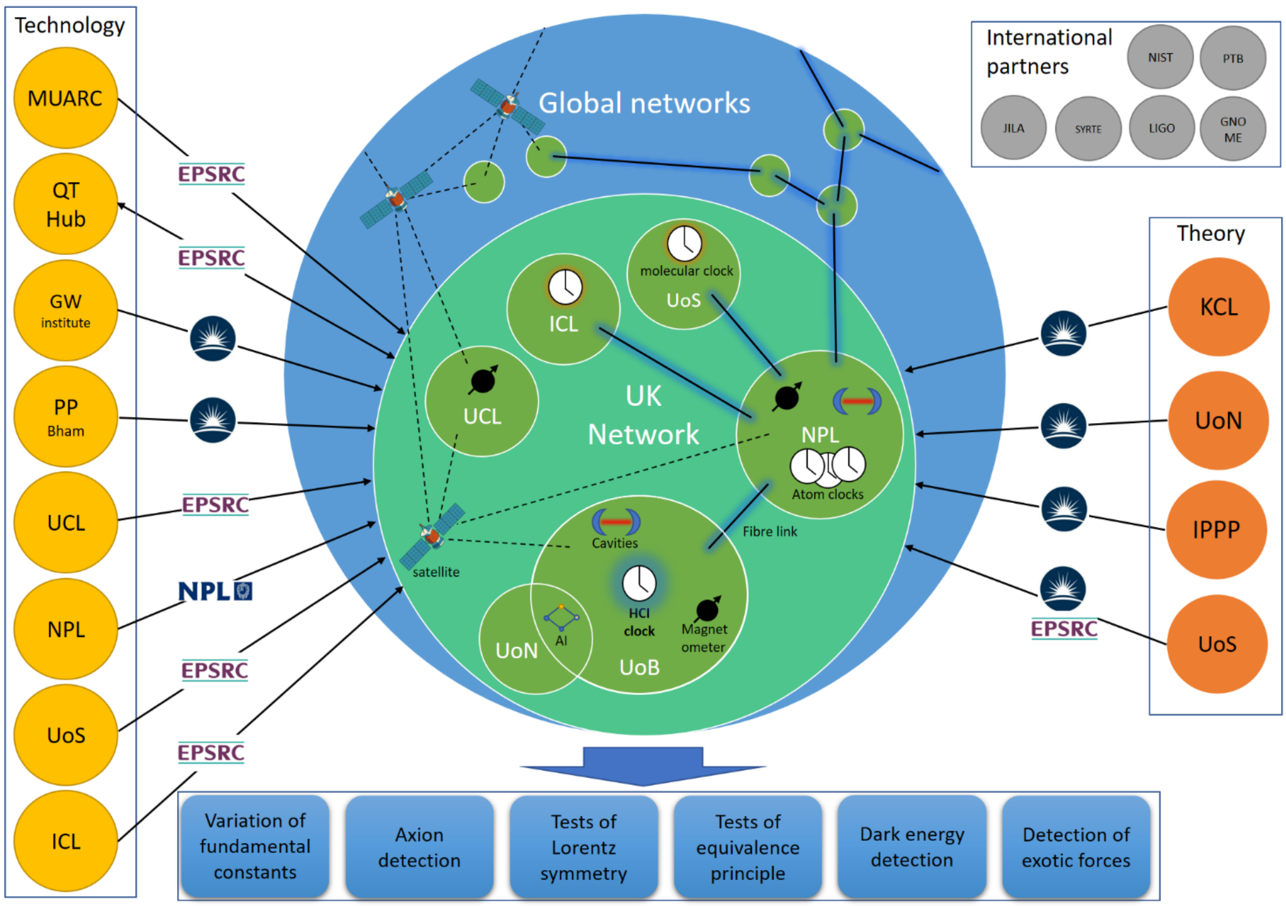
QSNET: NETWORKED QUANTUM SENSORS FOR FUNDAMENTAL PHYSICS

We propose to create an expandable network of innovative quantum sensors across the UK and with links into international networks. The sensors will include atomic and molecular clocks, magnetometers, atom interferometers and optical cavities. Individually, these sensors allow searches for dark matter and dark energy, variations in fundamental constants, Lorentz symmetry breaking, new forces, tests of the equivalence principle, neutrino oscillations and quantum gravity. Collectively, the network will allow greater sensitivity and also enable detection of transient effects through correlations in the data from different locations.

As a large-scale collaborative project supported by the Strategic Priorities Fund, the network will enable world-leading physics measurements by bringing together expertise and linking existing investment in quantum technologies from the Midland Ultracold Atoms Research Centre **(Birmingham & Nottingham)**, the Quantum Hub for Sensors and Metrology **(Birmingham),** the Gravitational Wave Institute and Particle Physics Groups **(Birmingham),** the Atomic, Molecular, Optical and Positron Physics Group **(University College London),** the Quantum Metrology Institute **(National Physical Laboratory)**, the Sussex Centre for Quantum Technologies **(Sussex**) and the Centre for Cold Matter **(Imperial College London)**. This world-class expertise is backed by substantial support from the UK theory community, provided by King's Theoretical Particle Physics and Cosmology Group **(King's College London)**, the Centre for Astronomy & Particle Theory **(Nottingham)**, the Institute for Particle Physics Phenomenology **(Durham)** and the Theoretical Particle Physics group **(Sussex)**. The unique breadth of expertise of QSNET therefore encompasses world-leading theoretical and experimental competences in Ultracold Atoms, Quantum Sensors, Quantum Metrology, Gravitational Waves and Particle Physics research. QSNET will provide access to cutting-edge quantum sensors for the entire UK community and has created substantial interest in international partners including from Europe, Canada and Australia.

QSNET will be an **internationally unique and world leading programme**, the first worldwide to provide an integrated and networked approach using a range of different sensing modalities, which opens up completely new capabilities in cross-correlating different measurements for tests of fundamental physics.

Key to the proposal is the networked approach, in which multiple quantum sensors will be linked. The **clock network** will feature experiments on cold highly-charged ions (HCI), high accuracy optical atomic clocks and high precision molecular spectroscopy systems. This unique network of different clocks allows to probe a large range of theoretical models. HCI are the most sensitive systems to variations of the fine structure constant α. When linked to other clocks to provide a



frequency reference, deviations can be monitored that allow us to perform tests of fundamental symmetries (e.g. Lorentz symmetry) and probe new very light fields linked to a hidden sector, dark matter or new forces, with unprecedented sensitivity. Built within a newly-established Centre for Fundamental Physics (CFP) at the UoB, this is a very ambitious and complex experiment that can be realised only with a large-scale collaborative programme, and provides the UK with a unique opportunity to have impact and leadership in a new field. NPL is uniquely positioned to support the clock network in these next-generation measurements by developing the UK's leading atomic clocks to provide a state-of-the-art frequency reference for the comparison. Additionally, NPL will be able to carry out complementary measurements with its own local network of atomic clocks, and connect with European networks for fundamental physics tests over large baselines. The clock network will be completed with an atomic clock and a molecular ion clock at UoS and an ultracold molecular fountain clock at ICL. Molecular transitions are particularly well suited for searches of changes in the electron-to-proton mass ratio. Linking high resolution molecular spectroscopy (UoS and ICL) with the other clocks in the network provides an unparalleled range of theoretical models that can be experimentally explored.

This large-scale experimental platform for atomic clocks will be complemented and synchronised with other networks that can measure exotic spin-dependent interactions and neutrino oscillations (atomic magnetometers), test general relativity and gravitation (clock-transition-atom interferometers) and detect dark photons (optical cavities).

The **magnetometer network** will include the CFP, NPL and UCL nodes and will target tests of Local Lorentz Invariance, CP and CPT symmetries, the detection of spin-dependent forces, and the search of effects of axion stars or Q-balls transiting through the Earth. At CFP, two atomic co-magnetometers based on alkali-metals (K, Rb) and a noble gas mixture (Xe, Ne) will be developed. The use of this mixture will boost the attainable sensitivity while reducing the impact of external magnetic fields. In a similar but complementary fashion, the NPL node will develop a novel spin co-magnetometer, based on (Cs, Rb) and (He, Xe), which is characterized by long spin coherence times. The above co-magnetometers target a precession-frequency stability of better than 7 nHz and an absolute accuracy at the sub-ppm level. The UCL node will design, realise and test an atomic magnetometer with sensitivity better than 10fT/sqrt(Hz) in an unscreened environment, which has the important advantage of avoiding any possible form of attenuation of the axion field determined by the magnetic shields. The network will provide the UK reference for the GNOME global network and will be a powerful tool for rejection of systematic noise.

A clock-transition-**atom interferometer** will be set up at the CFP to test violations of the equivalence principle with a factor one million improvement over existing tests of quantum effects in this area. This will be enabled by the use of transitions in the visible spectrum instead of in the microwave regime. Additional improvement factors will be provided by employing optimal interferometric schemes developed in the UoN node. These will include design of new interferometer types, use of engineered quantum states and different probing configurations.

The CFP will be completed by developing a **cavity-**based light-through-the-wall experiment that will be used to test the coupling of dark matter with photons. The setup will exploit techniques developed by the gravitational-wave community to overcome the existing limits on the coupling coefficient between axions and photons by an order of magnitude in the axion mass range from 10^{-13} up to 10^{-11} eV.

Networked quantum sensors provide a new and promising way to search for fundamental physics. By linking together and synchronising instruments, an initial phase UK-scale network can achieve an effective detection baseline of hundreds of kilometres, while maintaining modest sensor sizes, to probe different couplings with dark matter and exotic fields or to make precise comparisons between distant experiments. In this spirit, QSNET will develop a **world-unique fibre network** between the NPL, CFP, ICL and UoS and a **GPS network** between the CFP, NPL, UCL and UoN, therefore realising the core of a multifunctional national quantum network, which can be easily expanded. This in turn will be implanted into existing global networks, allowing the UK to play a leading role in global measurement campaigns. Importantly, our expandable, interdisciplinary and connected approach will be the ideal vehicle for the training of the future generations through the establishment of a **dedicated training network**.

The consortium will benefit from **strong theoretical physics expertise**, which will be essential in guiding the overall experimental approach as well as in the analysis and interpretation of the data. Networked quantum detection opens new and exciting avenues for the theory community. A prominent activity, led by the UoS unit, will be the development of new theoretical tools for the exploitation of networked quantum sensors and the design of novel schemes to take advantage of correlated networks and to investigate the role of entanglement in probing fundamental physics and quantum gravity.

The UoS unit will concentrate also on the development of tests of fundamental theory such as quantum gravity using effective field theoretical methods to do model independent calculations and perform a comprehensive study of bounds on models with very light boson fields. Particular attention will be devoted to searches for time variation of fundamental constants which could help to understand the unification of all forces. This is an area of fundamental physics greatly enabled by the proposal, especially by the huge leap in sensitivity to α provided by the HCI utilising Sm14+. This HCI is three orders of magnitude more sensitive to the variations of α than are neutral atoms and singly-charged ions, and can measure linear variations and also hypothetical oscillations as well as occasional jumps in the parameter. The same HCI will be used also for Lorentz violation tests, as already its ground state enables sensitivities that can be reached only by excited states of standard clocks. In a complementary fashion, molecular clocks can provide a direct measurement of the stability of the electron-to-proton mass ratio independent of the fine-structure constant. Taking advantage of the network, we will compare the vibrational transition frequencies of two molecular clocks (ultracold CaF and molecular nitrogen ion) using as reference atomic clock transitions, allowing a direct measurement of the stability of the electron-to-proton mass ratio with a precision of 10^{-16} per year.

Another area of physics illuminated by these techniques is the search for dark matter and dark energy, which will be guided by the theory units at KCL, IPPP, UoS and UoN. Spanning 40 orders of magnitude in mass, many different kinds of coupling to ordinary matter have been proposed. The low-mass end of the spectrum (axions) has not been thoroughly probed. Networked quantum sensors can provide techniques to survey the widest possible range within a single programme, where different kinds of couplings can be probed (in a synchronised fashion) at different orders of magnitude on the low end of the spectrum. Here magnetometers can probe the coupling of dark matter with spin (pseudo-scalar field), interferometers the mass, light-through-the-wall experiments the coupling to photons and atomic clocks dilatonic interactions. Networking all these devices both locally and remotely should allow a more complete and thorough scan of axion parameter space, and allow sensitivity to events on increasingly larger scales, like the passage of domain walls or dark stars.

The network will target also the detection of chameleon fields that are, like axions, a spin-zero extension of the Standard Model. The search for these kinds of fields will be guided by the UoN unit and complements the axion dark matter searches, by looking for related models of new physics in a regime where dark matter does not play a role, but fifth force effects are detectable. These searches will employ the whole range of the network's sensors. The KCL unit will additionally work on the extension of the network towards the exploration of new forces, the study of Lorentz invariance as a fundamental symmetry of physics and the use of quantum detectors for measuring neutrino properties. An important aim is the determination of their total mass and detection of the neutrino background emitted at the Big Bang.

The consortium will benefit from the support of and the interaction with **several international partners** including the major metrology institutes in Europe (SYRTE, PTB, INRIM) and in North America (NIST, INMS), LIGO, VIRGO, JILA, the GNOME global network, the Canada research Council, the Italian Research Council, the universities of Zaragoza, Madrid, Bologna, Moscow and Dubna.

The experiments in our consortium have already produced **world-leading limits** on several tests of fundamental physics like time-variation of fundamental constants and Lorentz Invariance in special relativity. We will now take this even further by developing new capabilities in the UK. The proposed work will expand the existing quantum sensor portfolio with modern, forward-looking physics and quantum technologies which are capable of delivering disruptive discoveries over a broad range of fundamental physics themes. While initially modest in scope, the networked approach places the **UK as precursor and leader of global initiatives** involving high precision measurements for fundamental physics with quantum sensors. The impact will be felt in the fundamental physics programme, where we aspire to seed international networks capable of delivering the next "big discovery".

Budget for six years (in thousands of pounds):

	Year 1 & 2	Year 3	Year 4, 5 & 6
Highly-charged ion clock	3000	750	1000
Co-magnetometers	800	200	600
Unscreened magnetometer	500	100	200
Clock-interferometer	1200	600	900
Test-mass interferometer	350	175	250
Optical lattice clock	2600	250	300
Molecular ion clock	1000	300	750
Cavities	400	100	300
Frequency ratios	200	100	200
Ultracold molecular fountain	1000	200	600
Instrumentation	300	100	300
Theory support	600	300	900
Fibre link UoB-NPL-UoS-ICL	1700	850	1000
Satellite comms	100	50	50
Management & Travel	200	100	300
Studentships (x12+supervision)	900	100	900
Total	14850	4275	8550
Total 3 years		19125	
Total 6 years			27675

Plan of work

Our existing expertise and technology base allow us to immediately start to build sophisticated devices and initiate measurement campaigns. QSNET will be able to deliver important results already in the first two years, and will provide increasingly impactful and disruptive results as the project continues and the most sophisticated detectors are built up. The theoretical activities will guide and inform the experiments of the network, will design optimal measurement campaigns and will provide future directions.

Deliverables	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6
Measure frequency ratios between existing Yb^+, Sr and Cs clocks	■		■			
Build a cold HCI setup	■	■				
Sm^{14+} spectroscopy		■				
Cold HCI clock			■	■		
Build a molecular ion clock	■					
Measurement of the vibrational spectrum of molecular nitrogen ion		■				
Frequency comparison with the molecular ion clock and calcium ion clock			■			
Build a continuously running optical lattice clock	■	■				
Launch ultracold molecules into a fountain and demonstrate 100ms coherence time	■					
Drive vibrational transition in ultracold molecules		■				
Frequency comparison campaigns with EU partners		■				
National and international fibre link comparison			■	■	■	■
Build a (K,Rb)+(Xe,Ne) co-magnetometer	■					
Build a (Cs,Rb)+(He,Xe) co-magnetometer	■					
Build an unscreened magnetometer	■					
Installation and integration with UK and GNOME networks		■				
Magnetometer measurement campaigns (National and international)		■	■	■	■	■
Build a clock-interferometer	■	■				
Build an atom interferometer with test mass	■					
Develop advanced interferometric schemes		■				
Interferometer measurement campaigns			■	■	■	■
Build a light-through-the-wall experiment	■					
Set up the control system and automatic alignment system		■				
CFP local network measurement campaigns		■	■	■	■	■
Correlated national networks measurement campaigns				■	■	■
Preparation of the fibre link, acquisition of satellite kits	■					
Implementation of national networks and link to global networks		■				
Implementation of correlated networks			■	■	■	

Institutional contacts

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Workshop

We request £20k to organize a dedicated work package workshop from the ST/S002227/1 grant. The list of invited international speakers includes Piet Schmidt (PTB), Dave Hume (NIST), Viktor Flambaum and Julian Berengut (UNSW), Mariana Safronova (NIST), Andrei Derevianko (Reno), Szimon Pustelny (Cracow), Asimina Arvanikati (Perimeter), Dimitri Budker (Berkley), Jun Ye (JILA), David DeMille (Yale), Guglielmo Tino (Florence), Peter Wolf (Syrte).