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Constraining Ultra-Light Scalar Dark Matter with Pulsars

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Binary pulsars can serve as natural dark matter detectors. We consider an ultralight scalar dark matter, which interacts directly with the binary pulsar components via a universal effective interaction, characterized by one coupling constant. This causes a perturbation of the dynamics of the binary system. The perturbation is manifested by a change in the arrival time of pulses from the pulsar on Earth. The aim of our work is to determine the limiting value of the coupling constant, enabling the measurement of this effect. In other words, time residuals can serve as a proxy for ULDM. In this proceedings, a simple approach to sensitivity curve construction (i.e., a plot of the coupling constant versus particle mass) is presented. Further details and a comprehensive analysis can be found in [1].

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1. Introduction

Pulsars serve as exceptionally precise cosmic timekeepers and have found diverse applications (see [2]). Within these applications, binary pulsars offer potential as detectors for dark matter with masses falling within the lower range of ultra-light dark matter (ULDM), typically spanning 10^{-23} eV $\lesssim m \lesssim 10^{-18}$ eV. The ULDM can carry a direct force between it and the matter that makes up the components of pulsars. This direct interaction subsequently perturbs the dynamics of these systems, namely the orbital parameters become functions of time. In the papers [3–6] it has been shown that binary pulsars can be used to impose strong constraints on the coupling constants of these interactions, for ULDM models with spin 0, 1 and 2. However, all works were limited to a very special case, namely resonances where $m = n\omega_b$, where n is a natural number and $\omega_b = 2\pi/P_b$, while P_b is the period of the binary system. Moreover, these papers considered that the dark matter effect is hidden in the uncertainty in the measured orbital parameters, ignoring the actual time evolution of these parameters.

Our aim is to build on these works and generalize their results in three directions: 1) we do not restrict ourselves to the special case of $m = n\omega_b$ (resonance), thus covering a larger area of phase space; 2) we take into account the full time evolution of the orbital parameters induced by ULDM; 3) we combine a set of pulsars to enhance the sensitivity limit.

If we build a timing model to predict the time of arrival of pulses but forget to include the ULDM influence, it produces extra time residuals (on top of noise at least) [7]. We can use this effect to estimate the sensitivity limit from pulsar binaries to detect ULDM. In this context and for the purpose of this proceedings, we presume that, barring noise, these residuals stem exclusively from ULDM. For sensitivity evaluations, we employ the low eccentricity pulsar PSR J1909-3744 from the NANOGrav 2023 dataset [8]. In [1], we broaden the analysis to account for potential additional sources contributing to time residuals, employing a larger sample of pulsars.

2. The perturbed orbital motion induced by ULDM

Each binary system is described by six orbital parameters that can be chosen in different ways. Pulsars with small eccentricity can be described using the following set: $(x, \iota, \Omega, \eta, \kappa, T_{\rm asc})$ - x is related to the semi-major axis as $x := a \sin\iota$; ι is the inclination of the orbital plane; Ω is the longitude of the ascending node; η, κ are Laplace-Lagrange parameters, linked to the eccentricity e and the argument of periapsis ω as $\eta := e \sin\omega$, $\kappa := e\cos\omega$; $T_{\rm asc}$, representing the time of passage through the ascending node. In fact, it is suitable to replace $T_{\rm asc}$ by Ψ defined as:

$$\Psi := \int_{T_{\rm asc}}^{t} \omega_b dt.$$

We will prefer to work with a set of orbital parameters chosen as $(x, \iota, \Omega, \eta, \kappa, \Psi)$.

If a perturbing force acts on a binary system, its time evolution is described by the post-Keplerian formalism. This formalism assumes that the bodies follow instantaneous ellipses characterized by time-varying orbital parameters. We assume that this perturbing force arises from scalar ULDM, which displays homogeneity near the binary system and is described by a time-dependent function Φ:

$$\Phi(t) = A\cos(mt + \Upsilon).$$

Here, A represents the amplitude of the ULDM field, Υ denotes the phase, and the mass m serves as the frequency. While Υ is treated as a random variable with a uniform distribution, it is important to note that A is also nondeterministic:

$$A = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m}\varrho,$$

where ρ_{DM} is the density of dark matter and ϱ follows the Rayleigh distribution. This factor originates from the description of ULDM in the late universe as a superposition of oscillators, making ϱ an interference factor. [9]

Following [3, 4], the direct interaction is expected as follows:

$$M_A^{(\alpha)}(\Phi) = M_A(1 + \alpha\Phi),$$

where $A \in \{1, 2\}$, with M_1 being the pulsar's mass and M_2 the mass of the companion. In other words, we assume that the dark matter affects the mass of the components of the binary system, with α representing the effective coupling constant. We observe that among the six orbital parameters, only four have non-trivival variations: $\dot{x}, \dot{\eta}, \dot{\kappa}, \dot{\Psi}$, while $\dot{\Omega} = \dot{\imath} = 0$, where the dot represents the time derivative.

3. Sensitivity limit from time residuals

As we already know, the timing model describes the arrival times of pulses from the pulsar on Earth, and if the model is incomplete, it leads to additional time residuals. For the sake of simplicity, we assume that the residuals R arise from a combination of ULDM and noise, denoted as $R = R^{\mathrm{DM}} + R^{\mathrm{PN}}$, where the noise is modeled as white Gaussian noise.

When employing Bayesian analysis and considering δ-function priors for Υ and ϱ, we determine the sensitivity limit as:

$$|\alpha| \simeq \sigma_\alpha,$$

where σ_α^2 represents the variance of the probability distribution function for α at a given mass m. The numerical factor in the equation is of order $O(1)$. In principle, each variation—i.e., δx, $\delta\kappa$, $\delta\eta$, $\delta\psi$—contributes to σ_α but possesses differing degrees of constraining power regarding α. Figure 1 shows, as an illustrative example, sensitivity plots where only the contribution of δx (or $\delta\kappa$) was considered. To plot the sensitivity curves, we sample ϱ from the Rayleigh distribution and Υ from the uniform distribution.

4. Conclusions

Binary pulsars have the potential to serve as detectors for ULDM and we have outlined a straightforward method to estimate the sensitivity limit. This method can be expanded to consider diverse non-ULDM influences by utilizing Bayesian analysis and to include the incorporation of non-δ-priors for ϱ and Υ. Moreover, it is adaptable to incorporate multiple pulsars, including those with higher eccentricity, to enhance the sensitivity limit. Further detailed analysis regarding these aspects is provided in [1].

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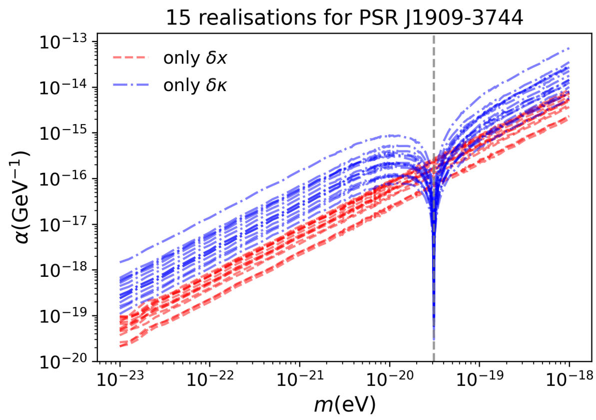

Figure 1: Individual sensitivity limits from δx and $\delta \kappa$.

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