Quantum Sensors for the Hidden Sector

7th 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

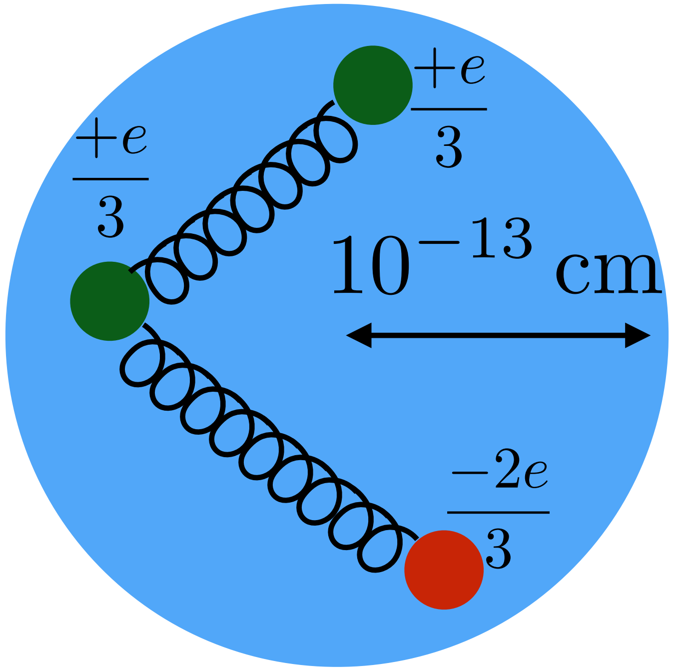
Standard model symmetry group is $\underbrace{SU(3)}_{\text{NON-ABELIAN}} \times \underbrace{SU(2)}_{\text{NON-ABELIAN}} \times \underbrace{U(1)}_{\text{ABELIAN}}$

	NON-ABELIAN	NON-ABELIAN	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

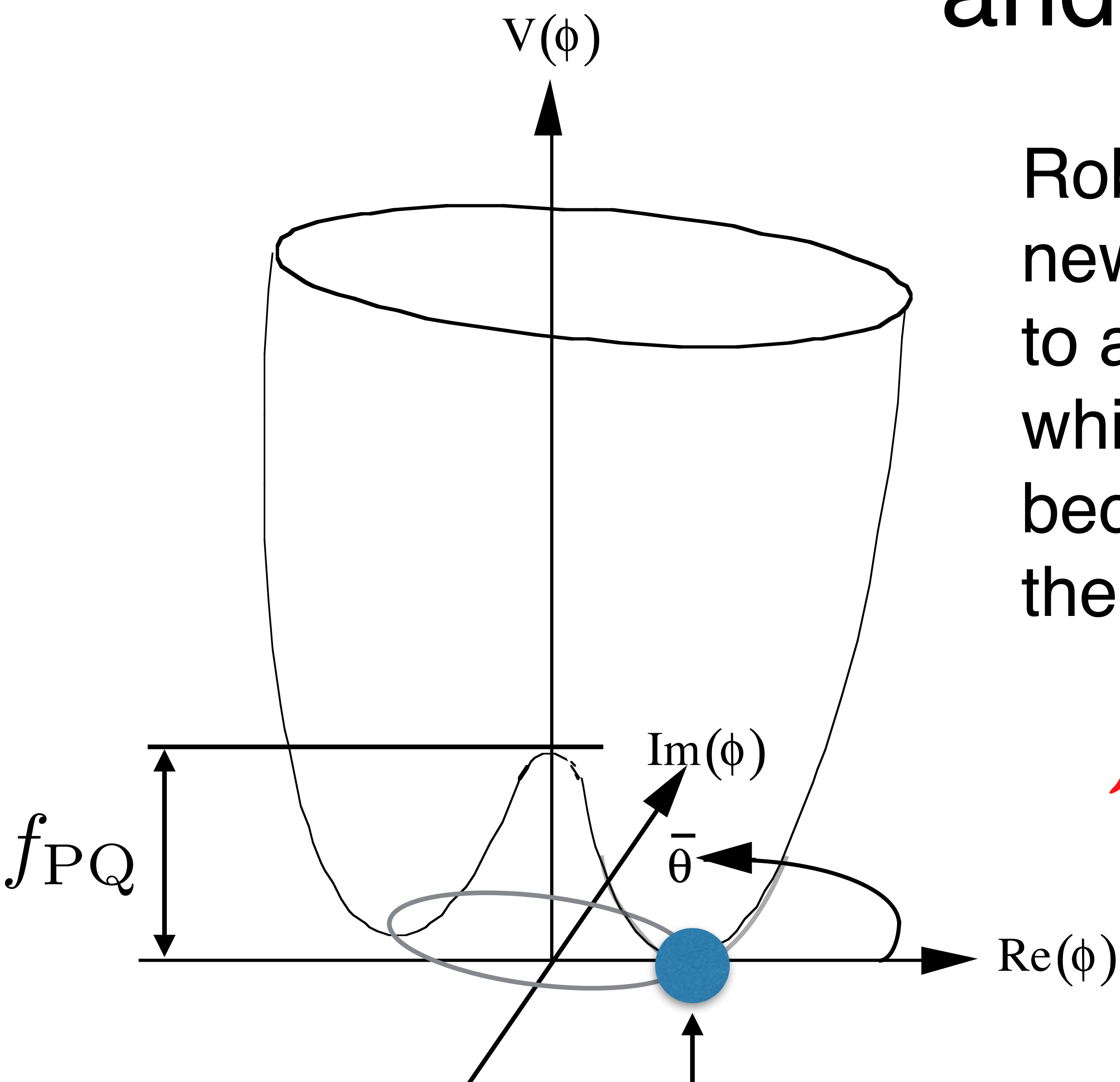
Evidence for CP conservation in the SU(3) strong interactions from multiple measurements of neutron and nuclear electric dipole moments. For example, neutron EDM < 10^{-26} e-cm.

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.

NEUTRON



The Peccei Quinn Mechanism and Axions



Robert Peccei, Helen Quinn proposed a new phase transition in QCD giving rise to a post-phase-transition condensate in which CP is precisely conserved. $\overline{\Theta}$ becomes a variable which is zero in the ground state of the broken theory.

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

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

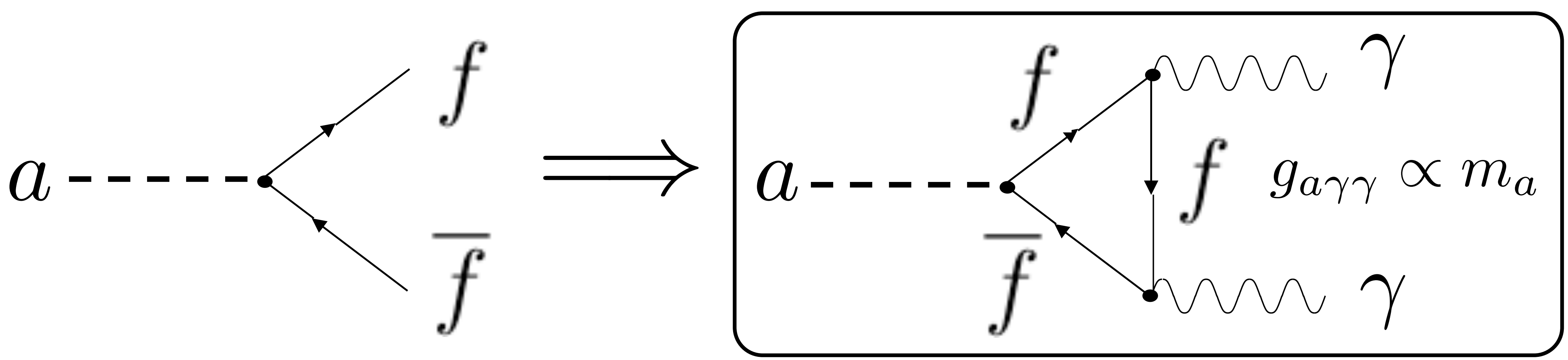
About Minimum: small curvature (hence small mass) with respect to $\bar{\theta} = \arg(\phi)$

Axion DOF

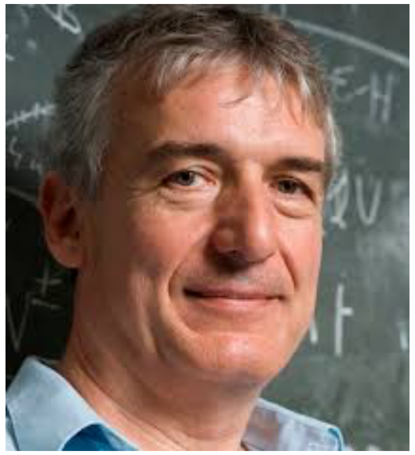
Axion Phenomenology

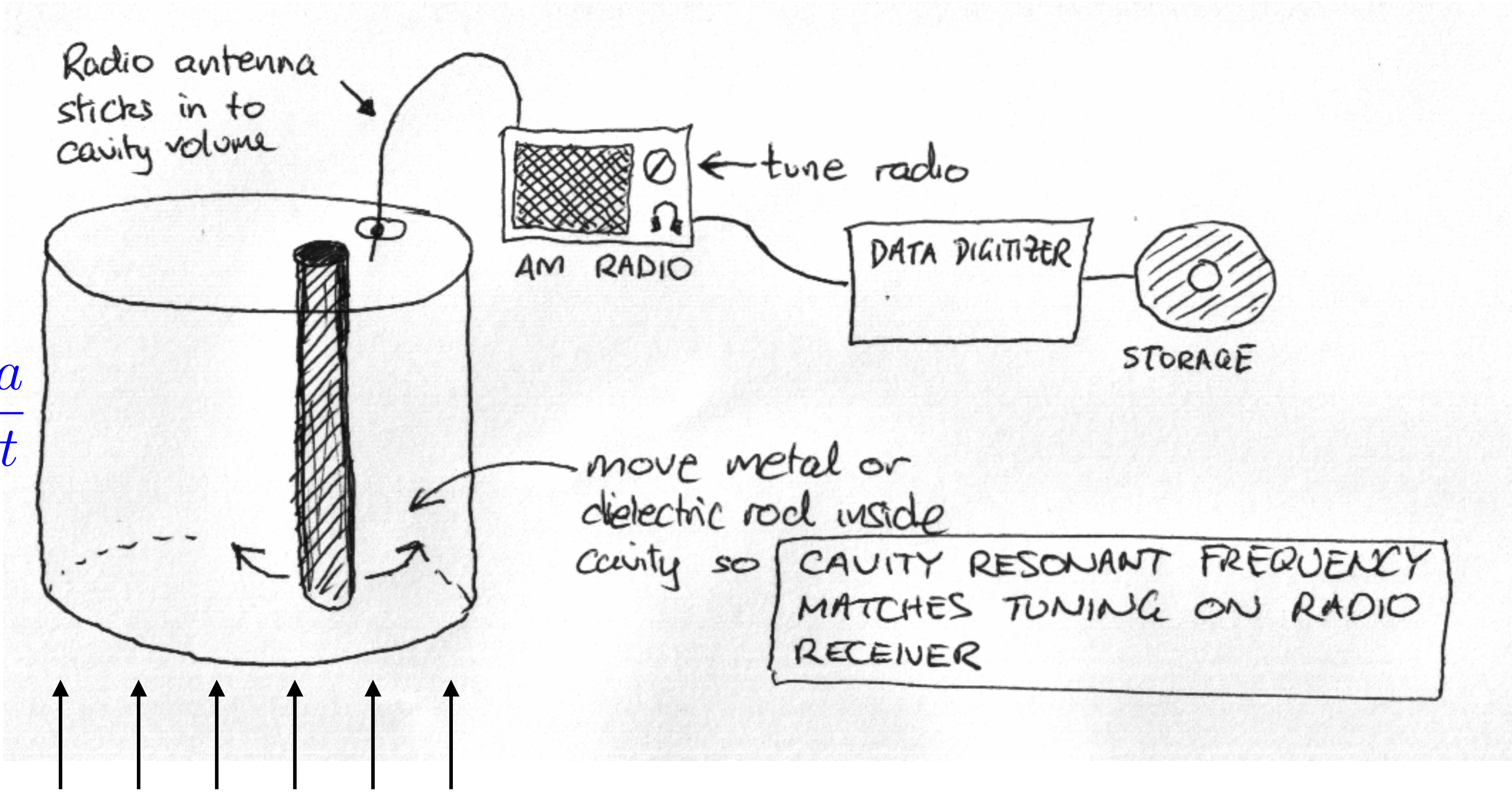
The axion is a pseudoscalar; has the same quantum numbers as the π^0, and the same interactions, but with coupling strengths scaled by the axion mass

$$f_{\mathrm{PQ}} \sim 10^{13}\,\mathrm{GeV}\left(\frac{3\,\mu\mathrm{eV}}{\mathrm{m_a}}\right) \qquad \Omega_{PQ} \propto \frac{1}{m_a^{\frac{7}{6}}}$$



Sikivie-Type Resonant Cavity Axion Search





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

$$\vec{B}$$

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

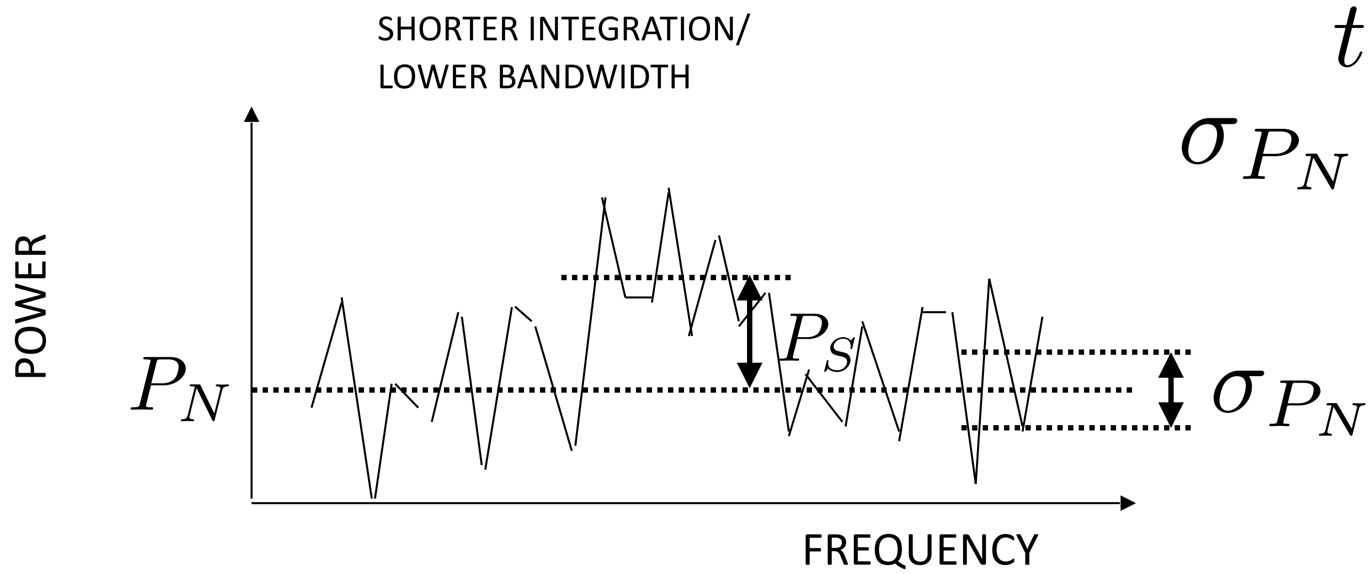
$$\begin{aligned} P_N &= k_B T_S B \\ &= 1.4 \times 10^{-23}[J\,K^{-1}] \times 4[k] \times 500[Hz] \\ &= 2.8 \times 10^{-20}\,W \end{aligned}$$

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

The Radiometer Equation.

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

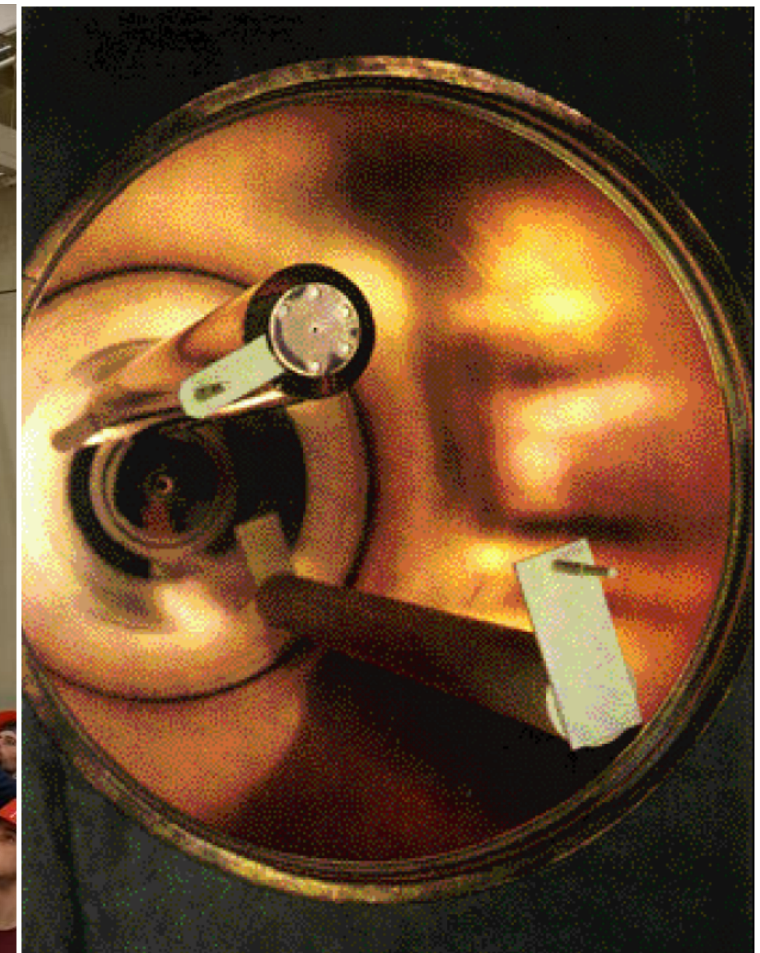
B : bandwidth
P_S : signal power
P_N : noise power
t : integration time
σ_{P_N} : r.m.s. of bin-to-bin fluctuations in noise



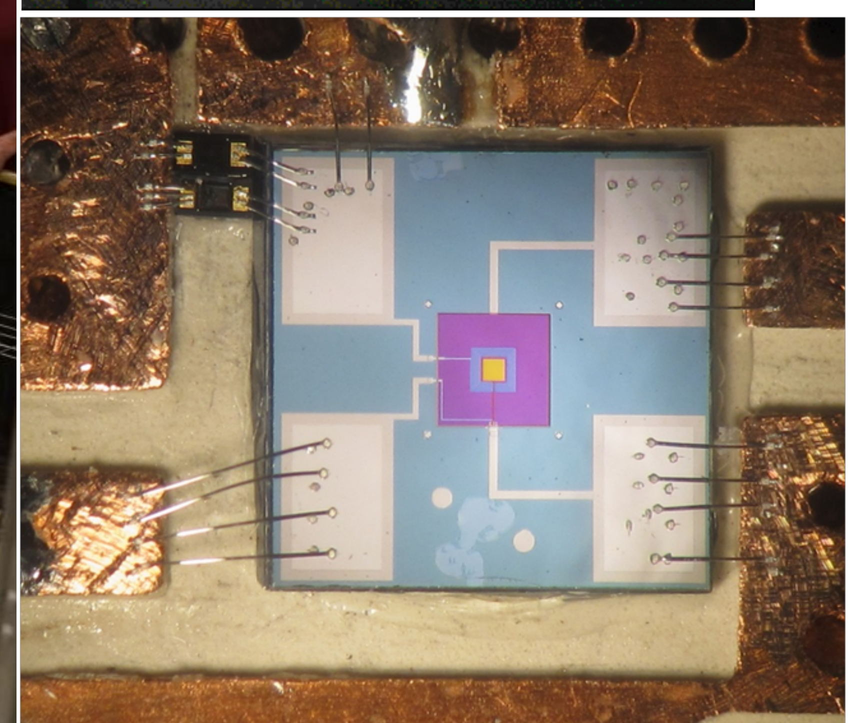
The radiometer equation is useful here because the signal is at a static frequency, and the noise at surrounding frequencies is relatively flat (because the cavity resonance is much wider band than the signal peak). Thus the signal appears as *excess power* in its bandwidth on top of the noise power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

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

ADMX experiment

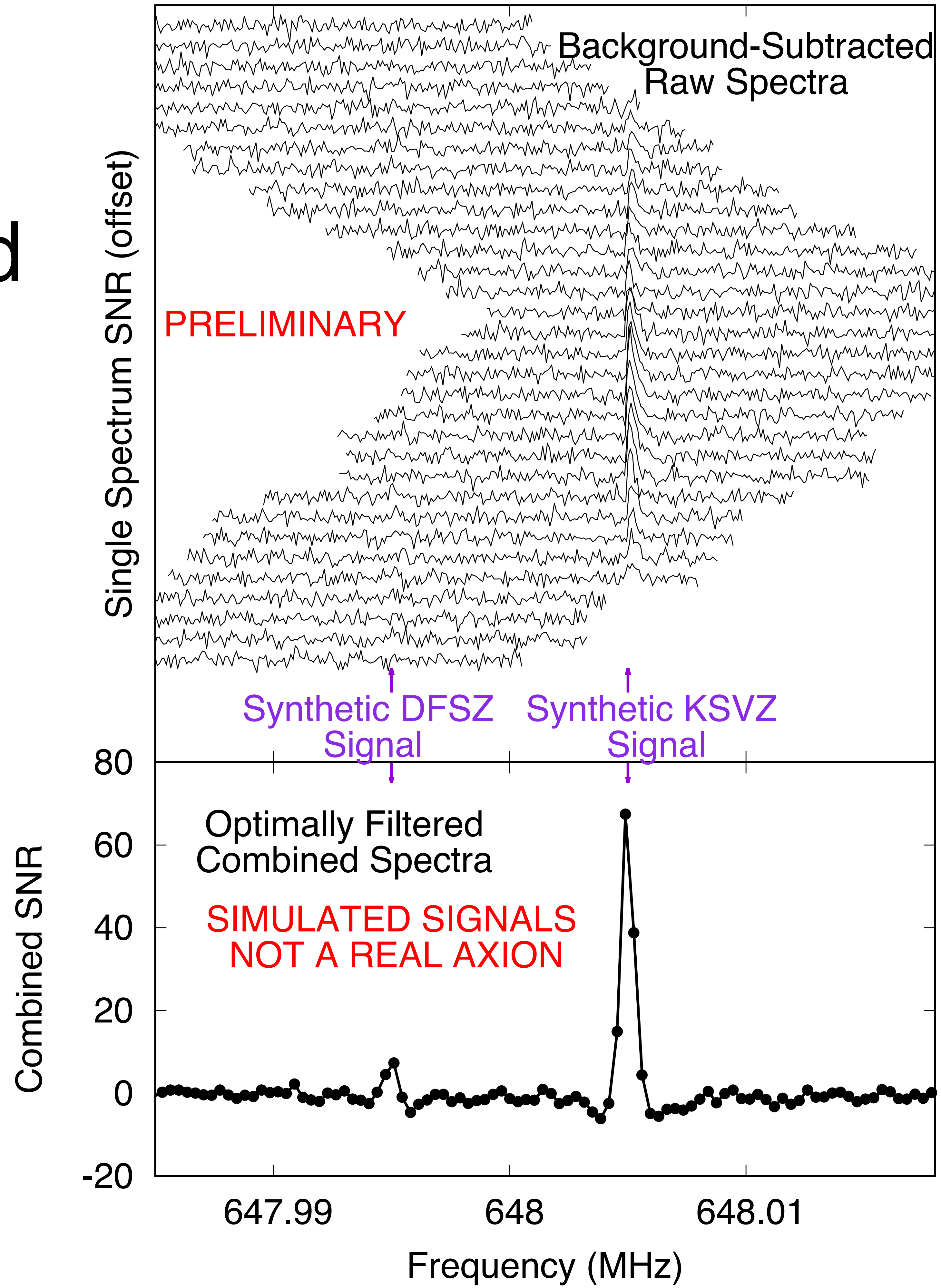


50cm

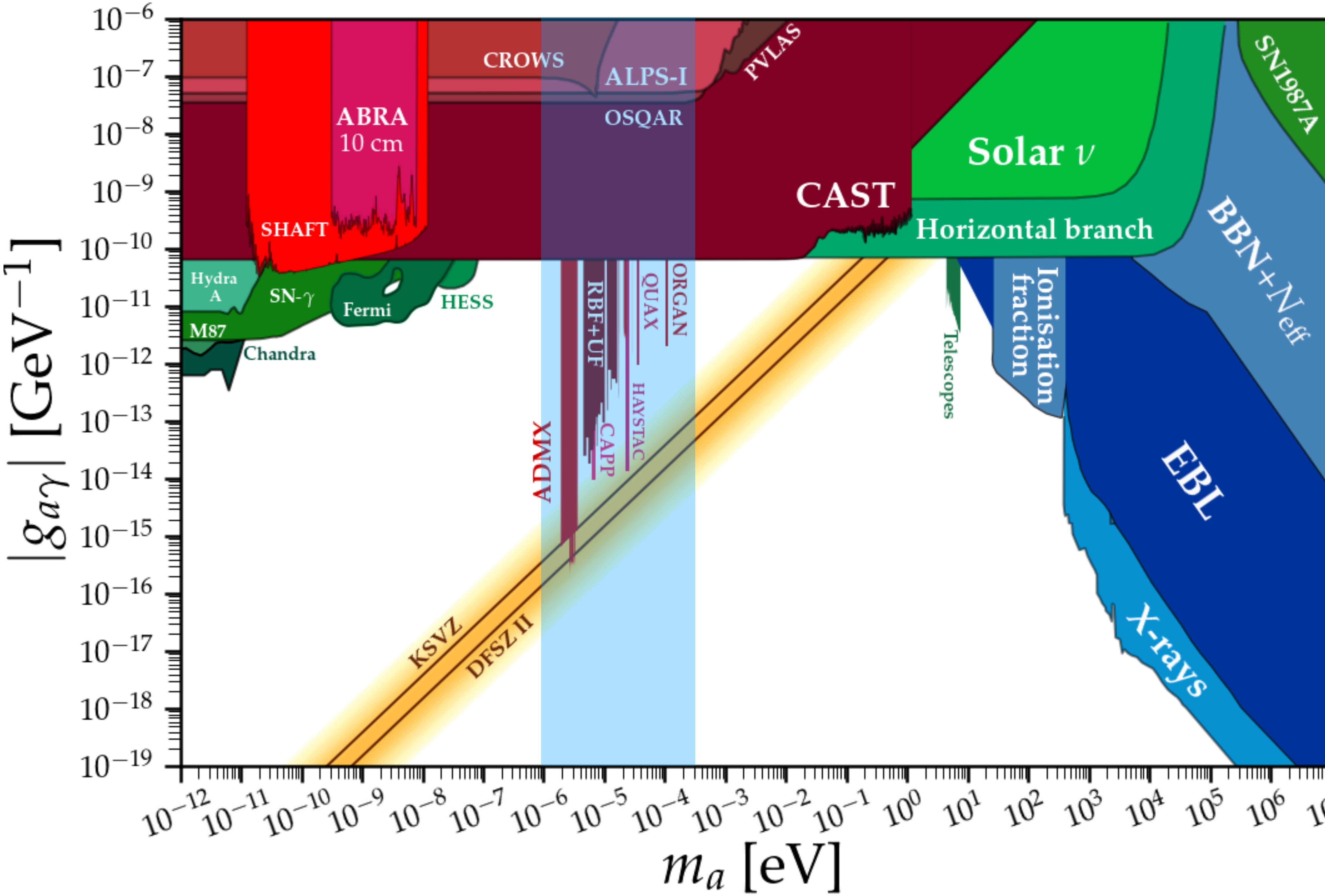


Microwave Squid Amplifier (MSA)

Calculated Signal Strengths in ADMX2

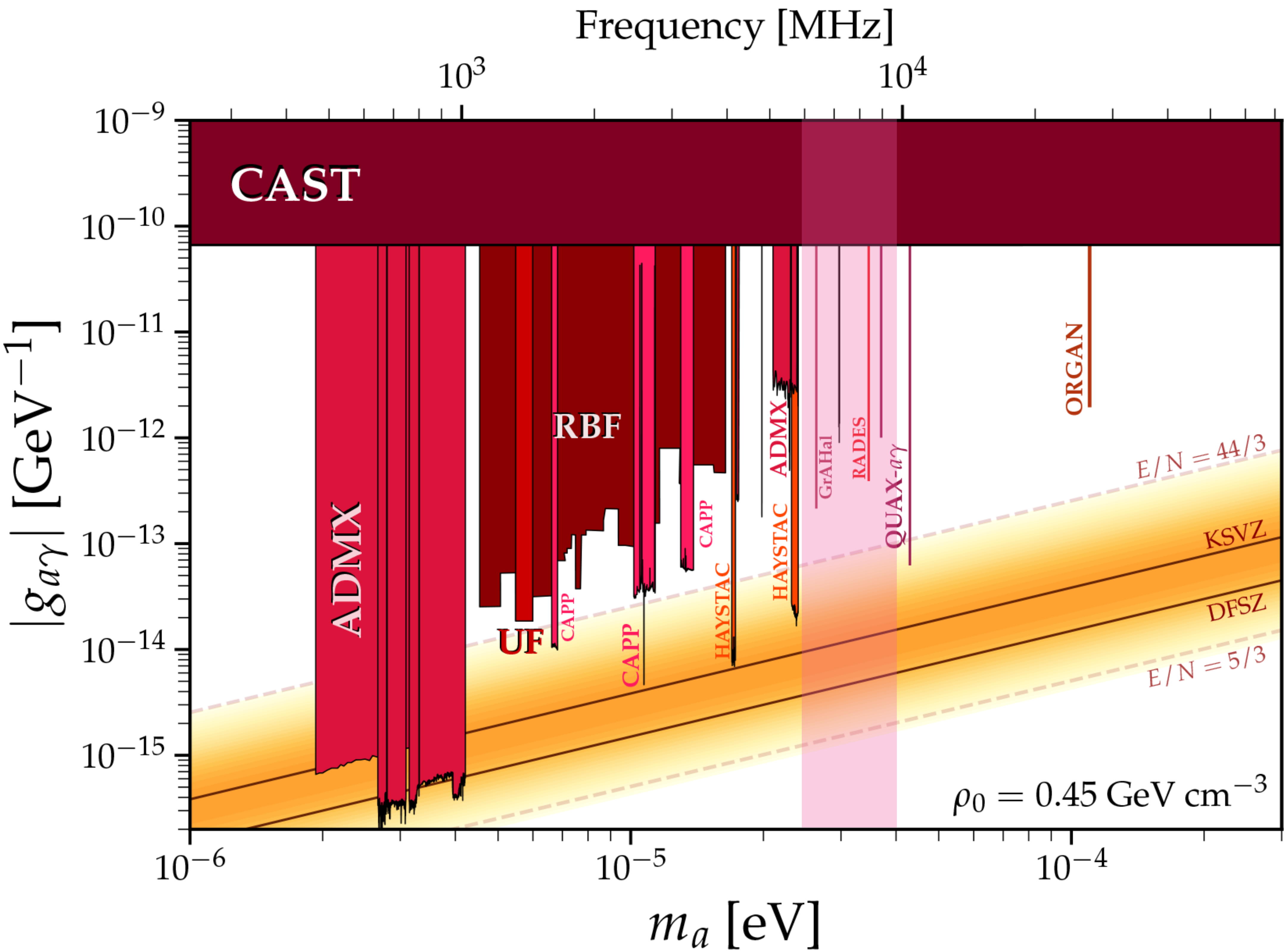


Exclusion Limits World-Wide



[4] C. O'Hare, "cajohare/axionlimits: Axionlimits," (2020), URL https://doi.org/10.5281/zenodo.3932430.

Resonant Cavity Searches



[4] C. O'Hare, "cajohare/axionlimits: Axionlimits," (2020), URL https://doi.org/10.5281/zenodo.3932430.

Figure of merit for cavity axion detectors

$$\frac{B^2V}{T}$$

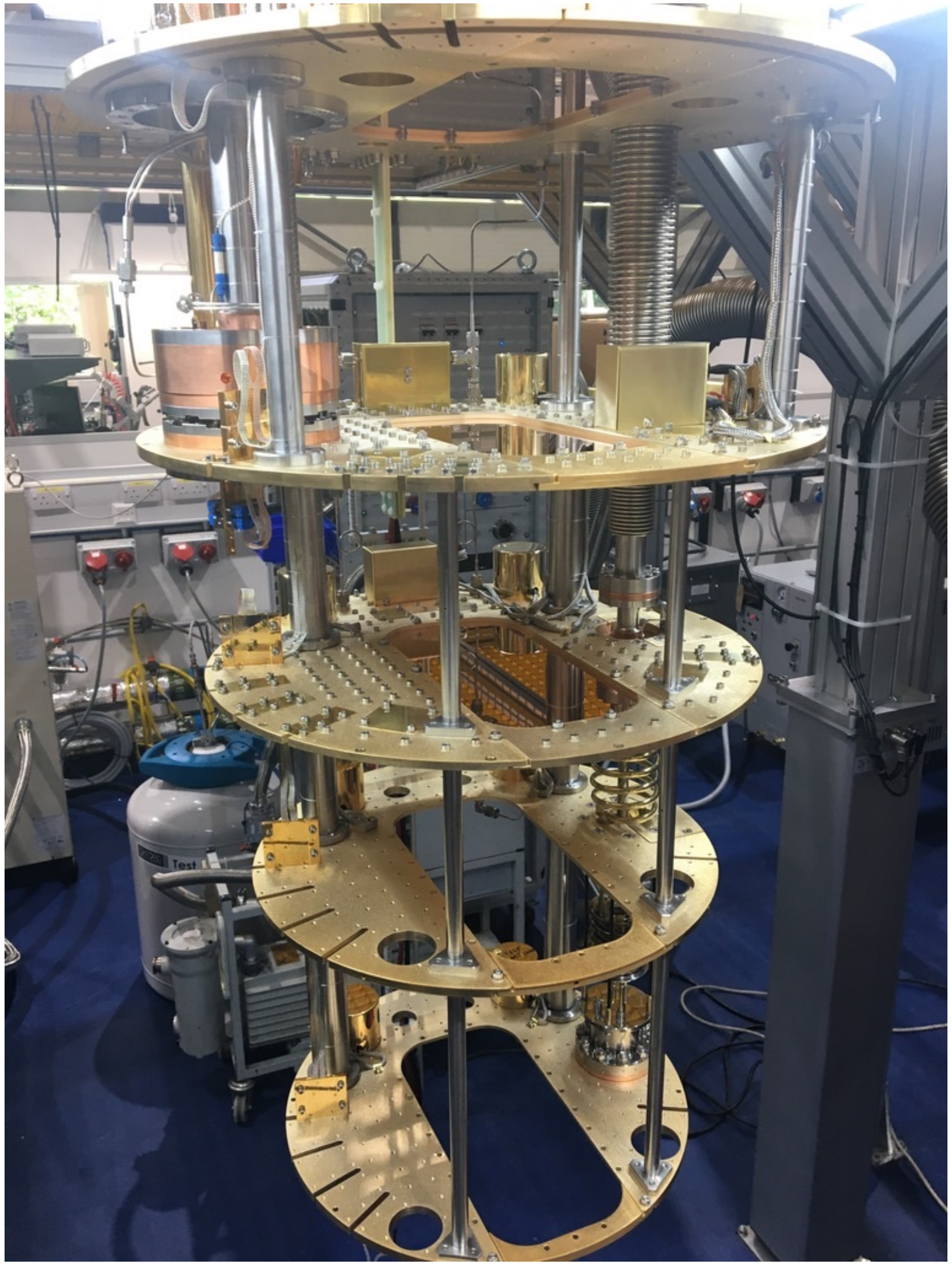
T is the system noise temperature. Minimise it by cooling the apparatus to 10 millikelvin in a custom dilution refrigerator, and by employing new custom low noise readout.

B is the applied magnetic field and V is the volume of the resonant structure in the magnet bore.

Best strategy for B and V turns out to be to go for an 8T field, allowing you to use relatively low risk magnet windings of NbTi / NbSn, but over as large a volume as possible.

QSHS aspires to an 8T, 1m bore, 1m long magnet. Our test stand detector has an 8T field, with a 20cm bore, 20cm long magnet.

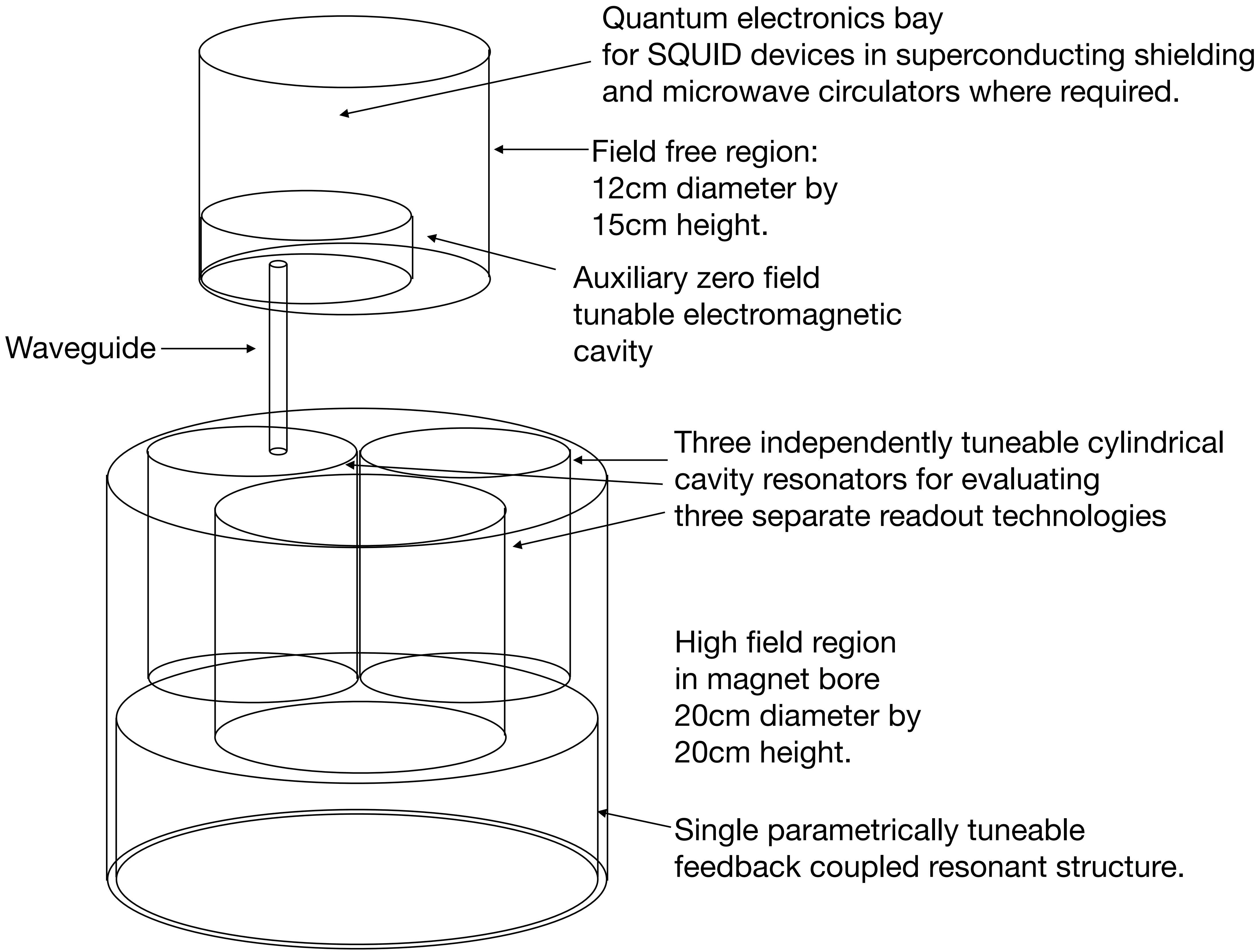
Custom dilution fridge based on Oxford Instruments Proteox MX platform, 8T dual NbTi / NbSn magnet with stray field cancellation



Test Stand Lab

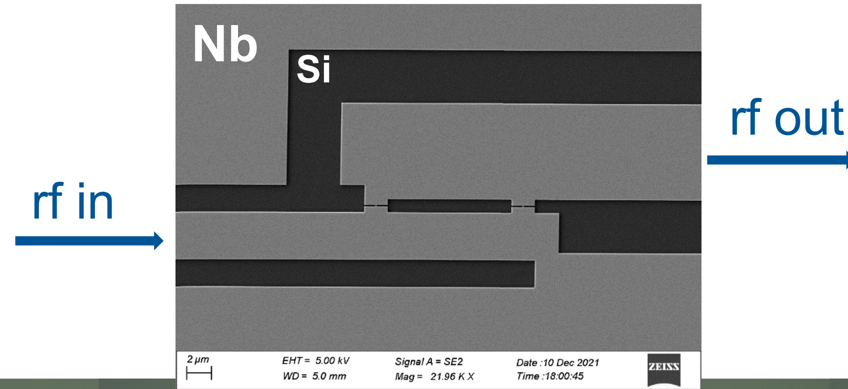
WP10 continued - target design

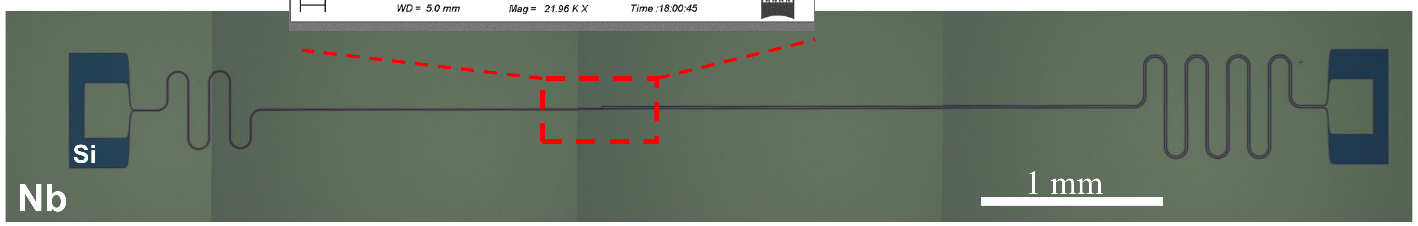
Early conceptual design work on the target has begun.



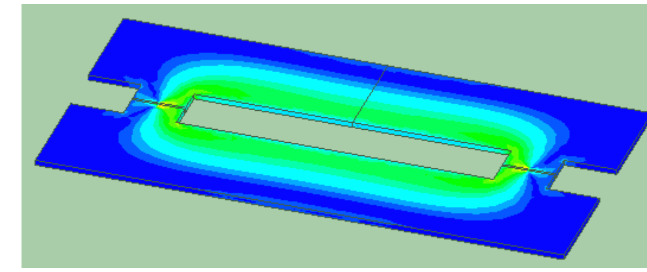
Examples of QSHS Linear Amplifier and Device Technology

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

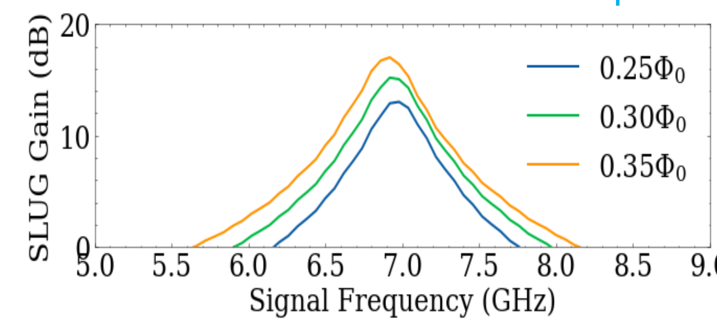


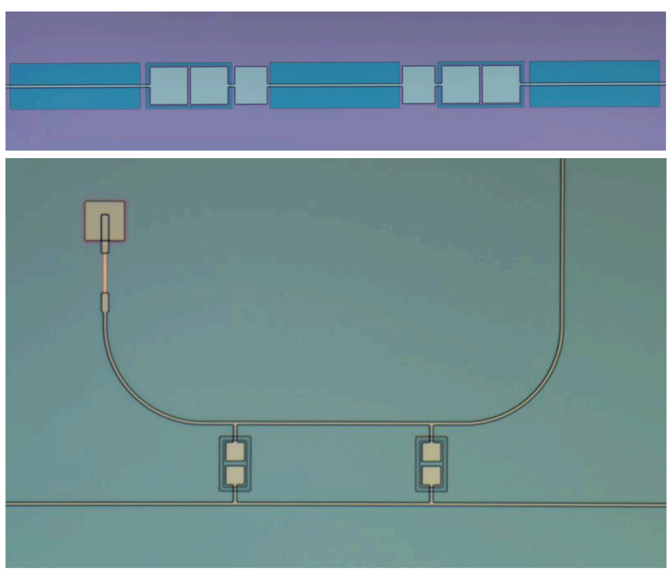


Ansys Maxwell – simulated inductance / capacitance of SLUG loop

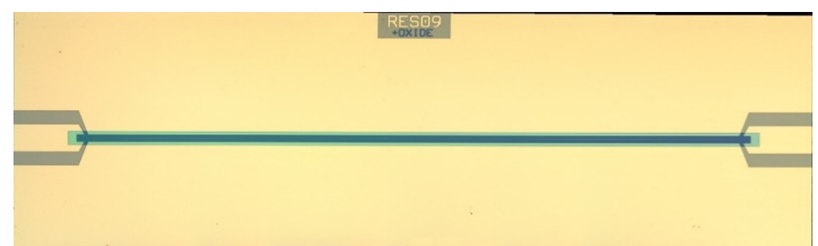


Python – simulated frequency-dependent gain of SLUG amplifier





Filter, directional coupler



Resonator paramp. ~20dB gain at frequencies up to 18GHz.

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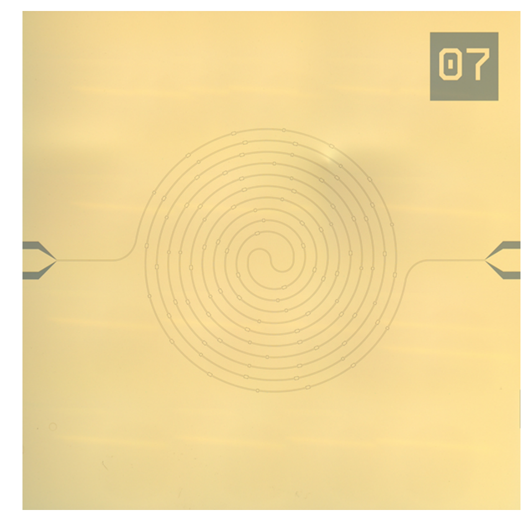

Traveling wave paramp.

Energy measurement / photon counting technologies

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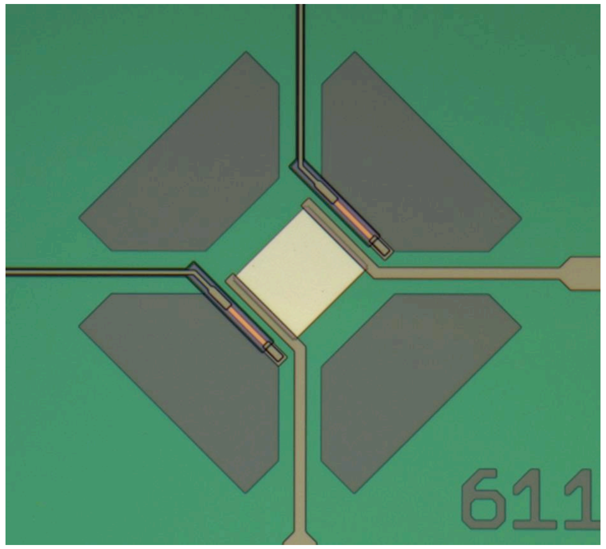
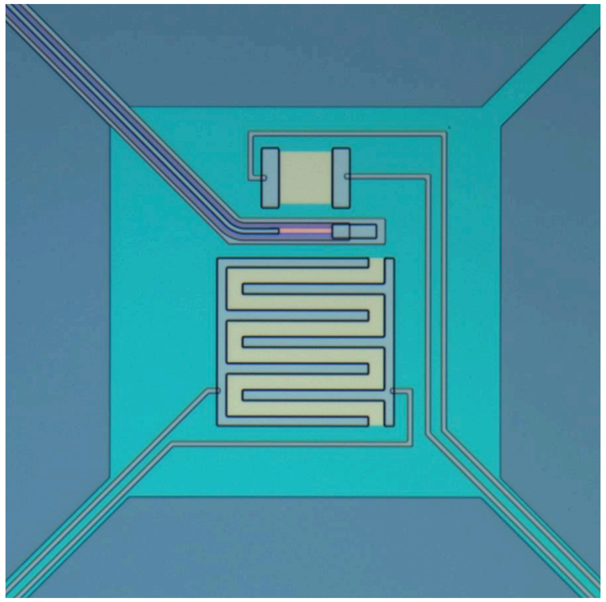


Microstrip coupled transition



Two microstrip channel

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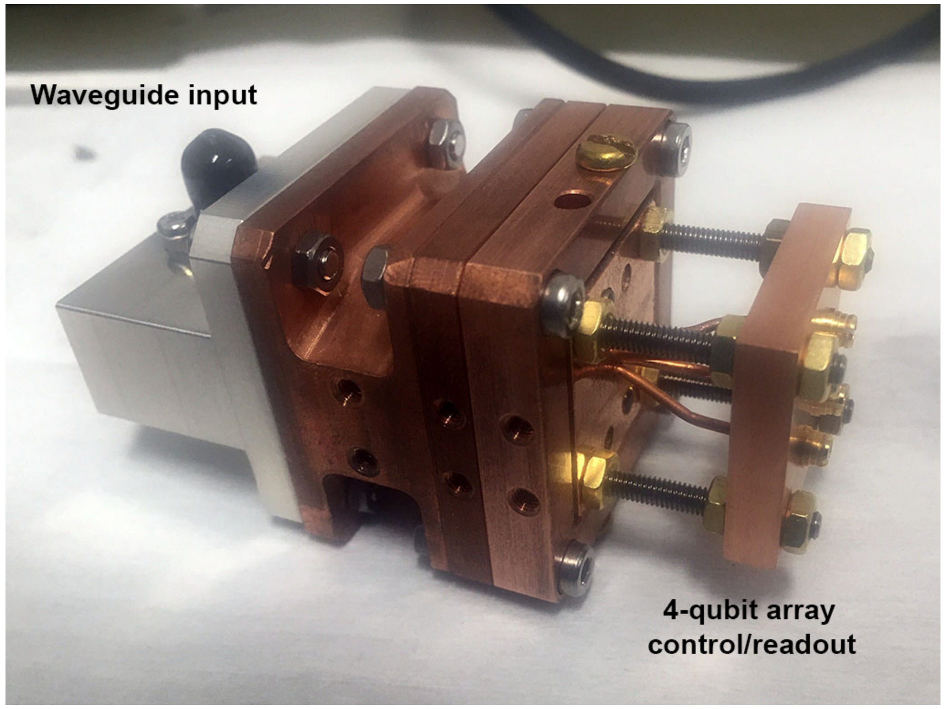
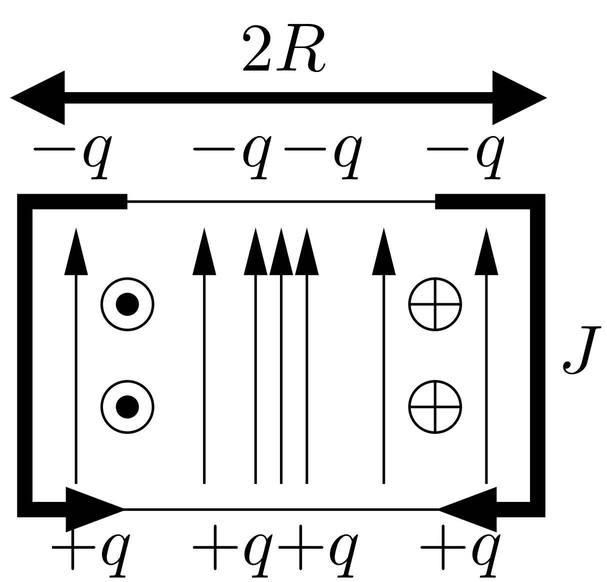
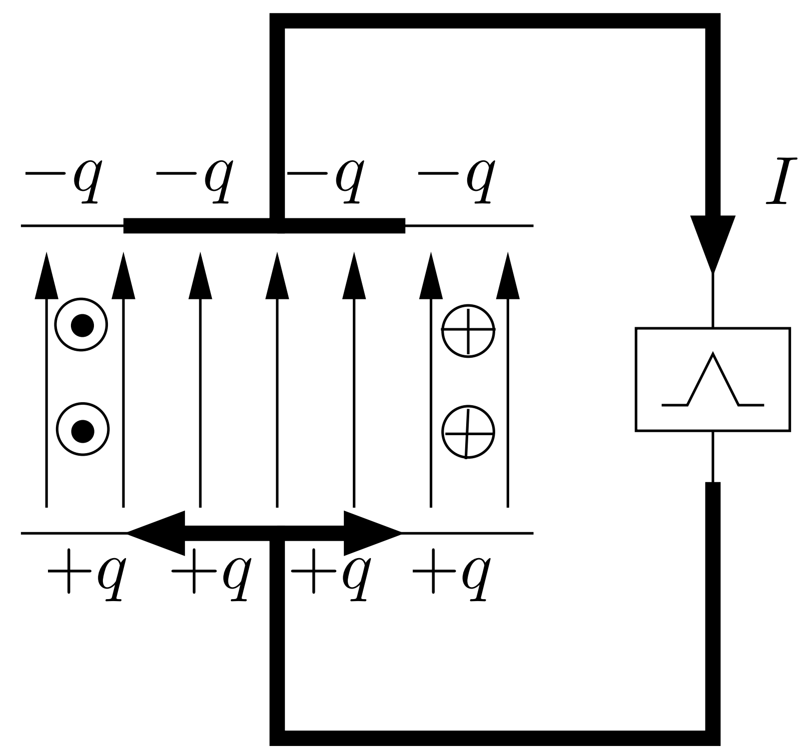


Resonant feedback concept

Cavity

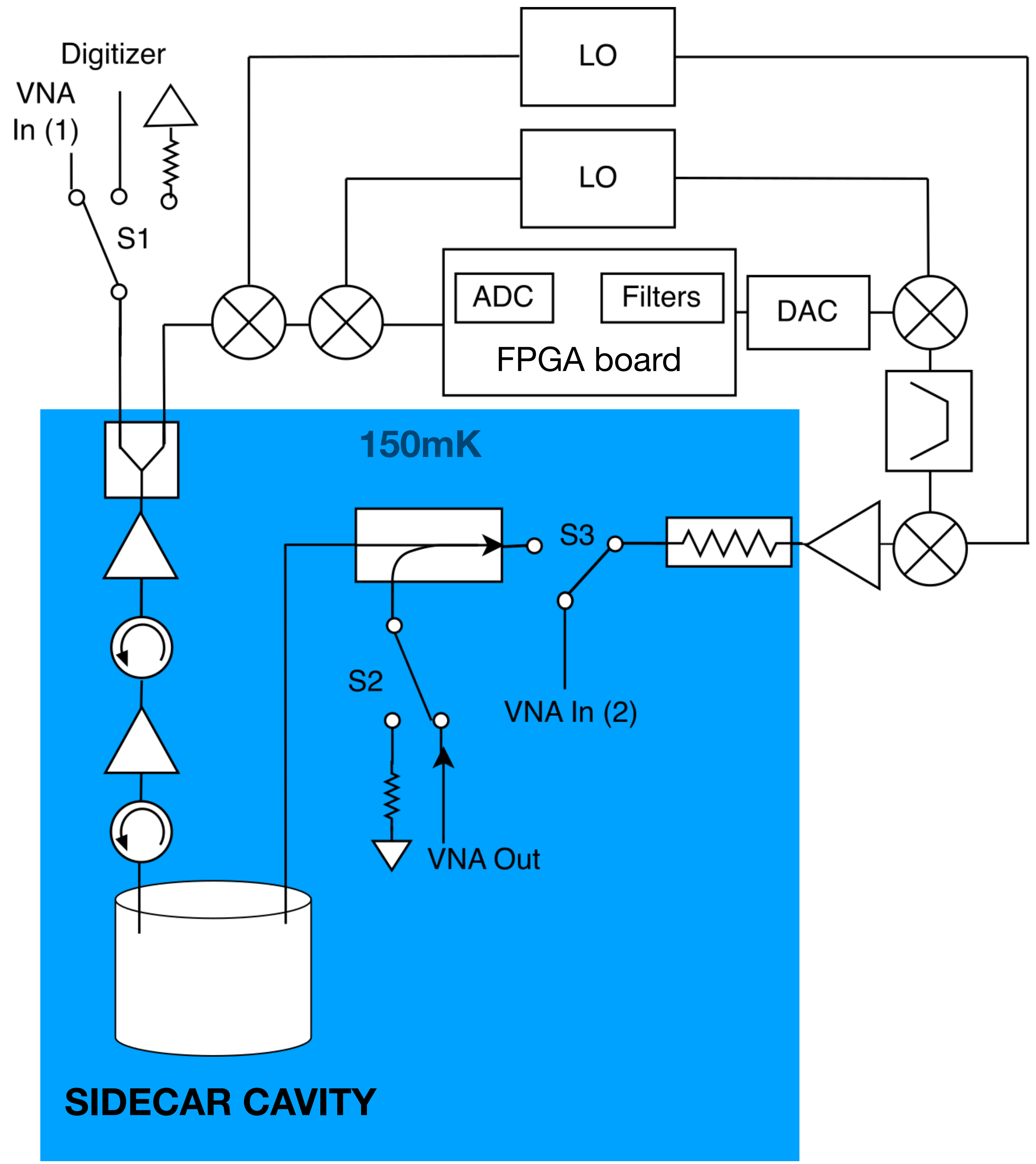


Resonant feedback

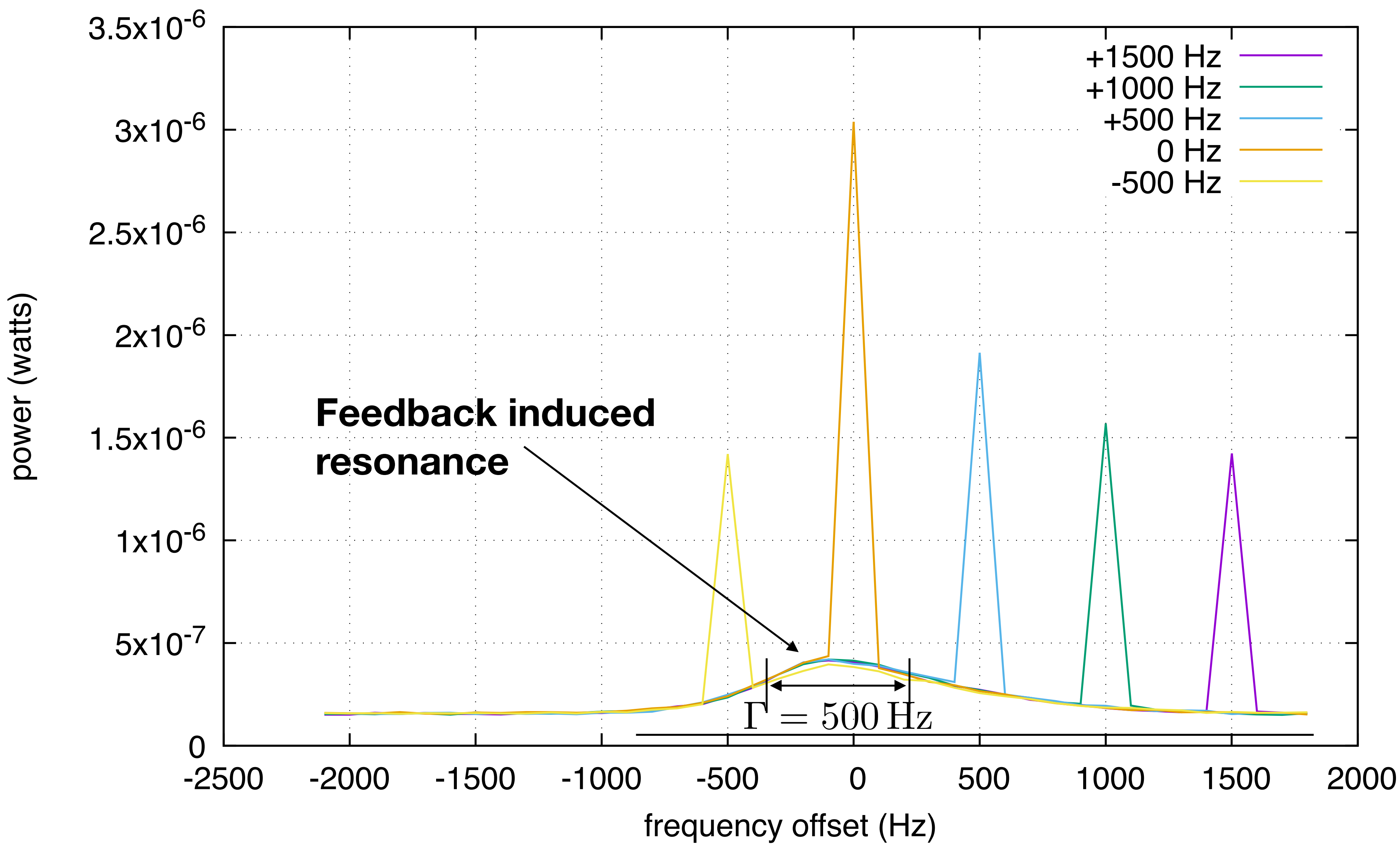


Nuclear Inst. and Methods in Physics Research, A, Volume 921, p. 50-56.
https://arxiv.org/abs/1805.11523

Cryogenic Test at ADMX



Closed loop power spectra with an injected sine wave



Peaks at 5 injection frequencies. All signals were injected at the same power level.

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

Note that the power level induced by the injected signal is enhanced in the vicinity of the induced resonance, exactly as we see for natural cavity resonances

Research Programme

- Acquire the world's largest B^2V magnet for hidden sector searches.
- Advance Hidden sector theory/phenomenology.
- Collaborate with ADMX on cavity design, analysis...
  - ✦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.
- Propose high-field low-temperature facility exploiting UK infrastructure.
- First science data from UK target.
- Further investigation of the resonant feedback concept in the new test stand.
- Exploit ongoing major investments by funding agencies in R&D on quantum devices.

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