Ultralight Dark Matter Resonates with Binary Pulsars

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We consider the scenario where dark matter (DM) is represented by an ultralight classical scalar field performing coherent periodic oscillations. We point out that such DM perturbs the dynamics of binary systems either through its gravitational field or via direct coupling to ordinary matter. This perturbation gets resonantly amplified if the frequency of DM oscillations is close to a (half-)integer multiple of the orbital frequency of the system and leads to a secular variation of the orbital period. We suggest using binary pulsars as probes of this scenario and estimate their sensitivity. While the current accuracy of observations is not yet sufficient to probe the purely gravitational effect of DM, it already yields constraints on direct coupling that are competitive with other bounds. The sensitivity will increase with the upcoming radio observatories such as the Square Kilometer Array.

Introduction.—Despite years of intensive research, the nature of dark matter (DM) remains unknown. An interesting possibility is that DM is represented by a very light boson with extremely weak, if any, coupling to the fields of the standard model; see Ref. [1] for a recent review. Such DM candidates are common in many models of new physics including the axion solution to the strong CP problem [2–4], the relaxion mechanism for the origin of the electroweak symmetry breaking [5], and string theory [6,7].

Huge particle occupation numbers required to reproduce the DM density imply that such ultralight dark matter (ULDM) is well described by a classical scalar field $\Phi$. For a single field to be all of the DM, the anharmonics of the potential are constrained to be small when the field starts oscillating at $H \sim m_\Phi$ (with $H$ the Hubble rate) [8]. Since the amplitude of the field at that moment is larger than its present amplitude in the galactic halo, we will neglect possible self-interactions of $\Phi$.

A lot of effort has been devoted to identify observations and experiments sensitive to ULDM. Very light candidates with masses $m_\Phi \lesssim 10^{-24}$ eV are excluded as the dominant DM component by the observations of the cosmic microwave background and large-scale structure [9]; future observations are expected to push the lower bound to $m_\Phi \sim 10^{-23}$ eV [10]. Slightly heavier ULDM in the range $m_\Phi \sim 10^{-23}$–$10^{-21}$ eV can be probed by the Lyman-$\alpha$ forest, galaxy formation history, and the structure of galactic halos [11–16]; a complementary probe is provided by the Pulsar Timing Arrays (PTA) [17,18]. The mass range up to $m_\Phi \sim 10^{-18}$ eV can, in principle, be accessible to 21 cm surveys [19]. Scalar fields with $m_\Phi \sim 10^{-14}$–$10^{-10}$ eV would be produced by rotating stellar mass black holes via superradiance, which implies various observable signatures including gravitational wave emission in the LIGO sensitivity band [20,21]. Future studies of supermassive black holes can potentially access lighter masses $m_\Phi \sim 10^{-20}$–$10^{-15}$ eV. The gravitational effect of ULDM on laser interferometers was explored in Ref. [22].

The previous observations probe purely gravitational interactions of ULDM. If ULDM has a direct coupling to ordinary matter the possibilities to test it are more diverse and depend on specific models. A rather generic effect of ULDM is periodic modulation of the standard model couplings and particle masses with time. A number of proposals have been recently put forward to search for such variations using atomic clocks [8,23–27], accelerometers [28], resonant-mass detectors [29], laser and atom interferometry [30–33].

In this work we propose using observations of binary pulsars as a probe of ULDM in the mass range $m_\Phi \sim 10^{-23}$–$10^{-18}$ eV. The exquisite precision of the measurements combined with the clean theoretical description makes binary pulsars highly sensitive to new physics that affects the dynamics of massive objects [34,35]. This property has already been exploited to constrain alternatives to general relativity [36,37] and led to the suggestion to use binary pulsars as resonant detectors of the stochastic gravitational wave (GW) background [38] (see Refs. [39–43] for related earlier works). The influence of DM composed of weakly interacting heavy particles on the dynamics of binary pulsars was studied in Ref. [44].

The main idea of our approach is close in spirit to Refs. [38–43] and can be summarized as follows. The

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ULDM field $\Phi$ in the galactic halo represents a collection of plane waves with frequencies (we use units $c = \hbar = 1$) $\omega_\Phi = m_\Phi + m_\Phi v^2/2$ and momenta $k_\Phi = m_\Phi v$, where $v \sim 10^{-3}$ is the typical virial velocity in the halo. Neglecting the term $m_\Phi v^2/2$ in the frequency we obtain the general form of the ULDM field,

$$
\Phi(x, t) = \Phi_0(x) \cos(m_\Phi t + \Gamma(x)),
$$

where $\Phi_0(x)$ and $\Gamma(x)$ are slowly varying functions of position. A binary system embedded in the DM background (1) will experience periodic perturbation due to the change in the gravitational field of $\Phi$ and, in the presence of a direct coupling, due to the change in the masses of the stars in the binary. If the frequency of the perturbation happens to be close to an integer multiple of the binary orbital frequency, its effect is resonantly amplified and leads to a secular change in the orbital period that can be searched for experimentally. We now proceed to the quantitative discussion. We start with the case when DM and ordinary matter interact only gravitationally.

**ULDM interacting only through gravity.**—The energy-momentum of a free massive oscillating field (1) corresponds to the density and pressure [17],

$$
\rho_{DM} = \frac{m_\Phi^2 \Phi_0^2}{2}, \quad p_{DM} = -\rho_{DM} \cos(2m_\Phi t + 2\Gamma).
$$

The latter generates an oscillating perturbation of the metric. To find this we use the Newtonian gauge,

$$
ds^2 = -(1 + 2\phi)dt^2 + (1 - 2\psi)\delta_{ij}dx^i dx^j.
$$

and write down the trace of the $(ij)$ Einstein equations,

$$
6\psi + 2\Delta(\phi - \psi) = 24\pi G \rho_{DM}.
$$

Neglecting the spatial gradients and using Eq. (2) we obtain,

$$
\psi = -4\pi G \rho_{DM} \cos(2m_\Phi t + 2\Gamma).
$$

This can be viewed as a standing scalar GW. Similarly to the usual GW’s, it produces an extra relative acceleration between the bodies in a binary system. This is conveniently written in the Fermi normal coordinates associated with the center of mass of the binary [41],

$$
\delta\mathbf{r} = -\mathbf{r}_0 \delta R_{0i}^i = -\mathbf{r}^i, \quad \delta R_{0i}^i = \rho_{DM} \cos(2m_\Phi t + 2\Gamma).
$$

where $\mathbf{r}^i$ is the vector connecting the two bodies and $\delta R_{0i}^i$ is the contribution of GW into the corresponding components of the Riemann tensor. In the last equality we evaluated $\delta R_{0i}^i$ in the conformal gauge (3) since it is coordinate independent at the linearized level.

Next, we compute the change in the energy of a binary system with masses $M_{1,2}$ during one orbital period $P_b$ due to its interaction with ULDM,

$$
\delta E_b = \mu \int_0^{P_b} r^i \dot{r}^j \delta R_{0i}^j dt = 4\pi G \rho_{DM} \int_0^{P_b} \dot{r}(t) r(t) \cos(2m_\Phi t + 2\Gamma) dt,
$$

where $r$ is the distance between the bodies and $\mu = M_1 M_2/M_1 + M_2$ is the reduced mass of the system. The energy exchange is most efficient when the orbital period is close to an integer multiple of the period of metric oscillations. Given that $P_b \propto |\dot{E_b}|^{-3/2}$, the change in Keplerian energy leads to a secular drift of the orbital period. Defining

$$
\delta\omega = 2m_\Phi - 2\pi N/P_b, \quad |\delta\omega| \ll 2m_\Phi,
$$

and using the standard formulas of Keplerian mechanics, we obtain the time derivative of the period averaged over time intervals $\Delta t$ satisfying $P_b \ll \Delta t \ll 2\pi/\delta\omega,$

$$
\langle \dot{P}_b \rangle = -6G \rho_{DM} P_b^2 J_N(Ne) f(t),
$$

where

$$
f(t) = \sin(\delta\omega t + 2m_\Phi t_0 + 2\Gamma),
$$

$J_N(x)$ are Bessel functions, $e$ is the orbital eccentricity, and $t_0$ is the time of the first periastron passage since $t = 0$. In the second line of Eq. (7) we have normalized $\rho_{DM}$ to the local DM density $\sim 0.3$ GeV/cm$^3$ in the neighborhood of the Solar System. We observe that, depending on the relative phase between the orbital motion and the ULDM oscillations, the sign of $\langle \dot{P}_b \rangle$ can be negative (decrease of the binary system energy) or positive (increase of the energy). Furthermore, the sign alternates in time with the period $2\pi/\delta\omega \gg P_b$, which can be used to discriminate this effect from other contributions to the measured $\dot{P}_b$, such as, e.g., those due to the acceleration of the binary with respect to the Solar System.

The expression (7) implies that the effect vanishes for circular orbits ($e = 0$) and grows with the orbital eccentricity. Besides, it is stronger for systems with large orbital periods. These points are illustrated in Fig. 1. We see that slow nonrelativistic systems with orbital periods of tens to hundreds of days and high eccentricity present suitable targets to search for ULDM in the mass range $m_\Phi = 10^{-23}$--$10^{-21}$ eV. At present there is a dozen of known binary pulsars satisfying these requirements [45]; this number is expected to increase dramatically with the operation of the Square Kilometer Array [46]. Note that for such systems the strength of the resonance on higher harmonics ($N \geq 2$) is comparable to the strength of the
A complementary way to improve the sensitivity to ULDM is to look for binary systems in a denser DM environment. The Navarro-Frenk-White halo profile [50] predicts an increase of $\rho_{\text{DM}}$ up to $\sim 10$ GeV/cm$^3$ within 0.5 kpc distance from the Galactic center (In the ULDM scenario the inner part of the Milky Way halo can contain a solitonic core which may further increase $\rho_{\text{DM}}$ in the vicinity of the Galactic center [51]. However, the size of the core is smaller than 0.5 kpc.). The impact of such increase on $\langle \dot{P}_b \rangle$ is shown in Fig. 1 by gray lines.

The possibility to discover the previous effects in future measurements strongly depends on the characteristics of each individual observed system. Since these are currently unknown, a precise forecast of detectability is impossible at the present stage. An insight can be gained from the analysis of simulated mock samples. This study must be performed in the future to assess the actual measurability of the purely gravitational effect.

**ULDM directly coupled to matter.**—We now assume that ULDM interacts directly with the bodies in the binary by affecting their masses,

$$M_{1,2}(\Phi) = M_{1,2}(1 + \alpha(\Phi)), \quad |\alpha(\Phi)| \ll 1. \quad (8)$$

For simplicity, we focus on the case of universal coupling (Namely, we assume all particle species couple to the same effective metric that depends on the scalar field and hence the weak equivalence principle is preserved.), the case of different couplings will be treated elsewhere [49]. In what follows we will neglect the gravitational interaction between ULDM and the binary. Then in the nonrelativistic limit the system is described by the Lagrangian,

$$L = M_1(\Phi) \left(1 + \frac{v_1^2}{2}\right) + M_2(\Phi) \left(1 + \frac{v_2^2}{2}\right) + \frac{GM_1(\Phi)M_2(\Phi)}{r}.$$ 

By combining the equations of motion of the two bodies we obtain that their relative acceleration acquires a contribution proportional to the direct coupling,

$$\delta a^i = - \frac{d\alpha}{d\Phi} \dot{\Phi}^i - \alpha(\Phi) \frac{G(M_1 + M_2) r^i}{r^3}. \quad (9)$$

As in the case of the pure gravitational interaction, this leads to the change in the Keplerian energy and hence a secular drift of the orbital period. Below we consider two choices for the function $\alpha(\Phi)$.

**Linear coupling** $\alpha(\Phi) = \Phi/\Lambda_1.$—In this case the condition for the resonance reads,

$$\delta \omega = m_\Phi - 2\pi N/P_b, \quad |\delta \omega| \ll m_\Phi.$$ 

Evaluating the energy change due to Eq. (9) and relating it to the derivative of the orbital period we obtain,
\[ \dot{P}_b \simeq 2.5 \times 10^{-12} \left( \frac{\rho_{DM}}{0.3 \text{ GeV}/\text{cm}^3} \right)^{1/2} \left( \frac{P_b}{100 \text{ d}} \right) \times \left( \frac{10^{21} \text{ GeV}}{\Lambda_1} \right) J_N(N_e) \sin(\delta \omega t + m_{\Phi} t_0 + \Upsilon). \] (10)

**Quadratic coupling** \(\alpha(\Phi) = \Phi^2/(2\Lambda_2^2).\)—Here we are back to the resonant condition (6) and the ULDM-induced variation of the orbital period is

\[ \dot{P}_b \simeq 1.1 \times 10^{-11} \left( \frac{\rho_{DM}}{0.3 \text{ GeV}/\text{cm}^3} \right) \left( \frac{P_b}{100 \text{ d}} \right)^2 \times \left( \frac{10^{16} \text{ GeV}}{\Lambda_2} \right)^2 J_N(N_e) \frac{N}{N} \sin(\delta \omega t + 2m_{\Phi} t_0 + 2\Upsilon). \] (11)

Similar to Eq. (7), the expressions (10) and (11) vanish for circular orbits implying that systems with higher eccentricity are preferred to search for the effect.

Current constraints on \(\Lambda_{1,2}\) come from several sources. Linear coupling to a light scalar field modifies the attraction between massive bodies. This occurs even if \(\Phi\) is not the DM and has been constrained by Doppler tracking of the Cassini spacecraft [52] yielding \(\Lambda_1 \gtrsim 10^{21} \text{ GeV}\). On the other hand, this bound does not apply to the quadratic coupling, leaving a much milder constraint from astrophysical processes and short-distance tests of gravity \(\Lambda_2 \gtrsim 10^8 \text{ GeV}\) [23,53]. For a scalar field comprising ULDM additional bounds arise due to the constraints on the GW background. Indeed, the direct coupling of the scalar field to masses (8) can be absorbed by a redefinition of the metric to the so-called Jordan frame

\[ g_{\mu\nu} \to \tilde{g}_{\mu\nu} = g_{\mu\nu}(1 + 2\alpha(\Phi)). \]

Test bodies move along geodesics of \(\tilde{g}_{\mu\nu}\) which has an oscillatory component due to oscillations of \(\Phi\)—this is a scalar GW. The amplitude of such oscillations has been constrained by PTA data [18] in the low frequency region \((f < 10^{-7} \text{ Hz})\) and by Cassini tracking (Ref. [54]) presents the limits on the amplitude \(h_c\) of the stochastic background of transverse GW’s that can be translated into a bound on the scalar GW amplitude \(\psi_c\) by identifying \(h_c = \sqrt{15}\psi_c\). This is slightly different from the identification \(h_c = 2\sqrt{3}\psi_c\) used in Refs [17,18] because, unlike pulsar timing, the light time between the spacecraft and Earth is less than the GW period, which leads to a different expression for the average of the stochastic signal.) [54] in the frequency range \(f = 10^{-6} - 10^{-3} \text{ Hz}\).

Limits on an ULDM-induced contribution into \(\dot{P}_b\) in the timing model of binary systems can be used to put further bounds on the couplings \(\Lambda_{1,2}^{-1}\). Taking the reported error in the determination of intrinsic \(\dot{P}_b\) for several known systems as an upper limit on the ULDM-induced contribution we obtain the constraints presented in Figs. 2, 3. In deriving them we have set the oscillating factors in Eqs. (10), (11) to one for the sake of the argument. One observes that they are competitive with the existing bounds. In particular, the Hulse-Taylor pulsar B1913+16 [55] provides the most sensitive probe of the direct ULDM coupling for \(m_{\Phi}\) satisfying the appropriate resonance condition; whereas the systems J1903+0327 [56] and J1748-2021B [57] give the strongest constraints on the quadratic coupling \(\Lambda_2^{-1}\) in the range of \(m_{\Phi}\) from \(2 \times 10^{-22}\) to \(2 \times 10^{-21} \text{ eV}\). The situation will further improve with the increase of precision in binary pulsar timing and discovery of new binary systems. To illustrate this, we report the bounds one would obtain assuming that the systems considered before are timed at the best current precision (orange symbols in Figs. 2 and 3). Realistically, this precision may not be achievable for some of the systems presented in the plots due to various sources of intrinsic uncertainty in determination of \(\dot{P}_b\). Nevertheless, it is reasonable to expect that future surveys will discover new binary pulsars suitable for precision timing and having periods and eccentricity similar to those of already existing systems. Note that valuable constraints on ULDM with masses \(m_{\Phi} \sim 10^{-19} - 10^{-18} \text{ eV}\) can be obtained even from
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