Searching for Wave-like Dark Matter with QSHS

IDM 2022, Vienna, 18-22 July 2022

Mitchell G Perry standing in for

Paul J Smith, The University of Sheffield, for the Quantum Sensor for the Hidden Sector Collaboration

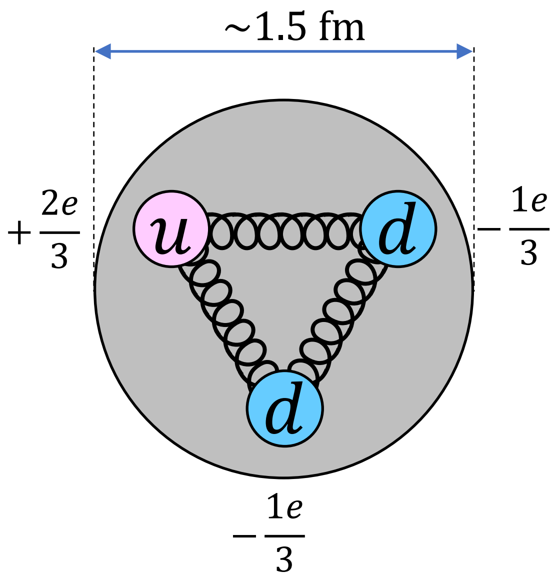
The Strong CP Problem

Conservation of Charge-Parity (CP) in the strong interaction is unexpected.

$$\mathcal{L}_{CPV(QCD)} = \frac{(\Phi + \arg\det|M|)}{32\pi^2} \vec{E}_{QCD}.\vec{B}_{QCD} \approx \bar{\theta} \cdot (10^{-16}\ e\ \mathrm{cm})_{\mathrm{neutron}}$$

A well known example of conservation of strong CP is the neutron Electric Dipole Moment (EDM):

- The current experimental limits on $|d|$ give $10^{-26} e$ cm therefore $\bar{\theta} < 10^{-10}$
- Either it is coincidentally small, or the CP violating effects must add up to zero, driving the minimisation of $\bar{\theta} = (\Phi + \arg\det|M|)$



neutron

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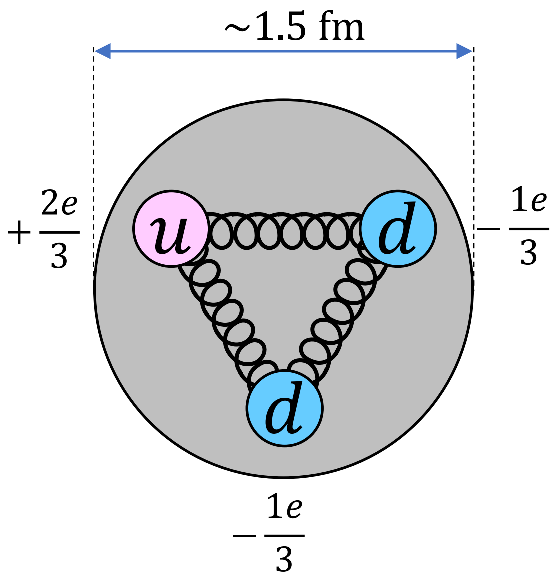
- The Peccei-Quinn (PQ) mechanism adds an additional QCD Lagrangian term that turns $\bar{\theta}$ into a dynamic variable.
- This naturally minimises $\bar{\theta}$ and solves the 'Strong CP' problem.
- The PQ mechanism produces Axions – are these DM candidates?



neutron

$$m_a f_a \sim m_\pi f_\pi$$

$$m_a = 5.70\ \mu eV \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)$$

Why is Axion DM Wave Like

If the local halo density $\rho_H = \sim 0.45 \text{ GeV cm}^{-3}$
And the virial velocity in the local halo is 230 kms^{-1}

For example, assume:

1) Axions have a mass that provides a good fraction of the closure density, i.e. all DM is axions
2) 2) $m_a c^2 = 4 \text{ μeV}$

- High number density of 10^{14} axions per cm^3
- Long Wavelength - This gives us de-Broglie wavelength of about 400 m.

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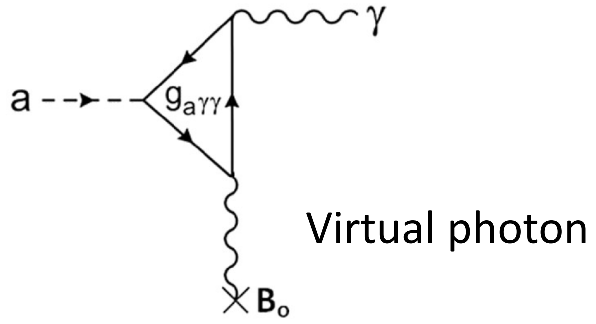
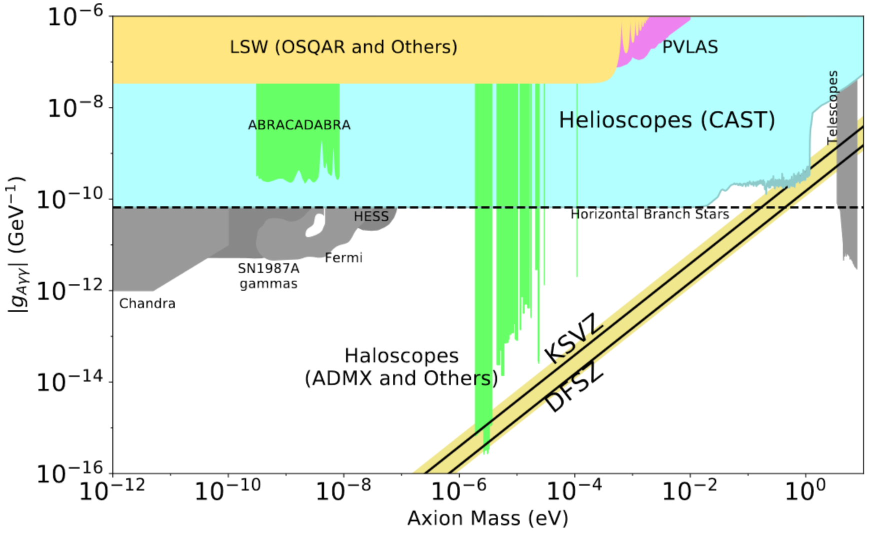
- This could be a useful characterisation when it comes to their detection.
- Method of detection is the reverse Primakoff effect.
- Axions are very light, may be detectable by conversion to RF/UHF photons in a cryogenically cooled resonant cavity.
- ***Photon signal at the yocto-watt (10^{-24} W) level***



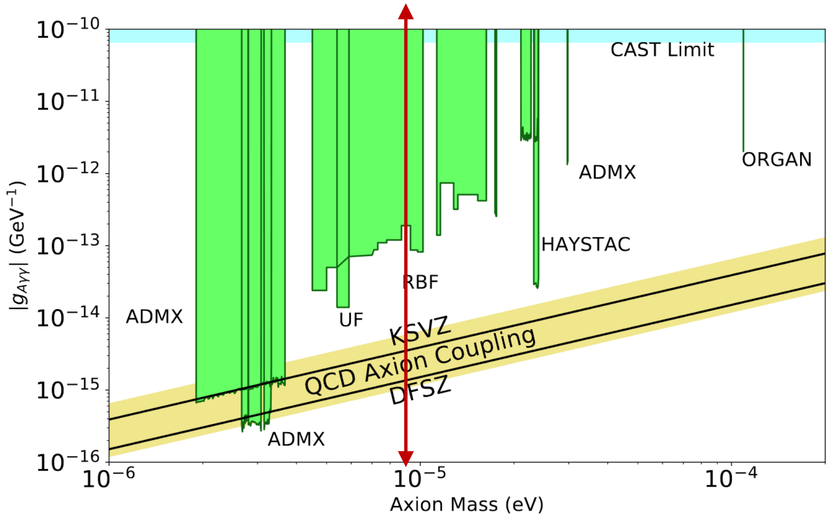
Inverse Primakoff effect in a static Magnetic field $g_{a\gamma\gamma} \sim 10^{-15} \mathrm{GeV}^{-1}$

Axion Resonant Detectors

https://pdg.lbl.gov/2020/reviews/rpp2020-rev-axions.pdf



Location of 5 GHz



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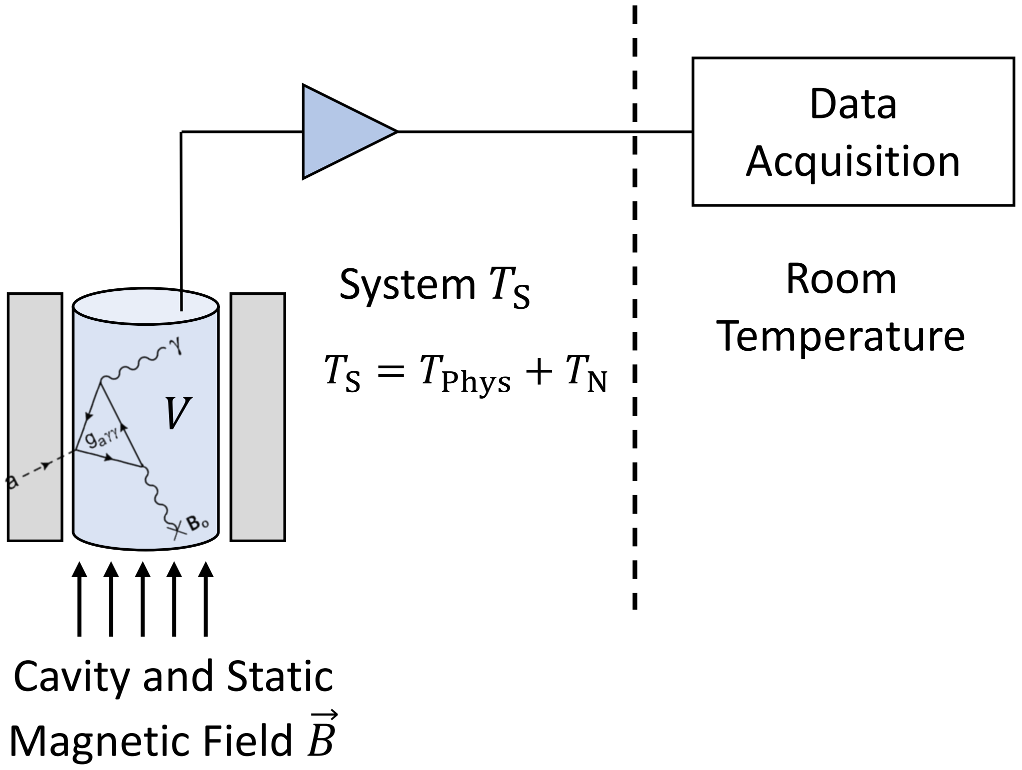

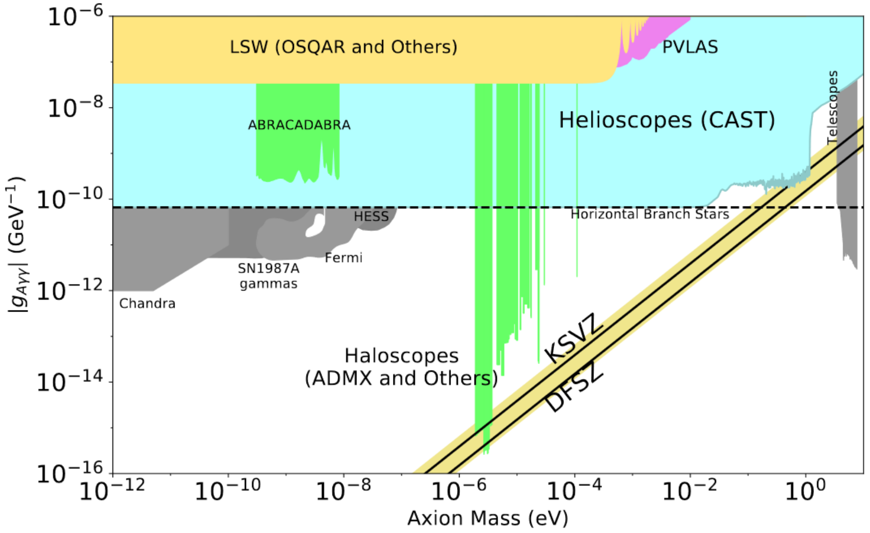

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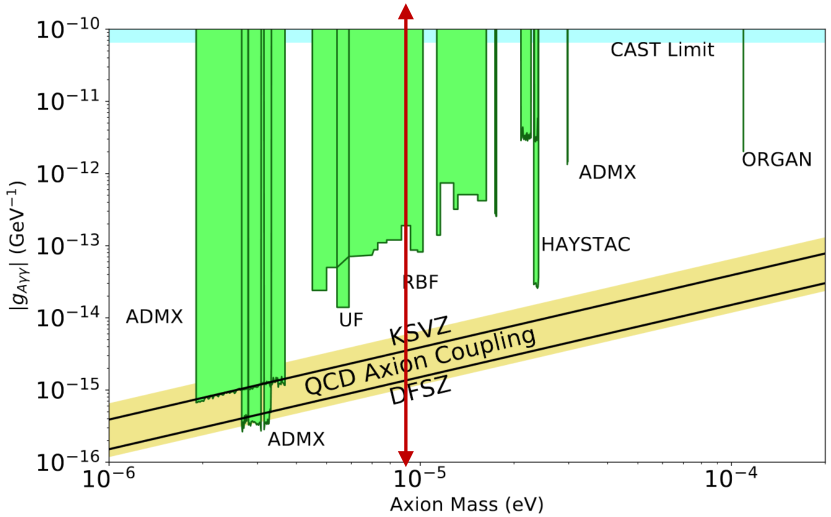
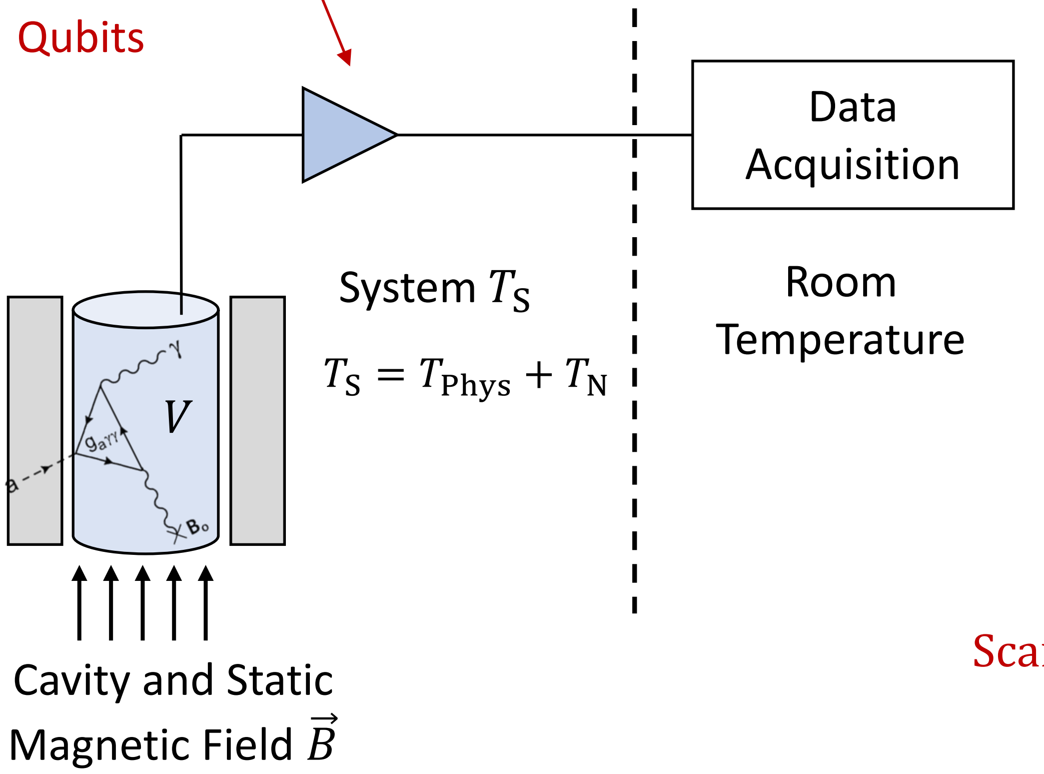
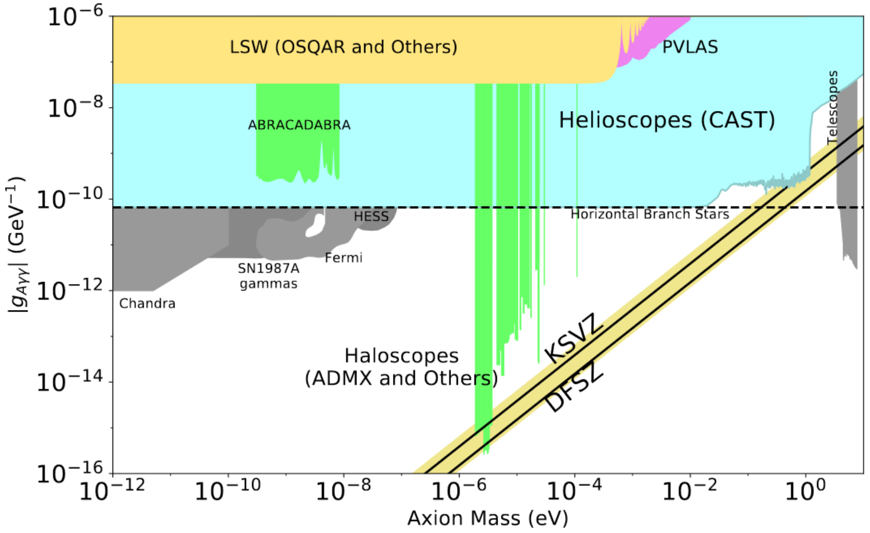


Axion Resonant Detectors

https://pdg.lbl.gov/2020/reviews/rpp2020-rev-axions.pdf

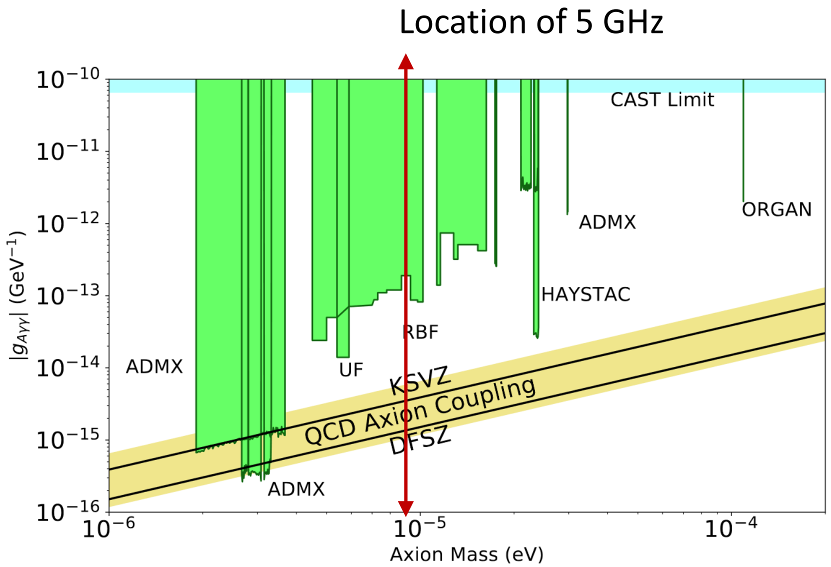
- SQUIDS
- Josephson Parametric Amplifiers & Travelling Wave Parametric Amplifiers
- Bolometers
- Qubits





$$\text{SNR} \propto \frac{B^2 V}{T_S}$$

$$\text{Scan Rate} \propto \frac{B^4 V^2 Q_L}{T_S^2}$$



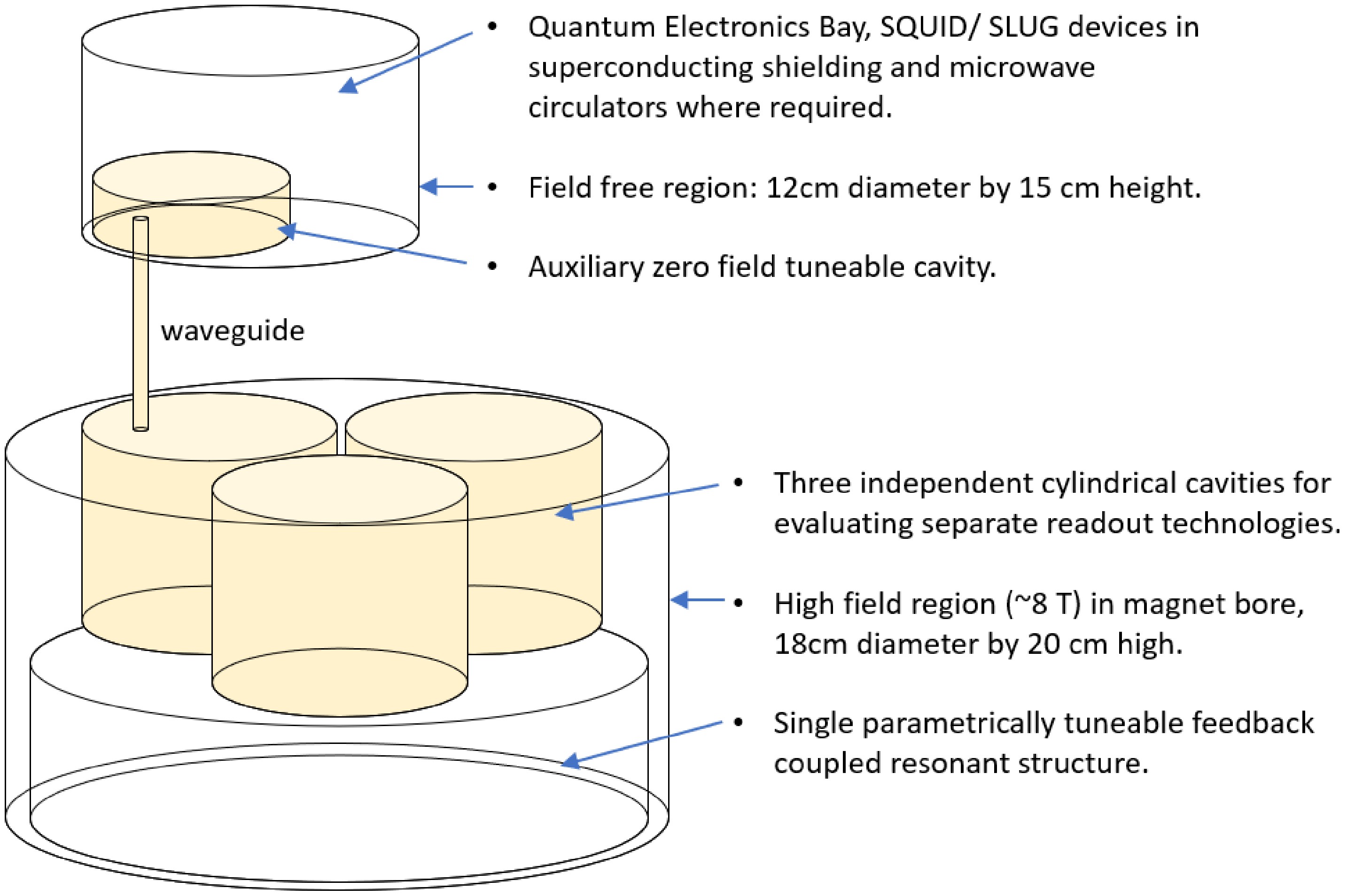
- The huge improvement in SNR and scan-rate over the last few decades is due to the improvement in system noise T_S.
- Significant further improvements in T_S needs to be made to help create a tractable scan through the frequencies available to resonant detectors.

QSHS Test Facility – Science

Science Goals

- Test of ultra-low-noise electronics developed by the collaboration
- Tests of tuneable resonator hardware
- Science from a search of QCD axions ($\sim$5 GHz $\approx$ 20 μeV)
- Test of active resonant feedback.

I won't discuss this here but see: E.J. Daw, Resonant feedback for axion and hidden sector dark matter searches, Nucl. Instrum. Meth. A 921 (2019) 50 [arXiv:1805.11523].



QSHS Test Facility

An STFC funded facility to be located in Sheffield, UK

- We have a MOU with ADMX
- 10 mK target temperature
- At least a 8 T magnetic Field
- 20 cm bore by 20 cm high

DF Lab

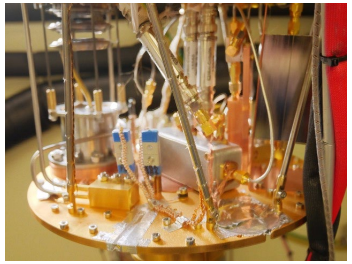
DF Aux Lab – Compressors, pumps, benches, etc

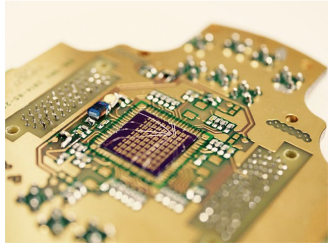
- A Dilution Fridge (DF) and 8 T Superconducting magnet are on order – delivery expected in 12-14 months
- Refurbishment of lab space about to commence.

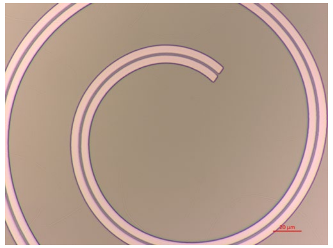
Quantum Electronics for QSHS 1

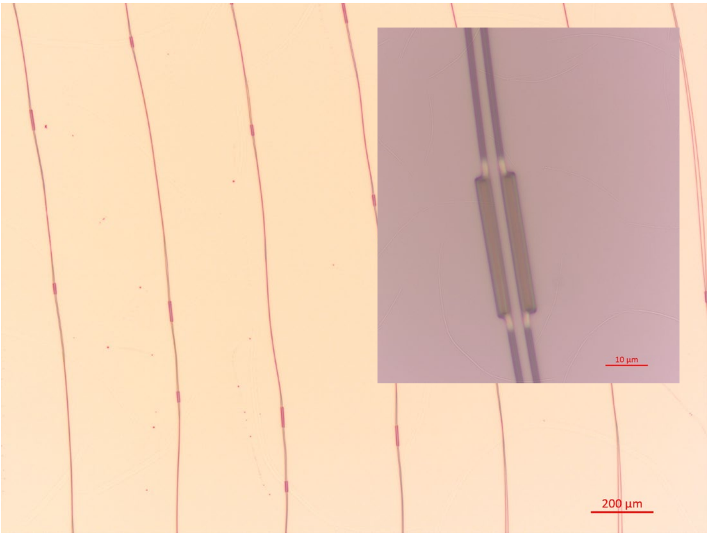
Parametric Amplifiers

Josephson Parametric Amplifiers
Travelling Wave Parametric Amplifiers



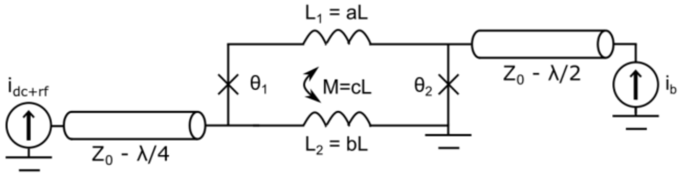


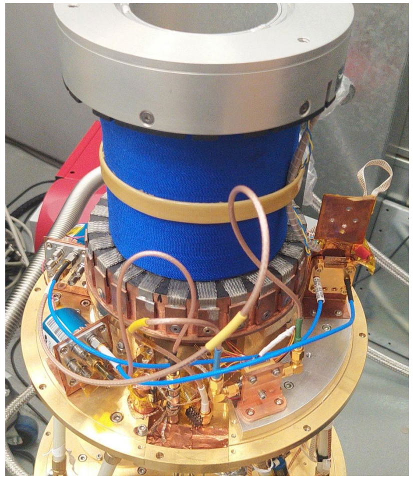


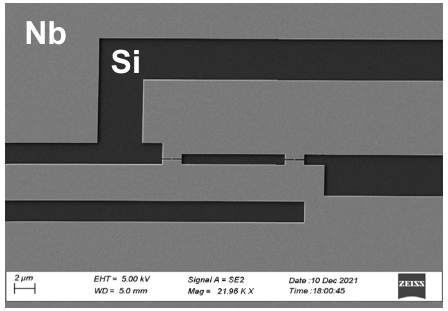


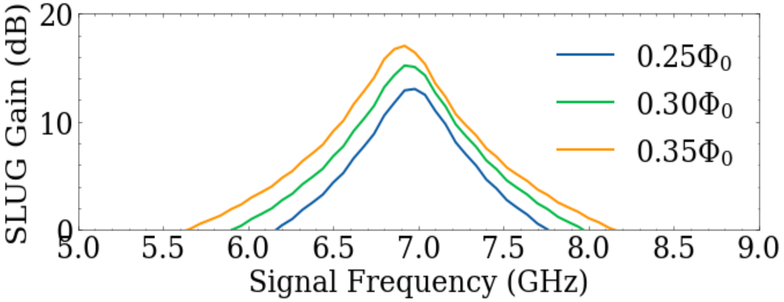
SLUG loaded (SQUID) Amplifiers

High frequency RF amplifiers







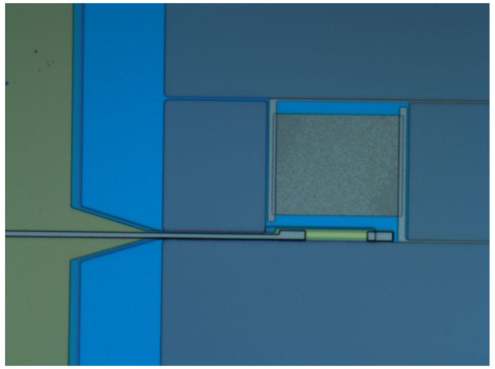


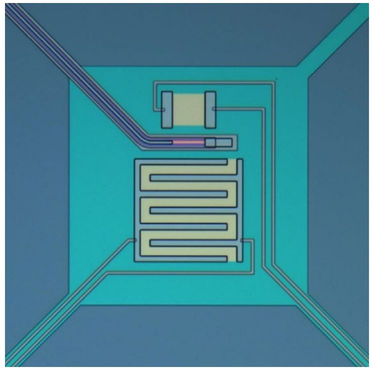
Calculated frequency-dependent gain of a SLUG amplifier. The signal is input to the SLUG via a $\lambda/4$ transmission line resonator with characteristic impedance $Z_0 = 2\ \Omega$ and bare resonant frequency f_{res} = 8 GHz.

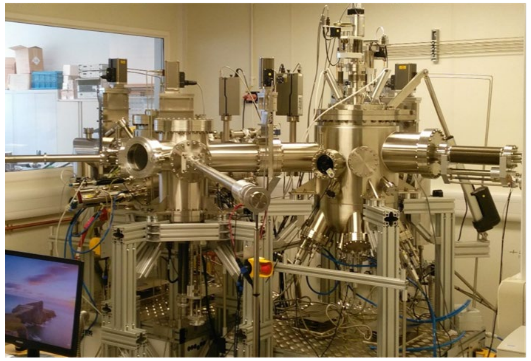
CMD29 (Manchester, Aug. 2022) – Developing a SLUG Microwave Amplifier for Axion Detection

Quantum Electronics for QSHS 2

Bolometers



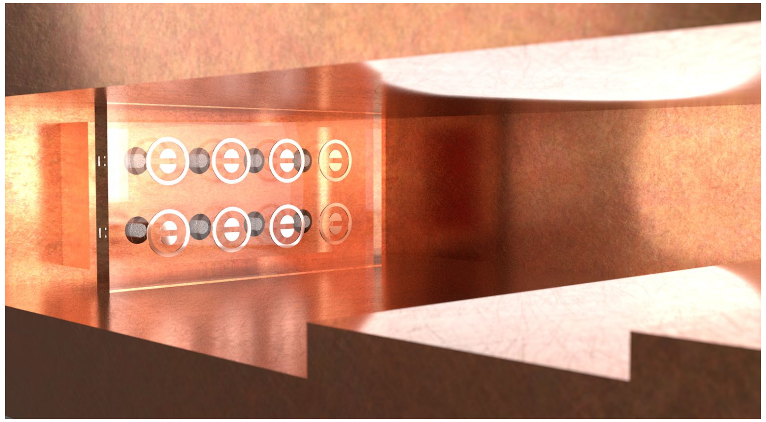


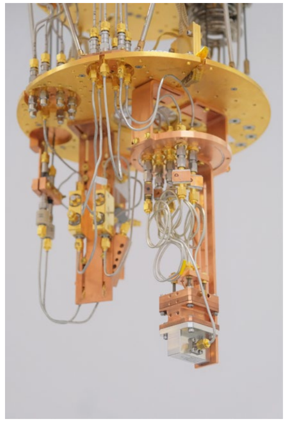


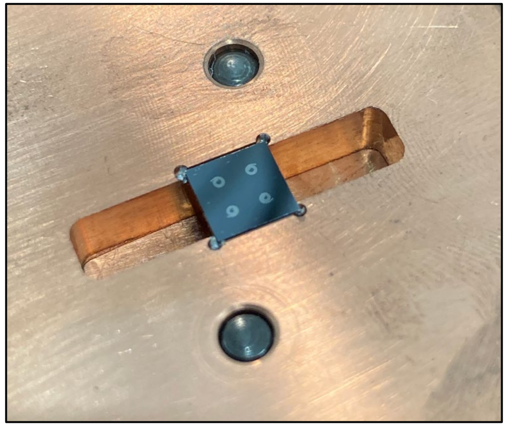
UNIVERSITY OF CAMBRIDGE

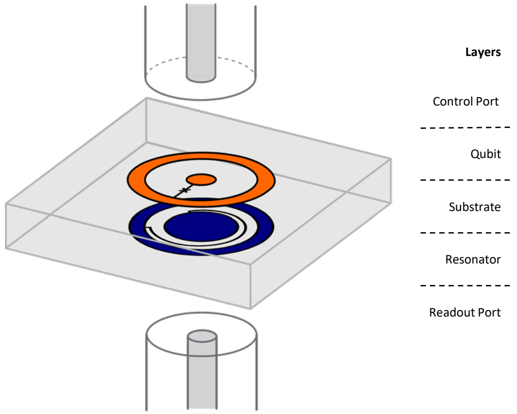
- At ~ 10 mK, noise equivalent powers (NEP's) of $< 10^{-21}$ WHz$^{-1/2}$ should be possible.
- Will permit a broad-range search over the cavities resonant bandwidths

Qubits









UNIVERSITY OF OXFORD

ROYAL HOLLOWAY UNIVERSITY OF LONDON

- Fabricated a test device with qubits and resonators
- Built and measured a waveguide sample holder
- Demonstrated feasibility of multiplexed readout with waveguide architecture

Summary

- The QSHS collaboration is building a world-class programme in this area over eight institutions

- A new UK based facility is being built that will search for axions via the resonant cavity method.

- A dilution fridge has been ordered and space is being refurbished.

- Development of quantum devices is taking place to improve scan rate and detection of very faint signals:
  - Amplifiers
  - Qubits
  - Bolometers

- Collaboration with US colleagues (ADMX) on resonators.

- The long term goal is a large scale UK facility.