



SPITZER OBSERVATIONS OF OGLE-2015-BLG-1212 REVEAL A NEW PATH TOWARD BREAKING STRONG MICROLENS DEGENERACIES

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ABSTRACT

Spitzer microlensing parallax observations of OGLE-2015-BLG-1212 decisively break a degeneracy between planetary and binary solutions that is somewhat ambiguous when only ground-based data are considered. Only eight viable models survive out of an initial set of 32 local minima in the parameter space. These models clearly indicate that the lens is a stellar binary system possibly located within the bulge of our Galaxy, ruling out the planetary alternative. We argue that several types of discrete degeneracies can be broken via such space-based parallax observations.

Key words: binaries: general – Galaxy: bulge – gravitational lensing: micro – planets and satellites: detection – space vehicles

1. INTRODUCTION

Strong discrete degeneracies appear generically in the solutions to microlensing light curves. Very often these have little practical importance, either because they are adequately broken by high-quality data or because they prove to have very similar scientific implications. Nevertheless, there are many cases for which an unbroken degeneracy has serious consequences and thus is quite frustrating, and some cases (including the one reported here) where it has major implications for the event in question. Therefore, any new methods for breaking these degeneracies deserve the greatest consideration.

To be clear, by “strong” degeneracies, we mean those that lead to very similar light curves over the whole event (or the great majority of the event). There is another class of “accidental” degeneracies in which the two solutions have very different features during gaps in the data. The obvious remedy for the latter is to ensure a full coverage of the microlensing event even in the wings, something that with the advent of new, near-continuous surveys (or combinations of surveys) will become a standard for the great majority of the events. We will therefore concentrate on strong degeneracies, which produce light curves that are indistinguishable from ground-based observatories and thus cannot be solved just by increasing the sampling rate or the coverage.

From theoretical considerations, there is good reason to expect that observations from a “microlens parallax satellite” in solar orbit might play a powerful role in breaking such degeneracies. We illustrate this expectation by considering the most deeply understood degeneracy: the so-called “wide/close” binary degeneracy. This is a degeneracy between binary solutions for which the companion lies outside the Einstein ring ($s > 1$, where s is the projected separation normalized to the angular Einstein radius θ_E) and solutions for which the companion is inside the ring ($s < 1$). This ($s \leftrightarrow s^{-1}$) degeneracy was discovered empirically in data for MACHO-98-SMC-1 (Figure 8 from Afonso et al. 2000) at roughly the same time that Griest & Safizadeh (1998) and Dominik (1999)

derived its fundamental cause: a deep symmetry between a tidal expansion of the lens equation in the limit $s \gg 1$ and a quadrupole expansion in the limit $s \ll 1$. Nevertheless, even though this symmetry is exact in these limits, in the practical example of MACHO-98-SMC-1 it was already clear that the full two-dimensional (2D) caustic structure differed significantly for the two cases. That is, even though the 2D caustic structures looked manifestly different, the light curves generated by 1D tracks through this structure were virtually identical. After this same behavior was noticed for MACHO-99-BLG-47 (Albrow et al. 2002) (see especially their Figure 4), An (2005) was able to explain the apparent relative “rotation” of the two caustics by pursuing the expansion of the lens equation in each limit to second order (see also Bozza 2000).

The potential for a parallax satellite to break such degeneracies can be recognized by considering Figure 8 of Afonso et al. (2000) or Figure 4 of Albrow et al. (2002). This degeneracy arises because the magnification patterns of the two solutions differ only by an overall scale factor along the source trajectory, but deviate considerably from this single scale factor away from this trajectory. Observing the event from a satellite introduces a second source trajectory that probes a different part of the magnification pattern. For simplicity, consider first that the satellite is not moving with respect to Earth. Then the apparent source trajectory through the caustic structure as seen from the satellite is perfectly parallel to that seen from Earth but is offset by a 2D vector that (together with the known Earth–satellite separation) essentially determines the parallax vector π_E . Then any physical offset between observatories will produce caustic crossings in the second trajectory at distinctly different times for each caustic, exactly because they are rotated, thereby distinguishing between the solutions. The only exception would be if the offset were exactly along the trajectory (i.e., the source motion is along the Earth–satellite axis), so that there would be identical light curves, just displaced in time. The same argument applies even though the Earth–satellite projected separation changes with time. In this more general case, the trajectories are not perfectly parallel, but they are still rigidly determined (and separated) for any fixed choice of π_E .

When the source does not experience caustic crossings, the effect of the binary (or planetary) nature of the lens on the light curve is primarily via cusp approaches. These can create

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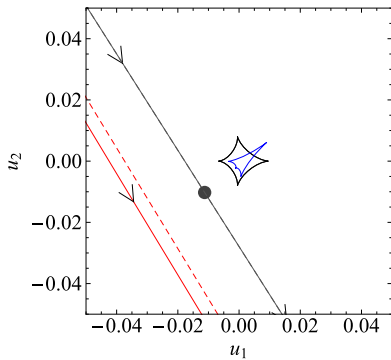


Figure 1. Caustics of the best binary model (in black) and the best planetary model (in blue). Also displayed are the source trajectories for the two models: in solid style for the binary and dashed for the planetary; gray for the source as seen from ground observatories, red as seen from *Spitzer*. In order to compare the two models, the planetary one has been rotated and rescaled so as to make the source trajectories match as seen from the ground (in practice, they are on top of each other). The corresponding light curves are shown in Figures 2 and 3. This figure also illustrates the degeneracy discussed by Han & Gaudi (2008).

dramatic bumps if the source passes close to one or several cusps, but can also generate weak, long-term distortions for distant passages. For roughly equal mass binaries, these caustics are roughly symmetric (concave) quadrilaterals, so that a source can pass at most two cusps (see Figure 1). For planets (with mass ratios $q \ll 1$), the caustics assume a kite-like form, with three cusps at one end and one at the other (Figure 1). On the three-cusp side, the two outer cusps protrude much further than the central cusp (which is close to the host).

If, for example, the light curve experiences two bumps near its overall peak, these could in principle be due to either the source passing two neighboring cusps from a binary caustic or the two outer cusps from a planetary caustic (Han & Gaudi 2008; Choi et al. 2012; Park et al. 2014). As shown by Han & Gaudi (2008), however, if the passage is close enough, then the shape of the light curve clearly distinguishes between these two cases: for the binary caustic the interval is rounded, while for planetary caustics the effect of the central cusp tends to flatten the intervening light curve. However, for more distant passages, these weaker cusp approaches open up the possibility of a new class of degeneracy between central caustics due to binaries and planets.

Here we present ground-based and *Spitzer* observations of OGLE-2015-BLG-1212. The ground-based observations show exactly two such bumps near peak, which could be due to either a binary or a planet. In contrast to the cases analyzed by Han & Gaudi (2008), however, the passage is too distant for the central cusp to create obvious features that would distinguish between the planetary and binary solutions. While there remain subtle differences in the models that permit the ground-based data to distinguish between them at a moderate level, these are at the level of occasional systematic effects in microlensing data. However, the light curve obtained by *Spitzer* from its vantage point well displaced from Earth decisively confirms the preference of ground-based data for the binary solution.

This result directly impacts the ability of *Spitzer* observations to measure the Galactic distribution of planets, which is one of the major goals of the *Spitzer* microlensing program (Gould et al. 2014). As shown by Calchi Novati et al. (2015a) and Yee et al. (2015), one can determine the relative frequency of planets as a function of distance from the Galactic center by comparing

the cumulative distribution of planet sensitivity of microlensing events in *Spitzer* (or other space-based parallax samples) to that of the planets detected in these surveys. An implicit assumption of this approach is, however, that it is known whether a planet is detected or not, given some specified criteria (e.g., $\Delta\chi^2$). In the present case, the event OGLE-2015-BLG-1212 is high-magnification (and therefore has substantial sensitivity to planets; Griest & Safizadeh 1998; Gould et al. 2010) and has strong deviations from a Paczyński (1986) point-lens light curve (meaning that “something” has clearly been detected). However, without breaking the planet/binary degeneracy, it would not be known whether this “something” was a planet. While it is possible in principle to take statistical account of such ambiguous cases, they significantly degrade the statistical power of the experiment, particularly because the total number of planets detected in space-based microlensing surveys is small. Therefore, the fact that *Spitzer* itself can resolve this degeneracy, at least in some cases, adds to its power to investigate the Galactic distribution of planets.

2. OBSERVATIONS

2.1. OGLE Alert and Observations

On 2015 June 1, the Optical Gravitational Lensing Experiment (OGLE; Udalski et al. 2015) alerted the community to a new microlensing event, OGLE-2015-BLG-1212, based on observations with the 1.4 deg² camera on its 1.3 m Warsaw Telescope at the Las Campanas Observatory in Chile using its Early Warning System real-time event detection software (Udalski et al. 1994; Udalski 2003). Most observations were in *I* band, but with eight *V*-band observations during the magnified portion of the event to determine the source color. At equatorial coordinates (17:52:24.79, $-29:10:52.0$) and Galactic coordinates (0.56, -1.40), this event lies in OGLE field BLG500, which implies that it is observed at roughly hourly cadence.

2.2. Spitzer Observations

Street et al. (2015) have reviewed how the *Spitzer* team applied the strategy outlined in Yee et al. (2015) to select *Spitzer* targets, so we do not repeat those discussions here. We just summarize that OGLE-2015-BLG-1212 was “subjectively” chosen for observations on June 7 UT 23:49 (HJD = 7181.498), shortly before the Monday upload. It was assigned daily cadence but was observed about twice per day that week (beginning Thursday) owing to a general shortage of targets near the beginning of the program. The following Monday (June 15) it was found to meet the objective criteria for a rising event (Yee et al. 2015 criteria “B”), meaning that all planets discovered from before the “subjective” alert could be incorporated into the sample, provided that a microlens parallax could be measured from the post-objective-alert observations. At this time, the 1σ lower limit for the magnification during the next observing interval was predicted to be $A > 80$, which triggered an increase in the cadence to 8 per day. The following week, the event returned to normal cadence, after which *Spitzer* observations were halted under provisions (“C”) specified by Yee et al. (2015), essentially that the ground-based light curve was well outside the Einstein ring. In fact, this decision was triggered by an erroneous estimate of the Einstein timescale $t_E \sim 8$ days based on automated point-lens fits to what was in fact a subtly anomalous light curve. Nevertheless,

since the erroneous fit reflected the true brightness evolution (even though the wrong Einstein-ring position), it accurately foretold when the target would be too faint to usefully observe, so that there was no loss of useful observations. Altogether, *Spitzer* observed this event a total of 90 times, each with six dithered 30 s exposures (Calchi Novati et al. 2015b).

2.3. Other Survey Observations

2.3.1. MOA Observations

Microlensing Observations in Astrophysics (MOA) independently identified this event on June 16 and monitored it as MOA-2015-BLG-268 using their 1.8 m telescope with 2.2 deg² field at Mt. John New Zealand. In contrast to most other observatories, which observe in *I* band, MOA observes in a broad *R-I* bandpass. The MOA cadence for this field is 15 minutes.

2.3.2. KMTNet Observations

The event lies in one of four 4 deg² fields monitored by Korea Microlensing Telescope Network (KMTNet; Kim et al. 2016) with roughly 15-minute cadence from its three 1.6 m telescopes at CTIO/Chile, SAAO/South Africa, and SSO/Australia. Most KMTNet observations are in *I* band, although some *V*-band observations are taken to determine the source color. The latter are not used in the present case, as being of poorer quality.

2.3.3. Wise Observations

The event lies inside the Wise microlensing survey footprint, which typically uses the 1 m telescope at Wise Observatory, Israel (Shvartzvald & Maoz 2012). Owing to readout electronics problems with the 1 m telescope camera, as an alternative the Wise group used the Wise C18 0.46 m telescope to monitor the survey fields, including OGLE-2015-BLG-1212. Observations were in *I* band, with a cadence of ~ 1 hr⁻¹.

2.4. Follow-up Observations

In general, the protocols of Yee et al. (2015) discourage follow-up observations of events with the extremely dense survey coverage listed above, simply because there are more *Spitzer* events without dense survey coverage than can be adequately covered by available follow-up telescopes. However, the high magnification (and hence high planet sensitivity) of OGLE-2015-BLG-1212 attracted dense coverage from several follow-up groups, particularly over the double peak.

2.4.1. μ FUN CTIO Observations

The Microlensing Follow Up Network (μ FUN) observed OGLE-2015-BLG-1212 using the dual-channel ANDICAM camera mounted on the 1.3 m SMARTS telescope at CTIO. Observations started with one point at HJD = 7186.9 and ended at 7190.8, concentrating on the last two nights covering the double peak hourly. Most of the optical-channel observations were in *I* band, with four *V*-band observations taken near peak in order to determine the source color. All of the infrared channel data were in *H* band. These, again, are primarily intended for source characterization and are not included in the fit.

2.4.2. MiNDSTEp Observations

The MiNDSTEp consortium observed OGLE-2015-BLG-1212 using the first routinely operated multicolor instrument mounted on the Danish 1.54 m telescope at La Silla and providing Lucky Imaging photometry. The instrument itself consists of two Andor iXon+ 897 EMCCDs and two dichroic mirrors splitting the signal into a red and a visual part (Skottfelt et al. 2015). Observations started at HJD = 7189.6 and were continued until 7194.8 with 90-minute cadence.

2.5. Data Reduction

All ground-based data were reduced using image subtraction (Alard & Lupton 1998) except for the μ FUN CTIO data, which were reduced with DoPhot (Schechter et al. 1993). The *Spitzer* data were reduced with a new algorithm specifically developed for the *Spitzer* microlensing campaign (Calchi Novati et al. 2015b). For the analysis of this event, we used the light curve generated by method 3, as explained in that paper.

3. LIGHT-CURVE ANALYSIS

The basic code used for the calculation of binary microlensing light curves is the optimized contour integration routine developed by Bozza (2010). Since there is no caustic crossing, a detailed limb-darkening treatment is unnecessary for this event, and we can proceed assuming a uniform brightness profile (we have also explicitly checked that the conclusions are unchanged including limb darkening). A preliminary wide search in the parameter space has been performed by the RTModel software,⁵¹ designed so as to interpret events in real time. After the best preliminary model has been obtained, we have renormalized all error bars so that the total χ^2 equals the number of degrees of freedom in the fit. More in detail, each data set has been renormalized so that its individual contribution to the χ^2 is proportionate to the number of data points. We remind that the underlying assumption of this procedure is that the noise of all data sets is Gaussian in nature.

The light curve of OGLE-2015-BLG-1212 can be obtained by several lens configurations. In particular, we have identified several solutions in the planetary regime ($q \lesssim 0.01$) and others in the stellar binary regime ($q \gtrsim 0.01$). Figure 2 shows the light curves obtained from all the observatories together with the best binary and planetary models. The magnitude scale corresponds to the calibrated *I*-band magnitudes of the OGLE data. For all other observatories the magnitudes shown actually represent the magnification, i.e., equal “magnitudes” at different observatories represent equal inferred magnifications. Figure 1 shows the corresponding caustic structures and source trajectories (as seen from Earth and *Spitzer*) for the two cases.

Table 1 gives the model parameters for the two solutions shown in these figures. u_0 and t_0 refer to the closest approach to the center of mass of the lens. Note that the planetary solution comes with a mass ratio of 0.002, which, depending on the primary mass, would correspond to a giant planet similar to Saturn. This fact makes this event an extremely interesting study case to test the ability of *Spitzer* to distinguish between a possible planetary discovery and a simple stellar binary. As we explain below, each of the two solutions is representative of a group of possible solutions, but it is important to begin by understanding these representative solutions first.

⁵¹ <http://www.fisica.unisa.it/gravitationAstrophysics/RTModel.htm>

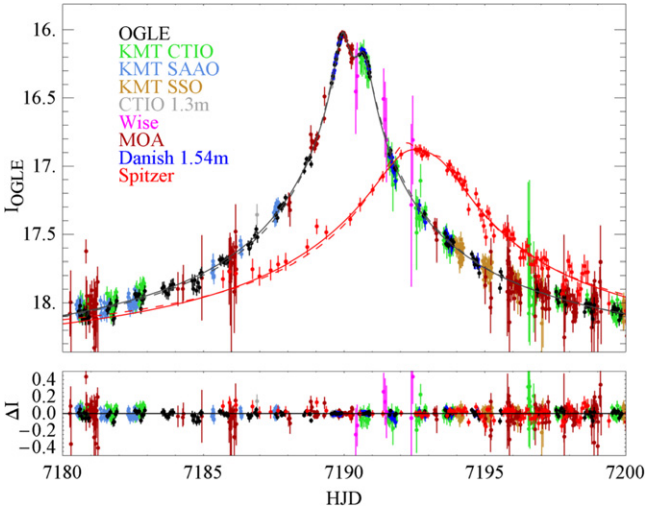


Figure 2. Light curve of OGLE-2015-BLG-1212 together with the best binary (solid) and planetary (dashed) models, whose parameters are given in Table 1.

Table 1
Comparison of the Best Binary and the Best Planetary Solutions

| Parameter | Binary | Planetary |
|-------------------|-----------|-----------|
| s | 0.1760 | 1.5463 |
| q | 0.174 | 0.002423 |
| u_0 | -0.01487 | -0.01488 |
| θ | 2.1386 | 1.4454 |
| ρ | 0.0025 | 0.0019 |
| t_E | 40.22 | 43.6 |
| t_0 | 7190.1980 | 7190.2313 |
| π_{\perp} | -0.0639 | -0.0575 |
| π_{\parallel} | -0.0043 | -0.00776 |
| χ^2 | 7952.7 | 8066.1 |

Note. s is the separation between the two lenses in units of the Einstein radius; q is the mass ratio; u_0 is the impact parameter to the lens center of mass in Einstein radii; t_0 (in HJD) is the time of closest approach to the center of mass; θ is the angle (in radians) between the source velocity at time t_0 and the lens axis; t_E (in days) is the Einstein time; ρ is the source radius in units of the Einstein radius.

Modeling a caustic-crossing binary (or planet) requires at least seven geometric parameters to specify the magnification $A(t)$ as a function of time. The first three (t_0 , u_0 , t_E) are the same as for a single-lens event, namely, the time of closest approach by the source to some fiducial point of the lens geometry (e.g., the center of mass), the impact parameter (in units of the angular Einstein radius θ_E), and the time required to cross the Einstein radius, i.e.,

$$t_E \equiv \frac{\theta_E}{\mu_{\text{geo}}}; \quad \theta_E \equiv \sqrt{\kappa M \pi_{\text{rel}}};$$

$$\kappa \equiv \frac{4G}{\text{au } c^2} \simeq 8.1 \frac{\text{mas}}{M_{\odot}}. \quad (1)$$

Here M is the total lens mass, μ_{geo} is the lens-source relative proper motion in the geocentric frame, and $\pi_{\text{rel}} \equiv \text{au}(D_L^{-1} - D_S^{-1})$ is the lens-source relative parallax. Note that only the parameter combination t_E enters the model at this stage, not the three physical parameters (M , μ_{geo} , π_{rel}) that determine it.

The next three parameters (q , s , α) describe the relation of the primary to the secondary component of the binary. These are their mass ratio and their 2D separation ($s \cos \alpha$, $s \sin \alpha$) relative to the lens-source trajectory. Finally, if the source passes over or near a “caustic” (closed curve of infinite magnification), then the light-curve profile is smeared out according to $\rho \equiv \theta_*/\theta_E$, i.e., the ratio of the angular source radius to the Einstein radius.

Some events (including all events that, like OGLE-2015-BLG-1212, are observed from a second observatory in solar orbit) require two additional parameters, the microlens parallax

$$\pi_E = \frac{\pi_{\text{rel}} \mu}{\theta_E \mu}. \quad (2)$$

The numerator of π_E gives the amplitude reflex deflection of the lens-source apparent position due to displacement by the observer of 1 au, while the denominator tells the size of this deflection relative to the Einstein radius, which is what determines the impact on the light curve. The direction of motion (μ/μ) is required to specify the time evolution of this effect.

From the overall ground-based light curve, it is obvious that this is a high-magnification event ($u_0 \ll 1$), so that the double bump near peak must be due to the effect of two cusps of a central caustic. As discussed in Section 1, these may be either consecutive cusps of a “binary” ($q \sim \mathcal{O}(1)$) lens or opposite prongs of a “planetary” ($q \ll 1$) lens. These topologies are shown in Figure 1. Because the *Spitzer* light curve is broader, the impact parameter as seen from *Spitzer* must be higher, and this is reflected in the fact that the model shows *Spitzer* peaking at lower magnification. The *Spitzer* light curve also peaks later. These two offsets (in u_0 and t_0) determine the parallax, a relation that can be approximately represented as

$$\pi_E = \frac{\text{au}}{D_{\perp}} (\Delta\tau, \Delta\beta); \quad \Delta\tau = \frac{t_{0,\oplus} - t_{0,\text{sat}}}{t_E};$$

$$\Delta\beta = \pm u_{0,\oplus} - \pm u_{0,\text{sat}}, \quad (3)$$

where the subscripts indicate parameters as measured from Earth and the satellite and D_{\perp} is the Earth–satellite separation projected on the sky.

As is well known, Equation (3) implies that for each geometry (as shown in Figure 1), there are three other candidate solutions (Refsdal 1966; Gould 1994). As illustrated in Figure 1 of Gould (1994), the fourfold degeneracy corresponds to (1) the source passing the lens on its right as seen from both Earth and the satellite ($\Delta\beta_{++} = |u_{0,\oplus}| - |u_{0,\text{sat}}|$), (2) both passing on its left ($\Delta\beta_{--} = -|u_{0,\oplus}| - (-|u_{0,\text{sat}}|)$), and (3, 4) passing on opposite sides ($\Delta\beta_{+-}$, $\Delta\beta_{-+}$). Note that the amplitude of the parallax is the same for (1, 2) and also the same for (3, 4), but different between the two pairs. These identities are exact in the approximation of Equation (3) but broken (usually weakly) by higher-order effects (Gould 1995). In the case of caustic-crossing binaries, this degeneracy can be strongly broken in some cases (Graff & Gould 2002; Shvartzvald et al. 2015), although it may also persist, particularly if there is only one caustic crossing observed from space (Zhu et al. 2015). In the present case, since there are no caustic crossings, we do not expect these degeneracies to be strongly broken. That is, the situation is qualitatively similar to the point-lens case.

For the planetary model, there is also the close/wide degeneracy, which is very common for central caustics as first discussed by Griest & Safizadeh (1998). Hence, for the planetary model, there are a total of $4 \times 2 = 8$ solutions. For the binary model, the situation is more complicated. As in the planetary case, there are both close and wide models (Dominik 1999; Bozza 2000). However, because the light-curve features are in this case due to passage of consecutive (rather than “opposite”) cusps of the quadrilateral caustic, there are in principle four possible orientations for the caustic for the wide solutions (compared to one in the planetary case) and two possible orientations for the close solutions. See Figures 2 and 4 of Liebig et al. (2015).

In the wide case, these four orientations may be thought of as having the companion mass on either the same side of the source trajectory (external cusp approach) or the opposite side (internal cusp approach), and in each case the companion mass may be passed by the source either before or after the mass associated with the perturbing caustic.

In the close case, there are in principle the same four orientations for the caustic, but the companion mass is always on the same side of the source trajectory. Hence, two of these “different” orientations actually just represent different mass ratios (i.e., $q \rightarrow q^{-1}$), rather than different topologies. Hence, there are a total of $4 \times 2 = 8$ close solutions and $4 \times 4 = 16$ wide solutions, and thus $8 + 8 + 16 = 32$ solutions altogether. These are all shown in Table 2, with cusp-approach notation from Liebig et al. (2015).

The values of the χ^2 reported in Table 2 are the final results of extensive Markov chains starting from the preliminary minima found by RTModel after all possible reflections discussed above have been applied.

As can be seen from this table, even without *Spitzer* data, the binary solutions are favored over the planetary solutions by $\Delta\chi^2 = 53$. This would be regarded as significant evidence for the binary solution, but not completely compelling owing to the possibility of correlated errors in microlensing data. See, for example, the detailed investigation of one high-magnification event by Yee et al. (2013), which they argued is particularly prone to such systematic errors. However, *Spitzer* data provide independent evidence of the correctness of the binary solution, raising the total difference to $\Delta\chi^2 = 114$. This seals the case.

In Figure 2 the planetary model for the ground-based light curve is practically indistinguishable from the binary one. However, we can clearly see that the *Spitzer* light curve is different in the two models. While the binary model predicts a smooth slightly asymmetric peak, the planetary model still preserves a concave structure between a main peak and a shoulder. The data point at HJD = 7192, however, contradicts the existence of a main peak as suggested by the planetary model. This model also predicts lower magnification during the rising part, being further disfavored.

Figure 3 zooms in the peak region as seen from ground-based observatories comparing the best binary and planetary models. In the double-peak region, both models perform quite well. However, we note that before the peak, during the night $7187.5 < \text{HJD} < 7188$, the data from OGLE and KMTNet SAAO are too high above the planetary model, while after the peak, during the night $7191.5 < \text{HJD} < 7192$, the points from OGLE, Danish, and KMTNet CTIO are too low. The binary model fits the data much better. This discrepancy is the primary origin of the $\Delta\chi^2 = 53$ using ground-based data only. This is

Table 2
All Relevant Minima Found with a Comparison of the χ^2 Obtained Including or Excluding *Spitzer* Data

| Close Binary Models | | | |
|---------------------|------------------------|----------|-----------------------------|
| Cusps Involved | $\Delta\beta_{\pm\pm}$ | χ^2 | χ^2 w/o <i>Spitzer</i> |
| A–C | -- | 7952.7 | 7846.2 |
| A–C | –+ | 7955.1 | 7845.8 |
| A–C | ++ | 7953.0 | 7846.0 |
| A–C | +– | 7953.3 | 7845.7 |
| C–A | -- | 8040.5 | 7912.8 |
| C–A | –+ | 8040.3 | 7913.3 |
| C–A | ++ | 8040.3 | 7915.6 |
| C–A | +– | 8040.6 | 7915.9 |
| Wide Binary Models | | | |
| Cusps Involved | $\Delta\beta_{\pm\pm}$ | χ^2 | χ^2 w/o <i>Spitzer</i> |
| A–B | -- | 7954.9 | 7858.0 |
| A–B | –+ | 7958.6 | 7853.6 |
| A–B | ++ | 7954.7 | 7851.9 |
| A–B | +– | 7954.1 | 7857.3 |
| B–A | -- | 8175.5 | 8042.2 |
| B–A | –+ | 8172.0 | 8040.1 |
| B–A | ++ | 8166.6 | 8053.0 |
| B–A | +– | 8168.5 | 8046.4 |
| D–B | -- | 8087.5 | 7984.5 |
| D–B | –+ | 8099.8 | 7991.0 |
| D–B | ++ | 8088.2 | 7986.1 |
| D–B | +– | 8105.2 | 7991.1 |
| B–D | -- | 8216.9 | 8100.1 |
| B–D | –+ | 8225.8 | 8087.5 |
| B–D | ++ | 8211.7 | 8089.3 |
| B–D | +– | 8223.5 | 8096.8 |
| Planetary Models | | | |
| Topology | $\Delta\beta_{\pm\pm}$ | χ^2 | χ^2 w/o <i>Spitzer</i> |
| Close | -- | 8066.8 | 7926.0 |
| Close | –+ | 8107.1 | 7926.1 |
| Close | ++ | 8066.8 | 7926.3 |
| Close | +– | 8108.4 | 7925.5 |
| Wide | -- | 8066.1 | 7901.5 |
| Wide | –+ | 8080.0 | 7898.1 |
| Wide | ++ | 8066.3 | 7901.3 |
| Wide | +– | 8083.9 | 7898.0 |

Note. The notation employed to indicate the cusps involved in the binary solutions is taken from Liebig et al. (2015).

also evident from the plot of $\Delta\chi^2$ between the planetary and binary model (Figure 4), which shows big steps corresponding to these two nights. We deduce that the planetary model forces the light curve to have an asymmetry not reproduced by the data. Nevertheless, the deviations from the model are still of the order of 1σ and could still be the outcome of some unknown systematics. The contribution by the *Spitzer* observations is decisive to discriminate between the two solutions. This example clearly shows how observations from a different vantage point of the same event are extremely important to correctly classify an ambiguous microlensing event.

We finally note that the best model fits the data so well that if any systematics are present they are well below the statistical error, thus supporting the work hypothesis of uncertainties dominated by random Gaussian noise.

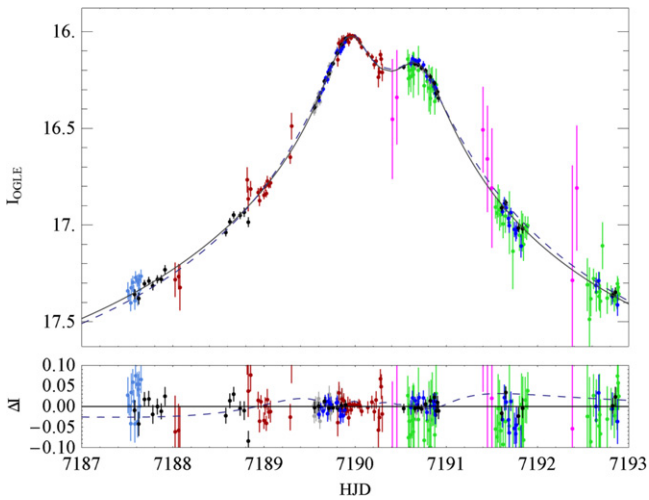


Figure 3. Comparison between the binary model (solid curve) and the planetary model (dashed curve) for the data acquired by ground-based observatories.

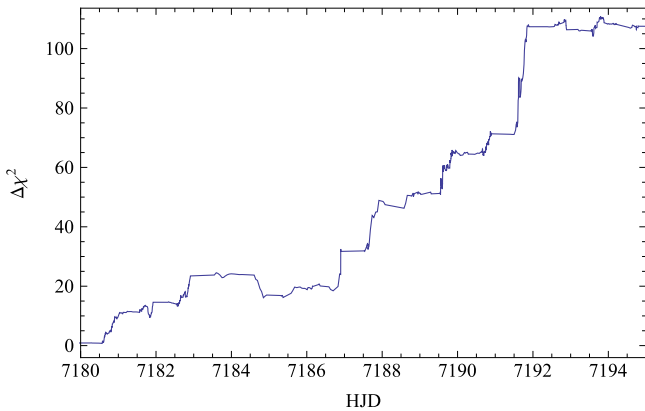


Figure 4. $\Delta\chi^2$ between the planetary and the binary model as a function of time.

4. PHYSICAL CHARACTER OF THE SYSTEM

The principal goal of our investigation is to determine whether the system is planetary or binary in nature because if the ambiguity remained, this would degrade the measurement of the Galactic distribution of planets. That is, the event is very sensitive to planets, so it is important to determine whether or not one was detected. As discussed in the previous section, this ambiguity is resolved by the *Spitzer* data in favor of the binary interpretation.

However, the remaining degeneracies within the binary solution are quite severe and limit the complete characterization of the system. Tables 3 and 4 contain full details of the four best close binary solutions and the four best wide binary solutions, respectively. The close binary solutions arise from the source approaching cusp *A* (along the lens axis) and then cusp *C* (off-axis cusp) of the central caustic. The wide solutions arise from the approach to cusp *A* (on-axis) and then *B* (off-axis) of the perturbed caustic of the heavier component. These caustics are very similar (Dominik 1999; Bozza 2000) and generate practically undistinguishable light curves. In principle, continuing *Spitzer* observations for some time after the main event would have probably helped constrain the existence of a second bump at the closest approach with the caustic of the secondary object in the wide configuration.

Apart from the wide/close degeneracy, we also have the fourfold parallax degeneracy discussed in Section 3. The symbols $--$, $-+$, $++$, $+--$ indicate the signs of u_0 for the source as seen from Earth and *Spitzer*, respectively. All eight solutions yield a nearly equal χ^2 , as can be read from the last lines of Tables 3 and 4, with a very slight preference for the close models by $\Delta\chi^2 \sim 1$. Interestingly, all models provide an upper limit for the source radius parameter $\rho = \theta_*/\theta_E$ of the order of 0.003, while only those solutions in which the source passes the caustic from the same side as seen from Earth and *Spitzer* (indicated by the symbols $++$ and $--$) are able to provide a lower limit as well. The resulting uncertainty is of the order 50%, which, combined with the 4% accurate parallax measurement obtained with *Spitzer*, is enough to constrain the lens mass and distance significantly. Note that both components of the parallax vector are accurately measured, something that is seldom possible from Earth.

In order to obtain the physical parameters of the system from the basic microlensing parameters, we need a complete characterization of the source involved in the microlensing event. A calibrated (V, I) color–magnitude diagram (CMD) has been obtained by CTIO observations, as shown in Figure 5. In particular, the source magnitude is one of the parameters of the fit, reported in Tables 3 and 4. The source color is obtained by linear regression on CTIO observations, which have been taken in both colors on the night HJD = 7189. We have $V - I = 1.54$. After locating the red clump centroid in the CMD of Figure 5 at $(V - I, I)_{\text{clump}} = (1.93, 18.62)$ and calibrating with $(V - I, I)_{\text{clump},0} = (1.06, 14.42)$ from Nataf et al. (2013), we obtain a de-reddened source $(V - I, I)_{\text{source},0} = (0.67, 17.87)$. This color index translates to $V - K = 1.435$, using the relations in Bessell & Brett (1988). Finally, from Kervella et al. (2004), we find an angular radius $\theta_* \simeq 0.81 \mu\text{as}$ for the best model. For each point in the Markov chains we can update this value with the parameters of each calculated model and derive accurate distributions for all secondary physical parameters.

Once we have the angular source radius, we can derive the Einstein angle, the proper motion, the total mass, and the distance from the formulae

$$\theta_E = \frac{\theta_*}{\rho}; \quad \mu = \frac{\theta_E}{t_E}; \quad M = \frac{\text{auc}^2 \theta_E}{4G \pi_E};$$

$$D_L = \left(\frac{\theta_E \pi_E}{\text{au}} + \frac{1}{D_S} \right)^{-1}. \quad (4)$$

In Tables 3 and 4 we present the results for these physical parameters. Of course, for those models for which only an upper limit on ρ is obtained from the light curve, these parameters are poorly constrained. On the other hand, for the models for which the source size is well constrained, we have relatively small ranges for the masses of the components of the binary system and for the lens distance.

Since the microlensing light curve is unable to break the degeneracy among these eight solutions, the only route we have to a final statement on the nature of our lens system is to build up a weighted combination of all probability distributions returned by our Markov chains. Each probability distribution is weighted by the likelihood $\exp(-\chi^2/2)$ evaluated on the local maximum and summed to the others. In the end, we obtain the confidence intervals reported in Table 5. The distributions for

Table 3
The Four Best Close Binary Solutions Found, with All Fit Parameters, Derived Physical Parameters, and Confidence Intervals at 68%

| Parameter | Close | | | |
|-------------------------|----------------------------------|----------------------------------|----------------------------------|--------------------------------|
| | -- | -+ | ++ | +- |
| s | $0.1760^{+0.0098}_{-0.0062}$ | $0.1698^{+0.0072}_{-0.0085}$ | $0.1735^{+0.0083}_{-0.0043}$ | $0.1690^{+0.0097}_{-0.0064}$ |
| q | $0.174^{+0.015}_{-0.023}$ | $0.188^{+0.029}_{-0.018}$ | $0.181^{+0.01}_{-0.020}$ | $0.186^{+0.025}_{-0.017}$ |
| u_0 | $-0.01487^{+0.00031}_{-0.00085}$ | $-0.01490^{+0.00038}_{-0.00064}$ | $0.01499^{+0.00054}_{-0.00047}$ | $0.01466^{+0.00092}_{-0.0001}$ |
| θ | $2.1386^{+0.0091}_{-0.0144}$ | $2.145^{+0.013}_{-0.01}$ | $10.4267^{+0.0116}_{-0.0079}$ | $10.422^{+0.012}_{-0.012}$ |
| ρ_* | $0.0025^{+0.0019}_{-0.0011}$ | <0.0031 | $0.001413^{+0.00225}_{-0.00025}$ | <0.0030 |
| t_E | $40.22^{+0.46}_{-2.31}$ | $39.99^{+0.85}_{-1.74}$ | $39.8^{+1.2}_{-1.3}$ | $40.52^{+0.16}_{-2.28}$ |
| t_0 | $7190.1980^{+0.003}_{-0.006}$ | $7190.2017^{+0.005}_{-0.005}$ | $7190.1992^{+0.003}_{-0.005}$ | $7190.2005^{+0.005}_{-0.004}$ |
| π_{\perp} | $-0.0639^{+0.001}_{-0.004}$ | $-0.0347^{+0.0014}_{-0.0023}$ | $-0.0462^{+0.0019}_{-0.0017}$ | $-0.07640^{+0.0008}_{-0.0043}$ |
| π_{\parallel} | $-0.0043^{+0.0016}_{-0.001}$ | $-0.0719^{+0.002}_{-0.004}$ | $-0.0445^{+0.0022}_{-0.0013}$ | $0.0235^{+0.0027}_{-0.0013}$ |
| π_E | $0.0640^{+0.004}_{-0.001}$ | $0.0798^{+0.004}_{-0.002}$ | $0.0641^{+0.002}_{-0.002}$ | $0.07991^{+0.0047}_{-0.0007}$ |
| θ_E (mas) | $0.22^{+0.14}_{-0.12}$ | <6 | $0.374^{+0.006}_{-0.255}$ | <5 |
| μ (mas yr $^{-1}$) | $2.0^{+1.4}_{-1}$ | <61 | $3.42^{+0.07}_{-2.32}$ | <46 |
| M_1/M_{\odot} | $0.36^{+0.25}_{-0.20}$ | <8 | $0.622^{+0.003}_{-0.426}$ | <6 |
| M_2/M_{\odot} | $0.064^{+0.042}_{-0.037}$ | <1.7 | $0.1081^{+0.0027}_{-0.0724}$ | <1.2 |
| D_L (kpc) | $7.18^{+0.4}_{-0.6}$ | <7.37 | $6.6748^{+0.854}_{-0.004}$ | <7.30 |
| s (au) | $0.28^{+0.14}_{-0.13}$ | <2.07 | $0.448^{+0.017}_{-0.283}$ | <2.057 |
| I_s | $22.081^{+0.017}_{-0.067}$ | $22.068^{+0.031}_{-0.044}$ | $22.066^{+0.030}_{-0.034}$ | $22.072^{+0.022}_{-0.051}$ |
| χ^2 | 7952.7 | 7955.1 | 7953.0 | 7953.3 |

Table 4
The Four Best Wide Binary Solutions Found, with All Fit Parameters, Derived Physical Parameters, and Confidence Intervals at 68%

| Parameter | Wide | | | |
|-------------------------|-----------------------------------|------------------------------|-------------------------------|----------------------------------|
| | -- | -+ | ++ | +- |
| s | $6.59^{+0.04}_{-0.30}$ | $6.6601^{+0.01}_{-0.251}$ | $6.839^{+0.05}_{-0.32}$ | $7.089^{+0.02}_{-0.32}$ |
| q | $0.2171^{+0.0007}_{-0.0294}$ | $0.2130^{+0.0026}_{-0.0234}$ | $0.233^{+0.001}_{-0.031}$ | $0.2455^{+0.0017}_{-0.0299}$ |
| u_0 | $-0.97^{+0.13}_{-0.02}$ | $-0.9793^{+0.117}_{-0.009}$ | $1.063^{+0.012}_{-0.14}$ | $1.1607^{+0.0086}_{-0.166}$ |
| θ | $2.138^{+0.002}_{-0.011}$ | $2.1384^{+0.0051}_{-0.0073}$ | $10.4262^{+0.0102}_{-0.0011}$ | $10.41544^{+0.01166}_{-0.00052}$ |
| ρ_* | $0.0032^{+0.0013}_{-0.0008}$ | <0.0033 | $0.0027^{+0.0009}_{-0.0013}$ | <0.004 |
| t_E | $44.87^{+0.04}_{-2.32}$ | $44.13^{+0.55}_{-1.62}$ | $44.3^{+1.0}_{-1.6}$ | $45.08^{+0.60}_{-1.91}$ |
| t_0 | 7216^{+1}_{-4} | $7217.29^{+0.2}_{-3.3}$ | $7220.58^{+0.2}_{-4.7}$ | $7223.895^{+0.005}_{-5.262}$ |
| π_{\perp} | $0.013909^{+0.000062}_{-0.00451}$ | $-0.0557^{+0.002}_{-0.003}$ | $-0.0249^{+0.0013}_{-0.0037}$ | $0.0445^{+0.0017}_{-0.0031}$ |
| π_{\parallel} | $0.0563^{+0.0036}_{-0.0002}$ | $0.0469^{+0.0014}_{-0.0026}$ | $0.0522^{+0.001}_{-0.002}$ | $0.05645^{+0.0037}_{-0.0002}$ |
| π_E | $0.05765^{+0.0033}_{-0.0005}$ | $0.0728^{+0.003}_{-0.002}$ | $0.0578^{+0.002}_{-0.001}$ | $0.0719^{+0.003}_{-0.001}$ |
| θ_E (mas) | <1.031 | <4.64 | $0.206^{+0.140}_{-0.073}$ | <8.51 |
| μ (mas yr $^{-1}$) | $1.40^{+4.34}_{-0.60}$ | <39.0 | $1.70^{+1.63}_{-0.60}$ | <75.1 |
| M_1/M_{\odot} | $0.30^{+0.87}_{-0.13}$ | <6.19 | $0.35^{+0.26}_{-0.11}$ | <12.13 |
| M_2/M_{\odot} | $0.066^{+0.038}_{-0.03}$ | <1.27 | $0.083^{+0.053}_{-0.03}$ | <2.776 |
| D_L (kpc) | $7.41^{+0.2}_{-0.3}$ | <7.4 | $7.31^{+0.2}_{-0.6}$ | <7.28 |
| s (au) | $8.5^{+3.4}_{-3}$ | <87 | $10.3^{+6.3}_{-3.6}$ | <94 |
| I_s | $22.0897^{+0.0038}_{-0.0633}$ | $22.056^{+0.040}_{-0.035}$ | $22.060^{+0.040}_{-0.037}$ | $22.067^{+0.037}_{-0.036}$ |
| χ^2 | 7954.9 | 7958.6 | 7954.7 | 7954.1 |

the mass of the primary component and the distance to the binary system are shown in Figure 6.

The best model indicates a red dwarf as a primary and a brown dwarf as a secondary. However, owing to the concurrence of the unconstrained minima, the mass ranges of this combined likelihood are much wider than in the previous tables. In particular, smaller values of ρ correspond to a larger Einstein angle and then a heavier mass and a smaller distance. In any case, the lens distance distribution still peaks as far as 7.375 kpc, which suggests that the lens belongs to the bulge of our Galaxy. Note that higher masses for the primary at lower distances would conflict with the constraints from the blending light. Furthermore, prior expectations favor low-mass

lenses, which are numerically more abundant than higher-mass stars.

5. CONCLUSIONS

Observations by the *Spitzer* satellite are rapidly revolutionizing the microlensing field. Traditional ground-based campaigns are plagued with degeneracies that often remain unsolved with observations from our planet alone. As a consequence, for some microlensing events we cannot give a closed scientific interpretation, and we must complement the models by statistical arguments that combine prior expectations from our knowledge of the Galaxy. The information on the presence of planets in microlensing data sets can then be expressed in terms

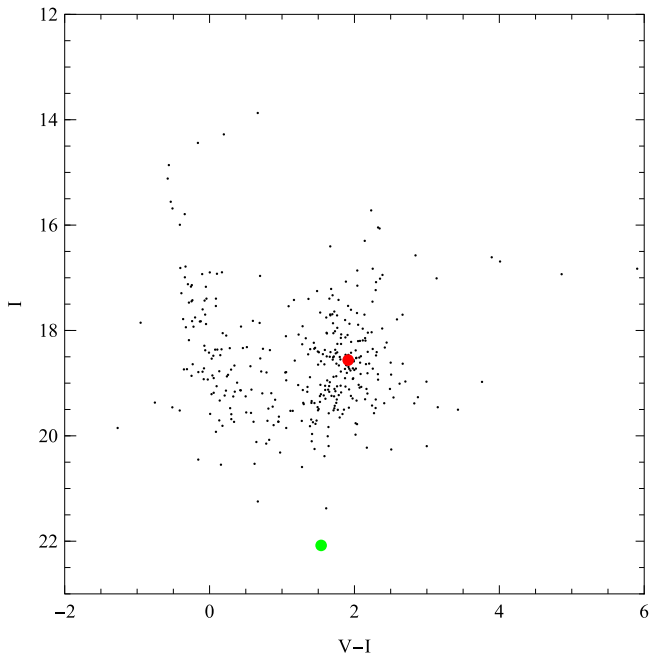


Figure 5. Color–magnitude diagram for the field of OGLE-2015-BLG-1212. The red dot is the centroid of the red giant clump, and the green dot is the position of the source.

Table 5

Physical Parameters from the Weighted Combination of All Minima Found

| Parameter | Value |
|-------------------------------|---|
| μ (mas yr ⁻¹) | 2.0 ^{+6.0} _{-1.2} |
| M_1/M_\odot | 0.36 ^{+1.12} _{-0.22} |
| M_2/M_\odot | 0.064 ^{+0.197} _{-0.041} |
| D_L (kpc) | 7.18 ^{+0.43} _{-1.68} |

of probability, which weakens the impact of the potential discoveries.

With the advent of *Spitzer*, the situation has radically changed. In this paper we have seen a clear example in which observations from a spacecraft far enough from Earth provide the key to breaking even some of the hardest degeneracies in microlensing. Thanks to *Spitzer* data, for OGLE-2015-BLG-1212 we have been able to definitely exclude the presence of a planet, which would have been allowed by ground-based data alone. In the path toward the construction of a map of the planets in our Galaxy, it is crucial that we have the highest confidence in the interpretation of the microlensing events that we accept as basic bricks. We have shown that the combination of the ground-based and *Spitzer* observations is able to establish the nature of individual microlensing events with unprecedented confidence.

Coming to the details of the modeling of this specific event, we also note that the measure of such a weak parallax is only possible thanks to *Spitzer* and would be impossible using Earth observatories only. Furthermore, even though the source is not crossing any caustics, it is very interesting to note that we obtain an upper and a lower limit for the source size for those models in which the source passes on the same side of the caustic as seen from Earth and from *Spitzer* (models “++” and

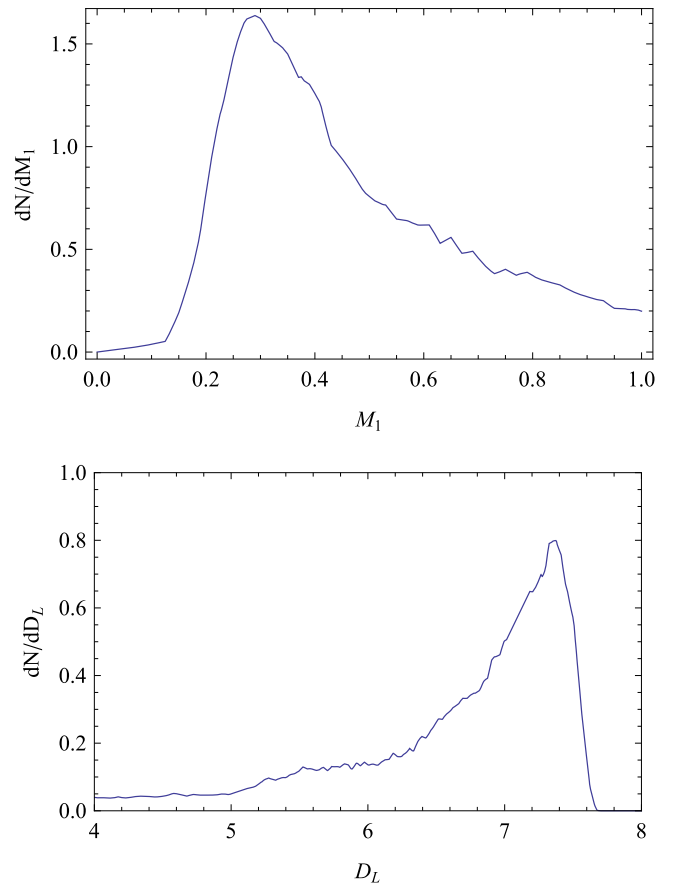


Figure 6. Combined probability distributions for the mass of the primary component and for the distance of the lens obtained by weighing the best eight minima shown in Tables 3 and 4.

“--”). This is an unexpected bonus from the presence of a second probe of the lens plane. Although *Spitzer* goes further from the caustic, its light curve still constrains the model in a region of the parameter space in which the ground-based light curve is better fitted by requiring a minimal size of the source. Summing up, even in the limiting case of an event far in the bulge with a non-caustic-crossing source trajectory, *Spitzer* has been able to provide a parallax and an indication of the source size sufficient to have a clear and complete idea of the lens system. This is a unique occurrence in the history of microlensing observations.

With *Spitzer* observation campaigns, a new era has been opened for the microlensing field. This era will continue in the next few years with the addition of precious observations by some more satellites already orbiting the Sun or that are being designed at present. In 2016 we will have the Campaign 9 of the *K2* mission that will observe the bulge for 3 months (Henderson et al. 2016). The separation from Earth is a fraction of an au, thus being comparable to *Spitzer*’s, but this satellite will operate in survey mode, with more than 100 microlensing events expected. The presence of a sufficiently long baseline for some events will provide an important additional constraint that will be extremely useful in the analysis. If some events will be simultaneously observed from the ground, *K2*, and *Spitzer*, we will have the incredible possibility to analyze events from three different points of view, which will dramatically reduce the possibilities for degeneracies to survive (Calchi Novati &

Scarpetta 2015). All these observations are a stimulating anticipation of the *WFIRST* mission,⁵² which is specifically designed to perform microlensing searches 10 years from now and that will likely yield several hundreds of microlensing planets (Yee et al. 2014; Zhu & Gould 2016). The current design considers a geosynchronous orbit or the Lagrangian point L2. These options would provide a shorter baseline with respect to *Spitzer* or *K2*, which would be compensated by a much higher quality of the photometry. The era of microlensing from space has just begun.

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