
# Abstracts of talks and pre-recorded talks

**In-person: 42 • Virtual 25 • Total: 67**

Symbols: In-person participant Remote participant

### Assessing the Impact of Binary Systems on Microlensing: Adding Binary Systems to SPISEA and PopSyCLE

Natasha Abrams • University of California, Berkeley

Gravitational microlensing provides a unique opportunity to probe the mass distribution of stars, black holes, and other objects in the Milky Way. However, population simulations are necessary to interpret results from photometric microlensing surveys. The contribution from binary objects is often minimized or neglected in these simulations despite the high percentage of binary systems and the potential microlensing holds to probe binaries. In order to simulate the population effects of binary and multiple systems on microlensing, we add resolved binary parameters based on Duchêne & Kraus (2013) to Stellar Population Interface for Stellar Evolution and Atmospheres (SPISEA), software that simulates stellar clusters. We then inject these multiples into Population Synthesis for Compact-object Lensing Events (PopSyCLE), a package that simulates Milky Way microlensing surveys. When making OGLE style cuts, we find that 27% of events have a multiple-lens and single source, 23% have a single lens and a multiple-source, and 16% have a multiple-lens and a multiple-source. This suggests that stellar and compact object binary source and even binary lens-binary source models should be included more frequently in event analysis. Since we do not yet include binary disruption, the black holes are all in binaries. Therefore, the higher masses of black holes leads them to have a higher average mass increase than stars, and the fraction of events with Einstein crossing time $> 120$ days caused by black holes increases from 22% to 41%. The mean Einstein crossing time shifts from 19.6 days for single events only to 27.9 days for singles and multiple events, after cutting obvious binary events with multiple peaks and high asymmetry. The Einstein crossing time distribution of PSPL-like events (i.e. single and multiple events that are not obvious binaries from light curves) is now well aligned with that from Mróz et al. (2017), indicating that multiple systems had been a significant missing piece between simulations and reality.

### An Ongoing HST SNAP Survey of Historical Microlensing Events

Jay Anderson • HST

We present early results from the ongoing Cycle 29 HST SNAP program GO-16716 (PI-Sahu). The goal of this program is to re-image historical microlensing events that have previous HST imaging. These follow-up observations will be made 10+ years after the initial observations so that—in the case where the lens can be seen—a clear separation between lens and source can be made. This will help pin-down degenerate microlensing parameters for those events with luminous lenses. For those events with no detectable lenses, it will bolster their interpretation as a low-mass planetary lens or a higher-mass WD/NS/BH lens. We have specified 70 targets and see this program as largely a community service program. Not all targets will get observed, but we have under-filled the orbits to maximize the number of targets that get observed.

### Unique opportunities of a Euclid-Roman joint survey

Étienne Bachelet • IAP

At the end of the decade, the Roman microlensing survey is expected to detect 30000 microlensing events, that includes 1500 cold planets. In 2022, the Euclid space mission will be launched and will start its main survey just after reaching its stable orbit at L2. I will present the capabilities of two Euclid-Roman joint surveys. I will first highlight the potential of a small survey of the Roman microlensing fields during the first month of the Euclid mission. I will show how these observations are efficient to collect unique constraints on the relative proper motions and lens fluxes of the microlensing events that Roman will detect $\sim 5$ years later. The second survey consist of simulatenous observation of the Roman and Euclid. Because Roman and Euclid will share similar orbit at L2, a joint-surveys allows the detection of the microlensing parallax for a large fraction of the microlensing events, including lenses of planetary mass. These constraints will be of first importance to reveal the distribution of low-mass lenses in the Milky Way.

### Candidate of the microlensing planet not toward the bulge

Makiko Ban • Astronomical Observatory, University of Warsaw

More than a hundred exoplanets have been found using microlensing method. All of them except one (Fukui et al. 2019) were found towards the Galactic bulge. We report the second microlensing planet that is not seen towards the bulge: AT2021uey, which was alerted by ASAS-SN, ZTF, and Gaia. The ground-based surveys ASAS-SN and ZTF successfully observed an anomaly of the event whilst Gaia failed to detect the anomaly due to its low cadence. The anomaly indicates the existence of a gaseous planet beyond the snow line.

### Differentiable modeling of binary and triple lens light curves using the "caustics" code

Fran Bartolić • University of St Andrews

I will present a new open-source code called "caustics" (`https://github.com/fbartolic/caustics`) which enables the computation of photometric light curves for binary and triple lens events. The code is implemented in the JAX Python framework which enables the computation of *exact* gradients of the model likelihood with respect to all input parameters of the model. This is made possible by the use of automatic differentiation.

"caustics" uses the contour integration method to compute the magnification of an extended limb-darkned source in *a fraction of a second* for either binary or triple lens configurations. It can run on both CPU-s and GPU-s and it is extensively tested. The availability of exact gradients of the likelihood for the first time enables the use of efficient optimization and MCMC sampling algorithms (for instance, Hamiltonian Monte Carlo) with binary and triple lens light curves.

Another innovation in "caustics" is the use of the Ehrlich-Aberth complex polynomial root solver implemented in custom CUDA C++ code which can compute the solutions to point-source binary and the triple lens equations in parallel on a GPU. Using this solver solving the lens equation at >100k points in the lens plane at once costs only a few tens of miliseconds of GPU time. The gradients of the lens equations solutions with respect to the input parameters can also be evaluated at the same cost by making use of the implicit function theorem.

### Cold Planet Demographics from Microlensing and Radial Velocity Surveys

Dave Bennett • NASA Goddard Space Flight Center & University of Maryland

I present a preliminary analysis of cold planet demographics using results from gravitational microlensing and radial velocity surveys. Unlike published exoplanet demographics analyses, I present microlensing results using host star mass measurements and limits, so the host mass dependence of the exoplanet distribution can be measured. The combination of microlensing and radial velocity surveys allows us to take advantage of the wide range of orbital separation sensitivity from the radial velocity data and the sensitivity down to low masses with the microlensing data.

### Mass Measurement Updates with Keck AO Image Analysis

Aparna Bhattacharya • University of Maryland

Mass measurement of the planets and their host stars is an essential precursor study for Roman Galactic Exoplanet survey. A big advantage if Keck is that it is also in IR just like Roman. In this talk I will demonstrate how this method has evolved over time with different events and measured really small separations to confirm that we can definitely measure most of them with Roman telescope. This study is also going to show the host mass dependence of the exoplanets which is very important since it will answer significant questions of planet formation.

### A Jovian Analog Orbiting a White Dwarf Star

Joshua Blackman • UTAS

I will discuss our recent published result regarding the non-detection of a main-sequence lens host in the microlensing event MOA-2010-BLG-477. Using constraints from re-modelling of the microlensing light curve together with high-resolution adaptive optics follow-up photometry from Keck, we show that the lens like most likely a white dwarf. There are only a handful of major planets and planet candidates detected around white dwarfs and this is the only one that resembles the expected fate of our solar system. The system contains a $\sim 0.5$ solar mass white dwarf orbited by a 1.4 Jupiter mass planet which likely formed at the same time as its progenitor star and survived the intermediate phases of the star's evolution.

### Search for intermediate mass black holes by combining MACHO and EROS data

Marc Moniez on behalf of Tristan Blaineau • IJCLab-IN2P3

The search for microlensing effects towards the LMC constrains the abundance of massive compact objects in the Galactic halo. Historical studies (MACHO, EROS, OGLE, MOA) have excluded objects lighter than 10 solar masses as a major component of Galactic dark matter. The detection of coalescences of heavier black holes by LIGO/Virgo has rekindled interest in dark matter as compact objects. The effectiveness of previous microlensing studies was limited for high lensing masses, due to the long duration of the expected events. The combination of the historical EROS and MACHO databases, which cover distinct periods, allows us to obtain light curves with a duration exceeding 10 years duration. As a result, the microlensing search sensitivity could be extended to mass lenses up to several hundred solar masses. I will present and discuss the results of this combination of the MACHO and EROS surveys.

### The MOA 16 Year Dataset

Ian Bond • Massey University

Since commencing observations in 2006, the MOA project has accumulated more 100 TB of imaging data with the 80 Megapixel camera attached to the 1.8 m telescope. Such a large data volume would have been considered unmanageable with the technology of the day at the start of our campaign. However, storage technology has now advanced to the stage that the entire MOA dataset can fit on a single mid to high range NAS. Work has now commenced on developing the

MOA dataset as a general science resource based on imaging data products. I will present the latest status and future plans for this resource.

### VBBinary Lensing's extension to astrometric microlensing

Valerio Bozza • Salerno

VBBinaryLensing is a public code for the computation of microlensing magnification. It is available in C++ and Python and has been embedded in most microlensing modeling platforms. It is based on contour integration with parabolic corrections and optimal sampling. Current and future missions such as Gaia and Roman will provide more and more detections of astrometric shifts during microlensing events. Such measurements represent important complements to photometry and require simultaneous astrometric and photometric modeling. We present the recent extension of VBBinaryLensing to astrometric microlensing, which comes at practically no additional computational cost with respect to photometry. We also discuss other improvements for limb darkening, orbital motion and the perspectives for an extension to multiple lenses.

### Interferometric observations of Gaia19bld

Arnaud Cassan • IAP

We present long-baseline interferometric observations of Gaia19bld, performed with the PIONIER instrument mounted on the VLTI. Our time-series observations allow us to measure the angular Einstein ring radius to a high accuracy, as well as the direction of the source-lens relative motion. Combining our measurements with parallax measurements from ground-based photometric follow-up yields the lens mass to a high accuracy. We will explain our observing strategy, how the modeling of the interferometric data was performed, and how it was combined to photometric measurements to derive the lens mass and distance. We will also discuss the accuracy of our measurements in comparison with previous published results.

### Black Holes Hiding in Plain Sight

Will Dawson • LLNL

We will present our investigation into the abundance and properties of black holes through photometric microlensing surveys. We have used the PopSyCLE simulation suite to estimate the abundance and characteristics of black holes in existing and future surveys, both for astrophysical and primordial (i.e., black hole dark matter) formation mechanisms. Based on these simulations we have determined optimal filters for black hole identification in photometric light curve surveys and used these simulations in conjunction with the microlensing survey data to estimate the mass and class (i.e., star, black hole, neutron star, etc.) probability density functions. Our method provides a new means of finding far more black holes than traditional approaches, as well as a new means of constraining the properties of the Milky Way. An underlying thread of the presentation will discuss the microlensing communities historical use of biased estimators (e.g., histograms of single point estimators), introduce alternative unbiased estimators, and discuss the impact to physical interpretations both past and present.

### Single epoch astrometric microlensing in lensed quasars

Raquel Forés-Toribio • Valencia University

Future improvements in astrometric instrumentation will allow centroid measurements of a few microarcseconds. In the scenario of quasar microlensing, such precision could be employed to infer lens systems properties (such as mass fraction in compact objects or quasars disks sizes) in a single campaign of observations. In this work we present how lens parameters such as convergence, shear, compact objects or source sizes affect centroid displacements.

### Tomo-e Gozen and MuSCAT3: new survey and follow-up facilities in the northern hemisphere

Akihiko Fukui • The University of Tokyo

The Gaia and ZTF surveys have been discovering dozens of microlensing events per year in the Galactic plane, providing valuable opportunities to discover nearby lensing systems in less dense fields. However, due to the limited observing cadences, these survey facilities alone are not sufficient to well characterize short-timescale events or planetary anomalies. Here we introduce new all-sky-survey and multiband-follow-up facilities named Tomo-e Gozen and MuSCAT3, respectively. Tomo-e Gozen is a wide-field CMOS camera mounted on the 1.05m telescope at the Kiso observatory in Japan, and has been surveying the entire northern sky once to several times per night for multi purposes since 2019. MuSCAT3 is a four-channel imager mounted on the 2m FTN at the Haleakala observatory in Hawaii, and has been robotically operated by LCO since 2020. We will present some example microlensing light curves obtained with these new facilities to show that they are useful in filling the longitudinal gap of telescopes in the northern hemisphere.

### The Roman Galactic Exoplanet Survey

Scott Gaudi • OSU

I summarize the properties of the Roman Galactic Exoplanet Survey (RGES), one possible realization of the Bulge Variability Survey, which itself is one of three core community surveys that will be carried out with NASA's Nancy Roman Space Telescope (Roman). The notional RGES survey will consist of photometric monitoring of a $\sim 2$ sq. degree area toward the Galactic bulge every 15-minutes in a wide, $\sim$1-2 micron filter. The survey will consist of six 72-days seasons, with most of the seasons being concentrated early and late in the nominal 5-year Roman prime mission. I will describe the activities of the RGES Science Investigation Team (SIT) over its 5-year tenure and advertise opportunities to get involved with the future preparation for, and further definition of, the Bulge Variability Survey.

### Modeling approaches for planetary events, the cases of OGLE-2018-BLG-0677 and KMT-2021-BLG-0919

Martin Herrera • Canterbury

Microlensing is a very effective method for detecting extrasolar planets. Lightcurves models describe these events, and they are used to study them. Here I present a description of how a Bayesian analysis uses these parameters in combination with a galactic model to obtain the physical description of the lens. In particular, a comparison in the approach used by the event OGLE-2018-BLG-0677 and KMT-2021-BLG-0919.

OGLE-2018-BLG-0677 was an event observed in 2018 by the KMTnet and OGLE telescopes. It presented a small dip that encouraged the presence of a binary lens. It presented a particular degeneracy, where two possible solutions are extremely close in the parameter space, and only the geometry of the lens plane is different. Due to its short duration, it is not possible to detect parallax, and only the crossing time and a finite effect provided the information for the galactic model. The analysis resulted in a super-Earth orbiting a brown dwarf with an average distance similar to the sun and venus. In comparison, KMT-2021-BLG-0919 was observed in 2021 by KMTnet. Given the duration, it was possible to obtain a parallax, and we compared the same galactic modeling approach as for OGLE-2018-BLG-0677, but contrasted with the case of a galactic prior for the lightcurve parameters to obtain direct feedback during the lightcurve modeling, also including an error renormalization as free parameters during the modeling process and information from the Gaia catalog with information of the source.

### Optimizing the Rubin LSST Survey Strategy

Knut Olsen (**invited**) • NSF's NOIRLab

Exploring the transient optical sky, of which microlensing is a key phenomenon, is one of the four science pillars of the Vera C. Rubin Observatory's 10-year Legacy Survey of Space and Time (LSST). In this talk, I will describe the approach of Rubin Observatory and the Survey Cadence Optimization Committee to designing LSST such that it balances the demands of its diverse science cases and maximizes its discovery potential for new phenomena, particularly in the time domain. While the SCOC is converging on broad recommendations on LSST's footprint and cadence, I will highlight a number of questions about the survey strategy that remain, particularly in the areas of strong interest to the microlensing community.

### Identifying Gravitational Microlensing Events in Photometric Light Curves with a Deep Neural Network

Stela Ishitani Silva • NASA Goddard Space Flight Center

We present an evaluation of our neural network pipeline applied to gravitational microlensing detection and event classification. Our generalized photometric neural network pipeline automatically identifies and characterizes events in photometric light curves. The pipeline uses the raw light curves and does not require any other prior modeling or information on the light curve. Using the flux of the light curve without pre-extracting extra features can have a few advantages. First, the approach has no intrinsic biases. Second, using only the network is very fast compared to other methods. Third, the neural network might be able to learn more complicated and detailed ways of detecting things. In previous work, we have successfully applied it to identify exoplanet transit candidates using light curve data from the Transiting Exoplanet Survey Satellite (Olmschenk et al. 2021), which indicated that a similar approach applied to gravitational microlensing was very promising. Now, we present the results of the pipeline when trained with 549,447 previously classified light curves acquired by the Microlensing Observations in Astrophysics (MOA) collaboration during nine years, from 2006 to 2014. The MOA collaboration conducted the first high cadence microlensing surveys towards the Galactic bulge and has previously reported the planet frequency as a function of planet-to-star mass ratio (Suzuki et al. 2016). The Suzuki et al. (2016) analysis defined the mass-ratio threshold $q < 0.03$ as the upper limit for planetary events because it was comprised of events that were detected as single-lens events by the MOA alert system. We expect to use this pipeline to determine the detection efficiency within the MOA data set for all mass ratios, through the brown dwarf desert to stellar binaries, which is required for the statistical understanding of the exoplanet and binary star distribution. We will also evaluate our pipeline as an alternative detection method.

### Nearby dark lens hiding in Gaia DR3 astrometry

Maja Jabłońska, Ilknur Gezer, Lukasz Wyrzykowski • Warsaw University Astronomical Observatory, Poland

Galactic massive lenses with large Einstein Radius should cause a measurable astrometric microlensing effect, i.e. the light centroid shift due to motion of two images. Such shift in the position of a background star due to microlensing was not included in the *Gaia* astrometric model, therefore significant deviation should cause *Gaia* astrometric parameters to be determined incorrectly.

Here we studied the photometric microlensing events reported by the Gaia mission in DR3 and selected those with potential astrometric signal. We identified one event, GaiaDR3-ULENS-001, for which Gaia poor goodness of fit and erroneous parallax could indicate presence of the astrometric signal. Base on the photometric microlensing model, we simulate Gaia astrometric time-series with astrometric microlensing effect. We find that adding microlensing with Einstein Radius of 1.5, reproduces well the astrometric quantities reported by Gaia.

We estimate the mass of the lens to about 0.6 sun masses and its distance, proposing the lens is a nearby isolated white dwarf.

## Predictions of the Roman Galactic Bulge Time Domain Survey: Constraints on the Frequent of Earth-Analogs

Samson Johnson • OSU

The frequency of Earth-like planets in the habitable zone of Sun-like stars (eta-Earth) is a fundamental input in estimating the occurrence rate of life resembling that on Earth, and therefore an important parameter for designing future direct imaging missions. eta-Earth is currently best estimated by the Kepler transit survey, but Earth-analog systems with long periods and shallow transits are on the edge of the survey's sensitivity. The Roman Galactic Bulge Time Doman Survey will be able to detect Earth-analog systems through microlensing, but similarly they will be on the boundary of its sensitivity due to low-mass ratios and small projected separations. We perform simulations of the Roman Galactic Bulge Time Domain Survey to estimate its ability to measure eta-Earth. We incorporate the Galactic Model presented by Koshimoto et al. (2021) in these simulations and we investigate the impact of observational cadence on Roman's sensitivity to these systems. Roman's ability to estimate eta-Earth will hinge on the extrapolation from systems with larger mass-ratios and wider projected separations.

## The promise of Gaia and Roman for astrometric microlensing

Zofia Kaczmarek • Cambridge

Gravitational lensing provides a great tool for studying dark objects, however degeneracies make it very hard to recover their physical parameters (such as lens mass and distance) from observations. Observing astrometric deviations can bring new information and tackle those degeneracies. As astrometric effects are very subtle, it has long been impossible to detect them; however, ongoing and future space missions have great potential to bring new, exciting advances to this field. The Gaia mission has just reached its third data release and continues to provide precise all-sky astrometry. The future Roman Space Telescope mission will survey the Galactic Bulge in the infrared with unprecedented cadence and precision, casting new light on the dense, largely unexplored regions of the sky.

Each of these datasets will pose particular challenges. Gaia brings a unique scanning pattern and 1D astrometry; its low cadence in the Galaxy makes it difficult to constrain complicated microlensing event lightcurves. Moreover, until Gaia Data Release 4, time-series astrometry will not be available. 5-parameter fits from Gaia DR2 and DR3 can be used as an indicator of astrometric lensing signal, but caution must be taken in interpreting such limited datasets. On the other hand, the cadence of Roman observations of the Galactic Bulge will result in large, computationally demanding datasets.

I will introduce open source codes we are developing that could be helpful for simulating and fitting photometric and astrometric microlensing in the context of those missions. In particular, I will present astromet.py (a package for building and fitting astrometric tracks for single stars, binary systems and lensing events, including a close emulation of the Gaia pipeline) and nested_ulens_parallax (application of the nested sampling algorithm to characterising degenerate posterior distributions of microlensing event parameters). I will show simulations and fits of realistic mock Gaia and Roman data obtained using those codes; in case of Gaia, I will also point to ongoing developments with real data.

### K2-2016-BLG-0005Lb: the first space based discovery of an exoplanet via microlensing

Eamonn Kerins on behalf of David Specht • Manchester

We present the first bound exoplanet to be discovered blindly from a space-based observatory. K2-2016-BLG-0005Lb occurred during microlensing Campaign 9 of Kepler's K2 mission (K2C9). The cadence of Kepler provided well sampled lightcurve photometry throughout caustic entry and exit. When supplemented with ground photometry from OGLE, MOA, CFHT and KMTNet, the data allowed a direct mass measurement through parallax and finite source effects that confirms the planetary companion. We report on the details of this object and its significance for the emerging era of space-based exoplanet microlensing.

### Gravitational lensing events in the Alpha Centauri system: opportunities for exoplanet detection and beyond

Pierre Kervella • LESIA

Thanks to their low galactic latitude and fast proper motion, the components of the nearest triple system Alpha Centauri (A, B and Proxima) approach distant background stars at small angular separations relatively frequently. Close approaches between Proxima and distant stars were observed with the HST and the VLT in 2016, enabling the estimation of its gravitational mass. The Alpha Cen A and B components are too bright to be measured by Gaia, but precise astrometry with ALMA and VLT/NACO enable us to accurately predict future lensing event configurations. We will present the conjunctions that will occur within the next decade (particularly the S5 star approach in 2028) and a preliminary report on our GRAVITY observations of the first conjunction that occurred in April 2021. These conjunctions offer promising opportunities to search for exoplanets in the Alpha Cen system, measure the gravitational masses of the stars, as well as dramatically improve the accuracy of the space velocity of the system. The latter is important, e.g., to assess the feasibility of a ballistic mission to Alpha Centauri such as the Breakthrough Starshot concept.

### Analysis of Planetary Microlensing Event OGLE-2014-BLG-0221, with a Jupiter Mass Ratio Planet Orbiting a Late-Type Star, or Possibly a Stellar Remnant

Rintaro Kirikawa • Osaka

We present the analysis of microlensing event OGLE-2014-BLG-0221, which was observed by both the MOA and OGLE Collaborations. Our light curve modeling reveals two degenerate models, one with a small microlensing parallax signal constrained only by an upper limit, and one with a large parallax signal of $\pi_{\rm E} \sim 0.4$.

The two models are similar in their planetary parameters with a mass ratio of $q \sim 10^{-3}$ and a separation of $s \sim 1.1$. The small parallax model implies that the lens system consists of a late-type star orbited by a gas giant, the large parallax model favors a nearby massive lens. Limits on the excess flux at the position of the source suggest a dark lens. If the dark lens model is true, this would be the second planet found around a stellar remnant. Since the models predict different relative proper motion and source and blending fluxes, future high angular resolution follow-up observations would be able to rule out either of the models and reveal true characteristic of the lens system.

### Prediction of astrometric microlensing events a unique option to derive single-star masses

Jonas Klüter • Louisiana State University

The mass is the most substantial quantities of a star. On the Main Sequence, it determines the temperature, surface gravity and the evolution or for White Dwarfs strongly correlates with the stellar radius. Currently, relations concerning stellar masses are mainly based on binary stars, where a direct measurement is possible. Since single stars evolve differently, it is important to derive the masses of single stars directly. Beside strongly model-dependent asteroseismology, astrometric microlensing is the only other usable tool to estimate single-star masses.

Mass measurements with an accuracy a few percent are possible by doing precise astrometric measurements of the lensed position of a background source in combination with accurate predictions of the positions of the lensing star and the unlensed source using data of the ESA Cornerstone Mission Gaia. Further, the precise astrometric data from Gaia can be used to predict at what epochs such astrometric microlensing events will happen.

I will present our analysis of the recently published eGaia DR3 catalogue for the prediction of a number of astrometric microlensing events in the near future. Especially, I will present an event to be caused by a white dwarf, which will happen in 2025, this will be a unique test case for the mass-radius relation of white dwarfs.

### Prediction of the Planet Detection Rates by the PRIME Microlensing Survey

Iona Kondo • Osaka

The PRime-focus Infrared Microlensing Experiment (PRIME) will start a NIR microlensing survey in the Galactic Center, which cannot be seen by conventional visible observation due to the high dust extinction. The main purpose of PRIME is to reveal the demography of low-mass planets outside the snow-line and the planet frequency in the Galactic Center.

PRIME will conduct a H-band high-cadence wide field of view (FOV) survey using a 1.8m telescope (f/2.29) with 1.45 deg$^2$ (0.5"/pix) NIR camera to be installed at South African Astronomical Observatory (SAAO) in Sutherland.

Here, we investigate the expected number and characteristics of the detected planets depending on various observation strategies. In order to maximize the number of planet detections, we optimize the observation field and the cadence between which there are trade-offs.

We estimate the detection efficiency of the primary events and planetary signals following the procedure bellow: (i) randomly simulate microlensing events toward different directions in the Galactic bulge based on the Galactic model (Koshimoto+2021), (ii) generate synthetic data points based on the observation condition and strategy of PRIME, (iii) exert detectability criteria to these simulated events. Finally, we calculate the statistics and planet yields for each observation strategy. In this talk, we will present the current results of our simulation and discuss the optimal survey strategies and predicted planet yields by the PRIME microlensing survey. We will also discuss the effect of changing the Koshimoto+2021 Galactic model to the Besançon Galactic Model (Robin+2003).

### No Large Dependence of Planet Frequency on Galactocentric Distance

Naoki Koshimoto • NASA Goddard Space Flight Center & University of Maryland

Gravitational microlensing is currently the only technique that helps study the Galactic distribution of planets as a function of distance from the Galactic center. The Galactic location of a lens system can be uniquely determined only when at least two of the three quantities that determine the mass-distance relations are measured. However, even if only one mass-distance relation can be obtained, a large sample of microlensing events can be used to statistically discuss the Galactic distribution of the lenses. In this study, we extract the Galactic distribution of planetary systems from the distribution of the lens-source proper motion, $\mu_{\rm rel}$, for a given Einstein radius crossing time, $t_{\rm E}$, measured for the 28 planetary events in the statistical sample by Suzuki et al (2016). Because microlensing is randomly caused by stars in our Galaxy, the observational distribution can be predicted using a Galactic model. We incorporate the planet-hosting probability proportional to $M_L^m R_L^r$ into a Galactic model for random-selected stars, where $M_L$ is the lens mass (∼host mass), and $R_L$ is the Galactocentric distance. By comparing the observed distribution with the model-predicted $\mu_{\rm rel}$ distribution for a given $t_{\rm E}$ at various combinations of (m, r), we obtain an estimate $r = 0.2 \pm 0.4$ under a plausible uniform prior for m of $0 < m < 2$. This indicates that the dependence of the planet frequency on the Galactocentric distance is not large, and suggests that the Galactic bulge does have planets.

### Microlensing event highlights in Gaia Science Alerts

Katarzyna Kruszyńska • Astronomical Observatory, University of Warsaw

On the 19th of December 2013 Gaia Space Satellite was launched by European Space Agency. Its main goal is to measure proper motions and parallaxes of over 1 billion stars in Milky Way. However, ever since the first data has been acquired in 2014, Gaia has observed much more than that.

Up to this day its alerting system of sudden change in brightness of observed sources AlertPipe has detected around 18,000 transients.

More than 300 of them have been classified as microlensing candidates from all over the sky, with Gaia16aye, Gaia18cbf, Gaia19bld, Gaia19dke and Gaia20fnr as spectacular examples among them.

Microlensing events detected and observed by Gaia offer a possibility for registering not only photometric effect, but also its astrometric counterpart. This will provide additional data, that will help break degeneracies for single source-single lens events, which might lead to mass measurements of lenses and, in particular, to discovering lensing black holes.

I will present the most interesting events discovered by the Gaia Alerts, in particular the analysis of one of the longest events ever found, Gaia18cbf with its time-scale of nearly 500 days. The lens properties derived based on Gaia and follow-up data suggest it is a dark remnant at about 4 Solar masses.

### Light Curve Calculations for Triple Microlensing Systems

Renkun Kuang • Tsinghua University

Multiple lens systems are not rare in microlensing, more than 15 triple microlensing events have been discoverd. Modelling such events is not straightforward due to the difficulty in calculating the light curve, as well as the high dimension parameter space. I will introduce a new public available code that we developed for calculating triple microlensing light curves. I will give example on applying this code to analyse real events.

### Searching for isolated black holes with astrometric microlensing using HST

Casey Lam • University of California, Berkeley

We present the analysis of five black (BH) hole candidates identified from MOA and OGLE between 2009-2011. Archival HST astrometric data from 2009-2017 is jointly analyzed with the MOA and OGLE lightcurves in order to measure the masses of the lens. One of the five targets is likely a low-mass BH. We also compare the full sample of 5 candidates to theoretical expectations on the number and masses of BHs in the Milky Way detectable via microlensing. Due to the small size as well as sample selection issues, the resulting constraints are weak; however, they are consistent with the theoretical expectation of 2 hundred million BHs in the Milky Way.

### Black Holes in the Milky Way

Jessica Lu (**invited**) • University of California, Berkeley

The Milky Way's black hole (BH) population is challenging to find outside of the 10s detected in accretion binary systems. Outside the Milky Way, merging BH binary populations are now found in large numbers through gravitational waves. Yet to fully interpret these results and place astrophysical constraints on the demographics, origin, and evolution of black holes, we require a more complete census of the isolated and binary black holes. We have embarked on a search for black holes in the Milky Way using advanced in high precision astrometry. This has allowed us to find and weigh isolated black holes that gravitationally lens background stars. Interestingly, the $\sim 2$ candidates found (out of 10 searched) are both low mass ($< 8\,M_\odot$); however the sample is too small to yet constrain population models. I will discuss these results and the landscape of planned and proposed missions, including Roman, ELTs, and a new CubeSat constellation concept called CuRIOS, to find and more precisely measure black hole and neutron star microlensing events. We have also found intermediate mass ($> 50\,M_\odot$) black hole candidates in astrometric binaries at the Galactic Center. While these need to be confirmed with spectroscopy, such black holes may be expected from theories of dynamical formation and successive mergers in this dense region. Such systems may be detectable through microlensing and self-lensing as well. As samples of BHs in the Milky Way expand, we show through simulations that we can constrain their binary fraction, kick velocity distribution, and the initial-final mass relation.

### Earth Two (ET) mission

Shude Mao • Tsinghua University

A space mission called "Earth 2.0 (ET)" is being developed in China, which consists of six transit telescopes and one microlensing telescope and will be launched to the L2 halo orbit around 2027. The microlensing telescope has a diameter of 35 cm, a field of view of 4 square degrees and will be operated at the diffraction limit. Combined with ground-based microlensing telescopes (e.g., KMTNet) and space telescopes (e.g., Roman), ET will be able to measure the masses of more than 300 bound and free-floating planets and constrain their mass functions to uncertainties within 10%. The transit and the microlensing telescopes will constrain the statistical properties of terrestrial planets and their formation theory.

### Discovery of new free-floating planet candidates with K2 Campaign 9

Iain Mcdonald • Manchester

The abundance of free-floating planets (FFPs) and their mass distribution is a key indicator of both star- and planet-formation processes. Here, I present our first steps towards a new estimation of these parameters with K2 Campaign 9, which observed the Galactic Bulge every 30 minutes for two months in 2016. I report on the discovery of five planet candidates (companion talks will discuss how we are confirming their planetary nature), describe their implications for the FFP abundance and mass distribution, and look ahead to future missions.

### Observing microlensing using optical interferometry: a bright future

Antoine Mérand • ESO

The recent successful observations of microlensing by optical interferometry opens new opportunity for accurate determination of microlensing parameters such as the mass and distance of the lens. The GRAVITY+ project (pending construction decision) will enhance the capabilities of ESO's Very Large Telescope Interferometer (VLTI), increasing greatly the number of observable microlensing targets. I will present the current status of VLTI and its future capabilities proposed by the GRAVITY+ collaboration. Microlensing is part of the GRAVITY+ identified science cases, opening the possibility to detect single stellar mass black holes.

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

Shota Miyazaki • Osaka

The Nancy Grace Roman Space Telescope (Roman) will provide an enormous number of microlensing light curves with much better photometric precision than ongoing ground-based observations. Such light curves will enable us to observe high-order microlensing effects that have been previously difficult to detect. In this talk, we investigate Roman's potential to detect and characterize short-period planets and brown dwarfs in the source systems using the orbital motion of source stars, the so-called xallarap effect. We show that the Roman Galactic Exoplanet Survey (RGES) can detect warm Jupiters with masses down to about 0.5 Jupiter-mass and orbital periods up to about 30 days. Assuming a planetary frequency nearby the solar system, we find Roman will detect 10 hot/warm Jupiters and 30 close-in brown dwarf companions in the Galactic bulge during the RGES. These detections are likely to be accompanied by the measurements of the companion's masses and orbital elements, which will aid in the study of the physical properties for the close-in planet and brown-dwarf populations in the Galactic bulge.

### Impact of binary sources in the estimation of the detection efficiency of microlensing

Marc Moniez • IJCLab-IN2P3

When calculating the detection efficiency of the gravitational microlensing effect, the blending effects have so far been estimated without considering the binary systems that the HST cannot resolve at the distance of the LMC. The components of such systems, if sufficiently separated, are indeed not amplified in the same way, and these configurations must be taken into account in the study of blending. We used the GAIA catalog of nearby stars to estimate the rate of unresolved binary systems by HST in the LMC. We show that, in the case of the search for lenses heavier than 10 times the mass of the Sun, the rate of distant binaries is small enough that its impact on the detection efficiency of microlensing can be neglected.

### Measuring the dark stellar remnant mass function with OGLE and Gaia EDR3 data

Przemek Mróz • Astronomical Observatory, University of Warsaw

Detecting and directly measuring masses of isolated stellar remnants, especially neutron stars and black holes, is virtually impossible with traditional astrophysical methods. Our knowledge of the mass function of neutron stars and black holes is based on observations of binary systems but the binary evolution likely affects the final mass of the compact object. However, isolated neutron stars and black holes must ubiquitous in our Galaxy. Knowledge of their mass function would give us important clues about the evolution of massive stars, core collapse and supernova mechanisms, etc.

I will present the results of the study of a sample of over 15,000 gravitational microlensing events detected during the third and fourth phases of the OGLE survey. I estimated the masses of lensing objects by combining photometric data from OGLE and proper-motion information from OGLE and Gaia EDR3. I then selected high-probability dark lenses - white dwarfs, neutron stars, and black holes - which I used to measure the mass function of isolated stellar remnants. I will discuss how the shape of the remnant mass function depends on the environment (disk, bulge) and compare OGLE observations with the results from LIGO and Virgo and predictions of population synthesis models of black hole formation.

### Understanding Neural Networks for Photometric Data

Greg Olmschenk (**invited**) • NASA Goddard Space Flight Center

Neural networks, arguably the most powerful machine learning methods, are becoming commonplace in photometric data analysis. This presentation will provide a (hopefully) intuitive understanding of neural networks, including an insight into what they learn, how they learn it, and, importantly, why they often fail to do what we expect them to do. Neural networks are particularly valuable in areas with large quantities of data; As data collection rates continue to increase, the nearly limitless capabilities of neural networks are sure to play an increasingly larger role in future works. The goal of this presentation is that you walk away with the ability to see where neural networks may be valuable in your own work and to conceptually understand how neural networks are being used by others.

### A joint analysis of ground-based and space-based data for a short event K2C9-2016-BLG-1

Radoslaw Poleski • Astronomical Observatory, University of Warsaw

Studies of free-floating planets (FFPs) are one of the main focus of microlensing research nowadays. In order to estimate the masses of the FFPs, we would need to measure their microlensing parallaxes either by detecting subtle changes in the light curves caused by different locations of observatories on the Earth or by observing the event from the ground and from space. Such measurements have not yet been done. In order to measure the microlensing parallax of FFPs, a microlensing campaign was conducted by the K2 space mission. A recent analysis of the K2 bulge data by McDonald et al. (2021) revealed four candidates for FFPs. We searched ground-based archival datasets for microlensing signals and detected such a signal only for one of them: K2C9-2016-BLG-1 in the KMTNet data. I will present a joint analysis of K2C9 and KMTNet data for this event.

### Primordial Black Hole Dark Matter Simulations Using PopSyCLE

Kerianne Pruett • LLNL

Primordial black holes (PBHs), theorized to have originated in the early universe, are speculated to be a viable source of dark matter in our universe, and should be detectable via gravitational microlensing signals from local stars in the Milky Way. The Population Synthesis Code for Compact Object Microlensing Events (PopSyCLE) allows users to simulate microlensing surveys with both photometric and astrometric microlensing effects, making it a powerful tool for gaining insight into future PBH detection estimates. We first detail our addition of a PBH population model into PopSyCLE and compare our simulations with OGLE-IV results as a proof of concept. Then, we compare the resulting PBH parameter distributions to those of stellar evolved black holes, and estimate the order of detectable PBH microlensing events we expect from the planned Nancy Grace Roman Space Telescope microlensing survey.

### Lens Detection from High-resolution Follow-up Observations of OGLE-2006-BLG-332L breaks Microlensing Model Degeneracies

Clément Ranc • ARI, Zentrum für Astronomie der Universität Heidelberg

Gravitational microlensing occupies a unique niche with its sensitivity to planets beyond the snow line, down to below an Earth-mass. The microlensing planets sample has been used to derive occurrence rates of planets as a function of the planet-to-host-star mass ratio. The resulting mass-ratio function has then been used to test models of planet formation, resulting in a tension between predictions of the core accretion theory's runaway gas accretion process and the observations. To strengthen and expand these previous statistical findings on planet occurrence rates, the MOA collaboration is conducting a systematic analysis of the high-cadence MOA-2 survey observations, including more than ten years of observations performed at Mount John in New Zealand. Indeed, the detection efficiency is often much higher during a retrospective analysis. This systematic analysis led to the discovery of several missed exoplanets or unpublished detections. I will present the final analysis of one of these events, OGLE-2006-BLG-332/MOA-bin-17, the first newly detected planetary event from this retrospective analysis, for which high-resolution images have been obtained in 2018 (performed as part of the NASA Keck Key Strategic Mission Support program; PI: Dr. Bennett), and in 2021 using the OSIRIS instrument on a 10m-telescope at the Keck observatory in Hawaii. The planet-to-host mass ratio is $\sim 8 \cdot 10^{-3}$, but models with higher values are not ruled out from the light curve modeling only. This is mainly due to the lack of follow-up observations during the caustic entry. I will show how the joint interpretation of the high-resolution images with the light-curve best-fit models can be used to break microlensing model degeneracies and to measure the actual mass of the host and planet. In particular, the lens can be detected and separated from the source in the 2021 Keck data that strongly constrain the models. The resulting lens system consists of a $3\,\mathrm{M_J}$ planet orbiting a $0.4\,\mathrm{M_\odot}$ main-sequence star. This analysis is similar to the primary mass-measurement method that the Roman Galactic Bulge Time Domain Survey will use to detect >1000 planets with masses as low as Mars mass, around G, K, M stars.

### High angular resolution images yield a mass measurement of OGLE-2013-BLG-0132

Natalia Rektsini • UTAS

The event OGLE-2013-BLG-0132 was discovered by the OGLE Early Warning System on 2013 March 3. The event was also independently found by the MOA collaboration (as MOA-2013-BLG-148) on 2013 March 13. The anomaly observed in the light curve of the event was caused by a caustic-crossing. This caustic-crossing lasted almost $\sim 24$ hours and was covered by both photometric surveys. The photometric observations enabled a precise measurement of the planet-to-host mass ratio ($5.15 \cdot 10^{-4} \pm 0.28 \cdot 10^{-4}$) as well as the dimensionless lens-source projected separation ($1.150 \pm 0.004$) as reported in Mroz et al. (2017). More precisely, Mroz et al. show that the planetary anomaly was caused the source crossing a wide separation caustic. Meanwhile, due to the fact that the event was too short ($t_{\mathrm{E}} \sim 30$ days) and faint, a reliable measurement of the microlens parallax is not possible, leaving the lens absolute mass unknown at the time.

I will present the preliminary results obtained from the combination of high angular resolution images with the light curve model parameters. In order to achieve that I am using Keck OSIRIS high angular resolution adaptive optics follow up observations of the event, performed on July 2020, almost 7.5 years after the discovery of the planetary anomaly, where we can see that the source and the lens are almost resolved. These data yield a measurement of the lens-source relative proper motion as well as the flux ratio between the lens and the source. In addition to that, I use photometric observations of OGLE I and V band data as well as MOA R and V band data, which are recently reduced by an improved and optimised pipeline for MOA data. This method can restrict the range of solutions provided by the microlensing light curve, confirm the light-curve model, and finally provide a measurement of the host star mass, the planet's mass and the distance to the planetary system.

The high angular resolution observations, as well as this study, are performed in the context of the programme measuring the mass of most of microlensing planets detected so far (PI: Bennett), by using the primary mass measurement method that will be employed by the Nancy Grace Roman Space Telescope.

### Microlensing Events in the Galactic Plane with the Zwicky Transient Facility

Antonio Rodriguez • Caltech

The majority of previous efforts to search for gravitational microlensing events have been concentrated towards high-density fields such as the Galactic bulge, avoiding the Galactic plane. Microlensing events in the Galactic plane have the advantage of better constrained relative proper motions and therefore better constrained lens mass estimates, at the expense of a lower optical depth compared to events towards the Galactic bulge. We use the Zwicky Transient Facility (ZTF) Data Release 5 (DR5) compiled from 2018-2021 to survey the Galactic plane. We find a total of 60 candidate microlensing events including three that show a strong microlensing parallax effect. The number of events traces Galactic structure, decreasing exponentially as a function Galactic longitude. On average, we find Einstein timescales of microlensing events to be about three times as long towards the Galactic plane (60 days) compared to those towards the Galactic bulge (20 days). Our results demonstrate that microlensing towards the Galactic plane shows strong promise for characterization of dark objects within the galaxy that no other technique can do at the present time.

## Xallarap as a contaminant in planetary microlensing

Paolo Rota • Salerno

MOA-2006-BLG-074 was selected as one of the most promising planetary candidates in a retrospective analysis of the MOA collaboration: its asymmetric high-magnification peak can be perfectly explained by a source passing across a central caustic deformed by a small planet. However, after a detailed analysis of the residuals, we have realized that a single lens and a source orbiting with a faint companion provides a more satisfactory explanation for all the observed deviations from a Paczynski curve and the only physically acceptable interpretation. Indeed the orbital motion of the source is constrained enough to allow a very good characterization of the binary source from the microlensing light curve. The case of MOA-2006-BLG-074 suggests that the so-called xallarap effect must be taken seriously in any attempts to obtain accurate planetary demographics from microlensing surveys.

## Astrometric microlensing in the Gaia16aye event

Krzysztof Rybicki • Astronomical Observatory, University of Warsaw

Gaia16aye was a binary microlensing event detected by Gaia in 2016 as one of the first transients of that type reported by Gaia Science Alerts. The world-wide follow-up campaign resulted in enormous number of photometric data collected, which revealed one of the most complicated and demanding microlensing event ever observed. Multiple second-order effects detectable in the microlensing lightcurve, including Keplerian rotation of binary lens components, provided almost complete information about the system. Thanks to the large Einstein radius $\theta_{\rm E} = 3.04 \pm 0.24$mas and high brightness of the event, it was predicted to have an astrometric microlensing signal measurable by the Gaia mission. In this work we have analyzed the astrometric time-series for this event provided by the Gaia space mission. The 1-D projected positions of the light centroid could not be explained by the simple 5-parameter astrometric model ($\alpha_0$, $\delta_0$, $\varpi$, $\mu_\alpha$, $\mu_\delta$). Including the astrometric microlensing shift calculated based on the photometric model heavily improved the fit and allowed to measure the value of $\theta_{\rm E} = 3.06 \pm 0.06$ mas, which is consistent with the value derived from the photometric model. This is third detection of astrometric microlensing and the first for an event with unresolved source and lens. This also shows that measuring astrometric microlensing effect is possible with the 1-D Gaia astrometric time-series, and confirms that this is a viable method for measuring masses of lenses.

## Detection and Mass Measurement of Isolated Stellar-Mass Black Holes through Astrometric Microlensing

Kailaish Sahu • STScI

About 100 million black holes are estimated to exist in our Galaxy, a large fraction of which are expected to be isolated. Yet, not a single isolated black hole has been detected to date—all of the few dozen black holes detected in our Galaxy so far are in binaries. Furthermore, the measured masses of black holes in our Galaxy are inconsistent either with the theoretical expectations, or with the LIGO measurements of black hole masses in external galaxies. Mass determinations of even a small number of isolated black holes will provide important clues in our understanding of black hole properties, including their formation mechanism. Astrometric Microlensing is the only available technique capable of detecting isolated black holes and measuring their masses. Out of the hundreds of bulge microlensing events found annually by the OGLE and MOA surveys, a few are found to have very long durations ($> 200$ days), some of which are expected to be caused by isolated black holes. We have carried out high-precision astrometry of several such long-duration events using the WFC on HST. We will present new results from these HST programs aimed at the first detections of isolated stellar-mass black holes.

### Sensitivity to habitable planets in the Roman microlensing survey

Sedighe Sajadian • Isfahan

We study the Roman sensitivity to exoplanets in the Habitable Zone (HZ). The Roman efficiency for detecting habitable planets is maximized for three classes of planetary microlensing events with close caustic topologies. (a) The events with the lens distances of $D_l >\sim 7$ kpc, the host lens masses of $M_h >\sim 0.6\mathrm{M}_\odot$. By assuming Jupiter-mass planets in the HZs, these events have $q \lesssim 0.001$ and $d \gtrsim 0.17$ ($q$ is their mass ratio and $d$ is the projected planet-host distance on the sky plane normalized to the Einstein radius). The events with primary lenses, $M_\mathrm{h} \lesssim 0.1M_\odot$, while their lens systems are either (b) close to the observer with $D_\mathrm{l} \lesssim 1$ kpc or (c) close to the Galactic bulge, $D_\mathrm{l} \gtrsim 7$ kpc. For Jupiter-mass planets in the HZs of the primary lenses, the events in these two classes have $q \gtrsim 0.01$, $d \lesssim 0.04$. The events in the class (a) make larger caustics. By simulating planetary microlensing events detectable by Roman, we conclude that the Roman efficiencies for detecting Earth- and Jupiter-mass planets in the Optimistic HZs (OHZs, which is the region between $[0.5,\ 2]$ AU around a Sun-like star) are $0.01\%$ and $5\%$, respectively. If we assume that one exoplanet orbits each microlens in microlensing events detectable by Roman ( i.e., $\sim 27{,}000$ ), this telescope has the potential to detects 35 exoplanets with the projected planet-host distances in the OHZs with only one having a mass $\lesssim 10M_\oplus$. According to the simulation, 27 of these exoplanets are actually in the OHZs.

### OGLE-2019-BLG-0825 ; Identified Xallarap Effect of $\sim 5.5$ days Affects Binary-lens Parameters in Planetary Candidate Microlensing Event.

Yuki Satoh • Osaka

We report on the analysis of the microlensing event OGLE-2019-BLG-0825. This event has been labeled as a planetary event by preliminary modeling. From detailed analysis, we find non-negligible residuals from the best-fit static binary-lens model exists. We detect xallarap effect with $\sim 5.5$ days that can fit the residuals very well and significantly improves $\chi^2$ values in all data sets. On the other hand, by introducing the xallarap effect, we find that binary-lens parameters like q and s cannot be constrained well, i.e. various binary-lens models are possible. However, we also find the parameters for the source system like the orbital period and xallarap amplitude are consistent between all the possible models. We conclude that the source system consists of a main-sequence star (M-dwarf or K-dwarf) orbited by a low-mass companion (M-dwarf or brown dwarf) with $P \sim 5.5$ days and $a \sim 0.06$ AU. This analysis first demonstrates that xallarap effect with short periods can affect binary-lens parameters in planetary events.

### Towards the detection of isolated black holes

Noam Segev • Weizmann Institute of Science

The abundance and mass-function of black holes, the last stage of massive star evolution, is fundamental for understanding stellar death, and may provide clues regarding the explosion mechanism of core-collapse SNe, and the birth of BH-BH binaries.The study of astrometric microlensing events is currently the most promising path for detecting isolated black holes.

However, ameasurement of an astrometric microlensing event requires an astrometric precision of 1 mas, and high cadence.

We discuss the possibility to detect astrometric microlensing using seeing-limited ground-based observations. We discuss the limiting factor for ground-based astrometry and describe our efforts to obtain a sub-mas astrometric precision using such observations.

### Analysis of Gravitational Microlensing Event: OGLE-2018-BLG-0380

Sarang Shah • India TMT

We present the analysis of the microlensing event OGLE-2018-BLG-0380, that was observed towards the galactic bulge in the microlensing season of 2018. The light curve of this event had two prominent peaks and a third bump towards the decreasing side of the light curve. The conventional method of grid search failed to give any solutions that can explain the light curve. So, we performed a heuristic analysis of the light curve and found that the binary lens orbital motion explains the third perturbation. This is the highest orbital motion ever detected in a microlensing event. Since the event has $t_{\mathrm{E}} \sim 9$ days, we did not detect orbital parallax. We also investigated the occurrence of the event by binary lens and binary source. However, the binary lens and single-lens model is preferred by a significant probability. The Bayesian analysis of the galactic model priors that is constrained by the measured angular motion prefers the bulge location of the lens system by 91%. We find that the lens is comprised of an brown dwarf at the deuterium burning limit orbiting a M-dwarf mass host in the galactic bulge. The median projected separation between them is 0.85 AU. It is also found that the median value of $(\mathrm{K.E./P.E.})_{\perp} = 0.91$ which indicates a face-on system.

### Importance of and degeneracies in xallarap as illustrated by planeraty event OGLE-2017-BLG-0114

Jan Skowron • Astronomical Observatory, University of Warsaw

Binary sources are as common as binary lenses. Although strong magnification due to the second source is less frequent than due to the binary lens, the influence of its orbital motion on the light curve can be an important, and often overlooked effect. I will discuss this subject and present an interesting planetary and xallarap event, whose light curve can be described with multiple values of the orbital period despite having both complex and well measured shape.

### OMEGA Project: Microlensing across the whole sky

Rachel Street • LCOGT

Thanks to technological improvements in telescope design and data processing, it is now possible for deep, wide-field and high spatial resolution surveys such as ZTF, and ultimately the Vera C. Rubin Observatory, to monitor hundreds of square degrees every night.

These surveys are capable of discovering microlensing events in a much wider range of stellar environments than could previously be explored, paving the way to investigate low-mass star, brown dwarf, and planet populations in new regions of the galaxy, as well as probing the populations of isolated black holes. However, they generally provide lower-cadence survey data than traditional microlensing surveys, posing challenges for event identification and follow-up.

### Status of the PRIME NIR Microlensing Experiment

Takahiro Sumi • Osaka

We report the status of the NIR microlensing exoplanet search project, the Prime-focus Infrared Microlensing Experiment (PRIME).

We are building a new 1.8m wide field infrared telescope at the Sutherland in South Africa. One of the largest NIR camera will be build by using four H4RG-10 detectors loaned from the Roman project. Thanks to 1.3 deg.$^2$ FOV, we can conduct the first high cadence microlensing survey in H-band towards the central region of the galactic bulge, where high dust extinction prevents optical observations.

Because the stellar density is higher at the lower galactic latitude, we expect higher event rate. We can compare the planet abundances in high and low stellar density for the first time, which is important for the study of the planetary formation scenarios.

If the PRIME telescope and Roman observe the same fields simultaneously, different light curves will be observed due to the different line of sights, so-called the space-based microlensing parallax. This enables us to measure the mass and the distance of the lens system and enhance the Roman's yields. The telescope will also be used for the ToO observations for various transients including GW, GRB and so on.

### Extinction study toward the inner milky way with Subaru HSC

Daisuke Suzuki • Osaka

It is known that the extinction law toward the Galactic bulge (GB) is very different from the well-known Cardelli's standard extinction law. Most studies have been conducted with NIR and only a small portion of the inner GB has been studied with optical imaging due to the high extinction. These studies showed that the observed $A_V/A_K$ is 60-80 % higher than the estimate from the standard extinction law. To measure the intrinsic brightness of and/or distance to the objects toward the inner GB, it is critical to understand the amount of extinction that depends on the wavelengths. Also, such study will be important for optical precursor, concurrent and follow-up observations of the GB surveys such as, Roman's RGES, JASMINE and PRIME surveys. We observed bout 30 sq. deg around the Galactic center to measure the optical extinction with Subaru HSC using g, r2, i2 and z-band filters. We measure the color and magnitude of Red Clump Giant in the color-magnitude-diagram of each sight line by combining VISTA VVV survey data. We find that the extinction toward the inner GB could be explained by a hybrid model of the standard and NIR extinction model. In this talk, we report and discuss our result.

### A New Method to Break the Central Perturbation Degeneracy in High Magnification Microlensing Events

Sean Terry • University of California, Berkeley

I present Keck adaptive optics (AO) observations of the microlensing target OGLE-2011-BLG-0950, which enable the lens system to be directly detected. The initial analysis of Choi et al. (2012) resulted in two degeneracies resulting in four degenerate solutions. The lens system is a Jupiter mass ratio planetary system or a stellar binary, with close and wide versions in each case. This is a generic problem that plagues the interpretation of high magnification events that display a double cusp approach, and it can complicate the interpretation of exoplanet microlensing survey results. I present a new method to resolve such degeneracies. The lens detection and mass measurement analysis described in this work provides a pathway to resolve such degeneracies with the Nancy Grace Roman Space Telescope's Galactic Exoplanet Survey.

### Keck vs Spitzer: A new mass-measurement for OGLE-2016-BLG-1195

Katie Vandorou • NASA Goddard Space Flight Center & University of Maryland

OGLE-2016-BLG-1195 is a suspected cold super-Earth orbiting an M-dwarf star towards the Galactic bulge. However, two detection papers published on this system—Bond et al 2017 and Shvartzvald et al 2017, present differing results with the latter using a parallax derived from Spitzer photometry. We have conducted NIR high-resolution follow-up observations with Keck with a primary goal of resolving the source and lens. With a direct measurement of the lens flux we have found that our Keck results are not consistent with the Shvartzvald et al 2017 result. Therefore, we have investigated the Spitzer photometry, and conclude that it is likely dominated by systematic errors.

### Potential of Gaia to constrain Primordial Black Holes using astrometric microlensing

Himanshu Verma • IIT Bombay

The Gaia space telescope allows for unprecedented accuracy for astrometric measurements of stars in the Galaxy. In this work, we explore the sensitivity of Gaia to detect primordial black hole (PBH) dark matter through the glitches that they would create in the apparent trajectory of stars due to astrometric microlensing (AML) effect. By computing the AML event rate, we find regions of the sky that yield the most promising targets for PBH searches with Gaia. We also predict a distribution of observable event durations and centroid shifts of these AML events. We then compute the potential exclusion that could be set on the parameter space of PBHs with a monochromatic mass function. We find that Gaia is most sensitive to PBHs in the vicinity of $10\,M_\odot$ and has the potential to exclude PBHs that make up as little as $10^{-3}$ fraction of the dark matter.

### Microlensing by dense gas clouds

Mark Walker • Manly

It is widely appreciated that cold, dense molecular gas is very difficult to detect. Modelling has demonstrated that such gas can exist in the form of spherical, self-gravitating clouds with masses in the planetary range and radii in the AU range. Microlensing studies — both Galactic and extragalactic — are one of the main ways in which such objects can be revealed, or constrained, but the task is complicated by the non-point-like nature of the lenses. I will describe the microlensing signatures that are predicted by our physical models of cloud structure — including the effects of gravitational lensing, gas lensing and extinction — and the constraints that are imposed by the available data.

### Microlensing events from all over the sky from Gaia

Lukasz Wyrzykowski • Astronomical Observatory, University of Warsaw

I will present the status of the microlensing search with the Gaia space mission through the Gaia Science Alerts channel and planned in the forthcoming Gaia Data Release 3 in 2022. The photometric events from Gaia will be supplemented by Gaia astrometric time-series, which will help measure Einstein Radius for many events and hence identify the nature of the lenses. The strongest astrometric signal is expected from massive lenses like black holes hence Gaia is going to revolutionize the field of black hole studies via microlensing. I will present the microlensing events from Gaia as well as the organization of their ground-based follow-up arranged via a network of tens of telescopes from around the globe.

### KMTNet HighMagFinder opens a new phase of following up

Hongjing Yang • Department of astronomy, Tsinghua University

Follow-up observations are necessary to extract the full potential of microlensing events and find more microlensing planets. People usually select high magnification events to follow because of their high sensitivities, and the event selection is based on wide-field surveys. we used to manually track and monitor all the ongoing events to select follow-up targets. However, since the KMTNet stars its operation, there are $\sim 200$ ongoing (rising) events at the same time at any moment, it becomes difficult for the observer to monitor such a large number of events. So we build a new system, HighMagFinder, which is based on the KMTNet real-time data. This system runs every 3 hours and it can find and alert all the possible high magnification events. During the operation in 2021, the system has zero false negatives for $A > 50$. Based on it, we followed 35 events with 7 planetary events. The system reduced a lot of human work, and it is also friendly to future statistic works.

### Proposal to test a Newtonian galactic model by observing gravitationally lensed stars, brown dwarfs and planets found by the Argus Array

Phil Yock • Auckland

In 2020 Sipols and Pavlovich proposed a self-consistent Newtonian non-parametric model of galaxies without non-baryonic dark matter [1]. The model was shown to account successfully for a diverse sample of 214 spiral galaxies. A radially declining average star mass with increasing galactocentric radius was found. Here we propose a search by gravitational microlensing for low-mass stars and brown dwarfs in the galactic disk consistent with the Newtonian model. We propose that the wide-field Argus Array [2] be used to find microlensing events in the galactic disk with lenses at galactocentric radii $> 8\,\mathrm{kpc}$. We further propose that these events be monitored with auxiliary 1 m class telescopes to identify their lens and source stars, and to seek and identify exoplanets orbiting the lenses. We also comment on hypotheses made by Newton on particle physics.
[1] https://doi.org/10.3390/galaxies8020036
[2] https://arxiv.org/abs/2107.00664

### KMTNet AnomalyFinder: Systematic Planetary Anomaly Search

Weicheng Zang • Tsinghua University, Beijing

In order to exhume the buried signatures of "missing planetary caustics" in KMTNet data, we built KMTNet AnomalyFinder for a systematic planetary anomaly search. This search revealed many low mass-ratio planets, for which the planetary signals had not been noticed before, including one of the lowest mass-ratio microlensing planets to date. In this talk, I will introduce the basic algorithm and results of KMTNet AnomalyFinder, and our plan for obtaining the KMTNet mass-ratio function.

### A Ubiquitous Unifying Degeneracy in 2-body Microlensing Systems

Keming Zhang • University of California, Berkeley

While gravitational microlensing by planetary systems can provide unique vistas on the properties of exoplanets, observations of such 2-body microlensing events can often be explained with multiple and distinct physical configurations, so-called model degeneracies. An understanding of the intrinsic and exogenous origins of different classes of degeneracy provides a foundation for phenomenological interpretation. Here, leveraging a fast machine-learning based inference framework, we present the discovery of a new regime of degeneracy—the offset degeneracy—which unifies the previously known close-wide and inner-outer degeneracies, generalises to resonant caustics, and upon reanalysis, is ubiquitous in previously published planetary events with 2-fold degenerate solutions. Importantly, our discovery suggests that the commonly reported close-wide degeneracy essentially never arises in actual events and should, instead, be more suitably viewed as a transition point of the offset degeneracy. While previous studies of microlensing degeneracies are largely studies of degenerate caustics, our discovery demonstrates that degenerate caustics do not necessarily result in degenerate events, which for the latter it is more relevant to study magnifications at the location of the source. This discovery fundamentally changes the way in which degeneracies in planetary microlensing events should be interpreted, suggests a deeper symmetry in the mathematics of 2-body lenses than has previously been recognised, and will increasingly manifest itself in data from new generations of microlensing surveys.

### Chinese Space Station Telescope and its potential in microlensing

Wei Zhu • Tsinghua University, Beijing

With a 2m aperture and in a low-Earth orbit, the Chinese Space Station Telescope (CSST) will be a major science project of China Manned Space Program. CSST is expected to start its science operation in 2024 and will have a nominal mission lifetime of 10 years. Among the science instruments onboard CSST will be a Survey Camera. The primary goal is to study dark matter and dark energy. However, with a $\sim 1$ degree field of view, CSST is also capable of performing a space-based microlensing survey. This talk describes the CSST mission and the plan to use it for microlensing studies.

### Spectroscopic classification of microlensing events alerted by Gaia

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From the photometric data delivered by Gaia mission we are able to select a growing number of microlensing event candidates located mostly in the Galactic Plane. In order to early distinguish genuine microlensing events from other types of outbursts and variables, that are also reported in Gaia Science Alerts system, the spectroscopic follow-up observations are performed for selected transients. We use a wide range of world-class telescopes equipped with low-resolution spectrographs to measure the continuum and detect distinctive absorption and/or emission features in order to classify the targets. Such spectra help us select a sample of microlensing events for which an intensive photometric follow-up monitoring can be conducted. Moreover, for the most interesting targets we apply for high-resolution spectra and study spectral lines in detail to determine physical parameters of the source star in the microlensing event. Finally, the line-of-sight extinction and the distance to the source is obtained as well, therefore, the spectroscopic analysis is essential in constraining the microlensing model and the lens parameters. I will present the status of the spectroscopic study of candidates for microlensing events alerted by Gaia with recent examples of interesting results. Such small-scale operations provide a good training ahead of the forthcoming influx of Galactic Plane transients from the LSST/VRO.

### Validating fast Fisher Matrix parameter uncertainty estimation for simulations of the Roman Galactic Exoplanet Survey

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The Roman Space Telescope will conduct a time-domain survey of the galactic bulge to search for and find over a thousand cold exoplanets using the microlensing technique. To date, estimates of the Roman survey yield using the gulls simulation code have focused only on the question of whether a planet will be detected and have neglected to address whether it will be possible to characterize the planet once detected. We have extended gulls to compute Fisher matrix estimates of the planet parameter uncertainties obtainable with Roman observations of individual microlensing events. Here we focus on validating the Fisher matrix calculations with uncertainty estimates derived from Markov Chain Monte Carlo (MCMC) posterior probability distributions. We will present results for the accuracy of fisher matrix parameter estimates for a series of more challenging microlensing models: single lens events, free-floating planet events, and ultimately bound planet events. For the latter two cases, we will estimate Roman's ability to measure planet masses in simulated events. Ultimately, validated, fast Fisher matrix uncertainty estimates will allow us to optimize the Roman Galactic Exoplanet Survey for characterizable planets rather than simply detectable planets.