Microlensing with Spitzer

uncover lens masses and distances by parallax measurements

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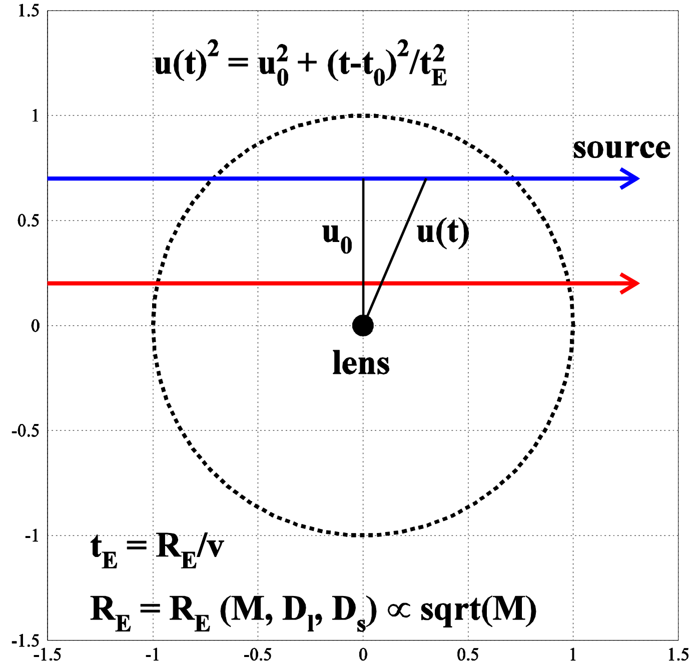
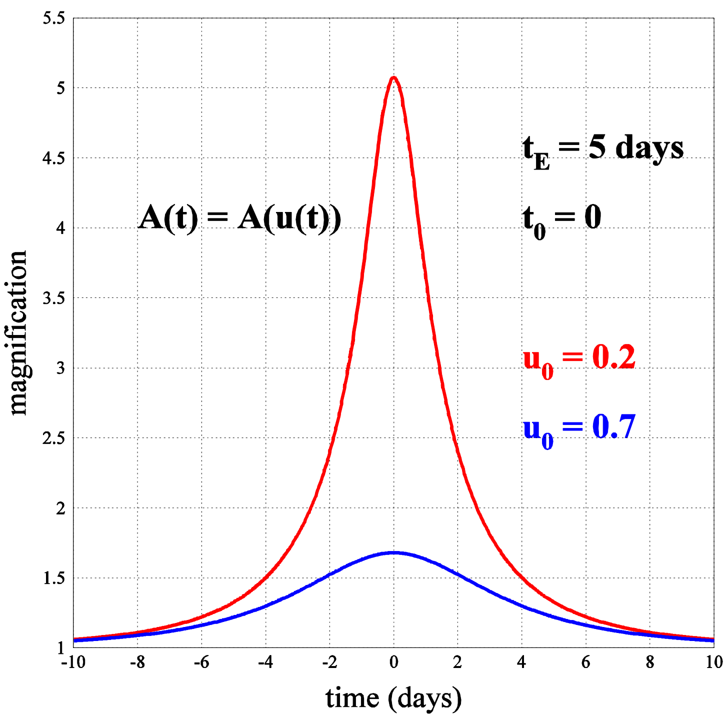
OUTLINE

- The Microlensing Parallax
  - Breaking the degeneracy in the lensing parameter space
- The *Spitzer* 2014 pilot program
  - Mass Measurement for OGLE-2014-BLG-0124L Planet
  - First Space-based Microlens Parallax Measurement of an isolated star
  - Parallax measurements of 21 Single-Lens events

The key astrophysical issues

- Determination of the lens **mass**
  - **Planetary** events (binary lens systems)
  - Mass function for single lens systems (*not light-based*)
- Analysis of the lens **distances**
  - Measurement of Galactic distribution of planets





Microlensing event: the light curve

A single observable, the event duration, for three unknown physical parameter

Bottom line: degeneracy in the lensing parameter space

- **Lens mass ?**
- **Lens distance ?**
- **Relative lens-source velocity?**

Breaking the degeneracy ?

need for a ruler in the sky

❑ Source plane (source angular radius): Source finite size effect ($\rho = \theta_*/\theta_E$ vs u_0)

❑ Observer plane (projection of the Einstein radius): **parallax, $\boldsymbol{\pi_E}$** (need of a long baseline, $\sim AU$)

- Earth orbital motion (biased sample)
- Simultaneous observations from Earth and a satellite in solar orbit

Looking back and forward

Liebes, 1964; Refsdal, 1964: degeneracy in microlensing parameter space
Refsdal 1964: break degeneracy with microlensing parallax
(observation from solar orbit)

a long time ago….

Paczyński, 1986

Gould, 1992: parallax from Earth solar orbit
Gould 1994: parallax from simultaneous Earth and satellite observations
Alcock et al 1995 (MACHO): first parallax measurement (Earth motion)
Han and Gould 1995: the mass spectrum from parallax
Gaudi and Gould 1997: satellite parallaxes towards the Galactic Bulge
Gould 1999: Microlens parallaxes with SIRTF

Dong et al, 2007 First space-based Microlens Parallax : Spitzer for OGLE-2005-SMC-001
Gould, 2013: Geosynchronous Microlens Parallaxes
Yee, 2013: WFIRST *(if in L2 orbit)* planet masses from Microlens Parallax

today :
2014 Spitzer Microlensing pilot program

→

Udalski, Yee, Gould et al (SCN) 2014 (submitted)
Yee, Udalski, Calchi Novati et al 2014 (submitted)
Calchi Novati et al 2014 (in preparation)

Spitzer Microlens Planets and Parallaxes

a 100 hr (38 2.6hr windows) pilot program

PI: A. Gould, co-I: S. Carey, J. Yee (DDT #10036)

Measure of microlens parallaxes by simultaneous observations from *Spitzer*, at about 1 AU from Earth, of microlensing events toward the Galactic Bulge alerted and observed by the OGLE survey (~ 2000 new event/9 months in 2014)

Why (and why not) *Spitzer*

- ❑ **Solar orbit**
- ❑ **3.6 μm camera, $\approx 2'' PSF$**
- ❑ **Short notice**
- ❖ **Can only observe the Bulge for two ~38 d intervals/year**
- ❖ **Rapid responses are very disruptive to mission**

Observation carried out in June 2014 (HJD-245000=6814, 6850)

New protocol for «regular» ToO observations with 3-9 day turnaround (AG, JCY)

- ❑ 60 events observed (OGLE)
  - 1 planetary event
  - 4-5 binary (→ poster by W. Zhu)
  - 22 single-lens events analyzed
  - 15 (single-lens) under investigation
  - ~17 insufficient sampling

Scientific purposes

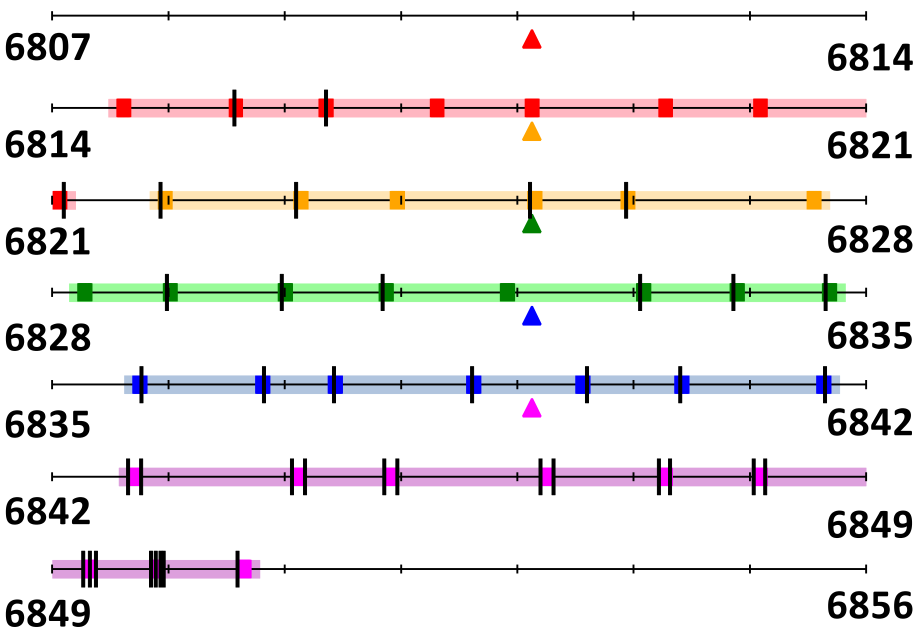
- ✓ *Probe feasibility (pilot program!)*
- ✓ *Microlensing lens masses and distances (planetary events)*

Spitzer 2014 pilot program

Typical event duration ~ 25 days (shorter for bulge than for disk lenses)

the challenge: predict the evolution of the event well before peak

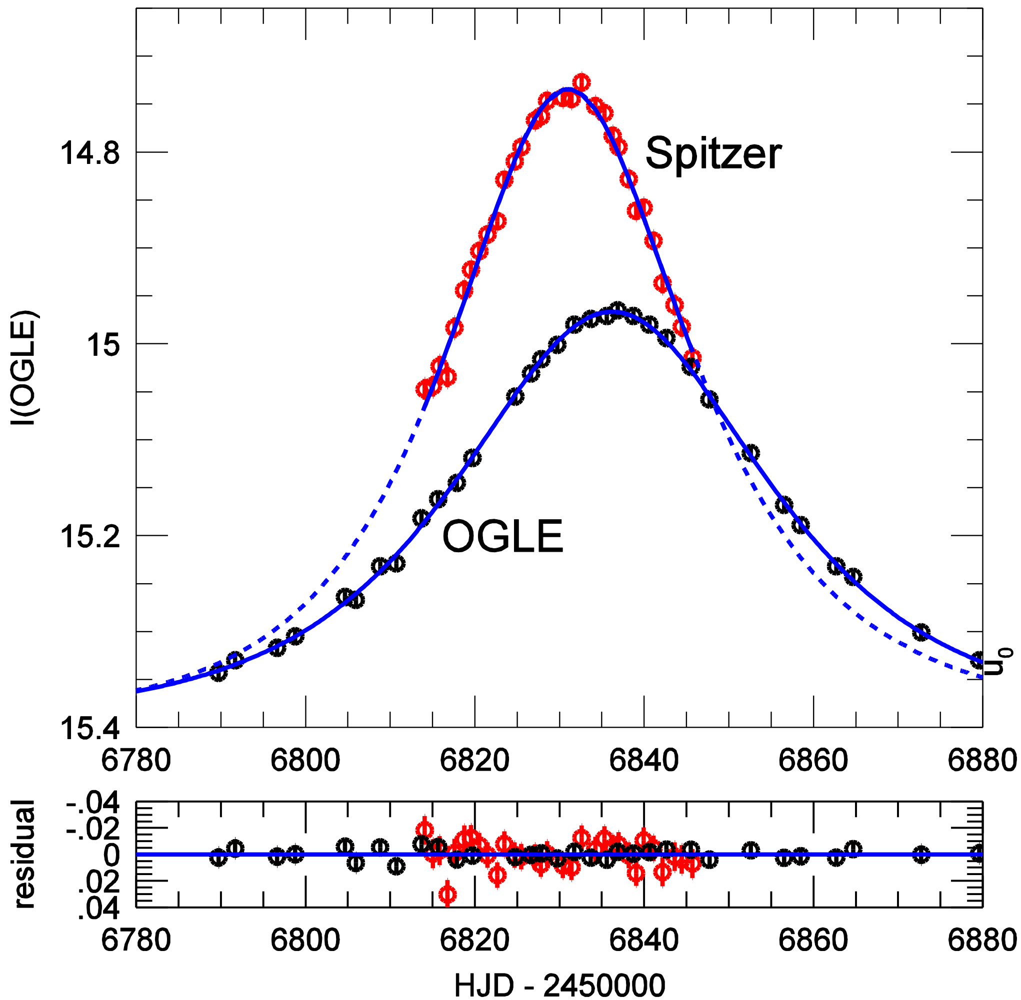
besides: the lightcurve from Spitzer is going to look different from that from Earth (that's the point of parallax observations!)



New protocol for regular (non-disruptive) target-of-opportunity observations
Target identified 3-9 days in advance: new sequence uplodaded to Spitzer
Each Monday to be carried out from Thursday to Wednesday

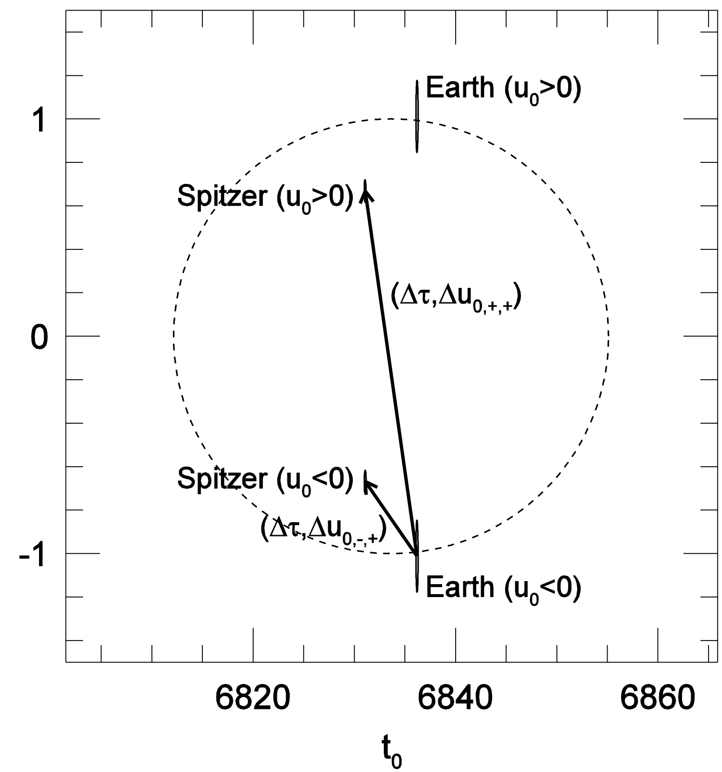
The protocol biases our sample in favour of the longer duration disk lenses

First space-based microlens parallax of an isolated star Spitzer observations of OGLE-2014-BLG-0939



Parallax measurements
and parameter space degeneracies

$$\boldsymbol{\pi}_E = \frac{AU}{D_\perp}\left(\frac{\Delta t_0}{t_E}, \Delta u_0\right)$$

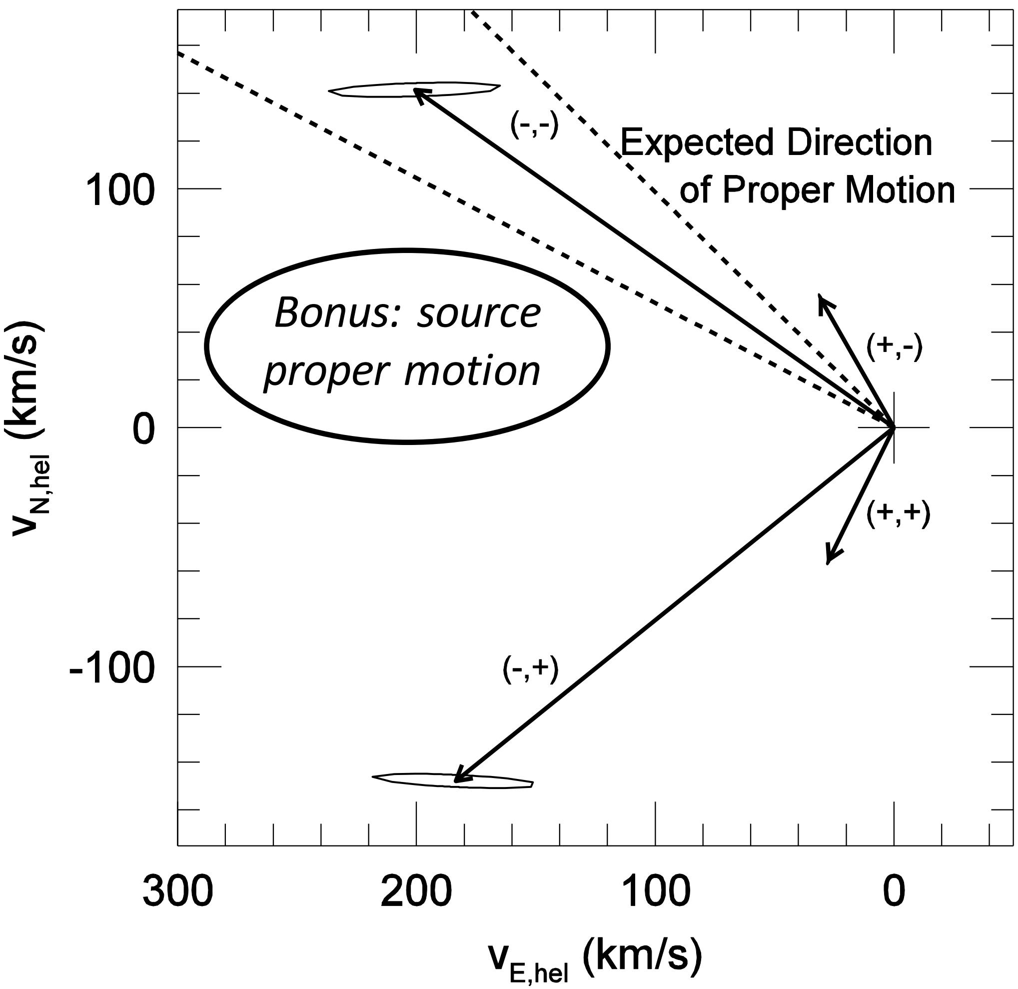


bottom line: 4 minima in χ^2 (4 $\boldsymbol{\pi}_E$ solutions) with 2 values for the amplitude π_E

Yee, Udalski, SCN et al 2014, submitted

OGLE-2014-BLG-0939 parallax measurements from *Spitzer* a Galactic disk lens: $M = 0.23 \pm 0.07\, M_\odot, D_l = 3.1 \pm 0.4\, kpc$

Yee, Udalski, SCN et al 2014, submitted



$$\boldsymbol{\pi}_E \equiv \frac{\pi_{rel}}{\theta_E}\frac{\boldsymbol{\mu}}{\mu}$$

$$\pi_{rel} = AU\,(1/D_l - 1/D_s)$$

$$\tilde{\boldsymbol{v}}_{hel} = \tilde{\boldsymbol{v}}_{geo} + \boldsymbol{v}_{\oplus\perp},$$

$$\tilde{\boldsymbol{v}}_{geo} = \frac{\boldsymbol{\pi}_{E,geo}}{\pi_E{}^2}\frac{AU}{t_E}$$

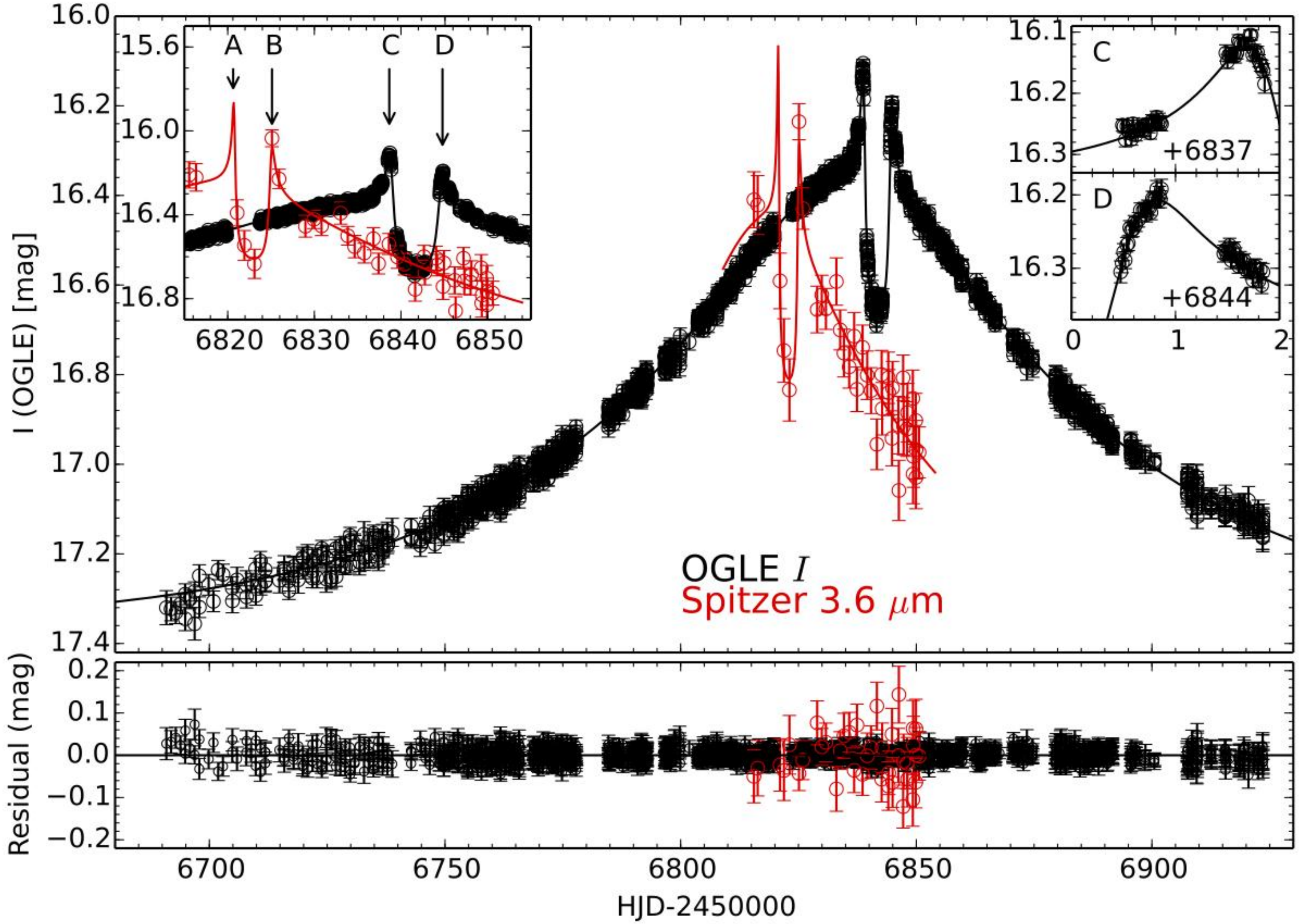
$$\boldsymbol{\mu} = \frac{\tilde{\boldsymbol{v}}}{AU}\pi_{rel}$$

$$M = \frac{\mu_{geo}\, t_E}{k\,\pi_E} = \frac{\theta_E}{k\,\pi_E}$$

a key point: the reduced velocity, $\tilde{v}$, depends on the kinematic properties of lens and source and is independent of the lens mass

Spitzer as Microlens Parallax Satellite: Mass measurement for the OGLE-2014-BLG-0124L Planet and its Host Star

$\theta_E = 0.84 \pm 0.26$ mas (for $M < 1.2\, M_\odot$) $\pi_E = 0.15$ (2.5%)



$M_{host} \sim 0.71\, M_\odot$

$M_{planet} \sim 0.51\, M_{jup}$

$D_l \sim 4.1$kpc

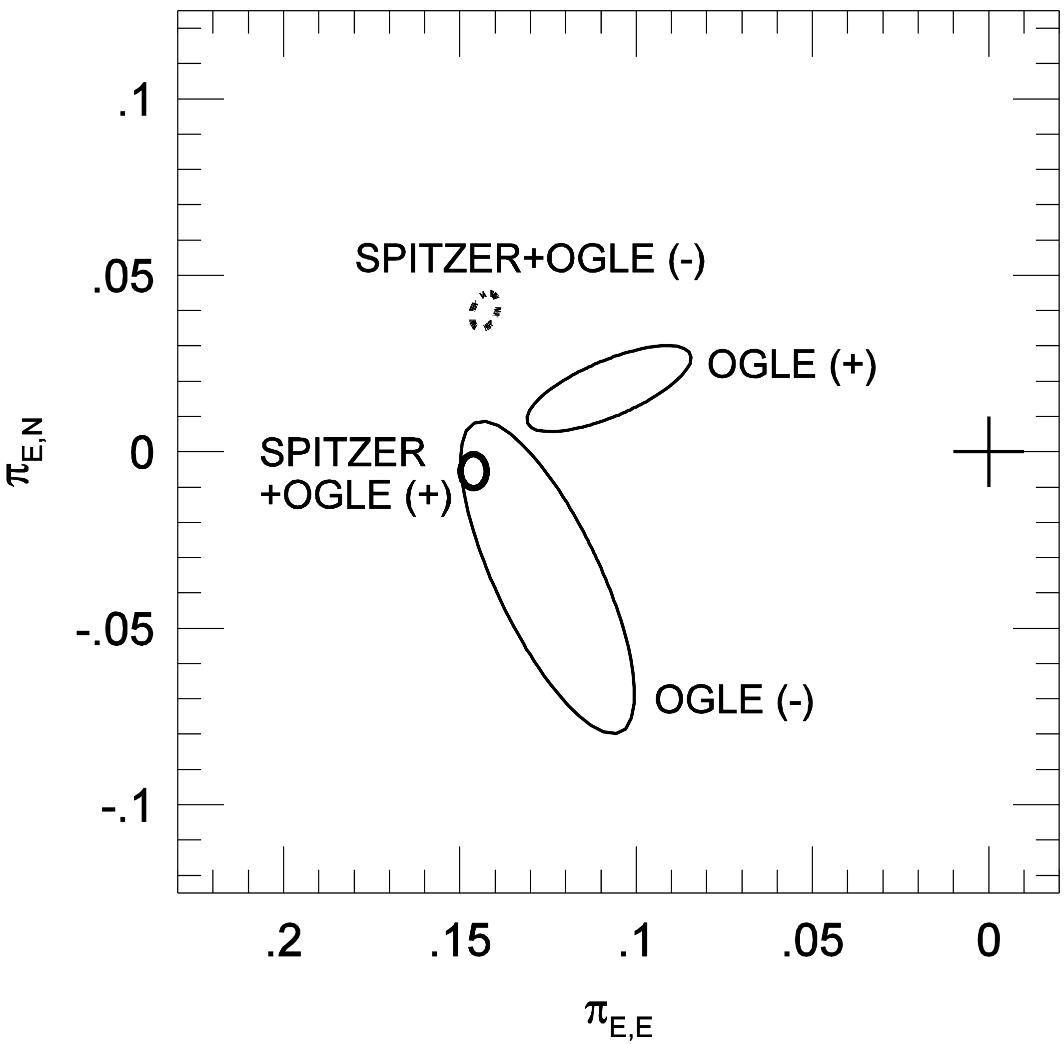
$a_\perp \sim 3.16$ AU

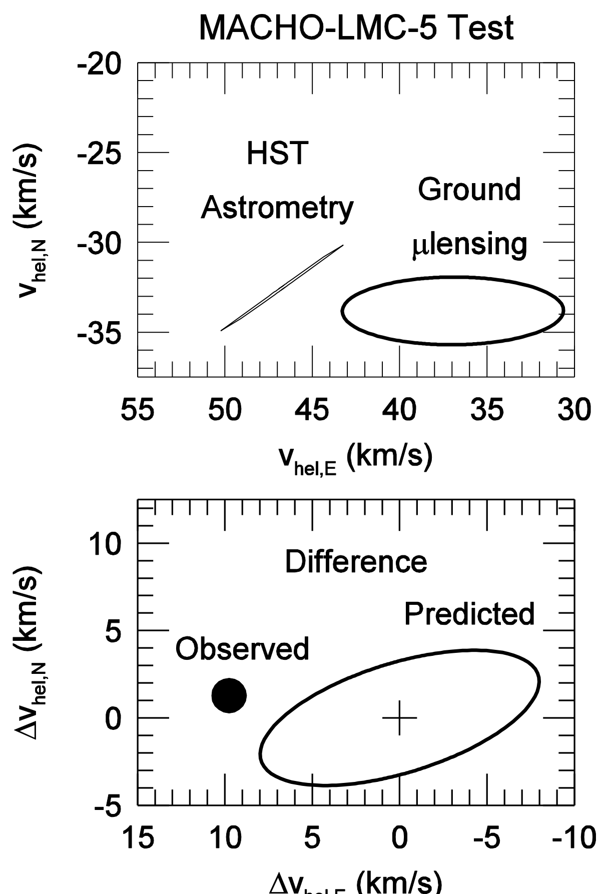
relative error ~ 30% from that on θ_E

Udalski, Yee, Gould et al (SCN) 2014, submitted

OGLE-2014-BLG-0124L: confirmation of (orbital motion) Earth parallax measurement ($t_E \sim 150\ d$) by OGLE alone

Second ever case (over a dozen) for which this test is possible after LMC-5 (Alcock et al 2001; Gould 2004; Gould et al 2004) where however only a 1-d test was carried out

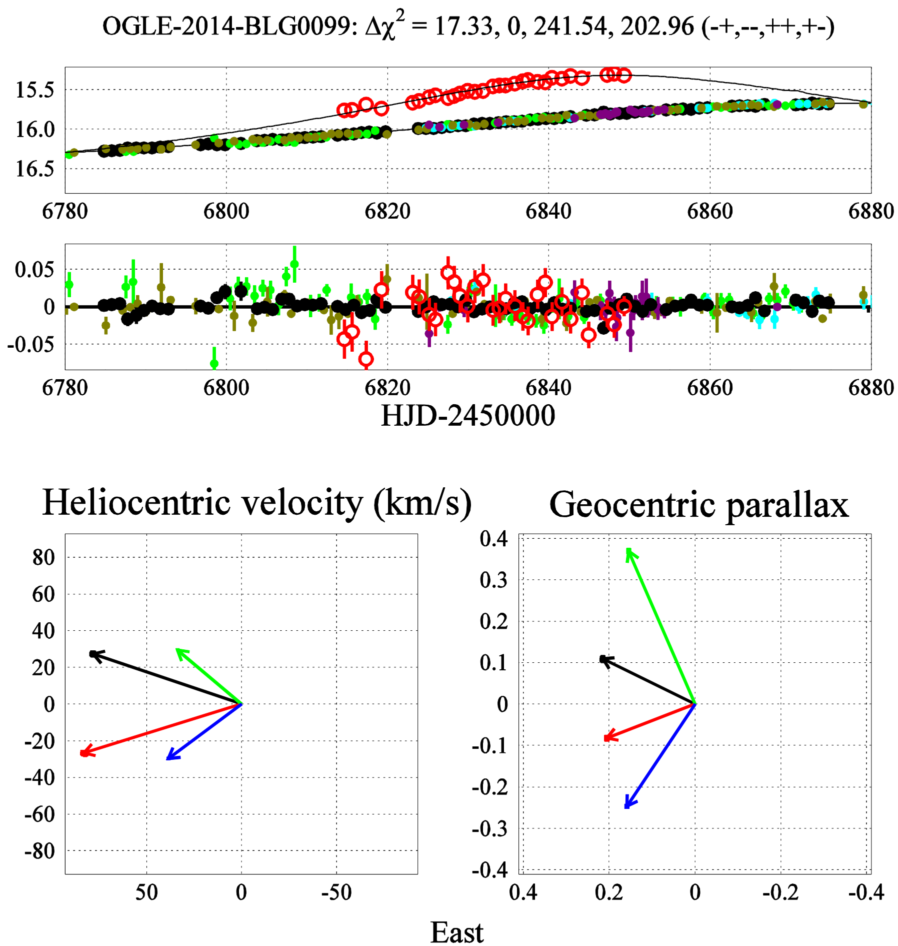


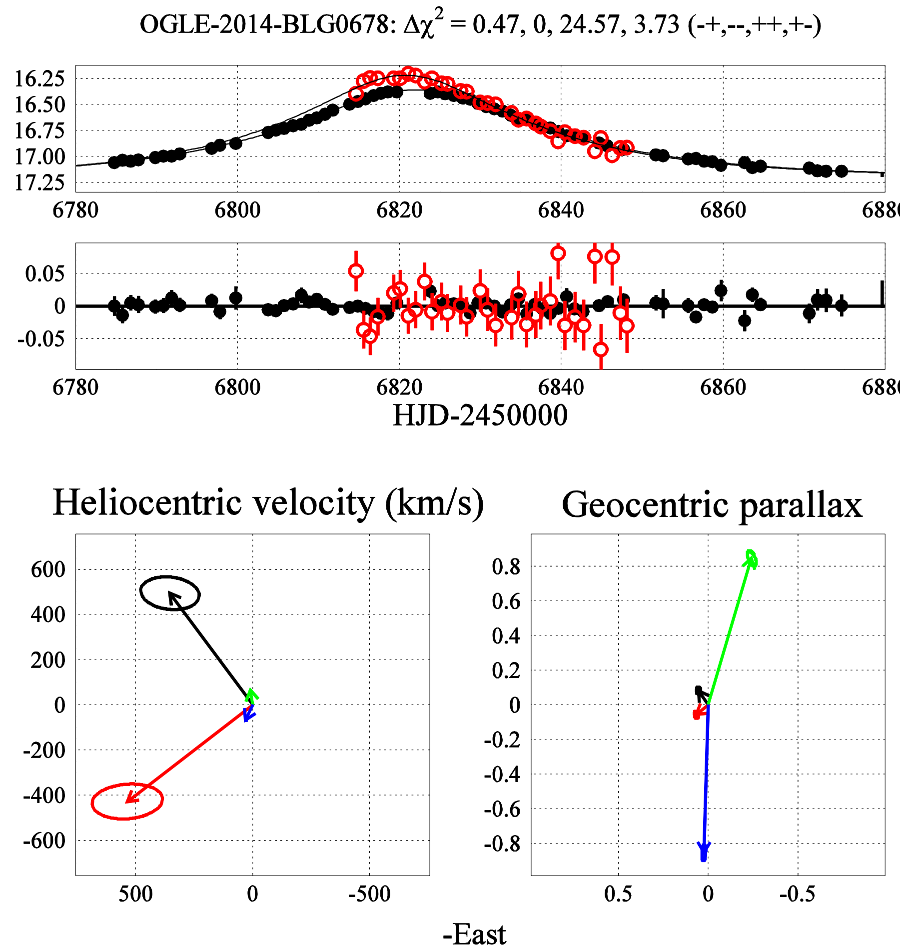


Udalski, Yee, Gould et al (SCN) 2014, submitted

Pathway to the Galactic Distribution of planets: Spitzer Microlens Parallax Measurements of 21 Single-Lens Events

OGLE+*Spitzer*+ MOA, Wise, MiNDSTEp (Chile+SUO), PLANET (SAAO), RoboNet (LCOGT)

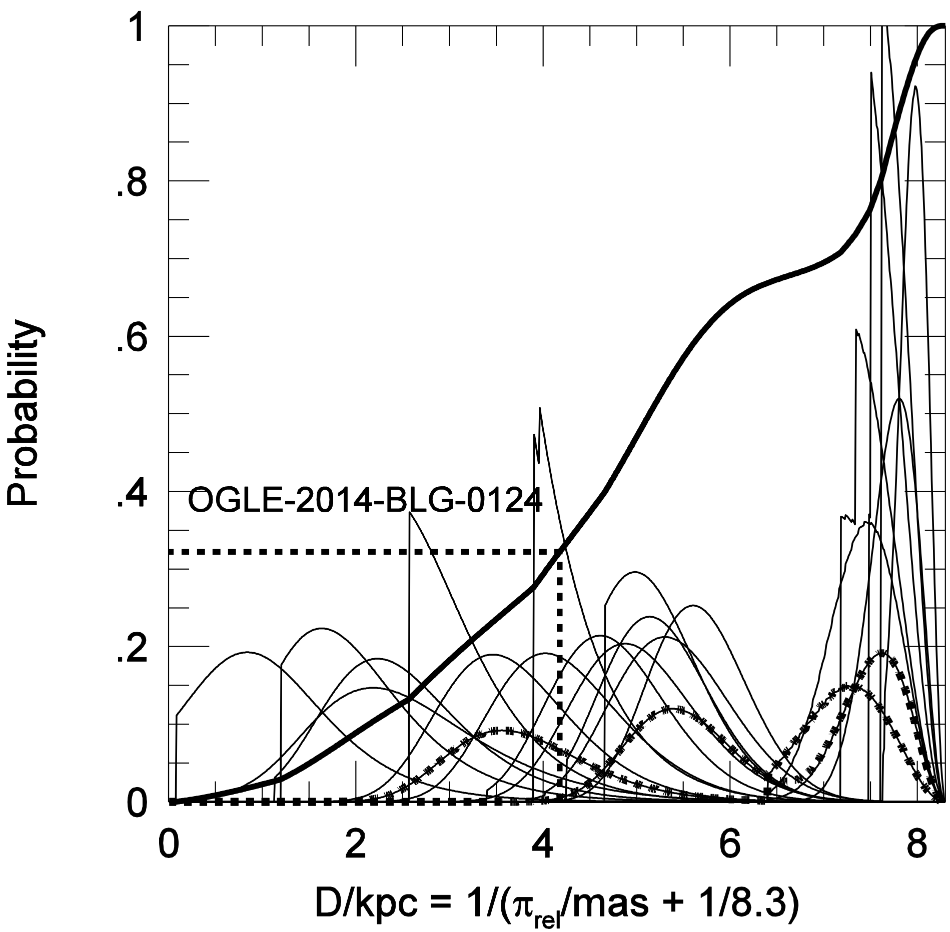




$\boldsymbol{\pi}_E$ space degeneracy breaking:
$\Delta\chi^2$ and Rich's argument (1997 ca.)

SCN et al, 2014, in prep.

From the Distribution of (Single) Lens Distances …



first, build a pdf for each lens

- Phase space density ($\Gamma = n\sigma v$)

(the model, given π_E, and $\tilde{v}$)

- $\Delta\chi^2$
- «Rich's argument»

$$\pi_{rel} = \mu_{geo} t_E \pi_E$$

$$D/kpc = 1/\left[\frac{\pi_{rel}}{mas} + 1/8.3\right]$$

$D_l \sim D$ for $D \lesssim D_s/2$

$D_s - D_l \sim 8.3\ kpc - D$ for $D \gtrsim D_s/2$

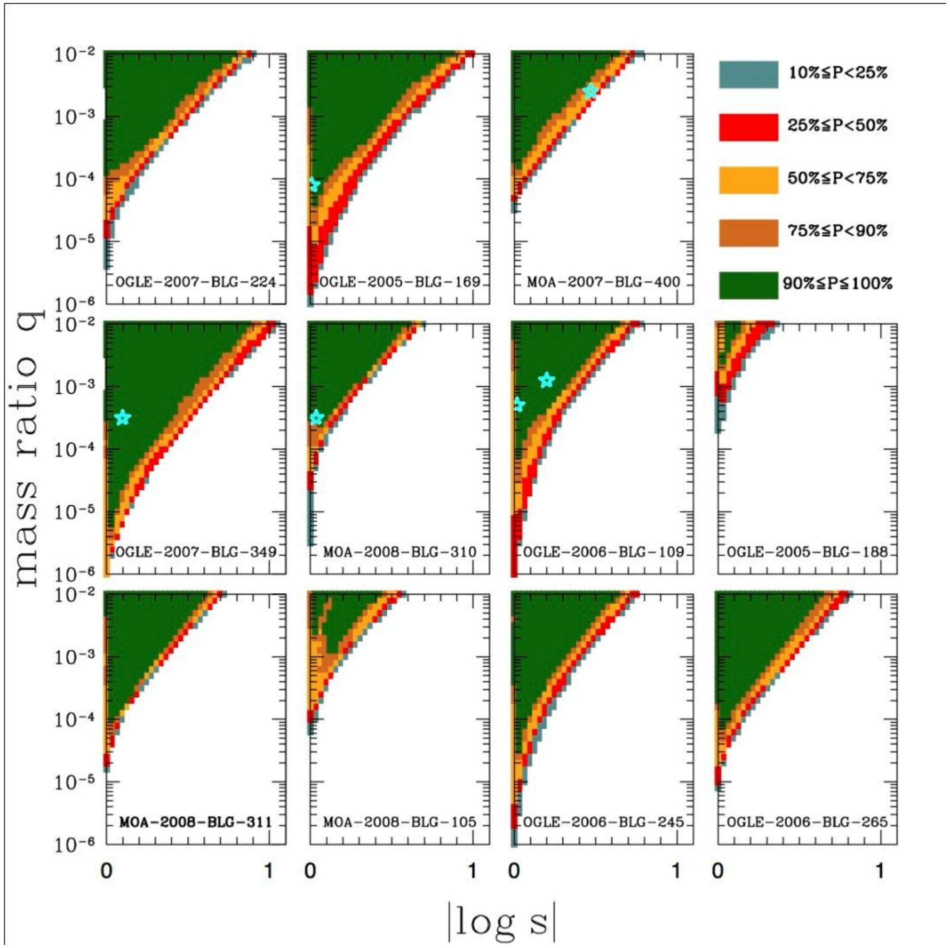
we find ~30% of bulge lenses vs ~60% expected for an unbiased sample: bias from observational protocol

SCN et al 2014, in prep.

…. to the Galactic Distribution of Planets

a test study: 1 planet only! *(SCN et al 2014, in prep.)*

a key issue: the planetary events are NOT chosen for Spitzer observations because they are known to have planets – they are a fairly-drawn sample from the ensemble of single lens events, regardless of any bias in this sample



a caveat: each point-lens lightcurve pdf must be weighted by the corresponding planet sensitivity (Gould et al 2010), in order to compare the resulting cumulative distribution, namely the cumulative distribution of planet detectability, with the Galactic distribution of planets

Fig. 4 from Gould et al 2010

Conclusions

- **First results out of a 100-hr (38 d) *Spitzer* Microlens Planets and Parallaxes pilot program**

  (a caveat) first ever study of a large sample of microlens parallax measurements: ongoing work

- ✓ OGLE-2014-BLG-0124L: parallax for a 0.5 M_{jup} (Udalski et al, 2014, sub.)
- ✓ OGLE-2014-BLG-0939: first microlensing parallax for an isolated star (Yee et al 2014, sub.)
- ✓ Spitzer Microlens Parallax for 21 single lens : Pathway to the Galactic Planet Distribution (SCN et al 2014, in prep)

- **Looking forward: increase the number of microlensing planetary events detected in space-based campaign: a larger *Spitzer* program, *Kepler* (K2) …… *WFIRST***