Snowmass 2021 Letter of Interest: Opportunities in Gravitational Physics

Giorgio Gratta[1], Jason Hogan[1], Brian Lantz[1], Monika Schleier-Smith[1], and Ariel Schwartzman[2]

[1]*Stanford University; Stanford, California 94305, USA*
[2]*SLAC National Accelerator Laboratory; Menlo Park, California 94025, USA*

August 2020

Thematic areas:

- (CF7) Cosmic Probes of Fundamental Physics
- (IF1) Quantum Sensors
- (TF10) Quantum Information Science

Contact Information:
Jason Hogan, Stanford University (hogan@stanford.edu)
Ariel Schwartzman, SLAC National Accelerator Laboratory (sch@slac.stanford.edu)

Abstract: During the last decade, spectacular advances in theory, metrology, quantum sensing and quantum information science, atomic physics, and material science, have enabled new experimental probes of gravity. From a broad perspective, gravity offers a unique window to explore the cosmos, search for physics beyond the Standard Model at much higher energies than those that can be reached at particle colliders, and gain deep insights on the fundamental nature of gravity and quantum mechanics. Examples include the full exploration of the gravitational wave spectrum, the search for new long-range forces at the micron scale, and the possibility to simulate quantum gravity in the laboratory. Exploiting the exciting scientific opportunities enabled by gravitational physics may significantly enhance the scope and reach of the High Energy Physics portfolio.

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1 Introduction

This letter of interest aims at highlighting the rich and exciting science opportunities related to gravity that may be of interest to the broad particle physics community. Such opportunities rely on spectacular advances over the last decade in quantum science (sensing, networks and computing), lasers, atomic clocks and sensors, and material science. Gravity experiments offer new and powerful ways to study the cosmos and probe fundamental physics. As the gravity physics community moves towards larger, more complex, experiments, it may benefit greatly from collaboration with US national labs and the particle physics community. For example, technical expertise related to accelerator design, such as ultra-high vacuum and magnetic field engineering, as well as operational experience coordinating large-scale international projects, is widely applicable to a variety of gravity-focused experimental efforts.

2 Gravitational waves

The direct detection of gravitational waves by LIGO is the beginning of a new era in astronomy [1–3]. Gravitational wave astronomy can provide information about astrophysical systems and cosmology that is difficult or impossible to acquire by other methods. Just like with electromagnetic waves, there is a wide spectrum of gravitational wave signals that must be explored to fully take advantage of this new source of information about the universe. LIGO and other terrestrial detectors are sensitive to gravitational waves between about 10 Hz and a few kilohertz [4, 5] while LISA is targeted at the 0.1 mHz - 100 mHz range [6, 7].

The "mid-band" between these two ($\sim$ 30 mHz to 10 Hz) is also scientifically rich and there is an opportunity to fill this gap using atomic sensors [8, 9]. In the near term, significant opportunities remain to move beyond the performance of the LIGO A+ and the Advanced Virgo+ detectors. In the medium and long term, third generation large facilities of 10 km–40 km in size will significantly expand the sensitivity and reach of gravitational wave detectors. Potential synergies with DOE national labs and particle physics expertise include the development of larger UHV vacuum systems, active alignment systems for large precision facilities, new materials for mirror coating that can reduce the coating thermal noise, and low-temperature science with high cooling rates and low vibration such as low-vibration cyro-coolers, low-vibration heat transport and low temperature vibration sensors. In the longer term, long-baseline atomic experiments promise to enable the exploration of the mid-band range of the GW spectrum. This frequency range will allow observation of white dwarf (WD) binary mergers, heavier black holes mergers, and cosmological signals such as those from the electroweak phase transition or cosmic strings. Scaling up existing atom sensing technology to very long baselines (thousand of kilometers) will benefit from particle physics and accelerator physics expertise in the construction, alignment, monitoring, operation, and data analysis of large, complex, instruments.

3 Search for new long-range forces at the micron scale

In recent times there has been significant interest in the possibility of modifications to the $1/R^2$ force law of gravity at or below millimeter distances. Many theories have been proposed to account for the vast difference in strength between gravitational interactions and the other fundamental forces (i.e., the "gauge hierarchy problem"). Theories which address the hierarchy problem through the addition of extra spatial dimensions (e.g. [10–14]) typically produce deviations from $1/R^2$ law of gravity at sub-mm length scales and are still mostly unconstrained by experiments. Even in the absence of additional spatial dimensions, $1/R^2$ law-violating interactions at length scales below a millimeter can arise as exchange forces in string theories with light moduli (e.g., [15,16]). Given the large variation in the predicted strength and length scale of the $1/R^2$ law-violating forces between different theories, a wide range of values for the length scale must be probed to comprehensively search for new physics in this sector. From a broader perspective, gravity is the least understood of the fundamental forces, so, irrespective of more sophisticated theoretical arguments, it is natural to seek new methods to investigate its fundamental properties.

Two main issues make the study of gravity and gravity-like interactions at distances below a millimeter exceedingly challenging: (i) gravity is a very weak interaction, and (ii) various effects of (electrical) polarization make residual electric forces, even for neutral objects, a very serious background.

Until recently, all gravity measurements at short scale have been performed using mechanical springs as a force sensors e.g. [17]. In the last decade substantial progress has been made in the area of optomechanics and, in particular, with optical levitation and cooling of dielectric objects e.g. [18]. New experimental approaches utilizing squeezing techniques will continue to increase sensitivity and extend the reach to probe for deviations. From a technical point of view, particle physicists are very well equipped to apply modern data analysis and statistical techniques to an area where discoveries are very challenging.

4 Simulating Quantum Gravity

One of the most profound developments of modern physics is the conjecture of gauge/gravity duality, which relates thermal states of strongly coupled quantum field theories to general relativity and curved space-time. The relation has been dubbed the holographic principle, because accounting for entanglement in the quantum system requires one extra spatial dimension in the corresponding gravitational theory. Remarkably, under holographic duality, certain strongly coupled quantum field theories can equivalently be viewed as black holes. This correspondence lies at the heart of intriguing synergies between the physics of black holes and such seemingly disparate realms as quantum error correction, quantum chaos, and transport in strongly correlated materials. To date, studies of holographic duality have largely been confined to the realm of theory. Yet a confluence of advances in devising testable predictions and in building programmable quantum simulators in the laboratory is opening new prospects for experimental investigation.

As an illustrative example, the holographic duals of black holes are predicted to be "fast scramblers" of quantum information, delocalizing information across all degrees of freedom at a fundamental speed limit [19, 20]. A necessary condition for fast scrambling is a non-local graph of interactions [19]. Such exotic interactions can be realized in quantum simulations with cold atoms or ions [21–24], e.g., by letting photons [25–28] or phonons [29,30] mediate couplings between distant qubits. Advances in programming these couplings, and increasingly sophisticated techniques for probing quantum dynamics [30–33], offer a route to testing whether insights obtained from theoretically tractable models extend to a wider class of quantum many-body systems. How generic is the principle that gravity emerges from quantum entanglement [34]? Can experimentally probing entanglement in a strongly interacting quantum system [35, 36] reveal its emergent spacetime geometry [37], even when a gravity dual is not *a priori* known to exist? Investigating these questions poses stringent demands on coherence and control in quantum simulators, which the expertise of DOE labs can help to address (e.g., superconducting RF cavities can enhance atom-photon interactions [38]). Potential discoveries include powerful new approaches to predicting and designing the properties of complex quantum systems and deep fundamental insights into the nature of gravity.

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