Project Description

Next-generation Readout Architectures and Data Quality Monitoring for SPT-3G and Beyond

1 Overview

The oldest surviving records of cosmological thought come from early Mesopotamia and describe a flat, circular Earth embedded in a cosmic ocean. Since then, humanity has come to understand that we live on a spherical planet, that this spherical planet is not the center of the universe, that the Sun it orbits is also not the center of the universe, that our galaxy is neither alone nor central, and that indeed there *is* no center. In 1948, Alpher and Hermann predicted a 5 K afterglow from a hot big bang. This afterglow, the cosmic microwave background (CMB), was measured in 1965 in Nobel Prize-winning work by Arno Penzias and Robert Wilson. We find ourselves now in an era of precision cosmology, where the CMB provides percent- or sub-percent- level constraints on many cosmological parameters, including H_0, which shows an increasingly fascinating tension with distance ladder measurements of the same parameter — a possible hint of new physics. Further and increasingly precise study of the CMB will provide a rich probe of a huge range of cosmological and astrophysical phenomena including the composition of the universe, cosmic inflation, neutrino number and mass, gravitational lensing, and galactic astronomy.

With implications across such a broad range of cosmological and astrophysical science outcomes, improved observations of the CMB will play a key role in the science landscape of the next decade. This key role has been called out in several important forums: The 2010 Astronomy and Astrophysics Decadal Survey found that CMB probes of inflation and exotic physics in the early universe are among the "projects thought compelling for the mid-scale innovations program" and that the search for primordial gravitational waves was "the most exciting quest of all" [1]. The 2014 Particle Physics Project Prioritization Panel (P5) report also recommended "support[ing] CMB experiments as part of the core particle physics program. The multidisciplinary nature of the science warrants continued multi-agency support"[2].

Clearly, continued ground-based study of the CMB has been recognized by the scientific community as an important facet of NSF-funded research. Several Stage-III instruments (with focal planes containing of order 10,000 detectors) have ongoing surveys with NSF support, or will begin surveys soon (SPT, AdvACT, PB2, etc [3, 4, 5]). These surveys will continue to push down the limits on r, the tensor-to-scalar ratio, which is a measure of the energy scale of inflation, measure foregrounds, characterize large scale structure, and constrain neutrino physics, but to advance the limits of precision cosmology with the CMB, a new epoch of ultra-large, ultra-sensitive instrumentation will be required.

Looking forward into the next decade, the ground-based CMB community has recently joined together to form a single collaboration aimed at deploying the next stage of ground-based CMB instrument, CMB Stage-IV (CMB-S4). The reference design for CMB-S4 describes 3 large aperture telescopes and 14 small aperture telescopes divided between sites at the South Pole and in Chile, with on the order of half a million background-limited transition edge (TES) detectors in total. This is more TES detectors in a single array than have been deployed on-sky in total across all astrophysical TES arrays to date; this puts in sharp relief the need for both highly scalable detector readout architectures and highly scalable data processing architectures as we embark on this new era of ultra-large CMB instrumentation and ultra-large datasets. The work I propose here will address one facet of each of those challenges.

In this proposal, **I describe a plan of research to take place at the University of Chicago under the guidance of Professor John Carlstrom and Dr. Amy Bender that advances the study of the CMB and contributes to the CMB science outcomes mentioned above and described in greater detail in the sections that follow by 1) developing a next generation digital frequency multiplexing architecture for readout of transition edge detectors with lower crosstalk, lower noise, and greater scalability than existing architectures, 2) developing a new, highly scalable machine learning-based data quality monitoring architecture for SPT-3G which could be extended to other instruments including CMB-S4.** In the sections that follow I will outline the scientific motivation for these efforts, a more detailed plan of work, and a summary of broader impact activities I will undertake. Section 2 describes the scientific motivation and merit of precision cosmology with the CMB. In section 3, I present a plan of work for development of a new readout architecture for CMB-S4 and new machine learning-based data quality monitoring techniques for SPT-3G that could be extended to CMB-S4. In section 4, I outline my program of outreach and broader impacts, including spearheading a new Deaf/hard-of-hearing/blind/low-vision accessibility program at Chicagos Adler Planetarium, volunteering in the existing Astronomy Conversations program at Adler, developing new South Pole-related visual aids for the Astronomy Conversations program, and advocating for young physicists though my service on the Junior Scientists Advancement Committee in the CMB-S4 collaboration. Finally, section 5 argues for the suitability of the University of Chicago as my host institution and for the essential role of the NSF AAPF in enabling these research and outreach activities.

2 Scientific Motivation

Precision cosmology with the cosmic microwave background has a wide-reaching impact across many areas of cosmology and astrophysics.

Cosmic Inflation

Cosmic inflation describes a model where the universe underwent a short period of exponential expansion a tiny fraction of a second after the big bang. This model offers a promising solution to problems in the 'standard' big bang model, including the horizon problem, monopole problem, and flatness problem [6]. However, the inflation model remains unconfirmed. Testing, constraining, and perhaps eventually confirming inflation is the leading goal of most CMB observations today. The energy scale of inflation is related to the amplitude of primordial gravitational waves, which leave an imprint on the CMB in the form of a large-angular-scale B-mode (zero divergence) polarization anisotropy. Detecting this nanoKelvin-scale anisotropy would be a smoking gun for inflation, but will require exquisite instrumental sensitivity and control of systematics.

Large Scale Structure and Lensing

Galaxy clusters are the largest gravitationally-bound structures in the universe, forming via gravitational infall from regions tens of Mpc in size. Clusters at different redshifts offer a probe of the evolution of large scale structure through the history of the universe, and by extension also probe properties of dark matter, neutrinos, and gravity. CMB surveys using the Sunyaev-Zel'dovitch (SZ) effect to detect clusters are the most efficient method for finding large clusters at $z > 1$ [7]. In addition to being a powerful tool on its own, SZ surveys are synergistic with optical surveys such as DES and LSST which are more efficient probes of the low-redshift universe.

Gravitational lensing of the CMB causes small distortions in the CMB temperature and polarization signals. Mapping the distribution of these distortions provides a measure of the amount of matter between us and the surface of last scattering. This integrated gravitational potential captures information about cosmological parameters and large structure formation. Having a detailed understanding of lensing of polarized E-modes into B-modes is also an essential step in cleaning B-mode anisotropy maps to support a possible discovery of inflationary B-modes.

Neutrinos

Neutrinos are the second most number-dense particle in the universe (after CMB photons) and have energy density at least twenty-five times that of the CMB [8]. Because of their extremely small mass, they have both radiation-like and matter-like properties. The number of neutrino species alters the photon diffusion scale relative to the sound horizon in the CMB, which can be observed as a suppression of power at small angular scales and a shift in the location of acoustic peaks in the angular power spectrum [8]. The sum of the neutrino masses also affects the observable CMB; deviations in Σm_{ν} would affect the CMB temperature and polarization via the integrated Sachs-Wolfe effect and via gravitational lensing by large scale structure [8, 9].

Galactic Astronomy

Between our telescopes and the surface of last scattering are several sources of galactic foregrounds, including galactic synchrotron radiation and galactic dust emission. Uncertainties in these foregrounds have been a key challenge in making high-confidence precision measurements of the CMB, including of primordial B-modes. Surveys like SPT and CMB-S4 with fine angular resolution and multiple frequency bands are useful not only in mapping these foregrounds so they can be subtracted in primordial B-mode analysies, but also in studying the foreground sources as their own science case.

Dark Matter

From the CMB temperature angular power spectrum, we know that dark matter makes up about 85% of the matter in the universe. Weakly interacting massive particles (WIMPs) are a class of particles which are favored candidates for dark matter. In some WIMP models, dark matter particles can annihilate into standard model particles which slightly distorts the CMB power spectrum [10, 7, 11, 12], which makes the CMB a useful probe of this process. Planck has ruled out WIMP masses below 16 GeV and CMB-S4 could improve this constraint by three fold [7]. Precision measurements of the CMB polarization and temperature could also improve constraints for axion dark matter, which is an alternative model to WIMPs [7].

3 Plan of Work

3.1 South Pole Telescope

Instrument Overview

The South Pole Telescope (SPT) is a 10 m microwave telescope located at the South Pole in Antarctica. SPT's third-generation camera (SPT-3G) saw first light in January 2017 and has ~16,000 TES detectors. SPT-3G observes a 1500-degree survey region in three bands (90, 150 and 220 GHz) with an angular resolution of ~1 arcmin. This very fine angular resolution enables study of galaxies and clusters, while the range of frequency bands and large survey area enables cleaning of foregrounds. The 1500-degree survey area has strategic overlap with other surveys including BICEP/Keck, Spider, ACT, Simons Array, and CLASS, which will enable joint analyses of the data and better constraints on key cosmological parameters. As the highest pixel-count CMB camera currently on-sky, SPT-3G is also an important pathfinder for the CMB-S4 instrument.

Past Work

My involvement in the SPT collaboration began in 2016 with SPTpol (the survey and camera that preceded SPT-3G). In the final year of the SPTpol 500-degree field survey, I wintered over at the South Pole, spending 11 months living and working at the South Pole, maintaining the telescope and conducting observations. On returning from the South Pole, I joined the SPT team at the University of Chicago as a postdoctoral scholar. Since then my work has been focused in two areas in roughly equal parts. First, with collaborators at Argonne National Laboratory and McGill University, I have been working on a next-generation readout architecture for CMB-S4 (described in section 3.2). Second, I spend time on a broad array of tasks within the SPT collaboration, including training students, working on low-level instrumental analysis, leveraging my past experience as a winterover to advise the current winterovers, deploying to the South Pole in the austral summer to help with annual telescope hardware integration and improvement tasks, validating new hardware for polar deployment, and developing fast-turnaround data quality monitoring tools.

Ongoing and Future Work

SPT-3G produces about an order of magnitude more data per hour than its predecessor camera, SPTpol, owing to the much larger focal plane. One new challenge posed by this very large quantity of data is effective data quality monitoring and timely detection of any new or unanticipated pathologies in the data. It is important to detect problems early so they can be corrected with minimal impact on the observing season, but with such large quantities of data, it is difficult to use brute-force human-based data quality monitoring as has been done in the past.

Over the past year I have implemented a simple data quality monitoring scheme for SPT-3G which uses basic statistical checks on our calibration data to help call out problems in the data as they arise. I am in the process of expanding these simple statistical checks to the primary CMB field observations as well, but this general idea could be taken much further. I propose to develop a machine learning (ML) based data quality monitoring scheme for SPT-3G which could eventually be extended to future instruments including CMB-S4. As a starting point, I will focus on implementing a support vector network (SVN) algorithm to classify our calibration and field observation data [13]. Human-generated labeled training sets will be used as a starting point, but the goal is to move towards unsupervised learning, perhaps using support vector clustering, which is an extension of SVN [14].

To enable this work, there are several open-source ML repositories available including TensorFlow [15] and Keras [16], which are well-documented and widely-used python libraries with a variety of tools directed at ML techniques. Developing the data quality assurance software in python will allow for straightforward integration of this work into the broader SPT data pipeline, which is also in python. To aid in reducing the dimensionality of our data, I plan to use t-SNE (T-distributed Stochastic Neighbor Embedding), which is an algorithm for reducing high-dimensional data into lower-dimensional spaces [17], which will be easier to both analyze and visualize. An open-source python implementation of this algorithm is available [18].

ML application to CMB research is an active area of work at the UChicago Kavli Institute [19], so there is ample opportunity to collaborate and to draw on local expertise in this proposed work. Additionally, I have past experience with ML techniques; my time at MIT Lincoln Laboratory included work on a project that used feature-based supervised learning in a computer vision application.

3.2 CMB-S4

Instrument Overview

CMB Stage Four (CMB-S4) is a recently-formed collaboration and an instrument in the design and proposal process which will bring ground-based CMB observing into the next era in terms of focal plane size, detector count, and ultimate sensitivity. Stage-III experiments such as SPT-3G, Polarbear2 (PB2), and AdvancedACT (AdvACT) are serving as pathfinders for this ultimate ground-based instrument, which will have on the order of half a million detectors divided among 14 small aperture and 3 large aperture telescopes located at the South Pole and in Chile. [7]

Ongoing and future work

One challenge posed by ultra-large focalplanes is multiplexability. With tens of thousands of detectors, it is advantageous both from a logistical and wiring complexity standpoint and from a thermal loading standpoint to have as few wires going from 300 K to the detector stage as possible. Various multiplexing techniques exist which reduce the number of wires by multiplexing many detectors together. There are three primary multiplexing schemes used for TESs: time domain multiplexing (TDM), frequency domain multiplexing (FDM, or dfMux in the case of digital frequency domain multiplexing), and microwave multiplexing (μmux). Currently, the largest on-sky CMB camera (SPT-3G) uses digital frequency domain multiplexing to read out its transition edge sensors [20]. DfMux is also used on PB2, Litebird, and Ebex [21, 22, 23]. TDM is currently being used on-sky with BICEP3 and Keck Array. μmux has not yet been demonstrated on-sky, but there are laboratory-demonstrated systems that will be ready for on-sky demonstration on BICEP3 in the near future [24].

In dfMux, an RLC resonator is constructed by connecting the bolometer (R) in series with an inductor-capacitor (LC) resonator. These LC resonators consist of a coiled, superconducting inductor in series with an interdigitated, superconducting capacitor[25, 26]. An array of these resonators is lithographed as a single layer on a silicon chip (an "LC chip") which is mounted on a custom PCB ("LC board"). Each capacitor is slightly different, so that each RLC resonator has a different center frequency. This assigns each TES a distinct readout frequency. Many RLC resonators (68, in the case of SPT-3G) are connected in parallel and voltage-biased with AC tones at each RLC frequency, summed together to produce a single combined 'carrier comb' which is passed to the TESs and LC filters. The combined signal from the TESs is amplified with a DC SQUID array.

Frequency scheduling density, and therefore maximum multiplexing factor, is limited by crosstalk. The dominant source of crosstalk in the dfMux architecture comes from the impedance of the wiring between the LC chip and the SQUID. Impedance in these wires creates a voltage divider such that as the resistance of a TES is modulated, the ratio of the voltage divider is likewise modulated. This in turn modulates the bias on all of the other detectors.

To address this dominant source of crosstalk, I have been developing a 'next generation' dfMux architecture which reduces the voltage divider crosstalk effect by moving the SQUID from the 4 K stage to the 250 mK stage, immediately adjacent to the LC chip, on the same LC board. This reduces the wiring between the LC chip and the SQUID from 20+ inches to less than an inch, substantially reducing the stray inductance. I have demonstrated a first prototype of this system in the laboratory, including operation of a full comb of 64 TESs overbiased and 47 TESs in the superconducting transition [27]. This prototype system demonstrates stray inductance reduced by a factor of ~8 and parasitic resistance reduced by a factor of ~3 compared to the existing dfMux system. This reduction in stray inductance will allow for denser frequency scheduling, working towards enabling operation with a 128x multiplexing factor. The reduced parasitic resistance will additionally enable operation of low-R_{normal} TESs, which is desireable because they require lower bias voltage and therefore have lower readout noise.

While the groundwork has been laid in this 'next generation dfMux' effort, there is still much work to be done to make it viable for on-sky demonstration. I propose the following steps to further improve this sub-Kelvin squid dfMux architecture: 1) improved circuit modeling will allow for better control and damping of circuit resonances to improve LC peak matching and will enable even greater optimization of stray inductance. 2) Based on this circuit modeling and testing results from the first prototype, a second version of the PC board will be designed and tested, followed by a third version if needed. These design iterations will also be used to improve connectorization and characterize thermal loading. 3) The final version of the sub-Kelvin SQUID design will achieve operation of a full comb of 68 SPT-3G bolometers with stray inductance less than 1/10 of the current dfMux design, parasitic resistance less than 1/3 of the current dfMux design, comparable noise performance, and comparable thermal loading. We expect that this will enable frequency scheduling dense enough to accomodate 128x multiplexing within the current readout band, using the existing room temperature hardware. 4) I will additionally design a 128x multiplexing LC chip based on the current 68x chip design. To reduce the physical size of the resonators, I will explore the possibility of using on-chip parallel plate capacitors in place of the existing interdigitated capacitors. For the dielectric, an amorphous silicon process was recently developed in the University Chicago Pritzker Nanofabrication Facility which could be useful in this application. Other options include moving to smaller traces or to a larger chip, or some combination of these. Sonnet EM simulation software is already available within the SPT collaboration and is one of the best available tools for planar microwave circuit simulation. Preliminary, exploratory fabrication process development for the 128x LC chips could be carried out by me (or an interested student) in the Pritzker Nanofabrication Facility (PNF) at UChicago. Optionalally, the fabrication and process development could be an opportunity for collaboration with the SPT-3G/CMB-S4 nanofabrication team at ANL or at Lawrence Berkeley National Lab (which fabricates the existing 68x chips). Testing of the new 128x chips could take place in one of the cryostats UofC in parallel with testing of the next generation dfMux sub-Kelvin SQUID architecture.

The work described in the preceding paragraph dovetails with other funded efforts already ongoing at collaborating institutions. SPT-3G collaborators at McGill are now finishing up development of new firmware that will enable 128x multiplexing on the existing warm electronics for dfMux. A preliminary release of this firmware is expected within the next month. Collaborators at Argonne National Laboratory are actively working on development of low-R_{normal} detectors, the operation of which will be enabled by a low-parasitic-resistance readout like the one I have proposed above. CMB-S4 collaborators at Stanford Linear Accelerator Center (SLAC) are engaged in a funded effort to develop new SQUIDs that are more appropriate for operation in a system like the one proposed here; the new SQUIDs will have low input inductance (to reduce current sharing [20]), low thermal dissipation (to enable operation of many squids on the detector stage), high transimpedance (to enable low-noise amplification), and will be designed specifically with sub-Kelvin operation in mind. Collectively, these other funded efforts at McGill, ANL, and SLAC in concert with the work I have proposed here would come together into a complete end-to-end 128x digital frequency multiplexed TES detector and readout chain suitable for use in CMB-S4.

4 Broader Impacts

I believe that science communication, public outreach, and promoting the advancement of young scientists (especially those who are members of underrepresented or disadvantaged groups) are important facets of being a responsible and productive member of the scientific community. I am already actively engaged in public outreach and young scientist advancement efforts, which I will continue as an NSF fellow.

4.1 Adler Planetarium

Astronomy Conversations

I volunteer regularly at the Space Visualization Laboratory (SVL) at Chicago's Adler Planetarium. In the Astronomy Conversations program at the SVL, a volunteer astronomer or physicist is on-hand to talk informally with the public at Adler for two hours every single day. These discussions take place in a room stocked with many physical models and computer-based visual aids dealing with myriad astronomy and cosmology topics, and Adler visitors are encouraged to stop in and ask questions or discuss the visualizations in an informal setting. Typical attendance for a two-hour Astronomy Conversations session on a weekend is about 200 people. I have been involved in the Astronomy Conversations program as a volunteer since early 2017 and will continue to volunteer there regularly for as long as I reside in Chicago.

Visual Media of South Pole Science

While the SVL has some images of the South Pole Telescope and surrounding station available, the material is limited in scope and is not available in a format that works well on the 3D displays in the SVL. I will be taking a specialized 3D camera (loaned by Adler SVL) with me to the South Pole to gather new and better footage of the experiments and the station. In collaboration with the Adler SVL team, I will develop this footage into a visualalization tool that will become part of the SVL collection and will be available to speakers and audiences for years to come, potentially reaching tens of thousands of members of the public.

Adler Accessibility Day

One facet of science outreach which is often overlooked is accessibility and inclusion. Communities of people who require accommodations such as sign language interpreters for the Deaf and hard-of-hearing or audio description for the blind and low-vision are often overlooked in science education and outreach efforts. Recently, disability access has become an area of increased interest and focus in the museum science community [28, 29], and I would like to help improve science outreach inclusivity for the Deaf/hard-of-hearing (DHH) and blind/low-vision (BLV) communities in the Chicago area.

To that end, I am collaborating with Chicago's Adler Planetarium (Adler) on a new program that will focus on making Adler more inclusive to these often-underserved members of the Chicago community. While Adler currently offers sign language interpretation for its planetarium shows to individuals who make a request at least two weeks in advance, they currently offer no other special programming for individuals who are Deaf, hard-of-hearing, blind, or low-vision. The Adler board of directors has agreed to collaborate with me to develop an 'Adler Accessibility Day,' where there will be ASL interpreters and live audio description interpreters available at a planetarium show and at a SVL Astronomy Conversations session. A key step in developing programming to reach these communities is advertising events in the appropriate venues (e.g. DHH- and BLV- specific monthly newsletters, online message boards, and community centers). Jeanine Pollard, a colleague of mine who has two years of experience developing accessibility programming at Chicago area museums, has agreed to help me get in contact with the appropriate DHH and BLV community leaders so that we can ensure information about these events reaches the appropriate groups. Adler has agreed to collaborate by offering appropriate staffing, organizational support, and reduced admission to event attendees. NSF postdoctoral fellowship funds will be used to support the cost of the ASL interpreters and audio description interpreters, and I will work with Adler, interpretation service providers, and the DHH and BLV communities to coordinate and advertise the event. ASL and audio interpretation services for a ~1hr planetarium show and ~2-hour SVL session will cost about $1000, which will be covered by funds from the NSF postdoctoral fellowship. We plan to hold the first such event in 2019, and hold these events at least twice a year thereafter. If demand and resources allow, these events could be ramped up in frequency and scale in subsequent years. The hope is to make this program a permanent fixture at Adler and to work with Adler towards embedding inclusive resources in other Adler programming, so that support for Deaf/blind access at Adler can continue for many years beyond this NSF fellowship. In the supplemental materials section, you will find a letter of commitment from Adler Planetarium detailing their commitment to collaborating with me on this effort. This program also dovetails well with an NSF-funded program with UofC Professor Mike Gladders as PI, recruiting Deaf and hard-of-hearing students from NTID (the National Technical Institute for the Deaf) to work with him on astronomy app development. It also ties in well with an ongoing NSF AAPF-funded program headed by Dr. Maria Weber, developing a set of 3D-printed models for use in Adler's SVL. These 3D printed models are great visual aids for the sighted and also great tactile teaching tools for individuals who are blind or low-vision.

4.2 Other Outreach

CMB-S4 Junior Scientist Advancement Committee

I am a member of the CMB-Stage Four (CMB-S4) collaboration's Junior Scientist Advancement Committee (JSAC). The JSAC strives to promote the careers of students and early-career collaboration members by advocating for students, fostering mentorship within the collaboration, planning career development workshops at collaboration meetings (our first such workshop occurred at the most recent CMB-S4 collaboration Meeting at Princeton University in June and consisted of a panel discussion aimed at helping junior collaboration members understand the Decadal Survey process), and by working with other committees in the collaboration to ensure authorship, speaker, and other policies are supportive and inclusive to students and early-career members. I plan to continue my work with the JSAC over the next several years.

Social Media Outreach

I also use social media as an outreach tool. On Twitter and Instagram (both @weblogarithms), I provide a regular glimpse into daily life as a scientist, with frequent posts showing what work I do on a daily basis, offering fun science tidbits and engaging with members of the public and with other science communicators. Non-traditional and 'new media' outreach techniques are playing an increasingly important role in public scientific engagement [cite] and are an effective way to reach groups that are not reached by more traditional science communication and outreach techniques [cite]. I have a growing following on both platforms, and will continue to use these platforms engage with both the science-interested public and with other science communicators.

4.3 Impact Assessment

Assesing the reach and impact of any outreach activity is an important part of optimizing how these resources are used. Adler already has embedded systems for measuring engagement SVL and in planetarium shows, based on attendance 'clickers' counting attendees at the door. These tools can be used to evaluate the effectiveness of the DHH/BLV program at Adler as well as my other Adler outreach activities. We could also offer short surveys at DHH and BLV events to get feedback from attendees.

The effectiveness of my social media public engagement effort can be evaluated by tracking the number of subscribers and post-specific engagement on each platform using embedded metrics including 'likes' and 'shares'. Statistics for both of these metrics are readily available on the user-interface of these platforms.

Evaluating the effectiveness of the activities of the JSAC is more difficult, however the CMB-S4 collaboration does track junior- and senior- membership separately, so it is possible to get a sense of retention rates of early-career scientists, and we can track attendance numbers for any events we hold.

5 Host Institution and Career Goals

5.1 Suitability of The University of Chicago as the Host Institution

The University of Chicago (UofC) has a long and rich history of contributions to cosmology across the spectrum from instrumentation to analysis to theory. The cosmology group at UofC spans across two institutes (the Kavli Institute for Cosmological Physics and the Enrico Fermi Institute) and two departments (the Department of Astronomy and Astrophysics and the Department of Physics). In addition, the Fermi National Accelerator Laboratory (FNAL) and Argonne National Laboratory (ANL) are nearby and offer collaborative opportunities with even more leading researchers and access to even more excellent facilities. The intellectual environment in the cosmology group at UofC is also unparalleled; there are eight postdocs, six graduate students, and six faculty working directly on SPT alone in the Chicago area (UofC, ANL and FNAL), in addition to the many postdocs, students, and faculty working on other cosmology projects at UofC. Such a large group of active researchers supports a rich schedule of seminars and colloquia by outside researchers and an engaging intellectual environment in general.

The laboratory facilities in the SPT group at UofC are well-suited to my proposed work. In the SPT laboratory are three cryostats, including two that are already fully outfitted for the proposed readout testing. Additionally, the SPT laboratories are just down the hall from the Pritzker Nanofabrication Facility, an ISO class 5 cleanroom user facility with all of the tools necessary for development of a 128x LC chip. The PNF is also staffed by four full-time professional nanofabrication engineers who are available to consult with users on process development and device fabrication. There may also be opportunities to collaborate on chip fabrication with SPT collaboration members who work in the ANL cleanroom facility.

My proposed sponsoring scientists are Professor John Carlstrom and Dr. Amy Bender. John Carlstrom is the department chair and Chandrasekhar Distinguished Service Professor in the UofC department of Astronomy and Astrophysics and holds additional appointments in the UofC Kavli Institute for Cosmological Physics, Enrico Fermi Institute, and Department of Physics, and at Argonne National Laboratory. He is the principle investigator of the South Pole Telescope and in the past has worked on DASI, SZA,and CARMA, all experiments that have made transformative contributions to CMB cosmology. Amy Bender is a staff scientist at Argonne National Laboratory and holds an additional appointment as an associate fellow of the University of Chicago Kavli Institute for Cosmological Physics. She has worked on ALMA, PB2, SPTpol, and SPT-3G, led the development of the current dfMux architecture, and is one of the leading experts in TES readout. Both of my proposed sponsoring scientists have extensive experience in CMB instrumentation and with fielding and operating telescopes. Their advice and mentorship will be invaluable as I continue in my work on CMB readout instrumentation and as I navigate the next steps of my career.

5.2 Relevance to Career goals

As we move towards the era of CMB-S4, which is expected to see first light in the late 2020s, other areas of cosmology are also moving towards ultra-large surveys, including LSST, DES, Euclid, and others. The next decades will be a compelling era of multi-survey precision cosmology which will lead to new insights into the history of the universe. It's an exciting and hopeful time to be a cosmologist and an engaging time to work in instrumentation, as design (and eventually construction) of CMB-S4 moved forward.

In the long term, I believe that passing on knowledge and enthusiasm for science to the next generation of researchers is one of the most important activities in academic life. To that end, I hope to become a professor at a major research institution, so that I can be fully engaged in the scientific community, both as a researcher and as an advisor and mentor of students. However, I am also very aware that the supply of tenure track jobs at top research universities is markedly smaller than the number of excellent researchers pursuing those positions. I have had many positive experiences working with scientists at national labs, both in my graduate career when I worked in the detector development lab at NASA Goddard and in my postdoctoral career where the UofC SPT group works very closely with counterparts at ANL and FNAL; a career of work as a scientist in the national lab system would also be a good fit for my experience and career path. The research experience, training, and mentoring I will receive as part of AAPF will be very beneficial to me as I forge professional relationships and focus my research interests in preparation for the next stage of my career in academia or in the national lab system.

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