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Constraints on minimally and conformally coupled ultralight dark matter with the EPTA

Clemente Smarra[a,*]

[a] *SISSA — International School for Advanced Studies, Via Bonomea 265, 34136, Trieste, Italy and INFN, Sezione di Trieste*

[a] *IFPU — Institute for Fundamental Physics of the Universe, Via Beirut 2, 34014 Trieste, Italy*

E-mail: csmarra@sissa.it

Millisecond pulsars are extremely stable natural timekeepers. Pulsar Timing Array experiments, tracking subtle changes in the pulsars' rotation periods, can shed light on the presence of ultralight particles in our Galaxy. In this conference paper, we start by reviewing the most conservative scenario, in which ultralight particles interact only gravitationally. In this setting, we show that Pulsar Timing Arrays are able to constrain the presence of ultralight fields up to a few tenths of the observed dark matter abundance. Then, we consider conformally coupled ultralight candidates, demonstrating that the constraints on the universal scalar coupling of the field to Standard Model particles improve on existing bounds by several orders of magnitude, in the relevant mass range analyzed by Pulsar Timing Arrays. The discussion presented here is based on [1, 2].

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1. Introduction

The Cold Dark Matter (CDM) paradigm has been remarkably successful in explaining many aspects of the large-scale structure of the Universe. However, it encounters notable challenges below the kiloparsec scales. For instance, flat density profiles observed in the inner regions of galaxies are in tension with the steep power-law behavior predicted by pure CDM models (*cusp-core problem*) [3–5]. To address these issues, it may be argued that dark matter (DM) consists of ultralight scalar fields with masses $m \sim 10^{-22}$ eV and negligible self-interactions [6, 7]. The de Broglie wavelength of such fields in galaxies spans ~ kpc scales, naturally suppressing small-scale power while preserving the CDM successes at larger scales.

In Ref. [8], it was pointed out that the universal gravitational coupling of ultralight dark matter (ULDM) to ordinary matter influences the light travel time of radio signals emitted by pulsars. Based on this principle, Pulsar Timing Array (PTA) experiments have established 95% upper limits on the local energy density of ULDM, reaching $\rho \lesssim 0.15$ GeV/cm^3 in the mass range $10^{-24.0}$ eV $\lesssim m \lesssim 10^{-23.7}$ eV [1, 9].

However, a natural possibility that respects the weak equivalence principle is that ULDM may be universally (conformally) coupled to gravity, or (equivalently, in the Einstein frame) to the Standard Model. In this context, ULDM may be regarded as a scalar-tensor theory of the Fierz-Jordan-Brans-Dicke [10–13] or Damour-Esposito-Farèse type [14, 15], in the presence of a (light) mass potential term [16]. As a result of the strong gravitational fields active inside neutron stars, the universal coupling to gravity produces a gravity-mediated interaction between neutron stars (and thus pulsars) and the scalar ULDM field [14, 17–21].

This work is organized as follows. In Section 2, we introduce the Lagrangian of a minimally coupled ULDM field and provide a brief overview of key features relevant to our study. Then, we examine the impact of such a candidate on the times of arrival (TOAs) of pulsar radio beams, presenting bounds constraining the local ULDM abundance to values *below* the measured local DM density in a specific mass range. In Section 3, we analyze the case of a conformally coupled ULDM candidate. Consequently, we derive constraints on the coupling strength, achieving bounds that surpass those from Cassini tests of General Relativity [22, 23] and observations of the pulsar in a triple stellar system [24–26] by several orders of magnitude within the mass range probed by pulsar timing arrays (PTAs). Conclusions are summarized in Section 4.

2. Minimally coupled ULDM

The action for an ultralight scalar field ϕ with negligible self-interactions and no couplings with the Standard Model is as simple as:

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{1}{2}m_\phi^2\phi^2\right], \tag{1}$$

where m_ϕ stands for the mass of the scalar field. Given its high occupation number and non-relativistic nature, the ULDM scalar field can be treated as a classical wave [8]:

$$\phi(\vec{x},t) = \frac{\sqrt{2\rho_\phi}}{m_\phi}\hat{\phi}(\vec{x})\cos\left(m_\phi t + \gamma(\vec{x})\right), \tag{2}$$

where ρ_ϕ is the scalar field density, $\hat{\phi}(\vec{x})$ is a stochastic parameter, extracted from the Rayleigh distribution ($P(\hat{\phi}^2) = e^{-\hat{\phi}^2}$) [27] and encoding the interference pattern near $\vec{x}$ arising from the wave-like nature of ULDM, and $\gamma(\vec{x})$ is a spatially dependent phase. The ULDM scalar field is described by Eq. (2) on timescales shorter than its *coherence time* or, equivalently, on length scales smaller than its *coherence length*

$$\tau_c \sim \frac{2}{mv^2} = 2 \times 10^5 \text{ yr} \left(\frac{10^{-22} \text{ eV}}{m} \right), \qquad l_c \sim \frac{1}{mv} \sim 0.4 \text{ kpc} \left(\frac{10^{-22} \text{ eV}}{m} \right), \tag{3}$$

where $v \sim 10^{-3}$ is the typical DM velocity in our Galaxy. The oscillating ULDM field leads to a periodic displacement δt of the TOAs of radio pulses emitted by pulsars, which reads [8, 9]:

$$\delta t = \frac{\rho_\phi}{2m_\phi^3} [\hat{\phi}_\text{E}^2 \sin(2m_\phi t + \gamma_\text{E}) - \hat{\phi}_\text{P}^2 \sin(2m_\phi t + \gamma_\text{P})], \tag{4}$$

where $\gamma_\text{P} \equiv 2\gamma(\vec{x}_\text{p}) - 2m_\phi d_p/c$ ($\gamma_\text{E} \equiv 2\gamma(\vec{x}_\text{e})$) is related to the phase of Eq. (2) evaluated at the pulsar (Earth) location, with d_p labeling the pulsar-Earth distance. Current uncertainties in pulsar distance measurements are of the order of $O(0.1 \div 1)$ kpc [28]; therefore, these redefinitions produce effective pulsar-dependent random phases. Depending on the typical Earth-pulsar distance, we can distinguish three different scenarios: the *correlated regime*, when both the typical inter-pulsar and pulsar-Earth separations and the typical Galacto-centric region probed by the most precise MW rotation curves measurements (approximately the inner ~ 20 kpc [29]) are smaller than the ULDM coherence length; the *pulsar-correlated regime*, when the ULDM coherence length is larger than the inter-pulsar and pulsar-Earth separations, but does not extend to the typical Galacto-centric radius probed by rotation curves; the *uncorrelated regime*, when the average inter-pulsar and pulsar-Earth separation is larger than the ULDM coherence length. We present our results for the three regimes in Fig. 1.

3. Non minimally coupled ULDM

As a next step, we can explore scenarios in which the ultralight field is non minimally coupled to gravity. Maintaining the same notation as Section 2, the action for a non minimally coupled field in the Einstein frame is expressed as [1]:

$$S = M_\text{P}^2 \int \text{d}^4x\sqrt{-g} \left[\frac{R}{2} - g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + m_\phi^2\phi^2 \right] + S_m[\psi_m, \tilde{g}_{\mu\nu}] \ .$$

The matter action S_m incorporates a universal *conformal* coupling of the scalar field to the matter content ψ_m through the (Jordan) effective metric $g_{\mu\nu} = \mathcal{A}^2(\phi)$, with $\mathcal{A}^2(0) = 1$. Firstly, we specialize to the Fierz-Jordan-Brans-Dicke (FJBD) theory [10–13], which features a linear conformal coupling

$$\mathcal{A}(\phi) = e^{\alpha\phi} \sim 1 + \alpha\,\phi. \tag{5}$$

[1] Notice that, contrarily to Section 2, ϕ has a non canonical normalization, and appears in the action as an adimensional quantity multiplied by the Planck mass M_P. We stick to this convention, as it simplifies comparisons with gravitational phenomena.

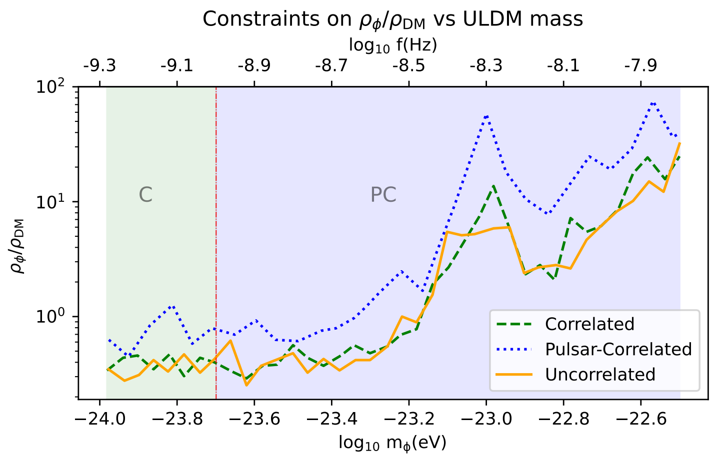

Figure 1: Upper limits on the ratio of the scalar field density to the local abundance of DM, $\rho_\phi/\rho_{\rm DM}$, at 95% credibility versus the ULDM mass. We plot results for the *uncorrelated* (U), *pulsar-correlated* (PC) and *correlated* (C) scenarios in solid, dotted and dashed lines, respectively. Moreover, we color-identify the regions of relevance of each of the three regimes. We truncate the plot at $\log_{10} m_\phi({\rm eV}) \sim -22.5$, as the upper bounds are not much informative anymore. As a result, the domain of validity of the uncorrelated limit is not shown here, and we refer to Ref. [1] for more details. The priors on the parameters of the analysis are summarized in Table I of Ref. [2].

The Cassini mission provides a bound on the *scalar coupling* α to the level of $\alpha^2 \lesssim 10^{-5}$ [22], while the triple system PSR J0337+1715 provides a more stringent limit of $\alpha^2 \lesssim 4\times 10^{-6}$ [26]. Secondly, we focus on the Damour-Esposito-Farèse (DEF) theory [14, 15], with a quadratic universal coupling:

$$\mathcal{A}(\phi) = e^{\beta\phi^2/2}. \tag{6}$$

The non-observation of deviations from the General Relativity (GR) predictions in binary pulsar data imposes a constraint on β, requiring $\beta \gtrsim -4.3$ (depending on the specific equation of state (EoS) for the neutron star model), to prevent non-perturbative spontaneous scalarization phenomena [15, 33]. In these models, the analogous of Eq. (2) reads [2]:

$$\phi(\vec{x},t) = \frac{\sqrt{\rho_\phi}}{m_\phi M_P}\hat{\phi}(\vec{x})\cos\left(m_\phi t + \gamma(\vec{x})\right). \tag{7}$$

In the Jordan frame, an oscillating scalar field, as presented in Eq. (7), leads to a temporal variation of Newton's constant, which affects the gravitational mass and radius of the neutron star [14]. This dependence is captured by the sensitivities, defined as:

$$s_I = -\frac{1}{2\alpha(\phi)}\frac{{\rm d}\ln I}{{\rm d}\phi}\bigg|_{N,J} = \frac{1}{2\alpha(\phi)}\frac{{\rm d}\ln \Omega_{\rm obs}}{{\rm d}\phi}\bigg|_{N,J}, \tag{8}$$

evaluated at constant pulsar's baryon number N and Einstein-frame angular momentum J, where $\alpha(\phi) = {\rm d}\log\mathcal{A}/{\rm d}\phi$. We use the code from Ref. [30] to compute s_I. With this relation at hand, a variation in the scalar field value directly reflects to a change in the pulsar's spin frequency, which in turn affects the TOAs.

[2]The factor of 2 of difference in the numerator arises from the non canonical normalization of the field ϕ in Eq. (1).

3.1 FJBD gravity theory

In this scenario, inspecting Eq. (5) and using the definition of $\alpha(\phi)$, we find that $\alpha(\phi) = \alpha$, where α is constant. Furthermore, the numerical analysis conducted in Ref. [30] demonstrates that the angular momentum sensitivity s_I exhibits only a very weak dependence on the scalar coupling α. Given this, we neglect this dependence in our analysis.
In analogy to Eq. (4), the timing residuals in this context are given by:

$$\delta t = 2\alpha \frac{\sqrt{\rho_\phi}}{M_{\rm P} m_\phi^2} s_I \hat{\phi}_{\rm P}(\vec{x}) \sin(m_\phi t + \gamma(\vec{x}))\Big|_{t_{\rm start}}^{t_{\rm end}} . \quad (9)$$

We refer the reader to Ref. [2] for details on the derivation of this result. Defining $f_{\rm DM} \equiv \rho_\phi/\rho_{\rm DM}$ as the fraction of the total abundance of DM, assumed to be fiducially $\rho_{\rm DM} = 0.4$ GeV/cm^3, our ULDM candidate accounts for, we can present results in terms of $\alpha\sqrt{f_{\rm DM}}$. This is indeed the quantity constrained by Eq. (9), enabling a straightforward determination of the bound on α once a specific value for the scalar field density ρ_ϕ is assumed. Fig. 2 shows the upper limits for the *correlated, pulsar correlated* and *uncorrelated* scenarios.

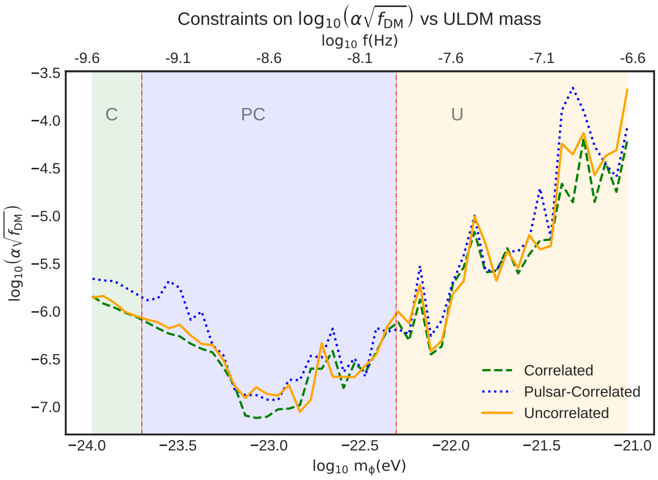

Figure 2: Upper limits on $\log_{10}\left(\alpha\sqrt{f_{\rm DM}}\right)$ at 95% credibility versus the ULDM mass. We plot results for the *uncorrelated* (U), *pulsar-correlated* (PC) and *correlated* (C) scenarios in solid, dotted and dashed lines, respectively. Moreover, we color-identify the regions of relevance of each of the three regimes. To produce the results, we used the AP4 EoS [31], and the priors on the parameters of the analysis are summarized in Table I of Ref. [2].

3.2 DEF gravity theory

In this case, by looking at Eq. (6), we have $\alpha(\phi) = \beta\phi$. In contrast to the FJBD scenario, here the angular momentum sensitivity depends non trivially on the coupling β. Therefore, we write $s_I = s_I(\beta)$ to keep this in mind. The expression for the timing residuals is given by

$$\delta t = \frac{\rho_\phi}{2m_\phi^3 M_P^2} \beta s_I(\beta) \hat{\phi}_{\rm P}^2(\vec{x}) \sin(2m_\phi t + \gamma(\vec{x}))\Big|_{t_{\rm start}}^{t_{\rm end}} . \quad (10)$$

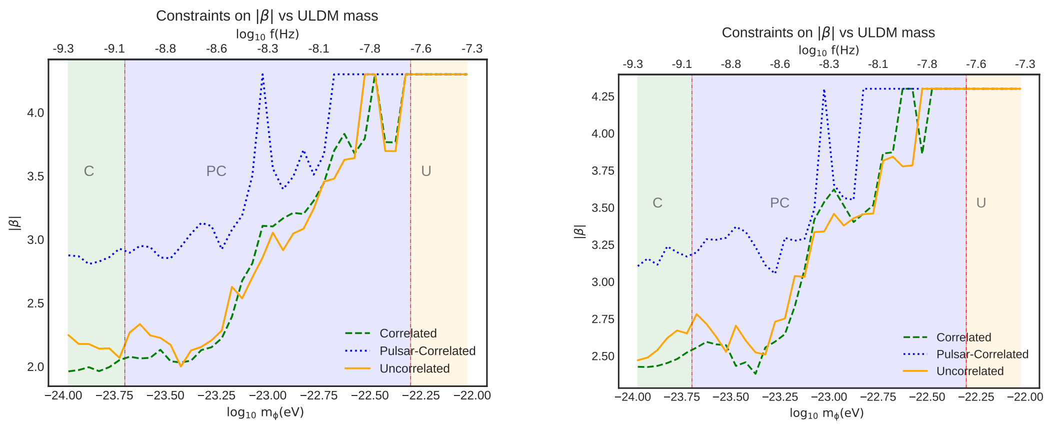

Figure 3: Upper limits on $|\beta|$ ($\beta < 0$) at 95% credibility versus the ULDM mass. We show bounds assuming $\rho = \rho_{\rm DM}$ and $\rho = 0.5\ \rho_{\rm DM}$ in the left and right panels, respectively. We plot limits for the *uncorrelated* (U), *pulsar-correlated* (PC) and *correlated* (C) scenarios in solid, dotted and dashed lines, respectively. Moreover, we color-identify the regions of relevance of each of the three regimes. To produce the results, we used the MPA1 EoS [32]. In cases where the data are not constraining, the upper limits correspond to the maximum value allowed by our prior. The priors for the parameters relevant to this analysis are defined according to the scheme outlined in Table I of Ref. [2].

The ULDM signal (10) depends separately on ρ_ϕ and β, which must therefore be treated as two independent parameters in the analysis.
To address this, we select two benchmark values for the scalar field density, namely $\rho_\phi = \rho_{\rm DM}$ and $\rho_\phi = 0.5\ \rho_{\rm DM}$, and we present the resulting bounds on β in Fig. 3.
Here, we restrict to negative values of β, and we choose $\beta = -4.3$ as the lower bound for the prior, as more negative values would induce $O(1)$ deviations from GR and are excluded by binary pulsars [33]. We refer the reader to Ref.[2] for an extended discussion of this model, which includes also positive values of β.

4. Conclusions

In this work, we reviewed the constraints that the EPTA sets on scalar ULDM density and couplings to gravity [1, 2]. In the minimally coupled case, scalar ULDM is allowed to contribute at most up to a few tenths of the observed DM abundance in the mass range $m_\phi \in [10^{-24}\ \text{eV}, 10^{-23.7}\ \text{eV}]$, in order to escape detection. In the non minimally coupled scenario, we specialized to the FJBD and the DEF gravity theories, and we considered the effects of a conformally coupled ULDM candidate on the observed TOAs. In the FJBD, our bounds improve by several orders of magnitude previous constraints, set by the Cassini spacecraft mission [22] and the PSR J0337+1715 system [26], across the entire mass range the EPTA is sensitive to. In a specific mass range, our results yield improved bounds compared to the previous literature in the DEF case as well [33–35]. We also refer the interested reader to Refs. [36, 37] for an extended discussion on how to constrain ULDM couplings to the Standard Model and to Ref. [38] for an interesting approach on how to constrain the ULDM coupling to photons using polarization data.

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