Sunil Golwala — Curriculum Vitae

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Research Interests

Observations of the Sunyaev-Zeldovich effect to study dark energy and cluster astrophysics
Direct and indirect searches for dark matter
Measurements of the cosmic microwave background that probe inflation, dark matter, and dark energy
Development of cryogenic detectors for particle physics, cosmology, and astrophysics

Education

Ph. D., Physics, University of California, Berkeley, 2000
Dissertation title: *Exclusion Limits on the WIMP-Nucleon Elastic-Scattering Cross Section from the Cryogenic Dark Matter Search*
Advisor: Bernard Sadoulet
M. A., Physics, University of California, Berkeley, 1995
B. A., Physics, with general and subject honors, University of Chicago, 1993

Employment

Assistant Professor of Physics, California Institute of Technology, 2003–
Millikan Postdoctoral Scholar, Physics, California Institute of Technology, 2000–2003
Graduate Student Research Assistant, Center for Particle Astrophysics and Department of Physics, University of California, Berkeley, 1994–2000
Graduate Student Instructor, Department of Physics, University of California, Berkeley, 1993

Fellowships and Awards

Department of Energy High Energy Physics Outstanding Junior Investigator, 2006 – 2009
Alfred P. Sloan Foundation Research Fellow, September, 2004 – September, 2006
Millikan Postdoctoral Fellowship, Physics, California Institute of Technology, 2000–2003
Mitsuyoshi Tanaka Dissertation Award in Experimental Particle Physics, American Physical Society, 2001
Department of Education Graduate Fellowship, University of California, Berkeley, 1993–1994
Richter Grant for Undergraduate Research, University of Chicago, 1992–1993

Professional Memberships

American Physical Society
American Astronomical Society
Society of Photo-Industrial Engineers

Teaching

Physics 1c, Spring 2005, freshman electricity and magnetism (teaching assistant).
Physics 106ab, Fall 2004-Winter 2005, Fall 2005-Winter 2006, Fall 2006-Winter 2007, analytical mechanics
Physics 125ab, Fall 2007-Winter 2008, Fall 2008-Winter 2009, quantum mechanics
Physics 135c, Spring 2007, seminar course on non-accelerator particle physics

Advisees

Postdoctoral:

Dr. Philippe Rossinot, June 2004–April 2006, antenna-coupled bolometer arrays. Current position: chargé de mission, Centre d'Analyse Stratégique – département recherche technologie et développement durable

Dr. Gensheng Wang, September 2004–August 2007, antenna-coupled bolometer arrays, MKID noise physics, and CDMS data analysis. Current position: Postdoctoral researcher, Materials Science Division, Argonne National Laboratory.

Dr. J. Sayers, January 2008–June 2008, currently NASA Postdoctoral Program Fellow, JPL (Adviser: Dr. H. Nguyen, June 2009–). Bolocam massive cluster Sunyaev-Zeldovich effect observations and analysis, atmospheric noise studies, submm/mm-wave MKID camera, CCAT Sunyaev-Zeldovich effect science planning

Dr. R. Walter Ogburn, January 2008–, Moore postdoctoral scholar, BICEP2/Keck Array CMB polarization experiments

Graduate:

Jack Sayers, July, 2003–December, 2007, Bolocam Sunyaev-Zeldovich survey analysis/atmospheric noise studies. Ph. D., physics, Fall, 2007. Current position: NASA Postdoctoral Program Fellow, JPL (Adviser: Dr. Hien Nguyen)

Zeeshan Ahmed, September, 2005–, CDMS data analysis, development of a multiwire proportional chamber for radioactivity screening. 4th year physics graduate student, candidacy completed.

Nicole Czakon, July, 2008–, development of submm/mm-wave MKID camera, Bolocam massive cluster Sunyaev-Zeldovich effect observations.

Justus Brevik, April, 2006–, (offical adviser: A. Lange). Development and commissioning of focal plane hardware and readout system for BICEP2/Keck Array/SPIDER. 4th year physics graduate student, candidacy completed.

Matthew Ferry, September, 2006–June, 2008, Bolocam massive cluster Sunyaev-Zeldovich effect observations, development of submm/mm-wave MKID camera. 2nd-year physics graduate student, leave of absence taken at end of 2007-2008 academic year.

David Moore, April, 2007–, Development of MKID-based dark matter and optical/UV photon detectors, CDMS data analysis. 3rd year physics graduate student, candidacy completed.

Randol Aikin, September, 2007–, Receiver design for BICEP2/Keck Array/SPIDER CMB polarization experiments, 2nd year physics graduate student.

Ran Duan, September, 2008–, Design of photolithographic bandpass filters for MKIDCam, software-defined radio readout of MKIDs. 1st year electrical engineering graduate student.

Undergraduate, etc.:

Jonathan Bird, Caltech B.S. Physics (2003), research assistant shared with CSO and CCAT, 2005-2006, atmospheric noise simulations.

Callum Lamb, Caltech B.S. Physics (2006), research assistant, development of focal plane hardware for SPIDER and BICEP2/Keck Array. Began graduate school in astronomy at University of Chicago, Fall, 2007.

Randol Aikin, University of Colorado B.A. Astronomy (2006), research assistant, worked on receiver design for SPIDER and BICEP2/Keck Array. Began graduate school in physics at Caltech, Fall, 2007.

Edward Perepelitsky, Caltech B.S. Physics (2008). Bolocam and MKID camera physical optics modeling for SURF and senior thesis projects. Began graduate school in physics at University of California, Santa Cruz, Fall, 2008.

Two prior Caltech Summer Undergraduate Research Fellowship students

A local high school teacher (Tobias Jacoby, Blair High School, PUSD) and five high school students

Committee Memberships, Scientific Service, etc.

Member of the Bolocam instrument team. Bolocam has been available as a facility instrument at the Caltech Submillimeter Observatory from Spring, 2004, onward. 50% of the Observatory's time is available to the international astronomical community. Nine refereed publications have been produced from Bolocam data to date, one is undergoing review, and at least three more are in preparation.

Bolocam representative to Caltech Submillimeter Observatory Time Allotment Committee, Fall, 2003–.

Physics Graduate Admissions Committee, Caltech, 2003–2007.

Cahill Astrophysics Building Commitee, Caltech, 2004–2008.

Keck Institute for Space Studies Committee, Caltech, 2004–2007.

Chair, CMB/Sunyaev-Zel'dovich science working group and member, instrumentation working group, Cornell-Caltech Atacama Telescope (25-m submillimeter/millimeter telescope in Chile under study), 2004–

Proposal Review Panels:

NSF Office of Polar Programs Antarctic Aeronomy and Astrophysics FY2005 panel reviewer

NSF Astronomical Sciences Division Extralactic Astronomy FY2006 mail reviewer

NSF Astronomical Sciences Division Astronomical Technologies and Instrumentation FY2008 mail reviewer

Governing Board, Moore Astrophysics Sensor Initiative, 2006-2012, Caltech.

Author of two companion white papers for the Astro2010 Decadal Survey, *Understanding the State of the Intracluster Medium in Galaxy Clusters* and *Calibration Clusters as a*

Tool for Cosmology via Studies of the Intracluster Medium [5].

Outreach Activities

Participant in Longfellow School Outreach Program, 1994–1996. This program was a partnership between the Center for Particle Astrophysics (UC Berkeley) and Longfellow Middle School (Berkeley), providing materials for hands-on astronomy- and physics-related class activities.

Participant in Caltech Classroom Connection, Fall 2004–. CCC is a program that couples Caltech researchers (faculty, postdocs, and graduate students) with high school science teachers in the Pasadena Unified School District. The Caltech participants aid in development and execution of (math- and physics-related) classroom activities and act as role models for students thinking about career plans. A portion of my research group (1 postdoc, 2 graduate students, and myself) engages in biweekly in-class activities with 3 physics classes at Gabrielino High School (San Gabriel) led by Kevin McClure and, in the past, with 2 physics classes at Pasadena High School led by Ben Taylor. We are exploring a new partnership with J. Thuku.

Participant in Siemens Summer Research Connection, 2008. Jack Sayers and I mentored a local high school teacher and three high school students in a research project on Bolocam sky noise measurements.

Public lecture for middle- and high-school students at Onizuka Visitors' Information Center (Mauna Kea, Hawaii) on the accelerating expansion of the universe, May 2002. Associated article published in local Hawaii newspapers, including the Hawaii Tribune-Herald. The Visitors' Center is run by the Mauna Kea Observatories Outreach Committee and provides educational resources for the children, residents, and visitors on the island of Hawaii through programs and outreach activities.

Public lecture, Caltech Associates, Northern California Commitee, Palo Alto, CA, May 14, 2005.

Public lecture, Caltech Seminar Day, May 21, 2005.

Sunil Golwala — Publications

Asterisks indicate accepted, refereed publications. *Harzing's Publish or Perish*[1] reports a *h*-index of 10 for 14 years since first publication, based only on published papers.

1. S. R. Golwala, S. Ameglio, E. Pierpaoli, and J. Sayers, "A Joint Thermal Sunyaev-Zeldovich Effect and X-ray Deprojection Analysis of 17 Massive Galaxy Clusters," in preparation for *Astrophysical Journal*.

2. D. C. Moore, B. A. Mazin, *et al.*, "Titanium superconducting coplanar waveguide microwave resonators," in preparation for *Journal of Applied Physics*.

3. S. R. Golwala, R. Mahapatra, *et al.*, "Identification of Surface Electron Background in the Cryogenic Dark Matter Search Experiment," in preparation for *Physical Review D*.

4. S. R. Golwala, S. Ameglio, E. Pierpaoli, and J. Sayers, "Sunyaev-Zeldovich Effect Studies of Galaxy Clusters with Bolocam (and Future Instrumentation)," to appear in *Submillimeter Astrophysics and Technology: A Symposium Honoring Thomas G. Phillips*, ASP Conference Series.

5. S. R. Golwala, J. E. Aguirre, *et al.*, "Understanding the State of the Intracluster Medium in Galaxy Clusters," Astro2010 Decadal Survey Science White Paper, (2009).

6. J. Sayers, S. R. Golwala, *et al.*, "Studies of Millimeter-Wave Atmospheric Noise Above Mauna Kea," **astro-ph/0904.3943**, submitted to *Astrophysical Journal*.

7. *J. Sayers, S. R. Golwala, *et al.*, "A Search for Cosmic Microwave Background Anisotropies on Arcminute Scales with Bolocam," *Astrophysical Journal* **690**, 1597–1620 (2009).

8. *Z. Ahmed, D. S. Akerib, *et al.*, "Search for Weakly Interacting Massive Particles with the First Five-Tower Data from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory," *Physical Review Letters* **102**, 011301/1–5 (2009).

9. *C. J. MacTavish, P. A. R. Ade, *et al.*, "Spider Optimization: Probing the Systematics of a Large-Scale B-Mode Experiment," *Astrophysical Journal* **689**, 655–665 (2008).

10. J. Glenn, P. K. Day, *et al.*, "A microwave kinetic inductance camera for sub/millimeter astrophysics," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* (SPIE, Bellingham, Washington, 2008), Vol. 7020.

11. J. Sayers, S. R. Golwala, *et al.*, "Studies of atmospheric noise on Mauna Kea at 143 GHz with Bolocam," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* (SPIE, Bellingham, Washington, 2008), Vol. 7020.

12. D. S. Akerib, C. N. Bailey, *et al.*, "Present Status of the SuperCDMS program," *Journal of Low Temperature Physics* **151**, 818–823 (2008).

13. Z. Ahmed, D. S. Akerib, *et al.*, "Status of the Cryogenic Dark Matter Search Experiment," *Journal of Low Temperature Physics* **151**, 800–805 (2008).

14. J. Schlaerth, A. Vayonakis, *et al.*, "A Millimeter and Submillimeter Kinetic Inductance Detector Camera," *Journal of Low Temperature Physics* **151**, 684–689 (2008).

[1] http://www.harzing.com/resources.htm#/pop.htm

15. S. Golwala, J. Gao, *et al.*, “A WIMP Dark Matter Detector Using MKIDs,” *Journal of Low Temperature Physics* **151**, 550–556 (2008).

16. B. A. Mazin, M. E. Eckart, *et al.*, “Optical/UV and X-Ray Microwave Kinetic Inductance Strip Detectors,” *Journal of Low Temperature Physics* **151**, 537–543 (2008).

17. *G. W. Wilson, J. E. Austermann, *et al.*, “The AzTEC mm-wavelength camera,” *Monthly Notices of the Royal Astronomical Society* **386**, 807–818 (2008).

18. D. S. Akerib, M. J. Attisha, *et al.*, “Surface Event Rejection Using Phonon Information in CDMS,” *Nuclear Physics B Proceedings Supplements* **173**, 137–140 (2007).

19. D. S. Akerib, M. J. Attisha, *et al.*, “CDMS, Supersymmetry and Extra Dimensions,” *Nuclear Physics B Proceedings Supplements* **173**, 95–98 (2007).

20. *B. A. Mazin, B. Bumble, *et al.*, “Position sensitive x-ray spectrophotometer using microwave kinetic inductance detectors,” *Applied Physics Letters* **89**, 222507/1–4 (2006).

21. C. L. Kuo, J. J. Bock, *et al.*, “Antenna-coupled TES bolometers for CMB polarimetry,” in *Proceedings of the SPIE, Vol. 6275: Millimeter and Submillimeter Detectors and Instrumentation for Astronomy III*, edited by Jonas Zmuidzinas, Wayne S. Holland, Stafford Withington, and William D. Duncan (SPIE, Bellingham, Washington, 2006).

22. G. J. Stacey, S. R. Golwala, *et al.*, “Instrumentation for the CCAT Telescope,” in *Proceedings of the SPIE, Vol. 6275: Millimeter and Submillimeter Detectors and Instrumentation for Astronomy III*, edited by Jonas Zmuidzinas, Wayne S. Holland, Stafford Withington, and William D. Duncan (SPIE, Bellingham, Washington, 2006).

23. T. E. Montroy, P. A. R. Ade, *et al.*, “SPIDER: a new balloon-borne experiment to measure CMB polarization on large angular scales,” in *Proceedings of the SPIE, Vol. 6267: Ground-based and Airborne Telescopes*, edited by Larry M. Stepp (SPIE, Bellingham, Washington, 2006).

24. *K. E. Young, M. L. Enoch, *et al.*, “Bolocam Survey for 1.1 mm Dust Continuum Emission in the c2d Legacy Clouds. II. Ophiuchus,” *Astrophysical Journal* **644**, 326–343 (2006).

25. C. L. Kuo, P. Ade, *et al.*, “Antenna-coupled TES bolometers for the SPIDER experiment,” *Nuclear Instruments and Methods in Research A* **559**, 608–610 (2006).

26. D. S. Akerib, M. J. Attisha, *et al.*, “The SuperCDMS proposal for dark matter detection,” *Nuclear Instruments and Methods in Research A* **559**, 411–413 (2006).

27. D. S. Akerib, M. J. Attisha, *et al.*, “Limits on WIMP nucleon interactions from the Cryogenic Dark Matter Search at the Soudan Underground Laboratory,” *Nuclear Instruments and Methods in Research A* **559**, 390–392 (2006).

28. D. S. Akerib, M. J. Attisha, *et al.*, “Characterization, performance, and future advanced analysis of detectors in the cryogenic dark matter search (CDMS-II),” *Nuclear Instruments and Methods in Research A* **559**, 387–389 (2006).

29. *M. L. Enoch, K. E. Young, *et al.*, “Bolocam Survey for 1.1 mm Dust Continuum Emission in the c2d Legacy Clouds. I. Perseus,” *Astrophysical Journal* **638**, 293–313 (2006).

30. *D. S. Akerib, M. J. Attisha, *et al.*, "Limits on Spin-Independent Interactions of Weakly Interacting Massive Particles with Nucleons from the Two-Tower Run of the Cryogenic Dark Matter Search," *Physical Review Letters* **96**, 011302/1–5 (2006).

31. *D. S. Akerib, M. S. Armel-Funkhouser, *et al.*, "Limits on spin-dependent WIMP-nucleon interactions from the Cryogenic Dark Matter Search," *Physical Review D* **73**, 011102/1–5 (2006).

32. *P. R. Maloney, J. Glenn, *et al.*, "A Fluctuation Analysis of the Bolocam 1.1 mm Lockman Hole Survey," *Astrophysical Journal* **635**, 1044–1052 (2005).

33. P. L. Brink, B. Cabrera, *et al.*, "Beyond the CDMS-II Dark Matter Search: SuperCDMS,"*Proceedings of the 22nd Texas Symposium on Relativistic Astrophysics, http://www.slac.stanford.edu/econf/C041213/* (Stanford Linear Accelerator Center Conference Proceedings Archive, Palo Alto, CA, 2005), p. 2529.

34. *G. T. Laurent, J. E. Aguirre, *et al.*, "The Bolocam Lockman Hole Millimeter-Wave Galaxy Survey: Galaxy Candidates and Number Counts," *Astrophysical Journal* **623**, 742–762 (2005).

35. T. Herter, R. Brown, *et al.*, "The large Atacama submillimeter telescope," in *Proceedings of the SPIE, Vol. 5498: Millimeter and Submillimeter Detectors for Astronomy II*, edited by J. Zmuidzinas and W. S. Holland (SPIE, Bellingham, Washington, 2004), pp. 55–62.

36. D. J. Haig, P. A. R. Ade, *et al.*, "Bolocam: status and observations," in *Proceedings of the SPIE, Vol. 5498: Millimeter and Submillimeter Detectors for Astronomy II*, edited by J. Zmuidzinas and W. S. Holland (SPIE, Bellingham, Washington, 2004), pp. 78–94.

37. D. S. Akerib, J. Alvaro-Dean, *et al.*, "Installation and commissioning of the CDMSII experiment at Soudan," *Nuclear Instruments and Methods in Research A* **520**, 116–119 (2004).

38. R. W. Schnee, D. Abrams, *et al.*, "Results from the 1998-1999 runs of the Cryogenic Dark Matter Search," *Nuclear Physics B (Proceedings Supplements)* **124**, 185–188 (2003).

39. *D. S. Akerib, J. Alvaro-Dean, *et al.*, "New results from the Cryogenic Dark Matter Search experiment," *Physical Review D* **68**, 82002/1–4 (2003).

40. J. Glenn, P. A. R. Ade, *et al.*, "Current status of Bolocam: a large-format millimeter-wave bolometer camera," in *Proceedings of the SPIE, Vol. 4855: Millimeter and Submillimeter Detectors for Astronomy*, edited by T. G. Phillips and J. Zmuidzinas (SPIE, Bellingham, Washington, 2003), pp. 30–40.

41. *D. Abrams, D. S. Akerib, *et al.*, "Exclusion Limits on the WIMP-Nucleon Cross Section from the Cryogenic Dark Matter Search," *Physical Review D* **66**, 122003/1–35 (2002).

42. P. Mauskopf, P. Ade, *et al.*, "Results from the first engineering run of BOLOCAM and plans for the future," in *AIP Conference Proceedings 616: Experimental Cosmology at Millimetre Wavelengths* (American Institute of Physics, Melville, New York, 2002), pp. 107–115.

43. J. Glenn, B. Knowles, *et al.*, "Millimeter-Wave Cosmology with Bolocam: Discovering Galaxies and Clusters with Deep, Unbiased Surveys," in *ASP Conference Series 283: A New Era in Cosmology* (Astronomical Society of the Pacific, San Francisco, 2002), pp. 398–+.

44. T. Shutt, M. Kesden, *et al.*, "Charge collection and electrode structures in ionization and phonon based dark matter detectors," in *AIP Conference Proceedings 605: Low Temperature Detectors, Ninth International Workshop on Low Temperature Detectors* (American Instititute of Physics, Melville, New York, 2002), pp. 513–516.

45. T. A. Perera, D. Abrams, *et al.*, "Present results and future goals of the Cryogenic Dark Matter Search," in *AIP Conference Proceedings 605: Low Temperature Detectors, Ninth International Workshop on Low Temperature Detectors* (American Instititute of Physics, Melville, New York, 2002), pp. 485–488.

46. B. Cabrera, R. Abusaidi, *et al.*, "Status of the CDMS Search for Dark Matter WIMPs (Plenary Talk)," in *AIP Conference Proceedings 586: 20th Texas Symposium on Relativistic Astrophysics* (American Instititute of Physics, Melville, New York, 2001), pp. 107–+.

47. S. R. Golwala, "Exclusion Limits on the WIMP-nucleon Elastic-Scattering Cross-Section from the Cryogenic Dark Matter Search," Ph.D. thesis, University of California, Berkeley, 2000.

48. *R. Abusaidi, D. S. Akerib, *et al.*, "Exclusion Limits on the WIMP-Nucleon Cross Section from the Cryogenic Dark Matter Search," *Physical Review Letters* **84**, 5699–5703 (2000).

49. S. R. Golwala, R. Abusaidi, *et al.*, "Exclusion Limits on the WIMP-Nucleon Scattering Cross-Section from the Cryogenic Dark Matter Search," *Nuclear Instruments and Methods in Research A* **444**, 345–349 (2000).

50. D. S. Akerib, P. D. Barnes, *et al.*, "Limits on the WIMP-Nucleon Cross Section from the Cryogenic Dark Matter Search," *Nuclear Physics B (Proceedings Supplements)* **80**, 235 (2000).

51. A. Sonnenschein, D. A. Bauer, *et al.*, "Results of the Cryogenic Dark Matter Search (CDMS) Obtained with Thermistor-Instrumented Germanium Calorimeters," in *The Identification of Dark Matter* (World Scientific, Singapore, 1999), pp. 347–+.

52. D. S. Akerib, P. D. Barnes, *et al.*, "Preliminary Limits on the WIMP-Nucleon Cross Section from the Cryogenic Dark Matter Search," *Nuclear Physics B (Proceedings Supplements)* **70**, 64–68 (1999).

53. *J. Jochum, C. Mears, *et al.*, "Modeling the power flow in normal conductor-insulator-superconductor junctions," *Journal of Applied Physics* **83**, 3217–3224 (1998).

54. T. Shutt, M. Cunningham, *et al.*, "Studies of the Dead Layer in BLIP Dark Matter Detectors," in *Proceedings of the Seventh International Workshop on Low Temperature Detectors*, edited by S. Cooper (Max Planck Institute of Physics, Munich, 1997), pp. 224–226.

55. J. Jochum, S. Golwala, *et al.*, "Modeling the Power Flow in NIS Junctions," in *Proceedings of the Seventh International Workshop on Low Temperature Detectors*, edited by S. Cooper (Max Planck Institute of Physics, Munich, 1997), pp. 60–63.

56. S. R. Golwala, J. Jochum, and B. Sadoulet, "Noise Considerations in Low Resistance NIS Junctions," in *Proceedings of the Seventh International Workshop on Low Temperature Detectors*, edited by S. Cooper (Max Planck Institute of Physics, Munich, 1997), pp. 56–59.

57. R. J. Gaitskell, R. Therrien, *et al.*, "Performance of 165 g Ge BLIP Detectors in CDMS Experiment," in *Proceedings of the Seventh International Workshop on Low Temperature Detectors*, edited by S. Cooper (Max Planck Institute of Physics, Munich, 1997), pp. 221–223.

58. O. B. Drury, J. P. Castle, *et al.*, “Effect of Geometry and Film Thickness on Self-Cooling of SIN Junctions Intended for Particle Detector Applications,” in *Proceedings of the Seventh International Workshop on Low Temperature Detectors*, edited by S. Cooper (Max Planck Institute of Physics, Munich, 1997), pp. 224–226.

59. J. Jochum, P. D. Barnes, *et al.*, “Looking for WIMPs: The Cryogenic Dark Matter Search,” in *Dark Matter in Astro- and Particle Physics (DARK 96)*, edited by H. V. Klapdor-Kleingrothaus and Y. Ramachers (World Scientific, Singapore, 1997), pp. 445–+.

60. T. Shutt, D. S. Akerib, *et al.*, “Progress of the Cryogenic Dark Matter Search (CDMS) experiment,” *Nuclear Physics B (Proceedings Supplements)* **51**, 318–322 (1996).

61. P. D. Barnes, A. da Silva, *et al.*, “Installation of the Cryogenic Dark Matter Search (CDMS),” *Nuclear Instruments and Methods in Research A* **370**, 233–236 (1996).

62. F. Azgui, C. A. Mears, *et al.*, “Non-equilibrium normal metal superconducting tunnel junction detectors,” *Nuclear Instruments and Methods in Research A* **370**, 121–123 (1996).

63. T. Shutt, D. S. Akerib, *et al.*, “Recent results with a 62 g Ge cryogenic dark matter detector,” *Nuclear Instruments and Methods in Research A* **370**, 165–167 (1996).

64. B. Sadoulet, D. Akerib, *et al.*, “Particle detection and non-equilibrium phonons: Experience with large germanium crystals and NTD Ge thermistors,” *Physica B Condensed Matter* **219**, 741–743 (1996).

Sunil Golwala — Research Activities

Bolocam

As a Millikan scholar at Caltech during the period 2000–2003, I led the commissioning and first science observations with Bolocam, a 144-pixel bolometer camera operating at 1.1 mm and 2.1 mm wavelength at the Caltech Submillimeter Observatory (CSO). This work was done in collaboration with James Aguirre (University of Pennsylvania), Jamie Bock (Jet Propulsion Laboratory), Jason Glenn (University of Colorado), Andrew Lange (Caltech), and Phil Mauskopf (University of Wales, Cardiff). This involved rebuilding much of the camera, solving assorted optical, cryogenic, electronics, and data acquisition problems, and developing many of the data analysis algorithms.

The primary science topic of my research in connection to Bolocam is the study of galaxy clusters using the thermal Sunyaev-Zeldovich (tSZ) effect. The tSZ effect is a spectral distortion of the cosmic microwave background due to Compton scattering of the CMB with free electrons in the hot (10^8 K) intracluster medium of galaxy clusters. The tSZ effect has the unique characteristics of being largely redshift independent (because the CMB was hotter at the time it encountered a more distant galaxy cluster) and a fairly good measure of the total cluster mass (because it depends linearly on the number of electrons).

The tSZ effect is thus both interesting as a means for finding galaxy clusters with an approximately mass-limited selection function and for studying them in detail. A survey for galaxy clusters using the tSZ effect can constrain cosmological parameters because the angular density of clusters and their number density as a function of lookback time depend strongly on the amounts of dark matter and dark energy present in the universe and on the normalization of the power spectrum of density fluctuations, σ_8. The tSZ anisotropy power spectrum alone is quite sensitive to σ_8. Imaging the tSZ effect is interesting because it provides a new and possibly more robust means than X-ray or optical imaging to measure cluster mass and test scaling relations, which are expectations for how observables like total tSZ flux scale with cluster mass or electron temperature. The slopes and normalizations of these scaling relations are sensitive to various physical effects such as radiative cooling, entropy and metal injection from star formation and cosmic rays, merger history, magnetic fields, and shocks. Combining tSZ and X-ray data via deprojection analysis provides a means to measure the density and temperature profile of the intracluster medium without requiring X-ray spectroscopic data.

Thus, we have undertaken two complementary tSZ programs with Bolocam: 1) a survey to constrain tSZ-induced anisotropy due to the ensemble of clusters between us and the surface of last scattering; and 2) imaging of known massive clusters in the tSZ effect with high spatial resolution and signal-to-noise. The survey work has been supported by startup funds and a NASA GSRP fellowship to former physics graduate student Sayers. The imaging work has been supported by startup funds, NASA GSRP fellowships to physics graduate students Matthew Ferry and Nicole Czakon, and the Moore Foundation. A proposal has been submitted to NSF for continuing support.

For the anisotropy/cluster search, we surveyed two science fields totaling 1 $\deg^2$ at 2.1 mm. The fields are in the Lynx and Subaru/XMM SDS1 fields. Our survey is sensitive to angular scales with an effective angular multipole of $\ell_{eff} = 5700$ with $\mathrm{FWHM}_\ell = 2800$ and has an angular resolution of 60 arcseconds FWHM. Our data provide no evidence for anisotropy. We are able to constrain the level of total astronomical anisotropy, modeled as a flat bandpower in angular power spectrum C_ℓ, with frequentist 68%, 90%, and 95% CL upper limits of 590, 760, and 830 $\mu\mathrm{K_{CMB}}^2$. We statistically subtract the known contribution from primary CMB anisotropy, including cosmic variance, to obtain constraints on the tSZ anisotropy contribution. Now including flux calibration uncertainty, our frequentist 68%, 90% and 95% CL upper limits on a flat bandpower in C_ℓ are 690, 960, and 1000 μK_{CMB}^2. We obtain a 90% CL upper limit on σ_8 of 1.57. While this constraint on σ_8 is not competitive as a determination of a cosmological parameter — current best constraints are $\sigma_8 = 0.81 - 0.85$ with uncertainties of $0.03 - 0.04$ — these are the first constraints on anisotropy and σ_8 from tSZ survey data at this range of angular scales at millimeter wavelengths. This work has been published in *Astrophysical Journal* [9] and was the topic of the Ph. D. dissertation of physics graduate student Jack Sayers, defended in December, 2007. This work has only recently been superceded by a similar survey with APEX-SZ, submitted for publication in April, 2009, that yields a factor of 10 tighter constraint on the anisotropy power spectrum (three times more sensitive in map rms).

Obtaining the best possible sensitivity is of course critical when one is trying to detect or constrain such a low-level signal as the tSZ anisotropy. We established pointing and flux calibration to 5-6% precision, unprecedented for arcminute-scale millimeter-wave observations and limited primarily by the overall 5% uncertainty of the temperature of Mars. We fully analyzed the phenomenology of the sky noise (fluctuations in atmospheric thermal emission due to variations in line-of-sight water vapor column) and optimized the sky noise removal. We developed algorithms to make pseudo-optimal maps of the data and to estimate the signal transfer function of the analysis pipeline. Our analysis of the sky noise is the most complete to date at millimeter wavelengths and for arcminute-scale observations. It has been submitted for publication in *Astrophysical Journal* [6].

Using our now deep understanding of the Bolocam instrument, we are also imaging massive galaxy clusters in the tSZ effect. This project has waited until the instrument was well understood because, to efficiently image cluster fields that are comparable in size to the instrument field-of-view, we must use an unorthodox scanning pattern in which the telescope is driven in a variable speed Lissajous pattern. The constant acceleration and modulation of spillover could in principle be problematic, but we have demonstrated successful reductions of four fields already. We have data at 2.1 mm on 19 clusters in hand.

Approximately 60 clusters have been imaged in the tSZ effect at radio frequencies (15-30 GHz) using interferometers. The tSZ effect has been robustly detected in 10-20 clusters at millimeter wavelengths. However, to date, there are no more than handful of published *images*. Interferometric observations inevitably impose a spatial filter and have their own possible systematics, of which the most problematic is radio point source contamination given the lower frequency at which interferometry has been used. We therefore think it is valuable to image tens clusters with Bolocam at 2.1 mm to test the interferometric observations and to perform our own independent study of cluster scaling relations and measurements of radio profiles. We expect to submit a publication on an initial analysis of the 19 clusters in hand during 2009 followed by a more refined analysis. We are also engaging the groups pursuing similar observations with SZA and CBI2 at 30 GHz to do joint analyses. Finally, this project feeds into a follow-on pointed cluster program with the CSO MKID camera, described below.

Aside from the scientific impact of the above work — the first blind surveys for the tSZ effect at arcminute scales at millimeter wavelengths, the first extensive millimeter-wave imaging of the tSZ effect in massive clusters — it is clear from interactions with colleagues working on the APEX-SZ, ACT, and SPT surveys (more ambitious surveys of the kind we have undertaken) that they have appreciated and adopted many of our technical developments. Sayers' dissertation was made made available to these groups, and our paper has already been cited in most of the later published work in this field.

In addition to the above work led by Caltech, a number of other surveys have been done with Bolocam. The instrument team itself 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 co-author [34, 32], 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. 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 are unique in being 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. This has allowed us to dig deeper than has been previously possible and obtain the deepest available constraints on the power law of the number counts of submillimeter galaxies. Even the massive SHADES survey using the JCMT over many months has to date produced constraints no better than ours. My group contributed 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. This latter algorithm has been widely adopted by other tSZ survey programs, as noted above. We also contributed in an advisory role to the science analyses.

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 [29, 24], 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. These galactic studies have mapped larger regions to lower protostellar core mass ($\sim$ 0.2 M$_\circ$) than have been done to date with any other instrument. My group played an important role in the development of a novel iterative mapmaking scheme 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.

The Spitzer program has been very scientifically productive. When combined with Spitzer and other data, the surveys indicate approximately equal numbers of starless cores and embedded protostars in each cloud, yielding a Class 0 lifetime of 1–2$\times10^5$ yr. This lifetime, only a few free-fall timescales, is considerably shorter than the timescale predicted by the scenario of magnetic field support and thus suggests that turbulence is the dominant process controlling the formation and evolution of dense cores. However, dense cores in all three clouds are found only at high cloud column densities, $A_V \gtrsim 7$ mag, and the fraction of cloud mass in these cores is less than 10%, indicating that magnetic fields must play some role as well. The prestellar core mass distribution has a slope of $\alpha = -2.3 \pm 0.4$ for $M > 0.8\ M_\odot$, similar to measurements of the slope of the stellar initial mass function, providing support for the hypothesis that stellar masses are determined during the core formation process.

CSO MKID Camera

With Jonas Zmuidzinas, JPL scientists Peter Day, Rick LeDuc, and Hien Nguyen, Ben Mazin of the University of California at Santa Barbara, and Jason Glenn of the University of Colorado, we are constructing a new camera for the CSO using antenna-coupled microwave kinetic inductance detectors (MKIDs). The antenna-coupling technology, developed by a team led by Bock, Lange, and Zmuidzinas, provides a means to define beams without bulky metal feedhorns; instead, a phased array of photolithographed dipole antennae is used. The antenna functions over an octave of bandwidth. The power exiting the antenna can be sorted into colors using in-line photolithographic bandpass filters, developed by Zmuidzinas's group. Finally, the power in each color is detected by

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

a MKID, a revolutionary superconducting detector, also developed by Zmuidzinas's group, that is easily multiplexed. The entire focal plane array, from beam-defining elements to detectors, is fabricated photolithographically on a single wafer at JPL's Microdevices Laboratory. This novel array enables a multicolor camera that covers the available CSO field-of-view with 600 spatial pixels, each sensitive in each of four colors (740 μm, 850 μm, 1.1 mm, and 1.3 mm). The NSF ATI program has funded a \$1.2M proposal by Glenn and myself to build this camera, to be fielded in 2010. Additional support is being provided by the Moore Astrophysics Sensor Initiative (a grant from the Gordon and Betty Moore Foundation to Lange, Zmuidzinas, and myself), NASA APRA grants to Zmuidzinas and Day, and JPL Research and Technology Development funds. Former graduate student Jack Sayers has moved to a NASA Postdoctoral Program Fellowship position at JPL with Nguyen to work on this camera. The Caltech team also includes postdoctoral scholar Matt Hollister, who did his dissertation on the construction and commissioning of SCUBA-2, incoming postdoctoral scholar Tom Downes (University of Chicago), and graduate students Nicole Czakon (physics), Ran Duan (EE), and Omid Noroozian (EE).

This camera will have impact in a number of scientific areas. My primary interest is to use it to map galaxy clusters in the tSZ effect at 1.1 mm, where the signal is an increment instead of a decrement. The multicolor design of the camera will provide for spectral sky noise removal — correlation of the atmospheric signal in the different colors seen in each pixel. Comparison of Bolocam 2.1 mm data with older SuZIE data indicates that this method will be much more effective than the spatial correlation methods used for Bolocam. (A wide-field, multicolor camera was not feasible at the time we began Bolocam.) Thus, the maps we obtain at 1.1 mm should thus have better sensitivity and suffer less spatial filtering than our existing Bolocam 2.1 mm maps. We will be able to access structure on larger and smaller angular scales as well as robustly test our Bolocam 2.1 mm maps. The 1.3 mm band of this camera will be sensitive to the kinetic SZ (kSZ) effect, which is a Doppler shift of the CMB due to its scattering with a moving galaxy cluster. And, the higher frequency bands will be critical for detecting dusty submillimeter point sources that may contaminate the maps (and which will be more problematic at 1.1 mm than at 2.1 mm).

Other projects will include surveys for and photometry of dusty submillimeter galaxies and of star-forming regions in our own galaxy. The multiple bands and large pixel count of the camera will render it comparable to the upcoming SCUBA-2 850 μm/450 μm submillimeter camera in mapping speed at 5% of the cost. The multicolor information will give us greater ability to find the most interesting sources — those with unexpected spectra, reflecting perhaps either a very high redshift or unusual dust properties — without resorting to follow-up observations. We will make multicolor maps of thermal emission from dust in our own and nearby galaxies, probing the properties of the dust that will be useful in understanding more distant sources and, hopefully, providing new information on dust foreground emission for CMB polarization anisotropy experiments (see below).

As part of this project, our collaboration built, under my direct leadership, a small camera to demonstrate and learn how to use antenna-coupled MKIDs. In April, 2007, we obtained first light with this camera and imaged Jupiter, Saturn, and some bright galactic sources, making use of the Bolocam software pipeline to obtain first maps only three hours after first pointing at the sky [14]. Lessons learned from this demonstrator are proving critical to the success of the full-size camera — we are encountering and solving a number of problems that we might not have otherwise seen until this year. The demonstrator camera serves as our primary laboratory test dewar and will return to the CSO in Fall, 2009, for an engineering run in which we expect to demonstrate background-limited sensitivity in a sub-array (1/16 of the full camera).

For the past year, laboratory work by Czakon and Hollister has proceeded primarily under my supervision. We have exhaustively tested and understood, to the extent possible, the devices used in the 2007 demonstration using a number of novel techniques developed by Zmuidzinas' student

Tasos Vayonakis during 2007 and 2008. We have fabricated a new array design that incorporates innovations developed by Zmuidzinas, Noroozian, and others to reduce fundamental device noise by a factor of three. It also incorporates test structures to enable fuller characterization and understanding of the MKIDs. With Colorado student Schlaerth, we have carefully studied the dependence of mapping speed on resonator and readout parameters and have optimized the design of the new array, also seeing that performance is a mild function of the design. Schlaerth has modifed the optical design and Day has modified the antenna design to provide better coupling in our bands. Duan has studied in detail the bandpass filter electromagnetic design and has optimized the bandpasses for astronomical sensitivity. We have installed a magnetic shield that has reduced the signal induced by external magnetic fields by a factor of 1000. Our Colorado collaborators have set up a parallel optical test dewar using a conventional spiderweb bolometer with a NTD Ge thermistor to validate the optical design independent of our understanding of the MKID devices. And we are expecting delivery of prototype readout electronics this summer, which will provide our first chance to simultaneously read out ~ 100 resonators. Sayers will lead the testing of this component. These changes are being tested and integrated this summer in preparation for a Fall, 2009, engineering run.

Simultaneously, Sayers and Nguyen have taken delivery of the full-size camera dewar and demonstrated its cryogenic performance at JPL. They are currently testing optical filtering configurations to minimize thermal IR loading. Sayers is designing the readout electronics installation for the cryostat. Hollister is designing the focal plane assembly, having designed the most recent iteration of the prototype camera FPU box. This will benefit greatly from our experience with the FPU assembly for BICEP2/Keck Array and SPIDER (discussed below).

CCAT

Cornell University, Caltech, and NASA's Jet Propulsion Laboratory (JPL) are undertaking a project to build a 25-m submillimeter telescope on a high peak above the Atacama desert in Chile. This site, likely the driest in the world, will enable unprecedented sensitivity in submillimeter and millimeter-wave observations. My group has participated in a feasibility study of this ∼$100M project, analyzing the telescope's capabilities for SZ science and defining the facility camera for wavelengths from 740 μm to 2.1 mm. Bolocam sky noise analysis is informing the design of the telescope, placing requirements on scan speeds to ensure good separation of astronomical signal from sky noise. With the completion of our sky noise analysis [6], we have a quantitative, empirically validated sky noise model that we will use to simulate CCAT observations as the telescope enters its detailed engineering phase. We also plan to analyze in detail our ability to separate SZ and submillimeter point source signals in deep maps of galaxy clusters, as well the impact of confusion from tSZ anisotropy. The CSO MKID camera is a pathfinder for the long-wavelength facility camera, demonstrating a number of the technologies necessary for such a large camera. We will likely take a lead role in the final design and construction of the long-wavelength camera, a ∼$8M component of the project.

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. The first, BICEP2/Keck Array (PI: J. Kovac), 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 (Chiang *et al.*, 2009). BICEP2/Keck Array are funded by the NSF Office of Polar Programs and the Keck Foundation. The second, SPIDER (PI: A. Lange), is a NASA APRA-funded balloon payload to survey approximately half the sky in CMB polarization. These complementary experiments will have by far the best sensitivity to this signature of any proposed or ongoing experiment short of a NASA satellite.

The BICEP2/Keck and SPIDER efforts involve a large number of senior personnel at Caltech and JPL, including Kovac (currently a senior postdoctoral scholar, moving to a tenure-track position at Harvard in Fall, 2009), Marcus Runyan (senior postdoctoral scholar), Bock, Lange, and myself, and thus supervisory responsibilities are broadly distributed. Roughly speaking, my group has 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 microphonics and magnetic field response.

We anticipate first light of BICEP2 in the lab during summer, 2009, with one telescope at 150 GHz, followed by deployment to the South Pole in late 2009. 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 take lead roles in analyzing CMB data.

Future CMB work will likely be in two directions: 1) finer angular resolution studies of CMB polarization to study the matter power spectrum and to measure the neutrino mass; and 2) implementation of a MKID-based receiver for Keck Array to demonstrate MKIDs for CMB observations.

CDMS, SuperCDMS, and GEODM

A variety of cosmological observations indicate that 80% of the matter in the Universe is nonbaryonic and dark, presumably in the form of elementary particles produced in the early Universe. Because no such particles have yet been identified in particle accelerators, these observations require new fundamental particle physics. Weakly Interacting Massive Particles (WIMPs) are a particularly interesting generic class of candidates for this dark matter because independent arguments from cosmology and particle physics converge on the same conclusion. A WIMP is generically defined as a massive particle created in the early universe that couples via a weak-scale interaction, allowing it to decouple and stop annihilating when non-relativistic. A weak-scale annihilation cross section naturally results in the observed relic density of nonbaryonic dark matter. Simultaneously, new particle physics at the W and Z scale is required to solve the "hierarchy problem" by canceling radiative corrections that would push the Higgs mass higher than precision electroweak data indicate. The most popular solution, 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. The lightest such partner is stable and is an excellent WIMP candidate with a mass of ~ 1 TeV. The implied galactic WIMP abundance and weak-scale cross section for scattering with nucleons are large enough to render such scattering detectable. Thus, searches for astrophysical dark matter particles seek to solve fundamental problems in both cosmology and particle physics. Recent reports from the National Research Council, OSTP, and P5 have pointed out 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) Collaboration. 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 [10]. 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.

I did my dissertation with this experiment; those results (published in 2000 [48] and 2002 [41]) led the field in sensitivity for two years and were the first interesting exclusion limits on particle dark matter from an experiment using cryogenic detectors. Most importantly, the results were the first test of a claimed detection of particle dark matter by the DAMA experiment, disagreeing with that claim under most model expectations. Other experiments have since also published results that disagree with the claimed detection, and the DAMA group has produced more data with a new setup supporting their original claim. The issue remains unresolved, but there is widespread skepticism in the community of the claim. In addition to the analysis leading to the scientific result, I developed the trigger electronics for the experiment, developed a software package to interface to the data, contributed to running and analysis of data runs prior to my dissertation, and managed the construction of the detectors and cold hardware for my dissertation run.

The CDMS detectors do an incredible job of separating 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 current participation in CDMS is 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. Additionally, we are pursuing low-energy analyses that test alternate interpretations of the DAMA signal. This work has been supported on startup funds, by a DOE Outstanding Junior Investigator grant, and by the Moore Foundation.

With other CDMS colleagues, we have developed an analysis [3] 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 scaling the experiment up by a factor of 4 in mass and sensitivity.

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 physics graduate student Zeeshan Ahmed.

In parallel, we have pursued a deeper understanding of the phonon physics and position reconstruction in the CDMS detectors. We use the phonon signal to define a fiducial volume in the detectors away from the surfaces, allowing us to reject the problematic surface electron events. During his tenure at Caltech, postdoctoral scholar Gensheng Wang continued work he began as a CDMS graduate student to do a simple simulation of the production and propagation of phonons in our detectors. Dr. Wang's work has resulted in analysis techniques that improve our ability to reject backgrounds by a factor of a few, and, more importantly, has opened up a new mode of analysis. A paper on this topic is being prepared for publication. Graduate student Zeeshan Ahmed has improved the position reconstruction algorithm in for the ongoing analysis of the full CDMS II data set, while will require a factor of three improvement in surface-event rejection with the correspondingly larger exposure. This has placed our group in a lead role for the analysis of the full CDMS II data set. During May/June, 2009, we hosted a month-long analysis workshop at Caltech to bring the analysis team together, with typically 5-6 members present at any one time. This substantially increased the rate of progress and should lead to a preprint during July, 2009.

Additionally, graduate student David Moore has been pursuing an analysis specifically tuned for maximal sensitivity at low energies in order to test low-mass WIMP interpretations of the DAMA result. This analysis is on hold because of the ongoing CDMS II full data set analysis, but will be restarted in Fall, 2009.

My group also took a lead role in the writing of the proposal for SuperCDMS Soudan, an upgrade that will reach a cross section of 5×10^{-45} cm^2 by increasing the detector mass from 4 kg to 16 kg, a factor of 10 better than published limits and 4 times better than our expected sensitivity from the full CDMS II data set. This experiment will also fully exploit the reach of the current experimental apparatus The first stage of this program was approved in 2007. We have submitted the proposal for the second stage in Fall, 2008, with approval likely coming by end of Summer, 2009.

The future of this effort lies in two successive generations of experiments. In the near term, we will propose SuperCDMS SNOLAB, an experiment with target mass of 45 to 120 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 for 100-kg target mass. We expect to propose this experiment in 2010. We are told by the agencies that the earliest such an experiment could be funded is FY2011.

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 at 60 GeV WIMP mass (90% CL upper limit). The large target mass will be enabled by significant automation of detector fabrication and testing. We have proposed 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.

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.

MKIDs for Dark Matter Searches

Finally, we are pursuing the use of microwave kinetic inductance sensors (MKIDs) in a CDMS-style phonon-mediated particle detector. We expect that a phonon-mediated detector using MKIDs instead of the current 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 and also opens up new device architectures that could render MKID-based detectors even easier to fabricate than initially expected. Such significant improvements in detector technology would substantially easy the extension of the CDMS technique to ton-scale detector masses.

Graduate student David Moore is performing this work in conjunction with JPL scientist Bruce Bumble and Ben Mazin (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 resulted in one published paper [20] and another one in preparation [2]. The development process has, however, been more difficult than expected — while the above papers demonstrated some basic proofs of principle, they also showed that the two 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 in the process of evaluating Mn-doped Al MKIDs, which we hope will combined the excellent properties of Al MKIDs with the reduced transition temperature needed to partner them with Al phonon absorbers. The recent development by Zmuidzinas and LeDuc of nitride compounds with very high kinetic inductance contributions *and* very low loss (unlike Ti) may enable a new, further simplified architecture. We are evaluating this option now, also.