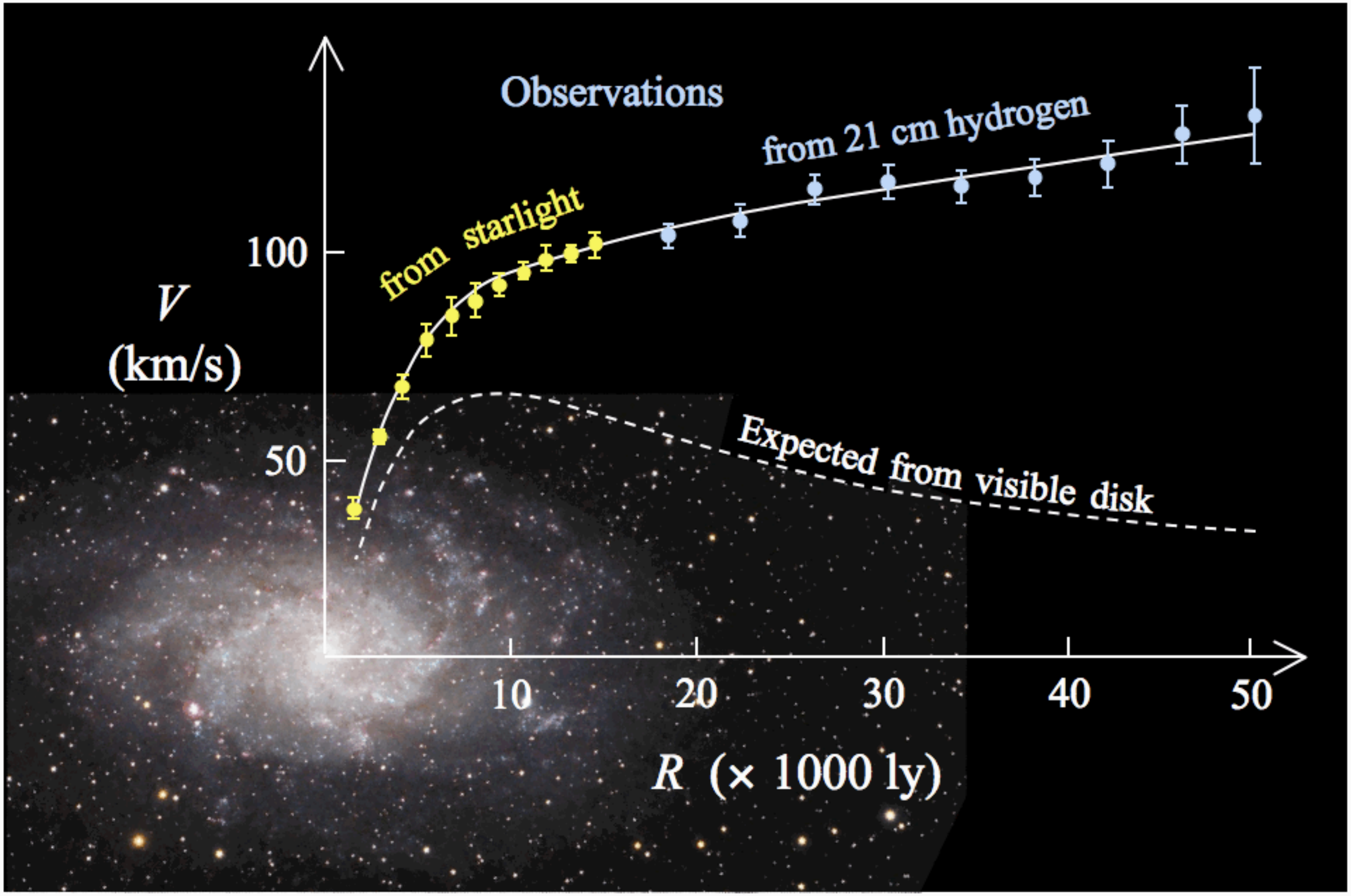
Quantum Sensors for the Hidden Sector

NYCREATES 4th November 2021

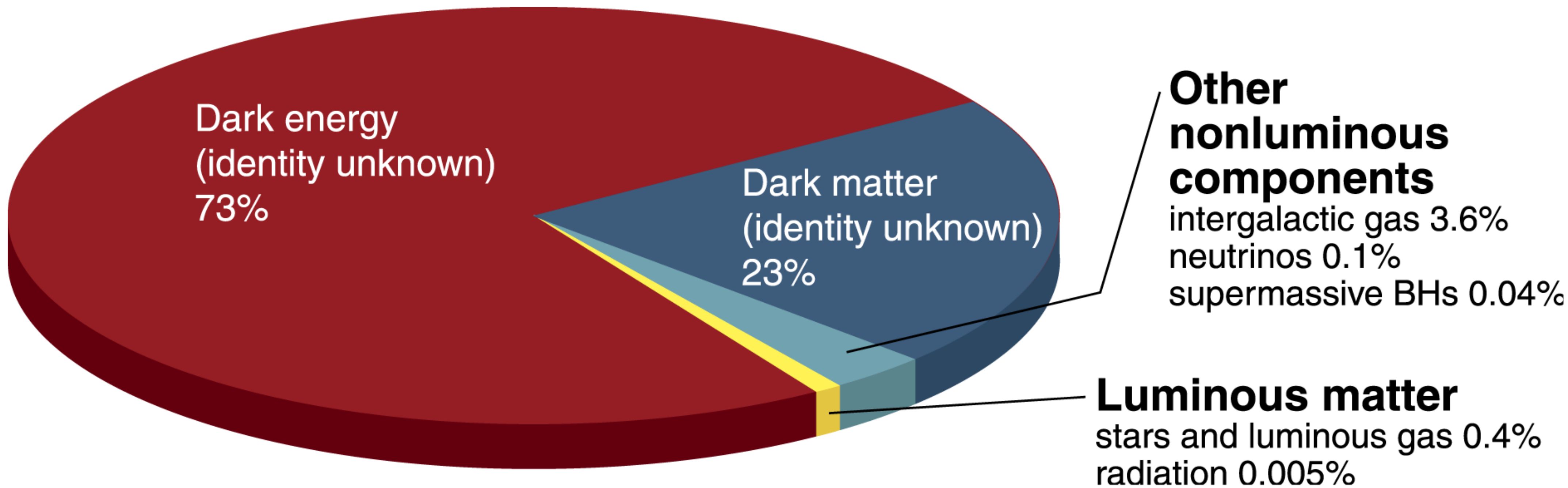
Ed Daw, The University of Sheffield, for the
Quantum Sensors for the Hidden Sector Collaboration

Galactic dark matter problem



M33 https://en.wikipedia.org/wiki/Galaxy_rotation_curve

Inventory of the Cosmos



Science (20 June 2003)

… but we know neither what the "dark energy" or the "dark matter" is. These are two of the most needling questions in modern astrophysics and cosmology.

Axions and the Strong CP problem

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

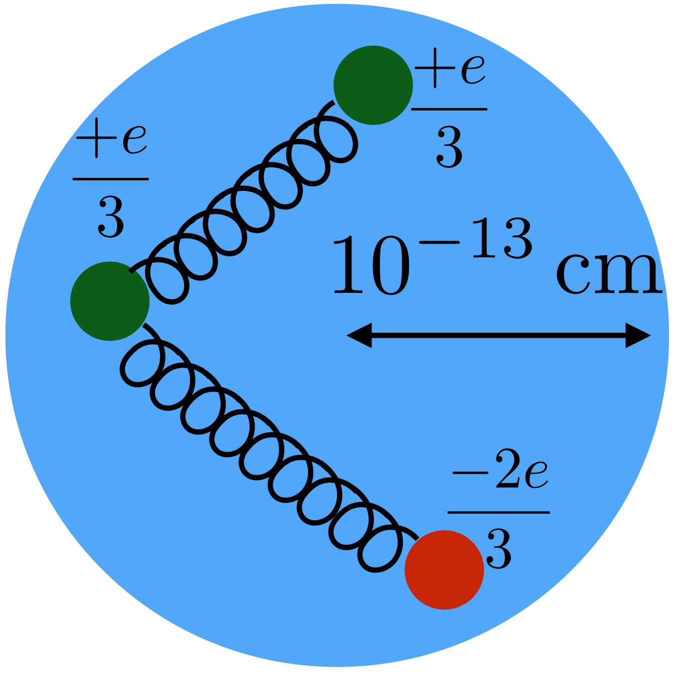
$$\mathcal{L}_{\mathrm{CPV}} = \frac{(\Theta + \arg\det M)}{32\pi^2} \vec{E}_{\mathrm{QCD}} \cdot \vec{B}_{\mathrm{QCD}}$$

SU(3)	SU(2)	U(1)
NON-ABELIAN	NON-ABELIAN	ABELIAN
CP CONSERVING!	CP VIOLATING	CP CONSERVING

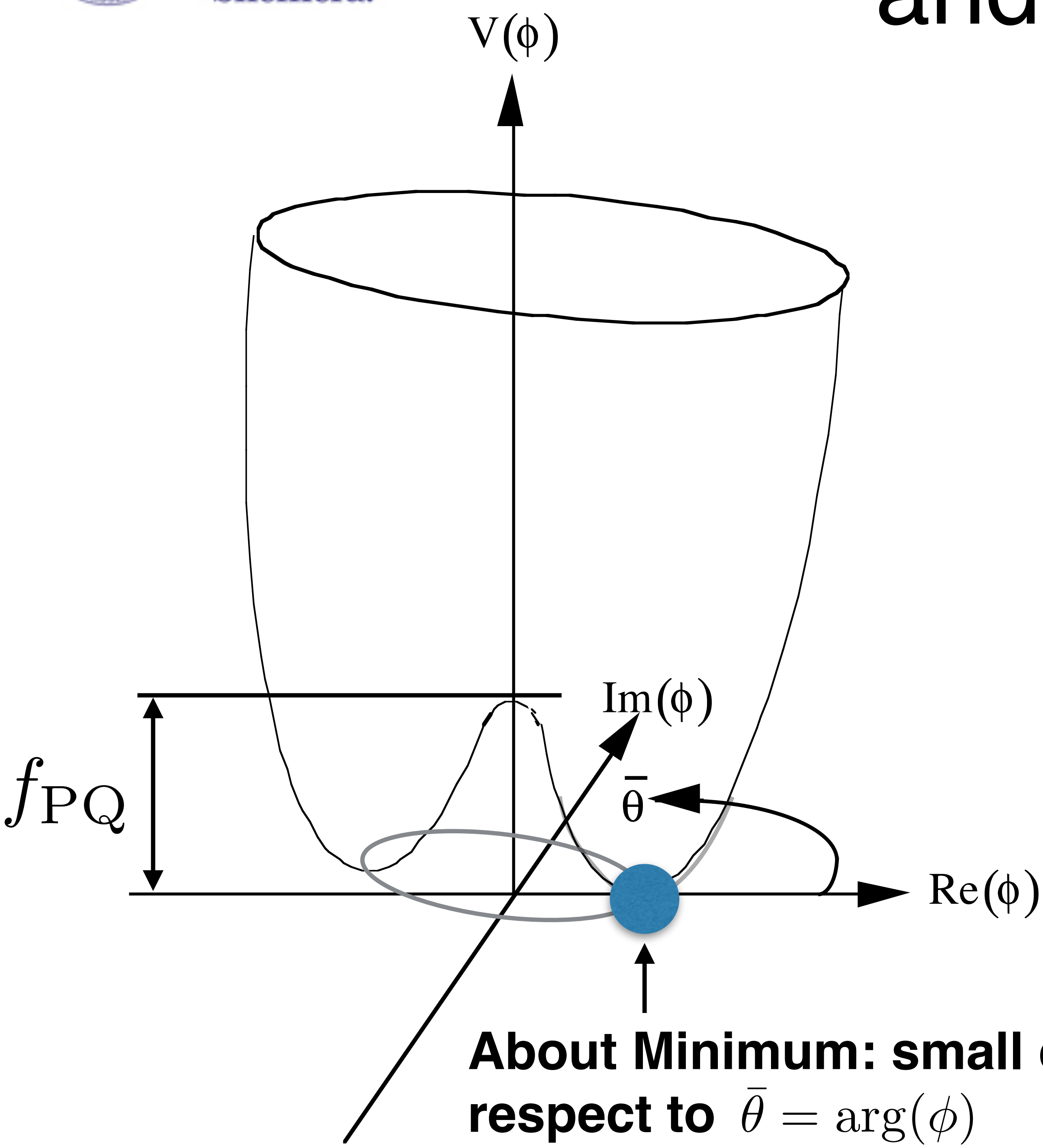
Evidence for CP conservation in the SU(3) strong interactions from multiple measurements of neutron and nuclear electric dipole moments. For example, neutron EDM < 10^{-26} e-cm.

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



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

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

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

Axion DOF

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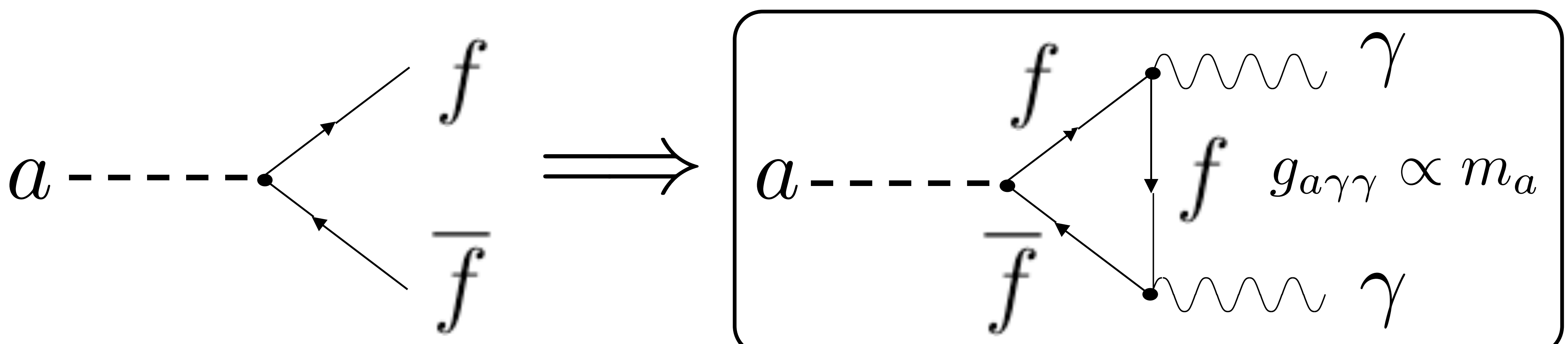
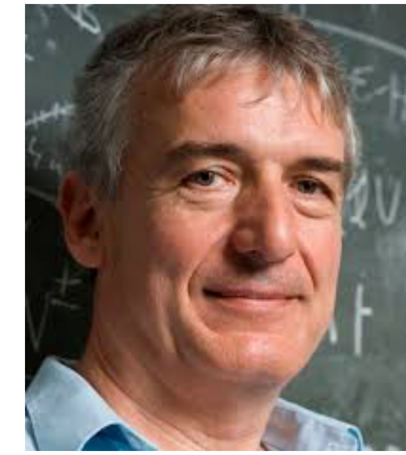
Axion Phenomenology

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

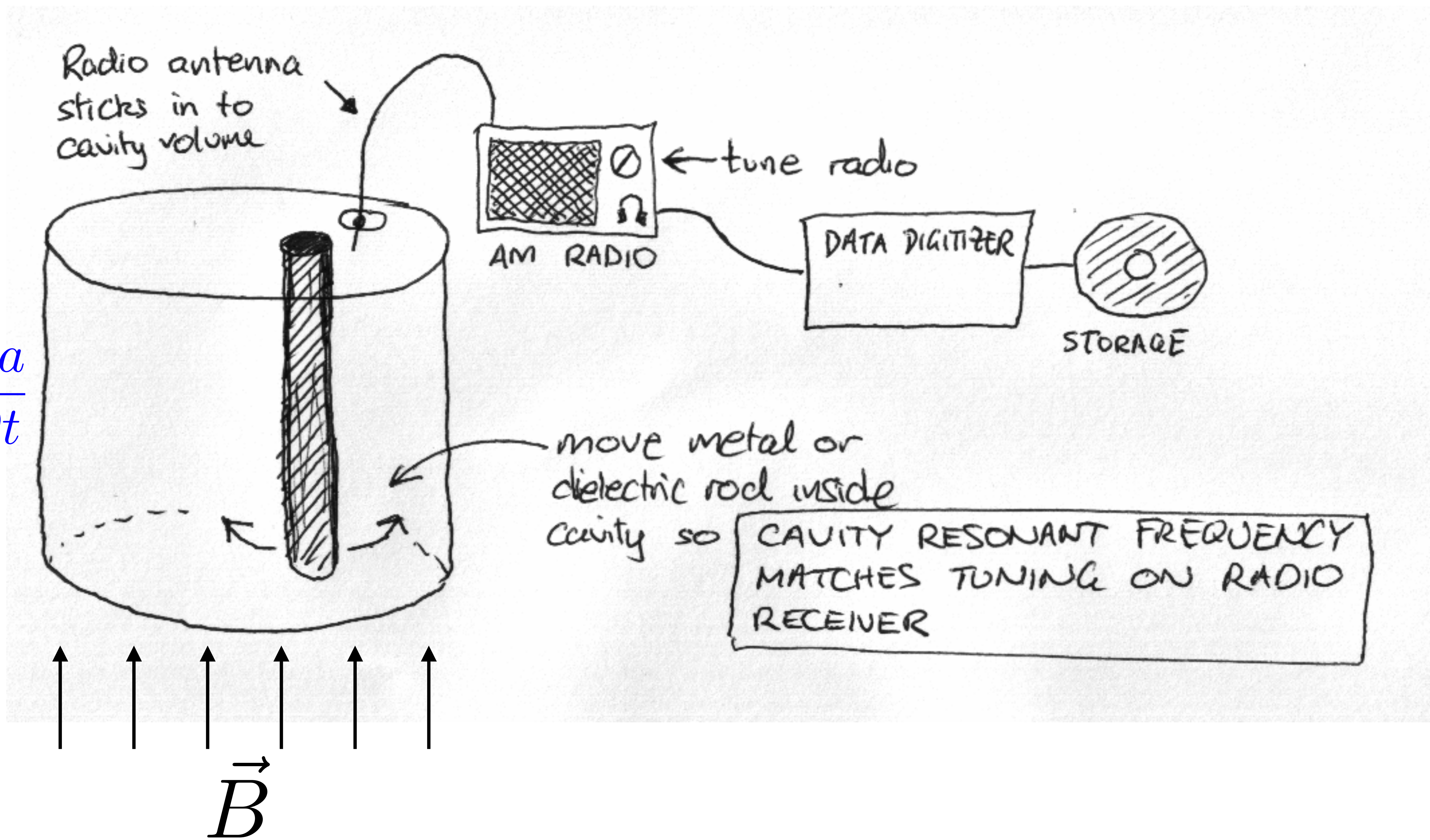
$$f_{\mathrm{PQ}} \sim 10^{13}\,\mathrm{GeV}\left(\frac{3\,\mu\mathrm{eV}}{\mathrm{m_a}}\right) \qquad \Omega_{PQ} \propto \frac{1}{m_a^{\frac{7}{6}}}$$



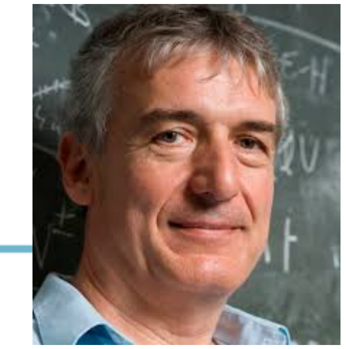
Sikivie-Type Resonant Cavity Axion Search

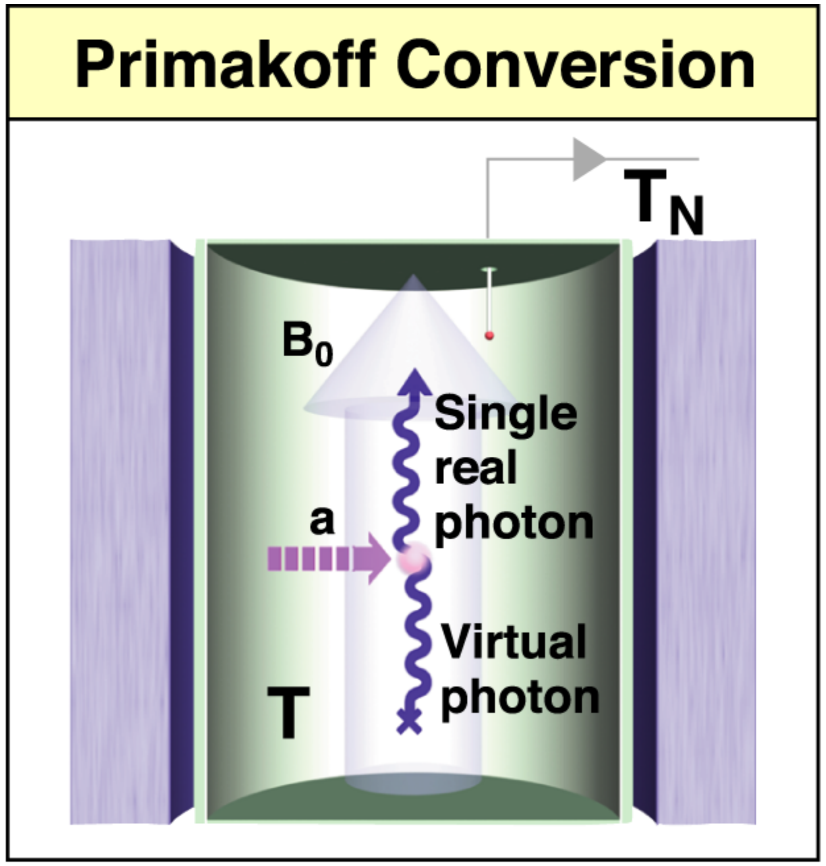


$$\vec{E}_a = g\vec{B}\frac{\partial a}{\partial t}$$



Some experimental details of the Sikivie RF-cavity technique





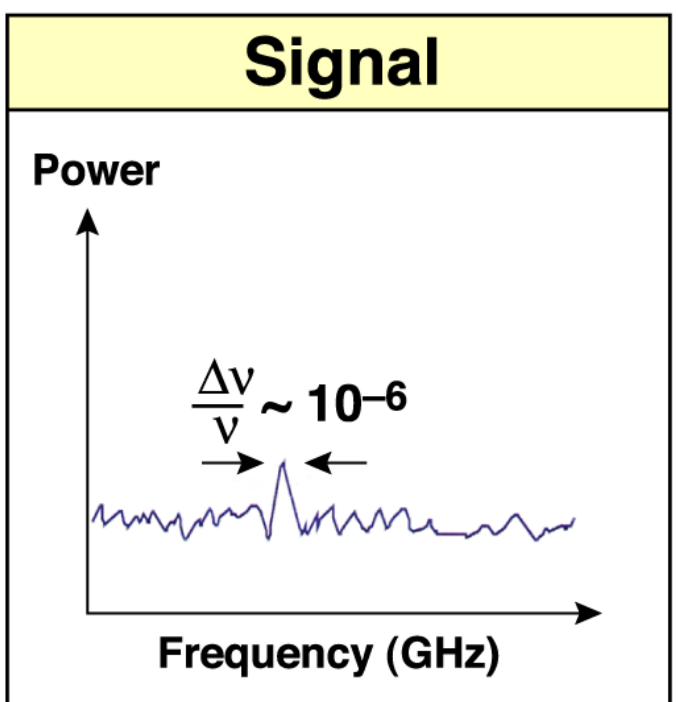
- **The conversion is resonant, i.e. the frequency must equal the mass + K. E.**
- **The total system noise temperature $T_S = T + T_N$ is the critical factor**

Currently $T + T_N$ = 150mK + 150mK = 300mK

Signal to noise ratio: the ratio of the signal power to the size of the bin-to-bin fluctuations in noise power

Radiometer Equation (Gibbs 1902)

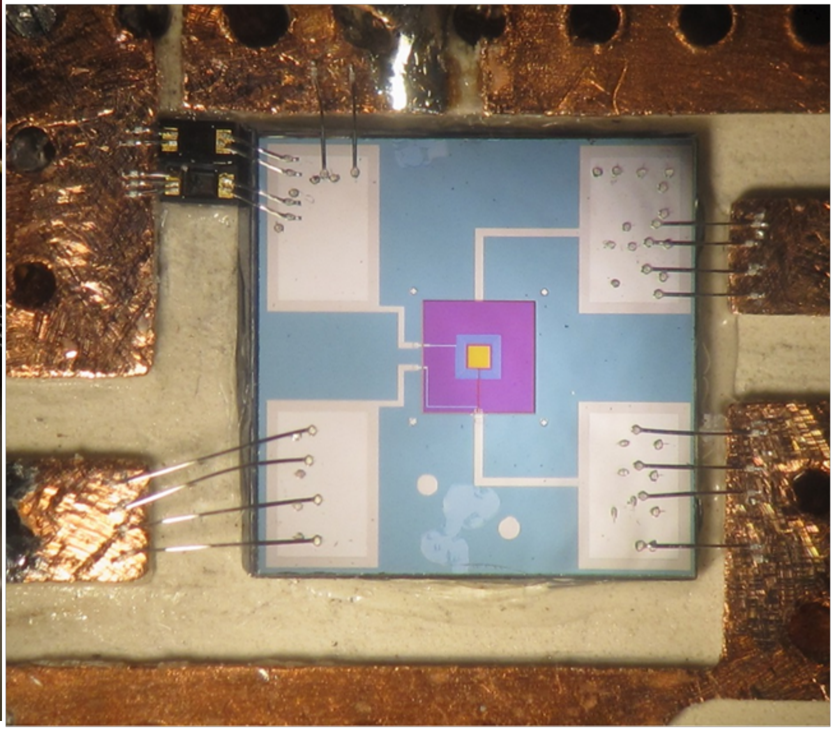
$$\mathrm{SNR} = \frac{P_s}{\sigma_{PN}} = \frac{P_s}{P_n}\sqrt{\Delta\nu\, t}$$



For DFSZ axion, ~1000 seconds per tuning rod position to achieve SNR of 4.

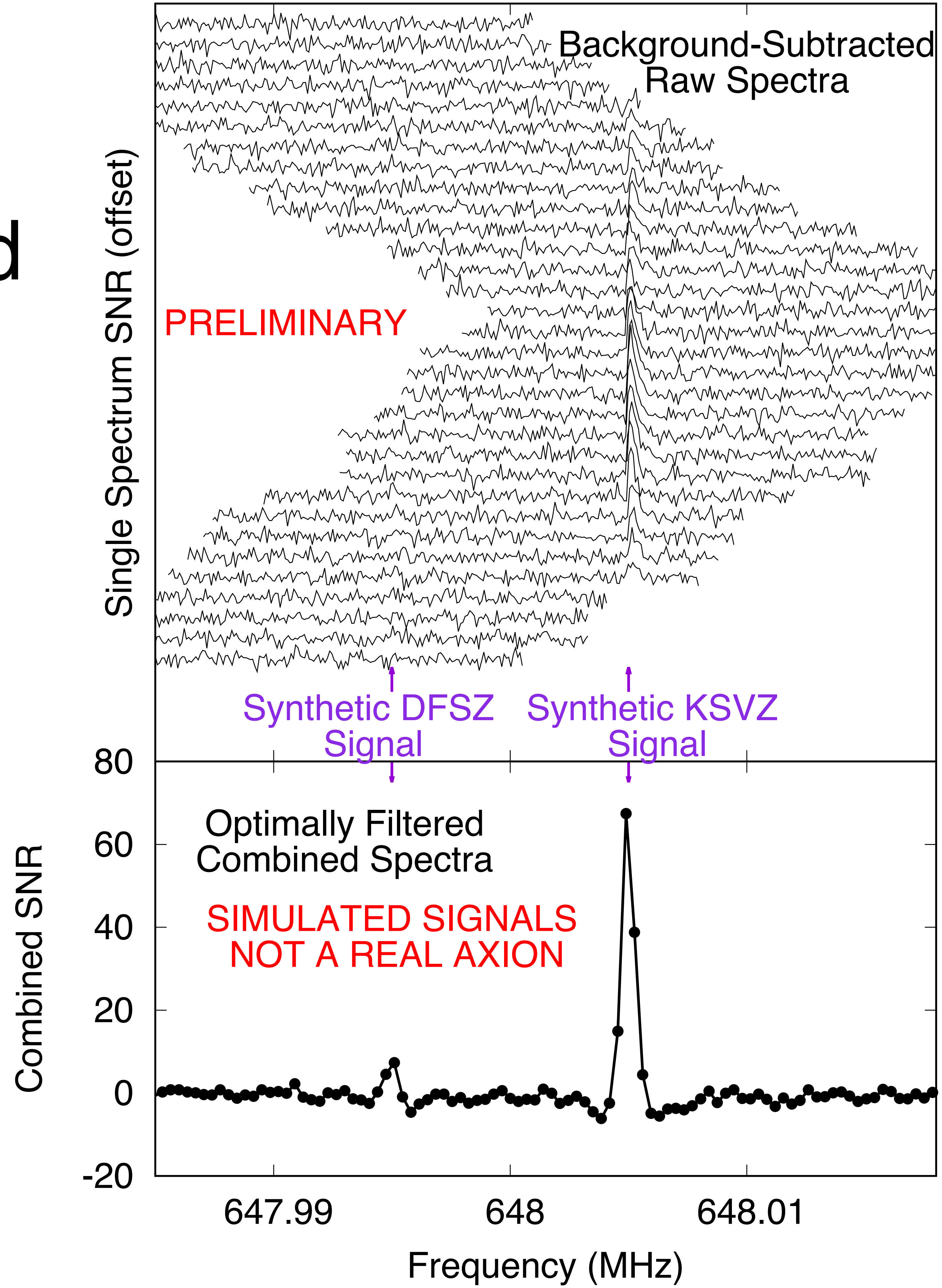
ADMX experiment

50cm

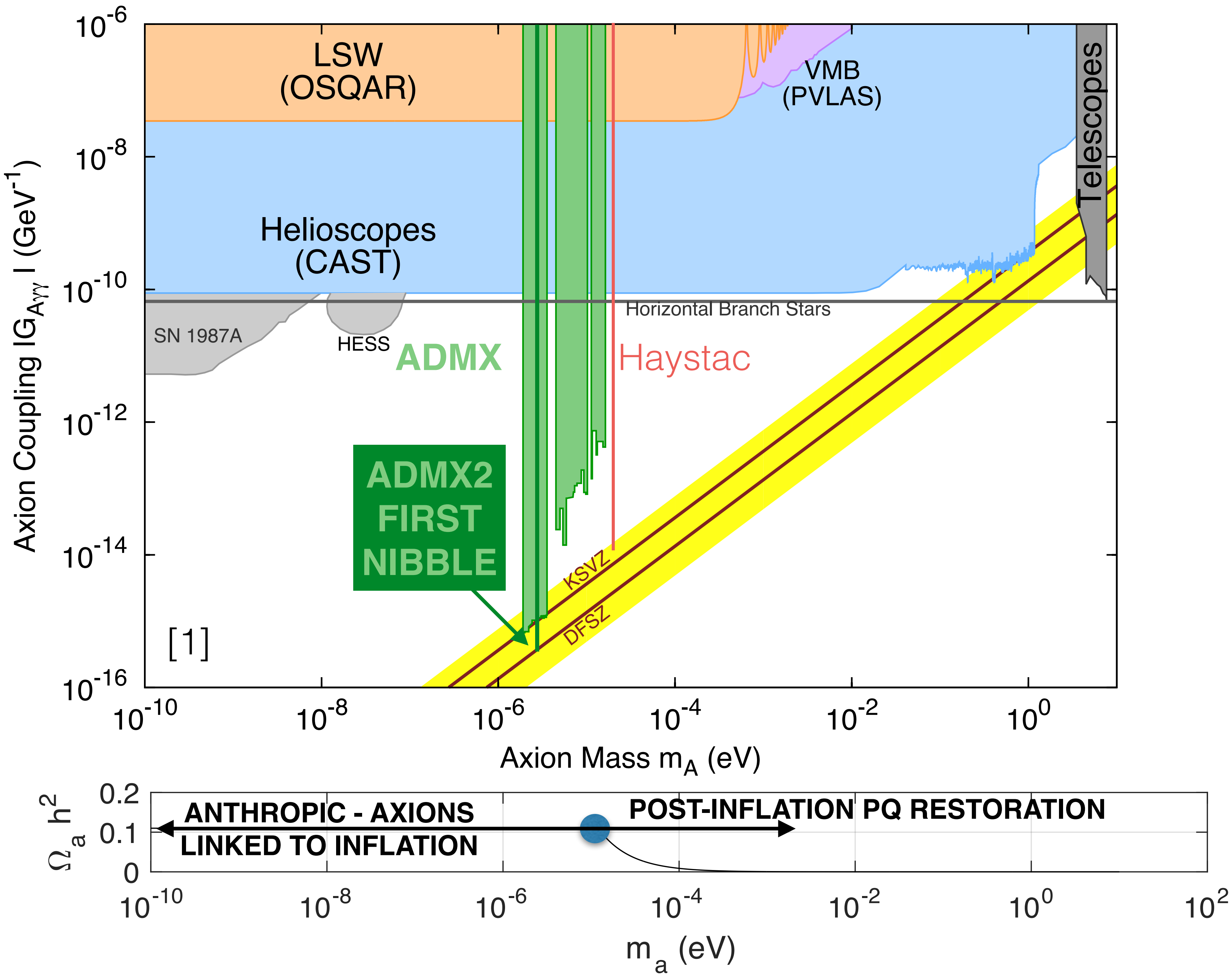


Microwave Squid Amplifier (MSA)

Calculated Signal Strengths in ADMX2

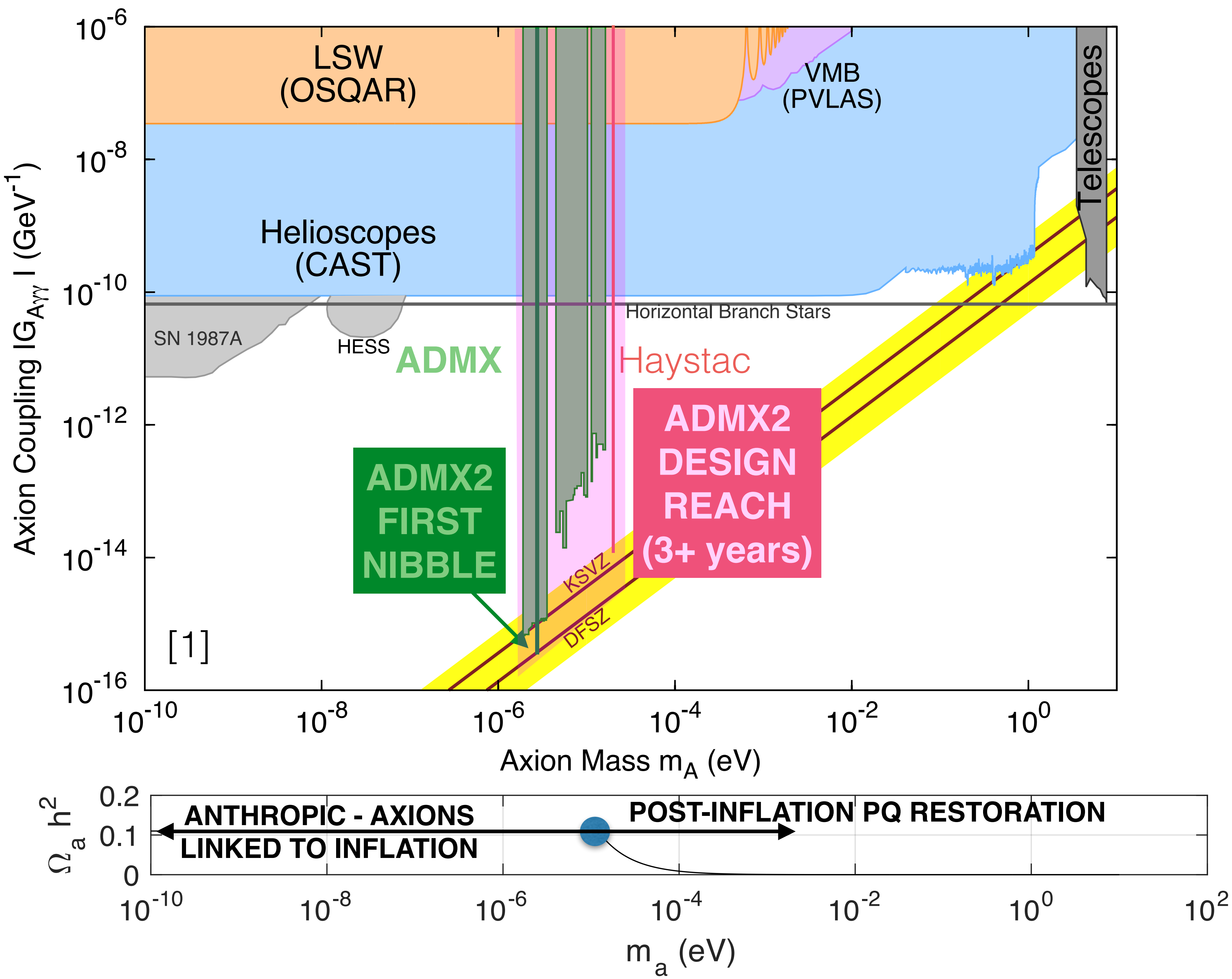


Recent Results from ADMX



[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,

Planned ADMX2 Reach



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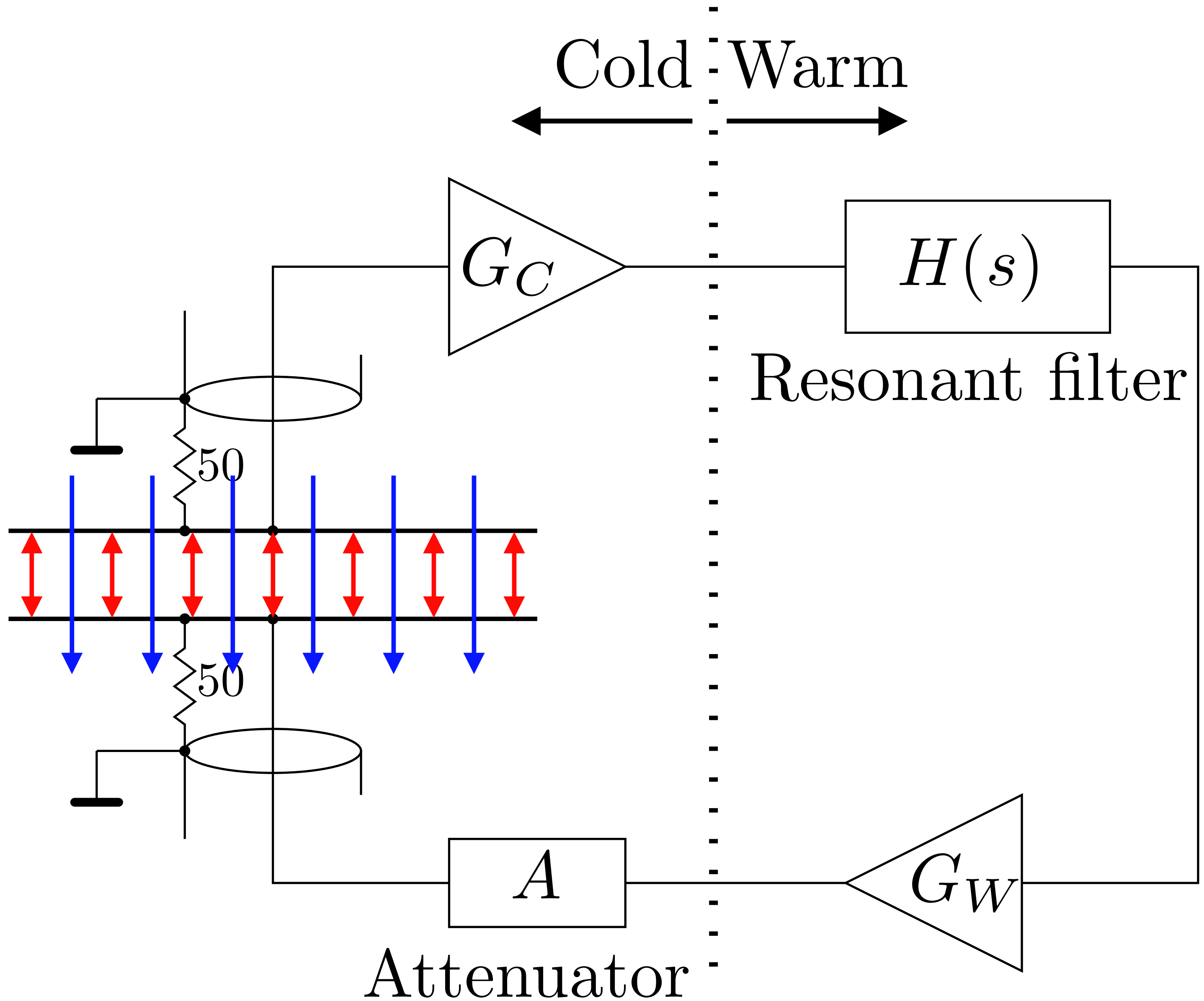
2016 revision by A. Ringwald, L. Rosenberg, G. Rybka,

A practical resonant feedback circuit

Courtesy of Holger Notzel,
www.kometamps.com

Feedback resonance

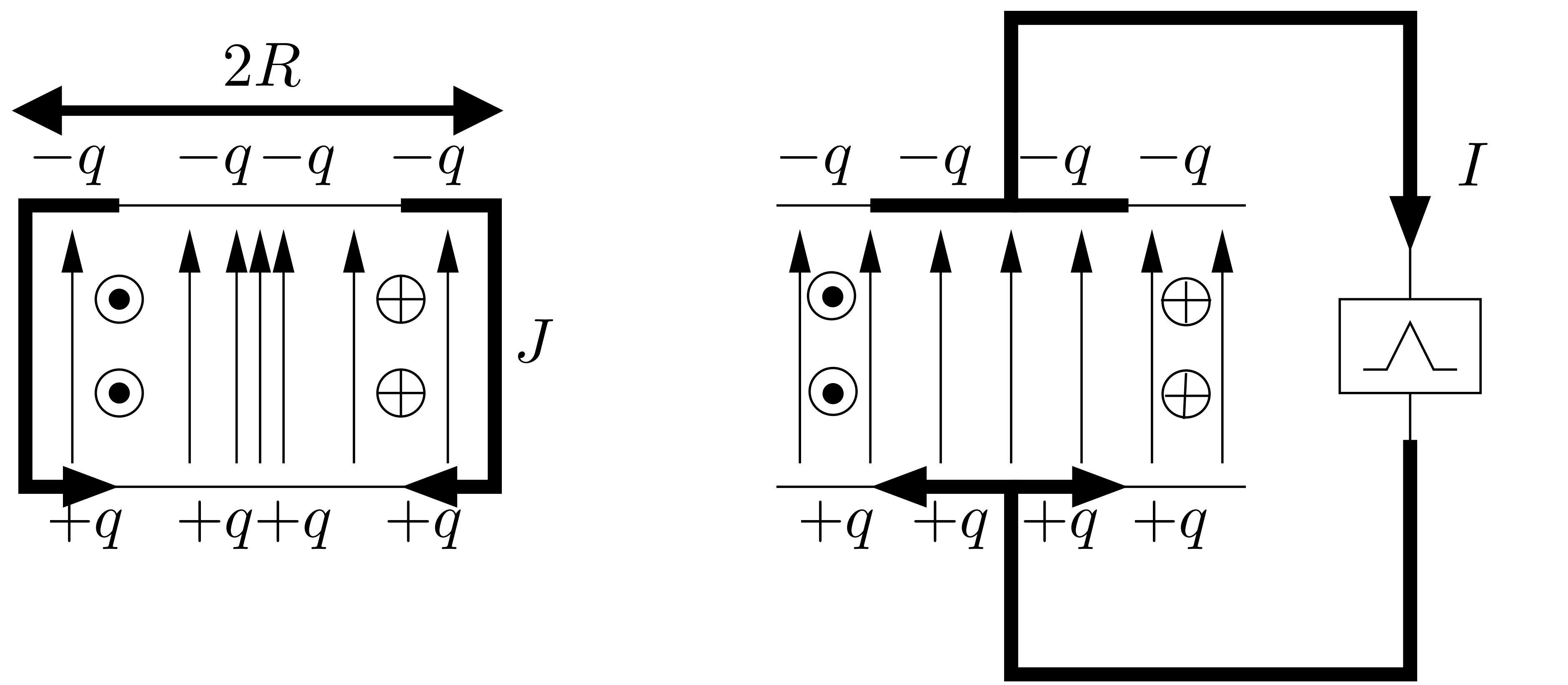


Maintain open-loop gain at <1 so the circuit doesn't start to oscillate by using a suitably large attenuator.

https://arxiv.org/abs/1805.11523

Is resonant feedback through a circuit equivalent to a cavity resonance ?

The answer is, not quite - but close enough for practical purposes.

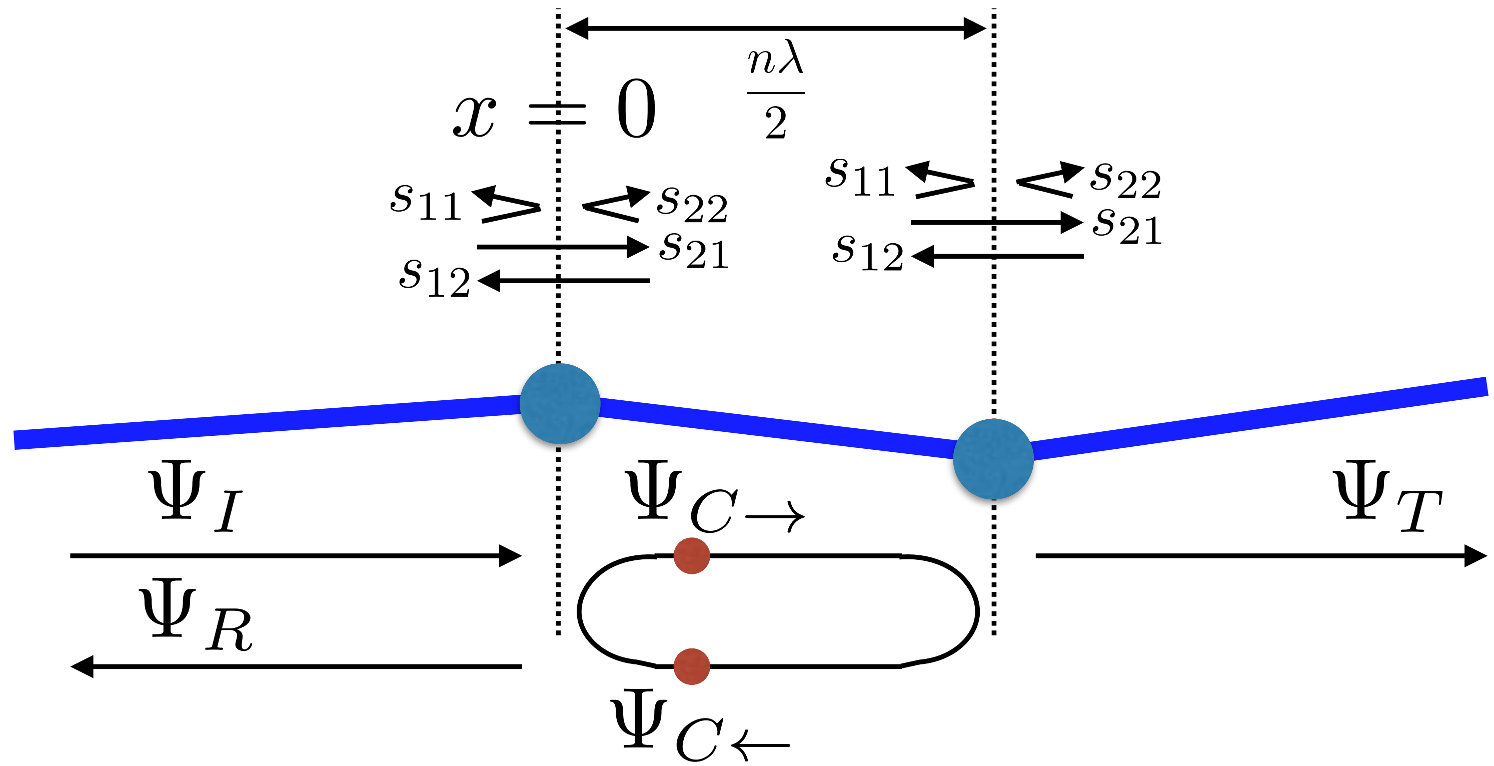


Cavity TM_{010} mode   Resonant feedback

Cavity Mode: currents in walls complete resonant circuit.

Capacitor+feedback: feedback loop completes circuit.

What is resonance?



1.) Resonance results when the circulating field, in this case between the masses, interferes constructively with itself around on a round-trip.

2.) For an incident field to drive the resonance to high amplitude, it must be coherent over multiple round trips of the circulating field, and losses around the loop must be small.

Cavity mode circulating field decomposition

Electric fields in the cavity TM_{010} mode are usually written

$$E(\rho, t) = E_0 J_0 \left(\frac{2.405\rho}{R} \right) \cos(\omega t)$$

This 'drum mode' standing wave can be re-cast in terms of counter-propagating travelling waves that move radial-cylindrically inwards and outwards, through the central axis, then bounce off the circular cavity wall, back through the axis, bounce off the opposite wall, and return again to the axis.

$$E(\rho, t) = \frac{E_0}{2} \Re \left\{ \left[H_0^{(1)} \left(\frac{2.405\rho}{R} \right) + H_0^{(2)} \left(\frac{2.405\rho}{R} \right) \right] e^{-i\omega t} \right\}$$

Propagating: **radially-outwards** **radially-inwards**

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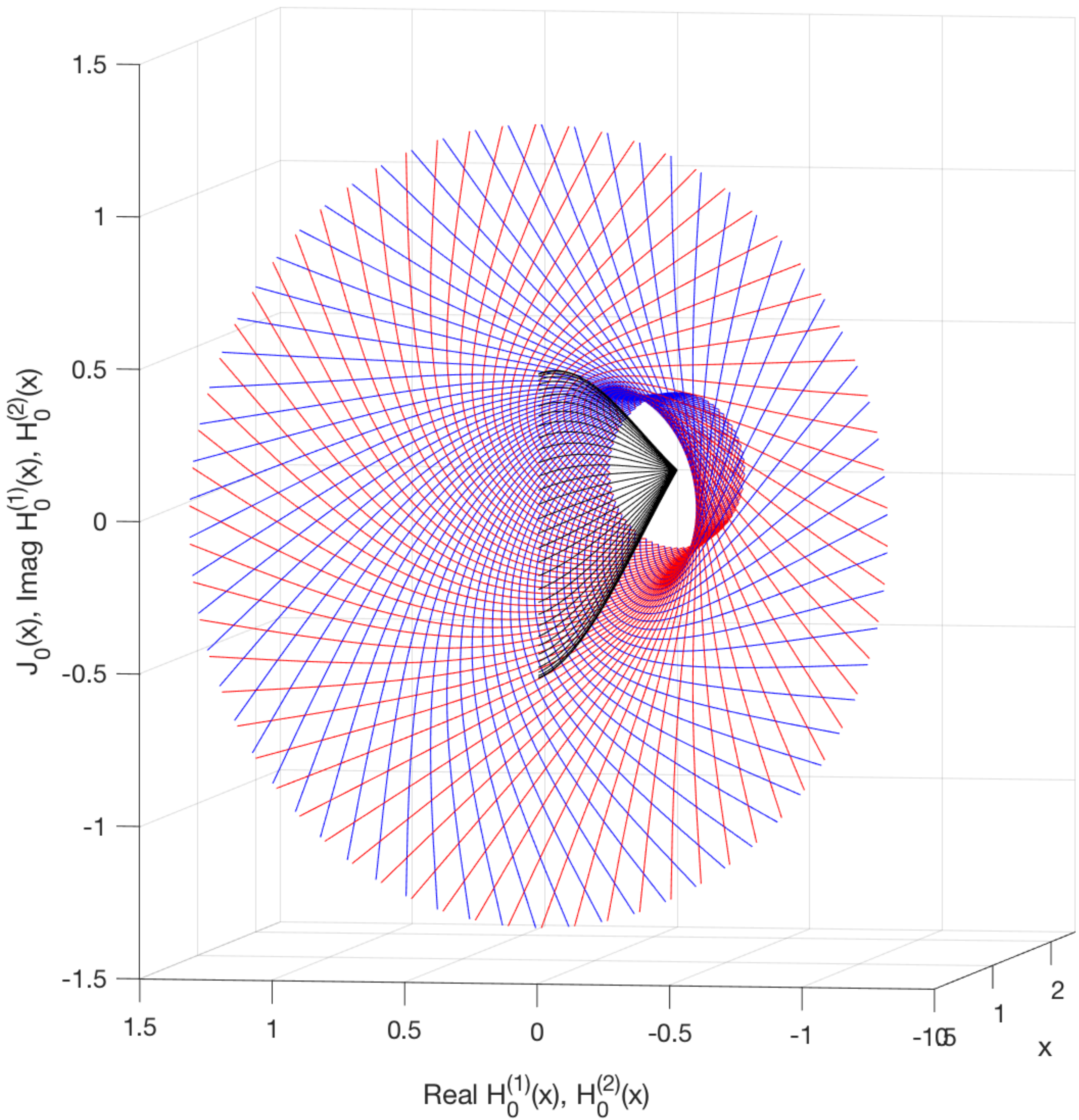

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Axion signal driving a cavity resonance

De Broglie wavelength of halo axions (assuming 1.8 microelectronvolts), $\lambda = \frac{2\pi\hbar c}{\beta m c^2} \simeq 830\,\mathrm{m}$

so the coherence time is $\tau_{\mathrm{coh}} = \frac{\lambda}{v_0} \simeq 3.4\,\mathrm{ms}$

Round trip time of a circulating field around the loop is 4R/c, which is 3.4ns.

Therefore within the coherence time the circulating fields from axions can make a million round trips. The fundamental upper limit on resonant enhancement of the cavity signal in this cavity mode is

axion intrinsic Q= $\pi N_{\mathrm{cav}} = 3.1 \times 10^6$

In practice, losses in the copper walls on reflection dominate, and the cavity mode Q is around 35,000.

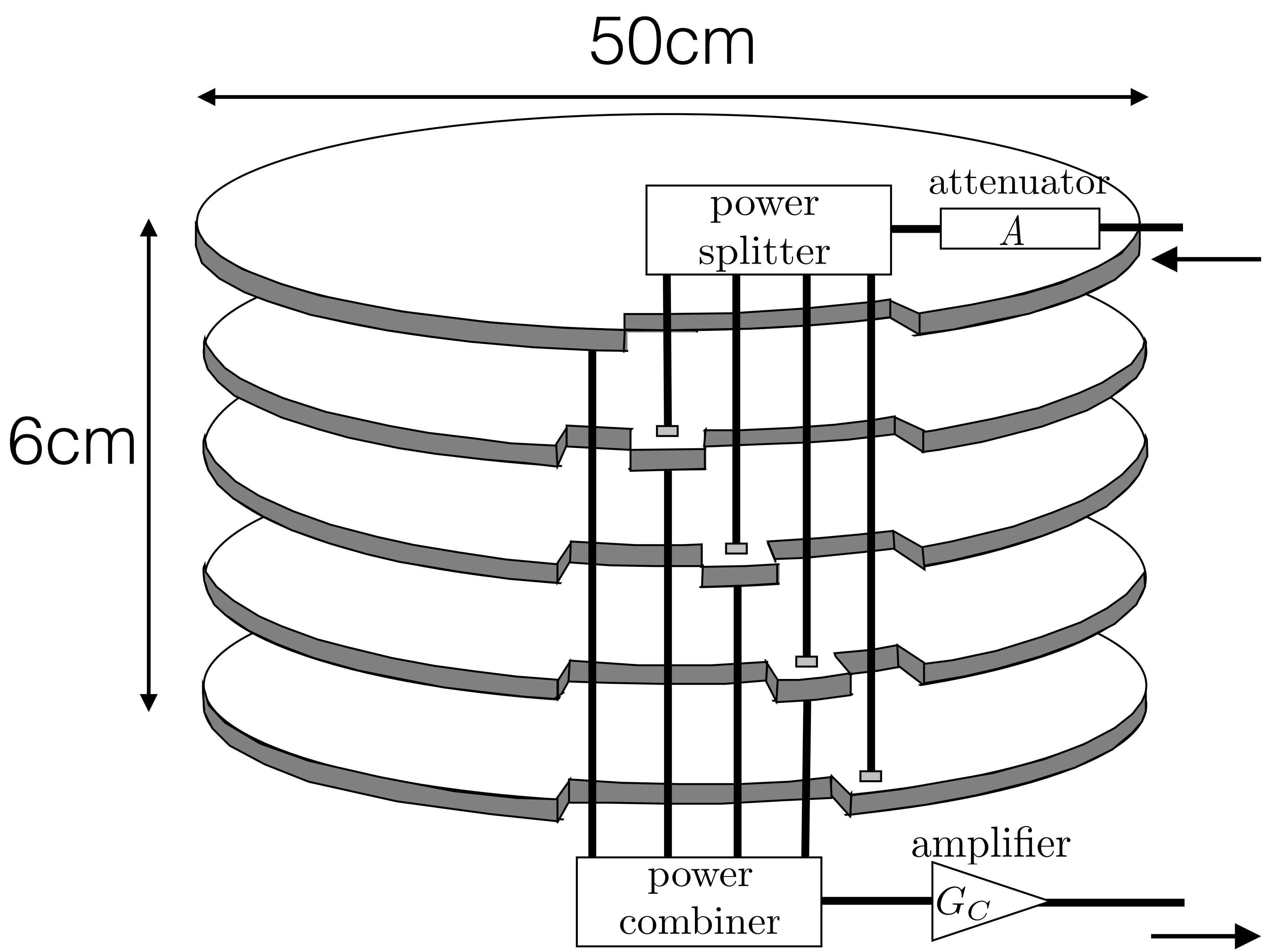
Coherence time and Q of axion-driven feedback circuit

Assume feedback loop involves 20m of RG401 coax and a 250MHz ADC/DAC pair, the total delay time round the loop is 103 ns (dominated by the cable). This means the 34,000 cycles around the feedback loop is 1 e-folding of coherence, equivalent to a Q of $\pi N_{\mathrm{coh}} = 107,000$

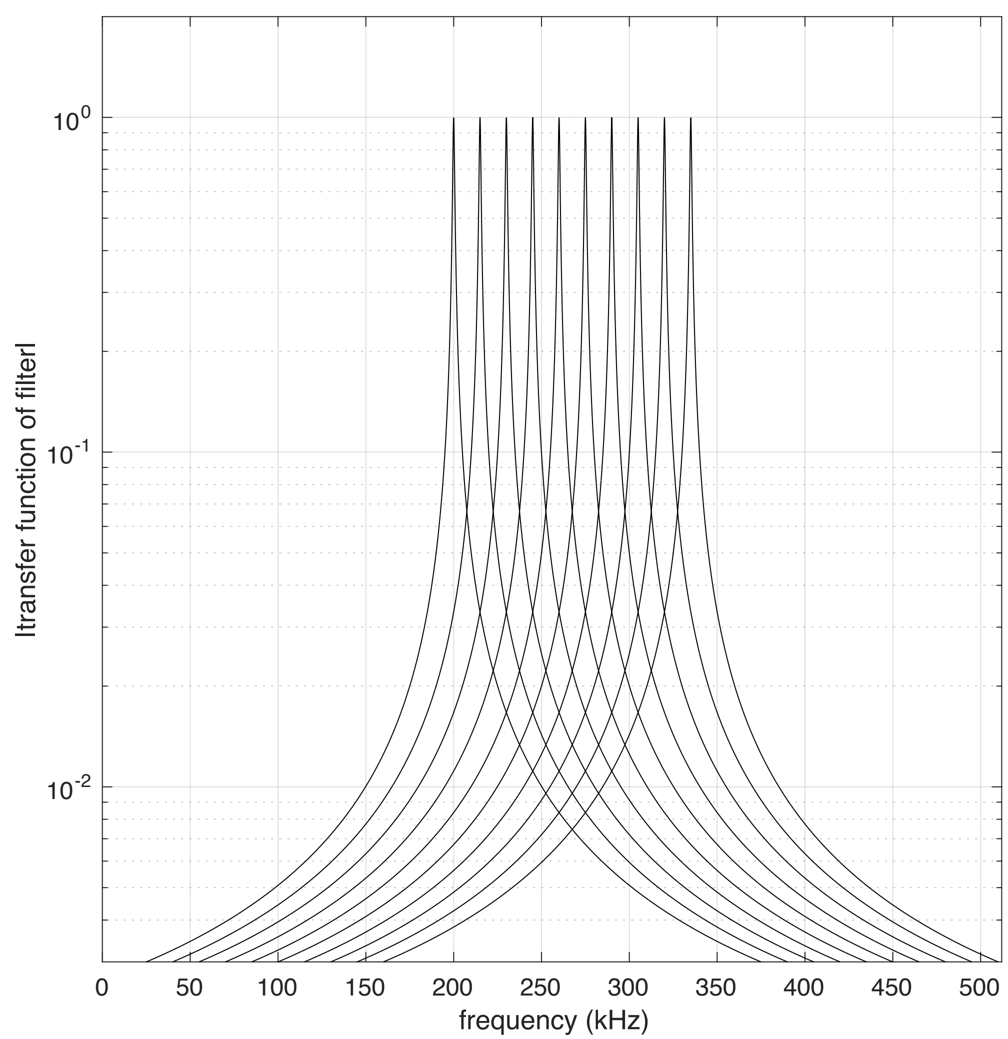
This Q is very competitive with that inherent in normal conducting cavity modes.

The equivalent here of the cavity wall losses is the Q of the external circuit, controlled by the parameters of the feedback filter. Experimental tests will inform the question of possible internal losses, but there should be no skin-depth losses at the end walls as electric fields terminate on surface charges.

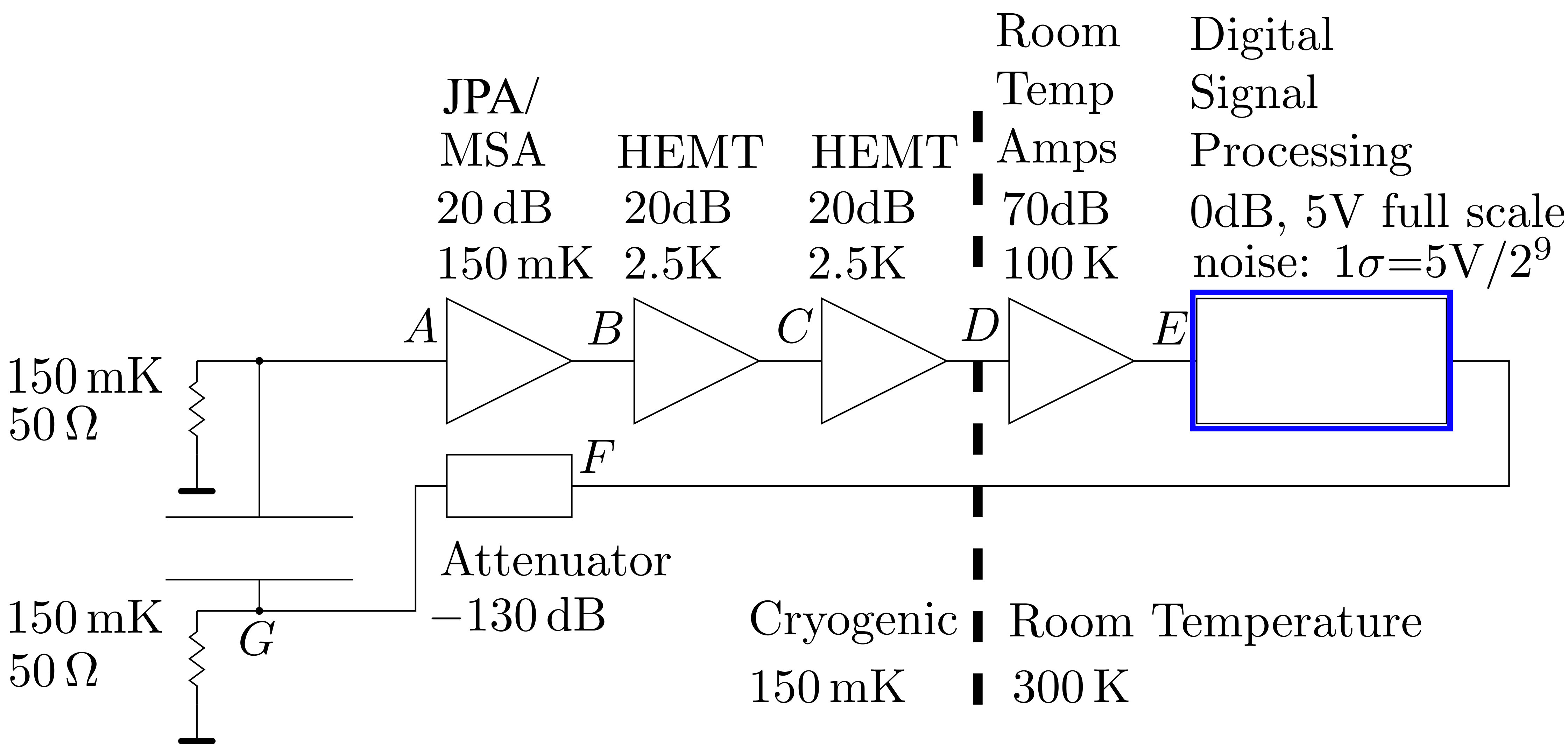
Capacitors in parallel - a prototype 4-capacitor model



Resonances in parallel



Electronics in practice



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ADMX

Total noise power

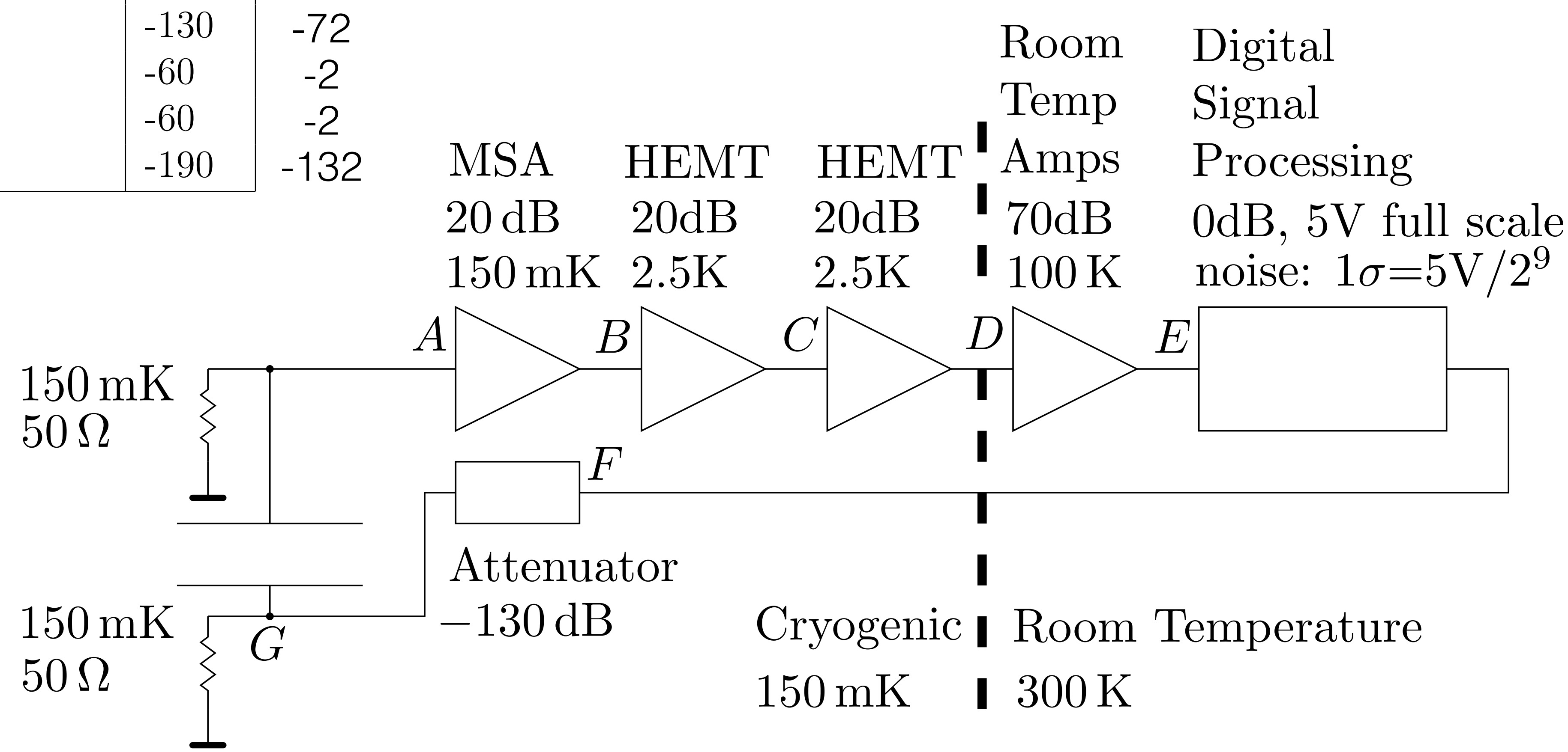
100 15kHz wide resonances, separated by 150kHz.
Q per resonance of approx 1GHz/15kHz=67000.
Total bandwidth into digital electronics 15MHz.
Noise in 15MHz band assuming system noise temperature of 300mK, -132dBm.

Total integration time for DFSZ

Assume an axion signal bandwidth of 750Hz, 300mK system noise, hence a signal-to-noise ratio of (10^{-22}W/ 3.1×10^{-21}W).DFSZ sensitivity requires an integration time of 1120s, during which we cover 1.5MHz.
2-40 micro eV corresponds to 4.34GHz bandwidth, so that the total integration time is 1120s x 4340/1.5 which is 37.5 days. This assumes a form factor of 0.4!

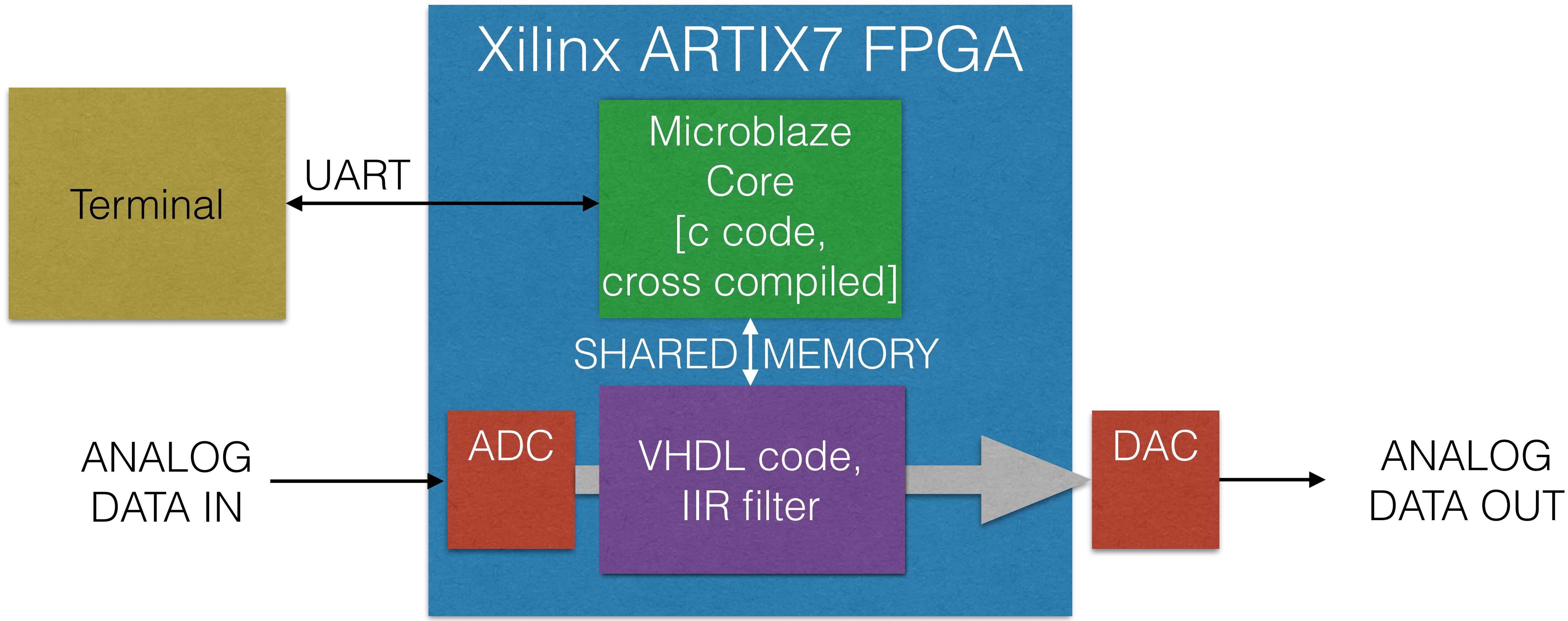
Noise budget

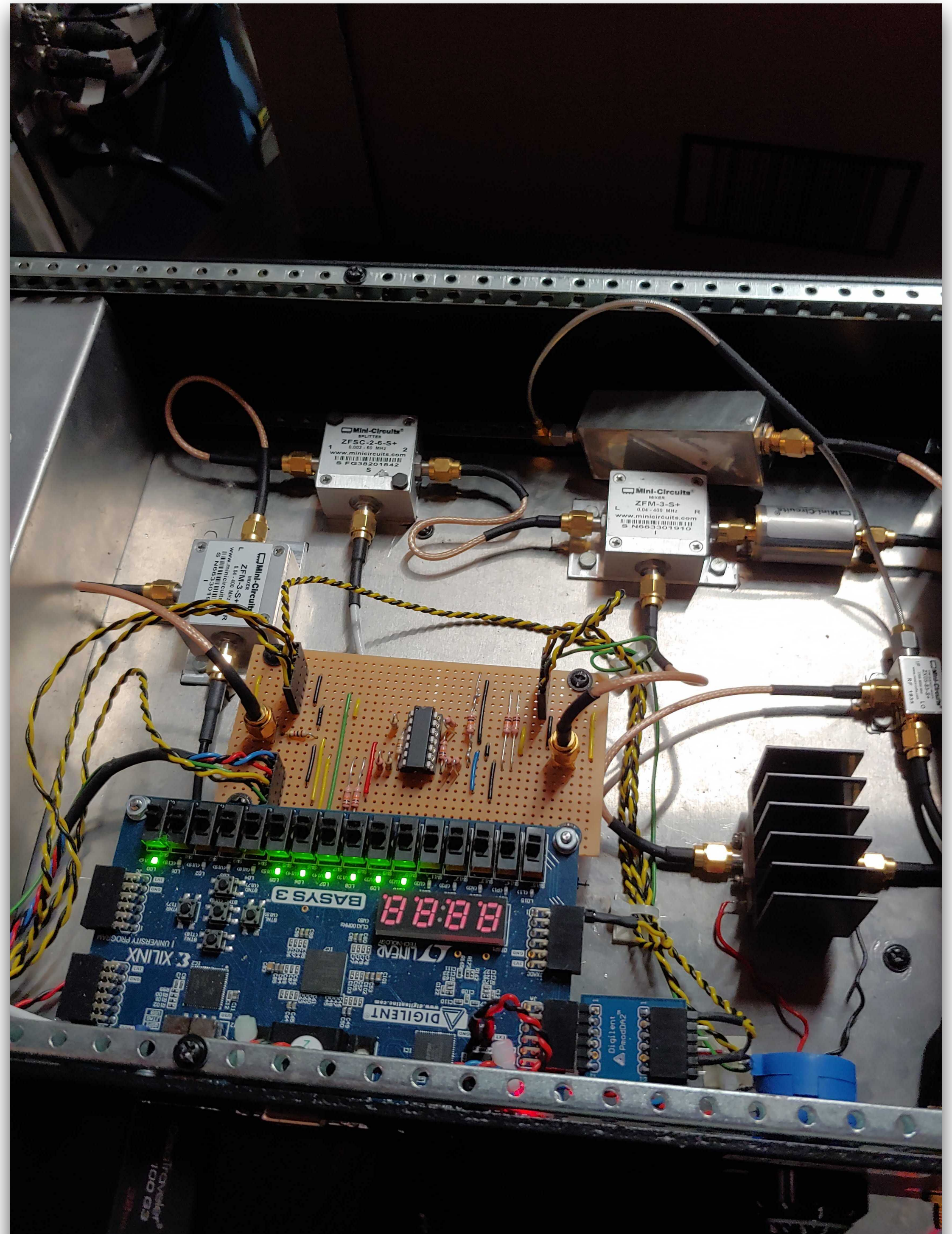
Location	Total summed noise into 750Hz bandwidth [dBm]	Noise from local component into 750Hz bandwidth [dBm]	Signal power [dBm]	Noise in 15MHz bandwidth [dBm]
A	-175	-178	-190	-132
B	-155	-166	-170	-112
C	-135	-166	-150	-92
D	-115	-150	-130	-72
E	-45	-76	-60	-2
F	-45	-178	-60	-2
G	-175	-178	-190	-132



1st prototype

Signal processing in 64 bit fixed point arithmetic on an FPGA





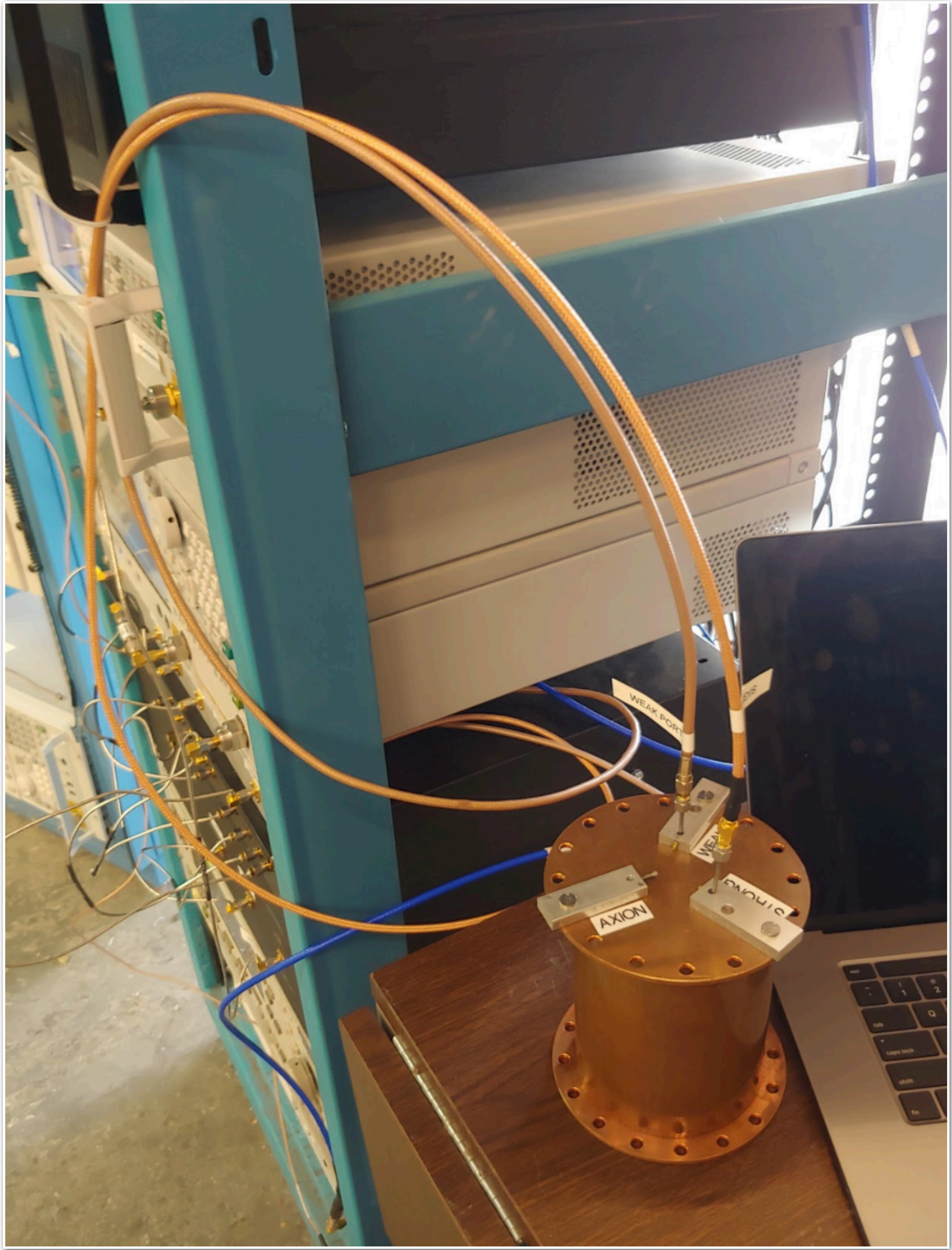
The DIGIBOX

- FPGA programmed by Mitch Perry and Ed Daw using Vivido.

- Multiple filters can be created.

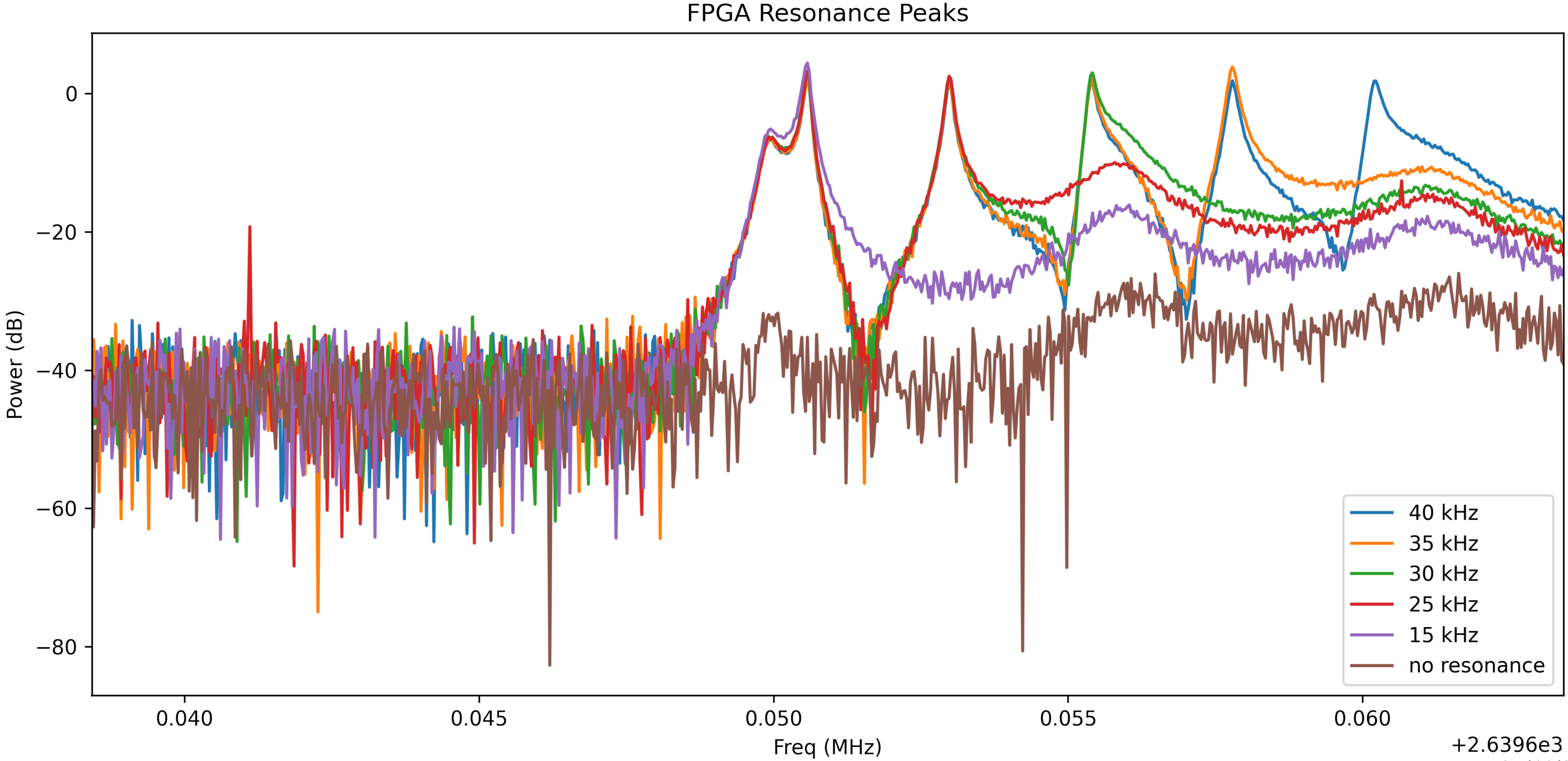
- Multiple mixing stages necessary at the moment due to board capabilities.

-
```
cbartram@digibox:~$ sudo python serial_digibox.py
Enter your commands below.
Insert "exit" to leave the application.
>> gain(0)=10


>> freq(0)=15000


>> quality(0)=100


>>
```


AXION


10.95.101.53

Digitally Creating Resonances



07/11/2021

Dr. Chelsea Bartram, ADMX, Spring 2021.

The University Of Sheffield.

Applications beyond Axion dark matter

- What we have here is a set of energy states of user-configurable spacing and lifetime.
- The output of the amplifier chain is in the GHz frequency regime, and will exhibit observable phase and amplitude properties of a quantum state.
- The configuration can be driven with injected signals, either electronic signals injected classically, particles, ions, or other things.
- More interesting digital filters could couple different frequency channels with time evolutions of channels using representations of groups other than U(1).
- Even if axions are not your bag, the properties of this system may be of interest to the community.

QSHS test facility

An STFC funded facility to be located at Sheffield.

- At least 8T magnetic field
- 10mK target temperature.
- 20cm bore by 20cm high target volume in field.
- Close proximity zero field quantum electronics bay

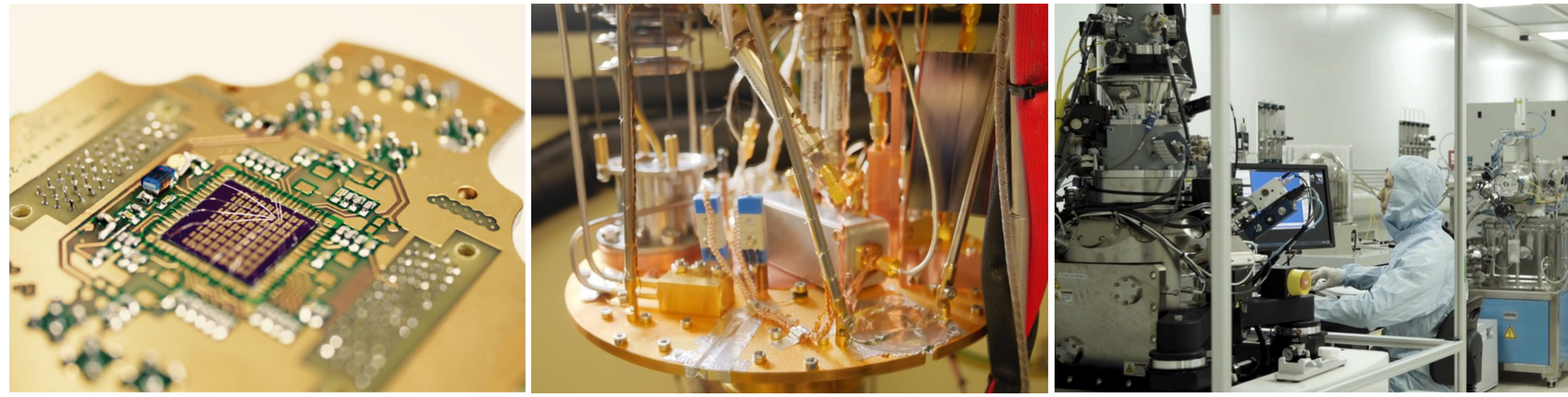
Science goals:

- Tests of ultra-low-noise electronics developed in the collaboration.
- Tests of tuneable resonator hardware. Resonator development is in partnership with the US ADMX group.
- Primary science from a search for QCD axions targeting the mass range 20-40 $\mu\mathrm{eV}$.
- Test of resonant feedback (see Mitch Perry's talk later this session!)

Quantum Electronics for QSHS

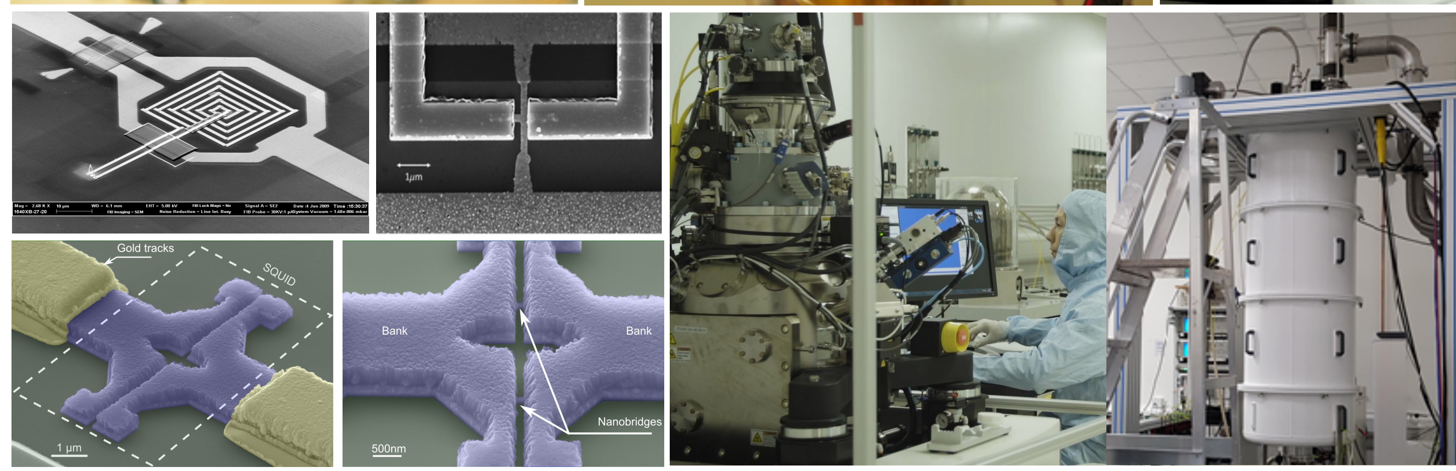
Josephson parametric amplifiers (JPAa) / Travelling wave parametric amplifiers (TWPAs)

Lancaster University | ROYAL HOLLOWAY UNIVERSITY OF LONDON | UNIVERSITY OF OXFORD



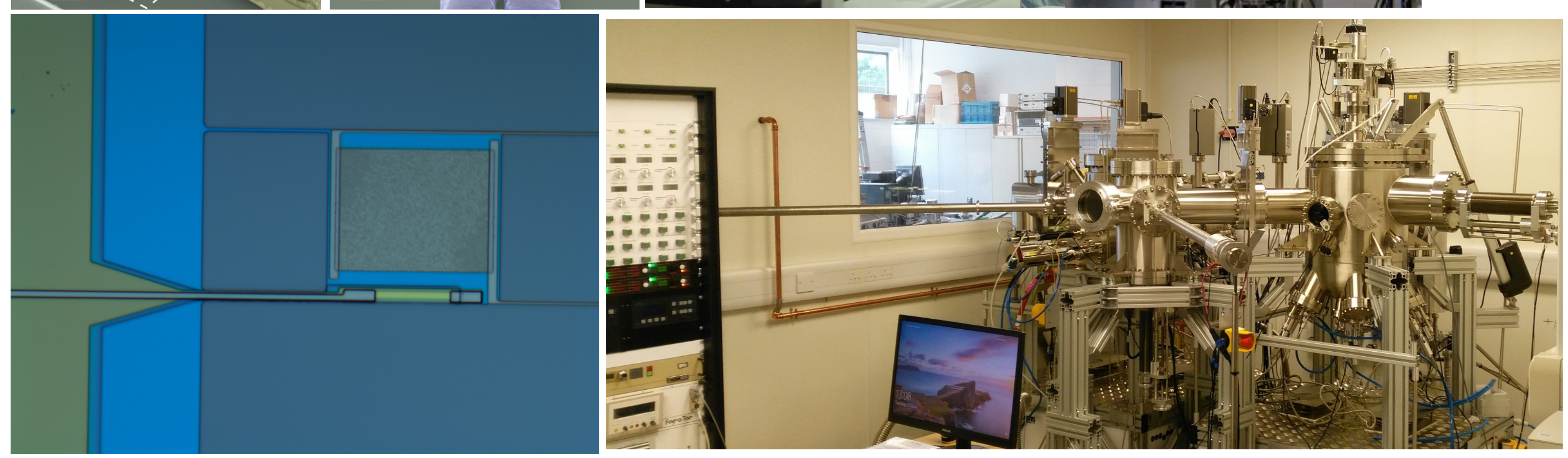
SLUG loaded SQUID amplifiers

UCL | NPL National Physical Laboratory



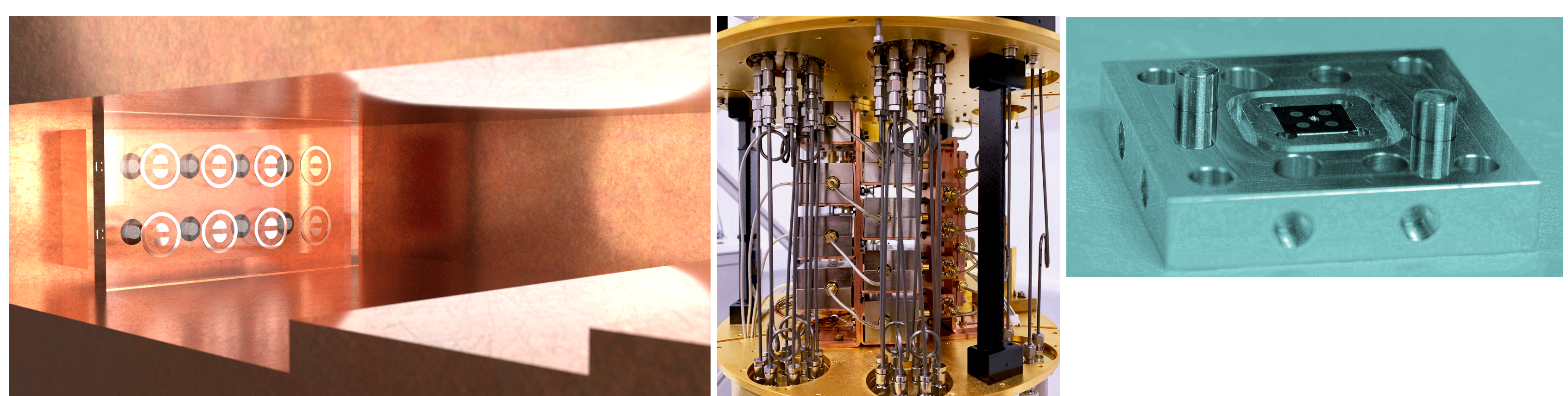
Cryogenic bolometer arrays

UNIVERSITY OF CAMBRIDGE



Qubit arrays

UNIVERSITY OF OXFORD | ROYAL HOLLOWAY UNIVERSITY OF LONDON



Summary

- Hidden sector fields could enormously enrich particle physics and solve the long-standing dark matter problem.
- The QSHS collaboration is building a world-class programme in this area over 8 institutions, including a UK based search for axions / other hidden sector particles. Long term goal is a large scale UK facility.
- Innovative quantum electronics is crucial for success, because by their nature these particles produce very faint signals. QSHS is active in four device areas. See poster 11881-40 by Javier Navarro (Oxford) and talk by Joe Longden (Oxford) on parametric amplifier development.
- Tunable resonant detectors are usually cavities. QSHS is working with ADMX researchers on resonator R&D.
- Non-cavity resonators may greatly increase the search rate. See Mitch Perry's talk later in this session.