

Optomechanical accelerometer search for ultralight dark matter

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Cavity optomechanical systems have recently been proposed as detectors for ultralight dark matter, leveraging their ability to cool and probe mechanical oscillators at the quantum limit. Here we present a resonant search for ultralight dark matter using a cavity optomechanical accelerometer. The detector consists of a cryogenic Si_3N_4 -membrane cavity mounted to a 4 K copper plate, with photothermal tuning used to scan its 39 kHz mechanical resonance. Shot-noise-limited displacement readout and radiation-pressure feedback cooling yield an acceleration sensitivity of $10\text{ ng}_0/\sqrt{\text{Hz}}$ over 30 Hz near resonance. The detector's material inhomogeneity gives access to direct vector coupling to the dark-matter field. We conduct a resonant search based on matched-filter statistics, yielding upper bounds consistent with thermal noise and above those set by equivalence principle tests. No signal is observed, but the experiment demonstrates stable, quantum-limited operation and validates a scalable approach to resonant detection. With optimized test masses, lower temperature, and multiplexed arrays, the platform offers a path toward competitive constraints on vector-mediated dark-matter interactions.

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Dark matter is one of the enduring scientific mysteries of our time. Astrophysical observations suggest that an unidentified particle or class of particles accounts for $\sim 85\%$ of the Universe's gravitating matter content; however, their specific mass and the nature of their coupling to Standard Model (SM) particles remain unknown, despite over 40 years of searching using a variety of direct and indirect techniques [1].

Advances in cooling and probing of solid state mechanical oscillators using optical cavities [2] have spurred widespread interest in using such cavity optomechanical systems as tabletop dark matter (DM) detectors [3–10], leveraging compatibility with cryogenics and rapidly maturing techniques that enable operation at fundamental quantum noise limits. Particlelike and wavelike DM detectors have been proposed, based on impulsive [11] and continuous [12] force measurement protocols, respectively. Massive arrays of optomechanical sensors might serve as DM track detectors [11,13] or phased antenna arrays [14], and have inspired their investigation as an application of entanglement-enhanced distributed force sensing [15,16].

In this Letter, we describe a search for wavelike, ultralight dark matter (UDM) using a cavity optomechanical system operating as an accelerometer. The concept of accelerometer-based UDM detection was introduced by [17] and later reframed as an optomechanical force sensing problem by [7,12]. The basic premise is that DM particles with mass $m_{\text{DM}} \lesssim 10\text{ eV}/c^2$ [18] (determined by the local DM energy density ρ_{DM}) coherently combine to create an oscillating field, and that this field may act on SM atoms similar to the electromagnetic force—but with electric charge replaced with a generalized charge such as a baryon minus lepton (B-L) number. As such, within the coherence time, two free-falling SM objects would experience a differential acceleration proportional to $\sqrt{\rho_{\text{DM}}}$ and their fractional charge difference Δ_{12} [7,12,17]:

$$a_{\text{DM}}(t) = g\Delta_{12}a_0 \cos[\omega_{\text{DM}}t + \phi_{\text{DM}}], \quad (1)$$

where g is an unknown coupling constant, ω_{DM} is the UDM Compton frequency, $a_0 = 2.1 \times 10^{11}\text{ m/s}^2$ [19] is a constant proportional to $\sqrt{\rho_{\text{DM}}}$, and ϕ_{DM} is a random phase reflecting the velocity dispersion of DM particles in the Galactic halo.

The design of our optomechanical accelerometer was proposed in [7] and experimentally realized in [45], and consists of a pair of Si_3N_4 membranes with different stiffnesses—a trampoline and a square membrane—vertically integrated on a Si chip, forming a Fabry-Perot cavity. As illustrated in Fig. 1, fixing the cavity to a Cu plate (possessing a larger B-L [neutron] density than Si_3N_4

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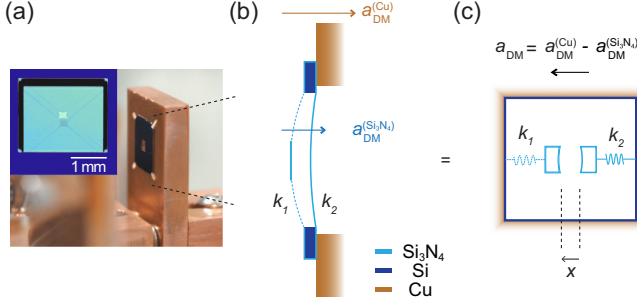


FIG. 1. Dual-membrane optomechanical dark matter detector. (a) Si chip with suspended Si_3N_4 membranes fixed to a Cu plate. Inset: microscope image of trampoline (foreground) and square membrane (background). Concept: (b) UDM differentially accelerates the Cu plate, Si_3N_4 membranes, and Si chip [21]. (c) In the reference frame of the base, the membranes experience a base excitation. Their different stiffnesses $k_{1,2}$ result in a relative displacement x [45].

and Si) translates the UDM signal into an effective chip acceleration a_{DM} . If coincident with the resonance frequency of the trampoline ω_m , the acceleration gets amplified by the mechanical quality factor into a displacement $x_{\text{DM}} = Q_m a_{\text{DM}} / \omega_m^2$ [46], yielding sensitivity to UDM with a thermal-noise-equivalent coupling strength of [7]

$$g_{\text{DM}}^{(\text{th})} \approx \sqrt{\frac{2k_B T}{m Q_m Q_{\text{DM}} \Delta_{12} a_0}} \times \left(\frac{2Q_{\text{DM}}}{\omega_{\text{DM}} \tau} \right)^{1/4}, \quad (2)$$

where T is the bath temperature, m is the effective mass of the trampoline (accounting for its mode shape and the finite stiffness of the square membrane [7]), $Q_{\text{DM}} \sim 10^6$ [47] is the effective Q factor (number of coherent cycles) of the UDM field, and τ is the measurement time, assuming $\omega_{\text{DM}} \tau > Q_{\text{DM}}$.

Equation (2) illustrates the desirability of a high $m \times Q_m$ mechanical oscillator operated at cryogenic temperatures for sustained intervals. To realize a novel sensitivity, [7] proposed an $\omega_m \sim 2\pi \times 1$ kHz, $Q_m \sim 10^9$, cm-scale Si_3N_4 membrane ($m \sim 1$ mg) operating in a closed-cycle dilution refrigerator ($T \sim 10$ mK) for a year ($\tau \sim 10^7$ s), enabling $g_{\text{DM}}^{(\text{th})} \sim 10^{-25}$ —two orders of magnitude below current constraints set by precision torsion balance tests of the equivalence principle [48,49].

Here we report a more modest, first generation search for UDM employing a $\omega_m \sim 2\pi \times 10$ kHz, $Q_m \sim 10^8$, millimeter-scale Si_3N_4 trampoline ($m \sim 10$ ng) operating in a closed-cycle 4 K cryostat for $\tau \sim 10^3$ s, targeting $g_{\text{DM}}^{(\text{th})} \sim 10^{-17}$. Our aim is to demonstrate the working

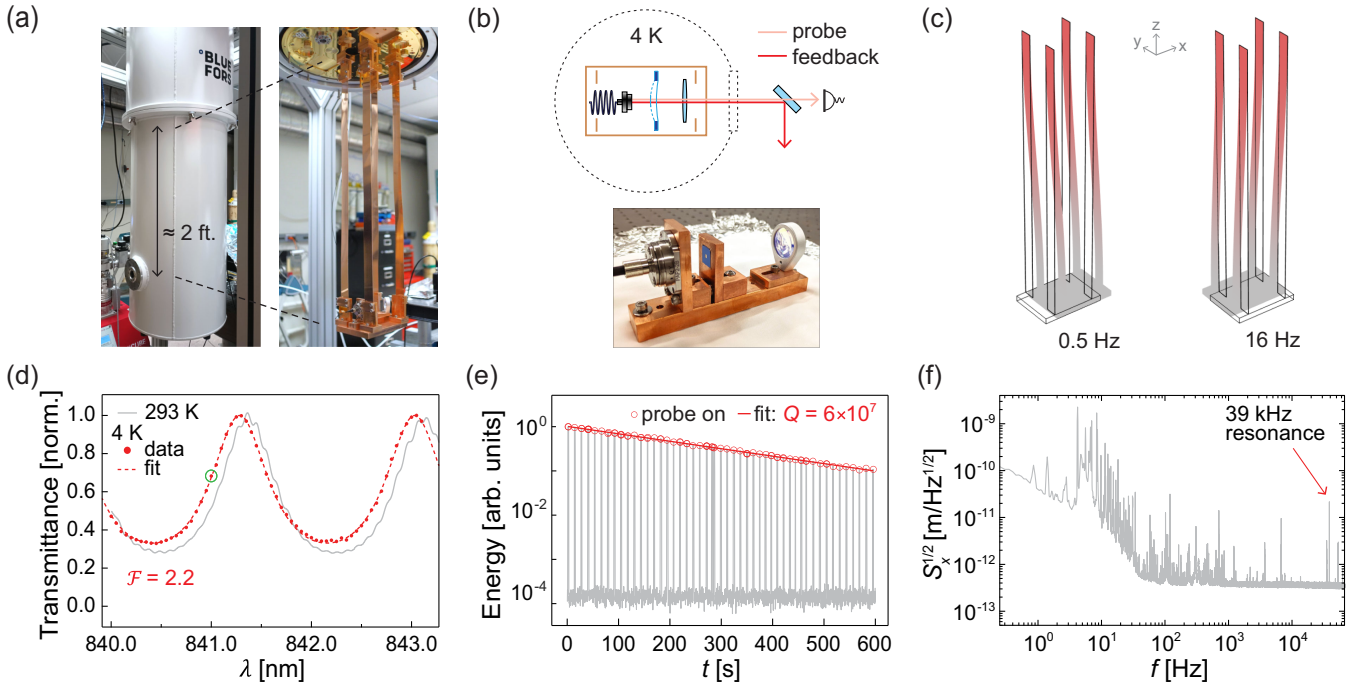


FIG. 2. Cryogenic operation enabled by vibration isolation. (a) Photos of Bluefors LD-4K cryostat (left) and custom vibration isolation system (VIS) based on thin Cu strips (right) suspended from the mixing stage. (b) Cavity alignment module (photo, bottom) and readout: probe and feedback laser beams are fiber-coupled and aligned to the dual-membrane cavity; the assembly is mounted on the VIS-platform (top, cartoon). A photodetector placed outside the cryostat records the cavity's transmission. (c) Finite-element simulations of the fundamental modes of the VIS along x (left) and y (right). (d) Transmission fringes obtained from a laser detuning sweep before and after cooldown, showing cavity alignment remains stable. The green circle highlights the detuning used for side-of-fringe readout. (e) Energy ringdown of the trampoline's fundamental mode at 4 K reveals Q_m of 60 million. (f) Broadband spectrum showing a reduction of vibration background above $f \sim 1$ Hz.

principle behind a cavity optomechanical vector UDM detector, highlighting the challenges of vibration isolation, how to improve signal averaging using radiation pressure feedback cooling, strategies to extend bandwidth exploiting quantum-noise-limited readout and photothermal frequency tuning, and routines for data analysis by template matching to a model for the UDM signal.

An overview of our cryogenic apparatus and device characterization is shown in Fig. 2. In conceiving such a system, we first emphasize the challenging acceleration sensitivity requirements implied by current UDM constraints in the “optomechanics” band, $f_{\text{DM}} = \omega_{\text{DM}}/2\pi \sim 1$ Hz to 1 MHz. For B-L UDM, for example, $g \lesssim 10^{-22}$ (see Fig. 4) corresponds to an acceleration sensitivity of $\sqrt{S_a} \sim g a_0 \Delta_{12} \sqrt{\omega_{\text{DM}}/Q_{\text{DM}}} \lesssim \Delta_{12} \times 10^{-11} g_0/\sqrt{\text{Hz}}$, where $g_0 = 9.8 \text{ m/s}^2$ is Earth’s standard gravity. This sensitivity has been achieved by the Laser Interferometric Gravitational Wave Observatory (LIGO) at frequencies below 1 kHz—indeed, B-L constraints from 100 Hz to 2 kHz currently belong to LIGO—however, at higher frequencies, we know of no such reported acceleration sensitivity, including with mechanical oscillators. Challenges include unfavorable thermal noise scaling $S_a^{\text{th}} = 4k_B T \omega_m / (m Q_m)$, ambient vibrations produced by cryostats, and difficulty thermalizing micromechanical resonators to sufficiently low T , while at the same time being able to resolve their thermal motion.

We adopt a conservative approach and house our detector in a field-upgradable Bluefors LD-4K cryostat (LD with the dilution unit removed) [52], using the extra sample volume for a two-foot-long (1 foot = 1 ft. = 30.5 cm) pendulum vibration isolation system (VIS) [53] [Fig. 2(a)]. The frequency of the pendulum, $f_p = 0.5$ Hz, is 5 orders of magnitude below the trampoline’s $f_m = 39$ kHz, implying access to an isolation factor of $(f_m/f_p)^2 \sim 10^{10}$. To mitigate pendulum swing, the accelerometer and fiber-optic delivery system are assembled and prealigned on a small optical bench mounted on the sample stage [Fig. 2(b)]. The cavity transmission is monitored through a viewport by a low-noise Si photodetector. As shown in Fig. 2(d), the cavity alignment survived cooldown with minimal loss of visibility, realizing the design finesse $\mathcal{F} = 2.2$ [54]. A mechanical ringdown revealed $Q = 6 \times 10^7$ [Fig. 2(e)], and thermal noise measurements (see below and the Supplemental Material [21]) confirmed that the fundamental trampoline mode thermalized to the cryostat base temperature of 3.5 K, corresponding to $\sqrt{S_a^{\text{th}}} = 3 \times 10^{-8} g_0/\sqrt{\text{Hz}}$, using $m = 12$ ng [45].

To search for UDM, we analyze acceleration spectra for the presence of a narrow spectral feature with width $\gamma_{\text{DM}} = \omega_{\text{DM}}/Q_{\text{DM}}$. Toward this end, Fig. 3 shows near-resonance estimates of the trampoline-membrane displacement power spectral density (PSD) $S_x[\omega]$ and, by inference, chip acceleration PSD $S_a[\omega]$, using a standard

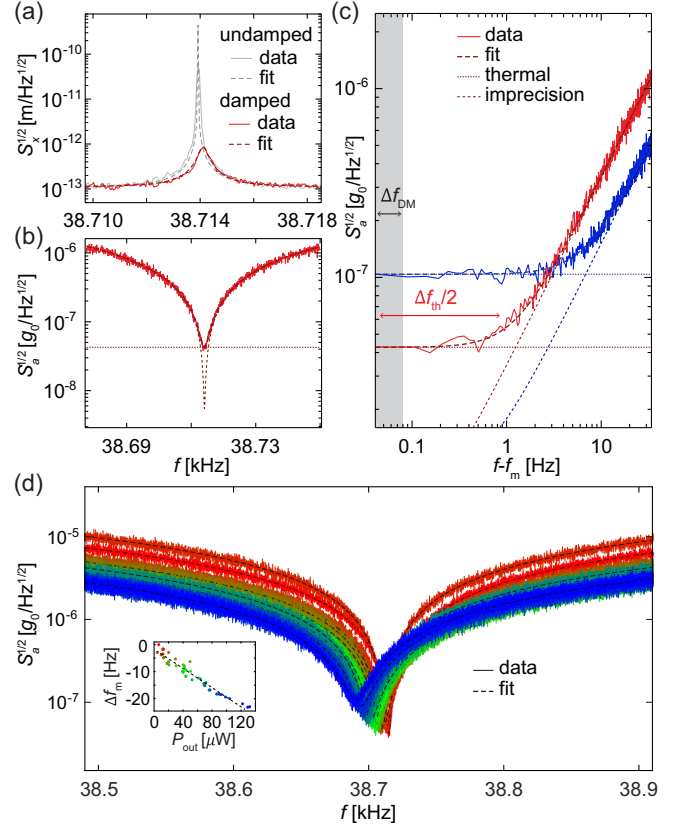


FIG. 3. Displacement and acceleration measurements. (a) Calibrated membrane-trampoline displacement PSD near trampoline’s fundamental mode frequency f_m , for a weak probe with transmitted power $P_{\text{out}} \approx 1 \mu\text{W}$. The red (gray) trace is obtained with (without) optical damping. (b) Corresponding closed-loop acceleration PSD after inverting the mechanical susceptibility. (c) Plots of acceleration noise versus frequency detuning from resonance at $P_{\text{out}} = 1 \mu\text{W}$ (red) and $100 \mu\text{W}$ (blue), illustrating the trade-off between bandwidth and sensitivity due to photothermal heating. The gray-shaded region corresponds to the UDM-signal linewidth $\gamma_{\text{DM}} \approx 2\pi \times 0.08$ Hz. (d) Photothermal frequency tuning of f_m . Increasing the probe power (inset) decreases f_m at the expense of increased thermal noise S_a^{th} [21].

feedback-assisted force sensing protocol [45,57–59]. For these measurements, the cavity was probed with a low noise wavelength-tunable (840–852 nm) diode laser, for displacement readout, and an auxiliary fixed wavelength (658 nm) diode laser, for radiation pressure feedback. The readout laser was tuned to the side of the fringe [Fig. 2(e)] to maximize sensitivity. The feedback laser was intensity modulated with a delayed copy of the readout photocurrent to damp the resonance by $\gamma > \gamma_{\text{DM}}$ [60] [Fig. 3(a)]. Periodograms were then averaged for $\tau = 800$ s in $N = 40$ intervals of $\tau_p = 20$ s $\approx 10\gamma_{\text{DM}}^{-1}$ [63], calibrated in displacement units using the fringe slope [45], and divided by the closed-loop acceleration susceptibility $\chi[\omega] = (\omega^2 - \omega_m^2 + i\gamma\omega_m)^{-1}$, yielding an acceleration PSD estimate $\hat{S}_a[\omega]$ with an ideal (Gaussian-distributed) mean and standard deviation of

$$S_a[\omega] = S_a^{\text{DM}}[\omega] + S_a^{\text{th}} + |\chi[\omega]|^{-2} S_x^{\text{imp}} \quad \text{and} \quad (3a)$$

$$\sigma_{\hat{S}_a}[\omega] = S_a[\omega]/\sqrt{N} \quad (3b)$$

respectively, where S_x^{imp} is the displacement readout noise (imprecision), and $S_a^{\text{DM}}[\omega]$ is the hypothetical UDM signal.

As shown in Fig. 3, for readout powers from $P_{\text{out}} \approx 1 \mu\text{W}$ to $100 \mu\text{W}$, we realize a shot-noise-limited displacement imprecision of $\sqrt{S_x^{\text{imp}}} \approx (10^{-13} - 10^{-14}) \text{ m}/\sqrt{\text{Hz}}$, corresponding to a thermal-noise-limited bandwidth of $\Delta\omega_{\text{th}} = \omega_m \sqrt{S_x^{\text{th}}/S_x^{\text{imp}}} \approx 2\pi \times 2 \text{ Hz}$, or $\Delta\omega_{\text{th}}/\gamma_{\text{DM}} \approx 26$ independent DM bins. We also observe photothermal heating at the level of $dT/dP_{\text{out}} \approx 0.4 \text{ K}/\mu\text{W}$ [64]. We leverage this heating to photothermally tune the resonance frequency over 25 Hz (330 DM bins), at the expense of a threefold increase in thermal noise $\sqrt{S_a^{\text{th}}}$ [21].

Our search algorithm [21] involves matched filtering $\hat{S}_a[\omega]$ to a model $S_a^{\text{DM}}[\omega] = \langle a_{\text{DM}}^2 \rangle G_{\text{DM}}[\omega]$, where $\langle a_{\text{DM}}^2 \rangle$ is the unknown UDM acceleration power and G_{DM} is the normalized line shape ($\int G_{\text{DM}}[\omega] d\omega/(2\pi) = 1$). Toward this end, we consider an astrophysically motivated line shape [4,14],

$$G_{\text{DM}}[\omega] \approx \frac{\sqrt{8\pi}}{e\gamma_{\text{DM}}} e^{-\frac{2(\omega-\omega_{\text{DM}})}{\gamma_{\text{DM}}}} \sinh \sqrt{1 + \frac{4(\omega - \omega_{\text{DM}})}{\gamma_{\text{DM}}}}, \quad (4)$$

reflecting the Maxwell-Boltzmann velocity distribution of massive bodies in the Milky Way. We implement a 45-step photothermal frequency scan by increasing the optical power from $5 \mu\text{W}$ to $132 \mu\text{W}$. We then construct a composite estimator for $\langle a_{\text{DM}}^2 \rangle \equiv D$ based on matched filtering (over frequency index k) and weighted averaging (over scan index i):

$$\hat{D}[\omega_{\text{DM}}] = \sigma_{\hat{D}}^2[\omega_{\text{DM}}] \sum_{ik} \frac{G_{\text{DM}}^{\tau_p}[\omega_k, \omega_{\text{DM}}]}{\sigma_{\hat{S}_a^{(i)}}^2[\omega_k]} \times \left(\hat{S}_a^{(i)}[\omega_k] - S_a^{n,(i)}[\omega_k] \right), \quad (5)$$

where $G_{\text{DM}}^{\tau_p}$ is UDM line shape binned over τ_p^{-1} and $S_a^n = S_a - S_a^{\text{DM}}$ is the total measurement noise. Applying frequentist and Bayesian frameworks [67], respectively, we implicitly define a detection threshold D_{DT} and an upper bound for the DM signal power D_{UL} , based on a confidence level

$$\text{CL} = \left(\int_{-\infty}^{D_{\text{DT}}} \rho(\hat{D}|D=0) d\hat{D} \right)^{N_b} = \int_{-\infty}^{D_{\text{UL}}} \rho(D|\hat{D}) dD, \quad (6)$$

where $\rho(\hat{D}|D=0)$ and $\rho(D|\hat{D})$ are the likelihood function and posterior distribution for the DM signal power,

respectively, and N_b is the number of independent frequency bins in the search span, accounting for the look-elsewhere effect [21].

Results of the UDM search are summarized in Fig. 4. As shown in Figs. 4(a) and 4(b), we observe a near-Gaussian distribution of weighted estimators $\hat{D}[\omega_k]/\sigma_{\hat{D}}[\omega_k]$, with variance $\sigma_{\hat{D}}^2[\omega_k]$ [21] minimized over the 25 Hz resonant scan window in Fig. 3(d). This motivates a likelihood function $\rho(\hat{D}|D) \propto \exp[(D - \hat{D})^2/2\sigma_{\hat{D}}^2]$, from which we determine the CL = 95% confidence threshold shown in Fig. 4(a). Accounting for the look-elsewhere effect over a search span of $\Delta f = 1 \text{ kHz}$ ($N_b = \tau_p \Delta f = 10^4$), we observe no detection events.

To set a limit on the DM coupling strength, we combine the experimentally determined likelihood function with Bayes theorem and a prior $\rho(D)$ that is uniform for $D > 0$, yielding a median limit $D_{\text{UL}} \approx \sqrt{2}\sigma_{\hat{D}} \text{Erf}^{-1}[\text{CL}]$ [21] and a 2σ bound,

$$g \leq \frac{\sqrt{2D_{\text{UL}}}}{a_0 \Delta_{12}} \approx \frac{2\sqrt{\sigma_{\hat{D}}}}{a_0 \Delta_{12}}, \quad (7)$$

for CL = 95%. We consider B-L coupling ($g_{\text{B-L}}$) as a canonical example [73,74] in which case $\Delta_{12} = Z_1/A_1 - Z_2/A_2$, where Z_i and A_i are the atomic and mass number of body i , respectively. For Si_3N_4 and Si, $Z/A \approx 0.50$, and for Cu, $Z/A \approx 0.46$, yielding $\Delta_{12} \approx 0.04$. Using this value presumes that the accelerometer behaves like a heterogeneous mechanical dimer (two bodies made of different material, attached by a simple spring) [7], as substantiated in [21].

Inferred $g_{\text{B-L}}$ constraints are shown in Fig. 4(c), assuming a perfectly rigid chip (gray) and correcting for the estimated chip response function (red) (see [21] for details). The lower bound $g_{\text{B-L}} \approx 1 \times 10^{-17}$ corresponds to an acceleration amplitude resolution of $\sqrt{\sigma_{\hat{D}}} \approx 4 \times 10^{-9} g_0$ and PSD resolution of $\sigma_{\hat{S}_a}(\omega_{\text{DM}}) \approx (2 \times 10^{-8} g_0/\sqrt{\text{Hz}})^2$, consistent with the variance of the lowest PSD estimate in Fig. 3 [21] (at $T \approx 8 \text{ K}$ due to photothermal heating). Shown in Fig. 4(d) is our bound combined with the best current constraints from the Eöt-Wash experiment [48,49] and various others at lower frequency.

Looking forward, realizing the original design sensitivity $g_{\text{B-L}} \sim 10^{-25}$ proposed in [7] requires operating at 10 mK, increasing the cavity finesse to $\mathcal{F} = 100$, increasing the size and Q of the membrane to 10 cm and 10^9 , respectively, vibration isolation at the $10^{-12} g_0/\sqrt{\text{Hz}}$ level, and integrating for a year [75]. Recent advances augur well for these upgrades: sub-100-mK, $\mathcal{F} \gtrsim 10^4$ cavity optomechanics experiments with Si_3N_4 membranes have been demonstrated [53,77], as have high reflectivity photonic crystal (PtC) membranes [78], including stable $\mathcal{F} \approx 10^3$ cavities employing a gradient-pitch PtC [55]. Decimeter-scale membranes are now commercially available [79], and

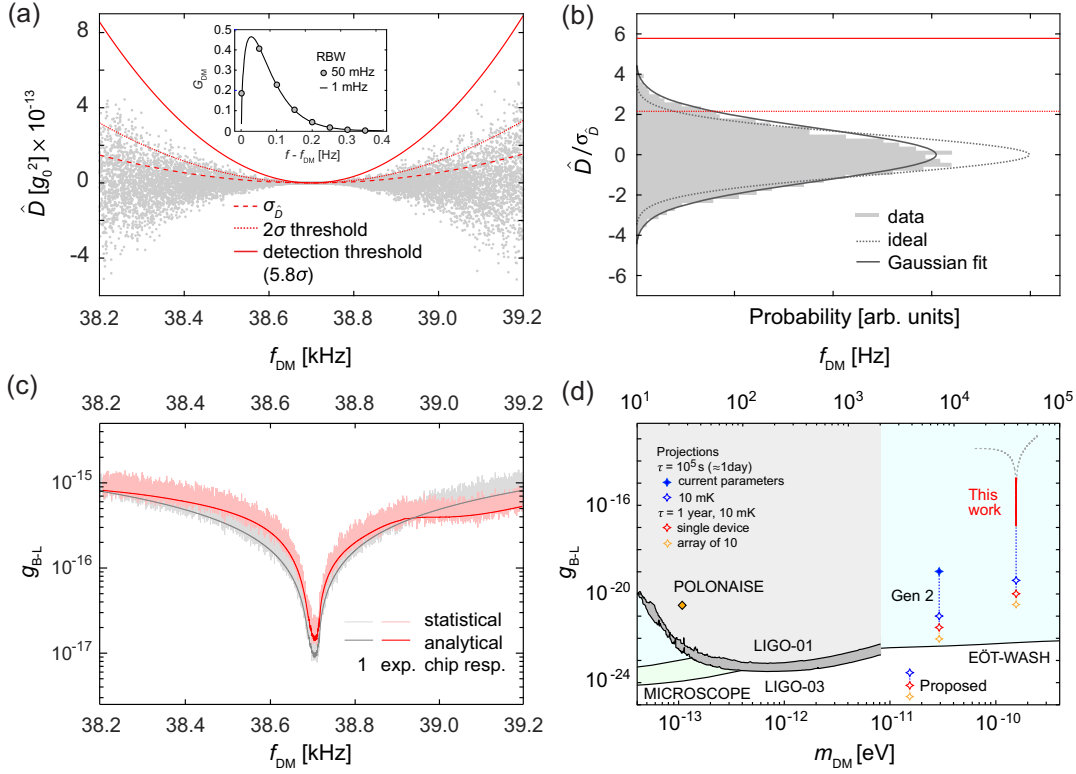


FIG. 4. Search for B-L UDM. (a) Estimates of UDM acceleration power $\langle a_{DM}^2 \rangle \equiv D$ obtained from the data in Fig. 3(d) using a matched-filter and weighted averaging, Eq. (5). Dashed lines are thresholds for confidence level CL = 68% (1σ) and 95% (2σ). The solid red line is our threshold, which includes the look-elsewhere effect [Eq. (6)]. (b) Histogram of normalized power estimates $\hat{D}/\sigma_D$. Solid and dotted curves show measured and ideal distributions expected from periodogram averaging [Eq. (3)]. (c) Constraints on g_{B-L} from data in (a). Light and bold traces are statistical and analytic estimates, respectively. Gray traces assume a rigid chip; red traces include the estimated chip transfer function [21]. (d) Comparison to current constraints from LIGO [69,70], the Eöt-Wash experiment [48], MICROSCOPE [50], and POLONAISE [71]. Gray dashed line is an extension of the analytical model in (c) assuming a displacement imprecision of $S_x^{\text{imp}} = (5 \times 10^{-14} \text{ m}/\sqrt{\text{Hz}})^2$ [21]. Markers indicate benchmark sensitivities for second-generation [72] and long-term proposed [7] configurations discussed in the main text and [21].

centimeter-scale PtC membranes [80,81] have been realized, driven by the Starshot project. The expected mechanical Q versus size scaling (due to dissipation dilution [82]) from 10^8 to 10^{10} has also been confirmed with centimeter-scale Si_3N_4 beams [83]. Finally, low vibration, closed-cycle (continuous operation) dilution refrigerator technology continues to advance in response to the superconducting quantum computing industry, with custom $10^{-11} g_0/\sqrt{\text{Hz}}$ VIS demonstrated for frequencies as low as 10 Hz [71].

A key component to realizing novel constraints will be optimizing the membrane geometry. In-plane patterning can enable ultrahigh Q [82]; however, a promising alternative is 3D mass loading [84–86], which can enhance the more relevant $Q - m$ product [Eq. (2)]. Toward this end, we highlight a recent demonstration of $m \sim 0.1$ mg, $f_m \sim 100$ Hz, $Q_m \sim 10^7$ torsion micropendula based on mass-loaded Si_3N_4 nanoribbons, which achieve $S_a^{\text{th}} \sim 10^{-9} g_0/\sqrt{\text{Hz}}$ at room temperature [87]. Cryogenically cooled, these devices could reach the desired sensitivity for novel UDM searches in the 10 Hz to 1 kHz band, in conjunction with quantum-limited

optical lever measurements [88,89]; they also provide a route to vibration isolation through heterogeneous mass loading [90], the latter of which has been demonstrated using a flip chip approach [86].

Finally, we highlight a recent proposal to search for UDM with an array of $N = 10$ cryogenic membrane accelerometers probed by a distributed squeezed light source [16], building on an $N = 2$ demonstration with two 0.1-mm membranes [91]. This approach enables enhanced sensitivity (as much as N -fold [16]) if the power per sensor is fixed and, therefore, improved UDM searches with a cryogenic detector limited by photothermal heating or other power constraints. Loss and scalability are key challenges. Recent demonstrations of vertically integrated $\mathcal{F} \approx 10^3$ PtC-membrane cavities [92] suggest a path toward scalable arrays using free-space squeezed light, while emerging photonic-integrated accelerometers [93] and squeezed-light sources [94] offer a fully integrated approach.

In the Supplemental Material, we compare various contemporary optomechanical accelerometers and their

projected performance as B-L UDM detectors, including a second-generation, $1\ \mu\text{g}$ Si_3N_4 membrane accelerometer [“Gen-2” in Fig. 4(d)], and an emerging class of electro-mechanical accelerometers based on magnetically levitated test masses, exemplified by the POLONAISE UDM detector [71]. We find that several of these systems could in principle reach competitive sensitivity to vector-mediated DM interactions, when operated for extended periods at millikelvin temperatures.

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Data availability. The data that support the findings of this study are publicly available [95].

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- [1] G. Bertone and T. M. Tait, A new era in the search for dark matter, *Nature (London)* **562**, 51 (2018).
 - [2] M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, Cavity optomechanics, *Rev. Mod. Phys.* **86**, 1391 (2014).
 - [3] D. Carney, G. Krnjaic, D. C. Moore, C. A. Regal, G. Afek, S. Bhave, B. Brubaker, T. Corbitt, J. Cripe, N. Crisosto *et al.*, Mechanical quantum sensing in the search for dark matter, *Quantum Sci. Technol.* **6**, 024002 (2021).
 - [4] D. Antypas, A. Banerjee, C. Bartram, M. Baryakhtar, J. Betz, J. Bollinger, C. Boutan, D. Bowering, D. Budker, D. Carney *et al.*, New horizons: Scalar and vector ultralight dark matter, [arXiv:2203.14915](https://arxiv.org/abs/2203.14915).
 - [5] A. Arvanitaki, S. Dimopoulos, and K. Van Tilburg, Sound of dark matter: Searching for light scalars with resonant-mass detectors, *Phys. Rev. Lett.* **116**, 031102 (2016).
 - [6] J. Manley, D. J. Wilson, R. Stump, D. Grin, and S. Singh, Searching for scalar dark matter with compact mechanical resonators, *Phys. Rev. Lett.* **124**, 151301 (2020).
 - [7] J. Manley, M. D. Chowdhury, D. Grin, S. Singh, and D. J. Wilson, Searching for vector dark matter with an optomechanical accelerometer, *Phys. Rev. Lett.* **126**, 061301 (2021).
 - [8] M. Hirschel, V. Vadakkumbatt, N. Baker, F. Schweizer, J. Sankey, S. Singh, and J. Davis, Superfluid helium ultralight dark matter detector, *Phys. Rev. D* **109**, 095011 (2024).
 - [9] C. G. Baker, W. P. Bowen, P. Cox, M. J. Dolan, M. Goryachev, and G. Harris, Optomechanical dark matter instrument for direct detection, *Phys. Rev. D* **110**, 043005 (2024).
 - [10] T. Deshpande, A. Ionescu, N. Miller, Z. Wang, G. Gabrielse, A. A. Geraci, and T. Kovachy, Demonstration that differential length changes of optical cavities are a sensitive probe for ultralight dark matter, *Phys. Rev. Lett.* **135**, 261001 (2025).
 - [11] D. Carney, S. Ghosh, G. Krnjaic, and J. M. Taylor, Proposal for gravitational direct detection of dark matter, *Phys. Rev. D* **102**, 072003 (2020).
 - [12] D. Carney, A. Hook, Z. Liu, J. M. Taylor, and Y. Zhao, Ultralight dark matter detection with mechanical quantum sensors, *New J. Phys.* **23**, 023041 (2021).
 - [13] C. Blanco, B. Elshimy, R. F. Lang, and R. Orlando, Models of ultraheavy dark matter visible to macroscopic mechanical sensing arrays, *Phys. Rev. D* **105**, 115031 (2022).
 - [14] A. Derevianko, Detecting dark-matter waves with a network of precision-measurement tools, *Phys. Rev. A* **97**, 042506 (2018).
 - [15] A. J. Brady, C. Gao, R. Harnik, Z. Liu, Z. Zhang, and Q. Zhuang, Entangled sensor-networks for dark-matter searches, *PRX Quantum* **3**, 030333 (2022).
 - [16] A. J. Brady, X. Chen, Y. Xia, J. Manley, M. Dey Chowdhury, K. Xiao, Z. Liu, R. Harnik, D. J. Wilson, Z. Zhang *et al.*, Entanglement-enhanced optomechanical sensor array with application to dark matter searches, *Commun. Phys.* **6**, 237 (2023).
 - [17] P. W. Graham, D. E. Kaplan, J. Mardon, S. Rajendran, and W. A. Terrano, Dark matter direct detection with accelerometers, *Phys. Rev. D* **93**, 075029 (2016).
 - [18] D. F. Jackson Kimball and K. Van Bibber, *The Search for Ultralight Bosonic Dark Matter* (Springer Nature, New York, 2023).
 - [19] Between coherence intervals, the UDM field amplitude is expected to fluctuate [20]; here a_0 is defined such that $\langle a_{\text{DM}}^2 \rangle = g^2 \Delta_{12}^2 a_0^2 / 2$ [21].
 - [20] D. W. Amaral, M. Jain, M. A. Amin, and C. Tunnell, Vector wave dark matter and terrestrial quantum sensors, *J. Cosmol. Astropart. Phys.* **06** (2024) 050.
 - [21] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/16yd-qj5v>, which includes Refs. [22–44].
 - [22] G. P. Centers, J. W. Blanchard, J. Conrad, N. L. Figueroa, A. Garcon, A. V. Gramolin, D. F. J. Kimball, M. Lawson, B. Pelssers, J. A. Smiga *et al.*, Stochastic fluctuations of bosonic dark matter, *Nat. Commun.* **12**, 1 (2021).
 - [23] J. Manley, *Searching for Ultralight Dark Matter with Mechanical Sensors* (University of Delaware, Newark, 2022).
 - [24] R. Catena and P. Ullio, A novel determination of the local dark matter density, *J. Cosmol. Astropart. Phys.* **08** (2010) 004.
 - [25] P. W. Graham, J. Mardon, S. Rajendran, and Y. Zhao, Parametrically enhanced hidden photon search, *Phys. Rev. D* **90**, 075017 (2014).

- [26] E. Gross and O. Vitells, Trial factors for the look elsewhere effect in high energy physics, *Eur. Phys. J. C* **70**, 525 (2010).
- [27] C. Röver, C. Messenger, and R. Prix, Bayesian versus frequentist upper limits, [arXiv:1103.2987](https://arxiv.org/abs/1103.2987).
- [28] D. Baxter, I. Bloch, E. Bodnia, X. Chen, J. Conrad, P. Di Gangi, J. Dobson, D. Durnford, S. Haselschwardt, A. Kaboth *et al.*, Recommended conventions for reporting results from direct dark matter searches, *Eur. Phys. J. C* **81**, 907 (2021).
- [29] L. Lyons, Comments on “look elsewhere effect”, Unpublished manuscript (2010).
- [30] COMSOL AB, Comsol multiphysics® v. 6.2 (2024) <https://www.comsol.com/>.
- [31] J. Gieseler, R. Quidant, C. Dellago, and L. Novotny, Dynamic relaxation of a levitated nanoparticle from a non-equilibrium steady state, *Nat. Nanotechnol.* **9**, 358 (2014).
- [32] W. B. Davenport, W. L. Root, and G. Weiss, *An Introduction to the Theory of Random Signals and Noise* (McGraw-Hill, New York, 1958), pp. 251–257.
- [33] D. Zheng, Y. Leng, X. Kong, R. Li, Z. Wang, X. Luo, J. Zhao, C.-K. Duan, P. Huang, J. Du *et al.*, Room temperature test of the continuous spontaneous localization model using a levitated micro-oscillator, *Phys. Rev. Res.* **2**, 013057 (2020).
- [34] A. T. Land, M. Dey Chowdhury, A. R. Agrawal, and D. J. Wilson, Sub-ppm nanomechanical absorption spectroscopy of silicon nitride, *Nano Lett.* **24**, 7578 (2024).
- [35] C. H. Metzger and K. Karrai, Cavity cooling of a microlever, *Nature (London)* **432**, 1002 (2004).
- [36] A. D. Hyatt, A. R. Agrawal, C. M. Pluchar, C. A. Condos, and D. J. Wilson, Ultrahigh-q torsional nanomechanics through bayesian optimization, *Nano Lett.* **26**, 3784 (2026).
- [37] P. Sadeghi, M. Tanzer, S. L. Christensen, and S. Schmid, Influence of clamp-widening on the quality factor of nanomechanical silicon nitride resonators, *J. Appl. Phys.* **126** (2019).
- [38] S. A. Fedorov, N. J. Engelsens, A. H. Ghadimi, M. J. Bereyhi, R. Schilling, D. J. Wilson, and T. J. Kippenberg, Generalized dissipation dilution in strained mechanical resonators, *Phys. Rev. B* **99**, 054107 (2019).
- [39] F. Xiong, L. Guo, Z. Chen, A. Du, C. Li, and T. Wu, Achievement of a vacuum-levitated metal mechanical oscillator with ultra-low damping rate at room temperature, *Commun. Phys.* **8**, 80 (2025).
- [40] J. Hofer, R. Gross, G. Higgins, H. Huebl, O. F. Kieler, R. Kleiner, D. Koelle, P. Schmidt, J. A. Slater, M. Trupke *et al.*, High-q magnetic levitation and control of superconducting microspheres at millikelvin temperatures, *Phys. Rev. Lett.* **131**, 043603 (2023).
- [41] J. Manley, C. Condos, S. Schlamminger, J. Pratt, D. Wilson, and W. Terrano, Microscale torsion resonators for short-range gravity experiments, *Phys. Rev. D* **110**, 1220 (2024).
- [42] A. Hines, A. Nelson, Y. Zhang, G. Valdes, J. Sanjuan, J. Stoddart, and F. Guzmán, Optomechanical accelerometers for geodesy, *Remote Sens.* **14**, 4389 (2022).
- [43] F. Guzman, L. M. Kumanchik, R. Spannagel, and C. Braxmaier, Compact fully monolithic optomechanical accelerometer, [arXiv:1811.01049](https://arxiv.org/abs/1811.01049).
- [44] A. Nelson, M. Warrayat, J. Dahn, J. Sanjuan, and F. Guzman, A six-axis optomechanical inertial sensing and navigation system for future mass change missions, in *AGU Fall Meeting Abstracts*, Vol. 2024 (American Geophysical Union, Washington, DC, 2024), pp. G11C–3504.
- [45] M. D. Chowdhury, A. R. Agrawal, and D. J. Wilson, Membrane-based optomechanical accelerometry, *Phys. Rev. Appl.* **19**, 024011 (2023).
- [46] This formula is generally valid in the frequency domain, where x_{DM} and a_{DM} are interpreted as Fourier amplitudes at ω_m . In the time domain, it is valid only if $Q_{\text{DM}} \gg Q_m$.
- [47] Here and throughout, we use “ $\sim$ ” to mean “roughly” or “on the order of.”
- [48] T. A. Wagner, S. Schlamminger, J. H. Gundlach, and E. G. Adelberger, Torsion-balance tests of the weak equivalence principle, *Classical Quantum Gravity* **29**, 184002 (2012).
- [49] We note that the Eöt-Wash (EW) torsion-balance experiment [48] and other equivalence-principle tests such as MICROSCOPE [50] probe composition-dependent, DM-mediated forces between SM test bodies, but do not access the temporal coherence of the UDM field. A direct B-L UDM search has been made with the EW balance at sub-Hz frequencies [51].
- [50] J. Bergé, P. Brax, G. Métris, M. Pernot-Borràs, P. Touboul, and J.-P. Uzan, Microscope mission: First constraints on the violation of the weak equivalence principle by a light scalar dilaton, *Phys. Rev. Lett.* **120**, 141101 (2018).
- [51] E. Shaw, M. Ross, C. Hagedorn, E. Adelberger, and J. Gundlach, Torsion-balance search for ultralow-mass bosonic dark matter, *Phys. Rev. D* **105**, 042007 (2022).
- [52] Commercial equipment, instruments, and materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology or the United States government, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.
- [53] E. Planz, X. Xi, T. Capelle, E. C. Langman, and A. Schliesser, Membrane-in-the-middle optomechanics with a soft-clamped membrane at millikelvin temperatures, *Opt. Express* **31**, 41773 (2023).
- [54] The double-membrane cavity finesse $\mathcal{F} \approx 2.2$ is determined by the membrane reflectivity [45] and can be enhanced using photonic crystal patterning [55] or the membrane-in-the-middle approach [56]. Here we operate with low finesse to simplify alignment and analysis of the differential acceleration sensitivity.
- [55] A. Agrawal, J. Manley, D. Allepuz-Requena, and D. Wilson, Focusing membrane metamirrors for integrated cavity optomechanics, *Optica* **11**, 1235 (2024).
- [56] C. M. Pluchar, A. R. Agrawal, and D. J. Wilson, Thermal intermodulation backaction in a high-cooperativity optomechanical system, *Optica* **10**, 1543 (2023).
- [57] E. Gavartin, P. Verlot, and T. J. Kippenberg, A hybrid on-chip optomechanical transducer for ultrasensitive force measurements, *Nat. Nanotechnol.* **7**, 509 (2012).
- [58] A. Pontin, M. Bonaldi, A. Borrielli, F. S. Cataliotti, F. Marino, G. A. Prodi, E. Serra, and F. Marin, Detection of

- weak stochastic forces in a parametrically stabilized micro-optomechanical system, *Phys. Rev. A* **89**, 023848 (2014).
- [59] T. Gisler, D. Halg, V. Dumont, S. Misra, L. Catalini, E. C. Langman, A. Schliesser, C. L. Degen, and A. Eichler, Enhancing membrane-based scanning force microscopy through an optical cavity, *Phys. Rev. Appl.* **22**, 044001 (2024).
- [60] Cold damping does not improve sensitivity [58,61], but reduces nonlinearities and mitigates the effect of spectral diffusion over the course of the measurement [62], especially relevant for high- Q oscillators.
- [61] A. Vinante, M. Bonaldi, F. Marin, and J. Zendri, Dissipative feedback does not improve the optimal resolution of incoherent force detection, *Nat. Nanotechnol.* **8**, 470 (2013).
- [62] E. Gavartin, P. Verlot, and T. Kippenberg, Reply to “dissipative feedback does not improve the optimal resolution of incoherent force detection”, *Nat. Nanotechnol.* **8**, 692 (2013).
- [63] Measurement time $\tau = 800$ s was limited by practical considerations such as the open stability of our laser and the manual procedure for frequency scanning. Future, longer searches will require more stringent stabilization and automation.
- [64] In [34] we observed local photoabsorptive heating as little as 10^{-5} K/ μ W in trampolines of similar dimensions at $\lambda = 850$ nm and room temperature, while in [45,65] we observed modal heating at the level of 10^{-2} K/ μ W. The observed increase in modal heating (0.4 K/ μ W) at 4 K is consistent with a reduction of both radiative and conductive heat transfer in the trampoline [34]; however, the strong dependence of modal heating on temperature profile [66] calls for further investigation.
- [65] C. M. Pluchar, A. R. Agrawal, E. Schenk, and D. J. Wilson, Towards cavity-free ground-state cooling of an acoustic-frequency silicon nitride membrane, *Appl. Opt.* **59**, G107 (2020).
- [66] R. Shaniv, C. Reetz, and C. A. Regal, Direct measurement of a spatially varying thermal bath using Brownian motion, *Phys. Rev. Res.* **5**, 043121 (2023).
- [67] In this work, we adopt a Bayesian framework for limit setting because it allows us to encode physical constraints such as $D > 0$ through the prior [68]. We note, however, that the positivity constraint $D > 0$ can also be enforced straightforwardly within a frequentist framework. In [21] we show that for our Gaussian matched-filter estimator at 95% confidence level, the two approaches yield limits that agree within 10%.
- [68] D. Palken, B. Brubaker, M. Malnou, S. A. Kenany, K. Backes, S. Cahn, Y. Gurevich, S. Lamoreaux, S. Lewis, R. Maruyama *et al.*, Improved analysis framework for axion dark matter searches, *Phys. Rev. D* **101**, 123011 (2020).
- [69] H.-K. Guo, K. Riles, F.-W. Yang, and Y. Zhao, Searching for dark photon dark matter in LIGO O1 data, *Commun. Phys.* **2**, 1 (2019).
- [70] R. Abbott, T. Abbott, F. Acernese, K. Ackley, C. Adams, N. Adhikari, R. X. Adhikari, V. Adya, C. Affeldt, D. Agarwal *et al.*, Constraints on dark photon dark matter using data from LIGO’s and Virgo’s third observing run, *Phys. Rev. D* **105**, 063030 (2022).
- [71] D. W. Amaral, D. G. Uitenbroek, T. H. Oosterkamp, and C. D. Tunnell, First search for ultralight dark matter using a magnetically levitated particle, *Phys. Rev. Lett.* **134**, 251001 (2025).
- [72] The second generation (“Gen 2”) device discussed in the Supplemental Materials [21] uses a modeshape-optimized Si_3N_4 trampoline with $m = 1.5$ μg , $f = 7.3$ kHz, and $Q = 7 \times 10^7$.
- [73] P. Fileviez Perez and M. B. Wise, Baryon and lepton number as local gauge symmetries, *Phys. Rev. D* **82**, 011901 (2010).
- [74] M. Bauer, P. Foldenauer, and J. Jaeckel, Hunting all the hidden photons, *J. High Energy Phys.* **07** (2018) 001.
- [75] We note that over this duration, a DM signal is expected to experience sidereal modulation due to Earth’s rotation, providing a cross-check of its astrophysical origin [20,76].
- [76] A. Caputo, A. J. Millar, C. A. O’Hare, and E. Vitagliano, Dark photon limits: A handbook, *Phys. Rev. D* **104**, 095029 (2021).
- [77] B. M. Brubaker, J. M. Kindem, M. D. Urme y, S. Mittal, R. D. Delaney, P. S. Burns, M. R. Vissers, K. W. Lehnert, and C. A. Regal, Optomechanical ground-state cooling in a continuous and efficient electro-optic transducer, *Phys. Rev. X* **12**, 021062 (2022).
- [78] F. Zhou, Y. Bao, J. Gorman, and J. R. Lawall, Ultrahigh reflectivity photonic crystal membranes with optimal geometry, *APL Photonics* **9**, 076120 (2024).
- [79] Norcada, Inc.
- [80] J. P. Moura, R. A. Norte, J. Guo, C. Schafermeier, and S. Groblacher, Centimeter-scale suspended photonic crystal mirrors, *Opt. Express* **26**, 1895 (2018).
- [81] L. Norder, S. Yin, M. H. de Jong, F. Stallone, H. Aydogmus, P. M. Sberna, M. A. Bessa, and R. A. Norte, Pentagonal photonic crystal mirrors: Scalable lightsails with enhanced acceleration via neural topology optimization, *Nat. Commun.* **16**, 2753 (2025).
- [82] N. J. Engelsens, A. Beccari, and T. J. Kippenberg, Ultrahigh-quality-factor micro- and nanomechanical resonators using dissipation dilution, *Nat. Nanotechnol.* **19**, 725 (2024).
- [83] A. Cupertino, D. Shin, L. Guo, P. G. Steeneken, M. A. Bessa, and R. A. Norte, Centimeter-scale nanomechanical resonators with low dissipation, *Nat. Commun.* **15**, 4255 (2024).
- [84] J. R. Pratt, A. R. Agrawal, C. A. Condos, C. M. Pluchar, S. Schlamminger, and D. J. Wilson, Nanoscale torsional dissipation dilution for quantum experiments and precision measurement, *Phys. Rev. X* **13**, 011018 (2023).
- [85] F. Zhou, Y. Bao, R. Madugani, D. A. Long, J. J. Gorman, and T. W. LeBrun, Broadband thermomechanically limited sensing with an optomechanical accelerometer, *Optica* **8**, 350 (2021).
- [86] N. Bawden, B. J. Carey, P.-M. Yeo, N. Arora, L. Sementilli, V. M. Valenzuela, E. Romero, G. I. Harris, M. Wegener, and W. P. Bowen, Precision optomechanical accelerometer via hybrid test mass integration, Precision optomechanical accelerometer via hybrid test-mass integration, *Phys. Rev. Appl.* **24**, 064008 (2025).
- [87] C. Condos, J. Pratt, J. Manley, A. Agrawal, S. Schlamminger, C. Pluchar, and D. Wilson, Ultralow loss torsion micropendula for chip-scale gravimetry, *Phys. Rev. Lett.* **134**, 253602 (2025).

- [88] C. M. Pluchar, A. R. Agrawal, and D. J. Wilson, Quantum-limited optical lever measurement of a torsion oscillator, *Optica* **12**, 418 (2025).
- [89] D.-C. Shin, T. M. Hayward, D. Fife, R. Menon, and V. Sudhir, Active laser cooling of a centimeter-scale torsional oscillator, *Optica* **12**, 473 (2025).
- [90] L. Sun, B. J. Slagmolen, and J. Qin, Differential torsion sensor for direct detection of ultralight vector dark matter, *Phys. Rev. D* **111**, 063064 (2025).
- [91] Y. Xia, A. R. Agrawal, C. M. Pluchar, A. J. Brady, Z. Liu, Q. Zhuang, D. J. Wilson, and Z. Zhang, Entanglement-enhanced optomechanical sensing, *Nat. Photonics* **17**, 470 (2023).
- [92] M. Khokhar, L. Norder, P. M. Sberna, and R. A. Norte, High-stress Si₃N₄ reflective membranes monolithically integrated with cavity Bragg mirrors, [arXiv:2603.02490](#).
- [93] C. Ge, D. Dominguez, A. Rubenok, M. Miller, and M. Eichenfield, Towards navigation-grade and deployable optomechanical accelerometry, [arXiv:2505.11751](#).
- [94] R. N. Clark, B. Puzio, O. M. Green, S. T. Pradyumna, O. Trojak, A. Politi, and J. C. Matthews, Integrated photonics for continuous-variable quantum optics, *Nat. Photonics* **20**, 489 (2026).
- [95] M. D. Chowdhury and D. J. Wilson, Data used to generate figures in this manuscript, [10.5281/zenodo.20283349](#) (2026).