Microlensing with Spitzer

Pathway to the Galactic Distribution of Planets

19th Microlensing conference
January 19-22, 2015
NASA, Goddard Space Flight Center
Annapolis, MD, US

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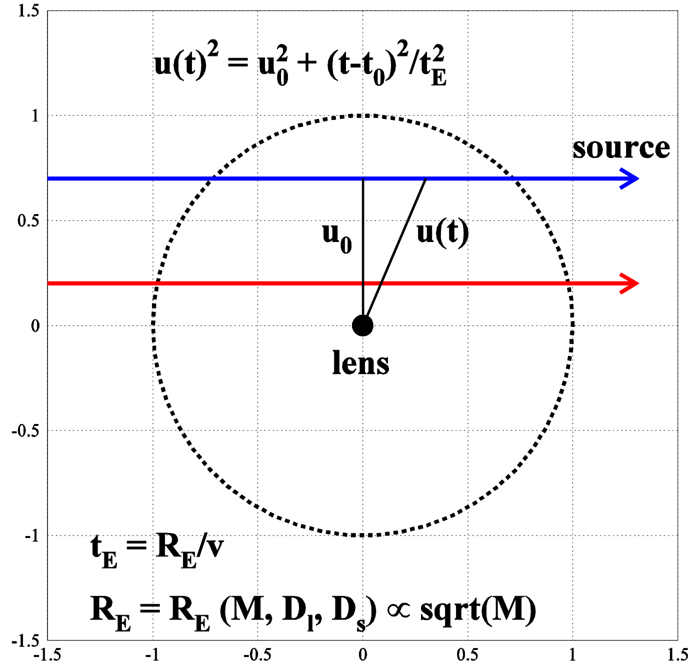
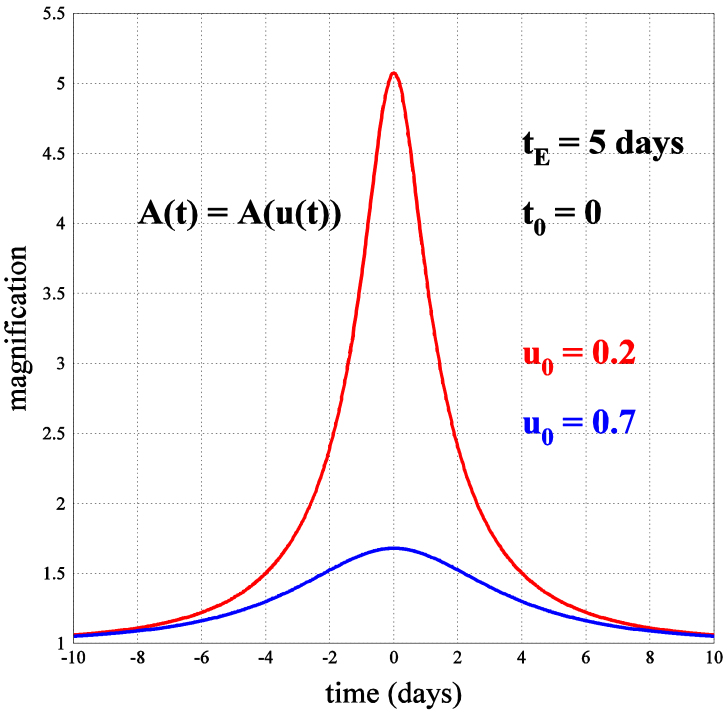
OUTLINE

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

The key astrophysical issues

- Determination of the lens **mass**
  - **Planetary** events (binary lens systems)
  - Mass function for single lens systems (*not light-b(i)ased*)
- 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 (lens) physical parameter

Bottom line: degeneracy in the lensing parameter space

$$t_E = t_E(M_L, D_L, D_S, v)$$

Lens mass ?
Lens (source) distance ?
Relative lens-source velocity?

Breaking the degeneracy ?

compare the physical characteristic length, the Einstein (angular) radius, to rulers 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
  - Simultaneous observations from Earth and a satellite in solar orbit (*Spitzer*!)

From the parallax to the lens mass and distance through the (projected) velocity

The parallax vector

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

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

The projected velocity (from the fit parameters)

$$\tilde{\boldsymbol{v}}_{geo} = \frac{\boldsymbol{\pi}_{E,geo}}{\pi_E{}^2}\frac{AU}{t_E} \qquad \tilde{\boldsymbol{v}}_{hel} = \tilde{\boldsymbol{v}}_{geo} + \boldsymbol{v}_{\oplus\perp},$$

A key quantity: kinematic properties only - indepedent of the lens mass - Discriminate bulge and disc lenses

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

Source-lens relative proper motion is within a factor of 2 of $\mu \sim 4\ mas\ yr^{-1}$ for bulge and disc lenses

$$\boldsymbol{M} = \frac{\boldsymbol{\mu}_{geo}\boldsymbol{t}_E}{\boldsymbol{k}\,\boldsymbol{\pi}_E} = \frac{\boldsymbol{\theta}_E}{\boldsymbol{k}\,\boldsymbol{\pi}_E}$$

Possible to get to statistical statements on M and π_{rel} also when θ_E is not measured (and therefore on D_L for fixed D_S)

Looking back and forward

Liebes, 1964; Refsdal, 1964: degeneracy in microlensing parameter space
Refsdal 1964: break degeneracy with microlensing parallax
(observations 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

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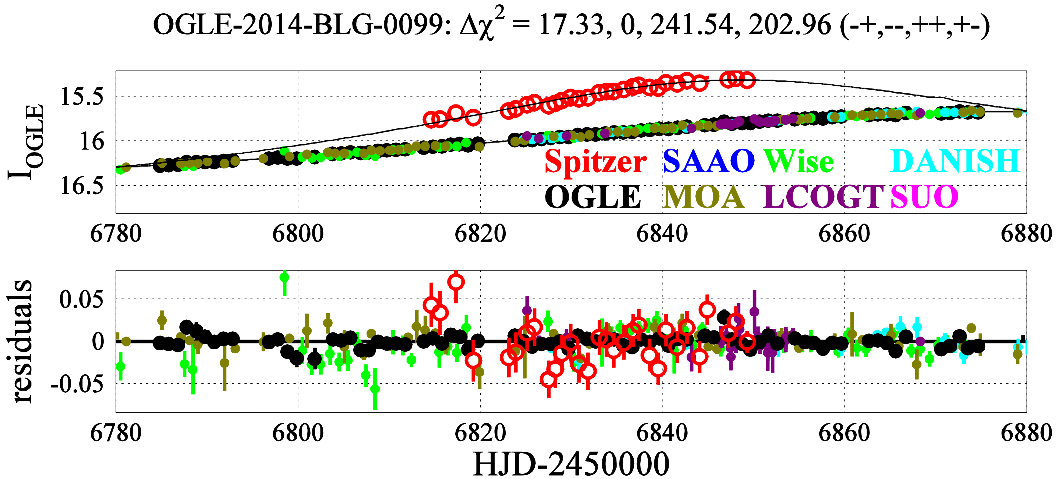
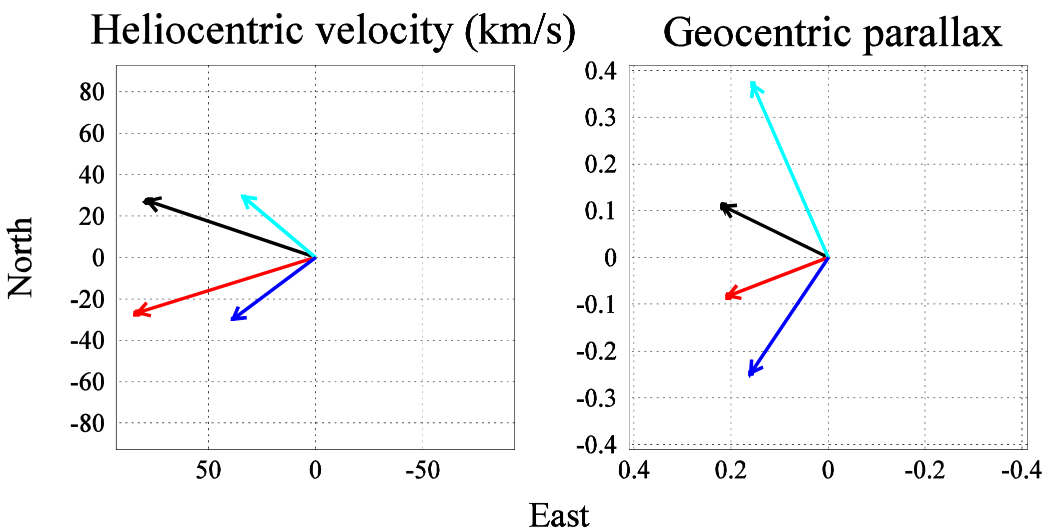
Udalski, Yee, Gould et al (SCN) 2014 (ApJ, accepted)
Yee, Udalski, Calchi Novati et al 2014 (submitted)
Calchi Novati, Gould, Udalski et al 2014 (submitted)

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





The parallax degeneracy ($A = A(u^2(t))$)

$$\boldsymbol{\pi}_E = \frac{AU}{D_\perp}\left(\Delta\tau, \Delta u_{0,\pm,\pm}\right)$$

roughly along E, N (equatorial)

$$\Delta\tau = \frac{t_{0,sat} - t_{0,\oplus}}{t_E}$$

$$\Delta u_{0,-,\pm} = \pm\left(\left|u_{0,sat}\right| - \left|u_{0,\oplus}\right|\right)$$

$$\Delta u_{0,+,\pm} = \pm\left(\left|u_{0,sat}\right| + \left|u_{0,\oplus}\right|\right)$$

$\Rightarrow \quad \pi_{E,\pm}$

bottom line: 4 minima in the χ^2 space with 2 values for the amplitude π_E (relevant to mass and lens distance)

SCN, Gould, Udalski et al, 2014, submitted

Rich argument (a statistical assessment)

The two components of $\boldsymbol{\pi}_E$ should (in general) be of the same order:
If we find $\pi_{E,+} \gg \pi_{E,-}$ then it is highly likely that the $\pi_{E,-}$ solution is correct

Consider an event with similar t_0 and u_0 from Earth and from *Spitzer*

Both components of $\boldsymbol{\pi}_{E,-} \propto (\Delta\tau, \Delta u_{0,-})$ are therefore *small*

There is then a second solution $\boldsymbol{\pi}_{E,+} \propto (\Delta\tau, \Delta u_{0,+})$ for which $\Delta u_{0,+} \sim 2u_{0,\oplus}$

Is there a way to underweight $\pi_{E,+}$ vs $\pi_{E,-}$? Let's assume $\pi_{E,+}$ is correct….

$\boldsymbol{\pi}_{E,+}$ is almost aligned with the y-axis which is unlikely assuming a random distribution for the parallax vector orientation : $P_{\Delta\tau} \sim |\Delta\tau| / |u_{0,\oplus}|$, which is small

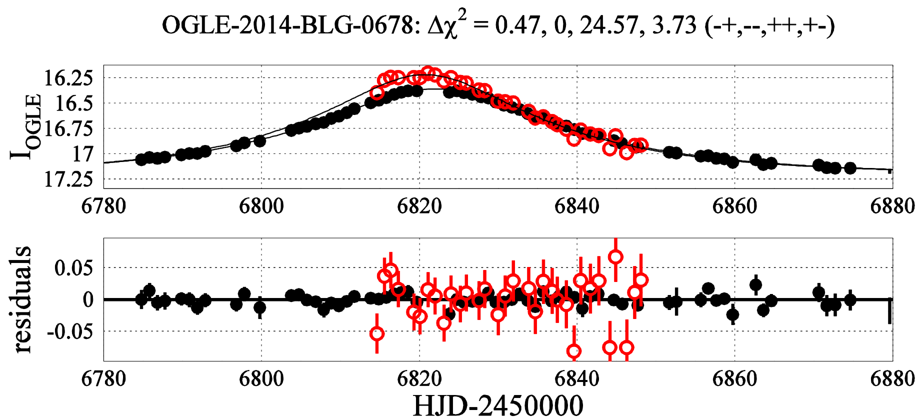
The event cross the Earth-Spitzer axis just such $u_{0,\oplus} \sim -u_{0,Spitzer}$ which (again) is unlikely (the event may pass everywhere): $P_{\Delta u_{o,-}} \sim |\Delta u_{o,-}| / |u_{0,\oplus}|$, which is small

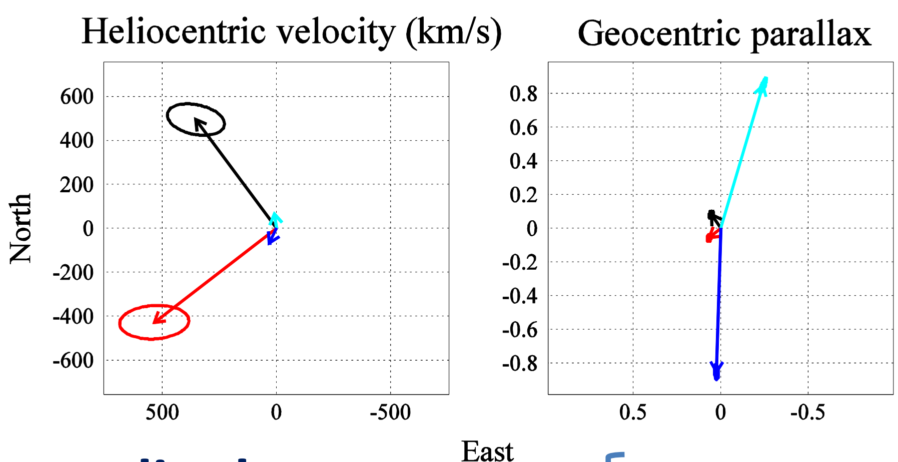
The probability for both simultaneously happen is even smaller

Such an argument cannot be considered decisive in any specific case, however its use is appropriate, in a statistical sense, if the objective is to find the (cumulative) distribution of lens distances

Rich argument in practice

A case where it does apply



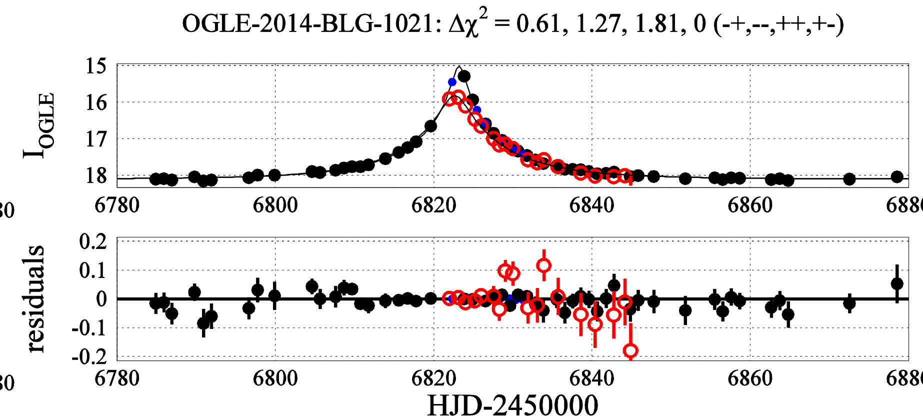


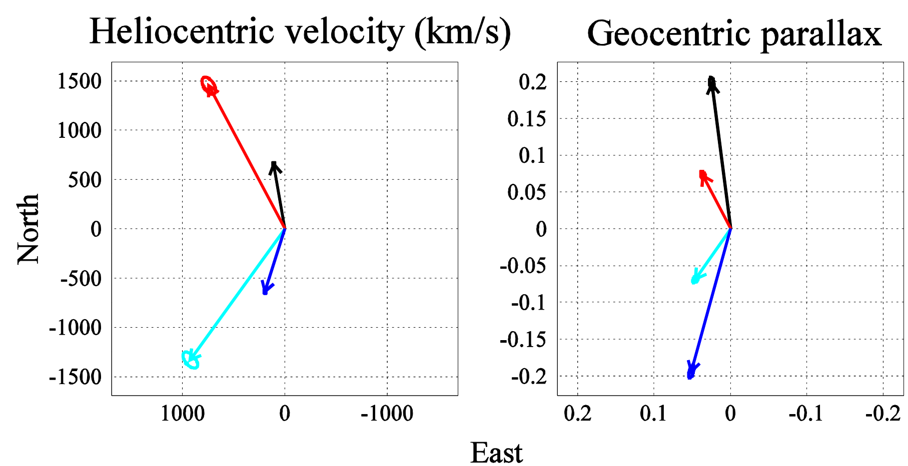
a disc lens

$\pi_{E,+}/\pi_{E,-} = 9$

$$\Delta\chi^2 = \begin{cases} 0.5,\ 0 & (\pi_{E,-,\pm}) \\ 25,\ 3.7 & (\pi_{E,+,\pm}) \end{cases}$$

A case where it does NOT apply



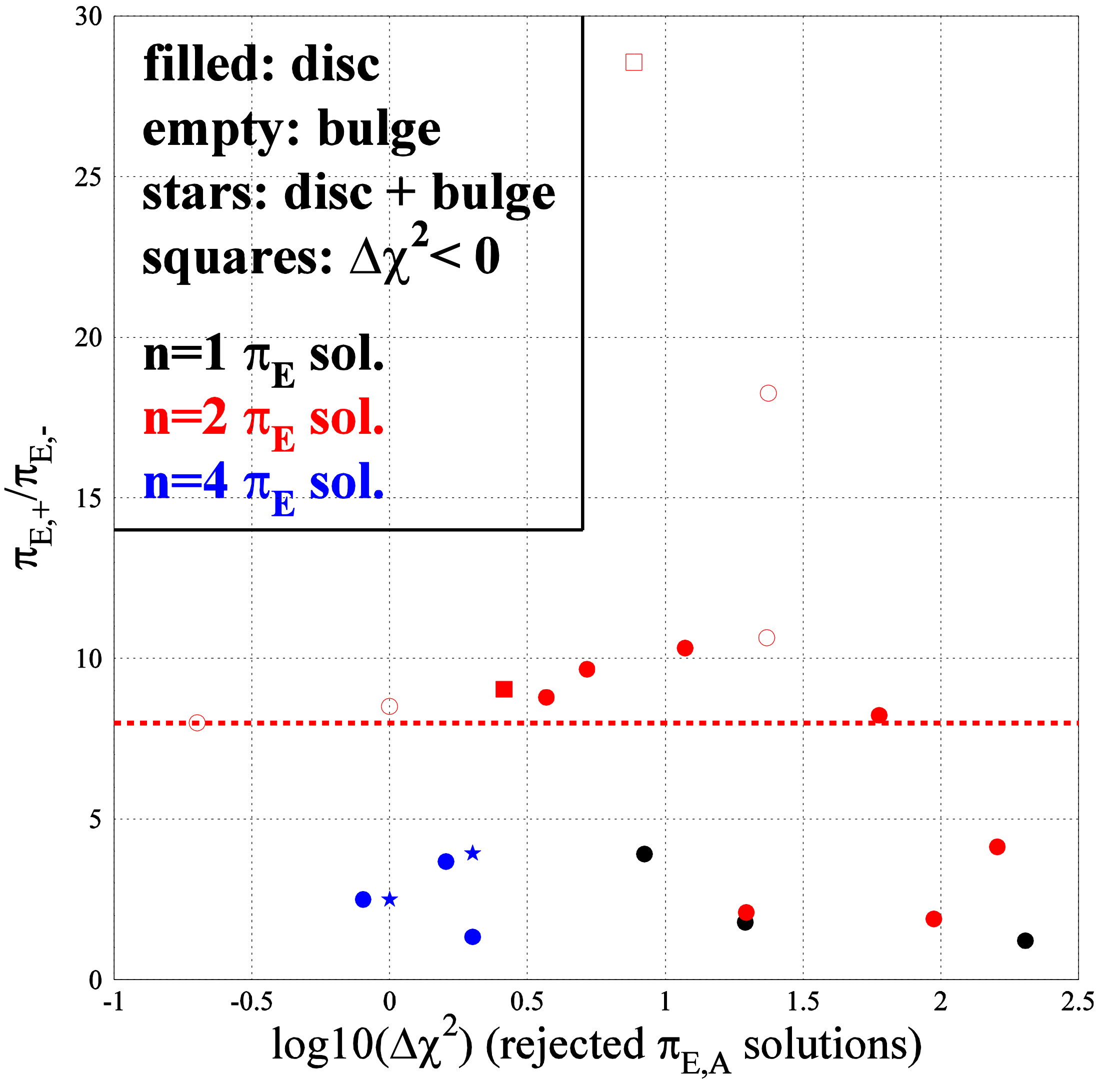


disc or bulge lens?

$\pi_{E,+}/\pi_{E,-} = 2$

$\Delta\chi^2 < 2$

Analysis of the 21 single-lens events



Singling out the correct $\boldsymbol{\pi}_E$ solution

- ❑ $\boldsymbol{\Delta\chi^2}$
- ❑ **Rich argument**

- 10 evts with Rich argument (4 with large $\Delta\chi^2$, and 1 «wrong»)
- 6 with large $\Delta\chi^2$ (small π_E ratio)
- 5 doubtful cases (3 disc + 2?)

Disc and bulge nature based on kinematic ($\tilde{v}$)

in the following statistical analysis we consider accordingly from 1 up to all the 4 solutions

Towards a distribution of lens distances

The phase space density, $\boldsymbol{\Gamma = n\sigma v}$, evaluated at the fit parameter values

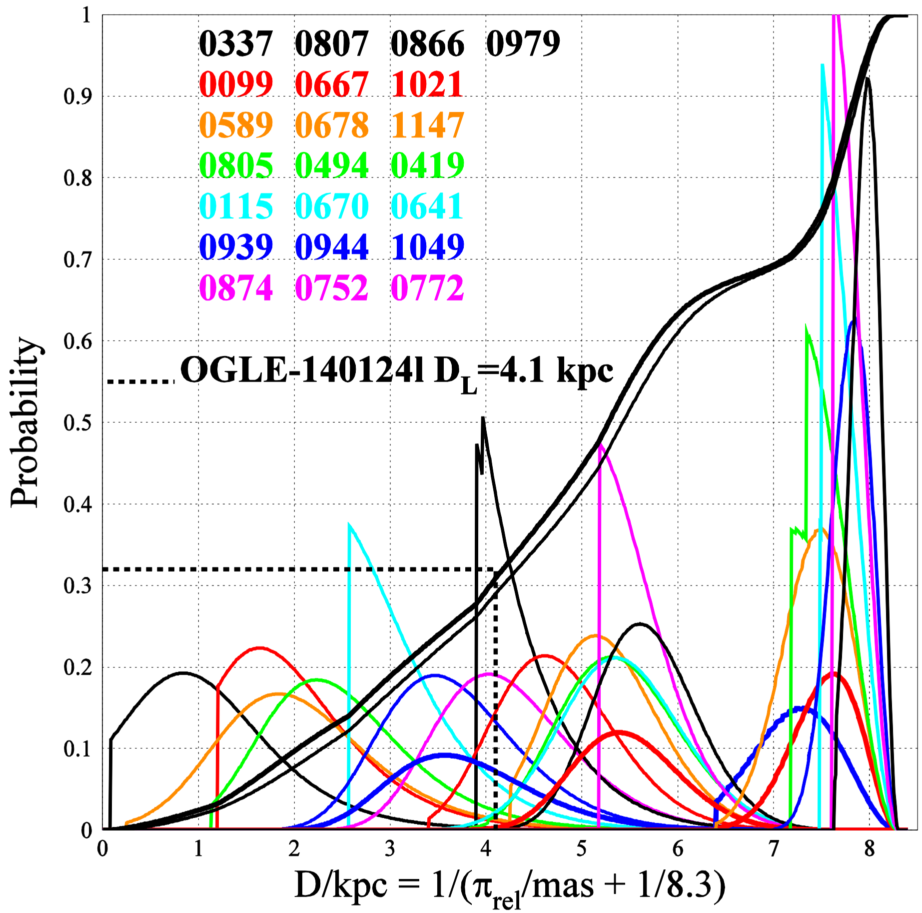
- The volume element : ${D_L}^2\,\Delta D_L$
- The kinematic prior: $P(\tilde{v}) = P(\tilde{v}, model, \pi_{rel}, D_L)$
- The cross section: $\theta_E = \pi_{rel}/\pi_E$
- The proper motion: $\mu = \pi_{rel}\,\tilde{v}$/AU
- (The lens mass: M= $\pi_{rel}/\kappa\,{\pi_E}^2$)

$$\boldsymbol{\Gamma \rightarrow p_\Gamma = \mathrm{d}\Gamma/\mathrm{d}(D_L) = p_\Gamma(\pi_{rel}, D_L)}$$

Discrimination among the 4 $\boldsymbol{\pi_E}$ solutions:

- **Rich argument (when appropriate: 10 evts/21)**
- $\boldsymbol{\Delta\chi^2 \rightarrow p \propto \exp(-\Delta\chi^2/2)}$

From the Distance Cumulative Distribution for (Single) Lens Systems …



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

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

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

- **single peak distributions (most cases)**

- broad distribution for disc lenses
- bulge stars (30% only, bias obs protocol ?)
- gap around 6.5 kpc (conjecture: los ?)
  - small statistics
  - Selection effects

the specific features of the distribution, and its possible biases, are irrelevant for the actual purpose of the analysis…..

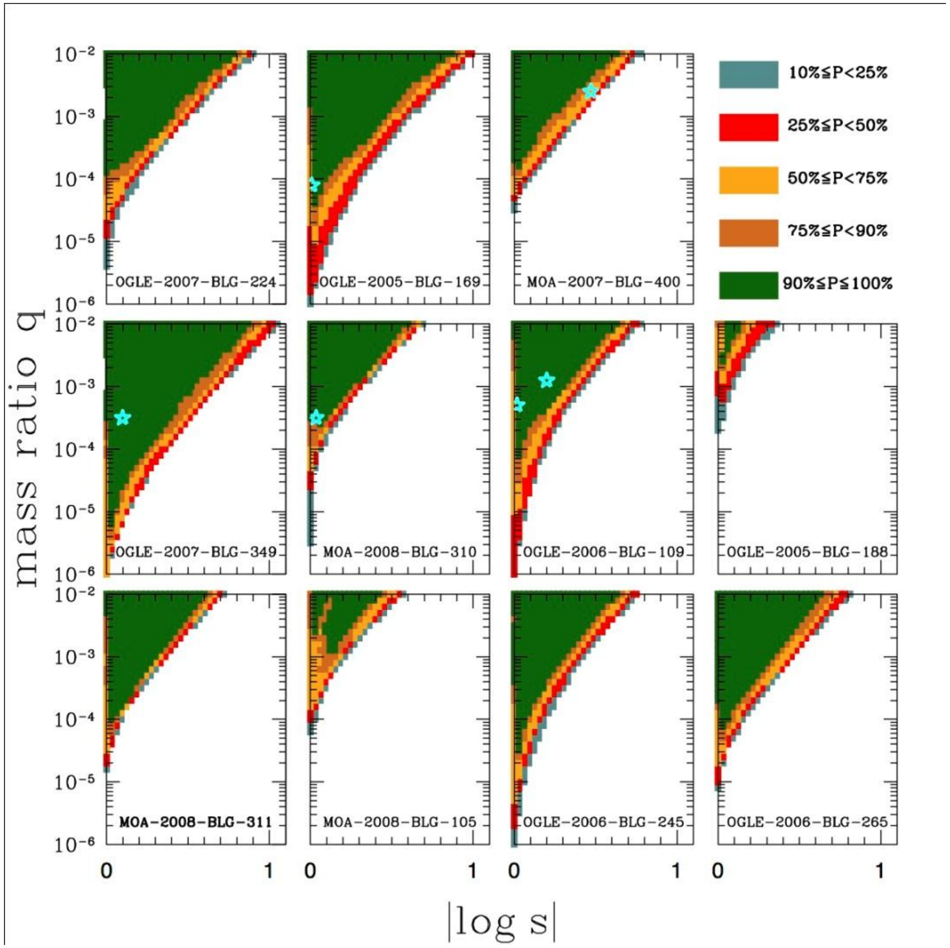
one planetary event OGLE-2014-BLG-0124

SCN, Gould, Udalski et al 2014, submitted.

.... to the Galactic Distribution of Planets

a test study: 1 planet only (OGLE-BLG-2014-0124)

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

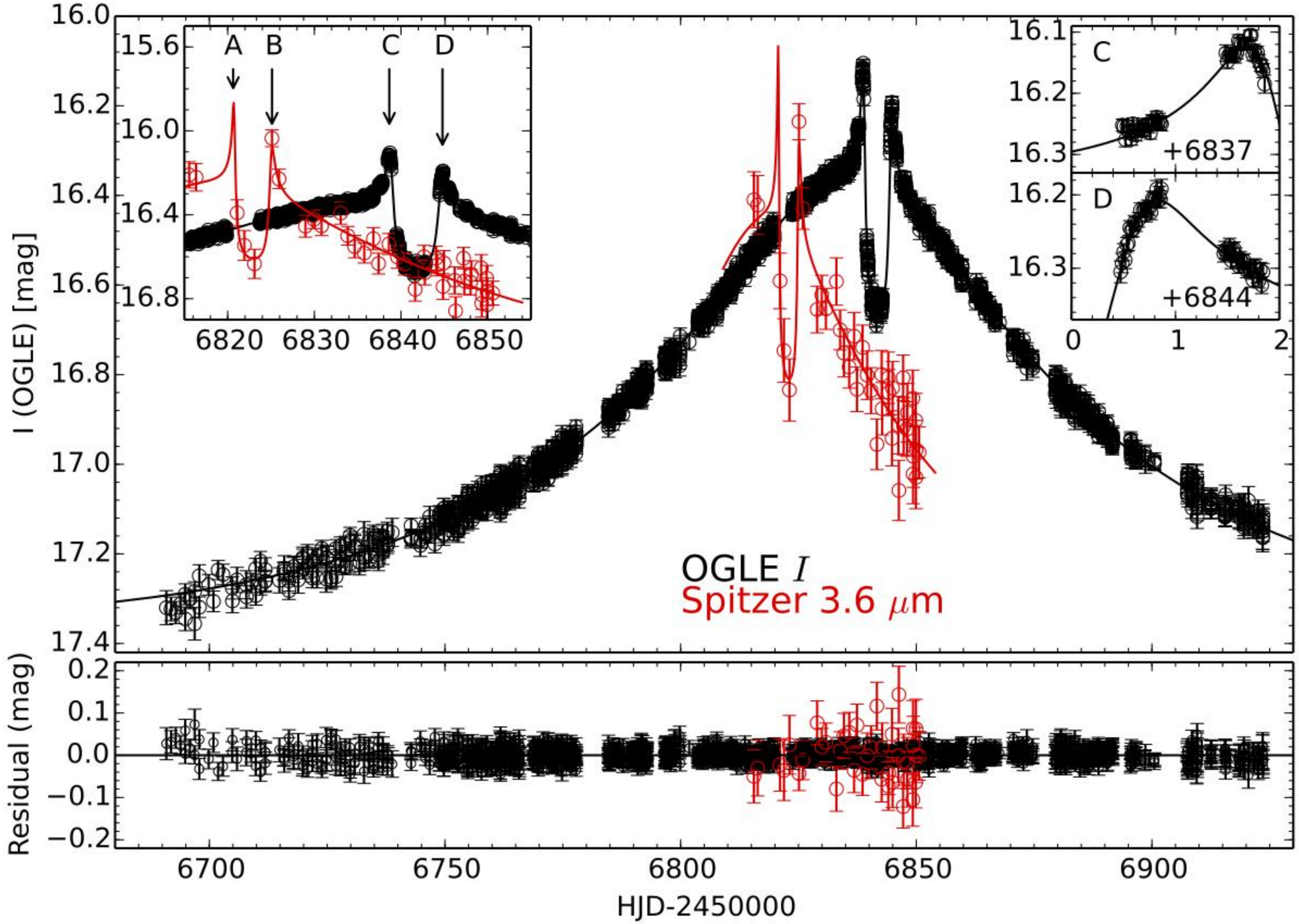


a caveat: each point-lens lightcurve pdf must be weighted by the corresponding planet sensitivity (Gould et al 2010), in order to compare the resulting cumulative distribution, namely the cumulative distribution of planet detectability, with the Galactic distribution of planets

Fig. 4 from Gould et al 2010

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, ApJ accepted

Conclusions

- **Results out of the 2014 100-hr (38 d) *Spitzer* Microlens Planets and Parallaxes pilot program (PI: Gould)**

✓ **OGLE-2014-BLG-0124L: parallax for a 0.5 M_{jup} (Udalski et al, 2014, accepted)**
✓ 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, sub.)
✓ Mass and Distance measurements of Binary Lens System OGLE-2014-BLG-1050 (Zhu et al, *in prep*)

- **Looking forward: increase the number of microlensing planetary events detected in space-based campaign:**
  - ❑ **a larger *Spitzer* program: 832h 2015 campaign (the entire available 38d Bulge Spitzer window, PI: Gould)**
  - ❑ ***Kepler* (K2)**
  - ❑ **…… *WFIRST* ?**