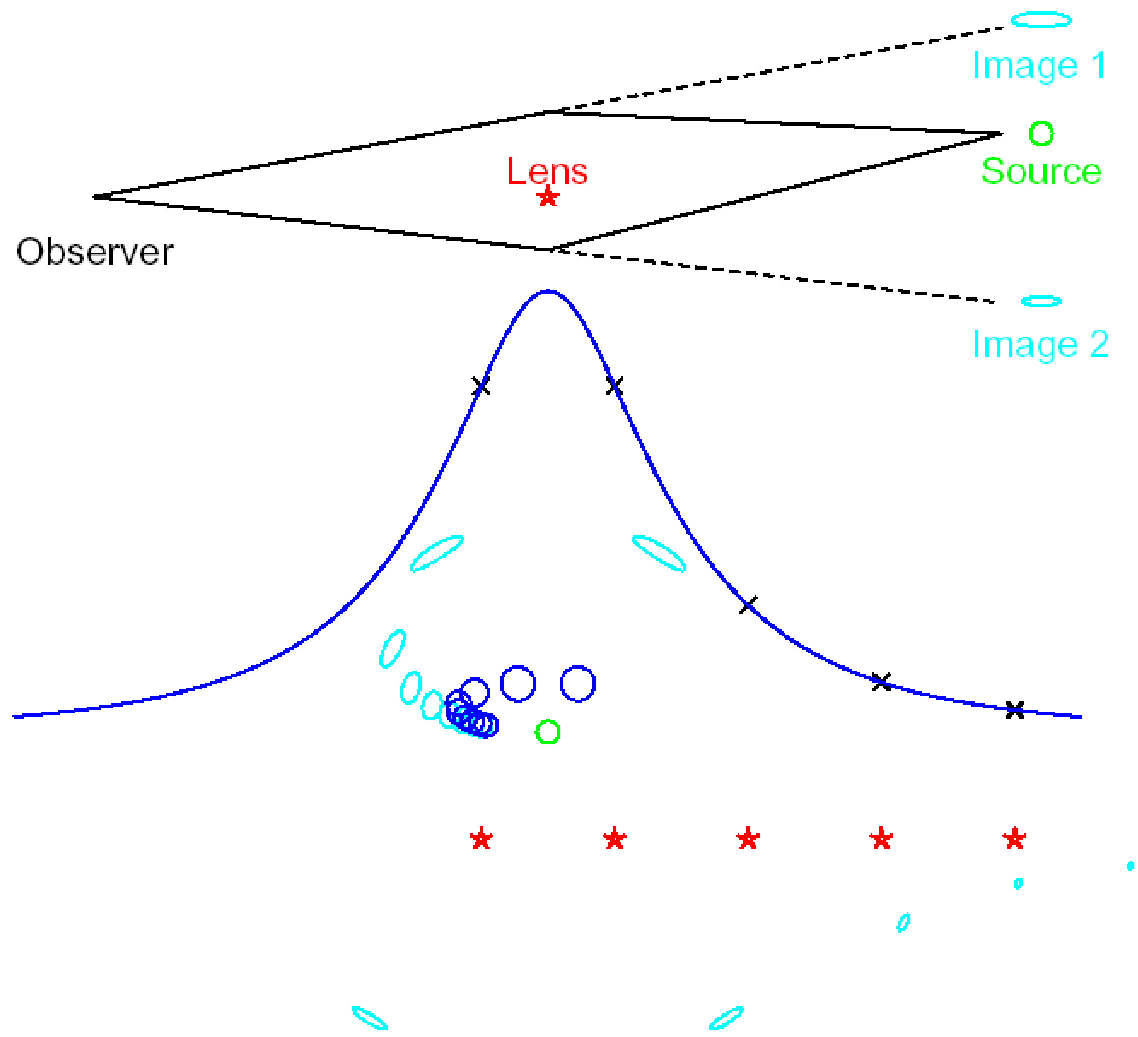
CMDs, Einstein Radii, and Parallaxes

in Planetary Microlensing

Andy Gould (Ohio State)



Mao & Paczynski

Central Caustics

GRAVITATIONAL MICROLENSING BY DOUBLE STARS AND PLANETARY SYSTEMS

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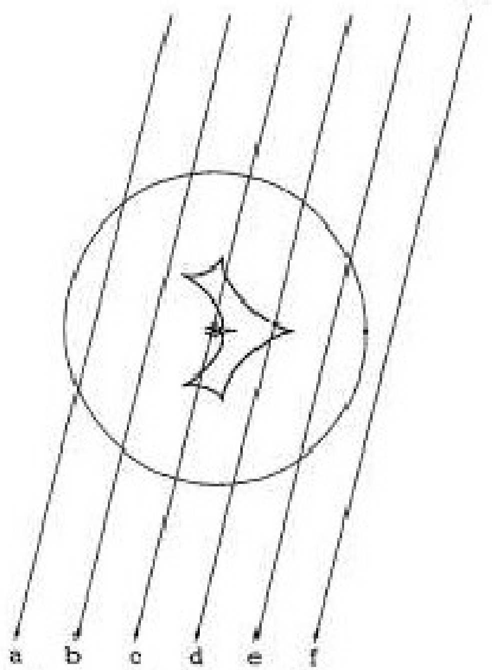
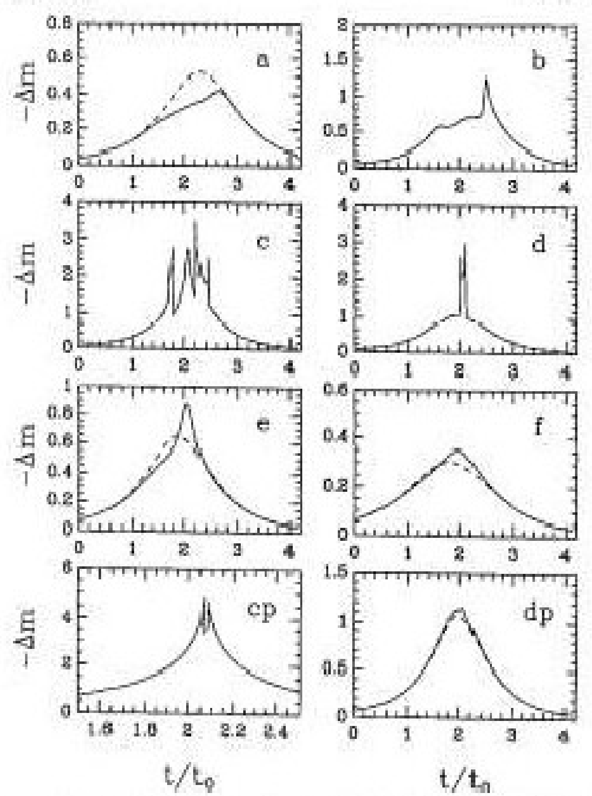
Received 1991 March 12; accepted 1991 April 2



. 1.—Geometry of microlensing by a binary, as seen in the sky. The y star of 1 $M_\odot$ is located at the center of the figure, and the secondary of ; or 0.001 $M_\odot$ is located on the right, on the Einstein ring of the y. The radius of the ring is 1.0 mas for a source located at a distance of 8 d the lens at 4 kpc. The two complicated shapes around the primary are



the lens. The effect is strong even if the companion is a planet. A massive search for microlensing of the Galactic bulge stars may lead to a discovery of the first extrasolar planetary systems.

Gould & Loeb

Planetary Caustics

DISCOVERING PLANETARY SYSTEMS THROUGH GRAVITATIONAL MICROLENSES

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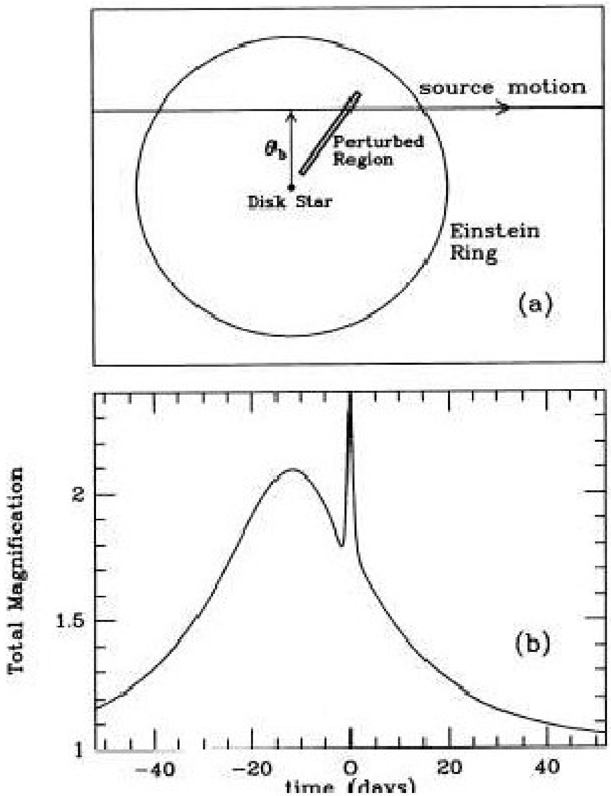
Received 1991 December 26; accepted 1992 March 9



5. OBSERVATIONAL REQUIREMENTS

Two distinct steps are required to observe a planetary system by microlensing. First, one must single out a disk star which happens to be microlensing a bulge star. Second, one must observe this star often enough to catch the deviation in the light curve due to the planet. The first step involves the observation of millions of bulge stars on the order of once per day. The second step involves the observation of a handful of stars many times per day. In the following we give a rough outline of what is required for each of these steps.

While observations from one site would be useful, there are advantages to be gained by observing from several sites. First,

two telescopes that were totally committed. Third, in view of the fleeting nature of the events, it would seem prudent to build in some redundancy in case of bad weather at a particular site. Thus, the optimal scheme would employ, say, a dozen telescopes. Each of these would be committed to carry out two observations per night. During the near-December season,

6 Features & 6 Parameters

- Time of Peak
- Height of Peak
- Width of Peak
- Time of Perturbation
- Height of Perturbation
- Width of Perturbation

- t_0
- u_0
- t_E
- Trajectory angle: alpha
- Planet-star separation: b
- Planet/star mass ratio: q

Clear Division Between

Known Knowns & Known Unknowns

- Planet/star mass ratio
- Separation in units of Einstein radius

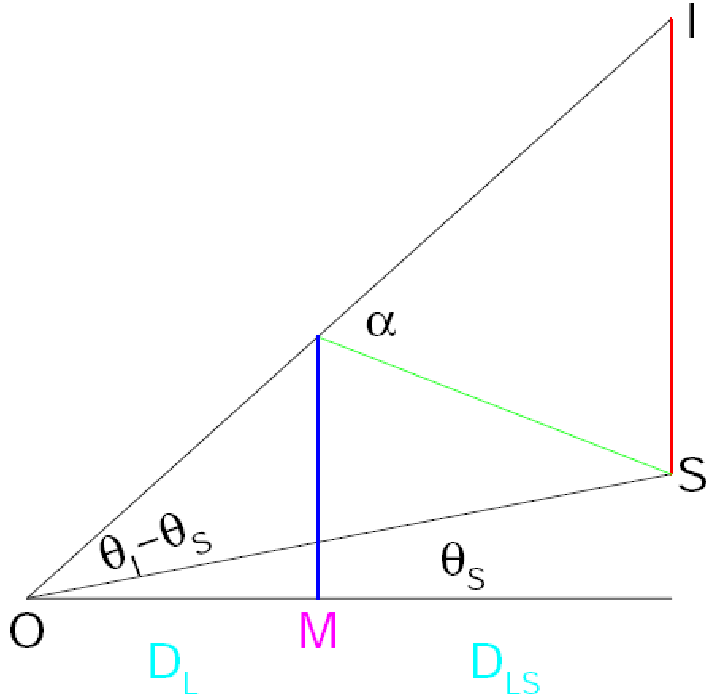
- Planet mass
- System distance
- Planet/star projected physical separation

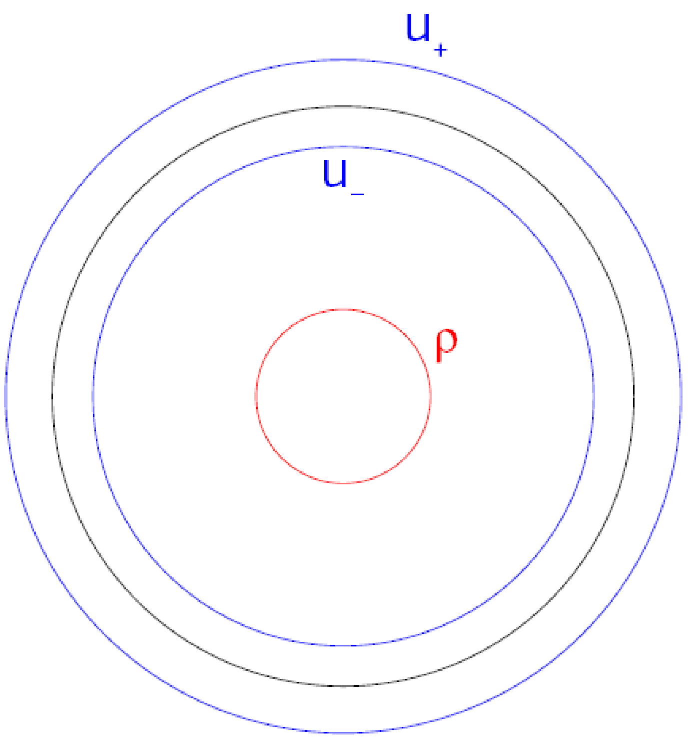
And inevitably: Unknown Unknowns

- Planet/star 3-D separation
- Planet Orbital Motion

What Happened?

- Most planets (so far) are in high-mag events
- High-mag events: richer and harder to interpret
- Planetary events are more susceptible to higher-order effect than regular events





$$(\theta_I - \theta_S) D_S = \alpha D_{LS}$$

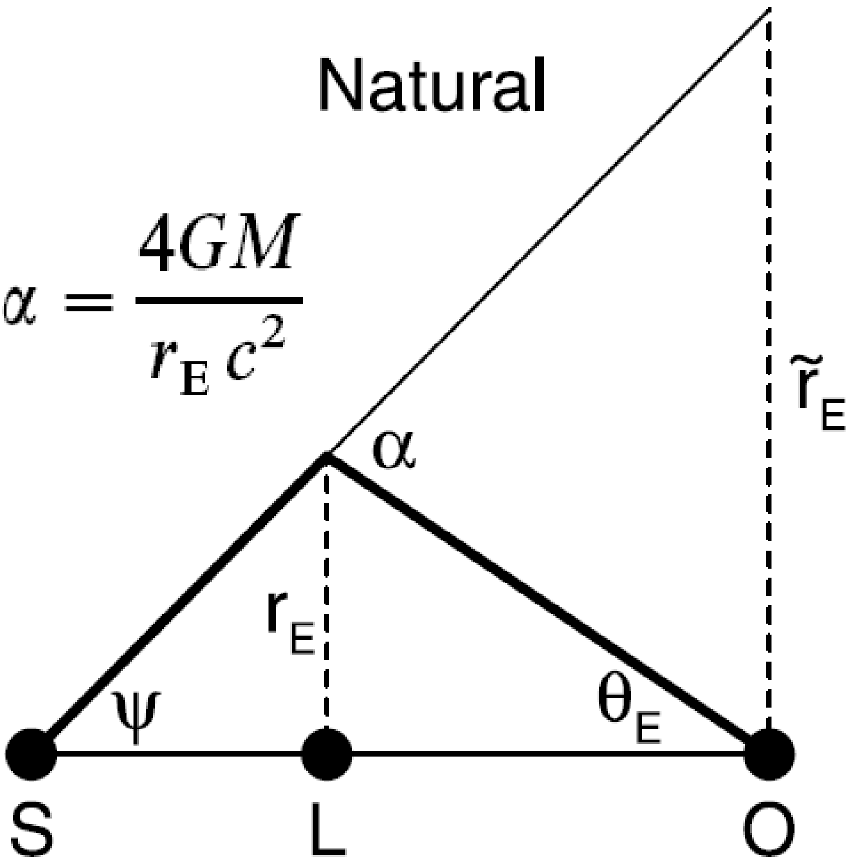
$$\alpha = 4GM/(D_L \theta_I c^2)$$

$$(\theta_I - \theta_S)\theta_I = \theta_E^{\,2} = (4GM/c^2)(D_{LS}/D_L D_S)$$

$$\theta_I/\theta_E = [u +/- (u^2 + 4)^{1/2}]/2; \;\; u = \theta_S/\theta_E$$

Relation of Mass and Distance to Lensing Observables

$$\alpha = \frac{4GM}{r_{\rm E}\, c^2}$$



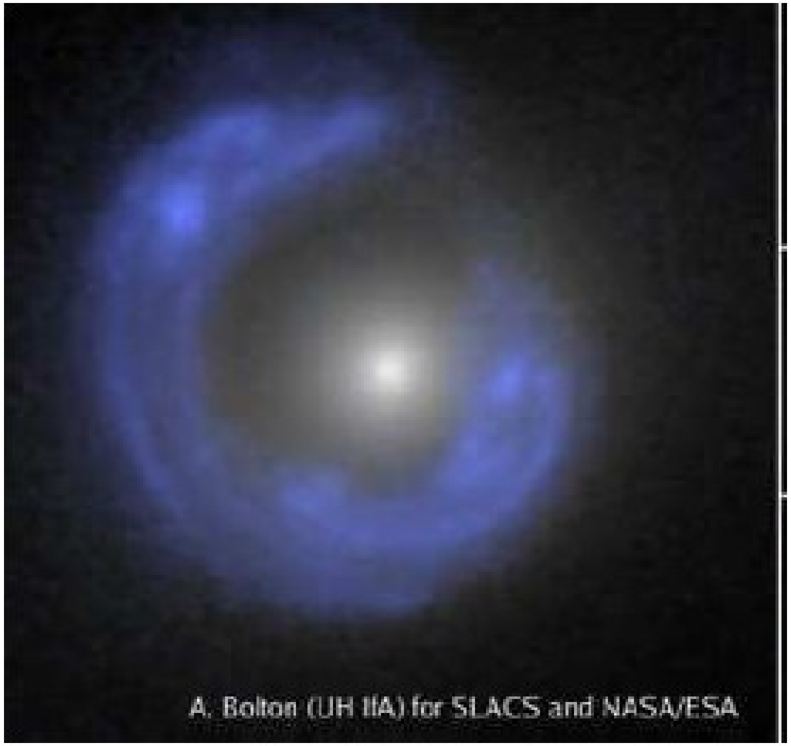
$$\alpha / \tilde{r}_{\rm E} = \theta_{\rm E} / r_{\rm E}$$

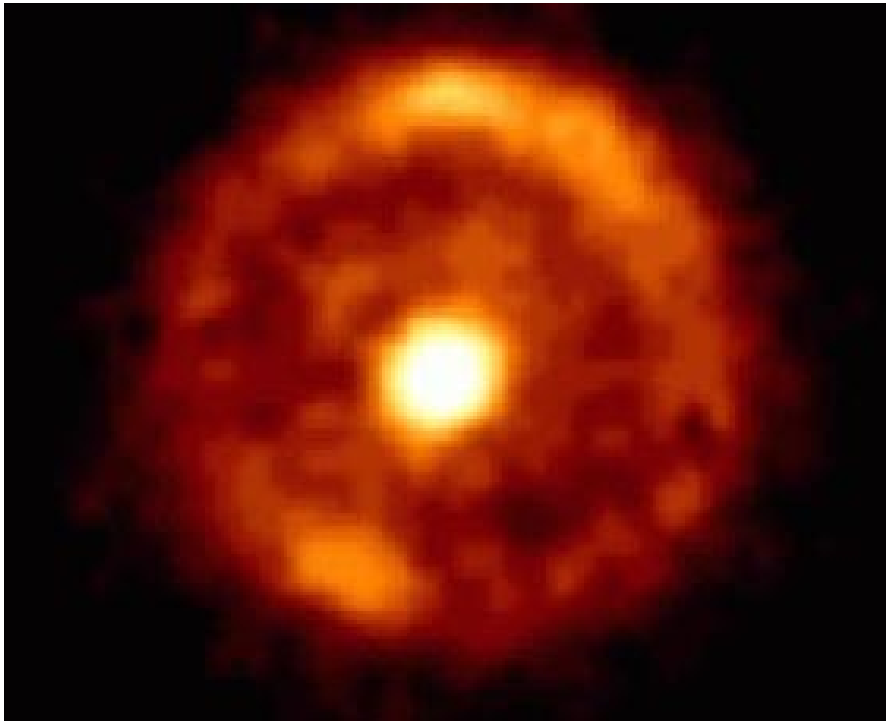
$$\theta_{\rm E}\, \tilde{r}_{\rm E} = \alpha r_{\rm E} = \frac{4GM}{c^2}$$

$$\theta_{\rm E} = \alpha - \psi = \frac{\tilde{r}_{\rm E}}{D_l} - \frac{\tilde{r}_{\rm E}}{D_s} = \frac{\tilde{r}_{\rm E}}{D_{\rm rel}}$$

$$\tilde{r}_{\rm E} = \sqrt{\frac{4GMD_{\rm rel}}{c^2}} \qquad \theta_{\rm E} = \sqrt{\frac{4GM}{D_{\rm rel}\, c^2}}$$

Some (Macro) Einstein Rings

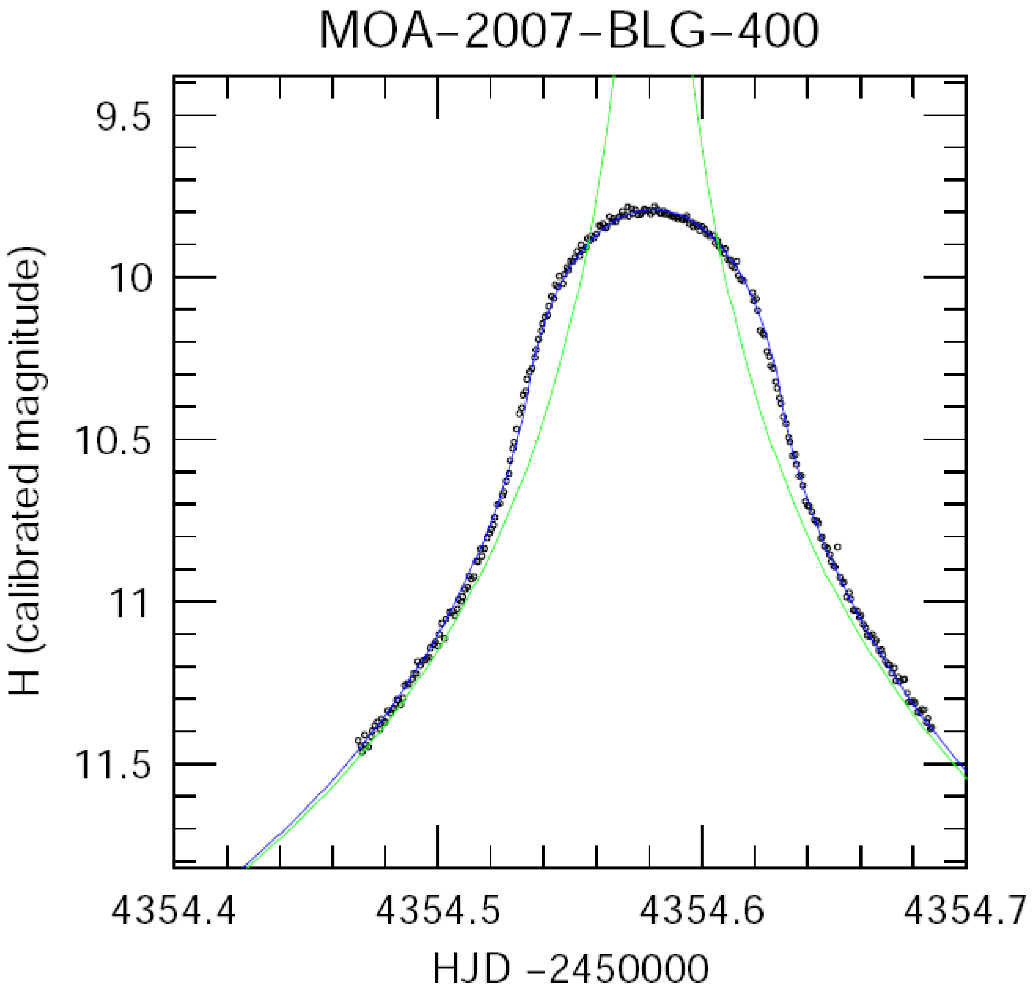


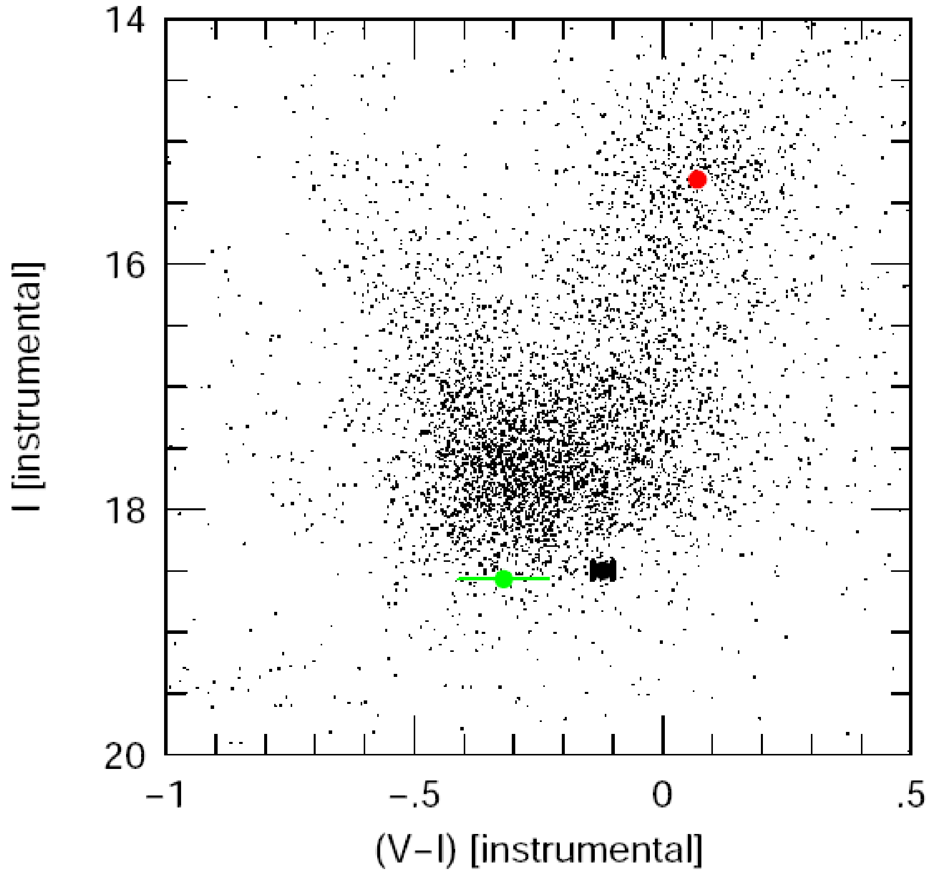


To measure angular Einstein radius:

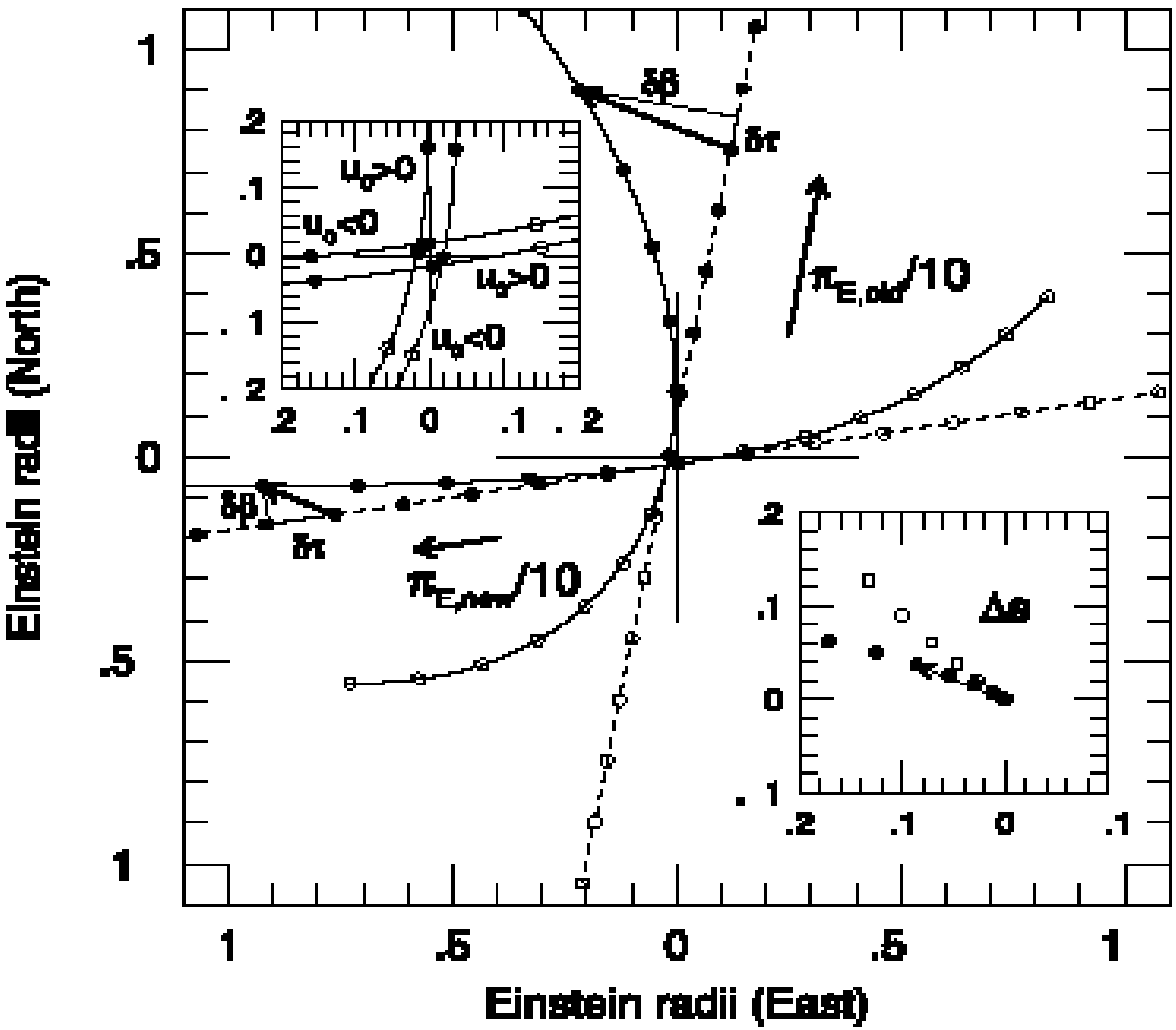
$t_* = 0.047$ day; $t_E = 14.4$ day; $\theta_* = 1.05$ μas

$$\theta_E = \theta_*(t_E/t_*) = 322 \text{ μas}$$



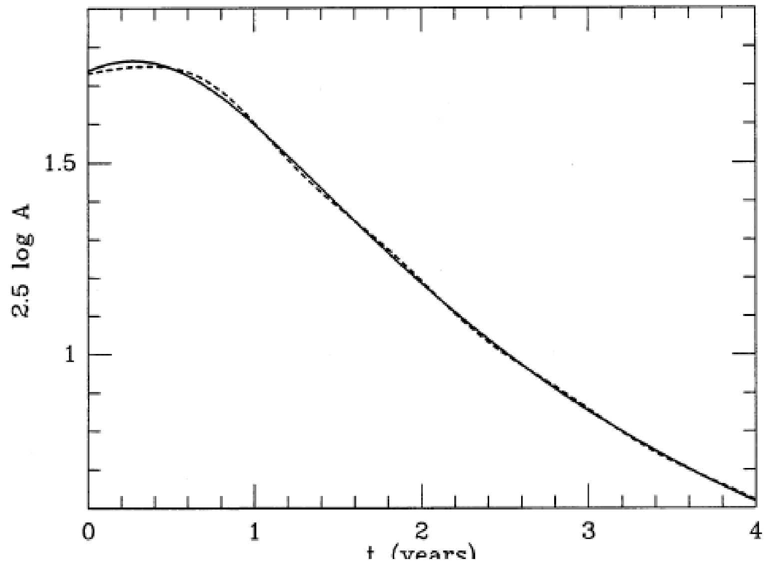


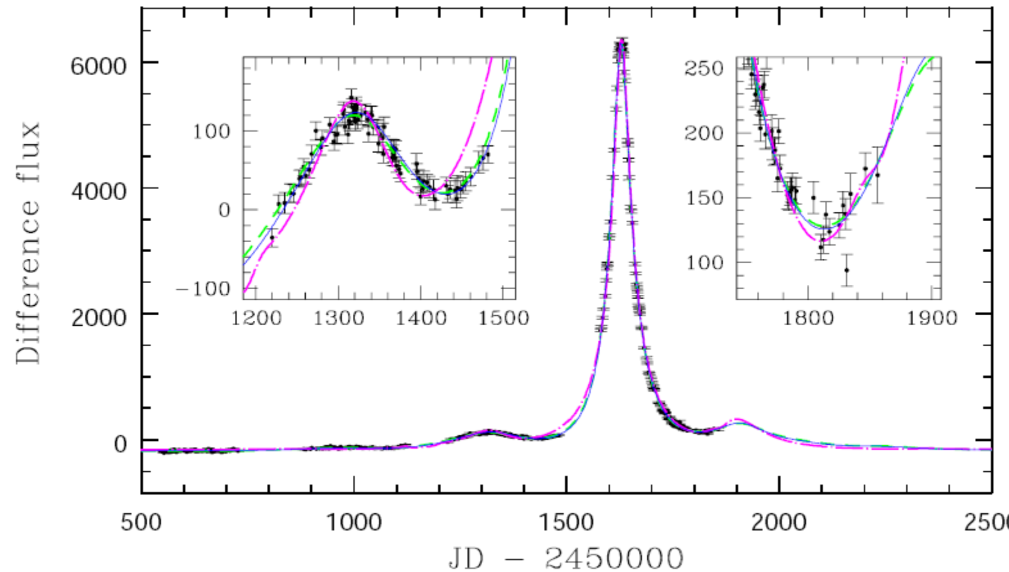
Accelerated motion of Earth induces non-linear motion in Einstein ring

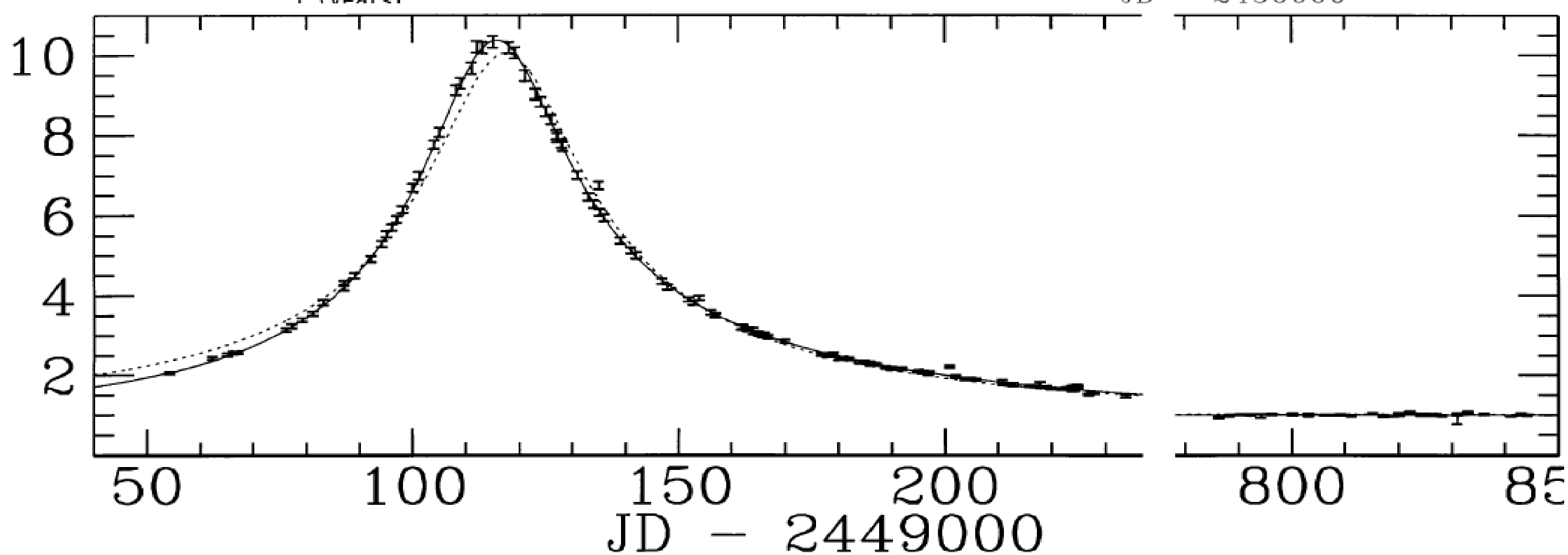


To determine microlens parallax:

Measure Resulting Lightcurve Distortion







Another Crackpot Idea:

Terrestrial Microlens Parallaxes

PHOTON STATISTICS LIMITS FOR EARTH-BASED PARALLAX MEASUREMENTS OF MACHO EVENTS

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Received 1995 March 8; accepted 1996 January 11

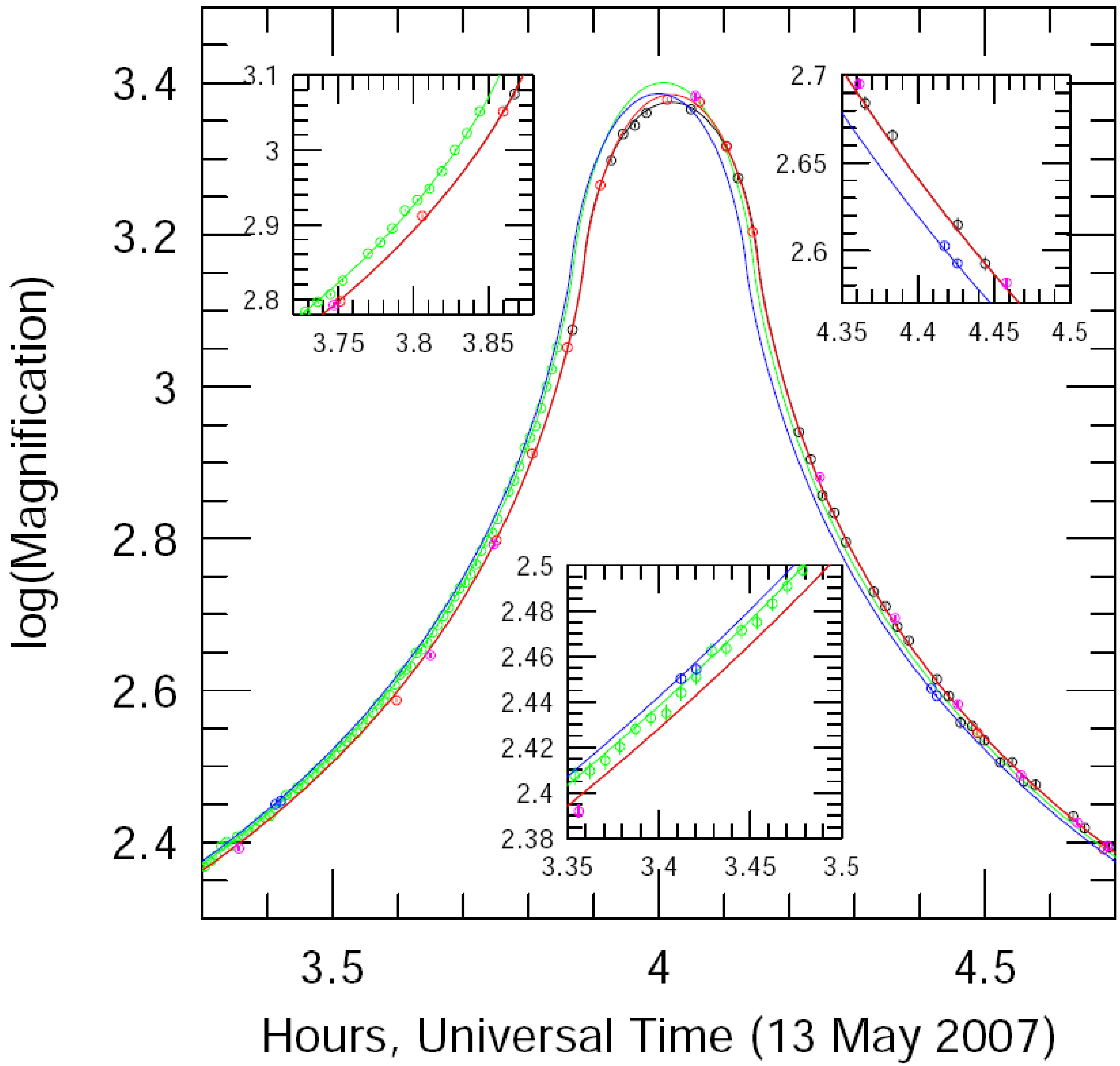
ABSTRACT

We analyze the limitations imposed by photon-counting statistics on extracting useful information about MACHOs from Earth-based parallax observations of microlensing events. We find that if one or more large (say 2.5 m) telescopes are dedicated to observing a MACHO event for several nights near maximum amplification, then it is possible, in principle, to measure the velocity of the MACHO well

issues. We thank Andrew Gould for pointing out an error in the original version of this manuscript. This research was

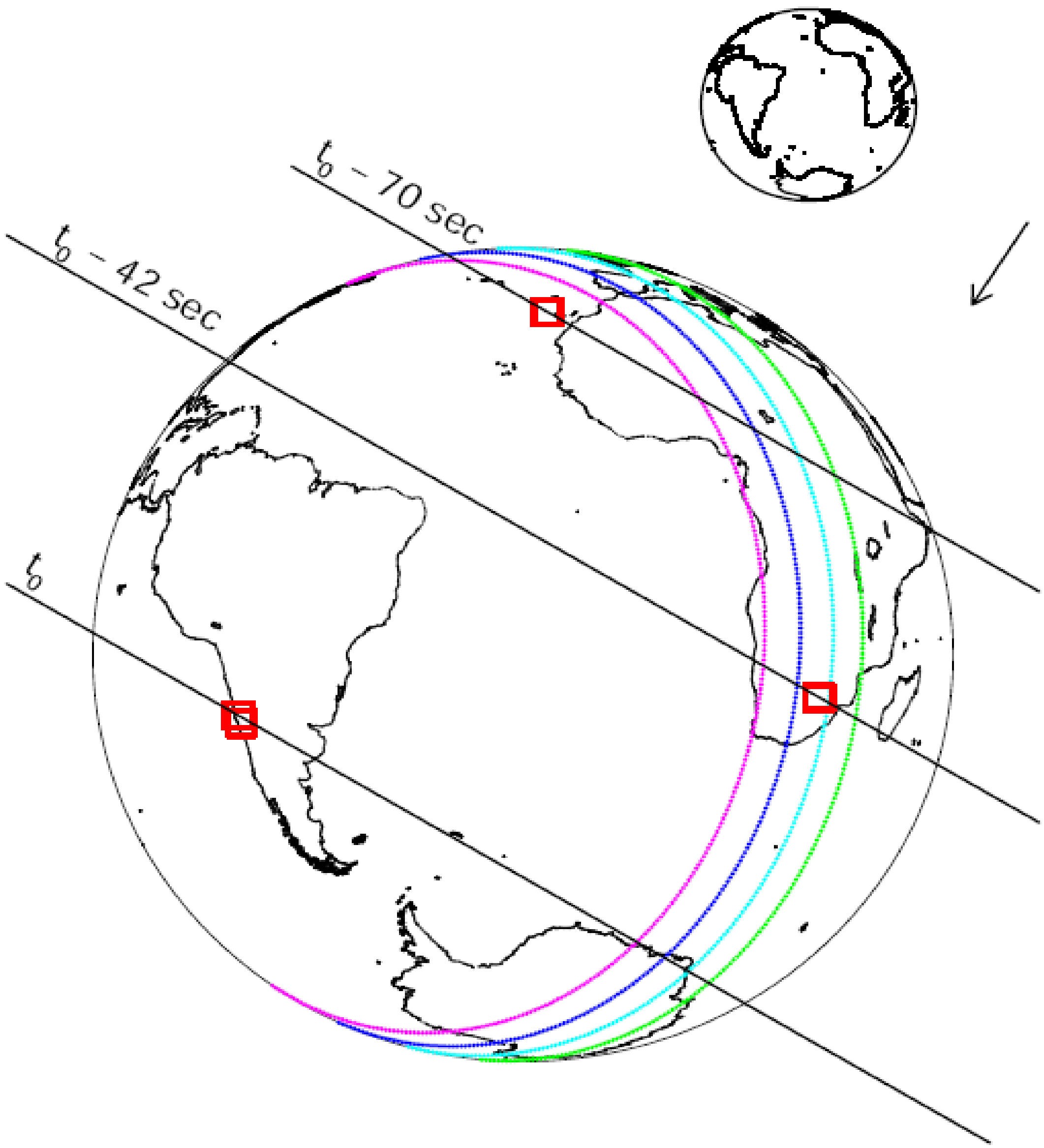
OGLE-2007-BLG-224

Canaries South Africa Chile

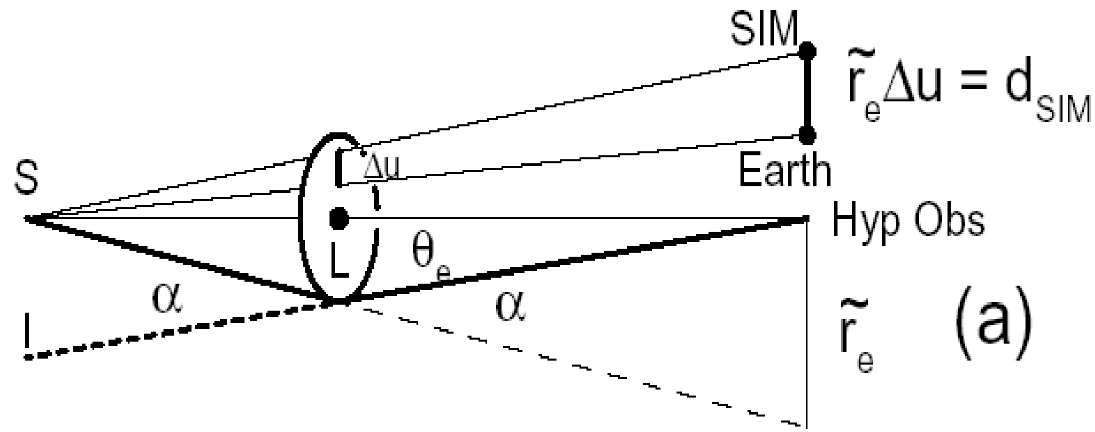


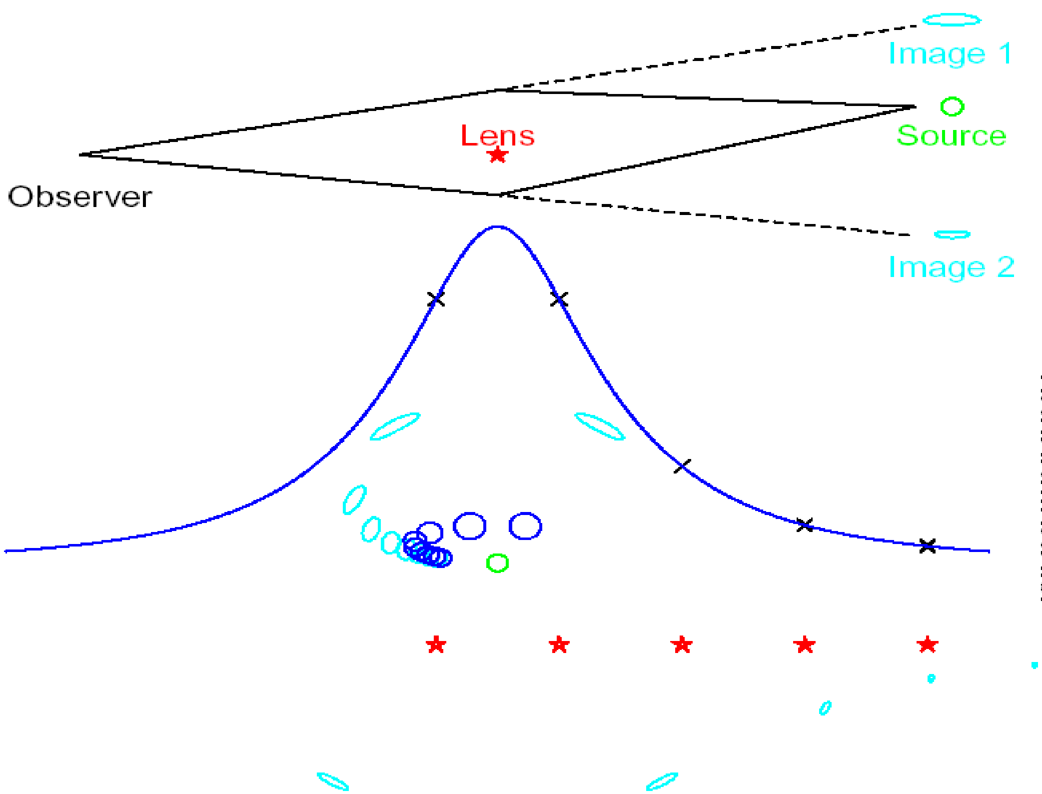
Terrestrial Parallax:

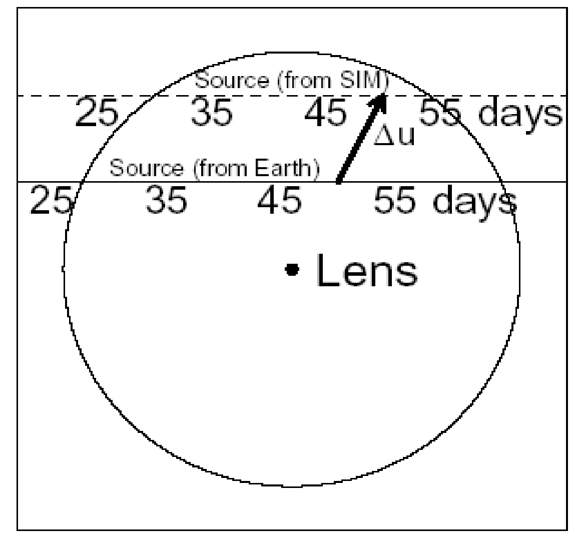
Simultaneous Observations on Earth



Space-Based Parallaxes & Einstein Radii : SIM

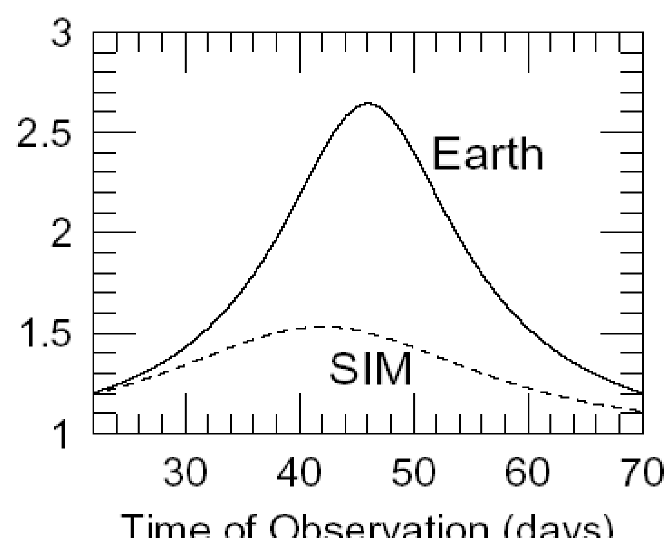






$$\tilde{r}_e = \frac{d_{SIM}}{\Delta u}$$

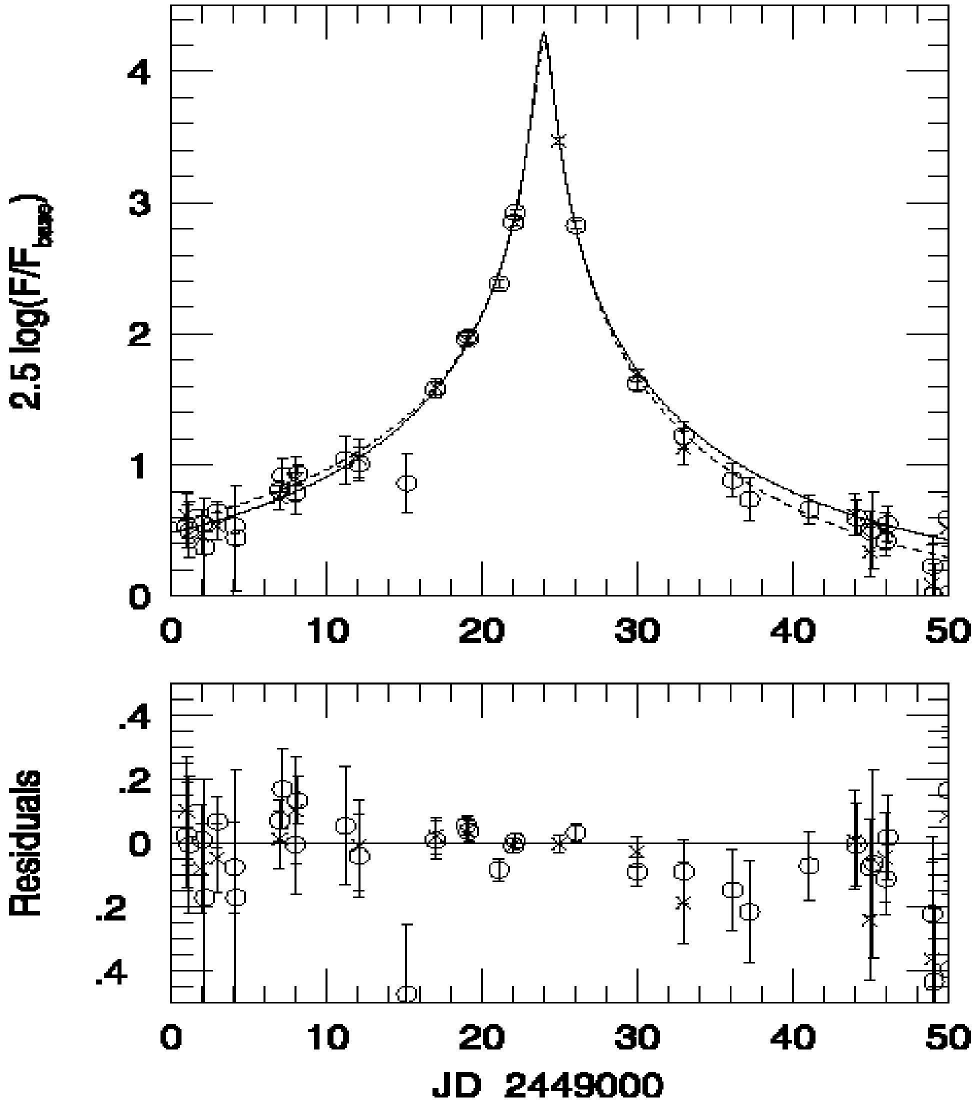
(b)

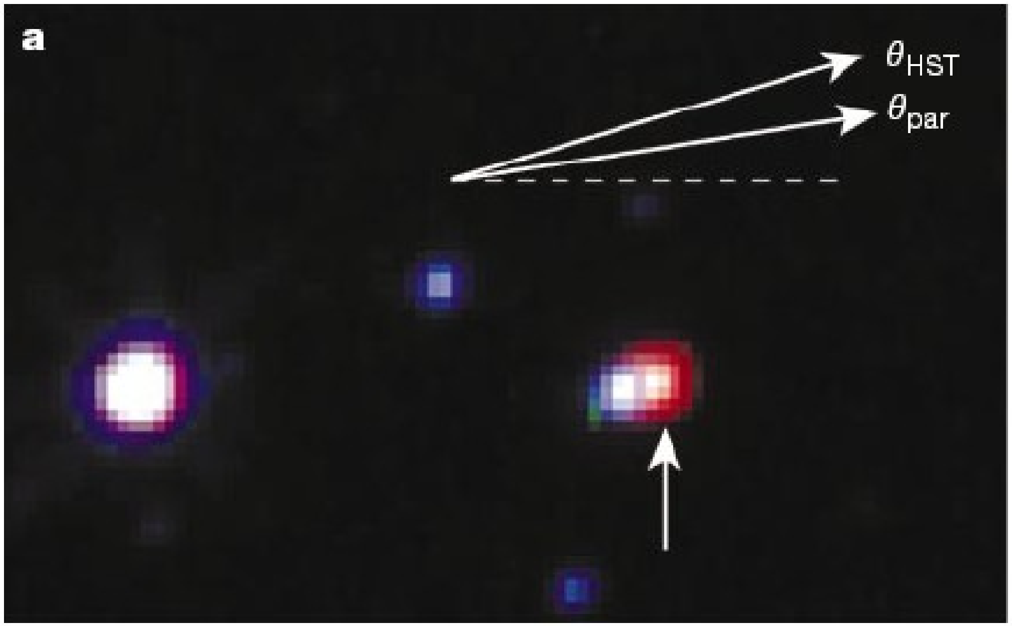


(c)

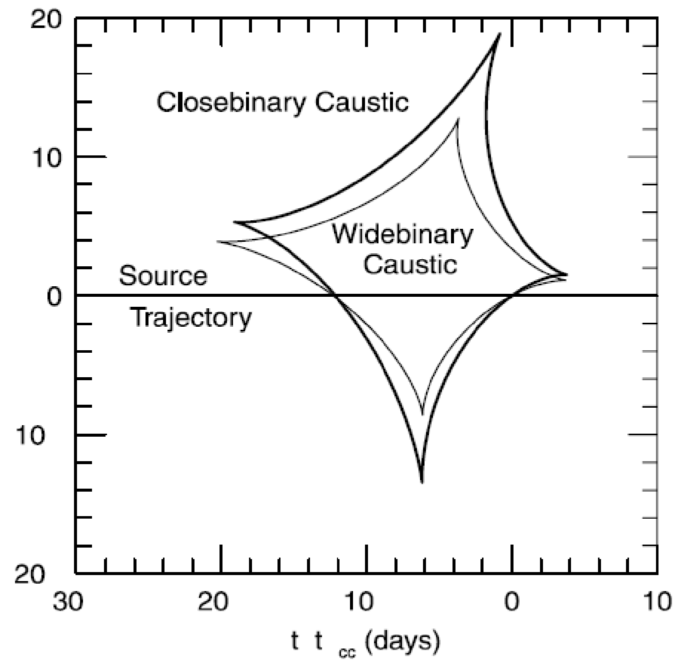
MACHO-LMC-5

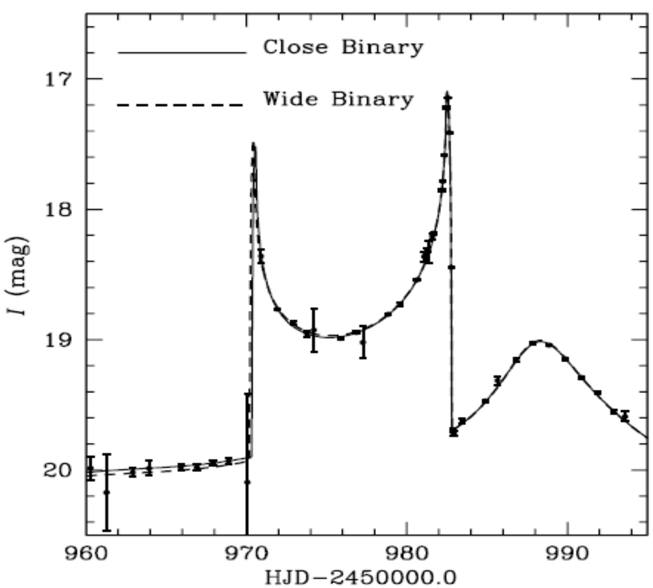
Angular Einstein radius from proper motion

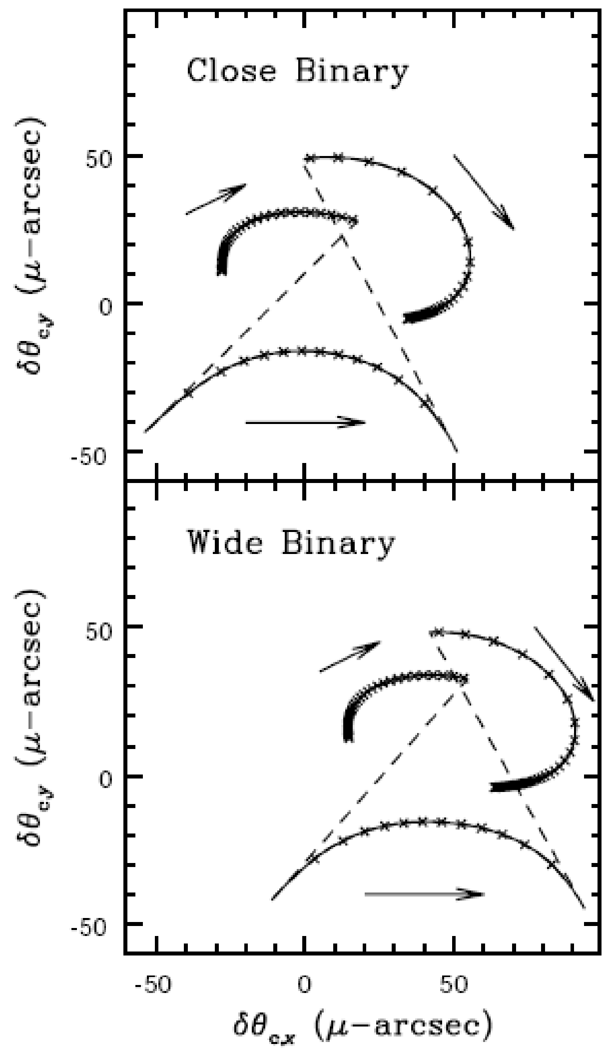


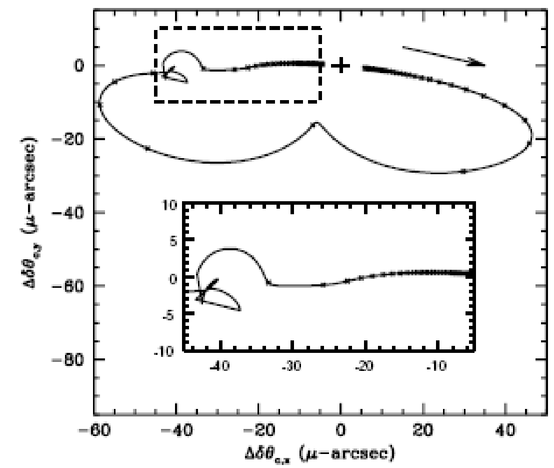


Geometry, Photometry, Astrometry



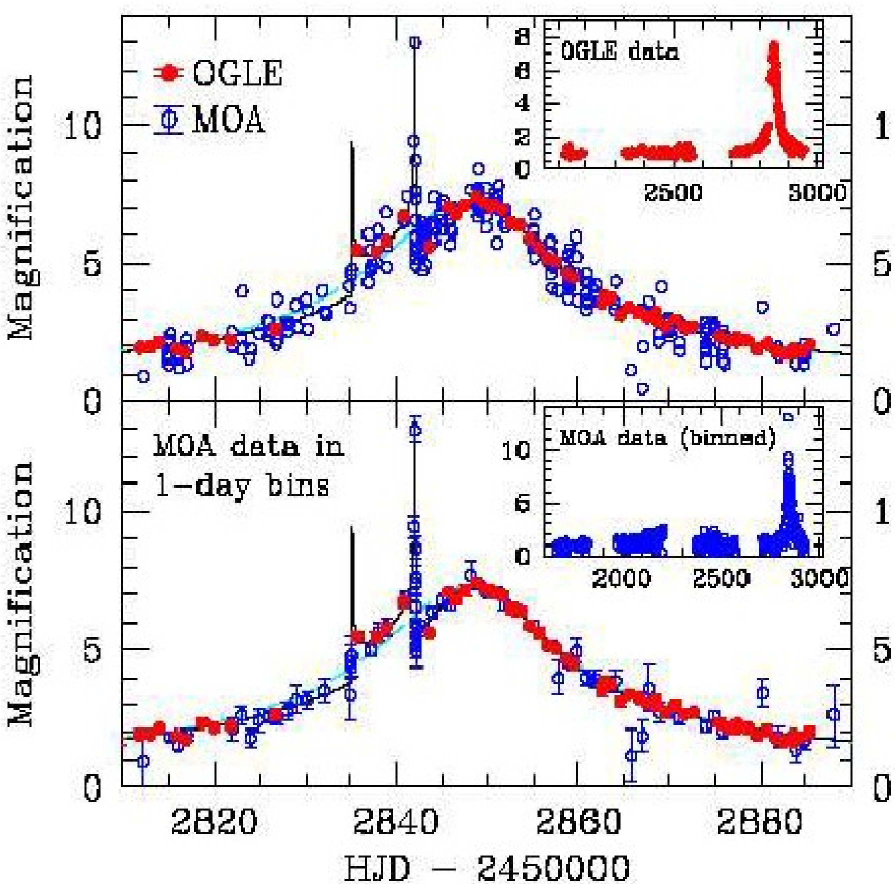


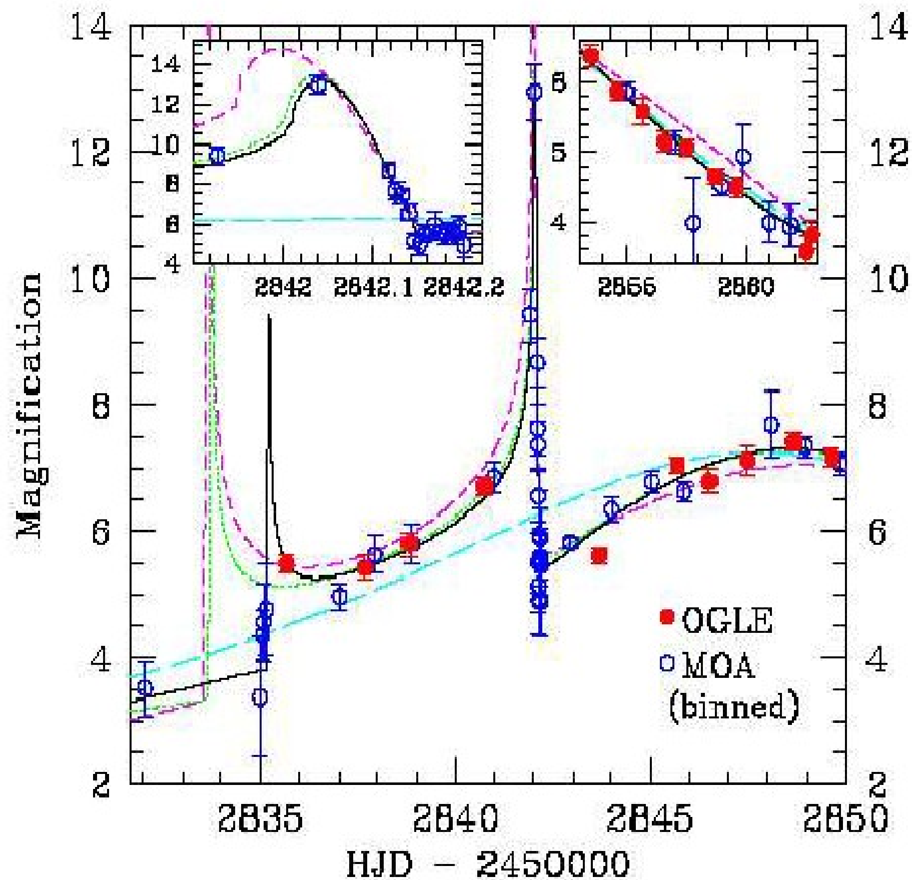




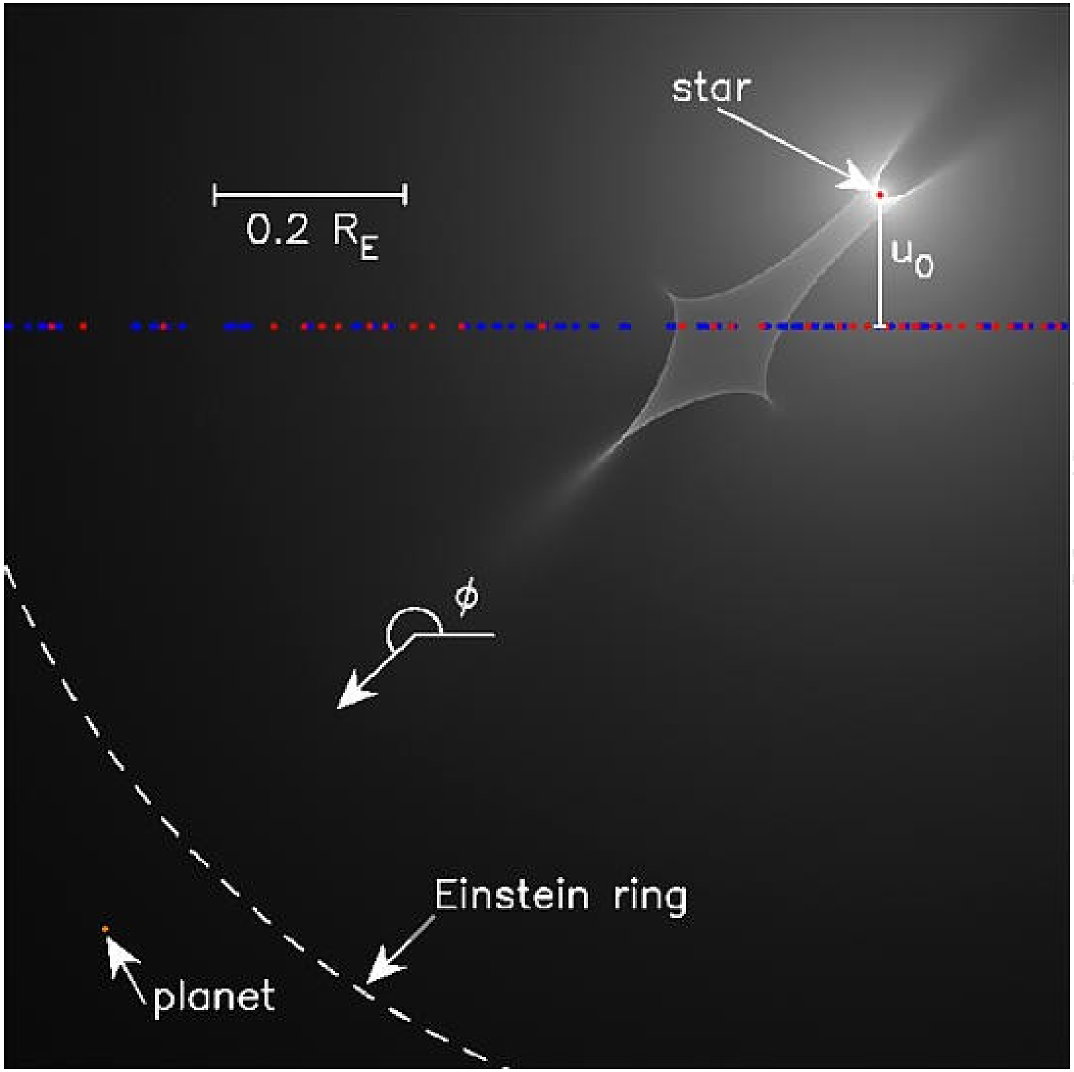
OGLE-2003-BLG-235/MOA-2003-BLG-53

"Pure-Survey" Detection

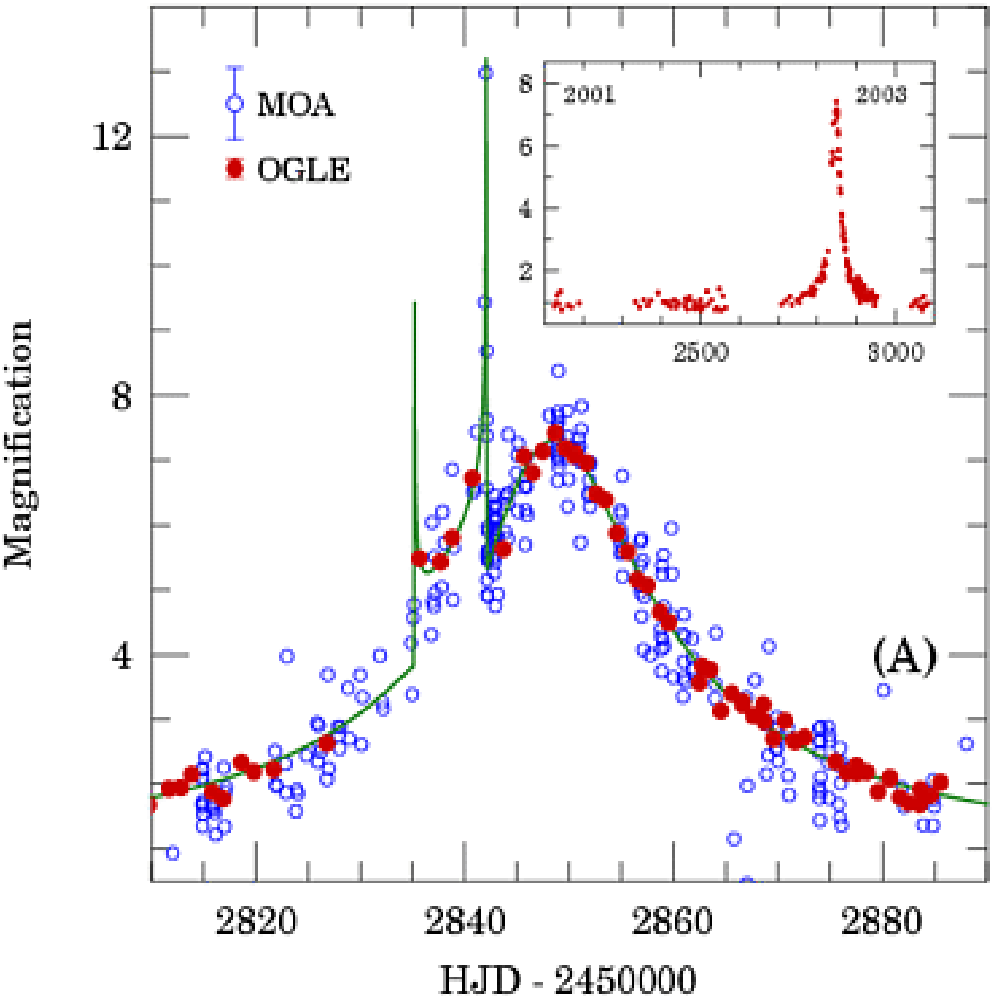




Bond et al. 2004, ApJ, 606, L155



star
0.2 R_E
u_0
φ
Einstein ring
planet



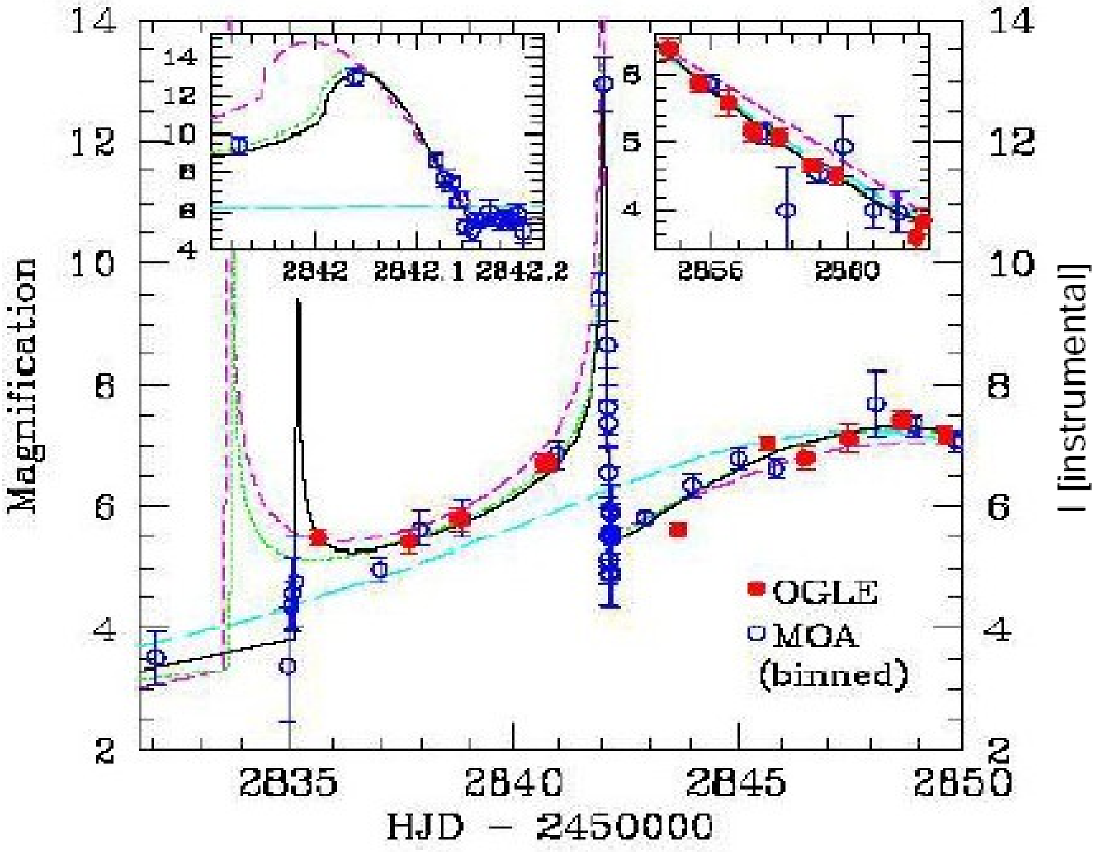
MOA
OGLE
Magnification
HJD - 2450000
(A)
2001
2003

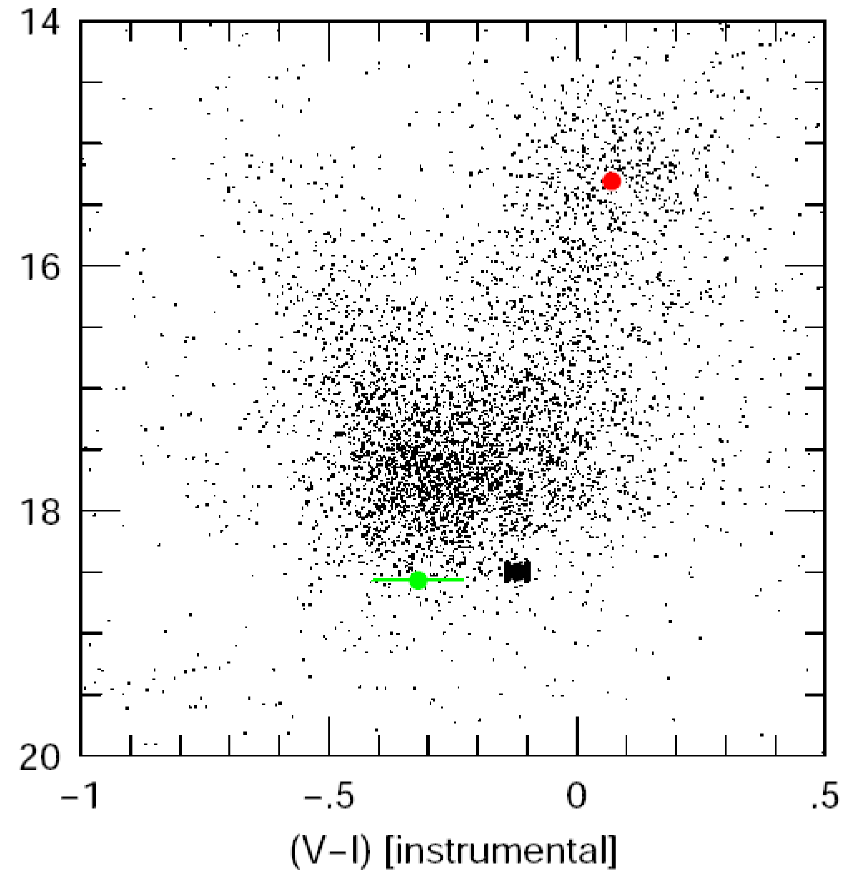
Resolving Degenercies I:

The Angular Einstein Radius

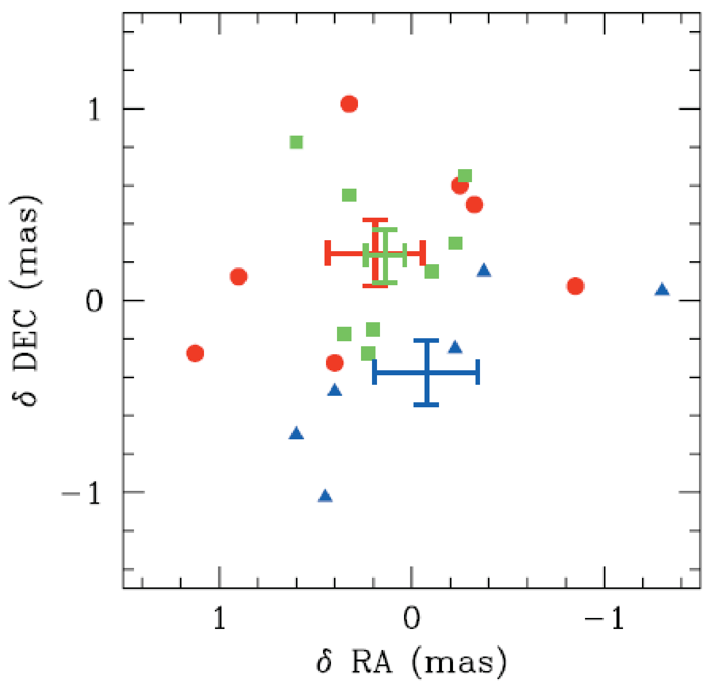
(==> proper motion)

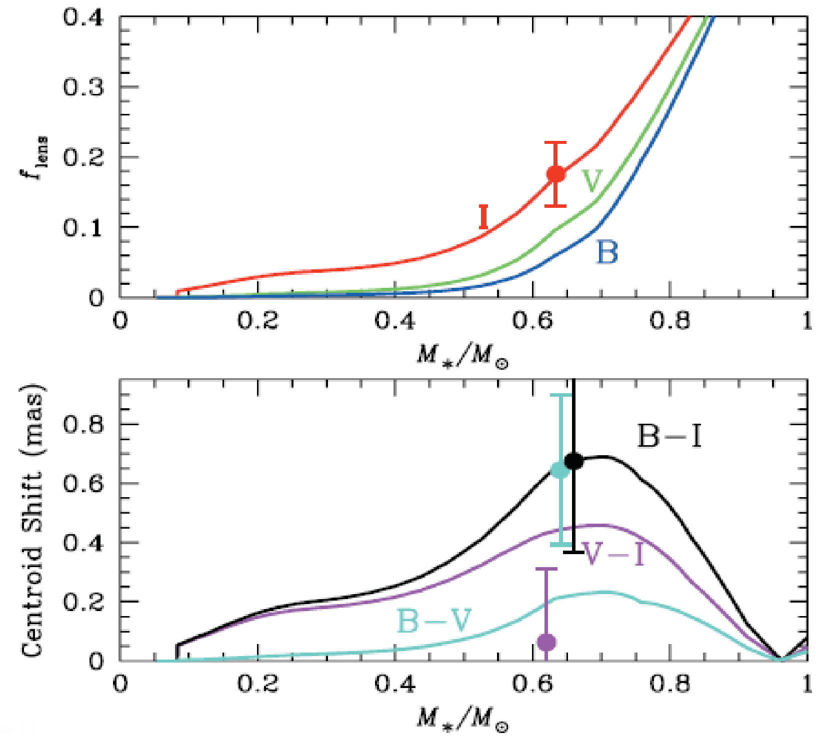
$$\theta_E = \sqrt{\frac{4GM}{D_{rel}\, c^2}}$$

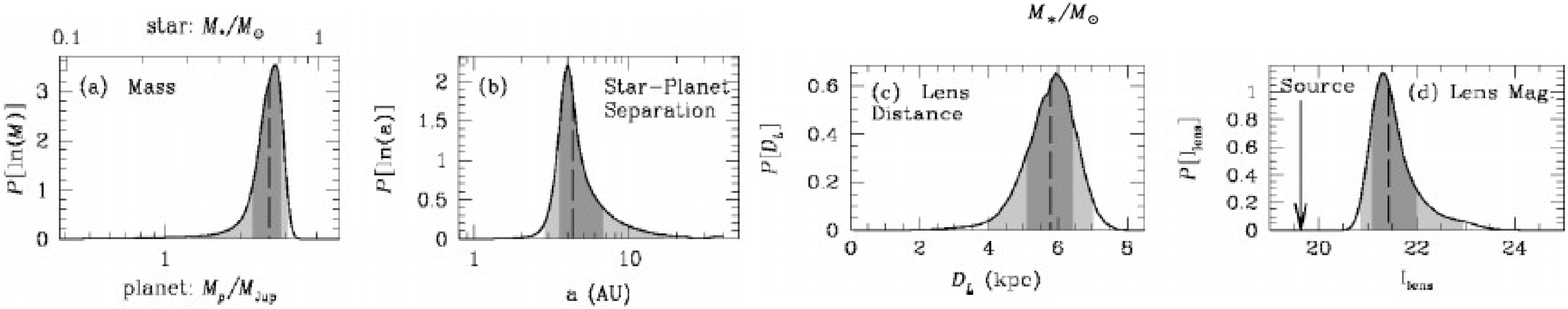




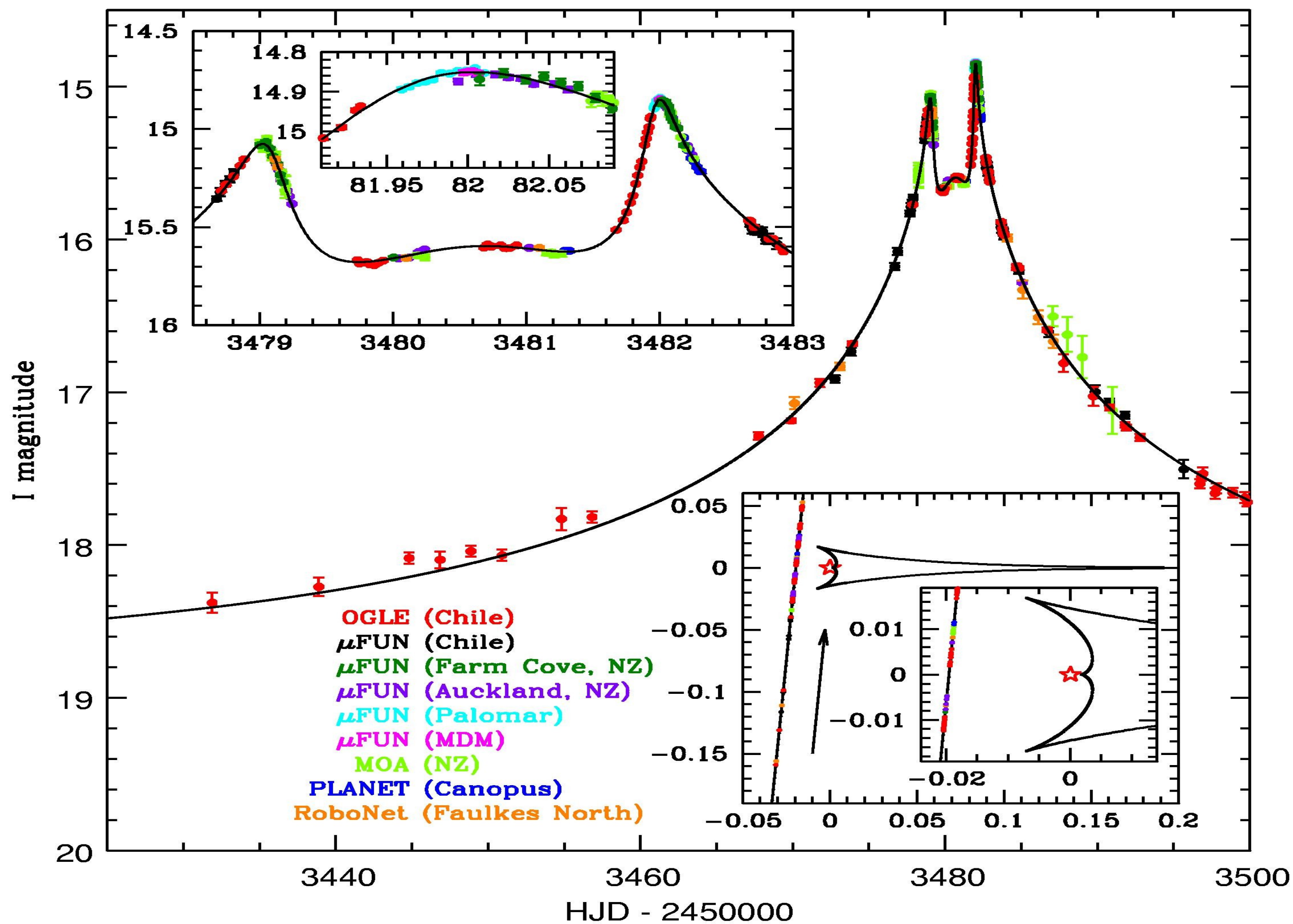
Resolving Degeneracies II: Centroid Motion (using known proper motion)





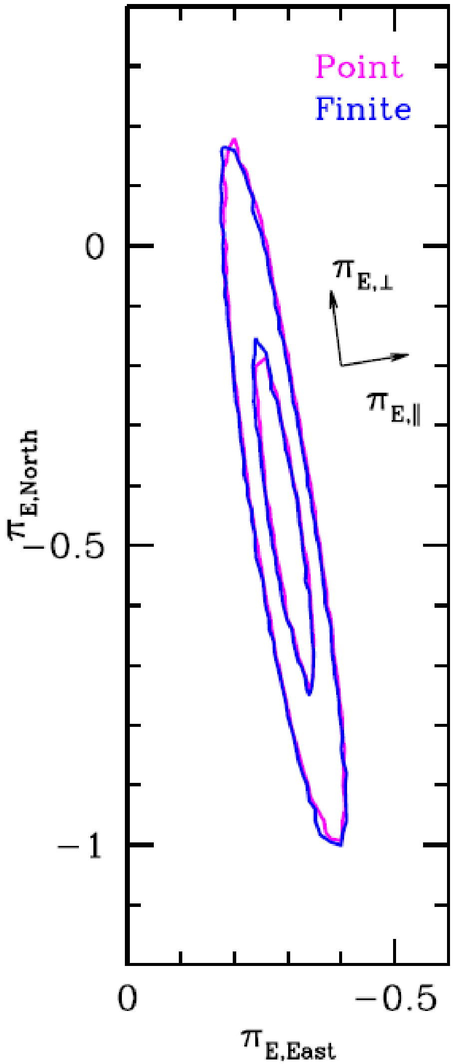


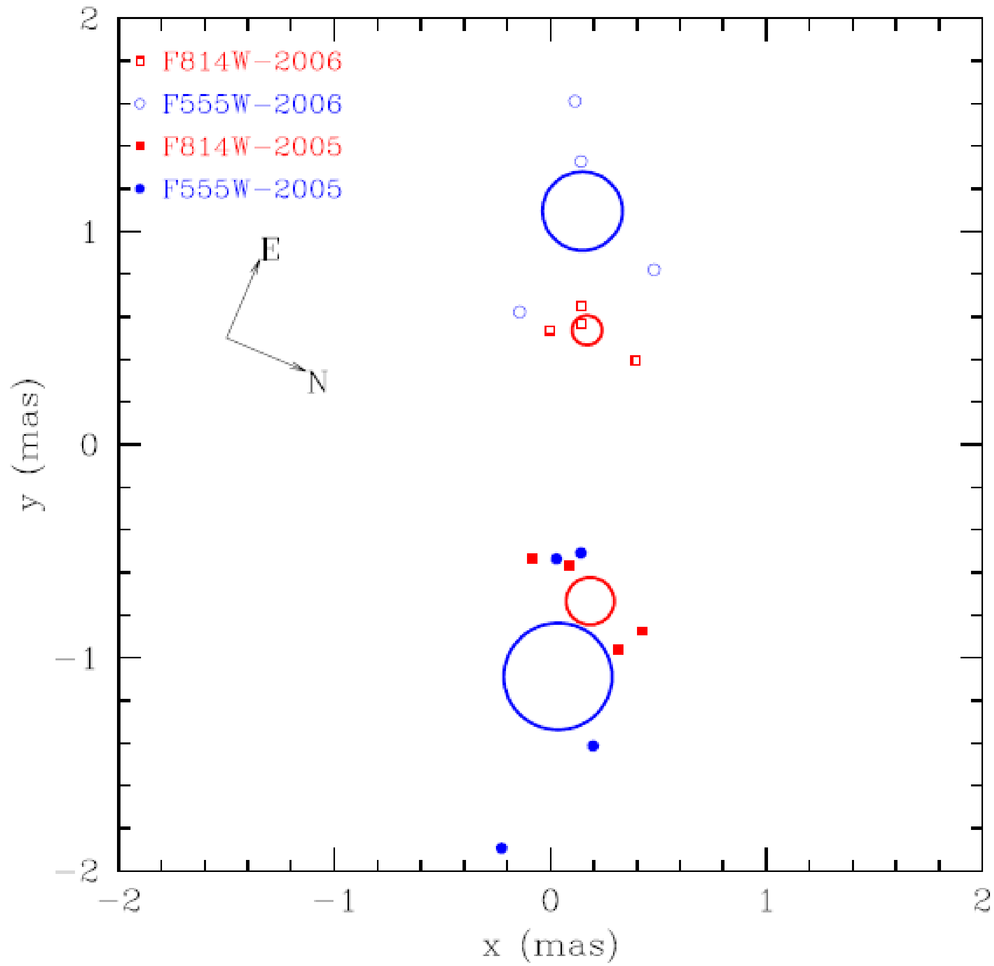
2nd Microlensing Planet



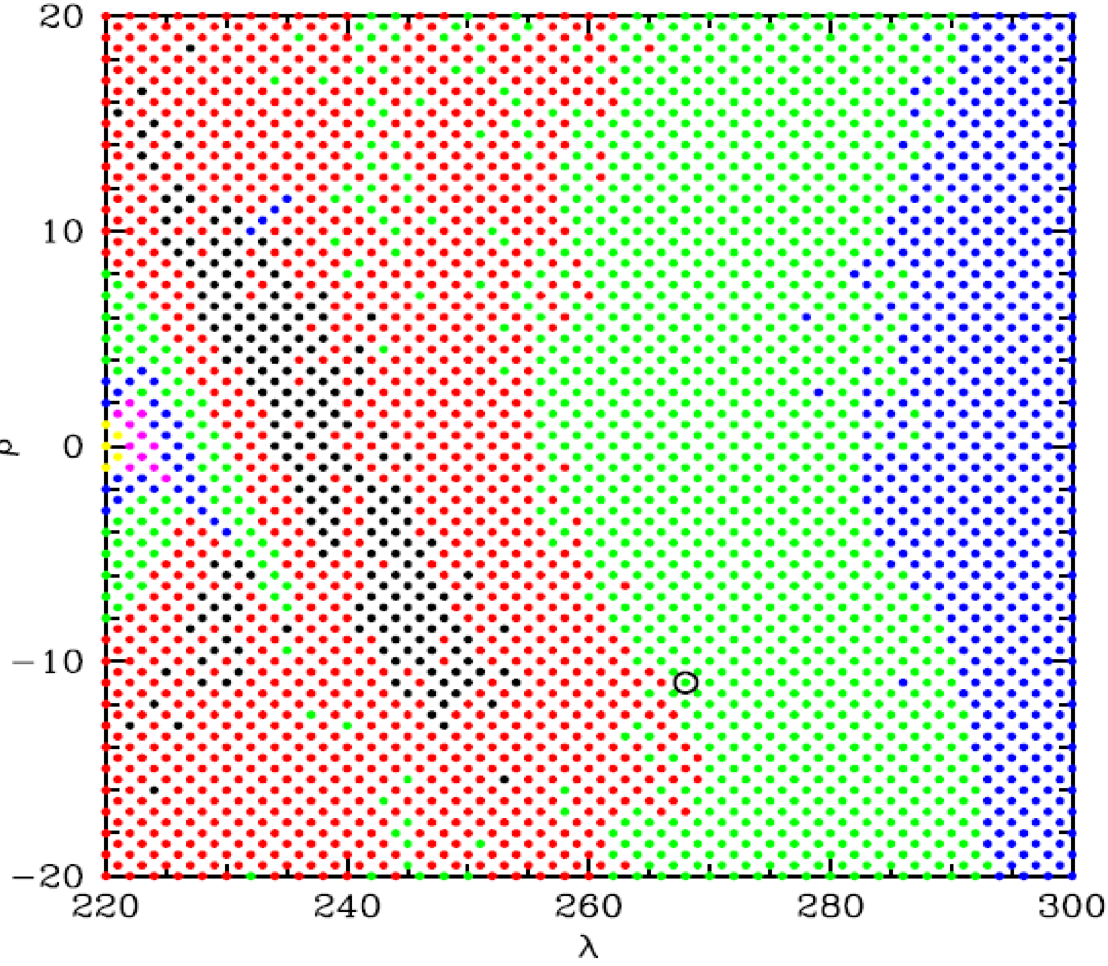
Udalski et al. 2005, ApJ, 628, L109

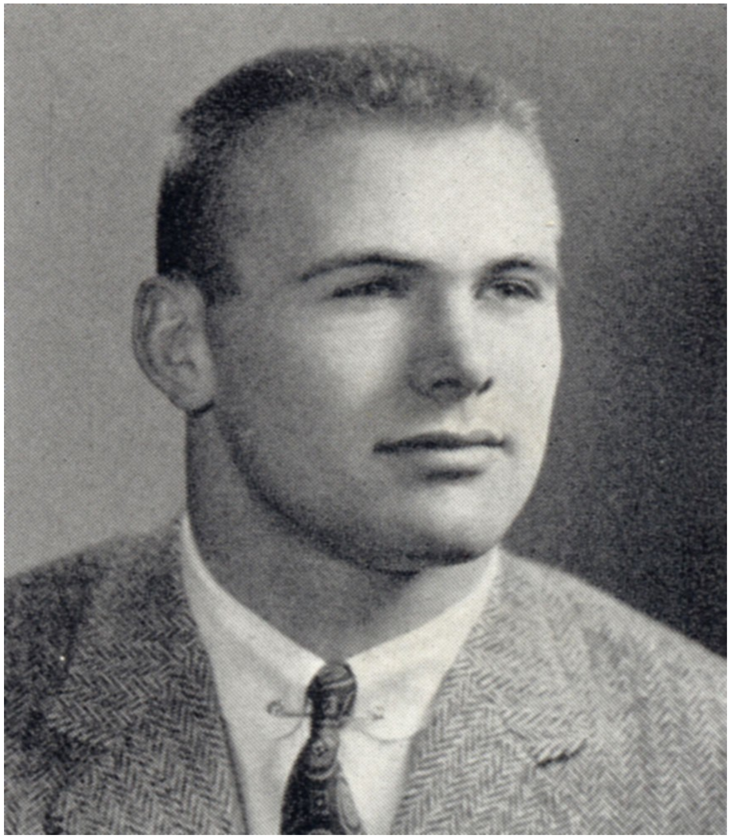
Resolving Degeneracies III:
Parallax





Xallarap vs. Parallax

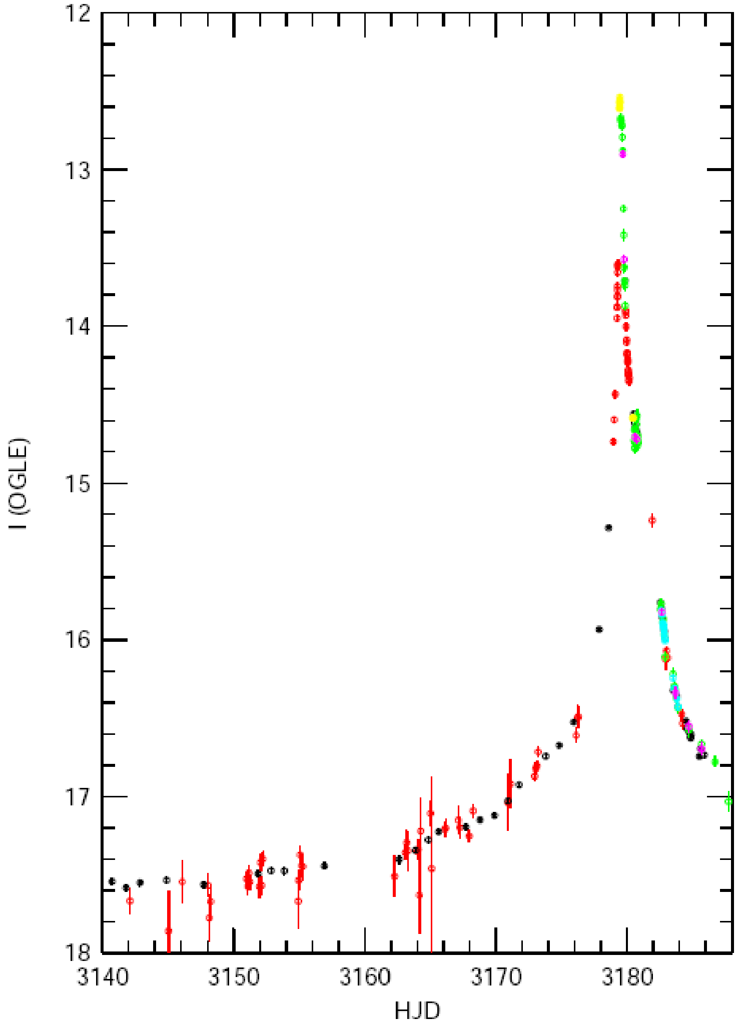


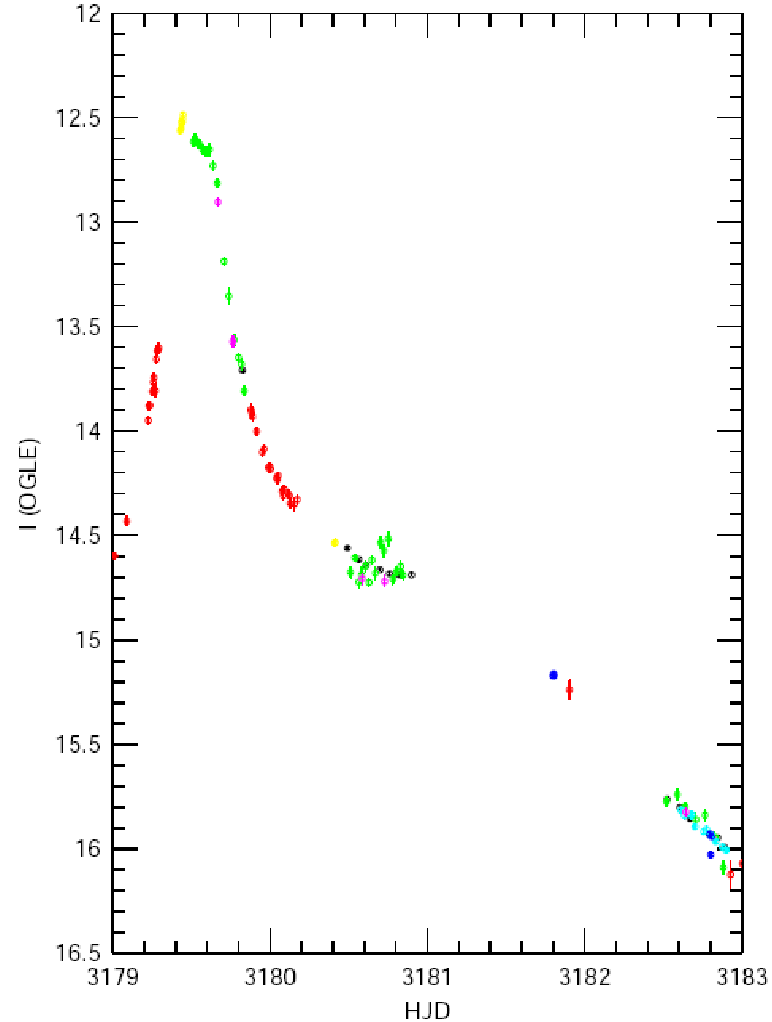


Princeton '54

Unknown Knowns

MOA-2004-BLG-033





Conclusions

- Contrary to original expectation, we can often measure the angular Einstein radius, and sometimes measure the microlens parallax
- When both are measured, we get the host and planet masses and distances