Snowmass2021 Letter of Interest: Long-baseline Atomic Sensors for Fundamental Physics

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Abstract: Long-baseline atomic quantum sensing is an exciting new field that offers new handles and opportunities to expand the exploration of the physics of the universe. Long-baseline atom interferometers can allow direct searches for ultralight wave-like dark matter at sensitivities orders of magnitude beyond current limits. Kilometer-scale baselines open the prospect of exploration of the gravitational wave spectrum in a new frequency range, between the peak sensitivities of LIGO and LISA, that is particularly sensitive to cosmological signals from the early universe and to a wide variety of astrophysical sources, complementing the rich program of future 3G laser interferometers, particularly for multi-messenger astronomy. The development and science exploitation of long-baseline atomic experiments will enable an ambitious long-term research program at the intersection of the of the energy, cosmic, and quantum information frontiers.

Long-baseline atom interferometry is a rapidly growing field with a variety of exciting fundamental physics applications. Science opportunities include gravitational wave detection [1–7], searches for ultralight wave-like dark matter candidates [8, 9] and for dark energy [10], tests of gravity and searches for new fundamental interactions ('fifth forces') [11–25], precise tests of the Standard Model [26, 27], and tests of quantum mechanics [28–37]. Such experiments take advantage of the ongoing evolution of the precision and accuracy of atomic sensors. Optical lattice clocks now regularly attain 18 digits of frequency resolution [38, 39] and beyond [40, 41], while atom interferometers continue to improve both in inertial sensing applications [42] and in precision metrology, including measurements of Newton's gravitational constant [11,43,44], the fine structure constant [26, 27], and the equivalence principle [14–25]. Several community reports [45–47] have recognized that long-baseline quantum sensor networks have a broad scientific potential, including searches for new fundamental forces, ultralight wave-like dark matter, and gravitational waves in an unexplored frequency range.

In the past several years, there has been widespread and growing international interest in pursuing long-baseline atomic sensors for gravitational wave detection and ultralight wave-like dark matter searches. An impressive number of efforts have begun around the world, including both terrestrial experiments and space-based proposals. In the US, MAGIS-100 [48] is an intermediate-size detector with a 100-meter baseline currently under construction at Fermilab. In Europe, significant progress has already been made on the construction of MIGA (Matter wave-laser based Interferometer Gravitation Antenna) [2], a 200 m baseline underground gravitational wave detector demonstrator located in France. To follow up on this, a new proposal has called for the construction of ELGAR (European Laboratory for Gravitation and Atom-interferometric Research) [3], an underground detector with horizontal 32 km arm length aiming to detect gravitational waves in the mid-band (infrasound) frequency range. In China, work has begun to build ZAIGA (Zhaoshan long-baseline Atom Interferometer Gravitation Antenna) [5], a set of multiple 300 m vertical shafts separated by km-scale laser links that will use atomic clocks and atom interferometry to explore a wide range of science including gravitational wave detection. In the UK, a broad collaboration of eight institutes has recently advanced a multi-stage program called AION (Atom Interferometer Observatory and Network) [7], which aims to progressively construct atom interferometers at the 10- and then 100-meter scale, in order to develop technologies for a full-scale kilometer baseline instrument for both gravitational wave detection and dark matter searches. To access lower frequencies, a variety of space-based detectors have also been proposed, based both on atomic clocks [49, 50] and atom interferometers [6, 51–53], and in fact these technologies are closely related [54].

The ambitious scope of these experiments and proposals is evidence of the enthusiasm in the community for the long-term science prospects offered by long-baseline atomic sensing. In addition, these many detectors have the potential to complement each other. The diversity of approaches taken by the various experiments is a clear strength, offering opportunities for different groups to develop alternate atomic sensing technologies in parallel. More directly, operating multiple detectors in different parts of the world as part of a network offers valuable scientific advantages [7]. In the spirit of the LIGO/Virgo/KAGRA collaboration, correlating data collected simultaneously by several atom interferometer gravitational wave detectors operating in the mid-band frequency range would be a powerful way to improve background rejection and increase overall sensitivity.

Gravitational Waves: In order to fully realize the potential of gravitational wave observations, we will need to cover as many different frequency bands as possible. Atomic sensors appear promising for observing gravitational waves in the *mid-band*, roughly 30 mHz to 10 Hz, between LIGO and other ground-based laser interferometers (10 Hz - 1 kHz) and LISA (1 mHz - 50 mHz), as shown in Figure 1a. Achieving the required level of sensitivity will be challenging, but the potential payoff

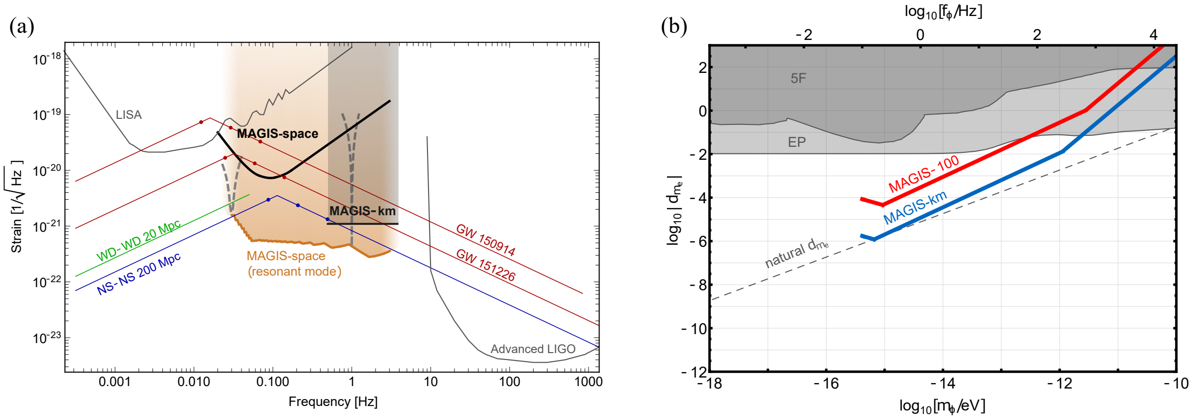

Figure 1: (a) Projected gravitational wave sensitivity for a future space-based sensor (MAGIS-space) and a kilometer-scale terrestrial detector (MAGIS-km) both based on the MAGIS concept [51, 52]. Matter wave interferometry supports a variety of detection protocols, including broadband (black, solid) and a narrow-band sweeping search mode (brown resonant mode envelope, with two dashed examples [55]). Several known astrophysics binary systems (red: black holes, blue: neutron stars, green: white dwarfs) are shown for reference. (b) Projected sensitivity of MAGIS-100 and MAGIS-km to an ultralight scalar wave-like dark matter model with coupling strength d_{m_e} to the electron mass, versus the mass of the scalar particle (existing bounds shown in gray) [8].

is huge. There are a number of compelling reasons to explore the mid-band. For example, the mid-band may be optimal for observing the highest energy scales in the very early universe. This frequency range is above the white dwarf "confusion noise" but can still be low enough frequency to see certain cosmological sources [55]. Furthermore, phase transitions in the early universe at scales above the weak scale [56] and networks of cosmic strings [57] may produce detectable gravitational wave signals in this band. The mid-band will also be sensitive to new astrophysics sources of gravitational waves such as heavier (hundreds of solar masses) black holes mergers and white dwarf binary mergers not observable at higher frequencies. Furthermore, the mid-band appears to be a promising band for measuring the spin of merging black holes. In addition, and very importantly, many black hole or neutron star binaries that are observed in the mid-band can later be observed by LIGO once they evolve to higher frequencies. Such joint observation would be a powerful new source of information. This would allow an atomic detector in the mid-band to give a prediction of the time and location of a merger event. Since the sources generally live a long time in this mid-frequency band, they can be localized on the sky even by a single-baseline detector, and in fact the mid-band is ideal for localization and prediction of such merger events [58].

Ultralight Dark Matter: Wave-like dark matter can lead to time-dependent signals in high precision quantum sensor networks, enabling a unique probe of its existence. In particular, these time dependent signals can be caused by ultra-light dark matter candidates. Well motivated theories indicate that the mass range from 10^{-22} eV to 10^{-3} eV is particularly interesting, and long-baseline atomic sensors offer a promising approach in the lower part of this range (e.g, Fig. 1b). Potential dark matter candidates within this range include the QCD axion, axion-like-particles, and the relaxion. Dark matter in this mass range has a large number density and can be described as a classical field that oscillates at a frequency determined by the mass of the dark matter particle. This results in time dependent effects that can be searched for using a quantum network. These effects arise because as the classical dark matter field oscillates, the properties of the sensor (such as the quantum energy level and spin) also change, leading to time dependent signals. Figure 1b shows sensitivity to an example dark matter model for an atomic sensor using the MAGIS configuration (see also the LoI on the MAGIS-100 demonstration experiment [59]).

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