

WP1: Quantum Sensors for Hidden Sector Physics (QSHSP)

A proposal to search for low-mass particles in the Hidden Sector

Stafford Withington and Edward Daw

On behalf of the Wp1 team

- Opportunities in Hidden Sector Physics are immense, and the potential rewards considerable, both in terms of discovering new particles, and placing quantitative constraints on theoretical models
- World-class scientific results certain, Nobel-class science potentially available, advanced quantum technology development and exploitation is guaranteed
- Truly quantum mechanical experiments, with instruments and devices interacting with the quantum fields under study in an intimate way – fundamental quantum sensing
- Sensitivity determines the rate at which searches can be carried out; quantum-limited sensitivities are needed from MHz to THz, depending on target mass range
- Only been achieved over a limited range of wavelengths, but potentially available, and so customised quantum device technology needed
- We wish to apply the best of the quantum sensor technologies developed in the last 10 years to Hidden Sector science.

Considerations:

- Essential to have a team of theorists working closely with a team of experimentalists: defining science case, assessing impact of different experimental techniques, and creating a requirements document – ongoing throughout duration of project
- Understanding at a theoretical level the relationship between the experimental methods used and the underlying quantum fields – what do various possible experiments actually measure
- Quantum instrument engineering for Hidden Sector Physics is an area where the UK could accrue a high international prominence in a short period of time.
- Assembled a strong team of theorists, experimentalists, and quantum technologists to build an experimental programme in Hidden Sector Physics.
- Not a loose collection of individuals, but a single team, with a set of targeted, complementary skills, aimed at delivering the specific vision of a world-class UK facility.

Management Team:

(theorists, dark matter experimentalists, laser specialists, and quantum technologists)

Dr Ian Bailey, Univ. Lancaster

Prof. Bob Bingham, STFC CLF/Strathclyde

Prof. Xavier Calmet, Univ. Sussex

Prof. Edward Daw, Univ. Sheffield (Coordinator)

Prof. Gianluca Gregori, Univ. Oxford

Dr Ling Hao, NPL

Dr Edward Harvey, Univ. Liverpool

Dr Ben King, Univ. Plymouth

Dr Edward Laird, Univ. Lancaster

Dr Peter Leek, Univ. Oxford

Dr Rhys Lewis, NPL

Prof. John March-Russell, Univ. Oxford

Prof. Yuri Pashkin, Univ. Lancaster

Dr Edward Romans, UCL

Prof. Subir Sarkar, Univ. Oxford

Dr Stephen West, Royal Holloway UL

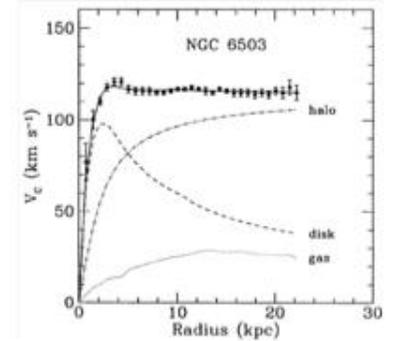
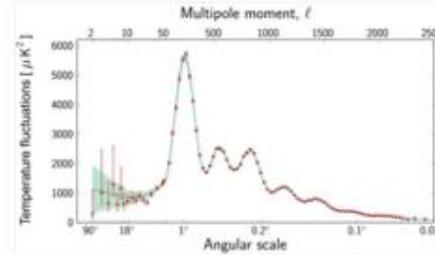
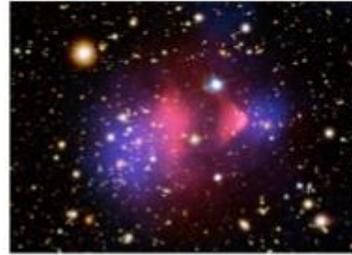
Prof. Stafford Withington, Univ. Cambridge (Coordinator)



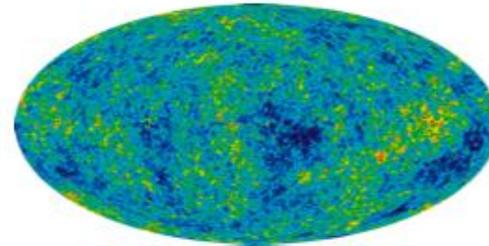
- Institutes represented bring a wealth of talent, experience, and facilities to project

Shortcomings of the standard model of physics & cosmology

- Dark matter
- Neutrino masses



- Baryogenesis
- CMB homogeneity & flatness



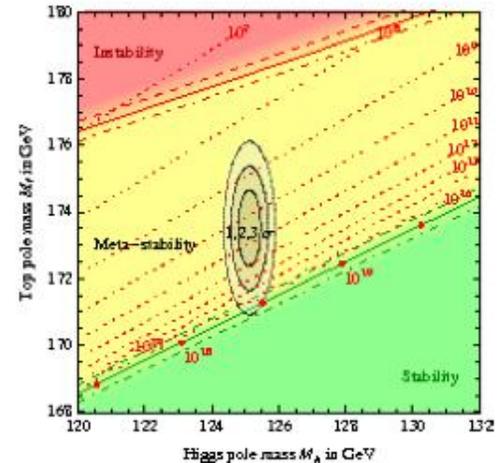
- Strong CP problem
- Flavour structure
- EW hierarchy problem.
- Cosmological constant problem
- SM only metastable at high energies



$$d_n < 2.9 \cdot 10^{-26} \text{ e cm}$$

$$\Lambda_{cc}^{1/4} \ll m_h \ll M_{Pl}$$

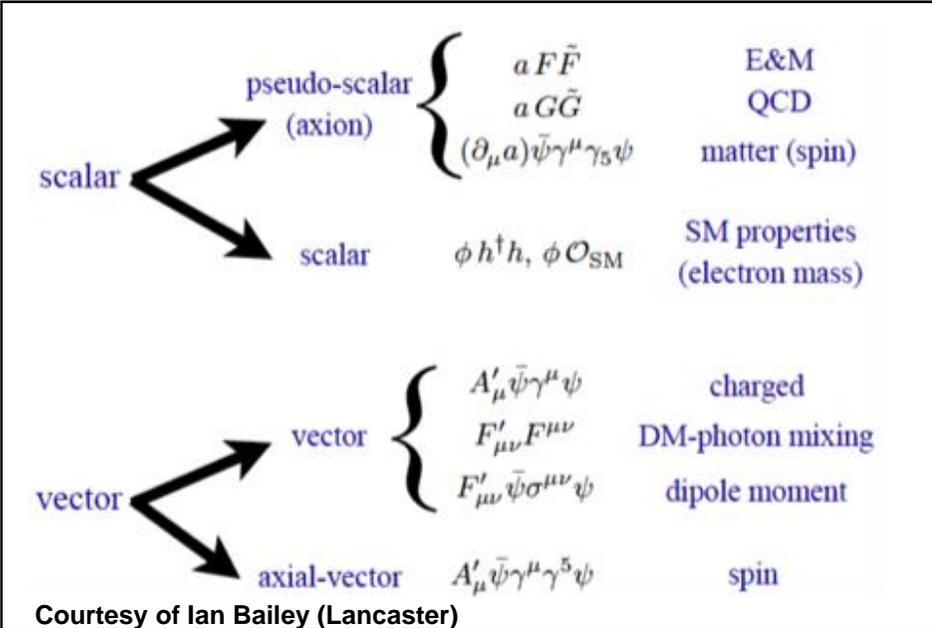
Quantum gravity?!



Many of the proposed solutions involve hypothesised low mass fields

- Dark matter WIMPs / asymmetric DM / black holes / ALPs / light scalars / light vectors
 - Neutrino masses Right handed neutrinos / new scalars?
 - Baryogenesis Modified EW phase transition / hidden sectors
 - CMB homogeneity & flatness Inflaton
 - Strong CP problem Axions
 - Flavour structure Flavons
 - EW hierarchy problem New dynamics around TeV scale / relaxation?
 - Cosmological constant problem
 - SM only metastable at high energies
- Quantum gravity?! Strings?
- Often involve new light particles*

Standard model extensions that may be light dark matter, and existing experiments



LAB (production-decay)

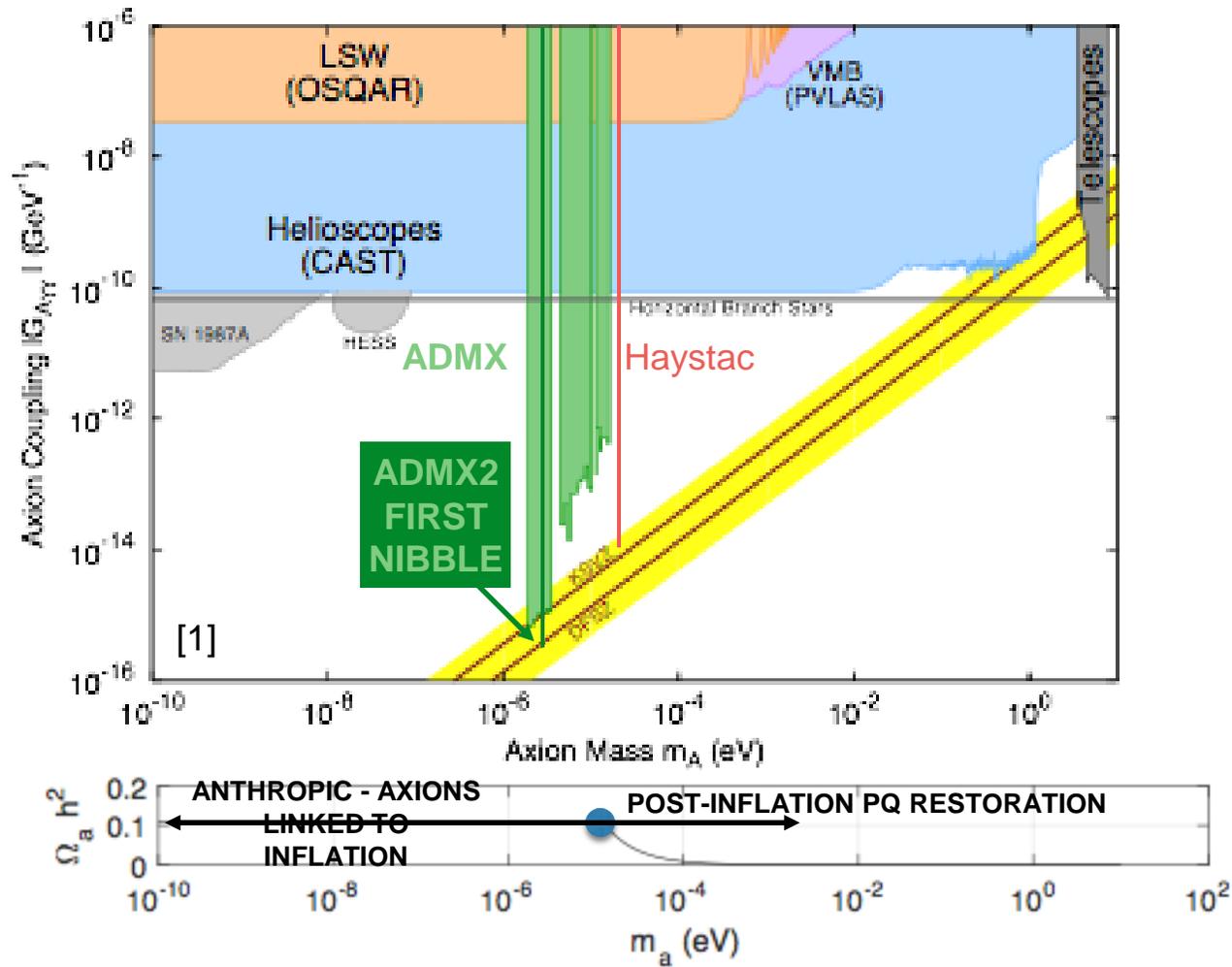
- PVLAS
- CROWS, OSQAR
- ALPS
- ALPSII/JURA/ALPSIII
- CASCADE, SHiP

HELIOSCOPES (produced in sun)

- CAST
- IAXO
- TASTE

HALOSCOPES (DM conversion)

- ADMX
- HAYSTAC
- ORGAN
- CULTASK
- MADMAX
- FUNK
- BRASS
- DMRADIO
- ABRACADABRA
- QUAX
- CASPER



[1] K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014) and 2015 update 2016 revision by A. Ringwald, L. Rosenberg, G. Rybka,

Axions

Proposed in 1978 as a consequence of the Peccei Quinn mechanism which potentially solves the strong CP problem (smallness of neutron, nuclear EDMs)

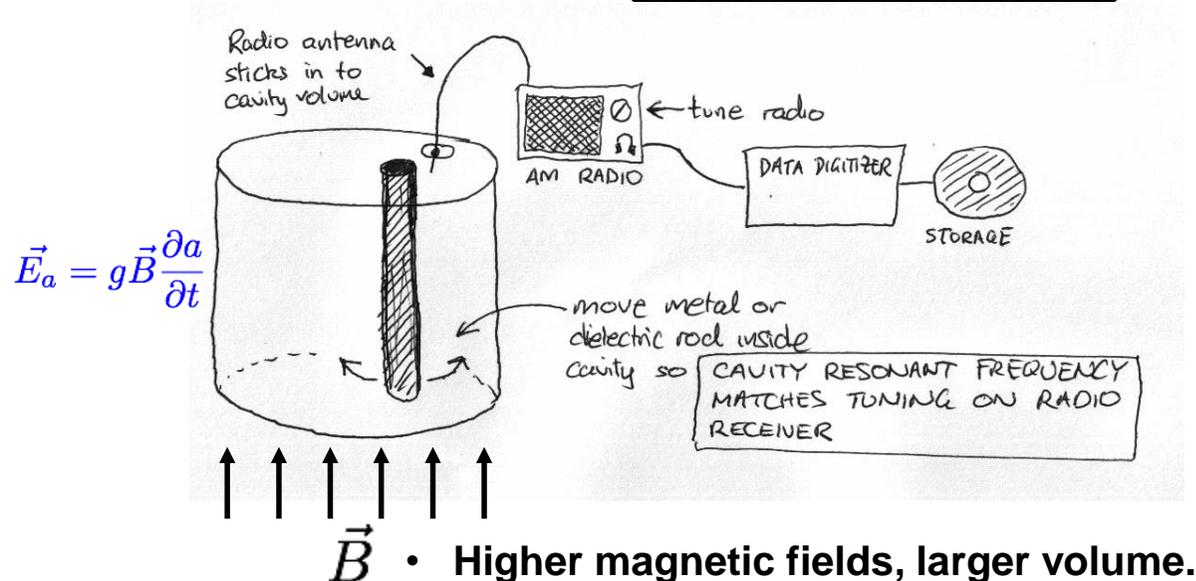
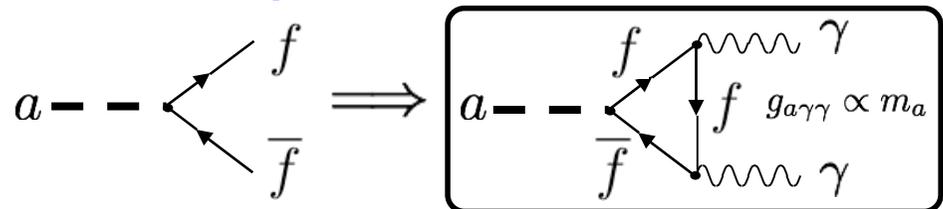
Axions produced by condensation in the early Universe are candidates for cold dark matter.

Pseudoscalar - an ultra light π^0 .

ADMX - existing UK involvement



Sikivie-type resonant cavity detector - assumes axions are component of local dark matter.



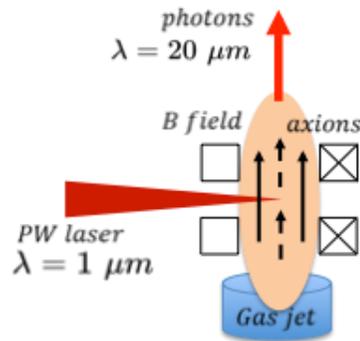
- [UK Idea] Improve hidden sector searches with feedback resonators arXiv:1805.11523.
- Already quantum limited SQUID/JPA electronics; enhance with improved devices, squeezing

New type of hidden sector searches that don't assume a dark matter source

Problem here is that you must first produce and then detect the hidden sector field, so often rates are suppressed by the 4th power of the hidden sector coupling!

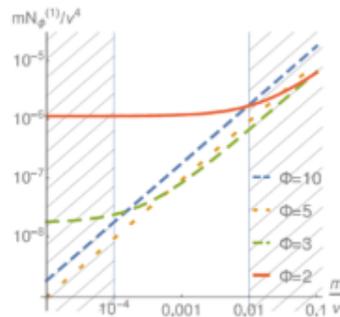
Advantage is that you probe the hidden sector without making the twin bold assumptions that (a) your hidden sector candidate is also dark matter, and that (b) this dark matter has an appreciable local density in your lab.

Proposal by Gianluca Gregori (Oxford) et al.: exploit non-linear effects induced in high intensity laser beams - lead to enhanced density of axions due to Unruh vacuum physics



- Low-Z gas jet (e.g., H, He, methane) with density $\sim 10^{21} \text{ cm}^{-3}$
- High intensity optical laser: 40 J, 40 fs into a 5 mm spot radius
- External magnetic field: 10 T (100 kG)
- Axions per shot converted into optical photons:

$$N_{\gamma} \sim 10^{-2} \left(\frac{n_e}{10^{21} \text{ cm}^{-3}} \right) \left(\frac{B_{\text{ext}}}{10 \text{ T}} \right)^2 \left(\frac{E_L}{40 \text{ J}} \right)^2 \left(\frac{\tau}{40 \text{ fs}} \right)^{-1}$$



Wadud et al., PLB 2018

- At 1 Hz rep rate, this requires 5 days to accumulate enough signal for positive detection
- Null experiment with magnets removed needed for discrimination against background

Outline programme:

- Numerous ways in which low-energy hidden sector particles might be sought
- Discussed a number of possible experiments, but decided not to focus on building a specific instrument during the first phase of the project
- Adopt an approach that develops the programme in a systematic and optimised way:

Yr 1-2: Build the team and institutional interfaces. Develop an optimised science case

Quantitatively assess and compare different instrumental approaches: resonant cavity, feedback methods, quantum circuits, dark-wall and high-power laser methods

Develop an instrument concept that meets the requirements: a 'shared' platform might well be possible

Flow down the concept into quantum technology transfer and development

Yr 2-3: Component technology development - superconducting electronics, etc.

Yr 3: Complete end-to-end signal-chain demonstrations through pathfinder – early science

Conceptual design study of national facility. Submit a comprehensive proposal.

Yr4-5/6: Build and commission national facility. Science operations

Work Package structure:

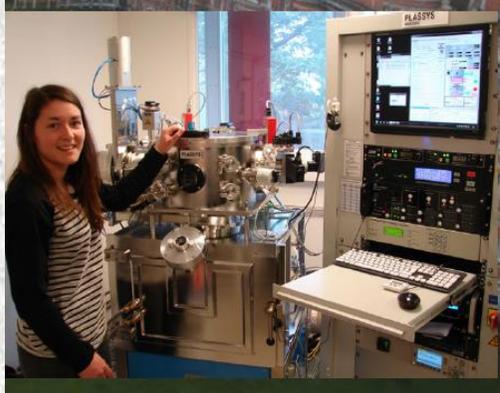
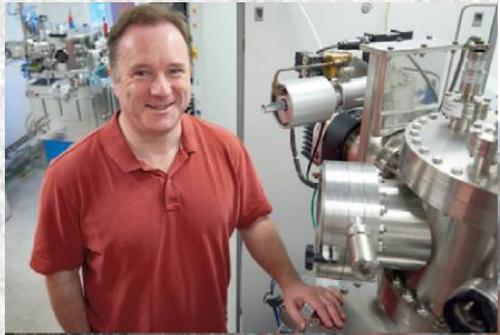
- Work Packages not by institution, but by subject matter (TBD)
- Each WP will have a WP leader, and defined objectives and milestones
- Report to Management Committee: written reports and face-to-face presentations
- WP's will form the basis of detailed costing over coming month

Typical content:

- Establish science case and priorities: $1\mu\text{eV}$ to 1meV ? Review merits of experimental techniques available: cavity methods, magnetic field provision, laser experiments? What mass ranges, wavelength, bandwidth? International competition and collaboration. Astrophysical constraints and synergies.
- Establish project strategy
- Write white paper summarising the Hidden Sector Challenge – what is needed and what is experimentally possible
- Theoretical and numerical analysis of proposed experimental methods. Consider how to increase the mass range and search speed. Application of quantum-circuit theoretic techniques: squeezed states, quantum Q, feedback methods, coupled cavities

- Conceptual design of instrument and quantitative assessment of performance in context of science case. Considerable innovation possible. Iterate on design concept to achieve requirements
- Identify specific quantum technologies needed, and start technology development programmes: feedback methods, microwave quantum parametric amplifiers, ultra-low-noise submillimetre wave technology, cavity technologies
- Demonstrate selected technologies and extend to TRL 5: consider environmental operating considerations – high field
- Construct pathfinder instrument to demonstrate the overall experimental scheme. Develop system engineering methods to guarantee ultra-low-noise, artefact free operation: magnetic and EMI shielding, readout electronics, analysis software
- Pathfinder science measurements, and data analysis development, calibration.
- Prepare detailed proposal to establish a national facility – many considerations relating to technology, location, operation, cost. *International Review at end of Phase 1*
- In Phase 2, engineer a full-scale instrument, bringing forward the technology base, and some of the components, created earlier
- Commission and begin full scale science operations

- Many £10's millions investment in capital equipment for **superconducting electronics**
- All of the clean-room facilities and expertise will be available to the programme (coordination through devolved work packages needed)



Existing Microwave SQUID System



We are developing this microwave SQUID system at NPL for single spin detection for Quantum Metrology and Technologies applications.

5T magnet, 100mm bore, HTS leads

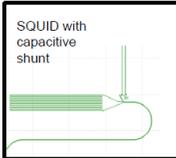


High Q OFHC Cu cavity TM010 6 GHz

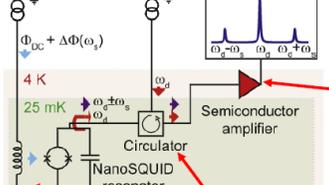
Microwave synthesised source to 6GHz, alternative source to 20GHz



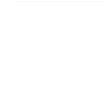
Low-vibration Entropy pulse-tube cooler base temp ~3K



Applied flux $\Phi_{DC} + \Delta\Phi(\omega_s)$



4 K
25 mK
Circulator
NanoSQUID resonator
Semiconductor amplifier
Cold circulator 4-8GHz [low noise factory]
Microwave amplifier, 4-8GHz [low noise factory]



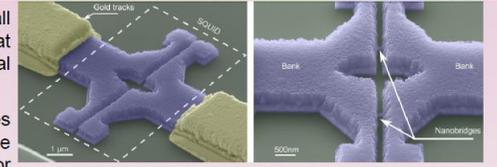
Cold circulator 4-8GHz [low noise factory]

Microwave amplifier, 4-8GHz [low noise factory]

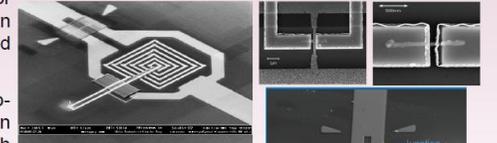
Dr Ed Romans: Superconducting Quantum Devices



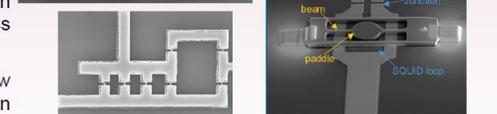
- Nano-SQUIDS to measure very small spin populations in magnetic materials at ultralow (mK) temperatures with National Physical Laboratory (NPL) and PTB.



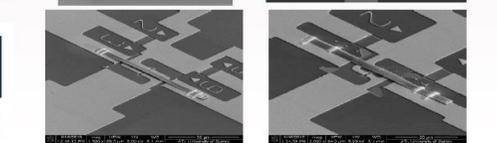
- Exotic nanoscale Josephson devices including gate tuneable graphene Josephson junctions, semiconductor or topological insulator barrier Josephson junctions for topologically protected quantum information processing.



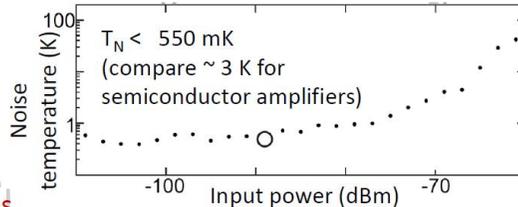
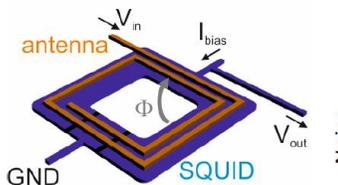
- Quantum Readouts for Nano-electromechanical systems (NEMS) in Quantum Metrology in collaboration with NPL and Surrey for ultrasensitive mass detection and chemical sensing.



- Nanobridge circuits with NPL/Glasgow for quantum metrology/single photon detector readout.

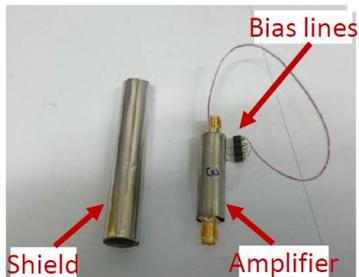


RF readout with a SQUID amplifier



Frequency = 196 MHz
Range $\sim \pm 10$ MHz

Details: Schupp et al. arXiv: 1810.05767 (2018)
Review: Muck & McDermott, SST (2010)



L³ London Low Temperature Laboratory Research at the frontier near absolute zero

Four nuclear demagnetisation cryostats, reaching around 100 microkelvin



Governance:

- Management as a coordinated team with a single strong vision: construction of specific national facility
- Members need to be in it for the long haul!
- Day to day coordination Stafford Withington and Edward Daw
- Core management team in place covering all areas of expertise needed – unique world-class team
- Flat structure, the core team can attend all management meetings - joint decision making wherever possible – all institutes represented
- Work packages topic based, not institute based – focus is on creating an instrument
- Work package leaders responsible for specified outcomes
- Regular team videocons, and face to face meeting at key project milestones

Deliverables:

- Build and established an interdisciplinary UK team – bringing together fundamental physicists with quantum technologists – new collaborations
- Substantial reports and white paper on science case, instrument concepts and modelling (substantive scientific papers possible)
- Quantum technology transfer, development and refinement
- Quantum systems engineering development, with many utilitarian benefits
- Pathfinder instrument, should already yield early science
- Detailed white paper proposing UK strategy, quantified design of proposed UK facility, logistics, costs, etc.
- Establish major national facility for exploitation by the broader UK science community
- Build scientific and technical international collaborations
- Major UK-led programme would bring prominence on the international stage

Costs:

PDRA's and scientific staff, engineers, clean room costs and consumables, test facilities, management, travel:

Definition and development Phase 1:

Year 1 £1M

Year 2 £2M

Year 3 £2M

Construction Phase 2:

Year 1 £2.5M

Year 2 £2.5M

Year 3 £2M

Total 6 year programme: £12M

Status to date:

- Team built, project structure defined, institutional capabilities and project offers compiled, governance established, regular meetings underway.

Next steps:

- Ongoing videocons to work on proposal. Set up web based repository of documents
- WP package descriptions, WP contributors, more detailed costing, detailed schedule
- Impact Case descriptions across partner institutes
- Open meeting, possibly in Cambridge, with international speakers to understand better the international landscape and possible collaborations
- More refined proposal to lan....

Feedback on outline proposal keenly sought