Snowmass2021 - Letter of Interest

Mechanical tests of the gravity-quantum interface

Thematic Areas: (check all that apply ☐/■)

■ (RF3) Fundamental Physics in Small Experiments
■ (IF1) Quantum Sensors

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Abstract:

Mechanical oscillators, ranging in mass from picograms to kilograms, have now been realized in a regime where the quantum fluctuations of their position are observable. This development represents a more than 4 orders of magnitude improvement in the displacement sensitivity of any object over the past decade. Further extension of this capability, to significantly smaller masses, or to better precision at intermediate masses, possibly in conjunction with quantum metrology techniques, holds promise for a host of small-scale tests of the gravity-quantum interface, a de facto BSM scenario. Here we collect some ideas being experimentally pursued within the field of cavity optomechanics with the aim of fostering links between the high-energy physics and precision quantum measurement communities.

Mechanical oscillators have been central to the study of gravity in the classical regime: low frequency torsion pendula have been used for precise measurements of the Newtonian gravitational constant [1], tests of the equivalence principle [2], and of the inverse square law of Newtonian gravity [3]. All such experiments have been limited by spontaneous thermal displacement fluctuations of the oscillator. Over the past decade, mesoscopic mechanical oscillators have been the subject of displacement measurements that are able to resolve the oscillator's zero-point ("vacuum") fluctuations (see Figure 1). This has been driven by the integration of ideas and tools from disparate fields such as gravitational-wave detection, quantum optics, nanomechanics, quantum metrology, and atomic physics [4–6]. In doing so, state of the art experiments [7–9] have resolved the zero-point motion of nanomechanical oscillators with an imprecision that is more than 40 dB below that at the standard quantum limit (SQL); more than 6 orders of magnitude better (where comparable, in units of zero-point motion) than torsion pendulum experiments. It is now ripe to deploy *quantum measurements* of mechanical oscillators to investigate questions at the interface of gravity and quantum mechanics, a de facto BSM scenario.

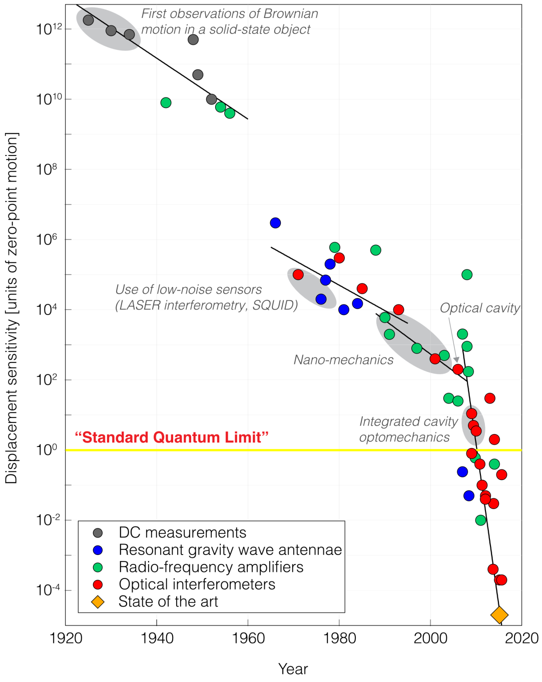

Figure 1: State of the art in displacement sensitivity of mechanical oscillators. At present, it is possible to resolve the quantum fluctuations (zero-point motion) of a solid state nanomechanical oscillator with an imprecision $\gtrsim$ 40 dB below that at the standard quantum limit.

Precision mechanical experiments to test several BSM scenarios have been proposed, and are in various stages of experimental development:

- **Precision tests of Newtonian gravity:** The smallest source mass with which Newtonian gravity has been tested is of the order of $\sim$ 100 g [10]; cavity-enhanced displacement measurements may allow source masses to be significantly smaller ($\sim 10^{-3}$ g). This capability can check systematic uncertainties in the measurement of the gravitational constant — the most imprecisely known fundamental constant [11] — that arise from density and shape inhomogeneities in large source masses [10]. Experimental advance to realize a milligram scale mass optomechanical system with the required displacement sensitivity has been rapid [12].

- **Gravitational entanglement and decoherence:** Experiments with mesoscopic objects that source gravity have the potential to test whether gravity is quantum [13, 14]. As Feynman argued [15], by preparing mesoscopic source masses in a quantum superposition, either their gravitational fields must also exist in a quantum superposition (see also [16]), certifying that gravity is quantum, or, if not, quantum mechanics must be modified at macroscopic scales. If indeed gravity is quantum, it can also be the agent of decoherence that prevents large masses from being prepared in quantum superpositions [17–22]. Experiments with larger masses, that are levitated so as to be free of extraneous decoherence mechanisms, have demonstrated that they can be measured in a quantum-noise-limited fashion [23, 24]. A distant goal of this research is to perform interference experiments on quantum superpositions of large masses to test gravity's relation with quantum mechanics [25–28]. The scale of these effects roughly scale as, $(M/M_P)^2$, where M is the mass of the mechanical oscillator, and $M_P \approx 22\,\mu$g is the Planck mass. In this sense, neutron interference experiments in earth's gravity have been verified to be consistent with the predictions of quantum theory [29, 30].

- **Tests of Planck-mass-scale physics:** Various quantum gravity scenarios, accommodating a minimal length scale, call for modifications of the quantum mechanical canonical commutation relations [31, 32]. Applied to a mechanical oscillator, these take the form of a mass-dependent deformation of the uncertainty principle, $\Delta x\, \Delta p \geq (\hbar/2)[1+\beta(\Delta p/M_P c)^2]$, that scales with the ratio $(M/M_P)^2$. Pulsed optical measurements to perform high-precision quantum state tomography can access this deformation [33]; however, the prevalence and precision of continuous measurements have already begun to set stringent limits on these kinds of modifications [34, 35].
- **Quantum vacuum in non-inertial frames:** Just as non-inertial motion in classical physics leads to apparent forces, quantum mechanics in non-inertial frames call for apparent quantum fluctuations of the vacuum [36, 37]. When the non-inertial motion is gravitational free-fall, the effect is that of Hawking radiation [38], whereas in a uniformly accelerated frame, this leads to the Unruh effect [39]. Analog simulations of both effects have been experimentally investigated [40, 41], however, a direct measurement of either remains elusive. The depolarization of electron bunches in storage rings is consistent with the Unruh effect [42, 43]. Table-top single-particle experiments will provide a controlled systemic-free arena to study the Unruh effect, and through it, quantum field theory in a non-inertial frame. By the equivalence principle, this may provide hints about quantum fields on curved backgrounds.

The effects described above issue from fundamental questions about gravity, or the gravity-quantum interface. Thought experiments and theoretical proposals to test this crucial seam in physics which have been proposed over the past half a century now stand within experimental grasp, largely owing to the advent of quantum-noise-limited measurements of mesoscopic mechanical oscillators. (Quite analogous to mechanical searches for dark matter [44].) Deeper interaction between the high-energy physics community and the quantum metrology/quantum optics community will hasten progress, and identify new conceptual links that remain undiscovered.

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