Quantum Sensors for Particle Physics

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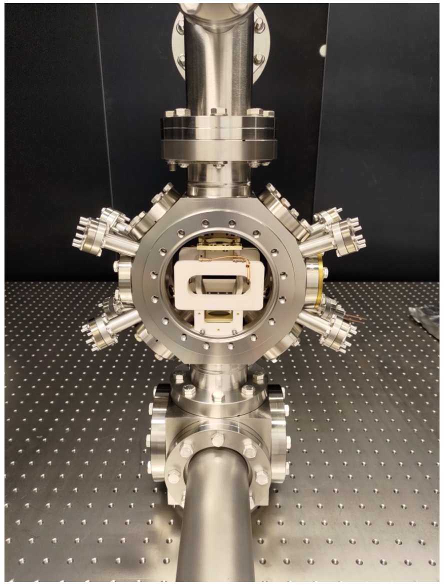
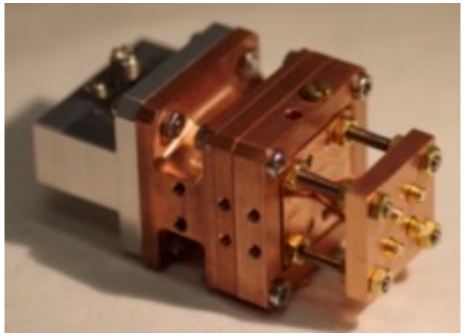
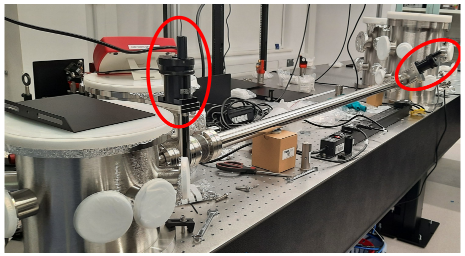
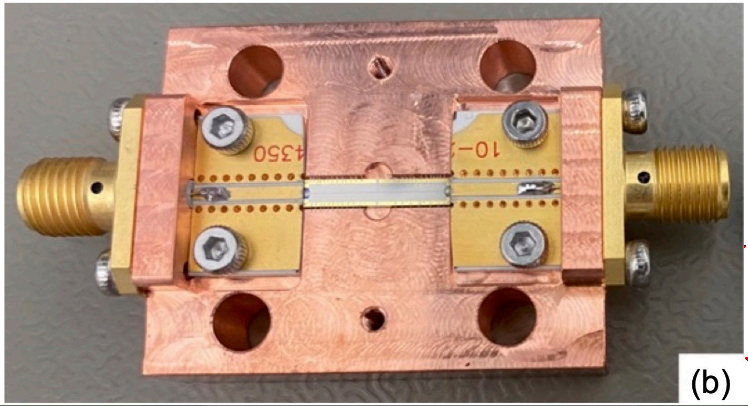
Muon Precision Physics 2024, Liverpool, 2024/11/13









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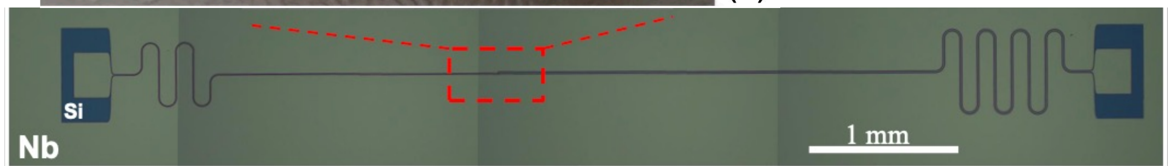
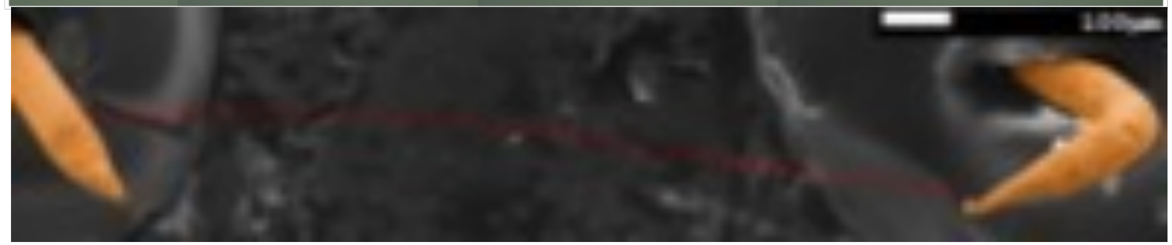
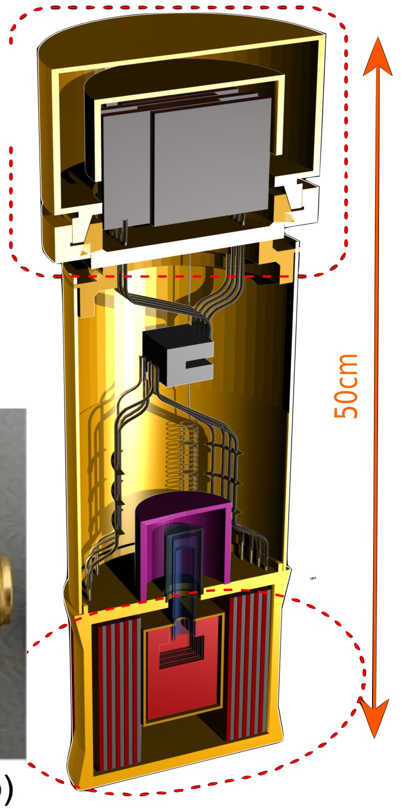
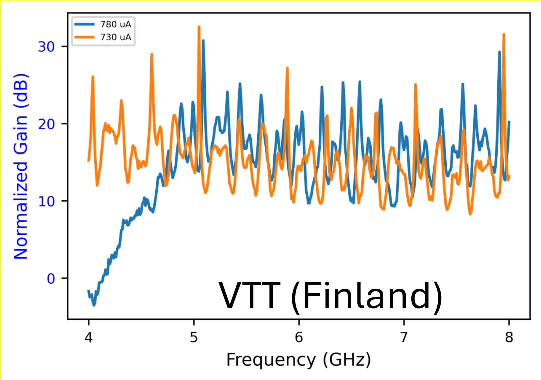






What Quantum Sensors?

Detector Control & Stabilisation



Detector

$$\frac{k_B T}{h\nu} \lesssim 1$$

Signal Frequency

$\sim 10^{(-2,+3)}$ Hz

- QUEST-DMC superconducting nanowire readout
- AION signal detection band
- Ground-based GW signal band

$\sim 10^{(3,7)}$ Hz

- Lumped-element wave-like dark matter searches like DMRadio

$\sim 10^{9}$ Hz

- QTNM – 18GHz microwave amplifier development.
- QSHS – 3 to 20GHz microwave sensor development.

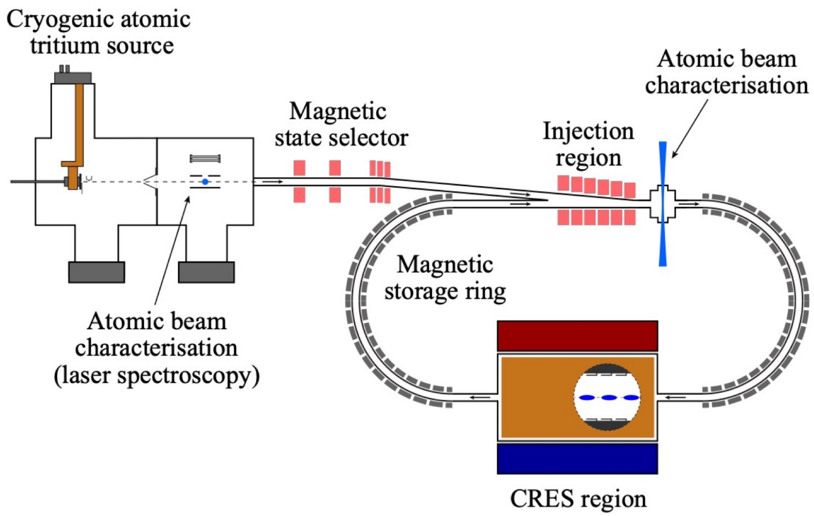
$\sim 10^{14}$ Hz

- Squeezing for GW detector readout
- QI group experiments
- ALPS2 @ DESY
- AION optical drive/probe for ion beams.

QTNM goals connected to DRD5

- QTNM aims to probe the neutrino mass in a tritium end point experiment with ultra-low-noise readout of GHz microwave radiation from magnetically trapped tritium.
- *O*(10 GHz) microwave amplifiers operating at (or below) quantum noise level
- Robust and repeatable fabrication, *quantum-noise limited* performance for multi-channel readout
- Quantum amplifier *systems* TRL 3-6 and above

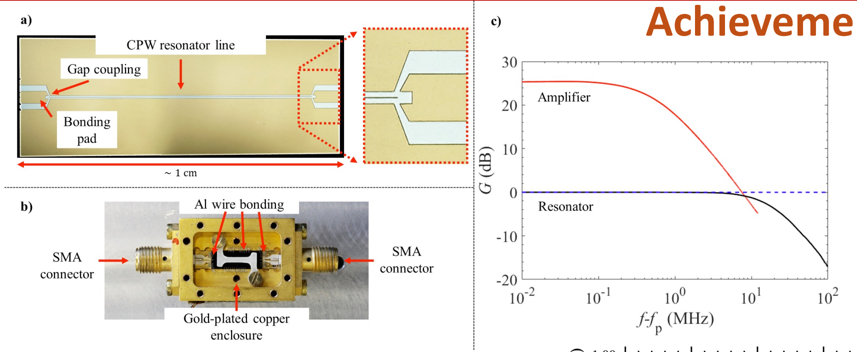
- Precision position sensitive *magnetometry* and *electrometry* with *Rydberg* atoms as *quantum sensors*

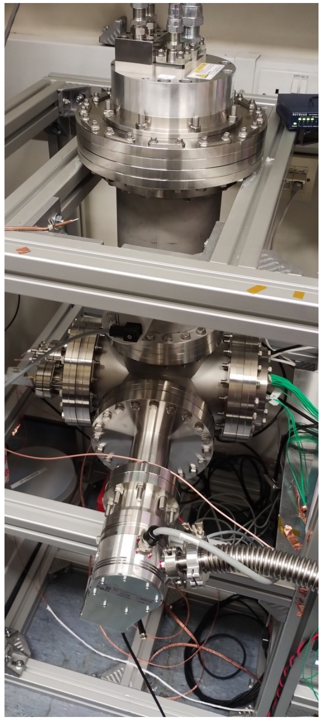


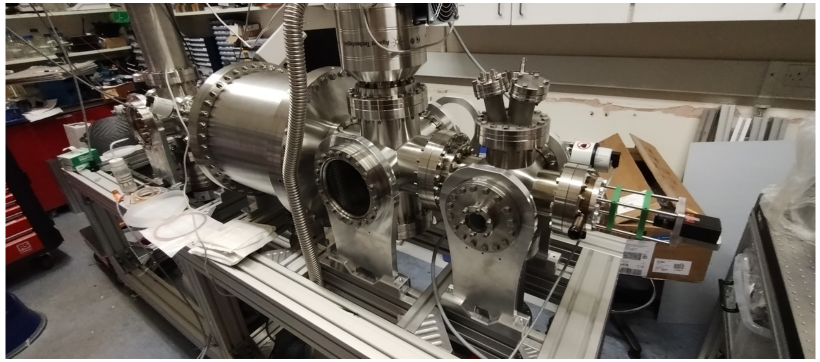
Penning electron source

Atomic hydrogen source.

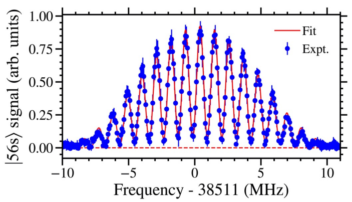
Achievements



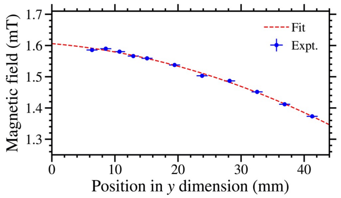




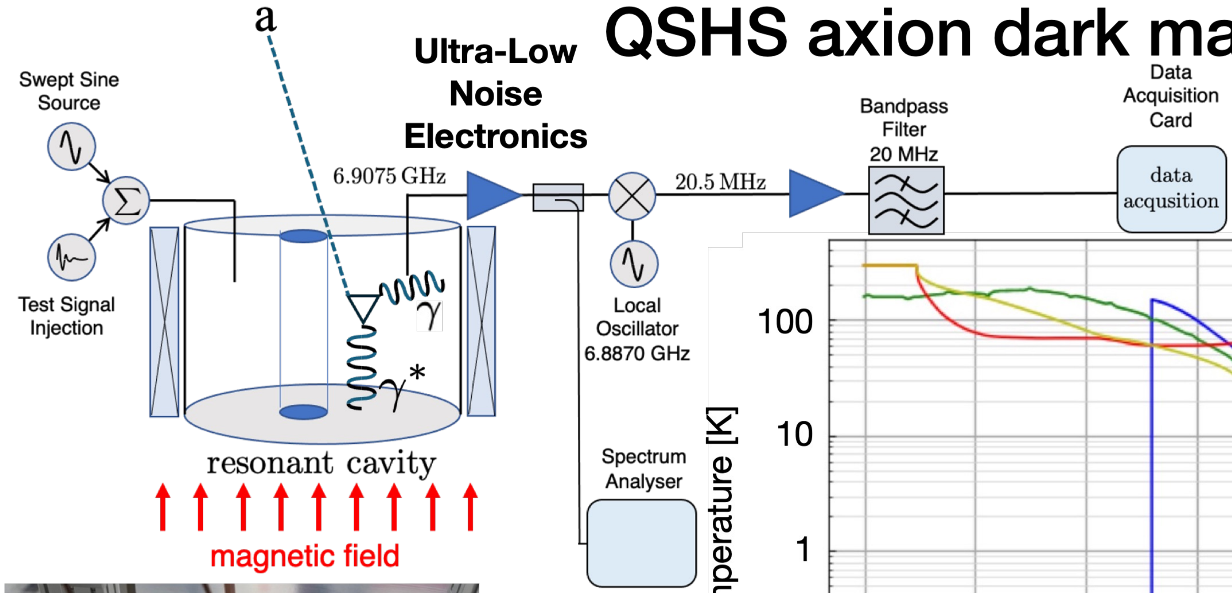
- NbN, Nb, Al, Ti paramps *fabricated* and *tested* at 18 GHz for QTNM
- Operation at ~100mK and 4K possible for two-stage readout

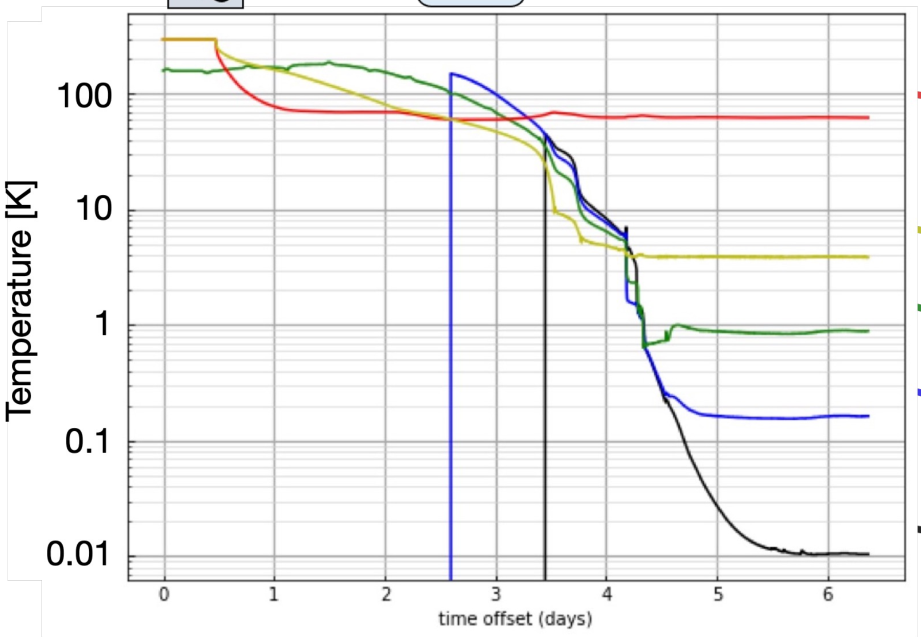


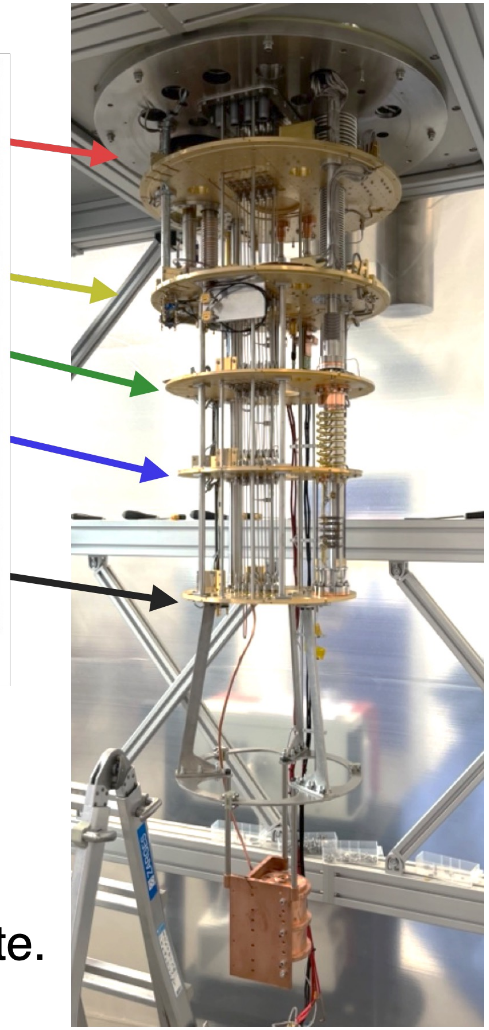
QTNM: 1μT with 0.9mm spatial resolution demonstrated



QSHS axion dark matter search



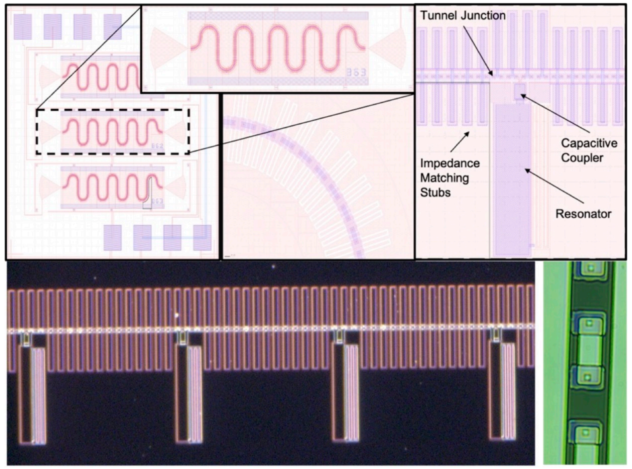


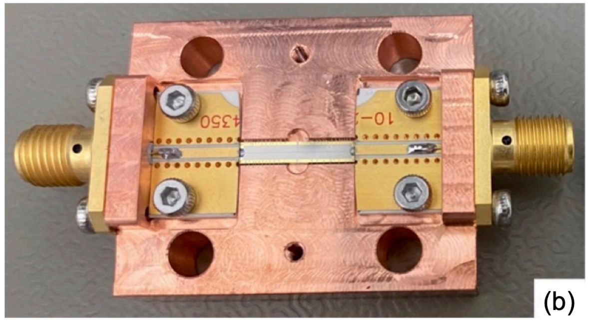


- Dilution fridge installed, cooled to 8.5mK
- Cavity installed, cooled to 18mK
- Magnet at Oxford Instruments for 8T retrofit
- Magnetic field shield installed
- Tests of ADMX superconducting tuning rod complete.
- Motor drive installation underway

Quantum Electronics for QSHS

Travelling Wave Parametric Amplifiers, Boon Kok Tan group, Oxford





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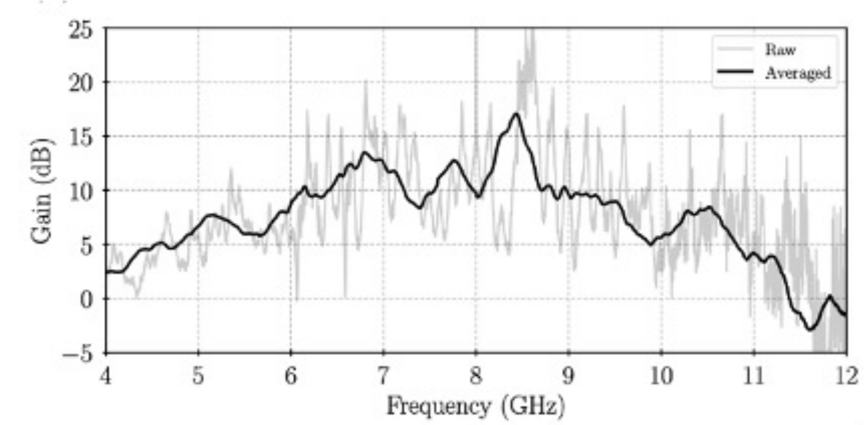
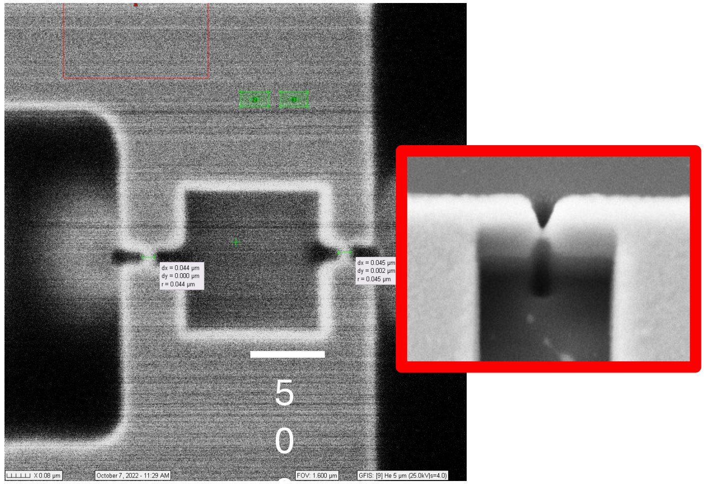
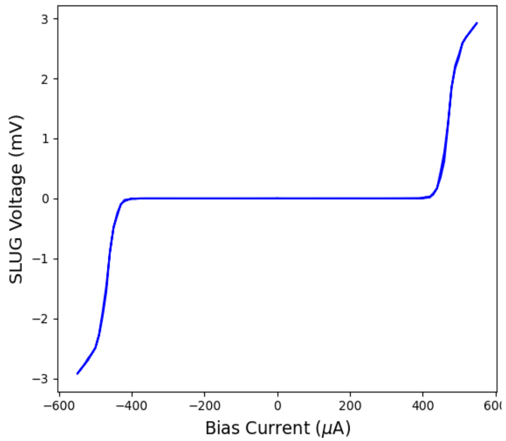
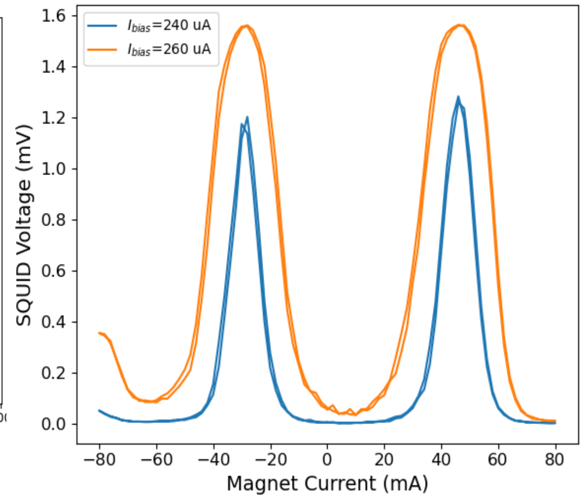


SLUG microwave SQUID amplifiers, Ling Hao, Ed Romans groups, NPL/UCL

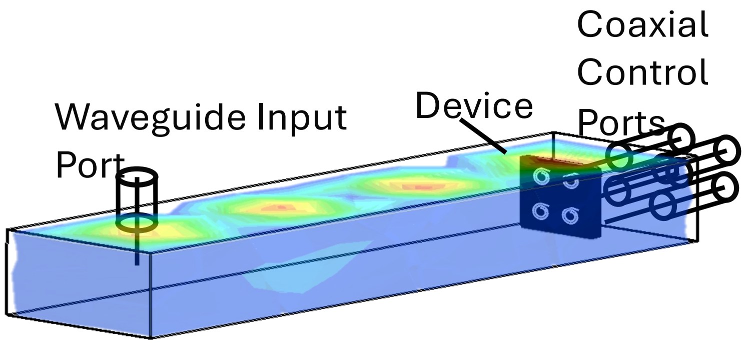


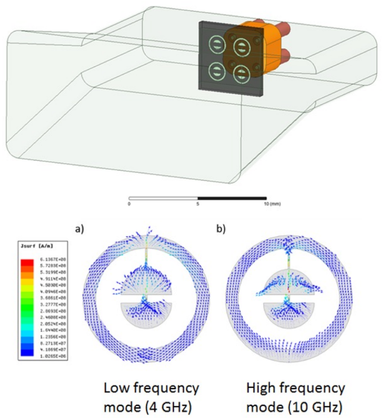


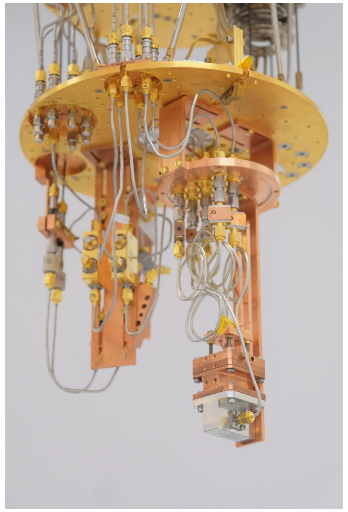


More Quantum Electronics for QSHS

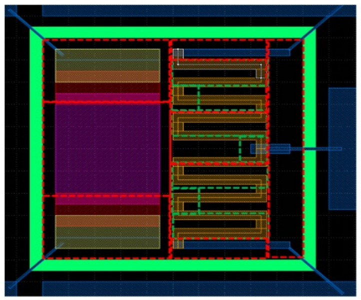
Transmon Qubit arrays, Leek group, Oxford

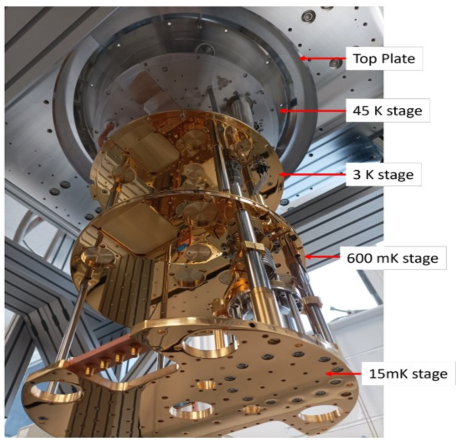


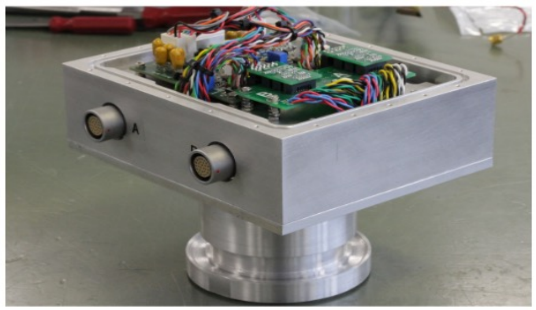




Homodyne Detection Schemes, Parametric Amplifier Design, Withington Group, Oxford







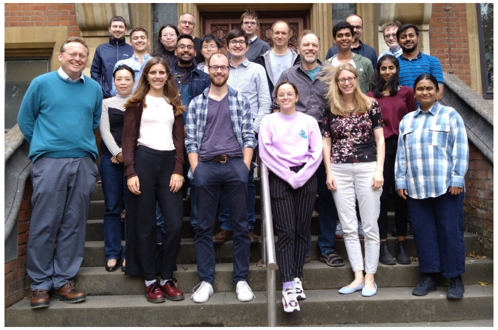
Optical Precision Measurements

- In HEP, energy scale of 1TeV probes a distance scale of about 1 attometer.
- This is about the same as the detected displacement of the LIGO mirrors from a binary inspiral event.
- This is possible because mirrors are heavy and macroscopic, hence their surfaces have an average position that is well defined on the attometer scale.
- The AVERAGE position of the surface can be measured without single particle TeV-scale collisions that tend to produce new particles, rather than permitting precision measurements of position.
- Further improvements in accuracy involve using squeezed laser light. Quantum effects appear at room temperature in the optical, which is in large part why quantum mechanics was first discovered through optical observations (atomic spectroscopy, photoelectric effect).
- Einstein telescope, ALPS2, QI experiments, and AION all rely on quantum optics in the quest to achieve sensitivity to small signals.
- QI in particular aims to probe hypotheses of quantized space-time (QUEST), ultra-light wave like dark matter AND gravitational waves using ‘table-top’ optics.

Quantum-Enhanced Interferometry for New Physics

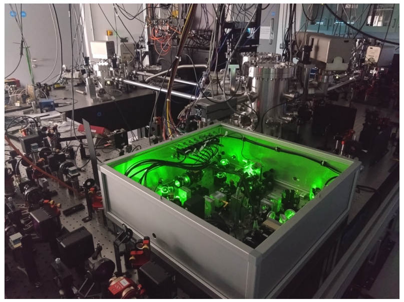
- Novel searches for dark matter and axion-like particles: LIDA, ALPS II
- Novel searches for signatures of quantum gravity: QUEST, CRYO-BEAT
- Quantum technologies: Squeezed light and TES single photon detection

- UK: Birmingham, Cardiff, Glasgow, Strathclyde, Warwick
- International Partners: Fermilab / U Chicago, NIST, MIT, Caltech (US), DESY, PTB, Max Planck (Germany), Vienna (Au), U Western Australia (A)



Status:

- Novel axion interferometer method
- established: 2307.01365; 2309.03394; 2401.11907
- TES detector is under commissioning and ALPS II design:
- 2009.14294, 2408.13218
- Scalar field dark matter searches: Nature 600, 424 (2021); PRL 128, 121101 (2022); PRL 133, 101001 (2024)
- QUEST Quantized space-time search: 1 engineering run completed. Theory work: 2306.17706
- Schrödinger-Newton Gravity search: cavities beat node achieved



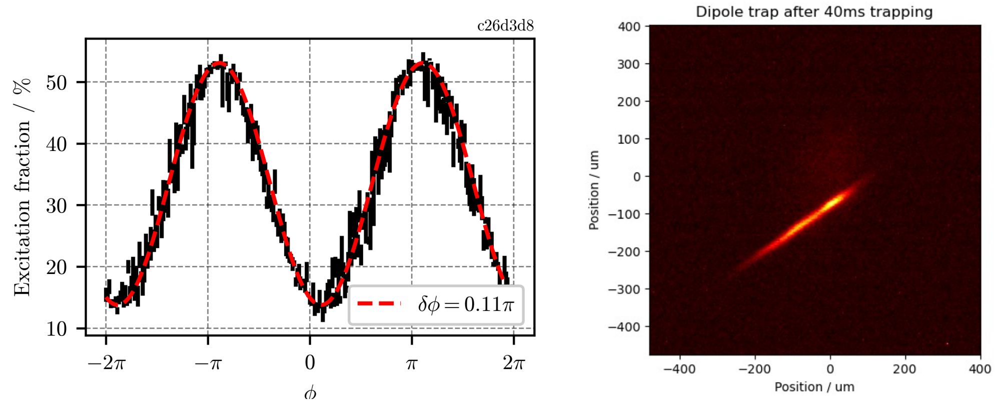
QUEST

AION – atomic beam interferometry

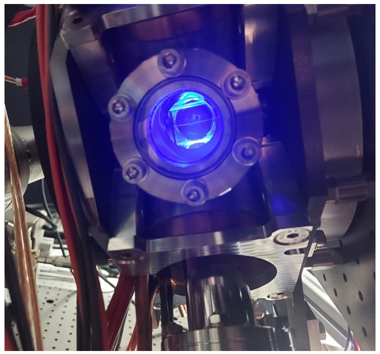
AION Labs (UoB, Cam, ICL, Oxf, RAL) participate in the Atom Interferometer (AI) WP-1b of DRD5, focus on High-Flux AI, Squeezing, and TVLBAI community building process.

Experimental Progress:

- Squeezing cavity installed, with 200k finesse
- Blue MOT, red MOT, dipole trap, 689 nm interferometry, and intracavity lattice-trapped atoms
- First LMT established

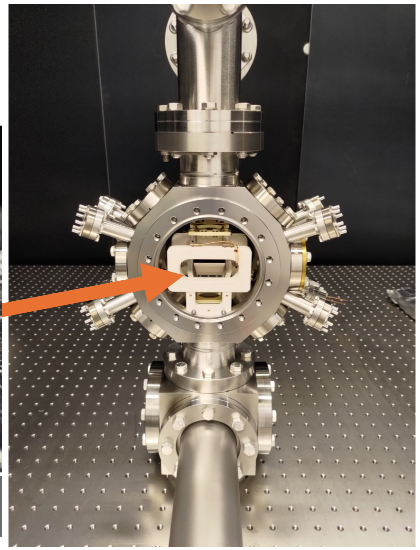


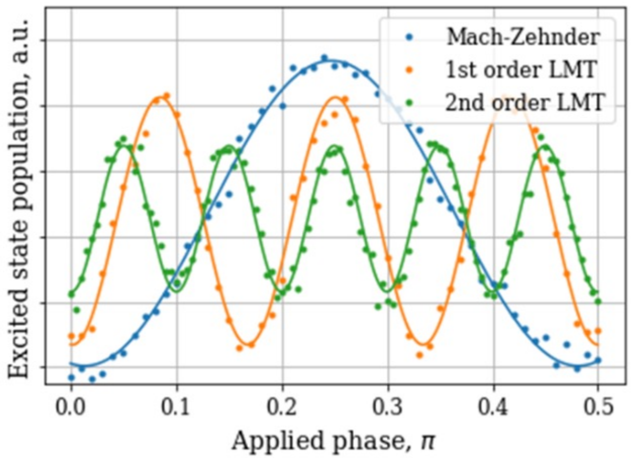
(left) Preliminary Mach-Zender configuration atom interferometry fringes using the $^1S_0$ to $^3P_1$ transition, with an applied phase shift ϕ. ***(right)*** Atoms confined in a dipole trap in preparation for squeezing / entanglement.



2D MOT source

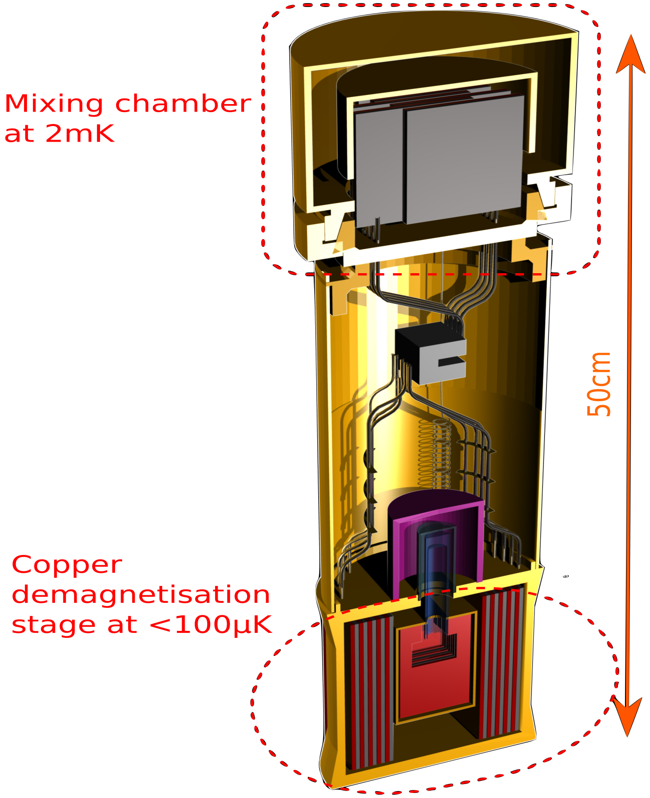
Squeezing cavity

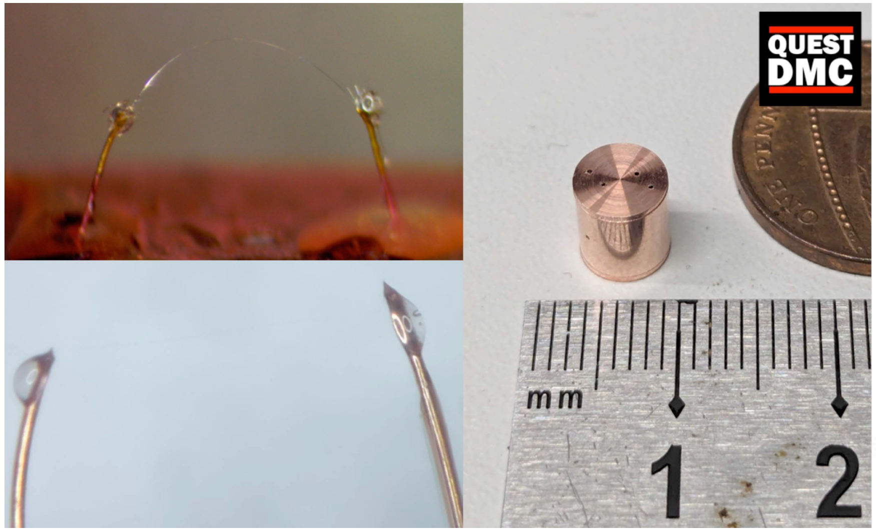


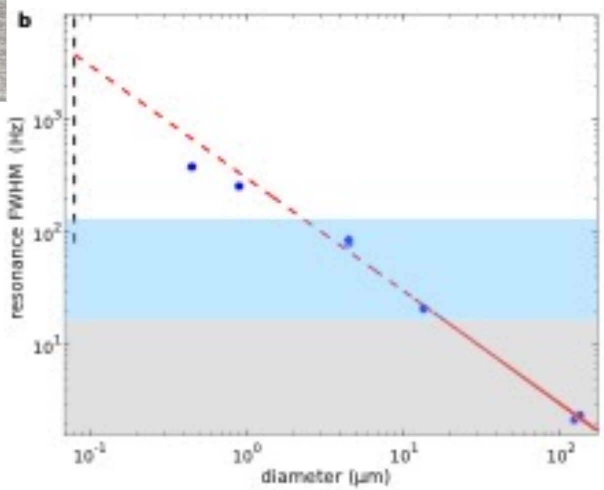


Atom interferometry outputs of the strontium apparatus at increasing orders of large momentum transfer.

Mechanical Readout of QUEST-DMC using Superconducting Nanowires







Autti, S., Casey, A., Eng, N. et al. QUEST-DMC: Background Modelling and Resulting Heat Deposit for a Superfluid Helium-3 Bolometer. J Low Temp Phys (2024).

Summary

1. Though the landscape is complicated, there are many cases of measurements at or below the standard quantum limit being critical for probing beyond-the-standard-model particle physics.
2. Several technology developments are critical in multiple experiments, notably microwave-band cryogenic amplifiers for QTNM/QSHS and squeezed light optical readout for QI and gravitational wave experiments.
3. Both electromagnetic and mechanical transducers are critical.
4. Ultra-sensitive detectors are frequently less naturally stable than their less sensitive cousins. CONTROL of quantum limited elements often by classical feedback circuits is a critical area of research.
5. Control circuitry may also need to be cryogenic in the future.
6. The QTFP programme of is complimentary to efforts to develop the next generation of high energy physics experiments.
7. QTFP interfaces with the quantum computing/instrumentation community. The quantum technology showcase last week in London had 2000+ attendees!