MICROLENSING EVENTS FROM THE 11 YEAR OBSERVATIONS OF THE WENDELSTEIN CALAR ALTO PIXELLENSING PROJECT

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ABSTRACT

We present the results of the decade-long M31 observation from the Wendelstein Calar Alto Pixellensing Project (WeCAPP). WeCAPP has monitored M31 from 1997 until 2008 in both R- and I-filters, and thus provides the longest baseline of all M31 microlensing surveys. The data are analyzed with difference imaging analysis, which is most suitable for studying variability in crowded stellar fields. We extracted light curves based on each pixel, and devised selection criteria that are optimized to identify microlensing events. This leads to 10 new events, and adds up to a total of 12 microlensing events from WeCAPP, for which we derive their timescales, flux excesses, and colors from their light curves. The colors of the lensed stars fall in the range \((R - I) = 0.56\) to \(1.36\), with a median of \(1.0\) mag, in agreement with our expectation that the sources are most likely bright, red stars at the post-main-sequence stage. The event FWHM timescales range from 0.5 to 14 days, with a median of 3 days, in good agreement with predictions based on the model of Riffeser et al.

Key words: dark matter – galaxies: halos – galaxies: individual (M31) – gravitational lensing: micro

1. INTRODUCTION

Almost four decades after evidence for dark matter in galaxies was revealed (Rubin et al. 1980), its nature is still unknown. Dark matter can be smoothly distributed, e.g., the weakly interacting massive particles (WIMPs), or in compact form. Since dark matter does not emit light, the best way to study it is through gravitational interaction. Paczynski (1986) was the first to conceive the idea of gravitational microlensing as a method to detect dark matter in the form of massive compact halo objects (MACHOs). Based on his calculation, the optical depth, \(^3\) i.e., at any time the probability of a source being closer along the line of sight (LOS) to a foreground lens than the lens’s Einstein angle and therefore being magnified by more than a factor 1.34, is of order \(10^{-8}\) toward the Magellanic Clouds. This has motivated several campaigns to search for microlensing toward dense stellar fields, see, e.g., the review by Moniez (2010). The first microlensing events were reported by the MACHO (Alcock et al. 1993), EROS (Aubourg et al. 1993), and OGLE (Udalski et al. 1993) teams, with MOA (Muraki et al. 1999) joining later on. In their 5.7 years of survey data, the MACHO team has announced\(^4\) 13 microlensing events toward the LMC (Alcock et al. 2000), while a later analysis (Bennett 2005) showed that one of them is a true variable star and two of them are likely to be variables from a simple likelihood analysis. This leaves ten of them as plausible microlensing events, and gives a MACHO halo fraction of \(16\%\) for MACHO masses between 0.1 and \(1 M_\odot\) (Bennett 2005). The EROS-1 and EROS-2 surveys resulted in a MACHO halo fraction of less than \(8\%\) for MACHO mass \(\sim 0.4 M_\odot\), and ruled out MACHOs with masses between \(0.6 \times 10^{-7}\) and \(15 M_\odot\) as a major component of the Milky Way halo (Tisserand et al. 2007). Analyzing the OGLE phase II and III data, Wyrzykowski et al. (2010, 2011a, 2011b) concluded that microlensing events toward the LMC and SMC can be reconciled with self-lensing by stars alone, i.e., without requiring compact halo objects in the Milky Way halo. Later on, Besla et al. (2013) studied the tidal streams between the Magellanic Clouds and used theoretical modeling to show that the microlensing signal can be reproduced by the stars in the stream, though their modeling requires further verification. Besla et al. (2013) outlined several observational tests to verify their theoretical modeling, e.g., the sources of the microlensing events are low-metallicity SMC stars, the sources have high velocities relative to the LMC disk stars, and the presence of a very faint stellar counterpart to the Magellanic Stream and Bridge (surface brightness \(>34\) mag arcsec\(^{-2}\) in the V-band).

In contrast to this, Calchi Novati et al. (2013) recently reanalyzed the OGLE and EROS data and found that some of the OGLE events can be attributed to halo lensing. The inconclusive results can be partially attributed to the fact that, by monitoring the Magellanic Clouds, we can only sample a small fraction of the Milky Way halo. In order to have a census of the Milky Way halo, we need targets that are distributed along different LOSs through the Milky Way halo. Other than the Milky Way, we could monitor a nearby spiral galaxy, for which we can have a complete view of its dark halo.

An alternative dense stellar target for a microlensing search for MACHOs is M31, as proposed by several authors (Croft 1992; Baillon et al. 1993; Jetzer 1994). The advantage of M31 is twofold. First, we can have multiple LOSs through a dark halo toward M31, in contrast to the single LOS toward the Magellanic Clouds due to our location in the Milky Way. The second advantage is that one probes not only the Milky Way halo but also that of M31. The structure of M31 is well known: with an inclination angle of \(77^\circ\) (Walterbos & Kennicutt 1987), we expect to see an asymmetry of the microlensing event rate between the near and far sides of M31’s disk. Such an asymmetry, however, can also originate from extinction along different sight-lines caused by dust. This has indeed been observed in the density distribution of variables from the

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\(^3\) We note that this value depends primarily on the lens population characteristics.

\(^4\) Alcock et al. (2000) found 13 microlensing events with tight criteria; they also presented 17 events with loose criteria, which contain more low signal-to-noise ratio (SN) events.
Pixellensing Observations with the Isaac Newton Telescope–Andromeda Galaxy Amplified Pixels Experiment (POINT-AGAPE) survey (An et al. 2004) and from the Wendelstein Calar Alto Pixellexs Project (WeCAPP) (Fliri et al. 2006).

To be able to account for this dust effect, we have studied the dust properties of M31 (Montalto et al. 2009) and derived an extinction map across the disk of M31, which can be used for quantifying detection efficiencies. Microlensing in M31 differs from the Magellanic Clouds, because at the distance of M31 (770 kpc, Freedman & Madore 1990), most of the sources for possible microlensing events are not resolved, and each pixel of a CCD image can contain hundreds of stars. Instead of monitoring individual resolved stars, one has to monitor pixel light curves and their variations toward dense stellar fields. The sources of microlensing events are usually not resolved before and after the high magnification phases and their “baseline fluxes” are thus unknown. In most cases the magnified source (at least at maximum magnification) appears as a resolved object. However, in order to achieve exquisite photometry in such crowded fields, we thus perform difference image analysis and search for microlensing events at the position of each individual pixel. In order to extract light curves at the position of each individual pixel, we use a point-spread function (PSF) constructed from resolved sources in the image to perform PSF photometry.

The theoretical aspect of pixel lensing has been laid down by Gould (1996) under the assumption of a small impact parameter. Riffeser et al. (2006) reformulated this theory in a more general context.

The first microlensing events toward M31 were reported by the Vatican Advanced Technology Telescope (VATT)/Columbia microlensing survey. They put the idea of Crotts (1992) into practice (Tomane & Crotts 1996) and presented six microlensing events discovered by the joint observations of the VATT and the KPNO 4 m telescope taken during 1994 and 1995 (Crotts & Tomane 1996). Their observations continued from 1997 to 1999, with the VATT and the 1.3 m telescope at the MDM observatory. With additional data from the Isaac Newton Telescope, they presented four probable microlensing events from their three years of data (Uglesich et al. 2004). At the same time, Ansari et al. (1997) also launched the AGAPE; they observed M31 with the 2 m telescope Bernard Lyot (TBL) in the French Pyrenees in 1994 and 1995, which led to the discovery of one bright, short microlensing event (Ansari et al. 1999). Following AGAPE, the POINT-AGAPE monitored M31 from 1999 to 2001; their first microlensing event was announced by Aurière et al. (2001), and three more by Paulin-Henriksson et al. (2002, 2003); another three were reported by Calchi Novati et al. (2003) with additional data from the 1.3 m telescope at the MDM observatory in 1998–1999. The full POINT-AGAPE data were analyzed with three different pipelines, where three (Belokurov et al. 2005), six (Calchi Novati et al. 2005), and ten events (Tsapras et al. 2010) were reported, respectively.

Using the same INT data, the Microlensing Exploration of the Galaxy and Andromeda (MEGA) survey has presented 14 events (de Jong et al. 2006). At the same time, the Nainital Microlensing Survey employed the 1.04 m Sampurnanand Telescope in India to observe from 1998 September until 2002 February. They have extracted one microlensing event from four years of data (Joshi et al. 2005). More recently, the Pixel Lensing Andromeda collaboration (PLAN) carried out observations using the 1.5 m Loiano telescope located in Italy (Calchi Novati et al. 2007) and reported two events in their data collected in 2007 (Calchi Novati et al. 2009). Their further incorporated observations from the 2 m Himalayan Chandra Telescope (HCT) taken in 2010 and reported another event (Calchi Novati et al. 2014). In the meantime, the Pan-STARRS 1 collaboration conducted a high-cadence, long-term Andromeda monitoring campaign (PanAndromeda) utilizing its wide-field ($\sim$7 deg$^2$) camera. Based on its first year of data, Lee et al. (2012) have reported six events in the central 40" $\times$ 40" area, with the promise of detecting more events by taking advantage of the larger survey area and higher cadence from Pan-STARRS 1.

It is worth noting that previous M31 microlensing event identifications may suffer from contamination by variables. For example, Crotts & Tomaney (1996) suspected that some of their events are contaminated by long-period red supergiant variables. Despite the efforts of various campaigns, the MACHO fraction in the mass range 0.1–1 $M_\odot$ is still under debate (see Calchi Novati 2010, for a detailed discussion). For example, the POINT-AGAPE collaboration has reported evidence for a MACHO signal (Calchi Novati et al. 2005), while the MEGA collaboration (de Jong et al. 2006) on the contrary concluded that their events can be fully explained by self-lensing.

Due to the small number of reported events, the origin of M31 microlensing remains an open issue. In this study, we aim to increase the number of microlensing detections and suppress contamination by variables with long-term observations of the M31 bulge. This paper is structured as follows. In Section 2 we present the observations of our long-term survey. Our data reduction is outlined in Section 3, followed by the event detection in Section 4. The analysis of these events is shown in Section 5. A discussion of our events, as well as results from previous M31 microlensing surveys, is presented in Section 6, with a summary and prospects in Section 7.

2. OBSERVATIONS

WeCAPP continuously monitored M31 from 1997 August until 2008 March using the Wendelstein 0.8 m telescope (Riffeser et al. 2001). The data were initially taken with a TEK CCD with 1024 $\times$ 1024 pixels with a field of view (FOV) of 8.3 $\times$ 8.3 arcmin$^2$ pointing at the bulge of M31, optimally on a daily basis in both $R$- and $I$-filters. Following the suggestions of Tomane & Crotts (1996) and Han & Gould (1996), we pointed at the far side of the M31 disk (F1 in Figure 1), where the halo lensing probability is maximized. From 1999 June to 2002 December we collected additional data using the 1.23 m (17/2 $\times$ 17/2 FOV) telescope at Calar Alto Observatory in Spain to increase the time sampling. This provided a FOV which is four times the Wendelstein FOV, and enabled us to survey the major part of the M31 bulge. After 2002, we used the Wendelstein telescope solely to mosaic the full Calar Alto FOV with four pointings, as indicated in Figure 1.

The number of observations taken in the four pointings differs significantly during the 11 seasons. Figure 2 shows a histogram of the number of observed nights by WeCAPP. The most complete seasons are 2000/2001 and 2001/2002 with joint...
observations from both Wendelstein and Calar Alto (see also Table 1).

To have an overview of the observing cadence, we show the daily sampling in Figure 3. Thanks to the joint observations at Wendelstein and Calar Alto, we achieved an average time coverage for F1 in $R$ of 42\% during the 2000/2001 season (peaking in 2000 August with 90\% on JD $\sim$ 2451770) and an average time coverage of 55\% during the 2001/2002 season, reaching more than 93\% in three months (2001 July and October, and 2002 January, around JD $\sim$ 2452110, 2452200, and 2452290, respectively). During the 11 seasons, we have obtained a total sampling efficiency\(^5\) of 14.9\% in $R$ and 11.5\% in $I$, with 11.3\% for $R$ and $I$ combined for all fields (F1–F4), which means that on 11.3\% of the nights we have both $R$ and $I$ observations.

However, not all images have the same quality. Rather than quantifying the fraction of nights we have observed through the

\(^5\) The sampling efficiency is a fraction with respect to the overall baseline length, i.e., including periods where no observations were scheduled.
Table 1
The Number of Analyzed Nights Per Year during the 11 WeCAPP Seasons

| Season       | Observatory | R-band | I-band | R or I-band | R or I-band |
|--------------|-------------|--------|--------|-------------|-------------|
|              | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 | F1 | F2 | F3 | F4 |
| 1997–1998    | WS | 36 | 7  | 1  | 4  | 33 | 7  | 0  | 3  | 37 | 7  | 1  | 4  | 38 |
|              | CA | 89 | 0  | 0  | 0  | 84 | 0  | 0  | 0  | 95 | 0  | 0  | 0  | 95 |
| 1999–2000    | WS or CA | 128 | 0  | 0  | 0  | 124 | 0  | 0  | 0  | 134 | 0  | 0  | 0  | 134 |
| 2000–2001    | WS | 75 | 0  | 16 | 0  | 68 | 0  | 15 | 0  | 75 | 0  | 16 | 0  | 75 |
|              | CA | 106 | 107 | 107 | 107 | 89 | 89 | 89 | 89 | 106 | 107 | 107 | 107 |
| 2001–2002    | WS or CA | 153 | 107 | 119 | 107 | 137 | 89 | 101 | 89 | 153 | 107 | 119 | 107 | 154 |
| 2002–2003    | WS | 106 | 0  | 23 | 0  | 93 | 0  | 21 | 0  | 106 | 0  | 23 | 0  | 106 |
|              | CA | 134 | 136 | 136 | 136 | 119 | 119 | 119 | 119 | 137 | 137 | 137 | 137 |
| 2003–2004    | WS | 35 | 24 | 29 | 31 | 33 | 21 | 26 | 29 | 35 | 24 | 29 | 32 | 39 |
|              | CA | 7  | 7  | 7  | 7  | 6  | 6  | 6  | 6  | 7  | 7  | 7  | 7  |
| 2004–2005    | WS | 25 | 23 | 26 | 25 | 19 | 16 | 19 | 19 | 26 | 23 | 26 | 25 | 47 |
|              | CA | 30 | 28 | 28 | 28 | 26 | 20 | 22 | 23 | 32 | 26 | 28 | 28 | 71 |
| 2005–2006    | WS | 107 | 106 | 103 | 103 | 48 | 45 | 46 | 47 | 107 | 108 | 104 | 103 | 124 |
|              | CA | 134 | 136 | 136 | 136 | 119 | 119 | 119 | 119 | 137 | 137 | 137 | 137 |
| 2006–2007    | WS | 62 | 56 | 52 | 58 | 36 | 35 | 35 | 38 | 63 | 58 | 55 | 61 | 92 |
|              | CA | 89 | 0  | 0  | 0  | 84 | 0  | 0  | 0  | 95 | 0  | 0  | 0  | 95 |
| 2007–2008    | WS | 64 | 0  | 0  | 0  | 60 | 0  | 0  | 0  | 65 | 0  | 0  | 0  | 65 |
|              | CA | 89 | 0  | 0  | 0  | 84 | 0  | 0  | 0  | 95 | 0  | 0  | 0  | 95 |
| Total        | WS | 600 | 253 | 295 | 261 | 468 | 155 | 202 | 172 | 606 | 258 | 301 | 266 | 765 |
|              | CA | 336 | 250 | 250 | 250 | 298 | 214 | 214 | 214 | 345 | 251 | 251 | 251 | 346 |
| Total        | WS or CA | 843 | 503 | 530 | 511 | 690 | 369 | 402 | 386 | 855 | 509 | 536 | 517 | 1015 |

Note. Note that from 1999 until 2002 we used both telescopes at Wendelstein (WS) and Calar Alto (CA). A season is defined to last from May 1 until April 30 of the next year. The total number of observed nights is 1015 nights out of 11 years. A total of 4432 stacked frames were analyzed in both filters and four fields.

Figure 3. Daily samplings of the four different fields F1, F2, F3, and F4 are colored in blue, red, yellow and green, respectively. Periods marked in gray show the 61 days from April 1 to May 31 during which M31 can hardly be observed. See also Table 1. The two seasons with the highest sampling are 2000/2001 and 2001/2002, i.e., those seasons where we could combine Wendelstein with Calar Alto data.

11 seasons we would like to have (as a function of location in M31) the fraction of nights where the noise is below a certain threshold. For this reason, we empirically chose a noise limit of the minimum signal-to-noise ratio (S/N) of 8.9 for our faintest event, i.e., 0.73 × 10^{-5} Jy/8.9, which corresponds to the 8.9σ detection criterion we present in Section 4. For pixels with noise levels above this value, the lensing signal would mix with the high noise and could not be detected. Hence these pixels cannot be used for the detection. The sampling thus depends on the x and y position of the pixel, as well as the observation time t, which we denote as ⟨S(x, y, t)⟩. In Figure 4, we show the area having a noise smaller than our noise limit for every observed night. By averaging over time t, we will get the positional dependence as shown in Figure 5.

3. DATA REDUCTION

We process the data using our customized pipeline MUPipe (Gössl & Riffeser 2002), where standard reduction processes—such as bias subtraction, treatment of bad pixels, flat-fielding, cosmic ray removal—are performed with per-pixel error propagation. To identify unresolved variables, we employ the difference imaging analysis (DIA) proposed by Alard & Lupton (1998), which enables us to detect variables with amplitudes at the photon noise level and to measure their flux excesses relative to high S/N reference images.

After the difference imaging, we perform PSF photometry on each pixel in the following manner. We first extract the PSF profile from several isolated, bright and unsaturated reference stars. Then we fit this PSF to all pixels to generate light curves of varying sources identified in the difference images. The flux of the source is estimated by integrating the count rates over the area of the PSF.

The results from a subset of data of this project have been presented in Riffeser et al. (2003, 2008) and partially contributed to Calchi Novati et al. (2010). In addition to the original microlensing targets, the high-cadence observations also yielded a sample of more than 20,000 variables in the bulge of M31 (Fliri et al. 2006) and 91 candidate novae (Pietsch et al. 2007; Lee et al. 2012).
Selection Criteria for the 11 years of Data Taken Between MJD = 685.5 and 4535.3

| Criterion | Number of Light Curves | Light Curves Left From I | Colors in Figure 6 |
|-----------|------------------------|--------------------------|--------------------|
| I         | Analyzed light curves with $\geq$ 50 data points | 3,872,240 | 100.0% | ... |
| II        | Three consecutive $3\sigma$ in $R$ | 719,628 | 18.6% | ... |
| III       | $\chi_R < 1.5$ and $\chi_I < 2.1$ | 152,753 | 3.9% | Yellow |
| IV        | $S/N > 8.9$ in $R$ and maximum with good PSF | 2247 | 0.5% | Black |
| V         | $-1.5 \leq E^{\text{peak}}_R \leq 1.5$ | 1379 | 10.4% | Green |
| VI        | $t_{\text{WHM}} < 1000$ days | 63 | 16.8% | Blue |
| VII       | $\text{samp}_R^{\text{pre}} > 0.18$ and $\text{samp}_R^{\text{post}} > 0.08$ and $\text{samp}_I^{\text{pre}} > 0.18$ and $\text{samp}_I^{\text{post}} > 0.08$ | ... | ... | ... |

Note. In the third column we show how applying each criterion (II, III, IV, V, VI, VII) to the 3,872,240 light curves (criterion I) reduces the number of filtered light curves.

where $t_0$ is the time of maximum amplification, $t_E$ is the Einstein ring crossing time, and $u_0$ is the impact parameter in units of the Einstein ring radius. The light curve (or the measured flux as a function of time) of the microlensing event can thus be expressed as

$$F(t) = F_0[A(t) - 1] + B,$$

(2)

where $F_0$ is the unlensed flux and $B$ is the blending within the PSF.

This conventional microlensing light curve formula is highly degenerate in $t_E$ and $u_0$ for microlensing events toward M31, because one can no longer resolve the source. For M31 microlensing, the only observables are the flux excess $\Delta F$ and the event timescale $t_{\text{WHM}}$. Gould (1996) has derived the pixel-lensing light curve formula in the context of high magnification. Riffeser et al. (2006) further revised the microlensing light curve formula of Gould (1996), such that microlensing light curves with moderate magnifications can also be well described. The formula for the pixel-lensing light curve from Riffeser et al. (2006) is expressed as

$$\Delta F(t) \approx F_{\text{eff}} \left[ \frac{12(t - t_0)^2}{t_E^2} + 1 \right]^{-1/2} + B,$$

(3)

where $F_{\text{eff}}$ is the effective flux, which for high magnifications is approximated by the flux excess $F_{\text{eff}} \equiv F_0/u_0 \approx \Delta F$. Since Paczynski (1986) was the first to present the simple analytical form of the microlensing light curve as Equation (2), we refer to Equation (2) as the Gould fit throughout this paper.

Since Gould (1996) was the first to introduce the approximated form of the microlensing light curve as Equation (3), we refer to Equation (3) as the Gould fit throughout this paper.

We use Equation (3) to identify microlensing events. Microlensing events are detected in the light curve of each pixel (based on the aforementioned PSF photometry) with several successive criteria. Compared to Riffeser et al. (2003), we introduce additional criteria to avoid human interaction during the selection process. We now describe our criteria; an overview of the number of pixel light curves passing each criterion is listed in Table 2.

1. Criterion I is applied to exclude pixel light curves which have too few data points to make them worth analyzing. Hence we exclude light curves with less than 50 data points in either $R$- or $I$-filters. This leaves us with 3,872,240 light curves.

4. EVENT DETECTION

Paczynski (1986) provided an analytic formula to describe the amplification of a microlensing event:

$$A(t) = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}, \quad u = \sqrt{\frac{(t - t_0)^2}{t_E^2} + u_0^2},$$

(1)
2. Criterion II identifies varying sources that warrant further analysis. We preselect variable pixel light curves with at least three consecutive $3\sigma$ outliers in the $R$-filter.

3. Criterion III is designed to find microlensing light curves with good $\chi^2$. We select pixel light curves that are well described by microlensing light curves. We use the microlensing light curve in Equation (3) with some modifications:

$$\Delta F(t) \approx F_{\text{eff}} \left[ \frac{12(t - t_0)^2 + 1}{(t^2 + 0.5)^2} \right]^{1/2} + c$$

where we set $t_{\text{fit}} = \sqrt{t_{\text{FWHM}} - 0.5}$, hence the FWHM event timescale is always greater than or equal to 0.5 day. We use $t_{\text{fit}}$ instead of $t_{\text{FWHM}}$ to avoid unphysically small $t_{\text{FWHM}}$ due to the limited time resolution (up to half a day) of our observation. The term $c$ takes into account the shift of the baseline flux by a constant in cases for which there is a variable source spatially close to the microlensing event and data from these variable phases enter the reference image. We then filter out light curves with a $\chi_k \equiv \sqrt{\chi^2}$ (where $\chi^2$ is the total $\chi^2$ divided by the degrees of freedom $k$) larger than 1.5 in the $R$-band and larger than 2.1 in the $I$-band. This is less strict than the value we used in Riffeser et al. (2003). The allowed $\chi_k$ in $I$ is slightly higher than in $R$, because the noise level is increased by unaccounted systematics such as the detector fringing and nearby variable stars in the $I$-band.

4. Criterion IV evaluates whether a high flux excess relative to the baseline is more likely caused by random noise or by a true microlensing signal. We consider the S/N of such a high flux excess measurement, $SN_{\text{con},i} \equiv \frac{\Delta F(t_i)}{\sigma_i}$, where the flux offset is $\Delta_{\text{con},i} \equiv y_i - c$, $y_i$ is the $i$th flux measurement at time $t_i$ and $\sigma_i$ is the error of the flux measurement. We take into account the probability of such a high flux excess measurement being close to the maximum of a microlensing light curve fit $p_{\text{fit},i} \propto \exp\left(-\frac{\Delta_{\text{fit},i}^2}{2\sigma_i^2}\right)$, where the flux offset is $\Delta_{\text{fit},i} \equiv y_i - \Delta F(t_i)$, and $\Delta F(t_i)$ is the model flux at time $t_i$ according to Equation (4). We also take into account the probability of such a high flux excess measurement being at the constant baseline $p_{\text{con},i} \propto \exp\left(-\frac{\Delta_{\text{con},i}^2}{2\sigma_i^2}\right)$. We then combine these three factors and define the S/N probability (SNP):

$$SNP = SN_{V} \times p_{\text{fit},i} \times (1 - p_{\text{con},i})$$

This ensures that light curves that have high S/N outliers, which are outside the time interval of the microlensing event, are filtered out.

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Table 3

| Criteria | Number | Percentage |
|----------|--------|------------|
| (1) I II | 719,628 | 100.00     |
| (2) I II III | 152,753 | 21.23 = (2)/(1) |
| (3) I II IV | 18,803 | 2.61 = (3)/(1) |
| (4) I II V | 402,746 | 55.97 = (4)/(1) |
| (5) I II III V | 106,200 | 14.76 = (5)/(1) |
| (6) I II IV V VI VII | 1338 | 0.90 = (10)/(6) |
| (7) I II III V VI VII | 41,214 | 0.03 = (10)/(7) |
| (8) I II III IV VI VII | 15 | 80.00 = (10)/(8) |
| (9) I II IV VI VII | 5382 | 0.22 = (10)/(9) |
| (10) I II III IV V VI VII | 12 | ... |

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Footnote 6: The difference between the individual flux measurement and the constant part/offset of the light curve is derived in two steps: after removing all data points with very high errors (larger than five times the median of all errors) we determine the constant part/offset of the light curve by iteratively fitting a line and clipping away all points that are more than $2\sigma$ errors above.
event, get a lower weight. To avoid multiple detections of the same microlensing signal in neighboring pixels, we only use the pixel with good PSF detections$^7$ to evaluate SNP, i.e., where the PSF fit has a minimum in $\chi^2$ with respect to neighboring pixels. We empirically require one data point in the light curve to have a SNP larger than 8.9 in the R-band to efficiently reject faint variable sources.

5. Criterion V quantifies the temporal correlations of the model–data mismatch (best-fit microlensing light curve versus measured light curve) and enables us to reject intrinsic variable sources more efficiently.

We combine the probabilities for positive $p_i^+$ or negative flux offsets $p_i^-$ from the best-fit microlensing light curve, and assign positive values for consecutive data points that are always on the same side of (either above or below) the best-fit model light curve. For consecutive data points alternating along the best-fit model light curve, we assign negative values. We then define the energy of a potential microlensing light curve as

$$E \equiv \frac{\pi}{\sqrt{n}} \sum_{i=1}^{n-1} \left( p_i^+ p_{i+1}^- + p_i^- p_{i+1}^+ - p_i^+ p_{i+1}^- - p_i^- p_{i+1}^+ \right)$$

where $n$ is the number of data points and the probabilities are defined as $p_i^+ = 0.5 \left[ 1 + \text{erf} \left( \frac{\Delta R_i}{2 \sigma_i} \right) \right]$ and $p_i^- = 1 - p_i^+$. For a random process the distribution of $E$ is a Gaussian with an expectation value of zero and a standard deviation of one. We derive the energy $E^20$ using the $n = 20$ closest data points to $t_0$ in the R-band. We find empirically that a value between $-1.5$ and $1.5$ efficiently rejects periodic variables and allows us to skip the previously used detection by eye in Riffeser et al. (2003).

6. Criterion VI filters out long-period variables. Since our light curves span a baseline of 11 years, contamination from the long-period variables is less severe than in any of the previous campaigns. We inspected the candidate light curves and found that false detections from systematics and moving objects have timescales longer than 1000 days. Hence we are able to empirically increase the upper $t_{\text{FWHM}}$ limit for microlensing searches to 1000 days (compared to, e.g., $t_{\text{FWHM}} < 20$ days in Riffeser et al. 2003). With this criterion we also filter out objects with proper motion. A moving object that passes through the field with constant angular velocity will cause variabilities at some (stationary) pixels that can mimic microlensing signals. These proper-motion objects can of course be excluded by inspecting postage stamps, but we would like to have a completely automatic selection here.

7. Criterion VII rejects light curves that look like microlensing events from their overall light curves but are not well sampled close to the light curve maximum, and hence could be variable sources. The contaminations are mostly from novae, e.g., not well sampled in their rising parts.

We define the sampling quality for the falling and rising parts of each light curve within $(t_0 - 15 \text{ days}, t_0)$ and $(t_0, t_0 + 15 \text{ days})$. The contribution of a single data point is then calculated by integrating the model light curve within $(t_i - 0.5 \text{ days}, t_i + 0.5 \text{ days})$. As sampling criteria we require a total sampling of the area under the light curve of at least 18% on the rising part of the light curve and at least 8% on the falling side in the R- and I-bands.

In the third column of Table 2 we show how applying each criterion (II, III, IV, V, VI, VII) to the 3,872,240 light curves (criterion I) reduces the number of filtered light curves. For example, 152,753/3,872,240 ~ 3.9% of light curves pass criterion III. Less efficient criteria show a high percentage of remaining light curves while efficient criteria filter out more light curves. Therefore criterion IV is our most efficient criterion.

Figure 6 shows the $t_0$ distribution of all pixel light curves under analysis. The colored histograms show how the number of light curves is reduced after each criterion. The total numbers correspond to those given in Table 2.

Because of large dome seeing and an inappropriate auto-guiding system, photometric errors are largest during the first

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$^7$ To find the good PSF detections we have carried out the following steps. (1) We sub-sample each pixel by a factor of 5. (2) We determine the flux at the position of each sub-pixel by fitting a PSF. (3) We compare the $\chi^2$ of the PSF with the adjacent eight pixels. If the pixel has the lowest $\chi^2$ among the adjacent eight pixels, we consider it as a good PSF detection. After the detection we refit the positions of the microlensing events and determine these positions at a sub-pixel level.
Table 4
Paczyński Parameters of the WeCAPP Microlensing Events

| R.A. (J2000) | Decl. (J2000) | $\Delta M_{31}$ (arcmin) | $t_0$ (day) | $t_{\text{FWHM}}$ (day) | $m_R$ (mag) | $\Delta f_R$ (10$^{-3}$ Jy) | $m_I$ (mag) | $\Delta f_I$ (10$^{-3}$ Jy) | $(R - I)$ | log($t_0$) (day) | log($u_0$) | $\chi^2_{\text{det}}$ |
|---------------|---------------|--------------------------|-------------|--------------------------|-------------|-----------------------------|-------------|-----------------------------|----------|-----------------|---------------|--------------|
| 00:42:30.03   | 41:13:01.5    | 4.08                     | 1850.84 ±0.02 | 1.62 ±0.10              | 18.68       | 10.29 ±0.54                 | 17.81       | 18.22 ±0.99                 | 0.88 ±0.03 | 0.03 ±0.01 | 7.85 ±0.04 | -8.18 ±0.02 |
| 00:42:33.01   | 41:19:58.5    | 4.36                     | 1895.41 ±0.71 | 5.85 ±0.24              | 20.81       | 1.45 ±0.37                  | 19.64       | 3.38 ±0.88                  | 1.17 ±0.09 | 1.61 ±0.29 | -1.36 ±0.55 | 1.20         |
| 00:42:57.03   | 41:12:27.9    | 4.40                     | 1585.35 ±0.14 | 2.44 ±0.28              | 20.47       | 1.99 ±0.10                  | 19.11       | 5.51 ±0.26                  | 1.36 ±0.04 | 2.64 ±0.62 | -2.79 ±0.62 | 1.23         |
| 00:42:54.07   | 41:14:37.0    | 2.48                     | 2178.86 ±0.06 | 3.40 ±0.27              | 20.18       | 2.59 ±0.10                  | 19.58       | 3.56 ±0.16                  | 0.60 ±0.05 | 0.99 ±0.11 | -0.93 ±0.15 | 1.40         |
| 00:43:02.03   | 41:18:29.2    | 4.09                     | 2177.85 ±0.39 | 6.34 ±0.16              | 20.94       | 1.29 ±0.12                  | 20.38       | 1.71 ±0.20                  | 0.56 ±0.11 | 1.47 ±0.33 | -1.18 ±0.39 | 1.38         |
| 00:42:49.01   | 41:14:55.3    | 1.52                     | 2317.23 ±0.03 | 0.43 ±0.13              | 18.15       | 16.79 ±2.47                 | 17.36       | 27.59 ±7.84                 | 0.79 ±0.04 | 8.27 ±0.02 | -9.18 ±0.14 | 1.67         |
| 00:42:55.03   | 41:18:50.9    | 3.38                     | 1847.44 ±0.14 | 1.24 ±0.26              | 20.47       | 1.99 ±0.37                  | 19.74       | 3.08 ±0.59                  | 0.73 ±0.13 | 8.68 ±0.07 | -9.13 ±0.05 | 1.02         |
| 00:42:50.03   | 41:18:40.6    | 2.75                     | 2111.55 ±0.10 | 0.58 ±0.14              | 19.11       | 6.93 ±0.47                  | 18.36       | 10.97 ±1.59                 | 0.74 ±0.06 | 1.01 ±0.31 | -1.77 ±0.38 | 1.17         |
| 00:42:44.07   | 41:12:54.9    | 3.22                     | 2231.67 ±0.40 | 14.04 ±1.38             | 21.17       | 1.05 ±0.05                  | 20.48       | 1.55 ±0.11                  | 0.69 ±0.07 | 1.53 ±0.14 | -0.86 ±0.20 | 1.42         |
| 00:42:12.01   | 41:09:21.5    | 9.07                     | 4026.88 ±1.13 | 2.75 ±0.42              | 21.01       | 1.20 ±0.12                  | 20.10       | 2.21 ±0.26                  | 0.92 ±0.11 | 0.81 ±0.33 | -0.83 ±0.39 | 1.38         |
| 00:42:46.02   | 41:15:11.9    | 1.01                     | 1198.81 ±0.18 | 6.41 ±0.79              | 21.09       | 1.13 ±0.08                  | 19.89       | 2.69 ±0.19                  | 1.20 ±0.08 | 1.21 ±0.47 | -0.88 ±0.43 | 1.62         |
| 00:43:07.08   | 41:17:40.7    | 4.64                     | 4018.87 ±0.24 | 4.92 ±1.20              | 20.64       | 1.69 ±0.25                  | 19.80       | 2.90 ±0.43                  | 0.84 ±0.12 | 1.02 ±0.25 | -0.79 ±0.41 | 1.17         |

Note. In the fourth column we also show the distance from the center of M31.

To determine the parameters of the light curve, we include data from POINT-AGAPE, as in Riffeser et al. (2003).
Figure 10. WeCAPP microlensing event light curves: WeCAPP 1–4 with corresponding cut-outs of the difference frames in \( R \)- and \( I \)-bands. The data points are color-coded in gray-scale according to their errors; measurements with larger errors in \( R \) (\( I \)) are shown in light red (light blue), while measurements with smaller errors are shown in dark red (dark blue).
During the second season (1998/99) we were able to decrease the FWHM of the PSF by a factor of 2, and therefore the photometric scatter also became smaller. The vast majority of our microlensing events are detected between the 2000/2001 and 2001/2002 seasons, where we have employed the Calar Alto telescope and the cadence is high.

Figure 11. WeCAPP microlensing event light curves: WeCAPP 5–8 with corresponding cut-outs of the difference frames in $R$- and $I$-bands.
This implies that deeper images with a larger telescope along with densely sampled observations are crucial to detect microlensing events. Our observations in other seasons are pivotal as well, as they serve the purpose of ruling out contamination from variables.

Figure 7 shows the properties of the 719,628 light curves passing criterion II. Since the major contaminations to microlensing detections are variables and novae, we overplot the 23,001 variable sources published in Fliri et al. (2006) in magenta and the 91 novae in Lee et al. (2012) in blue. In

Figure 12. WeCAPP microlensing event light curves: WeCAPP 9–12 with corresponding cut-outs of the difference frames in $R$- and $I$-bands.
Overview of the 56 Microlensing Events in M31 Presented in Different Papers

| Project          | Events | Multi. Detect. | Label in Figures 13 and 14 | Recent              | Citation               |
|------------------|--------|----------------|----------------------------|---------------------|------------------------|
| VATT/Columbia    | 6      | ...            | VC                         | Violet              | Crots & Tomanay (1996) |
| AGAPE            | 1      | ...            | Z                          | Gray                | Ansari et al. (1999)   |
| POINT-AGAPE      | 1      | ...            | N1                         | Blue                | Aurière et al. (2001)  |
| POINT-AGAPE      | 1      | ...            | S4                         | Blue                | Paulin-Henriksson et al. (2002) |
| POINT-AGAPE      | 2      | 2              | N, S                       | Blue                | Paulin-Henriksson et al. (2003) |
| WeCAPP           | 1      | 1              | W                          | Red                 | Riffeser et al. (2003) |
| MDM              | 3      | ...            | C                          | Brown               | Calchi Novati et al. (2003) |
| VATT/Columbia    | 4      | ...            | VC                         | Black               | Ugelshich et al. (2004) |
| MEGA             | 8      | 2              | ML                         | Green               | de Jong et al. (2004)  |
| POINT-AGAPE      | 3      | 4              | N2                         | Blue                | An et al. (2004)       |
| POINT-AGAPE      | 4      | 2              | L1, L2                     | Cyan                | Belokurov et al. (2005) |
| Nainital         | 1      | ...            | NMS                        | Magenta             | Joshi et al. (2005)    |
| MEGA             | ...    | 5              | ML                         | Green               | Cserecsjé et al. (2005) |
| MEGA             | 3      | 11             | ML                         | Green               | de Jong et al. (2006)  |
| WeCAPP           | ...    | 1              | W                          | Red                 | Riffeser et al. (2008) |
| PLAN             | 2      | ...            | OAB                        | Yellow              | Calchi Novati et al. (2009) |
| PLAN             | ...    | 1              | OAB                        | Yellow              | Calchi Novati et al. (2010) |
| PAndromeda       | 6      | ...            | PAnd                      | Orange              | Lee et al. (2012)      |
| PLAN             | ...    | 3              | OAB                        | Yellow              | Calchi Novati et al. (2014) |
| WeCAPP           | 10     | 2              | W                          | Red                 | This work              |

Total 56

Note. In the third column for the total number we counted republished detections only once. For comparison see Figure 14.

Figure 7 it is clear that criteria III and IV are efficient to filter out these two major sources of contamination.

We note that not all of the criteria are independent. To disentangle the issue of criteria overlapping with each other, we perform a test with a subset of the criteria. The results are shown in Table 3.

Crit II and IV overlap already by definition. All detections passing Crit IV are a subset of the detections passing II, because we fit only light curves that have three times $\sigma$ outliers (Crit II). As can be seen in row (3) only 2.6% of the Crit II light curves pass Crit IV, therefore Crit IV is much stricter than Crit II. A comparison between rows (7) and (10) shows that Crit IV is able to reduce the preselected light curves from all other criteria by a factor 3400.

The comparison between Crit III and V shows that Crit V is weaker than III, because it reduces the light curves only by 56% compared to 21% from Crit III. Two thirds of the light curves passing Crit II overlap with the light curves passing Crit V (14.8% as opposed to 21.2%); this shows a quite strong overlap. Also row (8) shows that Crit V has only a small impact on the detection as it reduces the number of detections only from 15 to 12.

In short, we are aware of the overlap among criteria. However, in the cases of Crit II and IV, we need Crit II prior to Crit IV to preselect the light curves of interest, so that we can analyze the full data set in a reasonable amount of time. Nevertheless overlapping criteria should not be an issue if the efficiency study is running through the same detection criteria.

Note that in Crit VI we deliberately set the upper limit of $t_{\text{FWHM}}$ to be 1000 days. The fact that our final set comprises only events with $t_{\text{FWHM}}$ smaller than 15 days may suggest that no rather long microlensing events in M31 exist. If we had set the limit to 20 days, we could not address this speculation.

This $t_{\text{FWHM}}$ limit is empirically chosen by looking into the $t_{\text{FWHM}}$ distributions of the 2247 detections that pass criterion IV, as shown in Figure 8.

We note that the long-timescale fits may arise from slowly moving objects. To test for this we inspect the positions of all detections passing criterion IV with $t_{\text{FWHM}} > 1000$ days. We find that they are homogeneously distributed (they appear in some spikes of bright stars) except for a small region close to a bright object with high proper motion. This object influences the difference imaging kernel and therefore mimics a proper motion of all other sources.

To demonstrate that 1000 days is a reasonable limit for $t_{\text{FWHM}}$, we plot the $t_{\text{FWHM}}$ and $\chi^2$ distributions of the events in Figure 9. The yellow points are all detections passing criterion IV and with $t_{\text{FWHM}} \geq 1000$ days. The green points are all detections passing criterion IV and with $t_{\text{FWHM}} < 1000$ days. The magenta points are variables from Fliri et al. (2006). The blue points are novae from Lee et al. (2012). The red points with black dot are the 12 microlensing events presented in this paper.

5. WeCAPP M31 LENSING EVENTS

In this section we present the 12 microlensing events found in the WeCAPP data. Table 4 gives an overview of the properties of these 12 events. In this table we focus on two observables, $t_{\text{FWHM}}$ and $\Delta_F$. We fit the light curves with Equation (2).

As shown in Table 4, the Paczynski fit provides additional information on the Einstein timescale $t_E$ and the impact parameter $t_0$.

We note that the parameters $t_{\text{FWHM}}$ and $\Delta_F$ are degenerate, which often leads to overestimated errors in these two parameters for very short-timescale events ($t_{\text{FWHM}}$ below...
Irrespective of this degeneracy, we can still determine these two parameters with reasonable uncertainty. To demonstrate the degeneracy, and our confidence in determining these two parameters, we show the 1σ, 2σ, and 3σ contour plot of $t_{\text{FWHM}}$ versus $\Delta F_R$ in the appendix.

The light curves of the 12 WeCAPP events are shown in Figures 10–12. To illustrate the microlensing nature we also present postage stamps from the difference images close to the light curve maximum. These images help to rule out artifacts overlooked by the pipeline, such as hot pixels or cosmic rays as origins of the events. Indeed, as inspection of the postage stamps shows, none of our events is due to such an overlooked artifact. In some cases (W2, W5, W7) the postage stamps also show positions of nearby variables. Because of improved photometric methods (see Riffeser et al. 2006), the light curves for W1 and W2 slightly differ from those published in Riffeser et al. (2003), but agree within the error bars.

6. DISCUSSION

In this section we summarize M31 microlensing events from previous surveys we are aware of and we compare our 12 events with previous studies.

Table 5 lists the project name, number of detected events, their label, and color as used in Figures 13 and 14, and the references for the events. In the second column we report the number of events that were solely detected by the corresponding survey. In the third column we list the number of events that were detected by more than one group. For example, Paulin-Henriksson et al. (2003) published four events from the POINT-AGAPE project, where two of them were only detected by POINT-AGAPE, and two of them were also detected by other projects. Altogether 56 different M31 microlensing events have been published to date (including those presented in this work). Their $t_0$, $t_{\text{FWHM}}$, $\Delta F_R$ distributions are shown in Figure 13. In Figure 14 we show the positions of microlensing events in a 50 × 70 arcmin$^2$ field from the second Palomar Sky Survey.

The first fact to note in the middle panel of Figure 13 is that WeCAPP (red), POINT-AGAPE (blue), and PLAN (yellow) surveys detected very short-timescale events and hardly any events with $t_{\text{FWHM}} > 15$ days. In contrast, the first events ever announced by VATT/Columbia (Crotts & Tomaney 1996, marked in violet color in Figure 13) have very long timescales (five of six events have $t_{\text{FWHM}} > 65$ days). In the same paper Crotts & Tomaney (1996) suspected that some of their events may be caused by long-period variables. The MEGA (green) and Belokurov L2 (cyan) events show an almost flat timescale distribution. Five of the MEGA events are (in deprojection) located in the disk, almost at the same distance from the center of M31. This makes them more suspicious, since they could be intrinsically varying disk stars that exist in a particular evolutionary timescale, which is over-represented at this particular radius within the disk.

Predicting event rates and their characteristics from the theoretical studies, Riffeser et al. (2008) show from their M31 microlensing model that the expected event rate of long-timescale events ($t_{\text{FWHM}} > 30$ days) is an order of magnitude smaller than the event rate of short-timescale events ($t_{\text{FWHM}} < 10$ days), see e.g., their Figure 12. The fact that the vast majority of the events presented in this paper are short-timescale events is therefore in good agreement with expectations. In contrast, the VATT/Columbia and MEGA surveys show an almost flat timescale distribution. Unless surveys analyzed by MEGA and Belokurov et al. (2005) have detection efficiencies that strongly suppress events with timescales <10 days, they should have detected more short-timescale microlensing. An alternative and more plausible explanation is that a large fraction of these long events are indeed long-period variables, but were not ruled out from the microlensing candidate light curves due to the relatively short time span of the survey.

The VATT/Columbia team use their observations in the 1994–1995 season to rule out objects of mass in the range 0.003–0.08 $M_\odot$ as the primary constituents of the mass of M31 (Crotts & Tomaney 1996). Uglesich et al. (2004) find four probable microlensing events with data collected between 1997
and 1999. They conclude that $29^{+30}_{-13}\%$ of the halo masses are composed of MACHOs, assuming a nearly singular isothermal sphere model. They also provide a poorly constrained lensing component mass ($0.02–1.5 M_{\odot}$ at 1σ limits).

Calchi Novati et al. (2005) present an analysis of the POINT-AGAPE data. They indicate that their microlensing event rate is much larger than self-lensing expectation alone. This leads to a lower limit of 20% of the halo mass in the form of MACHOs with mass between 0.5 and $1 M_{\odot}$ at the 95% confidence level. The lower limit drops to 8% for MACHOs of $\sim 0.01 M_{\odot}$.

In contrast, the MEGA team (de Jong et al. 2006) conclude that their 14 events are consistent with a self-lensing prediction. This rules out a MACHO halo fraction larger than 30% at the 95% confidence level. However, recent studies by Ingrosso et al. (2006, 2007) show that, when compared with the timescales, maximum fluxes, and spatial distributions from Monte-Carlo simulations, the MEGA events cannot be fully explained by self-lensing alone.

The evidence for MACHOs can be inferred from individual events provided there is good sampling of the light curves. For example, the WeCAPP-GL1/POINT-AGAPE-S3 event was independently discovered by the POINT-AGAPE (Paulin-Henriksson et al. 2003) and the WeCAPP (Riffeser et al. 2003) collaborations. Joint analysis of the light curves from these collaborations has led to the conclusion that this event is very unlikely to be a self-lensing event (Riffeser et al. 2008). This is because, with a realistic model of the three-dimensional light distribution, stellar population, and extinction of M31, a self-

Figure 14. 56 microlensing events in M31. The image shows a wide field ($50 \times 70$ arcmin) from the second Palomar Sky Survey (ESO Online Digitized Sky Survey —DSS-2-blue). The WeCAPP events are plotted in red, POINT-AGAPE events in blue, Belokurov events in cyan, MEGA events in green, AGAPE Z1 event in black, NMS event in magenta, PLAN events in yellow, PANdromeda events in orange, Slot-AGAPE in brown, VATT from Crotts & Tomaney (1996) in violet, and VATT from Uglesich et al. (2004) in black. We note that although our event W8 appears to be on top of the OAB-N2 event in this figure, their $t_0$ differ by more than 6.5 years ($W8$ has a $t_0$ of $JD = 2452112$ and OAB-N2 has a $t_0$ of $JD = 2454467$). In addition, from our difference images their positions differ by 0.5 arcsec.
A lensing event with the parameters of WeCAPP-GL1/POINT-AGAPE-S3 is only expected to occur every 49 years. In contrast, a halo lensing event (with 20% of the M31 halo consisting of 1 M\(_e\) MACHOs) would occur every 10 years. In addition, combining the data from PLAN and WeCAPP, Calchi Novati et al. (2010) have revealed the finite-source effect in the event OAB-N2. Calchi Novati et al. (2010) then used the finite-source effect to determine the size of the Einstein ring radius, and combined this radius with the time required for the lens to travel across it (\(t_E\)) to derive the proper motion of the lens. Hence they were able to put a strong lower limit on the latter. Since the proper motion of the lens in the halo lensing scenario is different (and much larger) than in the self-lensing scenario (see e.g., Figure 4 of Calchi Novati et al. 2010), their result thus favors the MACHO lensing scenario over self-lensing for this event.

To conclude, some statistical studies and individual microlensing events point to a non-negligible MACHO population, though the fraction in the halo mass remains uncertain. To pinpoint the MACHO mass fraction, a better understanding of the luminous population, i.e., self-lensing rate, is needed.

Determining the MACHO mass fraction requires precise detection efficiency studies which are beyond the scope of this publication. We have started such efficiency studies (J. Koppenhoefer et al. 2015, in preparation). By simulating artificial events in the WeCAPP images we will be able to account for true noise and systematics introduced by the processing and the detection procedure. The results will enable us to derive a robust estimate of the MACHO mass fraction using an improved M31 model for disk, bulge, and halo.

7. SUMMARY AND OUTLOOK

WeCAPP has monitored the bulge of M31 for 11 years, which is the longest time span among M31 microlensing surveys. We have established an automated selection pipeline and present the final 12 microlensing events from WeCAPP. The brightest of these events (see, e.g., Riffeser et al. 2008) is hard to reconcile with self-lensing alone, and hence hints at the existence of MACHOs in the halo of M31. A similar case has been found by Calchi Novati et al. (2010).

To gain insights into the MACHO fraction, in-depth understanding of self-lensing is required, which is only possible with microlensing experiments that monitor both the bulge and the disk of M31 simultaneously. With the advent of Pan-STARRS 1, we have conducted a dedicated project monitoring M31 with a FOV of \(\sim 7\) degree\(^2\). Preliminary results...
of six microlensing events in the bulge have been published in Lee et al. (2012), and a full analysis will follow soon (S. Seitz et al. 2015, in preparation).

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APPENDIX

We show the degeneracy between $t_{\text{FWHM}}$ and $\Delta_F$ for our 12 WeCAPP microlensing events in Figure 15. These two parameters are highly degenerate for very short-timescale events ($t_{\text{FWHM}}$ below 2 days). For events with long timescale, i.e., W3, W4, W5, W9, W10, and W11, their $t_{\text{FWHM}}$ and $\Delta_F$ are well constrained.

We also show the degeneracy between $t_e$ and $u_0$ for our 12 WeCAPP microlensing events in Figure 16. In the pixel-lensing regime, $t_e$ and $u_0$ are highly degenerate, hence the $t_e$--$u_0$ maps are much more degenerate than the $t_{\text{FWHM}}$--$\Delta_F$ maps.

Figure 16. $t_e$ vs. $u_0$ distribution on a log scale of the 12 WeCAPP microlensing events. We note that the $t_e$ and $u_0$ scales shown are different for each event. The 1σ, 2σ, and 3σ contours are marked in green, cyan, and blue, respectively. The best-fit parameter is marked in magenta.

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