The
University
Of
Sheffield.

Resonant searches for Axions and other Ultra-Light Dark Matter

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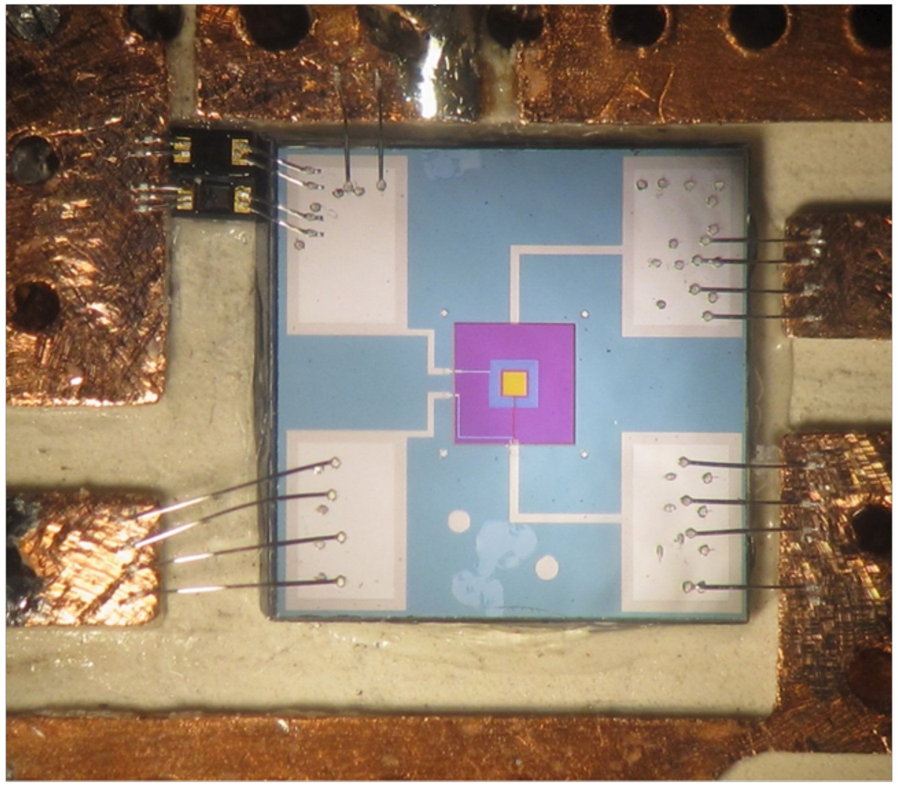
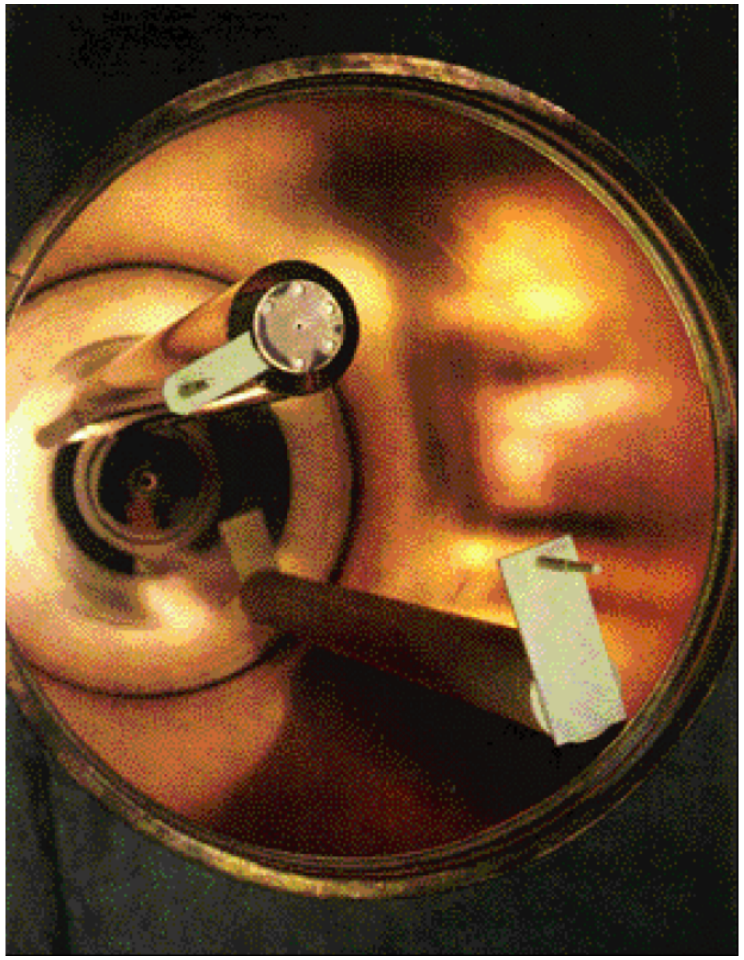
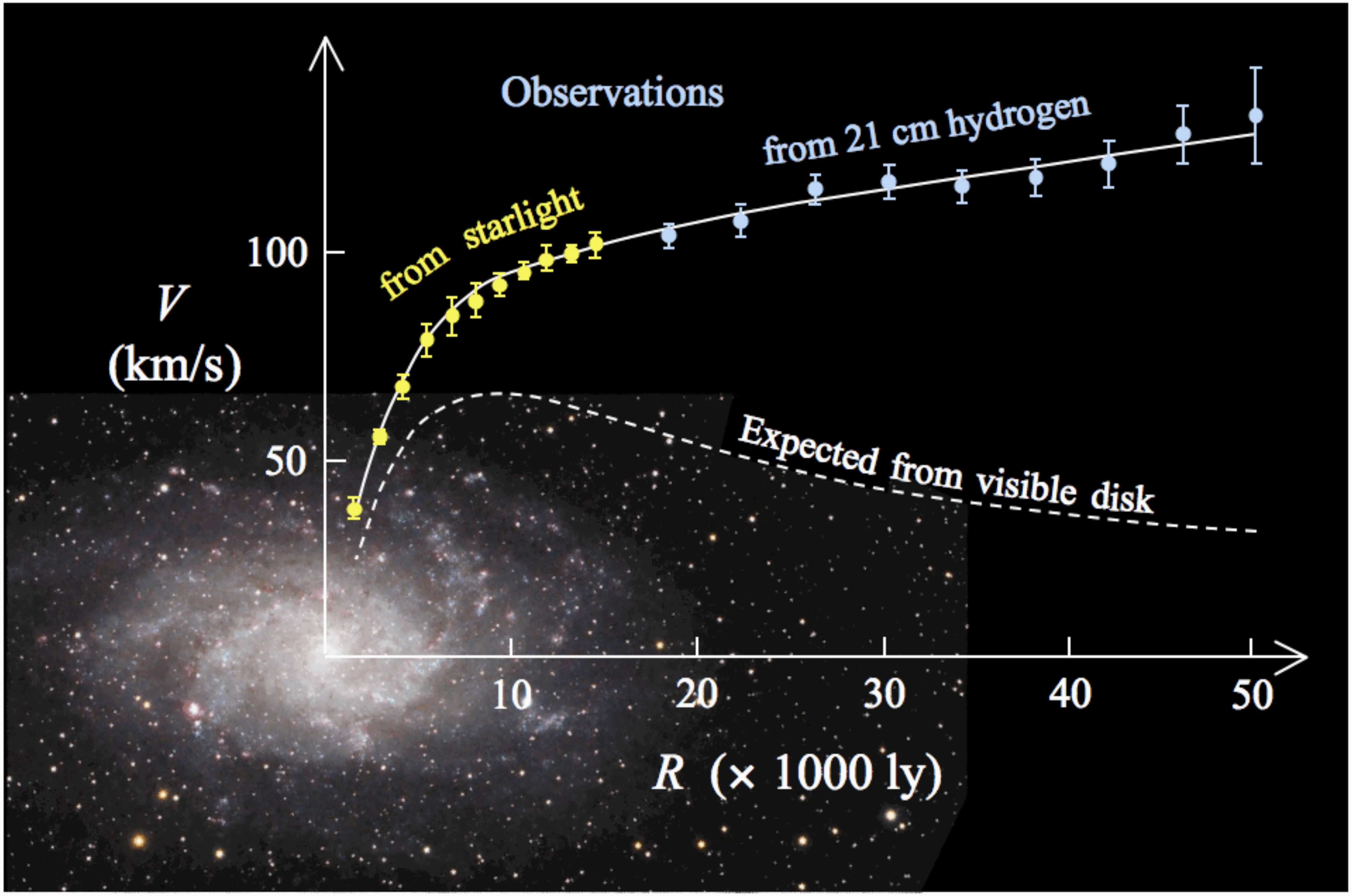
Quantum Sensors for Fundamental Physics
Oxford University
17th October 2018





Galactic dark matter problem



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

Axions and the Strong CP problem

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

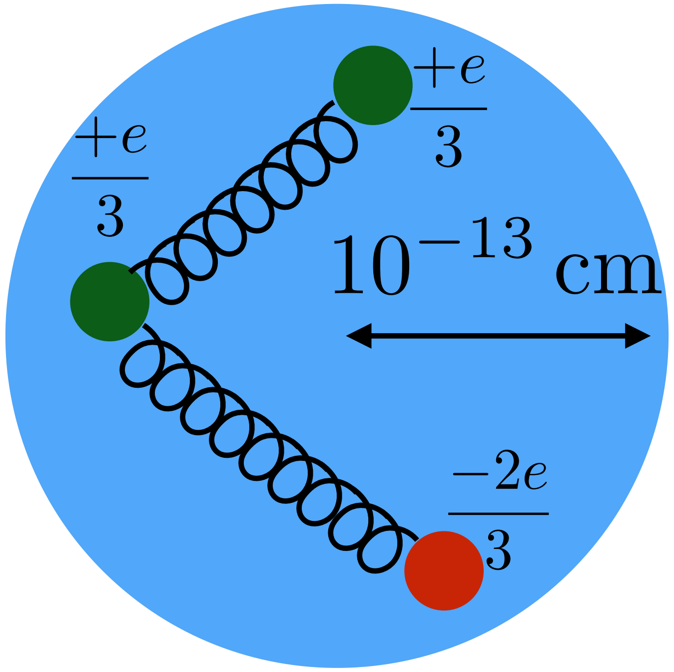
NON-ABELIAN	**NON-ABELIAN**	**ABELIAN**
CP CONSERVING!	**CP VIOLATING**	**CP CONSERVING**

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

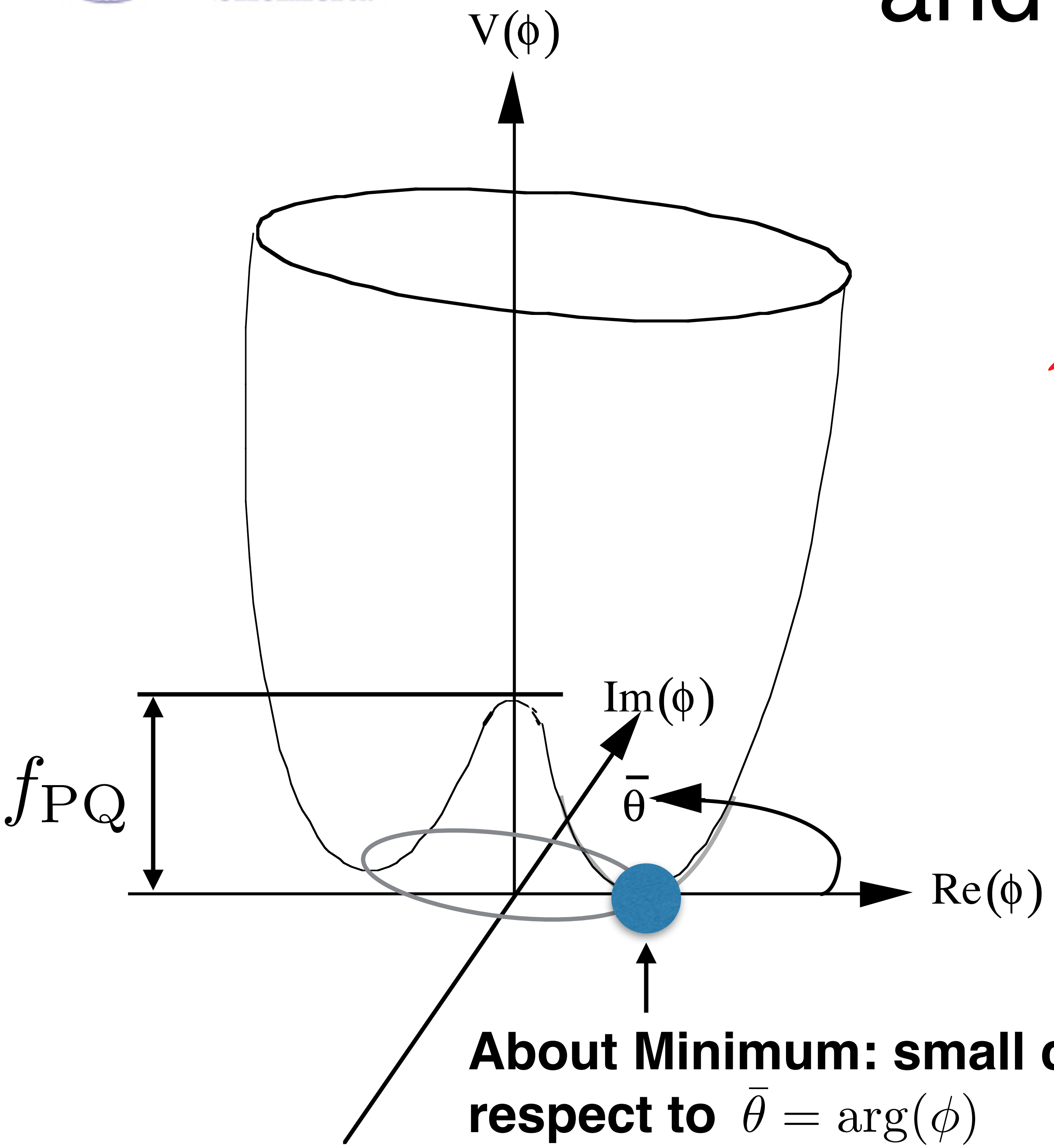
Evidence for CP conservation in the SU(3) strong interactions from multiple measurements of neutron and nuclear electric dipole moments. For example, neutron EDM < 10^{-26} e-cm.

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



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

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

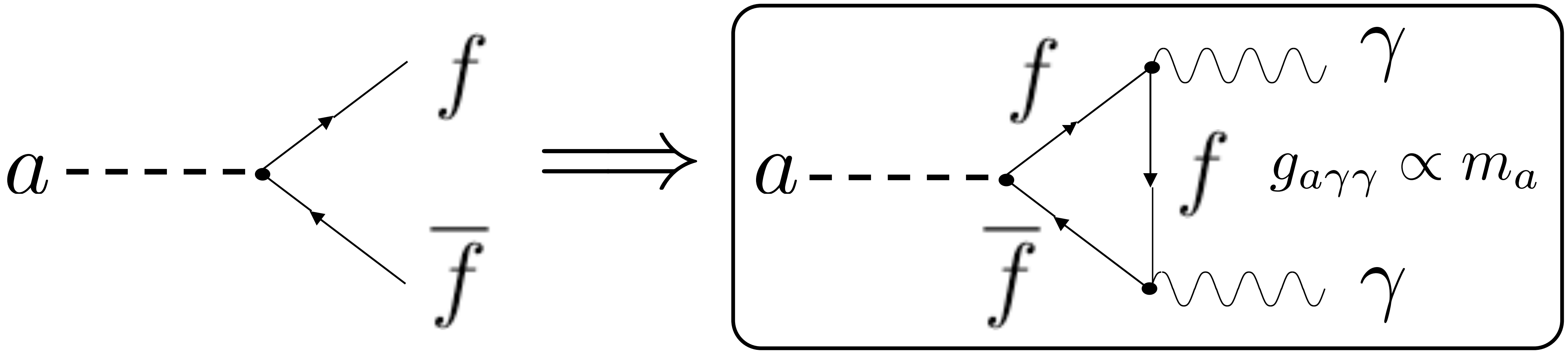
About Minimum: small curvature (hence small mass) with respect to $\bar{\theta} = \arg(\phi)$

Axion DOF

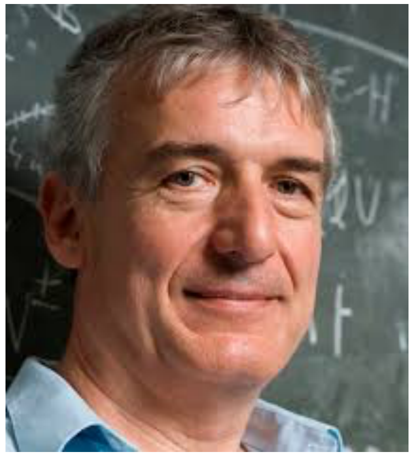
Axion Phenomenology

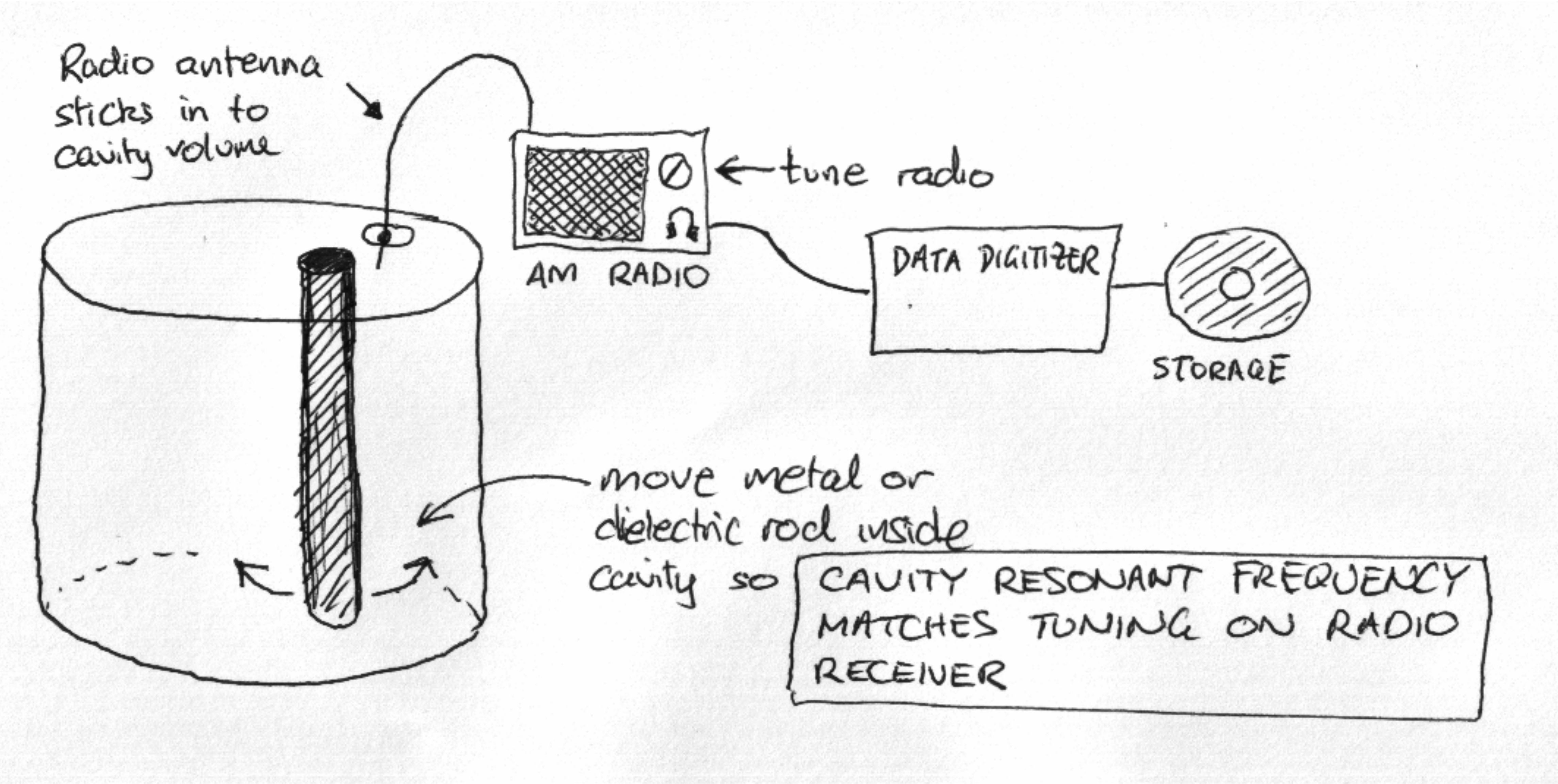
The axion is a pseudoscalar; has the same quantum numbers as the π^0, and the same interactions, but with coupling strengths scaled by the axion mass

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

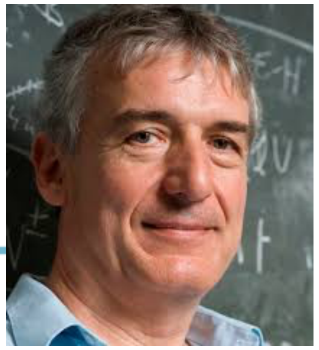


Sikivie-Type Resonant Cavity Axion Search

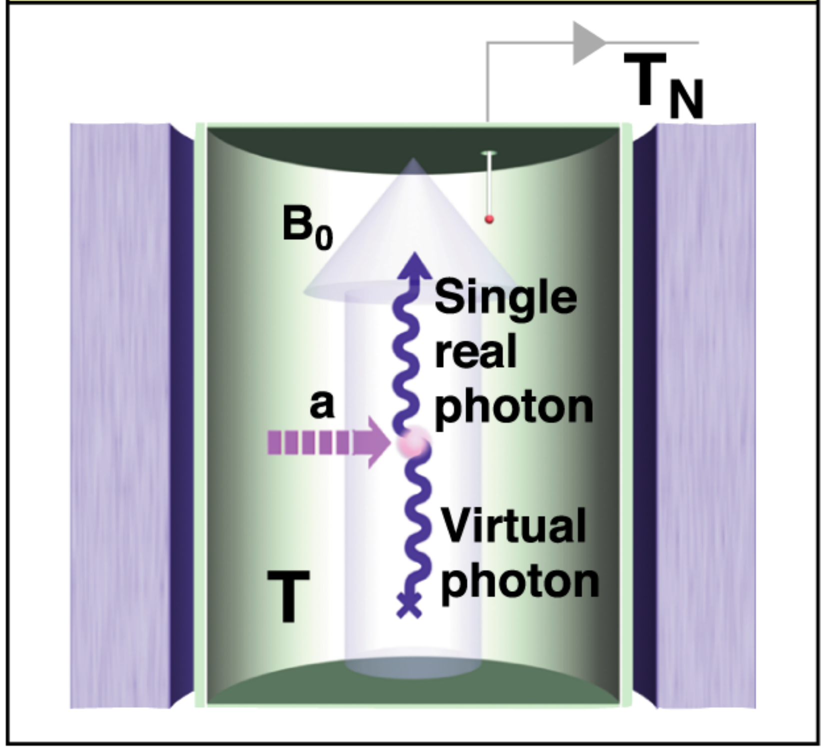




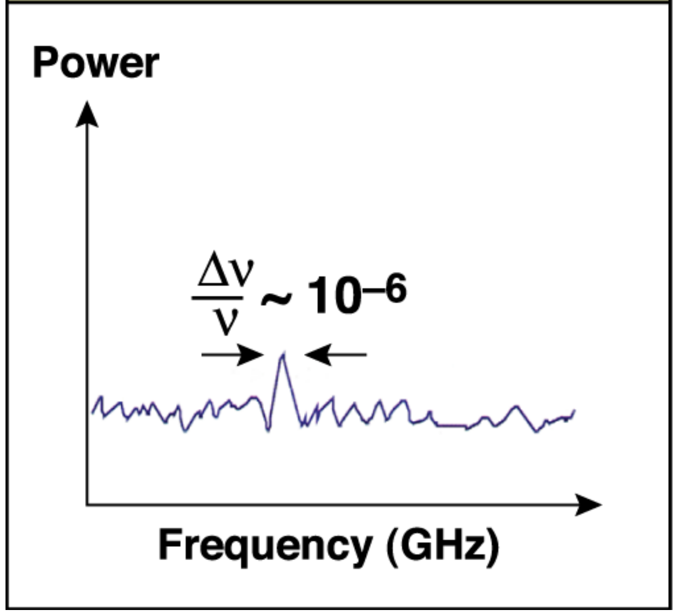
Some experimental details of the Sikivie RF-cavity technique



Primakoff Conversion



Signal



- **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

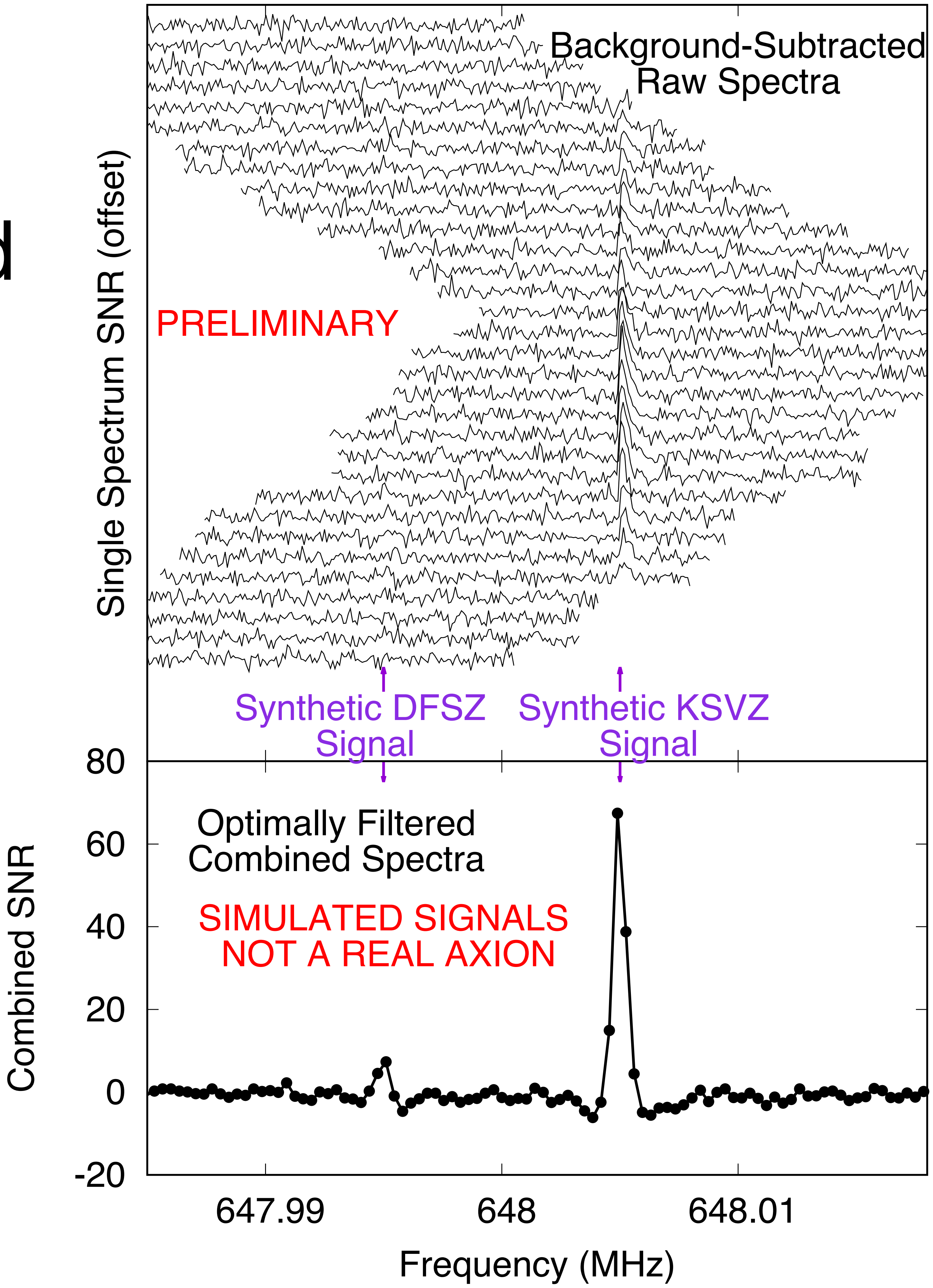
Signal to noise ratio: the ratio of the signal power to the size of the bin-to-bin fluctuations in noise power

Radiometer Equation (Gibbs 1902)

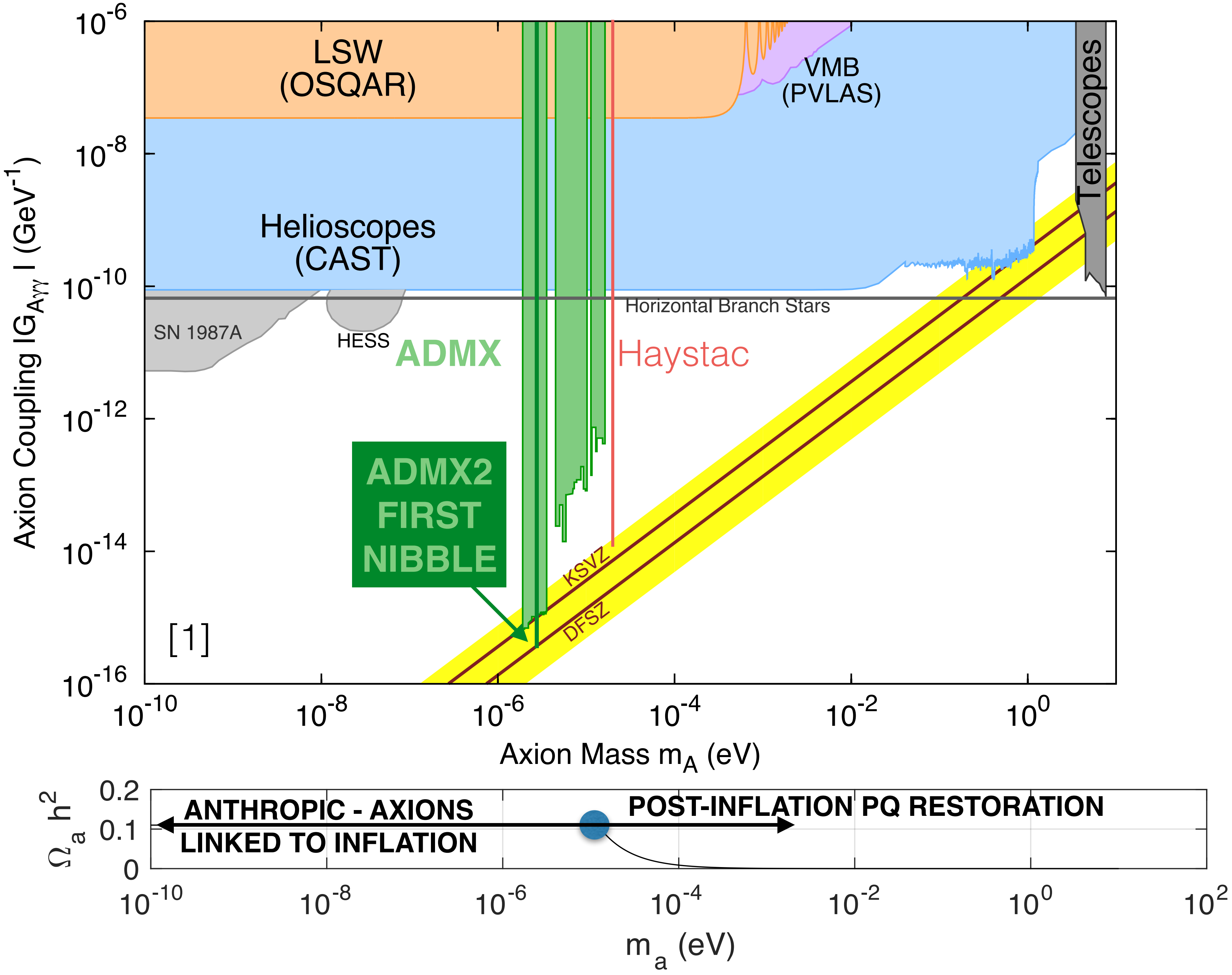
$$\mathrm{SNR} = \frac{\mathrm{P_s}}{\sigma_{\mathrm{PN}}} = \frac{\mathrm{P_s}}{\mathrm{P_n}}\sqrt{\Delta\nu\,\mathrm{t}}$$

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

Calculated Signal Strengths in ADMX2

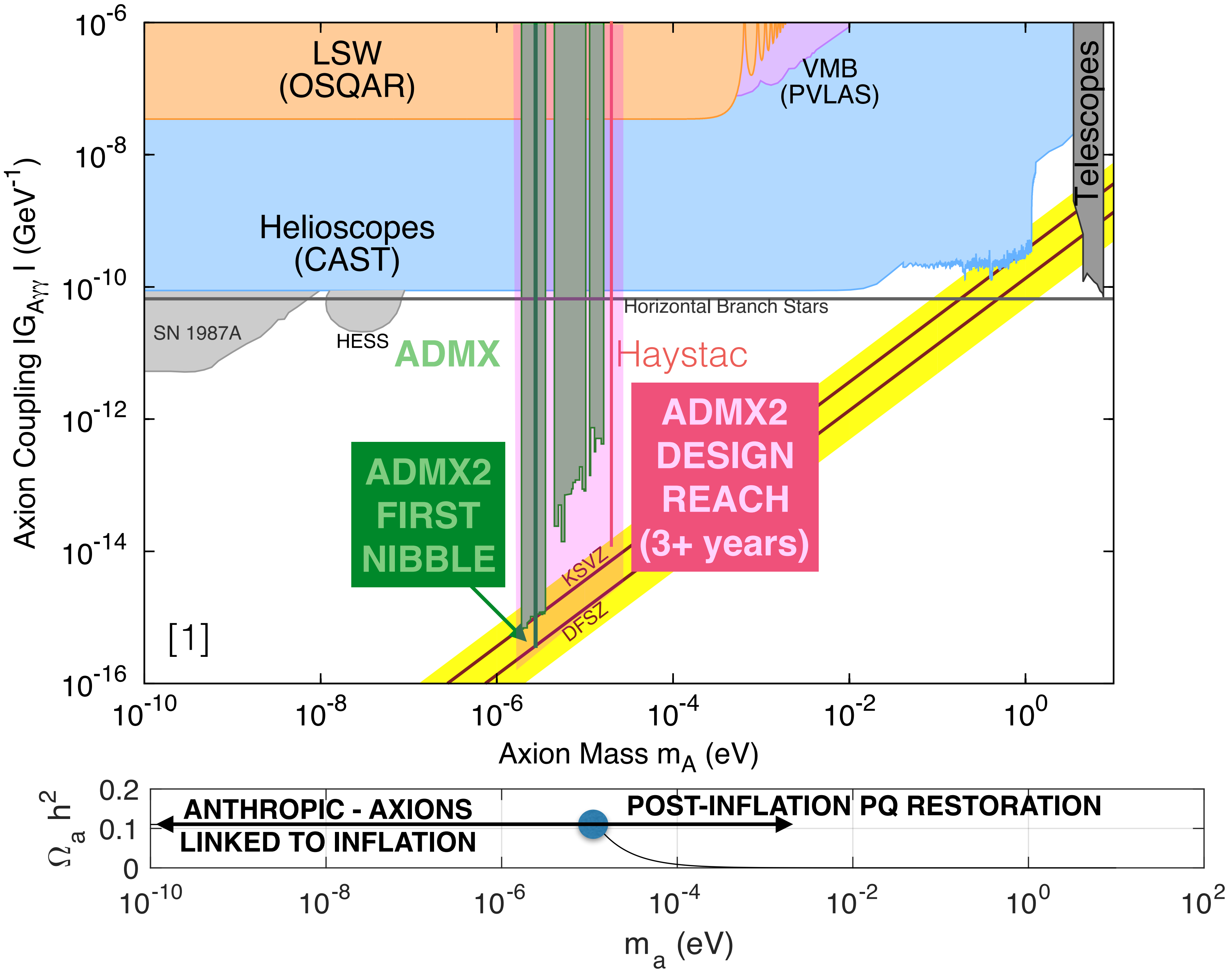


Recent Results from ADMX



[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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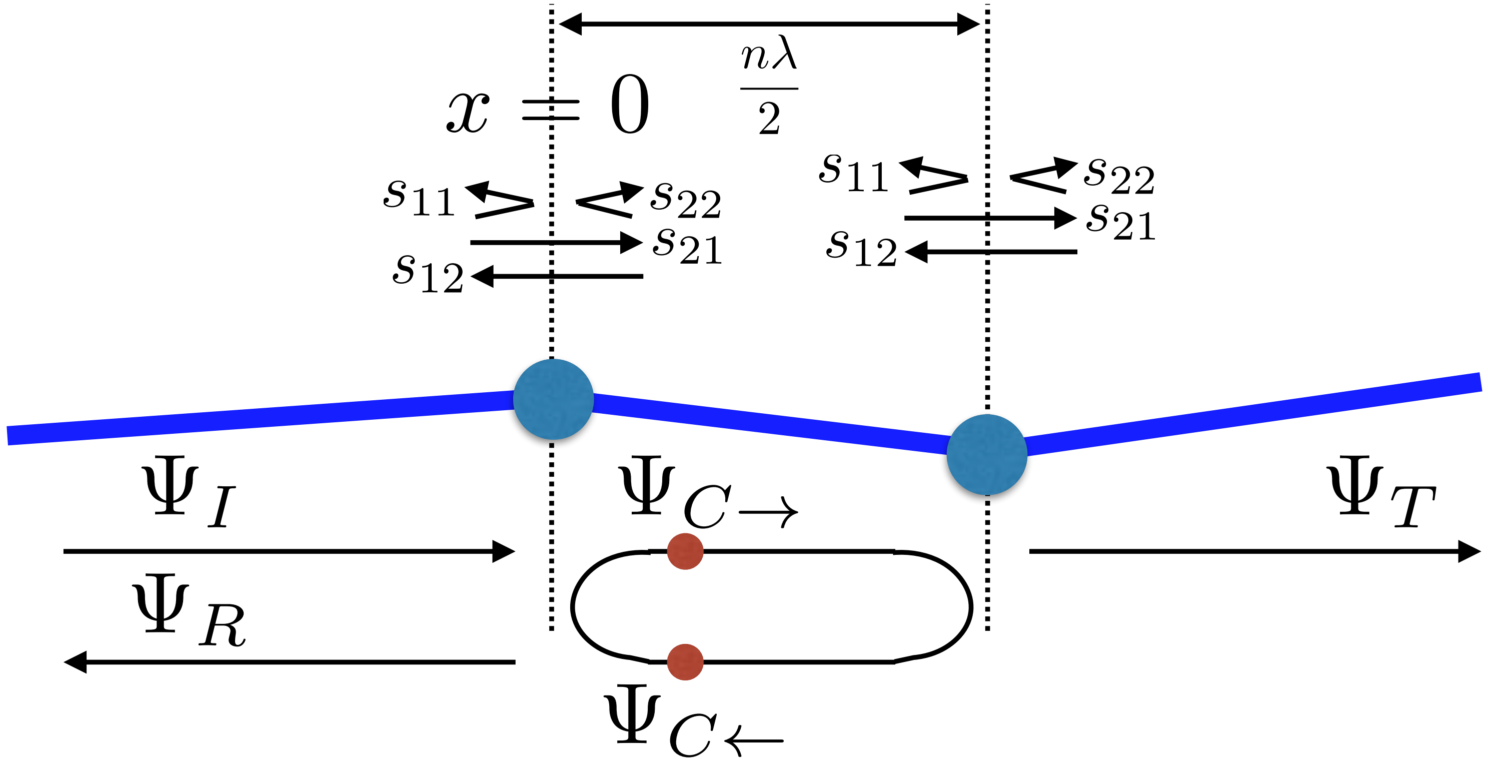
What is the resonant cavity actually doing? Storing energy.



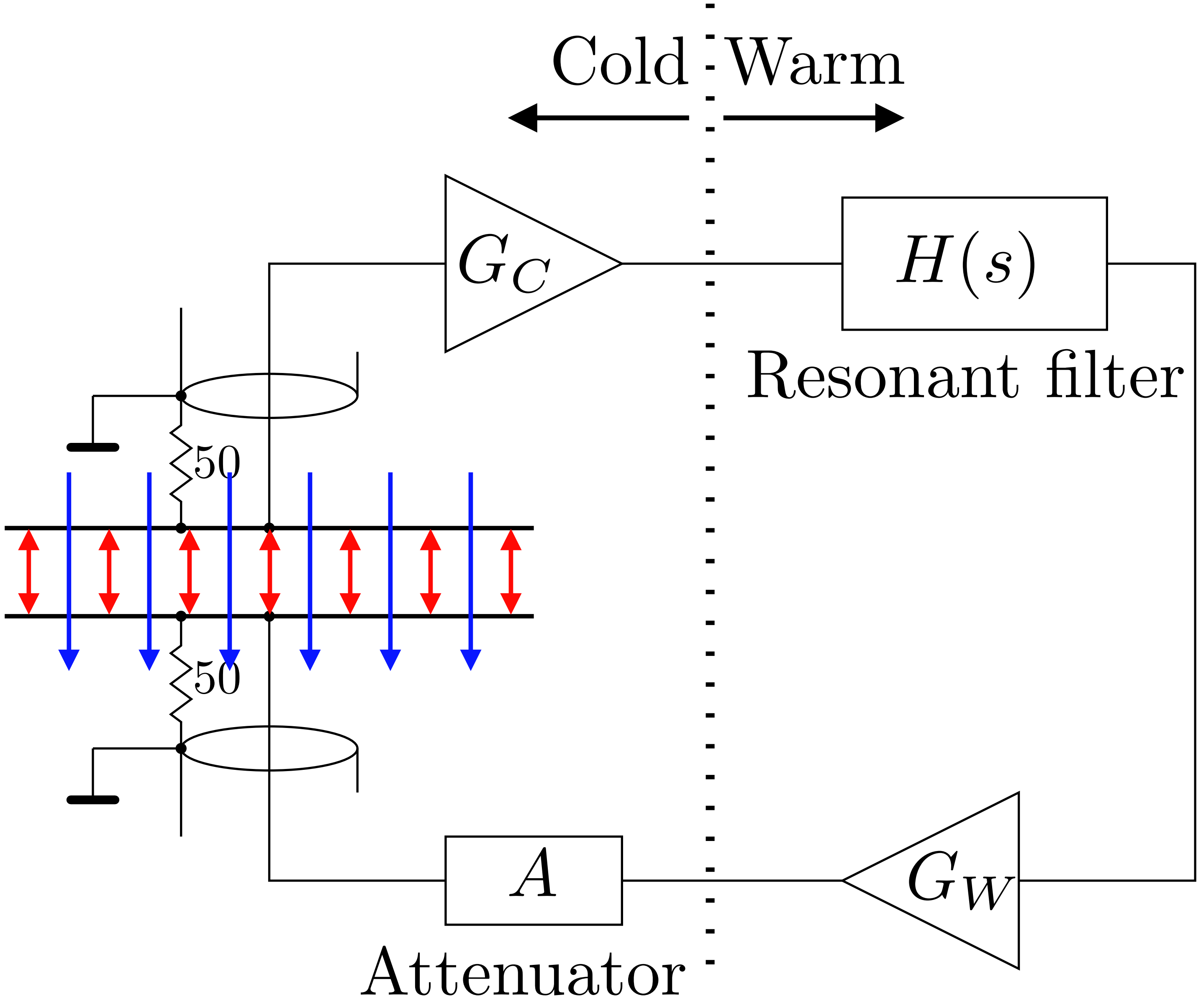
1.) So long as the circulating field aquires a phase of $2n\pi$ in a round-trip, **resonance** results. This is the Nyquist stability criterion, on which ALL resonators rely.

2.) For an incident field to drive the resonance to high amplitude, it must be coherent over the at least the round trip time of the circulating field.

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

Coherence time

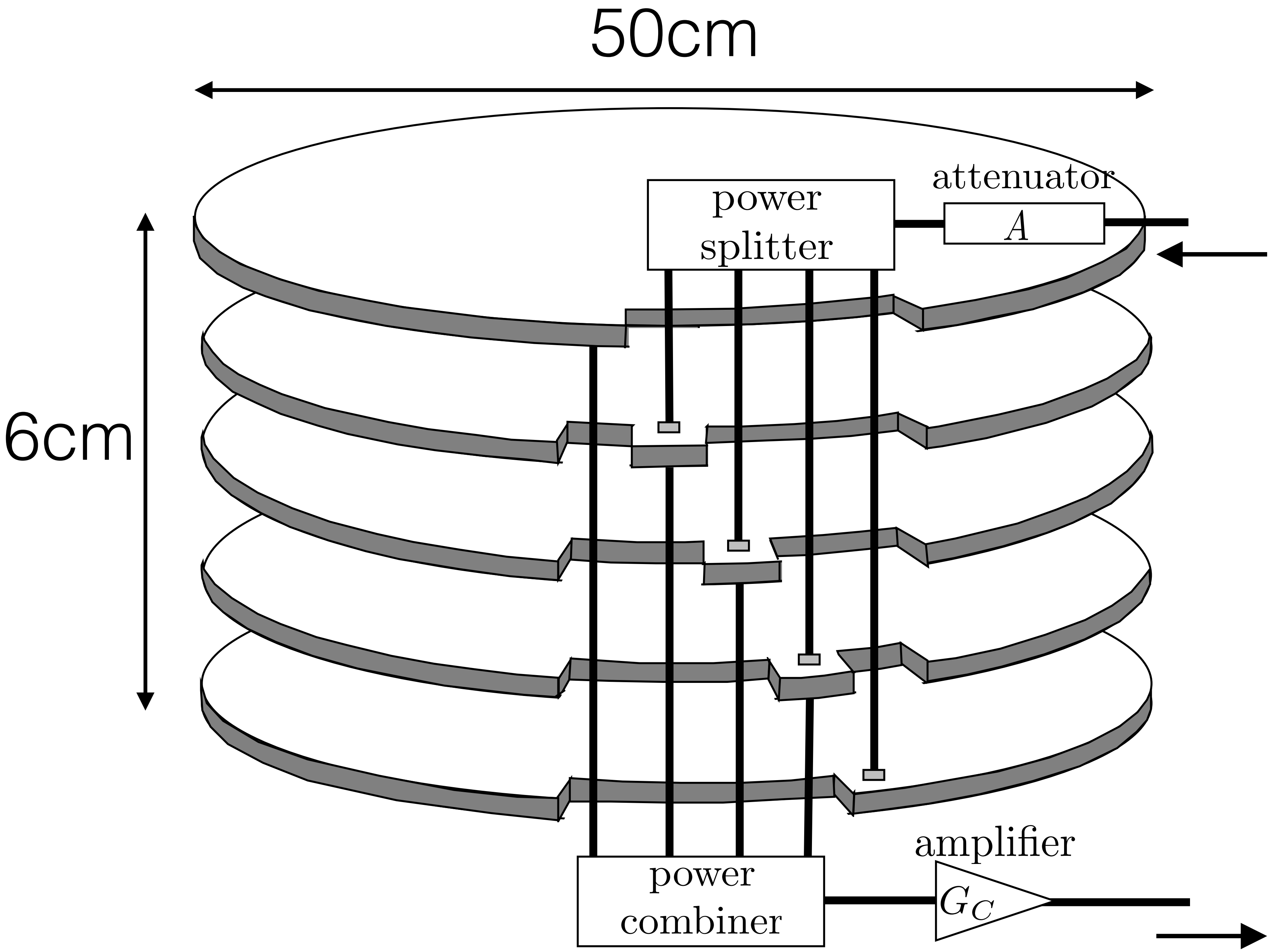
De Broglie wavelength of halo axions (assuming 4 microelectronvolts), $\lambda = \frac{2\pi\hbar c}{\beta m c^2} \simeq 500\,\mathrm{m}$

Virial velocity of cold dark matter is about 240 km/s, which is 8e-4c, so coherence time is **2ms**.

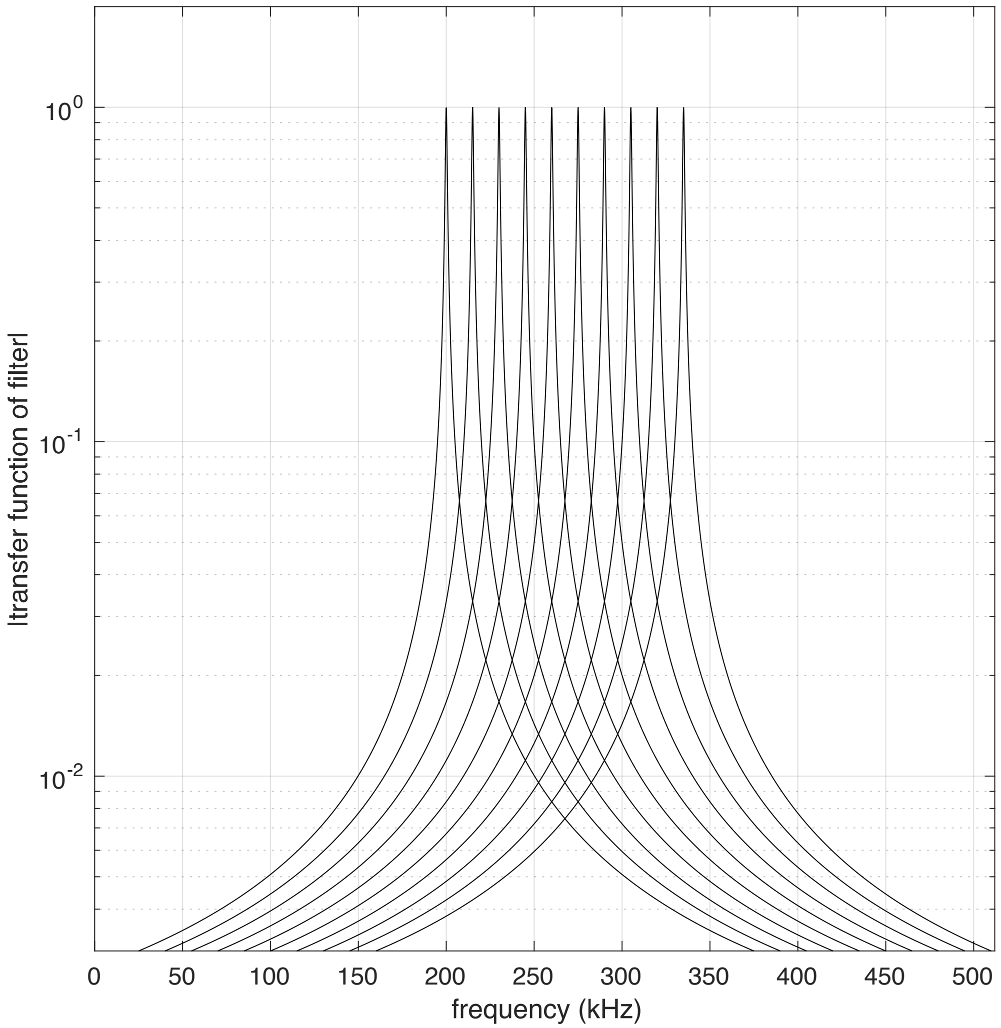
Assume feedback loop involves 20m of RG401 coax and a 250MHz ADC/DAC pair, the total delay time round the loop is 108 ns (dominated by the coax). This means the axion signal can circulate 18500 times around the feedback loop in 1 e-folding of coherence

Conclude that a feedback induced resonance is just as good as a cavity at enhancing the axion signal by a factor of Q.

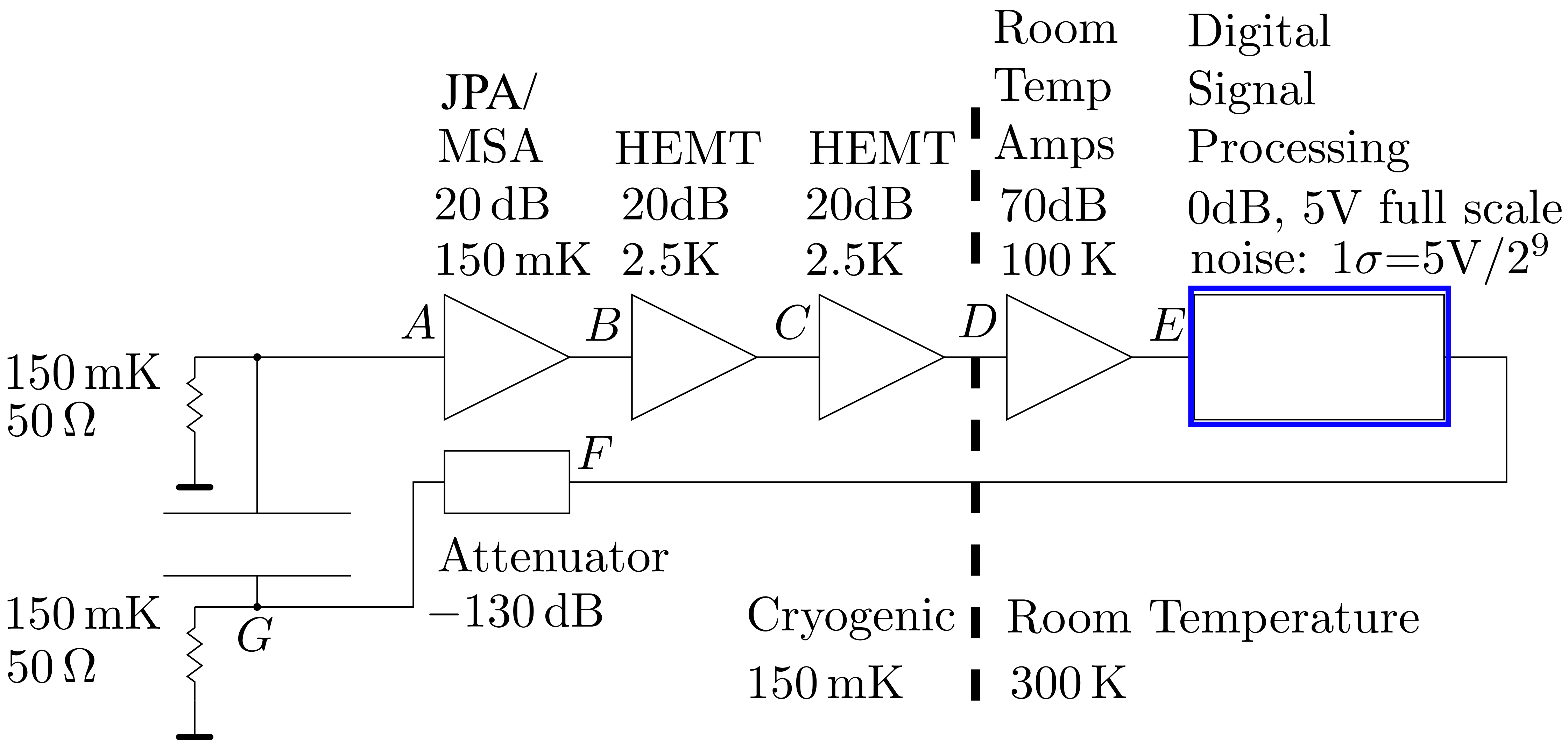
Capacitors in parallel



Resonances in parallel



Electronics in practice



150 mK 50 Ω

150 mK 50 Ω

JPA/ MSA 20 dB 150 mK

HEMT 20dB 2.5K

HEMT 20dB 2.5K

Room Temp Amps 70dB 100 K

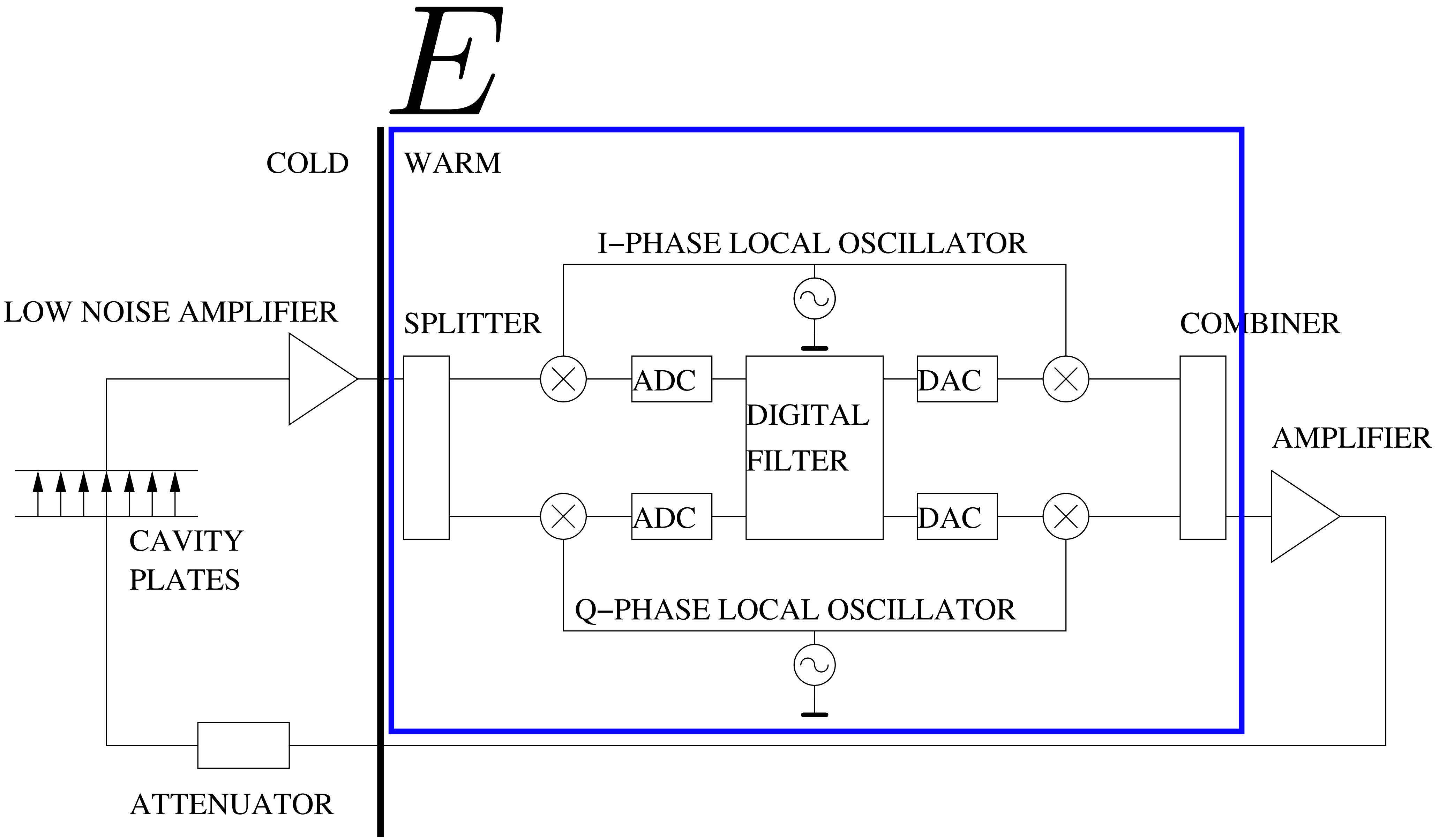
Digital Signal Processing 0dB, 5V full scale noise: $1\sigma = 5\text{V}/2^9$

Attenuator -130 dB

Cryogenic 150 mK

Room Temperature 300 K

Resonant electronics



Total noise power

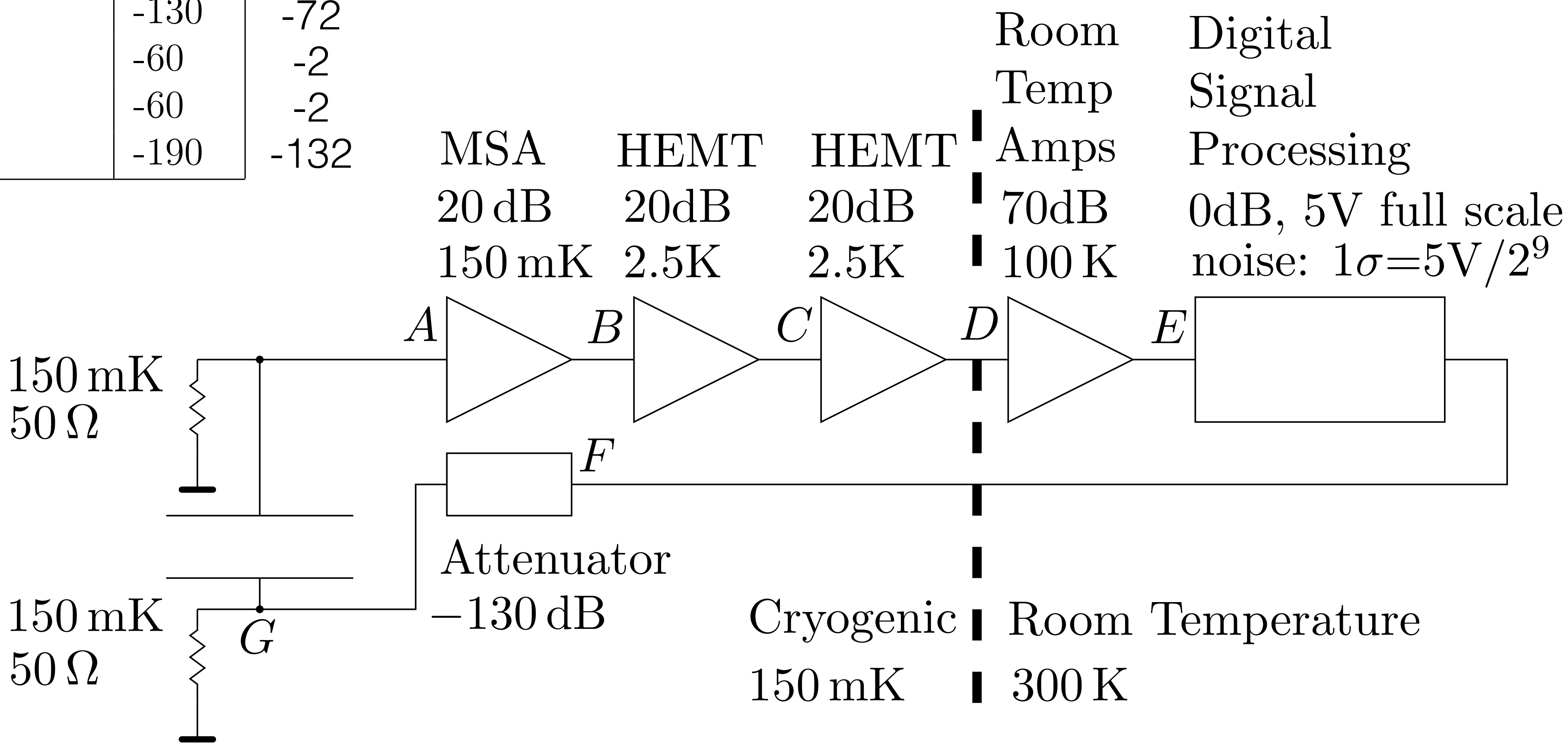
100 15kHz wide resonances, separated by 150kHz.
Q per resonance of approx 1GHz/15kHz=67000.
Total bandwidth into digital electronics 15MHz.
Noise in 15MHz band assuming system noise temperature of 300mK, -132dBm.

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

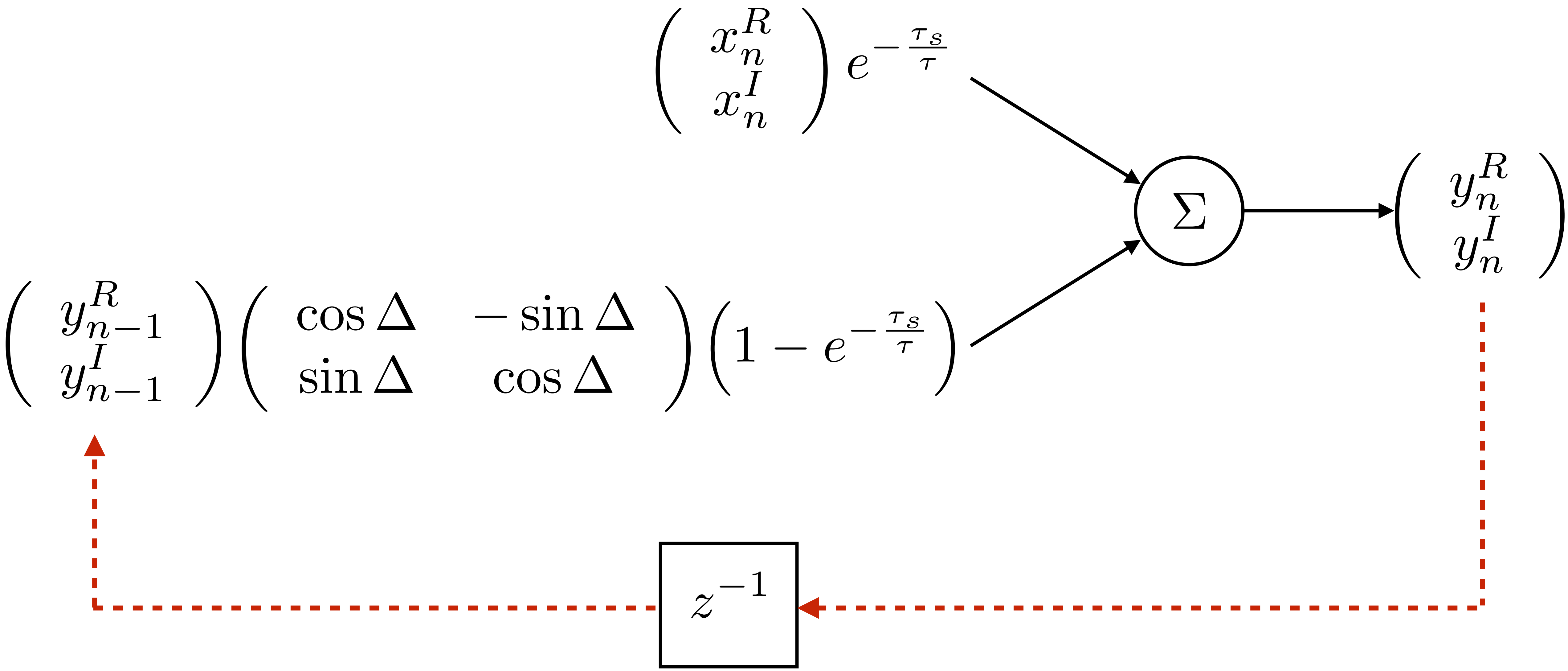
Location	Total summed noise into 750Hz bandwidth [dBm]	Noise from local component into 750Hz bandwidth [dBm]	Signal power [dBm]	**Noise in 15MHz bandwidth [dBm]**
A	-175	-178	-190	-132
B	-155	-166	-170	-112
C	-135	-166	-150	-92
D	-115	-150	-130	-72
E	-45	-76	-60	-2
F	-45	-178	-60	-2
G	-175	-178	-190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



Short term plans for resonant feedback axion detector

- Capacitor prototype to be installed on ADMX below main cavity by December 2018. Volume of 3 litres in a 7T magnetic field.
- 2nd FPGA prototype to be developed - 100MHz bandwidth. Implement 100 parallel filters and do warm test.
- Field test on ADMX prototype Easter 2019

Recursive IWAVE digital filter real representation



$$\begin{pmatrix} x_n^R \\ x_n^I \end{pmatrix} e^{-\frac{\tau_s}{\tau}}$$

$$\begin{pmatrix} y_{n-1}^R \\ y_{n-1}^I \end{pmatrix} \begin{pmatrix} \cos\Delta & -\sin\Delta \\ \sin\Delta & \cos\Delta \end{pmatrix} \left(1 - e^{-\frac{\tau_s}{\tau}}\right)$$

$$\Sigma$$

$$\begin{pmatrix} y_n^R \\ y_n^I \end{pmatrix}$$

$$z^{-1}$$

[Memory buffer]

Frequency response

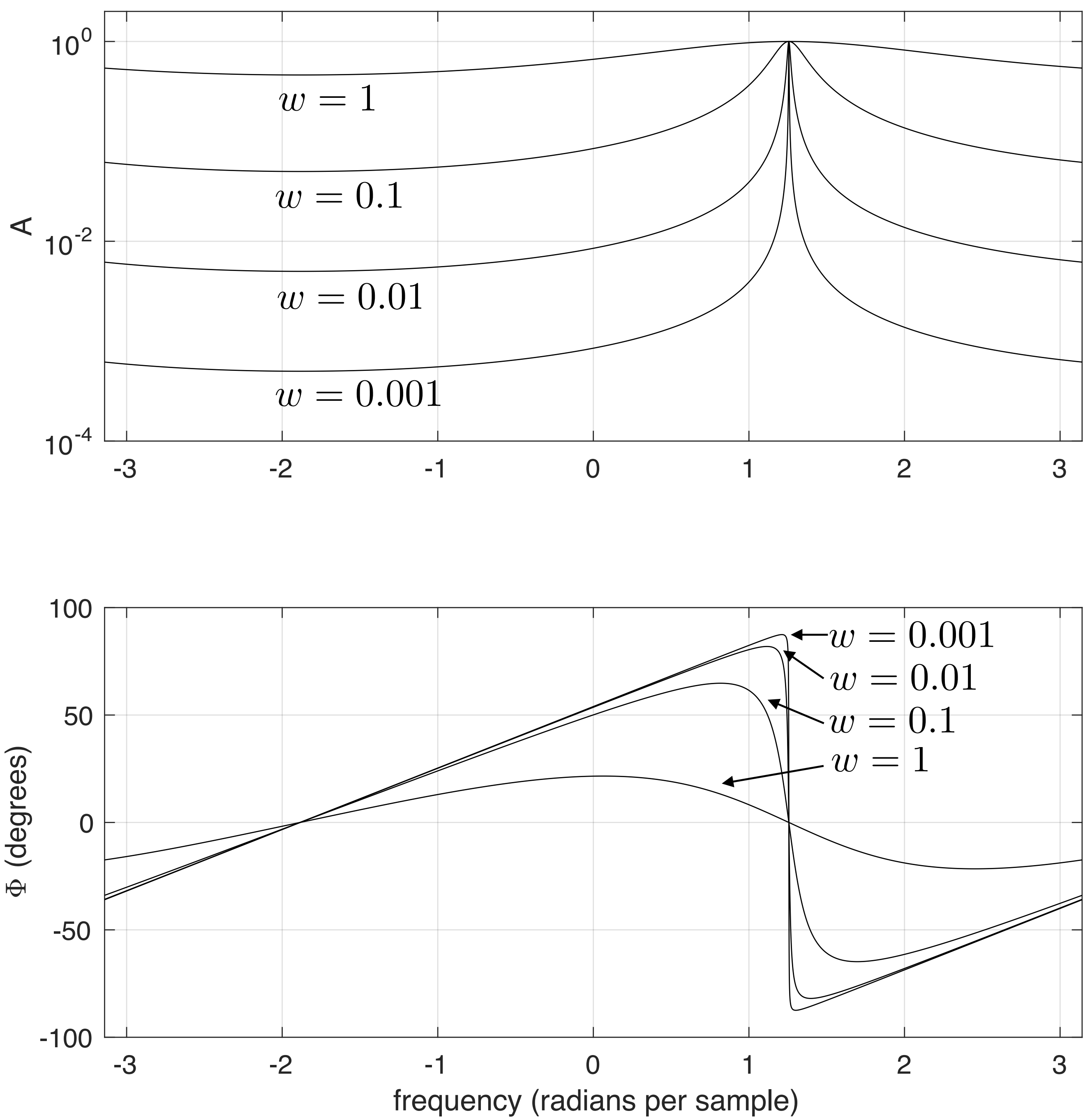


Fig. 2. The response of APL to phasor inputs as a function of the phasor frequency in radians per sample, for different values of the parameter w. Smaller w yield a sharper peak in the response at Δ, where Δ is the response frequency of APL in radians per sample.

Where is the quantum limit?

At 1GHz, a single quantum is at

$$hf = 6\,\mu\mathrm{eV}$$

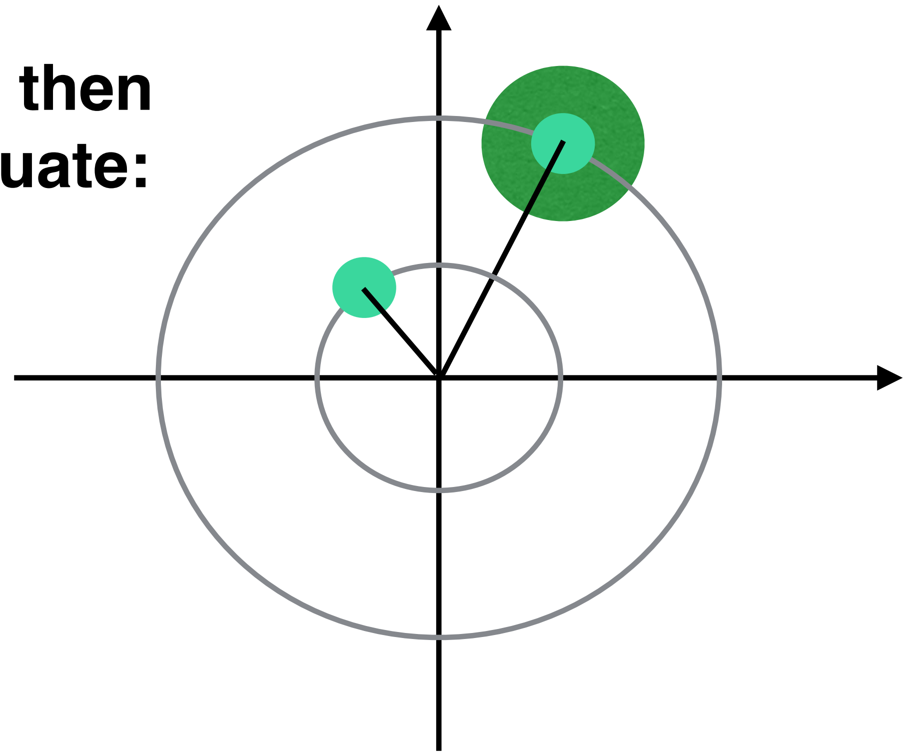
The ADMX electronics has a noise temperature of 300mK, so that $k_B T = 26 \mu e V$

This is 4.3 quanta of oscillation. The state of this feedback circuit is that of a not-very-highly-excited, software configurable quantum harmonic oscillator.

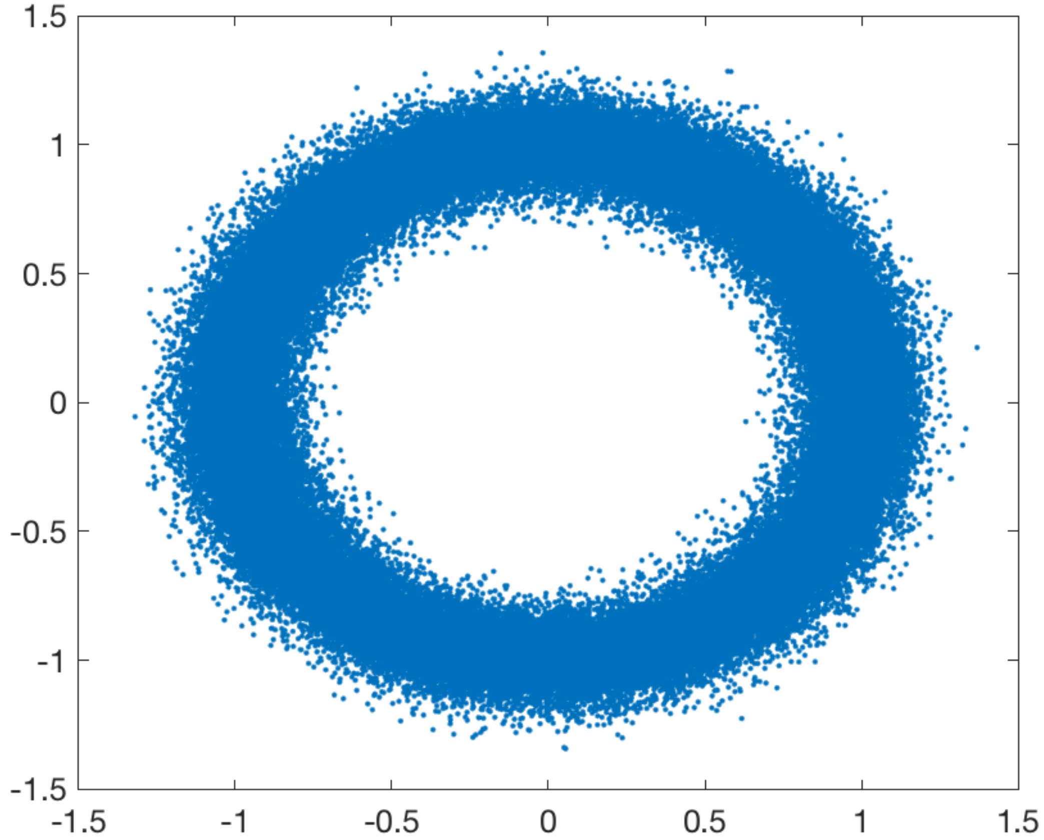
Action of IWAVE digital filter on a simulated Glauber state

45Hz input - Phasor with unit amplitude + r.m.s. 0.1 gaussian displacement, phase randomised over 2pi.
Response time of 1s
Filter Q of 142.

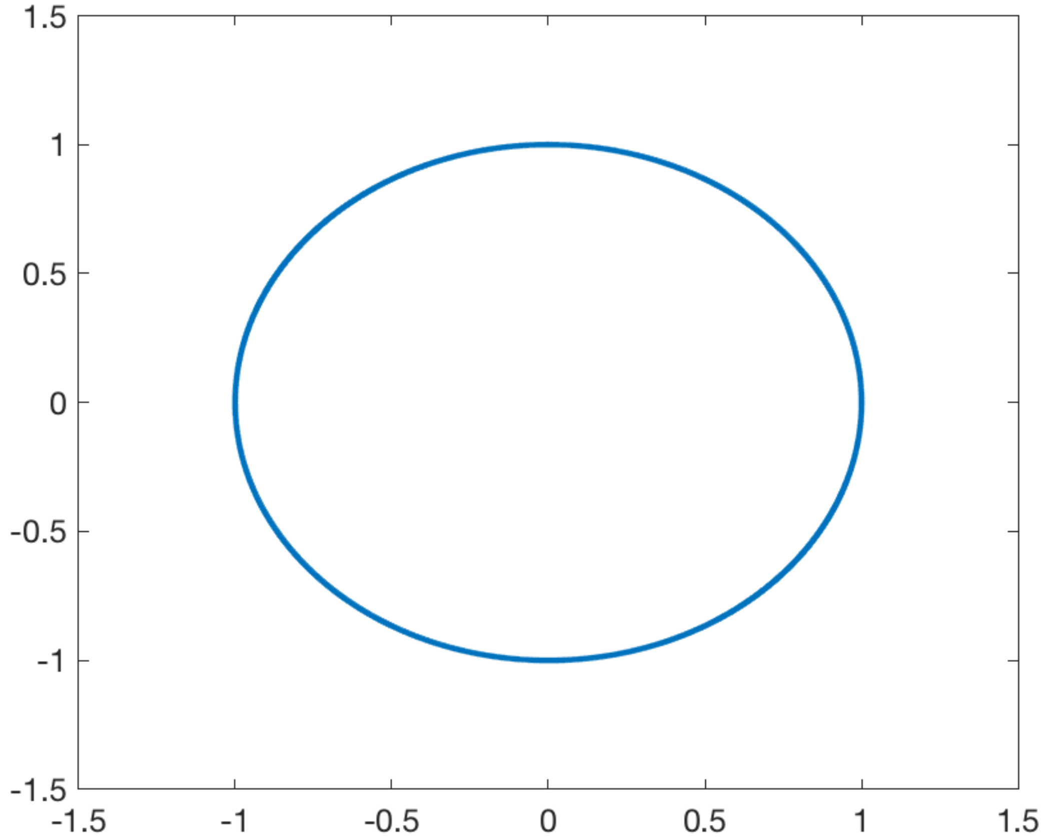
Filter then attenuate:



IN



OUT



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.

Summary

- Quantum measurement is already exploited through SQUID and JPA amplifiers developed for axion searches.
- Resonant feedback could speed up the search rate of these experiments to reasonable discovery potential.
- Same ideas applicable to other hidden sector probes.
- Careful study and prototyping towards these ideas is very well aligned with QSFP.
- Applications of quantum-limited resonant feedback beyond dark matter are intriguing (at least to me).