WP2: Macroscopic quantum superpositions for physics beyond the standard model (MaQS)

Full team: Michael Vanner & Myungshik Kim (Imperial), Hendrik Ulbricht & Alexander Belyaev (Southampton) Mauro Paternostro (QUB), Peter Barker, Tania Monteiro, Chamkaur Ghag & Sougato Bose (UCL), Gary Barker, Yorck Ramachers, Paul Harrison, Animesh Datta & Gavin Morley (Warwick), Andrew Steane, Christopher Foot, Hans Kraus & John March-Russell (Oxford), James Bateman (Swansea), Xavier Calmet (Sussex), Haixing Miao (Birmingham), James Millen (KCL), Clare Burrage & Pierre Verlot (Nottingham), Oliver Williams & Sean Giblin (Cardiff), Sheila Rowan & Giles Hammond (Glasgow), Andreas Nunnenkamp (Cambridge), Kishan Dholakia (St Andrews) and Michael Hartmann (Heriot Watt).

Management structure: The project will be run by the management team made up of the four SP leaders (Hendrik Ulbricht, Peter Barker, Michael Vanner and Sougato Bose) plus Clare Burrage, Sheila Rowan and John March-Russell, and the overall project coordinator, Gavin Morley. The management team will re-evaluate plans for **Per 2** and **Per 3** based on progress in the first two years (**Per 1**) but will not move **Per 1** resources without a good reason. The management team will meet monthly to check on progress.

Biographies of team members:

Gavin Morley is the coordinator of MaQS. He has worked on several novel quantum technology experiments using electron spins including the highest magnetic field for quantum control, the longest spin coherence with electrical detection and the highest precision and accuracy for g-factor measurements in the liquid or solid state. His work on diamond quantum sensors is funded by two of the UK Quantum Technology Hubs (NQIT and the Sensors Hub) where he is the PI on five Partnership Resource grants with four companies. His Royal Society University Research Fellowship funds the experiment he has jointly proposed on levitated nanodiamonds towards the creation of macroscopic superpositions.

Prof Sougato Bose is a pioneer in the theory of creating macroscopic superpositions using optomechanics with his two papers on the subject from late 90's having a total of 688 citations (Google Scholar). He has recently collaboratively proposed Ramsey techniques for preparing superpositions of mesoscopic objects, and found their applications in testing for the quantum nature of gravity. This work has received wide coverage including New Scientist, Physics World and Quanta Magazine. It is this same form of quantum interferometers that have a great potential for being useful for sensing new forces and phenomena from fundamental physics. He has a Google Scholar h-index of 54, with his work on transfer of quantum information through spin chains being cited 1199 times. Awards and fellowships include the Maxwell Medal and Prize of the IoP (2008), Advanced Research Fellowship (2006-2011), an ERC Starting Grant (2012-2017) and a Royal Society Wolfson Research Merit Award (2007-2012). He is the co-Director and co-I of the Doctoral Training Programme in Delivering Quantum Technologies. He won the first prize in the 1999 Millennium Science Essay Competition organized by the New Scientist and the Wellcome Trust.

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.

Giles Hammond's background is in experimental gravitational physics including fundamental physics tests using torsion balances, building suspensions & isolations for aLIGO and the future GW network (both room/cryogenic temperatures), as well as developing precision MEMS accelerometers for applications in gravity monitoring.

Yorck Ramachers is a Reader in Physics with the University of Warwick Experimental Particle Physics group. He has specialized in novel instrumentation for future neutrino physics projects since 2004. His career background consists of work on direct dark matter detection from 1994-2004 using germanium detectors and cryogenic bolometers and neutrino physics using CdZnTe semiconductors and liquid argon time projection chambers with some experience in liquid scintillator calorimeters. Background in instrumentation also includes close collaboration with surface physics on an STFC impact project for a novel type of UV light sensor.

Oliver Williams has 20 years diamond growth and processing experience, including doping, superconductivity and single photon centres. Cardiff Diamond Foundry fabricates superconducting diamond cantilevers and SQUIDS, single photon centres from nitrogen and silicon vacancies, high frequency surface acoustic wave devices etc. 50% of our output is based on the production and purification of diamond nanoparticles. Diamond facilities include three high-purity chemical vapour deposition systems with in-situ monitoring, unique chemical mechanical polishing, nanoparticle milling, size and zeta potential characterisation, comprehensive thin film metrology and low temperature facilities including a 7mK dilution fridge and a PPMS.

Paul Harrison does experimental particle physics and phenomenology of neutrino and quark flavour. His practical expertise is primarily software, simulations and data-analysis.

James Millen is a recognised expert in the optical trapping and manipulation of nanoparticles (Vamivakas, Monteiro, Millen, Rep. Prog. Phys. in press (2019)), with the goal of exploring macroscopic quantum physics. With Peter Barker, he introduced the concept of using an ion trap to levitate charged nanoparticles, which can then be cooled using optical fields (Millen et al., Phys. Rev. Lett. 114 (2015), Fonseca et al. Phys. Rev. Lett. 117 (2016)). He has developed a deep interest in studying nanoscale thermodynamics (Millen et al., Nature Nano. 9 (2014), Millen & Xuereb, New J. Phys. 18 (2016), Gieseler & Millen, Entropy 20 (2018)). James pioneered the control of the alignment and rotation of levitated particles (Kuhn et al., Optica 4 (2017), Kuhn et al., Nature Commun. 8 (2017)), and in collaboration has developed the tools and protocols to study macroscopic superpositions using rotational degrees-of-freedom (Stickler et al., New J. Phys. in press (2018)). Recently, he has embarked upon a research program to control the motion of levitated charged particles using only electrical fields and circuits (Goldwater et al. Quan. Sci. Tech. in press (2019)).

Animesh Datta has expertise in the theory of quantum sensing and metrology and its practice as applied to optical, atomic, and optomechanical systems. His present interests include the quantum-limited and quantum-enhanced sensing of multiple parameters simultaneously, including applications to quantum imaging and magnetometry. He also works on verification of quantum computations and simulations on noisy intermediate-scale quantum devices. He is an EPSRC Early Career Fellow, a co-I in the NQIT and

QUANTIC hubs, and a PI on an ESA grant on 'Quantum metrology for space-based tests of gravitational physics.'

Gary Barker is head of the Warwick Particle Physics group with many years experience of large-scale STFC particle physics projects at colliders and long baseline neutrino oscillation experiments. He is the Warwick PI for the T2K, Hyper-K and DUNE neutrino projects and the UK Deputy-PI for DUNE/LBNE where he oversees the DUNE detector workpackages - a £30M UK investment. He serves on various STFC-related bodies including the Particle Astrophysics Advisory Panel responsible for defining the UK particle-astro research roadmap which includes dark matter.

Xavier Calmet is a high energy theorist with very broad research interests which include GR and quantum gravity using very conservative methods (i.e. quantum field theory). He has worked on time variation of fundamental constants with applications in astrophysics and for atomic clocks and has co-authored papers with members of the atomic, molecular and optical physics community: both theorists and experimentalists.

Mauro Paternostro has a long-standing experience in the theoretical assessment of quantum optomechanics and the foundations of quantum theory. He has investigated the validity of quantum mechanics at the large-scale limit from both the information-theoretical perspective and the non-equilibrium statistical mechanics viewpoint, contributing to the building up of a non-equilibrium framework for fundamental quantum processes.

Andreas Nunnenkamp is currently Royal Society University Research Fellow and Winton Advanced Research Fellow at the Cavendish Laboratory, University of Cambridge. A central theme of his work is quantum coherence in atomic, mesoscopic, and optical systems and how to exploit them for fundamental table-top science as well as future quantum technologies. This puts his work at the interface of quantum optics, condensed matter theory, and quantum information science. In particular, he has worked on strong correlations, quantum-enabled technology, and control of ultracold atomic gases, superconducting circuits, and optomechanical systems. He is a PI of FET proactive grant 'Hybrid Optomechanical Technologies', with a total budget of EUR 10M.

Sean Giblin is a low temperature experimental physicist with a broad range of research interests generally encompassing correlated electron systems and instrumentation development. He has a strong record in frustrated magnetism explored with novel SQUID techniques and has recently started to work on macroscopic quantum systems based on superconducting diamond. There is a strong track record in the cutting edge design of instrumentation to explore quantum effects and extensive collaborative work which leads to a broad scientific output.

Haixing Miao has expertise in advanced quantum techniques for improving the quantum-limited sensitivity of gravitational-wave detectors and optomechanical devices in general. He is working on the fundamental quantum limits of these high-precision instruments and developing a unified framework that provides a systematic approach to implementing different quantum techniques. He is an STFC Ernst Rutherford Fellow and also Birmingham Fellow. He is leading the theoretical node of the instrument science in the Institute for Gravitational-wave Astronomy at the University of Birmingham.

Hendrik Ulbricht's main research interest is concerned with experimental tests of fundamental theories of Nature by table-top experiments. Some tests are concerned with the large-mass limit of the quantum superposition principle, which forms the basis of quantum mechanics. Other experiments are concerned with testing the interplay between quantum mechanics and gravitation in the low energy limit. He has a strong track record in both experiments, on optomechanics and matter wave interferometry with large-mass particles, as well as theoretical proposals/feasibility studies for fundamental table-top experiments. The Ulbricht group at Southampton performs quantum experimental research on the preparation and analysis of massive systems in non-classical states by various techniques. They pioneer so-called levitated opto- and magneto-mechanics experiments, where light and magnetic fields are used to both trap and control nano- and micro-particles in vacuum.

Myungshik Kim has been working on quantum optical tests of the foundations of quantum physics. In relation to the current proposal, his recent research interests include influence of relativity in macroscopic superpositions and sources of nonclassicalities in spatial and time correlations. His research focus is also to bridge our understanding of quantum mechanics in atoms and optics to a wider range of physical systems including mechanical oscillators of a large mass. Since his research at the Max-Planck Institute in Quantum Optics, he has been working with experimentalists to implement and test quantum protocols for foundations and their applications.

Pierre Verlot is an experimental physicist (PhD in quantum optics, LKB, ENS, Paris), with interest in cavity optomechanics and ultra-sensitive nanomechanical systems. Pierre has recently introduced a novel approach, based on the optical functionalization of carbon nanotube resonators. Such system proves to be the most sensitive solid state nanomechanical force sensor operating at room temperature do date, as he and co-workers have recently reported (Nature Communications **9**, 662, 2018). Pierre is currently setting up a new project, where he intends to trap hybrid nanotube resonators into the evanescent field of high-finesse whispering gallery mode cavities, with the aim to reach the quantum optomechanical regime at room temperature.

James Bateman (Swansea) is an experimental physicist interested in increasing sensitivity and reducing decoherence in levitated systems. With Hendrik Ulbricht, he proposed the nanoparticle Talbot interferometer, which promises a feasible test of macroscopic superpositions. His experimental demonstrations include feedback cooling and squeezing of thermal mechanical states. Recent endeavours include coherent feedback interfacing optical fibres and optomechanics, and nanoscale aerodynamics.

Chris Foot has carried out experiments on laser cooling and trapping of neutral atoms, and developed several novel types of confinement mechanism. Recently he has revisited the idea of trapping charged particles with very different masses in a Paul trap [Foot et al., Int. J. Mass Spec., 430, 117 (2018)], which was originally proposed by Hans Dehmelt for other purposes. This provides a novel way of manipulating micron-sized objects and leveraging the sophisticated techniques developed for atomic ions. His group is also working on the electrodynamic confinement and manipulation of non-spherical charged particles.

Alexander Belyaev from University of Southampton is working in the area of theory and phenomenology of elementary particle physics and cosmology beyond the standard model: supersymmetry, extra-dimensions and technicolor and their dark matter cosmological connections. Graduated from Moscow State University, followed by postdoc positions in IFT (Sao Paulo), CERN, Florida State University and Michigan State University prior the permanent position at Southampton. He has been working in close contact with experimental collaborations: he is the former member of DØ collaboration at Fermilab (1996-2004) and presently is the full member of the CMS collaboration at CERN since 2007. He is one of developers of the CalcHEP package which was created to enable one to go directly from the Lagrangian to the cross sections and distributions effectively, with a high level of automation. In 2011 Prof. Belyaev has pioneered High Energy Physics Model Database (HEPMDB) project which was created to facilitate connection between high energy theory and experiment, and it is a tool to store and validate theoretical models. The goal is to provide a dictionary of model signatures, cutting down calculation times thus enhancing productivity within the field of particle physics. At present he is working on collider and cosmological exploration of various dark matter models.

Michael Hartmann is an Associate Professor at Heriot-Watt University. Previously he held fellowships of the German science foundation (EUR 1.2M) and the Humboldt Foundation. More recently, he has won a visiting faculty award to join Google's quantum computing research for a year and a EU funded project (EUR 3M, as coordinator) to develop quantum neural networks. He has proposed several strategies for preparing 'macroscopic' mechanical oscillators in distinctly non-classical states. In this work his focus was mostly on generating stationary states of driven-dissipative scenarios that despite being manifestly non-classical, are stable and have a long lifetime.

Clare Burrage is a theorist working on observational tests of theories of dark energy and modified gravity. She has pioneered the use of precision laboratory measurements, such as atom interferometry and opto-mechanical measurements, to test such theories. In 2015 she was awarded the Maxwell Medal by the Institute of Physics for outstanding contributions to Theoretical Physics. In 2016 she won a Research Leadership Award from the Leverhulme Trust.

Tania Monteiro is a theorist interested in quantum dynamics including nonlinear dynamics. She has been developing understanding of the dynamics of levitated nanospheres in cavities experiments with Barker at UCL, funded by two joint grants "towards sensing at the quantum limit" EP/H050434/1 (completed) and "Quantum cavity optomechanics of levitated particles: from foundations to applications" EP/N031105/1(in progress), reported in Millen et al PRL 114,123602,(2015), and Fonseca et al PRL 117,123602,(2016) (both works selected as editors highlights). More recently she has been working on methods for detection of quantum optomechanics at room temperatures: PRL 119, 12360 (2018), arxiv:1801.08700. Contemporaneously TM's research group have begun developing methods for improved analysis of quantum spin sensing experiments, in particular single-spin sensing with electron spins of NV centres in diamond which are currently attracting enormous interest due to their potential to revolutionise nanoscale MRI, among a wide range of applications PRX 5, 041016 (2015) and Phys. Rev. Applied 7, 054009 (2017).

Michael R. Vanner is an internationally recognized early-career researcher who is principal investigator of the Quantum Measurement Lab at Imperial College London. Vanner is known for his contributions to many of the pioneering experiments in optomechanics such as laser cooling [Nature Physics **5**, 485 (2009)], and the first observation of optomechanical strong coupling [Nature **460**, 724 (2009)], as well as his theoretical work that proposed the use of quantum measurement for mechanical quantum state engineering [PNAS **108**, 16182 (2011), PRL **110**, 010504 (2013)]. Vanner and his team now use optomechanics for the development of quantum sensors, via EPSRC quantum technology funding, and testing the foundations physics. Together with Igor Pikovski and Myungshik Kim, he proposed how the generalized uncertainty principle can be tested using optomechanics [Nature Physics **8**, 393 (2012)], which opened a new area of research that helped to bridge the quantum optics and high-energy physics communities.