Optically levitated sensors for precision tests of fundamental physics Snowmass LOI

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We normally think of large accelerators and massive detectors when we consider the frontiers of elementary particle physics, pushing to understand the universe at higher and higher energy scales. However, several tabletop low-energy experiments are positioned to discover a wide range of new physics beyond the Standard model, where feeble interactions require precision measurements rather than high energies. In high vacuum, optically-levitated dielectric nanospheres achieve excellent decoupling from their environment, making force sensing at the zeptonewton level (10-21 N) achievable. In this SNOWMASS LOI we briefly describe several applications of these sensors for tests new physics, including testing the Newtonian gravitational inverse square law at micron length scales, searching for gravitational waves, searching for millicharged particles, and searching for Dark Matter.

Optically levitated dielectric objects in ultra-high vacuum exhibit an excellent decoupling from their environment, making them highly promising systems for precision sensing and quantum information science. In particular, the center of mass modes of optically-trapped silica nanospheres have exhibited high mechanical quality factors in excess of 10^7 [1] and zeptonewton (10^{-21} N) force sensing capabilities [2]. Such devices make promising candidates for sensors of extremely feeble forces [3], accelerations [4–6], torques [7], and rotations [8–10], testing foundational aspects of quantum mechanics [11], observing quantum behavior in the vibrational of modes of mechanical systems [12–14], and tools for quantum information science perhaps especially when coupled to other quantum systems [15]. One specific fundamental physics experiment enabled by optically trapped dielectric nanoparticles is to search for micron-scale deviations from Newtonian gravity [3]. There is a vast 16 order of magnitude disparity between the apparent energy scale of quantum gravity, and that of the other Standard Model (electro-weak) forces. However, as a number of recent theories have suggested, important clues related to this "hierarchy problem" can be obtained in low-energy experiments, by measuring how gravity behaves at sub-millimeter distances [16, 17]. But the gravitational force between massive objects becomes weak very rapidly as their size and separation distance decreases, thus making ultra-precise measurements a necessity at sub-millimeter length scales. Previous experiments have employed sensitive torsion balances [18], cryogenic microcantilevers [19], and torsional oscillators [20]. Trapped spheres can function as a test mass held using optical radiation pressure near the surface of an end mirror of an optical cavity. Non-Newtonian Gravity-like forces and Casimir forces can be tested by monitoring the motion of the sphere as a gravitational source mass is brought behind the cavity mirror. Other approaches involving an optical levitation trap are also being investigated [21]. Several orders of magnitude of improvement is possible in the search for new gravity-like forces at the micron distance scale due to the sensitivity of the technique. Fig. 1 shows the potential reach along with theoretical predictions for new fifth forces that are Yukawa-type corrections to gravity at short distance scales using spheres of sizes 300 nm and 20 μm, currenently being investigated at Northwestern [22]and Yale [21], respectively.

The extreme force sensitivity made possible by optical levitation lends itself to the search for weak astrophysical signals, including feeble strain signals from Gravitational waves or impulses from passing Dark Matter. One of the most interesting sources of Gravitational waves in the high-frequency regime arises from physics Beyond the Standard Model. The QCD axion is a well-motivated dark matter candidate that naturally solves the strong CP problem in strong interactions and explains the smallness of the neutron's electric dipole moment [30–33]. The Compton wavelength of the QCD axion with axion decay constant $f_a \sim 10^{16}$ GeV (at the Grand-Unified-Theory

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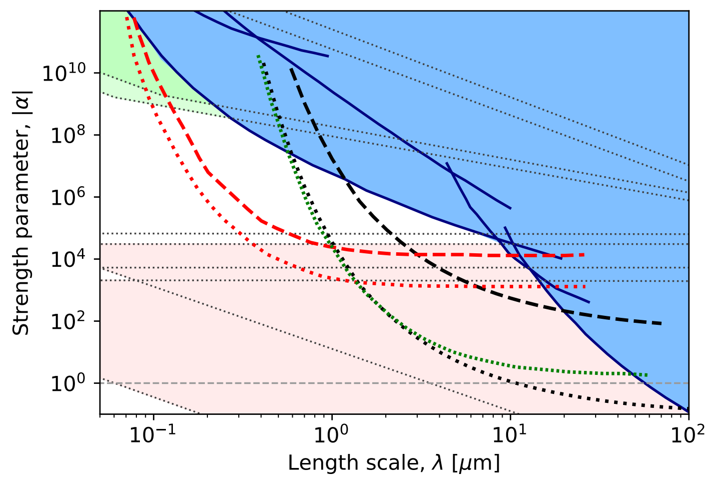

FIG. 1. Background free sensitivity projections to deviations from Newton's law for example optically levitated masses. Existing limits are denoted by the blue region [23–25], with allowed theory regions in a selection of models denoted in red and green [26]. The black dashed line shows the projected sensitivity for a 20 μm diameter sphere at the best currently demonstrated sensitivity for a sphere of this size [27] for a 10^5 s integration, assuming no backgrounds. The black dotted line shows the corresponding sensitivity at the Standard Quantum Limit. The red dashed/dotted lines show the current/future sensitivity possible for a nanosphere with diameter of 300 nm [28]. The green dotted line shows the projected sensitivity for a matter wave interferometer employing 13 nm diameter spheres [29].

[GUT] energy scale) matches the size of stellar mass BHs and allows for the axion to bind with the BH "nucleus," forming a gravitational atom in the sky. A cloud of axions grows exponentially around the BH, extracting energy and angular momentum from the BH [34, 35]. Axions in this cloud produce gravitational radiation through annihilations of axions into gravitons. For annihilations, the frequency of the produced GWs is given by twice the mass of the axion: $f = 145$ kHz, which lies in the optimal sensitivity range for optically leviated sensors when f_a is around the GUT scale. The signal is coherent, monochromatic, long-lived, and thus completely different from all ordinary astrophysical sources. The fraction of the BH mass the axion cloud carries can be as high as 10^{-3} [35], leading to strain signals detectable within the sensitivity band of optically levitated sensors [36].

Dark matter can also be detected by observing the interaction of passing massive particles with the levitated nano-objects. For example, a recent search has been performed for composite dark matter particles scattering from an optically levitated nanogram mass, cooled to an effective temperature $\sim$200 μK [21].

Finally, levitated objects have a long history in testing the neutrality of matter and searching for fractionally charged particles. Ashkin first proposed the use of optically levitated spheres to perform a modern, ultra-sensitive version of the Millikan experiment in 1980 [37], and as described above, results of such an experiment were first reported in 2014 [38].

Advances in sensitivity made possible by pushing the sensitivity of these sensors into the quantum regime along with improved understanding and mitigation of systematic effects due to background electromagnetic interactions such as the Casimir effect and patch potentials will enable several orders of magnitude of improvement in the search for new physics beyond that Standard model.

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