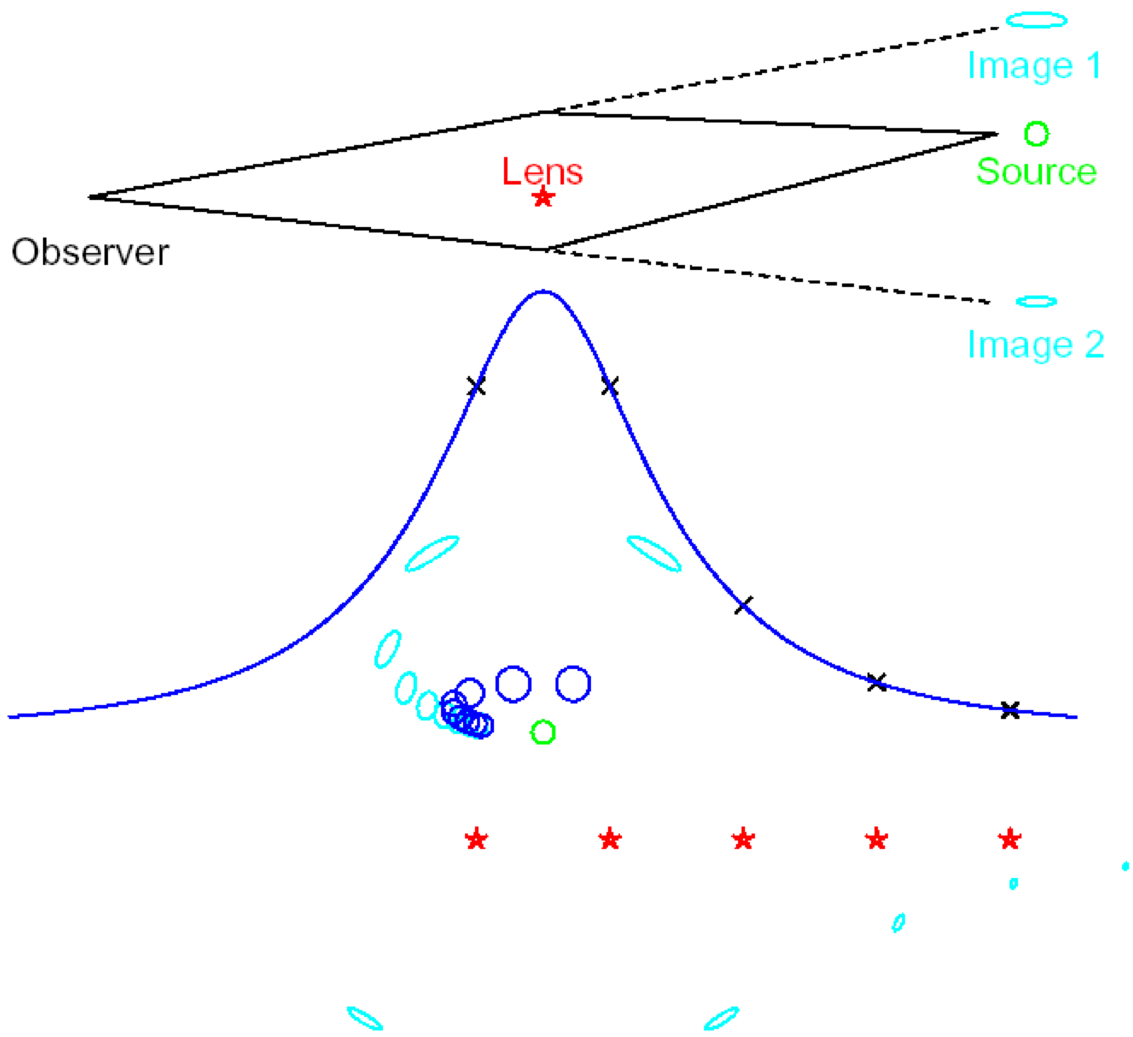
# Interpenetration of

# Astrometry and Microlensing

Andy Gould (Ohio State University)



# Generation 1

- Liebes 1964, Phys Rev, 133, B835
  - Many practical examples, including planets
- Refsdal 1964, MNRAS, 128, 259
  - Mass measurement of Isolated Star
- Refsdal 1966, MNRAS, 134, 315
  - Space-Based Parallaxes
- Paczynski 1986, ApJ, 304, 1
  - Proposed First Practical Experiment

# Generation 0

- Eddington 1920, Space, Time, and Gravitation
- Chwolson 1924, Astron. Nachr. 221, 329
- Einstein 1936a, Science, 84, 506

  "Some time ago R.W. Mandl paid me a visit and asked me to publish the results of a little calculation, which I had made at his request .... there is no great chance of observing this phenomenon."

- Einstein 1936b (private letter to Science editor)

  "Let me also thank you for your cooperation with the little publication, which Mister Mandl squeezed out of me. It is of little value, but it makes the poor guy happy."

# Generation -1: Einstein (1912)

[Renn, Sauer, Stachel 1997, Science 275, 184]

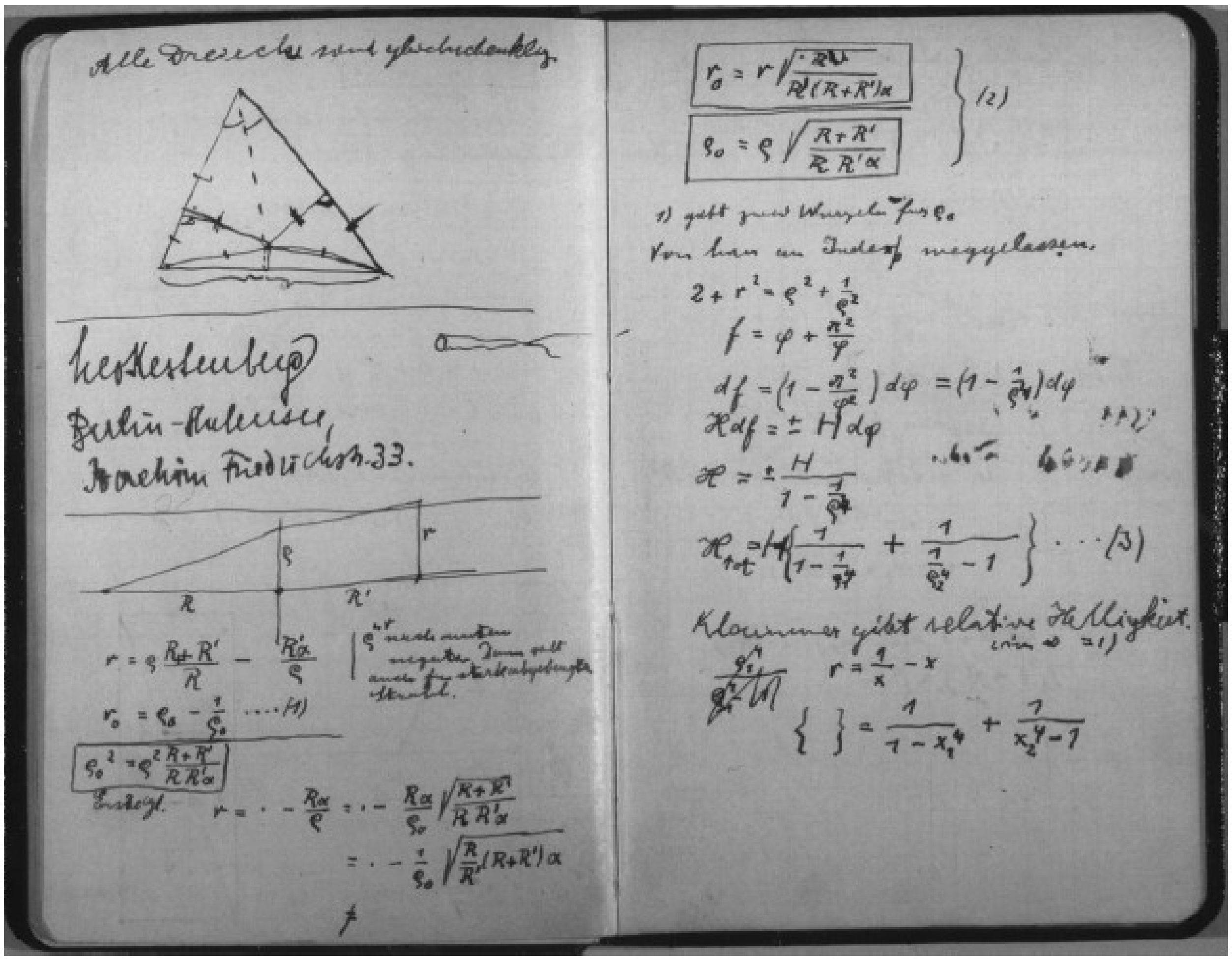


**Fig. 1.** Notes about gravitational lensing dated to 1912 on two pages of Einstein's scratch notebook (*12*). [Reproduced with permission of the Einstein Archives, Jewish National and University Library, Hebrew University of Jerusalem]

# Mao & Paczynski

# Microlens Planet Searches

## GRAVITATIONAL MICROLENSING BY DOUBLE STARS AND PLANETARY SYSTEMS

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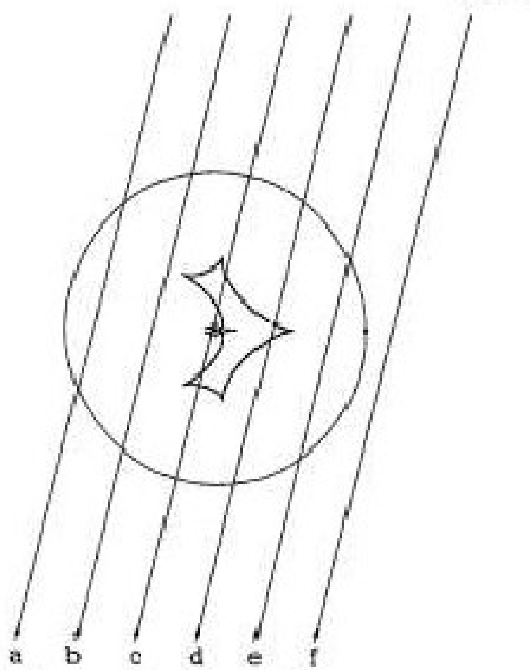
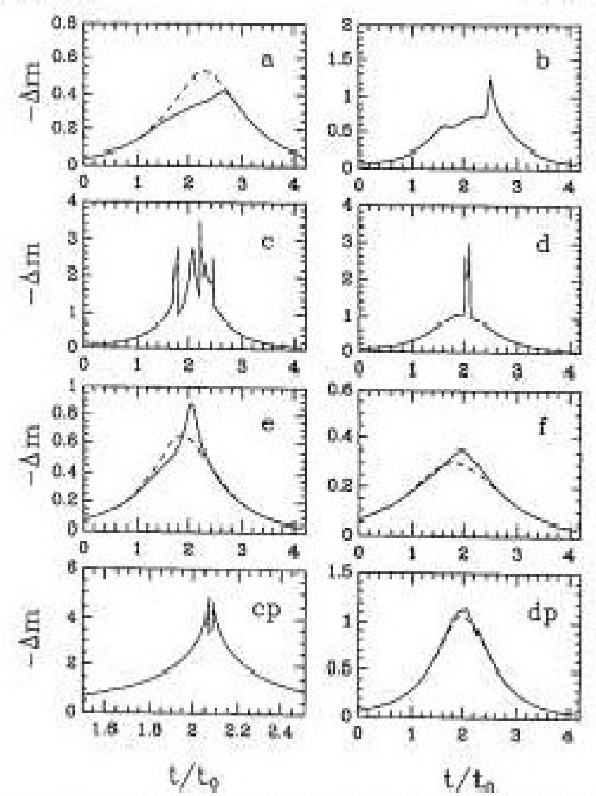
*Received 1991 March 12; accepted 1991 April 2*




. 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

# Survey + Follow-Up

DISCOVERING PLANETARY SYSTEMS THROUGH GRAVITATIONAL MICROLENSES

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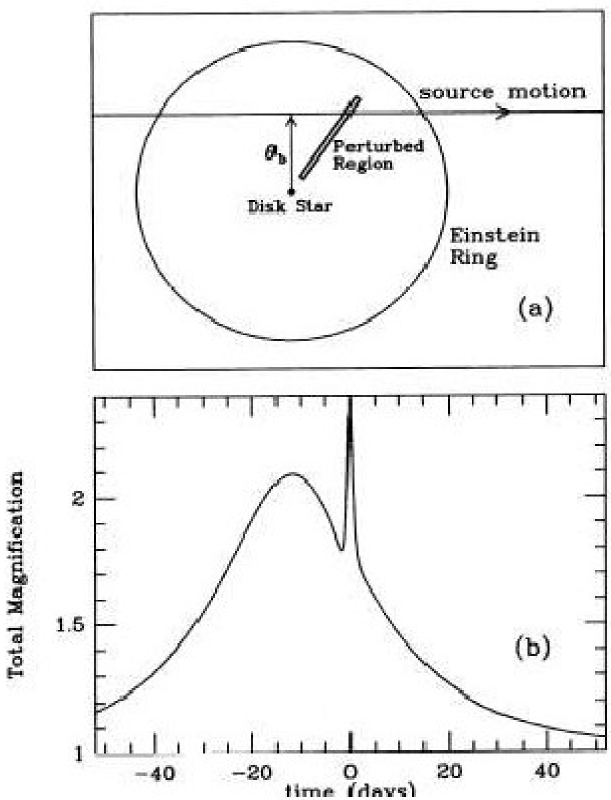
*Received 1991 December 26; accepted 1992 March 9*



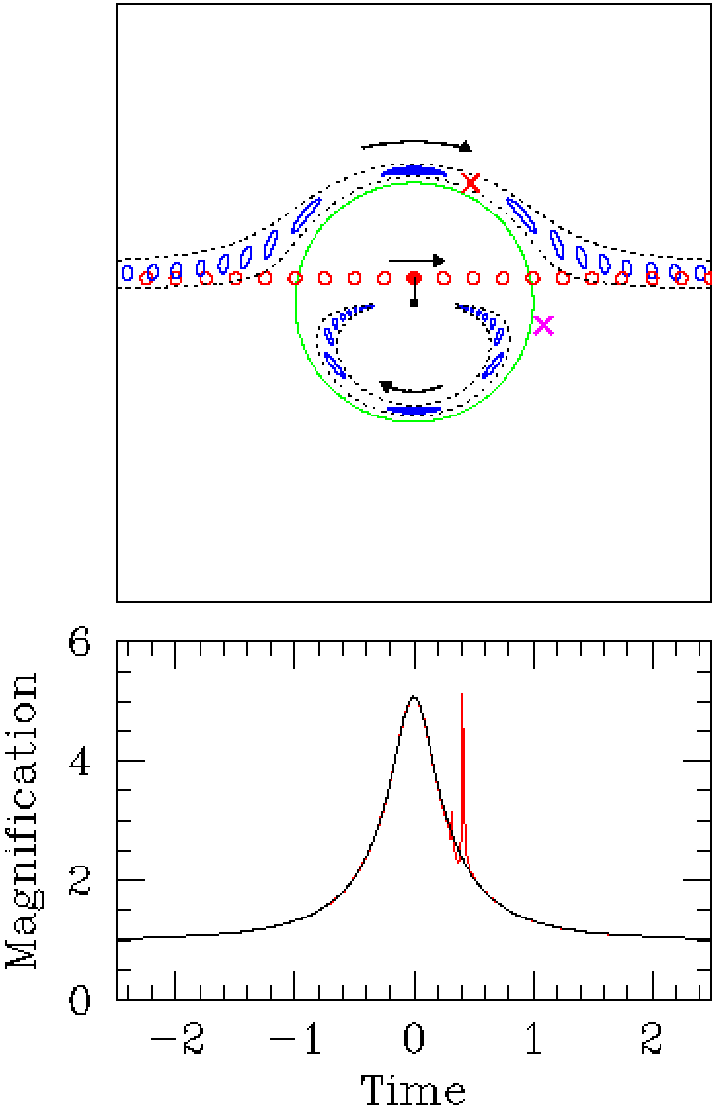

5. OBSERVATIONAL REQUIREMENTS

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,

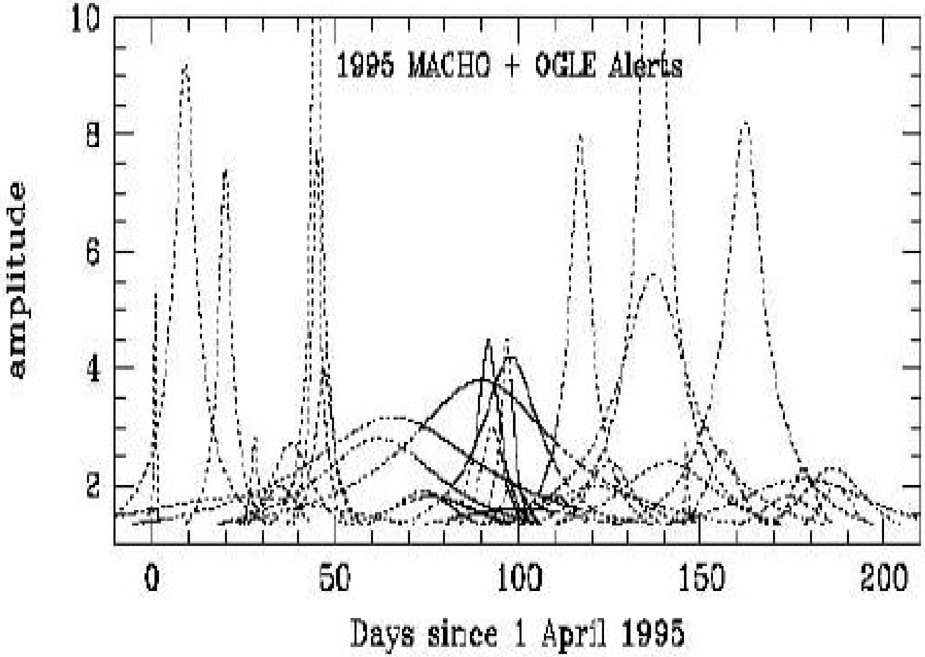
two telescopes that were totally committed. Third, in view of the fleeting nature of the events, it would seem prudent to build in some redundancy in case of bad weather at a particular site. Thus, the optimal scheme would employ, say, a dozen telescopes. Each of these would be committed to carry out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

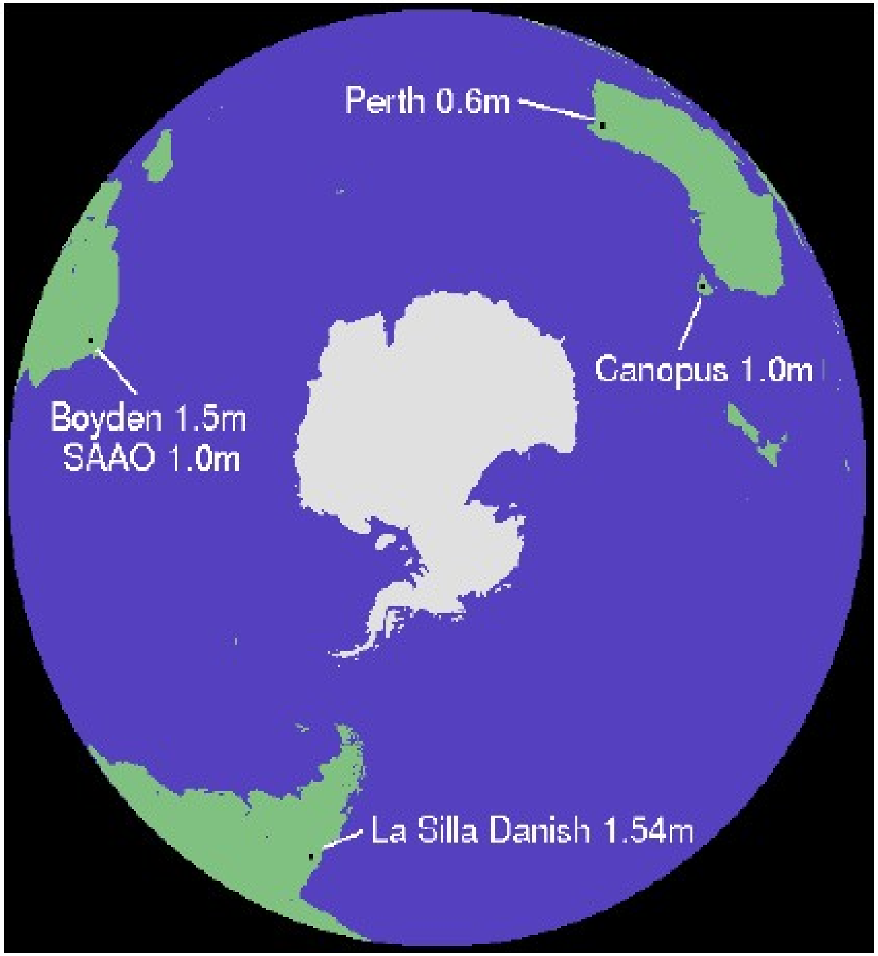
# How Microlensing Finds Planets



# 1995 PLANET Pilot Season

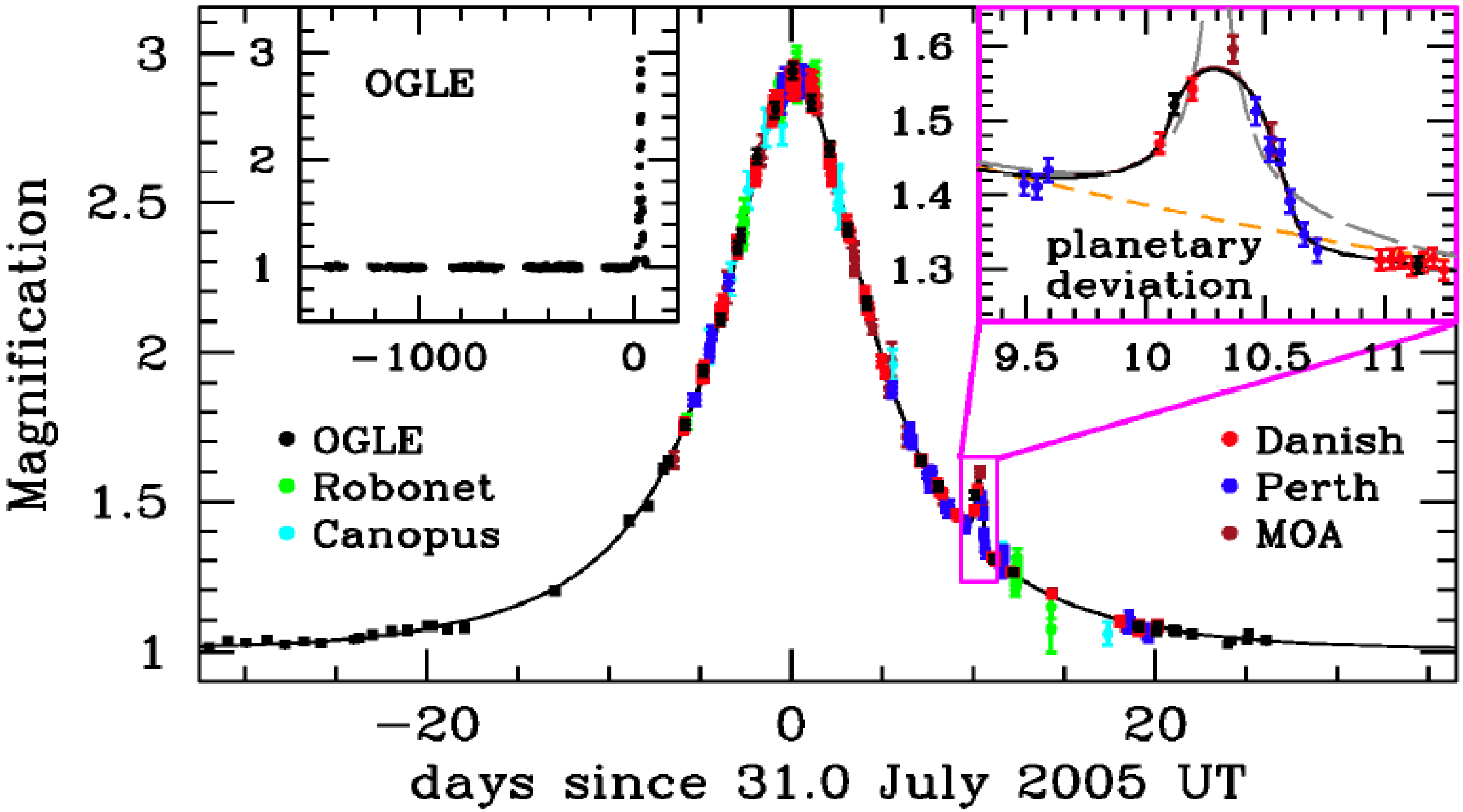
- Albrow et al. 1998 ApJ, 509, 687



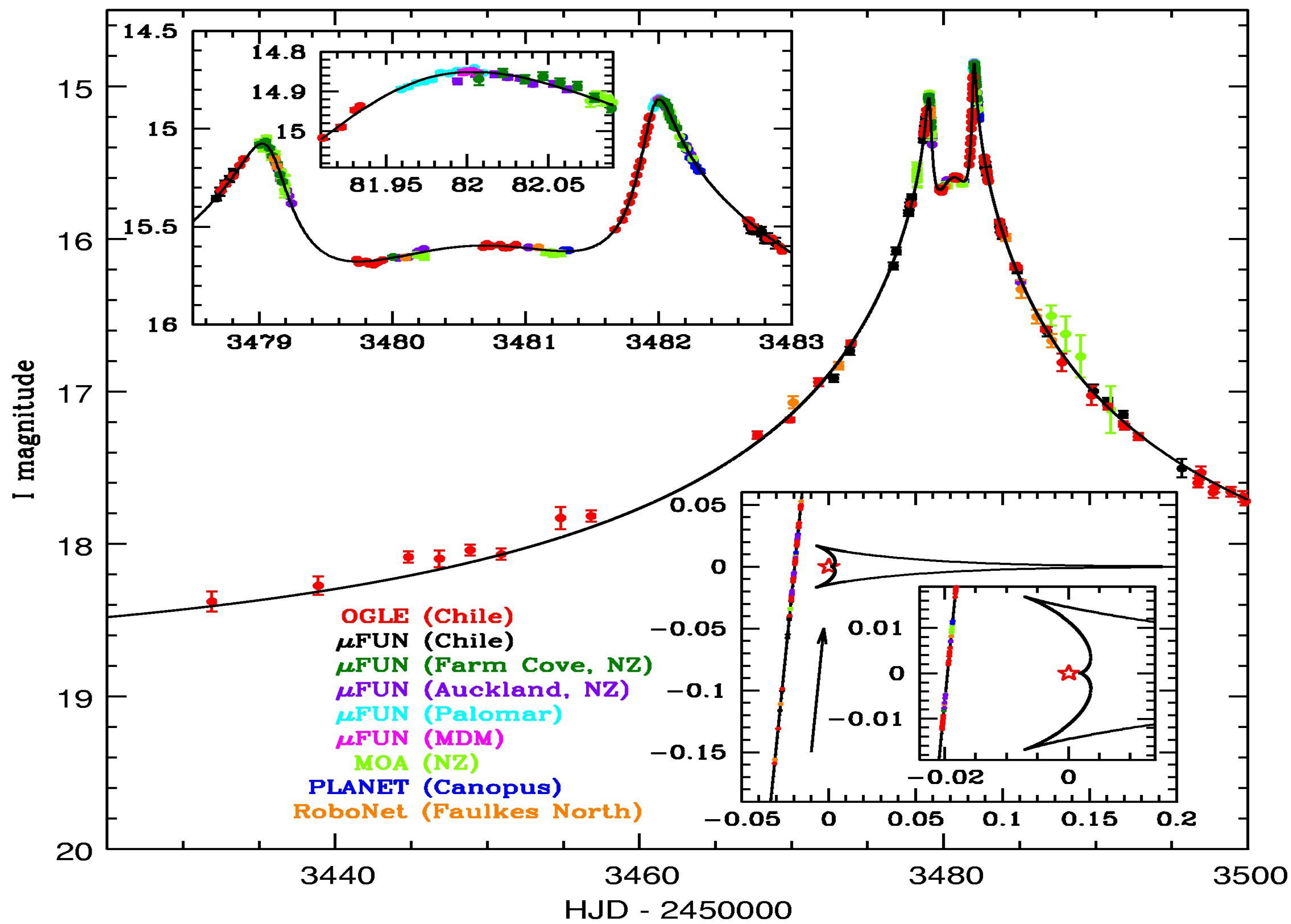
# OGLE-2005-BLG-390

## “Classical-Followup” Planetary Caustic




Beaulieu et al. 2006, Nature, 439, 437

# First “High-Magnification” Planet




Udalski et al. 2005, ApJ, 628, L109

# Amateurs + Professionals

## Grant, Ian, Jennie, Phil

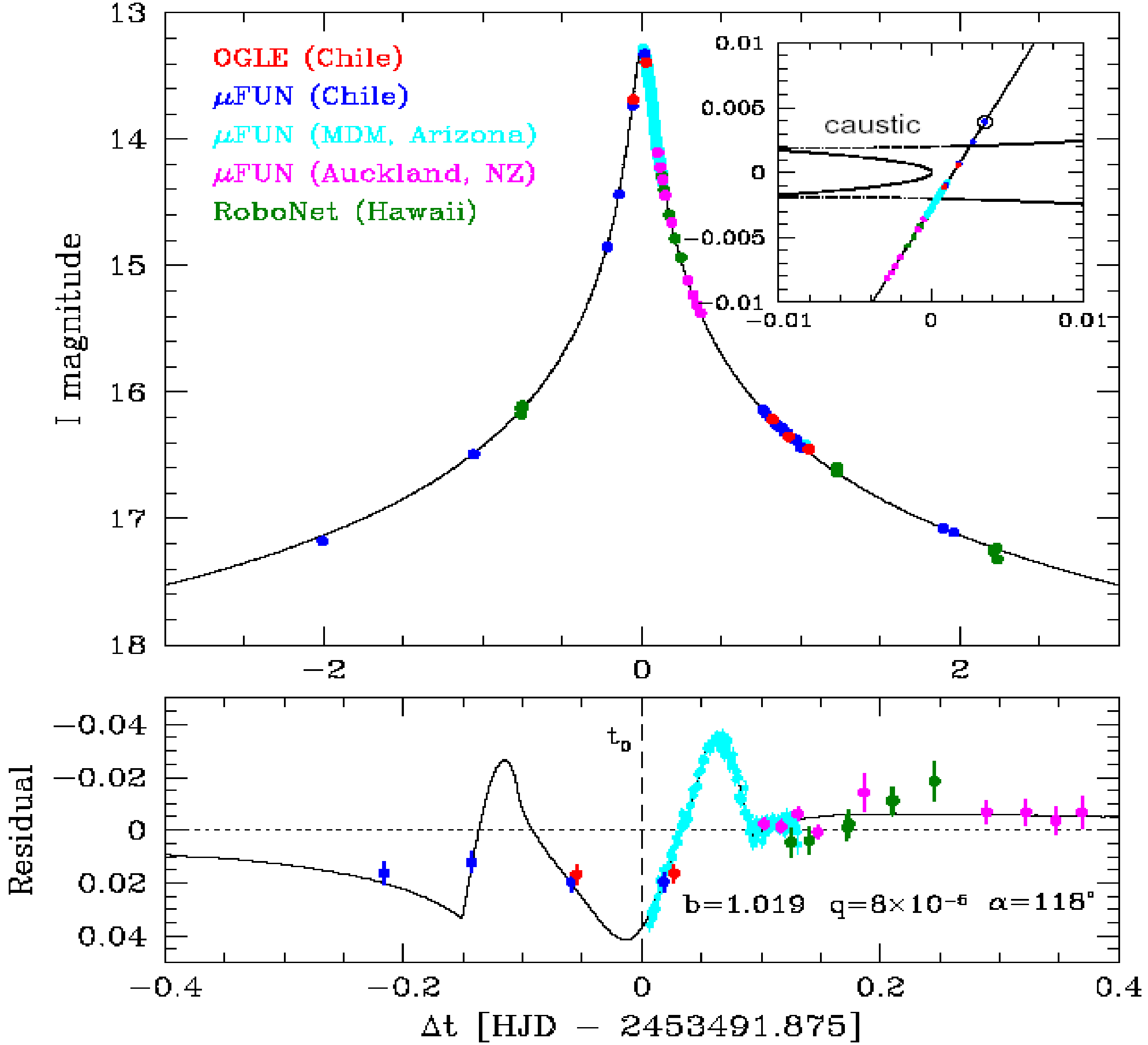
# Amateurs + Professionals

"It just shows that you can be a mother, you can work full-time, and you can still go out there and find planets."

Jennie McCormick

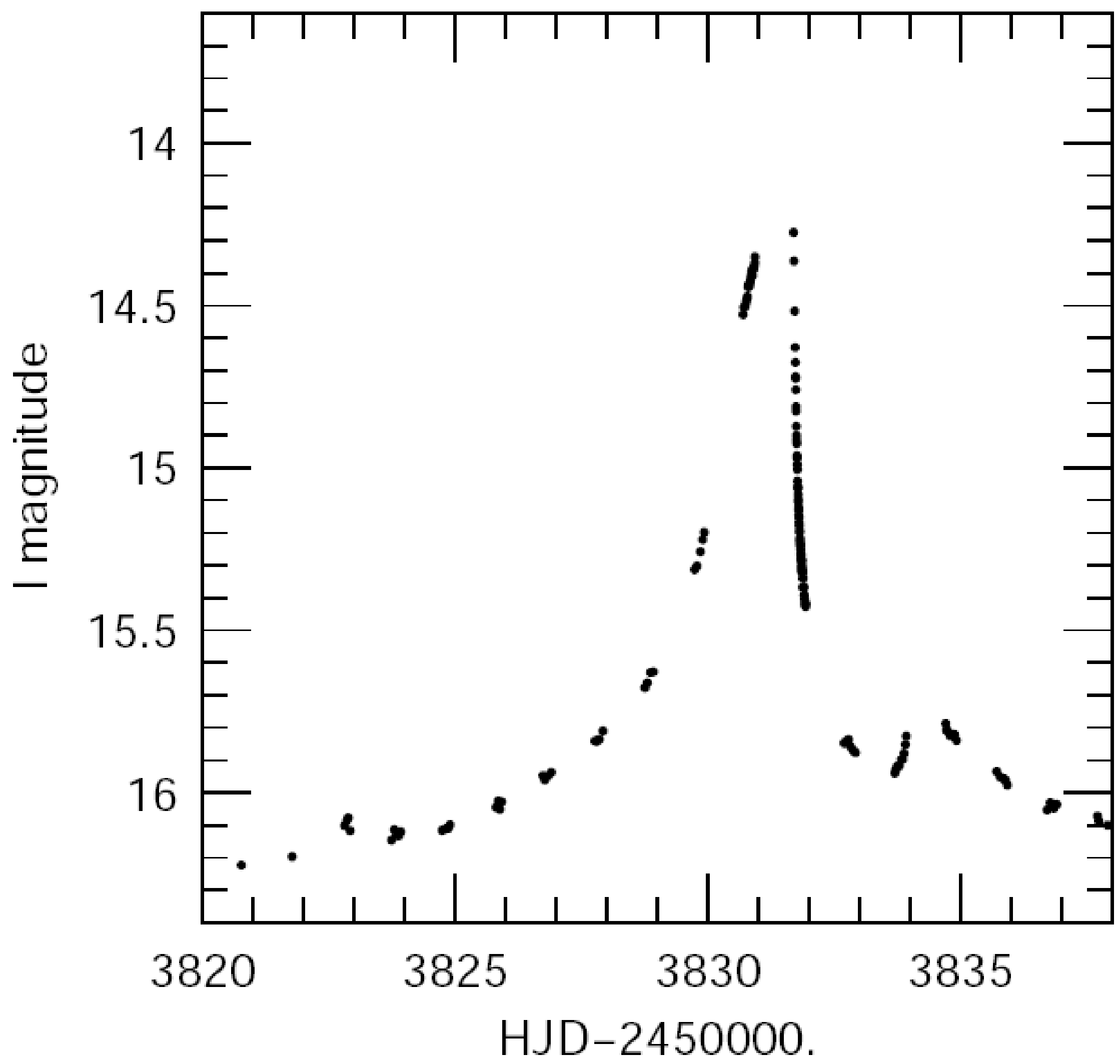
(Amateur Astronomer, Auckland, New Zealand)

# OGLE-2005-BLG-169:
# Second Cold Neptune



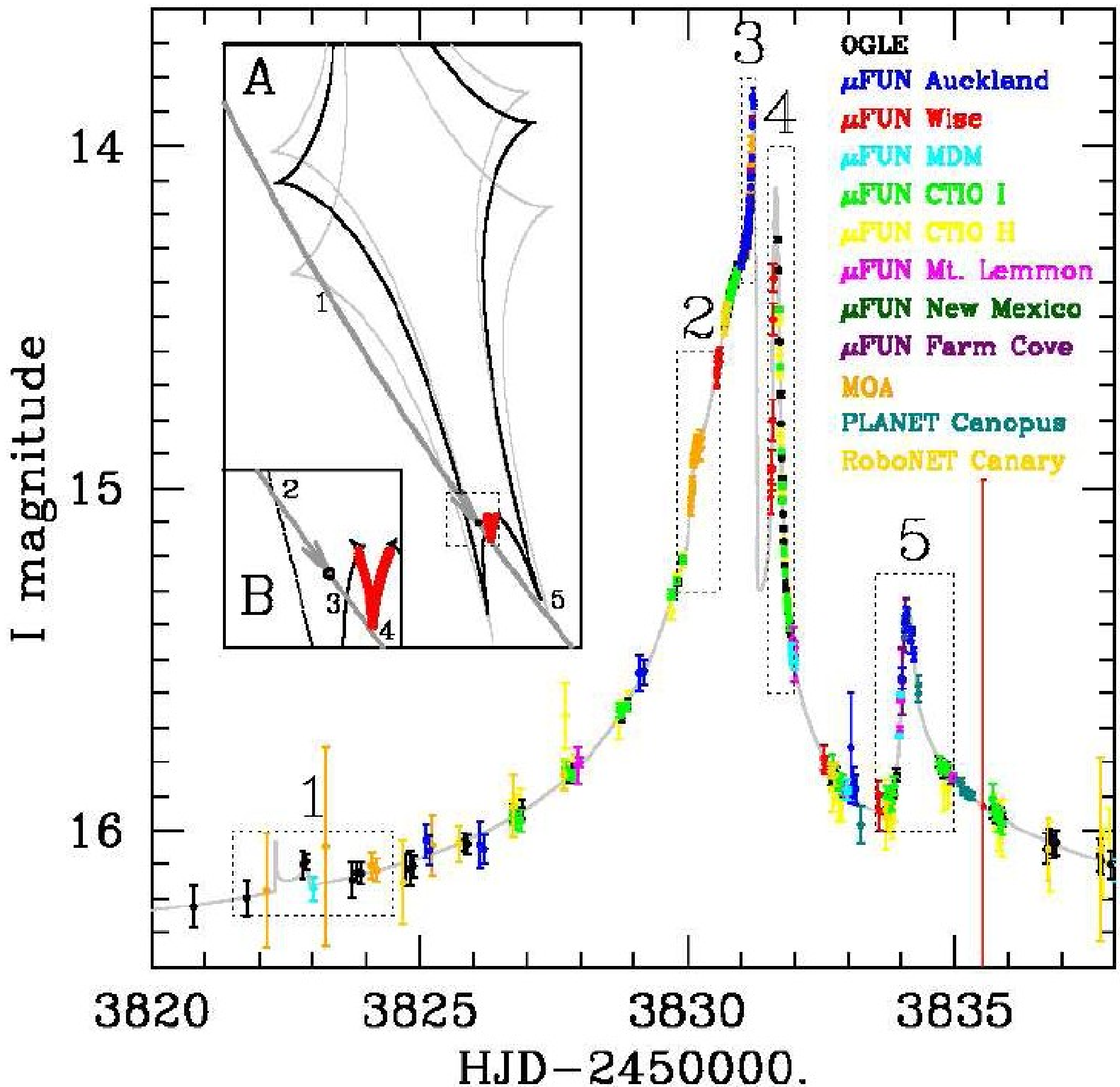
# Deokkeun An

# OGLE-2006-BLG-109:
# Without Followup Observations



# OGLE-2006-BLG-109

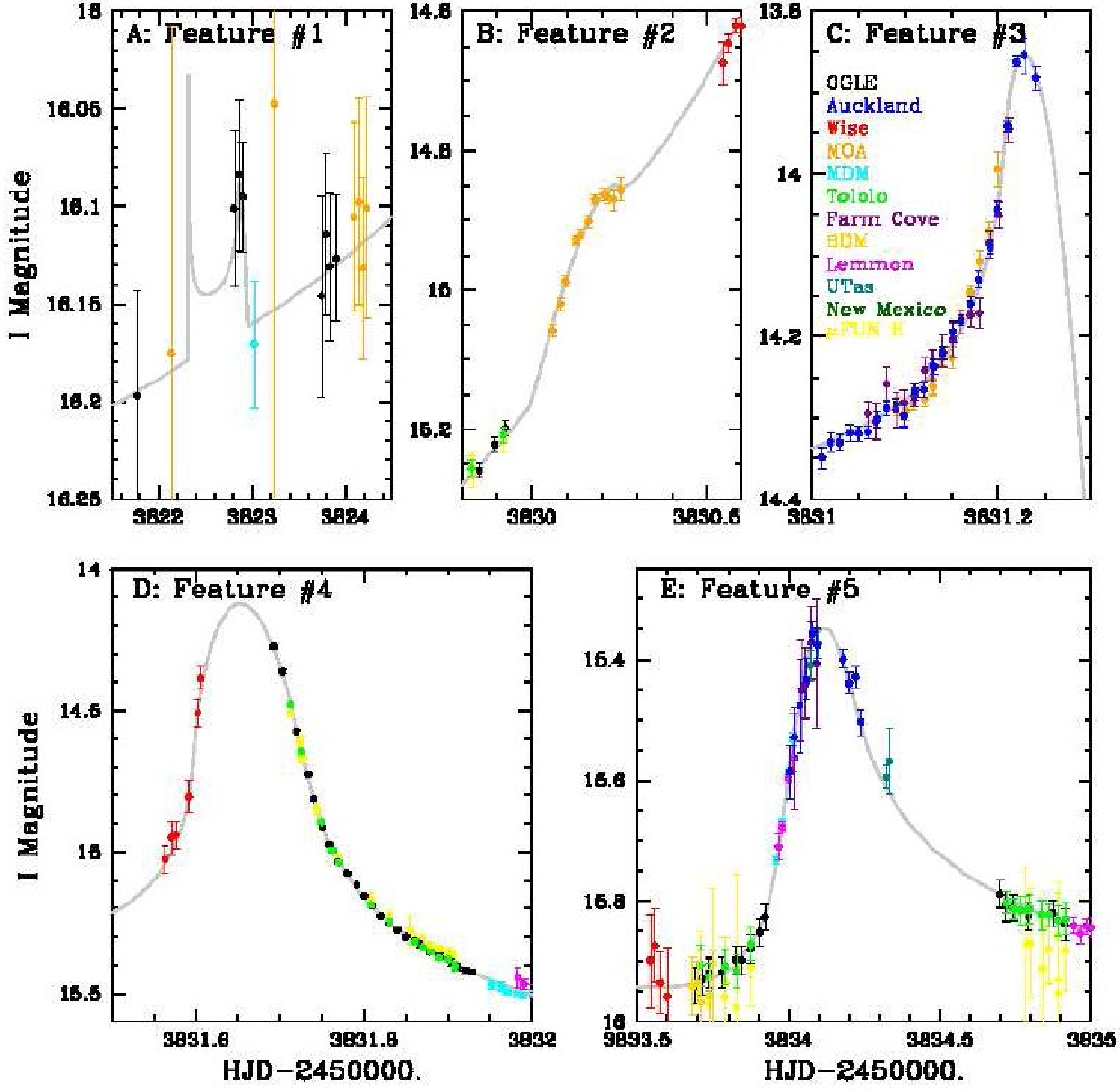
## Parallax+Finite-Source+Rotation+Blend



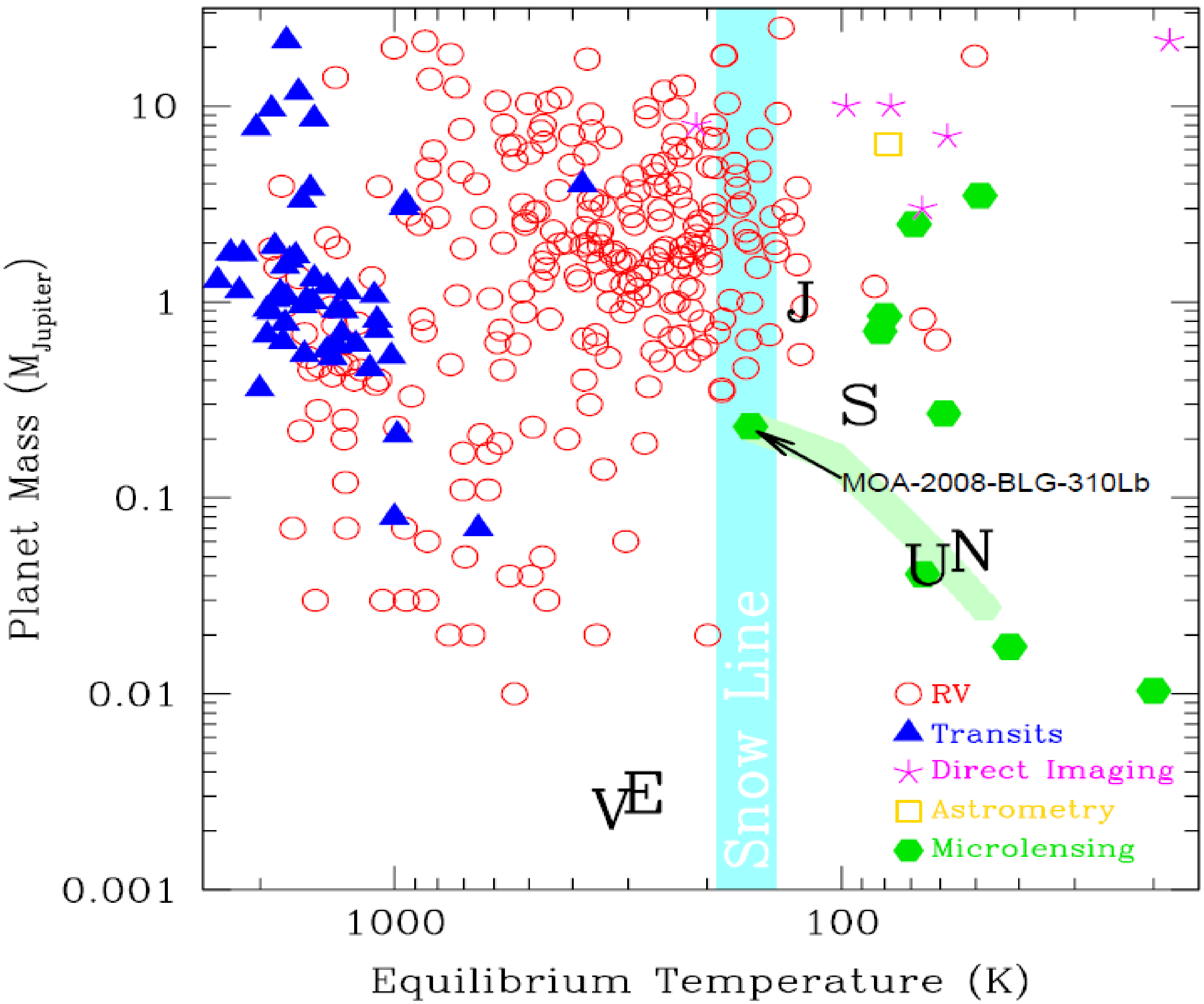

Gaudi et al. 2008, Science, 319, 927

# Five Lightcurve Features

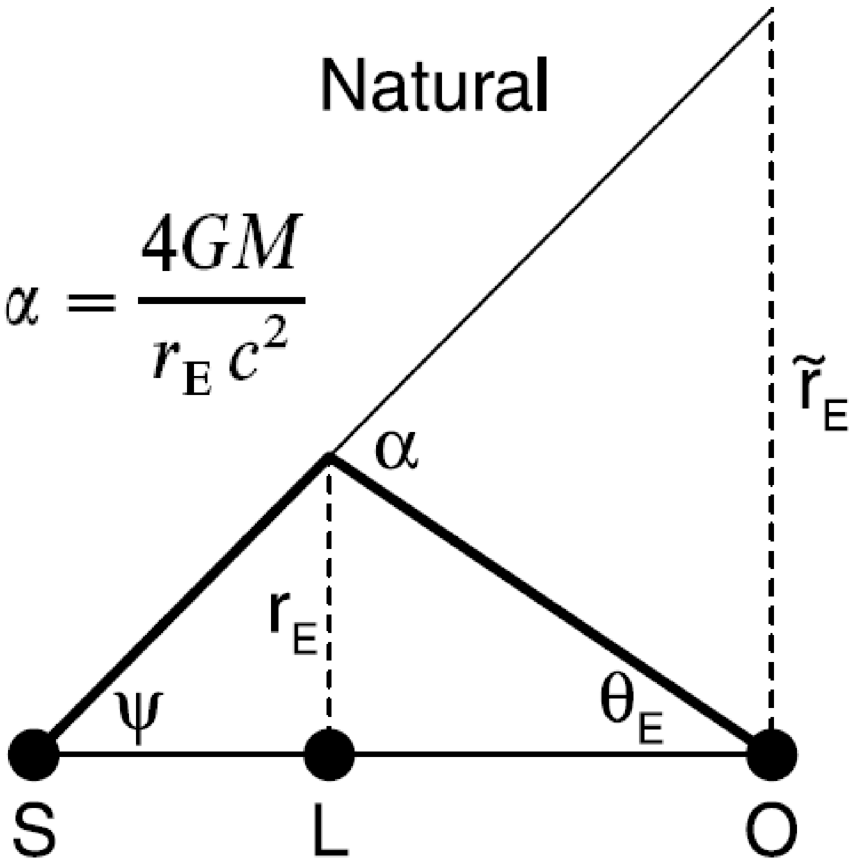
## 1+2+3+5=Saturn   4=Jupiter



# Microlensing vs. Other Methods



# Relation of Mass and Distance to Lensing Observables




$$\alpha = \frac{4GM}{r_E c^2}$$

$$r_E \quad \tilde{r}_E \quad \theta_E$$

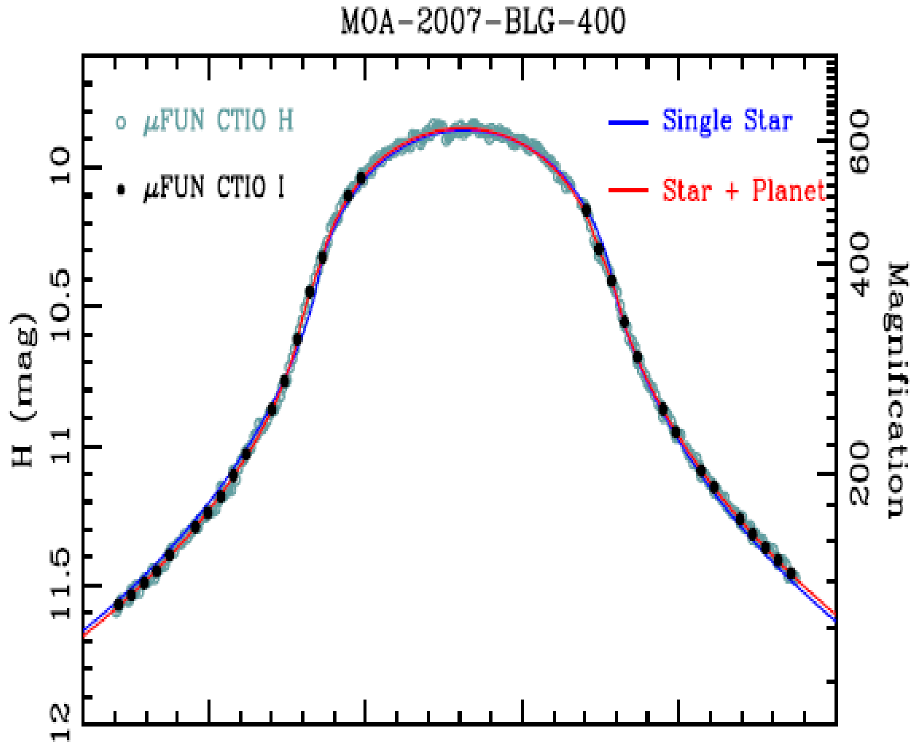
$$\alpha/\tilde{r}_E = \theta_E/r_E$$

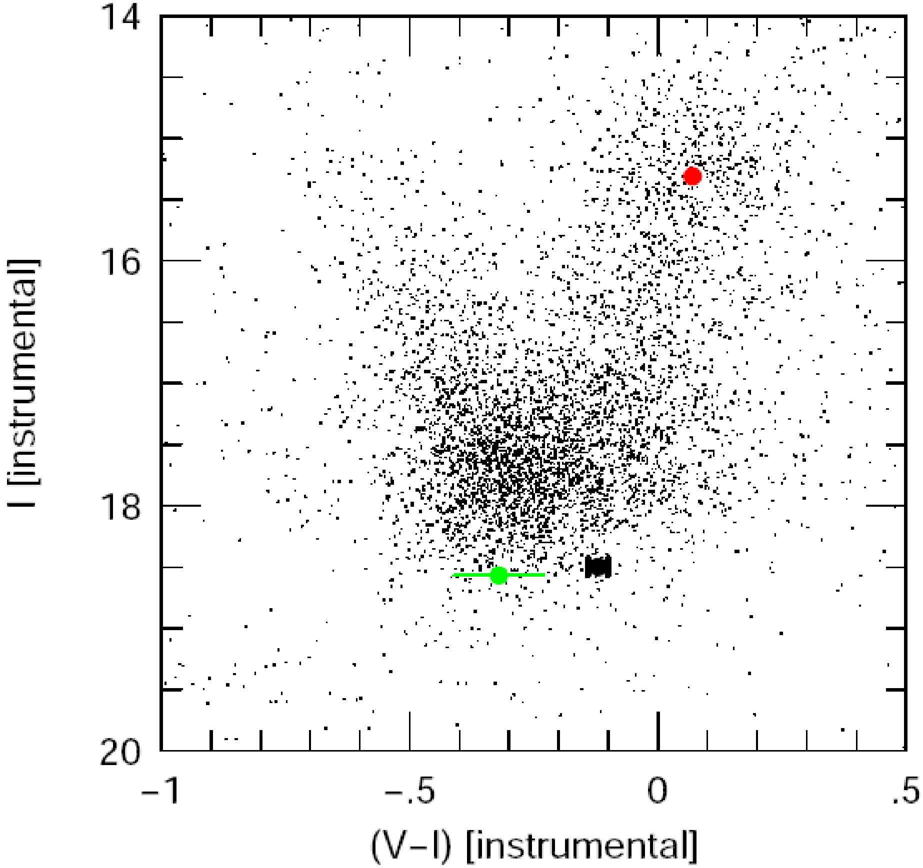
$$\theta_E \tilde{r}_E = \alpha r_E = \frac{4GM}{c^2}$$

$$\theta_E = \alpha - \psi = \frac{\tilde{r}_E}{D_l} - \frac{\tilde{r}_E}{D_s} = \frac{\tilde{r}_E}{D_{rel}}$$

$$\tilde{r}_E = \sqrt{\frac{4GMD_{rel}}{c^2}} \qquad \theta_E = \sqrt{\frac{4GM}{D_{rel}c^2}}$$

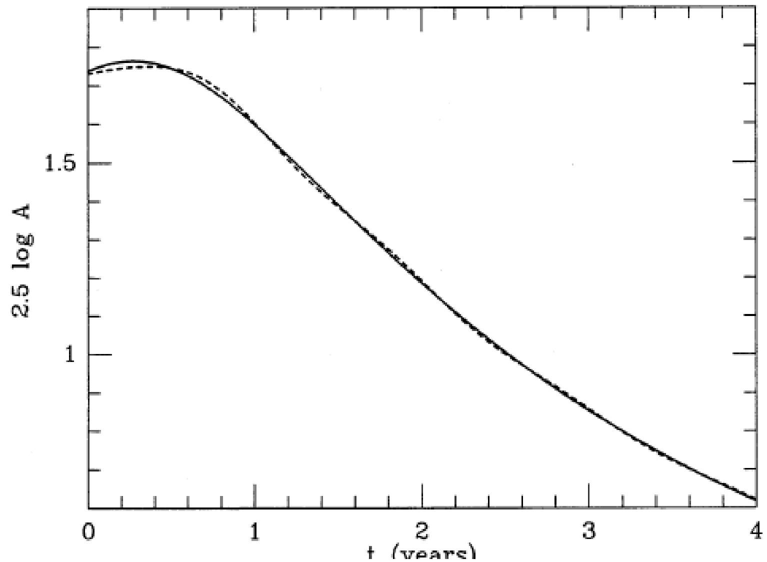
# To measure angular Einstein radius:
# Standard Sky-Plane Rulers

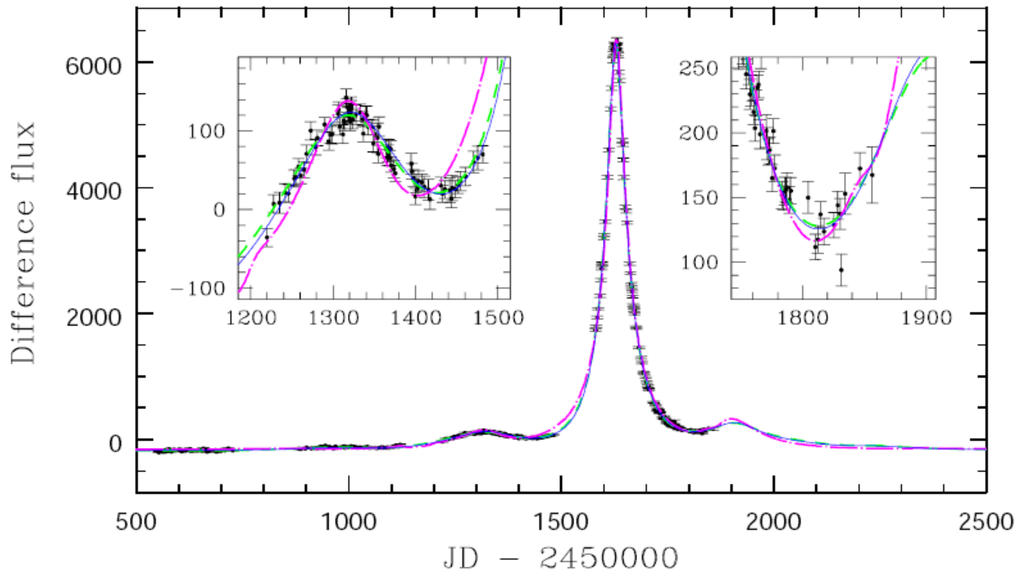


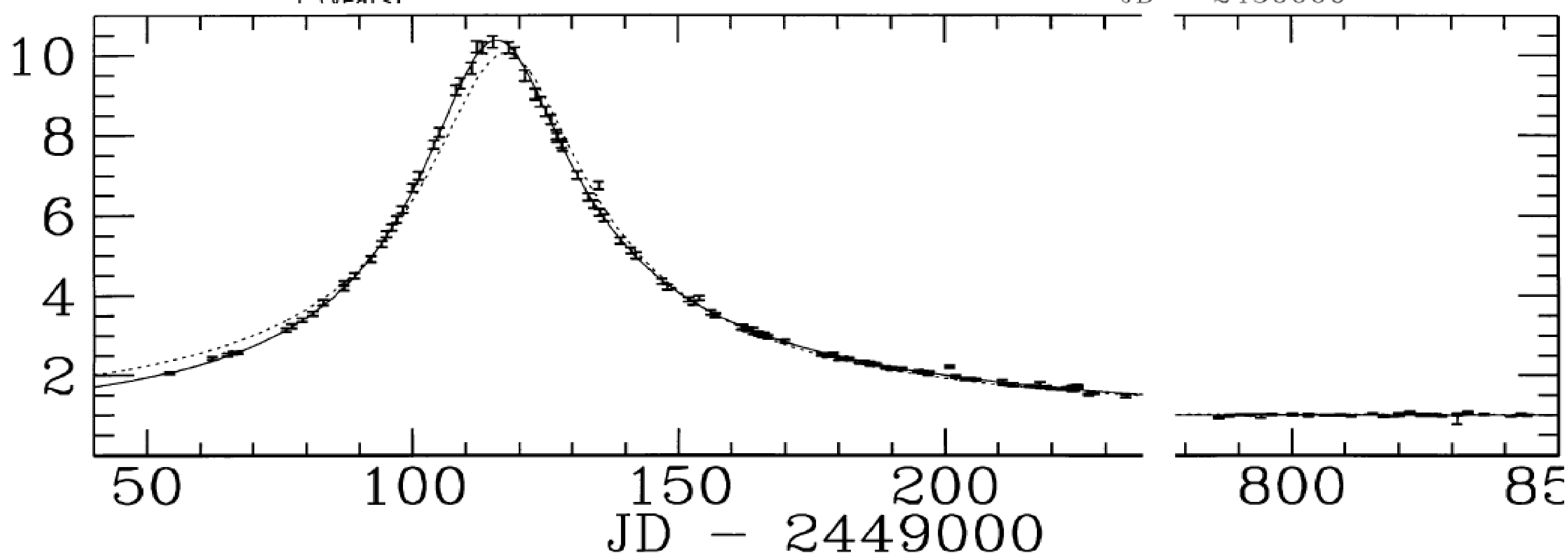



# To measure parallax:

# Standard Observer-Plane Rulers



# Another Crackpot Idea:

# Terrestrial Microlens Parallaxes

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

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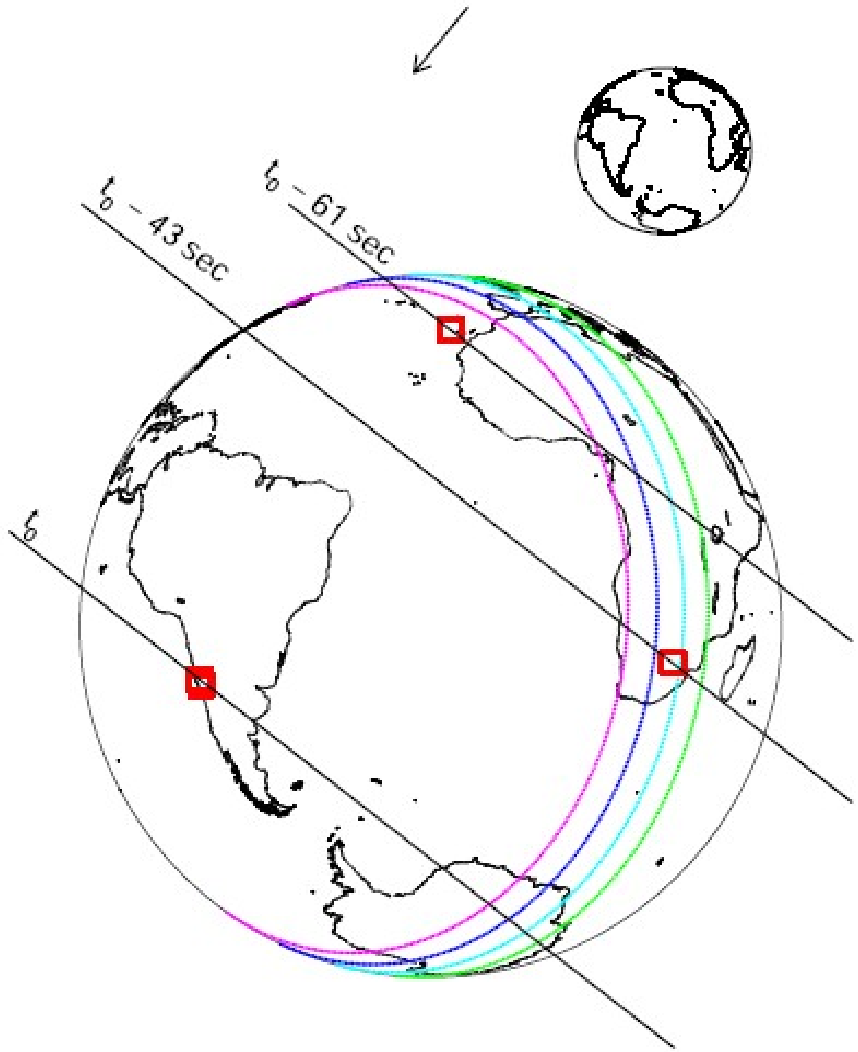
*Received 1995 March 8; accepted 1996 January 11*

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

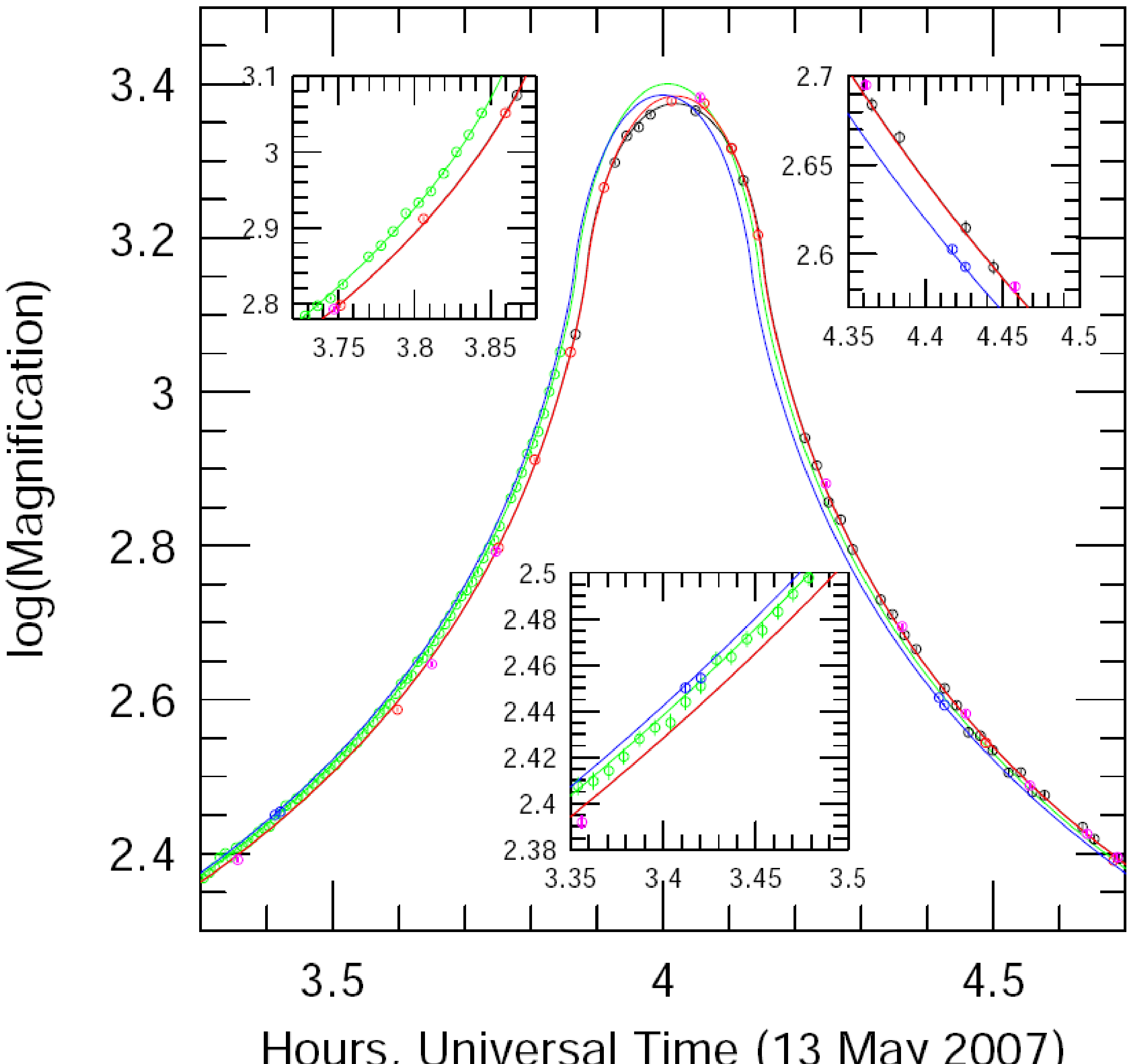
issues. We thank Andrew Gould for pointing out an error in the original version of this manuscript. This research was

# Terrestrial Parallax:
# Simultaneous Observations on Earth

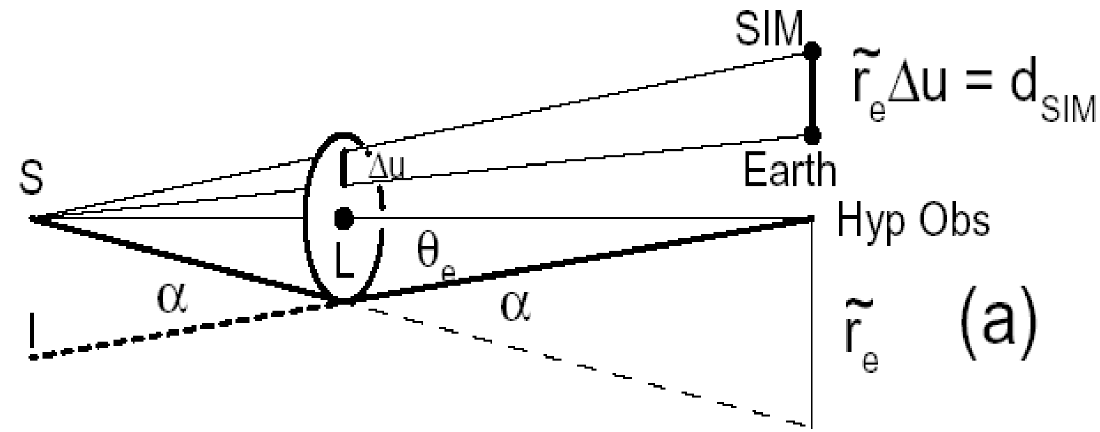


# OGLE-2007-BLG-224

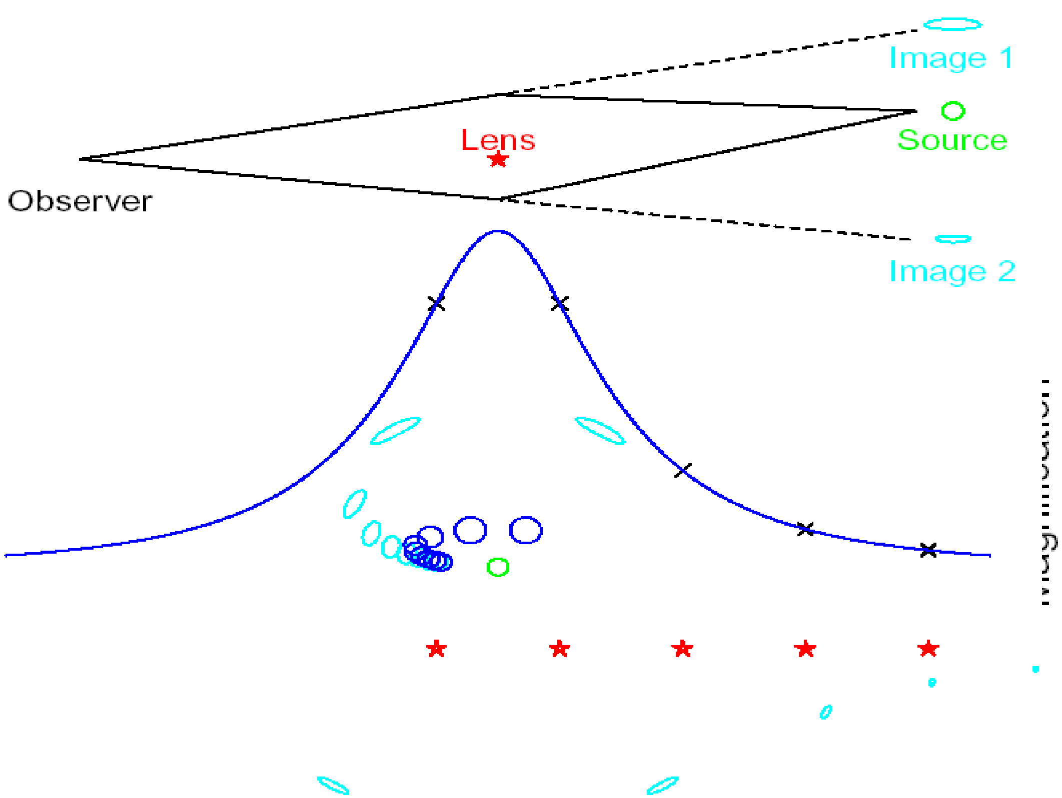
## Canaries South Africa Chile

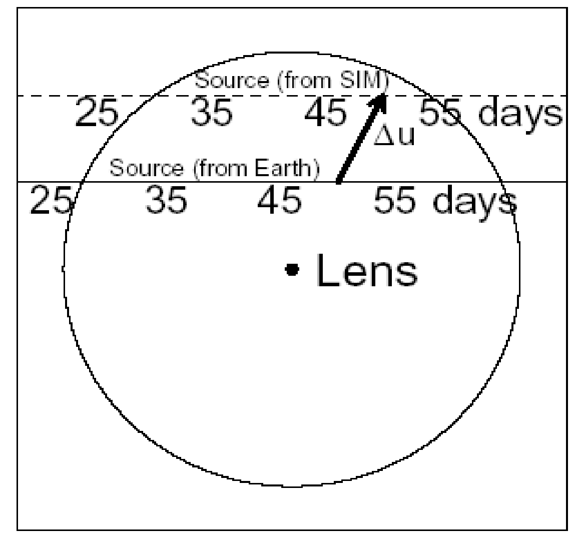


# Space-Based Parallaxes & Einstein Radii : SIM



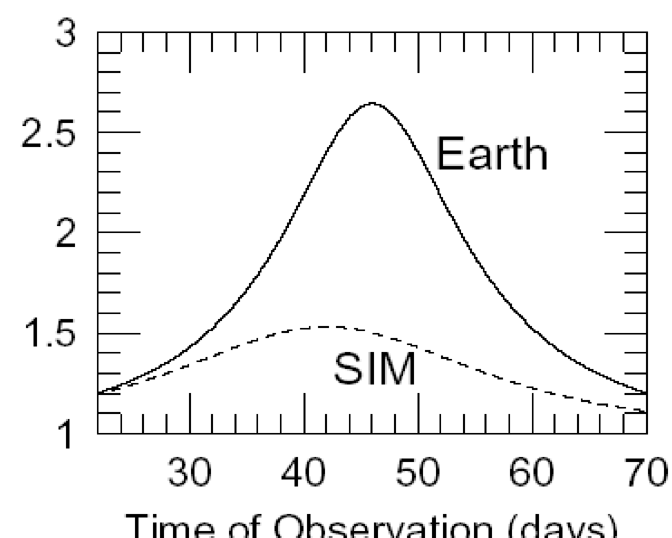

(a)




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

(b)

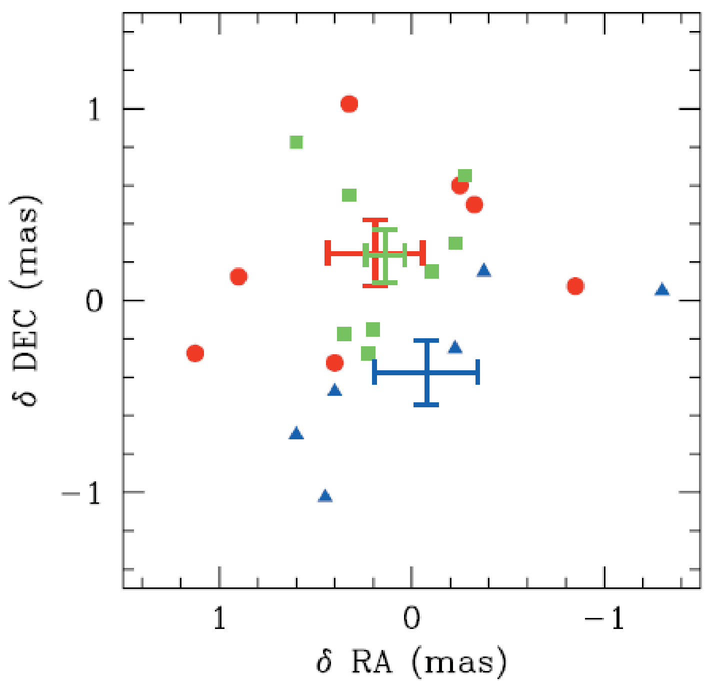


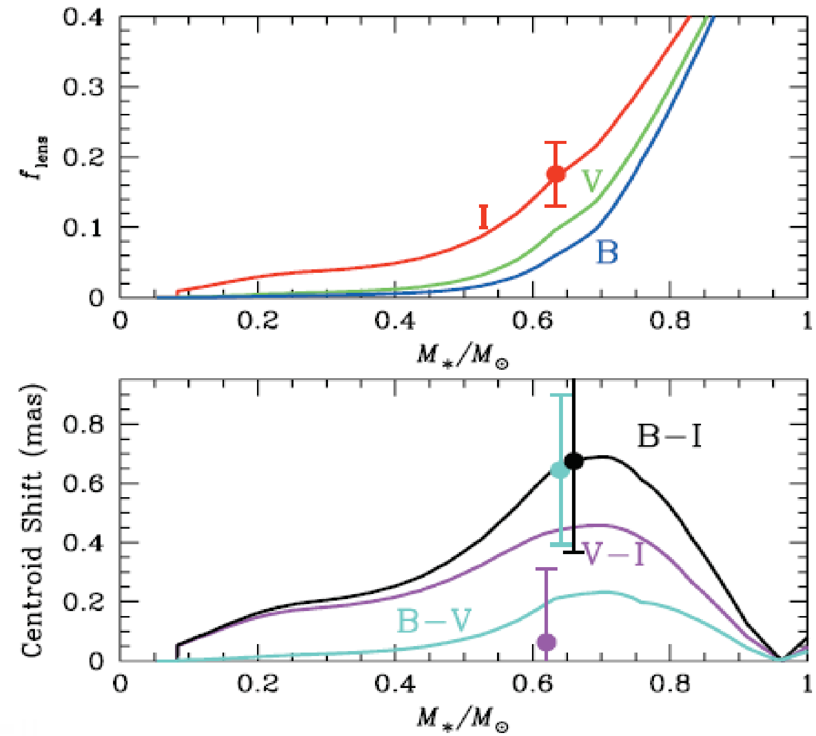

(c)

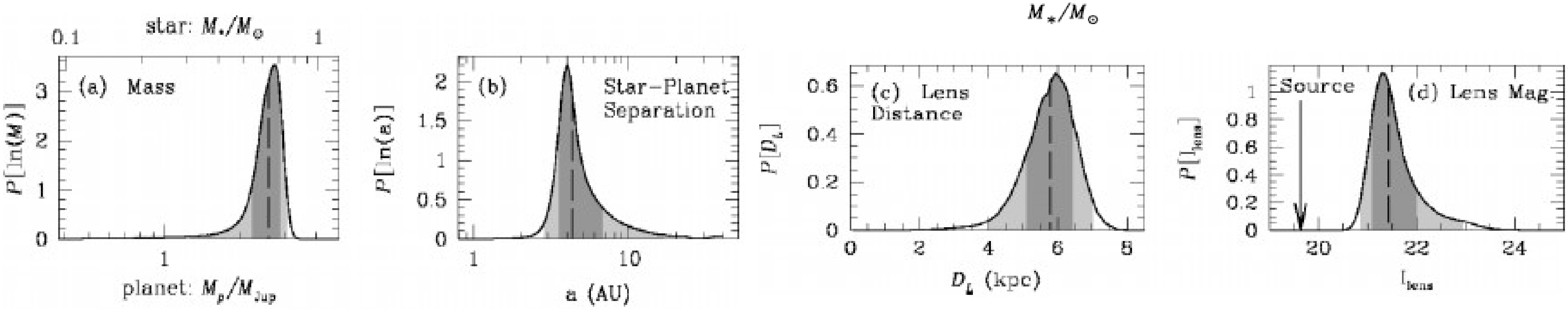
# “Direct Detection” of Lens

# From Centroid Motion

# (using known proper motion)

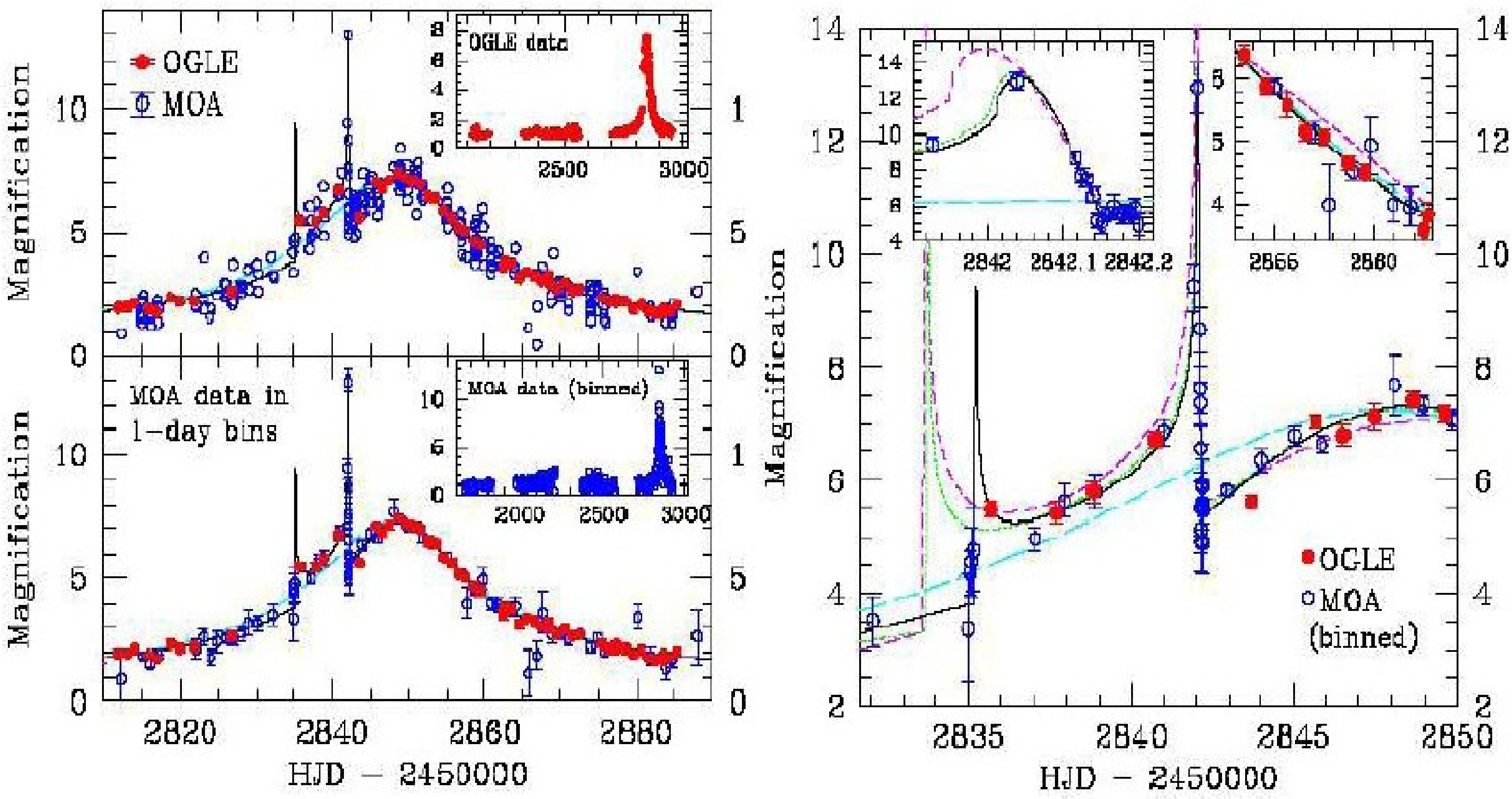


# OB-03-235/MB-03-053: 5.5 kpc

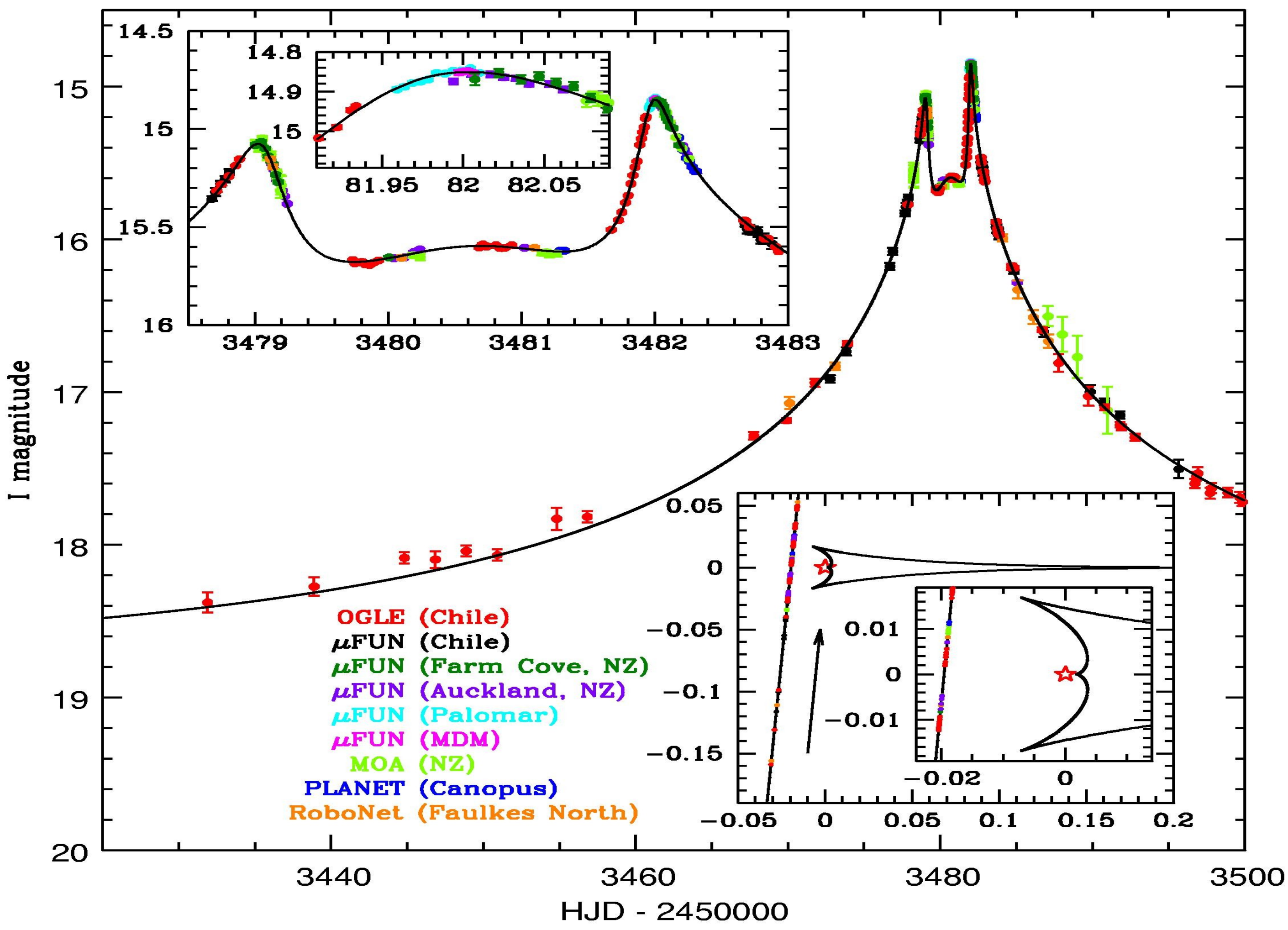
# Finite Source + Centroid Motion




Bennett et al. 2006, ApJ, 647, L171

# OGLE-2005-BLG-071: 3.3 kpc

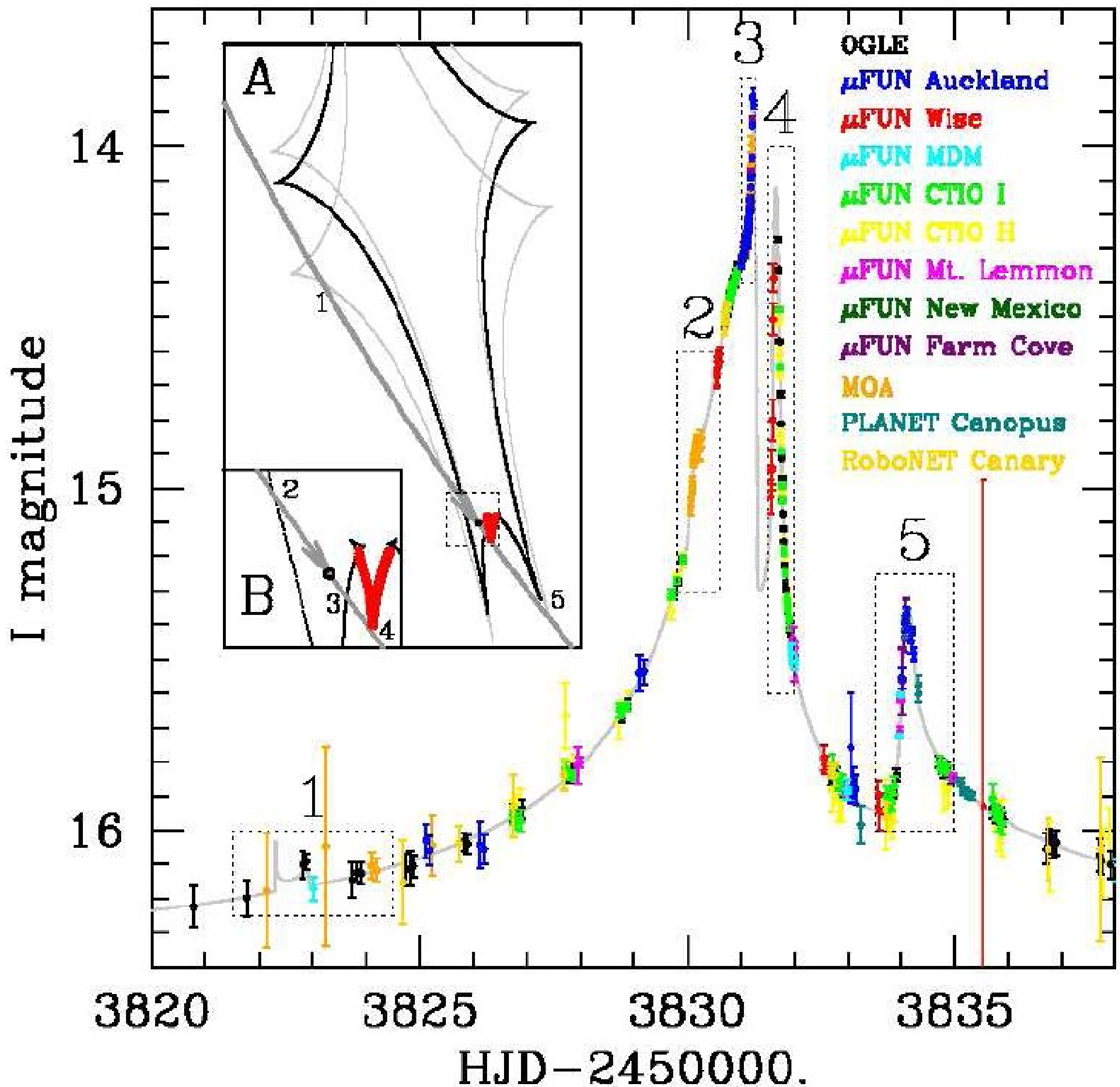
## Parallax + Finite Source + Centroid Motion




Dong et al. 2009, 695, 970

# OGLE-2006-BLG-109: 1.5 kpc

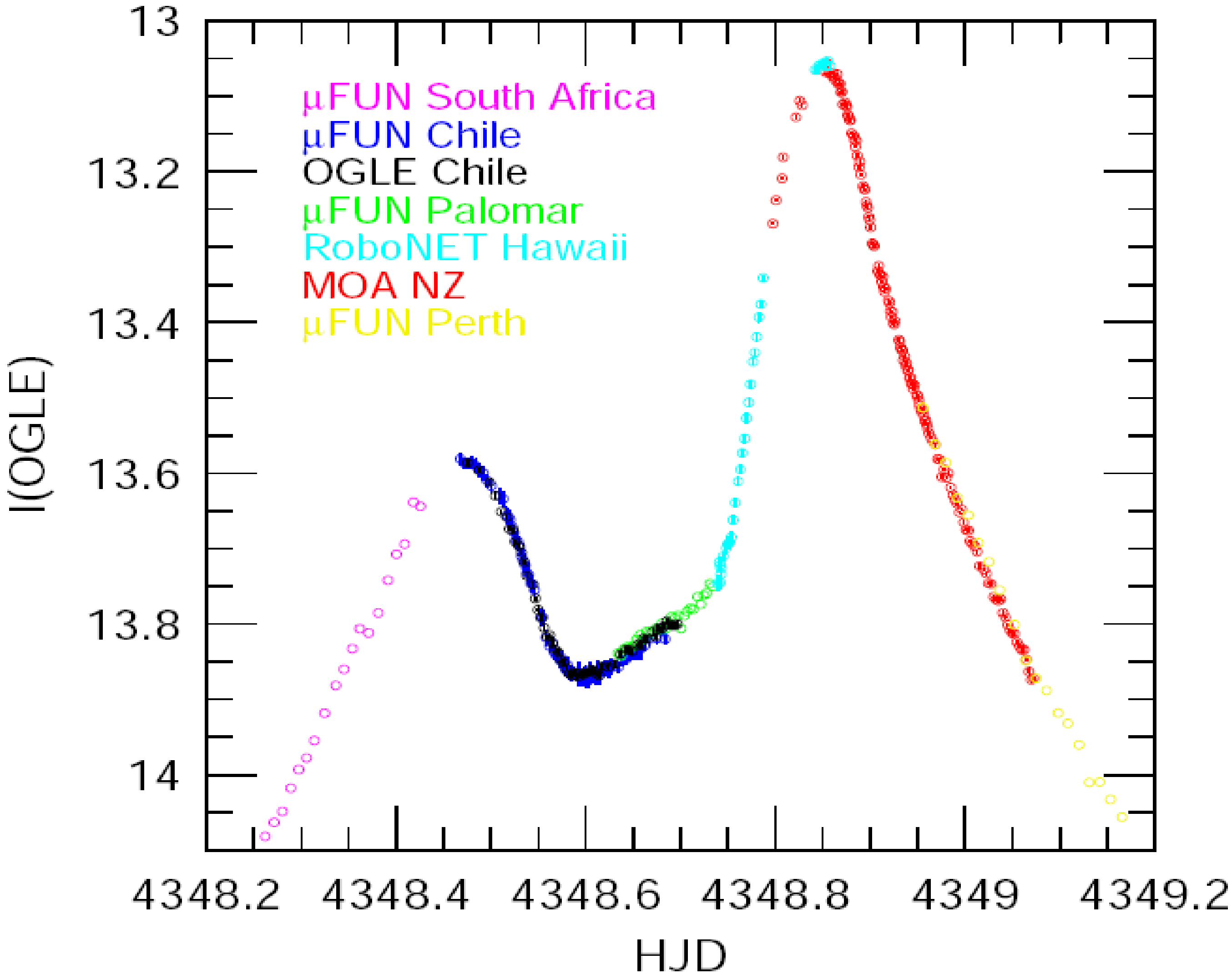
# Parallax + Finite Source + Blend




Gaudi et al. 2008, Science, 319, 927

# OGLE-2007-BLG-349: 3 kpc

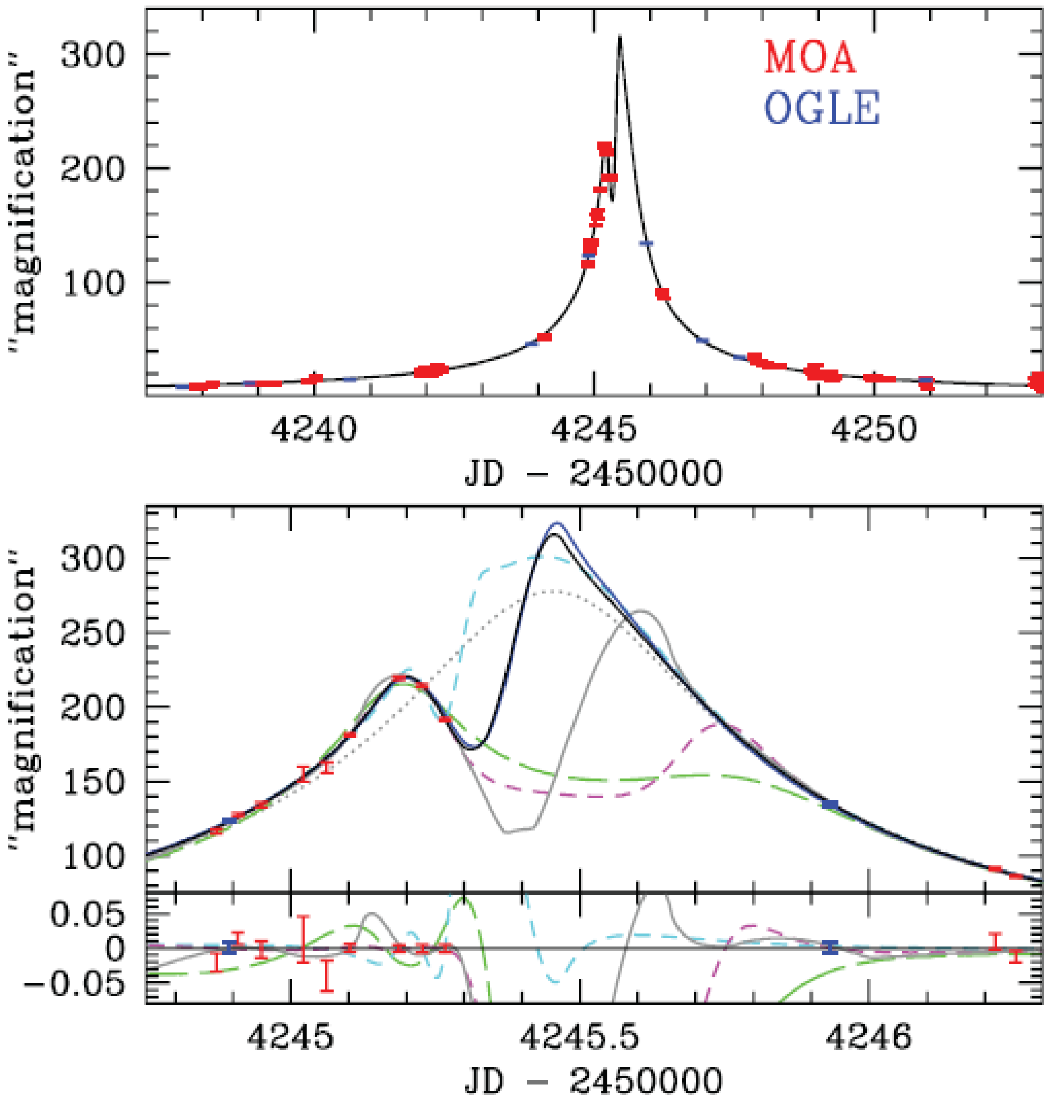
# Parallax + Finite Source + Blend




Dong et al. 2009, in prep

# MOA-2007-BLG-192: 1.5 kpc

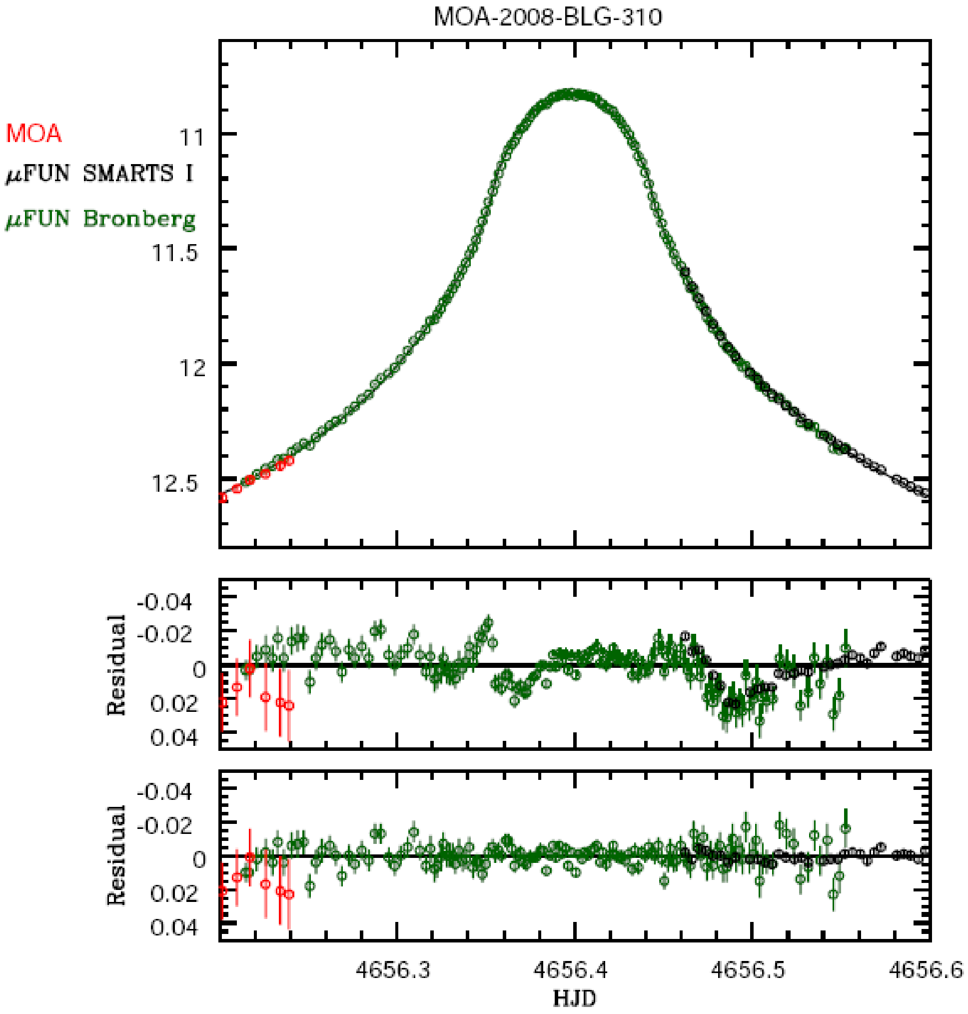
# Parallax + Finite Source

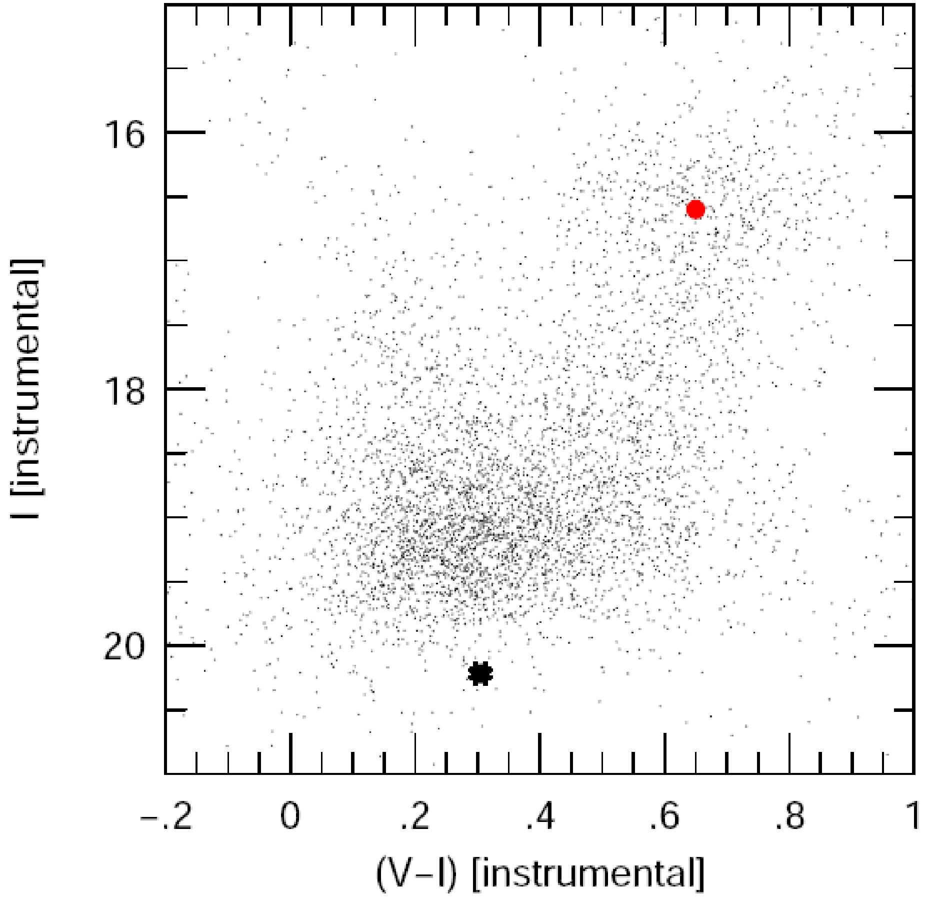



Bennett et al. 2008, ApJ, 684, 663

# MOA-2008-BLG-310

## A Verifiable Bulge Planet?

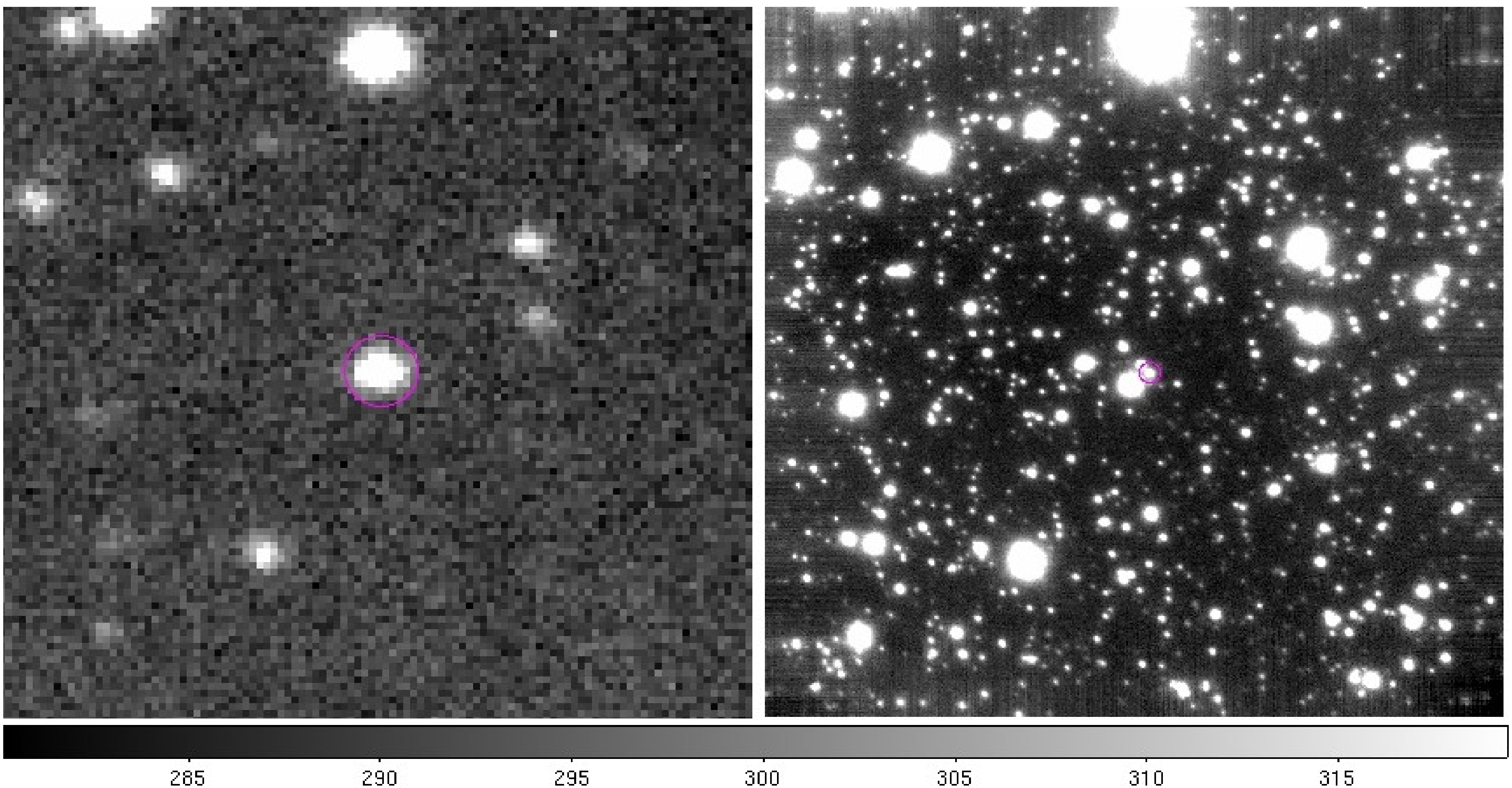


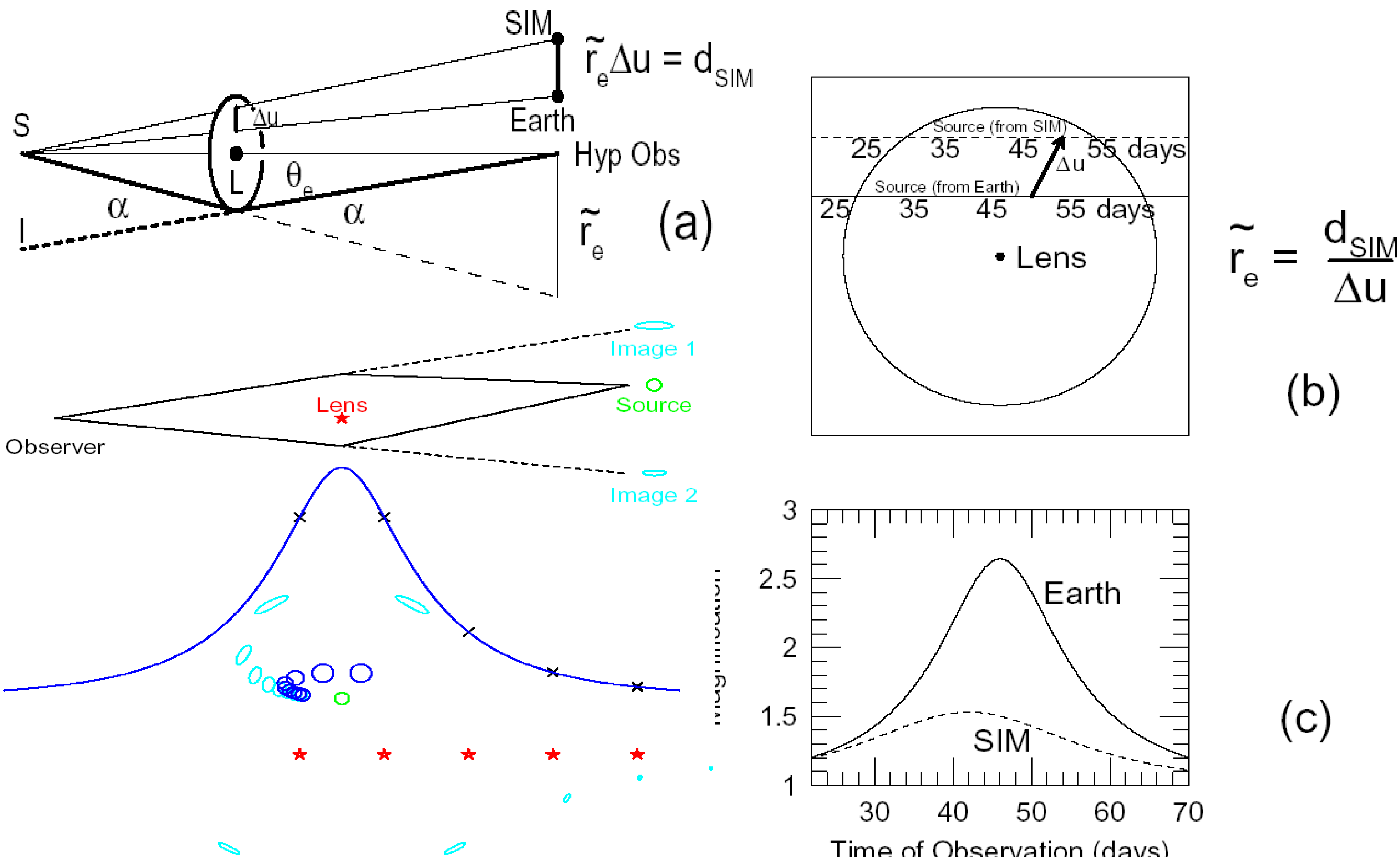

Janczak et al. 2009, in prep

# Julia Janczak

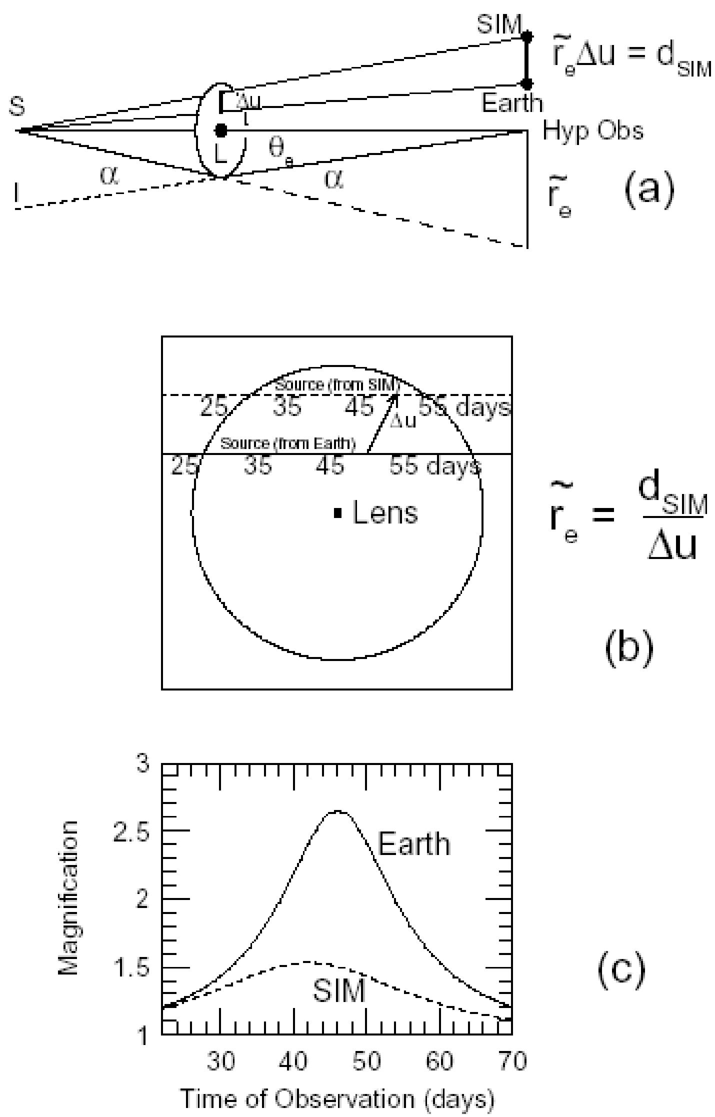
# CTIO ANDICAM vs VLT NACO

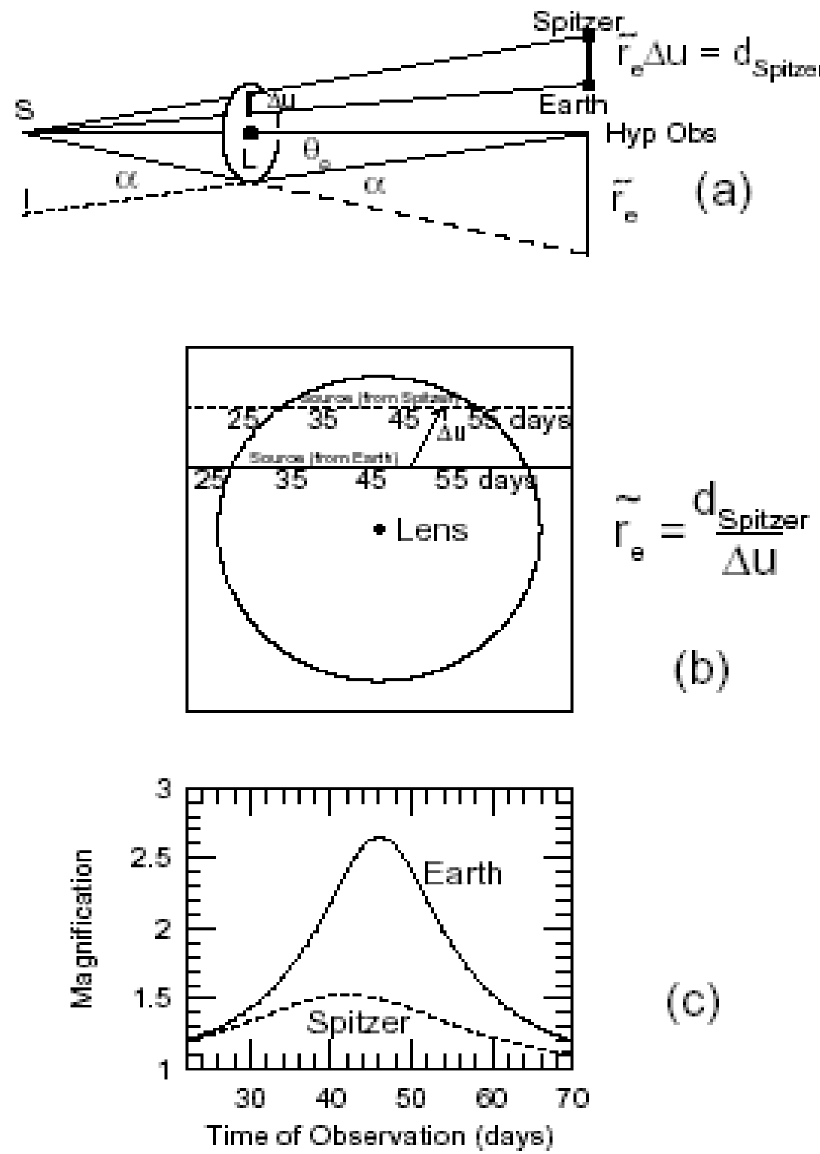


# To Fully Determine Lens Nature: SIM



# ... or, more immediately: Spitzer



# From a paper written 10 years ago ...

THE ASTROPHYSICAL JOURNAL, 514:869–877, 1999 April 1


MICROLENS PARALLAXES WITH SIRTF

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Received 1998 July 27; accepted 1998 November 2

$$t_{0,S} = t_{0,\oplus} + \Delta t_0 \,,$$

$$\frac{\Delta t_0}{t_{e,\oplus}} = \Delta u_x \cos\theta - 2(\Omega_\oplus t_{e,\oplus})^{-2}\gamma_\oplus \sin^2\theta \,; \qquad (13)$$

$$\beta_S = |\beta_\oplus \pm \Delta\beta| \,, \quad \Delta\beta = \Delta u_x \sin\theta + (\Omega_\oplus t_{e,\oplus})^{-2}\gamma_\oplus \sin 2\theta \,; \qquad (14)$$

$$t_{e,S} = t_{e,\oplus} + \Delta t_e \,,$$

$$\frac{\Delta t_e}{t_{e,\oplus}} = \Delta u_x \Omega_\oplus t_{e,\oplus} \sin\theta + (\Omega_\oplus t_{e,\oplus})^{-1}\gamma_\oplus \sin 2\theta \,; \qquad (15$$

$$\gamma_S = \Delta u_x (\Omega_\oplus t_{e,\oplus})^2 \cos\theta + \gamma_\oplus \cos 2\theta \,. \qquad (16$$

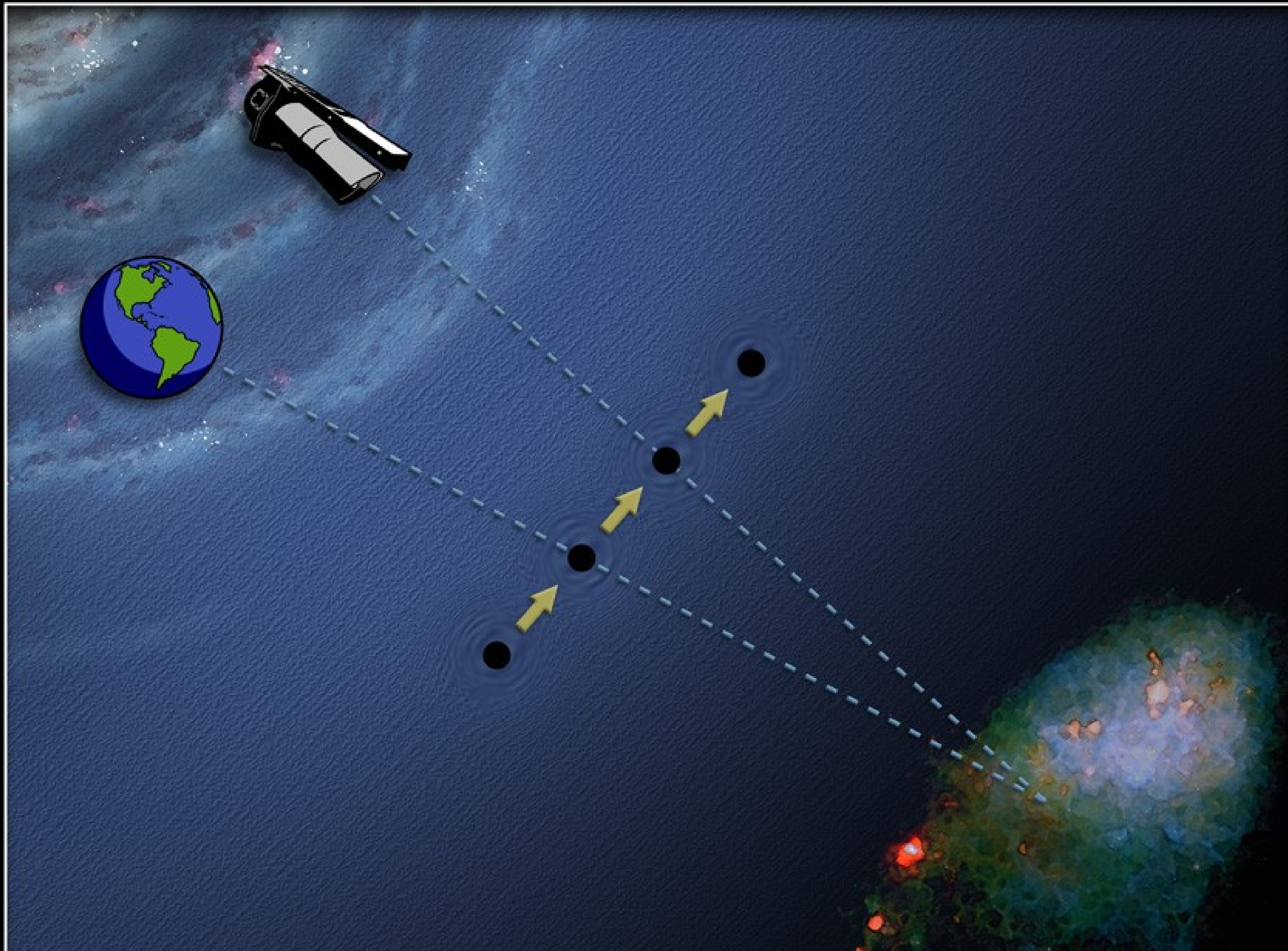
$$\frac{\sigma_{\Delta u_y}}{\Delta u} = \frac{\sigma_\gamma}{\gamma \sec\phi}$$

$$= 0.17 N^{-1/2} \frac{\sigma_0}{0.01} \frac{\tilde{v}}{275 \text{ km s}^{-1}} \left(\frac{t_e}{40 \text{ days}}\right)^{-3/2} \frac{S(\beta)}{8} \,. \qquad (21)$$

$$b_{ij}\left(\frac{t_0}{t_e}, \gamma\right) = \frac{64}{u^5(u^2+4)^{5/2}(u^2+2)\sigma_0^2} \begin{pmatrix} 2\tau^2 & -\tau^4 \\ -\tau^4 & \tau^6/2 \end{pmatrix} , \qquad (22)$$

$$\frac{\sigma_{t_0}}{t_e} \sim \left(\frac{25}{12}\right)^{1/2} \beta\sigma_* \,, \quad \sigma_* = \left(\frac{5}{3}\right)^{1/4} \beta^{1/2}\sigma_0$$

$$\left[\text{at } \tau = \left(\frac{2}{3}\right)^{1/2}\beta\right] , \qquad (23)$$

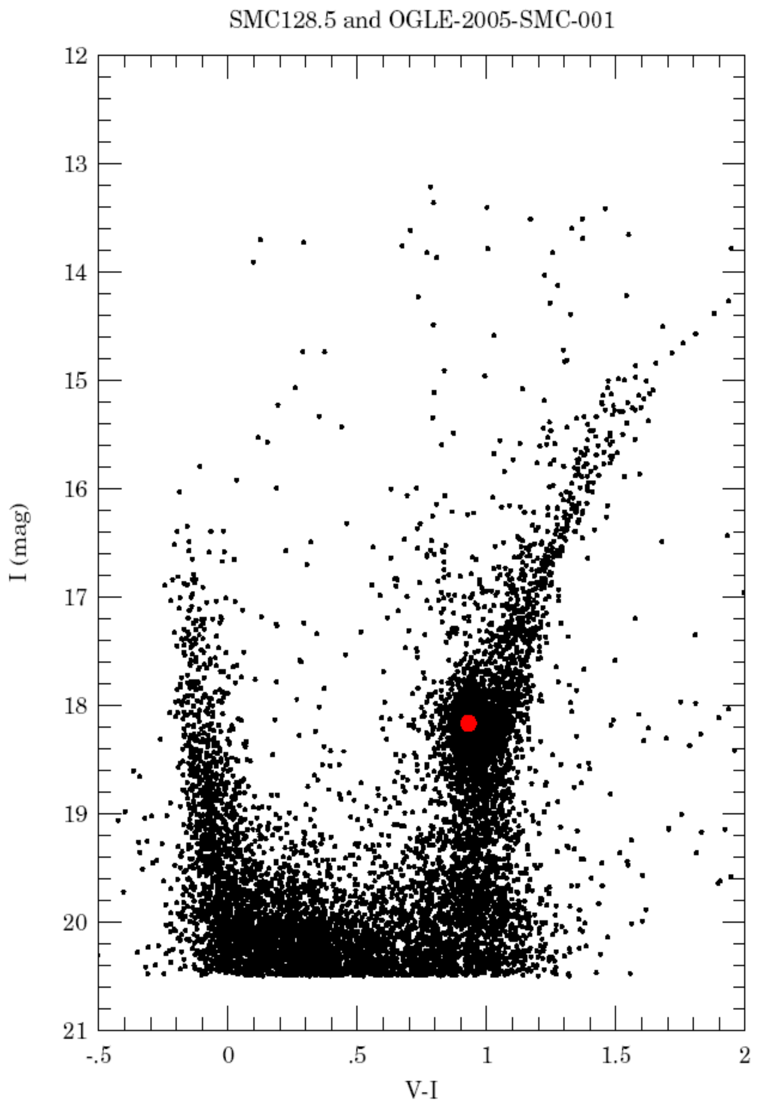


Microlens Parallax Observations of OGLE-2005-SMC-001 Spitzer Space Telescope • IRAC

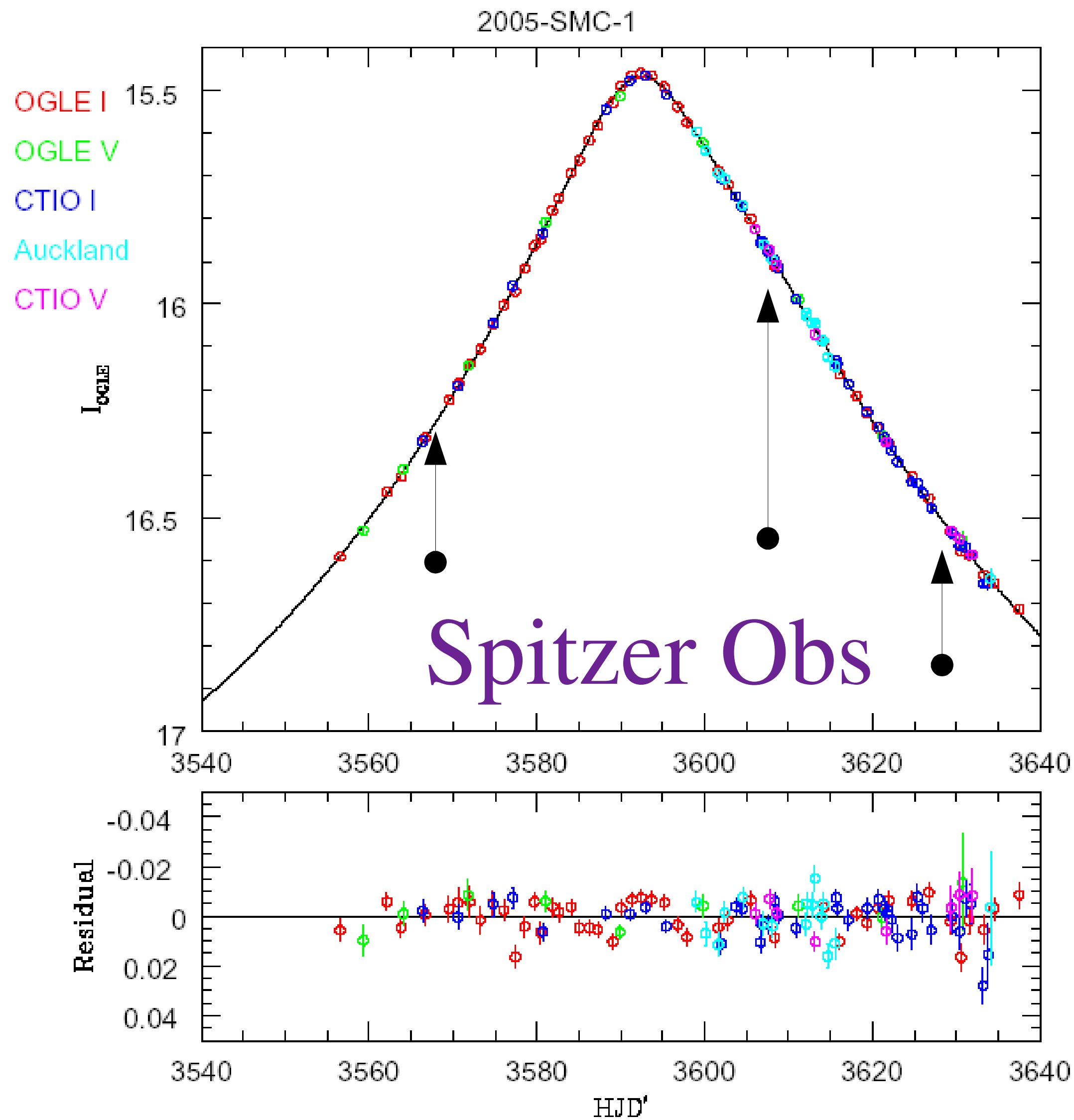
NASA / JPL-Caltech / S. Dong (Ohio State University) ssc2007-XX

# OGLE-2005-SMC-001

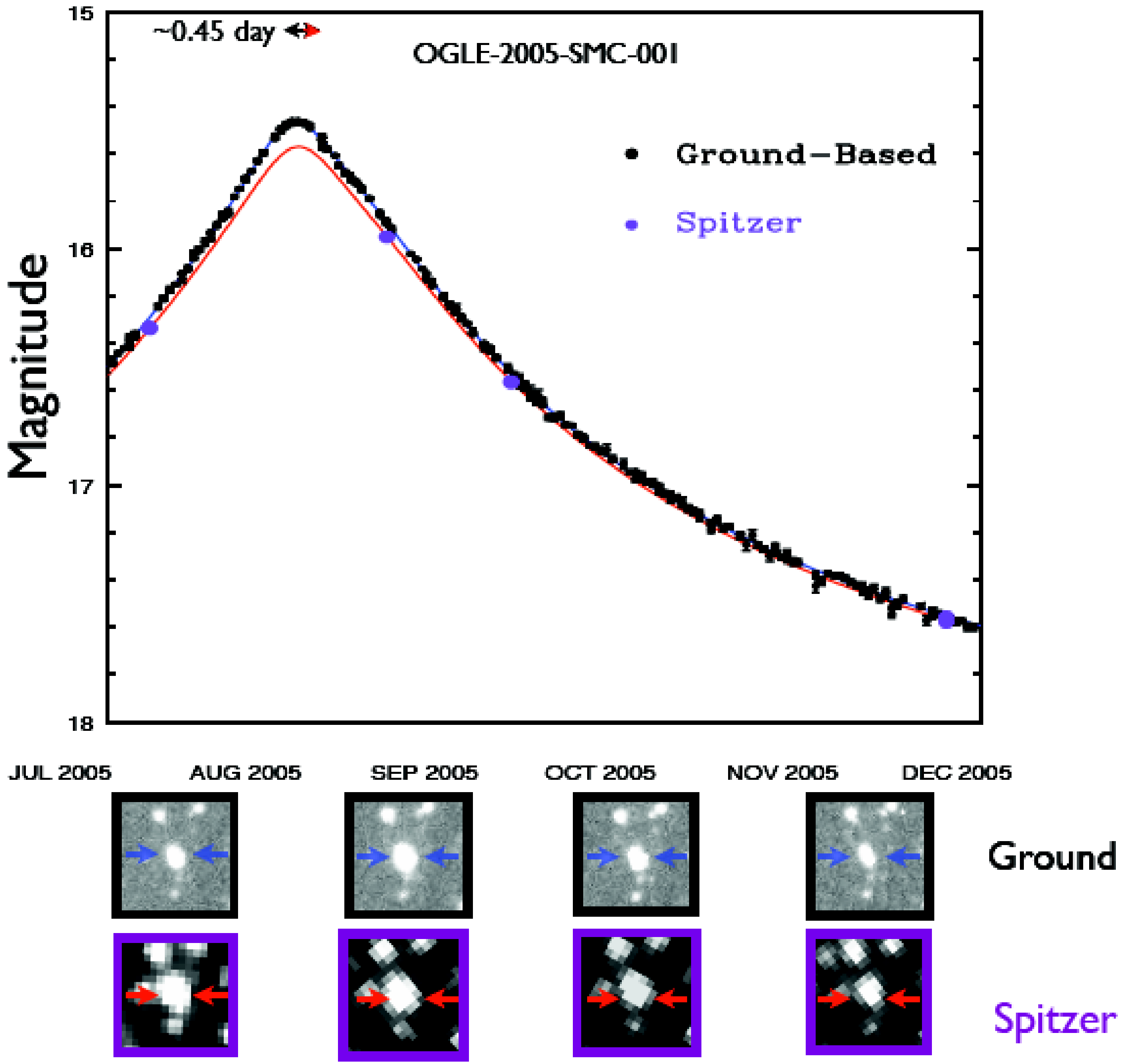
## CMD



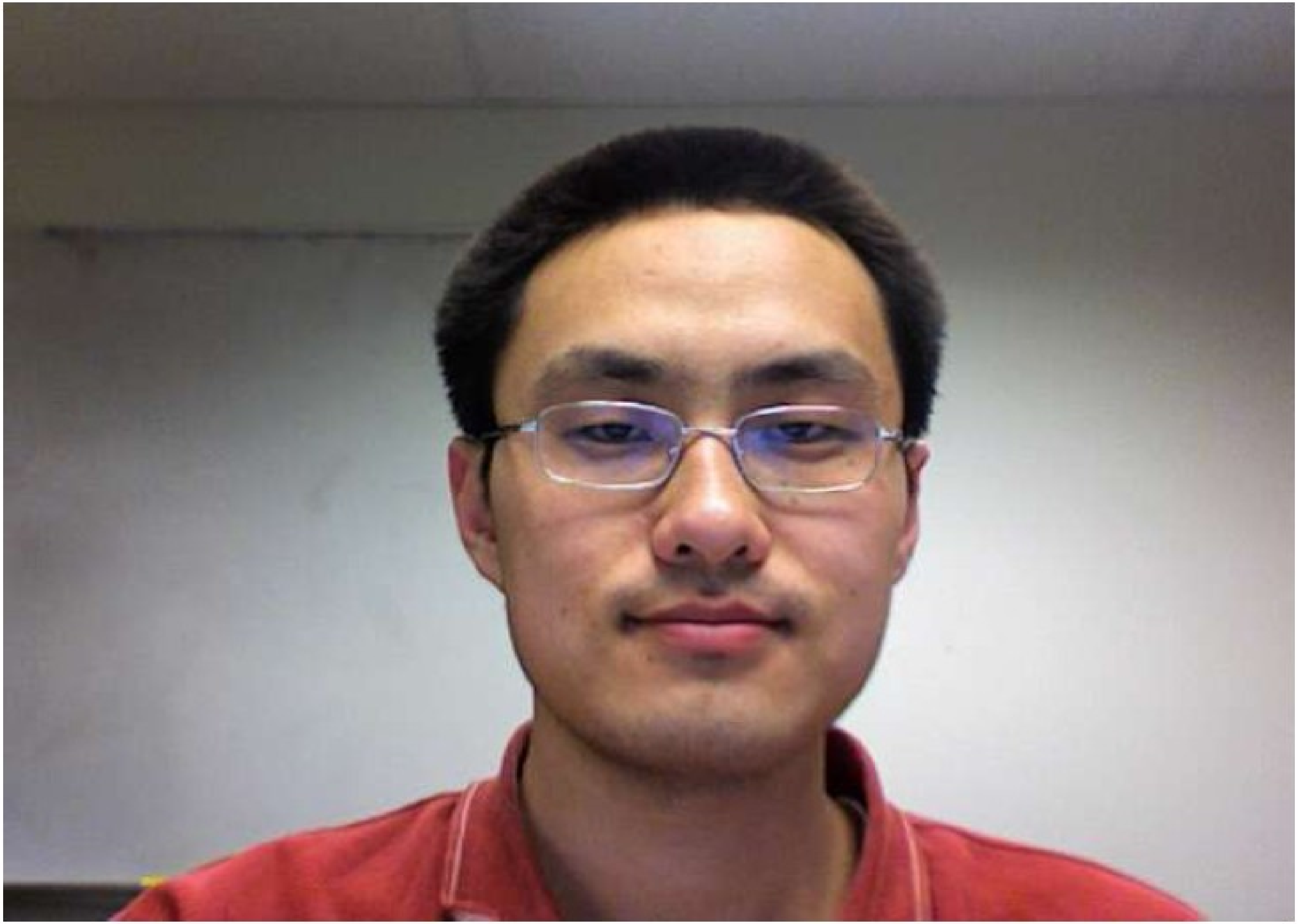

## Photometry



# Microlens Parallax

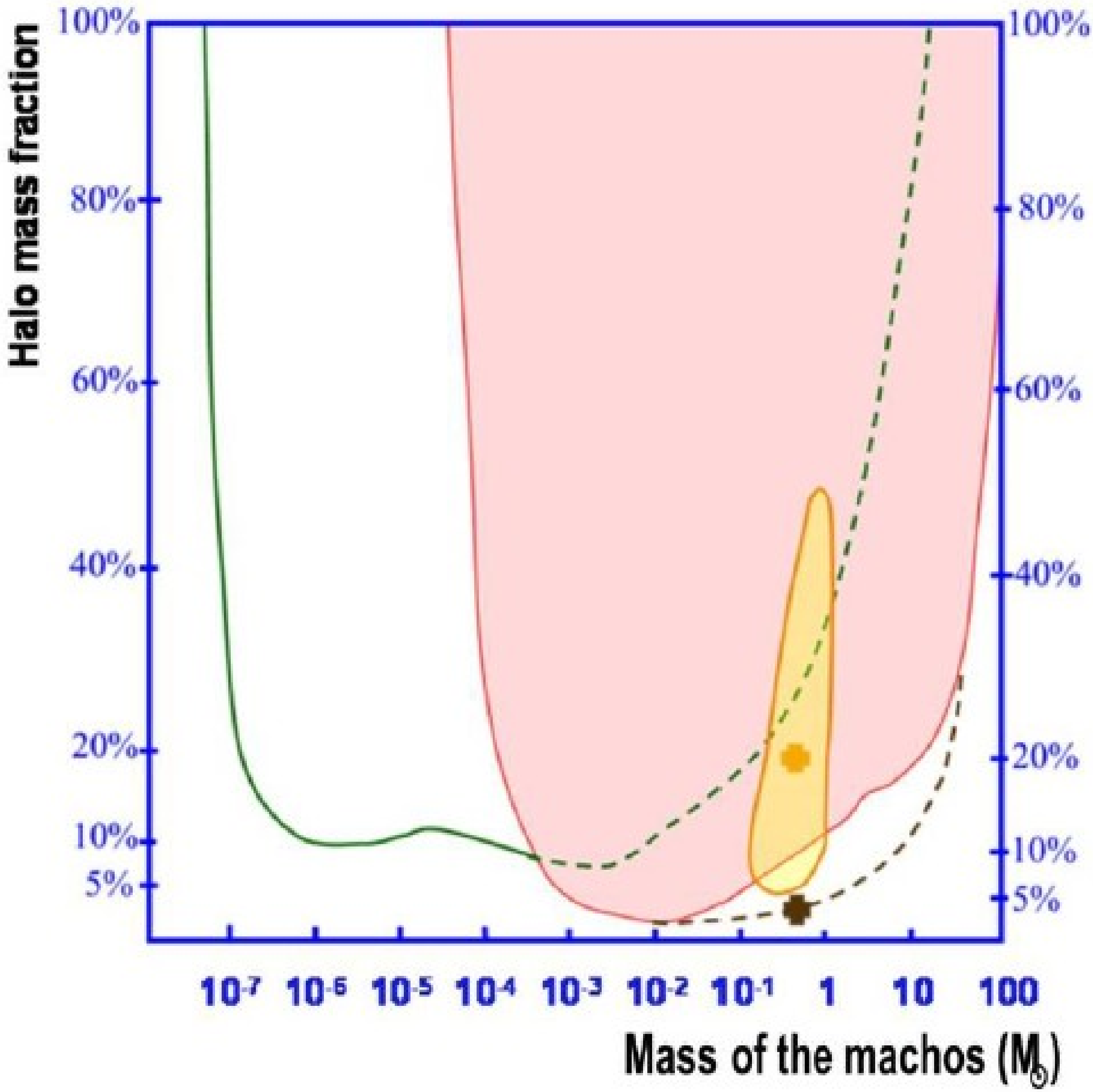


# Subo Dong

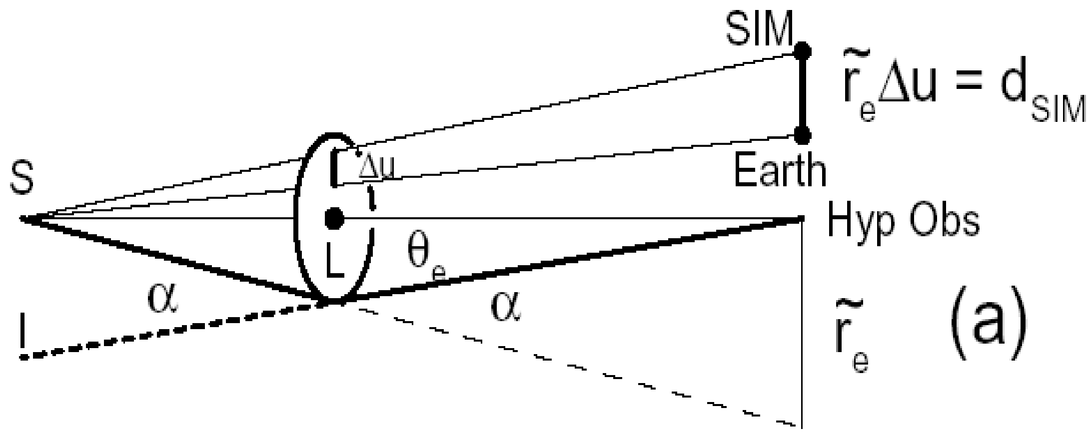


# Halo Macho Dark Matter?

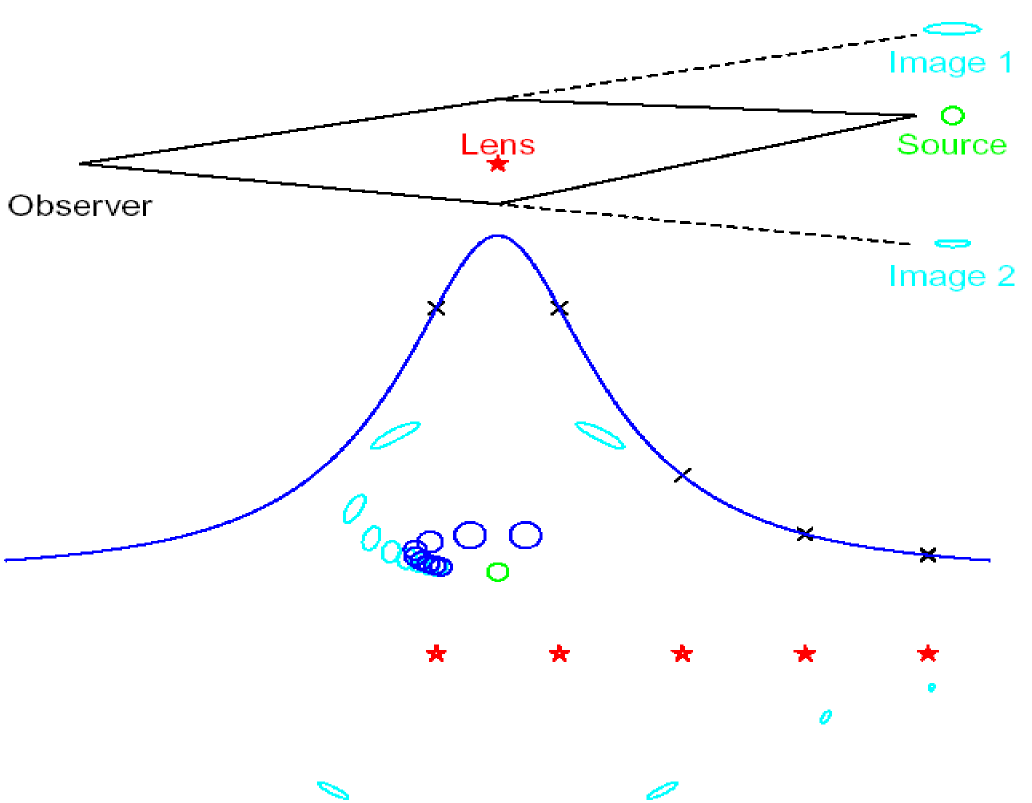
## MACHO "yes"/EROS "upper limits"

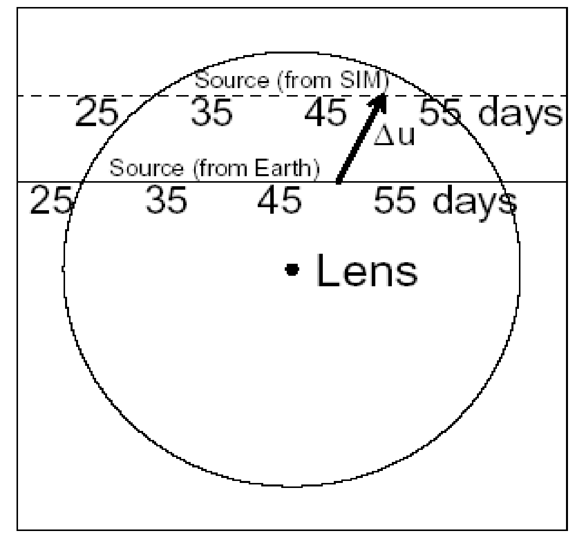


# Space-Based Parallaxes
# & Einstein Radii : SIM



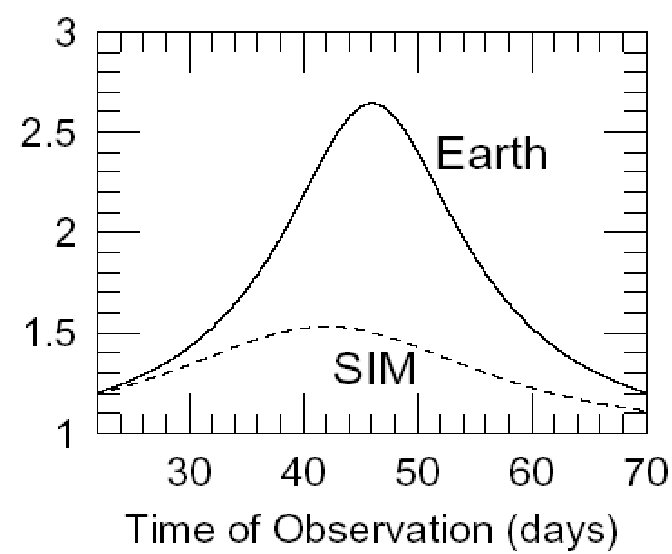

(a)



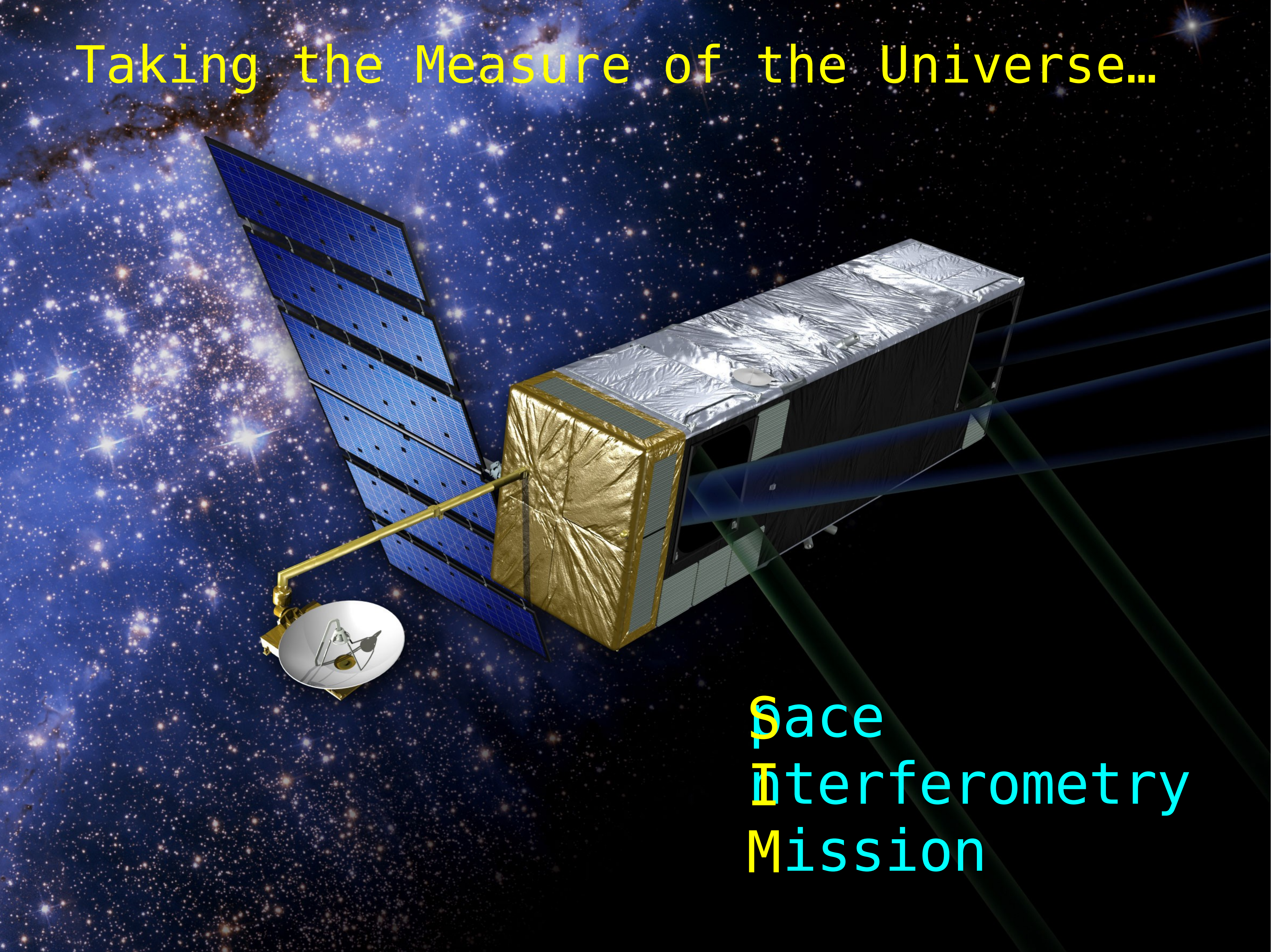




$$\tilde{r}_e = \frac{d_{SIM}}{\Delta u}$$

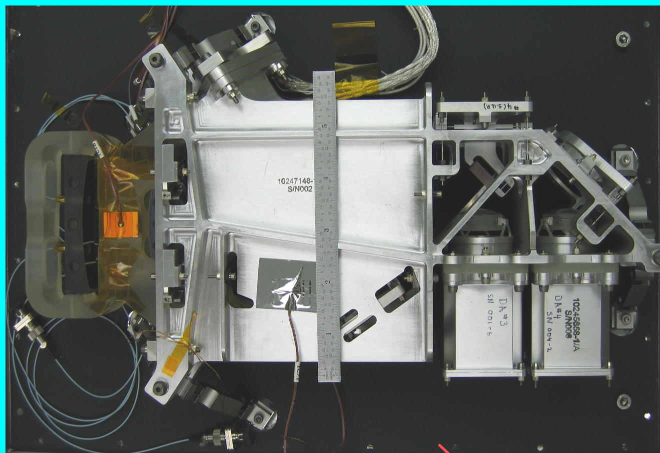
(b)



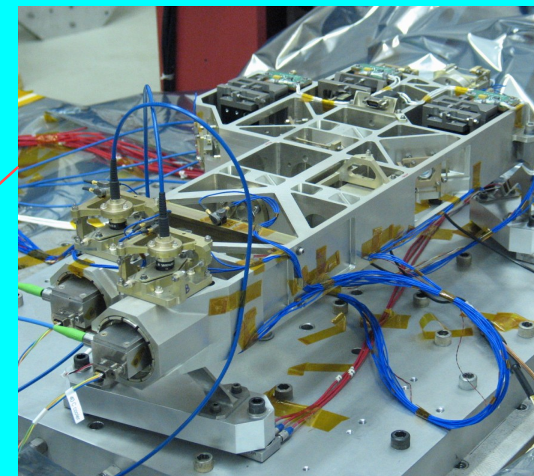

(c)


Taking the Measure of the Universe…
Space
Interferometry
Mission

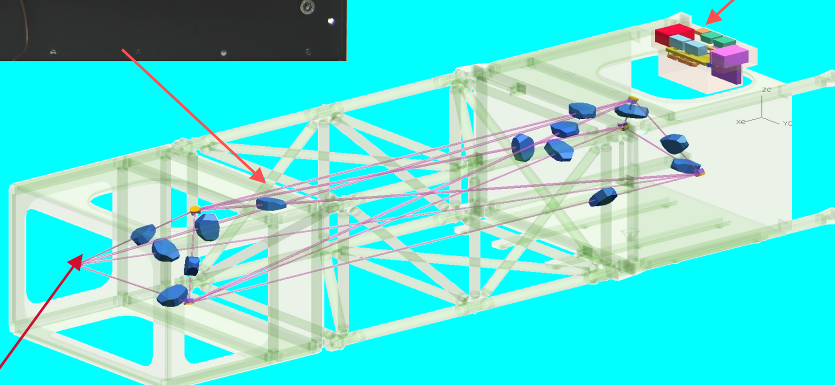
# We are ready!

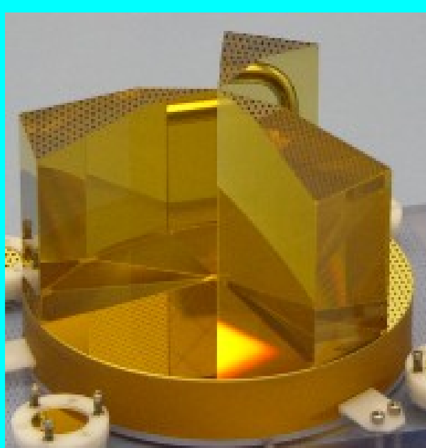


External Metrology Launcher



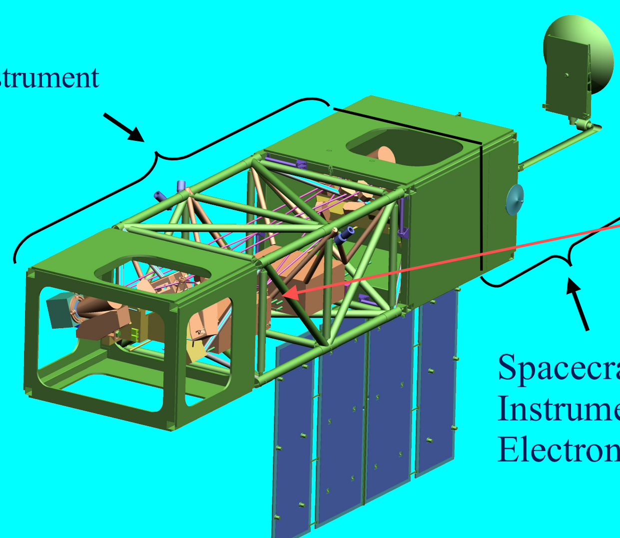
Metrology Source



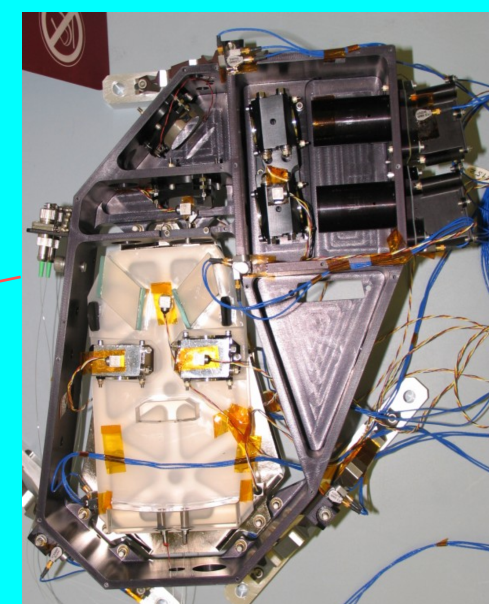


Double Corner Cube

Instrument



Spacecraft& Instrument Electronics

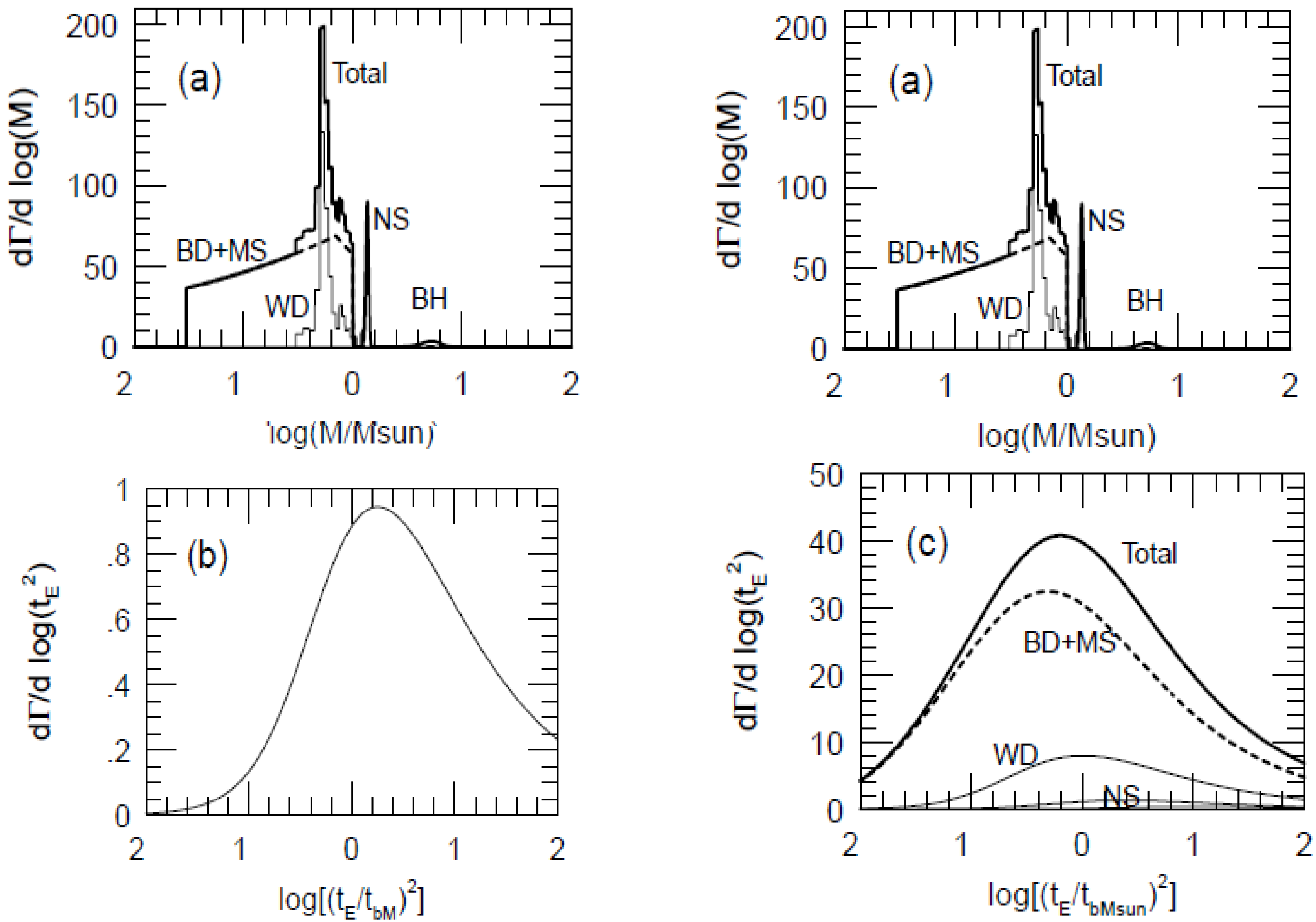


Internal Metrology Launcher

Nanometer Control & Picometer Knowledge: Flight Ready Hardware (TRL6)

# SIM: Unbiased Galactic Census

## By Unraveling Microlensing Events



# Conclusions

- Two Paths to Astrometric Microlensing
  - Deflection of Images
  - Photometric deviations
- Many planet distances are measured
  - Contrary to initial expectations
- SIM μas astrometry + space-based parallax will enable an unbiased Galactic census