Constraints on millicharged dark matter and axion-like particles from timing of radio waves

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We derive novel constraints on millicharged dark matter and ultralight axion-like particles using pulsar timing and fast radio burst observations. Millicharged dark matter affects the dispersion measure of the time of arrival of radio pulses in a way analogous to free electrons. Light pseudoscalar dark matter, on the other hand, causes the polarization angle of radio signals to oscillate.

We show that current and future data can set strong constraints in both cases. For dark matter particles of charge $\epsilon$, these constraints are $\epsilon/m_{\text{milli}} \lesssim 10^{-8}\text{eV}^{-1}$, for masses $m_{\text{milli}} \gtrsim 10^{-6}\text{eV}$. For axion-like particles, the analysis of signals from pulsars yields constraints in the axial coupling of the order of $g/m_{a} \lesssim 10^{-13}\text{GeV}^{-1}/(10^{-22}\text{eV})$. Both bounds scale as $(\rho/\rho_{\text{dm}})^{1/2}$ if the energy density $\rho$ of the components is a fraction of the total dark matter energy density $\rho_{\text{dm}}$. We do a detailed study of both effects using data from two samples of pulsars in the galaxy and in globular clusters, as well as data from FRB 121102 and PSR J0437–4715. We show that in both cases actual pulsar data constrain a new region of the parameter space for these models, and will improve with future pulsar-timing observations.

Unraveling the nature of dark matter (DMa) is among the most urgent issues in fundamental physics. Indirect searches aim at detecting the effects of DMa in astrophysical observations, beyond its pure gravitational interaction. Given the feeble interaction of DMa with standard model fields, precise measurements are particularly promising for these searches. When one requires precision, a particular measurement stands out in astrophysics: the time of arrival (TOA) of radio wave from pulsars and fast radio bursts (FRBs). The use of pulsar timing has already been suggested to study the effects of dark matter [11–9]. In this Letter we present new results for DMa models directly coupled to light from the propagation of radio pulses from pulsars and FRBs. A more comprehensive exploration will be presented elsewhere [10].

If DMa is coupled to the electromagnetic field, one expects modifications in the emission, propagation, and detection of radio pulses. We focus here on the effects during the propagation, which are robust under astrophysical uncertainties. In particular, we derive stringent constraints on millicharged DMa and axion-like particles (ALPs) based on dispersion measurements (DM) of radio signals from pulsars and FRBs, and on the modulation of the light polarization angle due to axion-like DMa in the Milky Way.

We give a unified treatment valid for both millicharged DMa and ALPs, considered as independent species. In the former case we consider that (a fraction of) the DMa is made of particles with mass $m_{\text{milli}}$ and electric charge $q = \epsilon e$ ($\epsilon \ll 1$) [11–17], whereas in the latter case we assume the existence of axion-like [18–20], pseudoscalar DMa. The field equations read

\[
(\Box - m_{a}^{2})\phi = -\frac{g}{4} F_{\mu\nu} F^{\mu\nu}, \tag{1}
\]

\[
\partial_{\mu} F^{\mu\nu} = 4\pi e j^{\nu} + 4\pi \epsilon e j_{\text{milli}}^{\nu} - \frac{g}{2} \epsilon_{\rho\lambda\nu} F_{\mu\rho} \partial_{\lambda} \phi, \tag{2}
\]

where $g$ is the ALP-photon axial coupling, $j^{\nu}$ is the ordinary electron current, whereas $j_{\text{milli}}^{\nu}$ is the current from millicharged particles.

**Dispersion in the TOA.** We consider the propagation of a light signal of frequency $\nu = \omega/(2\pi)$ along the $z$ direction in the presence of a homogeneous background magnetic field polarized along (say) the $y$ direction, $B = (0, B, 0)$. For the first part of this work, DMa is considered as a cold-medium with vanishing background values for the fields appearing in (1)–(2). When $\omega \gg m_{a}$, the propagation of the light signal in this medium is described by the first-order system $i\frac{\partial}{\partial t} \psi(z) = \mathcal{M} \psi(z)$, where the $|\psi(z)\rangle$ is a linear combination of the two photon polarizations along the $x$ and $y$ directions and of the ALP state $|a\rangle$. The $3 \times 3$ mixing matrix reads

\[
\mathcal{M} := \begin{pmatrix}
\omega + \Delta_{xx} & \Delta_{xy} & 0 \\
\Delta_{yx} & \omega + \Delta_{yy} & gB/2 \\
0 & gB/2 & \omega - m_{a}^{2}/(2\omega)
\end{pmatrix}. \tag{3}
\]

The off-diagonal terms $\Delta_{xy}$ and $\Delta_{yx}$ give rise to Faraday rotation by mixing the photon polarizations and do not play a role in this section. The terms $\Delta_{xx}$ and $\Delta_{yy}$ contain both QED vacuum polarization effects and plasma
effects \[21\] \[22\]. The former ones are of order $\Delta^{\text{QED}} \sim \Delta^{\text{QED}}_{\text{gy}} \sim \omega^2 \frac{d}{\pi \nu}$, where $B_c \approx 4 \times 10^{13}$ G \[23\]. We shall only consider interstellar magnetic fields, for which $B \ll B_c$ and $\Delta^{\text{QED}}$ effects are negligible. Plasma effects arise from the presence of free charges. In the limit where the photon energy is much smaller than the mass of the charged, cold particles \[24\] \[26\],

$$
\Delta_{\text{xx}}^{\text{plasma}} \sim \Delta_{\text{yy}}^{\text{plasma}} \sim -\frac{\omega_p^2}{2\omega},
$$

(4)

where $\omega_p := \sum_i \frac{4\pi q_i^2 n_i}{m_i}$ is the plasma frequency for particles with charge $q_i$, mass $m_i$, and number density $n_i$. The normal modes corresponding to these satisfy

$$
k_0 = \omega - \frac{\omega_p^2}{2\omega}, \quad k_{\pm} = \frac{4\omega^2 - \omega_p^2 - m_i^2 \pm \sqrt{\Delta_\omega}}{4\omega},
$$

(5)

with $\Delta_\omega = (m_i^2 - \omega_p^2)^2 + 4B^2 g^2 \omega^2$. The last term in $\Delta_\omega$ is always subdominant and we treat it perturbatively.

The TOA of a signal traveling at speed $v = \partial \omega / \partial k$ across a distance $d$ is $T = \int_0^d \frac{dt}{\omega} = \int_0^d dt \frac{\partial \omega}{\partial k}$ along the line of sight. From the previous expressions one finds for the relevant polarizations,

$$
v_0^{-1} = 1 + \frac{\omega_p^2}{2\omega^2}, \quad v_{-1}^{-1} = v_0^{-1} + \frac{B^2 g^2}{2(m_i^2 - \omega_p^2)} - \frac{3B^4 g^4 \omega^2}{2(m_i^2 - \omega_p^2)^2}.
$$

(6)

(7)

In the absence of new physics ($\epsilon = g = 0$), the previous modes propagate with velocity $v_0$. For a photon with frequency $\nu$, a background of cold free electrons yields a time delay

$$
\Delta t_{\text{DM}} \sim 4.15 \left(\frac{\text{DM}_{\text{astro}}}{\text{pc cm}^{-3}}\right) \left(\frac{\nu}{\text{GHz}}\right)^{-2} \text{ms},
$$

(8)

relative to a photon with infinite energy. Here $\text{DM}_{\text{astro}} := \int n_e dl$ is the standard dispersion measure (DM) from electrons with number density $n_e$ along the line of sight. Comparing this number with the ALP-photon coupling term in Eq. \[4\] one sees that the modifications from the interstellar or intergalactic magnetic fields are always negligible and we ignore them in the following.

**TOA constraints on millicharged DMAs.** We now focus on the case of millicharged DMAs, i.e. $g = 0$. In this case the DM in \[5\] is dominated by the sum of the contributions from ordinary electrons and millicharged particles (see also \[27\]), $\text{DM}_{\text{obs}} = \text{DM}_{\text{astro}} + \text{DM}_{\text{milli}}$, where

$$
\text{DM}_{\text{milli}} = \left(\frac{\epsilon}{m_{\text{milli}}}\right)^2 m_e \int dl \rho_{\text{milli}},
$$

(9)

where $\rho_{\text{milli}}$ is the density of millicharged particles, which is equal to or smaller than the DM density $\rho_{\text{dm}}$. While the effect of $\text{DM}_{\text{astro}}$ and $\text{DM}_{\text{milli}}$ are completely degenerate, for a source at a distance $d$ any measurement of the DM can be translated into a conservative upper bound on $\epsilon/m_{\text{milli}}$ by simply requiring that all the DM is due to DMAs, i.e. $\text{DM}_{\text{milli}} < \text{DM}_{\text{obs}}$. This yields

$$
\frac{\epsilon}{m_{\text{milli}}} \lesssim 10^{-8} \sqrt{\frac{0.3 \text{ GeV/cm}^3}{\rho_{\text{milli}}}} \sqrt{\frac{\text{DM}_{\text{obs}}}{20 \text{ pc/cm}^3}} \sqrt{\frac{400 \text{ pc}}{d}},
$$

(10)

where we normalized the quantities by typical values within the galaxy. This estimate gives already a rather stringent bound, which can be refined through a Bayesian analysis. In the following we closely follow \[28\]. Given our theoretical hypothesis ($\text{DM}_{\text{obs}} = \text{DM}_{\text{astro}} + \text{DM}_{\text{milli}}$), and the set of measurements of $\text{DM}_{\text{obs}}$ from $N$ pulsars, we construct the log-likelihood as

$$
\ln \mathcal{L} = -\frac{1}{2} \sum_{i=1}^N \left(\frac{\text{DM}_{\text{obs}}^i - \text{DM}_{\text{astro}}^i - \text{DM}_{\text{milli}}^i}{\sigma_i^2}\right)^2.
$$

(11)

Here $\sigma_i$ is the dispersion for each pulsar, obtained adding in quadrature statistical uncertainties on $\text{DM}_{\text{obs}}^i$ and the astrophysical ones on $\text{DM}_{\text{astro}}^i$. We used a uniform prior on $\epsilon/m_{\text{milli}} > 0$ and verified that our results do not depend on this choice.

We shall consider two datasets of pulsars extracted from the ATNF Pulsar Catalogue \[29\] as explained in the Supplement Material. In both cases we assume a homogeneous DM density $\rho_{\text{dm}} \approx 0.3 \text{ GeV/cm}^3$. The first dataset comprises $N = 13$ local pulsars with the smallest values of $\text{DM}_{\text{obs}}/d$ and for which parallax measurements of the distance $d$ are available. We only choose pulsars located away from the galactic plane. This is to minimize the effect of the evacuation of DMs from the galactic plane for millicharged DMs. While early studies argue that this effect is relevant for $\epsilon \gtrsim 5.4 \times 10^{-22} \left(\frac{\text{GeV}}{\text{eV}}\right)^2$ (a recent study \[31\] suggests that this bound may be too restrictive. We also consider a second dataset of $N_{\text{cluster}} = 13$ pulsars located in globular clusters within 8 kpc from the galactic center and off the disk, again with the smallest $\text{DM}_{\text{obs}}/d$. Distances of clusters can be determined by different methods \[32\] not relying on the DM, and their uncertainty is usually of a few percent. We therefore assign a conservative error of 10% to the value of $d$ for the pulsars in this second dataset. Even if the effect of the galactic magnetic field on the density of millicharged DMs away from the galactic disk is uncertain, we do not expect DMs to be evacuated at high galactic latitudes, and our analysis should provide realistic constraints.

For each pulsar we compute $\text{DM}_{\text{astro}}^i \approx \langle n_e \rangle d_i$, where $\langle n_e \rangle$ is an average electron density along the line of sight obtained using the YMW16 model \[33\], while $d_i$ is the pulsar distance obtained from parallax (for the first dataset) or from the location of the globular cluster (for the second dataset). In the former case, we assign $\langle n_e \rangle$ a 20% error to take into account potential systematics in
the electron density model. We perform a Monte-Carlo Markov chain analysis using the PYTHON ensemble sampler EMCEE [34] to explore the posterior distribution. For our datasets, $10^5$ samples are accumulated with 20 chains. The chains show good acceptance rate and convergence. The results are similar for the two datasets:

$$\epsilon \rho_{\text{milli}} \lesssim 4 \times 10^{-9} \quad \text{eV} \quad \sqrt{\frac{0.3 \text{GeV/cm}^3}{\rho_{\text{milli}}}} \quad \text{at} \quad 95\% \quad \text{C.L.} \quad (12)$$

which we compare to other existing bounds in Fig. 1. For completeness, we also show a similar (weaker) bound estimated from the dispersion of the fast radio burst FRB121102 [35]. A more comprehensive analysis for FRBs will be presented elsewhere [10].

The mass range in Fig. 1 is limited on the left because the expression (1) is valid as long as the energy of the photon is larger than $m_{\text{milli}}$. For radio waves from pulsars, $m_{\text{dm}} \gtrsim \omega \sim \text{GHz} \sim 10^{-6} \text{eV}$. Since the bound is more stringent for small masses, these constraints could improve if sub-GHz precision pulsar measurements become available, see e.g. Ref. [36]. Figure 1 shows that our bounds are competitive for masses below the Tremaine-Gunn bound on fermionic DM, $m_{\text{FG}} \gtrsim \text{keV}$ [37]. Hence, they apply to scalar charged DM or to models with a fraction of millicharged fermionic DM (see Eq. (12) for the scaling of the bound with $\rho_{\text{milli}}$).

**Polarization constraints on ALPs.** As discussed before, the modification of the TOA from the terms depending on $g$ in Eq. (7) is negligible and we ignore it. Nevertheless, due to their pseudo-scalar nature, ALPs also induce an oscillating variation of light polarization [40–44]. Parity-symmetry breaking leads to birefringence, i.e. different phase velocities for left- and right-handed modes, which in turn induces rotation of the linear polarization plane. At first approximation, we assume the ALP-DM background in the Milky Way rest frame to be described by the field configuration [45]

$$\phi(x, t) = \tilde{\phi}_0(x) \int d^3v \ e^{-\frac{\sigma^2}{2} e^{i(\omega t - m_e v \cdot \vec{x}) + \varphi_\nu + \text{c.c.}}} \quad (13)$$

where $\sigma_0 \approx 10^{-3}$ corresponds to the virialized velocity of the Milky Way and $\varphi_\nu$ are arbitrary phases. The value $\tilde{\phi}_0$ changes smoothly with $x$ to reproduce the DM energy density. For low DM masses, this field configuration has only slow modes as compared to the wavelength of radio signals and an eikonal approximation can be used to study the propagations of waves in this continuous background [46]. The leading result of this calculation yields an effect for the polarization angle of a photon propagating from time $t$ to $t + T$ [40 41]

$$\theta(t, T) \sim 1.4 \times 10^{-2} \sin(m_a t + \delta) \left(\frac{g}{10^{-12} \text{GeV}^{-1}}\right) \left(\frac{10^{-22} \text{eV}}{m_a}\right) \quad (14)$$

where $\delta$ is a phase over which we will marginalize. The characteristic time scale for the axion background oscillation is $T_{\text{ALP}} \approx \frac{10^{-22} \text{eV}}{m_a}$ yr; if one continuously observes the polarized light from the source during a time $t_{\text{obs}} \gtrsim T_{\text{ALP}}$, the observed variation of the polarization angle (14) may constrain the amplitude of the axion oscillations, i.e. the coupling $g$ for a given mass $m_a$. Pulsars are observed for long periods and the polarization...
angle is measured to be almost constant with a precision of roughly one degree, that can be compared with Eq. (14). We use the polarization data from Ref. 17 and in particular PSR J0437–4715, which is the pulsar with the highest number of observations of the polarization angle, spanning a period of roughly four years. The ionospheric contribution to the polarization angle was subtracted using the program GETRM-IONO [45]. We performed a likelihood estimation of the coupling $g$ for a set of fixed masses $m_a$. For each value of the mass, we marginalize over the unknown phase $\delta$ in Eq. (14) in the interval $[-\pi, \pi]$ and then obtained the 95\% C.L. exclusion value for $g$, which is our reported constraint.

The excluded region in Fig. 2 spans roughly four orders of magnitude in the mass range, from $m_a \sim 10^{-19}$ eV to $m_a \sim 10^{-23}$ eV. The lower limit is set by the total observation time ($\sim 4$ yr), whereas the upper limit is set by the folding time, that is 64 minutes for J0437–4715. The derived lower bounds scale as $1/m_a$ — with some modulation due to the fact that observations of the polarization angle for J0437–4715 are not homogeneous in time — and is stronger for smaller masses, i.e longer observation time. The bound scales as $\sim \sqrt{\rho_{\text{ion}}}$, so it can be competitive even if ALPs form only a small fraction of the DM.

Discussion. Several DMa models introduce dispersion effects in the photon propagation. Although small, these effects accumulate for photons coming from astrophysical sources and can be constrained through precision measurements. The effect of millicharged DMa is degenerate with that of ordinary plasma and improving models for the local plasma distribution will help strengthening the constraints from DM. On the other hand, the effect of ALP-photon coupling is more striking and requires a careful analysis of the TOA as a function of the frequency. In addition, in the upcoming era of the Square Kilometre Array, we will benefit from a much larger pulsar sample (possibly comprising sources near the galactic center, where the DMa density is higher than what assumed here), combined with a significantly improved timing precision [49,51]. The prospects of using radio waves in probing DMa are very promising in the near future. For ALPs, their coupling to photons generates an oscillation of the polarization angle of photons in the ultra-light DMa case. Our results in Fig. 2 show that, for the mass range $10^{-23} - 10^{-20}$ eV, the constraints derived here are the best available and will greatly improve in the future with more data.

We have considered propagation in a weak magnetic field for which dispersion due to the ALP-photon coupling and QED vacuum polarization effects are negligible. However, our formalism can be easily extended to include such effects, which might be relevant for propagation in strongly magnetized regions. A discussion of this effect will appear elsewhere [10].

Note: While this work was close to completion, Ref. 52 appeared on the arXiv, estimating constraints on ALPs using the polarization angle of radio waves from pulsars similar to those derived in the second part of our work. Even though the idea is similar, our analysis, based on real data, is distinct and the results differ from the ones in Ref. 52 by roughly a factor $\sqrt{\frac{10^{-23} \text{eV}}{m_a}} \sqrt{\frac{\text{200pc}}{d}}$ originating from a different assumption about the $\phi$ configuration.

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Appendix

Here we provide additional details of our analysis. For the millicharged DMa, we analyzed a first set of galactic pulsars selected for their minimal DM/\(d\), where \(d\) is derived from parallax, and for their good agreement with the electron density model (Table I). A second set of pulsars is selected in galactic clusters (Table II). In this case, in addition to the aforementioned criteria, we also require that the pulsars are not further from the galactic center than the Solar System, $\sqrt{X^2 + Y^2 + Z^2} < 8.3\text{kpc}$, and are also located far from the galactic disk, $|Z| > 1\text{kpc}$.

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| Pulsar          | Parallax (mas) | DM (pc cm^{-3}) | \(n_e\) (cm^{-3}) |
|----------------|---------------|-----------------|-------------------|
| J1024+0719     | 0.770 ± 0.23  | 6.4778 ± 0.0006 | 0.009036          |
| J1012+5307     | 0.710 ± 0.17  | 9.02314 ± 0.0007 | 0.007827          |
| J2010−1323     | 0.300 ± 0.10  | 22.177 ± 0.005  | 0.004931          |
| J2324+0611     | 0.700 ± 0.20  | 10.7645 ± 0.0015 | 0.008292          |
| J1909−3744     | 0.810 ± 0.03  | 10.3932 ± 0.01  | 0.016935          |
| B2020+28       | 0.370 ± 0.12  | 24.63109 ± 0.00018 | 0.012689          |
| B1508+55       | 0.470 ± 0.03  | 19.6191 ± 0.0003 | 0.004691          |
| J2017+6603     | 0.400 ± 0.20  | 23.92434 ± 0.00049 | 0.011004          |
| B1534+12       | 0.860 ± 0.18  | 11.61944 ± 0.00002 | 0.009608          |
| J0108−1431     | 4.200 ± 1.40  | 2.38 ± 0.19     | 0.009246          |
| B0301−07       | 0.930 ± 0.80  | 10.922 ± 0.006  | 0.008167          |
| J1023+0038     | 0.731 ± 0.22  | 14.325 ± 0.01   | 0.008209          |
| B1237+25       | 1.160 ± 0.08  | 9.25159 ± 0.00053 | 0.008940          |

**Table I.** List of local pulsars considered in this work.

| Pulsar          | Cluster | \(d(pc)\) | DM (pc cm^{-3}) | \(n_e\) (cm^{-3}) |
|----------------|---------|-----------|-----------------|-------------------|
| B1516+02B      | M5      | 8500      | 29.47 ± 0.11    | 0.000027          |
| B1516+02A      | M5      | 8500      | 30.08 ± 0.05    | 0.000027          |
| J1518+0204D    | M5      | 8000      | 29.3 ± 0.11     | 0.000042          |
| J1518+0204E    | M5      | 8000      | 29.3 ± 0.11     | 0.000042          |
| J1518+0204C    | M5      | 8000      | 29.3146 ± 0.006 | 0.000042          |
| J2140−2310A    | M30     | 9200      | 25.0640 ± 0.0041 | 0.000015         |
| J2140−2310B    | M30     | 9200      | 25.09 ± 0.12    | 0.000015         |
| J0024−204X     | 47Tuc   | 4690      | 24.539 ± 0.005  | 0.0083           |
| J0024−204Z     | 47Tuc   | 4690      | 24.47 ± 0.01    | 0.0083           |
| J0024−204X     | 47Tuc   | 4690      | 24.29 ± 0.03    | 0.0083           |
| J0024−204Z     | 47Tuc   | 4690      | 24.37 ± 0.02    | 0.0083           |
| B0021−72H      | 47Tuc   | 4690      | 24.236 ± 0.002  | 0.0083           |
| B0021−72E      | 47Tuc   | 4690      | 24.361 ± 0.007  | 0.0083           |

**Table II.** List of pulsars in globular cluster considered in this work.
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