Towards the Galactic Distribution of Exoplanets

Spitzer and the Microlensing Parallax

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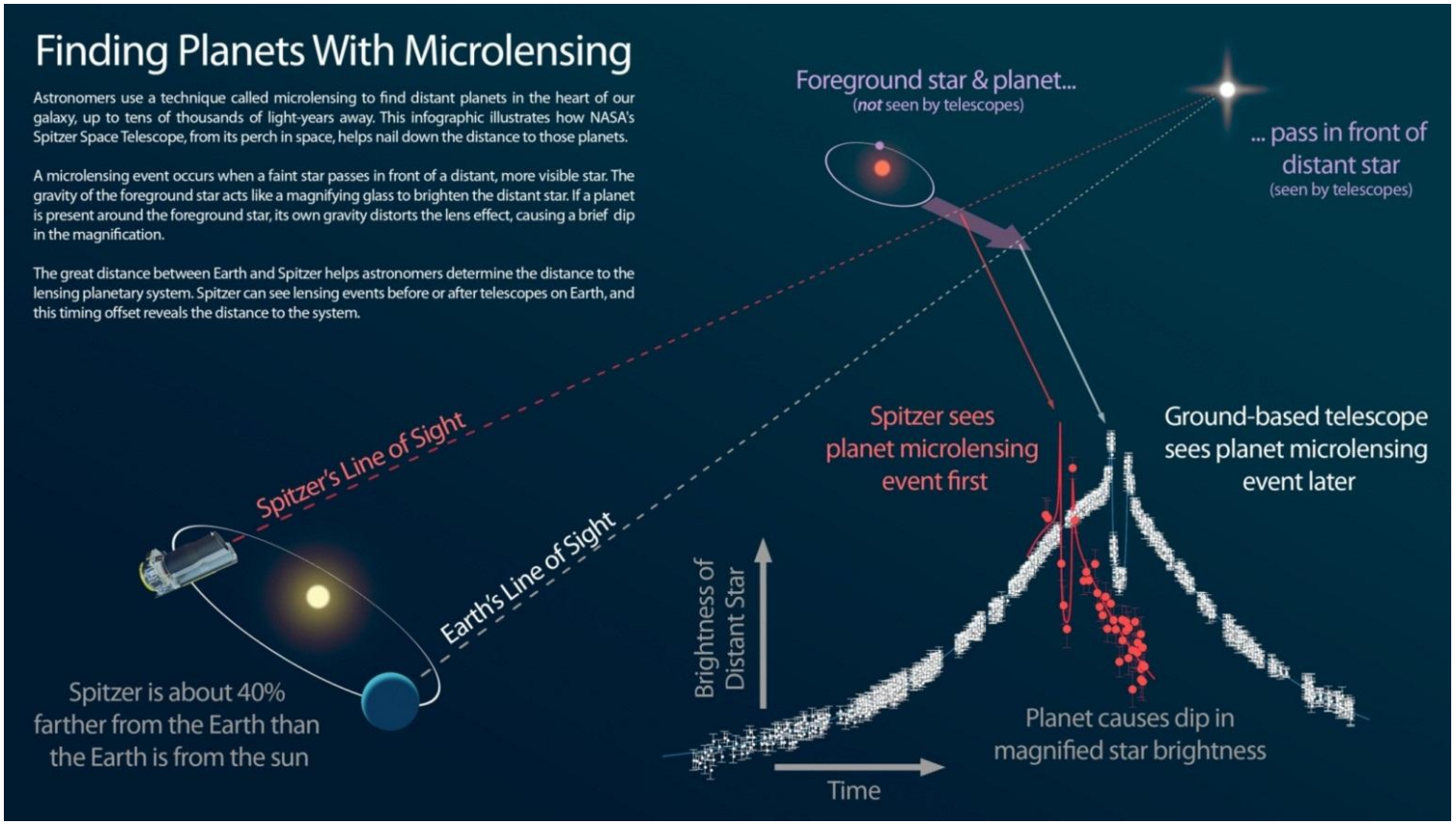
OUTLINE

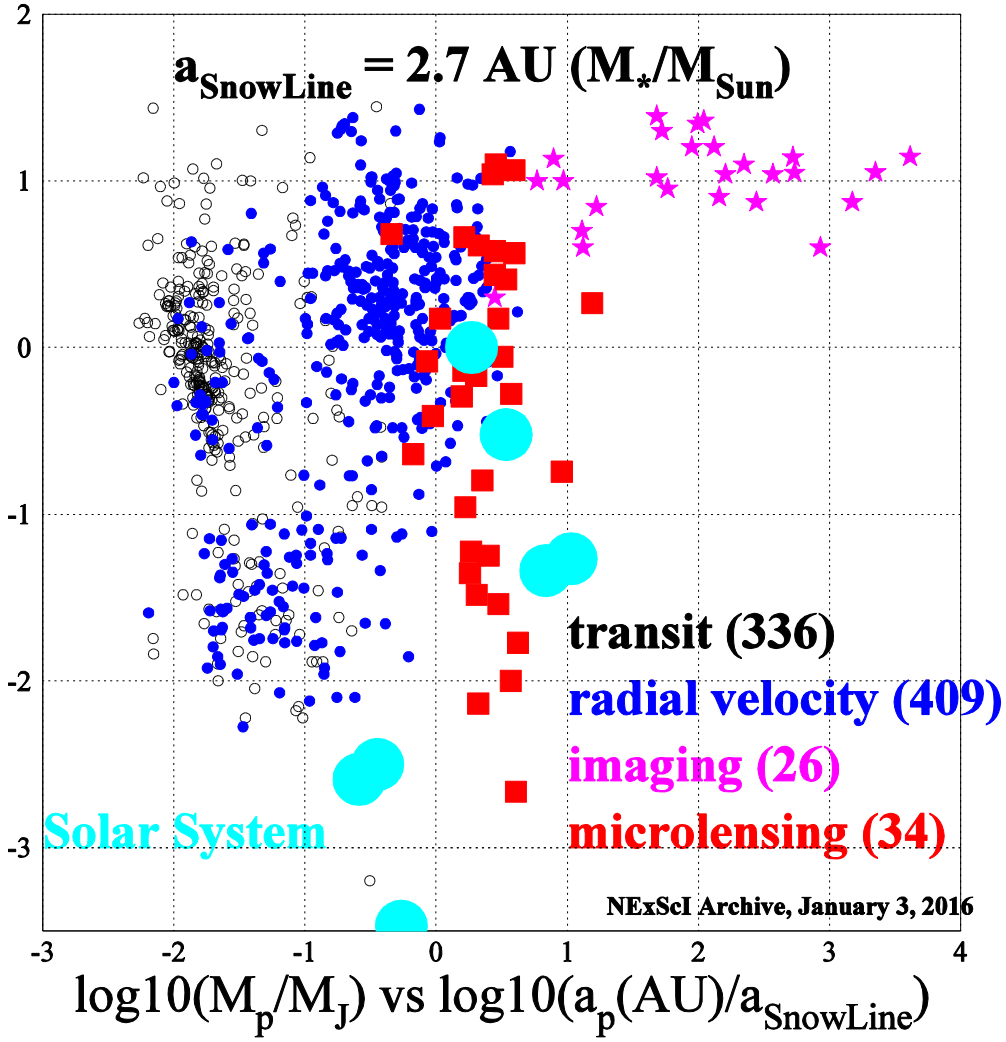
towards the Galactic distribution of exoplanets

- ❑ **Microlensing and the hunt for Exoplanets**
- ❑ **The Microlensing Parallax: a ruler in the sky**
- ❑ **The Spitzer Observational Campaign**



credit: NASA/JPL

Microlensing and Exoplanets Astrophysics



Peak sensitivity beyond the snow line ($\approx R_E$)

Sensitivity to low mass planets

Sensitivity to free-floating planets

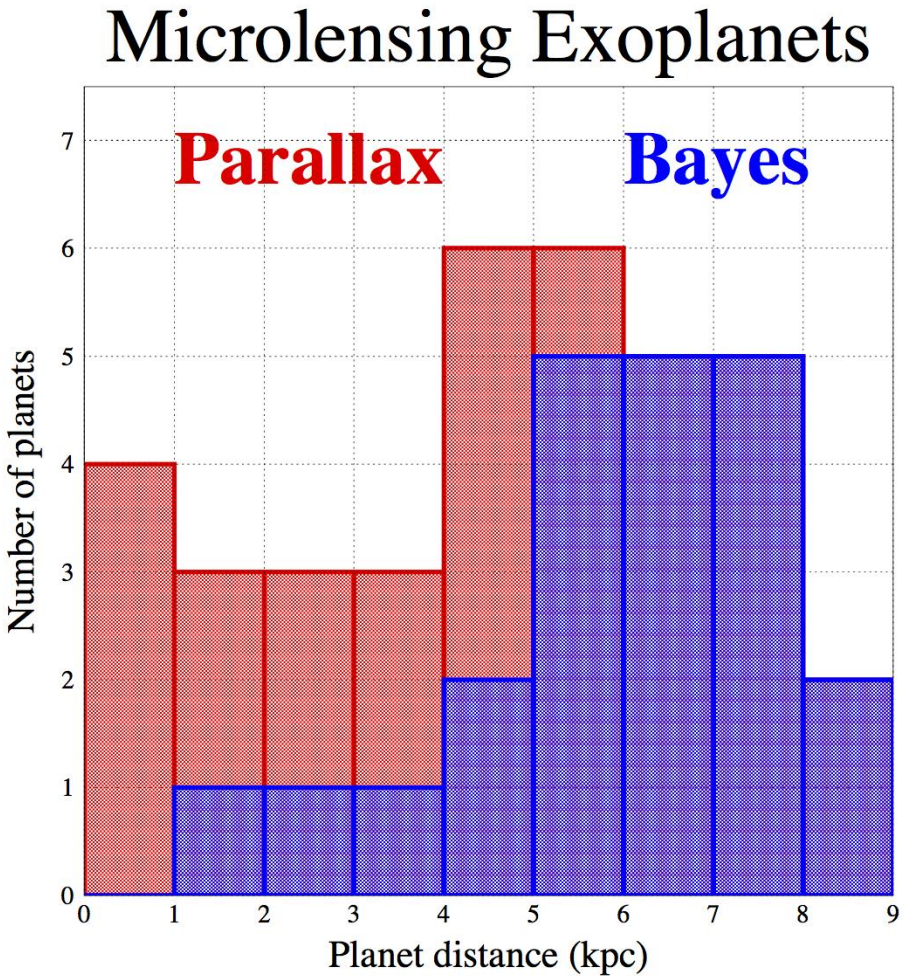
Sensitivity to planets throughout the Galaxy

key to the Spitzer campaign

Microlensing is sensitive to planets in regions of the parameter space difficult to impossible to probe with other methods

Microlensing and the Exoplanet Galactic Distribution

Looking for exoplanets all the way to the Galactic center



How do we evaluate the distance ?

Measure through the Microlensing Parallax (bias for nearby lenses)

Bayes: Statistical inference based on a prior Galactic model

This is what we observe, but how do we get to the underlying distribution ?

We need the distance distribution for the underlying single-lens event population

Microlensing Spitzer Observational Campaigns

follow up of microlensing events towards the Galactic Bulge

- **2014: 100 hr, DDT, A. Gould (PI), S. Carey, J. Yee**
  «*Spitzer* Microlens Planets and Parallaxes»
- **2015: 832 hr, A. Gould (PI), S. Carey, J. Yee**
  «Galactic distribution of Planets from *Spitzer* Microlens Parallaxes»
- **2016: 100hr, A. Gould (PI), S. Carey, J. Yee**
  «Galactic Distribution of Planets from High-Magnification Microlensing Events»
- **2016: 50 hr, DDT, A. Gould (PI), S. Carey, J. Yee**
  «Degeneracy breaking for K2 Microlens parallaxes»
- **2017-2018: 800 x 2 hr (?)**

The Spitzer team @ Pasadena: IPAC and JPL…

- **Charles Beichman (IPAC, JPL)**
- **Geoff Bryden (JPL)**
- **Sebastiano Calchi Novati (IPAC)**
- **Sean Carey (IPAC)**
- **Calen Henderson (JPL)**
- **Yossi Shvartzvald (JPL)**

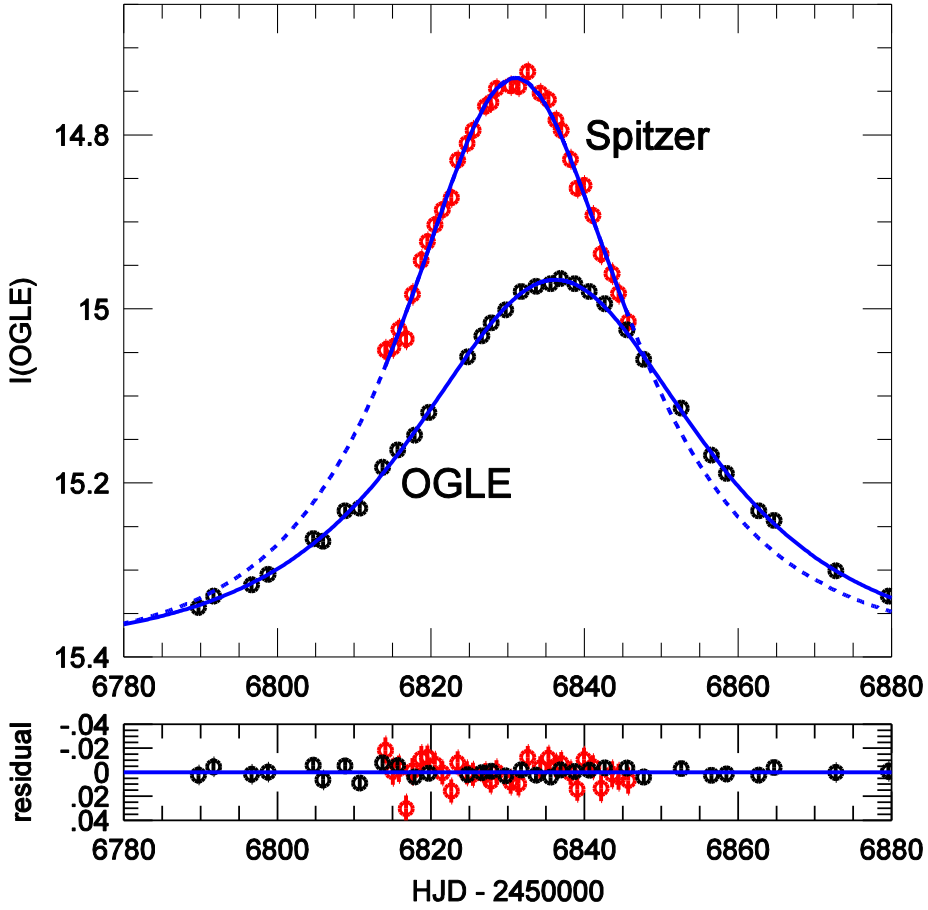
…. and in the rest of the world

- S. Gaudi (OSU)
- **A. Gould (OSU), PI**
- R. Pogge (OSU)
- J. Yee (CfA)
- W. Zhu (OSU)

The Microlensing Parallax in the Sky: Spitzer

π_E : projection of the Einstein radius ($\sim 2\ AU$) onto the observer plane

Microlensing Parallax from the Simultaneous Observation of the same Microlensing Event from Two Observers with relative distance ~ AU
(Refsdal 1966, Gould 1994, 1995, 1999, Dong et al 2007, Gould et al 2014 on….)



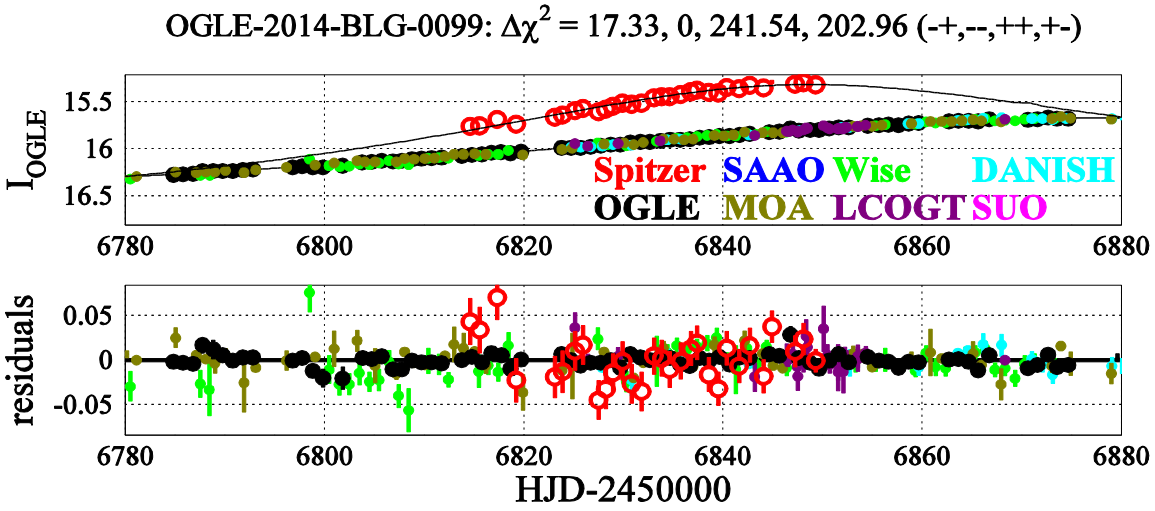
OB140939: First Space-based Microlensing Parallax Measurement of an Isolated Star
(Yee, Udalski, SCN et al ApJ 2015)

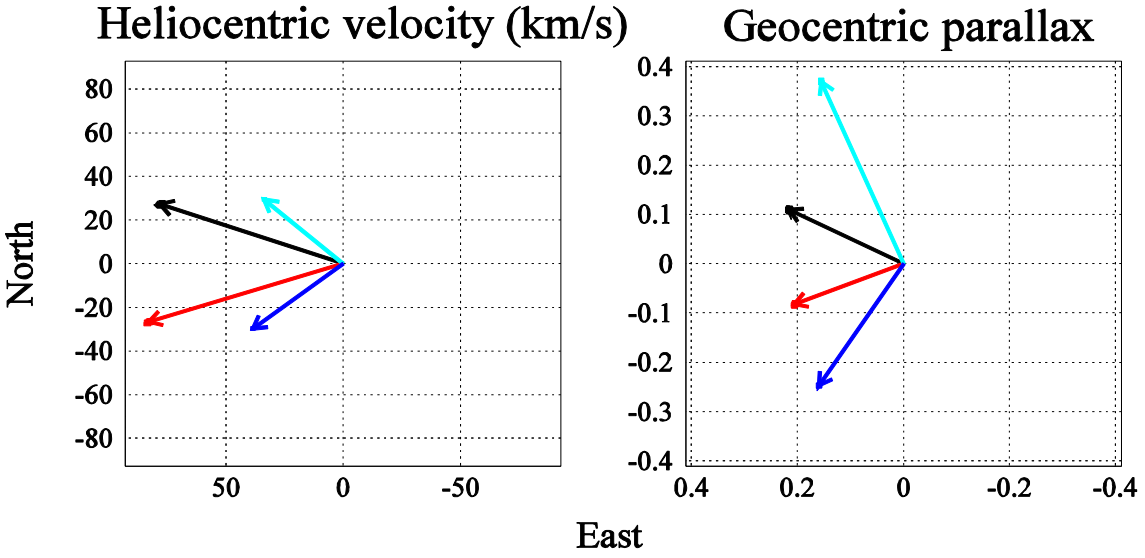
π_E measured, given t_E,
from the observers times
at maximum magnification, $t_{0,oss}$,
and impact parameters, $u_{0,oss}$

$$M = 0.23 \pm 0.07\ M_\odot$$
$$D_L = 3.1 \pm 0.4\ kpc$$

IT IS NOT A SMALL EFFECT!!

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





Determine the microlens parallax for single lens events, the underlying population for exoplanetary events , to build up the exoplanets Galactic distribution

Parallax analysis

⋆ Spitzer baseline short vs t_E

⋆ relative Spitzer-Ogle color

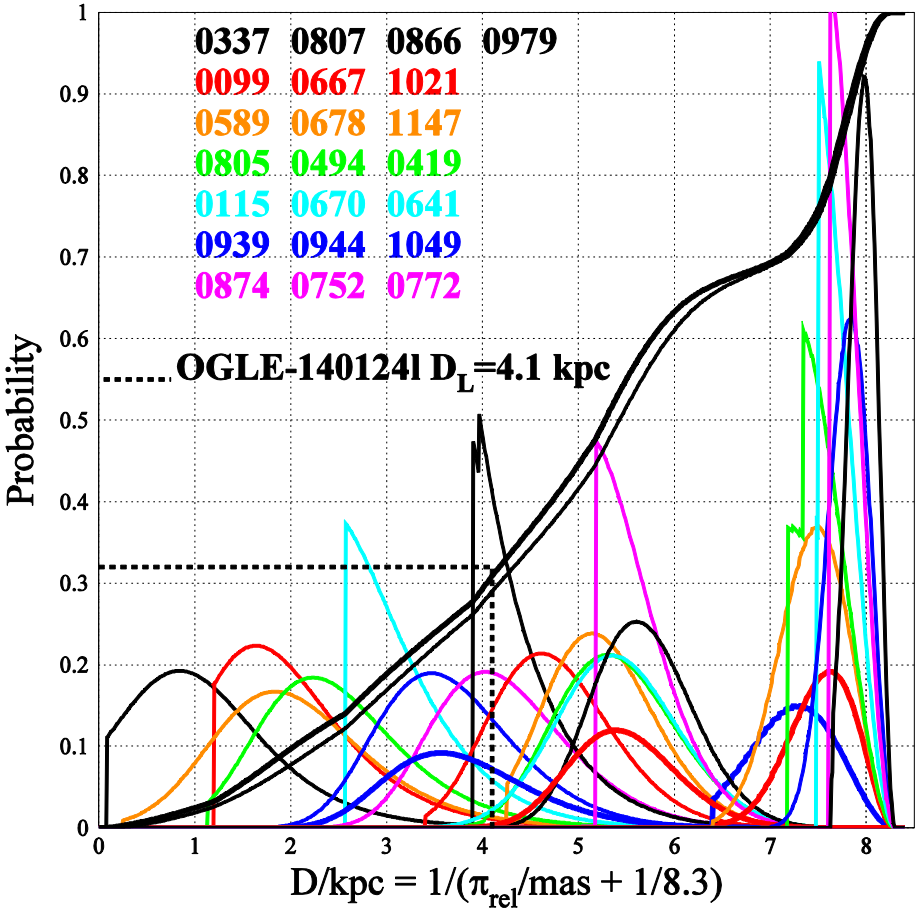
Parallax degeneracy

⋆ $\Delta\chi^2$ analysis

⋆ Rich's argument

SCN, Gould, Udalski et al, ApJ 2015

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



one planetary event
OGLE-2014-BLG-0124

- **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

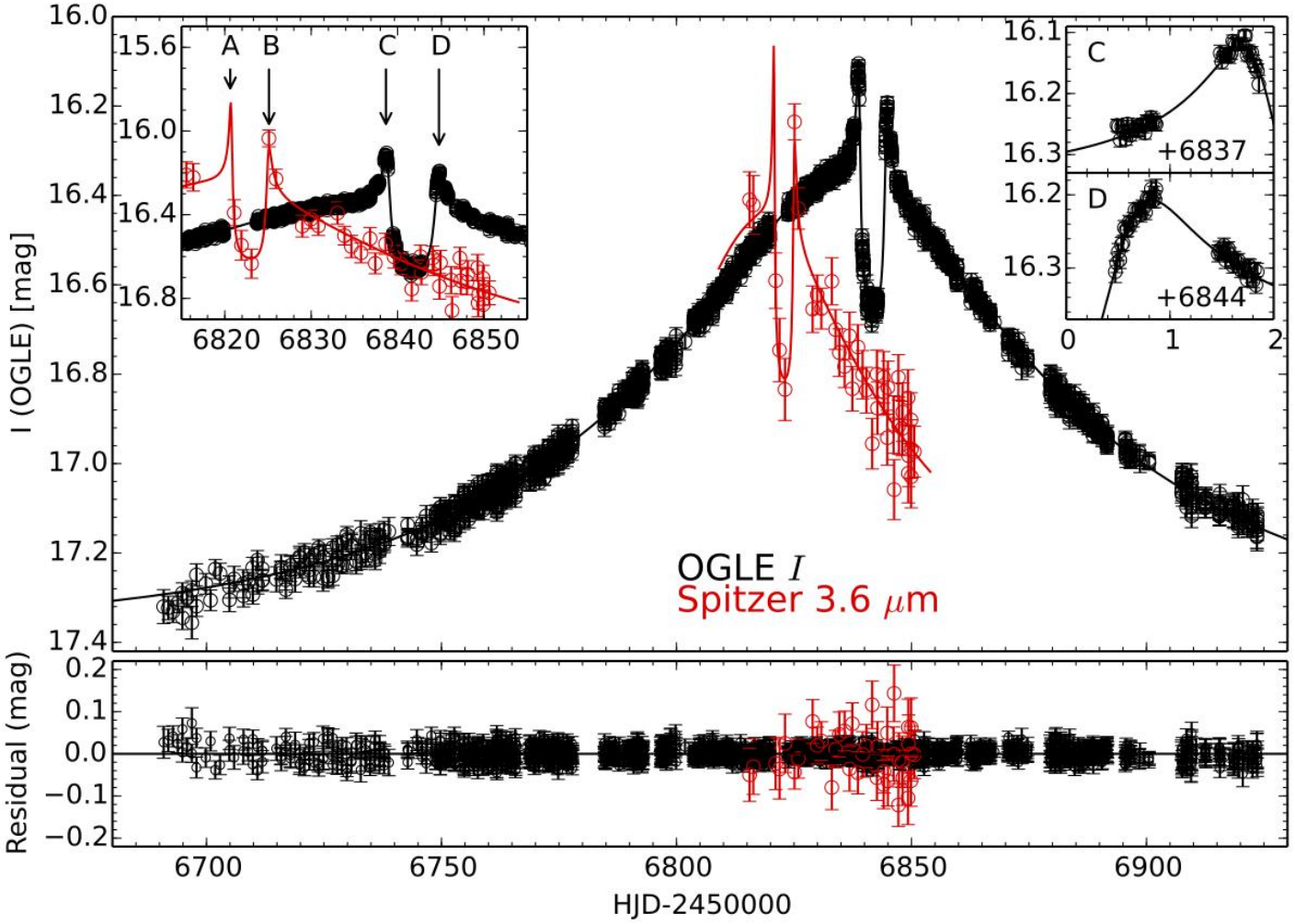
… to the Galactic Distribution of ExoPlanets (a test study)

the planets are a fairly-drawn sample from the ensemble of single lens events which then provides a probe for the measure of the underlying planets distance distribution (key point: we do not know about the planet when we select the event for observation!)

SCN, Gould, Udalski et al, ApJ 2015.

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%)



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

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

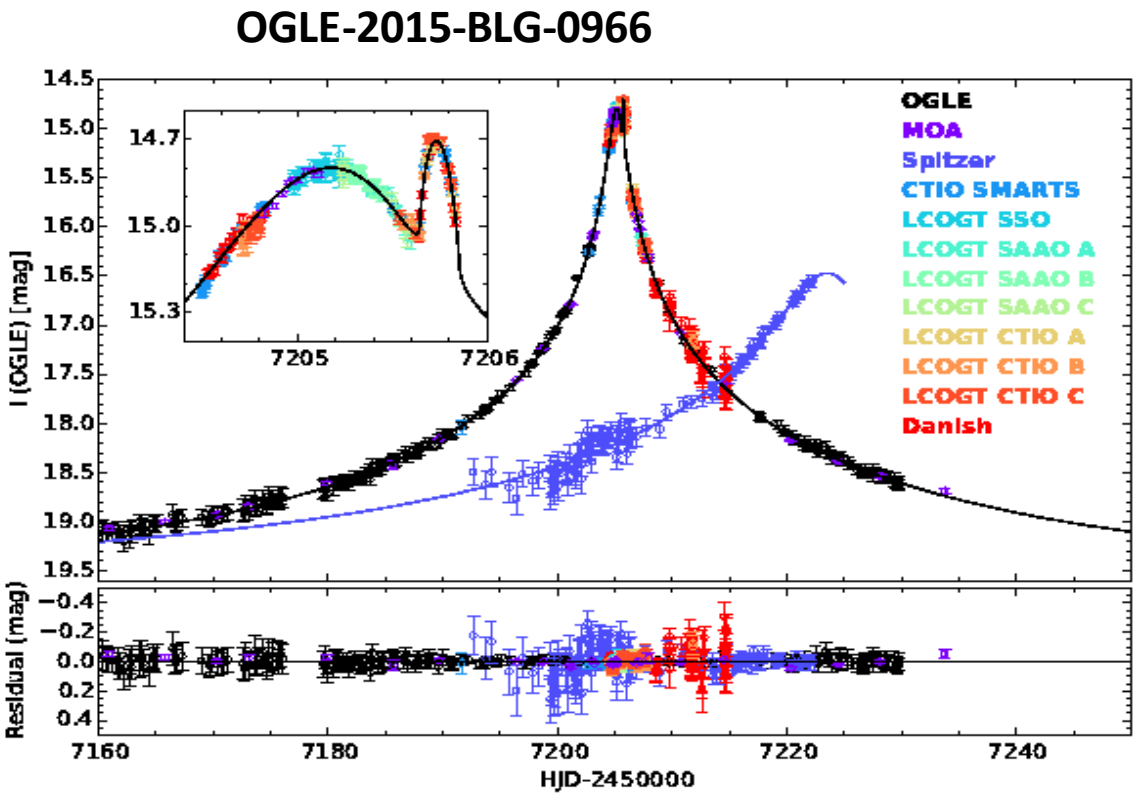
$D_l \sim 4.1$kpc

$a_\perp \sim 3.16$ AU

relative error $\sim 30\%$ from that on θ_E

Udalski, Yee, Gould et al (SCN) ApJ 2015

Spitzer Parallax of OB150966: a Cold Neptune in the Galactic Disk



$D_L = 3.3\ kpc$ (bulge source)

$D_L = 2.5\ kpc$ (disc source)

$M_L = 0.38\ \pm 0.04\ M_\odot$

$\boldsymbol{M_p = 21\ \pm 2\ M_\oplus}$

$a_\perp = 2.7\ AU$ (bulge source)

$a_\perp = 2.1\ AU$ (disk source)

Street, Udalski, SCN et al, ApJ 2016

Spitzer Microlensing Campaign besides Exoplanets

OB140939: Spitzer Microlensing Parallax for an Isolated Star
J. Yee, Udalski, SCN et al, ApJ 2015

$D_L = 3.1 \pm 0.4\ kpc$

Spitzer as a Parallax satellite: Mass and Distance for binary system OB141050
W. Zhu et al (SCN), ApJ 2015

$D_L \sim 3.5\ kpc$

Spitzer Microlens Measurement of a Massive Remnant in a Well-Separated Binary in the Galactic Bulge: OB151285
Y. Shvartzvald et al (SCN), ApJ 2015

$D_L = 7.5 \pm 0.2\ kpc$

OB151212: Breaking Strong Microlens Degeneracies with Spitzer
A (brown dwarf ?) binary system in the Bulge
V. Bozza et al (SCN), ApJ 2016

$D_L = 7.18^{+0.43}_{-1.68}\ kpc$

Mass Measurements of Isolated Objects from Space-Based Microlensing
Parallax + Finite source size effect
W. Zhu, SCN et al, 2016, submitted

OB150763: $0.50 \pm 0.04\ M_\odot$ **at** 6.9 ± 1.0 **kpc**
OB151268: $47 \pm 7\ M_J$ **at** 5.4 ± 1.0 **kpc**

Spitzer analysis for OB150448: a Probe for Globular Cluster Planets
R. Poleski et al (SCN), 2016, submitted

Most probably a Bulge lens

Conclusion and Outlook

towards the Galactic distribution of exoplanets

Microlensing is complementary to other techniques
Probe for exoplanets all the way to the Galactic Bulge

The Microlensing Parallax and the (*unbiased*) measure of the lens distance for both binary (planets) and single lens systems
Single-lenses: a probe for the underlying population

Spitzer Observational Campaign 2014-2016(-2018?):
Building up the statistics for the Galactic Distribution of Exoplanets

K2C9: the first space-based microlensing survey is NOW
The quest for free-floating planets

WFIRST microlensing survey: complete the statistical census of planetary systems in the Galaxy