Using Quantum Technology to Search for Low-mass Particles in the Hidden Sector: a UK Programme

December 4, 2018

1 Executive Summary

We propose a substantial collaborative effort in the UK to probe the hidden sector of particle physics. Our collaboration, drawing researchers from the previously disparate fields of fundamental particle astrophysics, quantum technology, and ground-based and space-based long-wavelength astronomical instrumentation, aims to search for new phenomena in the hidden sector. Our proposal is timely and important given the following considerations:

- Theoretical low-energy particle physics has developed rapidly in recent years. New particles at low masses are motivated by careful phenomenological study of the remaining inconsistencies in the standard models of particle physics. Experimental measurements are needed to place quantitative limits on key parameters and thereby guide further theoretical progress.

- The detection of hidden sector particles would be a major discovery in science. Such detections would usher in a new generation of instruments and discoveries, opening up a new window on the nature of reality.

- The UK has been a world leader in the development of sensitive detectors for dark matter at the high energy electroweak frontier (WIMPs), and more generally of searches for further new physics at the electroweak scale. The absence of new discoveries at the electroweak scale beyond the Higgs boson further motivates new searches at the low energy, hidden sector frontier for alternative sources of new physics and alternative dark matter candidates.

- The manifestation and peculiarities of dark matter pervade cosmology, galactic astrophysics, particle physics, and quantum mechanics. The discovery of hidden sector particles that contribute to dark matter in particular would have a profound impact on all these areas of science.

- Theoretically predicted hidden sector particles have evaded detection because to date our instruments have lacked sensitivity. However, rapid advances in quantum sensor technology have already yielded new technologies that can be used to search for hidden sector particles, and promise a continuing revolution in quantum electronics to further advance the field.

- Over the next 10 years, the notion of quantum systems engineering will grow out of the availability of individual quantum electronic components, and it is vital that the UK is part of this technological revolution. New quantum-instruments and quantum-measurement techniques will be developed, which will have substantial, utilitarian applications in areas outside of scientific research.

- Our proposed programme aims to exploit recently developed quantum technology, to develop new superconducting quantum technology, and to understand how quantum-technological components can be engineered into complete systems that push the limits of sensitivity and functionality across the RF, microwave, and submillimetre-wave regions of the spectrum. These techniques will be of great importance to other areas of science and engineering.

- Rapid advances have been made in the development of ultra-low-noise instruments for ground-based and space-based microwave, submillimetre-wave and far-infrared astronomy, quantum metrology, long-wavelength quantum amplifiers, and qubits and spin-based quantum memory, and the ultra-noise-noise engineering developed for these projects can contribute to solving the hidden sector problem.

To capitalise on this vision, we have assembled a team of theoretical physicists, quantum technologists, and instrumentalists (see Section 8) to seed the formation of a new hidden-sector community in the UK. The applicants have the expertise, facilities and profile to build a consortium that would be highly influential on the international stage. We hope, and it is likely, that other UK institutes will join the partnership as the work proceeds. We also have ample, direct evidence that several overseas facilities are keen to work with us on the proposed programme, and we will enhance our international collaborations, perhaps through the use of shared equipment, as the science case, instrument concept and technology are developed.

This vision can only be delivered through a properly funded, scientifically well-targeted, and technologically focused programme of work that brings together the team in a fully coordinated way. For the first 3 years, we propose a single, managed programme that develops the science case, that creates a technical requirements document, that develops an optimized instrument concept, that identifies, develops and demonstrates the needed quantum circuit technology, that solves the many systems engineering problems, and that develops and applies modern 'big-data' analysis methods to search for the signatures of hidden sector particles. At the end of this evaluation and definition phase, we would submit a detailed application to STFC recommending the construction of a specific UK-based science-grade facility. If the application is successful, the facility would be built and commissioned during years 4 and 5, according to STFC project-status rules, oversight and fair access.

Our assessment is that the first 3 years will cost £4.5M, and then the additional cost over the following 2 years to establish a UK facility for long-term scientific exploitation would be £5M to £7M. Because of matters relating to recruitment, procurement, experimental excellence, and PhD studentships we would discourage subdividing the first 3 years into smaller units. However, if this approach needs to be adopted, and taking into account the expense of establishing experimental infrastructure early in the project, we would wish to work according to £3.75M for years 1 and 2, and £0.75M for year 3.

2 Scientific Motivation

New light so-called 'hidden sector' fields having small masses and couplings to Standard Model particles are theoretically compelling and experimentally testable extensions to particle physics: Fig 1. Such particles lead to entirely new long-range forces of unusual types, can solve problems with the Standard Model (SM), and can constitute the mysterious dark matter. They arise in many proposed more-fundamental theories, including extra-dimensional theories and string theory, and provide a potential window on to the extremely high energy world, far beyond that probed by colliders.

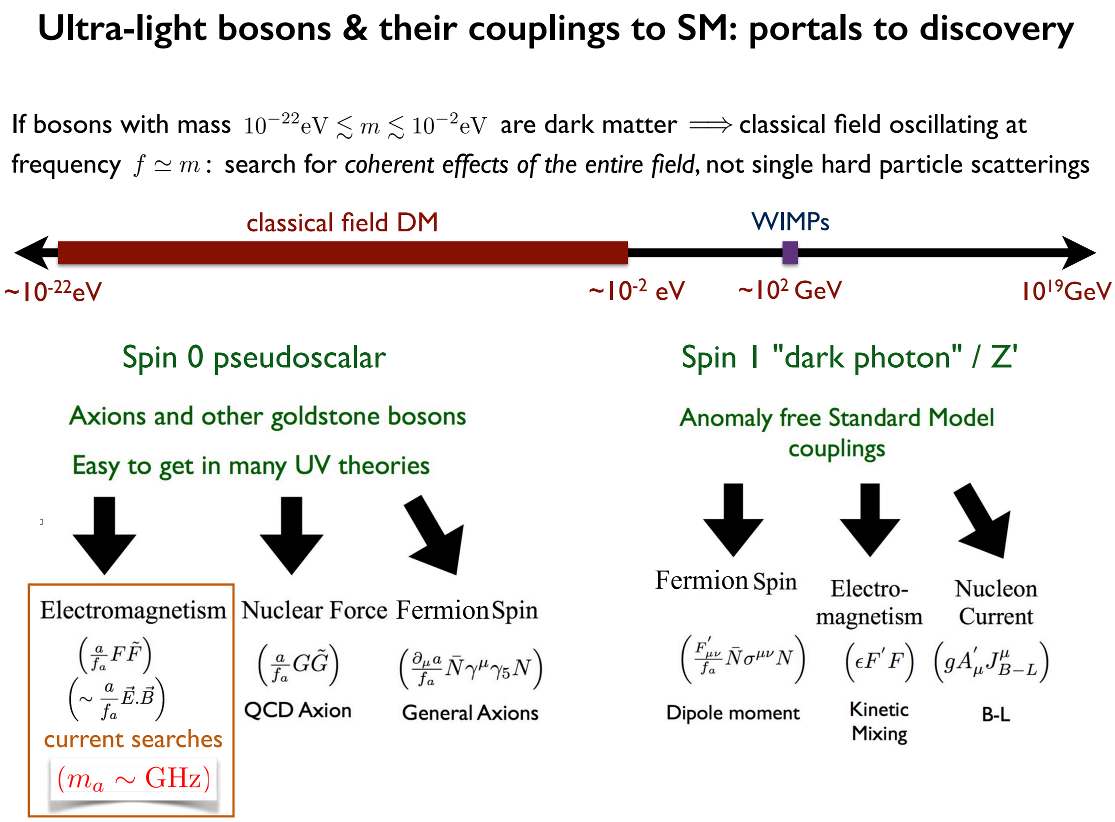

Figure 1: Portals to discovery

Foremost among these possible new states is the QCD axion. A core SM mystery is the tiny value of the CP-violating phase in the QCD sector which is observationally constrained by the experimental bound on the neutron electric dipole moment, $d_n < 3\times10^{-26}$ e cm, to be $\bar{\theta} \lesssim 10^{-10}$. While the SM provides no explanation for this, the spin-0 QCD axion automatically relaxes $\bar{\theta}$ to very near zero. QCD axions with μeV-scale masses are a particularly well-motivated target for experimental searches. If the symmetry that gives rise to the axion is unbroken at the end of inflation, soliton strings and domain walls subsequently form and release a population of axions in the early universe. The resulting dark matter density depends only on the axion mass m_a, and it is likely that the required dark matter abundance arises for $1\,\mu\mathrm{eV} < m_a < 100\,\mu\mathrm{eV}$, although significant theoretical uncertainty remains.

Other spin-0 pseudoscalar axion-like-particles (ALPs) with visible-sector couplings and masses that deviate from those of the QCD axion often automatically arise as remnants of ultra-high-energy physics, as can new super-light spin-1 particles, the so-called 'dark photons' (more correctly, dark Z'-bosons). It is also possible that new super-light, feebly-coupled, spin-0 bosons, often called moduli or dilatons, exist, complementing the spin-0 Higgs boson.

In addition to the post-inflationary mechanisms described above, QCD axions, as well as ALPs and dark photons, can also be produced by inflation itself, similar to early universe density fluctuations observed in the CMBR, in which case masses possibly much less than $1\,\mu$eV are of interest too, with viable masses

$m \gtrsim 10^{-22}$eV (below which the quantum De Broglie wavelength exceeds dwarf galaxy size).

In all the mass ranges discussed the particle phase space density is high, and dark matter is better described as a classical field oscillating in a narrow frequency band around $f = mc^2/h$, where the fractional line width $\Delta f/f \sim 10^{-6}$ is set by the galactic virial velocity. Such oscillating background fields to which the SM feebly couples motivate the need for extremely sensitive, high-Q, resonant experiments.

Experiments are differentiated by the spin and CP-properties of the particles being searched for, the couplings that are being exploited (e.g. to photons, electrons or gluons), and the assumed origin of the particles: terrestrial, solar or the galactic dark matter halo. The leading experimental bounds on dark matter axions coupling to photons for the well-motivated axion masses around $\simeq 3\,\mu$eV are from the US-based ADMX microwave cavity haloscope which already has some UK participation. Other variations on such cavity haloscopes have been proposed to increase sensitivity to the axion couplings and to increase the rate at which axion masses can be scanned e.g. dish antenna (BRASS), dielectrically-loaded cavities (MADMAX), LC circuits (ABRACADABRA), etc. In the same mass region, the UK participates in QUAX which searches for halo axions via the axion-electron coupling by measuring induced oscillations of the magnetization of various media. For dark photon and moduli dark matter, the details of the appropriate experimental set-up may change (e.g. magnetic fields are no longer necessary), but the fundamental detection strategies are similar.

Finally, as mediators of new forces, all the possible new super-light bosons can have measurable effects independent of any possible role they may play as all or part of the dark matter. In this case, it is advantageous to terrestrially source the new forces by oscillating suitable SM configurations to which the new bosons couple before subsequently being detected using similar experimental arrangements to those for haloscopes.

In all cases discussed above, low-noise resonant detection electronics operating at microwave frequencies with a high scan rate is the key enabling technology, and forms the focus of this proposal.

3 Experimental Considerations

A particularly sensitive hidden sector search technique uses an electromagnetic resonator in which photons from hidden sector particle conversion excite one or more of the resonator modes. To be sensitive to axions in particular, the resonant structure must be threaded by a strong magnetic field. Excitation of the resonator modes can be detected in a variety of ways, depending on the target mass, and therefore frequency range, of the experiment. Using quantum-noise limited electronics and a dilution fridge operating at 10-100 mK, a range of hidden sector particle masses can be probed, resulting in either the discovery of new physics or improved constraints on the underlying theoretical models. The need for long integration times and low systematics, combined with the need to sweep wide bands with high spectral resolution, $\Delta f/f \sim 10^{-6}$, means that an experiment must be designed so that statistically significant results can be achieved on a reasonable timescale. Even with quantum noise limited electronics, the total observing time required to cover a decade in mass is of the order 1-2 years using a single resonant mode as a detector. Combined with the fact that, in general, different cavity configurations and readout electronics must be used to cover different parts of the spectrum, the search for hidden dark matter needs to be a truly global and collaborative effort. Because of the long 'observing times' required, an increase in scan rate of a just a factor of a few across a large mass range would have a major impact on global capability, and therefore there is an opportunity for innovation, particularly in the application of quantum-circuit technologies and in the design of novel resonators.

To undertake statistically significant measurements requires the availability of ultra-low-noise electronics. In some cases, quantum noise limited phase coherent amplifiers are available, but this is not true of most of the frequency search range. In addition, even quantum noise limited amplifiers are at the limit of what is needed, and therefore the use of squeezing, and other quantum measurement techniques is highly desirable. A new generation of superconducting quantum electronics is starting to become available, and this opens the door to making fundamental observations of hidden dark matter. Given the extreme sensitivities needed, and the fact that the whole purpose of the experiments is to be able to make definitive statements about the existence, or otherwise, of fundamental physical processes, it is necessary to carry out experiments with a mindset akin to the measurement of fundamental constants, or the establishment of metric standards. This is the spirit of our application. The combination of dark matter theorists, ultra-low-noise instrument design specialists, quantum technologists, and a national standards agency provides a core team with all of the expertise, facilities and working practices needed to carry out a high-profile programme of work.

Experimental work is often described in terms of measuring the coupling parameter g between hidden sector particles and photons, which scales linearly with particle mass. Different theoretical models lead to different values of scale factor, and the aim is to measure or at least place limits on g. The actual mass is very poorly constrained, and could be anywhere in the range peV to meV. Standard production mechanisms relating the abundance of axions to the closure density of the Universe imply masses of the order of μeV, although, such modeling comes with signicant systematic uncertainties. A mass of order meV is suggested if the intergalactic magnetic fields of order 10^{-15} G inferred from observations of TeV blazars were in fact generated by axion-induced magnetogenesis at the QCD cross-over in the early universe. The wide range of possible mass means that experimental measurements need to cover kHz to THz, which is a substantial problem, even when a number of international teams work together. Most experiments to date, for example ADMX, have concentrated on frequencies in the range 500 MHz to 5 GHz, corresponding to masses of 2 μeV to 20 μeV. Indeed, these have been the only laboratory-based experiments to place experimental constraints on theoretical models. This frequency range is convenient because electromagnetic cavities are of reasonable size, and can be contained within the bore of a high-field magnet. A major effort is now needed to push experiments to much lower and much higher frequencies.

Low-frequency experiments (5 kHz to 500 MHz, 20 peV to 2 μeV) have the problem that resonant cavities are large, high-strength magnets are needed because the field-axion coupling strengths are low, and the provision of ultra-low-noise instrumentation working in a laboratory environment is exceedingly difficult. High-frequency experiments (500 MHz to 1THz, 2 μeV to 4 meV) have the problem that single longitudinal-mode resonant cavities become tiny, and the provision of quantum noise limited instrumentation becomes difficult. A variety of schemes have been proposed for overcoming these challenges, some of which seem secure while others are more speculative. A central element of our proposal is to understand how to increase the mass range of dark-matter searches through the use of quantum technologies, and how to speed up searches to enable large mass ranges to be covered on reasonable time scales. Our focus is on using quantum-theoretic superconducting circuits, novel resonators, and long-wavelength optical techniques in the search for dark matter. We emphasise that our guiding philosophy is to ensure that experiments are as clean as possible, avoiding possible artifacts, for example solid-state processes in amorphous and contaminated dielectrics, that might degrade the credibility of any positive result.

Although our focus is on resonant quantum-electronic techniques, we are acutely aware that there is a strong overlap with certain possible laser-based approaches. Indeed, the advent of Chirped Pulse Amplification (CPA) (for which Mourou and Strickland were awarded the Nobel prize in physics this year) has made extreme laser intensities available for laboratory-based studies. At such high intensities, the electric field at the laser focus becomes so large that new physics beyond the standard model may be accessible. The UK has been a key developer of CPA technology, namely the Gemini laser at the Rutherford Appleton Laboratory; and in the next few years a new set of laser facilities are due to open for users' experiments. These are the Extreme Light Infrastructure (a EU funded project) and the Apollon laser at Ecole Polytechnique (France). We are therefore now in a strategic position to develop a new type of dark matter search experiments whereby hidden particles can be produced directly in the laboratory. Axion and ALPs searches have also been performed by directly producing them using conventional, lower intensity, laser systems (e.g., ALPS at DESY). While this approach does not rely on assumption on the nature of dark matter, it has been so far significantly less sensitive than previous methods (due to the tiny efficiency in producing axions by the Primakoff effect). However, thanks to CPA technology, QED effects become important to the point that copious production of light scalar or pseudo-scalar by the Hawking/Unruh effect is possible. Given the potential importance of these laser based techniques, and their possible combination with quantum electronics, we will assess their relationship with the conventional approaches during the early stage of the work.

4 Programmatic Considerations

The programme of the work would be broadly as follows:

Stage 1 (4 months): The first stage of our work will focus on identifying the most experimentally secure and technologically realistic way of extending the frequency range of dark matter experiments within a laboratory environment. Clearly, for an experiment to be valuable it must be able to provide traceable quantitative results, and for it to be definitive it must be clean and free of artifacts. The first milestone will be to review possible and proposed methods, to discuss with international groups their experiences, and to carry out numerical simulations of possible experimental configurations. These simulations will be compared against dark-matter models to identify experimental techniques suitable for pushing dark-matter experiments into hitherto unexplored regions of parameter space, and for maximising the science return across the full range of accessible hidden sector physics.

During the first stage of the programme, we would also consider experimental configurations, identify the operating context of the work, and present a requirements document that can drive technology development. For low frequencies, we would undertake an assessment study of experimental configurations such as discrete-element (L-C) resonators, parallel-plate systems with closed-loop feedback, cavity resonators, SQUID amplifier and electronic readout needs. For the high frequencies, we would consider Fabry-Perot type resonators, discrete element and distributed superconducting parametric electronics, SIS down conversion with SQUID IF amplification. An interesting possibility relates to the use of high power lasers in blank wall experiments. Our study would not be complete without proper attention to the use of quantum sensors in enabling more sensitive experiments of this kind, and their close relation to dark resonant cavity experiments. The influence of axions can be handled through the inclusion of additional terms in Maxwell's equations, and this enables the coupling between the active volume of the experiment and the quantum readout electronics to be optimized in a formal way. Indeed, the use of quantum theoretic methods for analysing the expected behavior of experiments is an intellectually fruitful area of work in its own right. Of particular interest is the possibility of using a squeezed state in the main cavity to overcome the quantum noise limit, perhaps achieved through superconducting parametric up/down conversion. Further considerations relate to the use of arrayed cavities and correlation methods in the case of hidden particles with long coherence lengths. A high field magnetic is needed in most cases, and sensitivity calculations and experimental considerations will indicate the best technological solution for the targeted science. Finally, when considering the best approach, read out and scanning strategy is central, as well as data analysis methods. There is ample opportunity for innovation; for example, placing the low-noise electronics in a separate refrigerator to the main magnet, allowing the fast turn around of different experimental configurations without warming up the primary operating volume.

In summary, the first stage of work would be used to identify an optimized scientific programme, to identify innovative fundamental methods for carrying out dark matter searches, and to outline the design of an optimized experimental programme. Crucially we will converse with overseas colleagues to understand how we can best to contribute to the international search effort. We will hold a UK conference/workshop on resonant dark matter physics, and invite speakers from international teams.

The deliverables will be formal reports on the main areas of work. One particular deliverable will be a requirements document that will be used for steering subsequent technology development.

Stage 2 (4 months):

During this stage of the programme, we would down-select the technology required, and initiate technology development work packages. Rather than pursuing a wide range of technology, we will focus those specific items and techniques needed to deliver on the science target identified in Stage 1. Roughly speaking, the developments will break down into 'resonator and magnet configuration and design', 'superconducting readout electronics', 'cryogenic readout and AC signal processing', 'off-line data analaysis', and 'system design' including matters such as magnetic shielding vibration and EMI suppression' .

As a related activity we will create the conceptual design of a prototype low-temperature test facility. This test facility will be used later to test the various technological developments in a representative environment: assessing matters such as stability, 1/f noise, Allan Variance, magnetic shielding, microphonics, etc., in an ultra-low-noise configuration. The test system will also ideally be designed to allow experimental work to begin in the UK as a precursor to a full science-grade instrument. We note that the main international experiments find it difficult to carry out ongoing technology development because their high-field cryostats are tied up science observations. By having a test bed available, we can develop our own ideas, and perhaps provide selected overseas teams with tested technology for use in their own experiments.

Stage 3 (12 months):

In this stage of the the programme, we would design, build and test those technological developments identified in Stage 1. We would also design and build the UK test facility. This will require not only engineering design and production work, but also creating the necessary laboratory infrastructure at the chosen site. Throughout the whole of this activity, the technical work will be strongly coordinated with the work of the theory team to understand the implications of choosing certain operational parameters and methods, and the impact of technical performance achieved on the science case. We would also extend work on creating and simulating the necessary statistical methods for analyzing data. We would pay particular attention to matters such as calibration, drift, and extracting signals from non-stationary noise. During this stage we would continue to work with overseas colleagues, carrying out tests at overseas sites where appropriate. For example, a key requirement may be to ensure that the developed technology can work in, or near to, a strong magnetic field. Although the UK test facility could be equipped with a reasonably strong magnet, any testing of electronics in a high-field 10-30 T region, would be carried out using national facilities or operational experiments.

Stage 4 (12 months):

At this stage, a complete laboratory test facility would be operating with readout electronics. An extensive period of work would then follow to understand the operation and limitations of the signal chain at the system level. This will provide numerous insights into how best to operate experiments. For example, do we achieve the quantum limit, can we push below the quantum limit, what are the noise statistics of the data, how do we best calibrate and analyse the data, what is our absolute calibration reference, and what long-term stability can be achieved? The ambition will be to provide web-based access to the real-time data stream so that the analysis group can work on the data in the comfort of their own offices, and provide feedback to the experimentalists on a week-to-week basis, driving technical refinement such as filtering, shielding, wiring, etc. This will allow the idiosyncracies of the experimental various methods to be revealed, and fed back to the experimentalists to allow refinements of the test system. For example, a simple test would be to inject an exceedingly small test signal to see if it can be recovered from the noise; this would then lead to optimised methods for scanning and interleaving data blocks, and for applying Bayesian search and noise reduction techniques: there are many possibilities. Towards the end of this phase, we will already know whether the test system could be used to make limited science grade measurements. If so, a restricted set of observations with long integration times would be carried out. At the end of the initial 3-year programme, we would work on the science case and create the conceptual design of a major UK experiment. A technology roadmap would be created, and a comprehensive white-paper written, which would steer the way for a bid to UK funding agencies for a UK based hidden-sector science facility. Because of the focused and quantitative nature of our work, we would be able to present a firm well-defined project proposal to STFC.

Overall, the deliverables from the first 3 years of work will be the formation of an active team of UK scientists and technologists, the initial development and application of relevant quantum sensor technologies, the creation of an ultra-low-noise test bed in the UK, the conceptual design of a major UK science facility, and a white paper that recommends the way forward in experimental hidden sector physics in the UK. Because a number of PhD studentships will be requested, we would also be educating a future generation of experimentalists who could take forward this important area of science on the 5-15 year timescale.

Stage 5 (24 months):

We are not asking for stage 5 of the programme to be funded in our initial bid. Although we have many ideas about the kinds of experiments that could be built, we do not have a sufficiently detailed, quantitative understanding of the optimum science case, or indeed how best to use and develop the various possible quantum technologies to deliver on the science case. We much prefer a staged approach, where we carry out the programme of work described above and then propose a specific instrument, or related instruments, to STFC. By the end of Stage 4 we will have developed and demonstrated the needed quantum technology and systems engineering to TRL 5, and then the work would cease to be a development programme, and would become a fully fledged construction project, as defined by STFC. By following this proposed route, Stage 5 would become a fully costed and managed project to build a specific instrument, which would fall under the usual research-council requirements for formal schedules, management structure, costings, oversight, etc. At the proposal stage, we would also propose specific arrangements for making science-grade data available to participating groups, and the wider scientific community, under the usual rules governing the fair use of national infrastructure.

5 Governance and Management

The overall programme would comprise a number of work packages allocated to the participating institutes. The work package leaders would be responsible for coordinating the work described in their own package across the contributing partners. Each work package would have its own well-defined list of inputs, activities and deliverables, with well-defined start and end dates. The deliverables would take the form of reports, designs, experimental results, papers, etc. The work package descriptions would evolve as key project milestones are met.

The overall programme would be managed through fortnightly telecons, with verbal progress reports and actions being dealt with in the usual way. A web-based repository of management, scientific, and technical information would be created for team members. One-day face-to-face project meetings would be held twice per year, perhaps three times in the first year, which would rotate around the participating institutes. At the face-to-face meetings, scientific reports would be given, results and progress discussed, and strategic decisions made. All meetings will be open to all participating members of the collaboration. The major project milestones would be listed and timetabled at the outset, and would take the form of a Conceptual Design Review, Design Review, Test Readiness Review, Data Analysis Review, etc.

The project management structure would be as flat as possible, but coordination would be needed to ensure that the project proceeds in a focused and effective way. We emphasise that it is firmly not our intention to create a loose collection of individuals, but to create a strongly coordinated team, with a shared vision to deliver on a specific experimental vision. To ensure that a single vision is created and a single coherent team is maintained, the work of the Consortium would be actively coordinated by Withington (Cambridge) and Daw (Sheffield). To create a common understanding of project structure for Stages 1-4, an MoU will be agreed between all relevant parties before the project begins, and this will address matters such as publications policy, IP, etc.

In addition, to ensure that the UK team interacts with the international community, a two-day conference/workshop will be held in the UK early in the first year of the proposed programme, and international speakers will be invited. It is then expected that further exchange visits with overseas sites will take place. Ideally, we would also like to make provision for graduate students to make extended technical visits overseas.

6 Cost

Taking into account staff, equipment, laboratory costs, and international travel and collaboration, we estimate that a world-class activity covering Stages 1-4, years 1-3, having a high international profile, would cost £4.5M. The initial programme described above would last for 3 years, and would provide a solid foundation for the construction of a quantum-technology enabled, hidden sector search facility in the UK. A complete plan for the construction of a science-grade instrument would be fully assessed, documented, and costed during the final quarter of year 3. We envisage that the construction of a full science grade instrument would take place in years 4 to 6, and that the cost to the end of commissioning, but before operations, would be an additional £5-7M. We would carry forward as much technology as possible established in Stages 1-4 through to the full construction project in Stage 5.

7 Impact

We are confident of being able to build a strong impact case as part of our application. In additional to matters relating to scientific excellence, graduate and undergraduate teaching, and public outreach, we have substantial connections relating to national and overseas government laboratories, standards agencies, international space agencies, formal industrial contracts with large companies, and small start-up enterprises. Above all, the proposed programme is intrinsically an outreach activity, because it brings together a team of people from different scientific backgrounds who on the whole have not worked together in the past.

8 Proposers Experience

To carry out the proposed programme on quantum technology enabled hidden sector physics, we have assembled a core team of experts who cover the full range of work needed. A key consideration is that in addition to having particle physicists and experts in the relevant quantum technologies, it is necessary to have contributors who can take the quantum technologies and turn them into a complete fully-engineered ultra-low-noise experiment that performs in a clean, reliable and robust way.

Our team is as follows:

Dr Ian Bailey (Lancaster): is a particle and accelerator physicist who led the proof-of-principle CASCADE dark photon 'light shining through a wall' search at Daresbury Laboratory using microwave cavity resonators, and is developing a range of simulations of axion and dark photon fields in cavities and novel environments such as photonic structures and plasmas.

Prof. Xavier Calmet (Sussex): is a high energy theorist with very broad research interests ranging from particle physics, cosmology and gravitational physics including quantum gravity, dark matter and black holes to the foundations of physics and information theory. After graduating from the University of Karlsruhe in 1999, he moved to the Ludwig Maximilian University of Munich where he obtained his Ph.D. in 2002. He was then a postdoctoral scholar successively at the California Institute of Technology, the University of

North Carolina at Chapel Hill, the Free University of Brussels, the University of Oregon and the Catholic University of Louvain.

Dr Edward Daw (Sheffield): received his Ph.D. from M.I.T. in 1998 on the first result of the ADMX axion search. His research foci are dark matter searches through his continuing active collaboration on ADMX and through previous participation in the ZEPLIN2 search for WIMPS, and gravitational waves through his group working on LIGO. A recurring theme is filters and feedback for high Q resonators and phase locked loops.

Prof. Gianluca Gregori (Oxford): Prof Gianluca Gregori (Oxford): has since 2007 led a group in high-energy-density laboratory astrophysics. He has worked on laser experiments to study the generation and amplification of magnetic fields to mimic processes occurring during proto-galactic structure formation. Prof Gregori has also led experiments that have explored cosmic ray acceleration processes in laser produced turbulent plasmas. He is visiting Professor of Astrophysics at the University of Chicago (since 2013) and distinguished visiting Professor at Ecole Polytechnique (under the Gaspard-Monge programme) for 2018-19. He has been elected Fellow of the Institute of Physics (2017), and Fellow of the American Physical Society (2016).

Prof. Ling Hao (NPL): is a Principal Research Scientist who will lead the QSFP superconducting activity at NPL. She has extensive experience and expertise on superconducting quantum interference devices (SQUIDs), microwave resonators and measurement, nano-electromechanical resonators (NEMS) and many other aspects of nanoscale science.

Dr Edward Hardy (Liverpool): is a theoretical physicist working on the phenomenology of new light particles beyond the Standard Model. The focus of Edward's work is to understand which regions of parameter space are theoretically well motivated, and are compatible with existing observational constraints. For the QCD axion this involves determining the masses and couplings for which such a particle can make up the measured dark matter abundance, and for other states it involves calculating the constraints on their couplings from, for example, observations of the evolution of stars.

Dr Edward Laird (Lancaster): is an experimentalist in the field of quantum electronic devices. He was part of the team that developed the singlet-triplet qubit and thereby established experimental spin qubits in quantum dots. More recently, he has exploited quantum devices for measuring delicate nanomechanical resonators. He has worked with semiconductor quantum dots, carbon nanotubes and fullerenes, and superconducting devices. Recently he pioneered a SQUID amplifier for radio-frequency readout of a quantum dot.

Dr Peter Leek (Oxford): is a Lecturer in Physics at the University of Oxford. He is an experimental expert in superconducting circuits for quantum computing, is the superconducting lead in the UK's national quantum computing research hub 'NQIT', and is the founder of the quantum computing spin-out company 'Oxford Quantum Circuits'. He has particular expertise in the field of 'circuit QED' in which superconducting qubits are coupled to high quality superconducting microwave resonators for quantum optics and computing research.

Dr. Rhys Lewis (NPL): is Director of the Quantum Metrology Institute at NPL, and has experience and expertise on quantum sensor technology, and also strategy, management and the coordination of quantum-based projects.

Prof. John March-Russell (Oxford): is a theoretical physicist working in all areas of Beyond-the-Standard-Model particle and astro-particle physics, and aspects of condensed matter theory. A PhD from Harvard was followed by postdoctoral fellowships at Princeton and UC Berkeley, and faculty positions at IAS Princeton, CERN, and Oxford. He has received major prizes and awards from NATO, the Sloan Foundation, the Keck Foundation, the US Department of Energy, the Simons Foundation, the AHRB, the Galileo Institute, and the Royal Society. He was a Visiting Professor at UC Davis, UC Berkeley, and Stanford University (long-term), and holds a Distinguished Visiting Research Chair at the Perimeter Institute in Canada

Prof. Y. Pashkin (Lancaster): is Professor of Experimental Condensed Matter Physics at Lancaster. He is a pioneer of solid-state quantum computing who performed ground-breaking experiments with superconducting quantum circuits. His expertise also includes the physics of nanoelectronic devices, quantum metrology, ultrasensitive electrometry and nanoelectromechanics. He is a Fellow of the Institute of Physics and was the holder of the prestigious Royal Society Wolfson Research Merit Award.

Dr Edward Romans (UCL): Dr Edward Romans is a resident PI in the London Centre for Nanotechnology (LCN) and an Associate Professor in the Dept of Electronic and Electrical Engineering at University College London (UCL). Prior to moving to UCL, he was a Senior Research Fellow at the University of Strathclyde and a PhD student in the Low Temperature Physics Group at the University of Cambridge. He was a visiting Research Fellow at the National Institute of Materials Science in Japan (2003), and he held a personal EPSRC Advanced Fellowship (2003-8) to develop new types of SQUID-based sensors. He has considerably expertise in Josephson junctions, SQUIDs and superconducting electronics.

Prof. Subir Sarkar (Oxford): is Head of the Particle Theory Group in the Rudolf Peierls Centre for Theoretical Physics. He has a long interest in physics beyond the Standard Model, in particular particle dark matter. He received the IUPAP- Homi Bhabha award for Astroparticle Physics in 2017.

Dr Stephen West (Royal Holloway, UCL): is an astro-particle theorist with a long standing interest in beyond the standard model physics with a particular focus on the development and analysis of novel models of dark matter, hidden sector physics and early universe cosmology.

Prof. Stafford Withington (Cambridge): heads the Quantum Sensors Group in the Cavendish Laboratory. He overseas an extensive facility for developing superconducting sensors, from microwave to x-ray wavelengths, for ground based and space based astrophysics and Earth Observation. His team is playing a key role in developing the superconducting focal plane technology (30-200 μm) for the ESA/JAXA cooled-aperture space telescope SPICA. During the last 30 years he has developed many advanced instruments for ground-based and space-based astrophysics, and worked with many industrial partners and government laboratories. He has held a number of appointments, and holds a Visiting Chair at the University of Oxford. Early in his career, he worked with Rolls Royce Engines (1971) Ltd on the Olympus 593 engine (Concorde), and Marconi Space and Defence and Ferranti Microwave Electronics on various complex aircraft systems.

9 Institutional Experimental Facilities

The team members listed above bring extensive expertise and facilities for defining the science case, developing the needed technology, and building a world-class instrument. In addition to the considerable expertise in particle physics, the team brings extensive facilities. These have been established over many years through STFC investment in well found laboratories, and in recent times through EPSRC and institutional investment in superconducting quantum technology:

The Quantum Sensors Group at the **Cavendish Laboratory** was established 15 years ago through a major donation of the Thin Film Division of Oxford Instrument to the University of Cambridge. It has expertise and IP in superconducting sensors and electronics going back 30 years, in areas such as TESs, SIS mixers, SQUIDs, optical photon counting STJs, KIDs, DROIDs, etc. It's repetoire includes complex multi-layer microcircuits using materials such as Ti, Nb, Ta, Al, Mo, NbN, NbTiN, Hf, Ir as well as normal metals and oxides on SiN and SoI micromachined structures. In recent times, the Group has worked extensively in areas such as multi-layer superconducting science, superconducting resonator physics, the development of ultra-low-noise detectors for the FIR, and chip spectrometers for Earth Observation. It is currently working with Airbus on techniques for deploying sensitive superconducting electronics on space instruments, and has been selected as the European provider of superconducting focal-plane flight hardware for the space telescope SPICA. As part of the Government's recent investment in Quantum Technology Capital (EPSRC), the Quantum Sensors Group has installed a new dual-chamber UHV sputtering machine (£0.7M), with wide capabilities for fabricating quantum devices. This has initiated a programme in superconducting parametric electronics. All of the Group's device processing expertise and facilities and cryogenic test equipment (several fridges covering the range 10 mK to 100 mK) will be available to the proposed programme.

The **University of Sheffield** has microwave electronics up to 6 GHz, including vector network analysis, microwave CAD design, 4 GHz mixed signal (4 analog channel, 32 digital channel) oscilloscope. Digital signal processing with FPGAs including hardware description langauge (VHDL) design R&D. Low noise microwave amplification and heterodyne receiver design. Shared space in a 4x7m lab - able to bid for more space for funded projects. Part time Ph.D. student starting on axions in September 2019.

The **University of Lancaster:** has invested heavily in research infrastructure for quantum technologies. The in-house nanofabrication facility for quantum electronic devices is equipped with electron-beam lithography and a range of deposition and plasma processing machines. The IsoLab, opened in 2017, is a specialised characterisation facility housed in a custom building with ultralow acoustic, mechanical and electromagnetic noise. The Lancaster team has two cryogen-free dilution refrigerators capable of reaching temperatures below 10 mK in a large experimental volume and has access to home-built combined dilution/demagnetization fridges with sub-mK base temperatures and superconducting magnets, all housed in electromagnetically shielded rooms. LU researchers have complementary expertise in ultra-low temperatures, physics of superconducting quantum devices, microwave engineering and material science and are core members of the recently renewed European Microkelvin Platform, through which we access expertise in Europe's leading cryogenics labs. LU has experience of ultra-low-noise characterization of various kinds of superconducting devices, including qubits and SQUID amplifiers operating in the microwave (5-10 GHz) and RF range (200 MHz). Our team's expertise in quantum measurements at low temperature has led to recent grants from EURAMET to develop wideband Josephson parametric amplifier technology and the ERC to develop quantum nanomechanics.

The UK's **National Physical Laboratory** is one of the leading National Measurement Institutes in the world and in 2015 NPL established its Quantum Metrology Institute (QMI). NPL QMI can provide collaborations with a critical mass of NPL quantum scientists and is continuing to grow its capability in this area to support the UK national programme. With specific reference to this proposal, the Quantum Detection Group has extensive capability in quantum sensors and their application to fundamental physics. QMI scientists have a well-developed capability in using SQUIDs as quantum detectors for single photons and spins. Metrology for superconducting qubits and cryogenic high Q microwave resonators is another area where NPL is highly experienced.

The **University of Oxford** has recently opened the new Physics department Beecroft building, which contains >1000 m2 of brand new state-of-the-art atom/optics and cryogenic laboratories, including a suite of >100m2 of laboratories dedicated to mK dilution refrigerator experiments for quantum technology research such as superconducting circuits and detectors. The department also maintains a suite of 100m^2 of class 100-1000 research cleanrooms, and PL has recently acquired a (£0.6M) UHV e-beam evaporation tool for fabrication of superconducting qubits, through the EPSRC Quantum Technology Capital grant QUESST (EP/N015118/1). The Department of Physics is also in the process of upgrading the high-power laser laboratory, which will be hosting a 10 J, nanosecond pulse-length, laser system coupled to a multi-TW high power laser. Part of this work is funded by EPSRC grants EP/N014472/1 and EP/M022331/1. This laboratory will be used for development of axions and ALPs generation/detection techniques to be implement at the Extreme Light Infrastructure and other ultra-high-power laser facilities.

University College London (UCL) has a strong base in solid-state Quantum Technology centred around the UCL Quantum Institute (UCLQ) which brings together researchers from UCL Engineering, Computer Science and Physics. UCL was awarded £13m to set up an EPSRC Centre for Doctoral Training (CDT) in Delivering Quantum Technologies with an additional £12m to support QUES2T (solid state based quantum research including academic and commercial partners), and a new skills hub in Quantum Systems Engineering. Work at UCL would be based at the interdisciplinary London Centre for Nanotechnology (LCN) which houses 340sqm of cleanroom space (up to Class 100) including a full range of film deposition, patterning and characterisation equipment such as SEM/AFM. For nanodevice fabrication, LCN has two e-beam lithography tools (up to 100 keV), two Carl Zeiss XB1540 "Cross-Beam" Focused-Ion-beam (FIB) microscopes and a Carl Zeiss He/Ne FIB microscope with 2 nm resolution. UCL have extensive experience in the design, fabrication, readout and computer modelling of Josephson-based devices at both dc and rf frequencies, especially ultra-small Josephson-based devices such as Nb nano-scale Superconducting Quantum Interference Devices (SQUIDs) and nanobridge-based single flux quantum devices for cryogenic readouts. LCN has a full range of cryogenic systems and instrumentation for measuring and testing such quantum devices at ultralow temperatures down to 10 mK.