Snowmass2021 Letter of Interest: The Matter wave Atomic Gradiometer Interferometric Sensor (MAGIS-100) Experiment

Swapan Chattopadhyay[1,2], Jason M. Hogan[3], Tim Kovachy[4], Rob Plunkett[1], Steve Geer[1], Peter Graham[3], Surjeet Rajendran[5], Jonathon Coleman[6], Ariel Schwartzman[7], Valerie Gibson[8], John March-Russell[9], and the MAGIS collaboration

[1] *Fermi National Accelerator Laboratory; Batavia, Illinois 60510, USA*
[2] *Northern Illinois University; DeKalb, Illinois 60115, USA*
[3] *Stanford University; Stanford, California 94305, USA*
[4] *Northwestern University; Evanston, Illinois, USA*
[5] *The Johns Hopkins University; Baltimore, Maryland 21218, USA*
[6] *University of Liverpool; Merseyside, L69 7ZE, UK*
[7] *SLAC National Accelerator Laboratory; Menlo Park, California 94025, USA*
[8] *University of Cambridge, Cavendish Laboratory, Cambridge CB3 0HE, UK*
[9] *Rudolf Peierls Centre for Theoretical Physics, Oxford University, OX1 3PU, UK*

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- (CF2) Dark Matter: Wave-like
- (CF7) Cosmic Probes of Fundamental Physics
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Contact Information:
Swapan Chattopadhyay, FNAL, NIU (swapan@fnal.gov)
Jason Hogan, Stanford University (hogan@stanford.edu)

Abstract: MAGIS-100 is a next generation atom interferometer that builds on the successful work in the field of atomic sensors over the past two decades. The experiment is an order of magnitude larger than the previous generation of atomic sensors and will be located in the 100 m MINOS vertical access shaft at Fermilab, USA. The instrument will serve as an intermediate prototype for a future kilometer-scale device, and involves a diverse scientific program to realize large-scale quantum superposition and entanglement, to search for ultralight dark matter, and to develop technology for exploring the 'mid-band' (0.03 Hz – 3 Hz) of the gravitational wave spectrum – opening a window on the early and dark universe. MAGIS-100 design and construction started in 2020, and the experiment is expected to begin operations in 2022. The collaboration currently includes academic investigators from the USA and UK, working collaboratively with Fermilab. The experiment involves world leading expertise in atom interferometry, lasers, particle physics and accelerator technologies. MAGIS-100 is funded by the Gordon and Betty Moore Foundation and the DOE QuantiSED program. The MAGIS-100 research program is synergistic with research on 'Quantum Ensembles: Clocks and Interferometers' at SLAC/Stanford University and with the AION project in UK (approved by UKRI/STFC), forming a collaborative transatlantic network with common goals in atom interferometry for fundamental science.

The Matter-wave Atomic Gradiometer Interferometric Sensor (MAGIS) collaboration proposes to implement a quantum sensor based on spatial superposition of atomic states falling freely under gravity to explore the dark/early universe, search for new fundamental particles/interactions, and provide a novel pathway for detecting gravitational waves. The gravitational wave science targets include coherent waves from astrophysical sources, as well as possible primordial sources of incoherent, noise-like cosmic background gravitational radiation from the early universe in the mid-band freqency range, bridging the gap between LIGO and LISA. MAGIS-100 is an international collaboration which brings together university groups with substantial experience in atomic physics and atom interferometry, and particle physicists experienced in designing, constructing, and operating large experiments at the laboratory-scale. The MAGIS-100 experiment will use light pulse atom interferometry to search for physics beyond the Standard Model. It is currently under construction at Fermilab, in collaboration with Stanford University, Northwestern University, Johns Hopkins University, Northern Illinois University, University of Liverpool, University of Cambridge, University of Oxford, and SLAC. The project is funded by the Gordon and Betty Moore Foundation for five years and by US Department of Energy QuantiSED 2019 for three years, with preliminary results expected in 2022. MAGIS-100 is synergistic with research on 'Quantum Ensembles: Clocks and Interferometers' at SLAC/Stanford University [1] and with the AION project in UK (approved by UKRI/STFC) [2], forming a collaborative transatlantic network with common goals in atom interferometry for fundamental science.

The MAGIS-100 experiment will exploit the existing 100 m vertical MINOS access shaft (see Fig. 1a below) and will be an upgrade of the existing 10 m-scale experiment at Stanford with greatly increased sensitivity due to its increased length. MAGIS-100 will take advantage of the latest advances in atomic clock technologies using strontium atoms. The experiment also provides a critical step towards MAGIS-km, the next-but-one generation kilometer-scale experiment which might, for example, be located in a shaft at SURF in South Dakota, USA and which will be able to detect gravitational waves from known sources in an unexplored frequency range. Increasing the baseline from 10 m to 100 m will allow the experimental study of technical challenges associated with long-baseline atom interferometry, such as maintaining required vacuum levels, atom trajectory control, laser alignment and wavefront aberration tolerances, and suppression of gravity gradient noise – paving the way for MAGIS-km and performing critical technology development for an eventual space-based experiment.

Dark Matter Searches: Discovering the properties of the dark sector in laboratory experiments is one of the priorities of the DOE OHEP program (P5 report [3]). The key role of quantum sensors in this area was highlighted in several community reports [4, 5, 3, 6]. The dark sector can potentially weakly couple to the Standard Model, which can lead to fluctuating atomic levels via the resulting time-dependence of the fine structure constant and electron mass. Such fluctuations due to ultralight, wave-like dark matter would produce oscillatory signals in the MAGIS-100 atom interferometers by slightly perturbing the energy splitting of the narrow-linewidth Sr atomic clock transition. MAGIS-100 will be optimally sensitive to such signals in the $0.1 - 3$ Hz frequency band (i.e., mass range $10^{-15}\text{eV} < m < 10^{-13}\text{eV}$), improving significantly on existing bounds (Fig. 1d). Other ultralight dark matter models can also lead to time-dependent forces that depend on atomic species, a signature which MAGIS-100 will search for with an alternative operation mode using simultaneous dual-isotope atom interferometry [7]. These two detection modes will enable searches for complementary dark matter couplings. In addition to these dark matter searches, new fundamental particles may also be discovered by searching for new forces, as identified in [2]. Ultra-light particles that have highly suppressed interactions with Standard Model particles, often dubbed "dark-sectors", also emerge in a variety of Beyond-the-Standard-Model frameworks that can dy-

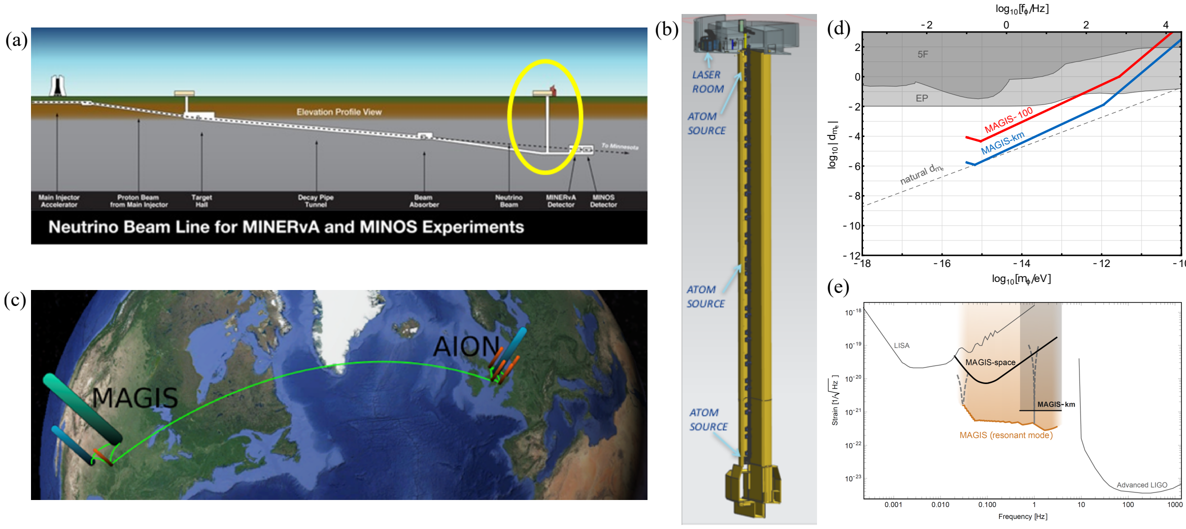

Figure 1: (a) MAGIS-100 underground site at Fermilab. (b) CAD model of MAGIS-100 instrument installed in existing MINOS access shaft at Fermilab, showing three atom sources and the vertical 100 meter baseline. (c) MAGIS and AION form a network of sensors to improve science reach. (d) Projected sensitivity of MAGIS-100 and MAGIS-km to an ultralight scalar dark matter model with coupling strength d_{m_e} to the electron mass, versus the mass of the scalar particle. (e) Projected gravitational wave sensitivity in the midband for a full-scale terrestrial detector (gray band, MAGIS-100) and a space-based detector (MAGIS-space) operating in both broadband (black, solid) and resonant modes (overall envelope in brown, with two dashed examples).

namically solve the hierarchy problem [8], involve extra dimensions [9] or supersymmetry [10].

Gravitational Wave Pathfinder: Atomic sensors are highly promising for observing gravitational waves in the "mid-band," (30 mHz - 3 Hz), filling the gap between LIGO and LISA (Fig. 1e). The midband is a promising range to detect known astrophysical sources such as compact binary inspirals before they reach LIGO's range, and is potentially the optimal range for sky position determination to facilitate multi-messenger astronomy [11]. Also, since gravitational waves are likely the only direct way to observe the earliest moments of the universe at the highest energy scales (e.g. inflation era), the most important discoveries could be a cosmic gravitational wave background, evidence for phase transitions in the early universe at scales above the weak scale, and networks of cosmic strings [12]. MAGIS- 100 will serve as a prototype to help demonstrate the technology and open the path to future full-scale terrestrial (km-scale) and satellite-based detectors [13].

Quantum Science at Large Scales: The key role of quantum science and technologies in a variety of scientific applications has been recognized by the DOE in multiple community reports [4, 5], identifying grand challenges and opportunities for investment in the field of fundamental and precision science. In particular, [4] recommends the development of measurement strategies that exploit quantum coherence and entanglement to probe fundamental physics with unprecedented precision. It calls for the development of quantum sensors that can yield powerful precision measurement tools, specifically those that can search for a wide range of time-varying weak signals. These goals were further enhanced and highlighted in [5], which noted the scientific potential of such quantum sensors in searching for new fundamental forces, dark matter and other dark sector ingredients, as well as the potential for atom interferometry and optical atomic clocks as precision space-time sensors. MAGIS-100 seeks to address these grand community challenges using atom interferometry and atomic clock techniques to realize quantum superpositions of matter waves that extend over macroscopic scales in space and in time, and that incorporate entangled atomic ensembles to achieve phase measurements with precision beyond the standard quantum limit.

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