Resonant vs. Broadband Axion Dark Matter Searches in the Background-free Limit – an amicus brief for Snowmass CF2 - IF1

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With the advent of new single photon detectors (qubits [1], atoms [2], superconducting nanowires and other Cooper pair-breaking sensors [3, 4], etc.) with ultralow dark rates operating in the microwave to infrared bands, it is timely to consider the possibility of background-free axion dark matter searches in the high-mass axion window. In this case, the sensitivity of an experiment is determined only by the shot noise in the expected signal photon rate, i.e. by the availability of signal photons to detect [5]. For the case of spontaneous emission from the dark matter wave into the photon vacuum state, the signal photon rate is given by:

$$R_{\mathrm{s}} = 1.2 \times 10^{-6}\ \mathrm{Hz} \times \left(\frac{\rho_{\mathrm{a}}}{450\ \mathrm{MeV/cm^3}}\right)\left(\frac{g}{0.36}\right)^2\left(\frac{B}{9\ \mathrm{T}}\right)^2\left(\frac{\mathrm{V}}{(3\ \mathrm{cm})^3}\right)\left(\frac{Q_{\mathrm{c}}}{1}\right). \tag{1}$$

In this equation, ρ_a is the local axion dark matter density, $g = 0.36$ controls the axion-photon coupling $g\alpha/\pi$, and B is the DC laboratory magnetic field. V is the volume of the cavity used in resonant searches like ADMX [6] or HAYSTAC [7] and is typically a cubic Compton wavelength $V \approx (1/m_a)^3$ to maintain the resonant condition and be free of an excessive number of level crossings. Alternatively, it can be the area of the dish antenna-like emitting surface multiplied by the axion Compton wavelength (V=Area$/m_a$) in the case of broadband searches such as BRASS or MADMAX [8, 9]. In either case, the signal falls with increasing signal frequency $f = m_a/2\pi$. A typical cavity volume is 1 cubic wavelength which is $(3\ \mathrm{cm})^3$ at 10 GHz frequency corresponding to 41 μeV mass. Q_{c} is the resonant enhancement factor from the cavity or from the multiplicity of dish antennas, and is set to unity here for reasons which will become apparent below. This formula holds for each tuned detector configuration, such as a cavity tuned to a particular resonant frequency to search for axion waves lying within the bandpass of the cavity.

A surprising result is that when in background-free operation, the logarithmic frequency scan rate or equivalently the scan time per frequency octave is independent of the quality factor Q_{c}. Suppose one wants to get $N_\sigma = 3$ statistical sensitivity to the rate predicted above. Then one must collect $R_{\mathrm{s}} \times t_{\mathrm{int}} = N_\sigma^2 = 9$ photons so that a 3σ downward Poisson fluctuation would not result in a vanishing signal. The integration time required at each cavity frequency tuning to achieve this sensitivity is therefore $t_{\mathrm{int}} = N_\sigma^2/R_{\mathrm{s}}$. The bandwidth of the cavity filter tuned to frequency f is $\Delta f = f/Q_{\mathrm{c}}$. The logarithmic frequency scan rate is therefore

$$\frac{d\log f}{dt} = \frac{1}{f}\frac{\Delta f}{t_{\mathrm{int}}} = \frac{1}{f}\frac{(f/Q_{\mathrm{c}})R_{\mathrm{s}}}{N_\sigma^2} \propto \frac{B^2 V}{N_\sigma^2} \tag{2}$$

where the RHS contains only experimental parameters and is independent of Q_{c}. In this case, the experiment should be designed with sufficiently small detection bandwidth so that the total background counts remain vanishing, or if there is an independent need to operate in a highly resonant mode – e.g. for dispersive quantum non-demolition readout. For a Boltzmann-suppressed thermal occupation number $N_{\mathrm{occ}} = (\exp(hf/kT) + 1)^{-1}$, the thermal photon rate is $R_{\mathrm{thermal}} = N_{\mathrm{occ}}\Delta f$, and one should choose Q_{c} to be sufficiently large to reduce Δf such that the number of collected background photons $N_{\mathrm{bkgd}} = N_{\mathrm{occ}} \times \Delta f \times t_{\mathrm{int}} = N_{\mathrm{occ}} \times (f/Q_c) \times (N_\sigma^2/R_s) \ll 1$. Using the above values with a temperature $T = 20$ mK, one finds that a cavity search with volume $V = 1/f^3$ is background-free above $f \gtrsim 16$ GHz when using the typical value $Q_c = 10^4$ for copper cavities compatible with the high magnetic fields used in axion searches. Above $f \gtrsim 20$ GHz the cavity experiment is background-free even with $Q_c = 1$, thus obviating the need for a resonant search. At frequencies $f > 1$ GHz, a single broadband dish antenna (i.e. $Q_c = 1$) of area $A = (30\text{ cm})^2$ provides a larger effective volume, and becomes background-free above $f \gtrsim 15$ GHz. If such low temperature operation can be achieved, then multiple dishes of multiplicity $Q_c > 1$ such as envisioned in the MADMAX configuration are in principle not necessary at higher frequencies.

In background-free operation, the logarithmic scan time for one octave in frequency is

$$t_{\text{octave}} = \frac{dt}{d\log f}\log 2 = \frac{N_\sigma^2 \log 2}{R_{\text{s}}} = \begin{cases} 5\times 10^6\text{ s}\times\left(\frac{f_{\max}}{10\text{ GHz}}\right)^3, & V = \lambda^3\text{ cavity} \\ 5\times 10^4\text{ s}\times\left(\frac{\text{Area}}{(30\text{ cm})^2}\right)\left(\frac{f_{\max}}{10\text{ GHz}}\right), & \text{Broadband dish} \end{cases} \quad (3)$$

for the experimental parameters given above, e.g. for an upward frequency scan ending at 10 GHz. The scaling with volume uses the highest frequency $f_{\max}$ in the scan because operations at these higher frequencies will dominate the integration time. Inefficiencies from form factor, quantum efficiency, and duty cycle including instrument commissioning are not included in this estimated scan time, and could increase the actual run time by a factor of 10. These predictions may be considered as “best-case” scenarios without need to resort to brute force (gigantic mode-crowded cavities or bank-breaking magnets) to further increase sensitivity.

Given that there are approximately 15 octaves in the remaining high-mass axion window between 1 GHz - 30 THz, it seems prudent to pursue a community strategy of operating several experiments in parallel, each targeting a different range of signal frequencies. In particular, single device experiments at the upper end of the resonant cavity regime $f \approx 20$ GHz and at the upper end of the broadband antenna regime $f \approx 1-30$ THz require extremely long integration times and even longer actual project durations. Another consideration is that while broadband searches may see an unexplained excess of single photon events, they cannot narrow down the precise frequency of the photons corresponding to the dark matter mass nor determine whether the signal is monochromatic. Furthermore, each single photon detection technology operates over only a limited range of frequencies, typically one decade. The low mass axion window has similarly been naturally partitioned by detection technology, including LC resonators and NMR methods. So both technology factors and the science goal of determining the putative dark matter mass to perform follow-up experiments, indicate that even background-free broadband experiments should optimally be partitioned into frequency ranges and conducted using separate apparati.

Finally, it should be noted that while $f \approx 20$ GHz is a natural dividing line between resonant and broadband experiments when evaluated by this particular metric of background-free sensitivity, the actual photon-sensing technology to approach this boundary is still under development. From below, quantum non-demolition using qubits has shown promising initial results, and non-classical initial cavity state preparations such as squeezed vacuum or Fock/Cat states are starting to be used to enhance the signal/noise ratio and boost the frequency scan rate [7, 10]. From above, single photon detection via Cooper-pair breaking has been demonstrated at THz frequencies [4], and work is underway to both understand the rather large athermal background rates in these detectors and to reduce the energy thresholds. This robust detector R&D effort draws on expertise not only from traditional particle physics but also from the fields of AMO and condensed matter physics, with participants funded by DOE, NSF, NIST, and NASA and has strong ties with the emergent quantum technology. This widespread and cross-displinary interest is evidence of the vitality of the growing field of wave-like dark matter.

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[1] A. V. Dixit, S. Chakram, K. He, A. Agrawal, R. K. Naik, D. I. Schuster, and A. Chou (2020), 2008.12231, URL `http://arxiv.org/abs/2008.12231`.

[2] S. Gleyzes, S. Kuhr, C. Guerlin, J. Bernu, S. Deléglise, U. Busk, M. Brune, J.-m. Raimond, and S. Haroche, Nature **446**, 297 (2007), ISSN 0028-0836.

[3] Y. Hochberg, I. Charaev, S. W. Nam, V. Verma, M. Colangelo, and K. K. Berggren, Physical Review Letters (2019), ISSN 10797114.

[4] P. M. Echternach, B. J. Pepper, T. Reck, and C. M. Bradford, Nature Astronomy (2018), ISSN 23973366.

[5] S. K. Lamoreaux, K. A. Van Bibber, K. W. Lehnert, and G. Carosi, Physical Review D - Particles, Fields, Gravitation and Cosmology **88**, 1 (2013), ISSN 15507998, 1306.3591.

[6] T. Braine, R. Cervantes, N. Crisosto, N. Du, S. Kimes, L. J. Rosenberg, G. Rybka, J. Yang, D. Bowring, A. S. Chou, et al., Physical Review Letters **124**, 1 (2020), ISSN 10797114, 1910.08638.

[7] K. M. Backes, D. A. Palken, S. A. Kenany, B. M. Brubaker, S. B. Cahn, A. Droster, G. C. Hilton, S. Ghosh, H. Jackson, S. K. Lamoreaux, et al., pp. 1–8 (2020), 2008.01853, URL `http://arxiv.org/abs/2008.01853`.

[8] D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo, and A. Ringwald, Journal of Cosmology and Astroparticle Physics (2013), ISSN 14757516, 1212.2970.

[9] P. Brun, A. Caldwell, L. Chevalier, G. Dvali, P. Freire, E. Garutti, S. Heyminck, J. Jochum, S. Knirck, M. Kramer, et al., European Physical Journal C (2019), ISSN 14346052, 1901.07401.

[10] K. Van Bibber, K. Lehnert, and A. Chou, Physics Today (2019), ISSN 00319228.