

# KMT-2021-BLG-0284, KMT-2022-BLG-2480, and KMT-2024-BLG-0412: Three microlensing events involving two lens masses and two source stars

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## ABSTRACT

**Aims.** We carried out a project involving the systematic analysis of microlensing data from the Korea Microlensing Telescope Network survey. The aim of this project is to identify lensing events with complex anomaly features that are difficult to explain using standard binary-lens or binary-source models.

**Methods.** Our investigation reveals that the light curves of microlensing events KMT-2021-BLG-0284, KMT-2022-BLG-2480, and KMT-2024-BLG-0412 display highly complex patterns with three or more anomaly features. These features cannot be adequately explained by a binary-lens (2L1S) model alone. However, the 2L1S model can effectively describe certain segments of the light curve. By incorporating an additional source into the modeling, we identified a comprehensive model that accounts for all the observed anomaly features.

**Results.** Bayesian analysis, based on constraints provided by lensing observables, indicates that the lenses of KMT-2021-BLG-0284 and KMT-2024-BLG-0412 are binary systems composed of M dwarfs. For KMT-2022-BLG-2480, the primary lens is an early K-type main-sequence star with an M dwarf companion. The lenses of KMT-2021-BLG-0284 and KMT-2024-BLG-0412 are likely located in the bulge, whereas the lens of KMT-2022-BLG-2480 is more likely situated in the disk. In all events, the binary stars of the sources have similar magnitudes due to a detection bias favoring binary source events with a relatively bright secondary source star, which increases detection efficiency.

**Key words.** gravitational lensing; micro

## 1. Introduction

Since the mid-2010s, the Korea Microlensing Telescope Network (KMTNet) team has been conducting gravitational microlensing experiments using a network of three wide-field telescopes deployed in the Southern Hemisphere (Kim et al. 2016). The data collected from these observations are transmitted almost in real-time to the headquarters of the Korea Astronomy and Space Science Institute (KASI) for processing. A self-developed algorithm (Kim et al. 2018) is employed to identify lensing events, and the light curves of these detected events are meticulously examined for any discontinuous anomalies. These anomalies undergo careful analysis by multiple researchers to

determine their origins and confirm whether they are caused by planetary companions to the lens, which is the primary objective of the experiment. Currently, the KMTNet experiment detects over 3,000 gravitational lensing events annually, with about 10% of these events exhibiting anomalies of various origins (Zang et al. 2021b, 2022). Of these anomalies, approximately 10% are confirmed to be of planetary origin (Gould et al. 2022).

Anomalies in lensing light curves can arise from various factors. The most common cause is the binarity of the lens (Mao & Paczyński 1991). In these binary-lens single-source (2L1S) events, caustics form on the source plane, and the source's passage through these caustics results in light curves that differ from those of single-lens single-source (1L1S) events

**Table 1.** Four-body lensing events.

Event	Type	Lens	Reference
OGLE-2006-BLG-109	3L1S	two planets + host	<a href="#">Gaudi et al. (2008)</a>
OGLE-2012-BLG-0026	3L1S	two planets + host	<a href="#">Han et al. (2013)</a>
OGLE-2018-BLG-1011	3L1S	two planets + host	<a href="#">Han et al. (2019)</a>
OGLE-2019-BLG-0468	3L1S	two planets + host	<a href="#">Han et al. (2022c)</a>
KMT-2021-BLG-1077	3L1S	two planets + host	<a href="#">Han et al. (2022a)</a>
KMT-2021-BLG-0240	3L1S	two planets + host	<a href="#">Han et al. (2022b)</a>
OGLE-2006-BLG-284	3L1S	planet + binary host	<a href="#">Bennett et al. (2020)</a>
OGLE-2007-BLG-349	3L1S	planet + binary host	<a href="#">Bennett et al. (2016)</a>
OGLE-2008-BLG-092	3L1S	planet + binary host	<a href="#">Poleski et al. (2014)</a>
OGLE-2016-BLG-0613	3L1S	planet + binary host	<a href="#">Han et al. (2017)</a>
OGLE-2018-BLG-1700	3L1S	planet + binary host	<a href="#">Han et al. (2020)</a>
KMT-2020-BLG-0414	3L1S	planet + binary host	<a href="#">Zang et al. (2021a)</a>
OGLE-2023-BLG-0836	3L1S	planet + binary host	<a href="#">Han et al. (2024b)</a>
KMT-2021-BLG-1122	3L1S	triple stellar lens	<a href="#">Han et al. (2023b)</a>
OGLE-2016-BLG-0882	2L2S	binary stellar lens	<a href="#">Shin et al. (2024)</a>
OGLE-2016-BLG-1003	2L2S	binary stellar lens	<a href="#">Jung et al. (2017)</a>
KMT-2019-BLG-0797	2L2S	binary stellar lens	<a href="#">Han et al. (2021b)</a>
KMT-2021-BLG-1898	2L2S	binary stellar lens	<a href="#">Han et al. (2022d)</a>
OGLE-2018-BLG-0584	2L2S	binary stellar lens	<a href="#">Han et al. (2023a)</a>
KMT-2018-BLG-2119	2L2S	binary stellar lens	<a href="#">Han et al. (2023a)</a>
MOA-2010-BLG-117	2L2S	planetary lens	<a href="#">Bennett et al. (2018)</a>
OGLE-2017-BLG-0448	2L2S	planetary lens	<a href="#">Shin et al. (2024)</a>
KMT-2018-BLG-1743	2L2S	planetary lens	<a href="#">Han et al. (2021a)</a>
KMT-2021-BLG-1547	2L2S	planetary lens	<a href="#">Han et al. (2023c)</a>
OGLE-2015-BLG-1459	1L3S	single lens	<a href="#">Hwang et al. (2018)</a>

([Schneider & Weiss 1986](#)). These caustics exhibit complex patterns depending on the separation and mass ratio between the lens components and, along with various source trajectories, produce a wide range of anomaly patterns ([Erdl & Schneider 1993](#); [Han 2006](#); [Cassan 2008](#); [Gaudi 2012](#)). Another important cause of anomalies is the binarity of the source. In these single-lens binary-source (1L2S) cases, the event's light curve is the superposition of the lensing events occurring for each individual source, which leads to deviations in the lensing light curves ([Griest & Hu 1992](#); [Di Stefano & Esin 1995](#); [Han & Gould 1997](#); [Dominik 1998](#); [Han & Jeong 1998](#)).

In some rare cases, the observed anomalies cannot be explained by a three-body lensing model (lens plus source) and require a four-body lensing model, which includes an additional lens or source component. To date, 14 events have been identified as 3L1S events, in which the lens consists of three masses. Of these, six events correspond to planetary systems consisting of a host star and two planets, seven involve binary systems that include a planet, and the remaining event has been identified as a triple stellar system composed of three stars. Another type of four-body event occurs when both the lens and the source are binaries, known as a 2L2S event. So far, ten such events have been identified, four of which involve binary lenses that include planetary companions. In Table 1, we provide a summary of some of the known four-body lensing events, along with a brief description of the corresponding lens systems.

We conducted a project in which KMTNet data were systematically analyzed to reveal the nature of events with complex anomalous features that are challenging to explain. In the initial phase, we examined lensing events from the KMTNet survey that exhibited anomalies in their light curves, which were then independently analyzed by multiple modelers. Most of these anomalies were successfully explained using either 2L1S or 1L2S models. However, for a small subset of events

in which these three-body models could not account for the anomalies, we carried out more detailed analyses using advanced models. These analyses revealed that the difficulty in explaining the anomalies in some events was due to significant higher-order effects, such as lens orbital motion, as seen in events like OGLE-2018-BLG-0971, MOA-2023-BLG-065, and OGLE-2023-BLG-0136 ([Han et al. 2024a](#)). In other cases, the anomalies were caused by the presence of an additional source or lens component, as shown in the 2L2S and 3L1S events summarized in Table 1. It is important to note that the list of four-body lensing events in the table is not complete, as the nature of the anomalies in some events remains unclear, and more advanced models are currently being tested to interpret them. In this work, we present analyses of three lensing events with complex anomalies in their light curves that were successfully interpreted using 2L2S models.

This paper is organized as follows. In Sect. 2 we detail the observations conducted to collect the data used for our analyses, including a brief description of the instrumentation. We also outline the procedures for data reduction and photometry. Section 3 begins with the definition of the lensing parameters used in our modeling across different interpretations of lensing events. We then describe the procedure of light curve modeling employed to determine these parameters. Subsequent subsections present the analysis process and results for each individual event. Each subsection discusses specific anomalies observed in the event's light curve, provides model parameters derived from the analysis, and outlines the configuration of the lens system. In Sect. 4 we identify the source stars associated with each event and estimate the angular Einstein radius based on the derived information on the source star. Section 5 outlines the physical quantities of the lens determined based on the observables of individual events. Lastly, Sect. 6 summarizes our findings and presents the conclusions drawn from the study.

**Table 2.** Coordinates, extinction, and baseline magnitude.

Event	(RA, Dec) <sub>J2000</sub>	( <i>l</i> , <i>b</i> )	<i>A<sub>I</sub></i>	<i>I</i> <sub>base</sub>	Other ID
KMT-2021-BLG-0284	(17:58:03.64, -32:18:10.30)	(−1°5363, −4°0171)	1.48	19.49	MOA-2021-BLG-072
KMT-2022-BLG-2480	(17:35:06.77, -29:54:43.27)	(−2°0414, 1°4213)	2.71	19.68	
KMT-2024-BLG-0412	(17:55:48.89, -29:54:40.79)	(0°2984, −2°4062)	1.54	18.79	OGLE-2024-BLG-0496

## 2. Observations and data

The three lensing events analyzed in this work are KMT-2021-BLG-0284, KMT-2022-BLG-2480, and KMT-2024-BLG-0412. In Table 2, we list the equatorial and Galactic coordinates of the events, along with the *I*-band extinction (*A<sub>I</sub>*) toward the field and the baseline magnitude (*I*<sub>base</sub>). The anomalous nature of the light curves for these events was identified from the inspection of the data collected by the KMTNet survey. This survey is conducted using three identical wide-field telescopes strategically deployed in the Southern Hemisphere for continuous observation. Each telescope is located at the Siding Spring Observatory in Australia (KMTA), the Cerro Tololo Inter-American Observatory in Chile (KMTC), and the South African Astronomical Observatory in South Africa (KMTS). Each KMTNet telescope features a 1.6-meter aperture, and the mounted camera covers a field of view of 4 square degrees.

Among the analyzed events, KMT-2021-BLG-0284 was additionally observed by the Microlensing Observations in Astrophysics (MOA; Bond et al. 2001; Sumi et al. 2003) survey, and KMT-2024-BLG-0412 was observed by the Optical Gravitational Lensing Experiment (OGLE; Udalski et al. 2015). The ID references for these events in the MOA and OGLE surveys are presented in Table 2. The MOA survey operates with a 1.8 m telescope mounted with 2.2 square degree field camera located at Mt. John University Observatory in New Zealand, while the OGLE survey uses a 1.6 m telescope equipped with a 1.4 square-degree field camera located at Las Campanas Observatory in Chile. In our analysis, we incorporated data obtained from these supplementary observations. Observations from the KMTNet and OGLE surveys were primarily conducted in the *I* band, while the MOA survey used a customized MOA-*R* band with a wavelength range of 609–1109 nm.

The reduction of the data and the photometry of the events were carried out using photometry pipelines tailored to each survey group: the KMTNet data utilized the Albrow et al. (2009) pipeline, OGLE data used the Udalski (2003) pipeline, and MOA data were processed with the Bond et al. (2001) pipeline. To optimize the data, the KMTNet dataset underwent a re-reduction process using the code developed by Yang et al. (2024). For each dataset, the error bars from the photometry pipelines were recalibrated to align with the data scatter and to normalize the  $\chi^2$  value per degree of freedom to unity. This normalization process followed the method detailed in Yee et al. (2012).

## 3. Light curve analyses

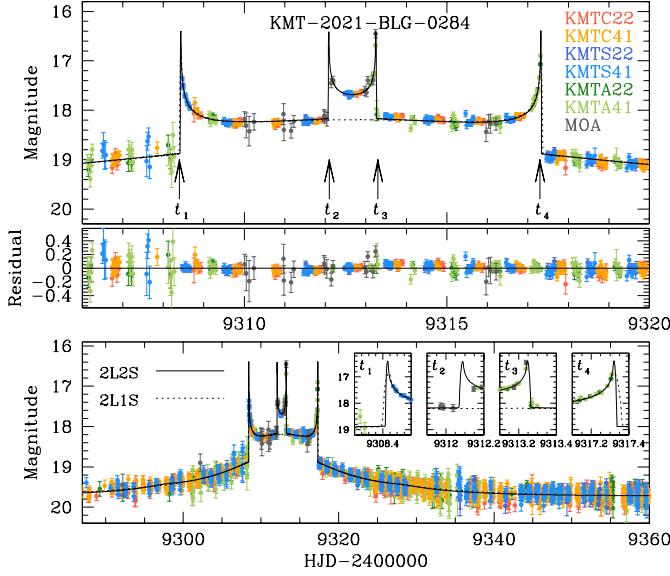
The light curve of a lensing event produced by a single mass exhibits a smooth and symmetrical shape with respect to the time of the closest lens-source approach (Paczynski 1986). This light curve is characterized by three parameters: the time of closest approach between the lens and the source (*t*<sub>0</sub>), the separation at that time (*u*<sub>0</sub>), and the timescale of the event (*t*<sub>E</sub>). The event timescale is defined as the time it takes for the source to traverse the Einstein radius ( $\theta_E$ ) of the lens, with the impact parameter scaled by  $\theta_E$ .

The departure from the 1L1S magnification pattern in a 2L1S lensing event is primarily caused by caustics. Caustics are locations at which the lensing magnification of a point source becomes infinite. These caustics form closed curves made up of concave segments. The number of these closed curves varies from one to three, depending on the separation and mass ratio between the lens components. Representative anomalies in lensing light curves caused by caustics include spike features occurring as the source crosses a fold of the caustic and bump features as it approaches a cusp of the caustic. Caustic spikes manifest as pairs due to the closed structure of the caustic curve, with the magnification pattern between them typically showing a U-shaped profile. To describe anomalies induced by caustics of a 2L1S event, additional lensing parameters are required. These parameters are (*s*, *q*,  $\alpha$ ,  $\rho$ ). The first two parameters represent the projected separation and mass ratio between the lens components (*M*<sub>1</sub> and *M*<sub>2</sub>). The third parameter denotes the angle between the *M*<sub>1</sub>–*M*<sub>2</sub> axis and the direction of the source motion relative to the lens. Here, the separation is scaled by  $\theta_E$ . The last parameter is defined as the ratio of the angular source radius ( $\theta_*$ ) to the angular Einstein radius. This parameter characterizes the deformation of the lensing light curve by finite source effects during caustic crossings or approaches. This parameter is essential for modeling a subset of 1L1S events with very high magnifications, where the lens comes extremely close to the source or crosses over the surface of the source star.

In a 2L2S event, which includes a secondary source (*S*<sub>2</sub>) alongside the primary source (*S*<sub>1</sub>), the lensing anomaly can deviate further from that of a 2L1S event. Consequently, analyzing a 2L2S event requires additional parameters to characterize the second source: (*t*<sub>0,2</sub>, *u*<sub>0,2</sub>, *q<sub>F</sub>*). These parameters represent the closest approach time and impact parameter of *S*<sub>2</sub>, as well as the flux ratio between the two sources.

Based on the caustic spikes commonly observed in the light curves of the analyzed events, we initially conducted an analysis based on the 2L1S model. During this analysis, we searched for the binary lens parameters (*s*, *q*), for which the lensing magnification changes discontinuously with the variation of the parameters, using a grid approach, while the remaining parameters, for which lensing magnification smoothly varies with the parameter variation, were found using a downhill approach. For the downhill approach, we utilized the Markov chain Monte Carlo algorithm. Subsequently, we refined the model by allowing all parameters to vary.

For the analyzed events, all of which displayed highly complex light curves with three or more anomaly features, it was found that the lensing light curves could not be adequately described by a 2L1S model alone. Subsequently, we investigated whether the 2L1S model could sufficiently describe segments of the light curve while excluding specific anomaly features. If this approach was feasible, we then considered a 2L2S model by introducing an additional source to determine if the second source could account for the omitted segments of the light curve. We also considered the possibility of explaining the unexplained portion by introducing an additional lens component. However,



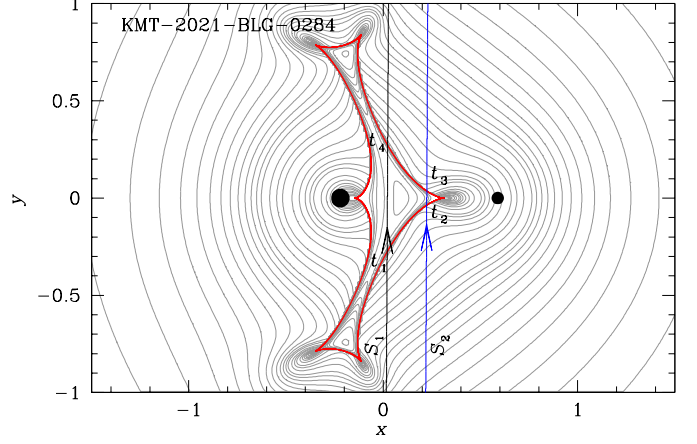
**Fig. 1.** Lensing light curve of KMT-2021-BLG-0284. The lower panel provides an overall view, while the upper panel offers a zoomed-in perspective of the anomaly region. Arrows labeled  $t_1$ ,  $t_2$ ,  $t_3$ , and  $t_4$  indicate the times of the caustic-crossing features. Insets within the lower panel present an enlarged view around each individual caustic peak. The colors of the data points correspond to the telescopes and observation fields, as indicated in the legend. The solid curve overlaying the data points represents the best-fit 2L2S model, while the dotted curve depicts a 2L1S model derived by fitting the data, excluding those around  $t_2$  and  $t_3$ .

3L1S models failed to account for the anomalies in all of the events analyzed.

### 3.1. KMT-2021-BLG-0284

The lensing event KMT-2021-BLG-0284 was initially detected by the KMTNet survey on April 6, 2021, two days after the first caustic peak. This date corresponds to the abridged heliocentric Julian date  $\text{HJD}' \equiv \text{HJD} - 2450000 = 9310$ . Figure 1 presents the light curve of the event. It features an intricate magnification pattern with four caustic spikes occurring at approximately  $\text{HJD}' = 9308.4$  ( $t_1$ ),  $9312.1$  ( $t_2$ ),  $9313.3$  ( $t_3$ ), and  $9317.3$  ( $t_4$ ). The source was situated in the narrow strip region for which the KMTNet BLG22 and BLG41 fields overlap. The observation cadence was 1.0 hour for the BLG22 field and 0.5 hour for the BLG41 field. One day after the KMTNet announcement of event detection, the MOA group also reported the detection of the event with a reference ID MOA-2021-BLG-072. As the event progressed, it exhibited three additional caustic-crossing features.

The anomaly pattern in the light curve was challenging to interpret using a 2L1S model. Based on its appearance, the first and fourth features (at  $t_1$  and  $t_4$ ) seem to form a pair of caustic spikes caused by the source star entering and exiting a caustic. Similarly, the second and third features (at  $t_2$  and  $t_3$ ) appear to be another pair of caustic spikes. The presence of this second pair in the region between the features of the first caustic pair strongly suggests a departure of the lens system from a 2L1S configuration. Based on this, Yuki Hirao of the MOA group released a triple lens (3L1S) model on April 16, 2021. Although this model roughly outlined the overall anomaly pattern, it left noticeable residuals. On April 21, 2021, Cheongho Han proposed another



**Fig. 2.** Lens system configuration of KMT-2021-BLG-0284. The red figures composed of concave curves represents the caustic. The two black filled dots indicate the positions of the lens components; the bigger one represents the heavier component. The black and blue arrowed lines represent the trajectories of the primary ( $S_1$ ) and secondary ( $S_2$ ) source stars, respectively. The arrow tips on the trajectories are shown at the same moment in time. The points marked as  $t_1$ ,  $t_2$ ,  $t_3$ , and  $t_4$  on the source trajectories represent the source positions at the times of the anomalies marked in Fig. 1. Gray curves encompassing the caustic are equi-magnification contours.

**Table 3.** Best-fit parameters of KMT-2021-BLG-0284.

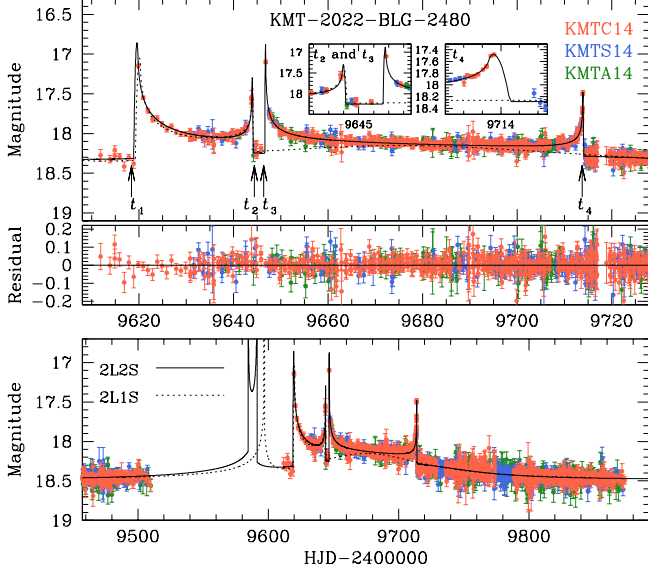
Parameter	Value
$t_{0,1}$ (HJD')	$9312.917 \pm 0.062$
$u_{0,1}$	$-0.0217 \pm 0.00329$
$t_{0,2}$ (HJD')	$9312.650 \pm 0.027$
$u_{0,2}$	$-0.2240 \pm 0.0051$
$t_E$ (days)	$16.25 \pm 0.29$
$s$	$0.8095 \pm 0.0080$
$q$	$0.3742 \pm 0.0096$
$\alpha$ (rad)	$1.5762 \pm 0.0083$
$\rho_1$ ( $10^{-3}$ )	$< 0.1$
$\rho_2$ ( $10^{-3}$ )	—
$q_F$	$0.766 \pm 0.01$

**Notes.**  $\text{HJD}' = \text{HJD} - 2450000$ .

interpretation based on a 2L2S model. Upon reanalysis using reduced data conducted after the event concluded, it was found that the 2L2S model significantly better explained the observed data than the 3L1S model.

The model curve of the 2L2S solution and its residual are displayed in Fig. 1. The estimated binary lens parameters are  $(s, q) \sim (0.81, 0.37)$ , and the event timescale is  $t_E \sim 16.3$  days. The complete lensing parameters of the solution are listed in Table 3. As illustrated in the four insets of the lower panel, none of the four caustic crossings were sufficiently resolved to reliably measure the normalized source radii for the first source ( $\rho_1$ ) or the second source ( $\rho_2$ ), with only a loose upper limit for  $\rho_1$  being constrained. The estimated flux ratio between the primary and secondary source stars is  $q_F \sim 0.77$ .

Figure 2 illustrates the lens system configuration, depicting the source trajectories of  $S_1$  and  $S_2$  relative to the positions of the lens and caustic. The solution indicates that the lens creates a resonant caustic, elongated in a direction perpendicular to the  $M_1$ – $M_2$  axis. The primary source passed through the region between the lens components, crossing the caustic at  $t_1$  and  $t_4$ .



**Fig. 3.** Light curve of the lensing event KMT-2022-BLG-2480. The notations are the same as those in Fig. 1. The insets in the upper panel show enlargements of the regions around  $t_2$ ,  $t_3$ , and  $t_4$ .

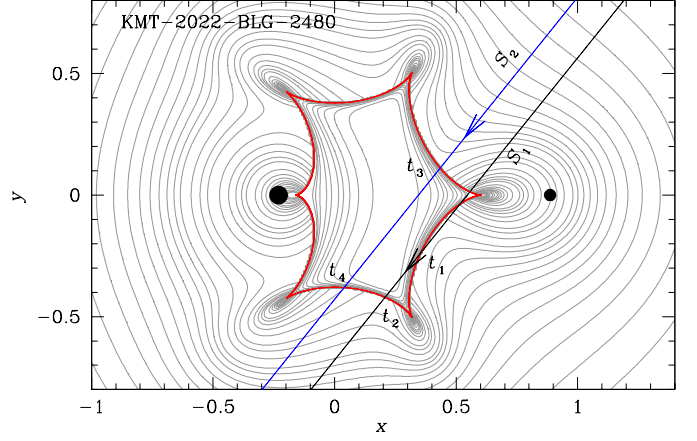
Meanwhile, the secondary source approached the caustic with a larger impact parameter, crossing the tip of the right-side caustic at  $t_2$  and  $t_3$ .

### 3.2. KMT-2022-BLG-2480

The lensing event KMT-2022-BLG-2480 was detected through the EventFinder algorithm (Kim et al. 2018) and observed exclusively by the KMTNet group. The lensing-induced magnification of the source flux started before the 2022 season and continued through to the end of the 2024 season. The source was located in the KMTNet BLG14 field, which was observed with an hourly cadence. Figure 3 displays the lensing light curve of event. Similar to that of KMT-2021-BLG-0284, it displays complex magnification pattern characterized by four caustic spikes occurring at around  $\text{HJD}' = 9618.5$  ( $t_1$ ),  $9644.4$  ( $t_2$ ),  $9646.6$  ( $t_3$ ), and  $9713.8$  ( $t_4$ ). The difference from the event KMT-2021-BLG-0284 is that the two pairs of caustic-crossing features are not overlapping but separated.

Upon analyzing the light curve, we found that the anomaly pattern of KMT-2022-BLG-2480 could not be adequately described by a 2L1S configuration. In order to assess whether a 2L1S model could fit a portion of the light curve, we conducted an additional modeling excluding the data between  $t_3$  and  $t_4$ . This analysis yielded a model that explains the anomaly patterns at  $t_1$  and  $t_2$ . Figure 3 illustrates the model curve of this 2L1S solution. Subsequently, we conducted 2L2S modeling to further elucidate the other caustic features at  $t_3$  and  $t_4$ . Through this, we identified a model that comprehensively describes all observed anomaly features. The 2L2S model found from the analysis and its residual are presented in Fig. 3. According to this model, there is another set of caustic features located around  $\text{HJD}' \sim 9685$ , which falls before the observation period and therefore was not observed.

Table 4 lists the lensing parameters of the 2L2S solution. The estimated binary-lens parameters are  $(s, q) \sim (1.1, 0.35)$ . The event timescale,  $t_E \sim 107$  days, is significantly longer than the typical 10–20 day timescales of lensing events produced by



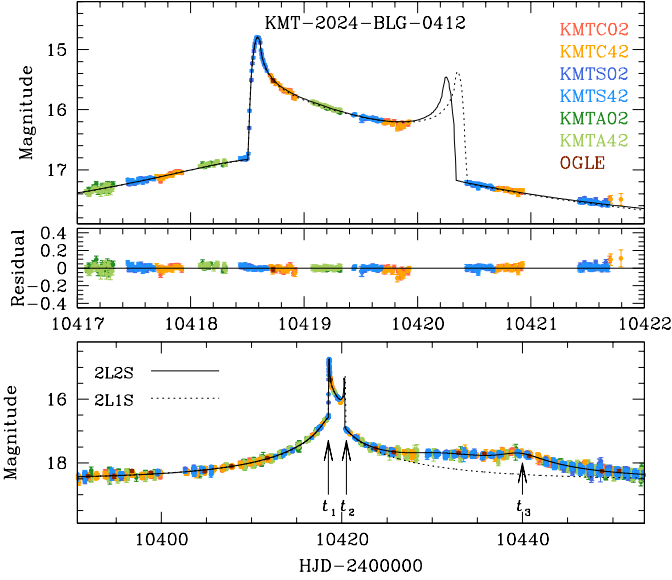
**Fig. 4.** Configuration of the KMT-2022-BLG-2480 lens system. Notations are the same as those in Fig. 2.

**Table 4.** Best-fit parameters of KMT-2022-BLG-2480.

Parameter	Value
$t_{0,1}$ (HJD')	$9623.007 \pm 0.856$
$u_{0,1}$	$0.4254 \pm 0.0046$
$t_{0,2}$ (HJD')	$9685.002 \pm 0.476$
$u_{0,2}$	$0.2689 \pm 0.0027$
$t_E$ (days)	$106.64 \pm 0.74$
$s$	$1.1173 \pm 0.0043$
$q$	$0.346 \pm 0.011$
$\alpha$ (rad)	$-0.893 \pm 0.013$
$\rho_1$ ( $10^{-3}$ )	—
$\rho_2$ ( $10^{-3}$ )	$0.89 \pm 0.06$
$q_F$	$0.682 \pm 0.019$

low-mass stars (Han & Gould 2003). Among the four caustics, only the last caustic is partially resolved. The first two spikes at  $t_1$  and  $t_2$  were produced by the caustic crossings of the primary source, and thus its normalized source radius could not be constrained. The normalized radius of the second source, derived from the partially resolved last peak, is  $\rho_2 \sim 0.9 \times 10^{-3}$ . The flux from the source generating the second set of caustic spikes ( $S_2$ ) is estimated to be 0.68 times less than the flux from the source producing the first set of spikes ( $S_1$ ). In events with a long timescale, signals caused by parallax effects, which arise from the deviation of the observer's motion from rectilinear due to Earth's orbit (Gould 1992), can often be detected in the light curve. However, in the case of the KMT-2022-BLG-2480 event, it was difficult to clearly detect the parallax effect due to significant photometric errors caused by the faintness of the source stars.

Figure 4 shows the configuration of the KMT-2022-BLG-2480 lens system. The binary lens forms a resonant caustic with six folds. The primary source crossed the caustic four times: it initially entered and exited the caustic by passing through the right on-axis cusp, then reentered and exited again through the lower right cusp. The first two crossings produced an unobserved pair of caustic spikes, while the latter two crossings resulted in spikes at  $t_1$  and  $t_2$ . The second source diagonally passed through the caustic, producing a spike at  $t_3$  upon entry and another at  $t_4$  upon exit.



**Fig. 5.** Light curve of the lensing event KMT-2024-BLG-0412.

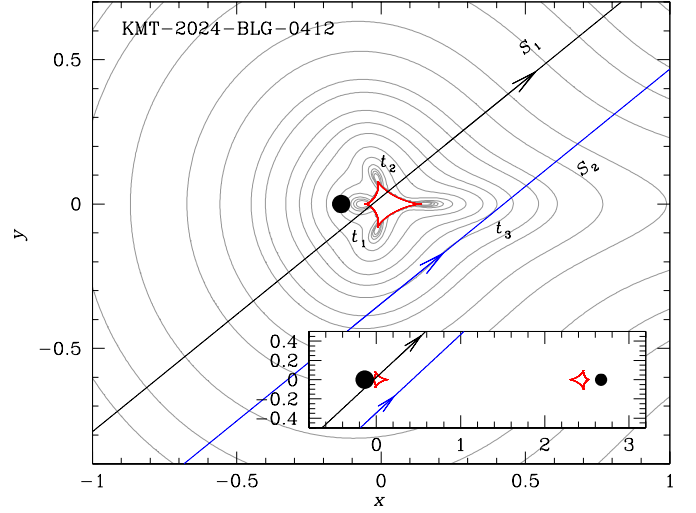
### 3.3. KMT-2024-BLG-0412

The lensing event KMT-2024-BLG-0412 was first detected by the KMTNet group on April 5, 2024 (HJD' = 10405) during its rising stage. The source lay in the overlapping region of the KMTNet prime fields BLG02 and BLG42, each observed with a 0.5-hour cadence, resulting in a combined cadence of 0.25 hours. The event was later identified by the OGLE survey, which observed it with a relatively low cadence. The OGLE ID reference of the event is OGLE-2024-BLG-0496. The light curve of the event is displayed in Fig. 5. On HJD' = 10418.5 ( $t_1$ ), the event's light curve exhibited a sharp rise due to a caustic crossing. Based on the U-shaped pattern, another spike was expected around  $t_2 = 10420.5$ , although this was not observed due to bad weather at the Australian site. After the caustic exit, the light curve did not descend but remained steady, then reached another weak peak around HJD' = 10440 ( $t_3$ ) before returning to the baseline.

As with the two previous events, the light curve of the KMT-2024-BLG-0412 event was difficult to explain with a 2L1S model. However, modeling conducted with data excluding the region around the  $t_3$  bump revealed that the caustic feature could be well described by a 2L1S model. The model curve of this 2L1S solution is shown in Fig. 5. From a subsequent modeling based on the 2L2S interpretation, we found a solution that explains all the anomaly features in the lensing light curve. A 3L1S interpretation does not yield a model with a fit equivalent to that of the 2L2S solution.

Table 5 presents the lensing parameters obtained from the 2L2S modeling. We identified a pair of solutions resulting from the close-wide degeneracy. The parameters describing the binary lens are  $(s, q)_{\text{close}} \sim (0.56, 0.26)$  for the close solution and  $(s, q)_{\text{wide}} \sim (2.79, 0.62)$  for the wide solution. It was found that the wide solution provides a significantly better fit than the close solution, with  $\Delta\chi^2 = 351.4$ . Therefore, subsequent analysis is based on the wide solution. The event timescale was measured as  $t_E \sim 22$  days.

The lens system configuration of KMT-2024-BLG-0412 is shown in Fig. 6. The binary lens system produced two sets of caustics: one located near the heavier lens component ( $M_1$ ) and



**Fig. 6.** Configuration of the lens system KMT-2024-BLG-0412. The inset provides an overall view, while the main panel presents a zoomed-in view of the area surrounding the heavier lens component.

**Table 5.** Best-fit parameters of KMT-2024-BLG-0412.

Parameter	Close	Wide
$\chi^2$	4877.6	4526.2
$t_{0,1}$ (HJD')	$10419.210 \pm 0.004$	$10419.307 \pm 0.011$
$u_{0,1}$	$2.240 \pm 0.065$	$1.872 \pm 0.029$
$t_{0,2}$ (HJD')	$10436.513 \pm 0.038$	$10433.324 \pm 0.093$
$u_{0,2}$	$-0.2852 \pm 0.0035$	$-0.2705 \pm 0.0059$
$t_E$ (days)	$16.34 \pm 0.07$	$21.80 \pm 0.22$
$s$	$0.563 \pm 0.001$	$2.794 \pm 0.016$
$q$	$0.262 \pm 0.003$	$0.624 \pm 0.024$
$\alpha$ (rad)	$2.3531 \pm 0.0033$	$2.4579 \pm 0.0046$
$\rho_1$ ( $10^{-3}$ )	$3.36 \pm 0.02$	$2.43 \pm 0.03$
$\rho_2$ ( $10^{-3}$ )	—	—
$q_F$	$0.814 \pm 0.013$	$1.118 \pm 0.025$

another near the other lens component ( $M_2$ ). The primary source first approached the lens, followed by the secondary source trailing behind. Caustic spikes at  $t_1$  and  $t_2$  were generated by the primary source star's crossings over the caustic lying near  $M_1$ , while the bump around  $t_3$  was produced by the approach of the secondary source to the protruding cusp of the caustic. Consequently, the normalized source radius of  $S_1$  was measured, whereas that of  $S_2$  could not be constrained. The estimated flux ratio  $q_F \sim 1.1$  suggests that the source star crossing the caustic ( $S_1$ ) is slightly fainter than the source star that does not cross the caustic ( $S_2$ ).

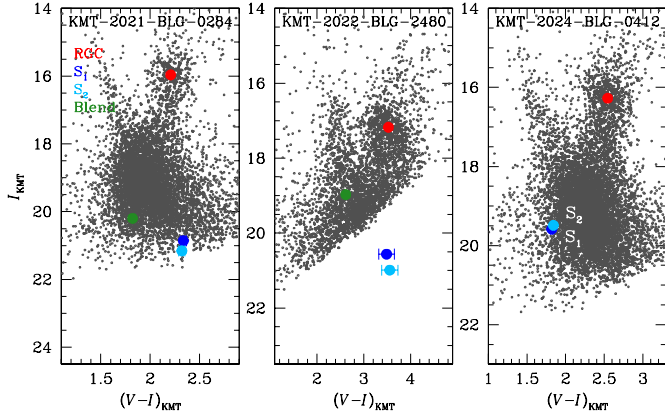
## 4. Source stars and angular Einstein radii

In this section we define the stars that make up the binary source. Accurately defining the source is crucial not only for comprehensively characterizing the events but also for measuring the angular Einstein radii of the events. The angular Einstein radius is estimated by combining the measured normalized source radius with the angular source radius  $\theta_*$ , using the relation

$$\theta_E = \frac{\theta_*}{\rho}. \quad (1)$$

**Table 6.** Source parameters, angular source radii, Einstein radii, and relative lens-source proper motions.

Parameter	KMT-2021-BLG-0284	KMT-2022-BLG-2480	KMT-2024-BLG-0412
$(V-I, I)_{S_1}$	$(2.336 \pm 0.031, 20.859 \pm 0.009)$	$(3.489 \pm 0.165, 20.563 \pm 0.013)$	$(1.889 \pm 0.020, 19.582 \pm 0.011)$
$(V-I, I)_{S_2}$	$(2.321 \pm 0.032, 21.156 \pm 0.009)$	$(3.556 \pm 0.174, 20.991 \pm 0.017)$	$(1.910 \pm 0.019, 19.486 \pm 0.011)$
$(V-I, I)_{\text{RGC}}$	$(2.208, 15.965)$	$(3.527, 17.175)$	$(2.544, 16.275)$
$(V-I, I)_{\text{RGC},0}$	$(1.060, 14.501)$	$(1.060, 14.526)$	$(1.060, 14.417)$
$(V-I, I)_{S_{1,0}}$	$(1.188 \pm 0.031, 19.395 \pm 0.009)$	$(1.022 \pm 0.165, 17.914 \pm 0.013)$	$(0.405 \pm 0.020, 17.723 \pm 0.011)$
$(V-I, I)_{S_{2,0}}$	$(1.173 \pm 0.032, 19.692 \pm 0.009)$	$(1.089 \pm 0.174, 18.341 \pm 0.017)$	$(0.426 \pm 0.019, 17.628 \pm 0.011)$
$(V-I, I)_b$	$(1.822, 20.200)$	$(2.618, 18.973)$	–
Type ( $S_1$ )	K4V	K3IV	F2V
Type ( $S_2$ )	K4V	K3IV	F2V
$\theta_{*,S_1}$ ( $\mu\text{as}$ )	$0.719 \pm 0.055$	$1.170 \pm 0.209$	$0.660 \pm 0.048$
$\theta_{*,S_2}$ ( $\mu\text{as}$ )	$0.613 \pm 0.047$	$1.03 \pm 0.19$	$0.702 \pm 0.051$
$\theta_E$ (mas)	–	$0.98 \pm 0.19$	$0.272 \pm 0.020$
$\mu$ (mas/yr)	–	$3.35 \pm 0.66$	$4.55 \pm 0.33$


**Fig. 7.** Locations of source stars (blue dot for the primary source and cyan dot for the secondary source) and the centroid of red giant clumps (RGC, red dot) for the lensing events KMT-2021-BLG-0284, KMT-2022-BLG-2480, and KMT-2024-BLG-0412. For KMT-2021-BLG-0284 and KMT-2022-BLG-2480, we also mark the location of the blend (green dot).

We defined the source star for each event by measuring its color and magnitude. To achieve this, we first determined the combined source flux from the primary and secondary source stars. This was done by regressing the photometric data ( $F_{\text{obs}}$ ) with respect to model  $A_{\text{model}}(t)$ :

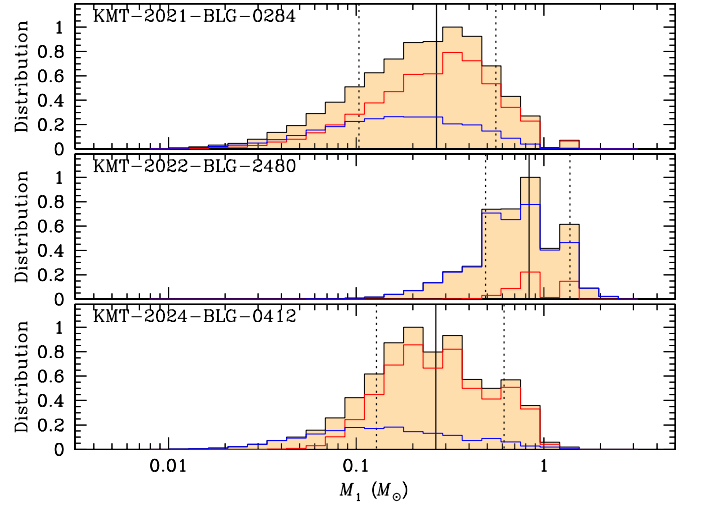
$$F_{\text{obs}}(t) = F_S A_{\text{model}}(t) + F_b. \quad (2)$$

Here,  $F_S$  represents the combined flux from the primary ( $F_{S_1}$ ) and secondary ( $F_{S_2}$ ) source stars, and  $F_b$  represents the flux from a blend. Using the measured flux ratio  $q_F$  between the source stars, the flux from each individual source star was estimated as

$$F_{S_1} = \left( \frac{1}{1 + q_F} \right) F_S; \quad F_{S_2} = \left( \frac{q_F}{1 + q_F} \right) F_S. \quad (3)$$

We measured the flux values in the two passbands of  $I$  and  $V$  for the estimation of the source color. This process was done with the use of the photometric data processed using the pyDIA code Albrow et al. (2017).

Figure 7 illustrates the source positions for the events on the instrumental color-magnitude diagrams (CMDs) of stars near the source. These CMDs were created using KMTC datasets, and the photometry of the stars was performed with the same pyDIA


**Fig. 8.** Bayesian posteriors of the mass for the heavier lens component. In each posterior, the red and blue curves illustrate the contributions from the disk and bulge lens populations, respectively, while the black curve represents the combined contributions from the two populations. The solid vertical line marks the median, and the two dotted lines denote the  $1\sigma$  range of the distribution.

code used for measuring the source flux. For KMT-2021-BLG-0284 and KMT-2022-BLG-2480, we identified the positions of the blend. Table 6 lists the colors and magnitudes of the primary source star,  $(V-I, I)_{S_1}$ , secondary star,  $(V-I, I)_{S_2}$ , and blend,  $(V-I, I)_b$ . In all events, the binary stars that make up the source are found to have similar magnitudes, with a magnitude difference of less than 0.5 mag. Han & Jeong (1998) noted that binary-source events are detected less frequently than binary-lens events because the effect of the secondary star's flux in a binary source event is relatively minor compared to the mass effect in a binary lens event. The similarity in brightness of the stars in the binary source for the analyzed lensing events is likely due to the higher detection efficiency for binary source events with a relatively bright secondary source star. We observe that the source stars of KMT-2024-BLG-0412 are substantially bluer than typical bulge main-sequence stars, suggesting they may be located in the far disk behind the bulge.

The measured instrumental color and magnitude of the source,  $(V-I, I)_S$ , were calibrated using the method of Yoo et al. (2004). This method utilizes the centroid of the red giant clump (RGC),  $(V-I, I)_{\text{RGC}}$ , in the CMD as a reference for calibration.

**Table 7.** Physical lens parameters.

Parameter	KB-21-0284	KB-22-2480	KB-24-0412
$M_1 (M_\odot)$	$0.27^{+0.29}_{-0.17}$	$0.83^{+0.55}_{-0.34}$	$0.27^{+0.35}_{-0.14}$
$M_2 (M_\odot)$	$0.10^{+0.11}_{-0.06}$	$0.29^{+0.19}_{-0.12}$	$0.17^{+0.22}_{-0.09}$
$D_L$ (kpc)	$6.86^{+1.33}_{-1.73}$	$4.71^{+1.52}_{-1.27}$	$7.43^{+0.97}_{-1.21}$
$a_\perp$ (AU)	$1.81^{+0.35}_{-0.46}$	$5.11^{+1.65}_{-1.37}$	$5.94^{+0.78}_{-0.96}$
$p_{\text{disk}}$	32%	88%	23%
$p_{\text{bulge}}$	68%	12%	77%

By measuring the offset between the source and the RGC centroid in the CMD,  $\Delta(V - I, I)$ , and using the known de-reddened color and magnitude of the RGC centroid,  $(V - I, I)_{\text{RGC},0}$ , the de-reddened color and magnitude of the source are calibrated as

$$(V - I, I)_{S,0} = (V - I, I)_{\text{RGC},0} + \Delta(V - I, I). \quad (4)$$

We adopted the  $(V - I, I)_{\text{RGC},0}$  values from [Bensby et al. \(2013\)](#) and [Nataf et al. \(2013\)](#). The positions of the RGC centroids in the CMDs for each event are indicated in Fig. 7, with their values detailed in Table 6. This table also presents the estimated de-reddened colors and magnitudes of the binary source stars for each event:  $(V - I, I)_{S1,0}$  for  $S_1$  and  $(V - I, I)_{S2,0}$  for  $S_2$ .

The angular radius of the source is determined based on its measured color and magnitude. For this determination,  $V - I$  was initially converted to  $V - K$  using the color-color relation established by [Bessell & Brett \(1988\)](#). Subsequently, the angular source radius was derived from the relation between  $(V - K, V)$  and  $\theta_*$  provided by [Kervella et al. \(2004\)](#). Using this angular radius, the Einstein radius is calculated using Eq. (1). Additionally, in conjunction with the event timescale, the relative proper motion between the lens and source is estimated as  $\mu = \theta_E/t_E$ . Table 6 presents the estimated values of  $\theta_*$ ,  $\theta_E$ , and  $\mu$  for each individual event. For KMT-2021-BLG-0284, the angular Einstein radius was not measured for either the primary or secondary source star. For KMT-2022-BLG-2480, where the normalized source radius was measured only for the secondary source, the angular Einstein radius was estimated as  $\theta_E = \theta_{*,S2}/\rho_2$ . In contrast, for KMT-2024-BLG-0496, the normalized source radius was measured only for the primary source, and the angular Einstein radius was estimated as  $\theta_E = \theta_{*,S1}/\rho_1$ .

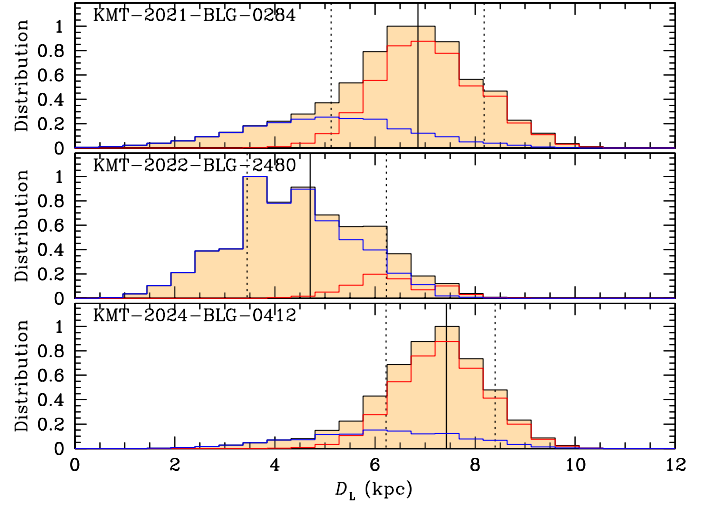
## 5. Physical lens parameters

In this section we determine the physical lens parameters, including the mass ( $M$ ) and distance ( $D_L$ ) to the binary lens systems. The lens parameters are constrained by the lensing observables  $t_E$ ,  $\theta_E$ , and  $\pi_E$ , where  $\pi_E$  represents the microlens parallax. These observables are related to the lens parameters as

$$t_E = \frac{\theta_E}{\mu}; \quad \theta_E = (\kappa M \pi_{\text{rel}})^{1/2}; \quad \pi_E = \frac{\pi_{\text{rel}}}{\theta_E}, \quad (5)$$

where  $\kappa = 4G/(c^2 \text{AU}) \simeq 8.14 \text{ mas}/M_\odot$ ,  $\pi_{\text{rel}} = \text{AU}(D_L^{-1} - D_S^{-1})$  represents the relative lens-source parallax, and  $D_S$  denotes the distance to the source. Of the observables, the event timescale is measured for all events, while the microlens parallax is measured for none. The angular Einstein radius is measured for KMT-2022-BLG-2480 and KMT-2024-BLG-0412.

We determine the physical lens parameters through a Bayesian analysis using priors on the physical and dynamical

**Fig. 9.** Bayesian posteriors of the distance to the lens. Notations are same as those in Fig. 8.

distributions, as well as the mass function of lens objects within the Galaxy. Using these priors, we generated numerous artificial lensing events, each assigned a set of physical parameters  $(M, D_L, D_S, \mu)_i$  from a Monte Carlo simulation. For the simulation, we employed the Galaxy model detailed in [Jung et al. \(2021\)](#) and the mass function model described in [Jung et al. \(2021\)](#). For each artificial event, we compute the lensing observables  $(t_E, \theta_E)_i$  using the relations in Eq. (5). We then constructed the posteriors for the lens mass and distance by assigning a weight to each artificial event. The weight was calculated as

$$w_i = \exp\left(-\frac{\chi^2}{2}\right); \quad \chi^2 = \frac{(t_{E,i} - t_E)^2}{\sigma(t_E)^2} + \frac{(\theta_{E,i} - \theta_E)^2}{\sigma(\theta_E)^2}. \quad (6)$$

Here,  $(t_E, \theta_E)$  denote the measured values of the observables, while  $[\sigma(t_E), \sigma(\theta_E)]$  represent their respective measurement uncertainties.

Figures 8 and 9 display the posteriors for the primary lens mass and the distance to the lens systems. The estimated values for the primary and companion lens masses, the distance to the lens, and the projected separation ( $a_\perp$ ) between  $M_1$  and  $M_2$  for each event are listed in Table 7. Based on these parameters, it was found that the lenses of KMT-2021-BLG-0284 and KMT-2024-BLG-0412 are binaries composed of M dwarfs. For KMT-2022-BLG-2480, the primary lens is an early K-type main-sequence star, and the companion is an M dwarf. The table also includes the probabilities of the lens being in the disk ( $p_{\text{disk}}$ ) or the bulge ( $p_{\text{bulge}}$ ). It was found that the lenses of KMT-2021-BLG-0284 and KMT-2024-BLG-0412 are likely located in the bulge, while the lens of KMT-2022-BLG-2480 is more likely in the disk.

## 6. Summary and conclusion

We conducted a project involving the systematic analysis of microlensing data from the KMTNet survey. The objective of the project is to identify lensing events characterized by intricate anomaly features that are challenging to explain using conventional binary-lens or binary-source models.

Our investigation reveals that the light curves of microlensing events KMT-2021-BLG-0284, KMT-2022-BLG-2480, and KMT-2024-BLG-0412 exhibit highly complex patterns with

three or more anomaly features. While these features could not be fully explained by a binary-lens (2LIS) model alone, the 2LIS model could effectively describe certain segments of the light curve. By incorporating an additional source into the modeling, we identified a comprehensive model that accounts for all the observed anomaly features.

Bayesian analysis, based on constraints provided by the lensing observables of the event timescale and the angular Einstein radius, indicates that the lenses of KMT-2021-BLG-0284 and KMT-2024-BLG-0412 are binary systems composed of two M dwarf stars. For KMT-2022-BLG-2480, the primary lens is an early K-type main-sequence star and the companion is an M dwarf. The binary stars in the sources for all events exhibit similar magnitudes due to a detection bias that favors binary source events featuring a relatively bright secondary star.

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