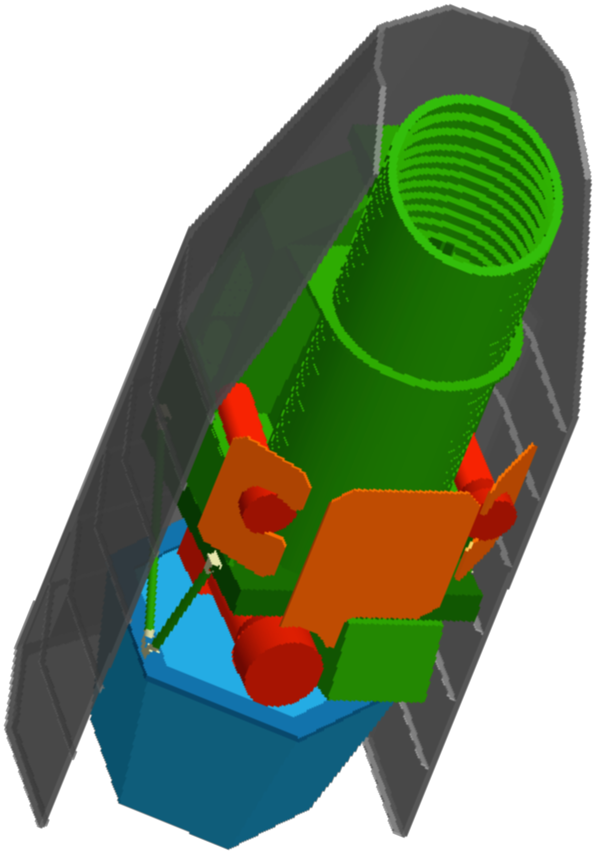
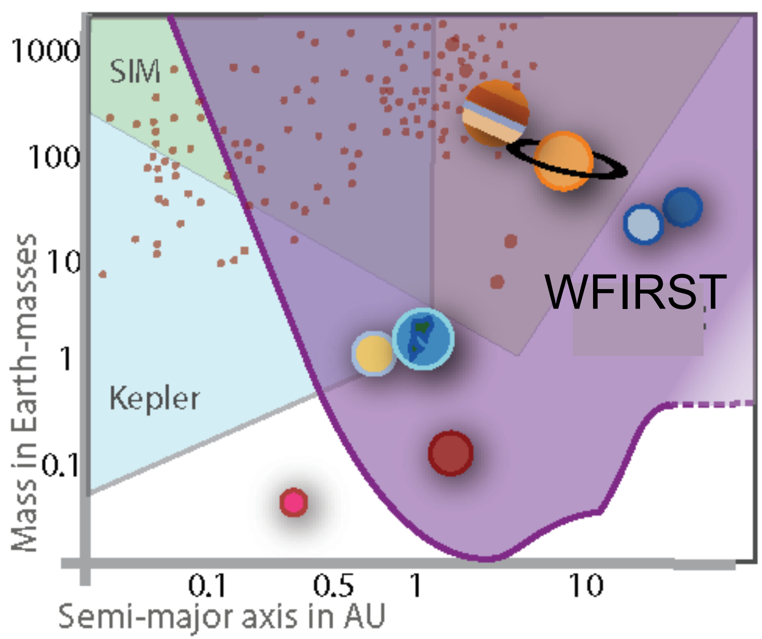
Implementation of a Space-Based Exoplanet Microlensing Survey

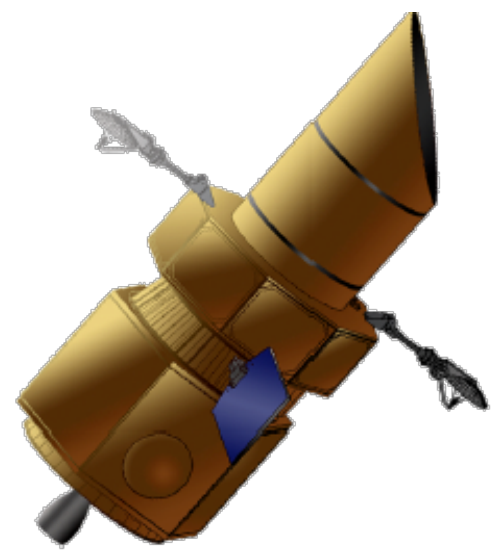


David Bennett

University of Notre Dame

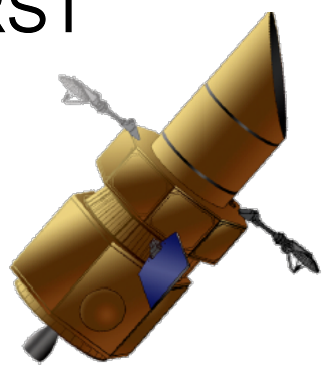
WFIRST
Wide-Field Infra-Red Survey Telescope





Space-based Exoplanet Microlensing

- Microlensing Planet Finder (MPF) was the cheapest of the 3 proposed missions combined to make WFIRST



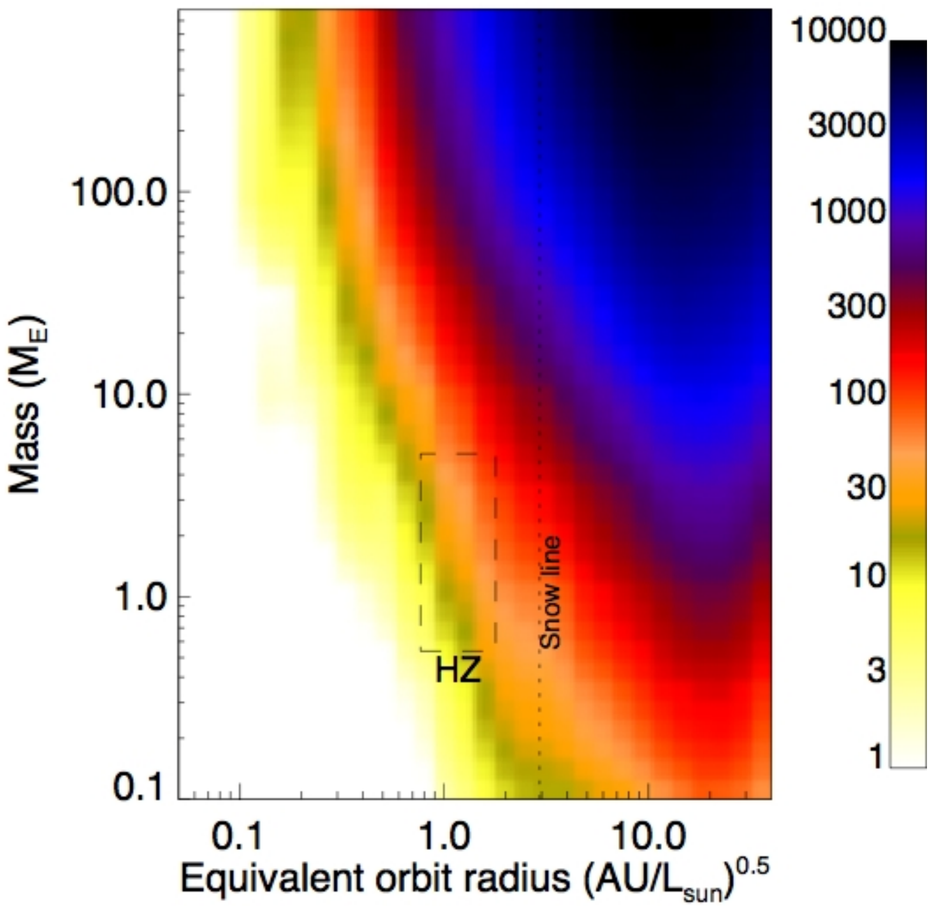
- 2006 Discovery Review
  - passed TMC review with “medium risk” rating
  - $425M cost cap (MPF was $396M w/ Delta-2 ELV)
  - 1.1m TAM, 35 H2RG detectors, but low performance specs
  - Did we fool them?
- Exoplanet Microlensing requirements are generally less stringent than requirements for other programs
- Microlensing requirements can probably be imposed as tweaks on a Dark Energy mission

Exoplanet Microlensing Requirements

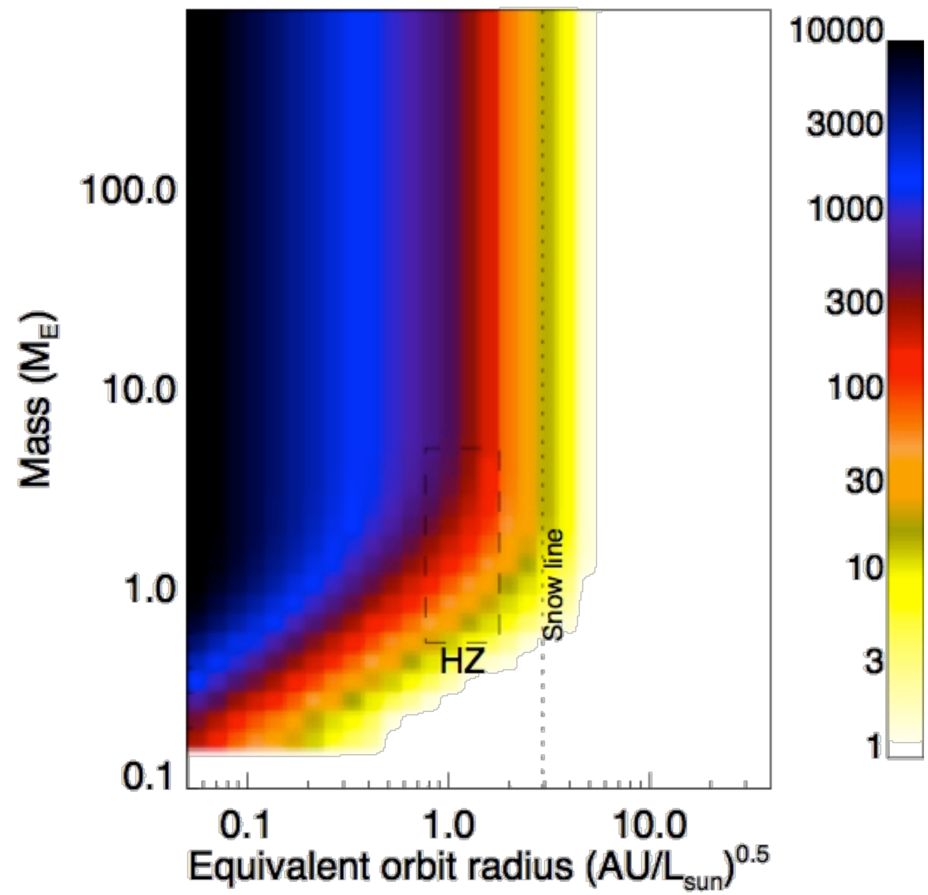
- Observe 100's of millions of main sequence star-years in the central Galactic bulge
  - microlensing rate ~(star density)^2
- Sampling interval ~15 minutes to sample main sequence star radius crossing time
- Moderate precision photometry, 0.2-1% depending on star brightness
- Measure masses of most host stars (and therefore planets)
  - implies that most lens stars must be detected and lens-source relative proper motion of ~5mas/yr must be measured
- Decent sampling of ~month-long stellar lensing events
- None of these requirements can be precisely stated because they can all can be traded against each other
- Instead, we can set a requirement on the sensitivity to Earth-mass planets in 2-year orbits, and other survey requirements will follow

WFIRST vs. Kepler

WFIRST – w/ extended mission



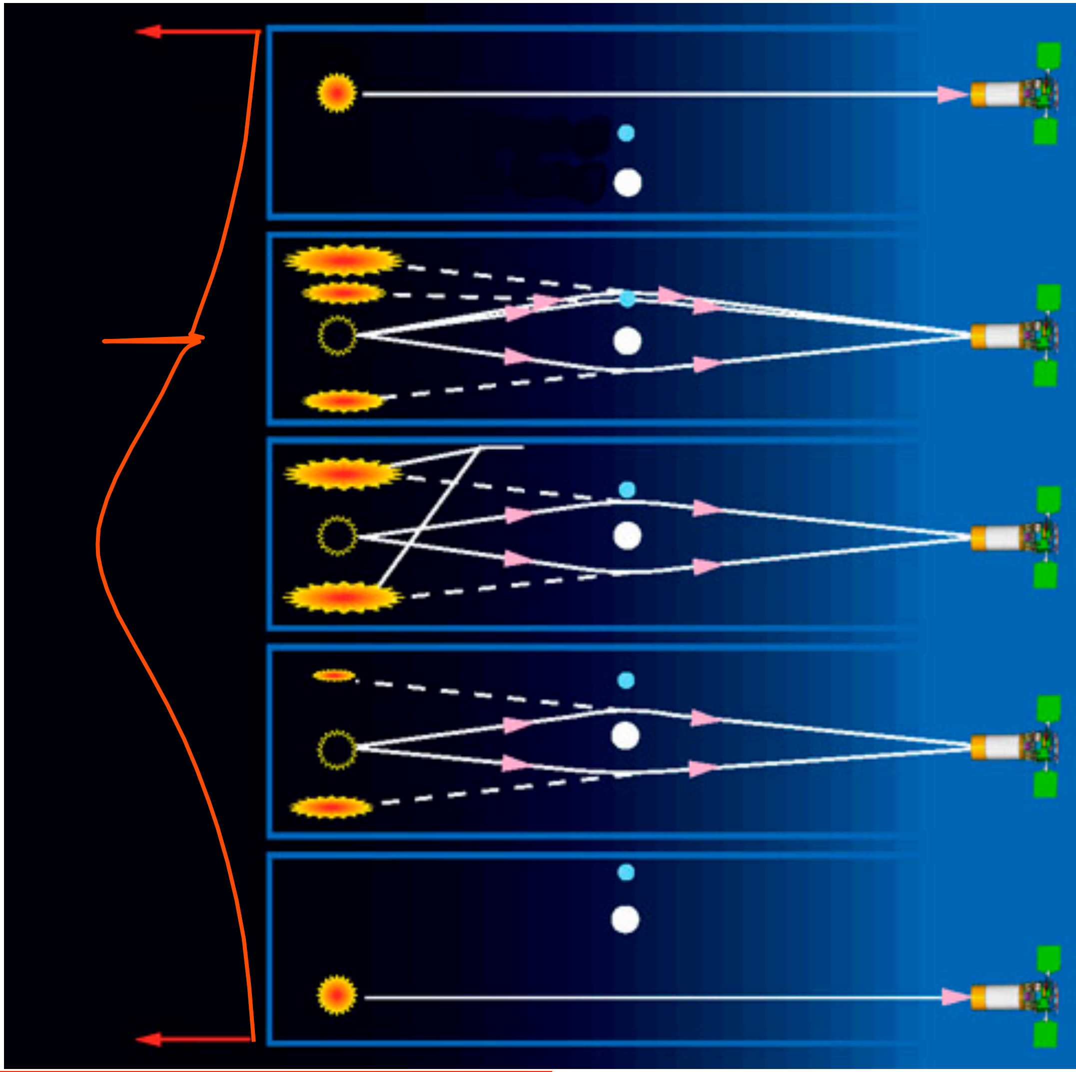
Kepler ~12 yr mission



Figures from B. MacIntosh of the ExoPlanet Task Force

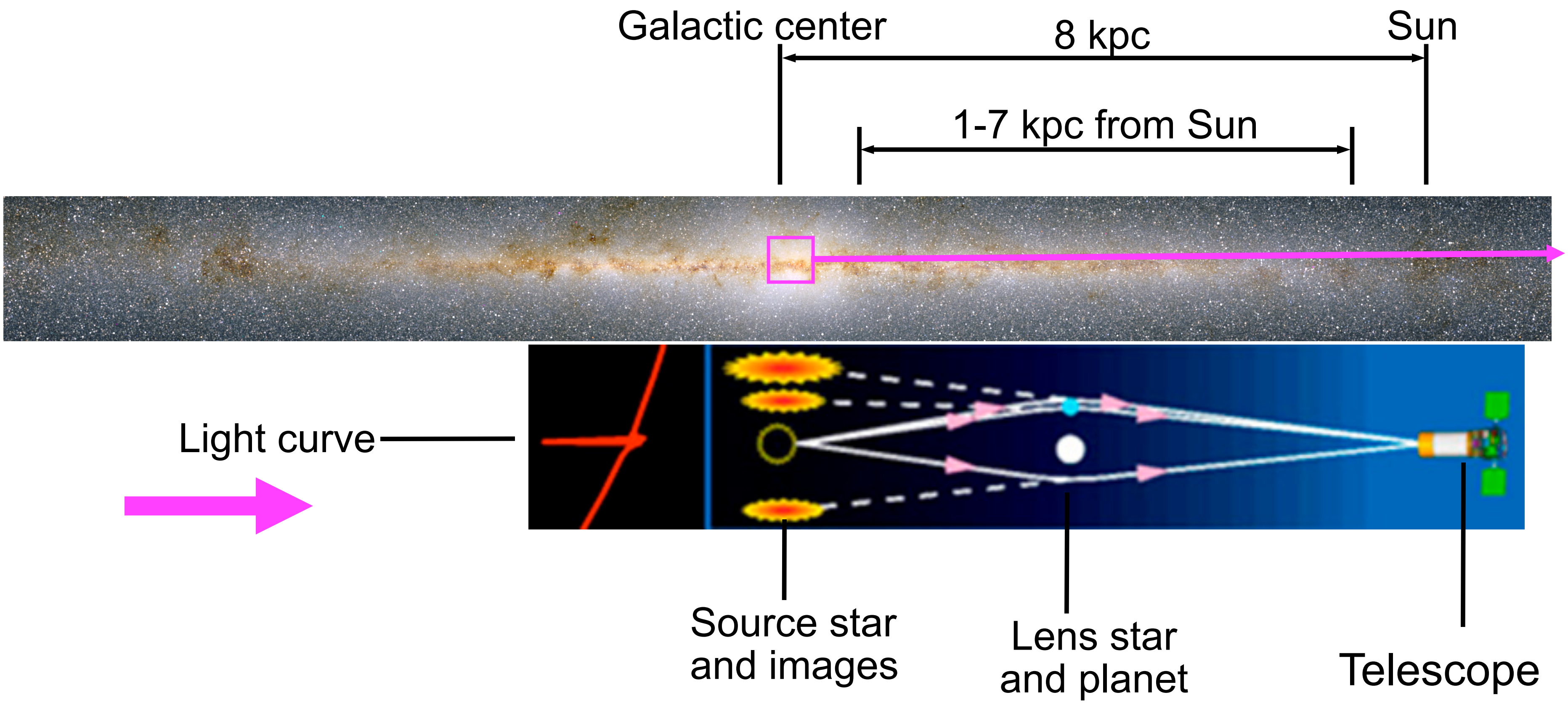
The Physics of Microlensing

- Foreground "lens" star + planet bend light of "source" star
- Multiple distorted images
  - Only total brightness change is observable
- Sensitive to planetary mass
- Low mass planet signals are rare – not weak
- Stellar lensing probability ~a few $\times 10^{-6}$
  - Planetary lensing probability ~0.001-1 depending on event details
- Peak sensitivity is at 2-3 AU: the Einstein ring radius, R_E



Key Fact: $1\ \text{AU} \approx \sqrt{R_{Sch} R_{GC}} = \sqrt{\frac{2GM}{c^2} R_{GC}}$

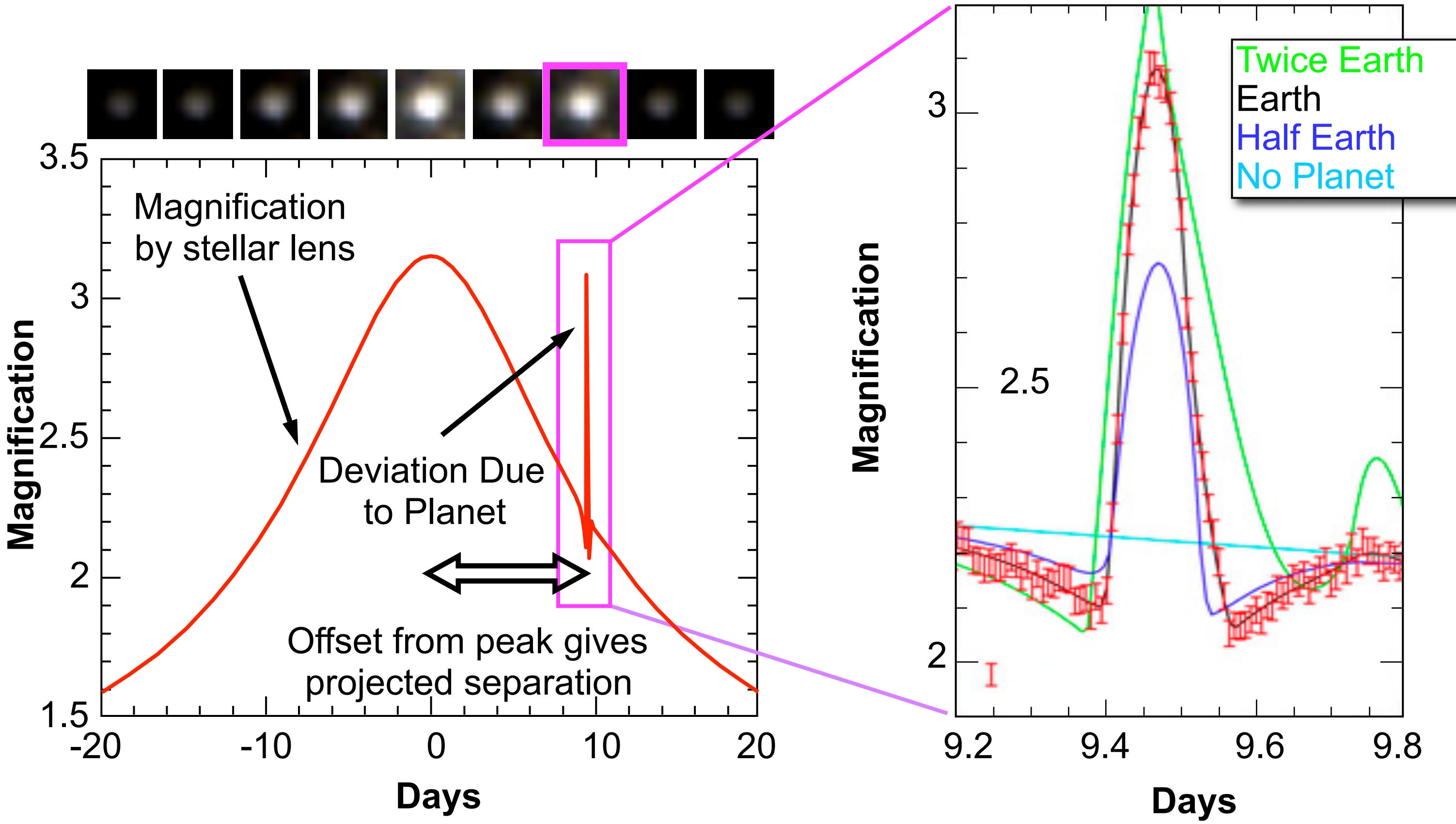
Microlensing Target Fields are in the Galactic Bulge



10s of millions of stars in the Galactic bulge in order to detect planetary companions to stars in the Galactic disk and bulge.

Extraction of Exoplanet Signal

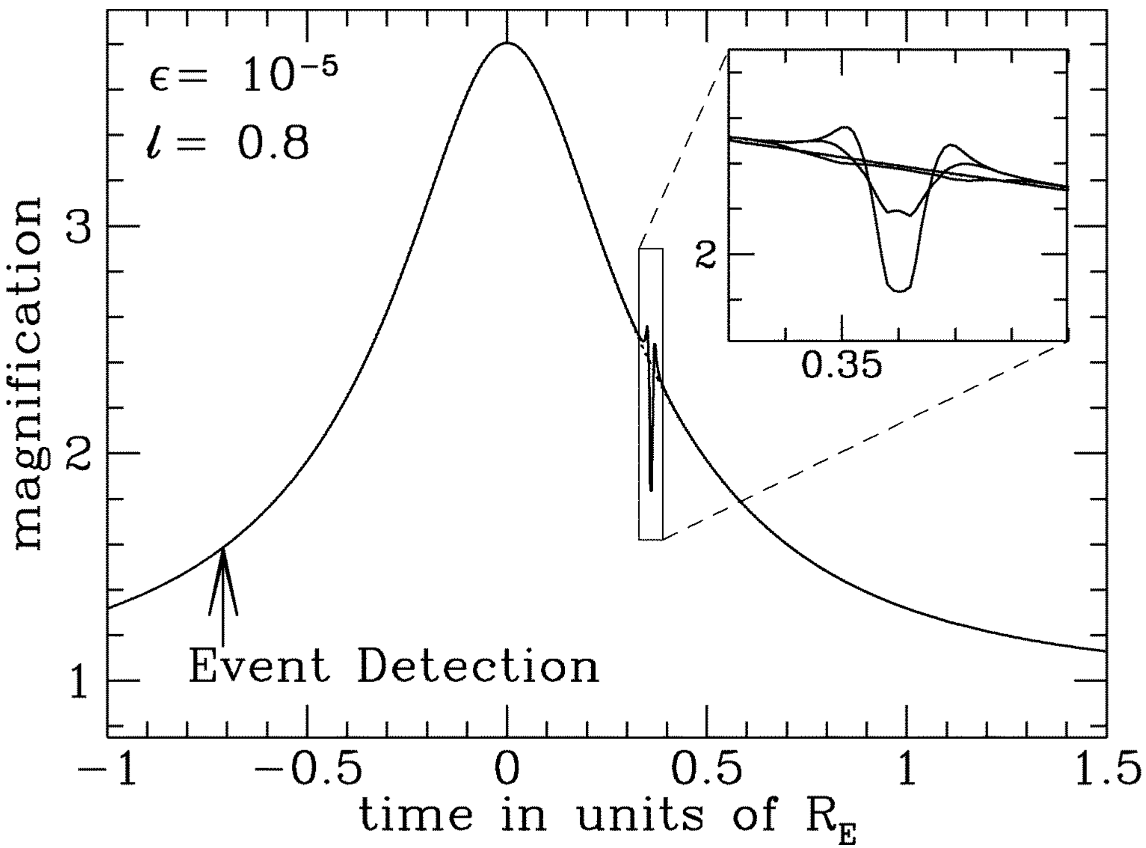
Time-series photometry is combined to uncover light curves of background source stars being lensed by foreground stars in the disk and bulge.



Planets are revealed as short-duration deviations from the smooth, symmetric magnification of the source due to the primary star.

Detailed fitting to the photometry yields the parameters of the detected planets.

How Low Can We Go?



(Bennett & Rhie 1996)

Limited by Source Size

angular Einstein radius

$$\theta_E \approx \mu\text{as}\left(\frac{M_p}{M_\oplus}\right)^{1/2}$$

$$\updownarrow$$

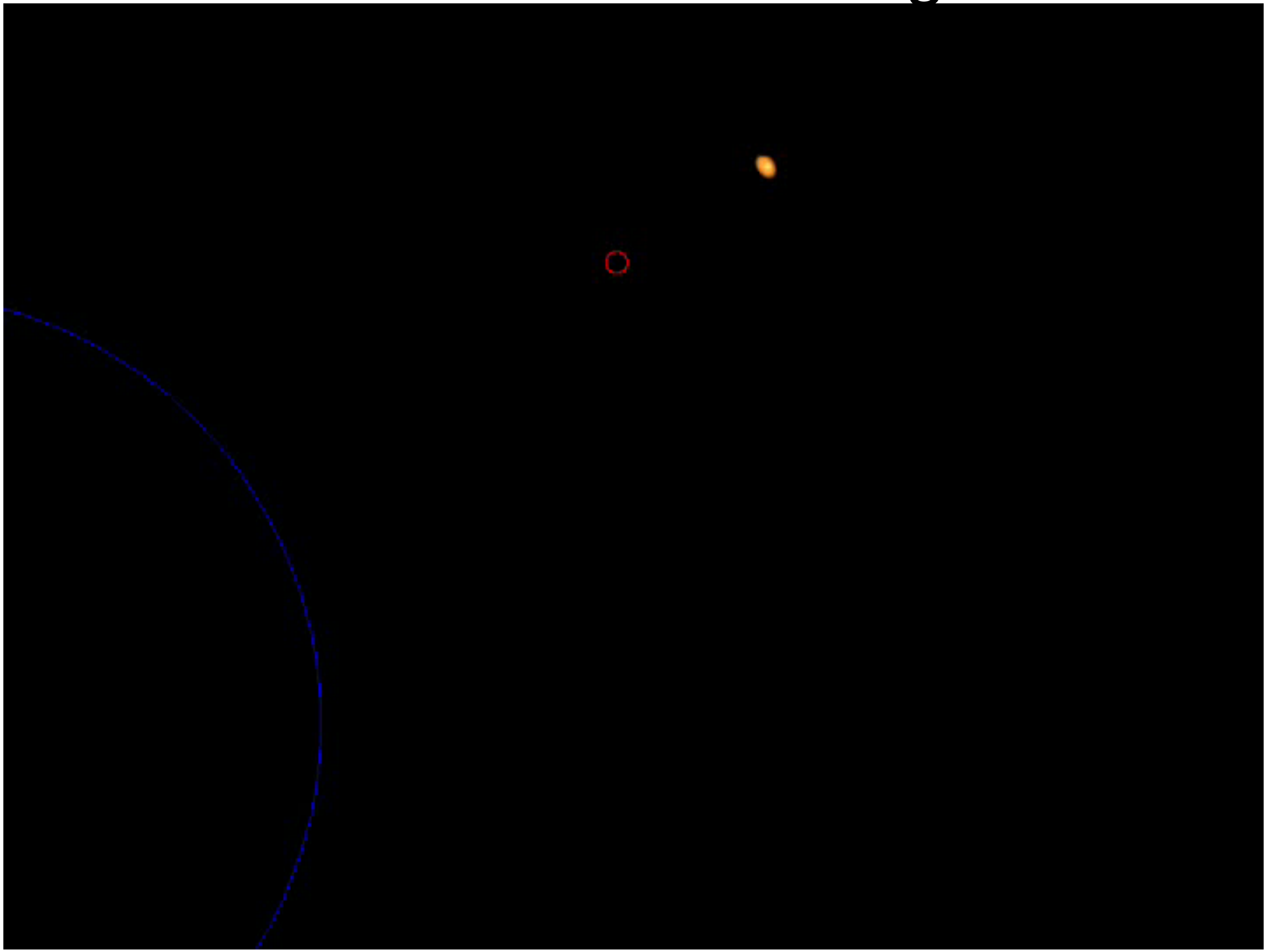
$$\theta_* \approx \mu\text{as}\left(\frac{R_*}{R_\odot}\right)$$

angular source star radius

For $\theta_E \geq \theta_*$:
low-mass planet signals are rare and brief, but not weak

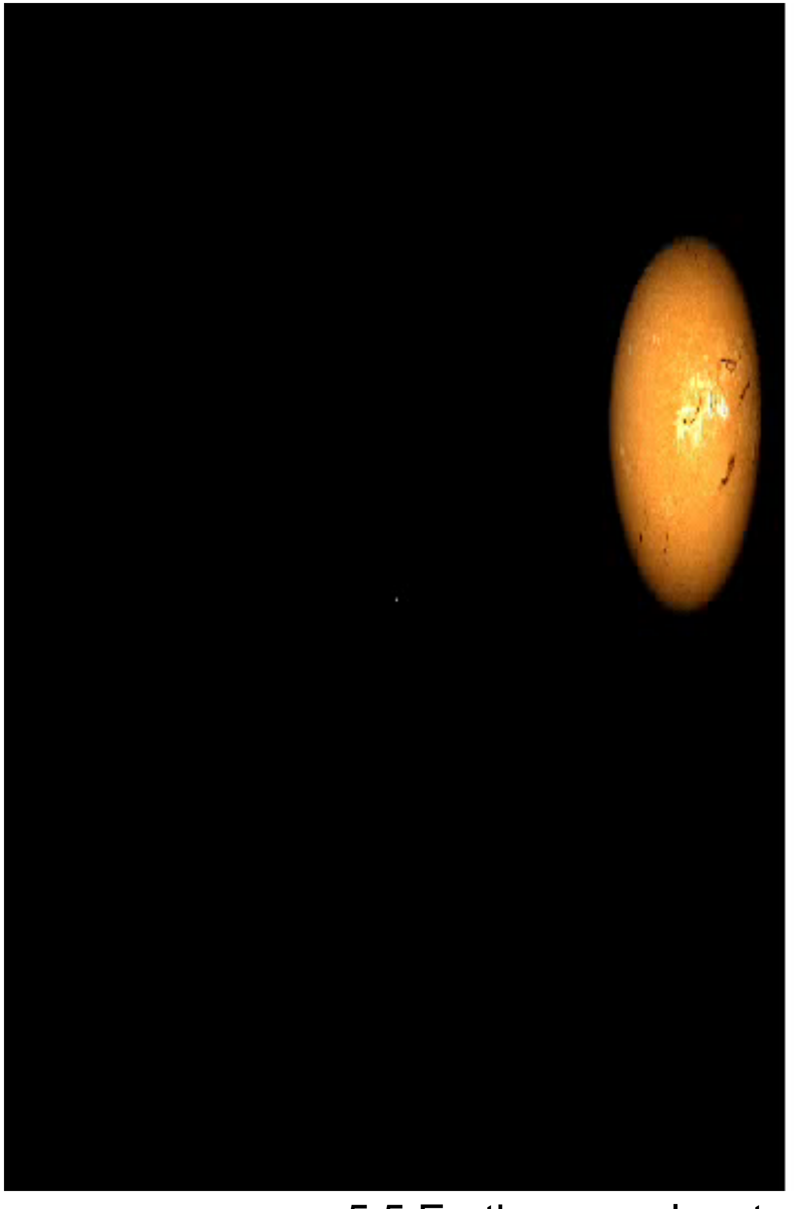
Mars-mass planets detectable
if solar-type sources can be monitored!

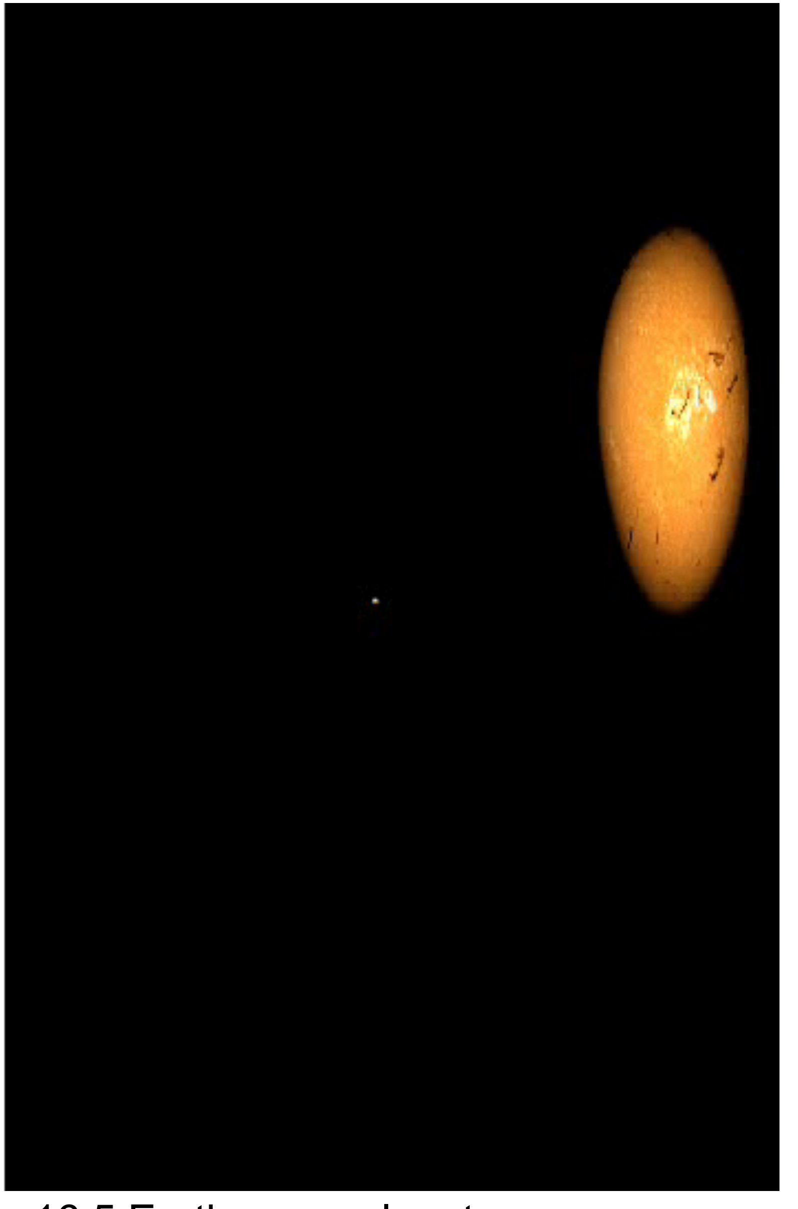
OGLE-2005-BLG-390Lb at high resolution



- Simulated view from 10,000 km aperture space telescope
- H-α filter Solar images generate cool videos!

OGLE-2005-BLG-390Lb at high resolution





5.5 Earth-mass planet vs. 16.5 Earth-mass planet.

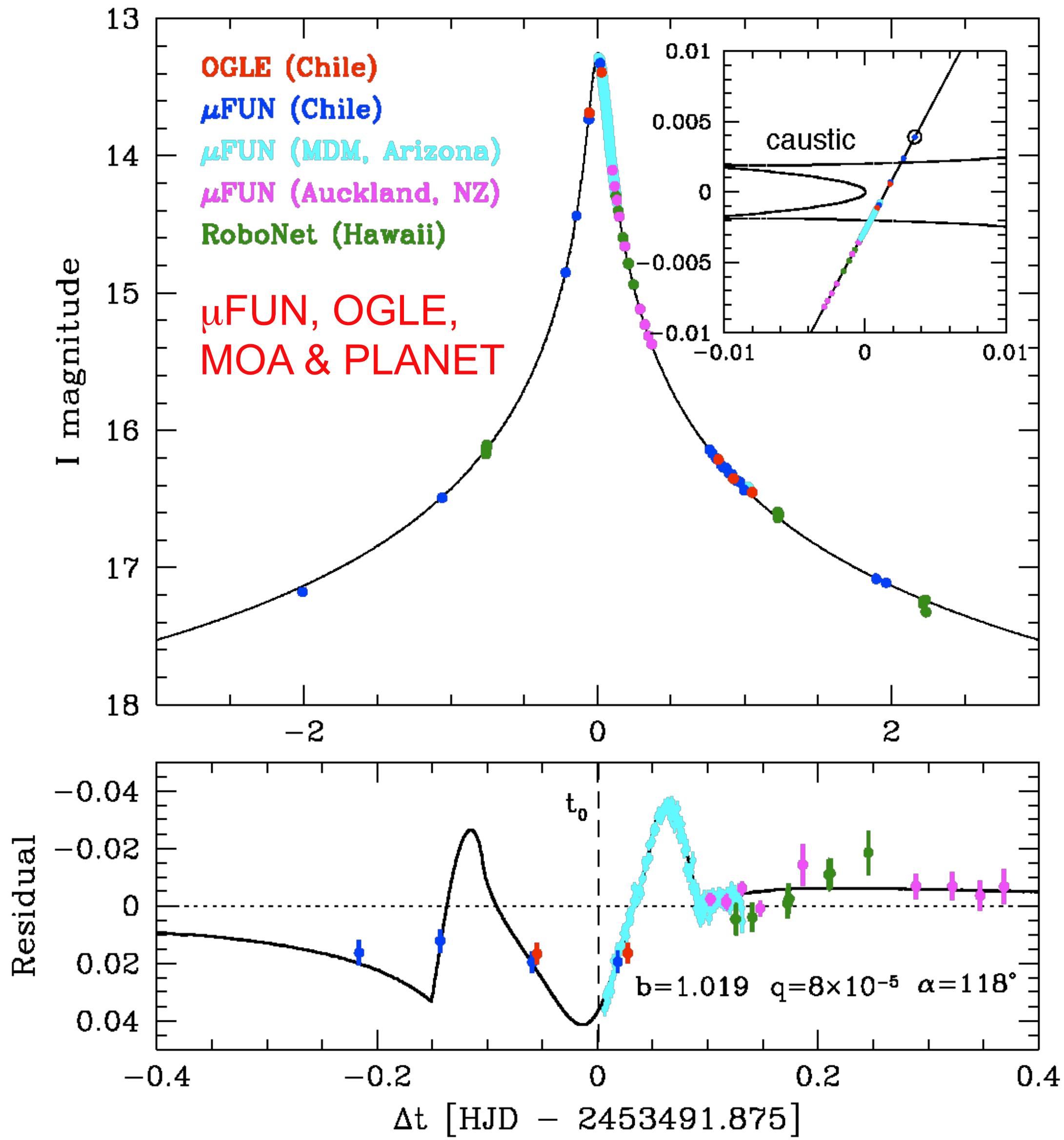
Only the total image area is observable. 5.5 Earth-mass is near limit for giant source.

High-magnification: Low-mass planets

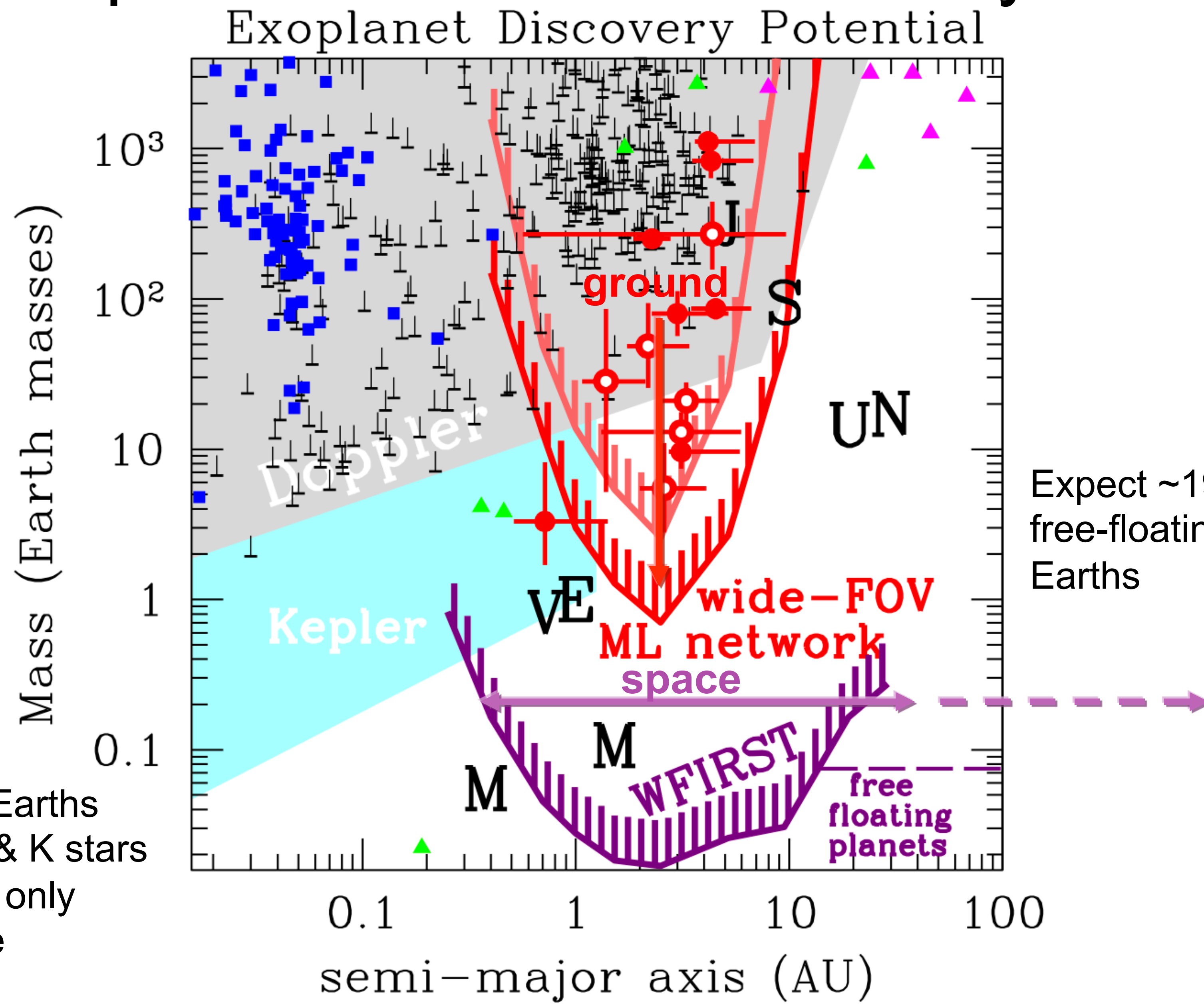
OGLE-2005-BLG-169Lb

- Detection of a ~17 $M_\oplus$ planet in a A_{max}= 800 event
- Caustic crossing signal is obvious when light curve is divided by a single lens curve.
- Detection efficiency for ~10 $M_\oplus$ planets is << than for Jupiter-mass planets

- Competing models with an Earth-mass planet had a signal of similar amplitude
- So, an Earth-mass planet could have been detected in this event!



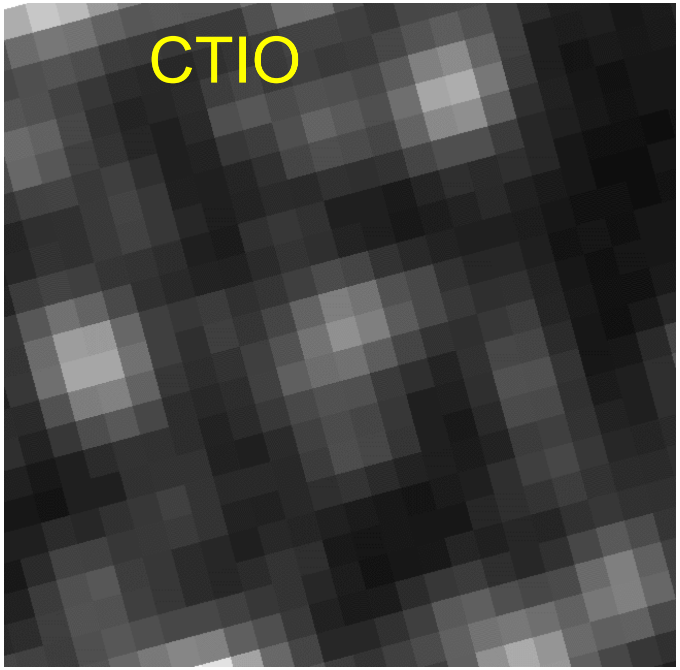
Space vs. Ground Sensitivity

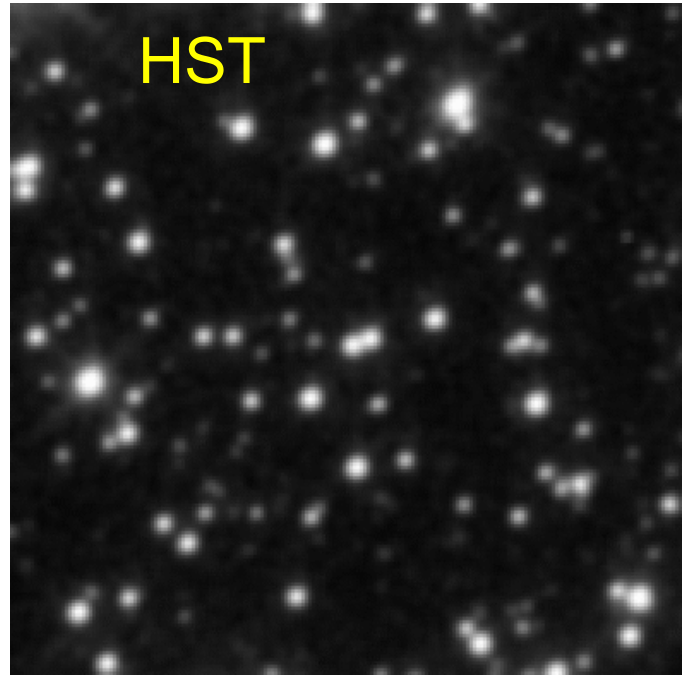


Expect ~190 free-floating Earths

Habitable Earths orbiting G & K stars accessible only from space

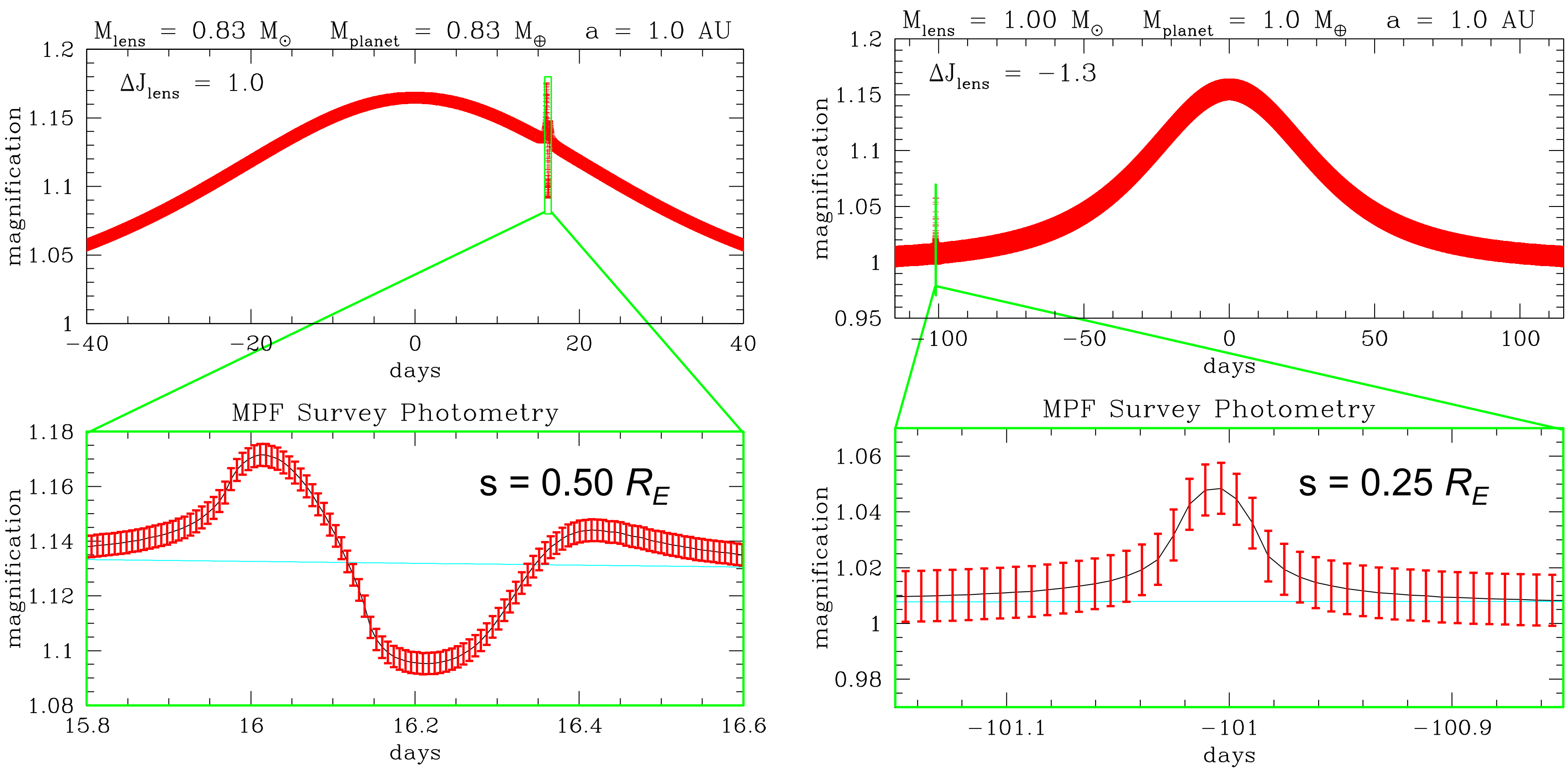
Ground-based confusion, space-based resolution





- Space-based imaging needed for high precision photometry of main sequence source stars (at low magnification) and lens star detection
- High Resolution + large field + 24hr duty cycle => Space-based Microlensing Survey
- Space observations needed for sensitivity at a range of separations and mass determinations

Close Separation planets by Microlensing



- Faint main sequences sources needed to detecting low-mass planets
- At separations < R_E, planetary signals occur at low stellar magnification
- Ground-based photometry seems to have systematic errors proportional to the flux of blended stellar light.
- For close-in (or HZ) planets, higher angular resolution & longer exposures help

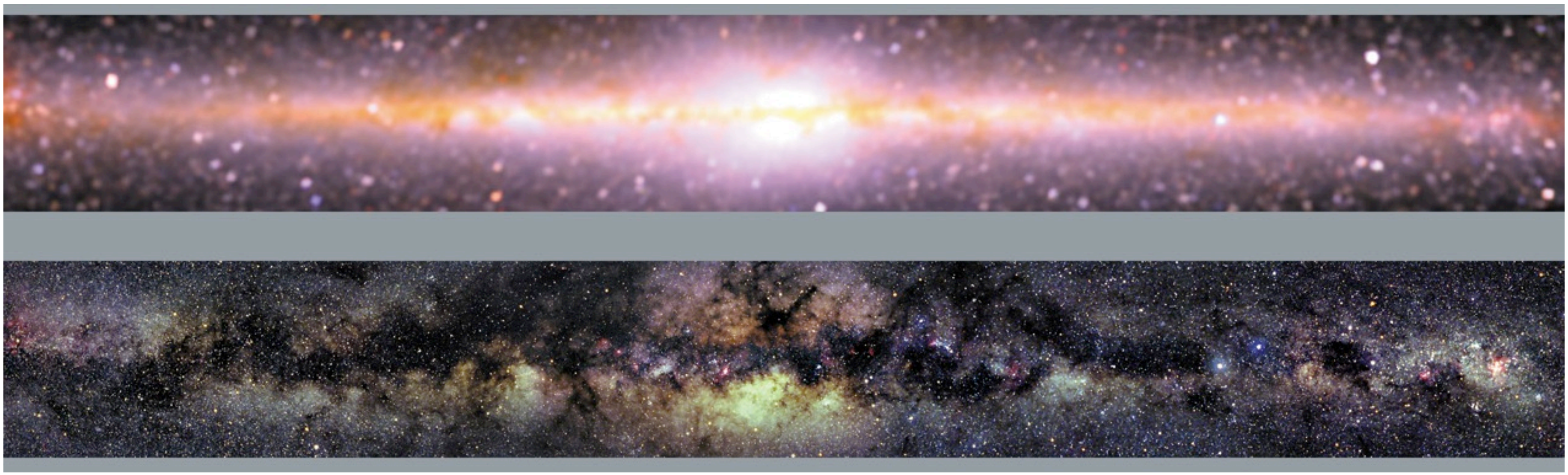
Exoplanet Microlensing Photometry from Space

- Minimum time scale for light curve features ~ $R_\odot$/(200km/s) ~ 1 hr
  - sample with ~4 data points
- But, event rate is low, ~10^{-5} /(star-year)
  - prefer large FOV – at least 2 sq. deg.
  - sampled multiple fields
- For a fixed FOV, small pixels are best
- Undersampling and modest blending are not a problem in space
  - ~100,000 images per field with a random dither give great sampling
  - stable PSF with a small # of d.o.f.
- For a fixed # of pixels, large pixels -> larger FOV
  - optimal pixel scale for photometry is relatively large, perhaps 0.25”
    - Euclid’s IR pixel scale of 0.3” is OK
  - some losses due to blending are compensated by larger FOV
  - but, planets at s ≤ 0.5 are the most sensitive to worse angular resolution
- But photometry is not the whole story

Infrared Observations Are Best

The central Milky Way:

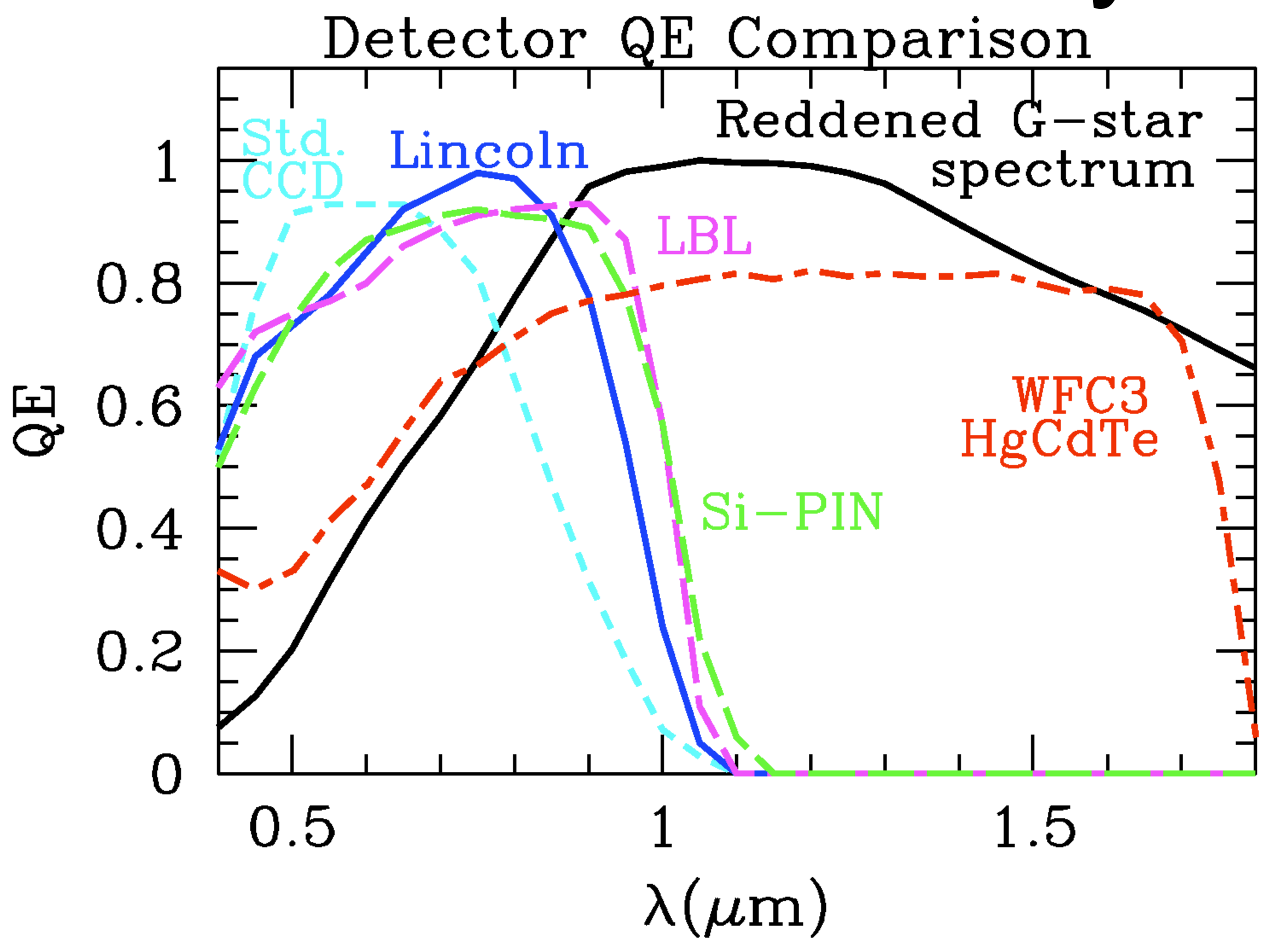
near infrared



optical

The optimal microlensing fields are highly obscured, and we detect 5× more photons in the IR. HgCdTe detectors are much better than CCDs, but not absolutely required. 2 deg^2 CCD FOV would be ok (i.e. GEST)

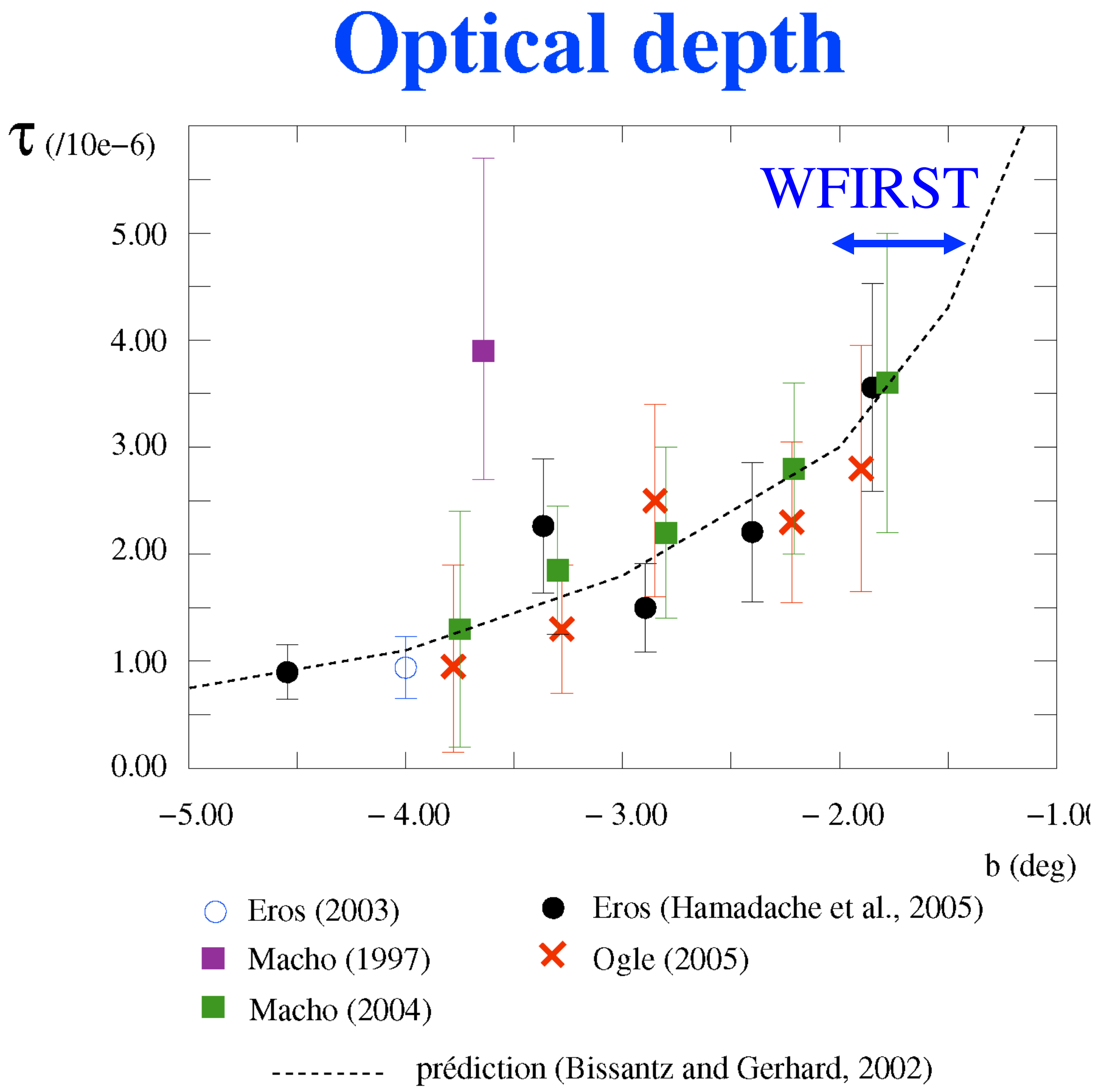
Detector Sensitivity



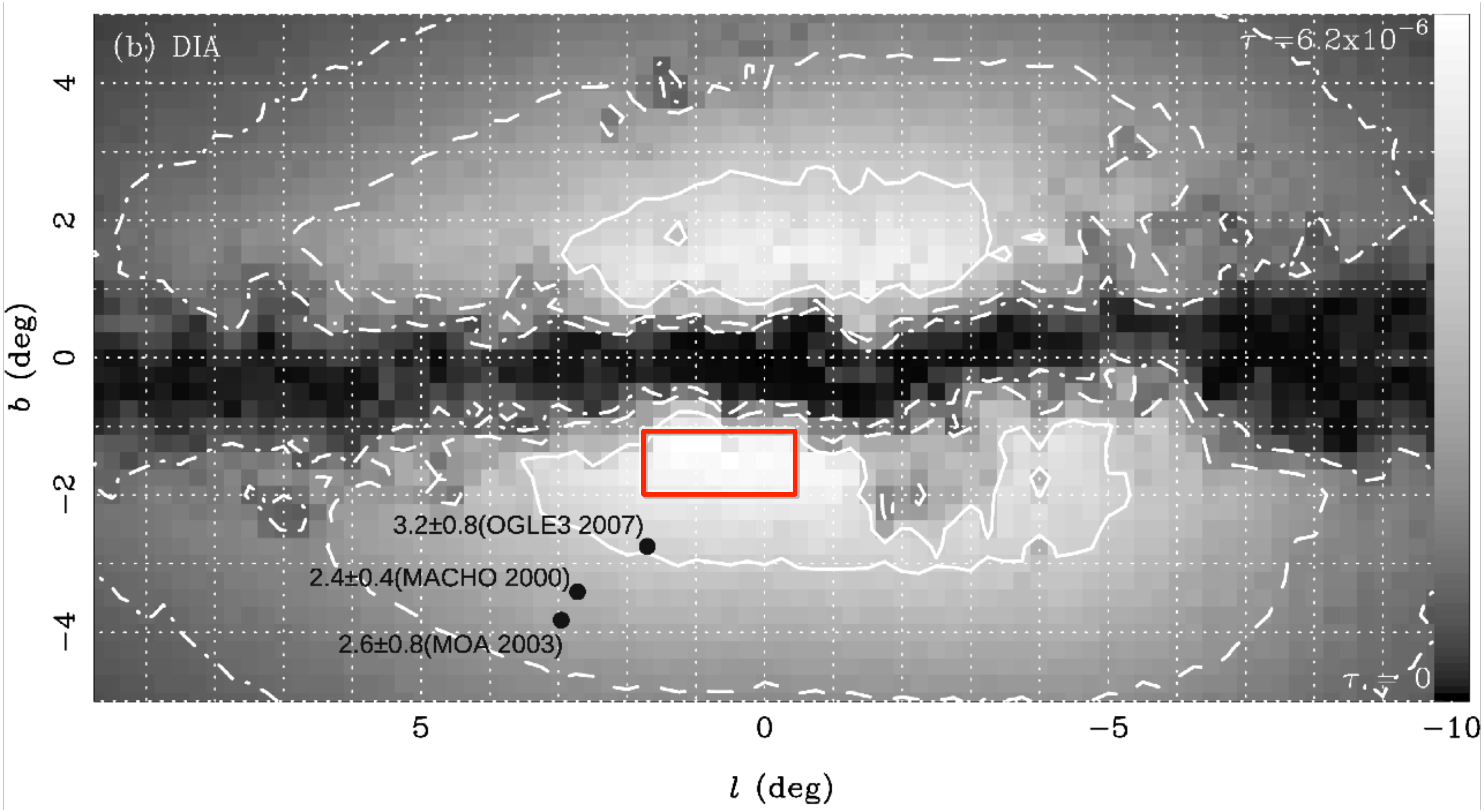
The spectrum of a typical reddened source star is compared to the QE curves of CCDs and Si-PIN detector arrays. The HgCdTe detectors developed for HST's WFC3 instrument can detect twice as many photons as the most IR sensitive Si detectors (CCDs or CMOS). MPF will employ 35 HgCdTe detectors. 3 filters: "clear" 600-1700nm, "visible" 600-900nm, and "IR" 1300-1700nm.

Microlensing Optical Depth & Rate

- Bissantz & Gerhard (2002) τ value that fits the EROS, MACHO & OGLE clump giant measurements
- Revised OGLE value is ~20% larger than shown in the plot.
- Observations are ~5 years old



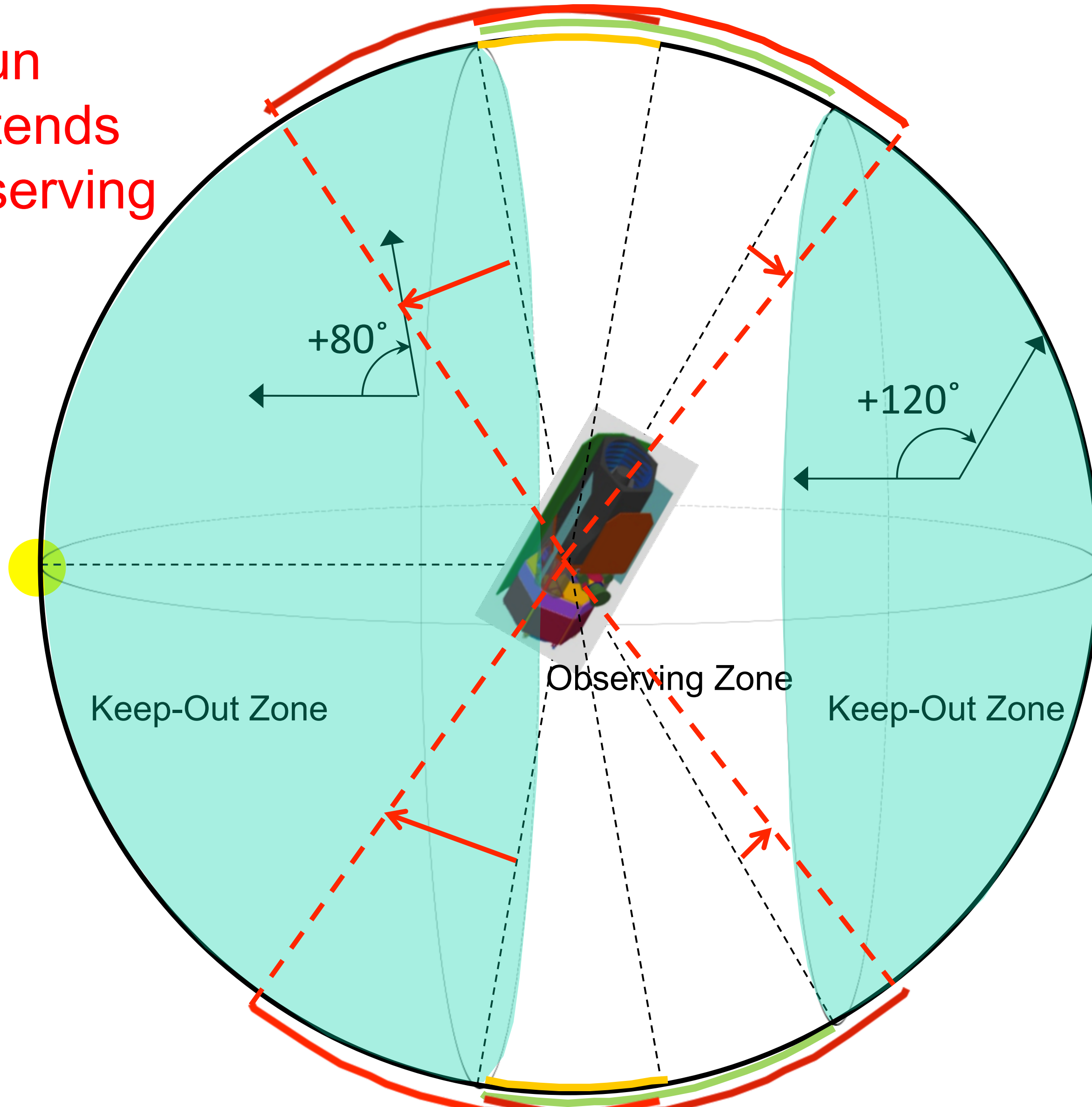
Select Fields from Microlensing Optical Depth Map (including extinction)



Optical Depth map from Kerins et al. (2009) in *I*-band
contours are 1, 2, & 4×10^{-6} (fraction of sky covered by Einstein rings)

JDEM ➔ WFIRST Transformation Expands Field of Regard

Larger Sun shield extends bulge observing window

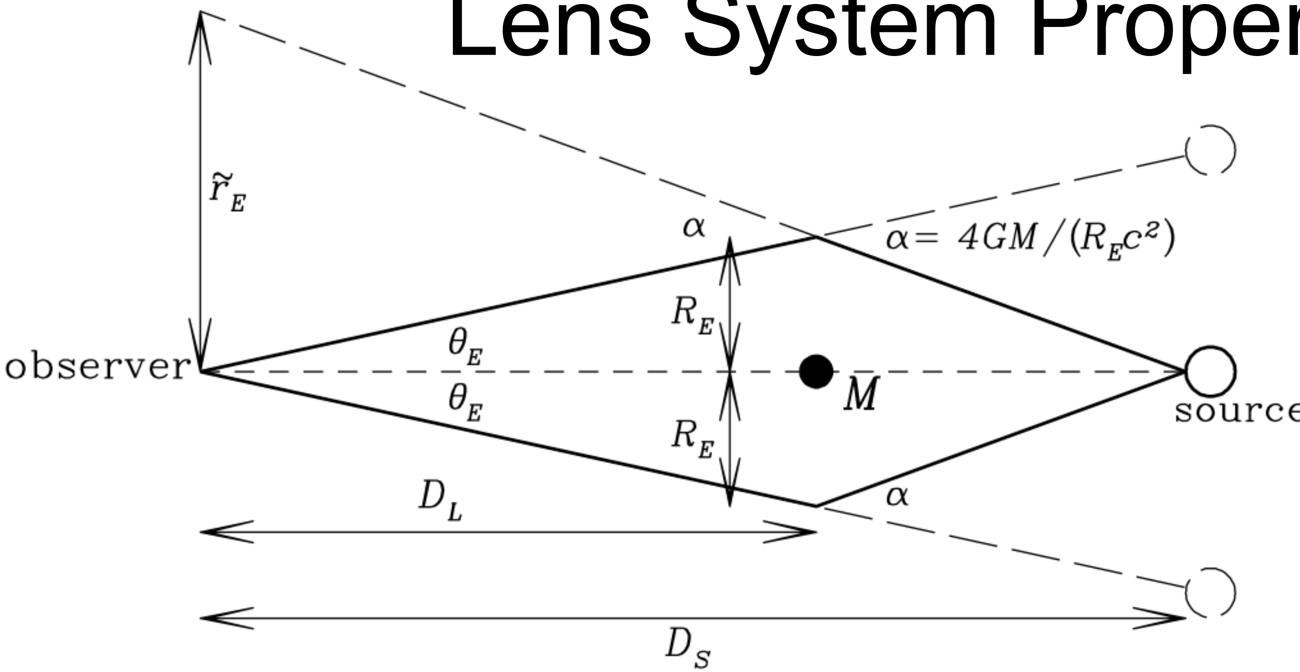


SNe FoR

WL/BAO FoR

JDEM had 40-day bulge observing season vs. 30-days for Euclid. WFIRST has 72-days seasons

Lens System Properties



- Einstein radius : $\theta_E = \theta_* t_E / t_*$ and projected Einstein radius, $\tilde{r}_E$
  - θ_* = the angular radius of the star
  - $\tilde{r}_E$ from the microlensing parallax effect (due to Earth's orbital motion).

$$R_E = \theta_E D_L, \text{ so } \quad \alpha = \frac{\tilde{r}_E}{D_L} = \frac{4GM}{c^2 \theta_E D_L} \text{ . Hence } M = \frac{c^2}{4G} \theta_E \tilde{r}_E$$

Finite Source Effects & Microlensing Parallax Yield Lens System Mass

- If only θ_E or $\tilde{r}_E$ is measured, then we have a mass-distance relation.
- Such a relation can be solved if we detect the lens star and use a mass-luminosity relation
  - This requires HST or ground-based adaptive optics
- With θ_E, $\tilde{r}_E$, and lens star brightness, we have more constraints than parameters

mass-distance relations:

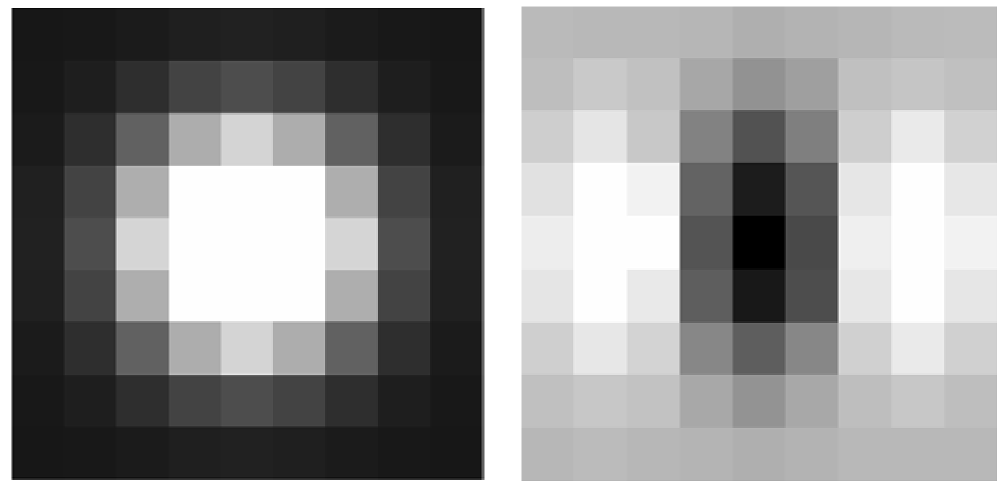
$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

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

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

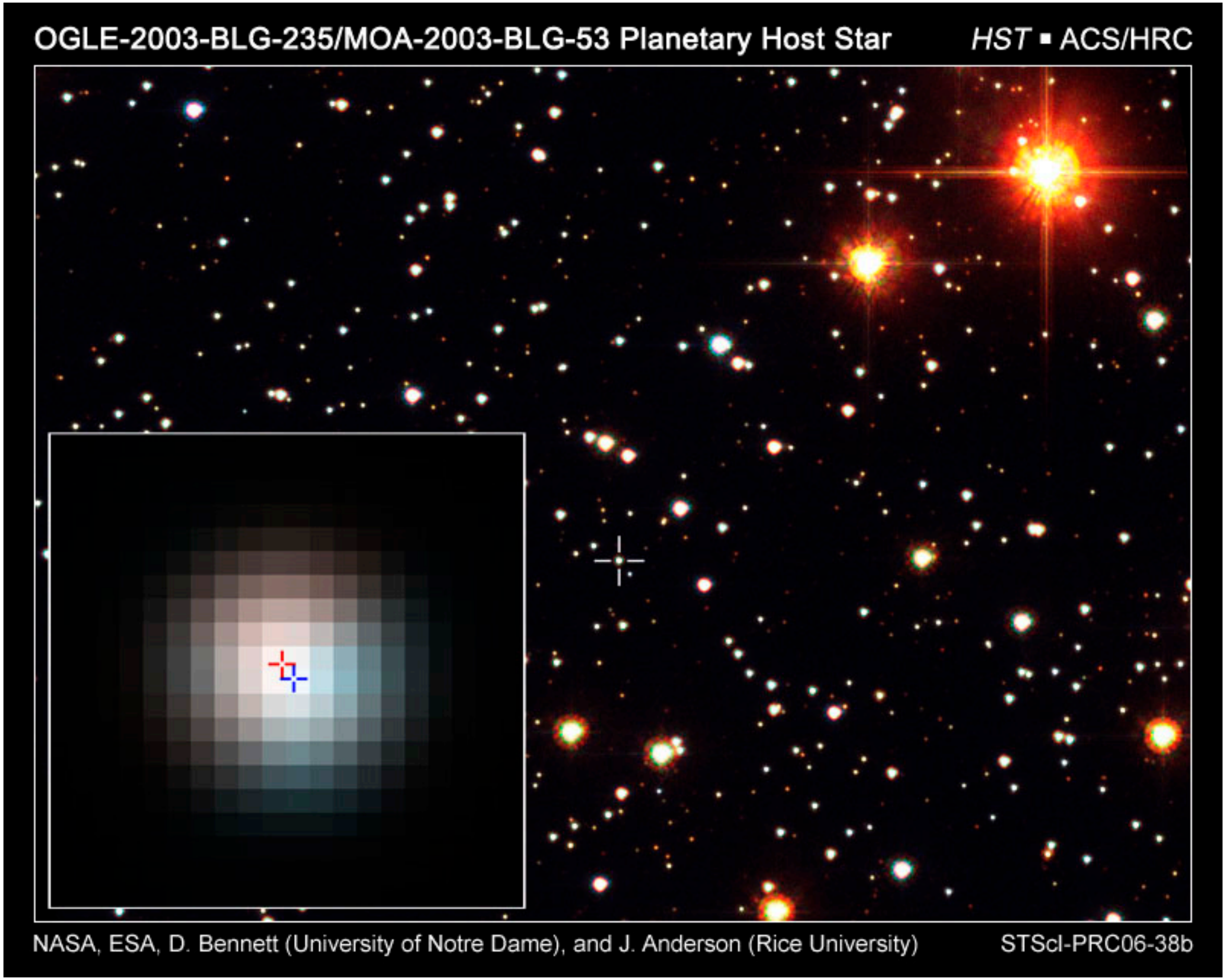
Lens Star Detection in WFIRST Images

- The typical lens-source relative proper motion is μ_{rel}~ 5 mas/yr
- This gives a total motion of >0.11 pixels over 4 years
- This is directly detectable in co-added WFIRST images due to WFIRST's stable PSF and large number of images of each of the target fields.
- μ_{rel} is also determined from the light curve fit.
- A color difference between the source and lens stars provides a signal of μ_{rel} in the color dependence of the source+lens centroid position



A 3× super-sampled, drizzled 4-month WFIRST image stack showing a lens-source blend with a separation of 0.07 pixel, is very similar to a point source (left). But with PSF subtraction, the image elongation becomes clear, indicating measurable relative proper motion.

Color Dependent Image Center Shift



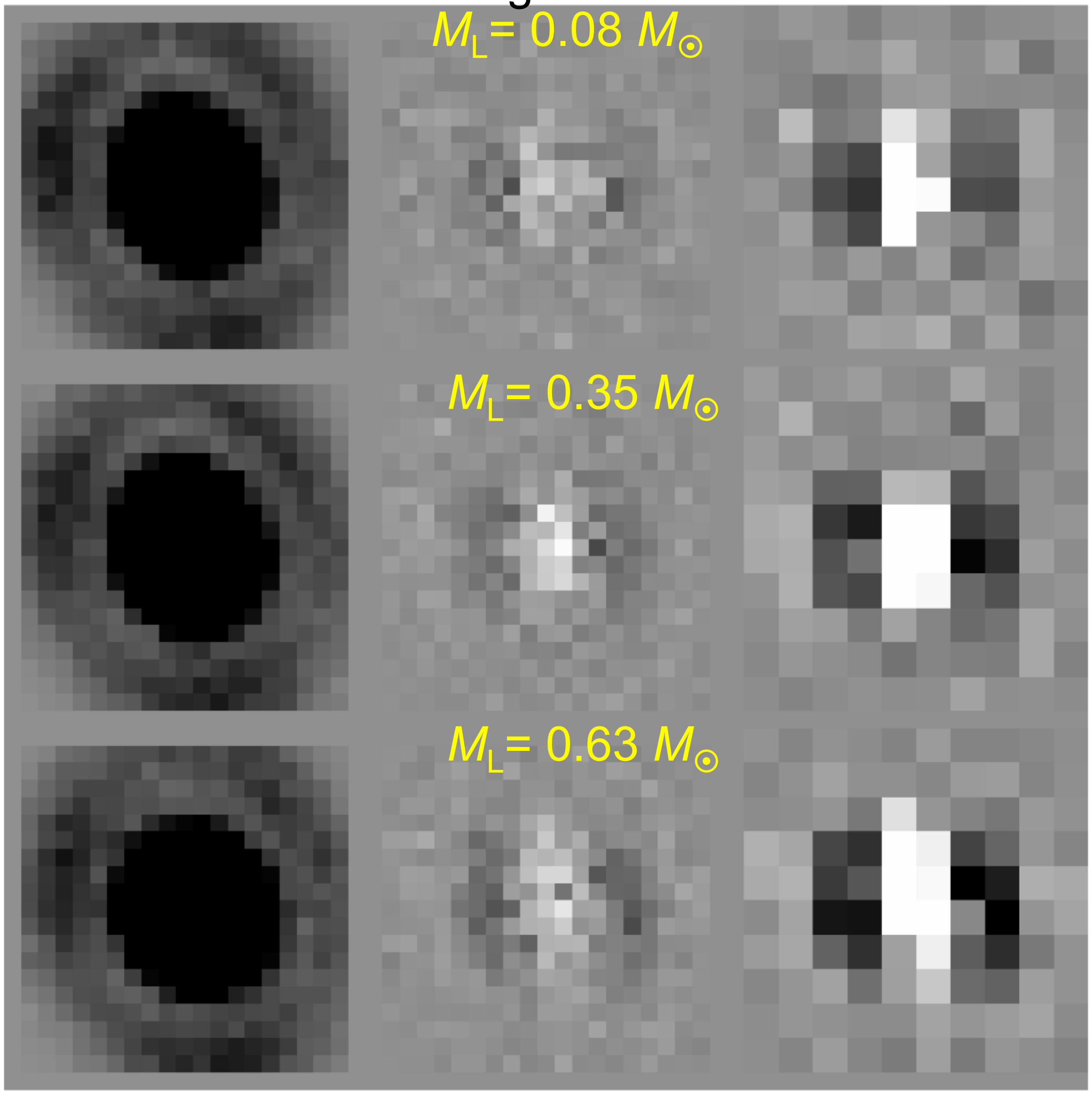
Source & Planetary Host stars usually have different colors, so lens-source separation is revealed by different centroids in different passbands

Lens Star Identification from Space

- Lens-source proper motion gives $\theta_E = \mu_{rel} t_E$
- μ_{rel}= 8.4±0.6 mas/yr for OGLE-2005-BLG-169
- Simulated HST ACS/HRC F814W (*I*-band) single orbit image "stacks" taken 2.4 years after peak magnification
  - 2× native resolution
  - also detectable with HST WFPC2/PC & NICMOS/NIC1
- Stable HST PSF allows clear detection of PSF elongation signal
- A main sequence lens of any mass is easily detected (for this event)

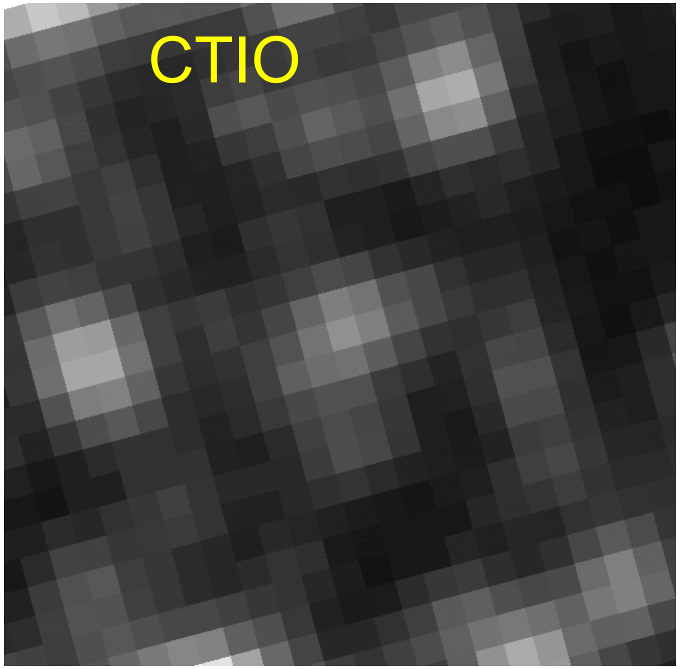
see J. Anderson's talk for HST measurements

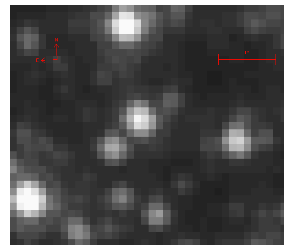
Simulated HST images:

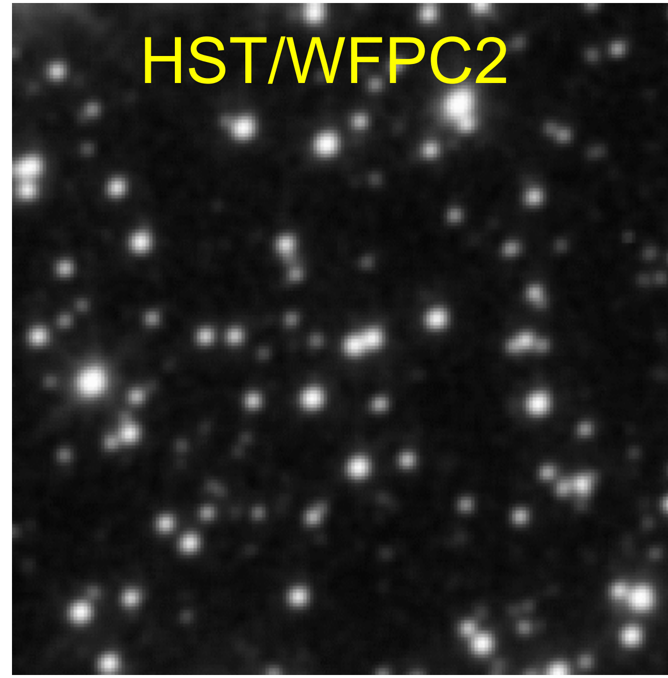


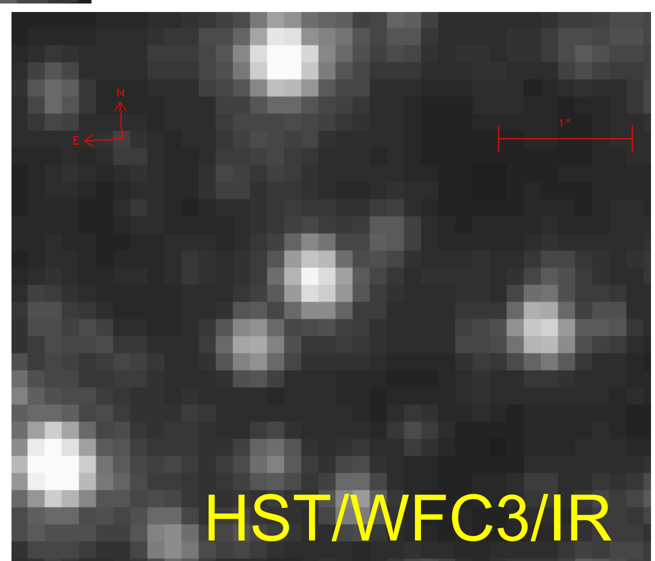
raw image PSF subtracted binned

However, the Central Bulge is More Crowded in the IR





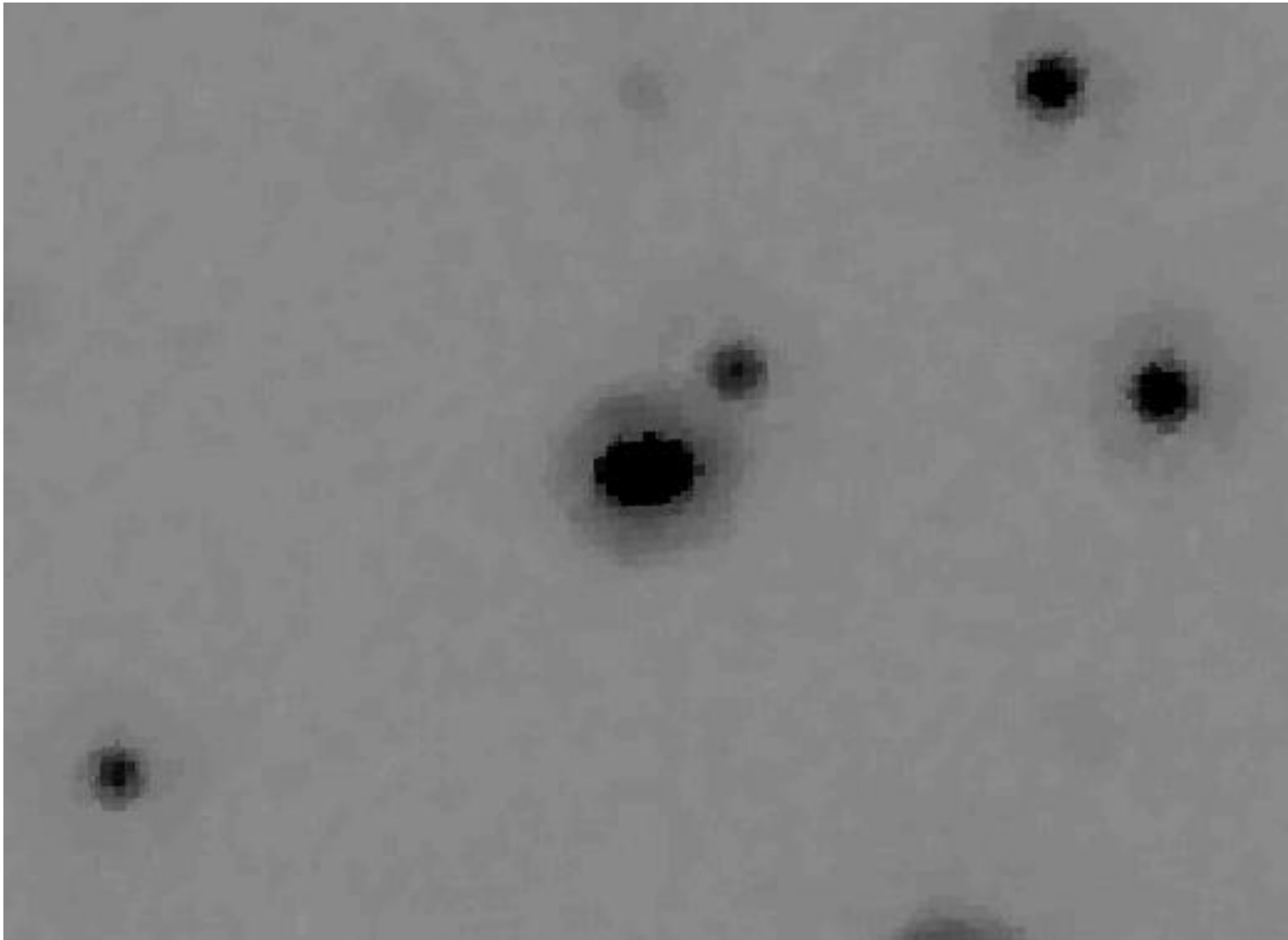




Crowded fields give higher lensing rate, but complicate mass determination -> redundancy needed

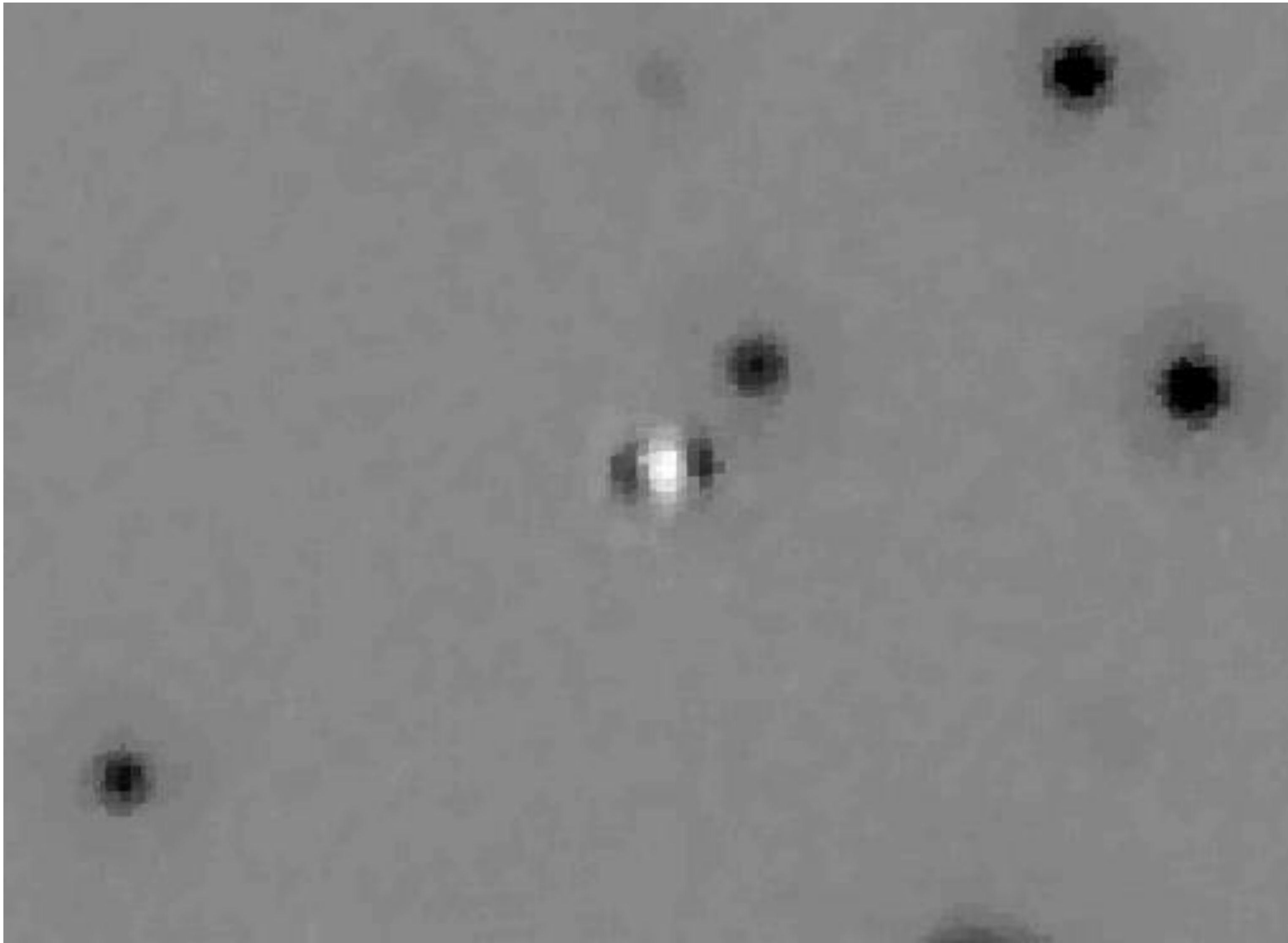
Stacked HST I-band Image of OGLE-2005-BLG-169 Source

Source *looks* elongated relative to neighbors



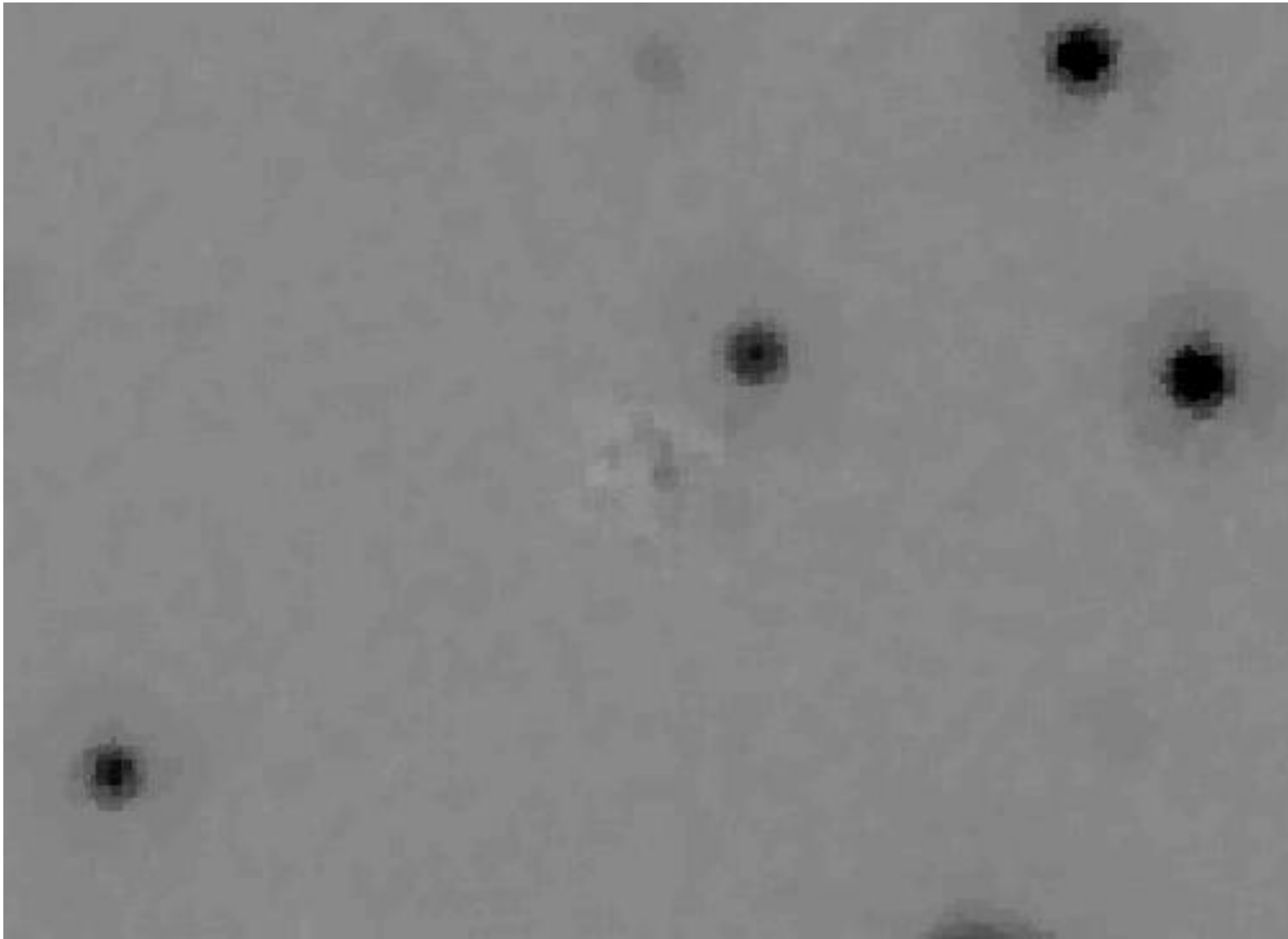
PSF for a Single Star Subtracted

Residuals in X when we subtract a PSF from each image and stack…

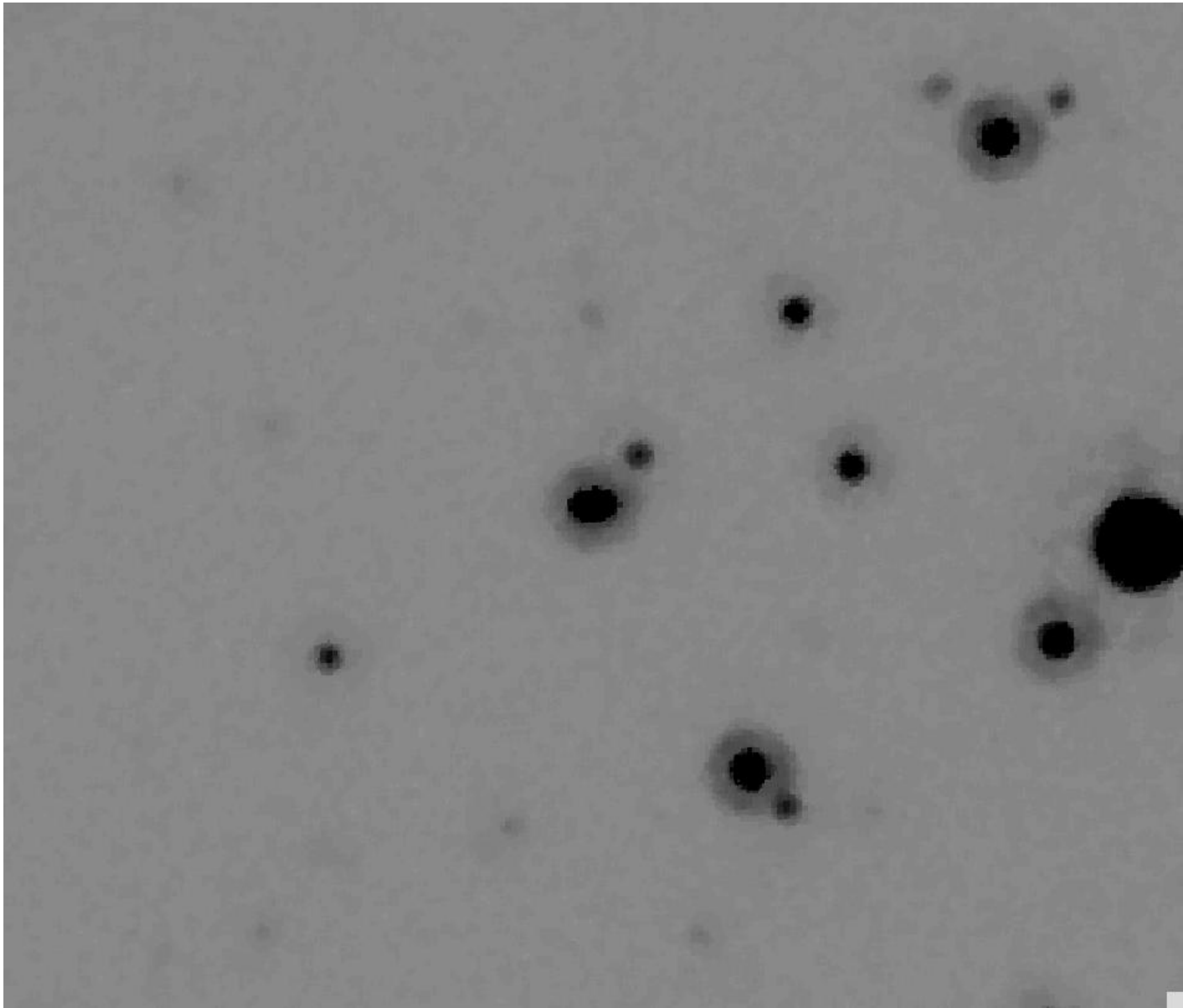


Fit and Subtract Two Stars: Source & Lens

Very good subtraction residuals when we fit for *two* sources



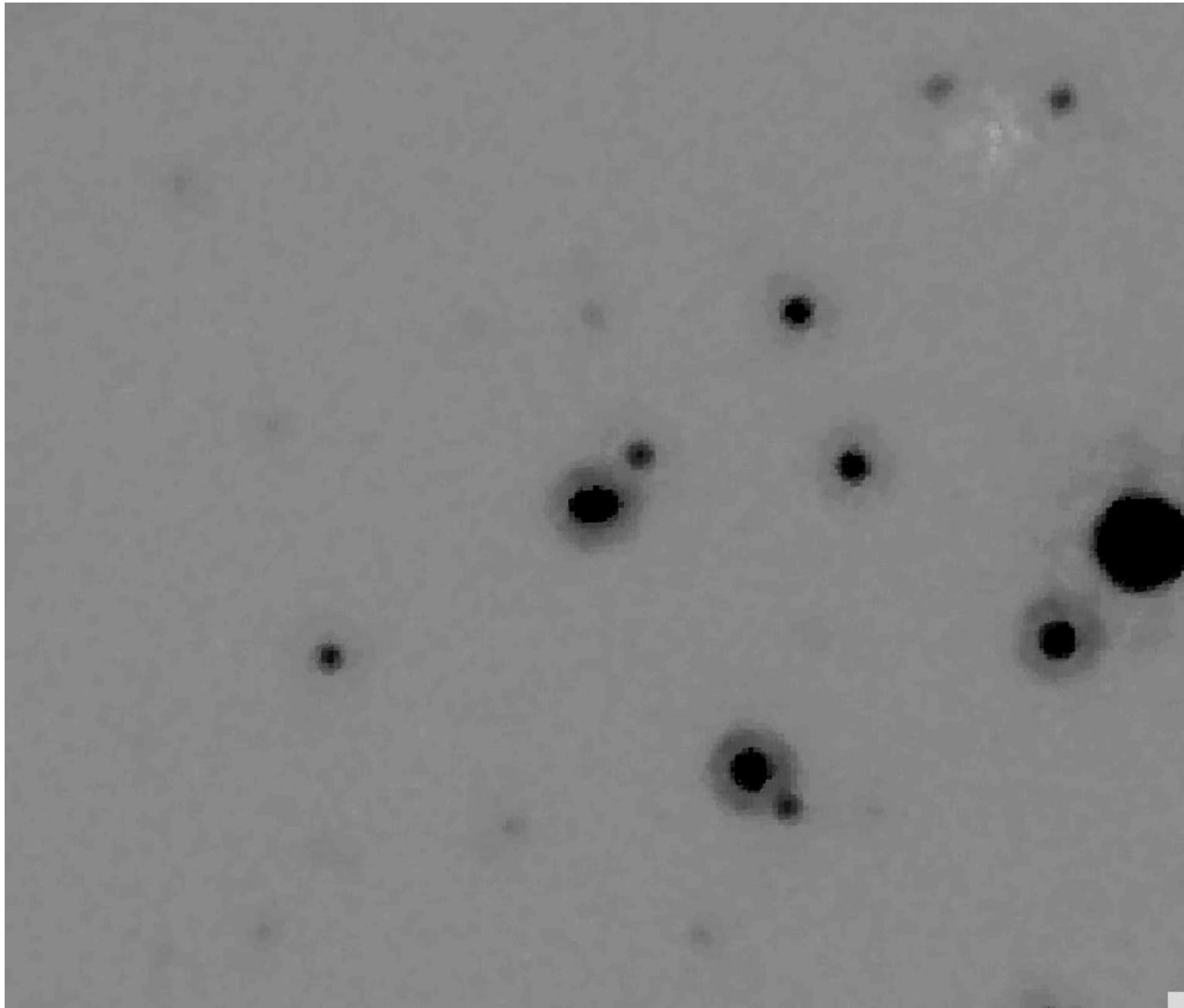
Stacked F814W Observations



Subtracted Neighbor…

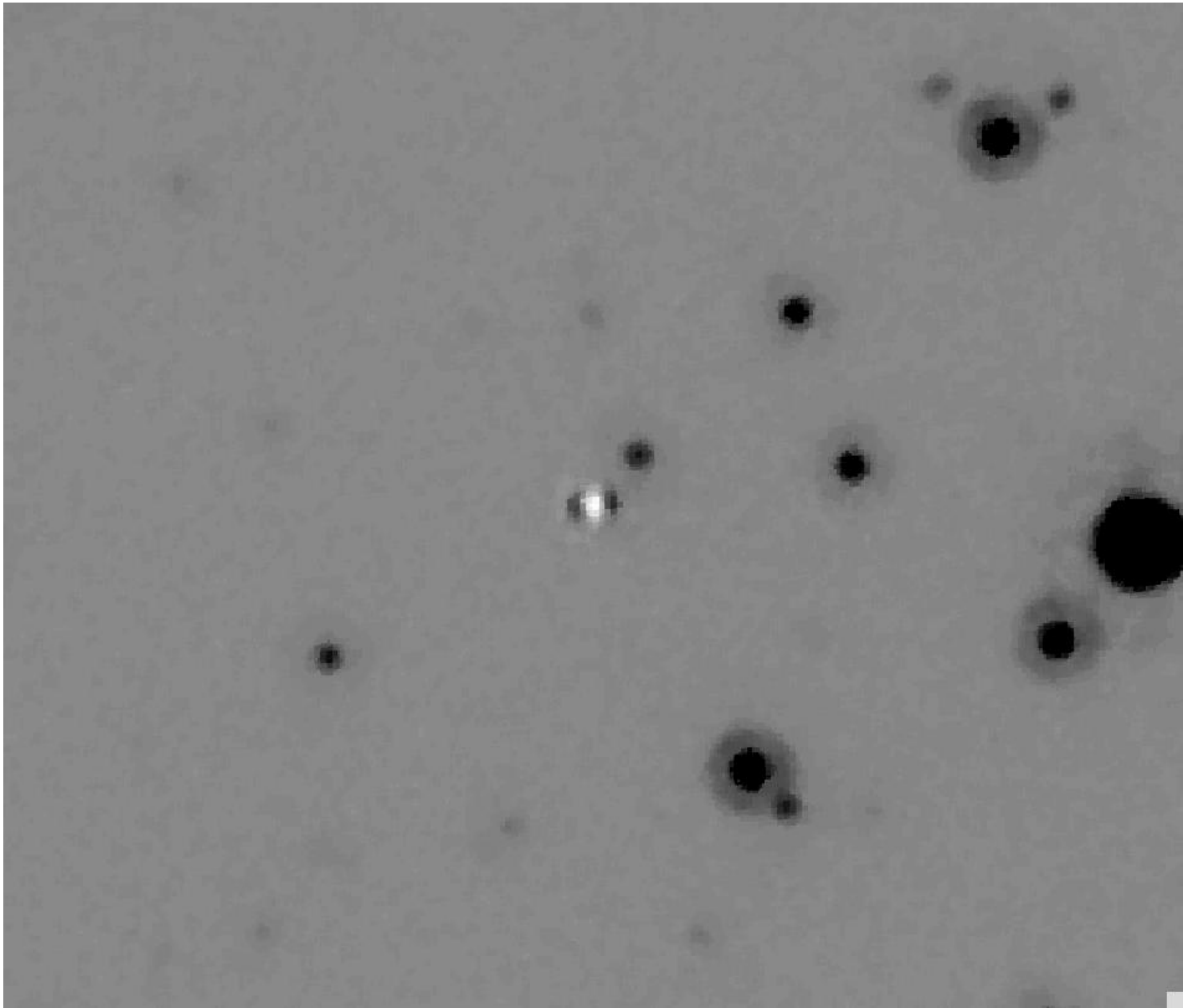
PSF IS GOOD!

Almost *no* residuals When we Subtract a PSF from a (brighter) neighbor



Subtracted F814W Stack

This means that the residuals of the target-star subtraction are *real*.



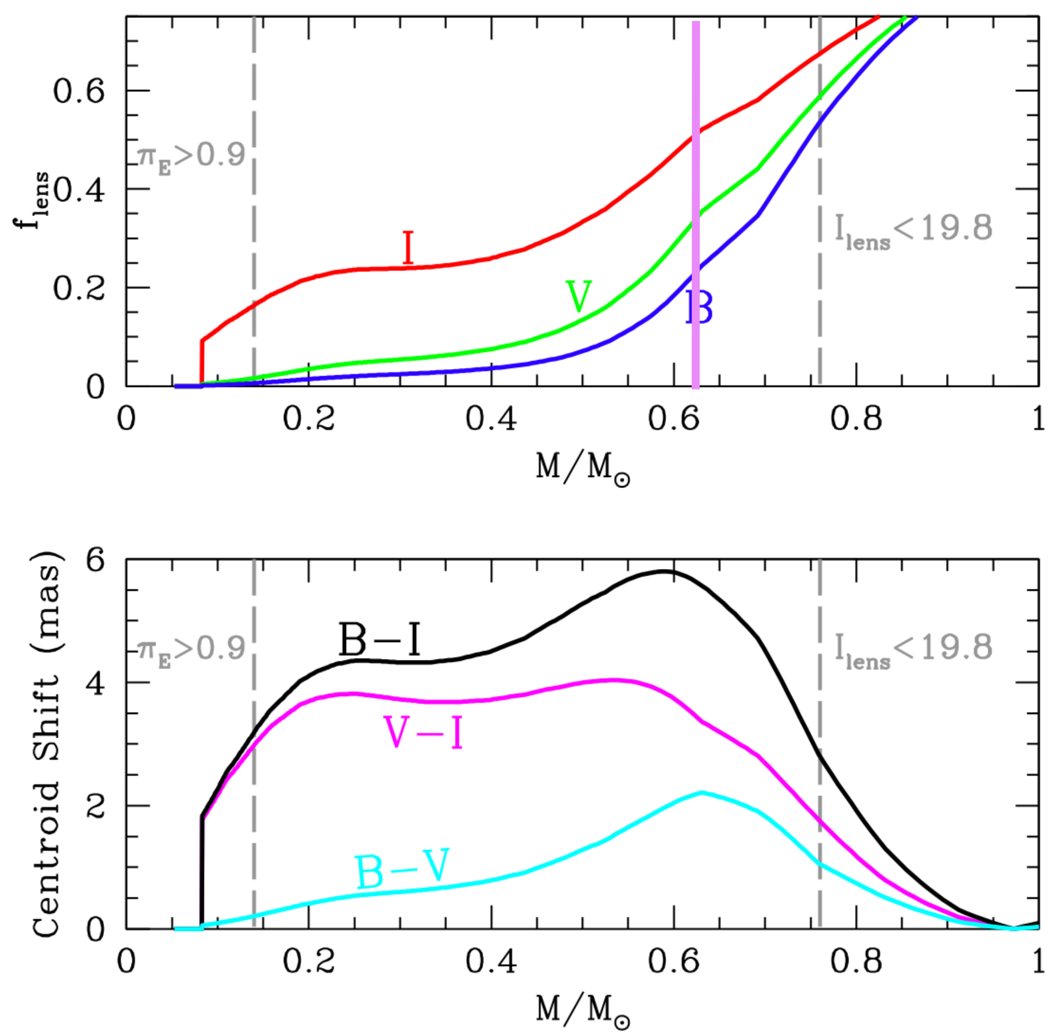
Two-source Solution:

- Offset consistent in the F814W, F555W, and F438W data:
  - Δx = 1.25 pixels = 50 mas
  - Δy = 0.25 pixel = 10 mas
  - FLUX: (left) (right)
    - F814W 3392 e^- 3276 e^-
    - F555W 2158 e^- 3985 e^-
    - F438W 338 e^- 1029 e^-
    - $f_I = 0.51$
    - $f_V = 0.35$
    - $f_B = 0.25$

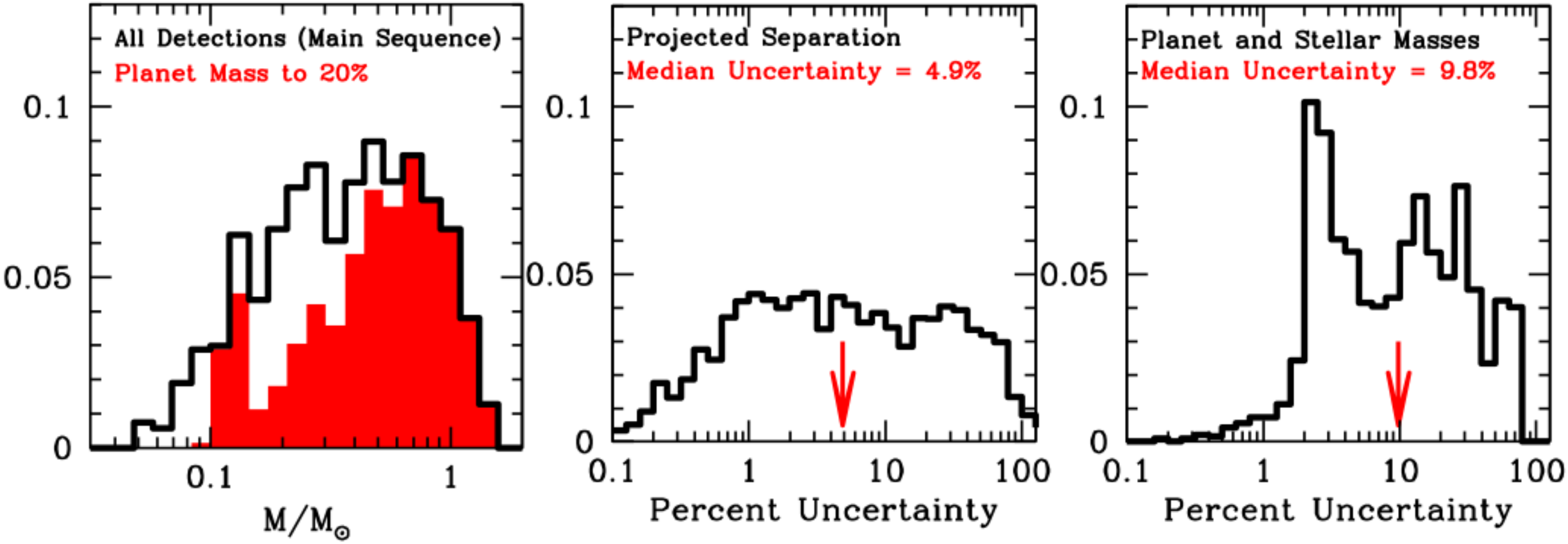
HST BVI observations imply

$M_* = 0.63\ M_\odot$

$M_p = 17\ M_\oplus$



Lens Detection Provides Complete Lens Solution



- The observed brightness of the lens can be combined with a mass-luminosity relation, plus the mass-distance relation that comes from the μ_{rel} measurement, to yield a complete lens solution.
- The resulting uncertainties in the absolute planet and star masses and projected separation are shown above.
- Multiple methods to determine μ_{rel} and masses (such as lens star color and microlensing parallax) imply that complications like source star binarity are not a problem.

Unique Science from Space-based Survey

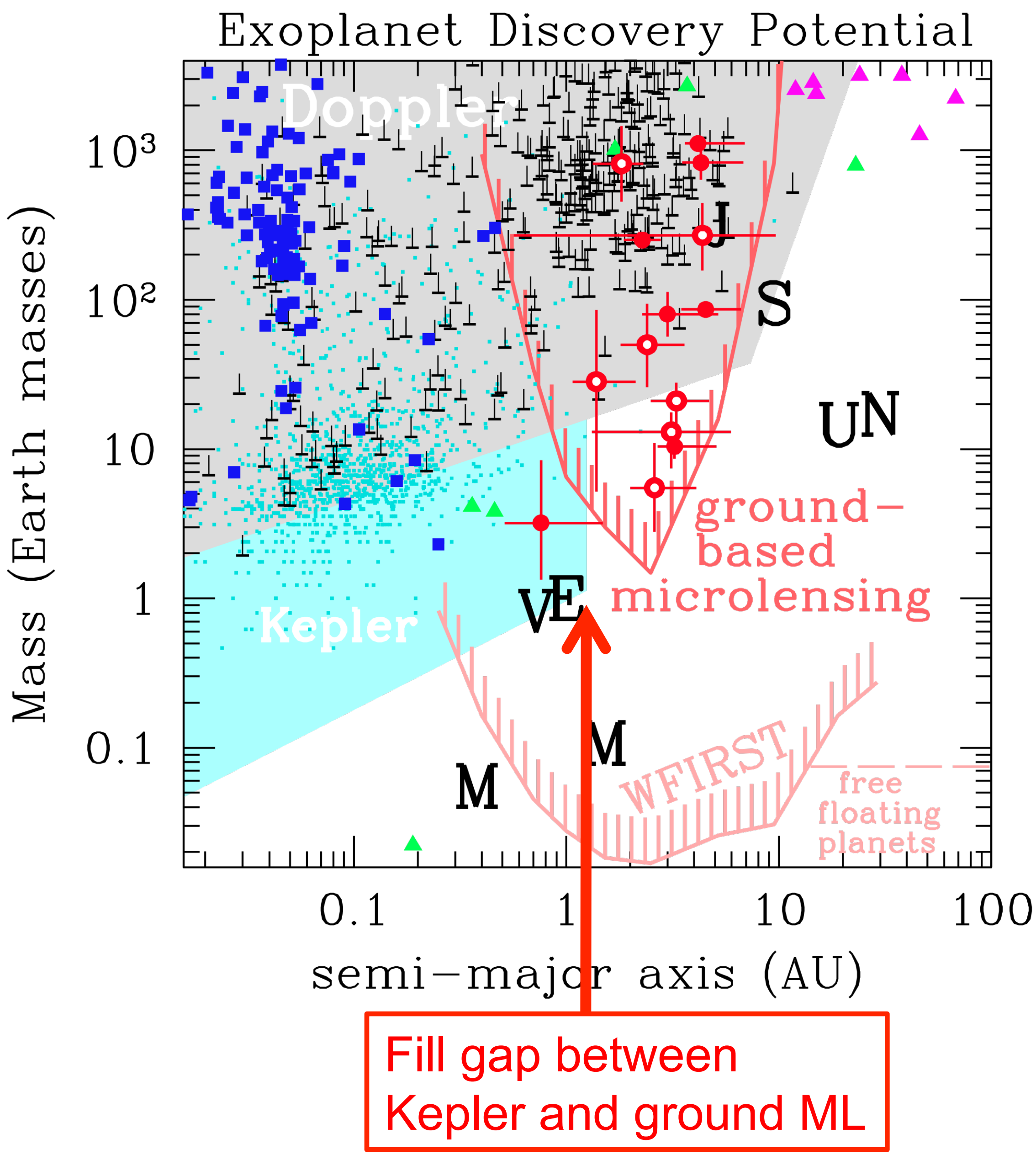
- ***Exoplanet Survey Question #1: How do planetary systems form and evolve?***
  - complementary to Kepler
  - Exoplanet sensitivity down to sub-Earth masses at 0.5 AU - ∞
  - down to 0.1 Earth-masses over most of this range
  - free-floating planets down to 0.1 Earth-masses
    - free-floating planet mass distribution is important for understanding planet formation.
- ***Exoplanet Survey Question #2: How common are potentially habitable worlds?***
  - $\eta_{\oplus}$ = fraction of planetary systems with an earth-like planet in the habitable zone
  - But what is earth-like?
  - Kepler results imply a wide variety of planetary systems
  - We need to answer question #1 to understand habitability

Exoplanet Microlensing Requirements

- Many parameters affect exoplanet sensitivity (aperture, FOV, passband, observing cadence, angular resolution, observing season duration, ….)
- Our main goal is a survey a wide variety of planetary systems
- But, we want a simple method to compare different design trades:
  - # of planets (~127) with a $M = M_{\oplus}$ and P = 2 yr, assuming every MS star has one such planet.
  - # of planets (~90) with a $M = M_{\oplus}$ and P = 2 yr, assuming every MS star has one such planet for which the masses can be measured to 20%
  - These are probably enough to ensure all science goals are met

Planet Discoveries by Method

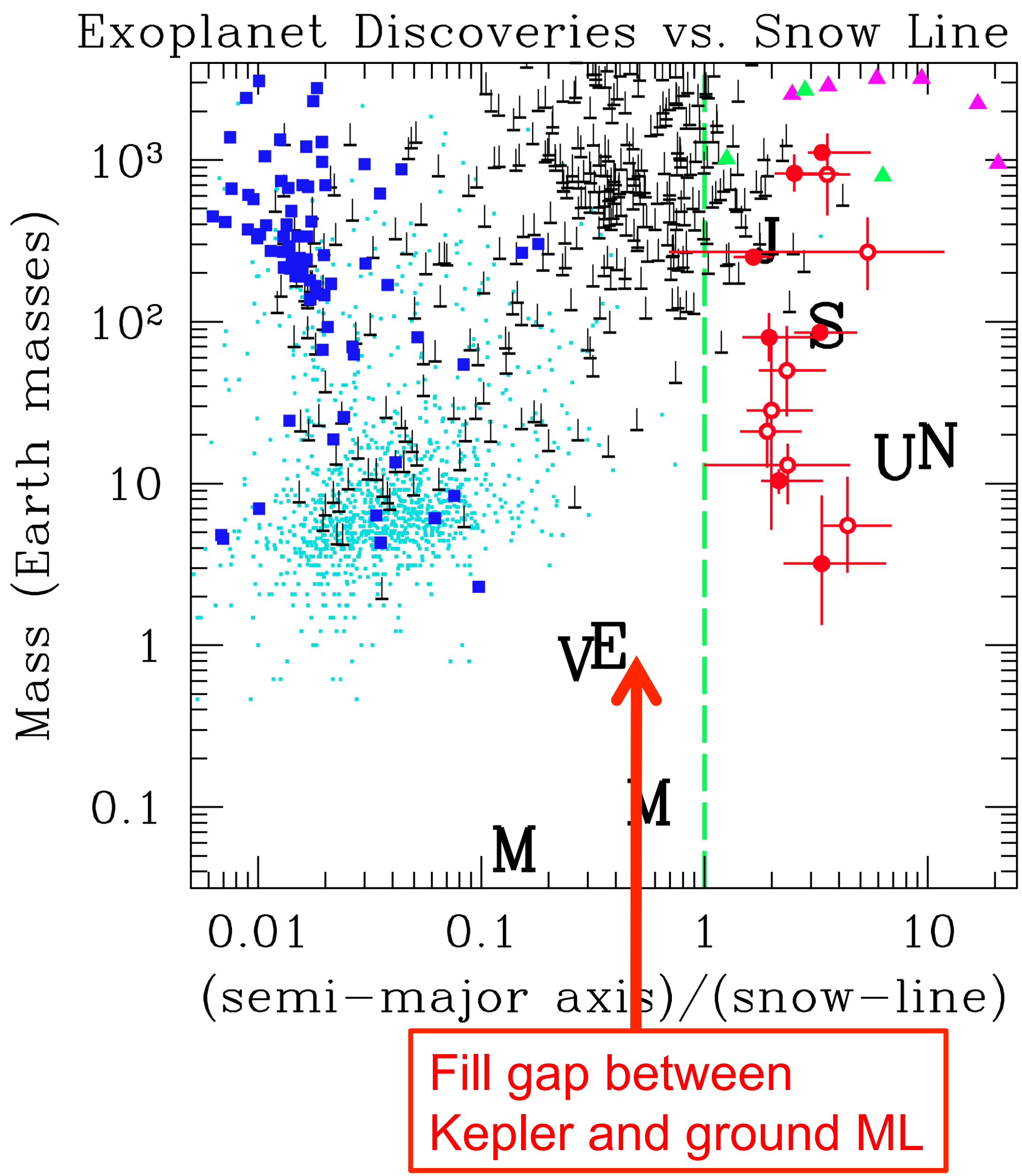
- ~400 Doppler discoveries in black
- Transit discoveries are blue squares
- Gravitational microlensing discoveries in red
  - cool, low-mass planets
- Direct detection, and timing are magenta and green triangles
- Kepler candidates are cyan spots



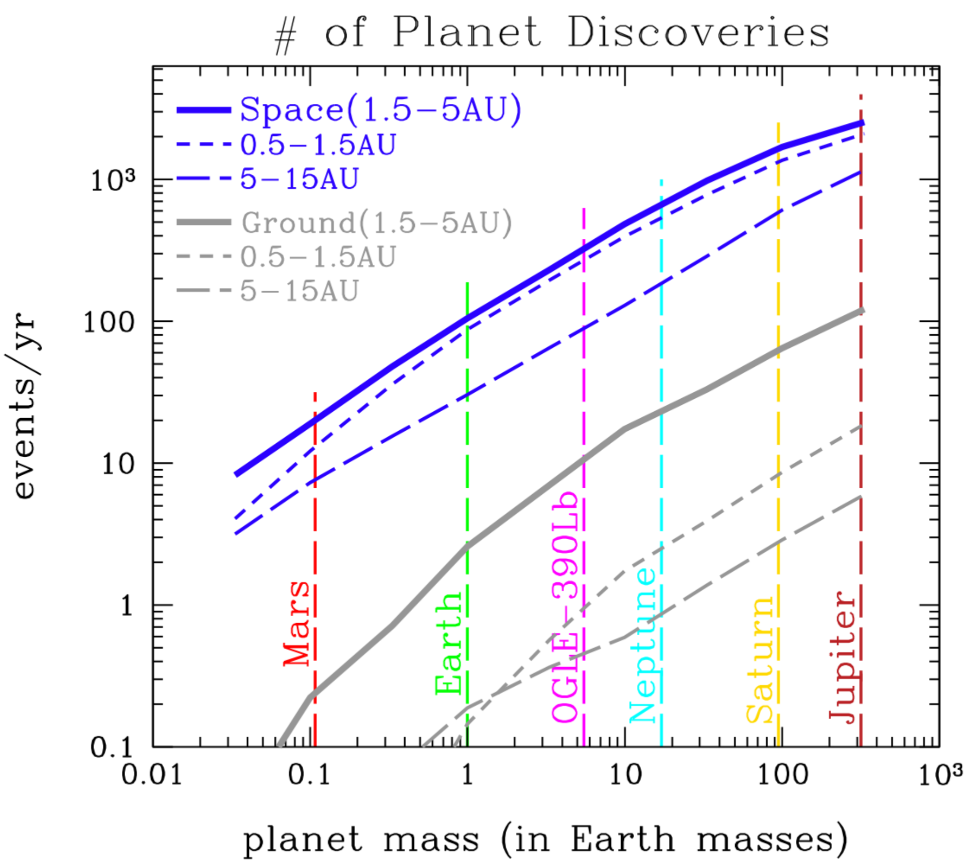
Planet mass vs. semi-major axis/snow-line

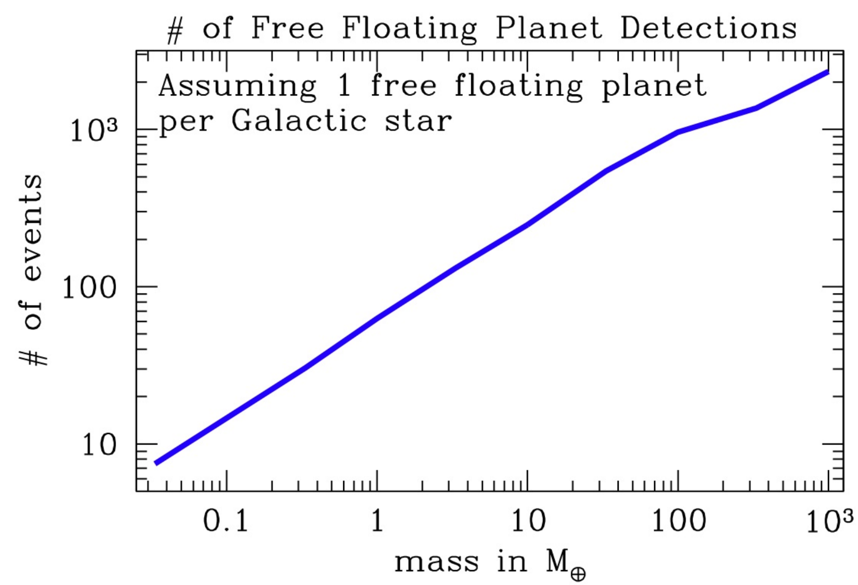
- "snow-line" defined to be 2.7 AU ($M/M_{\odot}$)
  - since L$\propto M^2$ during planet formation
- Microlensing discoveries in **red.**
- Doppler discoveries in black
- Transit discoveries shown as blue circles
- Kepler candidates are cyan spots

- Super-Earth planets beyond the snow-line appear to be the most common type yet discovered



WFIRST IDRM's Predicted Discoveries



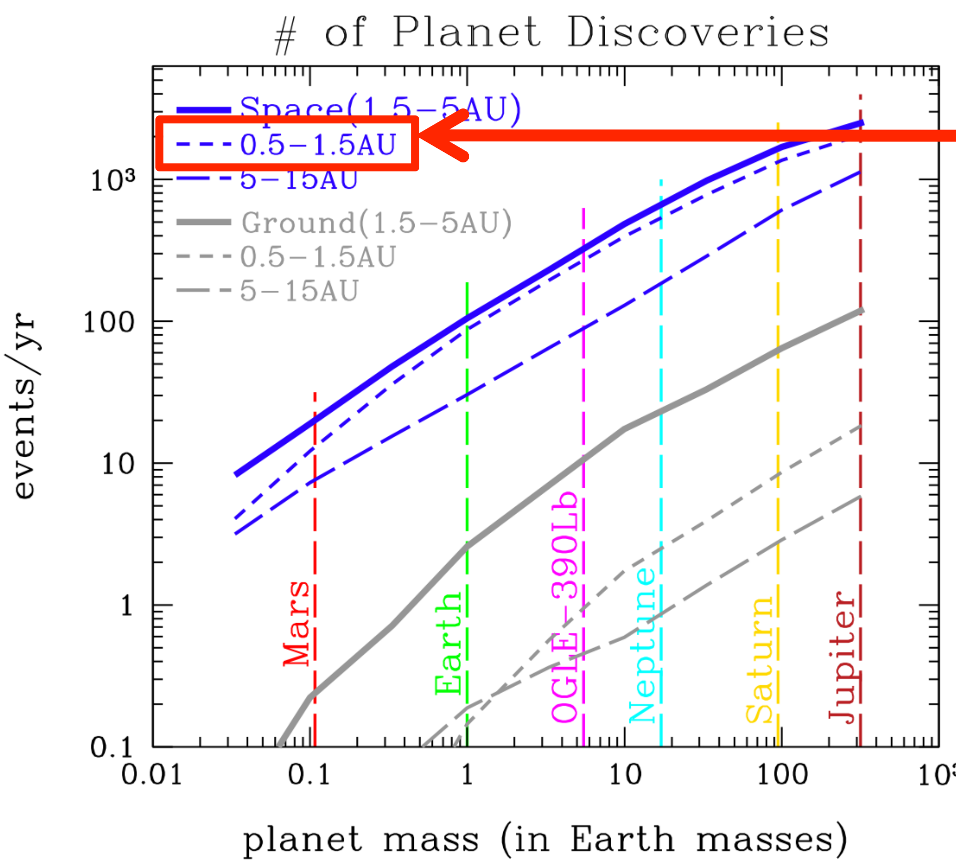


The number of expected WFIRST planet discoveries per 8-month observing season as a function of planet mass.

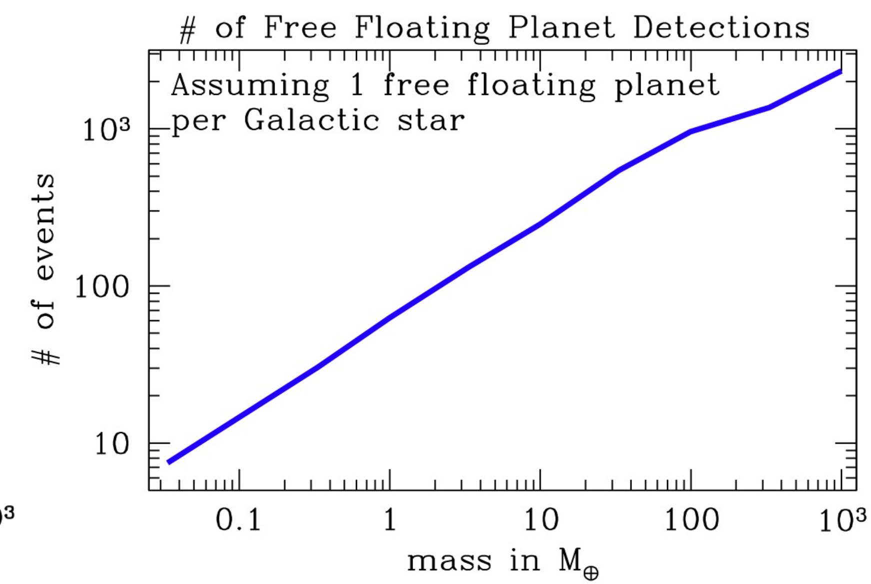
Current exoplanet statistics imply:

- 3250 exoplanet discoveries
  - 320 w/ $M < 1\ M_\oplus$
  - 1050 w/ $M < 10\ M_\oplus$
- 2080 free-floating exoplanets
  - 190 w/ $M < 1\ M_\oplus$
  - 480 w/ $M < 10\ M_\oplus$

WFIRST's Predicted Discoveries



Pick a separation range that cannot be done from the ground; wider separation planets will also be detected.



The number of expected WFIRST planet discoveries per 9-months of observing as a function of planet mass.

WFIRST Microlensing Figure of Merit

- FOM1 - # of planets detected for a particular mass and separation range
  - Cannot be calculated analytically – must be simulated
    - Analytic models of the galaxy (particularly the dust distribution) are insufficient
  - Should not encompass a large range of detection sensitivities.
  - Should be focused on the region of interest and novel capabilities.
  - Should be easily understood and interpreted by non-microlensing experts
    - (an obscure FOM understood only be experts may be ok for the DE programs, but there are too few microlensing experts)
- FOM2 – habitable planets - sensitive to Galactic model parameters
- FOM3 – free-floating planets – probably guaranteed by FOM1
- FOM4 – number of planets with measured masses
    - Current calculations are too crude

Figure of Merit

$$FOM \equiv (N_{\oplus} N_{HZ} N_{ff} N_{20\%})^{3/8} \propto T^{3/2}$$

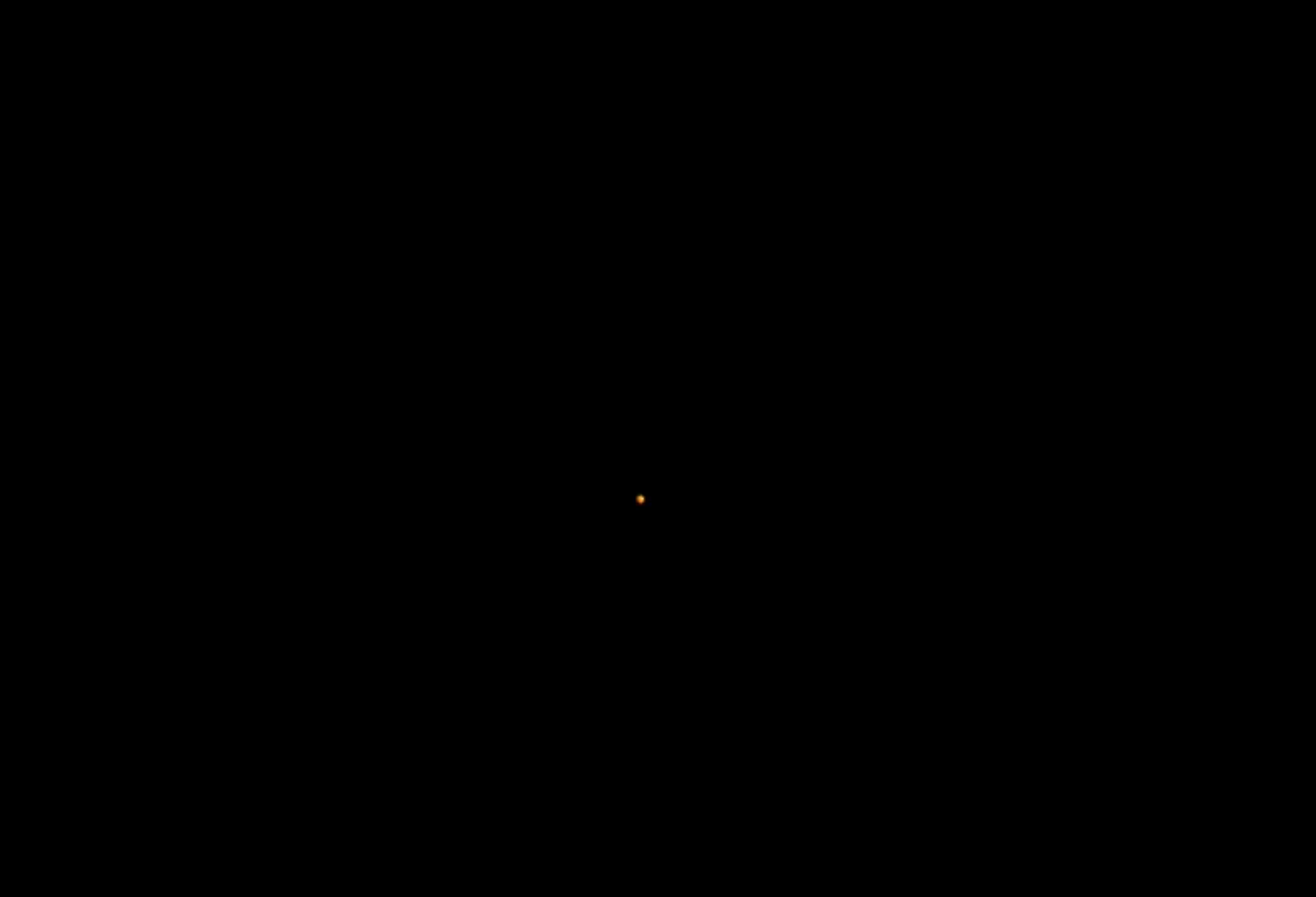
1. *$N_{\oplus}$*: Number of planets detected (at $\Delta\chi^2$=160) with a M=$M_{\oplus}$ and P = 2 yr, assuming every MS star has one such planet.
   - Region of parameter space difficult to access from the ground.
   - Uses period rather than semimajor axis as P/R_E is a weaker function of primary mass than a/R_E.
   - Designed to be diagnostic of the science yield for the experiment. If mission can detect these planets, guaranteed to detect more distant planets
2. *N_{HZ}*: Number of habitable planets detected assuming every MS star has one, where habitable means 0.5-10M_{Earth}, and [0.72-2.0 AU]$(L/L_{sun})^{1/2}$

3. *N_{ff}*: The number of free-floating 1M_{Earth} planets detected, assuming one free floating planet per star.

4. *$N_{20\%}$*: The number of planets detected with a $M=M_{Earth}$ and P=2 yr for which the primary mass can be determined to 20%.

WFIRST vs. MPF vs. Euclid

	MPF	IDRM	DRM1.2	DRM1.4	Euclid
aperture	1.1m obs.	1.3m	1.3m	1.3m	1.2m obs.
Image FOV	0.65 deg^2	0.29 deg^2	0.38 deg^2	0.56 deg^2	0.47 deg^2
IR detectors	35 2RG	28 2RG	36 2RG	15 4RG	16 2RG
opt detectors	0	0	0	0	36
det. grade	3	1	1	1	1
ASICs	7	28	36	15	16
pixel scale	0.24”	0.18”	0.18”	0.17”	0.3”/0.1”
μL passband	0.6-1.7μm	1.0-2.0μm	1.0-2.0μm	1.0-2.0μm	J or H
orbit	Incl. GEO	L2	L2	L2	L2
blg. seasons	270 days	2×72 days	2×72 days	2×72 days	2×30 days
μL program duration	3 yrs	1.5 yrs	~1.5 yrs	~1.5 yrs	0-? yrs



Videos by D. Bennett & A. Williams