Searching for Dark Matter with an Optomechanical Accelerometer

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Abstract: We show that a silicon nitride optomechanical membrane, acting as an ac-celerometer, can be used to search for dark matter.

1. Introduction

Dark matter accounts for 85% of the matter in all galaxies. Although its gravitational effects have been observed in numerous astrophysical and cosmological measurements, its composition remains unknown. One possibility is that dark matter is composed of ultralight particles with mass $10^{-22} \leq m_{\mathrm{DM}} \leq 1$ eV/c^2. This ultralight dark matter (ULDM) is accurately described as a coherent field that oscillates at a frequency determined by its particle mass (Compton frequency $f_{\mathrm{DM}} = m_{\mathrm{DM}} c^2/h$).

Several ULDM candidates are expected to interact with ordinary matter to produce a weak mechanical signal, such as a vector force/acceleration or scalar strain. Here we focus on acceleration signals due to vector ULDM in the 1 kHz - 10 MHz range (particle masses $10^{-11} - 10^{-7}\mathrm{eV}/c^2$), which coincide with the resonance frequency of mechanical resonators used in contemporary cavity optomechanical systems. We argue that such systems, operated as accelerometers, can be used to complement acceleration-based ULDM searches based on GW inteferometer [5], atom interferometer [3], and precision torsion-balance experiments [4]. Specifically, new constraints can be set by cryogenic optomechanical accelerometers with sensitivities of $\sqrt{S_{aa}} \lesssim 10^{-11} \frac{g_0}{\sqrt{\mathrm{Hz}}}$ in the 1-100 kHz range.

2. Experiment Principle

The ULDM candidates we focus on are vector (spin-1) bosons, also known as "dark photons," coupled to B-L (baryon minus lepton) charge. If such dark photons exist, the galaxy is filled with an oscillating vector field that causes objects to accelerate in proportion to their neutron-nucleon (charge-mass) ratio. This material-dependent acceleration would be observable as a differential acceleration of test objects made of different materials.

Optomechanical accelerometers employ a mechanical resonator as a test mass and and optical cavity for displacement-based readout. They can be used to search for $B-L$ dark matter by employing a mechanical resonator and a cavity made of different materials, a concept which is compatable with various experimental platforms. Importantly, the acceleration signal can be enhanced on mechanical resonance, motivating the use of a high Q, cryogenically cooled mechanical resonator. The bandwidth is limited by the sensitivity over which the thermal acceleration of the test mass can be resolved, motivating the use of a high finesse optical cavity.

The detector we envision involves a silicon nitride (Si_3N_4) photonic crystal membrane fixed to a beryllium mirror forming a finesse $\mathcal{F} \sim 100$ Fabry-Perot cavity. Si_3N_4 membranes are an attractive mechanical resonator platform for a variety of reasons, including the ability to achieve ultra-high $Q \times m$ products in compact form-factors compatible with cryogenic operation, the ability to pattern into a high reflectivity mirror using photonic crystal patterning (envisioned for this purpsose) [7], and the ability to frequency tune using radiation pressure [2], thermal [9, 10], or electrostatic forces [8], enabling enhanced bandwidth through frequency scanning.

3. Results

The results of this work are presented in Fig. 1, where the acceleration sensitivity of centimeter-scale Si_3N_4 membrane optomechanical accelerometers, pre-cooled to 10 mK, are expressed as a minimum B-L coupling strength $g_{\mathrm{B\text{-}L}}$ [6]. For our frequency range of interest ($1-100$ kHz), the sensitivity on resonance is limited by thermal motion of the membrane, $S_{aa}^{\mathrm{th}} = 4k_{\mathrm{B}}T\omega_0/(mQ_0)$. Off-resonance, the sensitivity is limited by laser shot noise from optical readout, which includes contributions from phase imprecision, $S_{xx}^{\mathrm{imp}} = \pi\hbar c\lambda/\left(64\mathcal{F}^2 P\right)$, and back action due to radiation pressure $S_{aa}^{\mathrm{ba}} = \hbar^2/\left(m^2 S_{xx}^{\mathrm{imp}}\right)$ [1]. For a single 20 cm membrane pre-cooled to 10 mK, we find that

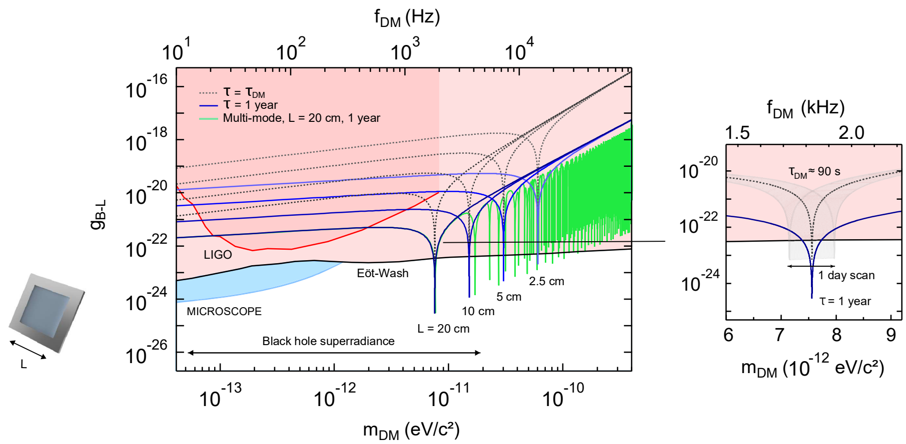

Fig. 1. Centimeter-scale Si_3N_4 membranes as vector B-L dark matter detectors. Dashed gray and solid blue curves are models for the acceleration sensitivity of four different membranes, for a measurement time equal to the DM coherence time τ_{DM} and one year, respectively. Each model assumes a mechanical quality factor of $Q_0 = 10^9$, an operating temperature of $T = 10$ mK, and a displacement sensitivity of $2\times10^{-17}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. A full multimode spectrum for the 20 cm membrane is shown in green. Pink, red, and blue regions are bounds set by the Eöt-Wash experiments, LIGO, and MICROSCOPE, respectively. At right, we zoom in on the resonance of the 20 cm membrane and illustrate a day-long scan (gray region) made in intervals $\tau_{DM} \approx 1.5$ min with a step size equal to the detection bandwidth $\Delta\omega_{det} \approx 2\pi\times0.2$ Hz.

sensitivity to vector B-L dark matter can exceed that of current experimental constraints in integration times of minutes, over a fractional bandwidth of $\sim 0.1\%$ near 10 kHz (corresponding to a particle mass of 10^{-10} eV/c^2).

Our analysis can be translated to alternative systems such as levitated particles, and suggests the possibility of a new generation of table-top experiments.

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