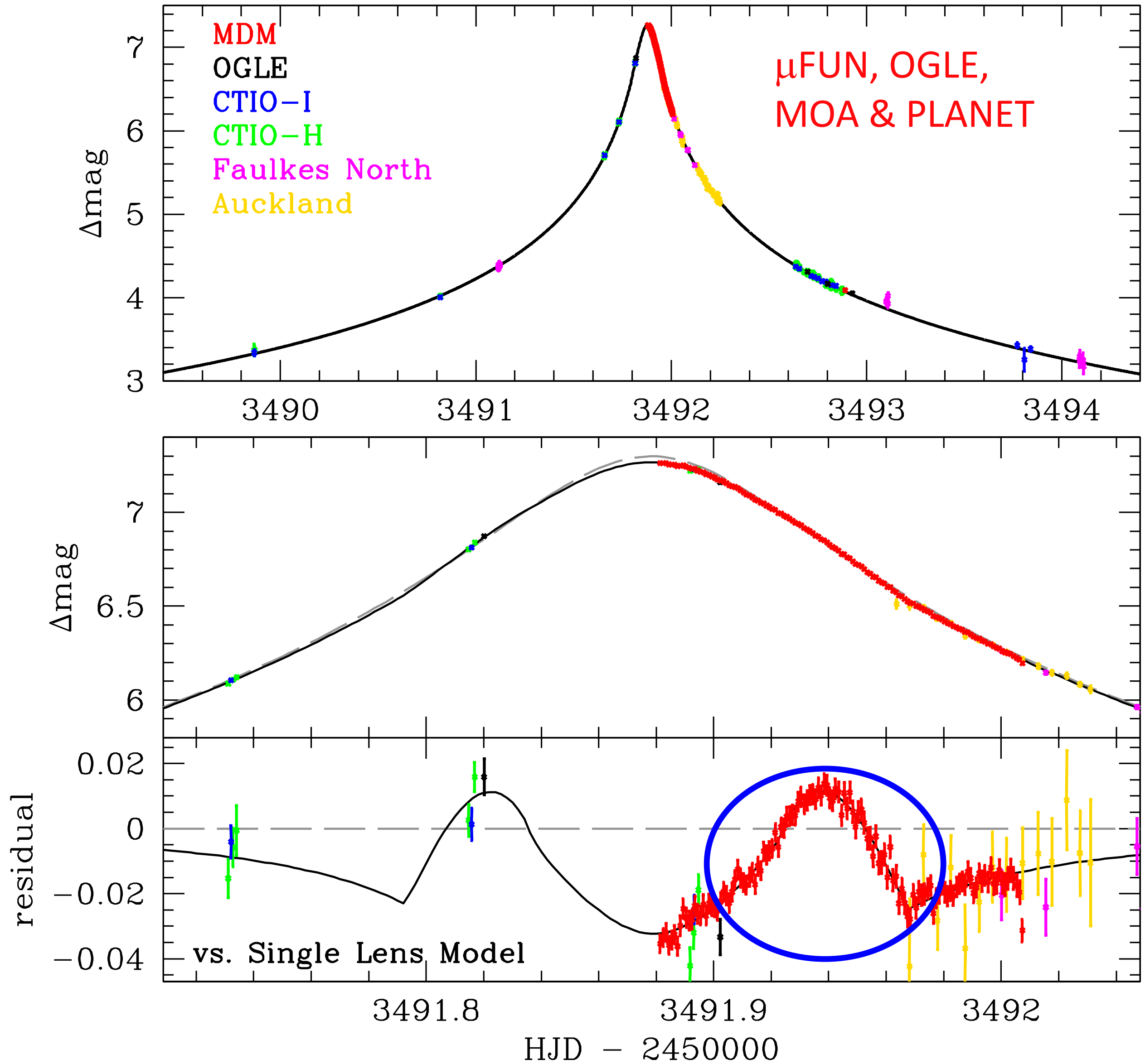


The lens star is always blended with the source, but there can be companions to the lens and source or even ambient stars

Naoki Koshimoto et al. (2017)

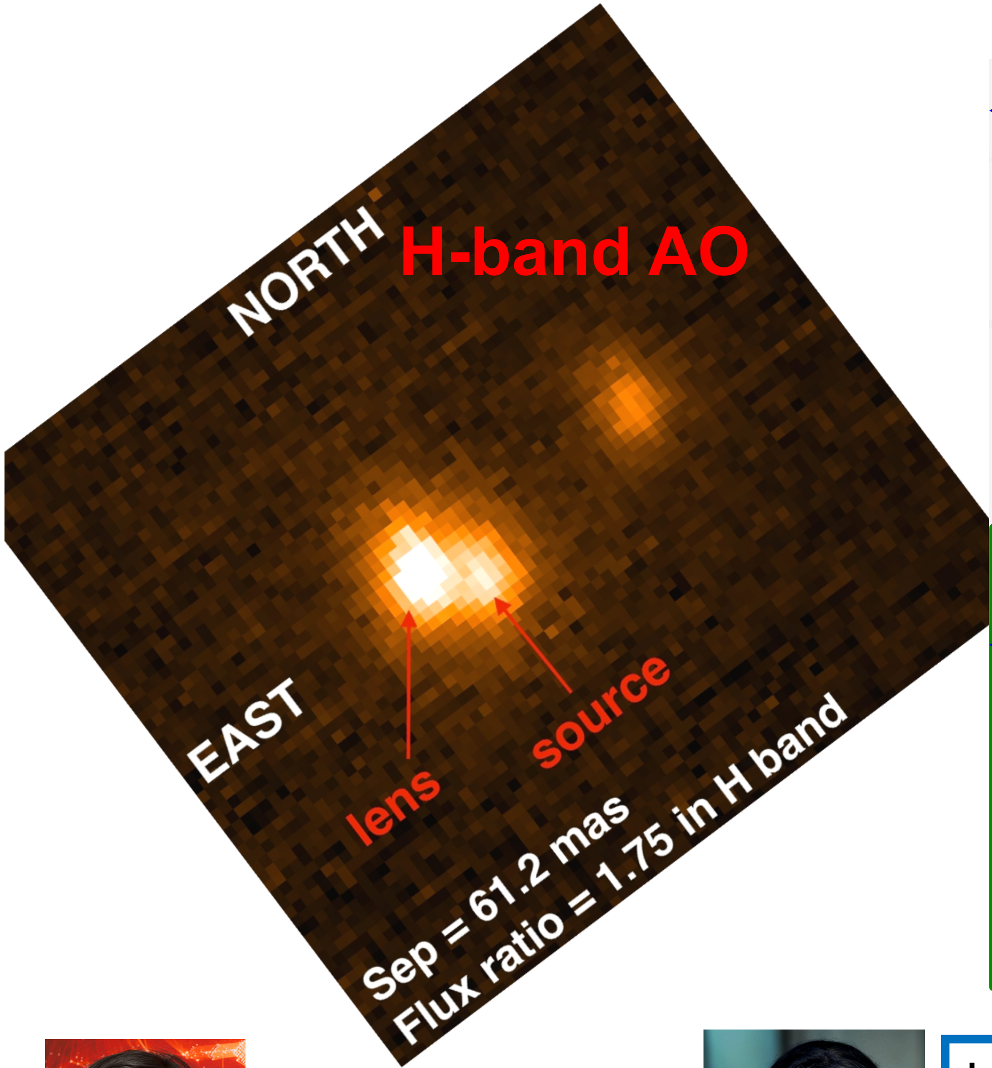
Planetary Feature Confirmed

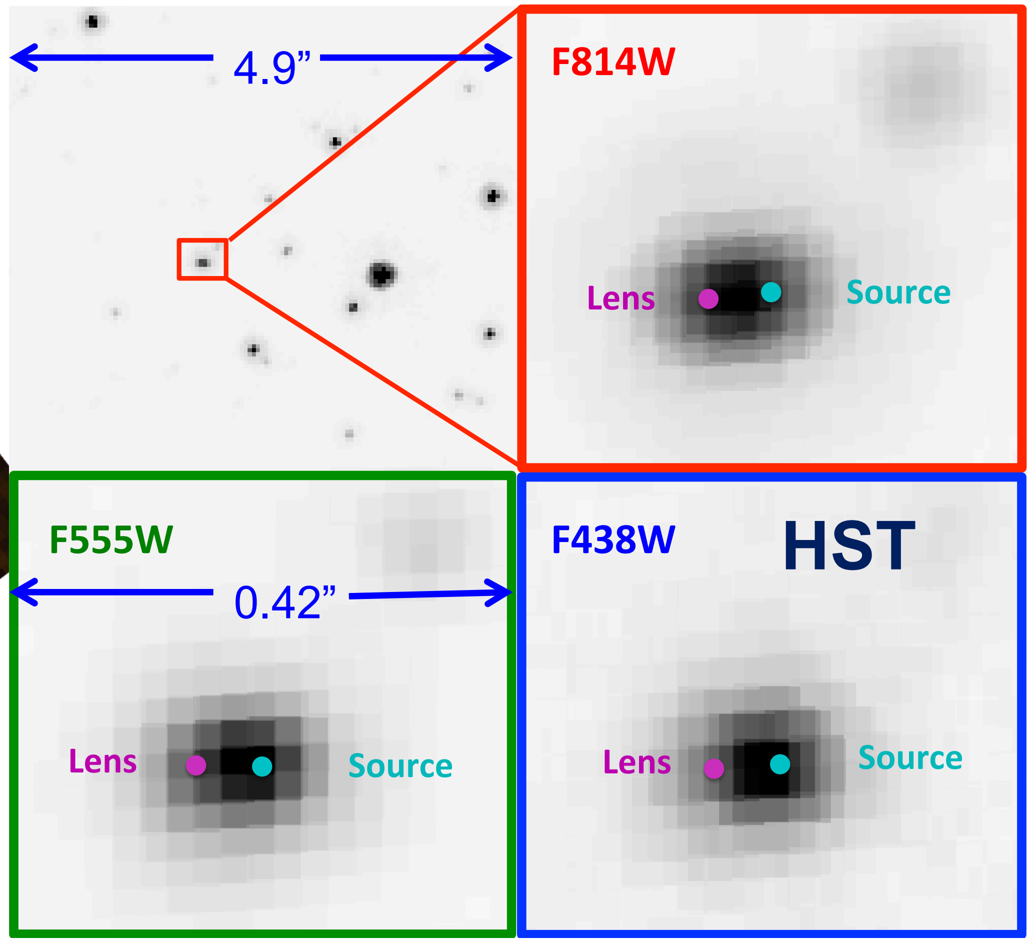
OGLE-2005-BLG-169Lb



This feature plus fit source brightness and color yields lens-source relative proper motion (angular velocity), μ_{rel}

Confirm Lens-Source Separation & Lens ID





Bennett et al. 2015
Keck result:
Batista et al. 2015

Aparna Bhattacharya

Virginie Batista

HST images 6.5 yrs after event and Keck AO images 8.3 yrs after event confirm prediction

$$M_* = 0.69 \pm 0.02 M_\odot$$
$$m_p = 14.1 \pm 0.9 M_\oplus$$
$$a_\perp = 3.5 \pm 0.3 \text{ AU}$$
$$a_{3d} = 4.0^{+2.2}_{-0.6} \text{ AU}$$
$$D_L = 4.1 \pm 0.4 \text{ kpc}$$

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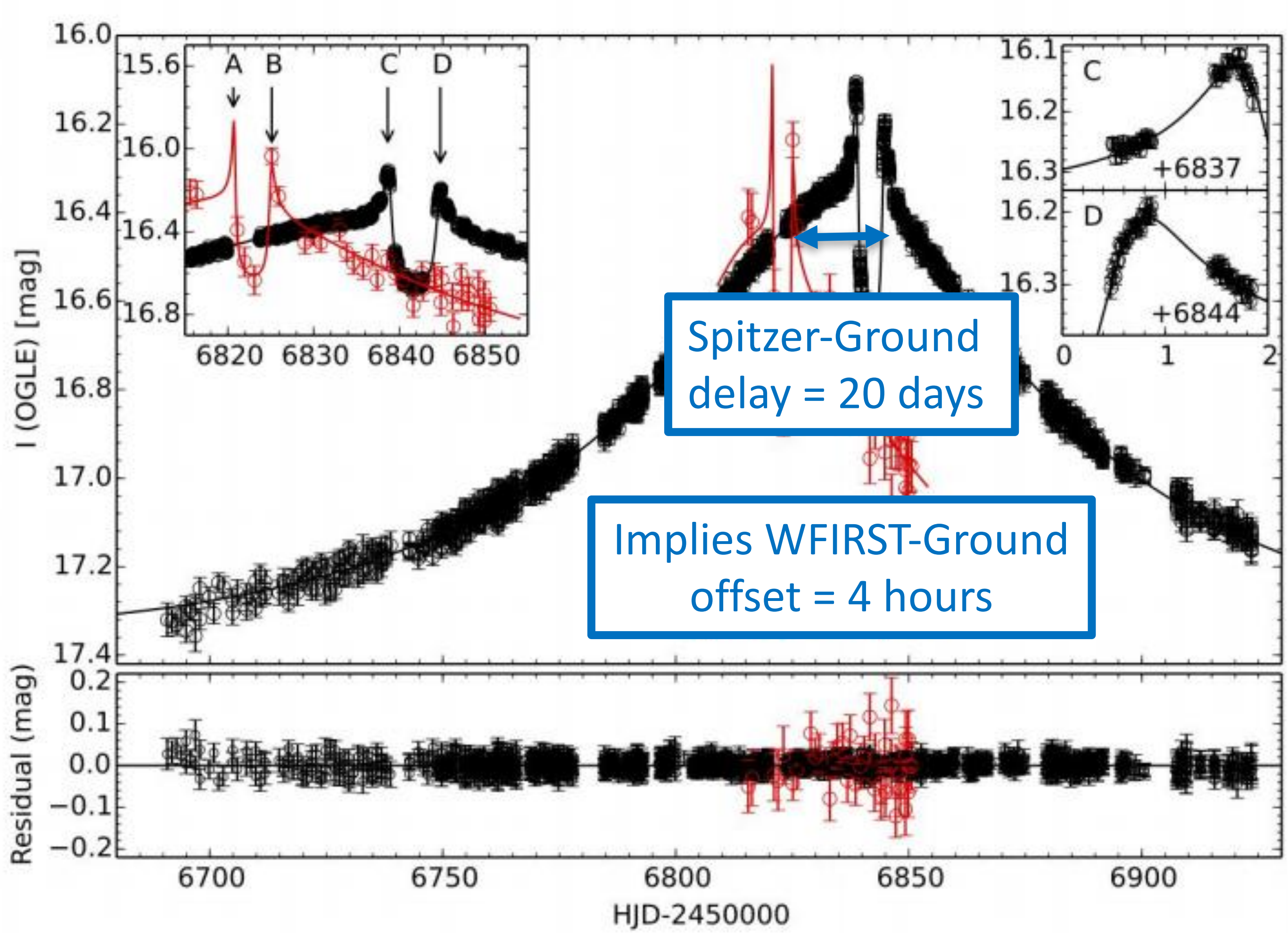
SPITZER Microlens parallax for OGLE-2014-BLG-0124L

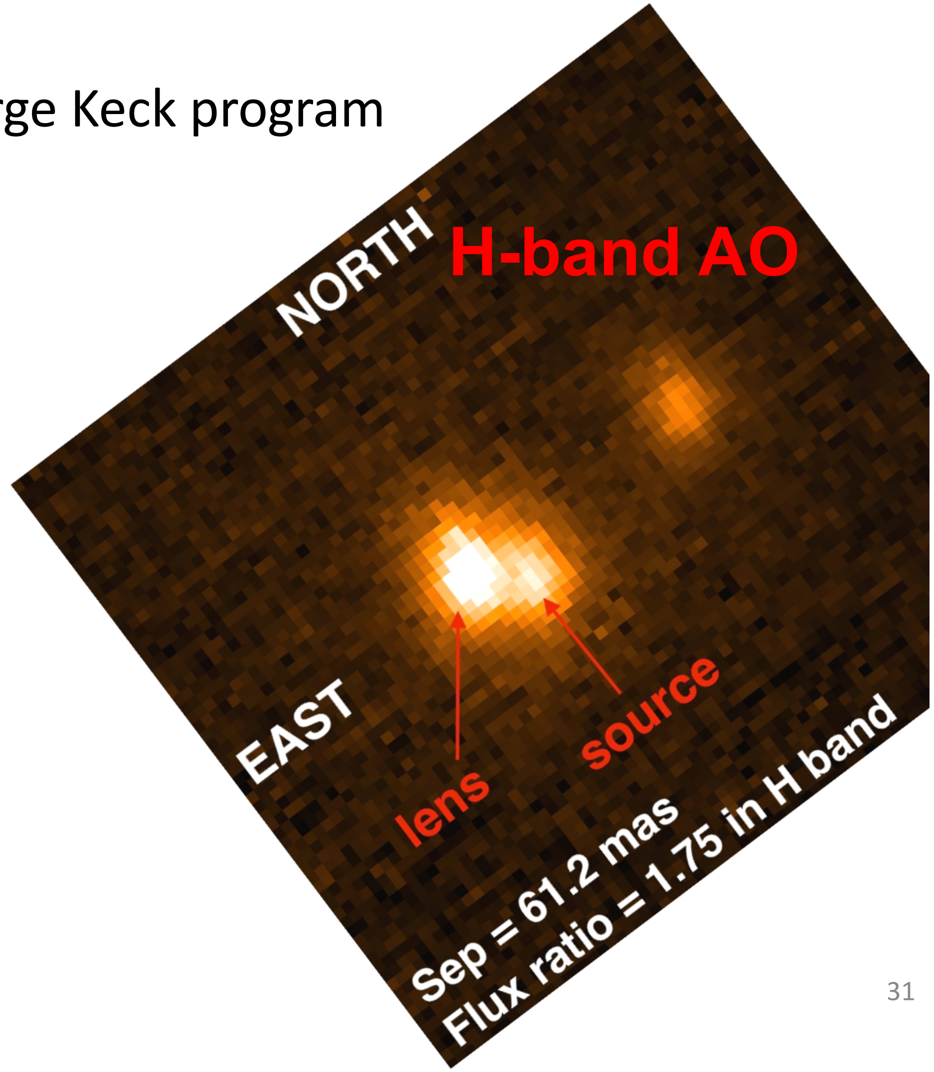


Udalski, et al., 201

~20 day offset between signals w/ Spitzer at 1.2 AU from Earth => 4 hour offset with WFIRST's 0.01 AU separation. A 4 hour offset will reveal microlensing parallax for **planets**, not stars!

Subaru Precursor Observations 1

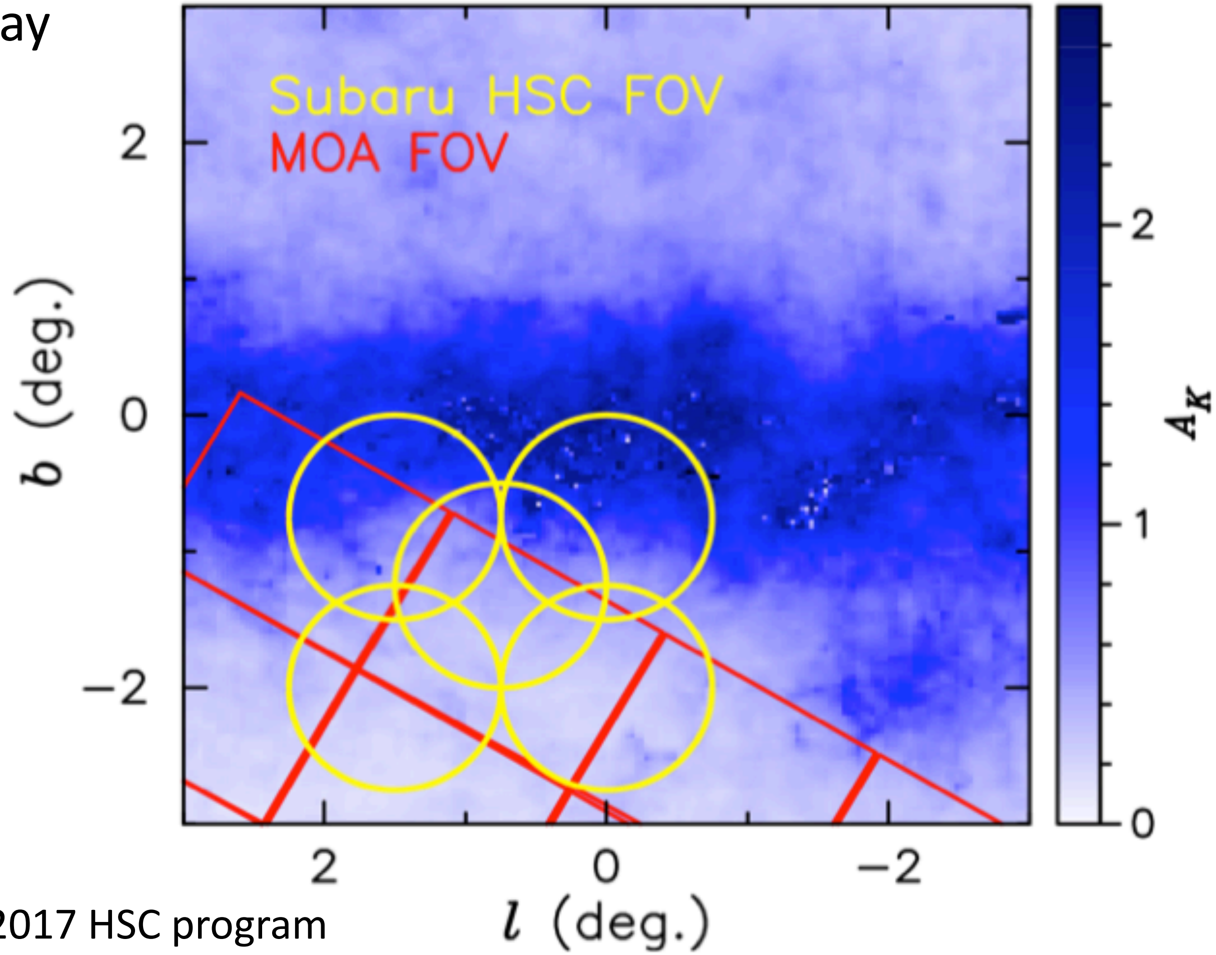
- Follow-up AO Observations of known planetary and stellar binary events to develop the WFIRST mass measurement method
- Best with improved AO system that can get to diffraction limit in K and H (under good conditions).
- 2020 or later (due to current large Keck program

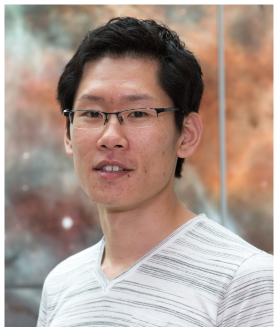


Akihiko Fukui
leads Subaru effort

Subaru Precursor Observations 2

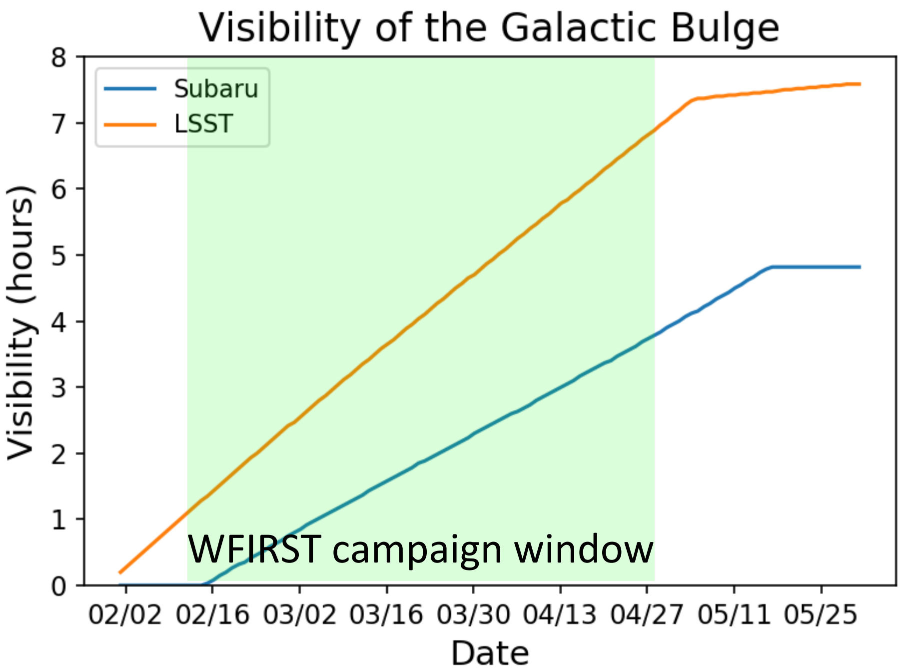
- Multi-band HSC Imaging of candidate WFIRST Microlensing fields
  - Mulit-wavelength calibration of stars in the fields
  - Use multi-wavelength data to estimate extinction
  - Will be used to aid field selection
- Already underway

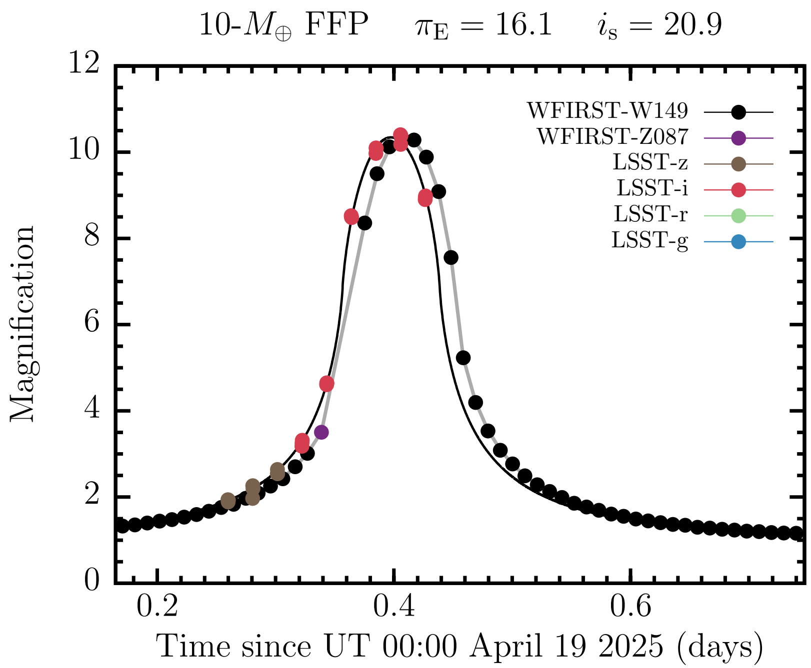




Suzuki – 2017 HSC program

Simultaneous HSC & WFIRST Imaging





- We propose simultaneous imaging with both LSST & Subaru HSC
  - 15-30 minute cadence
- WFIRST – LSST & Subaru microlensing parallax is only way to measure mass of free-floating planets
- WFIRST observing seasons are optimal for parallax signal, but not ground-based observations
- Only a small fraction of free-floating planets can be observed from the ground, but even weak detections will be useful.
- The only way to provide alerts – WFIRST will not have rapid alerts

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Exoclipse 2028

- WFIRST Exoplanet Microlensing Results
- Alice Springs, Australia
- July, 2028
- See you down under!

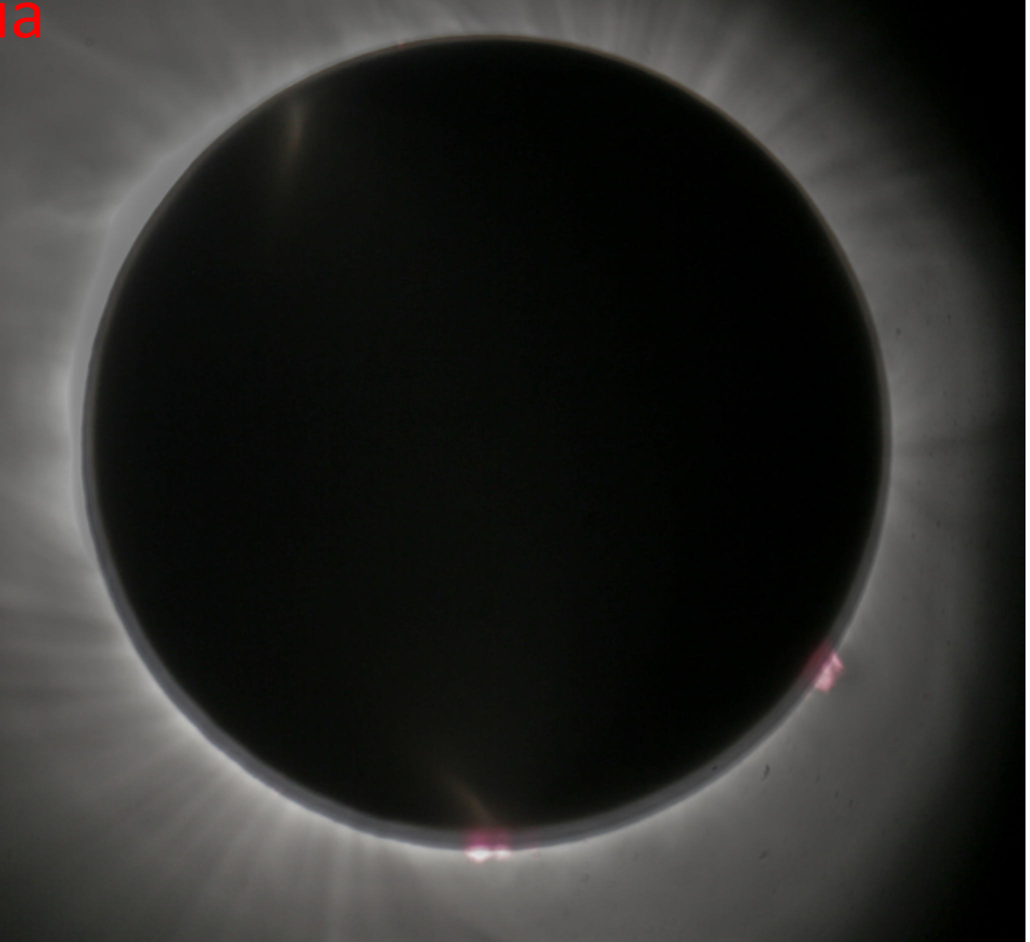

Photo by Radek Poleski taken at Exoclipse 2017