Revealing Short-period Exoplanets and Brown Dwarfs in the Galactic Bulge Using the Microlensing Xallarap Effect with the Nancy Grace Roman Space Telescope

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Abstract

The Nancy Grace Roman Space Telescope (Roman) will provide an enormous number of microlensing light curves with much better photometric precision than ongoing ground-based observations. Such light curves will enable us to observe high-order microlensing effects which have been previously difficult to detect. In this paper, we investigate Roman’s potential to detect and characterize short-period planets and brown dwarfs (BDs) in source systems using the orbital motion of source stars, the so-called xallarap effect. We analytically estimate the measurement uncertainties of xallarap parameters using Fisher matrix analysis. We show that the Roman Galactic Exoplanet Survey can detect warm Jupiters with masses down to 0.5 \( M_{\text{Jup}} \) and orbital periods of 30 days via the xallarap effect. Assuming a planetary frequency function from Cumming et al., we find Roman will detect \( \sim 10 \) hot and warm Jupiters and \( \sim 30 \) close-in BDs around microlensed source stars during the microlensing survey. These detections are likely to be accompanied by the measurements of the companion’s masses and orbital elements, which will aid in the study of the physical properties for close-in planet and BD populations in the Galactic bulge.

1. Introduction

Gravitational microlensing (Mao & Paczynski 1991; Bennett & Rhie 1996) has a unique sensitivity to low-mass exoplanets beyond the snow line (Hayashi et al. 1985) where planet formation is considered active by the enhanced surface density of solid materials. It has maximum sensitivity to planets (around the lens objects) with projected semimajor axes roughly equal to the projected Einstein ring radius \( R_E \), where

\[
R_E = \left( \frac{4GM_L}{c^2} \frac{D_L D_S}{D_S} \right)^{1/2}.
\] (1)

Here \( D_S \) and \( D_L \) are the distances of the source and lens from Earth, \( M_L \) is the mass of the lens, and \( D_{LS} = D_S - D_L \). For typical microlensing events toward the Galactic bulge (\( D_S = 8 \) kpc, \( D_L = 4 \) kpc, \( M_L = 0.3 M_\odot \)), \( R_E \) is \( \sim 2.3 \) au. Using this binary-lens channel of microlensing, the Nancy Grace Roman Space Telescope (Spergel et al. 2015, previously named WFIRST, hereafter Roman) will conduct the Roman Galactic Exoplanet Survey and discover \( \sim 1400 \) cold wide-orbit exoplanets (Penny et al. 2019, hereafter P19) and provide an otherwise inaccessible statistical sample of exoplanets in previously unprobed regions of exoplanet parameter space (see Figure 9 of P19).

Roman will detect many thousands of microlensing light curves which will generally have better photometric precision than many ground-based microlensing surveys. This will enable the measurement of high-order microlensing effects which have been previously difficult to detect. One of the high-order effects that can be measurable in the Roman light curves is xallarap (Griest & Hu 1992; Han & Gould 1997; Poindexter et al. 2005). Xallarap is a microlensing effect where the reflex motion of a source star in a binary system modulates the magnification of the source star. A more commonly known microlensing effect, orbital microlens parallax (Gould 2004), also causes the variations with the same mechanism by the orbital motion of an observer.\(^5\) The xallarap amplitude \( \xi_E \) corresponds to the semimajor axis of the source star \( a_S \) normalized by the angular Einstein radius \( \theta_E \) projected to the source plane, i.e.,

\[
\xi_E = \frac{a_S}{D_S \theta_E} = \frac{a_S}{\hat{r}_E},
\] (2)

where \( \hat{r}_E \) is the projected Einstein radii. We note that \( a_S \) is the distance between the source and the center of masses of the source system. Using Newton’s version of Kepler’s third law, we can derive following equations from the Equation (2),

\[
\xi_E = \frac{1}{\hat{r}_E} \left( \frac{M_P}{M_\odot} \right) \left( \frac{P_\text{i}}{1 \text{ yr}} \right)^{2/3} \approx 2 \times 10^{-5},
\] (3)

\[
M_S a_S = M_P a_P \Rightarrow a \equiv a_S + a_P = \left( 1 + \frac{M_S}{M_P} \right) a_S,
\] (4)

where \( M_S \) and \( M_P \) are masses of the source (host) and source companion, \( P_\text{i} \) is the orbital period, \( a_P \) is the semimajor axis of the source companion, and \( a \) is the distance between the host and companion in the source system.

\(^5\) Xallarap can be considered as the inverse of parallax and is a semordnilap.
Equation (3) means that when a solar-type source star in the Galactic bulge ($D_S = 8\, \text{kpc}$) is accompanied by a planet with $M_P = 10\, M_{\text{Jup}}$ and $P = 10 \, \text{days}$, the angular size of the semimajor axis of the source star orbit around the barycenter is a factor $10^{-4}$ smaller than $\theta_E$. Present ground-based microlensing survey observations do not have typical sensitivities to detect such small fluctuations induced by planetary-mass source companions.

In several microlensing analyses, xallarap has been investigated to explain light-curve deviations from a standard model (Paczynski 1986) that assumes uniform linear motions between the source, lens, and observers (e.g., Bennett et al. 2008; Sumi et al. 2016). However, identifying the xallarap signals clearly is rarely successful. For example, Sumi et al. (2010) analyzed a planetary microlensing event OGLE-2007-BLG-368 and found clear asymmetric features that can be interpreted as xallarap signals. However, they could not conclude it because possible unknown systematics in the light curve could not be ruled out. Recently, Miyazaki et al. (2020) identified a significant xallarap signal in a planetary microlensing event OGLE-2013-BLG-0911. Using the observed xallarap parameters, they concluded that there is a late-M dwarf orbiting the source star with a mass of $0.14^{+0.02}_{-0.02} \, M_\odot$ and an orbital period of $36.7^{+0.8}_{-0.7} \, \text{days}$. This is the first demonstration that dark, low-mass objects in the Galactic bulge can be detected and characterized via xallarap even with ground-based photometry. Rahvar & Dominik (2009) suggested a possibility that planets orbiting sources in the Galactic bulge are detectable via xallarap with sufficiently good photometry. With space-based photometry like Roman, planetary-mass objects might be detectable and characterized via xallarap.

In this paper, we investigate the possibility of detecting planetary xallarap signals in the Roman microlensing events. In Section 2, we describe our Fisher matrix analysis and analytical quantification of the ability of the Roman light curves to detect xallarap signals and characterize the physical properties of the source systems. To predict how many planets are detectable in the Roman mission via the xallarap effect, we apply our analysis to simulations of the Roman survey in Section 3. Finally, we give our conclusion and discussion in Section 4.

2. Fisher Matrix Analysis

In this section, we conduct the Fisher matrix analysis based on the expected Roman observations and evaluate its sensitivity for xallarap. Rahvar & Dominik (2009) adopted the value of $\Delta \chi^2$ between the xallarap and non-xallarap (standard) models as the detection threshold of the source companion. However, it could be insufficient for evaluating the ability to characterize the physical parameters of planets. Further discussion on this is presented in Appendix A. The mechanisms of how xallarap affects light curves are essentially identical to the microlens parallax. Therefore, we conduct the Fisher matrix analysis by modifying the formulas of parallax that are conducted by Gould (2013), Mogavero et al. (2016, hereafter M16), and Bachelet et al. (2018, hereafter B18).

2.1. Parameterization of the Xallarap Effect

Here we describe the xallarap effect observed by a single observatory. We follow the descriptions for the parallax effect observed by space-based observatories of B18 and then modify it for the case of xallarap effect.

In general, the observed flux of the microlensing event is

$$F = F_S + F_B = F[(1 - \nu)A + \nu],$$

where $F_S$, $F_B$, $F_S + F_B$ are the fluxes of the source, blend, and baseline, respectively. $\nu = F_B/(F_S + F_B)$ denotes the blend flux ratio. For a single-lens single-source (1L1S) model, the source flux magnification $A$ is described by

$$A(t) = \frac{u^2(t) + 2}{u(t)\sqrt{u^2(t) + 4}},$$

where $u$ is the magnitude of the lens–source separation vector normalized by the angular Einstein radius $\theta_E$, $\mathbf{u}$. For uniform linear motions between the source, lens, and observers, $u(t) = \sqrt{\tau^2 + u_0^2}$, where $\tau \equiv (t - t_0)/t_0$, $t_0$ is the time of the magnification peak, and $u_0$ is the lens–source impact parameter normalized to $\theta_E$.

Figure 1 gives a schematic view of the xallarap problem. Here we consider a planet in a circular orbit ($e = 0$) around a source star with orbital period $P$ and mass $M_p$. Then the source also orbits around the barycenter of the source system. In this paper, we assume that the source companion contributes no flux to the event, i.e., it acts as a 1L1S event, not a binary-source event (Han & Jeong 1998). The displacement of the source position due to the orbital motion can be described by

$$S(t) = \left( \frac{\lambda_1}{\lambda_2} \right) = \left( \begin{array}{c} \cos \Omega - \cos \phi_\xi \\ \sin \lambda_\xi \sin \Omega - \sin \phi_\xi \end{array} \right),$$

where $\Omega = \omega(t - t_0) + \phi_\xi$ and $\omega = 2\pi/P$. Here, $\lambda_\xi$ denotes the inclination of the source orbital plane with respect to the observer and $\phi_\xi$ denotes the orbital phase at $t_0$. We define $\theta$ as the angle between the direction of the lens–source relative motion and the major axis of the source orbit projected on the sky. When we define the xallarap vector $\xi = (\xi_\xi, \xi_\Omega) = \xi_\xi(\cos \theta, \sin \theta)$, the displacement of the source position due to the orbit relative to

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Figure 1. Schematic view of the xallarap problem. Due to the source orbital motion, the source trajectory (solid red curve) deviates from the inertial trajectory (dashed red line).

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6. $F$ and $\nu$ are nonstandard variables.
the inertial source position is
\begin{align}
\delta \tau &= \xi_E \cdot S \\
\delta \beta &= \xi_E \times S,
\end{align}

where \( |\xi_E| = a_S/(D_S d_H) \). The lens–source separation vector \( u(t) \) can be described by
\begin{align}
u(t) &= \left( \tau' \cos \theta - u' \sin \theta \right) \\
&\quad \left( \tau' \sin \theta + u' \cos \theta \right),
\end{align}

where \( \tau' = \tau + \delta \tau \) and \( u' = u_0 + \delta \beta \). The xallarap model can be described by 10 parameters as
\begin{equation}
\zeta = \left( \bar{F}, \nu, t_0, t_E, u_0, \xi_{E,\|}, \xi_{E,\perp}, \phi_z, \lambda_z, P_z \right).
\end{equation}

2.2. Fisher Matrix Analysis

To estimate the expected uncertainty of each parameter (\( \zeta \)) by the Roman microlensing survey, we calculate the Fisher matrix of the light-curve model \( F(t_E, \zeta) \) with given parameter set \( \zeta \). Under the assumption of independent errors, the Fisher matrix elements \( b_{ij} \) can be written as
\begin{equation}
b_{ij} = \sum_{k=1}^{N} \frac{1}{\sigma_k^2} \frac{\partial F(t_k)}{\partial \zeta_i} \frac{\partial F(t_k)}{\partial \zeta_j},
\end{equation}

where \( N \) is the total number of the data points and \( \sigma_k \) is the photometric error on data point at \( t_k \). Once the Fisher matrix is calculated, the covariance matrix for parameters, \( C \), is given by its inverse matrix, i.e.,
\begin{equation}
C = b^{-1}.
\end{equation}

We follow the logic of M16 and discard (negligible) the contribution of \( F \) from our Fisher matrix analysis.\(^7\) In principle, the uncertainties for the xallarap amplitude depend on the event geometry, i.e., \( \sigma^2_{\xi_{E,\perp},\xi_{E,\perp}} \). To produce the results which are independent from the geometric conditions, M16 analytically found the minimum uncertainty on the parallax measurement, \( \sigma^2_{\xi_{E,\perp},\min} \), which is independent of \( \theta \). We modify it for xallarap measurements \( \sigma^2_{\xi_{E,\perp},\min}(\phi_z) \) as
\begin{align}
\sigma^2_{\xi_{E,\perp},\pm}(\phi_z) &= \frac{\sigma^2_{\xi_{E,\perp}} + \sigma^2_{\xi_{E,\perp}}}{2} \\
&\quad + \sqrt{\left(\sigma^2_{\xi_{E,\perp}} - \sigma^2_{\xi_{E,\perp}}\right)^2 + 4 \text{cov}(\xi_{E,\perp}, \xi_{E,\perp})^2} \\
\sigma^2_{\xi_{E,\perp},\min} &= \min_{\phi_z \in [0,2\pi]} \sigma^2_{\xi_{E,\perp},\pm}(\phi_z).
\end{align}

As M16 noted, for \( P_z \ll u_0 t_E \), the covariance between the xallarap vector components \( \xi_{E,\|} \) and \( \xi_{E,\perp} \) disappear so that \( \sigma_{\xi_{E,\|}} \) becomes independent of \( \phi_z \).

In this work, we assume continuous observations of 72 days with a 15 minute cadence and Gaussian photometric errors that are consistent with simulated photometric error bars shown in Figure 4 of P19. Periodic correlated noise is expected to be mainly produced by spacecraft systematics and stellar pressure-driven (\( p \)-mode) oscillations. Detailed photometric simulations on all systematic errors are computationally expensive. P19 applied suboptimal aperture photometry in their simulated photometric pipeline and added a Gaussian systematic error floor of 1 mmag in quadrature into their photometric results to compensate for unmodeled systematic errors. Timescales of xallarap signals, which are typically \( >0.1 \) day, are much larger than the expected timescale of \( p \)-mode oscillations of main-sequence stars (Broomhall et al. 2009). Moreover, Gilliland et al. (2015) found that most Kepler stars have a median photometric variability of \( \sim 0.2 \) mmag, with a timescale of \( <0.6 \) hr. This is somewhat smaller than the error floor of P19 of 1 mmag.

We also assume the source mass and distance to be \( M_S = 1 M_J \) and \( D_S = 8 \) kpc, respectively, and the angular Einstein radius to be \( \theta_E = 0.3 \) mas, which approximately leads to
\begin{equation}
\xi_E \sim 4.6 \times 10^{-5} \left( \frac{M_P}{M_{\text{up}}} \right) \left( \frac{P_z}{\text{day}} \right)^{2/3}.
\end{equation}

In our analysis, we consider the orbital inclination of \( \lambda_z = 45^\circ \) and \( t_0 \) to be at the center of the 72 day Roman observing window. Our result is hardly dependent on \( \theta \) because we adopt \( \sigma_{\xi_{E,\perp},\min} \) which is independent of the event geometry. Here we set \( \theta = 45^\circ \). For each \( W146_S \), we adopt the value of the blend flux ratio \( \nu \) to be the same with the median value of the \( \nu \) distribution that is obtained by the P19 simulation. Note that we assume that the microlens parallax effect does not affect the measurement of the xallarap effect because the xallarap period we focus on here is much shorter than 365 days for the parallax, and is thus likely distinguishable. We do not consider the finite source effect (Witt & Mao 1994) because the effect can be easily modeled and is distinguishable from xallarap. We also do not consider binary-lens events. Although the binary-lens event would be more sensitive to the xallarap effect than the single-lens event, it is outside the scope of this work. We also ignore any accelerations induced by Roman’s orbit around L2.

The nominal expected fractional error on the companion mass can be derived from Equation (3) as
\begin{equation}
\frac{\sigma_{M_P}}{M_P} = \sqrt{\left( \frac{\sigma_{\xi_{E,\min}}}{\xi_E} \right)^2 + \frac{4}{9} \left( \frac{\sigma_{P_z}}{P_z} \right)^2},
\end{equation}

by assuming the uncertainties on \( \theta_E, D_S, \) and \( M_S \) are negligible. We set the detection threshold for the xallarap companions as \( (\sigma_{M_P}/M_P) = 0.3 \) in the following analysis. The impacts of uncertainties of \( \theta_E, D_S, \) and \( M_S \) on the measurements of companion’s masses is discussed in Appendix B.

2.3. Xallarap Light Curves

Figure 2 shows two samples of model light curves with and without the xallarap effect in the top panels. The residuals of the light curves between that with and without xallarap are shown in the second panels. The left figure represents an event with \( t_0 = 30 \) days, \( u_0 = 0.1 \), \( M_P = 2 M_{\text{up}} \), and \( P_z = 5 \) days. In this case, the maximum deviations from the standard model is about 0.5% of the source flux, which is comparable to the Roman photometric noise level for \( W146 \sim 20 \) mag (see Figure 4 of P19). This indicates that brighter and/or high-
magnification events are promising targets for Roman to detect xallarap features induced by a Jupiter-mass planet around the source star. In the three bottom panels, we plot the components of integrands of the Fisher matrix \( \partial F(t_k) / \partial \zeta_i \) at a given time \( t_k \). These panels imply that the observations during \( t_0 \pm P_\xi \) are most important to determine the xallarap parameters (\( \zeta_i \)) related to the mass of companion \( M_p \). However, note that observations further into the wings continue to add to the precision of the period estimate (see the bottommost panels).

For understanding what parts of light curves are important to constrain the parameters, we derive the parameter uncertainties using the Fisher matrix analysis each time a Roman observation is conducted. Figure 3 represents the cumulative precision on \( \xi_E \) and \( P_\xi \) as a function of time for the Roman light curve with \( W146s = 18 \text{ mag} \) (corresponding to Figure 2). We found that the parameter uncertainties are gradually constrained with increasing data points from the wing of the light curves. Moreover, we also derive the cumulative precision on the parameters as a function of the coverage duration for the light-curve peak (Figure 4). We found that the resultant parameter precision strongly depend on how long the light curves cover around the event peaks. Figures 3 and 4 indicate that the xallarap parameters can be measured with incomplete light curves that cover around \( t_0 \pm P_\xi \). This is particularly important for Roman, which has a short observing window of 72 days.
2.4. Xallarap Sensitivity Map

At a given \( t_E, u_0, W146S \), we conducted the Fisher matrix analysis on a grid of points over the ranges of \(-2 \leqslant \log(M_P/M_{\text{Jup}}) \leqslant 2\) and \(-1 \leqslant \log(P_{\text{day}}) \leqslant 3\) with \(20 \times 20\) grid points, respectively. In Figure 5, we present samples of xallarap sensitivity maps in the mass–orbital period plane for the Roman event with \( W146S = 18\) mag. The color maps in each panel represent the distributions of \(\sigma_{M_p}/M_p\) and the black lines correspond to contour lines of our detection threshold of \(\sigma_{M_p}/M_p = 0.3\). The row and column of a panel correspond to the labeled values of \(u_0\) and \( t_E \). For example, in the case of \(\log(t_E) = 2, \log(u_0) = -1.5\) (bottom right panel), the Roman light curve has the potential to precisely measure the mass of a warm Jupiter with an orbital period of 10–30 days via xallarap. We found that \(M_P\) is well constrained when \(t_E\) is longer and \(u_0\) is smaller in a given \((M_p, P_{\text{c}})\) grid. One also can find that there are sharp cutoffs of the sensitivity with the orbital period of a few dozen days. This might be because the Roman observing window of 72 days could not cover the full orbital period of the events beyond the cutoff and thus is insufficient to constrain the xallarap parameters.\(^8\) This can be expected from the results of Figures 3 and 4.

3. Prediction of the Yields of Close-in Exoplanets with Xallarap

3.1. Simulating on the Roman Observation

In this section, we estimate the detection number of close-in planets and brown dwarfs (BDs) in source systems via xallarap during the Roman mission. To simulate the Roman microlensing survey, we employ the single stellar lens module of the GULLS microlensing simulator (Penny et al. 2013, 2019) which uses version 1106 of the Besançon Galactic population synthesis model (Robin et al. 2003, 2012) to generate pairs of lens and source stars. In Table 1, we summarize the survey parameters for the Cycle 7 design that we use in our simulation. The full survey details are described in P19 and Johnson et al. (2020). Note that we consider only single-lens events whose peaks are within the Roman observing window.

We classified the simulated Roman events from GULLS by the values of \((u_0, t_E, W146S)\) into a bin of \(7 \times 10 \times 10\) over the ranges of \(14 < W146S < 28\) mag, \(-2 < \log(u_0) < 0\), and \(0 < \log(t_E/\text{day}) < 2.5\), respectively. We generated the sensitivity maps with the parameters at the center of each bin to be used for all events in each bin. Then we counted the number of detected events using the corresponding sensitivity maps at each \((M_p, P_{\text{c}})\) grid. Figure 6 shows the resultant detections, i.e., the expected planet yields during the Roman survey mission if all source stars were to have a planet at each \((M_p, P_{\text{c}})\) grid point. The black solid lines represent the contours of the planet yields for 1, 10, 100, and 1000. The detection sensitivity peaks around \(P_{\text{c}} = 20 \sim 30\) days and there it reaches to sub-Jovian or Saturn masses. In Figure 6, we also plotted observed exoplanets (open dots) from the NASA Exoplanet Archive\(^9\) (Akeson et al. 2013). Roman’s sensitivity to planets via the xallarap effect largely covers the parameter spaces of hot and warm Jupiters with \(M_P > 0.5 M_{\text{Jup}}\) and \(0.1 < P < 100\) days, which suggests that this method could be useful to probe the hot and warm Jupiter populations in the Galactic bulge. Note that we used only a single 72 day season for each event.

3.2. Planet Yields

In order to estimate the planet yields, we assume the secondary mass and period distributions. We describe the distribution function \(f\) as a double power law,

\[
\frac{\partial^2 f}{\partial \ln M \partial \ln P} = C_{\text{norm}} \left( \frac{M_P}{M_{\text{Jup}}} \right)^{\alpha_M} \left( \frac{P}{\text{day}} \right)^{\beta_P},
\]

\(^8\) When we derive the sensitivity maps, we consider only an observing window of a single season. The sensitivity might extend toward the longer orbital period if we consider all the observing windows. However, it is not expected to be so much because of the results of Figure 4 and because there are long time gaps between the Roman observing windows. Here we focus on only short-period planets and BDs.

\(^9\) https://exoplanetarchive.ipac.caltech.edu/
where $C_{\text{norm}}$ is a normalization factor. In this work, we adopted the power-law indexes of $\alpha_M = -0.31 \pm 0.2$ and $\beta_P = 0.26 \pm 0.1$ derived by Cumming et al. (2008, hereafter C08). These values are derived using 48 radial-velocity-detected planets ranging $0.3 < M_P < 10 M_{\text{Jup}}$ and $2 < P < 2000$ days that are around Sun-like stars. We adopted $C_{\text{norm}} = 0.036 \text{dex}^{-2} \text{star}^{-1}$ to be consistent with a planet frequency of 10.5% around Sun-like stars in these ranges derived by C08. Note that we simply extrapolate this power law of C08 to the ranges $0.01 < M_P < 100 M_{\text{Jup}}$ and $0.1 < P < 1000$ days because it is still uncertain. The extrapolation below $0.3 M_{\text{Jup}}$ hardly affects the final result because the sensitivities to low-mass planets with $<0.3 M_{\text{Jup}}$ is very low and the Kepler survey suggested that the occurrence rate does not significantly rise until below Neptune size of $\sim 5 M_{\oplus}$ (e.g., Fressin et al. 2013). Extrapolations to other ranges require caution as discussed below.

We also estimate the yields assuming a simple frequency model of $(\alpha_M, \beta_P) = (0,0)$ and $C_{\text{norm}} = 0.208 \text{dex}^{-2} \text{star}^{-1}$, which corresponds to single planet per star over the ranges. This can be considered as the reference yields.

Table 1 summarizes the expected yields.

### Table 1

Parameters for Roman Galactic Exoplanet Survey

| Parameter                  | Value |
|----------------------------|-------|
| Survey area                | 1.97 deg$^2$ |
| Mission baseline           | 4.5 yr |
| Seasons                    | $6 \times 72$ days |
| Observation fields         | 7     |
| Microlensing events with $|u_0| < 1$ | $\sim 27000$ |
| $W146$ exposures           | $\sim 41,000$ per fields |
| $W146$ cadence             | 15 minutes |
| Photometric precision      | $\sim 0.01$ mag @ $W146 \sim 21.15$ |

Note. The parameters for the Cycle 7 design we use are fully described in Penny et al. (2019) and Johnson et al. (2020). In this paper, we do not consider any observations with the Z087 filter and other filters that are to be conducted during the Roman microlensing survey, which could improve our prediction of planet yields to some extent.

Figure 5 represents the expected yields of the Roman observations assuming the extended C08 distribution. The three left panels show the distributions of $t_E$, $u_0$, and $W146$ for events in which the planet/BD companion around the source is detected. The yields are expected to largely come from the events with $18 < W146 < 22$ mag, which mostly consist of main-sequence source stars. Note that although the histogram with $u_0$ indicates that the detections increase toward larger $u_0$, as shown in Figure 5, the events with large $u_0$ are only sensitive to massive companions. The right panel in Figure 7 shows the distribution for the number of planet and BD detections over the parameter space of masses and periods assuming the frequency from C08.
assuming the two different distribution functions. Adopting the extended C08 distribution, we found that \( \sim 10 \) planets with \( M \leq 10 M_{\text{Jup}} \) would be detected by xallarap. We can expect \( \sim 30 \) companions with \( 10 < M_p < 100 M_{\text{Jup}} \) if the extrapolation of C08 is correct. However, due to the “BD desert” (Grether & Lineweaver 2006), BD discoveries may by much less common than predicted using the C08 frequencies.\(^{10}\) We can test the BD desert in the Galactic bulge by applying this method to the upcoming Roman light curves.

4. Discussion

4.1. How to Distinguish Lens Orbital Motion

If the lensing body is in a binary system, lens orbital motion (LOM) will provide a similar effect to that of xallarap, which has been pointed out in several papers (Rahvar & Dominik 2009; Penny et al. 2011). In a planetary system with an orbital period of \( P \leq 30 \) days, a projected angular separation between a lensing host star and its planet in units of \( \theta_E \), \( s = a/\theta_E \), is expected to be an order of \( s \leq 0.06 \). It is unlikely that a lens companion with such a small \( s \) provides noticeable light-curve deviations by their extremely small caustics. For example, Penny et al. (2011) found that periodic (caustic) features of a light curve due to LOM would be most detectable for binary lens with semimajor axes of \( \sim 1 \) au. Thus it is difficult to distinguish between xallarap and LOM. However the degeneracy may be resolved when the following additional high-order effects are observed in the light curves. The following effects can be observed only in the xallarap events, not in the LOM events.

Magnified planet flux. Planets orbiting source stars produce reflected light from their host and/or emit their own flux from thermal emission. If flux from these companions are magnified, we can observe these contributions in the light curve, as a so-called binary-source microlensing event (Graff & Gaudi 2000; Sajadian & Rahvar 2010). Typical flux ratios between solar-type stars and hot Jupiters in the \( W146 \) band is on the order of \( 10^{-3} \)–\( 10^{-4} \). Using this detection channel, Bagheri et al. (2019) estimated that Roman will discover \( \sim 70 \) exoplanets from single-lens events and \( \sim 3 \) exoplanets from binary-lens events.\(^{11}\) We expect that the binary-source effect might be observed in the Roman xallarap single-lens events of \( P < 5 \) days, which corresponds to \( \sim 50\% \) of the total yields. It would also help us to constrain the orbital parameters of source systems because it provides the geometric relation between the host and planet at the time when the planet is magnified. Full binary-source modeling including the xallarap effect (Miyazaki et al. 2020) is more realistic and might have more sensitivity, but is out of the scope of this work.

Transiting source stars. If the planet transits the source star, we can also simultaneously observe the transiting signal during the microlensing event (Lewis 2001; Rybicki & Wyrzykowski 2014). Typical amplitudes of the transit signal for a Jupiter-sized planet would be \( \sim 1\% \) of the

\(^{10}\) Under the extended C08 function, the existence frequency of BDs around solar-type stars is \( 3\% \) per star. Grether & Lineweaver (2006) reported that is \( <1\% \) per star. More recently, Santerne et al. (2016) reported the occurrence rate of BDs within 200 days of the orbital period with \( 0.29\% \pm 0.17\% \) in the Kepler transit candidates.

\(^{11}\) Note that most of their detection samples were composed of hot Jupiters with \( a < 0.05 \) au, and they assumed that a source star has an exoplanet per event.
source brightness, which will be easily detectable for most xallarap planetary events. For example, Roman is expected to detect thousands on transiting hot Jupiters, including in the Galactic bulge (McDonald et al. 2014; Montet et al. 2017). The geometric transit probability of warm Jupiters is $\sim 5\%$, so that $\sim 5\%$ of the xallarap planetary events could be distinguishable from LOM events by the transit signals. With the measurement of the planet radius by the transit, we can estimate the density of the planet in combination with the mass measurement by xallarap. And, this potentially can test how chemistry affects giant planet structures (e.g., Cabral et al. 2019).

Ellipsoidal variations. Ellipsoidal variations can be caused by tidal effects on the source from the companion (Morris 1985). The amplitude of the ellipsoidal variation is approximated by

$$A_{\text{ellip}} \approx \alpha_{\text{ellip}} \frac{M_P \sin \lambda_\xi \left( \frac{R_S}{a_{SC}} \right)^3 \sin \lambda_\xi}{M_S}$$

$$= 13 \text{ ppm} \left( \frac{M_P \sin \lambda_\xi \left( \frac{R_S}{R_\odot} \right)^3}{M_{\text{up}}} \right) \times \left( \frac{M_S}{M_\odot} \right)^{-2} \left( \frac{P_\xi}{\text{day}} \right)^{-2} \alpha_{\text{ellip}} \sin \lambda_\xi, \quad (18)$$

where $R_S$ is the radius of the source star. The coefficient $\alpha_{\text{ellip}}$ accounts for the stellar limb darkening and gravity darkening,

$$\alpha_{\text{ellip}} = 0.15 \frac{(15 + u)(1 + g)}{3 - u}, \quad (19)$$

where $g$ and $u$ are the coefficients of the gravity darkening and linear limb darkening, respectively (Shporer 2017). It would be difficult to observe this effect for the xallarap planetary events. However, it might be possible for events of substellar source companions.

Doppler beaming. It is known that a line-of-sight motion due to the orbit causes a periodic variation in the light curve, also known as Doppler beaming (Loeb & Gaudi 2003; Shporer 2017). The photometric amplitude of the beaming

$$A_{\text{beam}} \approx \alpha_{\text{beam}} \frac{M_P \sin \lambda_\xi \left( \frac{R_S}{a_{SC}} \right)^3 \sin \lambda_\xi}{M_S}$$

$$= 13 \text{ ppm} \left( \frac{M_P \sin \lambda_\xi \left( \frac{R_S}{R_\odot} \right)^3}{M_{\text{up}}} \right) \times \left( \frac{M_S}{M_\odot} \right)^{-2} \left( \frac{P_\xi}{\text{day}} \right)^{-2} \alpha_{\text{beam}} \sin \lambda_\xi, \quad (20)$$

Figure 7. Expected number of the planet and BD yields during the Roman mission assuming the extended C08 frequency. The left three panels are the histograms of the yields binned by $t_E$, $u_0$, and W149S. The color map in the right panel represents the yields per a given mass–orbital period grid.

| Table 2 | Expected Yields |
| --- | --- | --- |
| Companion Mass $M_P (M_{\text{Jup}})$ | Distribution Function | Simple Model$^a$ | Extend C08 $^b$ |
| $10 \leq M_P < 100$ | 409.6 | 30.9 |
| $1 \leq M_P < 10$ | 63.3 | 10.1 |
| $0.1 \leq M_P < 1$ | 1.05 | 0.37 |
| $M_P < 0.1$ | 0.0022 | 0.0014 |
| Orbital Period $P$ (days) | | | |
| $100 \leq P < 1000$ | 0.043 | 0.007 |
| $10 \leq P < 100$ | 112 | 15.7 |
| $1 \leq P < 10$ | 243 | 20.7 |
| $P < 1$ | 118 | 5.1 |
| Total | 474 | 42 |

Notes.

$^a$ Simple power-law function with $(\alpha_{M_P}, \beta_P) = (0, 0)$.

$^b$ The power-law function of Cumming et al. (2008) extended over ranges of $0.01 < M_P < 100 M_{\text{up}}$ and $0.1 < P < 1000$ days.
Fisher matrix analysis

### 4.2. Short-period Populations in the Galactic Bulge Revealed by Roman

Some observational results have suggested that there are possible differences in planetary populations between the local neighborhood and the distant region of our Milky Way. Radial velocity surveys around the local region close to the Sun indicate an occurrence rate of hot Jupiters of an order of 1% (Cumming et al. 2008). On the other hand, the Kepler transit survey toward the Cygnus region suggested the occurrence rate of 0.4% ± 0.1% (Howard et al. 2012), which is approximately half of that in the local neighborhood. Penny et al. (2016) used a sample of 31 microlensing exoplanetary systems and suggested that the abundance of planets might be less in the Galactic bulge than the disk. Such studies would be very important to help understand whether the planetary formations could depend on their surrounding environments in our Galaxy.

Montet et al. (2017) predicted that Roman is expected to discover ∼100,000 transiting planets and enable us to directly confirm several thousands hot Jupiters via its secondary eclipses in the light curves. A large fraction of the transiting planets will belong to the Galactic bulge. However, in general, most host stars are too faint to conduct follow-up radial velocity observations to constrain their planetary mass and avoid false positives. Montet et al. (2017) also suggested some feasibility for the validation for transiting planets and the estimation of their masses using phase curve variations, although it requires high photometric precision to observe. Applying our xallarap method to the Roman microlensing light curves, we can expect to discover some dozens of hot and warm Jupiters and close-in BDs with measured masses. These samples will help our understanding of the exoplanet demographics at short orbital periods in the Galactic bulge. For larger masses, they are also useful to probe the BD desert around main-sequence stars and study the stellar binary distribution in the Galactic bulge.

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**Software:** numpy (van der Walt et al. 2011), matplotlib (Hunter 2007).

### Appendix A

**Δχ^2** Threshold and Fisher Matrix Analysis

Δχ^2 has been often chosen as a detection threshold of planets in most microlensing simulations (e.g., Bennett & Rhie 1996; Penny et al. 2019; Johnson et al. 2020) possibly because quantifying the detectability cannot be analytically solved for binary-lens modeling (see Penny et al. 2011 for a discussion of the challenges). Rahvar & Dominik (2009) studied that xallarap induced by planetary companions also adopted the Δχ^2 threshold of 11.07 for the detection threshold of planets. However, we adopt the Fisher matrix analysis that allows us to quantify the ability to not only detect xallarap signals but to also characterize the physical parameters. To demonstrate this, we conduct both the Fisher matrix analysis and light-curve fitting in the same conditions and compare them.

Figure 8 represents an example of the result with a simulated Roman event of \((u_0, t_E, W1495) = (0.1, 31.6 \text{ days}, 18)\). In the
left panel, the $\Delta \chi^2$ distribution is shown as a color map over the mass–period diagram. Here $\Delta \chi^2 = \chi_{\text{xallarap}} - \chi_{\text{standard}}$ and $\chi_{\text{E}}^2$ value are calculated fitting each model to the simulated light curve. The right panel shows the uncertainty of xallarap amplitude $\xi_{\text{E}}$ estimated from the Fisher matrix analysis. In the parameter space of $(P_E \geq 40 \text{day}, M_P \geq 1 \text{M}_\text{ Jupiter})$, one finds it is not possible to constrain $\xi_{\text{E}}$ well though there should be large $\Delta \chi^2$ improvements if we fit the light curve by the xallarap model. This can be because the light curve is strongly affected by only the source acceleration of a single direction and thus only one component of the xallarap vector $\xi_{\text{E}}$ can be constrained. For constraining xallarap parameters, it would require observation of the source accelerations during the full time of the source orbits. However, we note that it might be possible that the periodogram analysis of the residuals from a standard single-lens fit can constrain the orbital period of the planet sufficiently to enable an estimate of the planet mass (Nucita et al. 2014; Giordano et al. 2017).

### Appendix B

#### Uncertainties on $D_S$, $\theta_{\text{E}}$, and $M_S$

The ability of Roman to measure $\theta_{\text{E}}$ and $D_S$ has been studied in several papers. It is expected that most Roman events will have their relative lens–source proper-motion $\mu_{\text{rel}}$ measured via the direct detection of lens light in the Roman images, which enables us to measure $\theta_{\text{E}}$ (Bennett et al. 2010, 2020; P19; Terry et al. 2020). Bhattacharya et al. (2018) estimated that Roman will measure the lens–source separations with less than 10% precision for most events. On the other hand, Gould & Yee (2014) analytically showed that events with photometric precisions of $\leq 0.01 \text{mag}$ have the chance to provide measurements of $\theta_{\text{E}}$ with $\leq 10\%$ precision via astrometric microlensing in space-based microlensing experiments. $D_S$ for bright source events can potentially be measured by the direct parallax (astrometry) measurements in the Roman survey data (Gould et al. 2015). Even if not for bright source events, the combination of the three measurements of the microlens parallax $\varpi_{\text{E}}$, lens flux $F_L$, and $\theta_{\text{E}}$ allows us to directly determine $D_S$. Moreover, $D_S$ can be statistically estimated with $\sim 20\%$ precision using priors of the standard Galactic model (e.g., Sumi et al. 2011; Bennett et al. 2014). For main-sequence stars, $M_S$ is expected to be approximately estimated from the source magnitude and color that are obtained by the multiband Roman photometry (we expect it with less than 20% precision using a stellar isochrone model, e.g., Bressan et al. 2012), and it will become more accurate if $D_S$ is also measured. For evolved source stars, the mass can be constrained via the age distribution of the bulge. In this paper, we evaluate the Roman ability to characterize the physical parameters of the xallarap companions by adopting $\sigma_{M_P}/M_P$ in Equation (16). Of course, the resultant errors on the companion’s masses will become somewhat larger than 30% ($\sigma_{M_P}/M_P = 0.3$) due to errors on $D_S$, $\theta_{\text{E}}$, and $M_S$. However, we expect that the mass measurements would be possible by Roman with less than 40% precision in most cases even if all the errors were included.

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12 They also show that source companions with short orbital periods of $P \leq 1 \text{yr}$ hardly affect the measurements of the astrometric signatures.