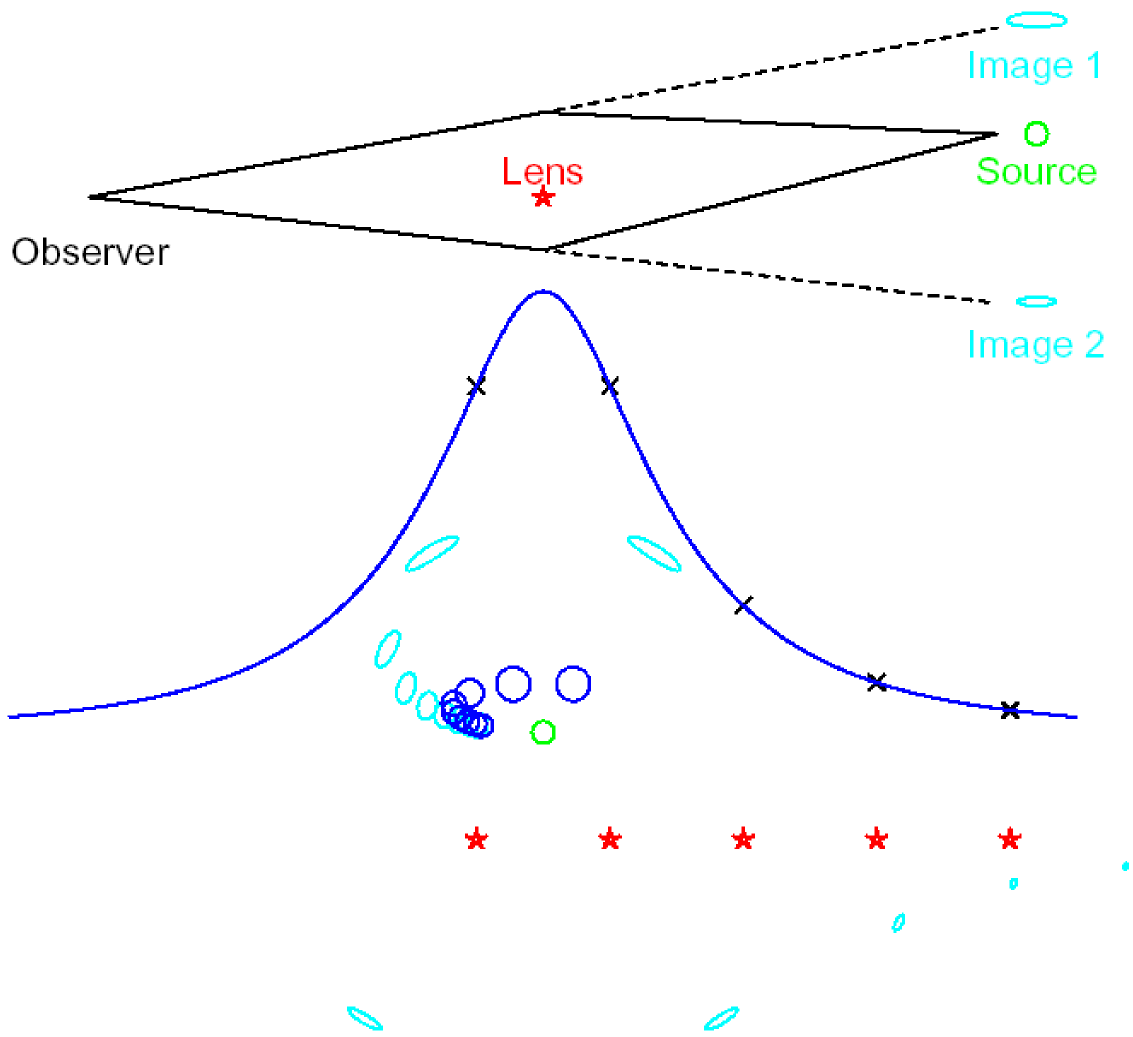
Exoplanet Microlensing IV:

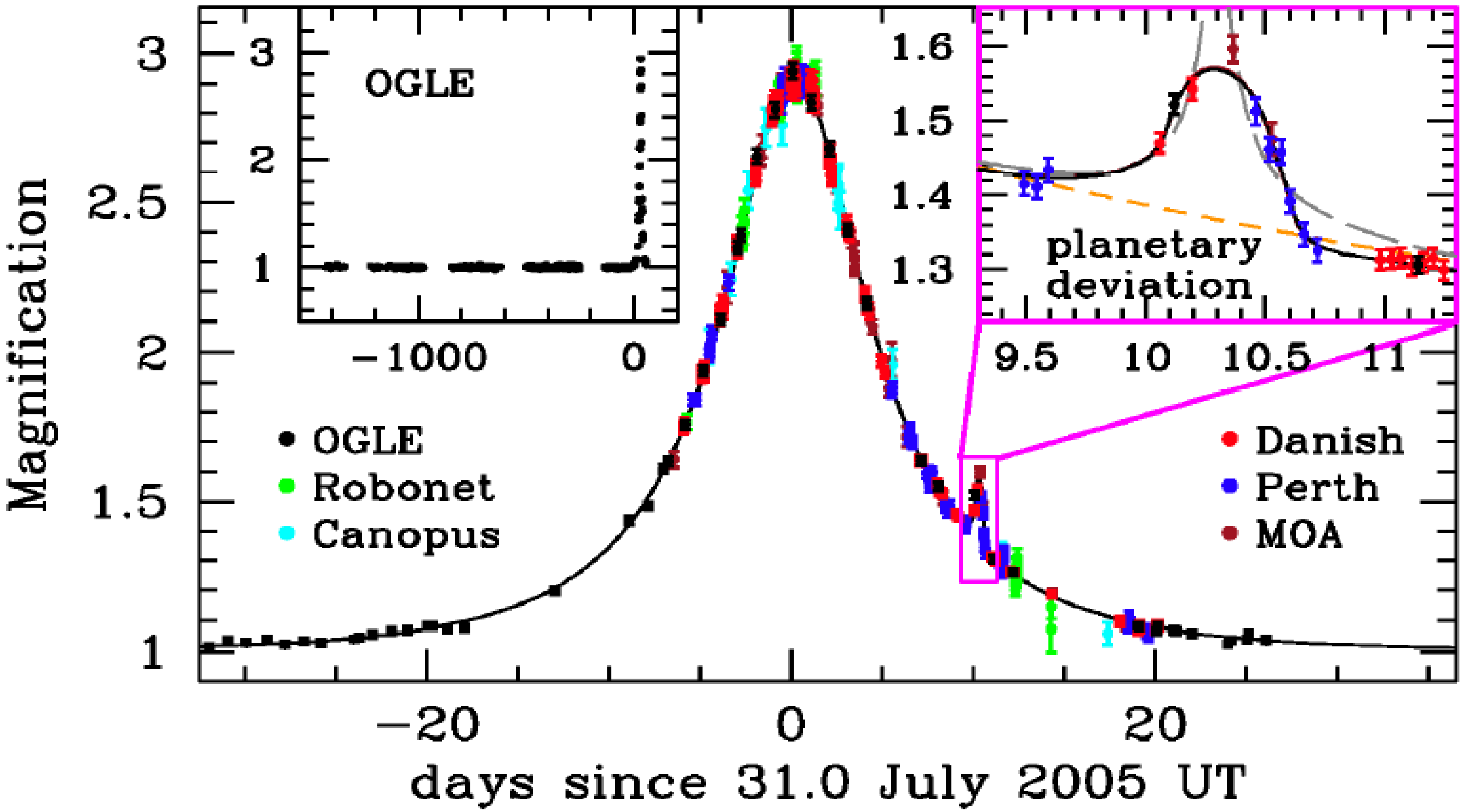
Multi-planet systems, Future of μlensing

Andy Gould (Ohio State)



One bump --> Many bumps??

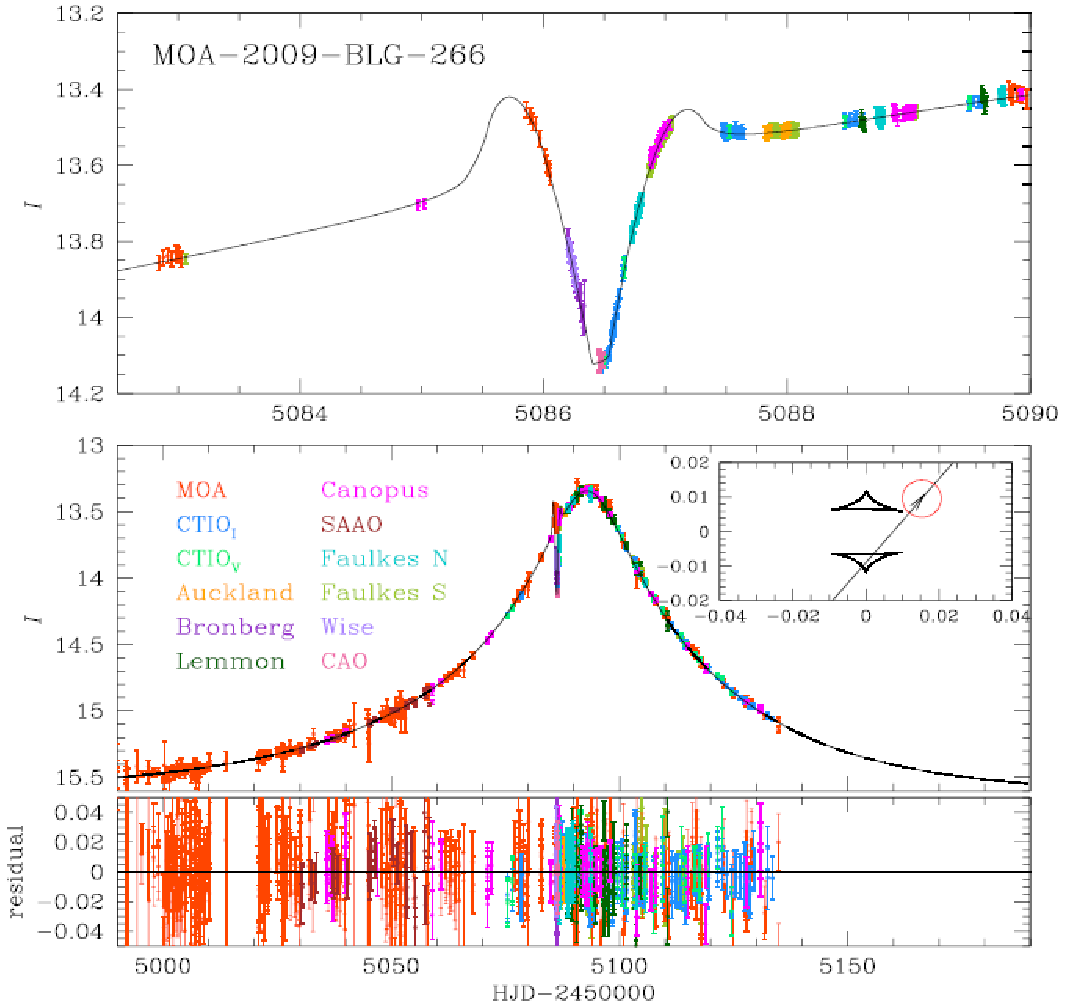
Probably not



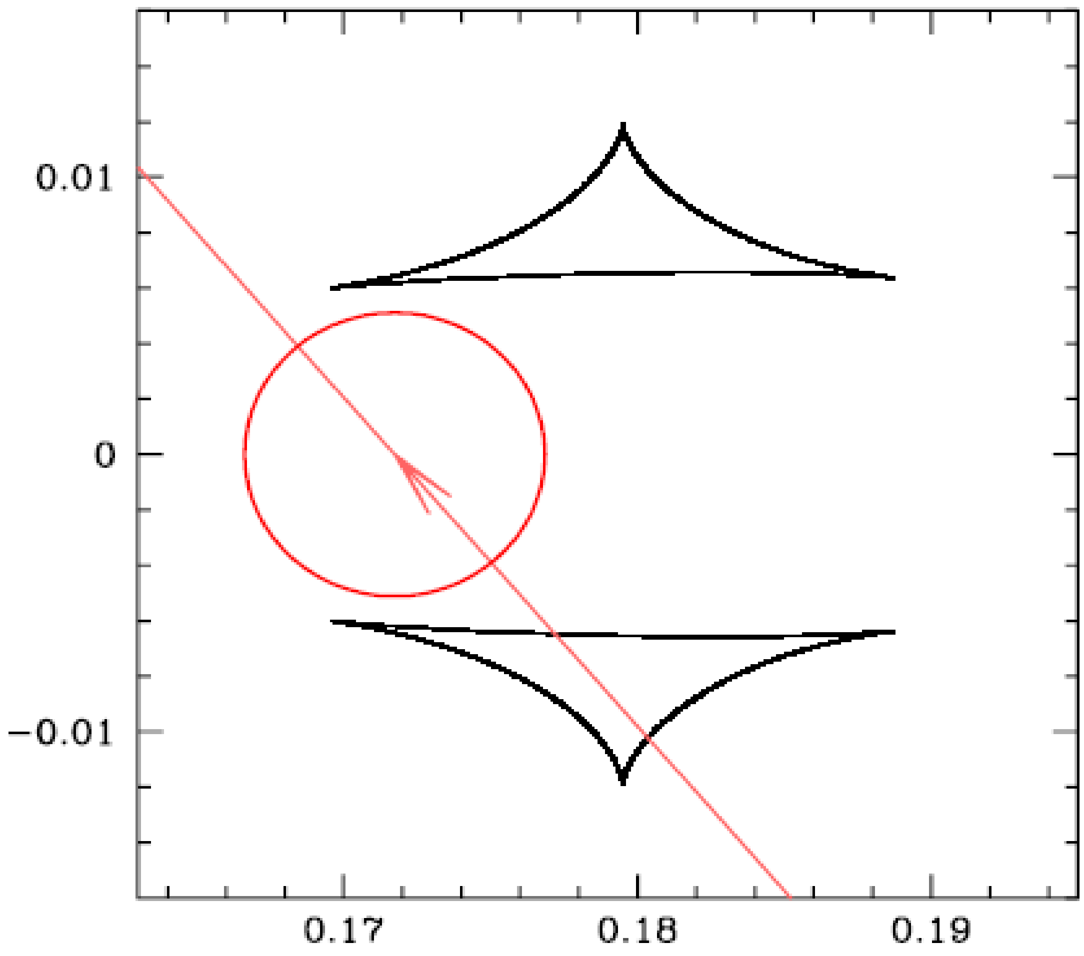
Beaulieu et al. 2006, Nature, 439, 437

MOA-2009-BLG-266

P(2-planets) = [P(1-planet)]^2



P(1-planet) ~ 10^{-2}



Why Planetary Caustics?

Because they are bigger!

$$\gamma = \frac{q}{s^2} \qquad (\gamma \ll 1)$$

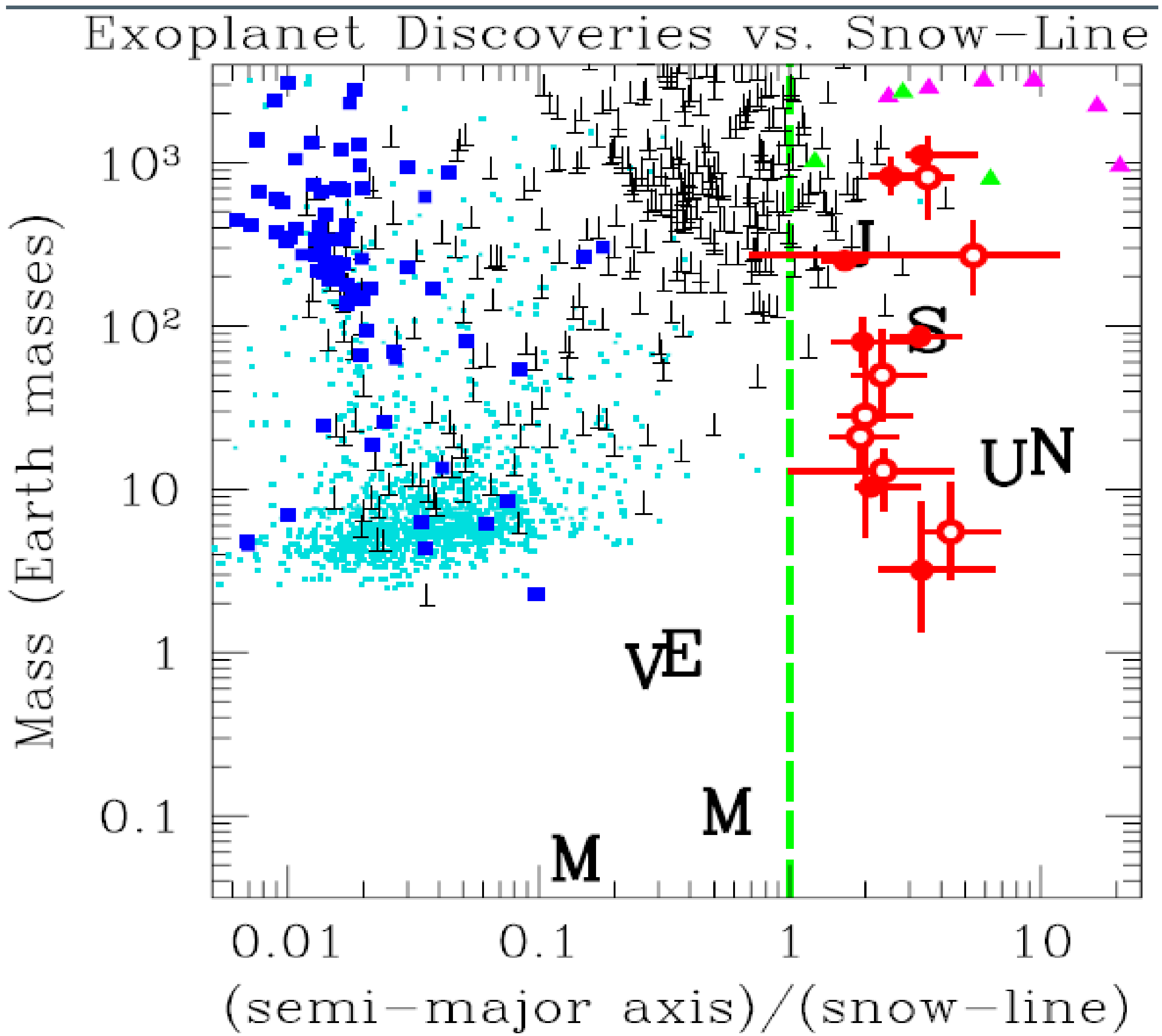
$$\theta_\gamma = 4\gamma\theta_{\rm E} = 4\frac{q}{s^2}\theta_{\rm E}$$

$$\theta_\gamma = 4\frac{m/M}{(\Delta\theta/\theta_{\rm E})^2}\theta_{\rm E} = 4\frac{m\theta_{\rm E}^3}{M(\Delta\theta)^2}$$

$$\theta_\gamma = 4\frac{m(\kappa\pi_{\rm rel}M)^{3/2}}{M(\Delta\theta)^2} = 4\sqrt{mM}\frac{(\kappa\pi_{\rm rel})^{3/2}}{(\Delta\theta)^2}m^{1/2}$$

Planets 2011

Not that many μlens planets



Looks Hopeless!

- N~15 planets discovered so far
- $P(2) \sim [P(1)]^2$
- $P(1) \sim 10^{-2}$
- $N_{2\text{-planet}} \sim N{*}P(1) \sim 0.15$

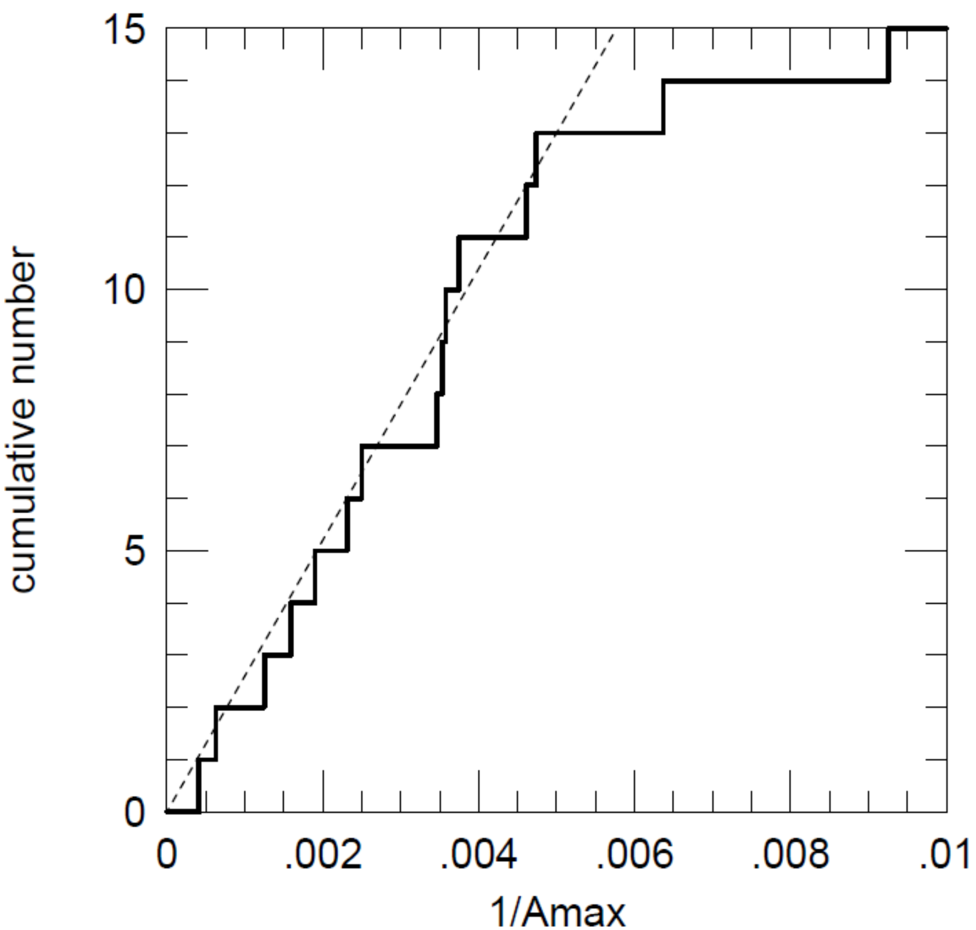
But ... $N_{2\text{-planet}} = 2$

- Prob ~ $e^{-0.15} * 0.15^2/2! < 1\%$
- ... Something not right

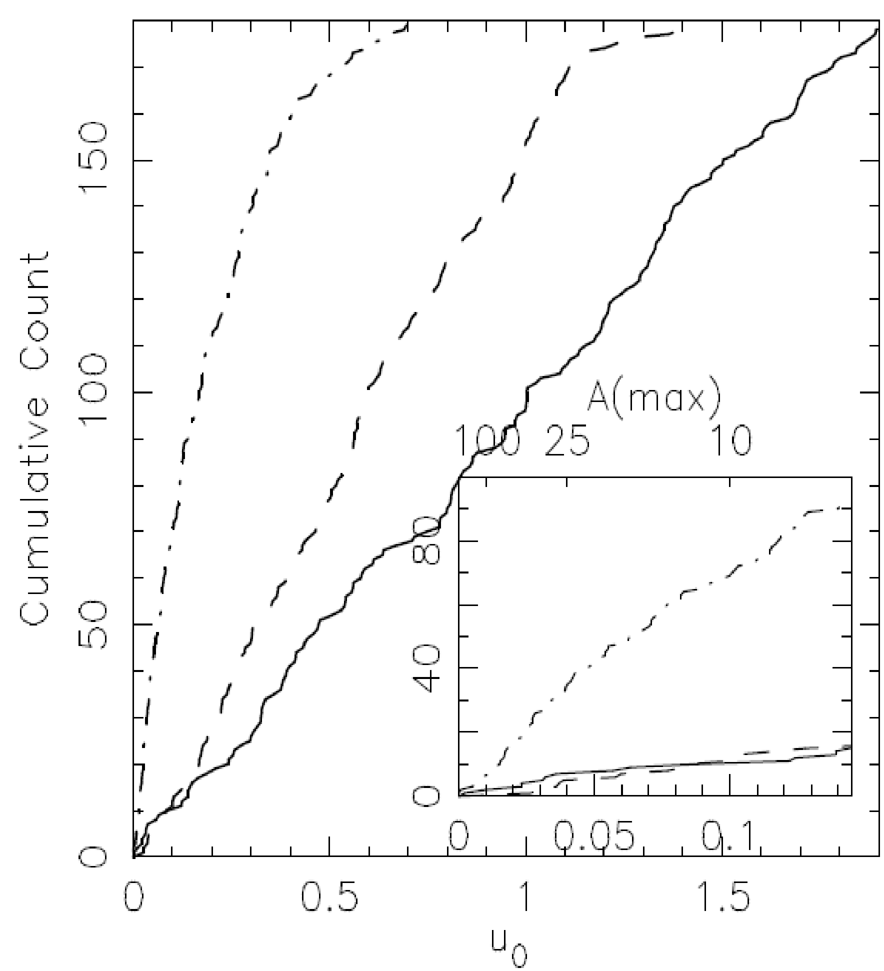
Recall Gould et al. (2010)

13 events with A_{max}>200

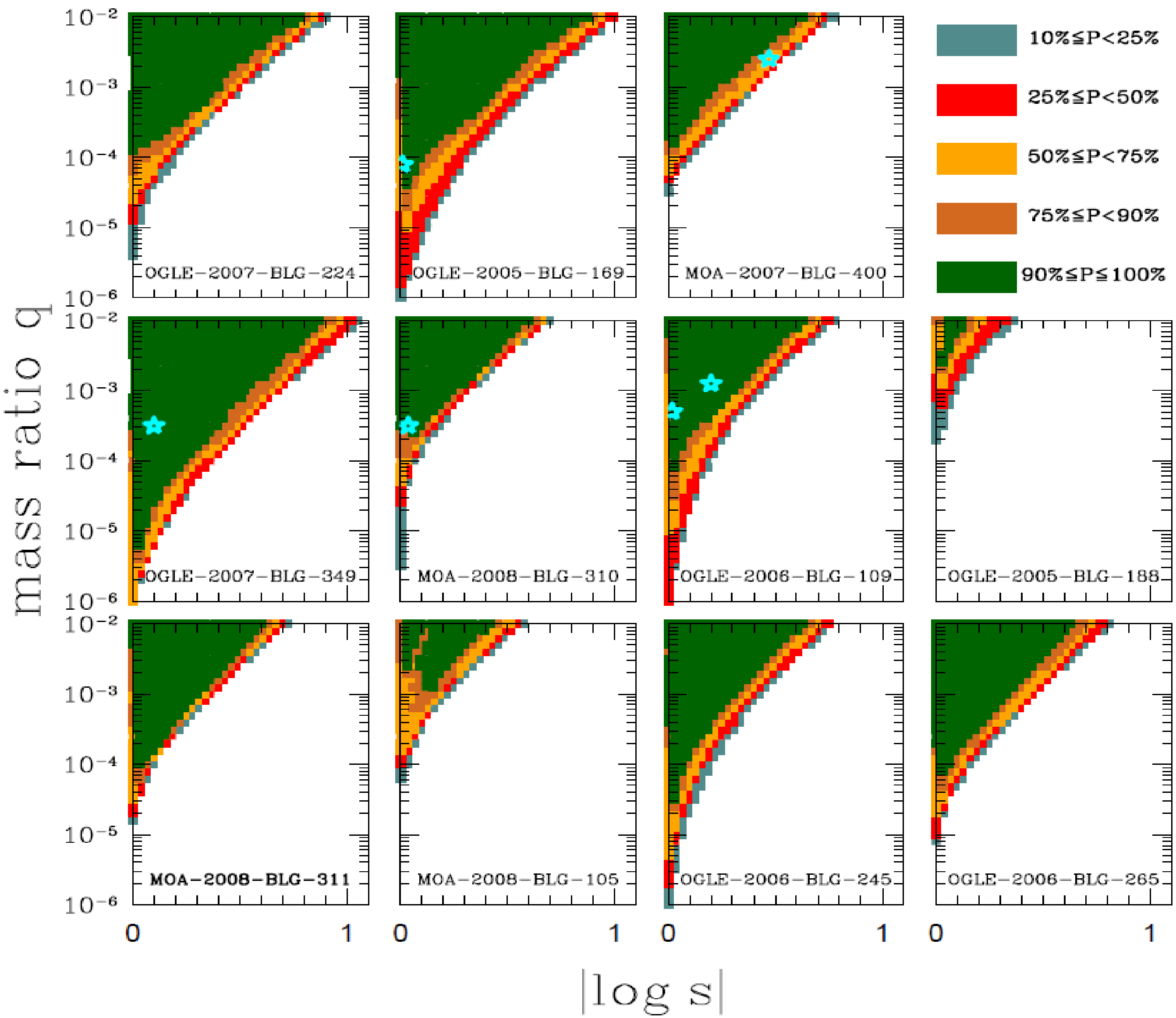
Well-Covered



All Events



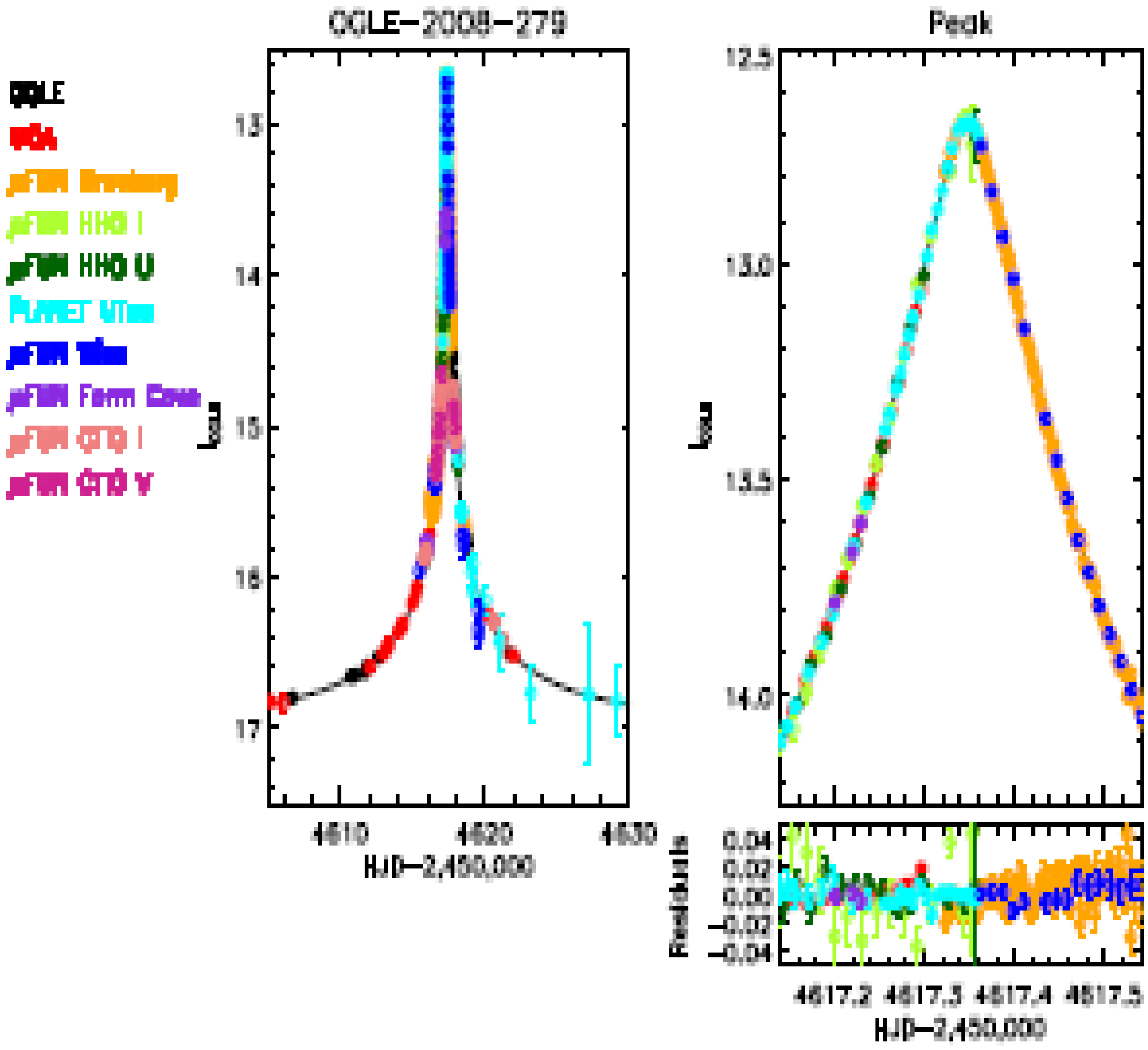
6 Planets



10%≤P<25%
25%≤P<50%
50%≤P<75%
75%≤P<90%
90%≤P≤100%
OGLE−2007−BLG−224
OGLE−2005−BLG−169
MOA−2007−BLG−400
OGLE−2007−BLG−349
MOA−2008−BLG−310
OGLE−2006−BLG−109
OGLE−2005−BLG−188
MOA−2008−BLG−311
MOA−2008−BLG−105
OGLE−2006−BLG−245
OGLE−2006−BLG−265
mass ratio q
|log s|

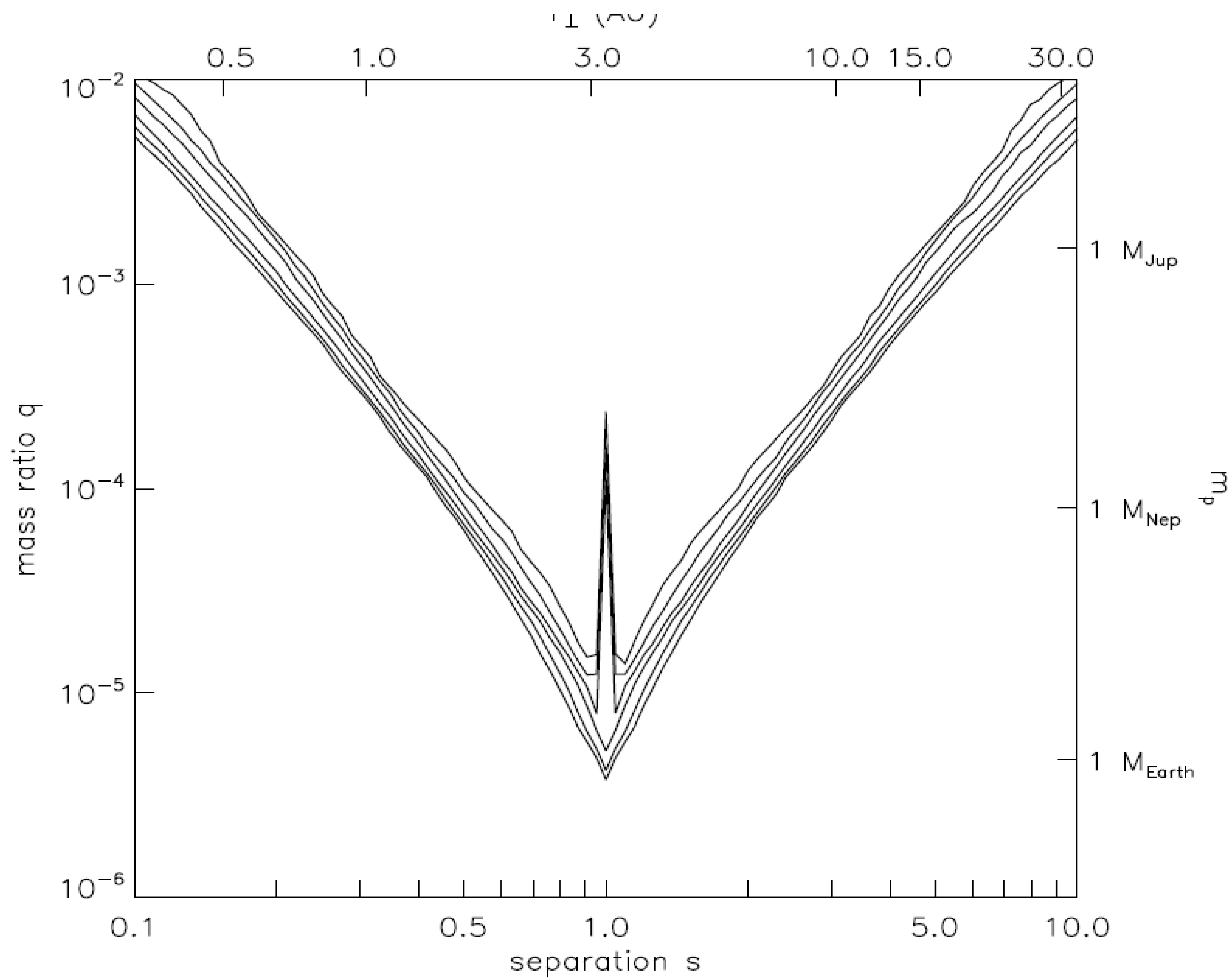
OGLE-2008-BLG-279 (A = 1600)

Probes CENTRAL Caustic

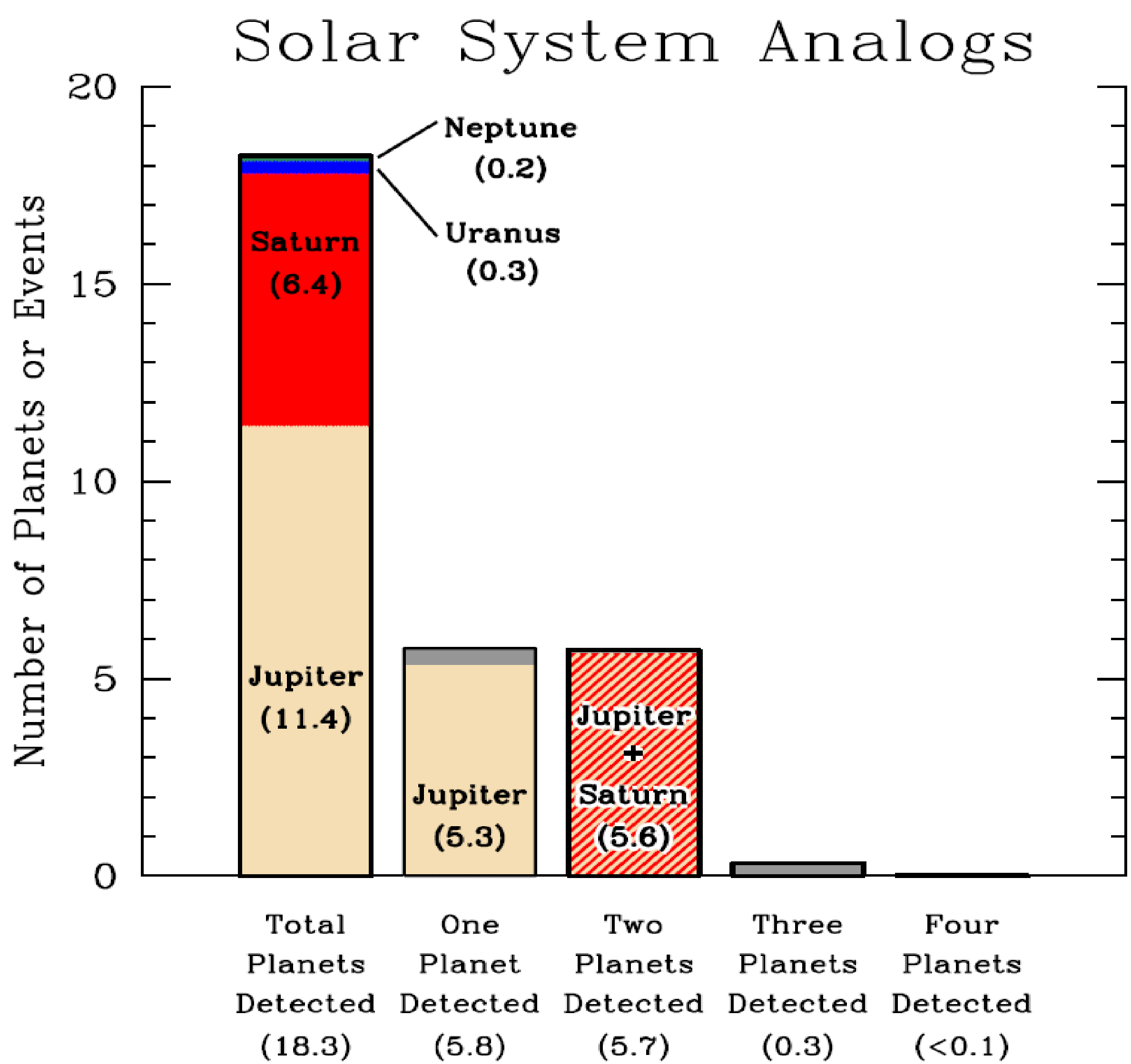


Yee et al. 2009, ApJ, 730, 2082

Caustic very small … but Sensitivity very big

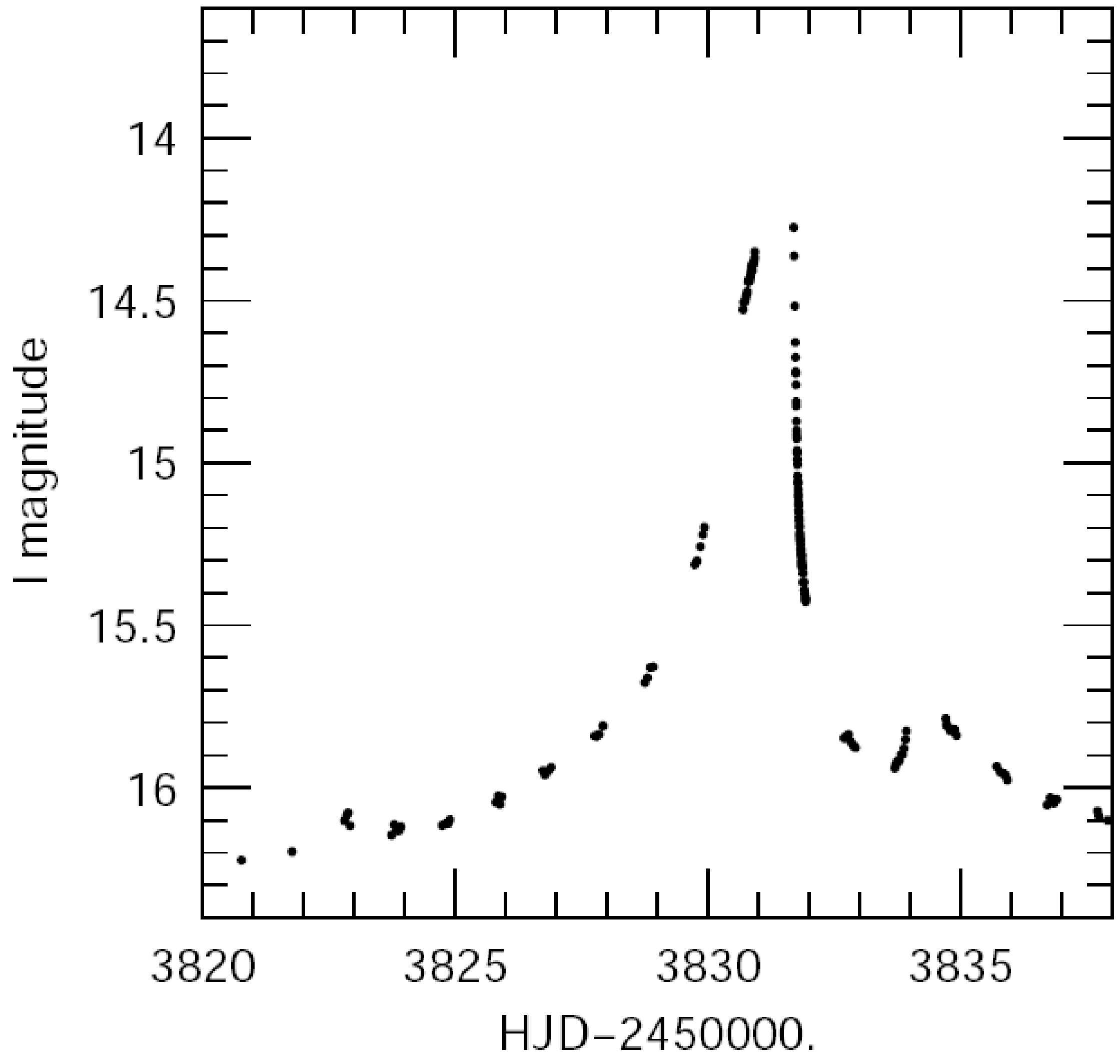


Solar System is Richer than Average
... But Not Dramatically So



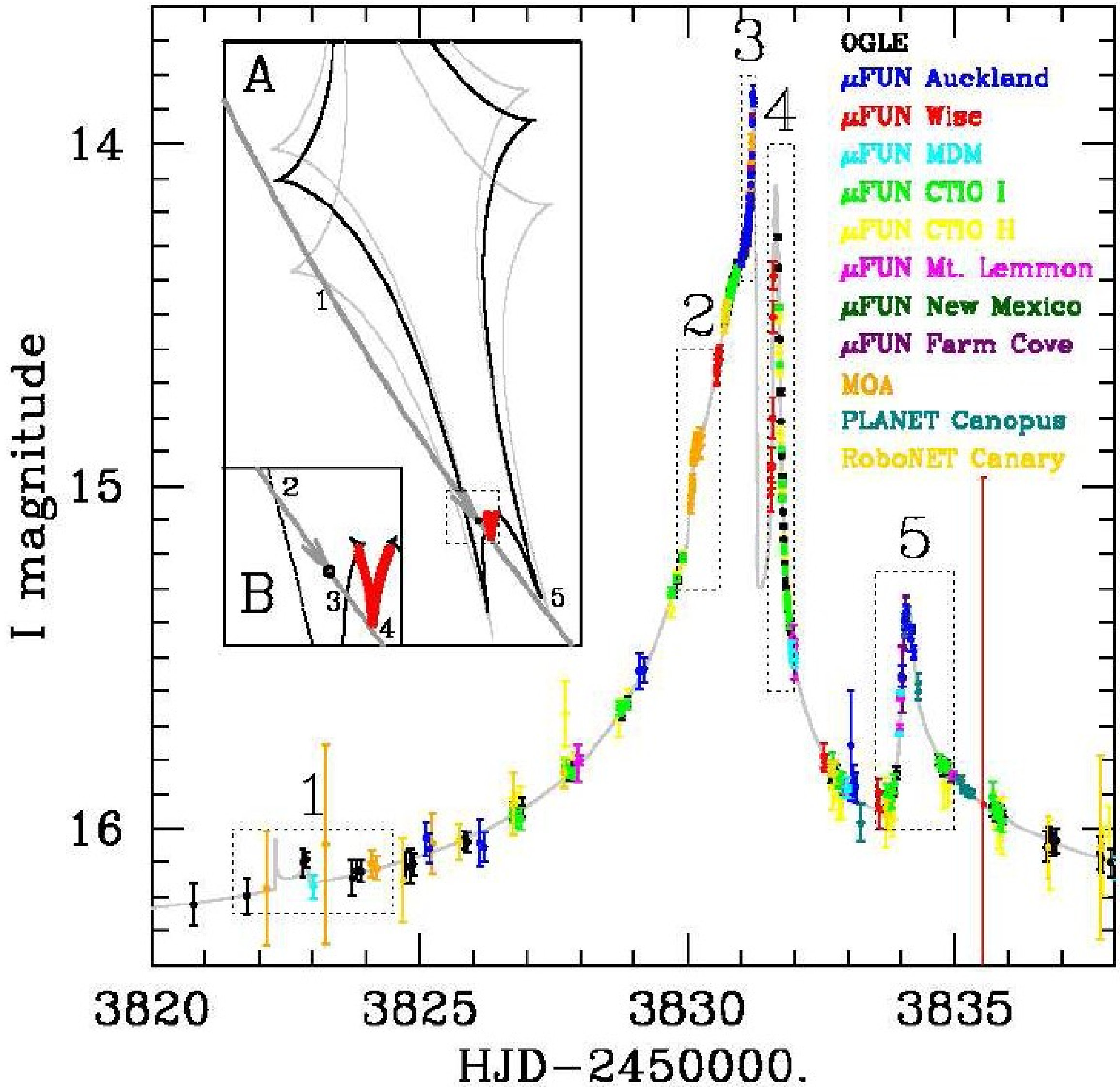
OGLE-2006-BLG-109:

Third High-Mag Event (OGLE only)



OGLE-2006-BLG-109

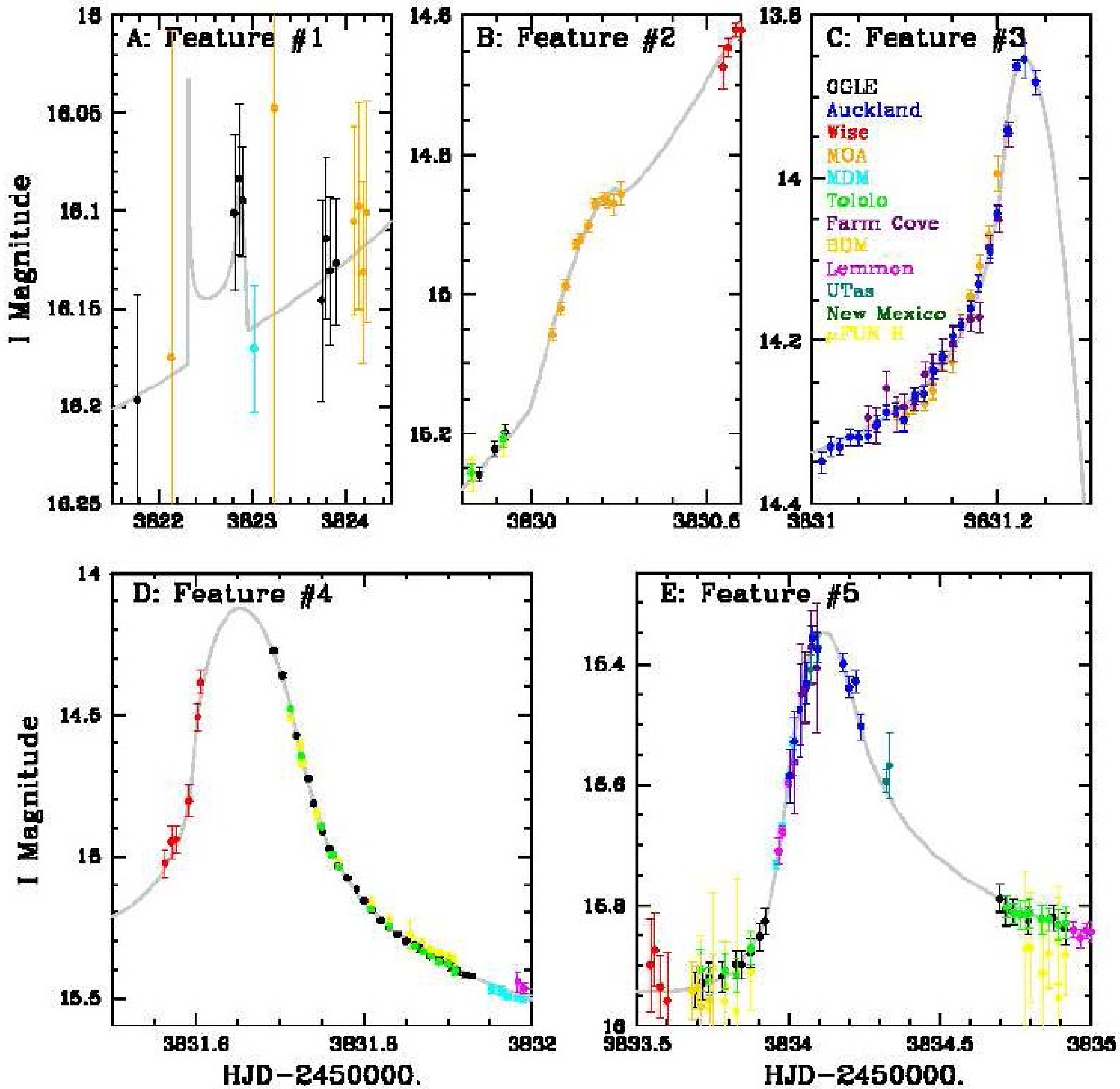
Parallax+Finite-Source+Rotation+Blend



Gaudi et al. 2008, Science, 319, 927

Five Lightcurve Features

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



OGLE-2006-BLG-109

Fit Parameters

Parameter	Units	Best-fit Value	MCMC Range
t_E	Days	127.300	128.1 ± 0.8
t_0	HJD − 2, 450, 000	3831.0197	3831.0204 ± 0.011
u_0		0.003479	0.00345 ± 0.00005
d_{1cm}		0.6272	0.632 ± 0.073
d_{23}		1.04185	1.0418 ± 0.0001
θ_{1cm}	Radians	2.52297	2.5232 ± 0.0007
ϕ_{23}	Radians	-0.23560	-0.2350 ± 0.0007
ϵ_1		1.3562×10^{-3}	$(1.350 \pm 0.013) \times 10^{-3}$
ϵ_2		5.0516×10^{-4}	$(5.017 \pm 0.030) \times 10^{-4}$
t_*	Days	0.03972	0.03949 ± 0.00016
$\dot{d}_{23x}$	Days^{-1}	0.00169	0.00171 ± 0.00004
$\dot{d}_{23y}$	Days^{-1}	0.00181	0.00179 ± 0.00014
$1/T_{orb}$	yr^{-1}	2.04×10^{-4}	$2.3 \pm 0.7 \times 10^{-4}$
π_E		0.3620	0.345 ± 0.014
ϕ_E	Radians	2.7296	2.728 ± 0.010
Fit χ^2	For 2557 dof	2542.06	

Bennett et al. 2010, ApJ, 713, 837

OGLE-2006-BLG-109

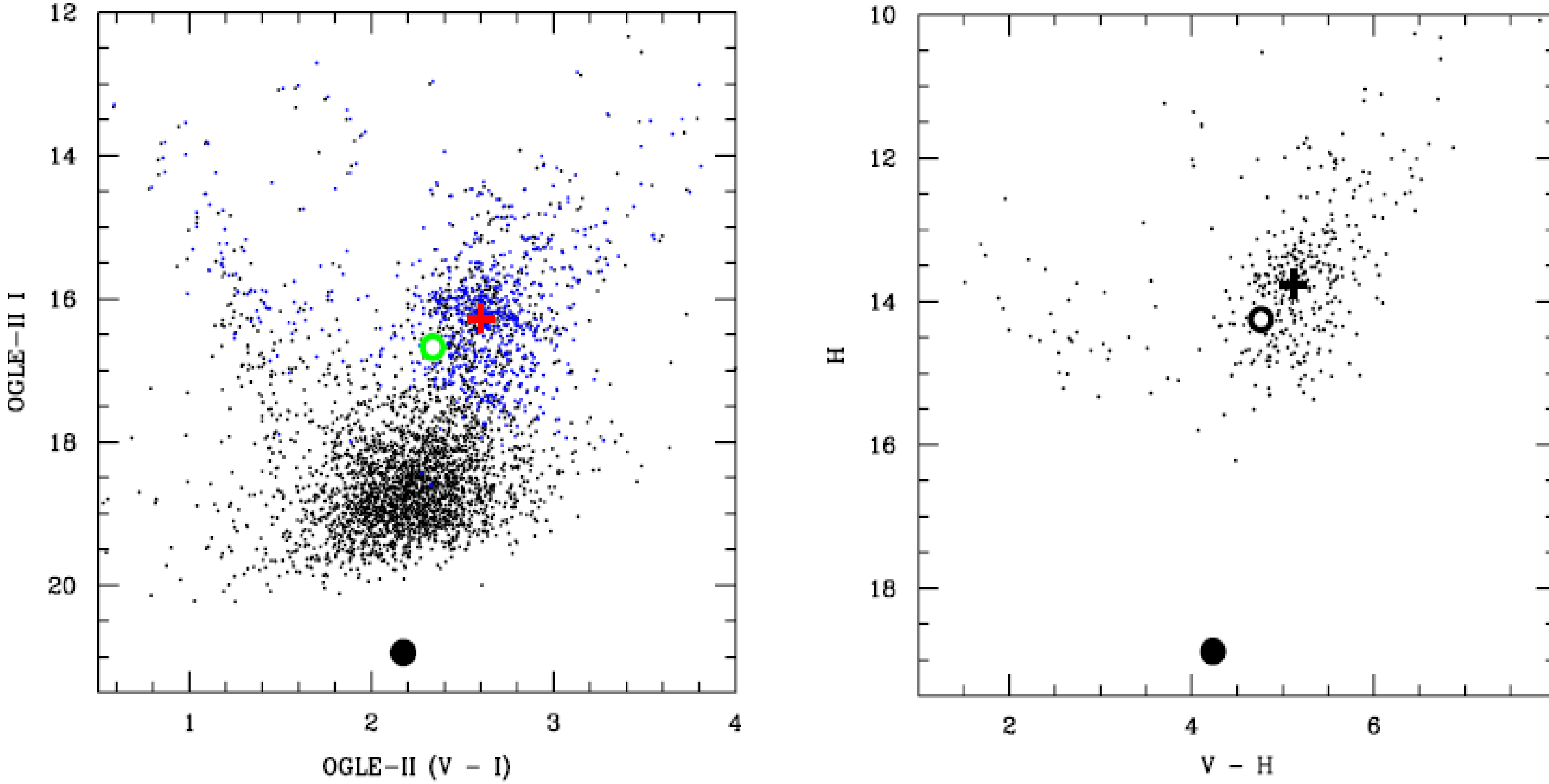
Derived Parameters

Parameter	Units	Parameter Limits				
		-2σ	-1σ	Median	$+1\sigma$	$+2\sigma$
D_L	kpc	1.30	1.39	1.51	1.62	1.74
M_A	$M_\odot$	0.43	0.47	0.51	056	0.60
m_b	$M_\oplus$	195	212	231	250	268
m_c	$M_\oplus$	73	79	86	93	99
$M_{\rm H}$		5.45	5.68	5.90	6.13	6.33
a_b	AU	1.6	1.8	2.3	2.8	3.4
P_b	Years	2.8	3.4	4.9	6.5	7.3
a_c	AU	2.9	3.5	4.5	6.6	13.5
P_c	Years	6.7	8.7	13.5	23.2	68
ϵ_c		0.007	0.05	0.15	0.32	0.62
α_c	deg	-50	-43	-36	-26	-16
i_c	deg	49	56	64	68	73
K_b	m s^{-1}	14.6	16.3	17.4	18.7	19.9
K_c	m s^{-1}	2.8	3.9	4.5	5.0	5.3

Bennett et al. 2010, ApJ, 713, 837

OGLE-2006-BLG-109

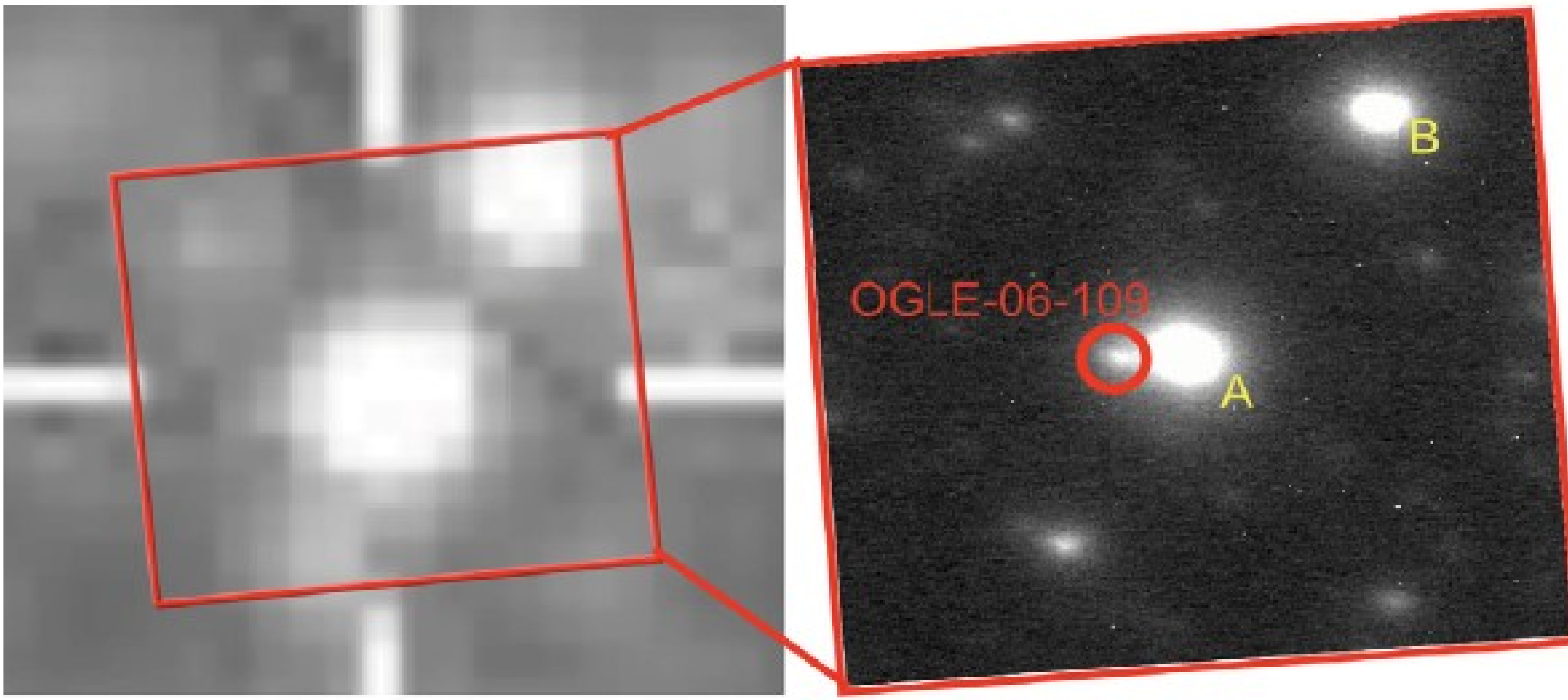
Source (MSTO) & Blend (Clump?) on CMD



Bennett et al. 2010, ApJ, 713, 837

OGLE-2006-BLG-109

Keck: Source+Blend Much Fainter than clump



Bennett et al. 2010, ApJ, 713, 837

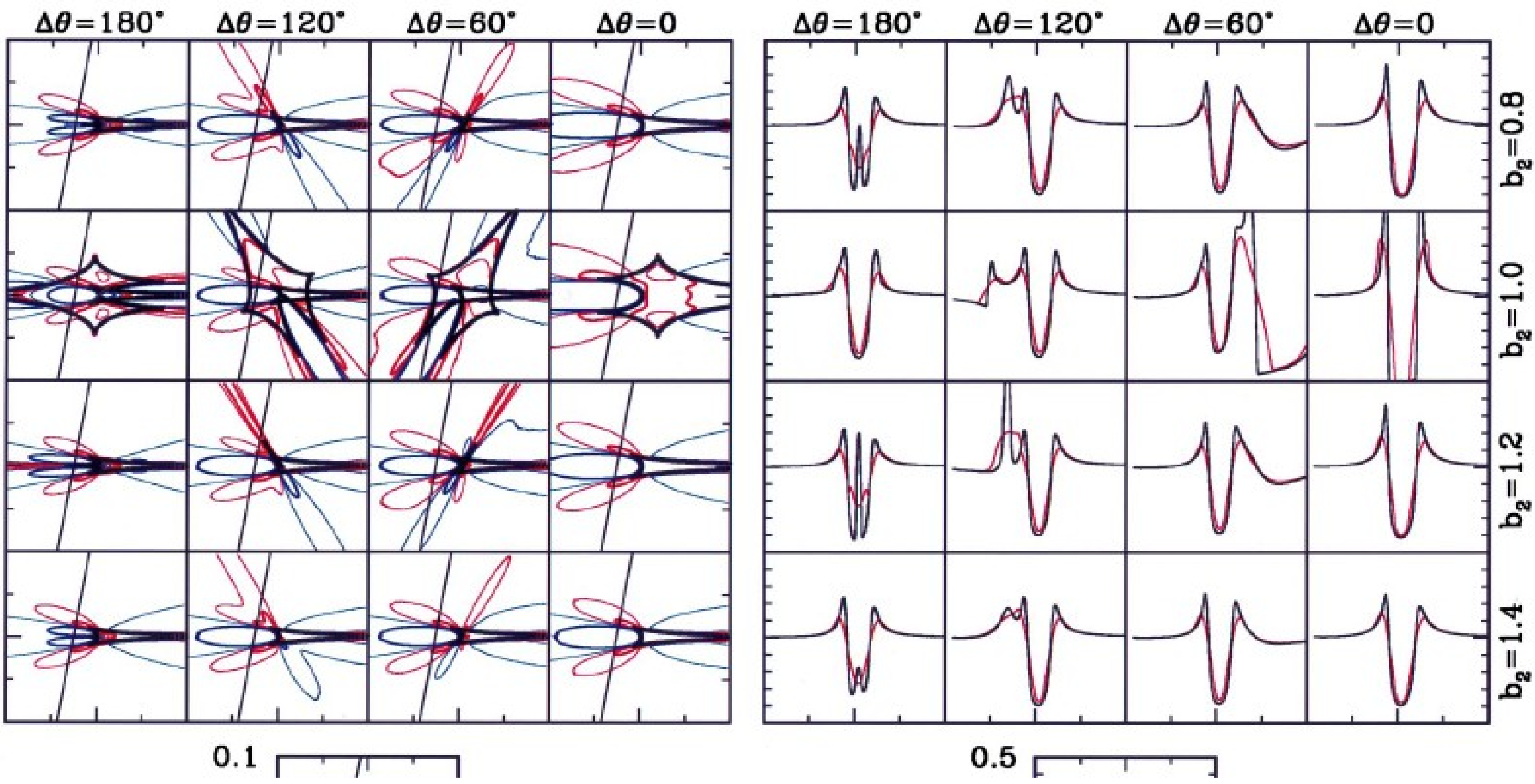
OGLE-2006-BLG-109

Lens H-band flux: observed vs. predicted

- H_{LS} = 16.99 +- 0.04 (Keck)
- H_S = 18.876 +- 0.014 (Event Fit to CTIO)
- H_L = 17.17 +- 0.05 (subtraction)
- H_L (predicted) = 16.79 + 0.3 = 17.09
- Lens directly detected

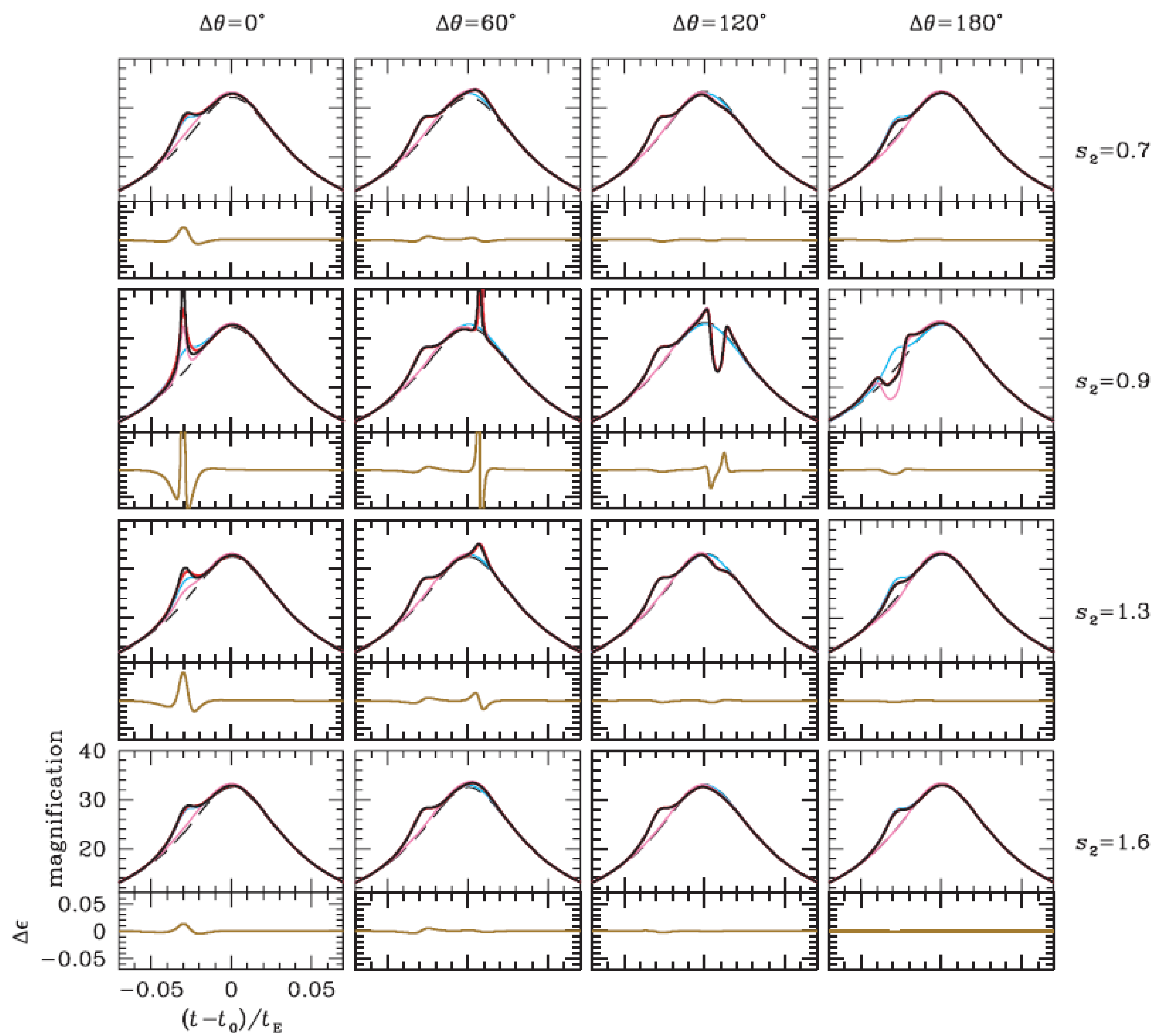
Bennett et al. 2010, ApJ, 713, 837

Predicted in the last millennium



Gaudi, Naber & Sackett 1998, ApJ, 502, 33

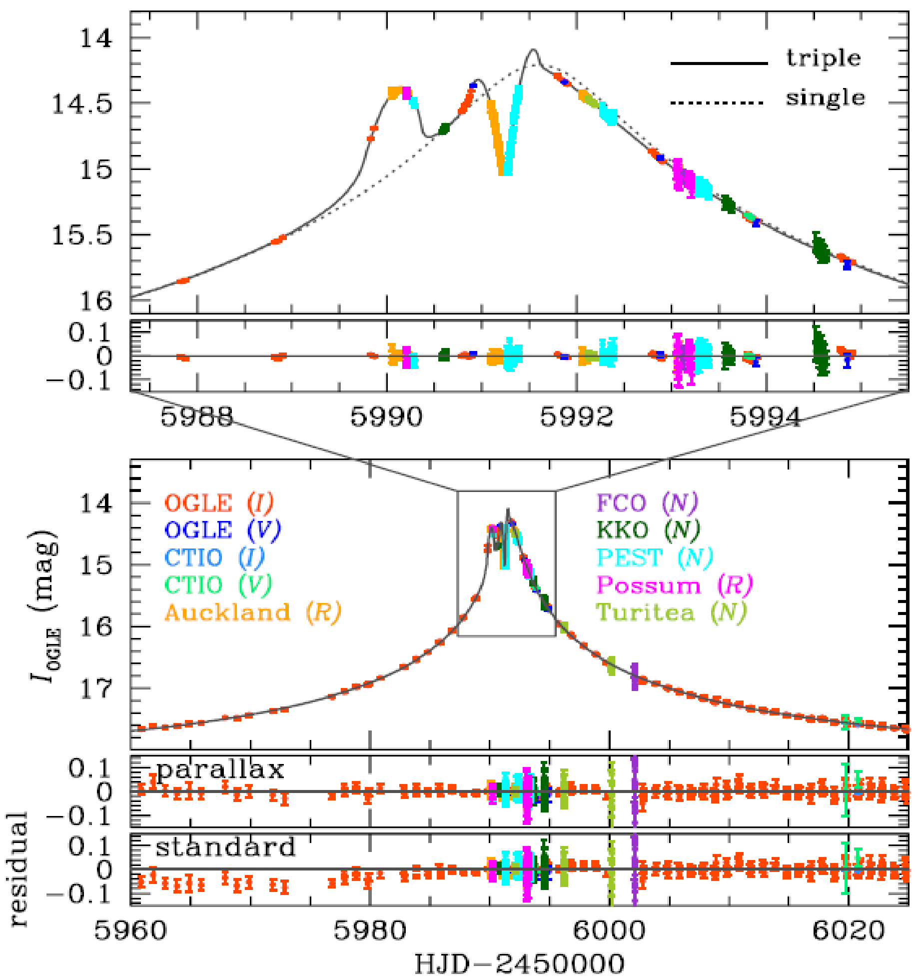
Two-Planet Superposition Principle



Han 2005, ApJ, 629, 1102

OGLE-2012-BLG-0026

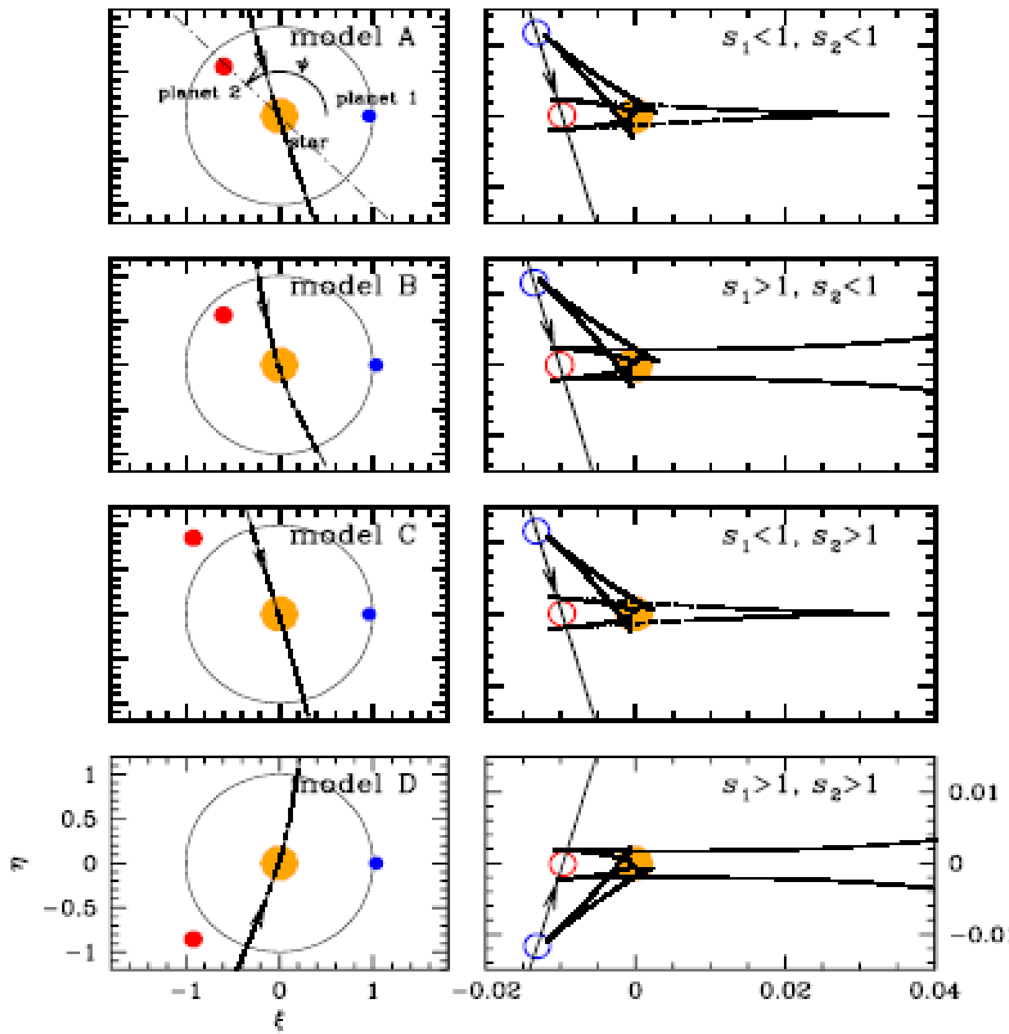
Second 2-planet system



Han et al, ApJL, submitted

OGLE-2012-BLG-0026

4-fold degeneracy: Unstable?



Han et al, ApJL, submitted

OGLE-2012-BLG-0026

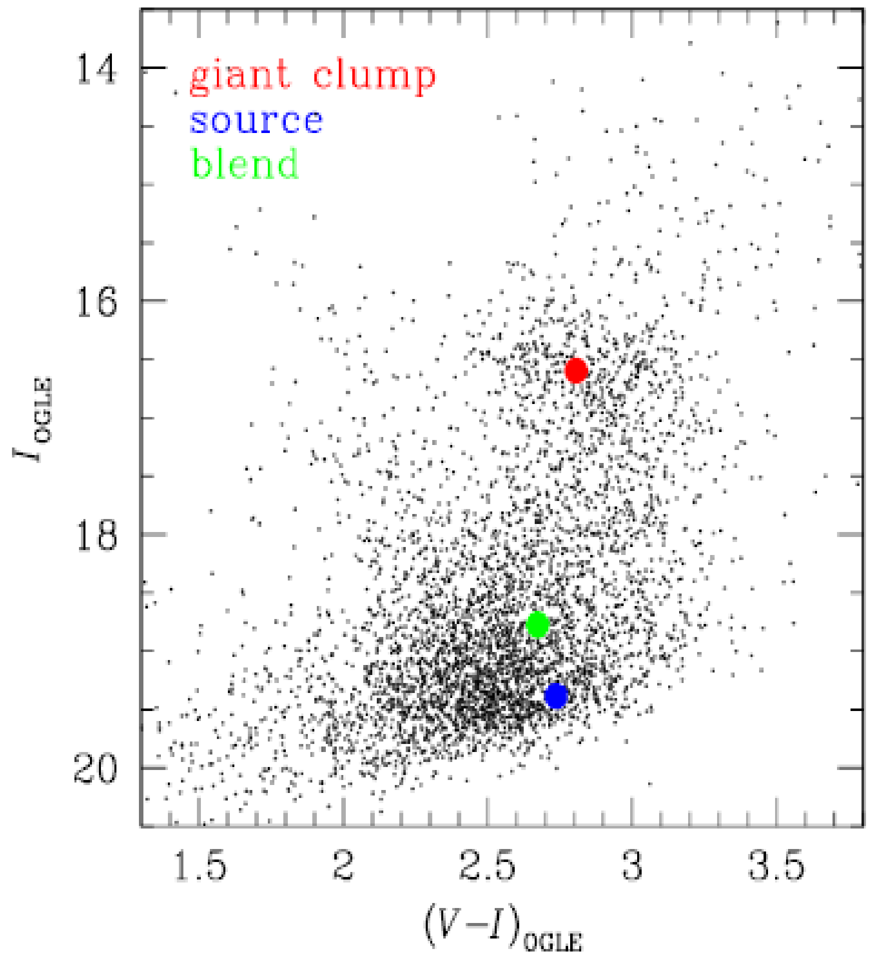
Fit parameters

parameters	model A	model B	model C	model D
χ^2/dof	2689.7/2667	2681.0/2667	2680.8/2667	2674.4/2667
t_0 (HJD')	5991.52 ± 0.01	5991.52 ± 0.01	5991.52 ± 0.01	5991.52 ± 0.01
u_0	-0.0094 ± 0.0001	-0.0097 ± 0.0001	-0.0094 ± 0.0001	0.0092 ± 0.0001
t_E (days)	92.45 ± 1.08	89.21 ± 0.17	92.85 ± 1.11	93.92 ± 0.58
s_1	0.957 ± 0.001	1.034 ± 0.001	0.957 ± 0.001	1.034 ± 0.001
q_1 (10^{-4})	1.32 ± 0.02	1.37 ± 0.01	1.30 ± 0.02	1.30 ± 0.01
s_2	0.812 ± 0.004	0.819 ± 0.004	1.257 ± 0.006	1.254 ± 0.006
q_2 (10^{-4})	7.97 ± 0.26	7.84 ± 0.25	8.04 ± 0.25	7.84 ± 0.21
α	1.283 ± 0.001	1.284 ± 0.001	1.284 ± 0.001	4.999 ± 0.001
ψ	2.389 ± 0.002	2.387 ± 0.001	2.391 ± 0.001	3.891 ± 0.001
$\rho_\star$ (10^{-3})	1.73 ± 0.02	1.81 ± 0.01	1.72 ± 0.02	1.72 ± 0.01
$\pi_{E,N}$	-0.029 ± 0.054	-0.097 ± 0.012	0.001 ± 0.028	-0.072 ± 0.051
$\pi_{E,E}$	0.123 ± 0.009	0.137 ± 0.003	0.123 ± 0.005	0.114 ± 0.004

Han et al, ApJL, submitted

OGLE-2012-BLG-0026

Lens Detected?



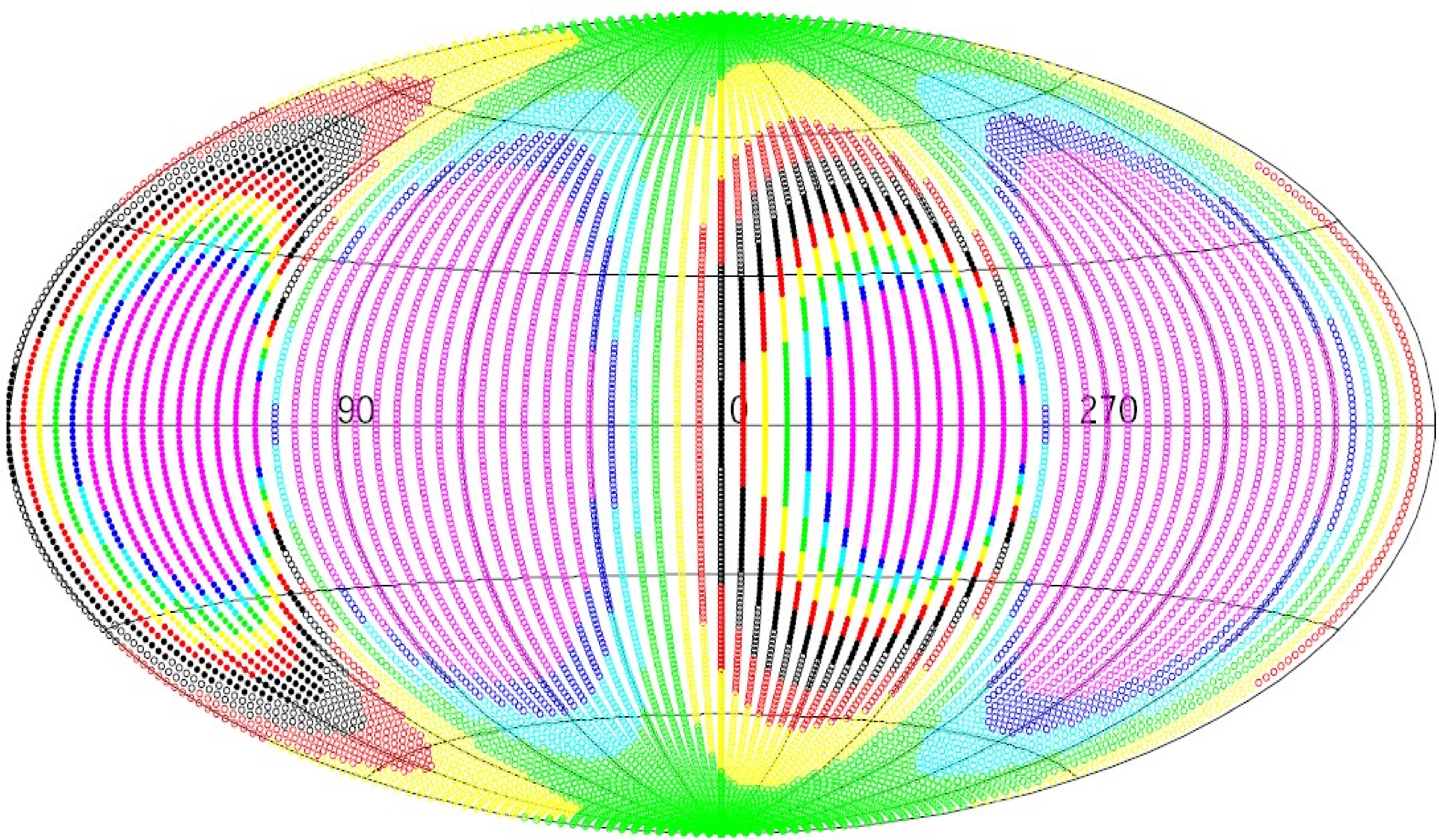
Han et al, ApJL, submitted

3-Body Lightcurve Modeling

- Static maps Difficult (5 map parameters)
  - q_1, s_1, q_2, s_2, ϕ_{12}
- Non-static Maps Very Difficult
- Contours or Ray-Shooting "easily" adapted to triple lens case

OGLE-2012-BLG-0026: Stability Analysis

$$|a_1-a_2|/[(a_1+a_2)(q_1+q_2)^{1/3}/2]>2.4$$



Second Generation Surveys

- “Pure Survey”: large camera, multi-continent
- “Continuous coverage” of all events
- No followup observations needed

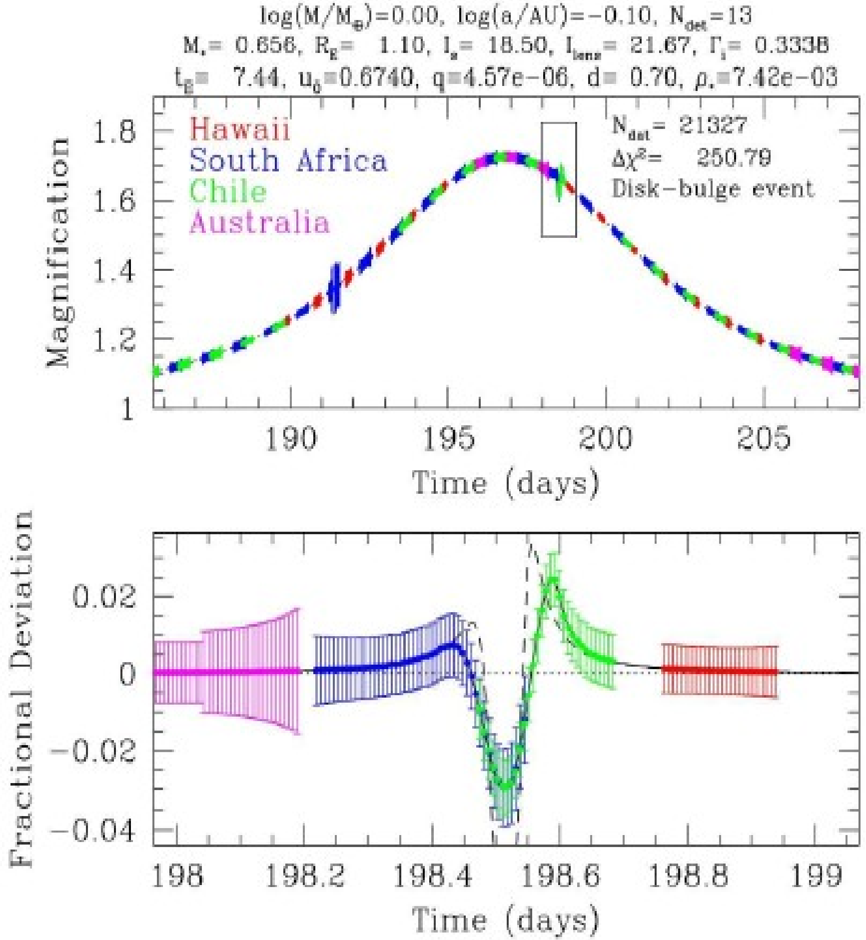
Approach: Threshold + Upgrades

- 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)

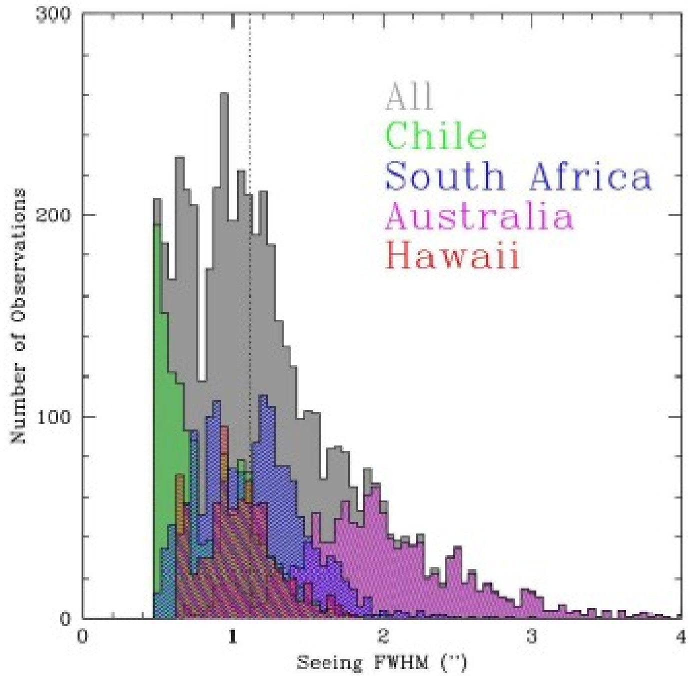
NextGen Microlensing Planet Search

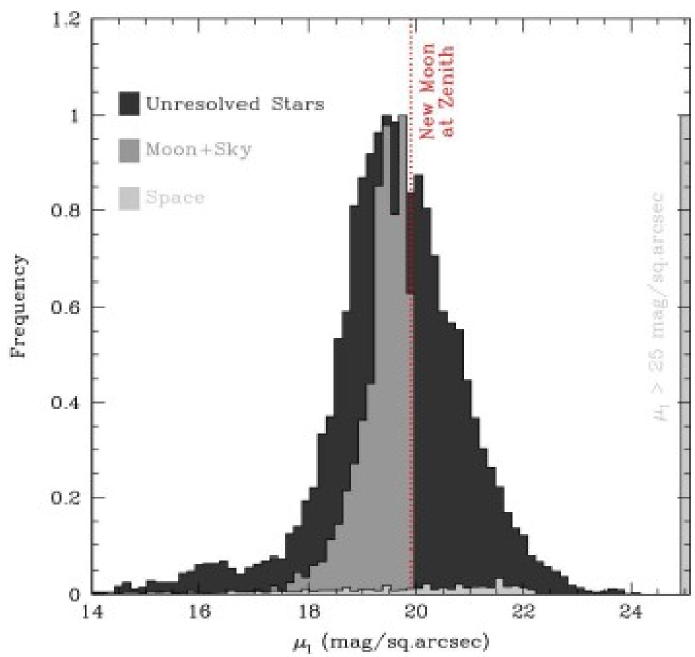
Simulations by Scott Gaudi

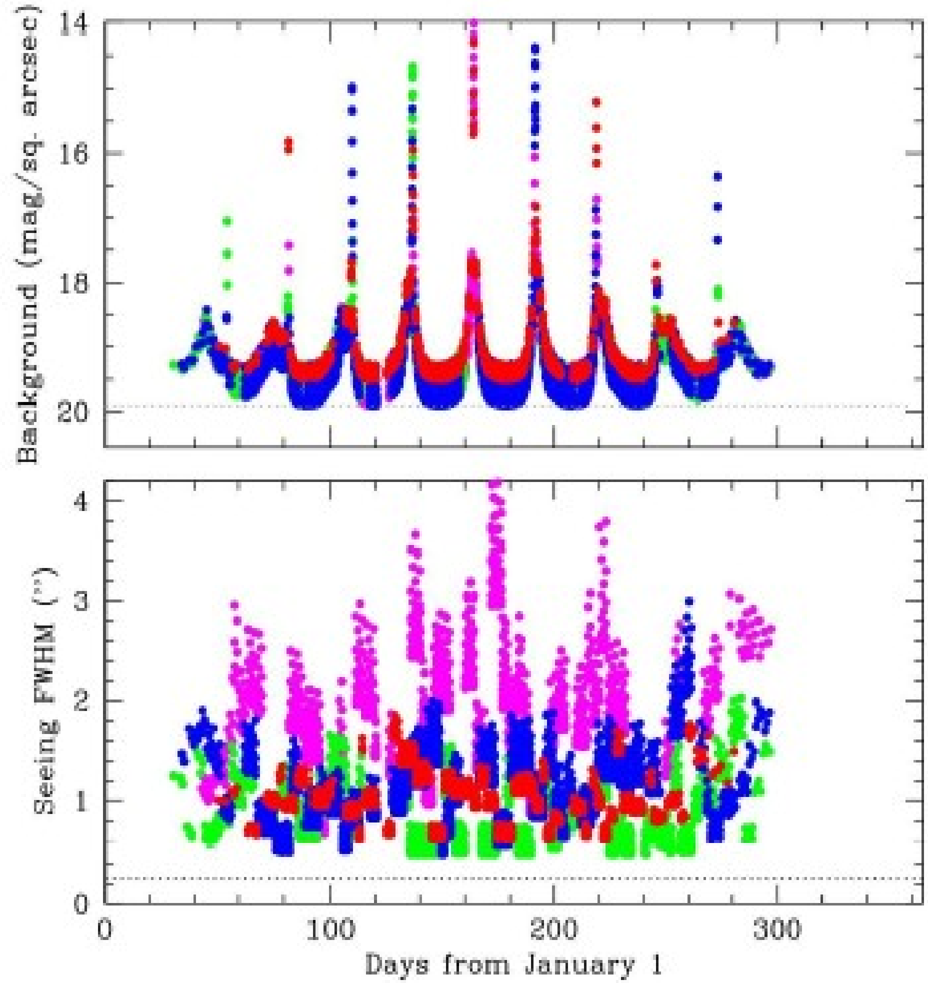
- 4 observatories
- 2m class telescopes
- 4 sq.deg. cameras
- Realistic seeing & weather
- photon-limited statistics down to systematics limit



Simulation Ingredients (abridged)

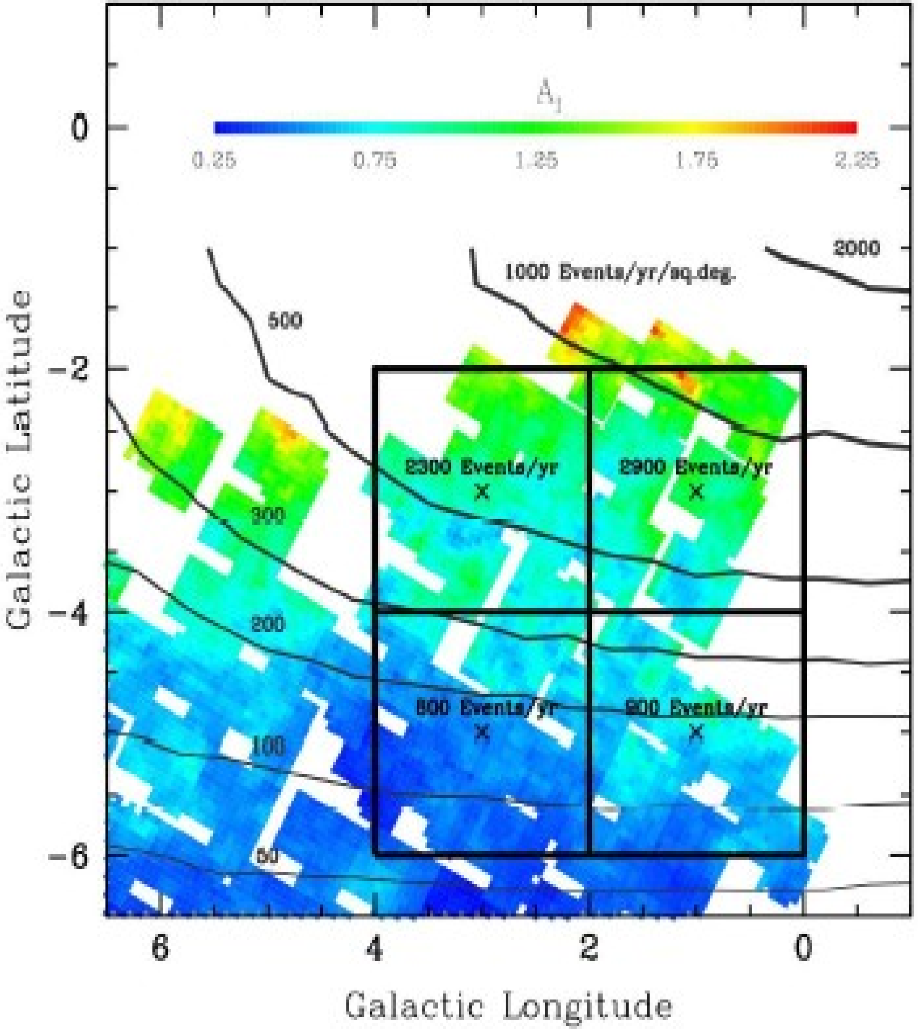


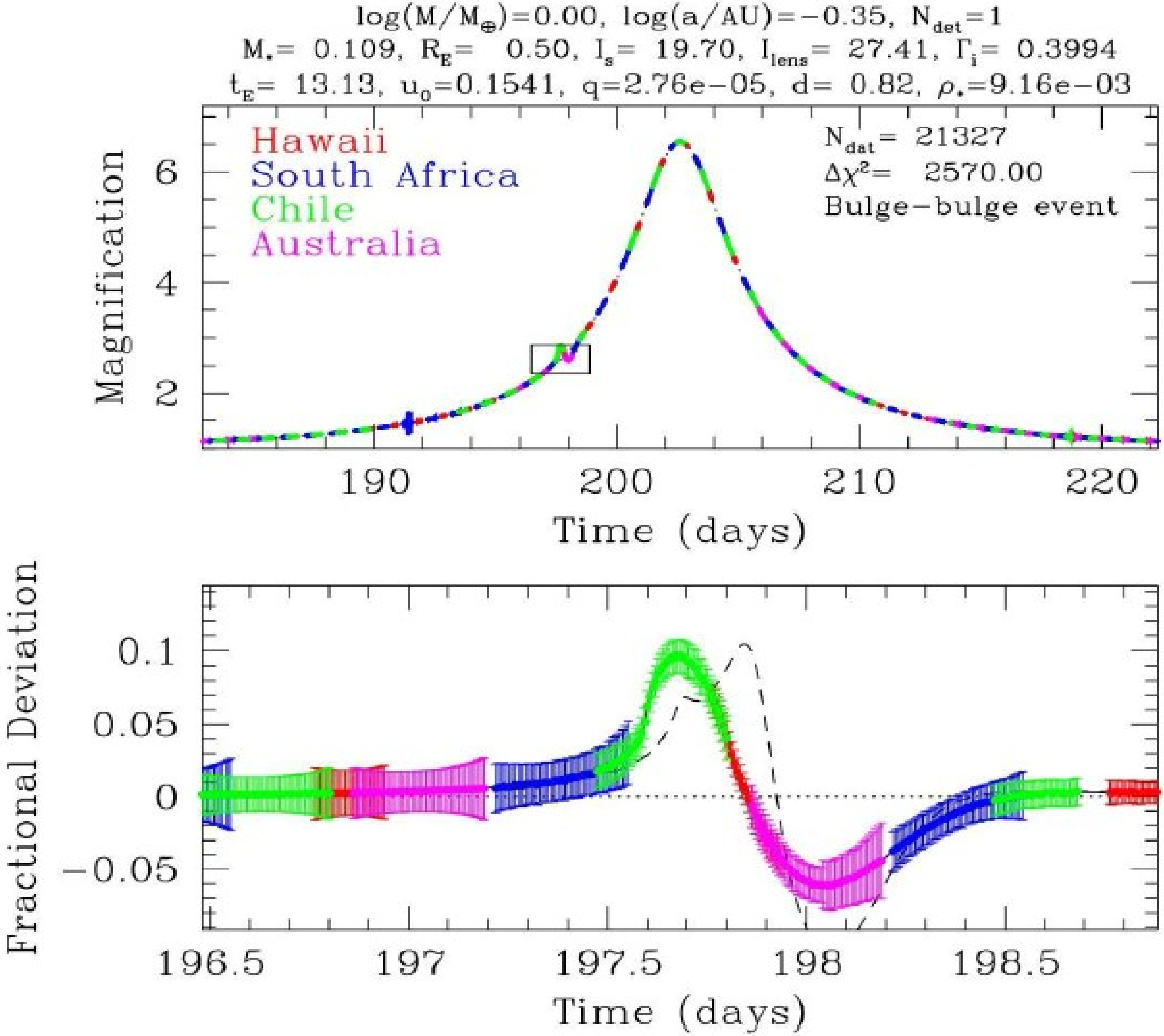


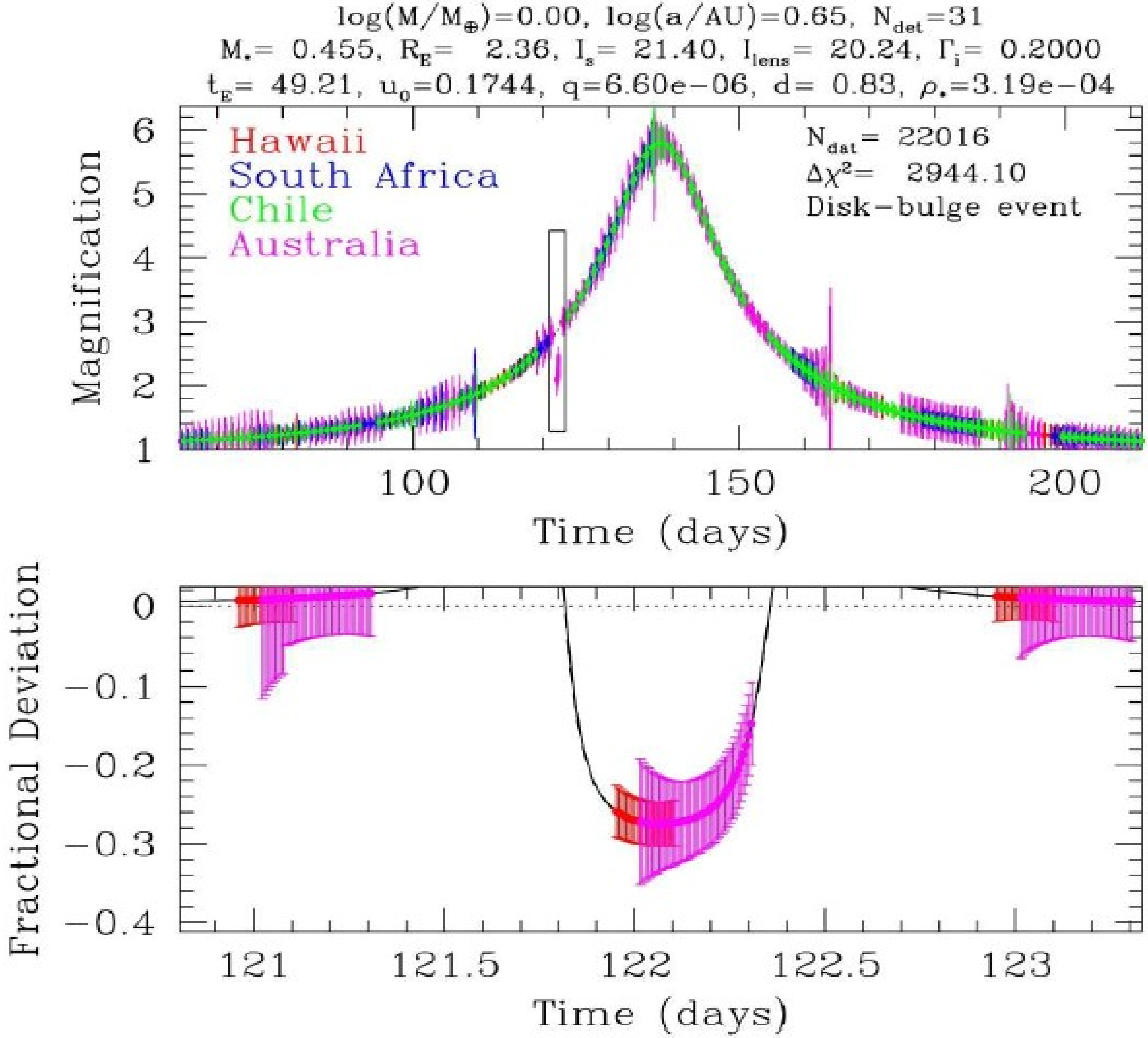


Target Fields

- 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)



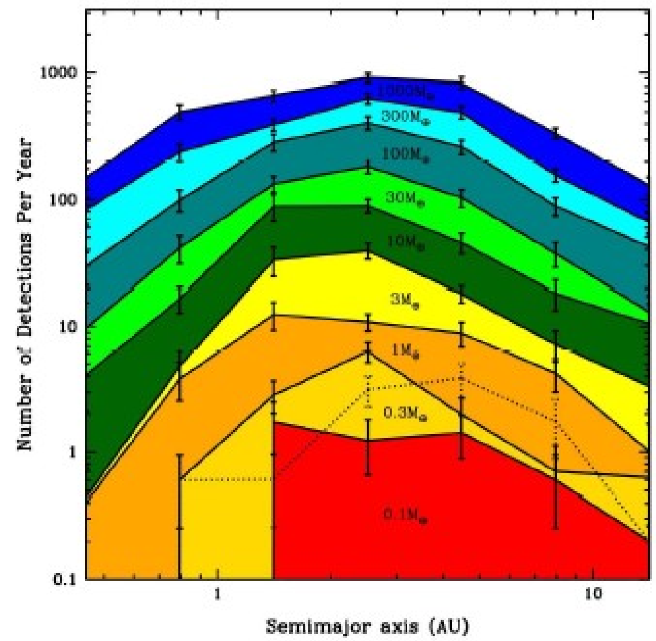
log(M/M⊕)=0.00, log(a/AU)=0.65, N_det=31
M*= 0.455, R_E= 2.36, I_s= 21.40, I_lens= 20.24, Γ_i= 0.2000
t_E= 49.21, u_0=0.1744, q=6.60e-06, d= 0.83, ρ*=3.19e-04
Hawaii
South Africa
Chile
Australia
N_dat= 22016
Δχ²= 2944.10
Disk-bulge event
Magnification
Time (days)
Fractional Deviation
Time (days)

Baseline Results

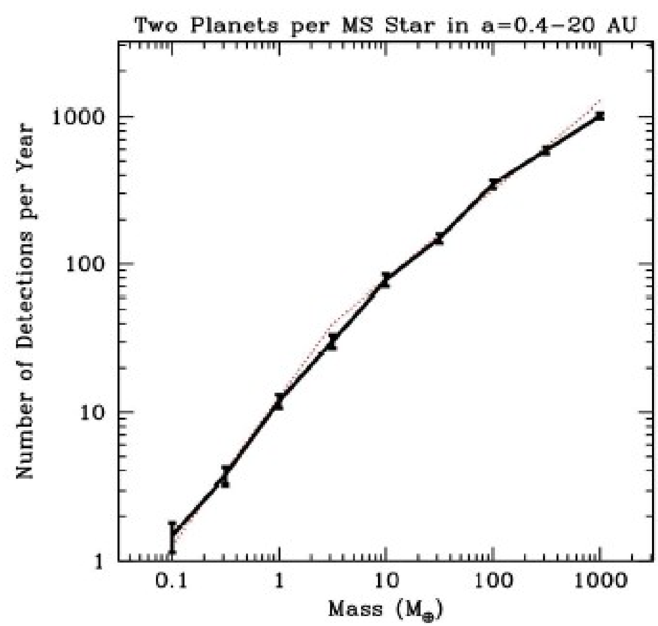
- Simulate:
  - Mass:

    $\log(M/M_{\oplus})$=-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

Heidelberg: November 2005

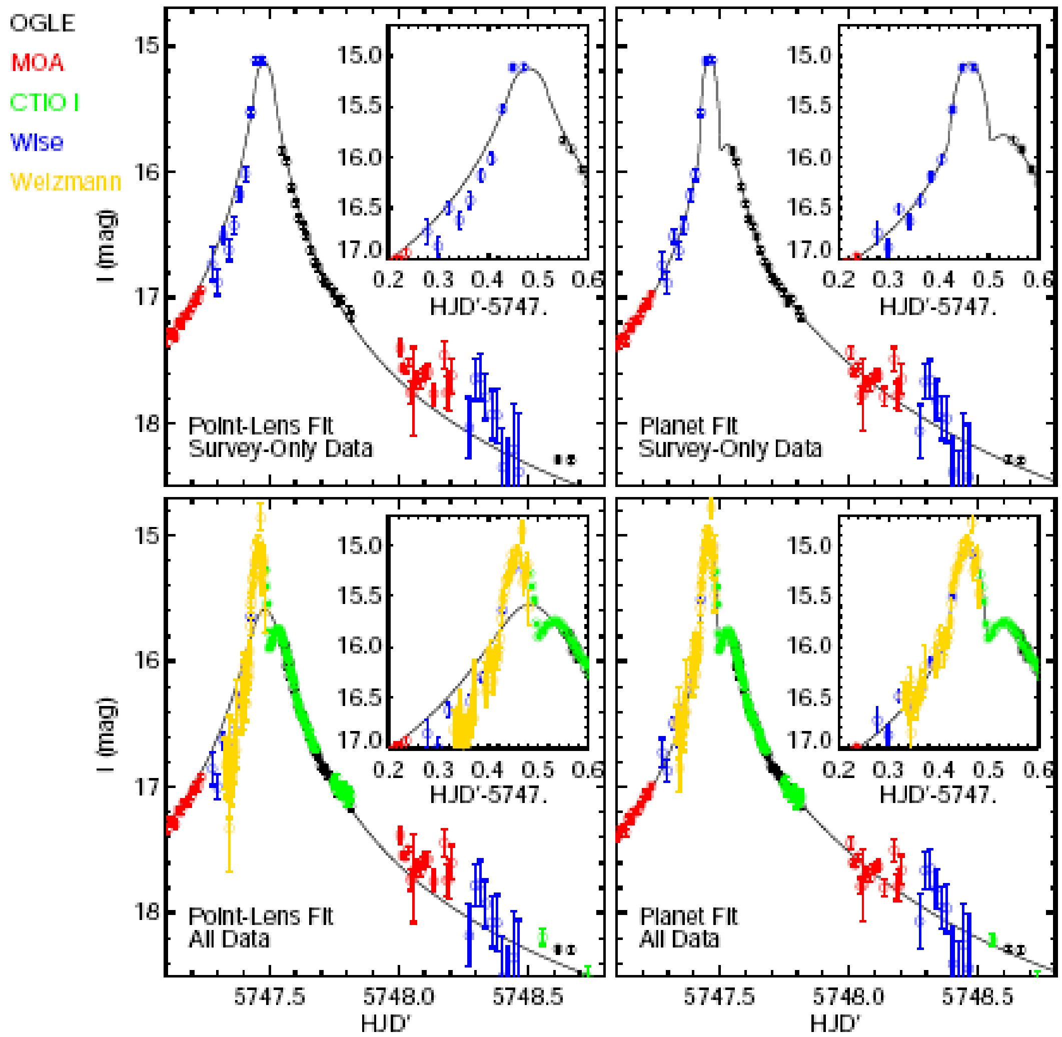
- Participants from France, Germany, Japan, Korea, New Zealand, Poland, UK, US
- Critically reviewed models to predict planet detection and their underlying assumptions
- Presentations about wide range of potential initiatives for implementation
- Generally enthusiastic response

Initiatives

- MOA: 1.8m tel, 2.2 sq.deg camera already planned (New Zealand) [began operations 2007]
- OGLE: 1.3m tel already exists, upgraded to 1.4 sq.deg. already proposed (Chile) [began 2010]
- 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] First light: 2013

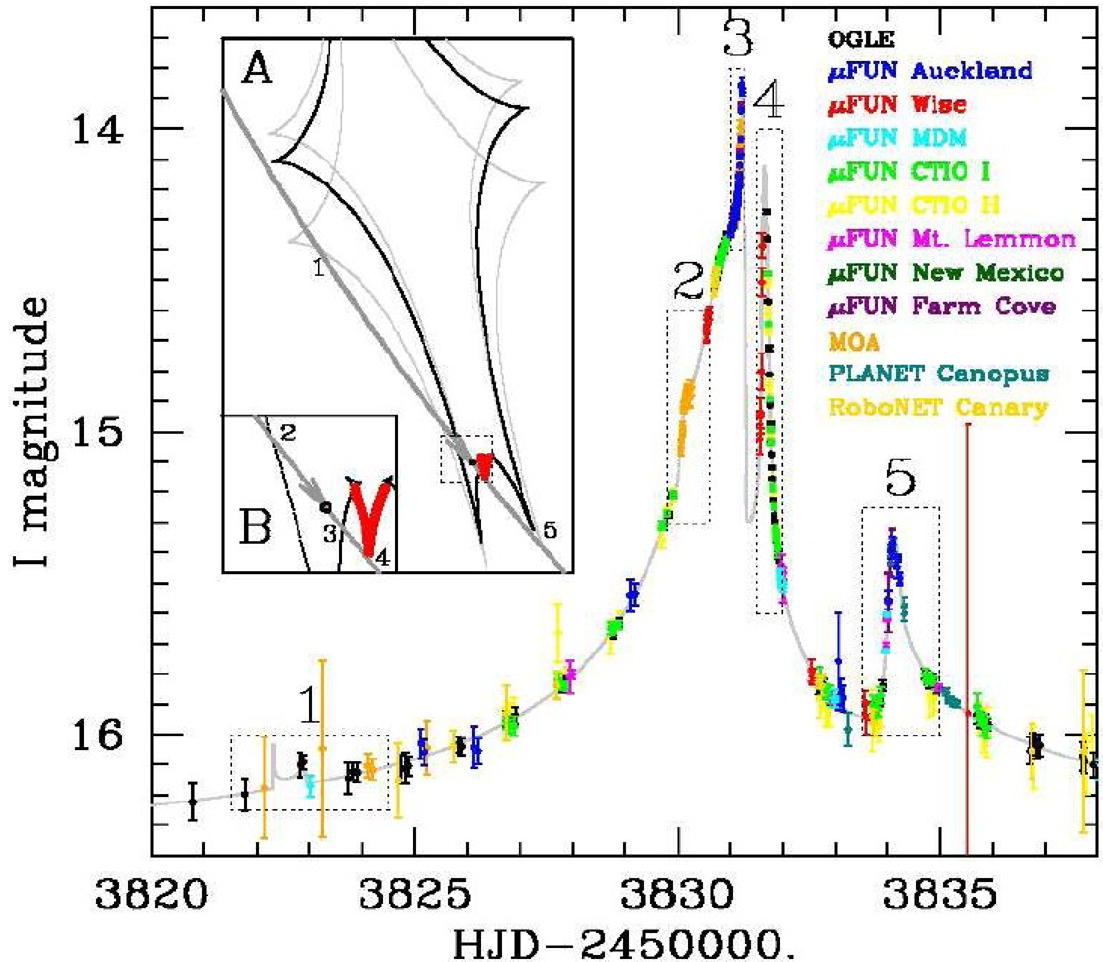
Really Eliminate Followup?

Example 1: MOA-2011-BLG-293



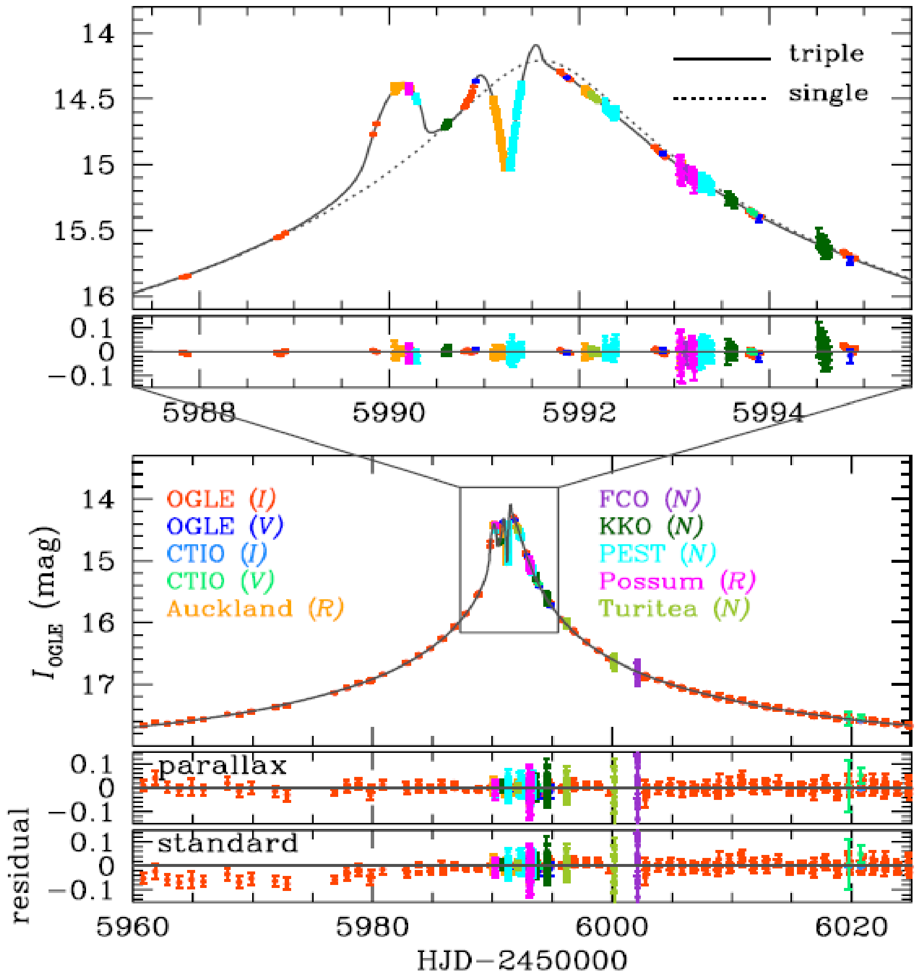
Really Eliminate Followup?

Example 2: OGLE-2006-BLG-109



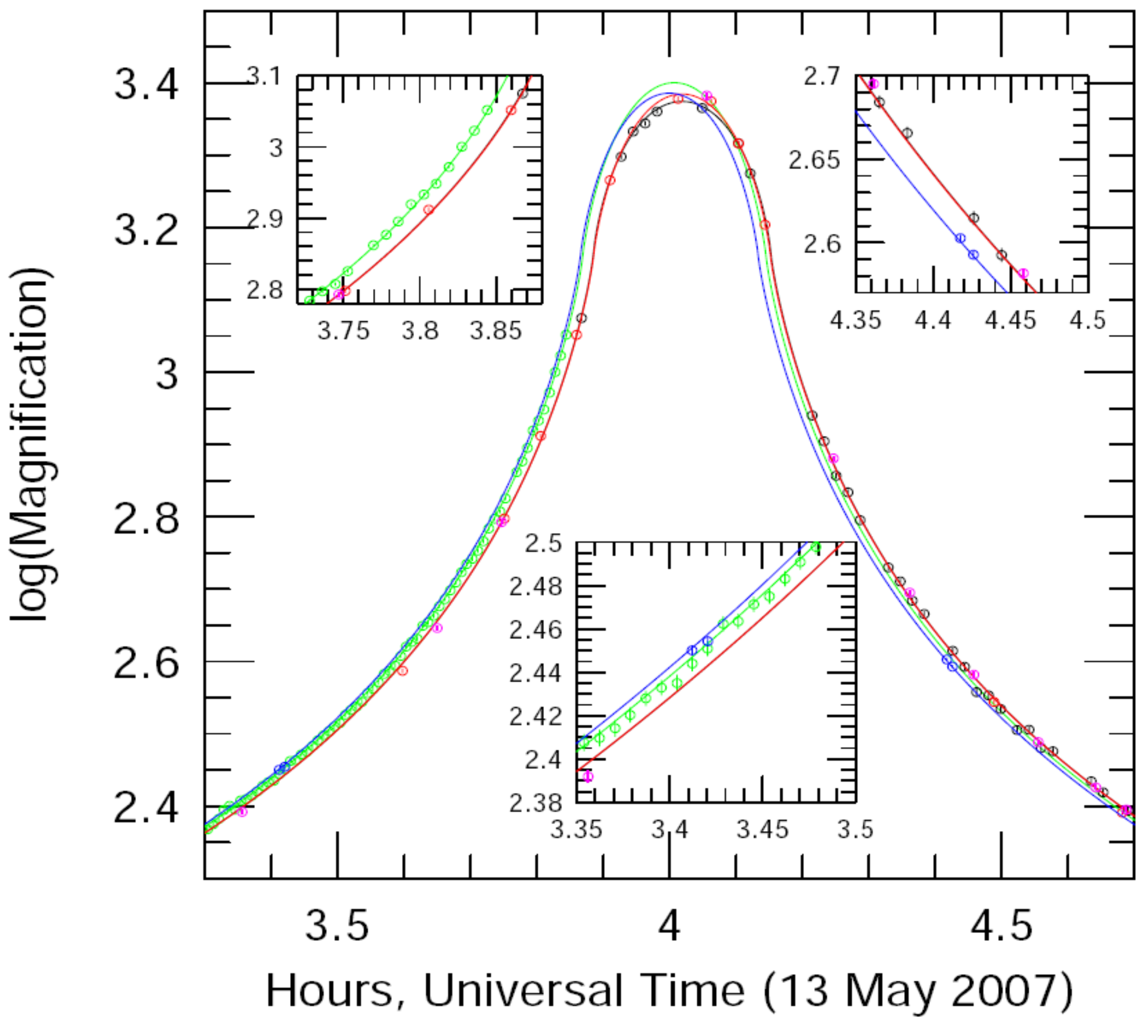
Really Eliminate Followup?

Example 3: OGLE-2012-BLG-0026

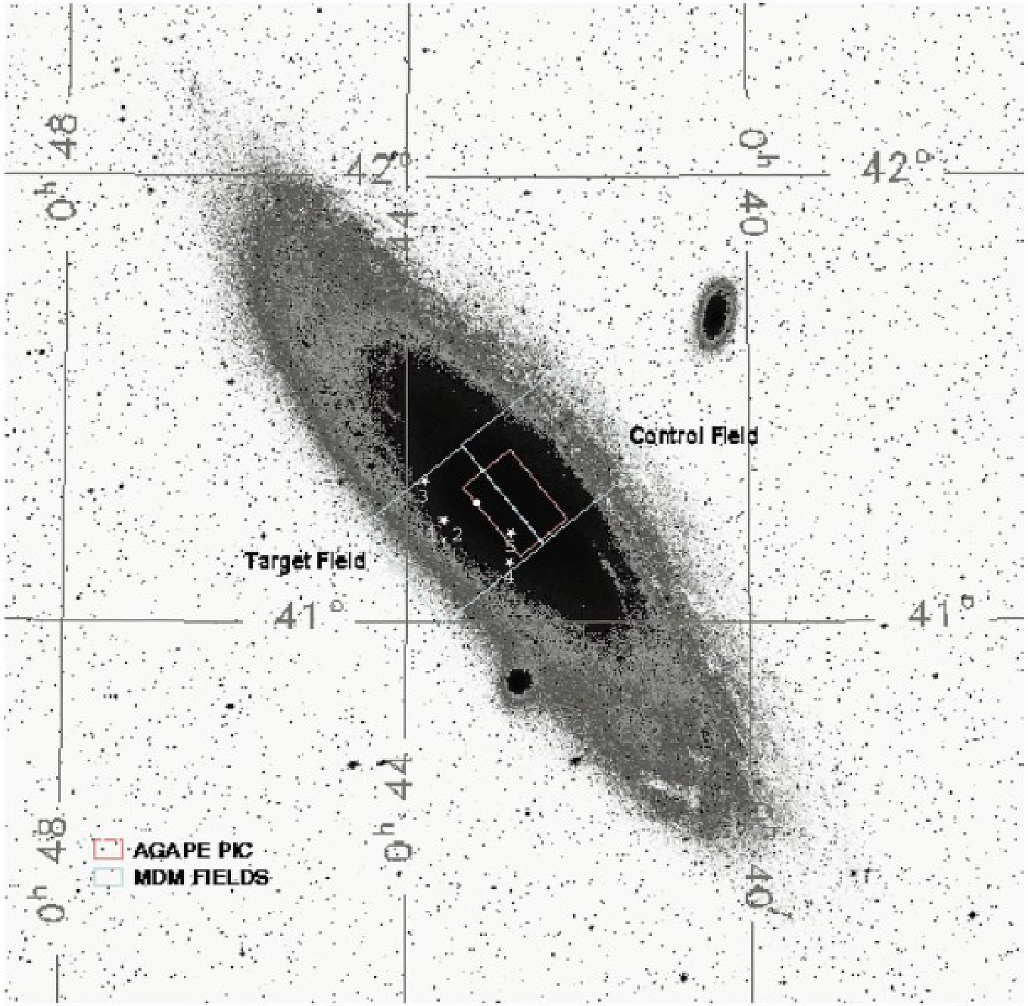


Really Eliminate Followup?

Example 4: OGLE-2007-BLG-224

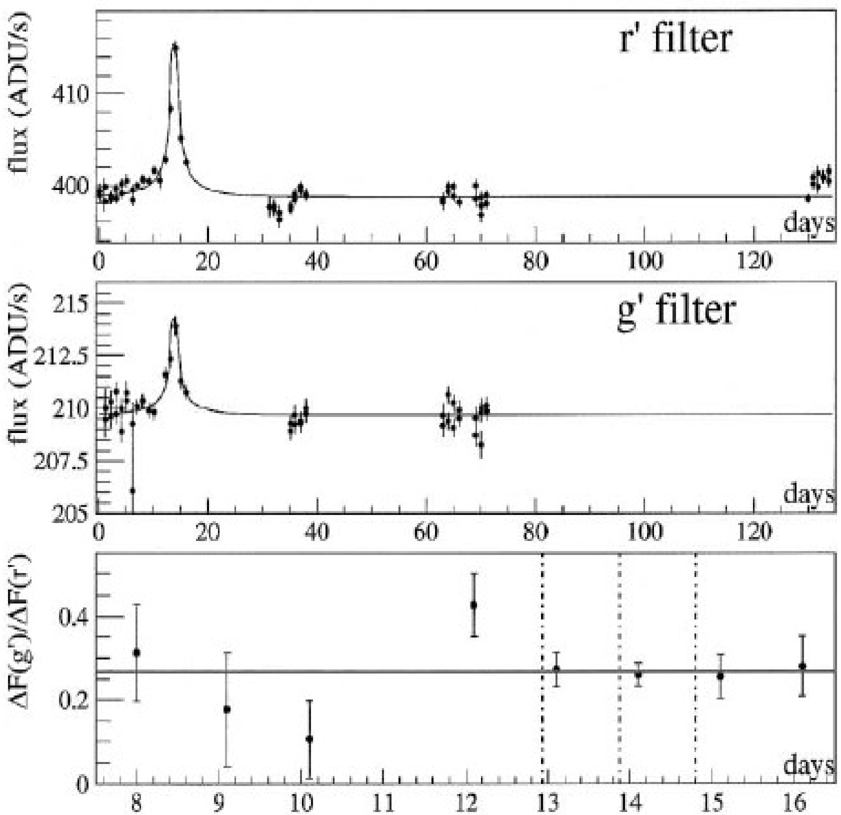


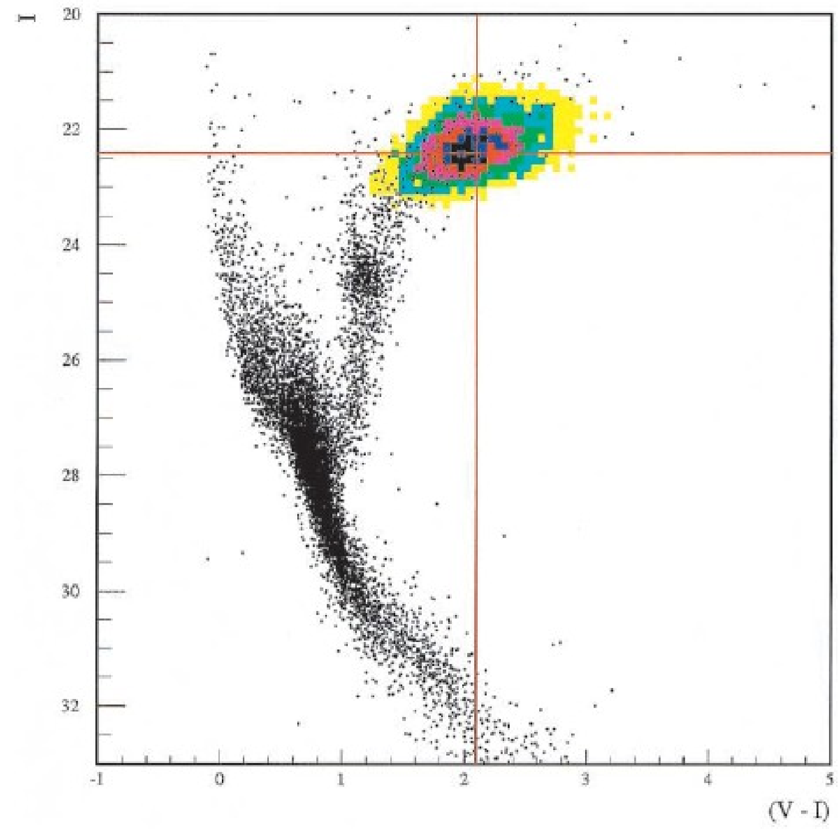
M31 microlensing planet searches?



Early M31 microlensing event

Bright Giant Source

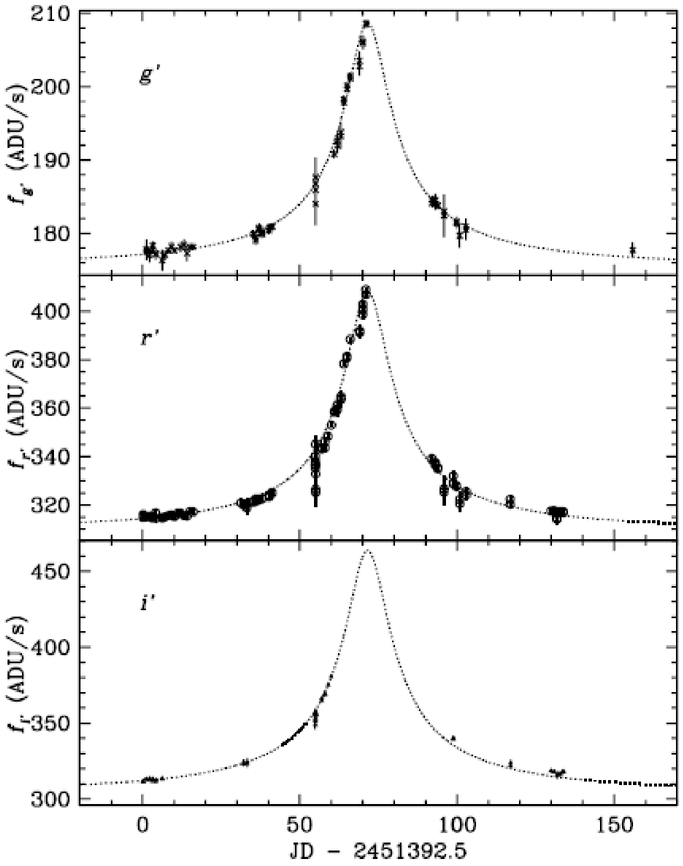




Auriere et al. 2001, ApJ, 553, L137

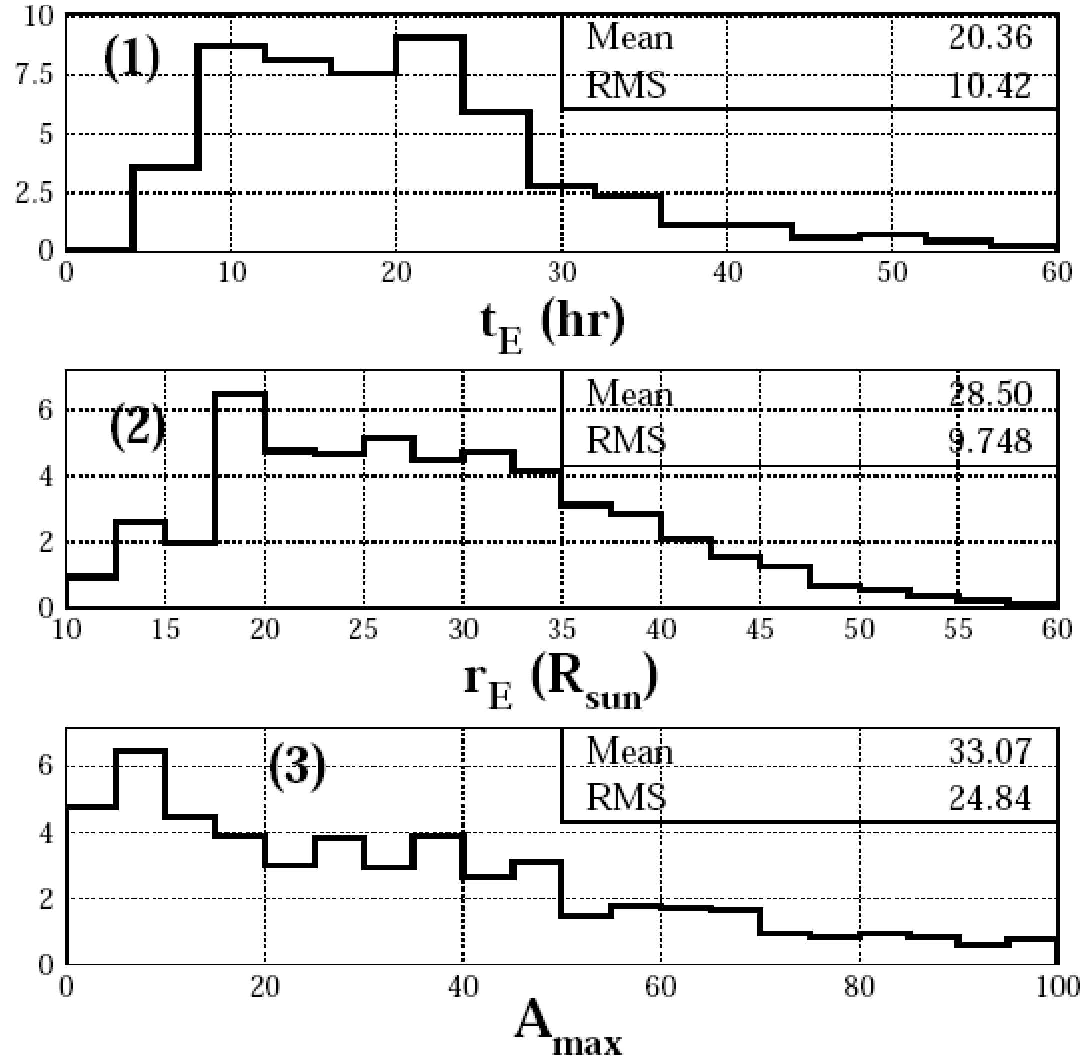
M31 possible planetary microlensing

Also Bright Giant Source

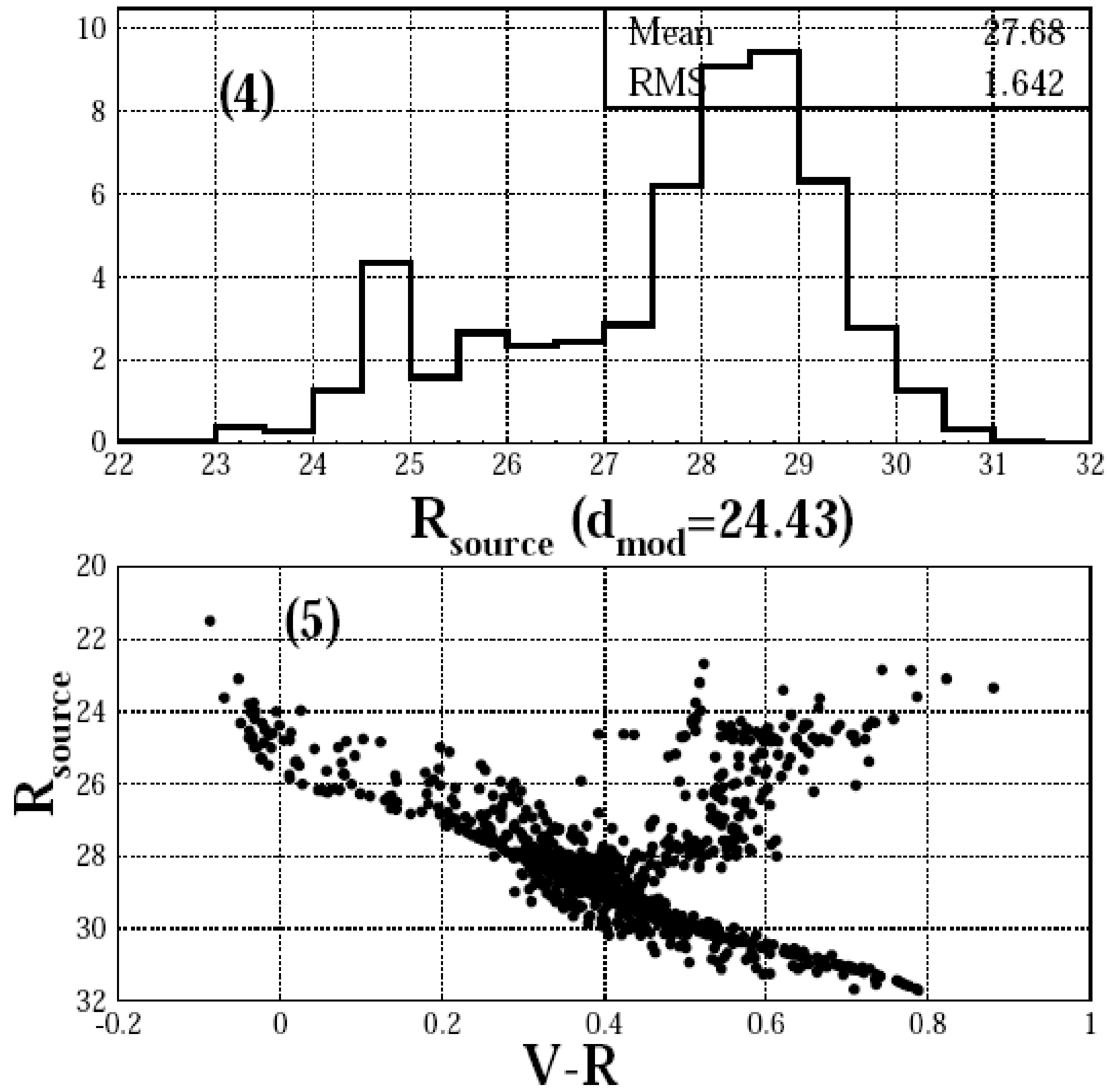


An et al. 2004, ApJ, 601, 845

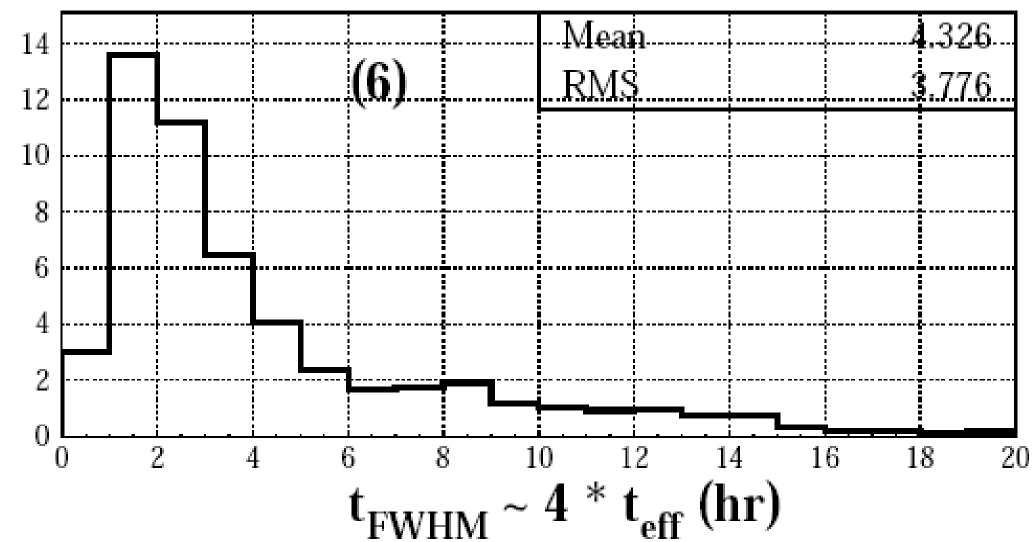
M31 FFP Event Characteristics (with LBT)

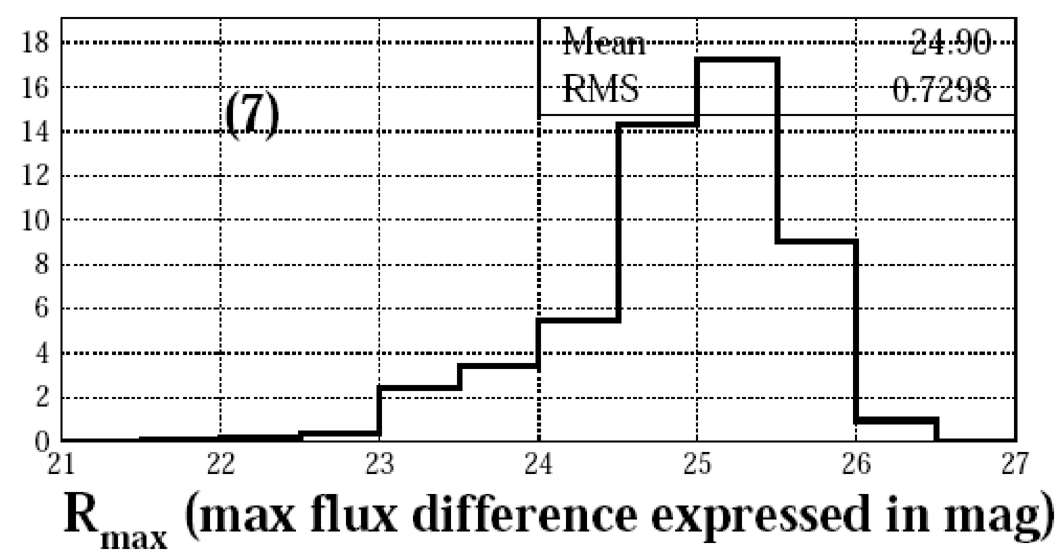


M31 Planet Event Characteristics

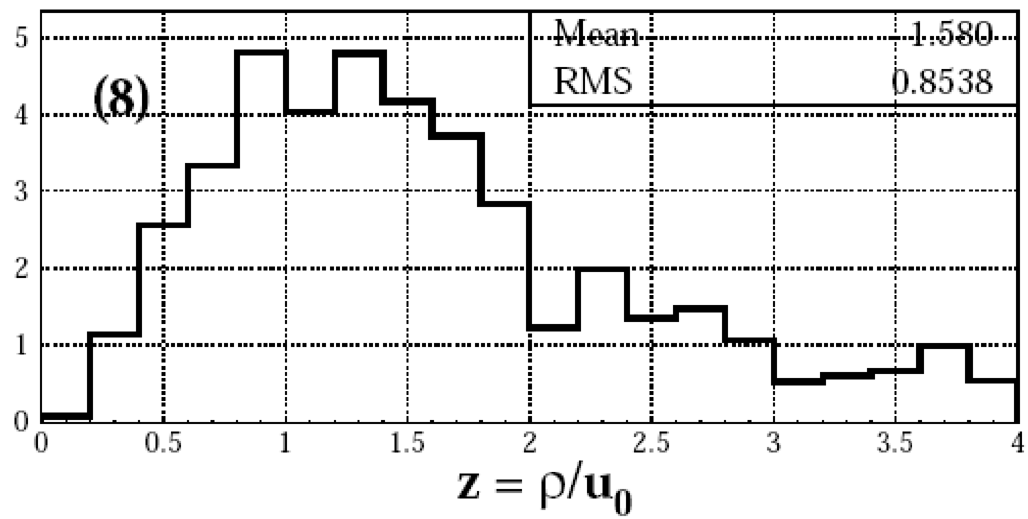


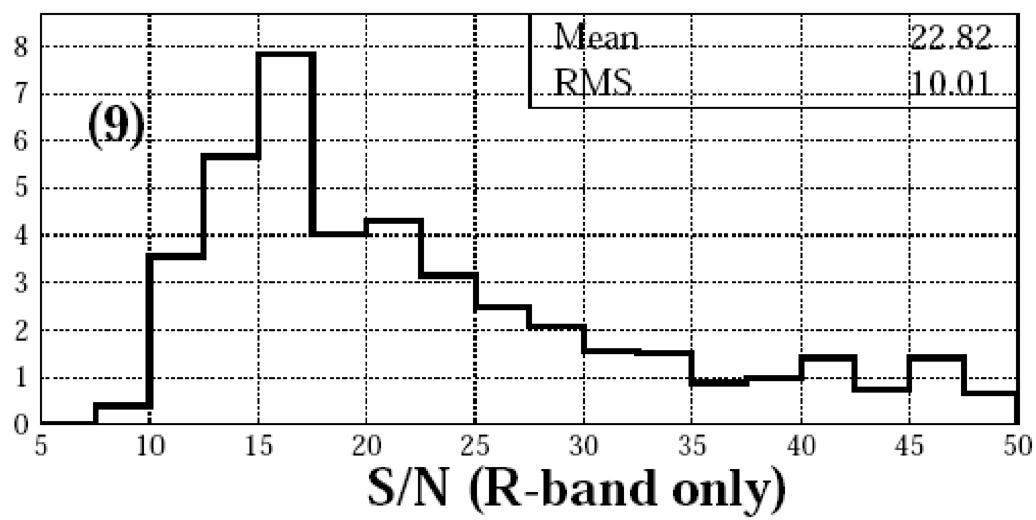
M31 Planet Event Characteristics



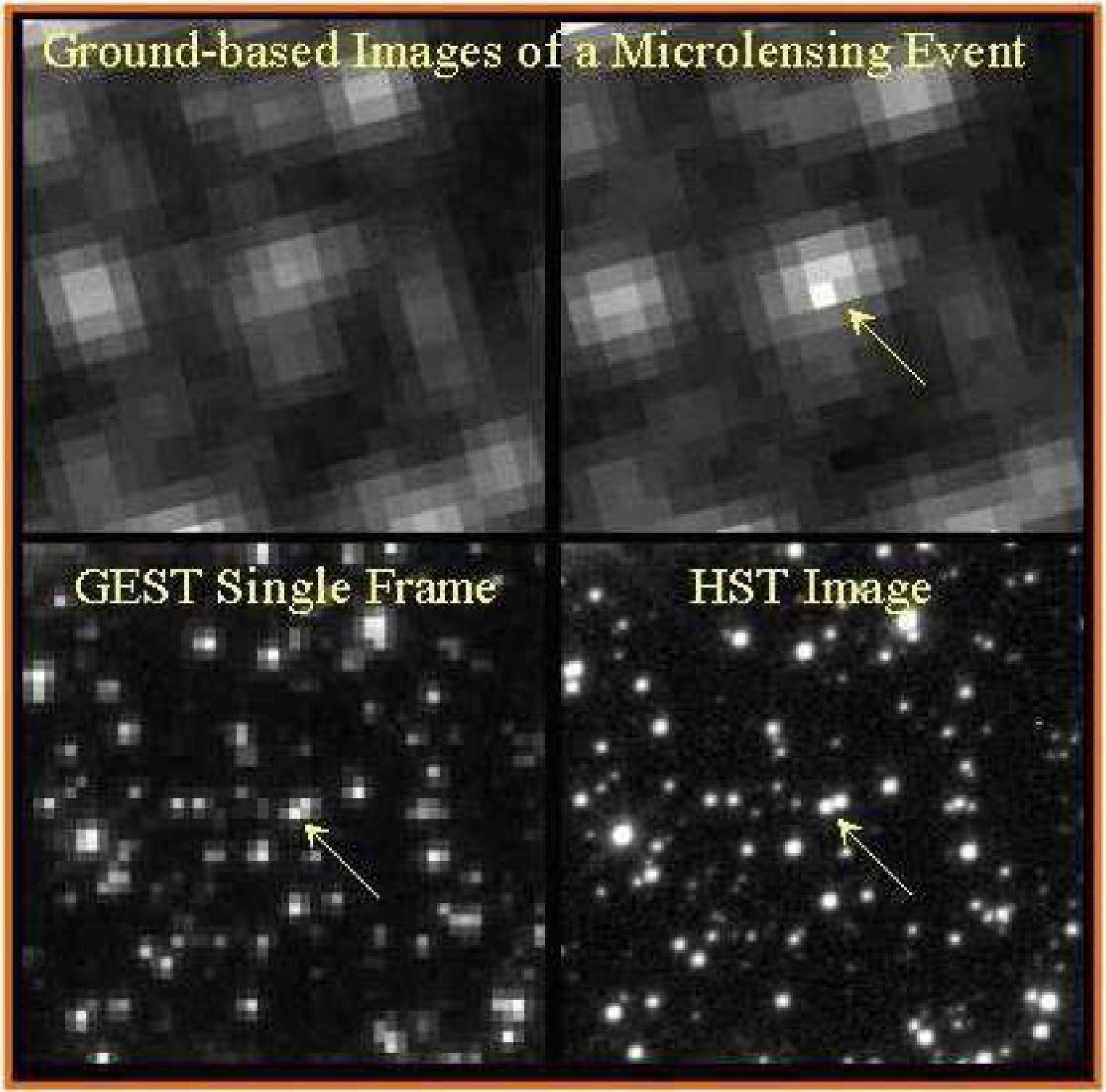


M31 Planet Event Characteristics





Seeing Better In Space (also weather)



Anti-Lemming

Wide Field Imager in Space for Dark Energy and Planets

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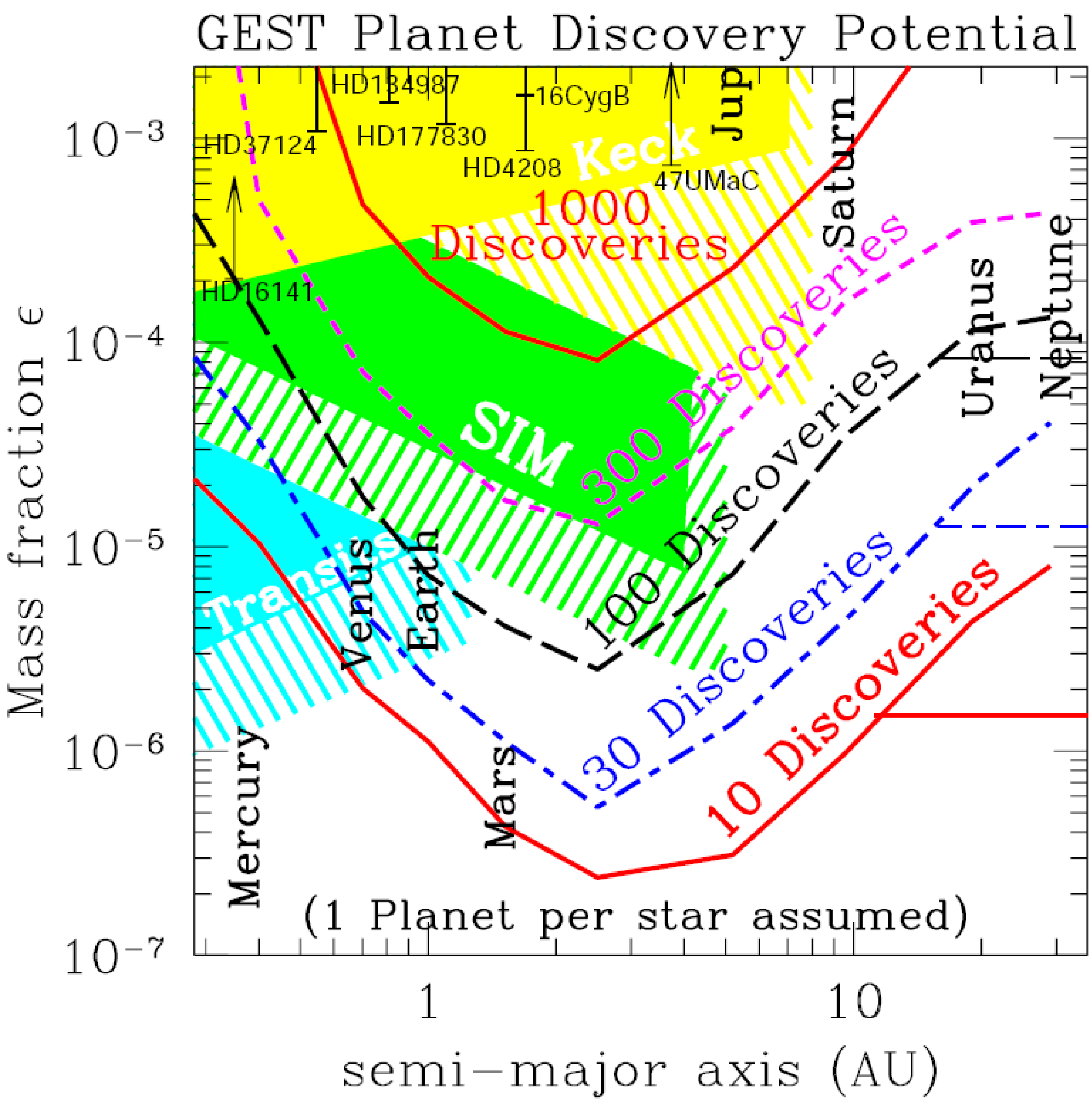
ABSTRACT

A wide-field imager in space could make remarkable progress in two very different frontiers of astronomy: dark energy and extra-solar planets. Embedding such an imager on a much larger and more complicated DE mission would be a poor science-approach under any circumstances and is a prescription for disaster in the present fiscal climate. The 2010 Decadal Committee must not lead the lemming stampede that is driving toward a DE mega-mission, but should stand clearly in its path.

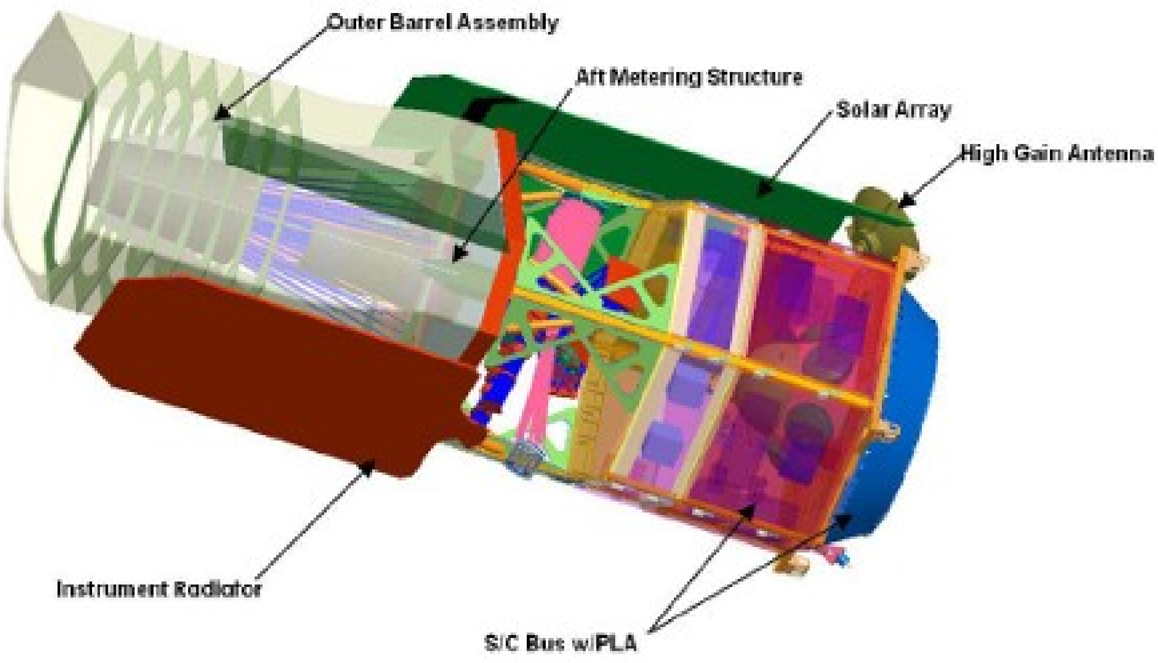
1. WMAP Model for DE: Faster, Cheaper, "Better"

Dark energy (DE) is arguably the most important physics problem of the 21st century, with major implications for astronomy, fundamental physics, and perhaps even philosophy.



Bennett & Rhie 2002, ApJ, 574, 985

WFIRST



Outer Barrel Assembly
Aft Metering Structure
Solar Array
High Gain Antenna
Instrument Radiator
S/C Bus w/PLA