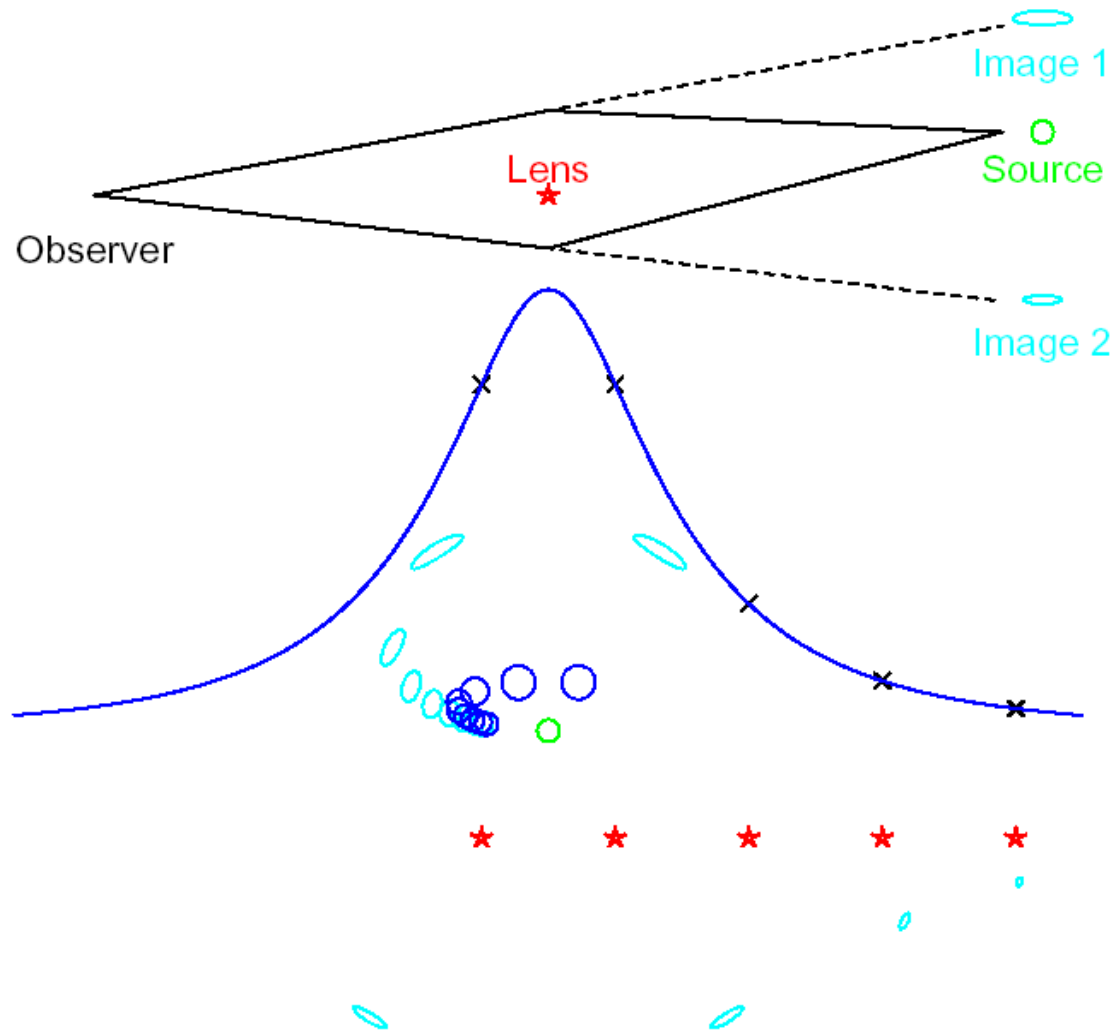


Microlensing Takes Off: Toward the Galactic Distribution of Planets

Andy Gould (Ohio State)



Mao & Paczynski

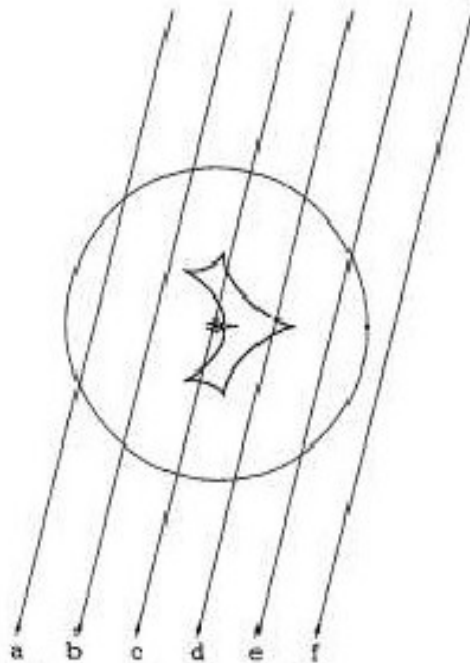
Central Caustics

GRAVITATIONAL MICROLENSING BY DOUBLE STARS AND PLANETARY SYSTEMS

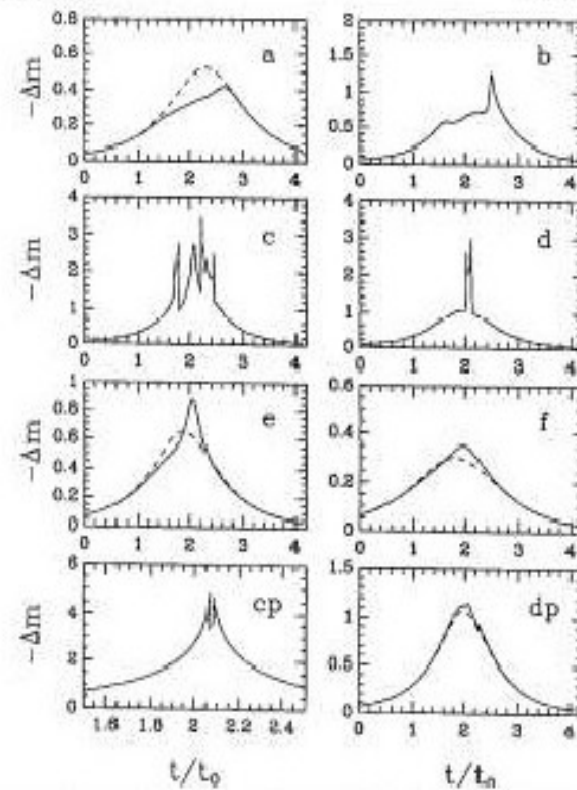
SHUDE MAO AND BOHDAN PACZYŃSKI

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 primary star of $1 M_{\odot}$ is located at the center of the figure, and the secondary of $1 M_{\odot}$ or $0.001 M_{\odot}$ is located on the right, on the Einstein ring of the primary. The radius of the ring is 1.0 mas for a source located at a distance of 8 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

Planetary Caustics

DISCOVERING PLANETARY SYSTEMS THROUGH GRAVITATIONAL MICROLENSSES

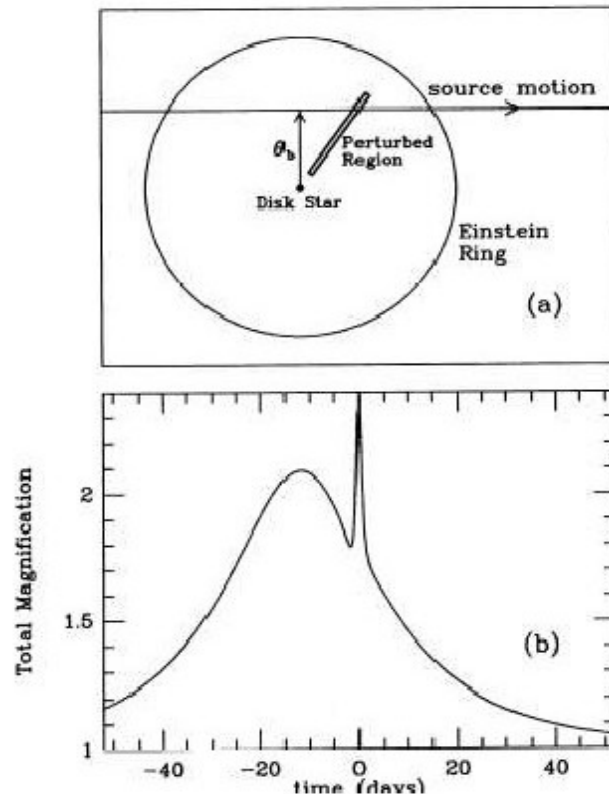
ANDREW GOULD AND ABRAHAM LOEB
Institute for Advanced Study, Princeton, NJ 08540
Received 1991 December 26; accepted 1992 March 9

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,



6 Features

& 6 Parameters

Time of Peak

t_0

Height of Peak

u_0

Width of Peak

t_E

Time of Perturbation

Trajectory angle: α

Height of Perturbation

Planet-star separation: s

Width of Perturbation

Planet/star mass ratio: q

6 Features

Time of Peak

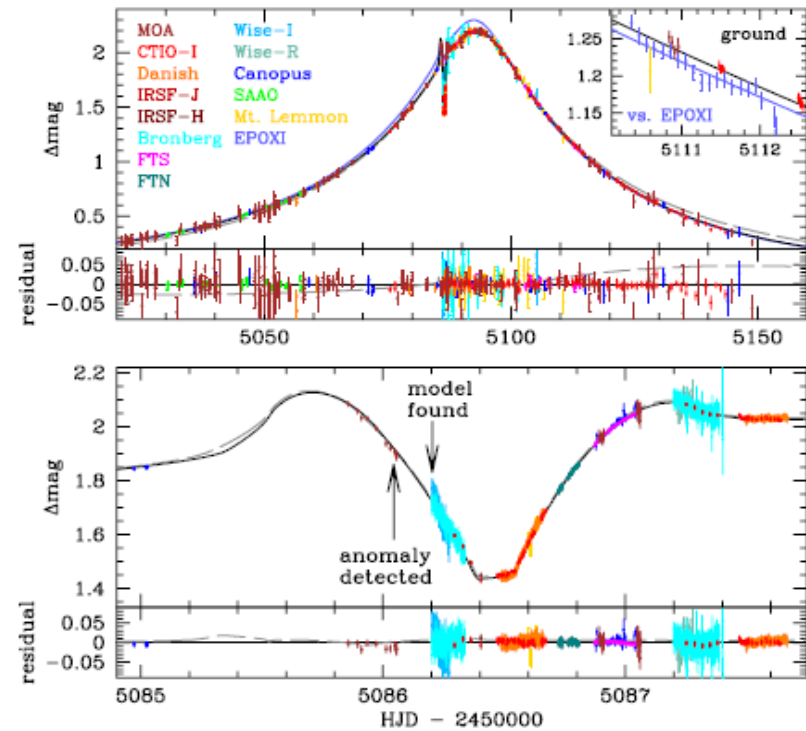
Height of Peak

Width of Peak

Time of Perturbation

Height of Perturbation

Width of Perturbation



7 Features & 7 Parameters

| | |
|------------------------|-------------------------------|
| Time of Peak | t_0 |
| Height of Peak | u_0 |
| Width of Peak | t_E |
| Time of Perturbation | Trajectory angle: α |
| Height of Perturbation | Planet-star separation: s |
| Width of Perturbation | Planet/star mass ratio: q |
| Width of Caustic Cross | Normalize source size: ρ |

7 Features

Time of Peak

Height of Peak

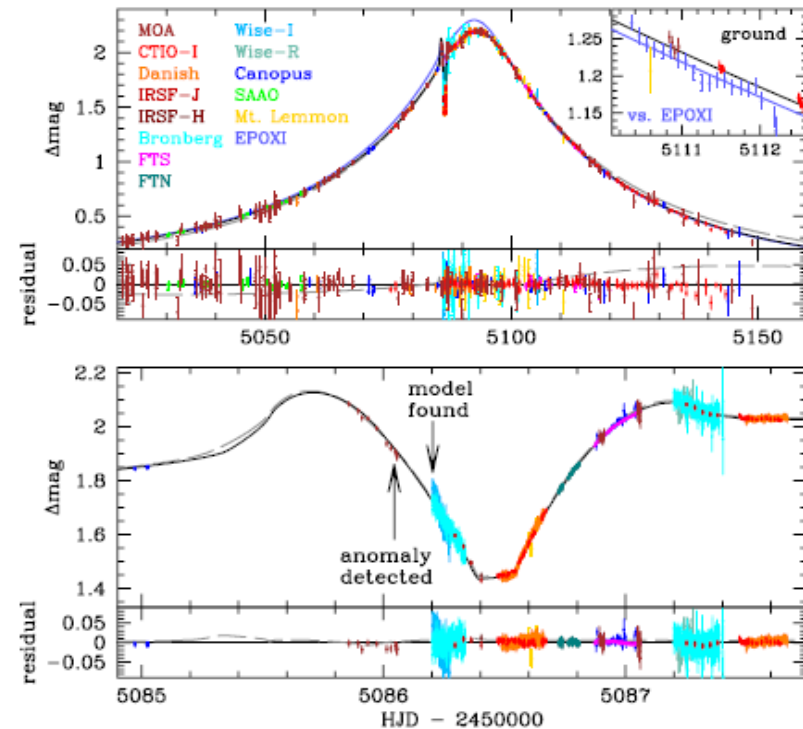
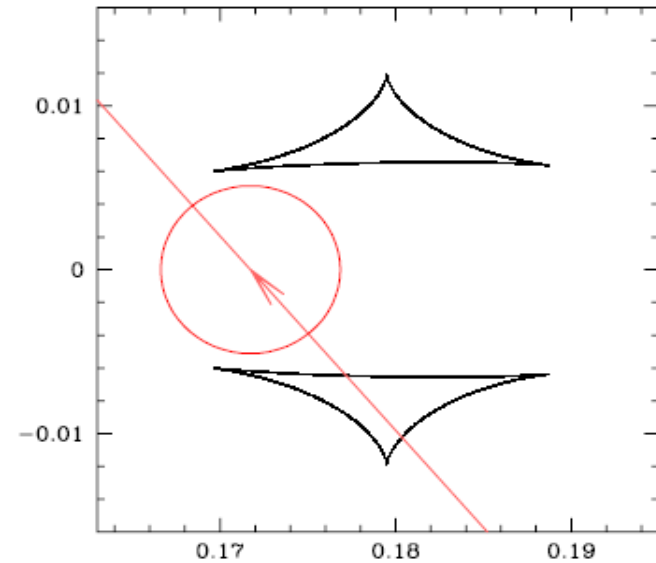
Width of Peak

Time of Perturbation

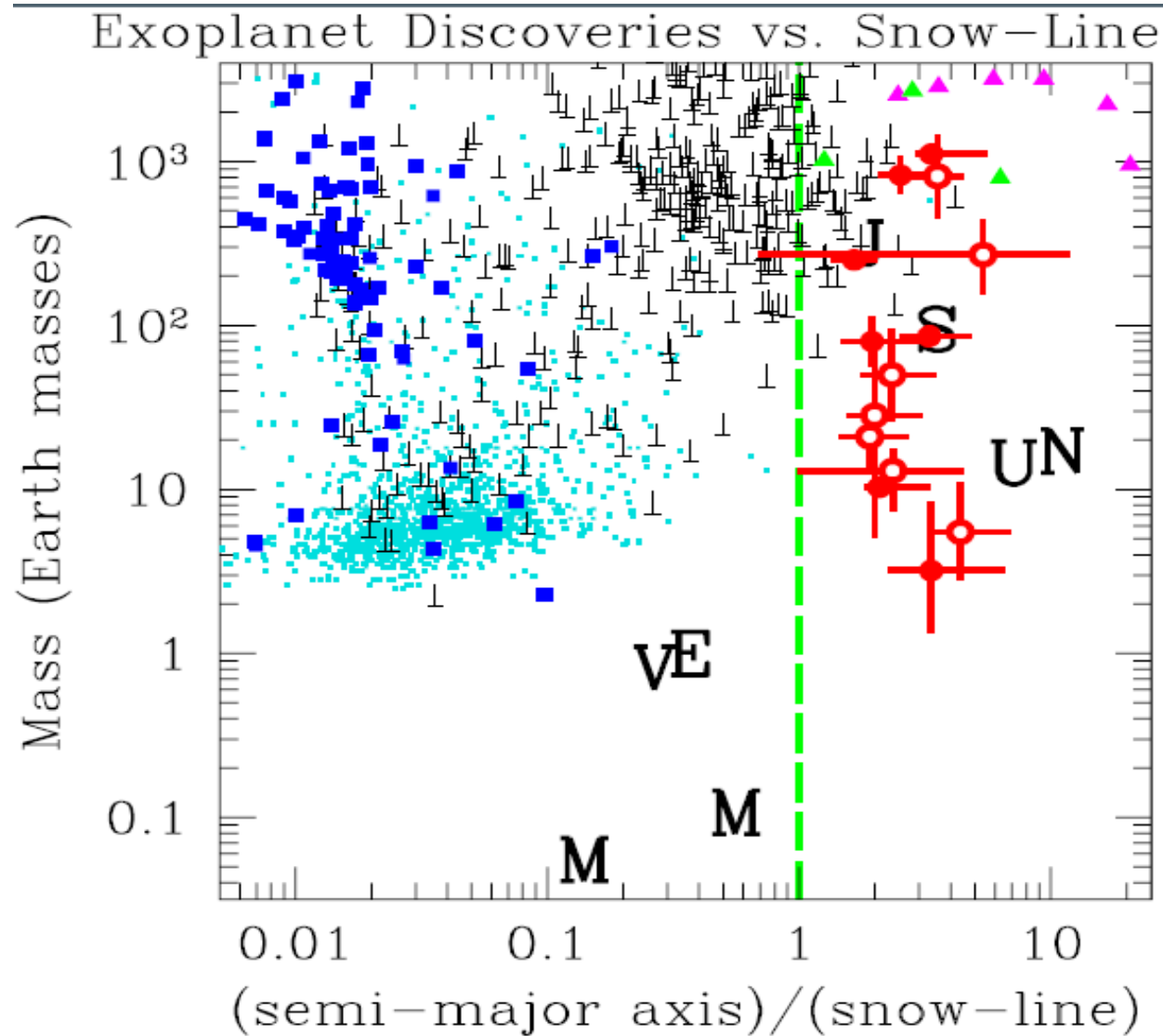
Height of Perturbation

Width of Perturbation

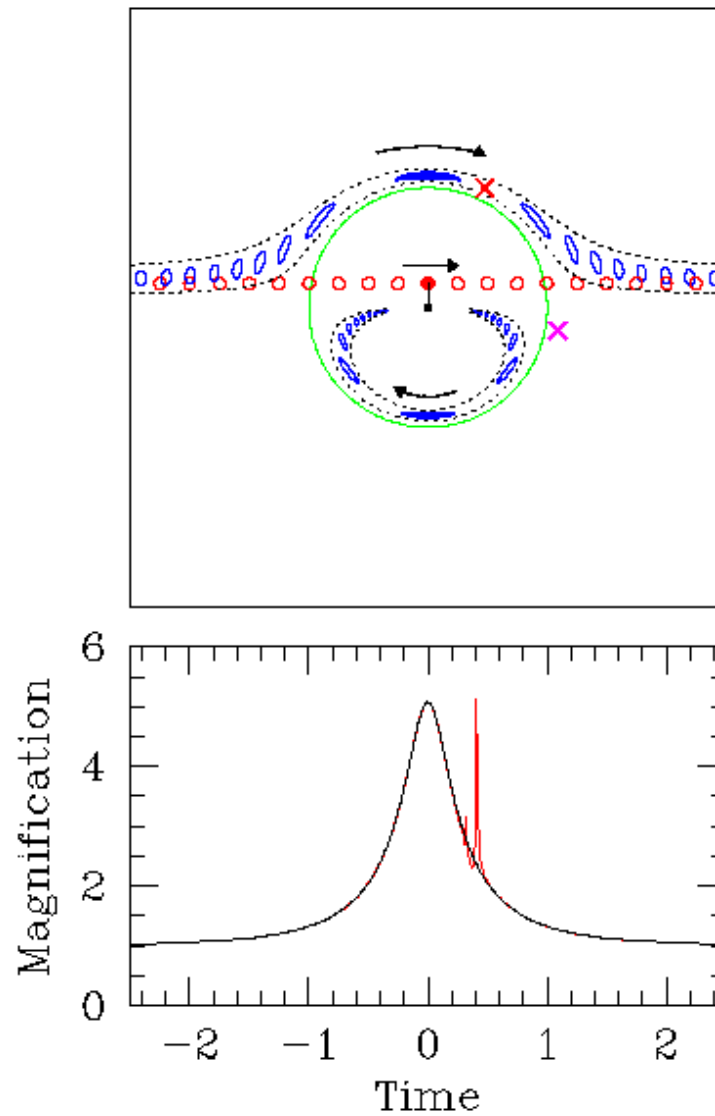
Width of Caustic Cross



Planets 2011

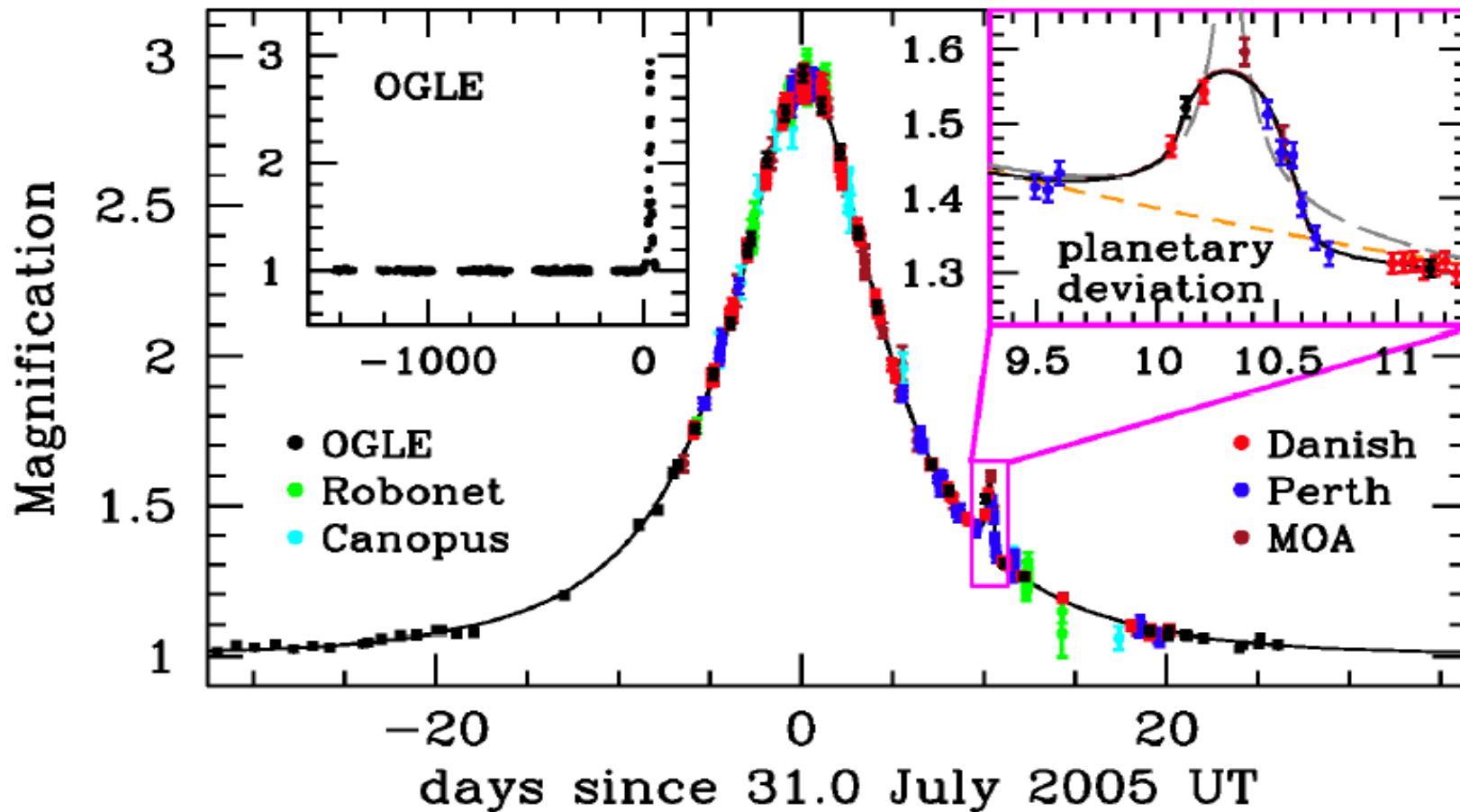


How Microlensing Finds Planets



OGLE-2005-BLG-390

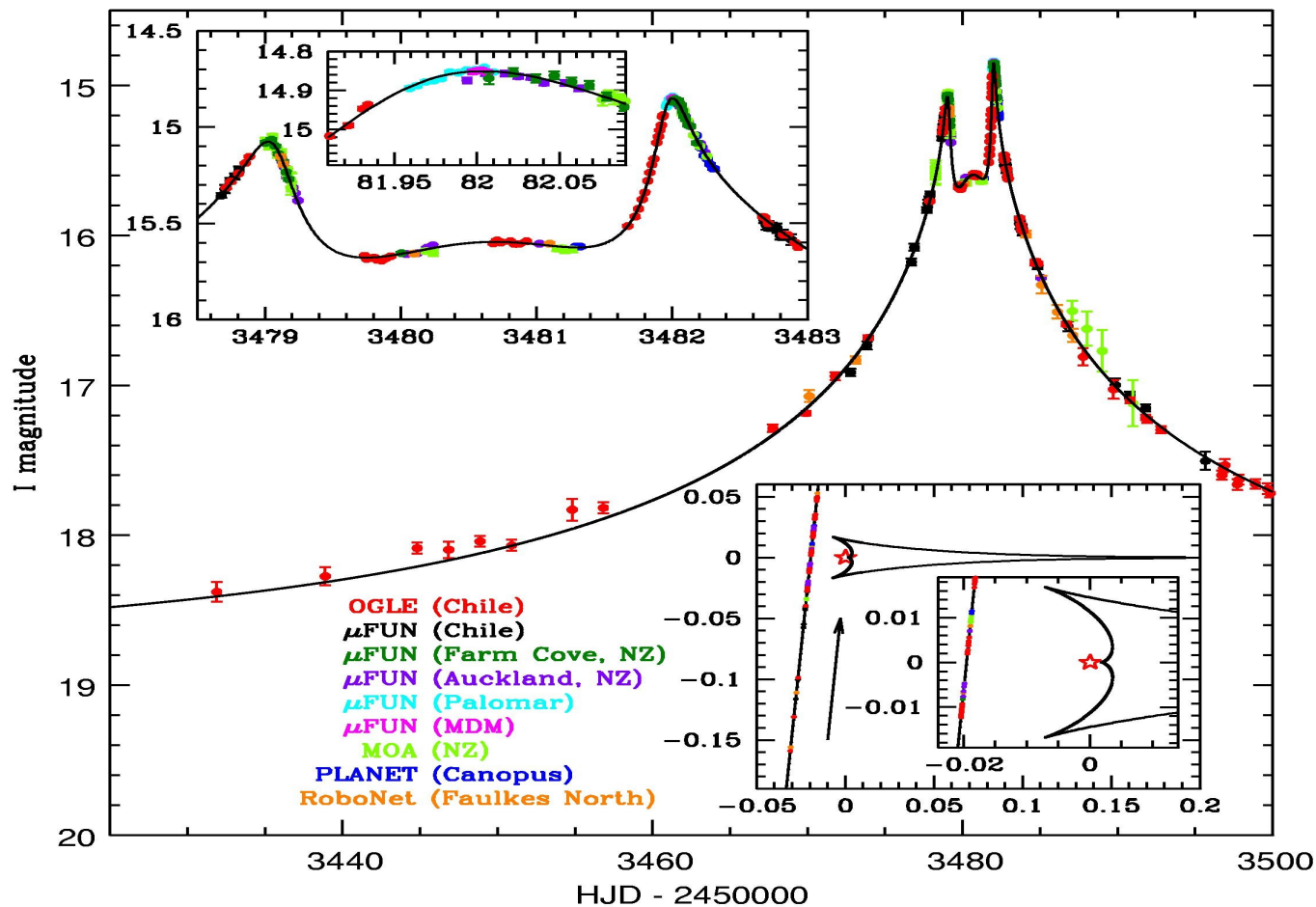
“Classical-Followup” Planetary Caustic



Beaulieu et al. 2006, Nature, 439, 437

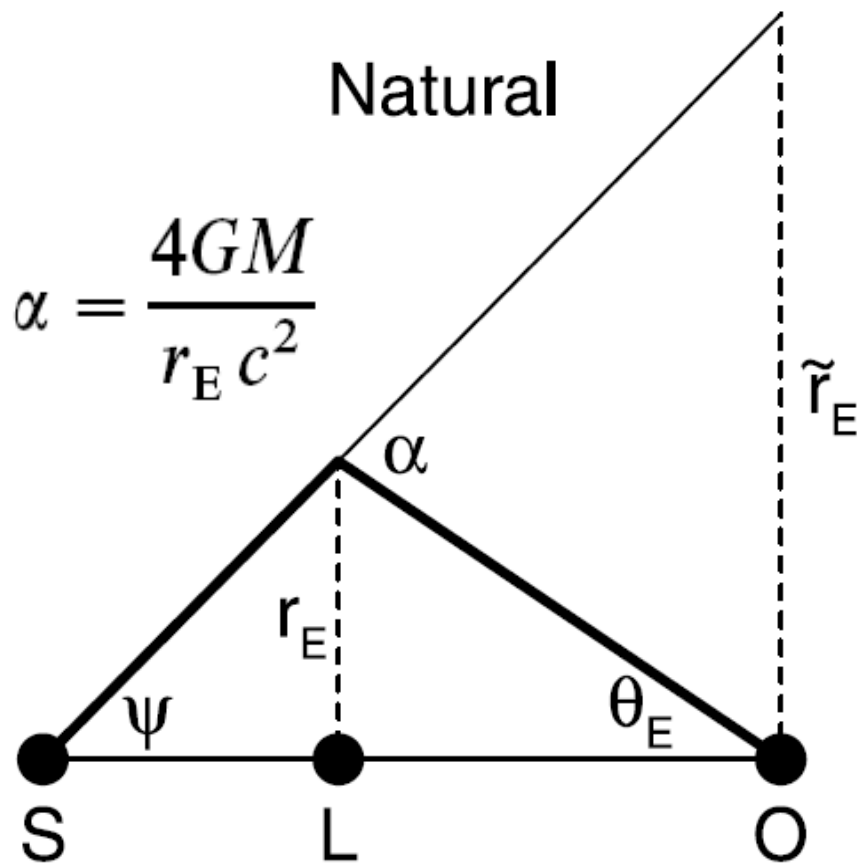
OGLE-2005-BLG-071

First “High-Mag” Event



Udalski et al. 2005, ApJ, 628, L109

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



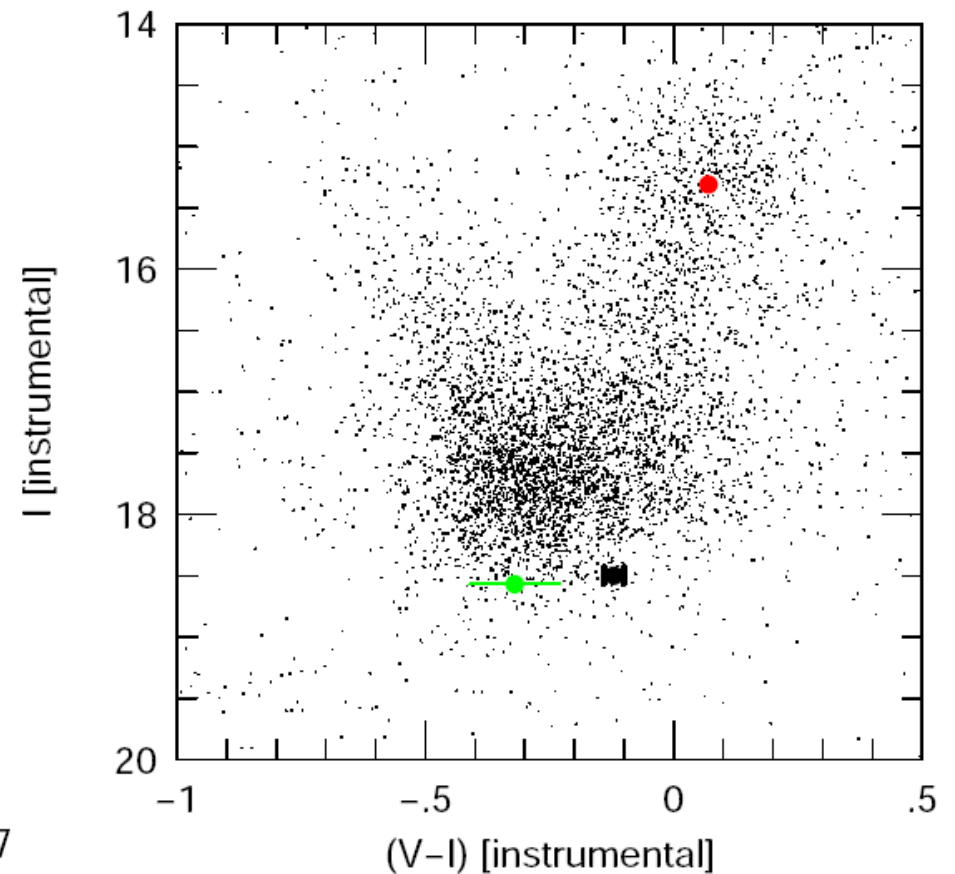
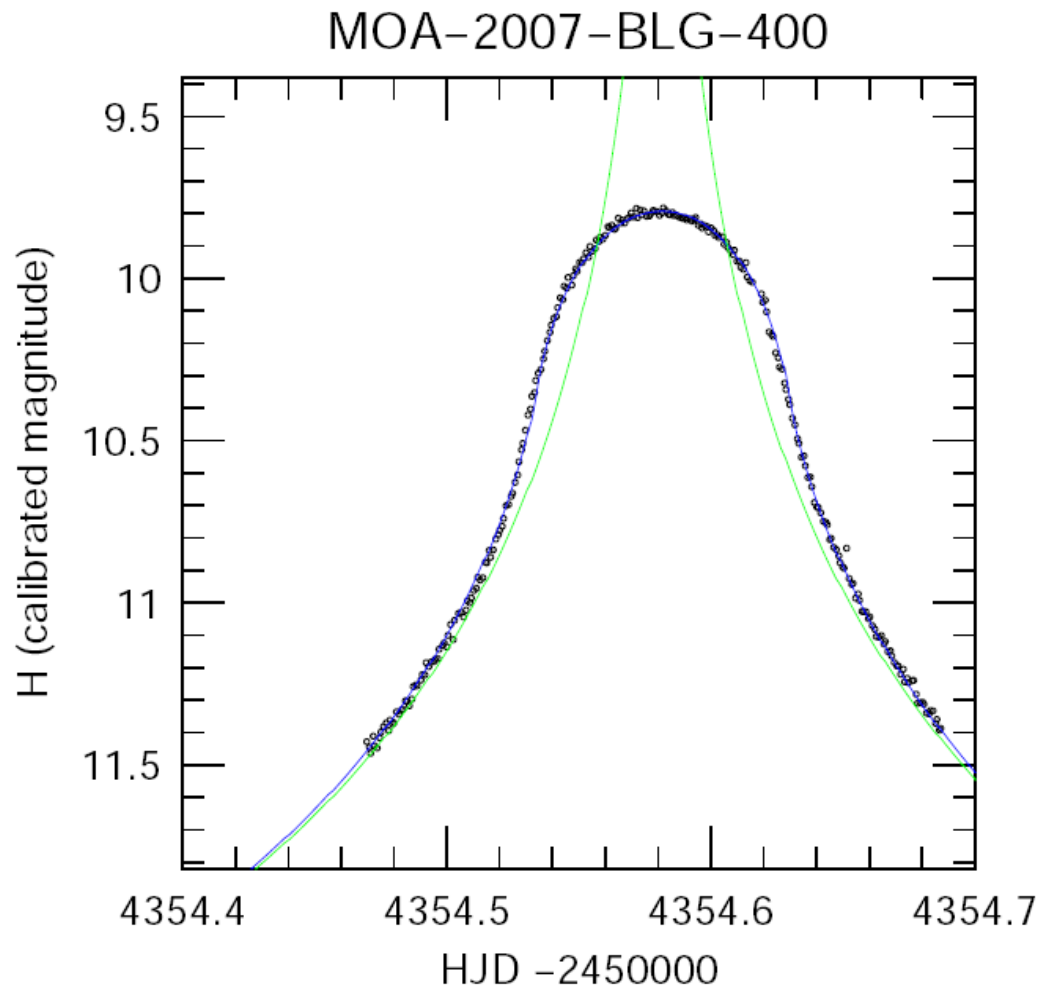
$$\alpha / \tilde{r}_E = \theta_E / r_E$$

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

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

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

To measure angular Einstein radius: Standard **Sky-Plane** Rulers



To measure angular Einstein radius: Standard **Sky-Plane** Rulers

$$\rho \equiv \frac{\theta_*}{\theta_E}$$

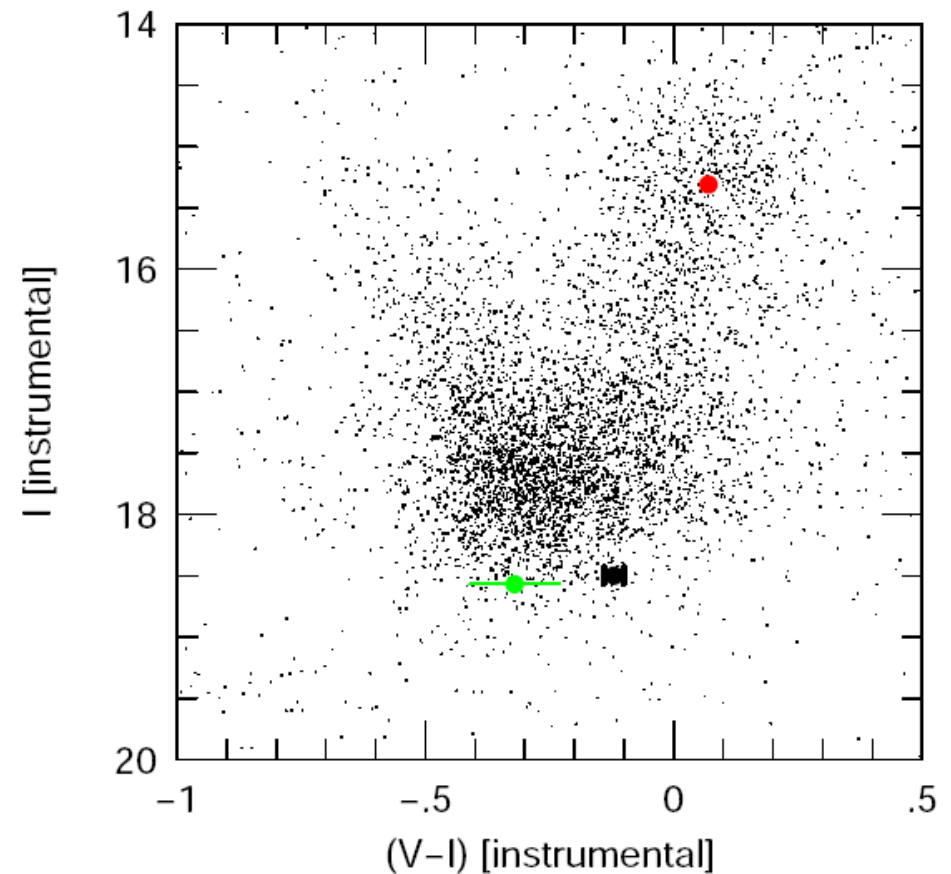
$$\theta_E = \frac{\theta_*}{\rho}$$

$$f_{s,0} = \pi \theta_*^2 S_0$$

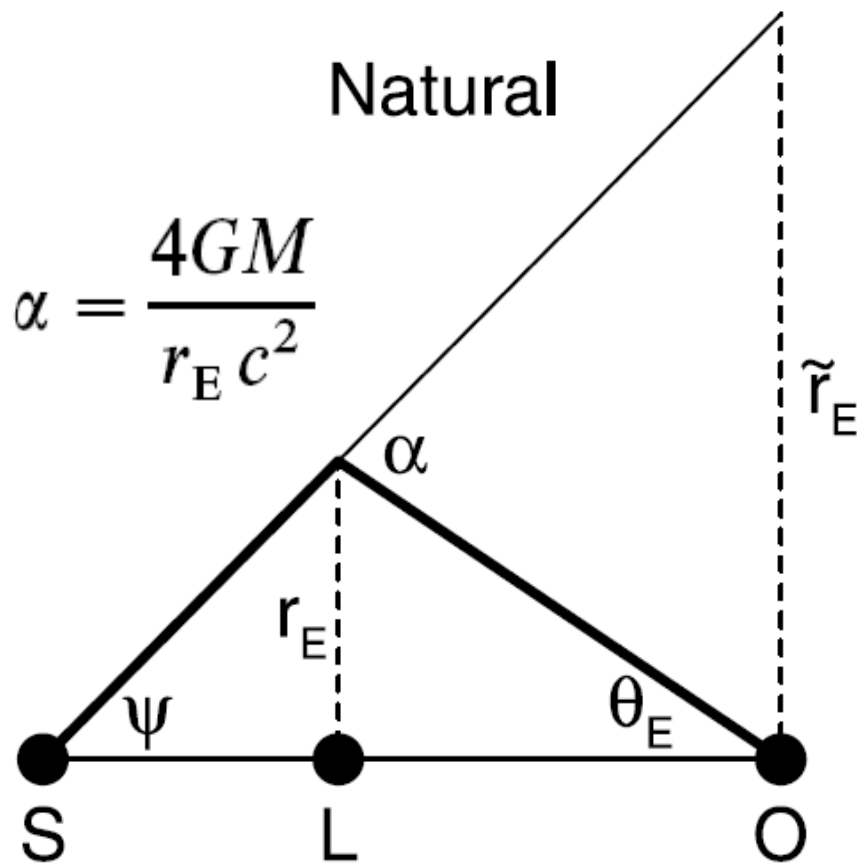
$$\theta_* = \sqrt{\frac{f_s(I_0)}{\pi S[(V - I)_{s,0}]}}$$

$$(V - I)_{s,0} = (V - I)_{clump,0} + \Delta(V - I)$$

$$I_{s,0} = I_{clump,0} + \Delta I$$



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



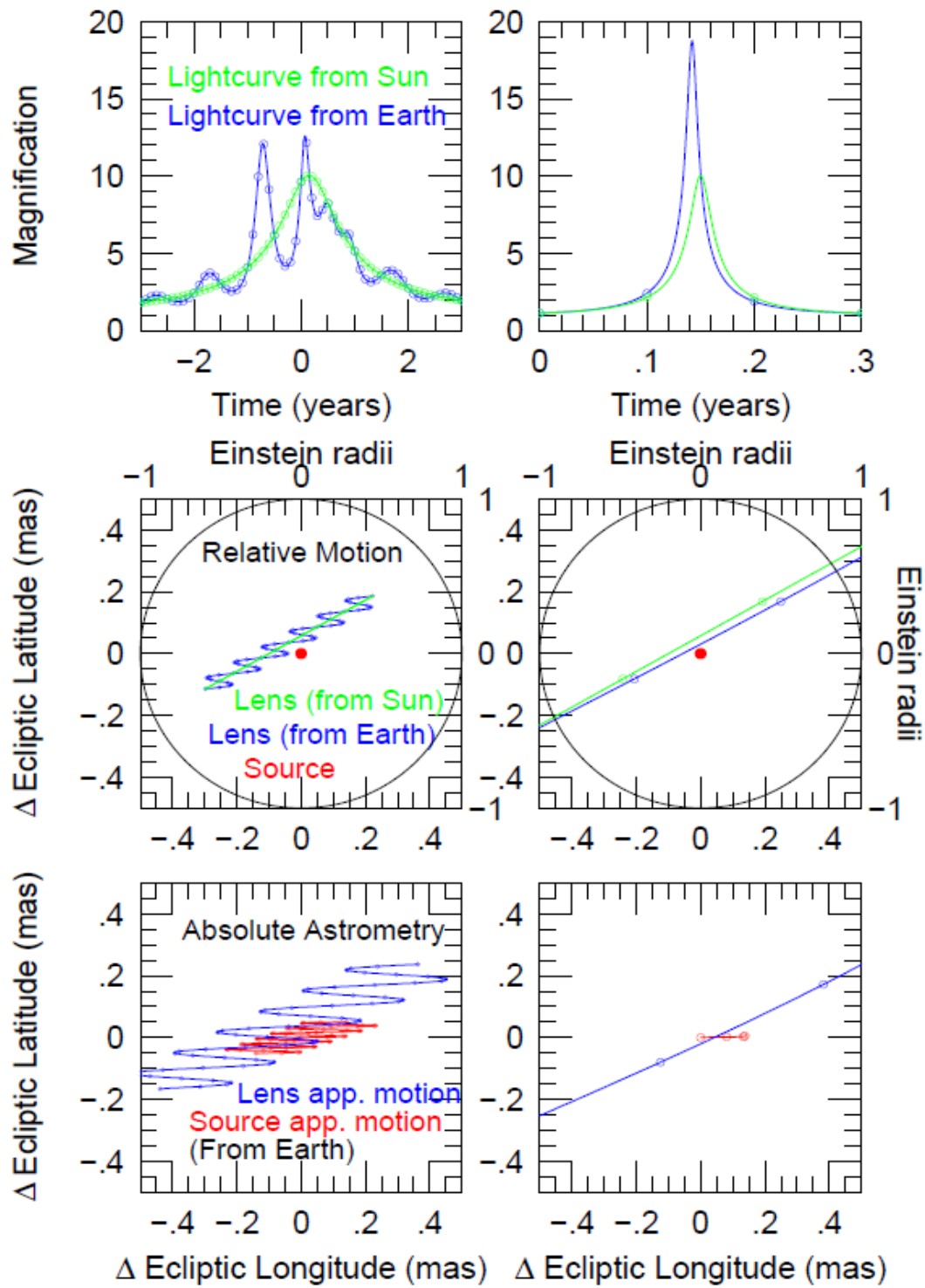
$$\alpha / \tilde{r}_E = \theta_E / r_E$$

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

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

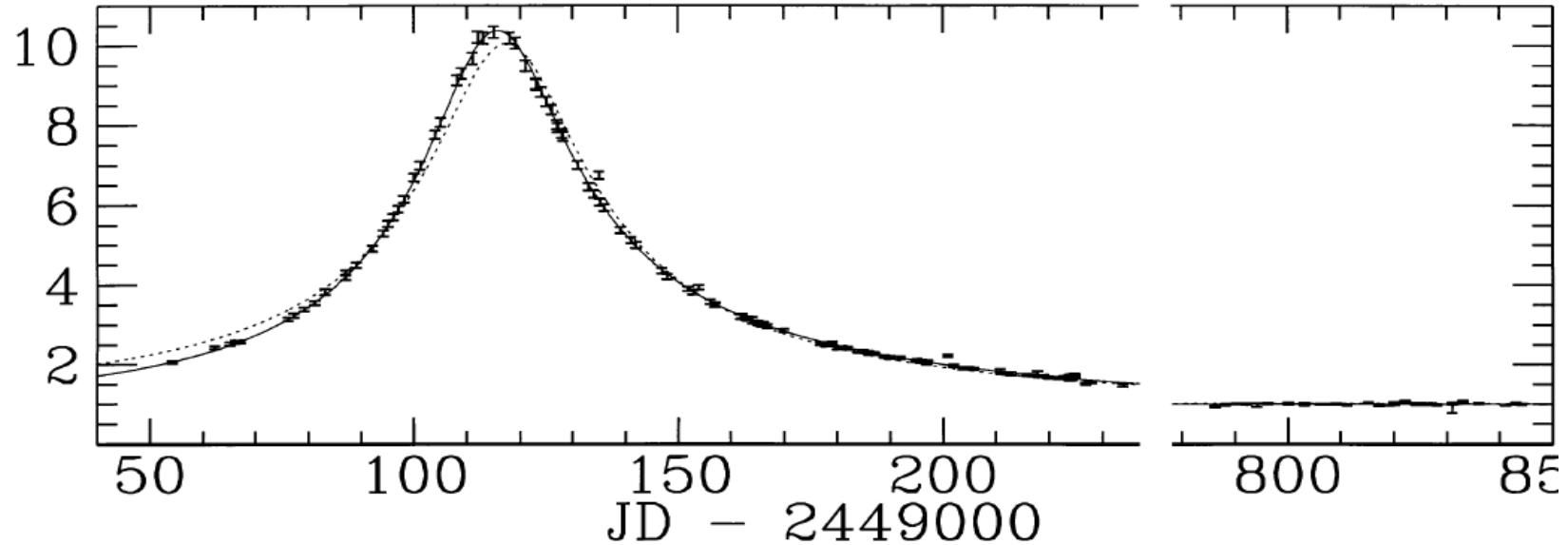
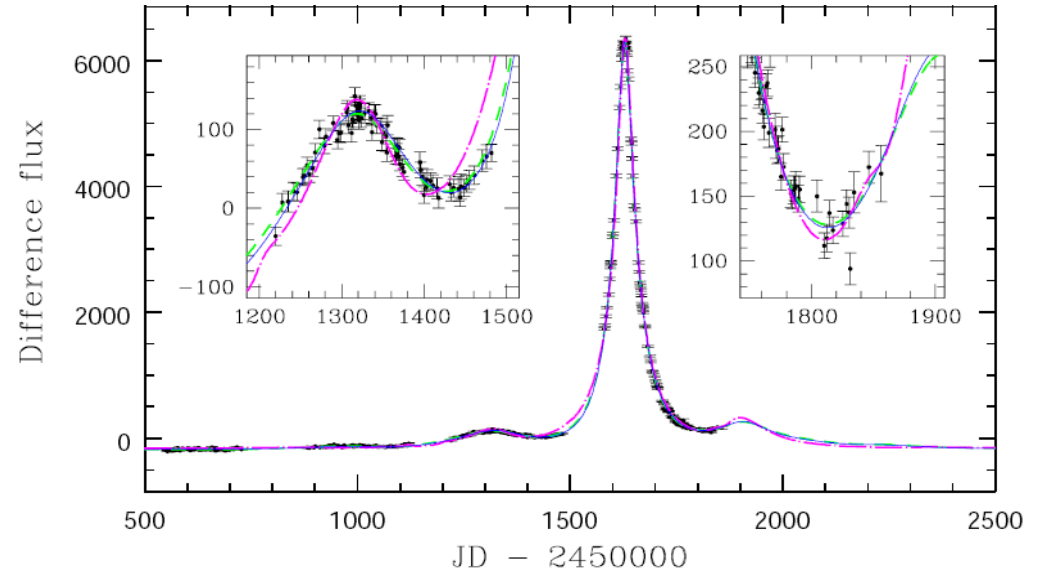
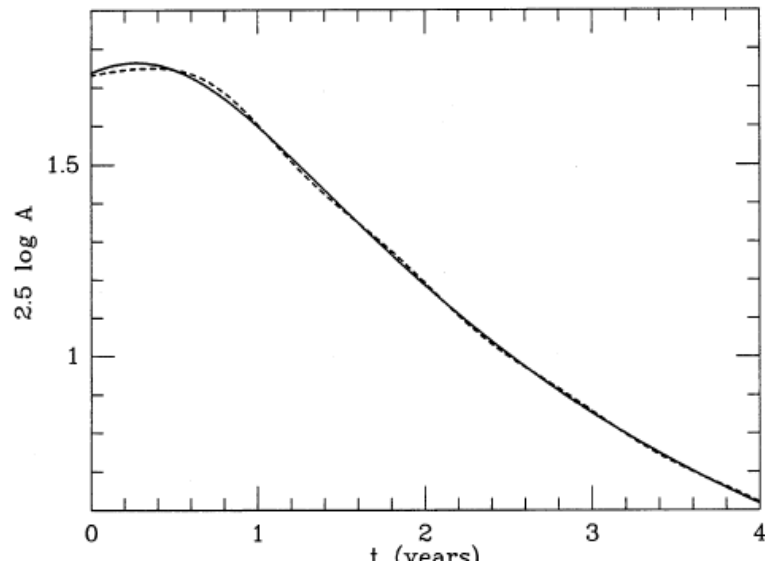
$$\tilde{r}_E = \sqrt{\frac{4GM D_{\text{rel}}}{c^2}}$$

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

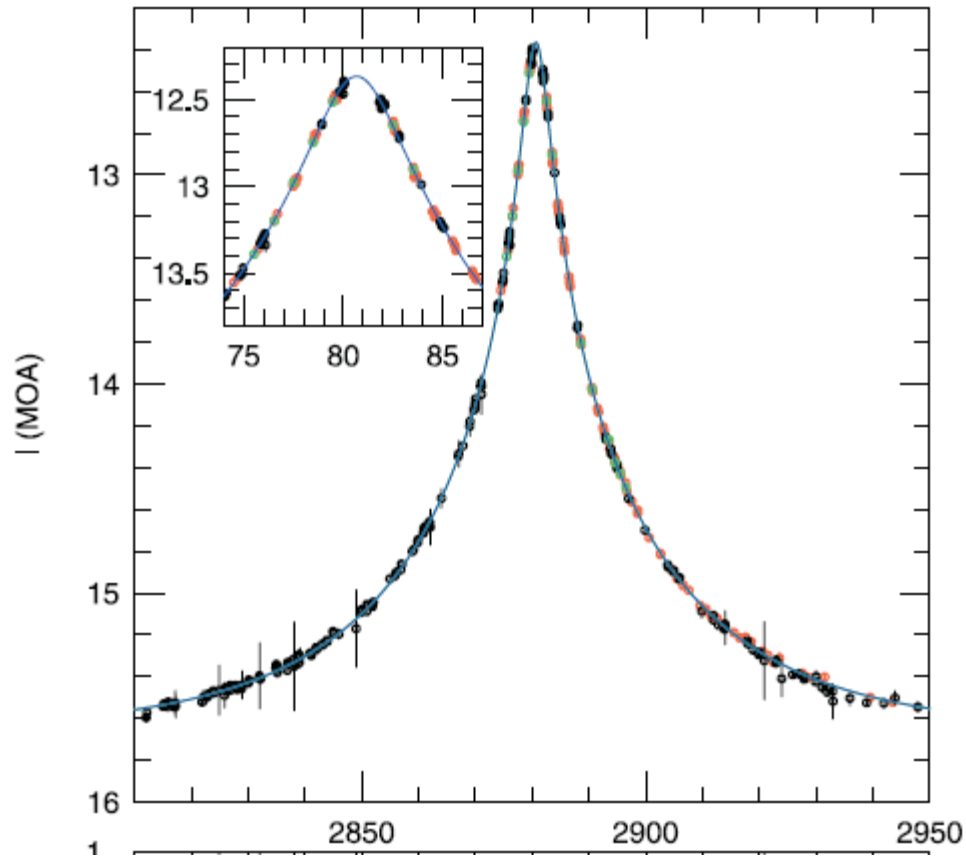


To measure parallax:

Standard Observer-Plane Rulers

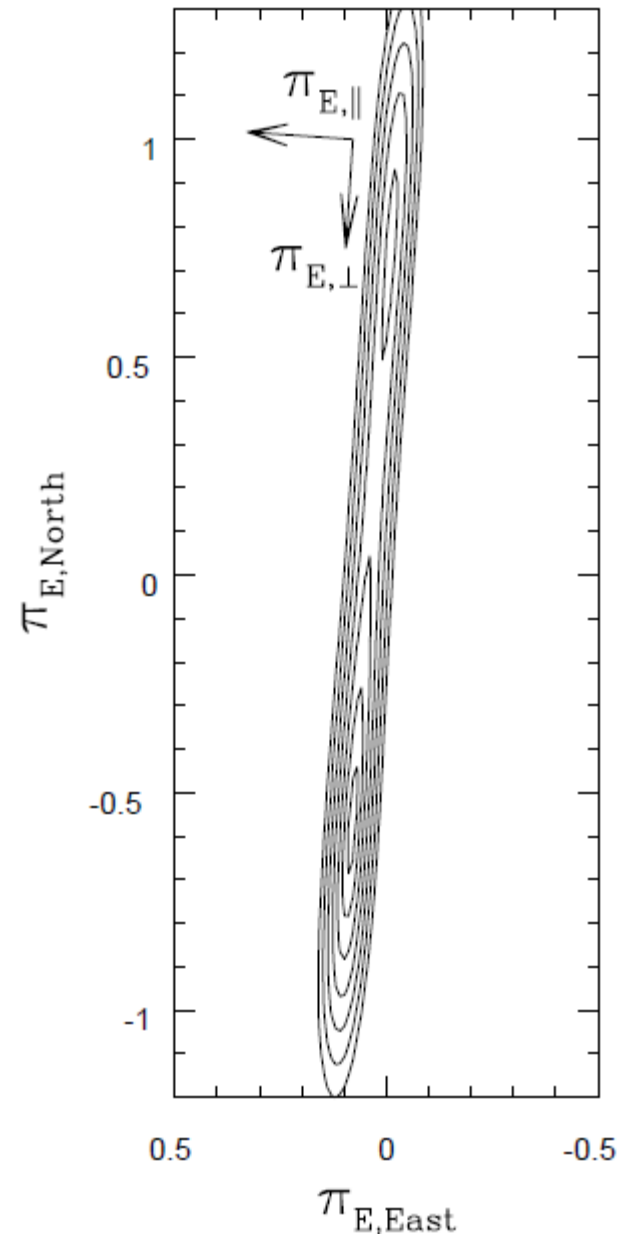


1-D Parallaxes Are “Common”

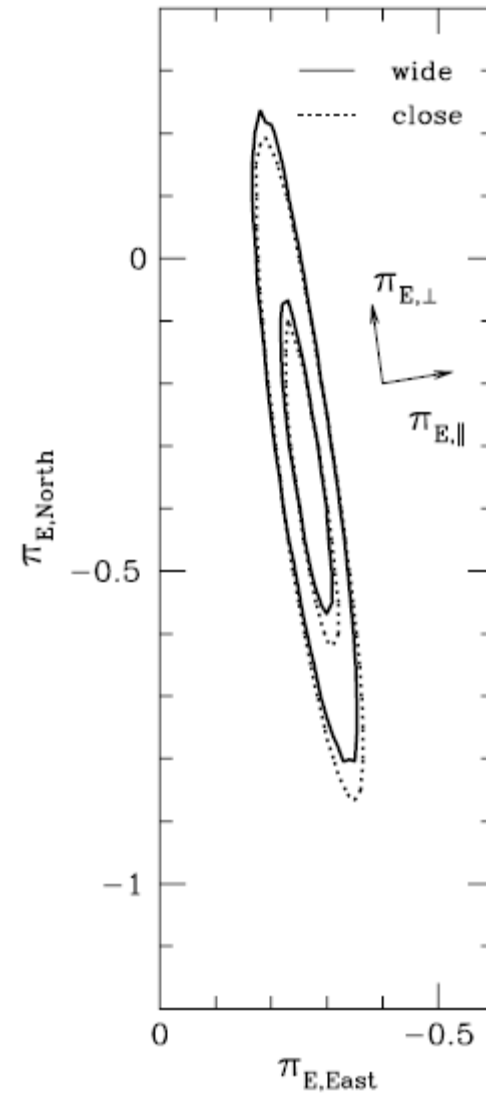
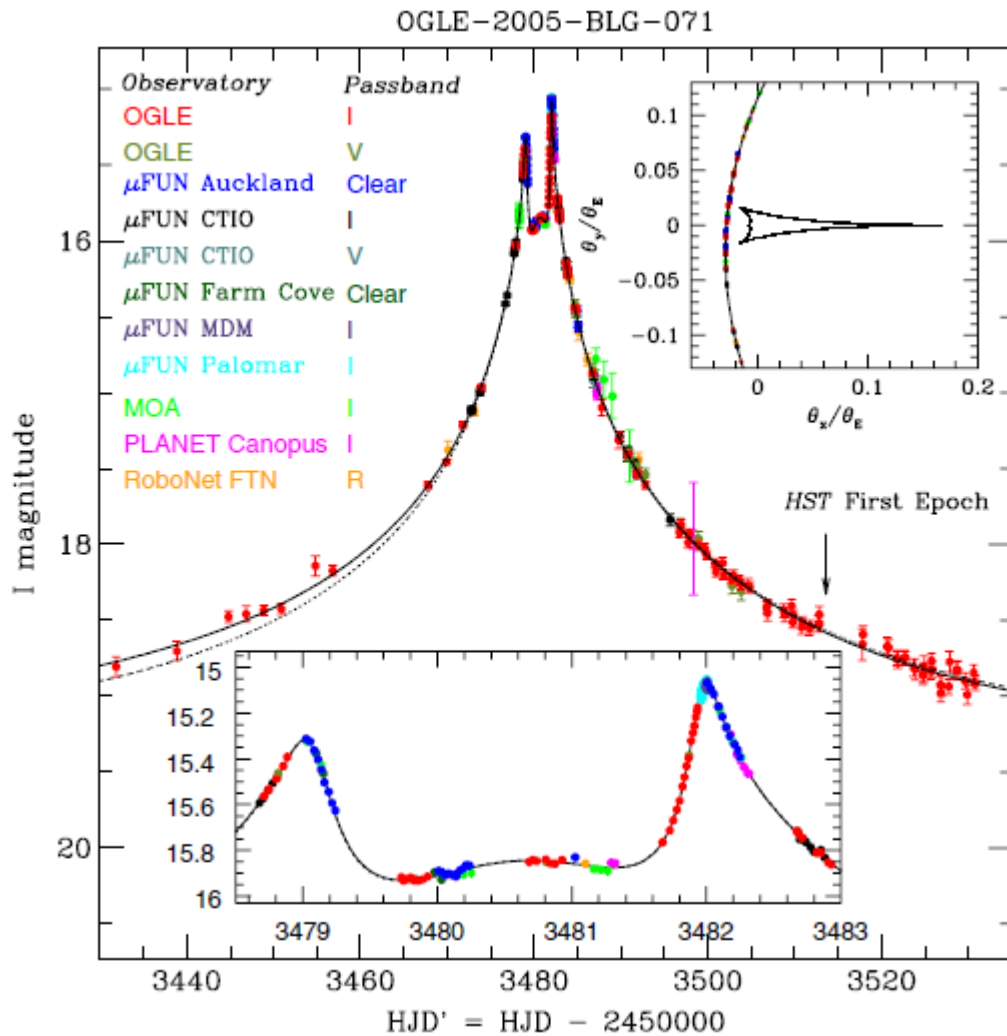


MOA-2003-BLG-37

Park et al. 2004, ApJ. 609, 166



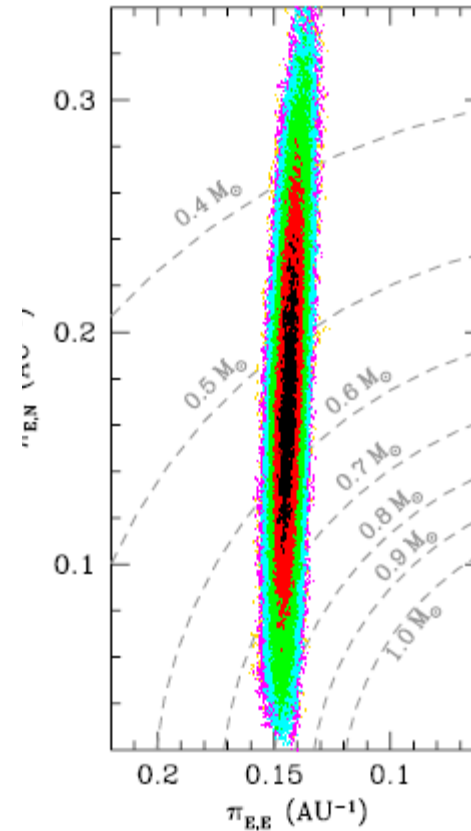
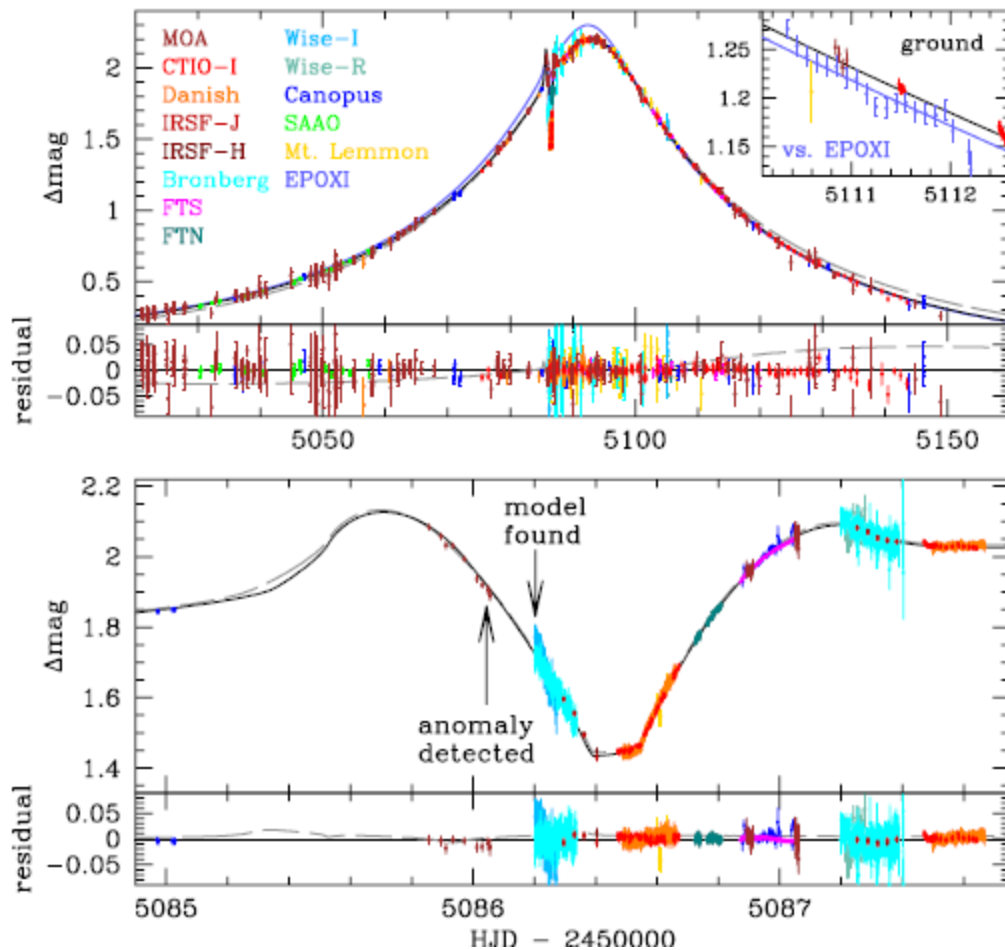
1-D Parallaxes Are “Common”



OGLE-2005-BLG-071

Dong et al. 2009, ApJ. 695, 970

1-D Parallaxes Are “Common”

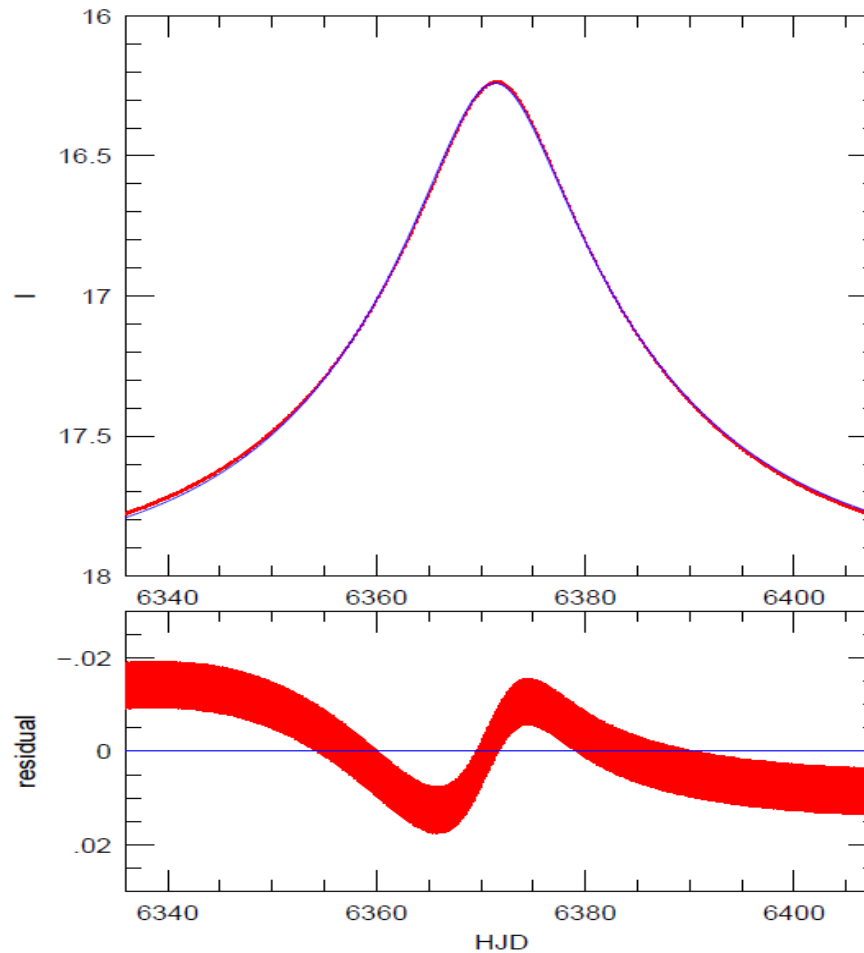


MOA-2009-BLG-266

Muraki et al. 2011, ApJ, 741, 22

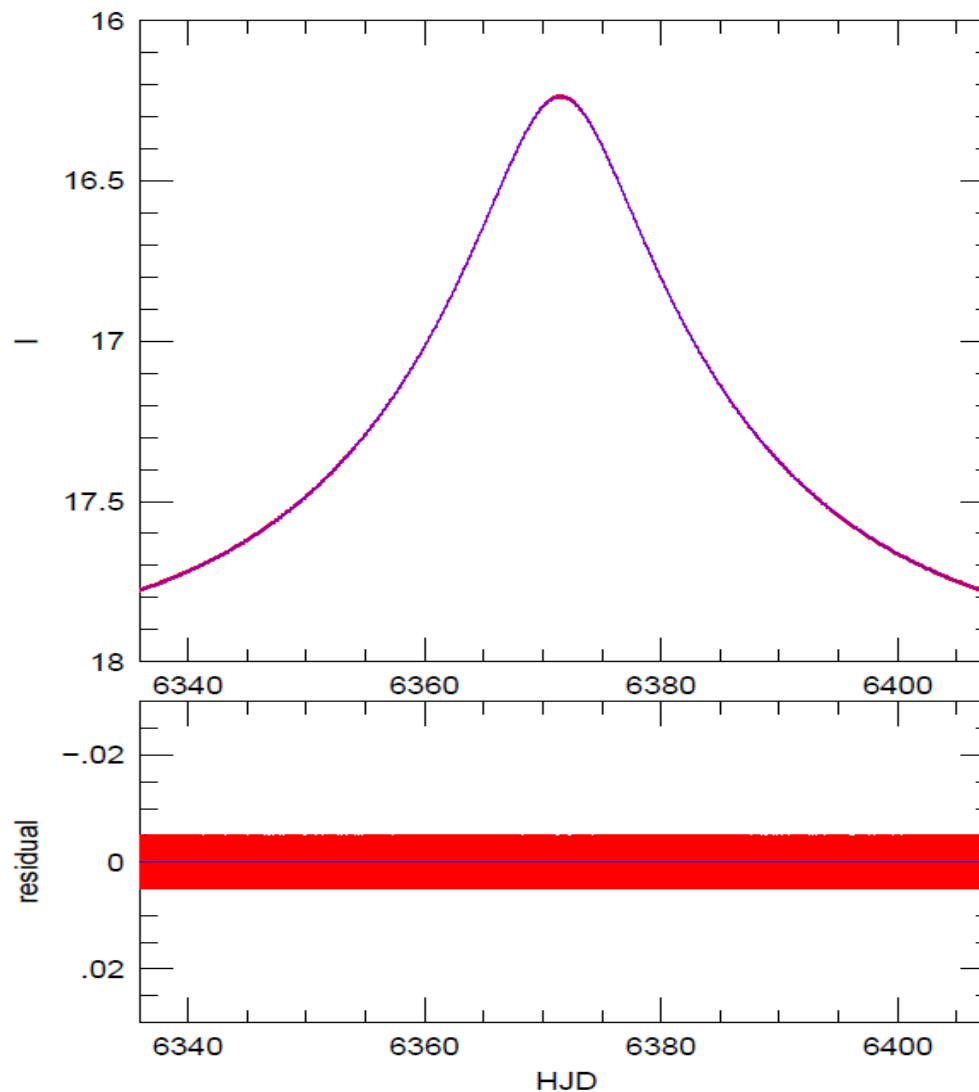
$\pi_{E,\text{parallel}}$ (square peg: round hole)

Component of π_E toward Sun



$\pi_{E, \text{perp}}$ (round peg: round hole)

Component of π_E perp to Sun



What can be done?

Focus on nearby
low-mass lenses

$$\pi_E^2 = \pi_{\text{rel}} / \kappa M; \kappa = 8 \text{mas} / M_{\text{sun}}$$

What can be done?

Focus on nearby
low-mass lenses

-Biased toward long t_E

$$\pi_E^2 = \pi_{\text{rel}} / \kappa M; \kappa = 8 \text{mas}/M_{\text{sun}}$$

$$\pi_{E,\text{parallel}} \quad (3^{\text{rd}} \text{ order in time})$$

$$\pi_{E,\text{perp}} \quad (4^{\text{th}} \text{ order in time})$$

$$u^2 = \sum_{i=0}^{\infty} C_i t^i$$

$$C_0 = u_0^2, \quad C_1 = 0, \quad C_2 = -\alpha u_0 \pi_{E,\perp} + t_E^{-2}$$

$$C_3 = \alpha \frac{\pi_{E,\parallel}}{t_E} + \frac{1}{4} \alpha^2 t_E u_0 \pi_E \times \pi_j,$$

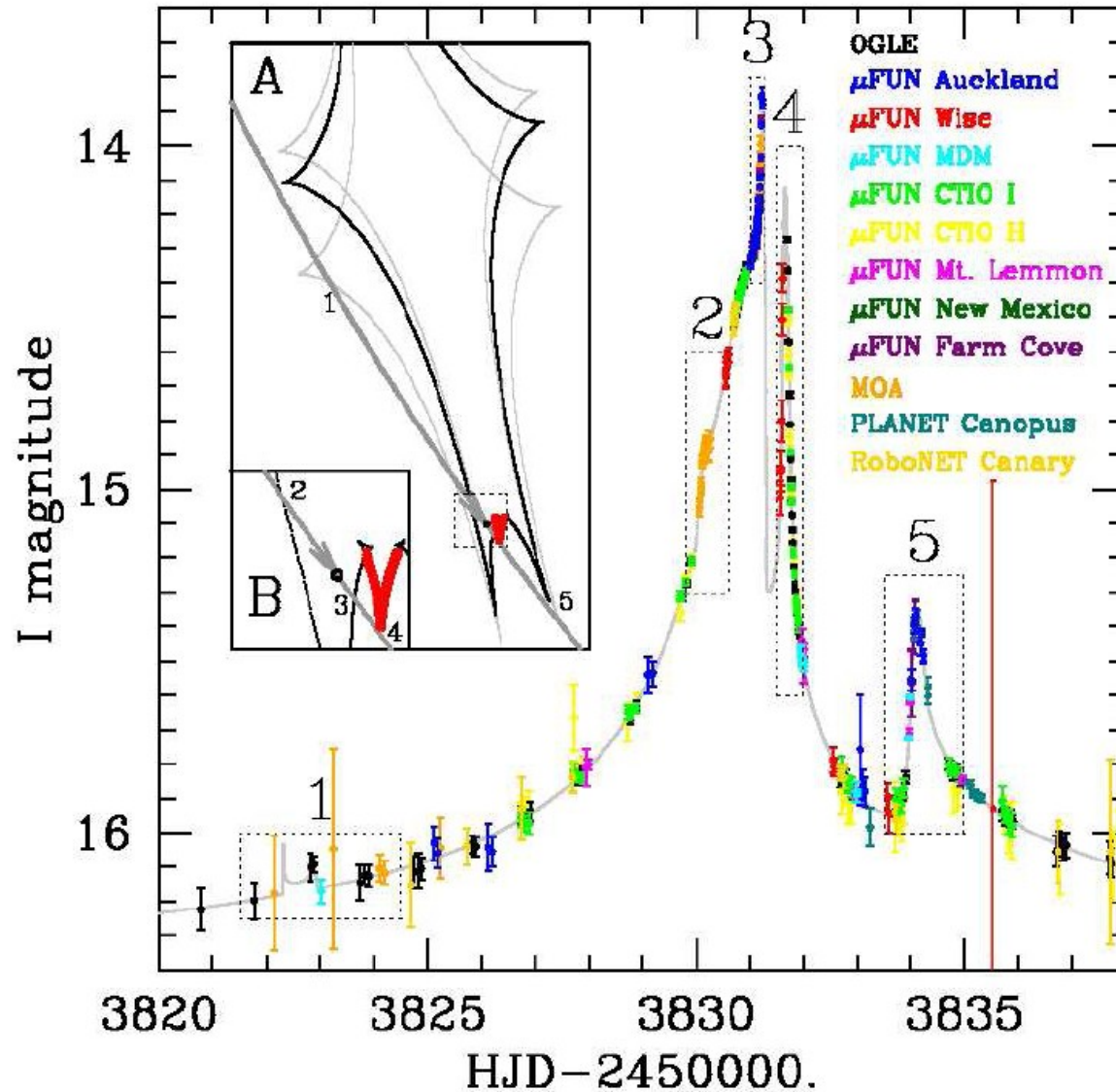
$$C_4 = \frac{\alpha^2}{4} (\pi_E^2 + \pi_j \cdot \pi_E) + \frac{1}{12} \frac{\Omega_{\oplus}^2}{\alpha} u_0 \pi_{E,\perp},$$

Table 1
Monitored Events with Magnification $A > 100$

| Name | A_{\max} | $t_0(\text{HJD})$ | t_E | M/M_\odot | Method |
|-------------------|------------|-------------------|-------|------------------------|--|
| OGLE-2007-BLG-224 | 2424 | 4233.7 | 7 | 0.056 ± 0.004 | $M = \theta_E/\kappa\pi_E$ |
| OGLE-2008-BLG-279 | 1600 | 4617.3 | 101 | 0.64 ± 0.10 | $M = \theta_E/\kappa\pi_E$ |
| OGLE-2005-BLG-169 | 800 | 3491.9 | 43 | $0.49^{+0.23}_{-0.29}$ | $\text{GM} \oplus \theta_E \oplus t_E$ |
| MOA-2007-BLG-400 | 628 | 4354.6 | 14 | $0.30^{+0.19}_{-0.12}$ | $\text{GM} \oplus \theta_E \oplus t_E$ |
| OGLE-2007-BLG-349 | 525 | 4348.6 | 121 | ~ 0.6 | $M = \theta_E/\kappa\pi_E$ |
| OGLE-2007-BLG-050 | 432 | 4222.0 | 68 | 0.50 ± 0.14 | $M = \theta_E/\kappa\pi_E$ |
| MOA-2008-BLG-310 | 400 | 4656.4 | 11 | $\leq 0.67 \pm 0.14$ | AO |
| OGLE-2006-BLG-109 | 289 | 3831.0 | 127 | $0.51^{+0.05}_{-0.04}$ | $M = \theta_E/\kappa\pi_E, \text{AO}$ |
| OGLE-2005-BLG-188 | 283 | 3500.5 | 14 | $0.16^{+0.21}_{-0.08}$ | $\text{GM} \oplus \theta_E \oplus t_E$ |
| MOA-2008-BLG-311 | 279 | 4655.4 | 18 | $0.20^{+0.26}_{-0.09}$ | $\text{GM} \oplus \theta_E \oplus t_E$ |
| MOA-2008-BLG-105 | 267 | 4565.8 | 10 | | |
| OGLE-2006-BLG-245 | 217 | 3885.1 | 59 | | |
| OGLE-2006-BLG-265 | 211 | 3893.2 | 26 | | |
| OGLE-2007-BLG-423 | 157 | 4320.3 | 29 | | |
| OGLE-2005-BLG-417 | 108 | 3568.1 | 23 | | |

OGLE-2006-BLG-109

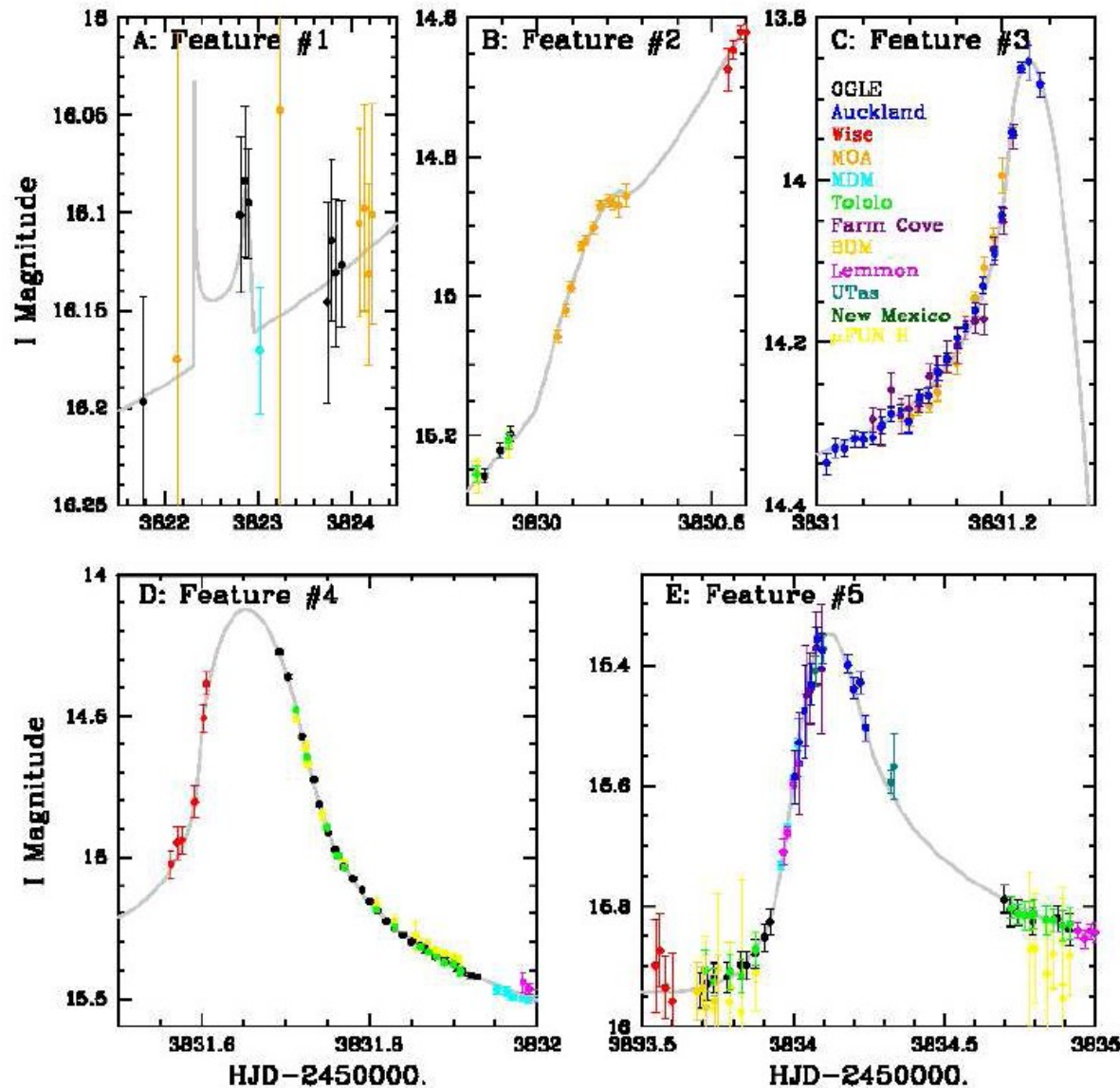
Parallax+Finite-Source+Rotation+Blend



Gaudi et al. 2008, Science, 319, 927

Five Lightcurve Features

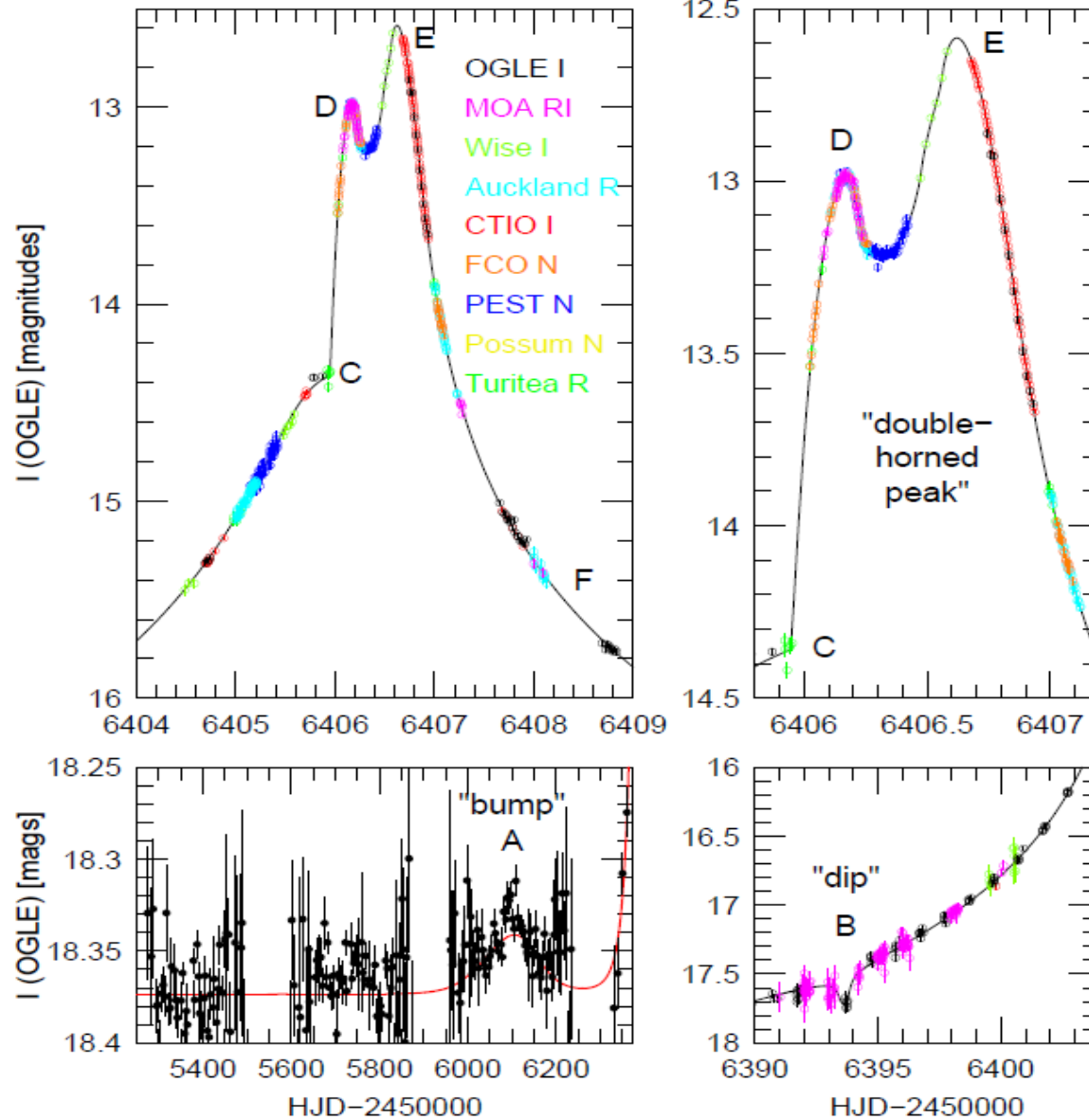
1+2+3+5=Saturn 4=Jupiter



Generation 1.5: Survey+Followup

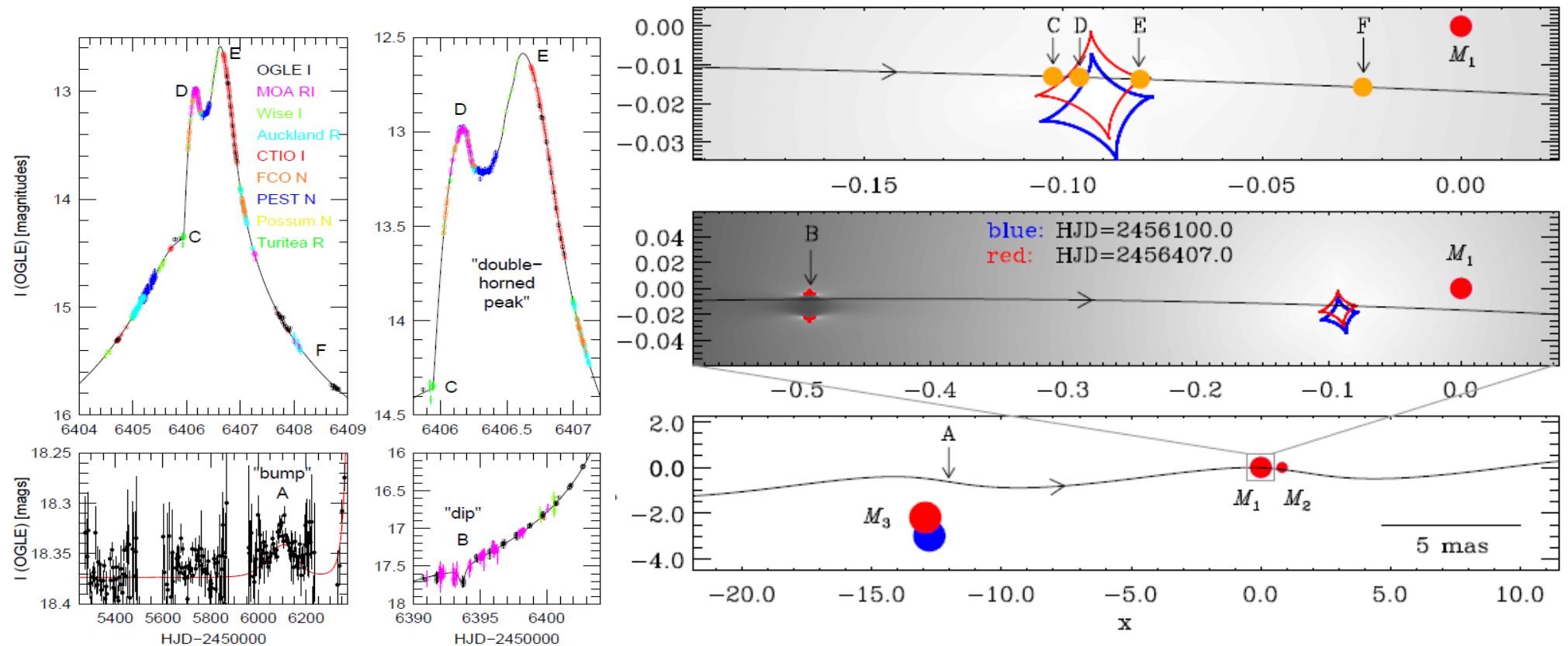
OGLE-2013-BLG-0341

Binary+ 2- M_{Earth} Planet at 1AU



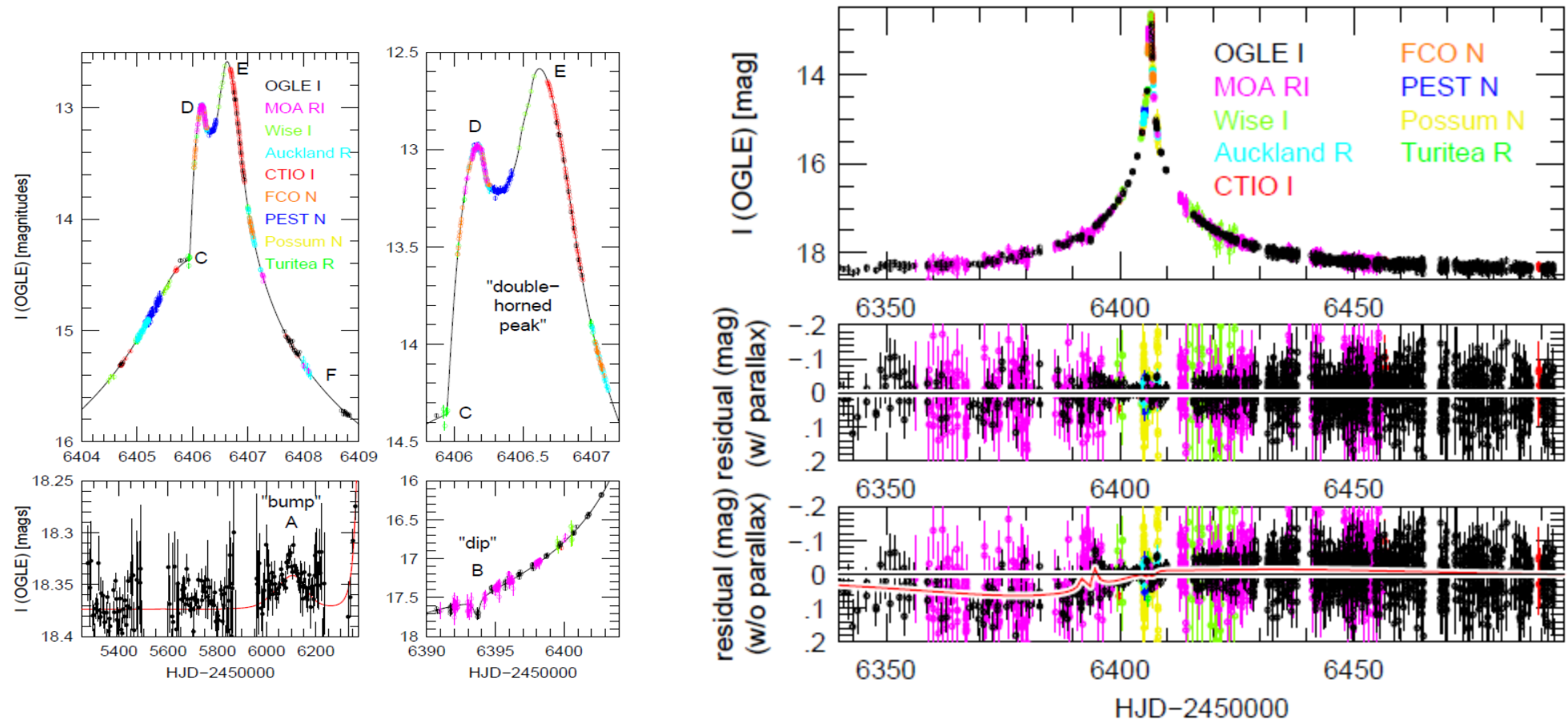
OGLE-2013-BLG-0341: Binary+Planet at 1AU

(Gould et al. 2014, Science, 345, 46)



OGLE-2013-BLG-0341: Binary+Planet at 1AU

Parallax Clearly Detected!



What can be done?

Focus on nearby
low-mass lenses

-Biased toward long t_E

$$\pi_E^2 = \pi_{\text{rel}} / \kappa M; \kappa = 8 \text{mas} / M_{\text{sun}}$$

$$\pi_{E,\text{parallel}} \text{ (3}^{\text{rd}} \text{ order in time)}$$

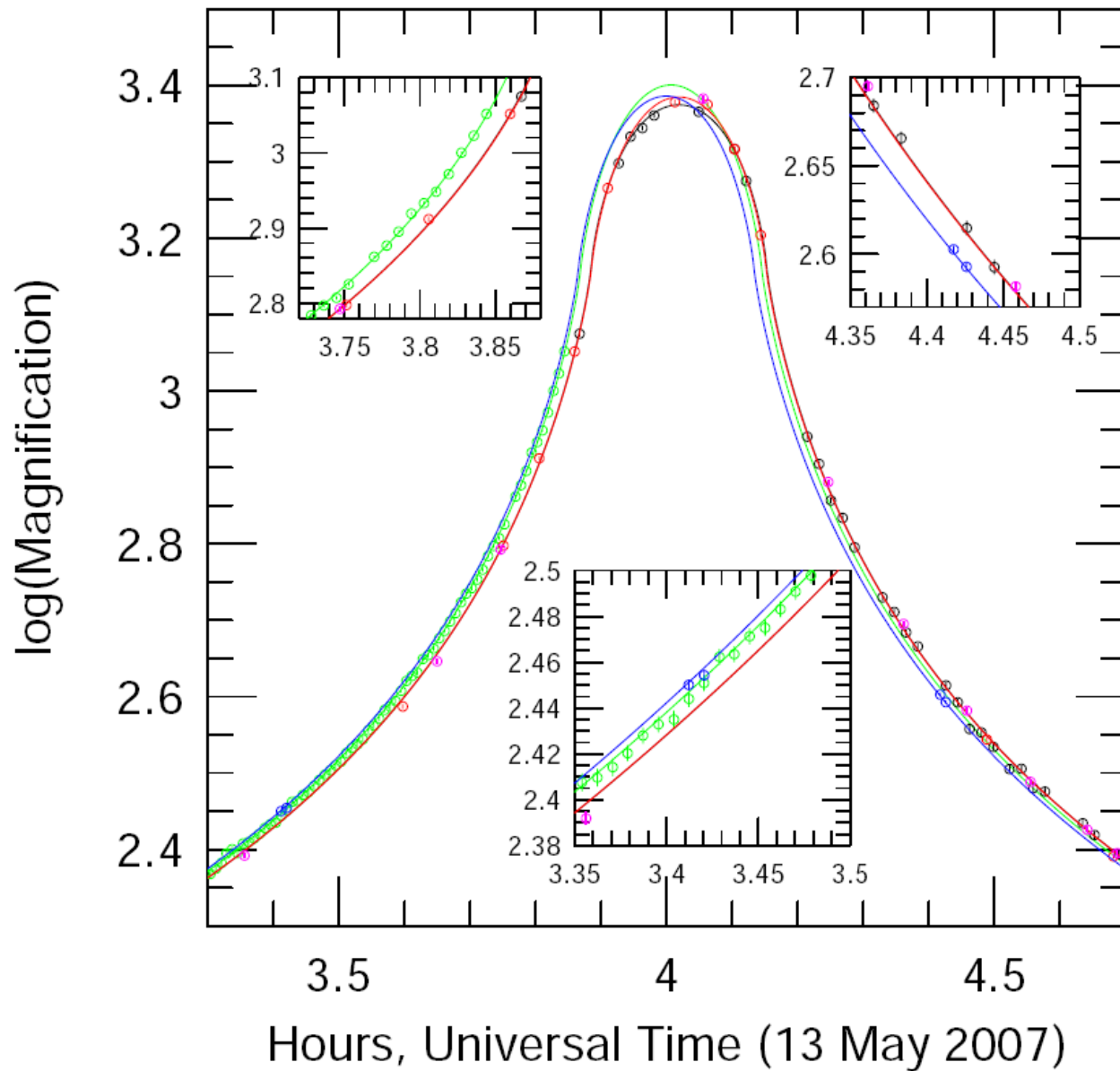
$$\pi_{E,\text{perp}} \text{ (4}^{\text{th}} \text{ order in time)}$$

Terrestrial Parallax

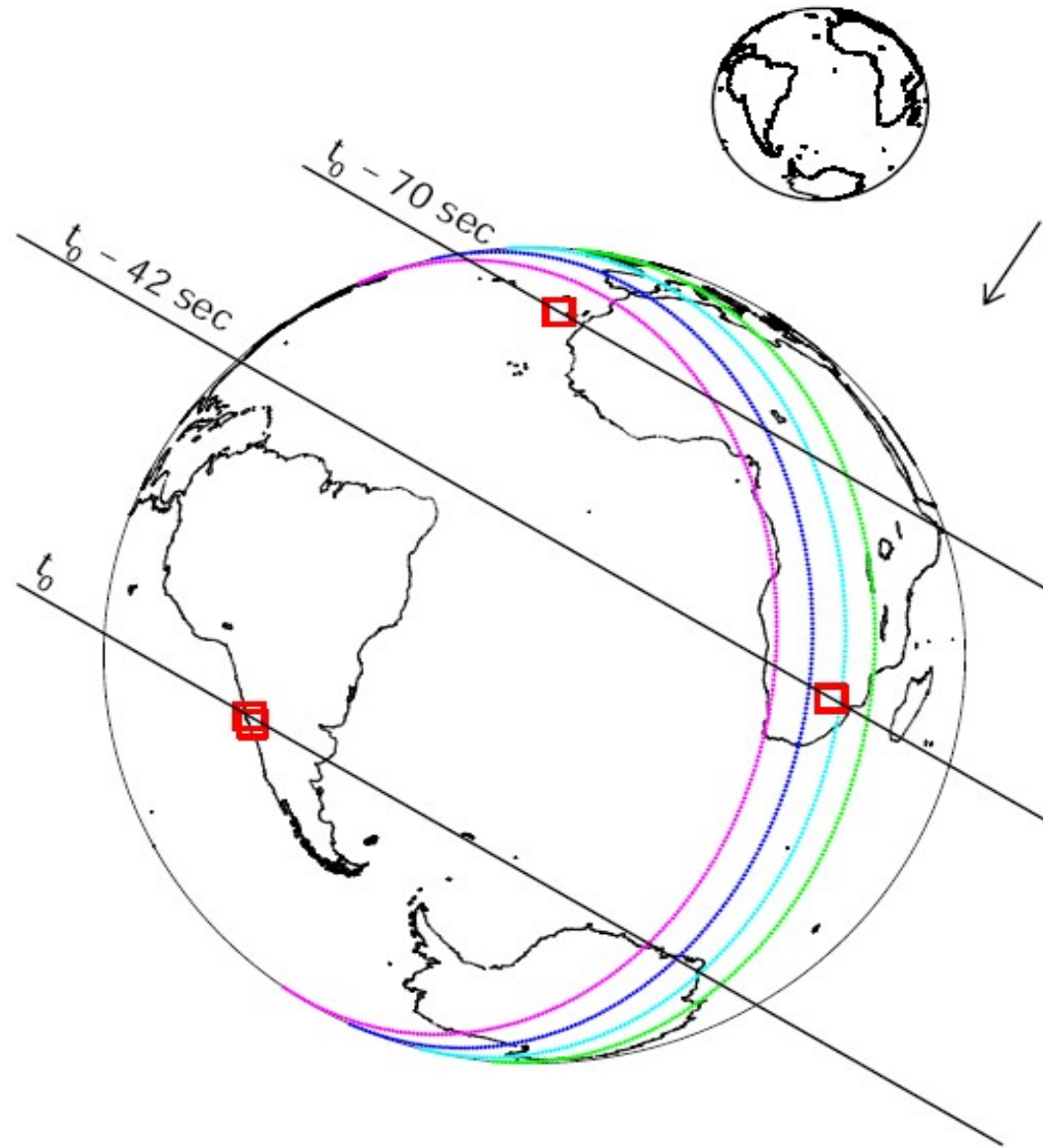
$$R_{\text{earth}} / \text{AU} = 1/23,000$$

OGLE-2007-BLG-224

Canaries South Africa Chile

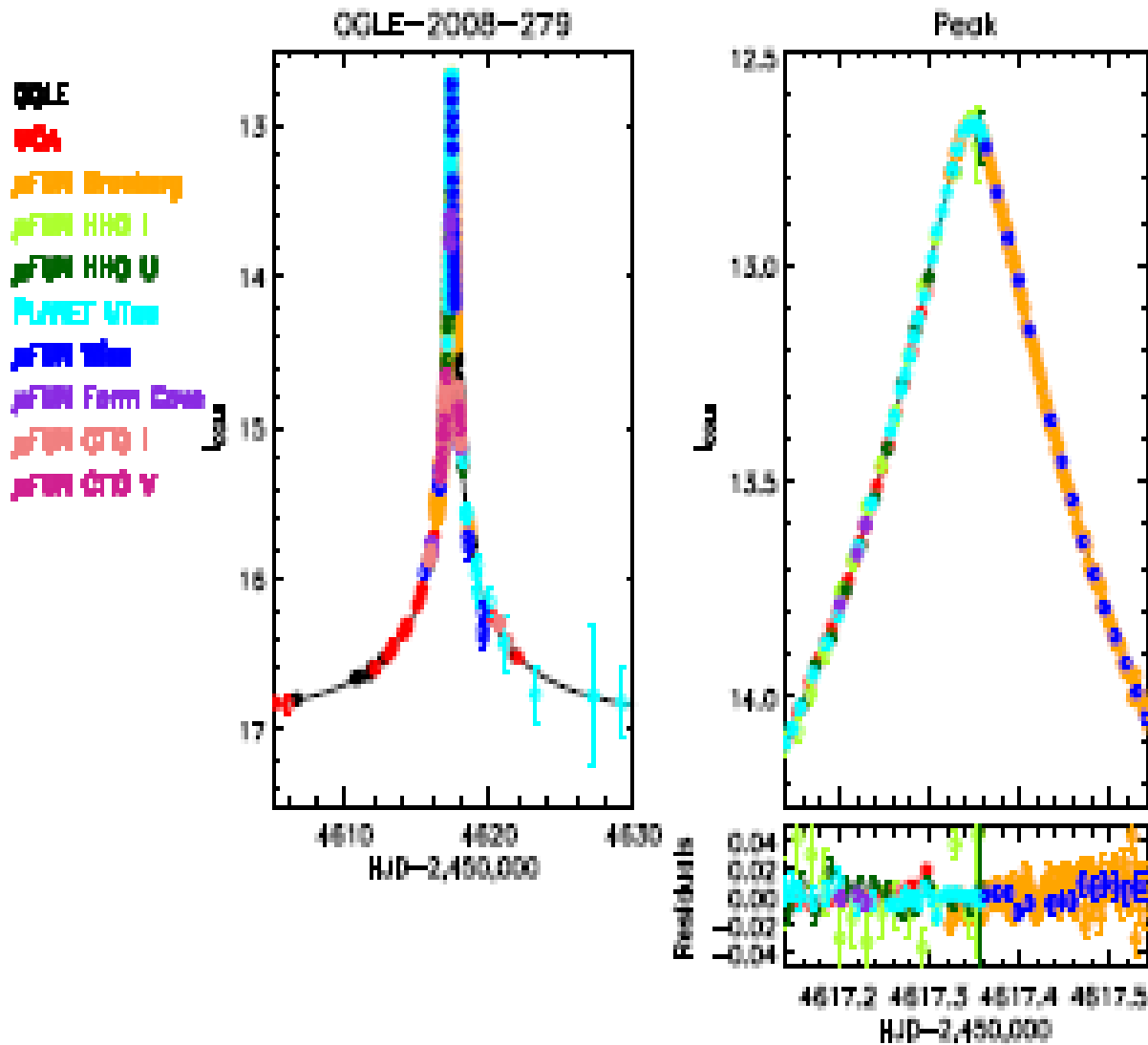


Terrestrial Parallax: Simultaneous Observations on Earth



OGLE-2008-BLG-279:

$$A = 1600$$



Yee et al. 2009, ApJ, 730, 2082

What can be done?

Focus on nearby
low-mass lenses

-Biased toward long t_E

Terrestrial Parallax

$$\pi_E^2 = \pi_{\text{rel}} / \kappa M; \kappa = 8 \text{mas} / M_{\text{sun}}$$

$$\pi_{E,\text{parallel}} \text{ (3}^{\text{rd}} \text{ order in time)}$$

$$\pi_{E,\text{perp}} \text{ (4}^{\text{th}} \text{ order in time)}$$

$$R_{\text{earth}} / \text{AU} = 1/23,000$$

Rare, Nearby

Events with Terrestrial Parallax

| Name | M | D_L | μ | θ_* | $\rho \tilde{r}_E$ | t_E | A_{\max} |
|-------------------|-------------|-------|------------------------|------------------|--------------------|-------|------------|
| | (M_\odot) | (kpc) | (mas yr^{-1}) | (μas) | (R_\oplus) | (day) | |
| OGLE-2007-BLG-224 | 0.056 | 0.5 | 48.0 | 0.77 | 10 | 106 | 2400 |
| OGLE-2008-BLG-279 | 0.64 | 4.0 | 2.7 | 0.54 | 100 | 7 | 1600 |

Gould & Yee 2012 ApJ, 764, 107

Events with Terrestrial Parallax

| Name | M | D_L | μ | θ_* | $\rho \tilde{r}_E$ | t_E | A_{\max} |
|-------------------|-------------|-------|-------------------|-------------|--------------------|-------|------------|
| | (M_\odot) | (kpc) | (mas yr $^{-1}$) | (μ as) | (R_\oplus) | (day) | |
| OGLE-2007-BLG-224 | 0.056 | 0.5 | 48.0 | 0.77 | 10 | 106 | 2400 |
| OGLE-2008-BLG-279 | 0.64 | 4.0 | 2.7 | 0.54 | 100 | 7 | 1600 |

$$\pi_{\text{rel}} = \theta_E \pi_E = \frac{\text{AU}}{\rho \tilde{r}_E} \theta_* \gtrsim 0.28 \text{ mas} \frac{\theta_*}{0.6 \mu\text{as}}$$

Gould & Yee 2012 ApJ, 764, 107

Events with Terrestrial Parallax

| Name | M | D_L | μ | θ_* | $\rho \tilde{r}_E$ | t_E | A_{\max} |
|-------------------|-------------|-------|------------------------|------------------|--------------------|-------|------------|
| | (M_\odot) | (kpc) | (mas yr^{-1}) | (μas) | (R_\oplus) | (day) | |
| OGLE-2007-BLG-224 | 0.056 | 0.5 | 48.0 | 0.77 | 10 | 106 | 2400 |
| OGLE-2008-BLG-279 | 0.64 | 4.0 | 2.7 | 0.54 | 100 | 7 | 1600 |

$$\pi_{\text{rel}} = \theta_E \pi_E = \frac{\text{AU}}{\rho \tilde{r}_E} \theta_* \gtrsim 0.28 \text{ mas} \frac{\theta_*}{0.6 \mu\text{as}}$$

$$\Gamma = 2 \langle \mu \rangle \theta_* \int_0^{D_{\max}} dD_L D_L^2 n(D_L) = 1.6 \text{ Gyr}^{-1}$$

$$\times \left(\frac{\langle \mu \rangle}{10 \text{ mas yr}^{-1}} \right) \left(\frac{\theta_*}{0.6 \mu\text{as}} \right) \left(\frac{D_{\max}}{2.5 \text{ kpc}} \right)^3 \left(\frac{\langle n \rangle}{1 \text{ pc}^{-3}} \right)$$

Gould & Yee 2012 ApJ, 764, 107

Events with Terrestrial Parallax

| Name | M | D_L | μ | θ_* | $\rho \tilde{r}_E$ | t_E | A_{\max} |
|-------------------|-------------|-------|------------------------|------------------|--------------------|-------|------------|
| | (M_\odot) | (kpc) | (mas yr^{-1}) | (μas) | (R_\oplus) | (day) | |
| OGLE-2007-BLG-224 | 0.056 | 0.5 | 48.0 | 0.77 | 10 | 106 | 2400 |
| OGLE-2008-BLG-279 | 0.64 | 4.0 | 2.7 | 0.54 | 100 | 7 | 1600 |

$$\pi_{\text{rel}} = \theta_E \pi_E = \frac{\text{AU}}{\rho \tilde{r}_E} \theta_* \gtrsim 0.28 \text{ mas} \frac{\theta_*}{0.6 \mu\text{as}}$$

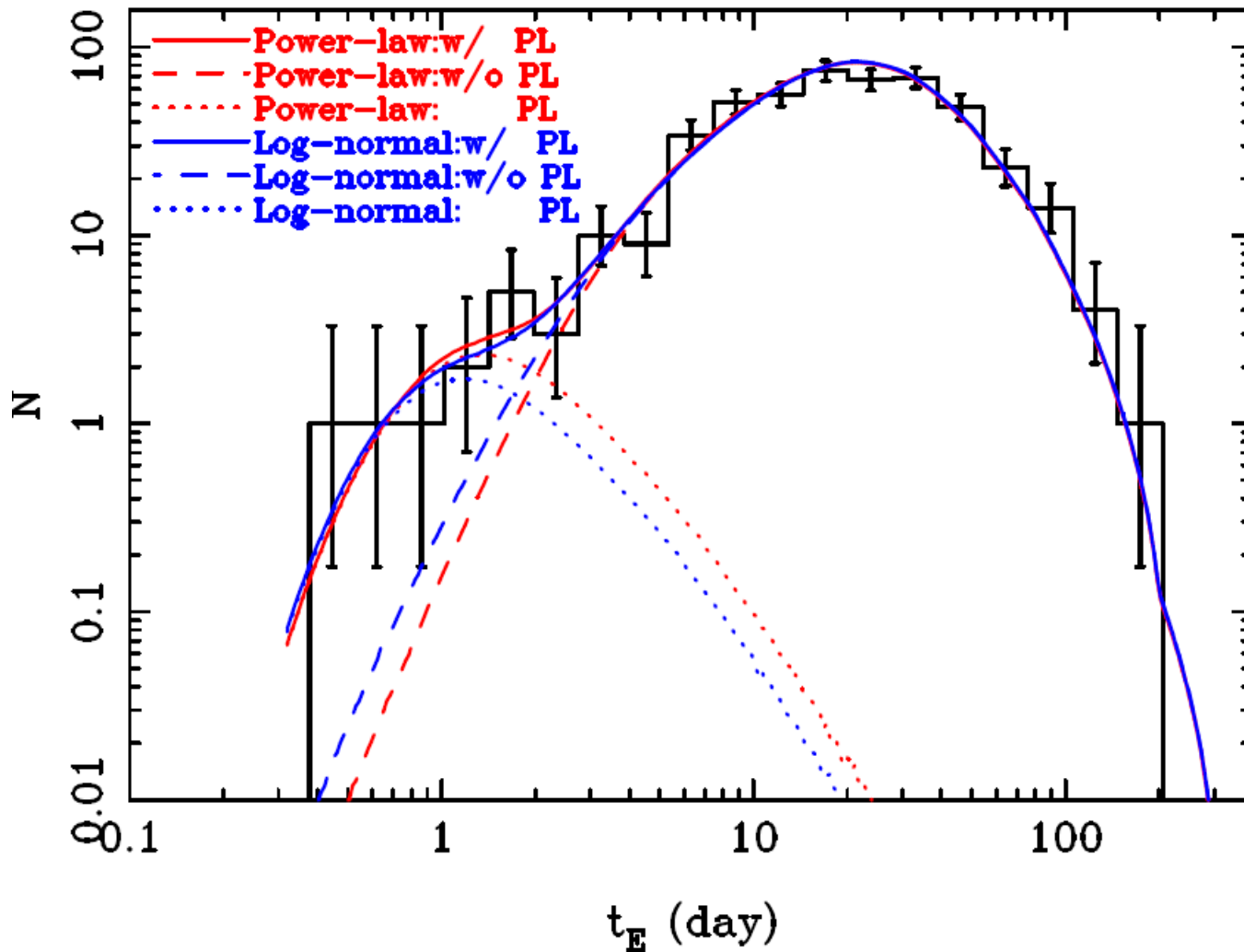
$$\Gamma = 2 \langle \mu \rangle \theta_* \int_0^{D_{\max}} dD_L D_L^2 n(D_L) = 1.6 \text{ Gyr}^{-1}$$

$$\times \left(\frac{\langle \mu \rangle}{10 \text{ mas yr}^{-1}} \right) \left(\frac{\theta_*}{0.6 \mu\text{as}} \right) \left(\frac{D_{\max}}{2.5 \text{ kpc}} \right)^3 \left(\frac{\langle n \rangle}{1 \text{ pc}^{-3}} \right)$$

$$(1/4)(1/10)(1/2)\Gamma N T = 0.1$$

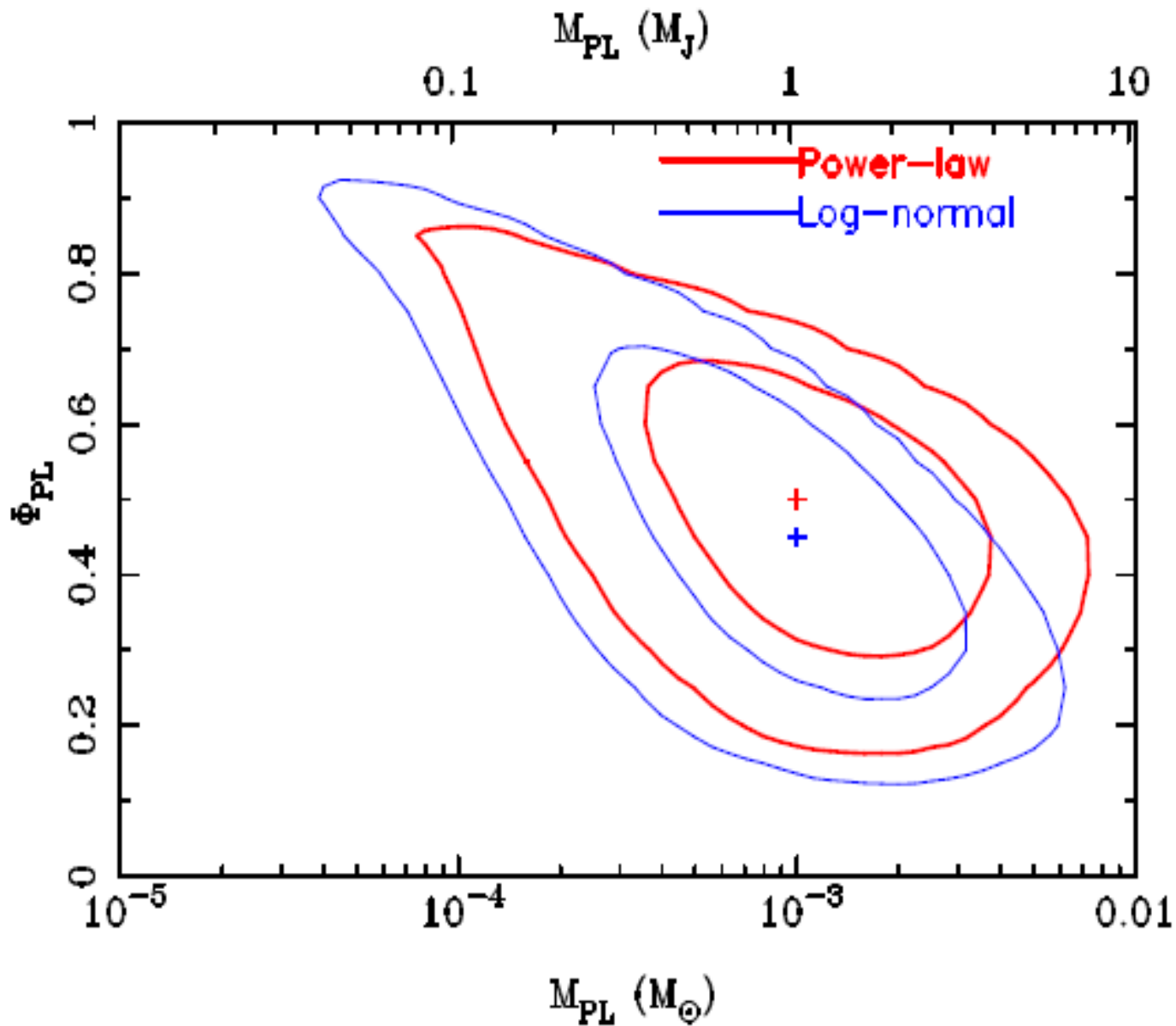
$$(N = 5e8; T = 10 \text{ yr})$$

MOA Point-Lens Events



Sumi et al. 2011, Nature, 473, 349

FFP Best-Fit Characteristics



Free-Floating Planets

Point-Lens Events w/o FFPs (short)

$$\Gamma \propto \int dM F(M) \int dD_L D_L^2 n(D_L) \int d^2\mu \mu f_\mu(\mu) \theta_E(M, D_L)$$

$$t_E = \frac{\theta_E}{\mu}, \quad \theta_E = \sqrt{\kappa M \pi_{\text{rel}}}$$

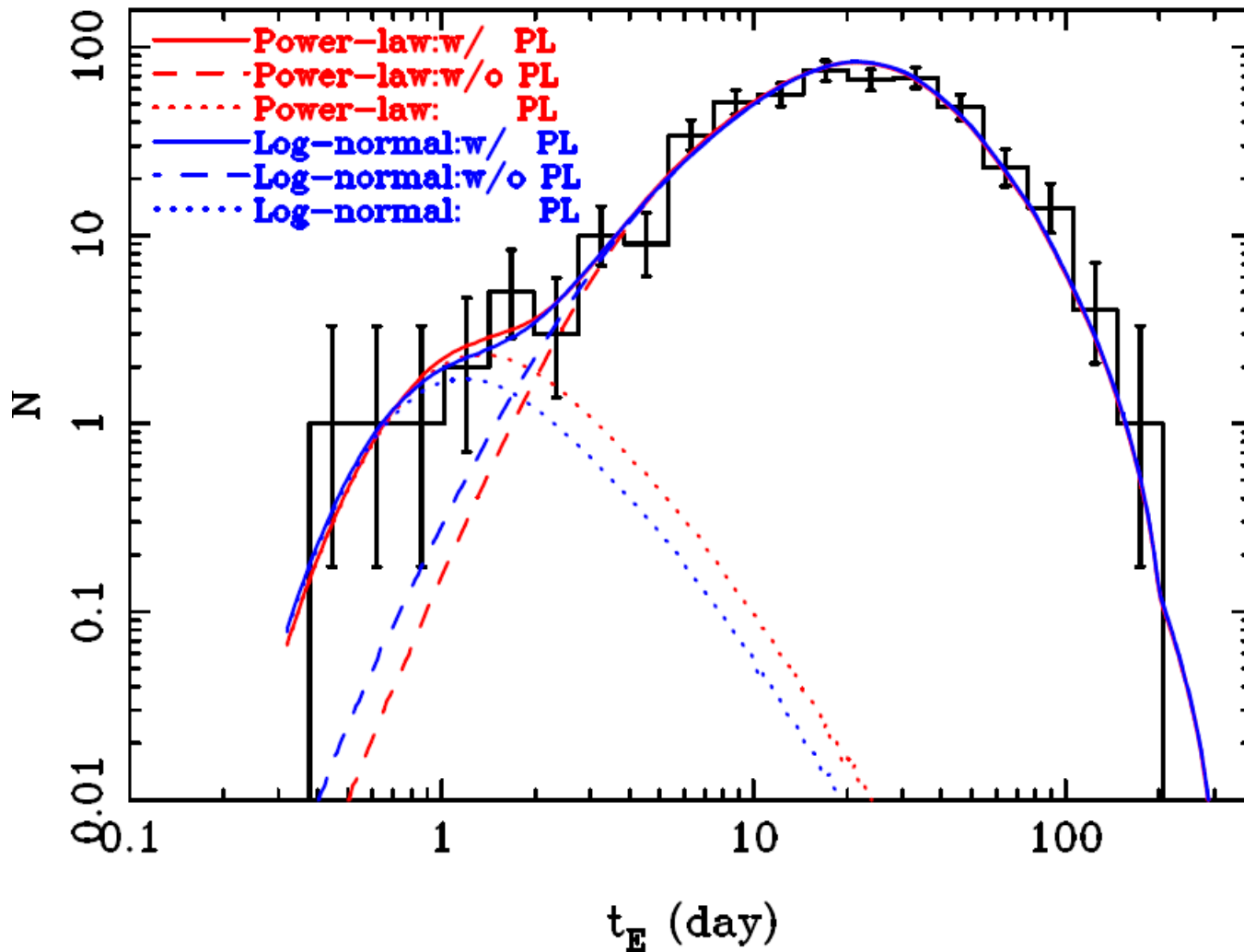
$$t_E \text{ small} \Rightarrow D_{LS} \ll D_S$$

$$dD_L D_L^2 n(D_L) \rightarrow dD_{LS} D_S^2 n(D_S) = K dD_{LS}; \quad \theta_E \rightarrow \sqrt{\frac{\kappa \text{AU} M}{D_S^2} D_{LS}}$$

$$\Gamma \propto \int dM F(M) M^{1/2} \int d^2\mu \mu f_\mu(\mu) \int d \ln D_{LS} D_{LS}^{3/2}$$

$$\frac{d\Gamma}{d \ln t_E} \propto t_E^3 \int dM F(M) M^{-1} \int d^2\mu \mu f_\mu(\mu)$$

MOA Point-Lens Events



Sumi et al. 2011, Nature, 473, 349

Satellite Parallaxes (Panacea?)

ON THE POSSIBILITY OF DETERMINING THE DISTANCES
AND MASSES OF STARS FROM THE GRAVITATIONAL
LENS EFFECT

S. Refsdal

(Communicated by Professor S. Rosseland)

(Received 1966 June 6)

Summary

It is shown that the distance and the mass of a star which acts as a gravitational lens can be determined if the lens effect can be observed from the Earth and from at least one distant space observatory. The distance from the Earth to the space observatory will usually have to be of the order of 5% of one astronomical unit or more.

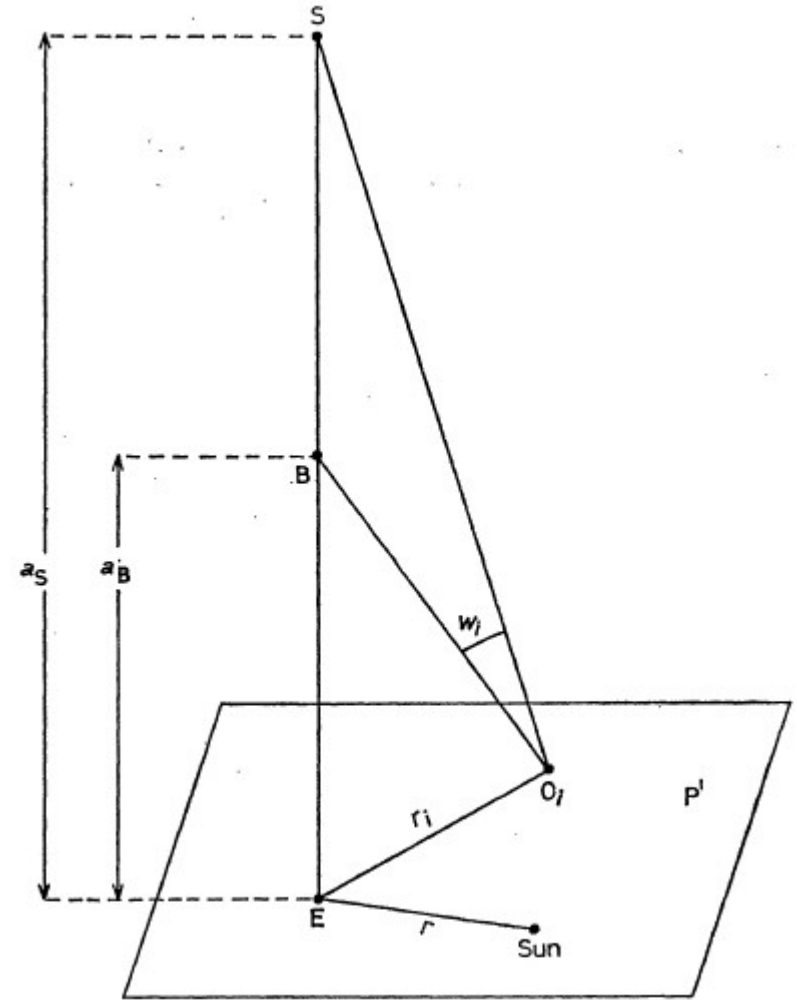
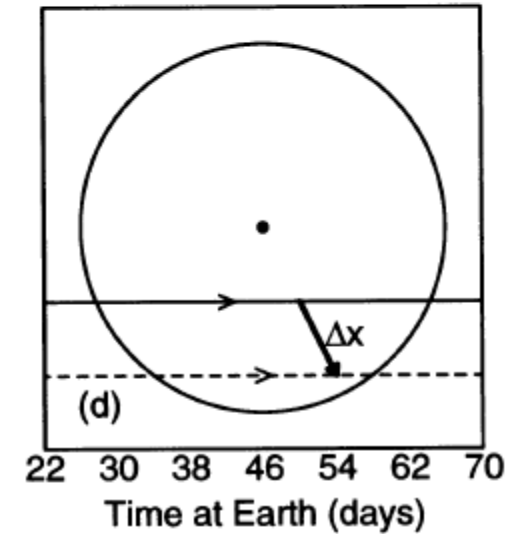
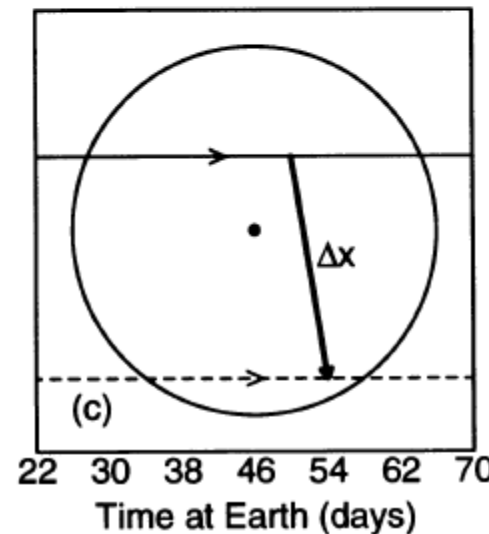
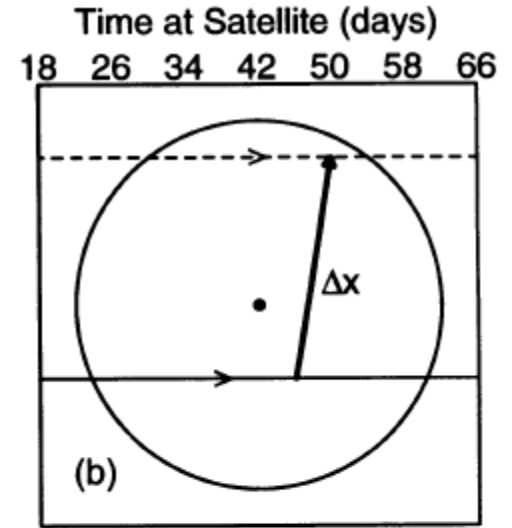
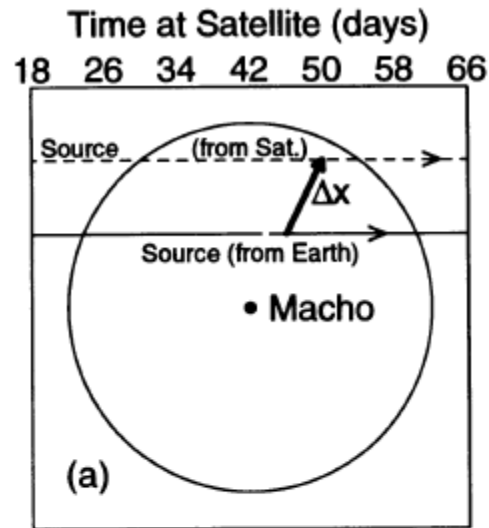
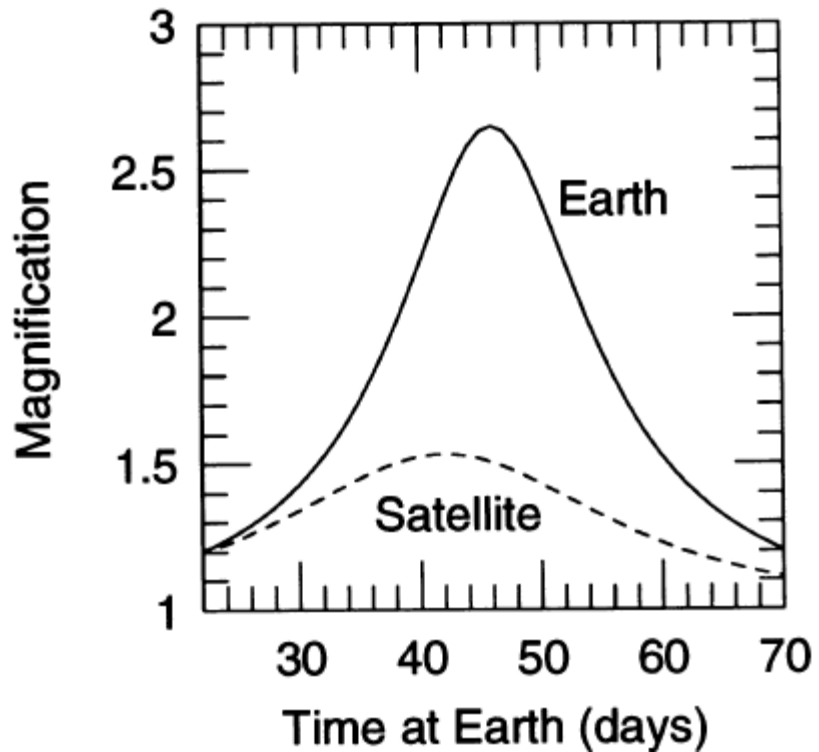


FIG. 1.

Satellite Parallaxes (Panacea?)



From a paper written 15 years ago ...

THE ASTROPHYSICAL JOURNAL, 514:869–877, 1999 April 1

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MICROLENS PARALLAXES WITH SIRTf

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Received 1998 July 27; accepted 1998 November 2

$$t_{0,S} = t_{0,\oplus} + \Delta t_0, \quad \frac{\sigma_{\Delta u_y}}{\Delta u} = \frac{\sigma_\gamma}{\gamma \sec \phi}$$

$$\frac{\Delta t_0}{t_{e,\oplus}} = \Delta u_x \cos \theta - 2(\Omega_\oplus t_{e,\oplus})^{-2} \gamma_\oplus \sin^2 \theta; \quad (13) \quad = 0.17 N^{-1/2} \frac{\sigma_0}{0.01} \frac{\tilde{v}}{275 \text{ km s}^{-1}} \left(\frac{t_e}{40 \text{ days}} \right)^{-3/2} \frac{S(\beta)}{8}. \quad (21)$$

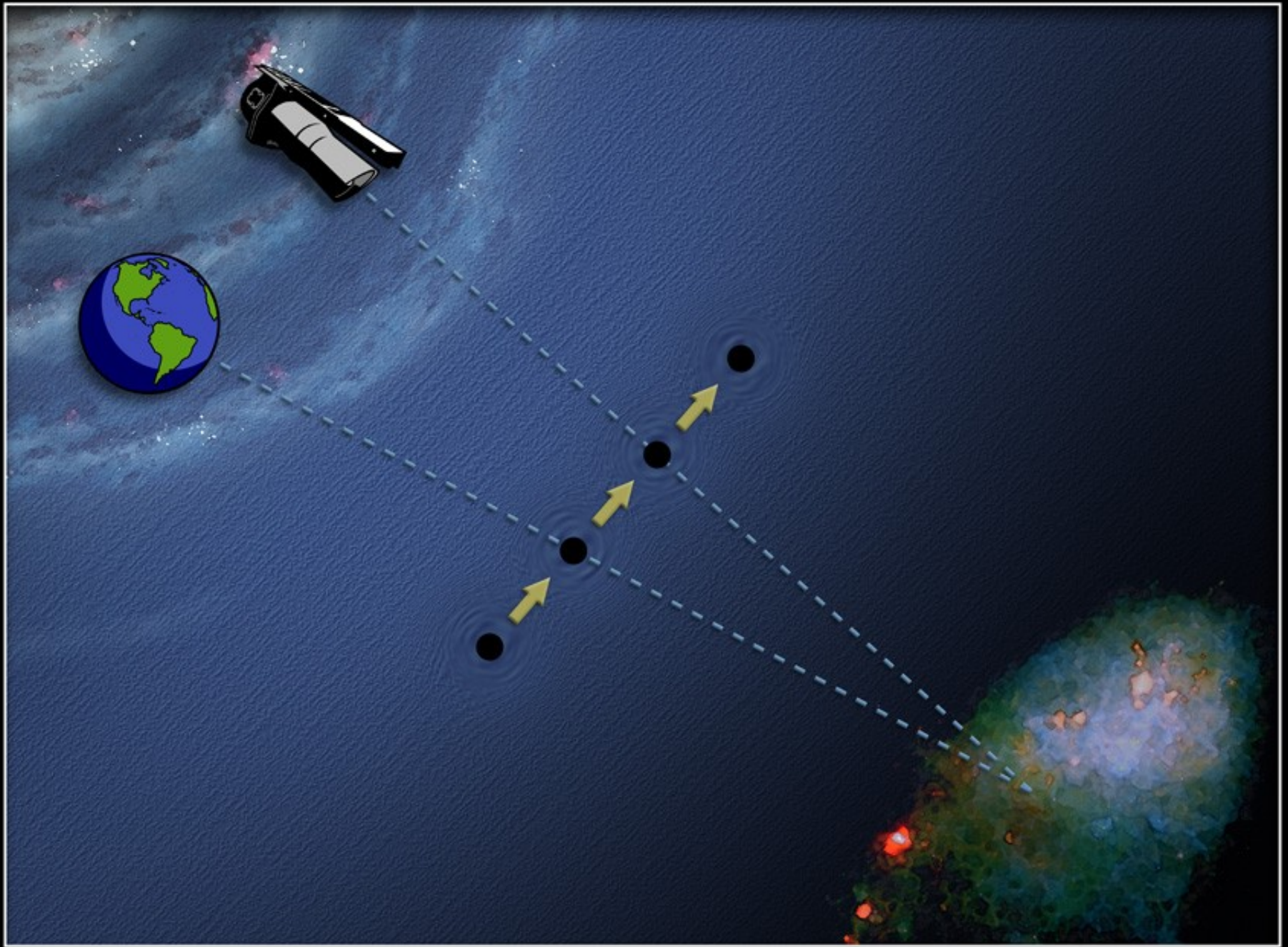
$$\beta_S = |\beta_\oplus \pm \Delta\beta|, \quad \Delta\beta = \Delta u_x \sin \theta + (\Omega_\oplus t_{e,\oplus})^{-2} \gamma_\oplus \sin 2\theta;$$

$$(14) \quad b_{ij} \left(\frac{t_0}{t_e}, \gamma \right) = \frac{64}{u^5 (u^2 + 4)^{5/2} (u^2 + 2) \sigma_0^2} \begin{pmatrix} 2\tau^2 & -\tau^4 \\ -\tau^4 & \tau^6/2 \end{pmatrix}, \quad (22)$$

$$t_{e,S} = t_{e,\oplus} + \Delta t_e,$$

$$\frac{\Delta t_e}{t_{e,\oplus}} = \Delta u_x \Omega_\oplus t_{e,\oplus} \sin \theta + (\Omega_\oplus t_{e,\oplus})^{-1} \gamma_\oplus \sin 2\theta; \quad (15) \quad \frac{\sigma_{t_0}}{t_e} \sim \left(\frac{25}{12} \right)^{1/2} \beta \sigma_*, \quad \sigma_* = \left(\frac{5}{3} \right)^{1/4} \beta^{1/2} \sigma_0$$

$$\gamma_S = \Delta u_x (\Omega_\oplus t_{e,\oplus})^2 \cos \theta + \gamma_\oplus \cos 2\theta. \quad (16) \quad \left[\text{at } \tau = \left(\frac{2}{3} \right)^{1/2} \beta \right], \quad (23)$$



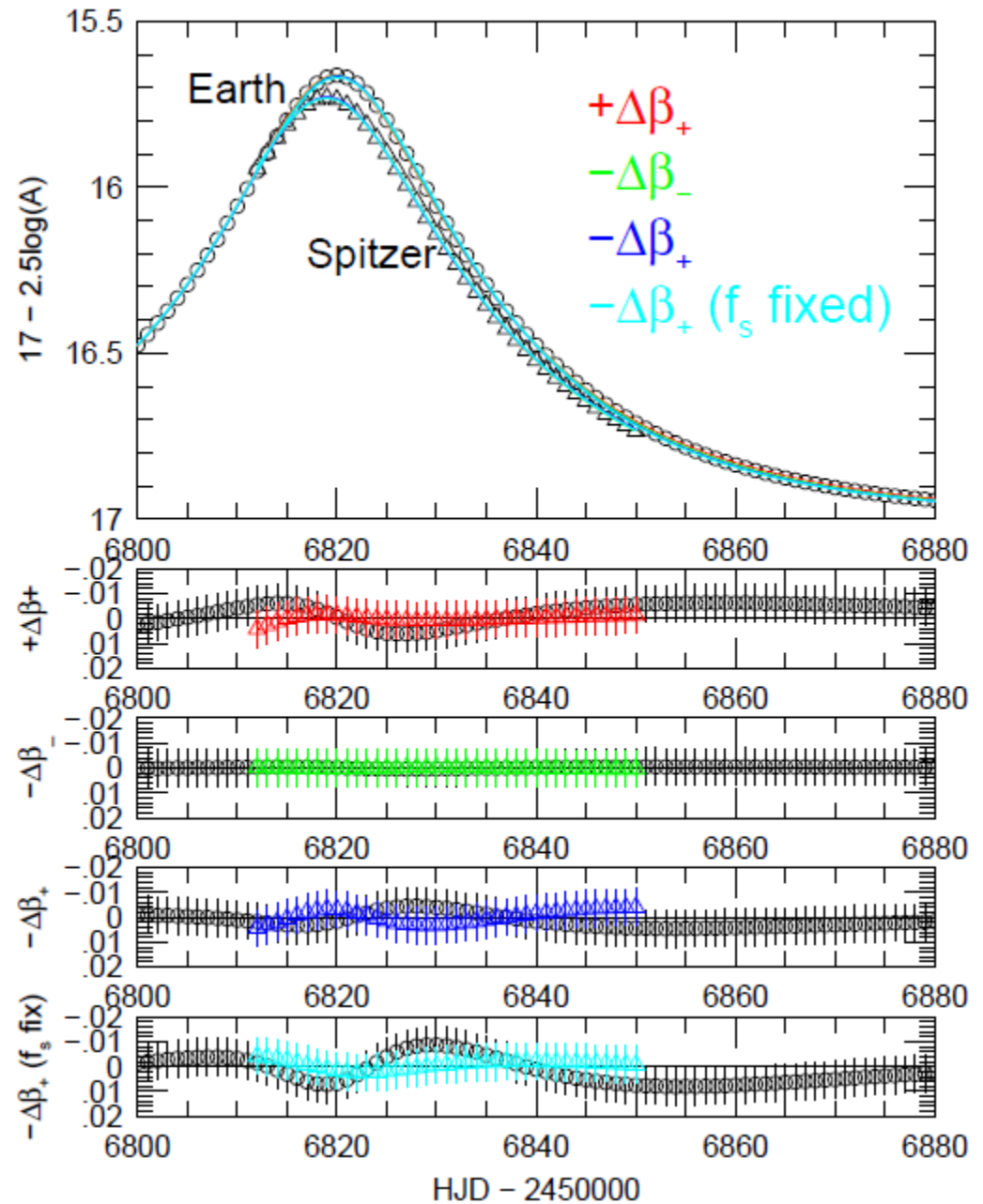
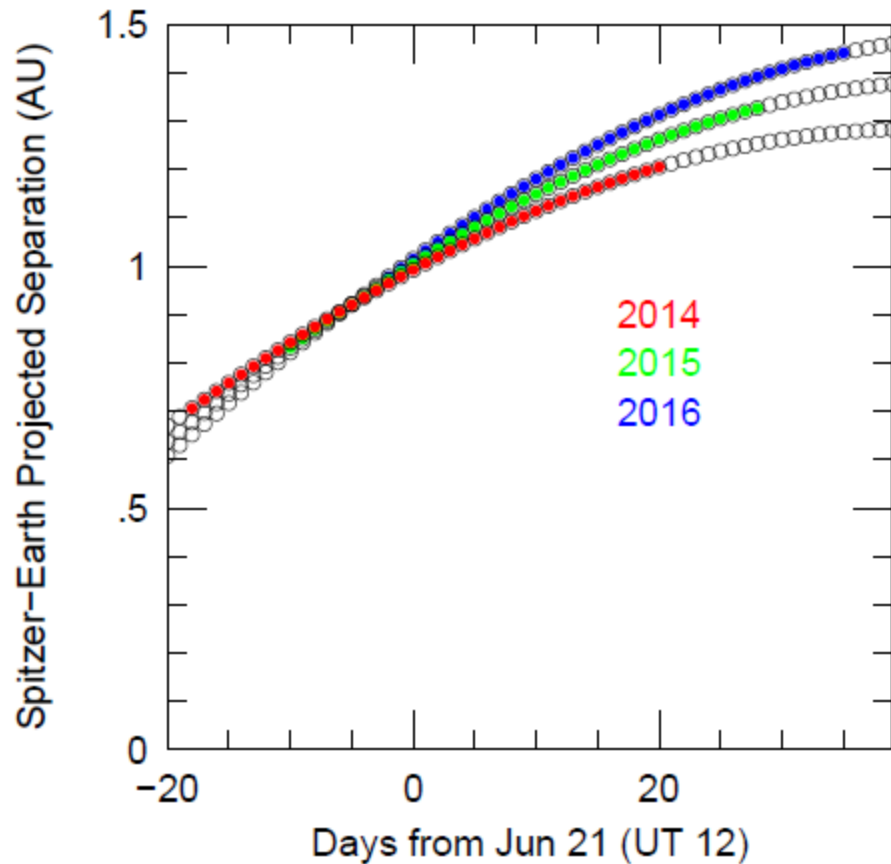
Microlens Parallax Observations of OGLE-2005-SMC-001

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

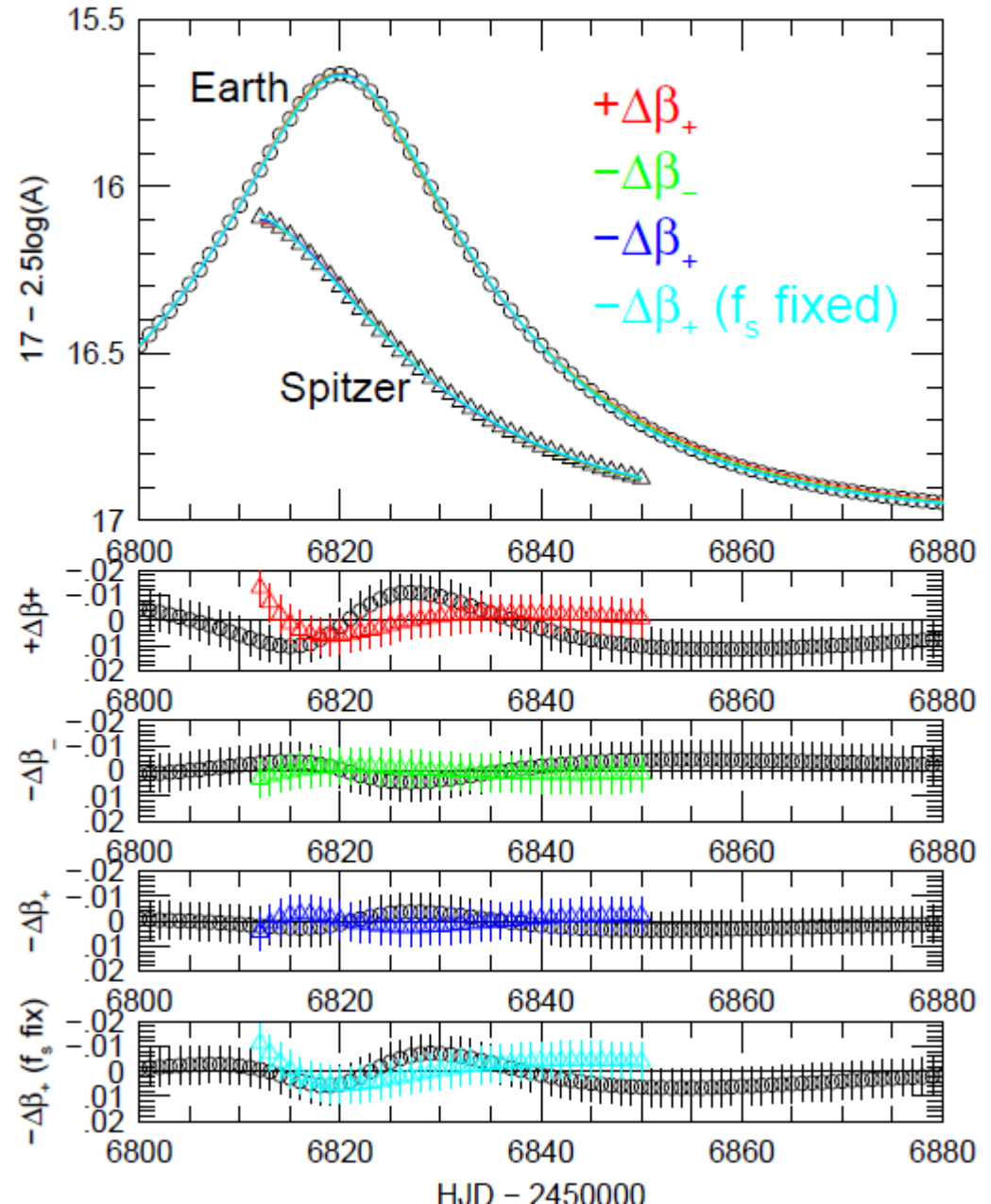
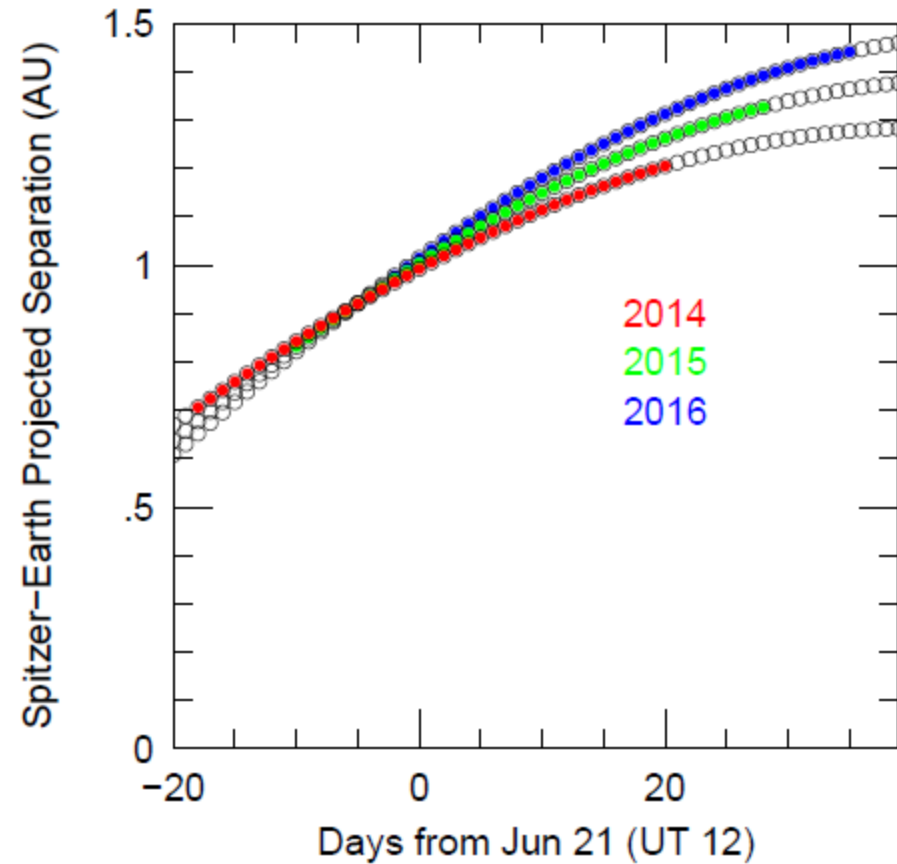
Spitzer Space Telescope • IRAC

ssc2007-XX

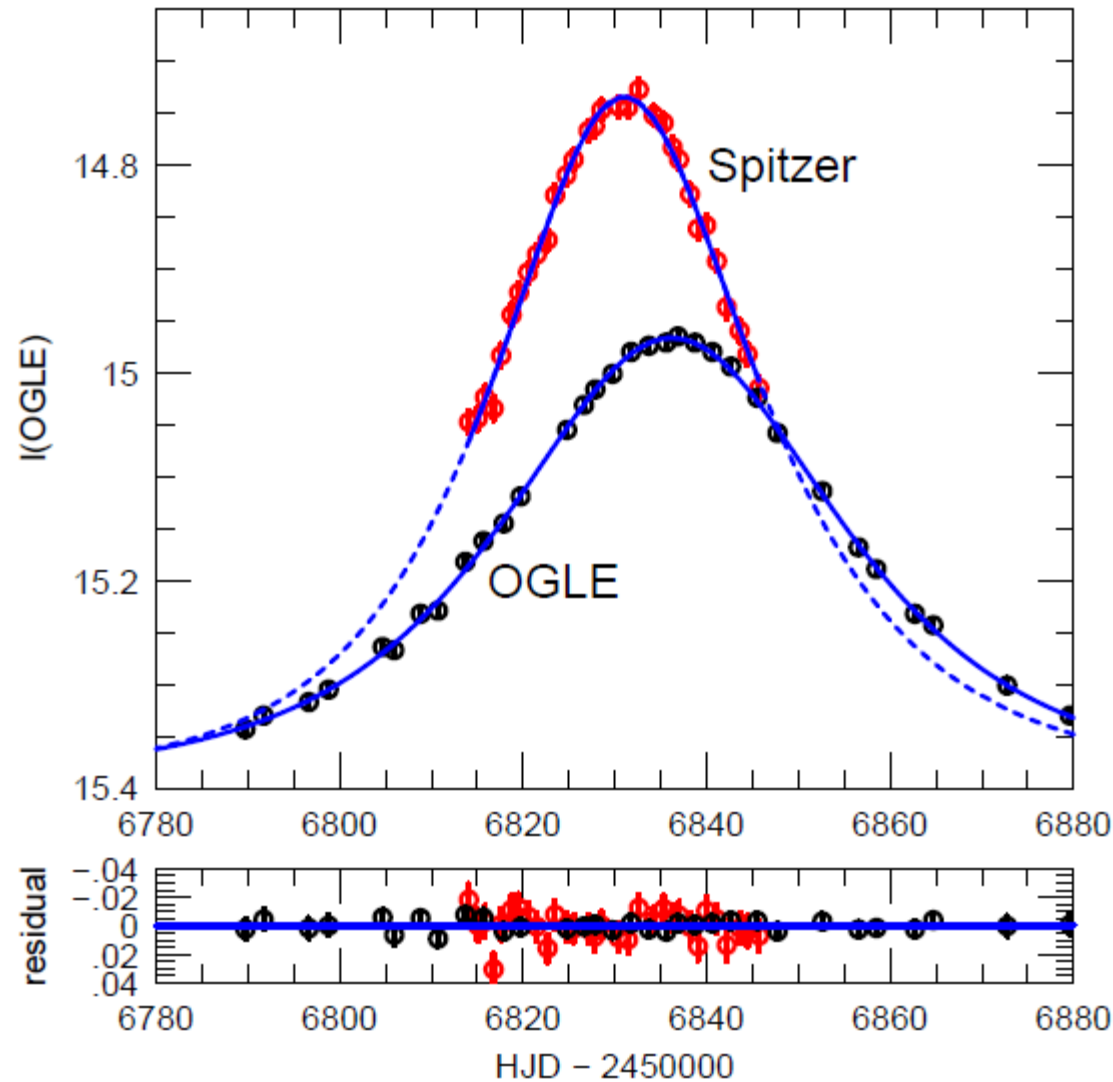
100-Hr Spitzer Feasibility Study 2014



100-Hr Spitzer Feasibility Study 2014

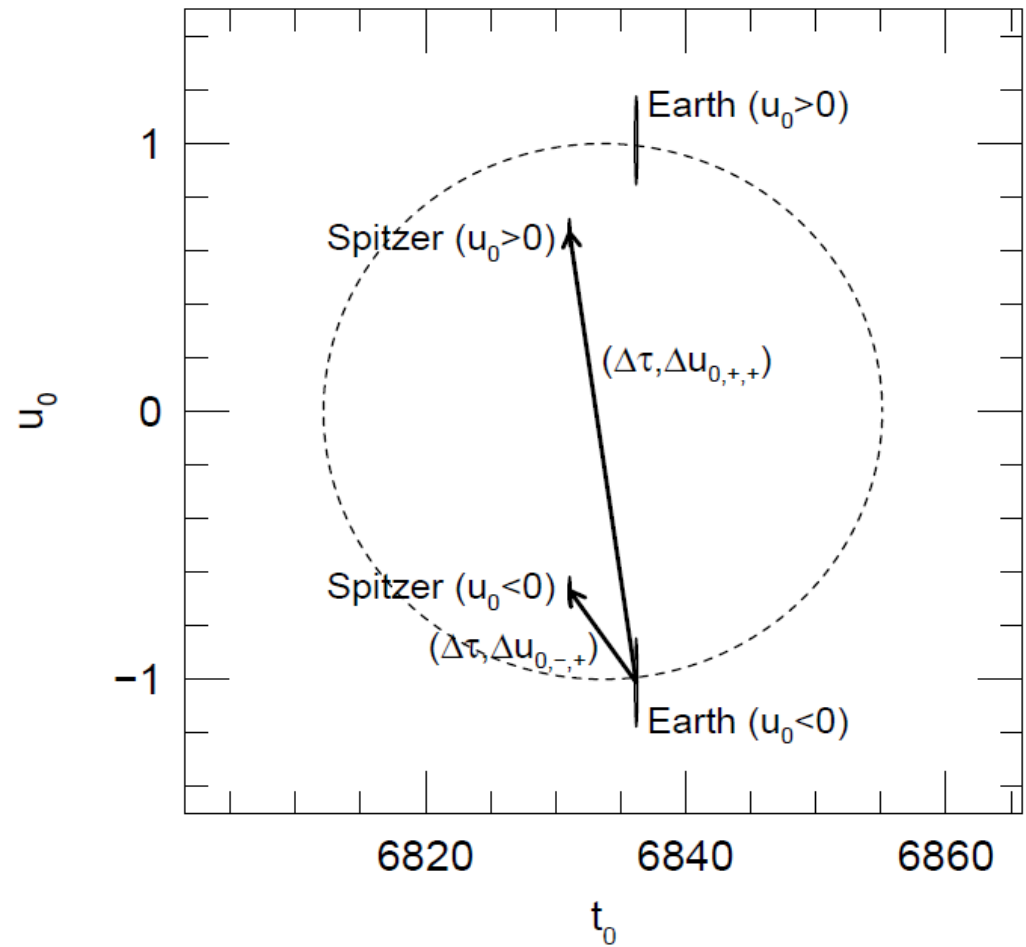
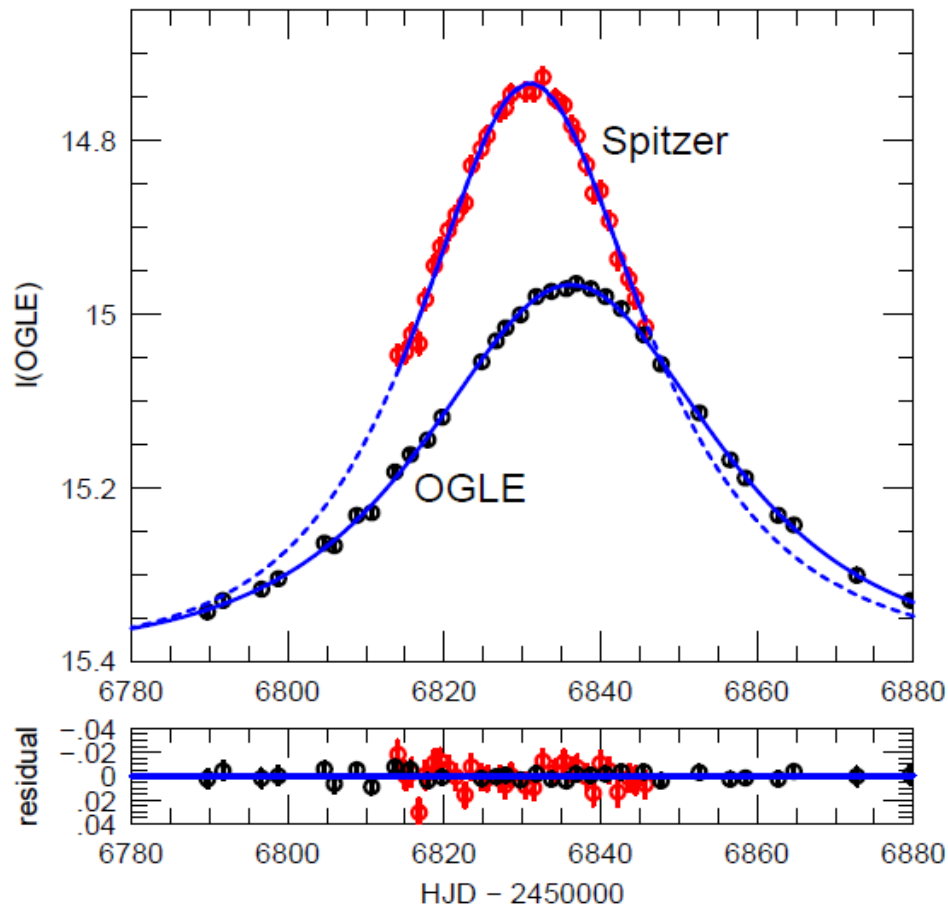


OGLE-2014-BLG-0939: First Isolated Lens with Spitzer Parallax



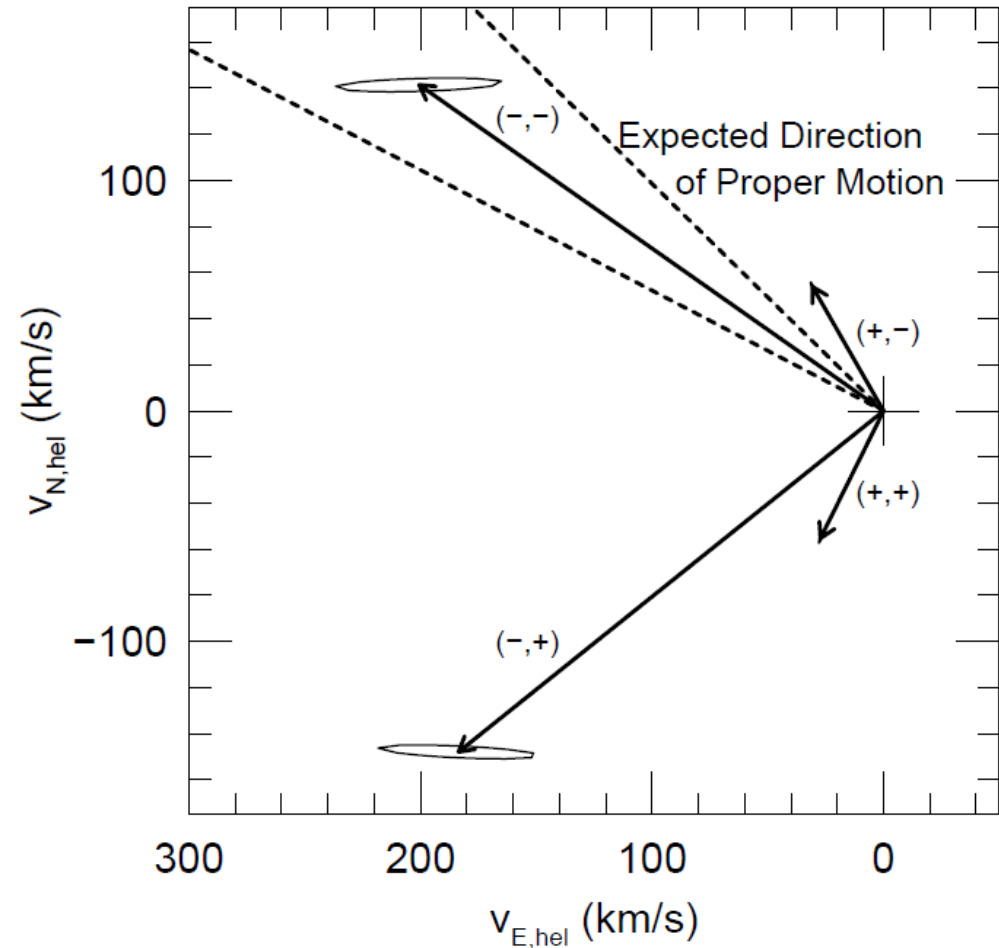
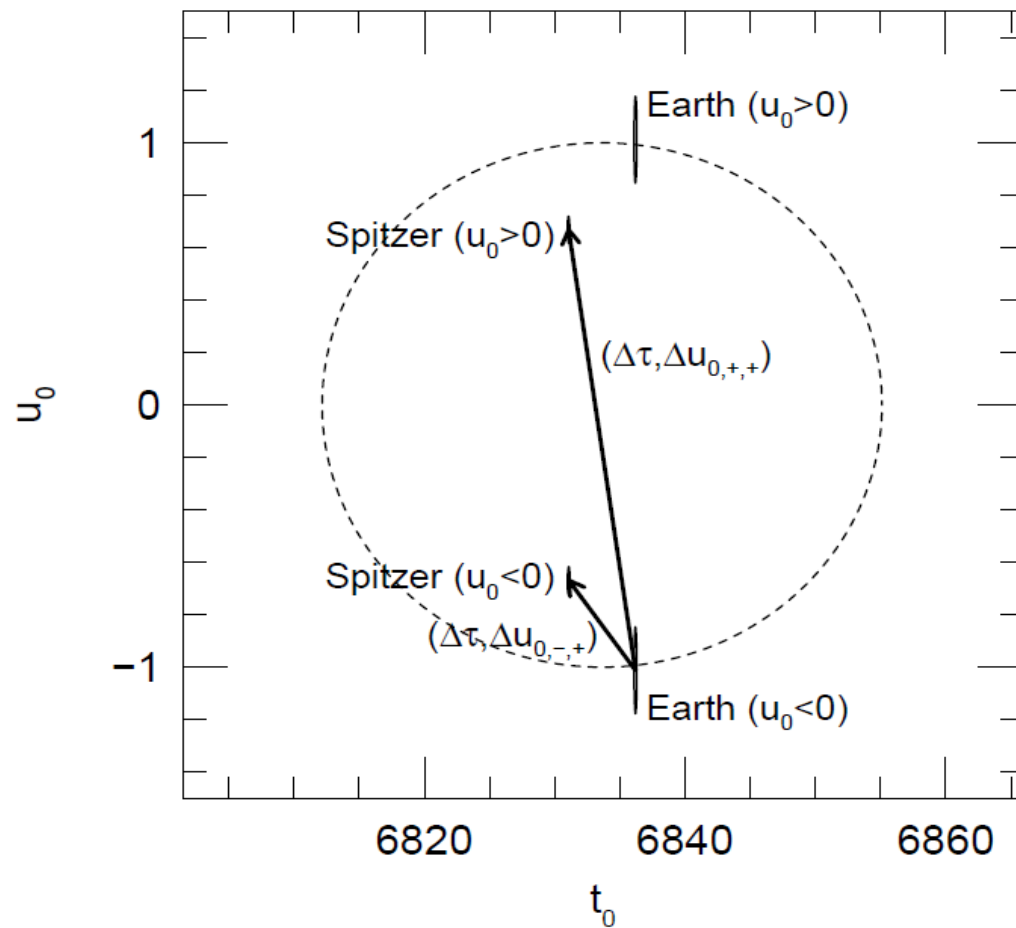
Yee et al. 2015, ApJ, in press

OGLE-2014-BLG-0939: Refsdal (1966) 4-fold Degeneracy



Yee et al. 2015, ApJ, in press

OGLE-2014-BLG-0939: 4-fold Degeneracy Expressed in Velocity



Yee et al. 2015, ApJ, in press

OGLE-2014-BLG-0939:

Degeneracy Broken => Mass & Distance

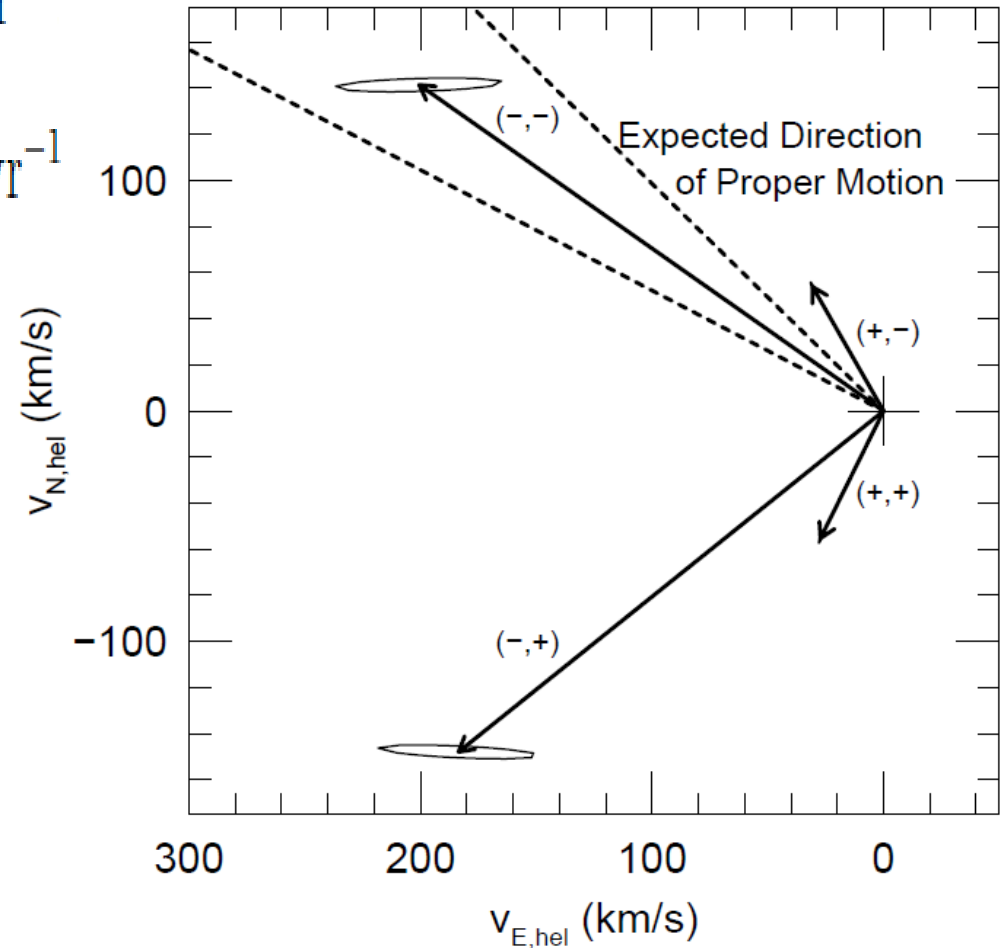
$$\mu_{S,\text{hel}}(\text{N}, \text{E}) = (-0.64 \pm 0.45, -5.31 \pm 0.45) \text{ mas yr}^{-1}$$

$$\mu_{\text{exp, hel}} = \mu_{\text{sgrA*}} \phi - \mu_{S,\text{hel}} = (6.2 \pm 0.5, 8.5 \pm 0.5) \text{ mas yr}^{-1}$$

$$\tan^{-1} \frac{\mu_{\text{exp, hel, E}}}{\mu_{\text{exp, hel, N}}} = 53.9^\circ \pm 8.5^\circ$$

$$\pi_{\text{rel}} \sim \mu_{\text{exp, hel}} \frac{\text{AU}}{\tilde{v}_{\text{hel}}} = 0.20 \text{ mas}$$

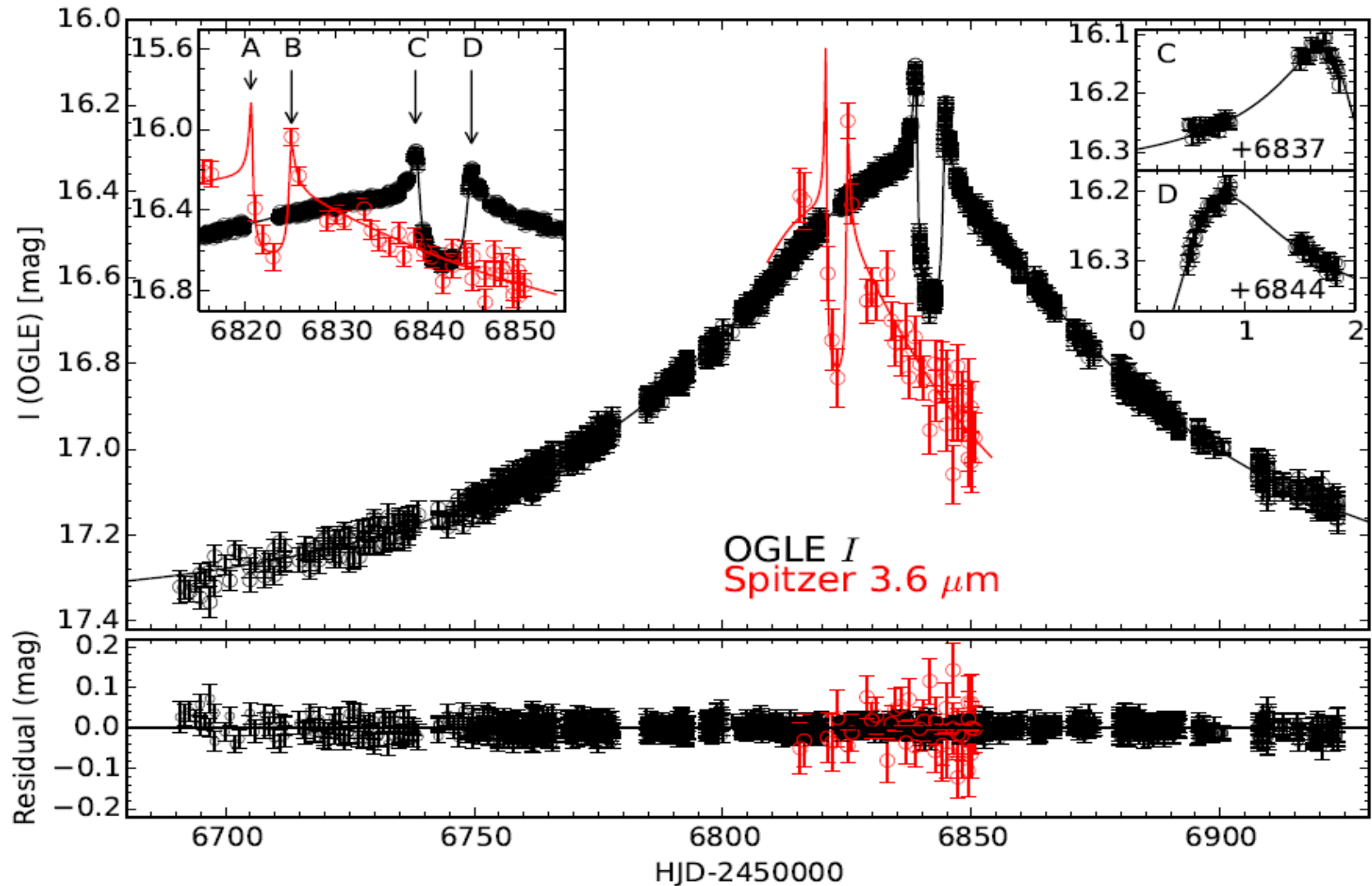
$$M = \frac{\pi_{\text{rel}}}{\kappa \pi_{\text{E}}^2} \sim 0.23 M_{\odot}$$



Yee et al. 2015, ApJ, in press

OGLE-2014-BLG-0124:

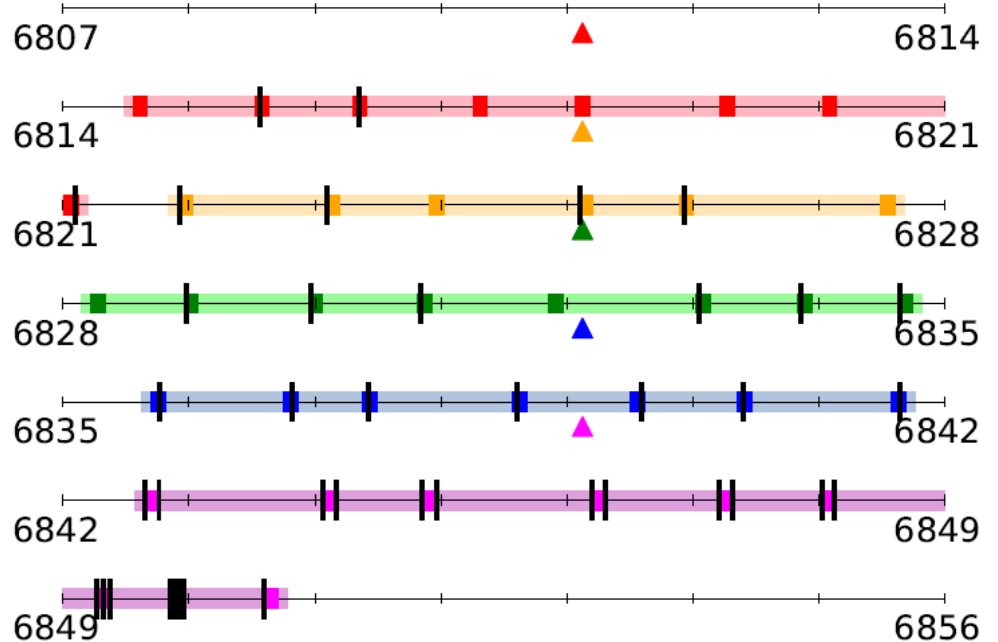
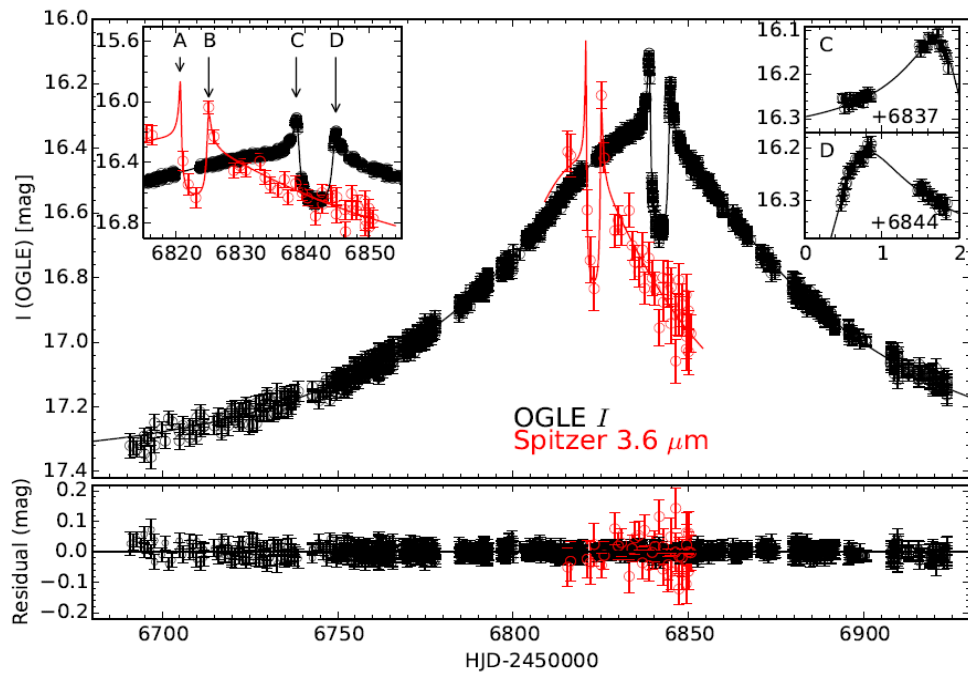
First Microlens Planet with Spitzer Parallax



Udalski et al. 2015, ApJ, in press

OGLE-2014-BLG-0124:

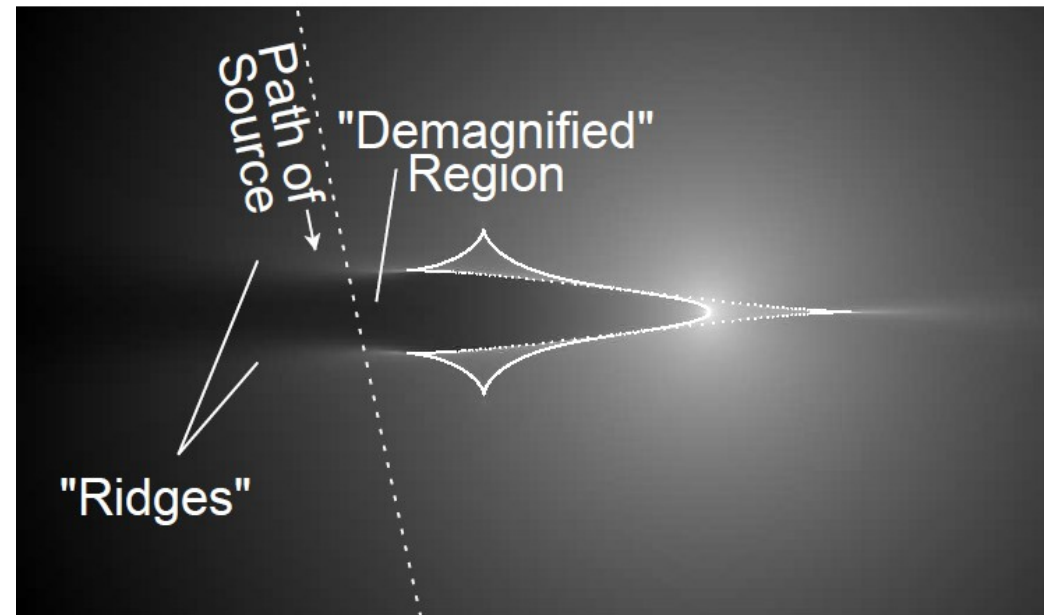
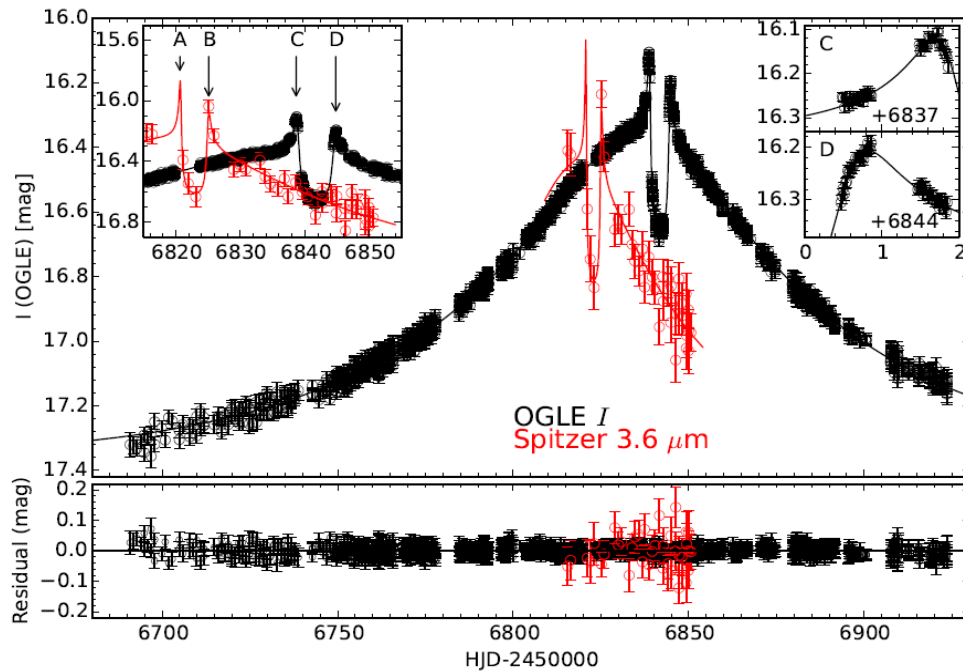
How Spitzer Observations Were Chosen



Udalski et al. 2015, ApJ, in press

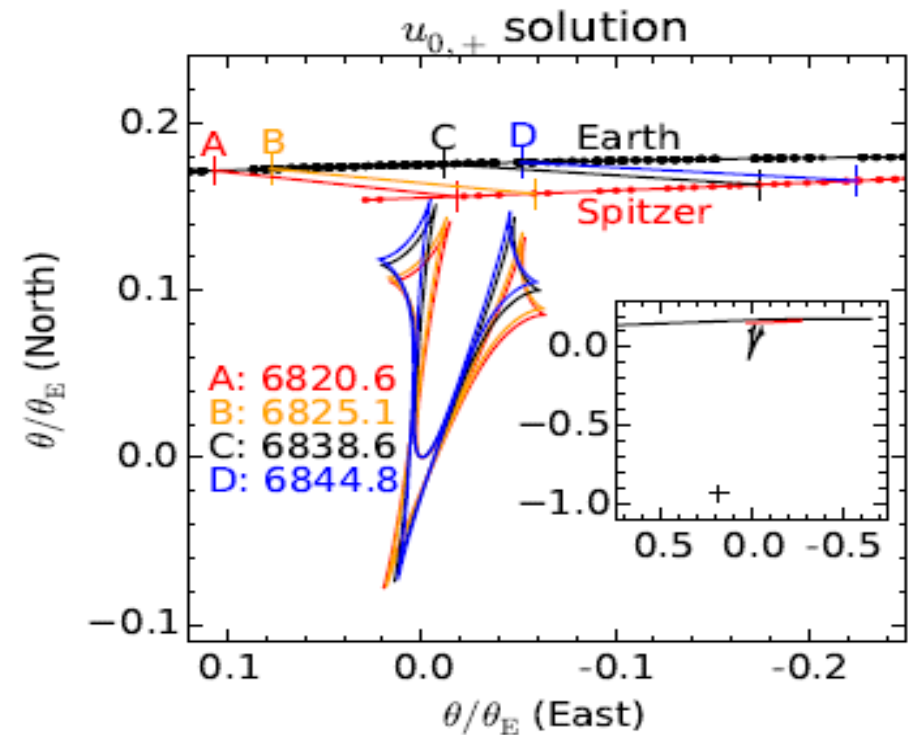
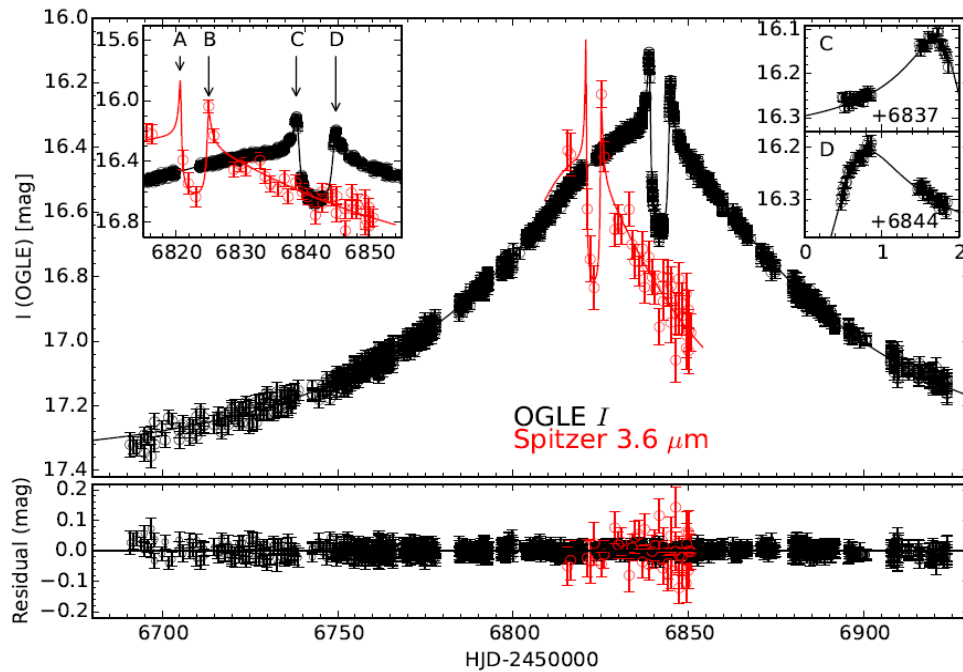
OGLE-2014-BLG-0124:

The "Big Dip"



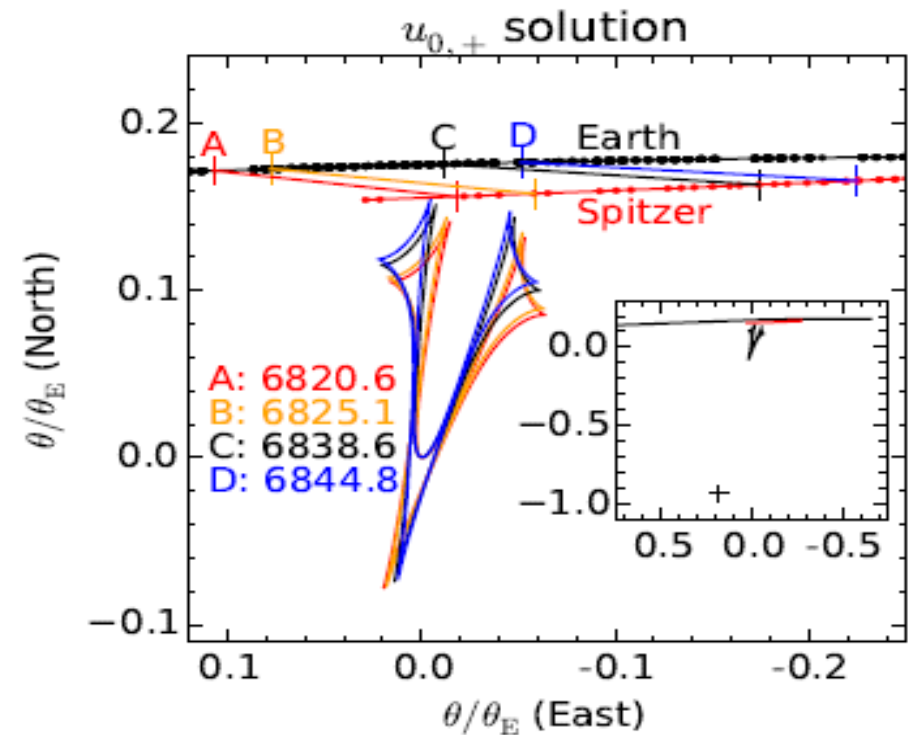
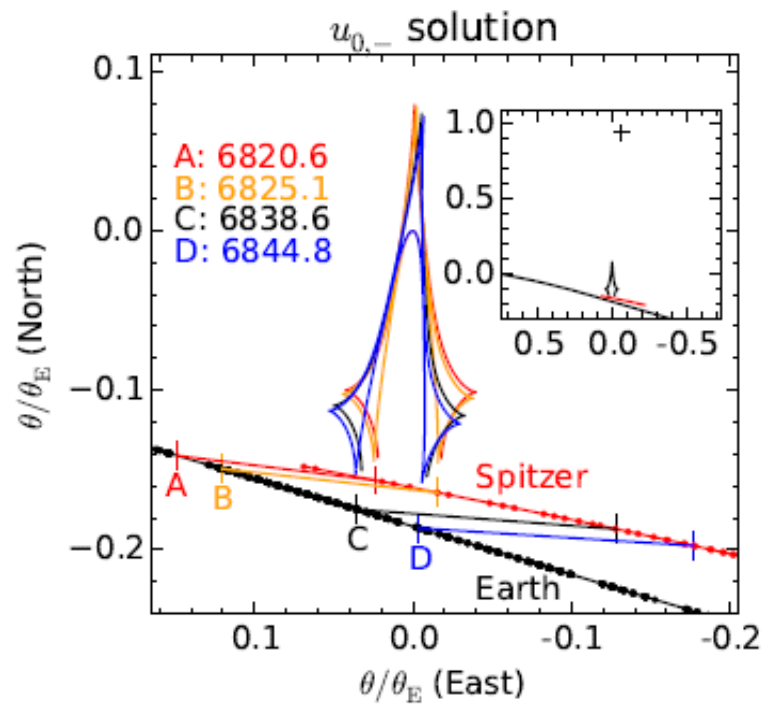
Udalski et al. 2015, ApJ, in press

OGLE-2014-BLG-0124: Source and Caustic Reconstruction



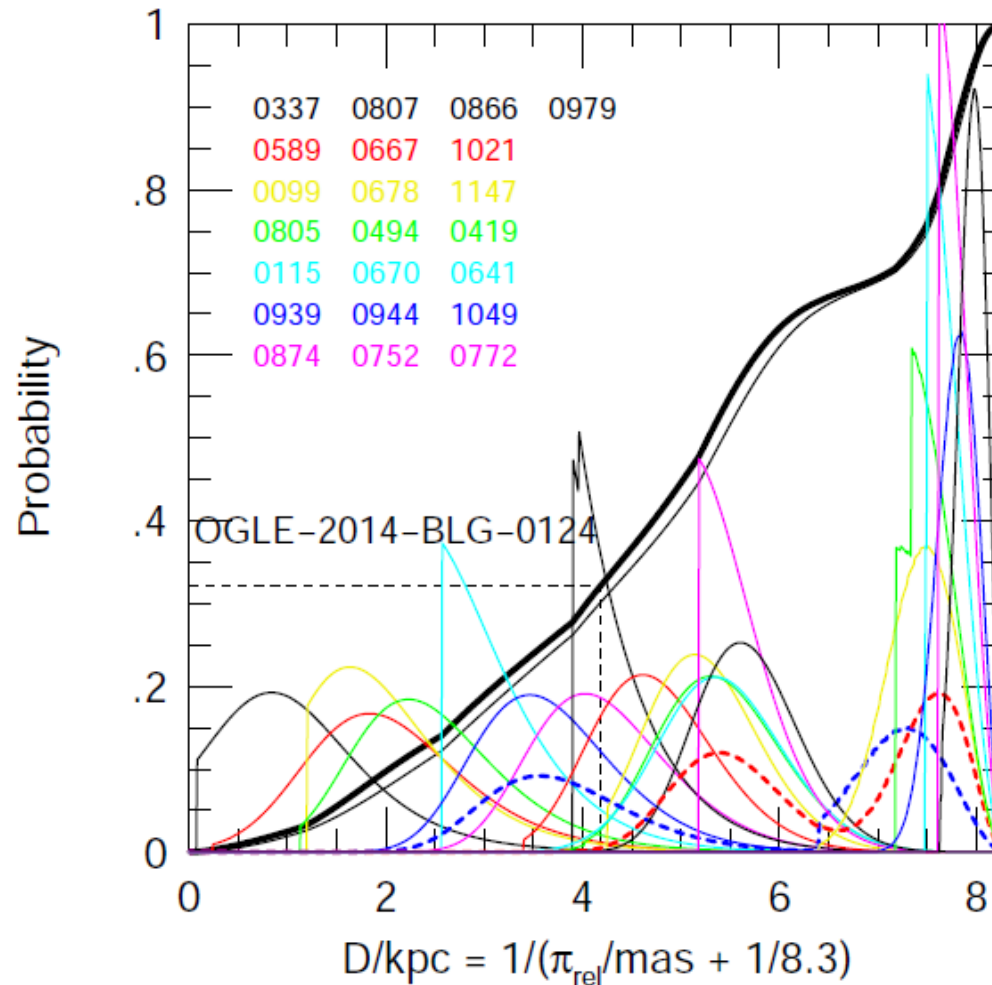
Udalski et al. 2015, ApJ, in press

OGLE-2014-BLG-0124: Source and Caustic Reconstruction



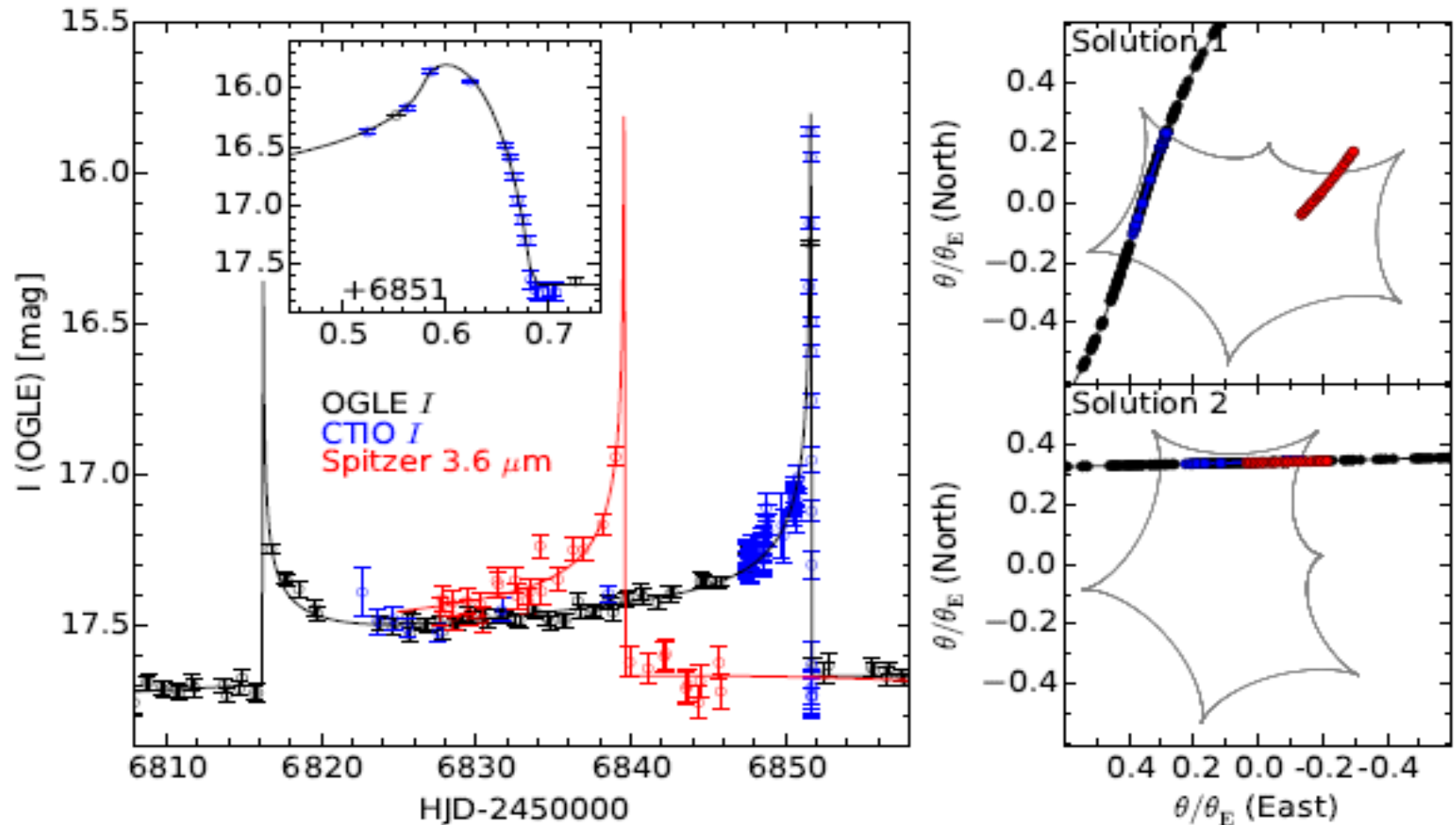
Udalski et al. 2015, ApJ, in press

22 Point-Lens Spitzer Parallax Measurements Versus 1 Planet



Calchi Novati et al. 2014, ApJ, submitted

OGLE-2014-BLG-1050: First Binary Caustic Crossing From Space



Zhu et al. 2015, ApJ, submitted

Kepler (MP)³

Gould & Horne 2013, ApJ, 779, L28

Kepler (MP)³
Multi-Plexing

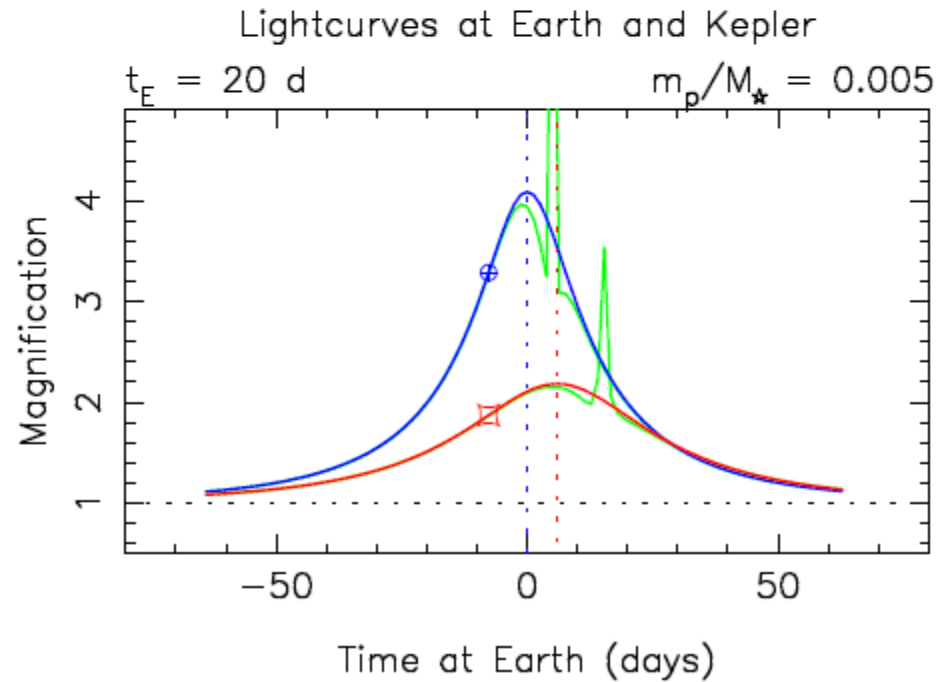
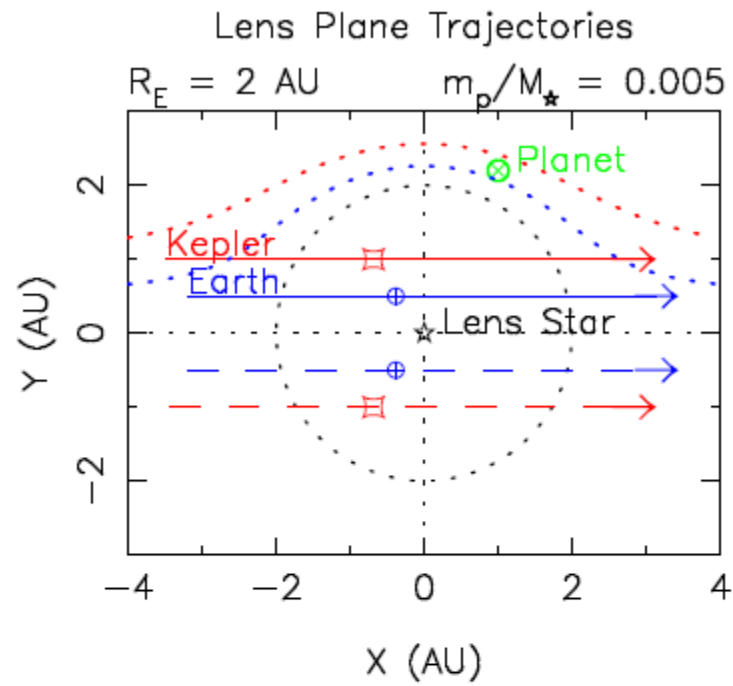
Gould & Horne 2013, ApJ, 779, L28

Kepler (MP)³
Multi-Plexing
for
Mass Production

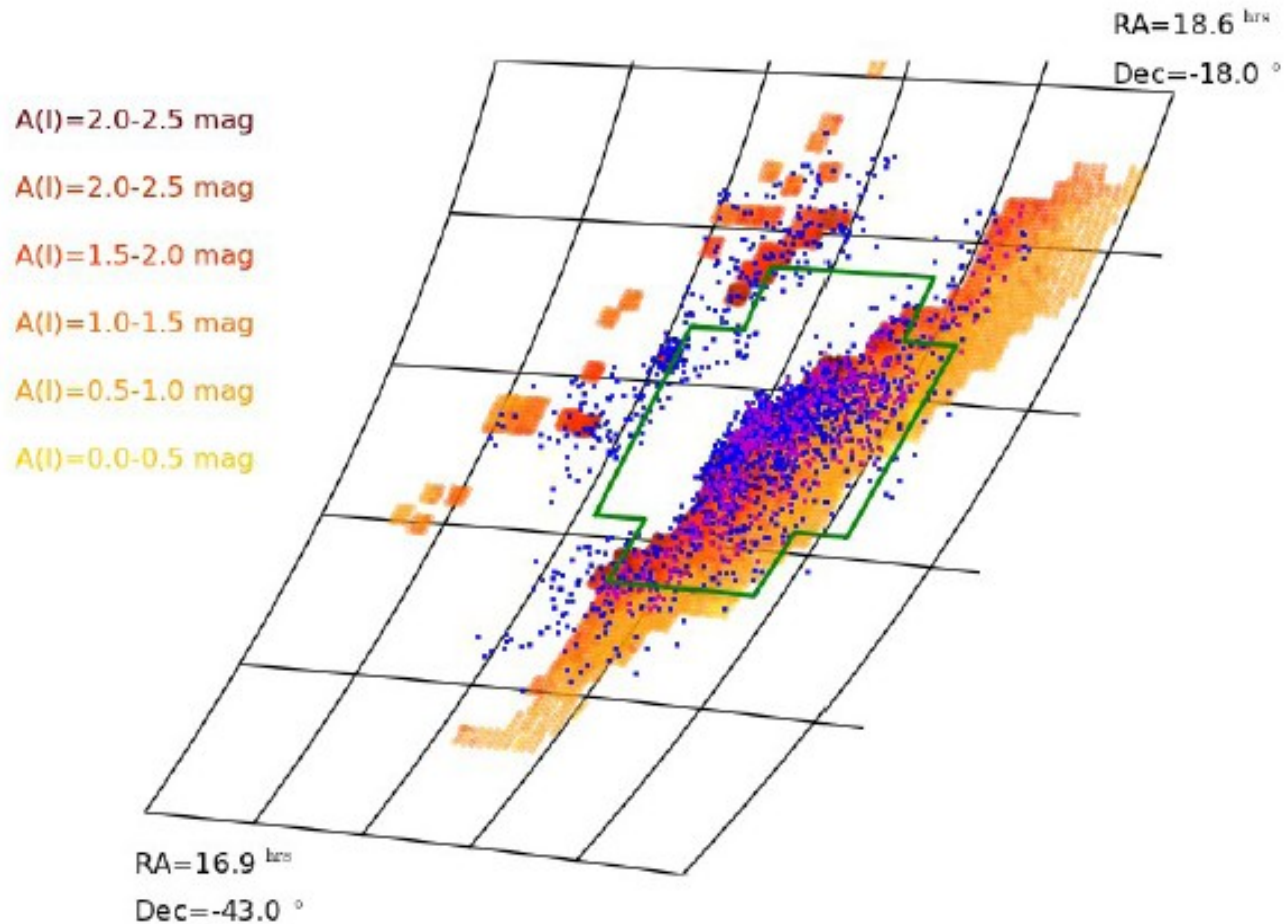
Gould & Horne 2013, ApJ, 779, L28

Kepler (MP)³
Multi-Plexing
for
Mass Production
of
Microlens Parallaxes

Gould & Horne 2013, ApJ, 779, L28

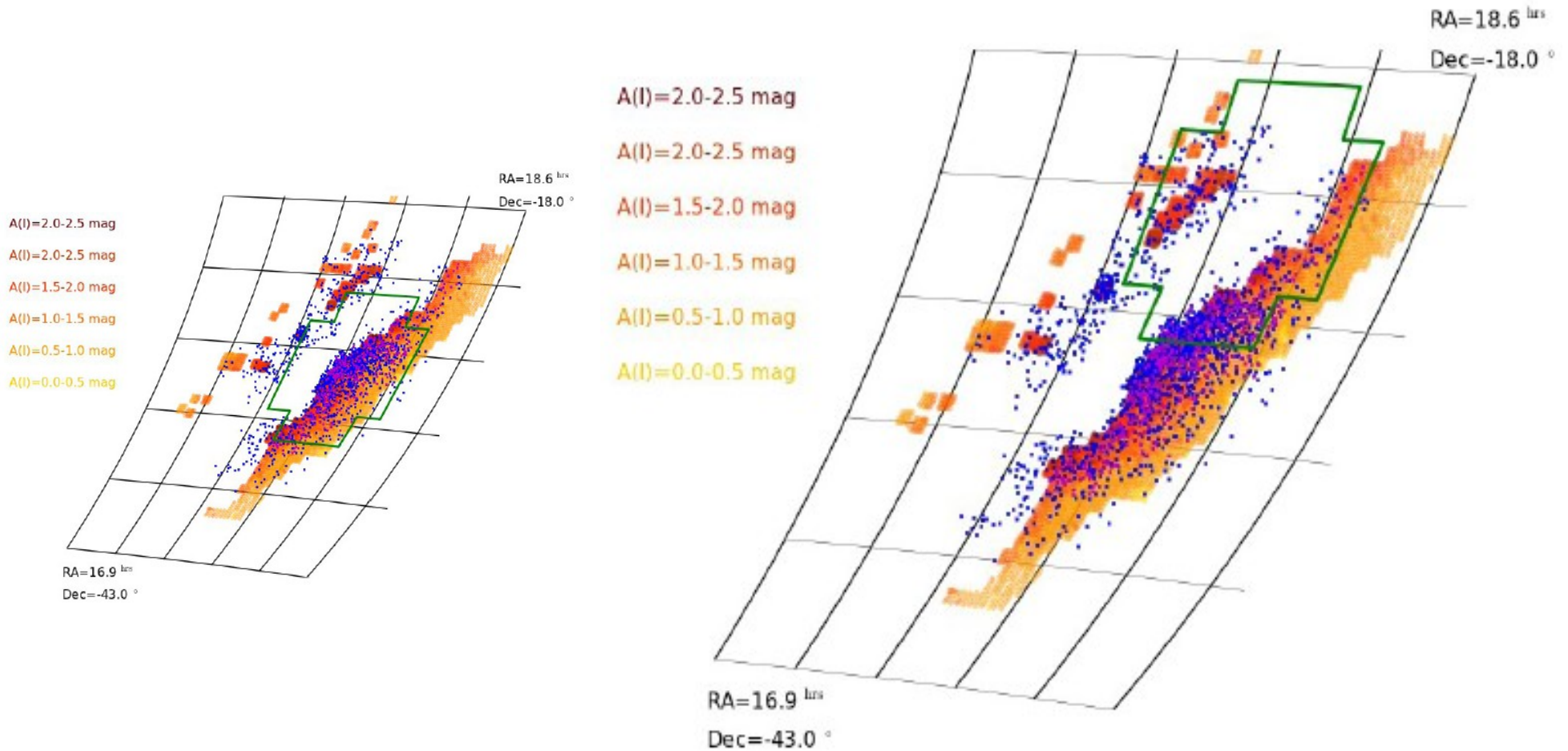


What we would like to do ...



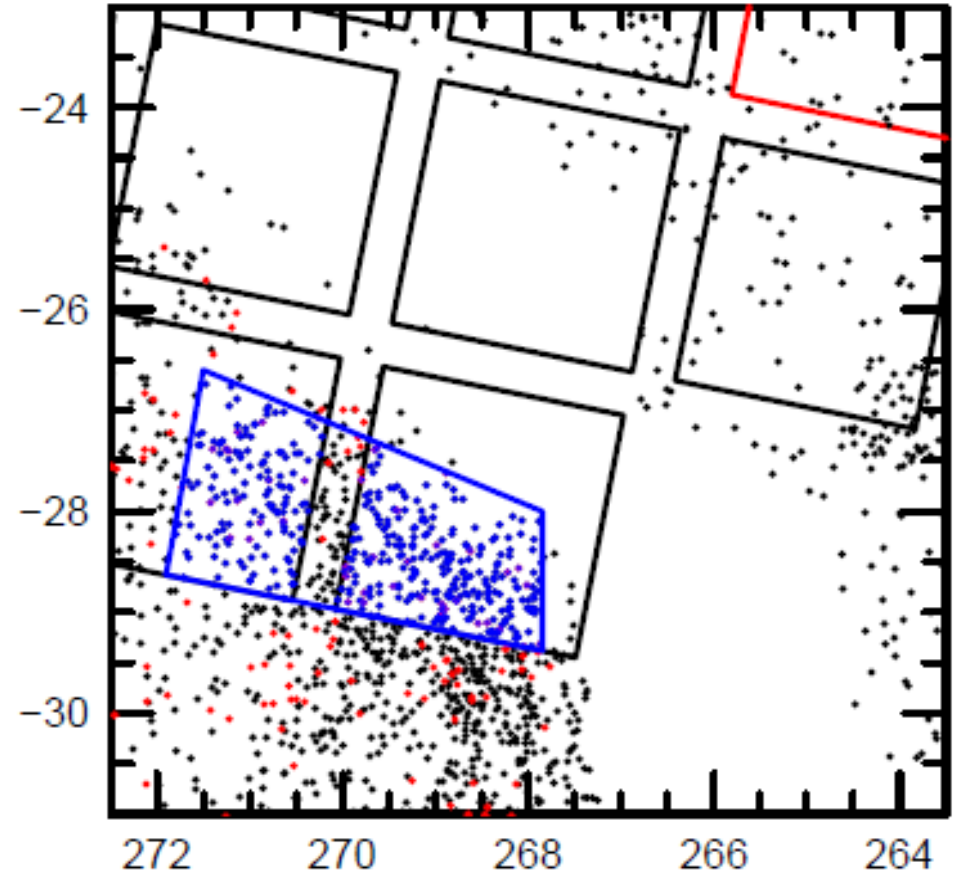
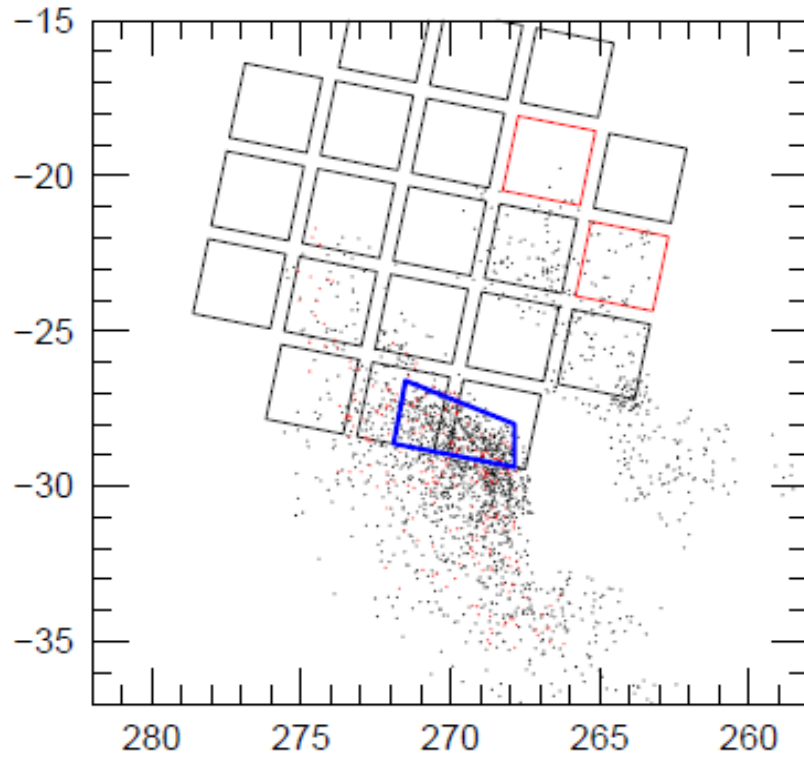
R. Street 2013, Kepler Science Meeting

... and what we can do!



R. Street 2013, Kepler Science Meeting

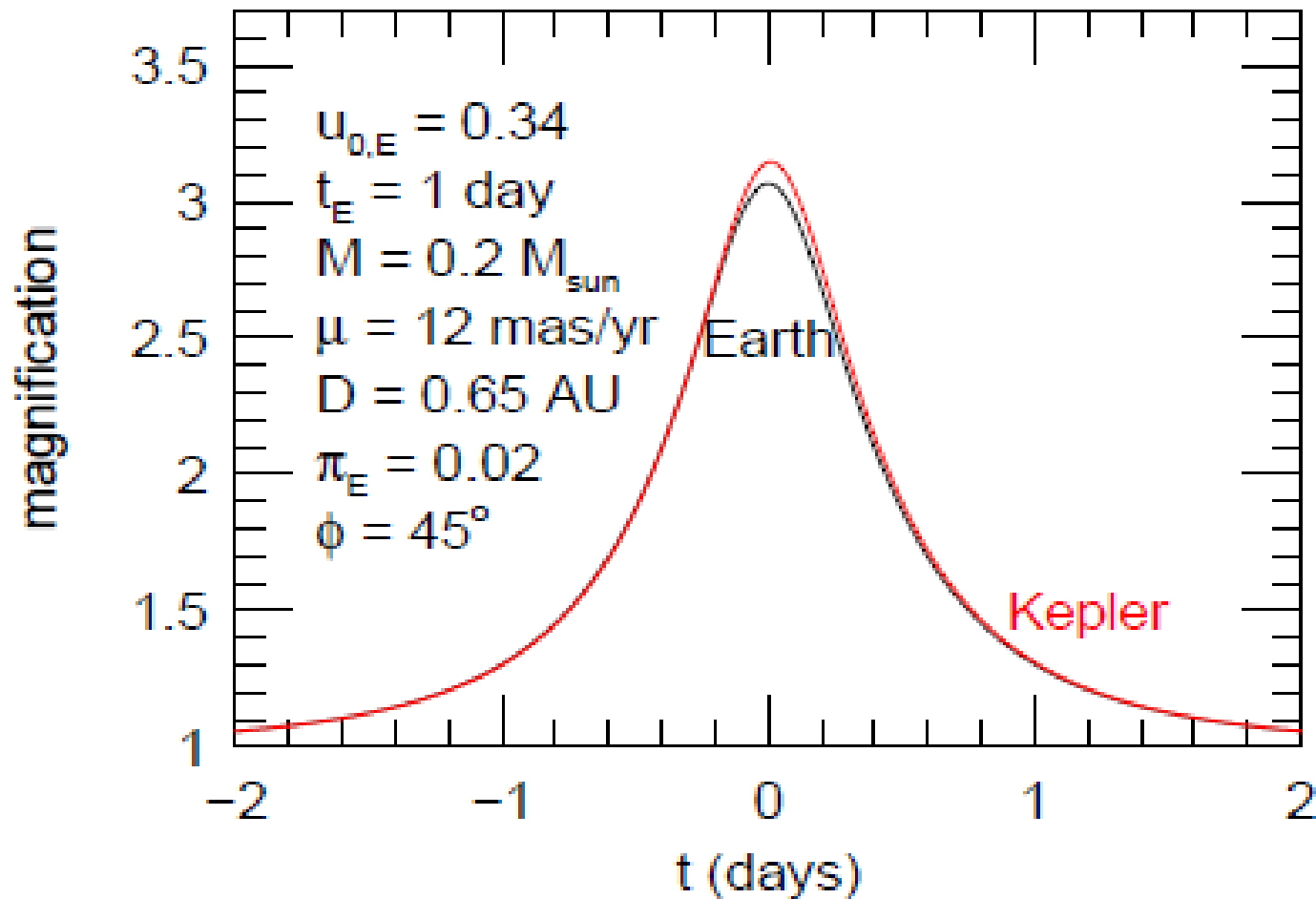
Proposal: K2 Field9 5.3 Mpxl



Gould, Horne, Street 2014, K2 White Paper

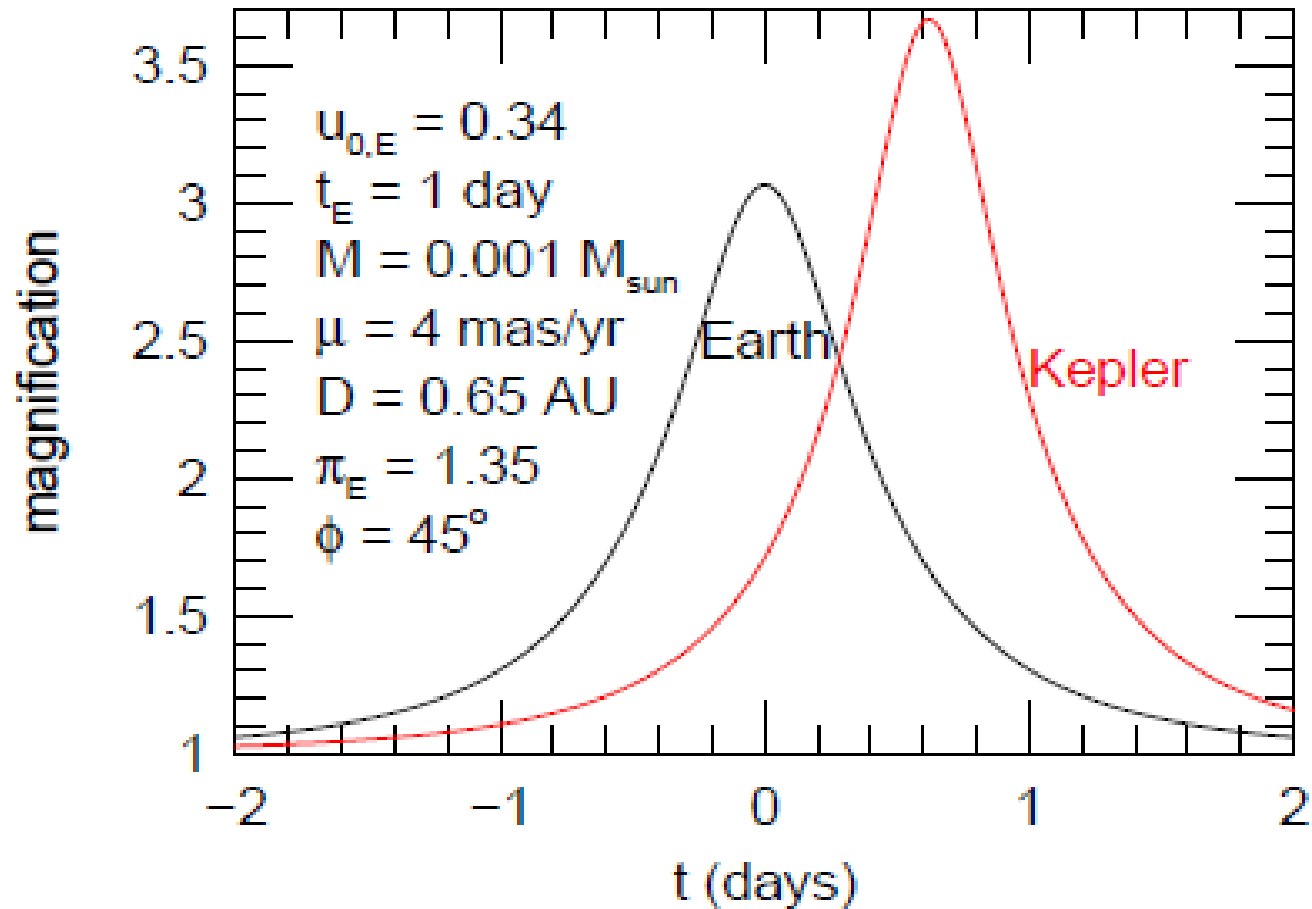
K2 Microlensing Science:

Short Event: If lens is a star



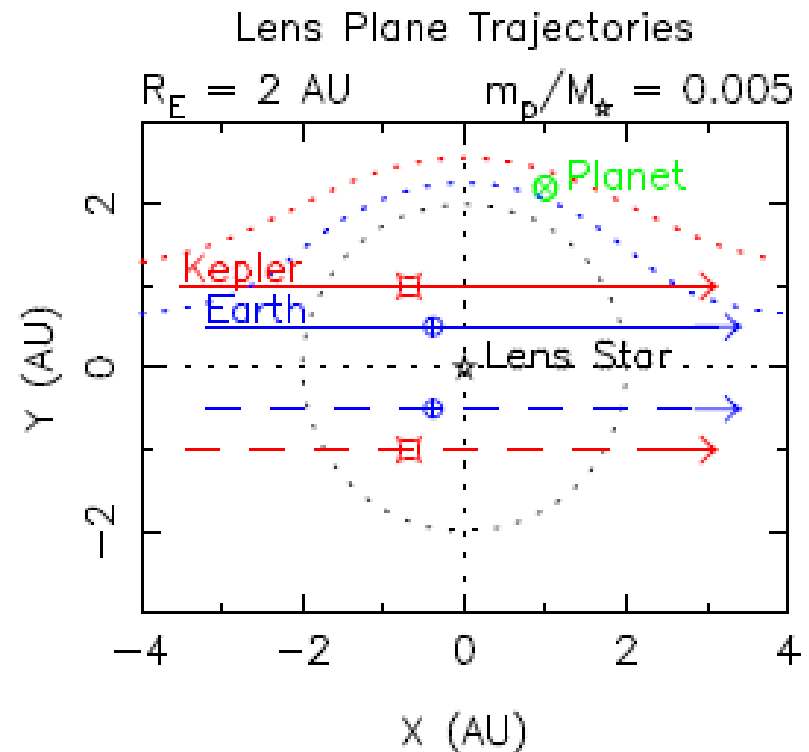
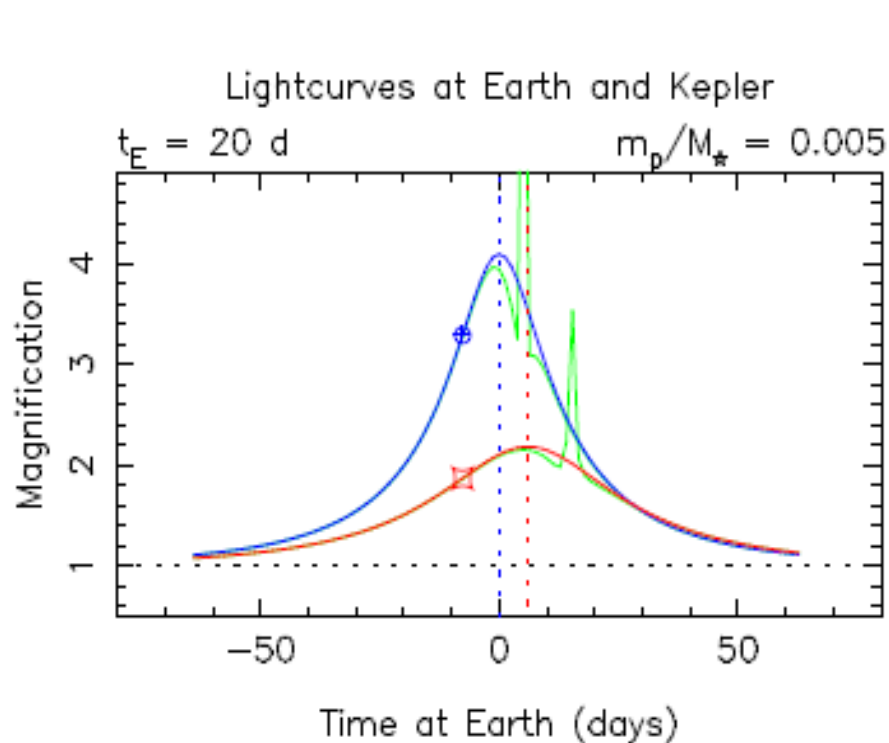
Gould, Horne, Street 2014, K2 White Paper

K2 Microlensing Science: Short Event: If lens is an FFP



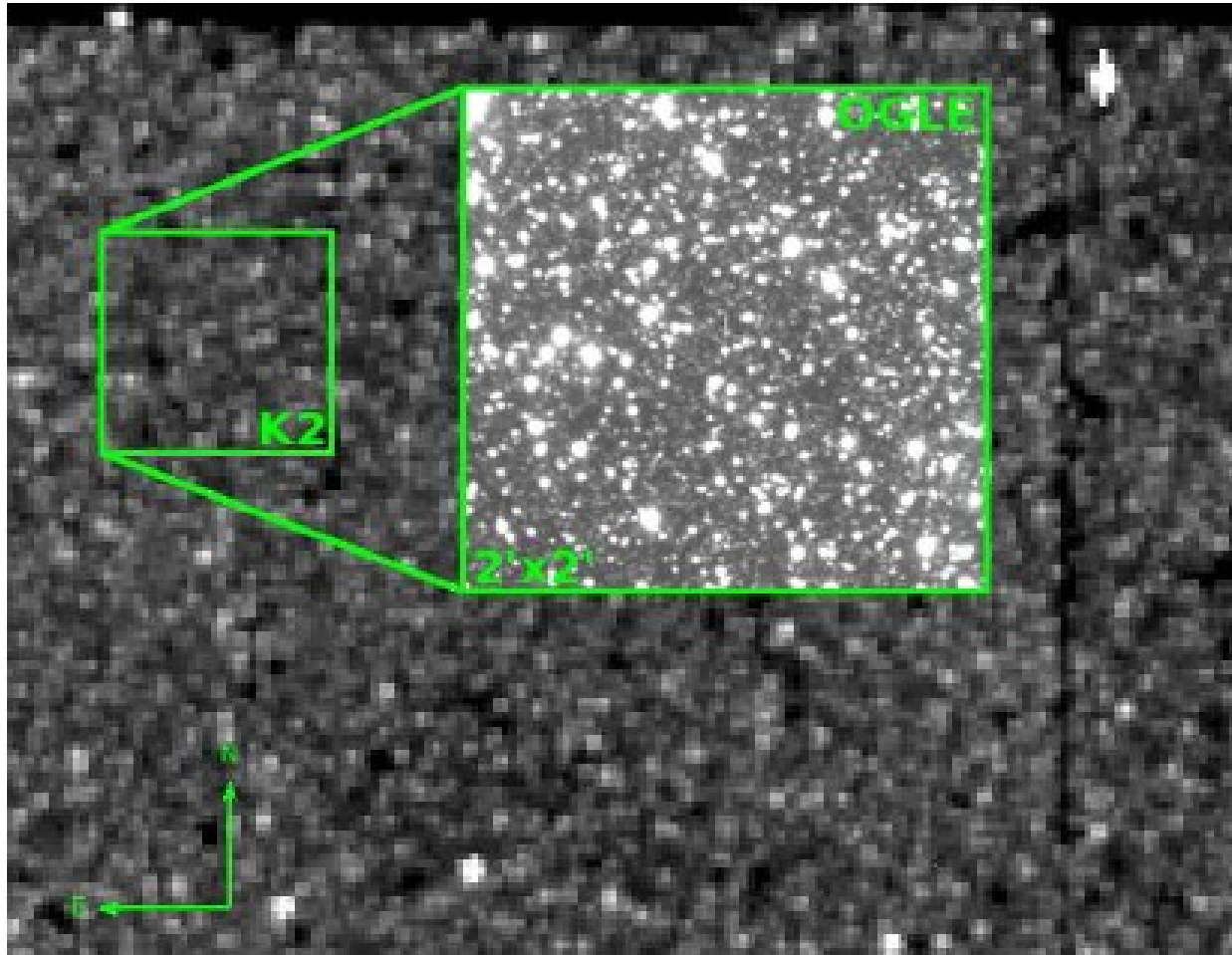
Gould, Horne, Street 2014, K2 White Paper

K2 Microlensing Science: Bound Planets: Mass and Orbit



Gould, Horne, Street 2014, K2 White Paper

K2 Microlensing: “Crowding” Significant



Gould, Horne, Street 2014, K2 White Paper

Korean Microlensing Telescope Network (KMTNet)



From Design ...

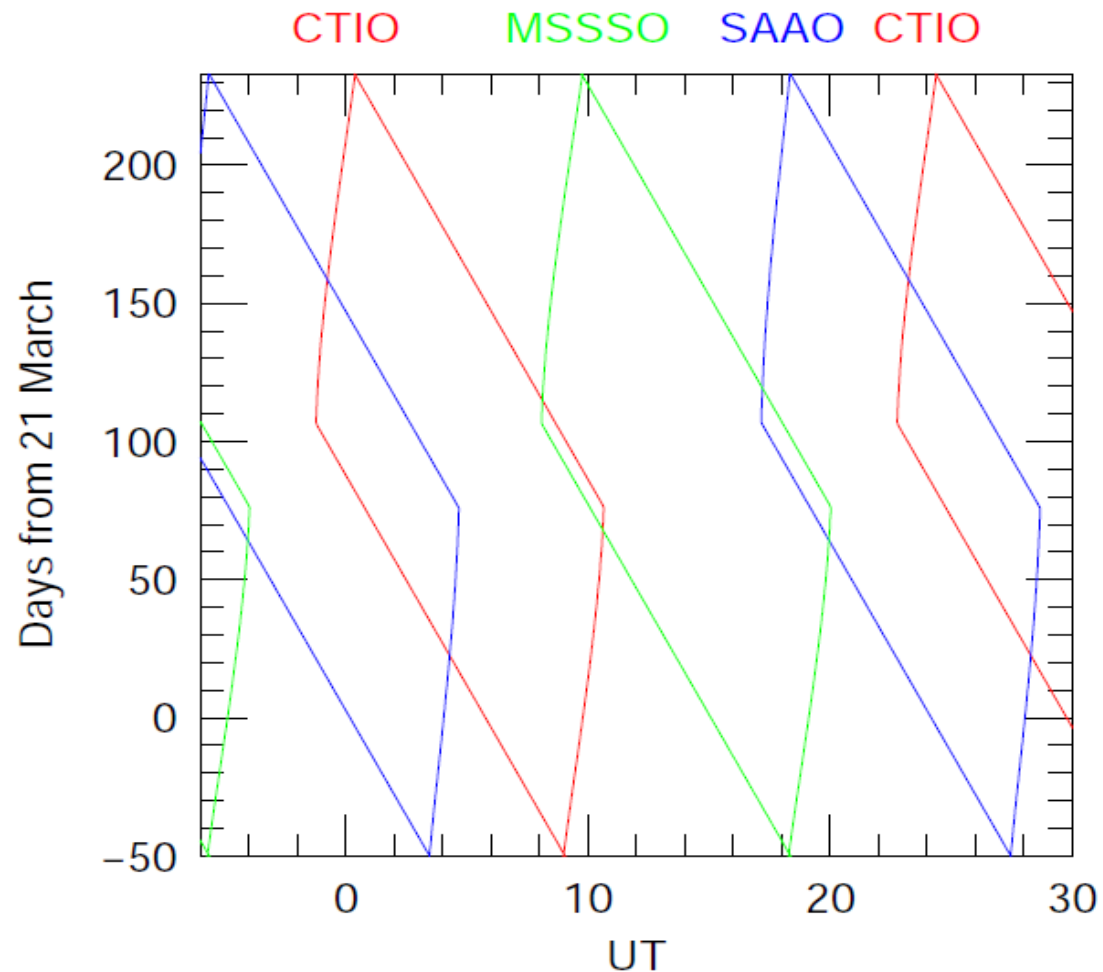


... To Construction

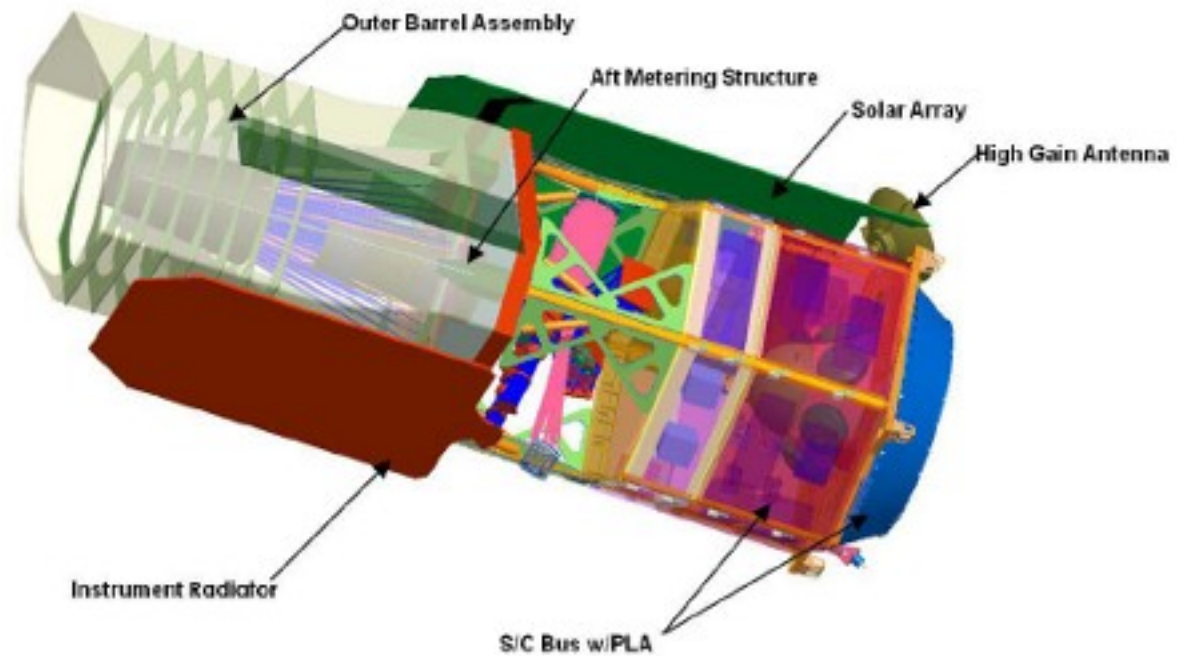


The Bulge Never Set on KMTNet

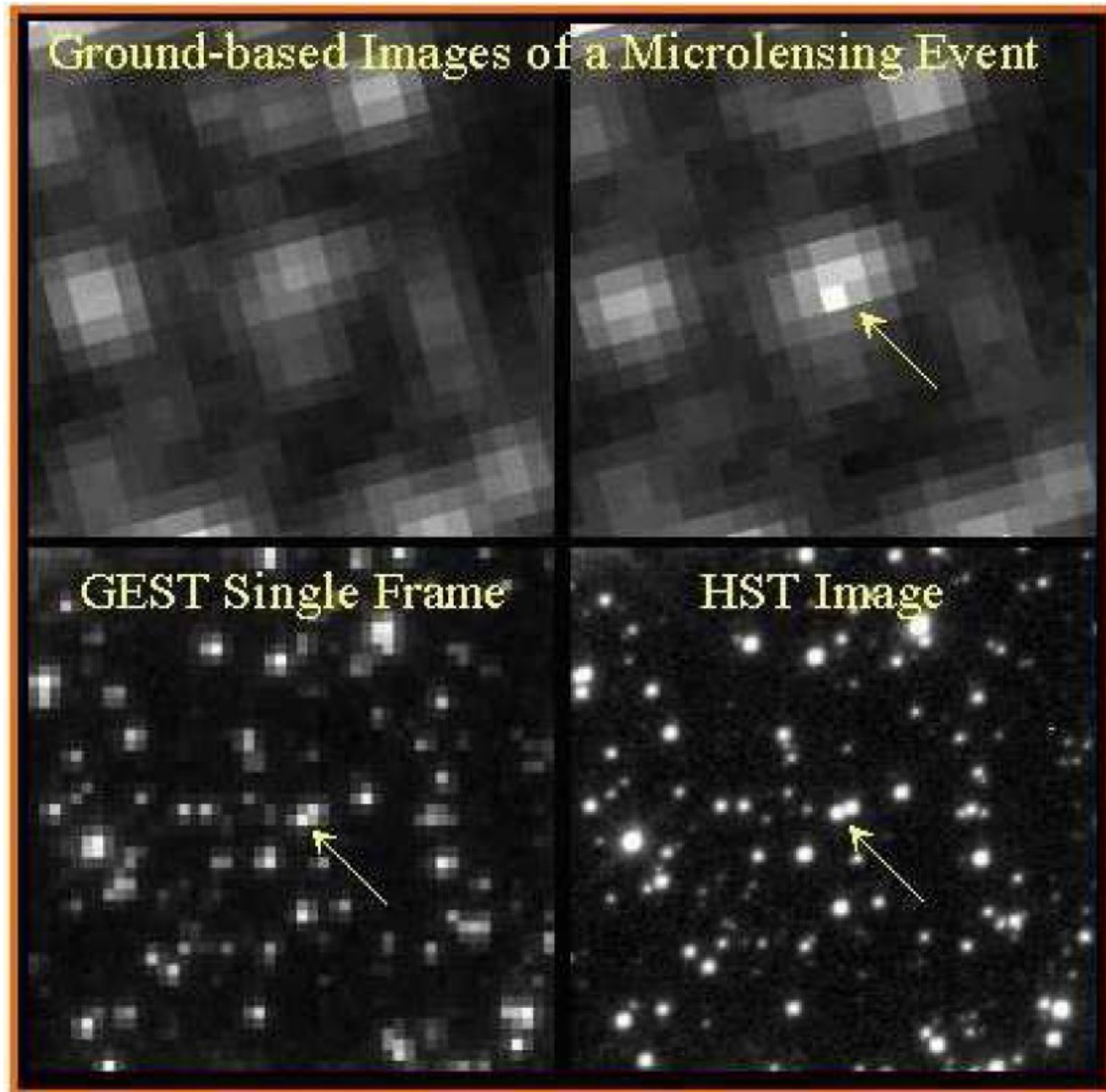
(at least in June)

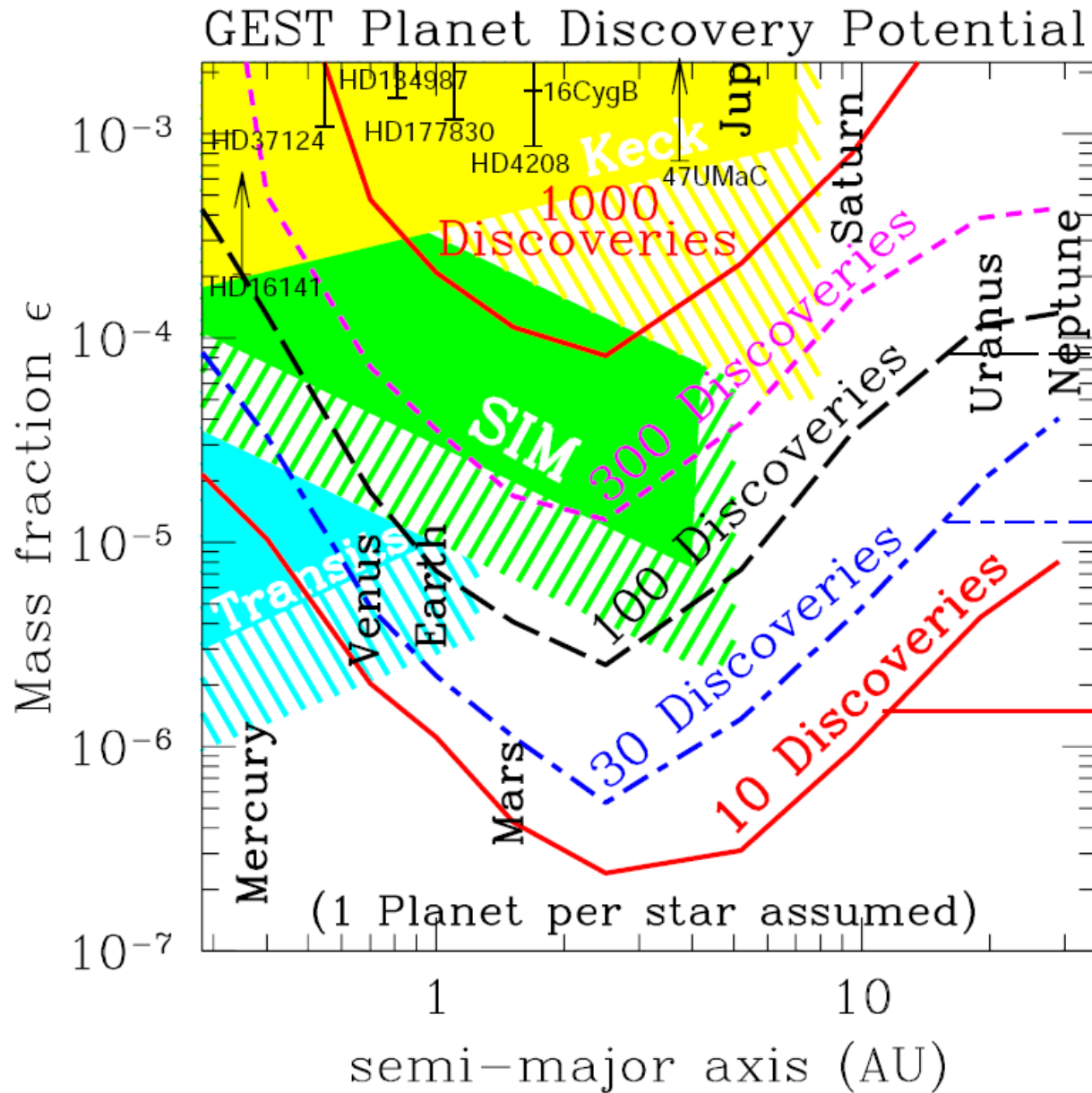


Next Stop: WFIRST



Seeing Better In Space (also weather)



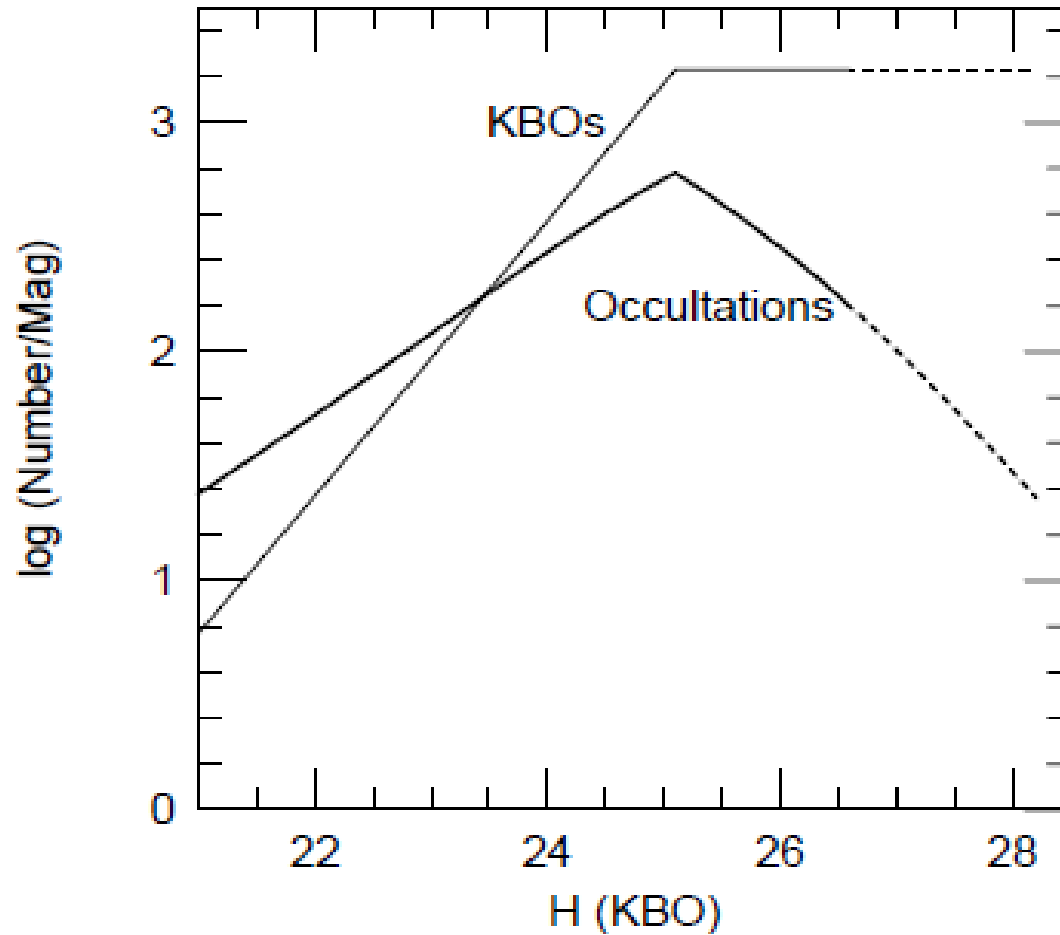


Bennett & Rhie 2002, ApJ, 574, 985

Non-Microlensing WFIRST Science: Overview

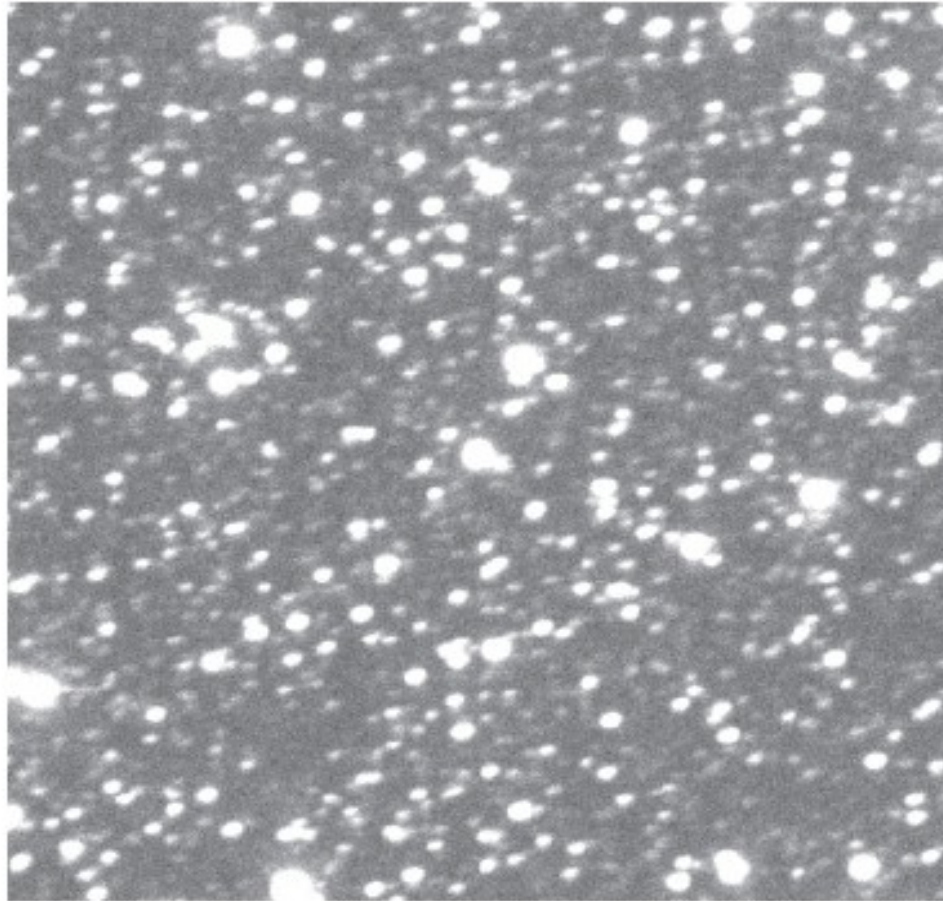
- 40,000 images (52 sec)
- 2.8 sq.deg.
- 6 continuous 72-day campaigns (at quadrature)
- 100 images per day
- $\text{SNR} = 10^{\{0.4(\text{Hzero}-H)\}}$ Hzero = 26.1

Non-Microlensing WFIRST Science: KBOs



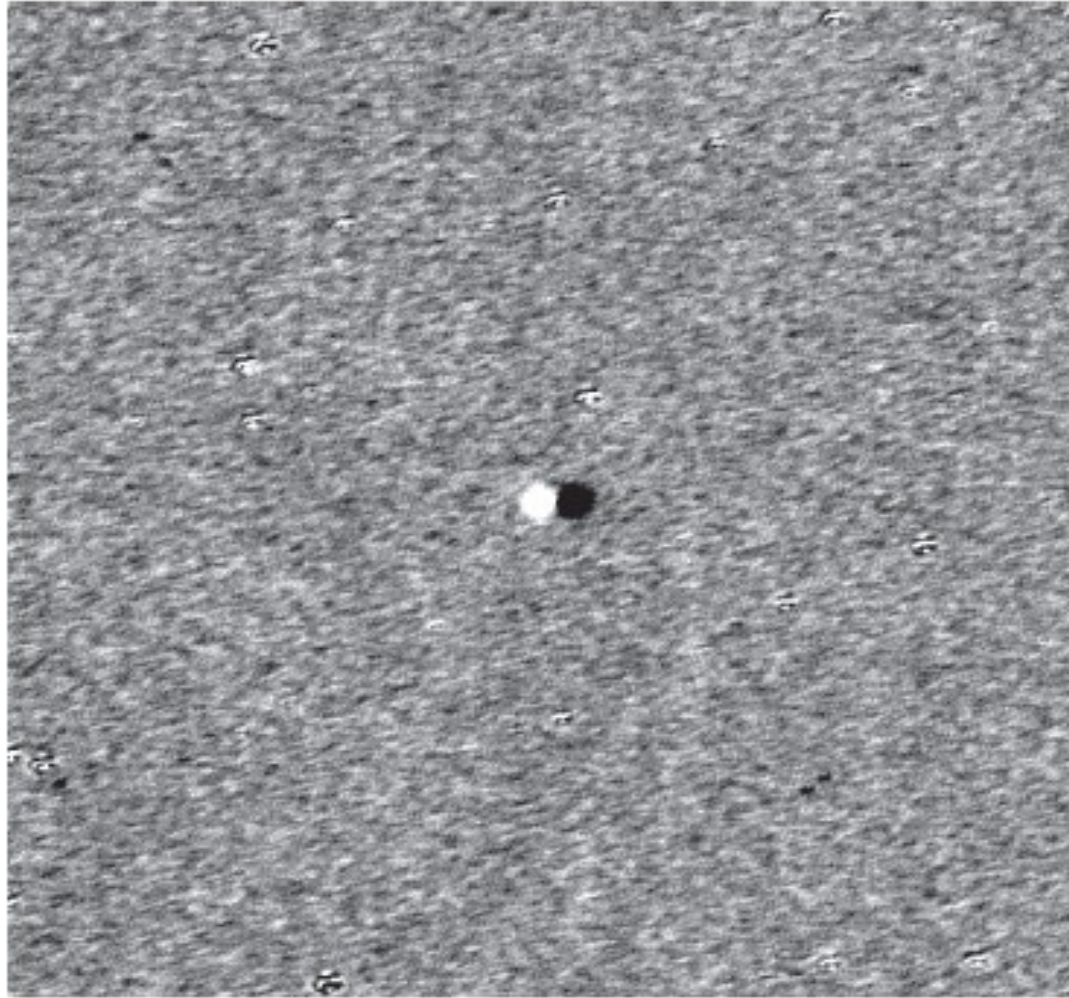
Gould 2014 JKAS, 47, 279

KBOs possible in microlensing fields?



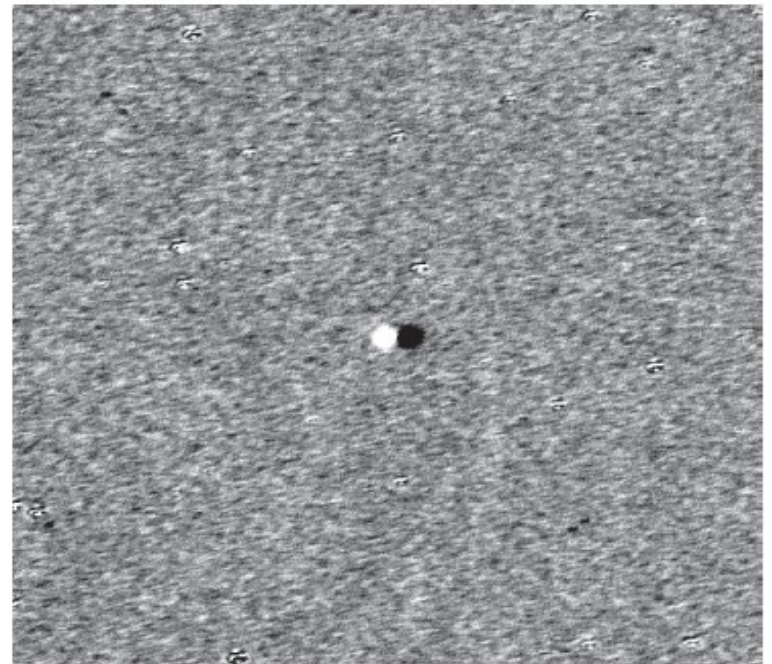
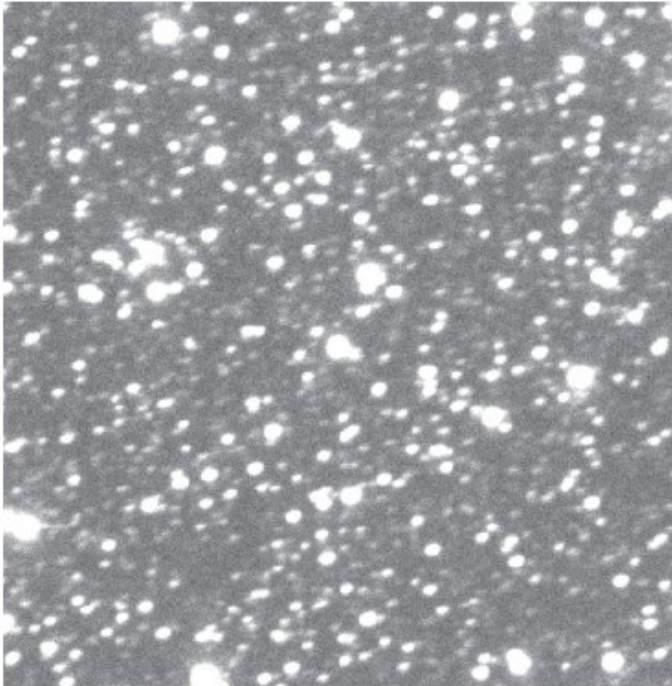
Shepard et al. 2011, AJ, 142, 98

Yes! Microlensing fields
are not crowded ...



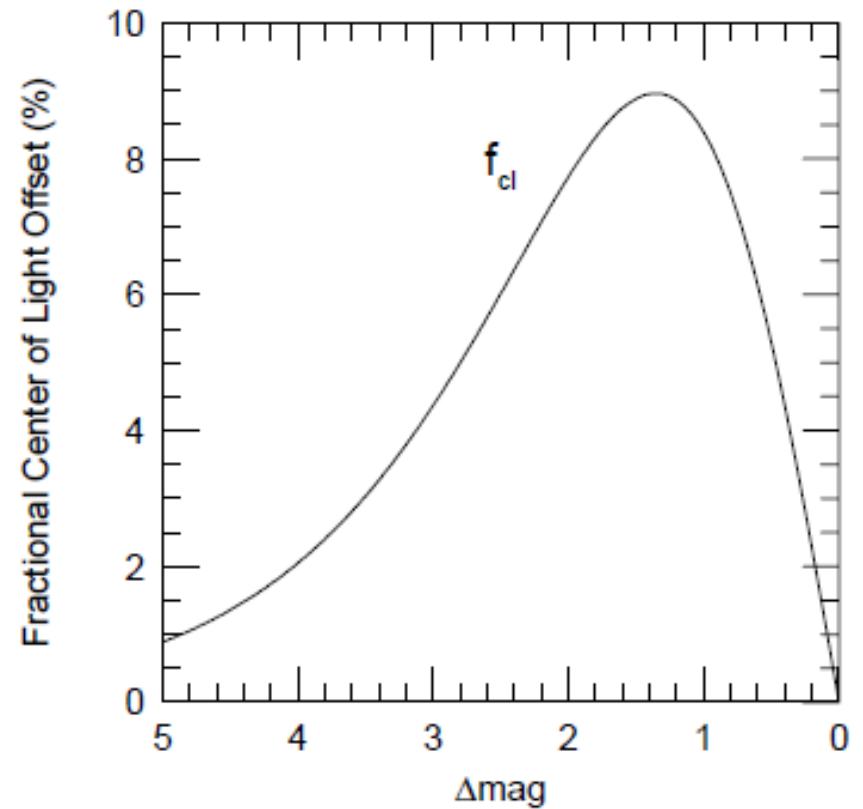
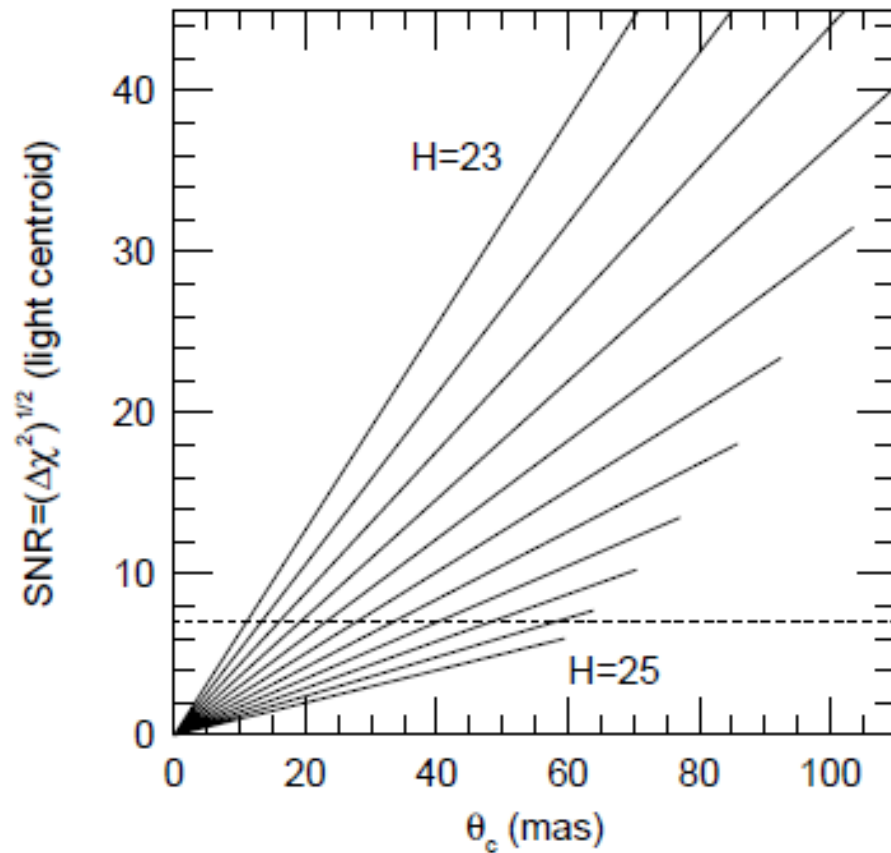
Shepard et al. 2011, AJ, 142, 98

Yes! Microlensing fields are not crowded
after image subtraction!



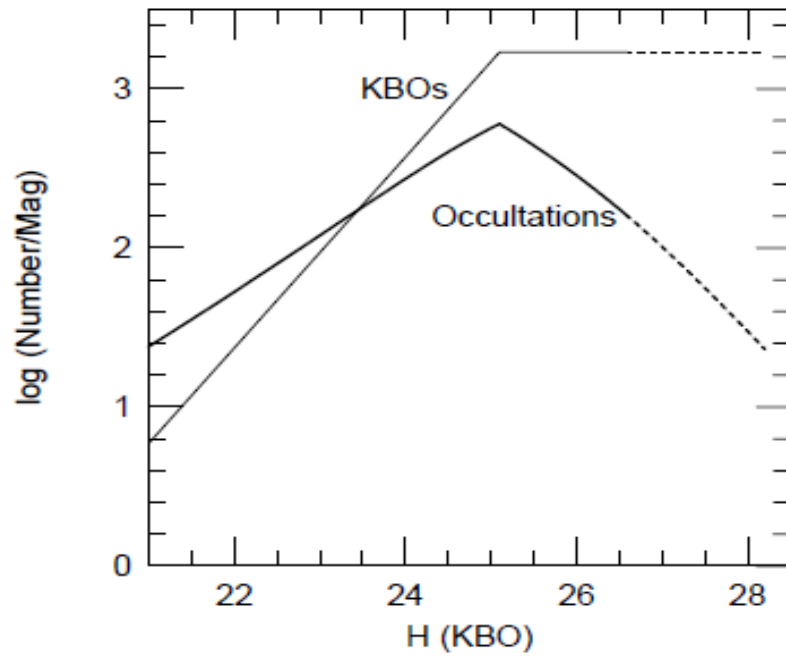
Shepard et al. 2011, AJ, 142, 98

Non-Microlensing **WFIRST** Science: KBO Binaries



Gould 2014 JKAS, submitted

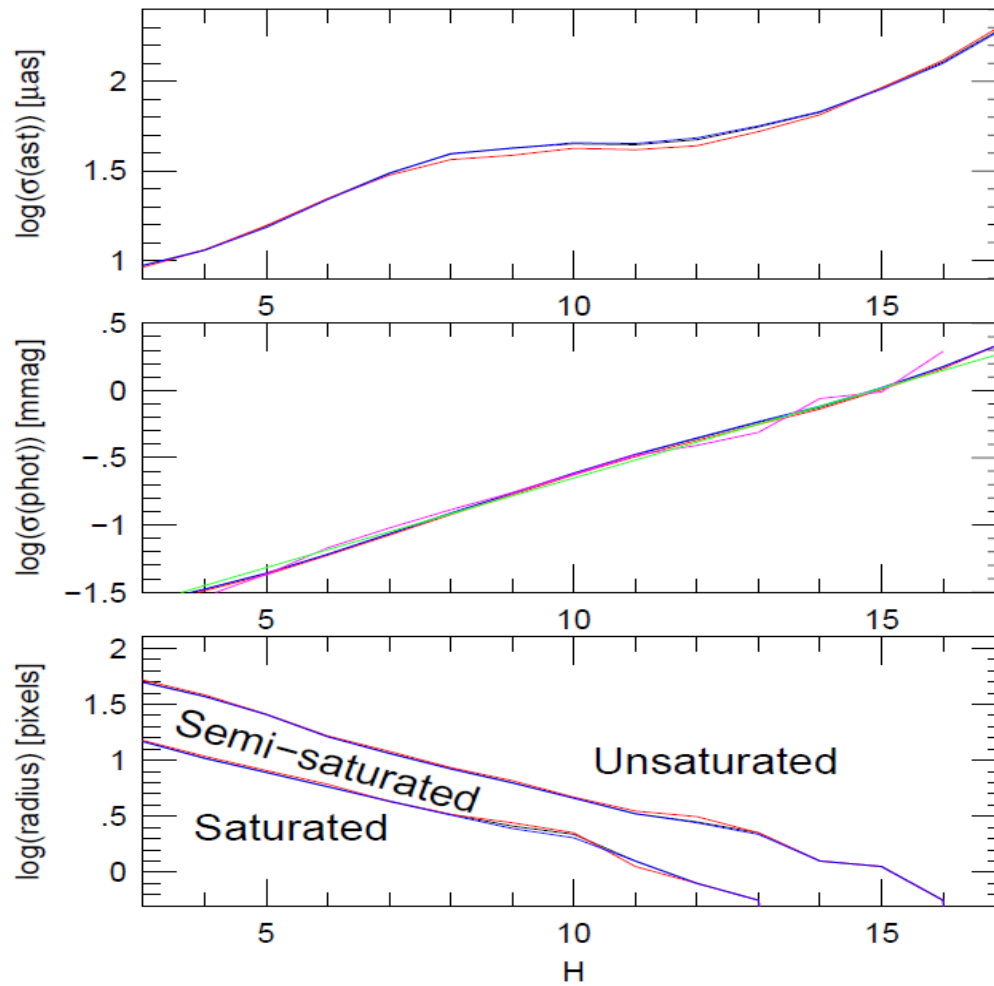
Non-Microlensing WFIRST Science: KBO Precision orbits



$$\sigma(P)/P \sim 0.09\%$$

$$H \sim 25.1$$

Non-Microlensing WFIRST Science: Ultra-precise Parallaxes



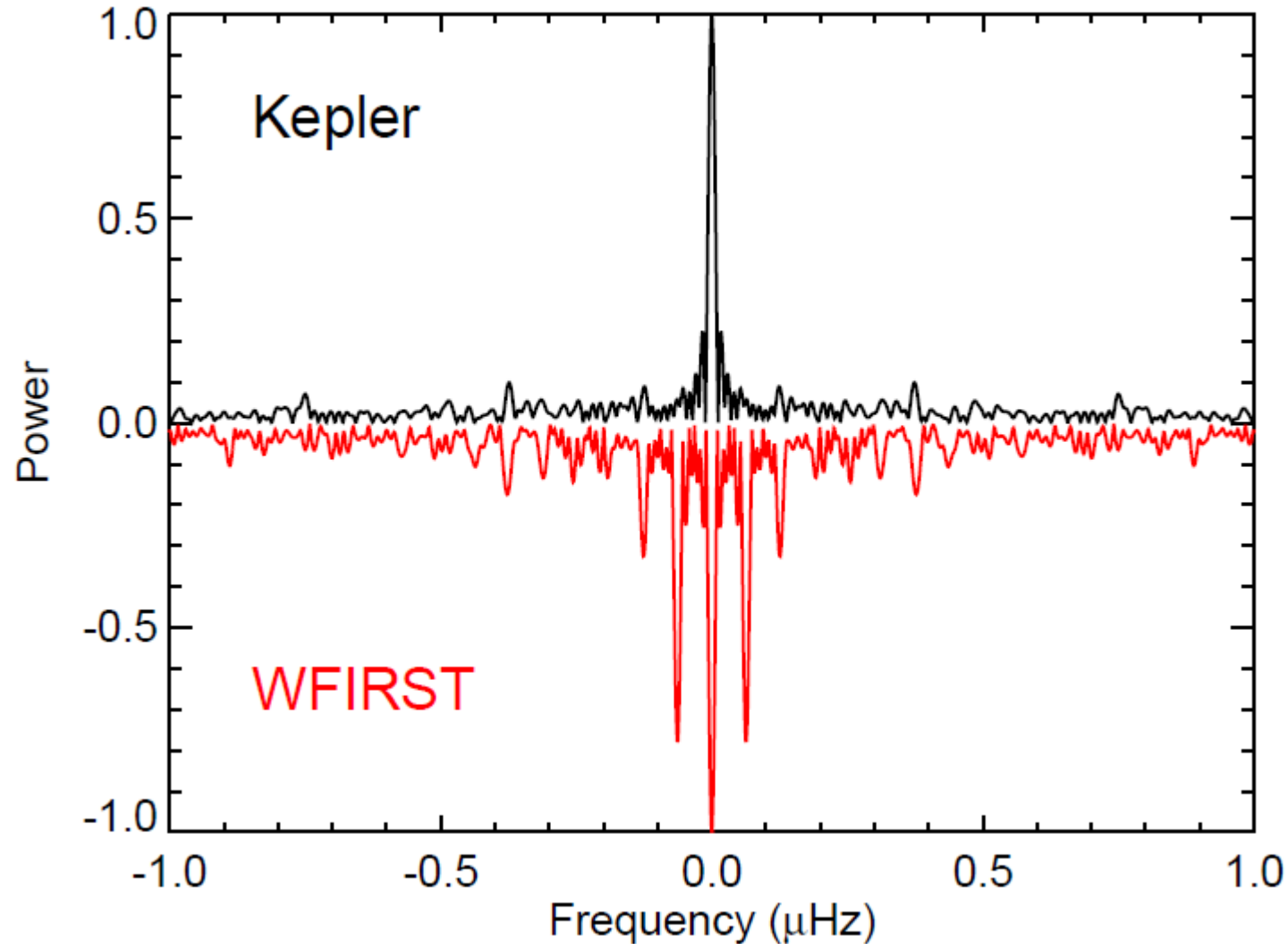
Gould, Huber, Penny, Stello, 2015 JKAS, in press

Non-Microlensing WFIRST Science: Ultra-precise Parallaxes

- $H < 14.0$; $\sigma(\pi) < 0.3 \mu\text{as}$; 1,000,000 stars
- $H < 19.6$; $\sigma(\pi) < 3.7 \mu\text{as}$; 40,000,000 stars
- $H < 21.6$; $\sigma(\pi) < 10 \mu\text{as}$; 120,000,000 stars

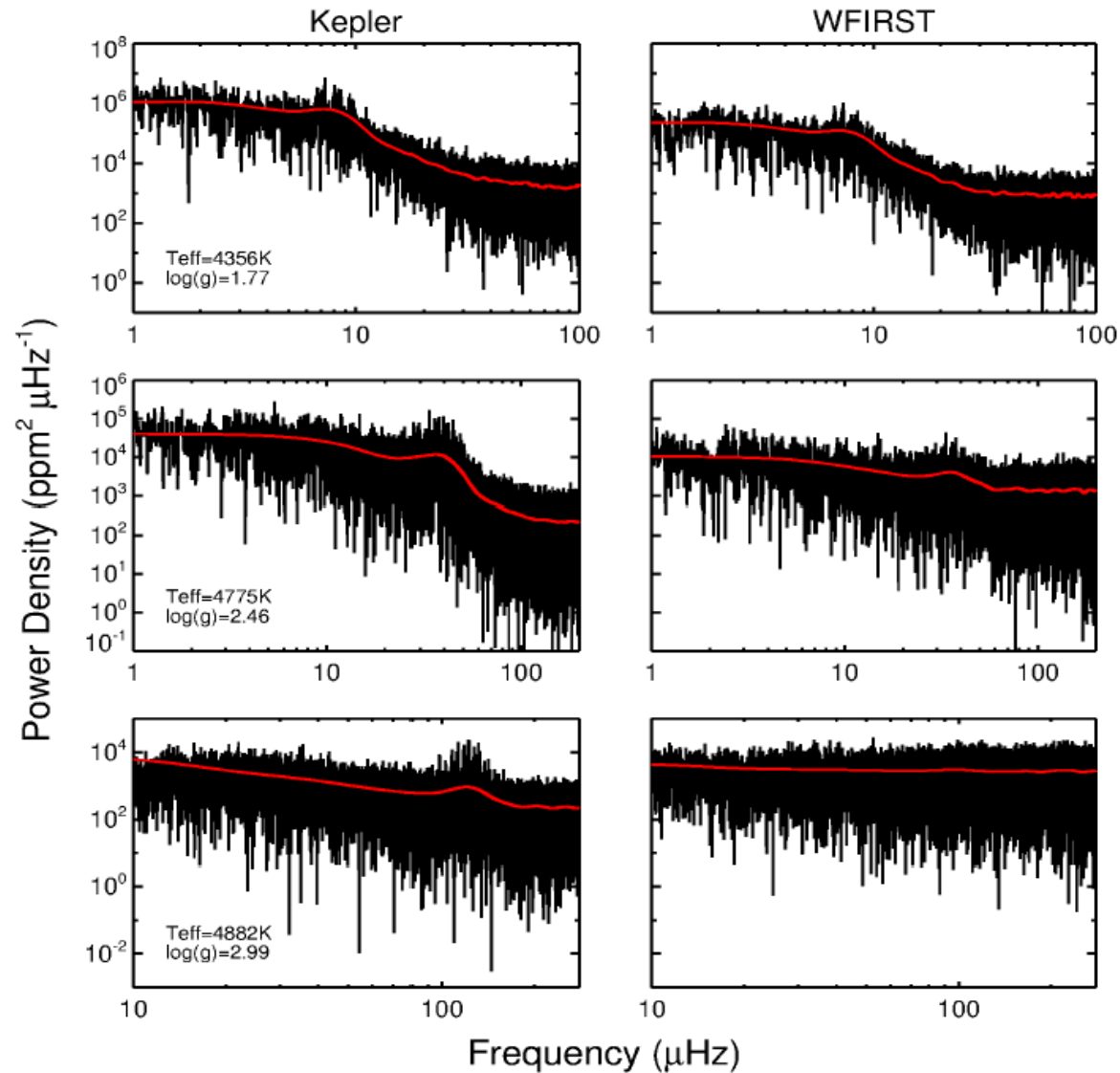
Gould, Huber, Penny, Stello, 2015 JKAS, in press

Non-Microlensing WFIRST Science: Asteroseismic Window Function



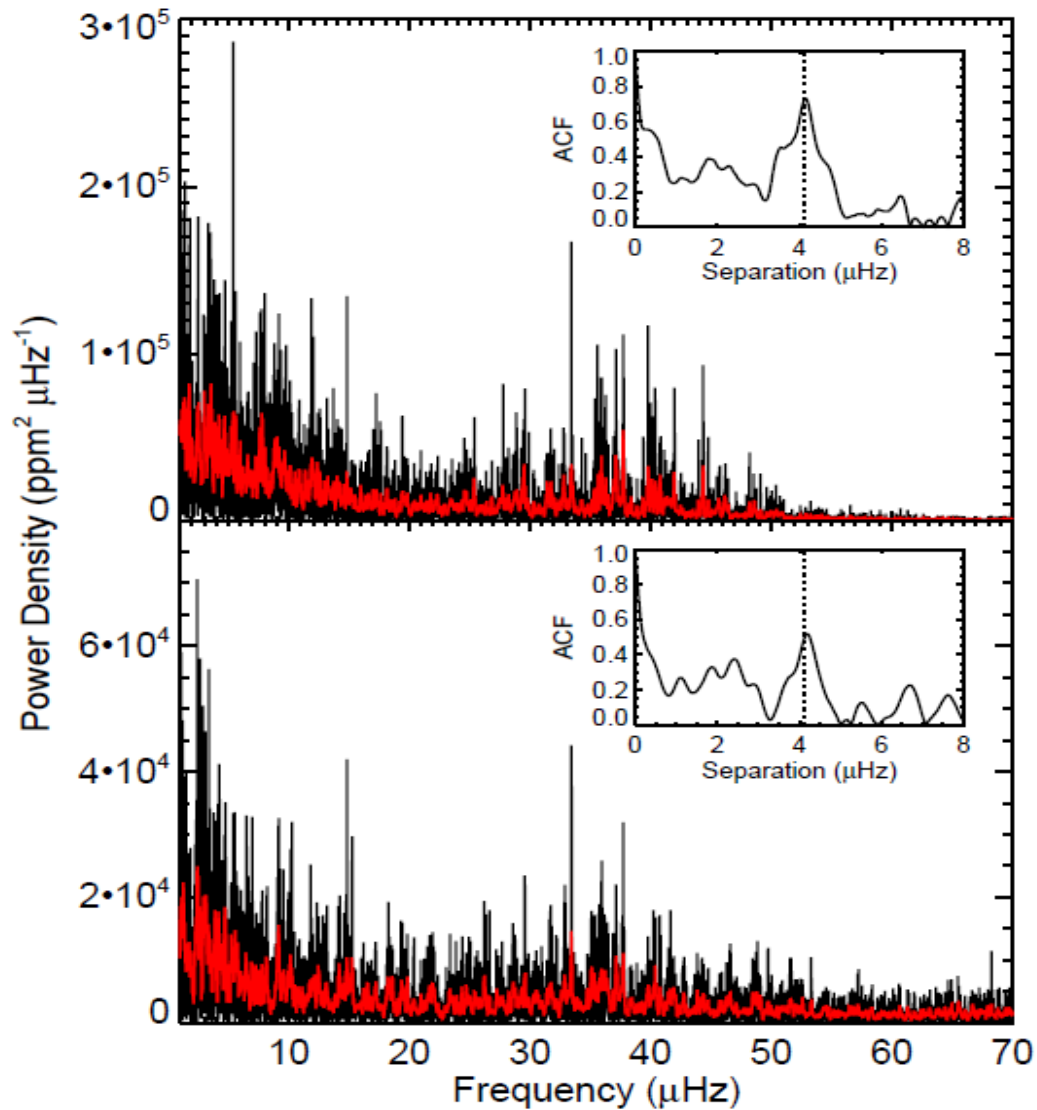
Gould, Huber, Penny, Stello, 2015 JKAS, in press

Non-Microlensing WFIRST Science:



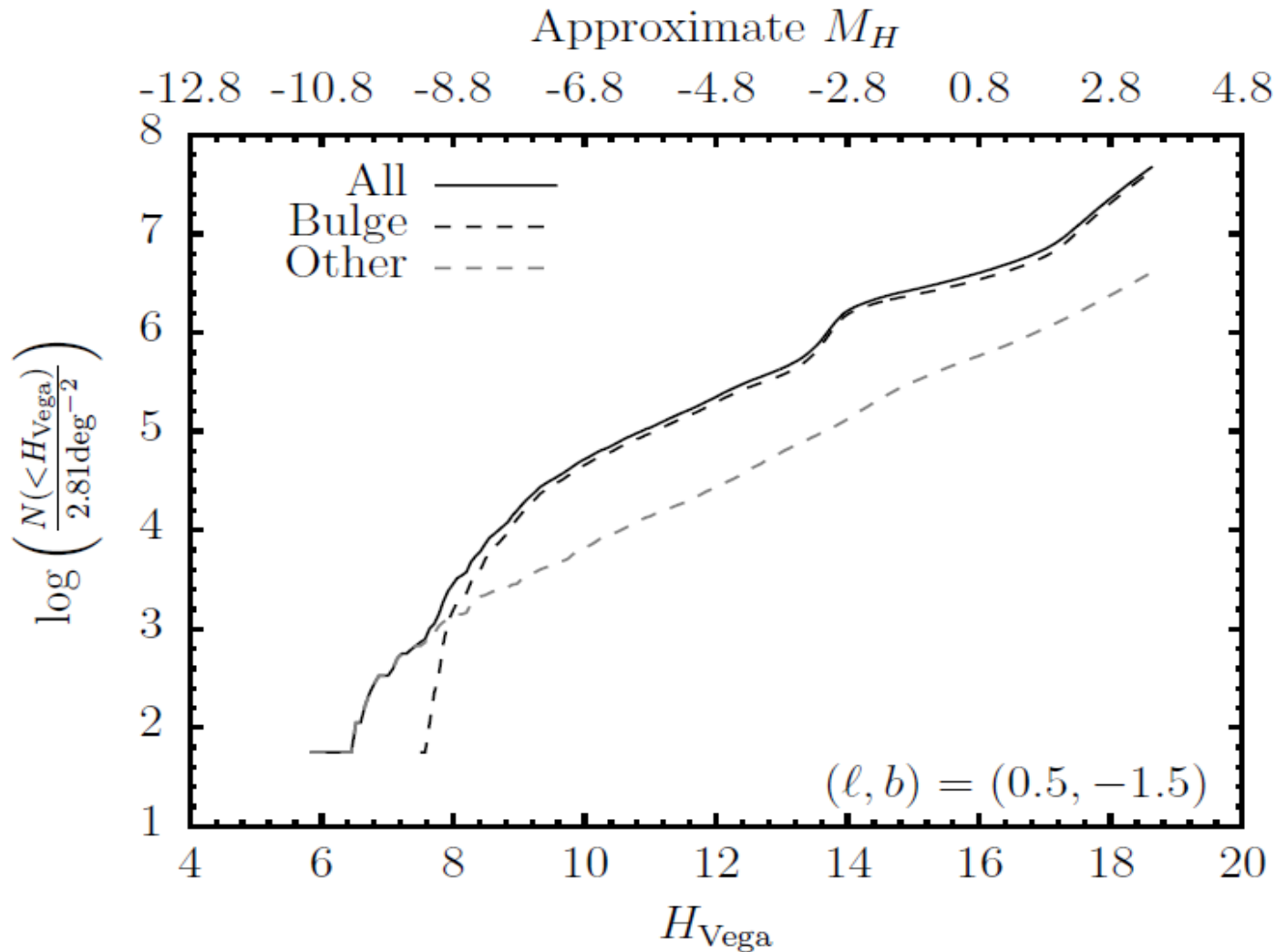
Gould, Huber, Penny, Stello, 2015 JKAS, in press

Non-Microlensing WFIRST Science:



Gould, Huber, Penny, Stello, 2015 JKAS, in press

Non-Microlensing WFIRST Science:



Gould, Huber, Penny, Stello, 2015 JKAS, in press

Conclusions

- **Microlens Mass Measurements now “common”**
 - But only for nearby lenses
- **Spitzer delivering dozens of μ lens parallaxes**
 - Longer program-> Galactic Planet Distribution
- **Multi-Plexing for Mass Production of Microlens Parallaxes (MP)³**
 - Kepler can measure Free-Floating Planets
- **WFIRST mlensing -> Planets +++**
 - Astrometry: 100 times better than Gaia
 - Asteroseismology of 1,000,000 stars
 - Precision orbits for 5000 ultra-faint KBOs