Cavity-optomechanical broadband searches for scalar wavelike dark matter: Snowmass LOI

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Progress in quantum optomechanics has paved the way for vastly improved searches for wave-like Dark Matter, conceivably within the next decade. In this SNOWMASS LOI, we briefly describe an approach based on differential readout of two ultra-stable optical reference cavities, one rigid and one suspended. A distributed network of such cryogenic, quantum-limited, optical cavities could provide several square decades of improvement in the coupling-strength versus mass parameter space for scalar wavelike Dark Matter.

Although it has been greatly successful in describing most of fundamental forces of nature and the elementary particles to high precision, the Standard Model is still lacking an explanation of several basic phenomena in our universe. Despite overwhelming evidence for the existence of Dark Matter (DM), its composition and non-gravitational interaction with Standard Model fields and particles remain unknown [1–4]. One well-motivated set of dark matter candidates are virialized ultralight fields, which are a type of wave-like Dark Matter [5, 6]. These ultralight (masses below ~ 10 eV) bosonic fields that can be best understood as coherently oscillating waves as opposed to individual particles. Natural production mechanisms for wavelike DM exist based on cosmic inflation, furthermore making the search for wavelike DM an opportunity to learn about early-universe cosmology. Ultralight scalar fields such as dilatons and moduli are an especially well-motivated class of wavelike DM, as they naturally arise in string theory [7]. These ultralight fields can lead to temporal oscillations fundamental constants like the fine structure constant or the electron mass. The oscillation occurs at the Compton frequency associated with the characteristic mass of the field [8]. This oscillation can result in an oscillation of the atomic Bohr radius, and thus the size of atoms. This can produce a small time-varying strain signal in material objects.

On timescales short compared to the DM coherence time, the DM field can be expressed as

$$\phi(t,\mathbf{r}) \approx \frac{\hbar}{m_\phi c}\sqrt{2\rho_{\rm DM}}\cos\left[2\pi f_\phi t - \mathbf{k}_\phi\cdot\mathbf{r} + ...\right], \tag{1}$$

where $\rho_{\rm DM} \approx 0.4\,{\rm GeV/cm^3}$ is the local DM energy density, m_ϕ is the mass of the DM field, $f_\phi = m_\phi c^2/(2\pi\hbar)$ is Compton frequency, and $k_\phi = m_\phi v/\hbar$ with v being the velocity of DM with respect to the instrument. A detailed discussion can be found in Ref. [9].

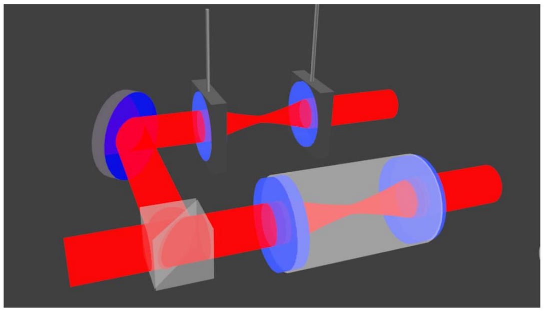

FIG. 1. A laser probes the resonant frequencies of two cavities. VULF dark matter oscillating the length of a rigid laser cavity in the audio frequency range (0.1-10 kHz) will change its resonance frequency with respect that of a suspended-mirror cavity that cannot change this rapidly.

In the dilaton-like models, DM drives oscillations of the electron mass and fine structure constant,

$$\frac{\delta m_e(t,\mathbf{r})}{m_{e,0}} = d_{m_e}\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r})\,, \tag{2}$$

$$\frac{\delta\alpha(t,\mathbf{r})}{\alpha_0} = d_e\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r})\,. \tag{3}$$

Here d_{m_e} and d_e are dimensionless dilaton couplings and $E_P \equiv \sqrt{\hbar c^5/G}$ is the Planck energy. These effects could be searched for with atomic

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clocks and interferometers [10, 11], however, due to the finite interrogation time, they are limited to Compton frequencies of order 1 Hz and below. At higher frequencies, DM-induced strain in solids is a promising approach [12].

As a method to detect this strain, it has been proposed that light from a common laser can be directed into two Fabry-Perot resonators, one with suspended mirror substrates and one with a rigid cavity spacer [13]. Modulation in e.g. the electron mass due to dilatonic DM at the 0.1-10 kHz frequency range results in periodic length changes in the rigid cavity, while the DM-induced length changes in the suspended interferometer are suppressed by the low frequency mechanical suspension.

Operating at cryogenic temperatures reduces thermal noise, in the cavity mirror substrates and coatings, as well as in the cavity spacers and suspension systems, allowing quantum-limited (photon shot noise) detection to be achieved at high frequencies. At high frequencies we expect the cavity length measurement will be limited by photon shot noise. This quantum noise can be reduced with increased cavity probe laser power, but one must balance this against the resulting unwanted heating of the mirrors. The improved measurement imprecision from a more precise phase measurement of an intense laser will be spoiled by quantum backaction from greater intensity fluctuations of the light, i.e. the Standard Quantum Limit (SQL). Measurement better than the SQL is possible using techniques including backaction evasion and squeezing. Quantum squeezing of the light that interrogates the cavities can be explored to push beyond the standard quantum limit to further enhance the sensitivity, as has been previously done in LIGO [17]. Additionally, a promising approach is to use a subluminal laser instead of a suspended cavity as the length reference. A subluminal laser (enabled by Raman gain in ^{85}Rb vapor and demonstrated recently [18]) can be made highly insensitive to cavity length change, by a factor as much as a hundred million, and can be implemented as the reference arm. This method has the potential to reduce technical complexity and noise associated with a suspension system.

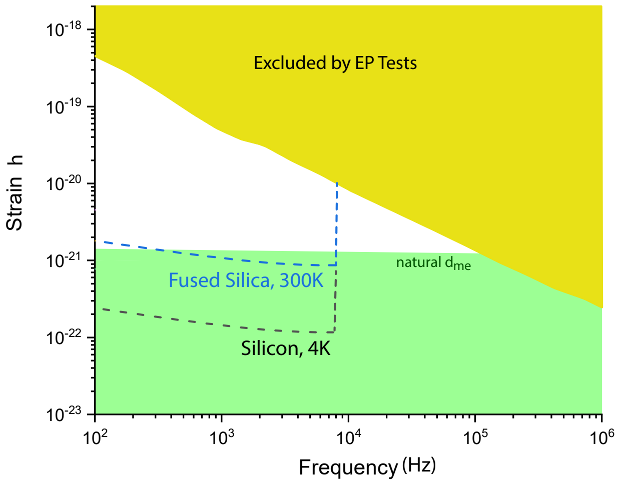

FIG. 2. Strain sensitivity of a 30 cm cavity pair limited by thermal noise vs. dark matter (DM) Compton frequency for a 10^7 s integration time, for an averaging time τ that scale as $\tau^{-1/2}$ up to the coherence time of the DM field ($\sim 10^6$ oscillations), and as $\tau^{-1/4}$ thereafter. The yellow area is excluded by equivalence principle bounds [14, 15]. The green region is considered theoretically natural for an electron Yukawa modulus [16].

Fig. 2 illustrates the advantage that can be attained at 4K as compared with room temperature. Several square decades of parameter space for ultralight Dark matter can be explored with the estimated sensitivity of a 30 cm cavity apparatus. A distributed network of cryogenic, quantum-limited, optical cavities would make an even more powerful approach for wavelike scalar DM, being able to search for spatial dependence, temporal coincidence and to further suppress background effects, as well as open the possibilty of detecting transient DM effects. Finally we note that other optomechanical accelerometer based searches have been proposed which are sensitive to vector DM [19], and these would provide a complementary technique for vector-like wavelike DM search for ultralight DM at frequencies from 1 kHz – 100 kHz, as reported in a different Snowmass LOI [20].

[1] J. L. Feng, Dark Matter Candidates from Particle Physics and Methods of Detection, Ann. Rev. Astro. Astrophys. **48**, 495 (2010).

[2] G. Bertone, D. Hooper, and J. Silk, Particle dark matter: evidence, candidates and constraints, Phys. Rep. **405**, 279 (2005).

[3] S. Profumo, *An Introduction to Particle Dark Matter* (World Scientific, 2017).

[4] A. Derevianko and M. Pospelov, Hunting for topological dark matter with atomic clocks, Nature Physics **10**, 933 (2014).

[5] A. A. Geraci, C. Bradley, D. Gao, J. Weinstein, and A. Derevianko, Searching for ultralight dark matter with optical cavities, Phys. Rev. Lett. **123**, 031304 (2019).

[6] M. S. Safronova, D. Budker, D. DeMille, D. F. J. Kimball, A. Derevianko, and C. W. Clark, Search for new physics with atoms and molecules, Rev. Mod. Phys. **90**, 025008 (2018).

[7] S. Dimopoulos and G. Giudice, Macroscopic forces from supersymmetry, Physics Letters B **379**, 105 (1996).

[8] T. Damour and J. F. Donoghue, Equivalence principle violations and couplings of a light dilaton, Phys. Rev. D **82**, 084033 (2010).

[9] A. Derevianko, Detecting dark-matter waves with a network of precision-measurement tools, Phys. Rev. A **97**, 042506 (2018).

[10] A. Arvanitaki, J. Huang, and K. Van Tilburg, Searching for dilaton dark matter with atomic clocks, Phys. Rev. D **91**, 015015 (2015).

[11] A. A. Geraci and A. Derevianko, Sensitivity of atom interferometry to ultralight scalar field dark matter, Phys. Rev. Lett. **117**, 261301 (2016).

[12] 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).

[13] A. A. Geraci, C. Bradley, D. Gao, J. Weinstein, and A. Derevianko, Searching for ultralight dark matter with optical cavities, Phys. Rev. Lett. **123**, 031304 (2019).

[14] S. Schlamminger, K.-Y. Choi, T. A. Wagner, J. H. Gundlach, and E. G. Adelberger, Test of the equivalence principle using a rotating torsion balance, Phys. Rev. Lett. **100**, 041101 (2008).

[15] T. A. Wagner, S. Schlamminger, J. H. Gundlach, and E. G. Adelberger, Torsion-balance tests of the weak equivalence principle, Classical and Quantum Gravity **29**, 184002 (2012).

[16] 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).

[17] J. Aasi, J. Abadie, B. Abbott, R. Abbott, T. Abbott, M. Abernathy, C. Adams, T. Adams, P. Addesso, R. Adhikari, *et al.*, Enhanced sensitivity of the ligo gravitational wave detector by using squeezed states of light, Nature Photonics **7**, 613 (2013).

[18] J. Yablon, Z. Zhou, N. Condon, D. Hileman, S. Tseng, and S. Shahriar, Demonstration of a highly subluminal laser with suppression of cavity length sensitivity by nearly three orders of magnitude, Opt. Express **25**, 30327 (2017).

[19] 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).

[20] S. Singh *et al.*, Snowmass LOI 2020, to appear.