No large population of unbound or wide-orbit Jupiter–mass planets

Przemek Mróz1, Andrzej Udalski1, Jan Skowron1, Radosław Poleski1,2, Szymon Kozłowski1, Michał K. Szymański1, Igor Soszyński1, Łukasz Wyrzykowski1, Paweł Pietrukowicz1, Krzysztof Ulaczyk1,3, Dorota Skowron1 & Michał Pawlak1

Planet formation theories predict that some planets may be ejected from their parent systems as result of dynamical interactions and other processes1–3. Unbound planets can also be formed through gravitational collapse, in a way similar to that in which stars form4. A handful of free-floating planetary-mass objects have been discovered by infrared surveys of young stellar clusters and star-forming regions5,6 as well as wide-field surveys7, but these studies are incomplete8–10 for objects below five Jupiter masses. Gravitational microlensing is the only method capable of exploring the entire population of free-floating planets down to Mars-mass objects, because the microlensing signal does not depend on the brightness of the lensing object. A characteristic timescale of microlensing events depends on the mass of the lens: the less massive the lens, the shorter the microlensing event. A previous analysis11 of 474 microlensing events found an excess of ten very short events (1–2 days)—more than known stellar populations would suggest—indicating the existence of a large population of unbound or wide-orbit Jupiter-mass planets (reported to be almost twice as common as main-sequence stars). These results, however, do not match predictions of planet-formation theories11–12 and surveys of young clusters8–10. Here we analyse a sample of microlensing events six times larger than that of ref. 11 discovered during the years 2010–15. Although our survey has very high sensitivity (detection efficiency) to short-timescale (1–2 days) microlensing events, we found no excess of events with timescales in this range, with a 95 per cent upper limit on the frequency of Jupiter-mass free-floating or wide-orbit planets of 0.25 planets per main-sequence star. We detected a few possible ultrashort-timescale events (with timescales of less than half a day), which may indicate the existence of Earth-mass and super-Earth-mass free-floating planets, as predicted by planet-formation theories11,12.

The sample of 2,617 microlensing events we analysed was selected from data collected during the fourth phase of the Optical Gravitational Lensing Experiment13 (OGLE-IV) during the years 2010–15. The survey is monitoring dense fields towards the Galactic centre, nine of which (about 12.6 square degrees in total) were observed with a cadence of either 20 min or 60 min, allowing the detection of extremely short microlensing events. We examined the light curves of almost 50 million stars identified on deep stacked images of each field; each light curve consisted of 4,500–12,000 data points.

The selection of events was conducted in three steps, described in detail in the Methods. First, we searched for ‘bumps’ in the light curves, which we define as at least three consecutive points 3σbase above the baseline level (where σbase is the dispersion of points outside a 360-day window centred on the bump). To minimize contamination from moving objects (like asteroids) and photometry artefacts, we required that the centre of the additional flux coincided with the centre of the star. Events with a very low signal-to-noise ratio and those exhibiting a variability in the baseline were also rejected by these criteria. Next, we removed any remaining artefacts located mainly near the edges of the charge-coupled device (CCD) camera, low-amplitude pulsating red giants, and other variable stars (dwarf novae, flaring stars) that have multiple bumps in their light curves.

Finally, we fitted the microlensing point-source point-lens model to the data and required that the model describe the data appropriately. The lensing model has three parameters: the time t0 and the projected separation u0 (in Einstein radius units) between the lens and the source during the closest approach, and the Einstein radius crossing time tE. (The angular Einstein radius θE of a lens depends on its mass M and relative lens–source parallax θparallax = 1 AU × (Dsource − Dlens)−1, where AU are astronomical units, and Ds and Dl are the distances to the lens and the source, respectively, as follows: θE = √4πMθparallax, where k = 8.14 mas per M⊙, and Ms is the solar mass). Two additional parameters describe the source flux Fs and blended unmagnified flux Fb from possible unresolved neighbours or the lens itself. To ensure that the shortest events were not mistaken for stellar flares, we required at least four data points on the rising branch of the light curve (two if the descending part of the light curve was also covered).

Using our detection efficiency simulations (see below), we found that the event timescales cannot be reliably measured for faint, highly blended events (that is, with blending parameter fblend = Fs/(Fs + Fb) < 0.1, that is, less than 10% of the baseline flux comes from the source), which was predicted theoretically13. Therefore, to ensure that our final results were robust, highly blended events were not included in our sample of high-quality events. Thus, regardless of the timescale, there is no systematic shift between measured and real timescales for simulated data. The final distribution of the event timescales is shown in Fig. 1.

To calculate the detection efficiency we conducted extensive image-level simulations, in which artificial microlensing events were injected into real OGLE images using the point spread function derived from the neighbouring stars. In total, 8.6 million artificial events were simulated. Parameters u0, t0 and logtE were drawn from uniform distributions, but sources were randomly drawn from the luminosity function of each subfield (Extended Data Fig. 1). For simulated events we applied exactly the same selection criteria as those applied to the observed sample of events. Detection efficiency curves for all analysed fields are shown in Extended Data Fig. 2.

The detection-efficiency-corrected histogram of event timescales is presented in Fig. 2 and, clearly, does not show the excess of events with timescales tE ≈ 1–2 days claimed in ref. 11. The difference (at a confidence level of 2.5σ to 3σ) can be explained in part by the relatively small number of events found in the earlier analysis11. In addition to the 2,617 events analysed in this work, we detected over twenty short-duration events that showed clear signatures of binarity19 and did not pass our strict selection criteria for the fit quality. Owing to lower photometric precision, such events may have been mistaken for single short-timescale events. It is also possible that event timescales measured in the previous work suffer from systematic effects (differential refraction,
We detected six possible ultrashort-timescale events ($t_E < 0.5$ d), which may be due to Earth-mass free-floating planets (grey histogram). Solid (dotted) green lines mark the expected microlensing signal assuming that 5-Earth-mass planets are ten (five) times more frequent than stars. Error bars are the 1σ Poisson uncertainties on the counts of the number of events observed in a given $t_E$ bin.

Figure 1 | Observed distribution of timescales of 2,617 high-quality microlensing events discovered by OGLE in 2010–15. The purple line is the best-fitting model. The dotted line constrains the 95% confidence limit on the number of wide-orbit or unbound Jupiter-mass planets of 0.25 planets per star. The dashed red line is the best-fitting model from ref. 11 predicting almost two Jupiter-mass free-floating planets per star. According to that model we should find 64 events with $0.3 < t_E < 1.8$ d, but only 21 were observed (the discrepancy is even larger for events with $0.3 < t_E < 1.3$ d, where 6 events were found out of 42 expected by ref. 11). We detected six possible ultrashort-timescale events ($t_E < 0.5$ d), which may be due to Earth-mass free-floating planets (grey histogram). Solid (dotted) green lines mark the expected microlensing signal assuming that 5-Earth-mass planets are ten (five) times more frequent than stars. Error bars are the 1σ Poisson uncertainties on the counts of the number of events observed in a given $t_E$ bin.

Figure 2 | Distribution of event timescales corrected for the detection efficiency. This distribution, at short timescales, can be well approximated as a power law with a slope of $-3$, consistent with theoretical expectations.27 There remains a small possible excess of events with timescales $0.5 < t_E < 1$ d. If they were caused by the Jupiter-mass lenses, the best-fitting models predict their frequency of 0.05 Jupiter-mass planets per star with a 95% confidence limit of 0.25 planets per star (dotted purple line). All symbols are the same as in Fig. 1. Error bars are the 1σ Poisson uncertainties on the counts of the number of events observed in a given $t_E$ bin.

unphysical treatment of negative blending). Thanks to better image quality (smaller pixel scale, better seeing) and a narrower filter, our photometry is less prone to such systematic effects.

We modelled the observed distribution of event timescales by maximizing the likelihood function $L = \prod \rho(t_E)$, where $\rho(t_E) = \rho_{\text{mod}}(t_E)/\varepsilon(t_E)$ is the normalized predicted timescale distribution (corrected for the detection efficiency $\varepsilon(t_E)$).11,16 We adopted a standard Galactic model17,18 of the distribution and kinematics of stars and tested several mass functions. In our best-fitting model, the initial mass function (IMF) can be approximated as a broken power law with slopes $-0.8$ in the brown dwarf regime ($0.01M_\odot < M < 0.08M_\odot$), $-1.3$ for low-mass stars ($0.08M_\odot < M < 0.5M_\odot$), and $-2.0$ for $M > 0.5M_\odot$. We assumed that all stars mass more massive than $1M_\odot$ evolved into white dwarfs, neutron stars and black holes, depending on their initial mass, and we assumed the binary fraction $f_{\text{bin}} = 0.4$. The model is marked with a purple line in Figs 1 and 2.

Our best-fitting model describes the observed timescale distribution well, but we found there remains a small possible excess of events with timescales $0.5 < t_E < 1.0$ d. If we assume that they can be attributed to Jupiter-mass lenses ($M_{\text{lims}} = 10^{-3}M_\odot$), the maximum-likelihood models predict their frequency of 0.05 per main-sequence star with a 68% confidence interval of $[0.0, 0.12]$ planets per star. The 95% confidence limit is 0.25 Jupiter-mass planets per star. These results agree with upper limits on the frequency of Jupiter-mass planets inferred from direct imaging surveys,23,24 which suggests that almost the entire possible excess of events with timescales $0.5 < t_E < 1.0$ d can be attributed to planets on wide orbits.23

The timescales of the six events passing our criteria for high-quality events are shorter than half a day and these events last less than one night (Fig. 3). We carefully checked CCD images by eye to ensure that these brightenings are real, which rules out problems such as photometry artefacts or asteroids. We also analysed historical light curves for these events; four of the six have been observed by the OGLE survey for 20 years and we did not find any evidence for other outbursts in archival data. Nevertheless, because these events were so short and the light curves were not fully covered, we cannot rule out the possibility that some of them might be flaring stars (especially BLG512.18.22725 and BLG500.10.140417).

The best-fitting microlensing models of these six short events constrain their Einstein timescales in the range $0.1 < t_E < 0.4$ d (Extended Data Table 1). Such short events should be caused by Earth- and super-Earth-mass objects, provided that they have kinematics that are similar to the brown dwarf, stellar and remnant lenses. They might be gravitationally unbound to any star or located at wide orbits (at least several astronomical units from the host star), given no signs of binarity in their light curves. Because the number of ultrashort events is very small and their nature is uncertain, we do not attempt to model their mass function. However, the mere detection of such ultrashort events means that Earth-mass lenses should be very common. If we assume that 5-Earth-mass planets are five times more common than main-sequence stars, the expected number of ultrashort microlensing events is 2.2. For a more realistic mass function12 the expected number of detections is 25% smaller.

According to planet formation theories, most Earth-mass and super-Earth-mass planets should form at relatively small orbital separations (<10AU).22 The most likely sources of wide-orbit and free-floating Earth-mass planets are dynamical interactions in young multi-planet systems.12,23,24 Other mechanisms (including ejections from multiple-star systems, stellar fly-bys, interactions in stellar clusters, and post-main-sequence evolution of the host star(s)) have also been proposed.3 Although these processes are unlikely to produce a sizeable population of Jupiter-mass free-floating planets, Earth-mass planets can be scattered and ejected much more efficiently. Thanks to the superb quality of photometry from space-based observatories and the possibility of continuous observations during approximately
100-day-long windows, future space-based missions, such as WFIRST and Euclid, will have the potential to explore the population of free-floating Earth-mass planets in more detail.

**Online Content** Methods, along with any additional Extended Data display items and Source Data, are available in the online version of the paper; references unique to these sections appear only in the online paper.

**Received 8 May; accepted 15 June 2017.**

**Published online 24 July 2017.**
15. Bennett, D. P. et al. Planetary and other short binary microlensing events from the MOA short-event analysis. *Astrophys. J.* **757**, 119 (2012).

16. Calchi Novati, S., de Luca, F., Jetzer, P., Mancini, L. & Scarpetta, G. Microlensing constraints on the Galactic bulge initial mass function. *Astron. Astrophys.* **480**, 723–733 (2008).

17. Han, C. & Gould, A. The mass spectrum of MACHOs from parallax measurements. *Astrophys. J.* **447**, 53 (1995).

18. Han, C. & Gould, A. Stellar contribution to the Galactic bulge microlensing optical depth. *Astrophys. J.* **592**, 172–175 (2003).

19. Lafrenière, D. et al. The Gemini Deep Planet Survey. *Astrophys. J.* **670**, 1367–1390 (2007).

20. Bowler, B. P., Liu, M. C., Shkolnik, E. L. & Tamura, M. Planets around low-mass stars (PALMS). IV. The outer architecture of M dwarf planetary systems. *Astrophys. J. Suppl. Ser.* **216**, 7 (2015).

21. Clanton, C. & Gaudi, B. S. Constraining the frequency of free-floating planets from a synthesis of microlensing, radial velocity, and direct imaging survey results. *Astrophys. J.* **834**, 46 (2017).

22. Ida, S., Lin, D. N. C. & Nagasawa, M. Toward a deterministic model of planetary formation. VII. Eccentricity distribution of gas giants. *Astrophys. J.* **775**, 42 (2013).

23. Pfyffer, S., Alibert, Y., Benz, W. & Swoboda, D. Theoretical models of planetary system formation. II. Post-formation evolution. *Astron. Astrophys.* **579**, A37 (2015).

24. Barclay, T., Quintana, E. V., Raymond, S. N. & Penny, M. T. The demographics of rocky free-floating planets and their detectability by WFIRST. *Astrophys. J.* **841**, 86 (2017).

25. Spiegel, D. et al. Wide-Field InfraRed Survey TelescopeAstrophysics Focused Telescope Assets WFIRST-AFTA 2015 report. Preprint at https://arxiv.org/abs/1503.03757 (2015).

26. Penny, M. T. et al. ExELS: an exoplanet legacy science proposal for the ESA Euclid mission—I. Cold exoplanets. *Mon. Not. R. Astron. Soc.* **434**, 2–22 (2013).

27. Mao, S. & Paczynski, B. Mass determination with gravitational microlensing. *Astrophys. J.* **473**, 57 (1996).

Acknowledgements We thank M. Kubiak and G. Pietrzynski, former members of the OGLE team, for their contribution to the collection of the OGLE photometric data over the past years. The OGLE project has received funding from the National Science Center, Poland through grant MAESTRO 2014/14/A/ST9/00121 to A.U.

Author Contributions P.M. analysed and interpreted the data, and prepared the manuscript. A.U. initiated the project, reduced the data, and conducted detection efficiency simulations. All authors collected the OGLE photometric observations, reviewed, discussed and commented on the present results and on the manuscript.

Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. Correspondence and requests for materials should be addressed to P.M. (pmroz@astrouw.edu.pl).

Reviewer Information Nature thanks C. Clanton, S. Raymond and T. Sumi for their contribution to the peer review of this work.
METHODS

Data. All data presented in this paper were collected as part of the OGLE-IV sky survey during the years 2010–15. The survey uses the 1.3-m Warsaw Telescope, located at Las Campanas Observatory, Chile. The observatory is operated by the Carnegie Institution for Science. The telescope is equipped with a mosaic, 32-chip CCD camera covering a field of view of 1.4 square degrees with a pixel scale of 0.26″ per pixel. All objects analysed are located within nine OGLE fields, observed with a cadence of either 20 min (BLG501, BLG505, and BLG512) or 60 min (BLG509, BLG504, BLG506, BLG511, BLG534, and BLG611), covering in total 12.6 square degrees. We analysed data collected between 2010 June 29 and 2015 November 8, that is, five and a half Galactic bulge observing seasons. Light curves consist of 4,500–12,000 data points, depending on the field, which gives a total of 360 billion photometric measurements. All analysed data were taken through the I-band filter.

Basic information about the fields analysed is presented in Extended Data Table 2. OGLE photometric pipeline is based on the difference image analysis method. For each field, a reference image is constructed by stacking several highest-quality and seeing frames. This reference image is then subtracted from incoming frames and the photometry is performed on subtracted images. Variable and transient objects that are detected on subtracted images are stored in two databases. The ‘standard’ database consists of all stellar-like objects detected on the reference frame, whereas ‘new’ objects (those that do not correlate with any identified stars) are stored separately; see the description of the OGLE photometric pipeline.

Event selection. We analysed 50 million light curves, from all the objects in the ‘standard’ database. We began our analysis by computing photometric uncertainties and transforming magnitudes into fluxes. It is known that uncertainties returned by the difference image analysis method are underestimated and ref. 31 provides an algorithm for their correction, so that these uncertainties match the observed scatter of the data. The purity of our sample is almost 100%. Over 90% of microlensing events detected in real time by the OGLE Early Warning System passed our cut 2 criteria. We detected an additional 20–30% events (depending on the field) compared to Early Warning System detections. The full distribution of timescales of detected microlensing events is shown in Fig. 1. Extended Data Table 4 presents the number of events detected in individual fields and timescale bins.

Detection efficiency. To calculate the event detection efficiency, we carried out extensive image-level simulations in which we injected artificial microlensing events into real OGLE frames using the PSF derived from neighbouring stars. In each iteration we simulated 5,000 events per CCD detector, so the star density did not increase much (by 5–10%). We carried out six iterations for each field, so in total 8,6 million events were simulated in all fields. Parameters \(t_0\) and \(\sigma_0\) were drawn from uniform distributions: \(0.0 \leq t_0 \leq 1.5\) and \(2455377 \leq \sigma_0 \leq 2455388\). Einstein timescales were drawn from a log-uniform distribution \(-1.0 \leq \log(E) \leq 2.5\). Sources were taken from the range 14 mag \(\leq I_s \leq 22\) mag from the luminosity function of each subfield, which was created as follows. We constructed a very deep luminosity function for the subfield BLG513.12, which was observed both by the OGLE-IV survey and by the Hubble Space Telescope. The OGLE-IV luminosity function and the Hubble Space Telescope luminosity function overlap in the range 16 mag \(\leq I_c \leq 18\) mag (Extended Data Fig. 1). This deep luminosity function was used as a template to generate artificial microlensing events in other fields, after shifting it so that the centroid of the red clump giant stars matched the centroid of the red clump stars, which serve as good standard candles, form a local maximum in the luminosity functions (in Extended Data Fig. 1). We therefore took into account variable bulge geometry and reddening. If there was evidence for differential reddening, we divided subfields into smaller parts. There were a few subfields (7% of the total analysed area) where we were not able to detect the red clump stars owing to extremely high extinction; such events were omitted from the final calculations (we detected only a negligible number of 48 microlensing events in these fields).

For the simulated events we applied exactly the same selection criteria as for the real events (Extended Data Table 3). The detection efficiency curves for all analysed fields are shown in Extended Data Fig. 2 and listed in Extended Data
Table 5. We note that the detection efficiency for events with \( t_E = 2 \) d is very high, up to 53% of the maximum efficiency for field BLG1512. Efficiencies for fields observed with 20-min and 60-min cadence are very similar, except for the shortest events with \( t_E < 0.5 \) d. In general, we found that detection efficiencies are most sensitive to crowding and interstellar reddening towards the given field (fields with higher reddening and higher crowding have lower efficiencies). We note that events were simulated using a standard point-lens point-source model. Higher-order effects, like the parallax (causing deviations in the light curve induced by the Earth’s motion\(^{50}\)) were not included and so detection efficiencies for long events (\( t_E > 100 \) d) may be slightly underestimated. Similarly, we did not include the finite source effect, which may reduce our detection efficiency for the shortest events (\( t_E \approx 0.1 \) d), when the Einstein ring size becomes similar to the source star radius\(^{48}\).

Parameter recovery. We also used our simulations to ensure that there is no systematic difference between measured and real timescales. In Extended Data Fig. 3 we plot timescales for simulated events passing all criteria from Extended Data Table 3. We found there is no systematic bias in measured timescales, unless events were faint and highly blended. This effect was predicted by ref. 14, where it was found theoretically that in such cases the event timescale, impact parameter and blending parameter may be severely correlated, because information on the event timescale comes mostly from wings of the light curve that can more easily be affected by the photometric noise. In Extended Data Fig. 4a we show the ratio between measured and ‘real’ (simulated) timescale \( t_{E,\text{real}}/t_{E,\text{meas}} \) versus the blending parameter \( f_b = F_b/F_l + F_s \). It is clear that timescales of highly blended and faint events are not well measured and are systematically underestimated. A similar effect was also noticed in earlier work\(^ {51} \), where it was found that \( t_{E,\text{in}} \) was systematically about 5% smaller than \( t_{E,\text{meas}} \) regardless of \( f_b \). Strong correlations between blending, impact parameter, and event timescale may also lead to the incorrect determination of parameters. For example, one short event reported by ref. 11, MOA-ip-1, has an about 5% smaller than \( t_{E,\text{meas}} \), where it was found that \( t_{E,\text{in}} \), consistent with our models from Extended Data Fig. 5a for fixed \( \alpha_{\text{bd}} \).

The IMF slope derived in the stellar regime is consistent with the ‘canonical’\(^ {53} \) value of \(-1.3\). Observations of brown dwarfs in open clusters and star-forming regions indicate \( \alpha_{\text{bd}} \approx 0.6-0.7 \) (ref. 55 and references therein) and our models are consistent with those values. On the other hand, censuses of nearby field brown dwarfs tend to prefer lower slopes. Ref. 56 found a 60% confidence interval of \( \alpha_{\text{bd}} \approx 0.6-0.7 \) and other studies (ref. 55 and references therein) support \( \alpha_{\text{bd}} \approx 0.6 \). However, mass function measurements for isolated field brown dwarfs are affected by difficulties in measuring their ages, distances, and masses.

**Planetary mass function.** To explain the excess of short events, ref. 11 modelled their event timescale distribution using a stellar IMF with \( \alpha_{\text{bd}} = 0.8, \alpha_{\text{stellar}} = 1.3 \) and \( M_{\text{break}} = 0.7M_{\odot} \) with an additional planetary component, approximated as a delta function at \( M = 10^{-5} M_{\odot} \). That model is shown in Figs 1 and 2 as a dashed red line. According to that model we should find 64 events with \( 0.3 \leq t_E < 1.8 \) d, but only 21 were observed (the discrepancy is even larger for events with \( 0.3 \leq t_E < 1.3 \) d, where 6 events were found but 42 expected). Moreover, the model of ref. 11 systematically underpredicts the number of long-timescale events (because of its very low sensitivity to long events, \( t_E > 100 \) d, the model found only five events in this range).

The best-fitting model described the observed timescale distribution well, but there remains a small possible excess of events with timescales \( 0.5 \leq t_E < 1 \) (Figs 1 and 2). If we assume, following ref. 11, that they are due to Jupiter-mass lenses (\( M_{\text{break}} = 10^{-5} M_{\odot} \)), the best-fitting models predict their frequency of 0.05 Jupiter-mass planets per star with a 68% confidence interval of [0, 0.12] planets per star. The 95% confidence limit is 0.25 Jupiter-mass planets per star. Our results agree with upper limits on the frequency of Jupiter-mass planets inferred from direct imaging surveys\(^ {53,54} \). For example, a high-contrast adaptive imaging search\(^ {55} \) for giant planets around nearby M-dwarf stars did not find any planets, proving very strong upper limits (at the 95% confidence limit) of 10–16% (depending on the model) for planets of between 1 and 13 Jupiter masses, at a distance of approximately 10–100 au. This suggests that almost the entire possible excess of events with timescales \( 0.5 \leq t_E < 1 \) d can be attributed to planets on wide orbits.

**Code availability.** We have opted not to make the event detection and simulation codes publicly available, because they were designed to work with internal photometric databases. The code for the modelling of the timescale distribution is available from the corresponding author upon reasonable request.

**Data availability.** The data that support the findings of this study are available from the corresponding author upon reasonable request.

28. Alard, C. & Lupton, R. H. A method for optimal image subtraction. Astrophys. J. 503, 325–331 (1998).
29. Wozniak, P. R. Difference image analysis of the OGLE-II bulge data. I. The data and the analysis. Acta Astron. 50, 421–450 (2000).
30. Udalski, A. The Optical Gravitational Lensing Experiment. Real time data analysis systems in the OGLE-III survey. Acta Astron. 53, 291–305 (2003).
31. Skowron, J. et al. Analysis of photometric uncertainties in the OGLE-IV Galactic bulge microlensing survey. I. Data analysis and results. Acta Astron. 66, 1–14 (2016).
32. Wyrzykowski, L. et al. OGLE-III microlensing events and the structure of the Galactic bulge. Astrophys. J. Suppl. Ser. 216, 12 (2015).
33. Wray, J. J., Eyer, L. & Paczyński, B. OGLE small-amplitude variables in the Galactic bulge. Mon. Not. R. Astron. Soc. 349, 1059–1068 (2004).
34. Park, B.-G. et al. MOA-2003-BLG-37: a bulge jerk-parallax microlens degeneracy. Astrophys. J. 609, 166–172 (2004).

© 2017 Macmillan Publishers Limited, part of Springer Nature. All rights reserved.
35. Jiang, G. et al. OGLE-2003-BLG-238: microlensing mass estimate for an isolated star. Astrophys. J. 617, 1307–1315 (2004).
36. Smith, M. C., Woźniak, P., Mao, S. & Sumi, T. Blending in gravitational microlensing experiments: source confusion and related systematics. Mon. Not. R. Astron. Soc. 380, 805–818 (2007).
37. Hawley, S. L. et al. Kepler flares. I. Active and inactive M dwarfs. Astrophys. J. 797, 121 (2014).
38. Holtzman, J. A. et al. The luminosity function and initial mass function in the Galactic bulge. Astron. J. 115, 1946–1957 (1998).
39. Gould, A. Extending the MACHO search to about 10^6 solar masses. Astrophys. J. 392, 442 (1992).
40. Bennett, D. P. & Rhie, S. H. Detecting Earth-mass planets with gravitational microlensing. Astrophys. J. 472, 660–664 (1996).
41. Kiraga, M. & Paczynski, B. Gravitational microlensing of the Galactic bulge stars. Astrophys. J. 430, L101–L104 (1994).
42. Han, C. & Gould, A. Statistical determination of the MACHO mass spectrum. Astrophys. J. 467, 540 (1996).
43. Bissantz, N., Debattista, V. P. & Gerhard, O. Large-scale model of the Milky Way: stellar kinematics and the microlensing event timescale distribution in the Galactic bulge. Astrophys. J. 601, L155–L158 (2004).
44. Wood, A. & Mao, S. Optical depths and time-scale distributions in Galactic microlensing. Mon. Not. R. Astron. Soc. 362, 945–951 (2005).
45. Dwek, E. et al. Morphology, near-infrared luminosity, and mass of the Galactic bulge from COBE DIRBE observations. Astrophys. J. 445, 716–730 (1995).
46. Zheng, Z., Flynn, C., Gould, A., Bahcall, J. N. & Salim, S. M dwarfs from Hubble Space Telescope star counts. Astrophys. J. 555, 393–404 (2001).
47. Gould, A. Measuring the remnant mass function of the Galactic bulge. Astrophys. J. 535, 928–931 (2000).
48. Williams, K. A., Bolte, M. & Koefer, D. Probing the lower mass limit for supernova progenitors and the high-mass end of the initial-final mass relation from white dwarfs in the open cluster M35 (NGC 2168). Astrophys. J. 693, 355–369 (2009).
49. Kozloń, B., Kottas, A., De Yoreo, M. & Thorsett, S. E. The neutron star mass distribution. Astrophys. J. 778, 66 (2013).
50. Özel, F., Psaltis, D., Narayan, R. & McClintock, J. E. The black hole mass distribution in the Galaxy. Astrophys. J. 725, 1918–1927 (2010).
51. Zoccali, M. et al. The initial mass function of the Galactic bulge down to 0.15 M_\odot. Astrophys. J. 530, 418–428 (2000).
52. Belczynski, K. et al. Compact object modeling with the StarTrack population synthesis code. Astrophys. J. Suppl. Ser. 174, 223–260 (2008).
53. Kroupa, P. On the variation of the initial mass function. Mon. Not. R. Astron. Soc. 322, 231–246 (2001).
54. Wegg, C., Gerhard, O. & Portail, M. MOA-II Galactic microlensing constraints: the inner Milky Way has a low dark matter fraction and a near maximal disc. Mon. Not. R. Astron. Soc. 463, 557–570 (2016).
55. Alves de Oliveira, C. The low mass end of the IMF. Mem. Soc. Astron. Ital. 84, 905 (2013).
56. Allen, P. R., Koerner, D. W., Reid, I. N. & Trilling, D. E. The substellar mass function: a Bayesian approach. Astrophys. J. 625, 385–397 (2005).
57. Quanz, S. P., Lafrenière, D., Meyer, M. R., Reggiani, M. M. & Buenzli, E. Direct imaging constraints on planet populations detected by microlensing. Astron. Astrophys. 541, A133 (2012).
Extended Data Figure 1 | Galactic bulge luminosity function used for simulations. a, Deep luminosity function (LF) for subfield BLG513.12, which was observed both by the OGLE-IV survey and by the Hubble Space Telescope (HST)\textsuperscript{38}. Both luminosity functions overlap in the range $16 \, \text{mag} < I < 18 \, \text{mag}$. This deep luminosity function was used as a template to generate artificial microlensing events in analysed fields, after shifting to match the centroid of the red clump giant stars in a given field. b, Comparison between the observed luminosity function for subfield BLG512.32 and the simulated luminosity function.
Extended Data Figure 2 | Detection efficiency curves. Detection efficiencies as a function of the Einstein timescale $t_E$ for all analysed fields (averages for all subfields in the given field). Fields BLG501, BLG505 and BLG512 were observed with a 20-min cadence, and the remaining fields with a 60-min cadence. Error bars are the $1\sigma$ Poisson uncertainties on the counts of the number of simulated events in a given $t_E$ bin.
Extended Data Figure 3 | Comparison between measured Einstein timescales $t_{E,\text{out}}$ and ‘real’ (simulated) timescales $t_{E,\text{in}}$ for simulated events. Only events passing selection criteria from Extended Data Table 3 (including the cut on the blending parameter $f_s > 0.1$) are shown. Note that the colour scale is logarithmic. There is no systematic offset between measured and real timescales.
Extended Data Figure 4 | Comparison between measured and ‘real’ (simulated) parameters. a, Ratio between the measured Einstein timescale $t_{E,\text{out}}$ and ‘real’ (simulated) timescale $t_{E,\text{in}}$ for simulated events versus the blending parameter $f_s = F_s/(F_s + F_b)$. Timescales of faint and highly blended ($f_s < 0.1$) events are not well measured and are biased by a strong degeneration between Einstein timescale, blending and impact parameters. Timescales of events showing a high negative blending ($f_s > 1.5$) are systematically underestimated, but the bias is relatively small and such events comprise a negligible fraction of all events. b, Distributions of $t_{E,\text{out}}/t_{E,\text{in}}$ for simulated events passing selection criteria from Extended Data Table 3 (including the cut on the blending parameter $f_s > 0.1$). Regardless of the timescale, there is no systematic bias between measured and real timescales within 1%. For 90% of simulated events $0.63 < t_{E,\text{out}}/t_{E,\text{in}} < 1.65$. The MAD is the median absolute deviation from the data’s median.
Extended Data Figure 5 | Constraints on IMF slopes. a, Assuming that all lenses are single; b, assuming binary fraction $f_{\text{bin}} = 0.4$. 
Extended Data Table 1 | Best-fitting parameters for ultrashort microlensing event candidates

| Star             | RA             | Decl. | $t_b$ (HJD) | $t_l$ (d) | $t_f$ (d) | $\omega_b$ | $i_s$ | $i_b$ | $\lambda_e$ | $\lambda_f$ |
|------------------|----------------|-------|-------------|-----------|-----------|------------|-------|-------|--------------|--------------|
| BLGS01.315900    | 17$^\mathrm{h}$50$^\mathrm{m}$42$^\mathrm{s}$45 | 29$^\mathrm{d}$24$^\mathrm{h}$49$^\mathrm{m}$7 | 2456175.648 | 0.241     |           | [0.21,0.78] | 0.772 | 18.20 | 0.97         |
| BLGS01.02127000  | 17$^\mathrm{h}$53$^\mathrm{m}$13s44 | 30$^\mathrm{d}$18$^\mathrm{h}$59$^\mathrm{m}$6 | 2457172.692 | 0.146     |           | [0.12,0.26] | 0.517 | 19.13 | 0.77         |
| BLGS00.10140417  | 17$^\mathrm{h}$53$^\mathrm{m}$16s89 | 28$^\mathrm{d}$40$^\mathrm{h}$51$^\mathrm{m}$4 | 2456116.554 | 0.246     |           | [0.23,0.37] | 0.377 | 19.08 | 1.24         |
| BLGS01.2633361   | 17$^\mathrm{h}$54$^\mathrm{m}$17s54 | 29$^\mathrm{d}$18$^\mathrm{h}$17$^\mathrm{m}$0 | 2455671.124 | 0.320     |           | [0.29,0.79] | 0.471 | 18.04 | 1.11         |
| BLGS05.27114211  | 17$^\mathrm{h}$59$^\mathrm{m}$04s18 | 28$^\mathrm{d}$36$^\mathrm{h}$51$^\mathrm{m}$7 | 2457157.780 | 0.158     |           | [0.15,0.21] | 0.597 | 19.14 | 1.38         |
| BLGS12.1822725   | 18$^\mathrm{h}$05$^\mathrm{m}$25s00 | 28$^\mathrm{d}$28$^\mathrm{h}$23$^\mathrm{m}$9 | 2456064.921 | 0.128     |           | [0.08,0.19] | 0.138 | 20.95 | 0.16         |

$i_s$ is the source brightness and $i_b = f_s/(f_s + f_b)$ is the blending parameter. We also show 1σ confidence intervals for $t_b$. The inclusion of the finite source effect does not improve $\chi^2$ much (typically $\Delta \chi^2 = 0.0–3.3$). Equatorial coordinates are given for the epoch J2000. RA, right ascension; Decl., declination.
Extended Data Table 2 | Basic information about analysed fields

| Field  | RA       | Decl.      | i    | b     | N_{stars} | N_{epochs} |
|--------|----------|------------|------|-------|-----------|------------|
| BLG00  | 17°51'60'' | -28°36'35'' | 0.9999 | -1.0293 | 4.0       | 4708       |
| BLG01  | 17°51'56'' | -29°50'00'' | -0.0608 | -1.6400 | 5.2       | 12117      |
| BLG04  | 17°57'33'' | -27°59'40'' | 2.1491 | -1.7747 | 5.8       | 6435       |
| BLG05  | 17°57'34'' | -29°13'15'' | 1.0870 | -2.3890 | 6.9       | 12083      |
| BLG06  | 17°57'31'' | -30°27'23'' | 0.0103 | -2.9974 | 5.3       | 4712       |
| BLG11  | 18°03'02'' | -27°22'49'' | 3.2835 | -2.5219 | 5.5       | 4595       |
| BLG12  | 18°03'04'' | -28°36'39'' | 2.2154 | -3.1355 | 6.9       | 10268      |
| BLG34  | 17°51'51'' | -31°04'15'' | -1.1356 | -2.2547 | 4.2       | 4652       |
| BLG61  | 17°35'33'' | -27°09'41'' | 0.3282 | +2.8242 | 5.0       | 4526       |

Equatorial coordinates are given for the epoch J2000. N_{stars} is the number of stars in millions and N_{epochs} is the number of collected frames during 2010–15. I and b are Galactic longitude and latitude, respectively.
## Extended Data Table 3 | Selection criteria for high-quality microlensing events

| Criteria | Remarks | Number |
|----------|---------|--------|
| $\chi^2_{\text{red}} / \text{dof} \leq 2.0$ | No variability outside the 360 day window centered on the event | |
| $n_{\text{OA}} \geq 3$ | Centroid of the additional flux coincides with the source star centroid | |
| $\chi^2_{s} = \sum (F_i - F_{\text{best}}) / \sigma_i \geq 32$ | Significance of the bump | 43,158 |
| $s < 0.4$ | Rejecting photometry artifacts | |
| $A > 0.1 \text{ mag}$ | Rejecting low-amplitude variables | |
| $n_{\text{bump}} = 1$ | Rejecting objects with multiple bumps | 11,989 |
| $\chi^2_{f_0} / \text{dof} \leq 2.0$ | Fit quality: | |
| $\chi^2_{b_{f,\text{E}}} / \text{dof} \leq 2.0$ | $\chi^2$ for all data | |
| $\chi^2_{b_{f,\text{E}}} / \text{dof} \leq 2.0$ | $\chi^2$ for $|f - b| < 4b$ | |
| $\chi^2_{b_{f,\text{S}}} / \text{dof} \leq 2.0$ | $\chi^2$ for $|f - b| < 2b$ | |
| $\chi^2_{b_{f,\text{T}}} / \text{dof} \leq 2.0$ | $\chi^2$ for $|f - b| < 1$ day | |
| $\chi^2_{b_{f,\text{S}}} / \text{dof} \leq 2.0$ | $\chi^2$ for $|f - b| < 5$ days | |
| 2455377 ≤ $t_0$ ≤ 2457388 | Event peaked between 2010 June 29 and 2015 December 31 | |
| $u_b \leq 1$ | The minimum impact parameter | |
| $t_b \leq 22.0$ | The minimum $f$-band source magnitude | |
| $n_{b} \geq 2$ if $n_{g} \geq 2$ | Rising and descending parts of the light curve should be sufficiently sampled | |
| $n_{b} \geq 4$ if $n_{g} < 2$ | | |
| $F_{b} > -0.25$ | The maximum negative blend flux, corresponding to $f = 19.5$ mag star | |
| $t_{b} > 0.1$ | Rejecting highly-blended events | 2617 |
Extended Data Table 4 | Number of events detected in individual timescale bins

| Bin $\log_10 t$ | BLG500 | BLG501 | BLG504 | BLG505 | BLG506 | BLG511 | BLG512 | BLG534 | BLG611 |
|----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 1              | -0.93  | 0      | 1      | 0      | 0      | 0      | 0      | 0      | 0      |
| 2              | -0.79  | 0      | 0      | 1      | 0      | 0      | 0      | 0      | 0      |
| 3              | -0.65  | 1      | 1      | 0      | 0      | 0      | 0      | 0      | 0      |
| 4              | -0.51  | 0      | 1      | 0      | 0      | 0      | 0      | 0      | 0      |
| 5              | -0.37  | 0      | 0      | 0      | 0      | 0      | 0      | 0      | 0      |
| 6              | -0.23  | 0      | 1      | 0      | 0      | 0      | 0      | 0      | 0      |
| 7              | -0.09  | 1      | 0      | 0      | 1      | 0      | 0      | 0      | 0      |
| 8              | 0.05   | 1      | 1      | 1      | 0      | 0      | 0      | 0      | 0      |
| 9              | 0.19   | 0      | 4      | 0      | 2      | 0      | 4      | 1      | 1      |
| 10             | 0.33   | 3      | 5      | 4      | 4      | 1      | 0      | 3      | 5      |
| 11             | 0.47   | 4      | 9      | 7      | 8      | 5      | 8      | 3      | 8      |
| 12             | 0.61   | 10     | 19     | 13     | 28     | 10     | 10     | 13     | 6      |
| 13             | 0.75   | 17     | 40     | 17     | 39     | 19     | 11     | 13     | 17     |
| 14             | 0.89   | 22     | 32     | 24     | 55     | 26     | 19     | 28     | 20     |
| 15             | 1.03   | 25     | 39     | 30     | 78     | 34     | 22     | 40     | 22     |
| 16             | 1.17   | 26     | 35     | 46     | 57     | 44     | 33     | 46     | 24     |
| 17             | 1.31   | 29     | 62     | 38     | 62     | 39     | 30     | 40     | 24     |
| 18             | 1.45   | 23     | 42     | 39     | 53     | 32     | 32     | 41     | 33     |
| 19             | 1.59   | 15     | 39     | 27     | 40     | 32     | 24     | 25     | 20     |
| 20             | 1.73   | 12     | 25     | 20     | 39     | 19     | 21     | 31     | 18     |
| 21             | 1.87   | 7      | 13     | 11     | 20     | 10     | 10     | 12     | 6      |
| 22             | 2.01   | 3      | 9      | 6      | 11     | 6      | 7      | 3      | 2      |
| 23             | 2.15   | 5      | 2      | 3      | 2      | 7      | 1      | 4      | 2      |
| 24             | 2.29   | 0      | 1      | 1      | 3      | 2      | 3      | 0      | 1      |
| 25             | 2.43   | 0      | 0      | 0      | 1      | 2      | 0      | 0      | 0      |

There are 25 bins equally spaced in $\log_10 t$ between −1.0 and 2.5.
### Extended Data Table 5 | Detection efficiencies for the analysed fields

| Bin | \( \log_{10} E \) | BLG500 | BLG501 | BLG504 | BLG505 | BLG506 | BLG511 | BLG512 | BLG534 | BLG611 |
|-----|-------------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 1   | -0.93             | 0.0016 | 0.0033 | 0.0021 | 0.0045 | 0.0015 | 0.0016 | 0.0039 | 0.0013 | 0.0012 |
| 2   | -0.79             | 0.0030 | 0.0071 | 0.0046 | 0.0078 | 0.0043 | 0.0038 | 0.0085 | 0.0033 | 0.0041 |
| 3   | -0.65             | 0.0041 | 0.0086 | 0.0061 | 0.0110 | 0.0057 | 0.0057 | 0.0126 | 0.0047 | 0.0053 |
| 4   | -0.51             | 0.0061 | 0.0118 | 0.0089 | 0.0139 | 0.0086 | 0.0077 | 0.0144 | 0.0068 | 0.0084 |
| 5   | -0.37             | 0.0096 | 0.0144 | 0.0126 | 0.0180 | 0.0120 | 0.0119 | 0.0186 | 0.0095 | 0.0121 |
| 6   | -0.23             | 0.0130 | 0.0209 | 0.0176 | 0.0248 | 0.0189 | 0.0181 | 0.0297 | 0.0160 | 0.0180 |
| 7   | -0.09             | 0.0194 | 0.0279 | 0.0255 | 0.0343 | 0.0299 | 0.0278 | 0.0381 | 0.0226 | 0.0290 |
| 8   | 0.05              | 0.0278 | 0.0365 | 0.0368 | 0.0423 | 0.0396 | 0.0388 | 0.0503 | 0.0335 | 0.0390 |
| 9   | 0.19              | 0.0371 | 0.0423 | 0.0461 | 0.0506 | 0.0495 | 0.0486 | 0.0603 | 0.0395 | 0.0525 |
| 10  | 0.33              | 0.0447 | 0.0506 | 0.0559 | 0.0571 | 0.0593 | 0.0596 | 0.0705 | 0.0484 | 0.0631 |
| 11  | 0.47              | 0.0508 | 0.0557 | 0.0630 | 0.0692 | 0.0675 | 0.0680 | 0.0790 | 0.0592 | 0.0755 |
| 12  | 0.61              | 0.0608 | 0.0630 | 0.0701 | 0.0753 | 0.0784 | 0.0758 | 0.0876 | 0.0641 | 0.0863 |
| 13  | 0.75              | 0.0658 | 0.0669 | 0.0750 | 0.0816 | 0.0866 | 0.0832 | 0.0940 | 0.0746 | 0.0874 |
| 14  | 0.89              | 0.0737 | 0.0746 | 0.0855 | 0.0876 | 0.0937 | 0.0907 | 0.0990 | 0.0772 | 0.1025 |
| 15  | 1.03              | 0.0760 | 0.0769 | 0.0910 | 0.0940 | 0.1011 | 0.0949 | 0.1056 | 0.0838 | 0.1107 |
| 16  | 1.17              | 0.0858 | 0.0826 | 0.0939 | 0.0950 | 0.1035 | 0.1035 | 0.1113 | 0.0899 | 0.1204 |
| 17  | 1.31              | 0.0872 | 0.0831 | 0.1026 | 0.1014 | 0.1079 | 0.1067 | 0.1131 | 0.0913 | 0.1252 |
| 18  | 1.45              | 0.0949 | 0.0898 | 0.1099 | 0.1055 | 0.1184 | 0.1151 | 0.1206 | 0.1012 | 0.1361 |
| 19  | 1.59              | 0.0964 | 0.0940 | 0.1145 | 0.1108 | 0.1191 | 0.1212 | 0.1286 | 0.1048 | 0.1389 |
| 20  | 1.73              | 0.1024 | 0.0973 | 0.1192 | 0.1134 | 0.1264 | 0.1249 | 0.1302 | 0.1105 | 0.1470 |
| 21  | 1.87              | 0.1000 | 0.1004 | 0.1207 | 0.1174 | 0.1288 | 0.1254 | 0.1336 | 0.1111 | 0.1525 |
| 22  | 2.01              | 0.1029 | 0.0965 | 0.1182 | 0.1124 | 0.1253 | 0.1218 | 0.1331 | 0.1085 | 0.1500 |
| 23  | 2.15              | 0.0989 | 0.0928 | 0.1122 | 0.1072 | 0.1148 | 0.1146 | 0.1160 | 0.1029 | 0.1458 |
| 24  | 2.29              | 0.0853 | 0.0788 | 0.0979 | 0.0890 | 0.0998 | 0.0914 | 0.0906 | 0.0888 | 0.1295 |
| 25  | 2.43              | 0.0618 | 0.0539 | 0.0638 | 0.0538 | 0.0596 | 0.0560 | 0.0548 | 0.0578 | 0.0891 |

There are 25 bins equally spaced in \( \log_{10} E \) between –1.0 and 2.5.