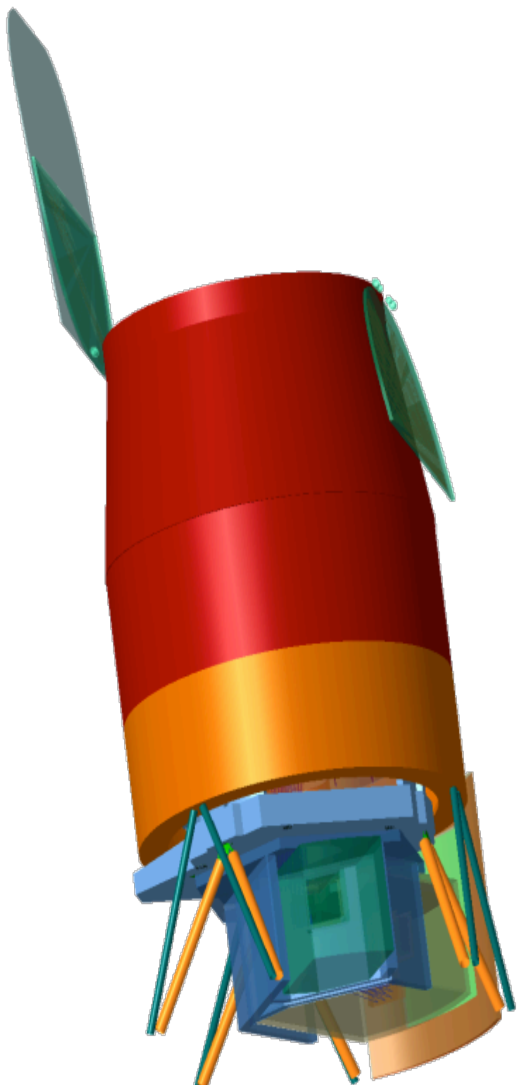
High Precision Photometry+Astrometry for Microlensing from Space



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with help from
Jay Anderson and
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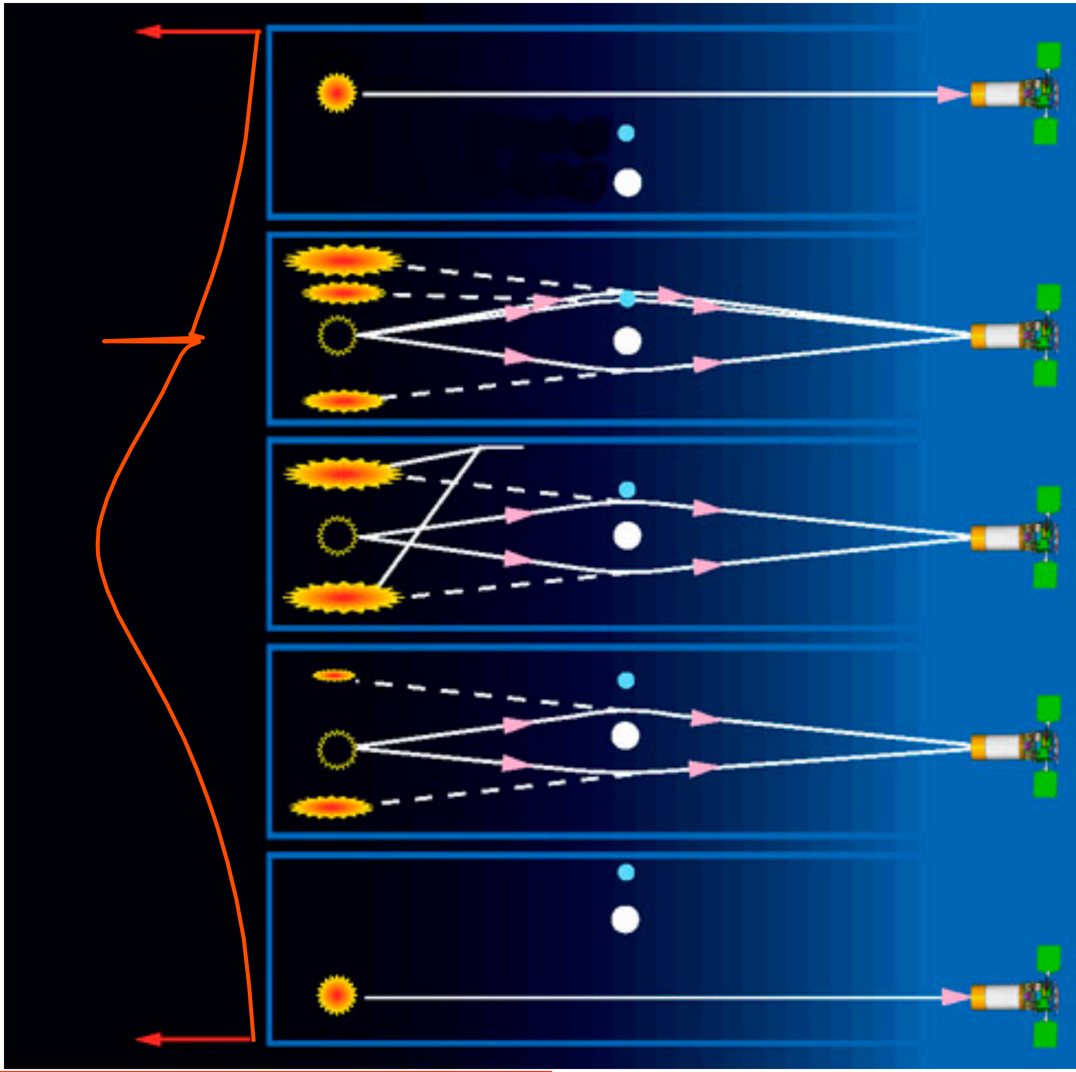
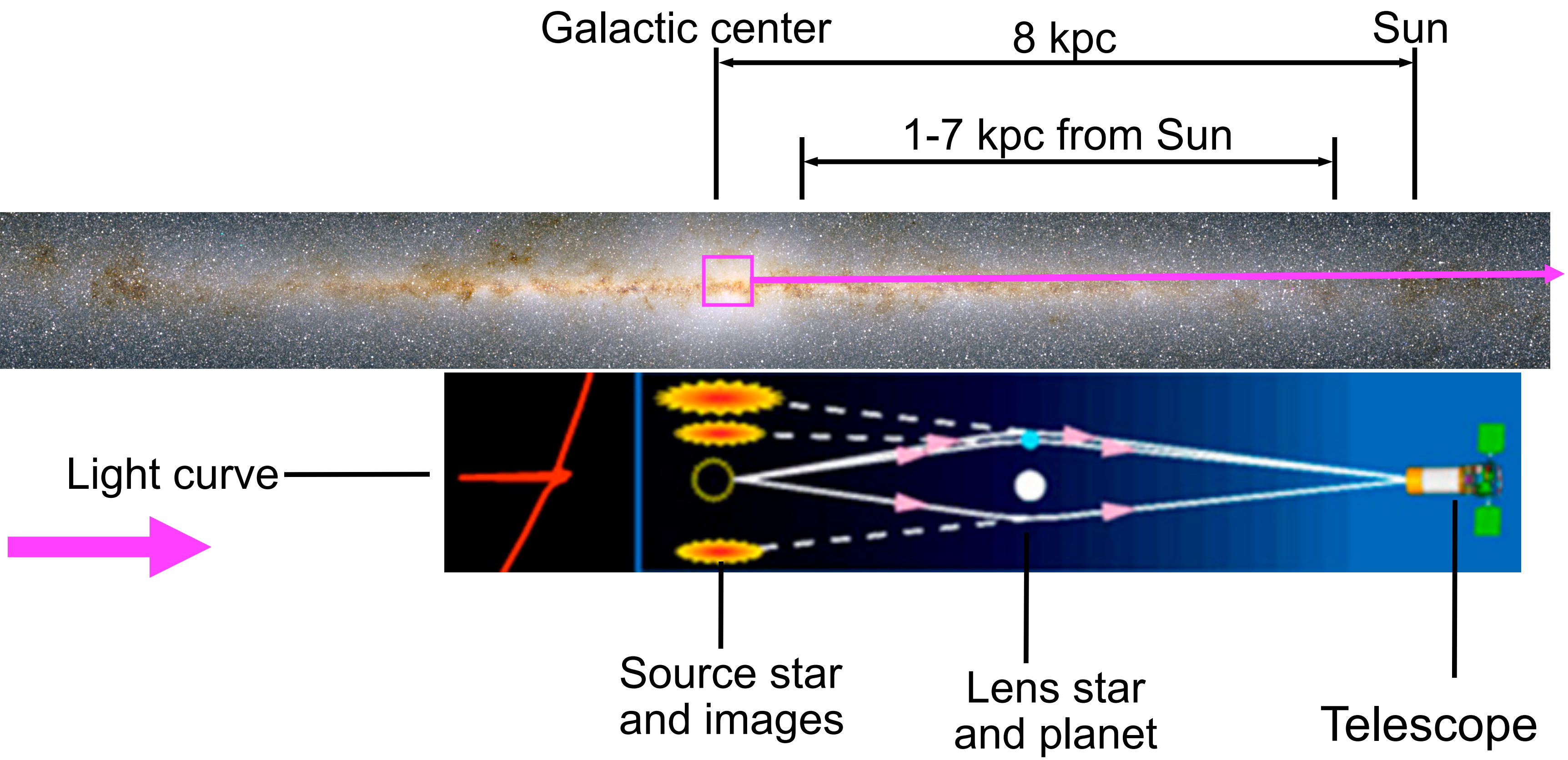
The Physics of Microlensing

- 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



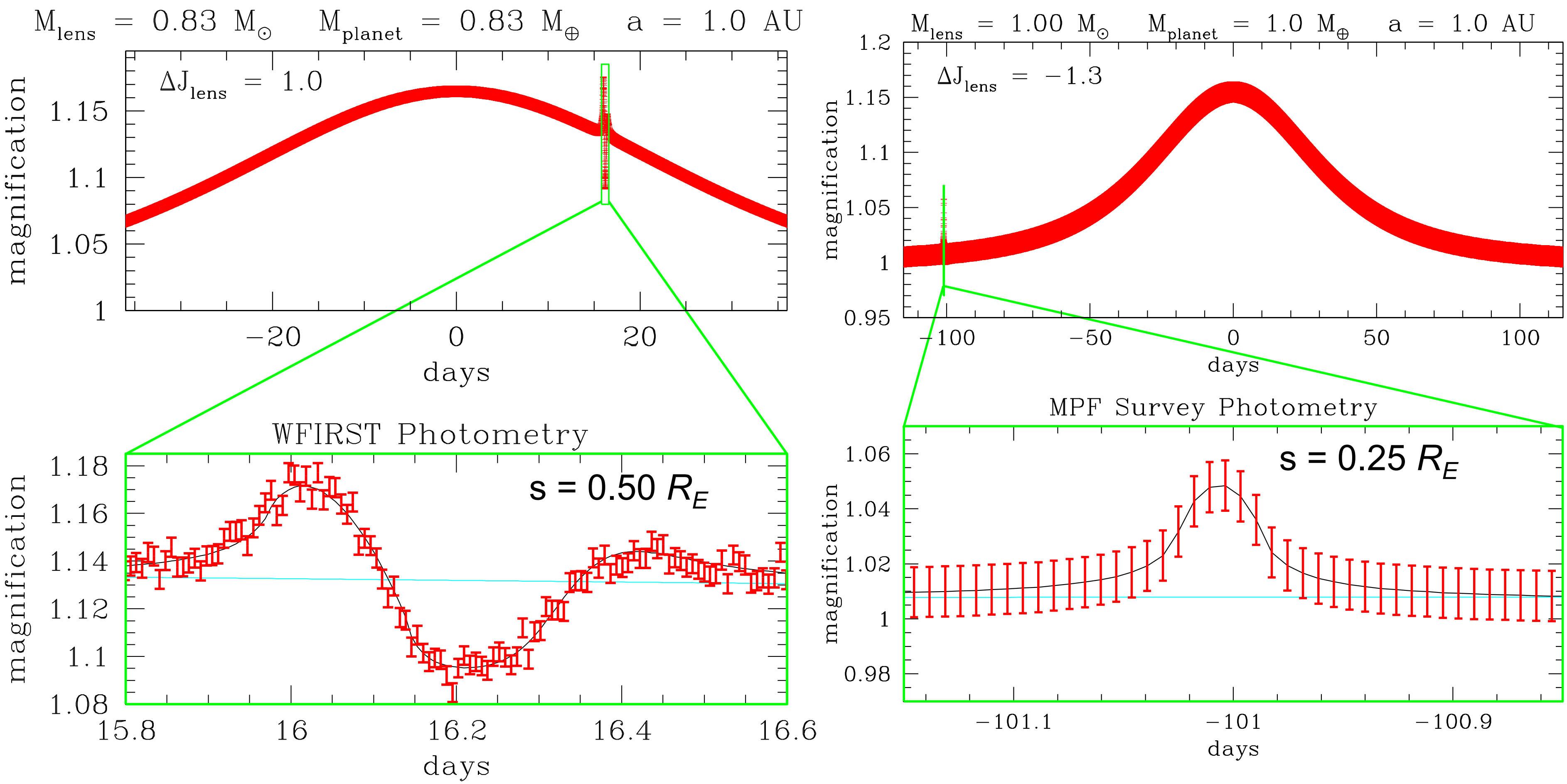
Key Fact: $1 \text{ AU} \approx \sqrt{R_{Sch} R_{GC}} = \sqrt{\frac{2GM}{c^2} R_{GC}}$

Microlensing Demands Crowded Galactic Bulge Fields



Lensing rate /area ~ (# of source stars)×(# of lens stars)

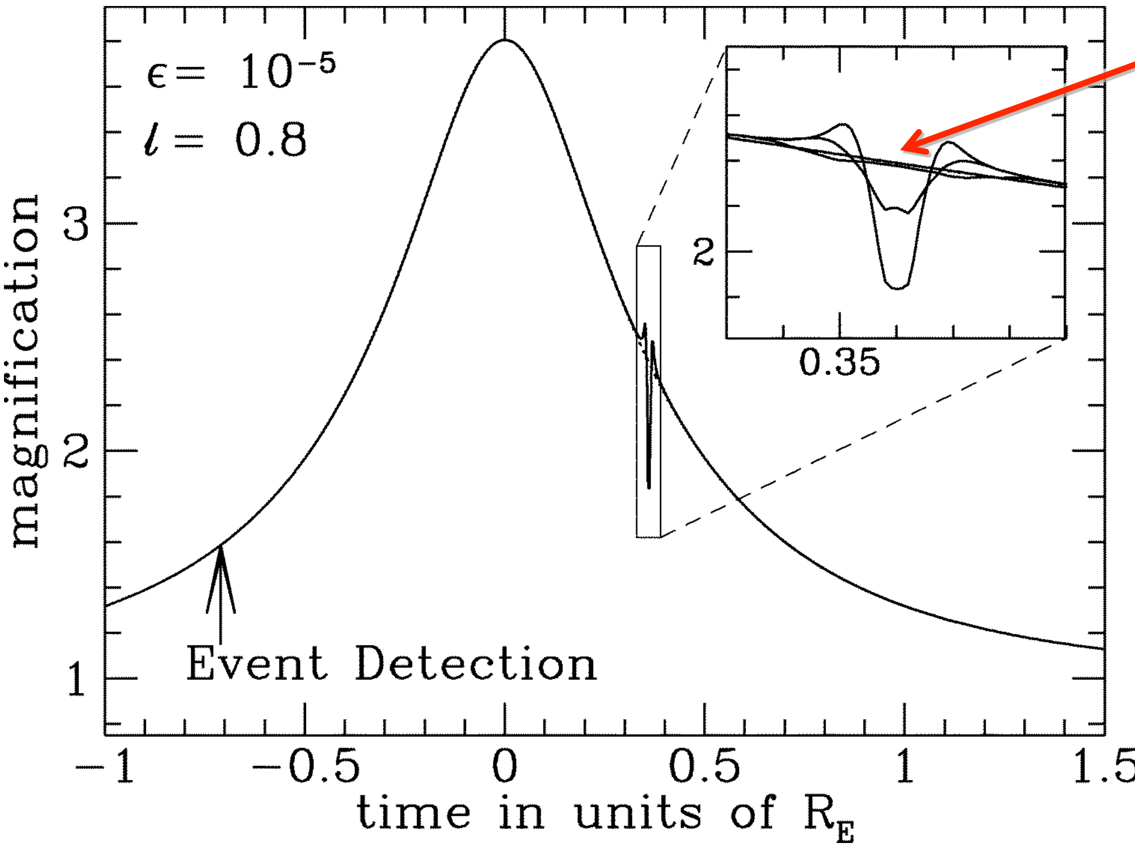
Close (HZ) Planets Found at Low Magnification



- Faint main sequences sources needed to detecting low-mass planets
- At separations < R_E, planetary signals occur at low stellar magnification
- Matthew Penny’s talk from yesterday

How Low Can We Go?

No signal for giant sources



(Bennett & Rhie 1996)

Limited by Source Size

angular Einstein radius

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

$\updownarrow$

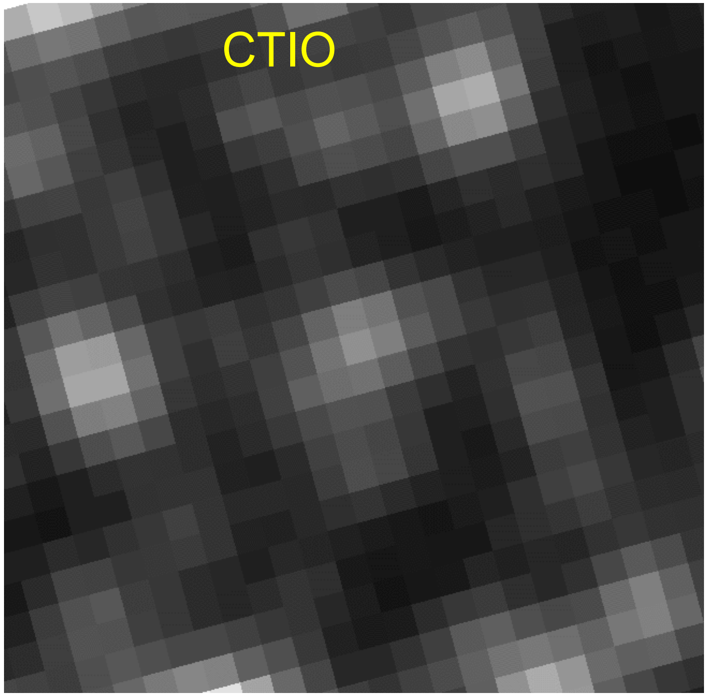
$$\theta_* \approx \mu\mathrm{as}\left(\frac{R_*}{R_\odot}\right)$$

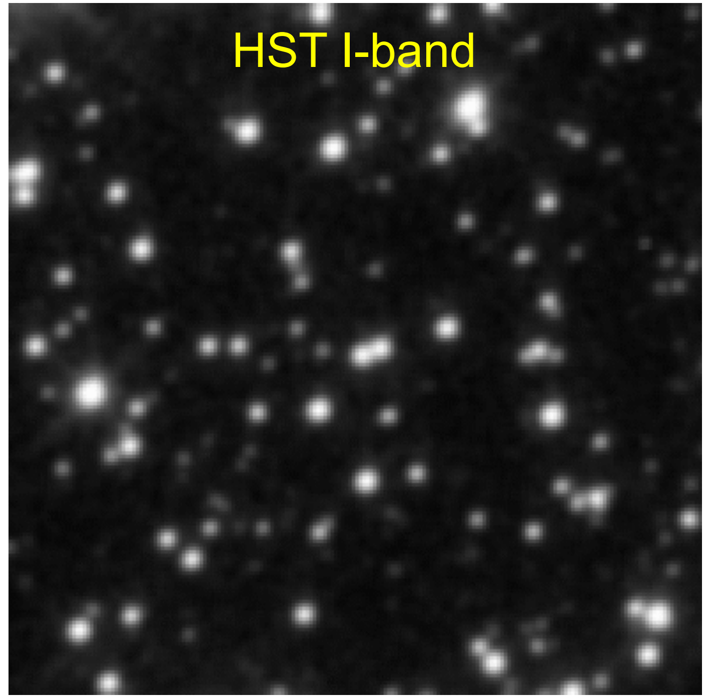
angular source star radius

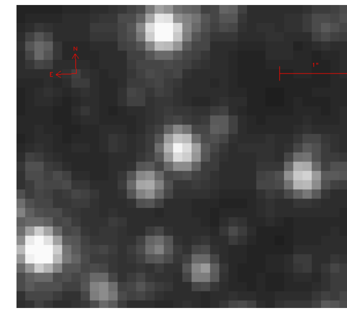
For $\theta_E \geq \theta_*$:
low-mass planet signals are rare and brief, but not weak

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

Space Imaging Resolves Source+Lens from Other Stars







HST J-band

- Bulge main sequence stars not resolved in seeing limited images
- WFIRST fields should be 2× more crowed
- Flatter luminosity function in the IR adds to crowding

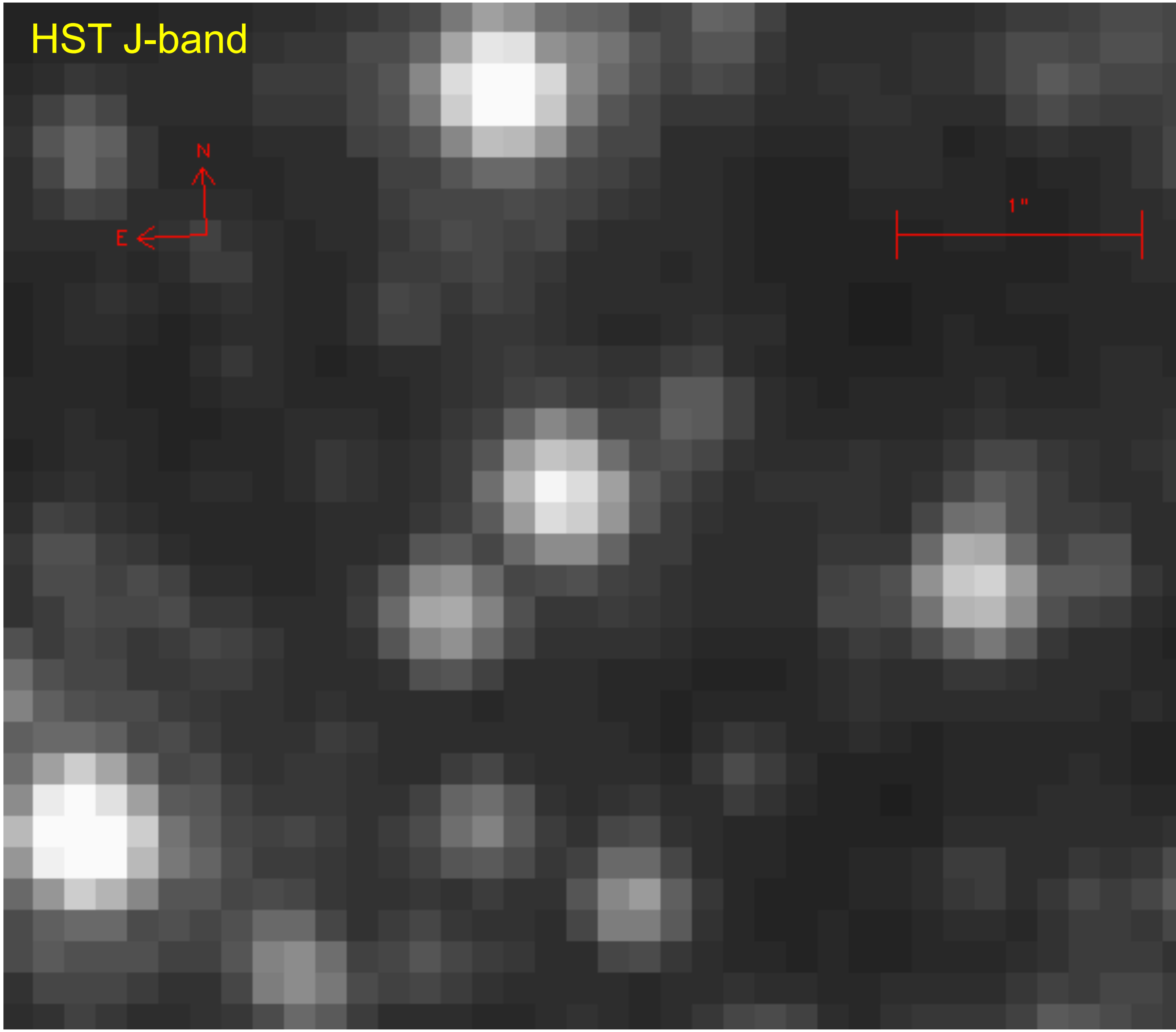
Galactic bulge photometry in the IR

Most stars are not completely blended, but the images overlap.

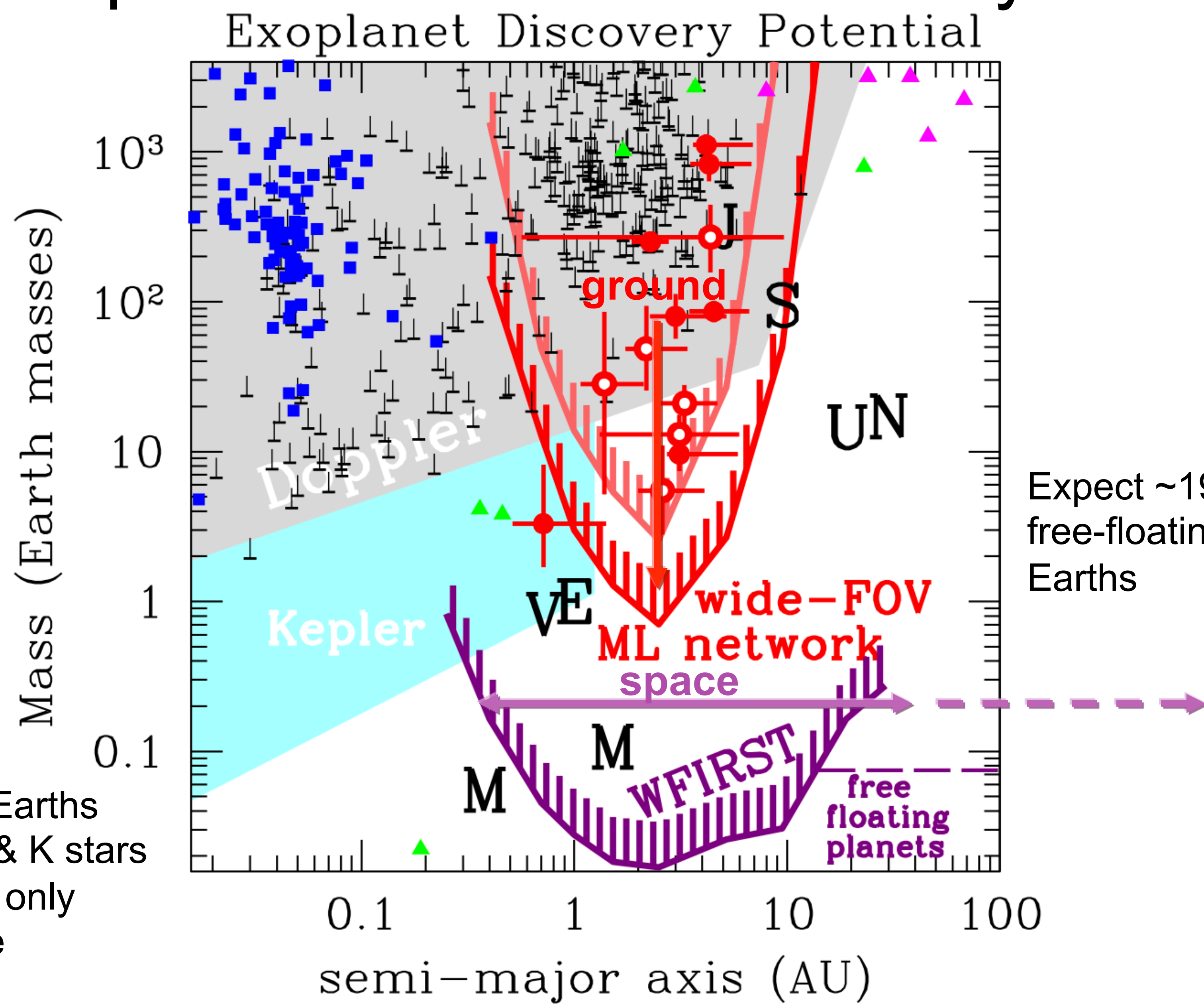
High precision photometry (~1 mmag) needed with overlapping images

Proper motion of neighbors must be accounted for:

Precision photometry requires precision astrometry



Space vs. Ground Sensitivity



Expect ~190 free-floating Earths

Habitable Earths orbiting G & K stars accessible only from space

Microlensing Survey Stars Will Not Be Isolated

- Proper motion of neighboring stars will contribute to photometry noise
- We need astrometry information for our determination of host star properties
- We want a WFIRST-AFTA exoplanet microlensing pipeline that generates
  - Photometry
  - Astrometry
  - A catalog of detector defects

- PSF-fitting photometry – similar to Jay Anderson's code for HST

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- Develop exoplanet microlensing photometry+astrometry pipeline pre-launch using HST/WFC3/IR data

Crowded Field Photometry

- PSF fitting photometry
  - not optimal for ground-based microlensing because we can't locate individual stars
- Difference image photometry (DIA)
  - Target star location clear from isolated signal in difference image

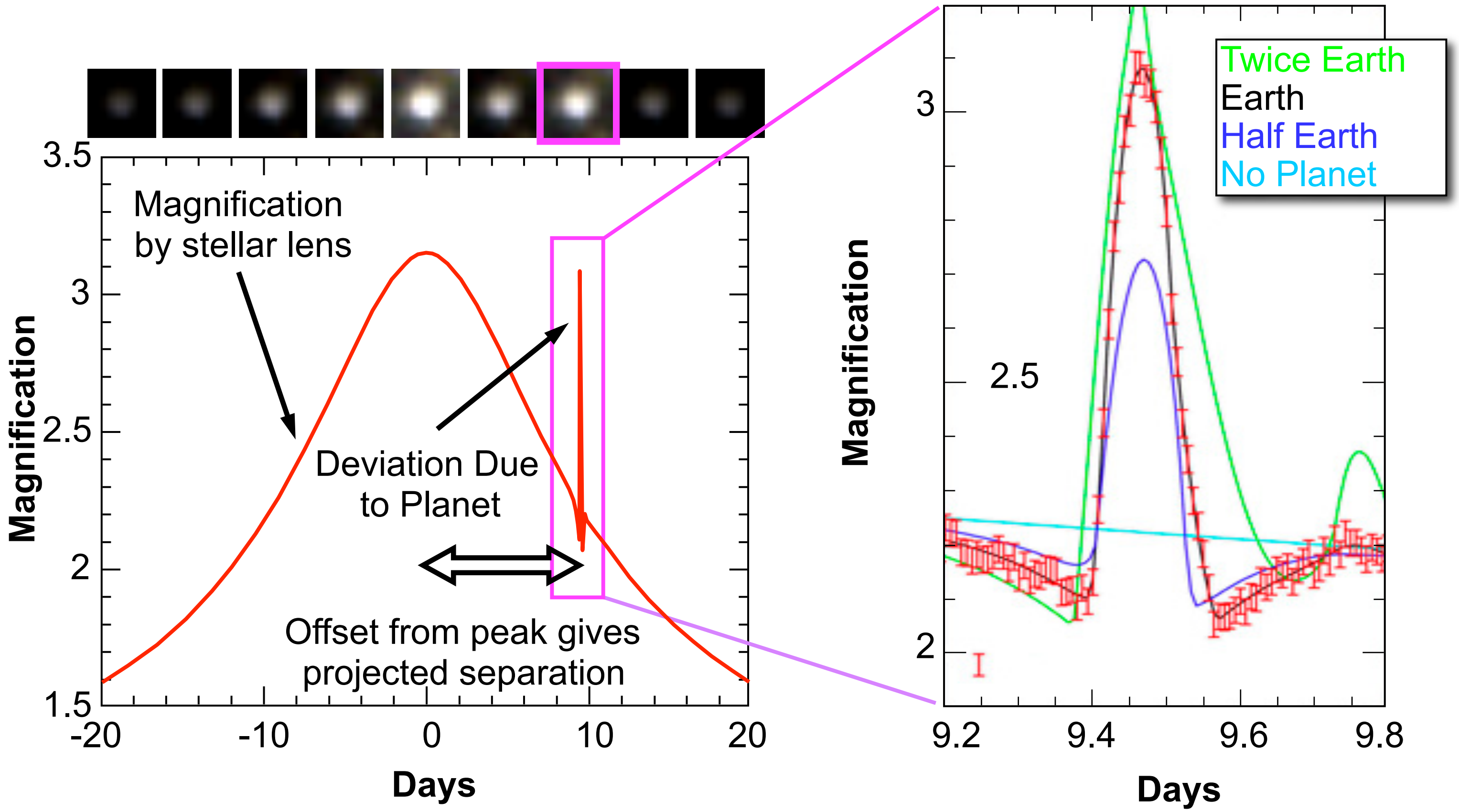
- WFIRST differs because
  - Very stable PSF (much better than HST)
  - Proper motion effects are large
    - Standard DIA not likely to be accurate
  - PSFs in W149 filter are color-dependent
  - Strong parallax effects between spring and fall seasons
- PSF fitting photometry is likely optimal
  - but should include proper motions, parallax and color dependent PSF
  - Jay Anderson's HST analysis code is a good starting point

WFIRST Microlensing Pipeline

- Solve for photometry, color, and astrometry (proper motion and parallax) of each star
  - Also, search for “new” stars
- Solve for detector effects, and their change in time
  - detector radiation effects
  - temperature effects
  - changing hot pixels
  - PSF shape changes
- What calibration data are needed by other programs?
- Microlensing pipeline can likely be used for a calibration field in the LMC, which is observable at anytime

Extraction of Exoplanet Parameters: Part 1

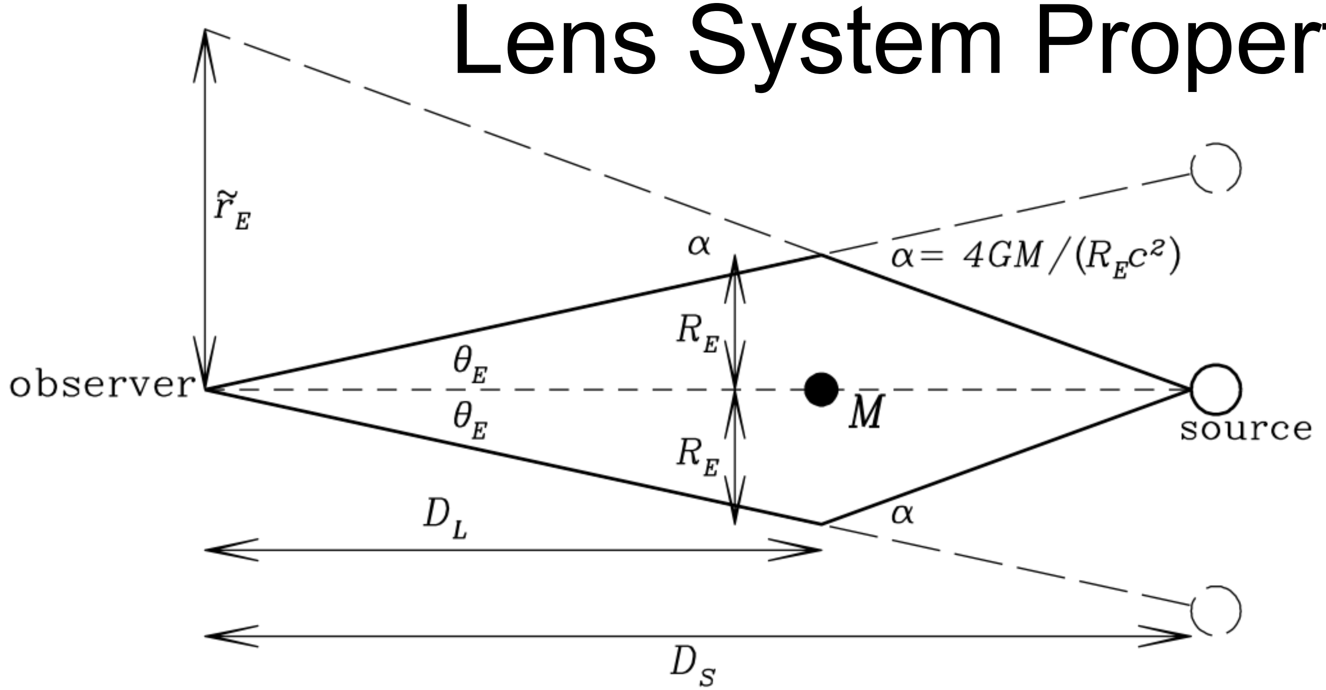
Time-series photometry is combined to uncover light curves of background source stars being lensed by foreground stars in the disk and bulge.



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.

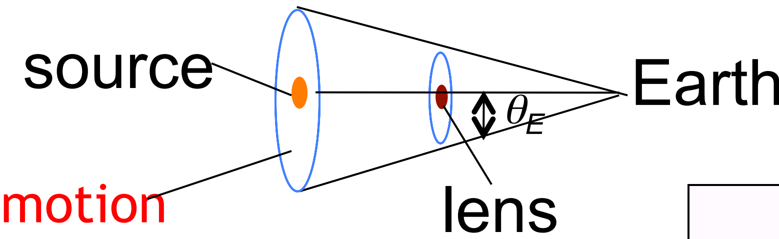
Lens System Properties



- 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).

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

Part 2: Finite Source Effects & Microlensing Parallax Yield Lens System Mass



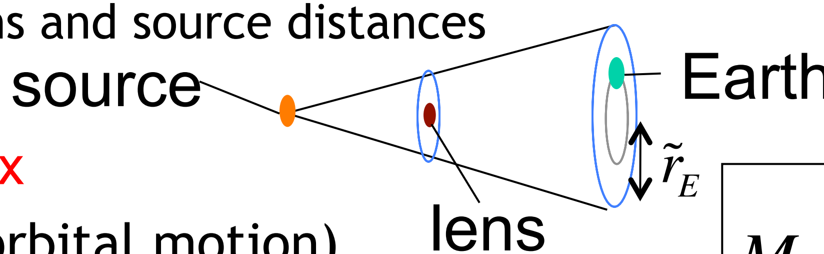
- Finite source effect or lens-source proper motion

  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

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



- 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

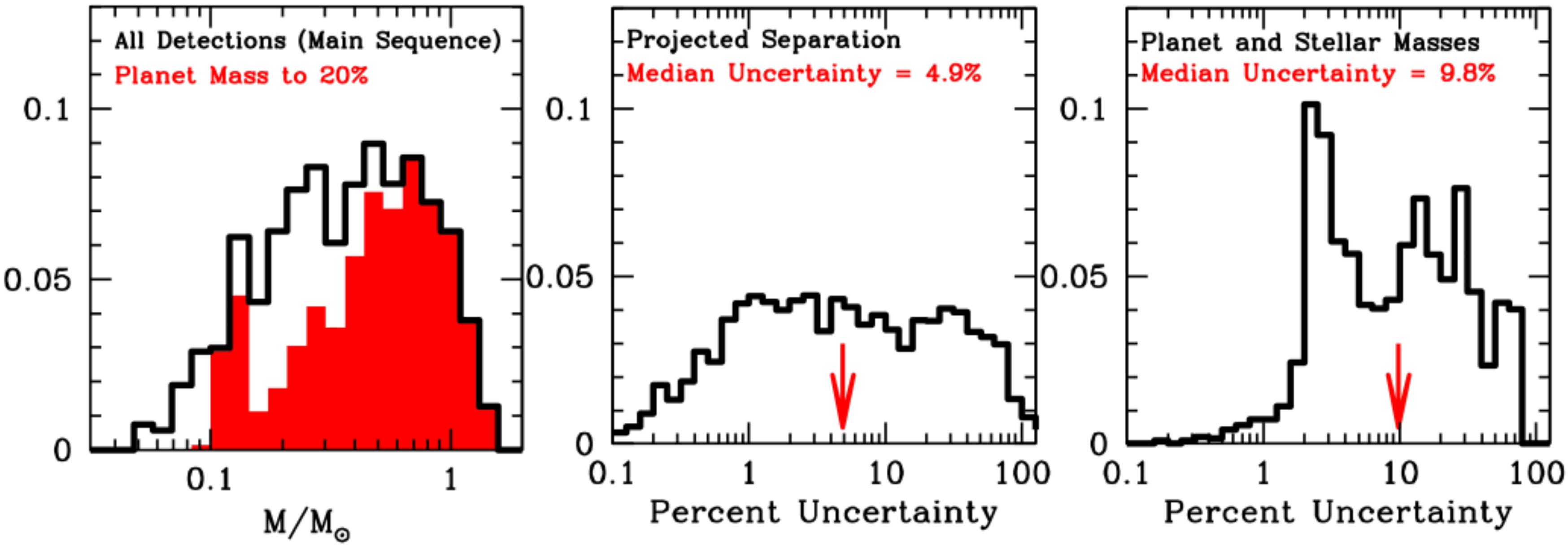
- One of above +

  Lens brightness & color(AO,HST)

  mass-distance relation → D_L

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

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.

Lens-Source Proper Motion is Needed

- Formally, we can get the lens mass with finite source radius, t_*, and lens brightness (say, combined flux – source flux from model), ***BUT***

- The source may have a binary companion, or a unrelated star may be blended with the source
  - Lens-source proper motion verifies the lens star ID
  - Multi-color observations exclude companion to the lens

- Microlensing Parallax measurements are often 1-dimensional
  - But, the parallax vector is parallel to $\boldsymbol{\mu}_{\mathrm{rel}}$, so a relative proper motion measurement sharpens a microlensing parallax measurement

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

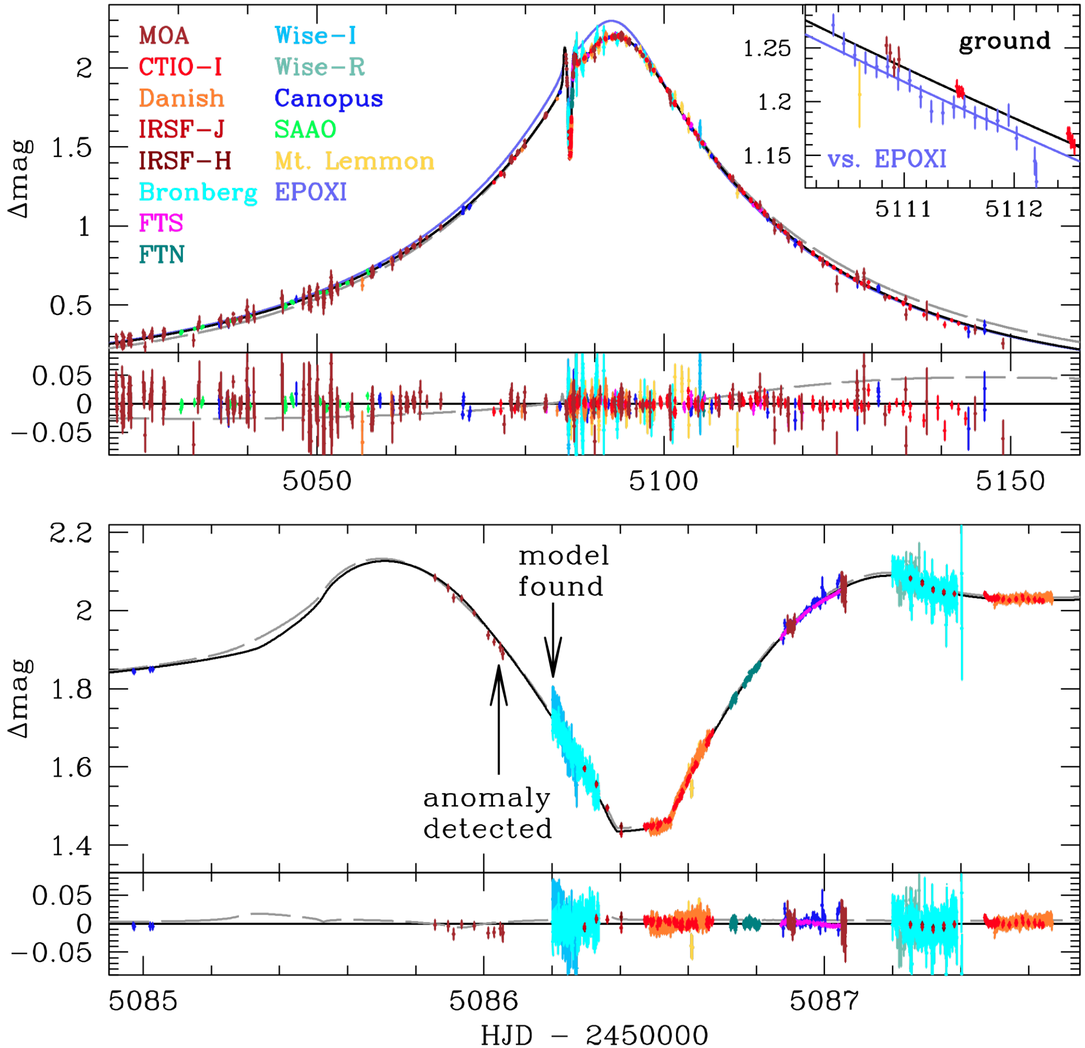
mass-distance relations:

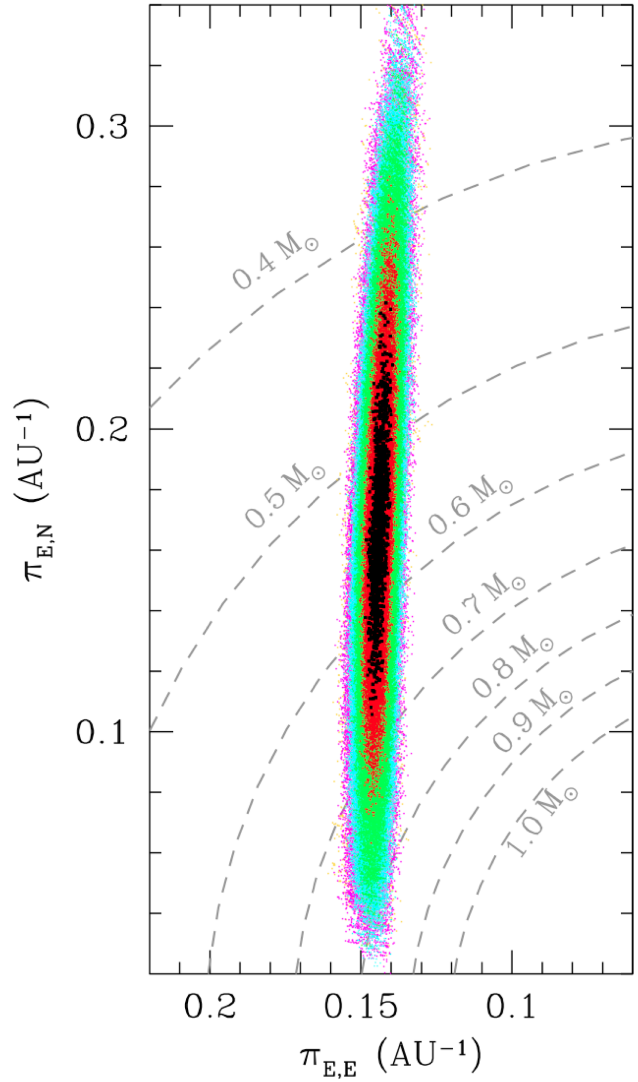
$$M_L = \frac{c^2}{4G}\theta_E^2 \frac{D_S D_L}{D_S - D_L}$$

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

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

MOA-2009-BLG-266 Orbital Parallax





$m_p = 10.4 \pm 1.7 M_\oplus$ $M_* = 0.56 \pm 0.09 M_\odot$

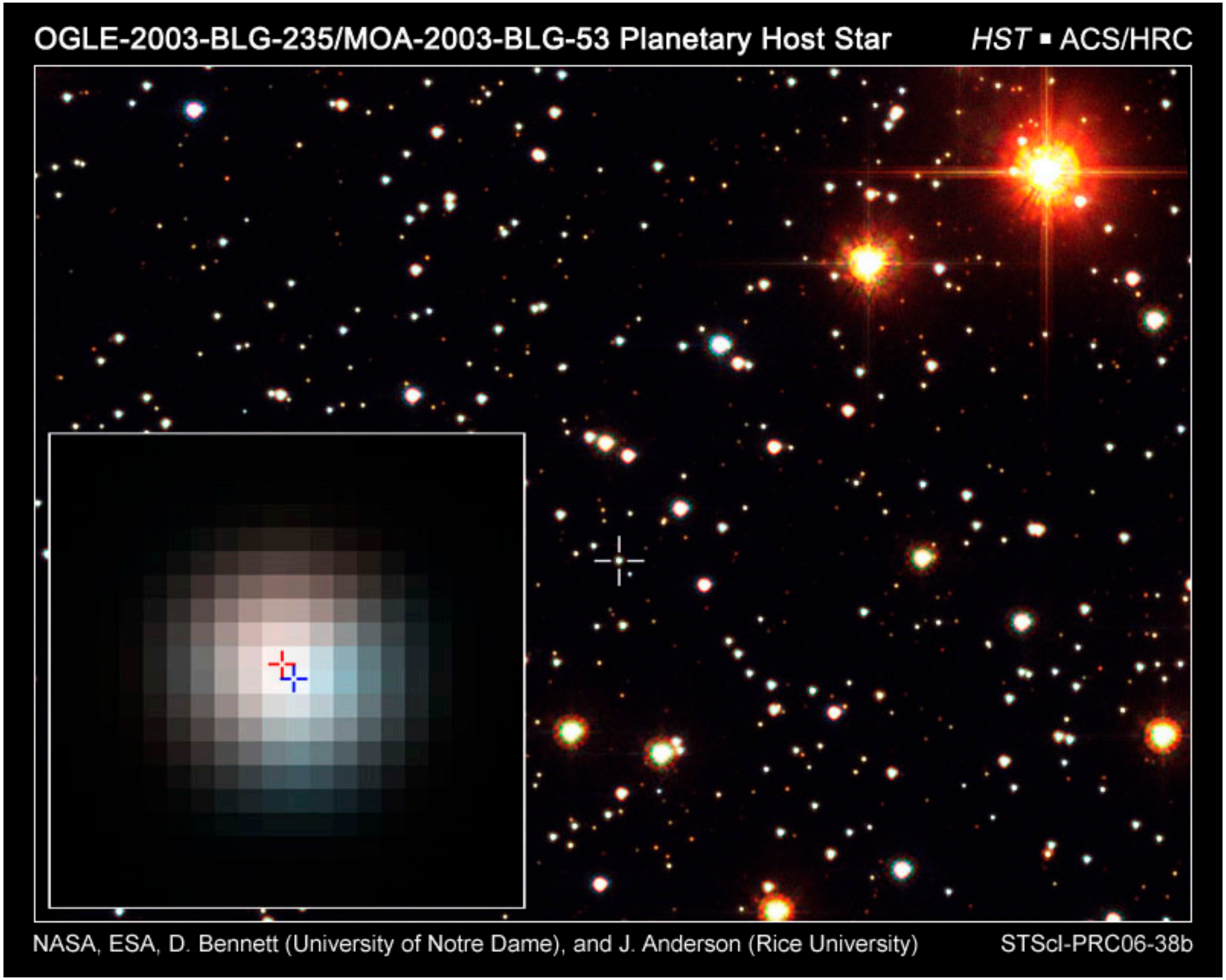
$a = 3.2^{+1.9}_{-1.5}$ AU $D_L = 3.0 \pm 0.3$ kpc

The bulge is near the ecliptic plane so parallax uncertainty is asymmetric

Lens-Source Relative Proper Motion

- Lens and source are not resolved at the time of the microlensing event
- 2 methods to measure $\boldsymbol{\mu}_{\rm rel}$:
  - Color Dependent Centroid shift
    - If lens and source have different colors, the centroid of the blended image will depend on the color
    - Precision scales as t
  - Image Elongation:
    - Blended image will be elongated in the $\boldsymbol{\mu}_{\rm rel}$ direction
    - works if lens and source have the same color
    - Precision scales as t^2
  - In practice, fit for lens and source location with constraints from light curve model

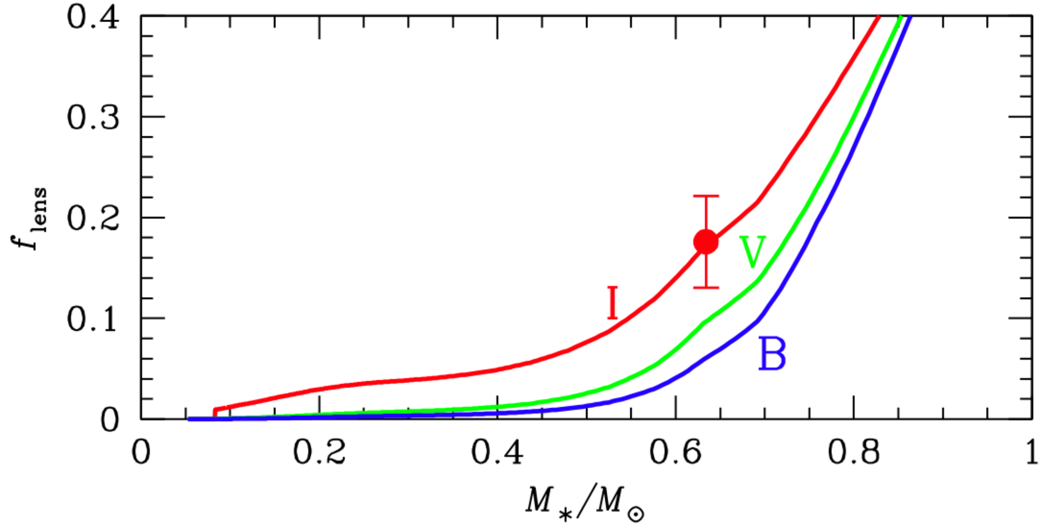
Color Dependent Image Center Shift



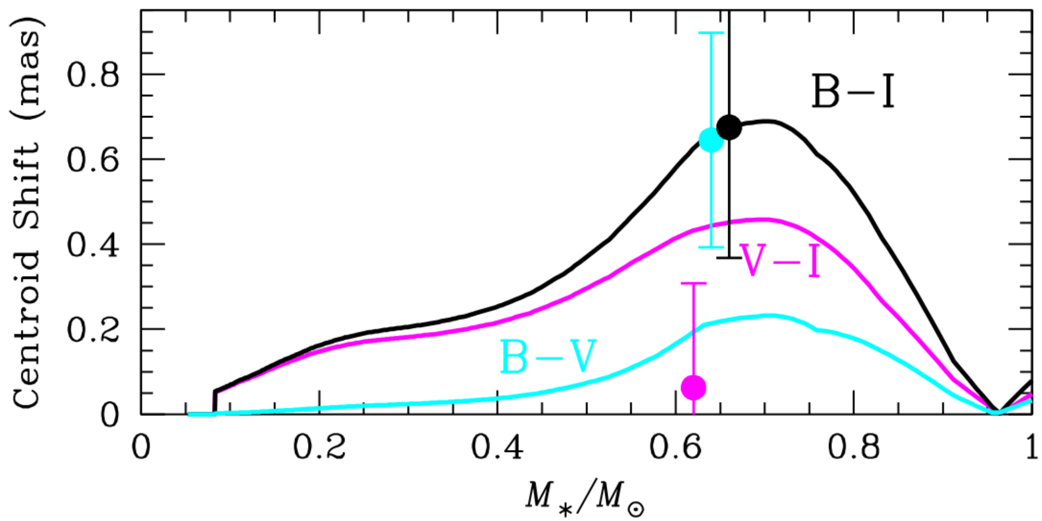
Source & Planetary Host stars usually have different colors, so lens-source separation is revealed by different centroids in different passbands

HST Observation Predictions for OGLE-2003-BLG-235L/MOA-2003-BLG-53L

Fraction of total flux due to lens star.



Centroid Shift between HST-ACS/HRC passbands for follow-up images. (Units are 25 mas pixels.)

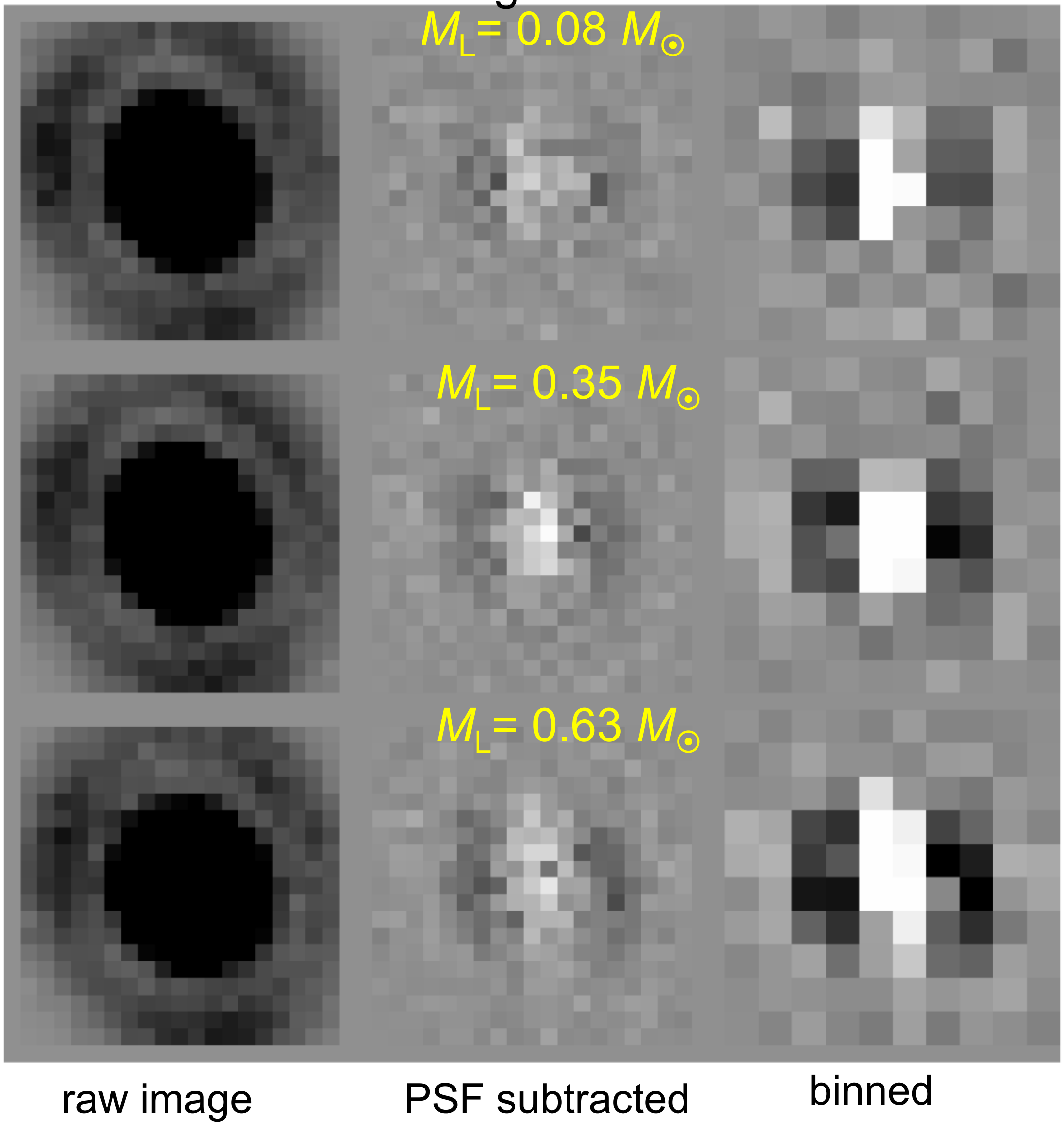


Relative proper motion μ_{rel}= 3.3±0.4 mas/yr from light curve analysis (μ_{rel}= θ_*/t_*)

Predicted Image Elongation

- Lens-source proper motion gives $\theta_E = \mu_{rel} t_E$
- μ_{rel}= 8.4±1.7 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)

Simulated HST images:



First Confirmation of a Planetary Microlensing Signal

- $\boldsymbol{\mu}_{rel}$ measured by HST (and Keck)
- Image elongation

See talk by Aparna Bhattacharya (next!)