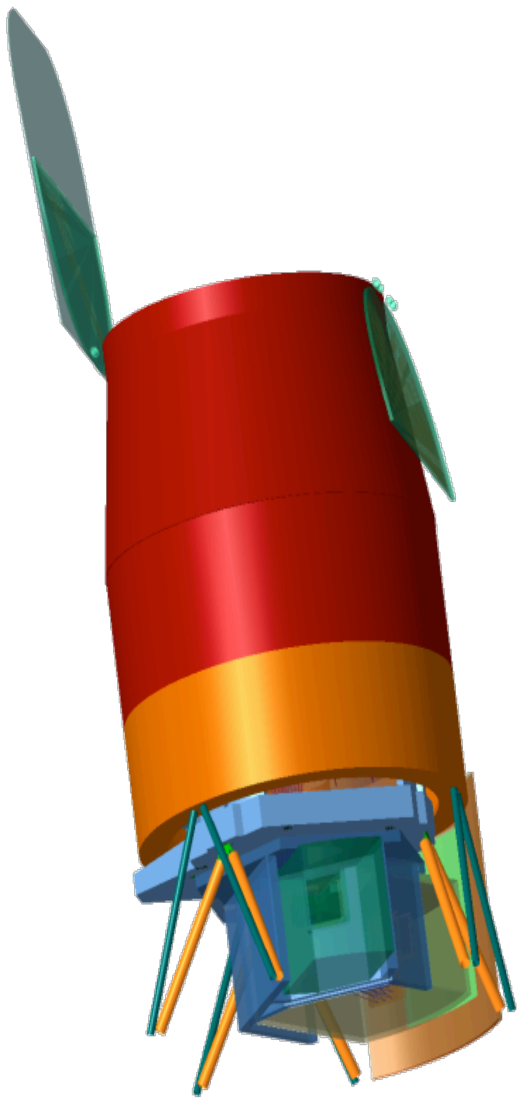
WFIRST-AFTA
Exoplanet Microlensing Precusor Observations



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ExoPAG SAG-11 Report

NASA ExoPAG Study Analysis Group 11:

Preparing for the WFIRST Microlensing Survey

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- Led by Jennifer Yee
- Just released (I think)
- Not a detailed study, but a description of several important precursor programs

Recommended Precursor Observations

- HST precursor observations
  - HST/WFC3/UVIS + ACS observations for pre-WFIRST astrometry
  - HST/WFC3/IR time series observations for photometry/ astrometry pipeline code development
- Ground-based IR microlensing survey to measure lensing rate and select WFIRST-AFTA fields
- Development of Microlensing Expertise
  - HST and AO follow-up of current planet detections
  - Kepler (K2) and Spitzer parallaxes
  - Develop microlensing analysis methods
    - 1 (out of ~50) ground-based planetary light curve not modeled
    - Possibly many stellar binary + planet light curves not recognized

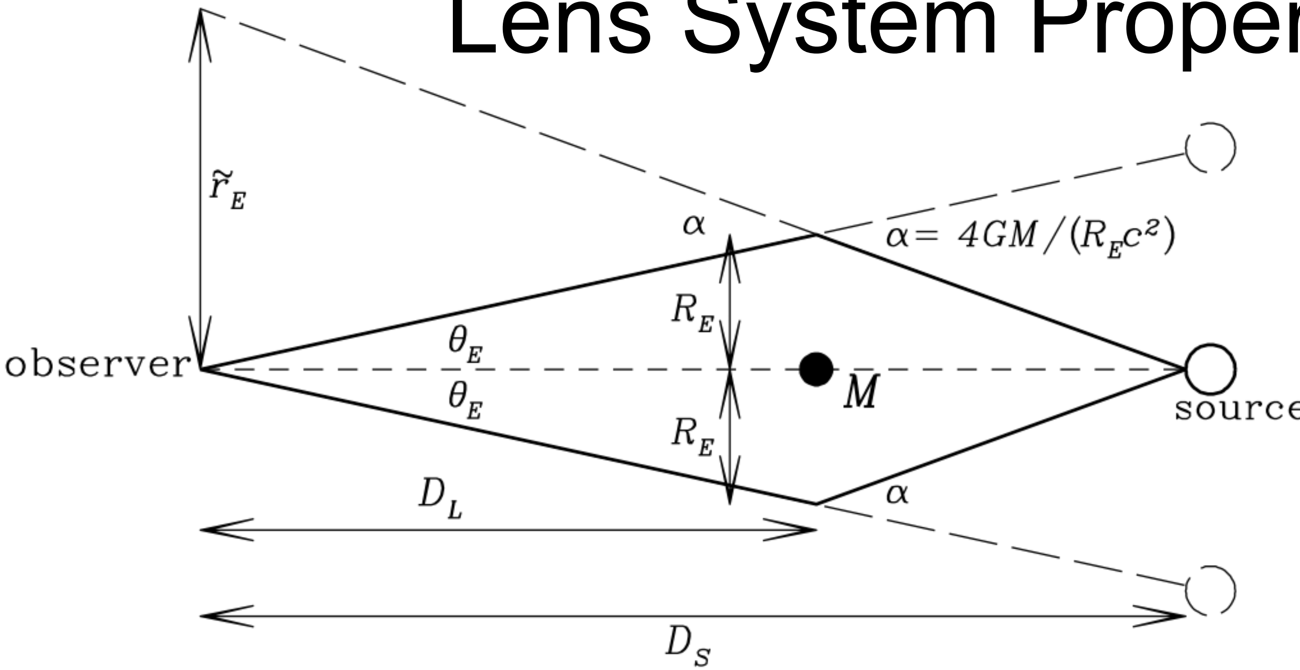
Lens System Mass and Distance from Microlensing Light Curves

- binary lens light curve gives mass ratio, q, and separation, s (in units of R_E)
- t_E depends on M_L, but also on $v_\perp$ and D_L

$$t_E = R_E / v_\perp \quad \text{where} \quad R_E = \sqrt{4GM_L D_S x(1-x)/c^2} \quad \text{and} \quad x = D_L / D_S$$

- There are two ways to improve upon this with light curve data:
  - Planetary light curves usually give source radius crossing time, t_*
  - Determine the angular Einstein radius : $\theta_E = \theta_* t_E / t_* = t_E \mu_{rel}$ where θ_* is the angular radius of the star and μ_{rel} is the relative lens-source proper motion
  - Measure the projected Einstein radius, $\tilde{r}_E$, with the microlensing parallax effect (due to Earth's orbital motion).

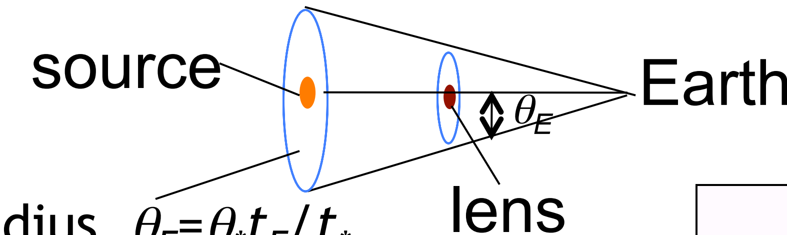
Lens System Properties



- 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).

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

Finite Source Effects & Microlensing Parallax Yield Lens System Mass



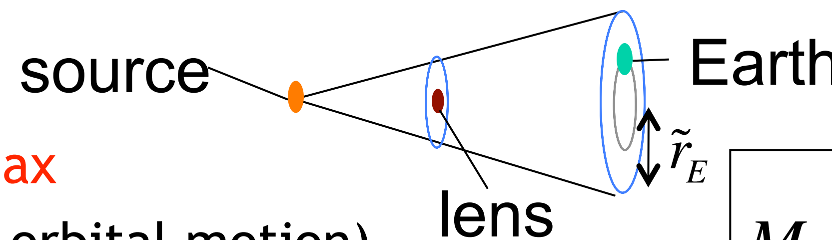
- Finite source effects

  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

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

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:

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

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

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

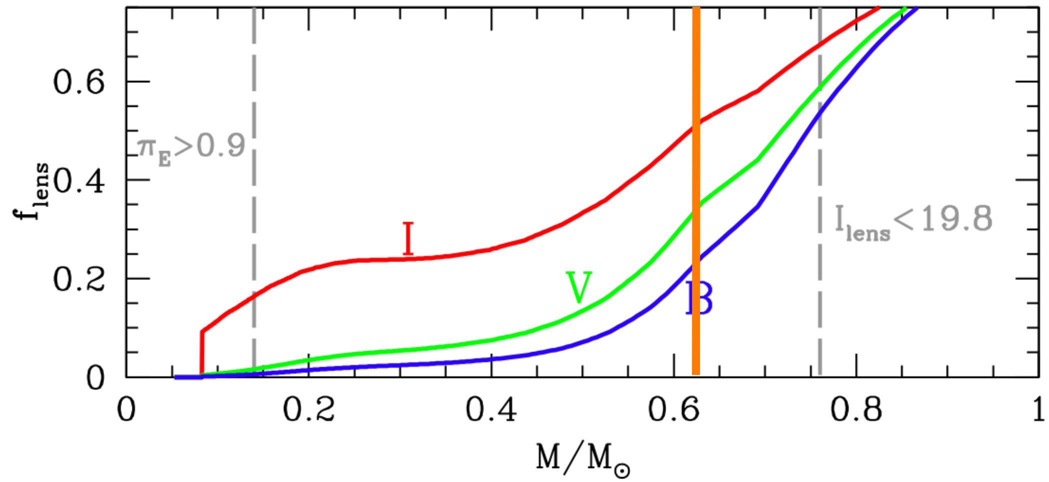
Lens+Source Solution:

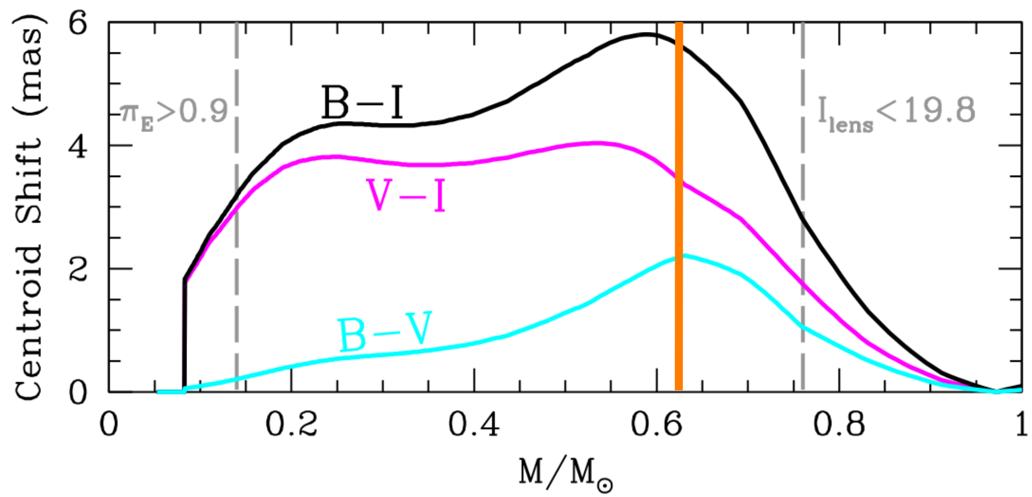
- Offset consistent in the F814W, F555W, and F438W data:
  - Δx = 1.25 pixels = 50 mas
  - Δy = 0.25 pixel = 10 mas
  - FLUX: (left) (right)
    - F814W 3392 e$^-$ 3276 e$^-$
    - F555W 2158 e$^-$ 3985 e$^-$
    - F438W 338 e$^-$ 1029 e$^-$
    - f_I = 0.51
    - f_V = 0.35
    - f_B = 0.25

HST BVI observations imply

$M_* = 0.63\ M_\odot$

$M_p = 17\ M_\oplus$



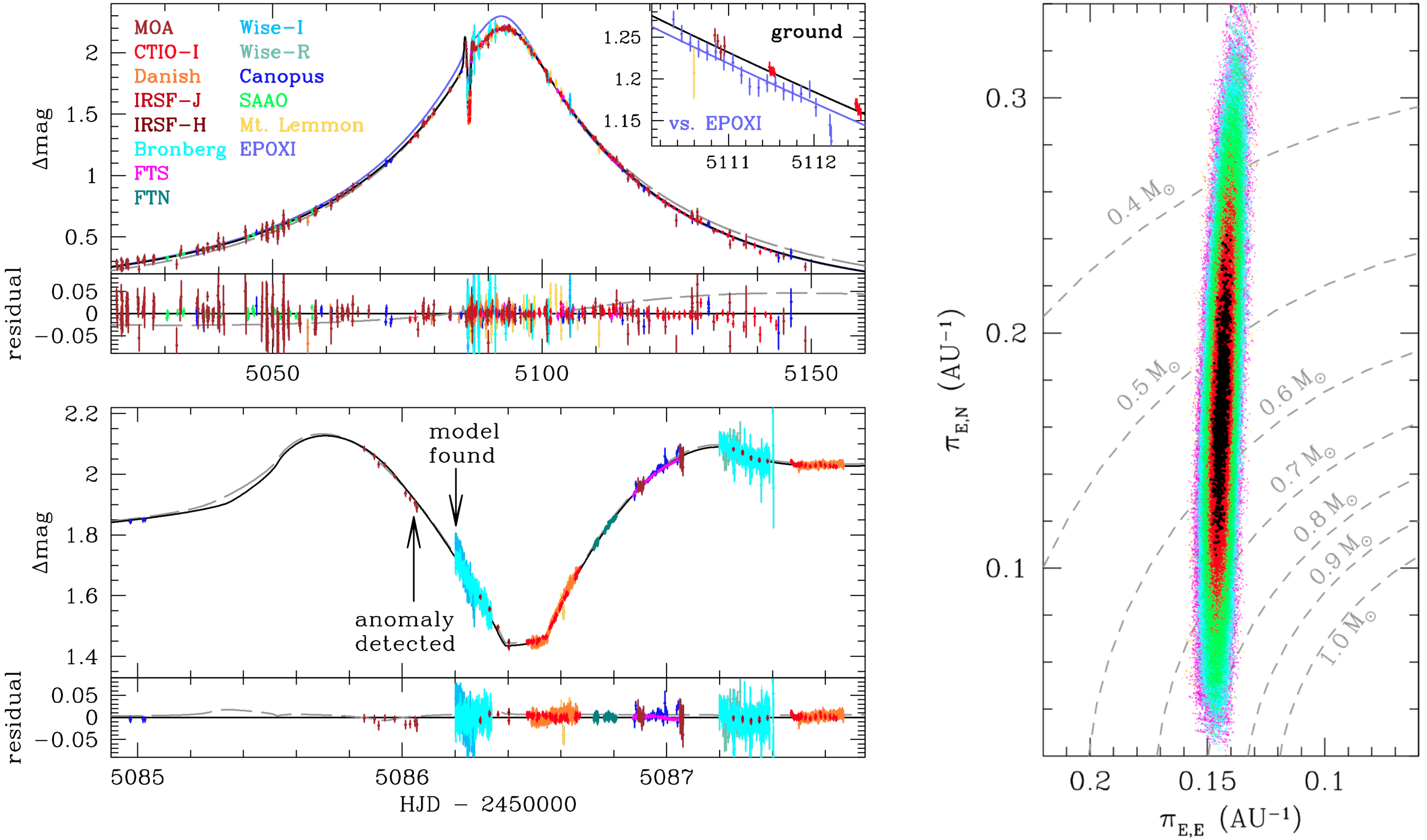


observed separation of 51 mas confirms planet model prediction of 54.3±3.7 mas

Parallax and Relative Proper Motion

- Microlensing parallax $\pi_E = \frac{1}{\tilde{r}_E}$ and
- relative proper motion $\mu_{\rm rel} = \frac{\theta_E}{t_E} = \frac{\theta_*}{t_*}$
- are both 2-d vectors – and they are parallel
- π_E is often measured more precisely in 1 direction (Earth's acceleration direction) than the other
- A measurement of μ_E improves the precision of $|\pi_E|$

MOA-2009-BLG-266 Orbital Parallax

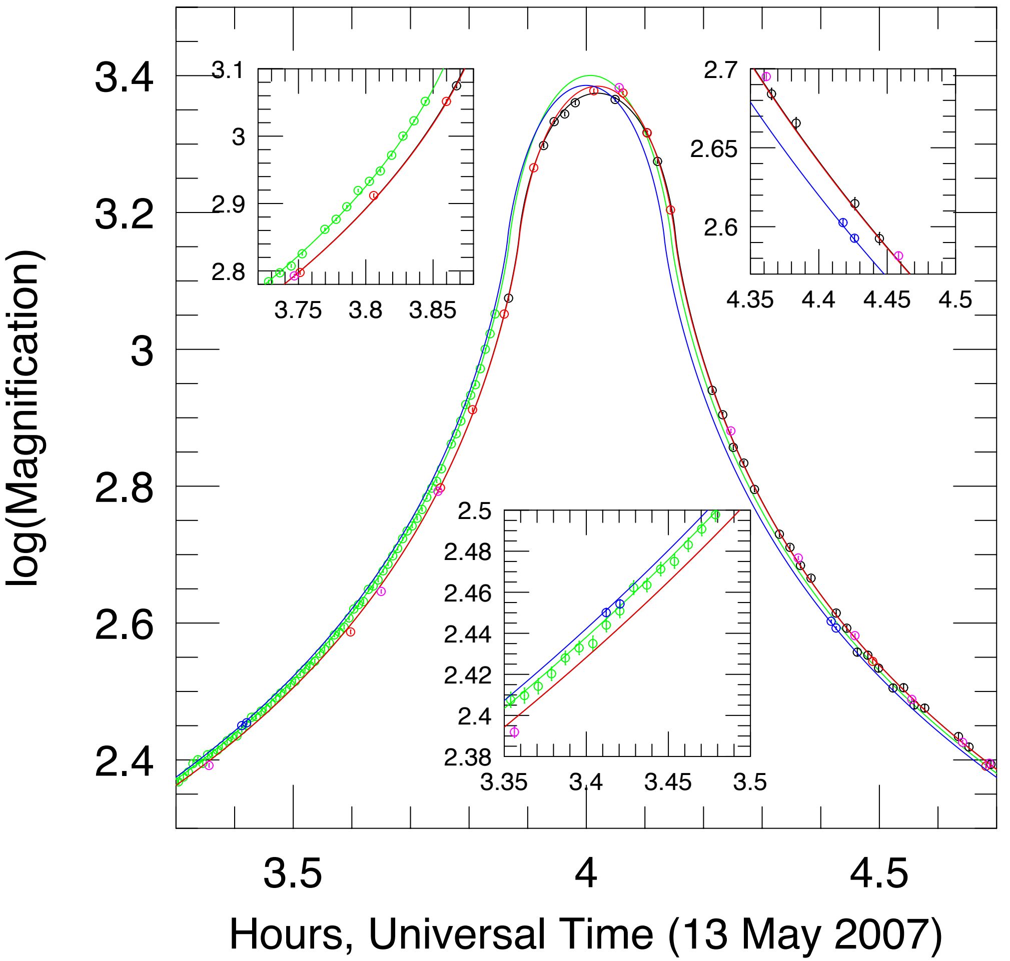


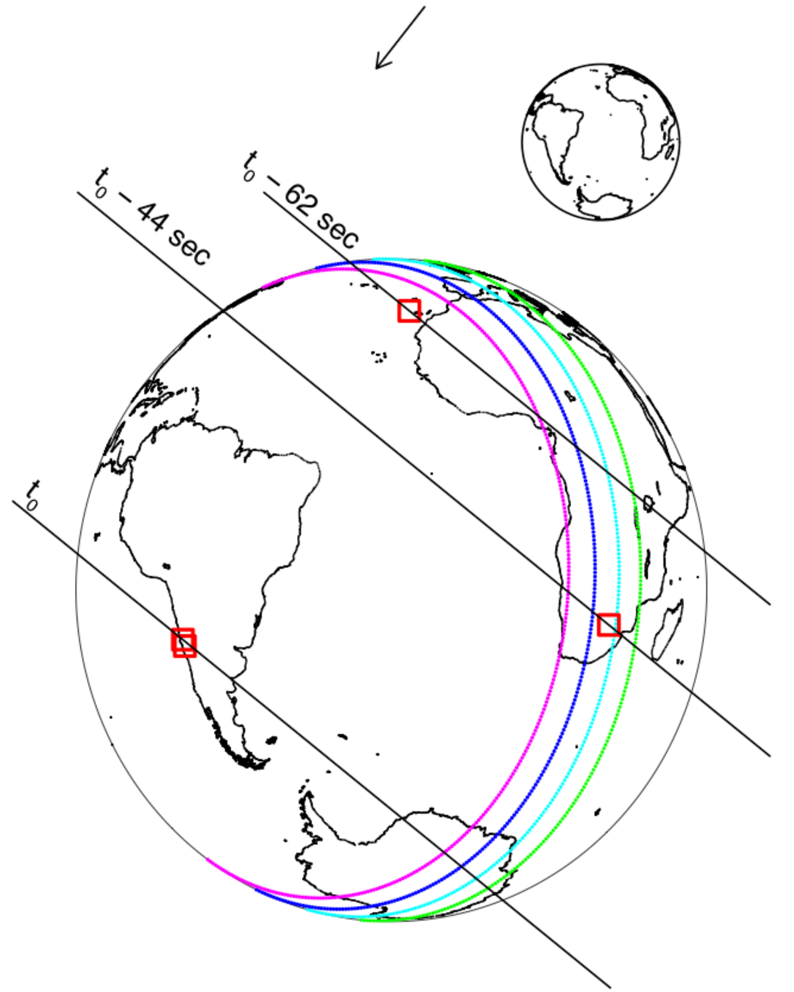
$m_p = 10.4 \pm 1.7 M_\oplus$ $\quad M_* = 0.56 \pm 0.09 M_\odot$

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

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

Terrestrial μlensing Parallax Measures Masses





OGLE-2007-BLG-224L mass, M_L = 0.056 ± 0.004 $M_\odot$ (Gould et al. 2009)

D_L = 525 ± 40 pc and $v_\perp$ = 113 ± 21 km s^{-1}

Multi-site observations needed!!

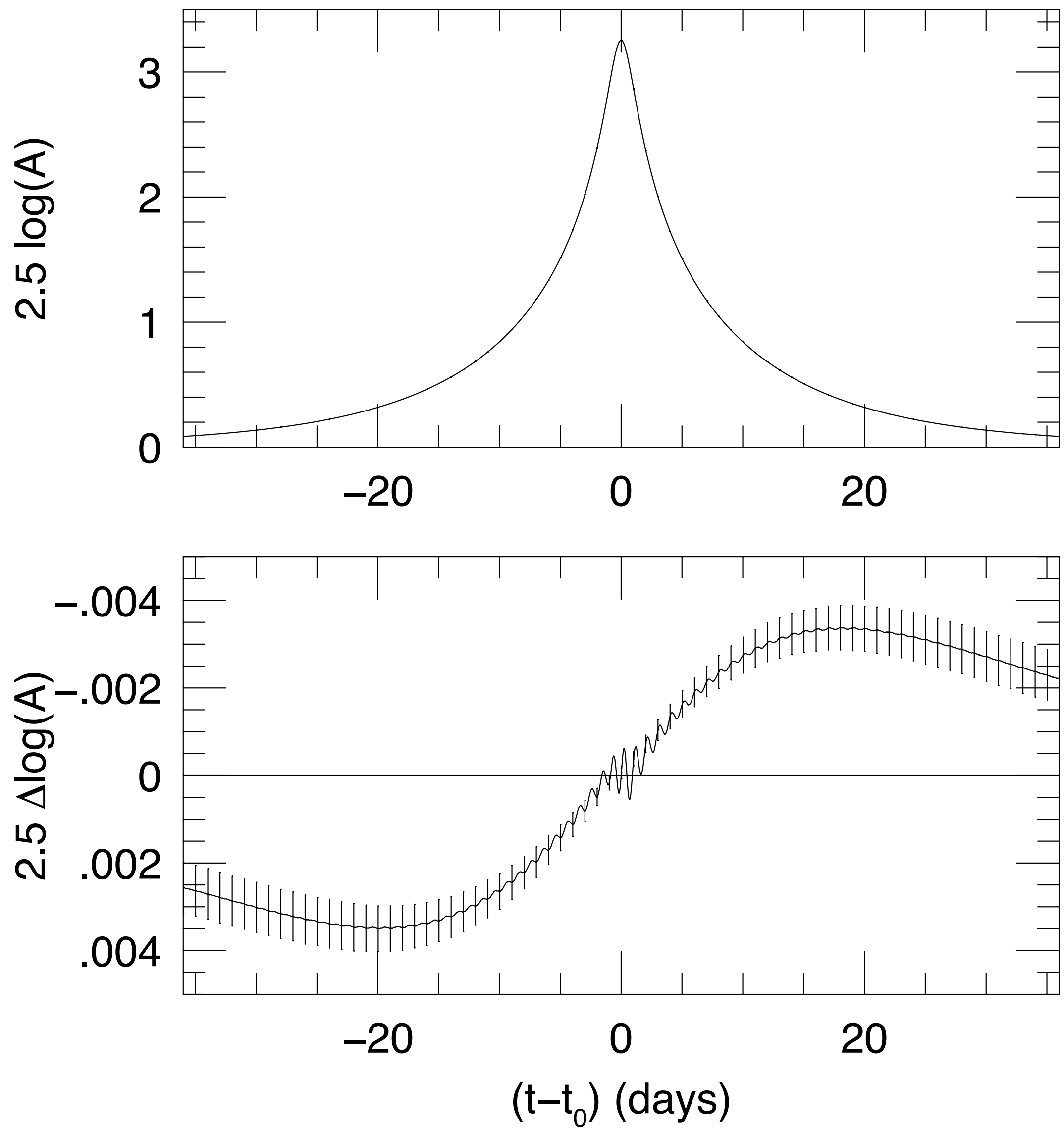
Geosynchronous Microlensing Parallax

WFIRST-AFTA orbit gives a small but potentially detectable parallax effect.

Earth orbit parallax effect is much larger.

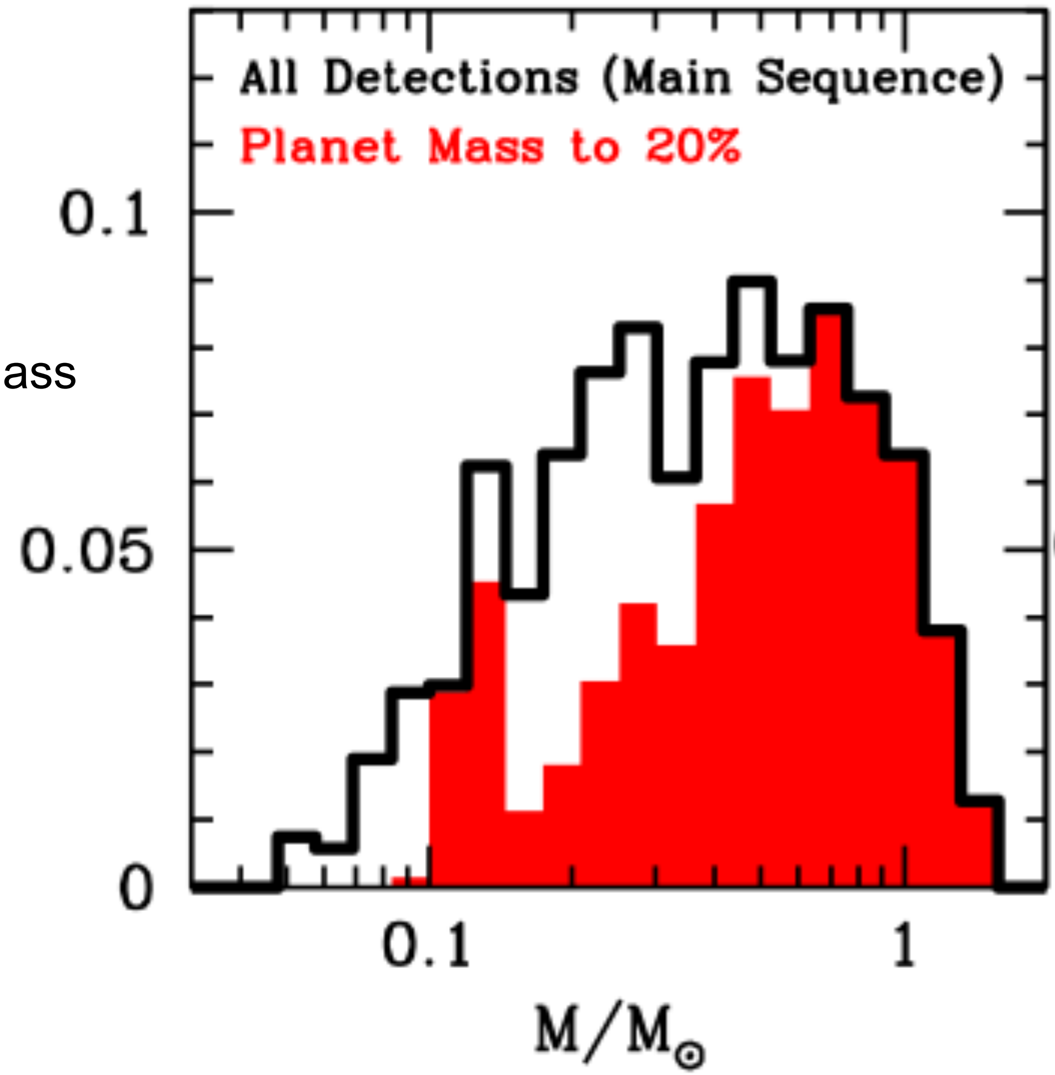
But, if lens was a rogue planet instead of a star, parallax signal is 0.01 mag instead of 0.0005 mag

Gould 2013



Bright Lens Stars Detected in WFIRST Frames

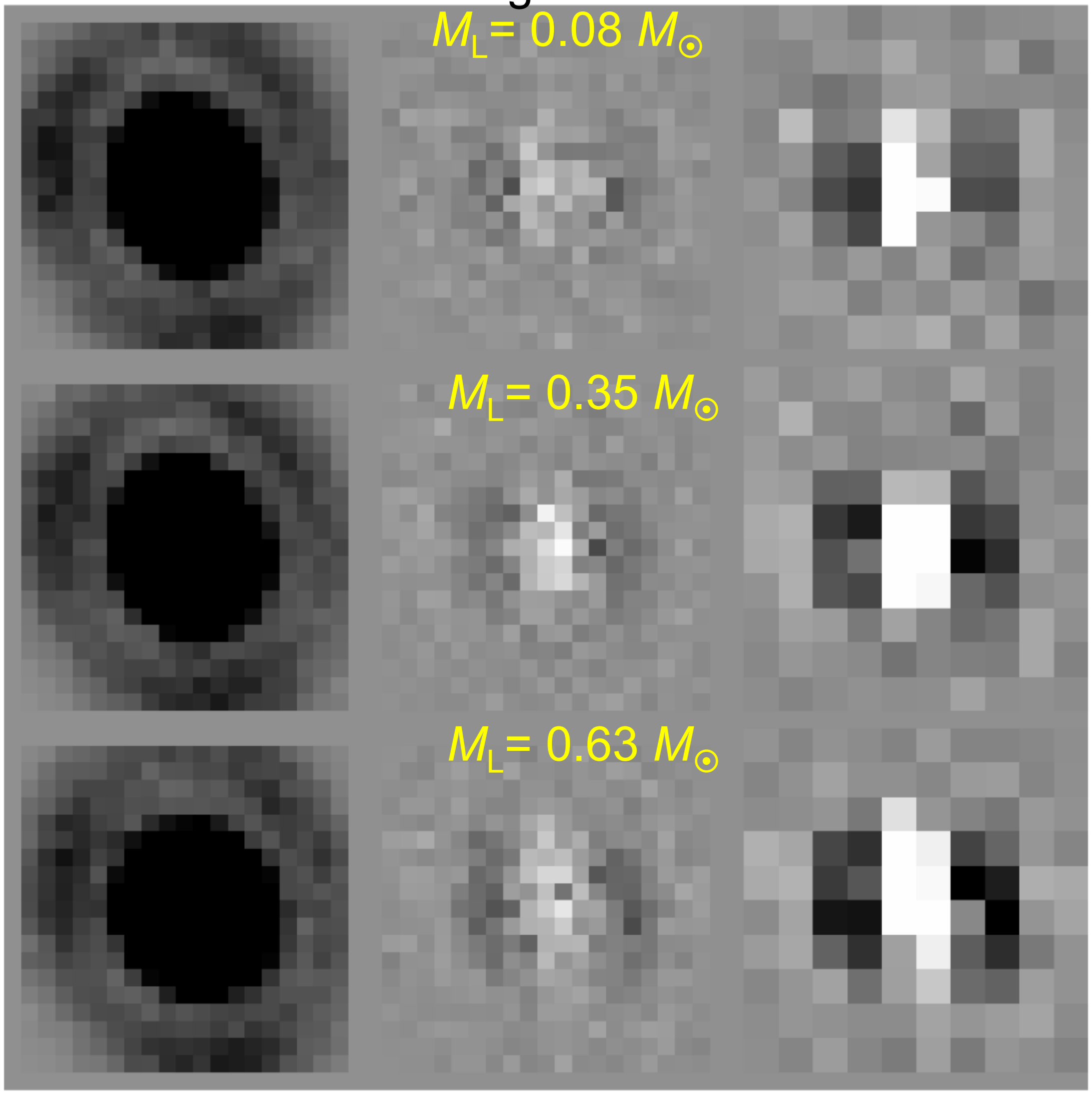
- The brightness of the lens can be combined with a mass-luminosity relation to yield the lens system mass
- The direction of the μ_{rel} helps determine $|\pi_E|$
- Masses of faint lens stars, brown dwarfs and stellar remnants are harder to determine.



Lens-Source Motion from Space

- Lens-source proper motion gives $\theta_E = \mu_{\rm rel} t_E$
- $\mu_{\rm rel}$= 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)

Simulated HST images:



Astrometric Microlensing

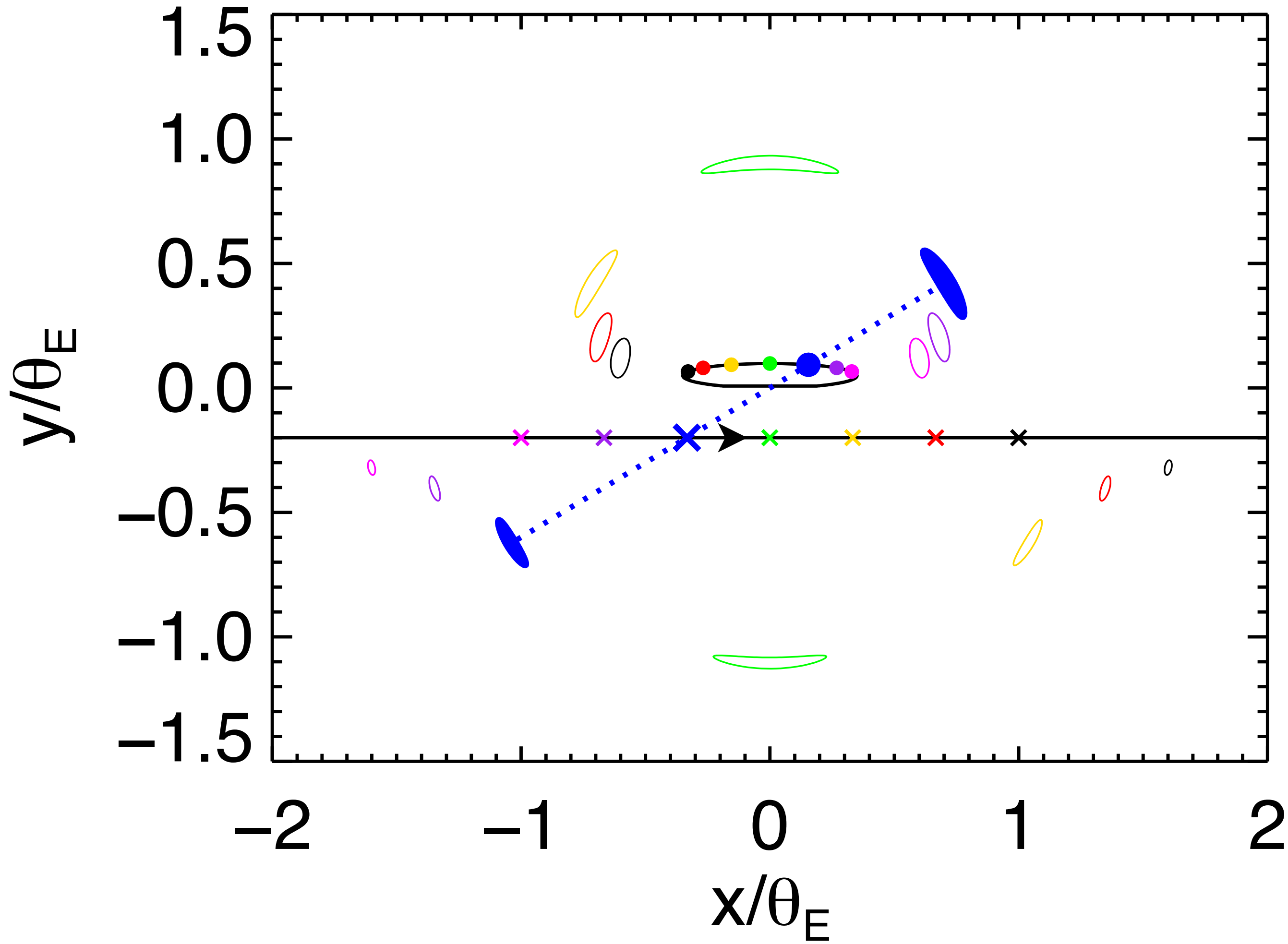


Image separation is ~1 mas or less, but the centroid moves, too. The effect is very small (~0.1 mas) except for black hole lenses (i.e. Sahu HST programs).

Long time baseline needed for a precise measurement – we need to know the source proper motion to high precision.

Early HST Optical Observations of WFIRST Fields

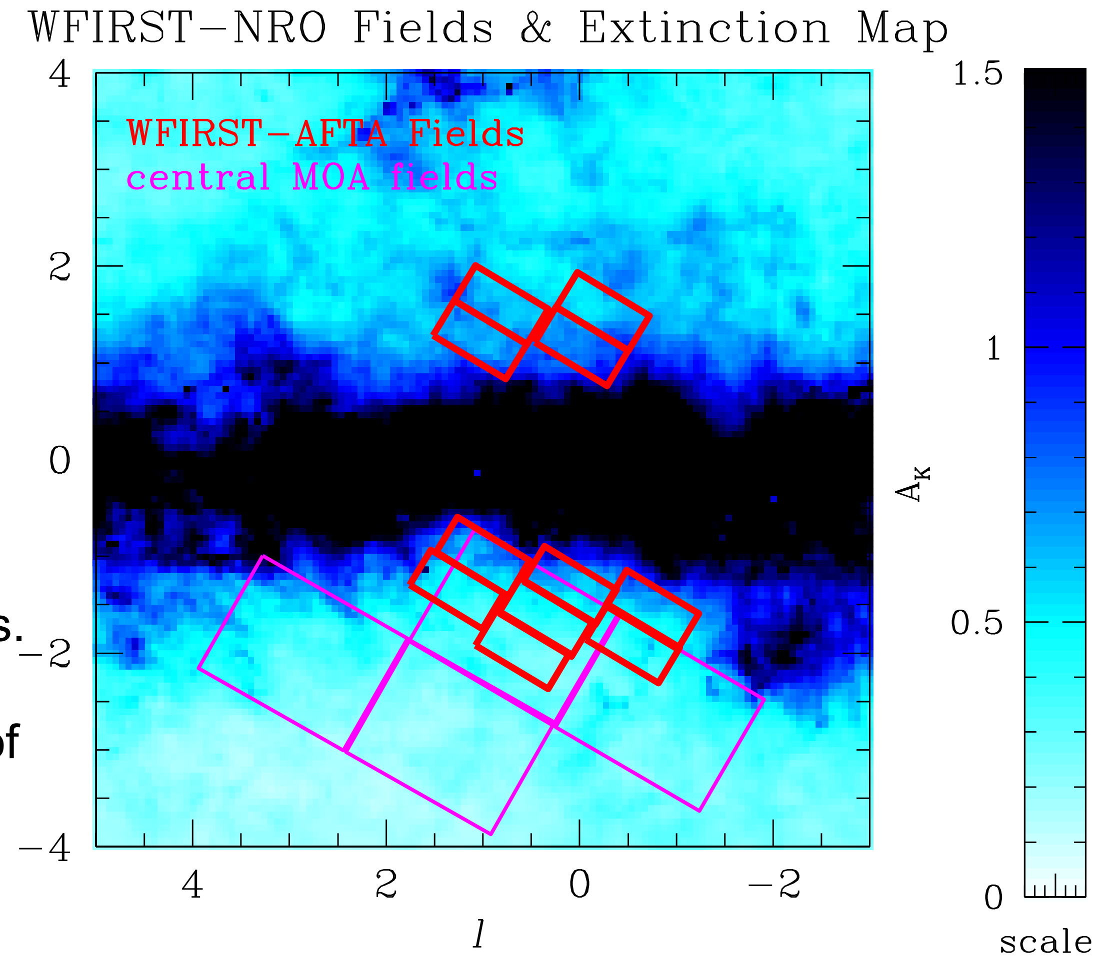
8-10 year time baseline

Relative proper motions for faint sources – resolved or nearly resolved in early observations

Long baseline for source proper motion – needed for astrometric microlensing

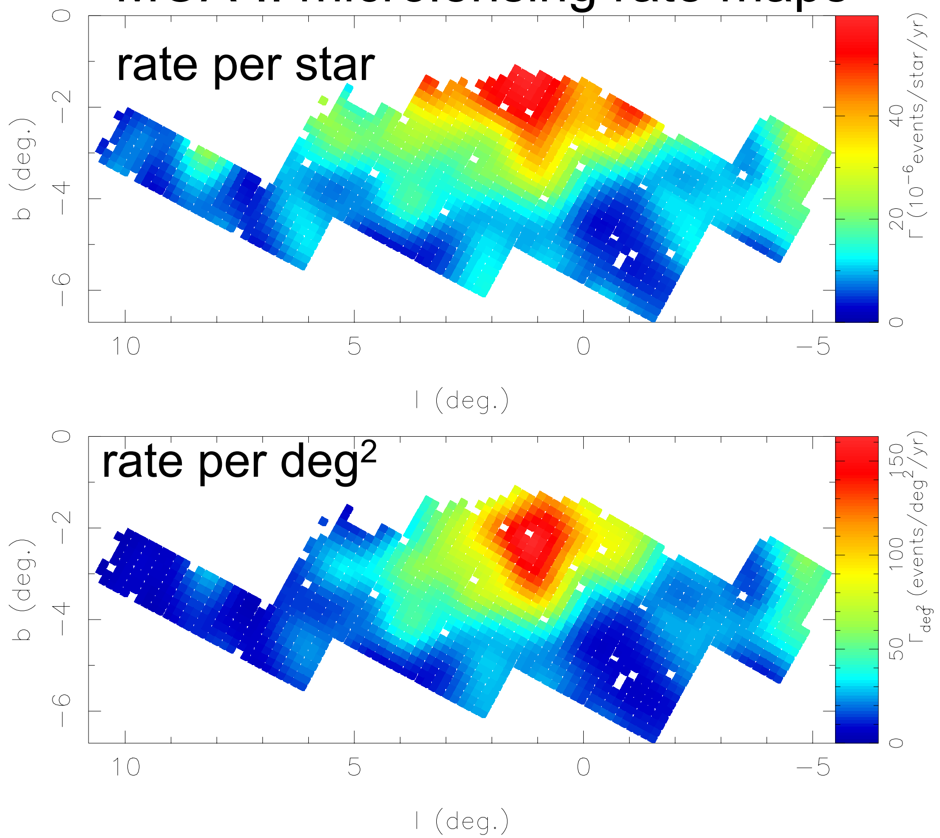
~750 orbits for all WFIRST ML fields.

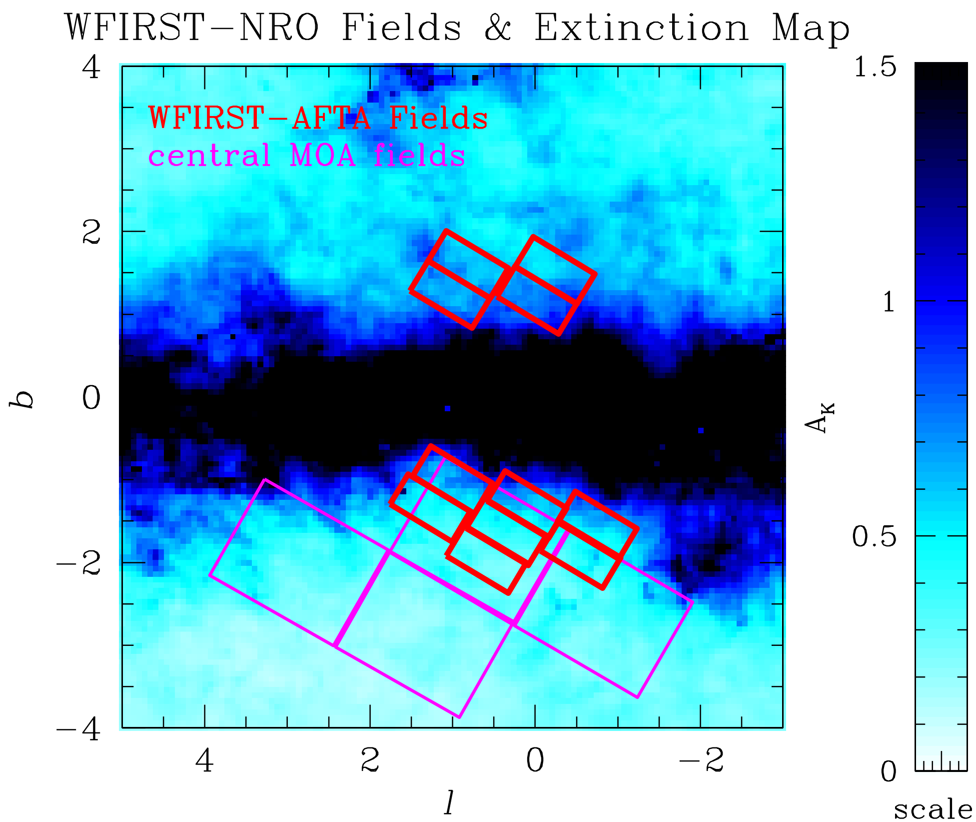
A smaller program will allow a test of astrometry from WFIRST data, which has high S/N due to ~40,000 observations



Measure the Microlensing Rate in Target Fields with an IR Survey

MOA-II microlensing rate maps



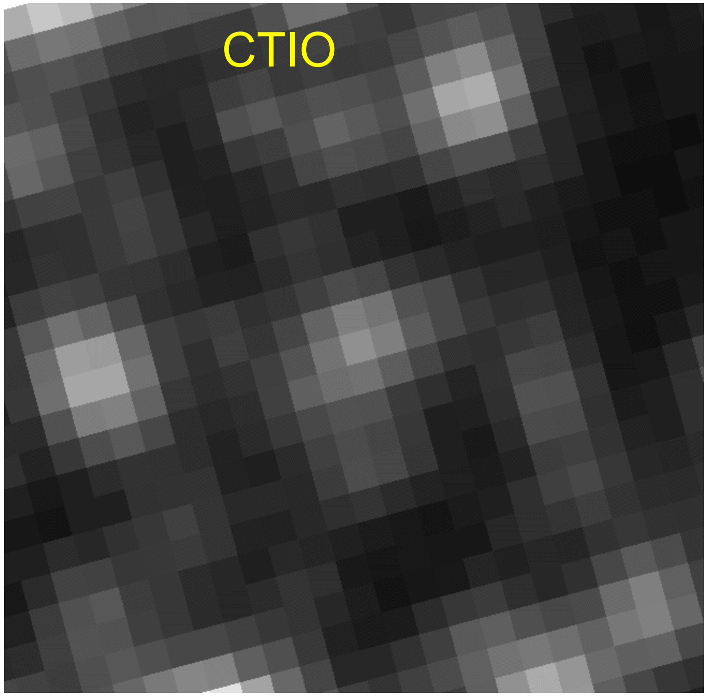


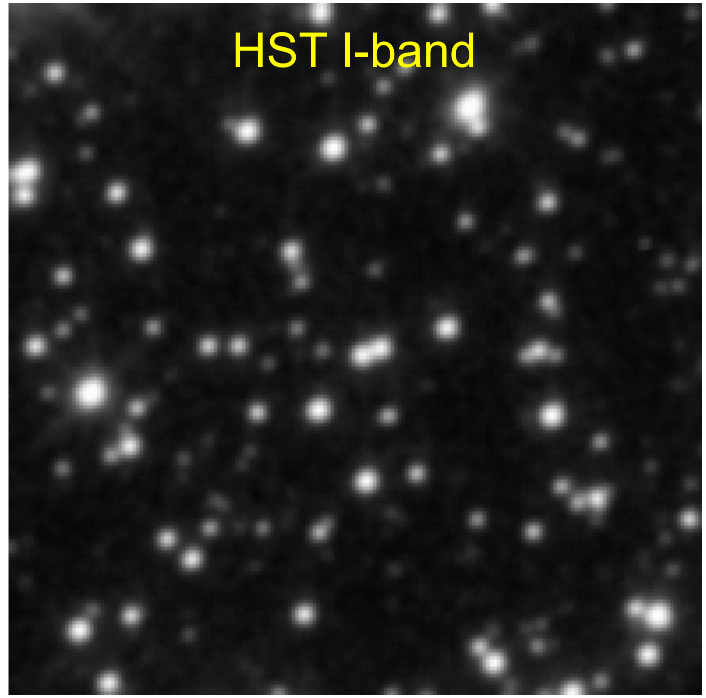
MOA-II measurements show maximum lensing rate at *l* = 1°, but this depends on extinction. Existing models are too simplistic to capture the detailed rate structure in *l* and *b*

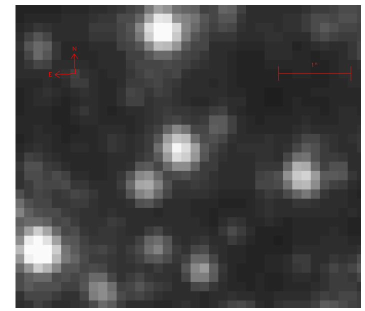
Ground-based IR Microlensing Survey

- WFIRST will go much deeper than a ground-based survey
  - We want to know how the lensing rate depends on source magnitude
  - Get rate of rare high magnification events => >1000 events
- VVV survey on Vista has too few observations
  - But telescope is capable if we could get a lot of time
- UKIRT
  - Need 2-3 hrs per night, 5 months per year for 3+ years
- Namibia Telescope
  - Sumi proposal (got to 2nd round this year)
  - H4RG detectors from WFIRST test program

New Photometry/Astrometry code needed



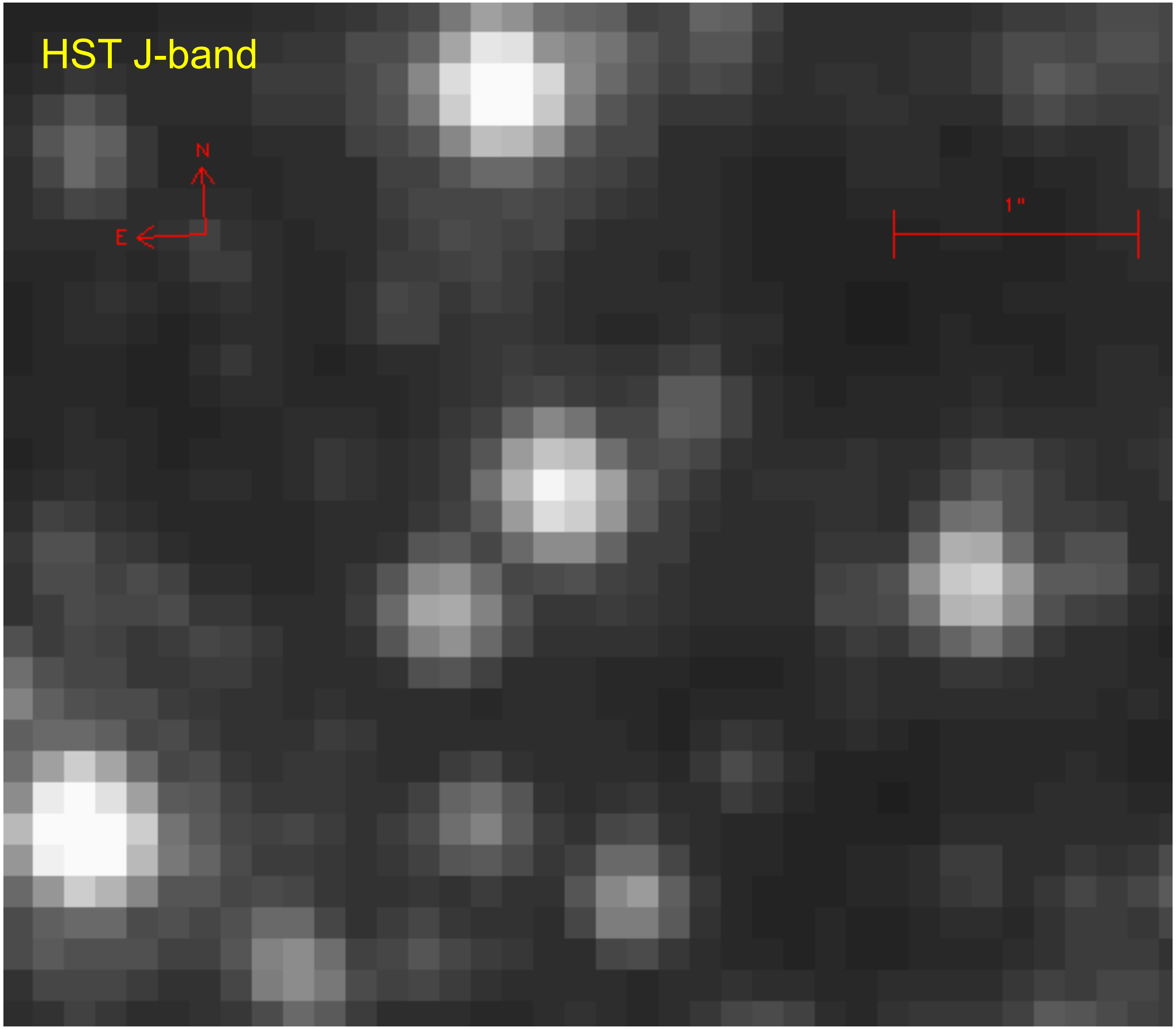




HST J-band

- These images are from MACHO fields with low extinction
- WFRIST-AFTA fields will be closer to the plane with 2-3 × the stellar density
- Proper motion of neighbor stars will be a significant source of photometry errors
- A time series of HST/WFC3/IR data will allow us to test photometry code

Blow-up of HST/WFC3/IR Image



Microlensing Survey Stars Will Not Be Isolated

- Proper motion of neighboring stars will contribute to photometry noise
- We want a WFIRST-AFTA exoplanet microlensing pipeline that generates
  - Photometry
  - Astrometry
  - A catalog of detector defects

- Develop exoplanet microlensing photometry+astrometry pipeline pre-launch using a time series of HST/WFC3/IR data
  - 3 epochs needed to get both proper motion and parallax

Microlensing Expertise

- Pre-2003 – microlensing yields only mass ratio and separation/R_E
- 2006 – lens identification and mass measurement from HST follow-up
- 2008 – microlensing can yield lens masses and orbital inclination
  - Microlensing parallax signals are stronger for binary and planetary events than for single lens events
- 2010-ish – circumbinary planet
- 2014 – planet in strong stellar binary system
  - perhaps some planets have been missed

- # of Dark Energy Scientists ≈ 10^2×(# of Microlensing Scientists)
  - Most major observing programs have no or only small US component
  - But US (ND and OSU groups) lead in microlensing theory & analysis

- Analysis of real data is key to developing expertise, so
  - More HST and Keck AO follow-up of planetary microlensing events
  - Satellite parallaxes with Spitzer, Kepler or other spacecraft far from Earth
  - Support of ongoing microlensing observing programs