Microlensing Parallax with Spitzer

Pathway to the Galactic Distribution of Planets

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OUTLINE

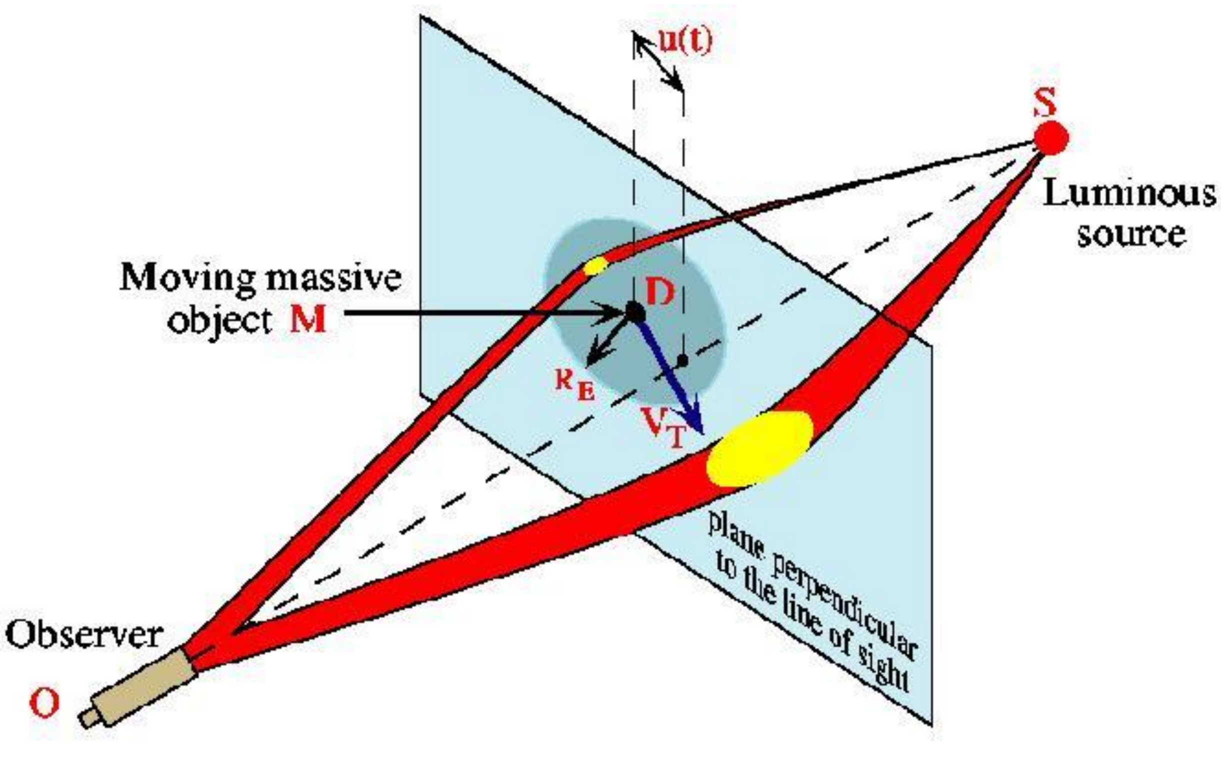
- ❑ **Microlensing: it's all about gravity**
- ❑ **Microlensing and the hunt for Exoplanets**
- ❑ **The Microlensing Parallax: a ruler in the sky**
  - ➢ Uncovering the lens mass and distance
- ❑ **The Spitzer 2014 Pilot Program**
  - ➢ OB140939: First Space-based Microlensing Parallax Measurement of an Isolated Star
  - ➢ OB140124: First Microlensing Planetary System with Space-Based Parallax
  - ➢ **Parallax measurements of 21 Single-Lens events**
- ❑ **The Spitzer 2015 Observational Campaign**

what this is all about: simultaneous observation of the same microlensing event from two observers (Spitzer and ground-based telescopes) separated by ~1 AU: measure the parallax and get the lens distance (also) for single-lens events, this leading to the Galactic distribution of exoplanets (for a large enough statistics)

Gravitational Microlensing

Light from a background source is deflected by intervening objects along the line of sight

Weak field / strong lensing / multiple images / micro: the lens is a stellar-mass compact object/ nearby stellar sources ⟹ *image separation $\Delta\theta \sim$ mas* ⟹ *observe the source change in magnification as a function of time because of the source-lens relative motion*

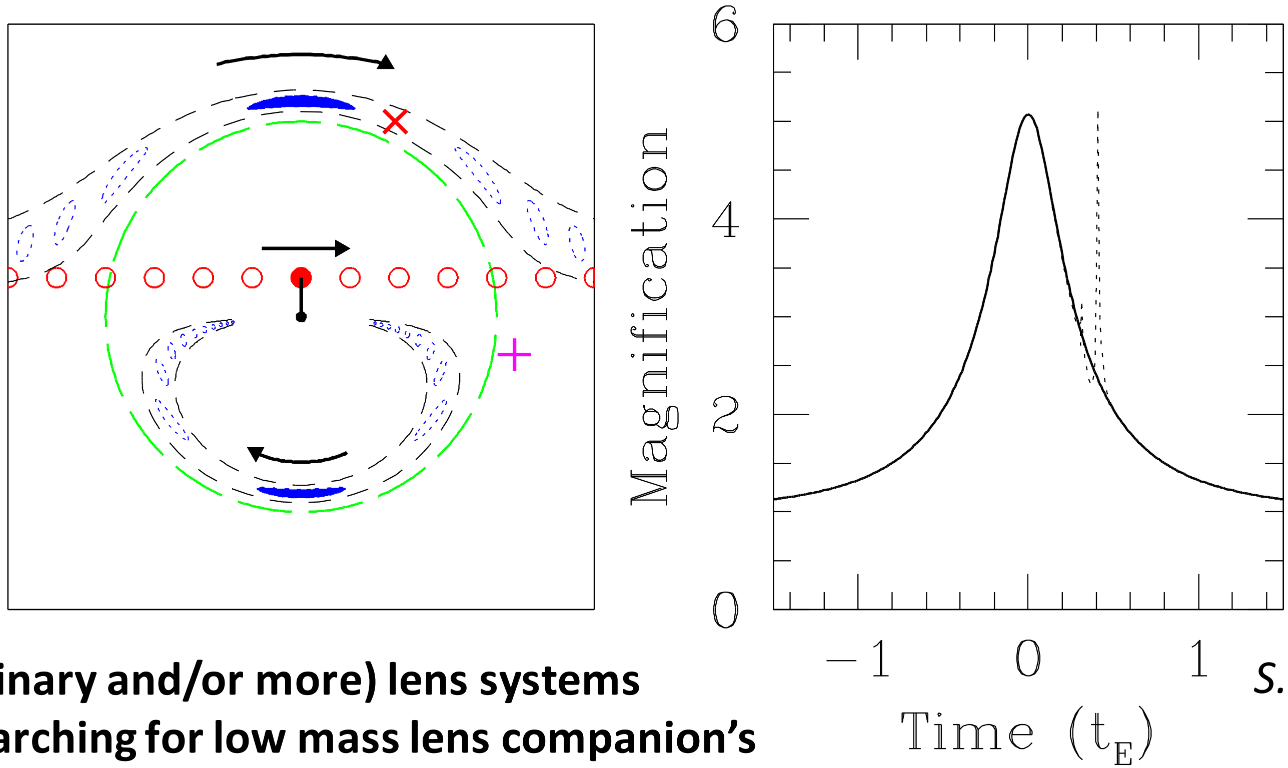


Characteristics length: Einstein Radius, $\mathrm{R_E}$ (microlensing cross section)
Bulge sources ($\mathrm{D_S} = 8$ kpc) and typical lens mass ($M_L \sim 0.3\ M_\odot$): $\mathrm{R_E} \sim 2.2$ AU

Microlensing and the Search for Exoplanets

(«standard») **Single lense systems**: 3 parameters: (t_0, u_0) characterize the event geometry
A single observable related to the (lens) physical parameters: $t_E = t_E(M_L, D_L, D_s, v)$

➡ **degeneracy in the lensing parameter space**



S. Gaudi, 2010

Multiple (binary and/or more) lens systems
planets: searching for low mass lens companion's

Images (blue ovals) of the source (red circles) moving across the Einstein ring (green)

The primary lens (black dot) hosts a planet (red cross) along the path of one of the images

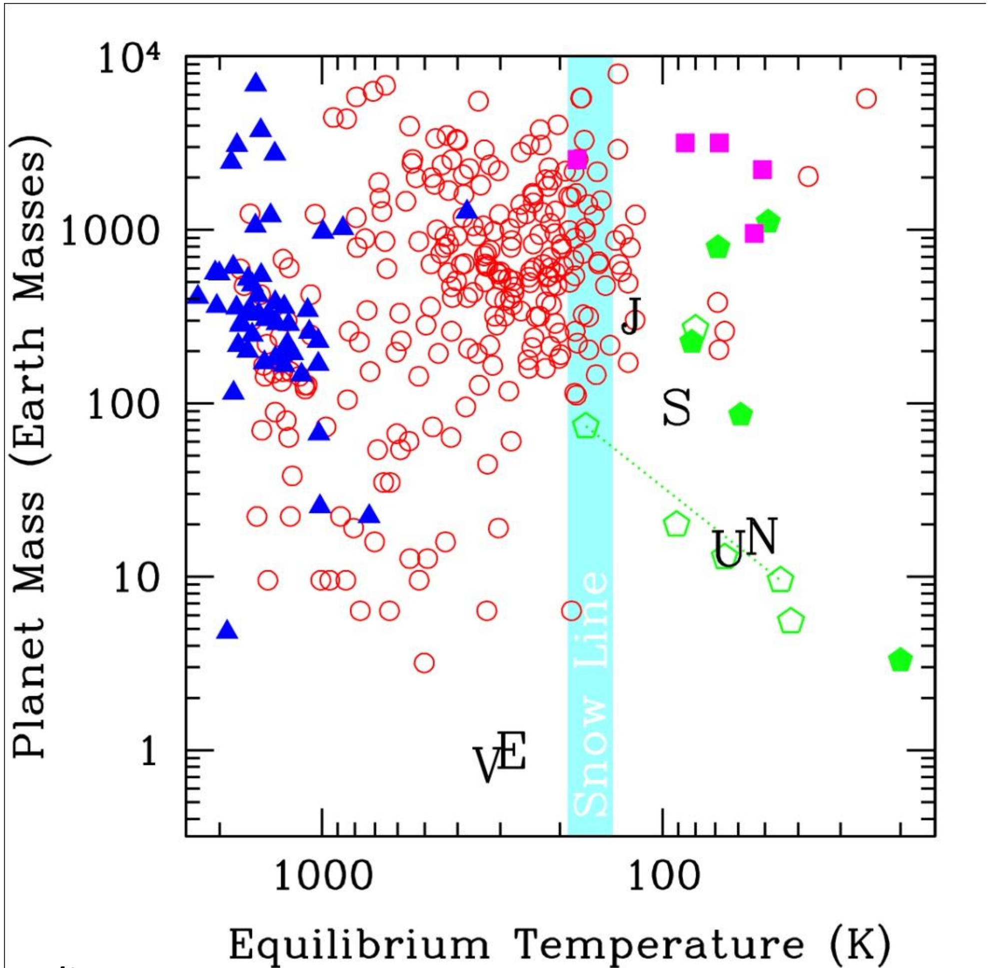
This creates a perturbation (here, a bump) along the primary single lens light curve

Note both magnification and demagnification for the source images

If ever the planet is at the magenta cross position… you just miss it!

Microlensing and Exoplanets Astrophysics

We can detect and characterize exoplanets through microlensing…. is that useful?



Gaudi, 2010

Peak sensitivity beyond the snow line ($\approx R_E \sim 2\ AU$)

Sensitivity to low mass planets

Sensitivity to free-floating planets

Sensitivity to planets throughout the Galaxy

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

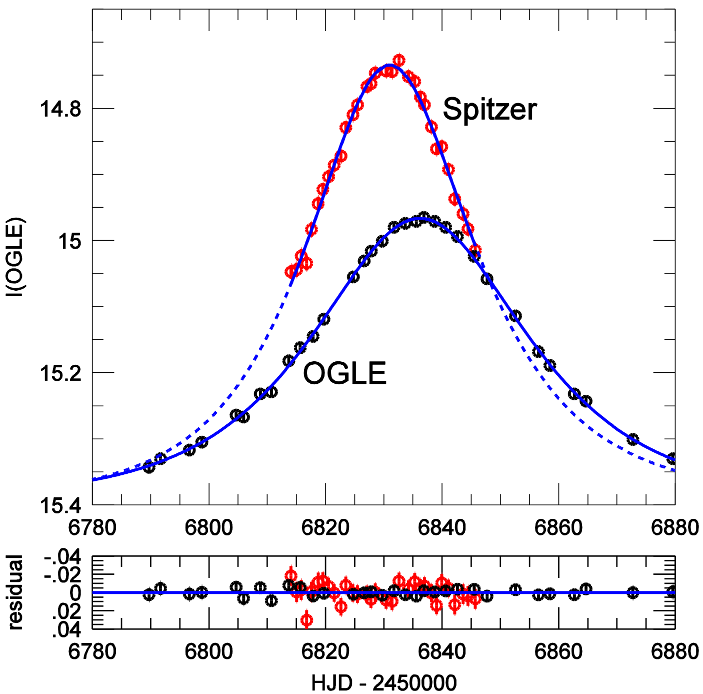
breaking the degeneracy in the microlensing parameter space

The Microlensing Parallax

Rulers In the Sky

measure the projection of the Einstein radius into the observer plane, π_E
given a known length of order AU in the observer plane

- **Orbital π_E: Earth acceleration for very long duration events (i) biased sample, ii) subtle distortions)**
- **Satellite π_E: Observers separated by a significant fraction of an AU** ***unbiased sample of events and …. this is NOT a small effect!***



Yee, Udalski, SCN et al, ApJ 2015

Finite size source effect

(a second ruler: the source angular size)

The effect depends on the projection of the Einstein radius into the source plane

$$u_0 \sim \rho = \frac{R_*}{R_E} = \frac{\theta_*}{\theta_E},$$

$$\theta_* \approx 10^{-6} mas \ll \theta_E$$

- almost never observed for single lens events
- θ_E routinely measured for planetary events (measure ρ from source crossing the planetary perturbation)

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

$$\pi_E = \frac{AU}{\tilde{R}_E} \qquad \tilde{R}_E = \frac{R_E}{1 - D_L/D_S}$$

The parallax amplitude

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

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)

Spitzer Microlens Planets and Parallaxes in 2014

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 events/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 (only one of which during the Earth Bulge visibility period)**
- ❖ **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 lenses
  - 22 single-lens events analyzed
  - 15 (single-lens) under investigation
  - ~17 insufficient sampling

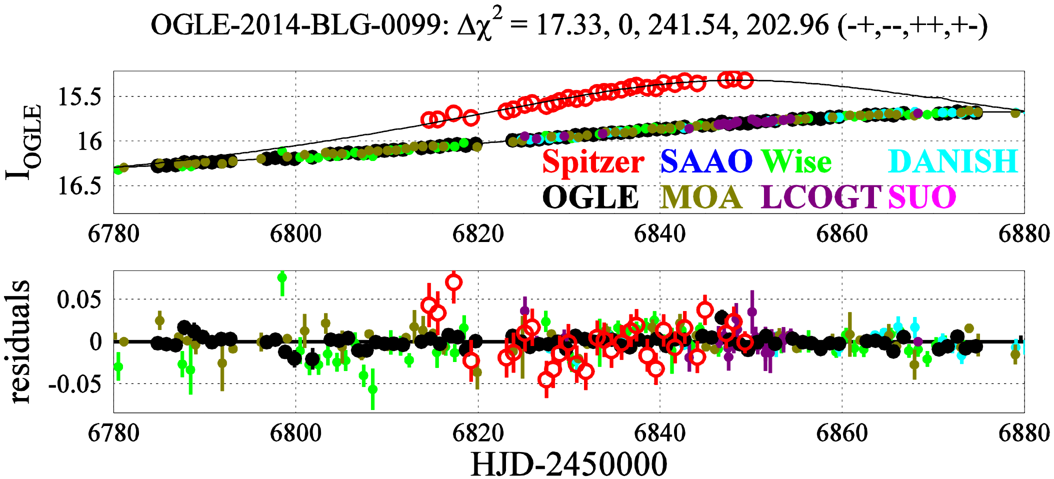
Scientific purposes

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

DONE!

Gould 2014 100hr *Spitzer* pilot program

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



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

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

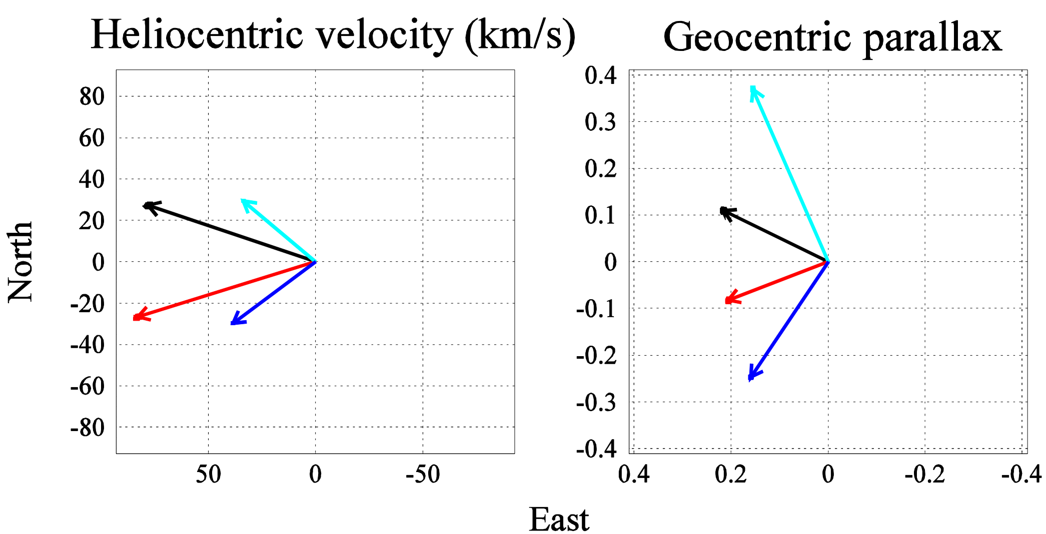
roughly along E, N (equatorial)

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

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

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

⇒ $\pi_{E,\pm}$



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, ApJ 2015

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

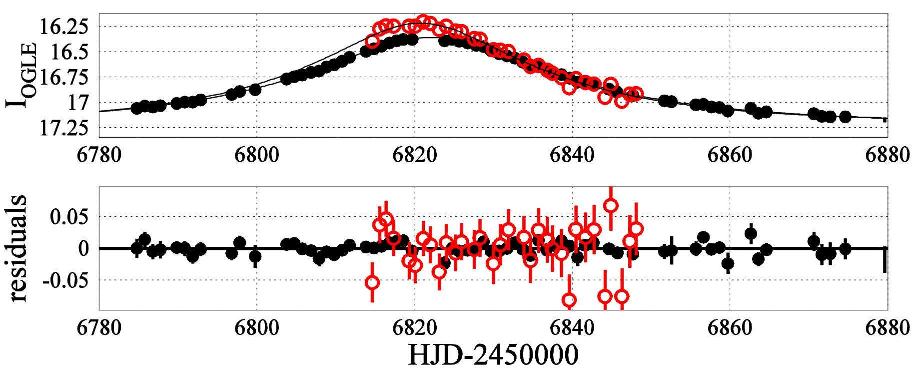
The probability for both simultaneously happen is even smaller

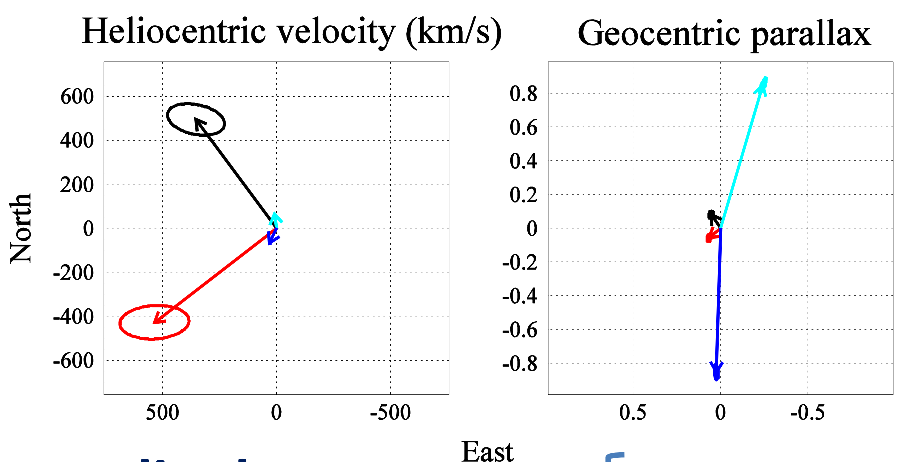
Such an argument cannot be considered decisive in any specific case, however its use is appropriate, in a statistical sense, if the objective is to find the (cumulative) distribution of lens distances

Rich argument in practice

A case where it does apply

OGLE-2014-BLG-0678: $\Delta\chi^2 = 0.47, 0, 24.57, 3.73$ (-+,--,++,+-)





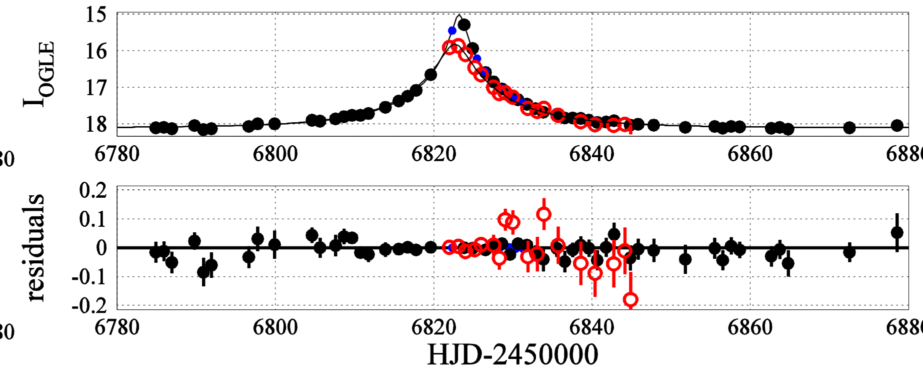
a disc lens

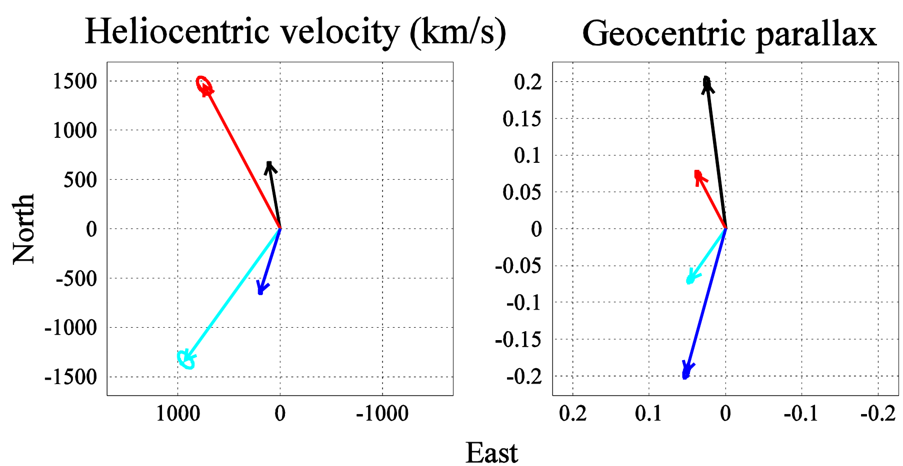
$\pi_{E,+}/\pi_{E,-} = 9$

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

A case where it does NOT apply

OGLE-2014-BLG-1021: $\Delta\chi^2 = 0.61, 1.27, 1.81, 0$ (-+,--,++,+-)



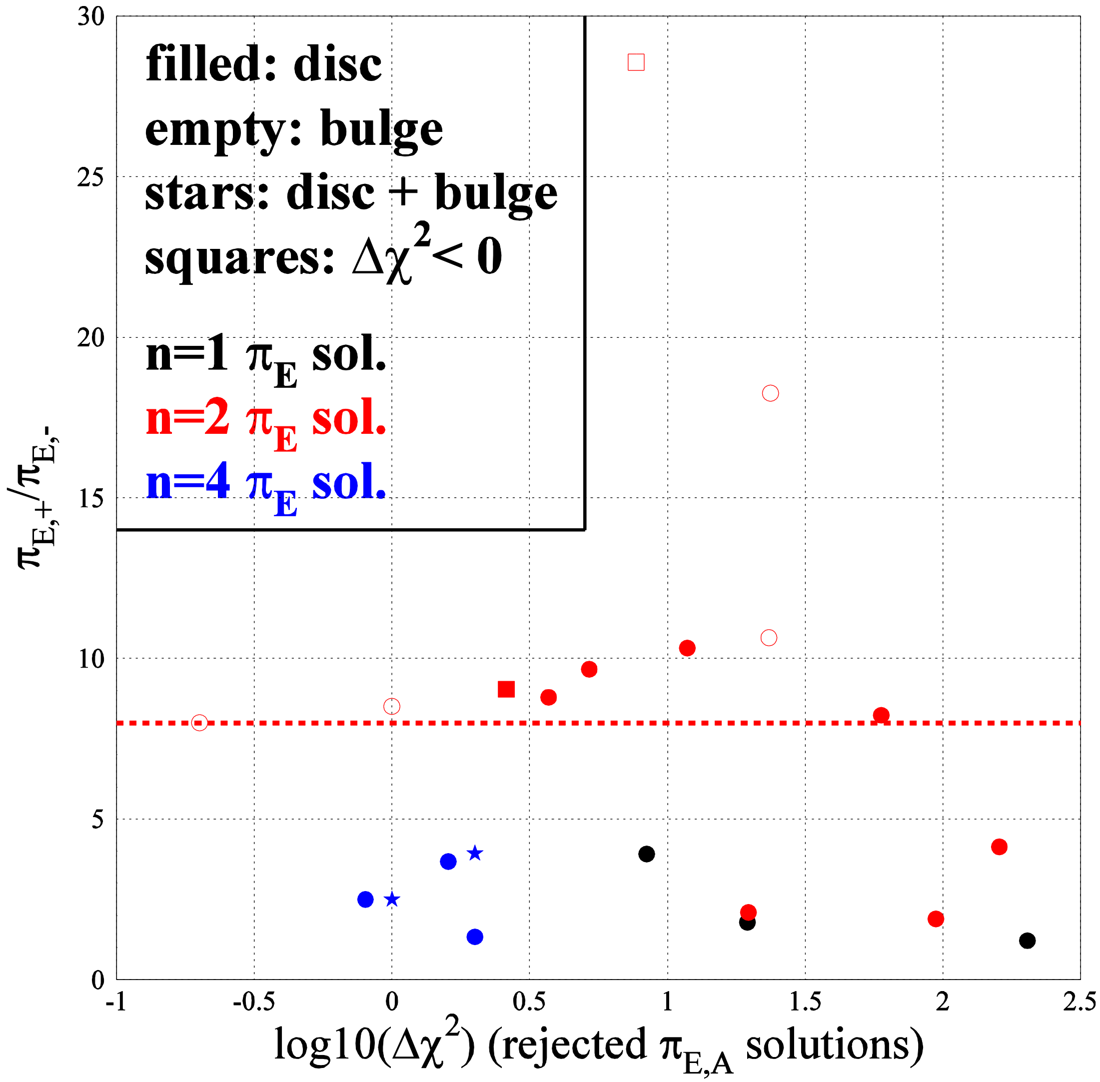


disc or bulge lens?

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

$\Delta\chi^2 < 2$

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 parallax*!) provided a kinematic model of the Galaxy

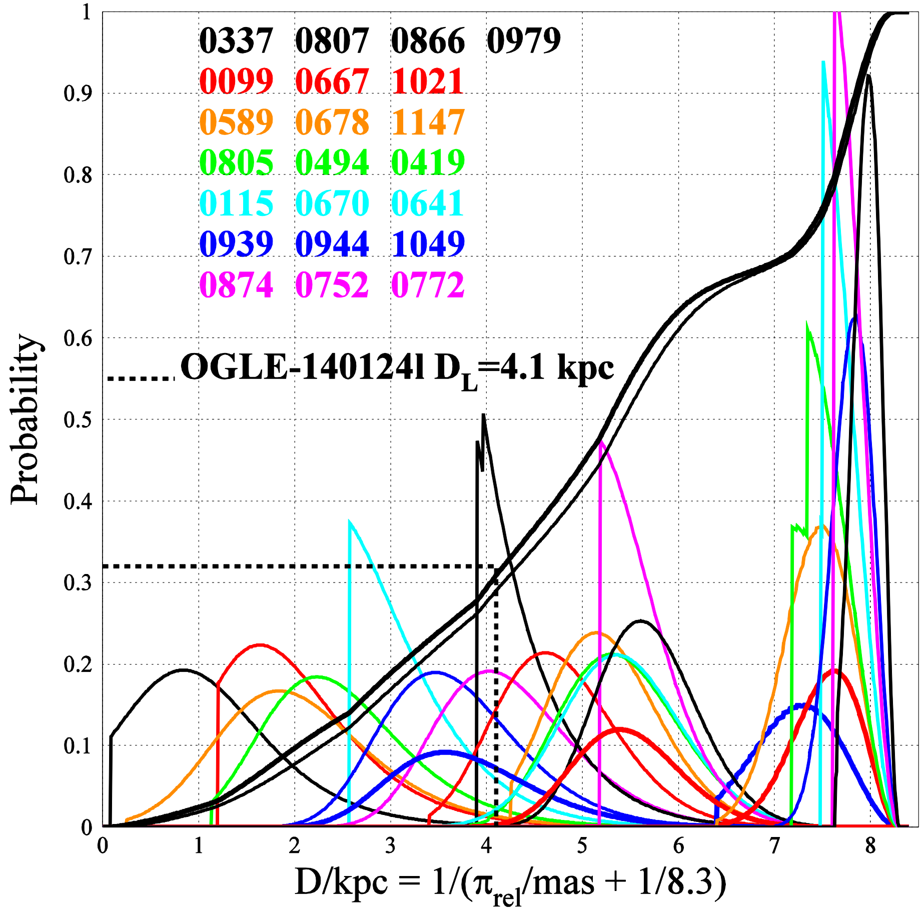
- The volume element : $D_L{}^2\,\Delta D_L$
- The kinematic prior: $P(\tilde{v}) = P(\tilde{v}, model, \pi_{rel}, D_L)$
- The cross section: $\theta_E = \pi_{rel}/\pi_E$
- The proper motion: $\mu = \pi_{rel}\,\tilde{v}$/AU
- (The lens mass: M= $\pi_{rel}/\kappa\,\pi_E{}^2$)

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

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 …



one planetary event OGLE-2014-BLG-0124

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

$D_l \sim D$ 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

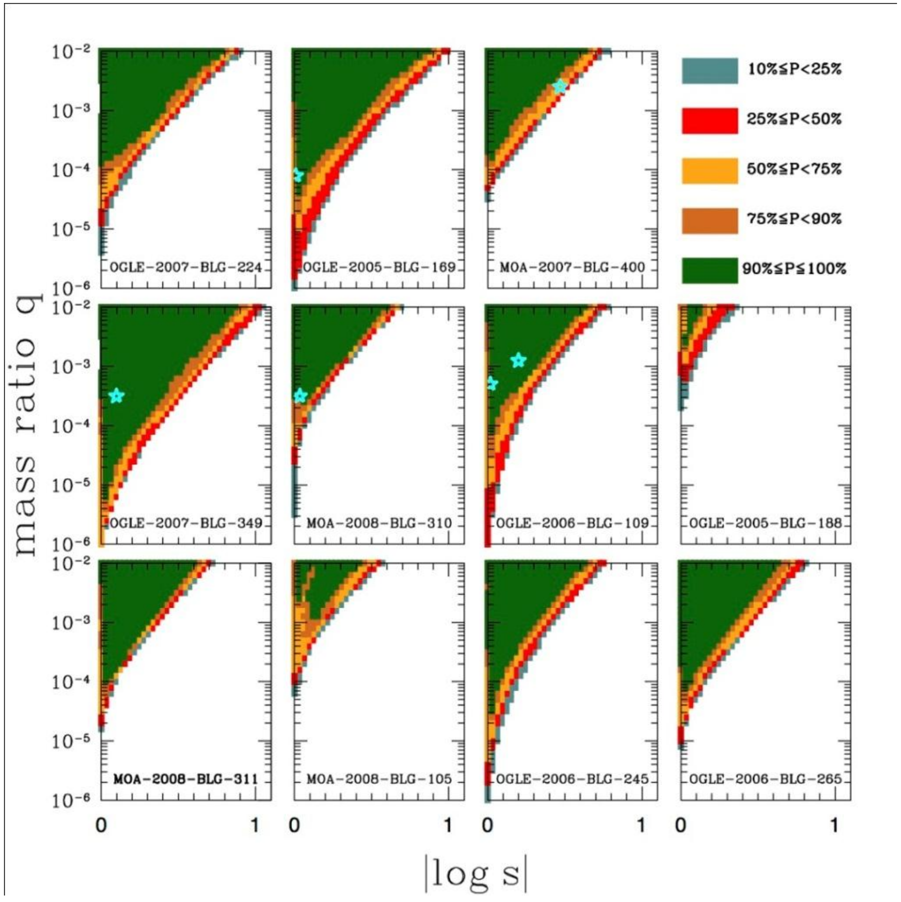
the specific features of the distribution, and its possible biases, are irrelevant for the actual purpose of the analysis.....

SCN, Gould, Udalski et al, ApJ 2015.

… 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 which then provides, regardless of any bias in this sample, a probe for a (relative) measure of the planets distance distribution

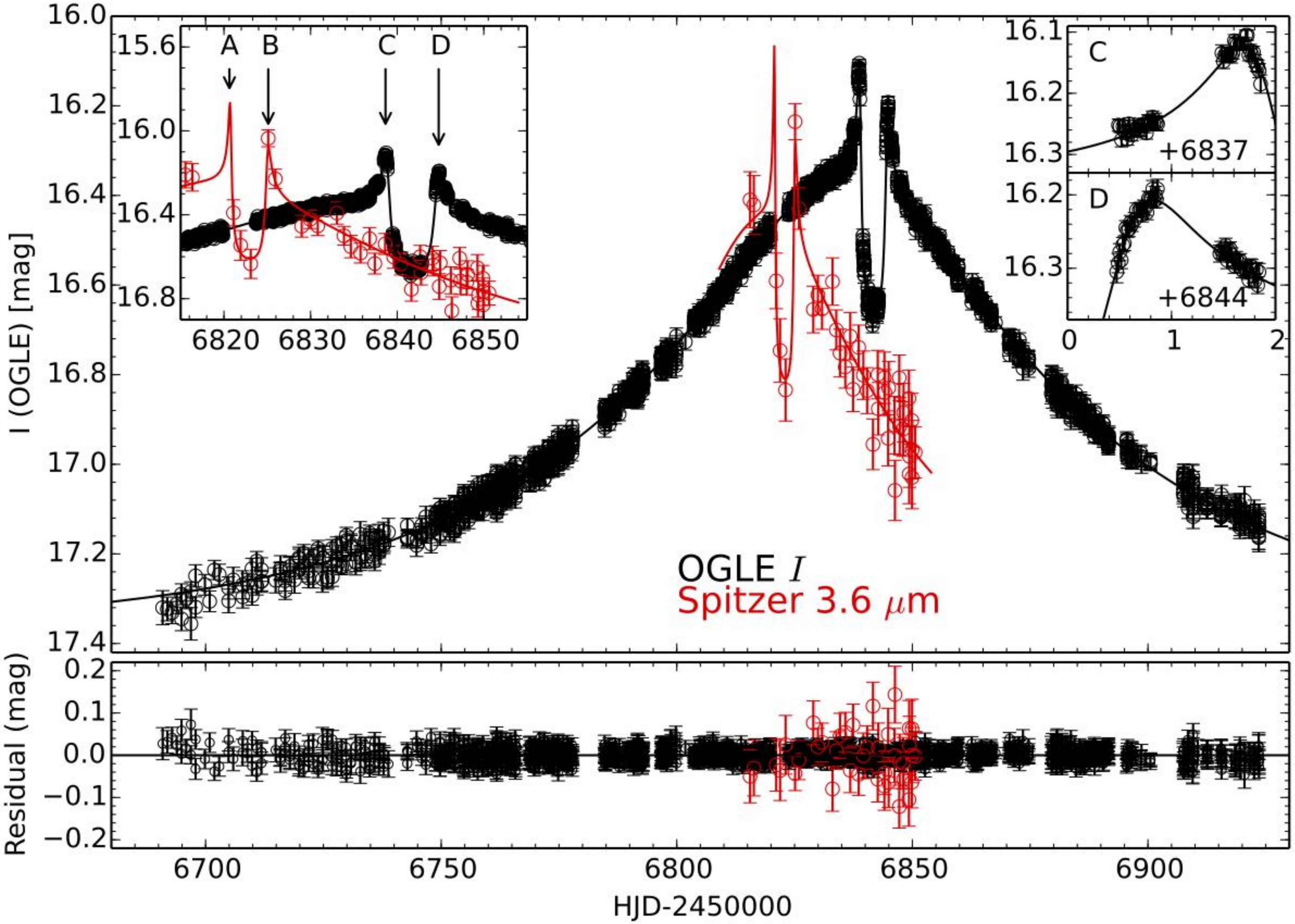


a caveat: each point-lens lightcurve pdf must be weighted by the corresponding planet sensitivity (Gould et al 2010), in order to compare the resulting cumulative distribution, namely the cumulative distribution of planet detectability, with the Galactic distribution of planets

Gould et al, ApJ 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) ApJ 2015

The 2015 Spitzer Observational Program

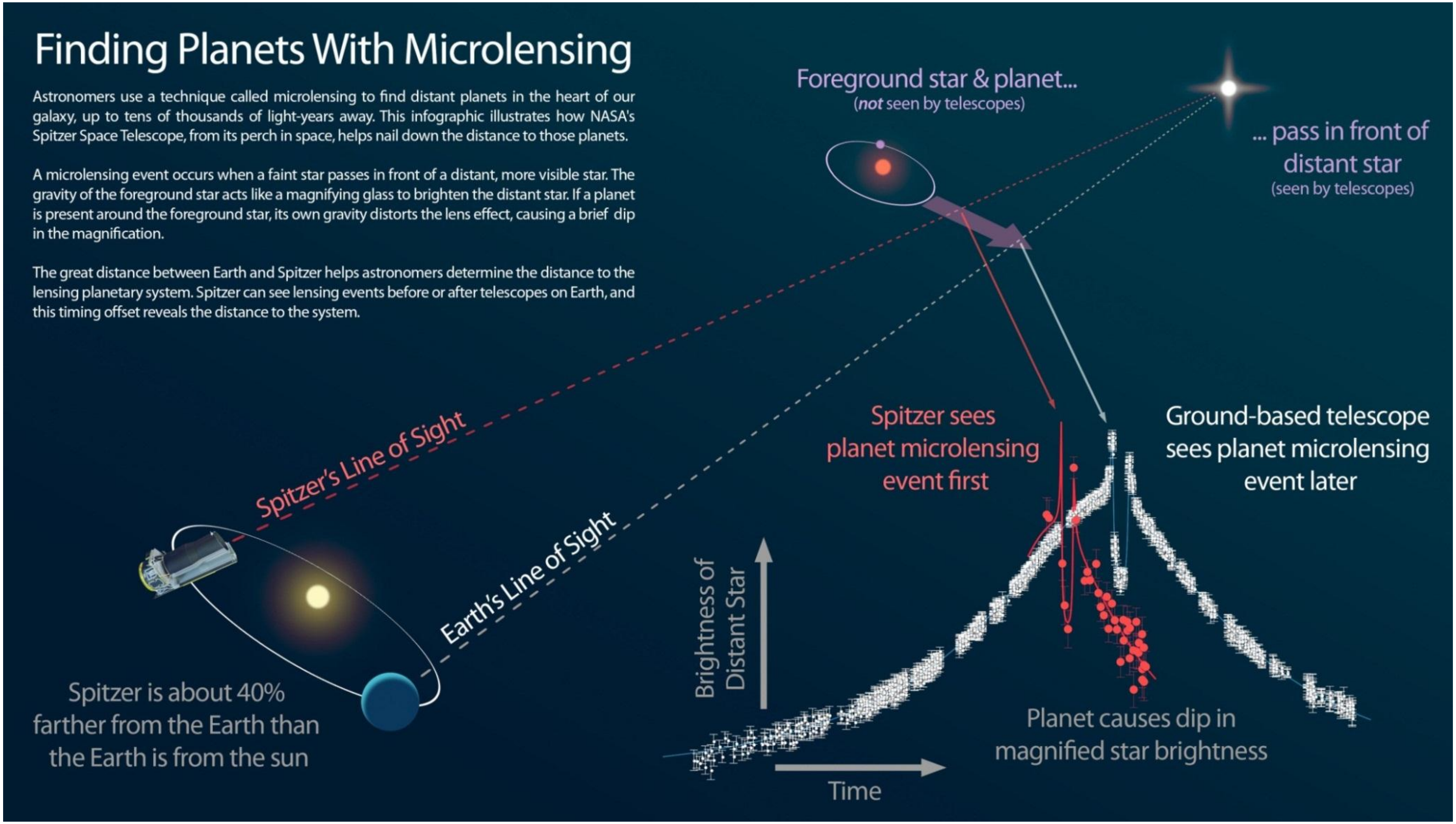
PI: A. Gould, proposal #11006, 832 h (≈ June 10th-July 10th)

The Microlensing Parallax in the Sky

Simultaneous Spitzer and survey+follow up ground-based microlensing observations with Spitzer observations triggered by ground-based microlensing survey

key point: measure of the lens distance (also) for single-lens events

- **A first probe of the Galactic distribution of planets** / vs 2014
  - Increase statistics
  - Strategy to Maximise Planet Sensitivity (*Yee et al, submitted*)
    (measure the parallax for as many as planetary events as possible…. without knowing a planet is there!)
    - ✓ Objective and Subjective selection criteria
      - *choice for the events and choice for the cadence*
    - ✓ Improve Spitzer photometry
    - ✓ Spitzer Real-Time analysis
- Probe for brown dwarf binaries
- First mass-based measurement of the stellar mass function (including dark objects such as black holes)



NASA press release on April 14, 2015
credit: NASA/JPL-Caltech