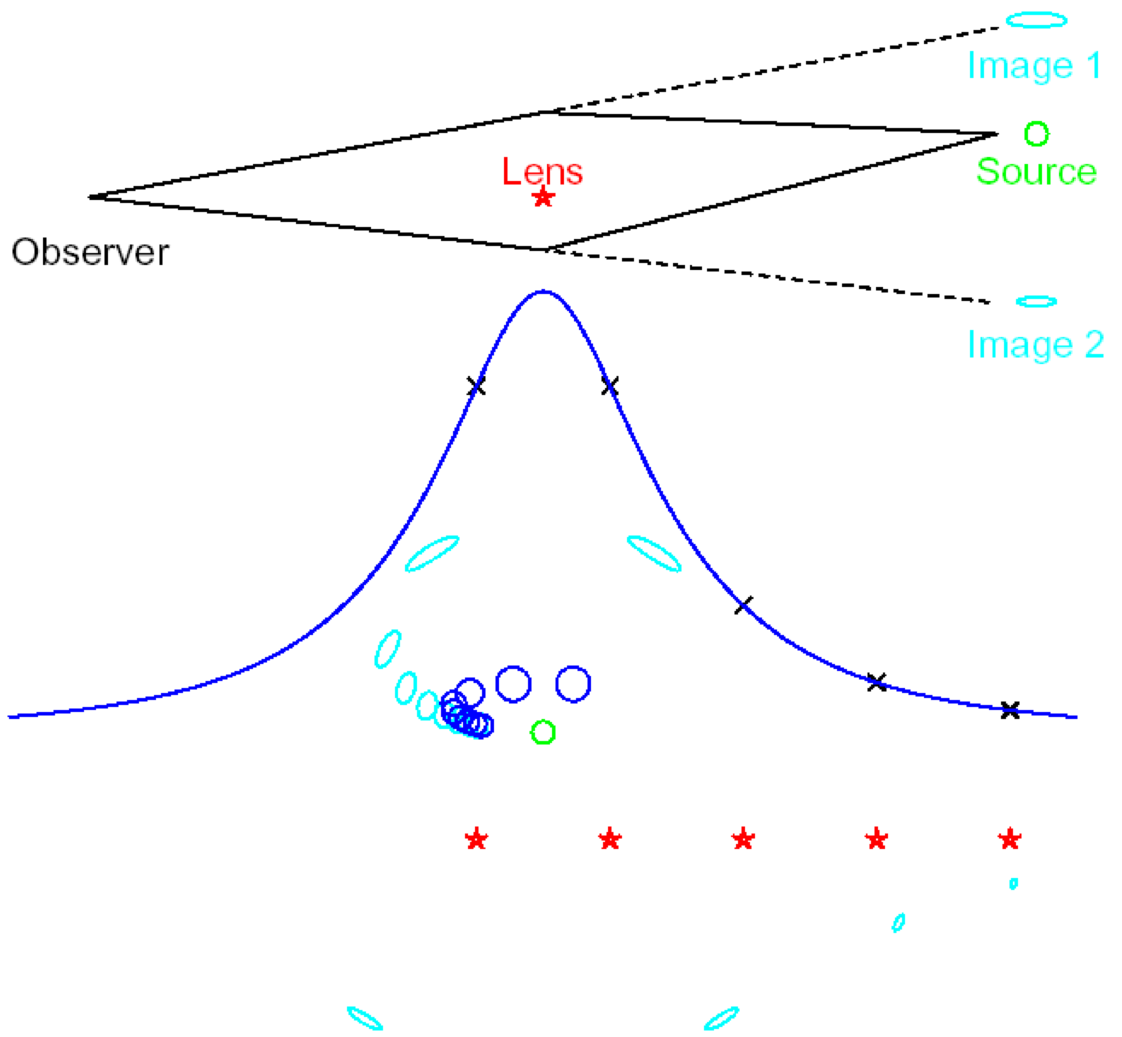
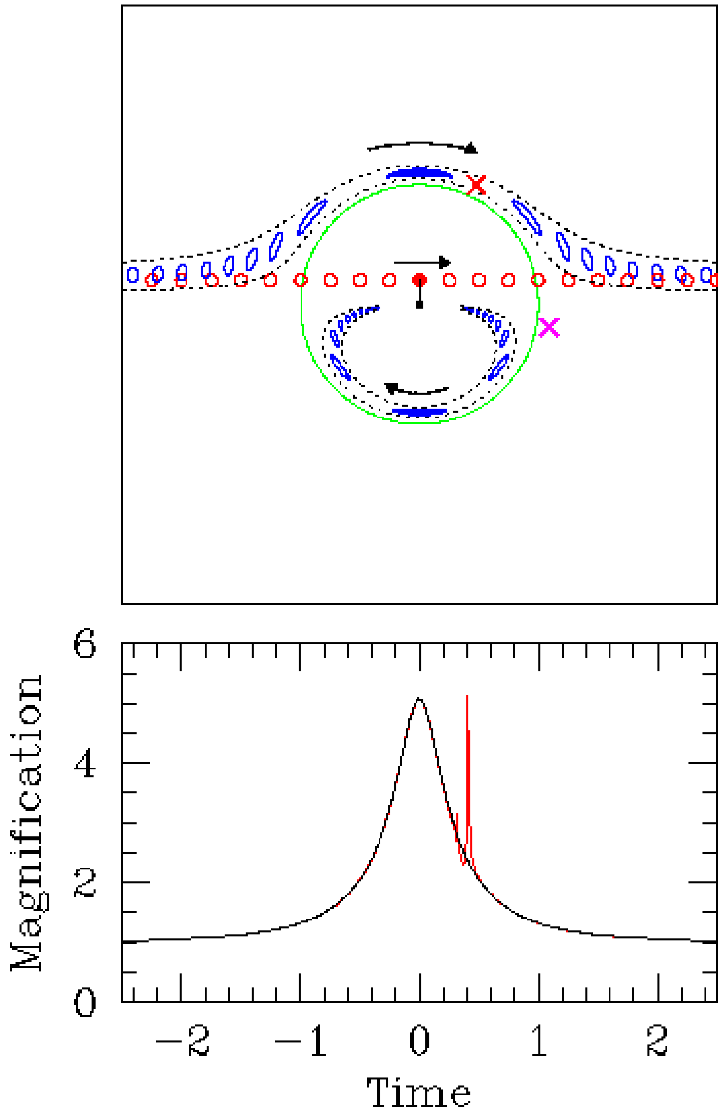
Microlensing At 5 AU

Andy Gould (OSU)



How Microlensing Finds Planets



Gould & Loeb

Survey + Follow-Up

DISCOVERING PLANETARY SYSTEMS THROUGH GRAVITATIONAL MICROLENSES

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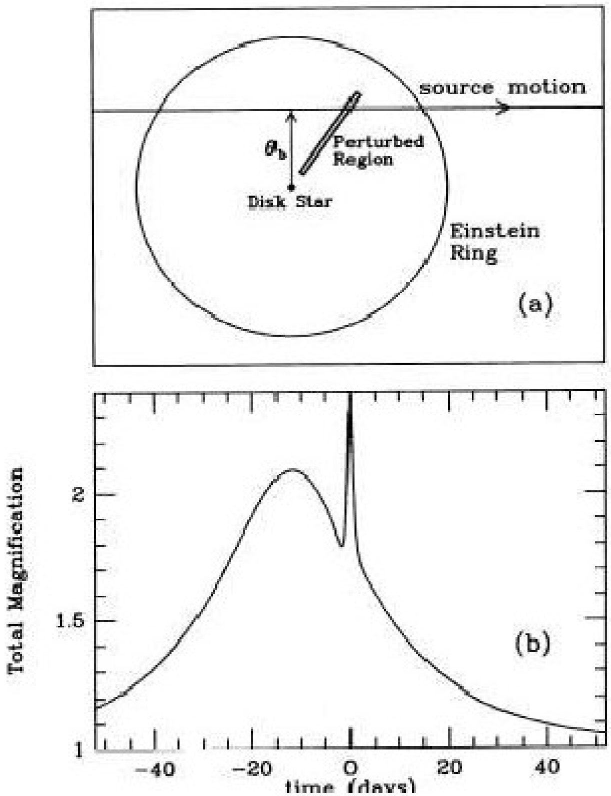
Received 1991 December 26; accepted 1992 March 9



5. OBSERVATIONAL REQUIREMENTS

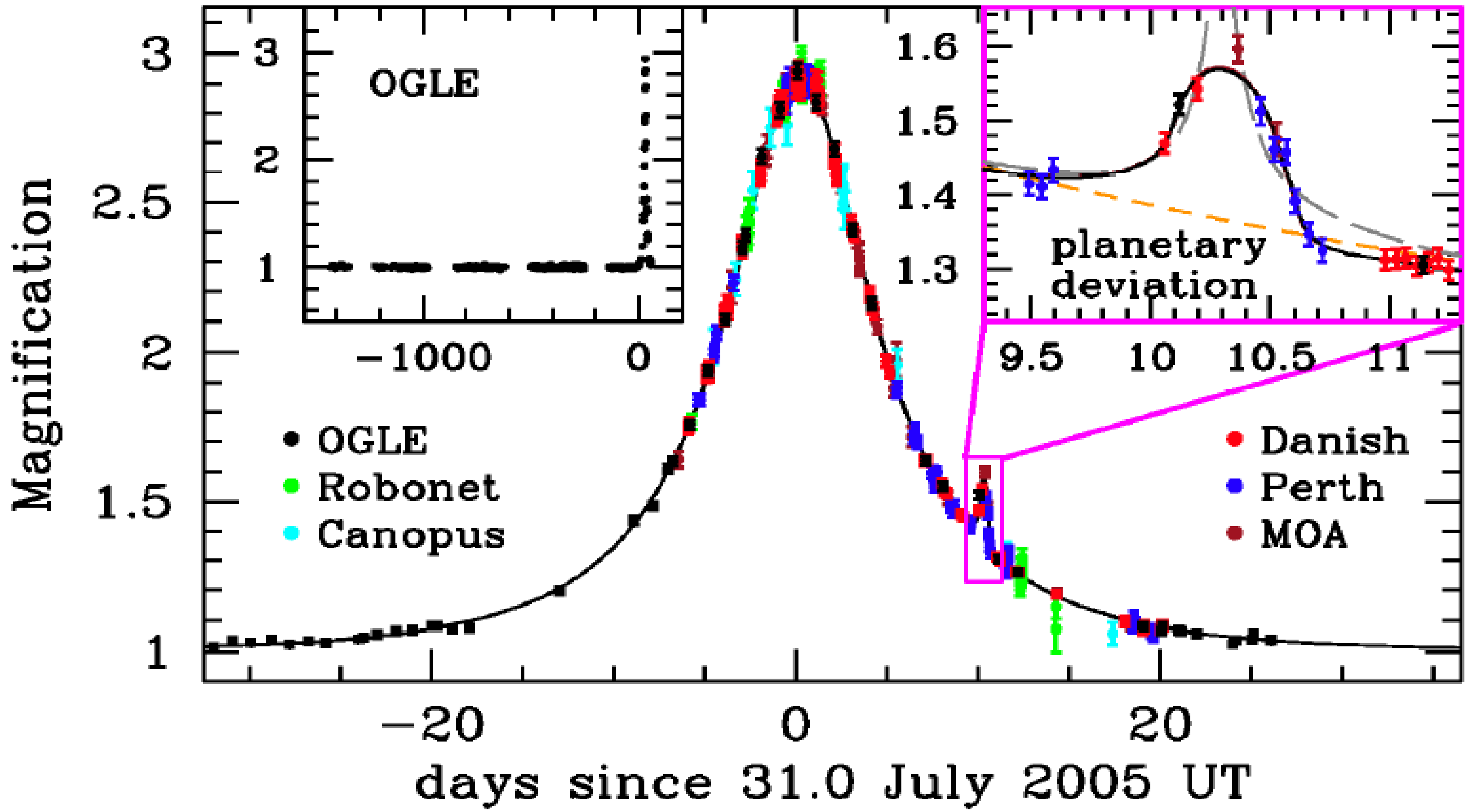
Two distinct steps are required to observe a planetary system by microlensing. First, one must single out a disk star which happens to be microlensing a bulge star. Second, one must observe this star often enough to catch the deviation in the light curve due to the planet. The first step involves the 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,

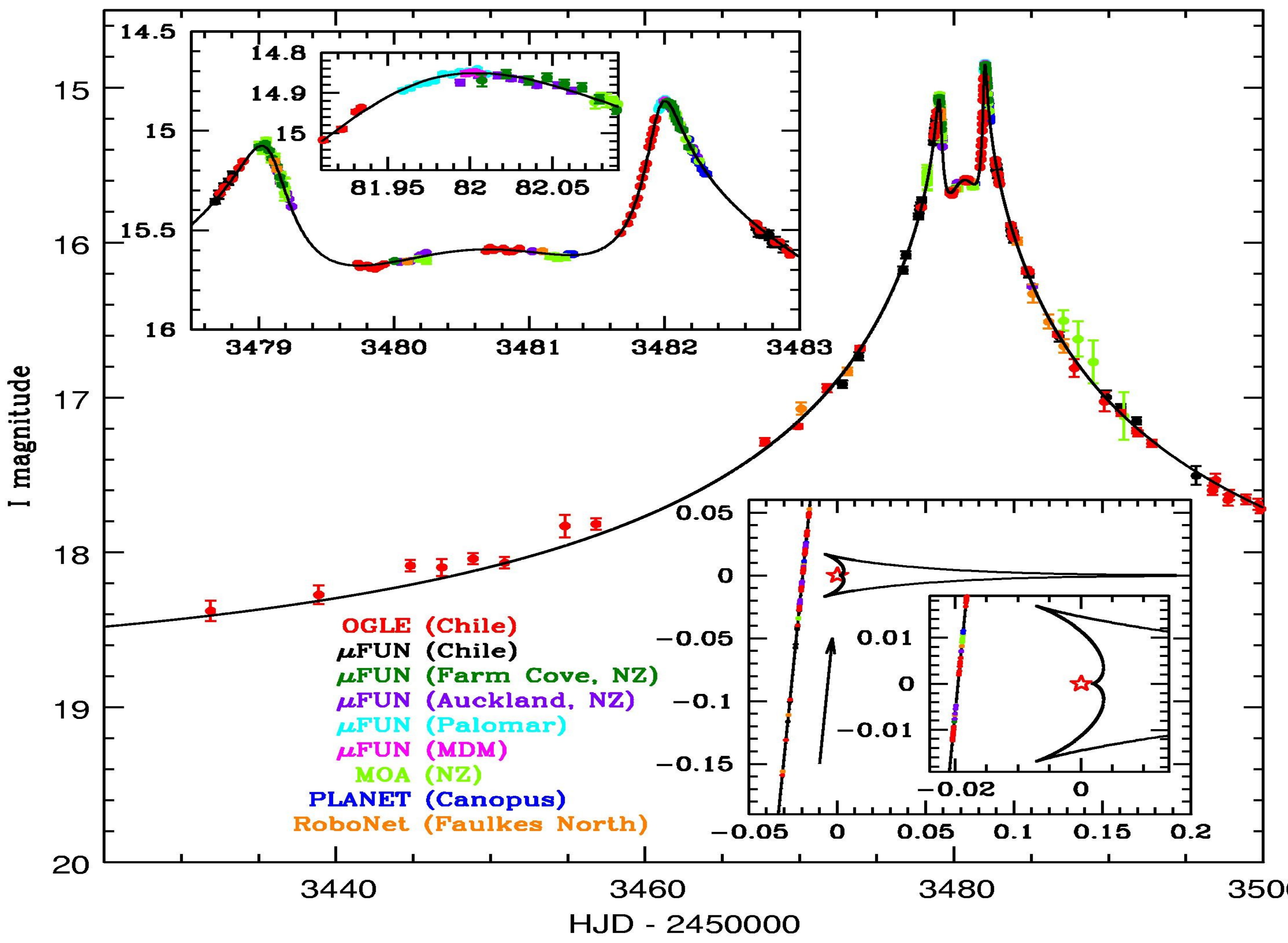
OGLE-2005-BLG-390

“Classical-Followup” Planetary Caustic



Beaulieu et al. 2006, Nature, 439, 437

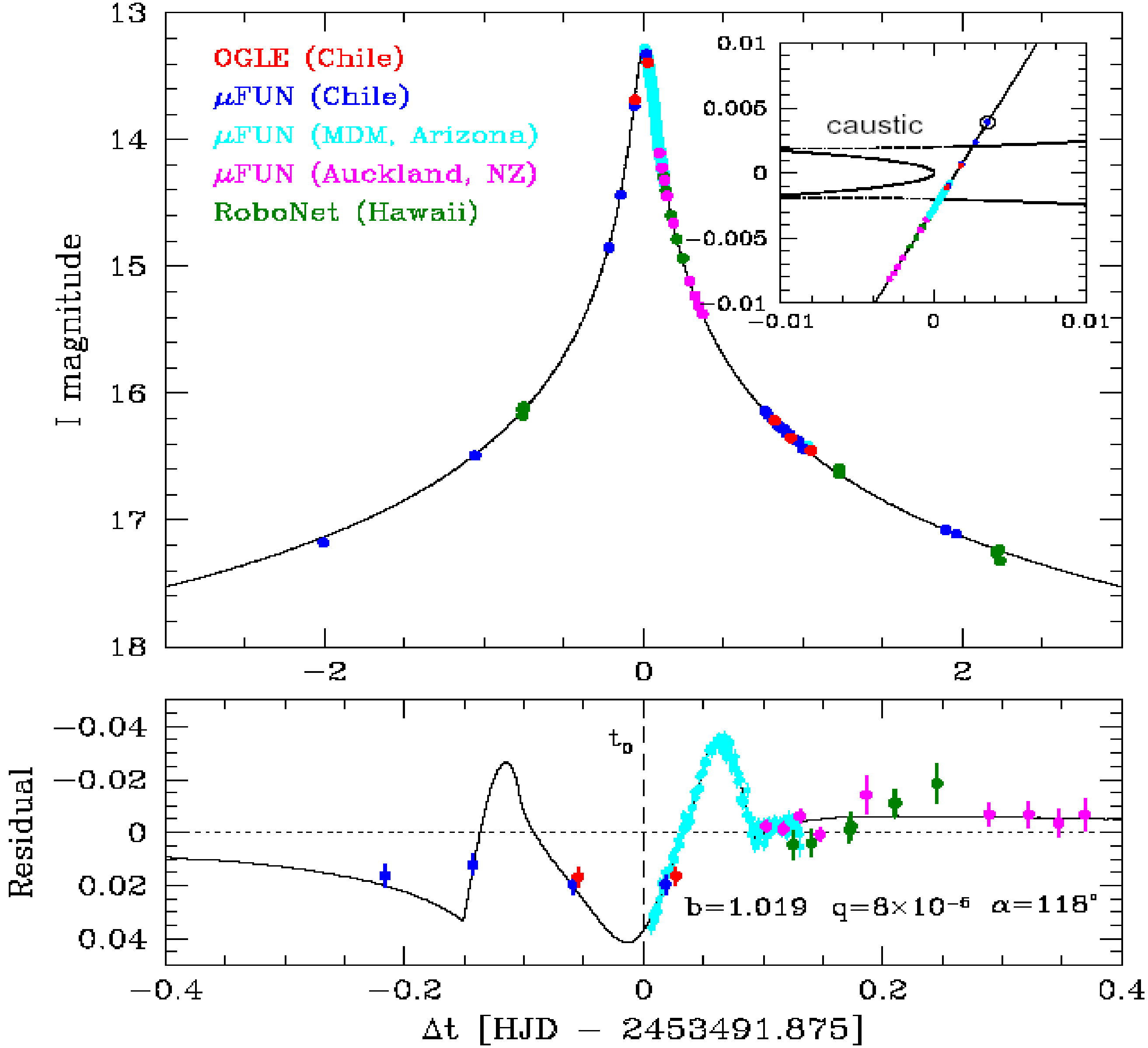
First "High-Magnification" Planet



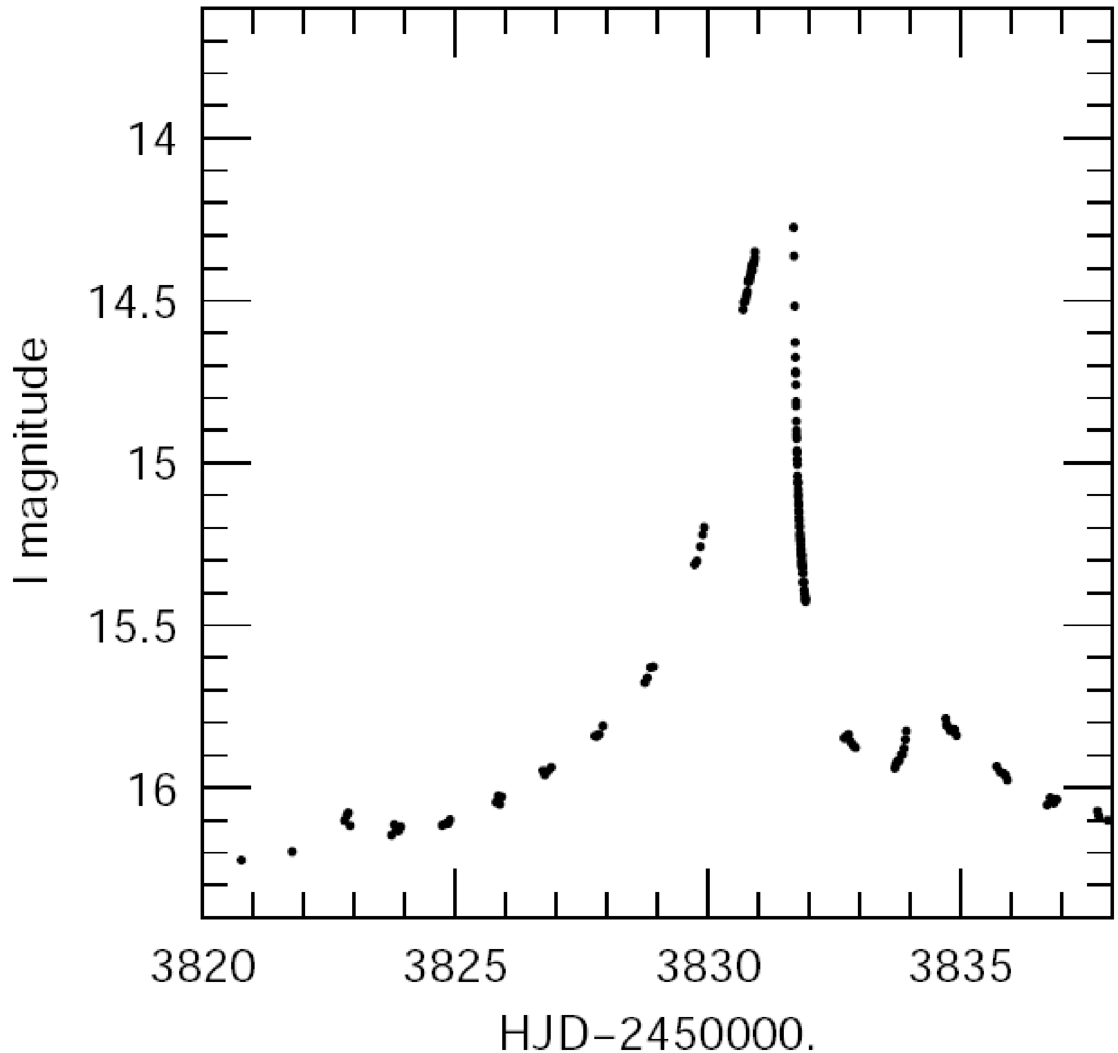
Udalski et al. 2005, ApJ, 628, L109

OGLE-2005-BLG-169:

Second Cold Neptune

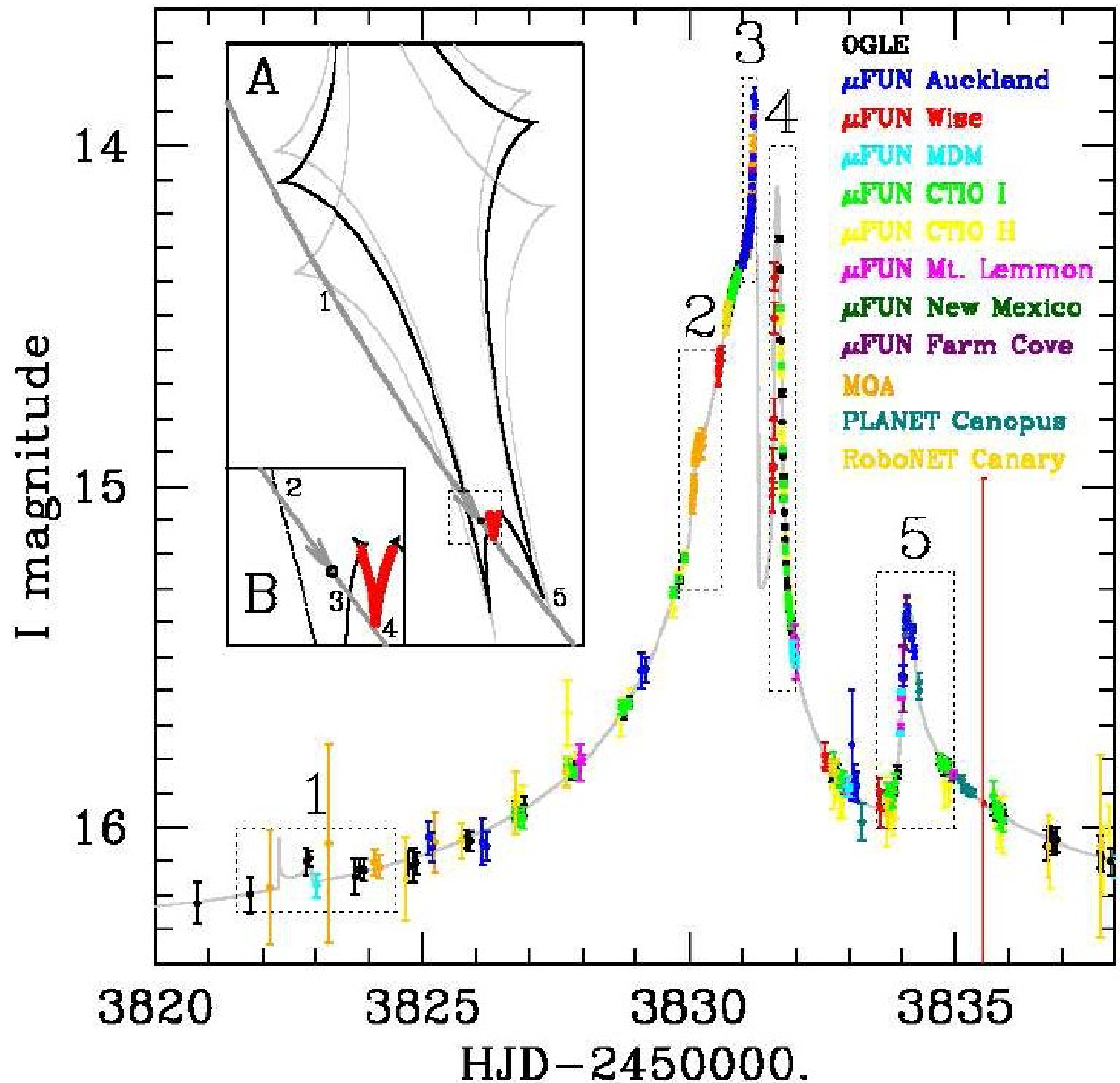


OGLE-2006-BLG-109:
Without Followup Observations



OGLE-2006-BLG-109

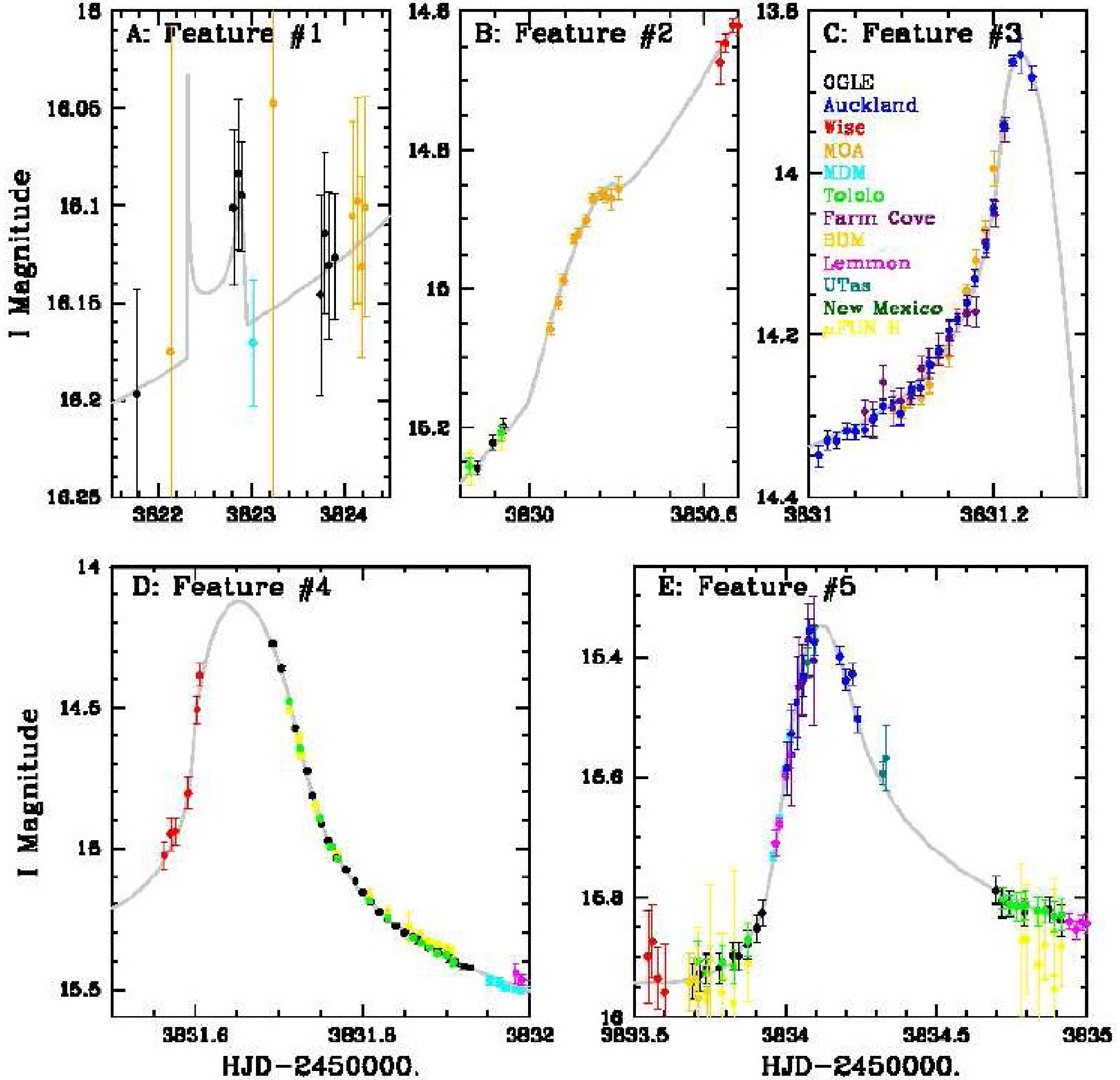
Parallax+Finite-Source+Rotation+Blend



Gaudi et al. 2008, Science, 319, 927

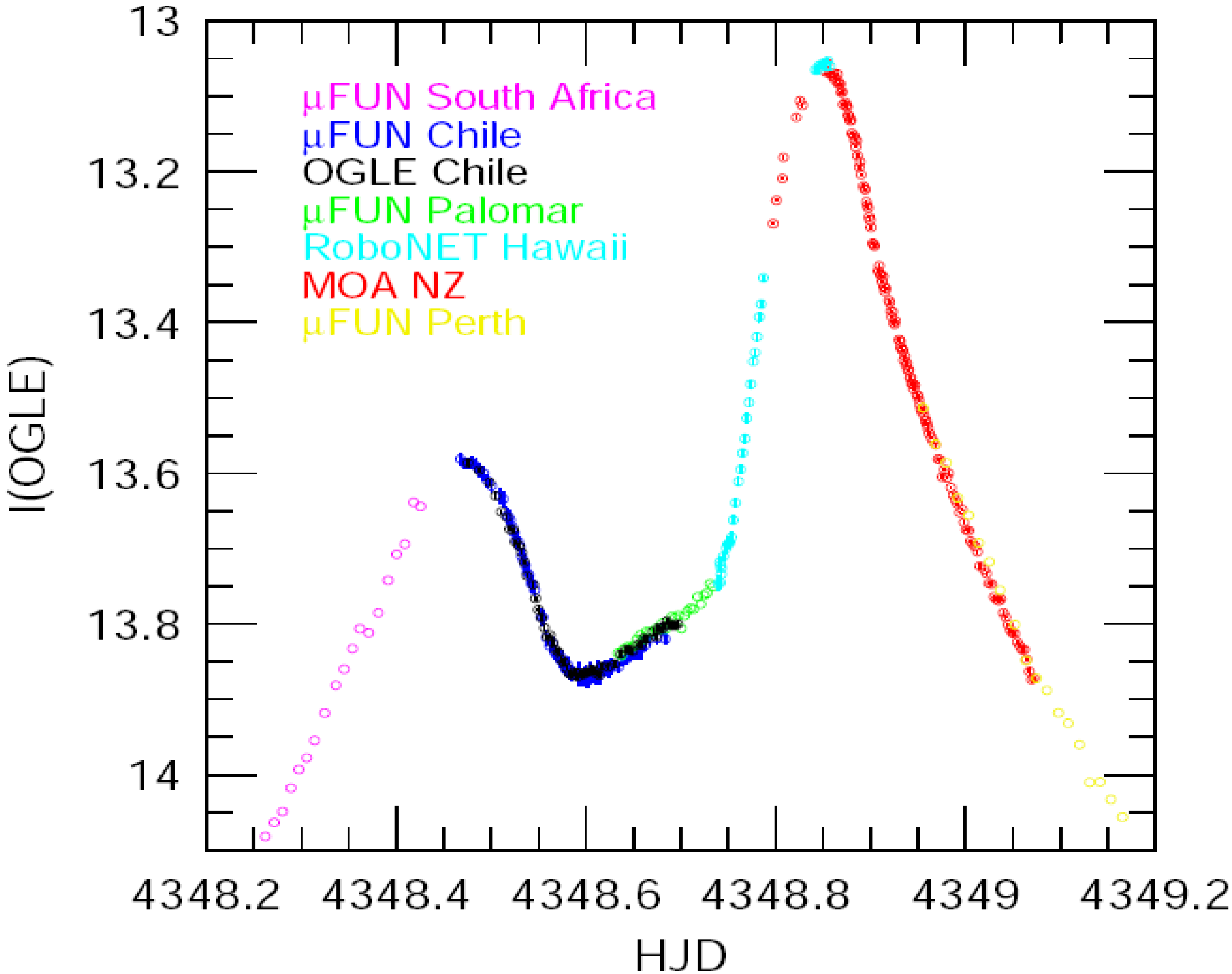
Five Lightcurve Features

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



OGLE-2007-BLG-349:

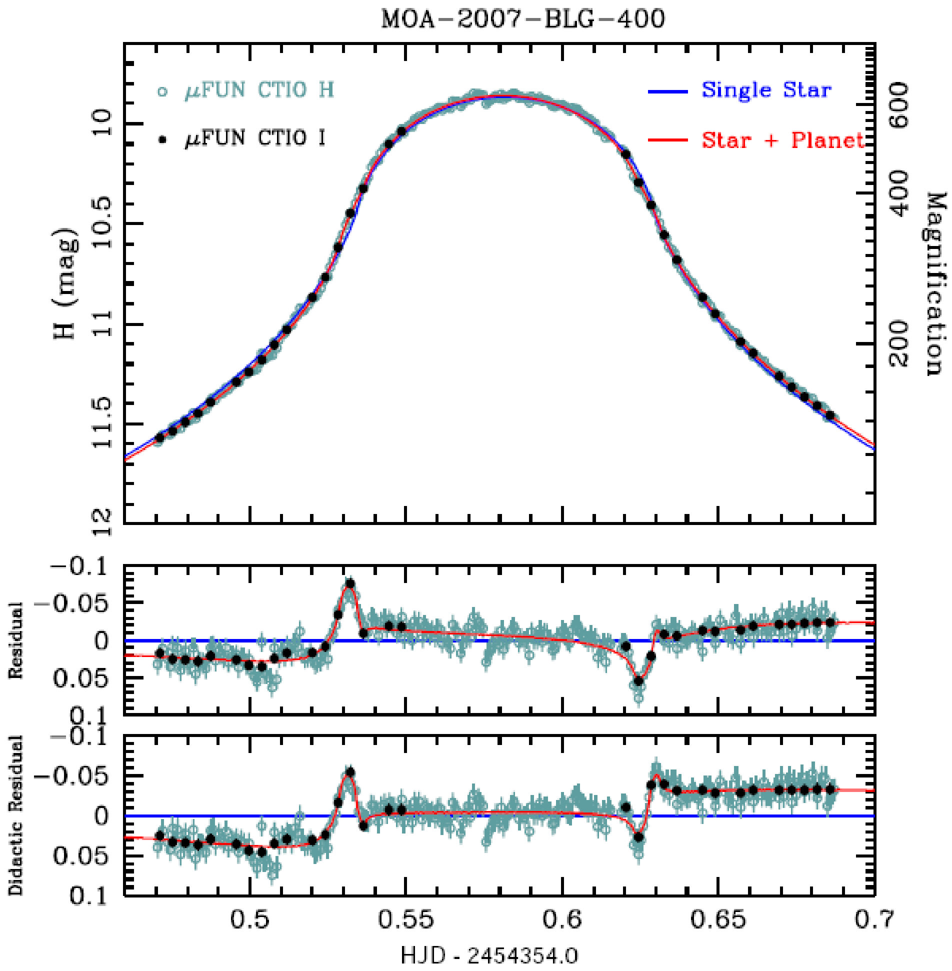
Saturn Mass-Ratio Planet +



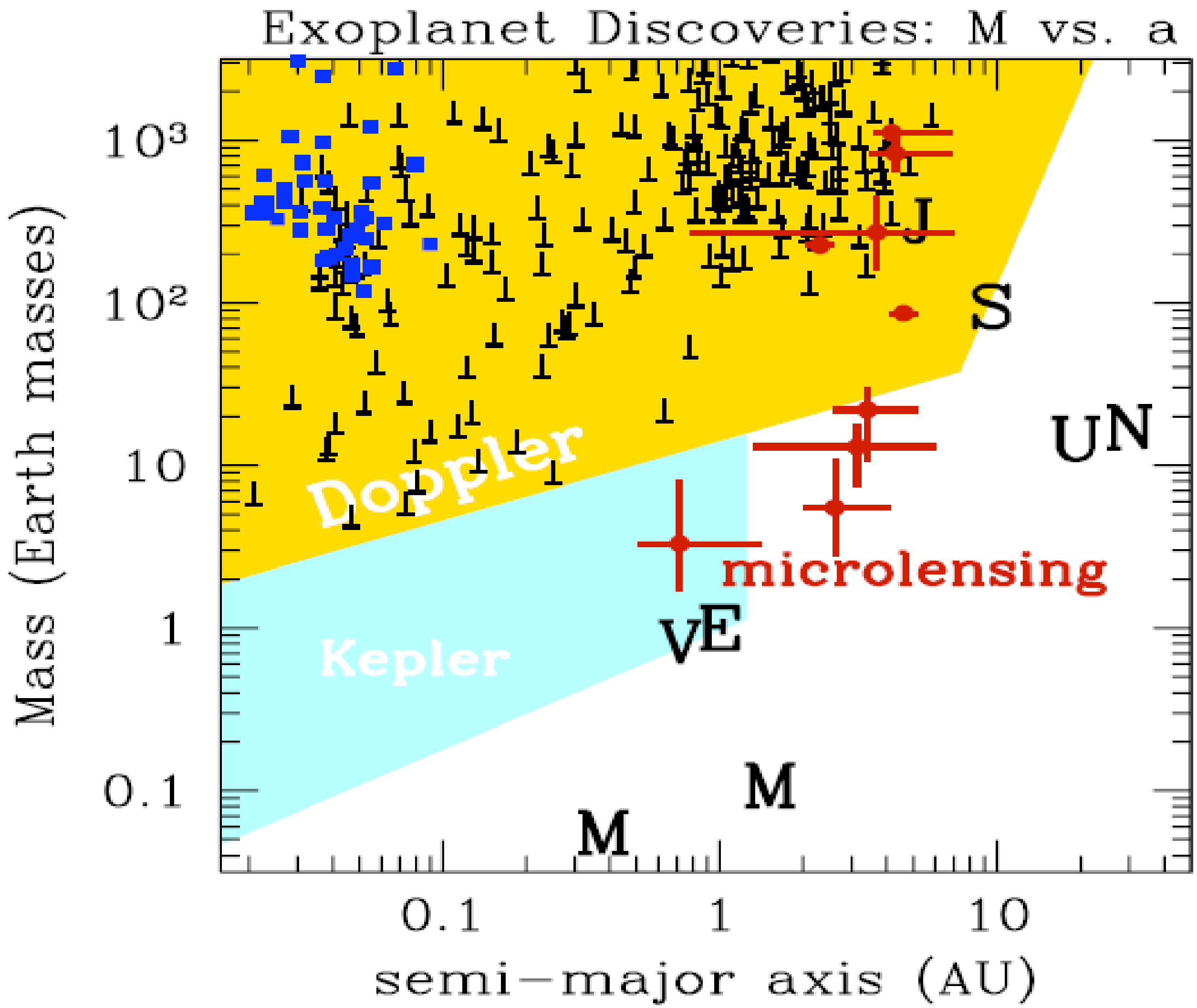
Dong et al. 2010, in prep

MOA-2007-BLG-400

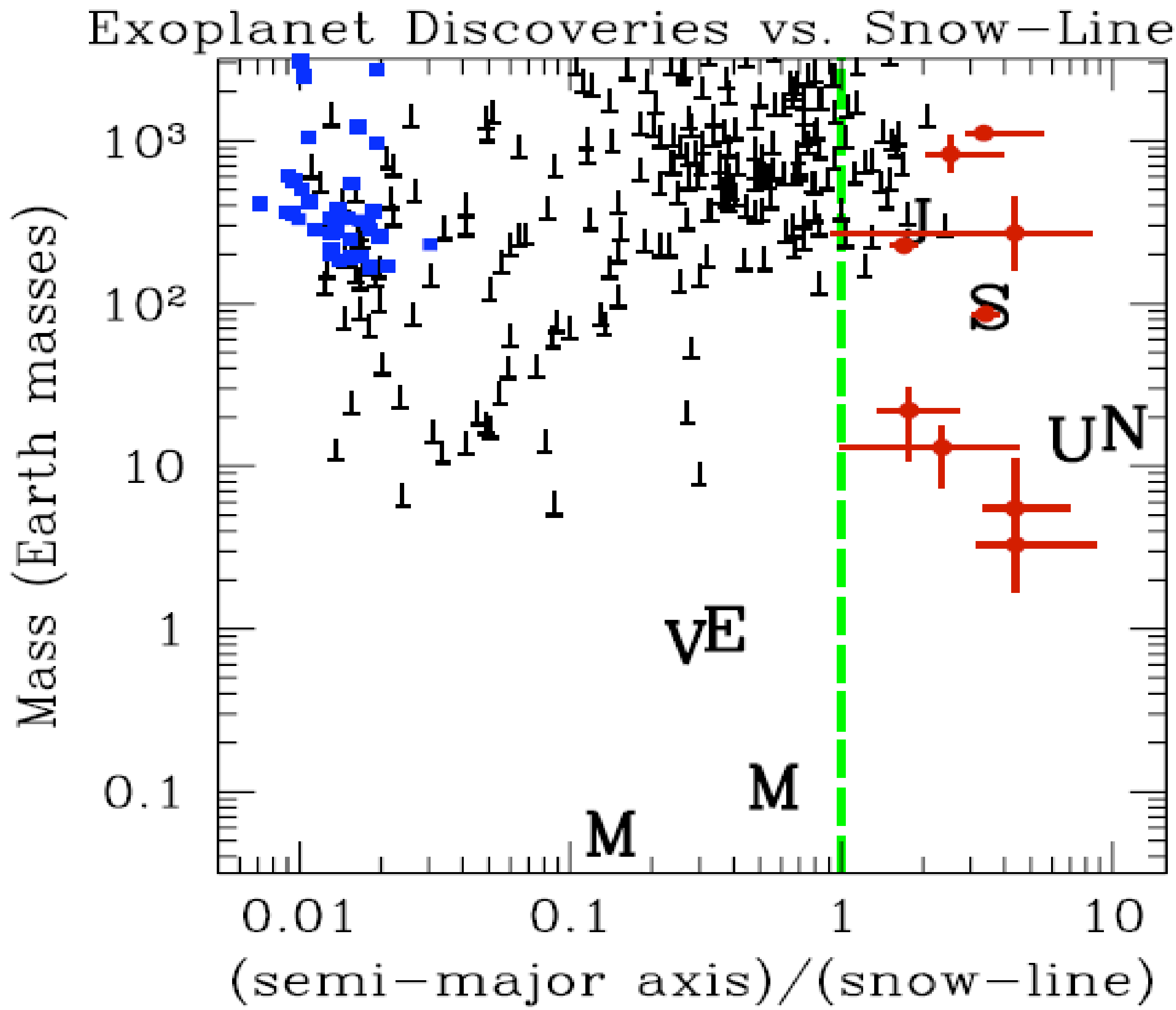
"Buried" Jovian-Mass Planet



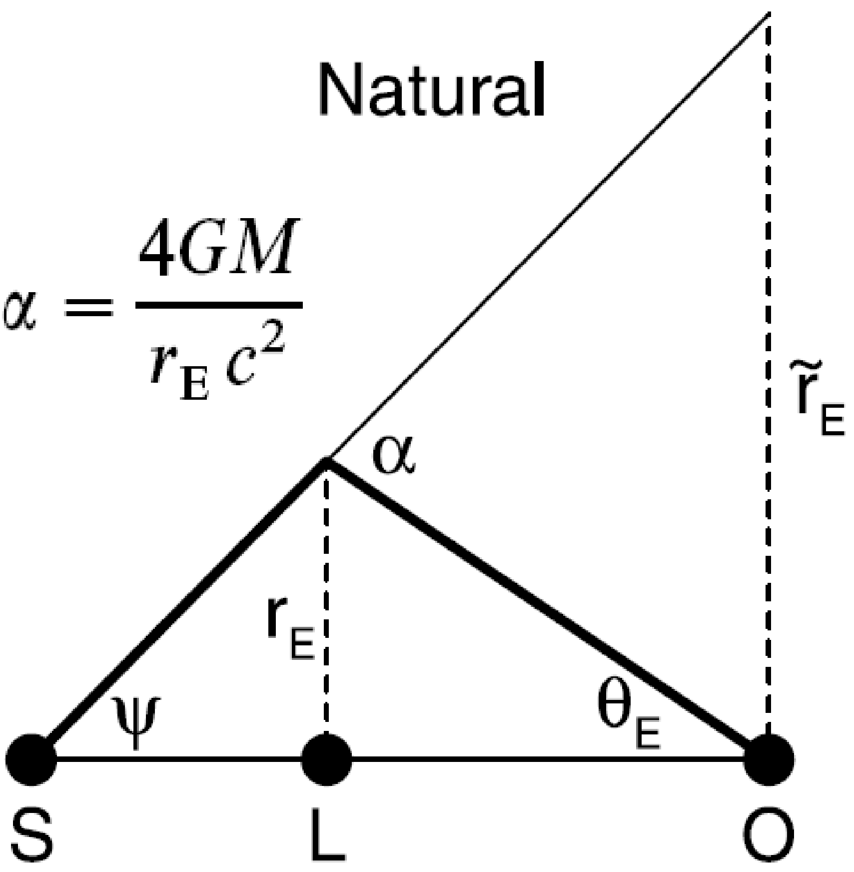
Microlensing vs. Other Methods



Microlensing and the "Snow Line"



Relation of Mass and Distance to Lensing Observables



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

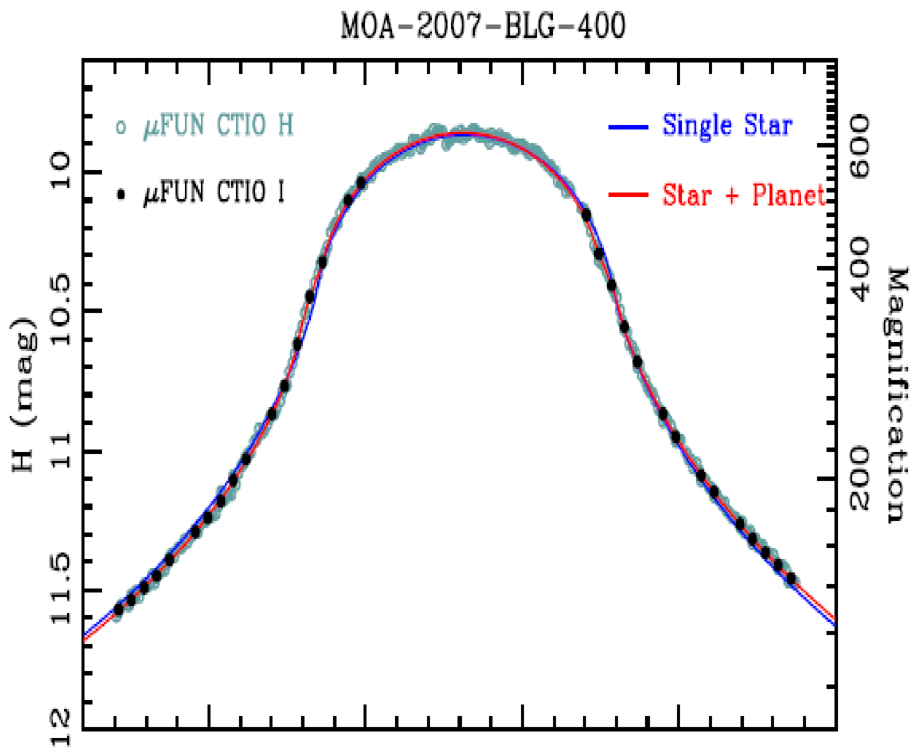
$$\alpha/\tilde{r}_E = \theta_E/r_E$$

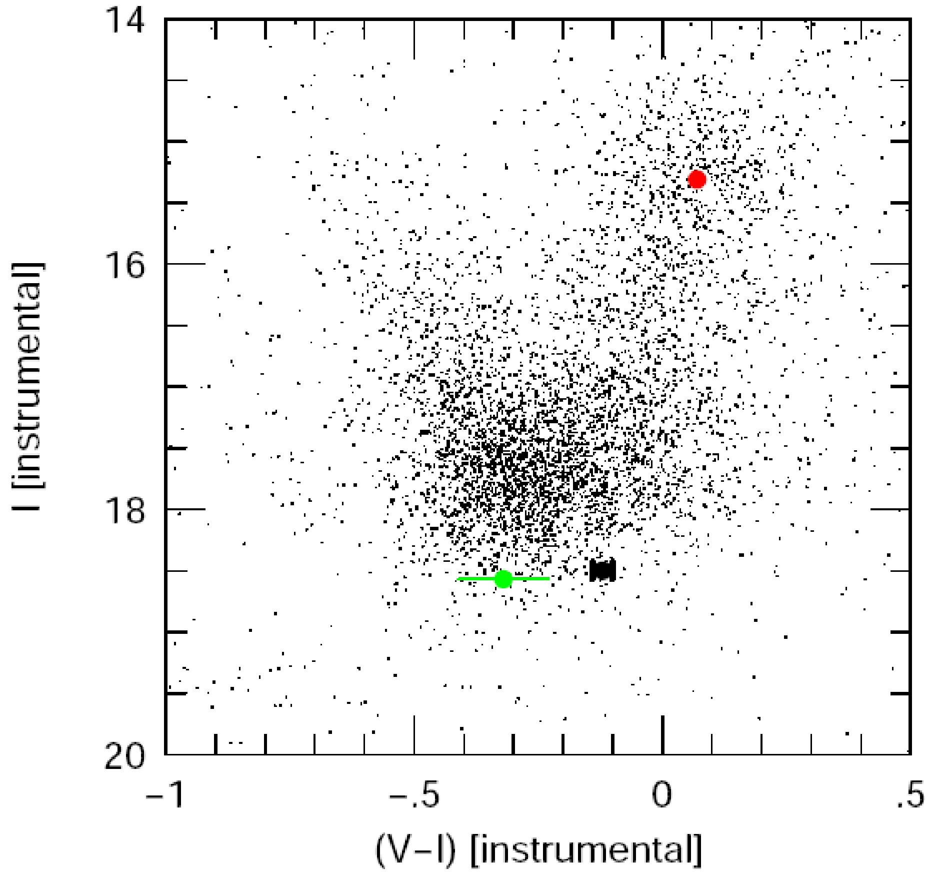
$$\theta_E \tilde{r}_E = \alpha r_E = \frac{4GM}{c^2}$$

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

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

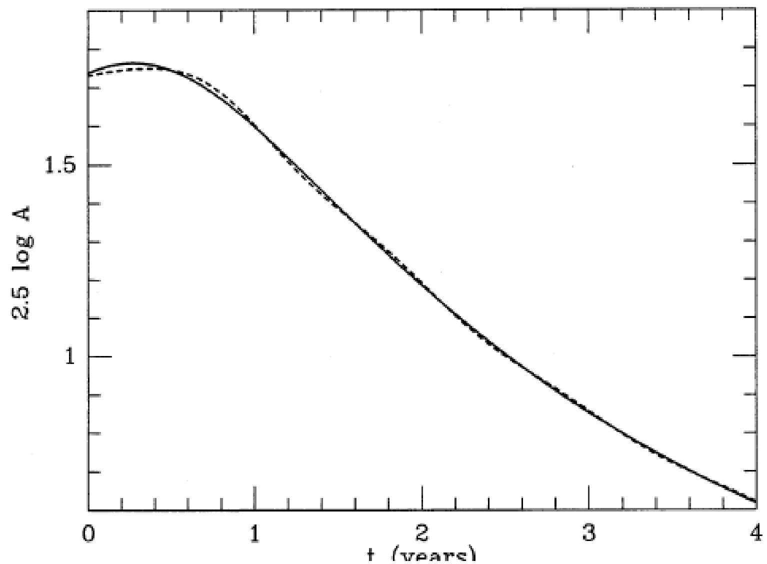
To measure angular Einstein radius:
Standard Sky-Plane Rulers

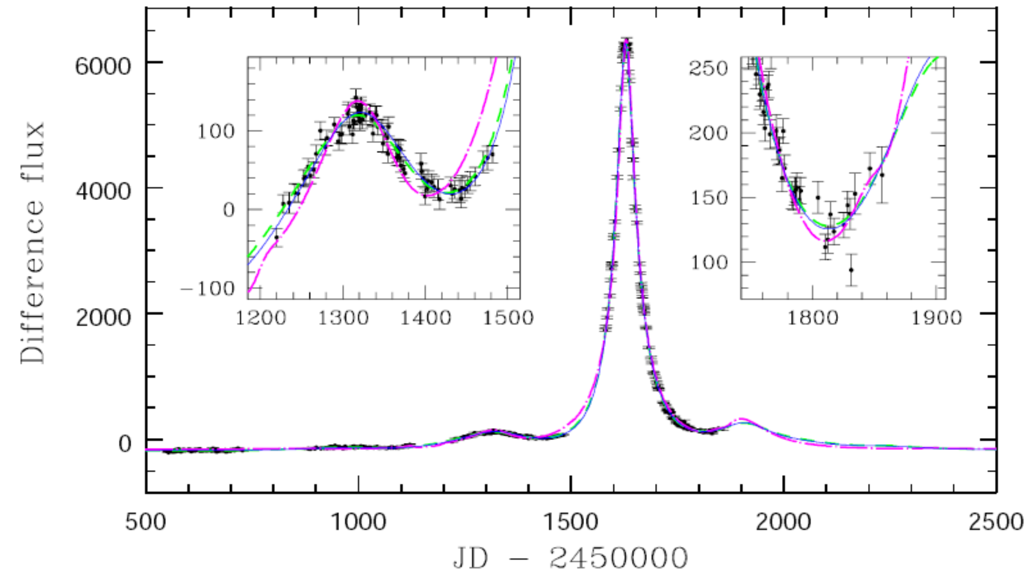


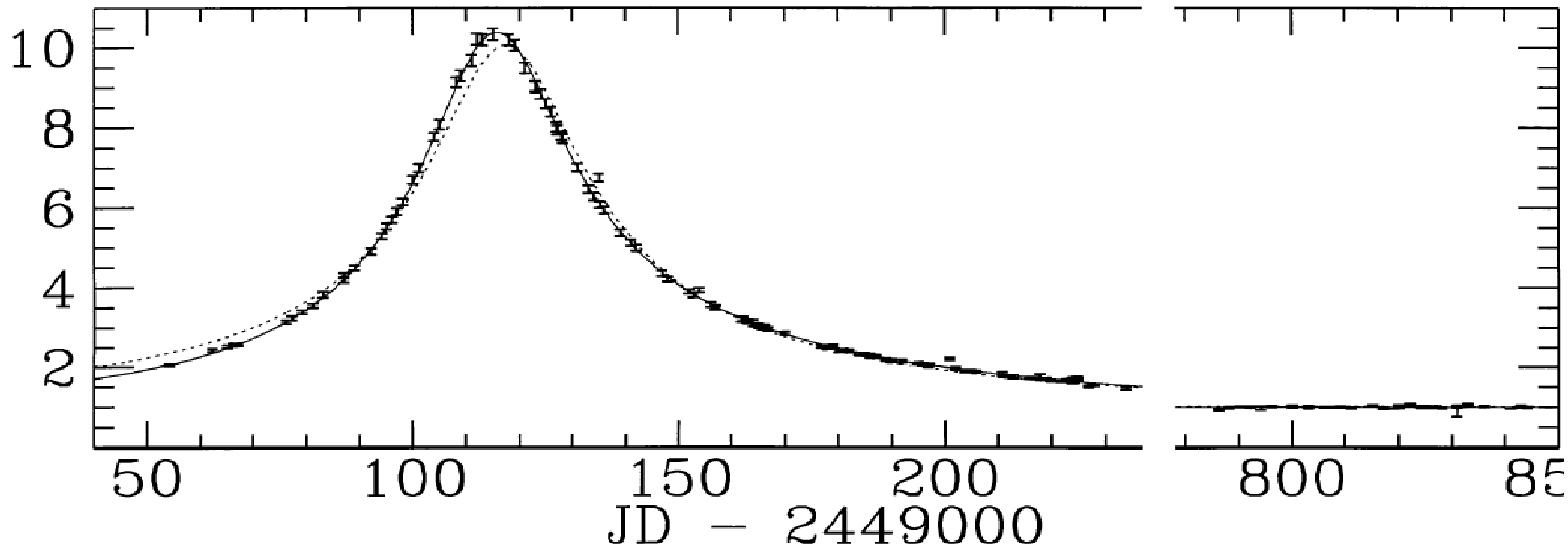


To measure parallax:

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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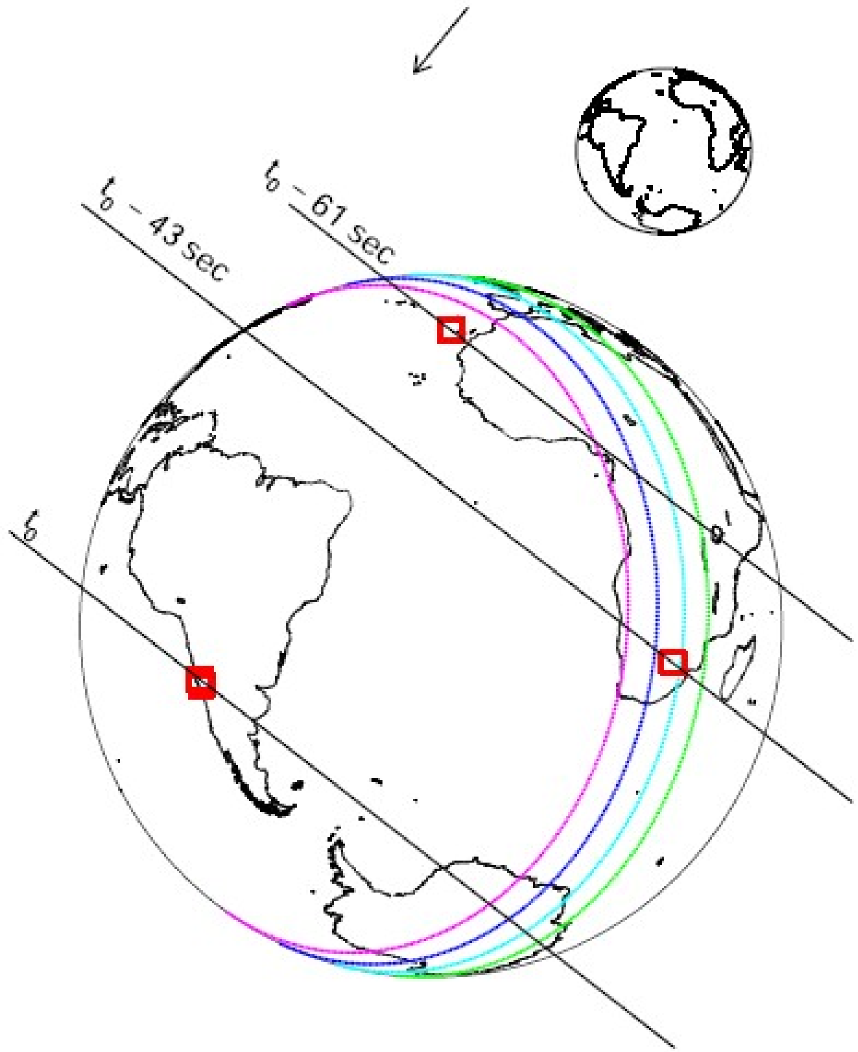
Received 1995 March 8; accepted 1996 January 11

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

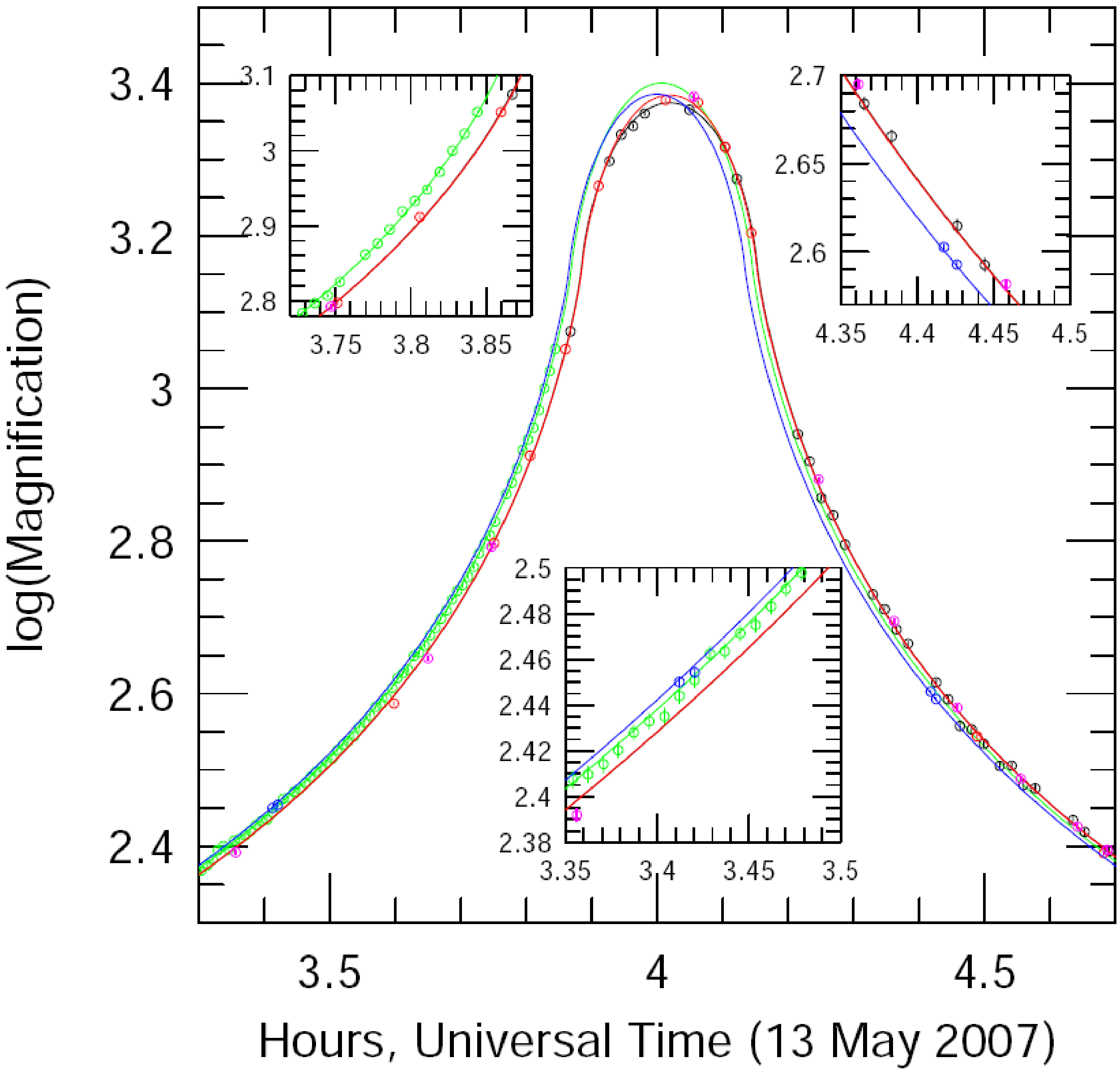
issues. We thank Andrew Gould for pointing out an error in the original version of this manuscript. This research was

Terrestrial Parallax:
Simultaneous Observations on Earth

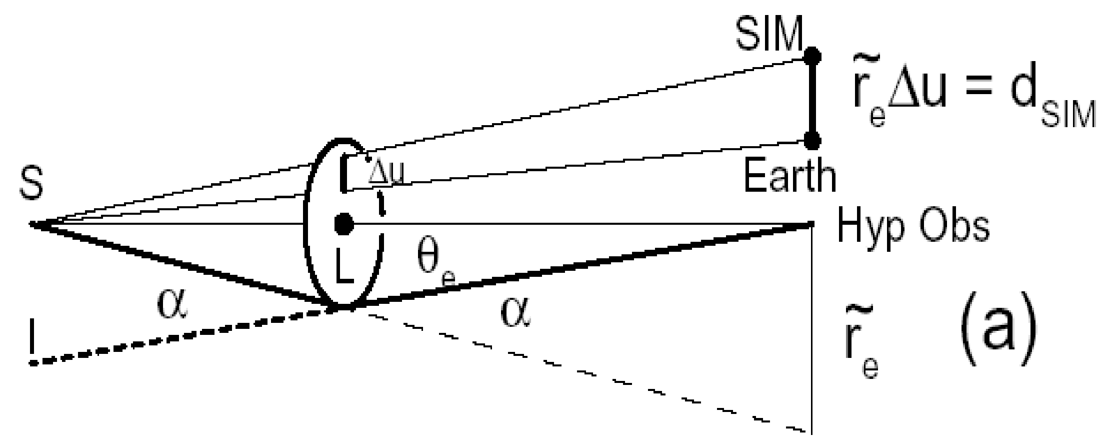


OGLE-2007-BLG-224

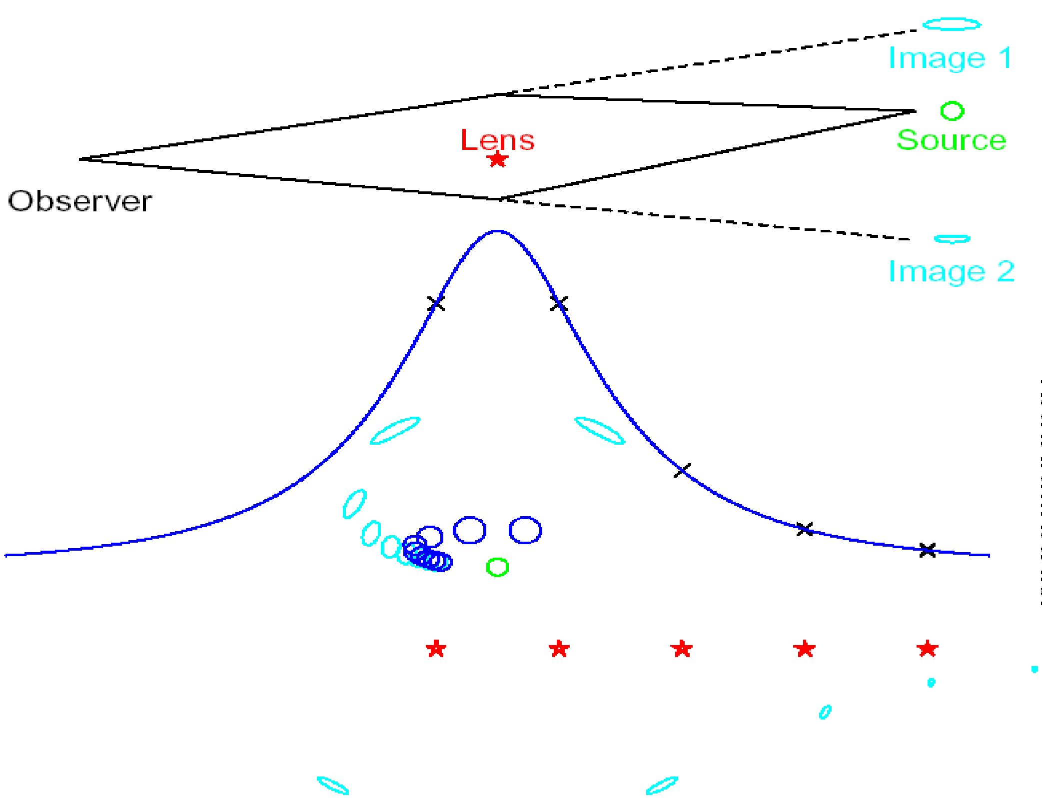
Canaries South Africa Chile

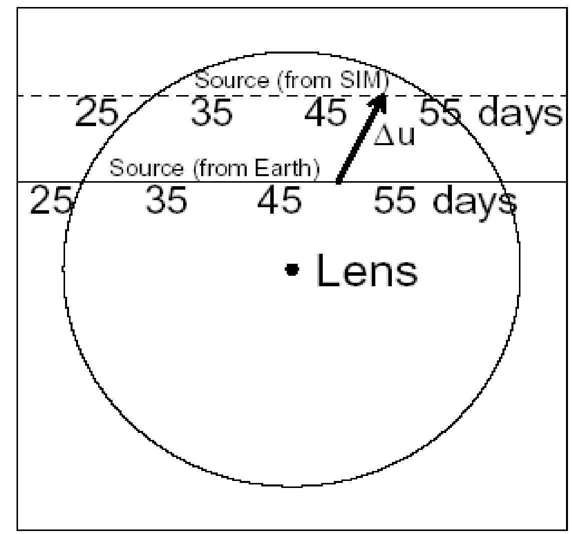


Space-Based Parallaxes & Einstein Radii : SIM



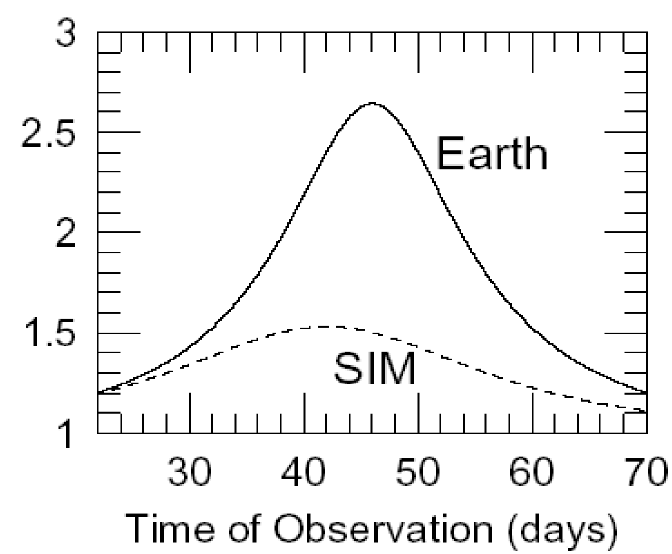
(a)





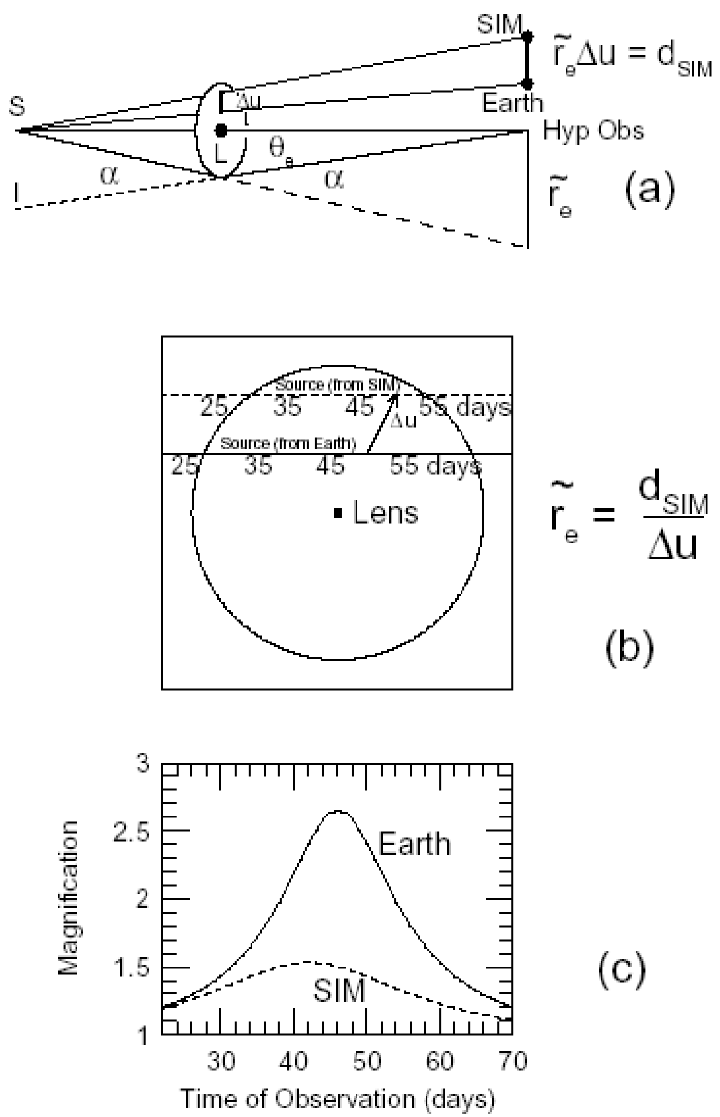
$$\tilde{r}_e = \frac{d_{SIM}}{\Delta u}$$

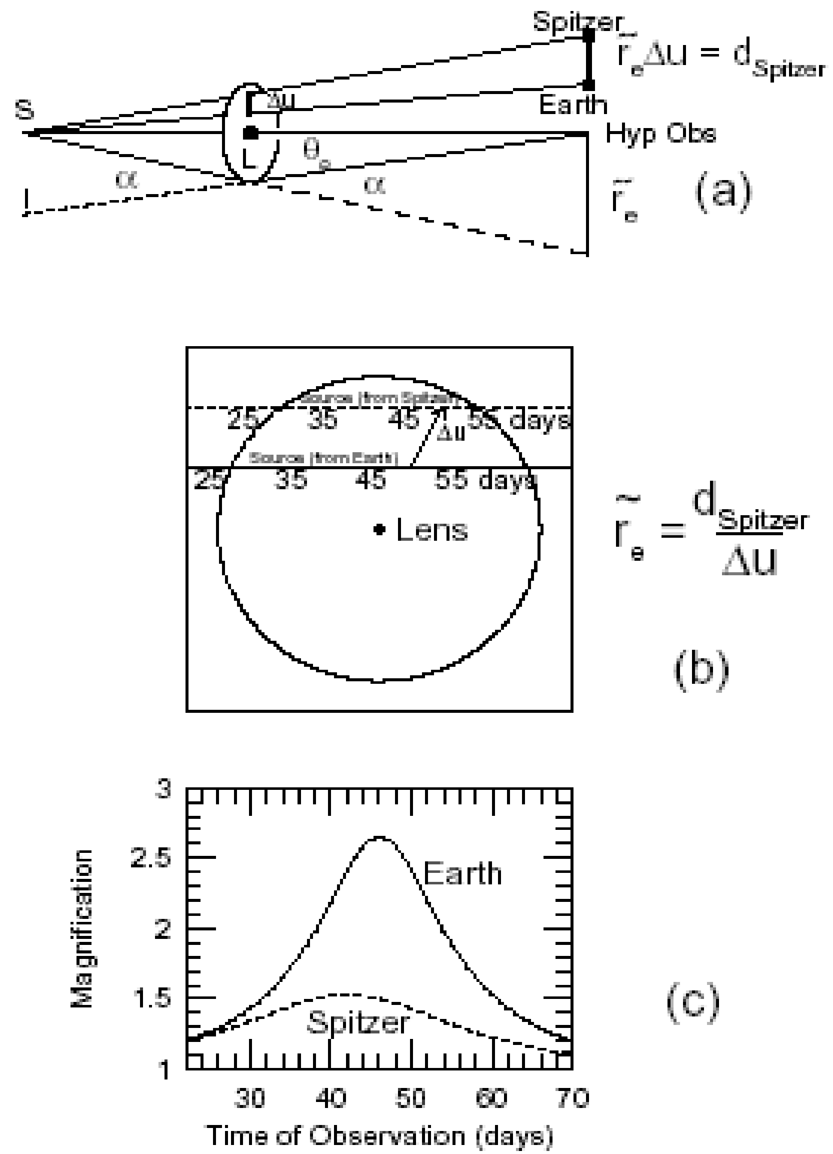
(b)

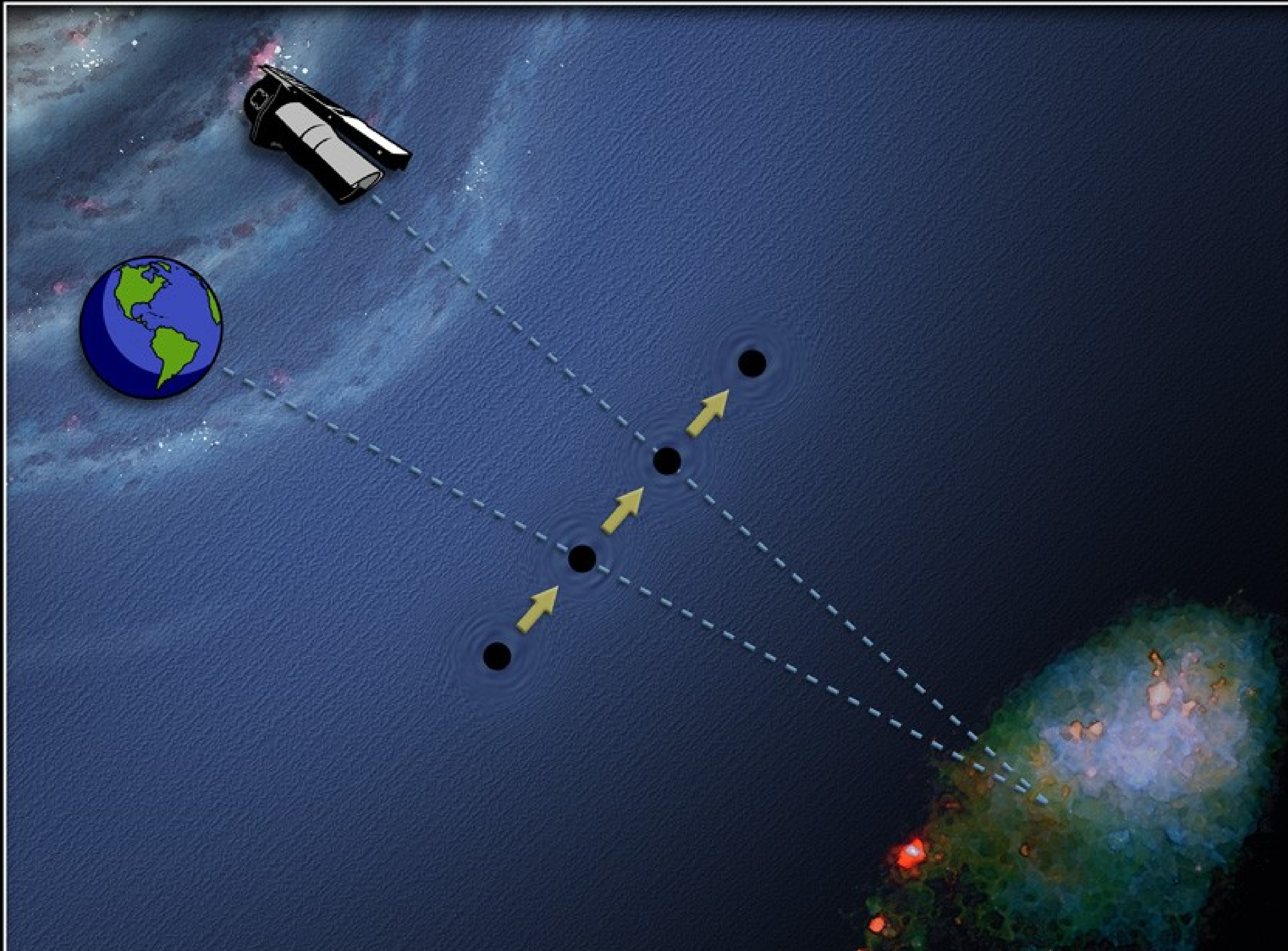


(c)

... or, more immediately: Spitzer







Microlens Parallax Observations of OGLE-2005-SMC-001

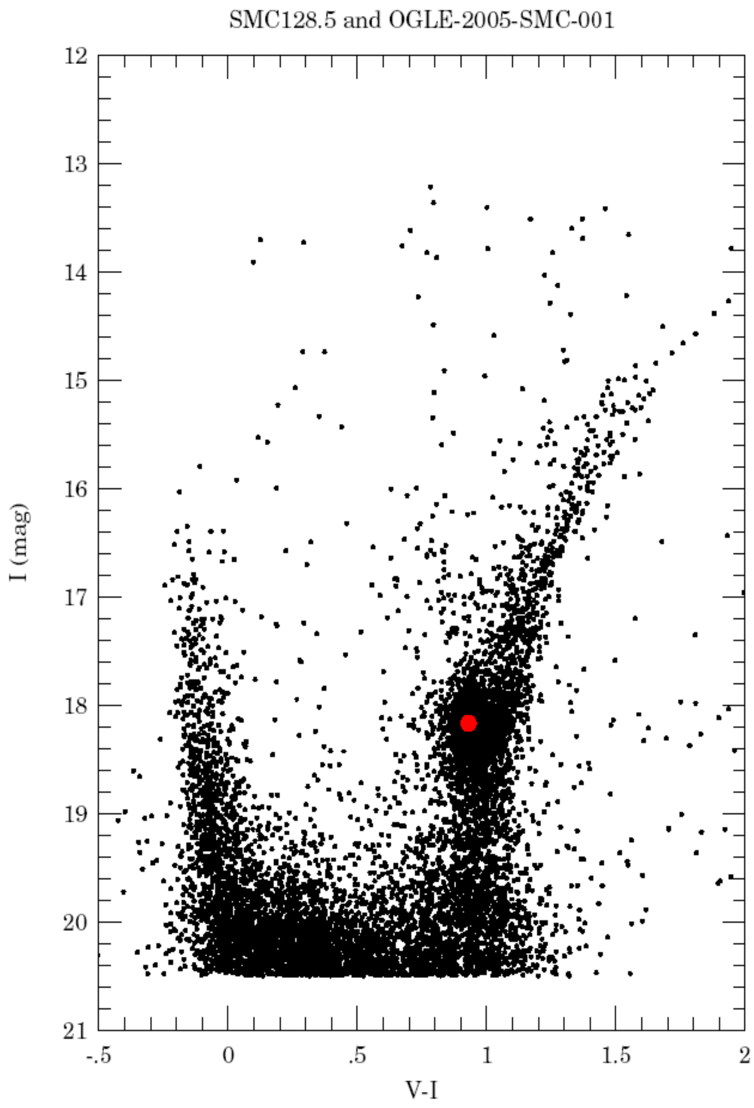
Spitzer Space Telescope • IRAC

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

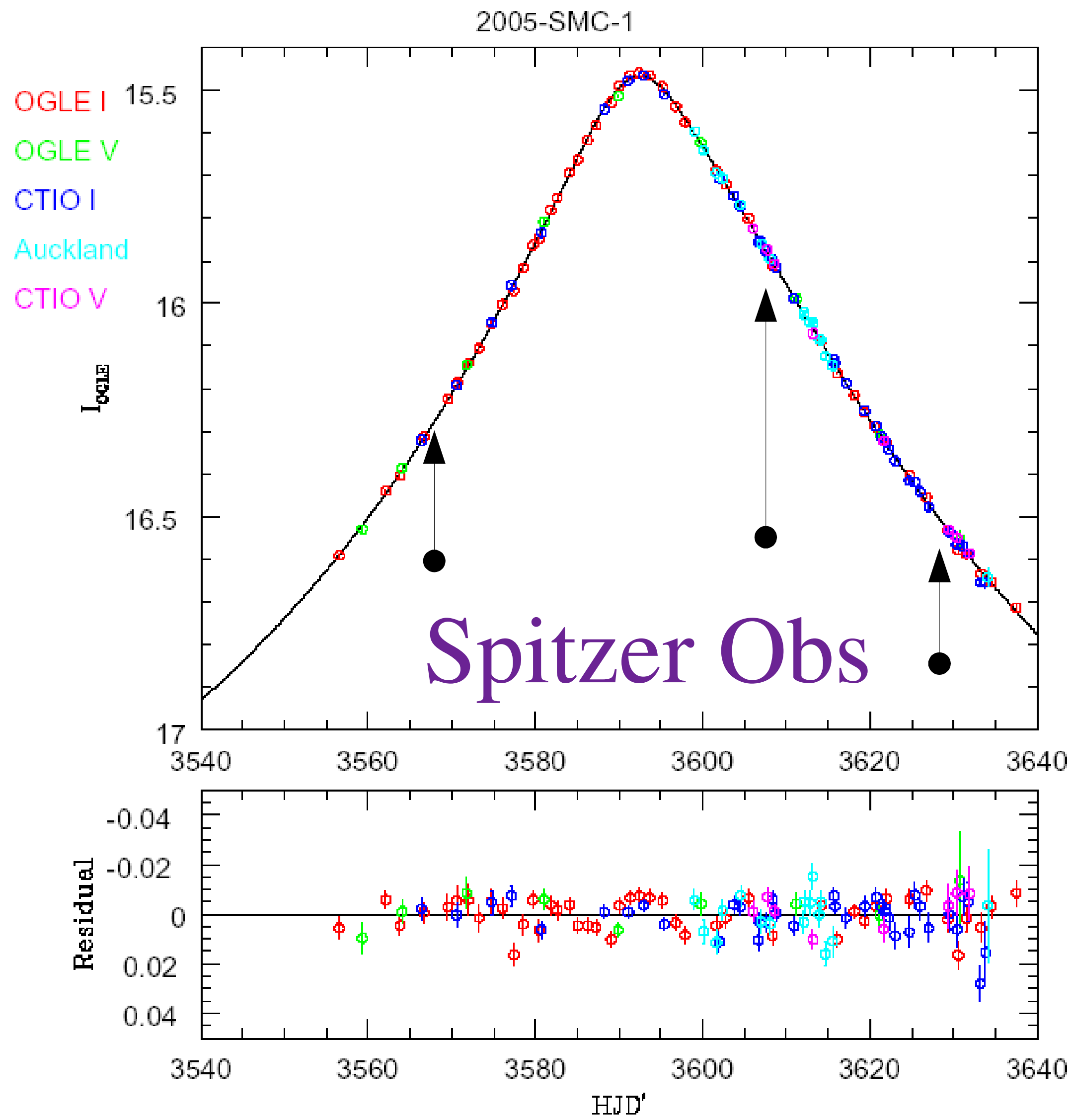
ssc2007-XX

OGLE-2005-SMC-001

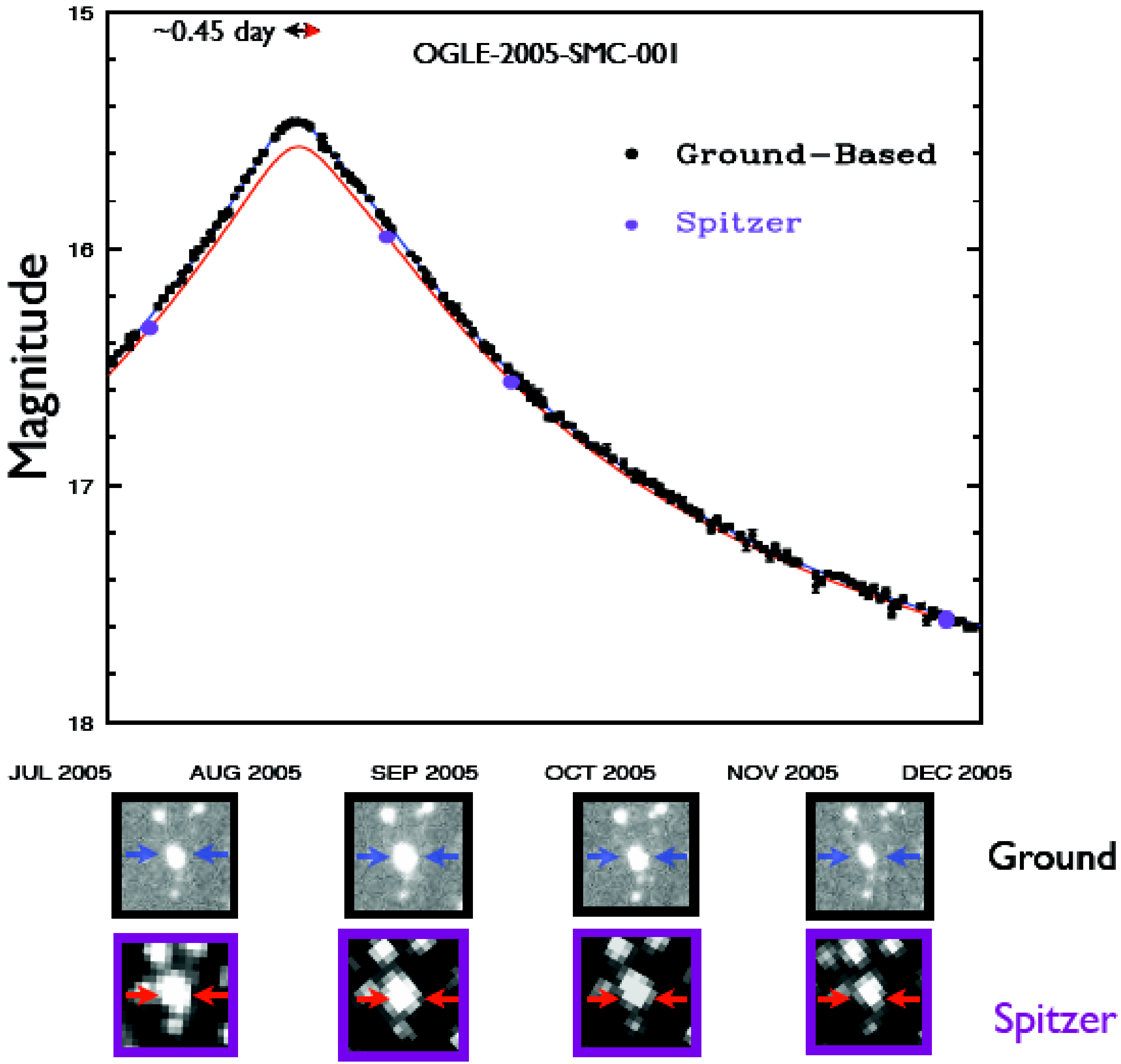
CMD



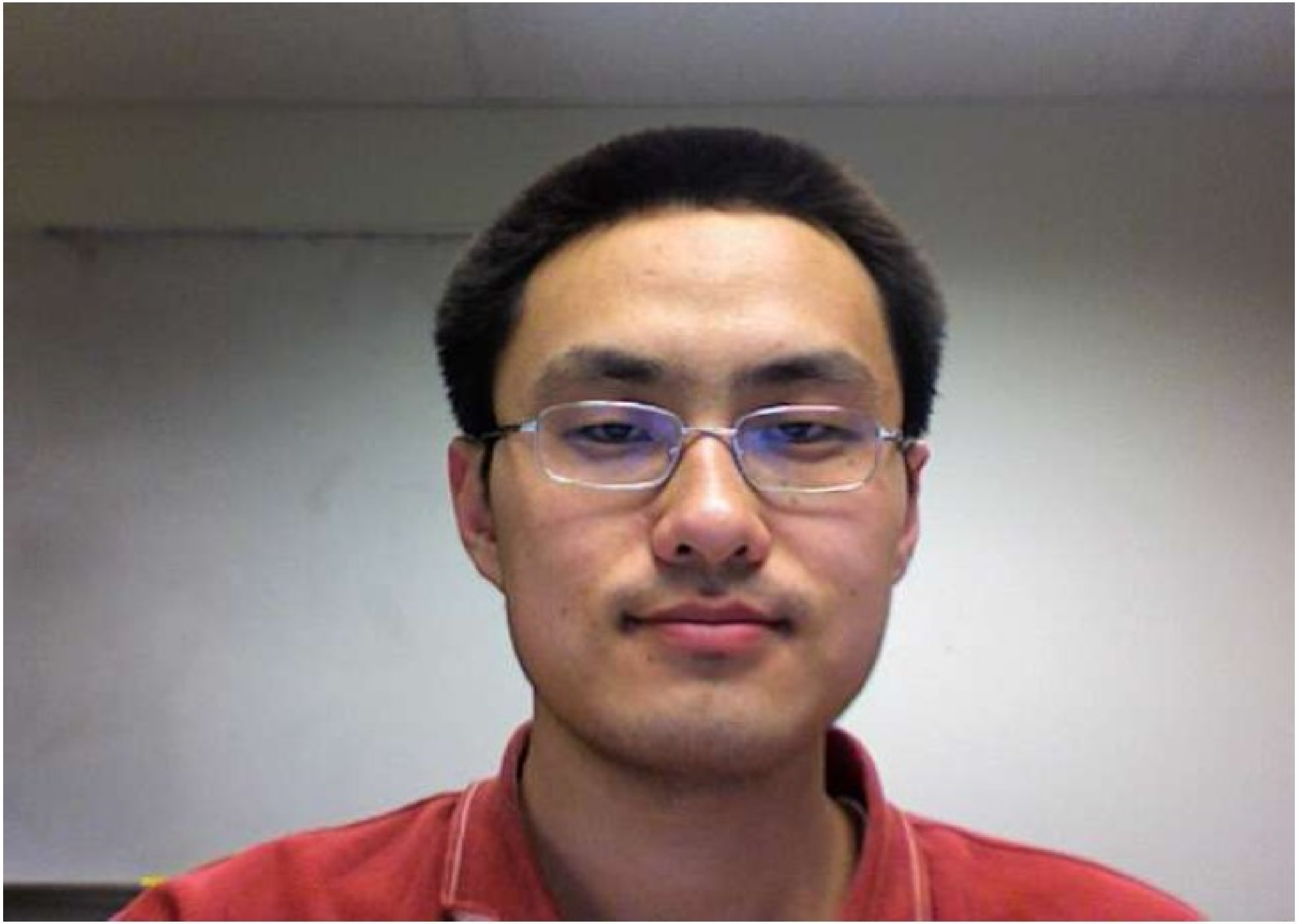
Photometry



Microlens Parallax



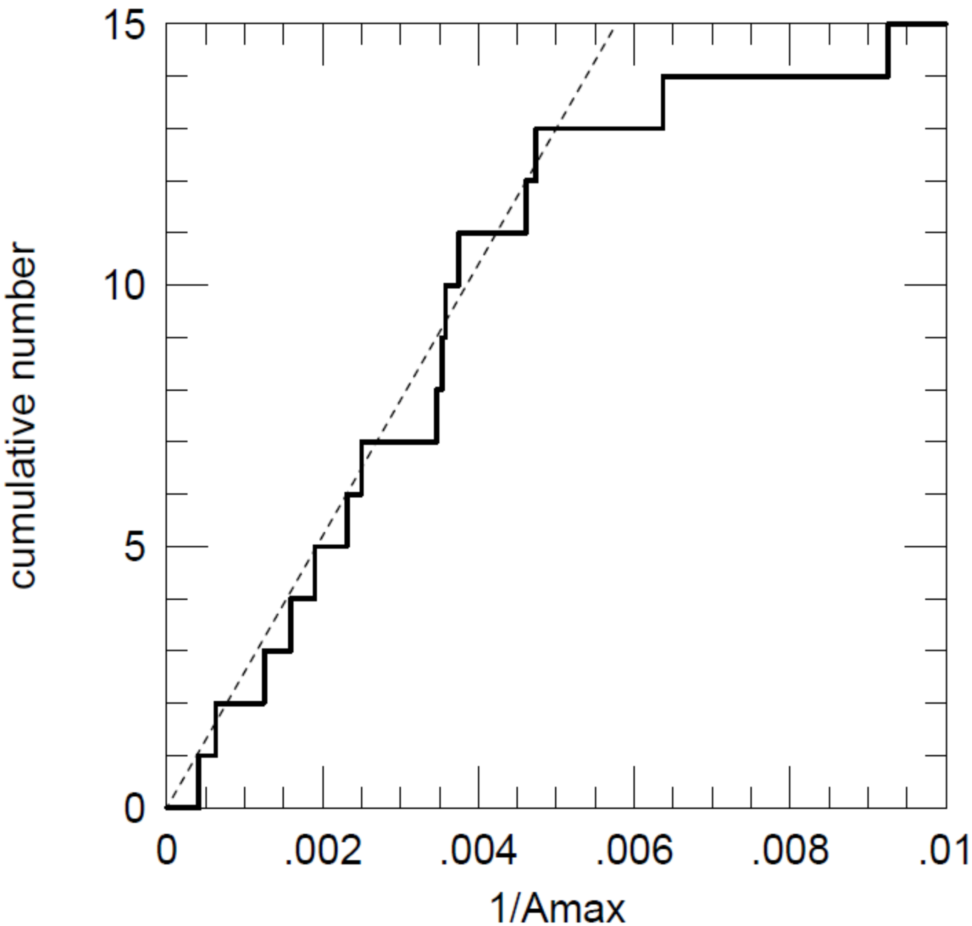
Subo Dong



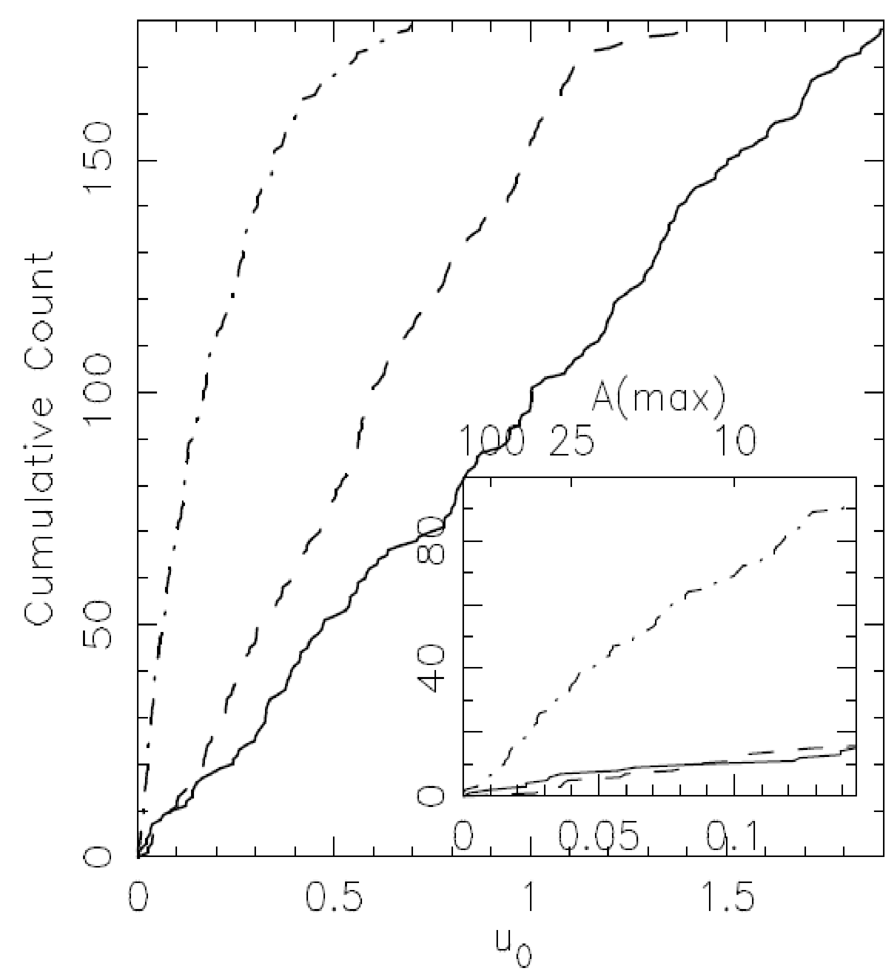
Well-covered events: fair sample

(Amax>200)

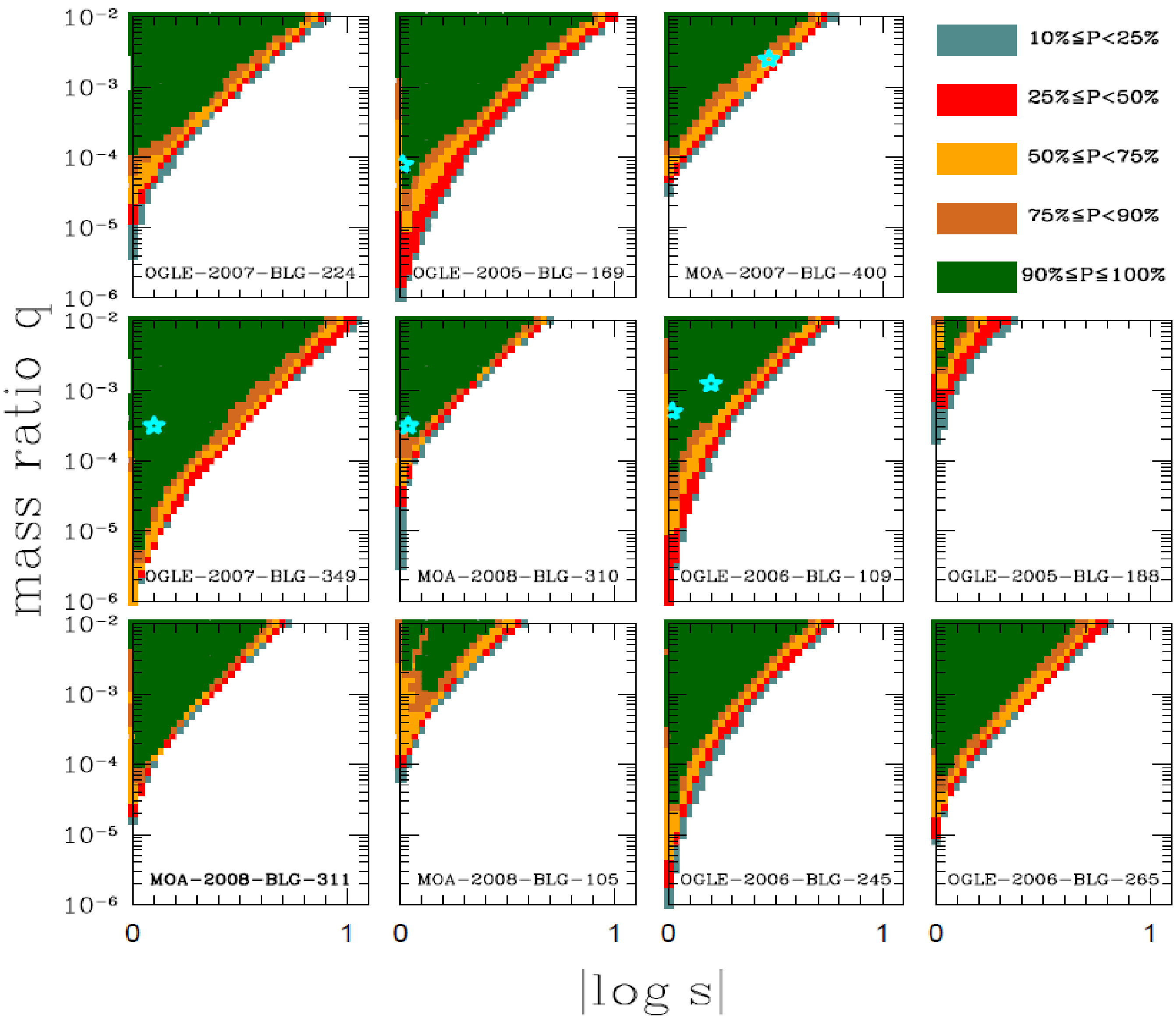
Well-Covered



All Events

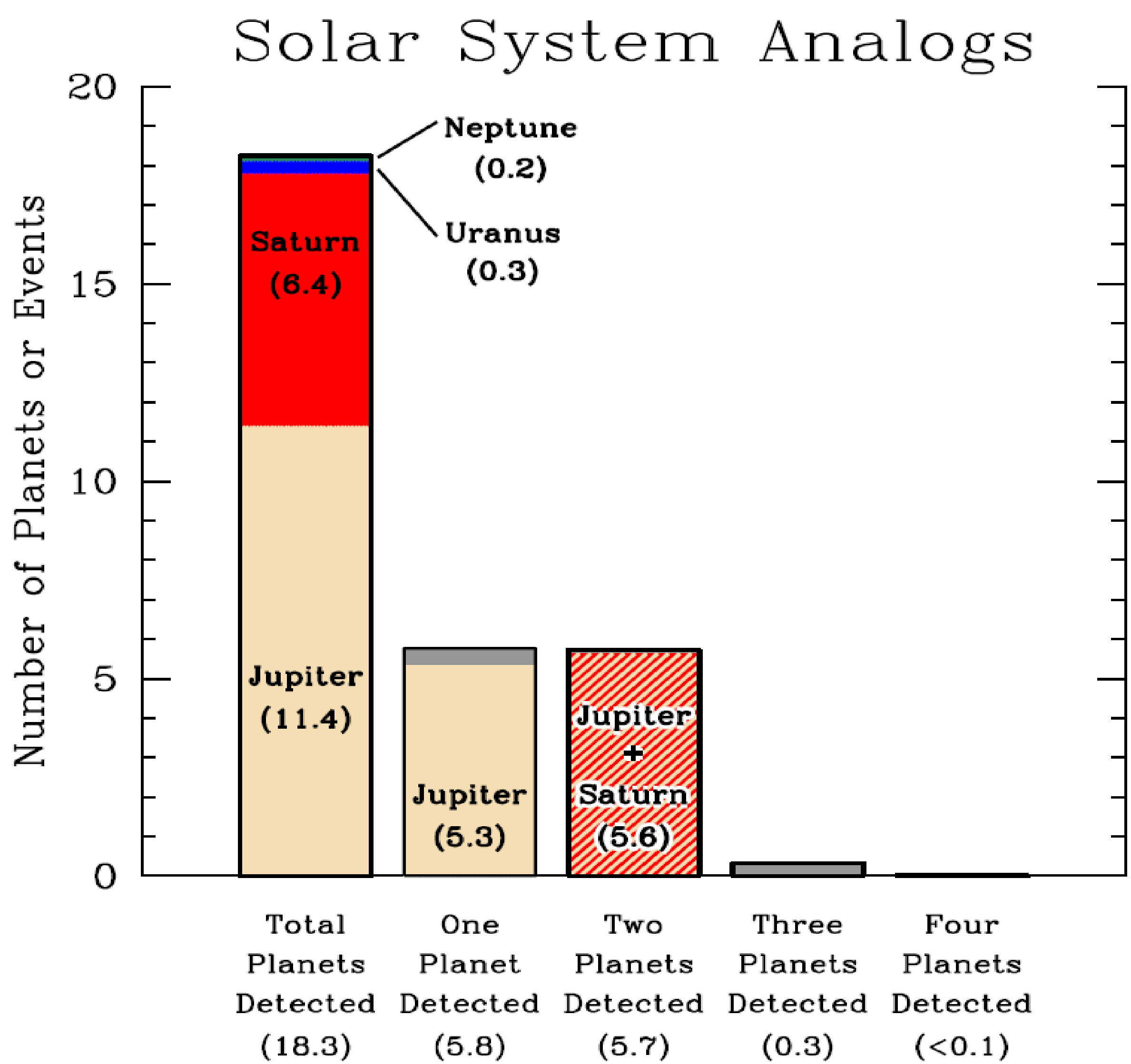


Planet Sensitivity Vs. Detections

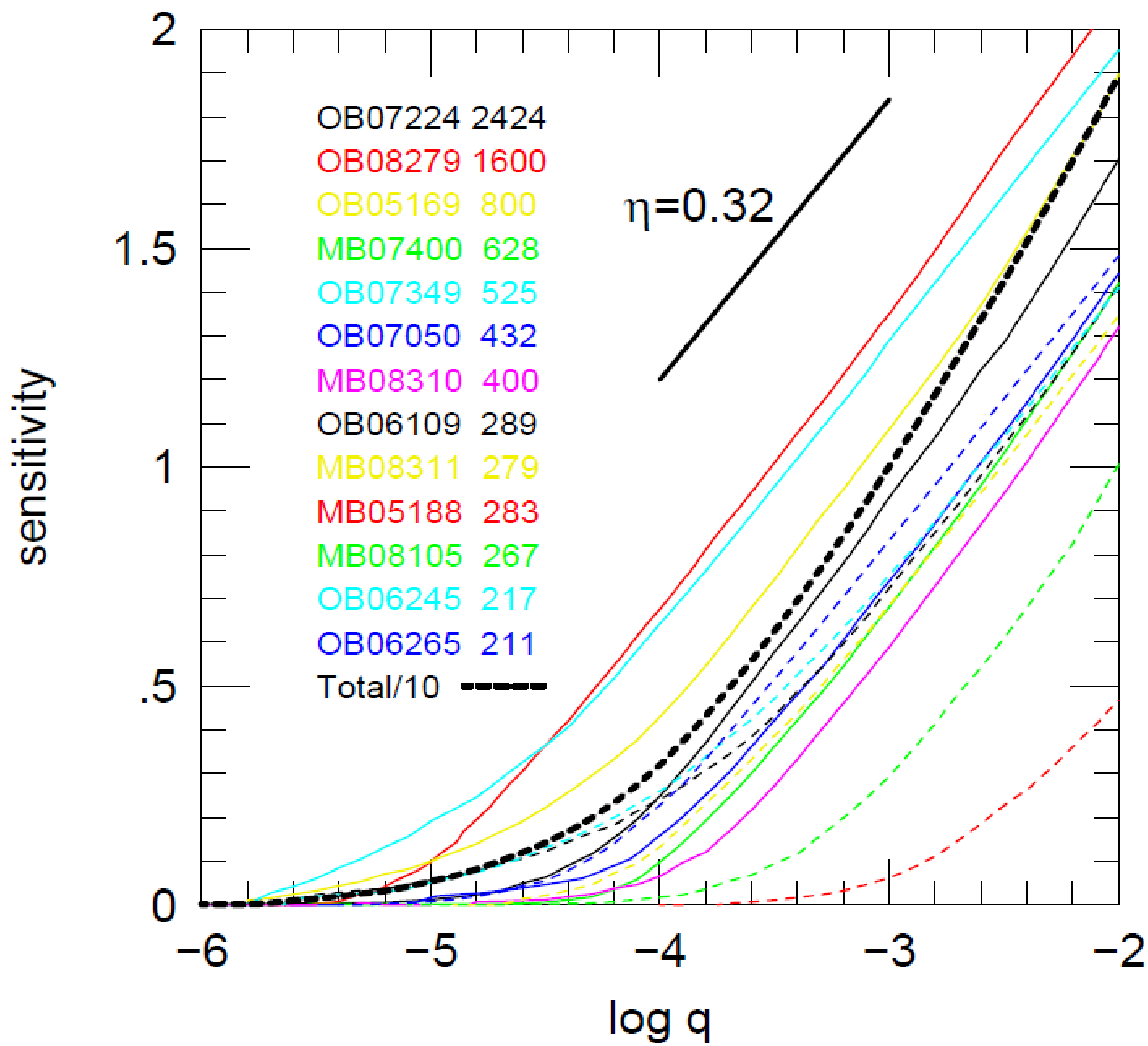


Solar System is Richer than Average

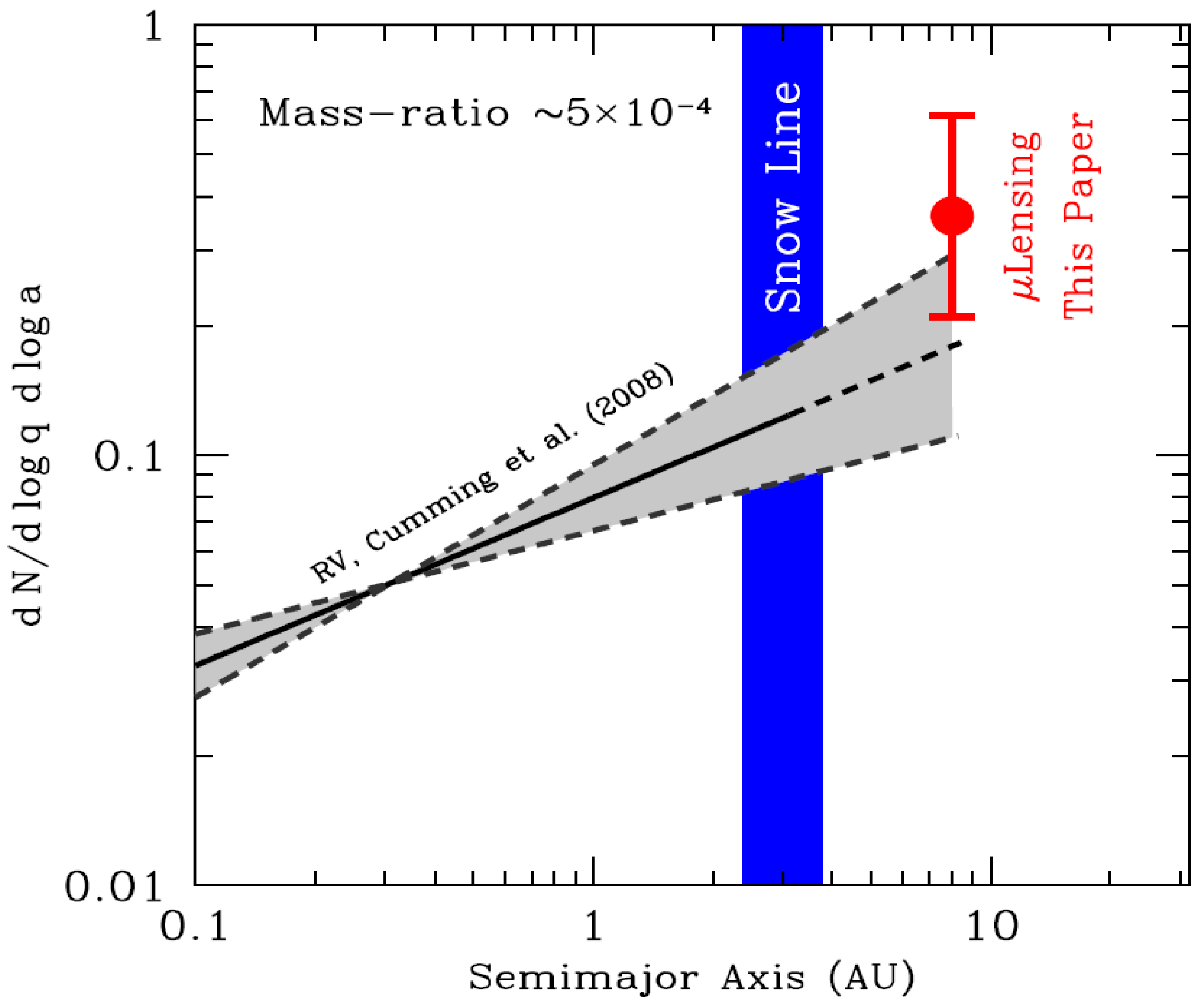
... But Not Dramatically So



Planet Sensitivity Vs. Mass Ratio

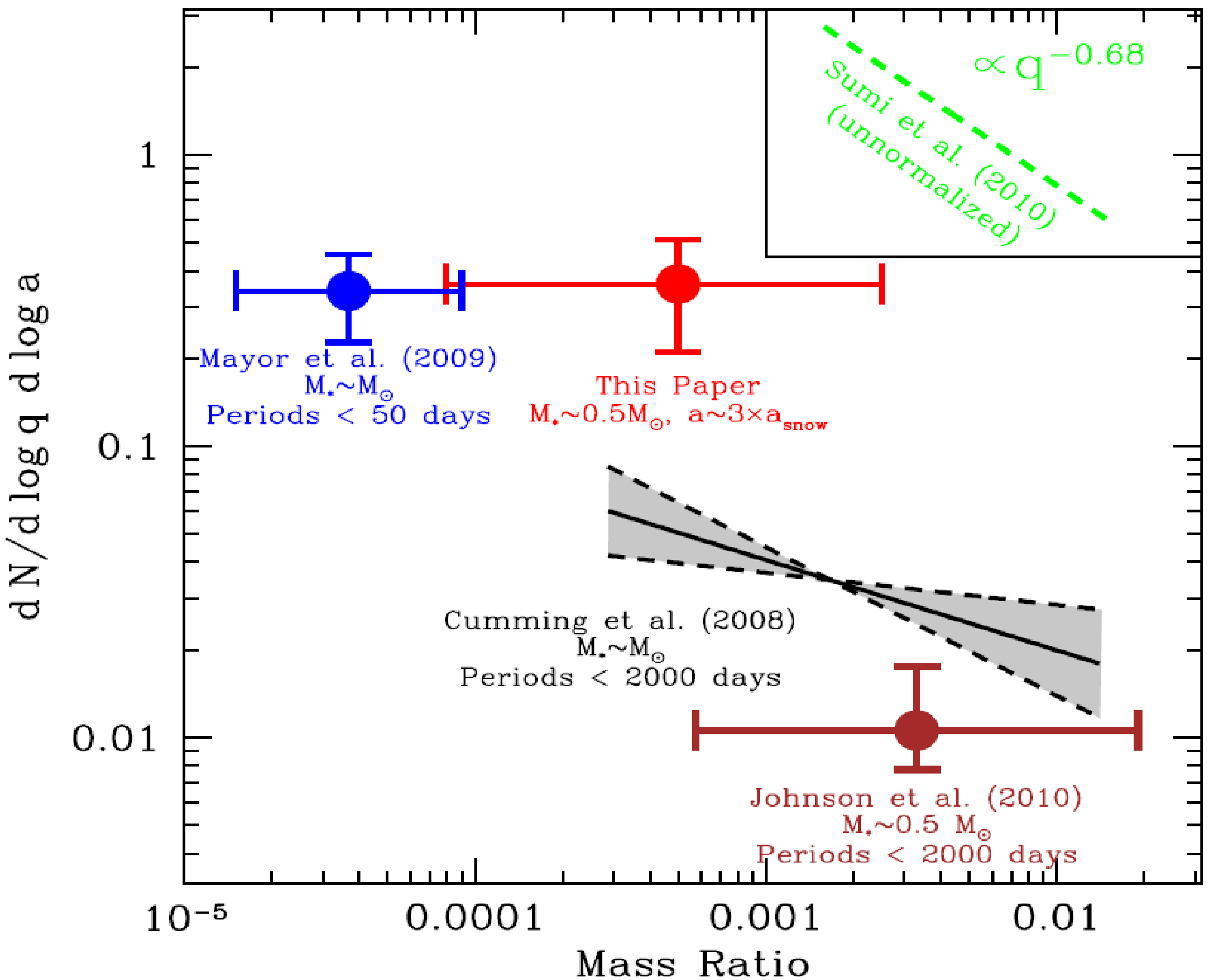


RV & Microlensing
Inside vs Outside Snow Line



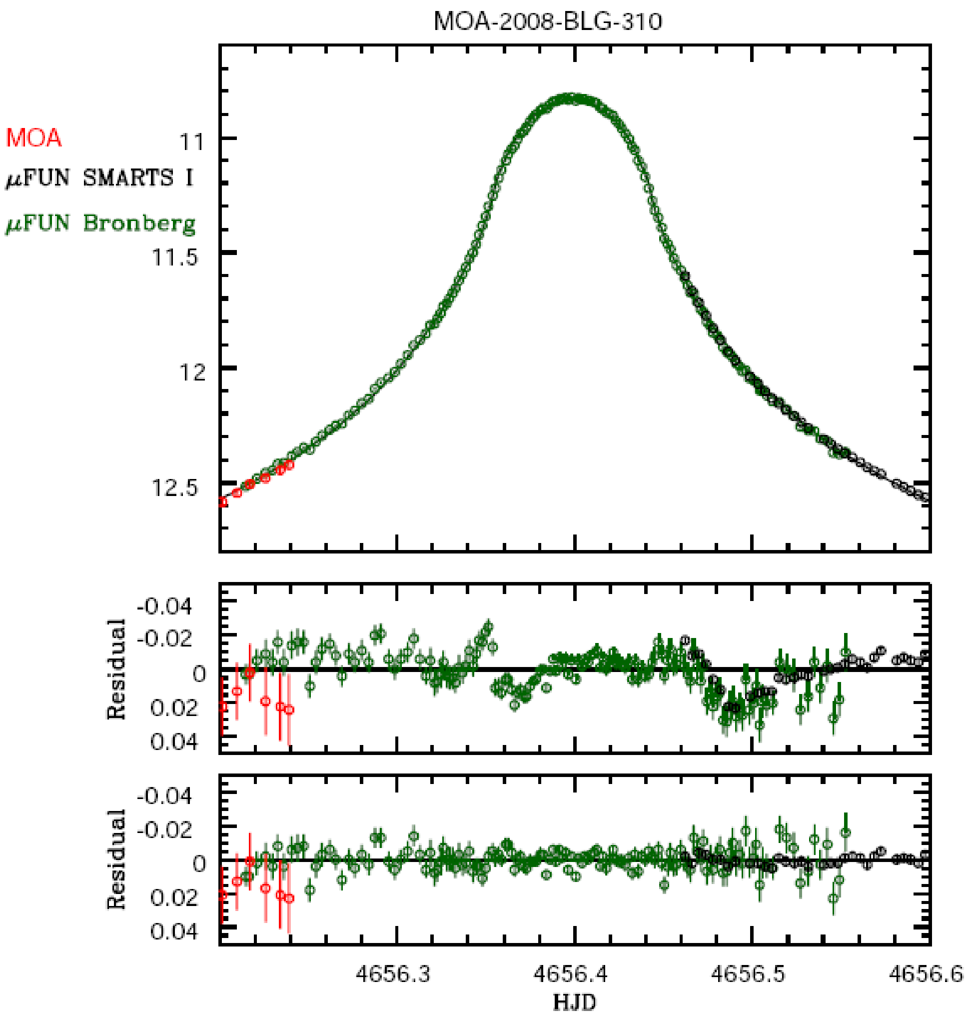
RV & Microlensing

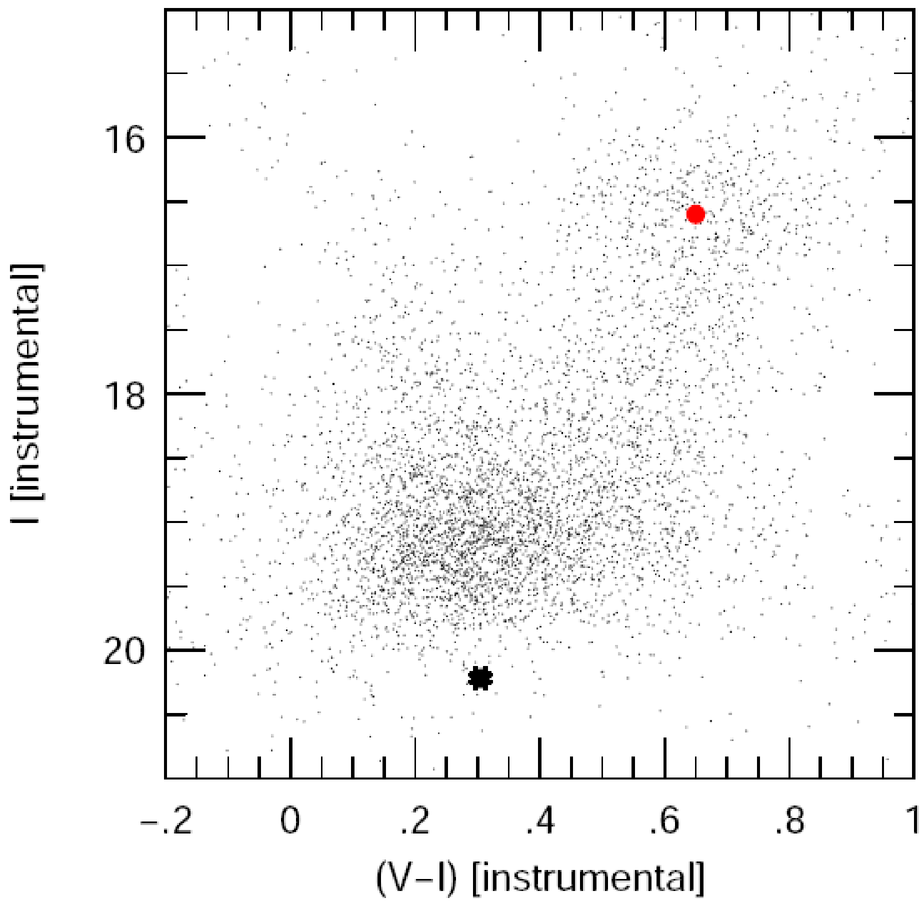
Frequency vs. Mass Ratio



MOA-2008-BLG-310

A Verifiable Bulge Planet?





Janczak et al. 2010, ApJ, in press

Why 5 AU?

$$\tilde{r}_{\rm E} = \frac{\rm AU}{\pi_{\rm E}}; \qquad \pi_{\rm E} = \sqrt{\frac{\pi_{\rm rel}}{\kappa M}}; \qquad \kappa \equiv \frac{4G}{{\rm AU}\, c^2} = 8.1\, \frac{\rm mas}{M_\odot}$$

"Typical" disk lens

$$\tilde{r}_{\rm E} = 5.7\,{\rm AU} \left(\frac{M}{0.5\, M_\odot}\right)^{1/2} \left(\frac{\pi_{\rm rel}}{125\,\mu{\rm as}}\right)^{-1/2}$$

"Typical" bulge lens

$$\tilde{r}_{\rm E} = 16\,{\rm AU} \left(\frac{M}{0.5\, M_\odot}\right)^{1/2} \left(\frac{\pi_{\rm rel}}{16\,\mu{\rm as}}\right)^{-1/2}$$

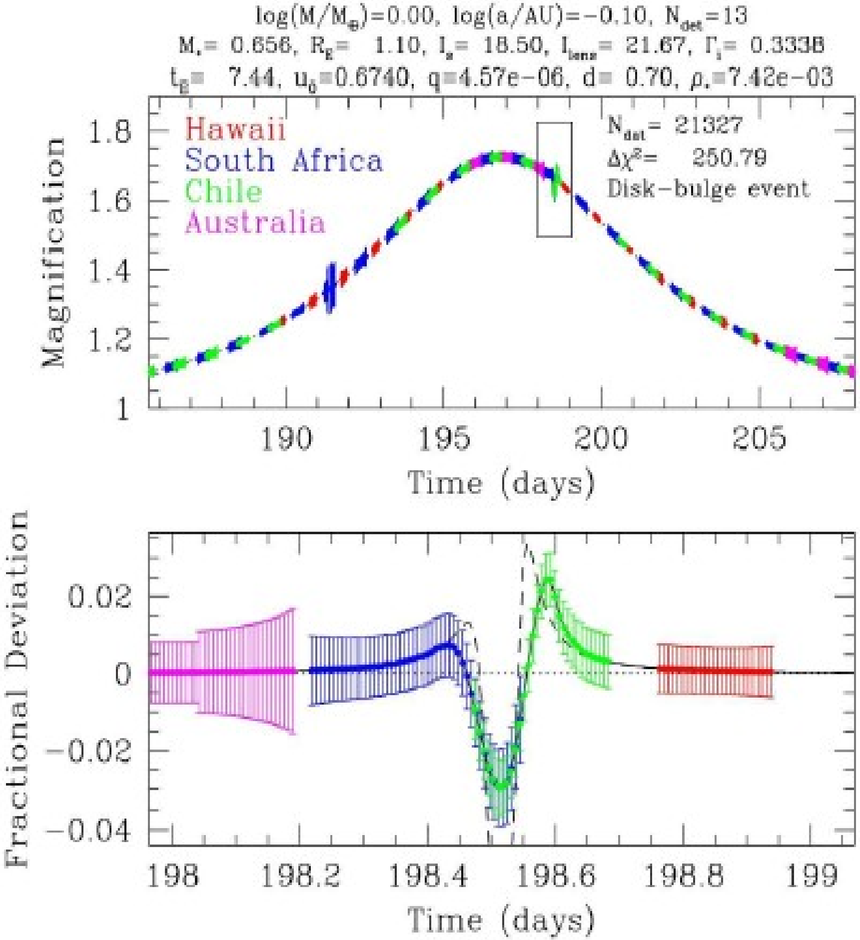
"Extreme" bulge lens

$$\tilde{r}_{\rm E} = 30\,{\rm AU} \left(\frac{M}{0.5\, M_\odot}\right)^{1/2} \left(\frac{\pi_{\rm rel}}{4.5\,\mu{\rm as}}\right)^{-1/2}$$

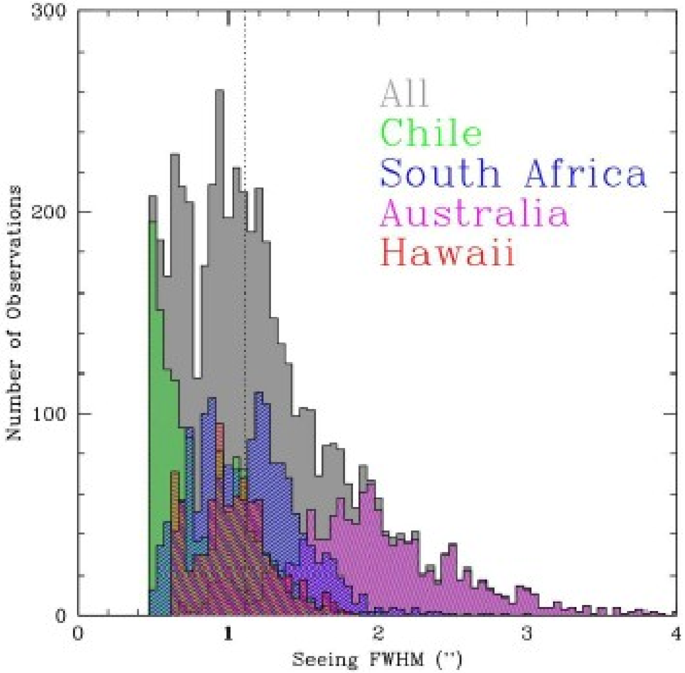
NextGen Microlensing Planet Search

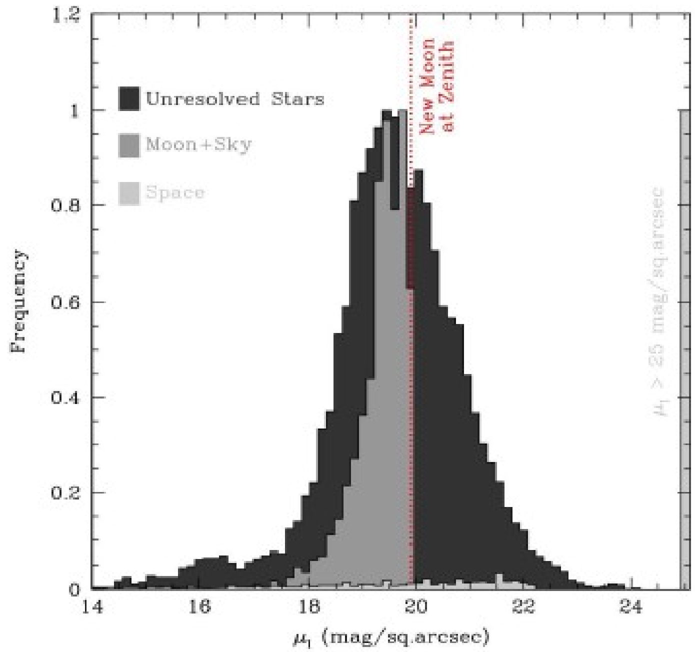
Simulations by Scott Gaudi

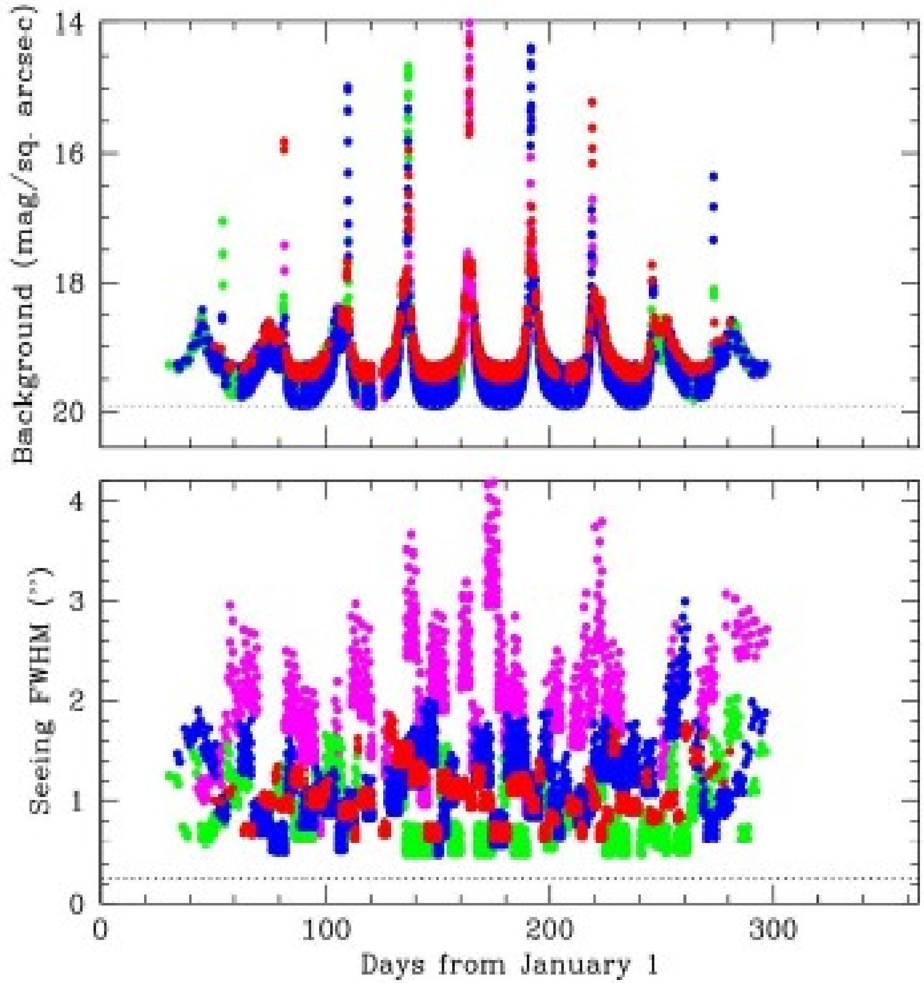
- 4 observatories
- 2m class telescopes
- 4 sq.deg. cameras
- Realistic seeing & weather
- photon-limited statistics down to systematics limit



Simulation Ingredients (abridged)

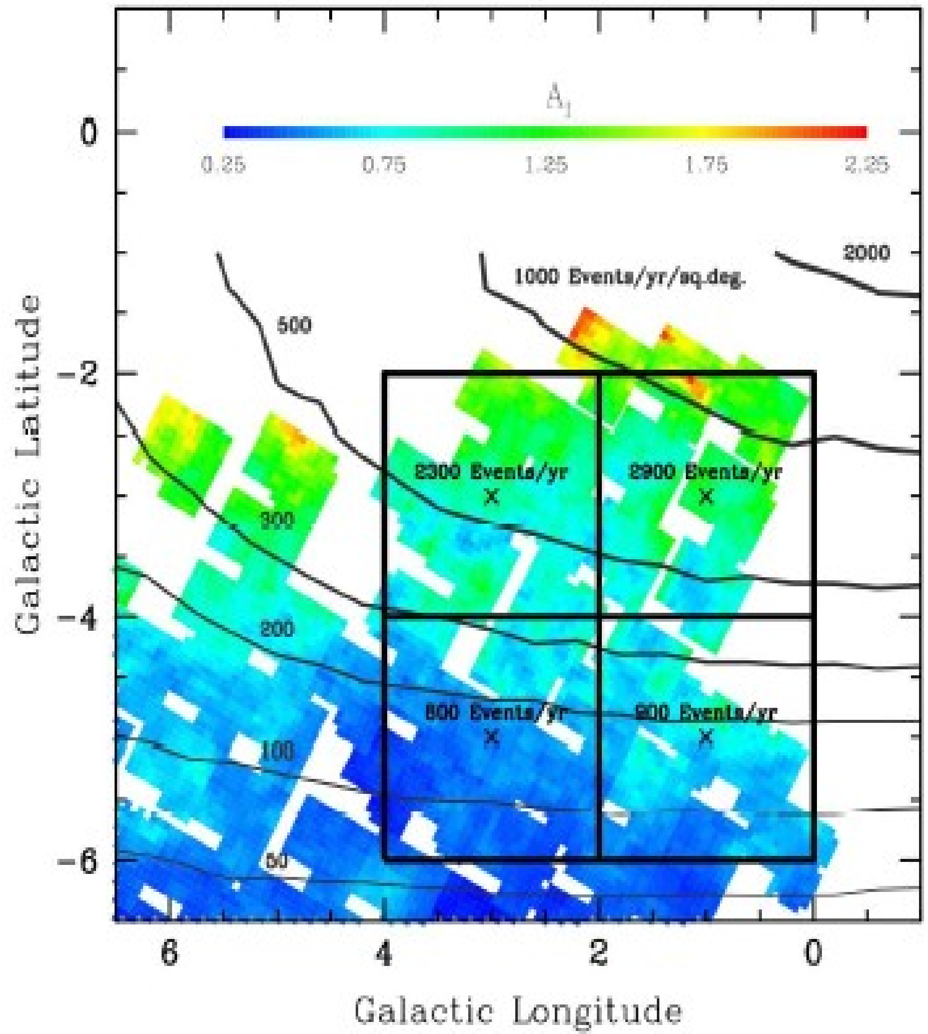


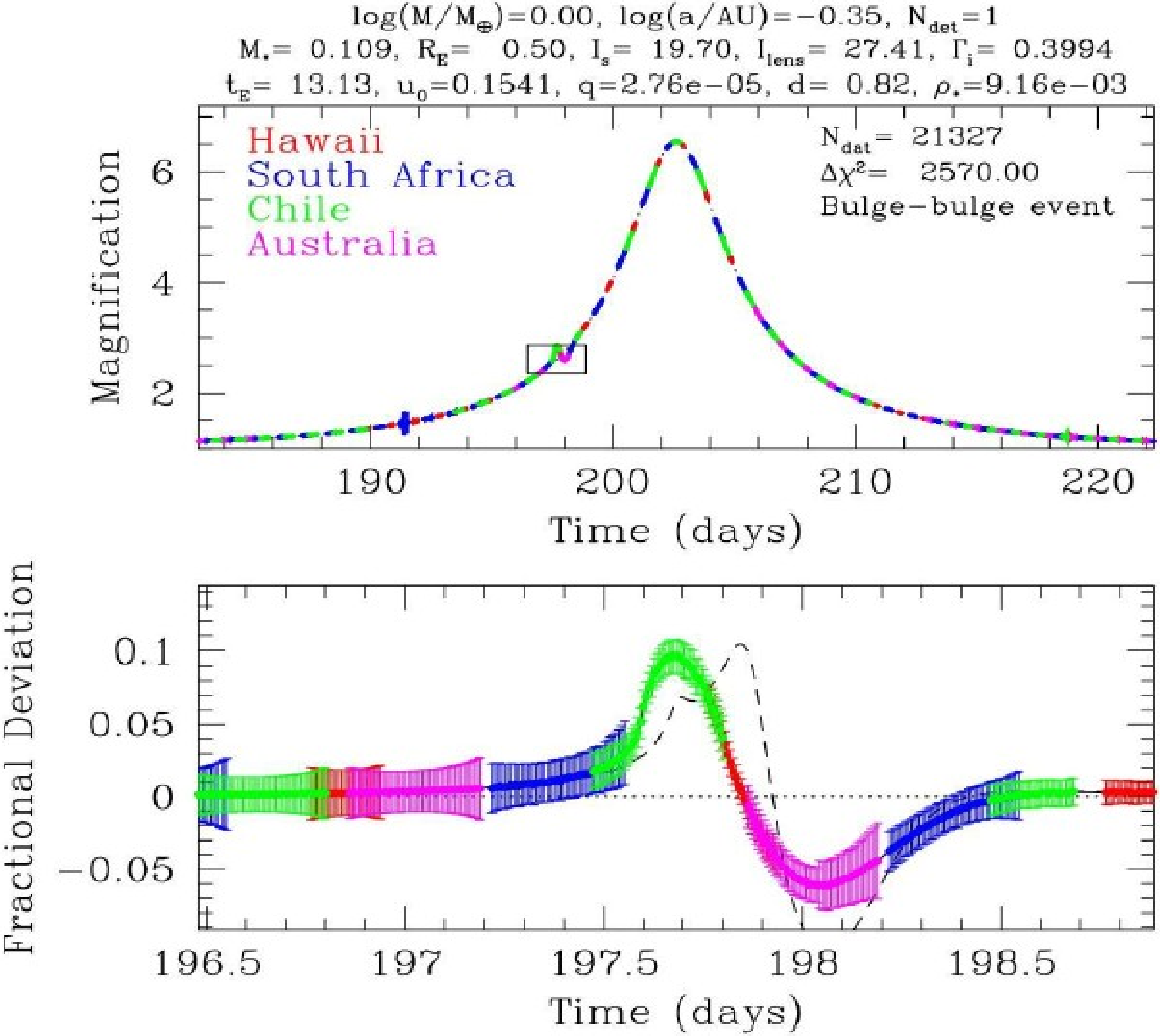




Target Fields

- Four Fields
  - (l,b)=(1,-3)
    - ~2900 Events/yr
  - (l,b)=(3,-3)
    - ~2300 Events/yr
  - (l,b)=(1,-5)
    - ~900 Events/yr
  - (l,b)=(3,-5)
    - ~800 Events/yr





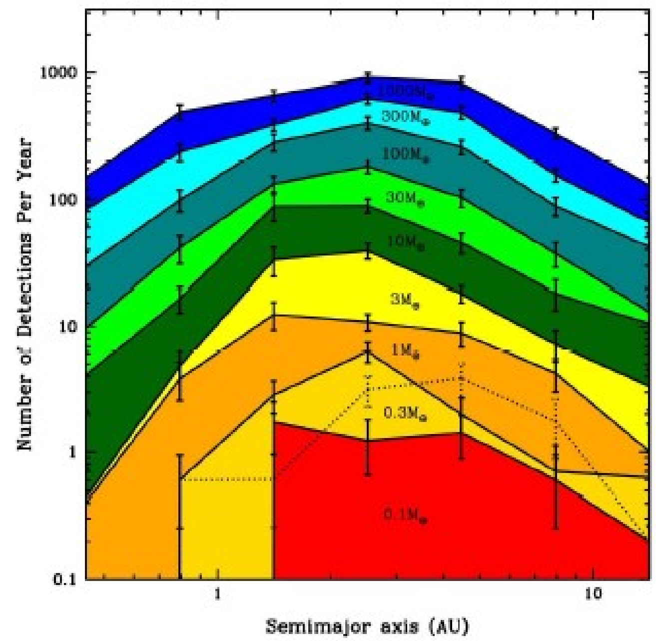
log(M/M⊕)=0.00, log(a/AU)=−0.35, Ndet=1
M*= 0.109, RE= 0.50, Is= 19.70, Ilens= 27.41, Γi= 0.3994
tE= 13.13, u0=0.1541, q=2.76e−05, d= 0.82, ρ*=9.16e−03
Hawaii
South Africa
Chile
Australia
Ndat= 21327
Δχ²= 2570.00
Bulge−bulge event
Magnification
Time (days)
Fractional Deviation
Time (days)

Baseline Results

- Simulate:
  - Mass:

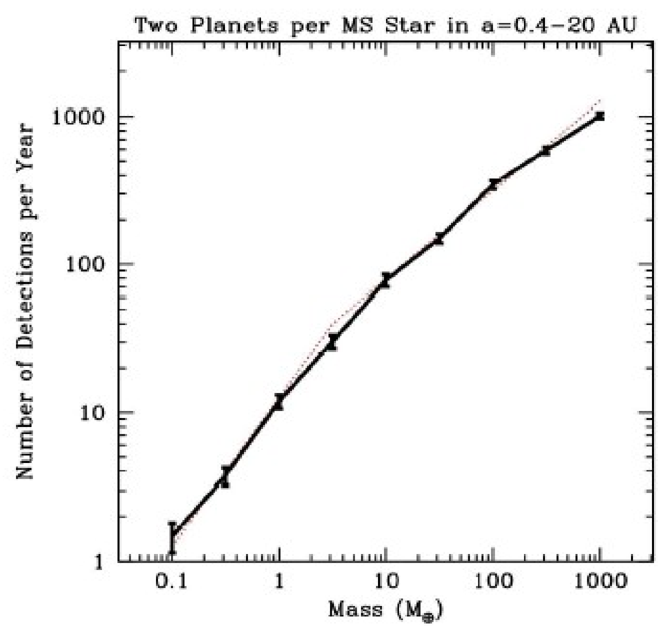
    $\log(M/M_{\oplus})$=-1.0,-0.5, 0.0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0
  - Semimajor Axis:

    $\log(a/AU)$=-0.35, -0.10, 0.15, 0.40, 0.65, 0.90, 1.15



- Average over *a*
  - $-0.35<\log(a/AU)<1.15$
  - Two planets per star

- Scaling with Mass:
  - $N \propto M$ for $M<3M_{\oplus}$
  - $N \propto M^{0.6}$ for $M>3M_{\oplus}$



Summary of Baseline Results

loga/AU)	-0.35	-0.10	0.15	0.40	0.65	0.90	1.15
Γ (yr^{-1})	0.4±0.4	3.8±1.2	12.5±3.1	10.9±1.7	8.8±1.9	4.3±1.2	1.0±0.7

Every MS star has one Earth-mass planet

loga/AU)	-0.35	-0.10	0.15	0.40	0.65	0.90	1.15
Γ (yr^{-1})	0	0.6±0.3	0.6±0.4	3.1±0.9	3.9±1.2	1.8±0.9	0.2±0.2

Every MS star has one Earth mass ratio planet

$\log(M/M_\oplus)$	-1.0	-0.5	0.0	0.5	1.0	1.5	2.0	2.5	3.0
Γ (yr^{-1})	1.5±0.3	3.7±0.5	12±1	30±3	78±8	150±10	350±20	590±30	1012±40

2 planets per star, uniformly distributed in log a in the range 0.4-20 AU

Initiatives

- MOA: 1.8m tel, 2.2 sq.deg camera already exists (New Zealand)
- OGLE: 1.3m tel already exists, currently being upgraded to 1.6 sq.deg. (Chile)
- KOREA: KASI entered national competition. Dec 2008: Korean Congress approved US$30M for three 2m tels, with 4 sq.deg cameras (Africa South America, Australia) [KMTNet]

Conclusions

- μlensing planets now found “routinely”
  - Now 3 per year
- Some planet distances are measured
  - Contrary to initial expectations
- Bulge lens IDs require satellite at 5 AU
  - Expected to contain MOST planets
- NextGen experiments will increase 10-fold
  - MOA/OGLE/KMTNet