Searches for ultralight vector and axion dark matter with KAGRA

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We have proposed utilizing laser interferometric gravitational wave detectors to search for ultralight vector and axion dark matter. Vector dark matter can be searched for by measuring oscillating forces acting on the suspended mirrors of the interferometers, while axion dark matter can be probed by detecting oscillating polarization rotation of laser beams. This paper reviews the current status of these ultralight dark matter searches using the KAGRA detector in Japan. We conducted the first search for vector dark matter using data from KAGRA's 2020 observing run and have installed polarization optics at the arm cavity transmission ports to enable axion dark matter searches during the upcoming 2025 observing run.

1 Introduction

The first direct detection of gravitational waves in 2015 marked the dawn of gravitational wave physics and astronomy [1]. Since then, the global network of gravitational wave detectors, including LIGO, Virgo, and KAGRA, has reported the observation of over 250 events. These detections have revealed new perspectives on the universe and have enriched our understanding of astrophysical phenomena.

The extraordinary sensitivity of gravitational wave detectors also enables the search for other types of fundamental physics, such as dark matter that alters the interference fringes. In particular, laser interferometers are well-suited for detecting ultralight dark matter, which produces oscillatory changes in the interference fringes at a frequency of $f \simeq 242\ \mathrm{Hz} \times (m_{\mathrm{DM}}/10^{-12}\ \mathrm{eV})$.

Recently, several novel approaches have been proposed to search for various ultralight dark matter candidates using laser interferometric gravitational wave detectors, some of which have already been demonstrated. Scalar dark matter, which induces time variations in the fine structure constant or particle masses, can be probed by measuring size changes in mirrors, and the first such search was conducted using the data from the GEO600 interferometer [2]. These fields

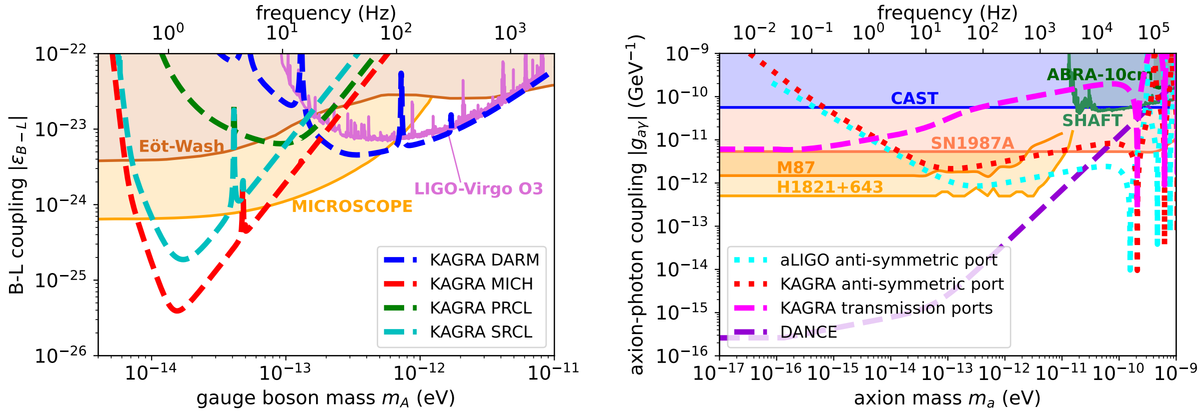

Figure 1 – The projected sensitivity of KAGRA for $B-L$ vector dark matter [13] (left) and axion dark matter [6,7] (right) with the measurement time of 1 year. The shaded regions show limits from fifth-fore searches with Eöt-Wash torsion pendulum [22,23] and MICROSCOPE satellite [24] and LIGO and Virgo's third observing run [15] (left), and limits from CAST [25], SHAFT [26], ABRACADABRA-10cm [27] experiments, astrophysical bounds from the gamma-ray observations of SN1987A [28] and the X-ray observations of M87 galaxy [29] and H1821+643 quasar [30] (right). The projected axion sensitivity for DANCE [5] and LIGO [7] are also shown for comparison.

can also be searched for by measuring the acceleration caused by the spatial gradient of mirror masses [3], with upper limits derived from the LIGO's third observing run [4].

Axion-like particles are another candidate that can be explored by detecting oscillating polarization rotation of laser beams due to axion-photon coupling [5,6,7]. While gravitational wave detectors have not yet been used for axion dark matter searches, initial results from tabletop interferometric experiments such as DANCE [8,9,10], LIDA [11] and ADBC [12] have been reported.

Vector dark matter weakly coupled to the standard model sector can be searched for by measuring oscillatory forces acting on mirrors [13,14]. Searches have already been conducted using data from the third LIGO-Virgo observing run [15], the KAGRA O3GK run [16], and the LISA Pathfinder mission [17,18]. Additionally, gravitational wave detectors can be used to probe spin-2 dark matter, as it produces signals similar to those of gravitational waves [19,20].

In this paper, we present the current status of vector and axion dark matter searches using KAGRA detector in Japan [21]. We adopt the natural unit system with $\hbar = c = \epsilon_0 = 1$.

2 Initial results from the vector dark matter search using KAGRA

The existence of dark matter suggests new physics beyond the standard model. One particularly appealing framework is the $B-L$ (baryon minus lepton) extension of the standard model, which provides a natural explanation for the small neutrino masses through the seesaw mechanism and addresses the matter–antimatter asymmetry via leptogenesis. In the standard model, $B-L$ is conserved, and the $U(1)_{B-L}$ symmetry can be gauged without requiring additional components. If the gauge boson associated with this new $U(1)_{B-L}$ symmetry acts as ultralight dark matter, it induces an oscillating force on the suspended mirrors of a laser interferometer, leading to detectable length changes.

Under a vector dark matter field, expressed as $\vec{A}(t,\vec{x}) = A_0 \vec{e}_A \cos(m_A t - \vec{k}\cdot\vec{x} + \delta_\tau(t))$ at location $\vec{x}$, the oscillating force on a mirror is given by $\vec{F} = F_0 \vec{e}_A \sin(m_A t - \vec{k}\cdot\vec{x} + \delta_\tau(t))$. The phase factor $\delta_\tau(t)$ varies on the coherence timescale of dark matter, given by $\tau = 2\pi/(m_A v^2)$, where $v \simeq 10^{-3}$ represents the local velocity of dark matter. For a mirror with mass M and $B-L$ charge q_{B-L}, the force amplitude is

$$F_0 = \epsilon_{B-L} e q_{B-L} m_A A_0 \simeq \epsilon_{B-L} q_{B-L} \times 6.1 \times 10^{-16}\ \mathrm{N} \simeq \epsilon_{B-L} M \times 1.8 \times 10^{-11}\ \mathrm{m/s^2}. \qquad (1)$$

Here, ϵ_{B-L} is the gauge coupling constant normalized to the electromagnetic coupling, $\vec{e}_A$ is the unit vector parallel to $\vec{A}$, and $k = m_A v$. We assumed that the field energy density equals the local dark matter density, $\rho_a = m_A^2 A_0^2/2 \simeq 0.4$ GeV/cm^3. The amplitude of the oscillating displacement caused by this force is proportional to g_{B-L}/M, differing between materials. For example, for sapphire, which is used for the test mass mirrors of KAGRA, $g_{B-L}/M \simeq 0.510/m_\mathrm{n}$, while for fused silica, used for other mirrors of KAGRA, $g_{B-L}/M \simeq 0.501/m_\mathrm{n}$.

Gravitational wave detectors are highly sensitive to differential arm length (DARM) changes in two perpendicular arm cavities, as gravitational waves induce such changes. However, displacements from the vector field are mostly common across the four test mass mirrors, canceling out most of the vector dark matter signal. The DARM channel sensitivity comes from residual effects due to oscillation phase differences and finite light-travel time [14]. Despite this, LIGO and Virgo have set some of the most stringent constraints, as shown in Fig. 1 (left).

KAGRA is the only gravitational wave detector that incorporates mirrors made of different materials. By measuring the distance changes between the sapphire test masses and the fused silica auxiliary mirrors, the sensitivity to $B-L$ vector dark matter can be enhanced [13]. Auxiliary length channels, such as the differential Michelson interferometer length (MICH), power recycling cavity length (PRCL), and signal recycling cavity length (SRCL), can be utilized to search for the signal. Once the detector achieves its designed sensitivity, it will surpass limits from equivalence principle tests, as shown in 1 (left).

Using data from KAGRA's first joint observing run O3GK with the GEO600 detector in 2020, we set upper limits on the $B-L$ gauge coupling at the 10^{-19} level in the mass range 10^{-13} eV $\lesssim m_A \lesssim 10^{-12}$ eV [16]. This analysis involved developing a new pipeline to search for oscillatory length changes while carefully accounting for the stochastic nature of ultralight dark matter signals [31]. Since KAGRA had not yet reached its planned sensitivity during the O3GK run, our limits remain several orders of magnitude less stringent than those set by previous experiments. Nonetheless, this study demonstrates the feasibility of utilizing auxiliary length channels in gravitational wave detectors for astrophysical observations. With dedicated noise reduction in these channels during future runs, previously unexplored regions could be probed.

3 Polarization optics for axion dark matter search implemented in KAGRA

Axions and axion-like particles are prominent dark matter candidates, and extensive efforts have been made to search for their signatures through diverse experiments and astrophysical studies. Recent measurements of isotropic cosmic birefringence from cosmic microwave background polarization data have attracted attention as a potential hint of axion physics, as axions exploit their parity-violating interaction with photons. It has also been suggested that cosmic birefringence induced by dark energy could be linked to the coupling of axion dark matter to photons in a two-axion model [32].

The axion-photon interaction, characterized by the coupling constant $g_{a\gamma}$, induces a phase velocity difference between left- and right-handed circular polarizations of light. Under the background axion field $a(t) = a_0 \cos(m_a t + \delta_\tau(t))$ with a mass m_a, the phase velocity difference $\delta c = |c_\mathrm{L} - c_\mathrm{R}| = \delta c_0 \sin(m_a t + \delta_\tau(t))$ for light with wavelength of $\lambda_\mathrm{l} = 2\pi/k_\mathrm{l}$ is given by

$$\delta c_0 = \frac{g_{a\gamma} a_0 m_a}{k_\mathrm{l}} \simeq 2.1 \times 10^{-24} \left(\frac{\lambda_\mathrm{l}}{1064\ \mathrm{nm}}\right) \left(\frac{g_{a\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right). \tag{2}$$

This phase velocity difference induces an oscillating polarization rotation with an amplitude given by

$$\delta\beta_0 = \frac{g_{a\gamma} a_0 m_a L}{2\sqrt{2}} \simeq 1.3 \times 10^{-14}\ \mathrm{rad} \left(\frac{L}{3\ \mathrm{km}}\right) \left(\frac{g_{a\gamma}}{10^{-12}\ \mathrm{GeV}^{-1}}\right), \tag{3}$$

for light propagation over a distance L [12]. Such effects can be investigated using table-top ring cavity experiments like DANCE [5], or linear cavities in laser interferometric gravitational wave detectors via the ADAM-GD scheme [6,7]. Both experiments can also probe majoron dark matter associated with the spontaneous breaking of $U(1)_L$ symmetry. [33].

Figure 1 (right) shows the projected sensitivity of the KAGRA detector using the ADAM-GD scheme. Since the arm cavities are over-coupled, the search using the cavity reflected beams at the anti-symmetric port generally offers better sensitivity [6]. However, the search using the arm cavity transmitted beams provides better sensitivity at lower masses. This difference arises because the light at the transmission ports travels through the cavity an odd number of times, and the polarization rotation effect is not canceled by polarization flipping due to mirror reflections [7]. In both cases, sensitivity peaks at $m_a = \pi(2N-1)/L_{\mathrm{cav}}$, where $L_{\mathrm{cav}} = 3$ km is the arm cavity length and $N \in \mathbb{N}$. To search for the polarization rotation of laser beams, we installed polarization optics at the transmission ports of the two arm cavities in 2021 and are now ready to collect the first axion data during the upcoming O4c observing run in 2025.

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