# Snowmass2021 - Letter of Interest

# *Searching for Dark Photons with an Optomechanical Accelerometer*

## Thematic Areas:

☐ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
$square$ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
■ (RF3) Fundamental Physics in Small Experiments
■ (RF6) Dark Sector Studies at High Intensities
■ (IF1) Quantum Sensors

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**Abstract:** "Dark photon" dark matter might produce a mechanical signal by accelerating atoms in proportion to their baryon ($B$) or baryon minus lepton ($B - L$) number. We propose to search for this signal using a high-$Q$ mechanical resonator coupled to an optical cavity, harnessing techniques that have enabled such "cavity optomechanical systems" to operate at the quantum limit in recent years. Specifically, we envision an optomechanical accelerometer based on a silicon nitride membrane fixed to a beryllium mirror, forming a Fabry-Pérot cavity. The use of different materials gives access to forces proportional to $B$ or $B - L$ charge, while the cavity gives access to quantum-limited displacement measurements. For a centimeter-scale membrane pre-cooled to 10 mK, we find that sensitivity to dark photons can exceed that of torsion balance equivalence principle tests 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.

**Background:** Mechanical dark matter (DM) detectors have seen a resurgence of interest for two reasons. First, various models predict that DM produces a force on standard model (SM) particles, for example, a strain due to coupling to fundamental constants[3,8,20]. Second, advances in the field of cavity optomechanics—largely driven by gravitational wave (GW) astronomy—have seen the birth of a new field of quantum optomechanics, in which high-$Q$ mechanical resonators are probed at the quantum limit using laser fields[4]. This has given access to exquisite force sensitivities over a range of frequencies (1 kHz - 10 GHz) which is relatively unexplored, but well-motivated, in the search for DM, corresponding to wave-like "ultralight" DM (ULDM).

Recently it has been proposed to search for ULDM with optomechanical accelerometers, a technology being pursued in a diversity of platforms ranging from levitated microspheres to whispering gallery mode resonators[15,17,18,22]. The concept of accelerometer-based ULDM detection is well-established[6,13,26], forming the basis for searches based on GW inteferometer[14], atom interferometer[11], and precision torsion-balance experiments[13]. From a theoretical viewpoint, it is motivated by the possibility that ULDM is composed of a massive vector field[1,25]—conceivable by various cosmological production mechanisms—which could couple to SM through channels such as baryon ($B$) or baryon-minus-lepton ($B-L$) number. This coupling would manifest as an equivalence-principle-violating[13] (material-dependent) force on uniform bodies or a differential acceleration on bodies separated by a distance comparable to the ULDM's de Broglie wavelength.

**Physical Goals:** We wish to highlight in this LOI that compact (mm to cm-scale) optomechanical accelerometers can be operated as resonant ULDM sensors, enabling high sensitivity at frequencies where current broadband ULDM searches are limited (1 - 100 kHz, i.e. particle masses $10^{-11} - 10^{-9}\mathrm{eV}/c^2$), in a form-factor amenable to array-based detection[6]. As an illustration, we consider a detector based on a $\mathrm{Si_3N_4}$ membrane fixed to a Be mirror, forming a Fabry-Pérot cavity. Through a combination of high mechanical $Q$, cryogenic pre-cooling, and quantum-limited displacement readout, we find that this detector can probe vector $B$ or $B-L$ ULDM with sensitivity rivaling the Eöt-Wash experiments[31] in an integration time of minutes, over a fractional bandwidth of $\sim 0.1\%$. Addressing challenges such as frequency tunability (to increase bandwidth) and scalability could enable these and similar optomechanical detectors to occupy a niche in the search for DM.

**Experimental technique:** The basic concept behind the detector is shown in Fig. 1a. Two mirrors made of different material are connected by a massless spring. In the presence of DM, each mirror experiences a force proportional to its $B$ or $B-L$ charge $q$, and therefore an acceleration proportional to its charge to mass ratio, which is purely a material dependent. The resulting *relative* mirror acceleration gives rise to a displacment between the mirrors, and is enhanced when the acceleration is modulated at the natural frequency of the lumped mass system. The enhancement factor is the mechanical quality factor, which can be large for a macroscopic solid state resonator. When combined with cavity-enhanced displacement readout, this allows for sensitive acceleration measurements

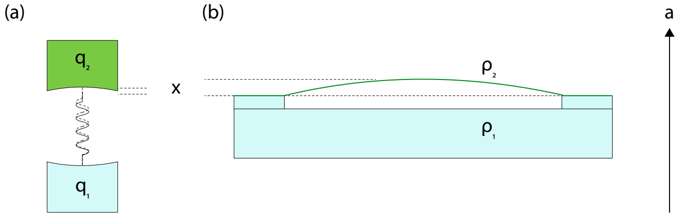

Figure 1: Concept for an optomechanical accelerometer sensitive to vector $B$ or $B-L$ ultralight dark matter. (a) Lumped mass model. (b) Membrane-mirror example. Colors represent masses (materials) with different $B$ or $B-L$ charge (charge density), $q_i$ ($\rho_i$).

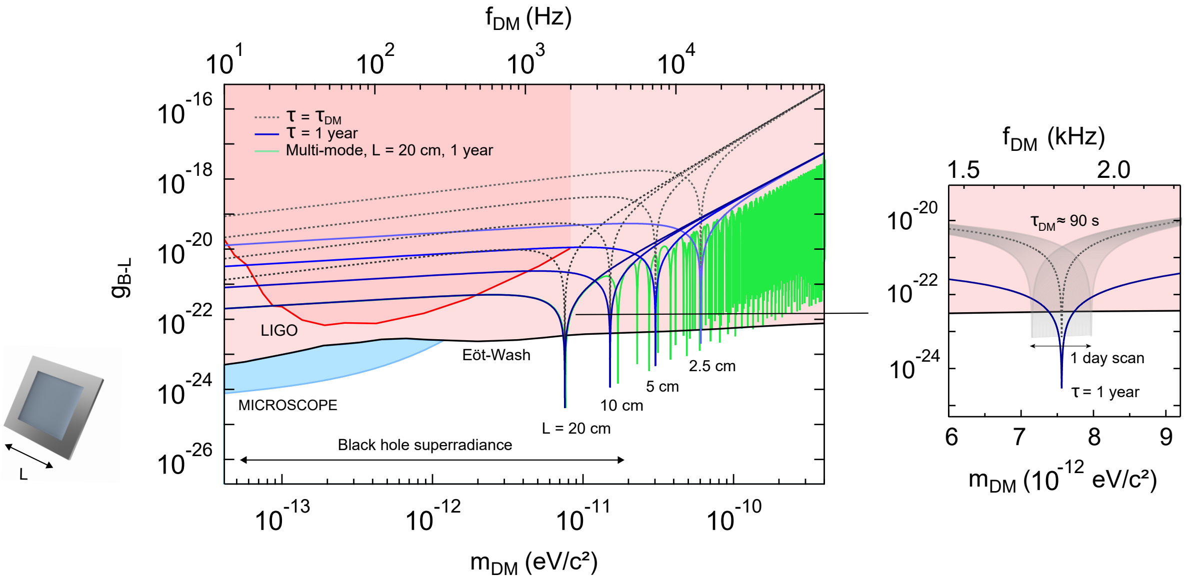

Figure 2: Centimeter-scale $Si_3N_4$ membranes as $B - L$ dark photon detectors. Dashed gray and solid blue curves are models for the acceleration sensitivity of different membrane sizes, expressed as an apparent DM coupling strength $g_{\mathrm{B-L}}$ [19], for a measurement time equal to the DM coherence time and one year, respectively. Each model assumes a mechanical $Q$ factor of $10^9$, an operating temperature of 10 mK, and a displacement sensitivity of $2 \times 10^{-17}\,\mathrm{m}/\sqrt{\mathrm{Hz}}$. 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 $\tau_{\mathrm{DM}} \approx 1.5$ min with a step size equal to the detection bandwidth $\Delta\omega_{\mathrm{det}} \approx 2\pi \times 0.2$ Hz [19].

near the mechanical resonance, typically limited by thermomechanical noise.

Building on this concept, we envision a detector based on a $Si_3N_4$ membrane fixed to a Be mirror, forming a Fabry-Pérot cavity (Fig. 1b) [19]. The use of a $Si_3N_4$ membrane is motivated by a set of features that represent the generic strengths of modern optomechanical devices. Among these are the ability to achieve ultra-high quality factors, exceeding 1 billion, using phononic engineering [12,30]; the ability to tune resonance frequencies using radiation pressure [9], thermal [27,28], and electrostatic forces [24]; parts-per-million optical loss [29]; and the ability to operate as a high reflectivity mirror by photonic crystal patterning [7,23] (necessary to realize the cavity-enhanced detector design).

**Sensitivity and Outlook:** As detailed in [[19]] and in Figure 2, the sensitivity of the detector can exceed that of torsional balance equivalence principle tests (the Eöt-Wash experiments) in an integration time of minutes, commensurate with the ULDM coherence time at Compton frequencies of 1 - 10 kHz. The bandwidth of the detector is determined by the displacement sensitivity of the cavity-based readout, which for $Si_3N_4$ membranes at 100 mK has been shown to be limited by quantum-backaction noise [16]. A combination of multi-mode resonant readout, frequency scanning, and array-based detection can yield an octave bandwidth with a relative small array of $\sim 10$ detectors, compatible with recent mechanical detector array proposals [6]. We anticipate a 5 year program to prototype the detector and 10 year program to realize a broadband detector array.

Finally, while we have focused on vector ULDM, we note that similar optomechanical approaches can be used to search for scalar ULDM [2,10,20] and heavier DM candidates [5,21], as discussed in other LOIs.

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