

# KMT-2019-BLG-0842Lb: A Cold Planet Below the Uranus/Sun Mass Ratio

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## ABSTRACT

We report the discovery of a cold planet with a very low planet/host mass ratio of  $q = (4.09 \pm 0.27) \times 10^{-5}$ , which is similar to the ratio of Uranus/Sun ( $q = 4.37 \times 10^{-5}$ ) in the Solar system. The Bayesian estimates for the host mass, planet mass, system distance, and planet-host projected separation are  $M_{\text{host}} = 0.76 \pm 0.40 M_{\odot}$ ,  $M_{\text{planet}} = 10.3 \pm 5.5 M_{\oplus}$ ,  $D_{\text{L}} = 3.3 \pm 1.3 \text{ kpc}$ , and  $a_{\perp} = 3.3 \pm 1.4 \text{ AU}$ , respectively. The consistency of the color and brightness expected from the estimated lens mass and distance with those of the blend suggests the possibility that the most blended light comes from the planet host, and this hypothesis can be established if high resolution images are taken during the next (2020) bulge season. We discuss the importance of conducting optimized photometry and aggressive follow-up observations for moderately or very high magnification events to maximize the detection rate of planets with very low mass ratios.

*Subject headings:* gravitational lensing: micro

## 1. Introduction

For the first 15 years of microlensing planet detections, there was no clear evidence for “cold planets” (i.e., beyond the snow line) with mass ratios below that of Uranus ( $q = 4.37 \times 10^{-5}$ ) neither in our Solar System nor in other systems. There are of course several cold, low-mass bodies in the outer Solar System, but these are more than 10 times less

massive than the smallest terrestrial planet (Mercury). The same applies to Ceres, which lies approximately on the snow line. Such bodies likely form by a distinct mechanism relative to planets, and they were therefore reclassified as “dwarf planets” by the IAU.

Cold, low-mass planets in exo-systems can only be detected by microlensing (Bennett & Rhie 1996; Beaulieu et al. 2006; Gould et al. 2006). However, there was no discovery of such a planet until one with a mass ratio  $q = 4.7 \times 10^{-5}$  was reported in 2017 (Udalski et al. 2018)<sup>1</sup>.

In principle, the lack of such detections could have been due to one of the following four causes: (1) poor sensitivity of microlensing searches to such planets; (2) extreme rarity (or complete absence) of such planets in nature; (3) adverse fluctuation of small-number statistics; or (4) some combination of these. Suzuki et al. (2016) showed that there was a break in the power-law distribution (in  $q$ ) below some threshold, estimated roughly at  $q_{\text{br}} \sim 1.7 \times 10^{-4}$ , arguing in particular that their MOA-based planet sample had significant sensitivity below the lowest- $q$  detections. Udalski et al. (2018) confirmed that if the mass ratio distribution of planets with  $q < 1 \times 10^{-4}$  were modeled as a power law, its slope was rising with  $q$ , in contrast to the well-established falling power law at higher  $q$ . Moreover, they showed that four of the seven planets that they analyzed would have been detected even if their mass ratios had been below  $q = 3 \times 10^{-5}$ , and one of these would have been detected even at  $q = 2 \times 10^{-6}$ , i.e., below the Earth/Sun mass ratio. Jung et al. (2019) argued that the dearth of planets below  $q = 4.7 \times 10^{-5}$  was due either to a break in the mass-ratio function at  $q_{\text{br}} \simeq 5.6 \times 10^{-5}$  or a “pile-up” of planets near the Neptune-mass-ratio threshold.

With a mass ratio  $q = (1.8 \pm 0.2) \times 10^{-5}$ , KMT-2018-BLG-0029 was the first reported planet that lay clearly below the previous apparent Uranus/Sun mass-ratio threshold (Gould et al. 2019). It provided proof for the existence of such planets, but a single detection yielded very limited information on their frequency. Gould et al. (2019) reviewed the history of the (by then, nine)  $q < 1 \times 10^{-4}$  planet detections, and concluded that with the advent of regular observations of the Korea Microlensing Telescope Network (KMTNet, Kim et al. 2018a,b,c) in 2016, the rate of such detections would be increasing, and that it should be possible to probe the frequency of such low-mass planets within a few years.

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<sup>1</sup>Within their sample of seven  $q < 1 \times 10^{-4}$  microlensing planets, OGLE-2016-BLG-1195, had the lowest mass ratio  $q = (4.7 \pm 0.5) \times 10^{-5}$ . Udalski et al. (2018) took the average from two groups who had made independent parameter determinations using disjoint data sets:  $q = [(4.2 \pm 0.7) \& (5.5 \pm 0.8)] \times 10^{-5}$  from Bond et al. (2017) and Shvartzvald et al. (2017), respectively. Udalski et al. (2018) excluded OGLE-2017-BLG-0173 from their sample because its solution was ambiguous by a factor 2.5 ( $2.48 \pm 0.24$  versus  $6.4 \pm 1.0$ )  $\times 10^{-5}$  at  $\Delta\chi^2 = 3.5$  (Hwang et al. 2018).

Although microlensing is sensitive to planets with mass ratios below  $q \sim 10^{-4}$ , the number of known microlensing planets with very low mass ratios is still small and these planets comprise a very minor fraction of all microlensing planets. Therefore, detecting more planets in the low mass regime is important to investigate the physical parameter distributions of these planets and to compare the distributions with those of planets in the higher mass regime. In this paper, we report the detection of a cold planet with a mass ratio of  $q = (4.09 \pm 0.27) \times 10^{-5}$ .

## 2. Observations

KMT-2019-BLG-0842, (R.A., Decl.)<sub>J2000</sub>=(17:53:50.03,  $-29:52:38.78$ ), corresponding to  $(l, b) = (+0.11, -2.02)$ , was discovered by the KMT alert-finder system (Kim et al. 2018d) and announced as a microlensing candidate on the KMTNet website<sup>2</sup> at UT 02:39 on 16 May 2019, about six days before the event reached its peak. The event was independently found by the Optical Gravitational Lensing Experiment (OGLE, Udalski et al. 2015) and the Microlensing Observations in Astrophysics (MOA, Bond et al. 2004) collaborations at UT 19:30 on 18 May 2019 as OGLE-2019-BLG-0763 and at UT 07:02 on 24 May 2019 as MOA-2019-BLG-232, respectively.

Observations by the KMTNet survey were conducted utilizing three identical 1.6m telescopes equipped with ( $2^\circ \times 2^\circ$ ) cameras, located at Cerro Tololo InterAmerican Observatory (KMTC), the South African Astronomical Observatory (KMTS), and the Siding Springs Observatory (KMTA) (Kim et al. 2016). KMT-2019-BLG-0842 lies in the overlapping KMT fields BLG02 and BLG42, each of which is observed at a nominal cadence of  $\Gamma = 2 \text{ hr}^{-1}$ . However, both fields were observed at an adjusted cadence of  $\Gamma = 3 \text{ hr}^{-1}$  from KMTS and KMTA prior to 15 June, i.e., until more than three weeks after the peak of the event. Hence, the effective cadence was  $\Gamma = 4 \text{ hr}^{-1}$  from KMTC and  $\Gamma = 6 \text{ hr}^{-1}$  from KMTS and KMTA. The observations were primarily conducted in the  $I$  band, but every tenth such observation was matched by a  $V$ -band observation in order to measure the source color.

The OGLE collaboration observed the event, located in their BLG501 field, with  $\Gamma = 1 \text{ hr}^{-1}$  cadence using the 1.3m telescope, equipped with a  $1.4 \text{ deg}^2$  camera, located at Las Campanas Observatory in Chile. OGLE observations were also primarily conducted in the  $I$  band.

The light curve derived from the KMTNet and OGLE observations is shown in Figure 1.

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<sup>2</sup><http://kmtnet.kasi.re.kr/~ulens>

The KMTNet data were reduced using pySIS (Albrow et al. 2009), which is a variant of difference image analysis (DIA, Tomaney & Crofts 1996; Alard & Lupton 1998; Alard 2000). The OGLE data were reduced using another variant of DIA (Woźniak 2000). The relatively brief ( $\sim 15$  hr) planetary anomaly was announced by W. Zang at UT 19:56 on 26 May 2019 ( $JD' = JD-2450000 = 8630.33$ ), but by this time the anomaly was already over, and thus no followup observations of the anomaly resulted from the announcement.

The MOA collaboration observed the object with a cadence of  $\Gamma = 4 \text{ hr}^{-1}$  using its 1.8m telescope at Mt. John, New Zealand, which is equipped with a  $2.2 \text{ deg}^2$  camera. However, observational conditions were poor on the night of the anomaly. The resulting observations therefore do not constrain the characteristics of the planet, although they do qualitatively confirm its existence. We therefore do not include these data in the primary fit, but rather use them to illustrate this confirmation (Figure 2). MOA observations were mainly taken using a broad  $R/I$  filter.

### 3. Light Curve Analysis

With the exception of the short anomaly peaking at  $t_{0,\text{anom}} = 8627.85$ , KMT-2019-BLG-0842 has the general appearance of a Paczyński (1986) single-lens single-source (1L1S) event. The light curve of a 1L1S event is characterized by three geometric parameters ( $t_0, u_0, t_E$ ), respectively the time of maximum, the impact parameter (in units of the Einstein radius  $\theta_E$ ), and the Einstein radius crossing time,

$$t_E \equiv \frac{\theta_E}{\mu_{\text{rel}}}; \quad \theta_E^2 \equiv \kappa M \pi_{\text{rel}}; \quad \kappa \equiv \frac{4G}{c^2 \text{AU}} \simeq 8.14 \frac{\text{mas}}{M_\odot}, \quad (1)$$

where  $M$  is the lens mass and  $(\pi_{\text{rel}}, \boldsymbol{\mu}_{\text{rel}})$  are the lens-source relative parallax and proper motion, respectively. From visual inspection,  $t_0 \simeq 8625.91$  and the full width at half maximum (FWHM) of the light curve is 1.0 days. The peak magnification is either moderately high or very high depending on the blending, which is difficult to estimate by eye, and in either case  $u_0 \ll 1$ , so  $t_{\text{eff}} \equiv u_0 t_E = \text{FWHM}/\sqrt{12} \simeq 0.29 \text{ day}$ . Hence (e.g., Gould & Loeb 1992), the source almost certainly passes at an angle

$$\alpha = \tan^{-1} \frac{t_{\text{eff}}}{t_{0,\text{anom}} - t_0} = \tan^{-1} 0.149 = 0.148, \quad (2)$$

or  $8.5^\circ$ , relative to the binary axis. The fact that the anomaly is very short, even though the source crosses the caustic structure at such an acute angle  $\alpha$ , suggests that the mass ratio between the binary lens components is very low. A similar inference can be drawn from the fact that there is no noticeable anomaly over the high (or very high) magnification peak.

That is, both effects tend to indicate a small, resonant (or near-resonant) caustic. However, detailed modeling is required to proceed further.

### 3.1. Binary Lens (2L1S) Analysis

We model the light curve as a 2L1S event with seven non-linear parameters  $(t_0, u_0, t_E, s, q, \alpha, \rho)$ , where  $s$  is the projected separation between the binary components (normalized to  $\theta_E$ ),  $\rho \equiv \theta_*/\theta_E$ , and  $\theta_*$  is the angular source radius. Notwithstanding the above estimate of  $\alpha$ , we conduct a broad grid search in the parameters  $s, q$ , and  $\alpha$ , in which  $(s, q)$  are held fixed and the remaining five parameters are allowed to vary in a Markov chain Monte Carlo (MCMC). The three parameters  $(t_0, u_0, t_E)$  are seeded at their Paczyński (1986) values,  $\rho$  is seeded at  $10^{-3}$ , and  $\alpha$  is seeded at six values drawn uniformly from the unit circle. There are two flux parameters  $(f_{s,i}, f_{b,i})$  for each observatory  $i$ , which are fit by linear regression to the observed flux  $F_i(t)$  for each model, according to  $F_i(t) = f_{s,i}A(t) + f_{b,i}$ . These are identified with the “source” and “blend” flux, respectively.

We find only two local minima in the resulting  $(s, q)$  map, which we then further refine by allowing all seven parameters to vary in the MCMC. Finally, these converge to  $(s, q) = (0.98, 4.1 \times 10^{-5})$  and  $(s, q) = (1.06, 3.9 \times 10^{-5})$ . See Table 1. These solutions are actually quite similar in all of their parameters, and in particular both agree with the analytically estimated value of the source trajectory angle  $\alpha$  in Equation (2). However, the “wide” solution ( $s > 1$ ) is disfavored relative to the “close” solution ( $s < 1$ ) by  $\Delta\chi^2 = 176$ . Furthermore, the “wide” solution has clear systematic residuals. See Figure 3. Hence, we exclude the “wide” solution. The caustic geometries for both the “close” and “wide” solutions are shown in Figure 4.

We investigate whether the microlens parallax vector  $\boldsymbol{\pi}_E$  (Gould 1992, 2000, 2004) can be meaningfully constrained, but we find that it cannot.

### 3.2. Binary Source (1L2S) Analysis

Gaudi (1998) pointed out that a short-lived “bump” on an otherwise normal Paczyński (1986) light curve could in principle be produced by a second source (1L2S) rather than a second lens (2L1S). This is of particular concern when (as in the present case) the “bump” does not exhibit any obvious caustic structure. Therefore, we check the degeneracy between the 2L1S and 1L2S interpretations by additionally conducting a 1L2S modeling. Our 1L2S model has eight nonlinear parameters:  $2 \times (t_0, u_0, \rho)$  for the two sources, plus a common

Einstein timescale  $t_E$  and the  $I$ -band flux ratio between the two sources,  $q_{F,I}$ . See Table 2.

We find that the 2L1S interpretation is favored over the 1L2S interpretation by  $\Delta\chi^2 = \chi^2(1L2S) - \chi^2(2L1S) = 495$ . To check the region of the fit difference, we also inspect the cumulative  $\Delta\chi^2$  distribution of  $\Delta\chi^2 = \chi^2(1L2S) - \chi^2(2L1S)$  (see Figure 3). From this, we find that the  $\chi^2$  difference largely comes from the anomaly region, in which the 1L2S solution provides a poorer fit to the observed light curve, especially in the rising part of the anomaly. In addition, the solution is unphysical in the sense that the flux ratio is  $q_{F,I} \simeq 0.013$  while the normalized sources sizes  $(\rho_1, \rho_2)$  are of the same order<sup>3</sup>. See Table 2. Hence, we exclude the 1L2S solution.

#### 4. Color-Magnitude Diagram and Einstein Radius

Although the planetary anomaly does not exhibit obvious caustic features, the results in Table 1 show that the normalized source size  $\rho$  is reasonably well measured<sup>4</sup>. This implies that we can estimate  $\theta_E = \theta_*/\rho$  provided that  $\theta_*$  is measured. Indeed, although the  $1\sigma$  error in  $\rho$  is relatively large, there is a very strong,  $3\sigma$ , upper limit  $\rho < 5.7 \times 10^{-4}$ , which will place important physical constraints on the lens system, as we discuss below.

We follow the standard approach (Yoo et al. 2004) of measuring  $\theta_*$  by placing the source on an instrumental color-magnitude diagram (CMD). See Figure 5. For this purpose, we reduce the KMTC42  $V$  and  $I$  data using pyDIA, which yields field-star and light-curve photometry on the same system. Using this instrumental system, we find source and red-clump-centroid positions of  $[(V - I), I]_S = (2.38, 21.73) \pm (0.03, 0.01)$  and  $[(V - I), I]_{cl} = (2.43, 16.04) \pm (0.03, 0.07)$ , respectively, and hence an offset of  $\Delta[(V - I), I] = (-0.05, 5.69) \pm (0.04, 0.07)$ . We adopt  $[(V - I), I]_{cl,0} = (1.06, 14.44)$  (Bensby et al. 2013; Nataf et al. 2013). We do not assign an error to this determination but rather add 5% error in quadrature to the final result for all aspects of the method. We then obtain  $[(V - I), I]_{S,0} = [(V - I), I]_{cl,0} + \Delta[(V - I), I] = (1.01, 20.13) \pm (0.04, 0.07)$ . Assuming that the source is located at the mean distance to the bulge, i.e.,  $D_S = 8.17$  kpc (Nataf et al. 2013), the source star has the color and absolute magnitude of  $[(V - I)_0, M_I]_S \simeq (1.0, 5.6)$ , which is typical of an early K dwarf.

We then convert the measured  $V/I$  color into  $V/K$  color using the  $VIK$  color-color

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<sup>3</sup>Strictly speaking,  $\rho_1$  is poorly constrained by the fit, but it has a strict upper limit  $\rho_1 < u_{0,1} = 56 \times 10^{-4}$ , which implies the same unphysicality.

<sup>4</sup>This was also the case for the low- $q$  planetary event OGLE-2016-BLG-1195 (Bond et al. 2017; Shvartzvald et al. 2017)

relations of Bessell & Brett (1988) and then apply the color/surface-brightness relations of Kervella et al. (2004) to obtain (after adding 5% error),

$$\theta_* = 0.416 \pm 0.031 \mu\text{as}. \quad (3)$$

We can then obtain “naive” estimates for  $\theta_E$  and  $\mu_{\text{rel}}$ ,

$$\theta_E = \frac{\theta_*}{\rho} = 0.96 \pm 0.22 \text{ mas}; \quad \mu_{\text{rel}} = 8.0 \pm 1.8 \text{ mas yr}^{-1} \quad (\text{naive}). \quad (4)$$

We refer to these two estimates as “naive” because, as will be discussed in Section 5, the proper evaluation of these quantities should be estimated from their Bayesian posteriors.

The estimated values of  $\theta_E$  and  $\mu_{\text{rel}}$  strongly imply that the lens lies in the disk. That is, from the definition of  $\theta_E$  (Equation (1)),  $\pi_{\text{rel}} = 0.12 \text{ mas}(\theta_E/\text{mas})^2/(M/M_\odot)$ . Thus, if we adopt the best-fit value of  $\theta_E$  and also take account of the fact that lenses significantly more massive than the Sun would be easily visible, then we would infer  $\pi_{\text{rel}} \gtrsim 0.12 \text{ mas}$ , i.e., lens distance  $D_L \lesssim 4 \text{ kpc}$ . Because the error in  $\theta_E$  is large (due primarily to the large error in  $\rho$ ), we must also consider how smaller values of  $\theta_E$  (i.e., below the best-fit value) would affect this argument. However, as mentioned above, the errors in  $\rho$  are highly asymmetric, so there is a very hard lower limit  $\theta_E > 0.65 \text{ mas}$ . This somewhat relaxes the above argument, but still requires  $\pi_{\text{rel}} \gtrsim 0.06 \text{ mas}$ , which puts the lens in the disk.

## 5. Physical Parameter Estimates

Because the microlens parallax  $\pi_E$  is not measured, one cannot directly infer the lens mass  $M = \theta_E/\kappa\pi_E$  and lens-source relative parallax  $\pi_{\text{rel}} = \theta_E\pi_E$  from the microlensing data. We therefore conduct a Bayesian analysis by incorporating priors from a Galactic model. In fact, the situation is somewhat more complicated than usual because the measurement error of the normalized source radius  $\rho$  is large and its distribution is asymmetric. Moreover,  $\rho$  is correlated with the planet-host mass ratio  $q$ . Thus, in sharp contrast to the usual case, the posterior estimate of this (seemingly) pure microlensing-light-curve parameter  $q$  is actually affected by the Galactic priors.

The fundamental features of the Galactic model and the Bayesian procedures are the same<sup>5</sup> as those presented in Jung et al. (2018). Here, we focus on describing what is different for the present case.

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<sup>5</sup>We note that Jung et al. (2018) do not specify their upper-mass cutoff for the mass function. For completeness, we note that this cutoff is  $63 M_\odot$ .

As usual, we incorporate constraints of both  $t_E$  and  $\theta_E$  determined from the light-curve modeling and CMD. For this, we weight the simulated events by  $W_{t_E} = \exp[-(t_E - t_{E,\text{best}})^2/2\sigma_{t_E}^2]$ , where  $t_E$  is the Einstein timescale of the simulated event and  $(t_{E,\text{best}}, \sigma_{t_E})$  are the values from Table 1.

We incorporate the  $\theta_E$  constraint in a different way from that of the  $t_E$  constraint. We first evaluate a function  $\Delta\chi^2(\rho)$  by running MCMCs for a series of fixed values of  $\rho$ . See Figure 6. Then, for each simulated event, we evaluate  $\theta_E = \sqrt{\kappa M \pi_{\text{rel}}}$  from the values of  $M$ ,  $D_L$ , and  $D_S$  of the individual simulated events. In this process, we draw  $\theta_*$  from a Gaussian distribution with the mean and standard deviation presented in Equation (3). We then evaluate  $\rho = \theta_*/\theta_E$  and finally determine the weight by  $W_{\theta_E} = \exp[-\Delta\chi^2(\rho)/2]$ .

The Bayesian analysis then carried out following a usual procedure, but with one major exception. In Figure 6, we show the best-fit value of  $q$  and its  $1\sigma$  error bar for each fixed- $\rho$  MCMC, that is carried out following the procedure described above, to evaluate  $\Delta\chi^2(\rho)$ . Over the region of principal interest,  $3 \lesssim \rho/10^{-4} \lesssim 5$ , this shows a logarithmic (power-law) gradient  $d \log q / d \log \rho \simeq -0.2$ . This gradient is present because the models account for the observed duration of the “bump” by the combination of  $q$  and  $\rho$ : for relatively large  $q$ , this duration is explained by the width of the ridge, but with decreasing  $q$  it must be increasingly explained by larger  $\rho$ . For most events, such a gradient would play little role because  $\rho$  would be well determined. However, in the present case, the error in  $\rho$  is large, so that the error in  $q$  induced by this correlation is comparable to the scatter in  $q$  at fixed  $\rho$ . Therefore, to properly evaluate the *posterior* value of  $q$ , we should incorporate the correlation into the Bayesian analysis.

We do so by evaluating  $q$  separately for each simulated event in the MCMC. We first find  $\rho$  (as above). We then find  $q(\rho)$  and  $\sigma_q(\rho)$  from a table that corresponds to Figure 6, and then draw  $q$  randomly from a Gaussian described by these two values. This value of  $q$  is then used both to evaluate the planet mass for the simulated event  $m_p = qM_{\text{host}}$  and to find the posterior distribution of  $q$  itself.

The results of the Bayesian analysis are shown in Table 3 and Figure 7. Although the lens is believed to lie in the disk from the estimated  $\theta_E$ , we formally consider both bulge and disk lenses in the Bayesian analysis. As expected, we find that the chance that the lens is in the bulge is very low,  $< 1\%$ .

### 5.1. Does the Lens Account for the Blended Light?

The best-fit position of the blended light  $[(V - I), I]_b = (1.68, 19.84)$  lies at a position with offsets  $\Delta[(V - I), I]_b = [(V - I), I]_b - [(V - I), I]_{cl} = (-0.75, 3.80)$  from the red-clump-centroid on the CMD. We discuss the error bars on this position below.

The  $I$ -band brightness offset  $\Delta I_b = 3.80$  is consistent with the lens mass and distance ranges derived from the Bayesian analysis above, as summarized in Figure 7. More specifically, assuming the lens distance as the median of the posterior distance distribution, at  $D_L = 3.3$  kpc, the lens would be at about  $z \simeq -0.1$  kpc below the galactic plane, and so plausibly behind about half the dust toward the bulge, toward which  $[E(V - I), A_I] = (1.28, 1.50)$  (Nataf et al. 2013). This would imply an absolute magnitude of the lens of  $M_I = (I_{cl,0} + \Delta I) - A_I/2 - [5 \log(3300) - 5] = 14.44 + 3.80 - 1.50/2 - 12.59 \simeq 4.9$ . This corresponds roughly to an  $M = 0.85 M_\odot$  star, which is quite compatible with the Bayesian host-mass estimation. Such a star would have (depending on its metallicity) roughly  $(V - I)_0 \sim 0.85$ , and therefore would be  $\Delta(V - I) = 0.85 - 1.06 - 1.28/2 \simeq -0.85$  mag bluer than the clump. Given the measurement errors (which we estimate just below), this is also quite compatible with the “observed” offset:  $-0.75$  mag bluer than the clump.

The baseline object is quite faint in the  $V$  band,  $V_{base} = 21.43$ . It is therefore barely detected, and hence the error in magnitudes is large. The contribution from the source to this baseline light is known quite precisely, so from a conceptual point of view, we should consider the errors in the point-spread-function (PSF) modeling of the remaining blended light  $V_b = 21.52$ . The error in this estimate is comprised of three distinct components: Poisson errors from finite photon statistics; systematic errors from the PSF modeling photometry program, operating under the assumption that the background is smooth; and statistical errors due to the fact that a mottled distribution of unresolved stars contributes significantly to the background.

Based on photon statistics, we estimate the systematic error as 0.19 mag. Because the PSF photometry program is relatively complex, it is difficult to reliably estimate the systematic errors. Hence, we ignore these errors for the moment. To estimate the statistical errors due to the mottled background, we apply the approach of Ryu et al. (2019), i.e., modeling the Holtzman et al. (1998) luminosity function adjusted for the local surface brightness of the bulge and the local extinction. In fact, the mottled background results in correlated errors between the  $I$  and  $V$  band measurements because there can be an excess or a “hole” in this background of stars that are predominantly redder than the apparent blend star. Hence, an excess at the location of the event would cause the apparent blend to appear brighter and redder, while a “hole” in the background would make it appear fainter and bluer.

Based on the surface density of clump stars (Nataf et al. 2013; D. Nataf, 2019, private communication), we find a normalization factor of 2.41 relative to Baade’s Window. We adopt  $[E(V - I), A_I] = (1.28, 1.50)$  from Nataf et al. (2013), and then evaluate the statistical errors using a 1.5'' FWHM seeing disk. We find that (from this effect alone), there is a 16% probability that the blend appears at least 0.20 mag bluer than it is, as well as a 16% probability that the blend appears at least 0.28 mag redder than it is. Hence, combining the two effects (systematic and statistical errors), the color error is at least  $\pm 0.28$  mag.

We should also ask how well the source is astrometrically aligned with the baseline object. We measure the position of the source and baseline object relative to the KMTC42 template and find in (west, north) 0.4'' pixel coordinates, that the baseline object lies (0.32, -0.12) pixels, or (0.13'', -0.05''), i.e., west and south of the source. Because the source position is derived from difference images (which removes both the resolved and unresolved backgrounds) and because the source is highly magnified in these images, the errors in the source position are negligible relative to the errors in the baseline object. Hence we ignore them.

The astrometric errors originate from the same three types of the photometric errors. The astrometry is done in the *I*-band, so we evaluate these errors in this band. We again only evaluate the errors of the first and third types. We estimate the fractional astrometric error (relative to the Gaussian half width  $\sigma = \text{FWHM}/\sqrt{\ln 256}$ ) as that of the fractional photometric error,  $(\ln 10/2.5)\sigma_I$ . That is,  $\sigma_{\text{ast}} = 0.39\sigma_I \text{FWHM} \rightarrow 0.6''\sigma_I$ . We find that the photon-error contribution to  $\sigma_I$  is 0.14 mag.

Next, we consider the error due to the mottled background. If we evaluate this without any constraint, we find  $\sigma_I = 0.6$ . However, if we restrict to cases where the background produces a “hole”, then  $\sigma_I = 0.3$ . Combined, these two sources of error imply  $\sigma_{\text{ast}} = 0.37''$  and  $\sigma_{\text{ast}} = 0.20''$  for the two cases. This is larger than the observed offset. Hence, the measured astrometric offset is not inconsistent with the hypothesis that the blend is the lens. However, we note that this hypothesis can be established by future high-resolution observations.

## 6. Discussion

### 6.1. Very Low Mass-Ratio Planets

It is found that the KMT-2019-BLG-0842Lb is a “cold” planet located beyond the snow line of its host, and the planet/host mass ratio is  $\mathbf{q} = (4.09 \pm 0.27) \times 10^{-5}$ , which is similar to the ratio of Uranus/Sun in the Solar system. The discovery of the planetary system,

together with similar systems previously discovered, provides an evidence that such planets are not rare. Nevertheless, further discoveries will be necessary to estimate the frequency and characterize the distribution of such planets.

As noted by Ryu et al. (2019), the detection pace of low-mass-ratio microlensing planets with  $q \leq 1 \times 10^{-4}$  has been accelerating since 2015, when KMTNet commenced. The 11 such planets (including KMT-2018-BLG-0029Lb and KMT-2019-BLG-0842Lb) occurred in (2005, 2005, 2007, 2009, 2013, 2015, 2016, 2017, 2018, 2018, 2019). That is, five during the 10 seasons before 2015 and six during the five seasons after. Moreover, the data from the 2019 season have not yet been fully analyzed. If indeed sub-Uranus/Sun planets are common, we can expect more detections based on the trend of increasing rate.

In this context, it is worthwhile to ask what features of low mass-ratio planetary events allow them to be detected. A related issue is how the planet detection strategy should be adjusted to maximize the detection rate.

A notable feature of KMT-2019-BLG-0842Lb is that the planetary signal appeared in a high-magnification event ( $u_0 = 0.0066$ ;  $A_{\max} = 150$ ), and at very low angle  $\alpha = 0.146$  ( $8.5^\circ$ ) between the source trajectory and the binary axis. That is, the magnification of the underlying 1L1S event at the time of the planetary anomaly was modest:  $A_{\text{anom}} \simeq \sin(\alpha)/u_0 = 22$ . This means that the source would have passed over the same part of the caustic structure if the event had had  $A_{\max} = 22$  ( $u_0 = 0.045$ ) and  $\alpha = 90^\circ$ . This is similar to the situations for OGLE-2016-BLG-1195, which had  $|u_0| = 0.053$ ,  $|\alpha| = 55^\circ$ , and a slightly higher mass ratio, and for KMT-2018-BLG-0029, which had  $|u_0| = 0.027$ ,  $|\alpha| = 88^\circ$ , and a substantially lower mass ratio. Thus, at first sight, it seems that such moderate-magnification events provide as fertile ground to hunt for low-mass planets as high-magnification events (as advocated by Abe et al. 2013). In fact, however, KMT-2019-BLG-0842Lb would have been discovered for values of  $\alpha$  covering most of the unit circle at its actual  $u_0$ , whereas at  $u_0 = 0.045$  the sensitivity would have been restricted to a relatively narrow range of angles.

However, the main feature to be noted is that the low source-trajectory angle caused the anomaly to be longer by factor  $\cot \alpha \simeq 7$  relative to an orthogonal transit of the caustic structure. That is, in an orthogonal crossing, the full duration would have been about two hours rather than 15 hours. This is just twice the source-diameter self-crossing time,  $2t_* \equiv 2\rho t_E = 0.9$  hr. Such a short anomaly would have been detected in the actual observations (provided that it did not fall in a gap) because the event was in a high-cadence KMT field, with  $\Gamma = 4\text{--}6$  hr $^{-1}$ . But if it had been in a field with a cadence  $\Gamma = 0.75\text{--}1$  hr $^{-1}$ , then a two-hour anomaly would have been missed, while a 15-hour anomaly (as in this case) can be readily detected.

These points are in some sense moot because the survey strategy is basically set. However, these anomalies are not necessarily noticed in the mode by which events are currently vetted, i.e., either manual or machine review of pipeline data, with optimized photometry only for those events that “look interesting”. The case of KMT-2019-BLG-0842 demonstrates that very low- $q$  planets can give rise to long-lived ( $\gtrsim 10$  hr) low-amplitude ( $\lesssim 0.1$  mag) “bumps” several mag below the peak of high-magnification events. Such planetary signals can be missed from the present search process. Hence, it would seem to be prudent to make optimized photometry of all high-mag events.

Moreover, there is a separate question as to how to marshal follow-up observations in order to probe to the lowest mass-ratio planets possible, i.e., planets of substantially smaller  $q$  than those that have been detected to date. At present, the rule of thumb is to intensively monitor high-magnification events within the FWHM around  $t_0$  because this region contains “most” of the sensitivity to planets. Specifically, “most” translates to a fraction  $\sim (\text{sec}^{-1} 2)/(\pi/2) = 2/3$ . However, planets like KMT-2019-BLG-0842Lb lie in the other (remaining)  $1/3$  of the circle. Although a minority, these planets can give rise to long lived perturbations even when the planet has low mass ratio  $q$ , which can be of exceptional interest. Thus, particularly in very high-magnification events, for which  $t_{\text{eff}}$  is short, follow up observations during  $t_{\text{eff}}$  are less expensive to carry out. Therefore, follow-up observations should be more aggressively pursued for very high-magnification events.

## 6.2. Future High-Resolution Imaging and Spectroscopy

As discussed in Section 5.1, both the photometry and astrometry indicates the possibility that most of the blended light is generated by the lens. This possibility can be tested with high resolution imaging, either with *Hubble Space Telescope* (*HST*) or ground-based adaptive optics (AO) mounted on very large ground-based telescopes. Based on the Bayesian estimates together with the star catalog of Pecaute & Mamajek (2013), we estimate the dereddened lens magnitude in the  $V$ ,  $I$ , and  $H$  band as  $(V, I, H)_{L,0} = (18.78_{-1.90}^{+4.95}, 17.86_{-1.62}^{+3.45}, 16.75_{-1.19}^{+2.63})$ . For the source, we estimate the dereddened magnitude as  $(V, I, H)_{S,0} = (21.14 \pm 0.07, 20.13 \pm 0.04, 18.85 \pm 0.07)$  based on our CMD analysis. These imply that the blended light is  $\sim 2$  magnitudes brighter than the source in the  $I$  band. Therefore, if *HST*  $I$ -band images show that this blended light is closely aligned with the source position, then this will provide strong evidence that the blended light is due to the lens. In principle, such aligned light may originate from a stellar companion to either the source or the lens. However, if the alignment is very close (10–20 mas), then this will rule out the possibility of the lens companion because such a companion would have generated significant deviations over the well-covered peak of

the event. The possibility of the source companion can ultimately be ruled out by re-imaging the field when the source and blend are separated far enough to measure their relative proper motion. Because the source and blend have substantially different colors, such a measurement does not require the two stars to be separately resolved, but can be carried out via a measurement of the astrometric offset between their combined light in different bands (Bennett et al. 2006).

Ground-based AO astrometry will also be useful to check whether the blended light is aligned with the lens. The excess flux from the blend will be somewhat more difficult to be measured in this case because such measurements will be conducted in near-infrared bands (e.g.,  $H$  band), for which there is no direct measurement of the source flux. Nevertheless, based on  $VIH$  color-color relations of nearby field stars, derived from the KMTC42 CMD (Figure 5) and the future AO measurements aligned to standard catalogs, it should be possible to predict the  $H$ -band source flux with reasonably good precision. Even though the blended light is much bluer than the source, it should still be substantially brighter in the  $H$  band than the source (because it is 2 mag brighter in the  $I$  band). Thus, ground-based AO measurements should be feasible.

The Bayesian posterior estimate of the lens-source relative proper motion is  $\mu_{\text{rel}} = 8.4^{+1.7}_{-1.2} \text{ mas yr}^{-1}$  (Table 3). Hence, to obtain the first measurement when the lens and source are still closely aligned, the observations should be made in 2020, if possible.

If the blended light proves to be aligned with the source, then it should be possible to spectroscopically classify the blend (Han et al. 2019). Such an observation may also plausibly measure the radial velocity (RV) offset between the source and the blend. If so, this will provide a second (and earlier) method to rule out the blend as being a companion to the source. Note that, to avoid generating a noticeable bump on the light curve, the blend (as companion) must have a projected separation  $\gtrsim 8 \text{ AU}$ , and so an RV offset of  $\lesssim 15 \text{ km s}^{-1}$  relative to the source.

If the blend proves not to be the lens (or, more precisely, not to be dominated by the lens light), then it should still be possible to characterize the lens with high-resolution followup. Depending on the flux and/or color differences between the source and the lens, this may be achieved even before the images are fully separated, e.g., by measuring the astrometric offset between the combined images in different bands (Bennett et al. 2006) or by measuring the elongation of the combined image (Bhattacharya et al. 2018). Even if the flux ratio is extreme, causing these combined-image techniques to fail, the lens can still be separately imaged when it has moved  $\sim 60 \text{ mas}$  (Batista et al. 2015) from the source, i.e., roughly by 2027. From Figure 7, the lens mass is almost certainly above the hydrogen-burning limit, so this method is almost guaranteed to work if all others fail.

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Table 1. Binary Lens Models

Parameters	Close	Wide
$\chi^2/\text{dof}$	10065.4/10332	10241.5/10332
$t_0$ (HJD')	$8625.914 \pm 0.010$	$8625.914 \pm 0.011$
$u_0$ ( $10^{-3}$ )	$6.565 \pm 0.202$	$5.393 \pm 0.183$
$t_E$ (days)	$43.859 \pm 1.287$	$52.915 \pm 1.708$
$s$	$0.983 \pm 0.013$	$1.063 \pm 0.013$
$q$ ( $10^{-5}$ )	$4.079 \pm 0.289$	$3.901 \pm 0.249$
$\alpha$ (rad)	$0.146 \pm 0.067$	$0.144 \pm 0.072$
$\rho$ ( $10^{-4}$ )	$4.246 \pm 0.966$	$0.282^{+0.913}_{-0.090}$
$f_s$	0.037	0.030
$f_b$	0.179	0.185

Note. —  $\text{HJD}' = \text{HJD} - 2450000$  days

Table 2. Binary Source Model

Parameters	1L2S
$\chi^2/\text{dof}$	10560.1/10031
$t_{0,1}$ (HJD')	$8625.907 \pm 0.013$
$u_{0,1}$ ( $10^{-3}$ )	$5.620 \pm 0.213$
$t_{0,2}$ (HJD')	$8627.886 \pm 0.032$
$u_{0,2}$ ( $10^{-3}$ )	$0.005 \pm 0.247$
$t_E$ (days)	$48.657 \pm 1.710$
$\rho_1$ ( $10^{-4}$ )	$7.6^{+16.0}_{-1.5}$
$\rho_2$ ( $10^{-4}$ )	$32.3 \pm 2.2$
$q_{F,I}$ ( $10^{-2}$ )	$1.291 \pm 0.043$
$f_s$	0.033
$f_b$	0.183

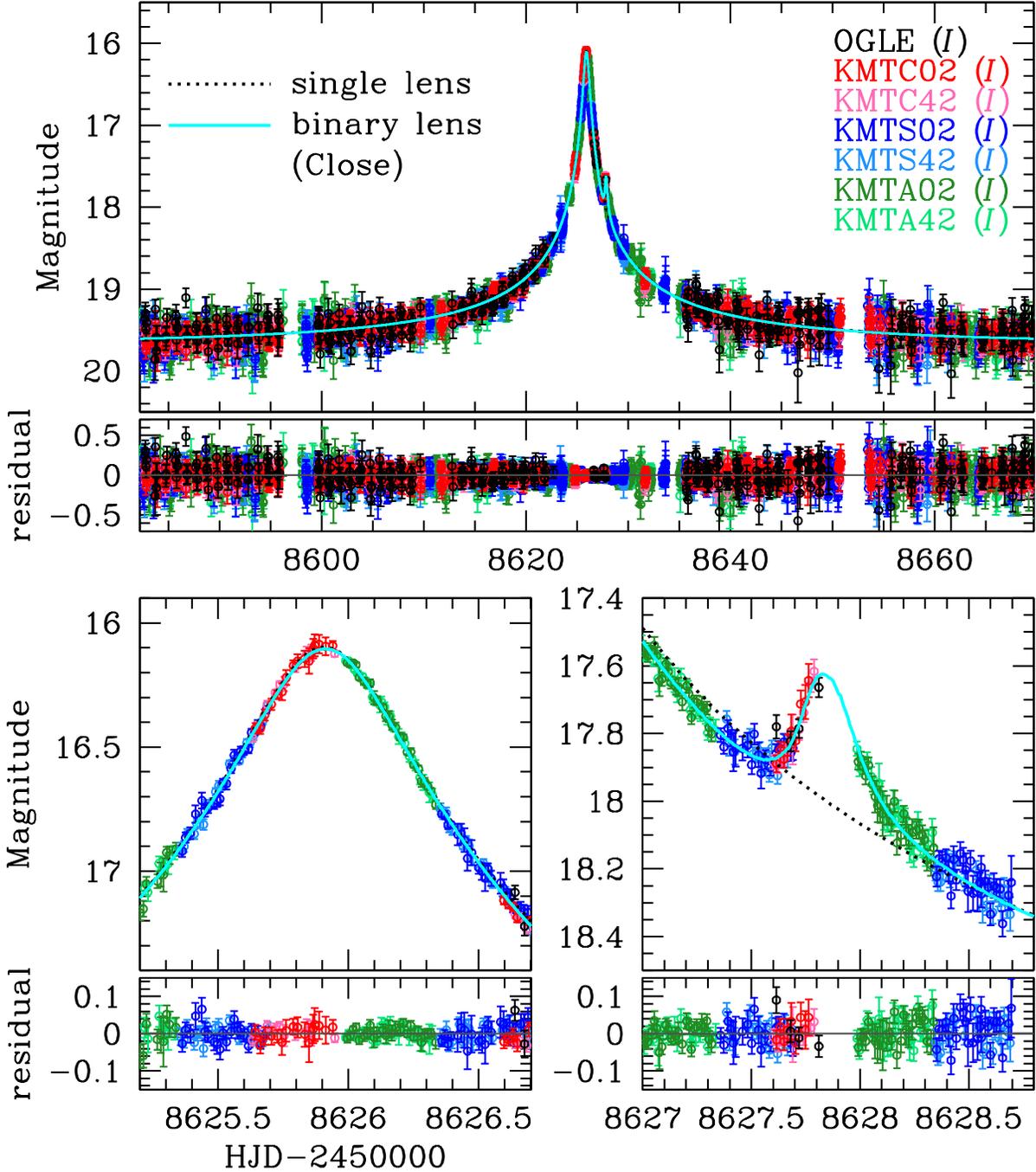


Fig. 1.— Light curve and “close” 2L1S model for KMT-2019-BLG-0842. Zooms of the peak and the anomaly are shown in the lower-left and lower-right panels, respectively. The anomaly lasts about 15 hours despite the very low planet-host mass ratio  $q = 4.1 \times 10^{-5}$  because the anomaly occurs  $\sim 7 \times t_{\text{eff}}$  effective timescales after peak, implying that the trajectory is at an acute angle  $\alpha \simeq \cot^{-1} 7 \sim 8.5^\circ$  relative to the planet-host axis.

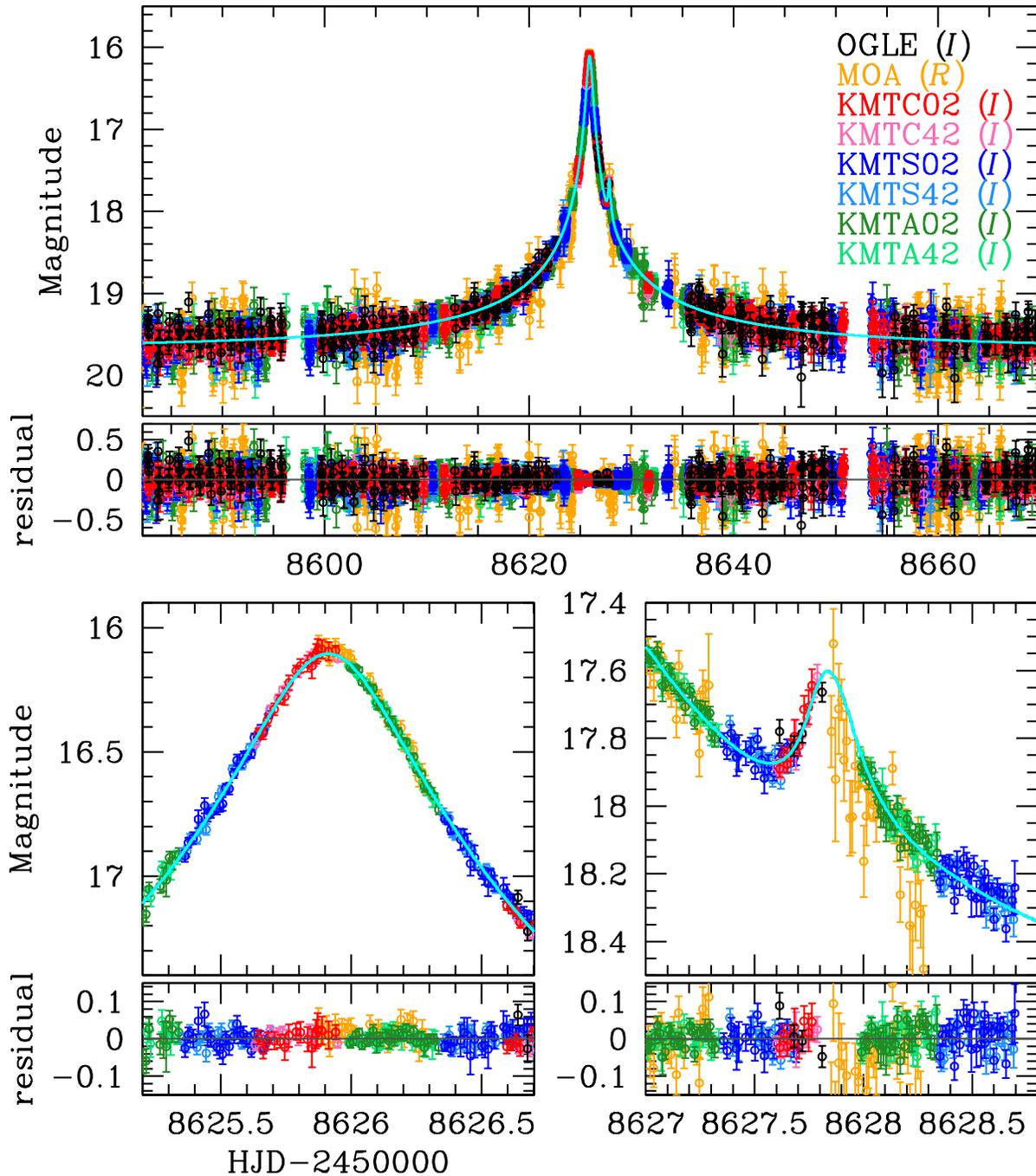


Fig. 2.— Light curve KMT-2019-BLG-0842, as shown in Figure 1, but with MOA data aligned to the best fit model. The MOA data confirm the anomaly but do not contribute to constraining the model and so are not included in the fit.

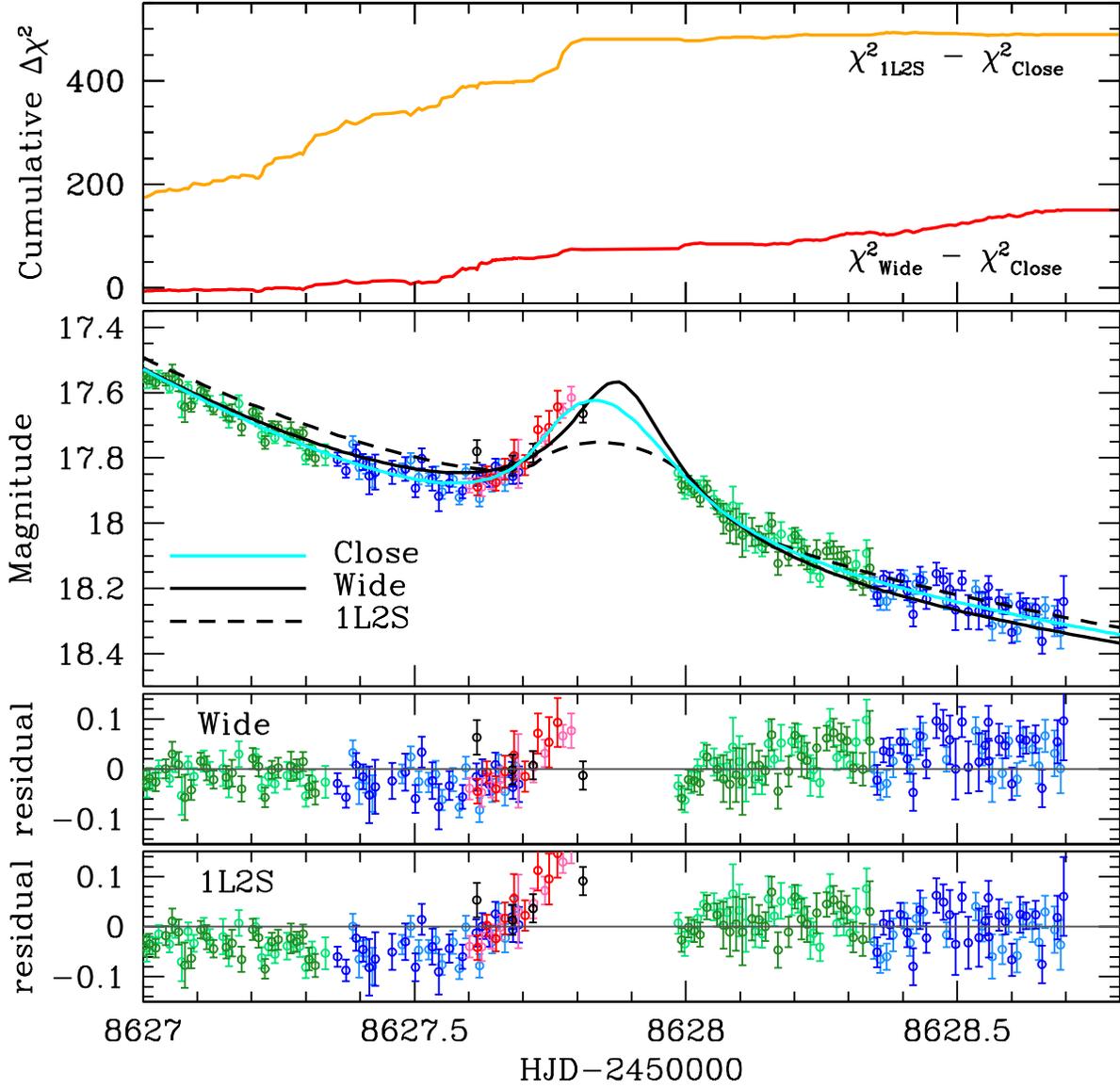


Fig. 3.— Upper panel:  $\Delta\chi^2$  difference relative to the only surviving model (2L1S “close”) of two other possible models, 2L1S “wide” (red) and 1L2S (yellow) for KMT-2019-BLG-0842. The second panel shows the anomaly region of the light curve together with these three models. The lower two panels show the residuals for the two excluded models. See Figure 1 for the corresponding residuals of the surviving (2L1S “close”) model.

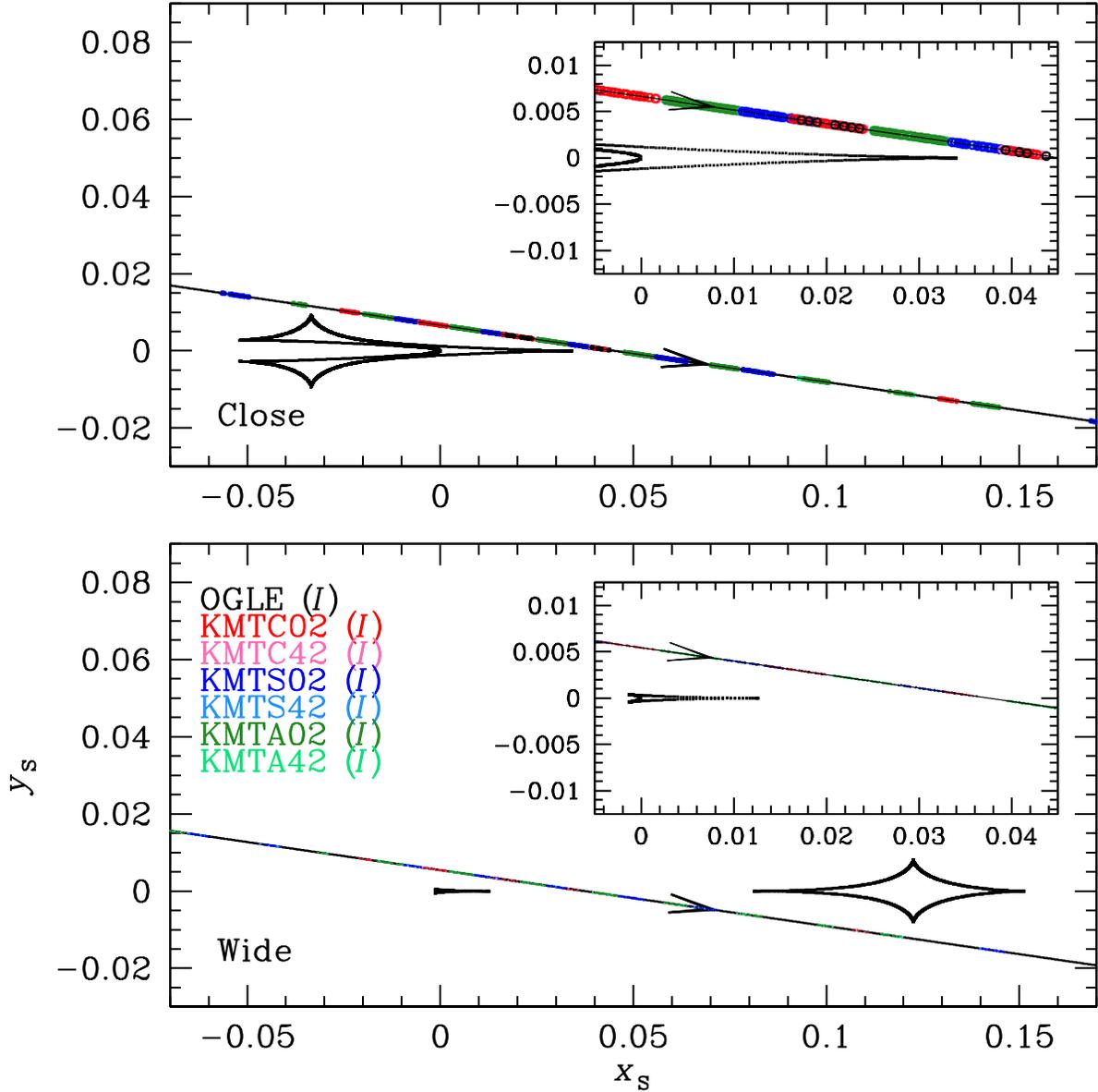


Fig. 4.— Caustic geometries for the two possible 2L1S solutions for KMT-2019-BLG-0842, i.e., “close” (top) and “wide” (bottom). In both cases, the anomaly (see zooms in Figures 1 and 3) is generated when the source passes over the planet-star axis about 1.94 days ( $\simeq 0.044$  Einstein units) after the peak. In both cases, the anomaly is due to a narrow high-magnification ridge that extends from the narrow end of a caustic centered on the host. For the “close” geometry, this caustic has a resonant (six-sided) topology, while for the “wide” geometry it is a central caustic that is connected to the planetary caustic by the ridge. However, the “wide” geometry is excluded by  $\Delta\chi^2 = 176$ . See text and Figure 3.

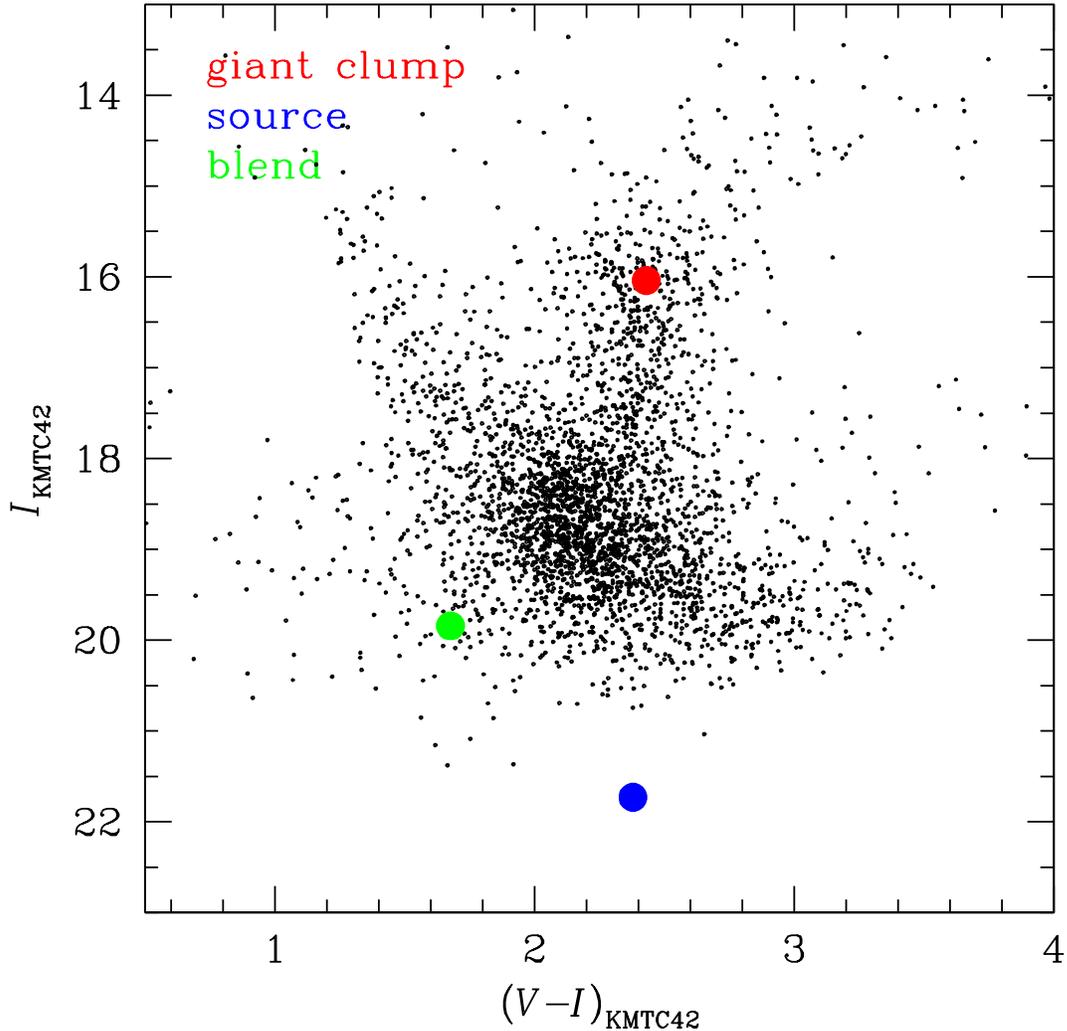


Fig. 5.— Color-magnitude diagram (CMD) for field stars in a  $2'$  square centered on KMT-2019-BLG-0842 derived from pyDIA reductions of KMTC42 data. The positions of the source (blue), the blend (green), and the centroid of the red clump (red) are indicated. The error bars for these determinations are discussed in the text. In particular, the blend color is relatively poorly determined. By cross-matching to the calibrated OGLE-III catalog (Udalski et al. 2008; Szymanski et al. 2011), we find  $I_{\text{calib}} = I_{\text{KMTC42C}} - 0.085$ ,  $(V - I)_{\text{calib}} = (V - I)_{\text{KMTC42C}} - 0.140$ .

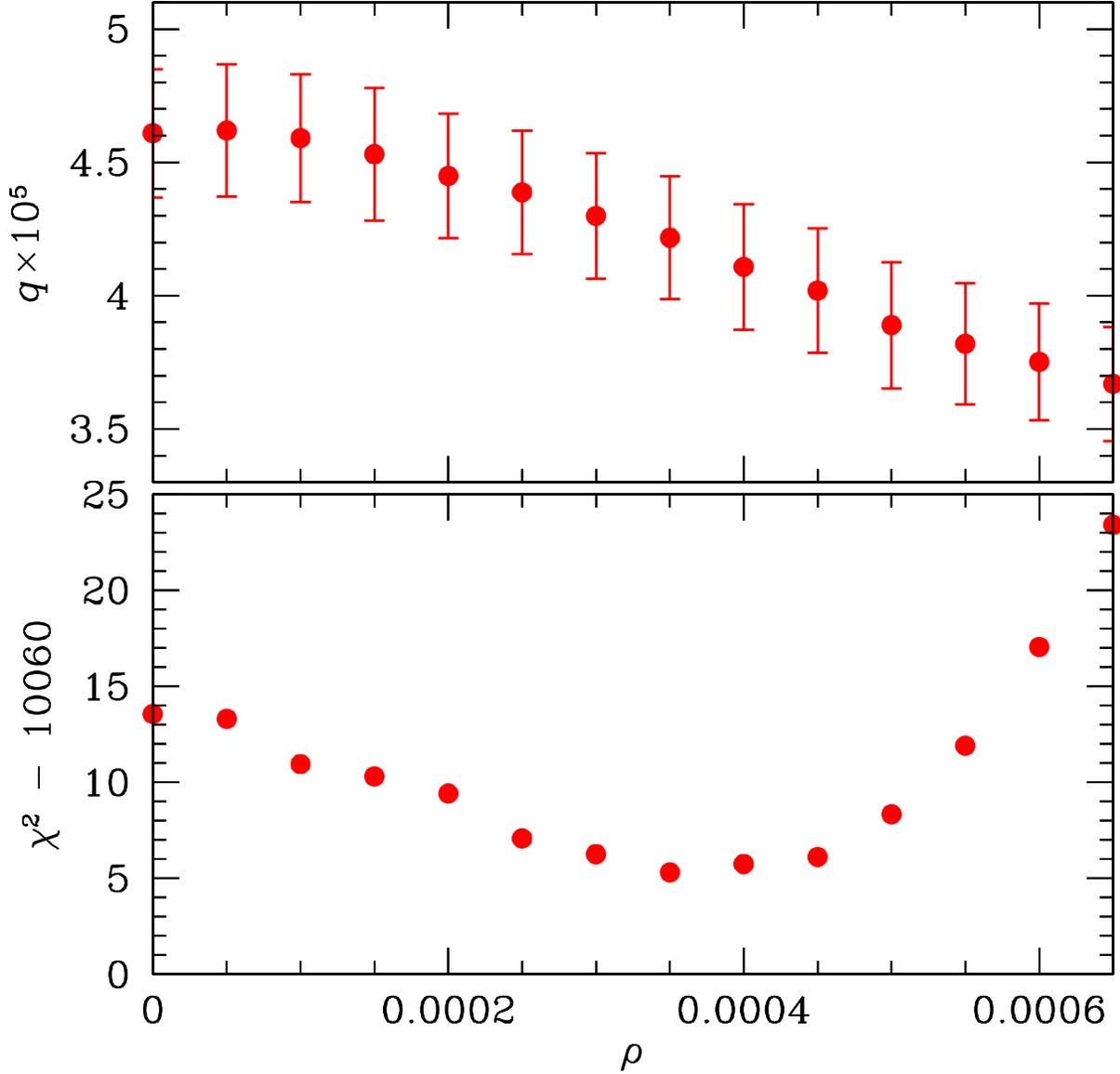


Fig. 6.— Lower panel: minimum values of  $\chi^2$  for a series of MCMC runs with the normalized source size  $\rho$  held fixed at the indicated values, each with 10,000 accepted elements on the chain. The minimum is overall relatively broad but high values (corresponding to small Einstein radii  $\theta_E = \theta_*/\rho$ ) are strongly ruled out. Upper panel: means and standard deviations of the planet-star mass ratio  $q$  for each of the MCMC runs carried out to make the bottom panel. Note that  $q$  is correlated with  $\rho$  over the broad  $\chi^2$  minimum of the latter. This correlation is taken into account in the Bayesian analysis (Section 5).

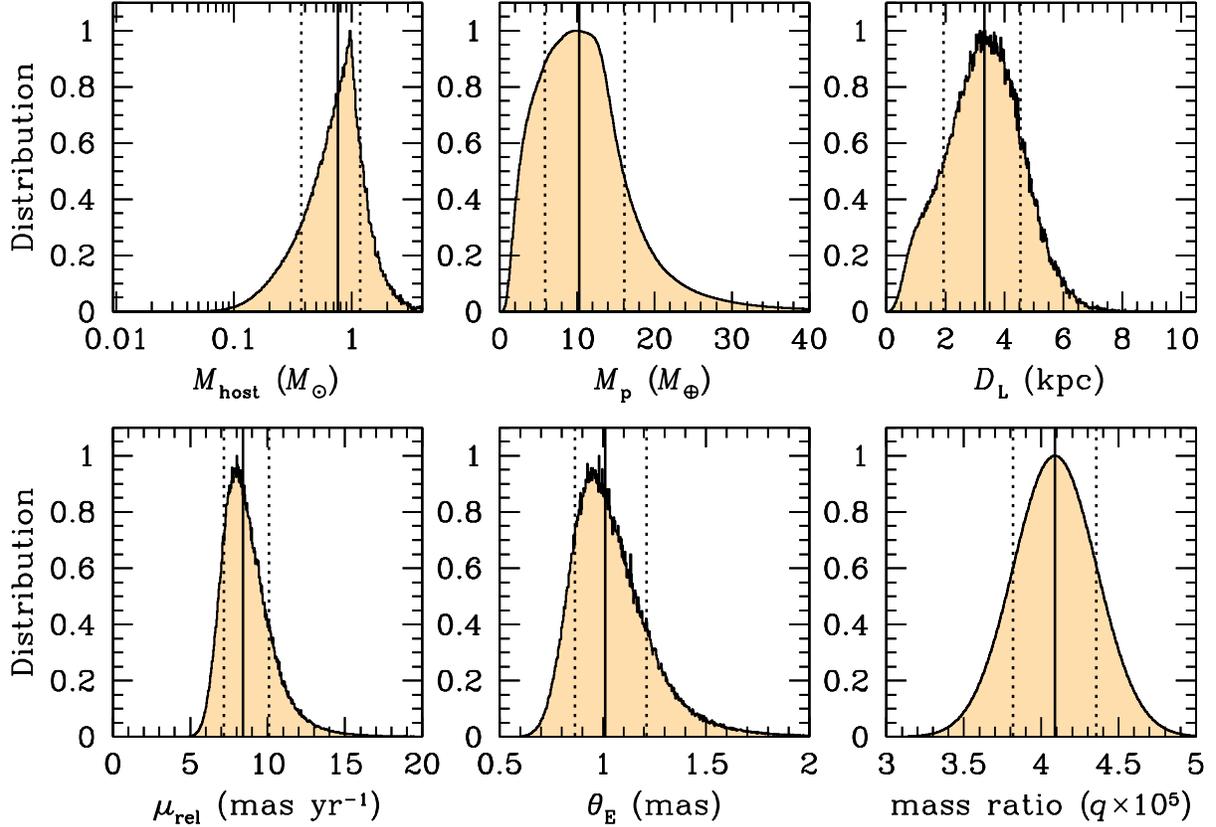


Fig. 7.— Bayesian posteriors for three physical parameters (host mass, planet mass, and system distance), along with three parameters that would normally be derived directly from the light curve and CMD (lens-source relative proper motion  $\mu_{\text{rel}}$ , Einstein radius  $\theta_{\text{E}}$ , and planet-star mass ratio  $q$ ). Bayesian posteriors are required for these three because  $\rho$  is relatively poorly determined and with significantly asymmetric errors. In particular,  $q$  is correlated with  $\rho$  (see Figure 6).

Table 3. Lens properties

Parameters	Values
$q$ ( $10^{-5}$ )	$4.09^{+0.26}_{-0.27}$
$\theta_E$ (mas)	$1.01^{+0.20}_{-0.15}$
$\mu_{\text{rel}}$ (mas yr $^{-1}$ )	$8.42^{+1.68}_{-1.24}$
$M_{\text{host}}$ ( $M_{\odot}$ )	$0.76^{+0.42}_{-0.39}$
$M_{\text{planet}}$ ( $M_{\oplus}$ )	$10.28^{+5.84}_{-5.28}$
$a_{\perp}$ (AU)	$3.31^{+1.38}_{-1.47}$
$D_L$ (kpc)	$3.32^{+1.22}_{-1.39}$