QSHS

ADMX

Quantum Sensors for the Hidden Sector

DMUK Meeting, 22nd September 2022

Ed Daw, The University of Sheffield, for the
Quantum Sensors for the Hidden Sector Collaboration

UNIVERSITY OF CAMBRIDGE
Lancaster University
The University Of Sheffield.
NPL National Physical Laboratory
UNIVERSITY OF OXFORD
ROYAL HOLLOWAY UNIVERSITY OF LONDON
UNIVERSITY OF LIVERPOOL
UCL

Axions and the Strong CP problem

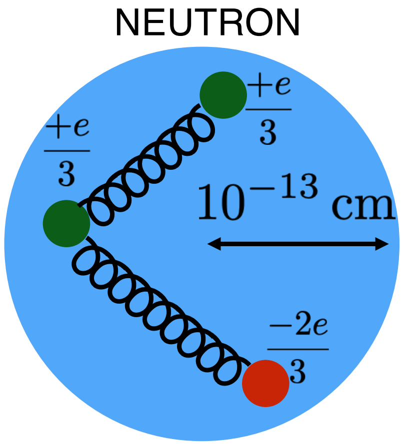
Standard model symmetry group is $\underline{SU(3)} \times \underline{SU(2)} \times \underline{U(1)}$

$$\mathcal{L}_{\rm CPV} = \frac{(\Theta + \arg\det M)}{32\pi^2}\vec{E}_{\rm QCD}\cdot\vec{B}_{\rm QCD}$$

$SU(3)$	$SU(2)$	$U(1)$
NON-ABELIAN	NON-ABELIAN	ABELIAN
CP CONSERVING!	CP VIOLATING	CP CONSERVING

Evidence for CP conservation in the SU(3) strong interactions from multiple measurements of neutron and nuclear electric dipole moments. For example, neutron EDM < 10^{-26} e-cm.

Even simple dimensional arguments show that this is unexpected. Why do the SU(3) QCD interactions conserve CP when SU(2) QED interactions do not? This is the strong CP problem.



Signal-to-noise-ratio

Theoretical signal power for KSVZ axions in ADMX

$$P = 1.52 \times 10^{-21}\,\mathrm{W}\,\mathrm{f_{nlm}} \left(\frac{B}{7.6\,T}\right)^2 \left(\frac{V}{220\,\mathrm{litres}}\right) \left(\frac{g_\gamma}{0.97}\right)^2 \times \left(\frac{\rho_a}{0.45\,\mathrm{GeV\,cm^{-3}}}\right) \left(\frac{f}{750\,\mathrm{MHz}}\right) \left(\frac{Q}{70,000}\right).$$

Signal power divides by 2 as half of the power from axion to photon conversion deposited in the amplifier

Noise power for thermalised axions at 700MHz, 500 Hz bandwidth

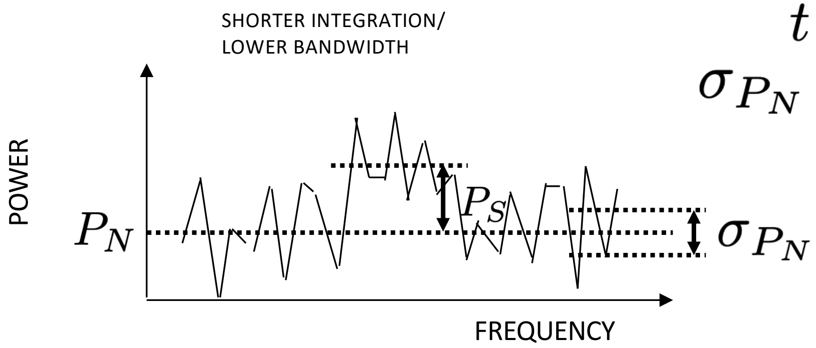
$$\begin{aligned} P_N &= k_B T_S B \\ &= 1.4 \times 10^{-23}[J\,K^{-1}] \times 4[k] \times 500[Hz] \\ &= 2.8 \times 10^{-20}\,W \end{aligned}$$

$$\frac{P}{2P_N} = \frac{1}{37}$$

The Radiometer Equation.

$$\mathrm{SNR} = \frac{P_S}{\sigma_{P_N}} = \frac{P_S}{P_N}\sqrt{Bt}$$

B : bandwidth
P_S : signal power
P_N : noise power
t : integration time
σ_{P_N} : r.m.s. of bin-to-bin fluctuations in noise

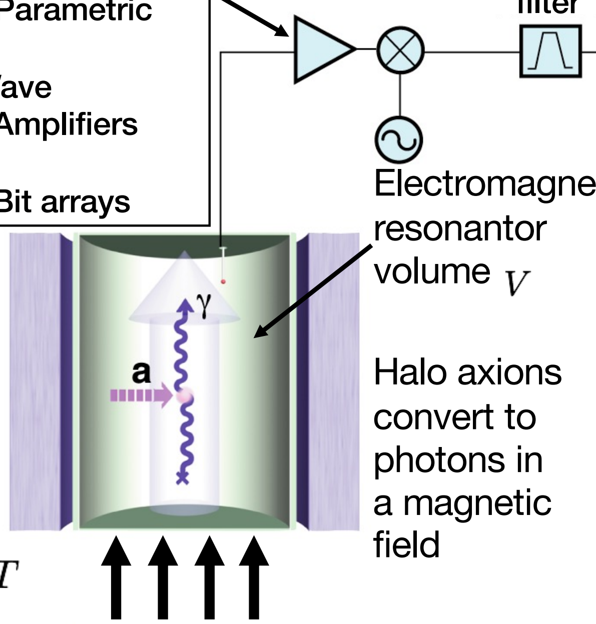


The radiometer equation is useful here because the signal is at a static frequency, and the noise at surrounding frequencies is relatively flat (because the cavity resonance is much wider band than the signal peak). Thus the signal appears as *excess power* in its bandwidth on top of the noise power that is in every bin.

Whether the signal is discernible or not depends on whether the bin-to-bin fluctuations in the
how long you have to integrate for to discern the signal against the background of these fluctuations.

Axion Detectors and the Current Landscape

SUPERCONDUCTING QUANTUM ELECTRONICS:
- SQUIDs
- Josephson Parametric Amplifiers
- Travelling Wave Parametric Amplifiers
- Bolometers
- Qubits / QuBit arrays



Bandpass filter

Data Acquisition

Figure of merit for detector sensitivity: $\frac{B^2 V}{T}$

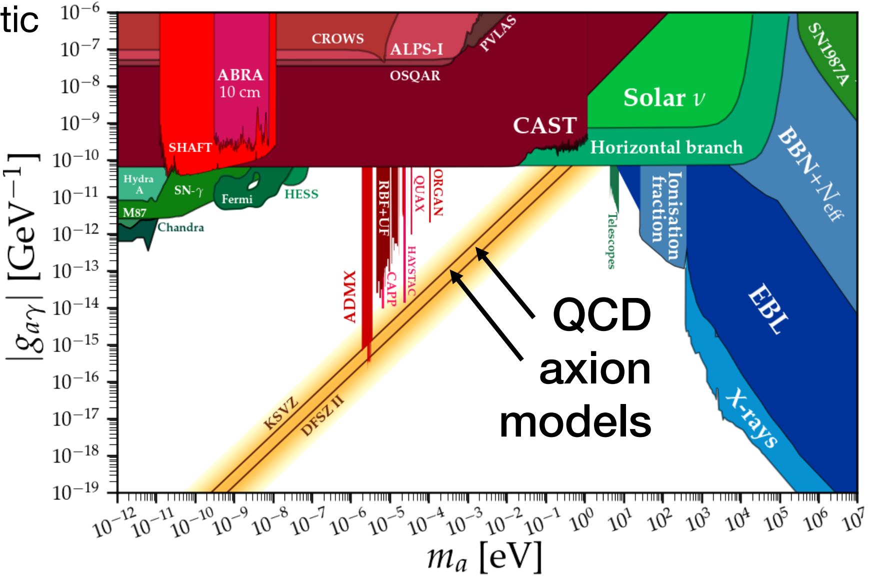
Electromagnetic resonantor volume V

Halo axions convert to photons in a magnetic field

System noise temperature: T

Static Magnetic Field B

Current experimental landscape



QCD axion models

- Non resonant experiments have broad mass coverage, but insensitive to QCD axions
- Resonant experiments much more sensitive. ADMX is the only experiment to have probed a broad range of existing axion models. However, mass coverage too slow. Can speed up: 1. By using a new generation of quantum electronics; 2. By using a larger, higher field magnet; 3. Using multiple resonators in parallel.

Discovery Potential Measure for Resonant Detectors

Figure of merit for detector sensitivity: $$\frac{B^2V}{T}$$

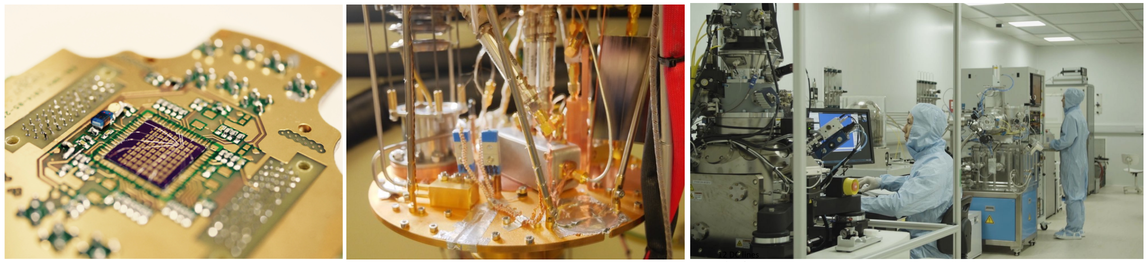
← Energy stored in magnetic field

← System noise temperature, proportional to energy per oscillator mode in thermal equilibrium

Experiment	B^2V / T
ADMX (US)	47
HAYSTAC (US)	0.33
CAPP-PACE (S. Korea)	0.36
CAPP-18T	0.36
CAPP-12TB	43
QSHS-SHEFFIELD PROTOTYPE	20
QSHS-UK FACILITY (proposed)	5000

Quantum Electronics for QSHS

Josephson parametric amplifiers (JPAa) / Travelling wave parametric amplifiers (TWPAs)



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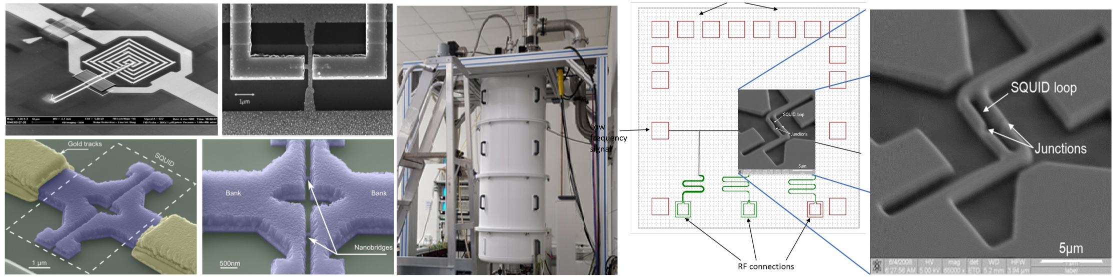
SLUG loaded SQUID amplifiers



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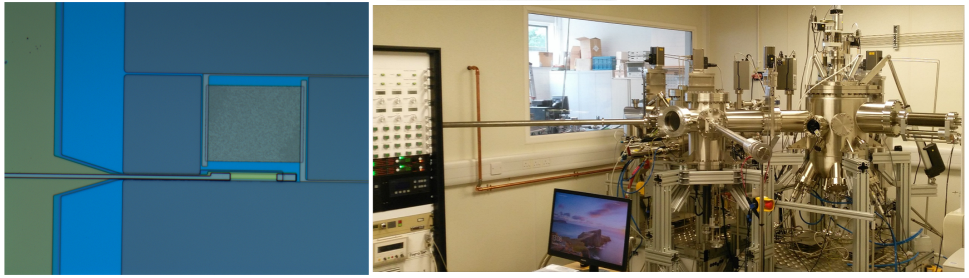
Cryogenic bolometer arrays



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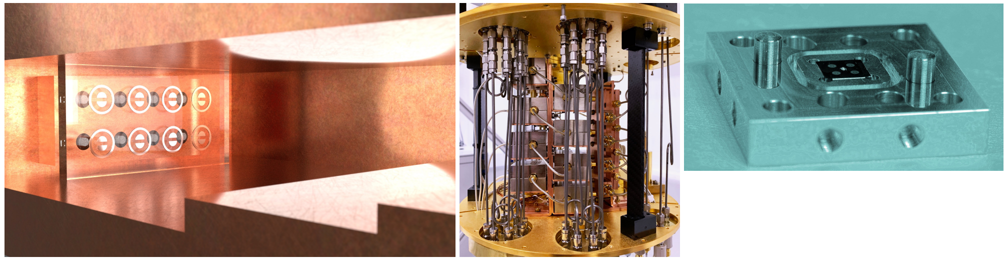
Qubit arrays



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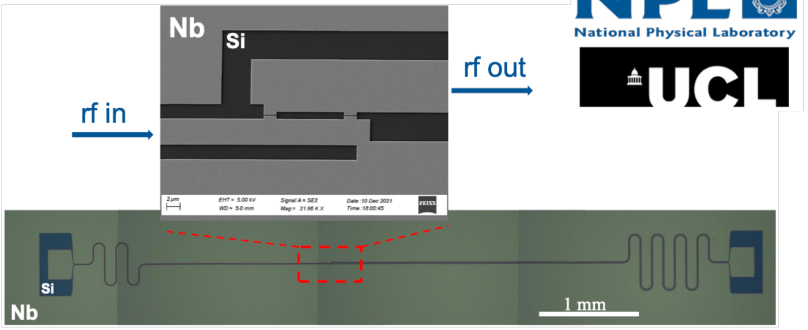
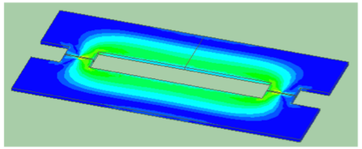
Progress

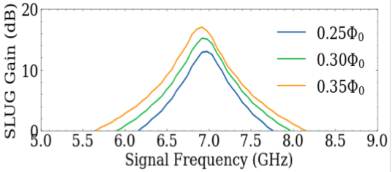
First SLUG loaded SQUID devices fabricated by the NPL/UCL group, Nov/Dec 2021. Currently under test.



Ansys Maxwell – simulated inductance / capacitance of SLUG loop



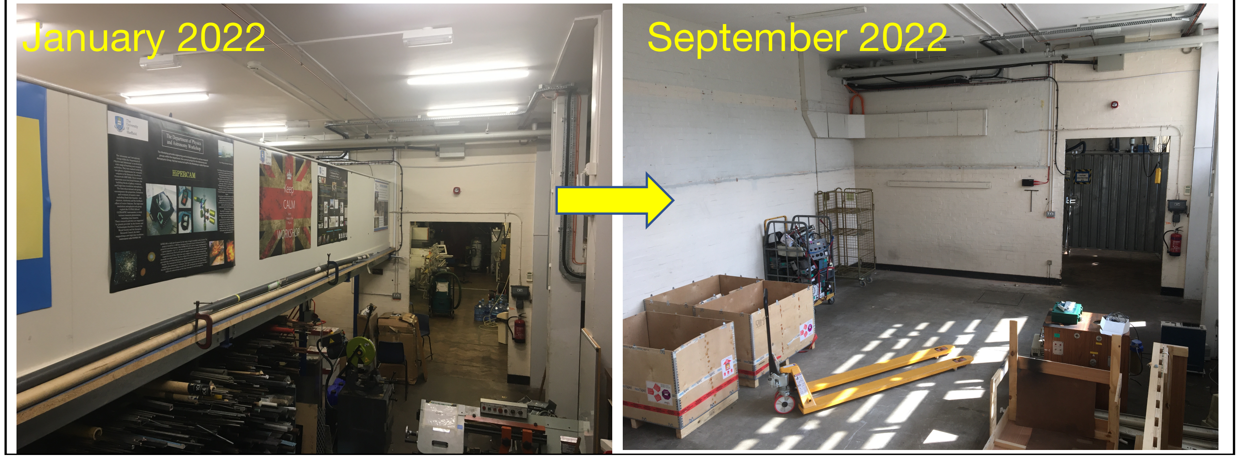
Python – simulated frequency-dependent gain of SLUG amplifier



Proteox MX with 8T, 20cm bore magnet ordered from Oxford Instruments. Delivery expected Autumn 2023. 10mK base Temperature.

QSHS PI Daw with similar fridge at Oxford.

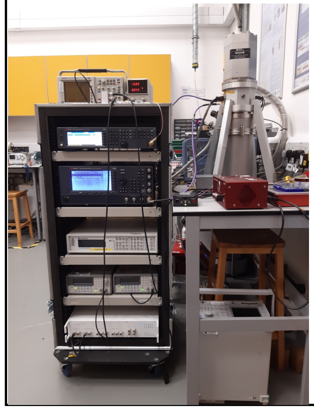
4m high lab space for the 20cm prototype at Sheffield

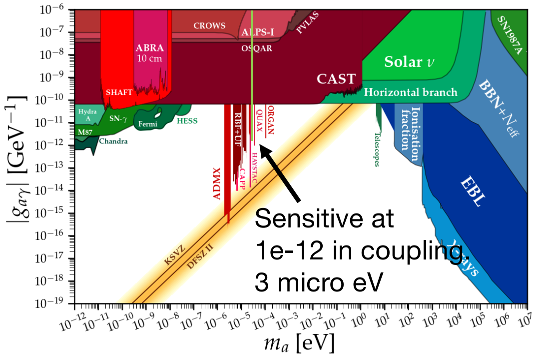


January 2022

September 2022

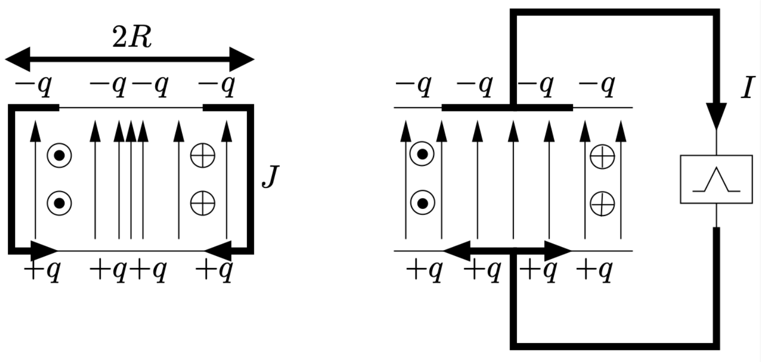
Preliminary sensitivity to 3e-5 micro eV using the 3K test stand at NPL.



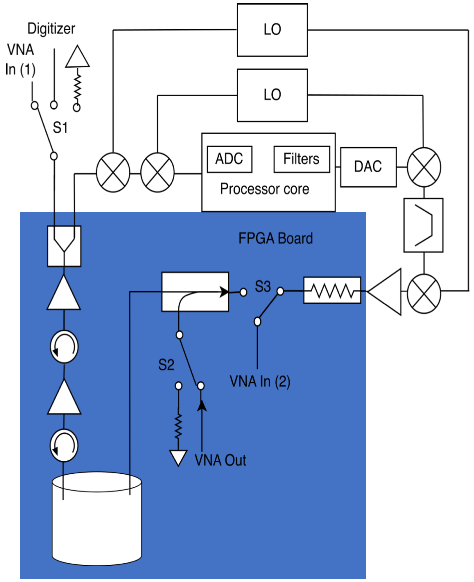


Sensitive at
1e-12 in coupling.
3 micro eV

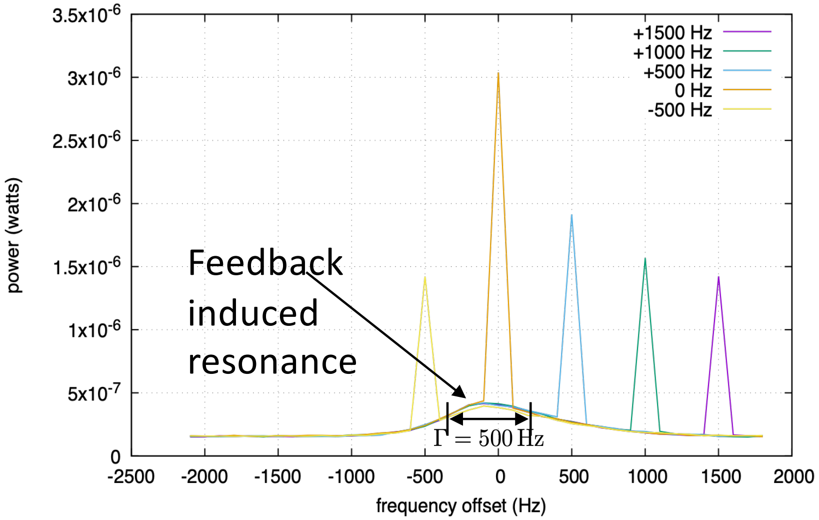
Resonant Feedback


Cavity

Resonant feedback



Test on ADMX sidecar cavity



$$Q = \frac{4.949\,\mathrm{GHz}}{500\,\mathrm{Hz}} \sim 10^7$$

Nuclear Inst. and Methods in Physics Research, A, Volume 921, p. 50-56.
https://arxiv.org/abs/1805.11523

Future Plans

QSHS Phase 1 (current STFC Support)

- Install and commission fridge and magnet at Sheffield
- Run 1 with a single cavity at around 5GHz, first untuned, then with a tuning rod. Start with a HEMT amplifier.
- Establish sensitivity to axion dark matter, extrapoloate to projected sensitivity at lower noise, larger volume.
- Develop 4 varieties of quantum electronics.

maybe during phase 1

- Deploy and test Quantum Electronics
- Run 2, with quantum electronics, measure revised noise temperature, search for axions, again around 5GHz.

QSHS phase 2 requires support.

- Develop and test resonant feedback and improved resonators in collaboration with ADMX.
- Study possible cosmic ray backgrounds.
- Engineering design for a UK scaled up national facility.