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Exoplanets / *Exoplanètes*

# Hunting for Cold Exoplanets via Microlensing

## *La chasse aux exoplanètes froides par la méthode des microlentilles*

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**Abstract.** Microlensing can detect planets at distances ranging from a few hundred parsecs all the way to the Galactic center. The maximum sensitivity is reached for systems that are located half way to the galactic center, with planets orbiting the lens star at a separation of few AUs. It is the only method currently probing exoplanets in the Earth-Saturn mass range beyond the snow line, where the core accretion theory originally predicted that most massive planets would form. Although the number of detected planets is relatively modest (~130 planets to date) compared to that discovered by radial velocity and transit methods, microlensing probes a part of the parameter space (host separation as a function of planet mass), which is mostly not accessible in the medium term to any other technique. Microlensing has discovered the first cold super-Earth, and the first Jupiter planet orbiting a white dwarf. It also detected a number of Earth, Super-Earth, Neptune, Saturn, Jupiter, super-Jupiter orbiting main sequence stars in the mass range $0.08 - 1M_{\odot}$. It also observed circumbinary planets, Jupiter in the habitable zone, the first exomoon candidate and free-floating planets. It has shown that having a planet is the rule for stars in our galaxy and shown that super-Earth and Neptune are more abundant than smaller mass telluric planets. Ground based microlensing will provide soon the mass function of cold planets down to few Earth Masses. The next phase, is a 450 days survey with the NASA Nancy Grace Roman Space Telescope from 2027. It will detect 3000+ planets and provide the mass function of cold planets down to the mass of Mars. If combined with the European Euclid Space mission, we will be able to probe for free-floating telluric planets and measure their masses.

**Résumé.** La méthode des microlentilles gravitationnelles permet de détecter des planètes à des distances allant de quelques centaines de parsecs jusqu'au centre de notre Galaxie. La sensibilité maximale est atteinte pour les systèmes situés à mi-chemin du centre galactique, avec des planètes orbitant autour de l'étoile lentille à une distance de quelques UA. C'est la seule méthode qui permet actuellement de sonder les exoplanètes dans la gamme de masse Terre-Saturne au-delà de la limite des glaces, là où les scénarios d'accrétion de coeur prédisent que la plupart des planètes massives se formeraient. Bien que le nombre de planètes détectées soit relativement modeste (environ 130 planètes à ce jour) comparé aux méthodes de vitesse radiale et de transit, les microlentilles sondent une partie de l'espace des paramètres (séparation de l'hôte par rapport à la masse de la planète), qui n'est accessible à moyen terme à aucune autre technique. Les microlentilles ont permis de découvrir la première super-Terre froide et la première planète Jupiter en orbite autour d'une naine blanche. Elles ont aussi détecté des Terres, super-Terres, Neptunes, Saturnes, Jupiters, super-Jupiters, naines brunes orbitant autour d'étoiles de la séquence principale dans la gamme de masse $0.08 - 1M_{\odot}$. Cette approche a aussi permis d'observer des planètes circumbinaires, des Jupiters dans la zone habitable, le premier candidat exolune et des planètes soit non-liées à une étoile, soit sur des orbites très lointaines. Les microlentilles ont été les premièrs à montrer que la présence d'une planète est la règle pour les étoiles de notre galaxie et que les super-Terres et Neptunes sont plus abondantes que les planètes telluriques de plus petite masse. Les observations actuelles fourniront très prochainement la fonction de masse des planètes froides jusqu'à quelques masses terrestres. La phase suivante sera un grand relevé de 450 jours avec le télescope spatial Nancy Grace Roman de la NASA à partir de 2027. Il donnera plus de 3000 planètes et fournira la fonction de masse des planètes froides jusqu'à la masse de Mars. S'il est combiné à la mission spatiale Européenne Euclid, il sera en mesure de rechercher des planètes telluriques non-liées, de mesurer leur masse et leur abondance.

**Keywords.** Exoplanets, Gravitational Lensing, Observations, Detection of Exoplanets, Planetary Systems, Micro-lensing.

**Mots-clés.** Exoplanètes, lentilles gravitationnelles, observations, détection des exoplanètes, systèmes planétaires, micro-lentilles.

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https://www.academie-sciences.fr/fr/Colloques-conferences-et-debats/exoplanetes.html.
**Note.** Fait suite à une conférence-débat de l'Académie des sciences intitulée "Exoplanètes : les nouveaux défis" tenue le 18 mai 2021, visible via
https://www.academie-sciences.fr/fr/Colloques-conferences-et-debats/exoplanetes.html.

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## 1. A brief history of microlensing planet hunt

Over the past 25 years, different methods have been used to detect exoplanets: radial velocity, stellar transits, direct imaging, pulsar timing, astrometry and gravitational microlensing. They have unveiled an incredible and unexpected diversity of planetary systems and have already challenged and revolutionised our theories of planet formation and dynamical evolution. The gravitational microlensing technique [1–3] explores a unique niche: cold planets down to the mass of the Earth orbiting any kind of stars (including stellar remnants), free-floating planets (unbound to a star) and exomoons orbiting planets. It is based on Einstein's theory of general relativity: a massive object (the lens) will bend the light of a background object (the source) for example located in the Galactic Bulge, and amplify its apparent flux. The key quantity is the Einstein ring radius($R_E$), which depends on the mass of the lens $M_L$ and the distance observer-lens $D_L$ and observer-source $D_S$. The angular Einstein ring radius is given by:

$$\Theta_{\mathrm{E}} = 0.902 mas\ (M/M_{\odot})^{1/2}\ \left(10kpc/D_L\right)^{1/2}\ (1 - D_L/D_S)^{1/2} \tag{1}$$

if observer-lens-source are exactly aligned, the source image is a ring of radius $\Theta_{\mathrm{E}}$. These images are unresolved and only the brightness of the background star is amplified. The source's apparent brightness varies as the alignment changes due to relative proper motion of the source with respect to the lens and the observer. Thus, a microlensing event is a transient phenomenon with a typical time scale $t_E \sim 20\sqrt{M/M_{\odot}}$ days. It is unfortunately a rare phenomenon: a Galactic Bulge star has a $\sim 10^{-6}$ probability to be magnified by more than 30 %. It is therefore necessary to monitor millions of stars every night to identifiy the on-going microlensing events.

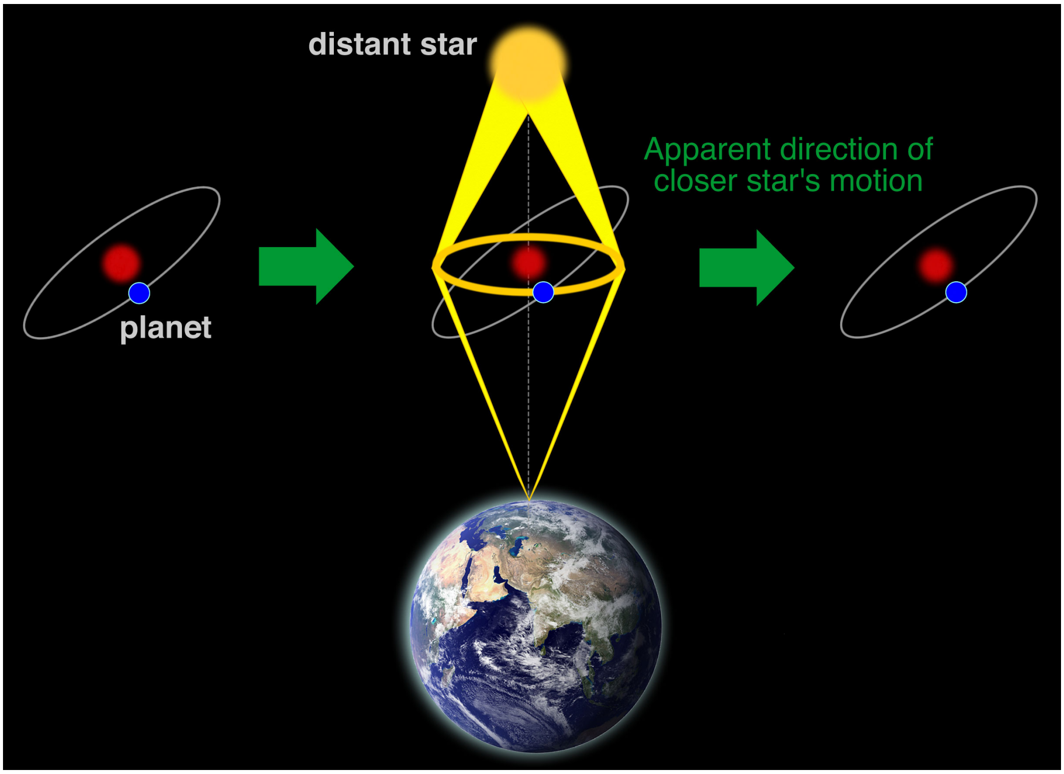


**Figure 1.** The Microlensing method. A lens star is refocussing and amplifying the light coming from a background star. If the alignement is perfect, then the image of the background star is a ring, the Einstein ring. If a planet is present close to the Einstein ring, it could induce perturbations that reveal its presence (Copyright NASA IPAC).

A star and planet system acting as lens produce caustic structures in the source plane[1], usually a small central one close to the centre of mass of the system and a large planetary caustic further away. As a consequence, there are two channels for detecting the presence of the planet:

(1) If the source star transits the large planetary caustic it will generate a large photometric fluctuation. A Jupiter orbiting a solar like star at 5 AU would have $\sim 10-20\%$ probability to produce a $\sim 30\%$ photometric fluctuation with a time scale of $\sim 1$ day [4]. If the source star is small *with respect to the Einstein Ring radius*, there could be a significant photometric signal due to an Earth Mass planet *(fluctuation of* $\sim 20\%$ *over* $\sim 2$ *hours.* It detected with an efficiency of $\sim 2\%$ [5]. However, the photometric fluctuation would be washed out if the source star is large compared to the planetary caustic. Given the angular resolution of ground based telescopes, the planet hunt will be mostly sensitive in favorable cases to a few Earth mass planets. Images with resolution of 0.1-0.2 arcsec over wide field would be allow to monitor smaller sources, and then will allow the detection of smaller planet mass.

[1] *A system composed of two objects acting as a lens would amplify the light of the background star and create several images. A caustic marks regions in the source plane corresponding to different images multiplicity, 1,3 or 5 for binary systems. When the source transits a caustic, amplification is strong, and a pair of images appear or disappear. As we will see later, the transit over these caustics helps to characterise the component of the lensing systems and allow the discovery of planetary companions.*

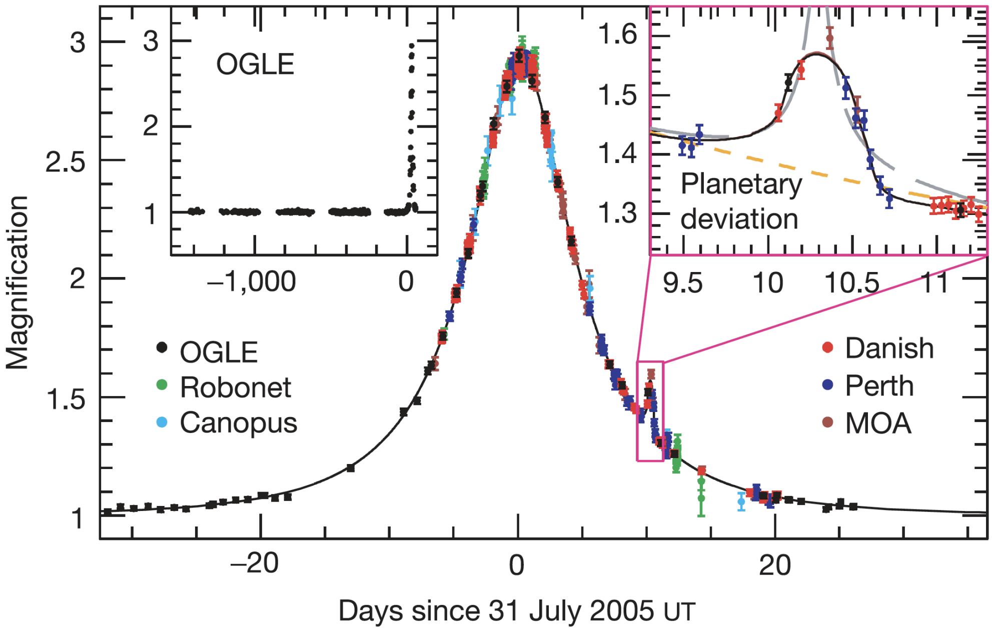


**Figure 2.** The observed light curve of the planetary microlensing event OGLE-2005-BLG-390. The top left inset shows the OGLE light curve extending over the previous 4 years, whereas the top right one shows a zoom of the planetary deviation, covering a time interval of 1.5 days. Different colors are the data from the different telescopes of the PLANET, OGLE and MOA collaborations. The solid curve is the best planetary lens model described in the text with a mass ratio $q = 7.6 \pm 0.7\ 10^{-5}$, and a projected separation of $d = 1.610 \pm 0.008 R_E$. The dashed grey curve is the best binary source model that is rejected by the data, and the dashed orange line is the best single lens model. The system is composed of a $0.22^{+0.21}_{-0.11} M_\odot$ orbited by a $5.5^{+5.5}_{-2.7} M_\oplus$ planet at $2.6^{+1.5}_{-0.6}$ AU [8].

(2) *When the impact parameter of the lens with respect to the observer-source line of sight is very small (less than* ~ $10^{-2}$ *of the Einstein Ring Radius)*, the flux will be highly amplified and the source will transit the central caustic or pass very close to it. It will generate a perturbation that could reveal the presence of the planet. The efficiency can be close to 100 % for Jupiters planets [6]. For amplification above 1000 (impact parameter of ~ $10^{-3}$) the efficiency goes up to 50 % for Earth-like planets [7]. However, the distribution of impact parameter is flat, therefore the small impact parameters are rare. Moreover, it is difficult to predict efficiently what will be the fate of a given event based on early data. We often can alert for a high magnification event, with high sensitivity to planets only few hours notice at best. It is perfectly fine for ground-based telescopes, but is a problem if we wanted to trigger observations from satellites such as the Hubble Space Telescope *or the former* Spitzer where sequences of observations have to be uploaded several days ahead.

In the years 1995-2002, it was looking fairly easy and promising. The microlensing community adopted a two-step approach with enthusiasm : wide-field imagers (OGLE, MOA) were monitoring a very large number of stars in order to detect real-time ongoing microlensing events and to alert them publicly. Note that their efficiency increased dramatically, from 30 events alerted in

1995 to 350 in 2002 and nearly 600 in 2005. Then, networks of telescopes (PLANET, then followed by $\mu FUN$ from 2003, then ROBONET and MINDSTEP) were monitoring a selected sample of the events with the highest sensitivity to exoplanets. A first Jupiter planet was published by OGLE and MOA in 2004 [9]. It was a particular configuration of a Jovian planet on orbit close to the Einstein ring, generating a very large caustic, observed only with the survey telescopes. Its nature was understood almost at the end of the phenomenon, so no follow up observations had been triggered manually at the telescope while the planetary anomaly was on going. A second planet was discovered when doing the monitoring of a high magnification microlensing event alerted by OGLE, with contributions from follow up telescopes [10]. The source transited very close to the central caustic of the system. Finally, the PLANET collaboration using his network of telescopes detected in August 2005 the archetype of planetary microlensing [8]. OGLE-2005-BLG-390 is a low amplification microlensing event alerted by the OGLE team, with a ~ 10 hours photometric fluctuation due to the transit of the source over the planetary caustic (figure 1). The system is composed of a cold ~ $5M_\oplus$ planet orbiting a M dwarf detected by lensing of a giant source star. If the mass of the planet would have been 1/3 smaller the photometric signal would have been washed out by finite source effects *(and be only few percent) and would likely not have been detected at the time.* It is an illustration of both the power and the limitation of the ground based telescopes at the time.

From 2006, the different microlensing teams decided to do a full coordination of their observing effort : all data were made available immediately and publicly, and the teams were sharing updated models and predictions. MOA and OGLE surveys increased their efficiency and from 2011, there were more than 1500 alerts per year, followed by some of the 40 registered telescopes. Detecting planets via microlensing became more streamlined and the rate increase to 4-7 planets per year. The focus was on the detection of more planets and statistics. An interesting system was a scaled 1/2 solar system, with two gazeous planets, of 1/2 the mass of Jupiter and Saturn, with a factor 2 in the major axis of their orbit [11]. It was followed by a number of super-Earth / mini-Neptunes /Neptunes [12–20], circum-binary planet [21], a first exomoon candidate system [22], planet in the Galactic Bulge [23–25], multiple planet systems [26], Jupiter in the habitable zone [27], massive Jupiter orbiting a M dwarf [28,29] that are not predicted by the core accretion theory [30–32]. Microlensing also provided the first detection of a Jupiter orbiting a white dwarf on a wide orbit [33], giving an example of the fate of our solar system once the sun would have go through a planetary nebulae phase in more than 5 Gyrs.

## 2. Statistics on cold exoplanets

Microlensing is most sensitive to planets beyond the distance where water ice forms (the snow line), and to masses down to the Earth (figure 3). The first measurement of the frequency of ice and gas giants beyond the snow line from the microlensing discoveries [34], has shown that this is about 7 times higher than closer-in systems probed by the Doppler method [35]. This comparison provides strong evidence that most giant planets do not migrate inwards very far. [36] has presented the first abundances of planets orbiting solar like stars within 0.25 AU using Kepler, while others have measured the abundance of Neptunes and super Earths using radial velocities [37]. These studies show that 17-30 % of solar like stars have planets on short orbits. With the microlensing technique, [38] measured the fraction of bound planets over 0.5-10 AU orbits from 10 Jupiter mass to 5 Earth mass and showed that planets around stars are the rule, rather than the exception. Then, a high planet occurrence rates for the Kepler GK dwarf sample was found [39], and the mass ratio $q$ function of cold planets was measured using the microlensing MOA data [40,41]. This mass ratio function rises steeply as $q^{-0.85\pm0.13}$ toward lower

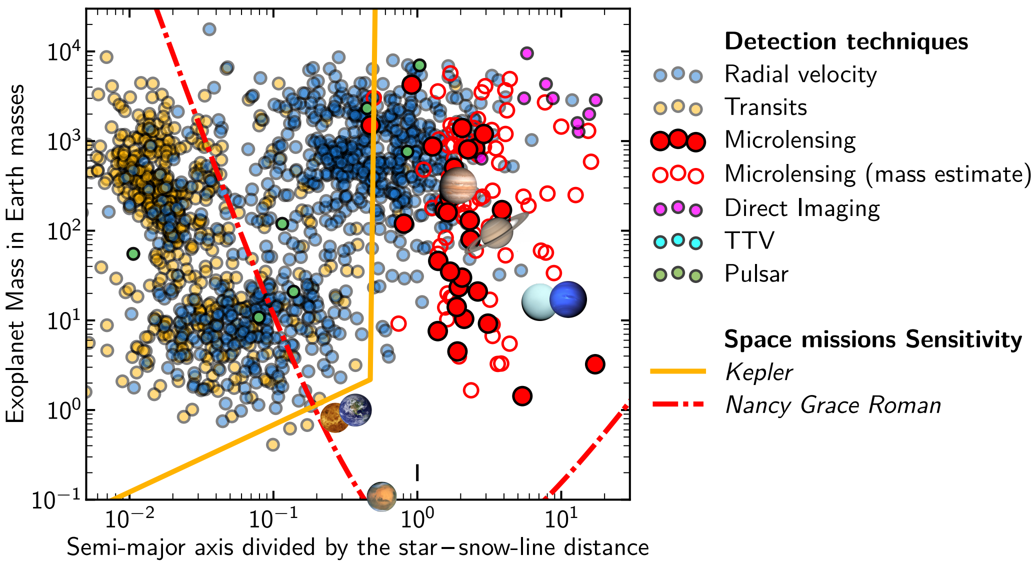


**Figure 3.** Distribution of known planets is plotted as a function of mass vs. semi-major axis normalized to the snow line. The snow line is approximated at $a_{snow} = (M/M_{\odot})^{2.7}$ AU. Doppler/RV method: blue, transits: yellow blue, microlensing: red (filled circle with precise mass measurements, open circles if from Bayesian analysis with a Galactic model), timing: cyan, direct measurement: magenta. Solar system planets are indicated. Short black line: snow line for a Solar-type host star. Notice the complementarity of the Kepler and Roman satellites. Courtesy Clement Ranc.

masses as down to $q \sim 10^{-4}$ where there is a break and possible peak in the mass ratio function (figure 4).

The core accretion theory predicts that growth from $q \lesssim 10^{-4}$ to $q \gtrsim 10^{-3}$ occurs in a rapid run-away gas accretion process. Planets beyond the snow line with $q \lesssim 10^{-4}$ are thought to be common because the disk gas often dissipates before the run-away growth begins, but if it does begin, planets are expected to quickly grow to $q \gtrsim 10^{-3}$. So, planets with $q \sim 2 \times 10^{-4}$ can only form if the gas in the disk dissipates in the middle of the short duration run-away growth phase. This might imply that the theory must be modified. Alternatively, it could be that there is some host star mass dependence of this run-away gas accretion gap that smooths out this feature when plotted as a function of mass ratio. These microlensing results are broadly consistent with radial velocity and direct imaging surveys [42], but only microlensing currently probes down to masses of Neptunes and super-Earth at these relatively wide separations [43]. The MOA collaboration is currently preparing a statistical analysis combining 9 years of data, while the new network KMTNeT of 3 telescopes equipped with 4 square degrees wide field imagers [44], and the ROME/REA survey [45] will provide their analysis on demographics of cold planets by 2024-2025.

In 2011 an analysis of short duration microlensing events claimed that they could be the smoking gun of a massive population of free-floating Jovian planets [46]. According to this study it could be as high as one free-floating Jupiter per star. A more recent analysis [47] concluded that at best this population would have been overestimated by a factor 10. It showed that there could be a nevertheless a smaller population of free-floating planets with masses in the regime super-Earth /Neptune [48–51]. Note that there is so far still an ambiguity about whether such

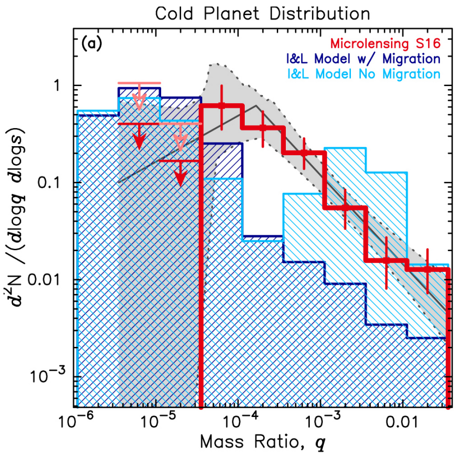


**Figure 4.** Planet to host-star mass-ratio function measured by microlensing compared to the planet distribution from core accretion theory population synthesis models by Ida and Lin. The red histogram shows the measured mass-ratio distribution, with the best-fit broken power-law model and its $1\sigma$ range indicted by the solid black line and gray shaded regions. The red and pink arrows indicate the $1\sigma$ and $2\sigma$ upper limits on the mass-ratio bins without planet detections. The dark and light blue histograms are the predicted mass-ratio functions from the default population synthesis models with migration, and the alternative migration-free models [31, 41].

candidate free-floating planets are really unbound or on very wide orbits (over 100+ AU) around an host star.

## 3. The current challenge, obtaining accurate physical masses instead of mass ratios

The major limitation of exoplanetary microlensing analyses are really specific to the method: The fit of the photometric light curve gives mass ratio and projected separation. They are usually well measured, often down to 10 % or better. The observation of additional effects such as source transiting a caustic, parallax, ground-space parallax, high angular resolution observations are giving additional informations that can be used to derive mass-distance relations for the lens. They are then used as constraints in a Bayesian analysis with a galactic model to derive the physical parameters of the systems. The precision obtained on the physical parameters depends on the constraints obtained from the observations. In practice, we can derive up to three different 3 mass-distance relations for the host star [52]:

- The angular size of the source star being known, when it transits over a caustic it gives a measure of the angular Einstein ring radius $\Theta_E$, hence it gives a mass-distance relation for the host star (see Eq. (1)).
- A second mass-distance relation is obtained when parallax due to the change of the alignment between observer source-lens during the event is measured from the microlensing light curve. Using ground-based data alone, the parallax is often not well constrained and there could be a degeneracy with the lens orbital motion. However, simultaneous ground and Spitzer observations (done in 2014-2019) can give strong parallax constraints when the source is bright enough [17, 25, 53, 54]. Nevertheless, this has been achieved on a small number of planetary events, but there are some ambiguities coming from the systematics in the Spitzer photometry for faint targets [18, 55, 56]. Other routes for low mass

lenses such as free-floating planets is to observe with a low Earth orbit satellite where the modulation along the orbit is used to constraint the mass of the lens [57], or combining a satellite at L2 and ground-based telescopes, or two satellites at L2 [58].

- A third mass-distance relation is obtained if the flux from the lens system can be reliably measured. Using high angular resolution observations with adaptive optics on Keck, VLT, SUBARU or HST it is possible to separate the contributions of the source and lens stars from blended stars at the subarc-second level. Knowing the luminosity of the source thanks to the light curve modelling, we can then constrain the lens flux, and using stellar evolution calculations [59], we can derive another mass-distance relation [60]. *Combining with the other mass-distance relations, it* is possible to measure masses to $\sim 20\%$ or better [26, 53, 61].

The strongest constrain is obtained when source and lens are resolved several years after the microlensing event [15, 16, 20, 62–64]. It gives not only a measurement of the flux of the lens, but also the amplitude and orientation of the relative source-lens proper motion. When the later is combined with parallax, it will then strongly constrain the physical parameters of the system. Typically, we can derive physical parameters to $\sim 10\%$ or better.

There is a fourth and elegant route to measure the Einstein Ring radius and constrain the system performing time critical observations with VLTI Interferometry [65], PIONEER [66] or GRAVITY instrument [67]. It is a difficult task requiring bright targets, good predictions and target of opportunity status at VLT. It has already been achieved twice for single lenses. In one case, the authors managed to measure the separation, and rotation rate on the two arcs during the event [66]. giving a mass measurement of the lens with a precision of 2 %. GRAVITY is the instrument of choice for such kind of measurements in the coming decade. It could likely be done at maximum few times per year in favorable circumstances, and could also be used to measure masses of black holes in the disk or bulge of our Galaxy [68].

## 4. The golden age of space-based microlensing

The $\sim 1 arcsec$ angular resolution of ground based wide field imagers implies that we cannot monitor 0.3-0.5 $M_\odot$ stars in the Galactic Bulge because of crowding, which sets a practical limitation to the detection of $\sim 2-3 M_\oplus$ mass planets in most cases. It had been shown in 2002 that a 1m class telescope with a wide field camera in space would be able to detect and monitor microlensing of faint (and small) source stars unresolved from the ground. It would push the detectability of exoplanets down to the mass of Mars [5, 69]. This was first proposed as a stand-alone mission, the GEST project submitted to NASA. Shortly after, having realised the synergies between the requirements for Cosmic Shear Measurements and exoplanet demographics via microlensing, a first microlensing survey was proposed as part of the DUNE project submitted to ESA, and it has been in the additional science of the ESA Cosmic Vision M2 mission Euclid [70–73]. In the USA, the concept matured from a dedicated microlensing mission to become a joint mission with Dark Energy probes as stressed Astro 2010 Decadal Survey [74, 75]: *"Space-based microlensing is the optimal approach to providing a true statistical census of planetary systems in the Galaxy, over a range of likely semi-major axes"*. They also added: *"This census, combined with that made by the Kepler mission, will determine how common Earth-like planets are over a wide range of orbital parameters"*. The Decadal survey ranked first the WFIRST mission, which has a proposed 450 days microlensing program. The fundamental difference between Europe and the USA has been the ability in the USA to put forward different science cases simultaneously, while in Europe Euclid was and remained a Dark Energy mission with potentially additional surveys. The first detailed simulations of space based microlensing surveys were done for the Euclid mission, showing the power of a 4 months survey to measure the mass function of cold planets down to the mass of Mars [76]. These simulations were then extended to WFIRST [77, 78]. WFIRST was then rebranded the Nancy Grace Roman Space Telescope (Roman for short) and is scheduled for launch in 2027. A recent study shows that a short Euclid survey of the fields to be observed by Roman can give an excellent base for quick constraint of relative source-lens proper motion of the survey by Roman. Moreover, simultaneous observations of the same field by Roman and Euclid is the only way to have individual mass measurements of free-floating telluric planets, thanks to parallax effects while both satellites would be on L2 orbit [79]. This is currently being discussed by the board of Euclid and ESA.

The Roman satellite microlensing survey will be a game changer for the demographic of planets beyond the snow line planets and exomoons. Its sensitivity will extend to the habitable zone Earth mass planets in the habitable zone. Combined with Euclid, Roman would give precise mass measurements from its first year of operation, and it is the way to get accurate mass measurements and statistics of free-floating telluric planets. Kepler was a game changer for transiting planets, Roman and Euclid will play the same role for cold planets. They will give unprecedented statistics probing the planet distribution in the disk and in the Bulge of our Galaxy at the horizon 2030.

## Conflict of interest

The author has no conflict of interest to declare.

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