Mechanical sensors as particle detectors: Snowmass LOI

Groups of Daniel Carney,* Gordan Krnjaic, Rafael F. Lang, Zhen Liu, Joseph Lykken, David C. Moore, Raphael Pooser, Cindy Regal, Martin Spinrath, and Jacob M. Taylor

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Ultra-high-precision mechanical sensors, operating in both the classical and quantum regimes, have been demonstrated with exquisite sensitivity to feeble signals like gravitational waves. In this SNOWMASS LOI, we discuss a development pathway toward using a large number of these devices in an array to search for dark matter and other particle physics targets. This scalable detection approach can provide exquisite directional sensitivity and low energy thresholds. In the near term, these techniques will enable searches for ultra-light bosonic dark matter candidates and composite, WIMP-scale objects. As a long-term goal, this approach can enable the direct detection of heavy dark matter through gravity alone.

I. INTRODUCTION

Recently, a number of authors have studied the use of mechanical sensing technologies as a novel detection strategy in particle physics, including dark matter [1] and neutrino physics [2, 3]. These sensors consist of a mechanical element like a suspended or levitated mass continuously monitored by optical or microwave light [4–6]. The prototypical example is the LIGO gravitational wave detector [7]. Increasingly, these devices are operated in the quantum-limited regime, where the sensitivity is set by noise caused by Heisenberg uncertainty [8]. These systems can be scaled in both the mass of an individual sensor and the total number of devices, enabling exquisite sensitivity to extremely weak forces. Because one is monitoring many atoms in aggregate (e.g. the center-of-mass motion of a nanogram-scale object), these devices offer particular advantages to the detection of signals which are coherent over distances $\gtrsim 1\ \mu$m. Moreover, the mechanical state can be monitored along multiple axes, enabling robust directional sensitivity.

As a long-term goal, an array of many mechanical sensors can thus provide a low-threshold, direction-dependent detector for a variety of particle physics targets that elude current detection schemes. For example, mechanical sensors could be used to search for heavy dark matter candidates ($m \sim m_{Pl}$, the Planck mass) *purely through their gravitational interactions with the standard model* [9]. Such an experiment would enable us to detect or exclude any sufficiently heavy dark matter candidate, in a regime that cannot be probed directly otherwise. This requires an array of a large number of sensors, each of large mass and operating at noise levels deep in the quantum-limited regime, and searching for "tracks" of small displacements of the sensors. To realize such a detector in practice, substantial R&D is needed, in both single-sensor sensitivity and coordinated operation of a large number of devices. However, many particle physics opportunities are open along the path to this target. A number of experiments which can be viewed as first-generation pathfinders, capable of novel dark matter searches, are already operating [10] or are in development [11, 12], with targets including ultra-light bosonic dark matter and WIMP-scale composite objects.

Developing and deploying mechanical quantum sensors for dark matter detection will necessarily involve deep collaboration between theorists and experimentalists from the particle physics, quantum sensing, and gravitational wave communities. We expect work will at first be based around smaller groups, with larger-scale, multiple-investigator collaborations a crucial component of longer-term developments.

* E-mail: carney@umd.edu

II. R&D PATHWAY

At the level of a single sensor, the fundamental technical noise floor is determined by interactions with the thermal environment and noise added by the quantum mechanics of measurement itself. At present, various "standard quantum limits" (SQL) serve as a benchmark, typically representing the ability to resolve a signal at the scale of vacuum fluctuations of the mechanical element [8]. Detecting some of the minute energy depositions required for novel detection, for example the gravitational field of a passing heavy DM particle, will require going to noise levels substantially below the SQL [9]. Numerous techniques for this exist in theory [8, 13] and practice [14–16]. A key R&D goal for the application to particle physics will be the demonstration of these techniques optimized to the relevant problem, namely the detection of sharp, weak impulses [17], a domain typically outside of current investigation as it focuses on force rather than position measurement.

Operation of multiple mechanical sensors in an array presents a unique set of challenges and opportunities [1]. The practical challenges of choosing a specific sensor architecture, array geometry, and readout scheme are still open. Development of a detector analysis framework, especially real-time data processing and track identification, is underway. Understanding correlations between sensors is crucially important and requires work both experimentally and in simulation. All of these issues are the subject of current work. In particular, the *Windchimes* collaboration (Purdue, Oak Ridge, Fermilab, Maryland) is pursuing the construction of an array of tens of mechanical accelerometers as a testbed system for these issues.

Various issues of single-sensor sensitivity and integration of multiple sensors are being pursued in parallel by independent groups. If these pathfinder efforts prove successful, the next logical step is to demonstrate an array of state-of-the-art devices. Given that currently available individual sensors are already capable of producing novel limits on particular dark matter candidates [10–12], we anticipate that such an array will be able to provide substantial value as a multipurpose dark matter detector. Development in these low-noise, lab-scale efforts will certainly dovetail with space-based experiments [18] and gravitational wave detectors .

III. FUNDAMENTAL PHYSICS TARGETS

At present, the dark matter sector provides the best-studied examples of detection targets with mechanical sensing technologies. More theoretical input is needed to fully explore the landscape of possible new physics objectives. To give a sense of the breadth of detection reach with these devices, we highlight here a pair of dark matter targets in completely different energy ranges.

Mechanical acceleration sensors are poised to contribute immediately to searches for ultra-light dark matter candidates, especially those with masses around $10^{-16} - 10^{-7}$ eV, corresponding to frequencies in the Hz-GHz range [12, 19]. This would provide a complement to searches coming online with large-scale atom interferometers [20, 21], which are ideally suited to sub-Hz signals. As these models produce signals coherent over very long distances $\gtrsim 1$ m, a large number N of sensors in an array can be used, leading to improvements in the signal to noise growing like $\sqrt{N}$. Furthermore, temporal correlations between the sensors can be used to provide directional information.

As mentioned previously, mechanical sensing has already been demonstrated in a search for heavier ($m_\chi \gtrsim 1$ GeV), composite dark matter models coupled to the standard model through a long-range force, using just a single levitated sensor [10]. This sensing problem is a prototype for the gravitational detection problem. The example here shows that there is a continuous parameter space to search between what is currently accessible and the ultimate, gravitationally-coupled limit. In particular, once multiple devices can be used in tandem to search for the "tracks" of these dark matter candidates, the detector will have complete directional information. This will enable searches for a wide swath of models, as well as providing robust background rejection.

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