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ISBN

9798288866302

Author

Keller, Aya

Publication Date

2025-05-15

Peer reviewed|Thesis/dissertation

Astronomical and Resonant Circuit Based Searches for Ultralight Dark Matter

By

Aya Keller

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Applied Science and Technology

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Karl van Bibber, Chair

Professor David Attwood

Professor Chiara Salemi

Spring 2025

Astronomical and Resonant Circuit Based Searches for Ultralight Dark Matter

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Aya Keller

Abstract

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Professor Karl van Bibber, Chair

While the overwhelming evidence for the existence of dark matter continues to build, progress towards its identification remains limited. This thesis discusses two complementary methods of searching for ultralight dark matter, specifically, astronomical and resonant circuit based searches.

In the first part, we explore a model-independent search for possible decay or annihilation of dark matter to a quasimonochromatic radio line using data from the Green Bank Radio Telescope, relying on as few assumptions as possible. More specifically, the search selects for a line that exhibits a Doppler shift with position according to the solar motion through a static halo and similarly varies in intensity with position with respect to the galactic center. Following a description of the full analysis pipeline as well as optimization of selected components of the analysis, we present exclusion limits of decay and annihilation in the L and S bands.

In the second part, we discuss a direct lumped-element resonant search for axions, DMRadio-50L. As a novel experiment meant to be an innovation platform as well as a sensitive axion detector, DMRadio-50L requires advanced engineering and unique solutions in many aspects of experimental design. Specifically, we examine the design, construction, and characterization of the cryogenic system housing the detector. Although not yet fully built, the cryogenic system has already undergone multiple rounds of improvement, which allows us to project success in reaching temperatures below 50 mK for the base temperature stage of the experiment.

To my family

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Acknowledgments

This thesis would not be possible without the contributions of many people throughout my PhD.

First of all, thank you to my advisor, Karl van Bibber, for the never-ending optimism and enthusiasm for science. I am grateful to have had the opportunity to grow from a mathematician to a computational astrophysicist to an experimentalist with your encouragement. Thank you to Chiara Salemi for serving on my committee after a great few years working together on DMRadio, and thank you to David Attwood for the reassurance and support throughout my preliminary exam, qualifying exam, and thesis writing process.

Thank you to the Berkeley Axion Works, especially Heather Jackson and Alex Droster for going through this experience with me.

Thank you to Kent Irwin for the warm welcome at Stanford and making me feel like part of the group. Thank you to Dale Li, Sherry Cho and Chelsea Bartram for the mentorship. Thank you to the rest of the group for being accepting and friendly: Nicholas Rapidis, Tori Ankel, Ameya Kunder, Cady van Assendelft, Jason Corbin, Jyotarmai Singh, Christina Bell, Dean Wright, Barkotel Zemenu. Thank you to Maria Simanovskaia for pushing me to my limits in science and life - I would not be here without you.

Thank you to the DMRadio Collaboration, including Lindley Winslow, Jessica Fry, Andrew Yi, Pam Stark, Johny Echevers, Betty Young, Saptarshi Chaudhuri, Roman Kolevatov, Nate Otto, Joe Wiedemann. I am grateful for the productive discussions and the wonderful experience of working on DMRadio-50L together.

Thank you to Miriam Rivkin for the everlasting friendship and solidarity. Thank you to Amy Jin, Ria Singla, and Michelle Zhou for continuing to be there.

Thank you to Monica and Nelson Nahum and the rest of the family for the love and encouragement.

Thank you to my family for keeping me in good spirits. Igor Keller, thank you for the help and occasional reminders to check under the desk for the dark matter. Thank you to Irena Keller for the unconditional support. Thank you Oren Keller and Allen Keller for the endless entertainment and occasional frustration.

Finally, thank you Gaby Nahum for being the best partner I could have imagined going through this with.

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Chapter 1

Thesis Structure

This thesis includes two thematically separate projects, both focused on searching for dark matter. The general background of dark matter along with the context for each of these projects is introduced in Ch. 2. The first project, a model-independent dark matter search using radio telescope data, is detailed in Ch. 3. This includes optimization and development of the entire analysis pipeline as well as the resulting limits in the L and S frequency bands. It becomes clear from these results that this broad model-independent search is best complemented by a sensitive direct search for dark matter, leading me to the second project, DMRadio-50L. Part of a suite of lumped-element axion searches, DMRadio-50L is currently in its commissioning phase, with extensive design and engineering work having been completed. In Ch. 4, I describe the design, construction, and testing of the cryogenic system for this experiment as well as some work related to understanding material properties at low temperatures.

Chapter 2

Introduction

2.1 Dark Matter

Modern physics faces a set of fundamental unanswered questions which lead us to conclude that the Standard Model (SM) of physics, the theory describing physics as we understand it, is inaccurate. One of these questions is what makes up the majority of the mass in the universe, as there is reason to believe that it is something beyond SM particles. The term “dark matter” was coined by Fritz Zwicky in 1933 to describe this mysterious matter when he uncovered the first hints of discrepancies between calculated and observed rotational velocities of galaxies and galaxy clusters. Over the last decades, evidence for the existence of dark matter has grown dramatically and numerous dark matter models have been proposed (Fig. 2.1). Despite the various studies demonstrating its existence, the exact nature of dark matter is still unknown, and progress towards its identification remains limited.

2.1.1 Evidence for Dark Matter

The first rigorous study accepted widely by the scientific community was Vera Rubin’s observations of galactic rotation curves in the 1970s [2]. Assuming that galaxies contain only luminous matter that has been identified, Newton’s Laws dictate that the velocity of visible stars and gases should decrease with increasing distance from the galactic center. However, Rubin’s studies showed that beyond the radius of most of the concentrated luminous matter, the rotation curves are flat (Fig 2.2), implying there is an invisible mass dominating the galaxy.

The case for dark matter was further strengthened by gravitational lensing studies [3, 4]. Gravitational fields of massive objects can bend the trajectory of light, distorting the images of astrophysical objects as viewed from Earth. The distortion of the light’s path based on the mass can be predicted by general relativity, offering an independent method to investigate the distribution of mass in the universe. One of the most significant studies using gravitational lensing was done in 2006 by Clowe et al. on the Bullet Cluster [5]. The Bullet Cluster is a pair of galaxy clusters which merged 150 million years ago. The gases

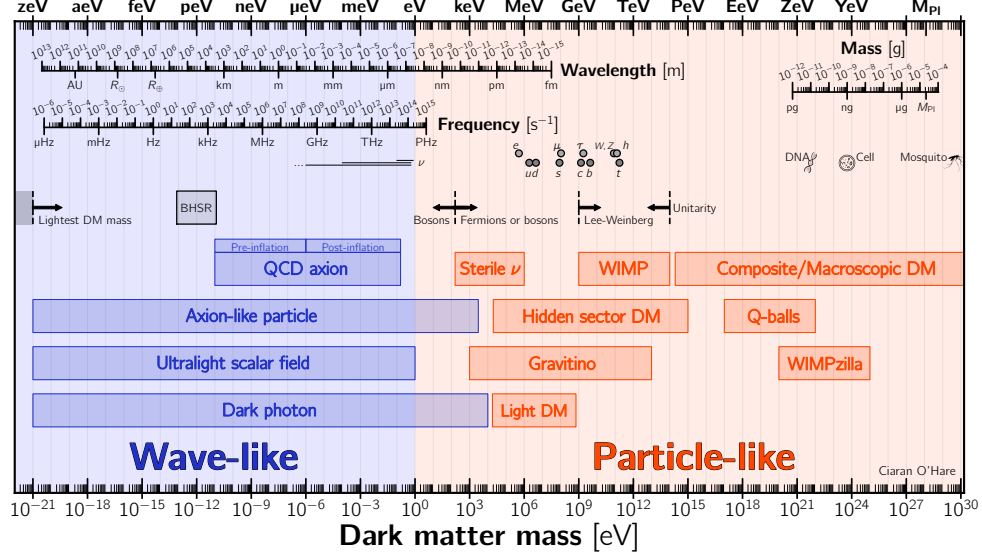


Figure 2.1: Different dark matter candidates as a function of their mass in eV. [1]

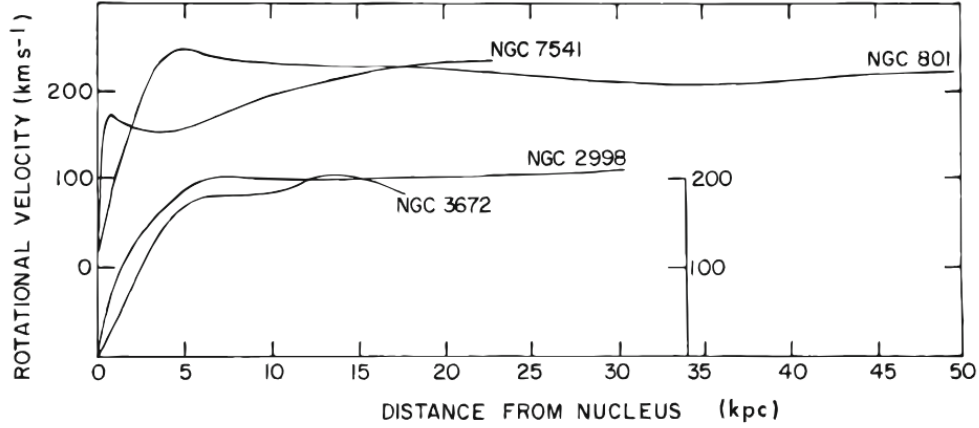


Figure 2.2: Plot of rotational velocity of visible matter as a function of distance from the galactic centers of four different galaxies. Adapted from Rubin's paper [2].

and plasmas dominating the baryonic matter emit X-rays which was observed by one of NASA's x-ray observatories, Chandra. The observations of this gas and plasma mapped a particular mass distribution, which did not agree with the mass distribution mapped using gravitational lensing. Evidently the baryonic matter collided during the merger and heated up, while the dark matter passed through the clusters without any observable effect. This strongly suggests that dark matter cannot be made up of ordinary baryonic matter.

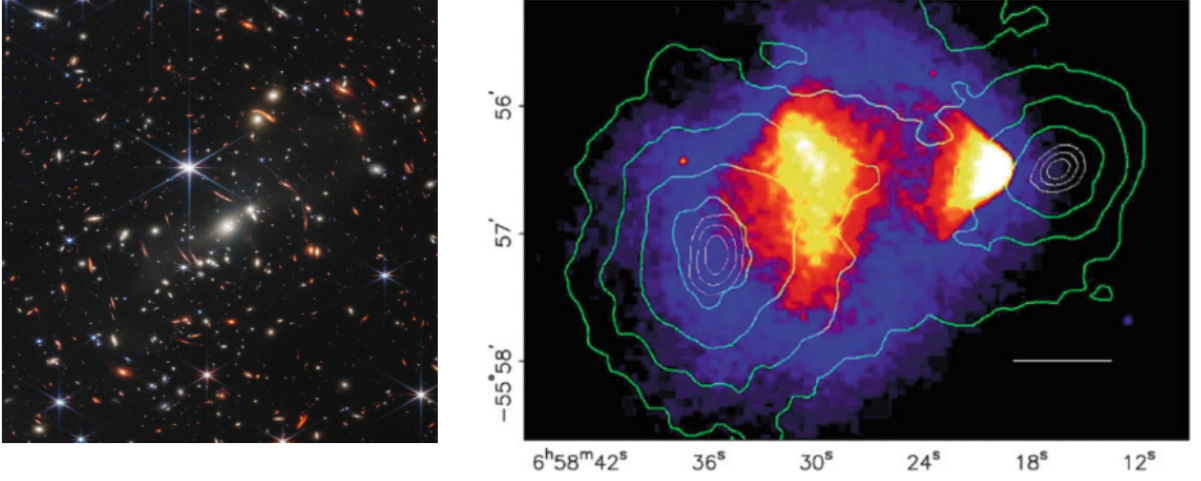


Figure 2.3: *Left*: A deep field image of the universe from the James Webb Telescope showing gravitational lensing (from the JWST public image release). *Right*: image of the bullet cluster, two colliding galaxy clusters [5]. The heat map shows the x-ray intensity and the contours denote the mass distribution deduced from gravitational lensing.

There is also reason to believe that dark matter was fundamental to structure formation and has been around since the fractions of a second after the Big Bang. Recent measurements of the cosmic microwave background (CMB) radiation gave us the earliest probes that we have of our universe [6]. The CMB is radiation that decoupled from baryonic matter about 400,000 years after the Big Bang and has been traveling through the universe ever since [7]. The decoupling is known as recombination, and it refers to the point when the universe cooled enough for the first atoms to form.

General relativity predicts that the spatial fluctuations of matter density should grow linearly with the expansion of the universe, i.e. as the universe expands, the density fluctuations grow. However, measurements of the CMB are remarkably uniform throughout the sky, implying that baryon density fluctuations at recombination could not possibly have seeded galaxy formation. This dilemma would be resolved if the mass of the baryonic matter in the universe was small compared to the mass of some cold dark matter (CDM) which could have begun clumping before recombination. This analysis is quantified by calculating and measuring the variation of the CMB temperature across the sky in terms of spherical harmonics. Measurements of the angular anisotropy spectrum of the CMB in this way agree with theoretical predictions of a CDM-dominated matter density, and the dark matter density to baryon density ratio derived from these measurements agrees with those found from velocity dispersion of galactic clusters and gravitational lensing studies [8], [9].

Yet another validation of dark matter lies in Big Bang Nucleosynthesis (BBN). BBN theory gives us the ratio of baryon density to photon density at the time when light elements

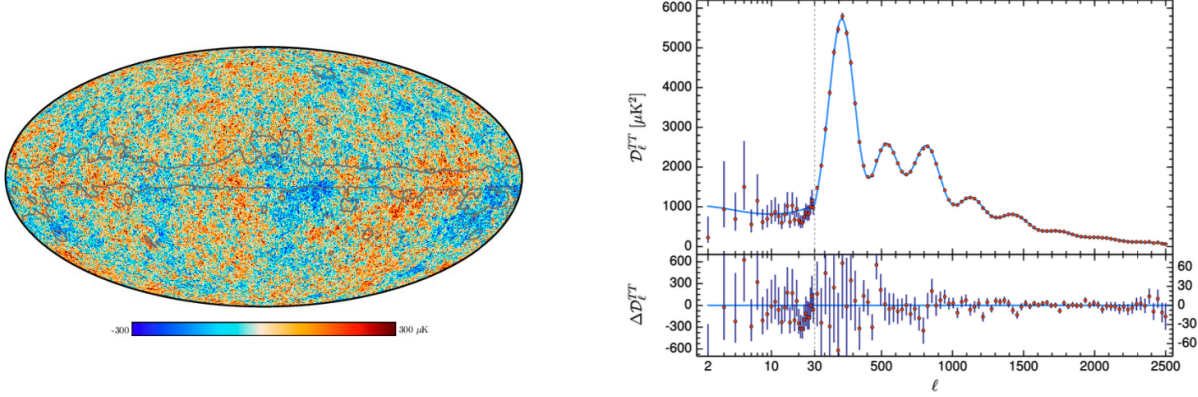


Figure 2.4: CMB measurements by Planck space observatory. On the left is the temperature fluctuations of the CMB, and on the right is a power spectrum of the fluctuations in terms of the multiple moments [6].

formed from measured ratios between abundances of ^1H , ^2H , ^3He , ^4He . Combined with the present Hubble parameter and the geometry of the universe determined from the CMB measurements, the density of nonbaryonic CDM can be determined [10]. This method gives a result consistent with all other lines of reasoning: over 80% of the universe is made up of dark matter.

2.1.2 The Axion

The axion was originally proposed in 1977 by Peccei and Quinn and independently by Weinberg and Wilczek to solve the strong charge-parity (CP) problem [11], [12], [13], [14]. A notable manifestation of the strong CP problem is the lack of an electric dipole moment in the neutron. Quantum chromodynamics (QCD) predicts a neutron electric dipole moment of

$$d_N = \frac{e}{m_N^2} \frac{m_u m_d}{m_u + m_d} \bar{\theta} \approx 10^{-16} \bar{\theta} e \text{ cm}, \quad (2.1)$$

where e is the electron charge, m_N , m_u , and m_d are the neutron, up quark, and down quark masses, respectively, and $\bar{\theta}$ is a parameter in the QCD Lagrangian [15]. The current experimental upper bound on the neutron electric dipole moment d_N is $3 \times 10^{-26} e \text{ cm}$ [15]. This implies a bound on $\bar{\theta}$ of $\bar{\theta} \leq 10^{-10}$, where $\bar{\theta}$ is allowed by the Standard Model to be between 0 and 2π . The fact that the value is unnecessarily so close to zero for an unknown reason (also known as “fine-tuning”) is the strong CP problem.

The solution proposed by Peccei and Quinn is to add a new global U(1) symmetry to the Standard Model which is broken at some high energy scale f_a and transforms $\bar{\theta}$ to a dynamic

variable with a classical potential that is minimized at $\bar{\theta} = 0$. The presence of this dynamic field introduces a term to cancel out the CP-violating term in the Lagrangian and leads to a new light pseudoscalar Nambu-Goldstone boson particle called the axion. The mass of the QCD axion m_a is approximately related to the Peccei-Quinn scale f_a by

$$m_a \approx 6 \frac{\text{eV}}{c^2} \left(\frac{10^6 \text{GeV}}{f_a} \right). \quad (2.2)$$

Soon after the original proposal by Peccei and Quinn, it was realized that the QCD axion also makes for a natural dark matter candidate, producing the observed abundance [16]. Axions are produced at zero temperature by the misalignment mechanism [17], under which the initial value of the field can deviate from the minimum of the potential. This makes them athermal, which allows them to be classified as CDM, (a thermal particle with sub-eV mass would necessarily be relativistic or “warm”).

A broader class of dark matter particle candidates is axion-like particles, or ALPs. These are particles that possess the same types of couplings to the SM as the QCD axion but not the mass linked to the Peccei-Quinn scale. This means they might possibly solve the dark matter problem but not the strong CP problem.

2.2 Indirect Dark Matter Searches

One method to search for dark matter is to look for an anomalous flux of photons, neutrinos, or cosmic rays produced in the possible annihilation or decay of dark matter. These searches are referred to as indirect searches since they focus on detecting products of dark matter interactions rather than observing the dark matter particle in the lab. The two main interactions that can be the subjects of indirect dark matter searches are the annihilation of two dark matter particles and the decay of an unstable dark matter particle.

2.2.1 Dark Matter Halos

The distribution of dark matter in the halos of galaxies is important in indirect dark matter searches because dark matter outside of our immediate local vicinity is being considered. N-body simulations of galaxy formation have given us required features of dark matter halos, and several proposals have come out describing the dark matter density distribution in galactic halos as a function of the distance from the center of the galaxy [18], [19], [20]. The shared feature between all the profiles is a denser and typically spherically symmetric region of dark matter in the galactic center and decreasing density with increasing radial distance to the center. The main difference between the models is the predicted shape of the central region, which has been referred to as the core-cusp problem [21]. The models based on N-body simulations of galaxy formation favor a step power-law behavior of dark matter near the center [18], while models obtained from observational data predict a constant dark

matter density near the core [19], [20]. A general parametrization of the dark matter halo describing a smooth distribution of dark matter can be written in the following form:

$$\rho_{DM}(r) = \frac{\rho_0}{\left(\delta + \frac{r}{r_s}\right)^\gamma \left(1 + \left(\frac{r}{r_s}\right)^\alpha\right)^{(\beta-\gamma)/\alpha}}, \quad (2.3)$$

where r is the distance from the Galactic Center, r_s is the scale radius, a characteristic length scale of the halo, ρ_0 is the density at the scale radius, and $\alpha, \beta, \gamma, \delta$ are parameters that vary with different halo models.

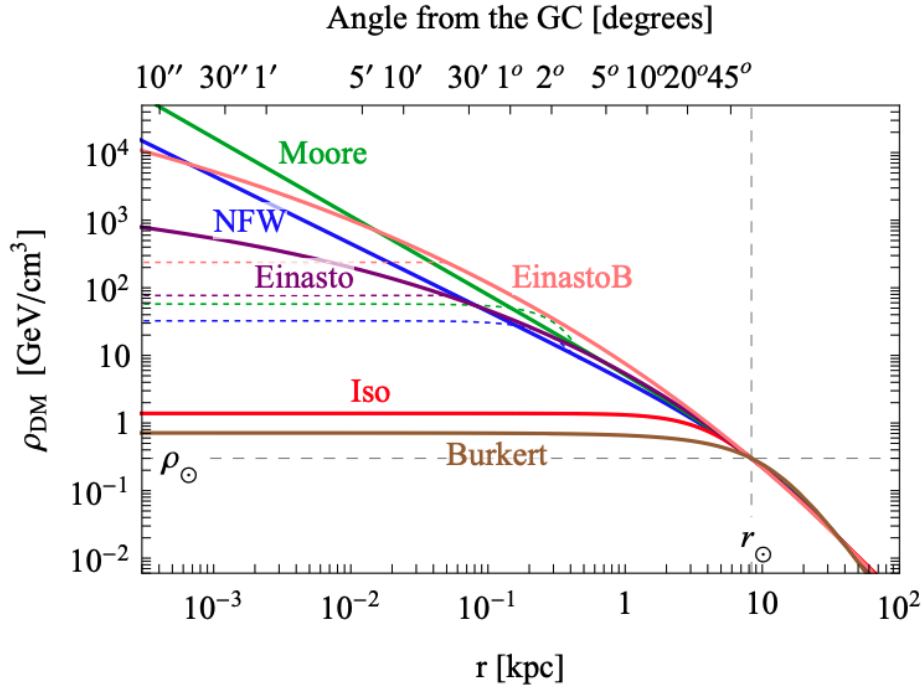


Figure 2.5: Commonly used Milky Way dark matter density profiles normalized to a local density $\rho_\odot = 0.3 \text{ GeV/cm}^3$ in the solar neighborhood, at $r_\odot = 8.3 \text{ kpc}$ from the Galactic Center [22]. Numerical simulations of structure formation in an expanding universe lead to the empirical NFW profile, which is used as the primary model for the analysis in Chapter 3.

2.2.2 Interactions

Given a specific dark matter halo, the flux arising from dark matter annihilation can be expressed as

$$\frac{dN_i}{dAdtdE_i} = \frac{1}{4\pi} \frac{\langle \sigma_A v \rangle}{2m_{DM}^2} \frac{dN_i}{dE_i} \iint_{\Omega \text{ l.o.s.}} \rho_{DM}^2(r) dr d\Omega, \quad (2.4)$$

where i is the type of particle, $\langle \sigma_A v \rangle$ is the velocity-weighted cross-section, ρ_{DM} is the dark matter density of the source, m_{DM} is the dark matter mass, and the l.o.s. stands for line of sight. The integral of the squared density along the line of sight will depend on the halo profile chosen, which means indirect dark matter searches must assume a specific halo model.

Dark matter decay can be probed in a similar manner by slightly modifying Eq. 2.4 to Eq. 2.5:

$$\frac{dN_i}{dAdtdE_i} = \frac{1}{4\pi} \frac{\lambda}{m_{DM}^2} \frac{dN_i}{dE_i} \iint_{\Omega \text{ l.o.s.}} \rho_{DM}(r) dr d\Omega. \quad (2.5)$$

The search in this case is for $\lambda = 1/\tau$, where τ is the candidate lifetime, rather than $\langle \sigma_A v \rangle$.

2.3 Direct Dark Matter Searches

Direct dark matter searches can be extremely sensitive, but they face practical challenges. The technologies developed for direct detection of dark matter in recent years have been designed with specific dark matter models and mass ranges in mind. This means that in order to exclude a new region in the dark matter parameter space, new experiments have to be designed and built, often increasing in cost to improve sensitivity. The mass ranges of dark matter can be roughly split into three groups: bosonic dark matter, fermionic dark matter, and composite dark matter. I will briefly summarize the leading candidate within each group and selected direct detection techniques.

2.3.1 Bosonic Dark Matter

Bosonic dark matter includes all candidates with mass less than approximately 1 eV. Because of their extraordinarily low mass and thus high occupation number, they can be thought of as a field as opposed to a particle. The main candidate within this category is the axion. In the presence of a DC magnetic field, axions can convert to photons via the inverse Primakoff effect [23], which is represented by the interaction Lagrangian

$$\mathcal{L}_{int,a} = g_{a\gamma\gamma} a F \tilde{F}. \quad (2.6)$$

Here a is the axion potential, F is the photon tensor field strength, $\tilde{F}$ is the dual tensor, and $g_{a\gamma\gamma}$ is the axion-photon coupling constant. Most axion experiments probing this interaction up until recently have used resonant microwave cavities placed in a strong magnetic field to facilitate the inverse Primakoff effect inside of a detector [24], [25]. The downside of resonant microwave cavity experiments is the cavity requires fine tuning, meaning only a tiny part of the parameter space can be covered at a time. Other axion searches look for couplings between axions and nuclear spins as well as axions and nuclear electric dipole moments [26], [27]. The exclusion plot for the axion-photon interaction is shown in Fig 2.6.

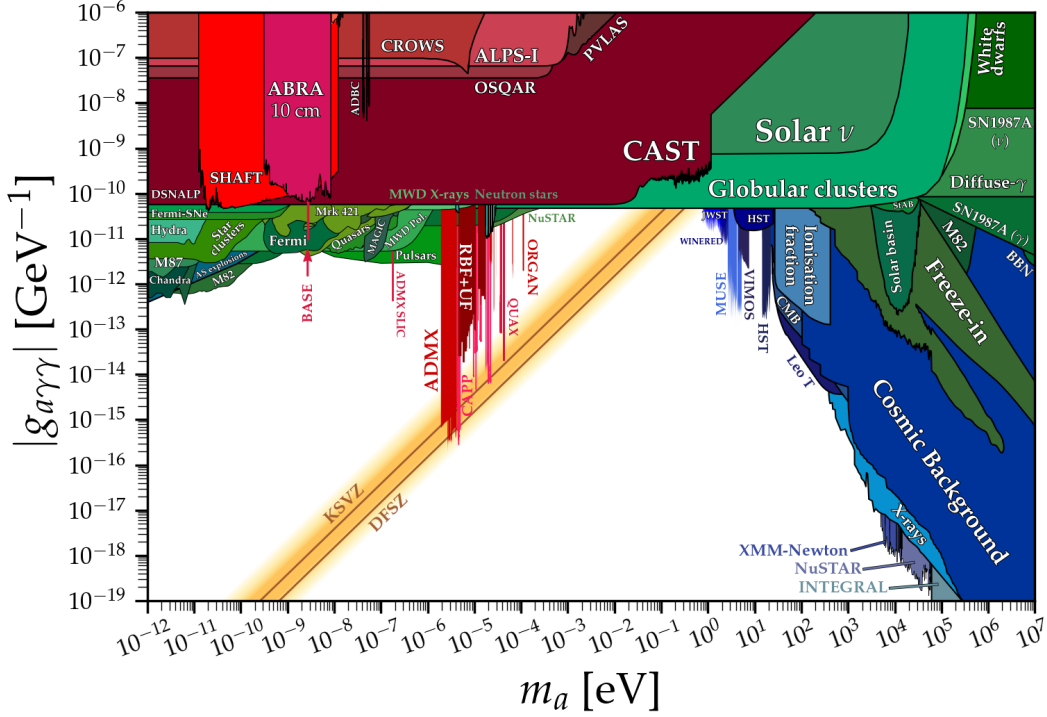


Figure 2.6: Exclusion plot for axion-photon coupling, with axion mass on the x axis and the axion-photon coupling constant on the y axis [28].

2.3.2 Fermionic Dark Matter

Fermionic dark matter includes candidates with mass between 1 eV and the Planck Mass ($\approx 10^{28}$ eV). The most investigated candidate within this category is the Weakly Interacting Massive Particle (WIMP). Unlike axion experiments, WIMP detectors search for rare events of WIMPs colliding with nuclei. One method uses the property of some noble gases to scintillate, or absorb energy from a particle and re-emit that energy as light. The XENON series of experiments is an example of this method [29]. Other techniques include bubble chambers with superheated liquid waiting for enough energy to trigger a phase transition [30] and crystal detectors using crystal lattices that can convert WIMP excitations to detectable vibrations [31].

2.3.3 Composite Dark Matter

Composite dark matter encompasses candidates with mass between the Planck Mass and Solar Mass. The leading candidate in this category is the primordial black hole (PBH), a black hole that formed very early in the universe without the collapse of a star. PBHs can be studied with a variety of methods, including Hawking radiation [32], CMB temperature

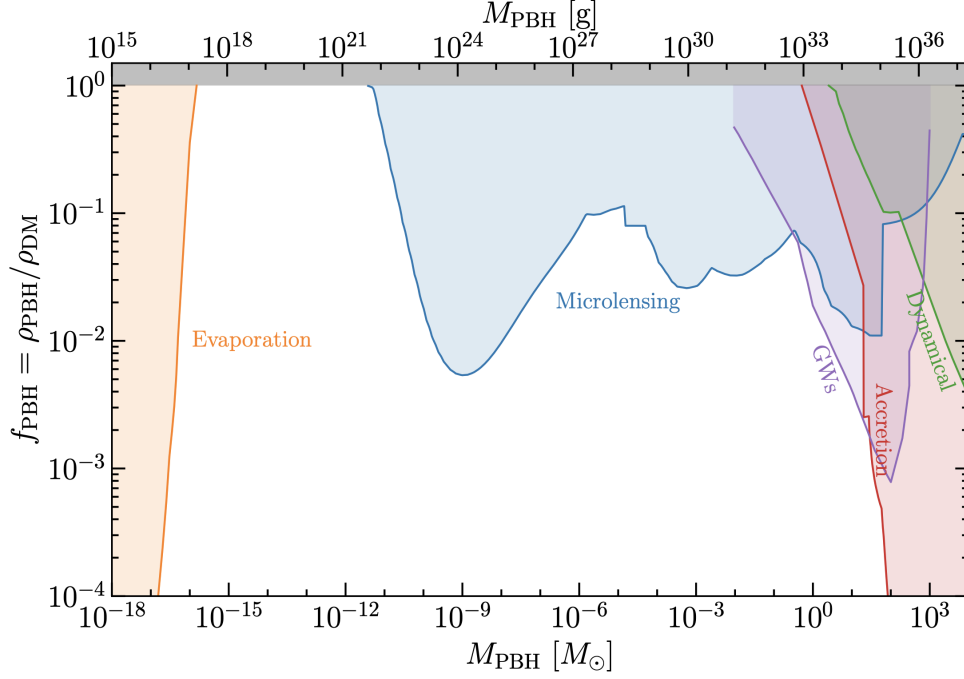


Figure 2.7: Constraints on the fraction of DM in the form of PBHs, as a function of mass, assuming all PBHs have the same mass. The bounds shown are from evaporation (orange), microlensing (blue), gravitational waves (purple), accretion (red) and dynamical (green). Figure adapted from [35].

anisotropies [33], and gravitational waves [34]. The current constraints on the fraction of dark matter that could be made up by PBHs is shown in Fig. 2.7.

Chapter 3

A Model-Independent Dark Matter Search

3.1 Introduction

As mentioned earlier, indirect dark matter searches have the advantage of being able to be relatively broad and assume less about the dark matter candidate as compared to direct detection methods. In this chapter, I will describe the development of a particular search strategy that relies on as few assumptions as possible while possessing sensitivity and selectivity to dark matter, resulting in a proof of concept [36] and analysis over the L and S bands [37].

3.2 Search Concept

This search focuses on the possible radiative decay or annihilation of ultralight dark matter within our Milky Way Galactic halo, leading to a quasimonochromatic radio line ($\Delta\nu/\nu \approx 10^{-3}$). This search is predicated on two generally accepted characteristics of dark matter in our Galactic halo. First, we assume that the dark matter constitutes a static halo through which our solar system is moving, with a characteristic velocity $v_S \approx 240 \text{ km s}^{-1}$ tangential to the disk. Consequently, such a radio line would be distinguished from any other source, conventional or otherwise, by a systematic Doppler shift with respect to the Sun's direction of motion: $(l, b) = (90^\circ, 0^\circ)$ in Galactic coordinates. While our galaxy and its halo likely include nonvirialized streams of both baryonic and dark matter due to late-time assimilation of smaller galaxies, overall our halo should be well represented by a static virialized spherical distribution. Second, the signal should reflect the spatial distribution as represented by a standard halo model; more specifically the signal power should follow the line-integrated density of the halo ρ for dark-matter decay, or ρ^2 for annihilation or any other two-body process producing a photon. This implies that in an all-sky data set, a radio line representing

a real dark matter signal should be maximized toward the Galactic center, $(0^\circ, 0^\circ)$, minimized looking outward, and roughly symmetric around that axis.

Dark matter decay here includes all processes $\chi \rightarrow \phi + \gamma$, including in principle two-photon decays from pseudoscalars such as the axion or an axion-like particle $\chi \rightarrow \gamma + \gamma$. We will assume the photon energy $h\nu = \frac{m_\chi c^2}{2}$. What for convenience we refer to as annihilation similarly subsumes all two-body initial states, including annihilation proper $\chi + \chi \rightarrow \phi + \gamma$ as well as Compton-like processes $\chi + \xi \rightarrow \phi + \gamma$, where ξ and ϕ represent any standard model or beyond-standard model particles; see Fig. 3.1.

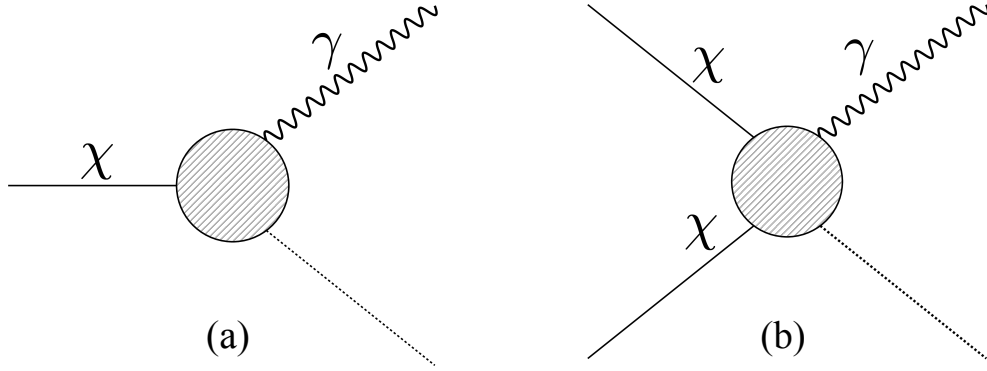


Figure 3.1: (a) Decay of a dark matter particle into a photon and another particle or photon. (b) Annihilation or Compton-like process leading to a two-body final state, one of which is a photon.

As mentioned in Chapter 2, the flux density in general for the two cases of annihilation and decay processes is given by:

$$\frac{P_A}{\Delta A \Delta \nu} = \frac{1}{8\sqrt{2\pi}} \frac{\langle \sigma v \rangle (\Delta \theta)^2 c^2}{M_\chi \eta^A \nu_0} e^{\left[-\left(\frac{\nu - \nu_0}{\sqrt{2}\eta^A \nu_0}\right)^2\right]} \int_0^\infty \rho(\mathbf{r})^2 d\mathbf{r}, \quad (3.1)$$

$$\frac{P_D}{\Delta A \Delta \nu} = \frac{1}{16\sqrt{2\pi}} \frac{\lambda (\Delta \theta)^2 c^2}{\eta^D \nu_0} e^{\left[-\left(\frac{\nu - \nu_0}{\sqrt{2}\eta^D \nu_0}\right)^2\right]} \int_0^\infty \rho(\mathbf{r}) d\mathbf{r}, \quad (3.2)$$

which depends on the particle physics through the velocity-weighted cross section $\langle \sigma v \rangle$ for annihilation, or the decay constant λ in the case of decay. Here η is the line width with σ_{vir} the halo virial velocity, $\rho(\mathbf{r})$ the halo density along the line of sight, c the speed of light, M_χ the mass of the dark matter particle, ν_0 the center frequency, and $\Delta \theta$ the frequency-dependent FWHM beamwidth of the telescope.

$$\eta^A = \frac{\sigma_{\text{vir}}}{\sqrt{6}c}, \quad \eta^D = \frac{\sigma_{\text{vir}}}{\sqrt{3}c}. \quad (3.3)$$

Specifically to the Green Bank Telescope (GBT), these are

$$\left(\frac{P_A}{\Delta A \Delta \nu}\right) \left[\frac{W}{m^2 Hz}\right] = 1.28 \times 10^{-17} \frac{\langle \sigma v \rangle [cm^3/s]}{M_\chi [\mu eV] (\nu [GeV])^3} (\Delta \theta)^2 \times e^{[-(\frac{\nu - \nu_0}{\sqrt{2} \eta^A v_0})^2]} I^A(l, b) \left[\frac{M_\odot^2}{kpc^5}\right], \quad (3.4)$$

$$\left(\frac{P_D}{\Delta A \Delta \nu}\right) \left[\frac{W}{m^2 Hz}\right] = 5.3 \times 10^{-8} \frac{\lambda [1/s]}{\eta^D (\nu [GeV])^3} (\Delta \theta)^2 \times e^{[-(\frac{\nu - \nu_0}{\sqrt{2} \eta^D v_0})^2]} I^D(l, b) \left[\frac{M_\odot^2}{kpc^5}\right], \quad (3.5)$$

where $I^{A,D}(l, b)$ are the respective line integrals, dependent on the specific halo model.

A high level step-by-step overview may be helpful to understand how limits on dark matter lifetimes and annihilation cross sections are derived, followed by detailed explanations of each step of the procedure in the next sections. (i) First, the data is time averaged and downsampled by a factor of 64 in the frequency domain, since the signal is wide compared to the raw resolution. (ii) The individual spectrograms are then unit-normalized by a procedure that preserves the structure of the expected signal width. (iii) The Doppler asymmetry spectrum is formed based on sorting the overall sample of spectra into Forward and Backward populations, relative to the Sun's vector velocity in the Milky Way. The Intensity asymmetry spectrum is similarly formed, relative to the vector to the Galactic center. (iv) For the halo model assumed with its specific parameters, the line integrals and Doppler shifts associated with the Galactic coordinates of each spectrum included in the samples above are calculated. Templates for the Doppler and Intensity asymmetries are calculated specific to the spectra included in the analysis. (v) The Doppler and Intensity correlation spectra are formed by taking the dot product between their asymmetry spectra and templates at each frequency. (vi) Finally the Doppler and Intensity correlation spectra themselves are cross correlated, and physics limits are established based on a p-value analysis.

The cases of dark matter decay and annihilation will be treated separately, as their observed line widths will differ. Assuming a static halo of uniform virial velocity, the Doppler broadening of the source along the line of sight for the two cases is given by

$$\frac{\sigma_D}{\nu} = \frac{\sigma_{\text{vir}}}{\sqrt{3}c} \quad \text{and} \quad \frac{\sigma_A}{\nu} = \frac{\sigma_{\text{vir}}}{\sqrt{6}c}, \quad (3.6)$$

where σ_D and σ_A denote the standard deviation in frequency associated with decay and annihilation, respectively, and σ_{vir} the virial velocity of the halo. Being the sum of Gaussian variates, the distribution of the two-body center of mass motion is narrowed by $\sqrt{2}$ relative to that of a single particle, and thus the line width for dark matter annihilation is correspondingly narrowed relative to decay.

For each frequency band, this analysis requires the combining of thousands of spectra taken over a year or more, at differing times of day, sky position, atmospheric conditions, hardware and software configurations, etc. Both the shape and magnitude of the spectra

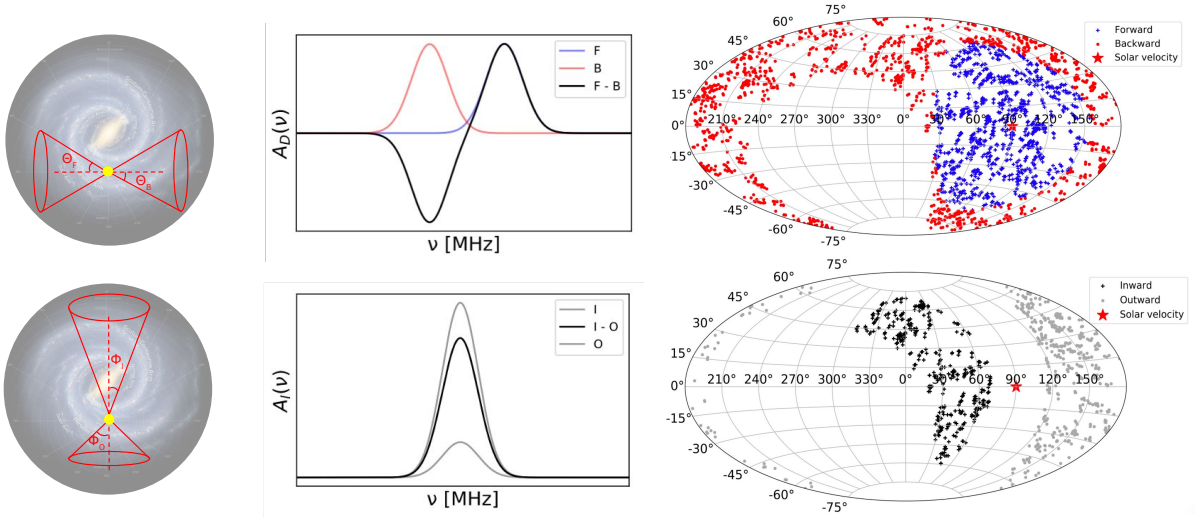


Figure 3.2: (a) Concept of asymmetry-based searches for dark matter within a large data set broadly sampling the observable sky. The angles defining the Forward and Backward samples, $\theta_{F,B}$ are chosen to maximize the signal-to-noise ratio. (b) The idealized dark matter signature in the Doppler asymmetry spectrum $A_D(\nu)$ would be a bipolar signal in frequency, prescribed by the $(V_S, \sigma_{\text{vir}})$ and the ensemble of specific targets selected. The idealized dark matter signature in the Intensity asymmetry spectrum $A_I(\nu)$ would be a unipolar signal centered at the frequency of the decay or annihilation photon in the dark matter's rest frame. In practice, due to the normalization scheme, the actual asymmetries are more complex in shape, but remain antisymmetric and symmetric respectively. (c) Mercator plots exhibiting the actual targets included in the analysis, the regions being demarked by $\theta_F = \theta_B = 65^\circ$ and $\Phi_I = 70^\circ$, $\Phi_O = 115^\circ$ (Adapted from [36]).

varied by several percent and often much more, even between sequential 5 minute observations taken only a few degrees apart. To search for a very small signal aggregated over such a large data set first required unit-normalization of the data. First, the spectra are co-averaged by 64 channels; this results in both improved sensitivity in the final analysis but more importantly a major reduction in computational time in the fitting procedure. The second step in the analysis consists of dividing the spectrograms by the polyphase filter bank function (PFB), followed by normalization of all the spectra individually. Both the PFB removal procedure and normalization procedure are detailed in the next sections.

The concept of the Doppler and Intensity asymmetries is schematically represented in Fig. 3.2. In the case of the Doppler asymmetry, under the assumption of a static halo, a dark matter signal is Doppler shifted according to its polar angle θ from the direction of the Sun's motion through the galaxy,

$$\nu' = \nu \left(1 + \frac{V_S}{c} \cdot \cos \theta \right), \quad (3.7)$$

where estimates for the solar velocity $V_S \approx 240 \text{ km s}^{-1}$ [38] are comparable to the local virial velocity of the galaxy, $\sigma_{\text{vir}} \approx 270 \text{ km s}^{-1}$ [39]. Owing to the observational and modeling uncertainties intrinsic to these numbers, we explored the variation of our analysis in excursions of V_S and σ_{vir} within the range $225 - 275 \text{ km s}^{-1}$ and find it to be not highly sensitive.

For each case, the asymmetry spectrum is formed:

$$A_D(\nu) = \frac{F - B}{F + B}, \quad A_I(\nu) = \frac{I - O}{I + O}, \quad (3.8)$$

with F (B) designating the average of all spectra within the Forward (Backward) acceptances defined by their polar angles $\theta_{F/B}$.

$$F(\nu, \theta_F) = \frac{1}{n_f} \sum_i f_i(\nu), \quad B(\nu, \theta_B) = \frac{1}{n_b} \sum_i b_i(\nu) \quad (3.9)$$

for some fixed θ_F and θ_B and similarly for I (O), the Inward (Outward) populations within their respective polar angle cuts $\Phi_{I/O}$. Forming asymmetry spectra has the virtue of canceling out to a high degree common-mode residual structure apparent in all normalized spectra at the $\approx 10^{-4}$ level, thus enabling a more sensitive search.

Finally, the template asymmetry is made by subjecting the template-injected spectra to the same normalization and asymmetry procedures, and the resulting template asymmetry is cross-correlated with the injected asymmetry. The cross-correlated spectra for Intensity and Doppler are combined, and this process is repeated for signals until they cross the 3σ line, thereby setting an exclusion limit at that frequency.

Note that this is not the first proposed use of a Doppler shift as a discriminant of dark matter; see [40] for its suggested application in regard to the 3.5 keV line reported by several X-ray observatories.

3.3 Breakthrough Listen Dataset

This analysis utilizes the Breakthrough Listen (BL) public data release from the 100 m Robert C. Byrd Green Bank radio telescope (GBT), shown in Fig. 3.3. The GBT is the world's largest fully steerable radio telescope, operating at 0.1 - 116 GHz with access to 85% of the local celestial hemisphere. The data in the BL public data release was taken between January of 2016 and March of 2019 [41, 42]. The BL program to date has focused on approximately 1700 nearby Hipparcos catalog stars, as well as some targets from other catalogs that were not used for this analysis [43], [44] and 100 nearby galaxies. Observations with the GBT have been taken with receivers covering the L, S, C and X bands (1.1-11.6 GHz), with the analysis described in this thesis covering most of the L and S bands, specifically 1020 - 2700 MHz. The L- to X-band range lends itself favorably to a search for monochromatic photons from dark matter, as the region is largely devoid of molecular lines, and radio frequency interference (RFI) lines are generally confined to the lower frequencies, whose identification can be confirmed by the GBT RFI scan archive [45].

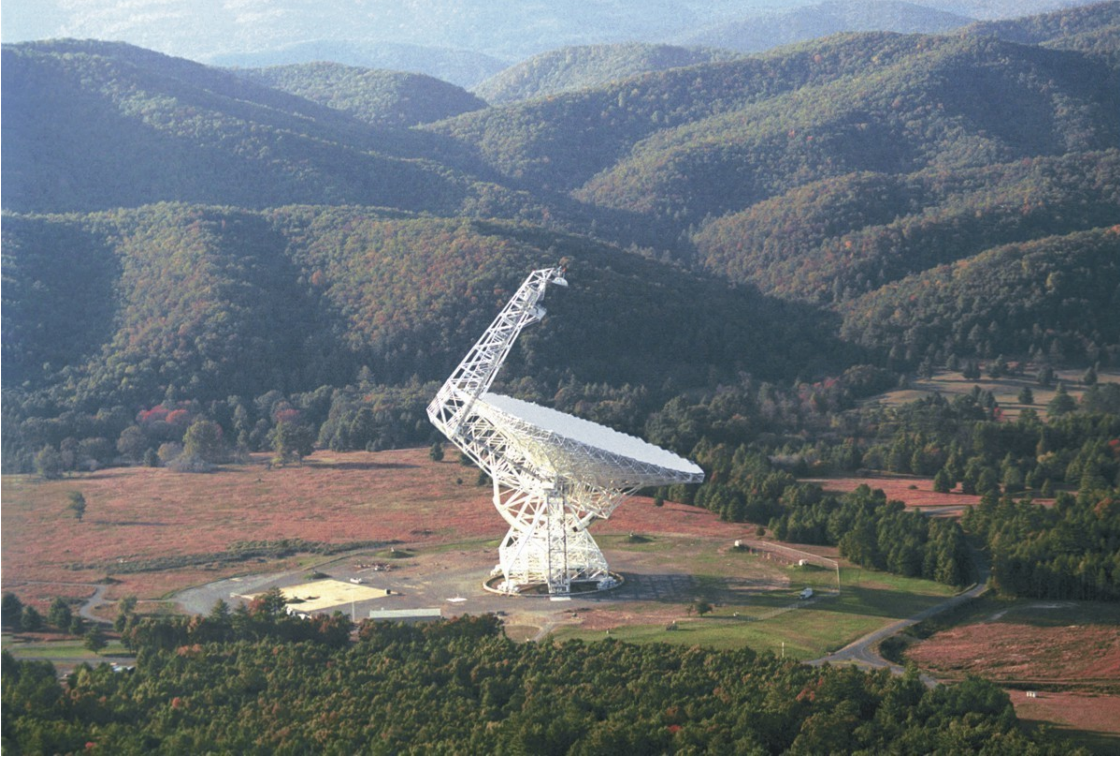


Figure 3.3: Photo of the Green Bank Telescope in West Virginia.

The BL observing cadence for each star comprises six 5 minute spectra with the pattern ABACAD, where A designates an on-target spectrum, with B, C, and D designating different off-target spectra, each a few degrees away from the target and from one another. All spectra A, B, C, D were included in the analysis, whether catalog stars or dark sky, after carefully examining for any evidence for differences between pairs of spectra, whether on- and off-star, or between pairs of distinct stars. Such contributions, which might bias the analysis, could be either from conventional astrophysics or extraterrestrial communication, technosignatures etc., as the Breakthrough Listen survey was conducted in support of the SETI program. The BL on-off observing strategy was designed for optimal subtraction of common background. Under the assumption that dark matter is smoothly distributed in the halo and not preferentially localized around any particular star, all spectra collected are useful to our analysis, independent of specific coordinates. The spectrograms used in this analysis are channels in the spectrogram data, or approximately 2.93 MHz. The spectra are additionally characterized by a quasi-periodic ≈ 15 MHz undulation, approximately 10% in magnitude. As will be described later, to usefully combine and manipulate thousands of spectra in our analysis requires that both the polyphase filter and undulatory structure be removed, as well as drifts in both shape and magnitude, evident even between successive 5

minute observations.

3.3.1 HI Line Calibration

To determine the particle physics parameters from the data, it is necessary to calibrate the raw data. Our calibration relied upon the System Equivalent Flux Density (SEFD) from the L-band receiver of the GBT and checked with a comparison of the HI line between our data and the Bonn all-sky survey [46]. The qualitative comparison for three targets is shown in Fig. 3.4.

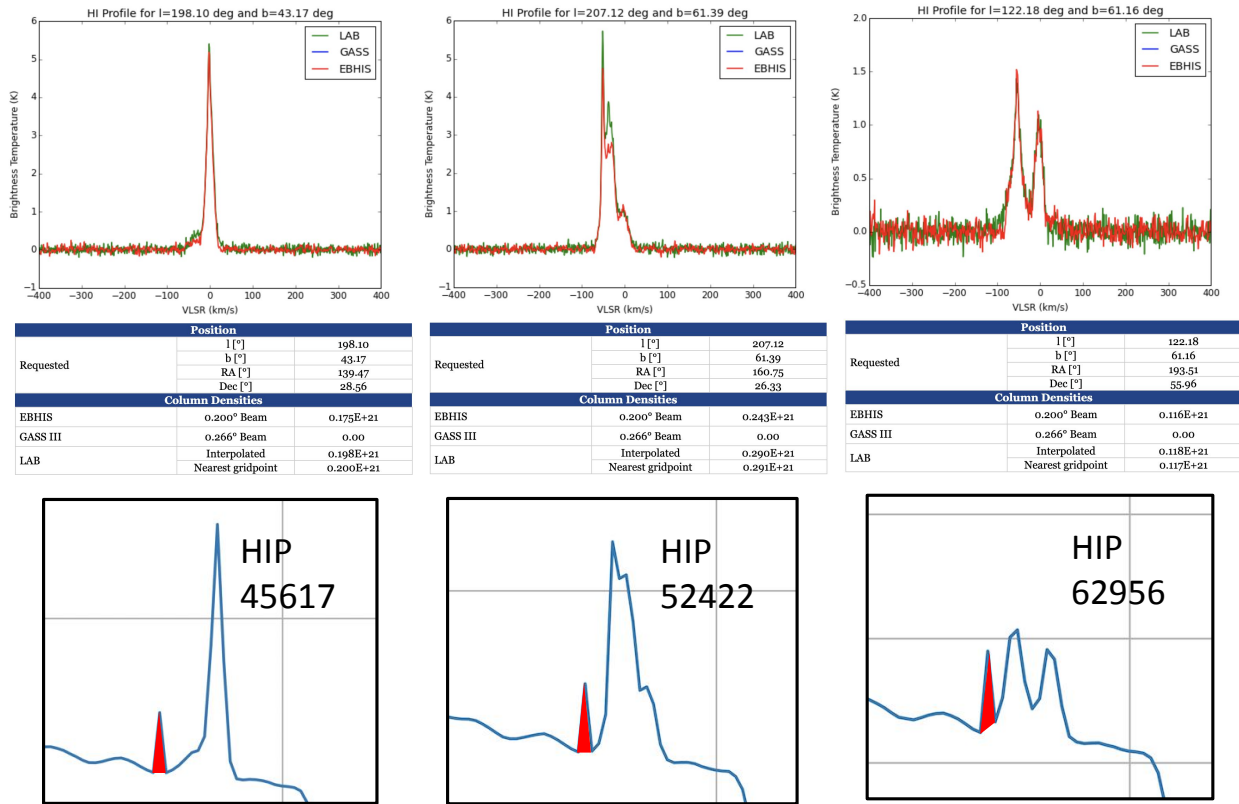


Figure 3.4: Comparison between the Bonn all-sky HI survey (top) and the GBT raw data (bottom) in the region of the HI line. The peak highlighted in red is an artifact.

3.4 Analysis Development and Optimization

In this section, I will describe the process of developing each component of the analysis and the optimizations that went into it.

3.4.1 Polyphase Filter Bank Structure Removal

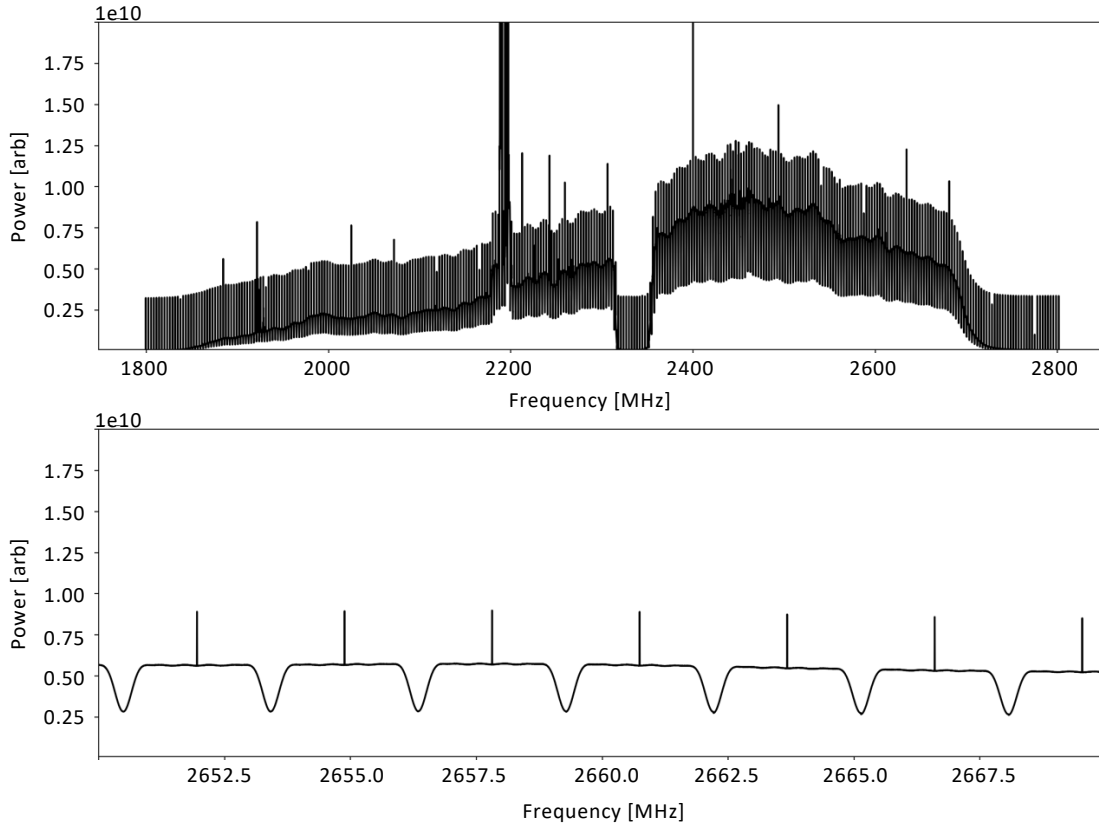


Figure 3.5: *Top:* Randomly selected raw spectrum across the entire S Band. *Bottom:* Same spectrum zoomed in to highlight the structure of the PFB.

The polyphase filter bank (PFB) technique is an improvement upon the straightforward discrete Fourier transform, specifically offering improved isolation between channels and flatter frequency response across each channel. However, it is impossible to analytically reconstruct this bandpass filter and remove it from the data perfectly due to the effects of the instrument's own bandpass shape as well as aliasing of power between adjacent channels. Therefore, numerous methods to extract the structure while preserving the possible signal were investigated. The shape of the PFB in the raw data is shown in Fig. 3.5.

The final procedure is as follows:

- Remove central spikes (1 channel out of 1024) and downsample by 64 with a moving average.

- Select some number (>5) of unit cells, also known as coarse channels, each located at a flat portion of the repeating undulating structure and normalize them such that the average of the top of the unit cell is ≈ 1 ; example of six such unit cells is shown in Fig 3.6. These will be used to construct the ideal unit cell.

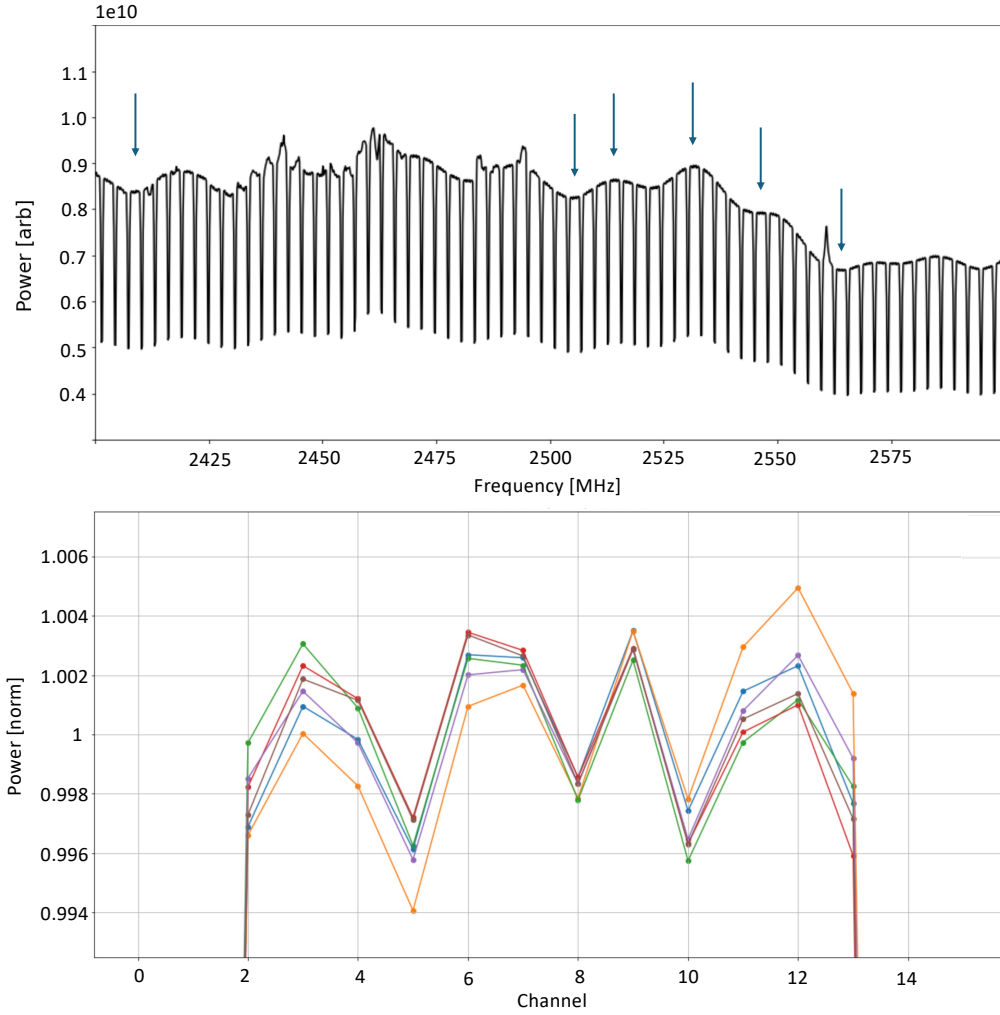


Figure 3.6: *Top*: 6 unit cells from flat regions of the undulating structure denoted by arrows. *Bottom*: Same 6 unit cells normalized to the middle of each unit cell and plotted all together, with a zoom to the flat region at the top to emphasize the underlying structures.

- Use least-squares to fit a 5th order polynomial to the top regions of the five unit cells centered on each selected unit cell from the previous step. Divide out this polynomial from each selected unit cell to eliminate the curvature; example shown in Fig 3.8.

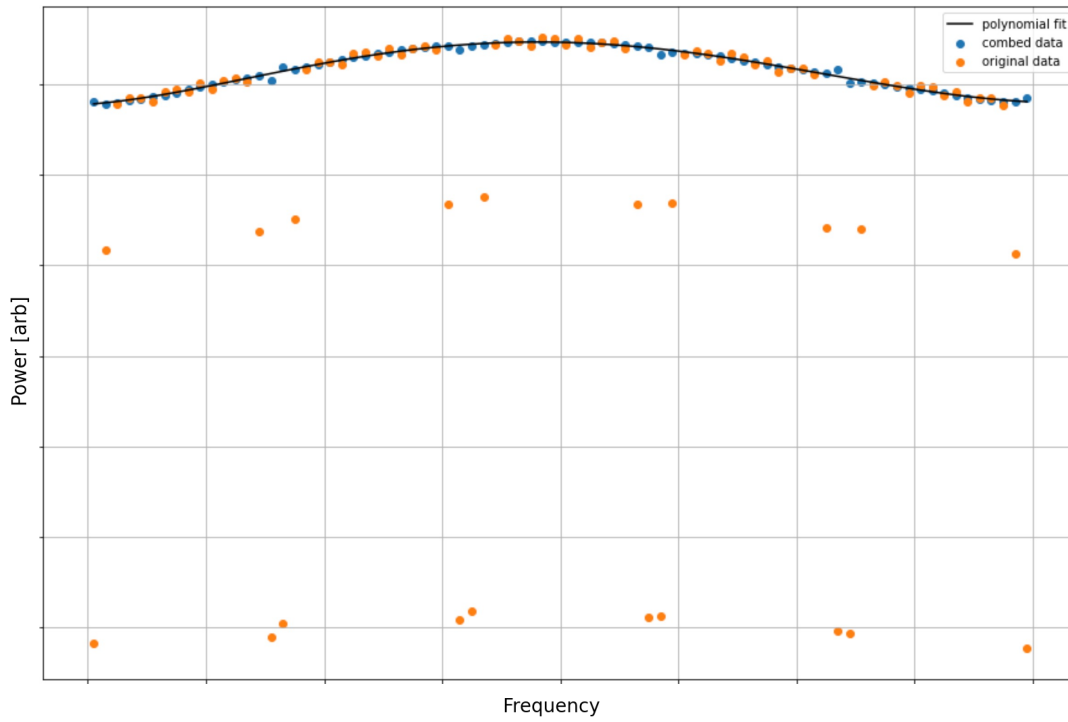


Figure 3.7: Example of a polynomial fit to the 5-cell neighborhood of a selected unit cell. The “combed” data refers to data that has already been divided by the normalized unit cell.

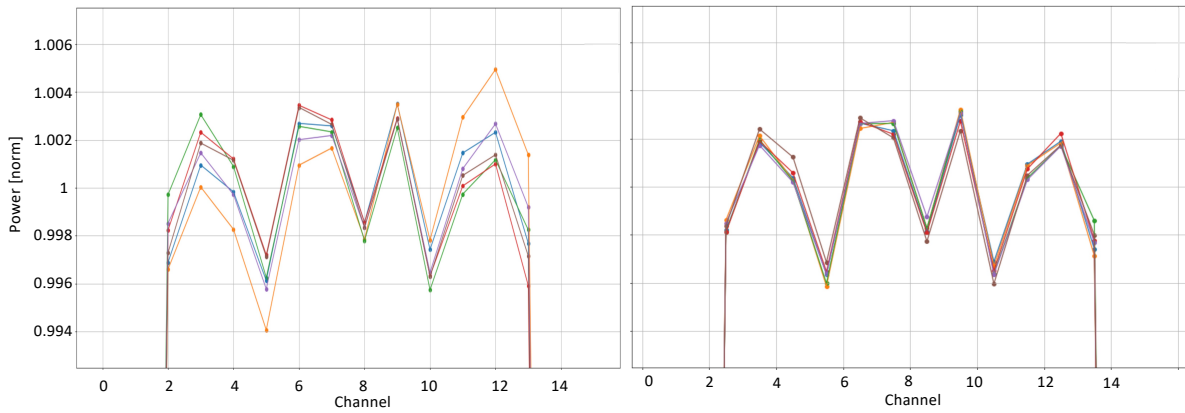


Figure 3.8: Six selected unit cells plotted together before (left) and after (right) dividing out the polynomial fit. The convergence to a representative unit cell is clear between the two plots.

- Repeat this procedure across all spectra and average resulting unit cells to create one

ideal unit cell, repeated as many times as the length of the spectrum requires. This will be referred to as the “comb”. As shown in Fig 3.9, dividing out the comb still leaves a residual structure in the 2-4 points on the edges of unit cells, so they will need to be interpolated later on in the procedure. However, this method of constructing the comb has proven to be the best way to eliminate any structure on the flat regions of the unit cells.

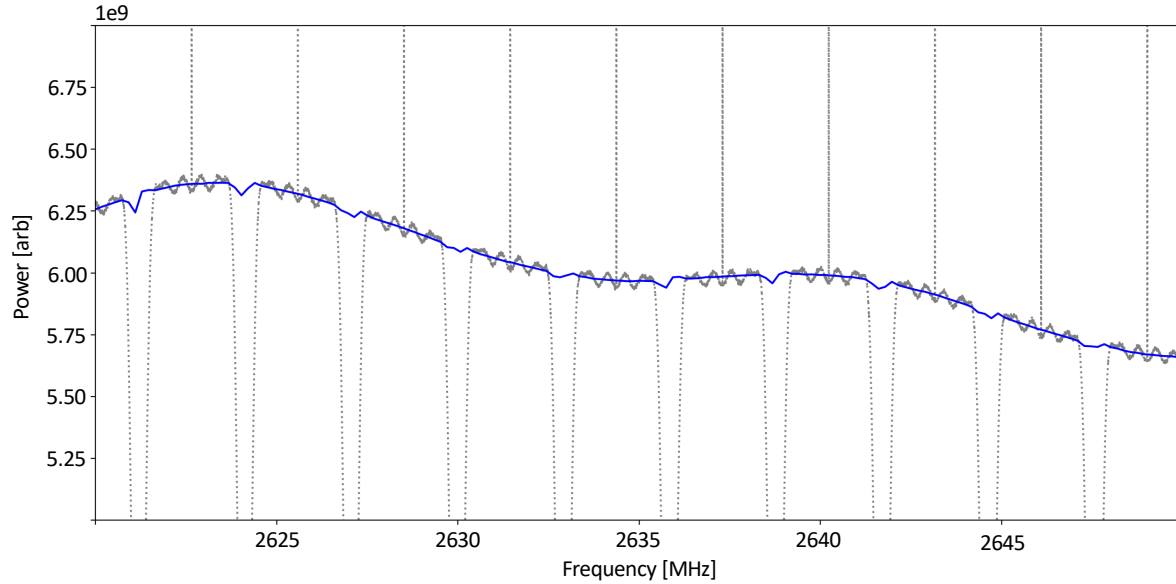


Figure 3.9: Combed spectrum (blue) plotted on top of the original raw data (dotted gray).

Note that this procedure was compared to optimization schemes using numerical methods such as gradient descent as well as a reconstruction algorithm used by the Breakthrough Listen Institute [47]. In all cases, this procedure resulted in the lowest standard deviation in the normalized spectra.

3.4.2 Normalization

As mentioned above, in order to combine a large set of data with varying scales of power, it is necessary to normalize every spectrum individually. Numerous normalization schemes were developed and tested, starting from mathematically simple expressions and progressing to more complicated algorithms. Throughout the course of these studies, a great amount of attention was paid to minimizing the remaining noise in the normalized spectra as well as understanding signal dilution and distortion. Ultimately, the last two schemes presented gave the best results and were used to perform the proof of concept and the complete analysis over the L and S bands.

Deterministic Integral Normalization

The simplest and least computationally expensive normalization method is a rolling polynomial of some order such that the integral of the polynomial over some number of sequential unit cells yields their integrated spectra over their range. For this set of normalization methods, the polyphase filter bank structure was left in. In the case of a 3-cell polynomial, the expression is:

$$y(x) = a + bx + cx^2$$

where

$$\begin{aligned} a &= \frac{13}{12}B - \frac{1}{24}(A + C) \\ b &= \frac{1}{2}(C - A) \\ c &= \frac{1}{2}(A + C) - B \end{aligned}$$

A, B, and C are integrals of the 3 unit cells, shown on the left side of Fig. 3.10. The normalized spectrum is then formed by dividing each point by the polynomial evaluated at the same frequency. For purposes of testing the normalization scheme, a small asymmetry was formed by averaging 12 forward spectra and 12 backward spectra and taking the following expression:

$$\frac{F + B}{F - B}.$$

The asymmetry for this method is shown on the right side of Fig. 3.10.

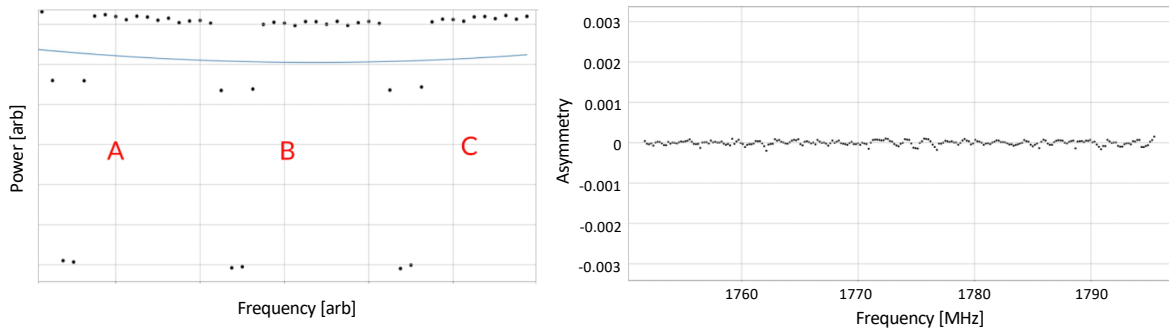


Figure 3.10: *Left*: An example of 3 consecutive unit cells and the deterministic polynomial in blue. *Right*: Asymmetry of 12 forward and 12 backward spectra over a clean frequency range using the 3-cell polynomial method.

The same thing can be done for a 5-cell window using a 4th order polynomial, shown in Fig. 3.11. Although these methods succeed in normalizing the spectra on a large scale, the

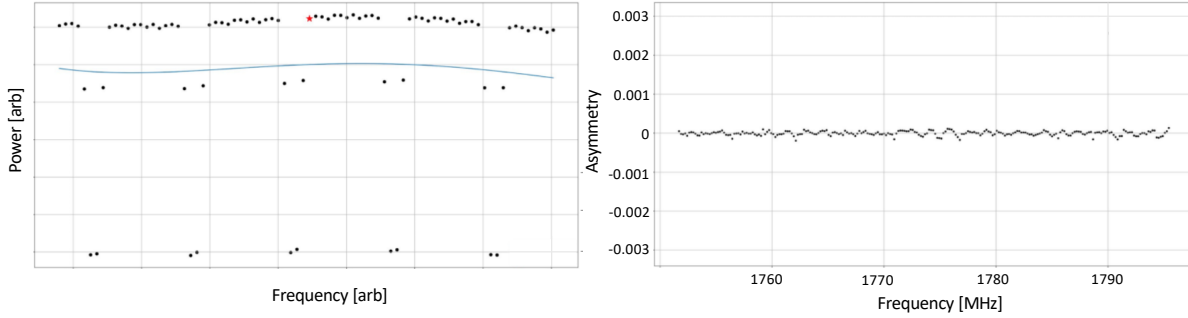


Figure 3.11: *Left:* An example of 5 consecutive unit cells and the deterministic polynomial in blue. The center point which is being normalized is highlighted with a red star. *Right:* Asymmetry of 12 forward and 12 backward spectra over a clean frequency range using the 5-cell polynomial method.

small-scale structure persists, since the noise narrower than the window of unit cells used for the integral does not get eliminated. Thus, they were not used in the analysis.

Savitzky-Golay Normalization

In 1964, Savitzky and Golay showed that a point-by-point least-square polynomial fit can be computed more efficiently [48]. Specifically, we can calculate a set of weighting coefficients for a given order and window size (M, N). Then, the fitted polynomial for each window turns out to be a fixed linear combination of the inputs using the weighting coefficients, meaning that recalculating the polynomial for each window is unnecessary.

While low standard deviation of the normalized spectrum is important, it is equally important to ensure that the potential signal in the data doesn't get diluted. Thus, in conjunction with the standard deviation study, we inspected the degree to which the Savitzky-Golay fit tracks a signal atop the raw data as well as the structure underneath. This study involved fitting the raw data and the injected data to the polynomial with given parameters (window, order) to see the effect of the fit on the normalized spectrum for both cases. Some examples are shown in Fig. 3.12.

Weighted Polynomial Normalization

The weighted polynomial scheme consists of a moving ratio of weighted polynomials. Specifically, each point is fitted to the following form:

$$R(\nu_i) = \frac{P(\nu_i; m, n; 0, 0)}{P(\nu_i; m, n; a, b)}. \quad (3.10)$$

For the polynomial $P(\nu_i; m, n; a, b)$ fit to the data within a window around ν_i , m is the number of data points within the window, and n is the order of the polynomial. The

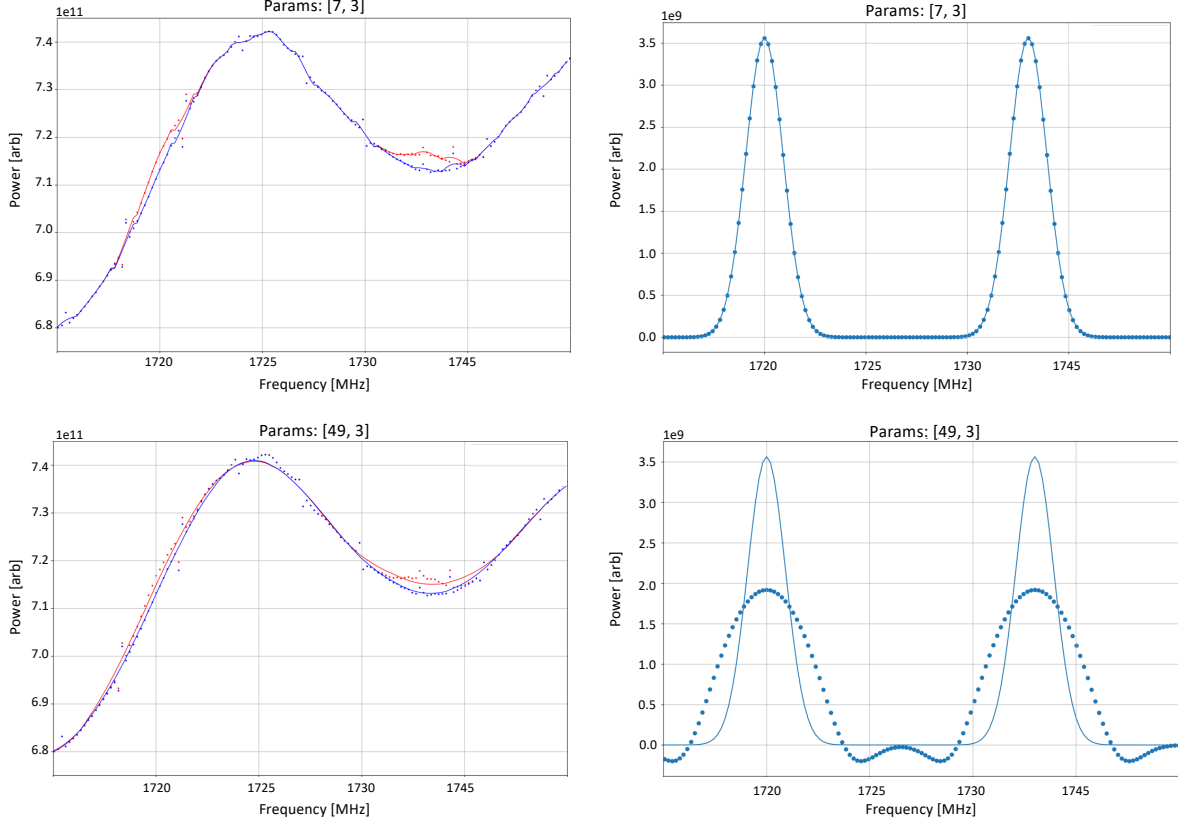


Figure 3.12: *Left:* Two sets of parameters (window, order) for a Savitzky-Golay (SG) fit over a selected frequency range with two injected signals. The raw data and the fit to the raw data are in blue, and the injected signals and the fit to the injected signals are in red. *Right:* The same two sets of parameters (window, order) showing the resulting shapes of the signals when subtracted from background. The solid line is an ideal Gaussian, and the dotted line is the subtracted SG fit.

values $(m, n) = (53, 5)$ were selected on the basis of maximizing the signal to noise of the spectral asymmetry for synthetic signals injected into the spectrum. Parameters (a,b) are the standard Gaussian function parameters that determine the de-weighting function applied to the data points within the rolling window around ν_i :

$$W(\nu, \nu_i) = 1 - a \cdot \exp \left[\frac{-(\nu - \nu_i)^2}{2b^2\sigma_{A,D}^2(\nu_i)} \right]. \quad (3.11)$$

For the unweighted polynomial in the numerator, the fit more closely tracks any signal atop the local background, whereas the de-weighted polynomial is desensitized to any putative signal around ν_i , and thus more closely interpolates the real background in the absence

of such a signal. This method proved to be a good compromise between simplicity and sensitivity and was used for an analysis in the test range of 1750 - 1800 MHz in a concept paper [36].

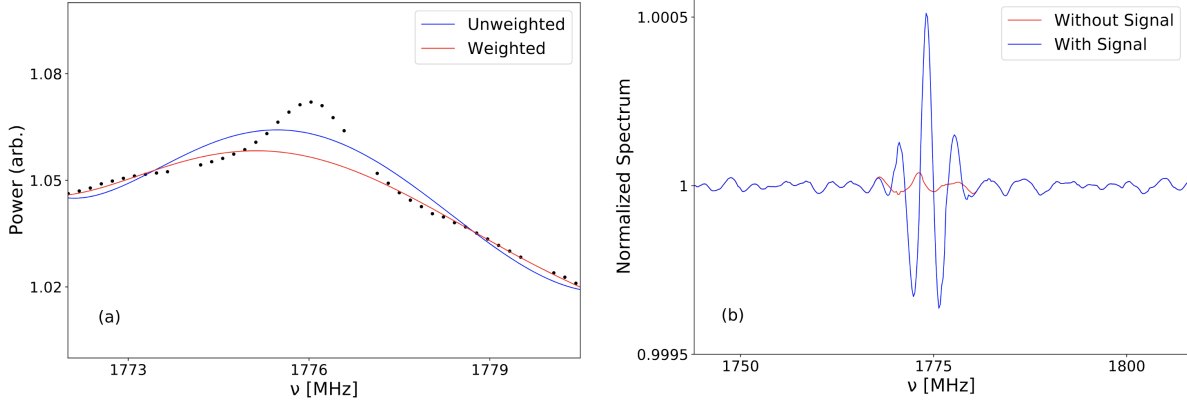


Figure 3.13: *Left:* A synthetic signal from dark matter annihilation with velocity weighted cross section $\langle\sigma v\rangle = 2.5 \times 10^{-58} \text{ cm}^3 \text{ s}^{-1}$ injected into one raw spectrogram, with the corresponding weighted and unweighted polynomial fits.

Ratio of Polynomial + Gaussian

For this method, spectra are unit normalized by forming a ratio of functions fit to the PFB-corrected spectrum within a window around each data point in the spectrum:

$$R(\nu_i) = \frac{G(\nu_i; \sigma) + P(\nu_i; m, n)}{P_D(\nu_i; m, n)}. \quad (3.12)$$

For the polynomial $P(\nu_i; m, n)$ fit to the data within a window around ν_i , m is the number of data points within the window, and n is the order of the polynomial. For the Gaussian function $G(\nu_i; \sigma)$, σ is specified based on the expected width of the signal at ν_i , and the coefficient and center are left as free parameters for the fit (with the condition that the coefficient is positive). The polynomial in the denominator, $P_D(\nu_i; m, n)$, is the same functional form as that in the numerator, but where a window representing the expected signal width around the center of the Gaussian is blanked out for the fit.

$$G(\nu_i; \sigma) = a^2 \cdot \exp \left[\frac{-(\nu - \nu_i)^2}{2\sigma^2} \right]. \quad (3.13)$$

$$P(\nu_i; m, 5) = b + c \cdot \nu_i + d \cdot \nu_i^2 + f \cdot \nu_i^3 + g \cdot \nu_i^4 + h \cdot \nu_i^5. \quad (3.14)$$

This procedure again ensures that the sum of the polynomial and Gaussian in the numerator more closely tracks any signal atop the local background, whereas the de-weighted polynomial

in the denominator is desensitized to any signal around the center of the Gaussian found by the fit and thus more closely interpolates the real background in the absence of such a signal. Fig. 3.14 shows both the numerator and denominator components in the vicinity of an injected decay signal for a decay constant $\lambda = 1 \times 10^{-30} \text{ s}^{-1}$ and the resulting normalized spectrum both with and without the injected signal.

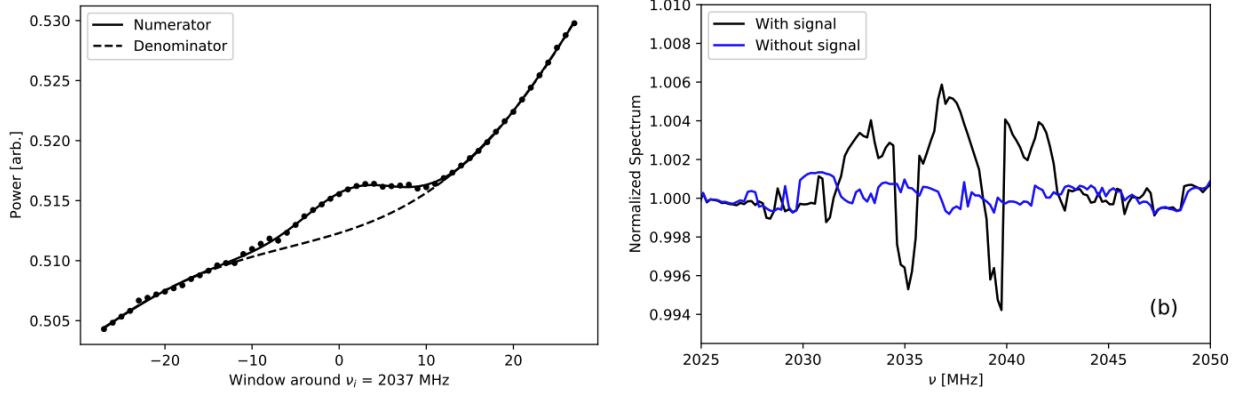


Figure 3.14: *Left:* A synthetic signal from dark matter decay with decay constant $\lambda = 1 \times 10^{-30} \text{ s}^{-1}$ injected into one raw spectrogram, with the corresponding numerator and denominator components. *Right:* Normalized spectrum with and without synthetic signal.

An attempt to further discern potential signals from noise was made by introducing a weighting factor involving the χ^2 value of the fit. Specifically, we defined a form of the Fermi function, visualized in Fig. 3.15:

$$F(\chi^2) = \frac{1}{1 + e^{\frac{\log(\chi^2) + \alpha}{\beta}}}. \quad (3.15)$$

And transforming the normalization ratio from before to the following:

$$N(\nu) = 1 + F(\chi^2) \frac{G(\nu)}{P(\nu)}, \quad (3.16)$$

where $G(\nu)$ is the fitted Gaussian, $P(\nu)$ is the fitted polynomial, and $F(\chi^2)$ is the Fermi function. Ultimately, this addition introduced too much unpredictable variation in the normalized spectra. Thus, the final analysis was performed without the χ^2 weighting [37].

Two points should be noted about the normalization method adopted for this analysis. First, as with many such schemes, the fitting procedure transforms a simple signal shape (here a Gaussian) superposed on a smooth background into a more complex form. This does not represent a fundamental problem, as the overall analysis can be adequately modeled. Second, as the normalization scheme is optimized to accentuate the signal, it also accentuates the residual structure associated with imperfect removal of the polyphase filter bank bandpass

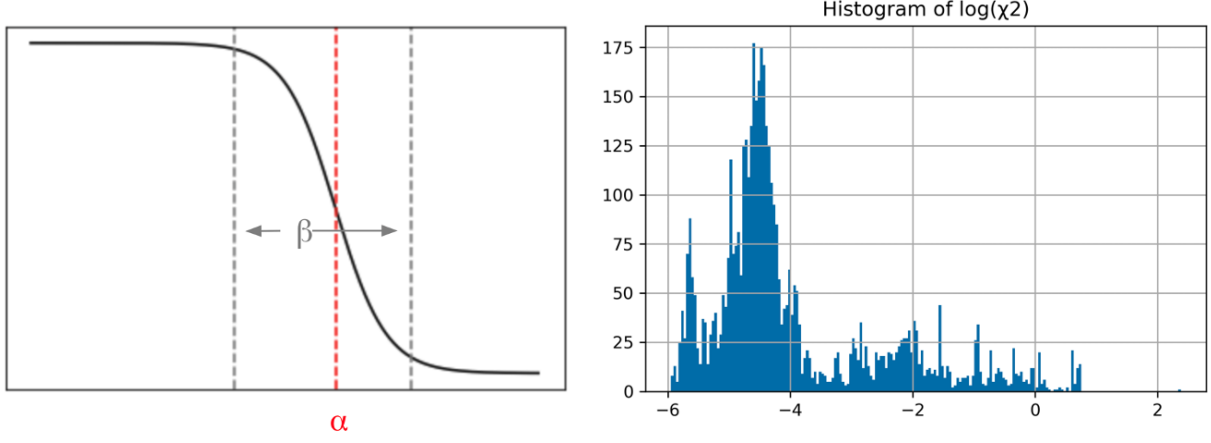


Figure 3.15: *Left:* A plot of the Fermi function defined in Eq. 3.15. *Right:* A histogram showing the χ^2 values over a single normalized spectrum. The value for α was chosen to be -4 based on this histogram.

response, as in this frequency range, they are of the same order in width, i.e. a few MHz. This is a more significant problem, but which the asymmetry analysis significantly cancels out.

3.4.3 Optimized Analysis Pipeline

The resulting limits are derived by a standard matched-filtering technique. A template of the asymmetry for a dark matter signal is created at each frequency ν in the spectrum, $\mathbf{T}(\nu)$, specific to the particle physics input $\langle\sigma v\rangle$ or λ , target samples $\theta_{F/B}$, galactic parameters $(V_S, \sigma_{\text{vir}})$, and halo model. This involves calculating the contribution of the expected signal for each target, transforming the input Gaussian line into the actual shape as it appears in the normalized spectrum, applying the coordinate-dependent Doppler shift, and finally summing and forming the asymmetry. At each frequency ν the template is integrated over the asymmetry spectrum to get the correlation spectrum $R_D(\nu)$. For the Doppler case, the expression is

$$R_D(\nu) = \mathbf{T} \cdot \mathbf{A}_D(\nu) \equiv \sum_{\nu'} T(\nu - \nu') A_D(\nu - \nu'). \quad (3.17)$$

Limits are derived by injecting synthetic signals at the raw spectrogram level, carrying through the analysis as described, and establishing the confidence level against the statistical distribution of $R(\nu)$ in the absence of a signal. The signal-to-noise ratio (SNR) is maximized by utilizing all of the data after the data quality cut.

The analysis based on the expected signal asymmetry between looking inward (I), toward the galactic center and outward (O), away from the galactic center follows in an essentially

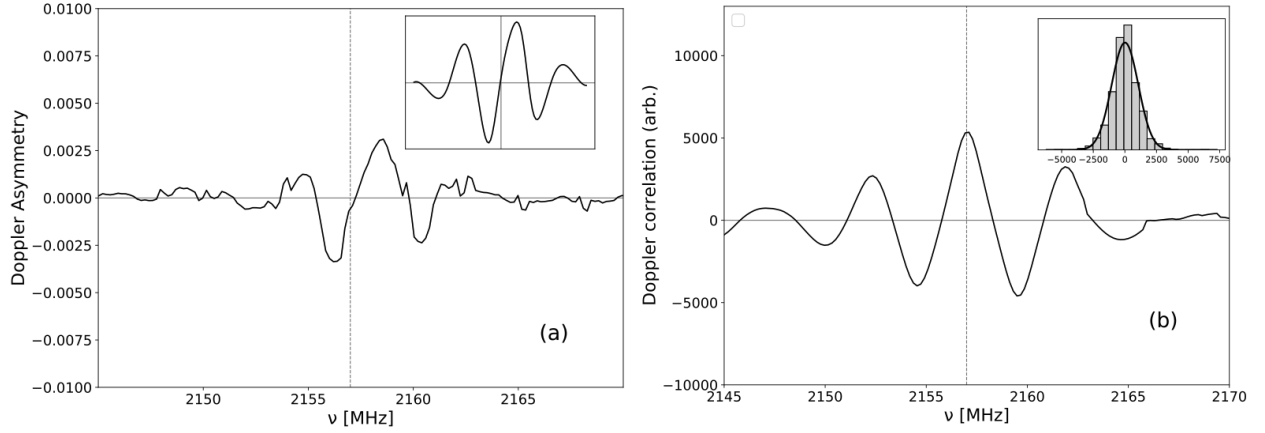


Figure 3.16: *Left:* Doppler asymmetry spectrum for the case $V_S = 225 \text{ km s}^{-1}$, $\sigma_{\text{vir}} = 250 \text{ km s}^{-1}$, for $\nu = 2157 \text{ MHz}$, and a decay constant $\lambda = 1 \times 10^{-30} \text{ s}^{-1}$ shown for scale. (Inset) Template formed for current parameters. *Right:* The Doppler correlation spectrum. (Inset) Doppler correlation spectral distribution in units of standard deviation σ_{corr} in the absence of a signal.

identical manner. As mentioned previously, here the SNR is maximized by more tightly restricting the cone defining the inward population, and leaving a large gap in angle ($\theta_I = 70^\circ$ $\theta_O = 115^\circ$). For this first analysis, a Navarro-Frenk-White (NFW) halo was used [49, 50]:

$$\rho(r) = \rho_c \left(\frac{r}{r_c} \right)^{-1} \left(1 + \frac{r}{r_c} \right)^{-2}, \quad (3.18)$$

with the critical density for closure $\rho_c = 1.4 \times 10^7 \text{ M}_\odot \text{ kpc}^{-3}$ and the scale radius $r_c = 16.1 \text{ kpc}$.

Stronger limits can be achieved by cross-correlating the Doppler and Intensity analyses, ensuring that the two analyses are absolutely independent. In particular, it is most important to ensure that there are no remnant velocity correlations inadvertently built in to the I,O populations of the Intensity analysis, owing to the incomplete GBT galactic coverage. To ensure that the total I,O contributions were coincident in frequency, that is, free of residual Doppler shift, while maximizing the number of spectra selected, the Hungarian matching algorithm is used for annihilation and a manual shift of the signal is used for decay as the decay signal is too wide to necessitate the matching [51]. Fig. 3.17 shows the corresponding Intensity asymmetry $A_I(\nu)$ and Intensity correlation $R_I(\nu)$.

For each synthetic signal, the size is scaled down until the figure of merit reaches 3σ , or equivalently the 99.7% confidence level, shown in Fig. 3.18. Although the plot shows injections only above the 3σ line, we made sure to scale down the amplitudes to at least one point below the 3σ line to extract an accurate crossing point.

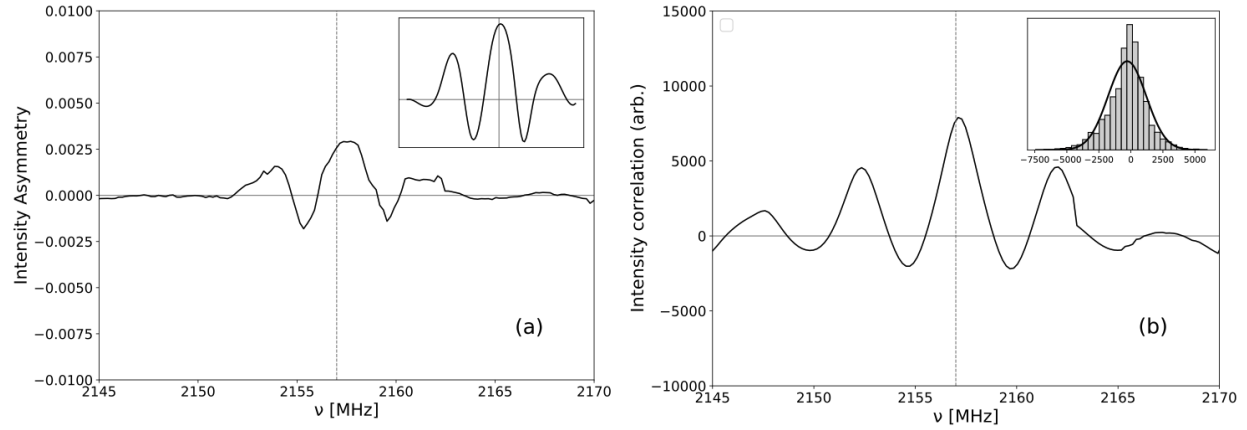


Figure 3.17: *Left*: Intensity asymmetry spectrum. *Right*: Intensity correlation spectrum and its spectral distribution, for the same case as in Fig. 3.16.

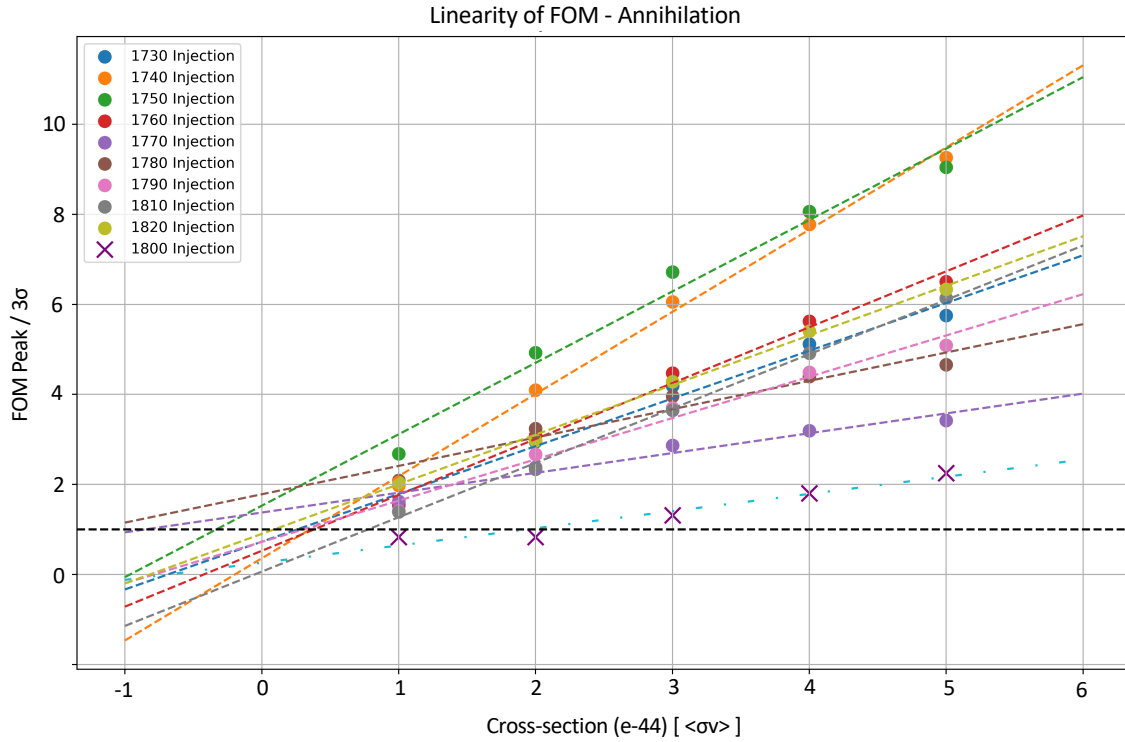


Figure 3.18: Figure of merit scaling for ten frequencies for the annihilation case, with the 3σ point shown by the black dashed line.

Another way to visualize the analysis is to use false-color maps of the normalized spectra sorted in way corresponding to the Doppler and Intensity analyses, shown in Fig. 3.19. This is particularly useful when inspecting signal candidates.

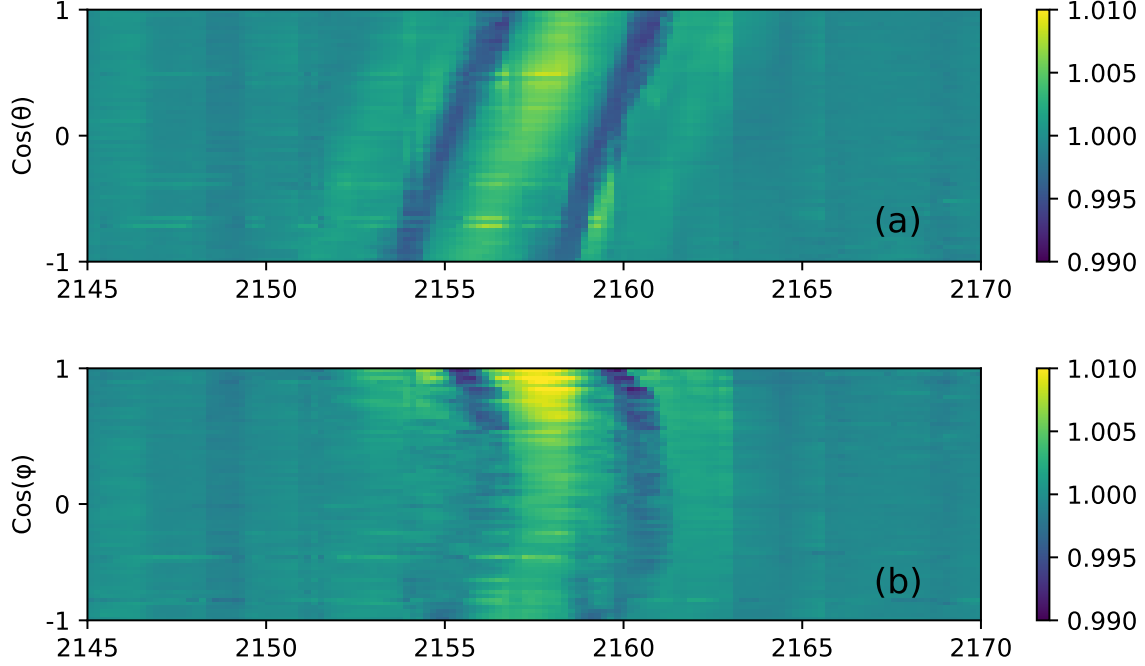


Figure 3.19: False-color maps of normalized spectra sorted by features of the data corresponding to the Doppler and Intensity analyses: (a) θ (angle from the sun’s direction of motion), ϕ (angle from the galactic center) for a signal of size $\lambda = 1 \times 10^{-30} \text{ s}^{-1}$.

As the analyses are independent and their individual template correlation spectra are approximately Gaussian distributed, application of the p-value on the cross correlation of the two analyses is straightforward. The p-value is in this case just a way to represent the figure of merit in a way that can be easily visualized in terms of standard deviations.

After the p-value arrays are computed, it is necessary to investigate all candidates above 3σ . This is done by looking closely at the data sorted in every way including θ , Φ , and time, as well as the raw data. An example of this investigation is shown in Fig. 3.21. The full analysis pipeline is visualized in Fig. 3.22. The analysis is done on a custom-built cluster with 2 compute nodes with 72 CPUs each and 44 TB of storage.

3.5 L and S Band Limits

Three comments are in order concerning determination of the limits. First, as the BL data set was lacking in any useful calibration targets, the system equivalent flux density (SEFD)

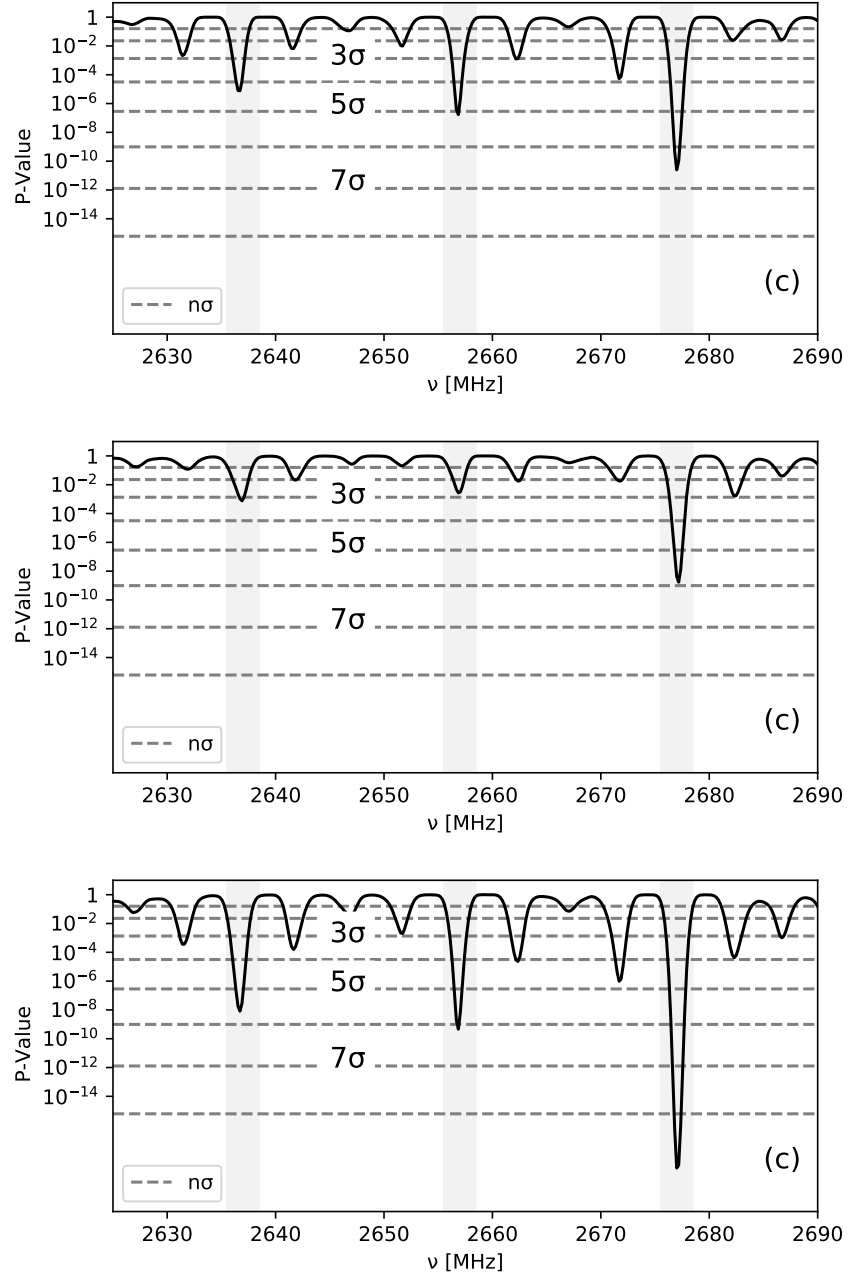


Figure 3.20: The p-statistic for 3 injected signals over a clean region in the S Band, for the decay case; $\lambda = 1 \times 10^{-30} \text{ s}^{-1}$. (a) Doppler p-value spectrum, (b) Intensity p-value spectrum, (c) combined p-value spectrum.

was calculated from the published GBT L- and S-band system noise temperature of $T_{\text{SYS}} = 20 \text{ K}$ and aperture efficiency 70%. To check our absolute calibration, a comparison was made

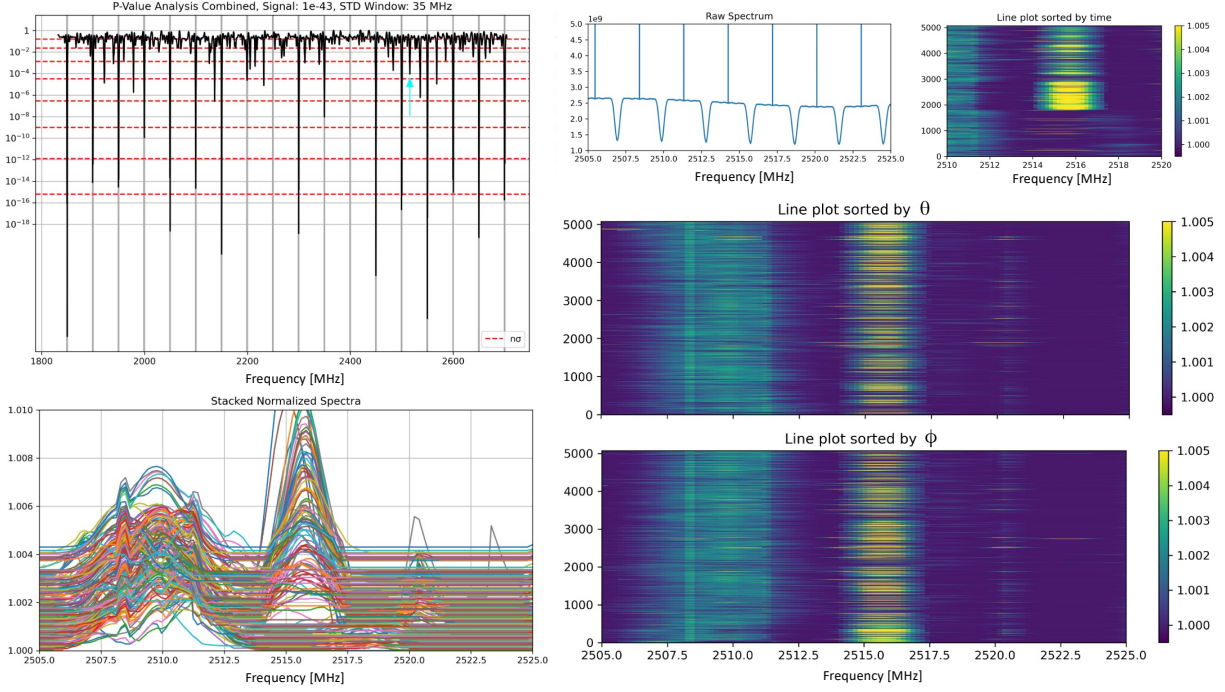


Figure 3.21: An investigation of a candidate at ≈ 2515 MHz. The time-sorted plot reveals a signal localized in time, meaning this can be dismissed as a potential dark matter signal.

of the inferred HI column density measured in our data with data from the Bonn Library [52]. The inferred value is within 1.5% of the older Leiden/Argentine/Bonn (LAB) survey and 15% higher than the newer Effelsberg/Bonn HI survey (EBHIS), thus giving us confidence in our procedure. Second, the limit above was derived with a search template of the same galactic halo parameters as the injected signal, $(V_S, \sigma_{\text{vir}}) = (225, 250)$ [km s $^{-1}$]. As we have no precise a priori knowledge of the halo parameters, we tested two additional cases in the L Band within current bounds of solar and virial velocities, $(V_S, \sigma_{\text{vir}}) = (225, 250), (200, 250), (225, 275)$ [km s $^{-1}$]. By mismatching the injection and search parameters, we measured the sensitivity of our search to our ignorance of these parameters. As shown in Fig. 3.23, the resulting limits differ by about 10% on average. Third, it may be inquired to what degree the physics exclusion limits depend on the exact choice of halo model. We have performed such a comparison between those derived from the NFW halo described above, and those from a Burkert halo, parameters of which were determined by fitting to the same Milky Way galactic observables by the same authors [50]. Whereas the NFW represents a cuspy halo, divergent at the galactic center, the Burkert model represents a cored halo with a central density of $4.13 \times 10^7 \text{ M}_s \text{ kpc}^{-3}$, where M_s is the solar mass. While both yield essentially the same local density, the quantity of interest to direct detection experiments, $\rho^{\text{NFW}}(r_s) = 0.471 \text{ GeV cm}^{-3}$ and $\rho^{\text{Bur}}(r_s) = 0.487 \text{ GeV cm}^{-3}$, their virial masses M_{vir} differ considerably, $1.53 \times 10^{12} \text{ M}_s$

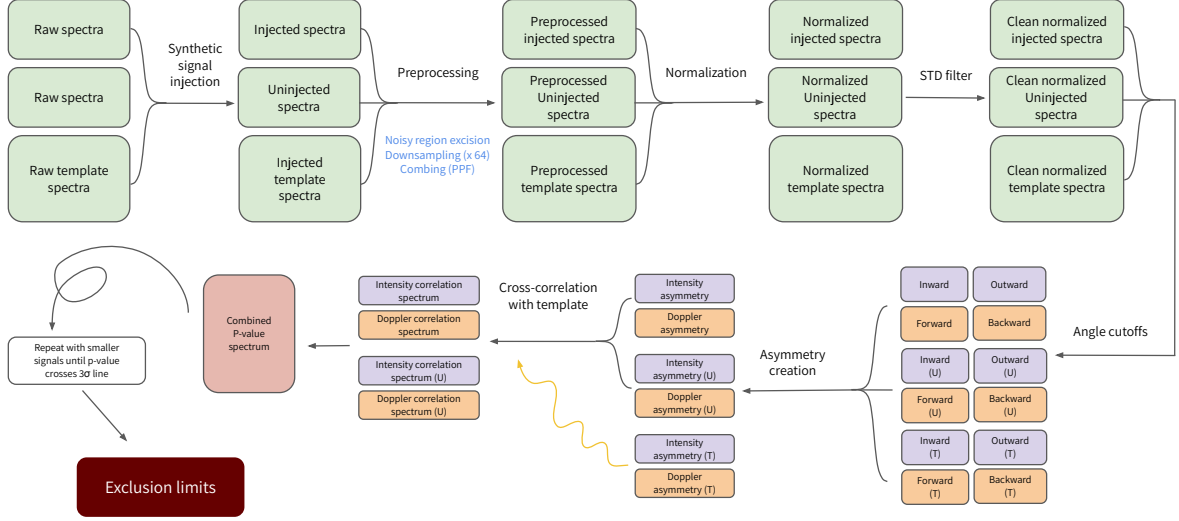


Figure 3.22: Analysis pipeline.

and $1.11 \times 10^{12} M_\odot$ respectively. As our radio survey method is sensitive to both the halo distribution and its total mass, it is not surprising then that the physics limits will vary with the choice of halo model and in fact the limit on the annihilation cross section for the Burkert model at 1775 MHz being weaker by 60%. Analogous uncertainties in direct detection limits arise from differing assumptions of local halo density, which varies among reports from 0.3 to 0.6 GeV cm^{-3} .

Resulting limits of annihilation and decay are shown in Fig. 3.25. These were calculated by reducing the injected signal until the resulting combined p-value reached 3σ for each frequency window of 5 MHz. Any other candidates above 3σ were excluded by investigation of RFI, temporal correlations, and lack of a systematic Doppler shift.

These limits also include the effect of stimulated emission. Caputo et al. have calculated the stimulated emission of axions within the radiation background of our galactic halo [53], but the results are readily generalized to any process with a photon in the final state. Specifically, the enhancement for the rate or cross section is a simple multiplicative factor of $2f_\gamma$, or f_γ if there is only a single photon in the final state, where f_γ is the photon occupation number. For our halo,

$$f_\gamma = f_{\gamma, \text{CMB}}(\nu) + f_{\gamma, \text{ext-bkg}}(\nu) + f_{\gamma, \text{gal}}(\nu; l, b), \quad (3.19)$$

where the three components represent the cosmic microwave background ($T_{\text{CMB}} = 2.725K$), the extragalactic radio background ($T_{\text{ext-bkg}} \approx 0.78K$ in the middle of our frequency range),

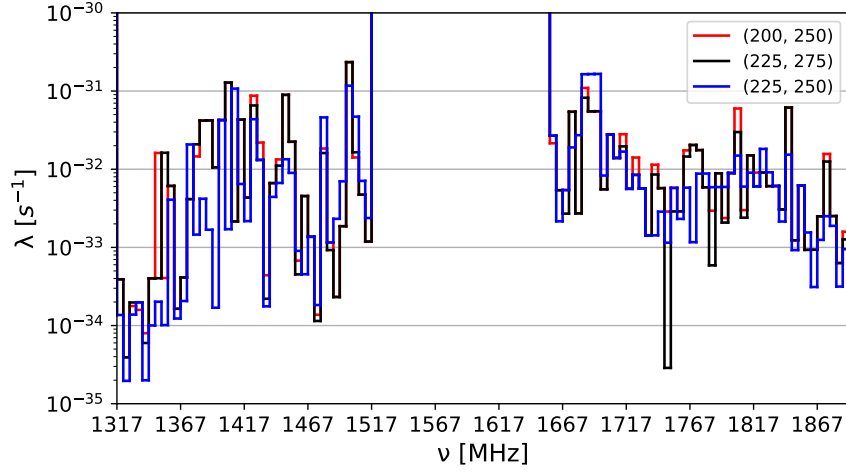


Figure 3.23: Decay limits across the L band for 3 cases of the injection parameters (V_{solar} , V_{virial}). For all cases, the search parameters were (225, 250). The region between ≈ 1517 and 1667 MHz is excluded due to high noise or damping.

and the galactic diffuse emission. The CMB and the extragalactic radio background are isotropic, whereas the galactic diffuse emission is sharply peaked around the galactic center, which being largely below the GBT horizon, can be neglected for this analysis.

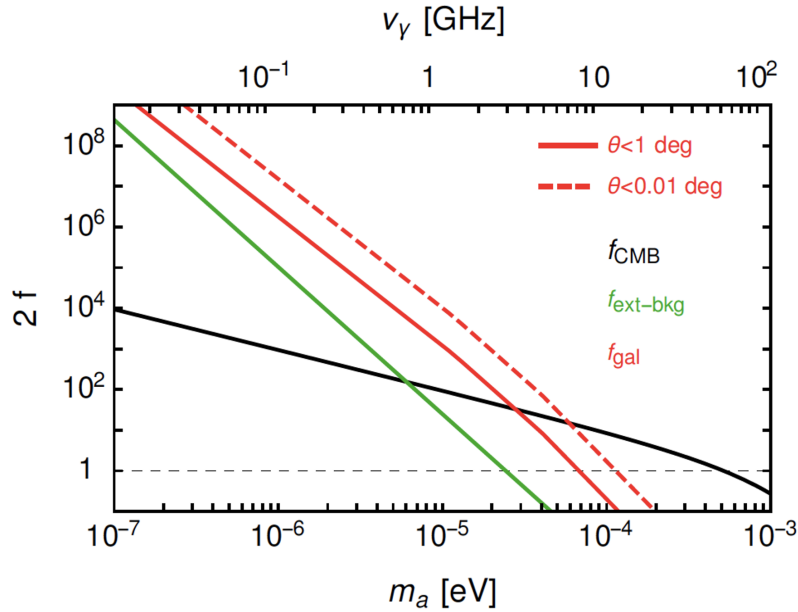


Figure 3.24: Stimulated emission contributions [53]

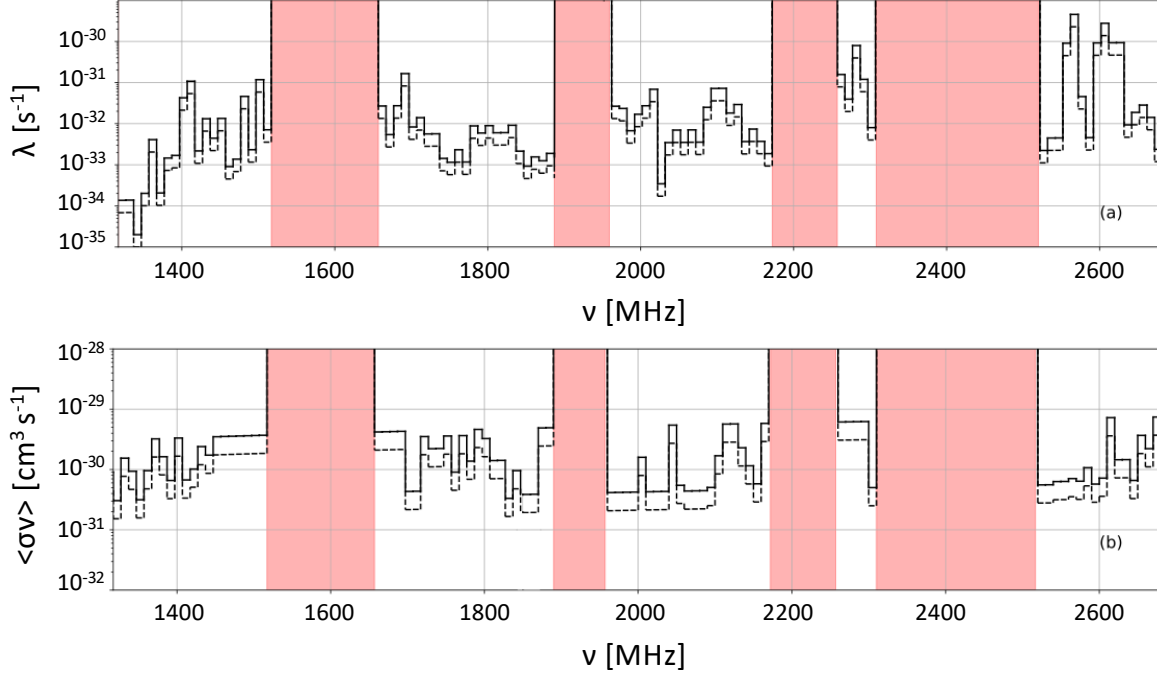


Figure 3.25: *Top:* Decay limits in the L and S Bands, with excluded regions highlighted in red (for reasons of high noise or damping). *Bottom:* Annihilation limits in the L and S Bands. In both cases, the solid line represents 1 photon final states and the dashed line represents 2 photon final states.

3.6 Limitations and Possibilities

The analysis above has been carried out assuming two-photon final states, and only for annihilation in the case of two-body initial states, which are of equal mass by construction. The results are readily generalized when deviating from these assumptions. In regard to the frequency dispersion of the search template, whereas for annihilation one expects a narrowing relative to the decay width of $\sigma_A = \sigma_D/\sqrt{2}$, for the asymmetric case $m_\xi \neq m_\chi$,

$$\frac{\sigma_D}{\nu} = \frac{\sigma_V}{\sqrt{3}c} \left[\left(\frac{m_\chi}{M} \right)^2 + \left(\frac{m_\xi}{M} \right)^2 \right]^{\frac{1}{2}}, \quad (3.20)$$

with $M = m_\xi + m_\chi$; note the bracketed factor is $\frac{1}{\sqrt{2}}$ for $m_\chi = m_\xi$, but approaches 1 for $m_\xi \ll m_\chi$. Thus anticipating all possibilities, including e.g. a Compton-like process involving an ultralight dark matter particle and a standard-model particle, annihilation of two dark matter particles, etc., one needs to carry out the analysis for the range of frequency dispersions between these two limits.

Also, in the case of a decay of a dark matter particle of mass m_χ to a final state of a particle of mass m_ϕ and a photon, the photon energy is given by $E_\gamma = \frac{(m_\chi^2 - m_\phi^2)c^2}{2m_\chi}$. As in the absence of other information concerning ϕ , the initial mass is unknown, the constraint on the actual decay rate $\lambda_{\phi,\gamma}$ and initial mass m_χ are coupled, $\lambda_{\phi,\gamma} = \lambda_{\gamma,\gamma} \frac{m_\chi c^2}{2E_\gamma}$, where $\lambda_{\gamma,\gamma}$ is the rate inferred assuming two-photon decay as shown in Eqn. 3.2.

The future Square Kilometer Array (SKA) ¹ will have the benefit of the very large Bose-Einstein enhancement factor associated with the galactic diffuse emission ($2f_\gamma \approx 10^{(3-4)}$ for the comparable L-band range as studied here), which could result in sensitivity exceeding current Horizontal Branch Star and CAST limits [54]. Whether the analysis techniques explored here, particularly the Doppler asymmetry, and the ability to make collateral use of every spectrum to be collected on the SKA could provide further improvement to their limits will require further study.

It should be noted that, while the technique here may not find any signature of dark matter, it may prove to be of utility in revealing weak conventional sources associated with the galactic disk.

¹<https://www.skao.int/en>

Chapter 4

DMRadio-50L

4.1 Introduction to DMRadio

As previously mentioned, a subset of direct detection experiments for axions search for axion conversion to photons via the inverse Primakoff effect in the presence of a DC magnetic field. The Compton wavelength of an axion is given by

$$\lambda_C = \frac{h}{m_a c} \approx 100 \text{ m} \frac{10^{-8} \text{ eV}}{m_a c^2},$$

where h is Planck's constant and m_a is the axion mass. For axion masses below $1 \mu\text{eV}$, the Compton wavelength is $\lambda_C > 1 \text{ m}$. A natural technique to search for such a large wavelength is with a lumped-element LC circuit [55, 56]. One present lumped-element axion experiment is DMRadio-50L, a part of the DMRadio suite of experiments [57], [58] with projected sensitivities shown in Fig. 4.1. This suite includes DMRadio-50L, DMRadio-m³ [59, 60], and DMRadio-GUT [61] and builds on the design of the first-generation lumped-element experiments ABRACADABRA-10cm [62] and DMRadio Pathfinder [63]. In addition to covering a significant portion of the axion-like particle (ALP) parameter space, DMRadio-50L aims to be a testbed for innovations in quantum sensors [64], high-Q resonators [65], and other technologies for axion detection. With these innovations, this experiment will be a pathfinder for DMRadio-GUT, a next-generation experiment targeting the particularly well-motivated range of GUT-scale axions.

4.2 DMRadio-50L Operating Principle and Design

The effect of axions can be modeled as an effective electromagnetic-current-density field modifying Maxwell's equations [66]. Neglecting any spatial gradients in the axion field, this current density is:

$$\mathbf{J}_{\text{eff}} = g_{a\gamma\gamma} \frac{\sqrt{\hbar c}}{\mu_0} \sqrt{2\rho_{\text{DM}}} \cos\left(\frac{m_a c^2 t}{\hbar}\right) \mathbf{B}. \quad (4.1)$$

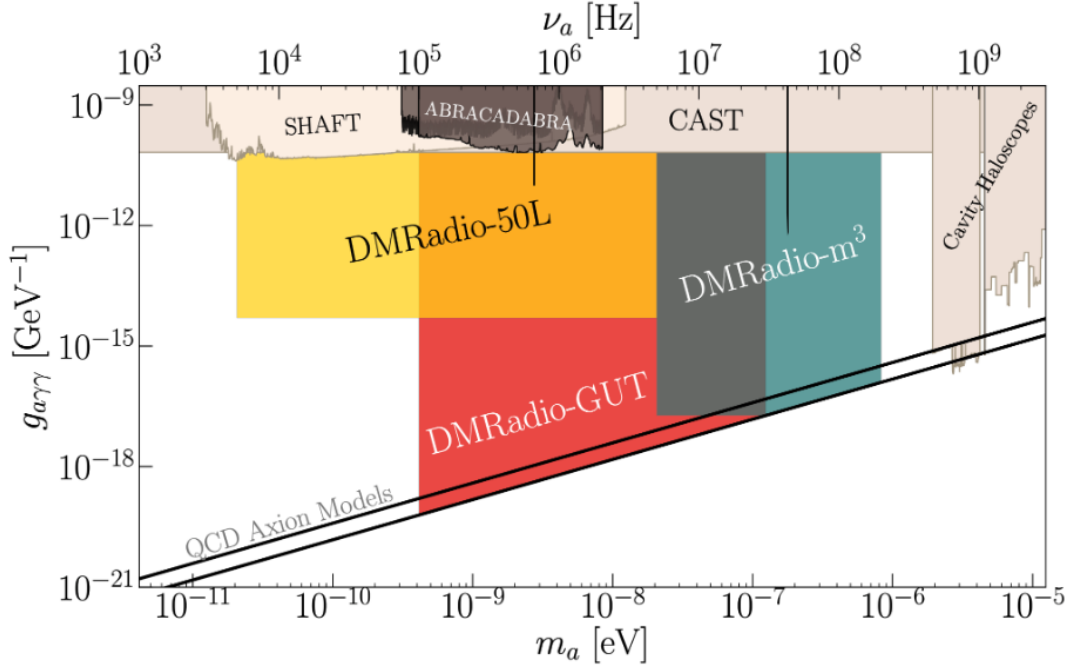


Figure 4.1: Projected sensitivities in the axion parameter space of the DMRadio experiments. Courtesy of Nicholas Rapis.

Here $g_{a\gamma\gamma}$ is the coupling constant for an axion-photon-photon interaction, ρ_{DM} is the local dark matter density, m_a is the axion mass, and $\mathbf{B}$ is the applied magnetic field. The DMRadio-50L experiment employs a toroidal magnet and a superconducting shield around the magnet referred to as the “sheath” to couple this current density to the resonator. As the effective axion current density oscillates along magnetic field lines, it induces a screening current on the inner walls of the sheath. By including slits in the sheath, the axion induced screening current is allowed to flow to the outer walls of the sheath. There it can inductively couple to an inductor that is part of an LC resonator whose current is subsequently read out using a dc superconducting quantum interference device (SQUID). This detection scheme is shown in Fig. 4.2.

One way to quantify the sensitivity of the experiment is the scan rate. The scan rate determines the frequency range that the experiment can cover per unit time with a given $g_{a\gamma\gamma}$. The equation is given by [60]

$$\frac{d\nu}{dt} = \left(\frac{(6.4 \times 10^5)}{\text{SNR}^2} \frac{h}{32c^8 m_a^4} \right) \times \frac{|V(m_a, \mathbf{B}, \rho_{\text{DM}}, g_{a\gamma\gamma})|^4}{L_{\text{eff}}(\nu_r)^2} Q(\nu_r) \bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)], \quad (4.2)$$

where the numeric prefactor is set by the physics of the standard dark matter halo model [67]

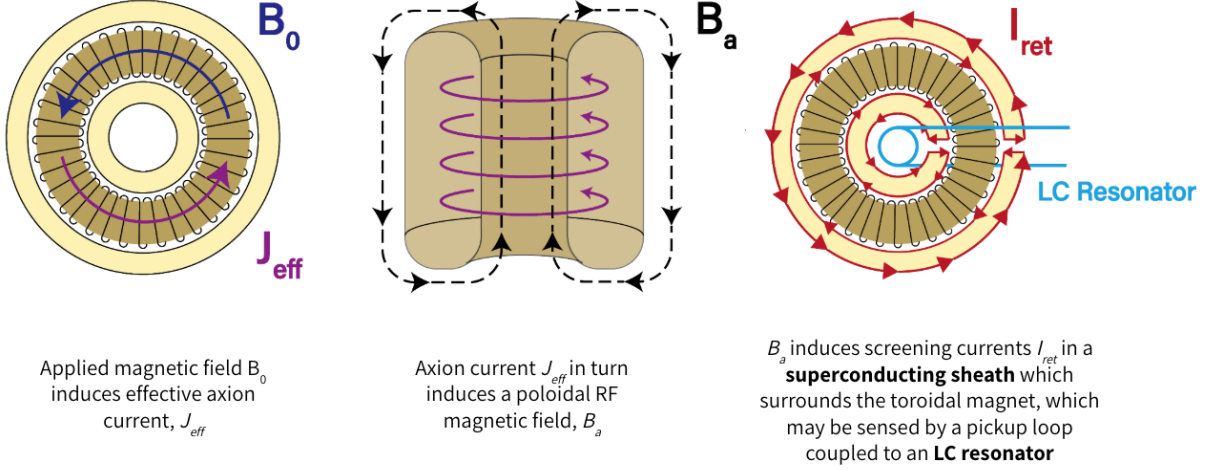


Figure 4.2: Detection scheme of DMRadio-50L. Courtesy of Jessica Fry.

and the signal-to-noise ratio (SNR) is chosen by the experimentalist. $|V(m_a, \mathbf{B}, \rho_{\text{DM}}, g_{a\gamma\gamma})|$ is the magnitude of the axion induced voltage across the resonator inductor. This voltage term relies on the design of the experiment as well as assumptions made in the analysis. Specifically, $|V(m_a, \mathbf{B}, \rho_{\text{DM}}, g_{a\gamma\gamma})| \propto g_{a\gamma\gamma} \sqrt{\rho_{\text{DM}}} \mathbf{B}$ due to $\mathbf{J}_{\text{eff}}$ which is responsible for the induced voltage. Since the axion interacts with the magnetic field within the sheath and the signal must propagate to the resonator inductor, the geometry of the magnet, sheath, and inductor determine the relevant mutual inductances between these components, thus entering into this voltage term. $\bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)]$ is a term that encodes all of the noise physics [68]; it depends on the quantity $\eta(\nu_r)$ which is defined as the ratio of the noise temperature to a half-photon of quantum noise:

$$\eta(\nu_r) \equiv \frac{k_B T_{N,\min}(\nu_r)}{h\nu_r/2}, \quad (4.3)$$

where $T_{N,\min}$ is the minimum achievable noise temperature. DMRadio-50L operates in the thermal limit where $k_B T/h\nu \gg 1$ and $k_B T/h\nu \gg \frac{1}{2}\eta$, allowing us to express $\bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)]$ in a simplified form:

$$\bar{\mathcal{G}}[\nu_r, T, \eta(\nu_r)] = \frac{h\nu_r}{6\sqrt{3}k_B T \eta(\nu_r)}. \quad (4.4)$$

Note that the dependence on T (temperature) is significant for the experimental design.

4.2.1 Experimental Setup

The main components of DMRadio-50L are a 1 T toroidal magnet, a superconducting sheath, an LC resonator, a tunable transformer, and an amplifier. In order to reach superconducting

temperatures and maximize the scan rate, components of the experiment are cooled as much as possible. To do this, DMRadio-50L uses a horizontal dilution refrigerator connected cryogenically to a larger custom cryostat (see Fig. 4.3 for a CAD rendering of this setup). The main mechanical support for the detector components is an aluminum octagonal ring held at 4 K. The magnet, superconducting sheath, and 1 K plate are supported directly by the 4 K ring. The base temperature plate hangs off the 1 K plate and supports the resonator, tunable transformer, amplifier, and shields. More detailed information on the instrumentation of this experiment can be found in [69].

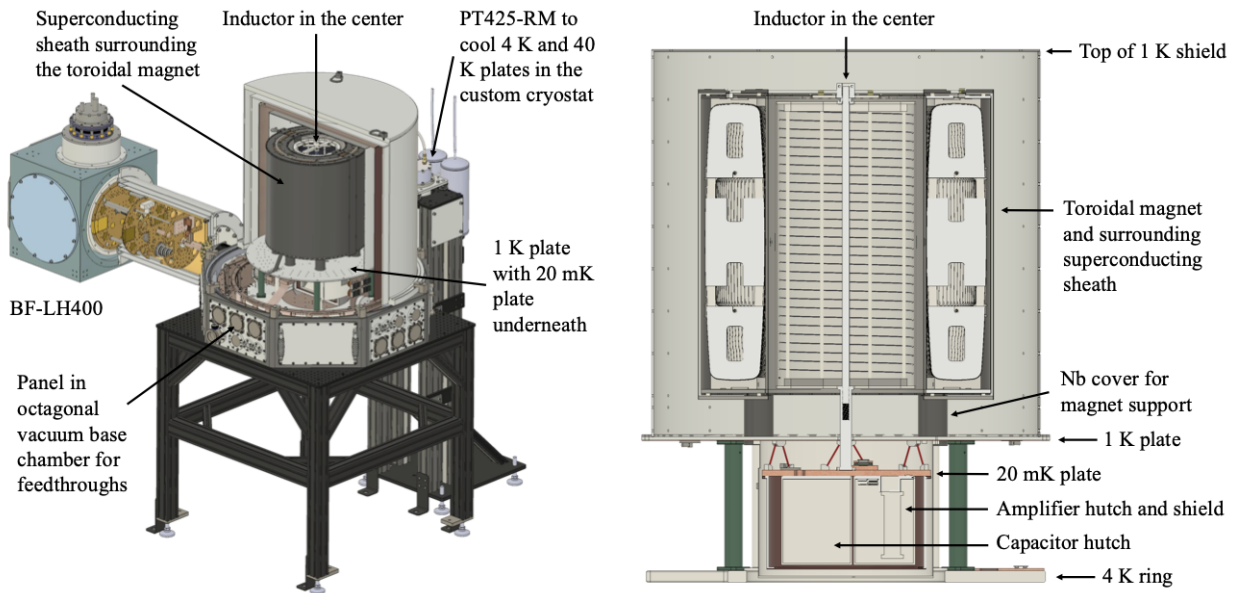


Figure 4.3: CAD renderings of the DMRadio-50L detector. *Left:* Custom cryostat housing the experimental components connected to the dilution refrigerator via the “cold snout.” *Right:* Cross section of the detector with the magnet, sheath, and 1 K plate supported by the 4 K ring. The 20 mK plate is below the 1 K plate and supports the resonator, tunable transformer, and SQUIDs. Courtesy of Maria Simanovskaia [69].

4.2.2 Description of Components

- **Magnet:** The persistent toroidal magnet is cooled to 4 K and has a peak field of 1 T. It has an outer diameter of 47 cm, height of 48 cm, and an inner diameter of 26 cm. Superconducting niobium titanium (NbTi) wires are wrapped around an aluminum (Al) mandrel made of two halves separated by 1 cm-thick alumina spacers. CAD and photos of the magnet are shown in Fig. 4.4. Each mandrel half is attached to an Al connector bracket on top and bottom. Each bottom bracket interfaces to two structural supports with PEEK insulating breaks attached to the 4 K ring and to one

copper connection consisting of a Cu101 rod and a flexible Cu110 braid that thermally and electrically anchors each half to the 4 K plate. The magnet is built by SSI Inc ¹.



Figure 4.4: CAD rendering of the DMRadio-50L magnet along with photos of the magnet being made at SSI Inc.

- **Resonator:** The DMRadio-50L resonator consists of an inductor coil and capacitor; the inductor is above the base temperature plate, and the capacitor is below. The inductor coil is centered at the top of the magnet with a Kevlar suspension structure. For the first phase of the experiment, a fixed parallel-plate capacitor will be used with a capacitance of $C \approx 500$ pF. The inductor coil is made of NbTi wire, with a self-inductance of $L \approx 10$ mH. This gives a resonance frequency of $\nu_r = 1/(2\pi\sqrt{LC}) \approx 71$ kHz for the initial stage of the operation. In the subsequent stages of the experiment, a tunable capacitor will be utilized to allow resonance frequency tuning.
- **Sheath:** The purpose of the superconducting sheath is to maximize the quality factor of the resonator by minimizing the inductor's coupling to the lossy components in the magnet while also allowing the axion induced current to flow from the inner walls of the sheath to the outer walls. The sheath consists of two superconducting toroidal halves with two slits, allowing the current to travel from the inside of the sheath to the outside. The slits are surrounded by superconducting “sleeves” to prevent inductive coupling to lossy components inside the sheath through the slits.

The sheath contains two semicircular rings that mate to the bottom of the magnet, and two that mate to the top. The top plates have an additional slit in the poloidal

¹<https://ssi.imris.com>

direction across which a phosphor bronze strip is attached; this gasket dissipates the screening currents from magnet ramping or a potential magnet quench.

The walls of the sheath are made of continuous sheets of niobium (Nb) foil, providing a phase coherent superconducting path for the axion current. The sleeves are also uniform pieces of Nb foil connected to Nb plates at the top and bottom of the sleeve. This is shown in Fig. 4.5.

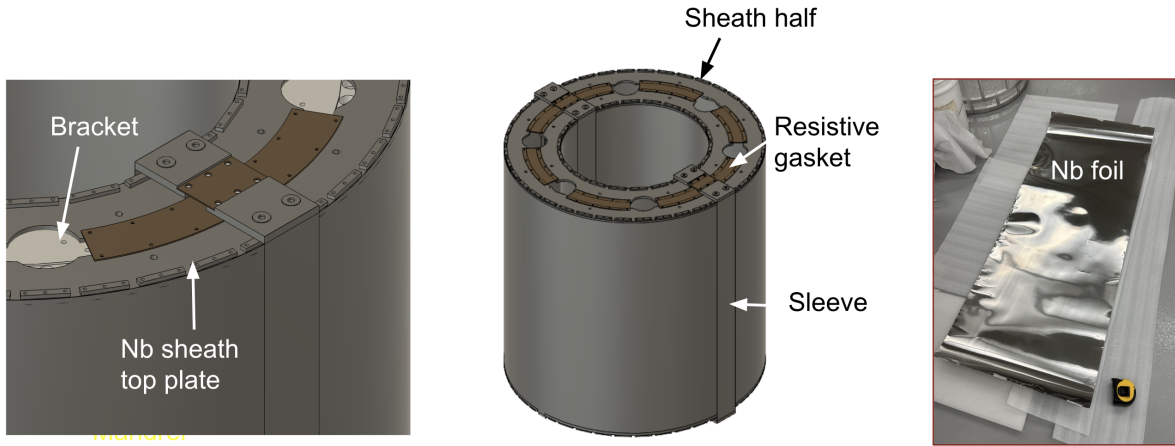


Figure 4.5: CAD renderings of the sheath as well as a photo of the Nb foil used to construct the sheath walls.

- Tunable Transformer:** In order to optimize the resonator-amplifier coupling in terms of noise, a tunable transformer is used, with the primary coil connected to the resonator and the secondary coil feeding into the amplifier input. Since the optimal coupling for noise is frequency-dependent, it must be dynamically tuned as the resonance frequency changes. The current prototype employs a piezoelectrically actuated, mechanically adjustable motion applied to gradiometrically wound superconducting transformer coils. Ongoing measurements at sub-K temperatures are expected to demonstrate the success of this tunable transformer design.
- Sensors:** The design of DMRadio-50L is uniquely well-situated to test quantum sensors and resonators because of the toroidal magnet which provides an area with no magnetic field which is cooled to base temperature. Thus, after the initial phase of using dc SQUIDs for sensing, novel sensors with the ability to outperform the Standard Quantum Limit will be tested and used. Specifically, Radio-frequency Quantum Upconverters (RQUs) will upconvert electromagnetic signal frequencies between 1 kHz and 100 MHz to microwave frequencies, where robust microwave hardware can be used. Prototype RQU devices have demonstrated signal upconversion and fidelity over the

range relevant to DMRadio axion searches and have shown phase-sensitive gain, which is a prerequisite for the development of backaction evasion protocols [64].

4.3 Cryogenic Design

In order to maximize scan rate, we must maximize the parameter $\bar{\mathcal{G}}$ as defined in Eq. 4.4. Due to its dependence on temperature, this means operating the experiment at the lowest temperature possible. Our goal is to build a multistage cryogenic system which allows the experiment to run at a system noise temperature of under 50 mK with all expected heat loads.

4.3.1 Overview

The DMRadio-50L cryogenic system consists of a base stage, 1 K stage, 4 K stage, and 40 K stage in a custom cryostat attached to a horizontal dilution refrigerator by a connection referred to as the “cold snout”. The custom cryostat cools the magnet and sheath to 4 K, and the dilution refrigerator cools the superconducting shield to 1 K through the still plate and the pickup inductor, tunable capacitor, tunable transformer, and amplifier to base temperature through the mixing chamber (MXC) plate. From now on, I will refer to the base temperature stage as the 20 mK stage, since we expect with the predicted heat loads the MXC will reach a temperature of around 20 mK. A CAD rendering of the entire setup is shown in Fig. 4.7.

4.3.2 Dilution Refrigerator

The dilution refrigerator (DR) used for DMRadio-50L is the horizontal Bluefors LH400² and is referred to as “Snoopy”. It has a cooling power of $> 12 \mu\text{W}$ at 20 mK on the MXC plate and $> 10 \text{ mW}$ at 1 K on the still plate, and the 4 K and 40 K plates of the DR are cooled by a Cryomech PT420 pulse tube cryocooler. The lowest temperature it can achieve on the MXC plate is 7 mK. A photo of Snoopy in the lab is shown in Fig. 4.8. In order to estimate the temperatures of the MXC and still plates with different heat loads, we took a set of data by applying different amounts of heat to the plates, shown in Fig. 4.6. For example, a heat load of 4 mW on the still plate and $3 \mu\text{W}$ on the MXC plate will result in a still plate temperature of $\approx 900 \text{ mK}$ and a MXC plate temperature of $\approx 10.5 \text{ mK}$.

²<https://bluefors.com>

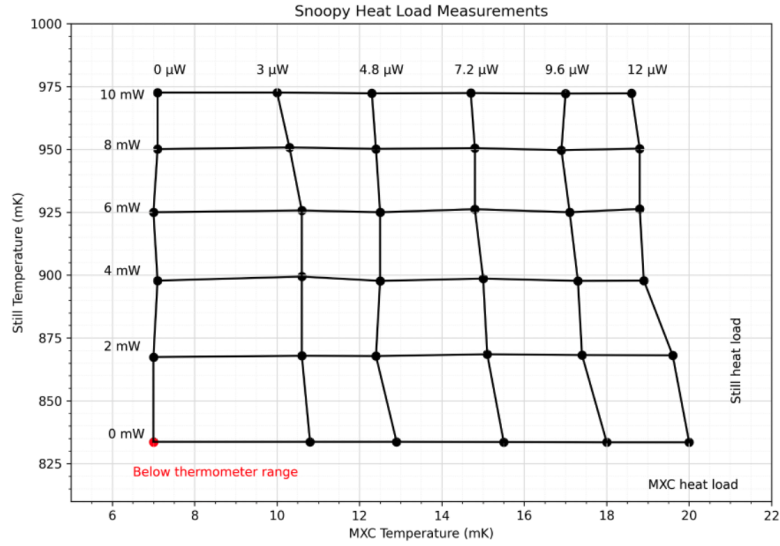


Figure 4.6: Measurements of the still plate and MXC plate of the DR with different applied heat loads.

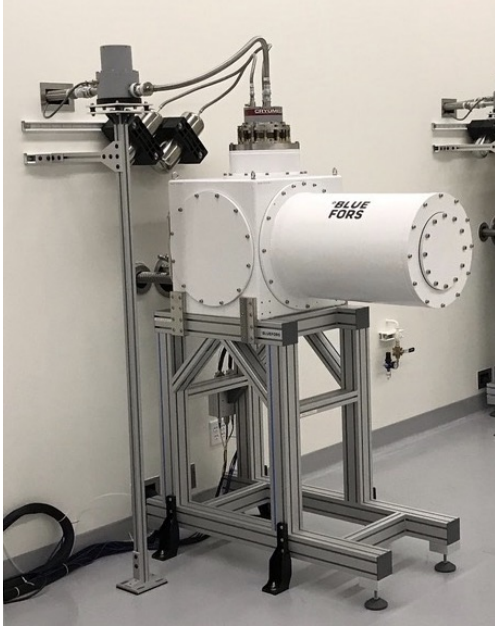


Figure 4.8: *Left:* Photo of the horizontal dilution refrigerator, Snoopy. *Right:* Photo of the custom 4 K cryostat, Woodstock.

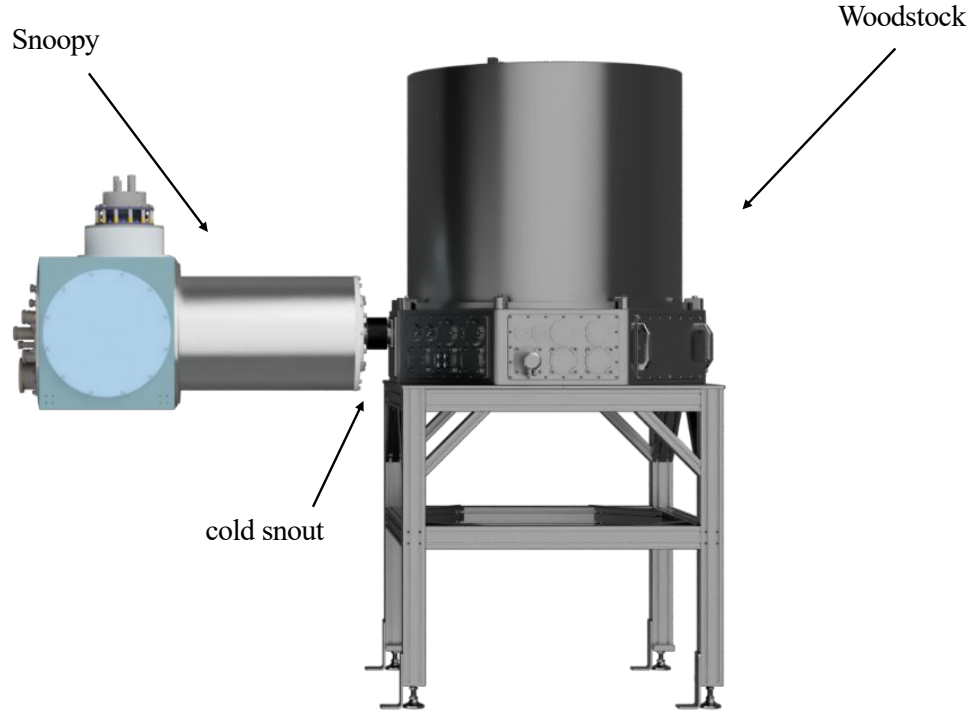


Figure 4.7: On the left is “Snoopy”, our horizontal dilution refrigerator. On the right is “Woodstock”, our custom-built 4 K cryostat. Between them is the connection we refer to as the “cold snout”.

4.3.3 Custom 4 K Cryostat

The custom cryostat is built by Four Nine Design ³ and is referred to as “Woodstock”. It uses a Cryomech PT425 pulse tube cryocooler with a remote motor and has a cooling power of 2.7 W at 4.2 K and 55 W at 45 K on the pulse tube stages. The lowest temperature it can achieve is 2.8 K. The pulse tube cools the 4 K and 40 K plates through flexible thermal connections made of highly conductive foil. The cryostat has an octagonal base chamber that connects to cylindrical shields on top at 300 K, 40 K, and 4 K. The vacuum chamber is made of Al, the 40 K plate of Cu110, and the 4 K plate of Cu101. The 4 K plate supports the 4 K ring which supports the 1 K plate and 4 K magnet. The 1 K plate is made of Al and has a diameter of 70 cm and thickness of 5.85 mm. This plate mates to the 1 K shield,

³<https://four9design.com>

which is also made of Al with a diameter and height of 66 cm. The purpose of the 1 K shield is to thermally and electromagnetically shield the sheath, magnet and resonator package. The 1 K plate supports the 20 mK space underneath it as well as the Attocubes and tunable transformer. The 20 mK plate will be made from hydrogen-free high-purity copper and will mate to the 20 mK shield made from Cu101. All wiring is fed through and thermalized to the panels in the octagonal vacuum base chamber, shown in Fig. 4.3. A photo of Woodstock being tested by Four Nine Design in Montana is shown in Fig. 4.8.

4.3.4 The Cold Snout

The “cold snout” is the connection between the dilution refrigerator and the 4 K cryostat which contains the cold fingers at the base stage and the 1 K stage. Its purpose is to provide cooling power to the experimental components that require sub-4 K temperatures. Because this horizontal-to-vertical cooling setup is uncommon, there are unique constraints for the design of this system.

The design constraints can be summarized with three broad categories: mechanical, thermal, and practical.

- Mechanical: We require that the cold fingers reach the experimental setup while accounting for thermal contraction (see Appendix B for calculation of thermal contraction estimates). Specifically, there can be no more than one rigid connection along the horizontal axis for each component. We must also ensure that the torques applied to the plates of the DR are acceptable.
- Thermal: We aim to minimize the thermal gradient along each path. This includes minimizing heat loads along the way and maximizing the area-to-length ratio of all components on the path.
- Practical: It is important that we be able to assemble and disassemble the cold snout as often as needed for the experiment. This means that a rigorous assembly procedure must exist for any completed design.

With these considerations in mind, the cold snout was designed, constructed and tested, with improvements made along the way. The following subsections include descriptions of each thermal stage, and testing details are reported in the next section.

20 mK Path

The 20 mK or base temperature stage is the most important thermal path for the resonator components and sensors, as they benefit from being as cold as possible for optimal performance. Thus, our primary goal was to maximize the conductance along the path while minimizing heat loads. The bulk of the path is made up of a gold-plated Cu101 cold finger with a diameter of 2 cm and a length 65 cm. The connection between the MXC plate on the

DR and the 20 mK cold finger is a custom-made thermal strap. The thermal strap is made of Cu101 endpieces which are tungsten inert gas (TIG) welded to a stack of twenty 0.127 mm thick Cu110 strips with a length of 5 cm and a width of 2 cm (shown in Fig. 4.9). The interfaces between the strap and the cold finger as well as the braid and the MXC plate will be gold plated in the final design in order to prevent oxidation of the copper surfaces and increase the clamped contact due to the low surface hardness of gold. The purpose of this connection is to provide a thermal path between the MXC and the rod, while the flexibility of the strap allows for small movements due to thermal contraction.

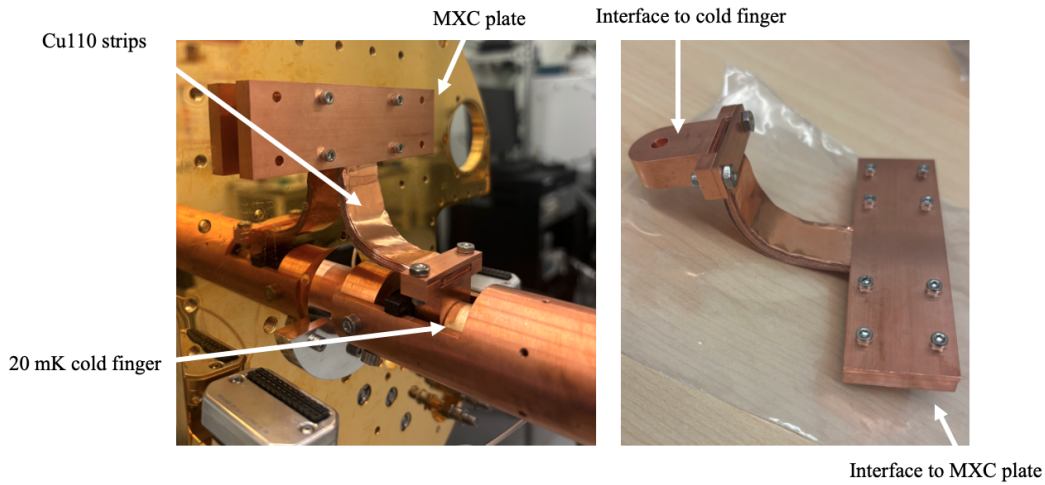


Figure 4.9: Prototype of the 20 mK thermal strap between the MXC plate on the DR and the 20 mK cold finger. One end is clamped to the MXC plate with eight M3 screws and nuts, and the other end is clamped to the cold finger with one M5 screw screwed directly into a helicoil on the end of the cold finger. All clamped surfaces will be gold plated.

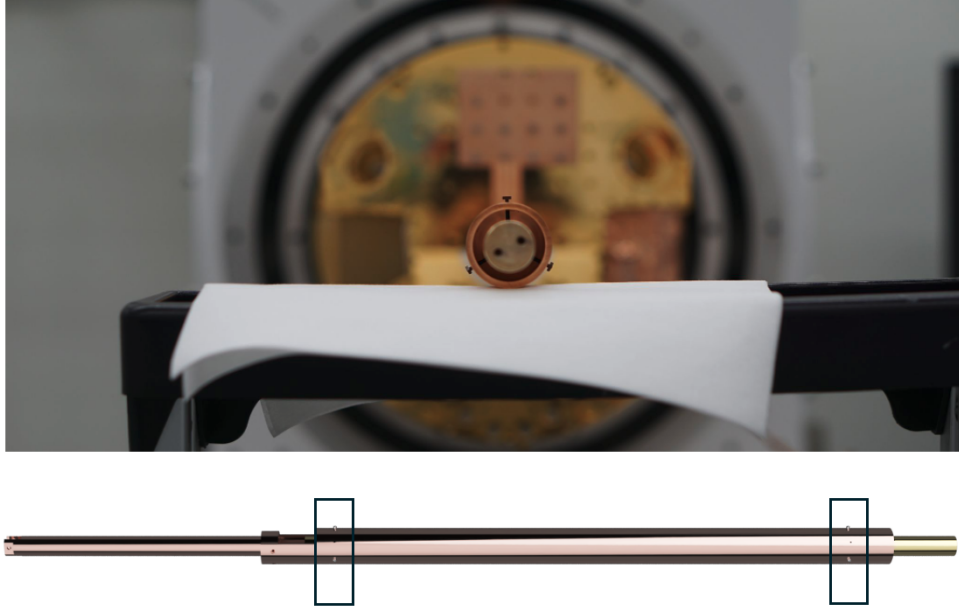


Figure 4.10: *Top:* 20 mK cold finger suspended inside the 1 K cold finger tube via three Vespel screws. *Bottom:* Locations of the Vespel screws along the length of the cold fingers.

The 20 mK cold finger is centered inside the 1 K cold finger, which is a hollow tube. Regarding the mechanical support for the 20 mK cold finger, two options were considered: a miniature web of Kevlar, a material known for its strength and low conductivity [70], inside the 1 K cold finger tube and a three-point suspension made from Vespel screws. We determined that although the Kevlar option would have lower thermal conductivity, it would limit the cross-sectional area of the 20 mK cold finger in order to fit inside the 1 K cold finger tube, therefore resulting in a higher thermal gradient overall. Therefore, we proceeded with the Vespel screws design, shown in Fig. 4.10.

The screws are M2 screws of length 8 mm and are made out of Vespel SP-1, a material known for its low thermal conductance [70]. Although the screws are 8 mm long, the distance between the outside of the rod and the inside of the tube is 5 mm, so this is the length used to calculate the path of the heat between the cold fingers. Note that Vespel SP-22 has even lower thermal conductivity, so this will be considered as an upgrade path in the future. The heat load transferred through these screws from the 1 K cold finger to the 20 mK cold finger was calculated to be $0.5 \mu\text{W}$ each. Assuming we can rest the cold finger on the bottom 2 screws and leave the top one as a “bumper,” we can consider the heat load from two screws on either end of the cold finger, giving us a total of $2 \mu\text{W}$ (also shown in Tab. 4.2).

The thermal gradient of this path can be estimated by calculating the conductance of each segment and interface and combining them in the following way:

$$G_{tot} = \left(\frac{1}{G_1} + \frac{1}{G_2} + \frac{1}{G_3} + \dots \right)^{-1}. \quad (4.5)$$

We take the thermal conductivity of high-purity copper below 4 K to be $.81T^{.97} \text{ W/cm}\cdot\text{K}$ [71] and the conductance of a gold-gold interface to be $(2 \times 10^{-1} \text{ W/K}) \left(\frac{F}{445 \text{ N}}\right) \left(\frac{T}{4.2 \text{ K}}\right)^{1.3}$ where F is the clamping force and T is the temperature [72]. Using the torque values recommended in [73] for Al7075 M5 and M3 screws and a temperature of 20 mK everywhere, we get the following values:

Component	Type	G [W/K]
20 mK cold finger	segment	7.8×10^{-4}
20 mK straps	segment	1.6×10^{-3}
MXC - strap endpiece	interface	3×10^{-3}
20 mK cold finger - strap endpiece	interface	1.9×10^{-3}

Table 4.1: Conductance G of components in the 20 mK thermal path.

This gives us a total conductance G_{tot} of $3.6 \times 10^{-4} \text{ W/K}$. With an expected heat load of $13 \mu\text{W}$ as explained in the next section, the thermal gradient is then expected to be 36 mK, or a temperature on the Woodstock end of the cold finger of 56 mK.

This is a pessimistic estimate for a couple of reasons. Firstly, we assume for these calculations that the temperature along the entire path is 20 mK. Realistically, there is a thermal gradient across the path, and since conductivity of copper at this temperature scales linearly with temperature, this will result in an increase of conductance. Secondly, the conductivity of copper used for these calculations was measured for 99.95% copper, while the cold finger is made of 99.99% copper.

Note that this estimate gives us the temperature on the Woodstock end of the cold finger, not taking into account the flexible thermal connection between the cold finger and the 20 mK plate in Woodstock. In order to reach a system noise temperature below 50 mK, we will need to both ensure that this thermal link does not degrade the overall conductance of the path and make improvements to the current path. Additionally, lower temperatures could be reached by minimizing the heat load on the 20 mK stage. Some potential avenues for improvement in both of these ways will be discussed at the end of this chapter.

1 K Path

The 1 K stage contains the 1 K plate and superconducting shield as well as the Attocubes and possibly the tunable transformer. Since the superconducting shield is made of Al1100 with a superconducting transition temperature of 1.2 K, it is necessary to ensure that the end of the 1 K thermal path remains below 1.2 K with all the expected heat loads. Although we have a layer of Nb covering the Al in case the temperature does not reach 1.2 K for some reason, we still want it to be as cold as possible to minimize loss.

The 1 K cold finger is composed of two parts. The 26 cm long segment from the still plate on the DR to the MXC plate on the DR is a Cu101 solid rod with a diameter of 2

cm. The 63 cm long segment from the MXC plate to the end of the cold snout is a tube with an inner diameter of 3 cm and an outer diameter of 3.6 cm. The tube surrounds the 20 mK cold finger, which is suspended with Vespel screws. The segments are connected with four Al M4 screws. The rigid mechanical connection of the 1 K cold finger is made up of a hinge supported by the still plate. A single Al M5 screw holds the 1 K cold finger at the end connected to the still plate but allows it to hinge up and down during assembly. The thermal connection between the still plate of the DR and the 1 K cold finger is another flexible thermal strap similar to that of the 20 mK stage. In this case, the strap is split into halves so that the hinge can fit in the middle of the still plate (Fig. 4.12). The strap is again made of a pair of stacks, each with fourteen 0.127 mm thick Cu110 strips with a length of 5 cm and a width of 2 cm TIG welded to Cu101 endpieces.

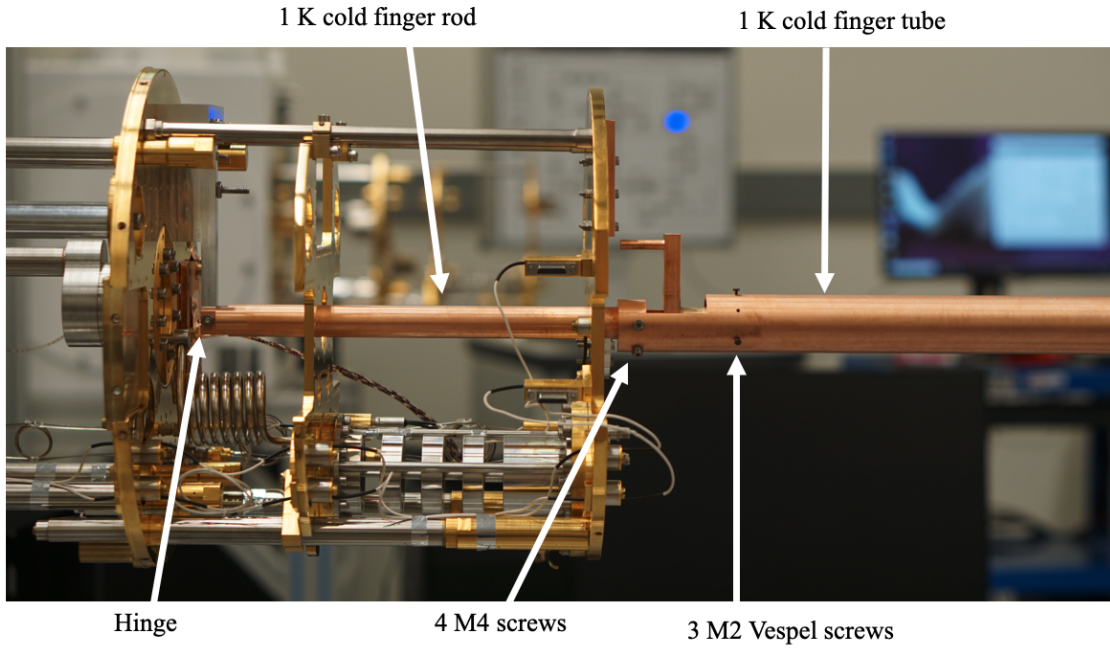


Figure 4.11: 1 K cold finger made up of two segments.

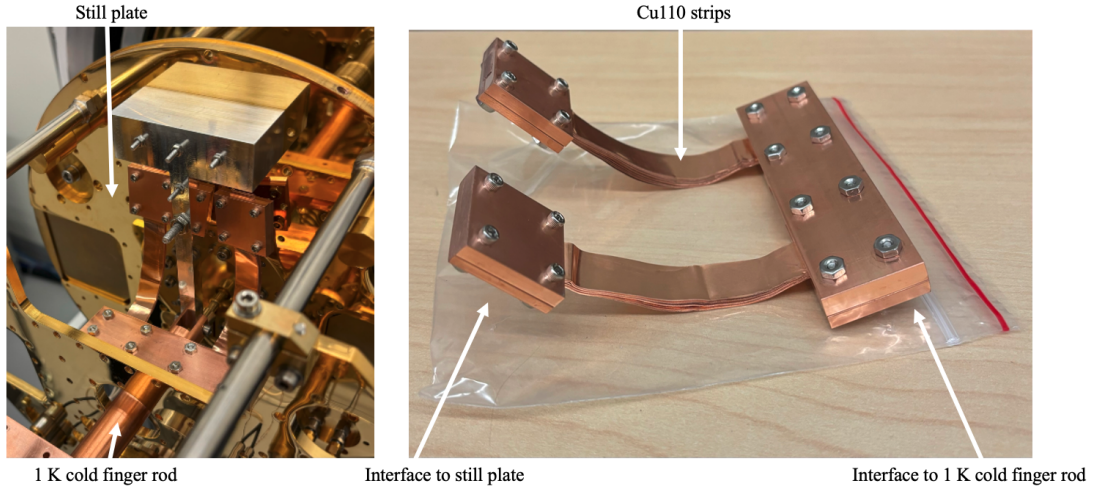


Figure 4.12: 1 K thermal strap between the still plate and 1 K cold finger.

To preserve the horizontal positioning of the 1 K cold finger to a high degree of accuracy, we require an additional mechanical support structure further down the length of the cold snout. This is done by inserting the cold finger into a web of tensioned Kevlar string supported by concentric metal components at different temperatures, shown in Fig. 4.13. This Kevlar suspension structure is referred to as a “puck” [74].

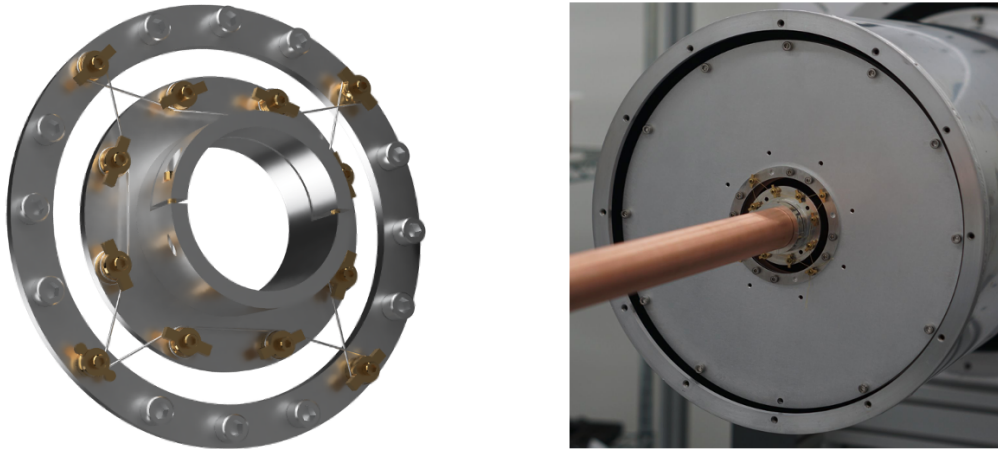


Figure 4.13: *Left:* CAD rendering of the puck design. *Right:* Photo of the puck connected to the 4 K can bottom and holding the 1 K cold finger. The full vacuum shield as well as the 40 K can bottom are missing from the photo.

4 K Path

The 1 K cold finger is enclosed in a 4 K shield to block radiation from higher temperatures. The shield is made of Al6063 and is 3 mm thick. It is clamped to the 4 K can bottom of the DR and extends to the 4 K panel in the cryostat. For testing purposes, there was an endcap attached to the end of the 4 K shield (Fig. 4.14). During operation, the 4 K shield will connect to the 4 K panel of the cryostat with a flexible connection made out of a series of overlapping high-purity Al strips of thickness 0.05 mm (Fig. 4.15). This connection is required to accommodate ≈ 7 mm of expected thermal contraction of the 4 K path.

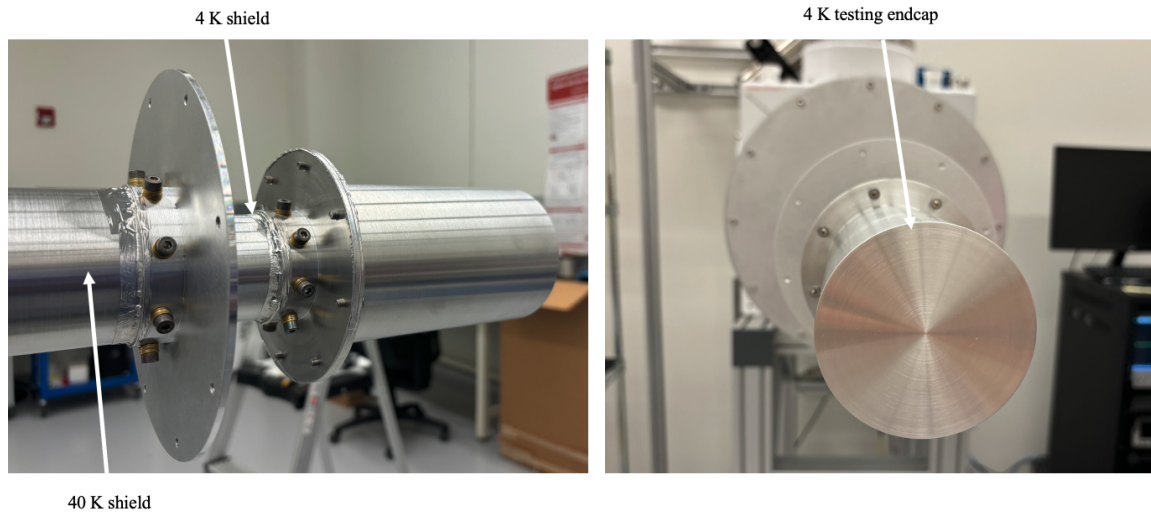


Figure 4.14: Assembly of the testing version of the 4 K shield and part of the 40 K shield (without the testing endcap).

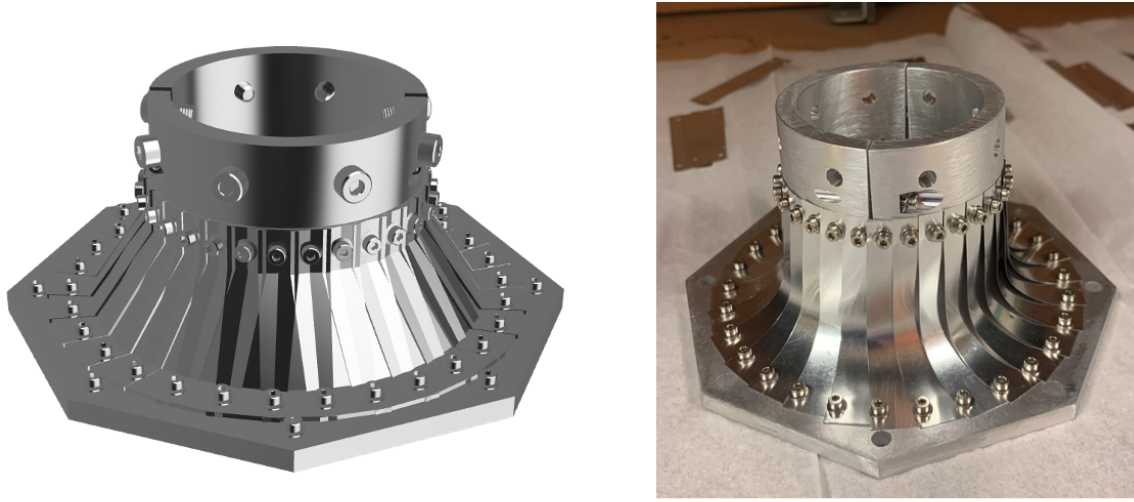


Figure 4.15: *Left:* CAD rendering of the 4 K flexible connection. *Right:* Photo of the assembled 4 K flexible connection. Courtesy of Roman Kolevatorov.

40 K Path

While the 40 K stage of the DR does not provide cooling power to the cryostat, we need to ensure there is a consistent thermal connection as well as radiation shielding, which is especially important at this stage due to the 300 K radiation beyond it. Space constraints prevented us from using a similar design to the flexible connection on the 4 K stage. Instead, the 40 K flexible connection is composed of a concentric cylinder surrounding the 40 K shield with BeCu fingerstrips on each end as well as Bock black coating [75], a type of black paint made of carbon, glass beads, and Stycast 2850 FT, on the inside and flanges making up a tortuous path for any possible light. In order to calculate the heat load from any remaining radiation, we used the original Bock black testing data [75], shown in Fig. 4.16. For the frequency range of 300 K radiation, we are beyond the range of the plot; however, we can take the pessimistic value of 0.05 reflectance with no glass beads. We want to avoid glass beads if possible since we are trying to minimize the thickness of the Bock black coating in the small gap between the concentric cylinder and the 4 K shield. Then for a gap size of about 5 cm^2 between the concentric cylinder and the 4 K shield and for a minimum of three photon bounces, the power at the end is given by the Stefan-Boltzmann law:

$$P = (5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}) (0.0005 \text{ m}^2) (300 \text{ K})^4 (0.05)^3 = 2.87 \times 10^{-5} \text{ W} \approx 30 \text{ } \mu\text{W}.$$

As this does not include the BeCu fingerstrips, which are expected to cover the vast majority of the gap, we conclude that this amount of heat load is negligible relative to the 0.3 W

expected at 4 K (see Tab. 4.2). This configuration also allows for the expected movement of ≈ 7 mm from thermal contraction.

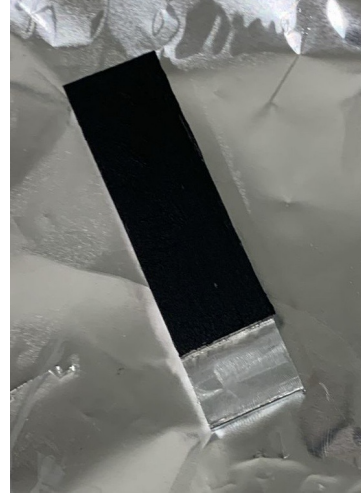
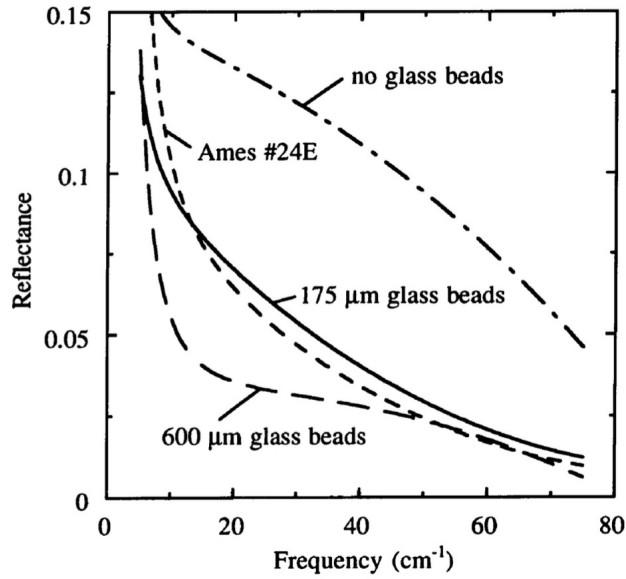


Figure 4.16: *Left:* Reflectance of Bock black for various recipes. Plot adapted from [75]. *Right:* A sample of Al coated with the version of Bock black with no glass beads.

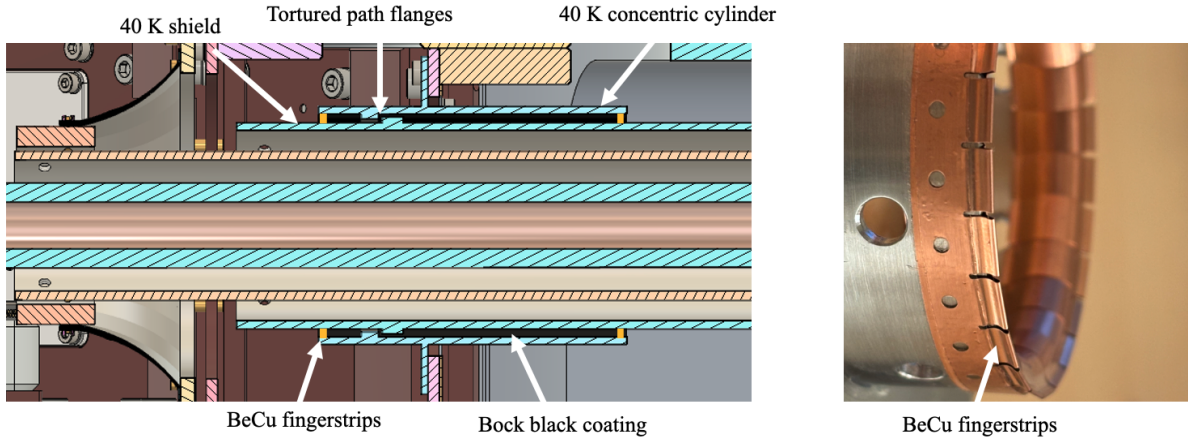


Figure 4.17: *Left:* Cross-sectional view of the CAD design of the 40 K flexible connection, including (from the outside in) the 40 K concentric cylinder, the BeCu fingerstrips, the 40 K shield, the 4 K shield, the 1 K cold finger tube, and the 20 mK cold finger. *Right:* Photo of a sample of BeCu fingerstrips in the expected configuration.

4.3.5 Heat Loads

Expected radiative and conductive loads on all the temperature stages are tabulated in Tab. 4.2 and summarized below; detailed calculations of the 20 mK and 1 K stages can be found in Appendix A.

- 20 mK:** The dominant heat loads on the base temperature stage are expected to come from the mechanical supports of the cold finger inside the 1 K tube as well as the supports of the 20 mK plate from the 1 K plate. Both of these mechanical support structures have practical upgrade paths to reduce the heat load in the future, specifically by using materials with even lower thermal conductivities. While radiative heat loads on the base stage are expected to be minimal, any leaks caused by holes or gaps for light to escape from higher temperatures will provide significant heat, meaning shielding must be thorough and robust.
- 1 K:** The 1 K stage heat load is dominated by the mechanical supports of the 1 K plate from the 4 K ring. These can be upgraded by changing either material or reducing the physical dimensions if this heat load becomes a problem. Ongoing measurements are expected to determine the heat load from the Attocube on the 1 K stage, which for now is unknown but estimated to be on the order of $300 \mu\text{W}$. As on the 20 mK stage, radiation from 4 K is minimal but can become significant with any leak from higher temperatures.

- **4 K:** On the 4 K stage, the main heating is radiation from 40 K components, followed by mechanical supports of the 4 K plate. Although the expected total heat load on 4 K is still minimal relative to the cooling power, more radiative shielding could be considered if the heat load does become an issue.
- **40 K:** The 40 K stage heat load is heavily dominated by the room temperature radiation. This is not projected to be a problem with the expected cooling power, but if necessary radiative shielding can again be considered. The magnet leads routed from room temperature to 40 K are the secondary heat load on this stage.

	Heat load source	40 K	4 K	1 K	20 mK
Radiative	300 K components	12.5 W	-	-	-
	40 K components	-	120 mW	-	-
	4 K components	-	-	7 μ W	-
	1 K components	-	-	-	< 0.1 μ W
Conductive	Plate supports	800 mW	71 mW	185 μ W	1.3 μ W
	Inductor centering puck	-	-	-	0.3 μ W
	Cold snout puck	-	-	3.7 μ W	-
	Vespel screw supports	-	-	-	2 μ W
	Attocube	-	-	?	-
	DC wiring	200 mW	30 mW	< 0.1 μ W	< 0.1 μ W
	RF wiring	70 mW	-	< 0.1 μ W	< 0.1 μ W
	Magnet leads	7 W	80 mW	-	-
Total		20.6 W	0.3 W	500 μ W	4.5 μ W

Table 4.2: Expected steady-state heat loads in DMRadio-50L.

4.4 Cryogenic Testing

4.4.1 Cold Snout Characterization

Four cooldowns to test and characterize the cold snout are described here, with a particular focus on the 20 mK thermal path. The results are summarized in Tab. 4.3 and detailed in the subsections below. The cold snout assembly procedure for Cooldown 3 is included in Appendix C. Further cryogenic testing and characterization of the cold snout are ongoing.

The initial design of the cold snout tested in these cooldowns differs from the design described in the previous section, primarily in the 1 K and 20 mK flexible connections. The 1 K flexible connection was made from two stacks of six Cu110 strips each connected to the cold finger with a clamp made of two halves which were tightened together with four M4 Al screws. The 20 mK flexible connection consisted of a Cu adapter plate, a Cu braid, and a

Cu “Vbar” piece. The adapter plate clamped to the MXC with twelve M3 Al screws, and the braid clamped to the adapter plate with two #10 stainless steel screws. The Vbar piece was made to mate the braid to the cold finger. On the braid side, the Vbar had a rod which inserted into another two-piece clamp at the end of the braid, and on the cold finger side, the Vbar was clamped to the cold finger with one M5 Al screw. This version of the cold snout design is shown in Fig. 4.18.

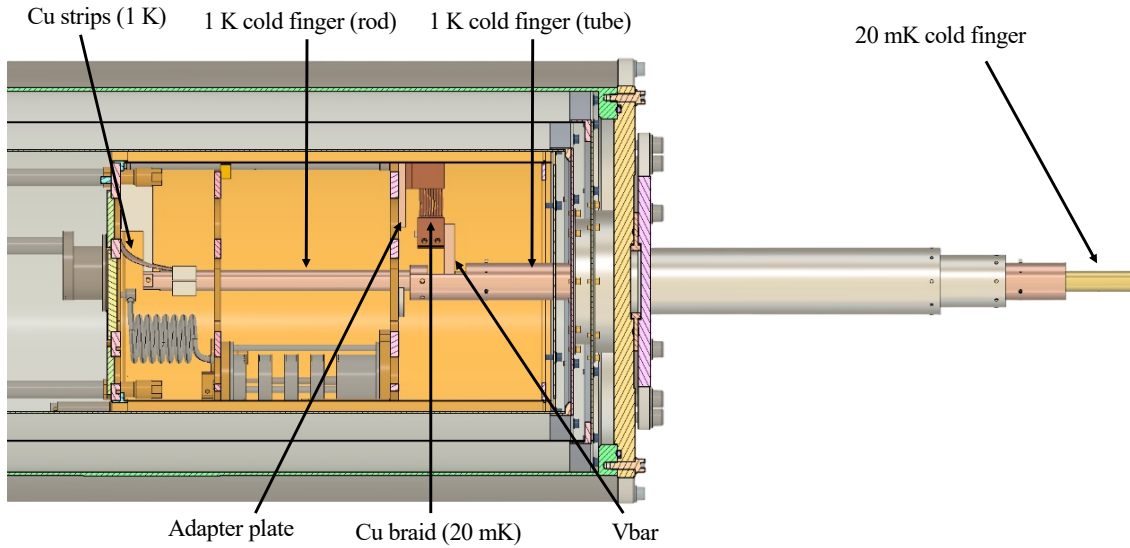


Figure 4.18: CAD rendering of the initial cold snout design used for testing and characterization.

Thermal observations are done with a 4-wire measurement, a particularly sensitive method for measuring resistance which minimizes errors caused by lead and contact resistance by separating the current path from the voltage measurement (Fig. 4.19). Resistance can then be converted to temperature following the calibration data either given by the thermometer

Cooldown number	MXC	20 mK cold finger	Still	1 K cold finger
1	-	-	-	-
2	33 mK	393 mK	880 mK	-
3	17.65 mK	176 mK	884 mK	914 mK
4	17.2 mK	80 mK	910 mK	1 K

Table 4.3: Cooldown summary of the lowest temperatures reached on the MXC and still plates as well as the 20 mK and 1 K cold fingers. The improvements made to the 20 mK thermal path after each cooldown are reflected in the “20 mK cold finger” column.

vendor or measured in our DR. Below 4 K, ruthenium oxide (RuOx) sensors were used, with niobium titanium (NbTi) or phosphor bronze (PhBr) wires.

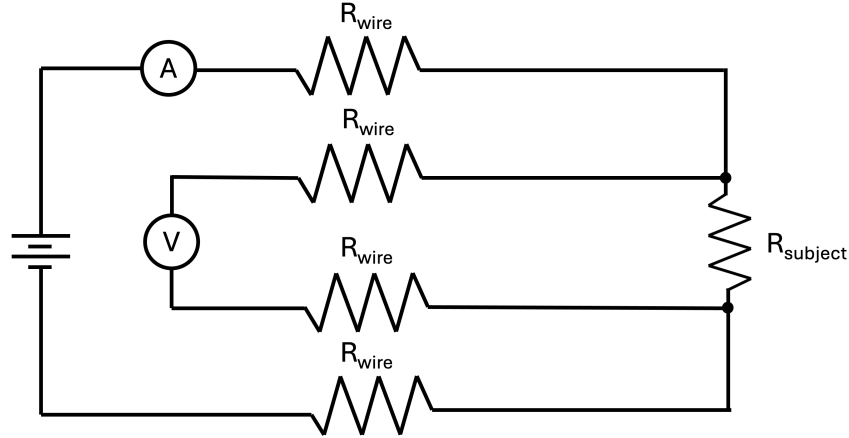


Figure 4.19: Circuit diagram of 4-wire resistance measurement. R_{subject} is then extracted by taking the ratio of the voltmeter indication to ammeter indication.

Cooldown 1

The first cooldown of the cold snout was done only to 4 K with a window at the end of the cold snout to observe movement due to thermal contraction. Because of the considerable heat load from the 300 K radiation of the lab through the window directly onto the base temperature cold finger, no temperatures were measured in this cooldown. Out of concern for the torque on the DR, a pulley system was designed and built to counteract the weight of the testing vacuum shield. The full setup of the first cooldown is shown in Fig. 4.20. Although no movement was seen during the cooldown, we noted an issue with the concentricity of the 4 K shield, potentially due to the relative angle of the DR plate.

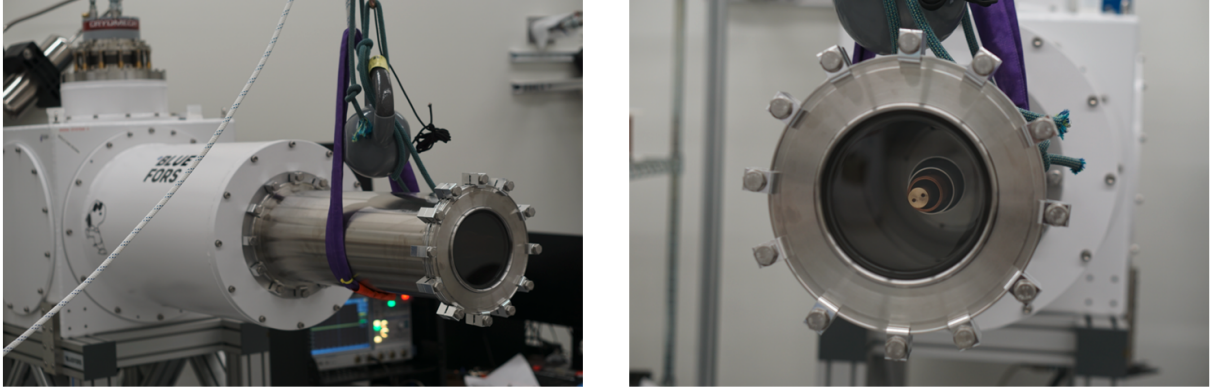


Figure 4.20: Cooldown 1: Photo of the setup of the first cooldown. A Kodial glass viewport is attached to the end of the testing vacuum shield.

Cooldown 2

The second cooldown included a pre-calibrated ultra-low temperature (ULT) RuOx thermometer from Lakeshore at the end of the 20 mK cold finger, along with a bobbin for thermalization and strain relief of the wires. Four heaters made of 1 k Ω resistors soldered onto small copper sheets were placed throughout the 20 mK path. Battery-powered voltage sources were used for all heaters to avoid ground loops. Thermometers were routed through the wiring of the DR and read out with a Lakeshore 372 AC resistance bridge. The lowest temperature reached on the MXC plate was 33 mK and on the end of the 20 mK cold finger was 393 mK, indicating a large heat load on the base stage. This was determined to be caused by holes on the 4 K and 40 K shields, allowing 300 K radiation to reach the 20 mK cold finger. This issue was fixed in the following cooldowns by plugging the holes with screws. The setup of the thermometer and heater on the end of the 20 mK cold finger is shown in Fig. 4.21.

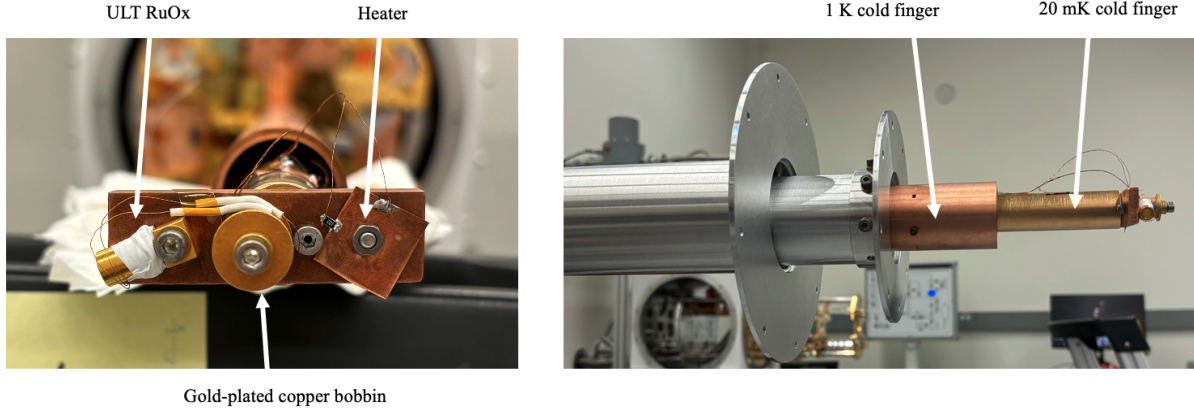


Figure 4.21: Cooldown 2: Photo of the thermometer and heater setup of the second cooldown.

Cooldown 3

The third cooldown included a similar setup of the ultra-low temperature RuOx, bobbin, and heater at the end of the 20 mK cold finger with a more compact design of the mounting plate for easier assembly. This time, a mount was also added to the middle of the 1 K cold finger, housing a RuOx, bobbin, and heater as well. The same 4 heaters made of 1 k Ω resistors soldered onto small copper sheets remained along the 20 mK path, and 2 heaters made of 10 k Ω resistors were added on either side of the 1 K cold finger connection. All the screw holes were plugged with screws, and Al tape was used to cover all the seams. The lowest temperature reached on the MXC plate was 17.65 mK and on the end of the 20 mK cold finger was 176 mK, demonstrating a large improvement after fixing the radiation leaks. The setup of the thermometers and heaters on both cold fingers is shown in Fig. 4.22.

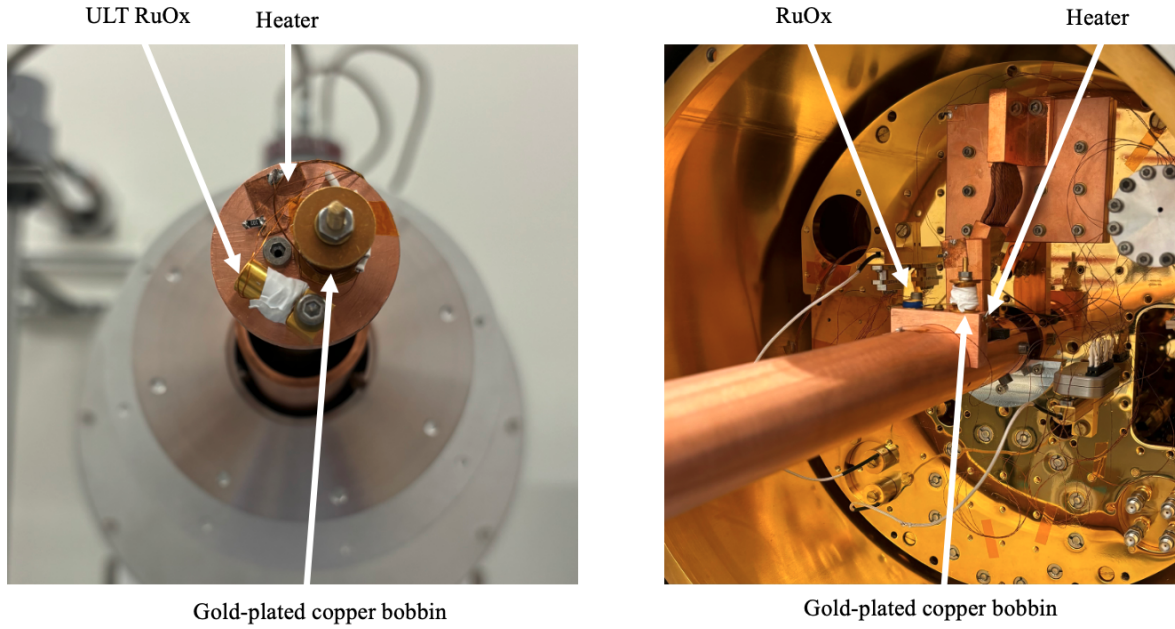


Figure 4.22: Cooldown 3: *Left*: Photo of the thermometer and heater setup on the end of the 20 mK cold finger. *Right*: Photo of the thermometer and heater setup in the middle of the 1 K cold finger.

In order to characterize the conductances of individual components along the thermal paths, we measured the temperature everywhere while applying the same heat to each location. The results of these measurements for each thermal path are shown in Fig. 4.23 and Fig. 4.24; specifically, the percent change of the temperature on each node of the thermal path is plotted against the location of the heat applied. Based on the significant increase in temperature between the adapter plate and Vbar for the 20 mK tests and the still and rod for the 1 K tests, we concluded that the bottleneck of the 1 K thermal path was the interface between the still plate and the rod and the bottleneck of the 20 mK thermal path was the 20 mK braid interface. Therefore, the 20 mK braid needed to be improved, specifically the mating of the rod to the clamp of the braid.

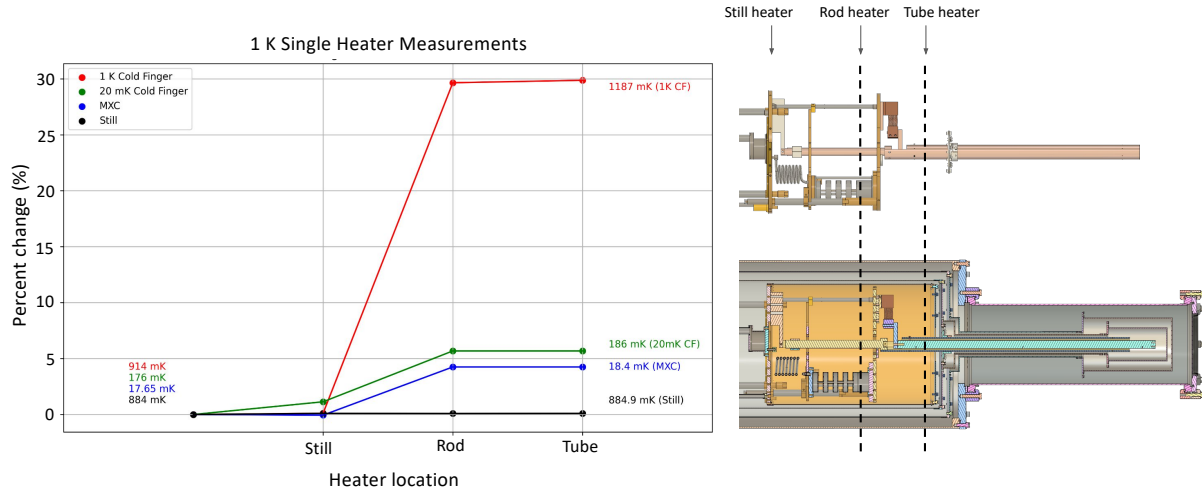


Figure 4.23: Cooldown 3: 1 K measurements. *Left:* Plot of the percent change from the initial temperature with no heat applied of the four thermometers in the setup. At each heater location, $53 \mu W$ was applied. *Right:* CAD diagram of the locations of the heaters, both without shields (top) and with shields (bottom).

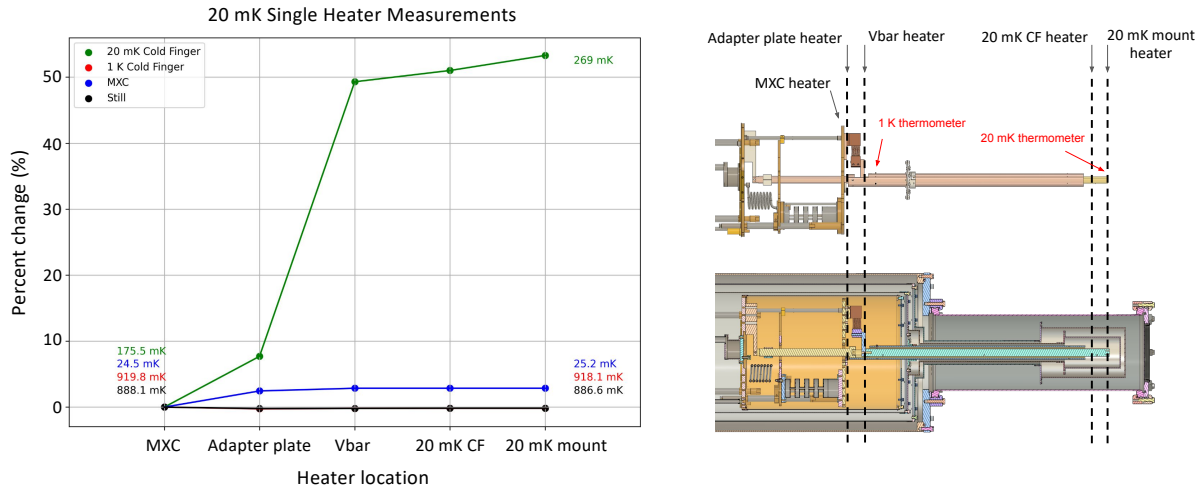


Figure 4.24: Cooldown 3: 20 mK measurements. *Left:* Plot of the percent change from the initial temperature with no heat applied of the four thermometers in the setup. At each heater location, $10 \mu W$ was applied. *Right:* CAD diagram of the locations of the heaters and thermometers, both without shields (top) and with shields (bottom).

Cooldown 4

The fourth cooldown included the same setup of the 20 mK and 1 K heaters and thermometers and an additional Si diode thermometer at the end of the 4 K shield. Informed by the results of the previous cooldown, the interface to the 20 mK braid was improved by increasing the diameter of the rod that mates to the braid. The lowest temperature reached on the MXC plate was 17.2 mK and on the end of the 20 mK cold finger was 80 mK, once again demonstrating a large improvement in the thermal gradient. The diode thermometer setup is shown in Fig. 4.25. The same single heater measurements were repeated and the results showed a significant improvement in the 20 mK braid interface. These results are shown in Fig. 4.26. The diode thermometer showed a temperature of ≈ 4 K, meaning that the 4 K path is acceptable and there is no unexpected radiative heat load on lower temperature stages coming from the 4 K shield. Once again, we see that the bottleneck is the thermal braid, albeit less extreme. For a direct comparison of the thermal braid before and after the improvement, we took a measurement regulating the MXC at the same starting temperature of 174 mK by applying heat directly to the MXC, shown on the right of Fig. 4.26. A clear improvement in the temperature increase between the adapter plate and Vbar can be seen between the two runs. Because the bottleneck remained the thermal braid, we concluded that we need to design and fabricate a custom thermal braid with the required conductance for this setup. While the final version is still being constructed, a prototype is shown in Fig. 4.9.

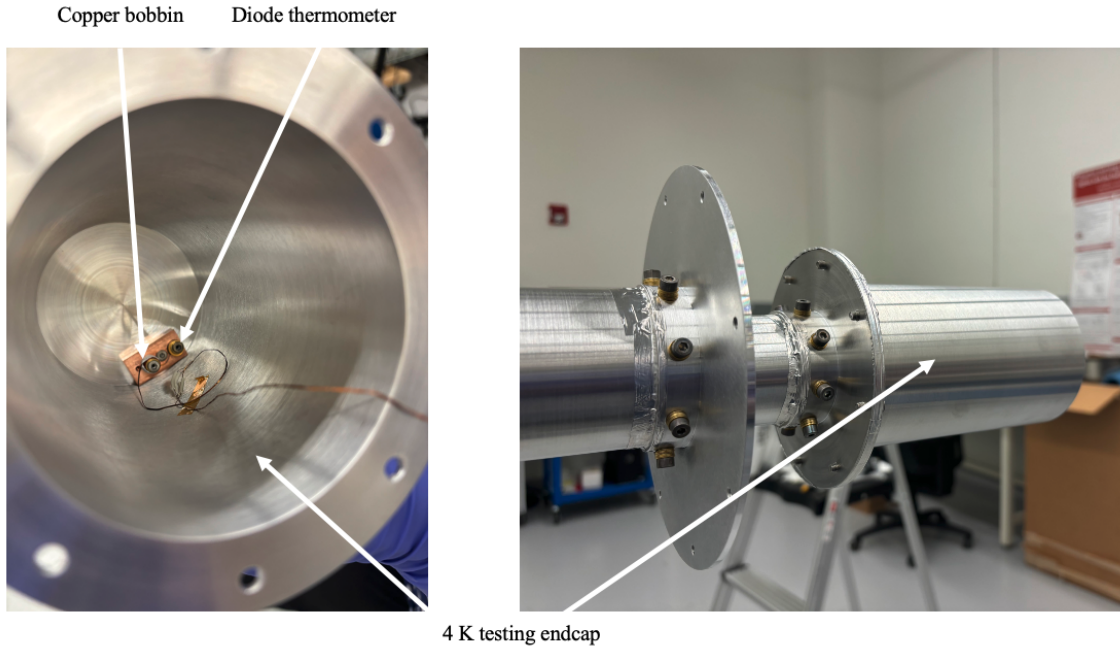


Figure 4.25: Cooldown 4: Photo of diode thermometer setup on the 4 K testing endcap, including the thermometer and bobbin.

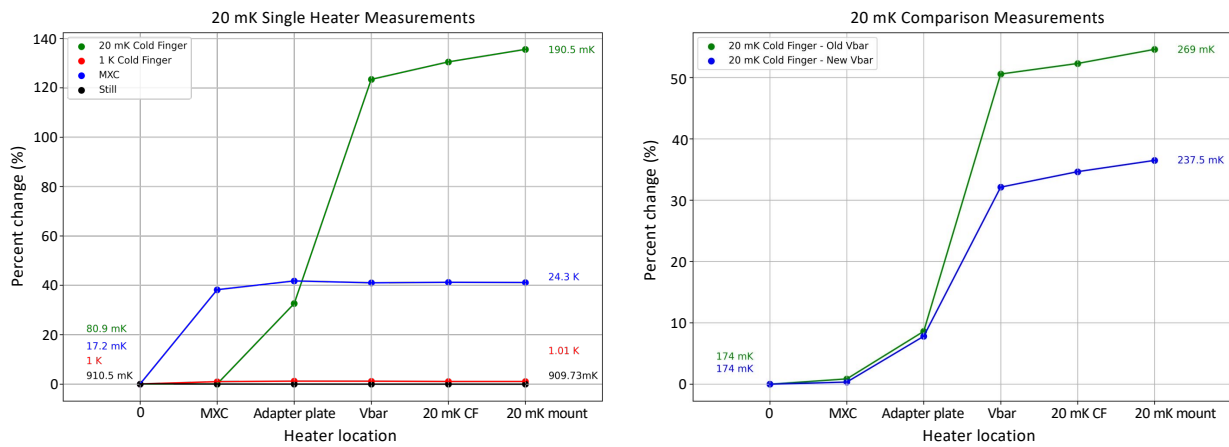


Figure 4.26: Cooldown 4: 20 mK measurements. *Left:* Plot of the percent change from the initial temperature with heat applied to the MXC plate of the four thermometers in the setup. At each heater location, $10 \mu\text{W}$ was applied. *Right:* Comparison of the measurements with the MXC plate regulated at the same starting temperature (174 mK) in order to directly compare the thermal gradient across each path segment.

4.4.2 Exploration of Material Properties

While designing the cold snout, we encountered a lack of comprehensive literature on certain materials and interfaces at temperatures as low as 20 mK. We conducted some studies to quantify conductances of materials that have been used in the construction of the cold snout and the system beyond it. Specifically, we investigated the thermal conductivity of Vespel SP-1 and the interface conductance of gold-gold as a function of torque.

Conductivity of Vespel

In order to quantify the conductivity of Vespel in our environment, we conducted a study of a Vespel SP-1 rod with a diameter of 0.25 inches and a length of 1 inch. The technique used is a two-heater technique, as it requires two heaters and one thermometer. The method is described below, where the heaters are referred to by their relative distance from the MXC plate (the heater closer to the MXC is H_1 , and the heater on the end of the Vespel is H_2).

1. Apply some heat Q to H_2 . Once at steady state, measure $T_0 = T_{MXC}$.
2. Apply heat corresponding to a set of points (q_1, q_2) on (H_1, H_2) such that $q_1 + q_2 = Q$. This ensures that the total heat flowing from both heaters into the MXC is always equal to Q , and thus the temperature at the end of the Vespel closest to the MXC is constant and equal to T_0 .
3. Fit the results to the equation $P = G(T_1 - T_0)$ to extract G .

As an additional check, we included another thermometer on the side closest to the MXC to monitor that it remained constant. Battery-powered voltage sources were used to apply the heat in order to avoid ground loops. The setup is shown in Fig. 4.27, and the measurements are plotted in Fig. 4.28. The conductivity extracted from this study was $\kappa = 6.8 \mu\text{W}/\text{cm}/\text{K}$, which falls within 30% of some previously measured values [76]. We also performed this study at two additional temperatures to quantify the scaling of κ as a function of temperature compared with previous results [76]. These measurements are shown in Fig. 4.29.

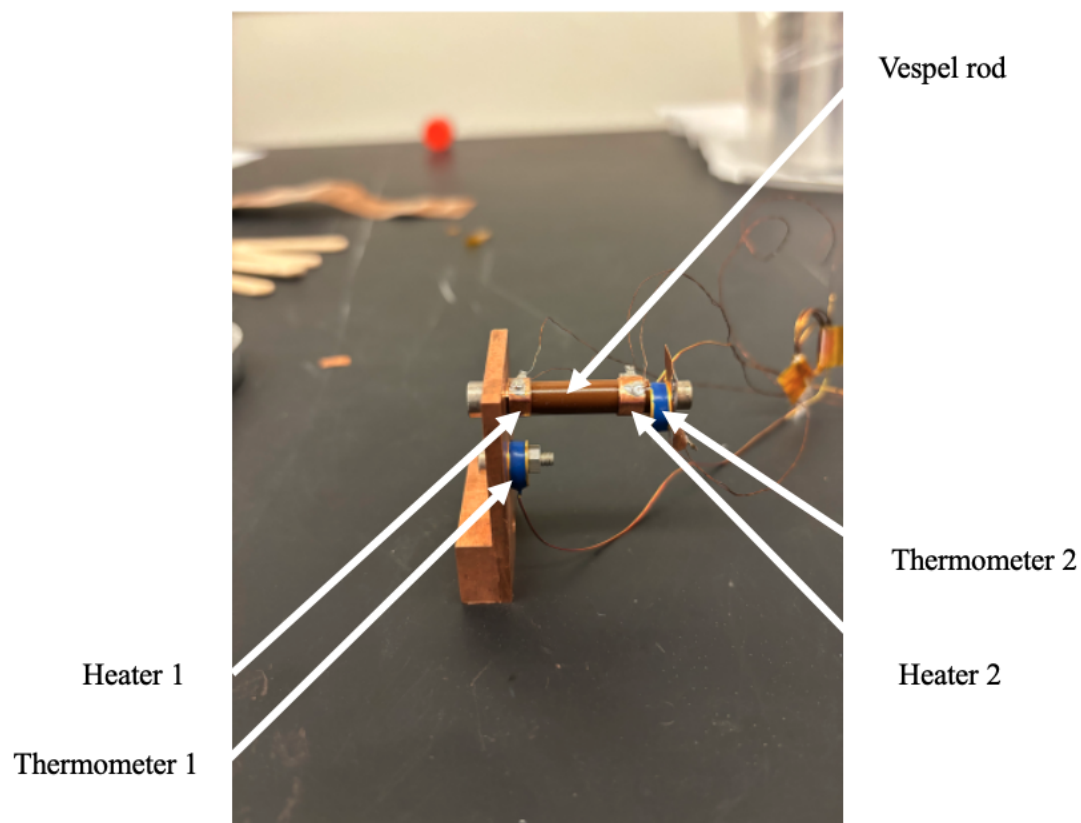


Figure 4.27: Photo of the setup of the Vespel conductivity measurement.

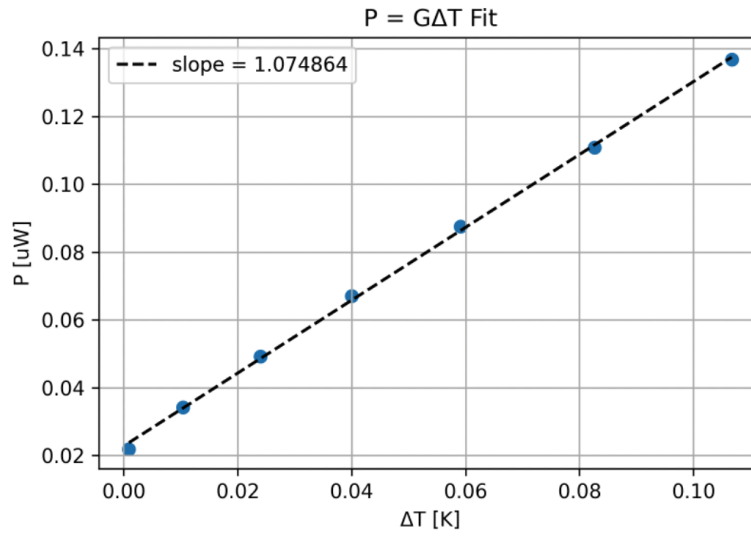


Figure 4.28: Plot of Vespel conductivity measurements at 300 mK.

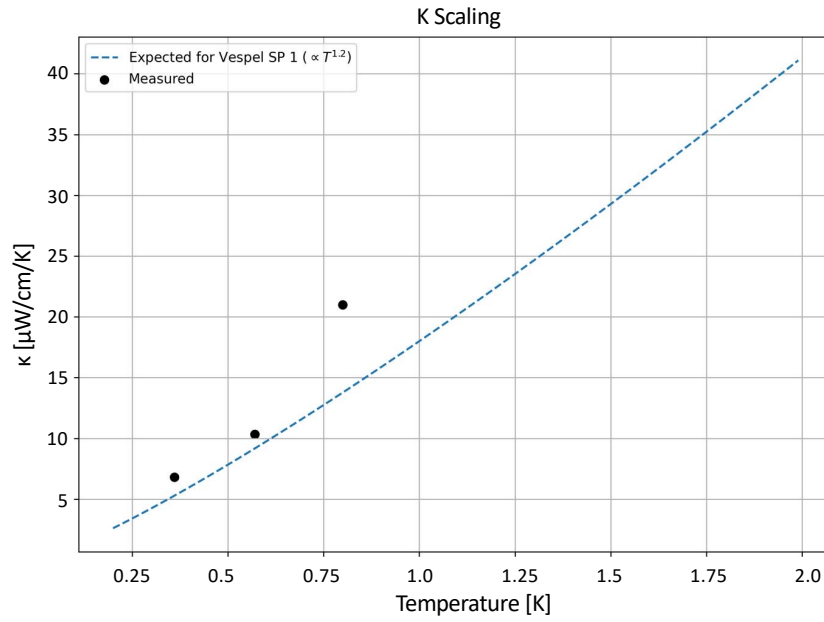


Figure 4.29: Plot of Vespel conductivity measurements at three different temperatures with expected scaling from [76].

Conductivity of Gold-Gold Interfaces

Wiedemann-Franz Law In 1853, Gustav Wiedemann and Rudolph Franz realized that the ratio of thermal conductivity to electrical conductivity was approximately the same for different metals at the same temperature [77]. This became known as the Wiedemann-Franz (W-F) law, which states that the ratio of a metal's thermal conductivity to its electrical conductivity is proportional to temperature. The proportionality constant was later specified by Lorenz and is known as the Lorenz number, given by

$$L = \frac{\kappa}{\sigma T} = \frac{\pi^2}{3} \left(\frac{k_B}{e} \right)^2, \quad (4.6)$$

where k_B is the Boltzmann constant, e is the elementary charge, κ is thermal conductivity, σ is electrical conductivity, and T is temperature.

For a non-superconductor like copper, the electrical conductivity becomes constant at low temperatures (Fig. 4.30). This means that the thermal conductivity must be linear with temperature to satisfy W-F.

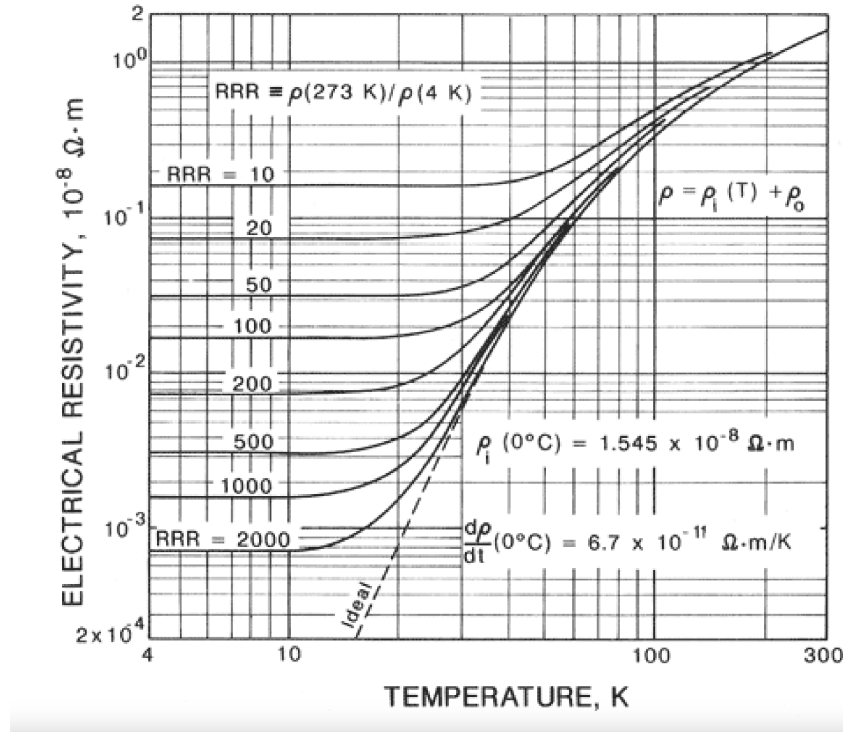


Figure 4.30: Electrical resistivity vs. temperature for different alloys of copper at low temperatures. Plot from [71].

We are interested in the conductivity of different kinds of interfaces that appear in our experiment. Specifically, we want to quantify the gold-gold interface that we will be using at all base temperature connections. For this study, we used two gold-plated copper bars attached to the MXC plate with different torques. Each bar contains a ULT RuOx as well as a heater. The setup is shown in Fig. 4.31. Raw measurements are shown in Fig. 4.32 and Fig. 4.33 and details tabulated in Tab. 4.4 and Tab. 4.5. These measurements were done with a two-thermometer/one-heater method:

1. Apply heat Q to the heater. The conversion from voltage to power takes into account the resistances along the path as well as the surface mount resistor on the heater.
2. Once at steady state, measure both temperatures.
3. Method 1: Assuming W-F, fit to $P = k(T_2^2 - T_1^2)$, where k is converted to G below.
4. Method 2: In a small enough temperature range, fit to $P = G(T_2 - T_1)$.

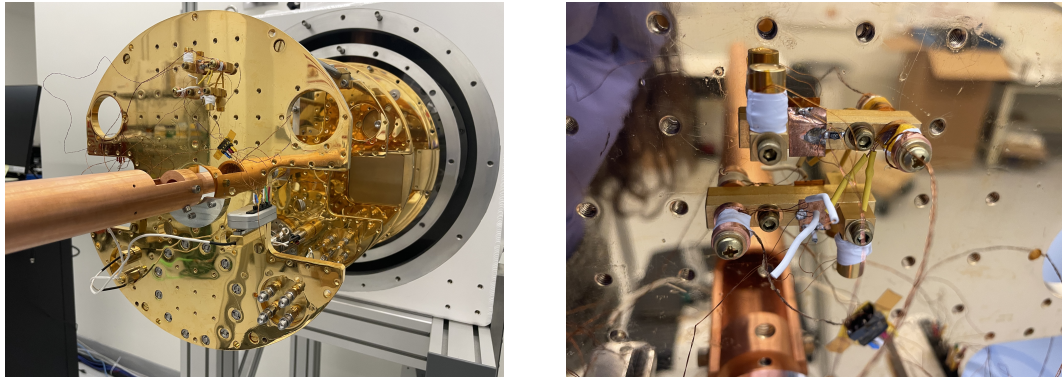


Figure 4.31: *Left:* Front of MXC. *Right:* Gold-plated copper bars on front of MXC. Brass screw torqued to .4 and .8 Nm (top and bottom) into an Al 6061 nut.

Power [μW]	0	2	4	6	8	10
Voltage [V]	0	2.794	3.952	4.840	5.589	6.249
Bar T [mK]	29.29 $\pm$.06	30.34 $\pm$.04	31.48 $\pm$.03	32.67 $\pm$.04	33.87 $\pm$.03	35.35 $\pm$.04
MXC T [mK]	10.13 $\pm$.02	11.74 $\pm$.02	13.83 $\pm$.02	15.90 $\pm$.04	17.83 $\pm$.04	19.50 $\pm$.04
$T_B^2 - T_{MXC}^2$	755 $\pm$ 4	783 $\pm$ 3	800 $\pm$ 2	815 $\pm$ 4	829 $\pm$ 3	869 $\pm$ 4

Table 4.4: Top bar measurements

Measurements were taken by averaging regions at equilibrium:

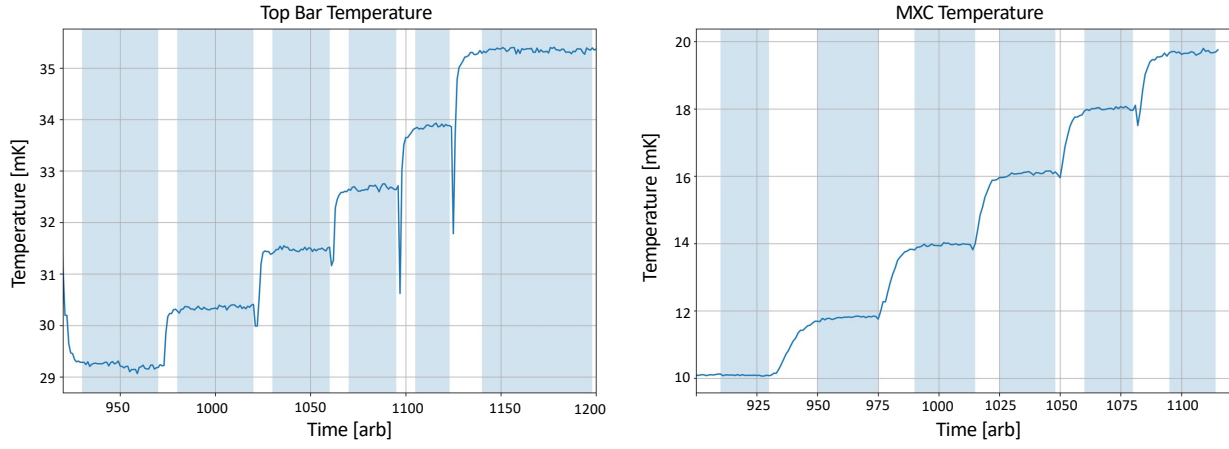


Figure 4.32: Raw measurements of top gold bar and MXC temperatures. Data in the shaded blue regions is averaged.

Power [μW]	0	2	4	6	8	10
Voltage [V]	0	2.794	3.952	4.840	5.589	6.249
Bar T [mK]	$38.24 \pm .05$	$38.48 \pm .08$	$38.67 \pm .05$	$38.95 \pm .05$	$39.30 \pm .06$	$39.70 \pm .05$
MXC T [mK]	$10.09 \pm .01$	$11.80 \pm .04$	$13.95 \pm .05$	$16.08 \pm .06$	$18.01 \pm .04$	$19.68 \pm .04$
$T_B^2 - T_{MXC}^2$	1360 ± 4	1341 ± 7	1300 ± 5	1259 ± 6	1220 ± 6	1189 ± 7

Table 4.5: Bottom bar measurements

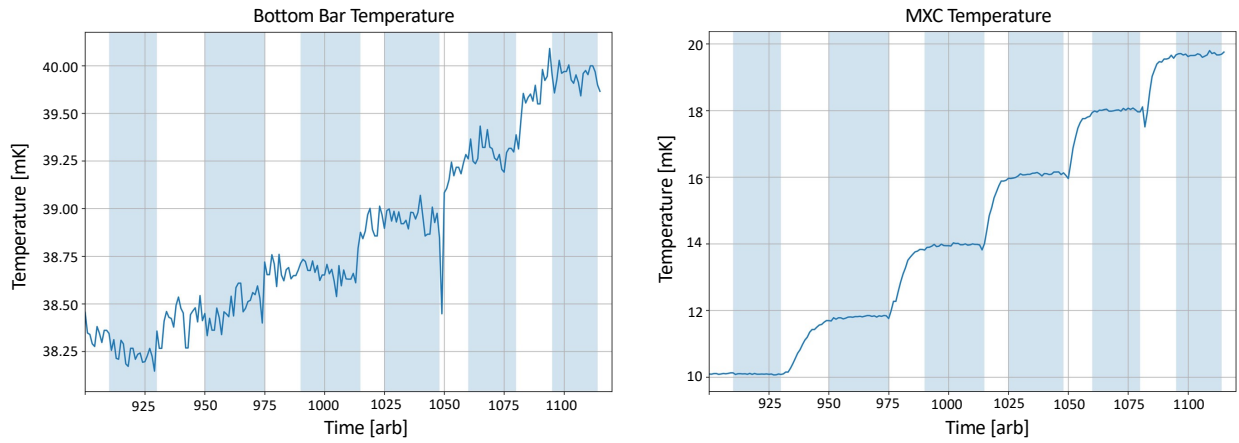


Figure 4.33: Raw measurements of bottom gold bar and MXC temperatures. Data in the shaded blue regions is averaged.

We fit our data to the following function:

$$P = k(T_B^2 - T_{MXC}^2) - P_0$$

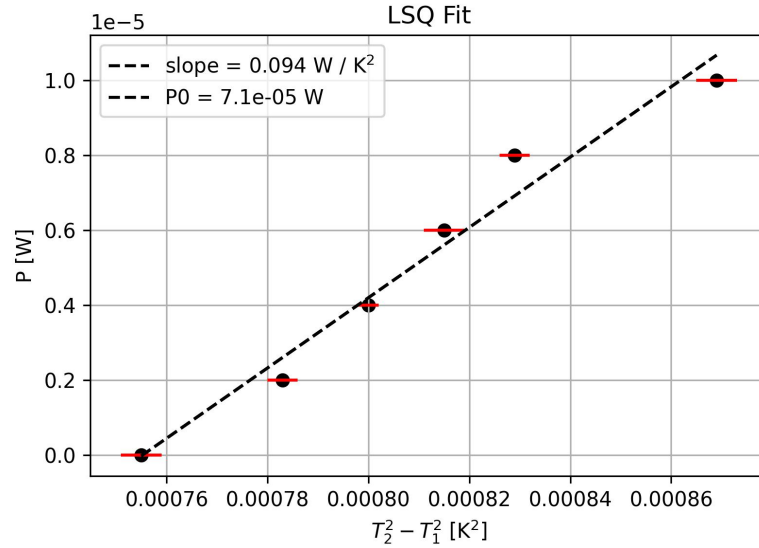


Figure 4.34: Least-squares fit to the data from the top gold bar.

We can extract a conductance G from the fit to k . The relationship between G and k is:

$$\kappa = 2KT \text{ and } G = \frac{A}{L}\kappa$$

$$P = \frac{A}{L} \int_{T_1}^{T_2} \kappa dT = \frac{A}{L} \int_{T_1}^{T_2} 2kT dT = \frac{A}{L} * K(T_2^2 - T_1^2)$$

So our k is equivalent to $\frac{A}{L} * K$ and

$$G = 2kT$$

So at 35 mK, we extract a G of 6.6 mW / K.

Because our P_0 is so high, we theorize that the thermometer undergoes electron-phonon decoupling and thus is unreliable under high radiation at low temperatures. To test this theory, we regulate the MXC at 50 mK and 100 mK and repeat the measurements.

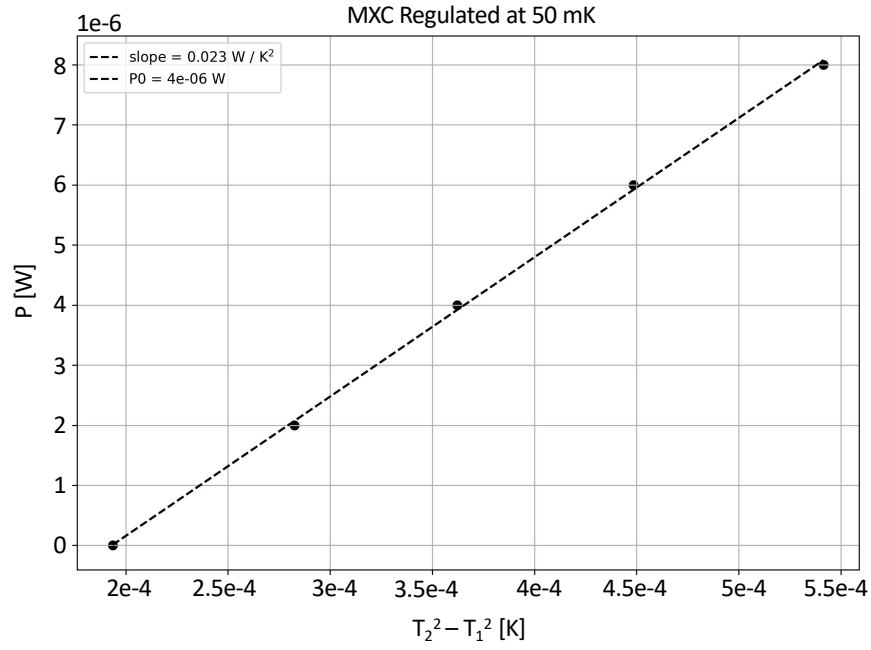


Figure 4.35: Regulating MXC at 50 mK - top bar.

This gives us a P_0 of $4 \mu\text{W}$, which is lower but still higher than we expect.

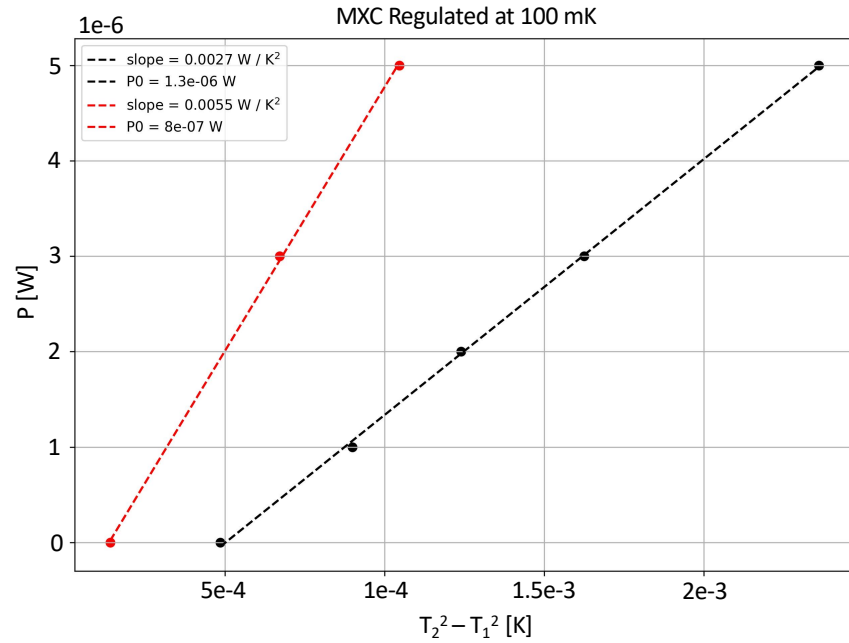


Figure 4.36: Regulating MXC at 100 mK - both bars.

This gives us a P_0 of $1 \mu\text{W}$ and shows the expected factor of 2 between the bars. Assuming W-F, the conductance we get at 20 mK is $1 \times 10^{-4} \text{ W/K}$ and $2 \times 10^{-4} \text{ W/K}$, or 0.1 and 0.2 mW / K. This is about a factor of 10 lower than the conductance we measured at 20 mK with no cold snout (thus no extra radiation).

However, if we fit to $P = G\Delta T$ using method 2, we get closer values, only about a factor of 2 off:

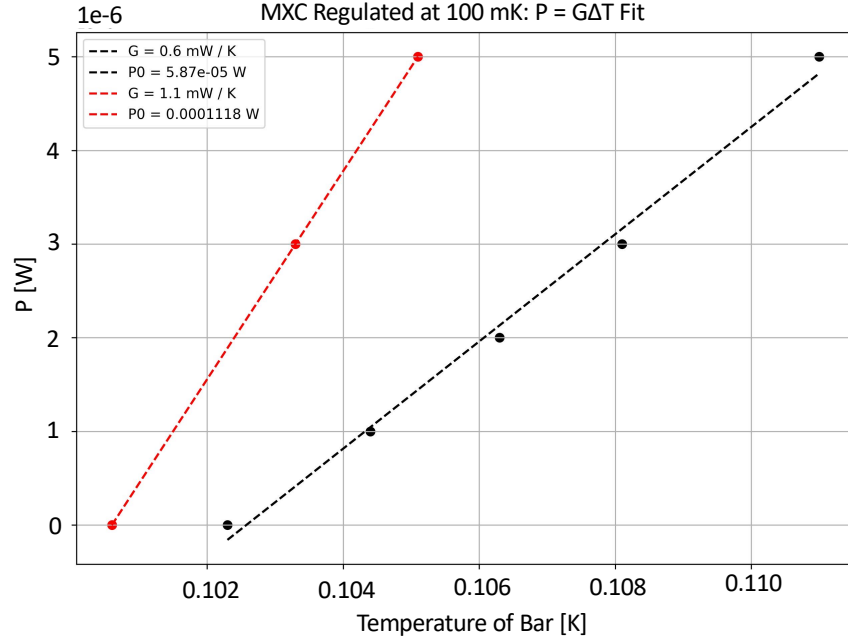


Figure 4.37: Regulating MXC at 100 mK - both bars. $P = G\Delta T$ fit.

This tells us that the ULT RuOxes are calibrated in a highly controlled environment and cannot be expected to perform exactly the same in a new environment, especially one with high radiation. In addition to purchasing a more sensitive SQUID-based temperature sensor, we will make sure to shield radiation appropriately during operation of the experiment.

4.4.3 Cold Snout Next Steps

To achieve lower temperatures at the ends of the cold fingers, there are a few aspects of the cold snout thermal paths we can improve. First, the conductances of the flexible thermal links (1 K braid, 20 mK braid, 4 K connection, 40 K connection) need to be tested in the DR; internal parts of the connection as well as interfaces should be tested independently (two-heater method can be used). If the results are lower than expected, the connections can be improved. For the internal parts of the braids, more strips can be added, widths of the strips can be increased, higher purity strips can be used, and different welding techniques can be explored. For the interfaces, the gold plating can be upgraded to a more rigorous

procedure, and clamping force can be adjusted with more screws, larger screws, or higher torque. Additionally, the endpiece of the flexible connection could be welded directly to the cold finger, eliminating the interface with the single screw.

After the flexible connections are no longer the bottleneck of the whole path's conductance, upgrades can be made in a few places along the 20 mK path. Firstly, the Vespel screws can be upgraded to Vespel SP-22 for a lower conductance and thus heat load. The 20 mK cold finger can be redesigned with a larger cross-sectional area or higher conductance; one idea is to anneal some inner part of the copper rod and place it inside a rigid un-annealed copper tube for mechanical support. Investigations should also be made into the potential issues from hydrogen content in copper.

For the 1 K path, the flexible connection can be bulked up and the clamping surfaces can be gold plated. The 1 K cold finger can be redesigned as well, optimizing the clamping area in the connection between the rod and the tube as well as increasing the cross-sectional area of the tube.

If the 4 K connection needs to supply more cooling power at 4 K, the Al strip connection may need to be replaced with higher purity Al, thicker strips or multiple layers.

Chapter 5

Conclusions

Even with the proliferation of dark matter detection experiments across the world, the dark matter parameter space remains largely unexplored. This thesis presented a pair of conceptually different but complementary searches, with the first aiming for a broad and model-independent approach and the second striving to be exquisitely sensitive to a specific model.

The first half of this thesis covered a method of searching for dark matter signatures using data from the Green Bank Radio Telescope, relying on the most basic and model-independent assumptions. This approach asks the most fundamental question: is there any signal which follows the expected phase space distribution of the galactic halo? Limits for annihilation and decay of potential dark matter to a quasimonochromatic radio line were presented over the L and S bands of the radio frequency spectrum. While these limits can be converted to limits on the axion-photon coupling constant, they are several orders of magnitude weaker than current constraints, so the immediate relevance of this approach is limited to different models. However, sensitivity could be improved in the future with more powerful instruments, such as the future Square Kilometer Array. Analysis of the C and X bands is ongoing, and will result in exclusion limits in the future.

The second half of this thesis concerned the DMRadio-50L search for the axion, focusing primarily on the cryogenic aspect of the experimental design. The DMRadio-50L experiment will come to fruition in the next year, leading us to advances in quantum sensing, cryogenic technologies, resonator design, and more. Being the first of its kind in many aspects, we have faced and will continue to face difficulties, particularly in the cryogenic engineering of the experimental setup; however, we are making rapid progress, and each iteration is teaching us valuable lessons. One of our immediate goals is finalizing the cryogenic system to allow the detector to reach temperatures below 50 mK. This may require further investigations of material properties at ultralow temperatures as well as experimentation with different setups. Still, with the cooldowns done so far, we have shown that we can confidently project success in reaching temperatures below 50 mK and ensuring an acceptable multistage cryogenic system for operation of the experiment. Immediate next steps for the experiment include performing a cooldown with both the DR and the 4 K cryostat, integration and testing of

the 1 K stage and magnet, finalizing the construction of the 20 mK stage, and testing the integrated data acquisition and analysis pipeline.

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Appendix A

Selected Heat Load Calculations

Radiation - 20 mK For all sources of radiation, we use the following equation (see eq. 22 and 23 of ref. [78]):

$$P_{s,rad} = \frac{\sigma A_s (T_s^4 - T_t^4)}{\epsilon_s^{-1} + \epsilon_t^{-1} - 1}, \quad (\text{A.1})$$

where σ is the Stefan-Boltzmann constant, T_s is the temperature of the source of radiation, T_t is the temperature of the target of radiation, A_s is the surface area of the source of radiation, and ϵ_s, ϵ_t are emissivities of the source and target material, respectively.

- 4 K sheath onto 20 mK wings and corset.

Note that these components have not yet been designed, so they have not been mentioned in the body of the thesis. This calculation is for the case where they are incorporated into the design. The dimensions of the aluminum wings and corset have not been set yet, but the “worst-case” scenario for loading assumes that the wings/corset and sheath have the same dimensions.

The sheath has dimensions inner radius $r_{I,sh} = 13.8 \text{ cm}$, outer radius $r_{O,sh} = 24.90 \text{ cm}$, and height $h_{sh} = 53.1 \text{ cm}$.

We assume that the niobium sheath possesses an emissivity of $\epsilon_{Nb} = 0.05$ and the aluminum wings possess an emissivity of $\epsilon_{Al} = 0.12$. (See ref. [79] and ref. 4 therein for niobium emissivity. See “Al as found” in Fig. 12 of ref. [78] for aluminum emissivity.)

Evaluating Eq. A.1 above for radiative heat load gives

$$P_{sh,rad} \approx 0.80 \text{ } \mu\text{W}.$$

Because the sheath is at 4 Kelvin, radiation load varies as the fourth power of temperature, and the sheath surface area/view factor is relatively large, its radiation onto the 20 mK stage will dominate the radiation budget. Nonetheless, the rest of the components are calculated to ensure that they are negligible.

- 1 K superconducting shield onto wings and corset.

The dimensions of the 1 K superconducting shield are: inner radius $r_{i,sc} = 33 \text{ cm}$, and height $h_{sc} = 66 \text{ cm}$, giving a surface area of $A_{sc} = 2 \text{ m}^2$.

We use $\epsilon_{Al} = 0.12$ for both the 1 K superconducting shield and the wings/corset. Evaluating gives

$$P_{sc,rad} \approx 7 \times 10^{-9} \text{ W} = 0.007 \mu\text{W}.$$

- 1 K superconducting shield onto inductor frame.

Since the 1 K superconducting shield will only radiate onto the top and bottom of the inductor frame, this area is much smaller than the wings and corset and therefore

$$P_{sc,rad} < .01 \mu\text{W}.$$

- 1 K cold finger onto 20 mK cold finger.

The dimensions of the 1 K cold finger tube are: inner radius $r_{i,cf} = 1.5 \text{ cm}$, and length $l_{cf} = 66 \text{ cm}$, giving a surface area of $A_{cf} = .06 \text{ m}^2$.

Using an emissivity of $\epsilon_{Cu} = 0.015$ from Tab. 5.1 of [80]. Evaluating gives

$$P_{CF,rad} \approx 2.5 * 10^{-11} \text{ W} = 2.5 * 10^{-5} \mu\text{W}.$$

- 4 K space onto 20 mK braid in Woodstock.

We assume the surface radiating onto the braid from 4 K is the same as the surface of the braid. Simplifying the braid shape to a rectangle with length $l_{br} = 10 \text{ cm}$ and perimeter $P_{br} = 6 \text{ cm}$, we get a surface area of $A_{br} = .006 \text{ m}^2$. Evaluating gives

$$P_{br,rad} \approx 1.2 * 10^{-9} \text{ W} = 1.2 * 10^{-3} \mu\text{W}.$$

Conduction - 20 mK For all conductive sources, we use

$$P = \int \frac{A}{l} \kappa dT = \int G dT,$$

where κ is the conductivity of the material, $G = \kappa \frac{A}{l}$ is thermal conductance, A is the cross section across which the heat is flowing, and l is the length down which the heat is flowing.

- 20 mK plate supports from 1 K plate.

We assume that the 20 mK plate is supported from the 1 K plate by struts made out of 12 poco graphite rods. For each rod, the diameter is 2 mm ($A_{pg} = 3.14 * 10^{-6} \text{ m}^2$) and the length is 40 mm . For the thermal conductivity, we use the pessimistic value of $.7 \text{ mW} / \text{m}$ integrated from 1.4 to .3 K from Tab. 3 of [81]. The best fit expression

given is integrated between .02 K and 1 K gives a value of .7 mW / m, but we stick with the pessimistic value since it is evaluated over the range of measurement. Then for 1 rod

$$P_{pg} = \frac{3.14 * 10^{-6}}{.04} m * 1.44 \frac{mW}{m} = .11 \mu W,$$

and for 12 rods,

$$P_{pg} = 1.32 \mu W.$$

- Inductor centering puck.

The z-coordinate of the inductor/corset will be fixed by the “pogo stick” that thermalizes the inductor frame. The x,y-coordinates of the inductor/corset will be set by a Kevlar puck supported from the sheath. We compute the conductive load between 4 K and 20 mK from the 8 Kevlar strings.

From [82], we have an expression for the conductivity of Kevlar:

$$\kappa_k(T) = 3.9 * 10^{-5} T^{1.71} \frac{W}{cmK}.$$

We are using Kevlar thread with diameter $D_k = .36 \text{ mm}$ and a distance between capstans of $L_k = 150 \text{ mm}$. Then we evaluate for 1 string:

$$P_{1k} = \frac{.001 \text{ cm}^2}{15 \text{ cm}} \int_{.02}^4 3.9 * 10^{-5} T^{1.71} dT \frac{W}{cm} = .04 \mu W.$$

For 8 strings, we get a total of

$$P_k = .32 \mu W$$

- Vespel screws in cold snout.

The conductivity of Vespel-SP1 is taken from [70] (p71):

$$\kappa_v = 18 * 10^{-3} * T^{1.2} \frac{mW}{cmK}.$$

We are using Vespel screws with diameter $D_v = 2 \text{ mm}$ and length $L_v = 5 \text{ mm}$. Then we evaluate for 1 screw:

$$P_{1v} = \frac{.0314 \text{ cm}^2}{.5 \text{ cm}} \int_{.02}^1 18 * 10^{-3} T^{1.2} dT \frac{mW}{cm} = .5 \mu W,$$

so for 4 screws,

$$P_v = 2 \mu W.$$

- DC wiring.

DC wiring includes wiring for SQUIDS and thermometry. We will be using NbTi wires with a diameter of $D_{NbTi} = 0.005 \text{ in}$ and length $L_{NbTi} \approx 25 \text{ cm}$ for both SQUIDS and thermometry.

From [70] (p71 Tab. 3.2) we have the conductivity over .1 - 1 K of NbTi:

$$k_{NbTi} = .2 T^2 \frac{mW}{cmK}$$

Then for 1 wire:

$$P_{1NbTi} = \frac{1.3 * 10^{-4} \text{ cm}^2}{25 \text{ cm}} \int_{.02}^1 .2 T^2 dT \frac{mW}{cm} = 3.5 * 10^{-4} \mu W.$$

Assuming a generous number of wires (100), this will be a total heat load of

$$P_{NbTi} = .035 \mu W.$$

- RF wiring.

We can use NbTi coax wiring for the RQUs. Since we do not yet know the dimensions of these wires and the material is the same, we can assume the heat load will be comparable to that of the DC wiring, i.e. $P_{NbTi} = .035 \mu W$

Radiation - 1 K Again, we use the following equation:

$$P_{s,rad} = \frac{\sigma A_s (T_s^4 - T_t^4)}{\epsilon_s^{-1} + \epsilon_t^{-1} - 1}, \quad (\text{A.2})$$

where σ is the Stefan-Boltzmann constant, T_s is the temperature of the source of radiation, T_t is the temperature of the target of radiation, A_s is the surface area of the source of radiation, and ϵ_s, ϵ_t are emissivities of the source and target material, respectively.

- 4 K sheath onto 1 K superconducting shield.

Again, we assume the worst case scenario of all the radiation from the 4 K sheath hitting the 1 K superconducting shield.

The sheath has dimensions inner radius $r_{I,sh} = 13.8 \text{ cm}$, outer radius $r_{O,sh} = 24.90 \text{ cm}$, and height $h_{sh} = 53.1 \text{ cm}$.

We use $\epsilon_{Nb} = 0.05$ for the sheath and $\epsilon_{Al} = 0.12$ for the 1 K superconducting shield.

Evaluating Eq.A.2 above for radiative heat load gives

$$P_{sh,rad} = 0.80 \mu W.$$

- 4 K shield onto 1 K superconducting shield.

The 4 K shield has dimensions inner radius $r_{I,sh} = 40 \text{ cm}$ and height $h_{sh} = 83 \text{ cm}$, giving a surface area of $A_{sh} = 2.6 \text{ m}^2$. Using $\epsilon_{Al} = 0.12$ for both shields, we get

$$P_{sh,rad} = 2.4 \text{ } \mu W.$$

- 4 K shield onto 1 K cold finger.

The 4 K shield in the cold snout has dimensions inner radius $r_{I,sh} = 2.3 \text{ cm}$ and length $l_{sh} = 38 \text{ cm}$, giving a surface area of $A_{sh} = .055 \text{ m}^2$. Using $\epsilon_{Al} = 0.12$ for the shield and $\epsilon_{Cu} = 0.015$ for the cold finger, we get

$$P_{sh,rad} = .01 \text{ } \mu W.$$

- Cryoperm onto 1K superconducting shield and plate.

The cryoperm has area $A_{cr} = .26 \text{ m}^2$ and a height of $h_{cr} = 26 \text{ cm}$. Using $\epsilon = 1$, we get

$$P_{cr,1K} = 3.8 \text{ } \mu W.$$

Conduction - 1 K For all conductive sources, we again use

$$P = \int \frac{A}{l} \kappa dT = \int G dT,$$

where κ is the conductivity of the material, $G = \kappa \frac{A}{l}$ is thermal conductance, A is the cross section across which the heat is flowing, and l is the length down which the heat is flowing.

- 1 K supports from 4 K.

The supports are made from G-10 and have an area of $A_{1Ksup} = 8 \times 10^{-4} \text{ m}^2$ and a length of $L_{1Ksup} = .223 \text{ m}$ each. From Tab. 3 of [81], we have that for G-10,

$$\int_{1.4}^{4.2} \kappa dT = 126 \text{ mW/m},$$

so

$$P_{1Ksup} = .4 \text{ mW},$$

and for four of them,

$$P_{1Ksupports} = 1.6 \text{ mW},$$

- Cold snout puck.

The Kevlar thread used for the cold snout puck has a diameter of $.36\text{ mm}$, the distance between capstans is 2 cm , and there are 12 strings between capstans total. From [82], we have that for Kevlar,

$$\kappa(T) = 3.9 \times 10^{-5} T^{1.71} \text{ W/cm} \cdot K,$$

so for 12 strings,

$$P_{puck} = 3.7 \text{ } \mu W.$$

Appendix B

Thermal Contraction Calculations

For all the following calculations, we use the equation for linear contraction:

$$\Delta L = \alpha L_0 \Delta T$$

where α is the linear expansion coefficient of the material and L_0 is the length at room temperature. We will use the integrated α value from 293 K to 4 K for all cases as this range is representative of where the bulk of the contraction happens. Integrated α values are taken from [72].

The components of Snoopy considered (not including the cold fingers) are labeled in the Fig. B.1.

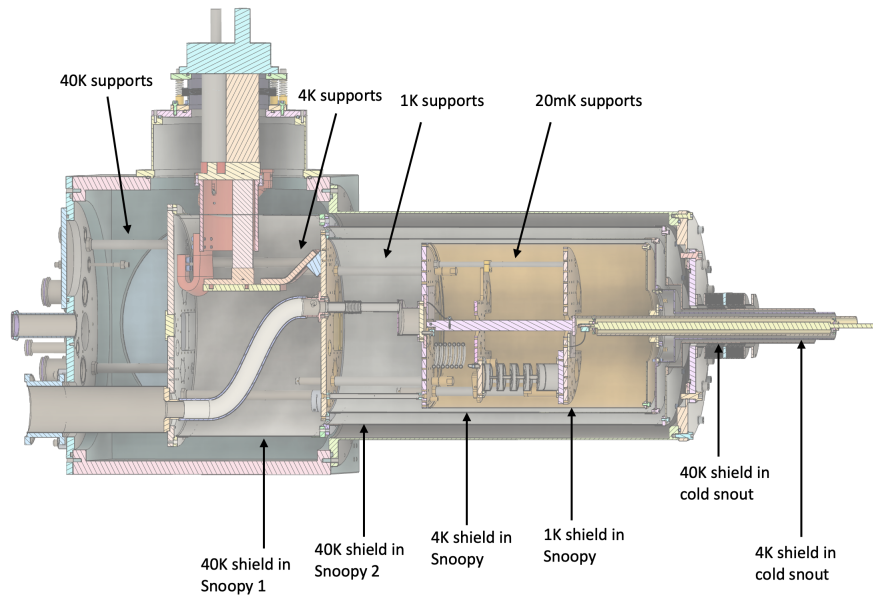


Figure B.1: Diagram of components considered for thermal contraction calculations.

40 K

The calculations of 40 K contraction are based on the simplified model shown in Fig. B.2.

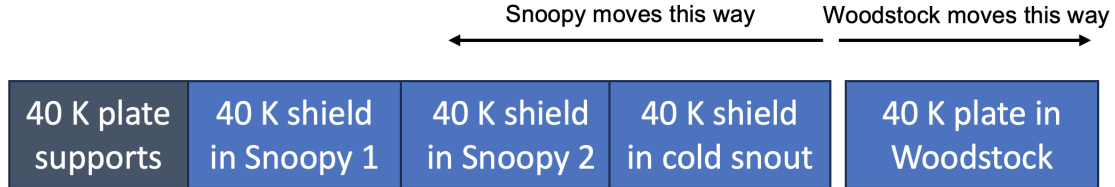


Figure B.2: Simplified model for 40 K contraction calculations. Snoopy components are on the left and Woodstock components are on the right.

	40 K plate supports	40 K shield in Snoopy 1	40 K shield in Snoopy 2	40 K shield in cold snout	40 K plate in Woodstock
Material	Steel	Al	Al	Al	Al
α int. [10^{-3}]	2.97	4.14	4.14	4.14	4.14
L_0 [cm]	17.6	27.7	64.1	27.8	46.5 (radius)
ΔL [cm]	.05	.11	.27	.12	.19

Table B.1: Materials and values used for the calculation of 40 K thermal contraction.

$\Delta L_{\text{Snoopy}} = .55 \text{ cm}$	$\Delta L_{\text{Woodstock}} = .19 \text{ cm}$	$\Delta L_{\text{Total}} = .74 \text{ cm}$
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Table B.2: 40 K thermal contraction values.

4 K

The calculations of 4 K contraction are based on the simplified model shown in Fig. B.3.

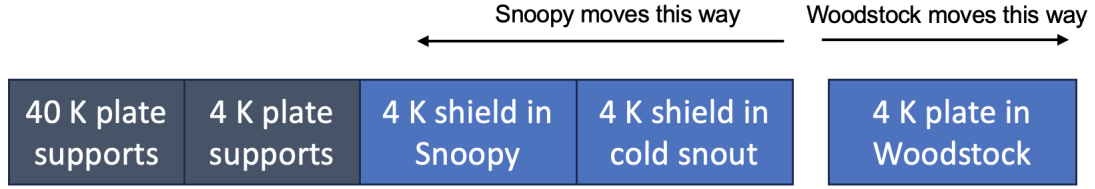


Figure B.3: Simplified model for 4 K contraction calculations. Snoopy components are on the left and Woodstock components are on the right.

	40 K plate supports	4 K plate supports	4 K shield in Snoopy	4 K shield in cold snout	4 K plate in Woodstock
Material	Steel	Steel	Al	Al	Al
α int. [10^{-3}]	2.97	2.97	4.14	4.14	4.14
L_0 [cm]	17.6	29	62.2	33.6	40 (radius)
ΔL [cm]	.05	.09	.26	.14	.17

Table B.3: Materials and values used for the calculation of 4 K thermal contraction.

$\Delta L_{\text{Snoopy}} = .54 \text{ cm}$	$\Delta L_{\text{Woodstock}} = .17 \text{ cm}$	$\Delta L_{\text{Total}} = .71 \text{ cm}$
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Table B.4: 4 K thermal contraction values.

1 K

The calculations of 1 K contraction are based on the simplified model shown in Fig. B.4.



Figure B.4: Simplified model for 1 K contraction calculations. Snoopy components are on the left and Woodstock components are on the right.

	40 K plate supports	4 K plate supports	1 K plate supports	1 K cold finger	1 K plate in Woodstock
Material	Steel	Steel	Steel	Copper	Al
α int. [10^{-3}]	2.97	2.97	2.97	3.26	4.14
L_0 [cm]	17.6	29	18.9	82	33 (radius)
ΔL [cm]	.05	.09	.06	.27	.14

Table B.5: Materials and values used for the calculation of 1 K thermal contraction.

$\Delta L_{\text{Snoopy}} = .47 \text{ cm}$	$\Delta L_{\text{Woodstock}} = .14 \text{ cm}$	$\Delta L_{\text{Total}} = .61 \text{ cm}$
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Table B.6: 1 K thermal contraction values.

20 mK

The calculations of 20 mK contraction are based on the simplified model shown in Fig. B.5.

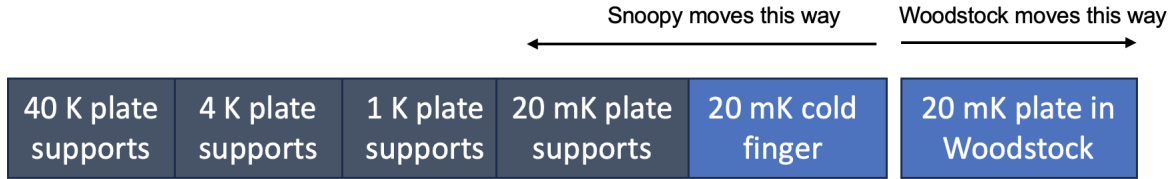


Figure B.5: Simplified model for 20 mK contraction calculations. Snoopy components are on the left and Woodstock components are on the right.

	40 K plate supp.	4 K plate supp.	1 K plate supp.	MXC supports	20 mK cold finger	20 mK plate in Woodstock
Material	Steel	Steel	Steel	Steel	Copper	Copper
α int. [10^{-3}]	2.97	2.97	2.97	2.97	3.26	3.26
L_0 [cm]	17.6	29	18.9	26.6	60	17.5 (radius)
ΔL [cm]	.05	.09	.06	.08	.2	.06

Table B.7: Materials and values used for the calculation of 20 mK thermal contraction.

$\Delta L_{\text{Snoopy}} = .48 \text{ cm}$	$\Delta L_{\text{Woodstock}} = .06 \text{ cm}$	$\Delta L_{\text{Total}} = .54 \text{ cm}$
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Table B.8: 20 mK thermal contraction values.

Appendix C

Cold Snout Assembly Procedure - Cooldown 3

List of components for Cold Snout Assembly

- Instrumentation: heaters, thermometers, bobbins, wiring
- 20 mK components:
 - 20 mK cold finger
 - Vbar
 - Thermal braid
 - Adapter plate
- 1 K components:
 - 1 K tube
 - 1 K rod
 - Tbar
 - Snoopy 1 K shield
 - Custom 1 K can bottom
- 4 K components:
 - Snoopy 4 K shield
 - Custom 4 K can bottom with puck attached
 - Cold snout 4 K shield
 - 4 K testing shield flange
 - 4 K testing endcap

- 40 K components:
 - Snoopy 40 K shield
 - Custom 40 K can bottom
 - Cold snout 40 K shield
 - 40 K testing shield flange
 - 40 K testing endcap
- Vacuum components:
 - Snoopy can with ISO200 hole
 - Two o-rings
 - Vacuum nipple
 - End flange
 - Pulley system

Puck assembly

1. Clean the puck parts and jig and put on fresh gloves.
2. Place the puck parts into the jig with the clamp facing up.
3. Screw outer ring into jig with 4 Al M4 x 8 mm screws.
4. Screw inner ring into jig with 4 Al M3 x 12 mm screws.
5. Screw capstans into inner and outer rings with 12 brass M2 x 8 mm screws and M2 brass washers (one terminal capstan with the rounded nubs on the outer ring) - do not tighten screws all the way.
6. Tie a knot on the terminal capstan, wind the puck, then tie another knot at the terminal capstan, making sure that the terminal capstan will tighten the wound string when the screw is tightened. Specifically, both ends of the Kevlar should enter the terminal capstan clockwise.
7. Rotate the terminal capstan with the puck wrench to tighten the Kevlar, making sure the other capstans are freely rotating.

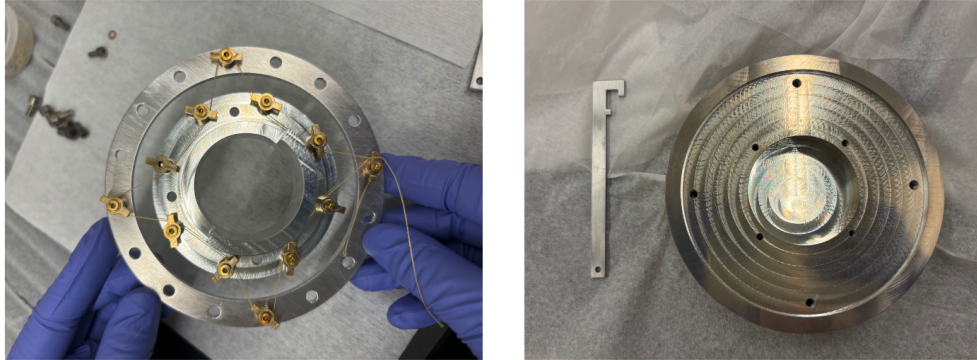


Figure C.1: *Left:* Puck with wound Kevlar string. *Right:* Puck jig and puck wrench.

8. When the Kevlar is sufficiently tight, tighten the terminal capstan screw and then the rest of the capstan screws.
9. Leave overnight so the Kevlar adapts to its new position. Next day: put a dab of Stycast Epoxy on the overlapping point of each capstan and a dab on each knot on the terminal capstan. Leave overnight to dry.

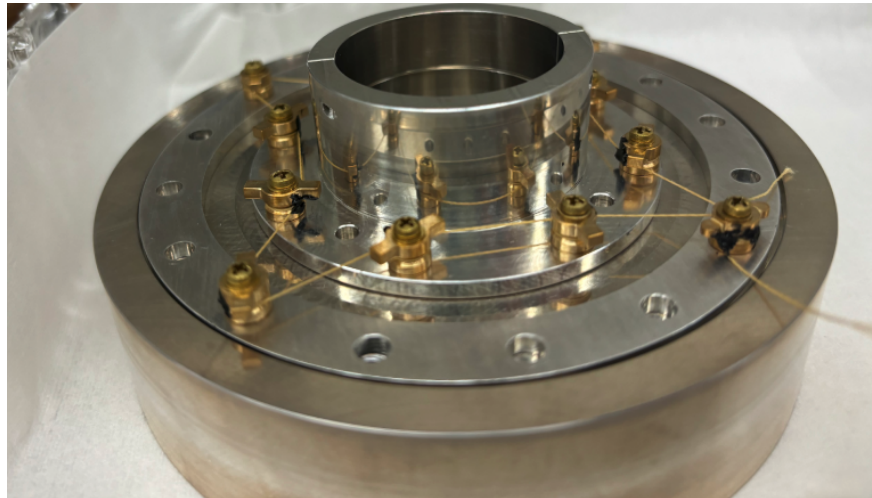


Figure C.2: Puck in jig with epoxy on Kevlar knots.

Cold Finger Assembly

1. Attach all instrumentation necessary (varnish heaters, screw thermometers). Tape wires along the cold fingers with Kapton tape, allowing some freedom for thermal contraction.

2. Slide 20 mK cold finger into 1 K cold finger tube with the end wrapped in clean wipes to avoid scratching and then slide assembly ring onto the end of the 20 mK cold finger.
3. Attach thermometer and heater mount to the end of the 20 mK cold finger.

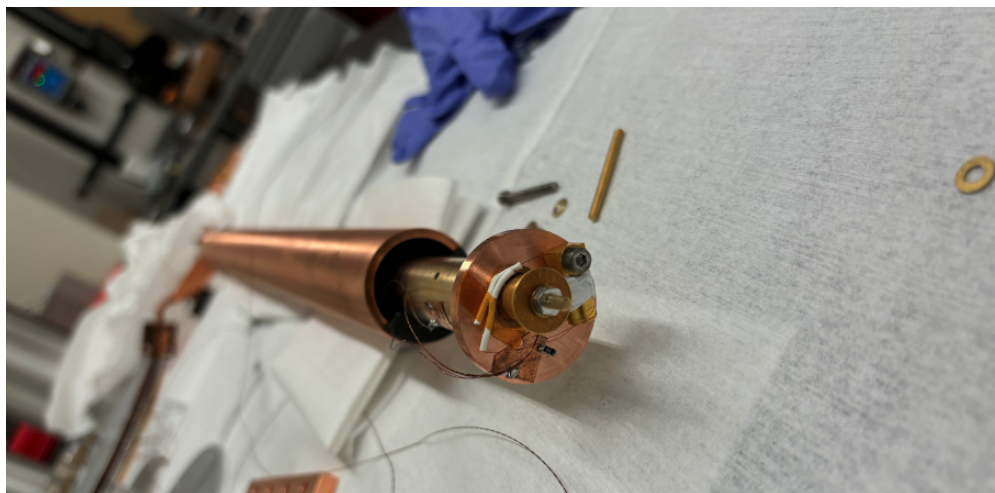


Figure C.3: 20 mK cold finger inside 1 K cold finger with thermometer and heater mount attached.

4. Attach v-bar to 20 mK cold finger with 1 Al M5 x 16 mm screw.
5. Attach 1 K cold finger rod to 1 K cold finger tube with 4 Al M4 x 10 mm screws.
6. Insert second assembly ring into the space between the 1 K cold finger rod and the v-bar.



Figure C.4: V-bar attached to the 20 mK cold finger. Note that in this photo, the Vespel screws are already inserted; this was done before the assembly ring method was adopted.

7. Attach thermal braid to vbar with 2 SS #10 x $\frac{1}{2}$ " screws and nuts.

Full Assembly

1. Attach T-bar to still plate with 4 Al #3 x 45 mm threaded rods with SS nuts and 1 Al #10 x 45 mm threaded rod with SS nuts. Lift the T-bar slightly so that it is not resting on the threads and tighten the nuts.

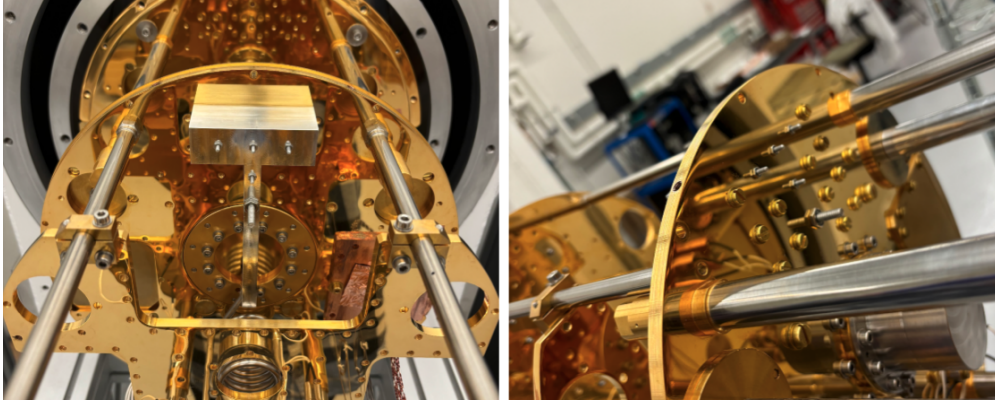


Figure C.5: T-bar attached to the still plate from the front (left) and back (right).

2. Attach hinge rest to MXC plate with 3 Al M3 x 20 mm screws and Al nuts and attach adapter plate to MXC with 10 Al M3 x 20 mm screws and Al nuts.

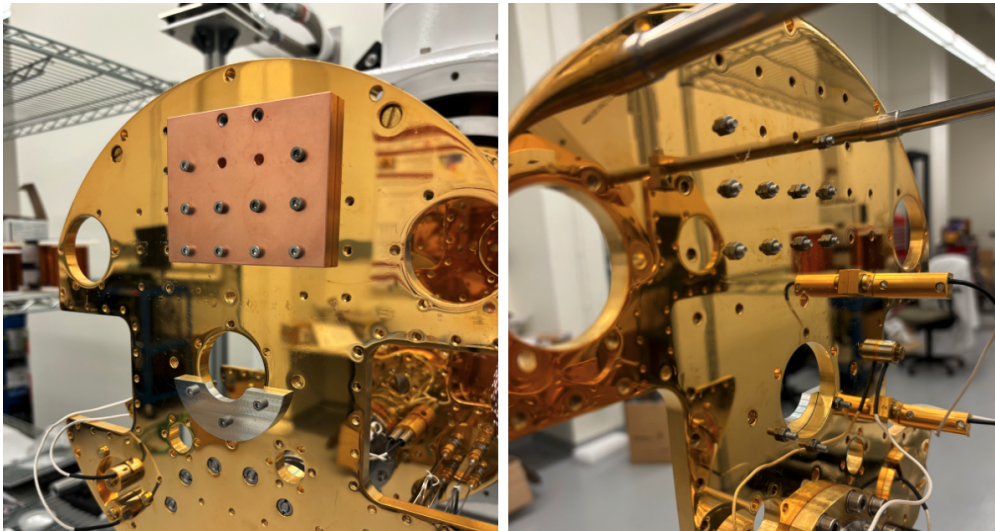


Figure C.6: Adapter plate and hinge rest attached to the MXC plate from the front (left) and back (right).

3. Slide cold finger assembly through the plate holes and screw hinge onto T-bar with 1 Al M4 x 20 mm screw and nut. Rest the cold finger assembly on ladder with clean wipes underneath or on the hinge rest.

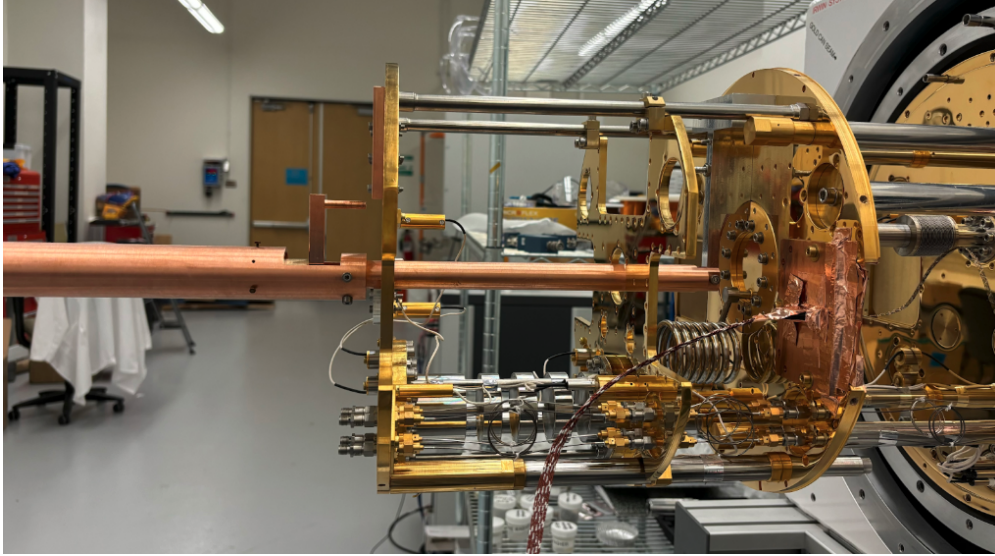


Figure C.7: Cold fingers inserted into place and attached to hinge. Note that the 20 mK braid is missing in this photo; it should be attached before this step.

4. Attach thermal straps and thermal strap clamp to 1 K cold finger with 4 Al M4 x 20 mm screws and attach the other ends to the still plate using existing M6 screws.

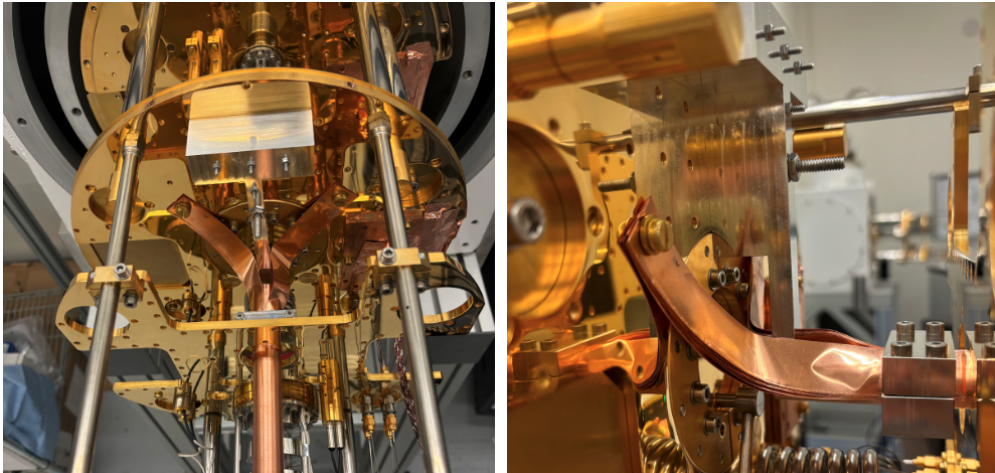


Figure C.8: Thermal straps clamped to still and 1 K cold finger from the top (left) and side (right).

5. Attach thermal braid to adapter plate with 2 SS #10 x $\frac{1}{2}$ " screws and nuts.

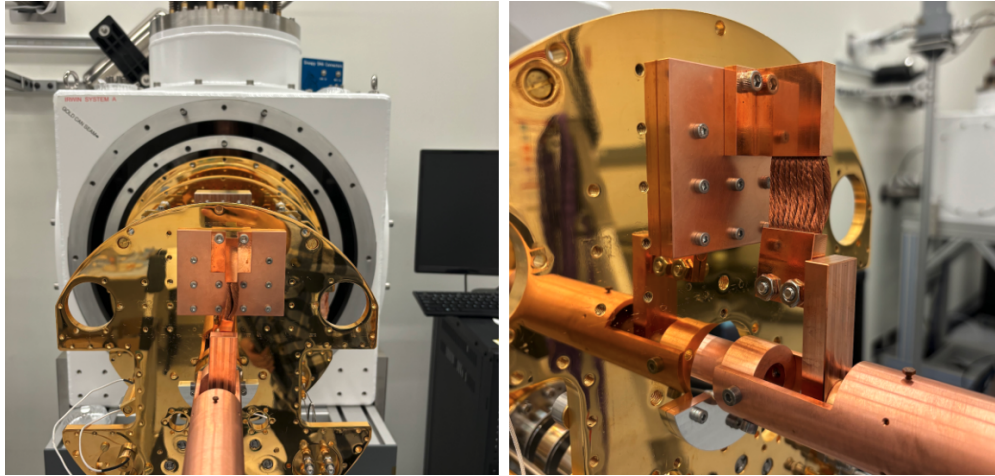


Figure C.9: Thermal braid attached to adapter plate on MXC and v-bar from the front (left) and side (right).

6. Attach 1 K can, making sure that it does not bump anything (two people are recommended for this).
7. Attach 4 K and 40 K cans similarly.

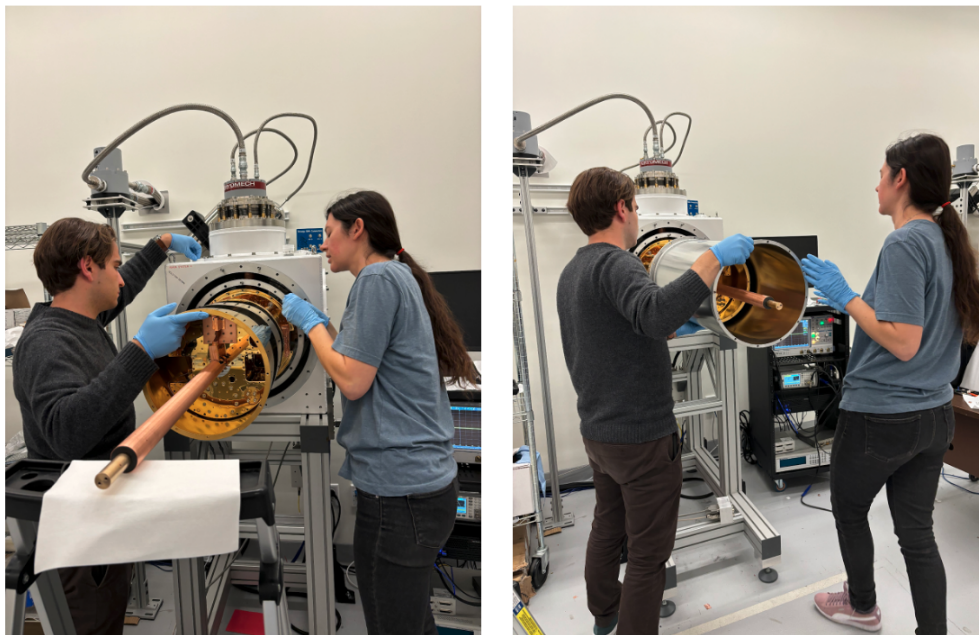


Figure C.10: Attachment of the 1 K can (left) and 4 K can (right) by Maria Simanovskaia and Nicholas Rapidis.

8. Slide 1 K can bottom and 4 K can bottom with puck attached by 12 Al M4 x 8 mm screws onto the cold fingers with a clean wipe and rest it on the clean wipe.

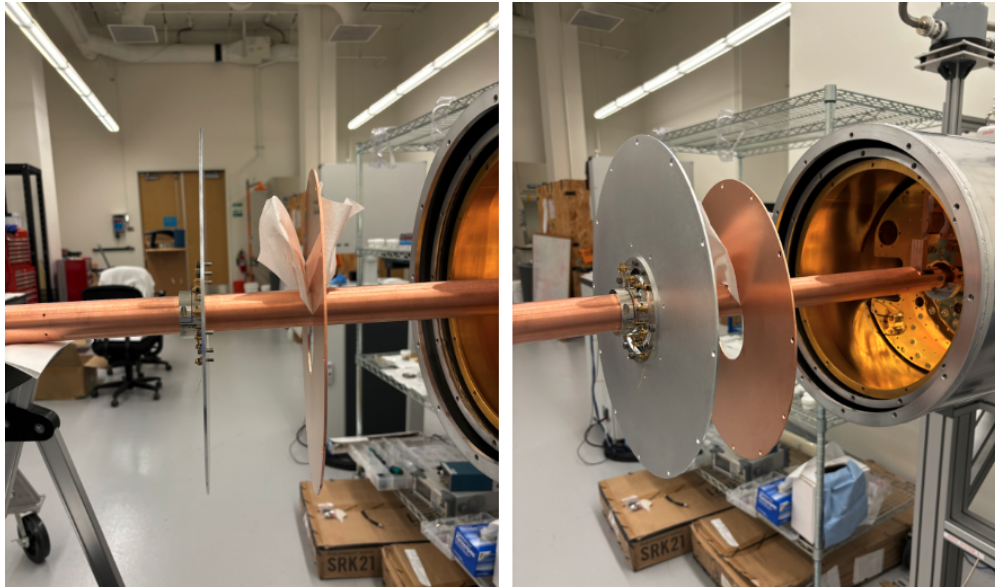


Figure C.11: 1 K and 4 K can bottoms resting on the cold fingers.

9. Adjust height of ladder to fix the alignment of the cold fingers so that 4 K can bottom can be screwed into 4 K can and screw in all screws to make sure alignment is perfect.
10. Unscrew 4 K can bottom and move it along with the 1 K can bottom back to the middle of the cold fingers
11. Replace 3D printed alignment piece closest to the fridge with vespel screws.
12. Screw in 1 K can bottom and then 4 K can bottom with existing screws.
13. Clamp puck onto 1 K cold finger with 2 brass M2 x 12 mm screws.
14. Attach 4 K shield onto 4 K can bottom with 8 Al M4 x 8 mm screws.
15. Attach 40 K can bottom onto 40 K can with 8 Al M4 x 8 mm screws.
16. Attach 40 K shield onto 40 K can bottom with 8 Al M4 x 8 mm screws.
17. Replace 3D printed alignment piece on the end of the cold finger with vespel screws



Figure C.12: Sliding the alignment piece out of the cold fingers after inserting Vespel screws. 4 K and 40 K shields are already attached.

18. Attach 40 K test flange with 8 Al M4 x 8 mm screws and 6-7 washers each.
19. Attach 4 K test flange with 8 Al M4 x 8 mm screws and 6-7 washers each.
20. Cover any seams with Al tape.

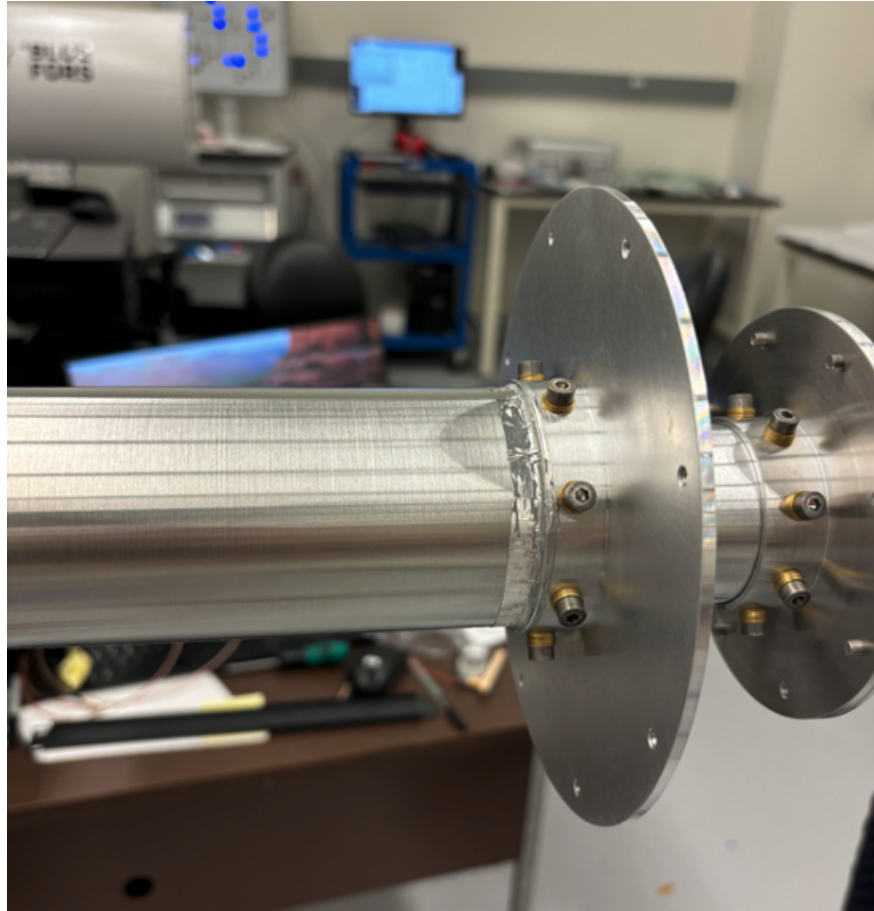


Figure C.13: 4 K and 40 K test flanges attached and seams covered with Al tape.

21. Attach 4 K test shield to 4 K test flange with 8 Al M4 x 8 mm screws.
22. Attach 40 K test shield to 40 K test flange with 8 Al M4 x 8 mm screws.

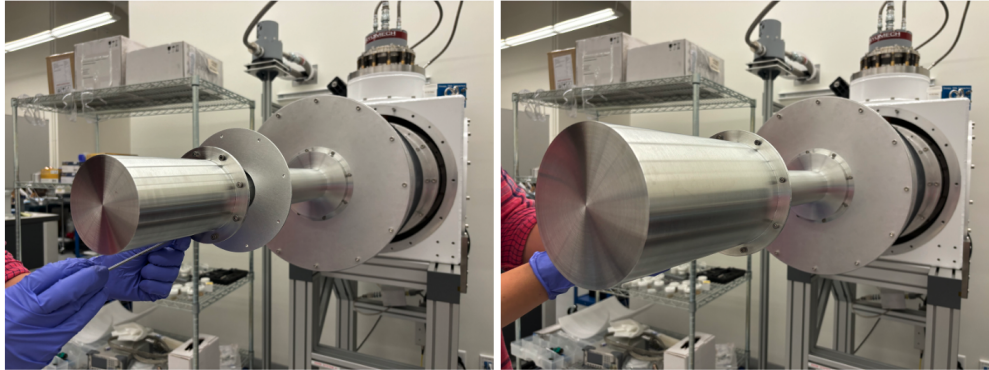


Figure C.14: 4 K testing endcap (left) and 40 K testing endcap (right) Attached to respective test flanges.

23. Attach Snoopy vacuum can (tighten screws in star pattern) and bring pulley system with sling over so that the sling is directly above the cold snout.
24. Attach vacuum nipple (tighten screws in star pattern), attach weight to the other side of pulley, and rest vacuum nipple in the sling.



Figure C.15: Vacuum nipple attached to Snoopy and resting in sling of pulley system.

Cold snout assembly now completed, cooldown procedure can begin.