Title: Microlensing Takes Off: Toward the Galactic Distribution of Planets

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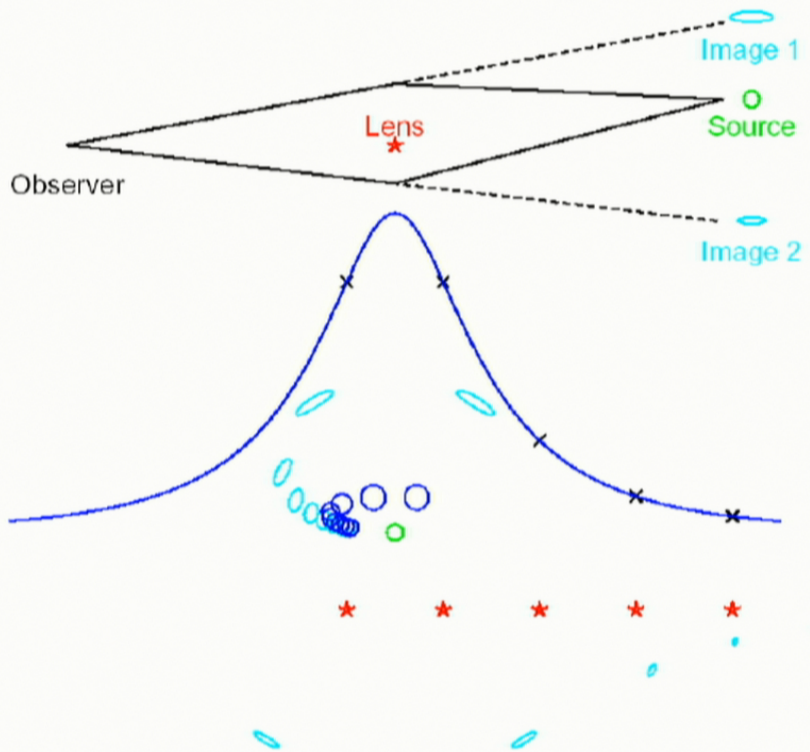
Abstract: <p>After 50 years of dreaming about it, space-based microlensing observations are now underway. A 2014 100-hr Spitzer Pilot Program generated "microlens parallaxes" for dozens of lenses, opening the prospect of measuring the Galactic distribution of planets. This program will be expanded 8-fold in 2015. Analogous observations by Kepler will measure the mass function of free-floating planets.</p>

<p>WFIRST microlensing observations will, as advertised, "complete the planetary census" but they will do an immense amount of astrophysics as well. I discuss how microlensing's take off builds on rapid, ongoing, ground-based developments.</p>

# 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
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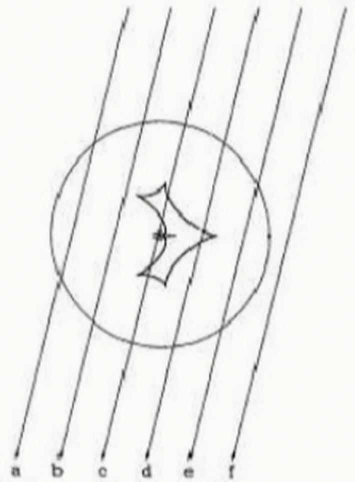
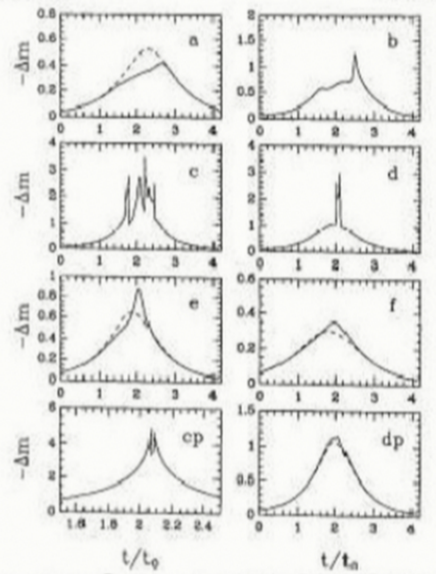
*Received 1991 March 12; accepted 1991 April 2*




. 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

# Planetary Caustics

DISCOVERING PLANETARY SYSTEMS THROUGH GRAVITATIONAL MICROLENSES

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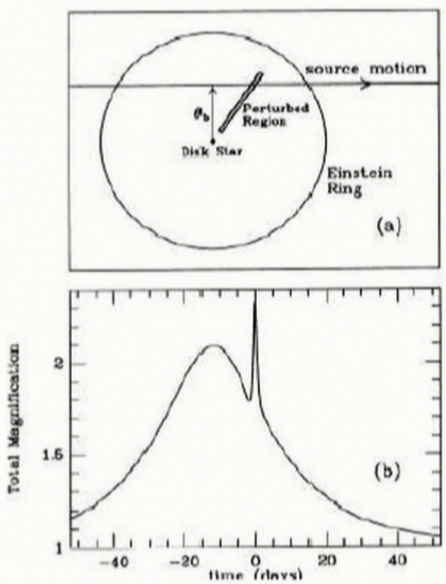
*Received 1991 December 26; accepted 1992 March 9*




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: $\alpha$ |
| Height of Perturbation | Planet-star separation: s |
| Width of Perturbation | Planet/star mass ratio: q |

# 6 Features

Time of Peak

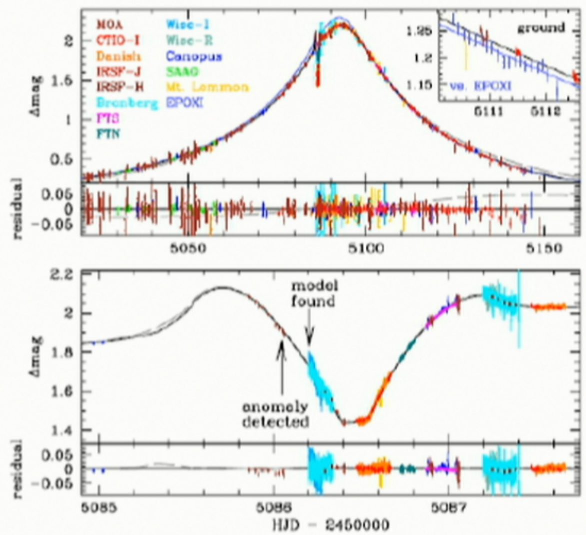
Height of Peak

Width of Peak

Time of Perturbation

Height of Perturbation

Width of Perturbation



# 7 Features & 7 Parameters

| 7 Features | 7 Parameters |
| --- | --- |
| Time of Peak | t_0 |
| Height of Peak | u_0 |
| Width of Peak | t_E |
| Time of Perturbation | Trajectory angle: $\alpha$ |
| Height of Perturbation | Planet-star separation: s |
| Width of Perturbation | Planet/star mass ratio: q |
| Width of Caustic Cross | Normalize source size: $\rho$ |

# 7 Features

Time of Peak

Height of Peak

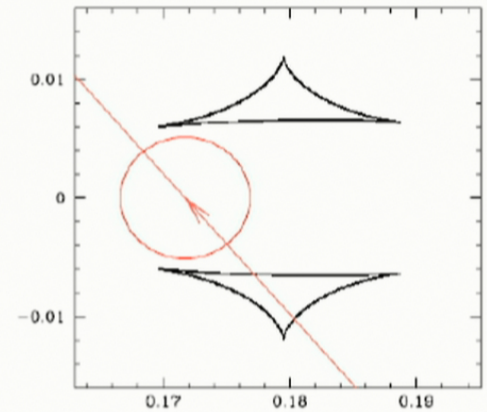
Width of Peak

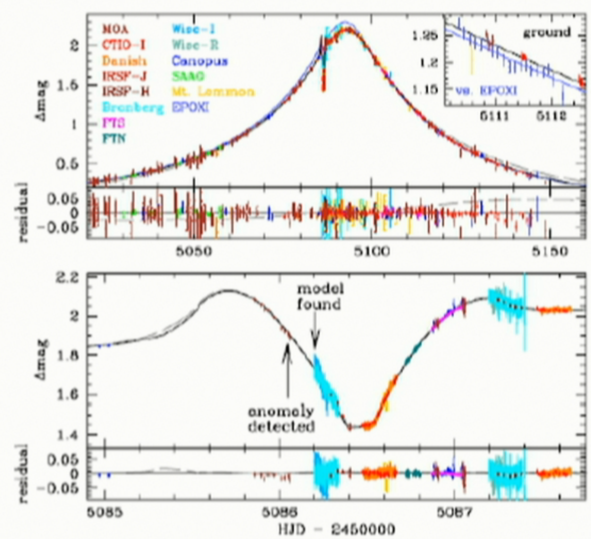
Time of Perturbation

Height of Perturbation

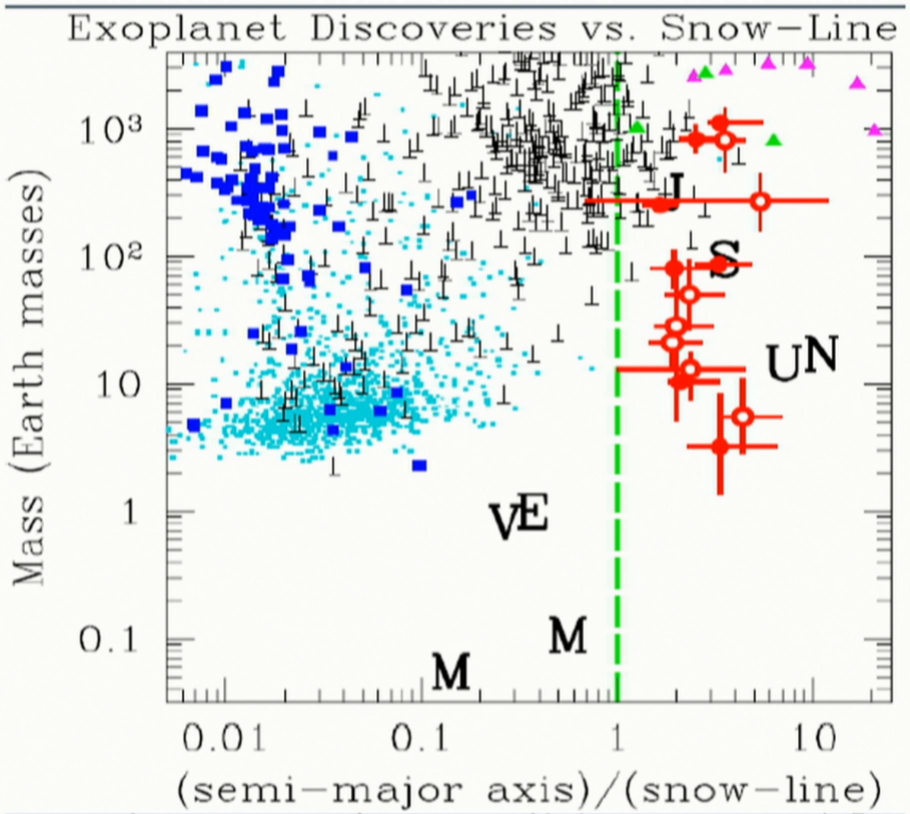
Width of Perturbation

Width of Caustic Cross

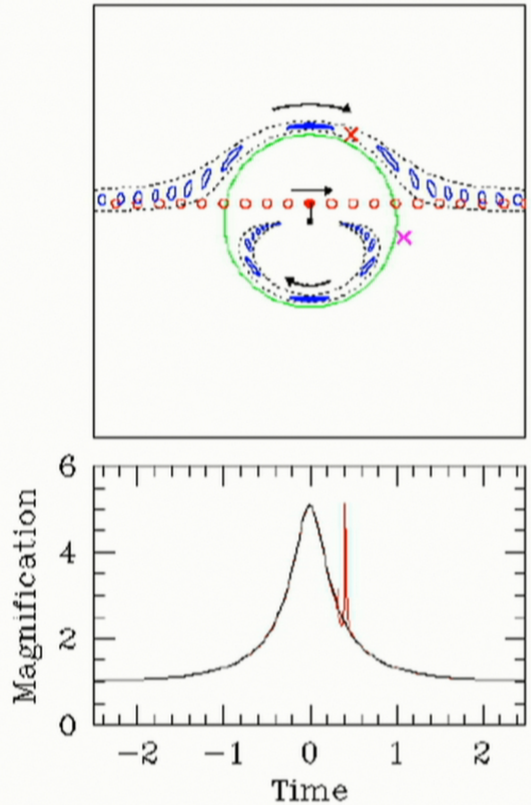


# Planets 2011

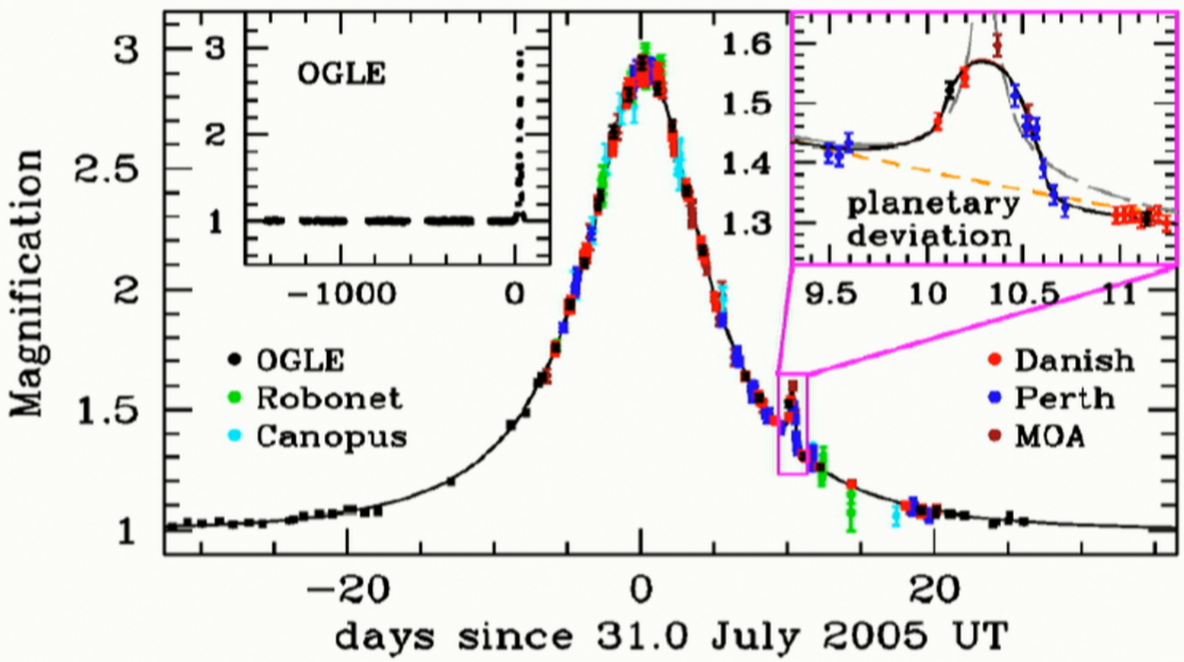


# How Microlensing Finds Planets



# OGLE-2005-BLG-390

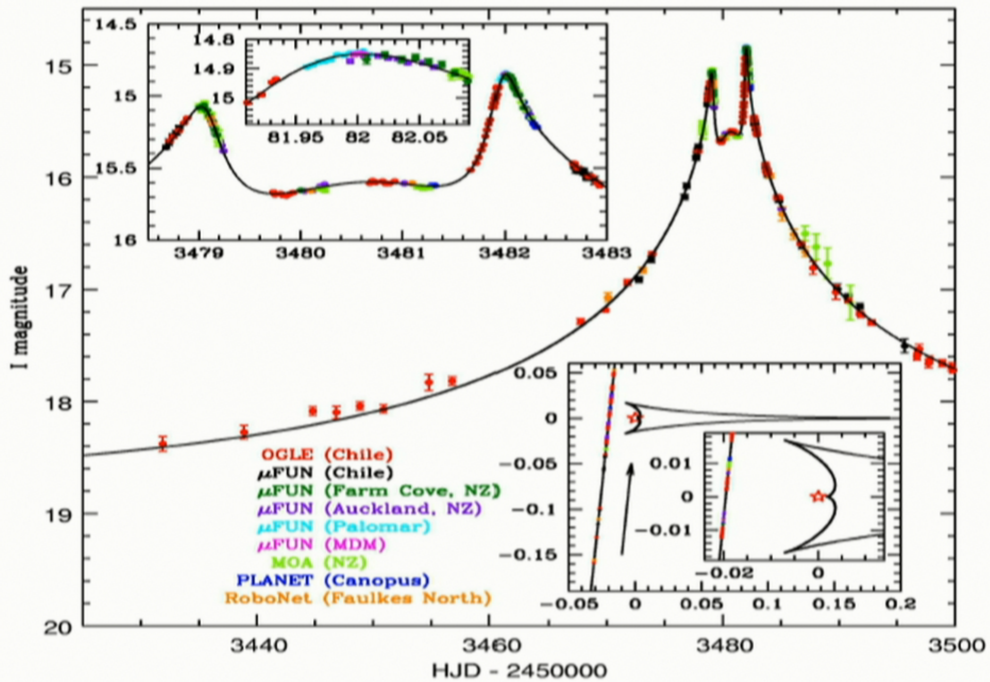
## "Classical-Followup" Planetary Caustic




Beaulieu et al. 2006, Nature, 439, 437

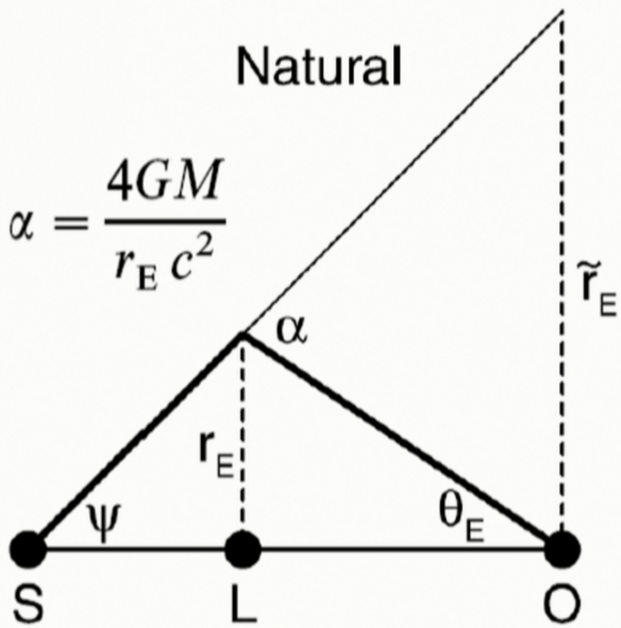
# OGLE-2005-BLG-071

## First "High-Mag" Event




Udalski et al. 2005, ApJ, 628, L109

# Relation of Mass and Distance to Lensing Observables



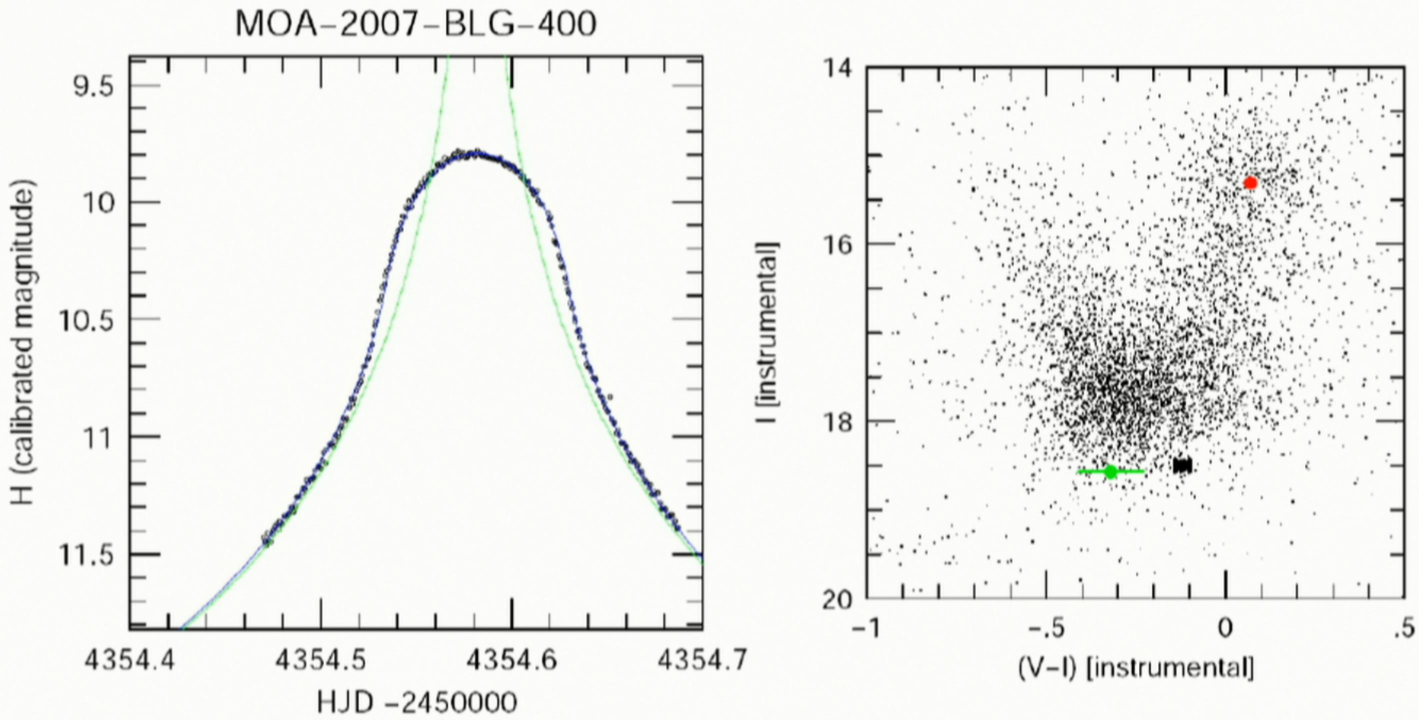

$$\alpha/\tilde{r}_E = \theta_E/r_E$$

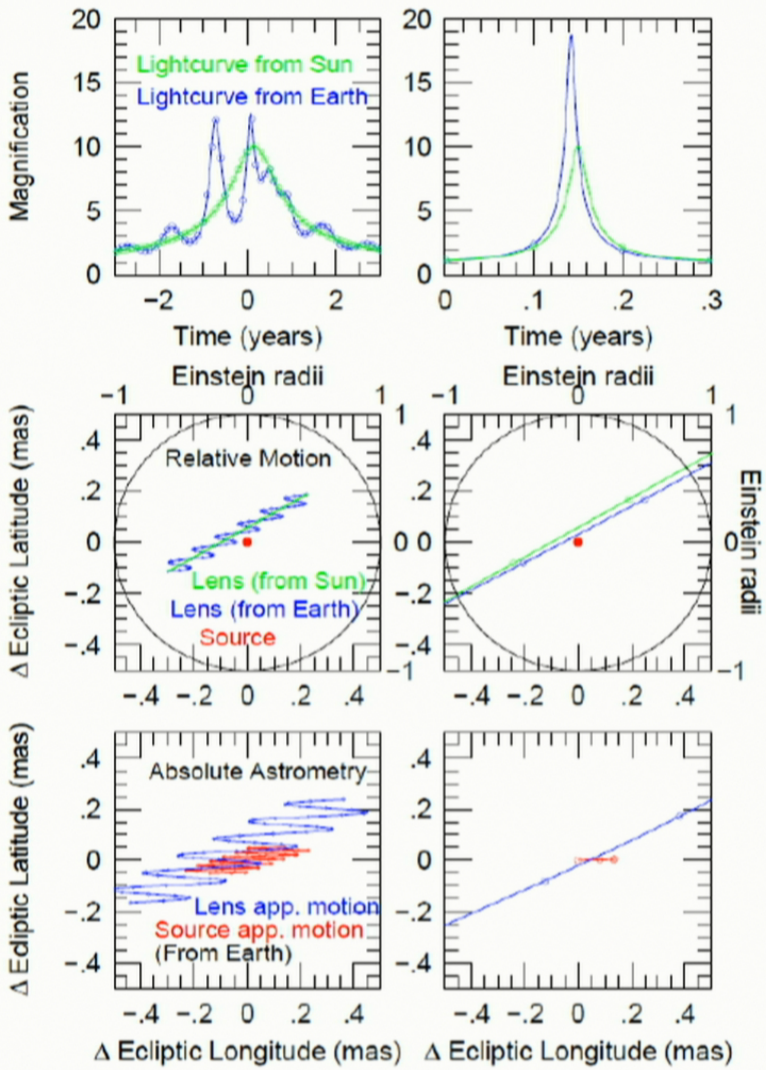
$$\theta_E \tilde{r}_E = \alpha r_E = \frac{4GM}{c^2}$$

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

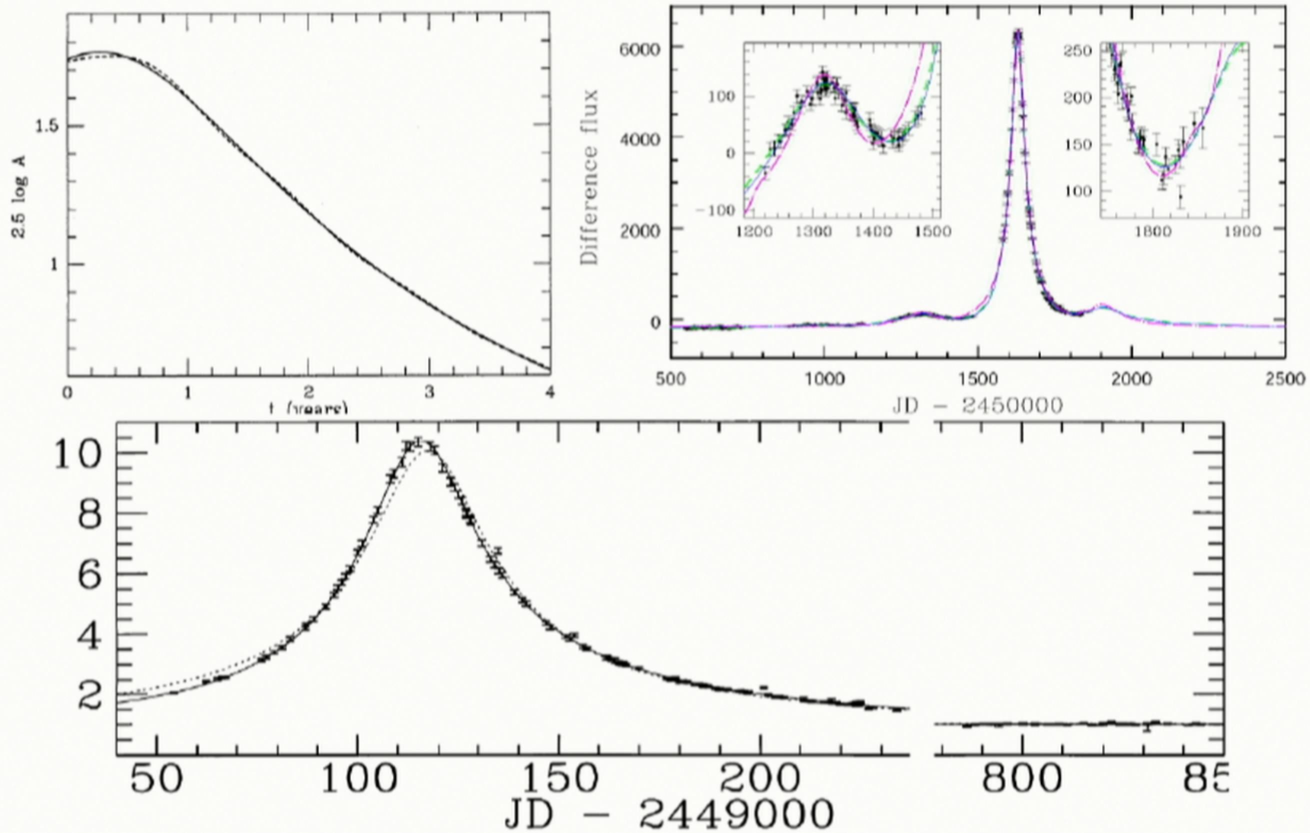
$$\tilde{r}_E = \sqrt{\frac{4GMD_{rel}}{c^2}} \qquad \theta_E = \sqrt{\frac{4GM}{D_{rel}c^2}}$$

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

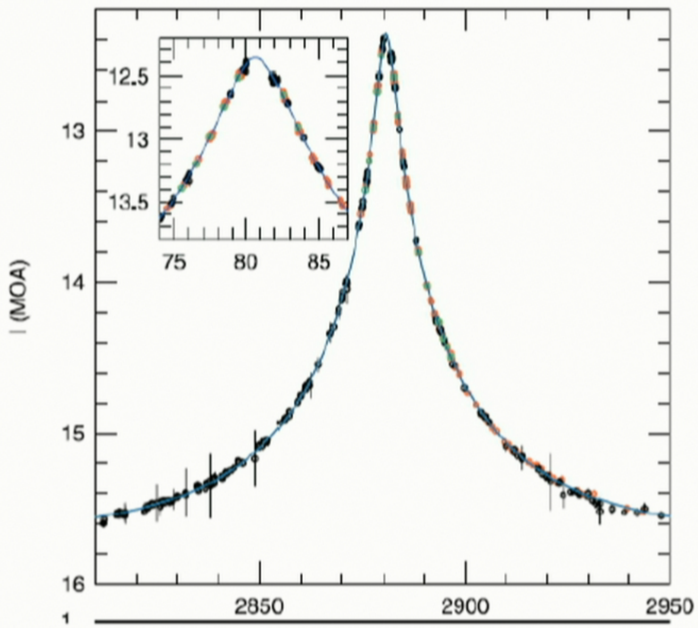



Lightcurve from Sun
Lightcurve from Earth
Magnification
Time (years)
Einstein radii
Relative Motion
Lens (from Sun)
Lens (from Earth)
Source
Δ Ecliptic Latitude (mas)
Absolute Astrometry
Lens app. motion
Source app. motion
(From Earth)
Δ Ecliptic Longitude (mas)

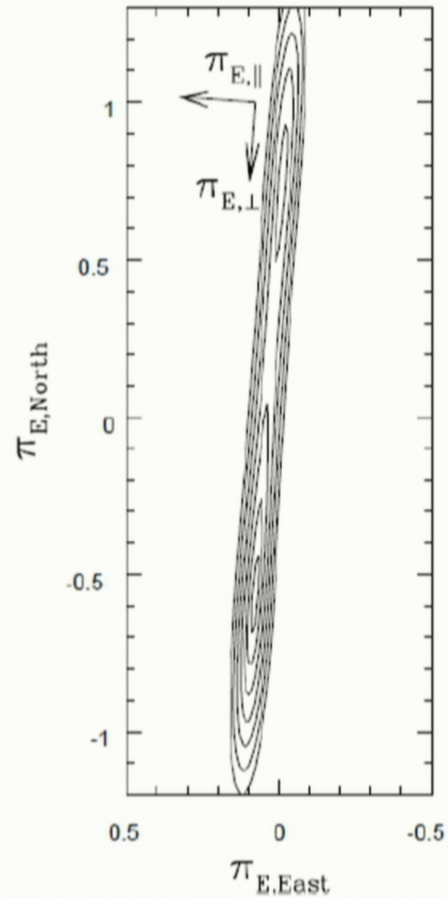
# To measure parallax:
## Standard Observer-Plane Rulers



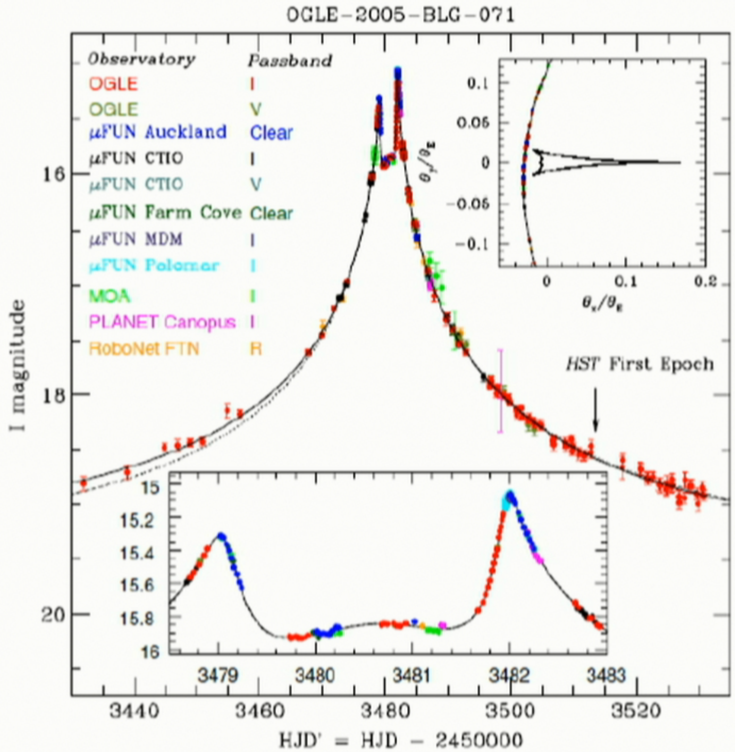
# 1-D Parallaxes Are "Common"

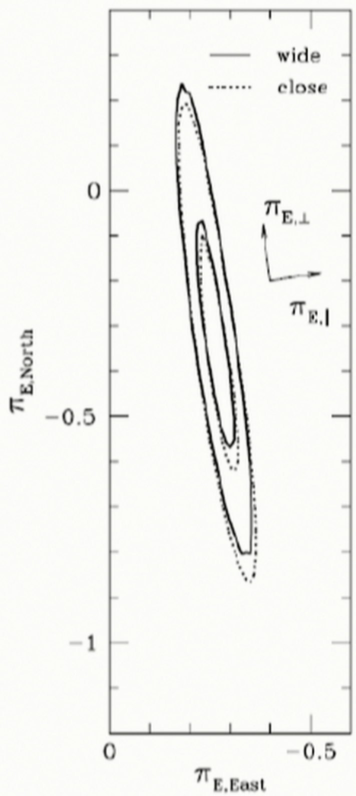



MOA-2003-BLG-37
Park et al. 2004, ApJ. 609, 166



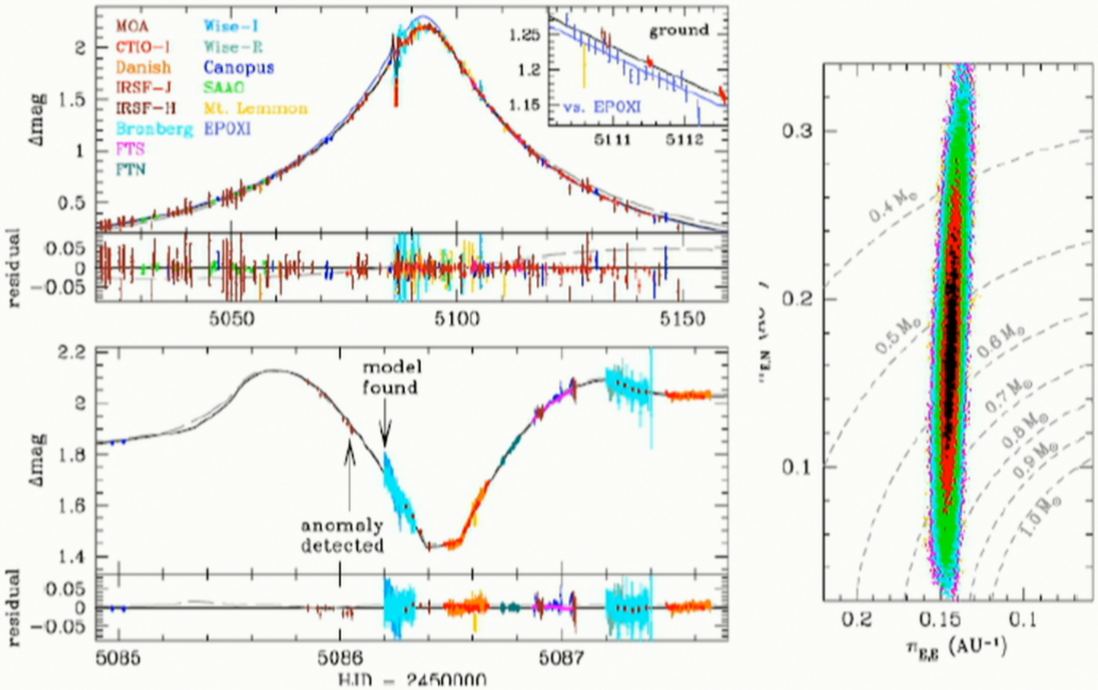
# 1-D Parallaxes Are "Common"




OGLE-2005-BLG-071
Dong et al. 2009, ApJ. 695, 970

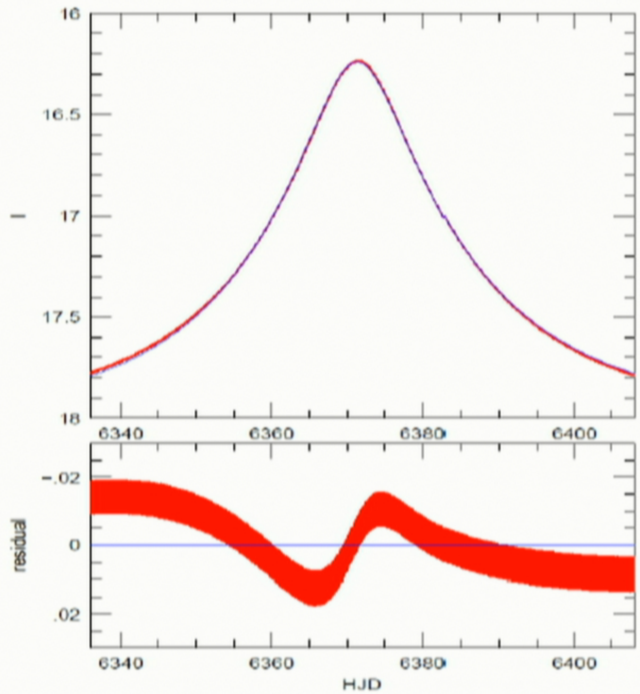
# 1-D Parallaxes Are “Common”




MOA-2009-BLG-266
Muraki et al. 2011, ApJ, 741, 22

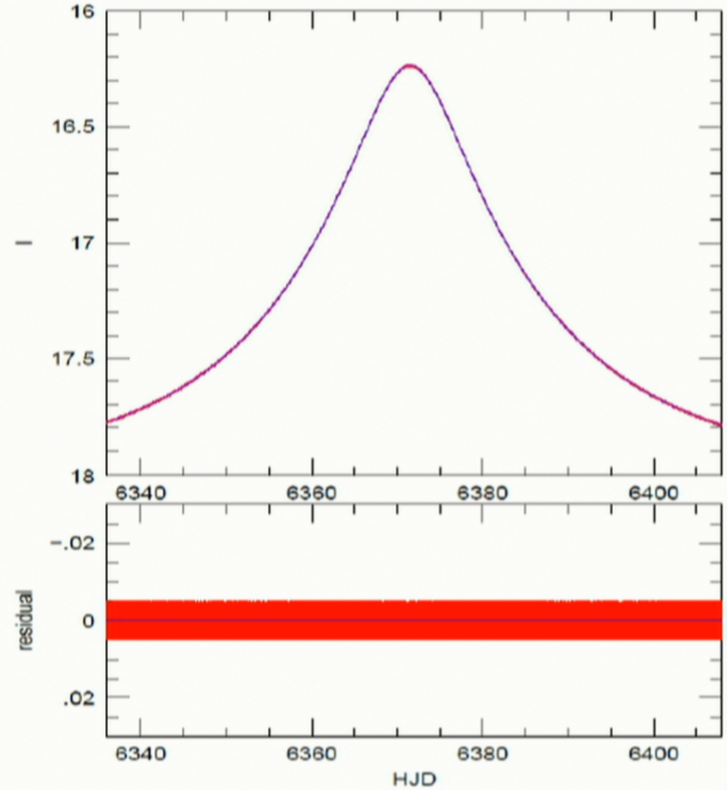
# $\pi_{E,parallel}$ (square peg: round hole)

# Component of $\pi_E$ toward Sun



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

# Component of $\pi_E$ perp to Sun



# What can be done?

Focus on nearby low-mass lenses

-Biased toward long $t_E$

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

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

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

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

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

$$C_3 = \alpha \frac{\pi_{E,\parallel}}{t_E} + \frac{1}{4}\alpha^2 t_E u_0 \boldsymbol{\pi}_E \times \boldsymbol{\pi}_j,$$

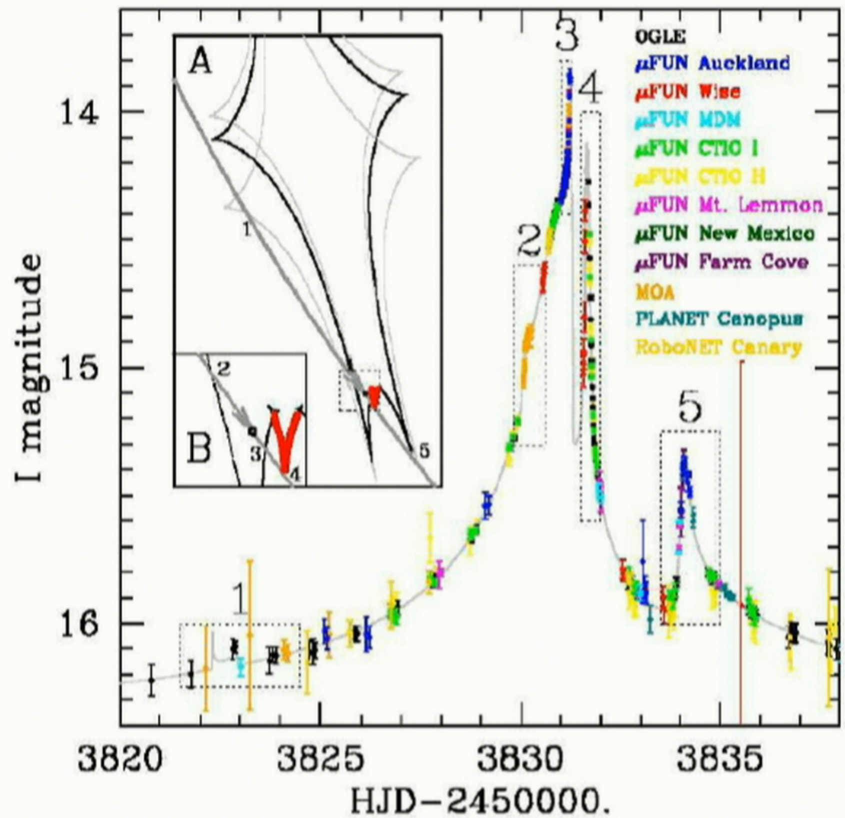
$$C_4 = \frac{\alpha^2}{4}(\pi_E^2 + \boldsymbol{\pi}_j \cdot \boldsymbol{\pi}_E) + \frac{1}{12}\frac{\Omega_\oplus^2}{\alpha} u_0 \pi_{E,\perp},$$

**Table 1**
Monitored Events with Magnification $A > 100$

| Name | $A_{max}$ | $t_0$(HJD) | $t_E$ | $M/M_\odot$ | Method |
|---|---|---|---|---|---|
| OGLE-2007-BLG-224 | 2424 | 4233.7 | 7 | $0.056 \pm 0.004$ | $M = \theta_E/\kappa\pi_E$ |
| OGLE-2008-BLG-279 | 1600 | 4617.3 | 101 | $0.64 \pm 0.10$ | $M = \theta_E/\kappa\pi_E$ |
| OGLE-2005-BLG-169 | 800 | 3491.9 | 43 | $0.49^{+0.23}_{-0.29}$ | $GM \oplus \theta_E \oplus t_E$ |
| MOA-2007-BLG-400 | 628 | 4354.6 | 14 | $0.30^{+0.19}_{-0.12}$ | $GM \oplus \theta_E \oplus t_E$ |
| OGLE-2007-BLG-349 | 525 | 4348.6 | 121 | $\sim 0.6$ | $M = \theta_E/\kappa\pi_E$ |
| OGLE-2007-BLG-050 | 432 | 4222.0 | 68 | $0.50 \pm 0.14$ | $M = \theta_E/\kappa\pi_E$ |
| MOA-2008-BLG-310 | 400 | 4656.4 | 11 | $\leqslant 0.67 \pm 0.14$ | AO |
| OGLE-2006-BLG-109 | 289 | 3831.0 | 127 | $0.51^{+0.05}_{-0.04}$ | $M = \theta_E/\kappa\pi_E$, AO |
| OGLE-2005-BLG-188 | 283 | 3500.5 | 14 | $0.16^{+0.21}_{-0.08}$ | $GM \oplus \theta_E \oplus t_E$ |
| MOA-2008-BLG-311 | 279 | 4655.4 | 18 | $0.20^{+0.26}_{-0.09}$ | $GM \oplus \theta_E \oplus t_E$ |
| 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

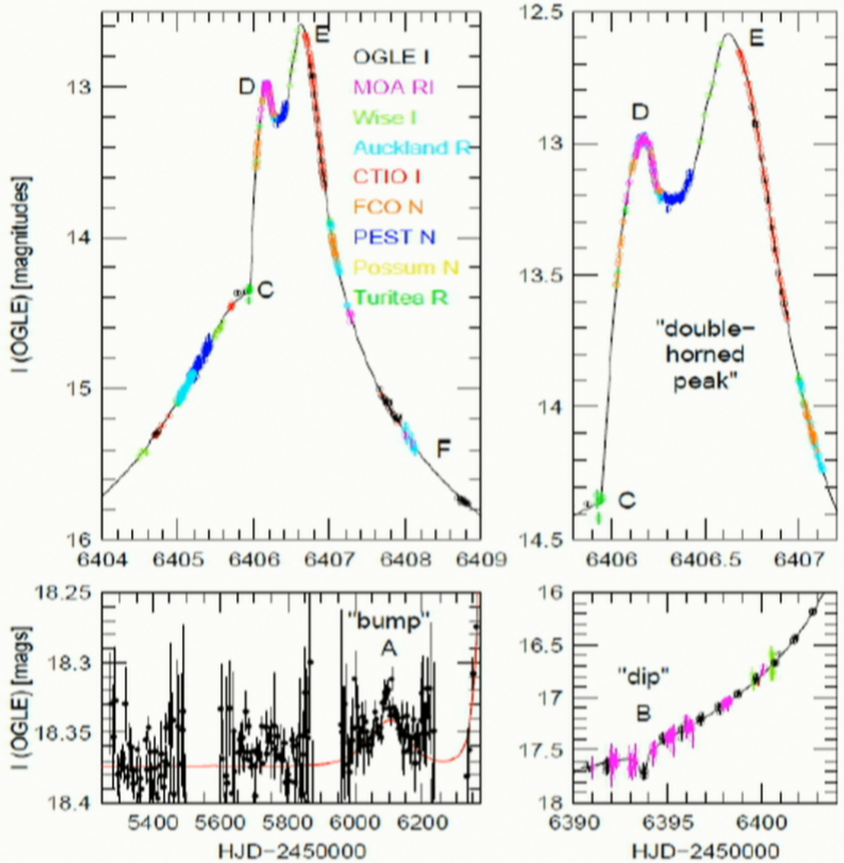



Gaudi et al. 2008, Science, 319, 927

# Generation 1.5: Survey+Followup

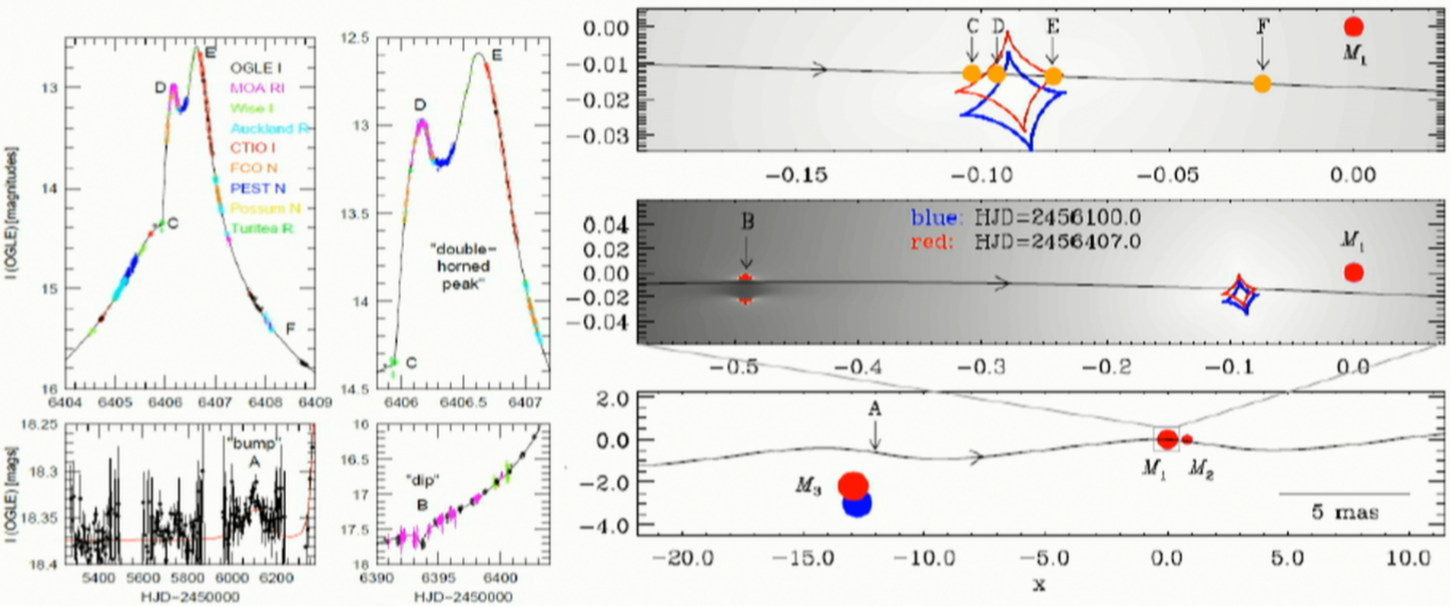
## OGLE-2013-BLG-0341

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



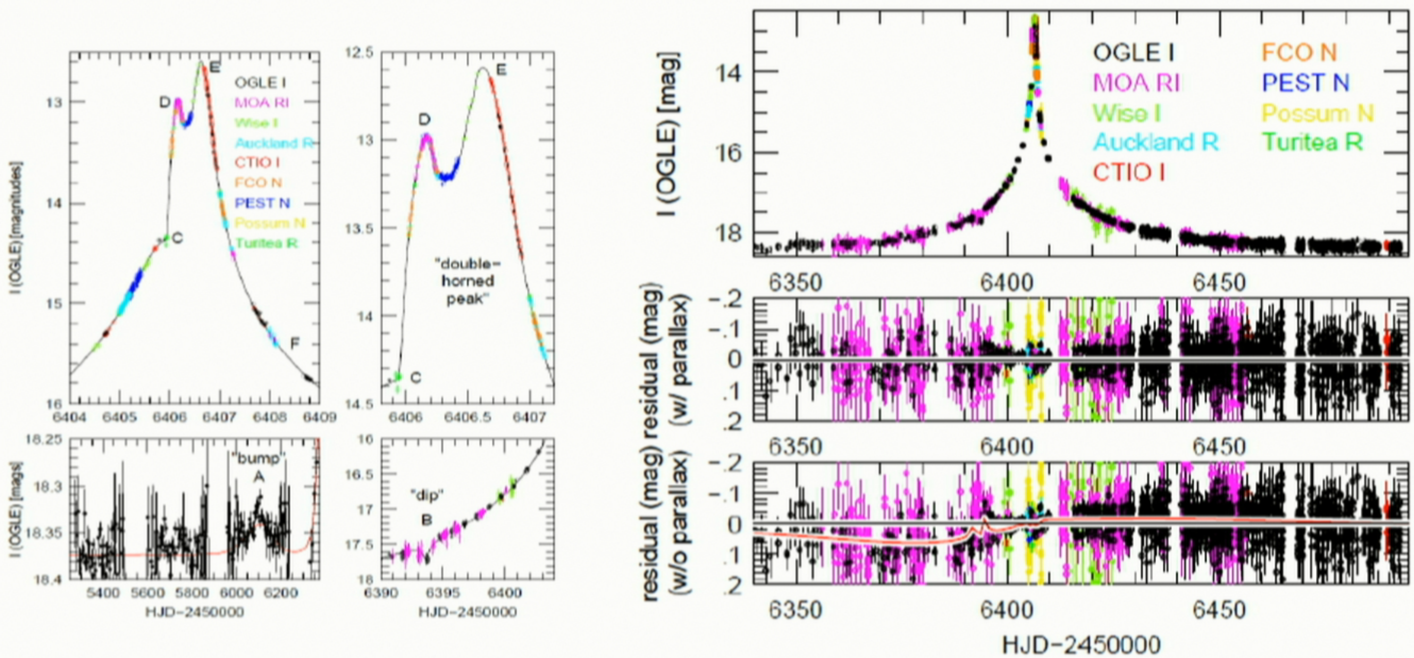
# OGLE-2013-BLG-0341: Binary+Planet at 1AU

## (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 $t_E$

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

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

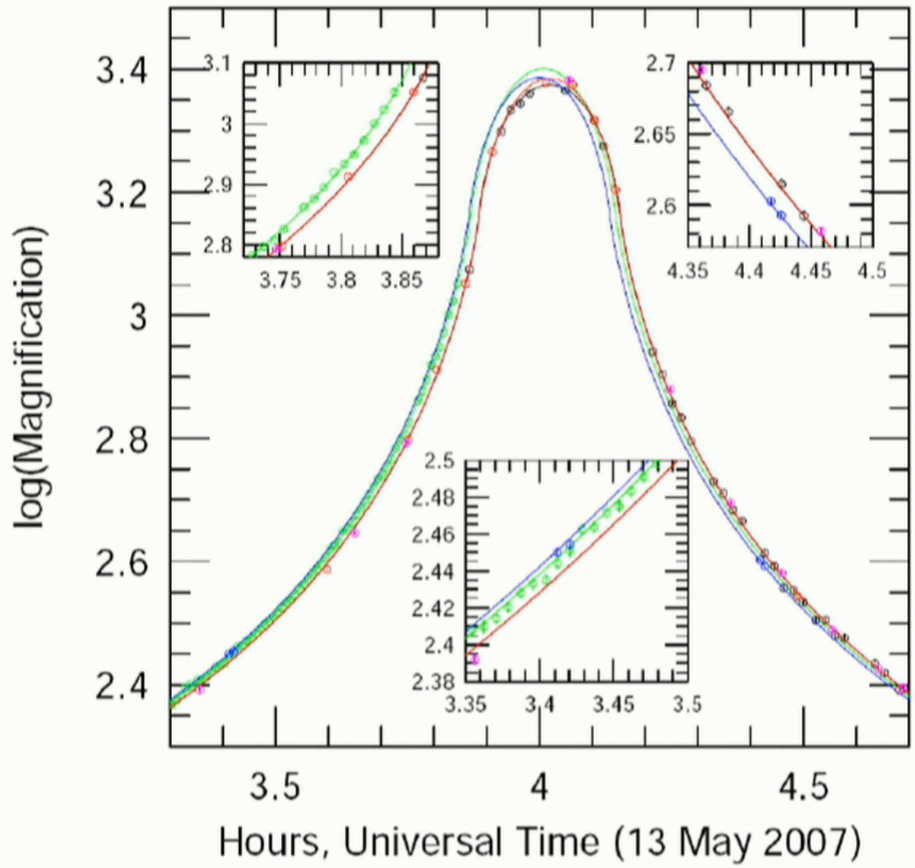
$\pi_{E,perp}$ (4th order in time)

Terrestrial Parallax

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

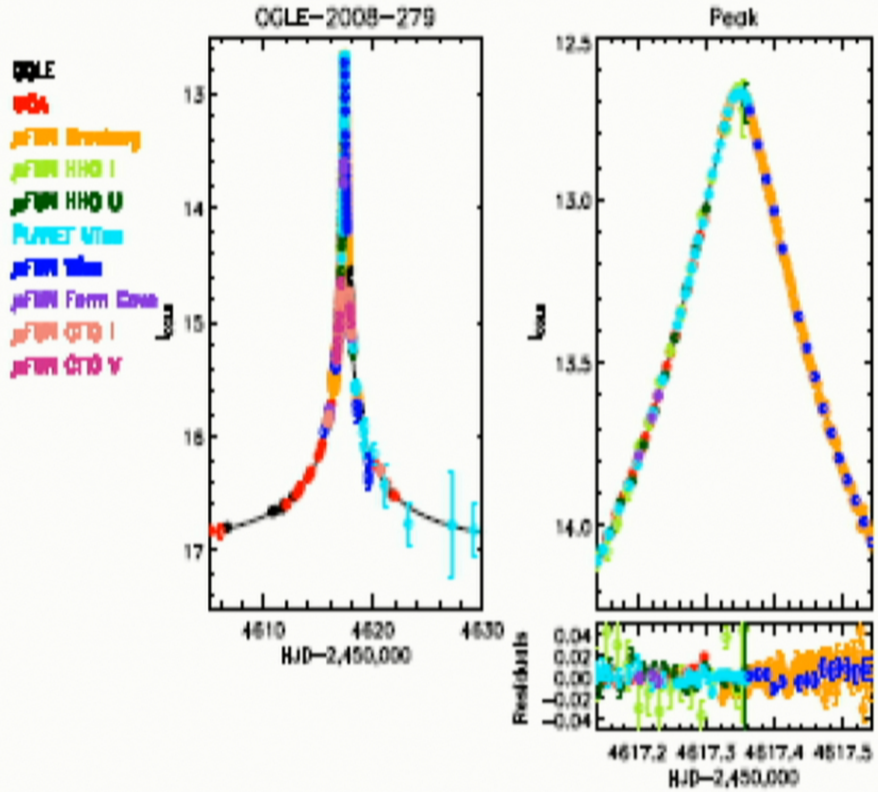
# OGLE-2007-BLG-224

## Canaries South Africa Chile



# OGLE-2008-BLG-279:

## A = 1600




Yee et al. 2009, ApJ, 730, 2082

Events with Terrestrial Parallax

| Name | $M$ ($M_\odot$) | $D_L$ (kpc) | $\mu$ (mas yr$^{-1}$) | $\theta_*$ ($\mu$as) | $\rho\tilde{r}_E$ ($R_\oplus$) | $t_E$ (day) | $A_{max}$ |
|---|---|---|---|---|---|---|---|
| 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 |

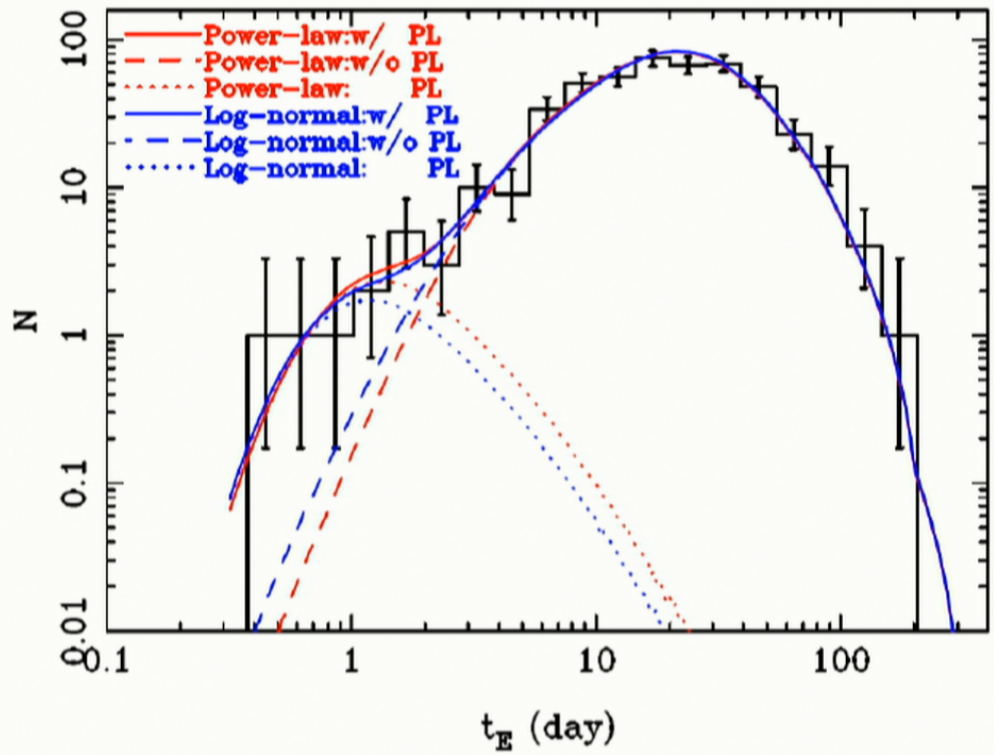
$$\pi_{\rm rel} = \theta_E \pi_E = \frac{\rm AU}{\rho\tilde{r}_E}\theta_* \gtrsim 0.28\,{\rm mas}\frac{\theta_*}{0.6\,\mu{\rm as}}$$

$$\Gamma = 2\langle\mu\rangle\theta_* \int_0^{D_{\rm max}} dD_L D_L^2 n(D_L) = 1.6\,{\rm Gyr}^{-1}$$
$$\times \left(\frac{\langle\mu\rangle}{10\,{\rm mas\ yr}^{-1}}\right)\left(\frac{\theta_*}{0.6\,\mu{\rm as}}\right)\left(\frac{D_{\rm max}}{2.5\,{\rm kpc}}\right)^3\left(\frac{\langle n\rangle}{1\,{\rm pc}^{-3}}\right)$$

$$(1/4)(1/10)(1/2)\Gamma N T = 0.1$$
$$({\rm N} = 5{\rm e}8;\ \ {\rm T} = 10\ {\rm yr})$$

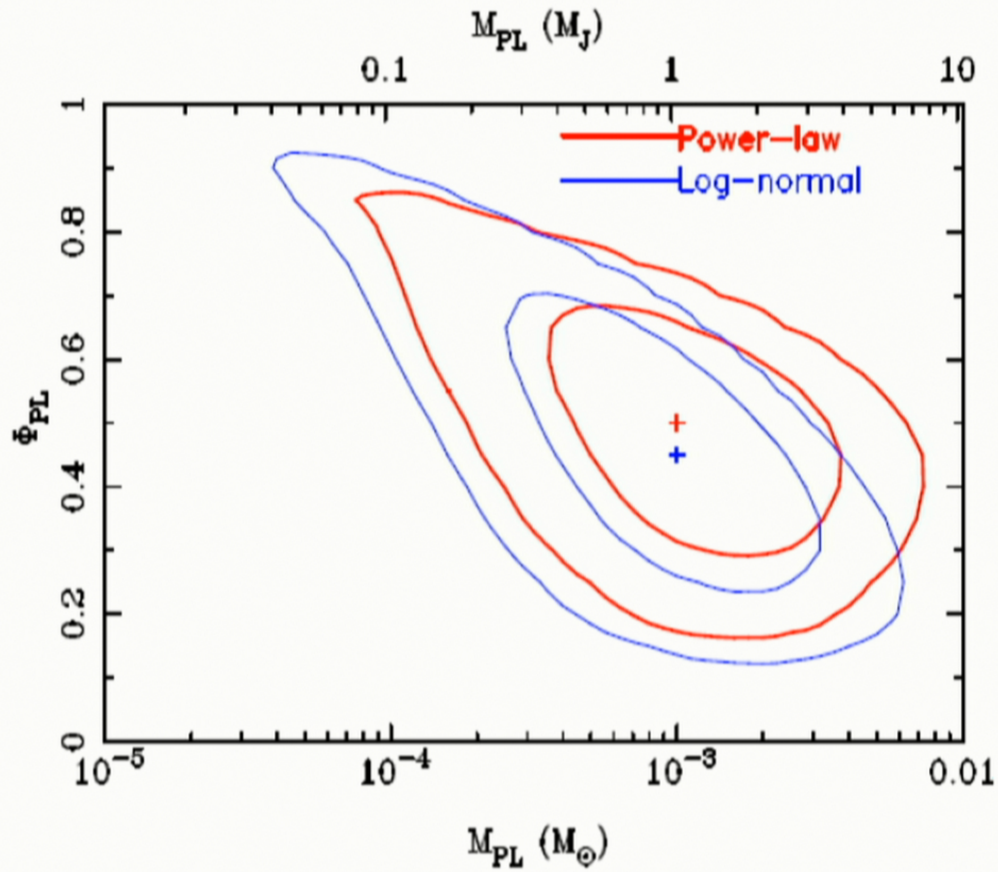
Gould & Yee 2012 ApJ, 764, 107

# 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)

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

$$t_E = \frac{\theta_E}{\mu}, \qquad \theta_E = \sqrt{\kappa M \pi_{\rm rel}}$$

$$t_{\mathbf{E}} \text{ small} \Rightarrow D_{LS} \ll D_S$$

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

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

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

# 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.

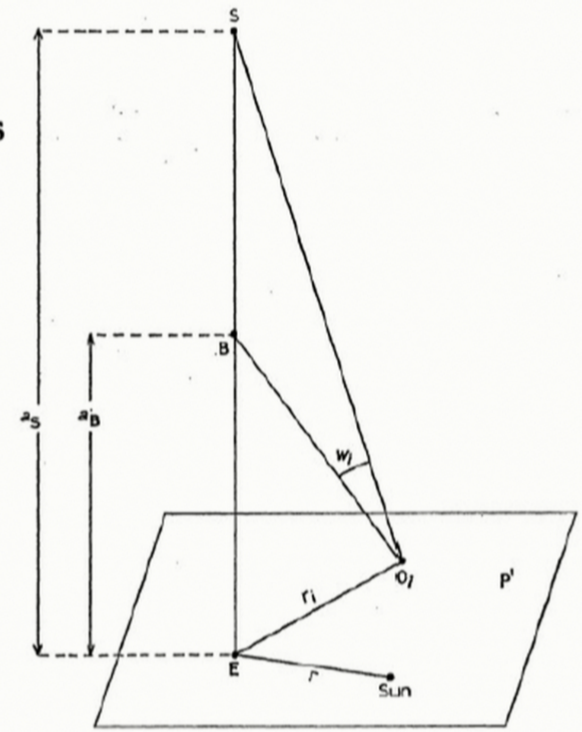
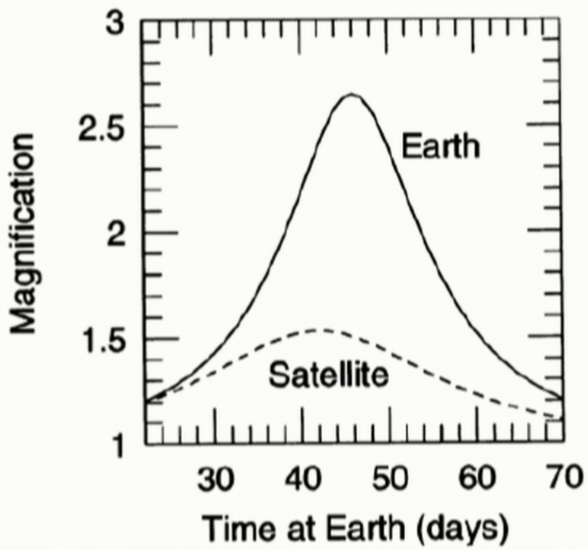
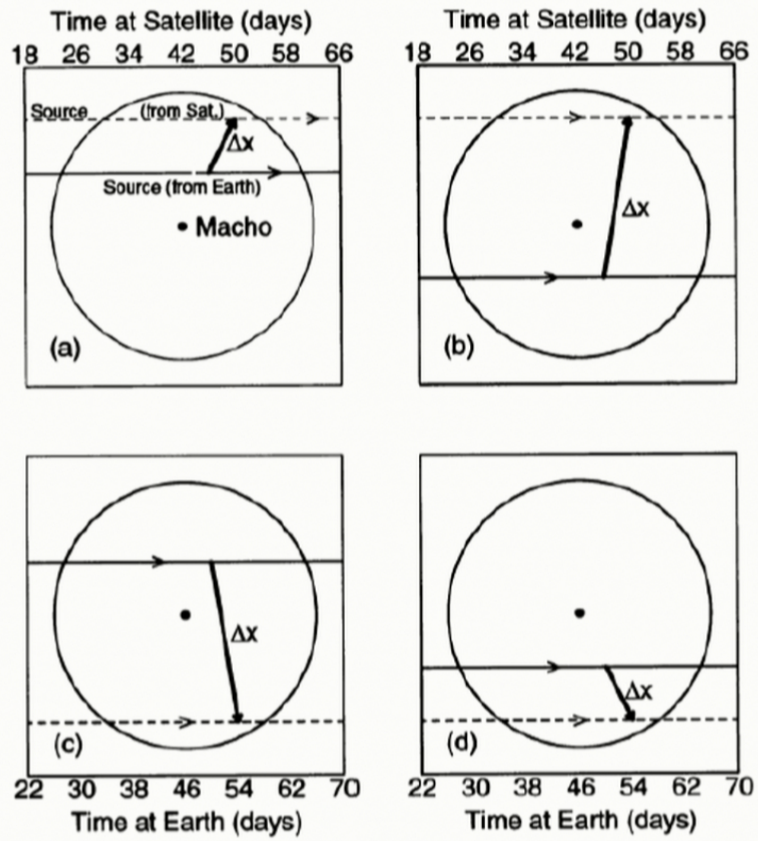


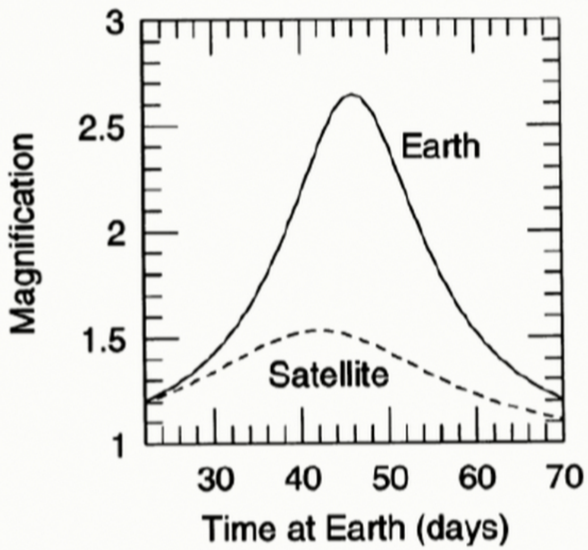

FIG. 1.

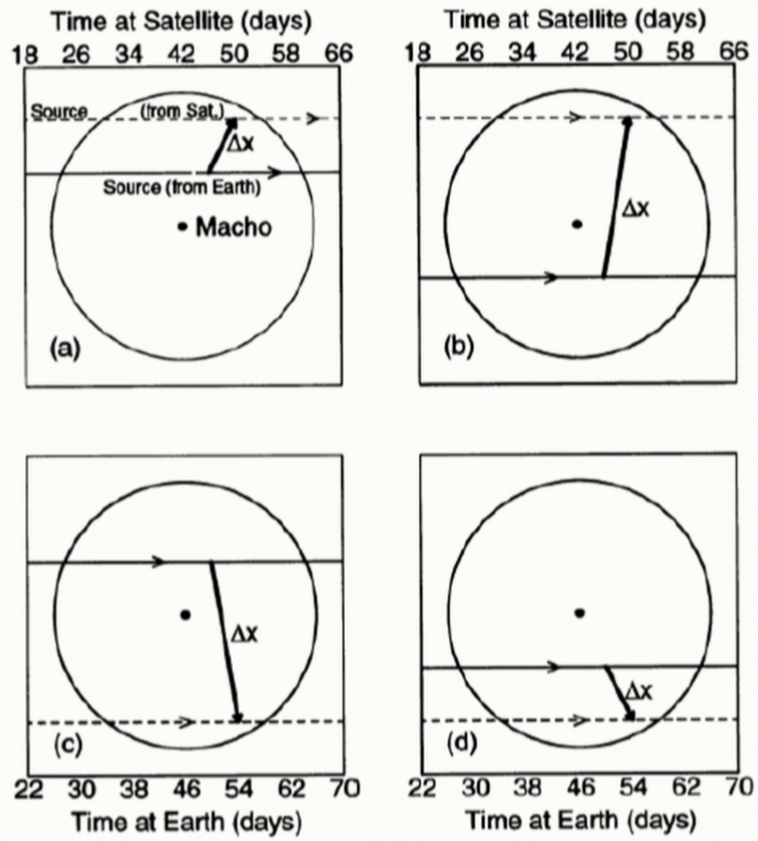
# Satellite Parallaxes (Panacea?)



# Satellite Parallaxes (Panacea?)



# From a paper written 15 years ago ...

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


## MICROLENS PARALLAXES WITH SIRTF

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Received 1998 July 27; accepted 1998 November 2

$$t_{0,S} = t_{0,\oplus} + \Delta t_0 \,,$$

$$\frac{\Delta t_0}{t_{e,\oplus}} = \Delta u_x \cos\theta - 2(\Omega_\oplus t_{e,\oplus})^{-2}\gamma_\oplus \sin^2\theta \,; \qquad (13)$$

$$\beta_S = |\beta_\oplus \pm \Delta\beta| \,, \quad \Delta\beta = \Delta u_x \sin\theta + (\Omega_\oplus t_{e,\oplus})^{-2}\gamma_\oplus \sin 2\theta \,; \qquad (14)$$

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

$$\frac{\Delta t_e}{t_{e,\oplus}} = \Delta u_x \Omega_\oplus t_{e,\oplus} \sin\theta + (\Omega_\oplus t_{e,\oplus})^{-1}\gamma_\oplus \sin 2\theta \,; \qquad (15)$$

$$\gamma_S = \Delta u_x (\Omega_\oplus t_{e,\oplus})^2 \cos\theta + \gamma_\oplus \cos 2\theta \,. \qquad (16)$$

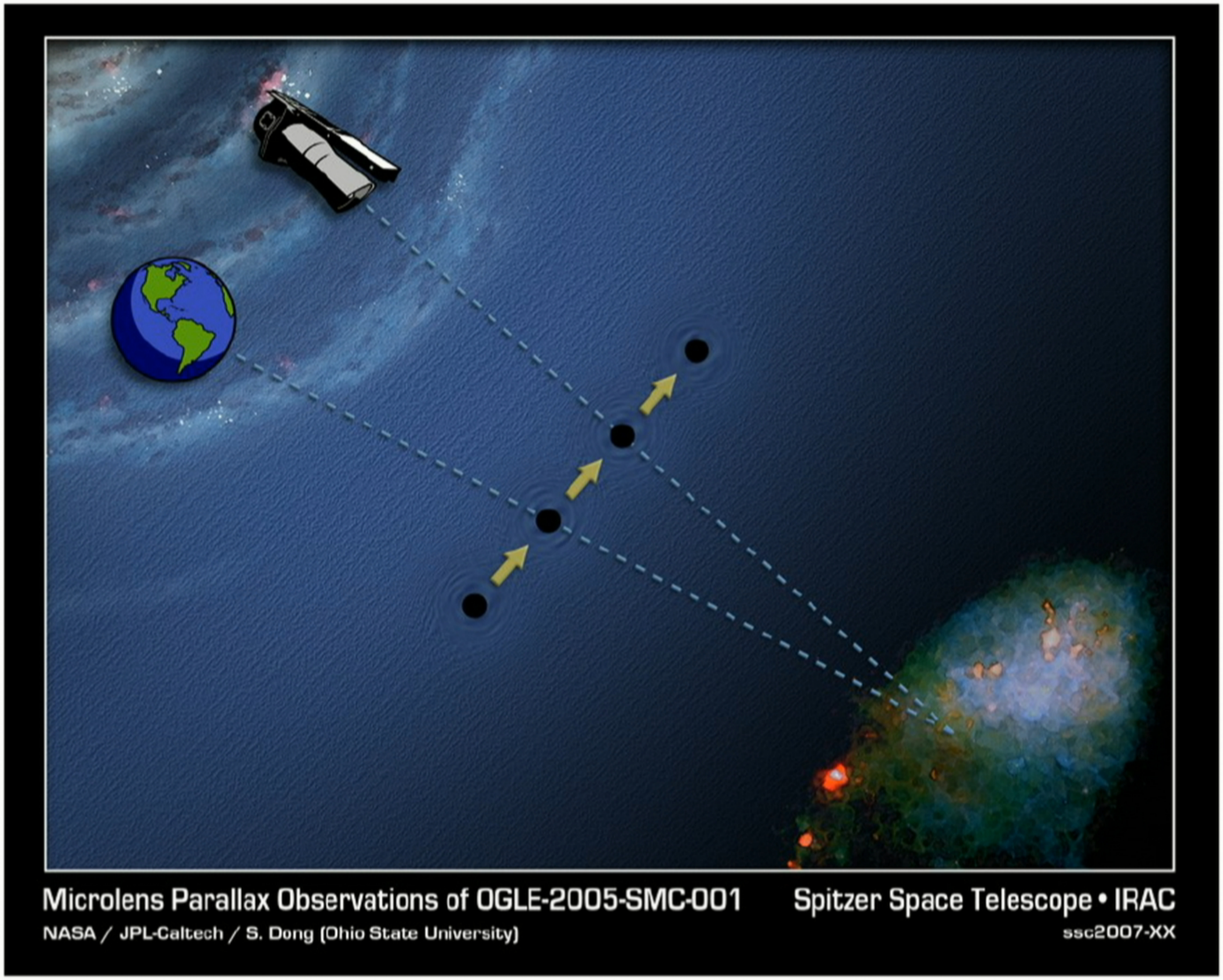
$$\frac{\sigma_{\Delta u_y}}{\Delta u} = \frac{\sigma_\gamma}{\gamma \sec\phi}$$

$$= 0.17 N^{-1/2} \frac{\sigma_0}{0.01} \frac{\tilde{v}}{275\ \mathrm{km\ s^{-1}}} \left(\frac{t_e}{40\ \mathrm{days}}\right)^{-3/2} \frac{S(\beta)}{8} \,. \qquad (21)$$

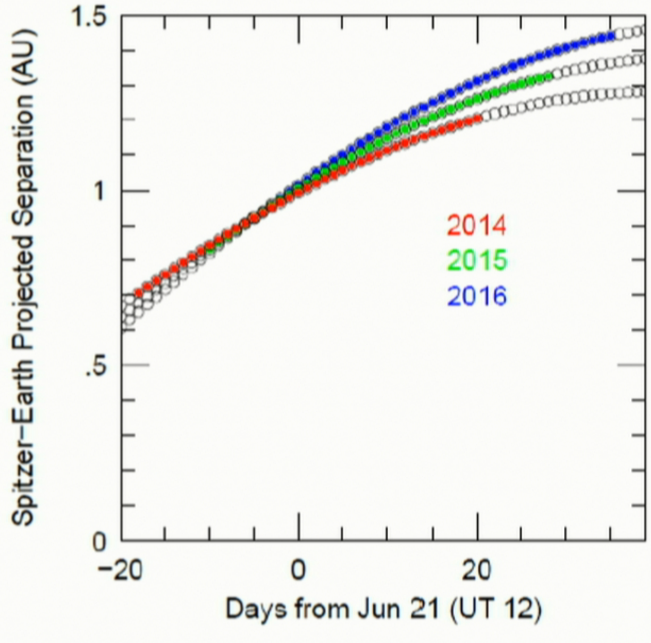
$$b_{ij}\left(\frac{t_0}{t_e}, \gamma\right) = \frac{64}{u^5(u^2+4)^{5/2}(u^2+2)\sigma_0^2} \begin{pmatrix} 2\tau^2 & -\tau^4 \\ -\tau^4 & \tau^6/2 \end{pmatrix} , \qquad (22)$$

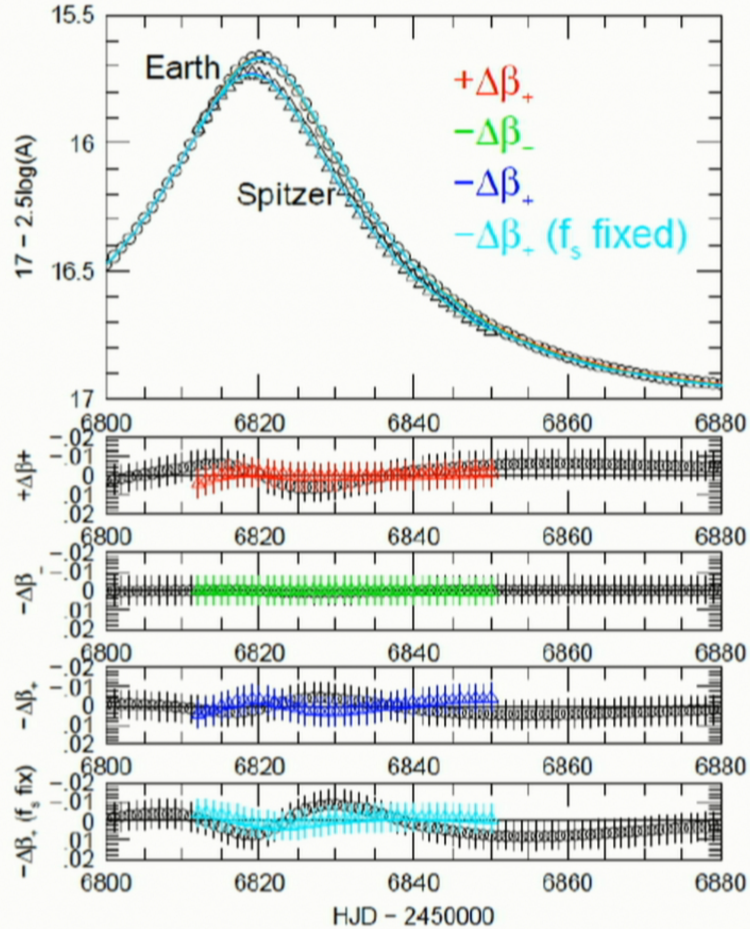
$$\frac{\sigma_{t_0}}{t_e} \sim \left(\frac{25}{12}\right)^{1/2} \beta\sigma_* \,, \quad \sigma_* = \left(\frac{5}{3}\right)^{1/4} \beta^{1/2}\sigma_0$$

$$\left[\text{at } \tau = \left(\frac{2}{3}\right)^{1/2}\beta\right] , \qquad (23)$$

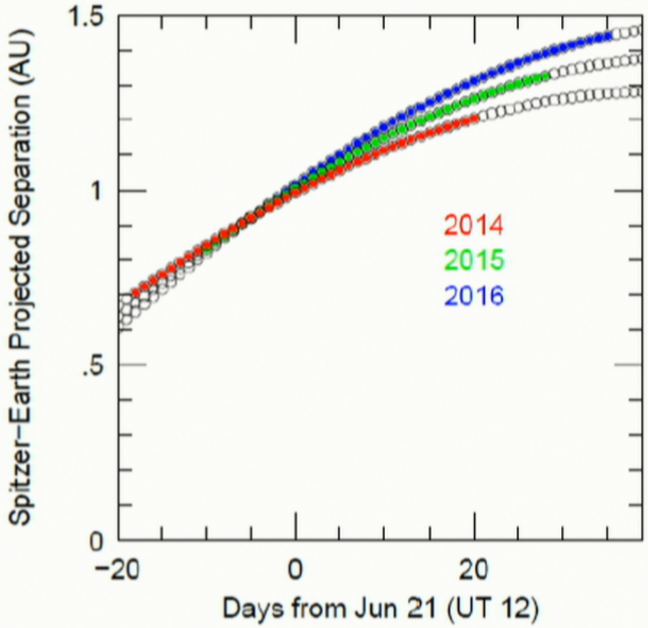

Microlens Parallax Observations of OGLE-2005-SMC-001
Spitzer Space Telescope • IRAC
NASA / JPL-Caltech / S. Dong (Ohio State University)
ssc2007-XX

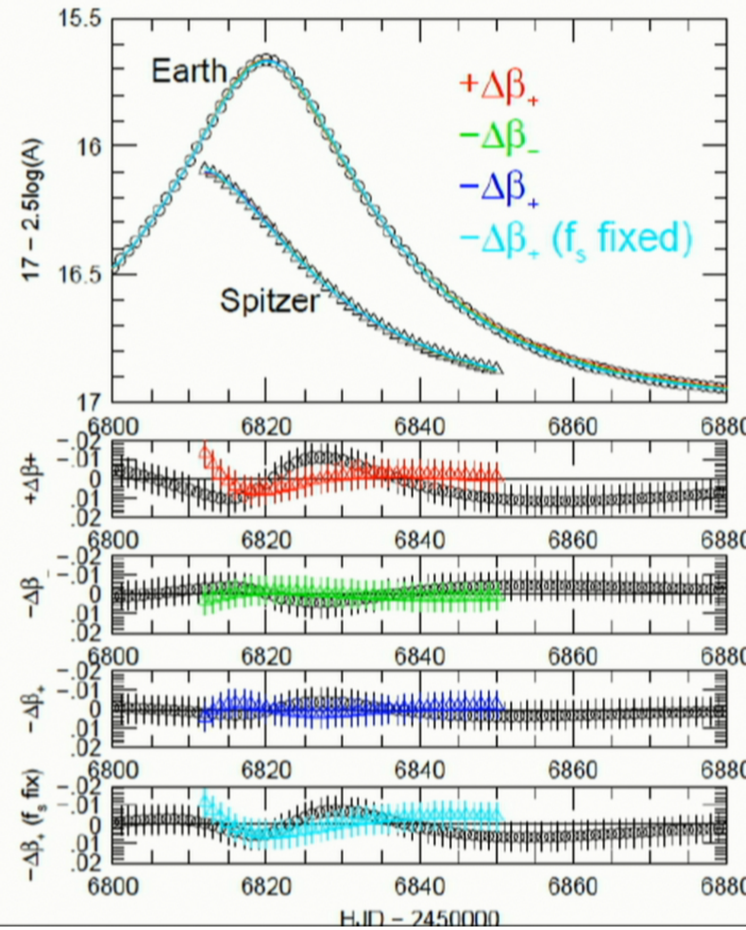
# 100-Hr Spitzer Feasibility Study 2014



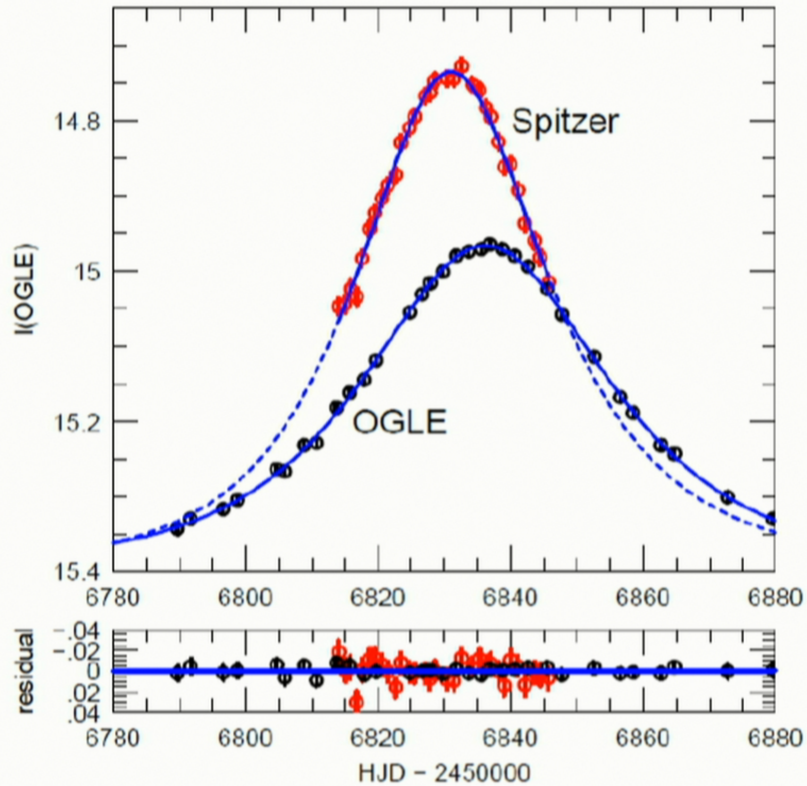
# 100-Hr Spitzer Feasibility Study 2014



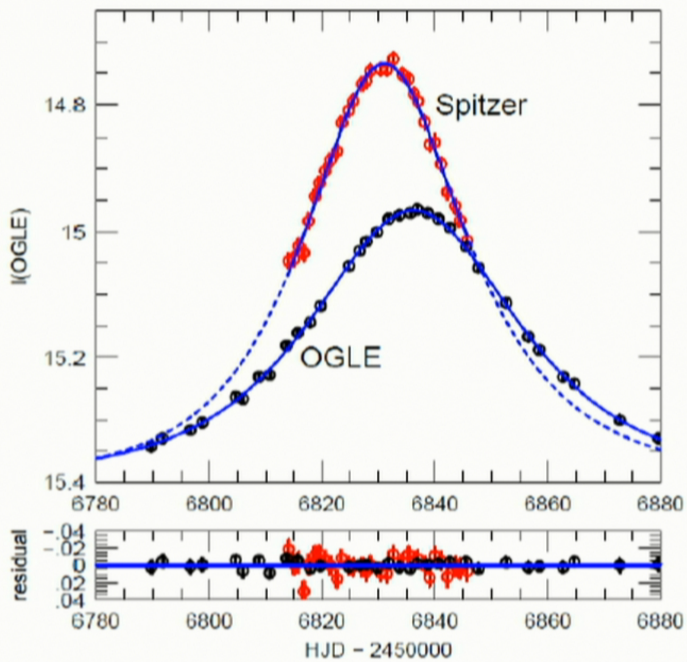
# OGLE-2014-BLG-0939:

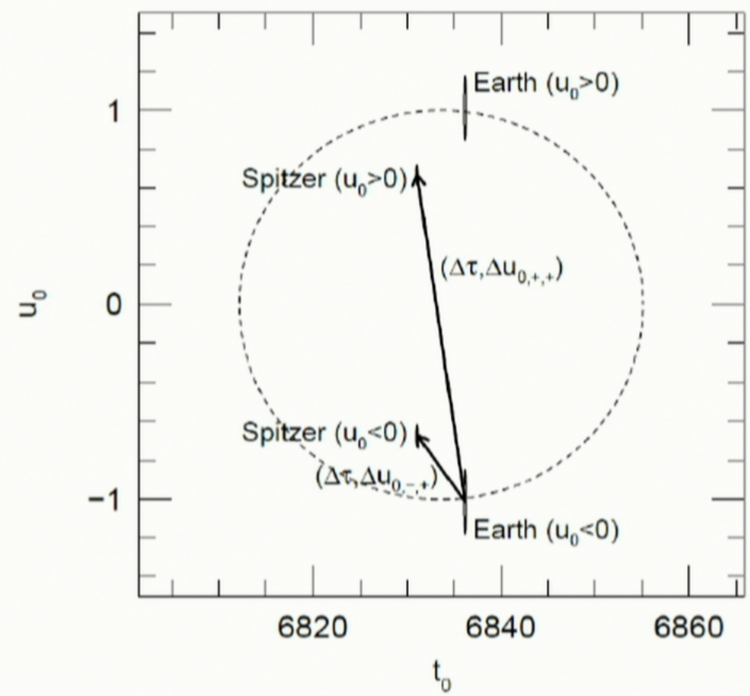
# First Isolated Lens with Spitzer Parallax




Yee et al. 2015, ApJ, in press

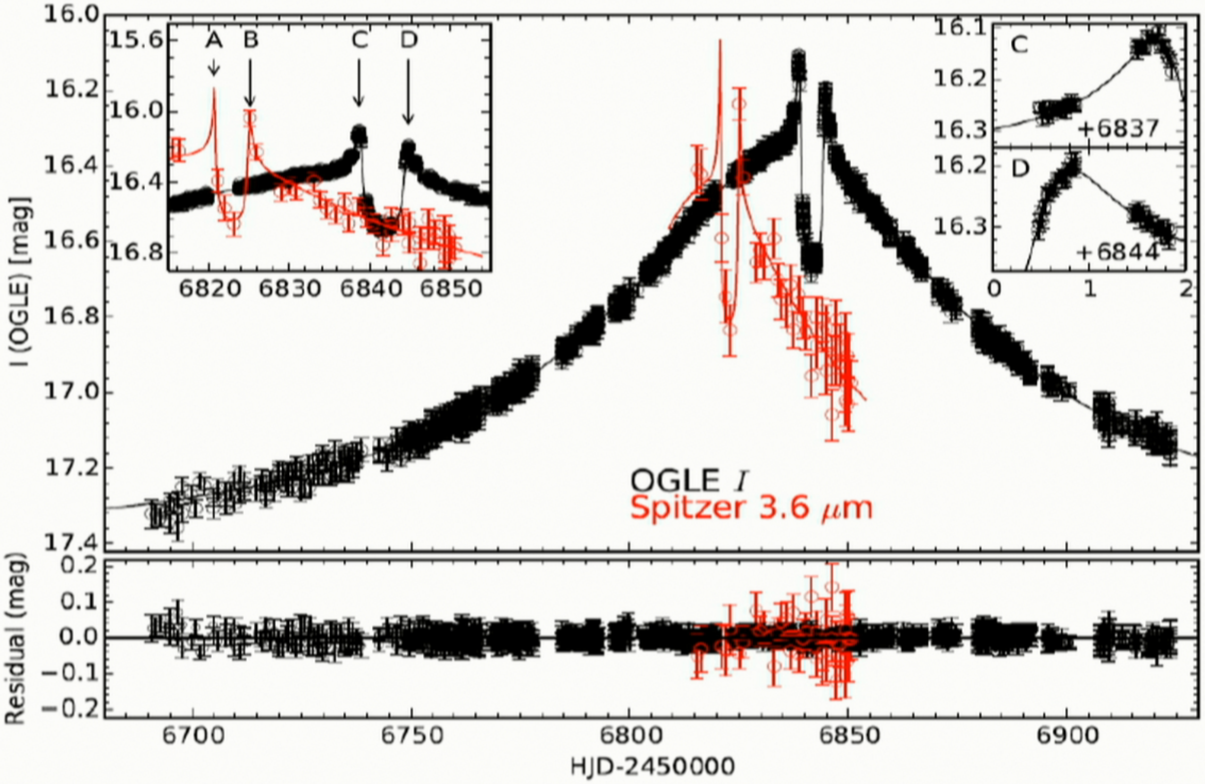
# OGLE-2014-BLG-0939:
# Refsdal (1966) 4-fold Degeneracy



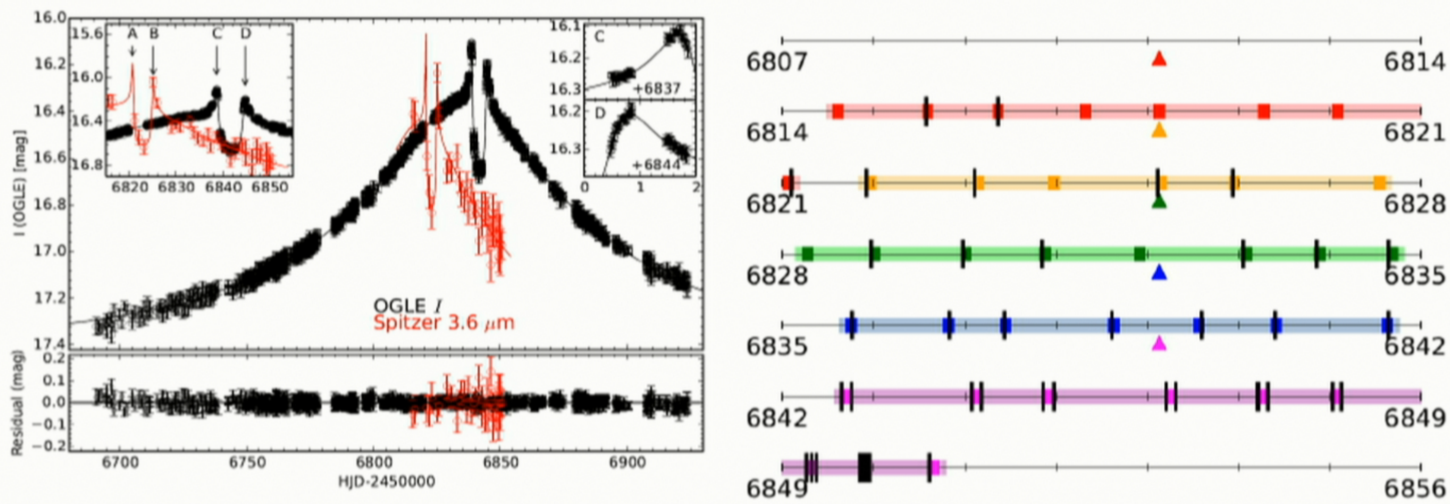

Yee et al. 2015, ApJ, in press

# OGLE-2014-BLG-0124:
## First Microlens Planet with Spitzer Parallax



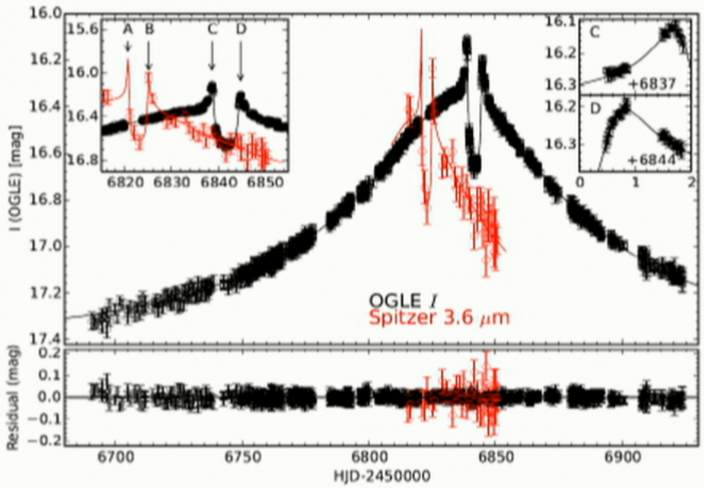

Udalski et al. 2015, ApJ, in press

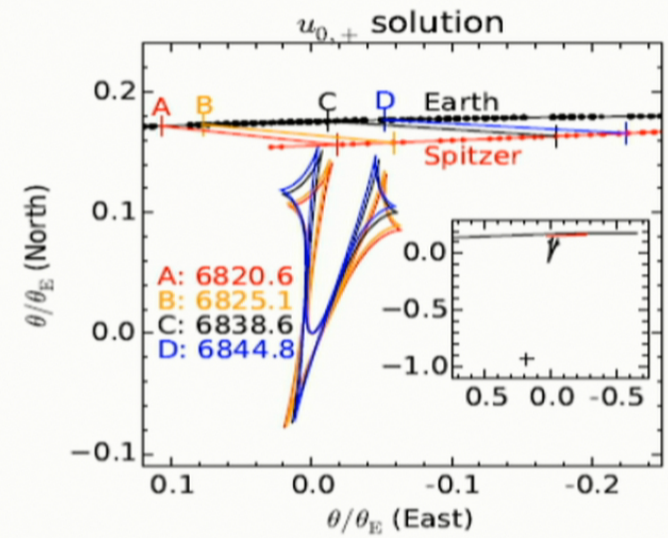
# OGLE-2014-BLG-0124:
## How Spitzer Observations Were Chosen




Udalski et al. 2015, ApJ, in press

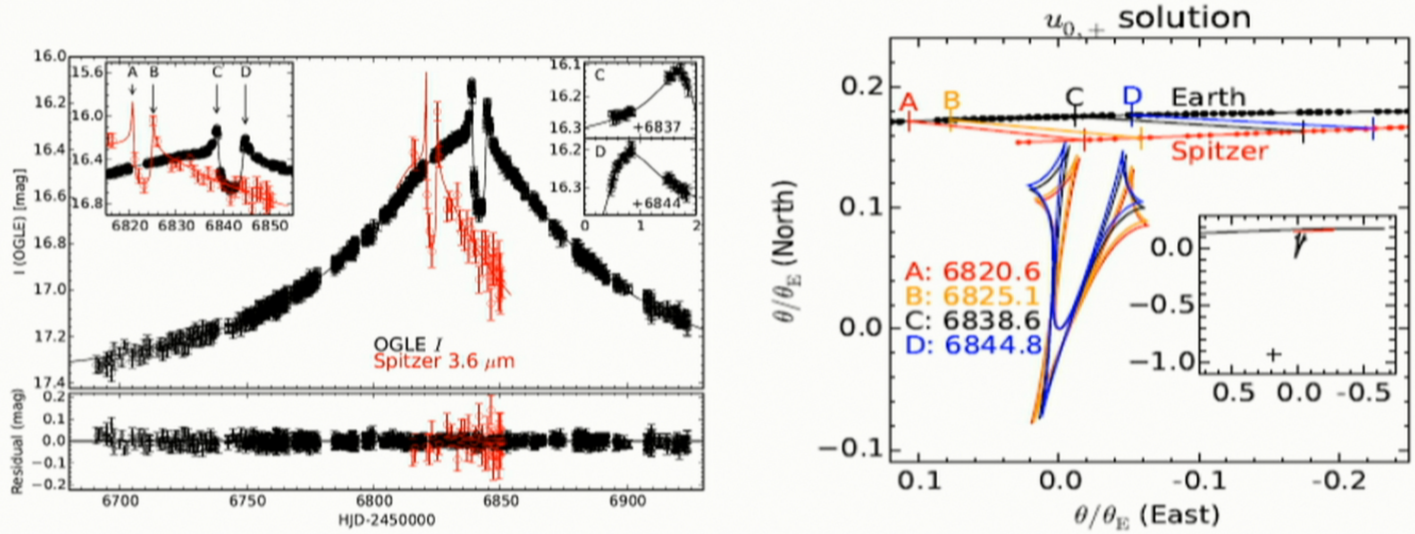
# OGLE-2014-BLG-0124:
## Source and Caustic Reconstruction



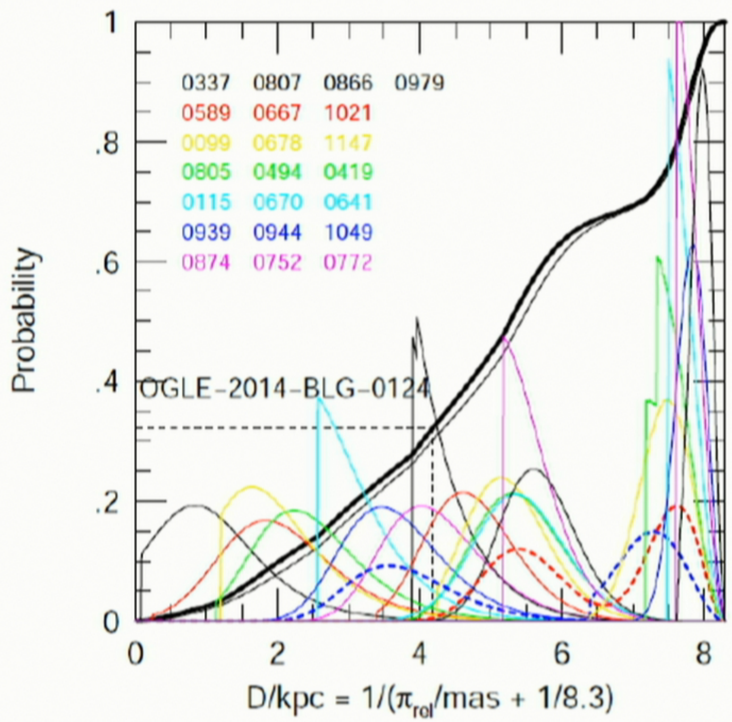

Udalski et al. 2015, ApJ, in press

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



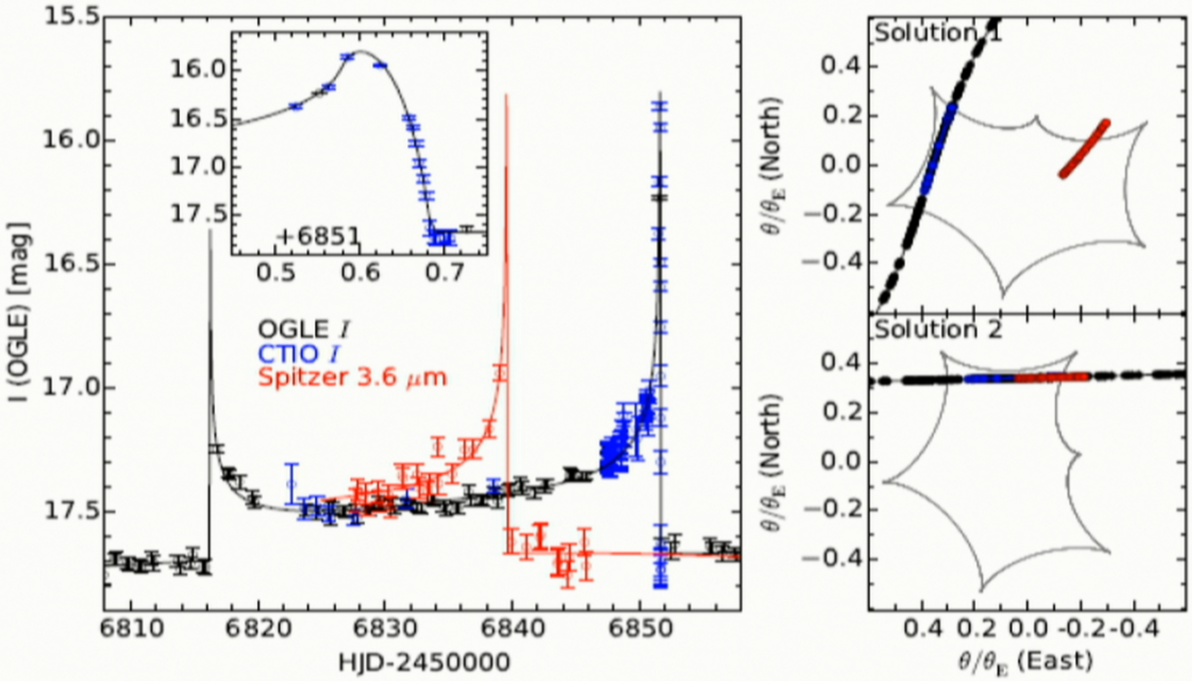

Udalski et al. 2015, ApJ, in press

# 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

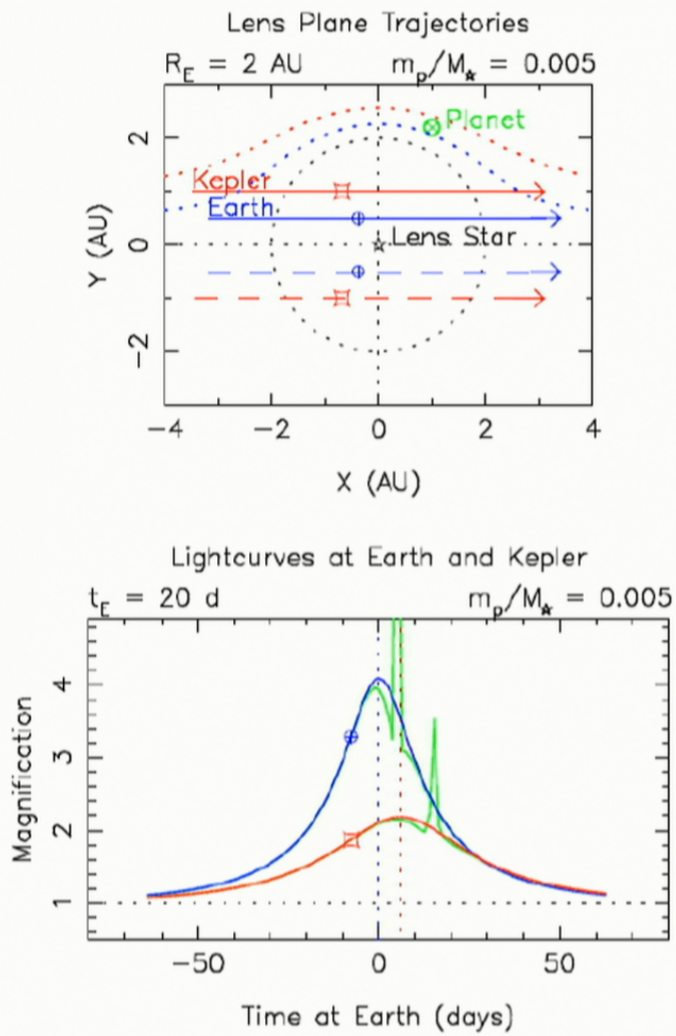



Zhu et al. 2015, ApJ, submitted

# Kepler $(MP)^3$

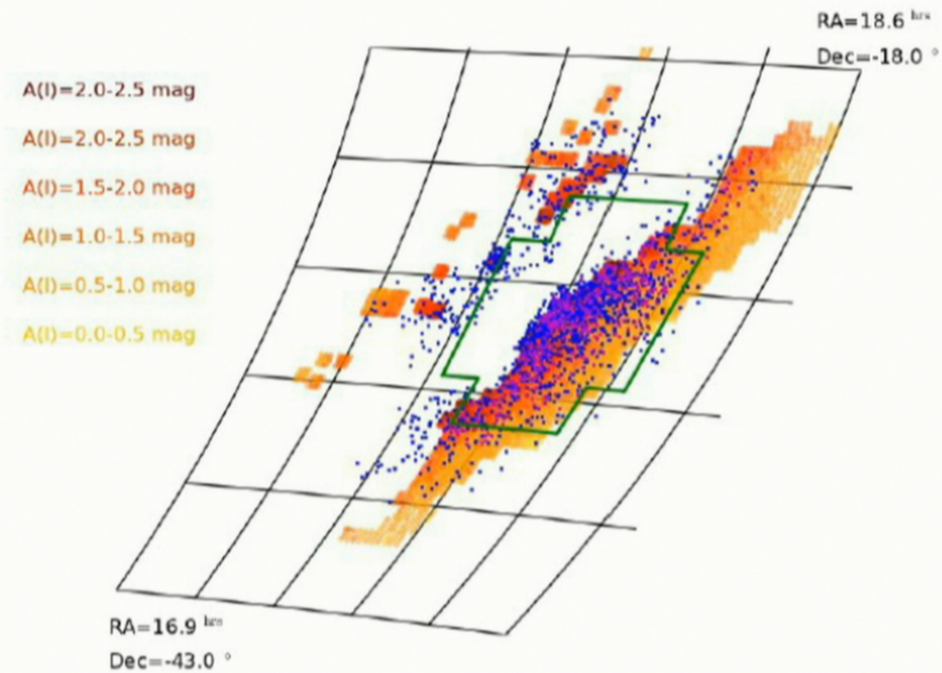
## Multi-Plexing

Gould & Horne 2013, ApJ, 779, L28



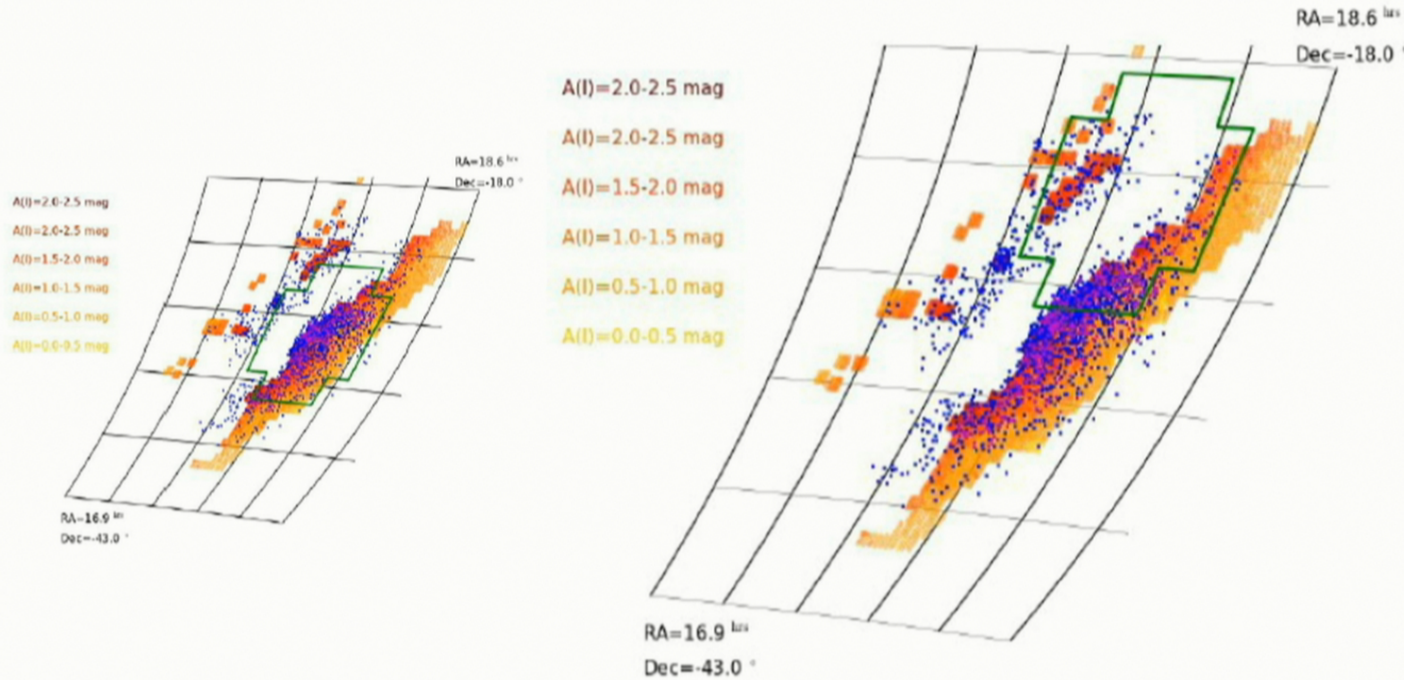

Gould & Horne 2013, ApJ, 779, L28

# What we would like to do ...



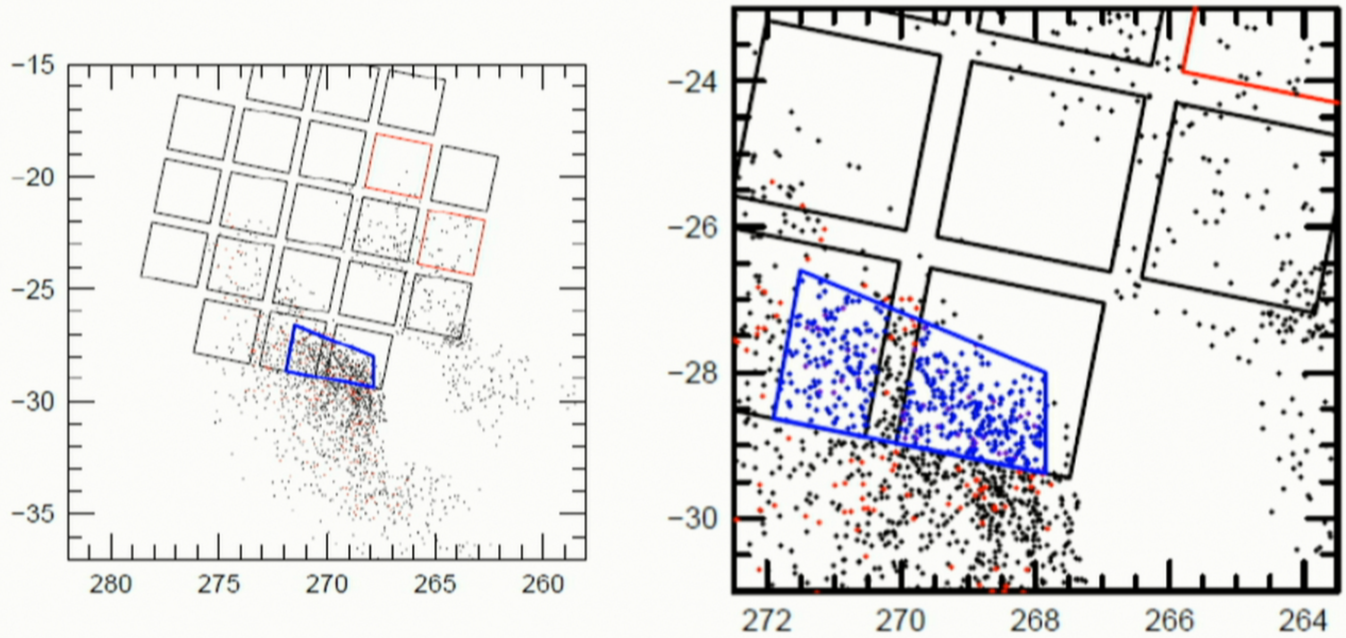

R. Street 2013, Kepler Science Meeting

# ... and what we can do!



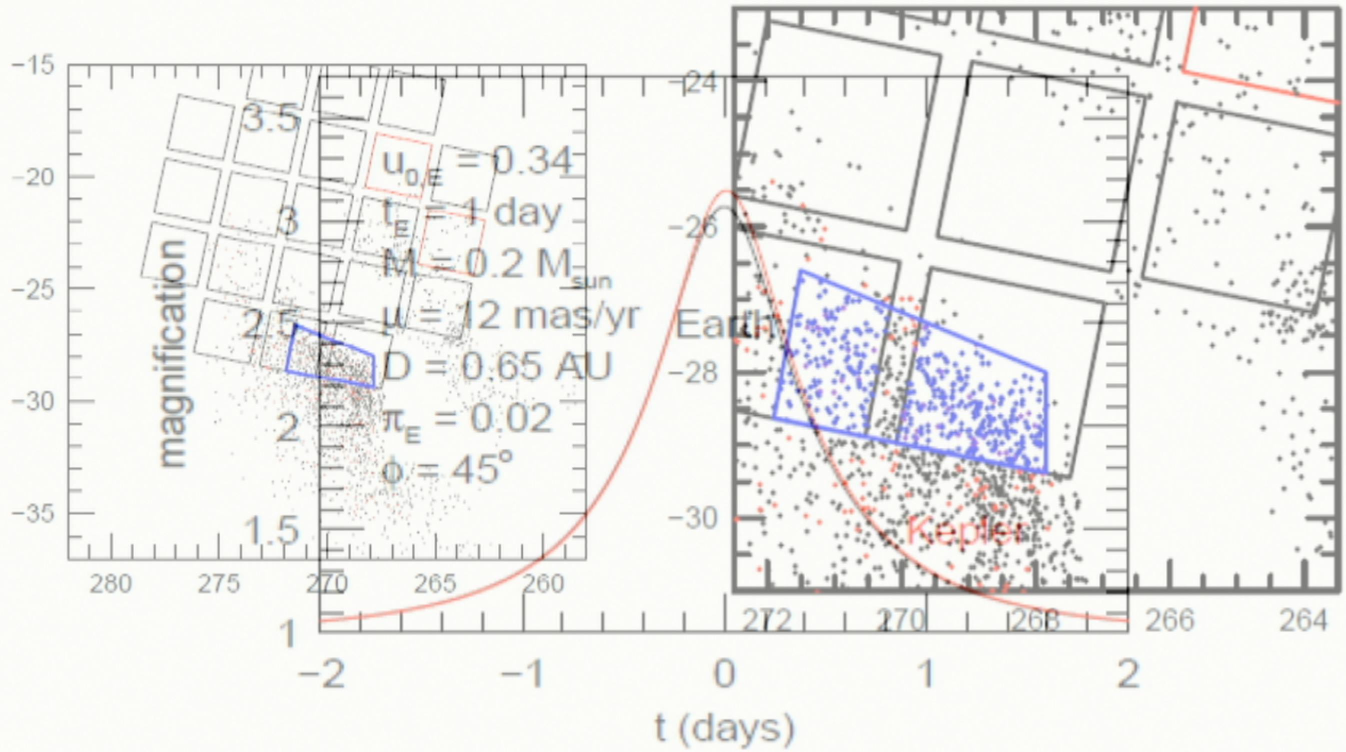

R. Street 2013, Kepler Science Meeting

# Proposal: K2 Field9 5.3 Mpxl



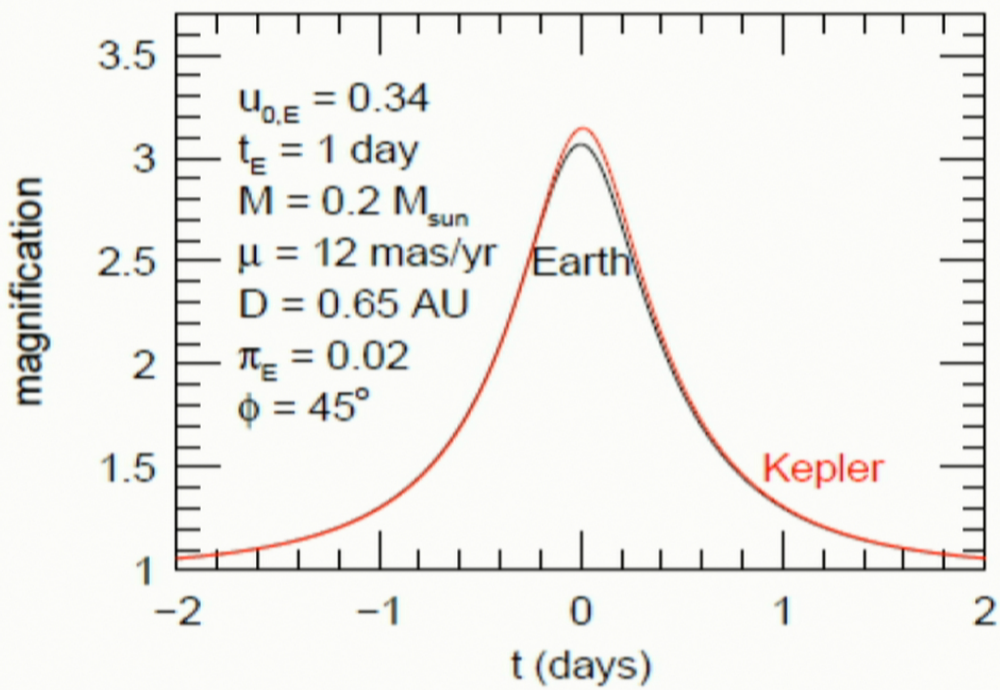

Gould, Horne, Street 2014, K2 White Paper

# K2 Microlensing Science:
# Proposal: K2 Field9 5.3 Mpxl
# Short Event: If lens is a star




Gould, Horne, Street 2014, K2 White Paper

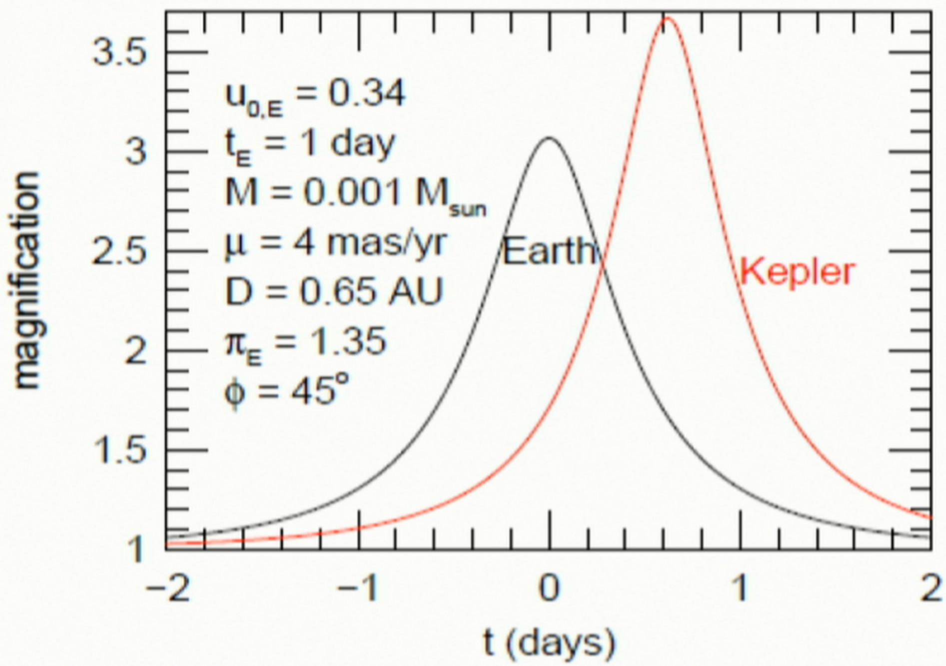
# K2 Microlensing Science:
## Short Event: If lens is a star




Gould, Horne, Street 2014, K2 White Paper

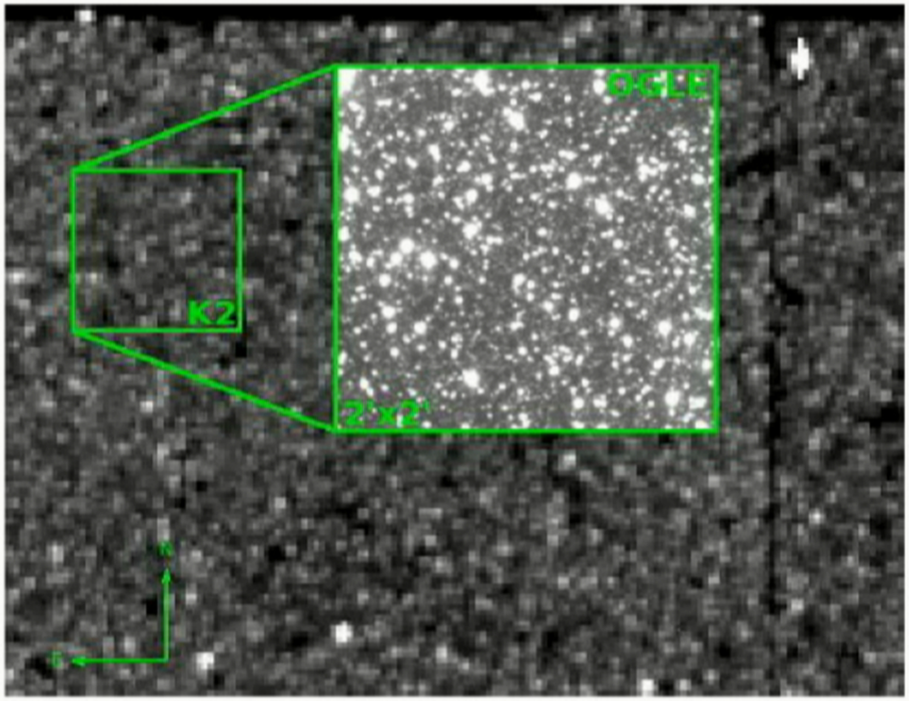
# K2 Microlensing Science:

## Short Event: If lens is an FFP




Gould, Horne, Street 2014, K2 White Paper

# K2 Microlensing:
# "Crowding" Significant

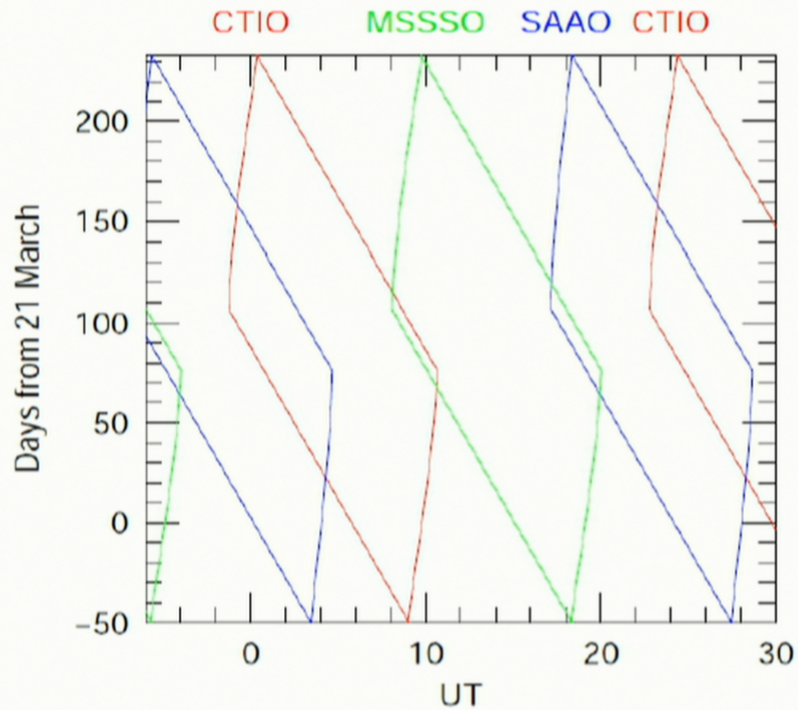



Gould, Horne, Street 2014, K2 White Paper

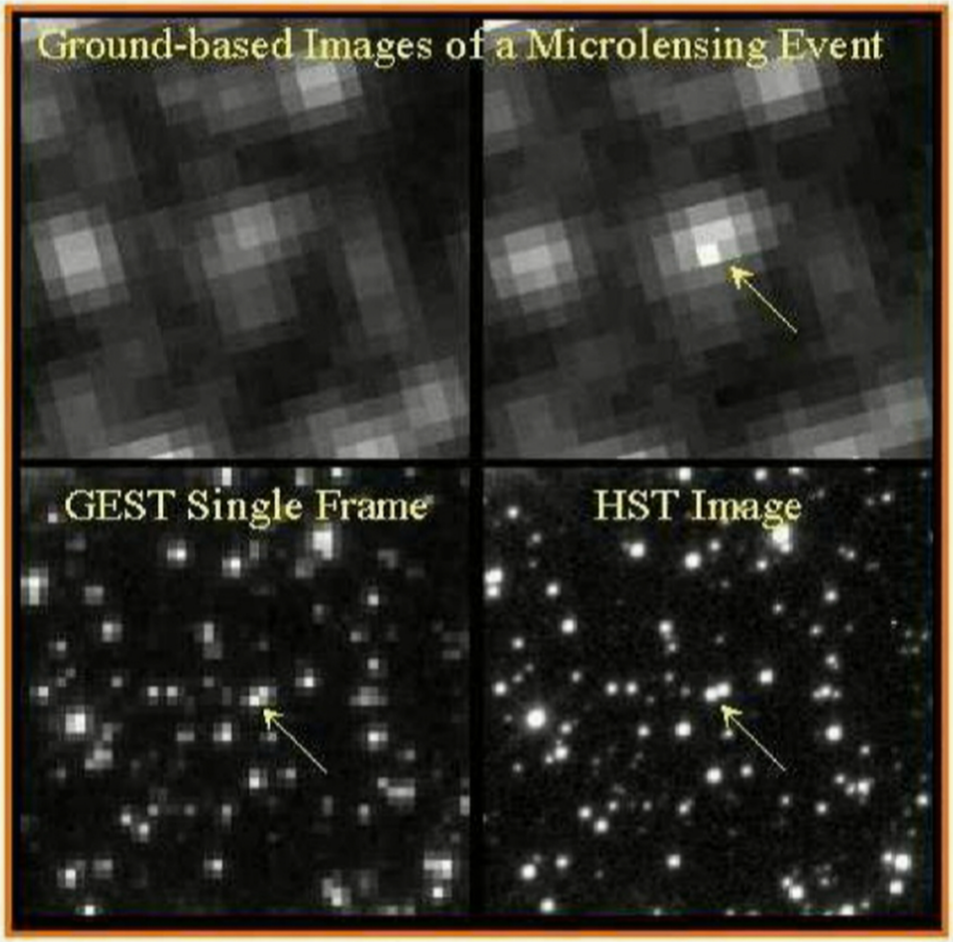
# Korean Microlensing Telescope Network (KMTNet)

# ... To Construction

# The Bulge Never Set on KMTNet
## (at least in June)



# Seeing Better In Space (also weather)

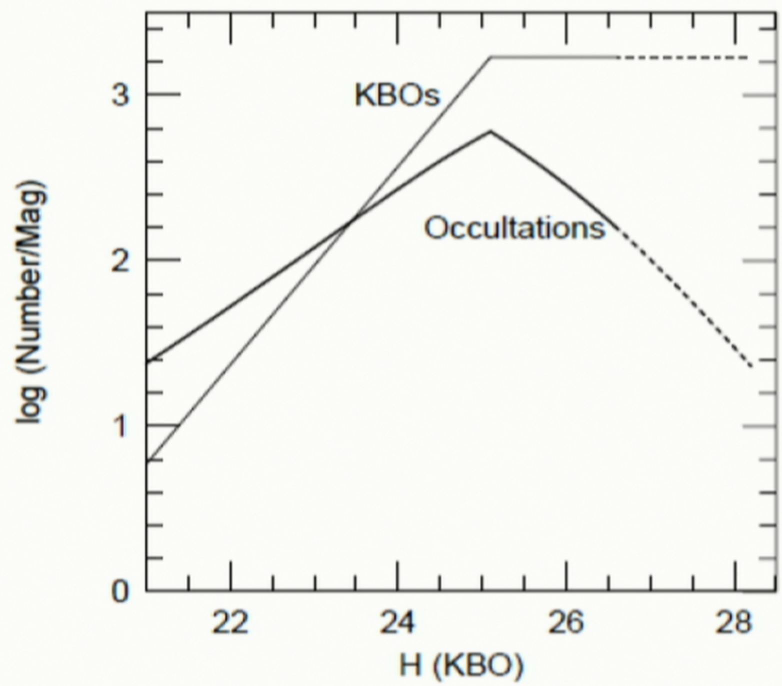


# Non-Microlensing WFIRST Science: Overview

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

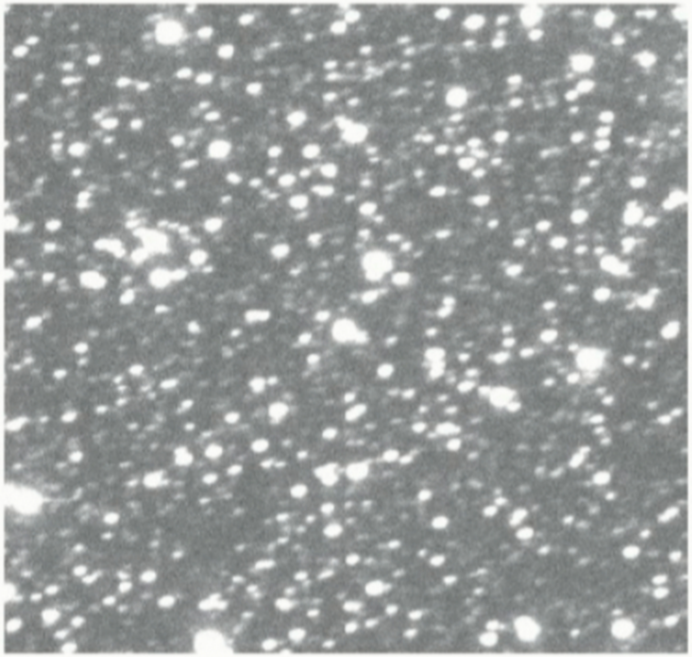
Gould 2014 JKAS, 47, 279

# Non-Microlensing WFIRST Science: KBOs



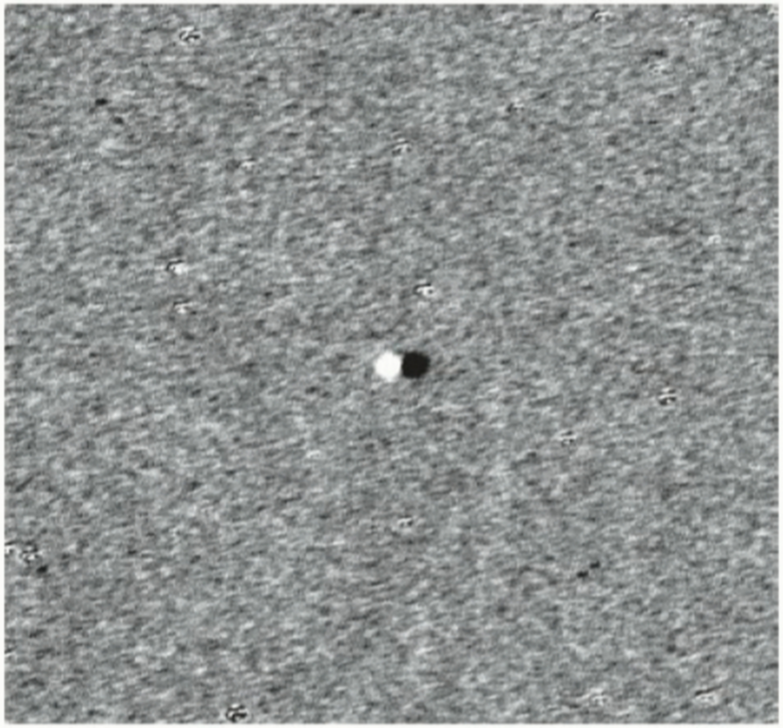

Gould 2014 JKAS, 47, 279

# KBOs possible in microlensing fields?



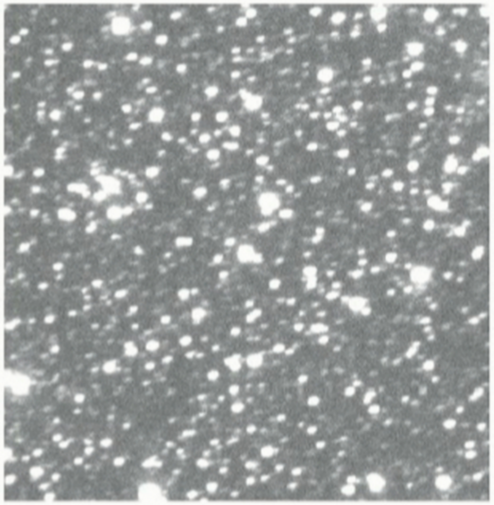
Shepard et al. 2011, AJ, 142, 98

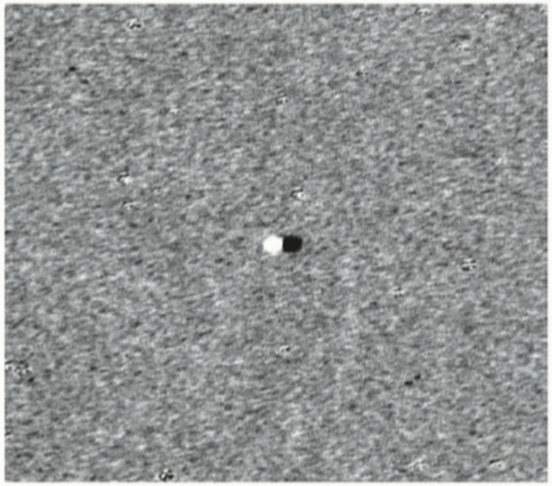
# Yes! Microlensing fields are not crowded ...



Shepard et al. 2011, AJ, 142, 98

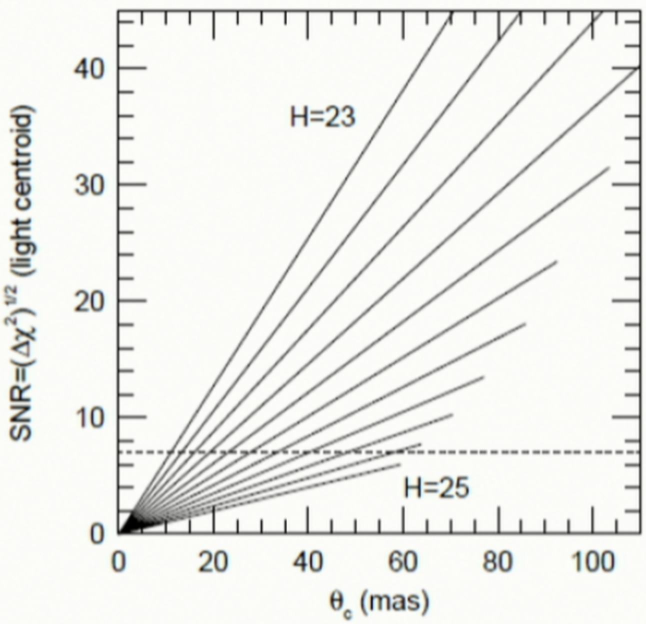
# Yes! Microlensing fields are not crowded after image subtraction!

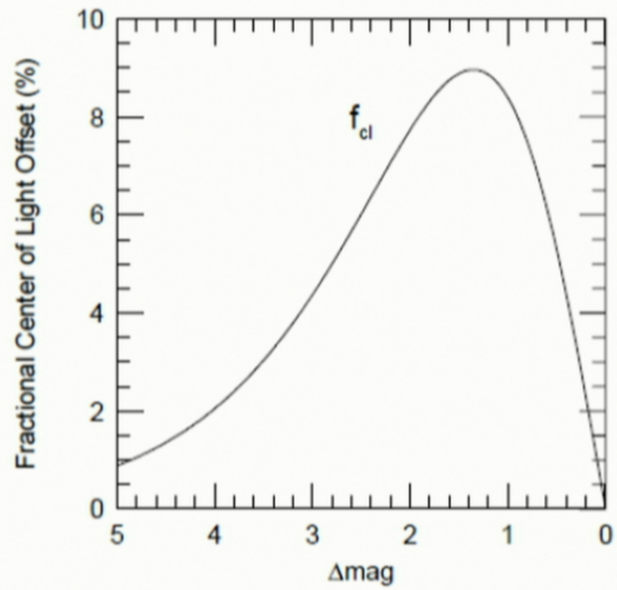




Shepard et al. 2011, AJ, 142, 98

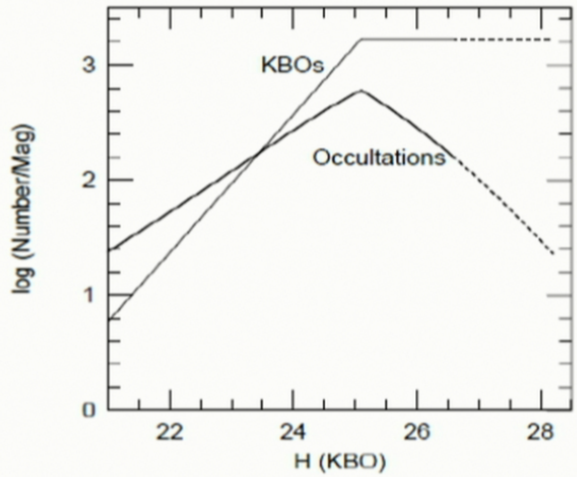
# Non-Microlensing WFIRST Science:
# KBO Binaries




Gould 2014 JKAS, submitted

# Non-Microlensing WFIRST Science:
## KBO Precision orbits

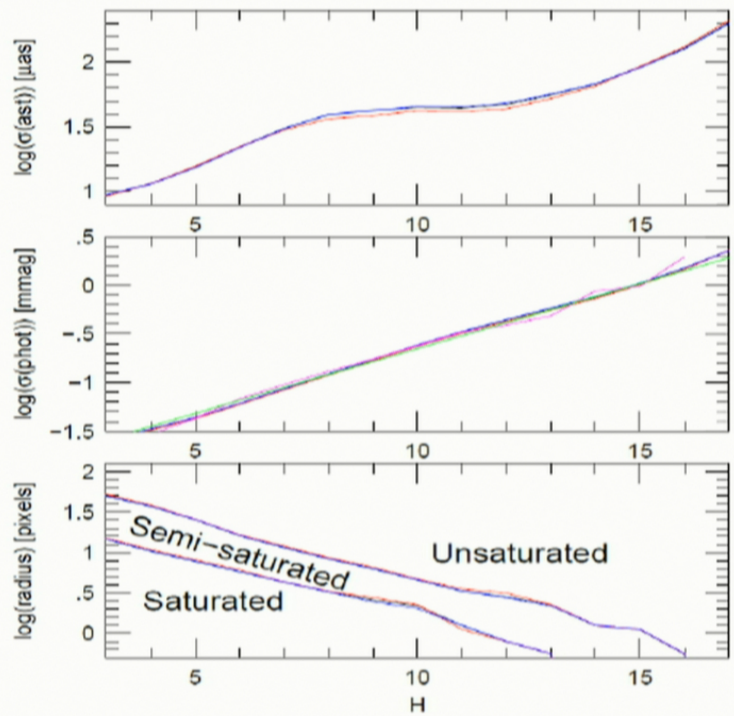



$$\sigma(P)/P \sim 0.09\%$$

$$H \sim 25.1$$

Gould 2014 JKAS, 47, 279

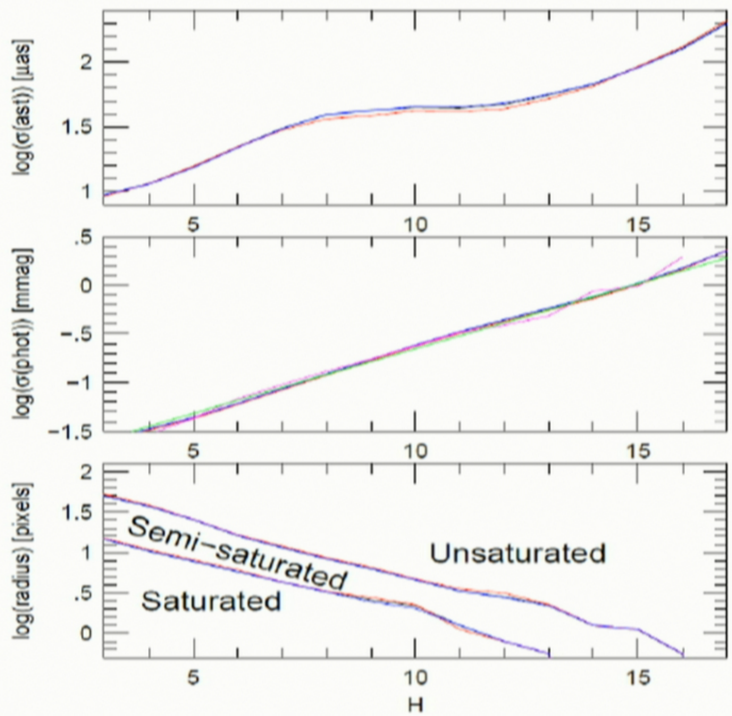
# Non-Microlensing WFIRST Science:
# Ultra-precise Parallaxes




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

# Non-Microlensing WFIRST Science:

## Ultra-precise Parallaxes



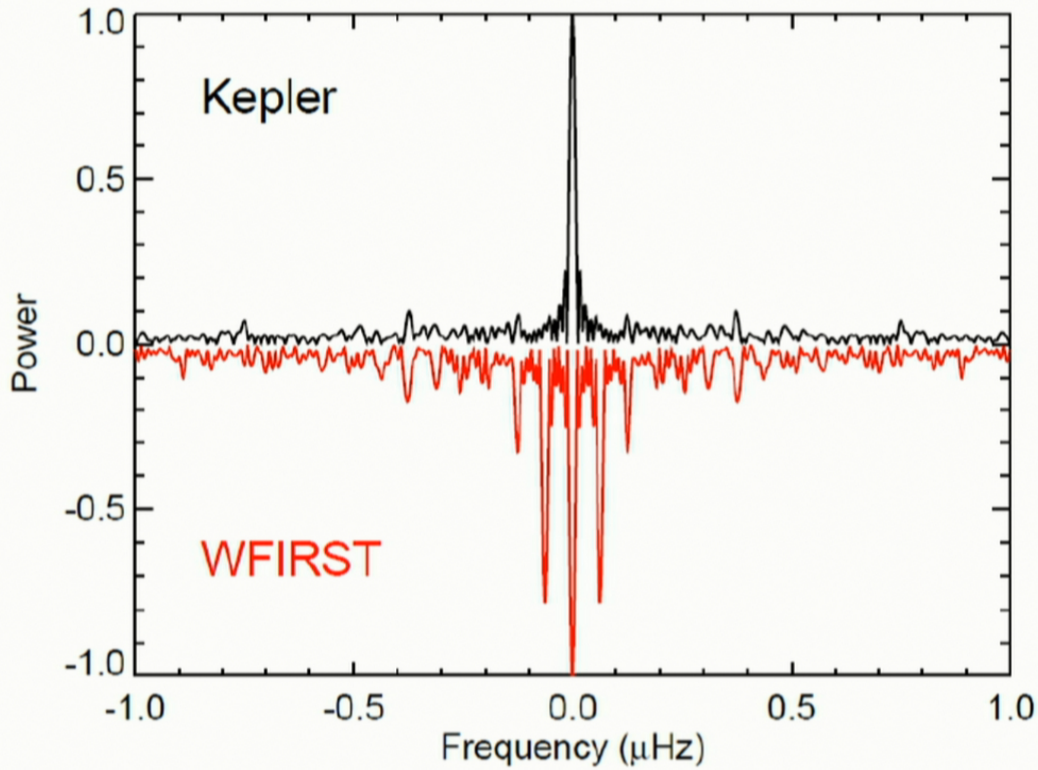

Gould, Huber, Penny, Stello, 2015 JKAS, in press

# Non-Microlensing WFIRST Science:
## Ultra-precise Parallaxes

- $H<14.0$; $\sigma(\pi) < 0.3$ μas; 1,000,000 stars
- $H<19.6$; $\sigma(\pi) < 3.7$ μas; 40,000,000 stars
- $H<21.6$; $\sigma(\pi) < 10$ μas; 120,000,000 stars

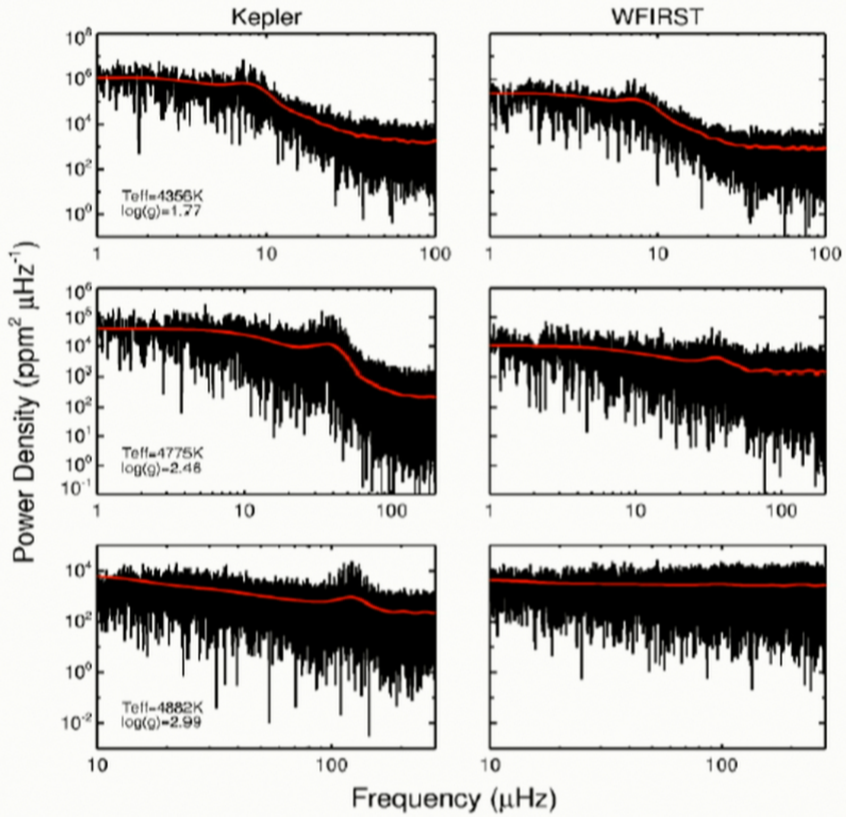
Gould, Huber, Penny, Stello, 2015 JKAS, in press

# Non-Microlensing WFIRST Science:
## Asteroseismic Window Function



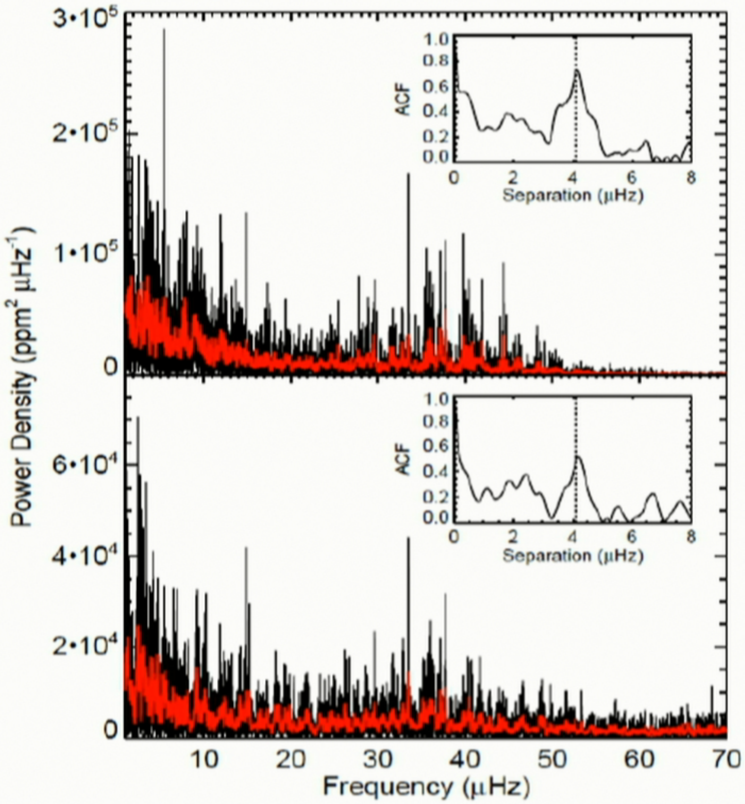

Gould, Huber, Penny, Stello, 2015 JKAS, in press

# Non-Microlensing WFIRST Science:



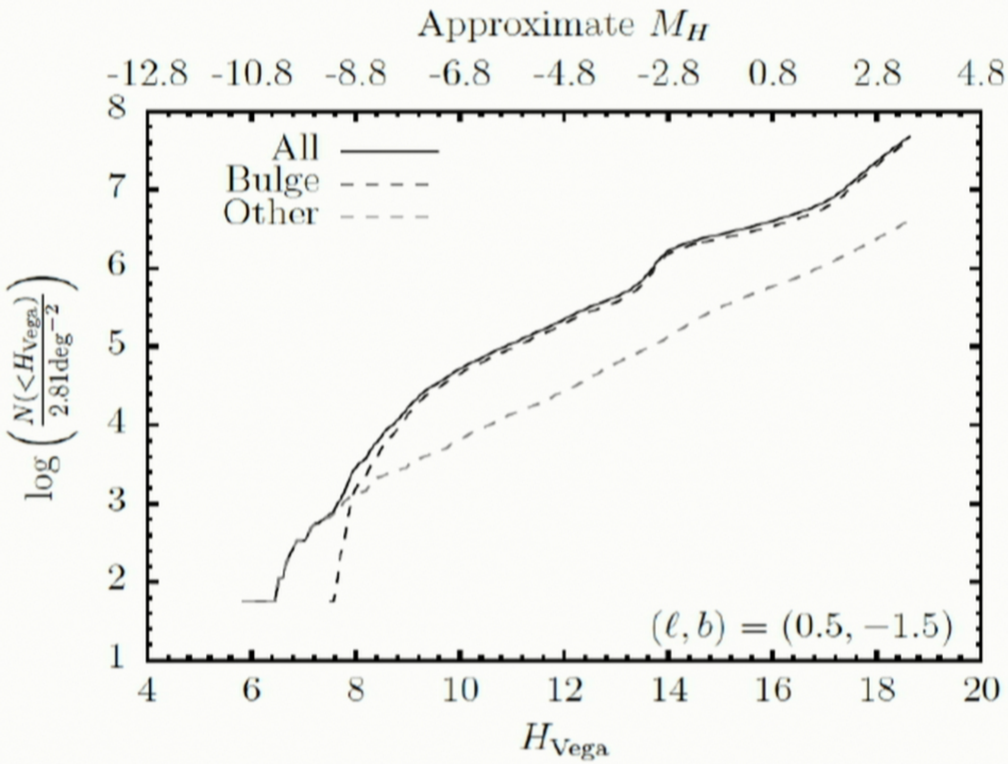

Gould, Huber, Penny, Stello, 2015 JKAS, in press

# 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 μlens 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