Noise Temperature Calibration in the Axion Dark Matter eXperiment

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(Dated: December 8, 2017)

The ADMX system noise temperature greatly impacts the scan rate and sensitivity of the experiment. In this paper, I quantify the noise temperature of a new Low Noise Factory (S/N 021H) HFET amplifier using the hot load or Y-factor method. At ∼ 10K physical temperature, the amplifier noise temperature was measured to be 1.2 ± 1.2 K. This agrees with the manufactures specifications to within 1 σ and thus it is recommended that this amplifier replace the current channel 1 HFET (Noise Temp ∼ 6K). This substitution alone has the potential to reduce the ADMX system temperature by ∼ 10% and therefore increase the scan speed by ∼ 20%.

I. INTRODUCTION

The axion is a hypothetical elementary particle first proposed by Pecci and Quinn in 1977 as a solution to the strong CP-problem [12, 16, 17]. It has since become a popular dark matter candidate and may also play an important role in some cosmological string theories [15]. The axion is theorized to couple weekly to normal matter and radiation, and thus provides a slight modification to Maxwell's equations. This forms the basis for Sikivie's proposed conversion of an axion signal into detectable microwave photons using the inverse Primakoff effect [10, 14] (Figure 1, right). This mechanism motivates the design of a large class of axion and axion-like particle detectors known as *axion haloscopes* (Figure 1, left). Axion haloscopes employ a large magnetic field and resonating cavity in hopes of observing the decay of an axion into two photons.

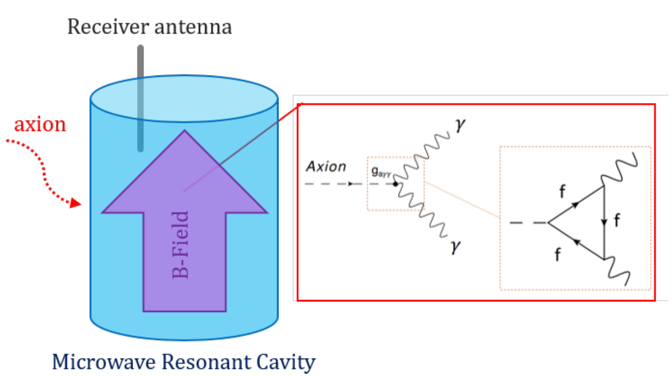

FIG. 1: A generic axion haloscope experiment (left) and the Feynman diagram describing the fermionic loop interaction mediating the decay (right). Figure adapted from Christian Boutan's thesis [3]

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The axion to photon conversion is governed by

$$\mathcal{L}_{\alpha\gamma\gamma} = -g_{\alpha\gamma\gamma}\phi_a \vec{E}\cdot\vec{B} \tag{1}$$

Where $\phi_\alpha$is the axion field, B is the magnetic field, and E is the electric field.The axion coupling constant, $g_{\alpha\gamma\gamma}$, will be discussed in more detail in section 1A.

The Pecci-Quinn solution to the strong CP problem proposes the axion mass is given by

$$m_a = \frac{(m_u m_d)^{1/2}}{m_u + m_d}\frac{f_\pi}{f_{PQ}/N}m_\pi \tag{2}$$

Where m_a, m_d, m_u, and m_π, are the masses of the axion, down quark, up quark, and pion, respectively. f_{PQ} is the symmetry breaking scale, and N is the PQ color anomaly. Experiments from astrophysics, particle physics, and neutrino physics have constrained the axion mass to between $\sim 1\mu eV$ and $1meV$[3].

The axion signal frequency is linearly related to the axion mass. Thus, based on the mass constraints, the axion signal is most likely to be found between 1-100GHz in an axion haloscope detector.

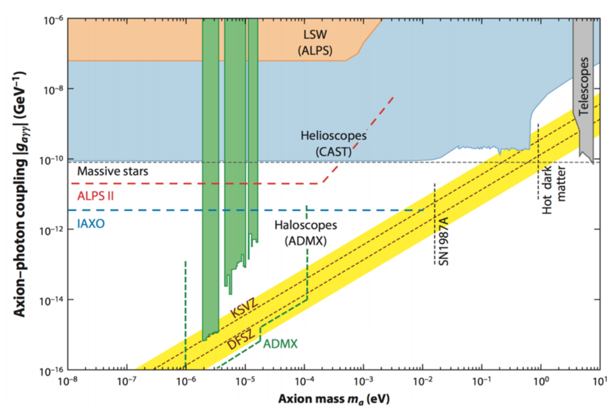

FIG. 2: Overview of axion detection experiments (figure reproduced from Graham 2015 [7]
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A. The Axion Dark Matter eXperiment

The Axion Dark Matter eXperiment (ADMX) is the largest and most sensitive axion haloscope experiment currently in operation. ADMX uses a large (2L) microwave resonant cavity, 8T superconducting magnet, and sensitive receiver and amplification system to search for cold dark matter axions. The resonant cavity is progressively tuned to different resonant frequencies and therefore steps through the possible axion masses. The expected axion singal power in the cavity is given by:

$$P_a = g^2_{\alpha\gamma\gamma} V B_0^2 \rho_\alpha C_{lmn} min(Q_L, Q_a) \tag{3}$$

Where V is the cavity volume, B_0 is the magnetic field, ρ_a is the local axion density, Q_L is the loaded cavity quality factor, Q_a is the axion signal quality factor (axion energy over energy spread $\sim 10^6$) and C_{lmn} is a form factor for the TM_{lmn} cavity mode [2]. Based on this equation, P_a is expected to be of order 10^{-22}W [2].

The detector sensitivity is given by the Dicke radiometer equation which defines the signal to noise ratio as

$$SNR = \frac{P_a}{P_N}\sqrt{Bt} = \frac{P_a}{k_B T_s}\sqrt{\frac{t}{B}} \tag{4}$$

Where P_N is the linear noise power of the system k_B is Boltzmann's constant, and B and t are the data acquisition bandwidth, and integration time, respectively [5]. At this point, the axion coupling constant, $g_{\alpha\gamma\gamma}$ becomes an important parameter because it dictates the axion power, and therefore the integration time needed to achieve an acceptable SNR through (4). The axion coupling constant is defined by

$$g_{\gamma\alpha\alpha} = \frac{\alpha g_\gamma}{\pi(f_{PQ}/N)} \tag{5}$$

Where α is the fine structure constant and g_γ is a model dependent constant [2]. This constant is fairly well constrained between two competing theories: Kim [9], Shifman, Vainshtein, and Zakharov (KSVZ) [13] and Dine, Fischler, Srednicki [6], and Zhitnitsky [18] (DVSZ). KSVZ theory proposes $g_\gamma = -0.97$ while DFSZ predicts the more pessimistic $g_\gamma = +0.36$.

For a given coupling constant, the scan rate is proportional to the inverse-square of the system noise temperature:

$$\text{scan rate} \propto (B_0^2 V)^2 \frac{1}{T_s^2} \tag{6}$$

Where B_0 is the magnetic field strength and V is the cavity volume [2]. If scan rate is held fixed, the weakest coupling constant ADMX could be sensitive to is proportional to the system noise temperature [2]

$$g_{\alpha\gamma\gamma} \propto \frac{T_s}{B_0^2 V} \tag{7}$$

Equations 6 and 7 show that it is critical to minimize the system noise temperature T_s. Doing so allows ADMX to scan faster while maintaining sensitivity, or scan at the same rate while increasing sensitivity.

B. Noise Temperature: Theory and Definitions

There are many sources of random noise in electrical systems. Some examples include the noise generated by conduction electron and hole vibrations (thermal noise) and the random and uneven spacing of quantized current flow (shot noise). These mechanisms all have relatively flat, uniform density noise power spectra over a broad range of RF and microwave frequencies [1]. It is often more convenient to treat these noise sources together as if they were all produced thermally− this characterizes a device's *noise temperature*.

Thermal noise power in watts is given by the Johnson-Nyquist noise $P = k_B T B$ where T is the temperature and B is the system's noise bandwidth [8, 11]. Thus, we can characterize the equivalent noise temperature of a device or system by $T_{equiv} = P/K_B B$. Where P is the total output linear noise power.

Amplifiers inevitably inject additional noise when amplifying a signal[1]. The degradation of the SNR ratio across a device under test (DUT) gives what is known as the *noise factor* for the DUT.

$$\text{noise factor} = \frac{SNR_i}{SNR_o} = \frac{S_i/N_i}{S_i/(N_a + N_i)} \tag{8}$$

Where S_i, N_i and SNR_i represent the input signal, noise, and corresponding SNR and the subscript "o" indicates the same quantities on the output. N_a is the total linear noise power added by the amplifier referred to the input. Thus the *noise temperature* of the amplifier is

$$T_{amp} = \frac{N_a}{k_B B} \tag{9}$$

Where B is the bandwidth containing the noise power N_a. [2]

1. *System Noise Temperature*

The system noise temperature is the sum of the input noise temperature and noise temperature of all downstream components scaled by the appropriate gain factors. To see an example, consider two amplifiers with gains and noise temperatures G_1, T_1 and G_2, T_2, respectively

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The system noise temperature is given by,

$$P_{out} = k_B B T_{sys}$$

[1] For this paper, I will follow the convention that the added amplifier noise is injected at the input before incurring the amplifier gain.

[2] This is usually the resolution bandwidth on a Spectrum Analyzer.

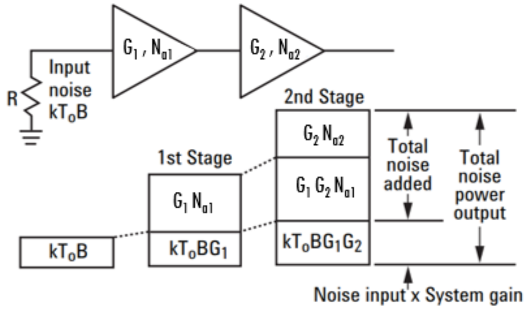

FIG. 3: A series of two cascaded amplifiers and the associated noise contributions. [a]

[a] Here the amplifier noise power N_a is being used interchangeably with the amplifier noise temperature T via equation 8

$$= G_2G_1(k_BT_0B) + G_2G_1(N_{a1}) + G_2(N_{a2}) \tag{10}$$

This example illustrates the importance of a low noise, high gain first amplifier in the chain. N_{a1} will be magnified by all subsequent gains along with the input noise; most importantly, it is the only noise to see G_1. Thus, if G_1 is large, this N_{a1} term will dominate the added system temperature noise. This effect had large implications for the design of the ADMX receiver/amplification chain.

Attenuators do not inject noise the same way amplifiers do. Instead they replace a percentage of the input noise temperature with the corresponding percentage of their physical noise temperature.

$$T_{out} = T_{in}(att) + T_{att}(1 - att)$$

Where T_{in} is the input noise temperature, T_{out} is the output noise temperature, T_{att} is the physical temperature of the attenuator, and att is the linear attenuation, $att = 10^{(-dB/10)}$. For example a 3 dB attenuator corresponds to a 1/2 reduction in power. Thus the output noise is $(T_{in} + T_{att})/2$.

II. EXPERIMENT AND RESULTS

The noise temperature of a Low Noise factory amplifier (S/N 021H) was measured using the Y-factor, or hot-load test. This test involves measuring the output noise power of an amplifier for two different, known input temperatures. It was determined that the spectrum analyzer noise floor was too high ($T_{SA} \sim 10^6 K$) to detect a change between the hot and cold output noise powers. This mandated the use of a second, MiniCircuits amplifier (S/N ZX60-2522M+). Based on the cascade amplifier equation (10) and the relevant parameters, this addition was calculated to contribute a $\sim$ 5% error. At room temperature, the output power of the circuit (figure 4) was measured when terminated at 77K and 300K.

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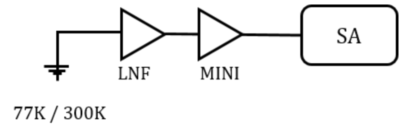

FIG. 4: A circuit diagram depicting the room temperature noise calibration setup.

The system temperature for the two input loads was calculated as described in section 1B and the system was solved for amplifier temperature.

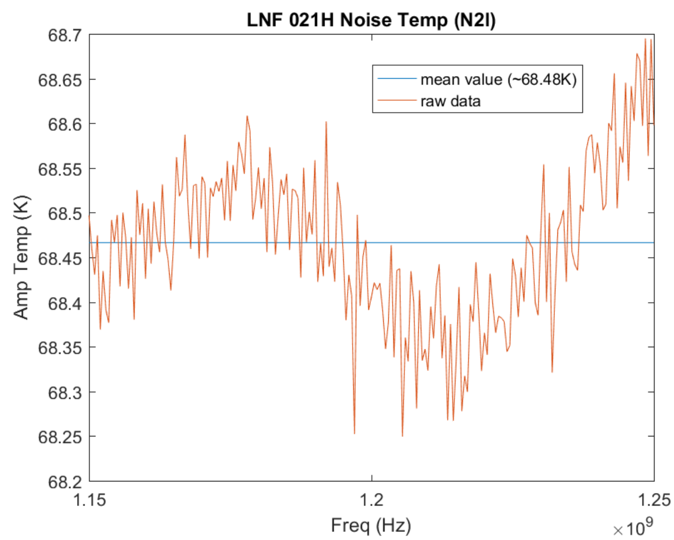

FIG. 5: LNF 021H noise temperature as a function of frequency at 300K. The mean value was 68.48K

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A modified setup was used to test the LNF noise temperature at 4.2K (figure 5).

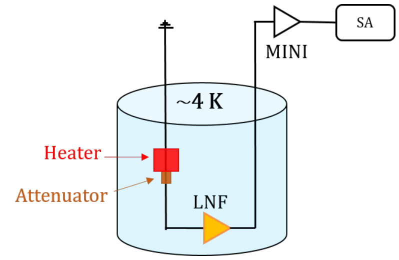

FIG. 6: A schematic diagram of the cryogenic hot load setup.

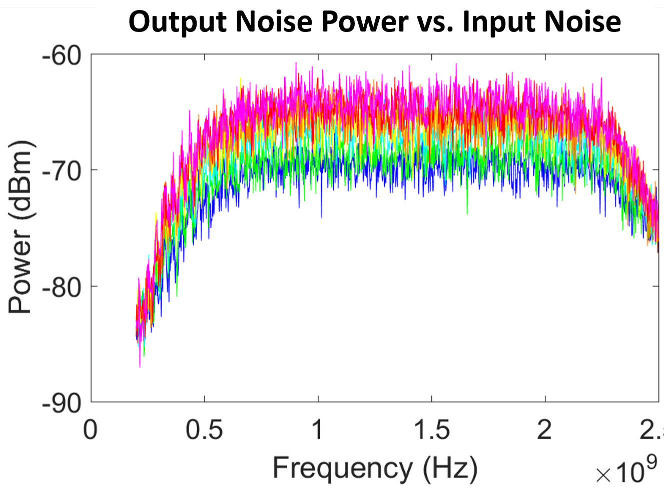

FIG. 7: The noise power change on the output of the circuit in dBm vs frequency in Hz as the input noise temperature is increased. The amplifier physical temperature was ∼10K

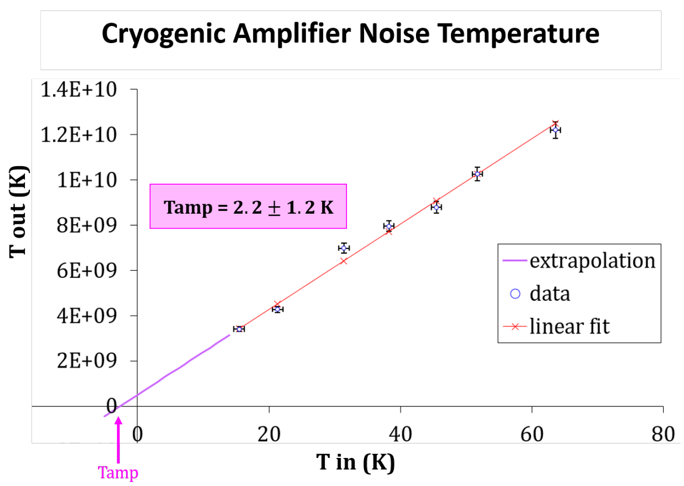

FIG. 8: Output noise vs input noise in Kelvin. The x-intercept corresponds to the noise temperature of the LNF 021H amplifier.

III. DISCUSSION

The noise temperature of LNF 021H agrees with commercial specifications with a measured noise temperature of 2.5 ± 1.5 K at $\sim$ 10K. This confirms that LNF 021H will be a good substitute for the current second-stage amplifier which had a 5K noise temp of $\sim$ 6K. This singular substitution is expected to lower the ADMX system temperature by $\sim$ 10% and therefore the scan rate is expected to be improved by $\sim$ 20%.

IV. CONCLUSION

AMDX had a hugely successful first data run and is the only axion search to have been able to reach DSFZ sensitivity [4].

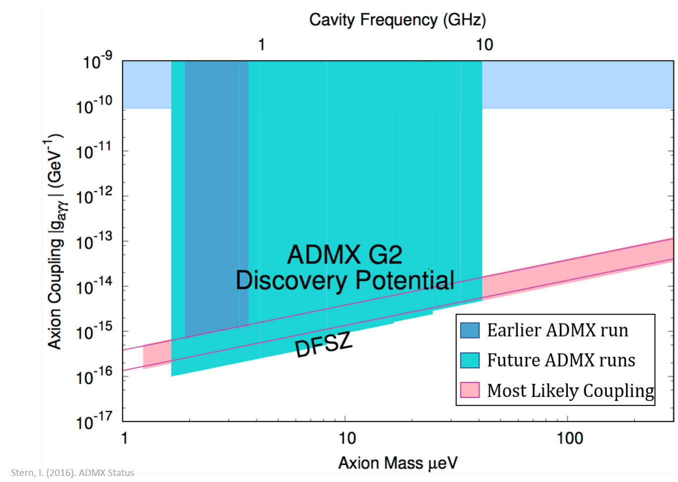

FIG. 9: ADMX generation 2 discovery potential with run 1B data shown in dark blue.

The next data run is slotted to begin in November 2017, and is expected to find or rule out axions in the 830 to 1000 MHz range. By incorporating the new LNF 021H amplifier, and accurately measuring the system's physical temperature, ADMX can reduce the system noise temperature. This means faster scanning rates, which saves time and valuable resources. Overall, ADMX is poised to find the axion. This hypothetical particle could be the key to solving the dark matter problem–one of the greatest problems in modern physics.

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