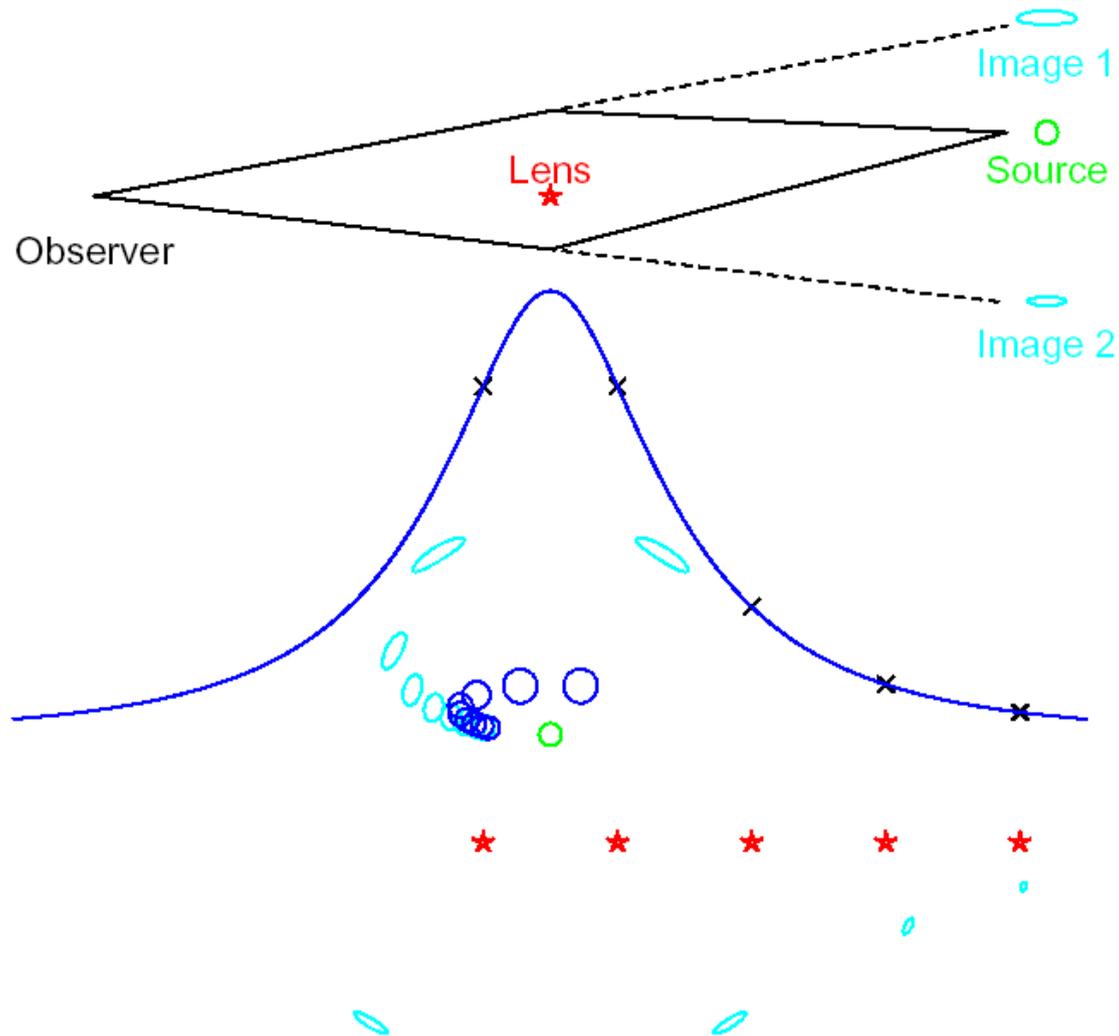
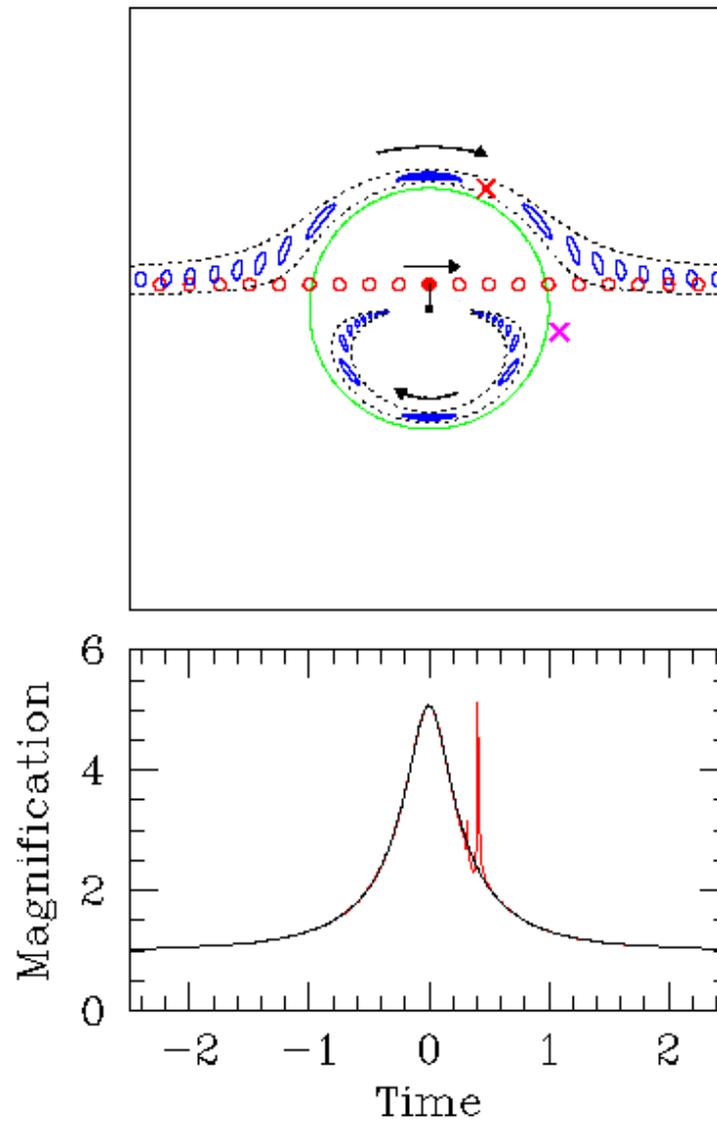


Toward a Galactic Planet Distribution Function

Andy Gould (Ohio State)

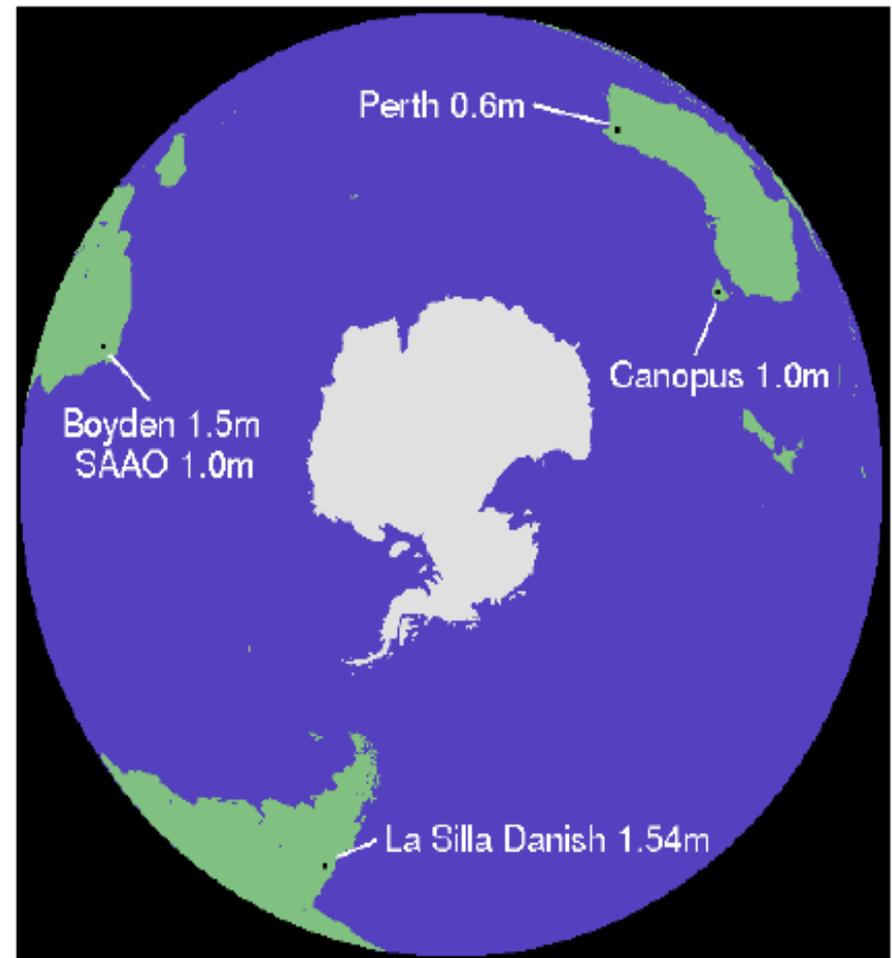
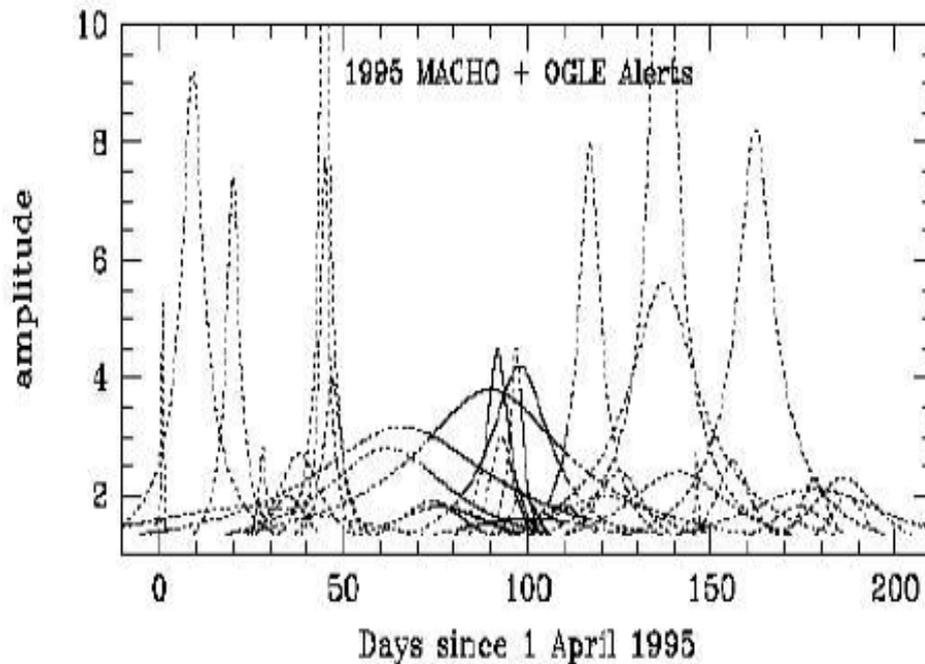


How Microlensing Finds Planets



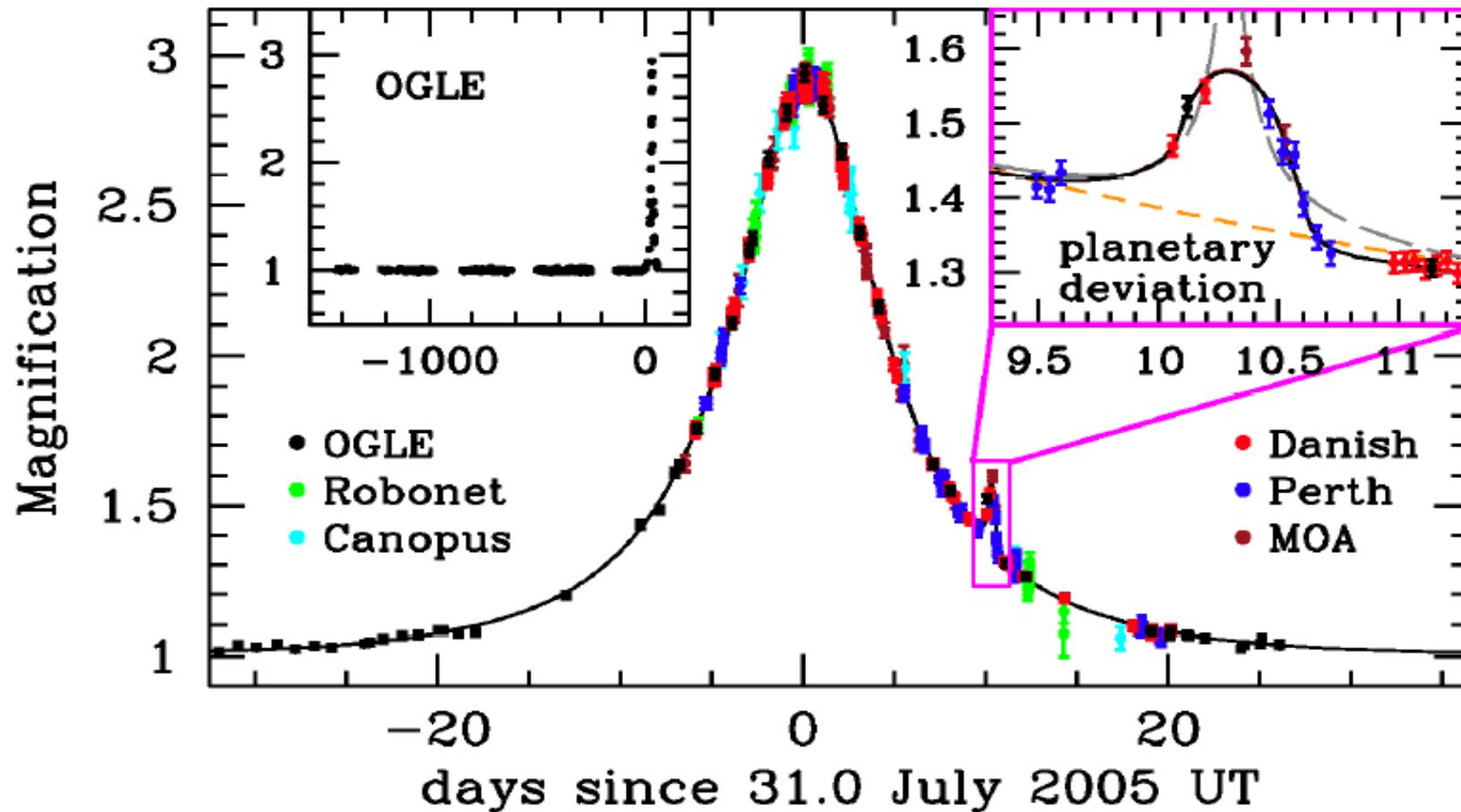
1995 PLANET Pilot Season

- Albrow et al. 1998
ApJ, 509, 687



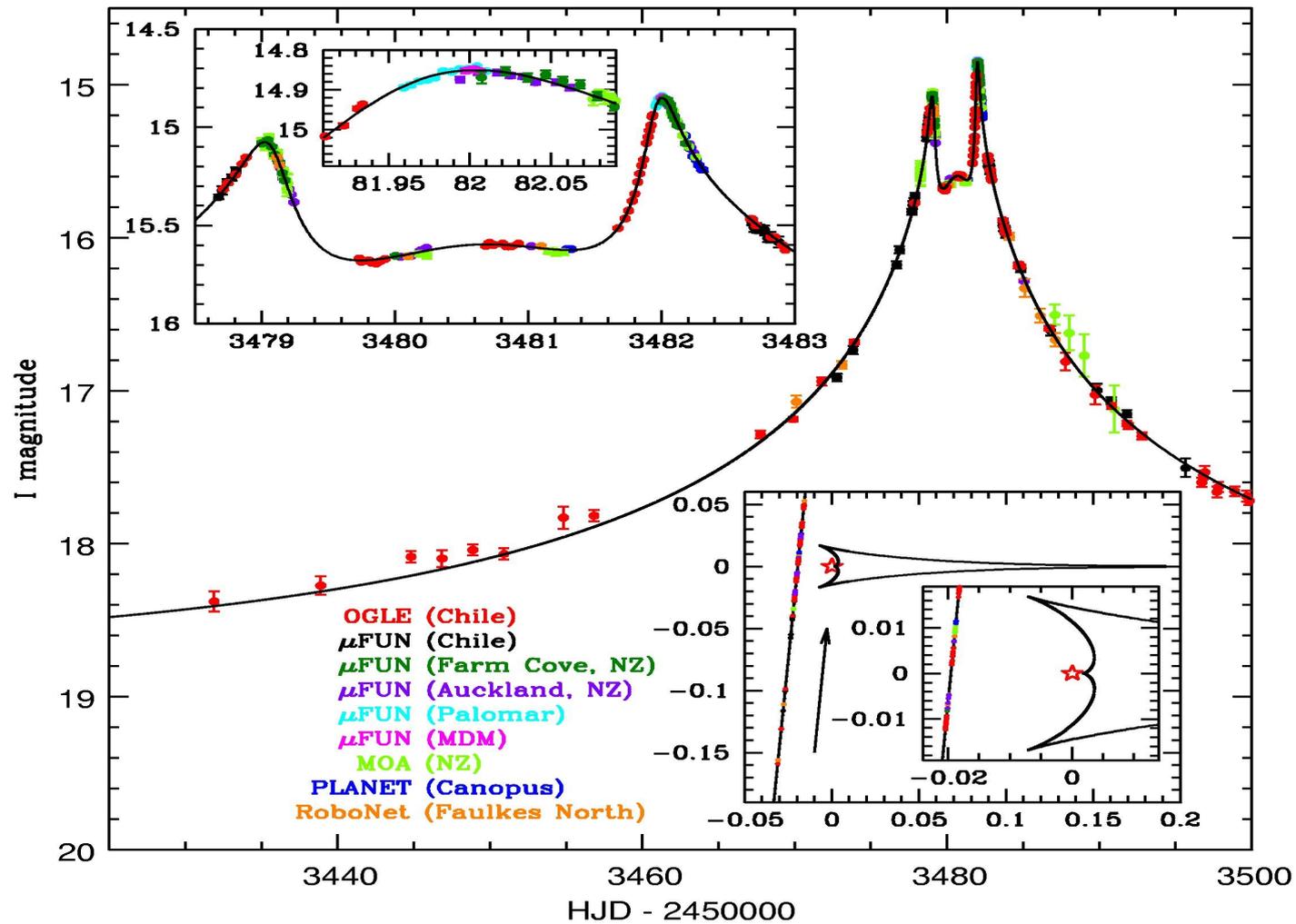
OGLE-2005-BLG-390

“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

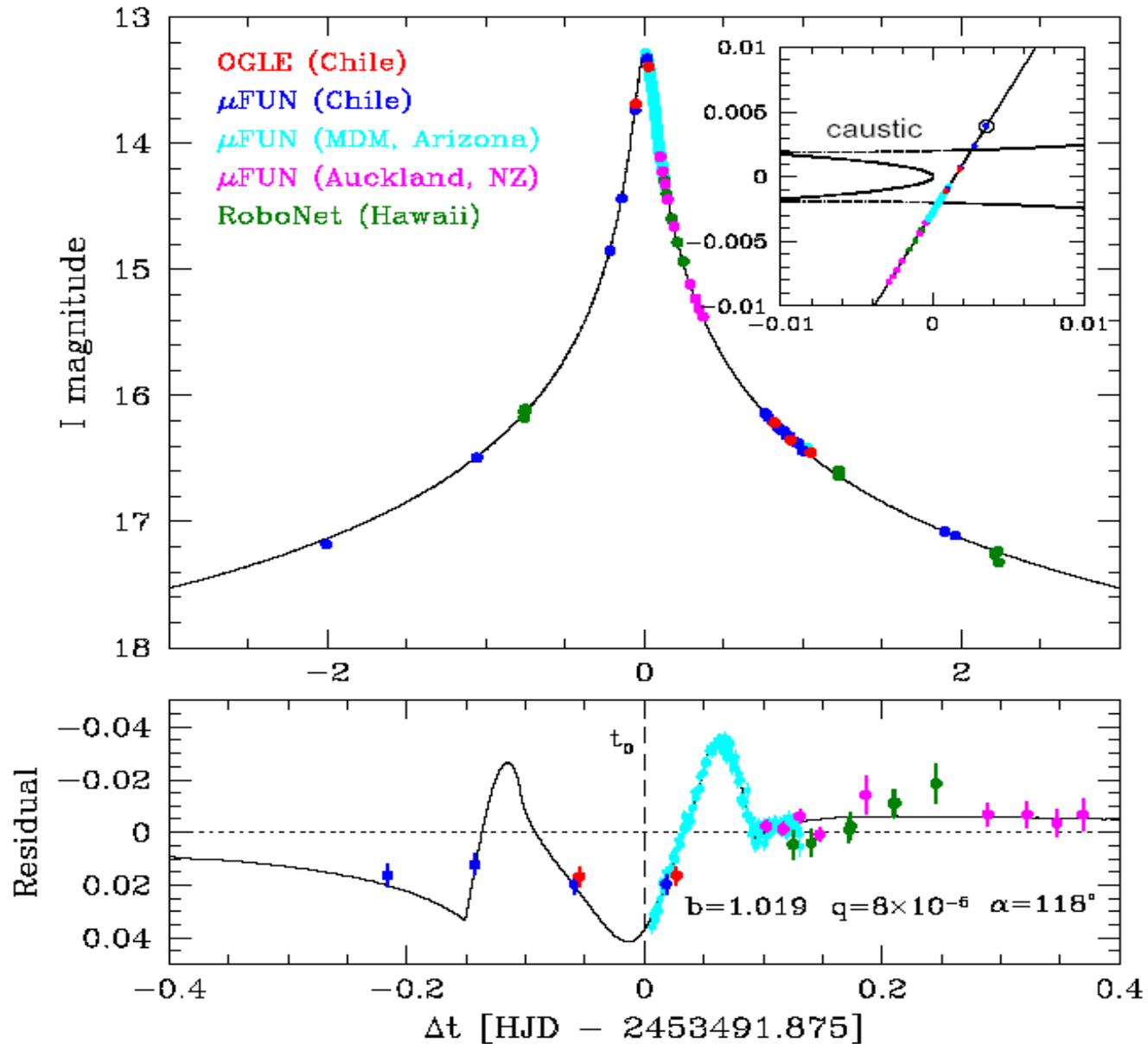
"It just shows that you can be a mother, you can work full-time, and you can still go out there and find planets."

Jennie McCormick

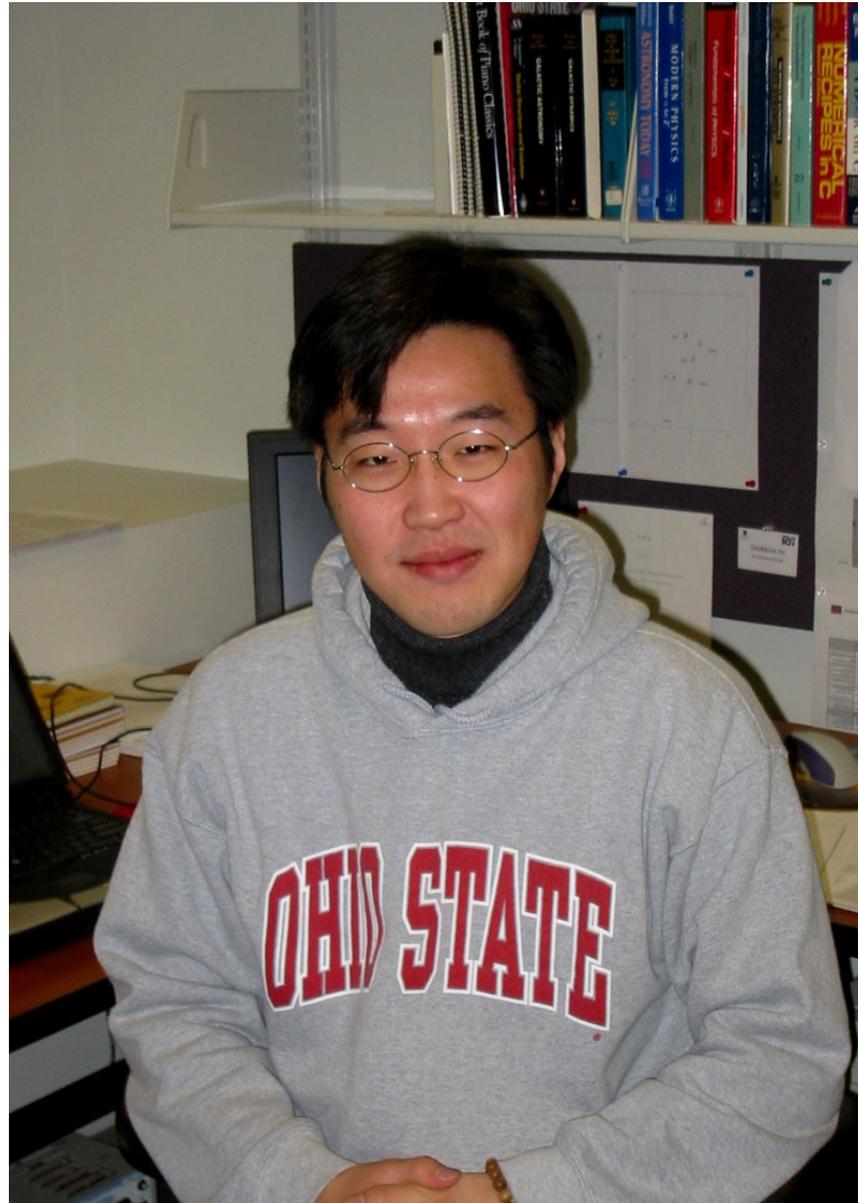
(Amateur Astronomer, Auckland, New Zealand)

OGLE-2005-BLG-169:

Second Cold Neptune



Deokkeun An



Tale of Two Planets

OGLE-2005-BLG-390

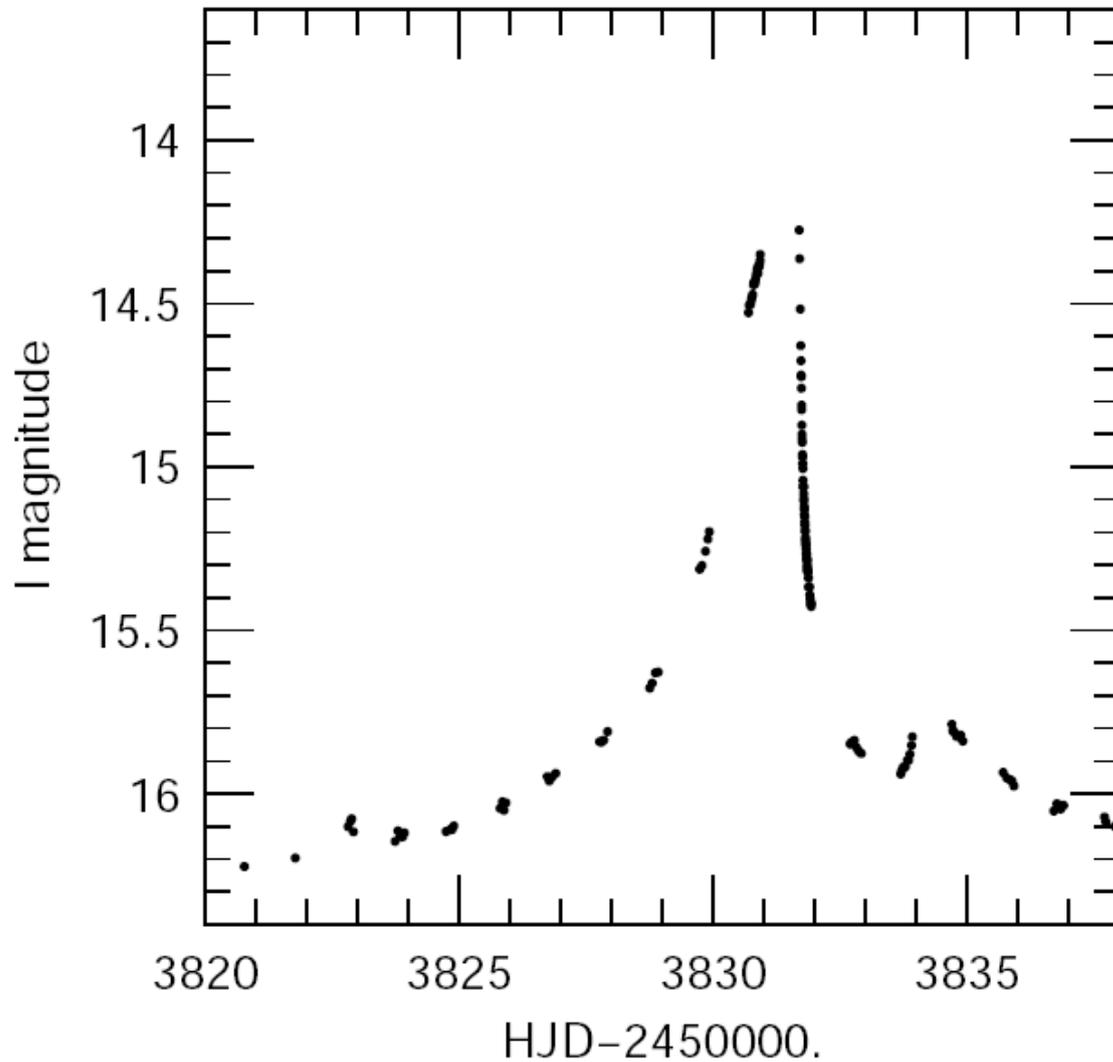
- $q = 8e-5$
- $M_* = 0.2 M_{\text{sun}}$
- $M_p = 5.5 M_{\text{earth}}$
- $D = 7 \text{ kpc}$
- $a = 3 \text{ AU}$
- $T = 50 \text{ K}$
- Low-mag Event
- (1 det)/(4.4 probed)

OGLE-2005-BLG-169

- $q = 8e-5$
- $M_* = 0.5 M_{\text{sun}}$
- $M_p = 13 M_{\text{earth}}$
- $D = 3 \text{ kpc}$
- $a = 4 \text{ AU}$
- $T = 70 \text{ K}$
- High-mag Event
- (1 det)/(2.25 probed)

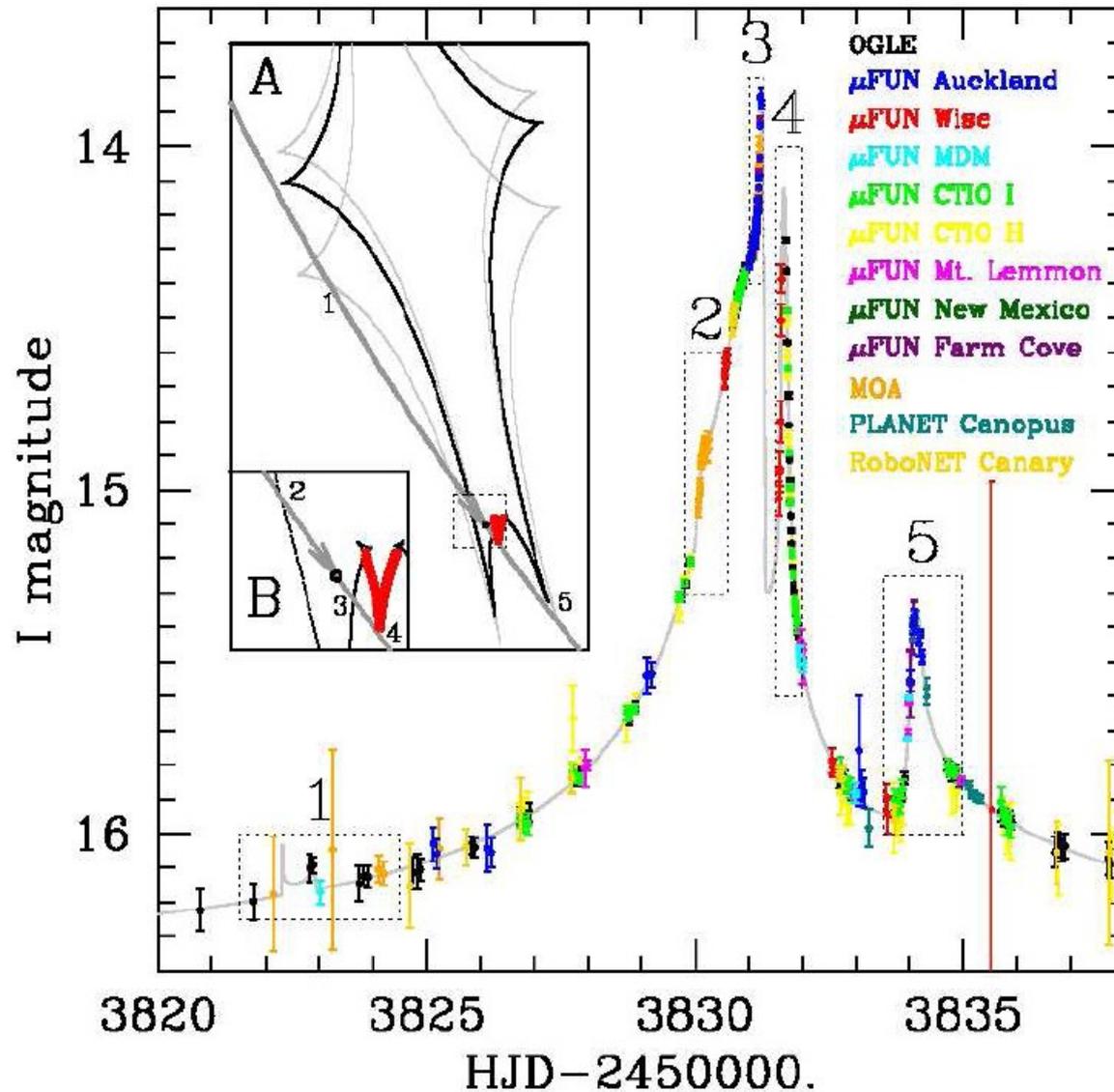
OGLE-2006-BLG-109:

Without Followup Observations



OGLE-2006-BLG-109

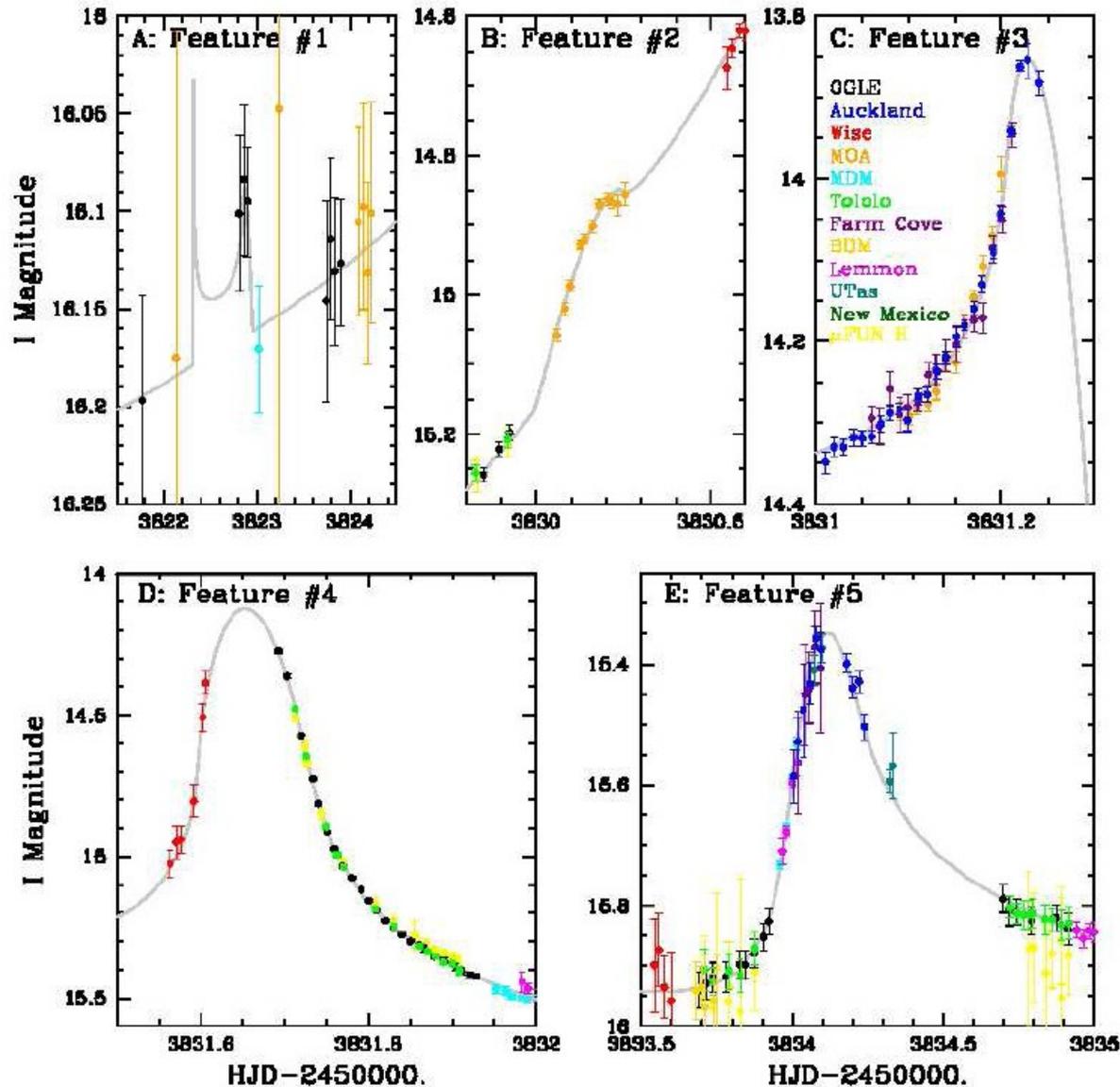
Parallax+Finite-Source+Rotation+Blend



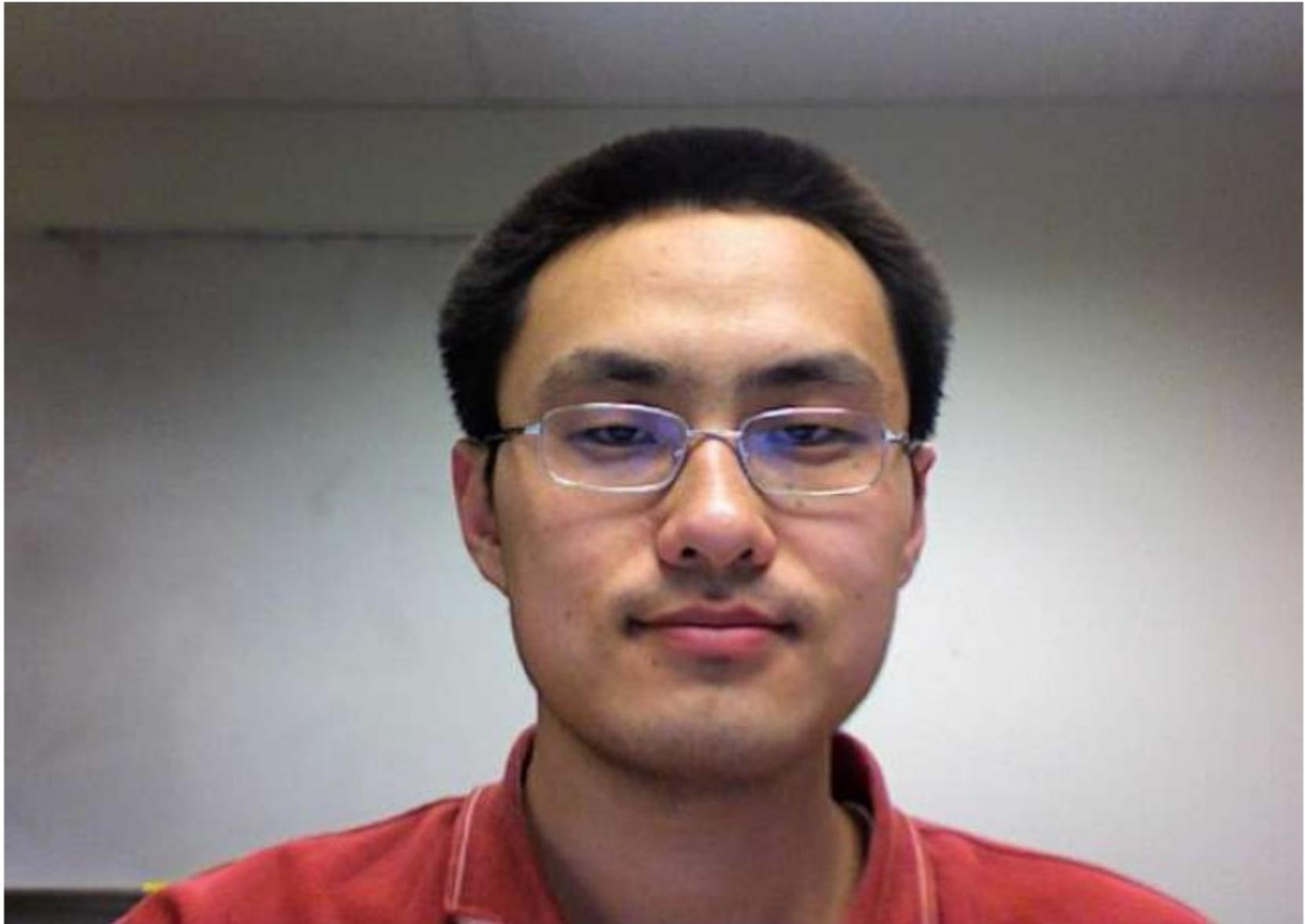
Gaudi et al. 2008, Science, 319, 927

Five Lightcurve Features

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

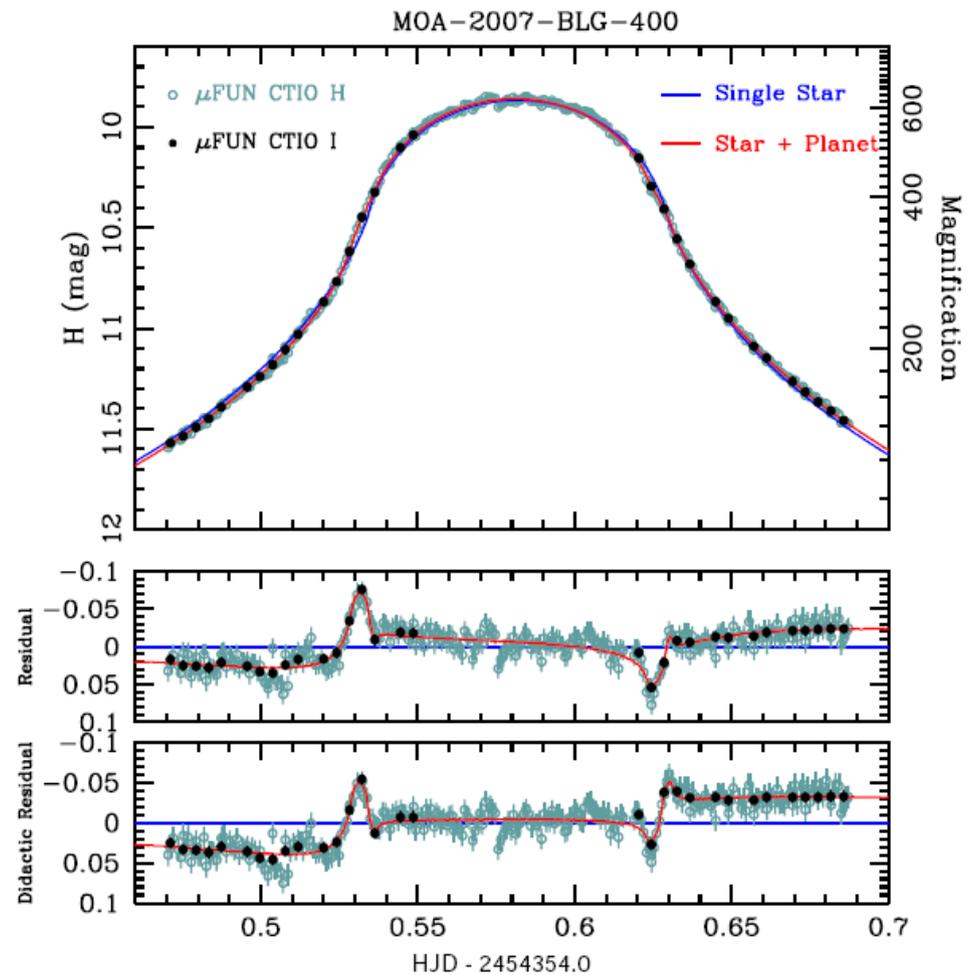


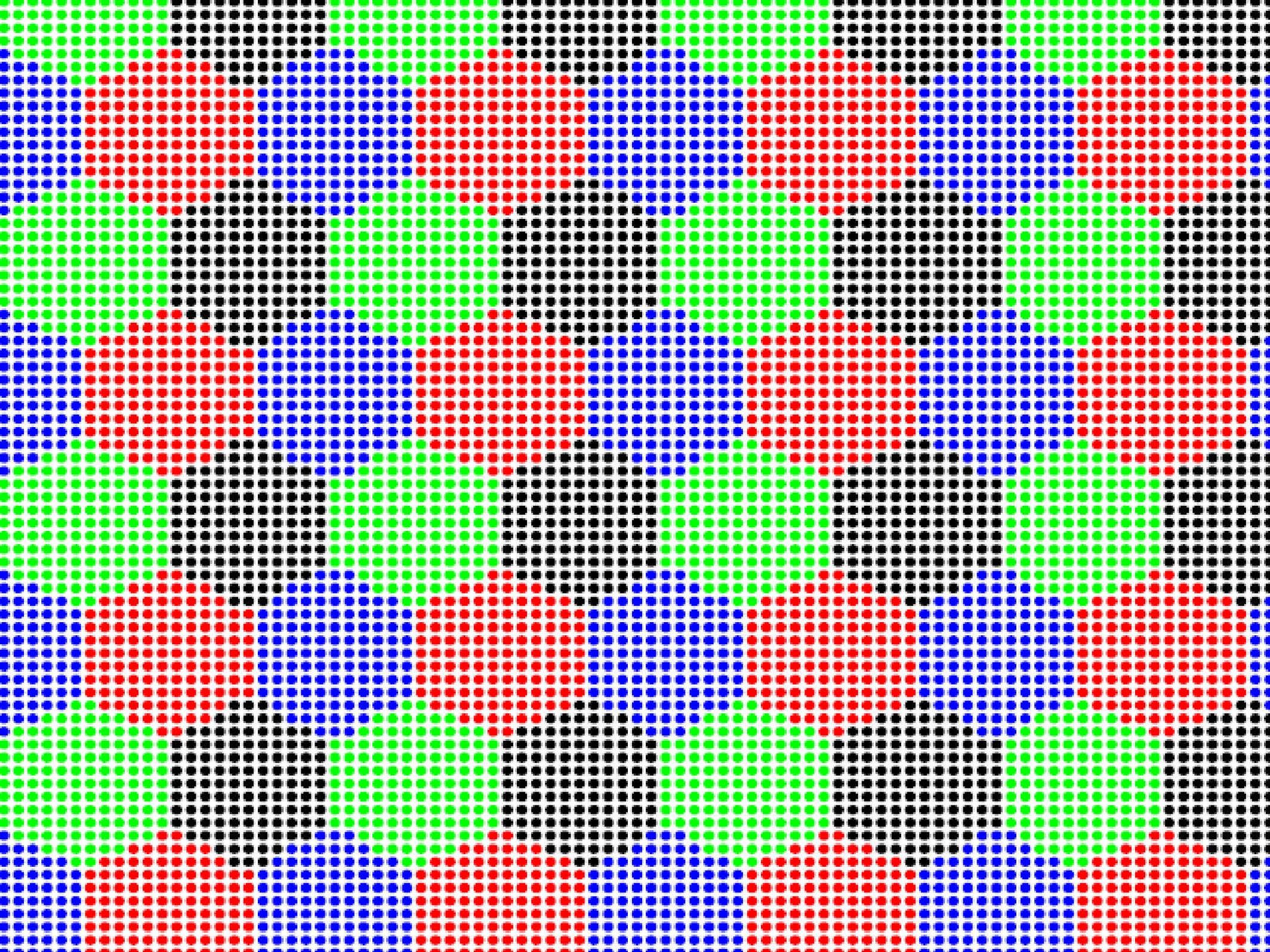
Subo Dong



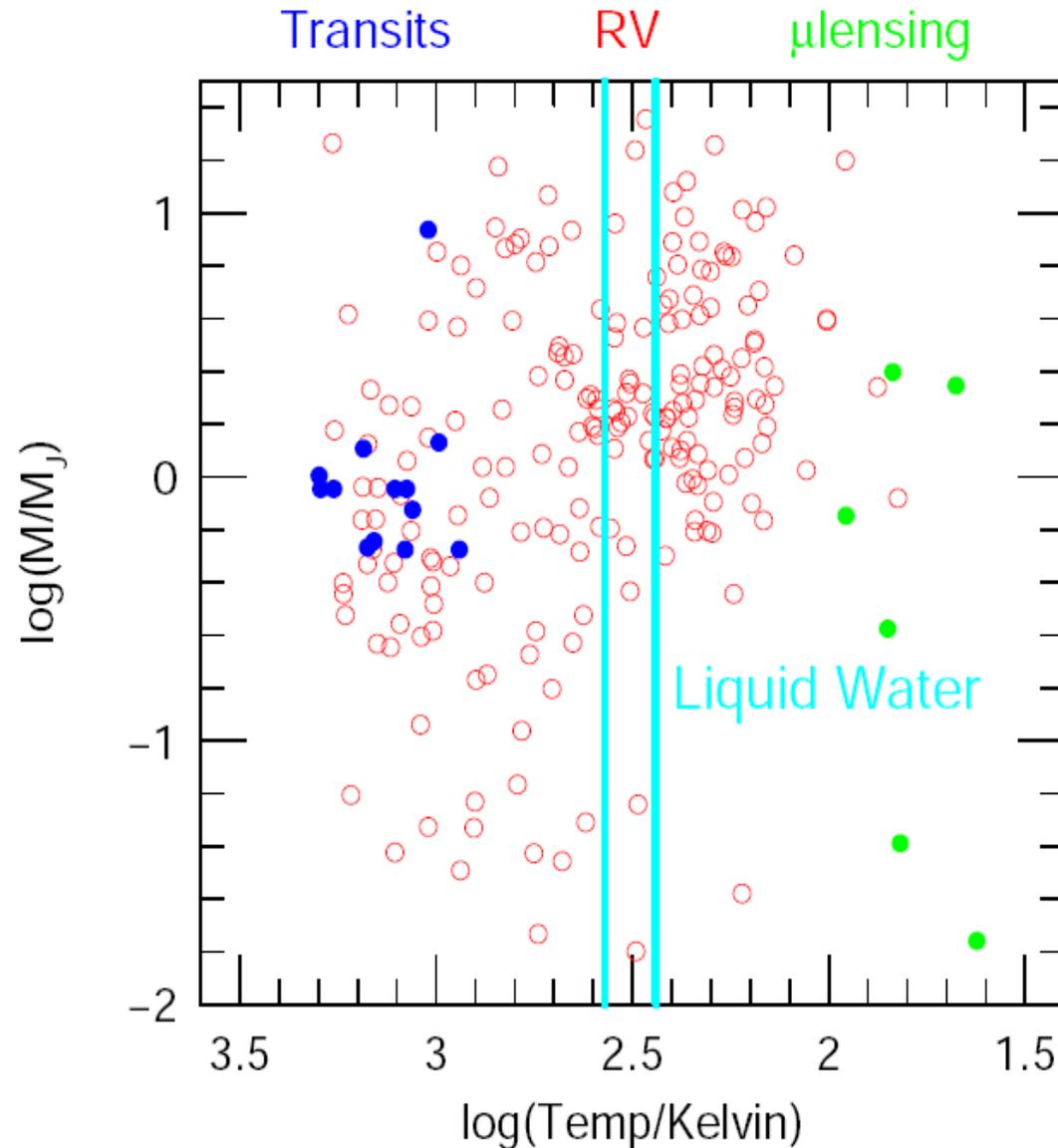
MOA-2007-BLG-400

“Buried” Jovian-Mass Planet



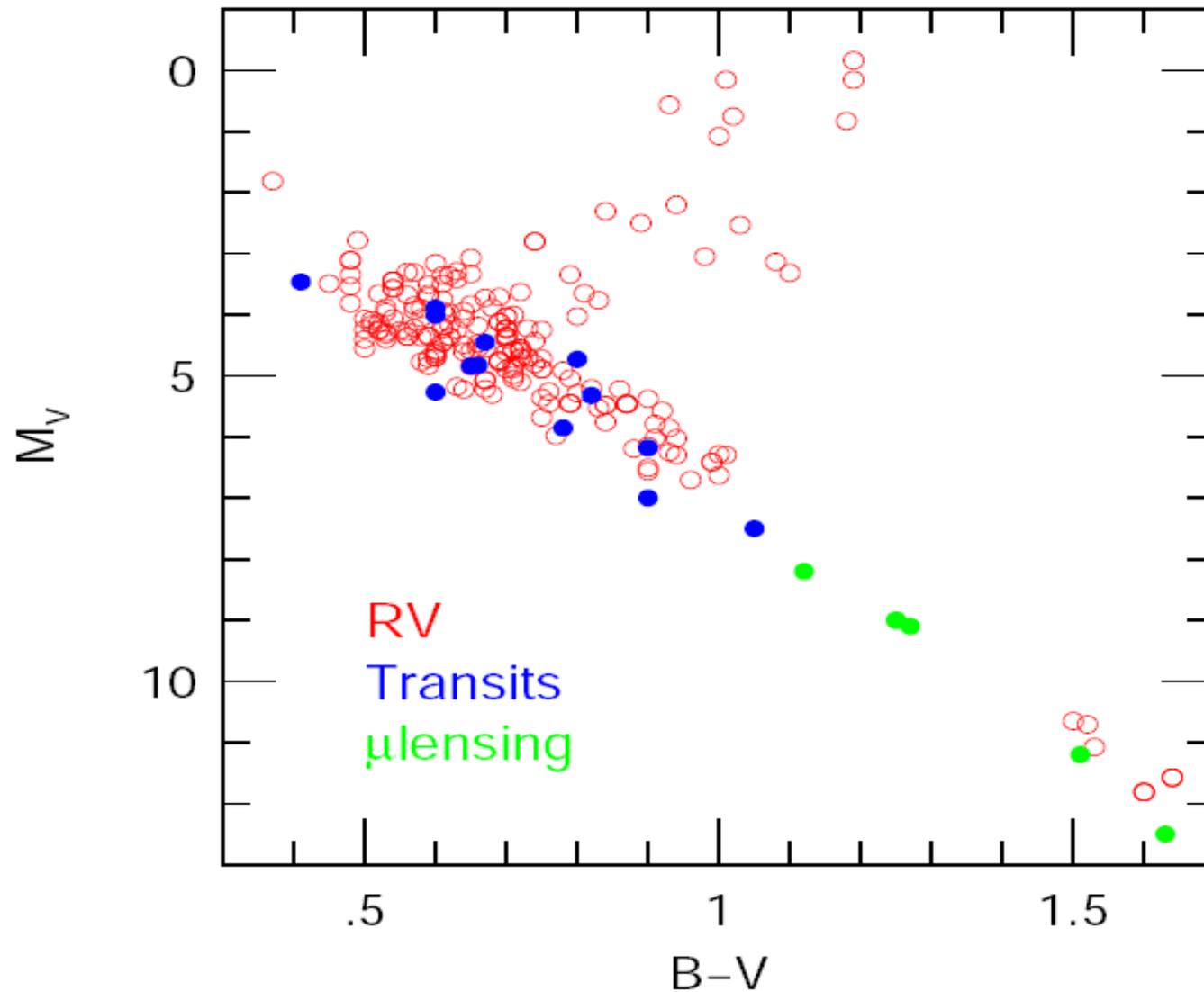


Equilibrium Temperature

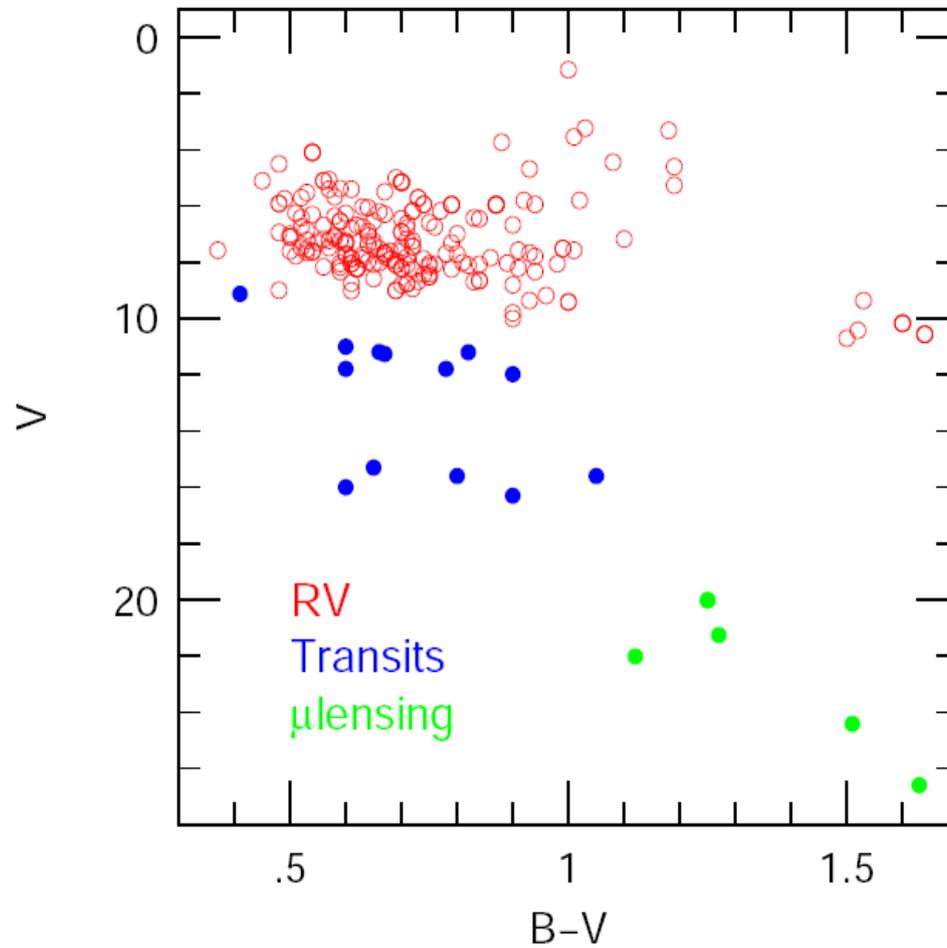


Selection biases:

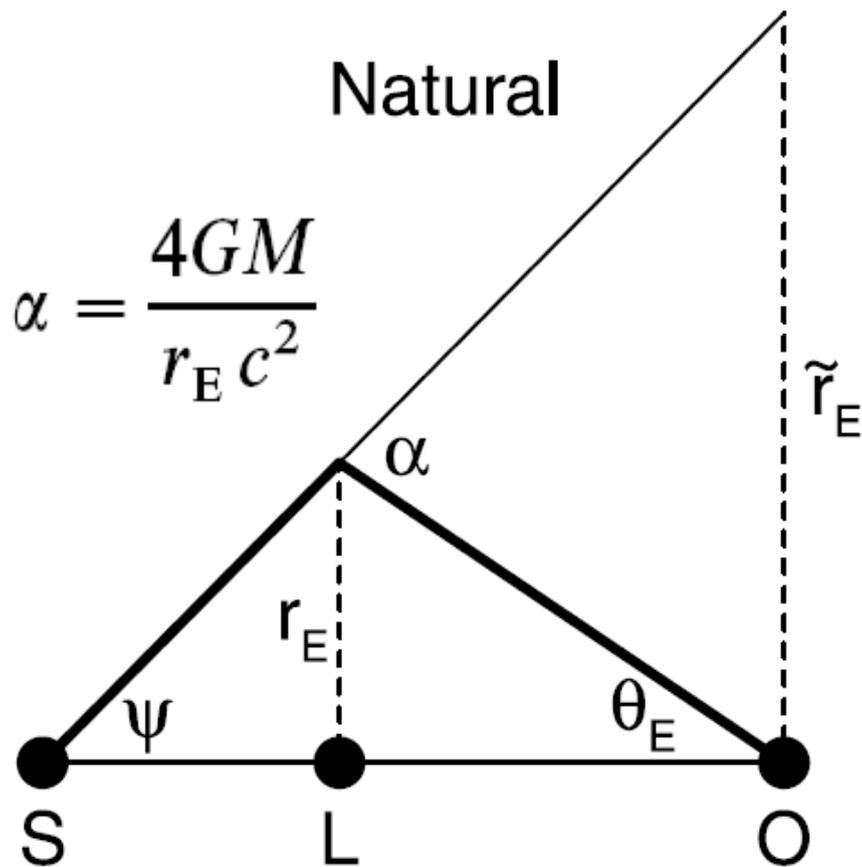
CMD (Absolute mags)



Selection Biases: CMD (Apparent Mags)



Relation of **Mass** and **Distance** to **Lensing Observables**



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

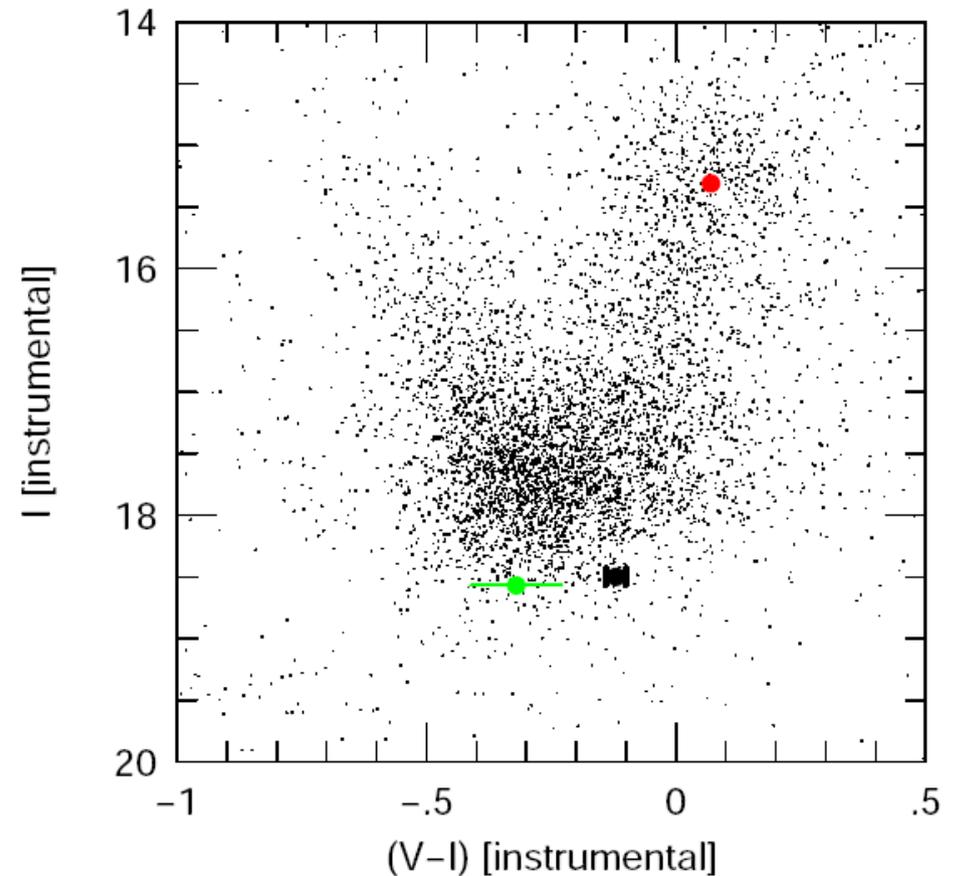
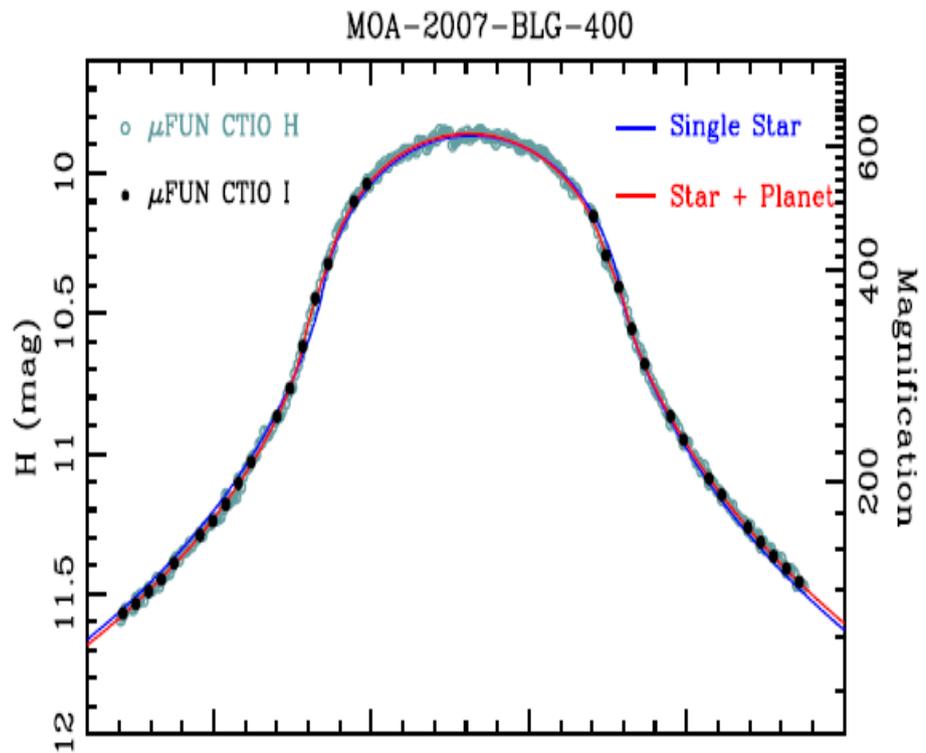
$$\theta_E \tilde{r}_E = \alpha r_E = \frac{4GM}{c^2}$$

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

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

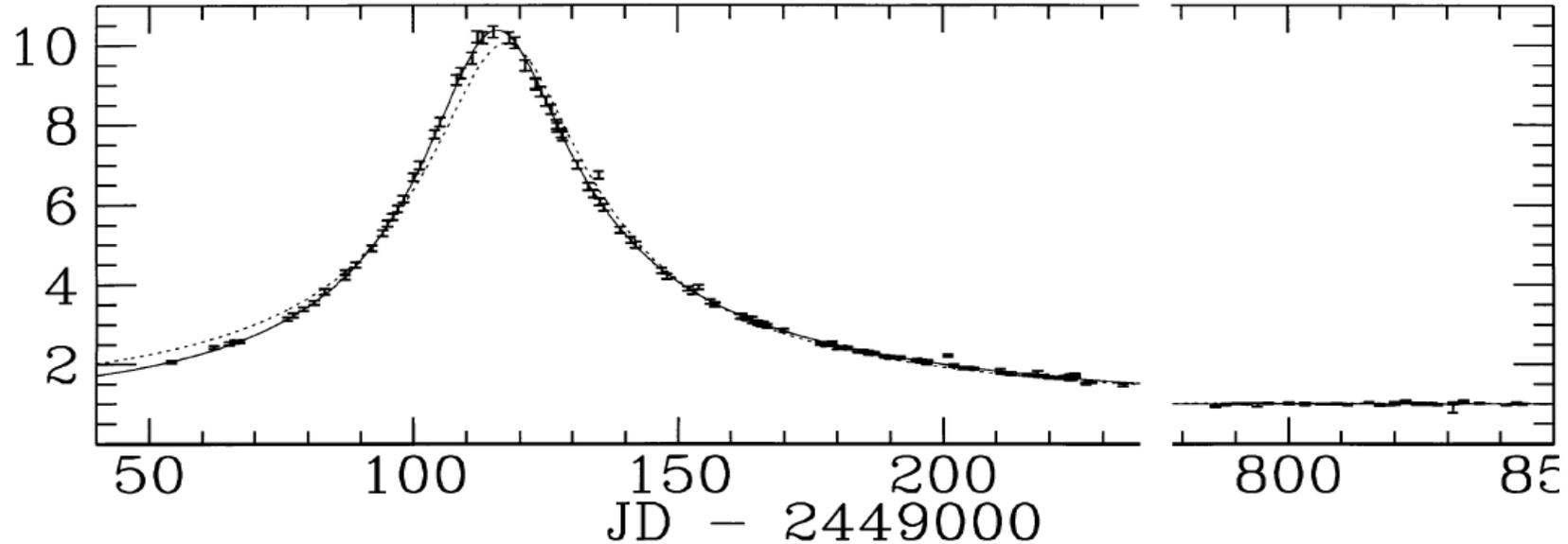
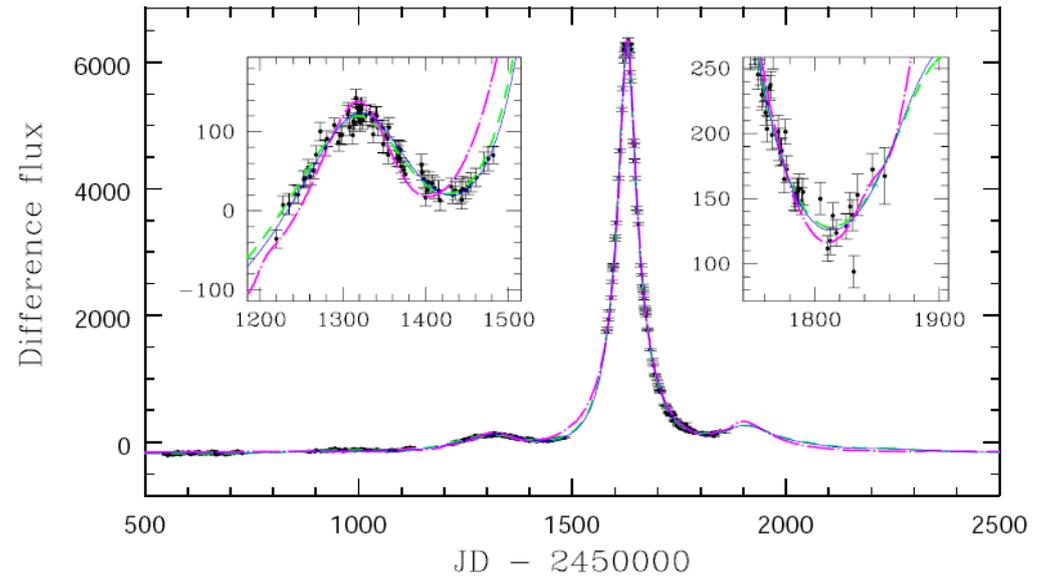
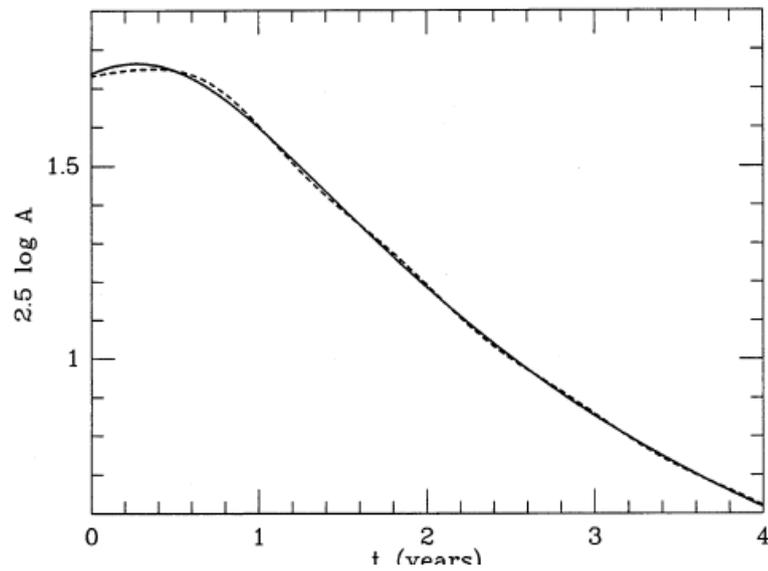
$$\theta_E = \sqrt{\frac{4GM}{D_{\text{rel}} c^2}}$$

To measure angular Einstein radius: Standard Sky-Plane Rulers

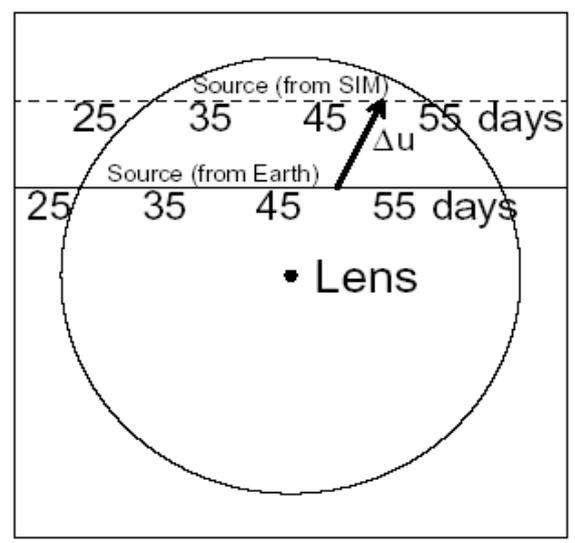
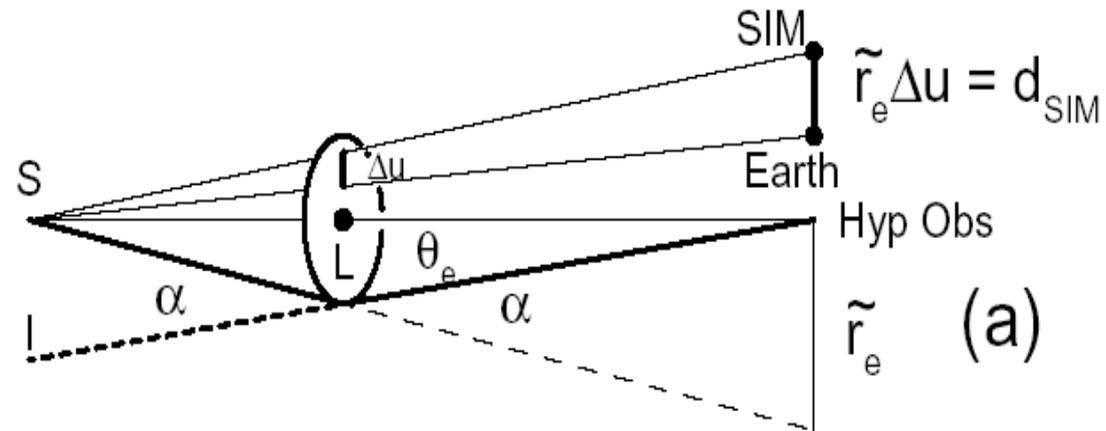


To measure parallax:

Standard Observer-Plane Rulers

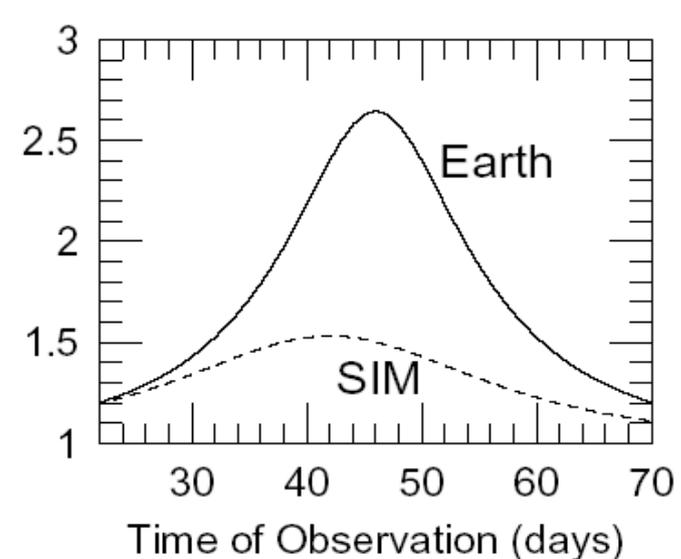
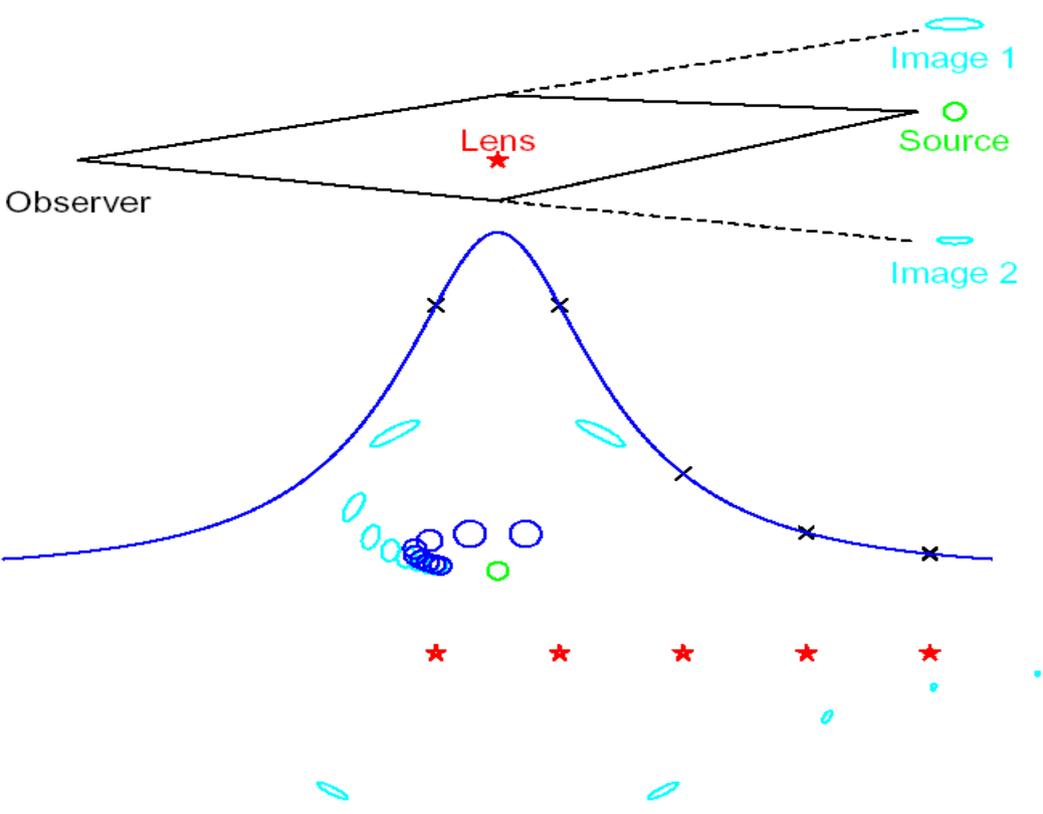


Space-Based Parallaxes & Einstein Radii : SIM



$$r_e \approx \frac{d_{SIM}}{\Delta u}$$

(b)

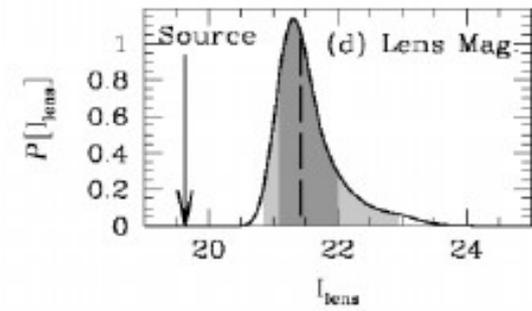
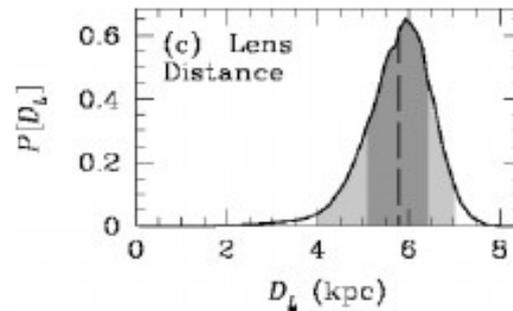
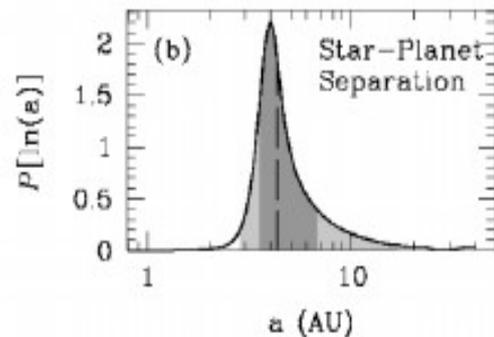
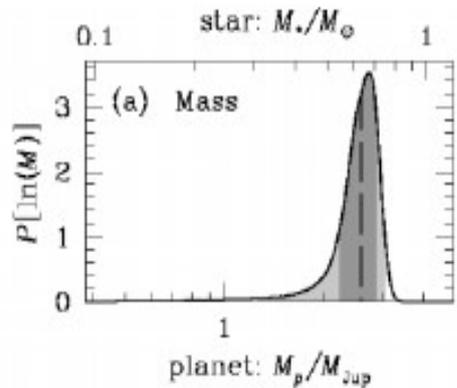
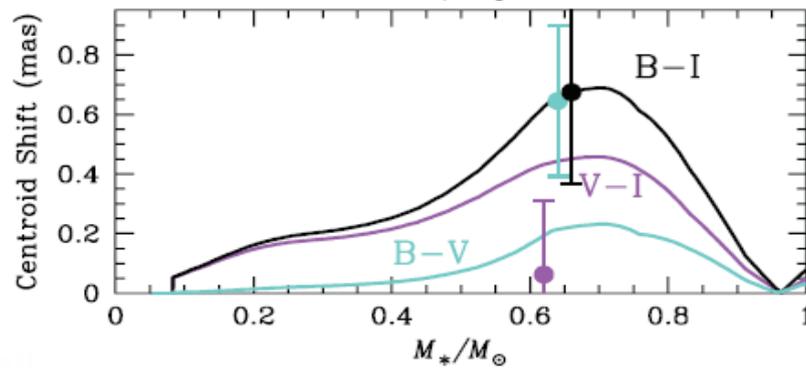
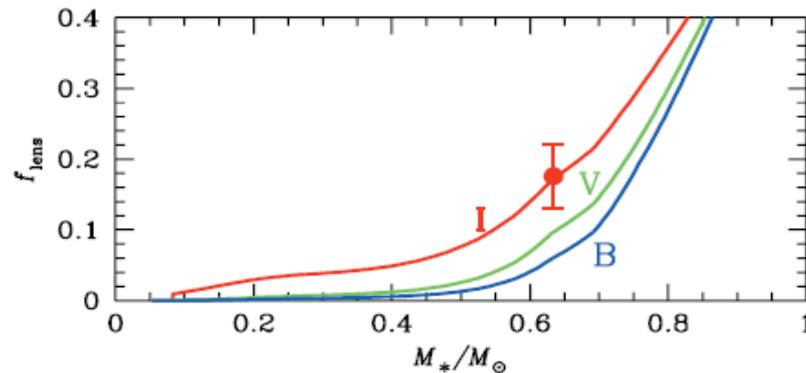
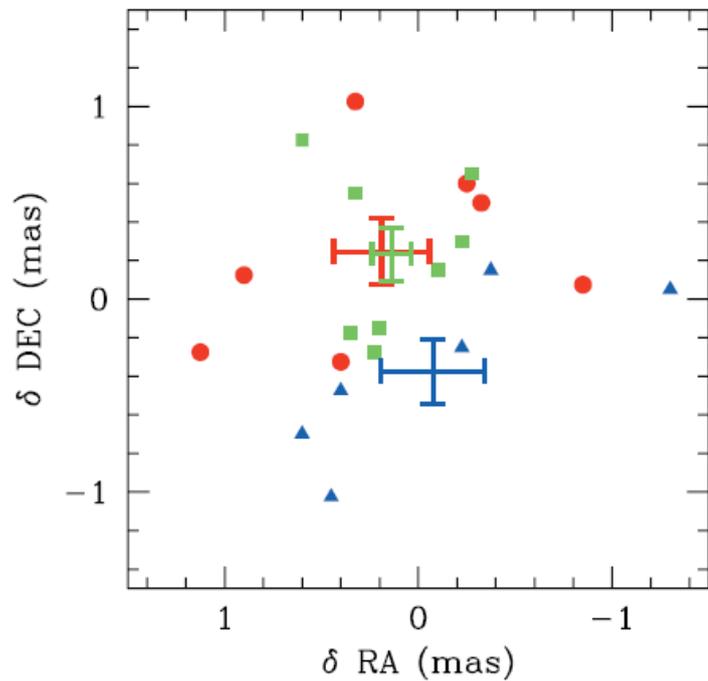


(c)

“Direct Detection” of Lens

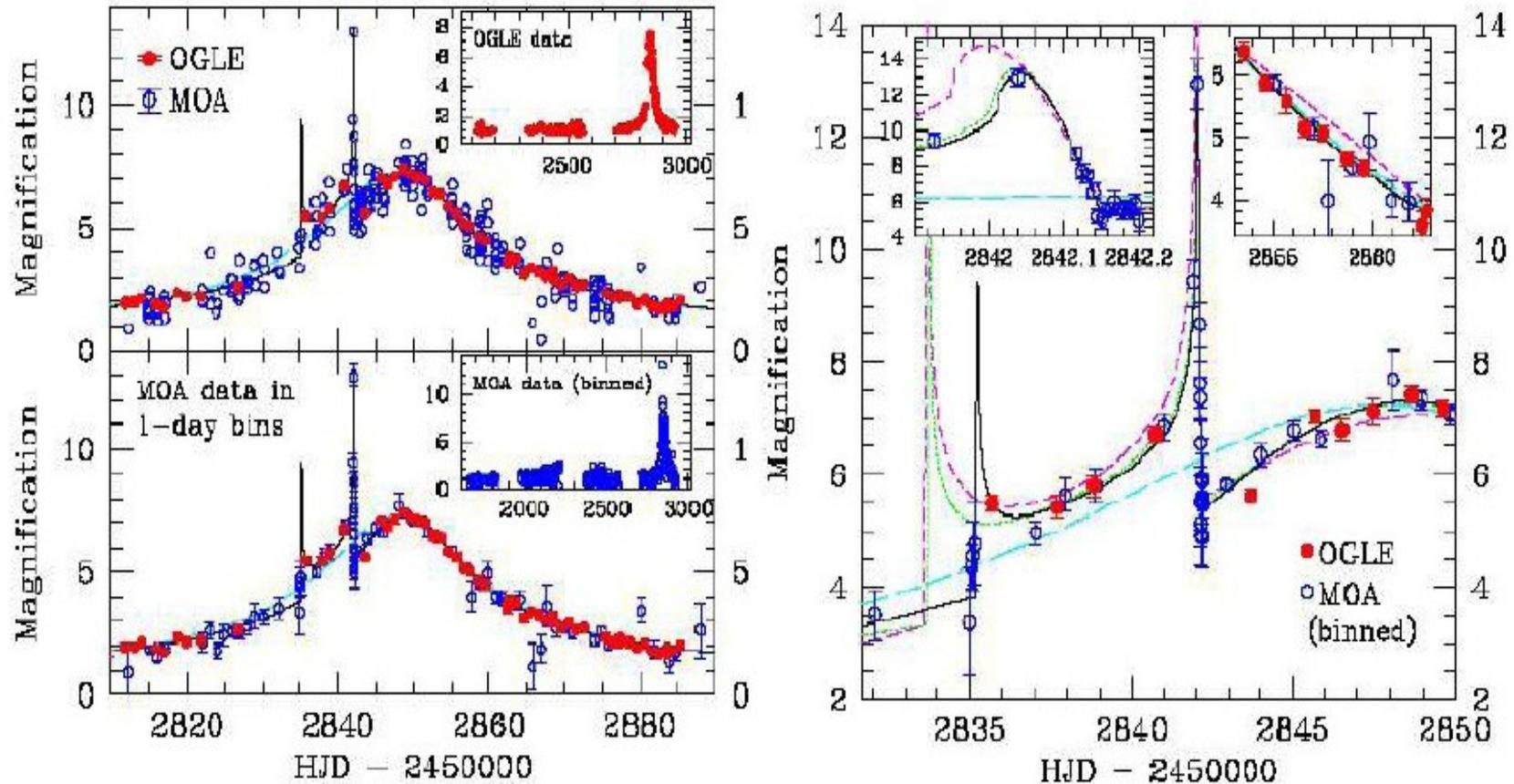
From Centroid Motion

(using known proper motion)



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

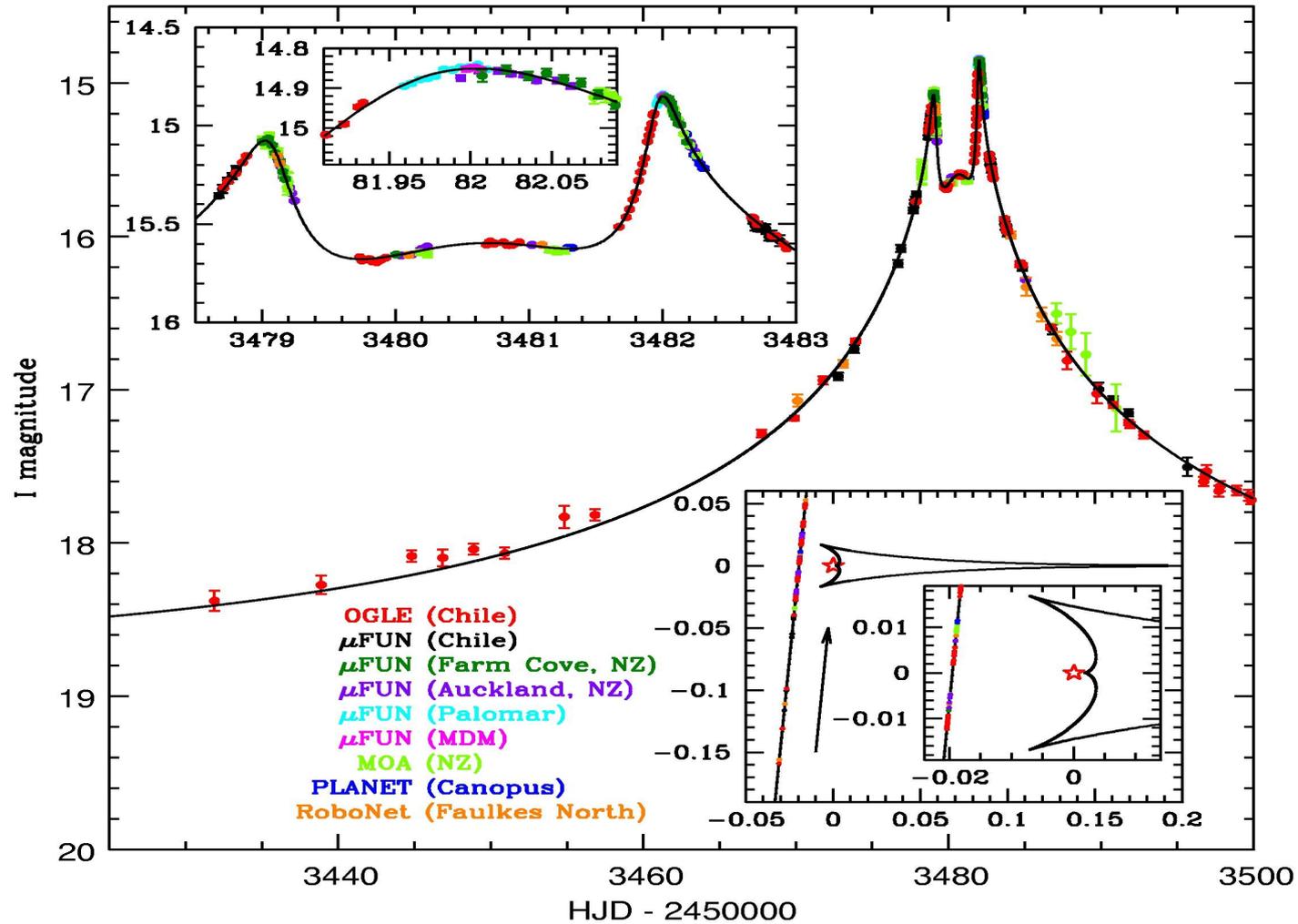
Finite Source + Centroid Motion



Bennett et al. 2006, ApJ, 647, L171

OGLE-2005-BLG-071: 3.3 kpc

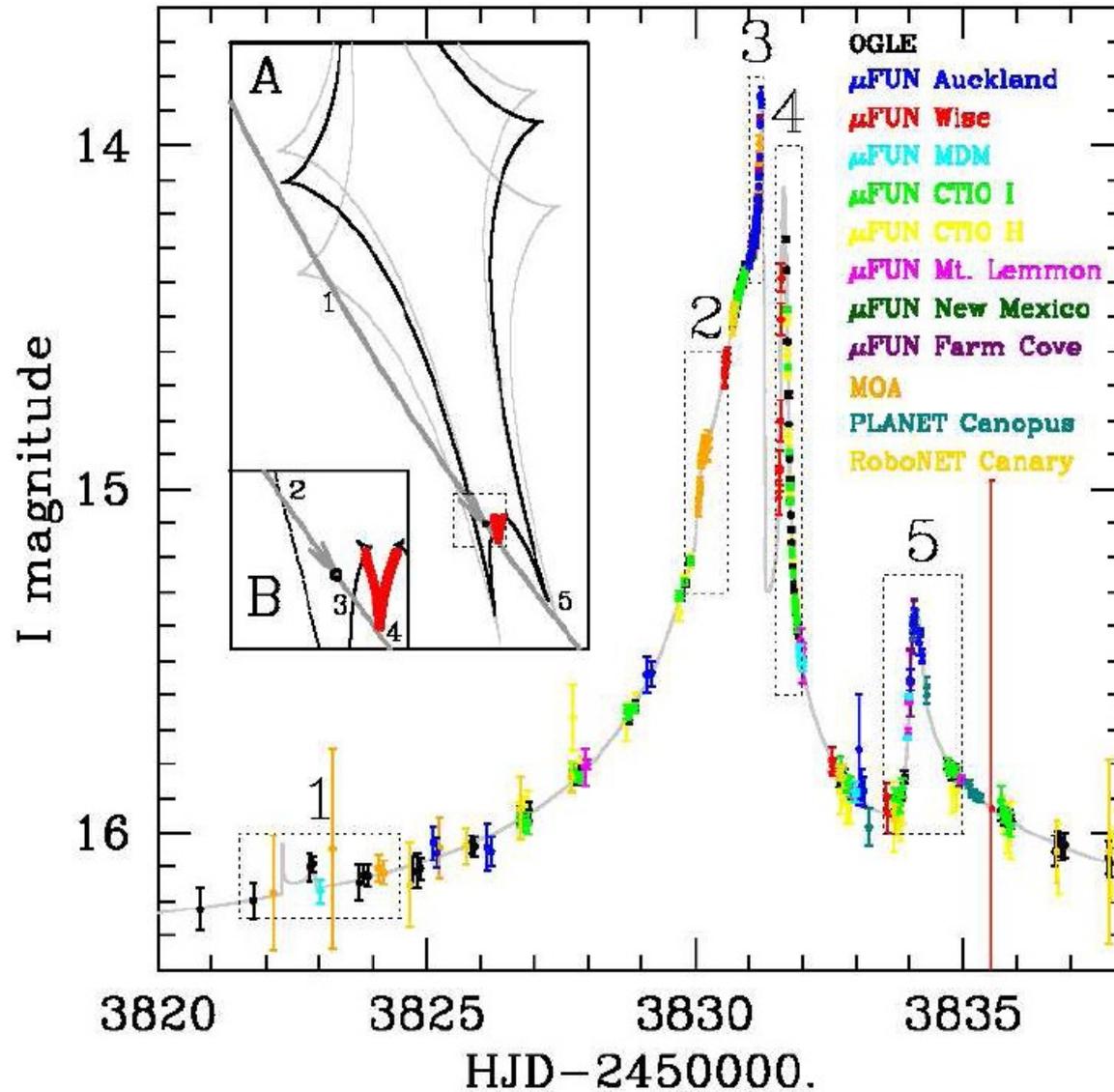
Parallax + Finite Source + Centroid Motion



Dong et al. 2008, [astro-ph/0804.1354](https://arxiv.org/abs/astro-ph/0804.1354)

OGLE-2006-BLG-109: 1.5 kpc

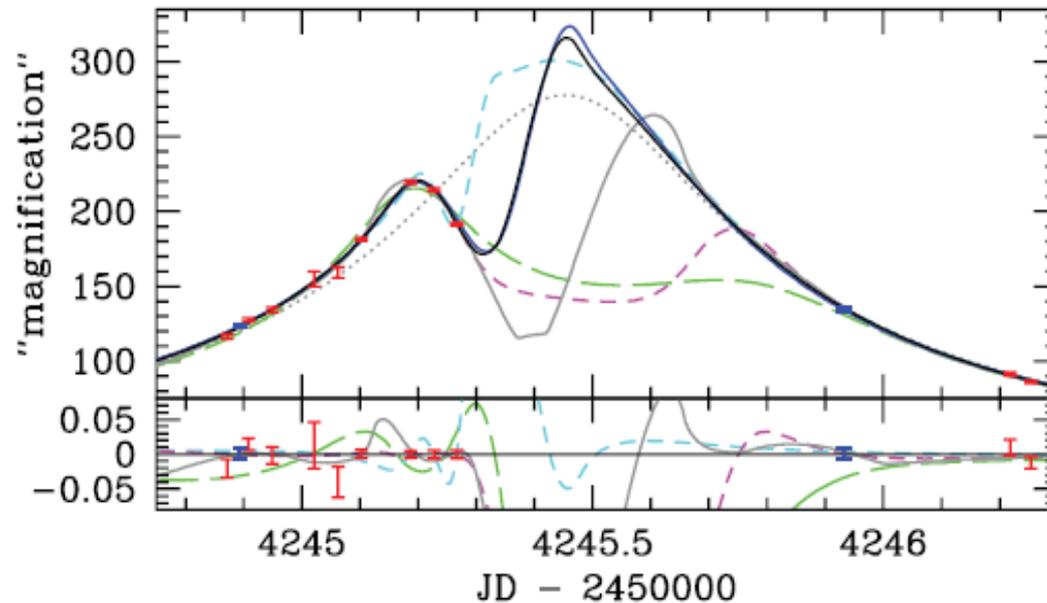
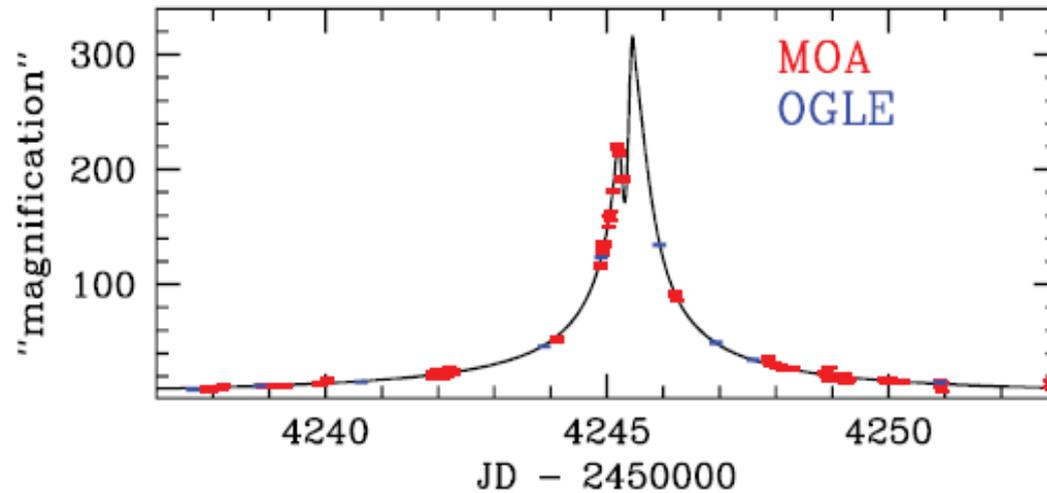
Parallax + Finite Source + Blend



Gaudi et al. 2008, Science, 319, 927

MOA-2007-BLG-192: 1.5 kpc

Parallax + Finite Source



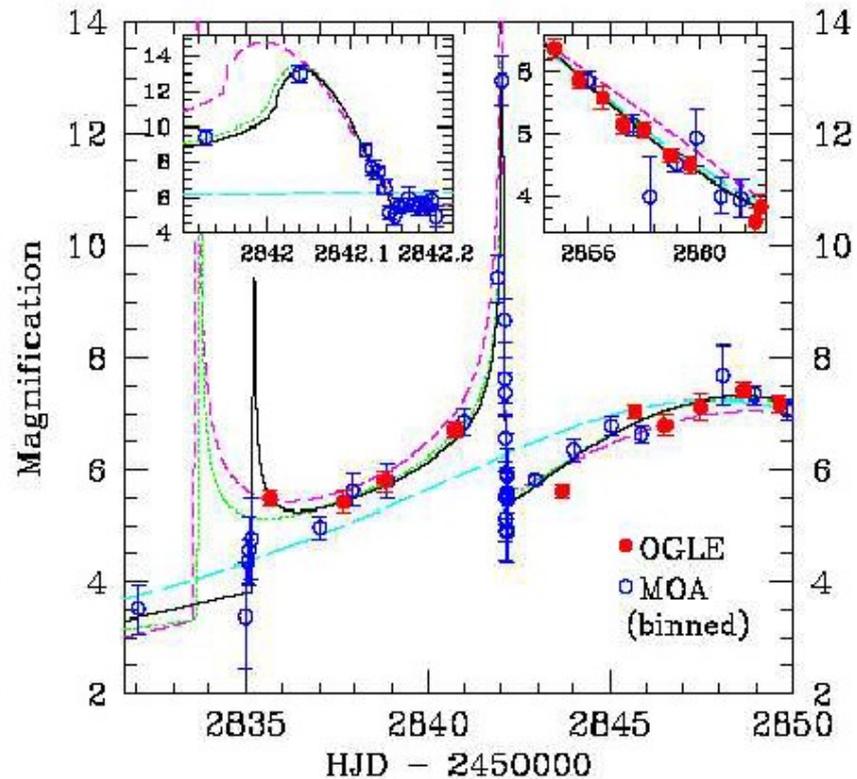
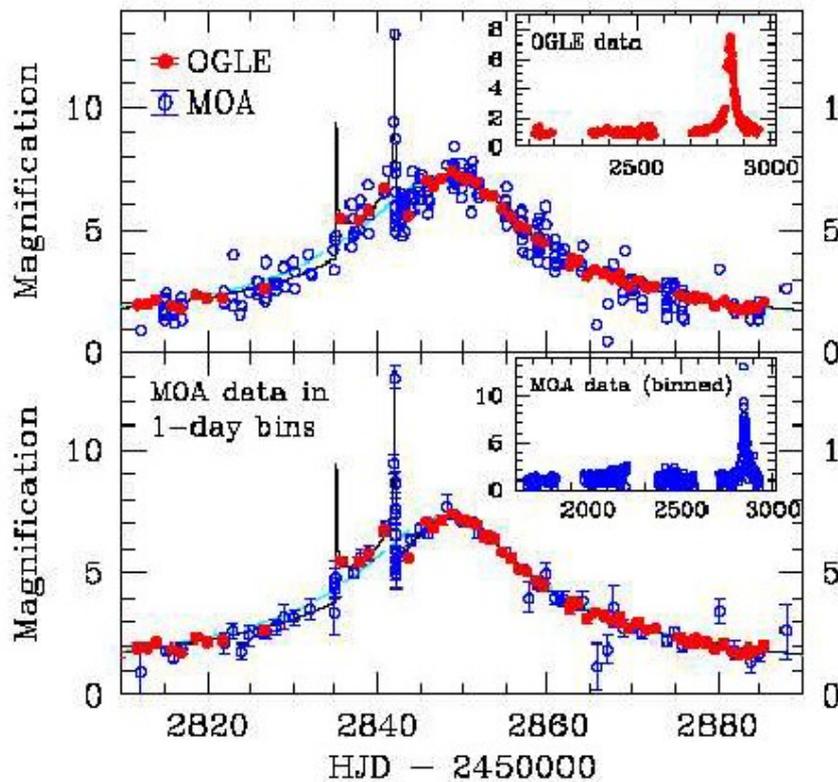
Bennett et al. 2008, ApJ, 684, 663

Julia Janczak

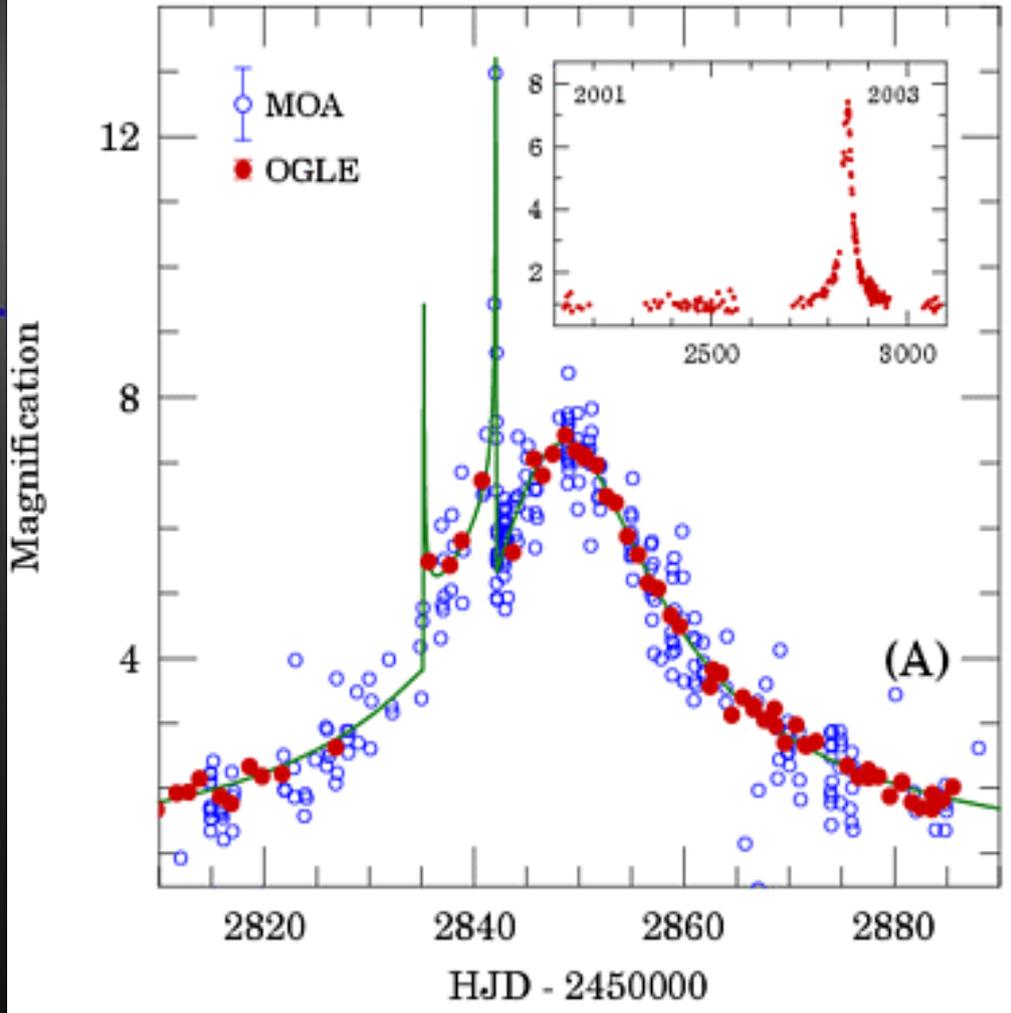
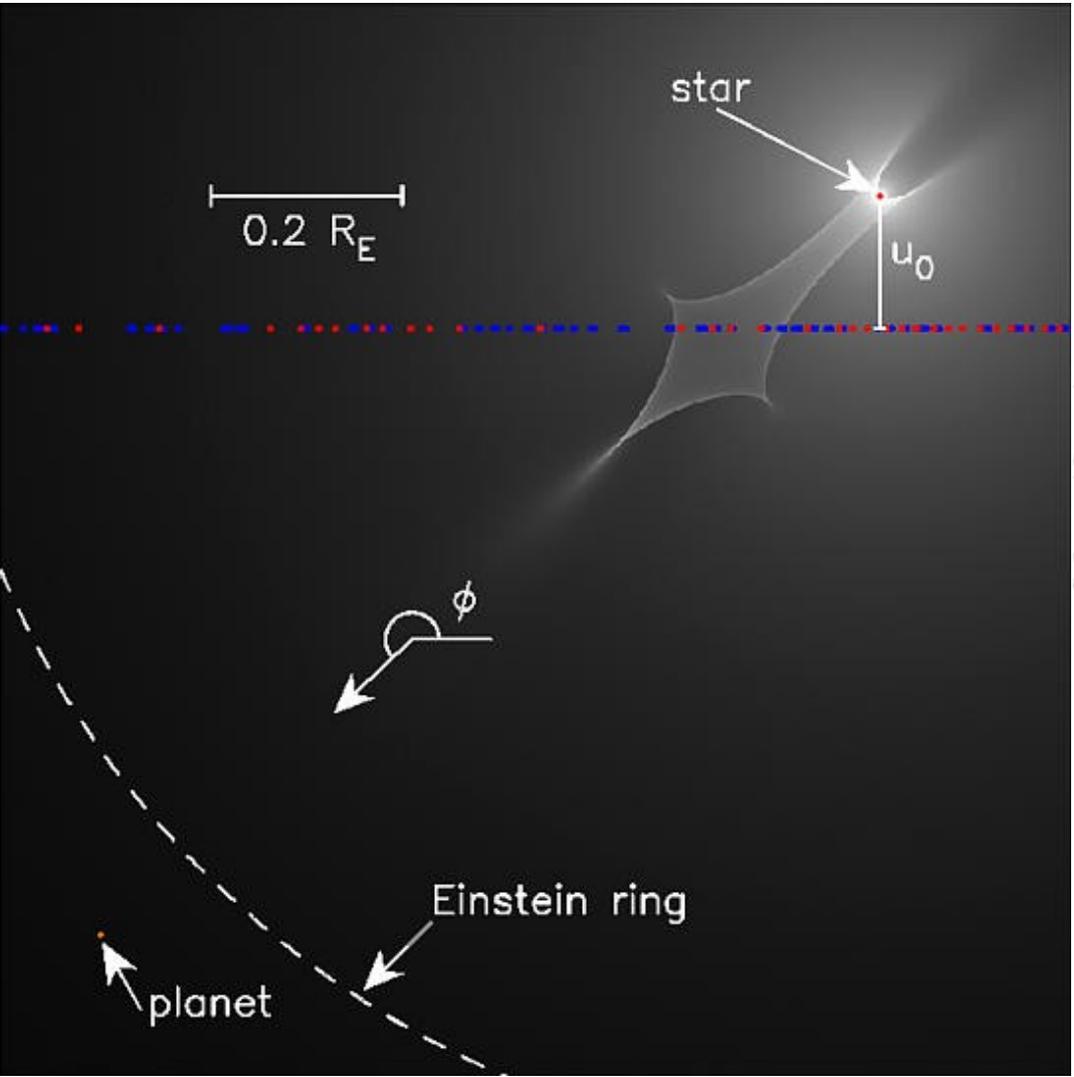


OGLE-2003-BLG-235/MOA-2003-BLG-53

“Pure-Survey” Detection



Bond et al. 2004, ApJ, 606, L155



OB-03-253/MB-03-53

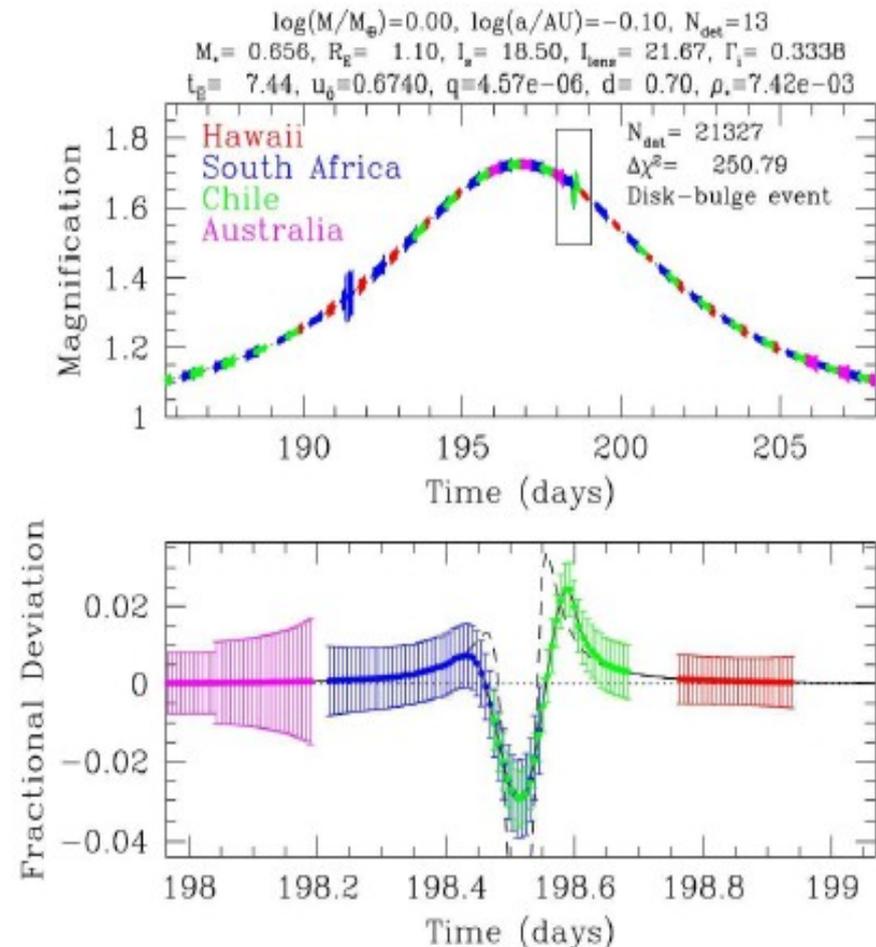
Points Way To Future: **End of Followup**

- Shows (even frenetic PLANET)
FOLLOWUP ALREADY MISSING
many good events.
- Better survey would make full
FOLLOWUP EVEN MORE IMPOSSIBLE.
- But higher-cadence survey would render
FOLLOWUP UNNECESSARY.
- Set cadence at 10 min ==> **FIND EARTHS**

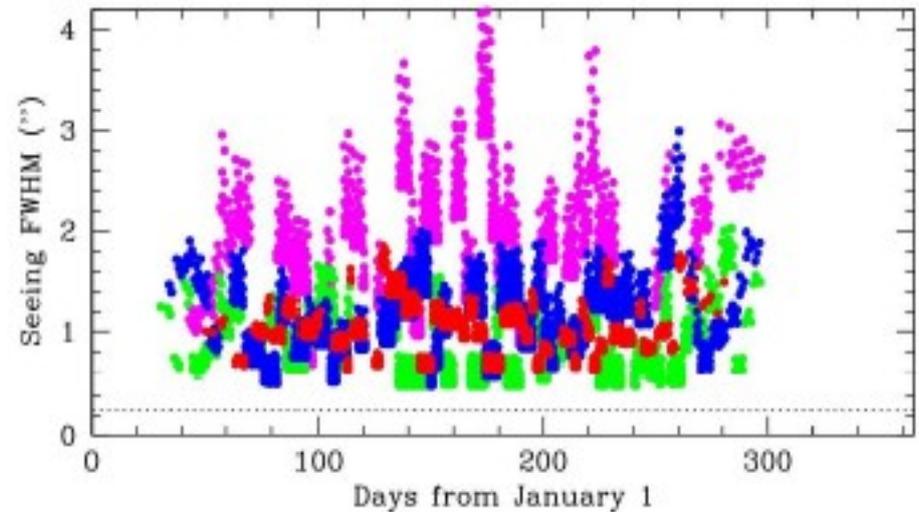
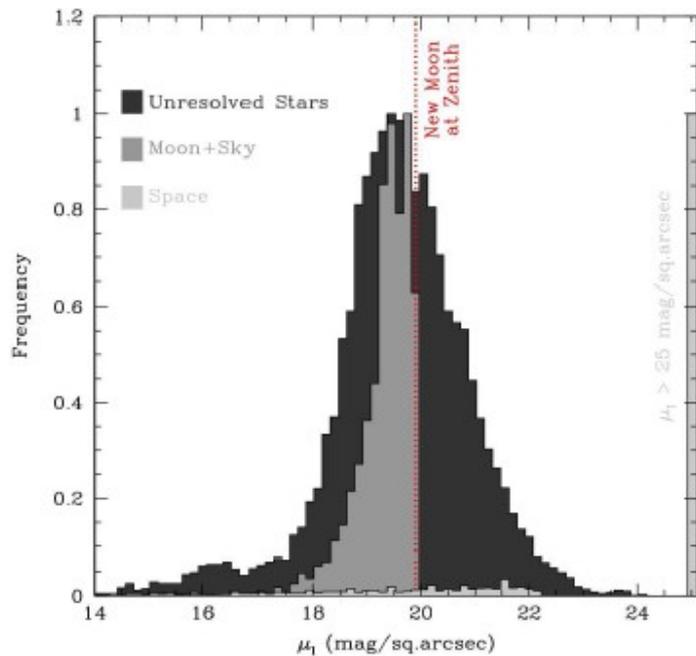
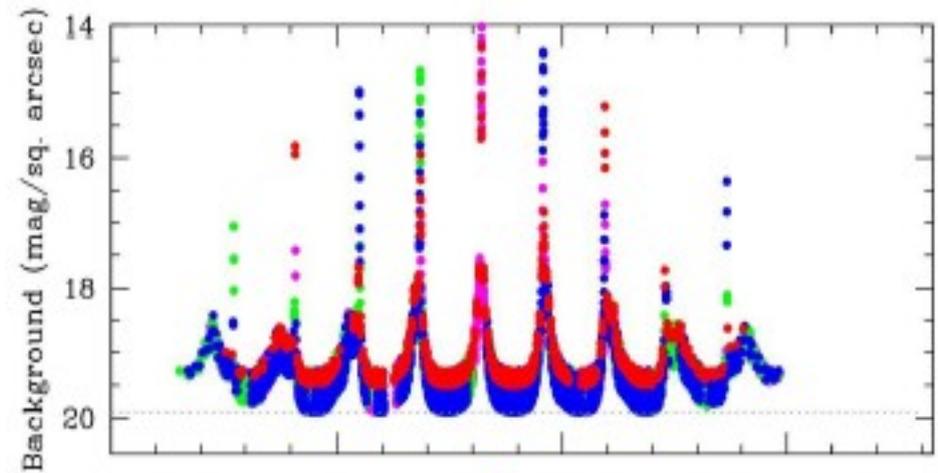
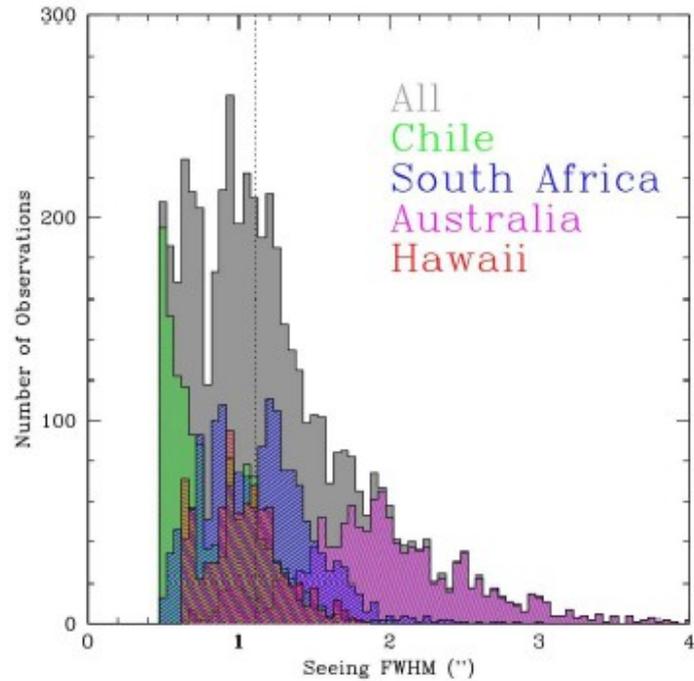
NextGen Microlensing Planet Search

Simulations by Scott Gaudi

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

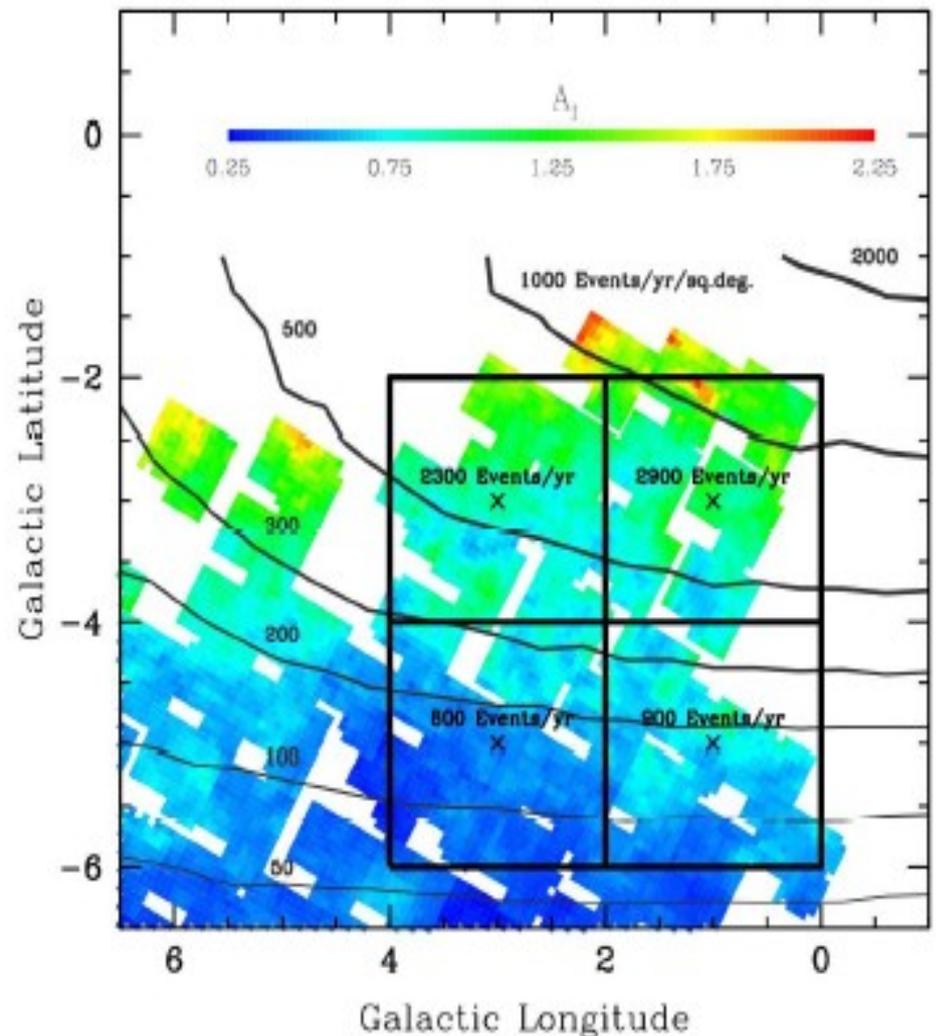


Simulation Ingredients (abridged)

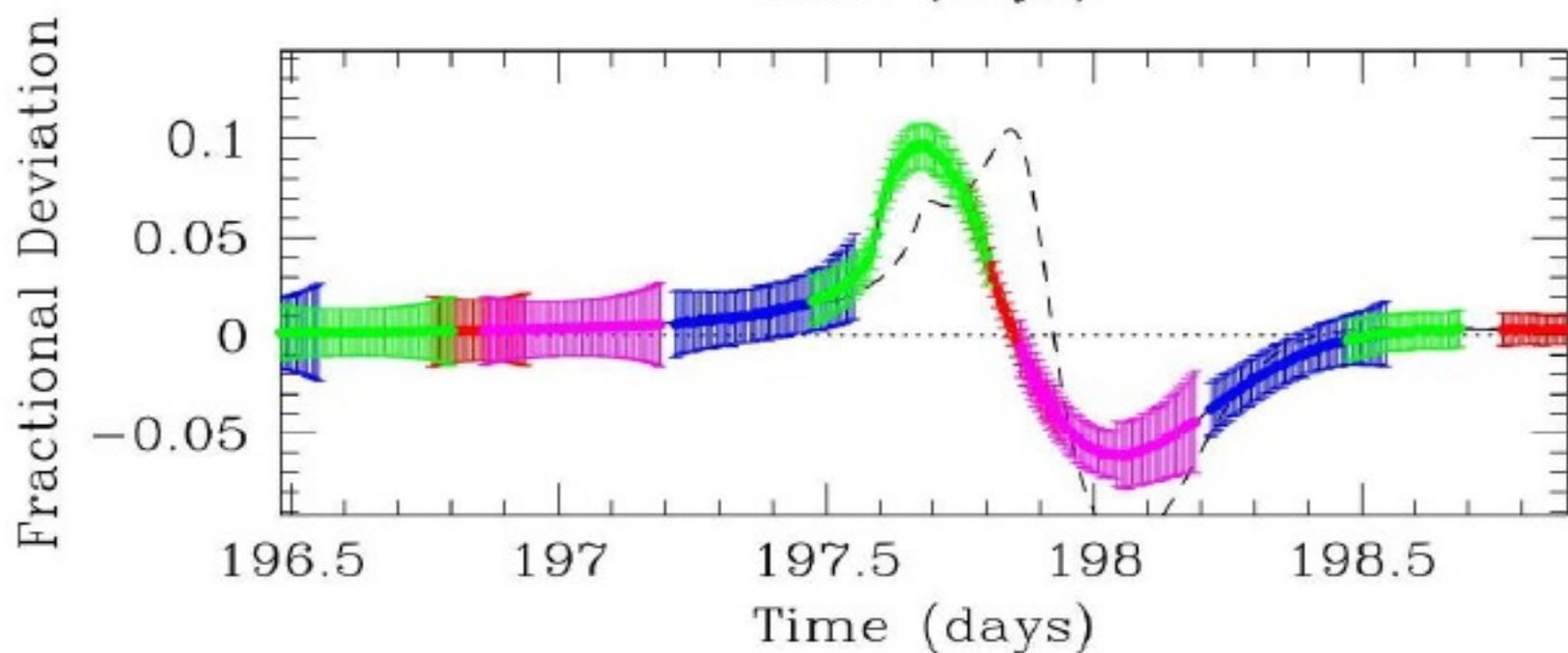
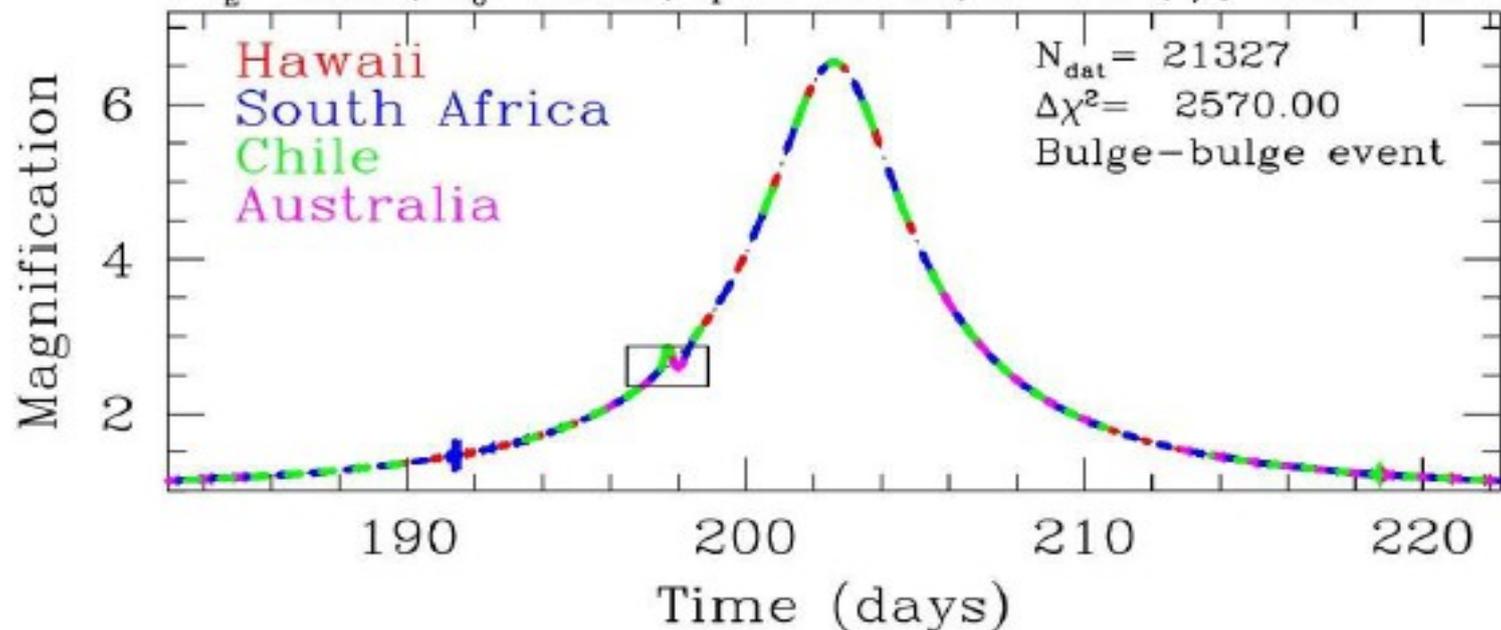


Target Fields

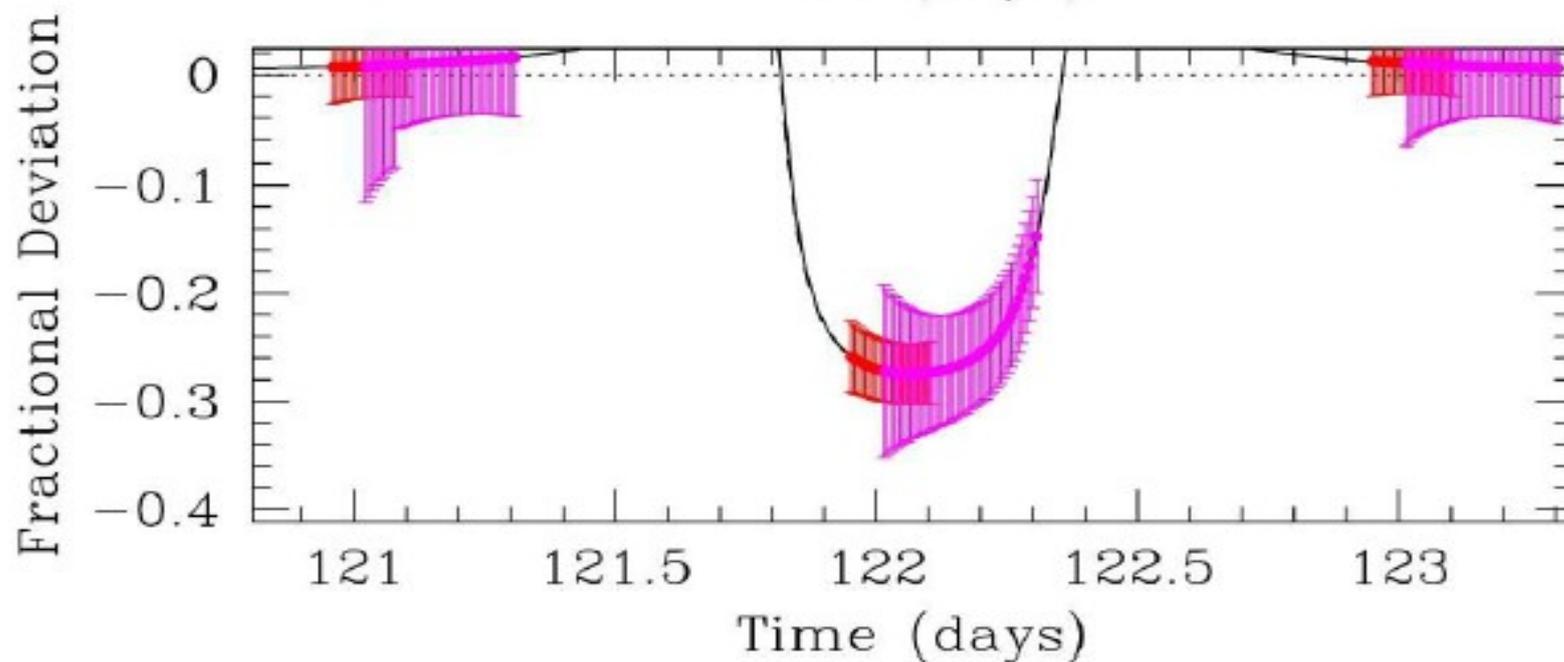
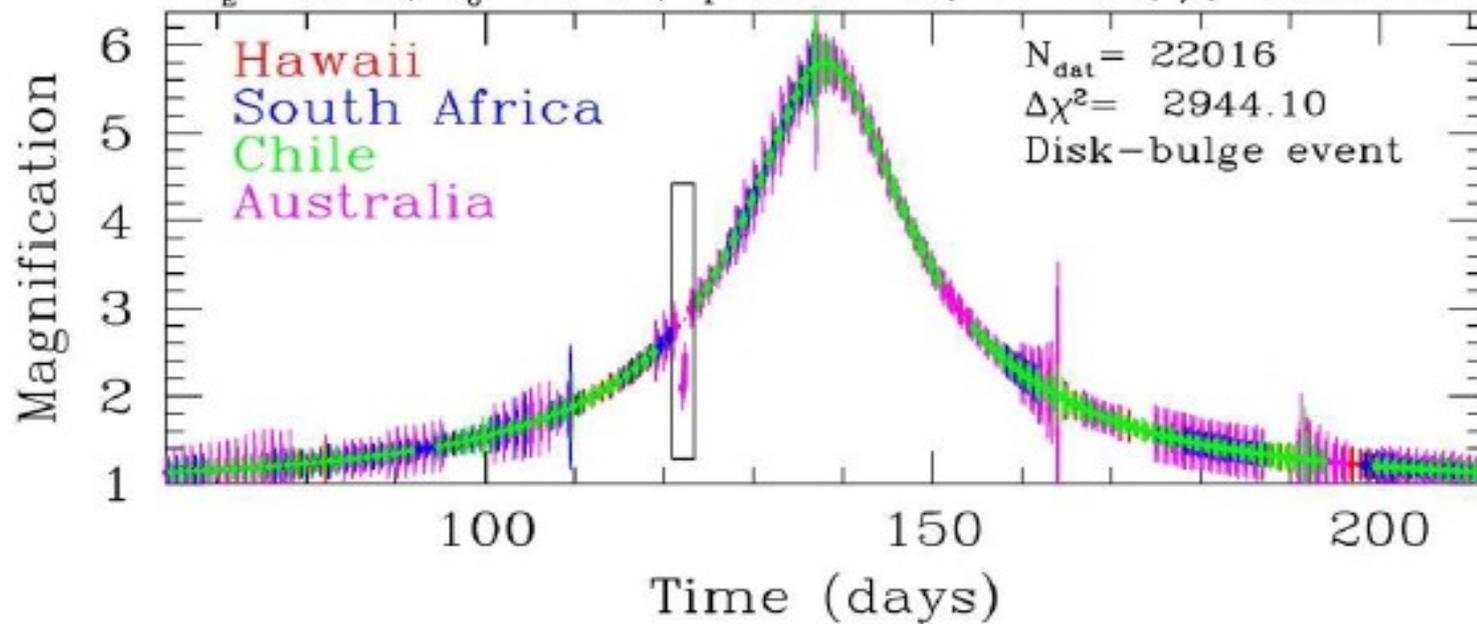
- Four Fields
 - (1,b)=(1,-3)
 - ~2900 Events/yr
 - (1,b)=(3,-3)
 - ~2300 Events/yr
 - (1,b)=(1,-5)
 - ~900 Events/yr
 - (1,b)=(3,-5)
 - ~800 Events/yr



$\log(M/M_{\oplus})=0.00$, $\log(a/\text{AU})=-0.35$, $N_{\text{det}}=1$
 $M_* = 0.109$, $R_E = 0.50$, $I_s = 19.70$, $I_{\text{lens}} = 27.41$, $\Gamma_i = 0.3994$
 $t_E = 13.13$, $u_0 = 0.1541$, $q = 2.76e-05$, $d = 0.82$, $\rho_* = 9.16e-03$



$\log(M/M_{\oplus})=0.00$, $\log(a/\text{AU})=0.65$, $N_{\text{det}}=31$
 $M_{\star}=0.455$, $R_E=2.36$, $I_s=21.40$, $I_{\text{lens}}=20.24$, $\Gamma_i=0.2000$
 $t_E=49.21$, $u_0=0.1744$, $q=6.60e-06$, $d=0.83$, $\rho_{\star}=3.19e-04$



Baseline Results

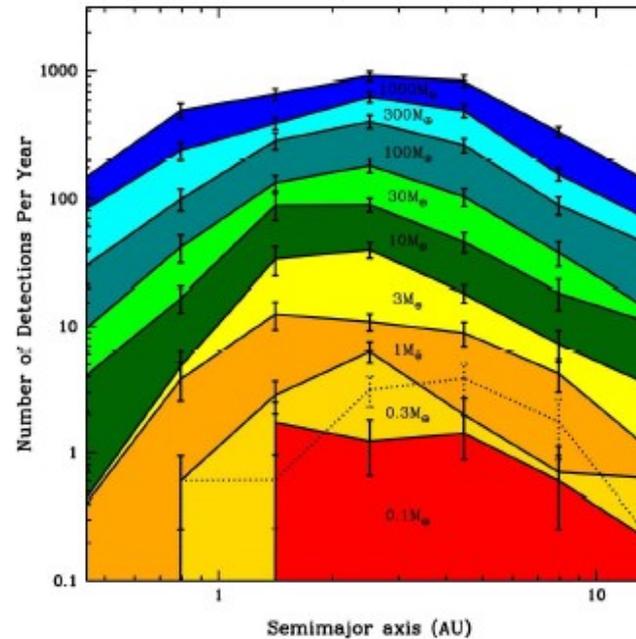
- Simulate:

- 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:

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

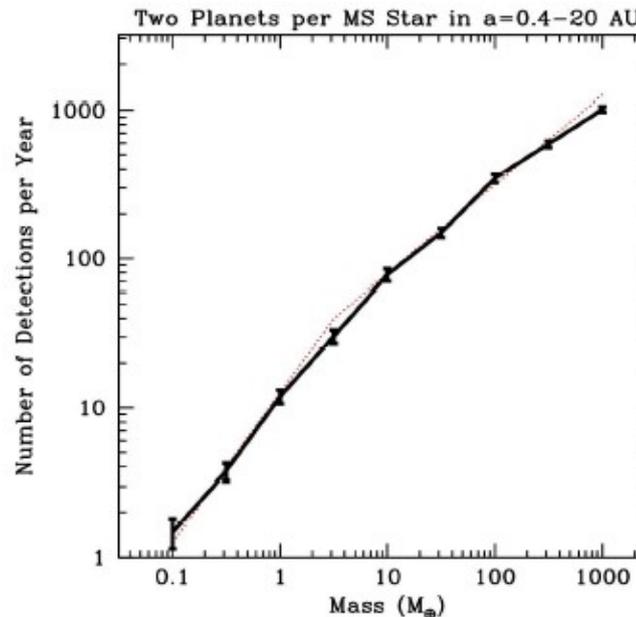


- Average over a

- $-0.35 < \log(a/\text{AU}) < 1.15$
 - 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 _⊙)	-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. Ministries of Science and Finance recommended US\$30M for two 2m tels, with 4 sq.deg cameras (Africa and South America) [KMT]

Conclusions

- Microlensing planets now found “routinely”
 - about 4 per year
- Many planet distances are measured
 - Contrary to initial expectations
- Identifying bulge lenses still tough
 - Possible with 5-yr-later follow-up
- NextGen experiments will increase 10-fold
 - MOA/OGLE/KMT