

Laboratory experiments in quantum gravity: Snowmass LOI

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Progress in the quantum readout and control of massive mechanical devices may enable a first generation of experiments probing the gravitational interaction in the quantum regime, conceivably within the next decade. In this SNOWMASS LOI, we briefly outline the possibilities and challenges facing the realization of these experiments. We then emphasize the need for a more robust understanding of the quantum theory of gravity in the IR regime ($E/L^3 \ll m_{\text{Pl}}/\ell_{\text{Pl}}^3$) in which these experiments operate, and relations to possible UV completions.

Moving forward into the 21st century, three broad paths to experimental quantum gravity have begun to open. Cosmological probes will continue to improve in sensitivity, offering new insights on gravity at the inflationary scale [1]. Simulation of models of quantum gravity like AdS/CFT on quantum computers offers the exciting possibility of non-perturbative insight [2, 3]. However, information from cosmology will necessarily be circumstantial and model-dependent (in particular, current observations can be mimicked by classical physics [4]). Quantum simulations of models or gravitational duals would give highly non-trivial information about the models or the nature of the AdS/CFT duality itself, but ultimately will still be simulations, incapable of directly probing the physical gravitational field. Thus, gaining information from physical, non-simulated, controllable laboratory experiments would provide a third and crucial component to the dawning era of experimental quantum gravity.

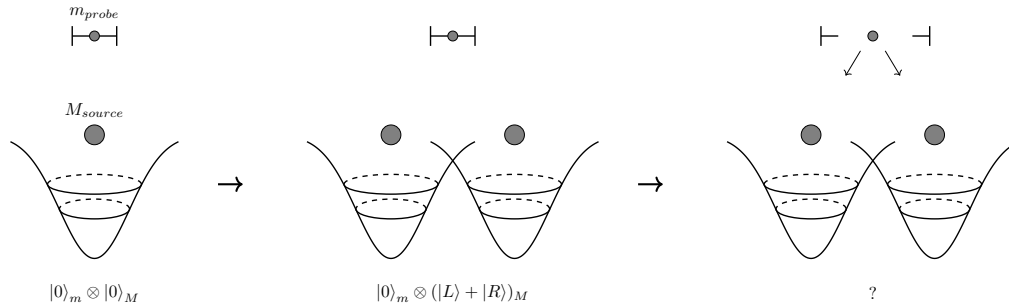
In recent years, building on foundational conceptual proposals [5, 6] and the classic experiment of Page and Geiker [7], a number of authors have discussed the idea of performing such lab-scale experiments to probe key questions about the quantum nature of gravity (see e.g. [8] for a review and extensive citations). The core question these experiments aim to answer is whether perturbatively quantized general relativity, viewed as an effective quantum field theory [9, 10], is the correct theory of nature at low energies. A number of alternative scenarios have been proposed. These include models involving the gravitational breakdown of quantum mechanics [11, 12], semiclassical models [13–15], models of gravity as an emergent force [16, 17] and ideas about holographic effects in the infrared [18]. Experiments which are conceivably realizable within the next decade can make decisive statements about these issues.

Clearly, any such experiment will be very difficult. In section I, we sketch the basic concepts for these experiments and discuss the central challenges to their realization. However, another crucial step will be translating the experimental results into statements which apply to models and basic concepts at the level of the fundamental theory. For example, to what extent do these experiments test for the existence of the graviton? Can they tell us anything about the emergent nature of gravity? Can precise models and calculations be formulated to describe scenarios beyond the EFT paradigm? In section II, we discuss some known theoretical results and open directions.

I. IDEALIZED EXPERIMENTS AND PATH TO REALIZATION

Broadly speaking, two classes of experiments have been proposed. Experiments in the first class look for anomalous sources of noise, heating, or decoherence in a single object. The basic question is to see if the rate of decoherence of the system is consistent with standard quantum mechanics (including the inevitable coupling to usual ambient baths, like gas particles in the lab). Examples include searches for anomalous decoherence and heating in mechanical systems [19, 20]

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and for noise acting on the light in a laser interferometer [21, 22]. In the second class, the goal is to prepare a non-classical state of a massive “source” system, and allow a second “test mass” system to respond to the resulting gravitational field (see figure). These experiments test the ability of the gravitational interaction to generate entanglement. Proposals in this class have been presented using mechanical resonators [23] and macroscopic superpositions of levitated nanoparticles read out with internal spins [24].

These experiments will be extremely challenging. They require the detection of effects induced by the extremely weak gravitational coupling in systems prepared in delicate quantum states. Achieving these goals will thus require substantial development in the quantum state preparation and readout in massive mechanical systems. A significant challenge in these experiments will be to avoid other non-gravitational interactions and other external environmental perturbations. However, progress in all of these areas continues to proceed quite rapidly, and there is good reason to believe some first generation experiments can come online within the next ten to twenty years.¹ It is thus an opportune time to develop a deeper understanding of fundamental gravitational theory applicable to these experiments, as discussed in the next section.

II. THEORETICAL LANDSCAPE AND OPPORTUNITIES

The concrete questions addressed directly by the experiments are essentially: Can objects maintain quantum coherence for extended times? Can the gravitational interaction be used to generate entanglement between systems? A crucial challenge will be translating the answers to these experimental questions into statements which apply to models of low-energy quantum gravity.

For a theorist following the general ideology of effective field theory [9, 10], a central question is to what extent these experiments can prove the existence of the graviton. There are thought experiments showing that if gravity can entangle a pair of objects, but does not have propagating quantized fluctuations, then severe problems with causality can arise [27]. This strongly suggests that demonstration of gravitational entanglement generation would imply the graviton, but a more robust understanding of this question would be desirable.

There are also more phenomenological questions that can be addressed. In the context of gravity as an emergent force [16, 17], these experiments should be able to distinguish between various detailed realizations, but this question is relatively understudied at present. Numerous models in which gravity somehow causes a breakdown of quantum mechanics or anomalous decoherence [11, 12] could also be addressed; formulating these ideas in self-consistent, relativistic models would be highly instructive. Finally, some authors have speculated that the holographic principle could have observable consequences at these low energy scales [18, 21]. Precise, calculable predictions (perhaps in the context of AdS/CFT) would be invaluable [28].

¹ These experimental developments will also enable substantial new detection reach for more traditional particle physics targets. See [25] for a review, or the related LOI [26]

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