Cross-correlation measurement techniques for cavity-based axion and weakly interacting slim particle searches

Ben T. McAllister, 1,* Stephen R. Parker, 1 Eugene N. Ivanov, 2 and Michael E. Tobar 1, †

1 ARC Centre of Excellence for Engineered Quantum Systems, School of Physics, The University of Western Australia, Crawley 6009, Australia
2 School of Physics, The University of Western Australia, Crawley 6009, Australia

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Weakly Interacting Slim Particles (WISPs), such as axions, are highly motivated dark matter candidates. The most sensitive experimental searches for these particles exploit WISP-to-photon conversion mechanisms and use resonant cavity structures to enhance the resulting photon signals. For WISPs to constitute Cold Dark Matter their required masses correspond to converted photons in the microwave and millimetre wave spectra. As such, searches for these types of WISPs are primarily limited by the Nyquist cavity noise as well as the first-stage broadband amplifier noise. In this work we propose and then verify a cross-correlation measurement technique to increase the sensitivity of cavity-based WISP searches. This is a two-channel measurement scheme where the cross-spectrum is computed, rejecting uncorrelated noise sources while still retaining correlated signals such as those generated by WISPs. The proposed technique cross-correlates individual cavity and amplifier systems, which can be spatially well-separated, thereby opening up opportunities for characterizing candidate dark matter WISP signals.

I. INTRODUCTION

Weakly Interacting Slim Particles (WISPs) are a broad class of theoretical particles with sub-eV masses that provide elegant and compelling solutions to a host of outstanding issues in particle physics and cosmology [1]. One of the most well known WISPs, the axion, arose out of a solution to the QCD Strong CP problem [2–5] yet also makes an ideal dark matter candidate [6–9]. Other WISPs, such as the Hidden Sector Photon [10–12] (Paraphoton [13]), can also be formulated as dark matter [14, 15].

Experimental searches for these particles typically involve exploiting WISP-to-photon couplings, which provide a sensitive portal for detection with minimal model dependency. The exact mechanism behind this coupling varies greatly between different WISPs. For example, the axion couples to two photons and axion-photon conversion can be induced when a magnetic field sources the required virtual photon (inverse Primakoff effect [16, 17]), while Hidden Sector Photons undergo spontaneous kinetic mixing analogous to neutrino flavour oscillations. In these processes the mass of the WISP directly translates to the frequency of the photons created. For Cold Dark Matter (CDM) WISP models the feasible mass range spans from ~1 µeV to ~1 meV [1, 5], which corresponds to photons within the microwave and millimetre-wave spectra (240 MHz to 240 GHz).

Two of the most sensitive and mature techniques for WISP searches in this region are the haloscope [16, 18, 19] and Light Shining through a Wall (LSW) [20, 21] experiments. Both approaches use microwave resonant cavity structures and low noise amplifiers as their enabling technologies. Haloscopes rely on converting the local WISP dark matter flux into photons within a cavity structure and detecting the resonantly enhanced power signal with a chain of amplifiers. LSW searches use two nominally identical cavity structures separated by an electromagnetically impenetrable barrier; one cavity is driven on resonance to generate WISP's while the second cavity functions in essence as a haloscope - although the origin of the WISPs is not galactic but rather due to WISPs from the first cavity traversing the barrier and reconverting to photons. Several microwave haloscope [22, 23] and LSW [24–28] experiments have been conducted to date, with no reports of any signals congruent with WISP detection. The majority of these searches have been conducted below 10 GHz due to a multitude of technical issues and limitations. Despite this, the higher frequency parameter space is theoretically well motivated and has even offered up some hints of possible CDM WISPs [29]. Some recent work suggests that 50-200 µeV, corresponding to 12.5-50 GHz is a promising region for axion searches [30]. Techniques such as the one detailed here will become increasingly useful in the push to larger numbers of cavities required for sensitive high frequency WISP searches, such as the planned ORGAN experiment [31].

In this work we outline new readout measurement techniques for cavity-based WISP searches. It is important to emphasize that the techniques and concepts discussed are readily applicable to a broad range of WISP searches, including LSW and proposals for new types of experiments [32–40].

II. WISP CAVITY RECEIVERS

An overview of a typical WISP cavity receiver, in this case an axion haloscope, is presented in Fig. 1. A static
external magnetic field is superimposed on the intrinsic (caused by thermal fluctuations) electric field of a microwave cavity such that the dot product of $\vec{B}_0$ and $\vec{E}$, the cavity-mode electric field, is ideally maximized. As axions traverse through the cavity and interact with the magnetic field they will convert in to photons, resulting in a build up of power in Watts,

$$P_a = \left( \frac{g_a \alpha}{\pi f_a} \right)^2 \frac{\rho_a}{m_a} V B_0^2 C \min (Q_L, Q_a),$$

where $g_a$ is a model-dependent parameter of $O(1)$ [5, 41–43], $\alpha$ is the fine structure constant and $f_a$ is the Peccei-Quinn symmetry-breaking energy scale [5]. The energy scale dictates the mass of the axion and the strength of its coupling to standard model particles; this is the parameter that haloscopes ultimately aim to measure or bound. The strength of the expected axion power signal also depends on the local density of axion dark matter, $\rho_a$. Cosmological observations provide an estimate for the local dark matter density (0.35 $\pm$ 0.08 GeV/cm$^3$ [44]), however it is important to note that to date axion haloscope searches have typically only excluded CDM axions under the assumption that they constitute all of the local dark matter. It is plausible that dark matter is comprised of more than one particle species and thus the local axion dark matter density is lower than has been assumed in previous haloscope searches. This opens up the possibility of needing to repeat axion searches in already excluded regions of parameter space to check for lower density axion CDM. The remaining factors of eq. (1) relate to the properties of the cavity used - $V$ is the volume, $Q_L$ is the loaded quality factor and $C$ is a form factor [45] describing the relative overlap of the axion-induced electromagnetic field and the electromagnetic field of the chosen cavity resonance, which is typically the TM$_{010}$ mode for haloscopes ($C \sim 0.69$). The so-called axion quality factor, $Q_a$, describes the expected structure of a virialized CDM galactic halo axion signal, where considerations of dispersion lead to a value of $\sim 10^6$. Nonvirialized axion CDM would have a narrower linewidth (higher $Q_a$) [23], approaching that of a quasi-monochromatic signal.

The aim of the cavity receiver is to resolve any signal generated by WISPs (such as axions, eq. (1)) over the intrinsic noise of the measurement system with some level of confidence. The two dominating noise contributions arise from the thermal noise of the cavity and the white technical noise of the first stage amplifier (A1), which we model as a noise source attached to a noiseless gain stage. Here we assume that the cavity and amplifier are critically coupled and in thermal equilibrium. We can express the Power Spectral Density (PSD, in units Watts/Hz) of cavity thermal fluctuations at the input of the amplifier as

$$S_{\text{pav}} = k_B T_0 \Gamma,$$

where $T_0$ is the physical temperature of the cavity and $\Gamma$ is the Lorentzian transmission coefficient of the cavity. Similarly the PSD of broadband amplifier technical noise at its input is given by

$$S_{\text{pmp}} = k_B T_{\text{eff}},$$

where $T_{\text{eff}}$ is the effective noise temperature of the first stage amplifier. This is assuming that the first stage amplifier and data acquisition system are operating at a frequency outside of the flicker noise regime for the amplifier. The gain of the first stage amplifier effectively suppresses the noise contributions of the later stage amplifiers to negligible levels [19]. We now define the SNR of a WISP cavity receiver as

$$\text{SNR} = \frac{S_x^{\text{max}} - \langle S_x \rangle}{\sigma_s}$$

(see Fig. 2, which illustrates many of these concepts). Where

$$S_x^{\text{max}} = S_{\text{sig}} + S_x.$$
Here \( S_x \), \( \langle S_x \rangle \) and \( \sigma_s \) are the value of the background noise PSD at the frequency of interest (essentially the sum of (2) and (3)) and the mean and standard deviation of the PSD in the absence of the WISP signal. \( S_{\text{sig}} \) is the value of the PSD of the WISP signal at the frequency of interest. The value of the noise PSD at the frequency of interest will be

\[
S_x = \langle S_x \rangle + k\sigma_s,
\]

where \( k \) is a random variable which tells us how many standard deviations the value of the noise PSD is away from its mean, in the absence of a WISP signal at the frequency of interest. Thus equation (4) becomes

\[
\text{SNR} = \frac{S_{\text{sig}} + k\sigma_s}{\sigma_s},
\]

So, combining the two terms in the numerator and noting that they represent the contributions to the combined PSD from the background noise and a WISP signal above the mean of the background at the frequency of interest, which we may call \( S_{\text{eff}}^{\text{sig}} \), we arrive at

\[
\text{SNR} = \frac{S_{\text{eff}}^{\text{sig}}}{\sigma_s}. \tag{5}
\]

Figure 2 illustrates this concept. When one considers that for a random noise spectrum averaged on a single channel

\[
\sigma_s = \frac{\langle S_x \rangle}{\sqrt{m}},
\]

where \( m \) is the number of averages, we arrive at

\[
\text{SNR} = \frac{S_{\text{eff}}^{\text{sig}}}{\langle S_x \rangle} \sqrt{m}. \tag{6}
\]

It should be stressed that \( S_{\text{eff}}^{\text{sig}} \) is simply a measure of how far the combined PSD is away from the mean at a given frequency. This definition of signal to noise is slightly different to the commonly used Radiometer equation, but it contains the same sources (ie the combined power on resonance from the WISP and the receiver, as well as the background noise from the receiver), and scales by root \( m \) as it should. We employ equation (4) for analysis in the following proof of concept experiments, whereas the above definition is presented for the purpose of reflecting the similarity between this expression and the more familiar Radiometer equation. Furthermore, it is a useful expression for comparing different measurement schemes. Detecting anything of value out of a WISP cavity receiver requires being able to confidently resolve the signal above the fluctuations of the spectrum. The measure of SNR presented in (4) is equivalent to how many standard deviations above the relevant level of background noise the signal is, ie an SNR of three is equivalent to a 3 sigma measurement, which is consistent with language in other areas of particle physics. We will utilise this expression, and (6), for the remainder of our discussion.

FIG. 3. Schematic of the measurement scheme used to demonstrate principles of cross-correlation. Both amplifiers were SR560 low-noise pre-amplifier models from Stanford Research Systems with separate 50 \( \Omega \) terminations attached to each input. Spectrums were recorded on the FFT with 1601 points in the frequency range 10-100 kHz, well outside of the flicker noise regime out of the amplifiers.

### III. CROSS-CORRELATION

Cross-correlation measurements [46–48] have been used for many years in the characterization of low noise devices such as microwave amplifiers and oscillators. The technique involves computing the cross-correlation function of two signals; any fluctuations that are not correlated between the signals are rejected, what remains is any process that is present in both signals and correlated. Applied correctly this provides a powerful tool to reduce or eliminate the noise contributions of measurement systems. Cross-correlation measurements are practically limited by the level of isolation between the two measurement channels, typically it is possible to achieve rejection of the uncorrelated noise on the order of 20 - 30 dB.

The cross-spectrum of two signals, \( a(t) \) and \( b(t) \), is defined as the Fourier Transform of the cross-correlation function,

\[
S^{ab}(f) = \mathcal{F} \left\{ \lim_{a \to \infty} \frac{1}{f} \int_0^f a(t)b(t - \tau)dt \right\}. \tag{7}
\]

However, experimentally we deal with digitized signals such that \( a(t) \) and \( b(t) \) have been sampled and now contain \( N \) discrete values. The discrete cross-correlation function is

\[
K_{ab}^{(i)} = \frac{1}{N} \sum_{k=1}^N a_kb_{k+|i-N|}, \tag{8}
\]

where the index \( i \) runs from 1 to \( 2N \). Hence the discrete implementation of eq. (7) is then

\[
S^{ab}(f_i) = \mathcal{D} \mathcal{F} \left\{ K_{ab}^{(i)} \right\}. \tag{9}
\]

where \( \mathcal{D} \mathcal{F} \) is the discrete Fourier transform. The cross-power spectral density (X-PSD) can then be obtained by normalizing eq. (9) over the resolution bandwidth (ie. multiplying by \( \tau_{\text{meas}} \)). We now consider the effect of averaging over \( m \) spectra and cross-spectra. During this process if \( a(t) \) and \( b(t) \) contain any signals that are uncorrelated they will be rejected from the cross-spectrum...
at a rate proportional to $\sqrt{m}$ [47, 48], until the limit of isolation between the two channels is reached.

For a single channel measurement, the error (standard deviation) is reduced with $\sqrt{m}$ while the mean, $\mu$, remains constant. In the cross-spectrum, the mean is reduced by $\sqrt{m}$ while the error (standard deviation) remains proportionally constant relative to the mean, but decreases by an absolute factor of $\sim 2\sqrt{m}$ (the actual factor, as given in [48] is $\frac{1}{\sqrt{\pi - 1}} \approx 1.912$). Once the limit of rejection is reached then the standard deviation of the cross-spectrum starts to reduce relative to the mean. Most WISP searches are unlikely to reach the limit of isolation between measurement channels.

We performed a simple measurement to demonstrate the principles of cross-correlation outlined in this section. Figure 3 shows the method used; data was collected for averages ranging from 4 to 1024. The mean of a single channel spectrum is shown (green circles) with error bars representing 1 standard deviation. The function $\mu_1/\sqrt{m}$ is plotted (red dashed line) as discussed in the text. The mean of the cross-spectrum (red circles) is also presented (grey dashed line) for the standard deviation. The function $\mu_2/\sqrt{m}$ is plotted (red dashed line) as discussed in the text.

FIG. 4. Mean of voltage spectra as a function of averages from the measurement scheme presented in Fig. 3. The mean of a single channel spectrum is shown (green circles) with error bars representing 1 standard deviation. A $\sqrt{m}$ dependence is shown (grey dashed line) for the standard deviation. The mean of the cross-spectrum is also shown (red circles) with error bars representing 1 standard deviation. A

IV. CROSS-CORRELATION WISP CAVITY RECEIVER MEASUREMENT TECHNIQUES

The cross-correlation WISP cavity receiver technique is illustrated in Fig. 5. Here two separate, nominally identical cavities are read out via independent channels. This is different to other multiple-cavity WISP receivers, where the cavities are power-combined and then read out via

FIG. 5. Schematic of the multi-cavity cross-correlation measurement technique. The axion simulator (green) is used in Sec. V to perform proof-of-concept measurements.

a single measurement channel [49, 50]. When the cross-spectrum is computed on the FFT the first-stage amplifier noise and the thermal cavity noise is rejected, while a signal due to a flux of WISPs is correlated between the two cavities and thus remains in the cross-spectrum. This is only true when the cavities are not separated by a distance greater than the relevant de Broglie wavelength, which for axions is of the order 10-100 m [51]. As the noise being rejected is thermal (random), the performance of the system should be independent of the relative phase of the two measurement channels.

This technique much like the Wilkinson power summing technique introduce the added complexity of having to tune the frequency of two independent cavities. Of course, the two cavities do not necessarily have to be tuned to overlap exactly, the cross-spectrum will reject all cavity noise and retain an axion signal regardless of the relative frequencies (within reason), but to optimize the experiment the WISP mass should coincide with the resonant frequencies of the cavities. If one of the cavities was frequency detuned this can be treated as a reduction in the effective Q-factor of the cavity [27], which would reduce our ability to resolve a signal. As long as the cavities are not frequency detuned further apart than the bandwidth of the resonant cavity mode being used then this technique is still applicable.

Assuming that the two cavities and readouts used are nominally identical to what would have been deployed in a single channel system, we can determine the scaling of (5) as follows

\[ \sigma_N \approx \frac{\langle S_N \rangle}{2\sqrt{m}} \]

\[ \text{SNR} = \frac{S_{eff}^{sig}}{\langle S_N \rangle} \approx 2\sqrt{m} \frac{S_{eff}^{sig}}{\langle S_N \rangle} \]

Which is a factor of $\sim 2$ (really 1.912) improvement over (6). It is important to stress that this factor is...
nearly the same result recovered if we simply Wilkinson power combined the two cavities and read out via one channel. This technique alone does not provide an improvement in SNR. This cross-correlation technique would, however, be useful in characterizing any candidate WISP signal. As each cavity output is immediately amplified it is possible to have the cavities separated by large spatial distances, while the standard power-summing approach requires the cavities to be co-located to avoid excessive losses along the individual transmission lines. Introducing amplifiers for each cavity would substantially increase the overall system noise. In contrast, the cavities in Fig. 5 can be spatially well separated and still maintain the same SNR, indeed the cross-spectrum may be computed later, in post-processing for two cavities in completely isolated systems. This cross-correlation measurement scheme could be used to scrutinize a candidate WISP signal and to measure the coherence length of a WISP, noting that as the cavities become separated by a distance greater than the coherence length of the particle, the generated power signal in each cavity will no longer be correlated and will be rejected from the cross-spectrum. Additionally, using the scheme presented in Fig. 5 we do not need to concern ourselves with the relative phase of the signals in each channel, as we must in a Wilkinson power combining scheme.

Furthermore, the scheme presented in Fig. 5 can be extrapolated to incorporate $n$ cavities. In such a case, we can compute the cross-spectrum of all the different possible combinations of cavities, resulting in $n(n-1)/2$ independent cross-spectra, which we can then average together. This is equivalent to increasing the number of averages taken by a factor of $n(n-1)/2$ and thus the resultant SNR increases by the square root of this factor, i.e.

$$\text{SNR} = 1.91\sqrt{\frac{mn(n-1)}{2}} \frac{S_{\text{eff}}^{\text{sig}}}{\langle S_N \rangle} \quad (10)$$

Which is a small improvement over the factor of $n$ that one acquires from Wilkinson power combining $n$ cavities, given by

$$n\sqrt{m} \frac{S_{\text{eff}}^{\text{sig}}}{\langle S_N \rangle}. \quad (11)$$

This improvement may seem counter-intuitive, but when one considers that cross-correlating $n$ cavities over $m$ measurements requires us to take $n \times m$ total measurements versus just $n$ measurements for the Wilkinson power combined scheme, this data is then post-processed and it is perhaps easier to intuit how an improvement can be achieved with a larger number of total measurements. This could result in an increased total measurement time if we were forced to take the measurements one after another, however, provided we have enough FFT-like devices (most have multiple measurement channels and can compute cross-spectra in situ) to sample the $n$ readouts simultaneously, we will not incur a time penalty.

![FIG. 6. A 1600 point PSD after 1024 averages for the two cavity cross-correlation technique illustrated in Fig. 5. Single channel trace is shown in blue and the X-PSD is shown in yellow. Note that the horizontal axis units are not Hertz, they simply refer to the number assigned to each of the 1600 points in the spectrum.](image)

**V. RESULTS**

Proof-of-concept measurements were made with a two cavity system. A microwave synthesizer was used to generate a simulated WISP signal that falls within the cavity bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box” bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box” bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box” bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box” bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box” bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box” bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box” bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box” bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box” bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box” bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box” bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box” bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box” bandwidth. Measurements were conducted at room temperature using commercial sapphire-based “black box”. As this is not an actual WISP search but rather a test of a measurement technique the mode structure of the cavity resonance is irrelevant. The cavities both had resonance frequencies at $\sim 9$ GHz and $Q$ factors of $\sim 2 \times 10^5$. The total gain in each channel was $\sim 30$ dB. A microwave synthesizer and mixers were employed to mix the channels down to 4 MHz so that the spectra could be recorded on a commercial FFT. Measurements were made from 2 to 4096 averages. With the appropriate equipment such as a FFT or multi-channel digitizer both channels can be sampled simultaneously and the cross-spectrum is computed in situ, meaning that there is no increase in acquisition time for cross-correlation measurements compared to single channel measurements. Single channel and dual channel results for the two cavity technique (Fig. 5) are shown in Fig. 6. Temperature control was used to perform minor frequency tuning to ensure that the resonant frequencies of both cavities were equal. After 4096 averages the single channel trace, representative of a typical WISP cavity receiver, has a linear SNR of 106$\sigma$ for the WISP signal. In the X-PSD, the first-stage amplifier noise and thermal cavity noise from both channels has been rejected (within the limitations of the instrumentation and the number of averages taken). The simulated WISP signal which is correlated between both cavities remains with an enhanced SNR of 218$\sigma$, which is a factor of $\sim 2$ improvement arising from the use of two independent measurement channels. Figure 7 shows the SNR for a single channel and the X-PSD as a function of the number of averages taken. Fitting to the X-PSD gives the function $3.3 \times \sqrt{m}$ and fitting to a single chan-
FIG. 7. Log-log representation of SNR as a function of averages for the simulated axion signal in single channel (blue circles) and X-PSD (yellow circles) obtained via the technique presented in Fig. 5. Fits to the data (coloured lines) are presented as discussed in the text.

FIG. 8. PSD (blue), X-PSD (green), and AX-PSD (yellow) after 16 averages for the four channel cross-correlation scheme described in the text. The broadband noise of the amplifier is seen to decrease for the X-PSD and AX-PSD when compared with the single channel.

one gives $1.6 \times \sqrt{m}$. This demonstrates that the system behaves as outlined in section IV and also shows that the X-PSD conserves relatively weak correlated signals, as the starting SNR for these measurements is less than 1 for the single channel. Averages below 4 have been omitted from the figure as the signal cannot be resolved above the background noise as the SNR is roughly unity. Another tabletop experiment was performed to verify the expected sensitivity predicted by Eq. (10) for cross-correlating combinations of $n$ channels. Four independent amplifiers were injected with a simulated monochromatic WISP signal of -106 dBm at 1200 Hz, the outputs being sampled directly by a 4 channel digitizer. The gain of each amplifier was set to 2 dB. The data was processed to compute PSDs for each channel, as well as all 6 possible combinations of X-PSDs for averages ranging from 1 to 16. Subsequently the averaged cross-power spectral density (AX-PSD) was computed via linearly averaging the 6 individual X-PSDs. Results for the single channel, cross-spectrum and averaged cross-spectrum after 16 averages are shown in Fig. 8. After 16 averages the average linear SNR for the single channel was $12.8 \sigma$. When examining the X-PSDs, the average linear SNR was $25.4 \sigma$, which is close to the factor of 1.9 expected. When examining the averaged cross-spectrum the linear SNR was found to be $65.2 \sigma$, which is slightly better than the factor of $1.9 \sqrt{6}$ expected from equation (10), when compared with the average single channel value. Figure 9 shows the SNR for PSD, X-PSD and AX-PSD as a function of the number of averages taken. Fitting to the AX-PSD gives the function $16.9 \sqrt{m}$, fitting to the X-PSD gives the function $6.48 \sqrt{m}$, and fitting to the single channel gives the function $3.28 \sqrt{m}$. These values show a factor of $\sim 2$ between the single channel PSD and the X-PSD as expected, and a factor slightly larger than the expected $1.9 \sqrt{6}$ between the PSD and the AX-PSD. This demonstrates that at least for the four independent amplifier channels the system performs as expected. It should be noted that this technique was not attempted with cavity structures due to technical limitations. Furthermore it is important to stress that for both the 2 cavity and 4 channel schemes tested here, much care must be taken to ensure that the signals in each channel are nearly identical. Discrepancy between the channels leads to deviation from the predictions outlined in this text.

For both measurement techniques the phase offset in each arm, or more importantly the phase difference between the channels, ultimately has minimal impact upon the SNR observed in the X-PSD. As the noise processes being rejected are of thermal (random) origin the power will be equally distributed between phase and amplitude; we cannot further improve on the results by having a phase-sensitive channel and an amplitude-sensitive channel. Regardless, it would be prudent to fully character-
ize any system deployed in an actual data-taking experiment.

VI. CONCLUSION

A cross-correlation measurement scheme for cavity-based WISP searches has been proposed and verified. This scheme allows for two cavity outputs to be effectively combined via computation of their cross-power spectral density. This allows for the cavities to be spatially well separated, thereby providing a way to measure the coherence length of any candidate WISP signal. As a further bonus the relative phase in the two channels has no impact on the combined sensitivity, which simplifies the experiment. Furthermore, such an approach can be scaled up to larger arrays of cavities by computing all the possible combinations of cavity cross-power spectral densities, which results in an improvement in SNR versus what can be achieved by power combining the same number of cavities. We require more total measurements, amplifiers and readout chains, but provided we have the requisite hardware this is not an issue, and we can reach an improved sensitivity in the same amount of time.

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