MANCHESTER 1824
The University of Manchester

Searching for Axions at Manchester (*and gravitational waves*)

Mark McCulloch
& Jamie McDonald

On Behalf of the MANCX Collaboration:
Ades, Battye, Blackett-May, Buck, Feasby, Gilles, Gramellini, Marchitelli, McCulloch, McDonald, Lancaster, Mohammadian, Piccirillo, Preston, Qureshi, Timbie, Upward, Wystemp

Introduction

- University of Manchester
  - Interested groups and their backgrounds
    - Jodrell bank Centre for Astrophysics
    - Centre for Quantum Science and Engineering
  - Manchester Axion Novel Cavity Experiment
    - Aims
    - Technologies that we have been developing
    - Future Plans
  - Summary

JBCA

Jodrell bank Centre for Astrophysics

Radio Astronomers

30+ Academic Staff

30+ Research Staff

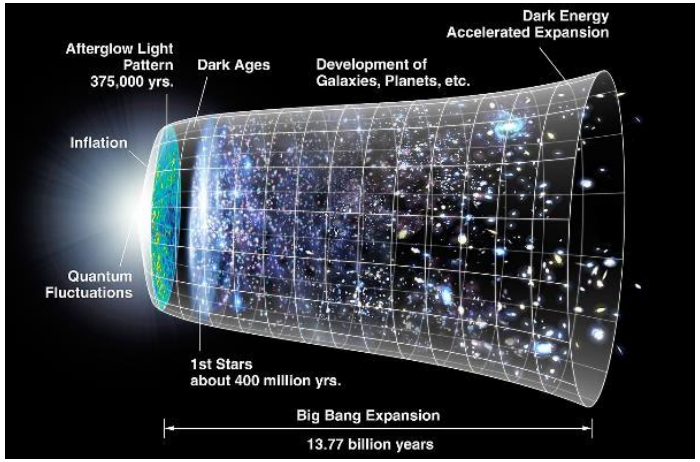
~ 50 Postgraduates

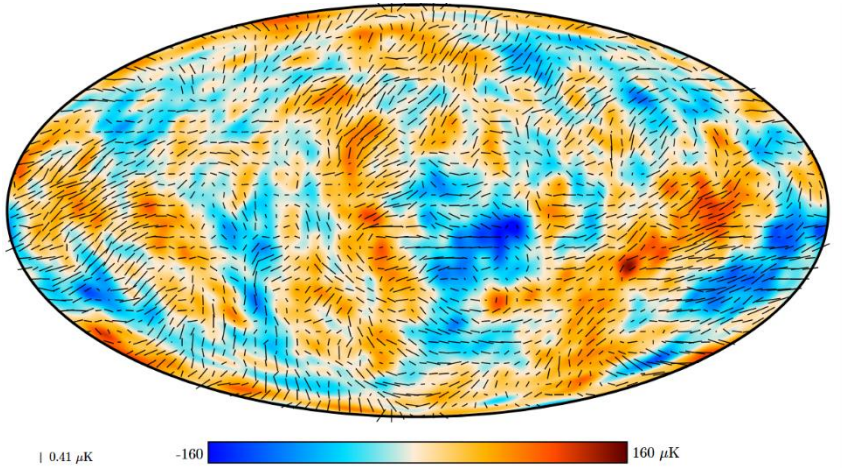
- CMB instrumentation
  - 26.5 to 150GHz
  - 100mK
- Square Kilometer Array

SO:UK

Collaboration with Simons Observatory

- Looking for B-modes
- Cerro Tocco 5200m
- Building 2 small aperture telescopes

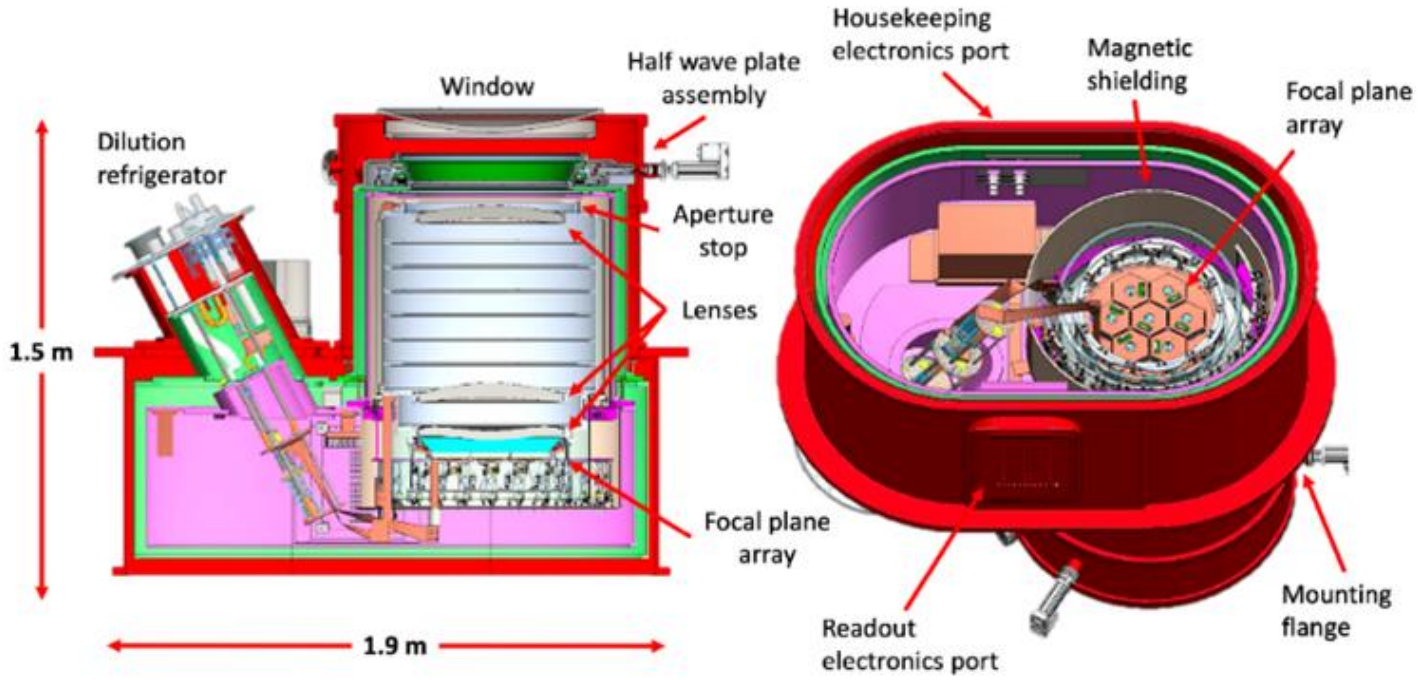


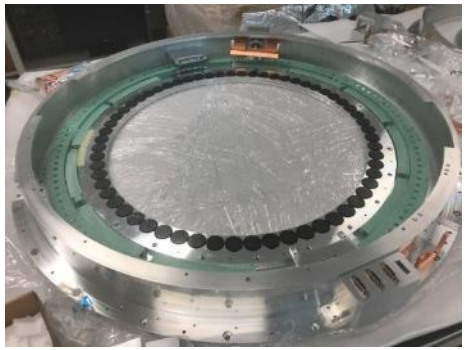


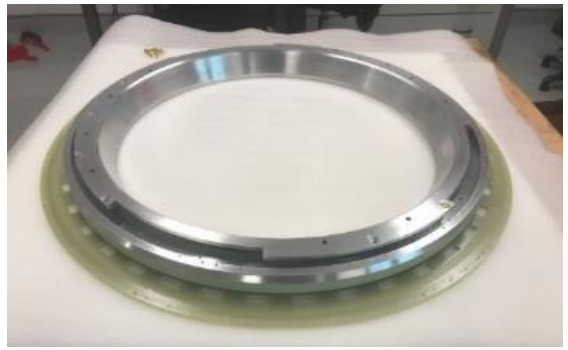
SO:UK

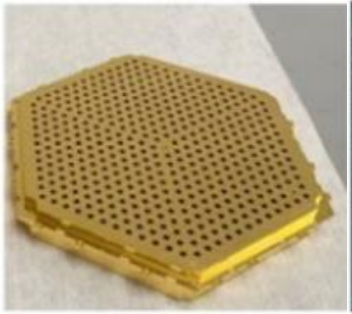
Our Receiver (90GHz, 150GHz)

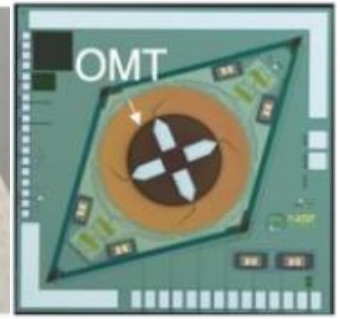
~10000 KID detectors

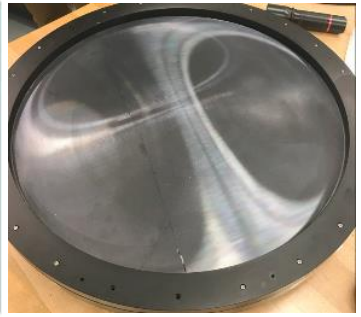


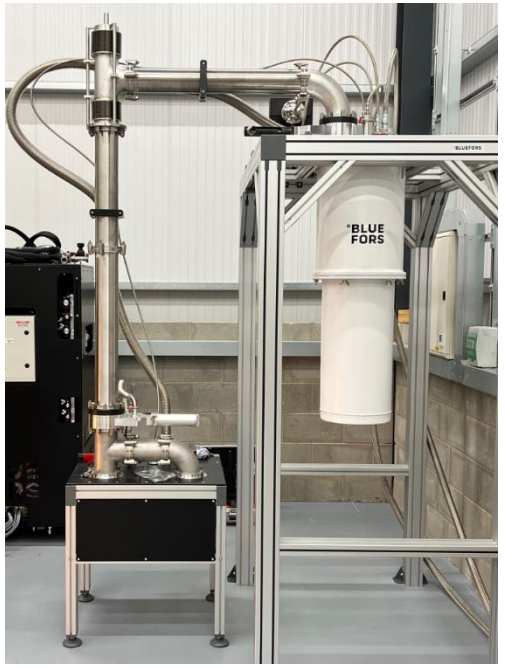












Centre for Quantum Science and Engineering (CQSE)

Launched in 2024 to promote, co-ordinate, and lead quantum science and engineering at Manchester:

- 50+ research groups spanning physics, chemistry, materials, maths, computer science, electrical and electronic engineering
- Facilities spanning three institutes – Advanced Materials, Photonics, and 2D Materials
- First cohort of 5 Quantum-specific PhD students recruited in 2024
- MANCX awarded CQSE studentship in 2025
- 3 tenure-track Dame Kathleen Ollerenshaw Fellowships



Background: CQSE

6 Themes

THEME 1
Information, Computation and Physical Foundations
Lead: Thomas Elliott (PHYS)

THEME 2
2D Materials & Condensed Matter
Lead: Artem Mishchenko (PHYS)

THEME 3
Spins & qubits
Lead: Alice Bowen (CHEM)

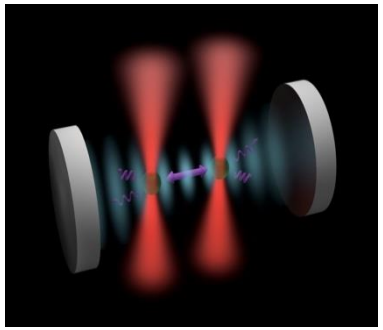
THEME 4
Quantum photonics
Lead: Jayadev Vijayan (EEE)

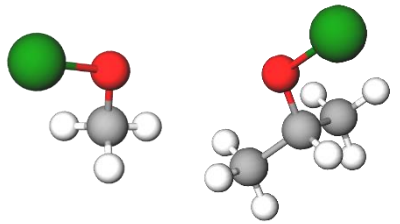
THEME 5
Materials for quantum
Lead: Maddison Coke (TECH)

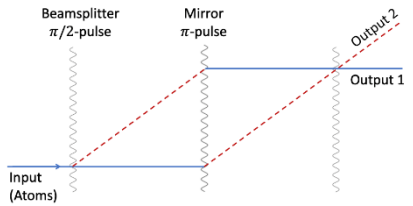
THEME 6
Quantum Technologies for fundamental physics
Lead: **Jamie McDonald** (PHYS)

Centre for Quantum Science: Theme 6 QTFP; Jamie McDonald

- Quantum levitated sensors to target dark matter high frequency gravitational waves
- Manchester Axion Novel Cavity eXperiment (MANCX)
- Cold atoms and molecules, CP violation
- 5th force tests of dark sectors, dark energy/modified gravity
- Terrestrial Very Long Baseline Atom Interferometry (TVLBAI) MoU signed







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Searching for Axions at Manchester

MAnchester Novel Cavity eXperiment (MANCX)

Ades, Battye, Blackett-May, Buck, Feasby, Gilles, Gramellini, Marchitelli, McCulloch, McDonald, Lancaster, Mohammadian, Piccirillo, Preston, Qureshi, Timbie, Upward, Wystemp.

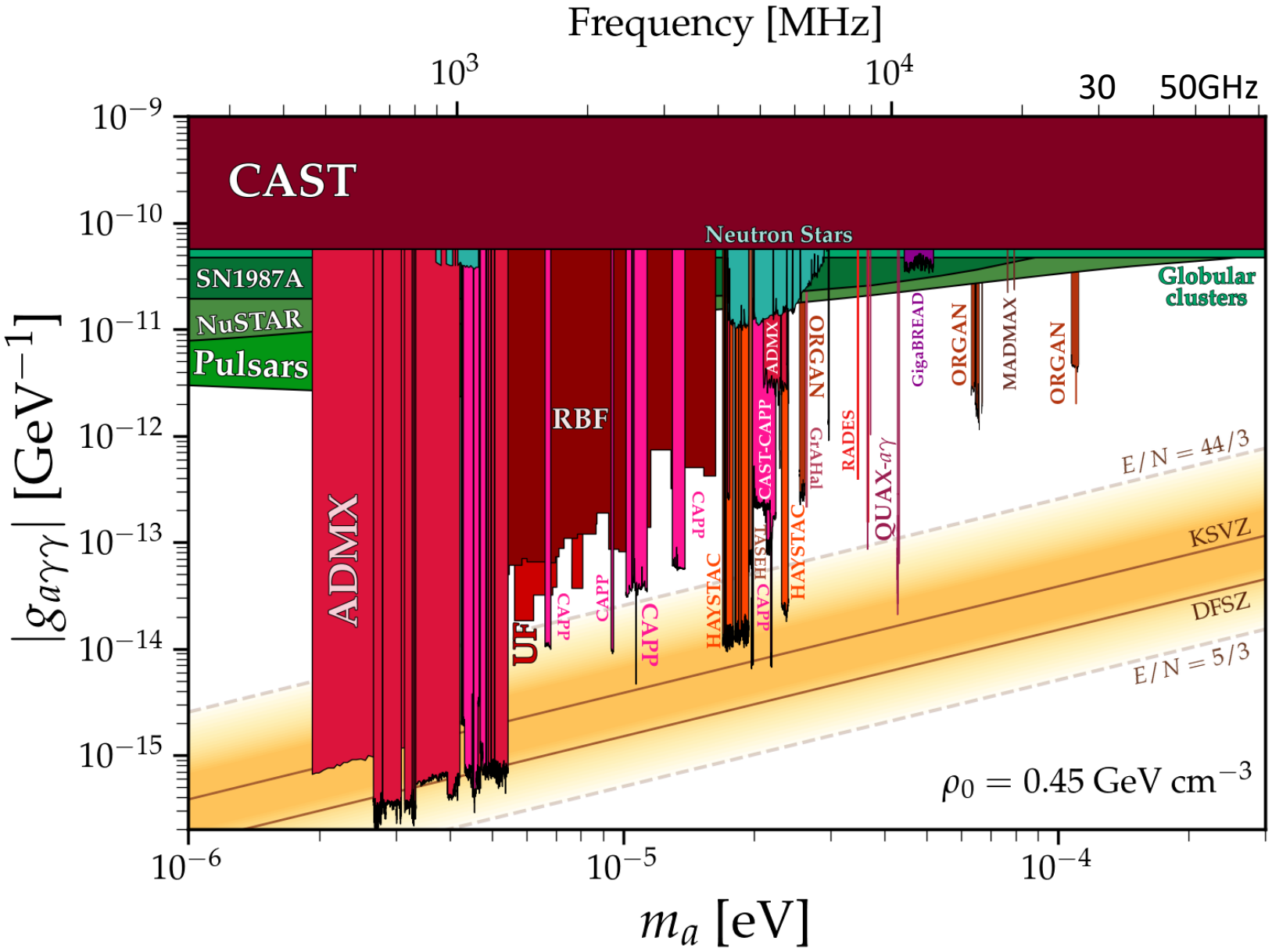
Who

- Manchester
  - Valerio Gilles (RF measurements)
  - Elena Gramellini (Signal analysis)
  - Mark McCulloch (RF simulations, cryostat and experiment design)
  - Jamie McDonald (Theory and RF simulations)
  - Babak Mohammadian (Fabrication)
  - Lucio Piccirillo (cryogenics)
  - Several 4th year undergraduates, BSc, Summer Students
- STFC Daresbury National Lab
  - Andrew May (senior cryogenics engineer)
  - Reza Shrikant (superconducting coatings)
- University of Wisconsin
  - Peter Timbie (magnets)

Science & Technology Facilities Council
Daresbury Laboratory

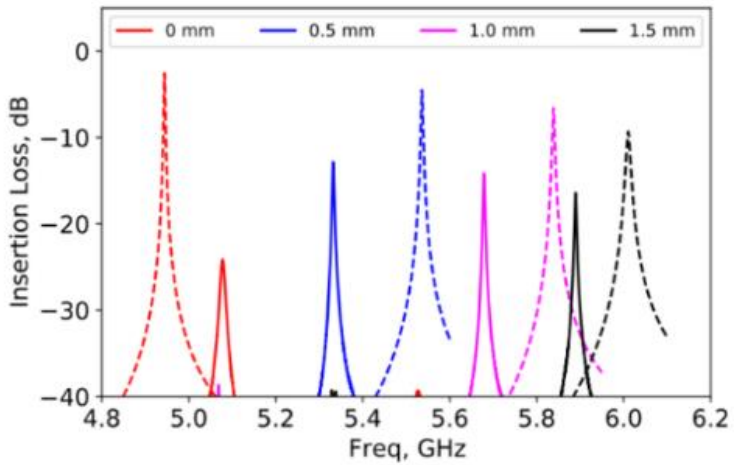
Where

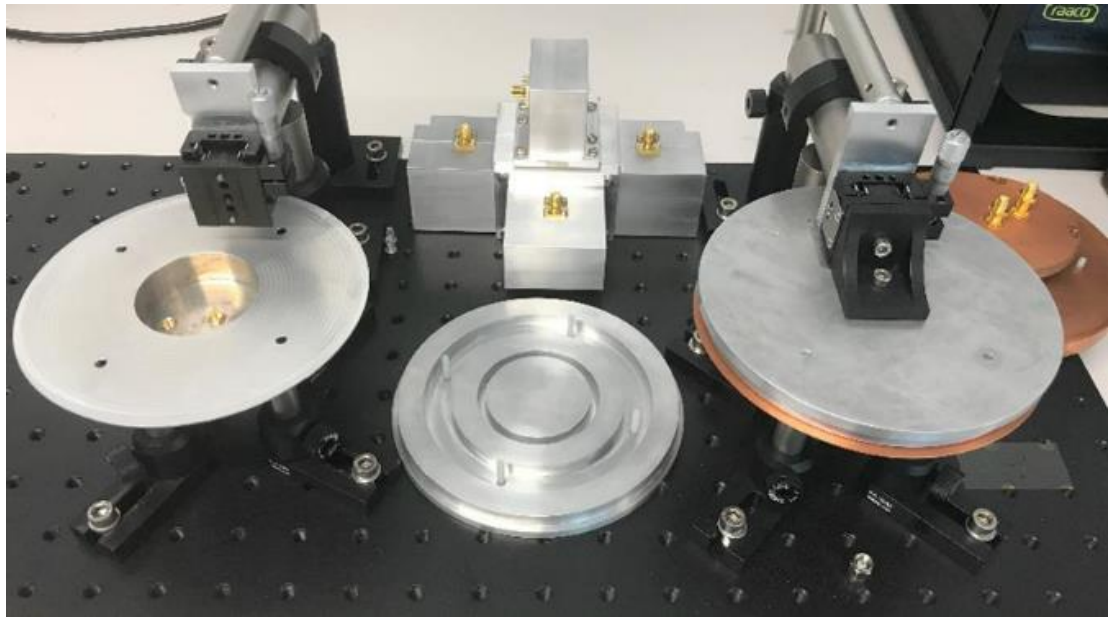
- Long history going back to Planck and the Very Small Array of developing technology at Ka-band (26-40GHz)



How it started: Fast Tuning

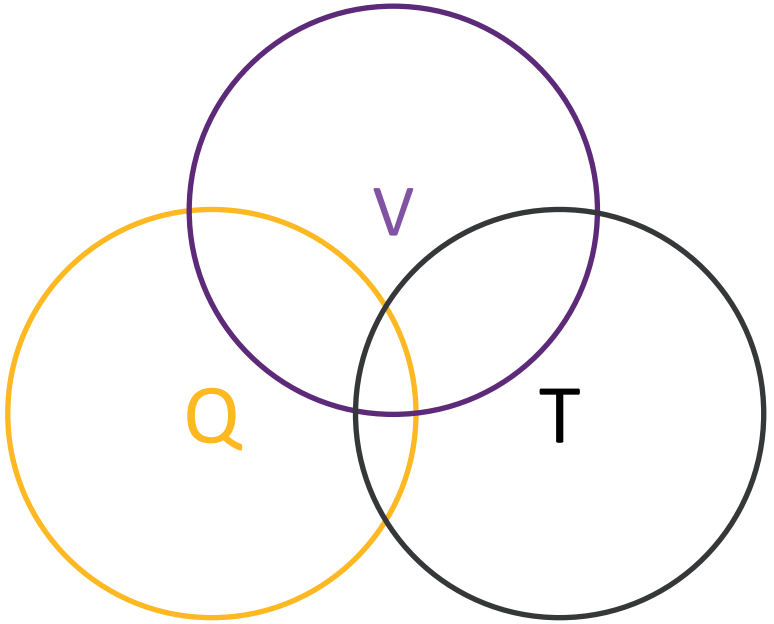
- We were developing a resonating cavity for another project
- Uses an electronic bandgap structure to tune a TM010 like mode by varying cavity height
- Could this be used for axions?
- Tuning becomes a challenge
  - Rods can stick
- Flat design -> Small volume
  $(not\ good\ for\ axions)$



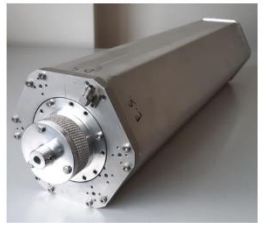


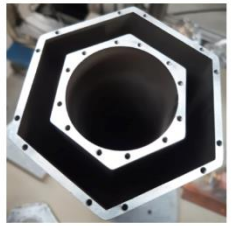
Cavities

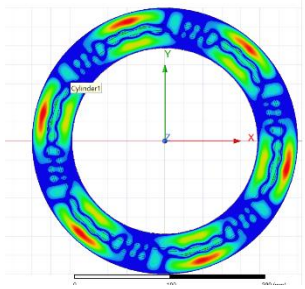
- Looking at higher frequencies we ran into the familiar
  - VQT problem
    - Volume
    - Q-factor
    - **Tuning**

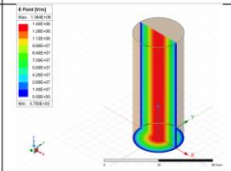
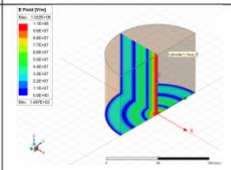
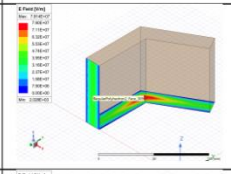
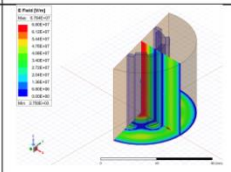
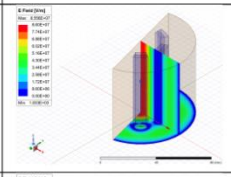
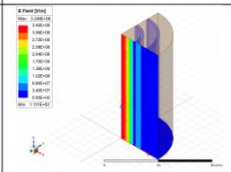
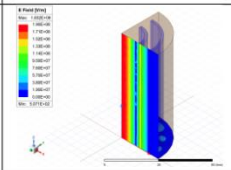
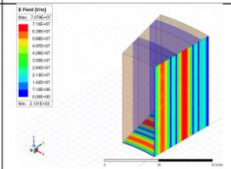


Cavities







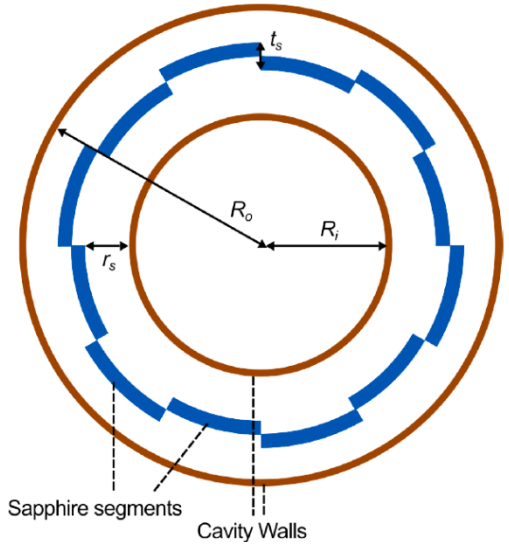
Design Type	Picture	Freq (GHz)	V (m^3)	C	Q	Mode	FoM
Empty Cylinder		8.03	4.56×10^{-5}	0.692	16068	TM010	1.60×10^{-5}
Empty Cylinder		8.03	5.93×10^{-4}	0.0534	40430	TM030	4.06×10^{-5}
Hexagonal		8.62	9.54×10^{-4}	0.756	10663	TM010	5.55×10^{-3}
Korean Cylinder (Closed)		7.20	4.51×10^{-4}	0.377	31847	TM030	9.21×10^{-4}
Korean Cylinder (Open)		6.83	4.51×10^{-4}	0.405	36963	TM030	1.23×10^{-3}
Italian Cylinder (Closed)		11.1	1.88×10^{-4}	0.0393	105381	TM030	5.75×10^{-6}
Italian Cylinder (Open)		10.5	1.88×10^{-4}	0.0363	92515	TM030	4.30×10^{-6}
Basic Ring†		9.70	2.79×10^{-3}	0.296*	44805*	TM050	3.05×10^{-2}

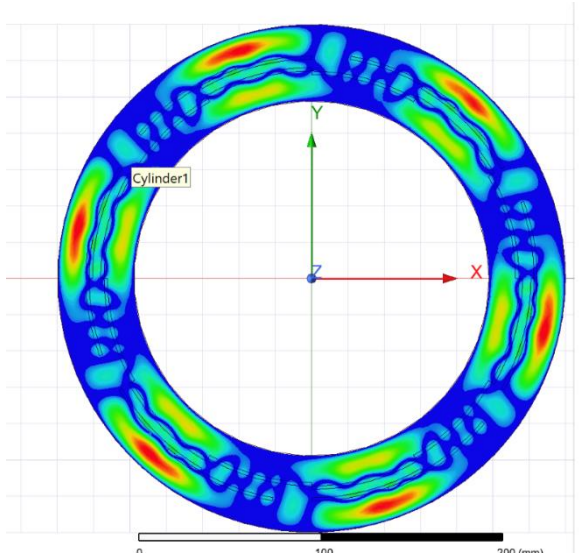
Scan Rate (m^3)

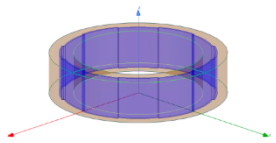
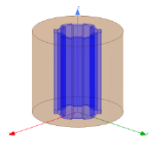
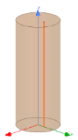
$$\frac{df}{dt} \propto (VC)^2 Q_c$$

with masters student *Hong-Kai Tan*

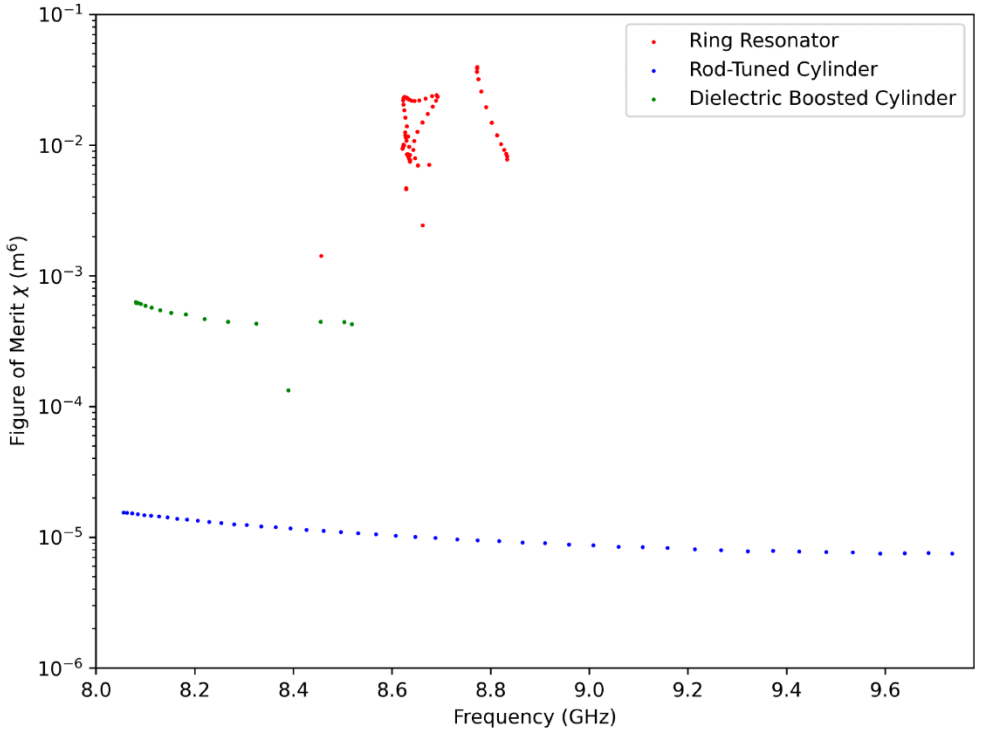
Cavities





Design	Picture	f_{res} (GHz)	$V\,(m^3)$	C_α	Q_c
Ring Resonator		$8.62-8.69$ $8.77-8.83$	2.38×10^{-3}	$0.123-0.357$	$3.3-5.5\times10^{4}$
Dielectric Boosted Cylinder		$8.08-8.51$	3.22×10^{-4}	$0.196-0.414$	$3.0-4.1\times10^{4}$
Rod-Tuned Cylinder		$8.05-9.78$	4.56×10^{-5}	$0.651-0.715$	$6.9-15.7\times10^{3}$

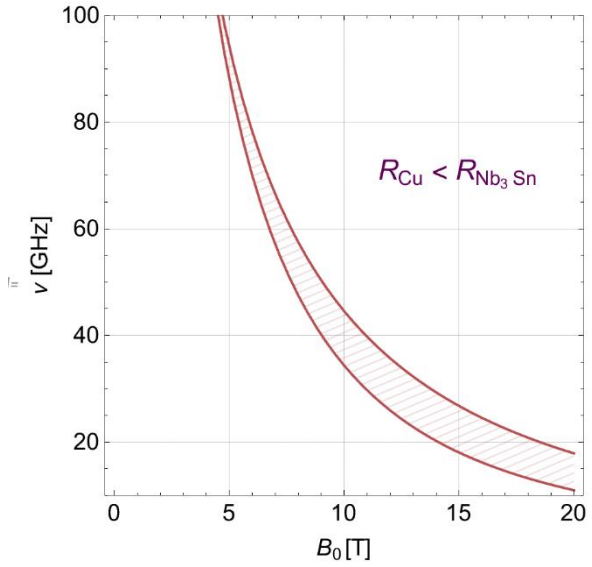
$$\frac{df}{dt} \propto (VC)^2 Q_c$$

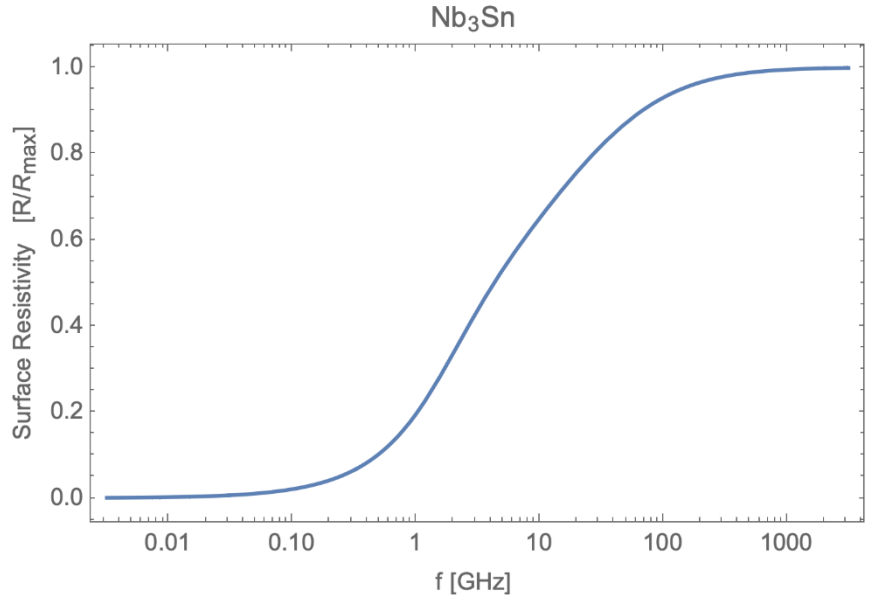


with an excellent masters student ***Hong-Kai Tan***

Q-factor and superconducting cavities

- Collaboration with Daresbury Laboratories
  - Normally work ~100MHz to ~GHz
  - To study the potential for improving Q-factor by use of thin film superconducting coatings (Nb, NbTi, NbSn) on copper at between 10 and 30GHz
  - Is copper better?

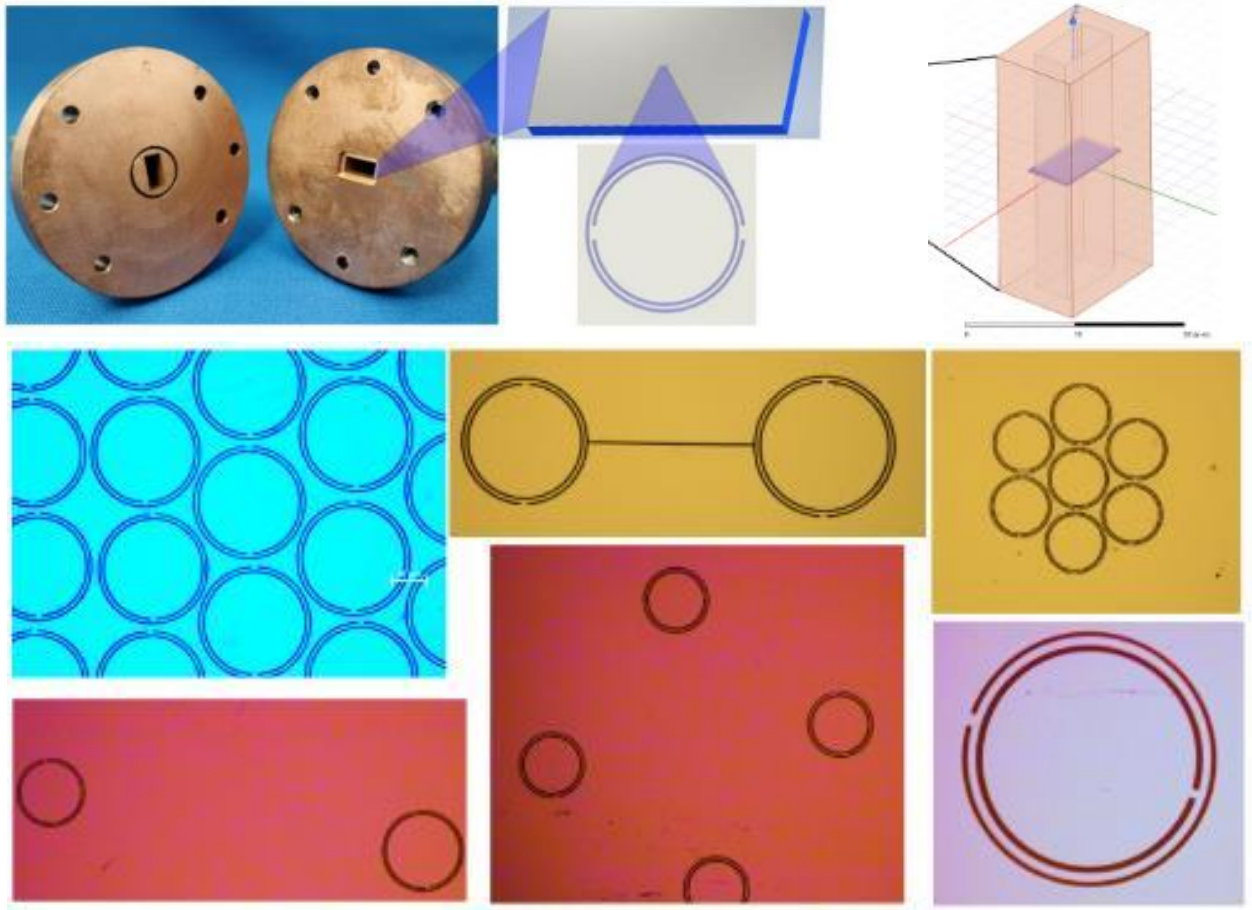




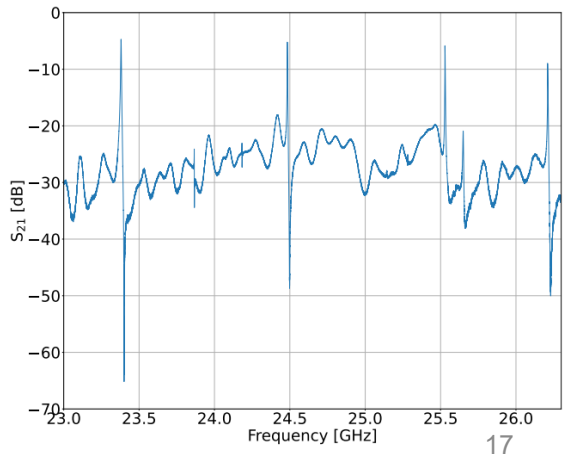
See https://arxiv.org/pdf/2201.10733

Readout: Amplifiers

- Long history of LNA research at JBCA
- LNAs @ 30GHz
  - Noise Temp is ~ 5-10x T_q (8K)
- Parametric amplifiers
  - NbTi thin film on sapphire
    - Kinetic inductance
    - Complementary split resonators
    - Four wave mixing

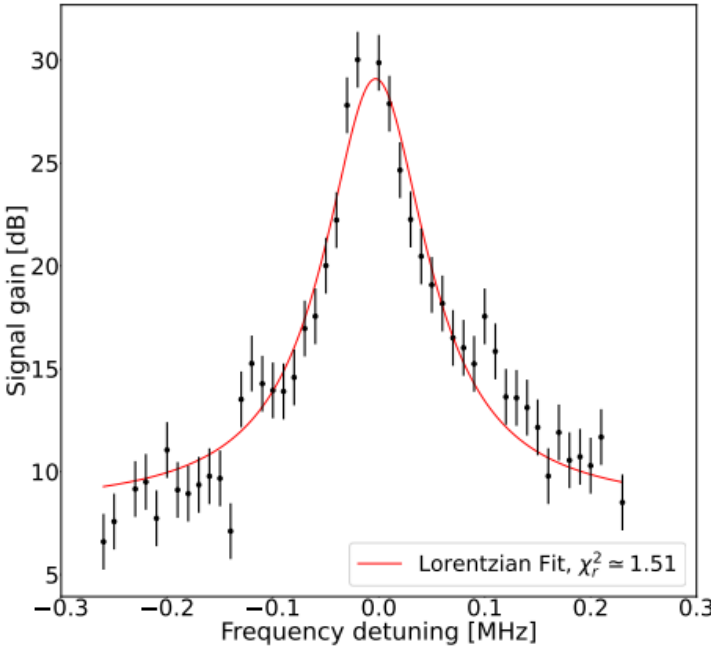


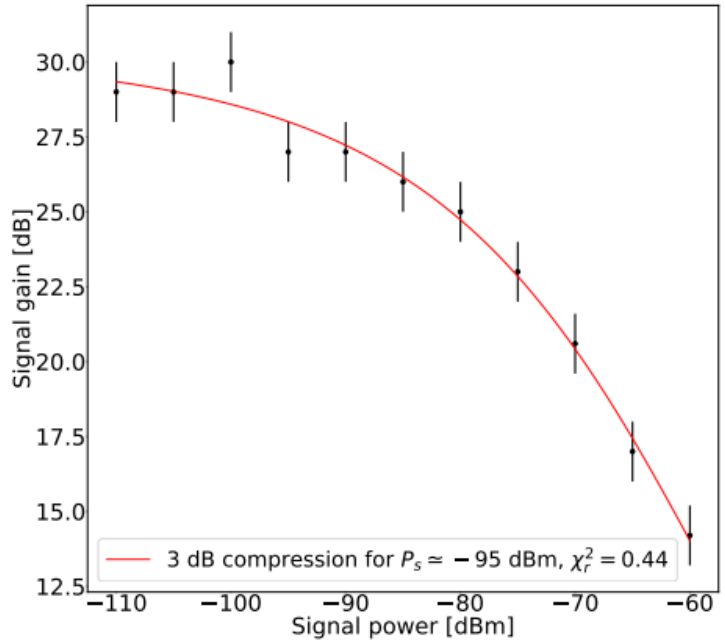
Paper in preparation
V Gilles et al



Amplifiers

- Performance
  - Gain ~20dB
  - Compress at ~-95dBm
  - Noise
- Get a useable bandwidth
  - Lower Q
  - Multiple resonators on a chip





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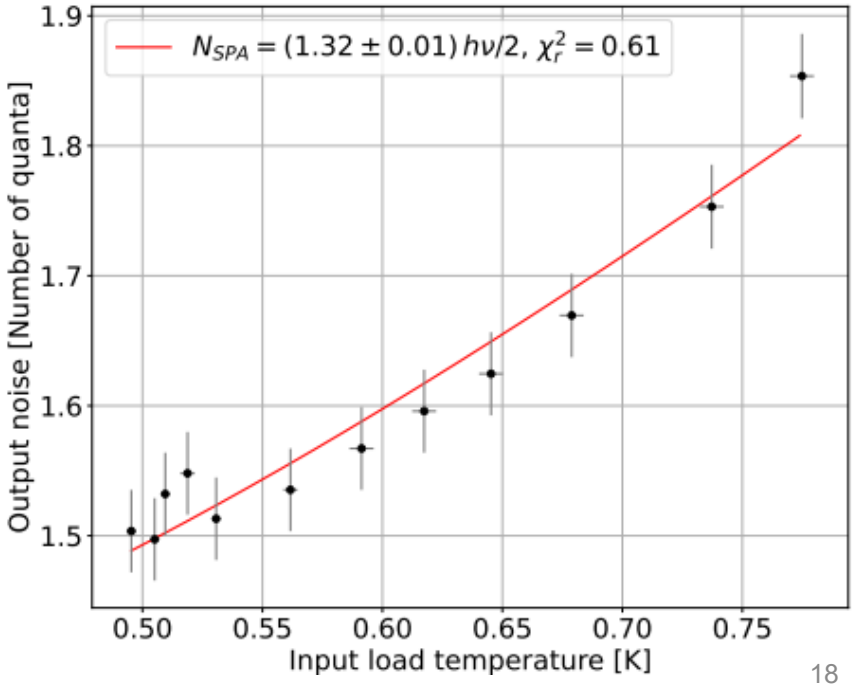
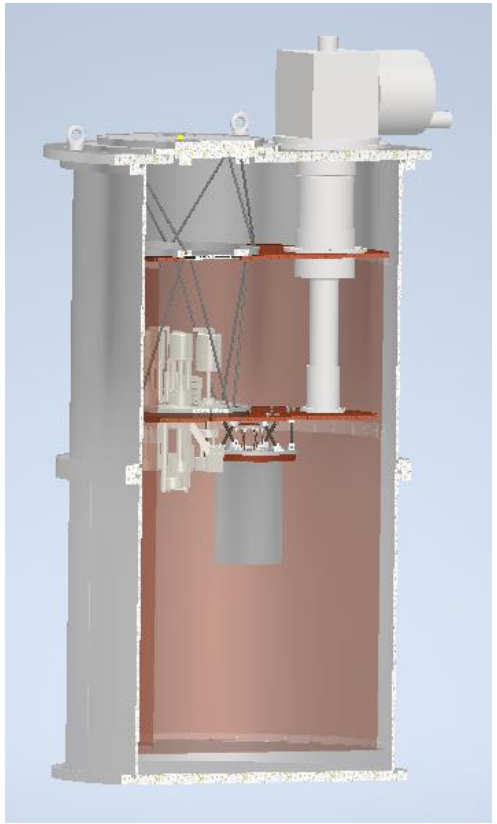
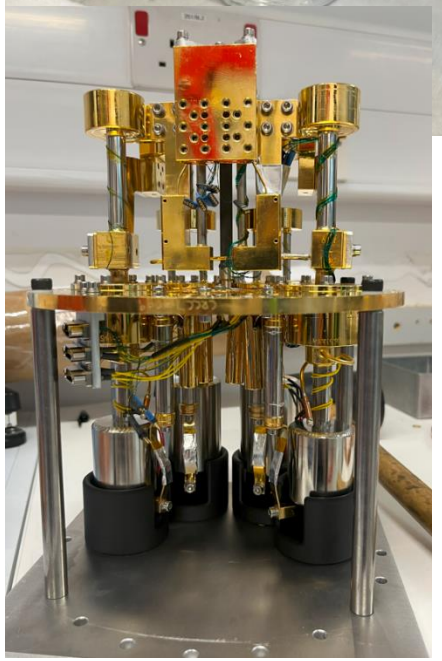


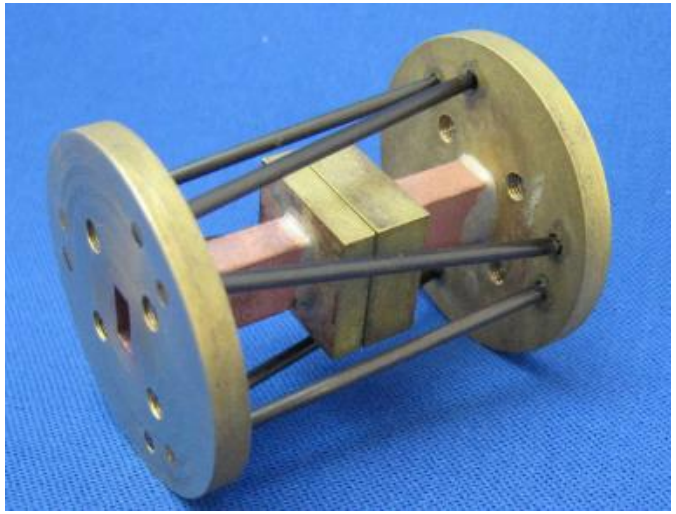
$$E_N^{\text{added}} \geq \frac{1}{2} h f_s$$

Cryostat

- Currently being assembled
- Uses a Coolworks Ltd Miniature Dilution Refrigerator
  - He3/He4 system takes us to 300mK
  - Dilution stage can give us 60mK
- Waveguide thermal breaks





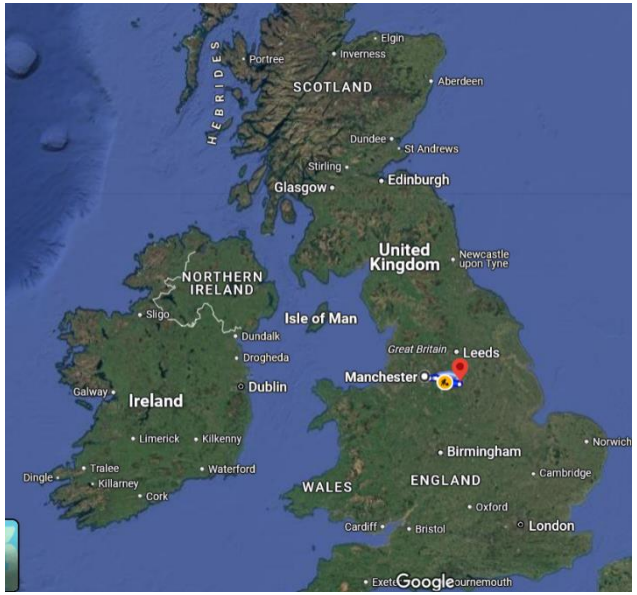


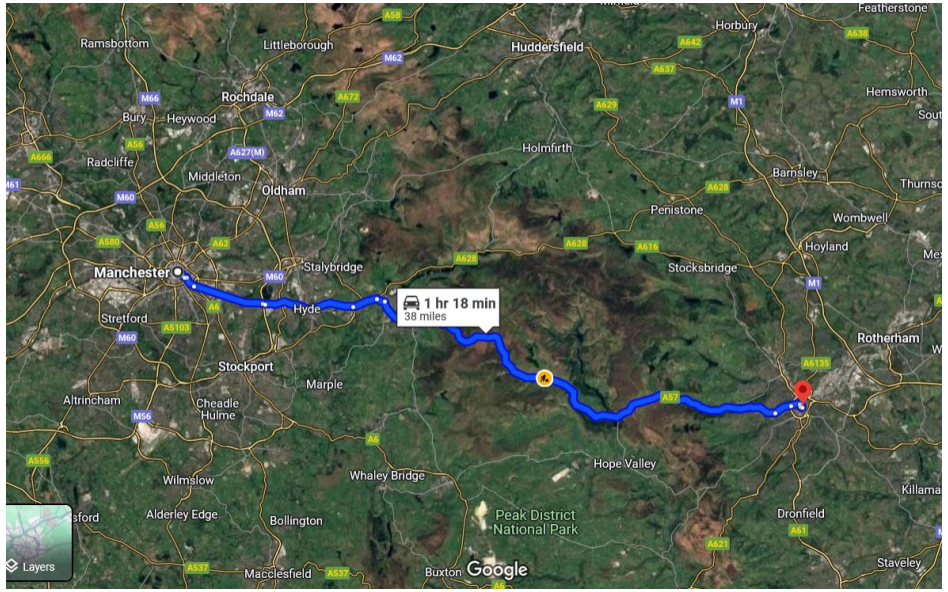
Magnets

- Two 3.5T magnets available
  - University of Wisconsin
  - Small bore ~30mm

- Possible future access to the University of Sheffield's 8T 20cm magnet
  - STFC's Future Tech Quan Phys – Quantum Sensors for Hidden Sector

Initial Magnet at Sheffield





Pathfinder

- Aim to build a pathfinding experiment to demonstrate technology and look at systematics
  - Monochromatic (simple) cavity with HEMT @ 4K / 1K and ~30GHz
    - Test thermal stability
    - Frequency stability
  - 30GHz cavity with parametric amplifier @ 300mK
    - Test using the parametric amplifier
  - 2 30GHz cavities with parametric amplifiers @300mK

Summary

- There is a lot of interest at the University of Manchester in applying our microwave, cryogenic, quantum sensing and experimental expertise to new areas.
- New quantum centre that aims to co-ordinate and lead quantum science at the University
- We have an active programme developing technology for higher frequency axion searches
  - Cavity development
  - Readout/quantum sensors