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Binary pulsars as fuzzy dark matter detectors

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The ultra-light dark matter (ULDM) model is a compelling candidate for cosmological dark matter. If ULDM exists and interacts directly with ordinary matter, it leaves a distinct signature in pulsar timing data. Even in the absence of a detected signal, such data can impose stringent constraints on the ULDM parameter space. We present recent advances in using two independent methods—Bayesian analysis and machine learning—to assess the sensitivity of binary pulsars to ULDM. With these approaches, we extend the existing literature and further establish pulsars as detectors of ULDM. For simplicity, we focus solely on spin-0 ULDM model with linear dilatonic coupling to ordinary matter, but our methods can be straightforwardly extended to other types of ULDM.

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1. Introduction

The nature of dark matter remains an enduring mystery, despite its critical role in the Universe. It constitutes approximately 27% of the Universe's energy content and is about five times more abundant than baryonic matter. Among the many proposed candidates, one particularly intriguing option is ultra-light dark matter (ULDM).

ULDM consists of particles with incredibly small masses, ranging from $m \sim 10^{-23}$ eV to 1 eV. Of particular interest is the lower end of this mass range, where the particles exhibit de Broglie wavelengths on astrophysical scales. If ULDM accounts for all dark matter, the particle number density must be extraordinarily high, allowing the dark matter to be modeled as a classical field oscillating at a frequency determined by the particle mass. While ULDM may exhibit wave-like behavior on astrophysical scales, giving rise to unique phenomena, it still closely reproduces the large-scale structure dynamics predicted by cold dark matter (CDM). Beyond gravitational interactions, ULDM may couple directly to ordinary matter, resulting in unique observable signatures that vary with specific ULDM models. For a detailed review, see [1].

Binary pulsars—systems where at least one of the two stars is a pulsar—are emerging as powerful tools to probe ULDM. Studies such as [2–5] demonstrate that both direct and gravitational interactions between ULDM and binary pulsar components induce perturbations in the system's dynamics (illustrated in Fig. 1). These perturbations appear as unique signals in pulsar timing data, manifesting as time residuals when not accounted for in the timing model.

While the gravitational influence of ULDM on pulsar timing is expected to be too weak to detect [3], direct interactions with ordinary matter could produce observable effects. The absence of such signals imposes stringent constraints on the coupling constants of specific dark matter models. Initial studies have explored ULDM models with spins 0, 1, and 2, within the mass range of 10^{-23} to 10^{-18} eV, where the binary pulsar's backreaction to dark matter is negligible [3].

This work summarizes the latest results on binary pulsars' sensitivity to ULDM, including Bayesian analysis findings first presented in [6]. Additionally, new results leveraging machine learning techniques are forthcoming [7].

2. ULDM and its detection

Four ULDM models have been proposed in the literature: scalar field models with linear or quadratic coupling [2, 3], vector ULDM [4], and tensor ULDM [5]. For simplicity, we focus on the linear scalar field model.

This model is described by the scalar field $\Phi(t) = \Phi_0 \varrho \cos(mt + \Upsilon)$, where m is the mass of the ULDM particle and Υ is a random phase. The field's amplitude Φ_0 is related to the dark matter density $\rho_{\rm DM} = 0.3\,{\rm GeV/cm^3}$, and ϱ is a Rayleigh-distributed random variable.

We assume that the coupling of ULDM to the stars can be described by an effective universal Φ-dependent mass of the binary components, $M^{\alpha}_{1,2} = M_{1,2}(1 + \alpha\Phi)$, where $M_{1,2}$ are the masses of the stars in the absence of the field. The dynamics of the binary system are perturbed by this oscillating field, causing the semi-major axis to evolve as follows:

$$\frac{\dot{a}}{a} = -2\alpha\dot{\Phi}\,.$$

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The variation in the semi-major axis introduces timing residuals, which depend on the oscillations of the dark matter field. In addition to the semi-major axis, other orbital parameters, such as eccentricity, also evolve over time due to ULDM, further contributing to the timing residuals.

Additional residuals may arise from inaccuracies in parameter values, secular effects, and various types of noise. Both Bayesian and machine-learning approaches can account for these effects.

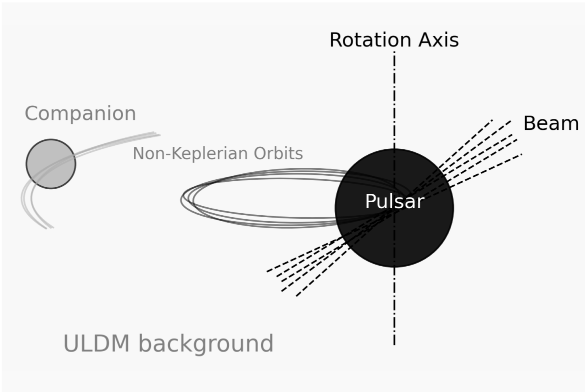

Figure 1: Illustration of a binary pulsar system

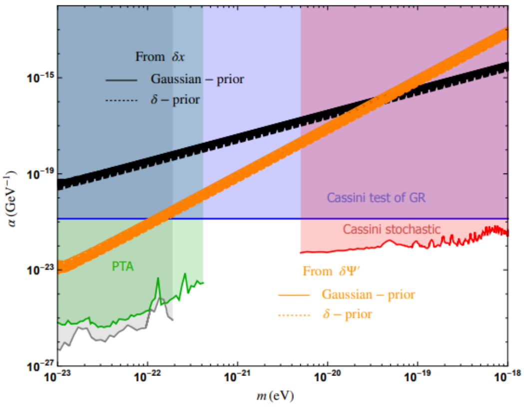

Figure 2: Bayesian sensitivity limit [6]

3. Sensitivity limit

In [6], we set Bayesian sensitivity limits for detecting ULDM using binary pulsars. These limits, denoted by curves $\alpha(m)$, exclude regions above the curves in the case of non-detection. This work extends prior studies investigating resonances between ULDM and binary systems, characterized by $m = N\omega_b$, where ω_b denotes the orbital angular frequency and N is the resonance number. Bayesian analysis incorporates nuisance effects and combines data from multiple binaries but requires sensitivity limits to be computed separately for each orbital parameter.

An alternative approach employs a machine-learning method known as an autoencoder. This neural network is trained to learn the features of a *normal dataset* (timing residuals without ULDM signals) and reconstruct it with minimal error. When applied to an *abnormal dataset* (containing ULDM signals), previously unseen features lead to a marked increase in the reconstruction error, flagging the dataset as anomalous, as illustrated in Fig. 3. The autoencoder thus functions as an anomaly detector, capable of identifying deviations and constraining the coupling constant strength, as illustrated in Fig. 4.

4. Conclusions

We presented two methods for constraining the coupling constant strength of direct interactions between ULDM and baryonic matter. In particular, we focused on the simplest case—a spin-0 ULDM model with linear coupling to ordinary matter. Using these approaches, we demonstrated that binary pulsars are viable detectors of ULDM, rivaling other experiments. Moreover, our results extend the existing literature by exploring parameter spaces beyond the resonance regime.

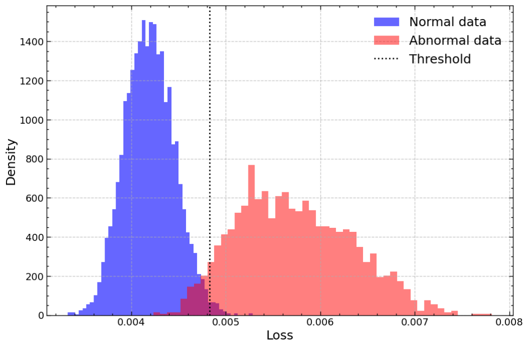

Figure 3: Comparison of reconstruction errors for normal and abnormal datasets. The increased error in the abnormal dataset highlights the autoencoder's effectiveness in detecting deviations.

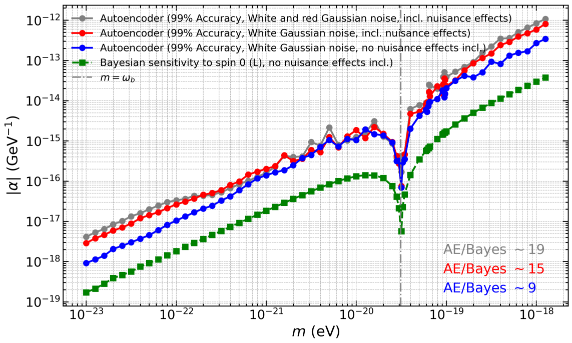

Figure 4: Sensitivity limits derived using the autoencoder. The plot shows the excluded parameter space for the ULDM coupling constant, based on anomaly detection trained on datasets of varying complexities.

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References

[1] E. G. M. Ferreira, "Ultra-light dark matter," Astron. Astrophys. Rev. **29** (2021) no.1, 7 [arXiv:2005.03254 [astro-ph.CO]].

[2] D. Blas, D. L. Nacir and S. Sibiryakov, "Ultralight Dark Matter Resonates with Binary Pulsars," Phys. Rev. Lett. **118** (2017) no.26, 261102 [arXiv:1612.06789 [hep-ph]].

[3] D. Blas, D. López Nacir and S. Sibiryakov, "Secular effects of ultralight dark matter on binary pulsars," Phys. Rev. D **101** (2020) no.6, 063016 [arXiv:1910.08544 [gr-qc]].

[4] D. López Nacir and F. R. Urban, "Vector Fuzzy Dark Matter, Fifth Forces, and Binary Pulsars," JCAP **10** (2018), 044 [arXiv:1807.10491 [astro-ph.CO]].

[5] J. M. Armaleo, D. López Nacir and F. R. Urban, "Binary pulsars as probes for spin-2 ultralight dark matter," JCAP **01** (2020), 053 [arXiv:1909.13814 [astro-ph.HE]].

[6] P. Kůs, D. López Nacir and F. R. Urban, "Bayesian sensitivity of binary pulsars to ultra-light dark matter," Astron. Astrophys. **690** (2024), A51 [arXiv:2402.04099 [astro-ph.HE]].

[7] P. Kůs, D. López Nacir and F. R. Urban, "Deep Neural Networks Hunting Ultra-light Dark Matter", *in preparation*.