QSHS

# The Quantum Sensors for the Hidden Sector Collaboration

Ian Bailey – Lancaster University

**On behalf of the QSHS collaboration, consisting of groups at:**

- 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

**IN COOPERATION WITH:** ADMX

# Introduction to QSHS

- In 2021 the **Quantum Sensors for the Hidden Sector** (QSHS) collaboration in the UK was founded and received funding to develop and demonstrate quantum devices with the potential to detect hidden sector particles in the ~1μeV to ~100μeV mass window.

- The collaboration is developing a range of “quantum” devices.

- Constructing a high-field, low-temperature facility at the University of Sheffield to characterise and test the devices in a haloscope geometry.

- For this talk we will focus on the QCD axion as the canonical “hidden sector” dark matter candidate. Other candidates are available!

# The QCD Axion

- Arises from Peccei-Quinn solution to the strong CP problem.
- Apriori no constraints on axion mass.
- If $U(1)_{PQ}$ unbroken at end of inflation:
  - Decay of solitons and domain walls produces axions
  - Observed dark matter density requires >100 μeV
- If $U(1)_{PQ}$ broken during inflation (realignment mechanism):
  - Masses ~1 μeV to ~100 μeV

*Axion interactions with SM fields*

| | Photons | Fermions | nEDMs |
|---|---|---|---|
| Source | $g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$ | $g_{aff} \boldsymbol{\nabla} a \cdot \hat{\boldsymbol{S}}$ | $g_{EDM} a \hat{\boldsymbol{S}} \cdot \boldsymbol{E}$ |
| Detection | Resonators in magnetic fields | Magnetometers | NMR |
| Example | ADMX, CAPP, MADMAX, … | GNOME, QUAX, ARIADNE, … | CASPEr, srEDM, … |

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# Axion-Photon Coupling

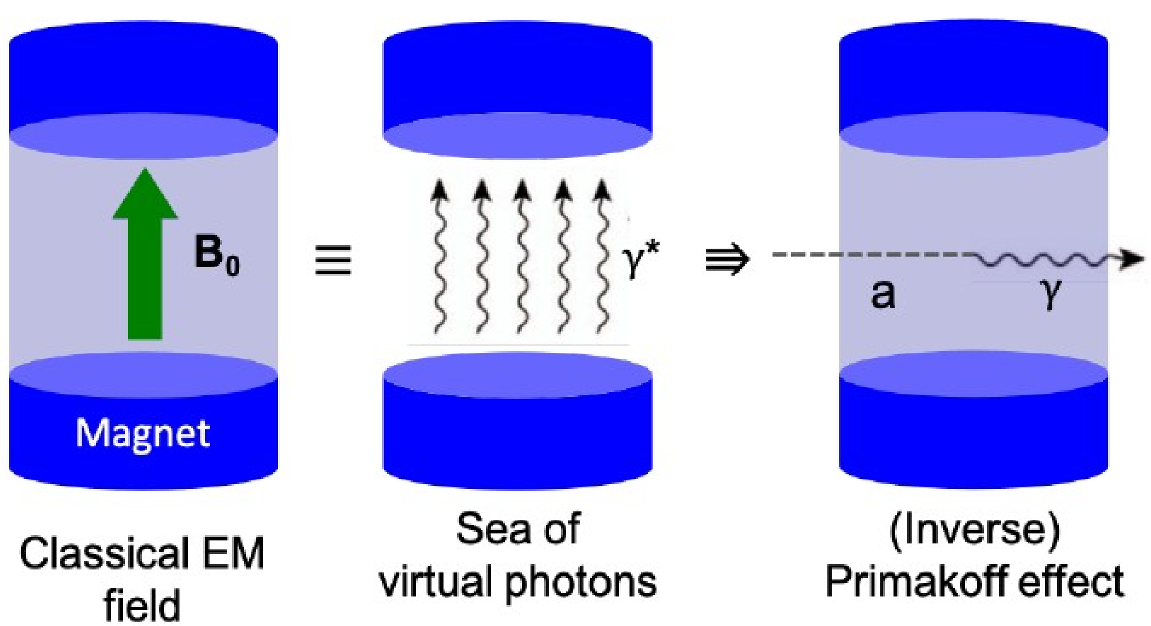
$$\nabla \cdot \mathbf{E} = \rho - g_{a\gamma\gamma} \mathbf{B} \cdot \nabla a,$$

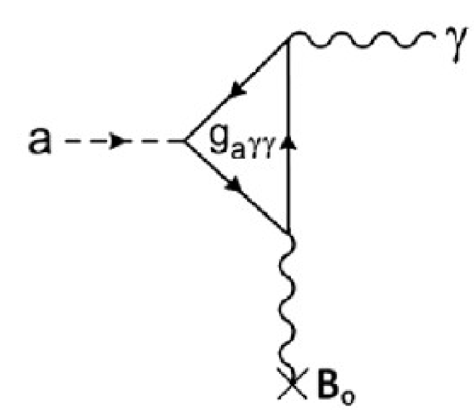
$$\nabla \cdot \mathbf{B} = 0,$$

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t},$$

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} + \mathbf{J} - g_{a\gamma\gamma}\left(\mathbf{E} \times \nabla a - \frac{\partial a}{\partial t}\mathbf{B}\right).$$

PRD99 055010 (2019)



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$$a(t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a}\sin(m_a t)$$

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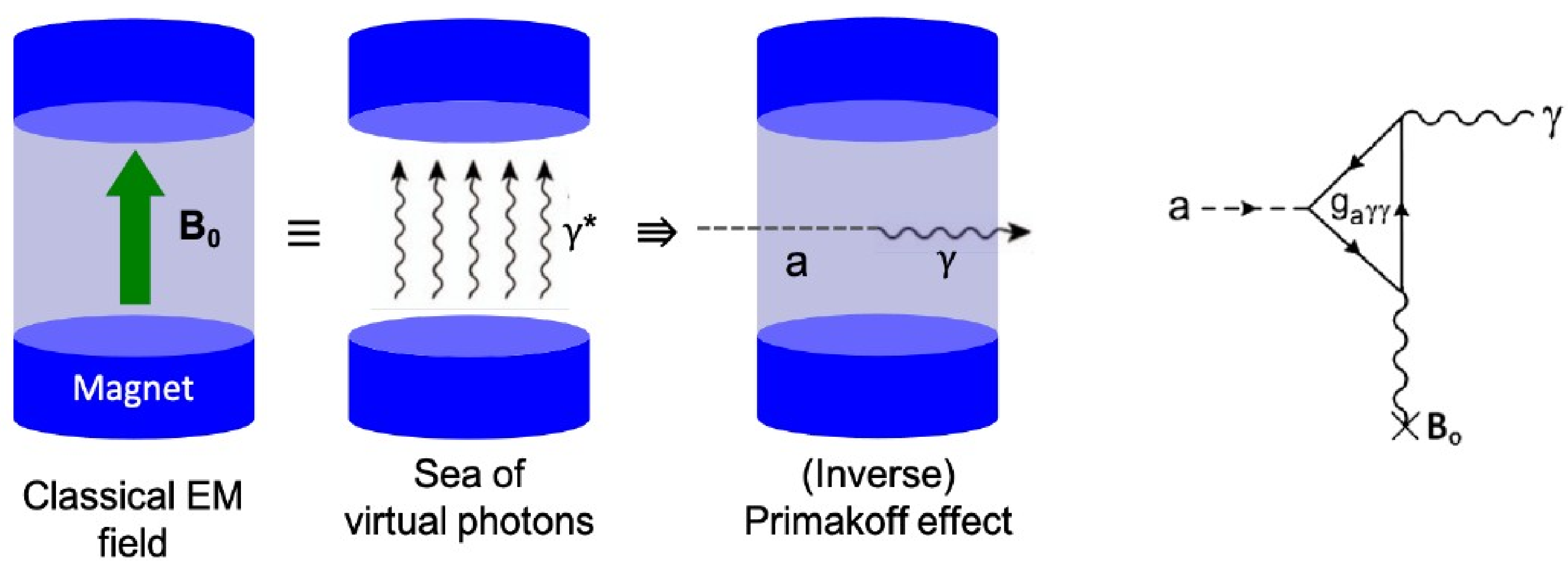
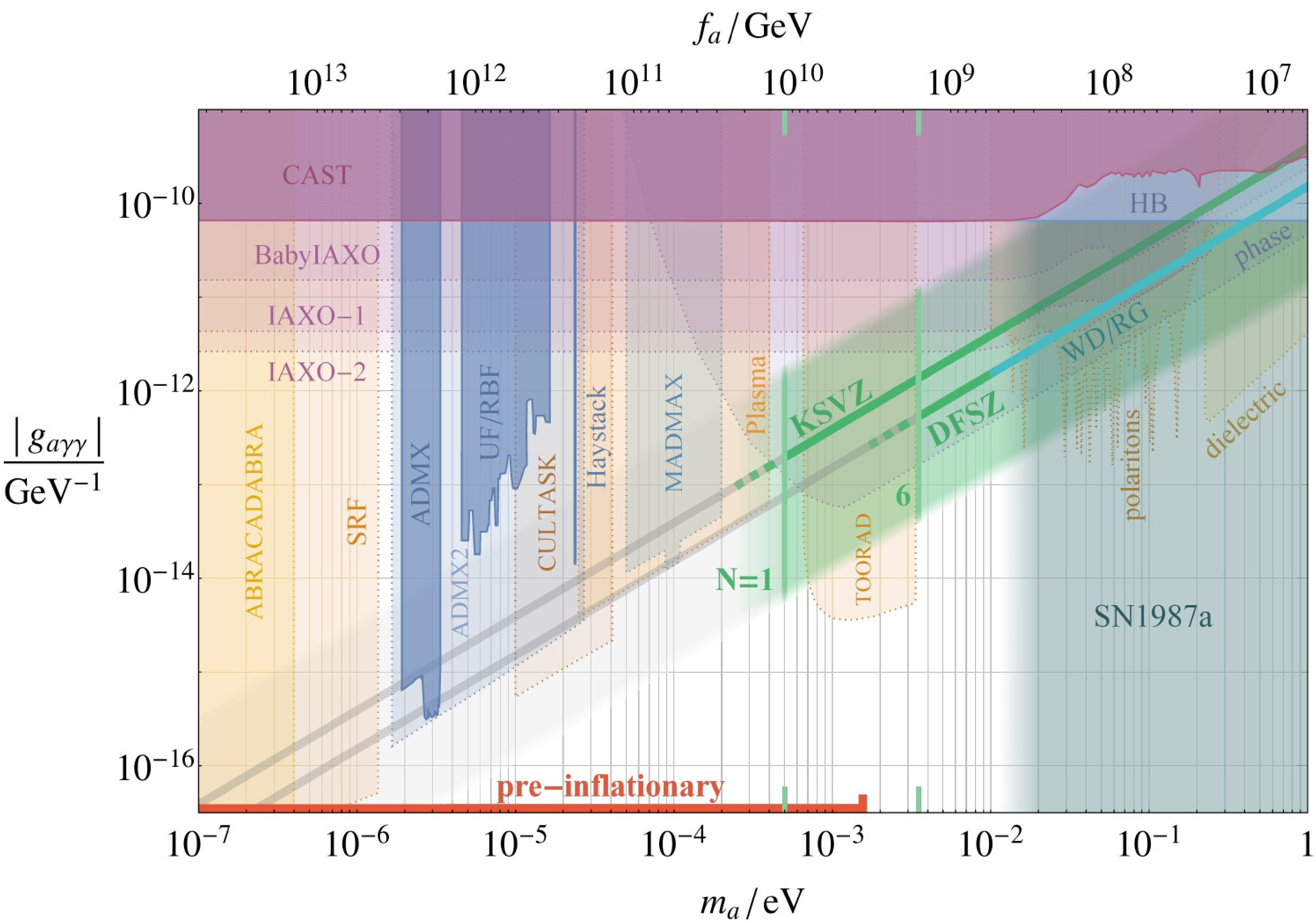


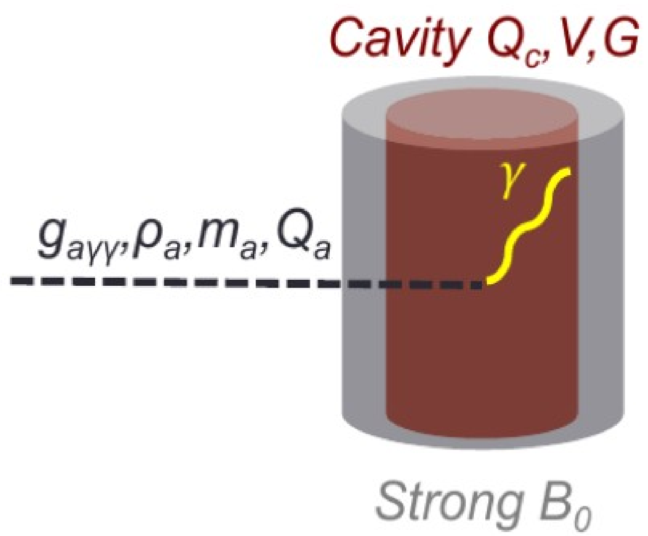
# The QCD Axion search landscape (axion-photon coupling)




E. Hardy, Liverpool

# Axion Haloscopes

$$P_{a\gamma\gamma} = 1.0\times10^{-23}\,W\left(\frac{C_\gamma}{0.75}\right)^2\left(\frac{\rho_a}{0.45\,\frac{GeV}{cm^3}}\right)\left(\frac{\nu_a}{1\,GHz}\right)\left(\frac{B_0}{10\,T}\right)^2\left(\frac{V}{30\,L}\right)\left(\frac{G}{0.5}\right)\left(\frac{Q_c}{10^5}\right)$$




Signal power

Measurement time

$$\frac{\text{Signal}}{\text{Noise}} = \frac{P_{a\gamma\gamma}}{kT_N}\sqrt{\frac{\tau}{\Delta f}}$$

Boltzmann's constant

Signal bandwidth

System noise temperature

# Axion Haloscopes

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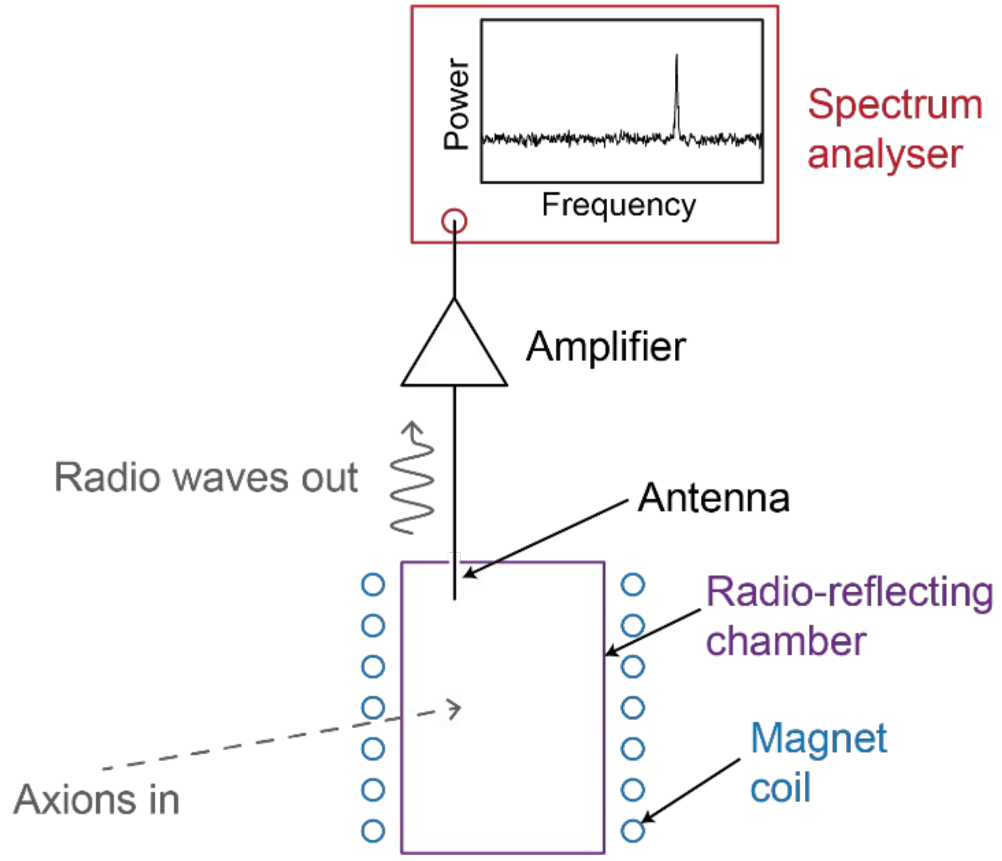
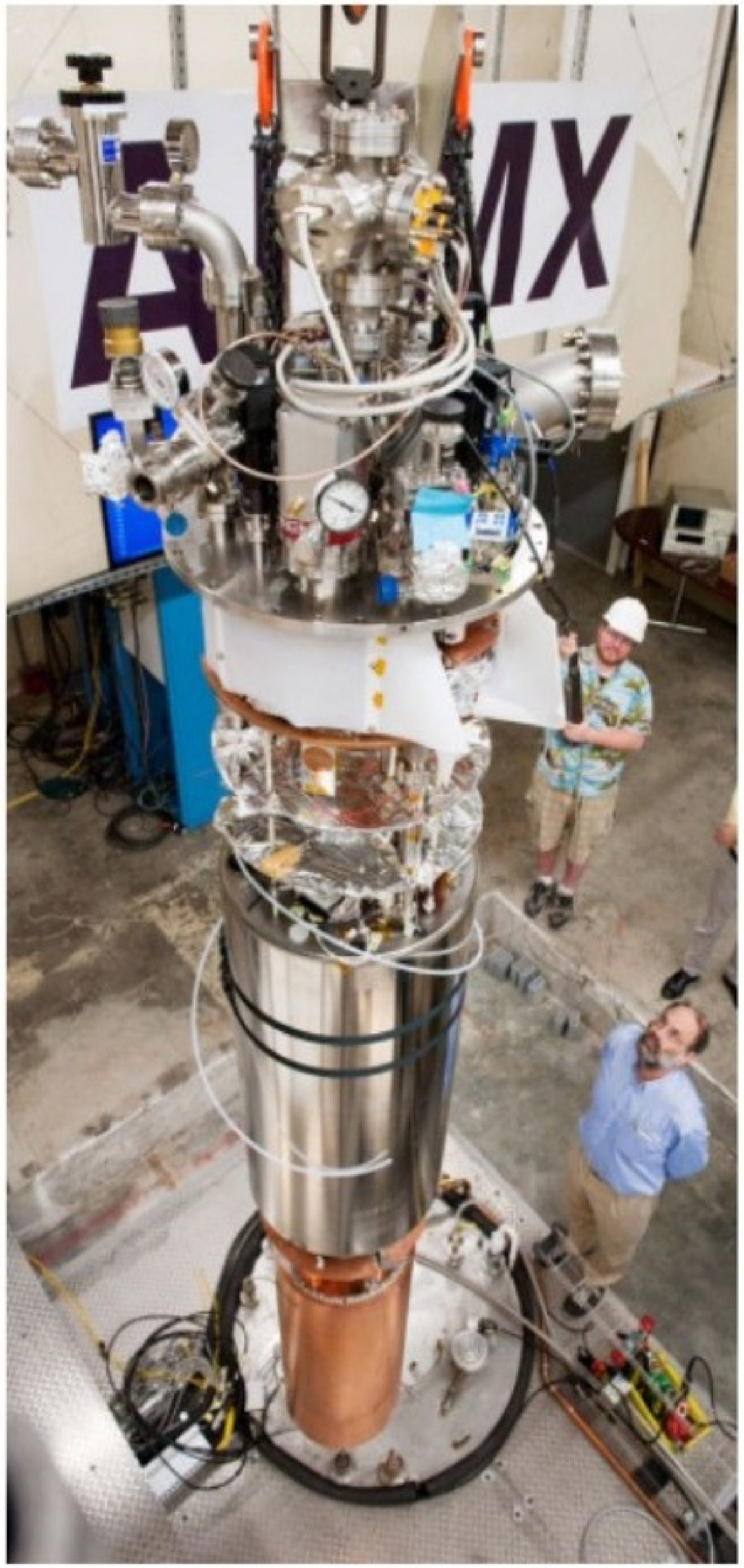
$$\frac{df}{dt} = \frac{1}{\mathrm{SNR}^2}\left(\frac{P_{a\gamma\gamma}}{kT_{\mathrm{N}}}\right)^2 \frac{Q_{\mathrm{axion}}}{Q}$$

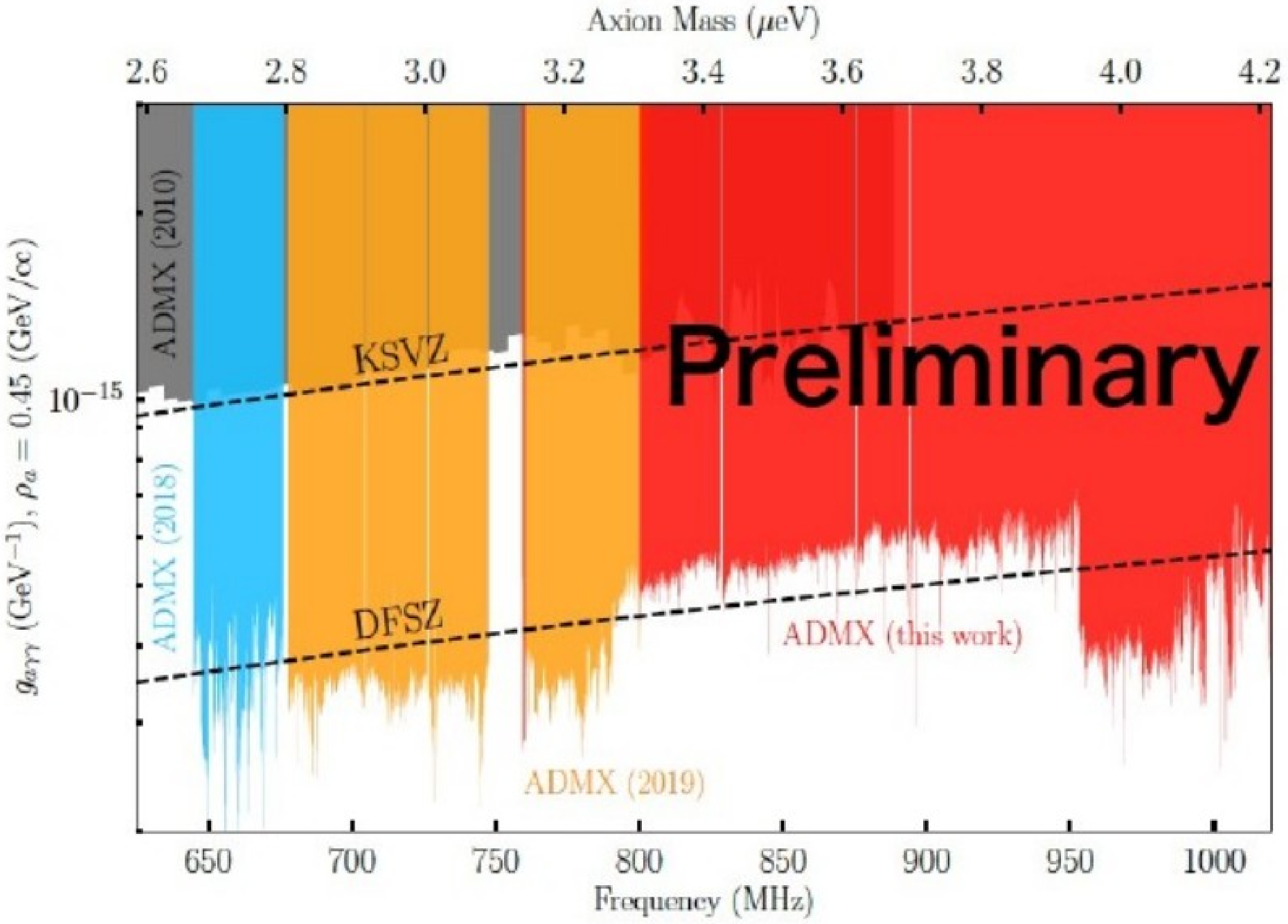


# ADMX




**A**xion **D**ark **M**atter e**X**periment

- Based at the University of Washington
- 7.6 T SC Solenoid
- 150 litre copper-plated cavity
- T~150mK
- Quantum-noise limited amplifiers ~200mK



# QSHS Work packages

1. **Hidden sector theory - Ed Hardy (Liverpool)**
2. **Quantum systems theory - Stafford Withington (Cambridge)**
3. **UK ADMX - Ed Daw (Sheffield)**
4. **Coherent electronics - Yuri Pashkin (Lancaster)**
5. **Incoherent electronics - Stafford Withington (Cambridge)**
6. **Qubits - Peter Leek (Oxford)**
7. **Data Analysis - Ian Bailey (Lancaster)**
8. **Magnet - Phil Meeson (Royal Holloway - RHUL)**
9. **UK Experiment Site - Ed Daw & Phil Meeson (Sheffield, RHUL)**
10. **High field test facility - Phil Meeson (RHUL)**
11. **Management & Operations - Project manager (Sheffield)**
12. **Future Exploitation - Daw (Sheffield)**

# New QSHS Scientific Staff

**Paul Smith** - Sheffield PDRA

Previous experience, MICE target mechanism, instrumentation and electronics.

**Bhaswati Chakaborty** - UCL PDRA

Previous experience, synthesis  of transition metal dichalcogenides, 2D materials, nanocomposites.

**Gemma Chapman - ** National Physical Laboratory. Previous experience, silicon based quantum technologies, low temperature electrical measurements, on-wafer microwave measurements.

**Mahesh Soni** - Lancaster PDRA. Previous experience, device simulation and fabrication, low temperature tests.

**Michele Piscitelli** - Oxford PDRA. Previous experience, detection of microwave photons with qubits, nanoscale magnetic resonance.

# Our Students

**Mitch Perry** Year 3 at Sheffield.
Expertise in embedded computing, hardware design and fabrication, system administration, electronics.

**Clementine Mostyn** Incoming year 1 STFC-sponsored Ph.D. student at Sheffield.

# Goals

1. Theoretical / numerical study of hidden sector science objectives and search strategy. Creation of instrument requirements specification.
   - **WHITE PAPER MOTIVATING FUTURE EXPERIMENT**

2. Design, realization, demonstration and characterization of a near-quantum-noise limited superconducting parametric amplifier operating at ~10mK.
   - **DEVELOP COHERENT AMPLIFIER**

3. Design, realization, demonstration and characterization of a superconducting qubit suitable for operation as an axion detector.
   - **DEVELOP QUBIT READOUT TECHNOLOGY**

4. Successful operation of a high-volume 5 GHz resonator coupled to a customized bolometeric sensor array, or calorimeter array, for measuring the zero static magnetic field ground state energy of a cavity at 10/50mK. Appraisal of quantum system engineering challenges, and experimental characterisation of techniques, including exploration of artefacts.
   - **DEVELOP BOLOMETRIC SENSOR ARRAY**

5. Carry out a conceptual design study, and a full engineering design study of a UK experiment on ADMX: understanding the science targets, instrument configuration, cryomechanical design, installation of quantum electronics in difficult EMI/stray-field environment; readout and data analysis pipeline.
   - **DESIGN STUDY FOR ADMX INSERT**

# Goals

6. Produce final engineering model, and delivery of components or subsystem to ADMX, and characterization of components at site with cavity in high-field.
   - **DEVELOP RECEIVER CHAIN**

7. Continue to build up a detailed understanding and project plan of all aspects of a possible future UK facility: site, magnet, cryomechanical engineering, quantum electronics, data readout and analysis pipeline. Produce interim science/design reports as appropriate.
   -**DESIGN STUDY FOR UK FACILITY**

# Hidden sector theory

Ningqiang Song, PDRA

* **arXiv:2203.10100, submitted to JCAP (follow-up paper in progress):**

**Dark Photon Stars:**
**Formation and Role as Dark Matter Substructure**


Marco Gorghetto[a], Edward Hardy[b], John March-Russell[c], Ningqiang Song[b], and Stephen M. West[d]

[a] *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Herzl St 234, Rehovot 761001, Israel*

[b] *Department of Mathematical Sciences, University of Liverpool, Liverpool, L69 7ZL, United Kingdom*

[c] *Rudolf Peierls Centre for Theoretical Physics, University of Oxford, Oxford OX1 3PU, United Kingdom*

[d] *Department of Physics, Royal Holloway, University of London, Egham, Surrey, TW20 0EX, United Kingdom*


* **Hardy (Liverpool) awarded a future leaders fellowship.**

* **In progress:**

**Post-inflationary ALPs: an easy target for axion haloscopes**


Edward Hardy[1,*]

[1] *Department of Mathematical Sciences, University of Liverpool, Mathematical Sciences Building Liverpool, L69 7ZL, UK*



An axion-like-particle in the post-inflationary regime with domain wall number $N > 1$ can be dark matter if the residual $Z_N$ symmetry has a small explicit breaking. Although challenging to analyse reliably, we argue that these theories have multiple interesting features, and we elucidate the crucial remaining uncertainties. We show that such a particle, with mass $m_a$, can have an axion-photon coupling as large as $g_{a\gamma\gamma} \simeq 10^{-12}\mathrm{GeV}^{-1}\left(m_a/10^{-6}\mathrm{eV}\right)^{1/2}$ while accounting for the full dark matter abundance and being consistent with complementary constraints. This is within the reach of numerous future detectors. Additionally, potentially observable dark matter substructure might automatically form in the early Universe. The resulting dark matter clumps would have masses $10^{-16}M_\odot$ to $10^{8}M_\odot$ depending on the parameters of the theory, and in some cases they would consist of solitonic 'axion stars'. If correlated with measurements of the axion mass and coupling to photons, such substructure would be a smoking gun signal of this scenario.

# Quantum system theory

Quantum System Theory Meeting
- IPPP (Durham)
- 5th-9th September 2022.

# UK ADMX Collaboration

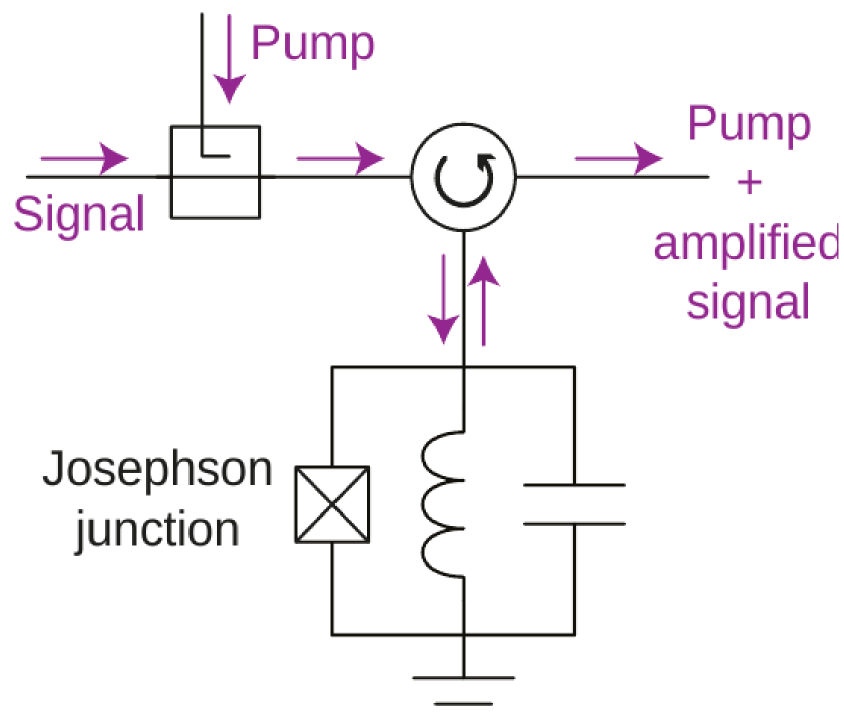
MoU signed with ADMX 13th December 2021.

Memorandum of Understanding (MOU)

This MOU is between the Quantum Sensors for the Hidden Sector (QSHS) collaboration and the Axion Dark Matter Experiment (ADMX). ADMX is an established U.S. collaboration, funded primarily by the US Department of Energy, searching for axions and other hidden sector dark matter candidates. QSHS is a UK collaboration, funded by the UK Science and Technology Facilities Council, conducting research developing a UK target for axions and other hidden sector particles. More detailed information on ADMX is given at https://depts.washington.edu/admx/index.shtml.

# WP4 - Coherent electronics

A parametric amplifier



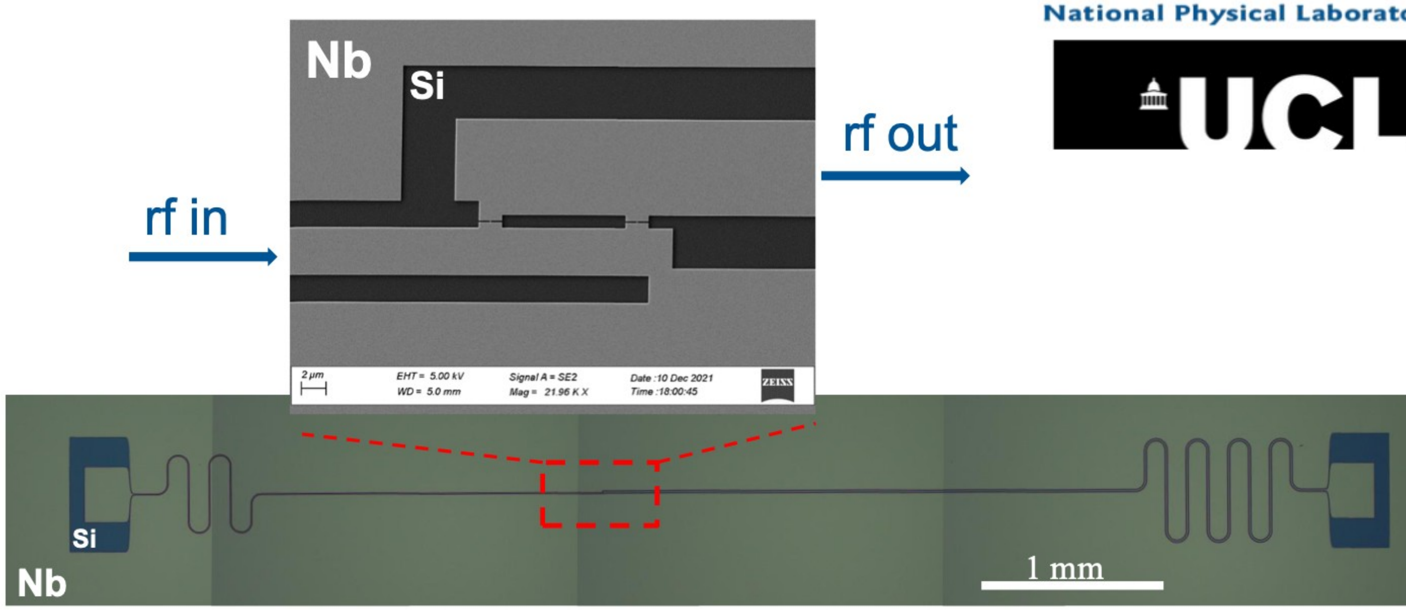

E. Laird, Lancaster

With ADMX parameters and choosing to require $\mathrm{SNR} = 3$ gives:

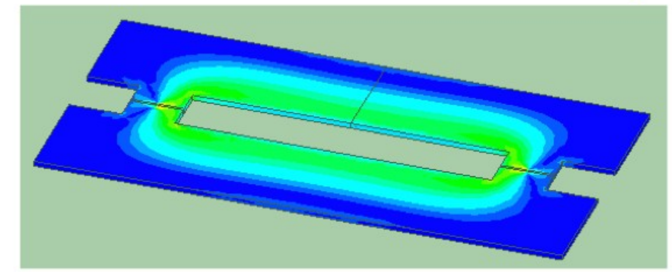
| | $T_N$ (K) | $\frac{df}{dt}$ (Hz/s) | $\frac{df}{dt}$ (GHz/yr) |
|---|---|---|---|
| **Semiconductor amplifier** | 4 | 0.6 | 0.019 |
| **Josephson parametric amplifier (so far)** | 0.32 | 92 | 2.9 |
| **Quantum limit at 740 MHz** | 0.018 | 29,000 | 17 |

# Coherent electronics

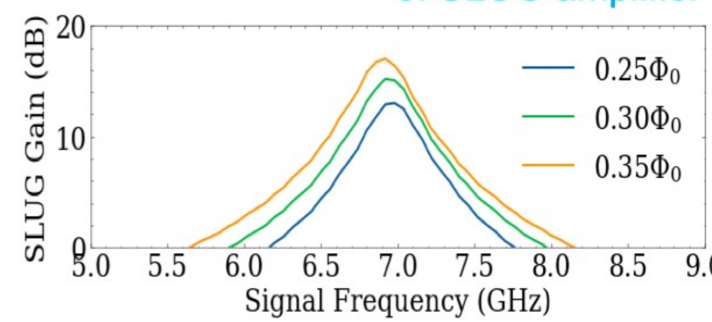
**NPL/UCL**
**-**First SLUG-loaded SQUID devices fabricated. Currently under test.



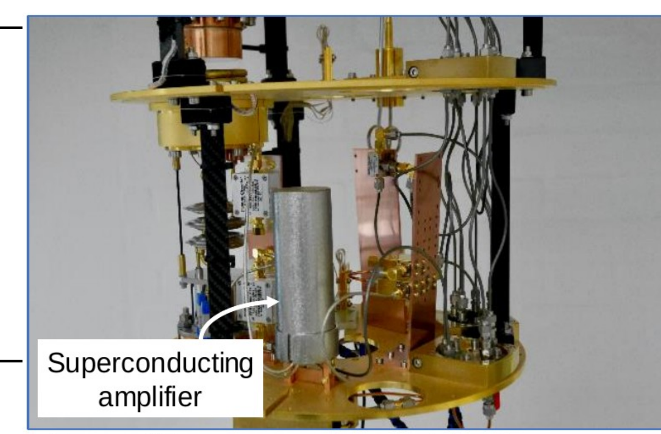

**Ansys Maxwell** – simulated inductance / capacitance of SLUG loop



**Python** – simulated frequency-dependent gain of SLUG amplifier

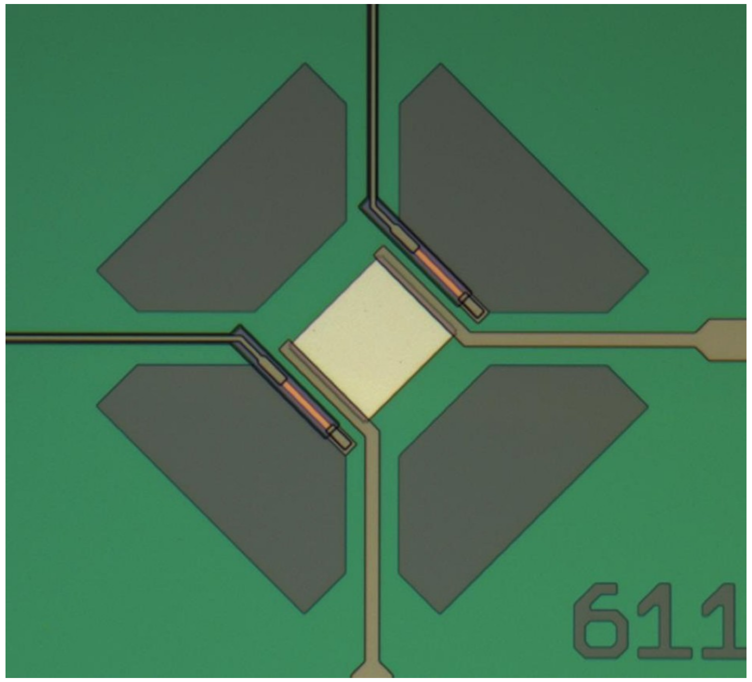



**Lancaster**
**-** Simulation and fabrication of first Travelling Wave Parametric Amplifier devices in TiN or NbTiN underway.

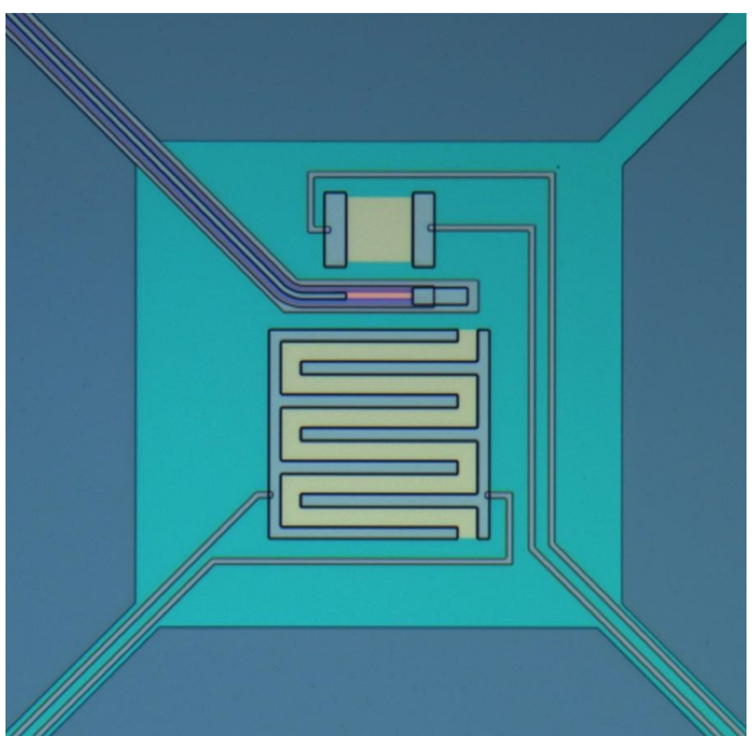



**Oxford**
**-** Simulation work on various configurations of travelling wave parametric amplifiers.

# Bolometers




Microstrip coupled transition edge sensor with calibration heater.



Two microstrip channel low-noise bolometer.

Cambridge

Fabricating microstrip coupled superconducting bolometers for millimetre wavelength.

At ~10 mK, (noise equivalent powers) NEP's of < $10^{-21}$ $WHz^{-1/2}$ should be possible.

This would be a new class of power detector allowing exceptional performance at microwave frequencies.

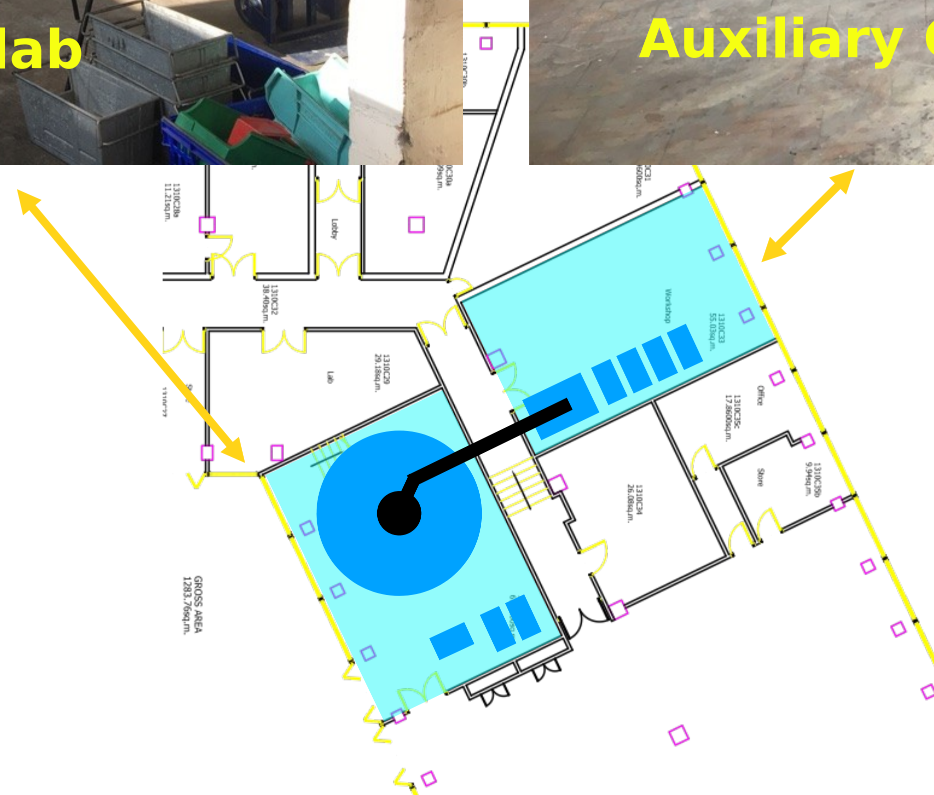
Another possibility is to use low-leakage tunnel junctions as microwave photon counters.

The bolometer would see the whole of the bandwidth of the cavity, allowing a coarse search to be carried out.

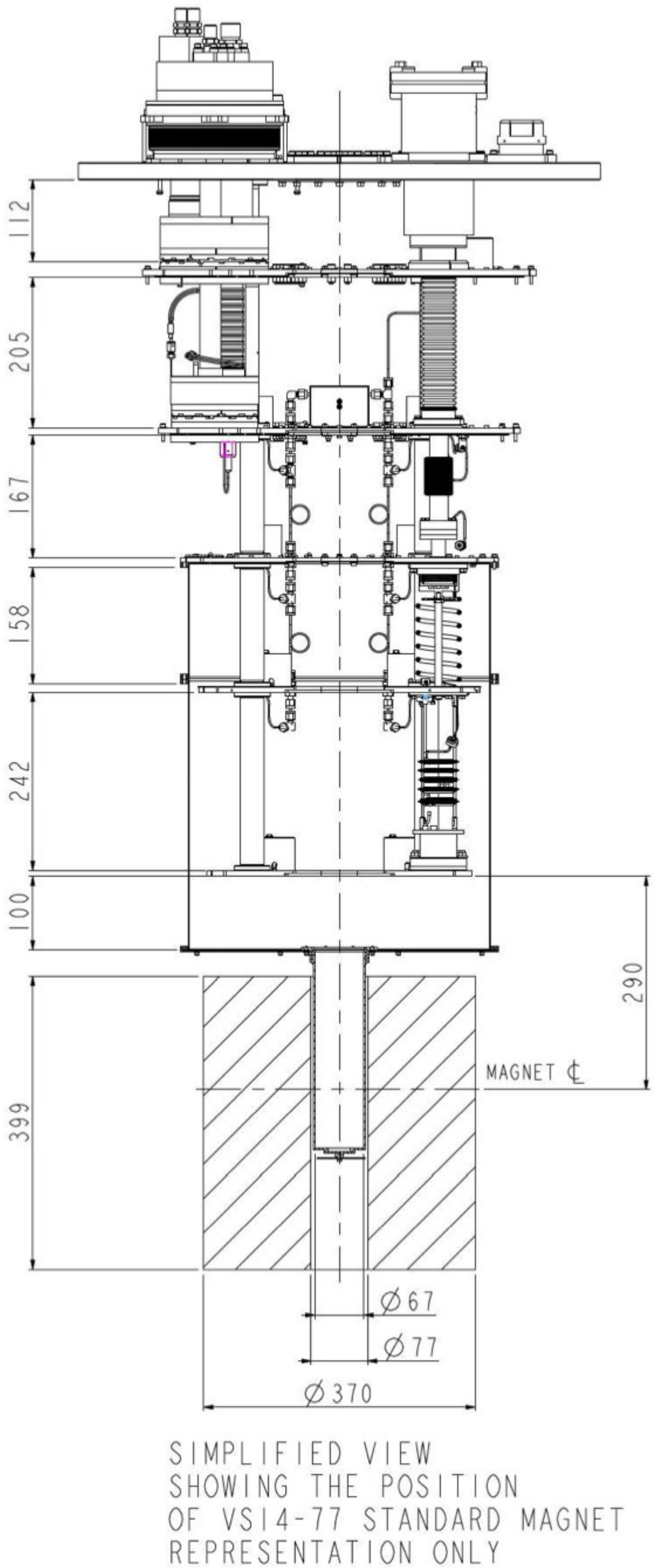
# Magnet, UK Experiment Site, Test facility 1

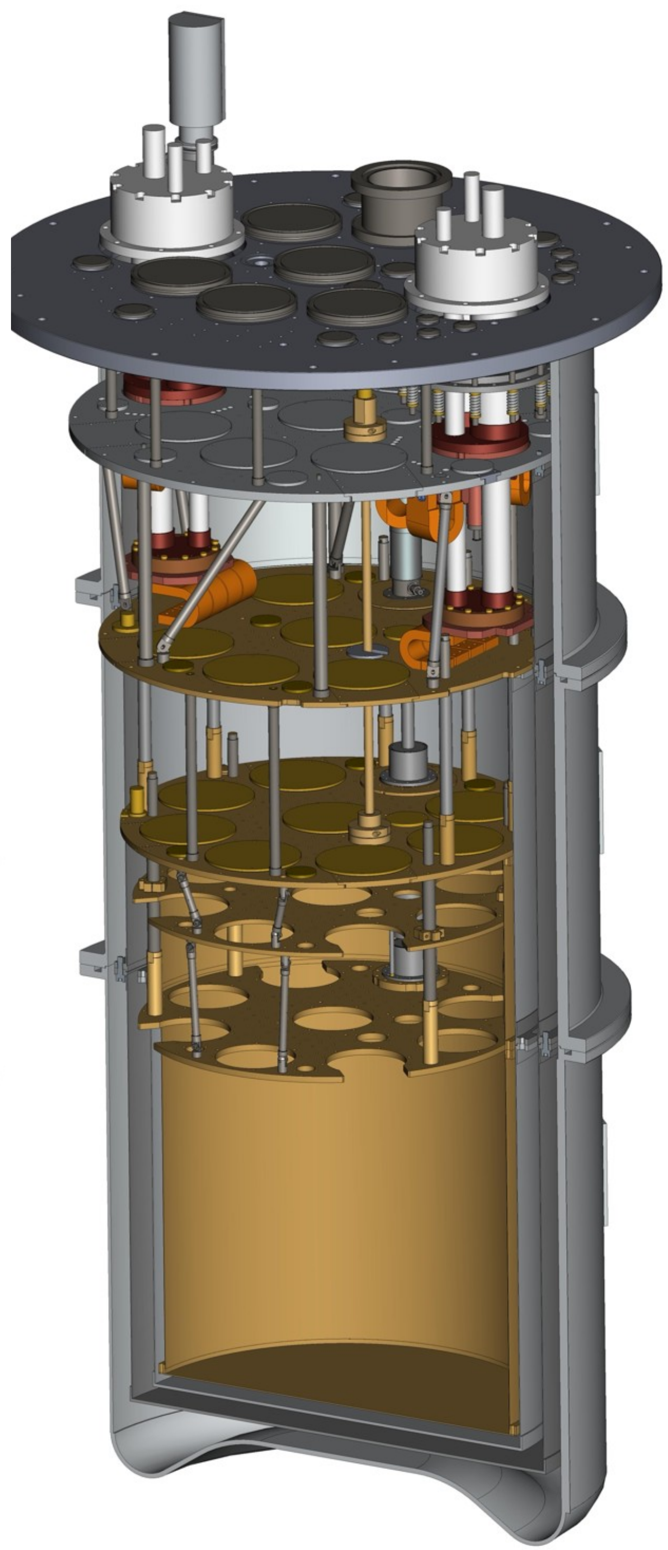
- Space at Sheffield has been identified
- Tenders for the dilution fridge / magnet have been received.





# Dilution Fridge / Magnet for Sheffield Test Facility



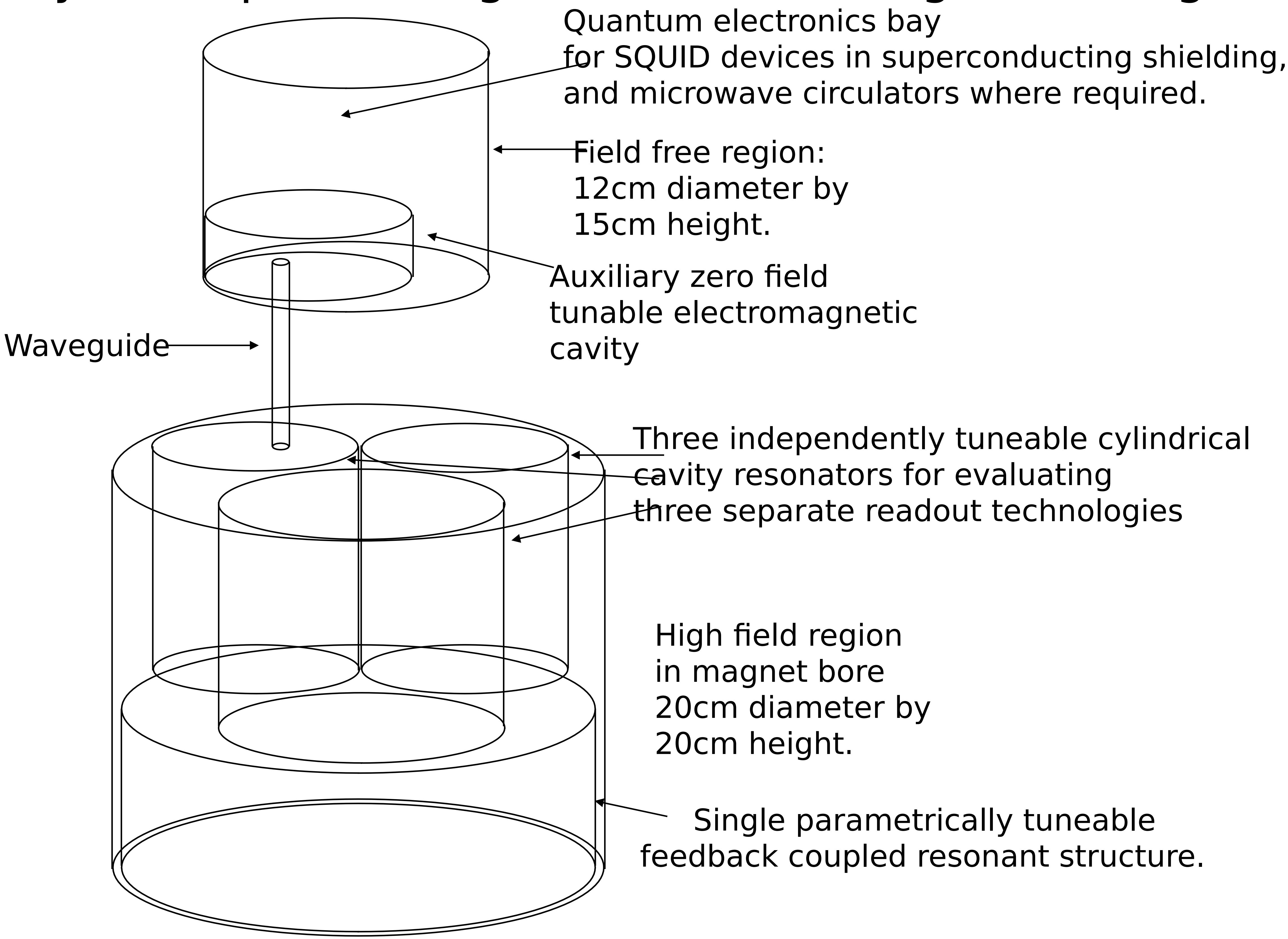
Dilution fridge
- base operating temperature ~10mK

Magnet
- nominal 8T field

Target volume
- ~20cm high by ~20cm diameter

# Preliminary target design

Early conceptual design work on the target has begun. E.g.



# Summary

Significant progress in last year.

Development of quantum devices
- Bolometers
- Parametric devices
- Qubits

Development of Sheffield test facility

Collaboration with ADMX