Sunil Golwala — Research Activities

Introduction

My research activities live at the intersection of particle physics and cosmology, focusing on probing the unseen components of the universe through the methods of particle physics and astronomy. These include dark matter, which is widely believed to be a new subatomic particle that may also be a sign of physics beyond the Standard Model, and dark energy, whose existence is well established and drives the current-day accelerating expansion of the universe, but whose fundamental nature is unexplained. This work also encompasses testing the inflationary paradigm, wherein an exponential expansion of the universe due to a very early dark-energy-like component would explain the flatness, smoothness, and homogeneity of the present-day universe. These varied efforts are unified by a set of experimental techniques that make use of sub-Kelvin detector technologies, a strong commitment to developing new technologies and building new tools to attack these problems, and integration of the training of student and postdoctoral researchers into cutting-edge research.

My current activities are: 1) The use of the formation and evolution of galaxy clusters as a tool for cosmology and astrophysics via the Sunyaev-Zeldovich (SZ) effect; 2) Direct detection of dark matter via its scattering interactions with normal matter in terrestrial detectors; 3) Testing the inflationary paradigm via the search for curl-mode polarization of the cosmic microwave background on $\geq 1^\circ$ scales due to primordial gravitational waves created during inflation.

The above projects promise to occupy all my research time for the next decade. However, should time become available, I see two very attractive activities that follow along the same theme of studying the unseen components of the universe. One would be measurements of CMB curl-mode polarization on few-arcminute scales that would set the absolute scale of the neutrino mass hierarchy and thereby measure the neutrino masses. The other would be the study of fluctuations in 21-cm emission during the dark ages, whose power spectrum would provide constraints on the nature of dark matter, dark energy, the details of inflation, and neutrino mass.

Cosmology and Astrophysics with the Sunyaev-Zeldovich Effect

The thermal Sunyaev-Zeldovich (SZ) effect is a perturbation of the cosmic microwave background due to Compton scattering with hot free electrons along the line of sight, yielding a characteristic spectral shift. The key feature of the technique that makes it attractive for cosmology is that, roughly speaking, the sensitivity of the SZ effect is independent of redshift because the fractional size of the effect depends only on the density and temperature of the scattering plasma. In practice, galaxy clusters are the primary objects observed in the SZ effect because the spectral deviation scales approximately with the product of the mass and temperature of the halo in which the free electrons reside, and clusters are the most massive objects in the universe sufficiently relaxed for infalling baryons to have virialized and formed a plasma. A number of groups have pursued two primary cosmological probes motivated by the SZ effect: measurement of the secondary anisotropy power spectrum due to the ensemble of all clusters between today and the surface of last scattering; and blind surveys for galaxy clusters using integrated SZ flux as the detection criterion. The former primarily probes the amplitude of the power spectrum of density fluctuations, as normalized by σ_8. The latter, when combined with cluster redshifts, measures a combination of the cosmological growth function and the redshift-dependent volume element, which are sensitive to the dark matter and dark energy densities and the nature of dark energy (as parameterized by the equation of state parameter w with $p = w\rho$ relating dark energy pressure and density). As the ability of these measurements to constrain cosmological parameters has been studied in more theoretical depth over the last decade, it has become clear that a more detailed understanding of galaxy cluster formation and evolution must be pursued in parallel in order to understand the relation between observed flux and underlying halo mass, which is critical to the relation to any of these applications.

My group has pursued studies of this type actively over the last few years. Our first effort was a search for SZ anisotropy on arcminute scales to detect clusters blindly and measure σ_8. We used the Bolocam at 150 GHz to map 1 $\square^\circ$ to 90 μK_{CMB}. Bolocam is the $8'$-field-of-view, mm-wave facility camera for the Caltech Submillimeter Observatory whose final construction and commissioning I led as a Millikan Postdoctoral Scholar at Caltech (2000–2003). The result was a 90% confidence level upper limit on flat (in $\mathcal{C}_\ell$) bandpower anisotropy of 960 $\mu K_{CMB}{}^2$ at angular multipole $\ell = 5700$ with $\Delta \ln_\ell = 0.63$ and a corresponding upper limit on σ_8 of 1.57 [1]. *This was the first anisotropy limit of any kind at* $\ell \gtrsim 3000$ *at 150 GHz.* This work has since been superseded by APEX-SZ, also an upper limit [2]. Parallel work at 30 GHz using the BIMA, CBI, and SZA interferometers has yielded more sensitive though ambiguous results, with no strong detection [3, 4, 5]. Two new experiments, the Atacama Cosmology Telescope (ACT) and the South Pole Telescope (SPT), are doing substantially deeper and wider surveys of this type by using special-purpose, 1°-field-of-view cameras on dedicated 10-m-class telescopes to map hundreds to thousands of square degrees to 10–20 μK_{CMB}. Both these efforts are an order of magnitude larger in manpower and funding than our initial Bolocam survey, reflecting the challenging nature of this work.

An important technical component of this work has been the study of sky noise — noise due to time-varying emission from the atmosphere arising from the fluctuating water vapor column depth along the line of sight. We have published two papers [6, 7] with exhaustive studies of sky noise observed with Bolocam at 150 and 275 GHz, which confirm the Kolmogorov-Taylor turbulent sky noise model in the to-date unexplored regime of large-field cameras on 10-m-class telescopes and advance a phenomenological scaling of sky noise with atmospheric water vapor content that explains the substantially lower sky noise at the South Pole relative to mid latitudes and makes predictions for sky noise for MUSIC and CCAT.

Both of these analyses were performed by Jack Sayers for his Ph. D. dissertation (Caltech, 2007). The SZ survey paper and associated Ph. D. dissertation [8] are well cited in publications by other active groups for their development of sky-noise removal and data reduction techniques [9, 10, 11].

With the Bolocam SZ survey complete, my group has undertaken a new effort with Bolocam to study massive galaxy clusters using the SZ effect in order to test scaling relations among observables and between observables and underlying mass. These tests will directly and indirectly probe the scatter and bias in the relation between SZ flux and cluster mass, which, as noted above, are critical for the ACT and SPT blind SZ surveys. To this end, we have assembled one of the largest catalogs of pointed SZ imaging of massive clusters, with 30 clusters in hand, all with existing X-ray imaging data. We have overlapped substantially with lensing measurements pursued by Richard Ellis and by the Local Cluster Substructure Survey (LoCuSS) and aim to also use velocity dispersion analyses based on Sloan Digital Sky Survey data (as derived by our collaborator E. Pierpaoli (USC)). We will perform robust measurements of the SZ effect radial profile in clusters and test scaling relations between observables. We are undertaking a joint deprojection analysis with X-ray data developed by collaborators E. Pierpaoli and S. Ameglio (USC). This work is being performed by Jack Sayers (now a NASA Postdoctoral Fellow at JPL), Nicole Czakon (Caltech physics graduate student), Tom Downes (Caltech postdoc), and myself. We expect a first publication on a subset of clusters in the coming months followed by an exhaustive study in two years for Czakon's dissertation.

A parallel effort is to develop more capable instrumentation. The Bolocam work made it absolutely clear that sky subtraction using spatial correlations results in substantial loss of sensitivity due to spatial filtering and residual unremoved noise. An alternate approach is to use spectral sky noise removal, which makes use of the fact that the same water vapor fluctuations cause sky noise at all wavelengths in the submillimeter and millimeter bands. Thus, sky noise observed at different frequencies is *fully* correlated. By viewing the same sky with multiple detectors, one can use these correlations, along with the orthogonality of the SZ and atmospheric spectra, to remove sky noise. This technique was first demonstrated with a few pixels by the SuZIE I.5 and II instruments [12, 13], but it was not straightforward to build large-format multicolor focal planes at the time. Advances in detector technology have changed the situation. To this end, I am co-PI with Jason Glenn (University of Colorado, Boulder) on the MUltiwavelength Sub/millimeter Inductance Camera (MUSIC), a four-color facility instrument for the CSO (bands at 150, 240, 275, and 350 GHz *in each of 600 spatial pixels*) [14], funded by NSF and the Moore Astrophysics Sensor Initiative. This camera uses three novel technologies developed at Caltech and JPL: photolithographic phased-array antennas to couple to the incoming light (rather than feedhorns or bare absorbers), photolithographic on-chip bandpass filters to define the colors (rather than metal-mesh optical filters), and microwave kinetic inductance detectors (a new, highly multiplexable type of bolometric detector). Performance of a demonstration camera has been published [14, 15]. We will have a second engineering run with a pseudo-final array design in February, 2010, followed by commissioning of MUSIC in Fall, 2010. The multiple colors observed in each pixel should provide MUSIC with background-limited[1] SZ sensitivity as well as the ability to simultaneously constrain contaminating submillimeter galaxies (SMGs). We will pursue a cluster program with MUSIC, larger in size and with deeper integrations than the existing data set in order to study a wider range of clusters at higher precision and out to larger radius. MUSIC construction and commissioning involves a large team at Caltech, JPL, CU-Boulder, and UCSB, including Caltech physics graduate students Nicole Czakon Ran Duan, and Seth Siegel, Caltech postdocs Matt Hollister and Tom Downes, JPL postdoc Jack Sayers, JPL scientists Peter Day, Rick LeDuc, and Hien Nguyen, and Jonas Zmuidzinas and myself. Construction and commissioning will be a portion of Czakon's Ph. D. dissertation and the cluster program will comprise Siegel's Ph. D. dissertation. Duan is pursuing an open-source software-defined-radio frequency-multiplexed readout system for the camera.

In the longer term, we are developing a science program and instrumentation for the Cerro Chajantor Atacama Telescope to extend this work. CCAT's prime benefits for SZ will be its fine angular resolution (25-m primary) and submillimeter coverage, which will permit CCAT to do SZ surveys to a lower cluster mass limit and a SZ anisotropy measurement to a higher angular multipoles than ACT or SPT. With a MUSIC-like camera, the combined benefits of spectral sky noise removal and simultaneous observation of contaminating SMGs could provide for a substantially deeper survey over hundreds of square degrees with CCAT. In parallel, CCAT will be able to study a much larger subset of clusters in detail, to lower mass, than possible with Bolocam or MUSIC, enabling a more extensive study of the astrophysics of clusters and how this impacts cosmological measurements using them. With the combined goals of SZ and SMG science, I have been leading the effort in the CCAT Instrumentation Working Group to define a long-wavelength MUSIC-like camera, one with an order of magnitude larger pixel count than MUSIC thanks to the finer angular resolution and larger field-of-view of CCAT relative to CSO.

Other Millimeter-Wave Science

While my research focus has been clusters and the SZ effect, Bolocam has been productive in a number of other astronomical areas, as will MUSIC and CCAT.

The Bolocam instrument team searched for dusty distant galaxies at 1.1 mm in a 0.1 deg^2 field in the Lockman Hole (yielding three *Astrophysical Journal* publications, on two of which I am a

[1]That is, sensitivity limited by the statistical fluctuations on the photons due to the incoming background optical power from the telescope, atmosphere, and CMB.

co-author [16, 17], the Ph. D. dissertation of Glenn Laurent (University of Colorado), and a publicly available data set[2]) and a 0.25 deg^2 field as part of the COSMOS HST Treasury program. This work has been led by Jason Glenn and James Aguirre (U. Penn.). This class of galaxies was only first discovered in the late 1990s, yet they emit roughly half of the radiation produced by stars over the history of the universe. Our Bolocam surveys were the first ones to be deep enough to be sensitive to confusion noise while also having very uniform noise properties due to the excellent stability of the detectors and instrument, yielding the deepest constraints on the power law of the number counts of submillimeter galaxies available at the time. My group contributed to this work by developing the algorithms for calibrating the astrometric registration and flux scale of our maps and a novel sky noise removal technique using principal component analysis. We also contributed in an advisory role to the science analyses. This work has since been superseded by the SHADES and AzTEC surveys [18, 19, 20, 21]; the former used SCUBA on the James Clerk Maxwell Telescope (JCMT) and included a team many times larger than the Bolocam team, while the latter used a camera that was a direct derivative of Bolocam and benefited from the retirement of SCUBA and the ensuing availability of the JCMT.

In close collaboration with us, the Spitzer Space Telescope Cores-to-Disks (c2d) Legacy program team surveyed 7.5 deg^2 in Perseus, 10.8 deg^2 in Rho Ophiuchus, and 1.5 deg^2 in Serpens for protostellar and star-forming regions (five published papers in *Astrophysical Journal*, on two of which I am a co-author [22, 23], and a Ph. D. dissertation by Melissa Enoch (Caltech)). John Bally (University of Colorado) has led an effort by the instrument team, a number of c2d collaborators, and others to map 150 deg^2 in the north galactic plane, providing an unbiased survey of a wide variety of star-forming regions in our galaxy. The data set is now public[3]. These galactic studies have mapped larger regions to a protostellar core mass of $\sim 0.2\ M_\circ$. My group played an important role in the development of a novel iterative mapmaker that minimizes the artifacts created in the map by removal of sky noise; this algorithm is central to the reliability of the maps. We also played an advisory role in the science analysis for c2d. We are not involved in the galactic plane survey.

For MUSIC, we are planning a next generation SMG survey. The multicolor information, especially when combined with Herschel data, will provide more robust SMG detections than has been possible in the past and will enable pre-selection of high-redshift objects. Jack Sayers and I led the effort to optimize MUSIC's choice of bands for this science [24]. MUSIC will be competitive with SCUBA-2, a new camera for the JCMT that is an order of magnitude larger in manpower and funding. MUSIC will also study the dust emissivity index in star-forming regions in our and nearby galaxies. These studies will continue in greater depth with CCAT.

Direct Detection of Dark Matter with CDMS, SuperCDMS, GEODM, and MKID-Based Detector Development

A variety of cosmological observations indicate that 80% of the matter in the Universe is nonbaryonic and dark, presumably in the form of as-yet-unknown elementary particles produced in the early Universe. Weakly Interacting Massive Particles (WIMPs) are a particular interesting generic class of dark matter candidates because independent arguments from cosmology and particle physics converge on the same conclusion: a new particle with electroweak scale mass and interactions could be the dark matter and also herald physics beyond the Standard Model [25, 26]. The most popular extension of the Standard Model, supersymmetry, naturally yields a WIMP in the form of the lightest superpartner (LSP). Alternative solutions incorporate compact or warped extra dimensions of order 1 TeV^{-1}, yielding Kaluza-Klein towers of partners to Standard Model particles with the

[2]http://irsa.ipac.caltech.edu/data/BOLOCAM/
[3]http://irsa.ipac.caltech.edu/data/BOLOCAM_GPS/

lightest such partner being an excellent WIMP candidate with a mass of $\sim 1\,\text{TeV}$. The implied galactic WIMP abundance and cross section for scattering with nucleons are large enough to render such scattering detectable. Recent reports from the National Research Council [27], OSTP [28], the Particle Physics Project Prioritization Panel (P5) [29], and the Particle Astrophysics Scientific Assesment Group [30] have emphasized the high priority of dark matter searches.

My group is engaged in the search for WIMP dark matter as a member of the Cryogenic Dark Matter Search (CDMS) and SuperCDMS Collaborations. The CDMS I and II experiments have led the field of WIMP dark matter searches for much of the last 9 years, regaining the lead with recently published results [31]. This analysis sets an upper limit on the WIMP-nucleon spin-independent cross section of 4.6×10^{-44} cm^2 at the 90% confidence level for a WIMP mass of 60 GeV/c^2.

We have played a lead scientific role in CDMS II. Caltech physics graduate student Zeeshan Ahmed is one of the leaders of the ongoing analysis of the final CDMS II data set, which will be published imminently and includes a factor of 2 increase in exposure over prior data sets. We hosted two analysis workshops at Caltech during 2009 to accelerate progress toward this result. Caltech physics graduate student David Moore has contributed substantially, too, particularly in estimating background leakage and optimizing sensitivity based on expected background. Moore is also pursuing a low-energy analysis that will test alternate interpretations of the DAMA claimed detection of the annual modulation signature of WIMP interactions and will do his dissertation analysis of the first SuperCDMS Soudan data set. The residence at Caltech of Jeff Filippini, who obtained his Ph. D. at Berkeley as the lead student on the prior CDMS II analysis and who is currently a Moore Postdoctoral Scholar working the SPIDER CMB receiver, has further strengthened our role. In addition, we have had substantial influence on the overall direction of the collaboration, including the important decision to upgrade the Soudan experiment from 4 kg to 15 kg target mass and thereby continue producing science while preparing a proposal for a more ambitious 105-kg experiment at SNOLAB. The SuperCDMS Soudan experiment was approved for funding in August, 2009, and will have a cross-section reach of 5×10^{-45} cm^2.

While the CDMS detectors have a remarkable ability to separate prospective particle dark matter events from the dominant background, interactions of high-energy photons emitted from surrounding materials. However, they have less ability to reject low-energy electrons that interact in a surface layer on the detectors of a few microns depth. Therefore, my group's technical participation in CDMS has been focused in two areas: 1) understanding the low-energy-electron background that is the experiment's most poorly rejected background; 2) improving the phonon-based event position reconstruction that defines the fiducial volume and thus determines the rejection of this background. With other CDMS colleagues, we have developed an analysis relating the rates of alpha particles and low-energy electrons observed in the detectors that convincingly demonstrates the dominant low-energy electron source is ^{210}Pb implanted into the detector surfaces, almost certainly from radon exposure. In addition to identifying the primary background, this analysis indicates that the newer CDMS detectors, having suffered lower radon exposure, meet the background levels necessary for the upgrade from 4 kg target mass in CDMS II to 15 kg in SuperCDMS Soudan. The same technique has established that the first few SuperCDMS Soudan detectors, running underground since August, 2009, meet these requirements. Also in this vein of background studies, we are working with Richard Schnee at Syracuse University to develop a time-projection chamber to screen witness samples for lower-level electron-emitting contaminants. The results will tell us how to modify detector production and handling to further minimize such contaminants, which could be critical for larger experiments seeking greater sensitivity to WIMPs. We have undertaken construction of a non-radiopure chamber to demonstrate proof-of-principle, which will be operational in 2010. We have also successfully obtained DUSEL R&D funds from DOE to build a full-size radiopure version. This work is being done by Caltech physics graduate student Zeeshan Ahmed.

In the near term, we will propose SuperCDMS SNOLAB with a target mass of 105 kg to be sited at the SNOLAB underground laboratory. The deeper site will render cosmogenic neutron backgrounds negligible. A new apparatus will reduce ambient photon and neutron backgrounds substantially. This experiment will have a reach of 3×10^{-46} cm^2. PASAG recently provided a strong endorsement of this experiment [30], their only endorsement of a specific direct detection experiment. We are requesting R&D funds for this experiment now and expect to submit a full proposal in 2010. Construction is expected to begin in 2012.

In the longer term, we propose to field a ton-scale experiment at the upcoming Deep Underground Science and Engineering Laboratory (DUSEL). This experiment, named the Germanium Observatory for Dark Matter (GEODM), will have a 1.5-ton target mass with a WIMP-nucleon elastic-scattering cross-section reach of 2×10^{-47} cm^2. The large target mass will be enabled by significant automation of detector fabrication and testing. Our proposal for an engineering study to pursue this automation work in response to the NSF DUSEL S4 solicitation in January, 2009, with Caltech as the lead institution, was successful. This effort is now underway, with substantial efforts on substrate production (Umicore), scaling up detector fabrication (R. Mahapatra, TAMU), and testing (U. Florida and U. Minn.). The intellectual leadership of the effort is provided by Caltech, and we are now working closely with SLAC on project management and planning, with the goal of preliminary design by the end of the engineering study phase in 2012.

SuperCDMS SNOLAB and GEODM will be, respectively, a factor of 150 and 2000 times more sensitive than current limits and 15 and 200 times more sensitive than SuperCDMS Soudan. SuperCDMS Soudan will test most of the "bulk" region of minimal supersymmetry and will be sensitive for the first time to the theoretically attractive "focus point" region, which lies at cross sections of a zeptobarn (10^{-45} cm^2). SuperCDMS SNOLAB will fully test this particularly interesting zeptobarn regime, which is home to the most natural Constrained Minimal Supersymmetry and Minimal Supergravity models, both of which impose GUT-scale SUSY parameter unification. Split Supersymmetry models, which fine-tune the physical constants via an anthropic argument, also live in this region. The only models untested by GEODM would be extremely fine-tuned to suppress scattering while providing a large enough annihilation cross-section to prevent overclosure.

Finally, we are pursuing the use of microwave kinetic inductance sensors (MKIDs) in a CDMS-style phonon-mediated particle detector [32, 33]. We expect that a phonon-mediated detector using MKIDs to replace the current transition-edge sensors would provide far more information about the phonon signal yet also be easier to fabricate and read out. Recent developments in the theory of noise in MKIDs has made the prospective improvements in signal-to-noise larger [34, 35, 36] and also opens up new device architectures that could render MKID-based detectors even easier to fabricate than initially expected. While the baseline design for GEODM uses a scaling of the existing phonon sensor design, there is risk that it will just cost too much to reliably fabricate such devices on larger substrates in such volume and therefore MKID-enabled improvements in detector technology could either simplify GEODM or keep its cost at a reasonable level.

Graduate student David Moore is performing this work in conjunction with JPL scientist Bruce Bumble and Ben Mazin's group at UCSB with support from a DOE Outstanding Junior Investigator grant, the Moore Astrophysics Sensor Initiative, a NASA APRA grant to Mazin, and JPL Research and Technology Development grants. Initial work has yielded one published paper [37], two conference proceedings [32, 33] and another publication in preparation. The development process has, however, been more difficult than expected — while we have basic proof of principle, we have also learned that the material combinations we tried, Al MKIDs with Ta phonon absorbers and Ti MKIDs with Al phonon absorbers, have unexpected fabrication challenges that render them poor choices for scaleup. We are evaluating Mn-doped Al MKIDs, which combine the excellent properties of Al MKIDs with the reduced transition temperature needed to pair them with Al phonon absorbers. First tests show good quasiparticle trapping, though further iteration is necessary to obtain a usable design. The recent development by Zmuidzinas and LeDuc of nitride compounds with very high kinetic inductance contributions *and* very low loss (unlike Ti) enables a new, further simplified architecture. Initial tests of direct phonon absorption in large-area resonators of this type have been very promising, showing high efficiency for collection of energy deposited in the substrate. We are designing a large-area (few cm^2) device that will provide our first test of position and energy reconstruction using the phonon signal simultaneously observed in many MKIDs. This would be a major milestone toward a scientifically interesting WIMP detector using MKIDs.

BICEP2/Keck Array and SPIDER

My research group is also involved in a series of instruments designed to measure precisely the polarization anisotropy of the cosmic microwave background with the goals of constraining the reionization history of the universe and searching for the unique signature of cosmological inflation in the CMB. They use the same set of developments described in the context of MUSIC — photolithographic antennas and bandpass filters and multiplexable sub-Kelvin detectors, in this case transition-edge sensors (TESs). BICEP2/Keck Array (PI: J. Kovac, Harvard), will map the CMB polarization in the 2% of the sky most free of astrophysical foreground emission. It is a series of follow-ons to the existing BICEP CMB polarization receiver that operated at the South Pole and recently published its first results [38]. BICEP2/Keck Array are funded by the NSF Office of Polar Programs and the Keck Foundation. SPIDER (PI: A. Lange), is a NASA APRA-funded balloon payload to survey approximately half the sky in CMB polarization. The two sets of experiments use the same focal plane technology and similar receiver architectures.

The BICEP2/Keck and SPIDER efforts involve many senior personnel at Caltech and JPL, including Kovac (formerly a senior postdoctoral scholar, now in a tenure-track position at Harvard), Marcus Runyan (senior postdoctoral scholar), Bock, Lange, and myself, and thus supervisory responsibilities are broadly distributed. Roughly speaking, I have been focused on focal plane design and integration, readout electronics, detector characterization, and magnetic field susceptibility testing. My group's contribution began with focal plane design work started by postdoctoral scholar Philippe Rossinot and completed by physics graduate student Randol Aikin in cooperation with JPL collaborators. Physics graduate student Justus Brevik (advisor: A. Lange) worked under my supervision to commission and test a prototype of this hardware, to commission a cryogenic time-domain-multiplexing SQUID-based readout system provided by collaborators at NIST and the University of British Columbia, and to obtain first full-focal-plane characterization data on detector arrays for these receivers. Brevik has been involved in focal plane assembly and in characterization of successive generations of detector arrays, in particular understanding in detail noise performance. Aikin designed the instrument insert and has been heavily involved in optics design and fabrication and in testing magnetic field sensitivity and shielding configurations. Moore postdoctoral scholar Walter Ogburn has played a significant role in developing software for detector characterization and magnetic field studies, in integration of telescope control and data acquisition, and in analyzing deep laboratory maps taken to characterize microphonic and magnetic field response.

BICEP2 is currently deploying one 150 GHz telescope to South Pole. Keck Array, which will put similar receivers at 100 GHz and 220 GHz in cryocooled dewars on the DASI mount, will follow soon after, deploying in 2010 and 2011. SPIDER will use similar focal planes at 100, 150, and 220 GHz and will have a first science flight in 2010, and a second science flight in 2011 or 2012. Aikin, Brevik, and Ogburn will continue to play important roles in instrument commissioning and will take lead roles in analyzing CMB data. I have recently taken on a new student, Rebecca Tucker, on SPIDER, and anticipate taking on a student on Keck Array soon, also.

Future Directions

It seems clear that my areas of interest will remain at the cutting edge for a substantial time — new measurements and discoveries in dark matter, dark energy, and inflation will either confirm or disprove our current paradigms. The latter will lead to new ideas to be tested experimentally. Confirmation will give rise to precision measurement efforts. A rich program of definitive studies in dark matter, dark energy, and CMB polarization, continuing the work begun above, could easily fill the next two decades. An alternate path would be to change experimental effort to 21-cm fluctuation measurements but maintain the same intellectual focus.

In the SZ arena, a CCAT SZ science program starting in the early part of the next decade would require 3-5 years to acquire the data followed by another 3-5 years to extract all the science, leading to a horizon for completion in the early part of the 2020s. There very well may be a need for follow-on programs extending well into the 2020s. In CMB polarization, a natural effort extending beyond the next five years would be an arcminute-scale measurement of curl-mode polarization to constrain the neutrino mass hierarchy and measure the neutrino masses via the neutrinos' effect on the large-scale structure power spectrum. A first foray has been a proposal for POLAR-1, an experiment using BICEP2/Keck/SPIDER-style focal planes led by Chao-Lin Kuo (Stanford). The scaling challenges are substanial, though, rendering a MKID-based option very attractive technically and also because of the synergy with MUSIC. Such an effort would naturally begin once MUSIC has demonstrated background-limited performance and would stretch out over a decade via a demonstrator followed by an array of receivers (à la BICEP1/BICEP2/Keck). Eventually, there will be CMB polarization missions requiring community-wide support and participation. In dark matter, GEODM will begin construction in the mid-2010s and extend out past 2020 if the development effort is successful. If a robust signal appears, or if this program is terminated due to competing development efforts, my interests will likely shift to development of time-projection chamber detectors capable of sensing the direction of the recoiling nuclei. This effort would build on the time-projection chamber expertise we are developing for SuperCDMS screening. Such detectors would conclusively demonstrate a signal is due to dark matter by detecting the expected anisotropy of the recoils in the terrestrial frame. They would directly probe the three-dimensional velocity distribution of dark matter in our local neighborhood to test the astrophysics of dark matter.

A more substantial change of course would be to study the density fluctuation power spectrum during the dark ages via 21-cm anisotropy measurements. Such work ties into the themes of dark matter, dark energy, inflation, and neutrino mass in multiple ways. The fundamental novelty is the number of modes available: the power spectrum does not decay on arcminute scales as primordial CMB anisotropy does and thus higher angular multipoles are accessible; and the third dimension, along the line of sight, is accessible via 21-cm redshift in a manner not available with the CMB. This larger number of modes, extending to smaller angular scales, can tell us many things. Within the inflationary paradigm, the detailed shape of the power spectrum will be reflective of the details of the inflaton potential. In other theories, the power spectrum will no doubt provide useful information about how density perturbations were primordially generated. Nongaussianity of the fluctuations may also be telling in the manner that nongaussianity of CMB fluctuations are expected to be. The rolloff of the power spectrum on small scales will be set by the neutrino mass and any deviations of dark matter from being a perfect collisionless gas. And, though dark energy is highly subdominant during the dark ages, the precise, time-evolving nature of the power spectrum information may enable more precise versions of late-time measurements or perhaps new measurements not currently considered. The experimental challenge is not as attractive as current work, as it seems to lie mostly in systems-level issues and analysis rather than physics-driven innovation, but the science is truly compelling.

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