August 22, 2015

FINAL REPORT FOR THE ADMX PHASE 2a PROJECT AT THE UNIVERSITY OF WASHINGTON DE-SC0000007068

Institution:	The University of Washington 4333 Brooklyn Ave NE Box 359472 Seattle WA 98195-9472
Principal Investigator:	Leslie J Rosenberg Department of Physics University of Washington Box 351560 Seattle WA 98195-1560 Phone 206 221-5856 email ljrosenberg@phys.washington.edu
Administrative point of contact:	Laurie Salehi Phone 206 543-4043 email salehil@u.washington.edu
DOE/Office of Science Program Office:	Office of High Energy Physics
DOE/Office of Science Program Office Technical Contact:	Michael Salamon Phone 301 903-5106 email michael.salamon@science.doe.gov

1 Project Overview

A light axion is a well-motivated dark-matter candidate. It has long been known that axions constituting the dark matter of our own Milky Way galactic halo may be stimulated to convert into a narrow-band microwave photon signal by an apparatus consisting of a microwave-cavity resonator permeated by a static magnetic field.

Our Axion Dark Matter eXperiment (ADMX) Collaboration has successfully developed this technology since the mid-1990's. Notably, our series of detectors achieved sensitivity to one of two important axion benchmark models (KSVZ). Because the sensitivity of RF cavity axion searches improves dramatically as the system noise temperature (the sum of cavity physical temperature and amplifier electronic noise) decreases, our collaboration embarked on development of broadband high-gain, ultra-low noise dc Superconducting QUantum Interference Device (SQUID) microwave amplifiers. With these, ADMX has developed by far the world's most sensitive spectral receiver of microwave radiation, thereby enabling these ultra-sensitive axion searches.

The Phase 2a ADMX is based on this SQUID technology and, when cooled with the Gen 2 dilution refrigerator (in commissioning), has sensitivity to allow detection of the more weakly-coupled but very compelling "DFSZ" axions even if they constitute a minority fraction of our local halo density. A search at this sensitivity is called a "definitive experiment," able to detect or reject the specific QCD-axion dark matter hypothesis with high confidence.

Our three-step ADMX ("Phase I", "Phase 2a", "Gen 2") upgrade path to the definitive experiment is as follows:

(Phase I) The original ("Phase I") ADMX [1, 2] was retrofitted to operate with SQUID amplifiers in place of the HFET transistor amplifiers; this is the Phase I ADMX. Results from this experiment, which operated from 2008–2010, have been published. [3–5] This experiment was sensitive to plausible dark-matter axions and established the feasibility of a large-scale RF-cavity axion search.

(Phase 2a) This is the final report for Phase 2a of ADMX. In 2011 we began the Phase 2a ADMX upgrade, featuring a redesign of the experiment insert to allow dilution-refrigerator cooling and reliquefaction of helium. Although the experiment is designed for dilution-refrigerator cooling, Phase 2a ADMX was also designed to be cooled instead with pumped ^{3}He. The pumped ^{3}He system can be deployed if problems develop with the more complicated dilution-refrigerator system. The pumped ^{3}He system also allows for the study of the experiment thermal environment Also importantly, the Phase 2a upgrade instruments the next higher-order TM mode, which effectively more than doubles the scan rate and extends the ADMX program to higher axion mass. Phase 2a data-taking started in the fall of 2013. Site operations ended in 2014 and data analysis continued into 2015. This phase of ADMX was incrementally yet more sensitive, and demonstrated the feasibility of operating SQUIDs in the very large magnetic field of ADMX. More details follow in this report.

(Gen 2) We are currently commissioning the Gen 2 ADMX upgrade. This upgrade phase is mainly directed to the procurement, installation and commissioning of a high flow-rate dilution refrigerator to cool the cavity and SQUID amplifiers. This completes the construction and operation of the "definitive experiment" to search for QCD dark-matter axions.

This phased-upgrade path has been consistently and strongly endorsed by the physics community over many years, from SAGENAP review panels through the more recent HEPAP reviews, Dark-SAG reviews and PA-SAG studies. These unanimous panel endorsements reiterate that scientific importance of the ADMX upgrade: It will have the ability to explore nearly the entire space of QCD dark-matter axion models over a broad range of axion masses. Starkly, this experiment has the sensitivity and mass-reach either to detect the specific QCD dark-matter axion or reject

the hypothesis with high confidence. Indeed, PA-SAG, made the unusual and strong recommendation that the ADMX upgrade be supported in all DOE funding scenarios, even draconian ones, considering ADMX a unique, cost-effective, high priority project.

Opportunities for DOE-HEP science over the next decade were evaluated by the 2013 Snowmass planning process. The Cosmic Frontier report (CF3) concluded: [6]

> "Some candidates are perceived as more motivated than others. For example, the axion has the advantage of being a natural solution to the strong CP problem. Furthermore, for a dark-matter candidate, the QCD axion is special in that it has a fairly well bounded parameter space. The axion-photon couplings $g_{a\gamma\gamma}$ over the range of benchmark models extend over an order of magnitude. The upper end of the QCD axion mass range is set at a few milli-eV by the limit from SN1987A (though there might be ways to evade this), the lower end, limited by the "misalignment" cosmological bound, is set at around a μeV (though, as discussed above, there are ways to evade this bound). The most promising approach to detecting the QCD axion is with the RF-cavity technique. Although the expected conversion into RF power within the cavity is extraordinarily weak, experiments will shortly start taking data for a definitive search. By "definitive", we mean one that will either find the axion with high confidence, if it exists, or if not, exclude it at high confidence. These experiments will sensitively explore the first two decades of allowed QCD axion mass where the dark-matter QCD axion is expected to be. Starkly, these searches have large discovery potential."

Following Snowmass 2013, the Particle Physics Project Prioritization Panel (P5) recommended a strategic plan for U.S. particle physics. The conclusions include: [7]

> The axion is another well-motivated candidate for the dark matter. Its existence would confirm a long-standing hypothesis that an additional symmetry in Nature is the reason that CP-violating terms are small in the strong interaction, and it also has the required properties to be the dark matter. The upcoming ADMX experiment is projected to be sensitive to axion masses up to 40 μeV. With continuing R&D, future experiments should probe higher masses, within the allowed range available within astrophysical constraints.

ADMX was featured in Science Magazine. [8] They remarked:

> "In the age of the 27-kilometer-long atom smasher and the 50,000-tonne underground particle detector, the Axion Dark Matter Experiment (ADMX) hardly looks grand enough to make a major discovery. A modest 4-meter-long metal cylinder, it dangles from a wall here at the University of Washington's Center for Experimental Nuclear Physics and Astrophysics, as shiny and inscrutable as a tuna hung up for display. A handful of physicists tinker with the device, which they are preparing to lower into a silolike hole in the floor. The lab itself, halfway down a bluff on the edge of campus, is far from the bustle of the university. Yet ADMX researchers will soon perform one of the more important and promising experiments in particle physics."

The goal of ADMX is to deploy a search with enough sensitivity to detect the more compelling DFSZ axions, even should they constitute only half our local halo's CDM density. This program, including targeted R&D, would access 2/3 of the allowed logarithmic axion-mass region, and, with better than DFSZ sensitivity, has a serious prospect for a discovery.

2 Scientific Context

2.1 Dark Matter

During the past decade, cosmology has evolved into a precision science. Most cosmological parameters are known to within a few percent, thereby establishing the so-called 'concordance cosmology'. The composition of the overall energy density of the universe is around 75% dark energy and 25% matter. Because the overall baryon contribution is considerably smaller, it follows there's a substantial non-baryonic dark-matter component. Further, this new and unknown form of matter must be collisionless (only gravitational interactions) and cold (slow-moving at decoupling in the early universe).

Spiral galaxies rotate faster than their luminous-derived Keplerian velocities out to their largest visible radii, implying their luminous disks are embedded in extended halos of unseen matter. Cold, collisionless dark matter particles naturally form such halos as CDM becomes gravitationally bound as the galactic potential well deepens during infall.

That substantial CDM exists in galactic halos seems a robust conclusion. However, the standard model of elementary particles does not by itself provide a CDM candidate. The nearest standard-model candidates are relativistic eV-mass neutrinos. However, there are compelling arguments against this proposition based on limits to the neutrino occupation in halos, erasure of structure by relativistic streaming, and mass inferences from flavor mixing and direct measurements.

Beyond the standard model, two leading cold dark matter candidates are the axion and a weakly interacting massive particle (WIMP). Both these highly compelling candidates were originally postulated as solutions to problems in particle physics, independent of the dark-matter problem. The axion provides an elegant solution to the 'strong CP problem,' whereas WIMP dark matter arises in supersymmetric extensions of the Standard Model.

There are contested claims that a WIMP has been detected. For instance, the DAMA-LIBRA group continues to claim an annual modulation WIMP signal, but no such signal is, *e.g.,* seen in the XENON and CDMS/germanium detectors and more recently the LUX detector. Claims and counter-claims abound. This confusing situation highlights the power of ADMX: Should ADMX observe a candidate axion, ADMX would simply average longer at that candidate frequency (and ADMX can average for a very long time, indeed), thereby either detecting the axion or excluding it at very high confidence. Hence, while WIMP searches are somewhat akin to magnetic monopole searches in that the follow-up to a very rare candidate event is another long enterprise, an ADMX observation more resembles the J/ψ discovery: if the machine energy could *a priori* be set to the J/ψ mass, a convincing discovery happens immediately; same for the ADMX cavity frequency. The discovery of axions in ADMX would be unambiguous.

The formation of our Milky Way galaxy is complicated. However, models of structure formation, particularly N-Body computer codes, provide considerable insight into this process. A simplified expected energy distribution of axions near Earth consists of a broad thermalized component containing axions that fell into the Milky Way a long time ago, plus narrower peaks containing axions that fell in more recently, including those falling in for the first time. The narrow peaks may each contain a few percent of the thermalized local halo density. Moreover, it's possible for one particular narrow peak to be much more prominent than the others if Earth happens to be close to a dark matter caustic. (Caustics are spatial over-densities of dark matter.) According to ref. [9, 10], this indeed seems to occur near Earth. In that case, the local narrow-line density by itself could be nearly as large as the entire local thermalized halo density. And in general, N-Body computer codes suggest the Milky Way's has a rich fine structure of dark matter. The ADMX detector is sensitive to all these axion structure scenarios, and indeed it may be the case that the dark matter

axion fine structure considerably increases the ADMX discovery potential.

3 Cavity Search Technique

Axions in our galactic halo were created in the early universe as an evolving dense Bose fluid (this, perhaps counter-intuitive, statement is now widely appreciated); for μeV masses, their local number density now is $\mathcal{O}(10^{14}/\mathrm{cm}^3)$. While axions travelled through our galaxy's potential well, they thermalized. The thermalized axion's virial velocity is now presumably around 270 km/sec, about that of normal matter, implying a broadening of its energy spectrum above its rest mass by $\Delta E/m_A \sim 10^6$. The very small momentum also implies a long de Broglie wavelength, around 100 m for a μeV axion. In 1983, Sikivie published an experiment concept by which these axions could be detected by a Primakoff interaction of axions and electromagnetic fields. [11] Specifically, because the axion has a two-photon coupling, like its cousin the π^0, it can be stimulated to decay into a single real photon carrying nearly the full axion energy on interacting with an external magnetic field. Furthermore, the interaction rate is enhanced when the interaction occurs within a high-Q microwave cavity tuned to the outgoing photon's frequency. Despite the prodigious local axion density, the expected electromagnetic power deposited in the a cavity nl mode is extraordinarily weak and is given by:

$$P_{nl} = (\frac{\alpha}{\pi} g_\gamma \frac{1}{f_a})^2 V B_0^2 \rho_a C_{nl} \frac{1}{m_a} Q_L$$

where B_0 and V are the strength and volume of the magnetic field, $Q_L \sim 10^5$ the loaded quality factor of the microwave cavity, and C_{nl} the form factor of the cavity for mode nl; this last parameter quantifies the overlap of the cavity mode E field with the applied B field. For ADMX hardware and assuming benchmark KSVZ axions saturate the local CDM, the converted-axion power is 5×10^{-23} Watts or less. The cavity must be tunable, because one does not know with precision *a priori* the axion mass. At each cavity tuning setting, the cavity's power spectrum is integrated long enough so noise averages sufficiently away, revealing the axion signal at a target signal-to-noise ratio (s/n). Up to where non-statistical processes intrude, the s/n is improved by having a stronger signal, reducing noise power, or integrating longer. In practice, the integration time at each tuning is limited by the need to explore a certain mass range within a fixed time. Hence, reducing noise power is therefore key to better s/n and a feasible axion search.

4 ADMX Program Goals

The goal of the ADMX project is to discover the QCD dark-matter axion. Thus, ADMX initially evolved from a small-cavity transistor-amplifier intrumentation study to a large-cavity configuration. This larger configuration demonstrated the feasibility of the technique in a production experiment and was the first axion search to be sensitive to realistic QCD dark-matter axions. Indeed, it was arguably the first direct dark-matter search to place meaningful limits on the axionic dark-matter density. [1,2] ADMX then incorporated SQUID amplifiers using pumped ^{4}He cooling. This demonstrated that SQUIDs could be successfully operated near the 8 tesla ADMX magnetic field. [3,4] ADMX Phase2a is an upgrade to allow pumped ^{3}He cooling and multi-mode readout. It also deployed the infrastructure for helium liquefaction and ^{3}He gas-handling. One of its technical goals is to retrofit the ADMX experiment insert to support the Gen 2 dilution-refrigerator, and demonstrate the data-acquisition system can control tuning in the dense mode structure at higher modes. The end result of the ADMX program is an experiment sensitive to even the more weakly-coupled, but compelling, DFSZ axion over a large fraction of its plausible mass range. As noted

earlier, starkly, this experiment has serious discovery potential. The final phase of ADMX, beyond the Gen 2 program, is to complete the search at the "definitive search" sensitivity over the final decade of the three plausible mass decades. This requires R&D on higher-frequency (and perhaps lower-frequency) resonant structures with properties appropriate to axion-to-photon conversion, plus R&D on the corresponding higher-frequency ultra-low noise receivers. In order for scanning to proceed rapidly, there's also R&D on electric replacements for the mechanical probe depth and tuning adjustments.

The ADMX Gen 2 project, currently undergoing commissioning, building on the ADMX Phase 2a project. Fig. 1 shows the ADMX Phase 2a insert being removed from the magnet bore in 2014 during ADMX Phase 2a data-taking operations.

5 Results from DOE-HEP Support

The overall scientific deliverable of the ADMX program is achieving DFSZ sensitivity (the lower end of the plausible axion couplings) over the lowest and next-lowest decade of the three-decade allowed axion-mass window.

5.1 Move Magnet to the University of Washington

An early task of the Phase 2a ADMX program was the move of the main ADMX magnet to its new site at the University of Washington. Before the arrival of the magnet, the site was substantially upgraded in support of the ADMX program. A "pit" for the magnet was constructed with non-magnetic materials (including stainless-steel rebar) and vacuum, gas and cryogenic equipment from a decommissioned superconducting electron linac was refurbished and moved to the ADMX area. After the magnet move, the magnet was cooled and brought up to operating current. Figure 2 shows the main ADMX magnet being lowered into place at the ADMX experiment site. The ADMX magnet is very delicate with tight constraints on applied accelerations. The move of the magnet was therefore highly engineered and the engineering and move itself a subject of an instrumentation publication. [12]

5.2 Helium Liquefaction System

Major components of the helium liquefaction system were delivered in November 2012 and installation began shortly thereafter. Regular operations of the liquefier began in 2013 and it has been in regular operation since. Figure 3 shows The major helium liquefaction components. The liquefier engine is at the left, the main compressor is the the right and behind. Also seen in the foreground is the 1000 liter main dewar. The ADMX infrastructure incorporates a large number of pumps and compressors. Figure 4 shows two pumps for high-pressure helium gas storage, a part of the helium liquefaction system.

5.3 Rebuild Insert

The ADMX Phase 2a experiment was completely rebuilt to support colder temperatures. Figure 5 shows the ADMX Phase 2a cavity being assembled. The cavity top is removed and seen are the two turning rods. Figure 6 shows a "1K pot" nestled into the ADMX Phase 2a insert. This refrigerator establishes the temperature of a 1K shield, one of a number of nested thermal shields. Figure 7 shows the nearly fully instrumented ADMX Phase 2a insert. The thermal shields are removed in this view. Figure 8 shows the ADMX Phase 2a "Squidadel". This assembly supports

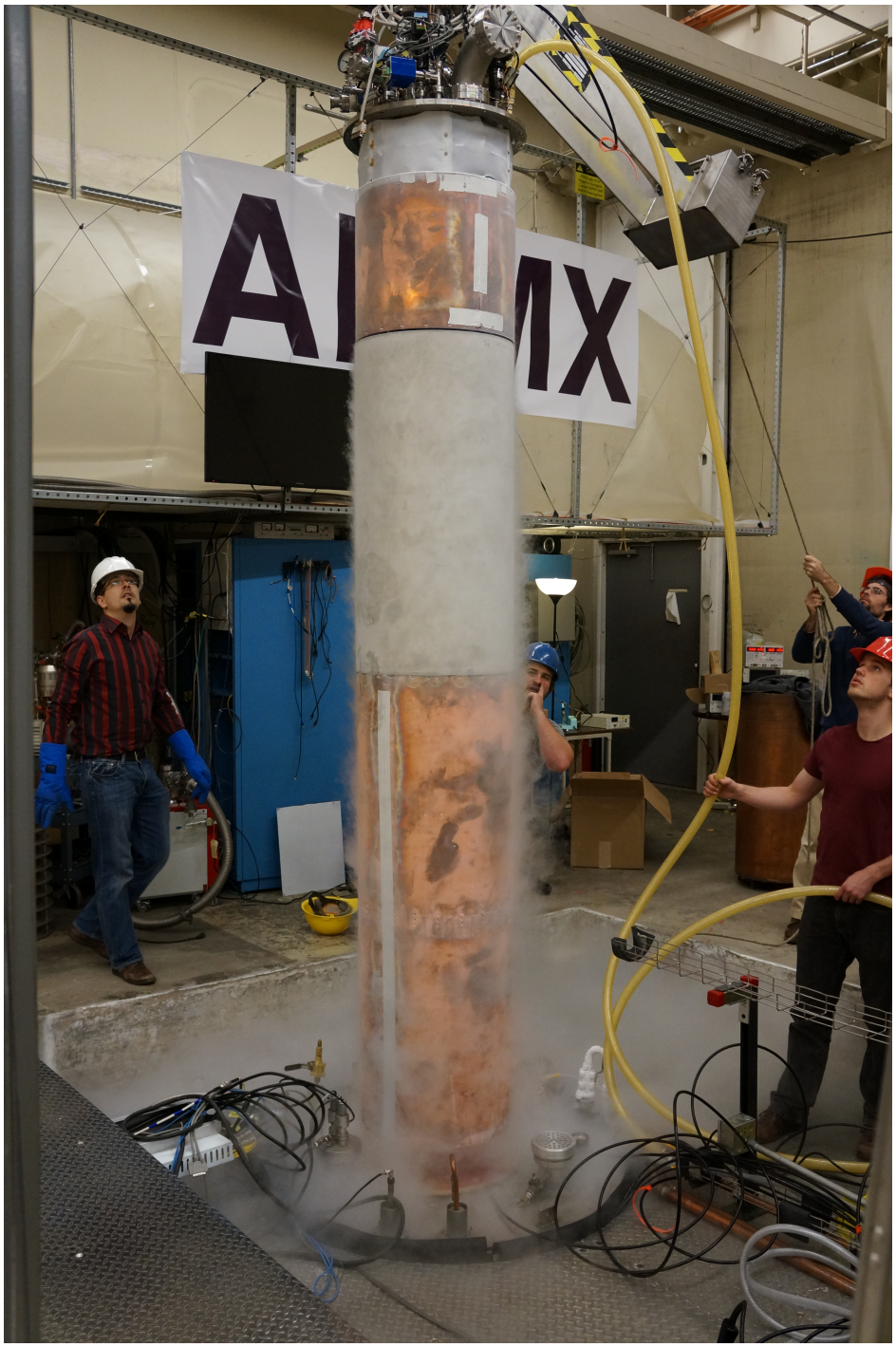

Figure 1: The ADMX Phase 2a experiment insert being removed from the magnet bore during Phase 2a data-taking operations. Vapor is seen streaming off the cold insert.

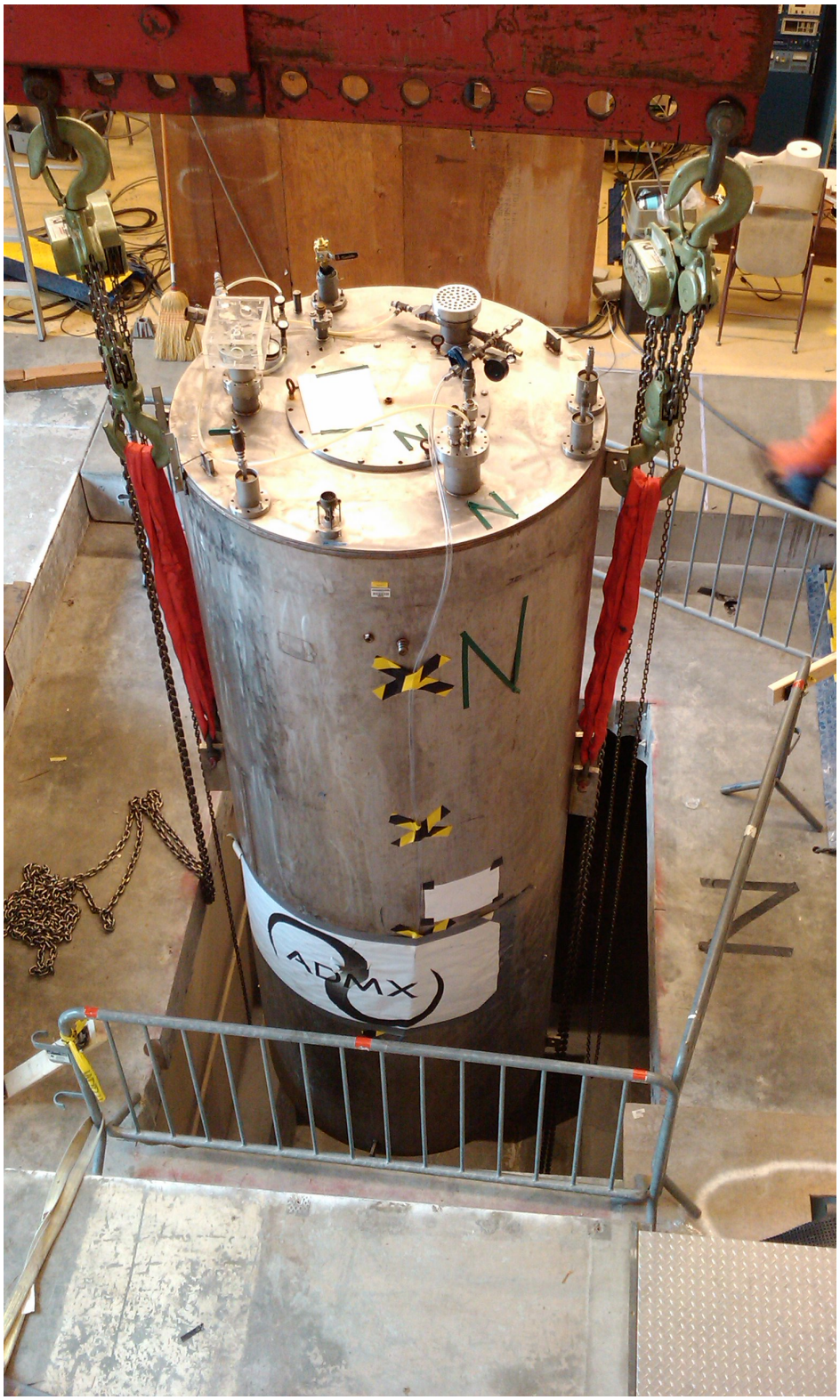

Figure 2: The ADMX main magnet being lowered into place at the experiment site.

Figure 3: The major helium liquefaction components. The liquefier engine is at the left, the main compressor is the the right and behind. Also seen in the foreground is the 1000 liter main dewar.

Figure 4: The ADMX infrastructure incorporates a large number of pumps. These two pumps are for high-pressure helium gas storage, a part of the helium liquefaction system.

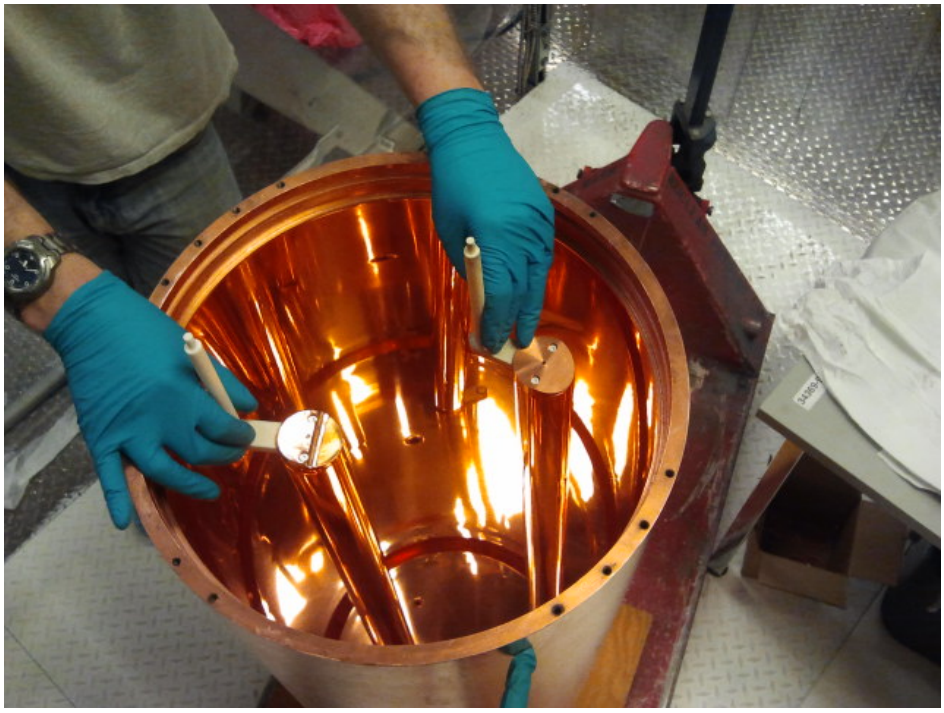

Figure 5: The ADMX Phase 2a cavity being assembled. The cavity top is removed and seen are the two turning rods.

the cold RF electronics. The silver cylinder is a magnetic shield housing the SQUIDs and JPAs (a SQUID variant). The components ringing the outside are passive cryogenic RF components.

5.4 Phase 2a Operations

The main Phase 2a ADMX operations occurred in 2014. A key science goal was to extend ADMX operations to higher frequencies (higher axion masses) by incorporating the TM_{020} cavity mode in the search. This analysis is being prepared for publication. Figure 9 shows a recent analysis of the Phase 2a ADMX data. This is a section of the TM_{020} frequency band at just below 1.4 GHz (axion masses around 5.7 μeV). The sensitivity is to that of a plausible axion. This is the most sensitive search for these higher mass axions, and extends the ADMX axion search to higher mass.

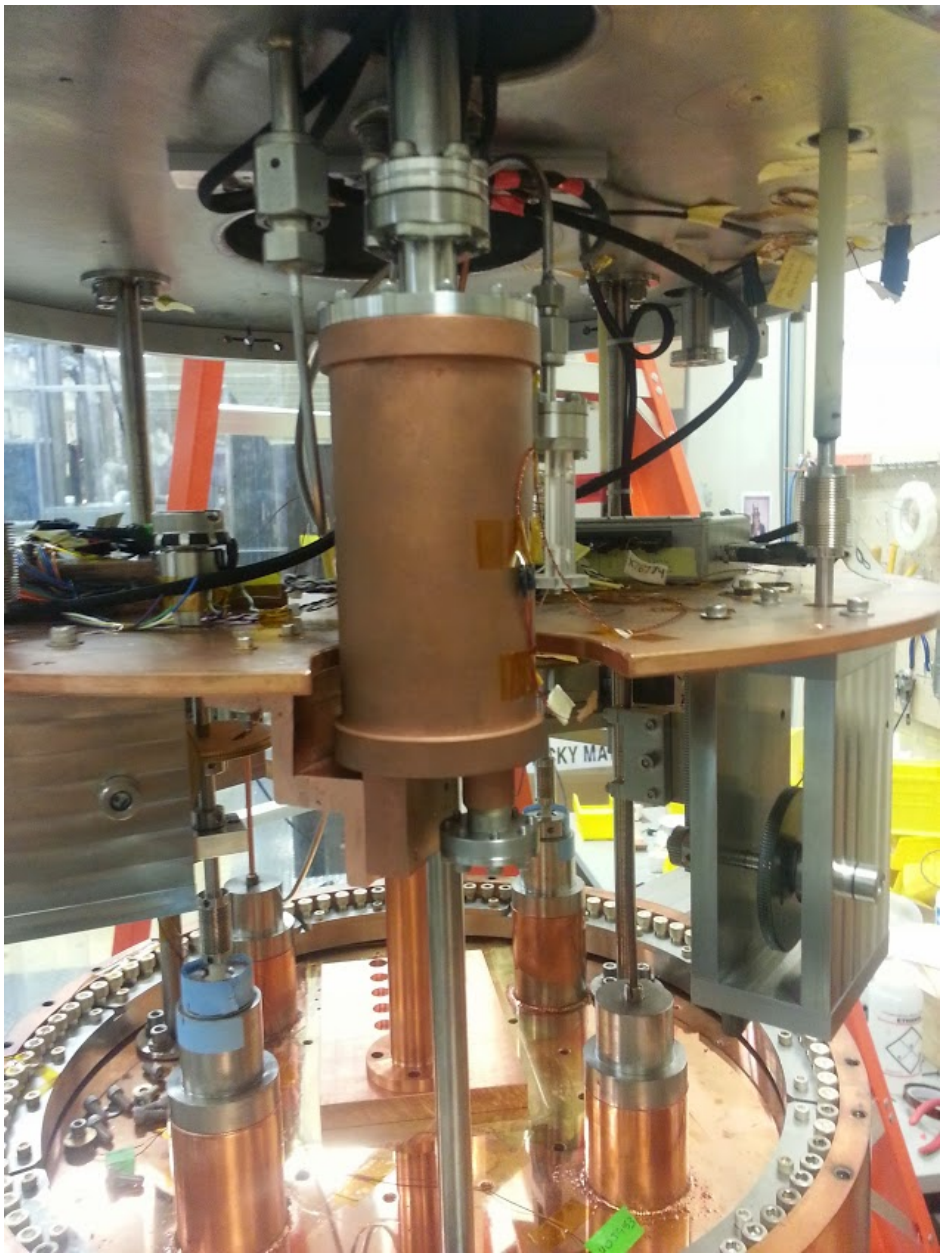

Figure 6: A "1K pot" nestled into the ADMX Phase 2a insert. This refrigerator establishes the temperature of a 1K shield.

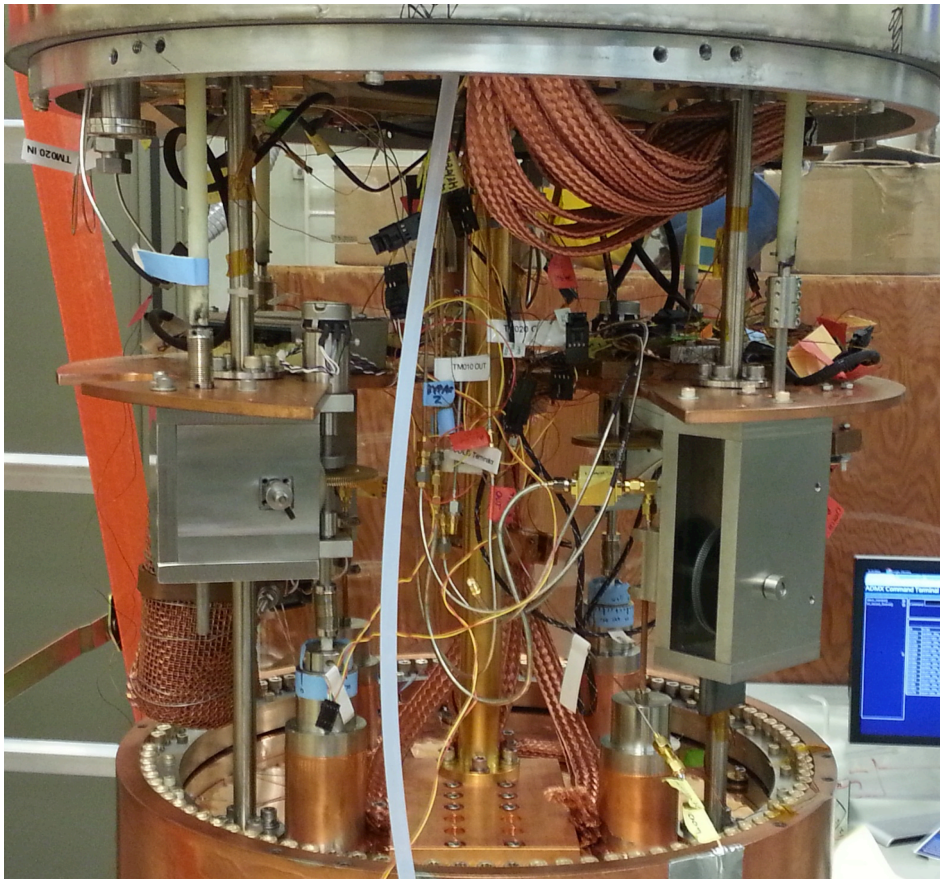

Figure 7: The nearly fully instrumented ADMX Phase 2a insert. The thermal shields are removed in this view.

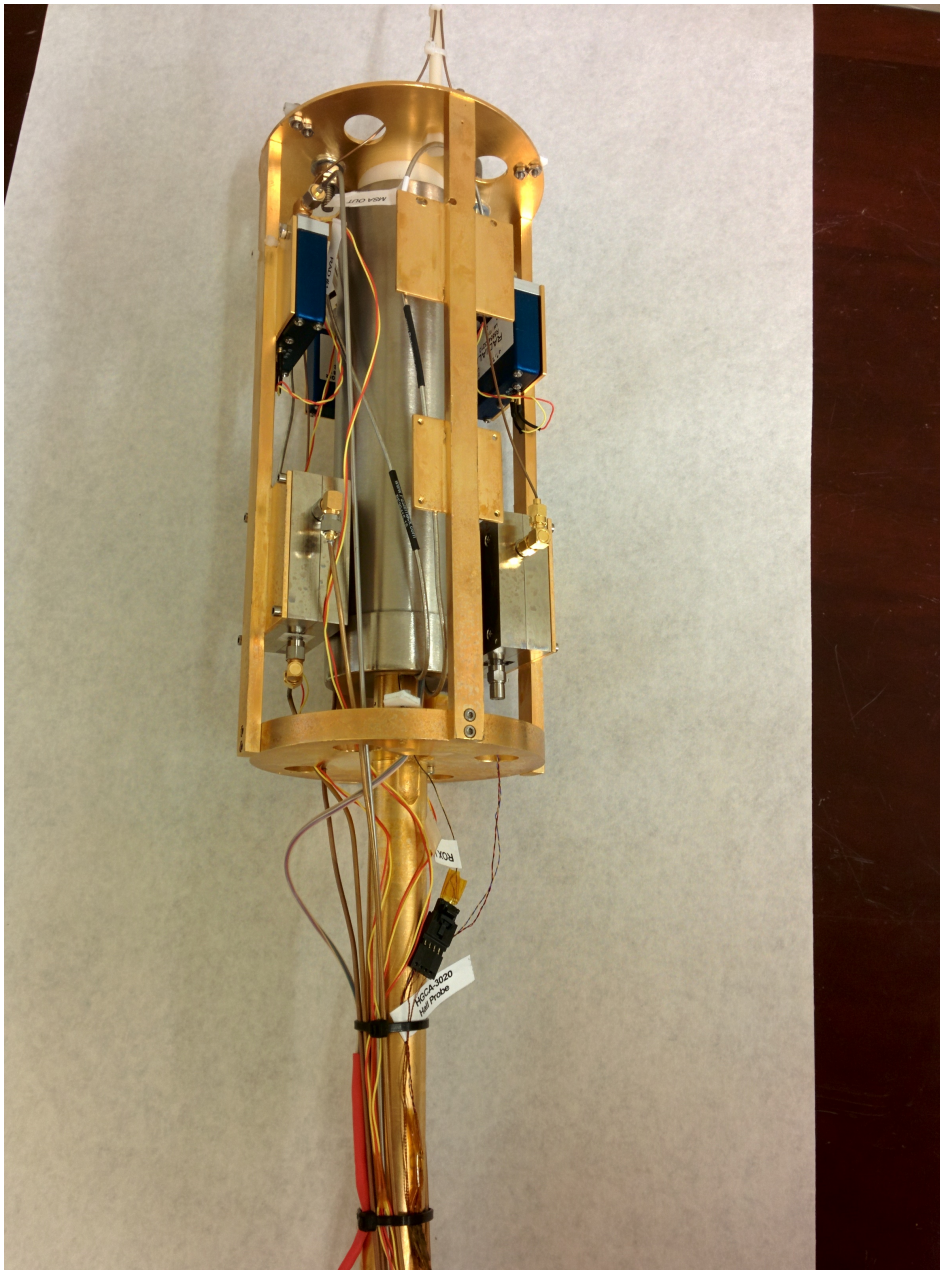

Figure 8: The ADMX Phase 2a "Squadel". This assembly supports the cold RF electronics. The silver cylinder is a magnetic shield housing the SQUIDs and JPAs. The components ringing the outside are passive cryogenic RF components.

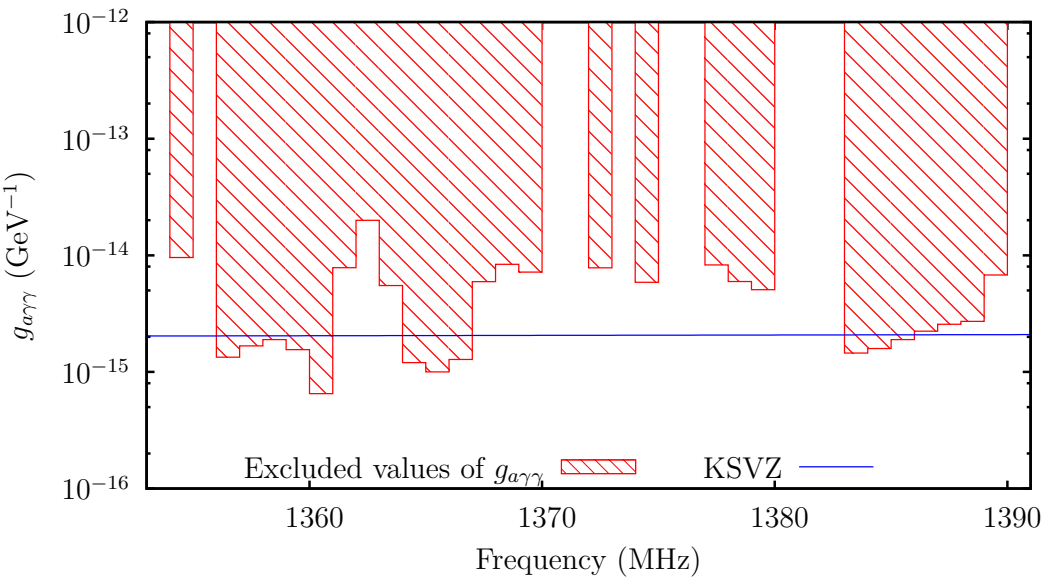

Figure 9: Recent analysis of the Phase 2a ADMX data. This is a section of the TM_{020} frequency band at just below 1.4 GHz (axion mass around 5.7 μeV). The sensitivity is that of a plausible axion. This is the most sensitive search for these higher mass axions, and extends the ADMX axion search to higher mass.

6 Ph.D.s Awarded

Jeffrey Hoskins (University of Florida)
Michael Hotz (University of Washington)
Dima Lyapustin (University of Washington)

7 Summary Accomplishments

We satisfied the principal milestone of the ADMX Phase 2a award. The new experiment site at the University of Washington was prepared. The ADMX main magnet was moved to its new "pit". The helium liquefaction system was deployed and in regular operation. The Phase 2a insert was completely rebuilt. Phase 2a data-taking occurred over much of 2014, with the new TM_{020} channel operational. We are preparing this analysis for publication.

References

[1] C. Hagmann, D. Kinion, W. Stoeffl, K. van Bibber, E. Daw, H. Peng, Leslie J Rosenberg, J. LaVeigne, P. Sikivie, N. S. Sullivan, D. B. Tanner, F. Nezrick, Michael S. Turner, D. M. Moltz, J. Powell, and N. A. Golubev. Results from a high-sensitivity search for cosmic axions. *Phys. Rev. Lett.*, 80:2043–2046, Mar 1998.

[2] L. D. Duffy, P. Sikivie, D. B. Tanner, S. J. Asztalos, C. Hagmann, D. Kinion, L. J Rosenberg, K. van Bibber, D. B. Yu, and R. F. Bradley. High resolution search for dark-matter axions. *Phys. Rev. D*, 74:012006, Jul 2006.

[3] S. J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, M. Hotz, L. J Rosenberg, G. Rybka, J. Hoskins, J. Hwang, P. Sikivie, D. B. Tanner, R. Bradley, and J. Clarke. Squid-based microwave cavity search for dark-matter axions. *Phys. Rev. Lett.*, 104:041301, Jan 2010.

[4] S.J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, M. Hotz, L. J Rosenberg, G. Rybka, A. Wagner, J. Hoskins, C. Martin, N.S. Sullivan, D.B. Tanner, R. Bradley, and John Clarke. Design and performance of the {ADMX} squid-based microwave receiver. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 656(1):39 – 44, 2011.

[5] J. Hoskins, J. Hwang, C. Martin, P. Sikivie, N. S. Sullivan, D. B. Tanner, M. Hotz, L. J Rosenberg, G. Rybka, A. Wagner, S. J. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, R. Bradley, and J. Clarke. Search for nonvirialized axionic dark matter. *Phys. Rev. D*, 84:121302, Dec 2011.

[6] Alexander Kusenko and Leslie J. Rosenberg. Snowmass-2013 Cosmic Frontier 3 (CF3) Working Group Summary: Non-WIMP dark matter. 2013.

[7] S. Ritz et al. Building for Discovery: Strategic Plan for U.S. Particle Physics in the Global Context: Report of the Particle Physics Prioritization Panel (P5). 2014.

[8] Adrian Cho. Dark Matter's Dark Horse. *Science*, 342:552–555, 2013.

[9] P. Sikivie, I. I. Tkachev, and Yun Wang. Secondary infall model of galactic halo formation and the spectrum of cold dark matter particles on earth. *Phys. Rev. D*, 56:1863–1878, Aug 1997.

[10] L. D. Duffy and P. Sikivie. Caustic ring model of the milky way halo. *Phys. Rev. D*, 78:063508, Sep 2008.

[11] P. Sikivie. Experimental tests of the "invisible" axion. *Phys. Rev. Lett.*, 51:1415–1417, Oct 1983.

[12] B. et al. Thomas. Move of a large but delicate apparatus on a trailer with air-ride suspension. *J. Appl. Packaging Res.*, 6:79, 2012.