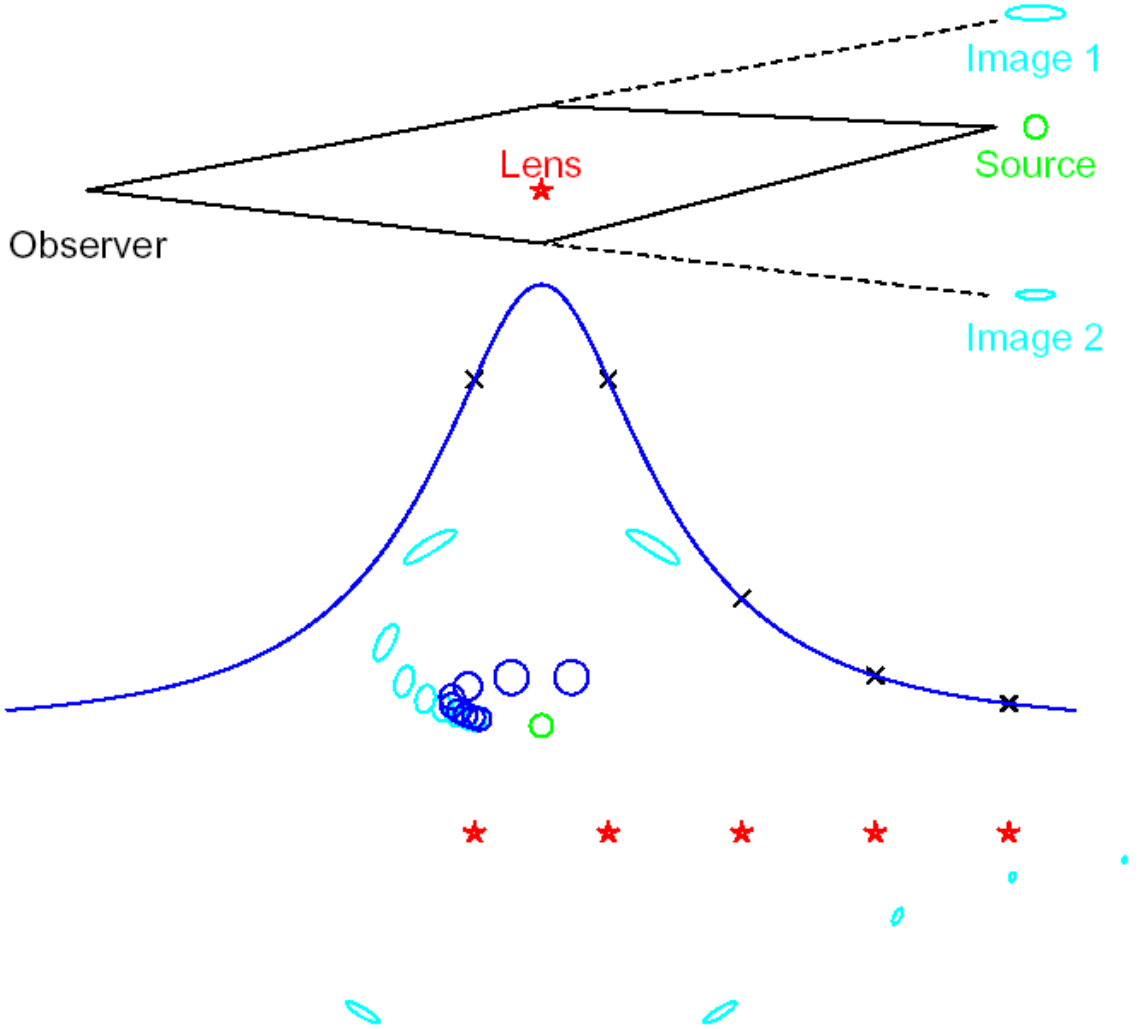
Microlensing: Planets, Dark Stars, and Stellar Magnifying Glasses

Andy Gould (IAP, 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]

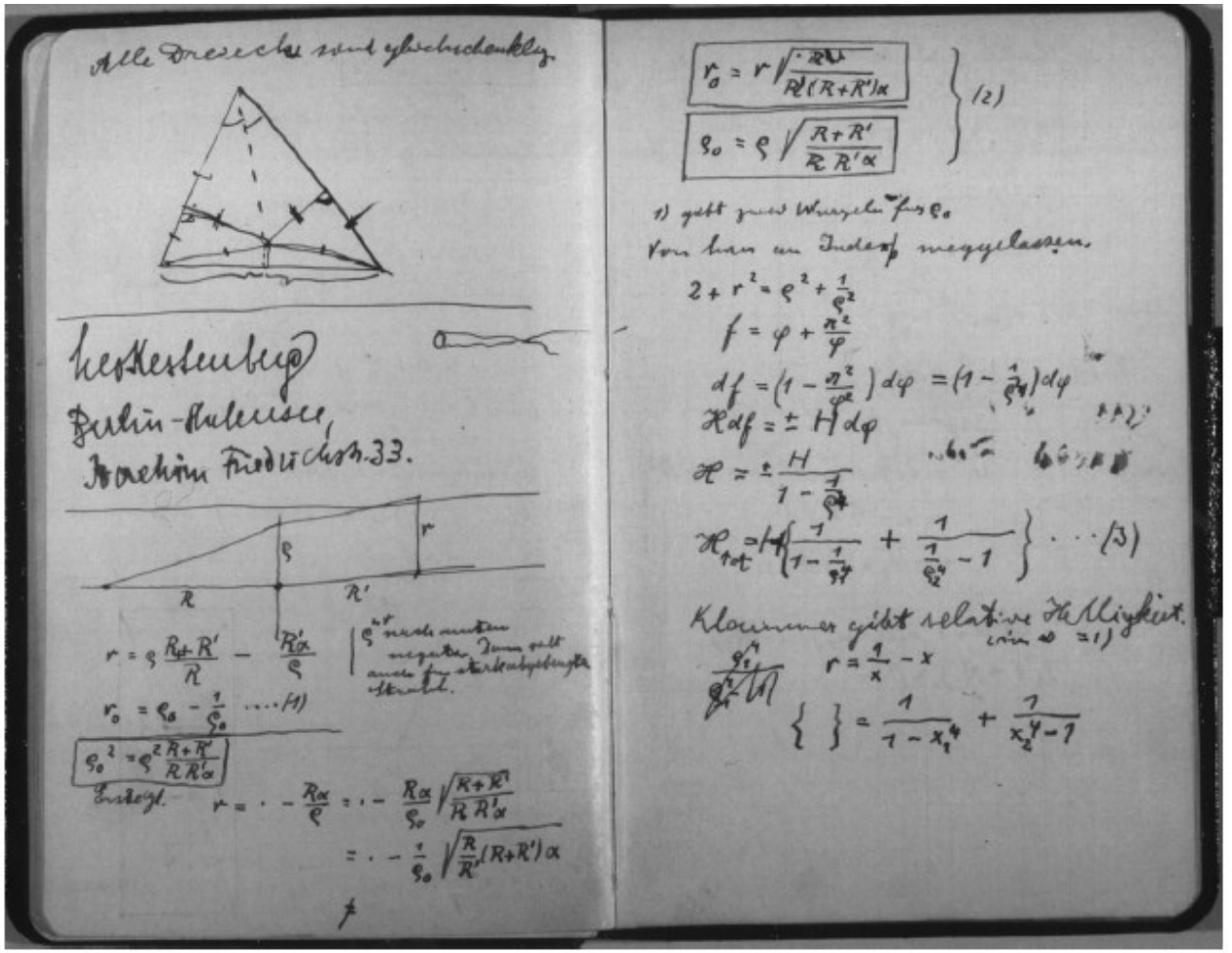


Fig. 1. Notes about gravitational lensing dated to 1912 on two pages of Einstein's scratch notebook (*12*). [Reproduced with permission of the Einstein Archives, Jewish National and University Library, Hebrew University of Jerusalem]

Mao & Paczynski

Microlens Planet Searches

GRAVITATIONAL MICROLENSING BY DOUBLE STARS AND PLANETARY SYSTEMS

SHUDE MAO AND BOHDAN PACZYŃSKI
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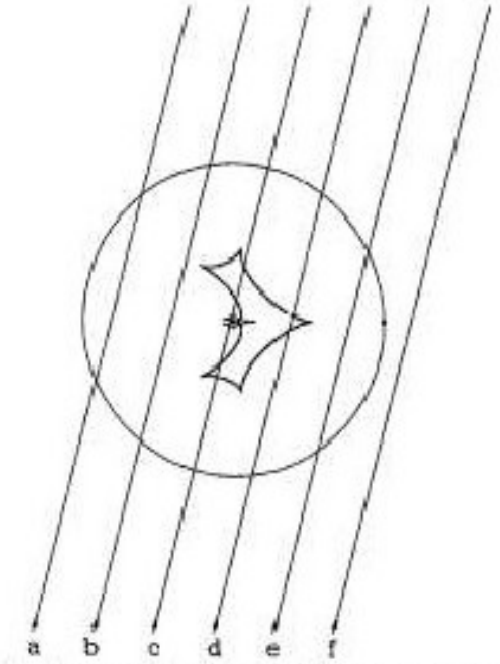
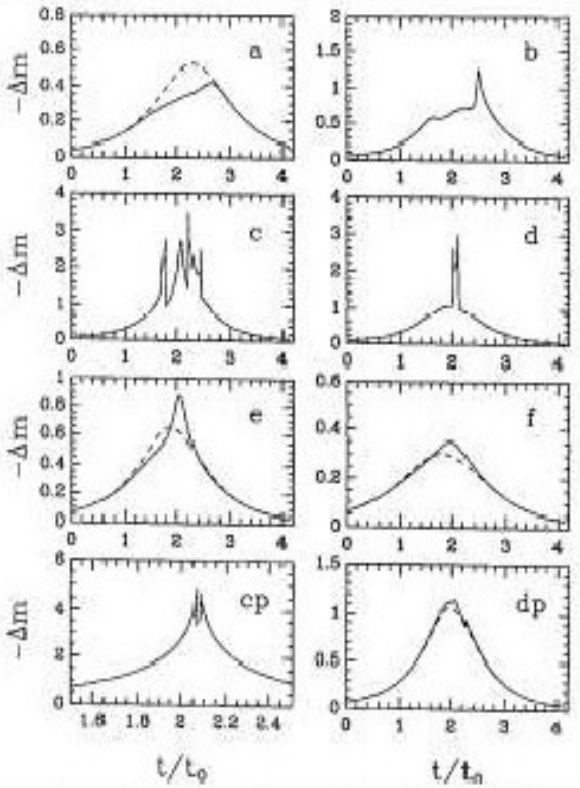
Received 1991 March 12; accepted 1991 April 2



. 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



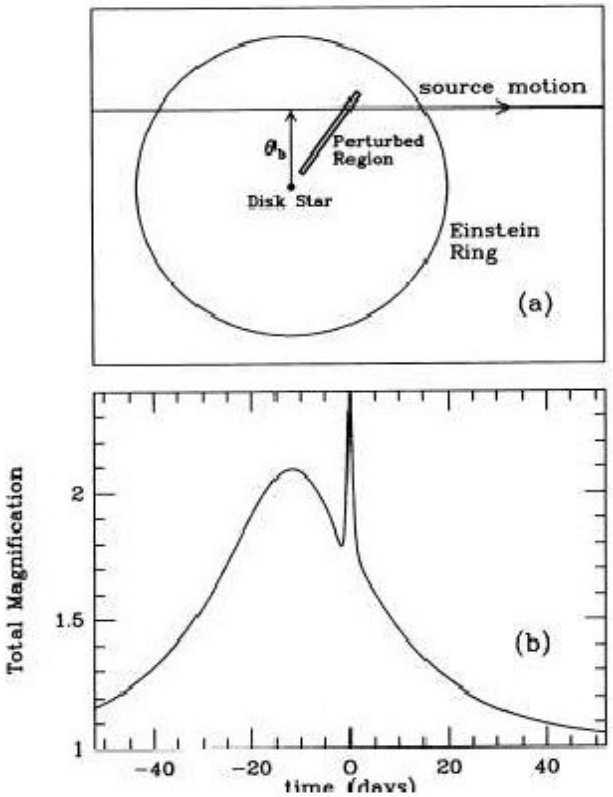
the lens. The effect is strong even if the companion is a planet. A massive search for microlensing of the Galactic bulge stars may lead to a discovery of the first extrasolar planetary systems.

Gould & Loeb

Survey + Follow-Up

DISCOVERING PLANETARY SYSTEMS THROUGH GRAVITATIONAL MICROLENSES

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

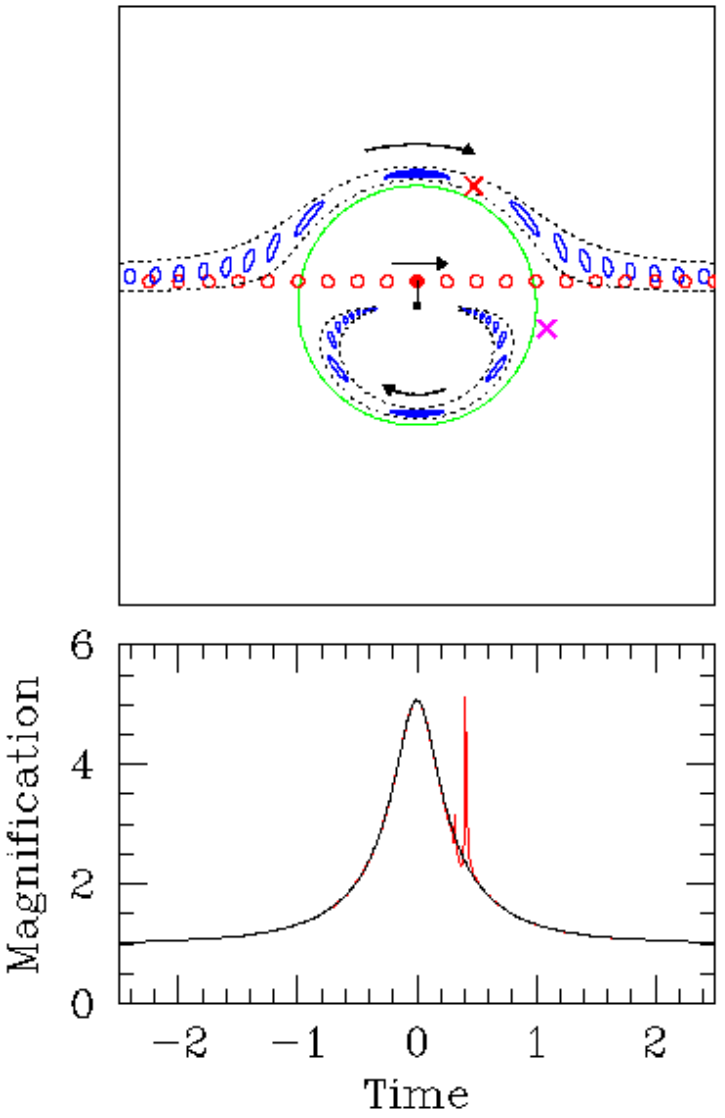


5. OBSERVATIONAL REQUIREMENTS

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.

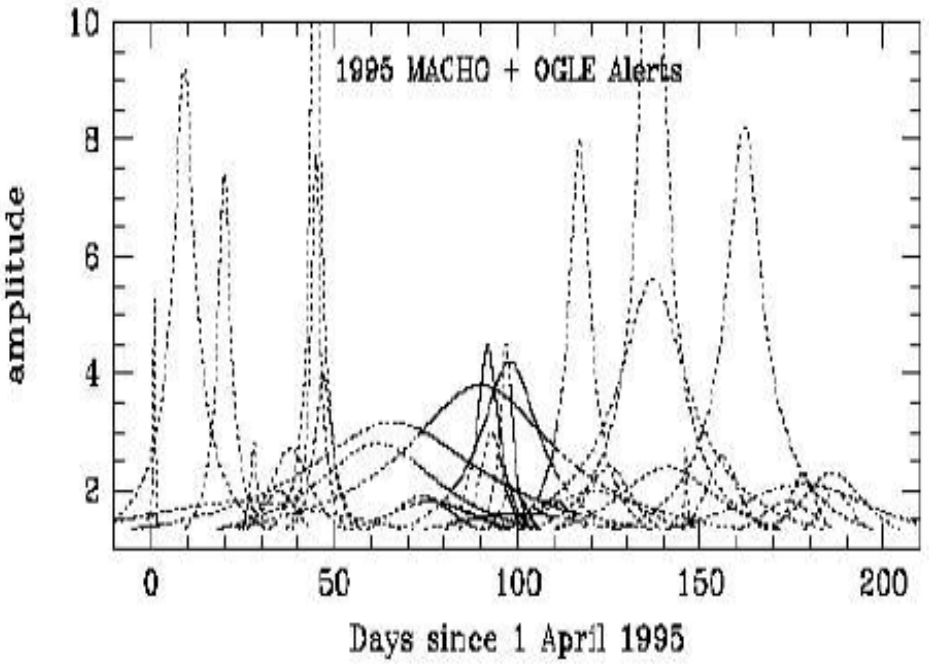
While observations from one site would be useful, there are advantages to be gained by observing from several sites. First, two telescopes that were totally committed. Third, in view of the fleeting nature of the events, it would seem prudent to build in some redundancy in case of bad weather at a particular 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,

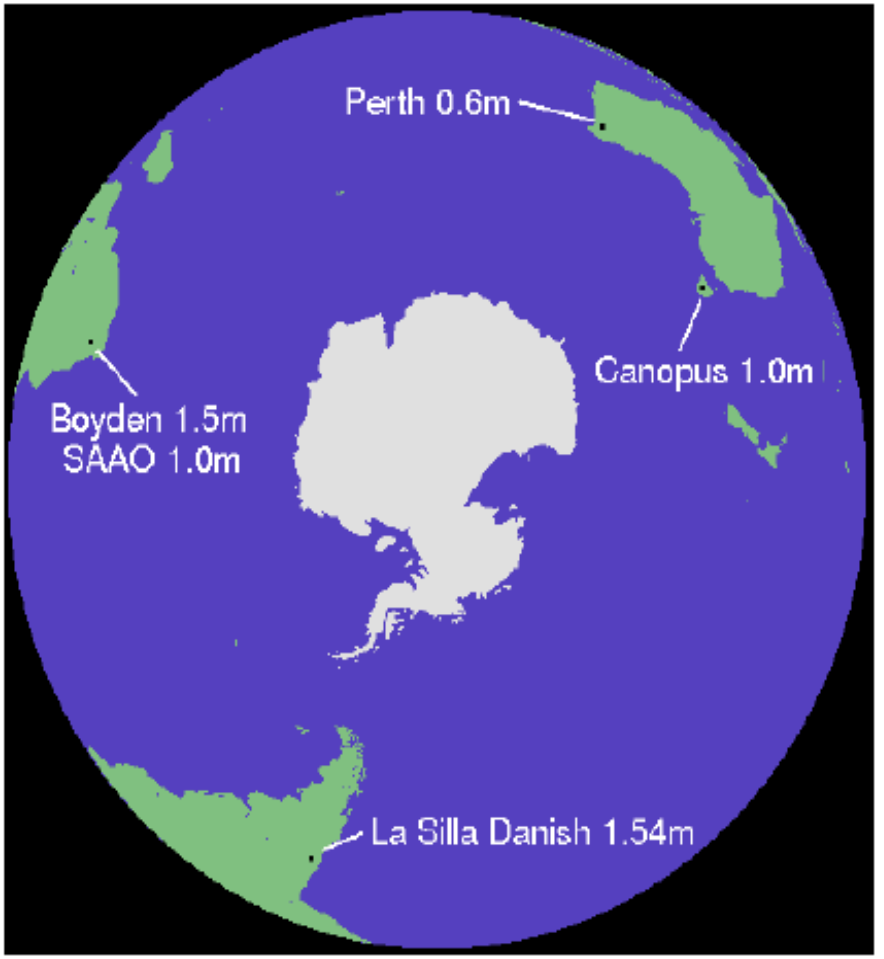
How Microlensing Finds Planets



1995 PLANET Pilot Season

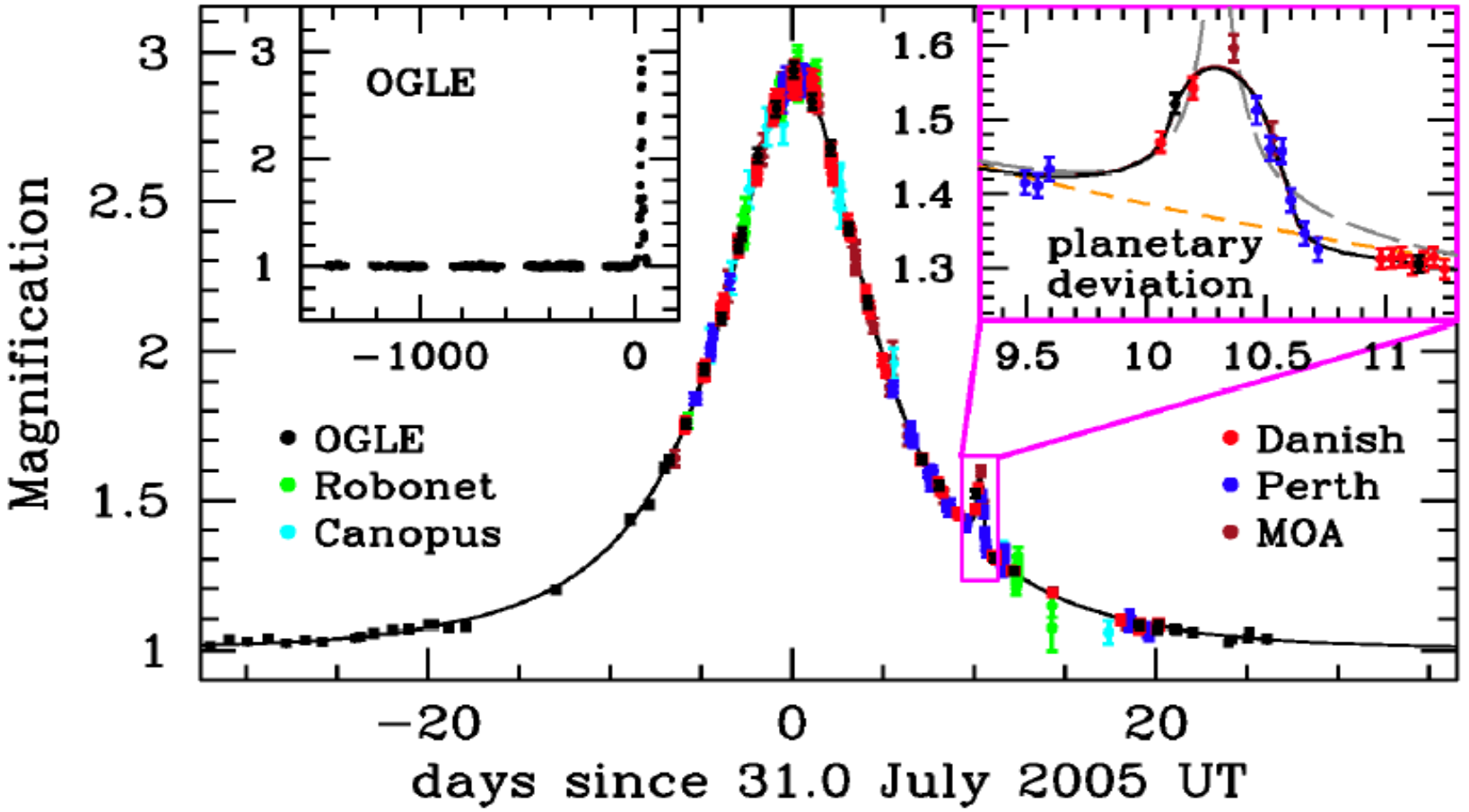
- Albrow et al. 1998 ApJ, 509, 687





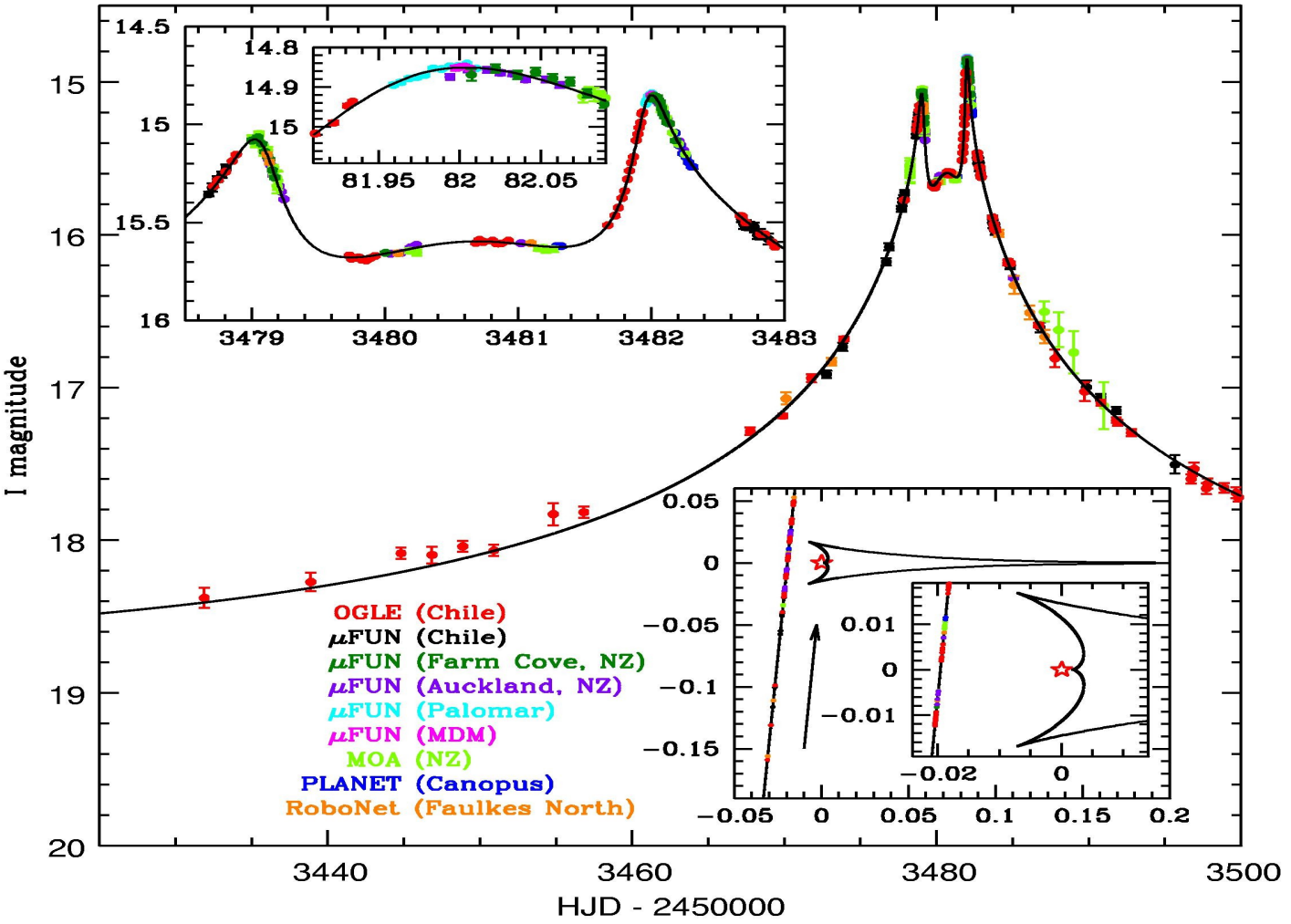
OGLE-2005-BLG-390

"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."

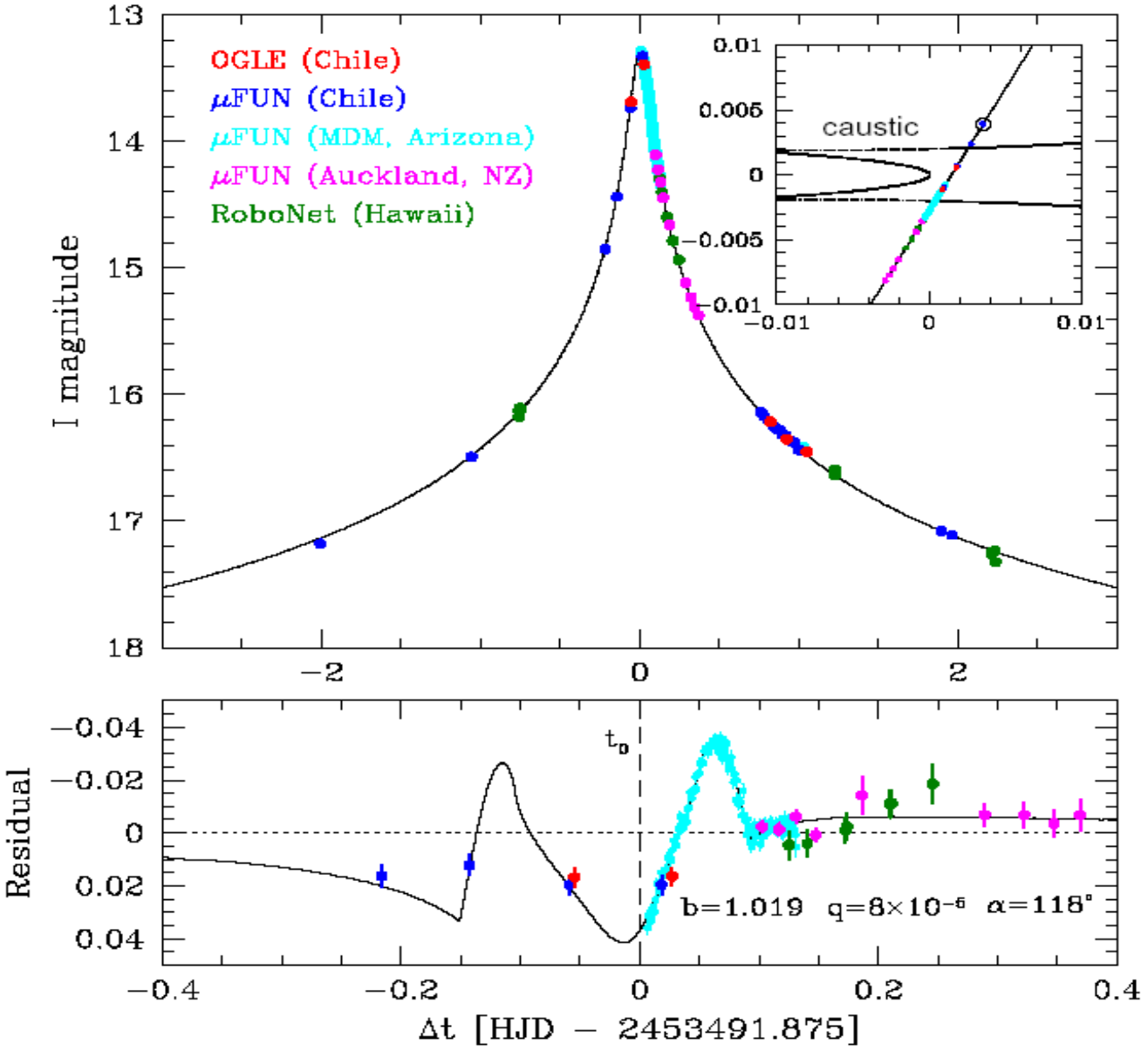
Jennie McCormick
(Amateur Astronomer, Auckland, New Zealand)

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

Book of Piano Classics
MODERN PHYSICS
NUMERICAL RECIPES in C
OHIO STATE

Tale of Two Planets

OGLE-2005-BLG-390

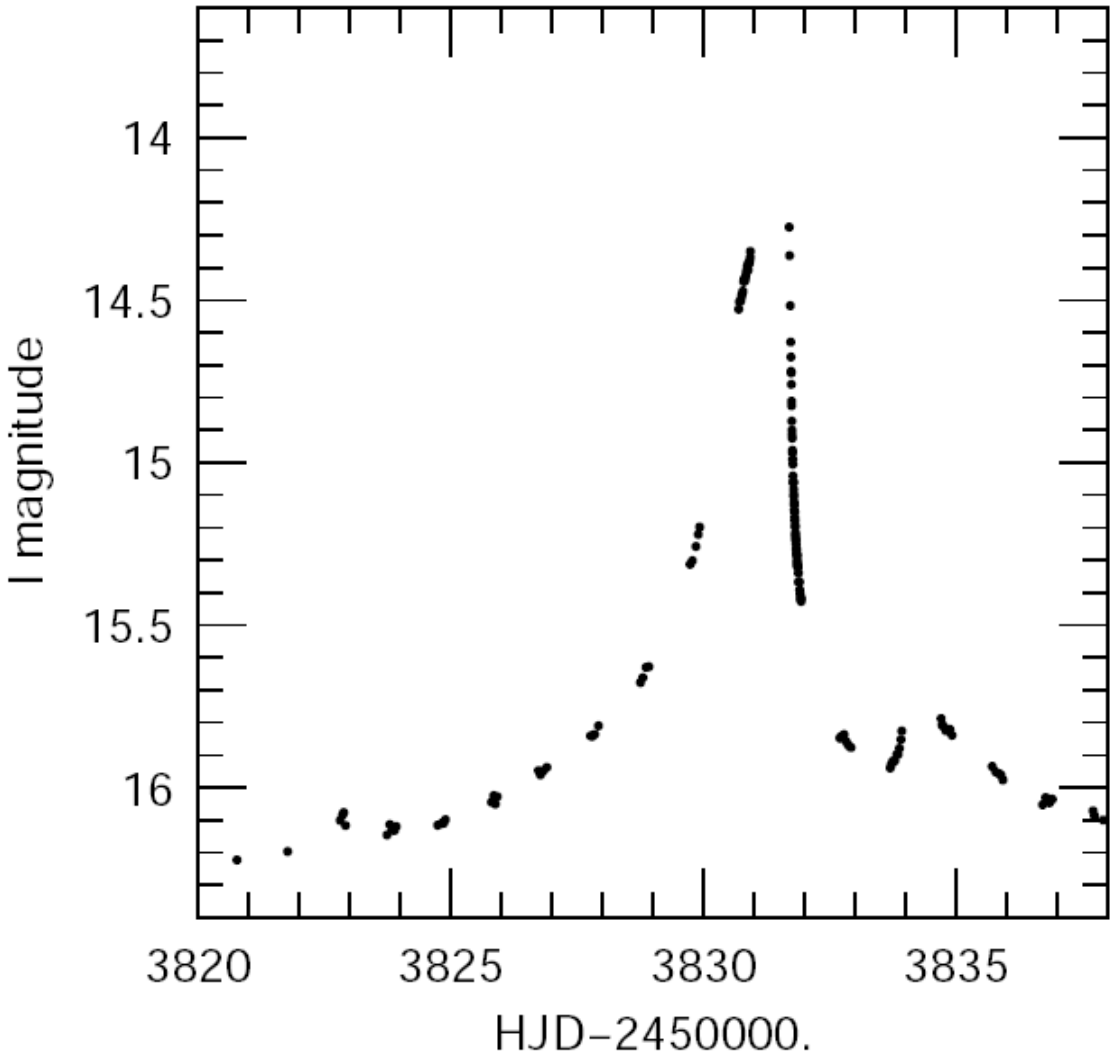
- q = 8e-5
- M_* = 0.2 M_sun
- M_p = 5.5 M_earth
- D = 7 kpc
- a = 3 AU
- T = 50 K
- Low-mag Event
- (1 det)/(4.4 probed)

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)

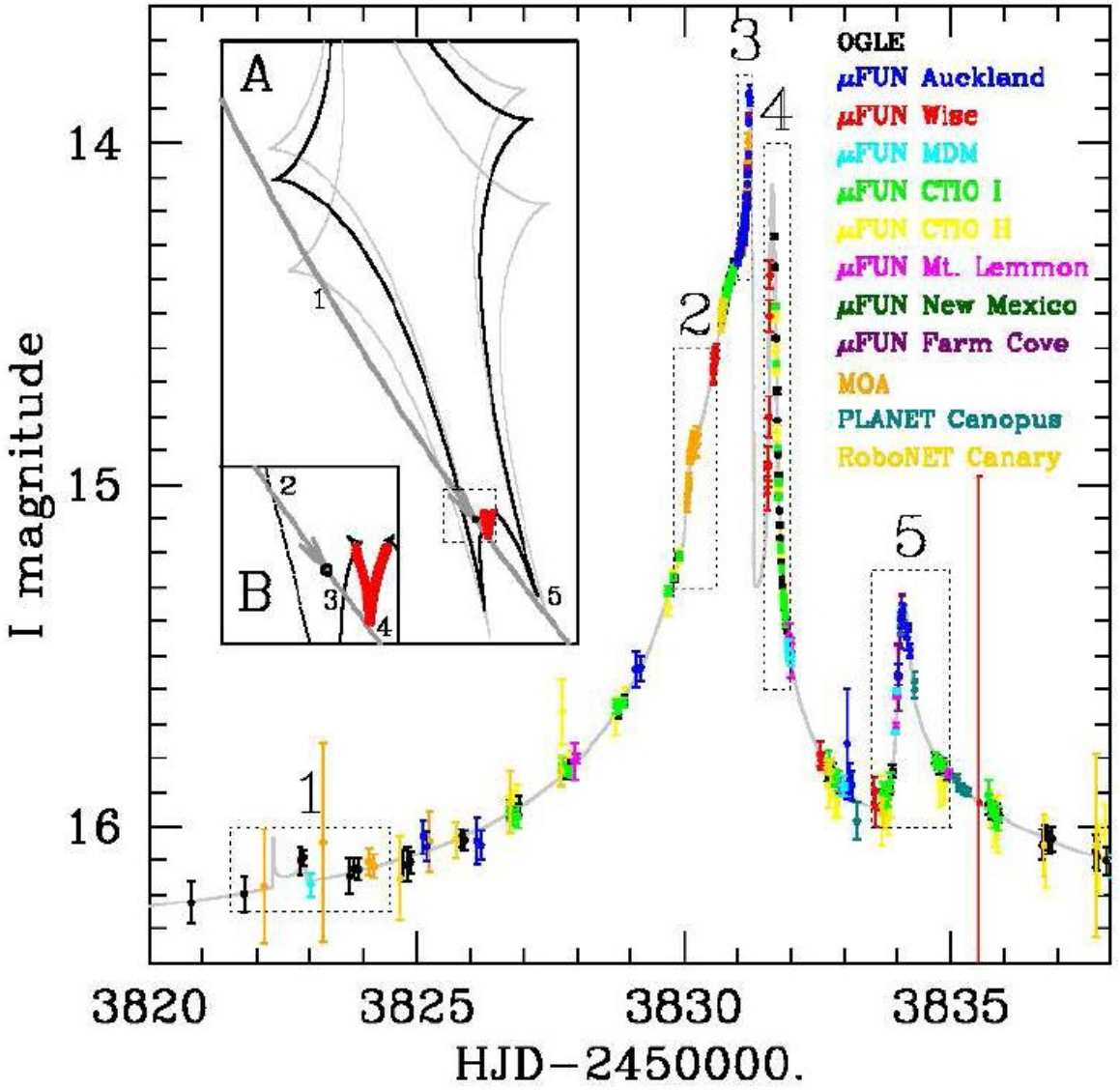
OGLE-2006-BLG-109:

Without Followup Observations



OGLE-2006-BLG-109

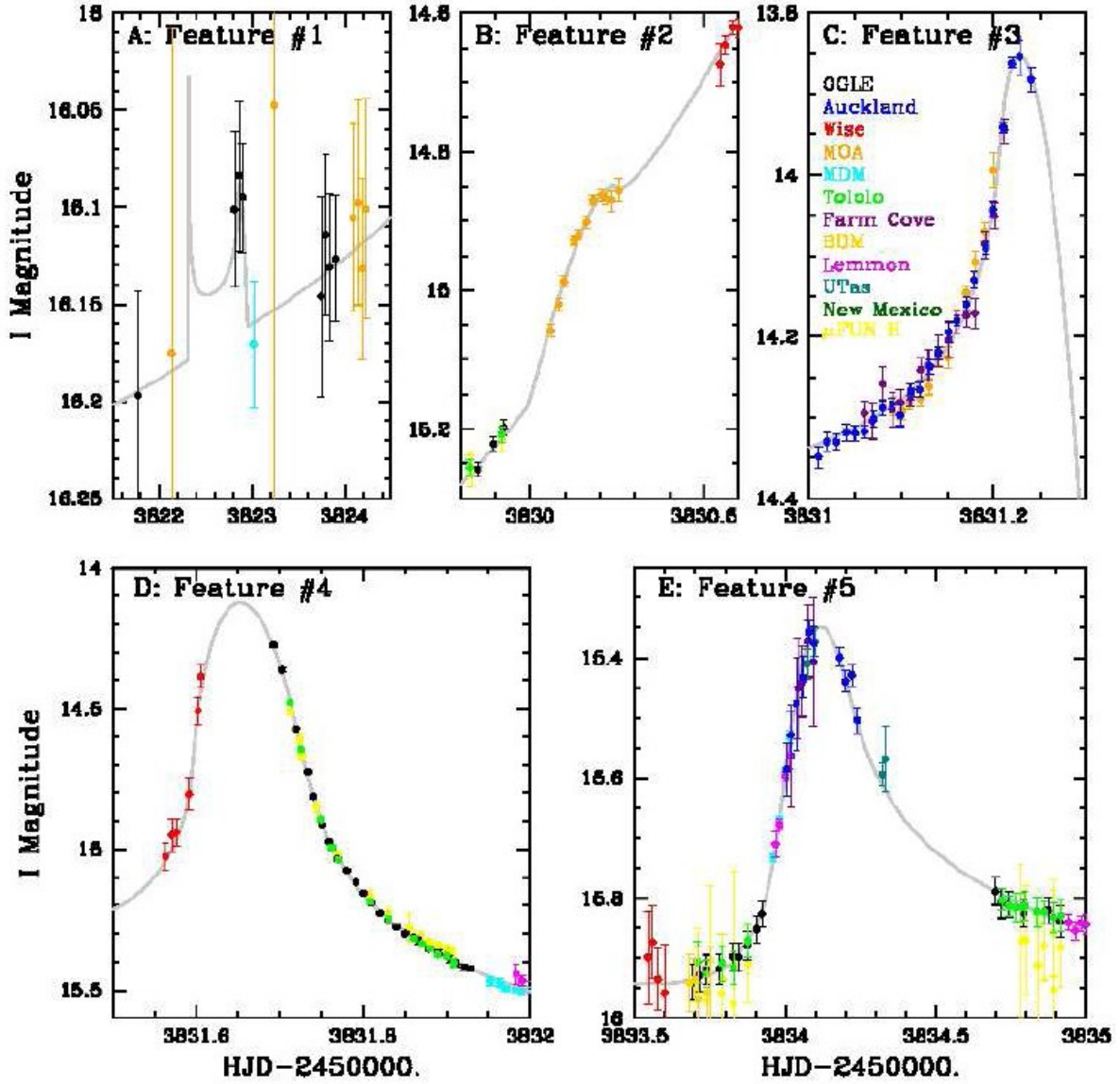
Parallax+Finite-Source+Rotation+Blend



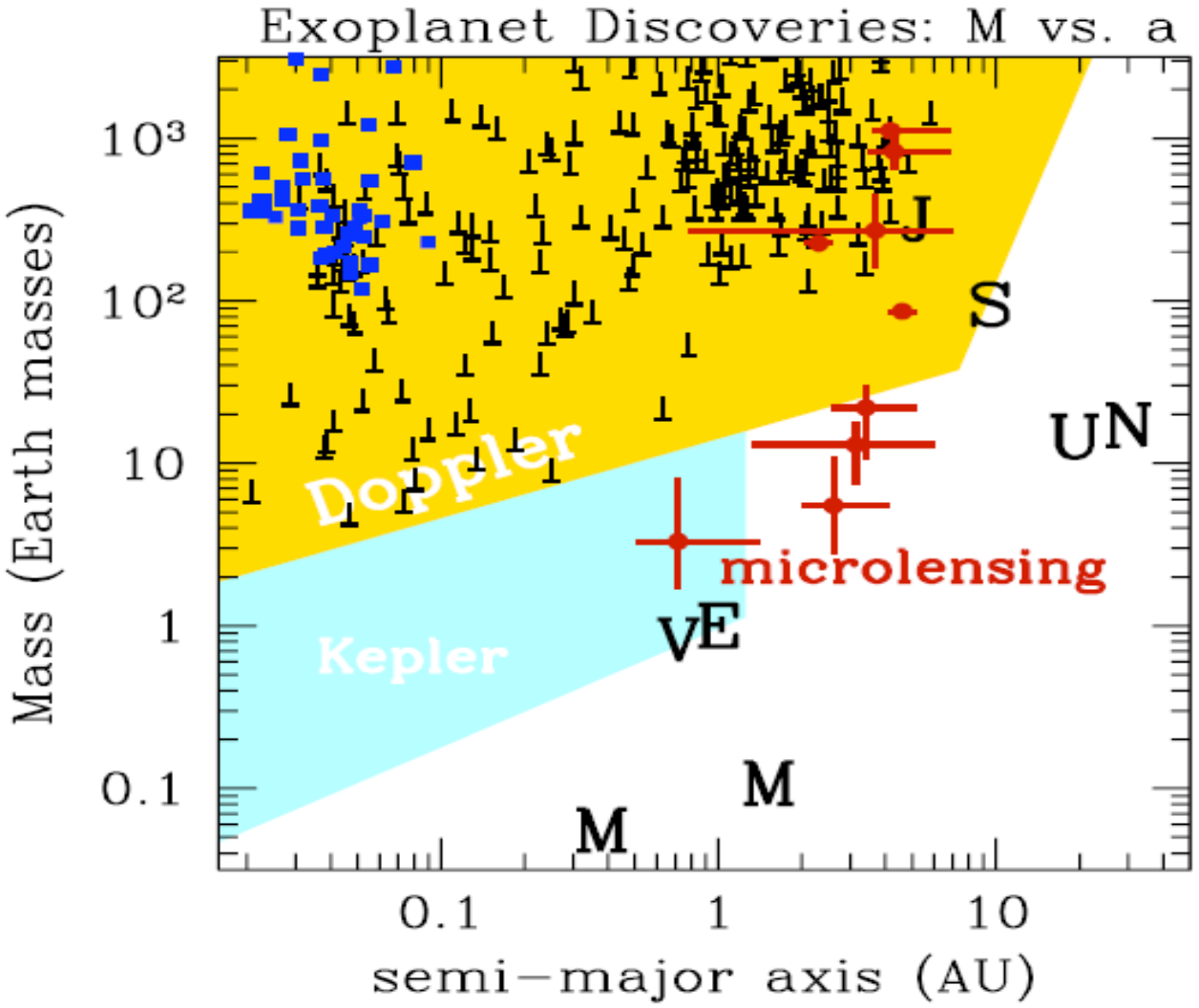
Gaudi et al. 2008, Science, 319, 927

Five Lightcurve Features

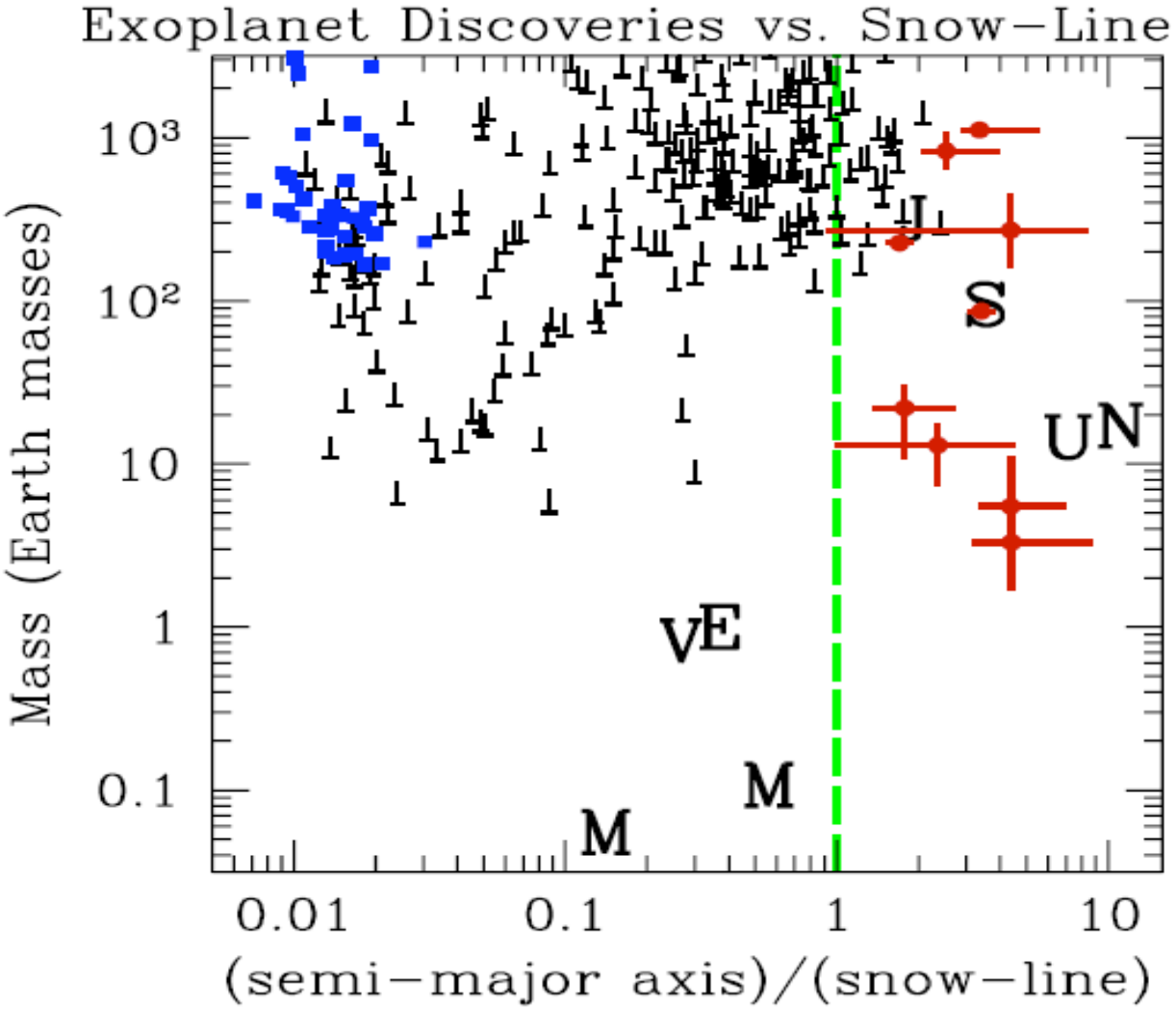
1+2+3+5=Saturn 4=Jupiter



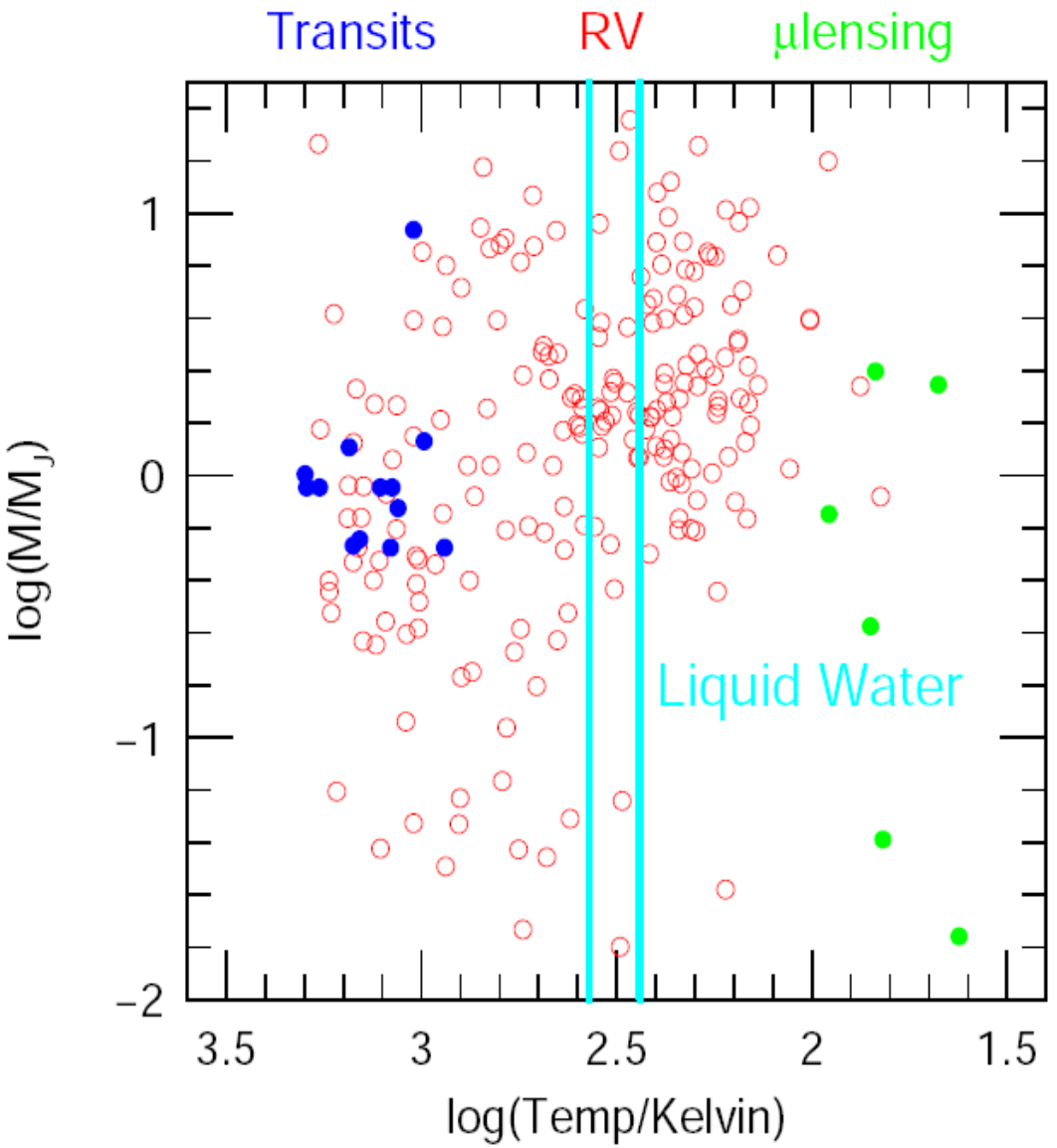
Microlensing vs. Other Methods



Microlensing and the "Snow Line"

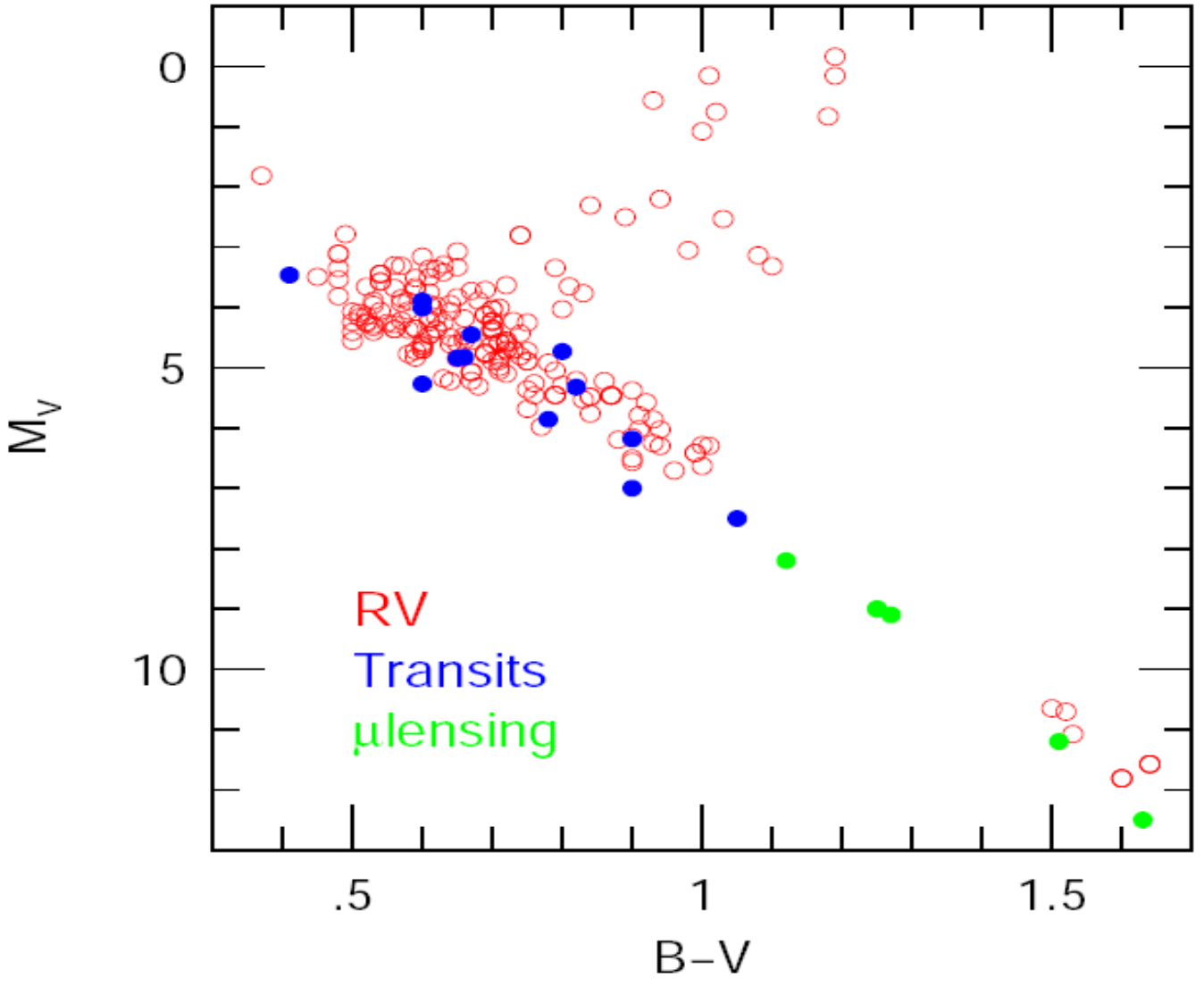


Equilibrium Temperature



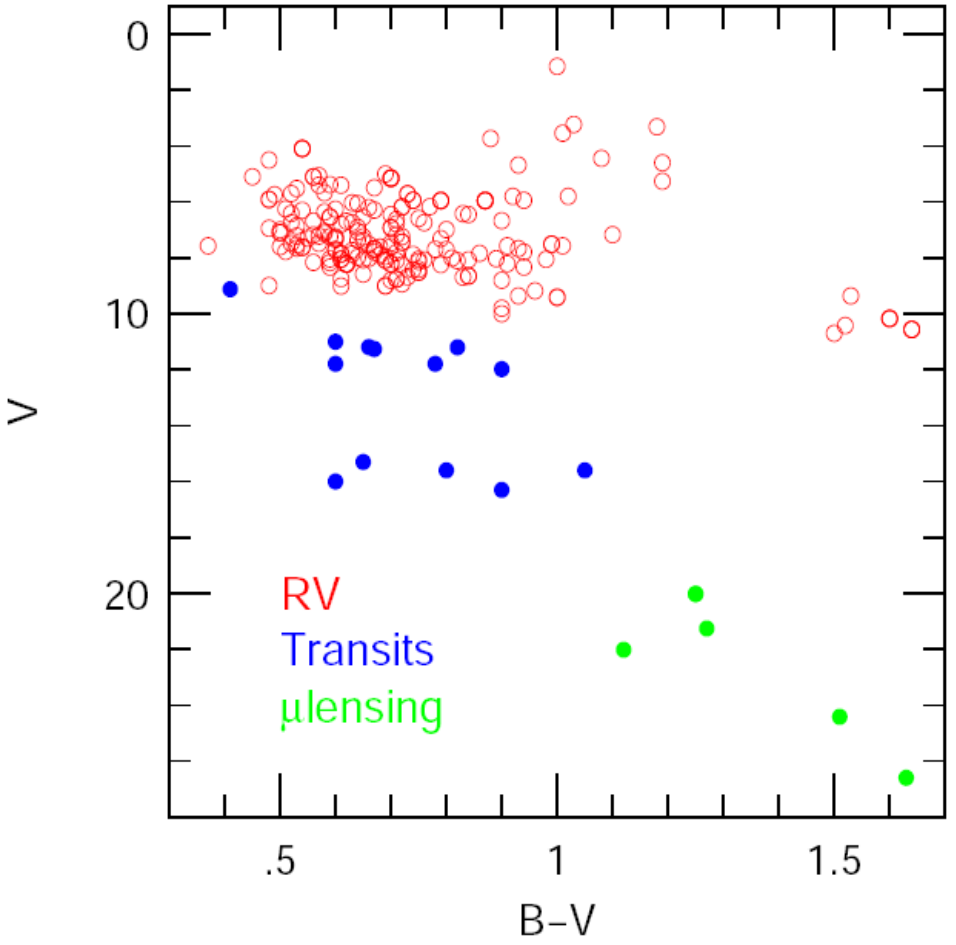
Selection biases:

CMD (Absolute mags)

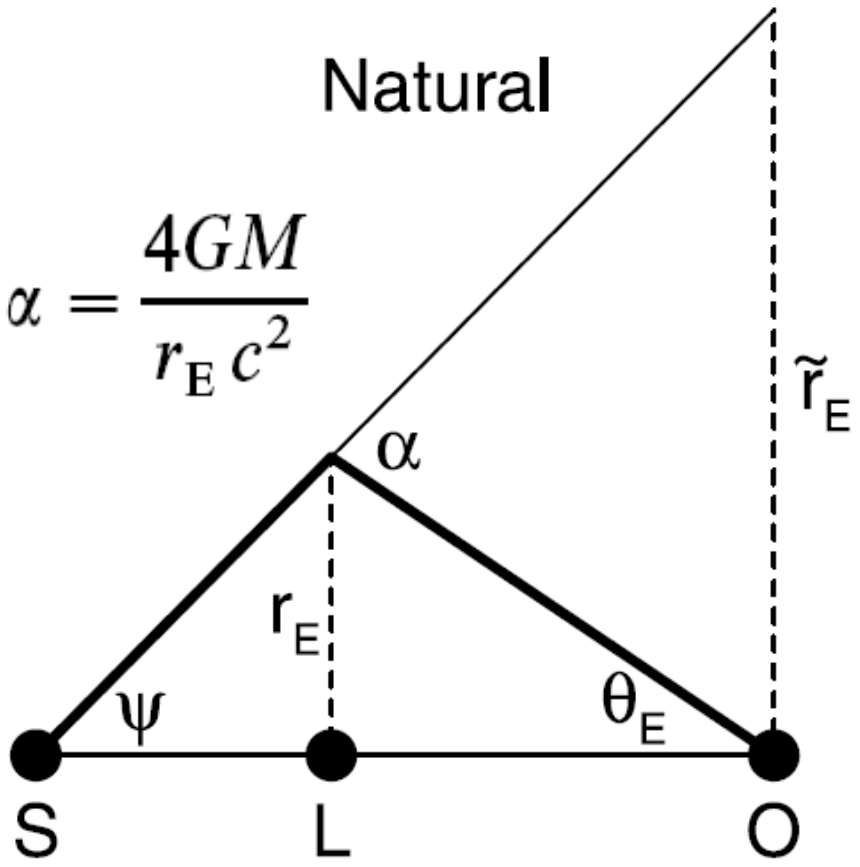


Selection Biases:

CMD (Apparent Mags)



Relation of Mass and Distance to Lensing Observables



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

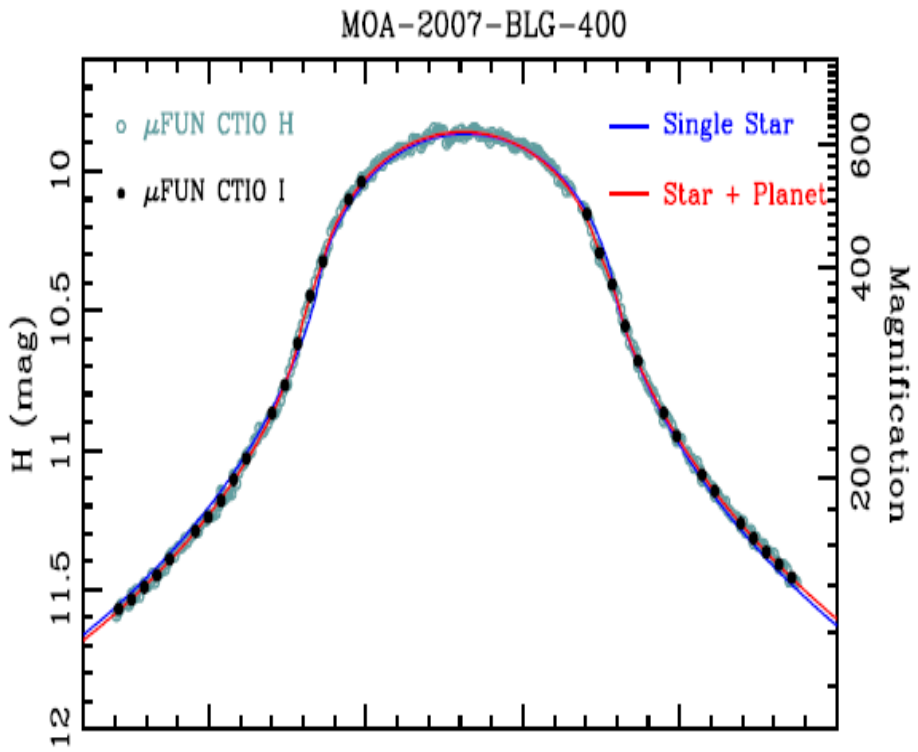
$$\theta_E \tilde{r}_E = \alpha r_E = \frac{4GM}{c^2}$$

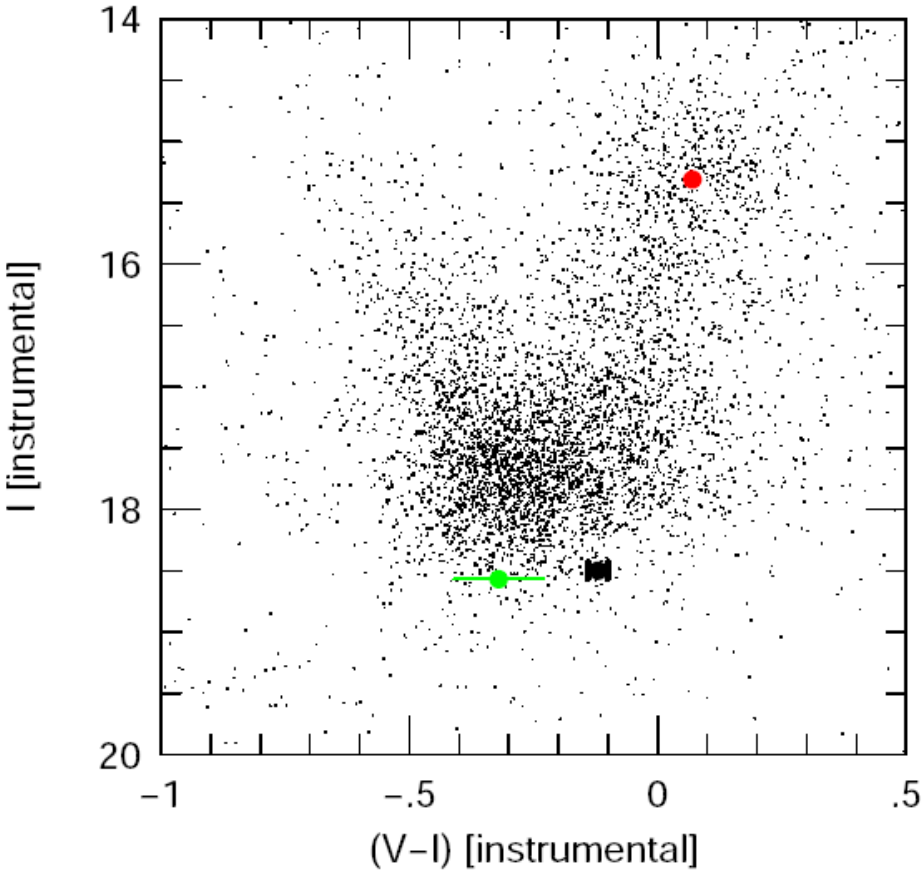
$$\theta_E = \alpha - \psi = \frac{\tilde{r}_E}{D_l} - \frac{\tilde{r}_E}{D_s} = \frac{\tilde{r}_E}{D_{rel}}$$

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

To measure angular Einstein radius:

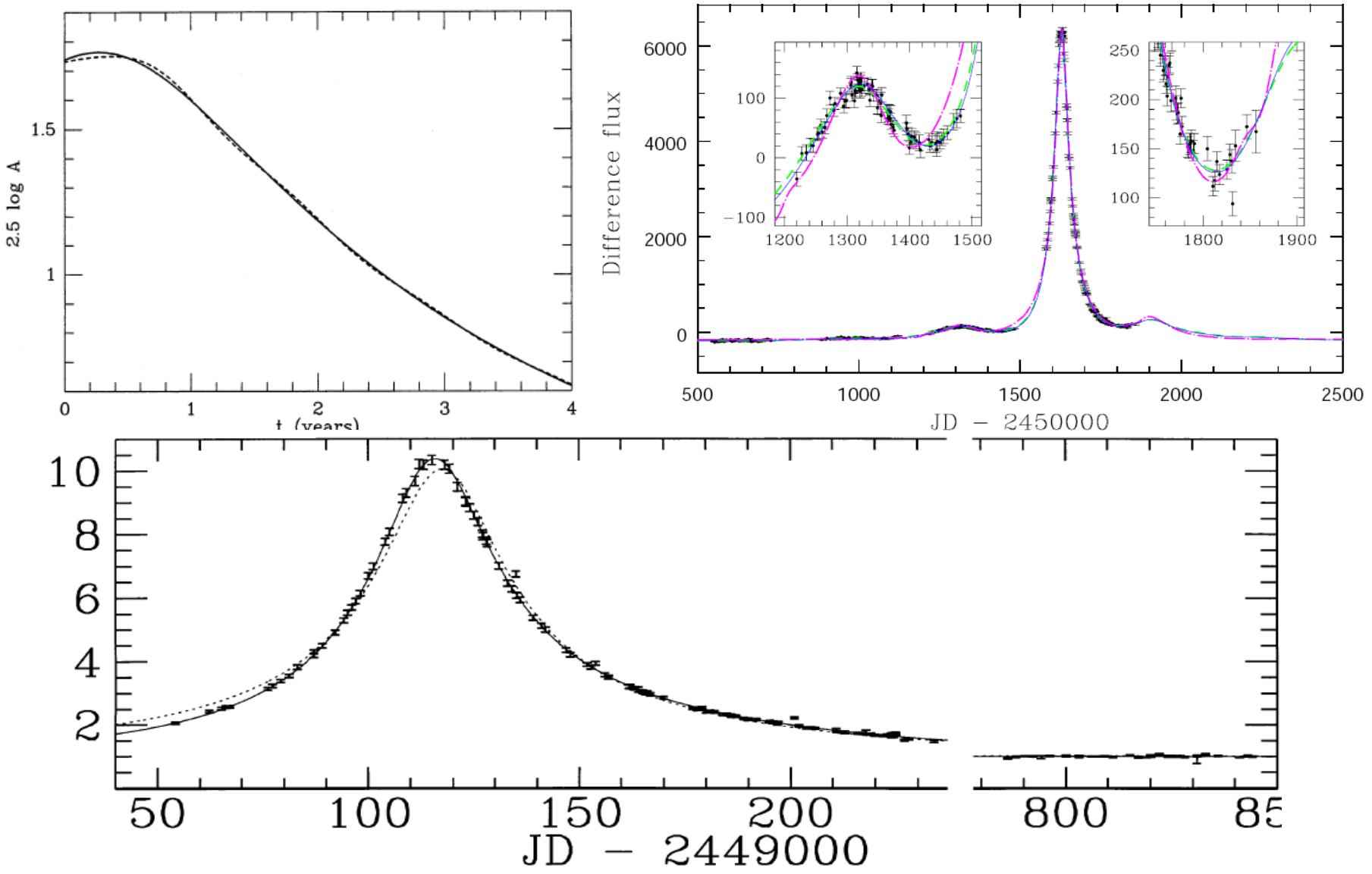
Standard Sky-Plane Rulers





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

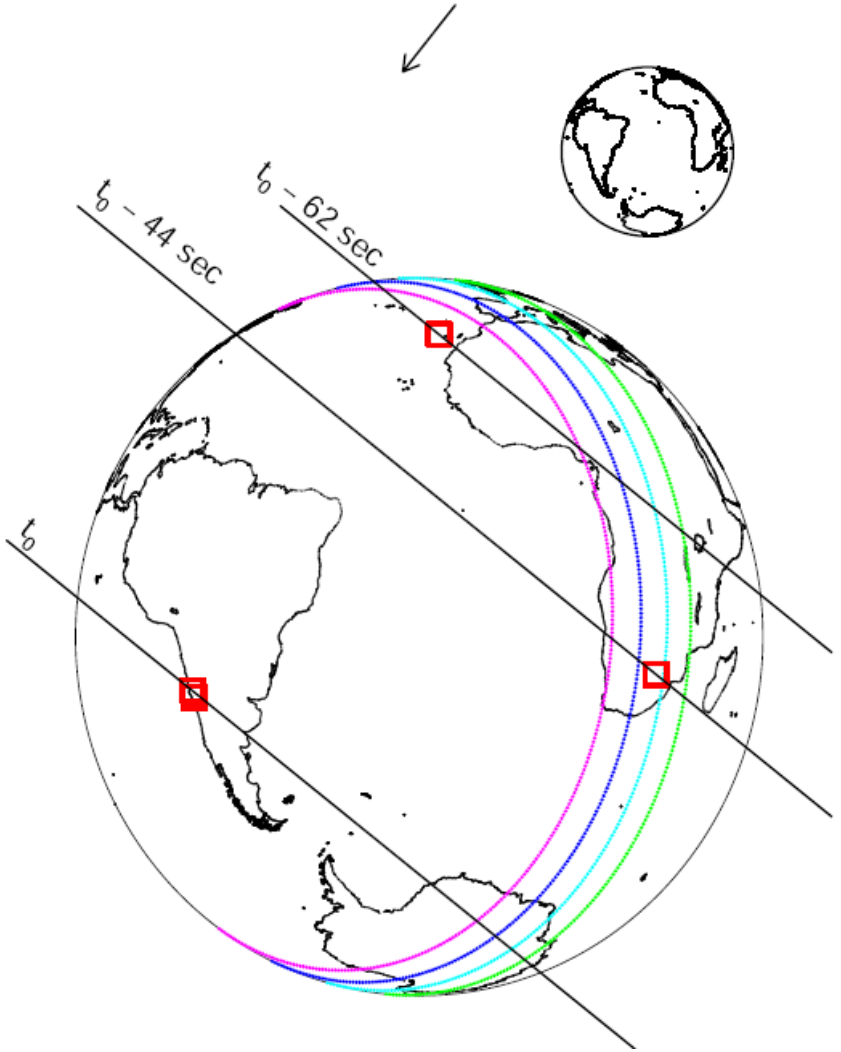
ABSTRACT

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

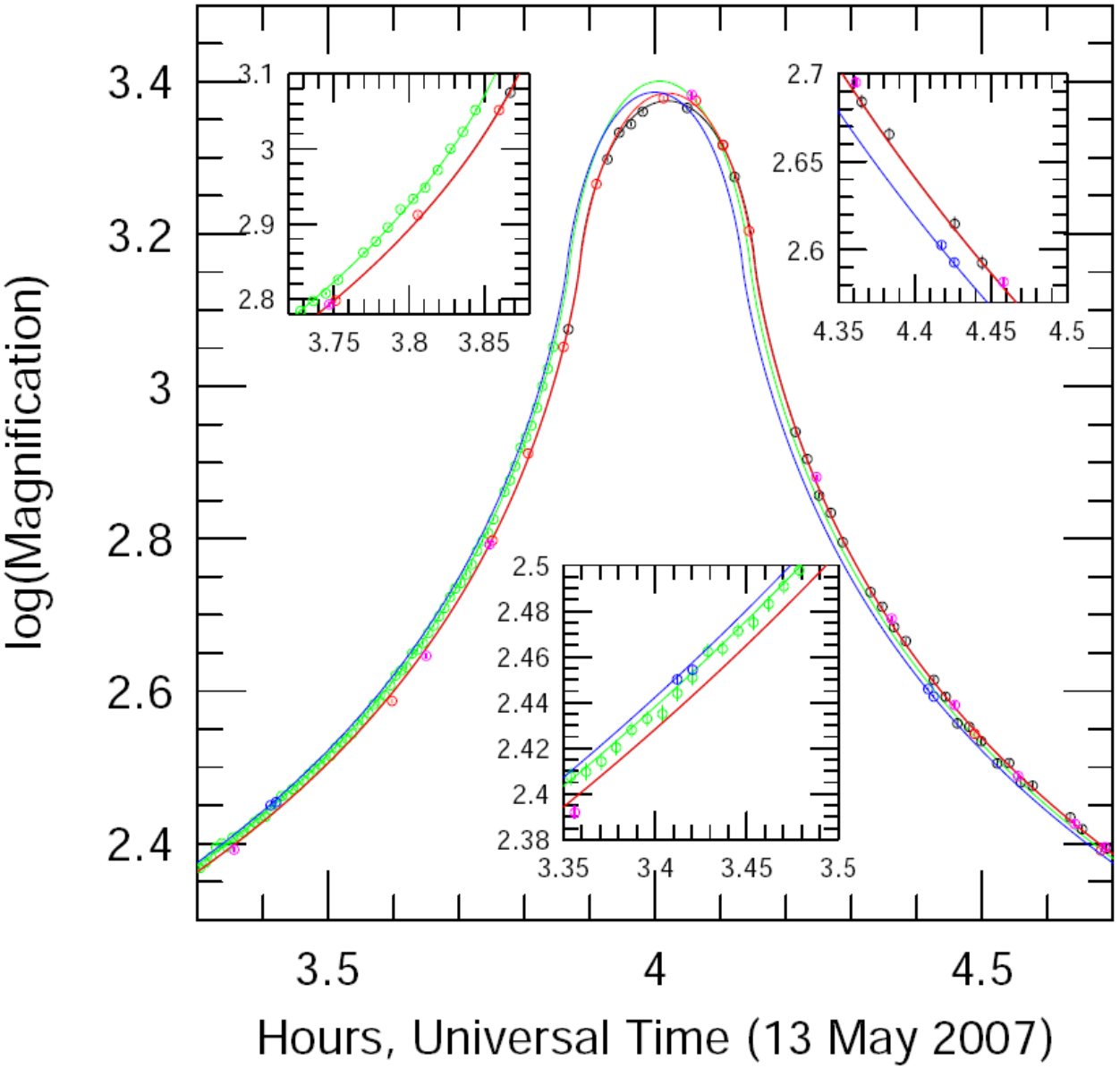
Terrestrial Parallax:

Simultaneous Observations on Earth



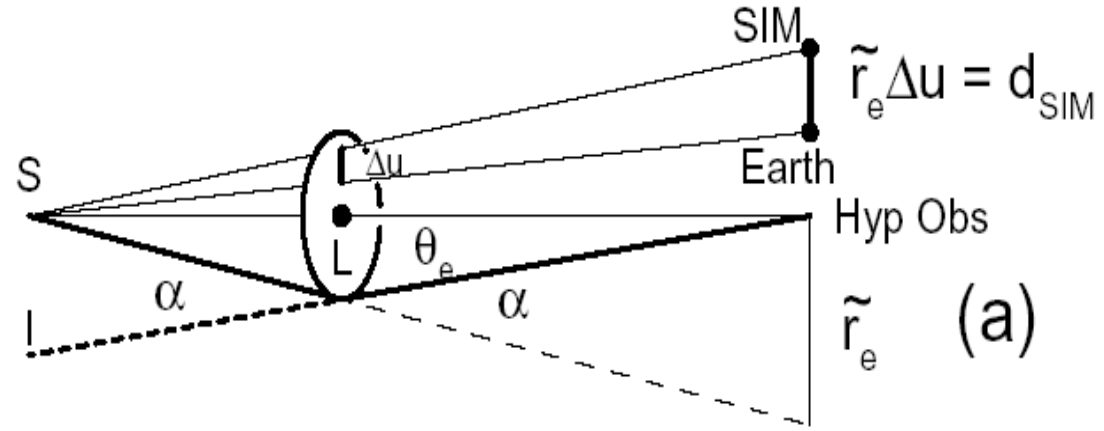
OGLE-2007-BLG-224

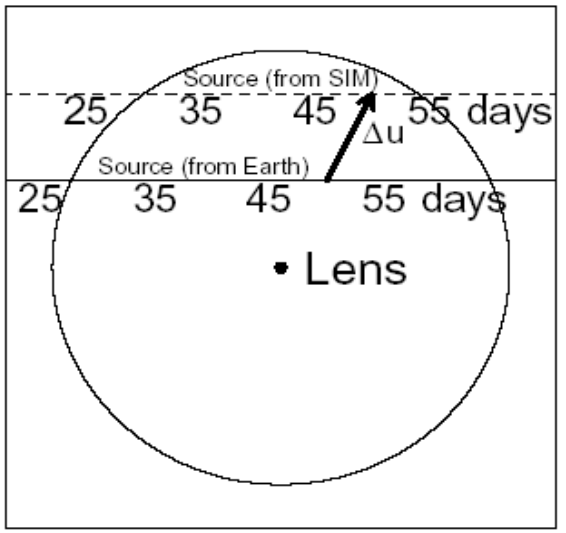
Canaries South Africa Chile



Space-Based Parallaxes

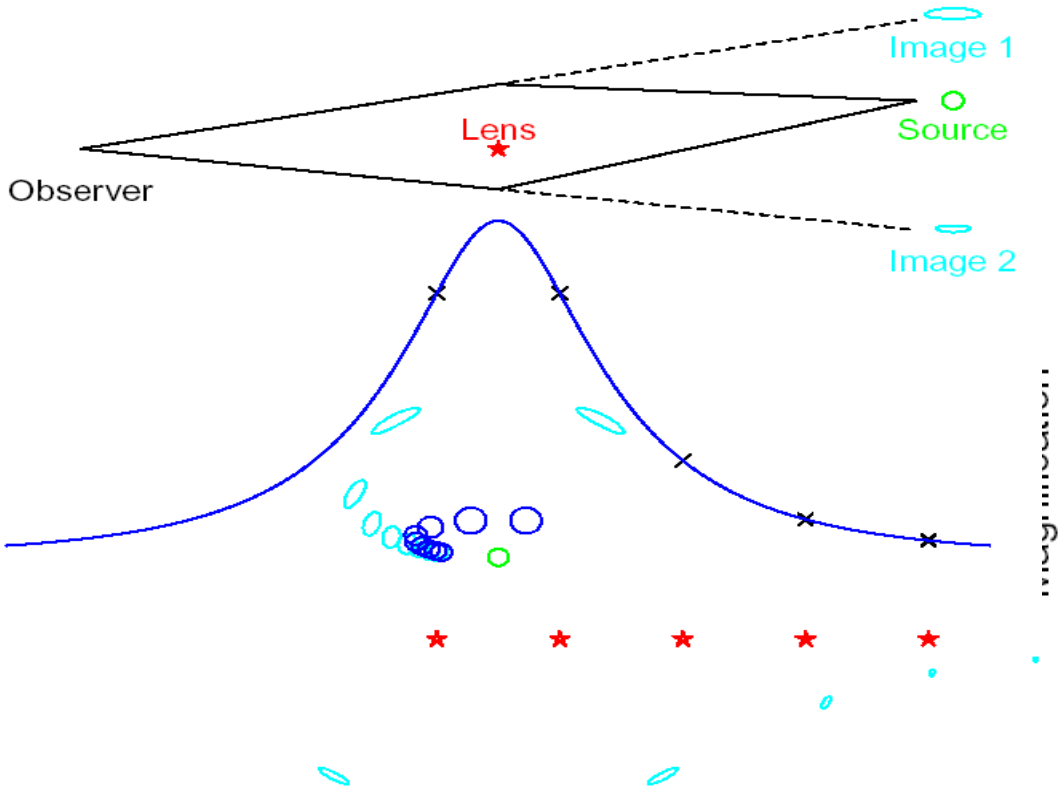
& Einstein Radii : SIM

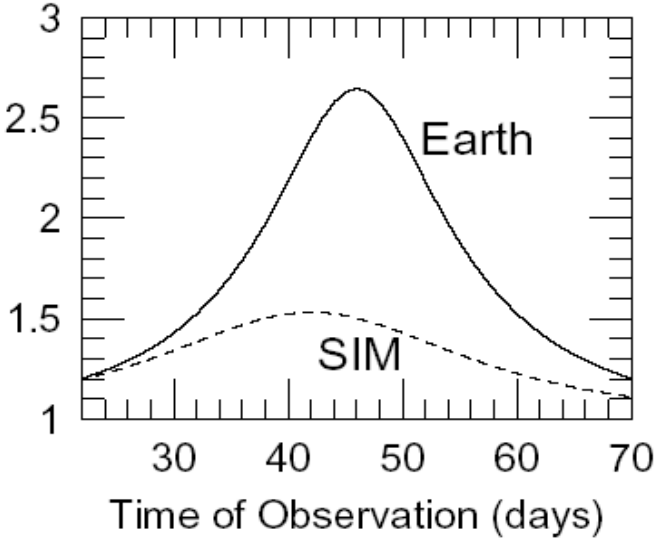




$$\tilde{r}_e = \frac{d_{SIM}}{\Delta u}$$

(b)

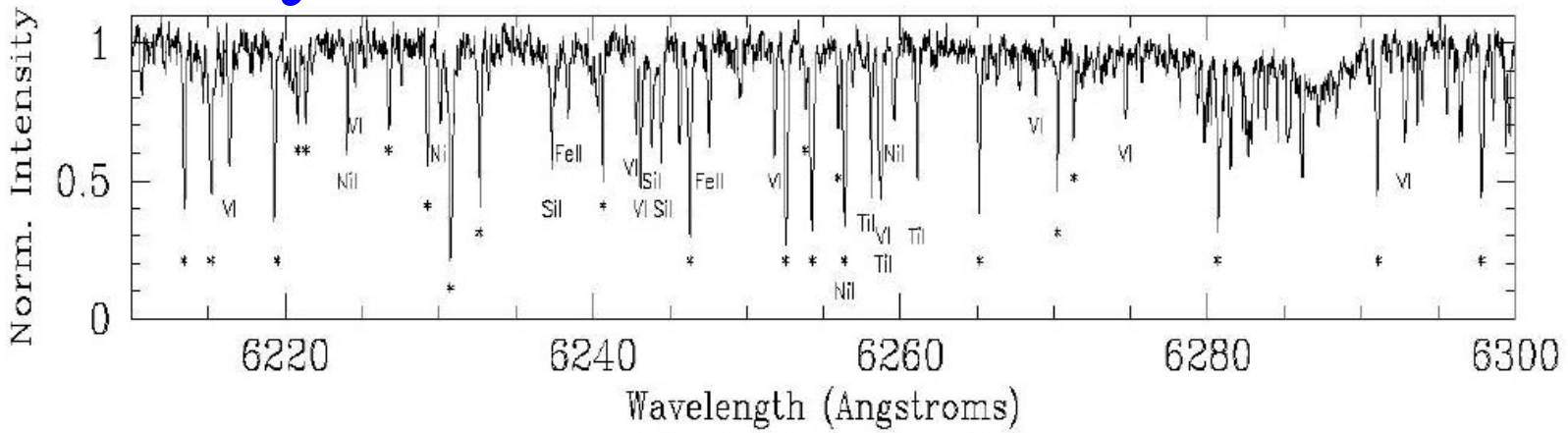




(c)

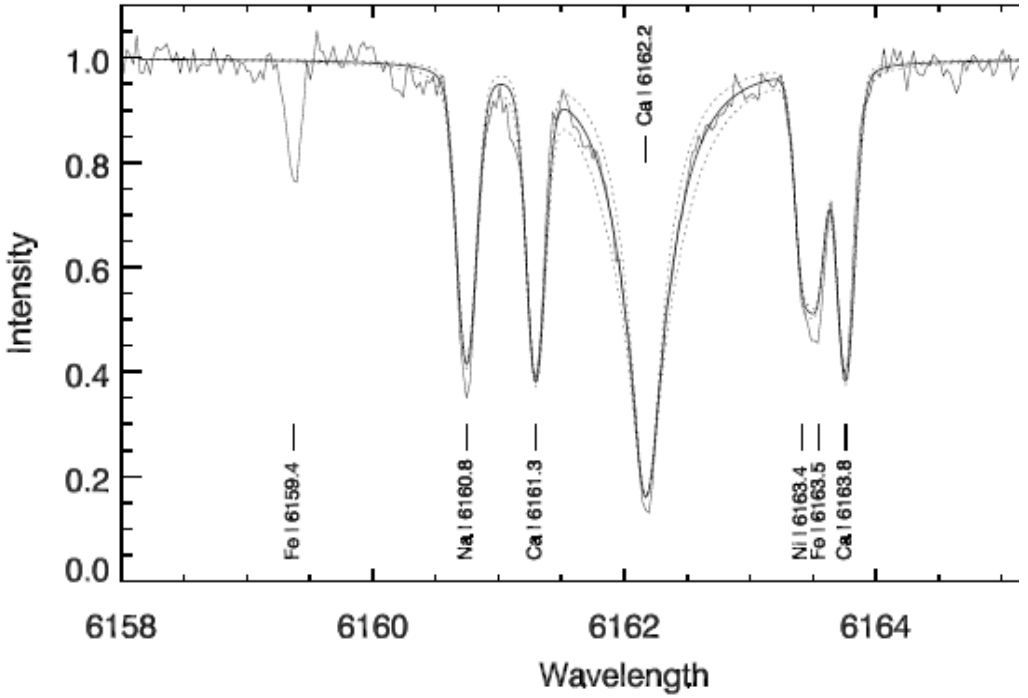
2006: 15 minute Keck Spectrum of OGLE-2006-BLG-265 at A=135

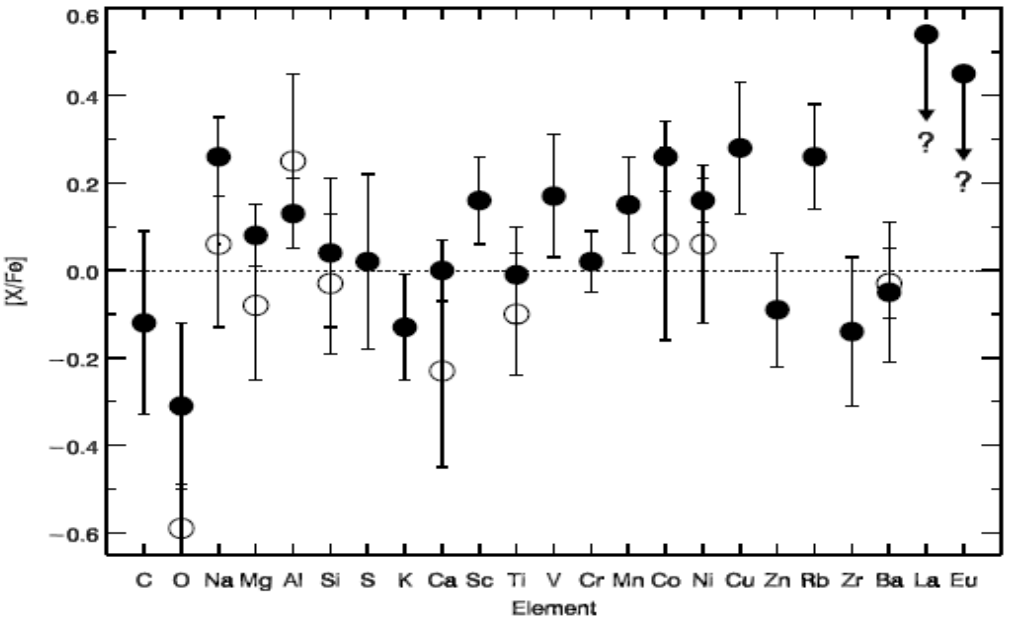
Avishay Gal-Yam & Joshua Simon

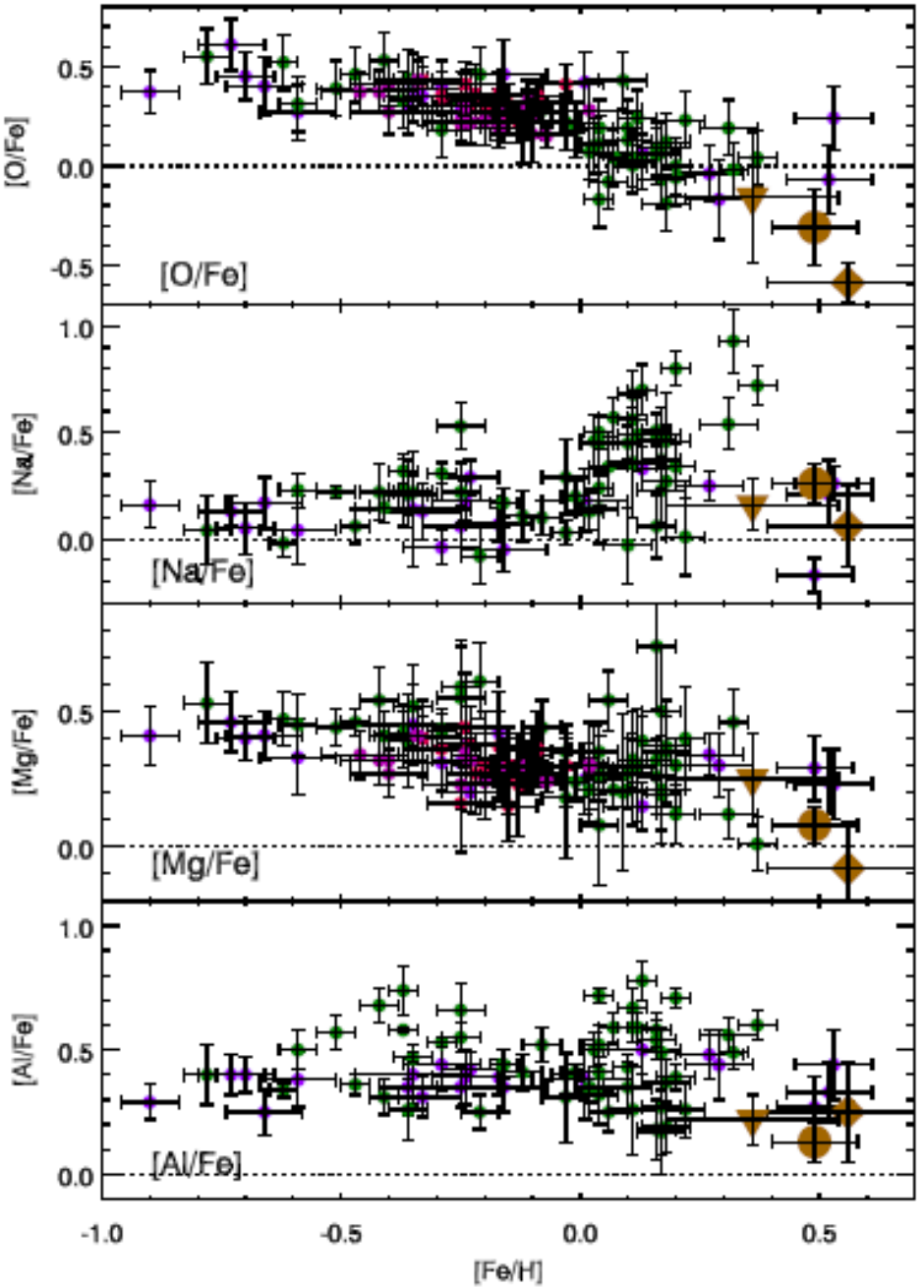


Plus: 40 minute Magellan Spectrum of MOA-2006-BLG-99 at A=110

Scott Gaudi

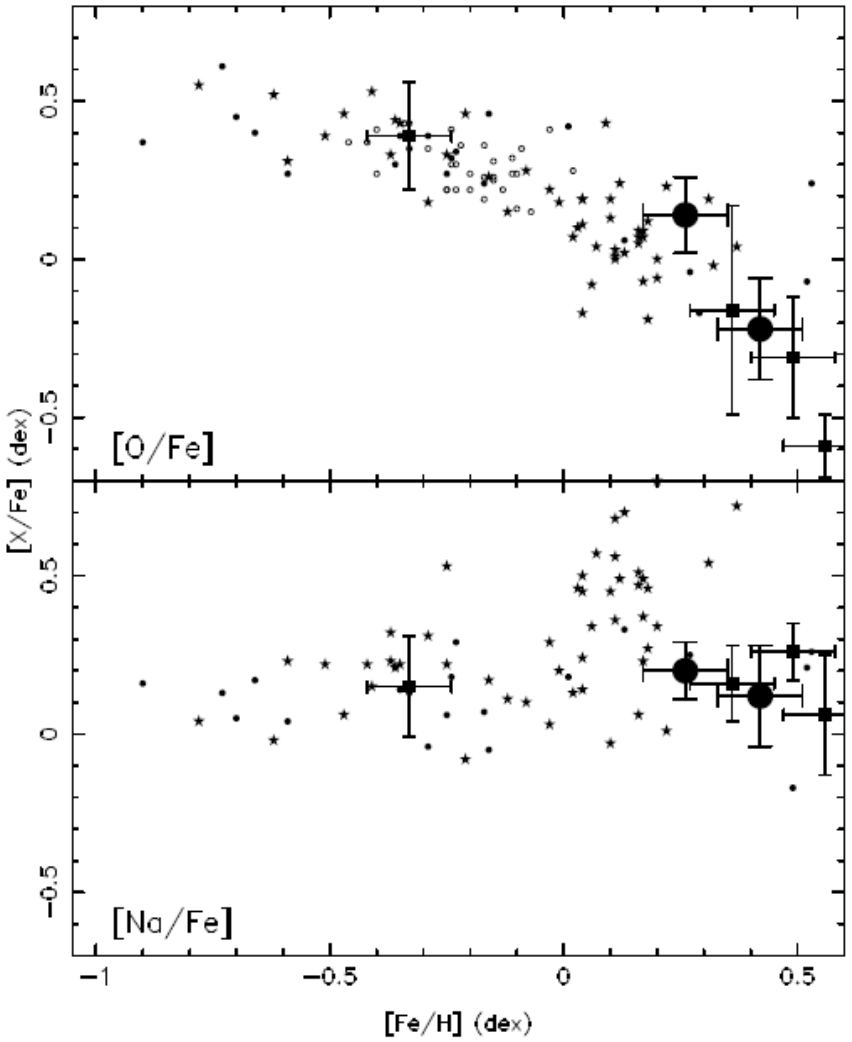

Intensity
Wavelength
Fe I 6159.4
Na I 6160.8
Ca I 6161.3
Ca I 6162.2
Ni I 6163.4
Fe I 6163.5
Ca I 6163.8

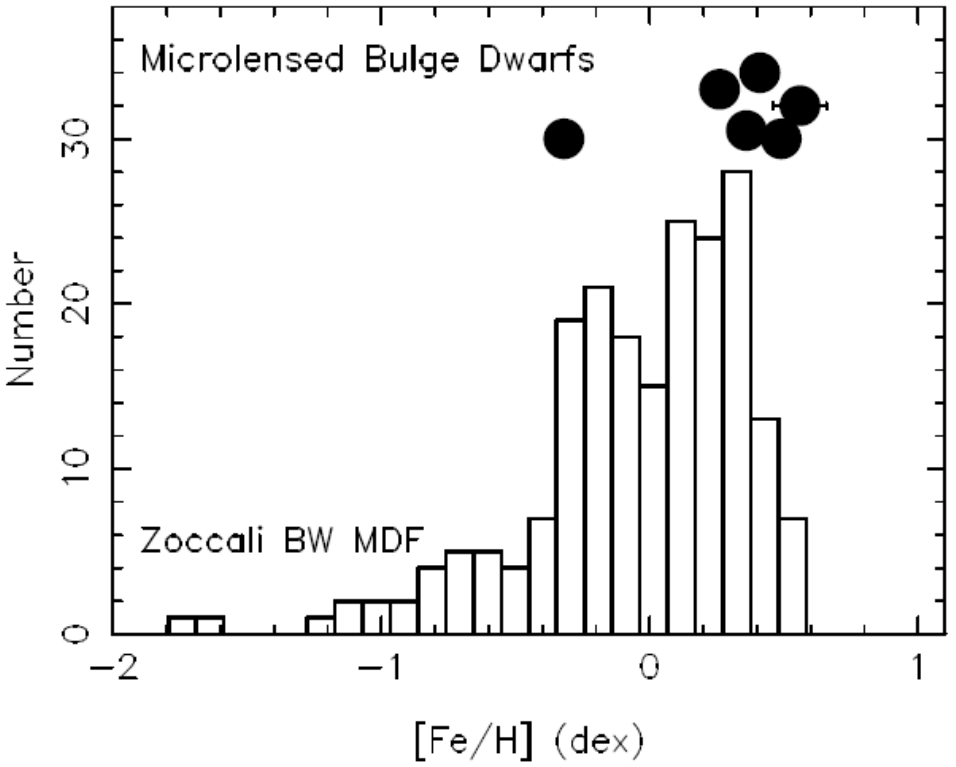

[X/Fe]
C O Na Mg Al Si S K Ca Sc Ti V Cr Mn Co Ni Cu Zn Rb Zr Ba La Eu
Element


[O/Fe]
[Na/Fe]
[Mg/Fe]
[Al/Fe]
[Fe/H]

6 Bulge Dwarfs:

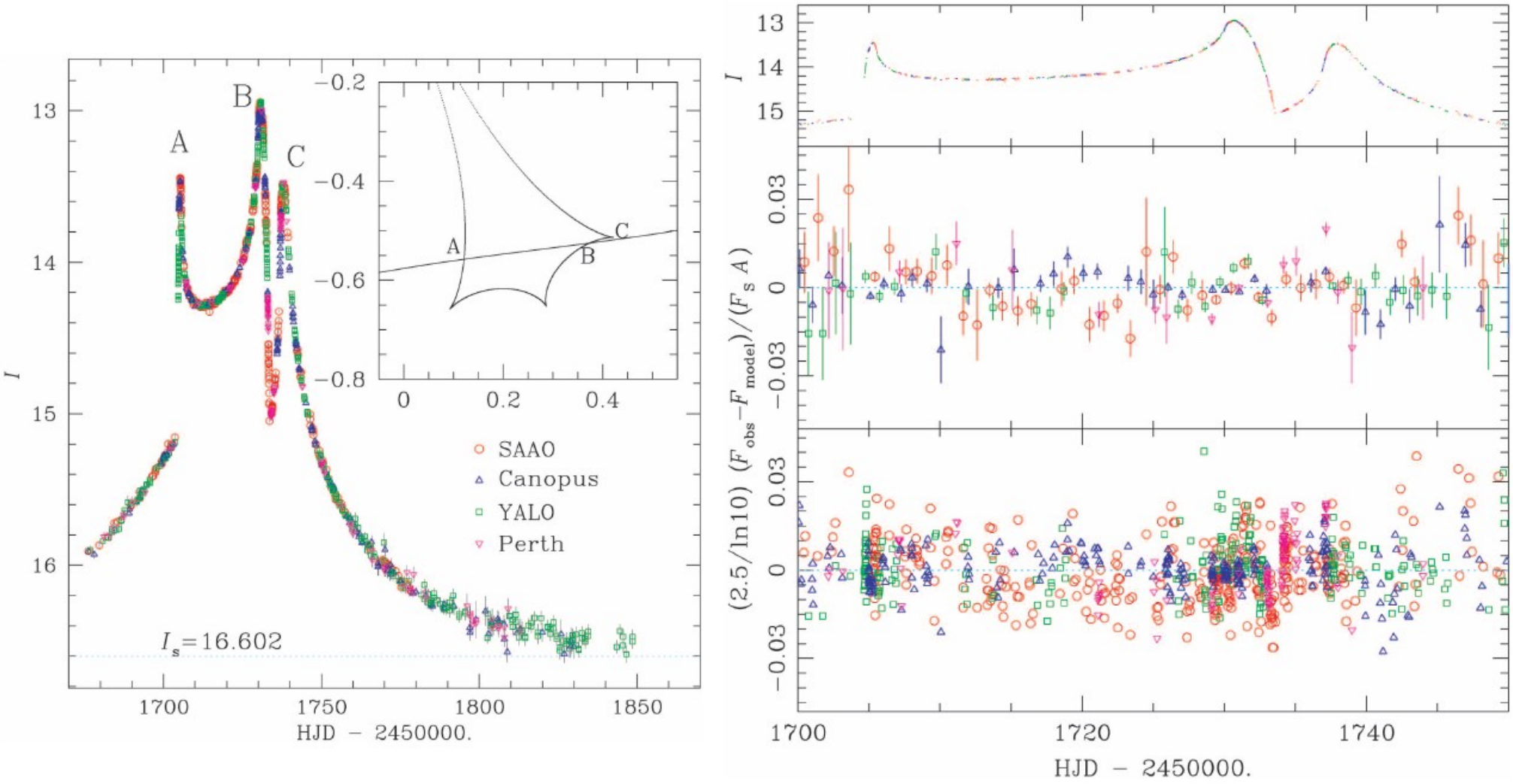
Tend Toward Metal Rich





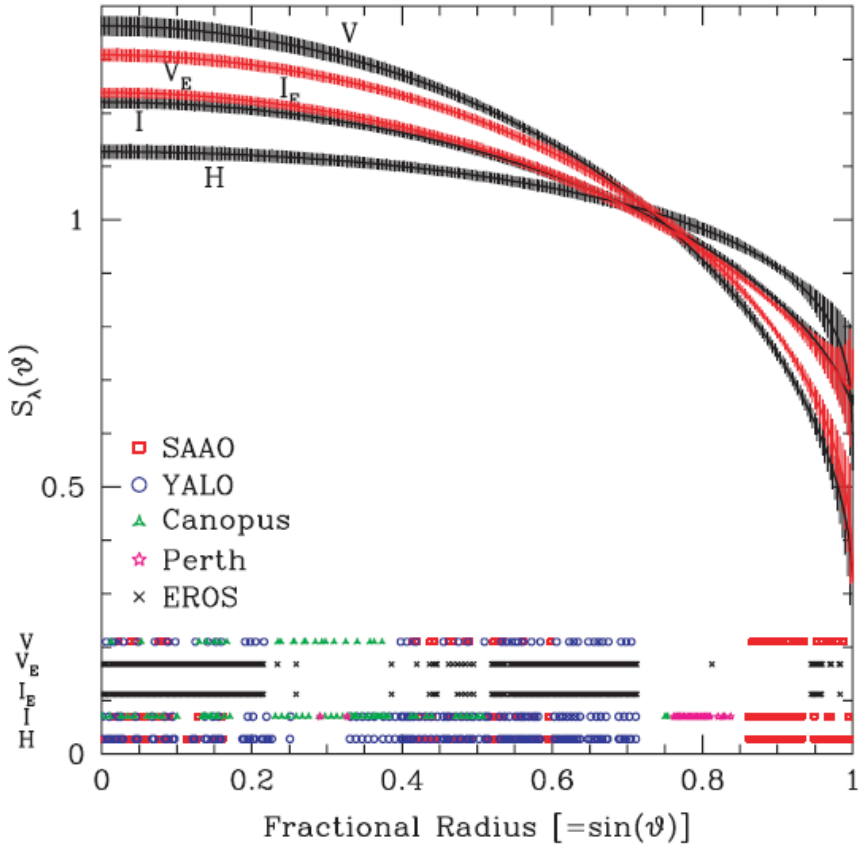
Cohen et al. 2009, ApJ (arXiv:0904.2020)

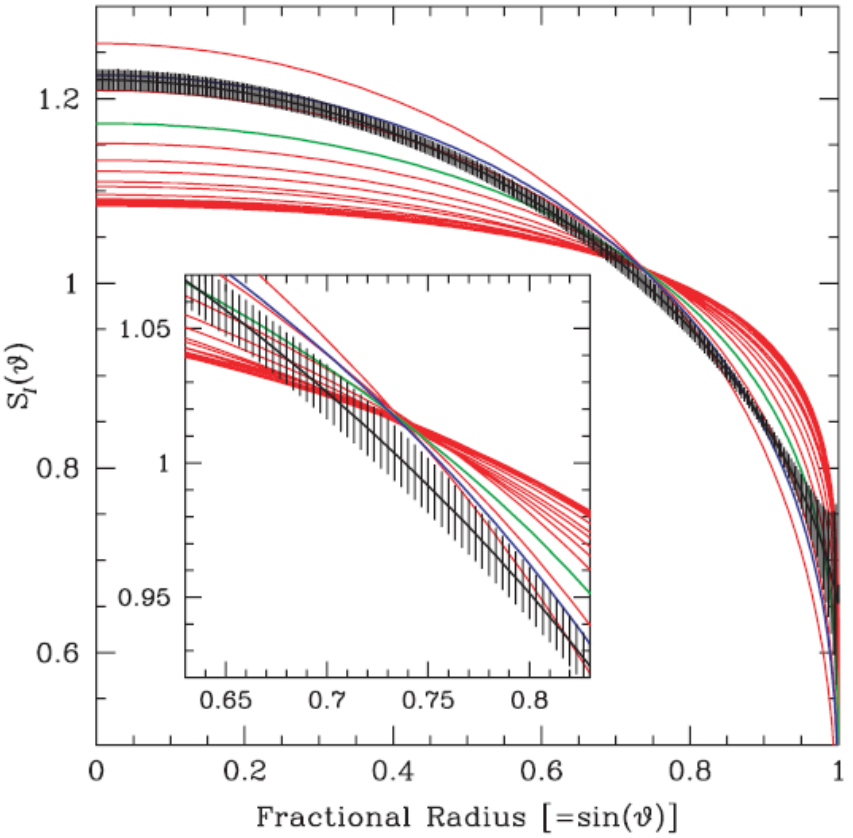
EROS-BLG-2000-5 ...



An et al. 2002, ApJ, 572, 521

Most Detailed Limb Darkening Profile of a Giant Star

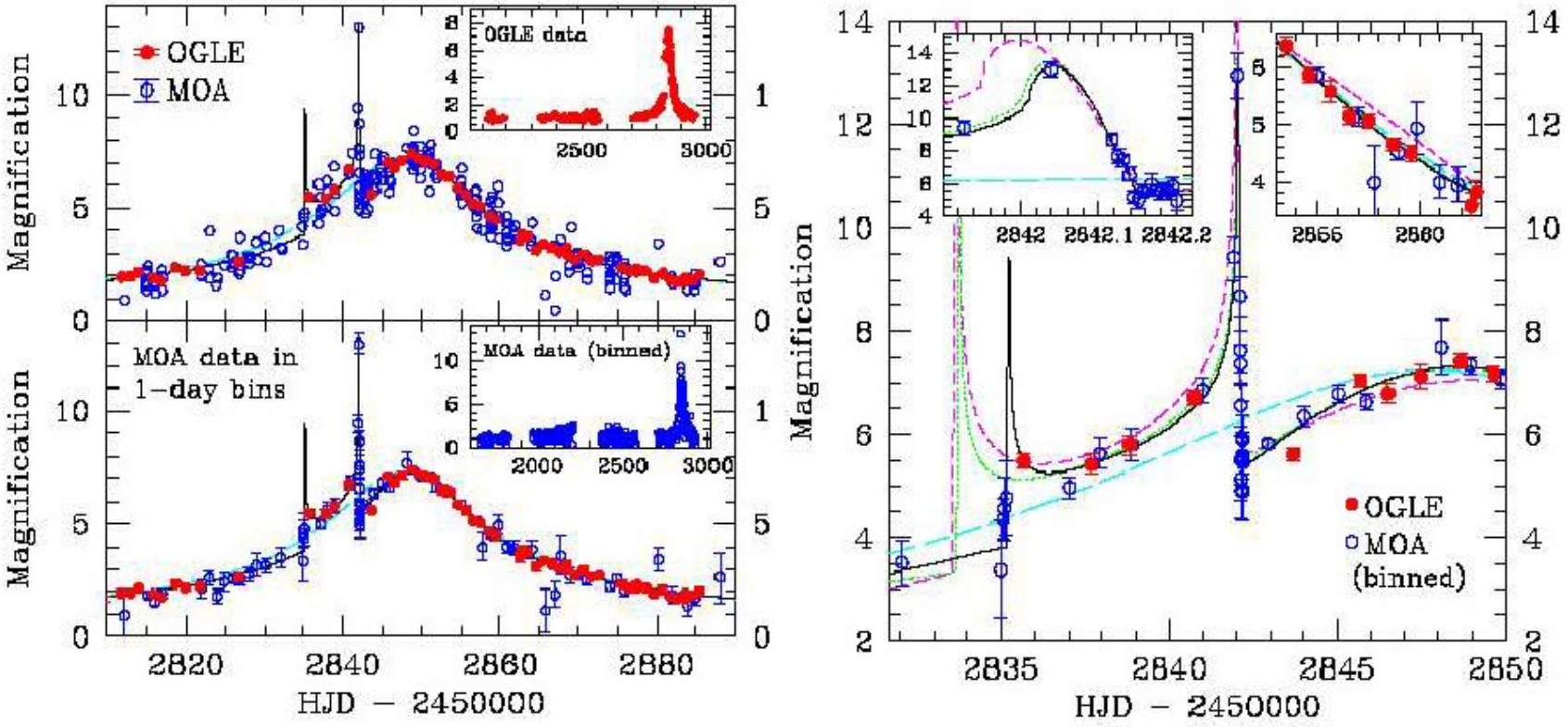




Fields et al. 2003, ApJ, 596, 1305

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

"Pure-Survey" Detection

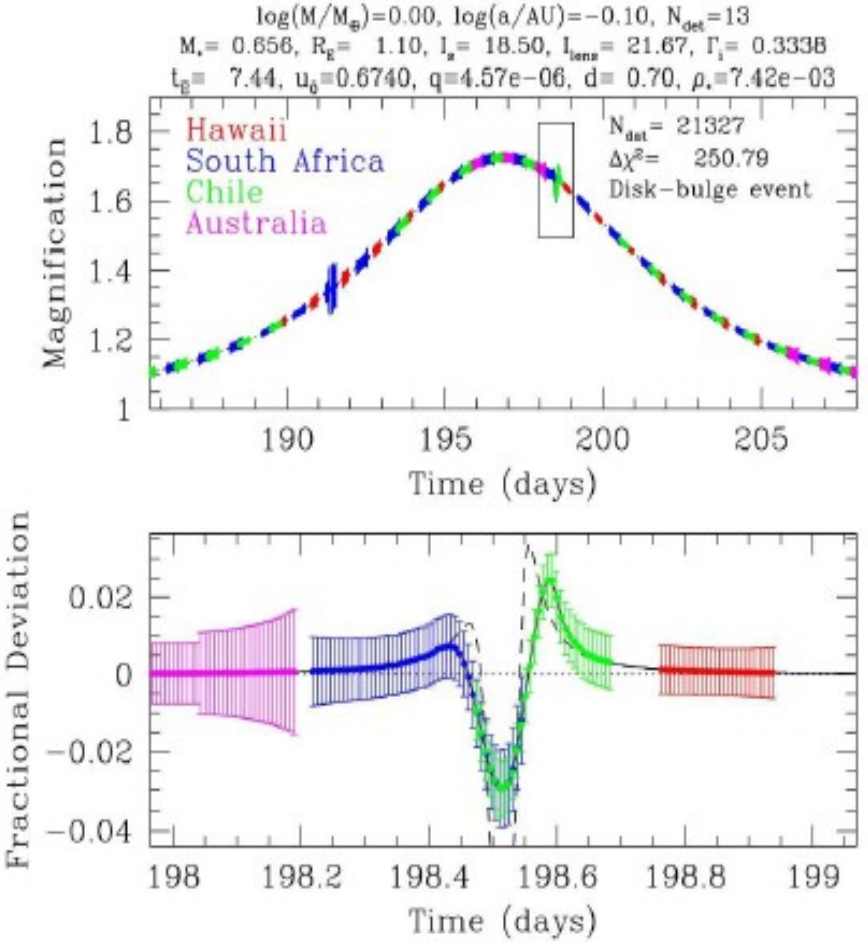


Bond et al. 2004, ApJ, 606, L155

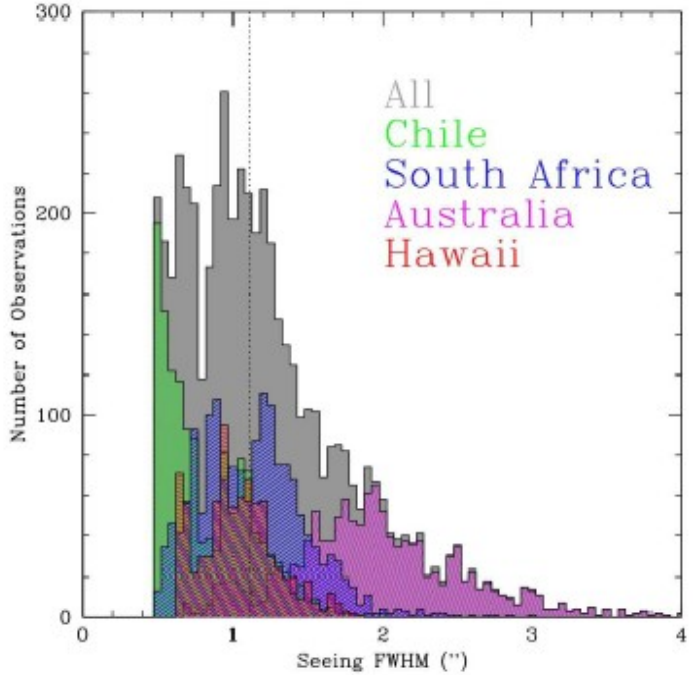
NextGen Microlensing Planet Search

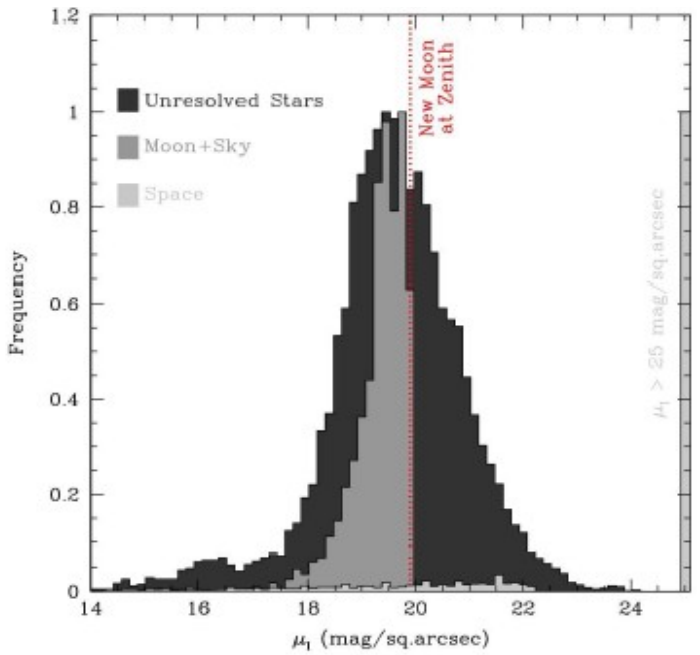
Simulations by Scott Gaudi

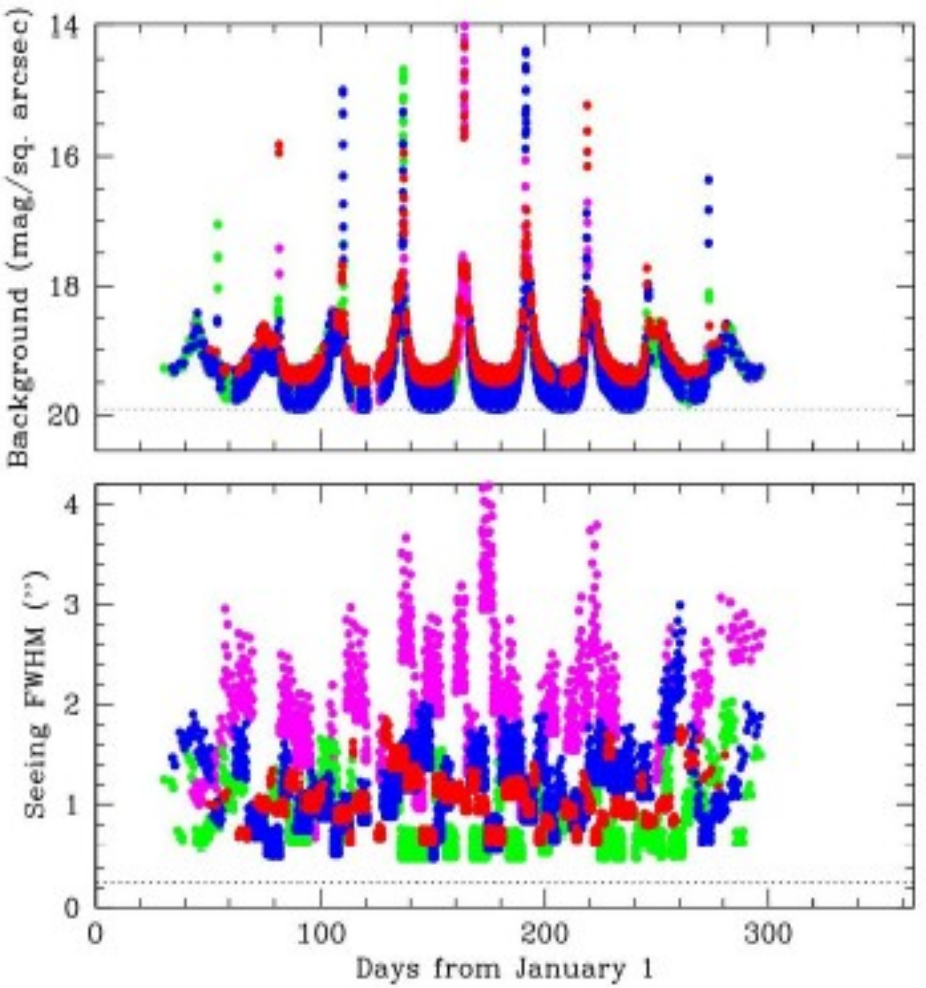
- 4 observatories
- 2m class telescopes
- 4 sq.deg. cameras
- Realistic seeing & weather
- photon-limited statistics down to systematics limit



Simulation Ingredients (abridged)

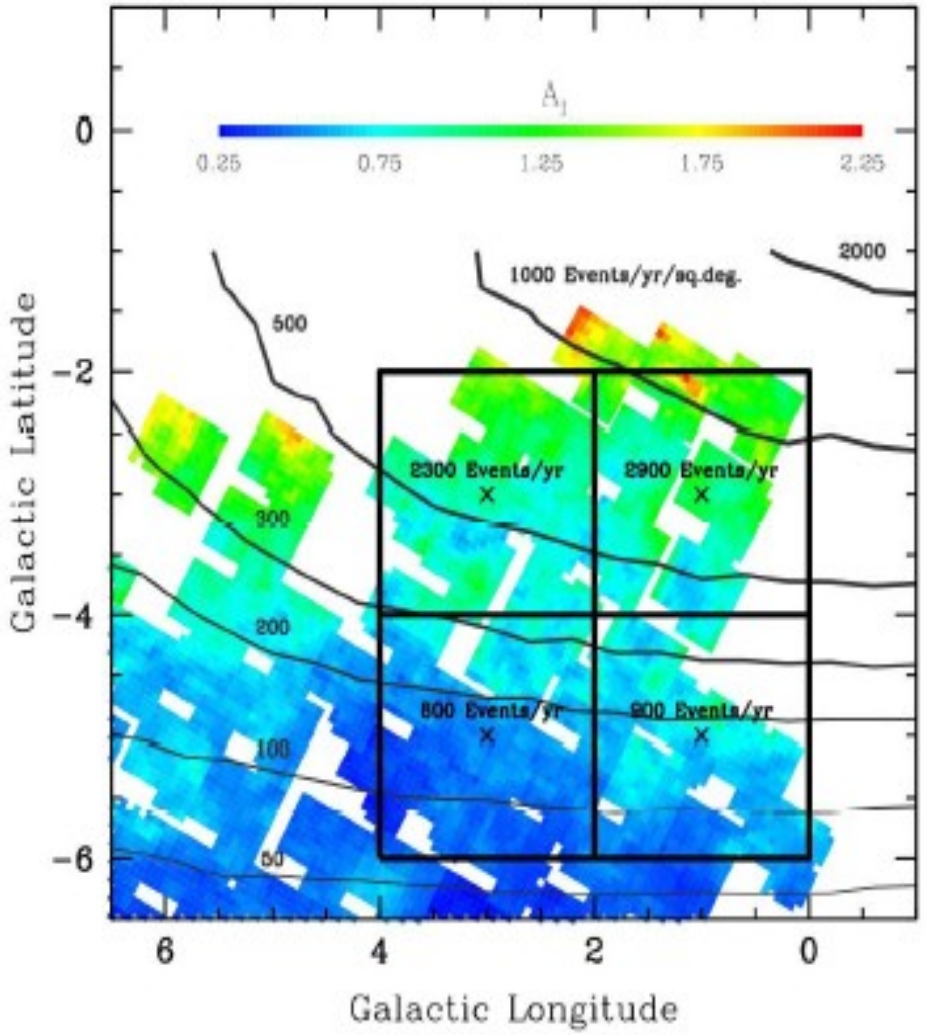


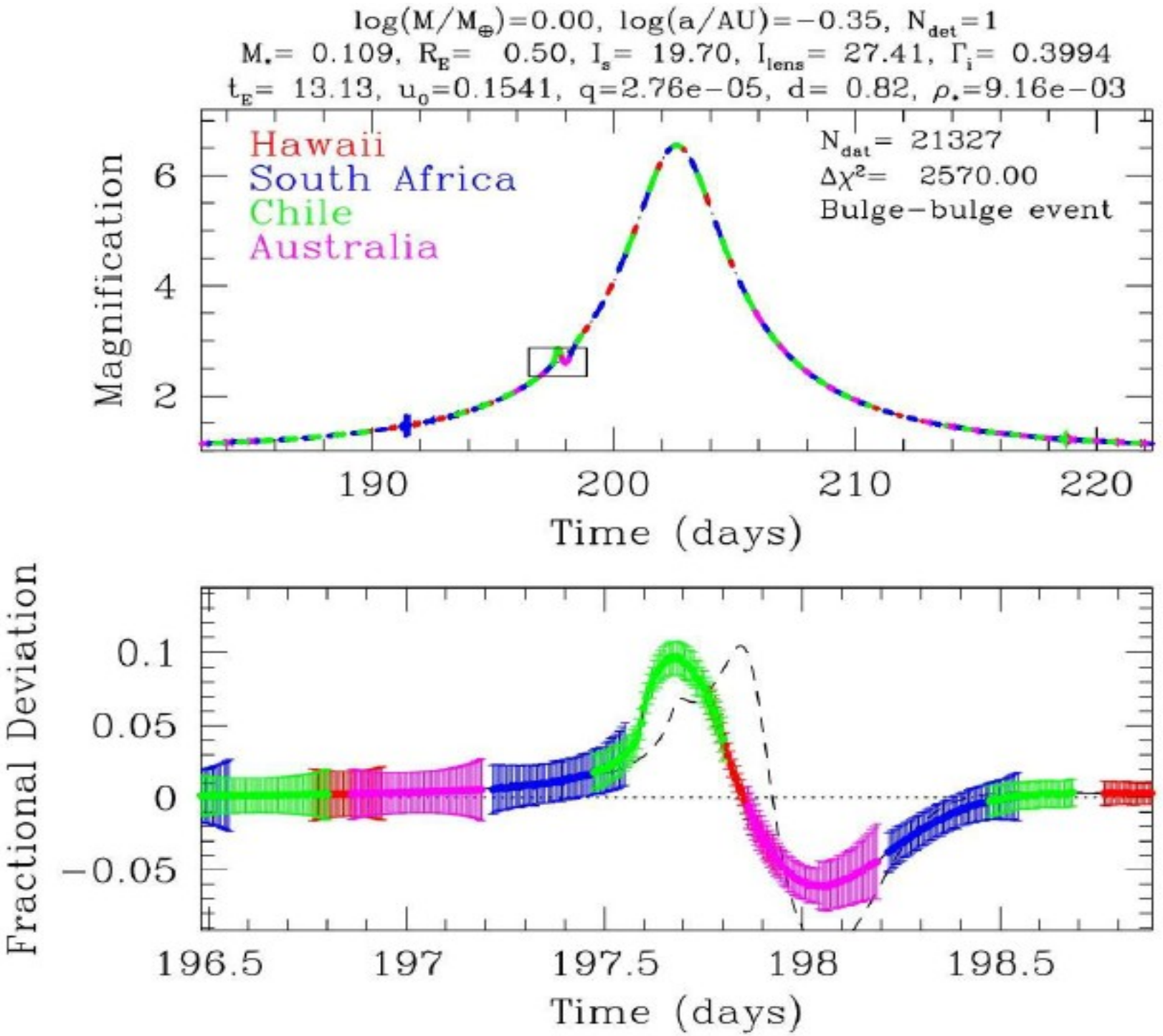


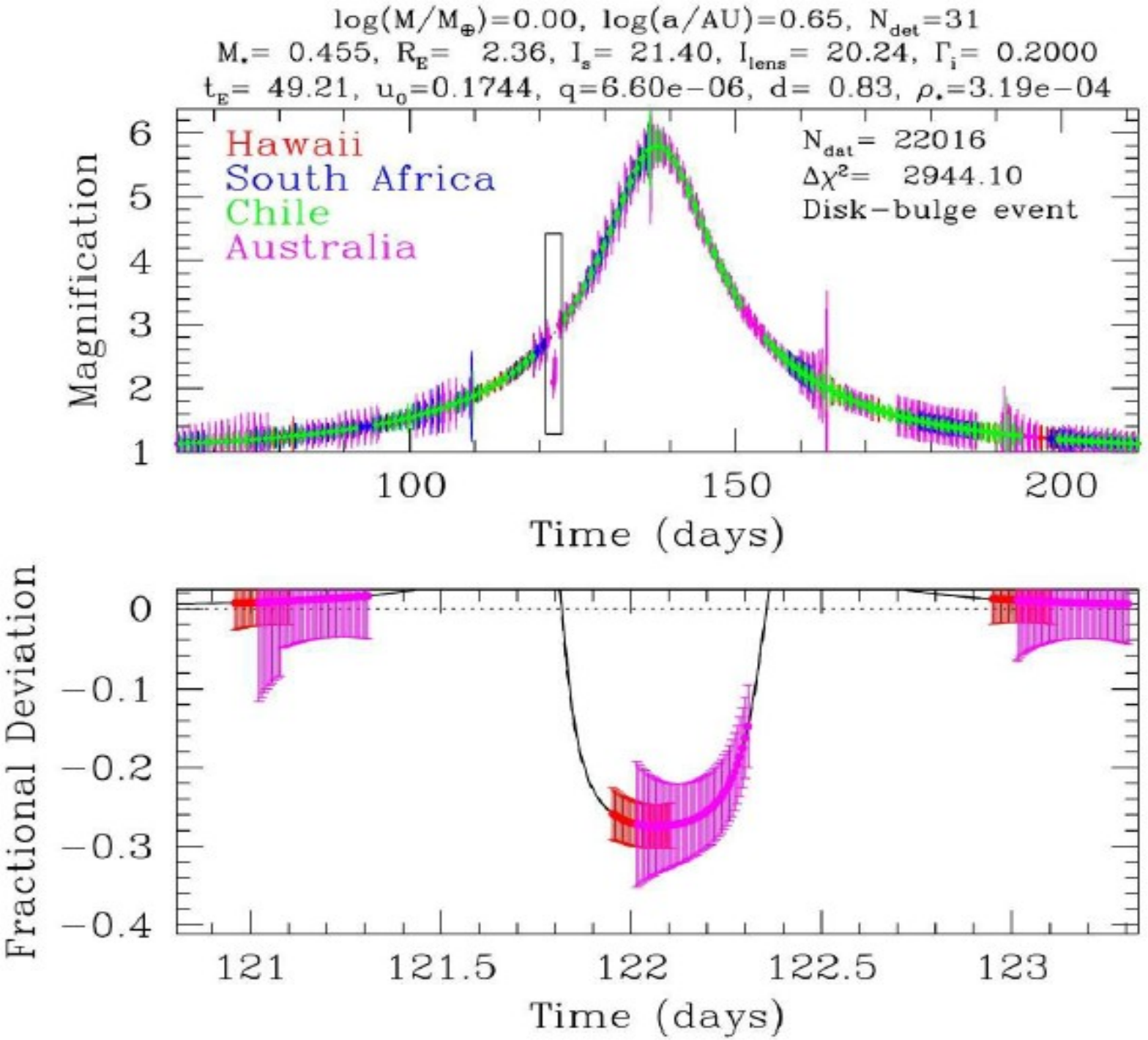


Target Fields

- 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, N_det=1
M*= 0.109, R_E= 0.50, I_s= 19.70, I_lens= 27.41, Γ_i= 0.3994
t_E= 13.13, u_0=0.1541, q=2.76e−05, d= 0.82, ρ*=9.16e−03
Hawaii
South Africa
Chile
Australia
N_dat= 21327
Δχ²= 2570.00
Bulge−bulge event
Magnification
Time (days)
Fractional Deviation
Time (days)

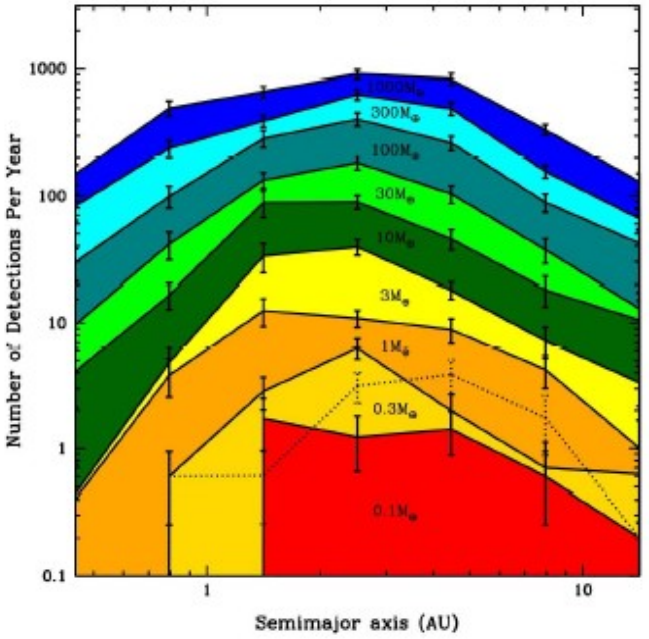

log(M/M⊕)=0.00, log(a/AU)=0.65, N_det=31
M*= 0.455, R_E= 2.36, I_s= 21.40, I_lens= 20.24, Γ_i= 0.2000
t_E= 49.21, u_0=0.1744, q=6.60e−06, d= 0.83, ρ*=3.19e−04
Hawaii
South Africa
Chile
Australia
N_dat= 22016
Δχ²= 2944.10
Disk−bulge event
Magnification
Time (days)
Fractional Deviation
Time (days)

Baseline Results

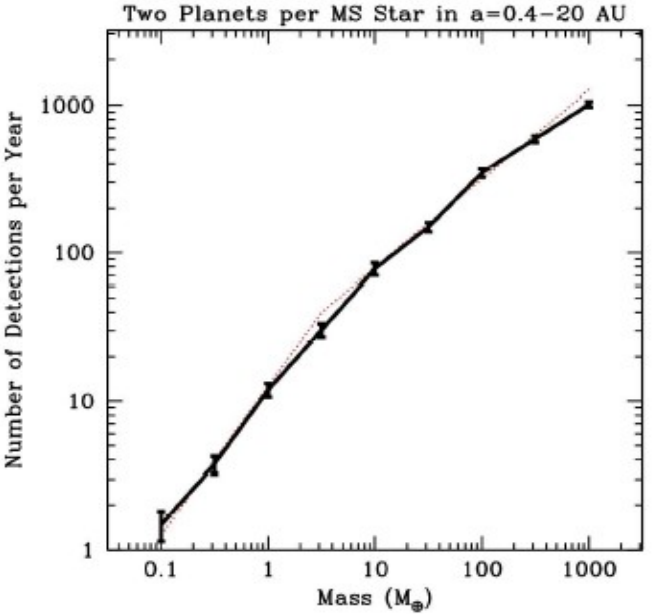
- Simulate:
  - Mass:

    $\log(M/M_\oplus)$=-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 1.6m tels, with 4 sq.deg cameras (Africa South America, Australia) [KMTNet]

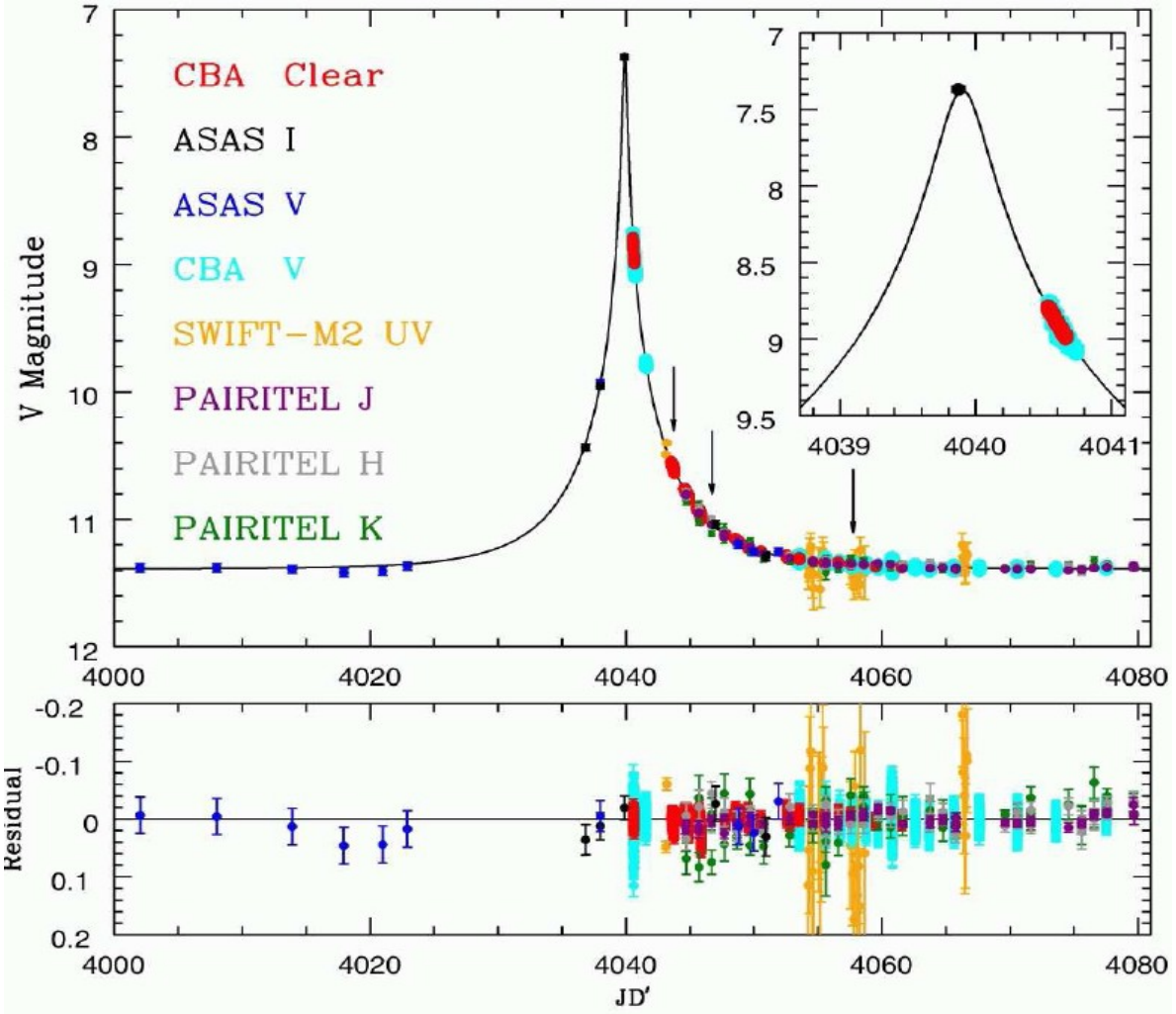
Coming Full Circle:
Domestic Microlensing

- 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."

A0 star GSC 3656-1328

A=40 Magnification at 1 kpc



Gaudi et al. 2008, ApJ, 677, 1268

Conclusions

- μlensing planets now found "routinely"
  - about 3 per year
- NextGen experiments will increase 10-fold
  - MOA/OGLE/KMTNet
- Powerful probe of bulge dwarfs
  - May be more metal-rich than giants
- Measuring masses of isolated stars/BDs
  - SIM could do this routinely