Letter of Interest for Snowmass 2021

The Atom Interferometric Observatory and Network (AION) for Dark Matter and Gravity Exploration

Thematic Areas:

☐ (CF1) Dark Matter: Particle Like
■ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (IF1) Quantum Sensors

AION Collaboration:

L. Badurina[1], S. Balashov[2], E. Bentine[3], D. Blas[1], J. Boehm[2], K. Bongs[4], D. Bortoletto[3], T. Bowcock[5], W. Bowden[6], C. Brew[2], O. Buchmueller[6], J. Coleman[5], G. Elertas[5], J. Ellis[1], C. Foot[3], V. Gibson[7], M. Haehnelt[7], T. Harte[7], R. Hobson[6], M. Holynski[4], A. Khazov[2], M. Langlois[4], S. Lellouch[4], Y.H. Lien[4], R. Maiolino[7], P. Majewski[2], S. Malik[6], J. March-Russell[3], C. McCabe[1], D. Newbold[2], R. Preece[3], B. Sauer[6], U. Schneider[7], I. Shipsey[3], Y. Singh[4], M. Tarbutt[6], M. A. Uchida[7], T. Valenzuela[2], M. van der Grinten[2], J. Vossebeld[4], D. Weatherill[3], I. Wilmut[7], J. Zielinska[6]

[1] King's College London, [2] STFC Rutherford Appleton Laboratory, [3] University of Oxford, [4] University of Birmingham, [5] University of Liverpool, [6] Imperial College London, [7] University of Cambridge

Abstract: We outline the scientific opportunities of a proposed programme of the Atom Interferometric Observatory and Network (AION) project [1] to search for ultra-light dark matter, to explore gravitational waves in the mid-frequency range between the peak sensitivities of the LISA and LIGO/Virgo/ KAGRA/INDIGO/Einstein Telescope/Cosmic Explorer experiments, and to probe other frontiers in fundamental physics. This programme would complement other planned searches for dark matter, as well as probe mergers involving intermediate-mass black holes and explore early-universe cosmology.

We propose to construct and operate a next-generation Atom Interferometric Observatory and Network (AION) [1], starting with a 10m device and progressing via a 100m experiment to a 1km instrument. AION will enable exploration of the properties of ultra-light dark matter (DM) and gravitational waves (GWs) from the very early universe and astrophysical sources in the mid-frequency band ranging from several mHz to a few Hz, inaccessible by other means. The AION science programme spans a wide range of fundamental physics and aligns fully with the top priorities of international communities. It has been approved by the UK STFC for initial funding.

Ultimate sensitivity of the programme is reached by interoperating and networking with other such instruments around the world, similar to the existing LIGO-Virgo network. This will provide science opportunities not accessible to single detectors. AION has a close collaboration with MAGIS [2–4] in the US, which also targets an eventual km-scale atom interferometer, and contributes strongly to the design study of a mission proposal for an Atomic Experiment for Dark Matter and Gravity Exploration in Space (AEDGE) [5], which was selected by European Space Agency (ESA) for presentation on the recent Voyage2050 workshop. This would make direct use of AION and MAGIS technology. AION and MAGIS complement several other terrestrial cold atom experiments that are currently being prepared, such as MIGA [6] and ZAIGA [7], or being proposed, such as ELGAR [8].

The direct search for Dark Matter (DM), which aims to detect the non-gravitational interaction of DM in the vicinity of the Earth, is one of the most compelling challenges in particle physics. Theoretical extensions of the Standard Model of particle physics provide many elementary particle candidates for DM over a wide mass range from 10^{-22} eV to the Planck scale (10^{18} GeV) [9]. There are many well-motivated candidates for ultra-light DM with a sub-eV mass, including the QCD axion and axion-like-particles (ALPs), dark vector bosons and light scalar particles such as moduli, dilatons and the relaxion. There are well-understood mechanisms to produce the required cosmological abundance, e.g., the misalignment mechanism [10–12], and the DM is naturally cold. Atom interferometers can measure a distinctive prediction of scalar DM [13, 14], namely oscillations of the electron mass and fine-structure constant in time, with a frequency set by the mass of the scalar DM and an amplitude determined by the local DM density. This in turn leads to temporal variations of atomic transition frequencies, and a non-trivial signal phase occurs in a differential atom interferometer when the period of the DM wave matches the total duration of the interferometric sequence [14]. The left panel of Fig. 1 shows the projected sensitivity of atom interferometer experiments to light scalar DM couplings to electrons with a signal-to-noise (SNR) equal to one after an integration time of 10^8 s. The grey regions show parameter space that has already been excluded. We see that a 100m experiment is projected to probe new ranges of the electron coupling for scalar DM masses $\sim 10^{-15}$ eV to $\sim 10^{-12}$ eV. A km-scale experiment extends the sensitivity to smaller values of the electron coupling while AEDGE further extends the sensitivity to even lower values of the scalar DM mass and electron coupling. Similar results are obtained for photon and Higgs portal coupling scenarios [1, 5]. These projections do not include the possible gravitational gradient noise, which may be fully measured and thus subtracted, and also assume that the interferometer runs in broadband mode so that it is sensitive to a wide range of scalar DM masses. However, it is also possible to operate the interferometer in resonant mode [17], in which case the AEDGE sensitivity could be extended further between 10^{-16} eV and 10^{-14} eV. [14]

The first direct evidence for GWs came from the LIGO/Virgo discoveries of emissions from the mergers of black holes (BHs) and of neutron stars [18], which open new vistas in the exploration of fundamental physics, astrophysics and cosmology. Additional GW experiments are now being prepared and proposed, including upgrades of LIGO and Virgo, KAGRA [19] and the Einstein Telescope

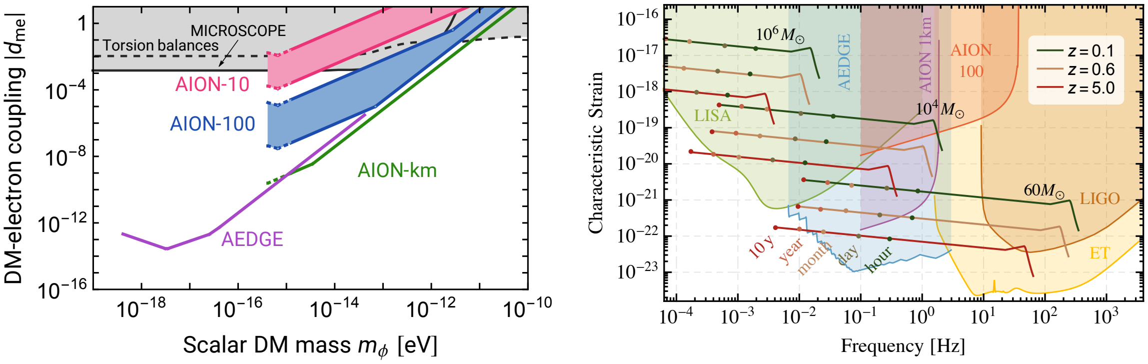

Figure 1. *The left panel shows the sensitivity of the different atom interferometer experiments to scalar DM interactions with electrons. The shadings indicate the sensitivity range bracketed by the 'initial' and 'goal' scenarios defined in [1]. The grey region of parameter space has been excluded by searches for violations of the equivalence principle [15] or by MICROSCOPE [16]. The right panel compares the GW strain measurements possible with atom interferometer and other experiments, showing their sensitivities to mergers of black holes of various masses at various redshifts. The assumptions entering the various projections are outlined in [1, 5].*

(ET) [20], which will provide greater sensitivities in a similar frequency range to the current LIGO and Virgo experiments, and LISA [21], which will provide sensitivity in a lower frequency band on a longer time-scale. Atom interferometers can provide complementary measurements in the mid-frequency range between 1 and 10^{-2} Hz, and offer synergies by networking with other detectors.

The BHs whose mergers were discovered by LIGO and Virgo have masses up to several tens of solar masses. Many galaxies are known to contain super-massive black holes (SMBHs) with masses in the range between 10^6 and billions of solar masses, and a first radio image of the SMBH in M87 has been released by the Event Horizon telescope (EHT) [22]. The LISA frequency range is ideal for observations of mergers involving SMBHs. It is expected that intermediate-mass black holes (IMBHs) with masses in the range 100 to 10^5 solar masses must also exist [23]. There is some observational evidence for IMBHs, which may have played key roles in the assembly of SMBHs. The mid-frequency range is ideal for observations of mergers involving IMBHs, to which LISA and the LIGO/Virgo/KAGRA/ET experiments are relatively insensitive, as seen in the right panel of Fig. 1.

In addition to these stand-alone capabilities, there are significant synergies with measurements in other frequency ranges. As seen in the right panel of Fig. 1, atom interferometers could observe early infall stages of ~ 100 solar-mass mergers that could later be measured by LIGO/Virgo/KAGRA/ET, providing predictions of their times and locations for those experiments. Conversely, LISA observations could be used to make predictions for subsequent 10^4 solar-mass mergers. These combined measurements would provide unparalleled lever arms for probing general relativity in GW propagation.

Many extensions of the Standard Model predict first-order phase transitions in the early Universe, e.g., extended electroweak sectors, effective field theories with higher-dimensional operators and hidden sector interactions, and cosmic strings are other possible cosmological sources of GW signals. These typically give a very broad frequency spectrum stretching across the ranges to which the LIGO/ET, AION/MAGIS [1, 5], LISA and SKA [24] experiments are sensitive. Probing the plateau in a wide range of frequencies would yield information not only on strings themselves but also on the evolution of the early Universe [25], including SM processes such as the QCD phase transition, BSM scenarios predicting new degrees of freedom, and epochs of early matter domination.

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