Searching for Axions with ADMX

Ed Daw, The University of Sheffield

Seminar at Birmingham, 31st January 2018

For the ADMX collaboration

Over the past few years, both direct and indirect searches for WIMPs have continued to place ever more stringent limits. In the meantime, the Higgs boson has been discovered, and the mystery of why CP is so precisely conserved in QCD remains to be solved. It is possible to draw these three threads together if the dark matter in our Universe consists of axions. I will describe a direct search for axions called ADMX, progress in running this experiment using ultra low noise SQUID amplifiers, and work at Sheffield on a idea to increase the search rate in cavity axion searches using a resonant feedback approach.

A Search for Halo Axions

by

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Doctor of Philosophy

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The Strong CP problem

Standard model symmetry group is $\underline{SU(3)} \times \underline{SU(2)} \times \underline{U(1)}$

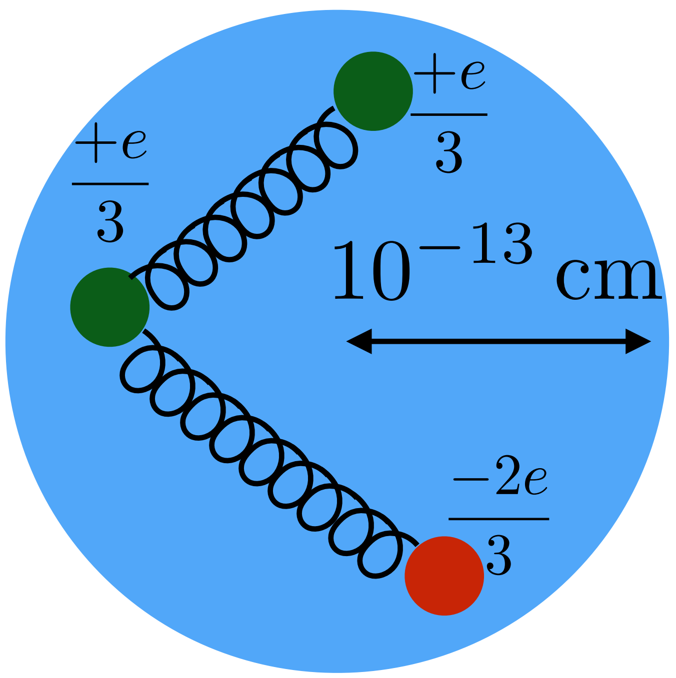
$SU(3)$	$SU(2)$	$U(1)$
NON-ABELIAN	NON-ABELIAN	ABELIAN
CP CONSERVING!	CP VIOLATING	CP CONSERVING

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

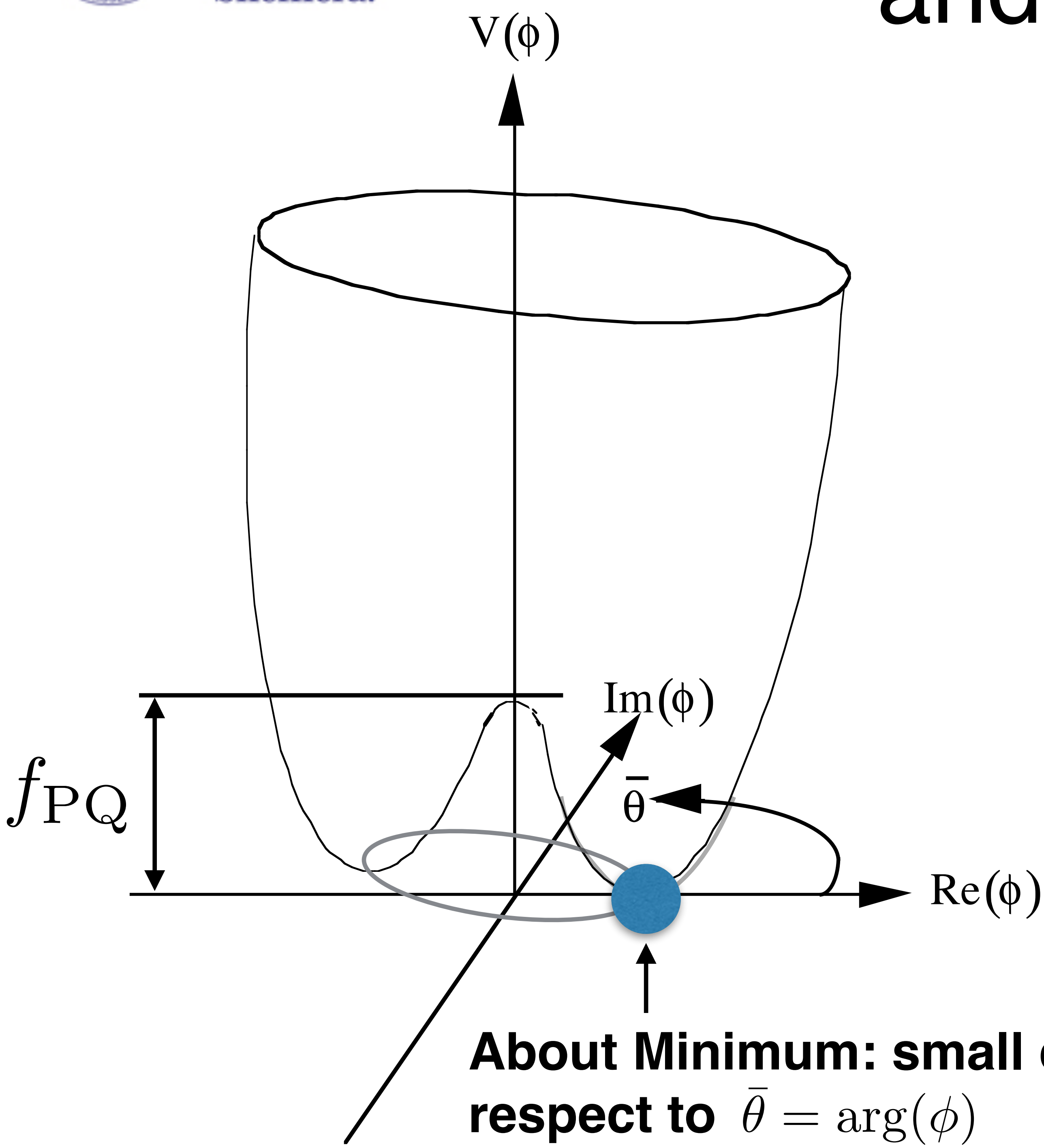
Evidence for CP conservation in the SU(3) strong interactions from multiple measurements of neutron and nuclear electric dipole moments. For example, neutron EDM < 10^{-26} e-cm.

Even simple dimensional arguments show that this is unexpected. Why do the intricate SU(3) QCD interactions conserve CP when the less intricate SU(2) QED interactions do not? This is the strong CP problem.

NEUTRON



The Peccei Quinn Mechanism and Axions



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

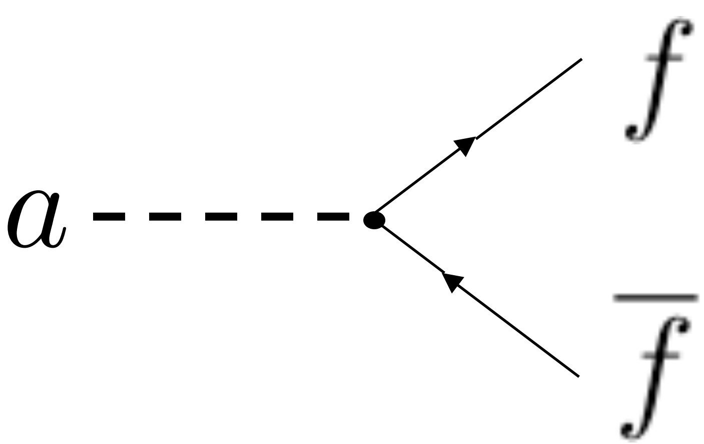
$$\overline{\Theta} = 0$$

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

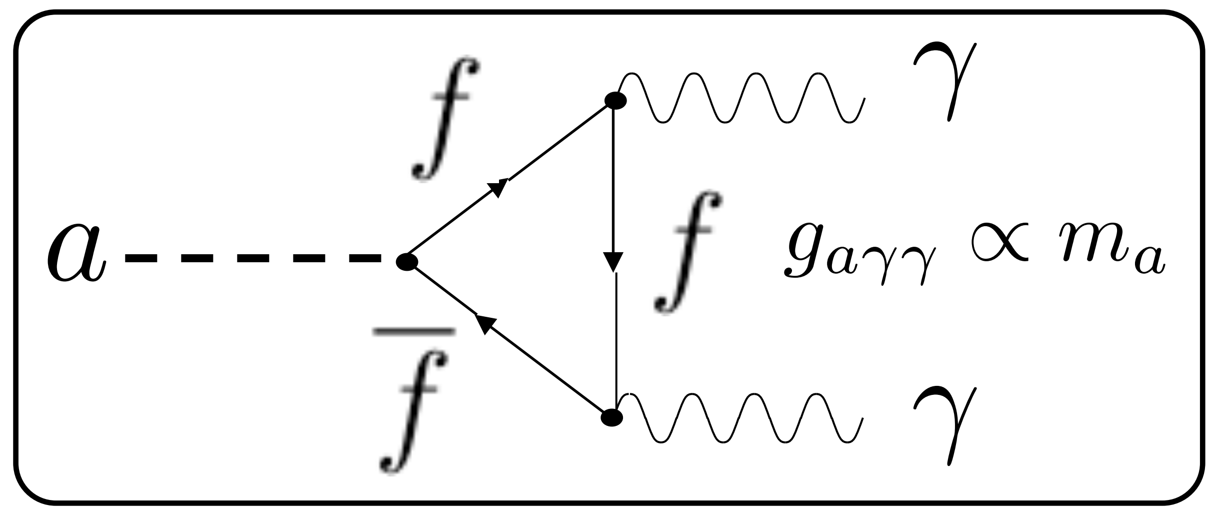
Axion DOF

Axion Phenomenology

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

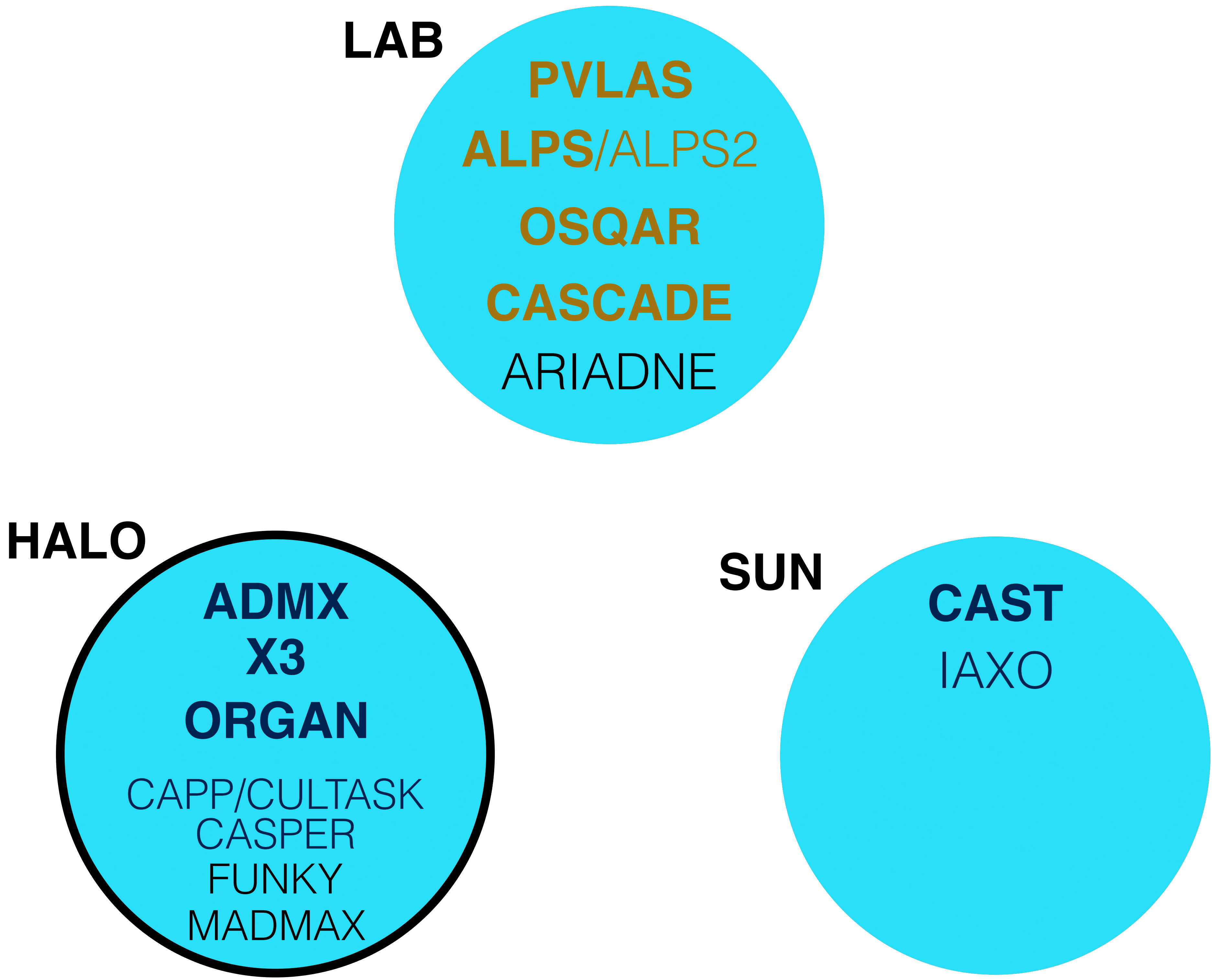


$\Longrightarrow$

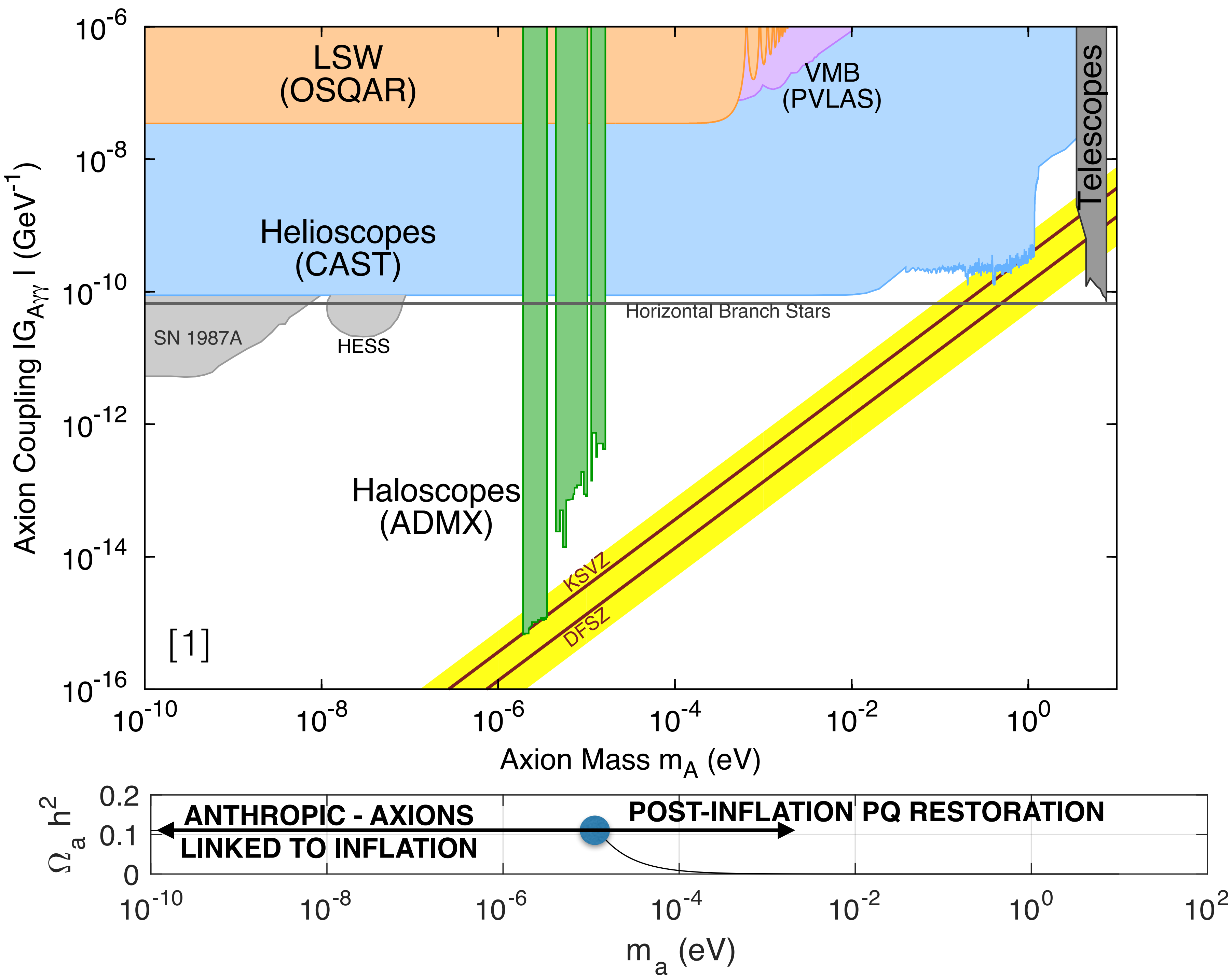


$$f_{PQ} \propto \frac{1}{m_a} \qquad \Omega_{PQ} \propto \frac{1}{m_a^{\frac{7}{6}}}$$

Axion Sources for Lab Searches



$g_{a\gamma\gamma}$ vs. m_a parameter space



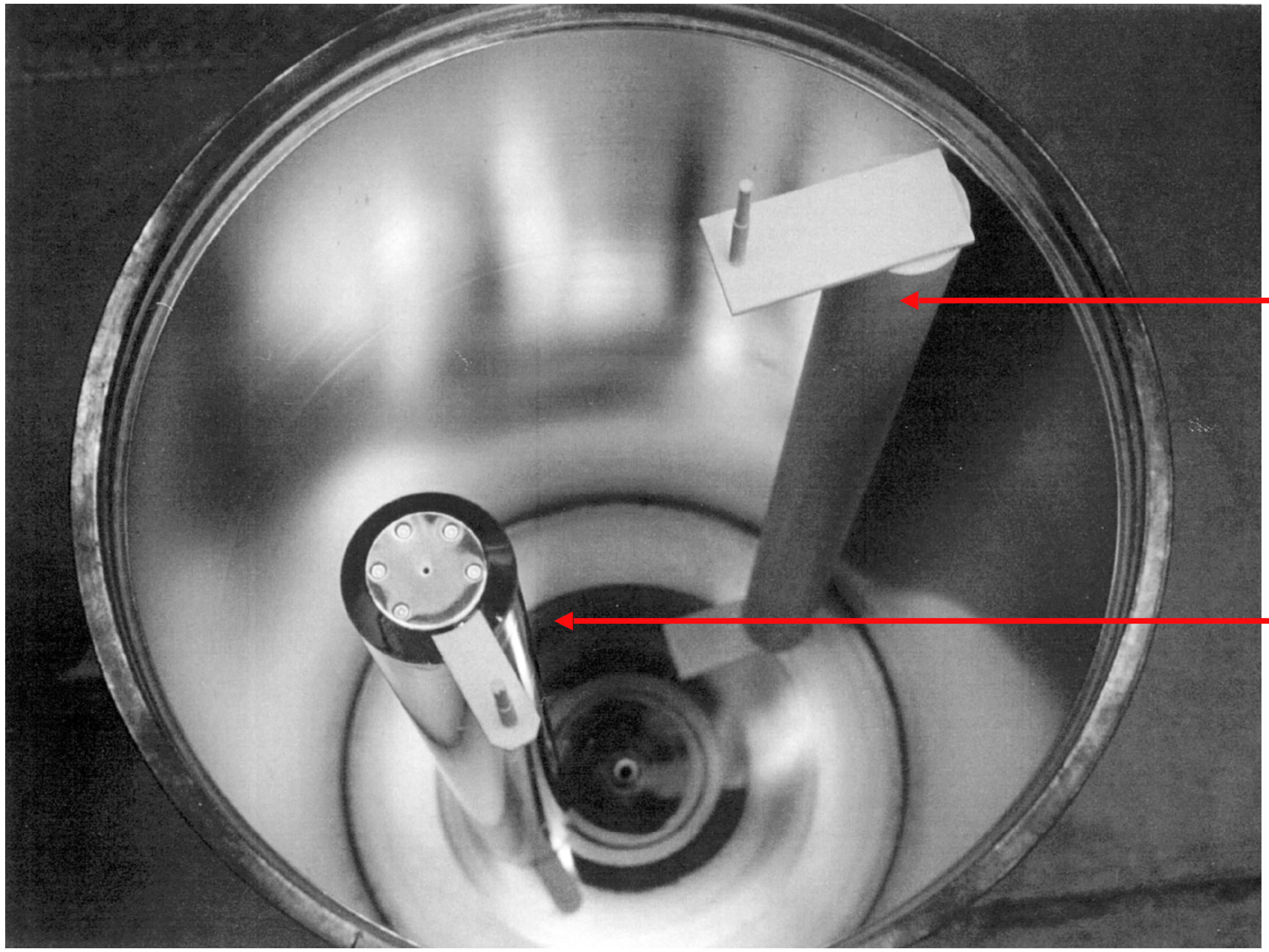
[1] K.A. Olive et al. (Particle Data Group), Chin. Phys. C, 38, 090001 (2014) and 2015 update
2016 revision by A. Ringwald, L. Rosenberg, G. Rybka,

How to Reveal 'Invisible' Axions

1. Don't try and create axions, then detect them. Your searches will have signal strength proportional to $g^4_{a\gamma\gamma}$
2. Instead, hypothesise that axions occupy the local halo at a mass density of about 0.3 $GeV/c^2/cm^3$, or a number density of about 10^{14} cm^{-3}.
3. Induce axion to photon conversion using as large a static magnetic field as you can afford. ADMX currently has a 7.6T magnet.
4. Surround the conversion region with a resonant energy storage structure. This works by providing a reservoir of oscillators with the possibility of promotion to an excited state at energy

$$\Delta E = m_a c^2$$

Resonant Cavity Detectors



50cm

alumina tuning rod

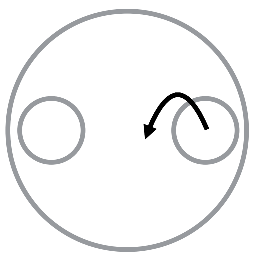
(a dielectric)

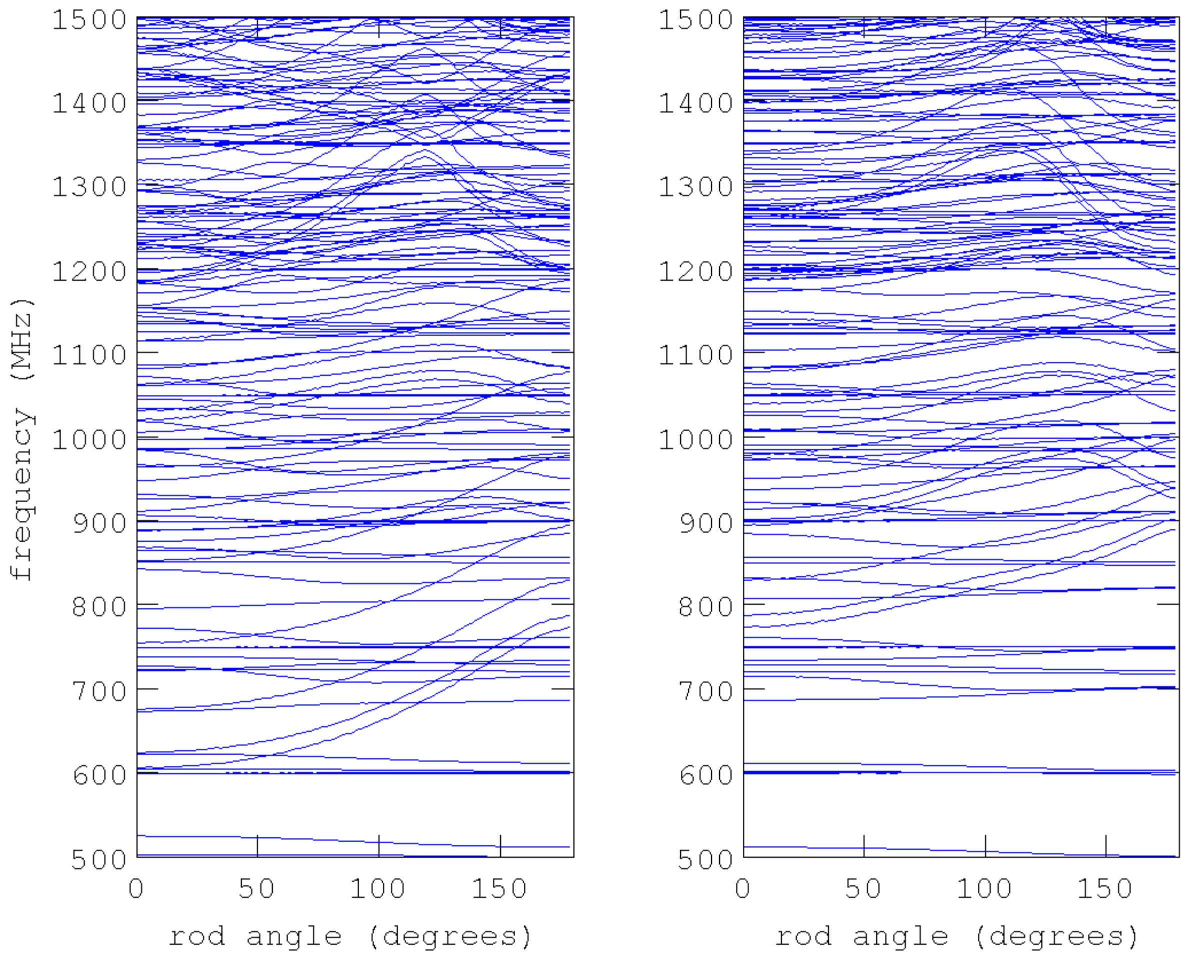
copper coated stainless steel

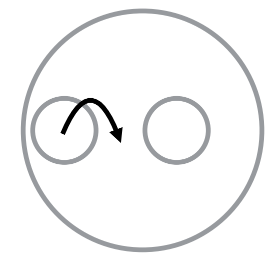
(a metal)

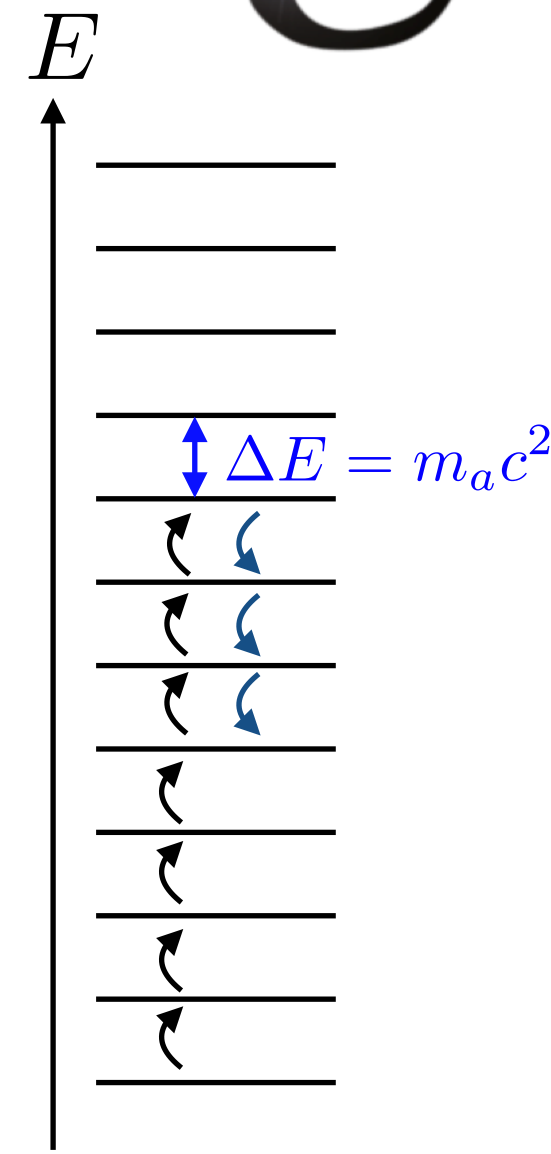
from above with lid removed. Depth is 1m.

Modes of a Resonant Cavity





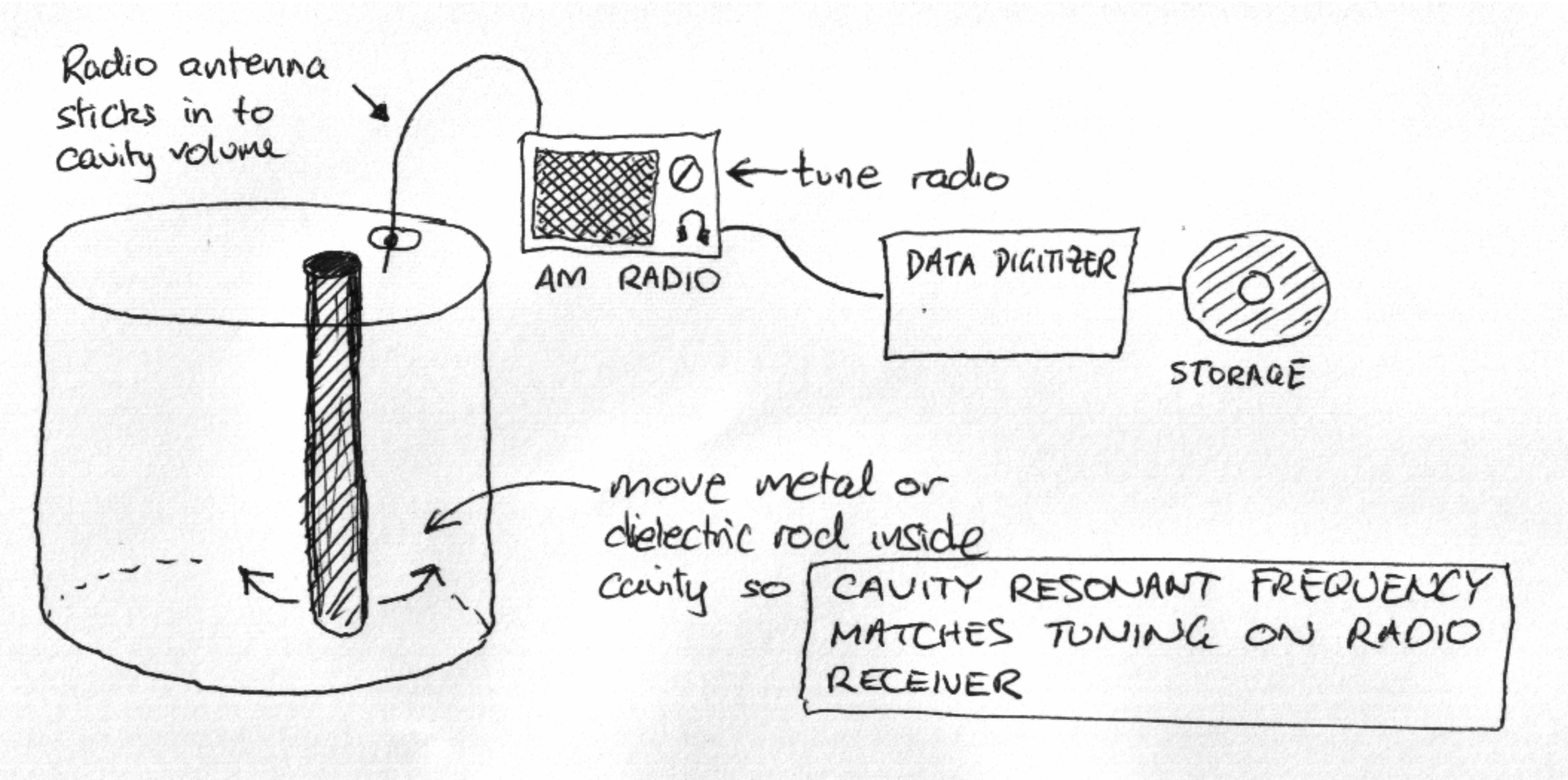




Incoming axions convert into quanta of excitation of TM modes of the cavity. Equilibrium between axion-stimulated excitation of the mode and spontaneous de-excitation due to thermal relaxation. Equilibrium population controlled by axion conversion rate, cavity Q

The University Of Sheffield.

ADMX



Anticipated Signal Strength

$$P_\gamma = \left(\frac{g_{a\gamma\gamma}^2 \rho_a \hbar^2}{m_a^2 c}\right) 2\pi c^2 \varepsilon_0 B_0^2 V f_{010} \nu_a Q$$

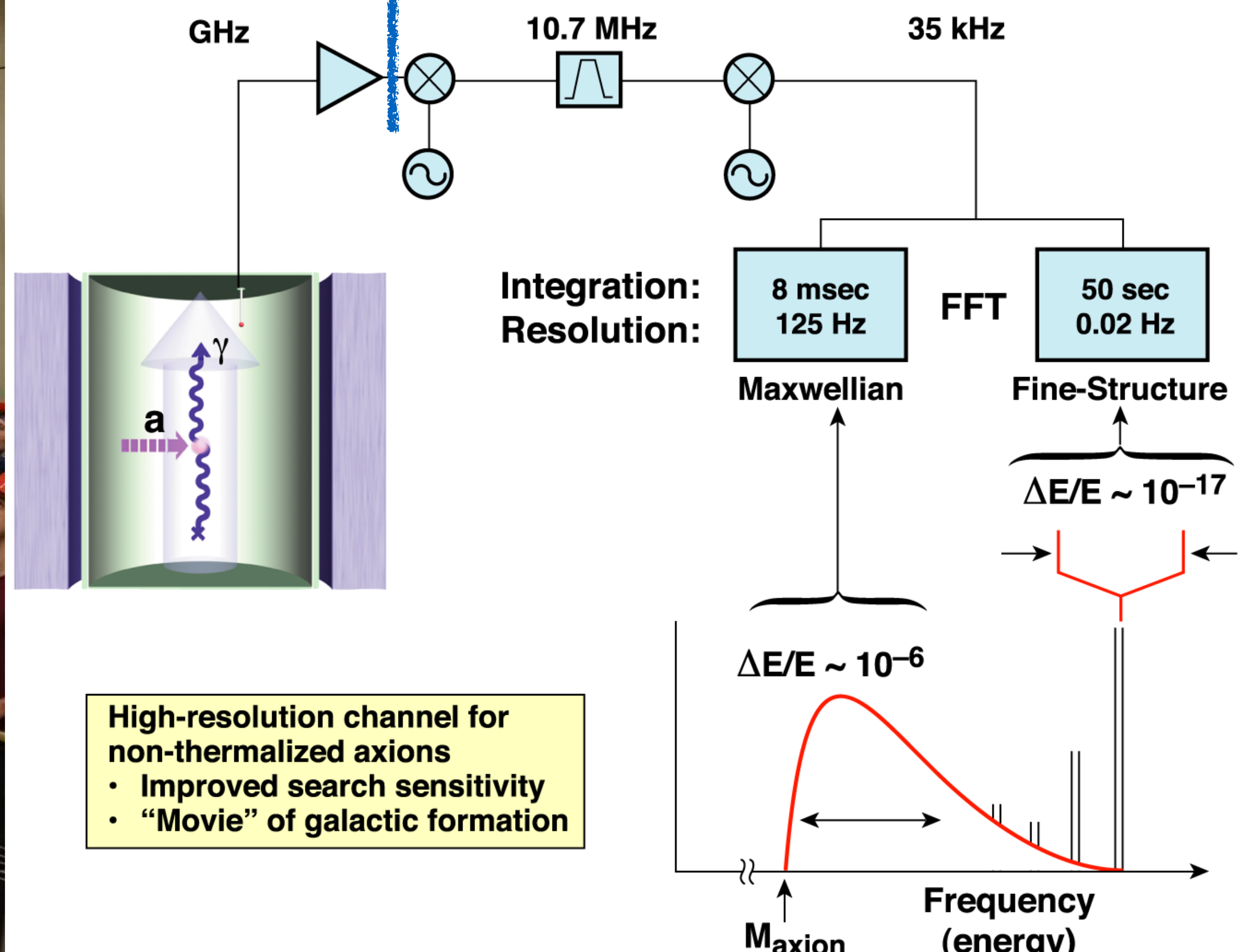
- Square of axion to photon coupling amplitude ($g_{a\gamma\gamma}^2$)
- Axion mass (m_a)
- Density of axions in local galactic halo (ρ_a)
- Magnetic field strength (B_0)
- Cavity volume (V)
- Cavity mode form factor, frequency, quality factor (f_{010}, ν_a, Q)

Expected signal power ~ $10^{-22}\,\mathrm{W}$

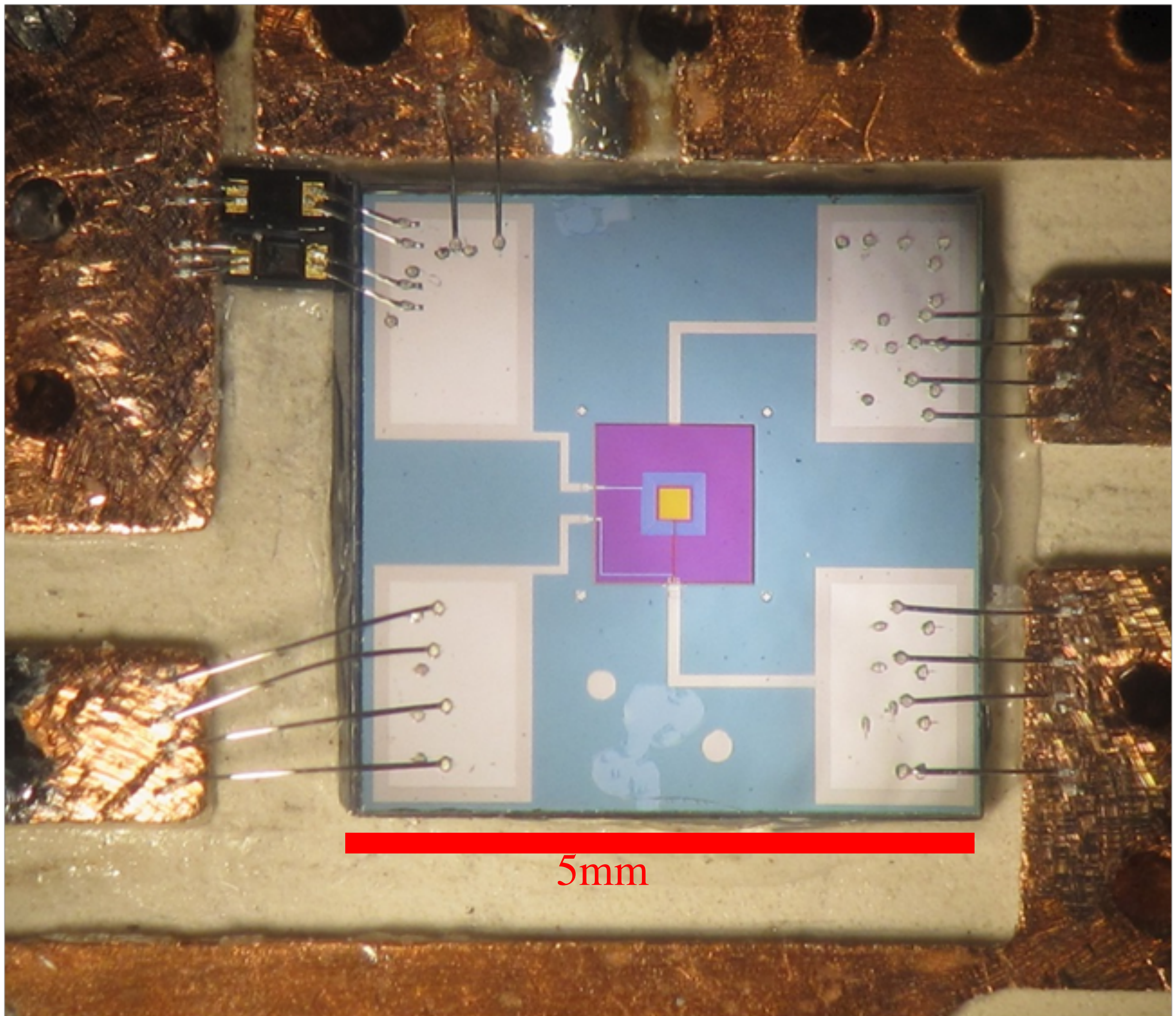
The ADMX detector

Cryogenic | Warm

AM Radio =
Double Heterodyne Receiver

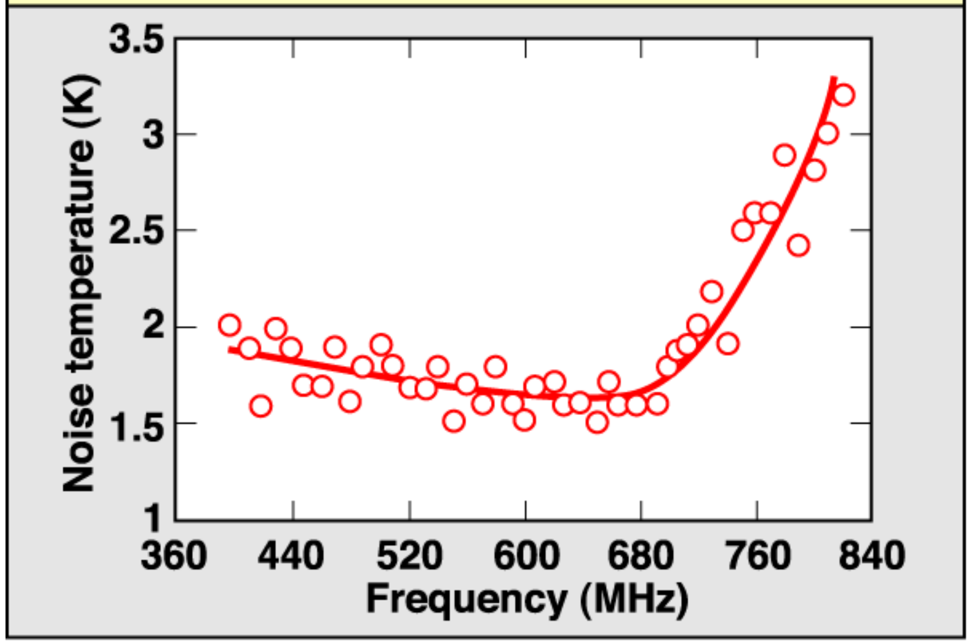


Cold Low-Noise Amplification
1st Stage: RF SQUID
2nd Stage: Balanced HFET amplifier

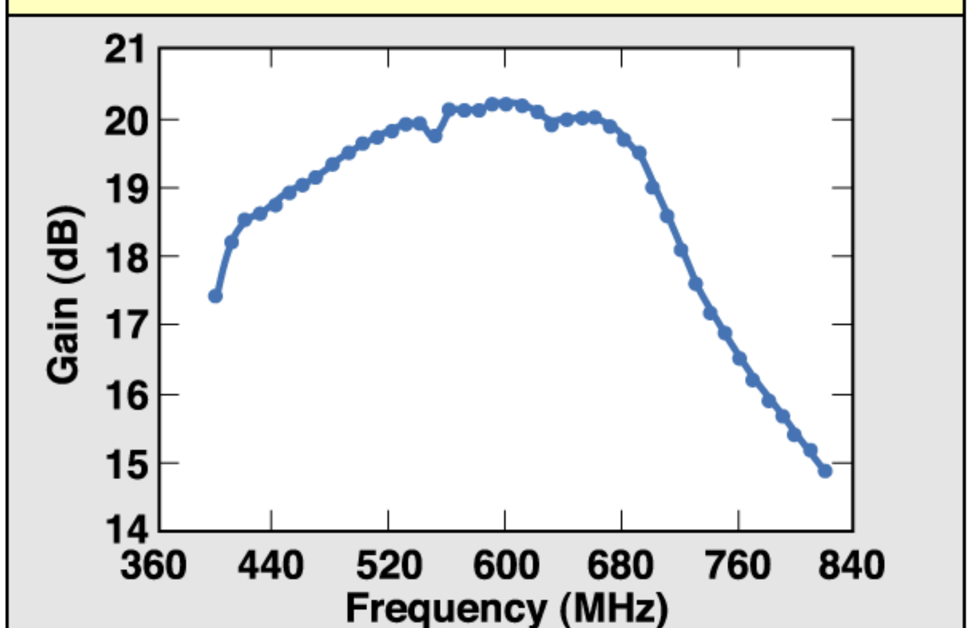


Noise Performance

HFET Noise Temperature

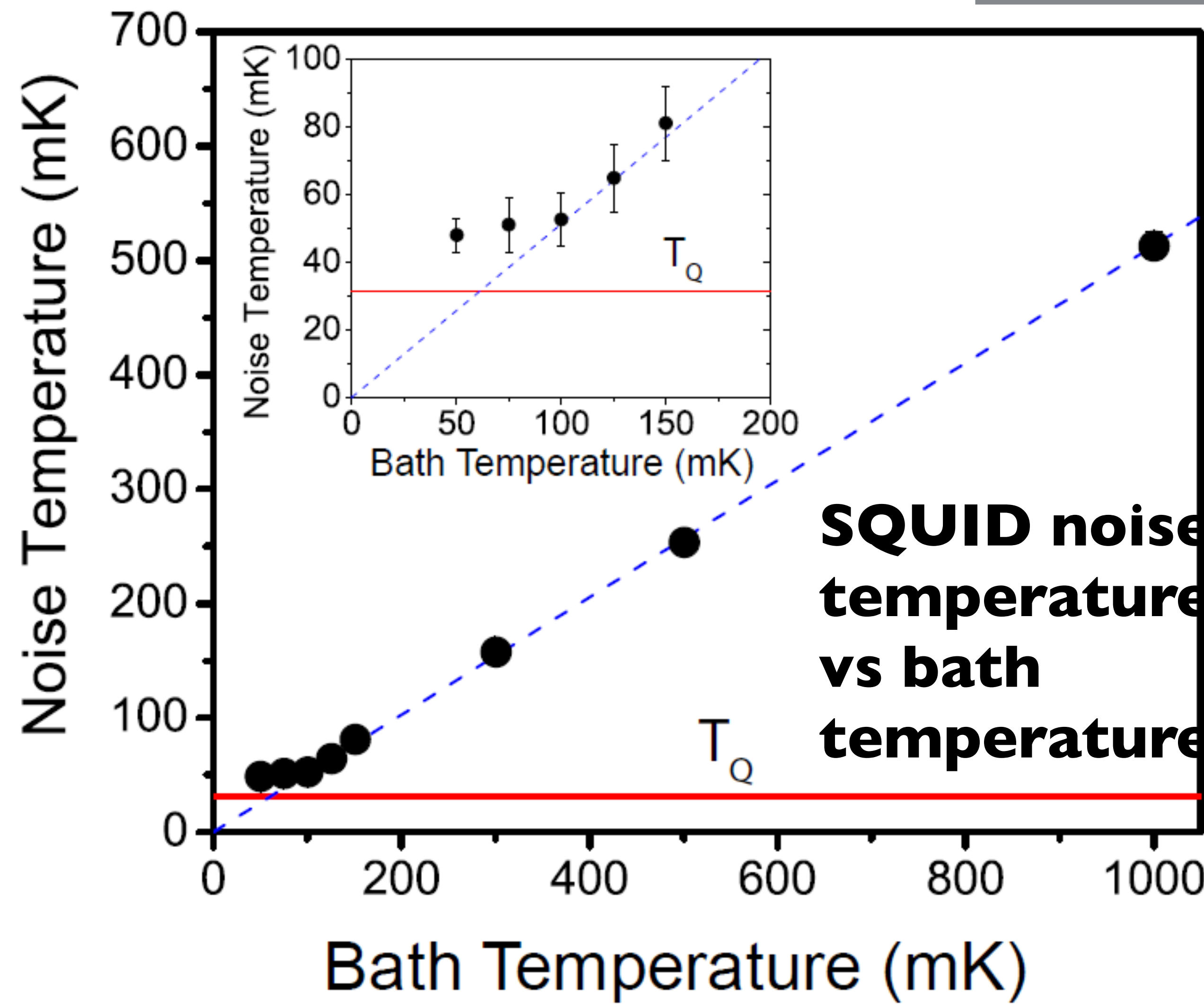


HFET Gain

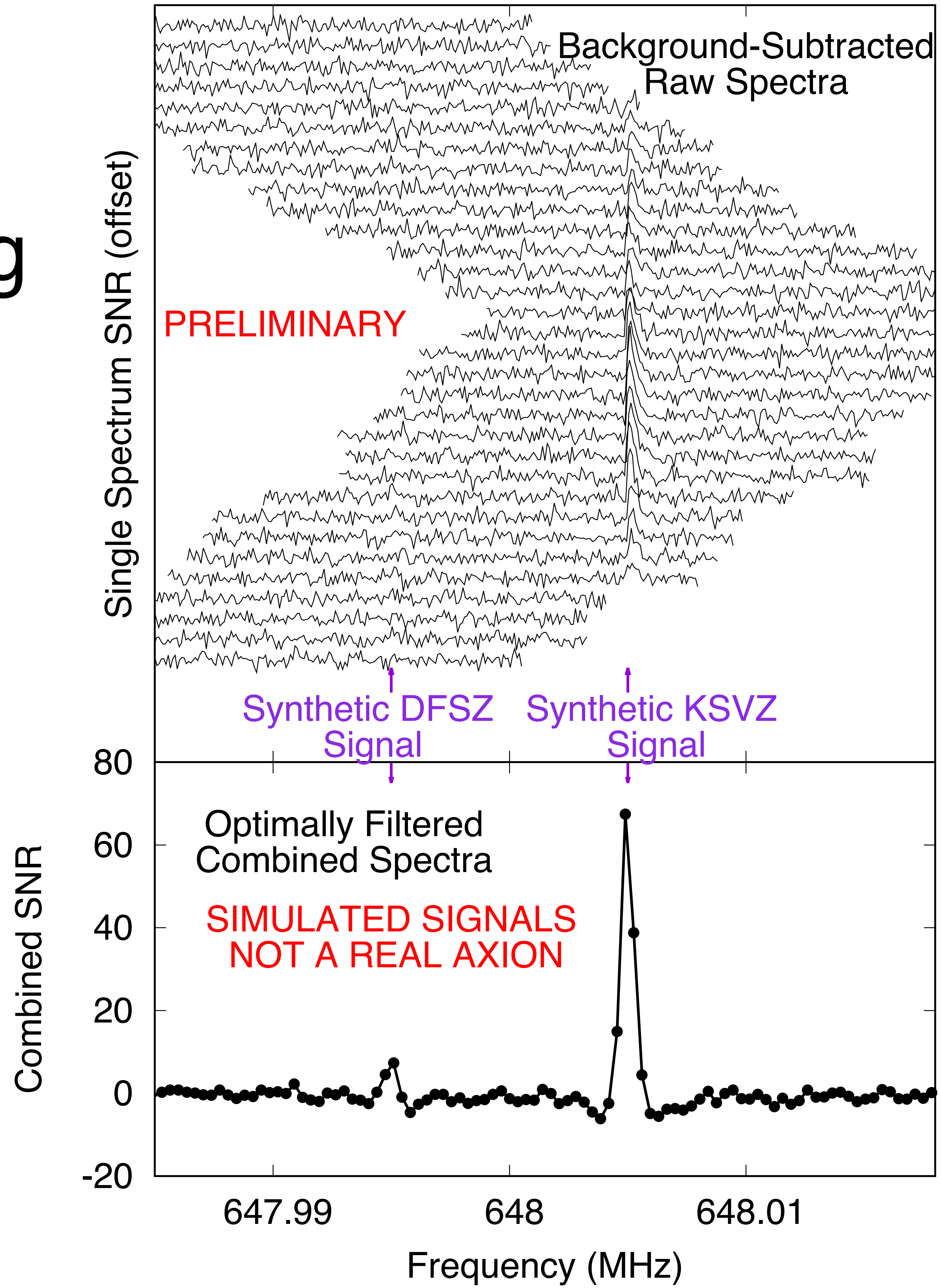


- **Currently HFET amplifiers (Heterojunction Field-Effect Transistor)**
  - **A.k.a. HEMT™ (High Electron Mobility Transistor)**
  - **Workhorse of radio astronomy, military communications, etc.**

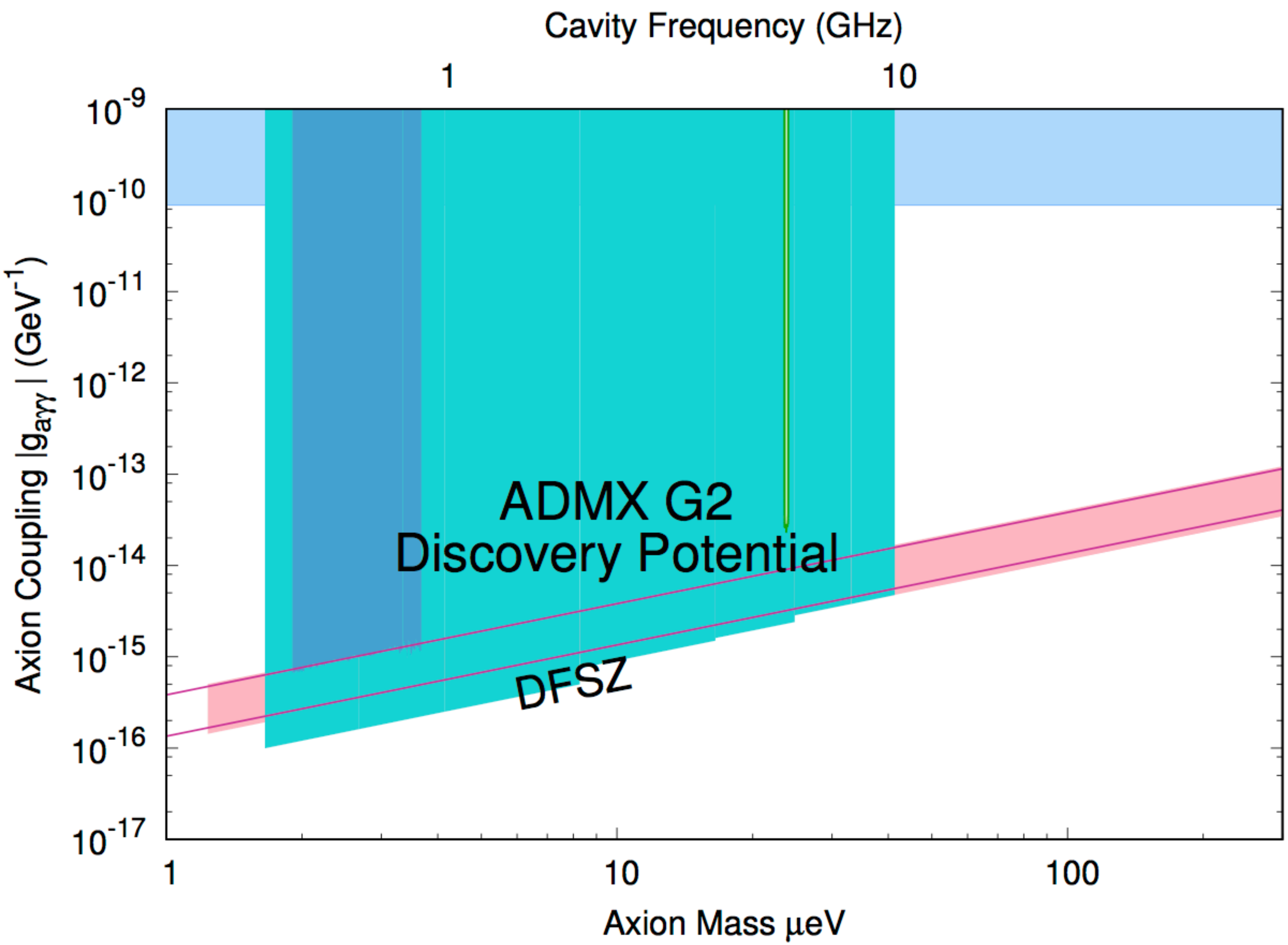
$$\left(\frac{1.5}{0.06}\right)^2 = 625$$



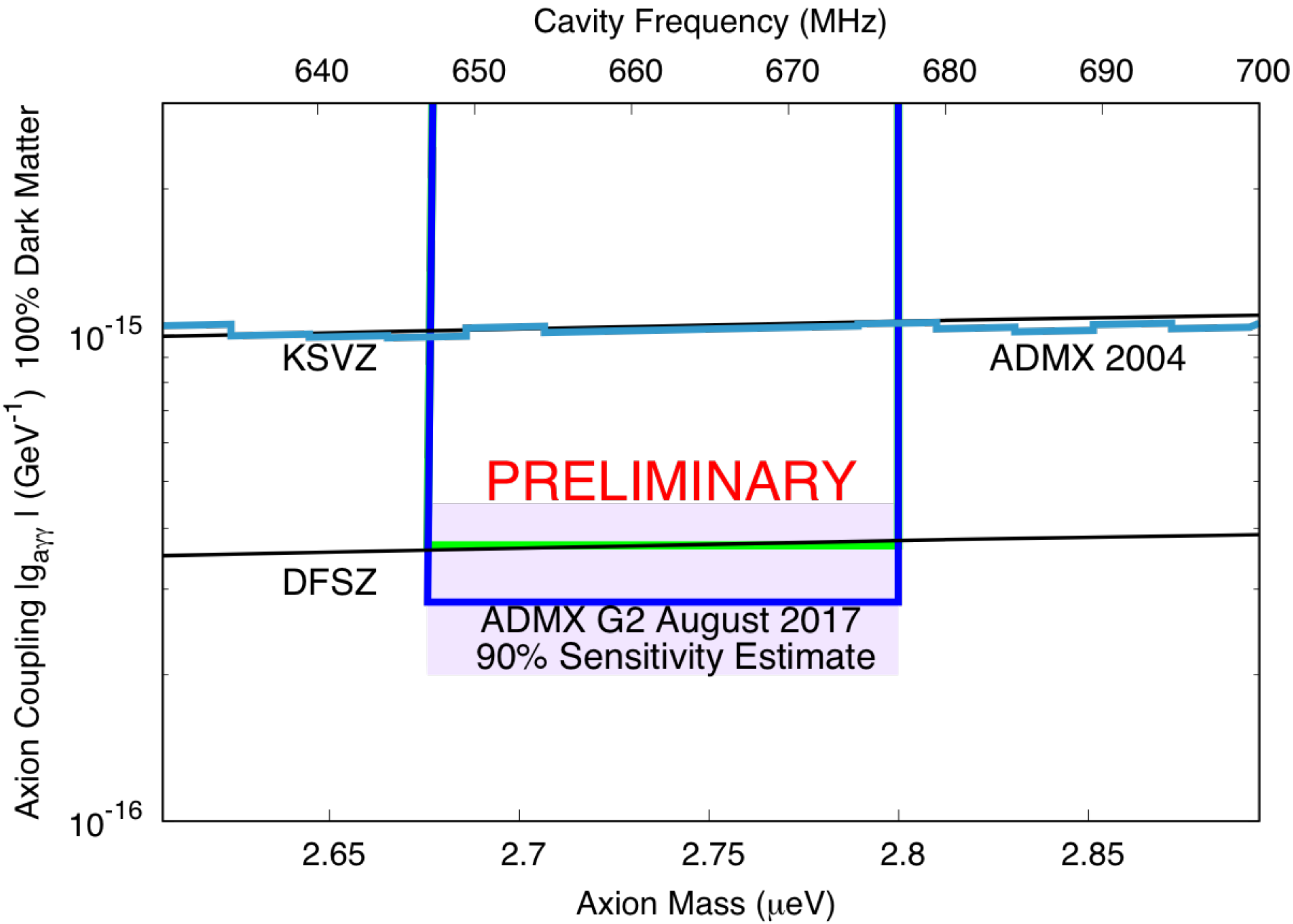
Combining Power Spectra



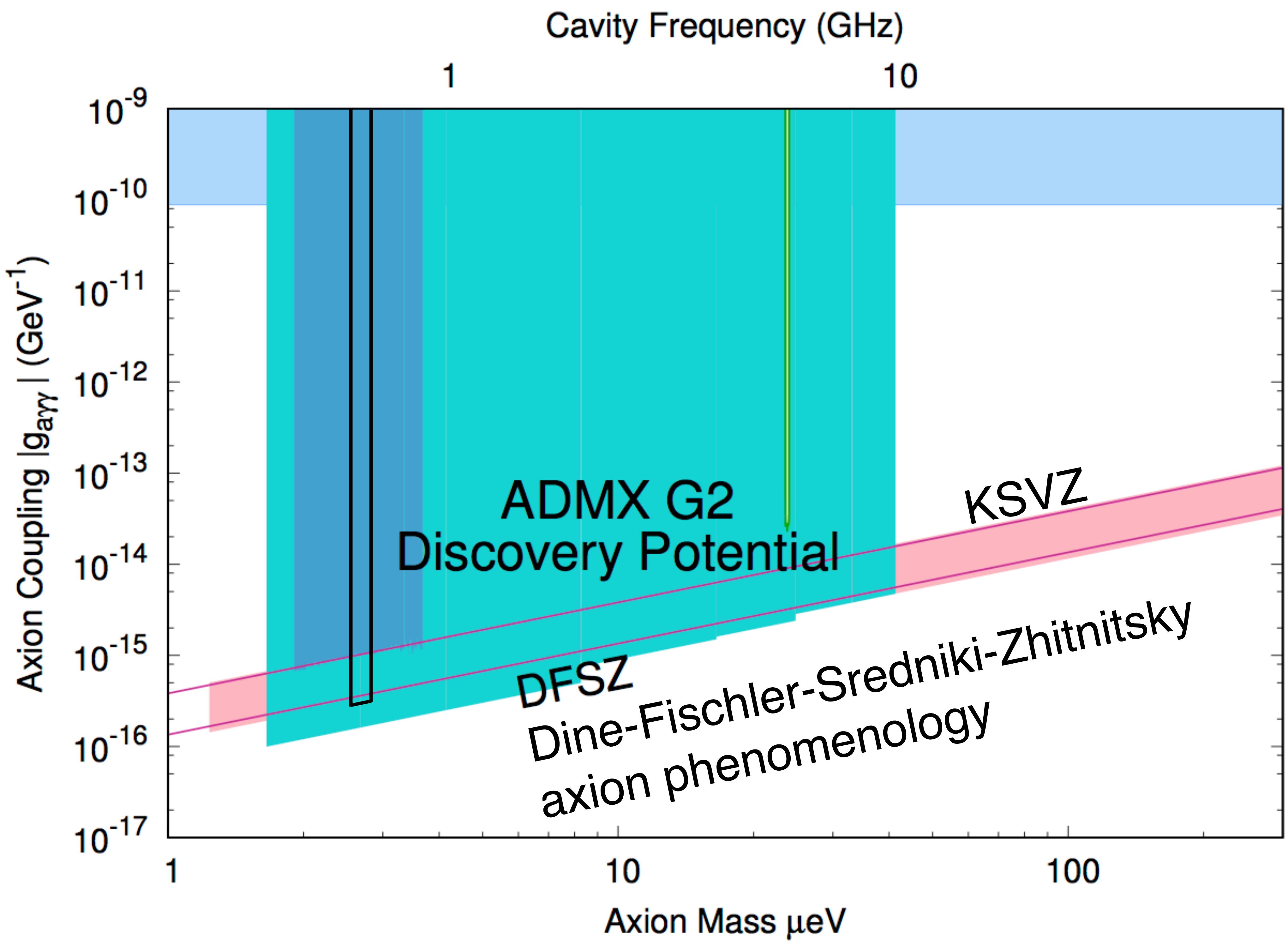
ADMX Reach


Cavity Frequency (GHz)
1
10
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
Axion Coupling $|g_{a\gamma\gamma}|$ (GeV^{-1})
ADMX G2
Discovery Potential
DFSZ
1
10
100
Axion Mass μeV

Sensitivity level in submitted first-results paper



Projected Sensitivity in First Data

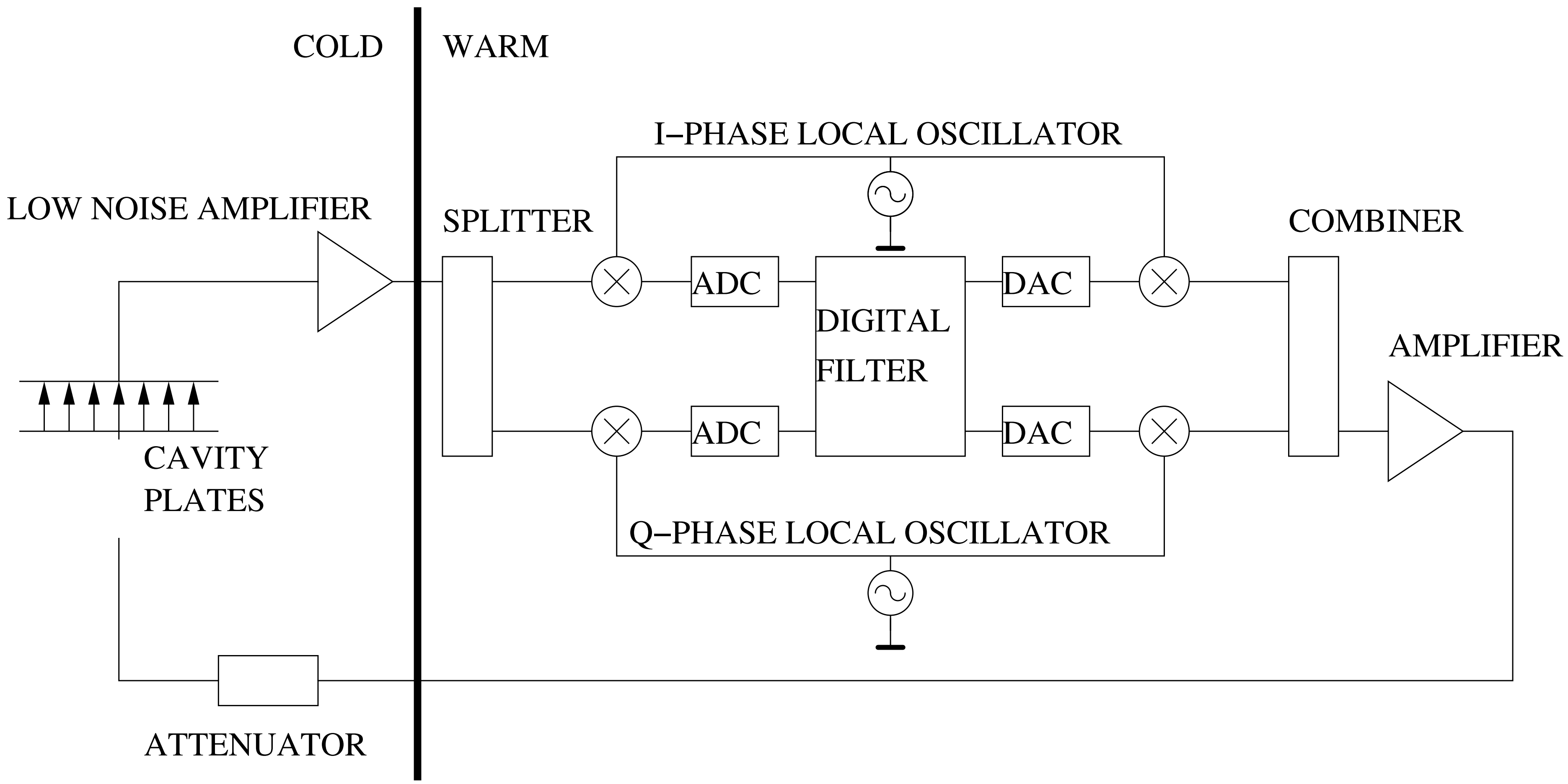


First Probe of sub-DFSZ coupling halo axions!

New approach: Digital Resonant feedback

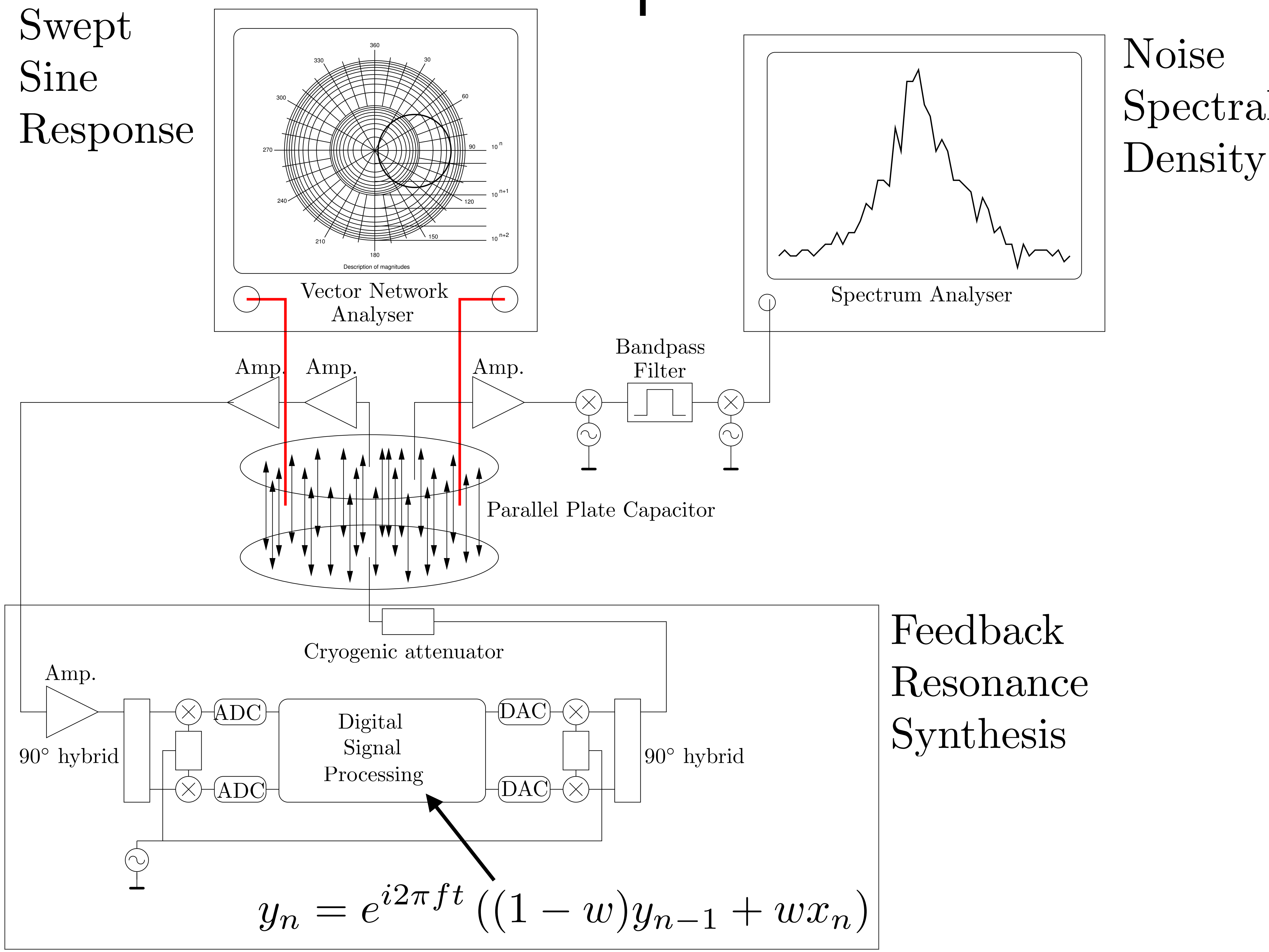
Maybe the resonant structure doesn't have to be in the cavity.

RF structure operated off-resonance

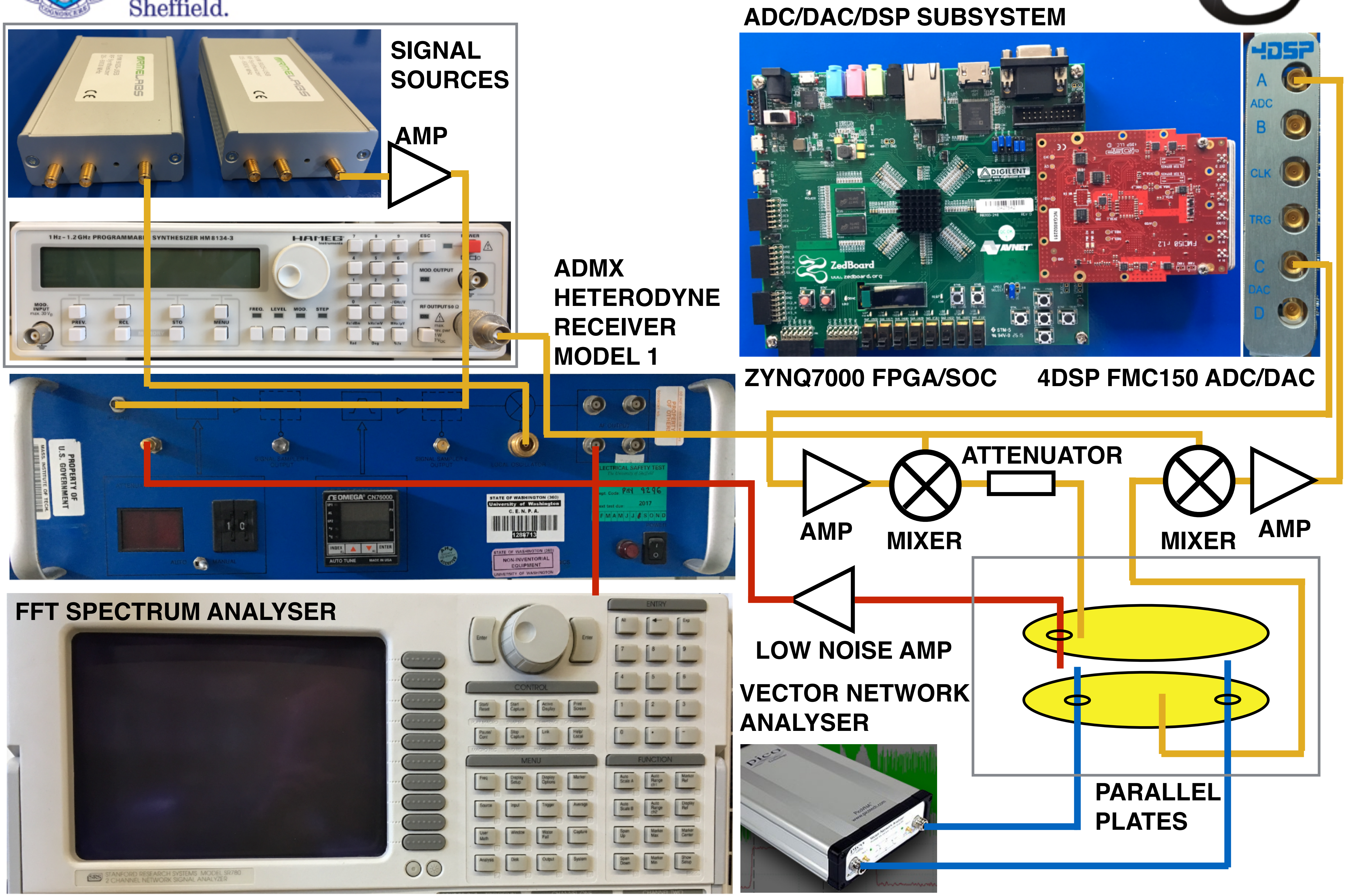


For high Q, but without oscillation, need servo control of the open loop gain so that it is marginally less than 1. Advantage of this method is that many resonators can run in parallel.

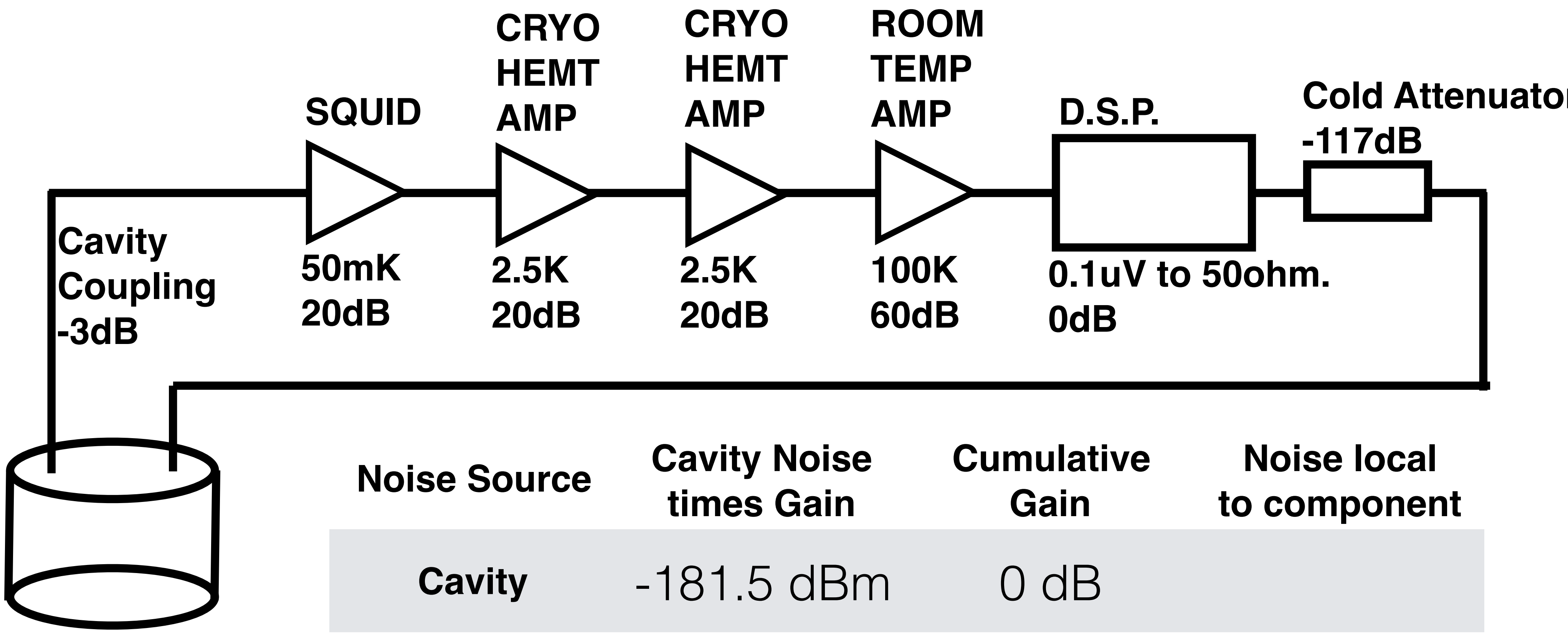
UKARC Experiment



UKARC Experiment 2



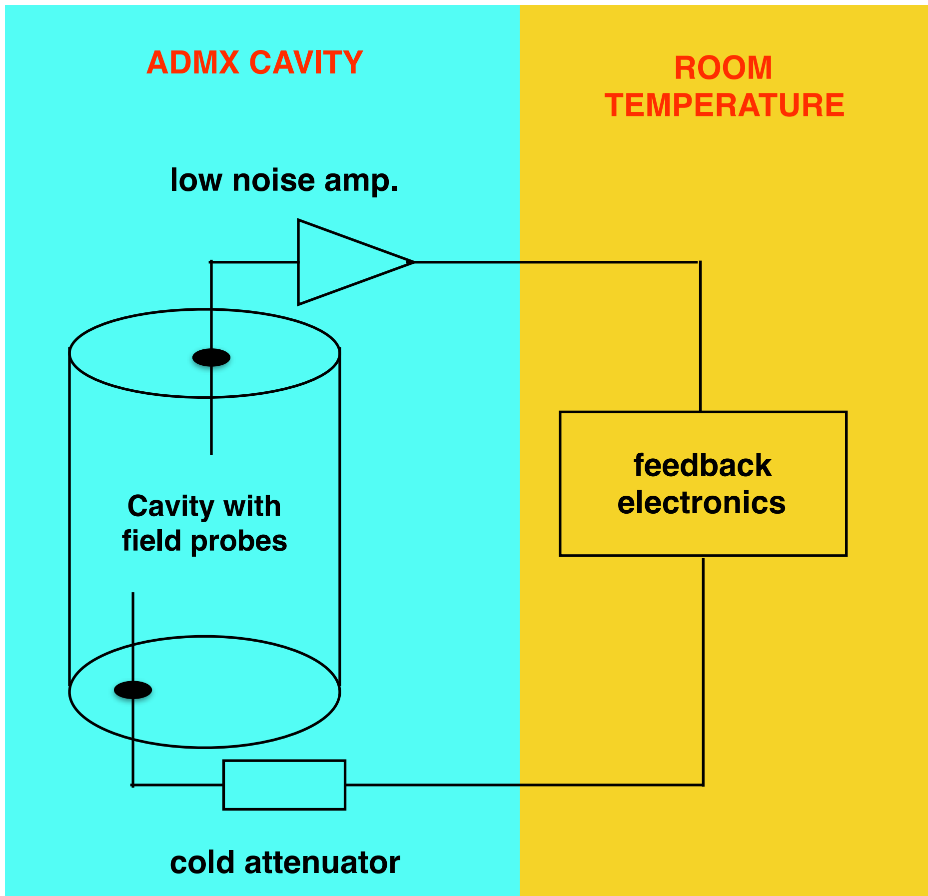
Digital Electronics in a Low Noise Experiment ?

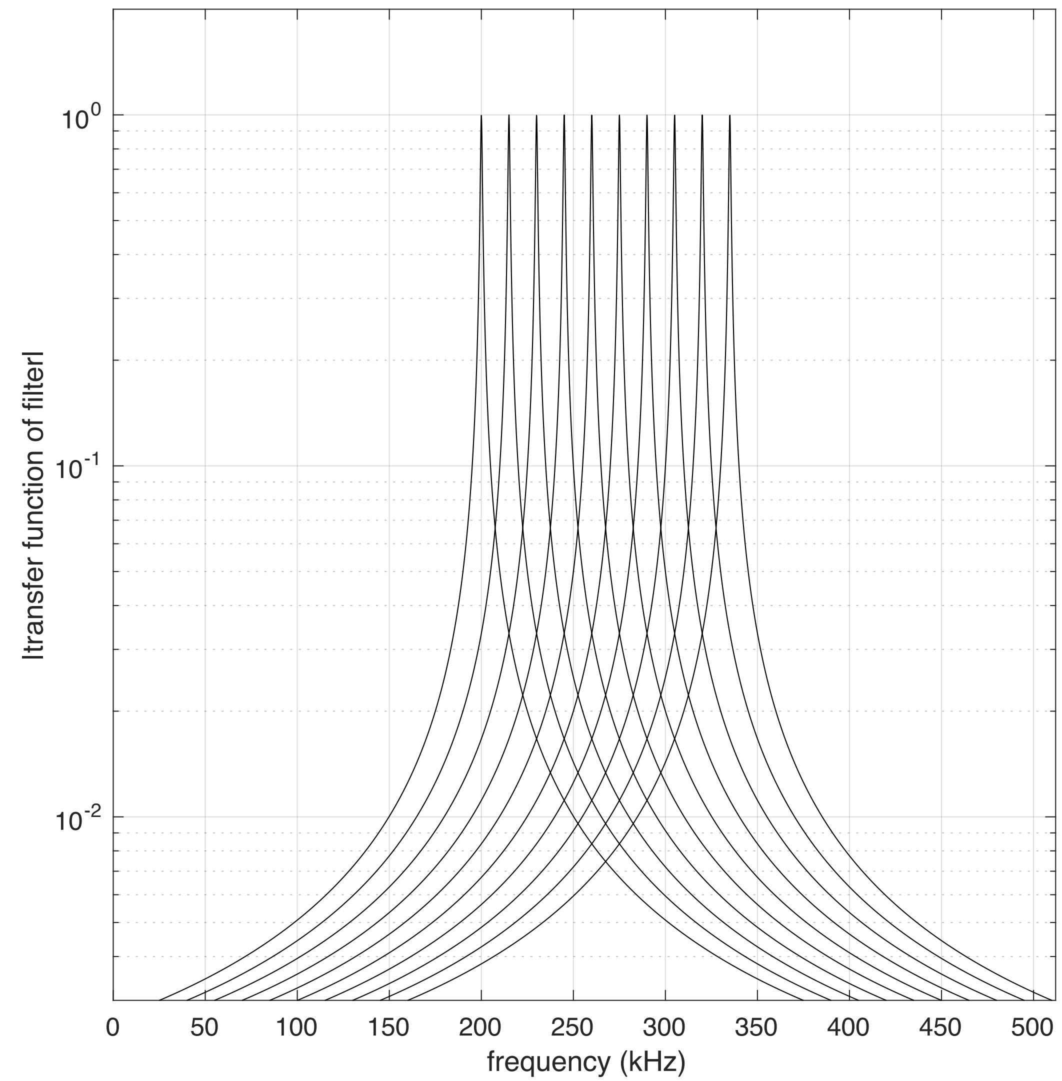


Noise Source	Cavity Noise times Gain	Cumulative Gain	Noise local to component
Cavity	-181.5 dBm	0 dB	
SQUID Amp	-181.5 dBm	-3 dB	-181.5 dBm
1st HEMT	-161.5 dBm	17 dB	-167.6 dBm
2nd HEMT	-141.5 dBm	37 dB	-167.6 dBm
Room Temp Amp	-121.5 dBm	57 dB	-151.6 dBm
Signal Processing	-61.5 dBm	117 dB	-127 dBm

$$-127\,\mathrm{dBm} - 117\,\mathrm{dB} = -244\,\mathrm{dBm} = 4 \times 10^{-23}\,\mathrm{W}$$

Testing on the ADMX Cavity





Mitch Perry
(Sheffield B.Sc. 2017)

The University Of Sheffield.

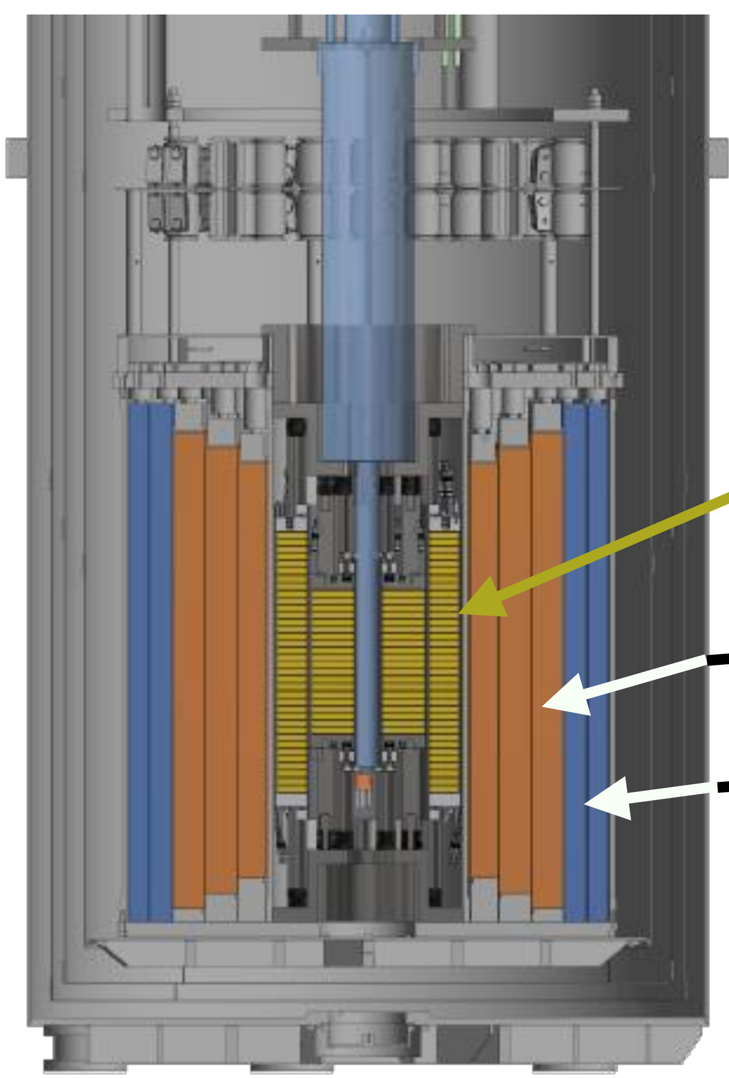
Future Magnet

NATIONAL HIGH MAGNETIC FIELD LABORATORY

[Florida]

Bore of 16cm in diameter - sensitivity to higher mass axions. 24T static field.

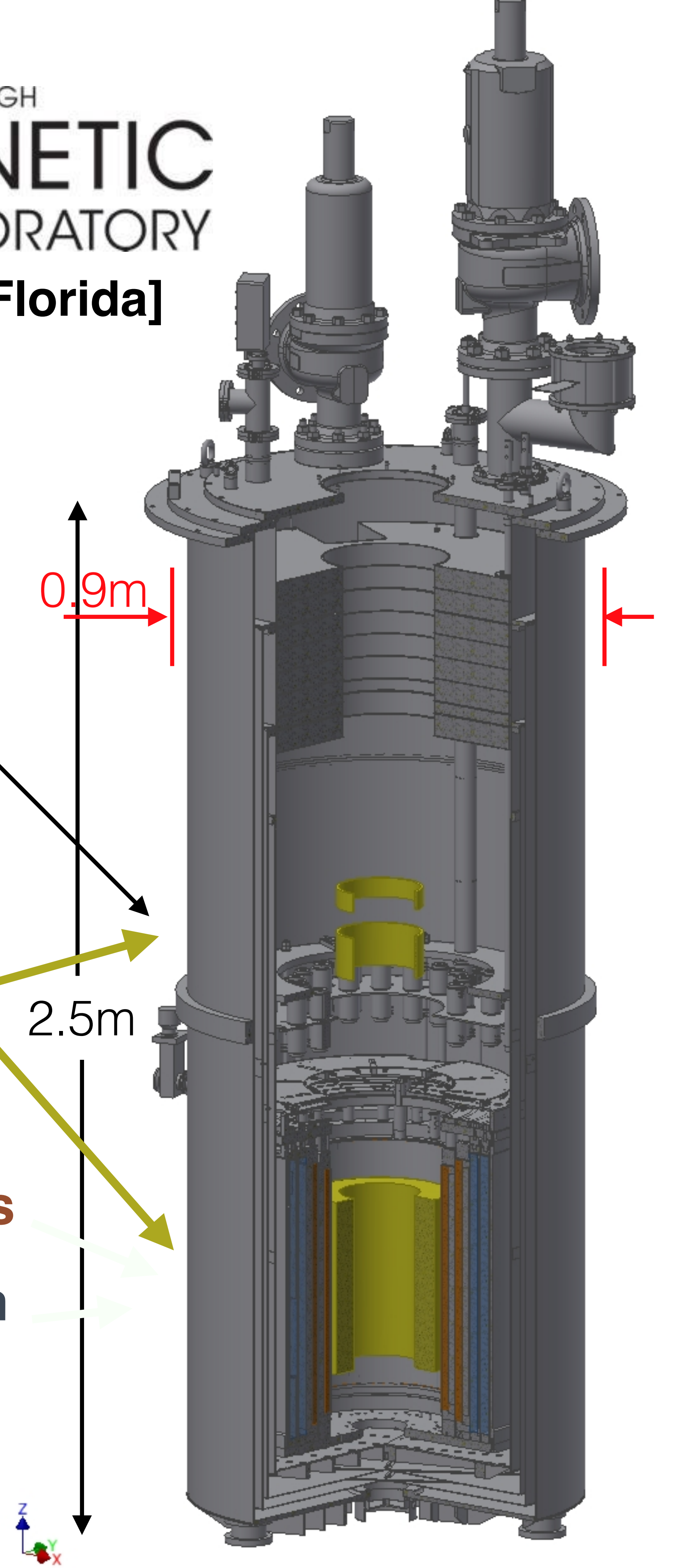
Bucking coils for field free region 60cm above the main magnet



High Temperature Superconductor Coils: 44 modules of YBCO tape

Niobium Tin (Nb_3Sn) coils

Niobium Titanium (NbTi) coils



Conclusions

- Axion dark matter is well motivated.
- ADMX is probing DFSZ halo axions already!
- Coverage of the full plausible mass range challenging. Higher field magnet would help, £££.
- Resonant feedback offers a potential solution.
- Proposed UK contribution [Daw, Bailey]:

★ **Build and test a prototype resonant feedback system.**
★ **Model the resonant structure, assess form factor.**
★ **Deliver the prototype for testing with the ADMX cavity.**

- Seedcorn money from UofS is getting this started.
- Sheffield, Lancaster UK collaboration.
- Maybe we will detect axions! I certainly hope so.