Looking for Axion Dark Matter in Dwarf Spheroids

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We study the extent to which the decay of cold dark matter axions can be probed with forthcoming radio telescopes such as the Square Kilometer Array (SKA). In particular we focus on signals arising from dwarf spheroidal galaxies, where astrophysical uncertainties are reduced and the expected magnetic field strengths are such that signals arising from axion decay may dominate over axion-photon conversion in a magnetic field. We show that with \( \sim 100 \) hours of observing time, SKA could improve current sensitivity by 2-3 orders of magnitude – potentially obtaining sufficient sensitivity to begin probing the decay of cold dark matter axions.

INTRODUCTION

Perhaps the most promising solution to the strong CP problem, i.e. the problem of explaining the smallness of the CP violating \( \theta \) term in the QCD Lagrangian, involves introducing a new global \( U(1) \) symmetry, referred to as the Peccei-Quinn (PQ) symmetry [1, 2]. When spontaneously broken at high energies, this symmetry produces a pseudo-Nambu-Goldstone (pNG) boson that naturally relaxes the aforementioned CP violating term to zero [3, 4], thus providing consistency with e.g. the observed smallness of the neutron electric dipole moment [5, 6]. This pNG has been dubbed ‘the axion’ (see e.g. [7] for a more recent review).

It has since been pointed out that there exists a range of masses for which the axion can simultaneously provide a solution to the strong CP problem and be sufficiently abundant to account for the entirety of dark matter. Despite the small requisite mass, the non-thermal axion production mechanisms, namely the vacuum realignment mechanism [8–10] and the decay of topological defects [11, 12], produce cold (i.e. non-relativistic) and non-interacting dark matter particles consistent with cosmological observations.

The potential of simultaneously solving two of the largest outstanding problems in particle physics has lead to a large and diverse experimental program aimed at probing the parameter space associated with axion dark matter (see e.g. [13] for a recent review of experimental search techniques). Many, if not most, of these experiments have been focused on exploiting the conversion of axions to and from photons, a process which occurs in the presence of a strong magnetic field via a coupling to a virtual photon; this is the so-called Primakoff Effect. In this work, we investigate signals arising from both magnetic field conversion and the often neglected process of the spontaneous decay of the axion into two photons, and show that near-future radio telescopes can significantly improve existing sensitivity to axions with masses \( m_a \sim 10^{-6} - 10^{-4} \) eV.

While the rate of axion-photon conversion in a magnetic field is typically larger than the rate of spontaneous decay, there do exist astrophysical environments and axion masses for which the later is the dominant process. For example, dwarf spheroidal galaxies (dSphs) typically contain small magnetic fields, implying the rate of axion decay may actually exceed that of magnetic conversion. Furthermore, dSphs are dark matter dominated objects with low radio background, and are thus capable of yielding significant unabated signatures of axion dark matter. Conventional astrophysical searches for axion conversion (e.g. targeting the Galactic Center [14] or highly magnetized pulsars [15, 16]), on the other hand, typically require targeting highly uncertain environments with large uncertainties on e.g. the magnetic field strength, the magnetic field distribution, radio backgrounds arising from synchrotron emission and free-free absorption, and the dark matter distribution.

The possibility of detecting axion decay in dSphs with a radio telescope was first explored in [17], and to our knowledge, not discussed since. The subsequent \( \sim 20 \) years have provided significant improvement in the sensitivity of radio telescopes and the discovery of many new dSphs. In this work we evaluate the sensitivity of current and future radio telescopes to axion decay in a variety of known dSphs. In particular, we show that with \( \sim 100 \) hours of observation, the Square Kilometer Array (SKA) [18] can potentially improve the constraints from helioscopes by \( \sim 2 - 3 \) orders of magnitude depending on the axion mass, even in the scenario where dSphs contain negligibly small magnetic fields.

THE SIGNAL

Axion Decay

The spontaneous decay of an axion with mass \( m_a \) proceeds through the chiral anomaly to two photons, each with a frequency \( \nu = m_a / 4\pi \), and with a lifetime given...
the axion number density at distance along the line of conversion \(a \rightarrow \gamma\) where \(\Delta = g\), and the intergalactic medium (grey) are also shown for comparison. Here, we have neglected the suppression factor \(f(m_a)\) arising from the inhomogeneity of the magnetic field [25]. In astrophysical environments this factor is expected to be very small, implying a net dominance of the decay could occur (even for large magnetic fields and at small axion masses).

by

\[
\tau_a = \frac{64\pi}{m_a^3 g^2}, \tag{1}
\]

where \(g\) is the axion-to-two-photon coupling constant.

The observed power per unit area per unit frequency from the spontaneous decay of an axion by a radio telescope is then given by

\[
S_{sd} = \frac{m_a}{4\pi \Delta \nu} \int d\Omega d\ell \frac{n(\ell, \Omega)}{\tau_a}, \tag{2}
\]

where \(\Delta \nu\) is the width of the axion line, given by \(\Delta \nu = v_{\text{center}} \sigma_{\text{disp}}\) where \(\sigma_{\text{disp}}\) is the dispersion of the line resulting from the rotation of the dwarf\(^1\), and \(n(\ell, \Omega)\) is the axion number density at distance along the line of sight \(\ell\) in the solid angle \(\Omega\). For convenience, we define the astrophysical quantity

\[
D(\alpha_{\text{int}}) = \int d\Omega d\ell \rho(\ell, \Omega), \tag{3}
\]

which allows us to write Eq. 2 as

\[
S_{sd} = \frac{m_a^2 g^2}{64\pi} D(\alpha_{\text{int}}) \frac{\Delta \nu}{\sigma_{\text{disp}}}, \tag{4}
\]

where \(\alpha_{\text{int}}\) is the angle of integration defined between the center of a given dwarf galaxy and the largest observable radius. From Eq. 4 it should be clear that given a radio telescope or interferometer (with a well-defined field of view), the dwarf galaxies providing the best sensitivity to axion decay are those with the largest \(D(\alpha_{\text{int}})/\sigma_{\text{disp}}\).

The angle \(\alpha_{\text{int}}\) depends on both the size of the dishes used for observation and the frequency (and thus the axion mass). The observed field-of-view of a particular telescope is given by

\[
\Omega_{\text{FoV}} \sim \frac{\pi}{4} \left(\frac{66 \lambda}{D_{\text{dish}}}ight)^2, \tag{5}
\]

where \(\lambda\) is the wavelength of the observed photons and \(D_{\text{dish}}\) is the diameter of the dish. Consequently, the maximum angle of the dwarf that can be probed is given by

\[
\alpha_{\text{int}} \sim 8.8 \times \left(\frac{\text{GHz}}{\nu}\right) \left(\frac{1\text{m}}{D_{\text{dish}}}ight) \text{ degrees}. \tag{6}
\]

Up until this point we have focused solely on the spontaneous decay of axions into photons. However, these decays take place in background of CMB photons with the same energy; this inherently enhances the photon production rate via stimulated emission. The power emitted by stimulated emission is given by

\[
P_{\text{se}} = m_a g(\nu) B_{21} \rho_{\text{cmb}}(\nu) \Delta N, \tag{7}
\]

where \(B_{21}\) is the Einstein coefficient, \(\rho_{\text{cmb}}(\nu)\) is the radiation density of CMB photons at a given frequency, \(\Delta N\) is the difference between the number of axions and the number of photons with energy \(m_a/2\) (which can be approximated as just \(N_a\)), and \(g(\nu)\) is the spectral line shape function (which we take to be a delta function). Taking the Einstein coefficient to be

\[
B_{21} = \left(\frac{\pi^2}{\omega^3}\right) \frac{1}{\tau} = \frac{g^2}{8}, \tag{8}
\]

one can express the observed power per unit area per unit frequency contributed from stimulated emission as

\[
S_{\text{se}} = 2 \frac{m_a^2 g^2}{64\pi} D(\alpha_{\text{int}}) \frac{1}{\sigma_{\text{disp}}} \left(\frac{1}{e^{m_a/(2\gamma_{\text{cmb}})} - 1}\right), \tag{9}
\]

which is identical to the contribution of the spontaneous emission multiplied by two times the photon occupation number. The total observed power \(S_{\text{total}}\) is then given by the sum of Eq. 4 and Eq. 9.

\(^1\) Note that we assume here that the velocity dispersion of dark matter follows that of the stellar component.
Magnetic Conversion

Signals arising from the conversion of axions to photons while traversing through a perpendicular magnetic field has been extensively studied in the context of both terrestrial and astrophysical environments (see e.g. [14–16, 19–24]). As will be discussed in the following sections, the shape and strength of magnetic fields in dSphs is highly uncertain; however the magnetic fields in these objects are likely less than magnetic fields in other types of dwarf galaxies containing higher rates of star formation. In this section we will make a number of simplifying assumptions to estimate the potential signal arising from axion conversion in a magnetic field under rather optimistic assumptions. As shown below, the rate of magnetic field conversion in large astrophysical environments is almost certainly subdominant to the contribution from axion decay, largely due to the suppression arising from the fact that realistic magnetic fields are not homogenous.

In the case of a static magnetic field, the flux arising from axion conversion is proportional to |\vec{B}(k) - m_a|^2, where \vec{B}(k) is the Fourier transform of the magnetic field. It is often convenient to characterize this contribution in terms of a characteristic magnetic field strength B_0 and a suppression factor f(m_a), as |\vec{B}(k) - m_a|^2 = B_0^2 f(m_a) (see e.g. Eq. 20 of [25]). Using this simplification, one can calculate the observed power per unit area per unit frequency from axion-photon conversion using [13, 25, 26]:

$$S_{\text{conv}} = \frac{B_0^2 g^2}{m_a^2 \sigma_{\text{disp}}} \int \rho(\ell, \Omega) \, d\Omega \, d\Omega \, d\ell \, \rho(\ell, \Omega),$$

where the integration runs over the volume containing the magnetic field, V_{B_0}. Naively, one may expect the astrophysical integral in Eq. 10 to be comparable to that of Eq. 3. Should this be the case, and should the suppression factor f(m_a) be \sim O(1), one may approximate the ratio between the rate of axion decay and the rate of axion conversion as

$$\frac{R_{\alpha \rightarrow \gamma}}{R_{\alpha \rightarrow \gamma}} \sim \frac{m_a^2}{64 \pi B_0^2} \left(1 + \frac{2}{\epsilon m_a/(2T_{\text{cmb})} - 1}\right).$$

In Fig. 1 we plot Eq. 11 as a function of the axion mass for various magnetic field strengths ranging from 100 \mu G to 10^{-4} \mu G. For comparison, we have also highlighted in Fig. 1 the approximate magnetic field strength expected in the galactic center [27–31], dSphs [32], and the intergalactic medium [33, 34]. This first order comparison between the rate of decay and magnetic field conversion clearly illustrates an important point: the rate of axion decay can supersede that of magnetic field conversion for axion masses probed by radio telescopes.

At this point we emphasize that the suppression factor for large-scale astrophysical environments is likely f(m_a) \ll 1. For example, it was shown in [25] that the rate of axion conversion in the Galactic Center is generically reduced by a factor of f(m_a) \sim 10^{-13}, assuming the magnetic field distribution follows a power law and the coherence length in the Galactic Center is of order ~ 1 pc. While the coherence length of the magnetic field in dSphs is likely considerably smaller than that of the Galactic Center, the length scales are still astrophysical and thus should reduce the overall rate of conversion by orders of magnitude. As will be shown below, even when f(m_a) \sim 1 the process of axion decay and surpass that of magnetic field conversion in dSphs.

Generically, however, it is also not valid to assume

$$\int d\Omega \, d\ell \, \rho(\ell, \Omega) \sim \int_{V_{B_0}} d\Omega \, d\ell \, \rho(\ell, \Omega).$$

If one considers a dSph at a distance d_{dSph} \sim 30 kpc from Earth (i.e. the approximate distance of Reticulum II and Willman I), than a magnetic field extending to a distance of 0.1 kpc restricts the maximum angle of integration \alpha_{\text{int}} \sim 0.19°. Small changes in the maximum angle of integration can have significant implications for the total predicted rate, potentially further enhancing the ratio provided in Eq. 11. In addition to modifying the angular integration, the line-of-sight component of the astrophysical integral in the case of magnetic field conversion must be truncated. Since the dark matter density is largest in the central region of the dSph, this effect is expected to be subdominant, however we have verified that for a generalized Navarro-Frank-White (NFW) profile with reasonable choices of the inner slope \gamma, scale density \rho_s and scale radius r_s, this correction can further suppress the astrophysical integral by a factor of \sim O(5). For concreteness, in our dSph analysis we adopt a suppression factor of 4.

In the sensitivity comparison presented below we will optimistically assume that the dSph under observation contains a constant magnetic field with modulus |B_0| = 1 \mu G within a radius r_s = 0.1 kpc, no suppression factor (i.e. f(m_a) = 1), and there no magnetic field elsewhere; while of course not entirely physical, this effectively reproduces the behavior of the exponentially decaying magnetic field adopted by [32] to model dSphs. Furthermore, since the rate of magnetic field conversion can depend sensitively on the distance of the dSph (though the value of \alpha_{\text{int}}^{\text{max}, B_0}), we will only consider the dSphs Reticulum II and Willman I, with the understanding that these provide the largest astrophysical enhancement.

Sensitivity

Is often conventional in radio astronomy to define the brightness temperature of an antenna induced by a flux
\[ S_{\text{total}} = \frac{A_{\text{eff}} S_{\text{total}}}{2}, \]

where \( A_{\text{eff}} \) is the effective collecting area of the telescope. Provided astrophysical backgrounds are low, the minimum observable temperature in a bandwidth \( \Delta B \) given an observation time \( t_{\text{obs}} \) is given by

\[ T_{\text{min}} \sim \frac{T_{\text{sys}}}{\sqrt{\Delta B \times t_{\text{obs}}}} \]  

(14)

where \( T_{\text{sys}} \) consists of the added sky/instrumental noises of the system. Throughout this analysis we will assume an observation time of 100 hours and a bandwidth such that at least two bins with the Nyquist width of the autocorrelation spectrometer are inside the axion signal [17].

In general, additional backgrounds arising from e.g. synchrotron emission and free-free absorption must be added to the total system temperature \( T_{\text{sys}} \). This effect may be particularly relevant for high density astrophysical environments with large magnetic fields such as the Galactic Center. DSphs, however, contain much smaller backgrounds; thus we assume here that the induced background temperature is subdominant to the system temperature.

Combining Eq. 13 with Eq. 14, one can estimate the smallest detectable flux of a given radio telescope as

\[ S_{\text{min}} = 2 \frac{T_{\text{sys}}}{A_{\text{eff}} \sqrt{\Delta B \times t_{\text{obs}}}}. \]

(15)

**DWARF GALAXIES**

In this analysis we focus on signals arising in dSphs, as these targets offer large dark matter densities, low background, and small magnetic fields. Note that this is not a generic feature of all dwarf galaxies; in particular, magnetic fields as large as \( \sim 10 \mu G \) have been measured in dwarf galaxies with high levels of star formation [35]. In particular the existence of turbulent magnetic fields have been inferred in irregular and high-mass spiral dwarf galaxies using radio observations of synchrotron radiation [36–38]. Nevertheless, the magnetic field properties of dSphs are poorly known and have proven difficult to measure, a consequence of the fact that dSphs have a lower content of gas and dust (for a review on magnetic field in Galaxies see [31]). Various groups have attempted to estimate the magnetic field properties of dSphs, with estimates yielding values from \( \sim 10^{-2} - \mathcal{O}(1) \mu G \) (see e.g. Table 3 of [32]). These estimations, however, do not provide a hard lower limit on the magnetic field strength, and often rely on comparisons between dSphs and other types of dwarf galaxies. It is sometimes argued that dSphs should have hosted a magnetic field similar to that of irregulars dwarfs [39] in the early stages of their lives, and the magnetic field strength should not have considerably depreciated over time. However, it is not clear whether such magnetic fields can be effectively sustained until present epoch, given that, after the initial phase, a large fraction of gas is swept away from dSphs. Such assumptions may be increasingly questionable if one considers the class of recently discovered ultra-faint dSphs, which are characterized by a low luminosity and ancient metal-poor stars, and are thus largely unlike the conventionally studied classical dwarf galaxies. Thus, we emphasize here that the adopted value of 1 \( \mu G \) should be seen as rather optimistic, and in principle there exists no fundamental reason to exclude negligibly small magnetic fields.

As previously stated, we restrict our analysis to only the most promising dSphs, i.e. those producing the largest \( D(\alpha_{\text{int}})/\sigma_{\text{disp}} \). The value of \( D(\alpha_{\text{int}}) \) for a wide variety of dSphs have been inferred from kinematic distributions (see e.g. [40–47]). In this work we use the publicly available data provided in [41, 42] to determine the value of \( D(\alpha_{\text{int}})/\sigma_{\text{disp}} \) at each \( \alpha_{\text{int}} \). In Fig. 2 we show the maximum value of \( D(\alpha_{\text{int}})/\sigma_{\text{disp}} \) for all dSphs considered in [41, 42] as a function \( \alpha_{\text{int}} \), assuming the median best-fit \( D(\alpha_{\text{int}}) \) (black line) and \( \pm95\% \) CI \( D(\alpha_{\text{int}}) \) (upper and lower green lines). The region bounded by the \( \pm95\% \) CIs has been shaded to illustrate the range of possible values. For each line and each value of \( \alpha_{\text{int}} \), the dSph giving rise to the largest value of \( D(\alpha_{\text{int}}) \) is identified. Note that the surprisingly continuous nature of the lines in Fig. 2 arises from the fact that a number of dwarfs considered have very similar values of \( D(\alpha_{\text{int}})/\sigma_{\text{disp}} \), thus the transitions between e.g. Willman I and Reticulum II are virtually invisible (this is why we have chosen to mark the transitions with a vertical line segment). The most promising dSph candidates are: Reticulum II, Willman I, Ursa Major II, and Draco.

**RESULTS**

In this section we present the projected sensitivity for the SKA-Mid, operated in the phase-2 upgrade which assumes an enhanced collection area of \((1\text{km})^2\) and a system temperature of \( T_{\text{sys}} = 11K \). We have also considered the sensitivity for various current and future radio telescopes, namely LOFAR, ASKAP, ParkesMB, WSRT, Arecibo, GBT, JVLA, FAST and SKA-Low, which will be presented elsewhere.

Fig. 3 shows the estimated sensitivity for SKA-Mid (phase-2) assuming a negligible magnetic field (dark red band), when only spontaneous decay is relevant, and assuming a constant magnetic field of strength \( B_0 = 1\mu G \) contained within a radius of \( r_s = 0.1 \) kpc (light red band) – note that this calculation assumes the suppression factor \( f(m_a) \) arising from the inhomogeneity of the magnetic field is \( \sim 1 \), while in realistic large-scale astrophys-
FIG. 2. Factor $D(\alpha_{\text{int}})\sigma_{\text{disp}}$ as a function of the field of view of the telescope. For each value of $\alpha_{\text{int}}$ (see Eq. 6), we plot the median (black line) and $\pm 95\%$ CI (green band) of $D(\alpha_{\text{int}})/\sigma_{\text{disp}}$ (see Eq. 3) for the dwarf galaxies providing the largest sensitivity. Depending on the field of view of a given radio telescope, the optimal dwarf galaxy is either Willman I, Reticulum II, Ursa Major II, or Draco.

FIG. 3. Sensitivity of SKA-Mid to the axion dark matter parameter space. The solid red line (dark bands) denote the median ($\pm 95\%$ CI) sensitivity to axion decay in the dSph providing the largest sensitivity. Depending on the field of view of a given radio telescope, the optimal dwarf galaxy is either Willman I, Reticulum II, Ursa Major II, or Draco.

In this letter, we have demonstrated that axion decay can be competitive with axion-photon conversion for axion masses probed by radio telescopes, depending on the astrophysical environment. Therefore, it should be included in the sensitivity studies searching for cold dark matter axions with radio surveys. Among the many canonical contexts is likely many orders of magnitude smaller. This result is compared with current constraints from helioscopes [49] and haloscopes [50–54, 56], and with the parameter space in which the QCD axion can account for the entirety of dark matter according to [48] (light green region). Note that in the pre-inflationary scenario, the predicted axion mass that accounts for all the dark matter has been computed to be $\sim 26\mu eV$ [55], which lies precisely in the range where the prospects of this paper are more relevant. Our results illustrate that SKA could potentially lead to the observation of the decay of the QCD axion, and will allow for improvement upon existing helioscope constraints by roughly two orders of magnitude.

For small axion masses, and assuming large magnetic fields, the signal primarily arises from axion-photon conversion (although again we emphasize that this may not be true for realistic calculations incorporating inhomogeneity); however, for $m_a \gtrsim 10^{-5} eV$ axion decay provides the dominant contribution to the observable signal, even for the most optimistic magnetic field strengths. Notice that these bounds are weaker than the ones obtained with a similar analysis in [14]; there the authors considered the sensitivity of future radio telescopes to axion-photon conversion signal coming from the Galactic Center. In the analysis of [14], the signal is enhanced due to the larger magnetic field and the larger dark matter density, but slightly reduced by the larger velocity dispersion. However, radio backgrounds are larger and more uncertain in the Galactic Center, and the radial dependence of the magnetic field distribution is also unknown. Thus, dSphs provide a more robust signal, insensitive to the uncertainties plaguing the Galactic Center.

Before continuing, we comment briefly on the origin of the improvement in sensitivity relative to the original analysis performed in [17]. At low masses, the contribution from stimulated emission is significant; specifically, considering $m_a \sim 10^{-6} eV$, stimulated emission enhances the signal by roughly a factor of $10^{3}$ (which reduces to a factor $\sim 10$ for $m_a = 10^{-4} eV$). With regard to telescope sensitivity, SKA-Mid offers more than one order of magnitude reduction in system temperature and an enhancement in the effective area of $\sim 4$ orders of magnitude. Lastly, the discovery of new dSphs in recent years has allowed for a 1-2 order of magnitude improvement of the overall observed flux.

DISCUSSION

In this letter, we have demonstrated that axion decay can be competitive with axion-photon conversion for axion masses probed by radio telescopes, depending on the astrophysical environment. Therefore, it should be included in the sensitivity studies searching for cold dark matter axions with radio surveys. Among the many can-
didate astrophysical sources, we have identified the best nearby dwarf spheroidal galaxies as a function of the telescope field of view. We have shown that SKA can identify axion cold dark matter by observing the axion decay inside nearby dwarf spheroidal galaxies. Our proposal complements new projects searching for cold dark matter axions in the unexplored mass region near $m_a \sim 10^{-3}$ eV [13]. Furthermore, we emphasize that the sensitivity obtained here surpasses the projected coverage of future axion experiments such as ALPS-II and IAXO in the mass range of interest [57, 58]. It should be understood that the projected sensitivity presented in this work represents what a particular planned experiment can accomplished with known astrophysical objects. In recent years, experiments such as the Dark Energy Survey have dramatically increased the rate of discovery of Milky Way dwarf galaxies, particularly those that offer promise for the indirect detection of dark matter [59, 60]. With ongoing and future experiments such as Gaia [61] and the Large Synoptic Survey Telescope [62] providing unprecedented sensitivity to the gravitational effects of dark matter in the Galaxy, one may expect the rate of dwarf discovery to continue increasing. If more promising dwarf targets are observed in the near future, the projected sensitivity shown here may prove to be conservative. Furthermore, should future radio telescopes be developed with strong sensitivity at higher frequencies, one may expect searches for axion decay to significantly probe the QCD axion parameter space for masses as large as $m_a \sim 10^{-3}$ eV. Such instruments, however, would require good frequency resolution, with a Nyquist width of the autocorrelation spectrum of $\sim 2$ MHz at 100 GHz. Finally, we emphasize that even in the absence of an axion detection, additional science can be obtained from observations of dSphs – for example, molecular line searches in dSphs can enhance the current understanding of the limited star formation in these objects [63].

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