Detecting axion-like particles at radio frequencies

Marco Taoso
Istituto Nazionale di Fisica Nucleare, Sezione di Torino, via P. Giuria 1, I–10125 Torino, Italy

Abstract. Dark matter in the form of axion-like particles can decay into monochromatic photons. We investigate the prospects for detection of these signals with radio telescopes. We show that the presence of an ambient radiation field induces a stimulated enhancement of the decay rate. Depending on the environment, this effect can boost the photon signal by several orders of magnitude. We analyze different astrophysical targets, namely dwarf spheroidal galaxies, the Galactic Center and galaxy clusters. For axion-photon couplings allowed by astrophysical and laboratory constraints, the signal is within the reach of next-generation radio telescopes such as the Square Kilometer Array.

1. Introduction

One of the best motivated dark matter candidate is the QCD axion, which appears in the Peccei-Quinn solution to the strong CP problem[1, 2, 3, 4]. The mass range where axions can account for the entirety of the dark matter depends on the interplay between different production mechanisms and whether the PQ symmetry (i.e. the symmetry introduced in the Peccei-Quinn solution to the strong CP problem) is broken before or after inflation. In the post-inflationary PQ breaking scenario one finds an axion mass around $m_a \sim \text{few} \times (10) \, \mu\text{eV}$ (see e.g. [5, 6] and references therein), while a larger window is obtained in the other case (PQ symmetry is broken before inflation and not restored during reheating). As we will show, radio telescopes searching for axion decay are ideally placed to probe this mass regime.

A rich and diverse experimental program is underway to probe the many unique facets of such a dark matter candidate, see e.g. [7] for a review. Many of the experiments, although not all, rely on the axion’s coupling to photons; this interaction is given by the operator $\mathcal{L} = -\frac{1}{4} g_{\alpha\gamma\gamma} a F_{\mu\nu} \tilde{F}_{\mu\nu}$, where $a$ is the axion field, $F_{\mu\nu}$ is the electromagnetic field strength, $\tilde{F}_{\mu\nu}$ its dual, and $g_{\alpha\gamma\gamma}$ the coupling constant. In axion models, the coupling $g_{\gamma\gamma}$ grows linearly with the axion mass, with a model-dependent proportionality constant. More generically, many extensions of the Standard Model predict light particles with similar properties to the QCD axion, but that might not be related to the strong CP problem and for which the relation between $g_{\gamma\gamma}$ and the mass could be different. These particles, dubbed axion-like particles (ALPs), can act as cold dark matter candidates. It is therefore important to explore all the parameter space of ALPs, beyond the well-motivated case of the QCD axion.

Of particular relevance here is the notion that one may be able to exploit the large number density of axions in astrophysical environments to indirectly infer their existence through the detection of low-energy photons produced by their decays. For axion masses in the ‘characteristic’ dark matter window (i.e. $\mu\text{eV} \lesssim m_a \lesssim 10^2 \mu\text{eV}$), the energy of a non-relativistic axion corresponds to a photon with a frequency ranging from $\sim \mathcal{O}(100) \, \text{MHz}$ to $\sim \mathcal{O}(10) \, \text{GHz}$; lying in the range of frequencies probed by radio telescopes. In this work we investigate the
prospects for detection of this signal, which would appear as a narrow spectral line, broadened by the axion velocity dispersion. We focus on the Square Kilometer Array (SKA), the most powerful radio telescopes available in the near future. We consider three targets of observations: the Galactic center, the Reticulum II dwarf galaxy, and the galaxy M87 in the Virgo cluster. The analysis is based on [8] (see also [9] for an exploratory study).

2. Radio Sensitivity

The flux density, i.e. the power per unit area per unit frequency, from the decay of an axion is given by

$$S_{\text{decay}} = \frac{\Gamma_a}{4\pi \Delta \nu} \int d\Omega \, d\ell \, \rho_a(\ell, \Omega) \, e^{-\tau(m_a, \ell, \Omega)} \left[ 1 + 2 f_\gamma(\ell, \Omega, m_a) \right], \quad (1)$$

where $m_a$ is the axion mass, $\Gamma_a = \frac{m_a^3 g_{a\gamma\gamma}}{4\pi}$ is the spontaneous decay rate of axions, $\rho_a(\ell, \Omega)$ is the axion mass density, $\Delta \nu$ is the width of the axion line, $f_\gamma(\ell, \Omega, m_a)$ is the ambient photon phase-space distribution evaluated at an energy $E_\gamma = m_a/2$, and $\tau$ is the optical depth. The integral in (1) should be performed over the solid angle covered by the radio telescope and the line of sight between the source and the location of Earth. In (1) we can recognized two contributions: the spontaneous decay and the stimulated emission. The latter arises from the presence of a background radiation in the medium where the axion decay occurs and it can be incorporated by simply multiplying the rate of spontaneous emission by a factor $2 f_\gamma$, as shown in (1). In Fig. 1, we compute the stimulated emission factor arising from the CMB (black), Galactic diffuse emission (red), and the extragalactic radio background (green), as a function of the axion mass. The stimulated emission induces a large enhancement of the decay rate, up to eight orders of magnitude for axion masses $\sim \mu$eV and in environments with large radio emission like the Galactic Center.

It is conventional in radio astronomy to work with effective temperatures rather than flux.
densities. The observed antenna temperature in a single radio telescope is given by

\[ T_{\text{ant}} = \frac{A_{\text{eff}} \langle S \rangle}{2k_b}, \]

where \( A_{\text{eff}} \) is the effective area of the telescope and \( \langle S \rangle \) is the bandwidth-averaged flux density. Throughout this work we take the bandwidth to be equal to that width of the axion line, i.e. \( \Delta B = \Delta \nu = \nu_a \sigma / c \), where \( \nu_a \) is the central frequency of the line and \( \sigma \) the velocity dispersion of the dark matter particles.

To derive the sensitivity of the radio telescope we should now compare the antenna temperature with the minimum (rms) observable temperature for a single telescope. The latter is given by

\[ T_{\text{min}} = \frac{T_{\text{sys}}}{\sqrt{\Delta B t_{\text{obs}}}}, \]

where \( t_{\text{obs}} \) is the observation time (set to be equal to 100 hours through this work), \( \Delta B \) is the bandwidth, and the system temperature \( T_{\text{sys}} \) is given by \( T_{\text{sys}} = T_{\text{rcvr}} + T_{\text{sky}} \). \( T_{\text{rcvr}} \) is the noise of the receiver, while \( T_{\text{sky}}(\ell, b) \) is the “sky noise” in the direction of observation. The signal-to-noise ratio for a single telescope and one polarization is simply given by the ratio between (2) and (3):

\[ (\frac{S}{N})_{\text{sd, single}} = \frac{T_{\text{ant}}}{T_{\text{min}}}. \]

The sensitivity of the radio instrument is then obtained combining the signal-to-noise ratio of all the dishes in the array, which depends inherently on the configuration of the array and on the mode of observation, i.e. interferometric or single-dish observation. We consider three configurations for SKA: phase one of SKA-Mid (labeled here as ‘SKA1-Mid’), the proposed upgrade (‘SKA2-Mid’) with a slightly wider frequency band, 10 times more telescopes and improved performances and a low frequency array (‘SKA1-Low’). We refer to [8] for more details.

3. Results

Below we present the projected sensitivity contours in the ALP parameter space for different astrophysical targets.

**Dwarf spheroidal galaxies** offer large dark matter densities, a low velocity dispersion and their angular size is within the field of view of the radio telescopes that we are considering. The signal depends on the so-called D-factor, i.e. the integral of the dark matter density distribution in the region of observation. We use of the publicly available data in [10], which provides the
median values of the D-factors and their uncertainty intervals for several dwarf galaxies. We focus on Reticulum II, one of the most promising dwarf galaxies that can be observed by SKA. We show our results in the right panel of Fig. 1. The bands refer to the 95% credibility interval on the D-factor provided in [10].

The Galactic center is among the most promising targets for indirect dark matter searches, due to its close proximity and high dark matter column density. The dark matter density in the inner region of our galaxy is largely unknown. In an attempt to account for this source of uncertainty, we present sensitivity studies for three distinct profiles, a reference distribution (the Navarro-Frenk-White profile, NFW), and two profiles intended to characterize the relative extremes (the cored Burkert profile and a cuspy distribution given by a generalized NFW profile). Our results are presented in Fig. 2 (left).

The M87 elliptical galaxy lies at the center of the Virgo cluster and accounts for a significant fraction of the cluster mass. The dark matter density distribution is modeled using the results of [11], where the mass density has been inferred by jointly analyzing the dynamics of stars, globular clusters, and satellites. The sensitivities are shown in Fig. 2 (right).

4. Conclusions
In this work we have studied the radio emission arising from axion decays in various types of nearby astrophysical structures. We have showed that with near-future radio observations by SKA, it will be possible to increase sensitivity to the ALP-photon coupling by nearly one order of magnitude. Interestingly, it has been shown that in this range of parameter space, axions provide a viable solution to a non-standard cooling mechanism identified in various stellar systems [12]. If forthcoming axion search experiments, such as ALPS-II and IAXO, find a signal consistent with axion dark matter in the $10^{-7} - 10^{-3}$ eV mass range, the technique proposed here might become the standard route to understand the properties of dark matter, such as e.g. its spatial distribution and clustering in cosmological structures.

Acknowledgments We acknowledge support from the INFN project Theoretical Astroparticle Physics (TAsP), the INFN grant LINDARK and the research grant The Dark Universe: A Synergic Multimessenger Approach No. 2017X7X85K funded by MIUR.

References

[1] R. D. Peccei and Helen R. Quinn. Phys. Rev. Lett., 38:1440–1443, 1977. [328(1977)].
[2] R. D. Peccei and Helen R. Quinn. Phys. Rev., D16:1791–1797, 1977.
[3] Steven Weinberg. Phys. Rev. Lett., 40:223–226, 1978.
[4] Frank Wilczek. Phys. Rev. Lett., 40:279–282, 1978.
[5] Sz. Borsanyi et al. Calculation of the axion mass based on high-temperature lattice quantum chromodynamics. Nature, 539(7627):69–71, 2016, 1606.07494.
[6] M. Buschmann, J. W. Foster and B. R. Safdi, arXiv:1906.00967 [astro-ph.CO].
[7] Igor G. Irastorza and Javier Redondo. 2018, 1801.08127.
[8] A. Caputo, M. Regis, M. Taoso and S. J. Witte, JCAP 1903 (2019) 027 doi:10.1088/1475-7516/2019/03/027 [arXiv:1811.08436 [hep-ph]].
[9] A. Caputo, C. P. Garay and S. J. Witte, Phys. Rev. D 98 (2018) no.8, 083024 Erratum: [Phys. Rev. D 99 (2019) no.8, 089901] doi:10.1103/PhysRevD.99.089901, 10.1103/PhysRevD.98.083024 [arXiv:1805.08780 [astro-ph.CO]].
[10] V. Bonnivard et al. Mon. Not. Roy. Astron. Soc., 453(1):849–867, 2015, 1504.02048.
[11] LJ Oldham and MW Auger. megaparsec scales. Monthly Notices of the Royal Astronomical Society, 457(1):421–439, 2016.
[12] Maurizio Giannotti, Igor Irastorza, Javier Redondo, and Andreas Ringwald. JCAP, 1605(05):057, 2016, 1512.08108.