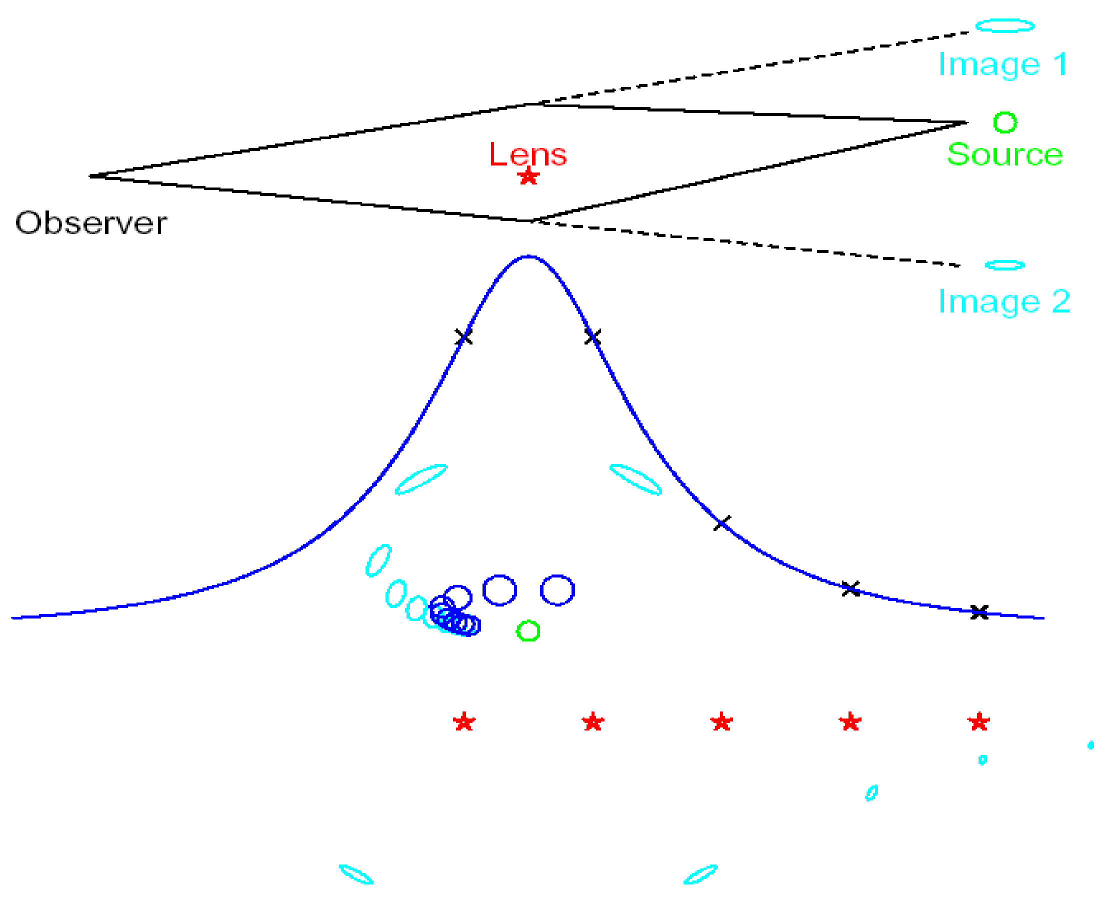
Microlensing Planets:

Probing the Extremes of Parameter Space

From Einstein's Putdown to Modern Surveys

Andy Gould (OSU)



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]

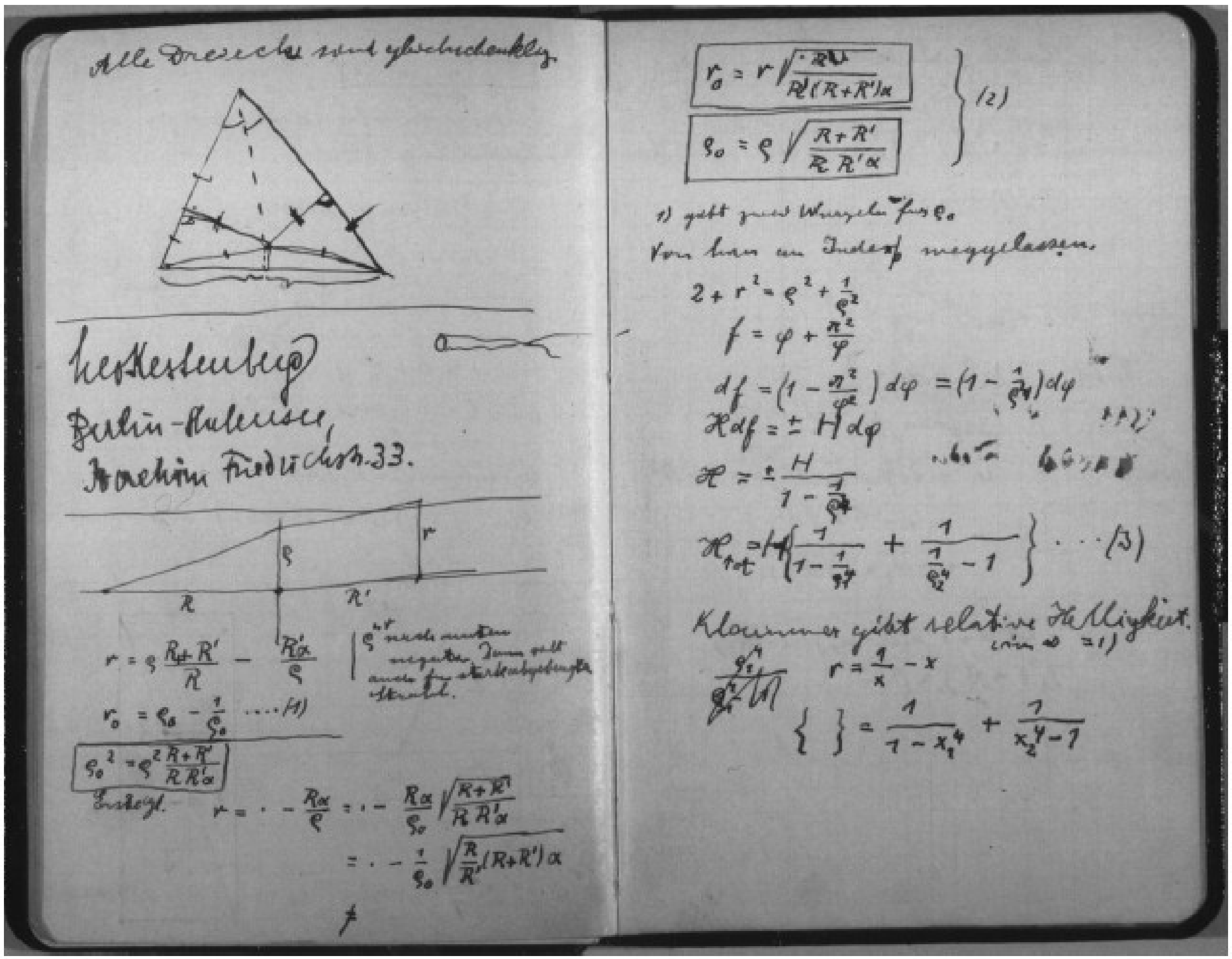
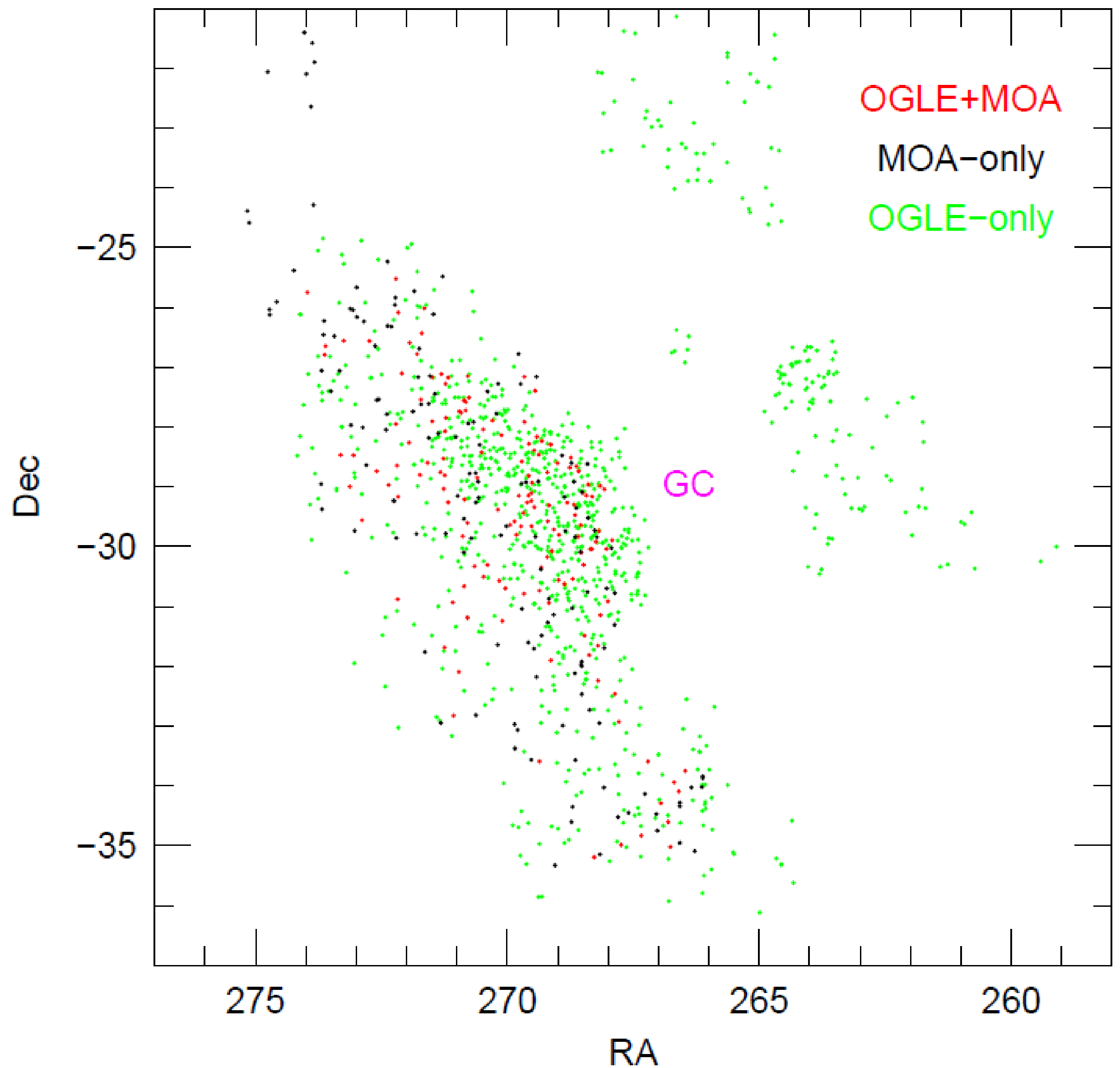


Fig. 1. Notes about gravitational lensing dated to 1912 on two pages of Einstein's scratch notebook (*12*). [Reproduced with permission of the Einstein Archives, Jewish National and University Library, Hebrew University of Jerusalem]

1136 Events (1st half of 2011)

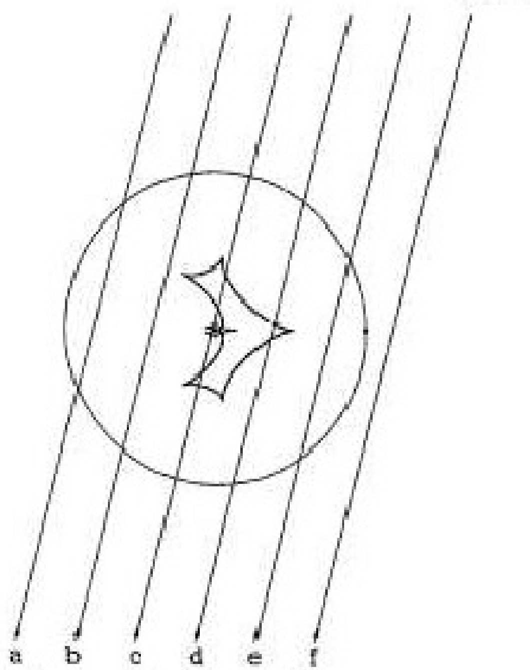


Mao & Paczynski

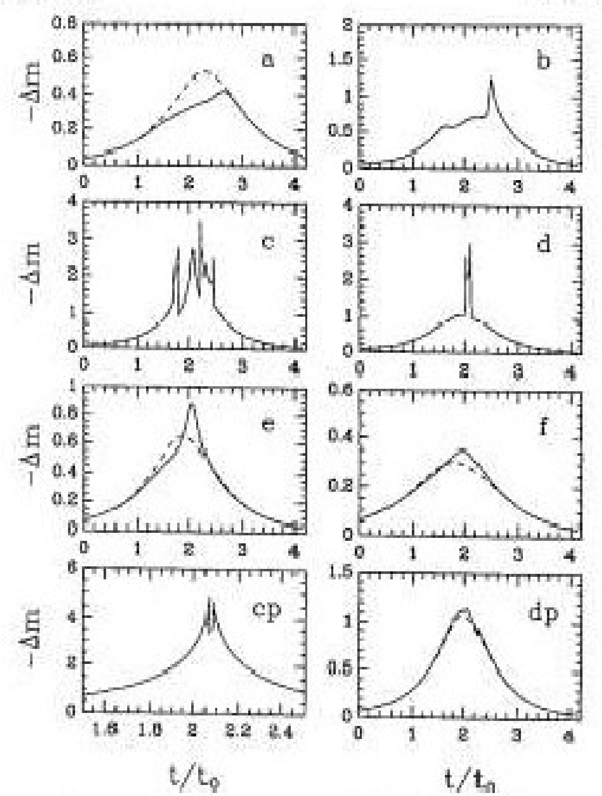
Microlens Planet Searches

GRAVITATIONAL MICROLENSING BY DOUBLE STARS AND PLANETARY SYSTEMS

SHUDE MAO AND BOHDAN PACZYŃSKI
Princeton University Observatory, Princeton, NJ 08544
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



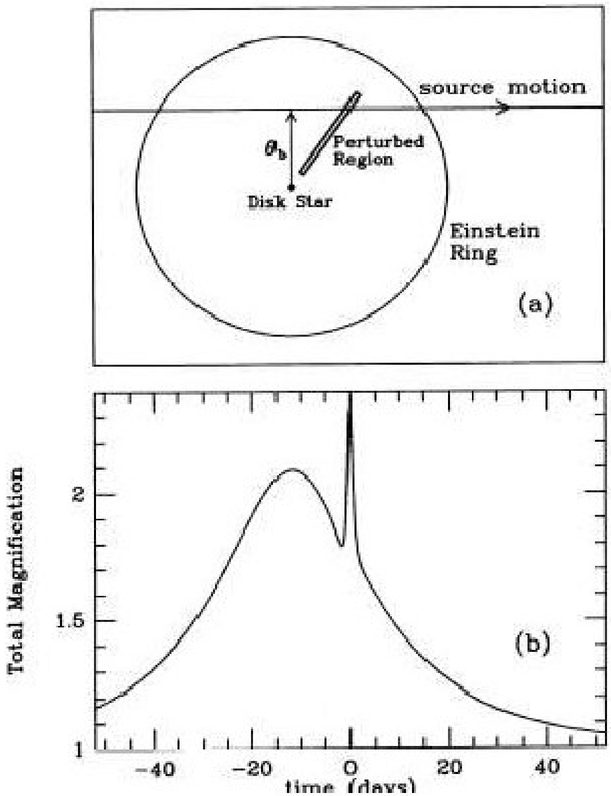
the lens. The effect is strong even if the companion is a planet. A massive search for microlensing of the Galactic bulge stars may lead to a discovery of the first extrasolar planetary systems.

Gould & Loeb

Survey + Follow-Up

DISCOVERING PLANETARY SYSTEMS THROUGH GRAVITATIONAL MICROLENSES

ANDREW GOULD AND ABRAHAM LOEB
Institute for Advanced Study, Princeton, NJ 08540
Received 1991 December 26; accepted 1992 March 9



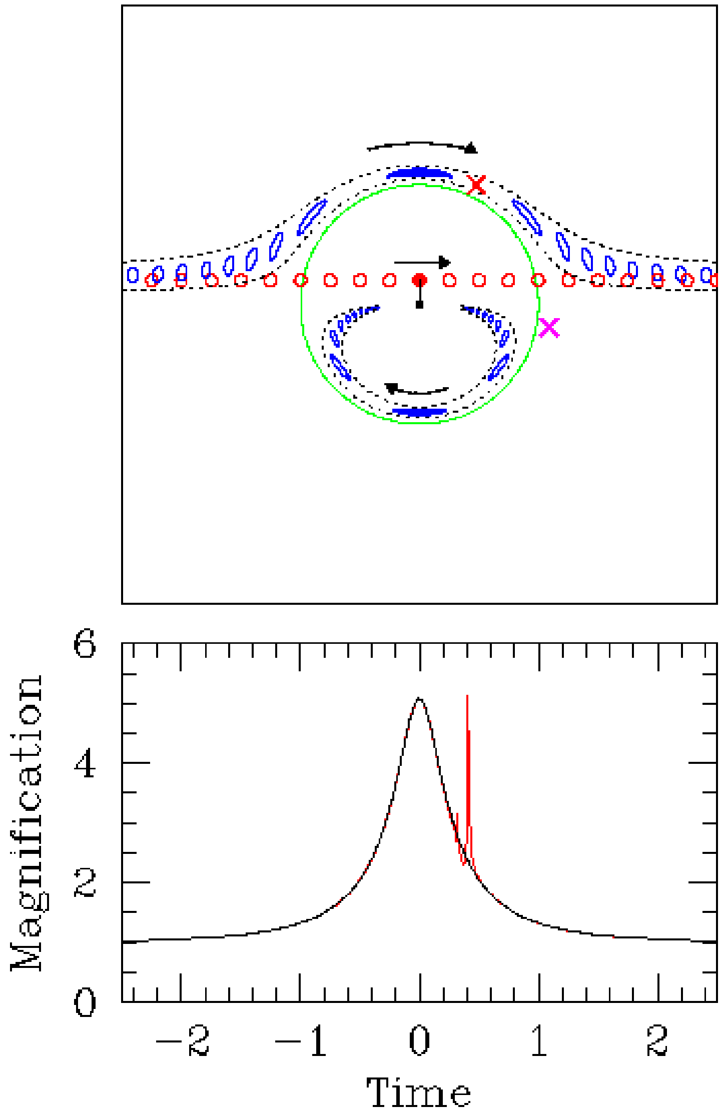
5. OBSERVATIONAL REQUIREMENTS

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,

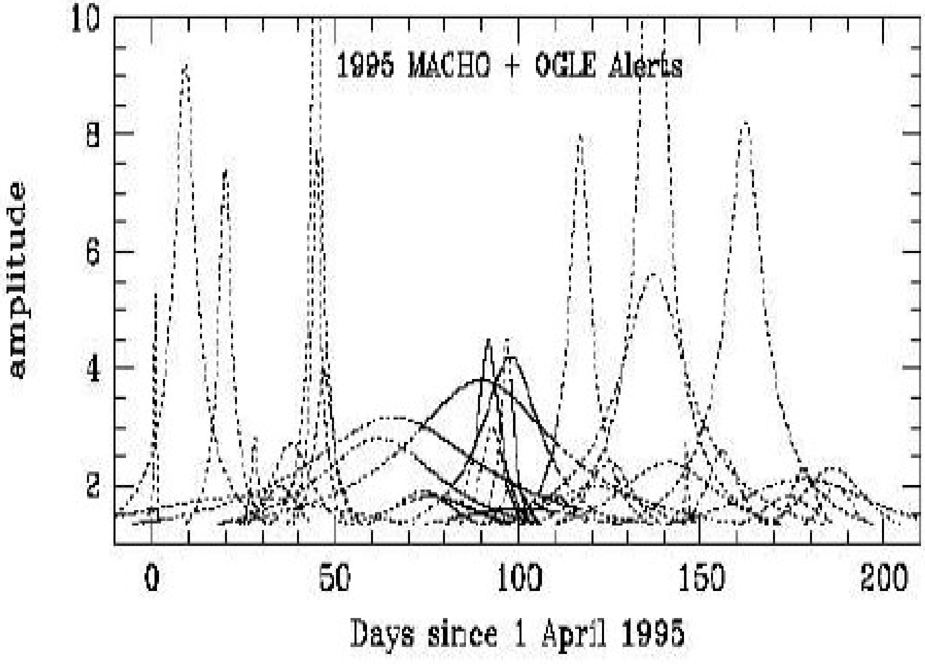
two telescopes that were totally committed. Third, in view of the fleeting nature of the events, it would seem prudent to build in some redundancy in case of bad weather at a particular site. Thus, the optimal scheme would employ, say, a dozen telescopes. Each of these would be committed to carry out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

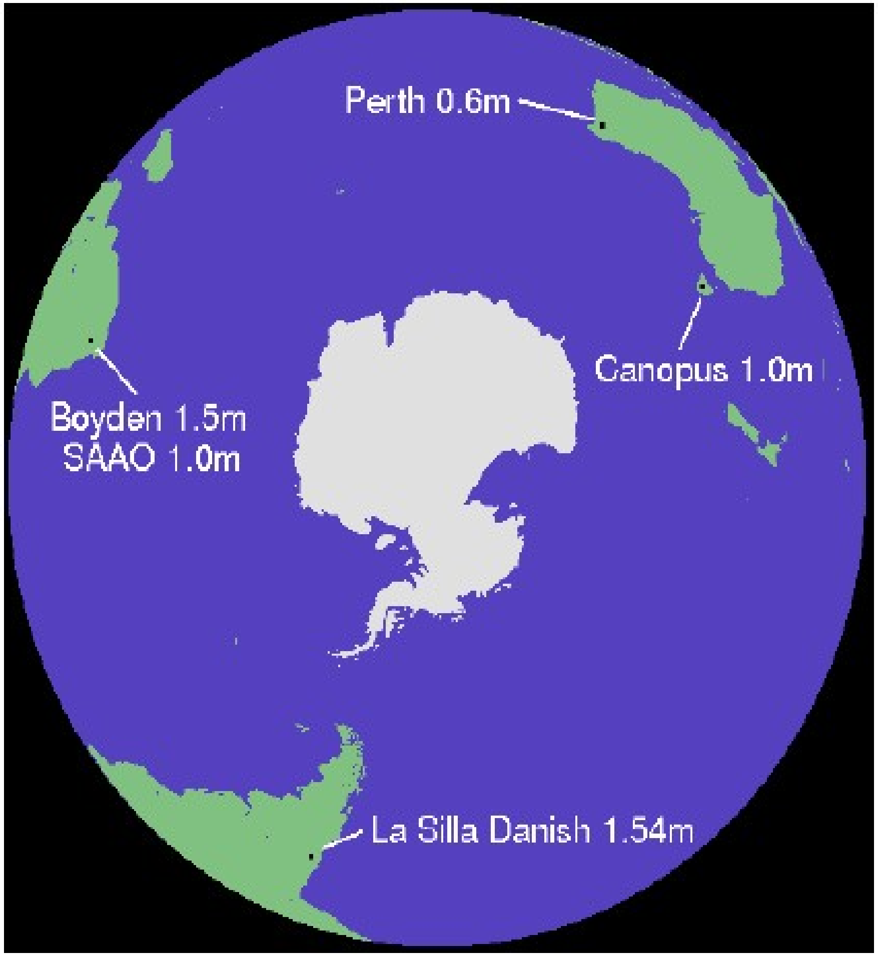
How Microlensing Finds Planets



1995 PLANET Pilot Season

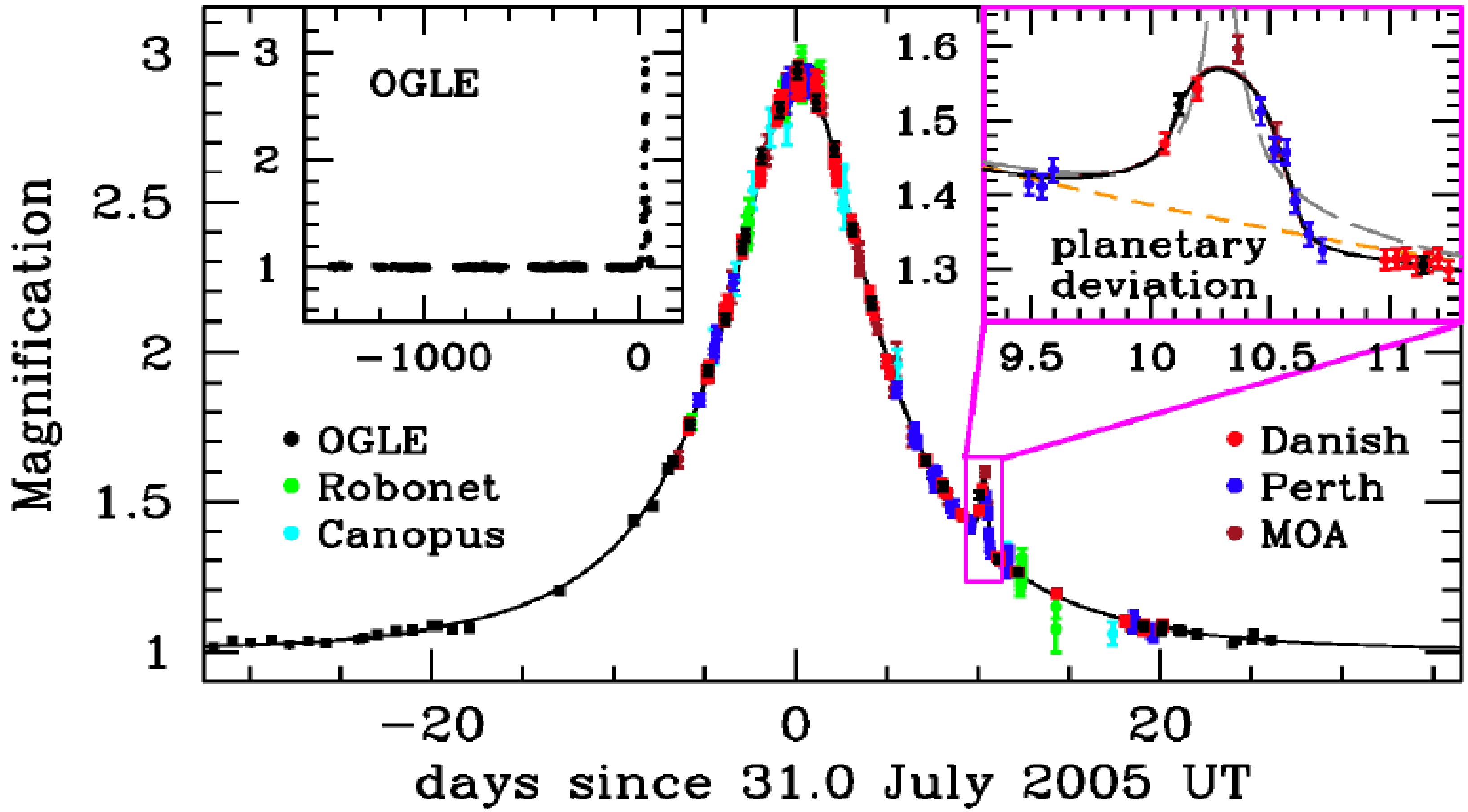
- Albrow et al. 1998 ApJ, 509, 687





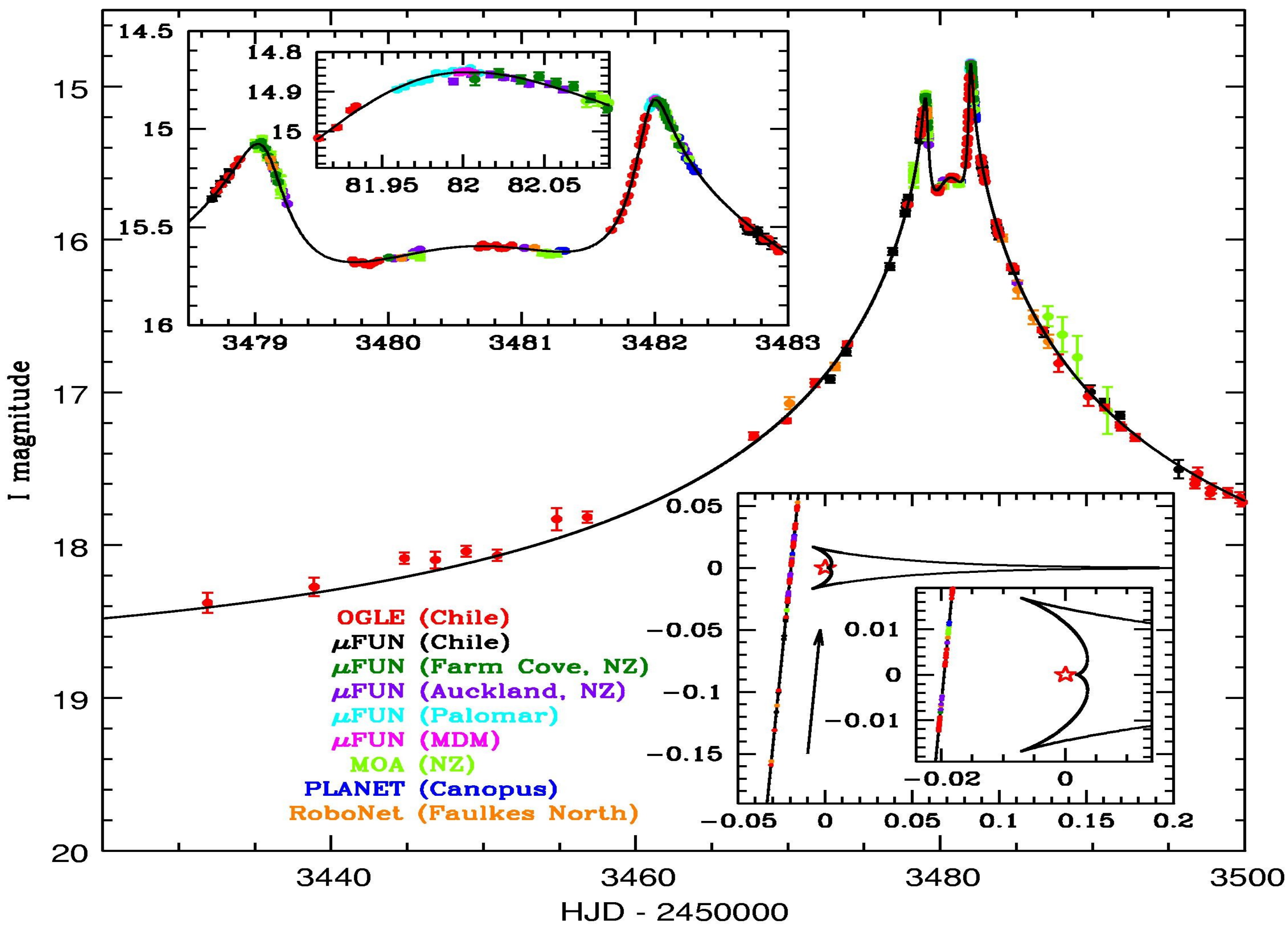
OGLE-2005-BLG-390

"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."

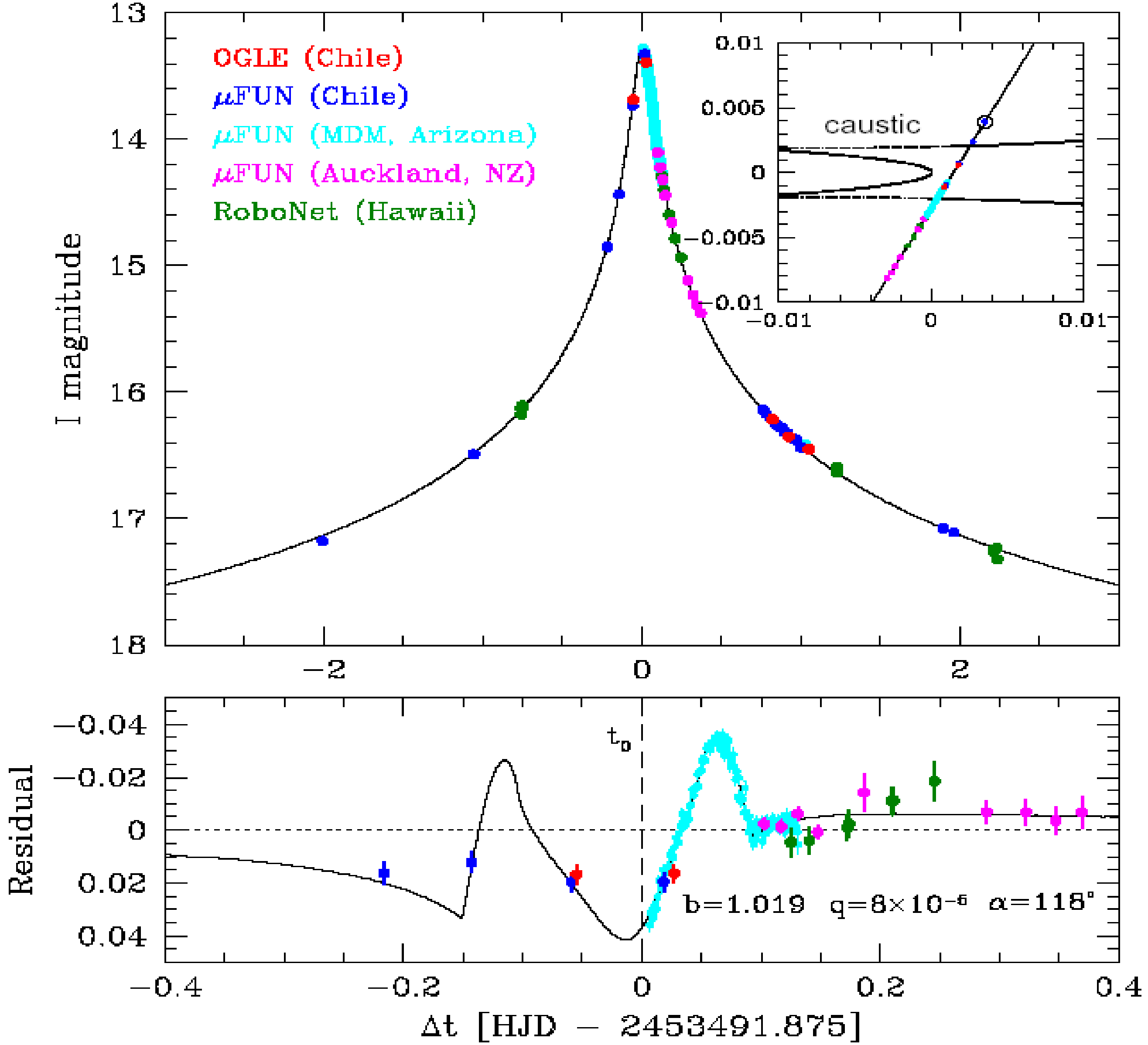
Jennie McCormick

(Amateur Astronomer, Auckland, New Zealand)

μFUN Observing Stations

+12 Auckland	NZ (Grant Christie)
+12 Farmcove	NZ (Jennie McCormick)
+12 Auckland	NZ (David Moorhouse & Guy Thornley)
+12 Nelson	NZ (Robert Rea)
+12 Patutahi	NZ (John Drummond)
+12 Blenheim	NZ (Bill Allen)
+10 Canberra	AU (David Higgins)
+08 Perth	AU (Greg Bolt)
+02 Pretoria	SA (Berto Monard)
+02 Wise	Israel
−04 CTIO	Chile
−04 CAO	Chile (Franco Mallia)
−07 Mt Lemon	AZ US
−07 MDM	AZ US
−07 Hereford	AZ US (Bruce Gary)
−08 Palomar	CA US
−10 Southern Stars	Tahiti (Roland Santallo)

OGLE-2005-BLG-169: Second Cold Neptune



Deokkeun An

Tale of Two Planets

OGLE-2005-BLG-390

- q = 8e-5
- M_* = 0.2 M_sun
- M_p = 5.5 M_earth
- D = 7 kpc
- a = 3 AU
- T = 50 K
- Low-mag Event
- (1 det)/(4.4 probed)

OGLE-2005-BLG-169

- q = 8e-5
- M_* = 0.5 M_sun
- M_p = 13 M_earth
- D = 3 kpc
- a = 4 AU
- T = 70 K
- High-mag Event
- (1 det)/(2.25 probed)

==> "Cold Neptunes Are Common"

The Astrophysical Journal, 644:L37–L40, 2006 June 10

MICROLENS OGLE-2005-BLG-169 IMPLIES THAT COOL NEPTUNE-LIKE PLANETS ARE COMMON

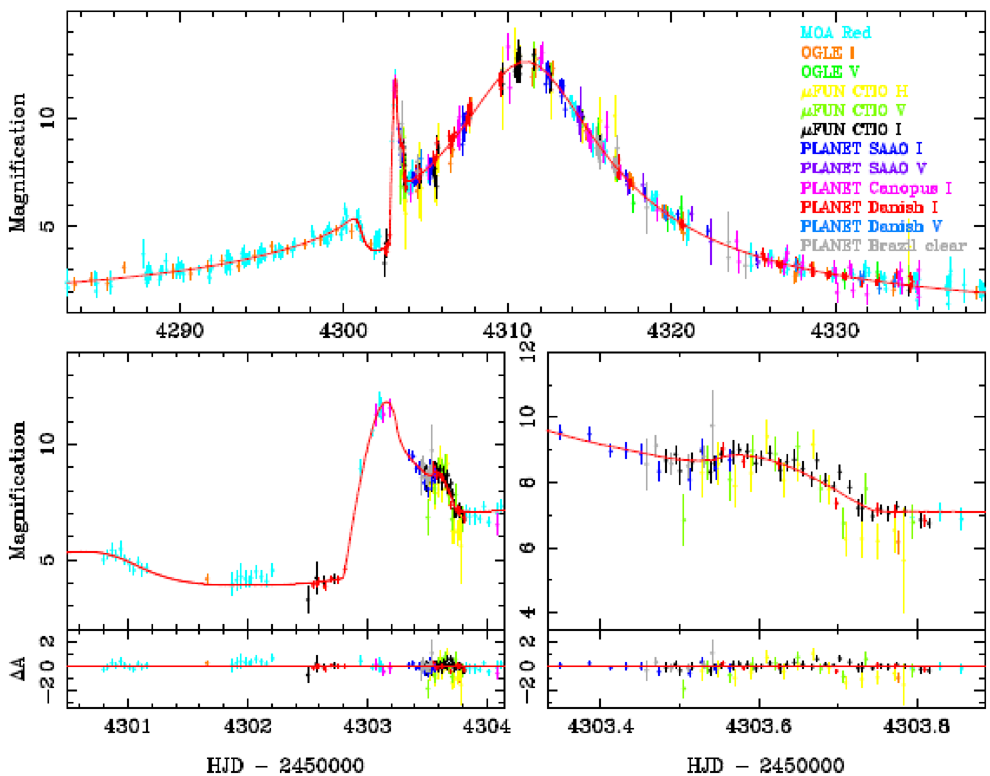
A. Gould,[1,2] A. Udalski,[3,4] D. An,[1,2] D. P. Bennett,[5,6,7] A.-Y. Zhou,[8] S. Dong,[1,2] N. J. Rattenbury,[5,9] B. S. Gaudi,[1,10] P. C. M. Yock,[5,11] I. A. Bond,[5,12] G. W. Christie,[1,13] K. Horne,[6,14,15] J. Anderson,[16] K. Z. Stanek,[1,2] D. L. DePoy,[1,2] C. Han,[1,17] J. McCormick,[1,18] B.-G. Park,[1,19] R. W. Pogge,[1,2] S. D. Poindexter,[1,2] I. Soszyński,[3,4,20] M. K. Szymański,[3,4] M. Kubiak,[3,4] G. Pietrzyński,[3,4,20] O. Szewczyk,[3,4] Ł. Wyrzykowski,[3,4,21] K. Ulaczyk,[3,4] B. Paczyński,[3,22] D. M. Bramich,[6,14,21] C. Snodgrass,[14,23] I. A. Steele,[14,24] M. J. Burgdorf,[14,24] M. F. Bode,[14,24] C. S. Botzler,[5,11] S. Mao,[9] and S. C. Swaving[5,11]
Received 2006 March 10; accepted 2006 April 27; published 2006 May 24

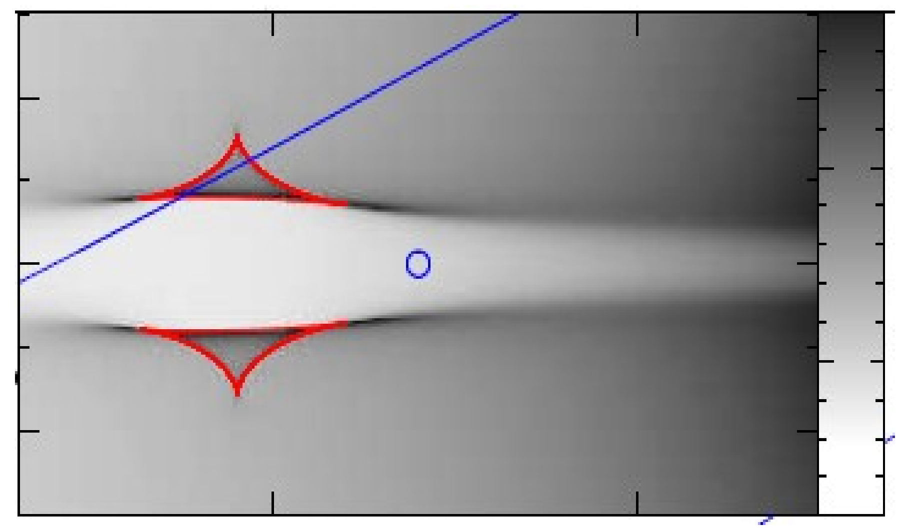
ABSTRACT

We detect a Neptune mass ratio ($q \simeq 8 \times 10^{-5}$) planetary companion to the lens star in the extremely high magnification ($A \sim 800$) microlensing event OGLE-2005-BLG-169. If the parent is a main-sequence star, it has mass $M \sim 0.5\ M_{\odot}$, implying a planet mass of $\sim 13\ M_{\oplus}$ and projected separation of ~2.7 AU. When intensely monitored over

OGLE-2007-BLG-368:

Cold Neptune #3

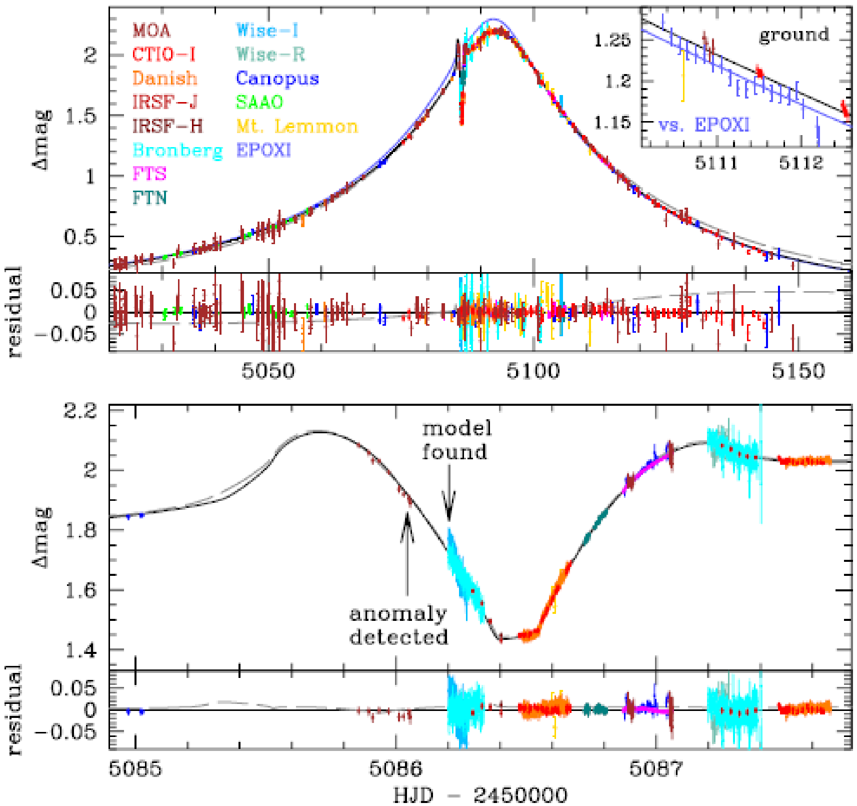


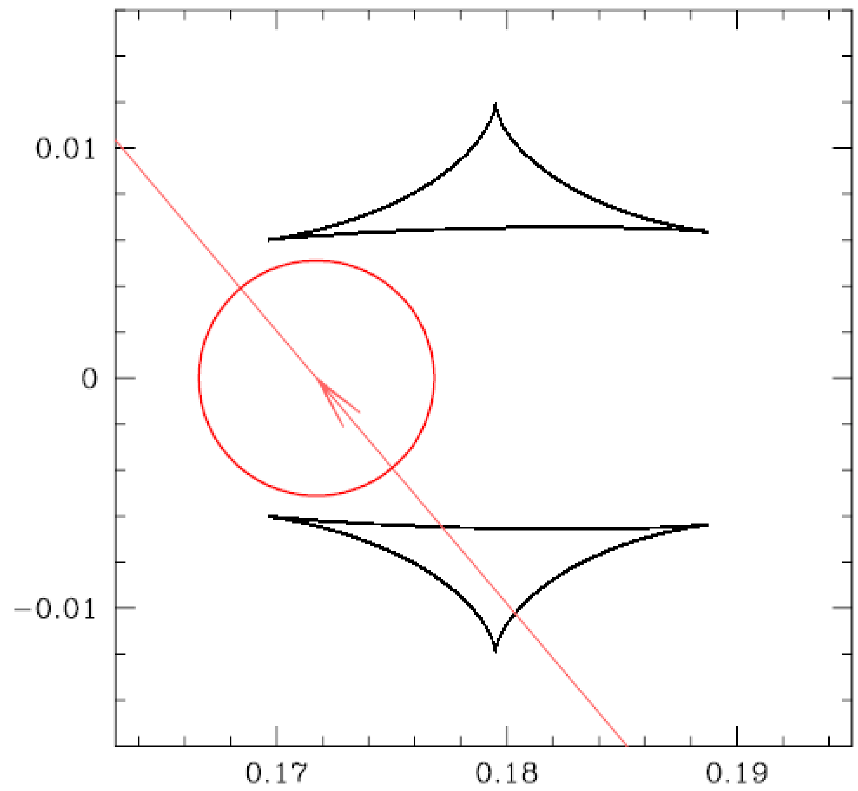


Sumi et al. 2010, ApJ, 710, 1641

MOA-2009-BLG-266:

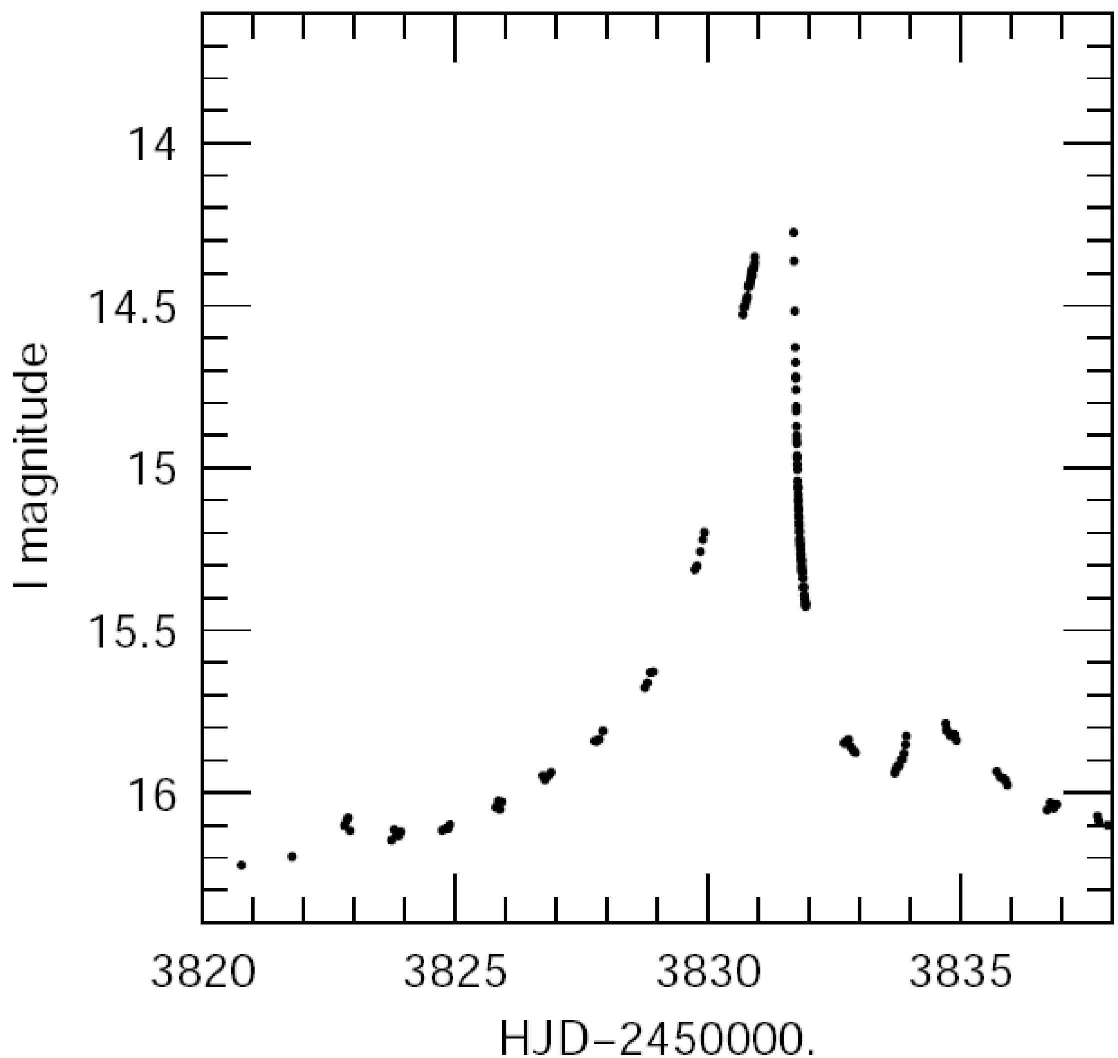
Cold Neptune #4





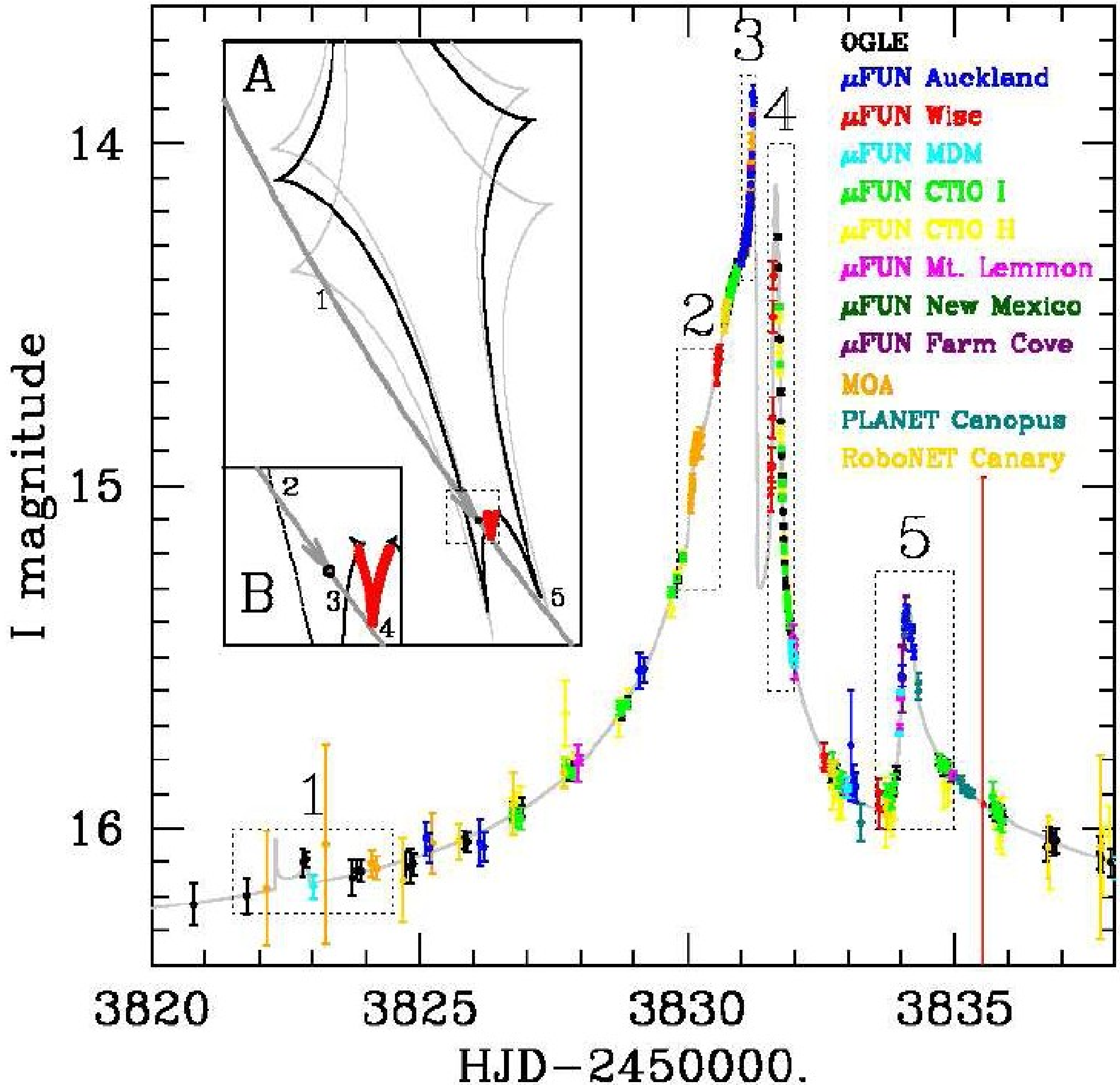
Muraki et al. 2011, ApJ, submitted

OGLE-2006-BLG-109:
Without Followup Observations



OGLE-2006-BLG-109

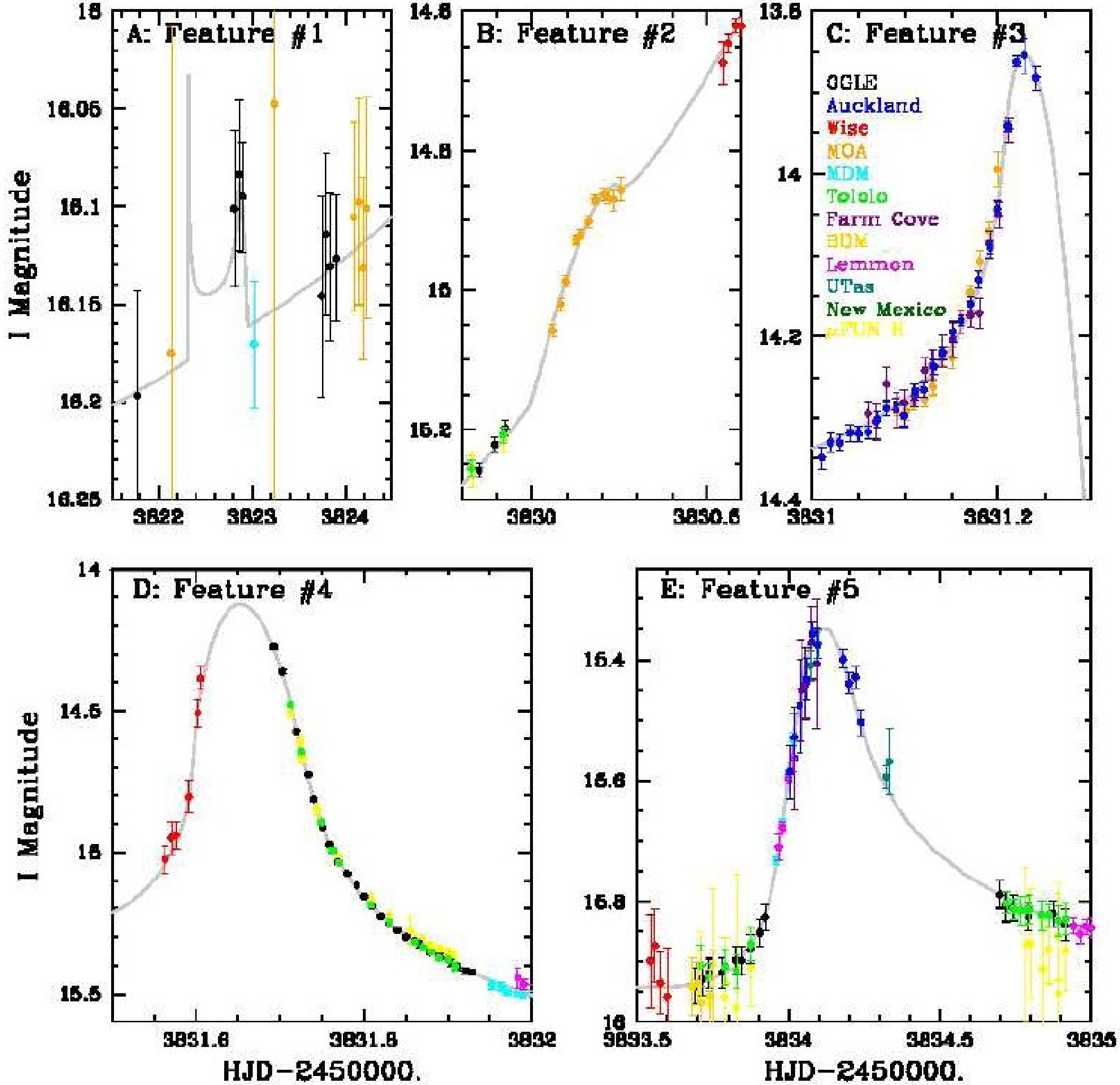
Parallax+Finite-Source+Rotation+Blend



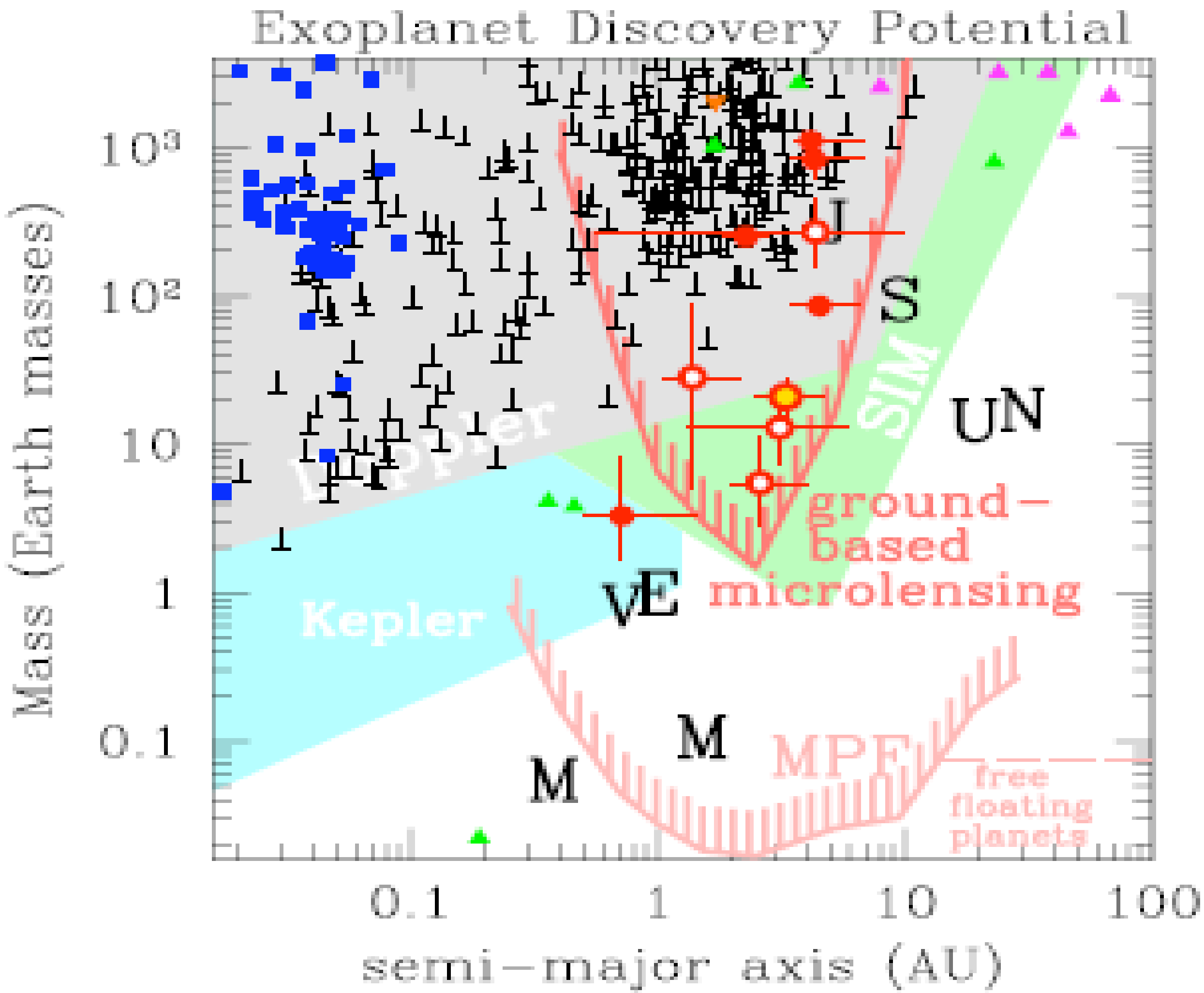
Gaudi et al. 2008, Science, 319, 927

Five Lightcurve Features

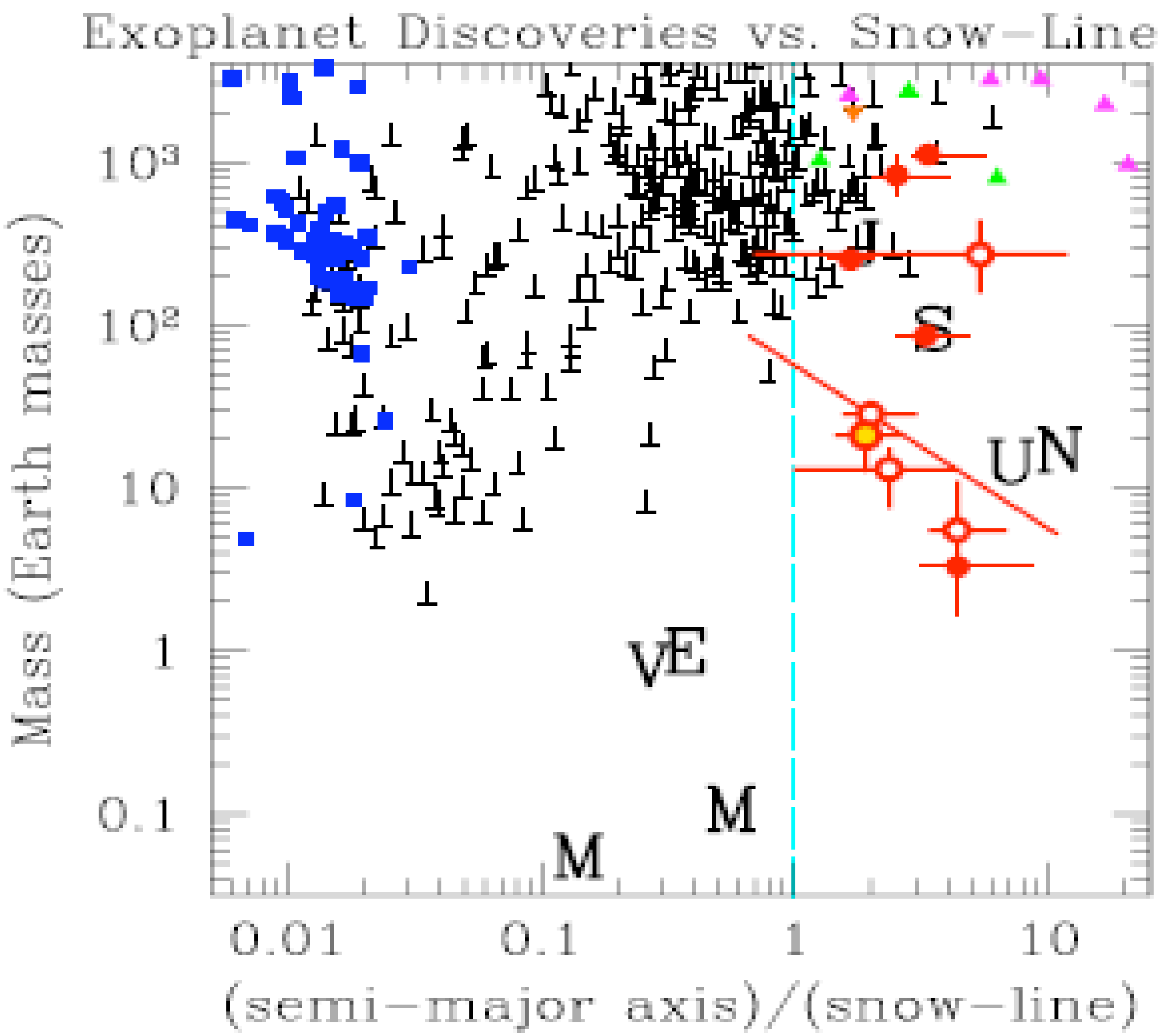
1+2+3+5=Saturn   4=Jupiter



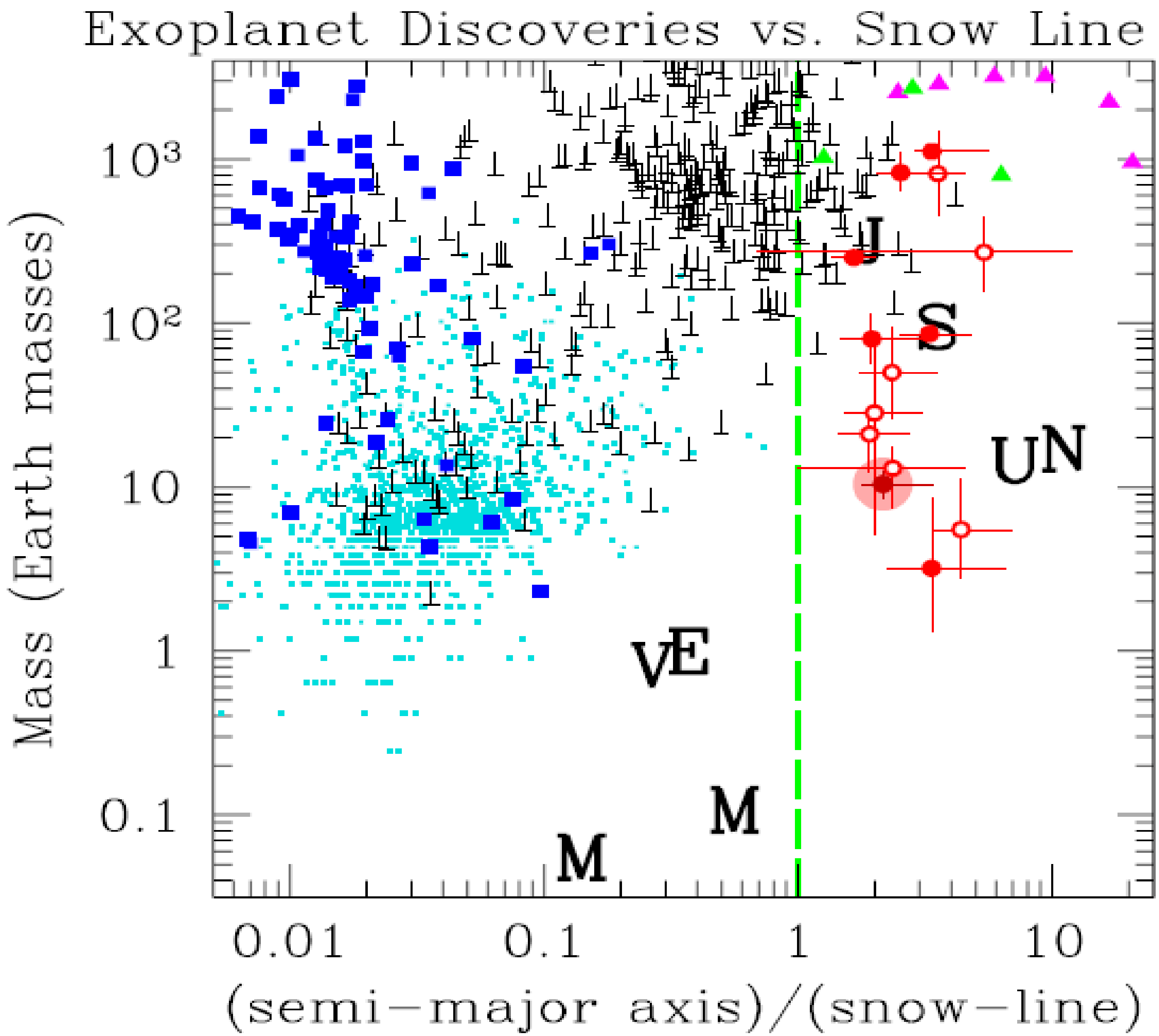
Planets 2010



Planets 2010

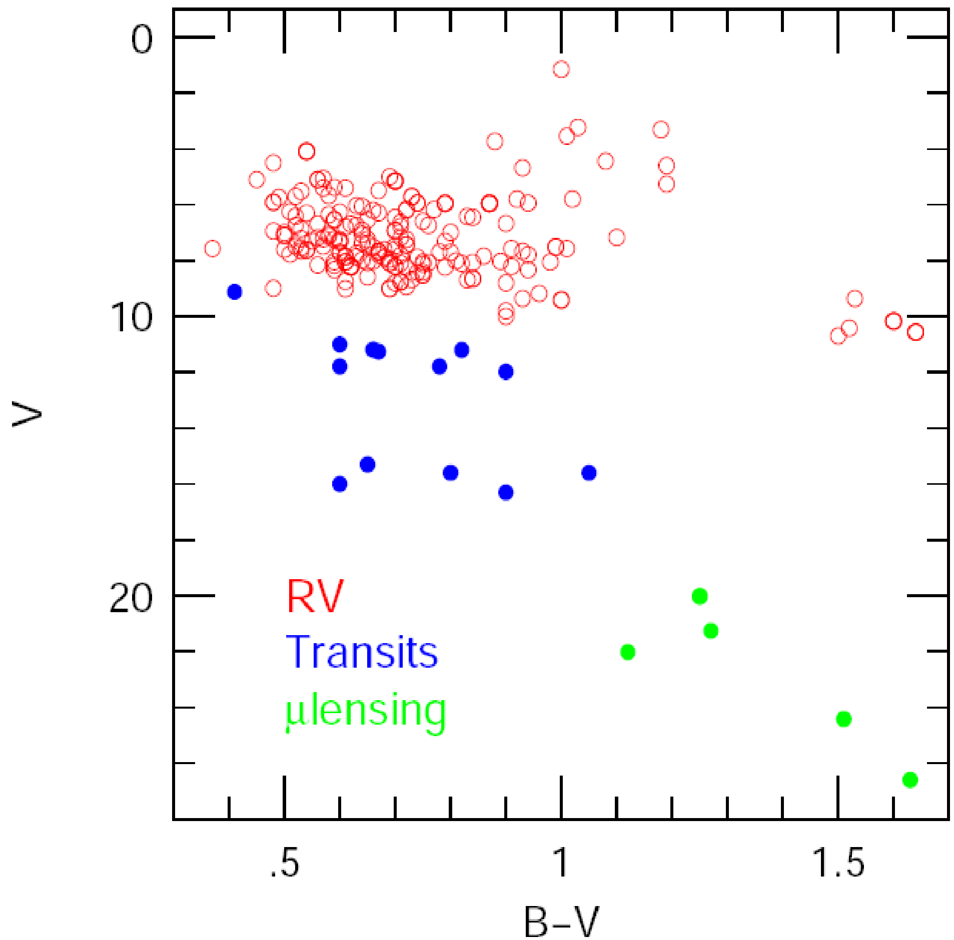


Planets 2011



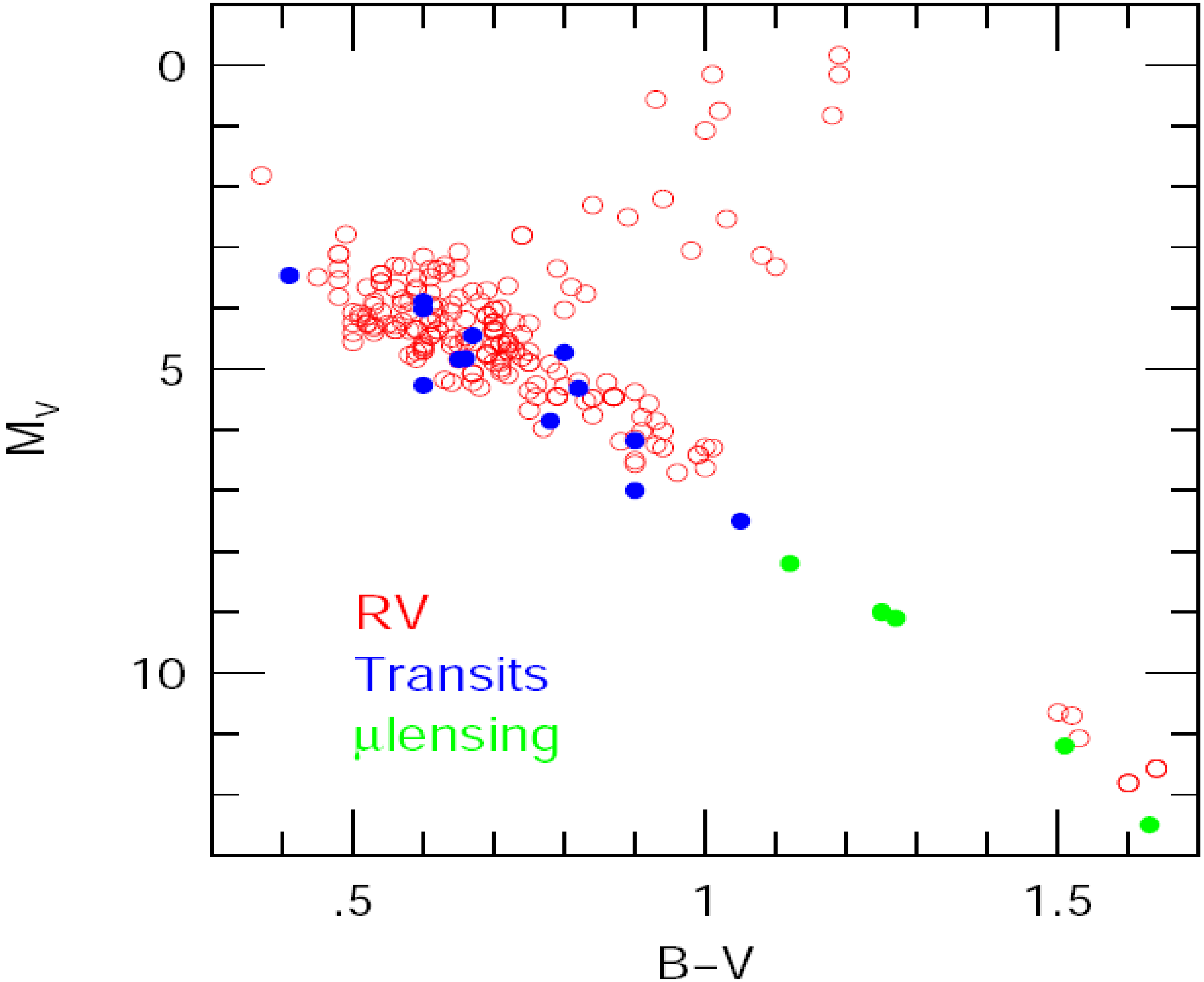
Selection Biases:

CMD (Apparent Mags)

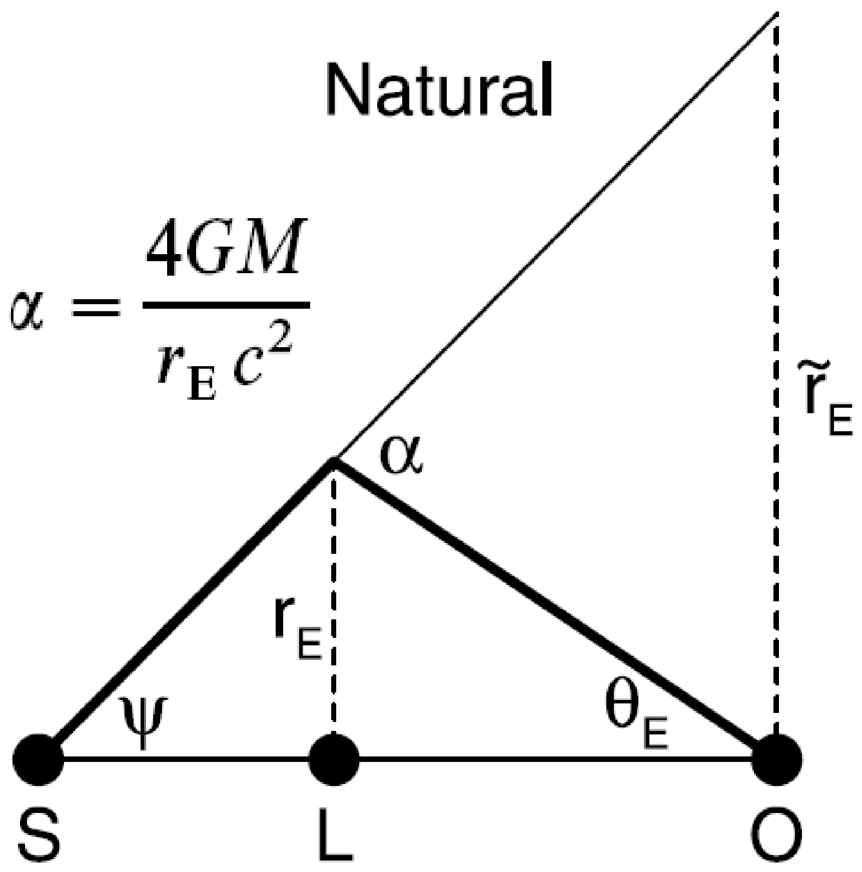


Selection biases:

CMD (Absolute mags)



Relation of Mass and Distance to Lensing Observables



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

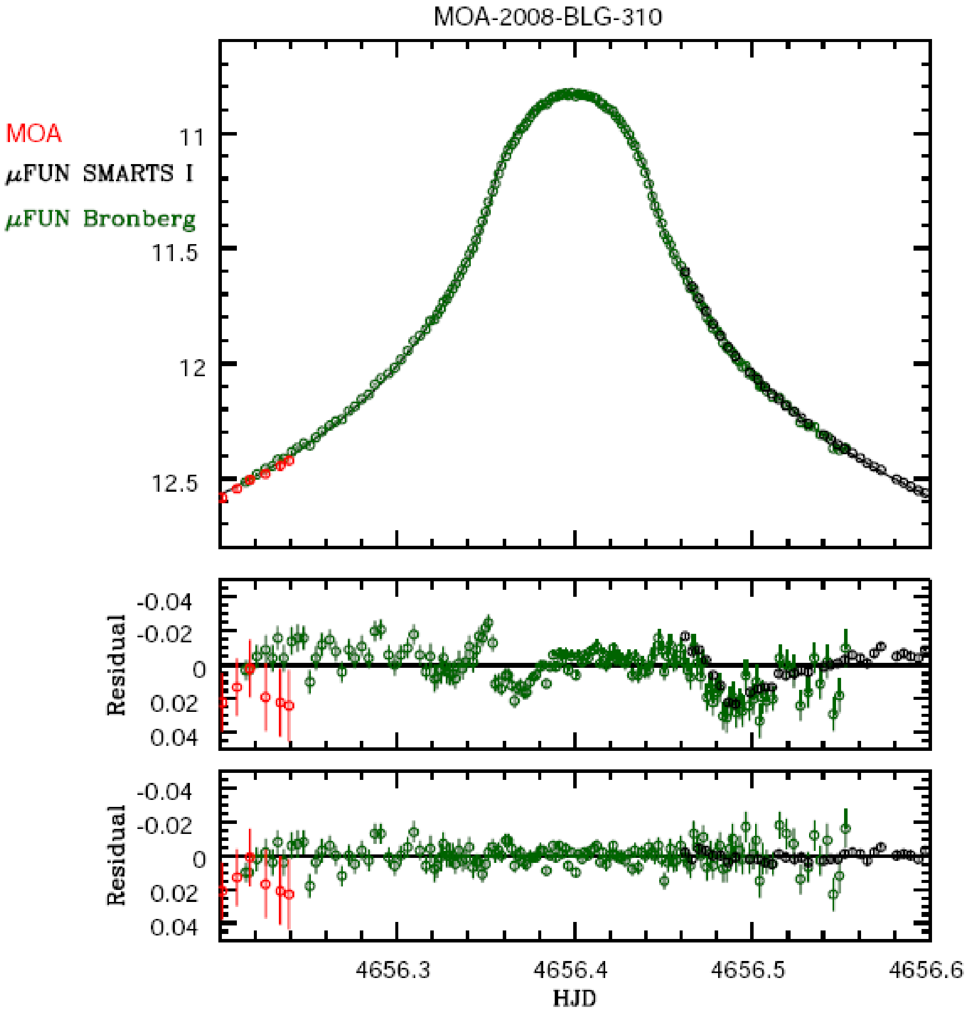
$$\theta_E \tilde{r}_E = \alpha r_E = \frac{4GM}{c^2}$$

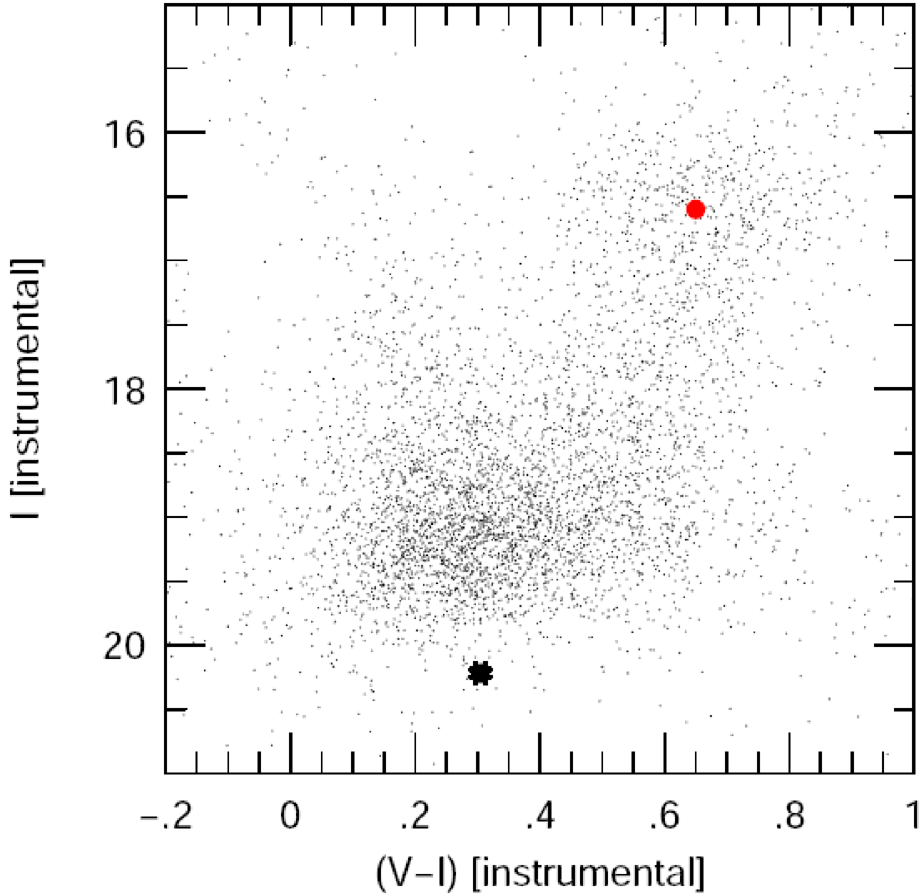
$$\theta_E = \alpha - \psi = \frac{\tilde{r}_E}{D_l} - \frac{\tilde{r}_E}{D_s} = \frac{\tilde{r}_E}{D_{\rm rel}}$$

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

To measure angular Einstein Radius:

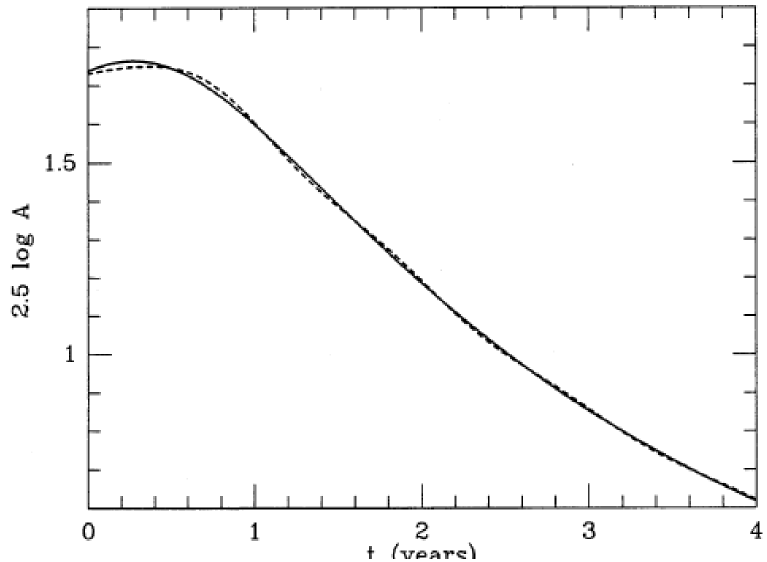
Standard Sky-Plane Rulers

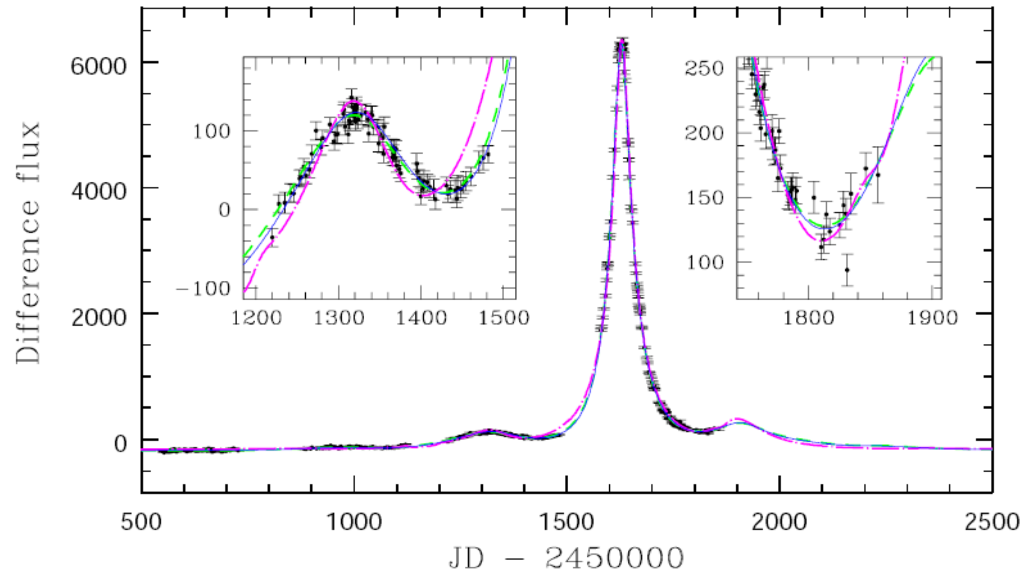


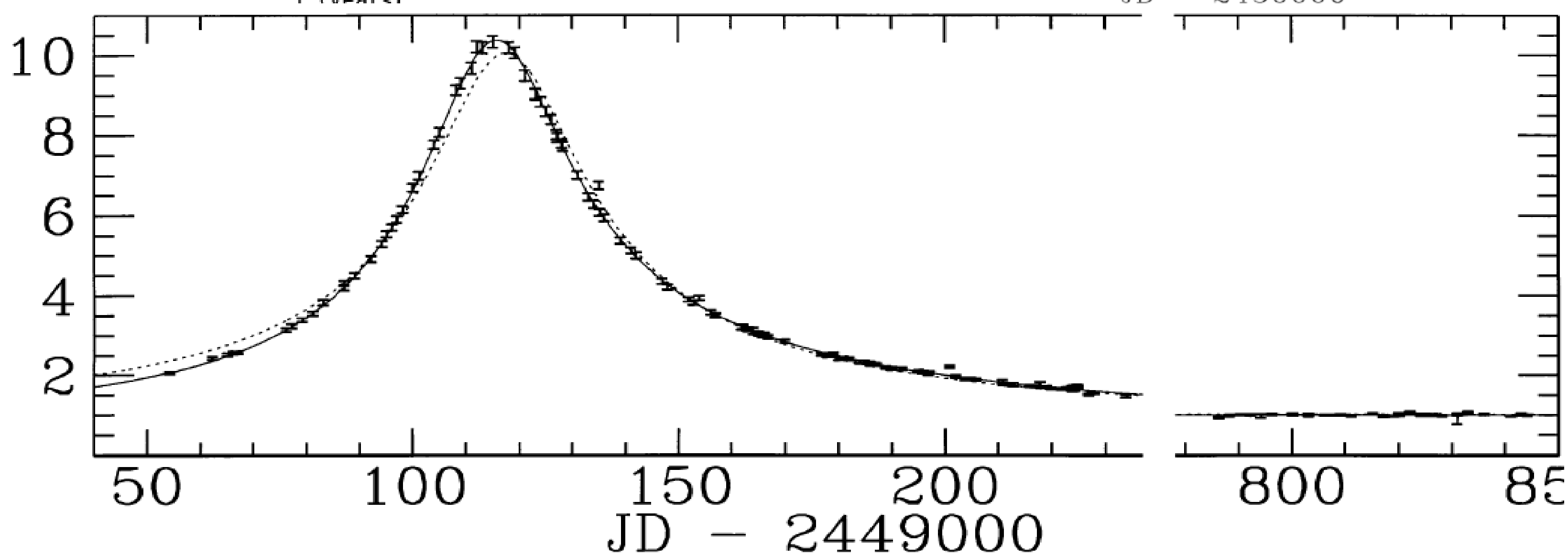


To measure parallax:

Standard Observer-Plane Rulers

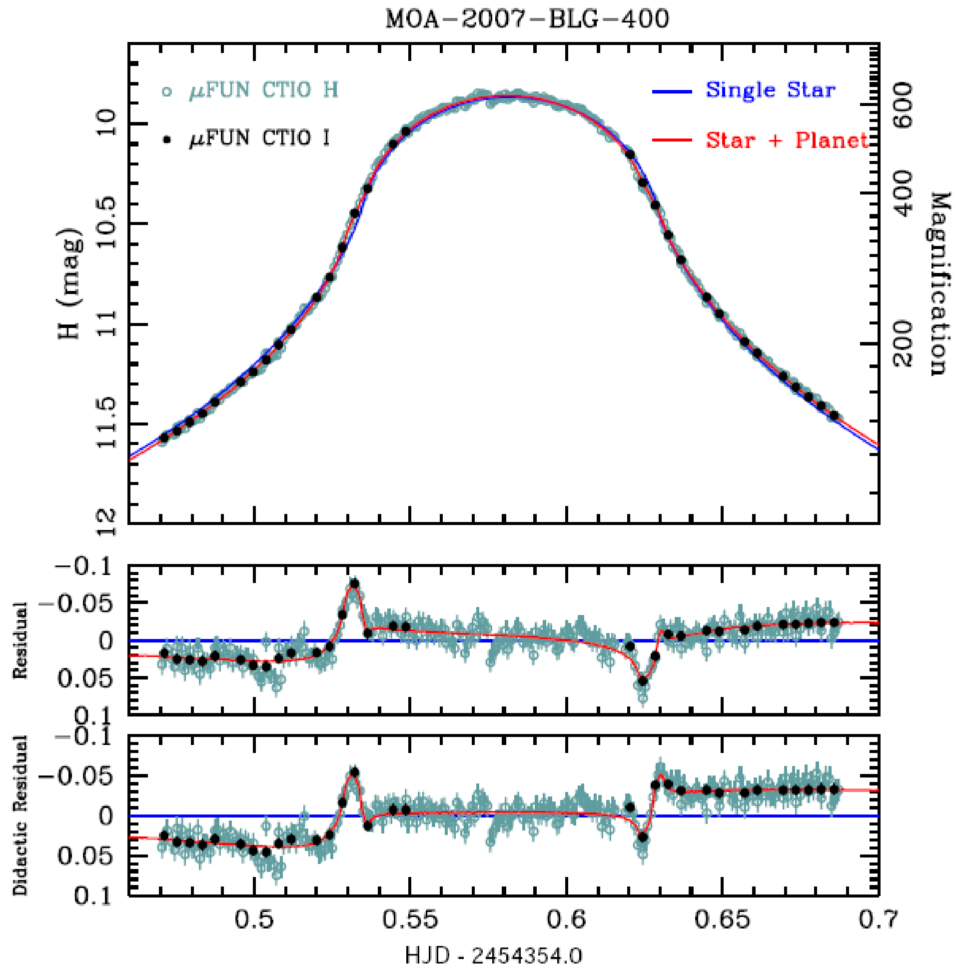






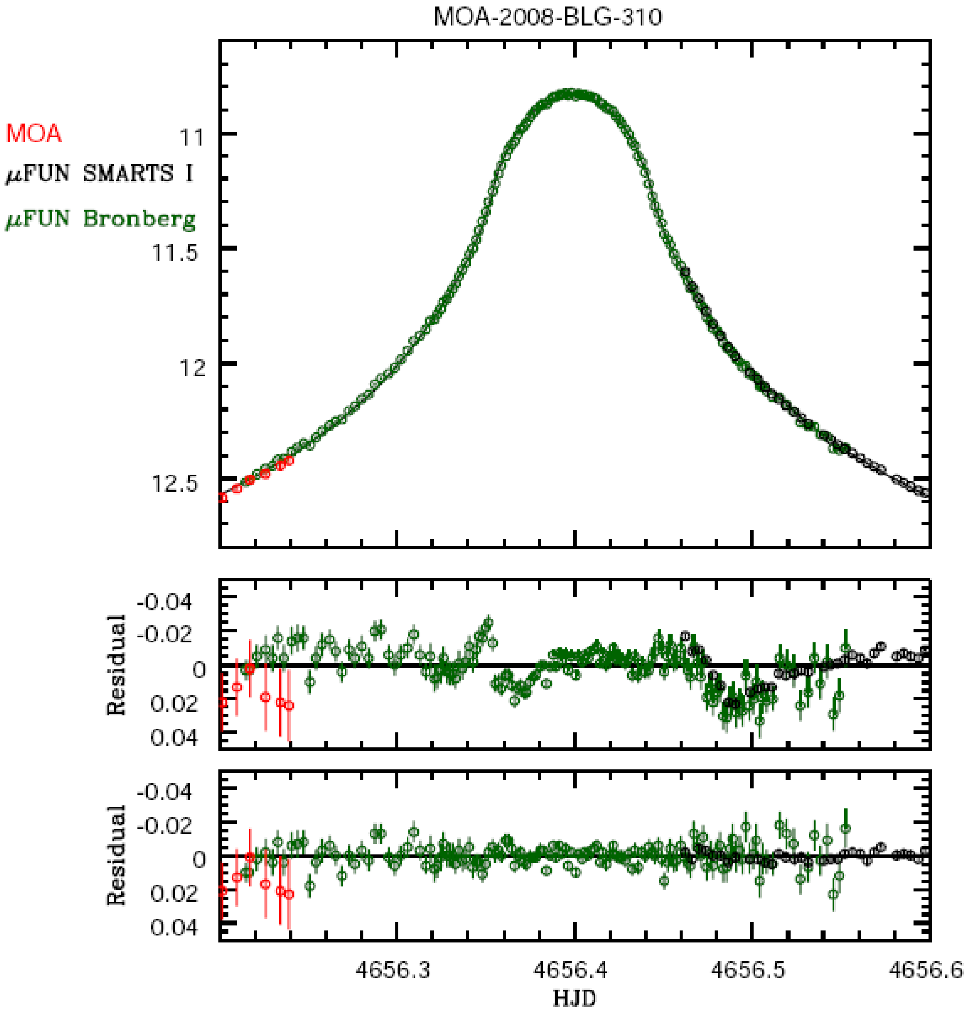
MOA-2007-BLG-400

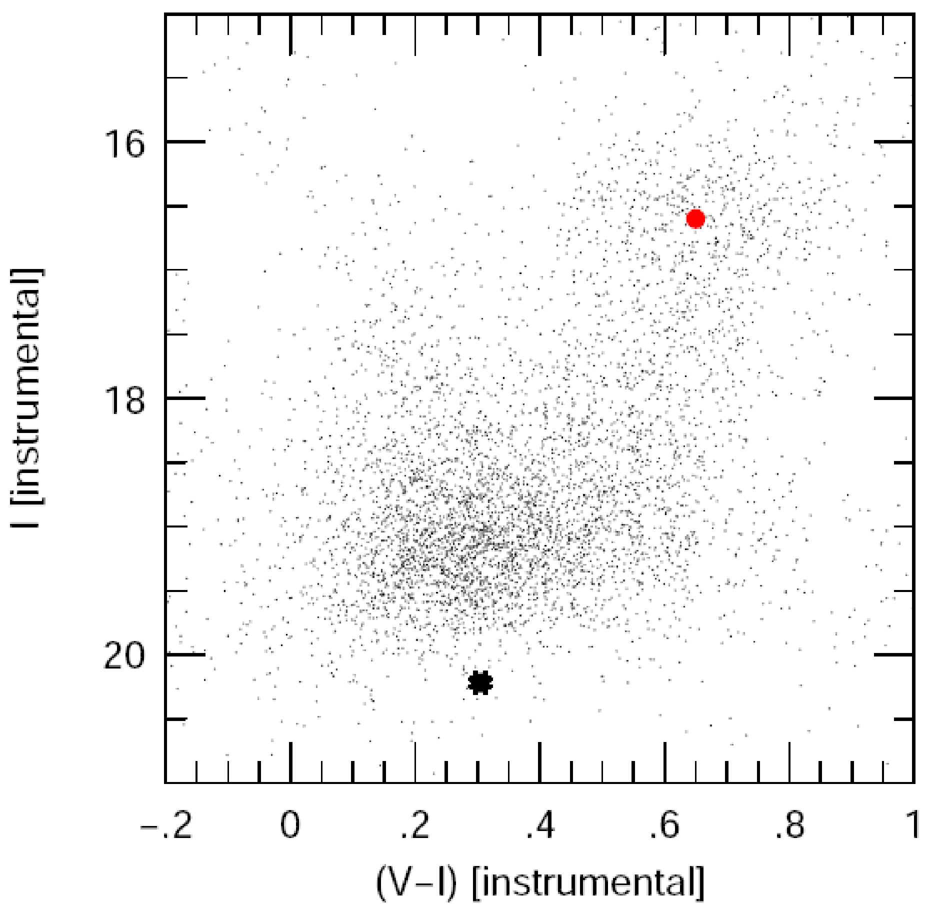
"Buried" Jovian-Mass Planet



MOA-2008-BLG-310

Another Buried Planet

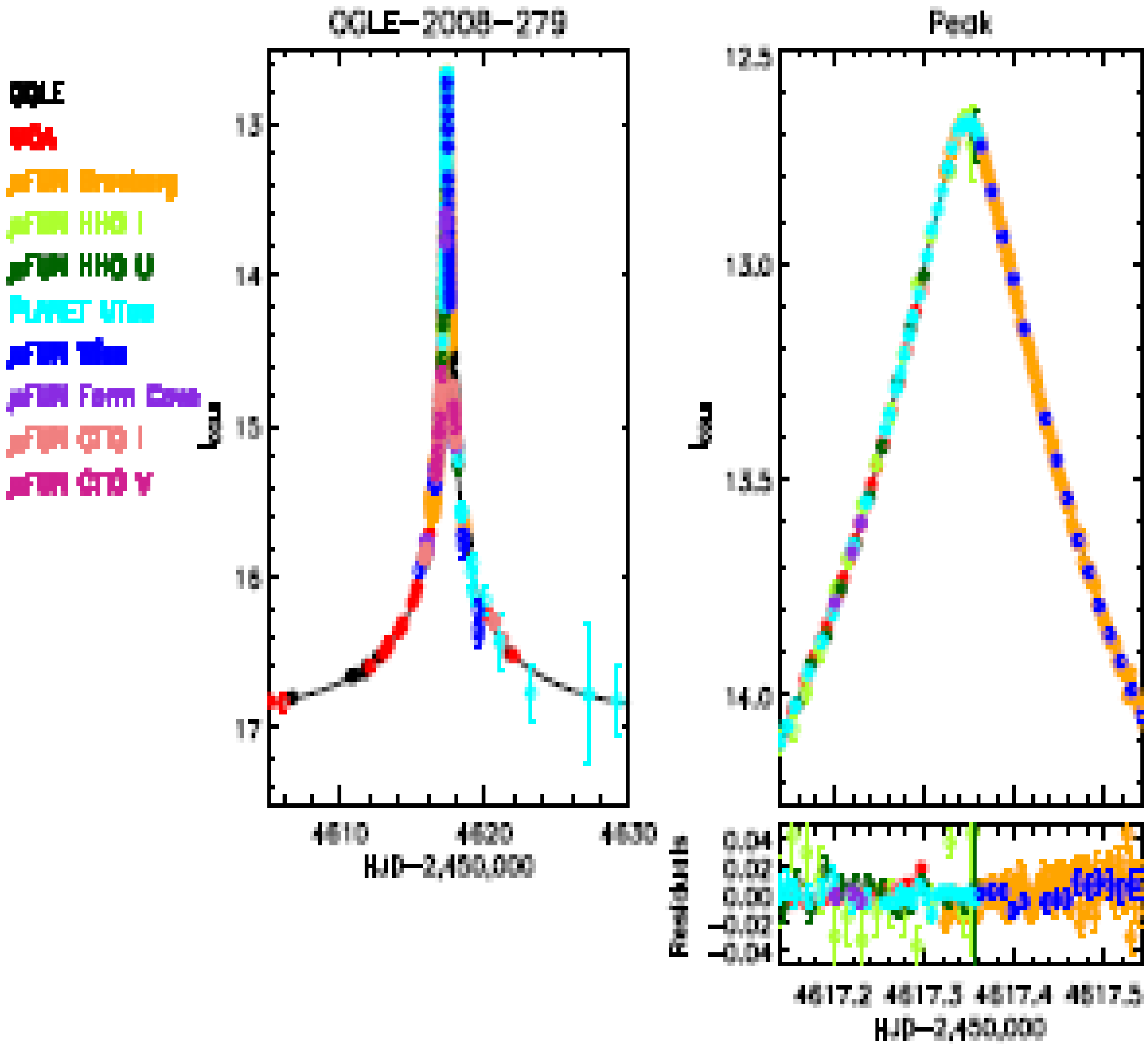




Janczak et al. 2010, ApJ, 711, 731

OGLE-2008-BLG-279:

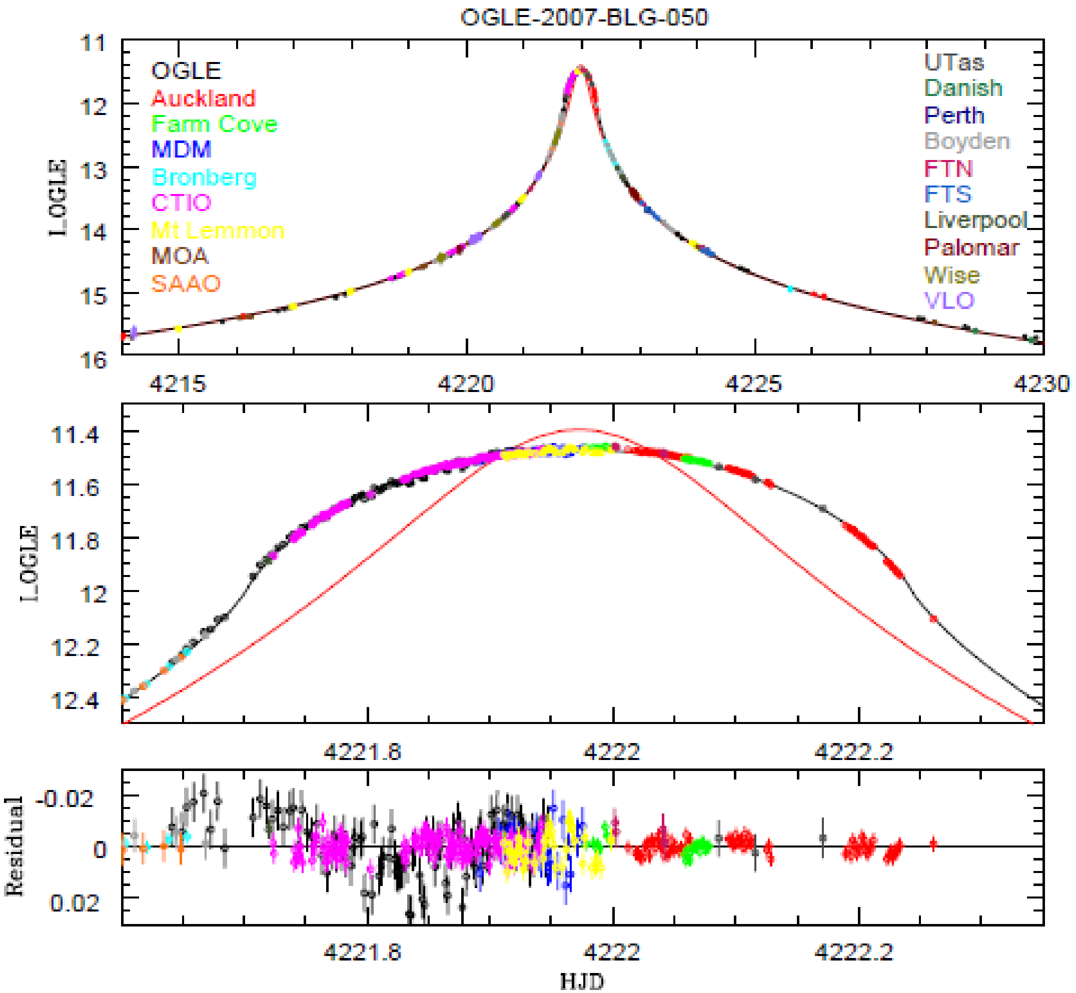
A = 1600



Yee et al. 2009, ApJ, 730, 2082

OGLE-2007-BLG-050:

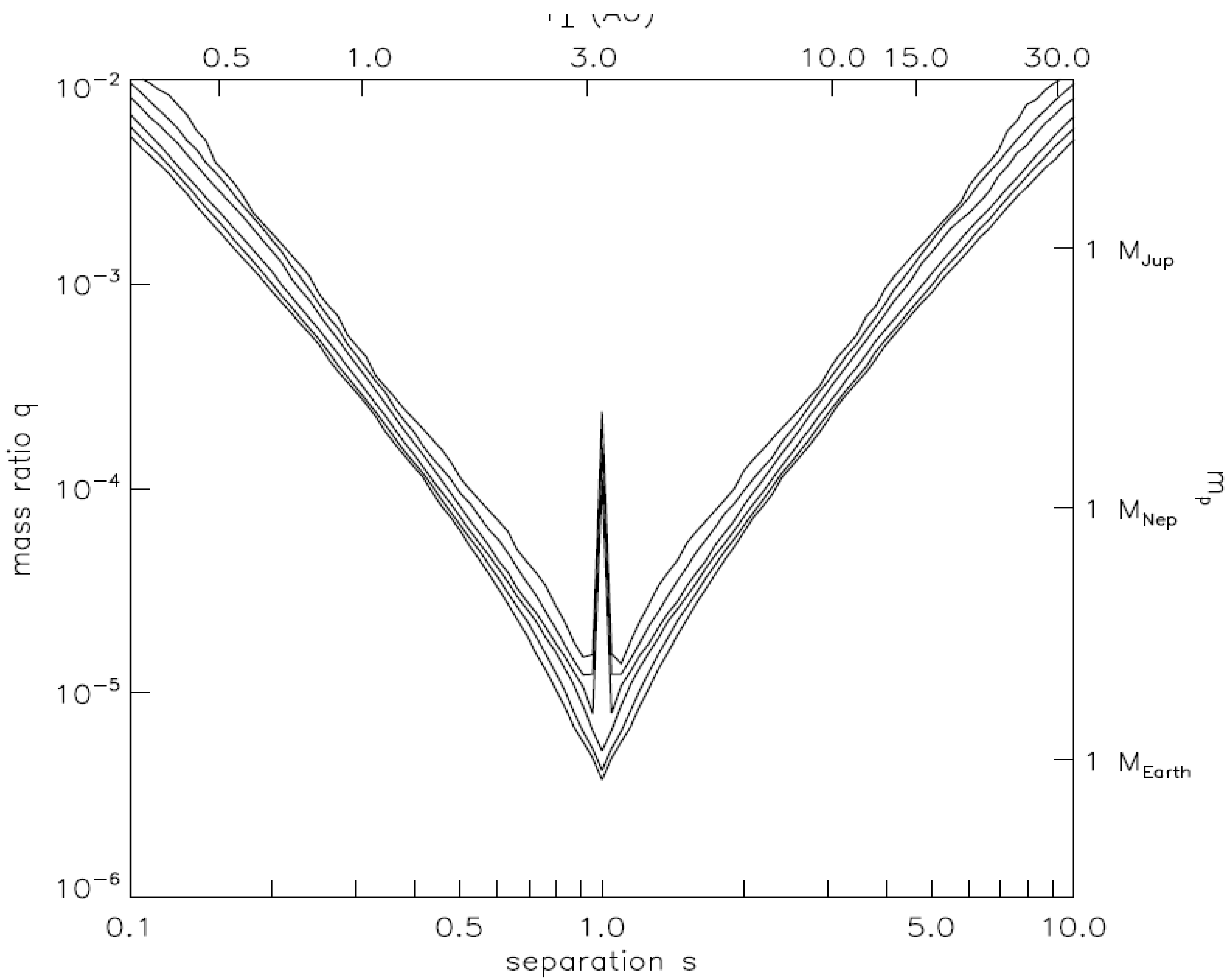
A = 432



Batista et al. 2009, A&A, 508, 467

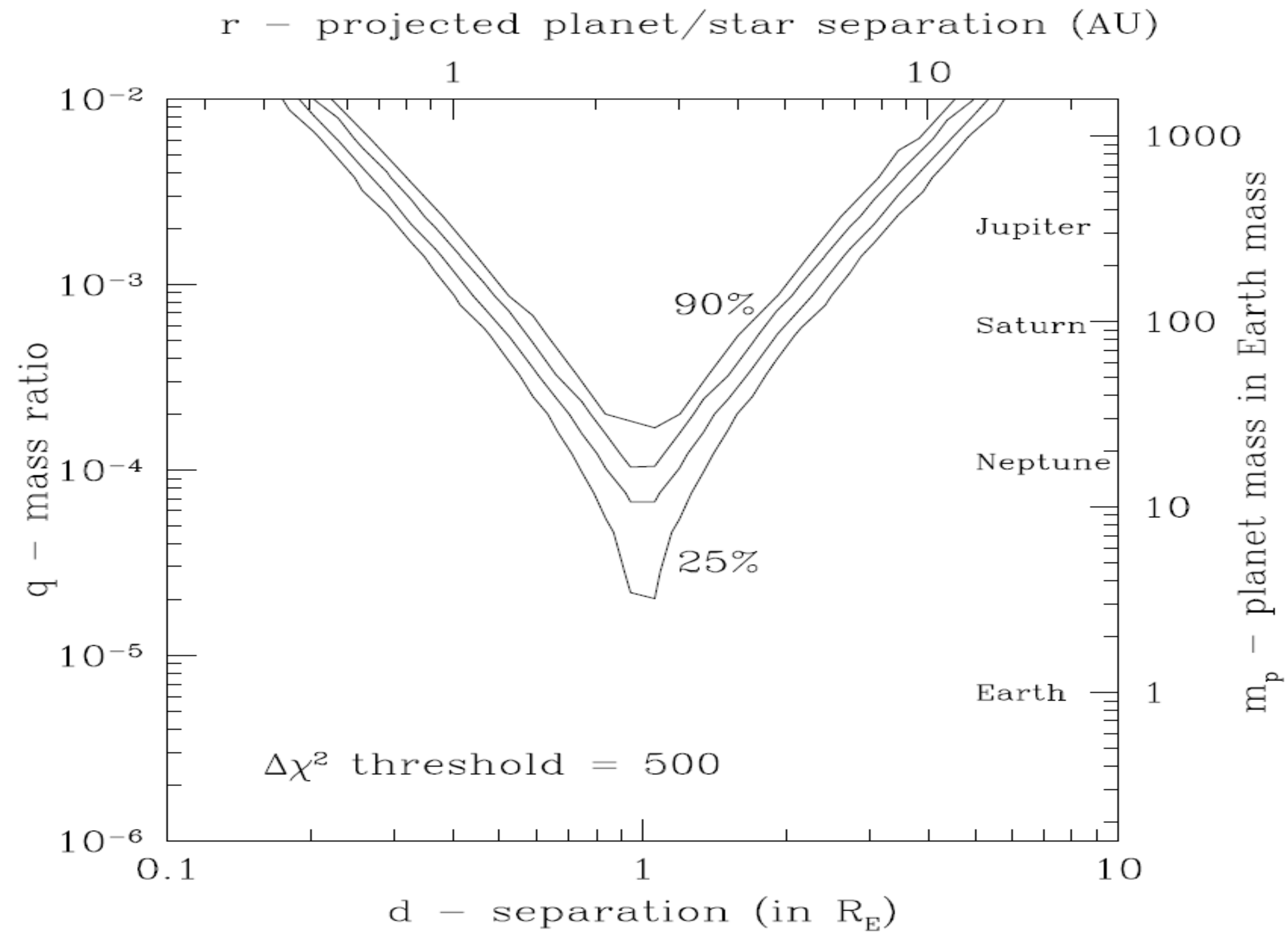
Planet Sensitivity

OGLE-2008-BLG-279



Planet Sensitivity

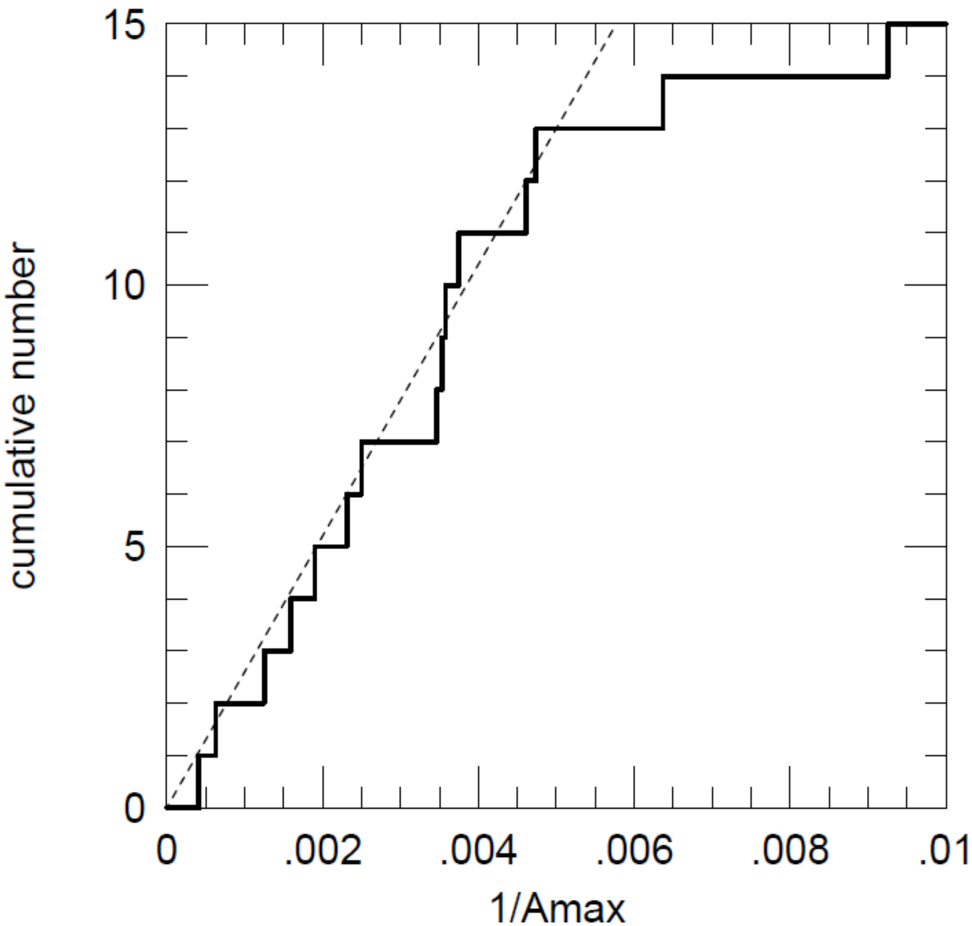
OGLE-2007-BLG-050



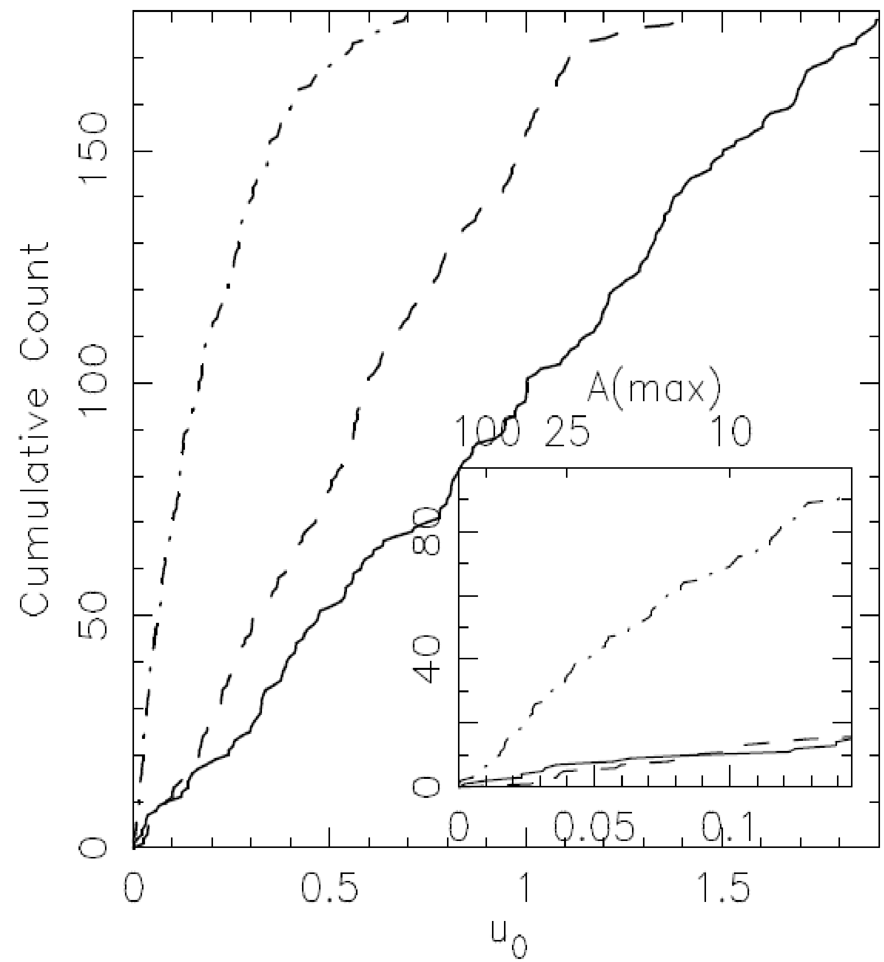
Well-covered events: fair sample

(Amax>200)

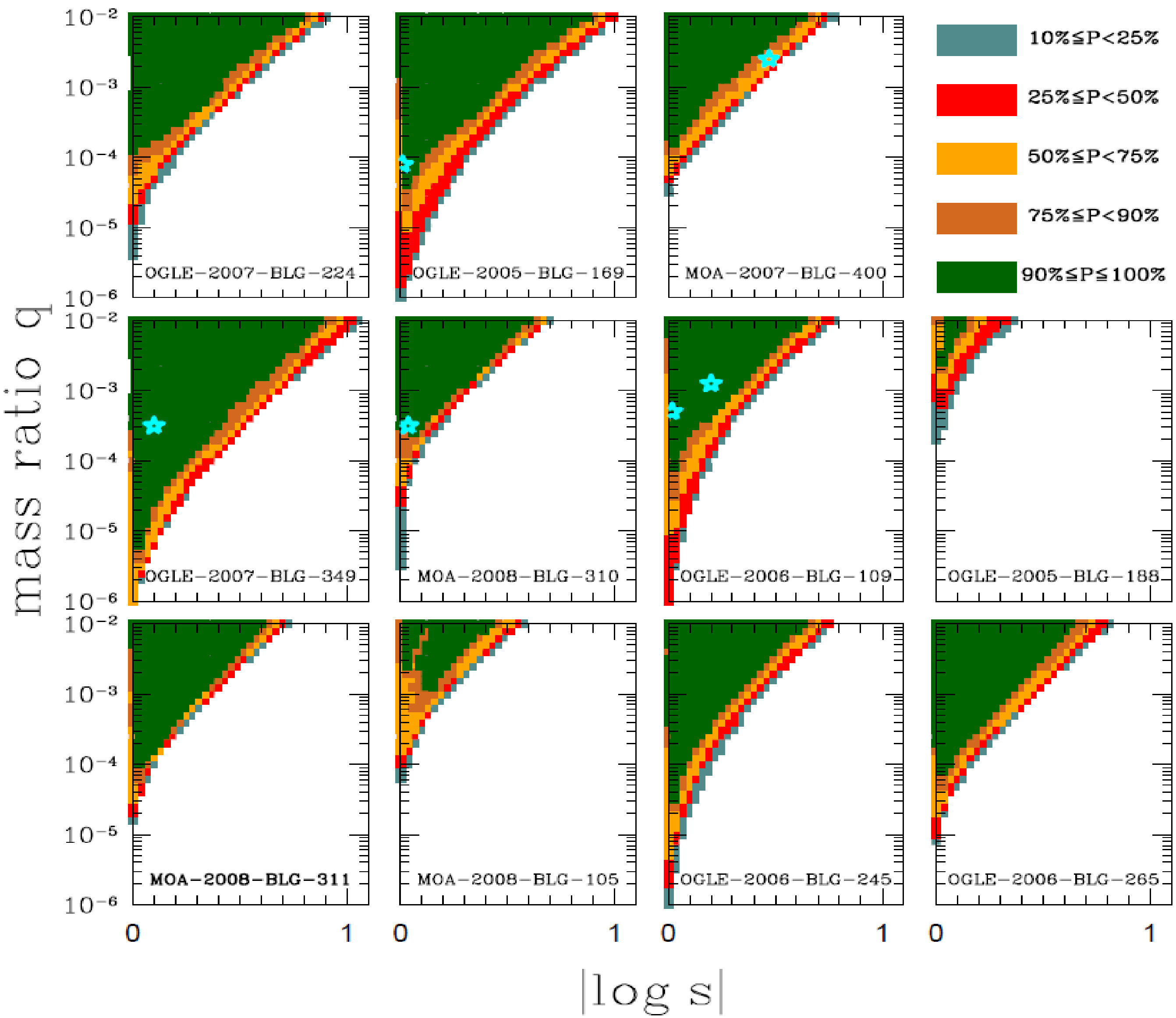
Well-Covered



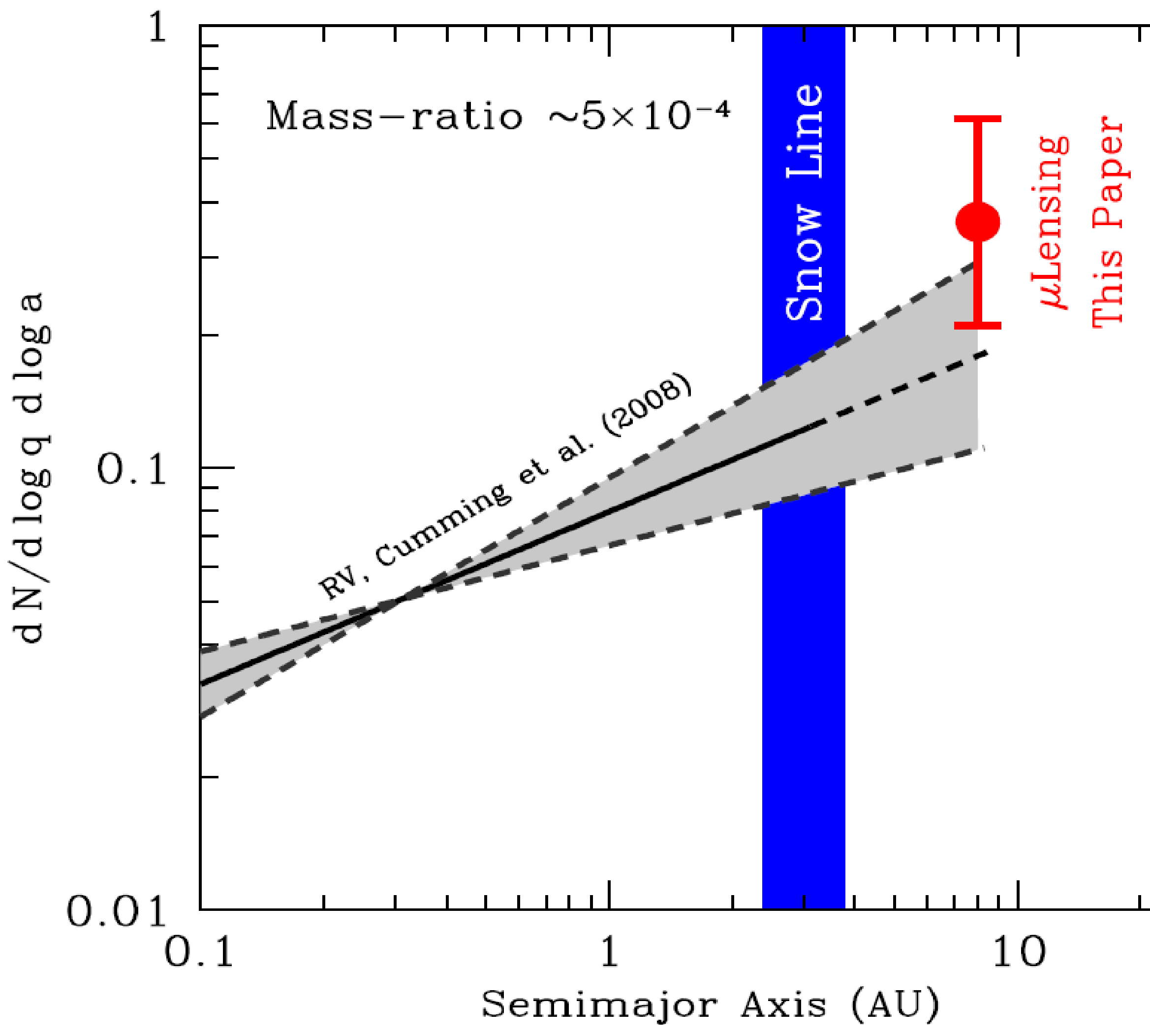
All Events



Planet Sensitivity Vs. Detections

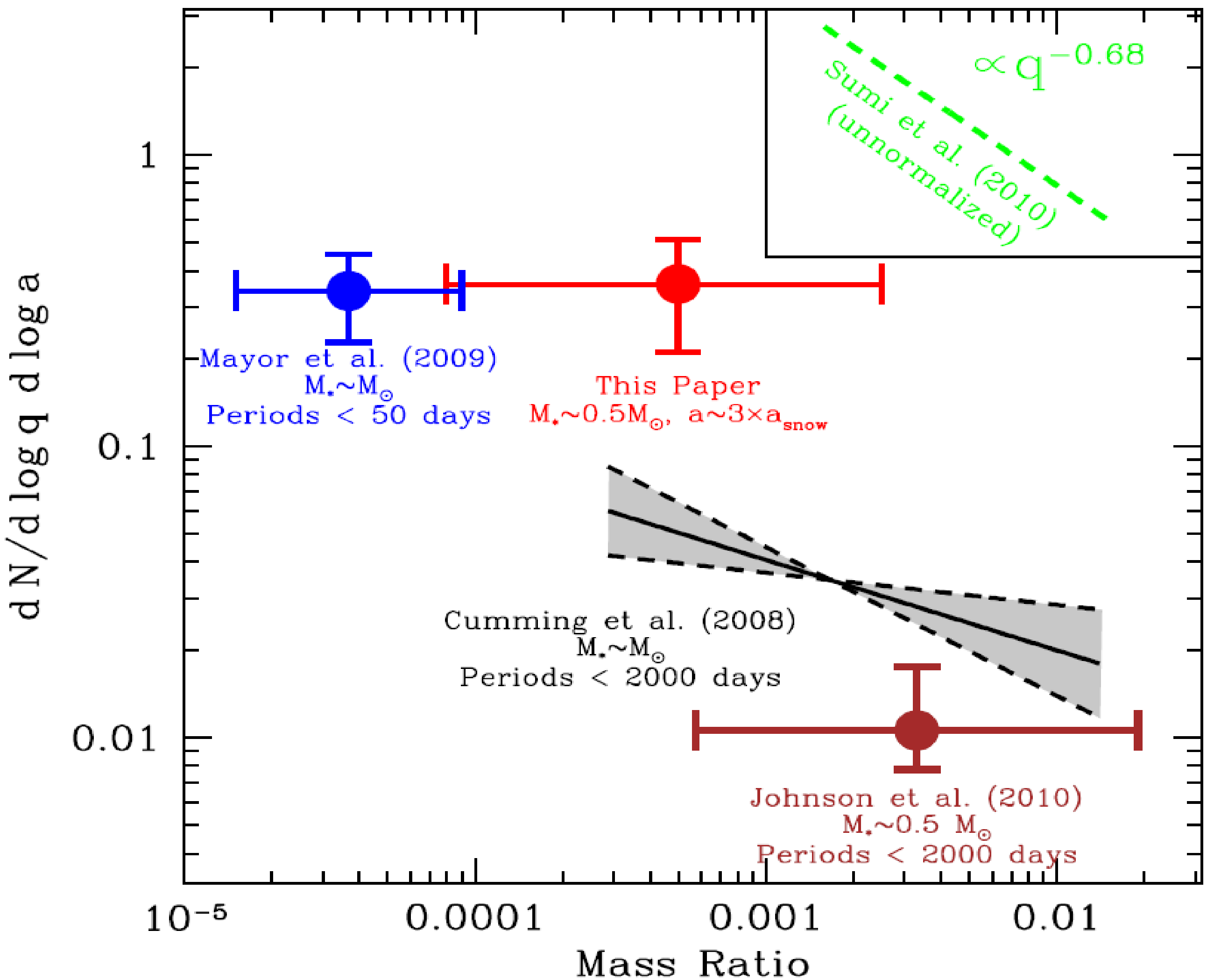


RV & Microlensing
Inside vs Outside Snow Line



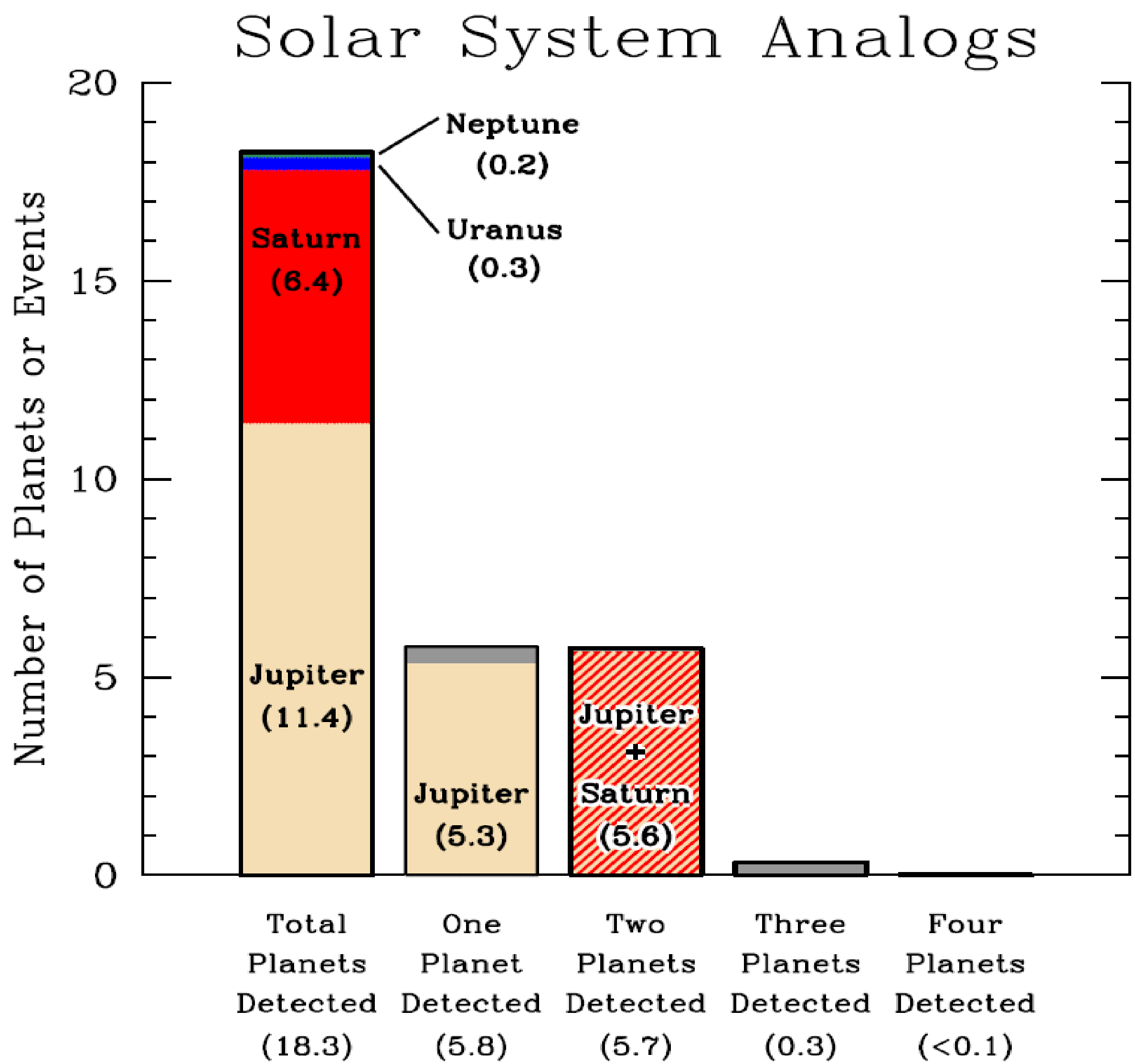
RV & Microlensing

Frequency vs. Mass Ratio



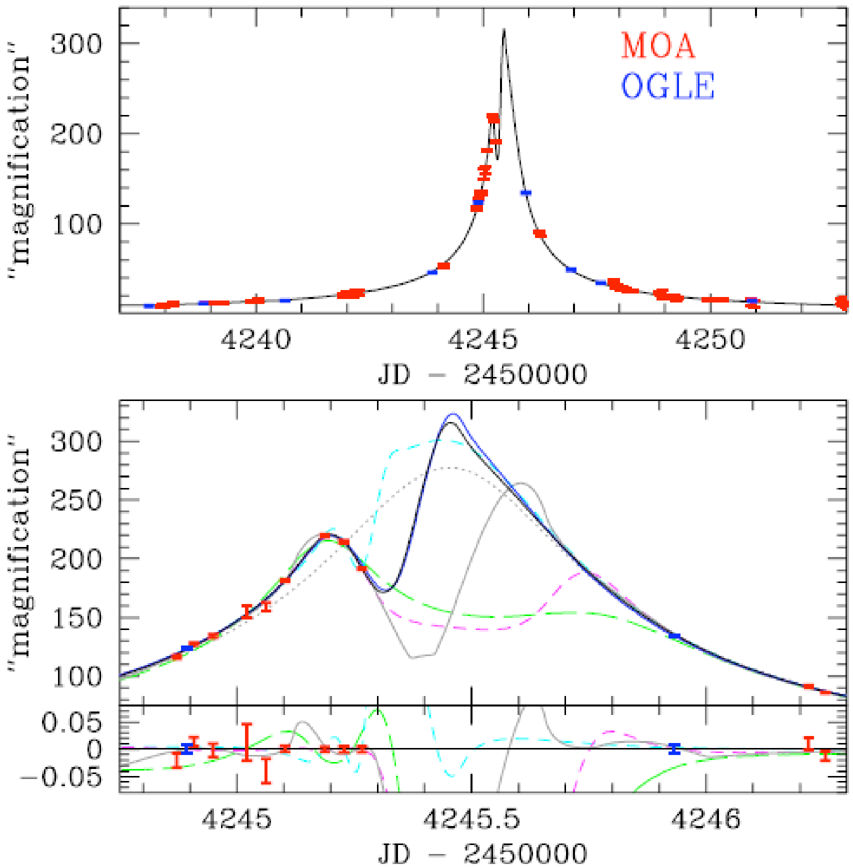
Solar System is Richer than Average

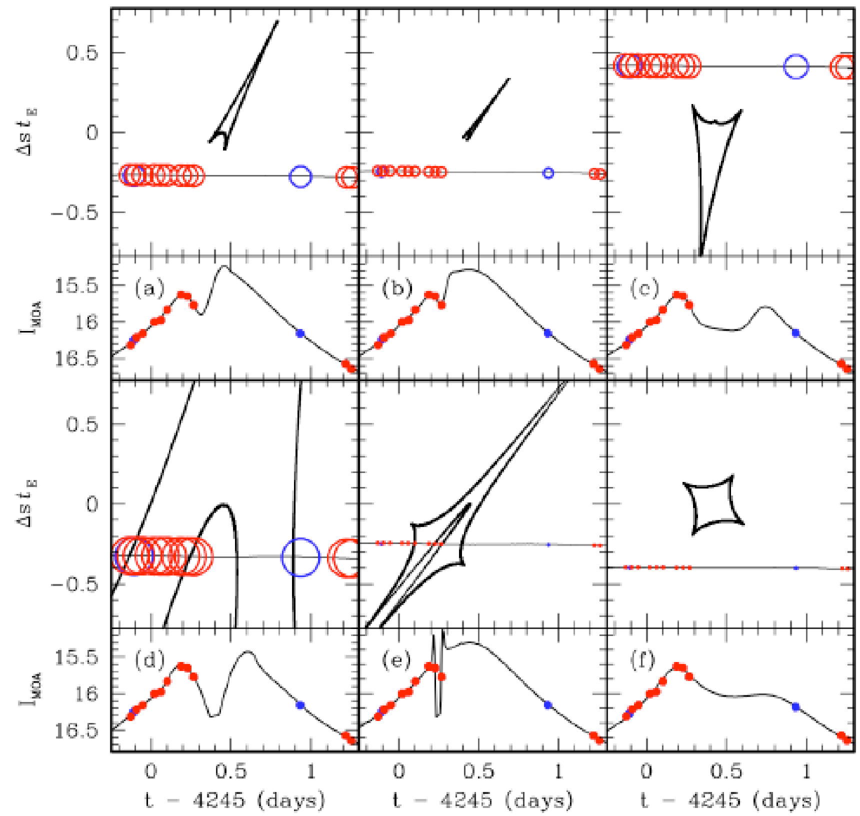
... But Not Dramatically So



MOA-2007-BLG-192:

Cold Super-Earth

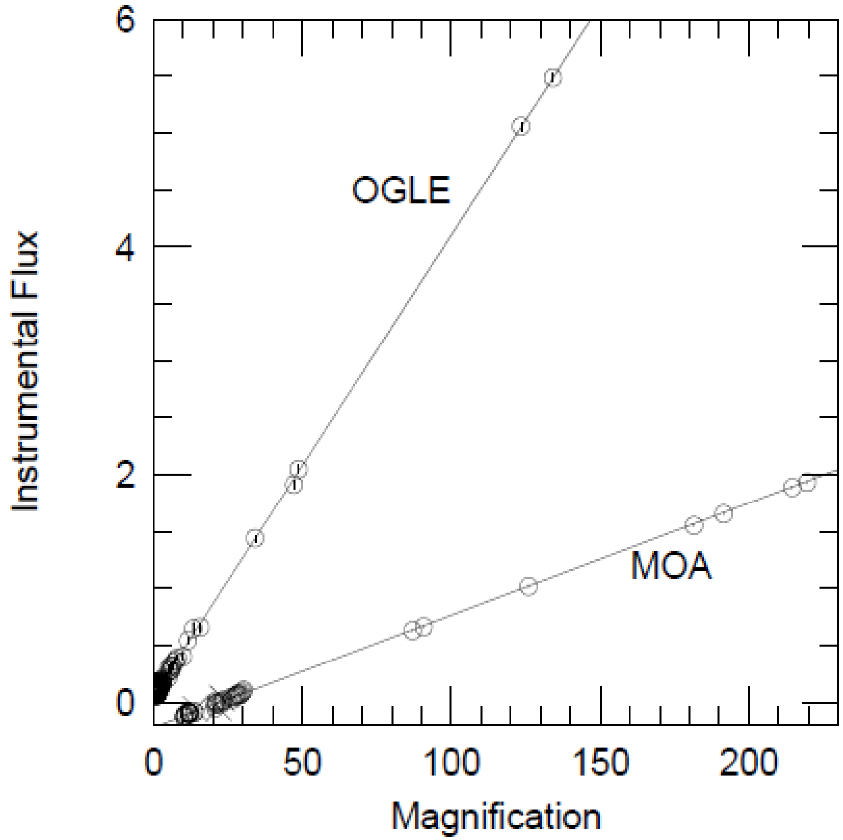


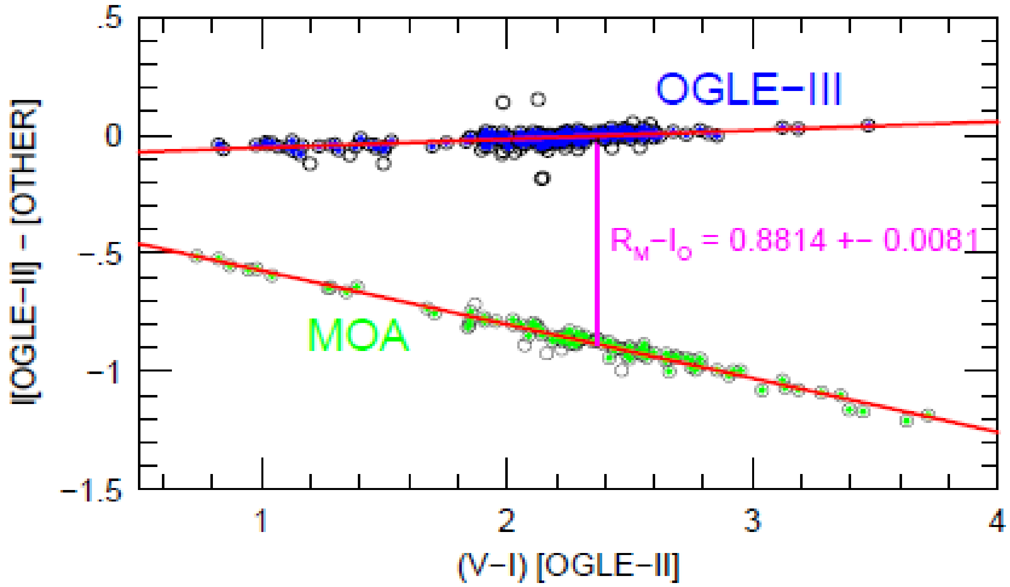


Bennett et al. 2008, ApJ, 684, 663

MOA-2007-BLG-192:

Step 2: V-I Source Color

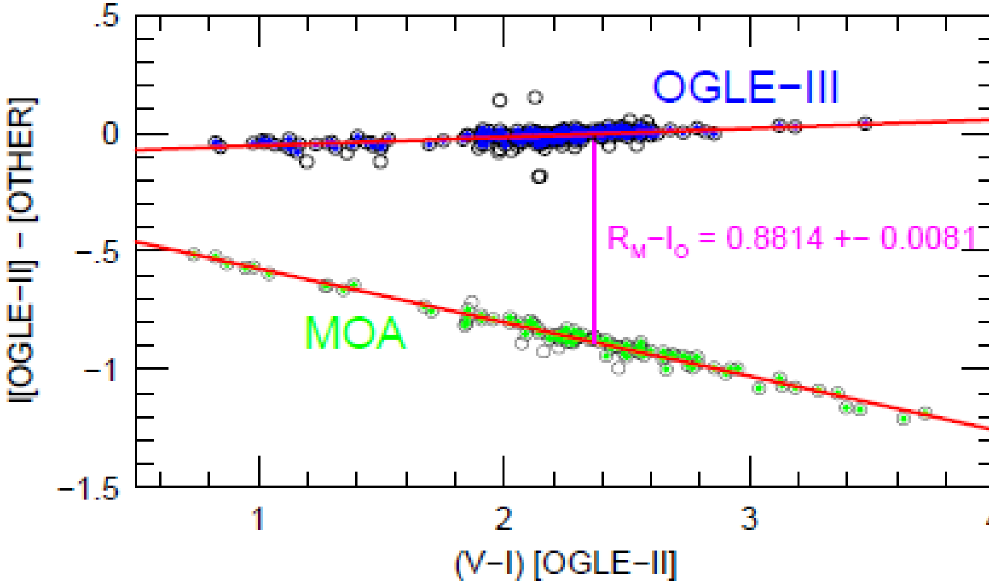


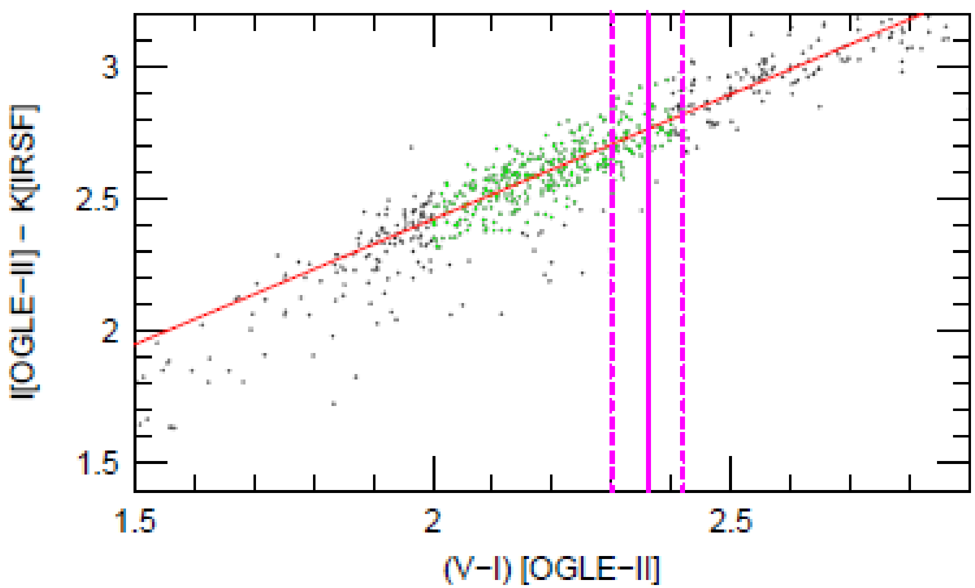


Gould et al. 2010, ApJ, 710, 1800

MOA-2007-BLG-192:

Step 3: V-I --> I-K: I_s --> K_s

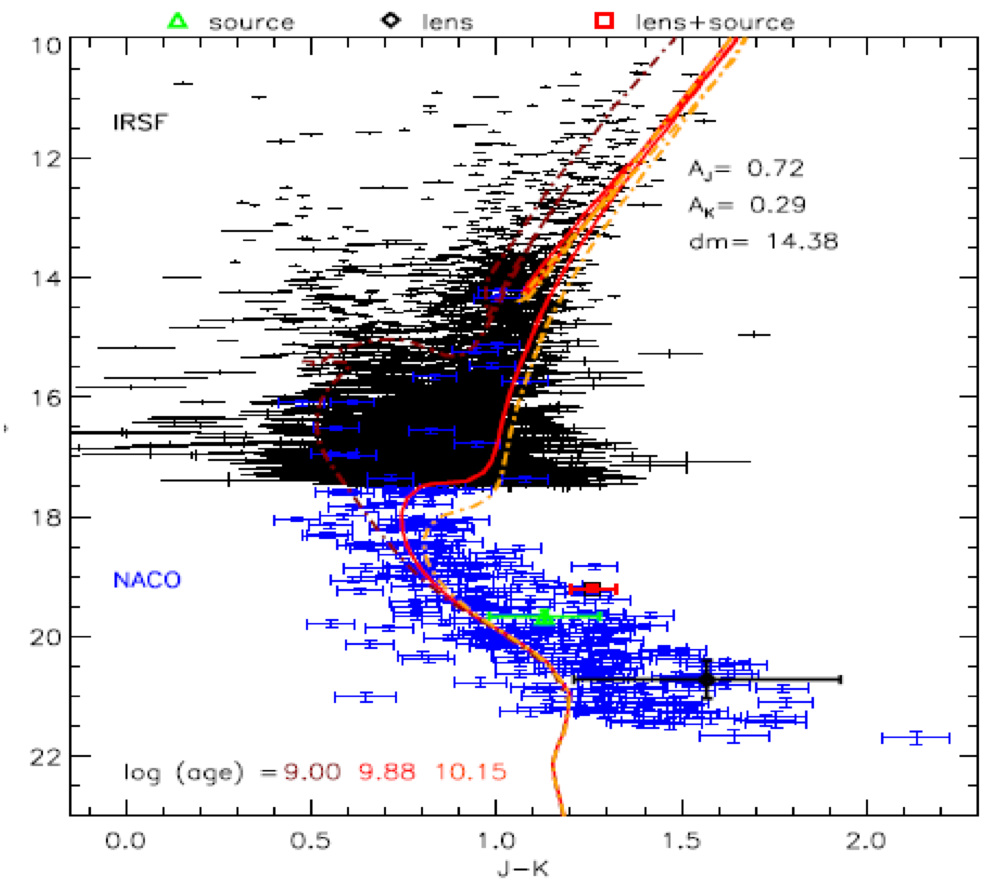




Kubas et al. 2011, ApJ, submitted

MOA-2007-BLG-192:

Step 4: VLT NACO: $K_{baseline}$

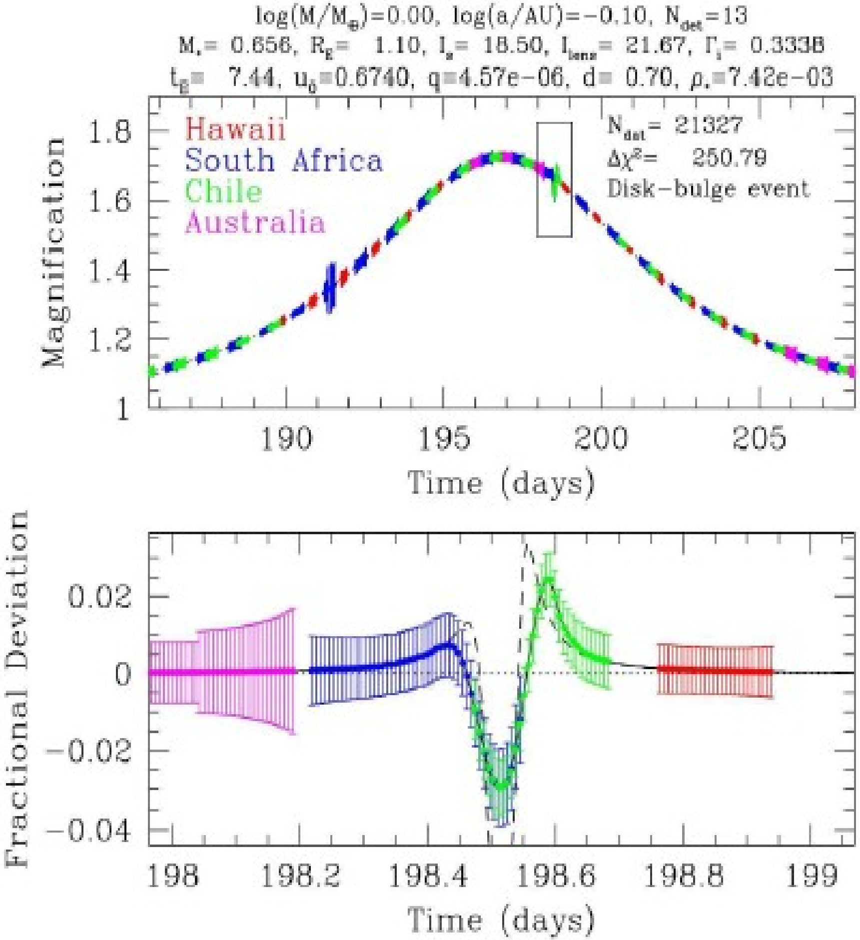


M_{host}=0.08 M_{sun}; M_{planet} = 3.2 M_{earth}

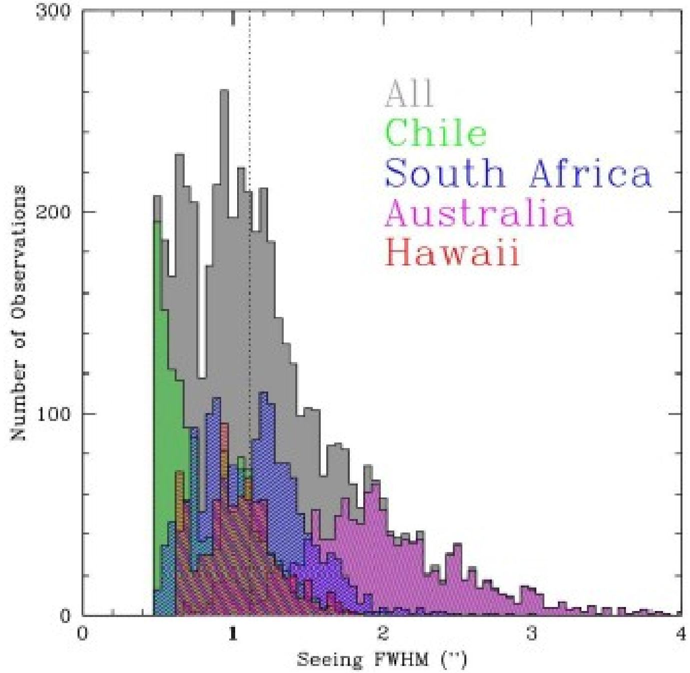
NextGen Microlensing Planet Search

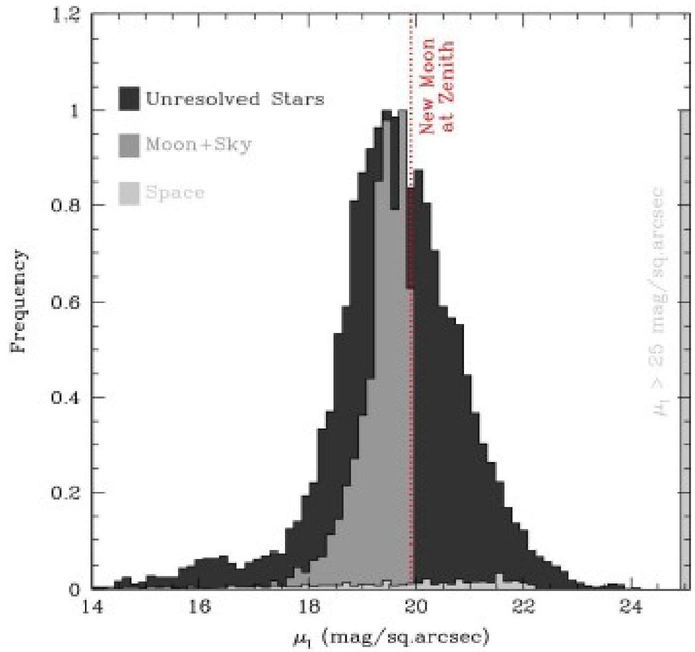
Simulations by Scott Gaudi

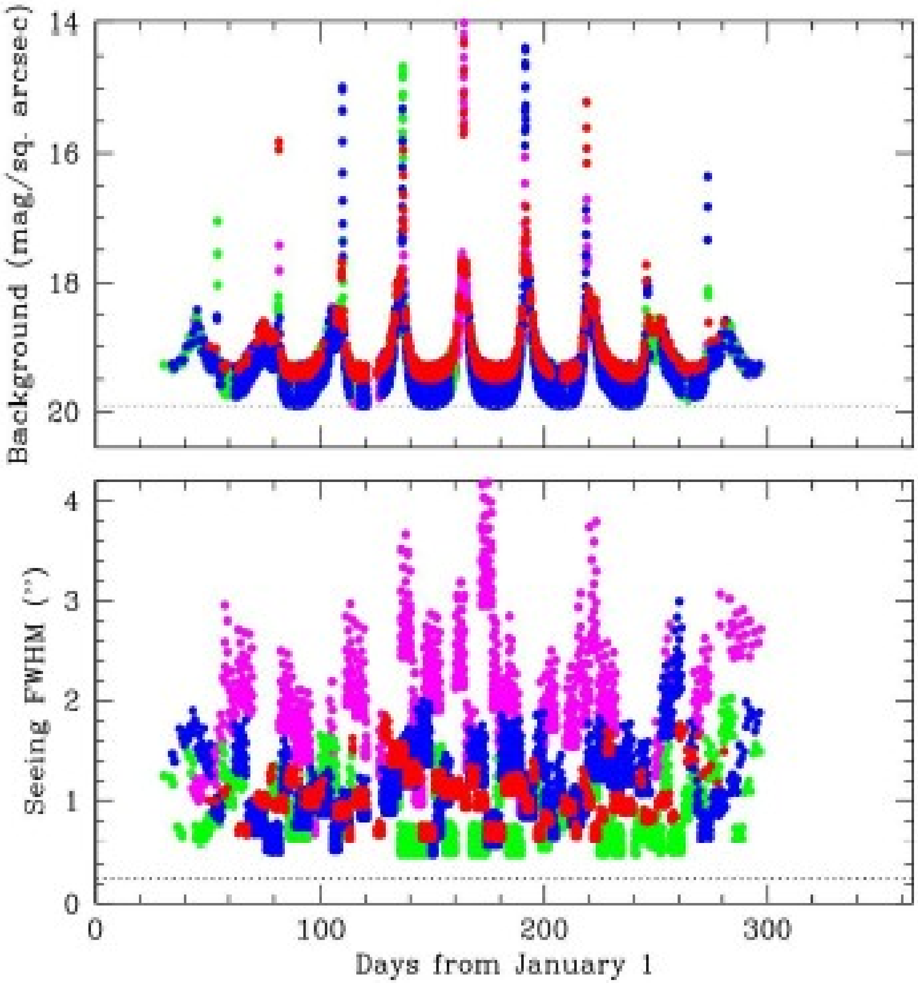
- 4 observatories
- 2m class telescopes
- 4 sq.deg. cameras
- Realistic seeing & weather
- photon-limited statistics down to systematics limit



Simulation Ingredients (abridged)

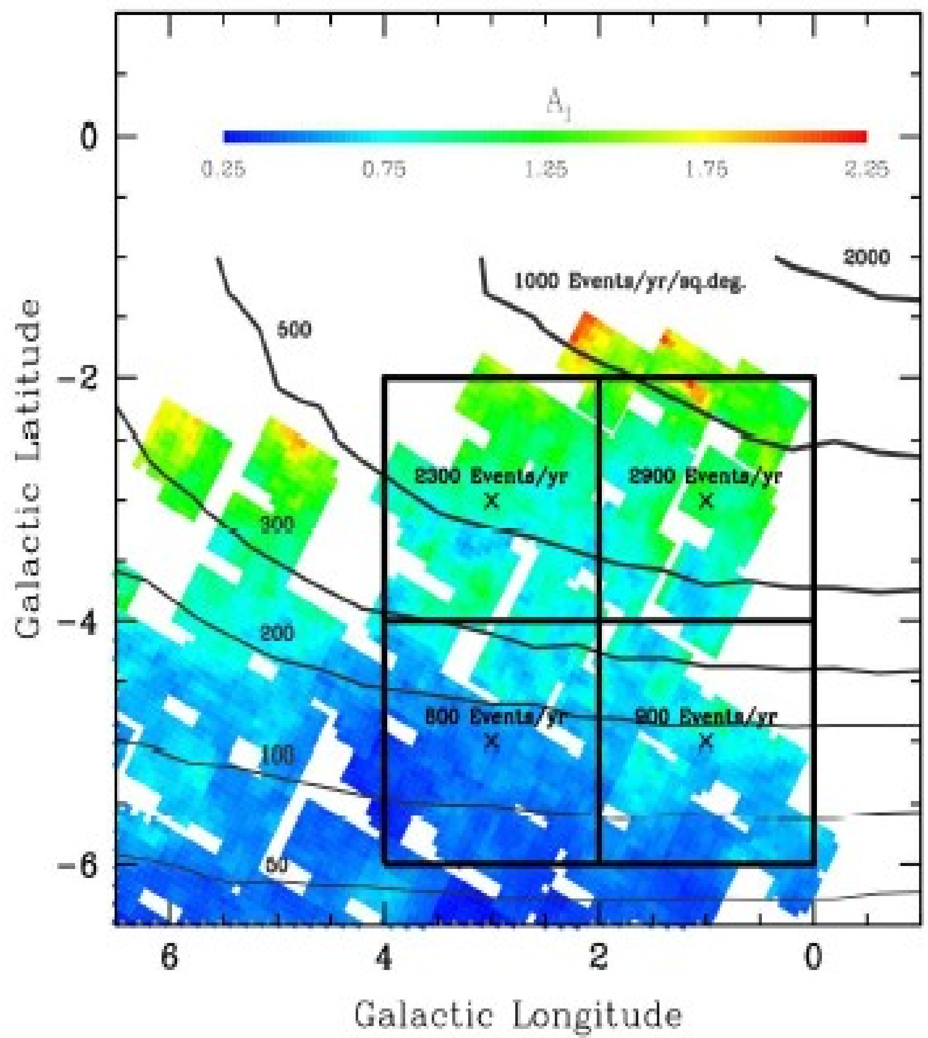


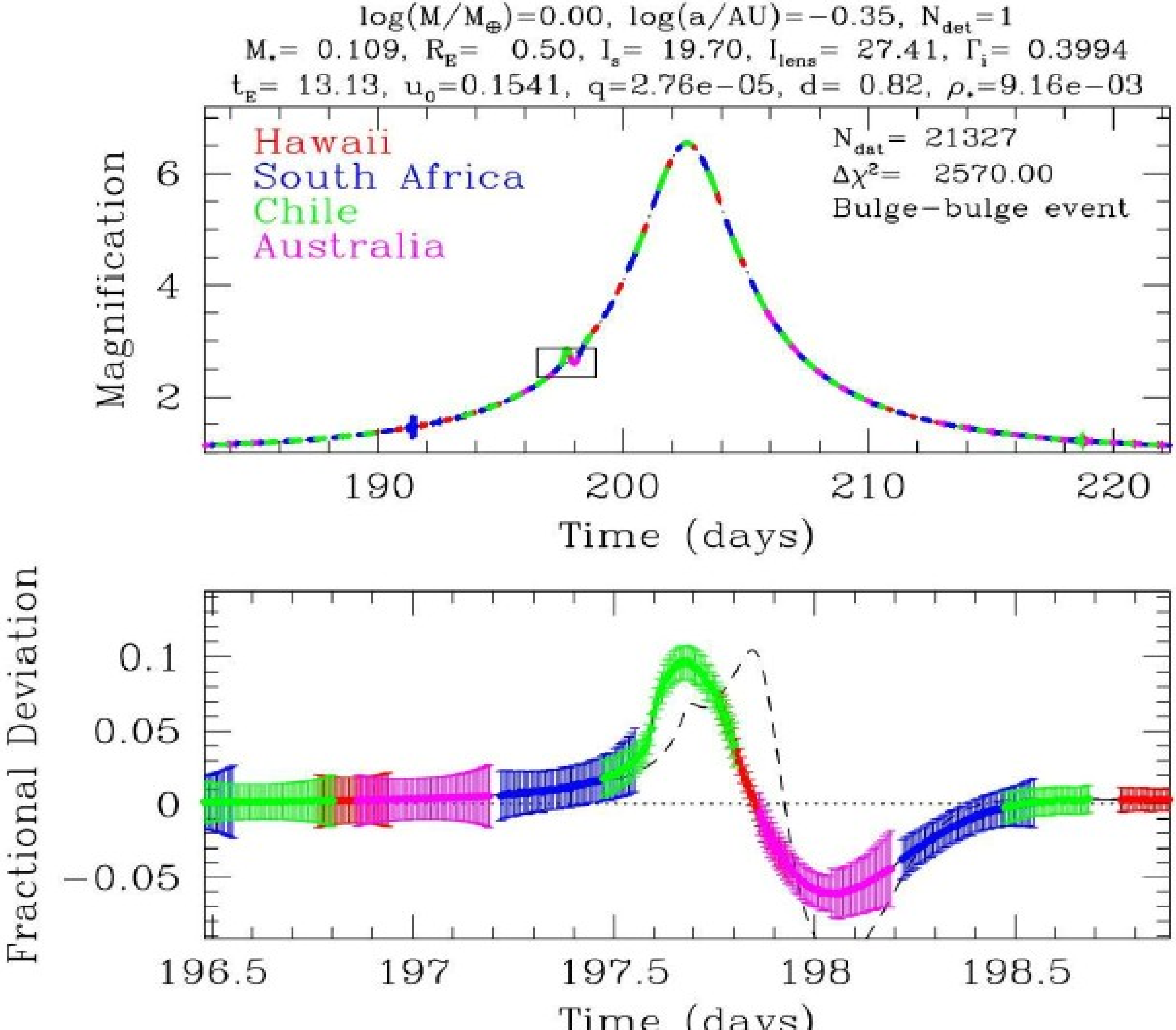




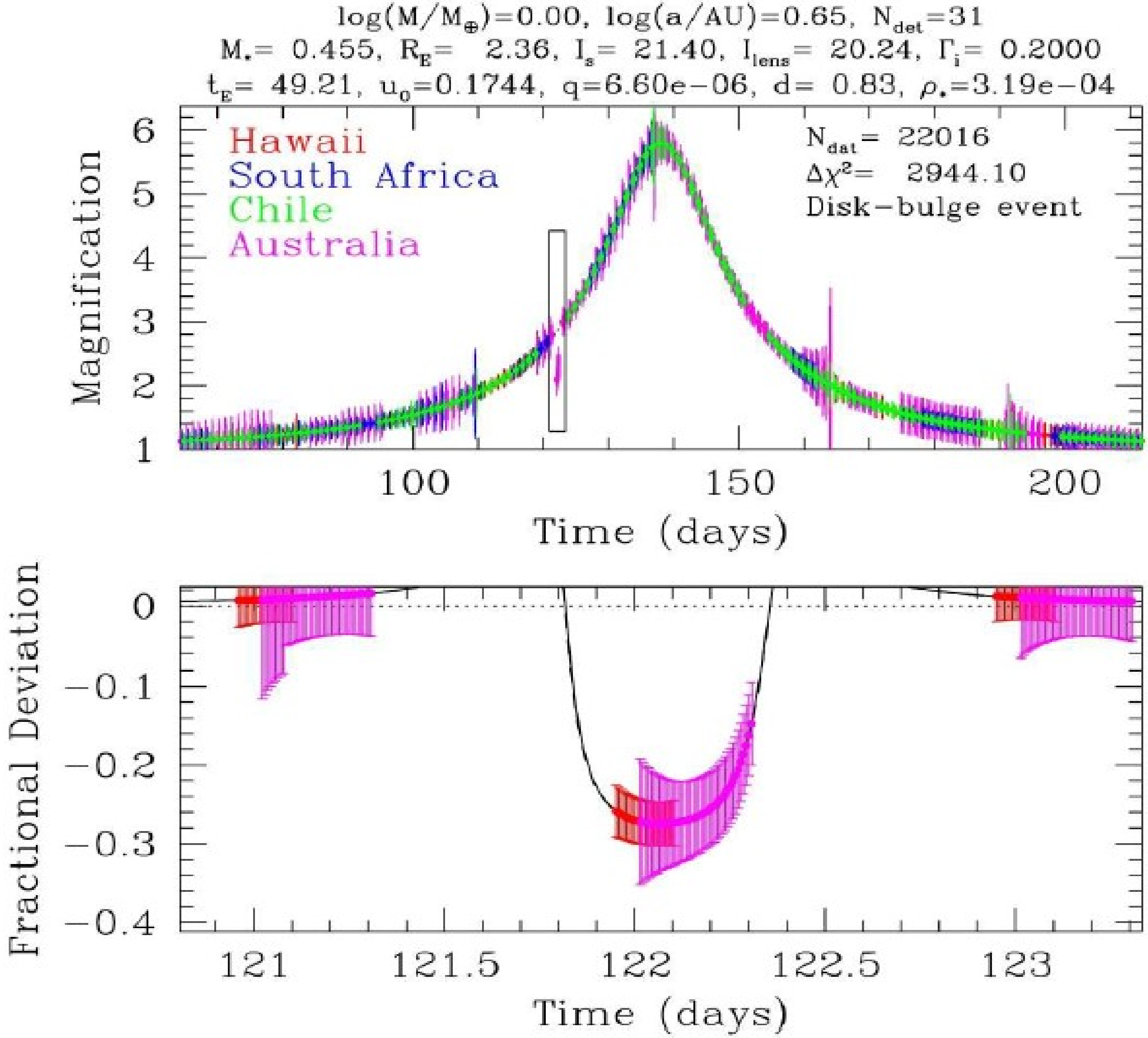
Target Fields

- 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)



log(M/M⊕)=0.00, log(a/AU)=0.65, N_det=31
M*= 0.455, R_E= 2.36, I_s= 21.40, I_lens= 20.24, Γ_i= 0.2000
t_E= 49.21, u_0=0.1744, q=6.60e−06, d= 0.83, ρ*=3.19e−04
Hawaii
South Africa
Chile
Australia
N_dat= 22016
Δχ²= 2944.10
Disk-bulge event
Magnification
Time (days)
Fractional Deviation
Time (days)

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

Approach: Threshold + Upgrades

- THRESHOLD: Major new telescope in Africa joined with existing/upgraded MOA and OGLE telescopes
- POTENTIAL UPGRADES:
  - Additional 2m/4sq.deg. telescope (Chile?)
    - Participation of other widefield telescopes e.g. PanStars (Hawaii), SkyMapper (Australia)

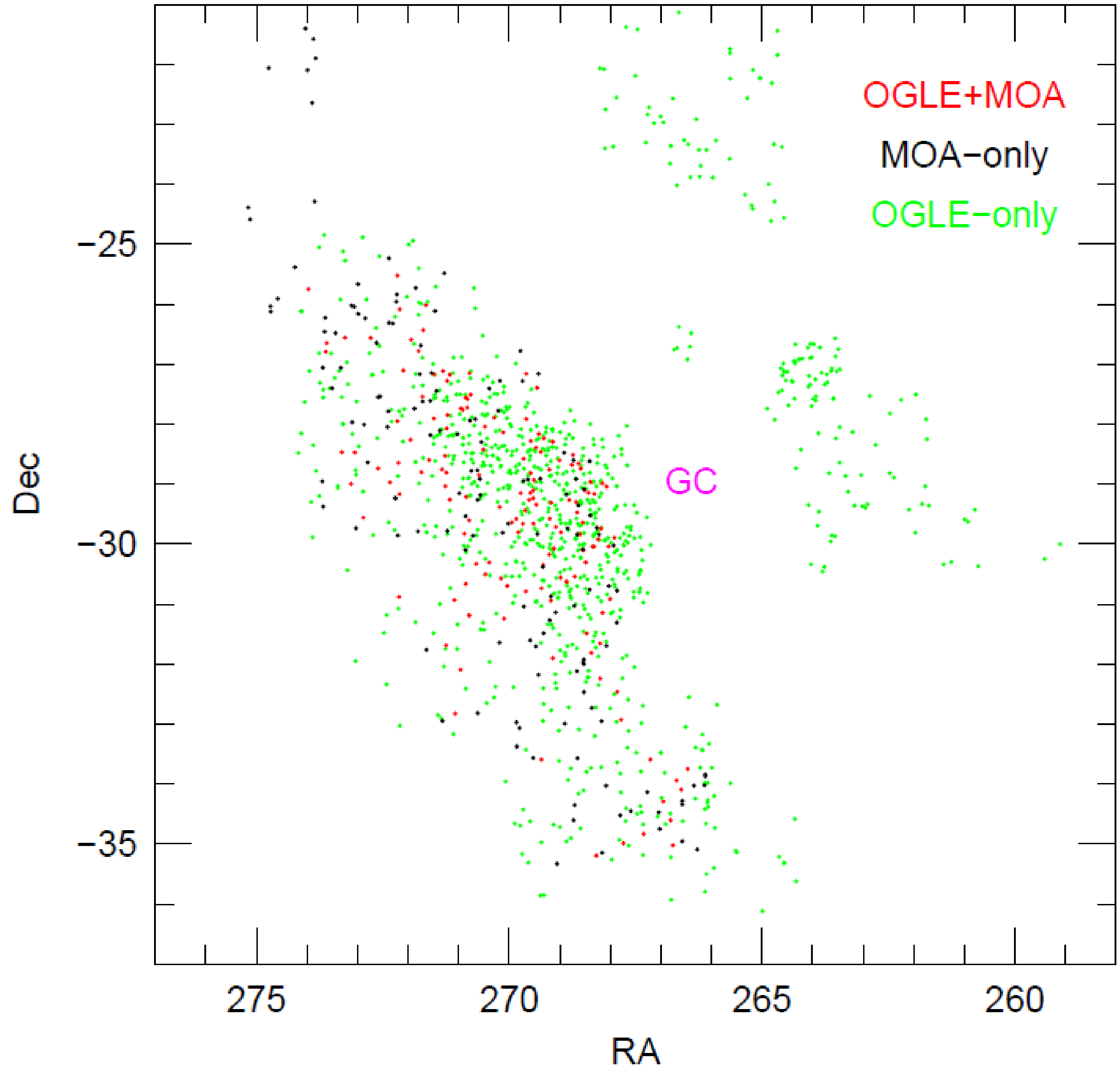
Heidelberg: November 2005

- Participants from France, Germany, Japan, Korea, New Zealand, Poland, UK, US
- Critically reviewed models to predict planet detection and their underlying assumptions
- Presentations about wide range of potential initiatives for implementation
- Generally enthusiastic response

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]

1136 Events (1st half of 2011)



Conclusions

- High-mag μlens events: “controlled sample
- 1st Frequency measurement past snow line
  - 0.36 +- 0.15 /dex^2 at $q = 5e-4$ (saturn mass ratio)
- Solar system: 3 X more giants than average
  - 6 X more likely to have 2 giants
- NextGen experiments will increase 10-fold
  - MOA/OGLE/KMTNet