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Polarimetric microlensing as a tool for breaking degeneracies in compact object lensing toward the Galactic bulge

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Marsida Laze[a,*] and **Lindita Hamolli**[b]

[a] *University of Elbasan,*
St: Ismail Zyma, Elbasan, Albania

[b] *Department of Physics, University of Tirana,*
Zogu I Boulevard, Tirana, Albania

E-mail: marsida.laze@uniel.edu.al, lindita.hamolli@fshn.edu.al

Abstract

Gravitational microlensing is a powerful method for investigating compact dark objects in the Galaxy. However, analyses based solely on photometric light curves are limited by degeneracies between lens mass, distance, and transverse velocity, since photometry mainly constrains the Einstein timescale that combines several parameters into a single observable. These limitations can be alleviated by higher-order effects such as parallax, astrometric shifts, and finite-source effects. When the source's angular size becomes significant, the point-source approximation fails and microlensing induces polarization signals through differential magnification across the stellar disc and circumstellar envelope, providing observables beyond photometry. This polarimetric framework applies to both standard and non-standard microlensing scenarios, including axion stars or axion–photon couplings, and by combining photometric with polarimetric data it reduces parameter degeneracies and opens new directions for probing compact dark matter candidates, providing a solid basis for future investigations.

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[*] Speaker

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1. Introduction

Gravitational microlensing occurs when a compact object passes close to the line of sight to a background star, bending its light and producing a temporary increase in brightness [1]. Because microlensing does not depend on the luminosity of the lens, it is an excellent tool for detecting dark or faint objects such as primordial black holes (PBHs), brown dwarfs, or free-floating planets. In the standard point-source approximation, the magnification of a microlensing event is described by the Paczyński profile [2]

$$A = \frac{u^2+2}{u\sqrt{u^2+4}}, \tag{1}$$

where $u(t) = \sqrt{u_0^2 + [t - t_0/t_E]^2}$ is the separation between the lens and the line of sight in units of the Einstein radius. It depends on u_0 (the minimum value), t_0 the time of maximum amplification and t_E, which is the Einstein timescale, representing the time it takes the lens to cross the Einstein radius R_E, moving with the relative transverse velocity V_T. The Einstein angular radius depends on the lens mass and the distances to the lens and the source. It is given by:

$$\theta_E = R_E/D_L = \sqrt{\frac{4GM_L}{c^2}\left(\frac{1}{D_L} - \frac{1}{D_S}\right)}. \tag{2}$$

Photometric microlensing light curves primarily constrain the t_E, a quantity that entangles the lens mass, distance, and transverse velocity, leading to strong degeneracies [3]. These degeneracies can be partially broken by including second-order effects, such as parallax, astrometric shifts, and finite-source effects. When the angular size of the source is non-negligible, the point-source approximation fails and the observed amplification must be averaged over the stellar disc:

$$A_{fs}(u') = \frac{1}{\pi\rho_*^2}\int_0^{2\pi} d\alpha \int_0^{\rho_*} p \frac{{u'}^2}{u'\sqrt{{u'}^2+4}} dp, \tag{3}$$

where $u' = \sqrt{u^2 + p^2 - 2up\cos\alpha}$ is the distance to the lens of the source element, located at polar coordinates (p, α), projected in R_E, u is the distance of the source center, ρ_* is the projected source radius in the lens plane, expressed in units of the R_E, and R_* is the physical source size [4]. Analyses of finite-source events allow constraints on the θ_E [5]. Beyond photometry, polarimetric observations provide a complementary probe, since differential amplification across the stellar surface induces a net polarization signal. Microlensing, independent of lens emission, has long been used to search for dark matter, with surveys such as MACHO, EROS, OGLE, and MOA [6] placing strong limits on compact object fractions. It is also effective for detecting exoplanets, particularly those with wide separations or low masses, inaccessible to radial velocity or transit methods [7]. Modern high-cadence surveys have extended sensitivity to Earth-mass lenses, probing compact dark matter candidates across a broad mass range [8]. Microlensing has further been proposed as a probe of non-standard dark matter, notably axions and axion-like particles, which may form bound structures known as axion stars. Studies using EROS-2 and Subaru HSC data have constrained their abundance and size [9], while some analyses suggest that ultra-short events in Hyper Suprime-Cam and OGLE could be explained by Earth-mass axion stars [10]. In addition, axion–photon couplings may induce birefringence, rotating the polarization plane as light propagates through an axion background, an effect studied in astrophysical and cosmological contexts [11]. These considerations motivate a general polarimetric microlensing framework, extending beyond point-like lenses and purely gravitational effects, to probe a wider class of compact dark matter scenarios.

2. Theoretical framework for polarimetric microlensing

Stars with spherical symmetry emit unpolarized light. During a microlensing event, the lens magnifies different parts of the stellar disc by different amounts. If the star has finite size and an extended atmosphere, this asymmetric magnification breaks the symmetry of the scattered light and produces a small net polarization [12-14]. For an extended source, the polarization is described through the Stokes parameters I, Q, U, V, where I is the total intensity, Q is the difference in intensity measured in two perpendicular directions, x and y, U is the difference in intensity measured in two perpendicular directions at 45° to the x and y axes and V measures any circular polarization [15]. The observable fractional polarization and its position angle are given: $P = \frac{\sqrt{F_Q^2+F_U^2+F_V^2}}{F_I}$, $\psi = \frac{1}{2} arctan \frac{F_U}{F_Q}$. The source stars are assumed to have a spherical envelope of density $n(r) = n_0 (R_h/r)^\beta$ and an inner radius R_h that depends on the dust-formation temperature: $R_h = 0.45\left(T_{eff}/T_h\right)^{2.5} R_*$, $T_h = 1400$ [16]. The scattered polarization depends on the optical depth of the envelope, given by [17]:

$$\tau_{sc} = 2 \times 10^{-3} \eta \kappa (\frac{\dot{M}}{10^{-9} M_\odot yr^{-1}})(\frac{30 kms^{-1}}{v_\infty})(\frac{24 R_\odot}{R_h}), \tag{4}$$

where v_∞ is the wind velocity and $\dot{M}$ the mass-loss rate. Following Simmons et al. (2002)[14], the total (normalized) lensed Stokes flux can be written in terms of three scalar integrals: $H_*(p_S)$, $H_I(p_S)$ and $H_P(p_S)$ and then the total flux amplification is given by: $M(p_S) = H_*(p_S) + \tau_{sc} H_I(p_S)$. The polarization degree and polarization angle can be defined as:

$$P(p_S) = \frac{\tau_{sc} H_p(p_S)}{H_*(p_S) + \tau_{sc} H_I(p_S)}, \ \Psi = \pi - \ tan^{-1}\left[\frac{\theta_0}{\mu_{rel}(t-t_0)}\right]. \tag{5}$$

During the polarimetric observations, at closest approach, when the magnification is maximum, the polarization direction aligns with the direction in which the lens moves on the sky, an information that cannot be obtained from photometry alone. Depending on the lens trajectory relative to the source, two classes of polarimetric microlensing events can be identified. *In transit events*, where the lens crosses the stellar disc and the inner circumstellar envelope, the polarization curve exhibits a characteristic double-peaked structure. The temporal separation between the two polarization maxima is given by: $\delta t = 2 t_E \sqrt{(\bar{R}_h/0.75)^2 - u_0^2}$, where $\bar{R}_h$ is the inner circumstellar radius projected onto the lens plane, expressed in units of the Einstein radius. *In bypass events*, where the lens passes outside the stellar disc, the polarization signal displays a single, broad peak with a lower amplitude, which may nevertheless remain detectable for sufficiently extended envelopes.

The detectability of polarization signals in microlensing events from compact dark lenses has been quantitatively examined in our previous study [18], using a combined strategy with the Roman Space Telescope and polarimetric follow-up from the VLT toward the Galactic bulge. That work focused on compact objects such as PBHs and identified the lens mass and distance regimes where polarization signals are measurable, with an estimated detection probability of ~1.6%. These events typically span from several days to several months. In the presence of axion–photon couplings, the polarization angle may vary with a period set by the axion mass; determining whether such variations can be resolved within the finite duration of a microlensing event is crucial, since rapid oscillations may average out while slow ones may appear as a constant rotation [19]. Overall, this framework underscores the potential of polarimetric microlensing to complement photometric analyses and extend microlensing studies to non-standard dark matter scenarios.

3. Conclusions

The polarization signal in microlensing events provides information beyond photometry, with curve shapes (single broad or double-peaked) constraining the lens trajectory relative to the source. Its amplitude depends on the circumstellar envelope size in units of θ_E, making it sensitive to both lens mass and distance. Thus, polarimetry offers complementary constraints that reduce the degeneracy of photometric microlensing. Moreover, the time evolution of the polarization angle reveals the lens motion on the sky, inaccessible to photometry. This framework also opens perspectives for studying non-standard scenarios, such as axion stars or axion-induced birefringence, which may affect polarimetric observables.

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