QSFT Work Package 3:
A UK Atom Interferometer Observatory and Network
Outline Case

Work Package Coordination & Team

The QSFT Work Package AION is coordinated by Oliver Buchmueller (Imperial) and Jon Coleman (Liverpool), with theory support led by John Ellis (KCL). Representatives of the following institutions: Aberdeen, Birmingham, Bristol, Brunel, Durham, Glasgow, Imperial College, Kings College London, University College London, Liverpool, Nottingham, Open University, Oxford, RAL, Sheffield, Strathclyde, Sussex, Swansea and NPL have expressed interest in participation. Members of these institutes will form the team working towards the full proposal that is due in June 2019. There is substantial interest in the community in this project and we expect a broader and more formal collaboration will be formed by the time of the AION workshop in March 2019. After this event the final scope and details of the individual AION work packages will be defined and work package managers will be assigned.

High-level Summary

The funding request is for a period of six years with the assumption that funding would start in Autumn 2019. The first stage of the project aims to consolidate UK expertise in the field, demonstrate the technology and build an atom interferometer network in the UK. The second stage extends the project to a 100 m atom interferometry experiment enabling searches for ultra-light dark matter and preparing for stage 3, AION-KM, for the exploration of gravitational wave physics in the mid-frequency band with a km-scale atom interferometer. A crucial component of the AION programme is based on collaboration with US and contributions to the MAGIS-100 experiment at Fermilab.

The proposed project enables searches for new fundamental interactions with a UK-based atom interferometry network utilizing expertise developed for MAGIS-100. The first three years will see the first output of the potential from the AION programme and the construction of MAGIS-100. The strong link with MAGIS will decrease technical risk and facilitate the first physics exploitation of the atom interferometry network. The following three years will see the initial investment flourish, with continued exploitation of the network and the preparation and construction of AION-100. In addition, this time period will see MAGIS-100 commissioning and operation leading to the first physics results from 100 m atom interferometry. The project will also open the opportunity to operate, for the first time, large-scale atom interferometers in the UK and US synchronously, which will lead to the optimal sensitivity of the proposed atom interferometry network in the UK.

The total funding envelope for this six-year programme is estimated to be £15M to £20M.

Introduction

In this project we propose to construct and operate a next-generation Atomic Interferometric Observatory and Network (AION) in the UK that will enable the exploration of properties of dark matter as well as searches for new fundamental interactions. In addition, it will provide a pathway towards detecting gravitational waves from the very early Universe and astrophysical sources in the mid-frequency band ranging from several mHz to a few Hz, which is mostly unexplored as yet.

We outline a staged plan to build a set of atom interferometers with progressive baselines up to a minimum of 10 m, which will pave the way for 100 m and eventually km-scale detectors in the future. The proposed quantum sensors are based on the superposition of atomic states and designs are taking advantage of features used by the world 's best atomic clocks [1] in combination with established techniques for building inertial sensors [2]. This programme will make the UK a leader in the exploitation of the enormous physics potential of this frequency band with several options for ground-breaking discoveries. It will also develop the foundation for future science with ultra-sensitive quantum sensors and lay the foundations for a new and potentially highly disruptive class of applications of precision measurement is surveying and prospecting.

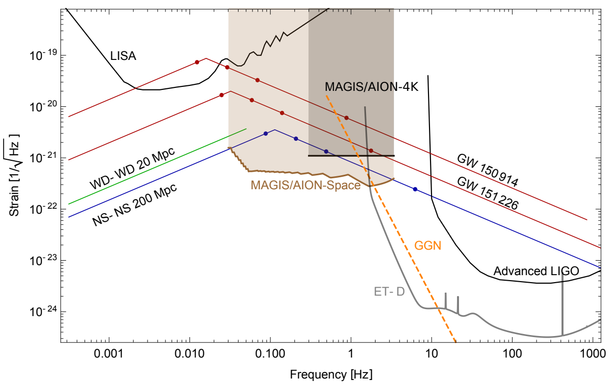

Figure 1 *Illustration of potential sensitivities for atom interferometer detectors, both land- and space-based devices, in comparison to other gravitational wave experiments (both current and future). The land-based design, labelled as MAGIS/AION-4K, assumes a km-scale atom interferometer detector, while the space-based version, MAGIS/AION-Space, assumes a satellite set-up similar to the size of LISA. The comparison shows the complementarity of the different approaches to cover the gravitational wave spectrum from 10^3 Hz to 10^{-3} Hz.*

The full AION programme consists of 4 stages. The first develops existing technology and the infrastructure for the 100 m detector, and produces detailed plans and assessment of performance before moving to Stage 2. The second stage, which is not part of this funding request, builds, commissions and exploits the 100 m detector and prepares a design study for the km-scale. The final two stages, full-scale terrestrial (kilometre-scale – Stage 3) and satellite-based (thousands of kilometres scale – Stage 4) detectors are the objectives of the continuing programme.

The science case has broad applications to fundamental physics and aligns well with the highest priorities in the UK and international science communities. It has unparallelled sensitivity to the physics of space-time and its distortion between the sensors. The detector is highly sensitive to time-varying signals that could be caused by ultra-light particles. The discovery of such particles and their associated fields would both reveal the nature of the, as yet undiscovered, dark matter and blueprint a novel method to probe the associated theoretical frameworks. There are several such candidate particles including string axions, relaxions and moduli that are able to produce a signal in the frequency range 100 nHz – 10 Hz [2]. In the case of dark-sector physics, like the search for ultra-light dark matter candidates or other hidden dark-sector fields, experiments in this frequency range have the potential to explore a large mass region (10^{-13} – 10^{-23} eV) with unprecedented sensitivity. These hidden sector particles could play a crucial role in particle physics beyond the Standard Model, astrophysics, and cosmology.

The detector will also be sensitive to other new fundamental interactions. This sensitivity arises because these interactions, mediated by new light particles, will affect the quantum sensors differently from any backgrounds expected from the Standard Model and gravity. Gravitational waves will induce time-varying signals in the sensors [4] opening a new window on the cosmos that lies between the Advanced LIGO and LISA experiments. It is expected that the gravitational wave spectrum from 0.1 Hz - 10 Hz will be mostly free of continuum foreground noise from astrophysical sources (such as white dwarf confusion noise). AION connects the fundamental research areas of particle physics and gravitational wave physics. It will enable studies of many of the fundamental puzzles of our Universe, like dark matter as well as processes occurring in the early Universe such as potential gravitational wave signals from inflationary fields, as predicted in Higgs cosmology, for example.

The AION science programme is summarized as follows:

- to build the instrument to explore these well-motivated ultra-light dark matter candidates several orders of magnitude beyond current bounds;
- to open the door to a new generation of generic precision searches for new particles and their fields complementing those performed at collider facilities;
- to explore mid-frequency band gravitational waves from astrophysical sources and from the very early Universe, such as space-time `tremors' produced either by inflation or reheating [5].

This third theme offers long-term, high scientific value outputs and is a cross-over between traditional particle physics, astrophysics and the physics of the early Universe and opens a new dimension to multi-messenger observations. In particular, with the eventual construction of the km-scale atom interferometer detector, new gravitational wave sources will become observable. AION will establish the large-scale interferometric infrastructure and techniques in the UK and provide UKRI with the ability to complement the observational breadth of LISA, Advanced LIGO and the proposed Einstein Telescope, crucially allowing complete coverage of the frequency spectrum. The 100 m baseline atom interferometer would, on its own, be sensitive to high ($O(10^3)$) solar mass events. At the 1 km scale, sources such as neutron star binaries or black hole mergers will be observed in the mid-frequency band, and then may be observed later by LIGO after the merger has passed to higher frequencies. Such joint observations will be a powerful new source of information, giving a prediction of the time and location of a merger event in LIGO – potentially months before it occurs. An example of the sensitivities that future atom interferometer detectors could reach, both land- and space-based devices, is shown in Figure 1. It is based on the design study of the MAGIS Collaboration [see below] and shows the complementarity of the different approaches to cover the gravitational wave spectrum from 10^3 Hz to 10^{-3} Hz.

From the outset this project will benefit strongly from close collaboration on an international level with the US initiative, MAGIS-100 [6], which pursues a similar goal of an eventual km-scale atom interferometer. MAGIS-100 was initiated in 2017 by physicists from Stanford, UC Berkley, NIU, FNAL, the University of Liverpool and the DoE Office of HEP. We would like to emphasize that collaboration with AION by the MAGIS experiment has already been endorsed by the community at Stanford and Fermilab, presenting the UK with an immediate window of scientific opportunity. In addition to being a vital ingredient of our short and mid-term objectives, the UK-US collaboration will serve as the test bed for full-scale terrestrial (kilometre-scale) and satellite-based (thousands of kilometres scale) detectors and build the framework for global scientific leadership in this area. The AION programme would reach its ultimate sensitivity by operating two detectors simultaneously, one in the UK and one in the US, thereby enabling unique physics opportunities not accessible to either detector alone.

Internal Work Package Structure (Preliminary)

To structure the project we propose 5 high-level Work Packages (WP) with the following outlines:

WP-Atom Interferometry: This WP will deliver the technology and expertise and will form a first network of atom interferometers in the UK.
The high-level deliverables are:

- Form UK collaboration to design and construct AION-1 and AION-10 and establish a first UK atom interferometry Network by building AION-1 in Liverpool and other selected places.
- Prototype AION-10 to demonstrate the technology and to establish UK expertise and leadership in the field.

- Commission AION-10 with a short baseline and compare with AION-1 Network.

WP-Physics: This WP will deliver the physics and phenomenology. The high-level deliverables are:

- Build a concrete plan to exploit the full physics programme for AION-1/AION-10 Network.
- Full physics exploitation of the AION-1/AION-10 Network.
- Establish the full, enormous potential of the physics option for AION-100 and beyond – i.e., its physics case.
- Support phenomenology both for atom interferometry in general and for the AION physics case in particular.

WP-AION-100: This WP will pave the way for Stage 2 and a corresponding funding request. The high-level deliverables are:

- Work towards AION-100 including design work for AION-100 in a tower or a shaft and establish the physics case.
- Full design study for AION-100 and start planning for the km-stage detector.
- Construction of AION-100.

WP-MAGIS: This WP will establish significant UK contribution to MAGIS and deliver the collaboration with the US. The high-level deliverables are:

- Collaborate with MAGIS to contribute to the construction and commissioning of the experiment.
- Strengthen the collaboration with Fermilab and the US.
- Initiate physics analysis and strategic publication plan in conjunction with MAGIS.

It should be noted that the scope and details of these WPs are still preliminary and the corresponding management and organisation will be defined later.

Budget Estimate (Preliminary)

The funding request is for a period of six years in total with the assumption that funding would start in Autumn 2019.

As outlined in the **Introduction** section, the first stage of the AION project consists of the 1 m and 10 m atom interferometry devices, which are intended to establish UK expertise in the field, demonstrate the technology, and build a first atom interferometry network. The second stage is an extension to a 100 m atom interferometry device that would enable competitive searches for ultra-light dark matter and improved sensitivity for searches for new fundamental interactions. It will also serve as the test bed for kilometre-scale terrestrial (Stage 3) and satellite-based (on a scale of thousands of kilometres – Stage 4) detectors and build the framework for global scientific leadership in this area. A successful execution of this programme would naturally open the options for future funding requests to proceed with Stage 2 of the programme.

In the first three years, AION-1 will have initial results and AION-10 will be in the commissioning phase by the end of this period. In addition, MAGIS-100 will be finishing the construction phase and preparing for commissioning with first results expected by the end of year 3. Stage 2 of the project, years 4-6, will see continued R&D and operation of the atom interferometry network as well as construction of AION-100. Furthermore, MAGIS-100 will be moving into physics exploitation delivering first results throughout Stage 2.

The estimated capital costs for the programme are outlined in Table 1. They are in part informed by the cost estimate of the MAGIS-100 programme. The differences between Stage 1 and Stage 2 in the capital request are mainly due to scaling the system from 10 m to 100 m and the required clock/phase synchronisation, which is needed for precision timing between multiple detectors. This is in part compensated by the MAGIS-100 contribution, which requires more capital in the first 3 years to enable the UK to participate and contribute to the construction. The networking will be prototyped at the 1 m and 10 m levels prior to the 100 m device. We will utilize enhanced-GPS to deliver the phase locking of the local clocks to a 1 ns level. The total capital cost is estimated to be about £11M.

Item	[Year 1 to 3]	[Year 4 to 6]
Materials	£2000K	£3300K
Operation	£100K	£100K
R&D	£1900K	£800K
Infrastructure	£100K	£200K
Network	£300	£500K
Computing	£100K	£300K
Total Capital	**£4500K**	**£5200K**

Table 1: Capital cost estimate for 6 years.

A first estimate for all the work packages suggests that about 8 postdocs and 4 technicians/engineers will be required for the period of the project. This leads to an estimated cost envelope of about £7.2M for RAs and technicians/engineers over the six-year funding period. This will be complemented buy approx. £600K (£100K a year) for travel.

A first preliminary budget estimate, capital plus staff, would amount to £9.7M + £7.8M **= £17.5M.** This total funding envelope is roughly equally distributed over the six-year period, corresponding to about £2.9M per year. With this simple assumption, a 2 year + 1 year + 3 year budgeting allocation would be: £5.8M (year 1 and 2), £2.9M (year 3), £8.8M (year 4,5, and 6). However, we would like to point out that a 2-year period for a first funding milestone is not ideal for an experimental programme, whereas a 3-year period would allow for greater scientific impact and achievements.

As the total cost of the project is strongly dependent on the tower/shaft decision, the above-mentioned preliminary budget estimate does NOT include any costing for the site. For example, we estimate the cost of hosting AION-100 in the STFC-Daresbury Tower would be about, £1M, while the cost of building a shaft at Boulby would be about £10M to £20M and take about 2 years to scope and excavate. We are also exploring an option to host AION-100 at CERN in one of the LHC access shafts. This would imply that the project could benefit from resources at CERN, which might, in turn, reduce the total budget request. The search for an appropriate site to host AION-100 is expected to proceed through the first phase of the funding request.

It should be noted that all details of this budget request are preliminary. It is expected that more details and a first allocation of budget items to work packages will be available by the time of the consortium meeting in January 2019.

AION Workshop

The first AION workshop that will take place on March 25 and March 26, 2019, at Imperial College London, South Kensington campus:

http://www.hep.ph.ic.ac.uk/AION2019

It follows the Quantum Sensors for Fundamental Physics event that took place in October in Oxford. The AION workshop will be a critical milestone for the assembly of a complete proposal to construct and operate a next generation Atomic Interferometric Observatory and Network (AION) in the UK that will enable the exploration of properties of dark matter as well as searches for new fundamental interactions. In addition, the proposal is intended to provide a pathway towards detecting gravitational waves in the, as yet mostly unexplored, mid-frequency band, ranging from several milliHertz to a few Hertz. The 2-day workshop will focus in the first day on the technology aspects of the project, while the second day will be devoted to discussions of the physics case and how to further develop and strengthen it. The project spans several communities: fundamental particle and astroparticle physics, atom interferometry, gravitational wave physics, and cosmology.

For support for international speakers [five invitations from overseas] and for contributions to the organisation, we request £15K from the Quantum Sensors for Fundamental Physics and Society grant.

References:

[1] B. J. Bloom, T. L. Nicholson, J. R. Williams, *et al.,* Nature 506, 71 (2014), 1309.1137
[2] S. M. Dickerson, *et al*., Phys. Rev. Lett. 111, 083001 (2013), 1305.1700
[3] A. Arvanitaki, P. W. Graham, J. M. Hogan, *et al*., Phys. Rev. D97, 7, 075020 (2018), 1606.04541
[4] P. W. Graham, J. M. Hogan, M. A. Kasevich, *et al.* (MAGIS) (2017), 1711.02225
[5] P. W. Graham, J. M. Hogan, M. A. Kasevich, *et al*., Phys. Rev. D94, 10, 104022 (2016), 1606.01860
[6] see: https://indico.cern.ch/event/686555/contributions/2977589/
and the associated proceedings https://arxiv.org/abs/1812.00482
[7] http://www.physics.ox.ac.uk/confs/quantum2018/index.asp