Correcting for ADMX Cavity Resonance Shifting Using Convolution

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Among the various candidates for dark matter, axions - a hypothetical particle proposed by Peccei-Quinn theory - offer a promising solution to both the strong CP problem and the mystery of dark matter. The Axion Dark Matter eXperiment (ADMX) seeks to detect axion-photon conversion in a resonant cavity. Shifts in the cavity's resonance frequency during data collection can compromise the experiment's sensitivity and lead to the loss of valuable data. This research aims to develop a method for tracking and correcting for mid-run resonance shifts, thus reclaiming previously discarded data and improving the signal to noise ratio (SNR), and by extension the rate at which ADMX can scan through frequencies. By analyzing high-resolution time series data and applying convolution techniques, this work successfully visualized the resonance shifts and implemented a corrected lineshape for the affected data. The results demonstrate a 6.5% increase in SNR across the frequency range, enabling a 13% faster scan rate. These findings allow ADMX to more efficiently search for axions, and provide a reduced systematic error in ADMX's results.

I. INTRODUCTION

Dark matter, a hypothetical form of non-luminous matter, is believed to constitute approximately 24% of the universe's mass-energy content. Despite its ubiquitousness, the nature of dark matter remains largely unknown. Several dark matter candidates have been proposed, but many have either been largely ruled out or provide an inelegant or esoteric description of dark matter.

CP symmetry, which combines charge conjugation (C) and parity (P), dictates that the laws of physics should remain unchanged if particles are swapped with their corresponding antiparticles (C) and if spatial coordinates are inverted (P). Despite current mathematical formulations predicting its occurrence, CP violation hasn't been observed in strong interactions. This is called the strong CP problem.

Peccei-Quinn theory offers a solution to the strong CP problem and postulates the existence of a new elementary particle called an axion [2]. Beyond addressing the CP violation issue, axions are also considered a viable candidate for dark matter due to their mass and weak coupling with electromagnetism. This weak coupling makes axions extremely difficult to detect if you don't know their mass. One promising method for detecting axions is through their conversion into photons in the presence of a strong magnetic field, a process that can be observed using a specialized instrument known as an axion haloscope.

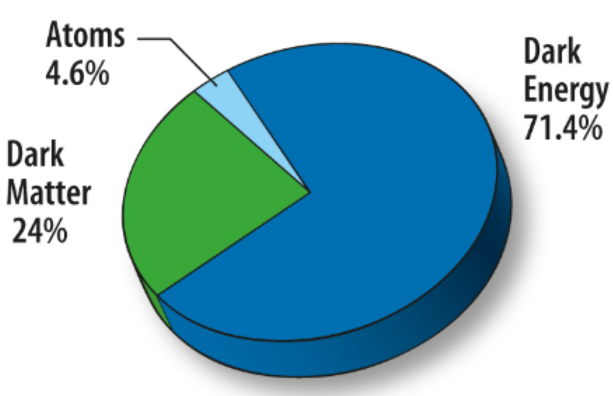

FIG. 1. Mass-energy content of the universe [1].

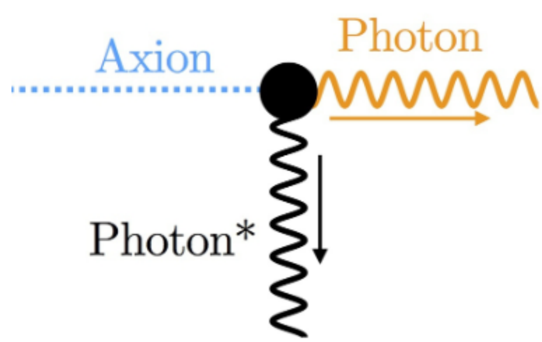

FIG. 2. Diagram of axion to photon conversion. Photon* represents a photon of the opposite polarization.

One example of this is the Axion Dark Matter eXperiment (ADMX), which is designed to detect the microwave photons generated by axions within a resonant cavity [3]. Since photons are massless, the mass of the axion translates directly into the energy of the photon, and by extension its frequency. The signal strength is de-

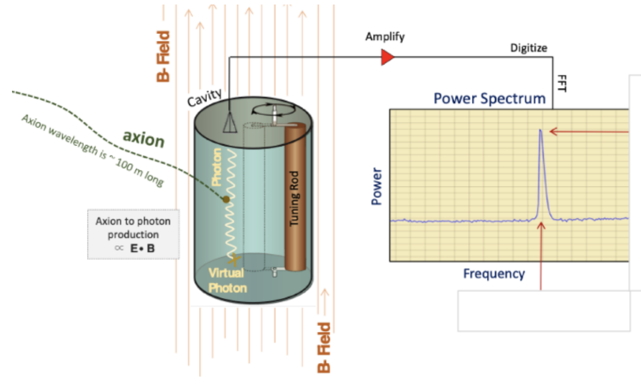

FIG. 3. Diagram of how ADMX - an axion haloscope - works [4].

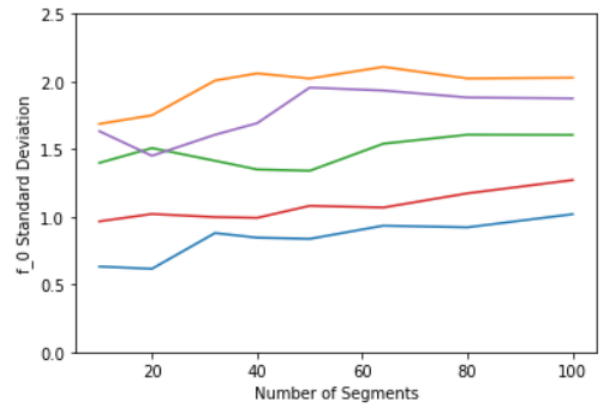

FIG. 4. Error (resonance frequency standard deviation) vs. number of segments.

pendent on the coupling between the axion field and the electromagnetic field, as well as the difference between the resonance frequency of the cavity and the frequency of the axion signal. The resonance frequency of the cavity is adjusted by moving a tuning rod within the cavity to change its shape. ADMX has excluded some of the parameter space of mass and coupling (Figure 8) by scanning over the frequencies associated with these masses and observing the lack of a signal greater than a specific strength associated with a specific coupling strength.

One of the challenges faced by ADMX is the phenomenon of cavity resonance shifting. During a 100 second run the resonance frequency should remain constant, but it has been observed to shift significantly in many runs. As the cavity resonance frequency shifts during data collection, a systematic uncertainty is introduced to the experiment's sensitivity, leading to the loss of data. This is because a shifting resonance frequency compromises the accuracy of the reconstructed cavity lineshape used to analyze the data for the run. This resonance shifting is likely due to mechanical issues with the tuning rod used to adjust the cavity.

The goal of this study is to develop a method for visualizing and correcting mid-run resonance shifts in ADMX data. By tracking these shifts and adjusting the lineshape accordingly, it is possible to reclaim previously discarded data and improve the SNR of the experiment, which can in turn increase the sensitivity or the rate at which ADMX scans through frequencies (scan rate).

II. METHODOLOGY

The raw data from ADMX is digitized in segments of 100 seconds, during which the cavity resonance frequency should remain constant. Spectra generated from the digitized data should ideally exhibit a peak that corresponds to the cavity resonance. This occurs when there is a temperature difference between the cavity and the off-resonance attenuator. To account for possible resonance shifts, the high-resolution time series data was divided into smaller segments. Each segment was then Fourier transformed independently of the others to obtain the power spectrum for that segment. This way, if the resonance frequency changes during a digitization, some segments will have a different cavity resonance peak position than others. Power excesses of over 3.5 sigma were identified and removed to minimize the influence of extraneous signals on the analysis.

The number of segments was chosen by balancing time resolution, data accuracy, and computational efficiency. The number of segments affects the ability to time-resolve shifts and, thus, the accuracy of the corrected lineshape created using the shifts (discussed later). A range of segment numbers was tested, and their effects on error (standard deviation) and computation time were evaluated. As seen in Figure 4, error varied inconsistently with the number of segments but generally trended upward as more segments were added. However, computation time increased significantly with the number of segments, becoming impractical beyond 100 segments. Based on these factors and the nature of the resonance shifts, it was determined that dividing the time series into 50 segments (2 seconds each) provided a sufficient resolution while maintaining reasonable computational demands and accuracy.

If the temperatures of the cavity and the off-resonance attenuator are too close, the peak structure corresponding to the cavity resonance frequency will be absent, resulting in a "flat" spectrum. There is also frequency dependent noise generated by the first amplifier, but the amplitude of this should be much less than that of the resonance peak. Flat spectra cannot be used to track resonance shifts, as there is no discernible peak to follow. To identify and exclude flat spectra, a Savitzky-Golay (SG) filter was applied to smooth the data, and the resulting fit was subtracted from the original spectrum, as seen in Figure 5. The standard deviation obtained from this subtraction was then compared to the total spectrum's standard deviation. If the ratio of baseline noise to total spectrum exceeded a threshold value, the spectrum was

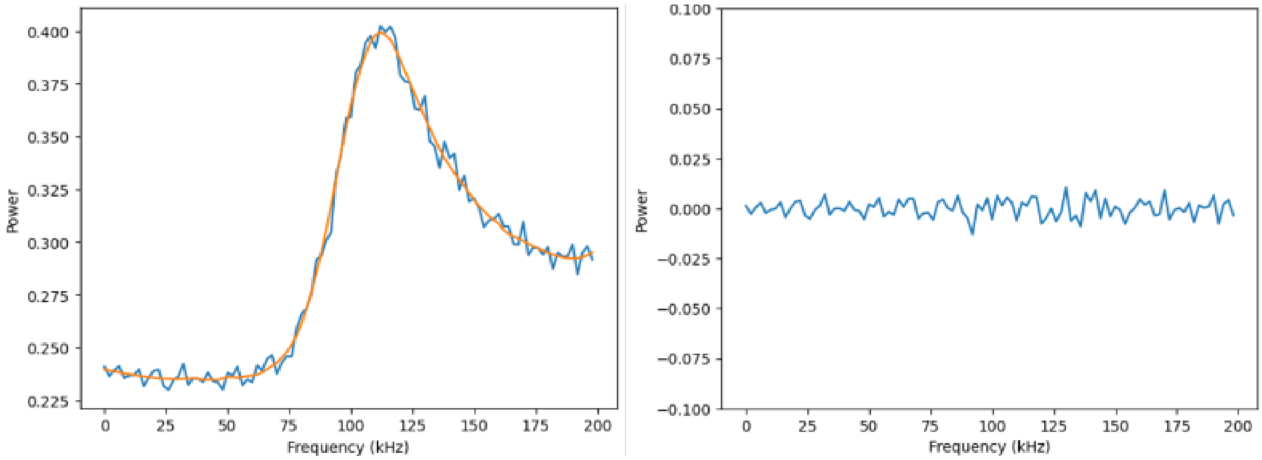

FIG. 5. How baseline noise was obtained for the flatness check. the orange line on the left is the SG fit of the blue line. The right graph is the baseline noise of the left.

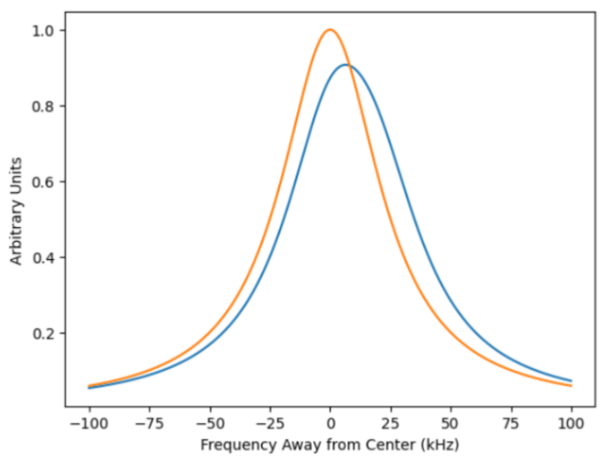

FIG. 6. Comparison of the lineshape used in the previous analysis (orange) with the adjusted lineshape (blue) for a file with significant shifts (25 kHz).

classified as flat and excluded from further analysis.

To track resonance shifts within the non-flat spectra, a convolution technique was employed. The central portion of the spectrum from the first two seconds of each digitization was selected as a kernel. This kernel, representing the initial resonance structure, was convolved with subsequent subspectra. The position in the spectrum where the kernel best fit was identified, providing the location of the resonance peak. If this peak shifted by more than 5 kHz across segments, a corrected lineshape was constructed and used in the analysis (discussed later). Some spectra exhibited cavity resonance structures that didn't look like peaks, and this technique allowed for any non-flat resonance structure - not just peaks - to be tracked.

Once the resonance shifts were identified, a corrected cavity lineshape was generated. For each 2-second segment, a Lorentzian lineshape was constructed based on the observed resonance frequency and the Q value of the cavity. These lineshapes were then averaged together to create a composite lineshape that accurately reflected the resonance structure over the entire 100-second digitization period. This corrected lineshape was used in the final analysis to ensure that the signal power extracted from the cavity was accurately represented as a function of frequency. By incorporating the corrected lineshape, previously discarded data could be reclaimed, and the overall sensitivity of the experiment was improved.

III. RESULTS

The convolution-based approach successfully visualized resonance shifts occurring within individual digitizations. In many cases, significant shifts in the cavity resonance frequency were observed over the 100-second digitization period, confirming the presence of mid-run frequency variations. The application of the corrected lineshape led to a significant improvement in the signal-to-noise ratio (SNR). Across the entire frequency range, SNR increased by an average of 6.5%, with improvements of up to 12% observed in specific 1 MHz frequency intervals as seen in Figure 7.

With the improved lineshape, ADMX can scan through frequencies around 13% faster on average. This increase in scan rate allows the experiment to probe a broader range of axion mass and coupling parameters in a given time frame. This corresponds to the colored sections in Figure 8 being 13% wider for the same length of run.

IV. DISCUSSION

While most spectra were found to have a trackable resonance structure, around 5% were found to be flat, and could not be recovered. Some of these digitizations were

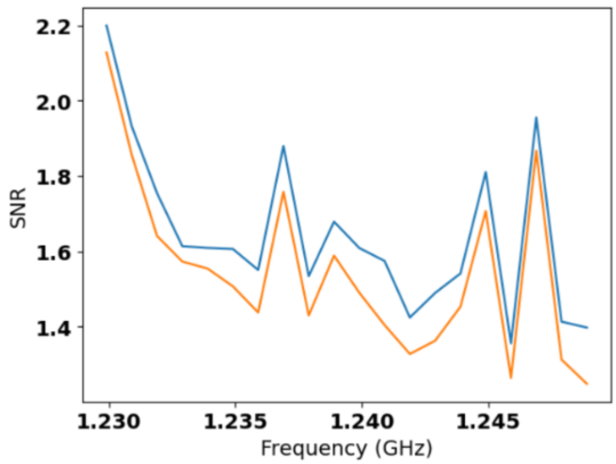

FIG. 7. SNR in each 1-MHz wide section of the data analyzed. Old method shown in orange, new in blue. The SNR increased in each range with the new method.

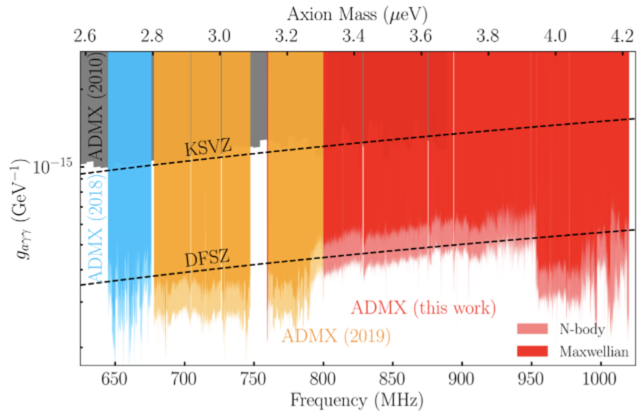

FIG. 8. axion mass-coupling parameter space exclusion for recent ADMX runs [5].

found to have a trackable structure on closer inspection, meaning the threshold value for the noise ratios could be improved to reclaim more data.

The form of the resonance shifts observed in this research suggests that they are caused by mechanical instabilities with the tuning rod that adjusts the cavity shape. While the current method compensates for these shifts effectively, understanding and mitigating their root causes will be essential for further improving the experiment's stability and sensitivity. Not only would fixing the root cause of the shifts improve the SNR, but it would remove the need for shift tracking altogether, resulting in much faster analysis computation times.

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