Quantum Sensors for the Hidden Sector

https://qshs.shef.ac.uk

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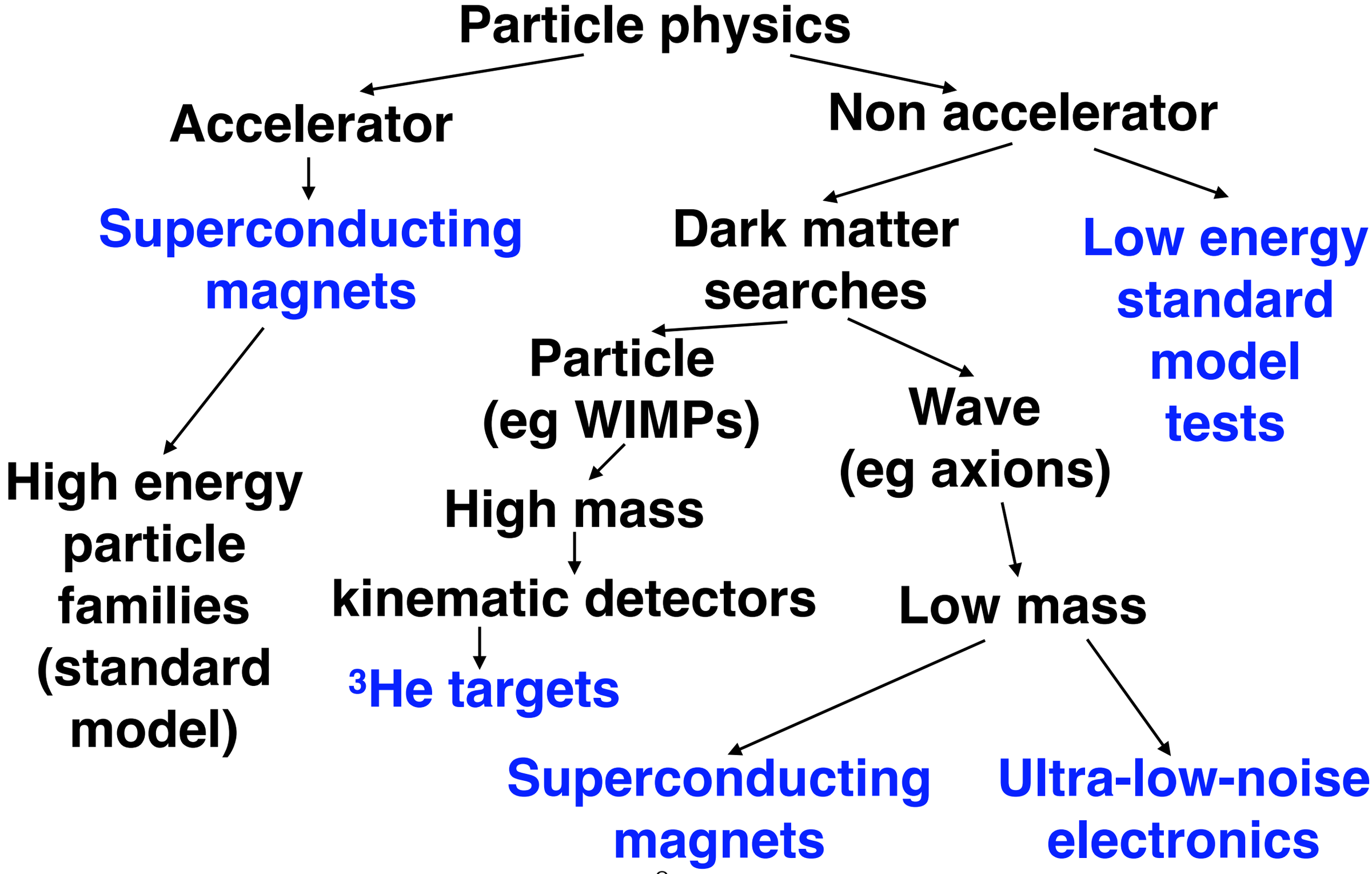
IN COLLABORATION WITH:

Broad view


Particle physics
Accelerator
Superconducting magnets
High energy particle families (standard model)
Non accelerator
Dark matter searches
Particle (eg WIMPs)
High mass
kinematic detectors
3He targets
Wave (eg axions)
Low mass
Superconducting magnets
Ultra-low-noise electronics
Low energy standard model tests

Axions and the Strong CP problem

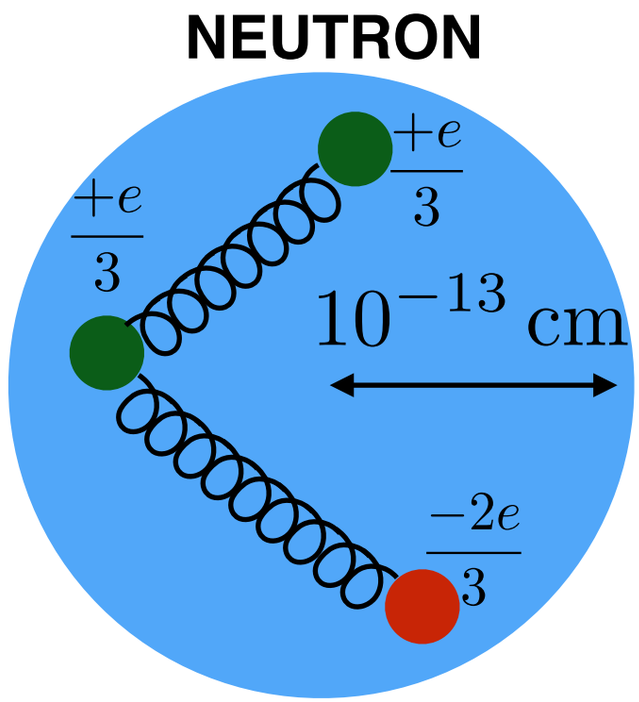
Standard model symmetry group is $\underbrace{SU(3)}_{\text{NON-ABELIAN}} \times \underbrace{SU(2)}_{\text{NON-ABELIAN}} \times \underbrace{U(1)}_{\text{ABELIAN}}$

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

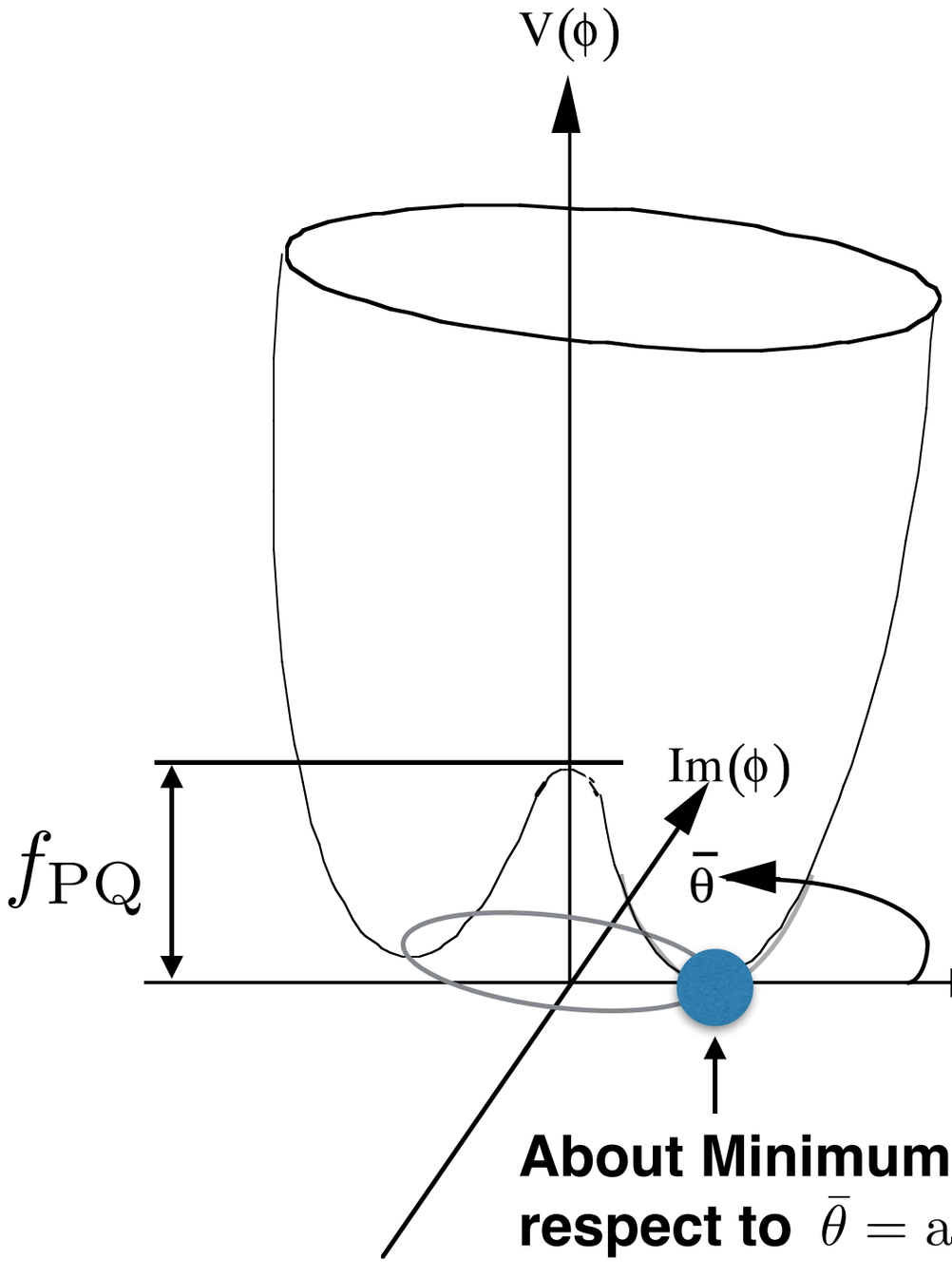
CP CONSERVING! **CP VIOLATING** **CP CONSERVING**

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.



The Peccei Quinn Mechanism and Axions



$$\mathcal{L}_{CPV} = \overline{\Theta}\mathbf{E}.\mathbf{B}$$

$$\overline{\Theta} = 0$$

About Minimum: small curvature (hence small mass) with respect to $\bar{\theta} = \arg(\phi)$

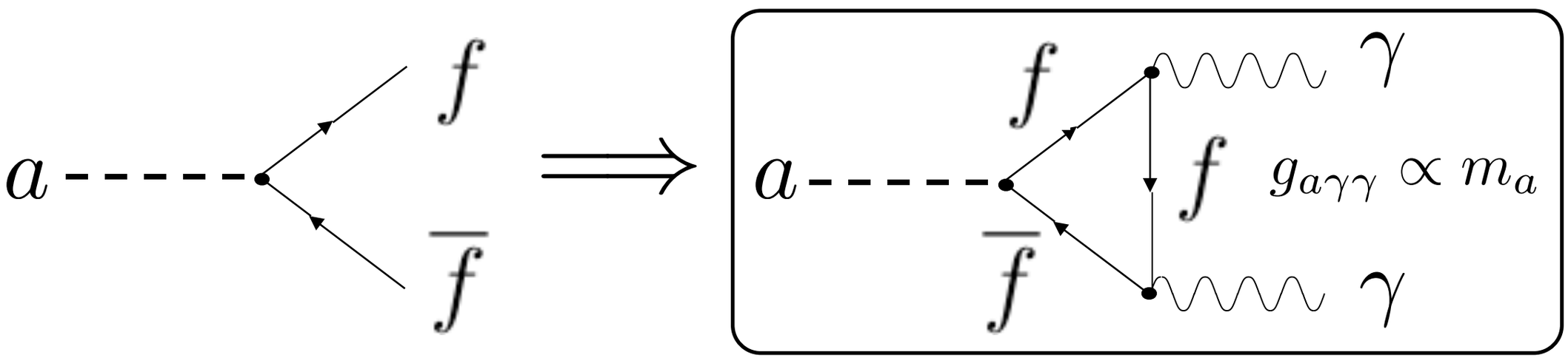
Axion DOF

QCD Axion Phenomenology

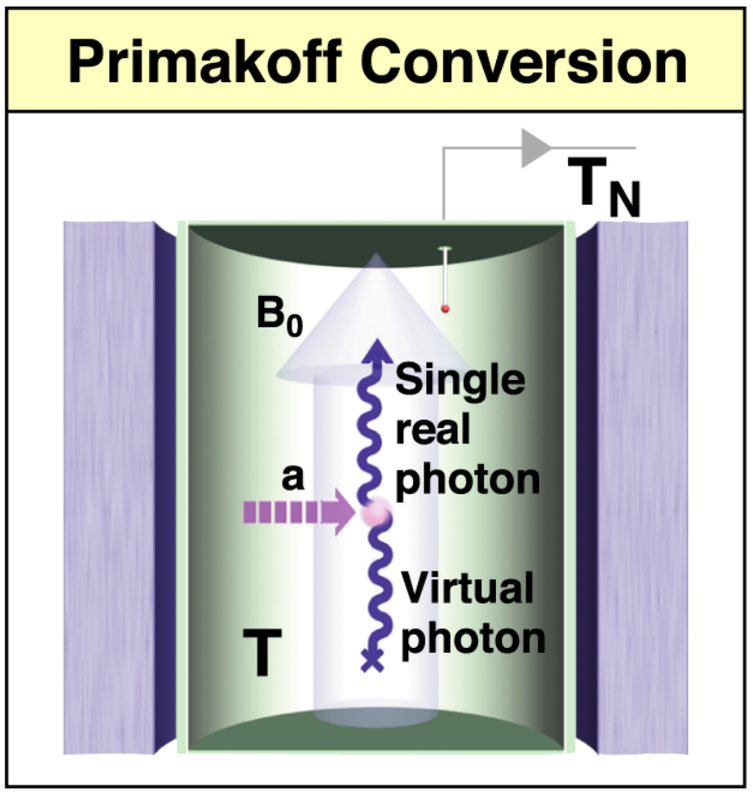
The axion is a pseudoscalar; has the same quantum numbers as the π^0, and the same interactions, but with coupling strengths scaled with the axion mass

Energy scale where axion produced is $\mathbf{f_{PQ}}$

$$f_{\mathrm{PQ}} \sim 10^{13}\,\mathrm{GeV}\left(\frac{3\,\mu\mathrm{eV}}{\mathrm{m_a}}\right)$$

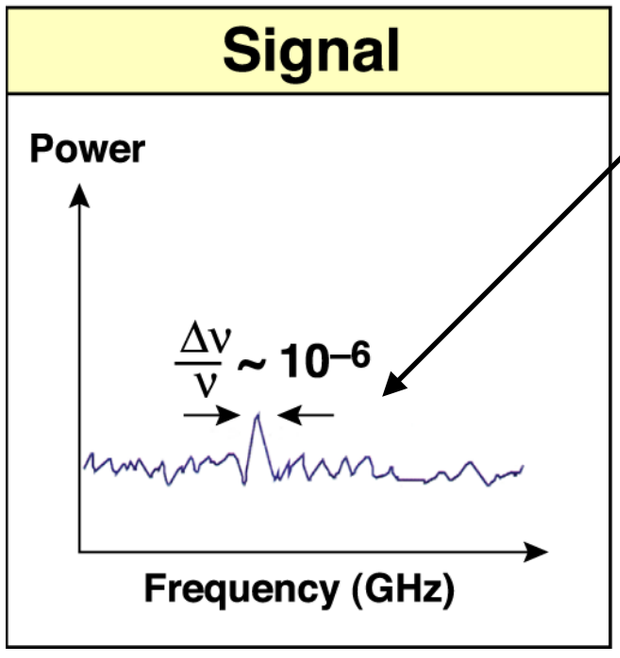


Sikivie-Type Resonant detectors for halo axions

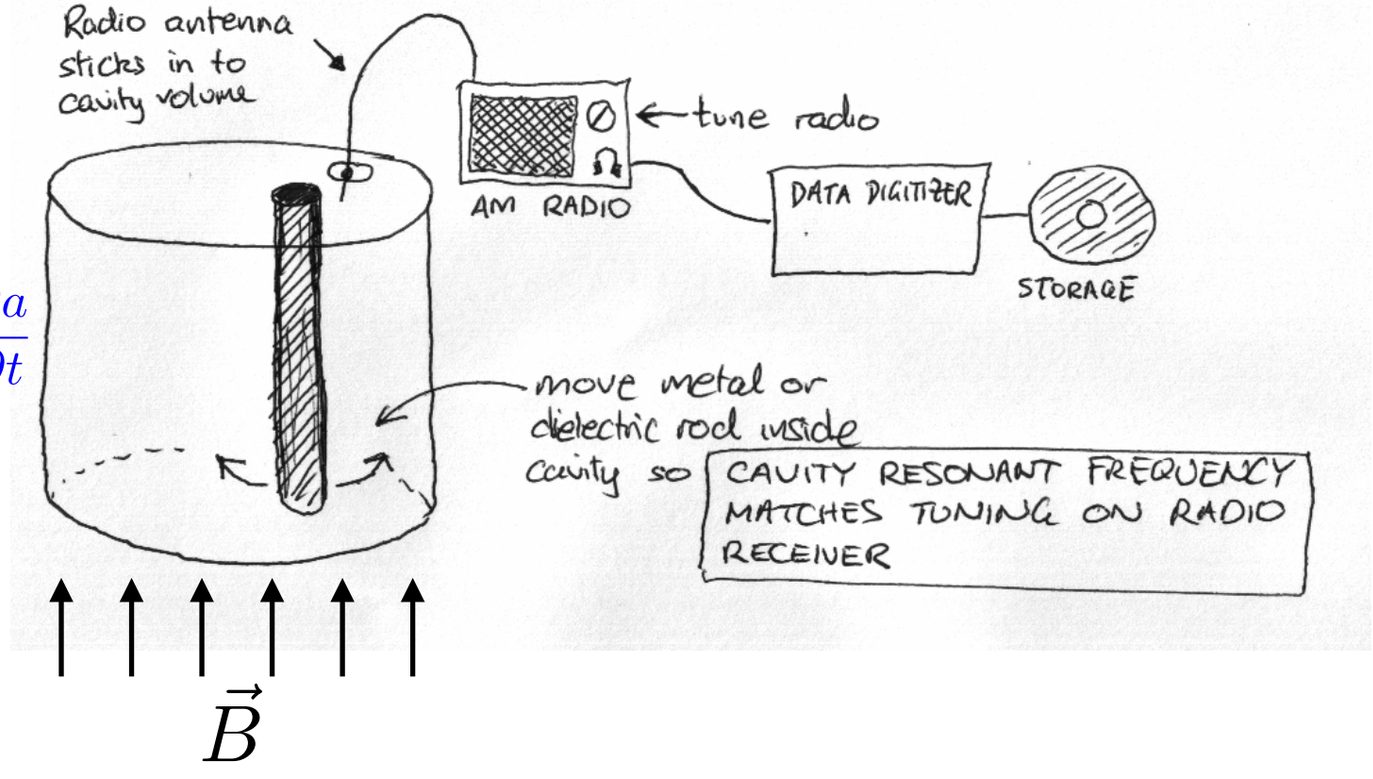


- The conversion is resonant, i.e. the frequency must equal the mass + K. E.
- The total system noise temperature $T_S = T + T_N$ is the critical factor

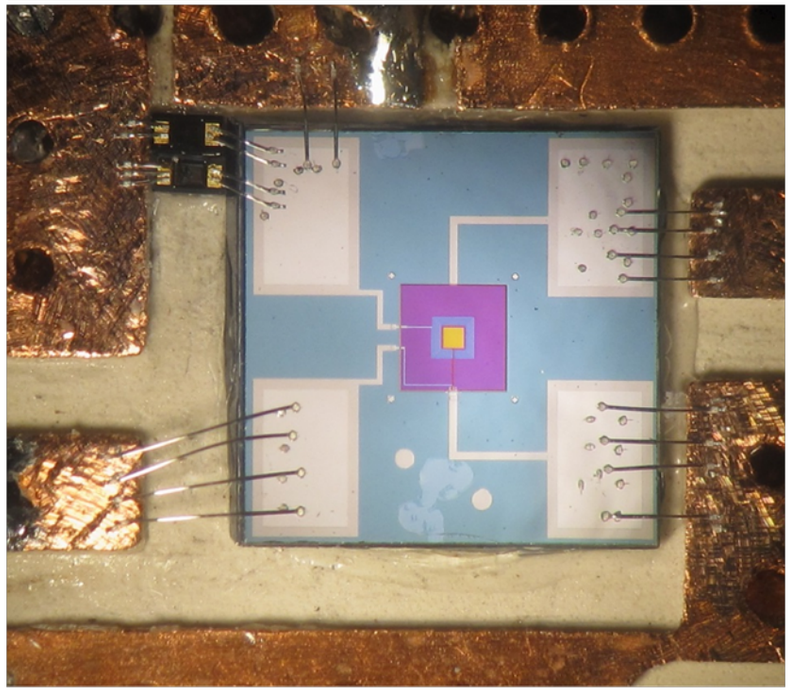
Signal of order yoctowatts, 10^{-24} W



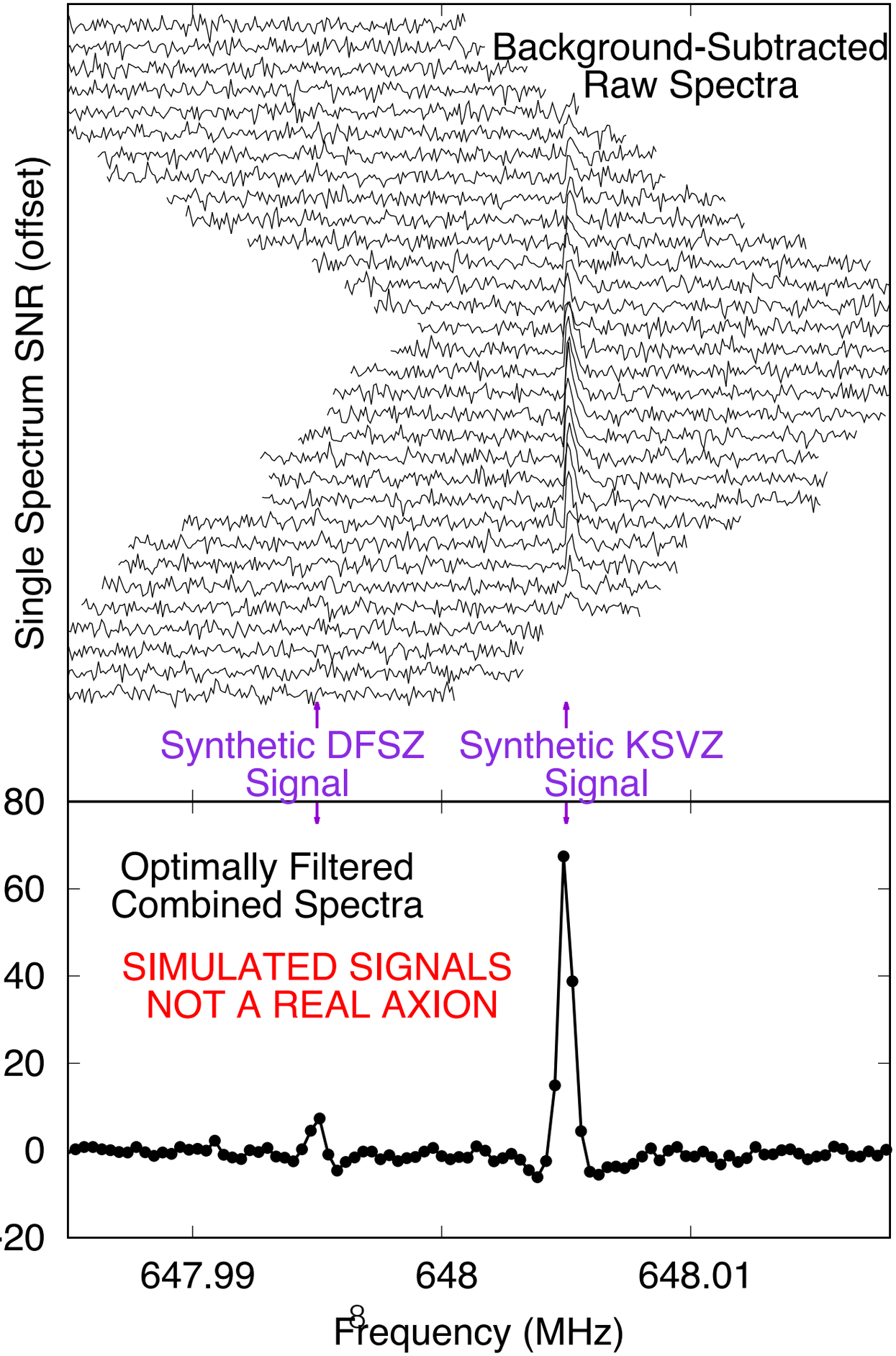
$$\vec{E}_a = g\vec{B}\frac{\partial a}{\partial t}$$



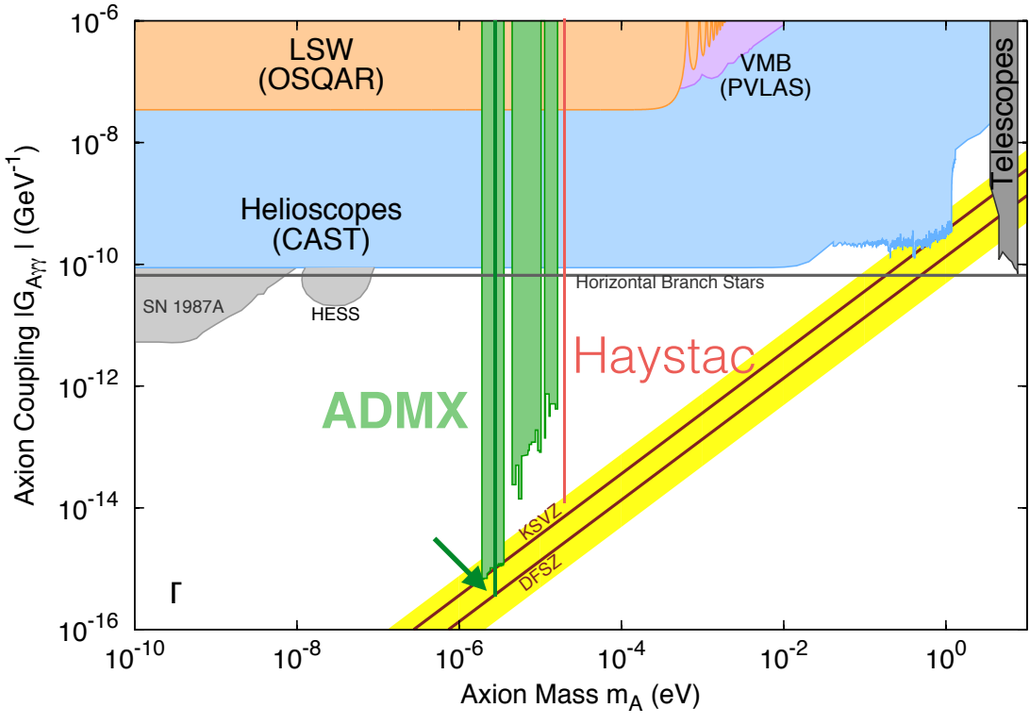
ADMX experiment

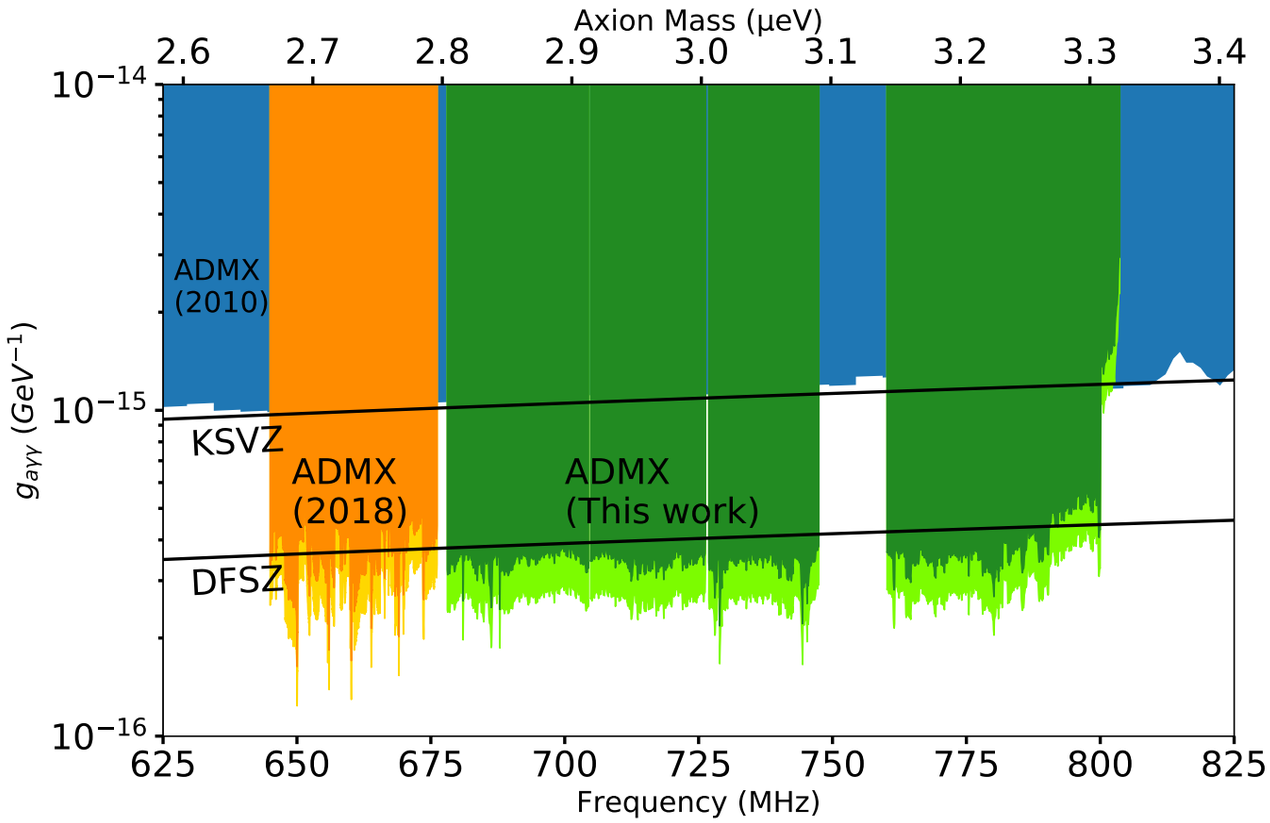


Calculated Signal Strengths in ADMX2



Latest results from ADMX

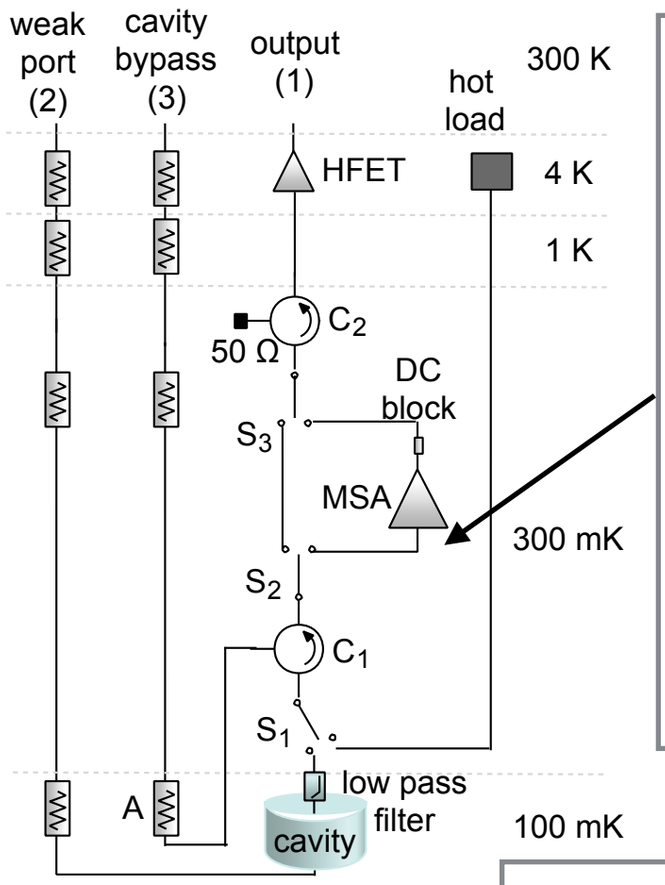




[1] K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014) and 2015 update 2016 revision by A. Ringwald, L. Rosenberg, G. Rybka,

Arxiv:2010.06183 - Axion Dark Matter Experiment: Run 1B Analysis Details Chelsea Bartram, ADMX Seattle

Quantum electronics of todays most sensitive axion detector



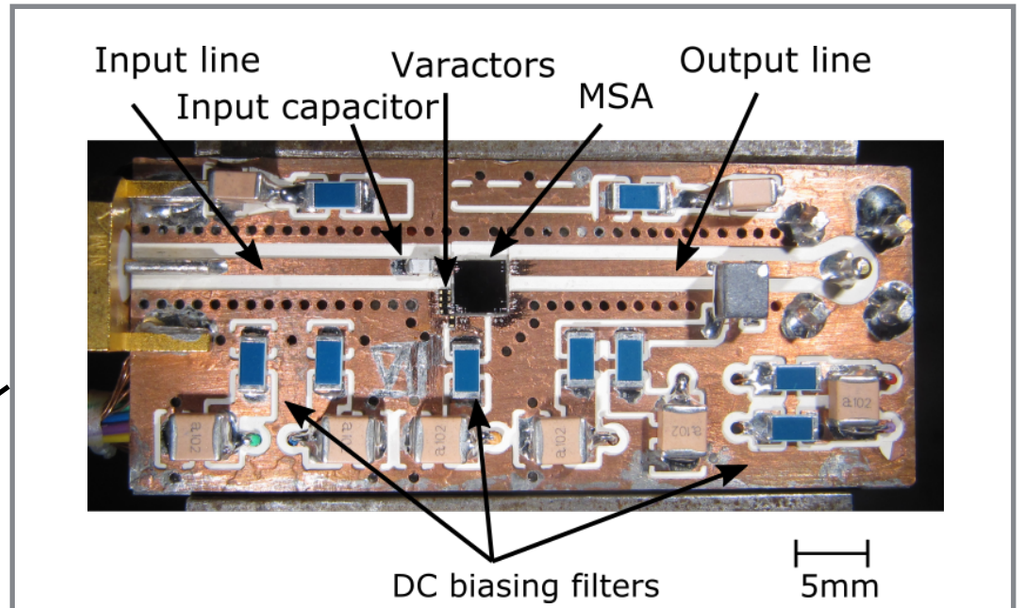
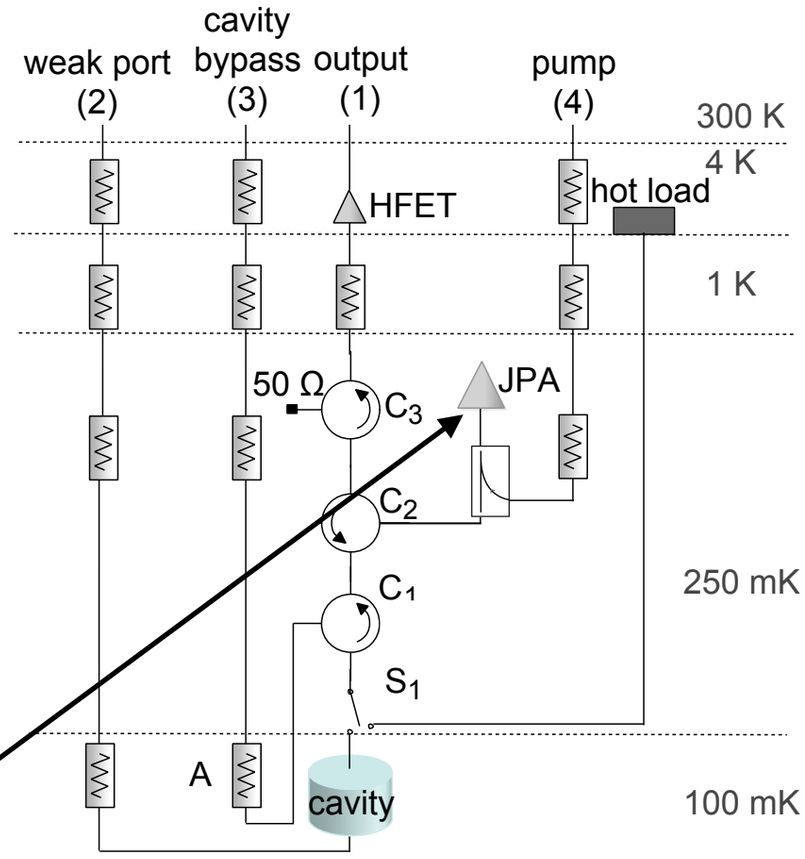
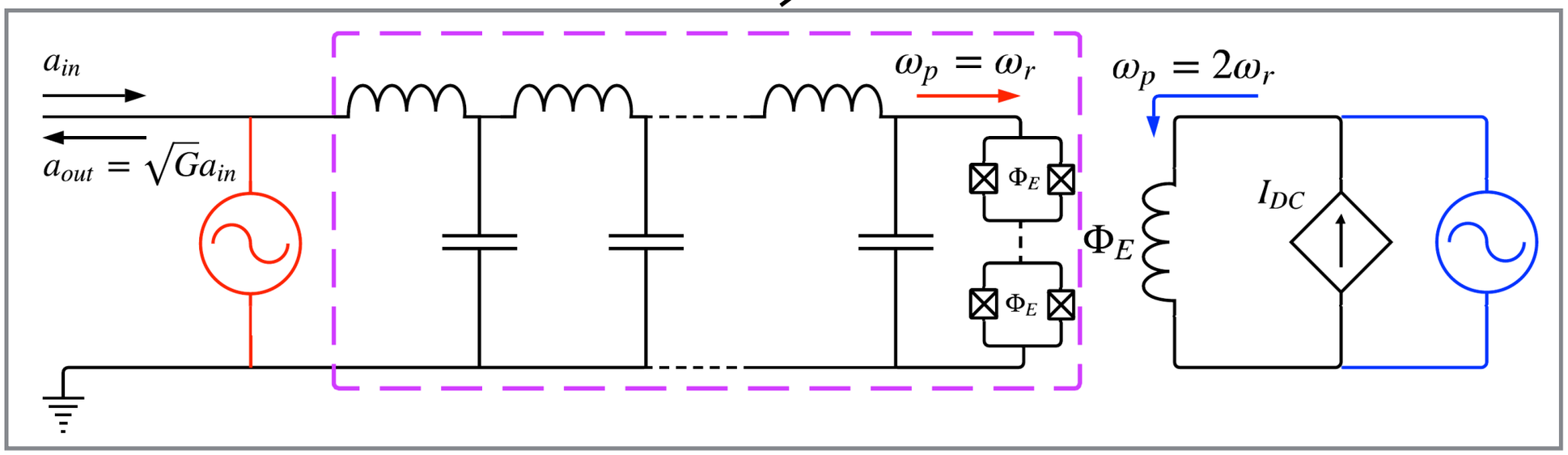


FIG. 13. Photograph of MSA.



ADMX microwave squid amplifier

Schematic of Siddiqui JPA (Berkeley)



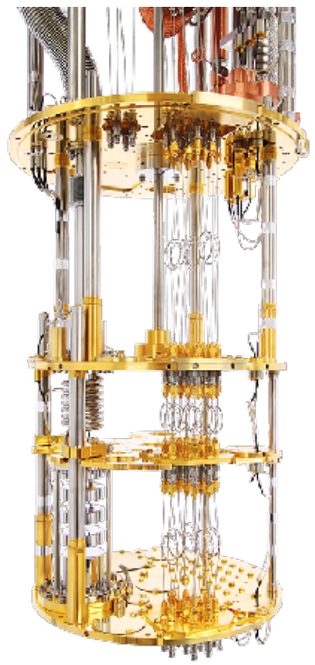
Wet cryogenics + dil fridge, 150mK base temperature

How can a UK experiment improve on the state of the art?

- Combination of a large magnet volume ‘high-ish' field AND a 10mK base temperature target.
- New low noise microwave amplifiers, bolometers, and Qubit devices for unparalleled low noise. Start in a well-motivated mass range, 25-41 micro-eV.
- Theoretical work to understand detector modelled as an integrated quantum measurement system
- Develop novel resonant structures to simplify the apparatus, speed up the search, widen mass range.

Research Programme

- Acquire the world's largest B^2V magnet for hidden sector searches.
- Hidden sector theory/phenomenology.
- Form collaboration with ADMX
  - ✦Science results in years 1-3.
  - ✦Benefit from considerable expertise in ADMX.
  - ✦Immediate profile in the field for our collaboration.
  - ✦Training pathway and early data for Ph.D. students.
- Develop four varieties of quantum electronics
  - ✦SLUG loaded SQUID amplifiers.
  - ✦Travelling wave parametric amplifiers.
  - ✦Bolometers.
  - ✦QuBITs.
- Quantum systems theory.
  - ✦Research into quantum systems composed of individual quantum devices.
- Commission high-field low-temperature facility at Daresbury Laboratory
  - ✦Established national facility with the right infrastructure for our needs.
  - ✦Appropriate lab already reserved.
- Generate science results from our receiver in ADMX.
- First science data from UK target.
- Exploit major investments by funding agencies in R&D on quantum devices.



Example fridge:
Bluefors/Oxford Insts
Dry dilution refrigerator
T< 5mK, Power > 400uW

Example magnet: Tesla Engineering - a UK company. 9.4 T x 830mm bore. Dry Cryogenics.

Proposed UK Experiment at Daresbury

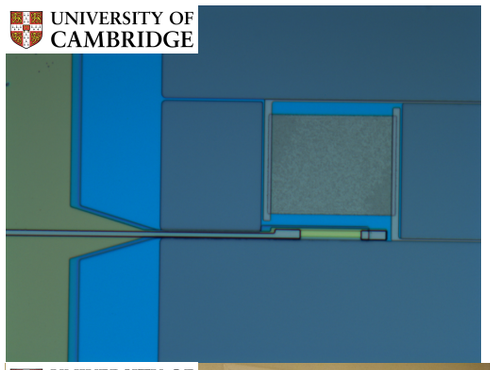
Daresbury site - hall at base of the Van-De-Graff accelerator tower.

Tesla Engineering - possible magnet vendor.

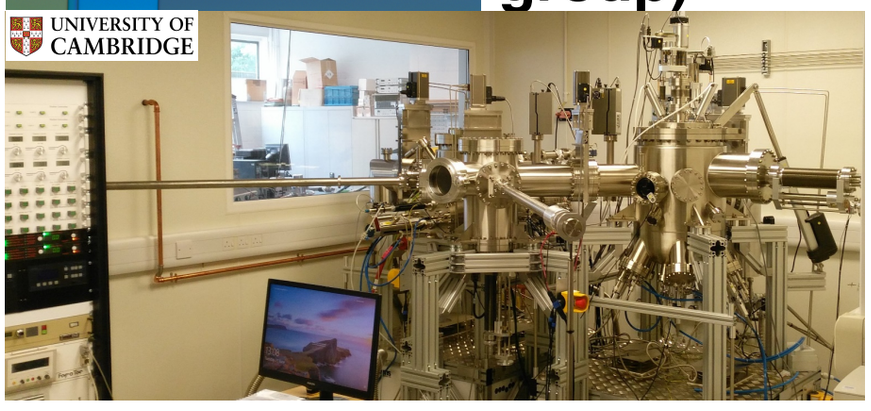
Quantum Electronics

QSHS groups are world leading in quantum electronics and quantum systems design critical to searches for axions and ALPS

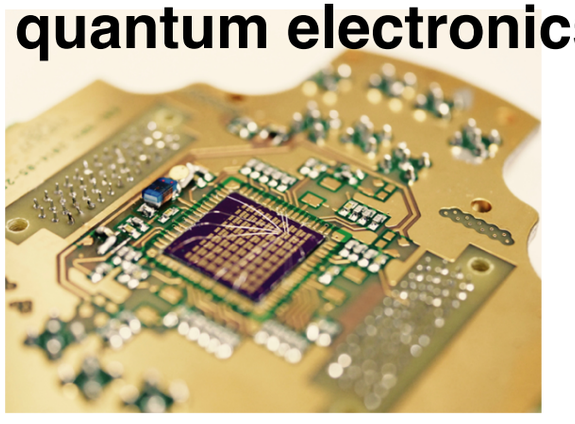
Josephson, Travelling Wave Parametric Amplifiers, Bolometric detectors, and Qubits



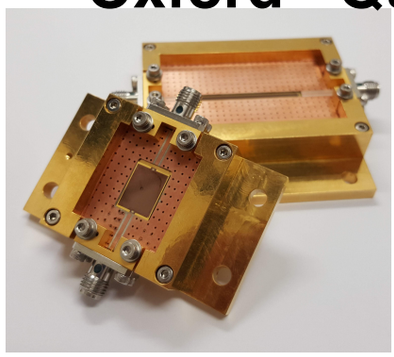
Cambridge (Withington group)

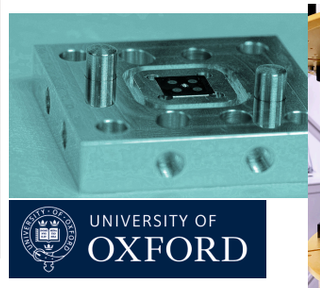


Lancaster - device physics, low noise quantum electronics



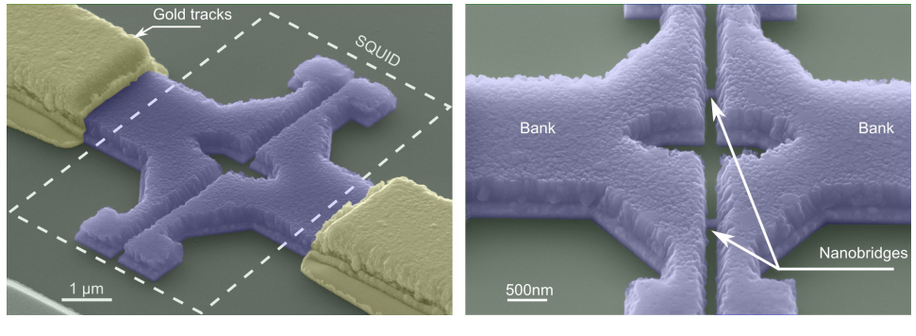
Oxford - QuBits and SIS mixer expertise, Leek, Tan





NPL- Hao, Lewis, Gallup Squids, high field facilities

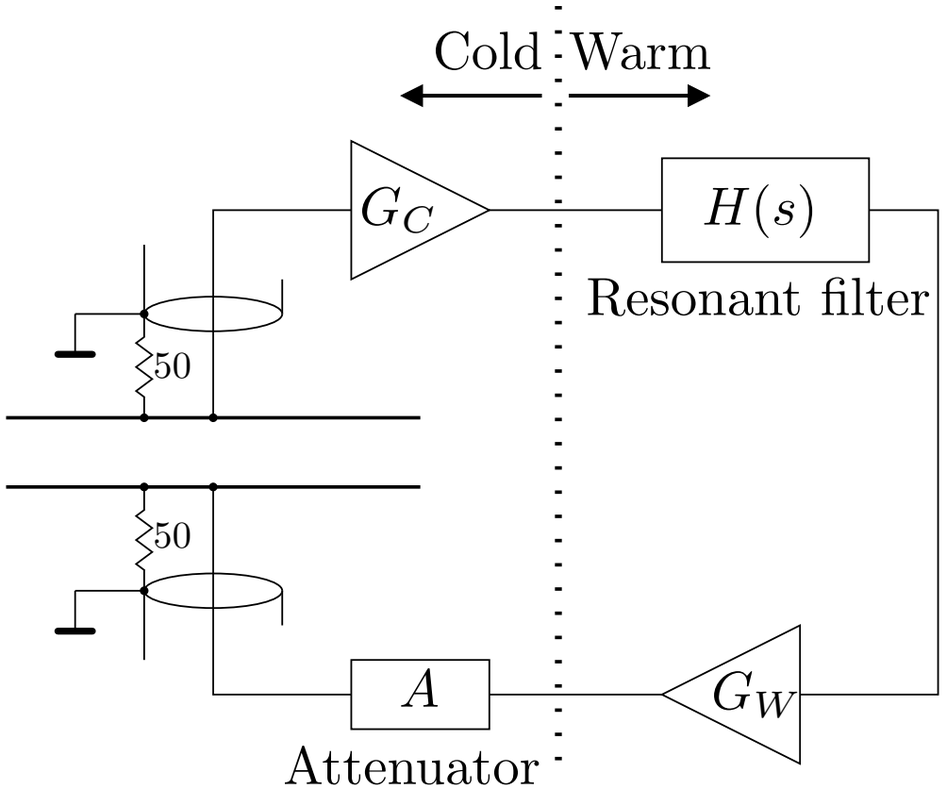
UCL (Romans) SQUIDS, nanoscale fabrication

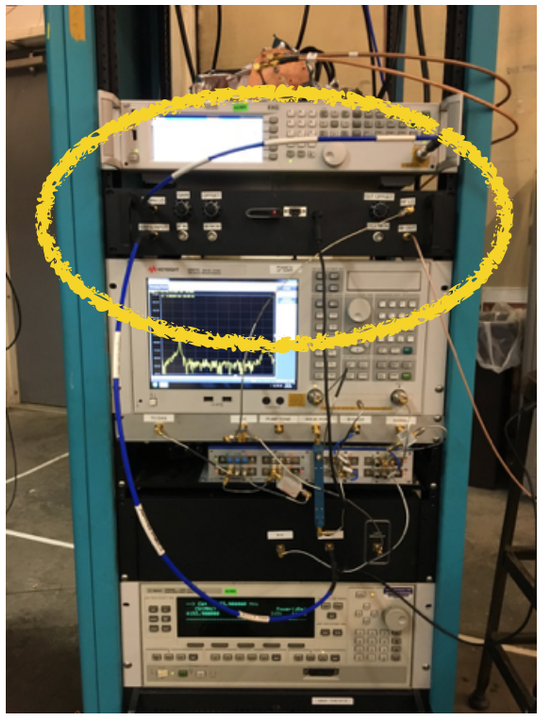


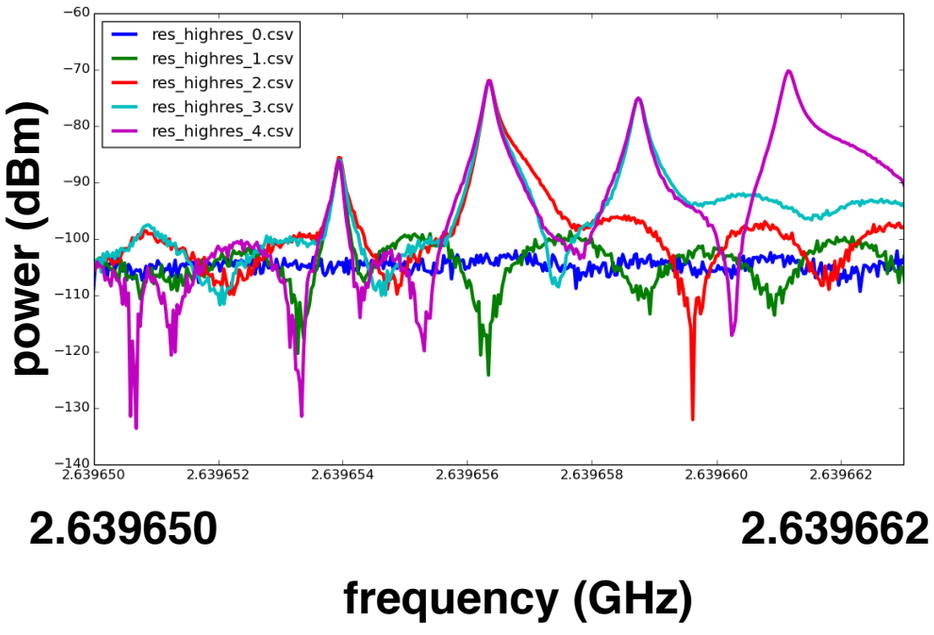
RHUL (Meeson)-fabrication, high B field, RF electronics

Resonant Feedback

- Idea to replace cavity natural resonance with a feedback circuit. 100 parallel axion searches
- Resonant frequency decoupled from detector geometry, so a wider range of masses can be probed.







Resonant feedback paper:
Nucl.Instrum.Meth.A 921 (2019) 50-56
Cited by recent preprint from Guido Müller on using the same concept for ALPS2:
https://arxiv.org/abs/2010.13204

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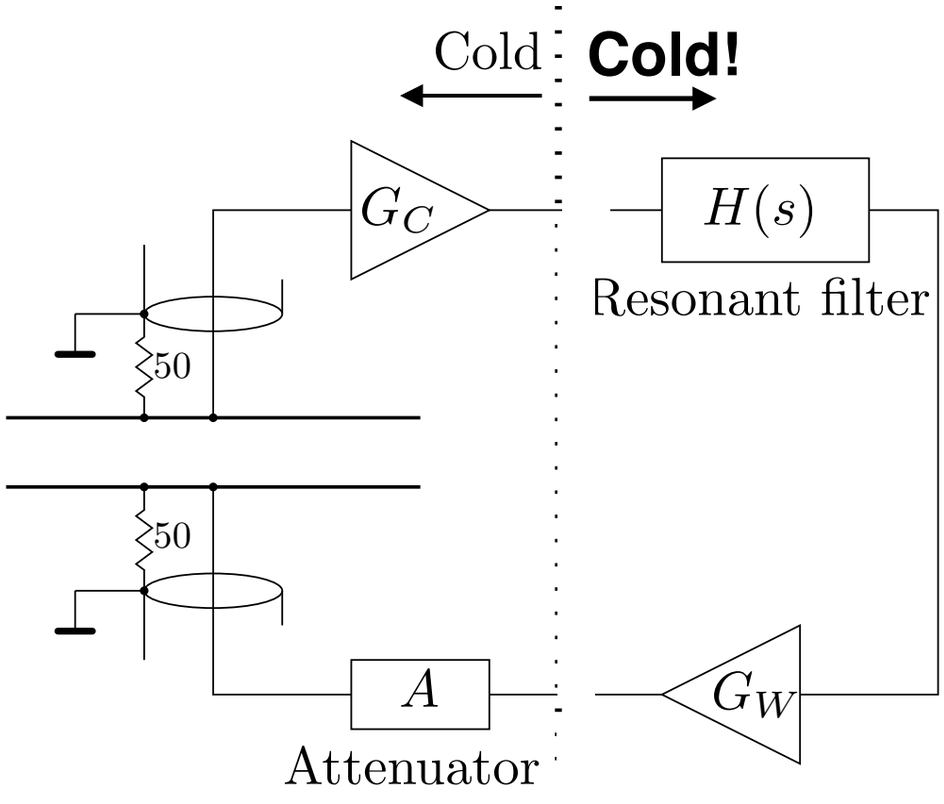

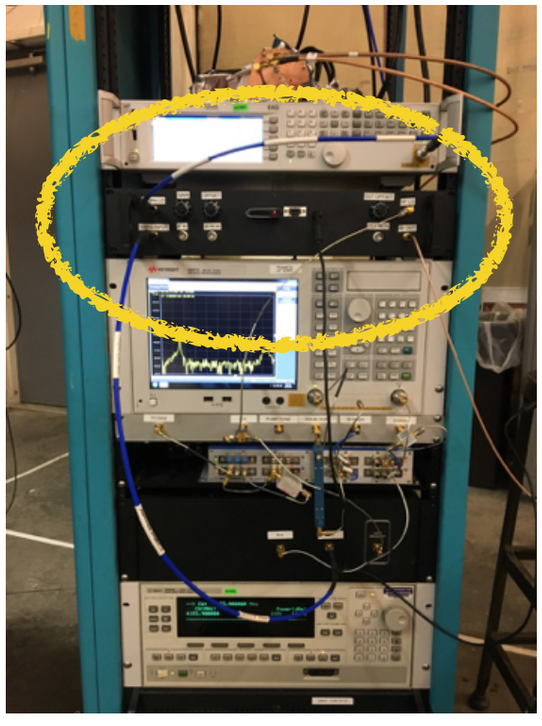

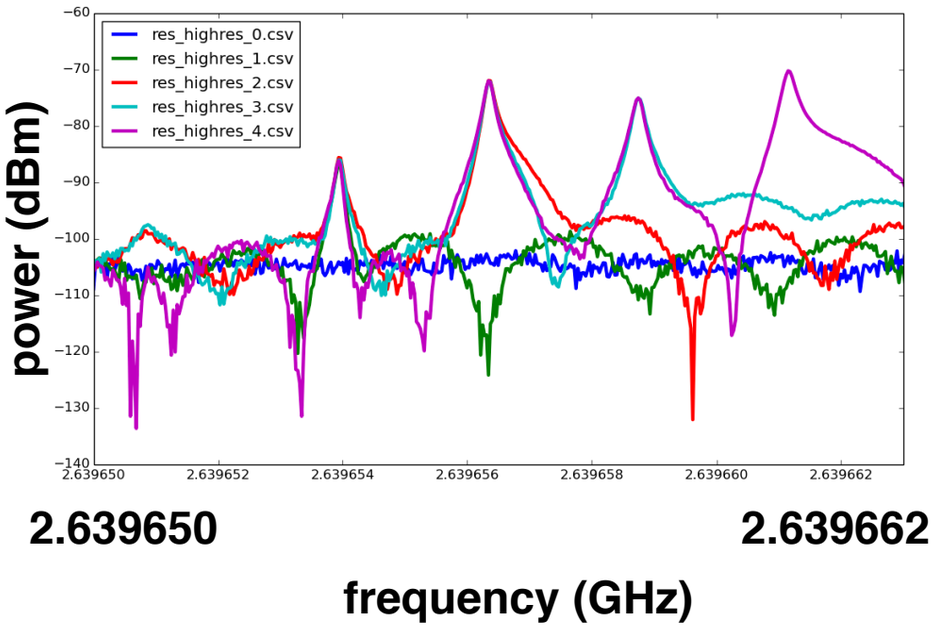

- **All-cryogenic version!**

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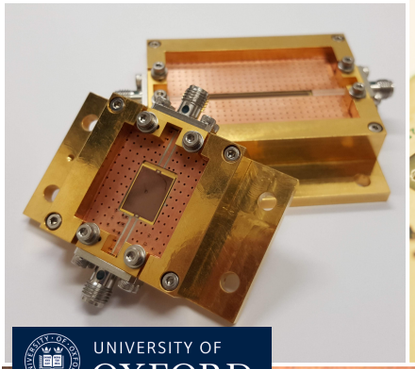
Cited by recent preprint from Guido Müller on using the same concept for ALPS2:
https://arxiv.org/abs/2010.13204

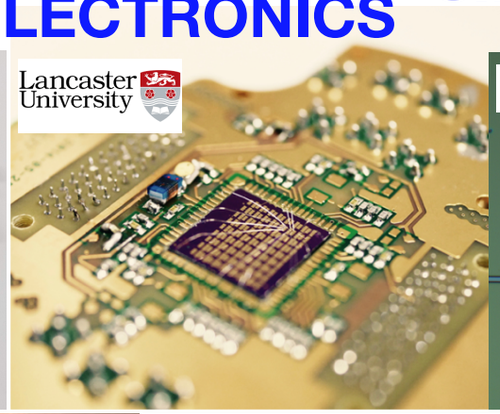
QSXS

In short:

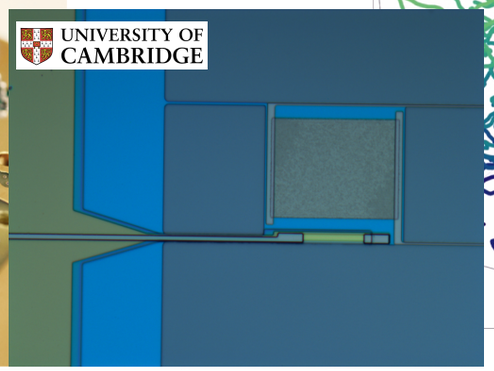
We have the expertise to create the world's most sensitive hidden sector search facility.

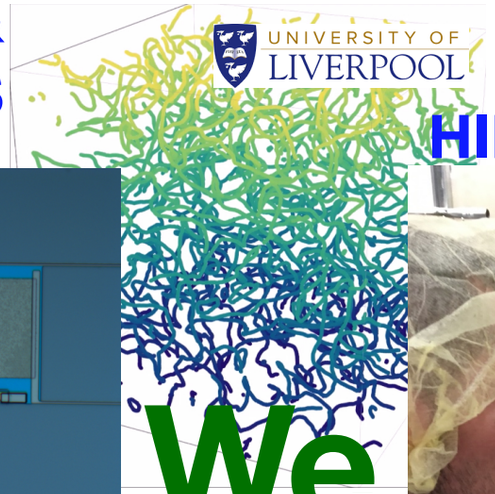
QUANTUM ELECTRONICS



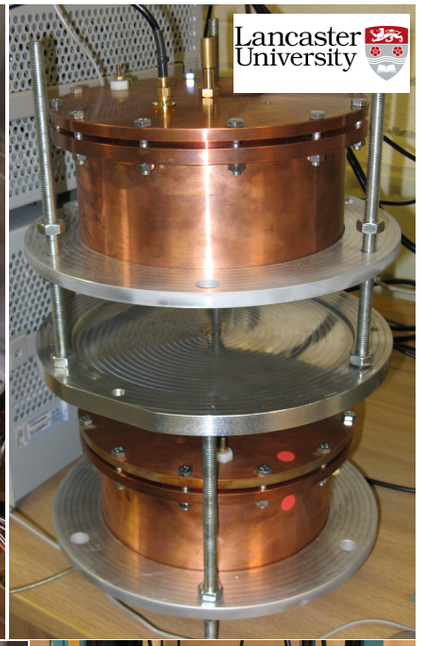


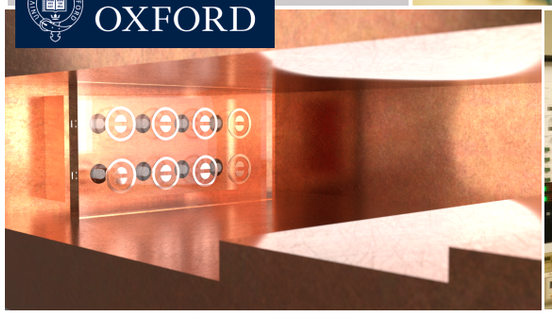
THEORY & SIMULATIONS

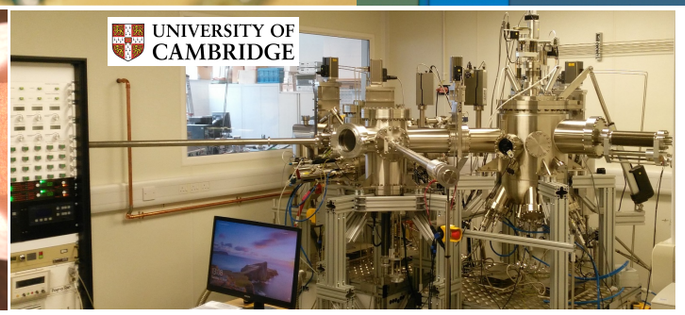


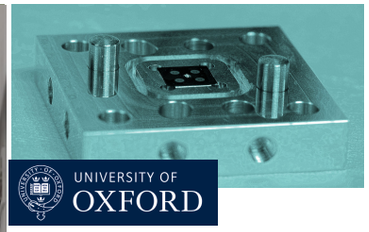


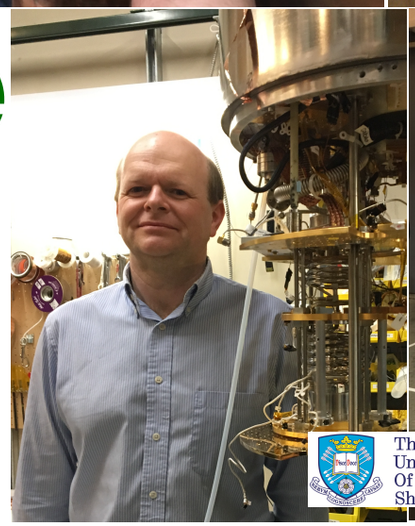
HIDDEN SECTOR SEARCHES

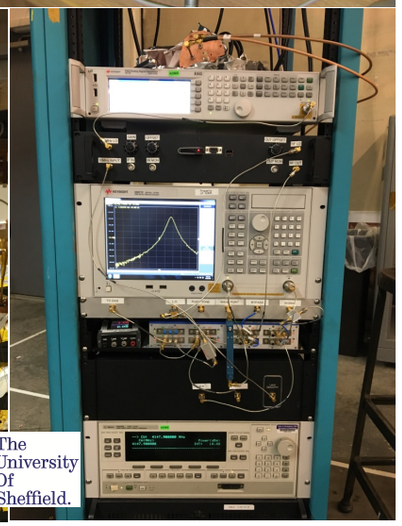




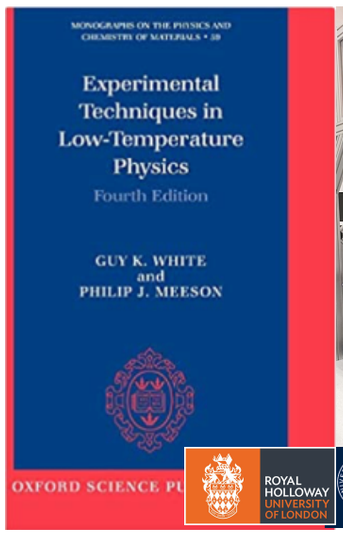


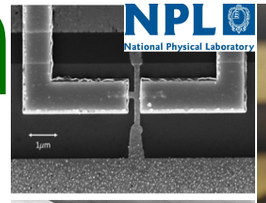


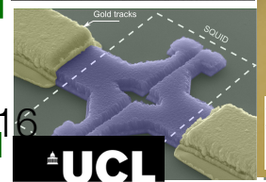


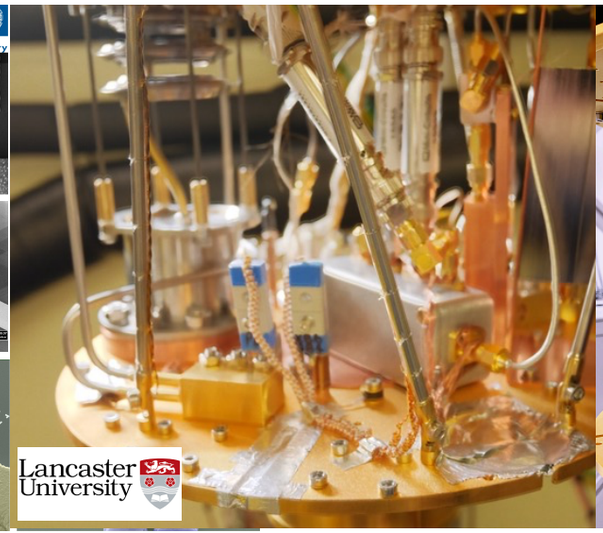


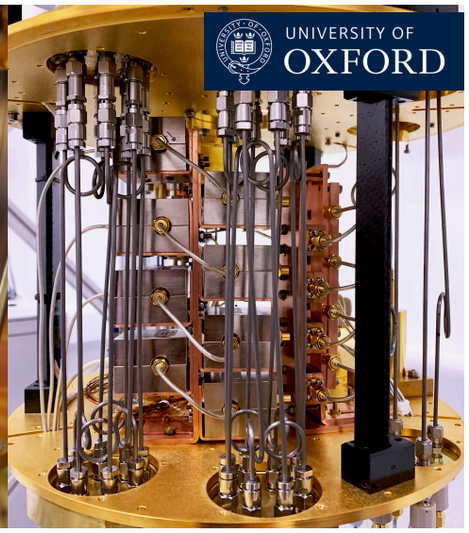
VACUUM & CRYOGENICS











MICROWAVE ELECTRONICS

Summary

- Bleeding edge quantum electronics is becoming crucial for some non-accelerator particle physics experiments.
- Activity in the UK through the new ‘Quantum Sensors for the Hidden Sector’ initiative (qshs.shef.ac.uk)
- Aim at a UK based axion / axion-like particle facility including a 1m bore magnet with a 10mK insert. Collaboration of Sheffield, Lancaster, Cambridge, RHUL, Oxford, UCL, NPL, Liverpool
- Collaboration with ADMX
- UK emphasis will be on an integrated, quantum systems approach to the design of cryogenic electronics.
- Realising this future is all about the technology.

Some references

Axion Dark Matter eXperiment: Detailed Design and Operations

ADMX Collaboration • R. Khatiwada (Fermilab and IIT, Chicago) et al.

e-Print: 2010.00169 [astro-ph.IM]

Axion Dark Matter eXperiment: Run 1B Analysis Details

ADMX Collaboration • C. Bartram (Washington U., Seattle) et al.

e-Print: 2010.06183 [astro-ph.CO]

Resonant feedback for axion and hidden sector dark matter searches

Edward J. Daw (Sheffield U.)

e-Print: 1805.11523 [physics.ins-det]

DOI: 10.1016/j.nima.2018.12.039

Published in: Nucl.Instrum.Meth.A 921 (2019), 50-56, Nuclear Inst. and Methods in Physics Research, A 921 (2019) 50-56