Subir Sachdev

Brief Curriculum Vitae

Complete C.V.: http://sachdev.physics.harvard.edu/cv.pdf.

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Employment

- Herchel Smith Professor of Physics at Harvard University, July 1, 2015 onwards.
- Chair, Department of Physics, Harvard University, January 1, 2018 to June 30, 2020.
- Professor of Physics at Harvard University, July 1, 2005 to June 30, 2015.
- Miguel Virasoro Visiting International Chair, International Centre for Theoretical Physics, 2024-28.
- Raman Chair, Indian Academy of Sciences, 2023-24.
- Jacques Solvay International Chair in Physics, International Solvay Institutes, Brussels, 2023.
- Visiting Scholar, Flatiron Institute, Simons Foundation, July 2019 onwards.
- Visiting Professor, College de France, May-June 2022.
- Maureen and John Hendricks Distinguished Visiting Professor at the Institute for Advanced Study, Princeton, July 1, 2021 to June 30, 2022.
- Cenovus Energy James Clerk Maxwell Chair in Theoretical Physics (Visiting) at the Perimeter Institute for Theoretical Physics, Feb 1, 2014 to Jan 31, 2019; Feb 1, 2022 to Jan 31, 2025.
- Stanley S. Hanna Visiting Professor, Stanford University, Fall 2017.
- Dr. Homi Bhabha Chair Professorship, Tata Institute of Fundamental Research, July 1, 2016 to June 30, 2019.
- Professor of Physics and Applied Physics at Yale University, July 1, 1995 to June 30, 2005.
- Associate Professor (tenured) of Physics and Applied Physics at Yale University, July 1, 1992 to June 30, 1995.
- Associate Professor (term) of Physics and Applied Physics at Yale University, July 1, 1989 to June 30, 1992
- Assistant Professor of Physics and Applied Physics at Yale University, July 1, 1987 to June 30, 1989
- Postdoctoral Member of Technical Staff at AT&T Bell Laboratories, Murray Hill, NJ from September 1, 1985 to August 31, 1987.

Degrees Received

- High school (upto 10th grade) at St. Joseph's Boys High School, Bangalore, India.
- 11th grade at Kendriya Vidyalaya, ASC Center, Bangalore, India.
- Freshman year at the Indian Institute of Technology, Delhi, 1978-79
- S.B. (Bachelor of Science) in Physics from the Massachusetts Institute of Technology, February 1982.
- A.M. (Master of Arts) in Physics from Harvard University, June 1984.
- Ph.D. in Theoretical Physics from Harvard University, November 1985. Thesis title: Frustration and Order in Rapidly Cooled Metals.
- M.A. (honorary) from Yale University, 1995.

Introduction to Research

Sachdev's research describes the consequences of quantum entanglement on the macroscopic properties of natural systems. He has made extensive contributions to the description of the diverse varieties of states of quantum matter, and of their behavior near quantum phase transitions. Many of these contributions have been linked to experiments, especially to the rich phase diagrams of the copper-oxide high temperature superconductors. Sachdev's research has also exposed remarkable connections between the nature of multi-particle quantum entanglement in certain laboratory materials, and the quantum entanglement in astrophysical black holes, and these connections have led to new insights on the entropy and radiation of black holes proposed by Stephen Hawking.

Research Highlights

See selected papers with commentaries.

Sachdev has studied the nature of quantum entanglement in two-dimensional antiferromagnets, introducing several key ideas in a series of papers in 1989-1992. He has developed the theory of quantum criticality, elucidating its implications for experimental observations on materials at non-zero temperature. In this context, he proposed a solvable model of complex quantum entanglement in a metal which does not have any particle-like excitations in Physical Review Letters **70**, 3339 (1993): an extension of this is now called the Sachdev-Ye-Kitaev (SYK) model. These works have led to a theory of quantum phase transitions in metals in the presence of impurity-induced disorder, and a universal theory of strange metals in Science **381**, 790 (2023); this theory applies to a wide variety of correlated electron materials, including the copper-oxide materials exhibiting high temperature superconductivity. Many puzzling features of the 'psuedogap' phase of these materials are addressed by his works on the interplay between antiferromagnetism and superconductivity. A connection between the structure of quantum entanglement in the SYK model and in black holes was first proposed by Sachdev in Physical Review Letters **105**, 151602 (2010), and these connections have led to extensive developments in the quantum theory of black holes.

Sachdev has written 3 books describing these works: *Quantum Phase Transitions* (1999), *Holographic Quantum Matter* (with Andrew Lucas and Sean Hartnoll, 2018), and *Quantum Phases of Matter* (2023).

See also the description of his work on the Wikipedia page: Subir Sachdev.

Quantum criticality, superconductors, and black holes

Extreme examples of complex quantum entanglement arise in metallic states of matter without quasiparticle excitations, often called *strange metals*. Such metals are invariably present in higher temperature superconductors, above the highest transition temperatures for superconductivity. The strange metallicity and superconductivity are manifestations of an underlying quantum critical state of matter without quasiparticle excitations. Remarkably, there is an intimate connection between the quantum physics of strange metals in modern materials (which can be studied in tabletop experiments), and quantum entanglement near black holes of astrophysics.

This connection is most clearly seen by thinking more carefully about the defining characteristic of a strange metal: the absence of quasiparticles. In practice, given a state of quantum matter, it is difficult to completely rule out the existence of quasiparticles: while one can confirm that certain perturbations do not create single quasiparticle excitations, it is almost impossible to rule out a non-local operator which could create an exotic quasiparticle in which the underlying electrons are non-locally entangled. Using theories of quantum phase transitions, Sachdev argued (*Quantum Phase Transitions*, Physical Review B **56**, 8714 (1997)) instead that it is better to examine how rapidly the system loses quantum phase coherence, or reaches local thermal equilibrium in response to general external perturbations. If quasiparticles existed, dephasing would take a long time during which the excited quasiparticles collide with each other. In contrast, states without quasiparticles reach local thermal equilibrium in the fastest possible time, bounded below by a value of order (Planck constant)/((Boltzmann constant)×(absolute temperature)). Sachdev proposed (Physical Review Letters **70**, 3339 (1993), Physical Review X **5**, 041025 (2015)) a solvable model of a strange metal (a variant of which is now called the Sachdev-Ye-Kitaev (SYK) model), which was shown to saturate such a bound on the time to reach quantum chaos (Journal of High Energy Physics **2016**, 106 (2016)).

We can now make the connection to the quantum theory of black holes: quite generally, black holes also thermalize and reach quantum chaos in a time of order (Planck constant)/((Boltzmann constant) x (absolute temperature)), where the absolute temperature is the black hole's Hawking temperature. And this similarity to quantum matter without quasiparticles is not a co-incidence: Sachdev argued (Physical Review Letters **105**, 151602 (2010)) that the SYK model maps holographically to the low energy physics of charged black holes in 4 spacetime dimension. Also key to this connection was the fact that charged black holes have a non-zero entropy in the limit of zero temperature, as does the SYK model when the zero temperature limit is taken after the large size limit (Physical Review B **63**, 134406 (2001)).

These and other related works on quantum criticality by Sachdev and collaborators have led to valuable insights on the properties of electronic quantum matter, and on the nature of Hawking radiation from black holes. Solvable models related to gravitational duals and the SYK model have led to the discovery of more realistic models of quantum phase transitions in the high temperature superconductors and other compounds. Advances in the theory of quantum transitions in metals in the presence of impurities have led to a universal theory of strange metals which applies across a wide range of correlated electron compounds. Such predictions (Physical Review B **78**, 115419 (2008), Science **381**, 790 (2023)) have been connected to experiments on graphene (Science **351**, 1055 (2016), Science **351**, 1058 (2016)) and the cuprate superconductors (Nature Communications **14**, 3033 (2023)). The SYK model plays a key role in the computation of the density of low energy quantum states of non-supersymmetric charged black holes in 4 spacetime dimensions (arXiv:2209.13608, arXiv:2304.13744), and provides the underlying Hamiltonian system upon which advances on the Page curve of entanglement entropy of evaporating black holes have been based (see arXiv:2201.03096 for a review).

Sachdev has also developed the theory of critical quantum spin liquids which feature fractionalization and emergent gauge fields, along with absence of quasiparticles. Such spin liquids play an important role in the theory of the cuprate superconductors.

Resonating valence bonds and $\mathbb{Z}_2$ quantum spin liquids

P.W. Anderson proposed in 1973 that Mott insulators realize antiferromagnets which could form resonating valence bond (RVB) or quantum spin liquid states with an energy gap to spin excitations without breaking time-reversal symmetry. It was conjectured that such RVB states have excitations with fractional quantum numbers, such as a fractional spin 1/2. The existence of such RVB ground states, and of the deconfinement of fractionalized excitations was first established by Read and Sachdev (Physical Review Letters **66**, 1773 (1991)) and Wen (Physical Review B **44**, 2664 (1991)) by the connection to a $\mathbb{Z}_2$ gauge theory. Sachdev was also the first to show that the RVB state is an 'odd' $\mathbb{Z}_2$ gauge theory, (Physical Review B **44**, 686 (1991), Journal of the Physical Society of Japan **69,** Suppl. B, 1 (2000), Reports on Progress in Physics **82,** 014001 (2019)). An odd $\mathbb{Z}_2$ spin liquid has a background $\mathbb{Z}_2$ electric charge on each lattice site (equivalently, translations in the x and y directions anti-commute with each other in the super-selection sector of states associated with a $\mathbb{Z}_2$ gauge flux (also known as the m sector)). Sachdev showed that antiferromagnets with half-integer spin form odd $\mathbb{Z}_2$ spin liquids, and those with integer spin form even $\mathbb{Z}_2$ spin liquids. Using this theory, various universal properties of the RVB state were understood, including constraints on the symmetry transformations of the anyon excitations. Sachdev also obtained many results on the confinement transitions of the RVB state, including restrictions on proximate quantum phases and the nature of quantum phase transitions to them.

The topological order (*i.e.* ground state degeneracies on 2-manifolds) and anyons of $\mathbb{Z}_2$ quantum spin liquids are identical to those which appeared later in the solvable toric code model, which plays a key role in quantum error correction in qubit devices.

$\mathbb{Z}_2$ spin liquids are ground states of spin models on the kagome lattice, and this has been connected to experiments on correlated electron materials and arrays of trapped Rydberg atoms.

Honors

- Miguel Virasoro Visiting International Chair, International Centre for Theoretical Physics, 2024-28.
- PROSE (PROfessional and Scholarly Excellence) Award Winner (2024) in the category of chemistry, physics, astronomy and cosmology. Awarded by the Association of American Publishers for Quantum Phases of Matter.
- Raman Chair, Indian Academy of Sciences, 2023-24.
- Foreign Member, The Royal Society, 2023.
  Citation: Subir Sachdev has made profound contributions to theoretical condensed matter physics research. His main interests have been in quantum magnetism, quantum criticality, and perhaps most innovative of all, links between the nature of quantum entanglement in black holes and strongly interacting electrons in materials.
- Jacques Solvay International Chair in Physics 2023, International Solvay Institutes, Brussels.
- Member of the American Academy of Arts and Sciences, 2019.
- Honorary Fellow of the Indian Academy of Sciences, Bengaluru, 2019.
- Foreign Fellow of the Indian National Science Academy, 2019.
- New England Choice Award, Academics, 2018.
- Dirac Medal, International Center for Theoretical Physics, Trieste, 2018; shared with Dam Thanh Son and Xiao-Gang Wen for "independent contributions towards understanding novel phases in strongly interacting many-body systems, introducing original transdisciplinary techniques".

Citation: Subir Sachdev has made pioneering contributions to many areas of theoretical condensed matter physics. Of particular importance were the development of the theory of quantum critical phenomena in insulators, superconductors and metals; the theory of spin-liquid states of quantum antiferromagnets and the theory of fractionalized phases of matter; the study of novel deconfinement phase transitions; the theory of quantum matter without quasiparticles; and the application of many of these ideas to a priori unrelated problems in black hole physics, including a concrete model of non-Fermi liquids.

- Lars Onsager Prize, American Physical Society, 2018.
  Citation: for his seminal contributions to the theory of quantum phase transitions, quantum magnetism, and fractionalized spin liquids, and for his leadership in the physics community.
- Star Family Prize for Excellence in Advising, Certificate of Distinction, Harvard University, 2016.
- Dirac Medal for the Advancement of Theoretical Physics, the Australian Institute of Physics, the University of New South Wales, and the Royal Society of New South Wales, 2015.
  Citation: The Dirac Medal was awarded to Professor Sachdev in recognition of his many seminal contributions to the theory of strongly interacting condensed matter systems: quantum phase transitions, including the idea of critical deconfinement and the breakdown of the conventional symmetry based Landau-Ginsburg-Wilson paradigm; the prediction of exotic 'spin-liquid' and fractionalized states; and applications to the theory of high-temperature superconductivity in the cuprate materials.
- Elected to the U.S. National Academy of Sciences, April 2014.
  Citation: Sachdev has made seminal advances in the theory of condensed matter systems near a quantum phase transition, which have elucidated the rich variety of static and dynamic behavior in such systems, both at finite temperatures and at $T = 0$. His book, *Quantum Phase Transitions*, is the basic text of the field.
- Salam Distinguished Lectures, The Abdus Salam International Center for Theoretical Physics, Trieste, Italy, January 27-30, 2014.
- Lorentz Chair, Instituut-Lorentz, 2012
- Distinguished Visiting Research Chair at the Perimeter Institute for Theoretical Physics, 2009 onwards
- Highly ranked in Diffusion of scientific credits and the ranking of scientists, F. Radicchi, S. Fortunato, B. Markines, and A. Vespignani, Physical Review E **80**, 056103 (2009).
- APS Outstanding Referee, 2009.
- John Simon Guggenheim Memorial Foundation fellow, 2003.
- Fellow of the American Physical Society, 2001.
  Citation: For his contributions to the theory of quantum phase transitions and its application to correlated electron materials.
- Creativity Award from the National Science Foundation, May 1998.
- Alfred P. Sloan Foundation Fellow, February 1989.
- Presidential Young Investigator Award, National Science Foundation, July 1988 - July 1993.
- LeRoy Apker Award, American Physical Society, January 1983.
- Honorable Mention in the William Lowell Putnam Mathematical competition, 1980.
- Ranked second (all India) in the Joint Entrance Examination to the Indian Institutes of Technology, 1978.

Named and plenary lectures

- Feenberg Lecture, Washington University in St. Louis, September 25, 2024.
- Raman Chair Public Lecture of the Indian Academy of Sciences, National College, Bengaluru, December 28, 2023.
- Rapporteur at the 29th Solvay Conference on Physics, The Structure and Dynamics of Disordered Systems, Brussels, October 19-21, 2023.
- 2023 Jacques Solvay International Chair in Physics, Inaugural Lecture, Brussels, June 20, 2023.
- Llewellyn G. Hoxton Lecture, University of Virginia, Charlottesville, April 6, 2023.
- Peterson Public Lecture, Kansas State University, Manhattan, Kansas, April 26, 2022.
- Arline and Michael Magde Colloquium, Boston College, March 2, 2022.
- Boltzmann Lecture, Scuola Internazionale Superiore di Studi Avanzati, Trieste, February 21, 2022.
- The Racah Memorial Lecture, The Racah Institute of Physics, The Hebrew University of Jerusalem, June 21, 2021.
- H. L. Welsh Lectures in Physics, University of Toronto, May 6,7, 2021.
- New Horizons in Physics-IPA50, Commemorating 50 years of Indian Physics Association, APS-IPA Joint Lecture, February 27, 2021.
- Distinguished Colloquium and Lectureship, Korea Advanced Institute of Science and Technology, Daejeon, South Korea, February 17-19, 2021.
- Helen and Morton Sternheim Lecture, University of Massachusetts, Amherst, March 10, 2020.
- Marker Lectures, Penn State University, State College, December 4-6, 2019.
- R.E. Bell Lecture, McGill University, Montreal, February 22, 2019.
- Physics Department Memorial Lectureship, University of California, San Diego, February 14, 2019.
- Homi Bhabha Memorial Public Lecture, IISER Pune, November 14, 2017.
- Distinguished lecture, Texas A&M University, November 9, 2017.
- Biard Lecture, California Institute of Technology, Pasadena, November 2, 2017.
- 13th Homi Bhabha Public Lecture, Tata Institute of Fundamental Research, Mumbai, January 17, 2017.
- Dirac Lecture, University of New South Wales, Australia, September 1, 2015.
- Salam Distinguished Lectures, The Abdus Salam International Center for Theoretical Physics, Trieste, Italy, January 27-30, 2014.
- Institute Lecture, Indian Institute of Technology, Kanpur, January 21, 2014.
- Arnold Sommerfeld Lectures, University of Munich, January 31 - February 3, 2012.
- HRI-Girdharilal Mehta Lecture, Harish-Chandra Research Institute, Allahabad, January 13, 2012.

- Rapporteur at the 25th Solvay Conference on Physics - The Theory of the Quantum World, Brussels, October 19-22, 2011.
- Plenary talk at the International Conference on Strong Correlated Electron Systems, August 30, 2011.
- Marc Kac Memorial Lectures, Los Alamos National Laboratory, May 3-5, 2011.
- Moshe Flato Lectures, Ben Gurion University, Israel, March 10, 2011.
- Subramanyan Chandrasekhar Lectures, International Center for Theoretical Sciences, Bangalore, Dec 6-8, 2010
- Plenary talk at the 24th International Conference on Statistical Physics, Cairns, Australia, July 2010.
- Niels Bohr Lecture, Niels Bohr Institute, May 5, 2010
- Colloquium Pierre et Marie Curie, University of Paris, May 3, 2010
- De Sitter Lecture Series in Theoretical Physics 2009, University of Groningen, November 2009
- Solvay colloquium, International Solvay Institutes, Brussels, October 2009
- Plenary talk at the 25th International Conference on Low Temperature Physics, Amsterdam, August 2008
- Rapporteur at the 24th Solvay Conference on Physics, Quantum Theory of Condensed Matter, Brussels, Oct 11-13, 2008
- Distinguished Lecture Series, Technion, Israel, March 2007.
- Plenary talk at the International Conference on Strongly Correlated Electronic Systems, Karlsruhe, Germany, July 2004
- Matsen Lecture at the University of Texas, Austin, October 2002.
- Ehrenfrest Lecturer at the Lorentz Institute in Leiden, Holland, May 1998.
- Plenary talk at the 19th International Conference on Statistical Physics, Xiamen, August 1995.

Ph. D. Students and Postdocs

See http://sachdev.physics.harvard.edu/students.html.

Research appointments

- Research at Harvard and Yale has been continually supported by grants from the Division of Materials Research of the National Science Foundation since 1988.
- Visiting professor at Harvard University, January-June 2001.
- Visiting professor at the University of Fribourg, Switzerland, June 2000.
- Visiting professor at the Institut Henri Poincare, Paris, July 1999.
- Visiting professor at Université Joseph Fourier, Grenoble, France, Nov-Dec, 1997.
- Visiting professor at Université de Paris VII, May-July 1993.

- Visiting Scientist at AT&T Bell Laboratories, 1987, 1988, 1989.
- Visiting Scientist at IBM Thomas J. Watson Research Center, August 1988.
- Ph.D. dissertation research under Prof. D.R. Nelson at Harvard University involving the statistical mechanics of liquids and glasses.
- Undergraduate thesis research under Prof. D. Kleppner at M.I.T. involving theory on atom-field interactions.

Professional

- Editor-in-Chief, Reports on Progress in Physics
- Co-editor, Annual Reviews of Condensed Matter Physics
- Scientific Council, International Center for Theoretical Physics, Trieste.
- International Advisory Committee, Higgs Centre for Theoretical Physics, Edinburgh.
- International Advisory Board, International Center for Theoretical Sciences, TIFR, Bangalore.
- Divisional Associate Editor, Physical Review Letters.
- Advisory board, Dutch Research School of Theoretical Physics.
- Chair of steering committee and advisory board, Kavli Institute for Theoretical Physics, Santa Barbara.
- General member and admissions committee, Aspen Center for Physics.
- Review panel for Condensed Matter Science, Brookhaven National Laboratory.

Teaching

See http://sachdev.physics.harvard.edu/teaching.html

Publications

Books

- *Quantum Phase Transitions*, by Subir Sachdev, published by Cambridge University Press, Cambridge (1999); paperback in 2001; expanded second edition in 2011. For reviews see
  - Physics Today, vol **54**, number 2, page 56 (February 2001).
  - Contemporary Physics, vol **42**, number 2, page 141, March 2001.
  - Physikalische Blatter, vol **57**, number 10, page 68 (2001).
  - Journal of Statistical Physics, vol **103**, 1139 (2001).
- *Holographic Quantum Matter*, by Sean Hartnoll, Andrew Lucas, and Subir Sachdev, published by MIT Press (2018).
- *Quantum Phases of Matter*, by Subir Sachdev, published by Cambridge University Press, Cambridge (2023).
  - PROSE (PROfessional and Scholarly Excellence) Award Winner (2024) in the category of chemistry, physics, astronomy and cosmology. Awarded by the Association of American Publishers.

For a listing of all journal publications, see http://sachdev.physics.harvard.edu/allpap.html

Talks

For files of all talks since 1999, see the web page http://sachdev.physics.harvard.edu/talks/talks.html