Subir Sachdev Research Highlights

I. QUANTUM CRITICALITY

1. *Gapless spin-fluid ground state in a random quantum Heisenberg magnet*, S. Sachdev and J. Ye, PRL **70**, 3339 (1993).
   This was the first soluble model of a quantum many-body system with the following properties:
   - No quasiparticle excitations.
   - Universal dissipative 'Planckian' dynamics on the time scale $\hbar/(k_B T)$.
   - Extensive zero temperature entropy *without* an exponentially large ground state degeneracy.

   Its impact has been diverse:
   - Already in the 1993 paper, Sachdev indicated the connection to "marginal Fermi liquid" behavior in cuprates. This connection has since seen extensive developments, summarized in *Sachdev-Ye-Kitaev Models and Beyond: A Window into Non-Fermi Liquids*, D. Chowdhury, A. Georges, O. Parcollet, and S. Sachdev, Reviews of Modern Physics **94**, 035004 (2022). This work has led to a theory of the quantum phase transitions of two-dimensional metallic systems in the presence of random impurities, which describes realistic strange metals, as discussed under paper 4.
   - *Holographic Metals and the Fractionalized Fermi Liquid*, S. Sachdev, PRL **105**, 151602 (2010)
     There has been a direct and extensive impact from the theory of quantum criticality in condensed matter physics to the quantum theory of black holes via the 1993 paper by Sachdev and Ye and this paper by Sachdev in 2010. The 2010 paper was the first to point out that 'certain mean-field gapless spin liquids' are quantum matter states without quasiparticle excitations realizing the low energy quantum physics of charged black holes. With 'mean-field gapless spin liquids' Sachdev was referring to what can now be called the SYK critical state. Based on results in A. Georges, O. Parcollet, and S. Sachdev, PRB **63**, 134406 (2001), Sachdev argued in the 2010 paper for a correspondence between the SYK model and charged black holes at the semiclassical level. The connection was based on the common Planckian dynamics and extensive zero temperature entropy, and implied that the Bekenstein-Hawking black hole entropy is *not* realized by an exponentially large ground state degeneracy. In 2015, Kitaev (Talks at KITP, University of California, Santa Barbara) showed that the correspondence held at the fully quantum level. This connection has undergone rapid development in recent years, and has led to an understanding of the generic universal structure of the low-energy density of states of non-supersymmetric charged black holes in $D \geq 4$ spacetime dimensions (L.V. Iliesiu, S. Murthy and G.J. Turiaci, arXiv:2209.13608, S. Sachdev arXiv:2304.13744). The SYK model has also been a key testing ground for recent advances in understanding Hawking radiation—see the review, R. Buosso *et al.*, arXiv:2201.03096.
   - The 1993 model was developed by A. M. Sengupta (arXiv:9707316, Phys. Rev. B **61**, 4041 (2000)), Qimiao Si and others into what is now known as "extended dynamical mean field theory", used as a local model of quantum criticality in heavy fermion compounds.

2. *Universal quantum critical dynamics of two-dimensional antiferromagnets*, S. Sachdev and J. Ye, PRL **69**, 2411 (1992).
   Non-zero temperature transport near quantum critical points, K. Damle and S. Sachdev, PRB **56**, 8714 (1997).
   These papers introduced ideas on what is now often called "Planckian dynamics" in the transport of quantum critical systems. The original motivations and applications were to antiferromagnetic, superfluid-insulator and quantum Hall transitions, but there have also been diverse applications across other quantum critical systems:

- *Quantum critical transport in clean graphene*, L. Fritz, J. Schmalian, M. Müller and S. Sachdev, PRB 78, 085416 (2008).

  In what was then viewed as a surprising development, the transport properties of pure graphene were interpreted along quantum-critical lines in this paper. This led to predictions for microwave conductivity which were experimentally observed in Gallagher *et al.* Science **364**, 158 (2019). M. Müller and S. Sachdev, PRB **78**, 115419 (2008) were the first to propose that graphene should display hydrodynamic transport near charge neutrality. This is now a flourishing subject with many experimental studies of hydrodynamics in two-dimensional materials, especially graphene *e.g.* Mark Ku *et al.*, Nature **583**, 537 (2020).

- *Quantum critical transport, duality, and M-theory*, C. P. Herzog, P. Kovtun. S. Sachdev, and D. T. Son, Physical Review D **75**, 085020 (2007).

  Theory of the Nernst effect near quantum phase transitions in condensed matter and in dyonic black holes, S. A. Hartnoll, P. K. Kovtun, M. Müller, and S. Sachdev, PRB **76**, 144502 (2007).

  The Damle-Sachdev paper motivated holographic models of transport in quantum-critical matter in these papers. This led to extensive work on holographic theories of strongly interacting matter, as reviewed in the book *Holographic Quantum Matter* by S. Hartnoll, A. Lucas, and S. Sachdev. It also led to the realization that transport in *clean* quantum critical systems is in the strong drag limit. A recent consequence has been a reconsideration of the structure of the optical conductivity of critical Fermi surfaces: in particular, such systems only display Drude d.c. conductivity, and do not have a high frequency tail, as discussed in Haoyu Guo, A. A. Patel, I. Esterlis, and S. Sachdev, PRB **106**, 115151 (2022).

3. *Fractionalized Fermi liquids*, T. Senthil, S. Sachdev, and M. Vojta, PRL **90**, 216403 (2003).
   Weak magnetism and non-Fermi liquids near heavy-fermion critical points, T. Senthil, M. Vojta and S. Sachdev, PRB **69**, 035111 (2004).
   These papers established the stability of metallic phases in which the Fermi surface does not enclose the Luttinger volume. This implies a new type of quantum phase transition in metals: one without any broken symmetry, involving a change in volume of the Fermi surface. It was also argued that the phase with the non-Luttinger volume (FL*) must have 'topological' features involving fractionalized excitations and emergent gauge fields. The quantum critical point also features these fractionalized excitations, and was an early example of a 'deconfined quantum critical point'. These ideas have had extensive application in the study of intermetallic compounds *e.g.* in $CeCoIn_5$ by Maksimovic *et al.*, Science **375**, 76 (2021).

4. *Universal theory of strange metals from spatially random interactions*, A. A. Patel, Haoyu Guo, I. Esterlis, and S. Sachdev, Science **381**, 790 (2023).
   Localization of overdamped bosonic modes and transport in strange metals, A. A. Patel, P. Lunts, and S. Sachdev, PNAS **121**, e2402052121 (2024).
   Strange metal and superconductor in the two-dimensional Yukawa-Sachdev-Ye-Kitaev model, Chenyuan Li, D. Valentinis, A. A. Patel, Haoyu Guo, J. Schmalian, S. Sachdev, and I. Esterlis, PRL **133**, 186502 (2024).
   These papers develop a theory of quantum phase transition of two-dimensional metallic systems in the presence of random impurities. Surprisingly, the various clean Hertz-Millis classes, and also the topological transitions without broken symmetries all fall into essentially the same universality class. There is a wide intermediate temperature regime over which a two-dimensional Yukawa-SYK model applies; both bosonic and fermionic modes are extended in this regime. But at the lowest temperatures there is a crossover to a regime were the bosonic modes are localized, while fermionic modes remain extended, similar to behavior discussed near the metal-insulator transition in M. Milovanović, S. Sachdev and R. N. Bhatt, PRL **63**, 82 (1989). These results describe both the quantum critical 'fan' and the extended critical 'foot' on the Fermi liquid side observed in the cuprates and other compounds *e.g.* Michon *et al.* Nature Communications **14**, 3033 (2023), R.A. Cooper

et al. Science **323**, 603 (2009).

II. QUANTUM MAGNETISM

5. *Valence bond and spin-Peierls ground states of low dimensional quantum antiferromagnets*, N. Read and S. Sachdev, PRL **62**, 1694 (1989).
Spin-Peierls, valence bond solid, and Néel ground states of low dimensional quantum antiferromagnets, N. Read and S. Sachdev, PRB **42**, 4568 (1990).

    - These papers first introduced a direct non-Landau-Ginzburg-Wilson transition between Néel and valence bond solid states on the square lattice, described by a $\mathbb{CP}^1$ U(1) gauge theory, and the Berry phases of monopoles. This has led to extensive developments in the theory of deconfined quantum criticality. A closely related transition applies to the Shastry-Sutherland lattice, as was first proposed in C.H. Chung, J.B. Marston, and S. Sachdev, PRB 64, 134407 (2001), and has been observed in $SrCu_2(BO_3)_2$ by Zayed *et al.*, Nature Physics **13**, 962 (2017) and Cui *et al.*, Science **380**, 6650 (2023).
    - These papers also established an equivalence between the QED theory of monopoles with Berry phases and the quantum dimer model on the square lattice.
    - On the honeycomb lattice, the predicted valence bond solid order was of the Kekulé type. Such order has been observed in graphene by Liu *et al.*, Science **375**, 321 (2021) and Coissard *et al.*, Nature **605**, 51 (2022).

6. *Action of hedgehog-instantons in the disordered phase of the* $2+1$ *dimensional* CP^{N-1} *model*, G. Murthy and S. Sachdev, Nuclear Physics B **344**, 557 (1990).
The first computation of monopole scaling dimensions in a conformal field theory in 2+1 dimensions. The $1/N$ corrections were computed in E. Dyer, M. Mezei, S. S. Pufu and S. Sachdev, Journal of High Energy Physics **1506** (2015) 037; Erratum **1603** (2016) 111, and were found to be quantitatively accurate at small N by S. M. Chester, É. Dupuis, and W. Witczak-Krempa Physical Review D **108**, L021701 (2023).

7. *Large* N *expansion for frustrated quantum antiferromagnets*, N. Read and S. Sachdev, PRL, **66**, 1773 (1991).
Large N *expansion for frustrated and doped quantum antiferromagnets*, S. Sachdev and N. Read, International Journal of Modern Physics B, **5**, 219 (1991).
The kagome and triangular lattice Heisenberg antiferromagnets: ordering from quantum fluctuations and quantum-disordered ground states with unconfined bosonic spinons, S. Sachdev, Physical Review B **45**, 12377 (1992).
The first proposal of a fractionalized state of quantum matter not requiring broken time-reversal symmetry. This is now called the $\mathbb{Z}_2$ spin liquid.

    - The topological and anyon properties of the $\mathbb{Z}_2$ spin liquid were described. Such properties are identical to those found later by Kitaev in the solvable toric code model, which plays a key role in quantum error correction in qubit devices.
    - $\mathbb{Z}_2$ spin liquids were found on square, triangular, and kagome lattices in regimes where the semiclassical theory led to non-collinear spin order. Evidence for a $\mathbb{Z}_2$ spin liquid in the triangular lattice compound $KYbSe_2$ was presented by Scheie *et al.*, Nature Physics **20**, 74 (2024) and arXiv:2406.17773. See also paper 20 for realization of $\mathbb{Z}_2$ spin liquids by trapped Rydberg atoms.
    - It was argued that quantum dimer models on the triangular and kagome lattices exhibit $\mathbb{Z}_2$ spin liquid phases.

8. *Spontaneous alignment of frustrated bonds in an anisotropic, three dimensional Ising model*, R. Jalabert and S. Sachdev, PRB **44**, 686 (1991).
This paper showed that it is the 'odd' $\mathbb{Z}_2$ spin liquid which describes the short-range resonating valence bond state of Anderson. Translations in the x and y directions anti-commute in the toric code m-particle super-selection sector in such a $\mathbb{Z}_2$ spin liquid. Details of the computation were published in S. Sachdev and M. Vojta, Journal of the Physical Society of Japan **69** Supplement B, 1 (2000); see arXiv:cond-mat/9910231 for the original paper and notes from 1991. This paper also gave an example of an anyon condensation transition, with the condensation of the toric code m-particle describing the transition from the $\mathbb{Z}_2$ spin liquid to the valence bond solid. This is an early realization of a deconfined quantum critical point, in the XY* universality class.

9. *Universal magnetic properties of frustrated quantum antiferromagnets in two dimensions*, A. V. Chubukov, T. Senthil, and S. Sachdev, PRL **72**, 2089 (1994).
Another early example of an anyon condensation transition, with the condensation of the toric code e-particle describing the transition from the $\mathbb{Z}_2$ spin liquid to the non-collinear antiferromagnet. This is a deconfined quantum critical point, in the O(4)* universality class, and relates to the observations of Scheie *et al.*, Nature Physics **20**, 74 (2024) and arXiv:2406.17773.

10. *Low temperature relaxational dynamics of the Ising chain in a transverse field*, S. Sachdev and A. P. Young, PRL **78**, 2220 (1997).
Low temperature spin diffusion in the one-dimensional quantum O(3) nonlinear σ-model S. Sachdev and K. Damle, PRL **78**, 943 (1997).
Spin dynamics and transport in gapped one-dimensional Heisenberg antiferromagnets at nonzero temperatures, K. Damle and S. Sachdev, PRB **57**, 8307 (1998).
These papers provided an exact description of low temperature transport and damping in one-dimensional quantum systems with an energy gap. The results were successfully compared quantitatively to experiments in M. Takigawa *et al.*, PRL **76**, 2173 (1996), G. Xu *et al.*, Science **317**, 1049 (2007), and A. W. Kinross *et al.*, Physical Review X **4**, 031008 (2014).

11. *Quantum impurity in a nearly-critical two dimensional antiferromagnet*, S. Sachdev, C. Buragohain and M. Vojta, Science **286**, 2479 (1999).
Spectral function of a localized fermion coupled to the Wilson-Fisher conformal field theory, A. Allais and S. Sachdev, PRB **90**, 035131 (2014).
The traditional Kondo effect involves a local quantum degree of freedom interacting with a Fermi liquid or Luttinger liquid in the bulk. These papers described cases where the bulk was a strongly-interacting critical state without quasiparticle excitations, leading to novel boundary conformal field theories which have since been much studied. The impurity was characterized by a Curie susceptibility of an irrational spin, and a boundary entropy of an irrational number of states.

12. *Landau theory of quantum spin glasses of rotors and Ising spins*, N. Read, S. Sachdev, and J. Ye, PRB, **52**, 384 (1995).
Equilibrium dynamics of infinite-range quantum spin glasses in a field, M. Tikhanovskaya, S. Sachdev, and R. Samajdar, PRX Quantum **5**, 020313 (2024).
Theory of the infinite-range quantum Ising and rotor spin glasses, describing the transition from a 'trivial' quantum paramagnet to a quantum spin glass state with replica symmetry breaking. First papers to obtain the dynamic spin spectrum within the spin glass state.

III. SUPERCONDUCTIVITY

13. *Sign-problem-free quantum Monte Carlo of the onset of antiferromagnetism in metals*, E. Berg, M. A. Metlitski and S. Sachdev, Science **338**, 1606 (2012).
    Showed that many quantum critical models of physical interest were amenable to quantum Monte Carlo studies. This method has been used extensively, and has led to the demonstration of d-wave superconductivity near the onset of spin density wave order.

14. *Electronic spectra with paramagnon fractionalization in the single band Hubbard model*, E. Mascot, A. Nikolaenko, M. Tikhanovskaya, Ya-Hui Zhang, D. K. Morr, and S. Sachdev, PRB **105**, 075146 (2022).
    A microscopic theory of the pseudogap metal phase of the hole-doped cuprates, with comparisons to photoemission experiments of He *et al.*, Science **331**, 1579 (2011) and Chen *et al.* Science **366**, 1099 (2019). The pseudogap phase has pocket Fermi surfaces of conventional quasiparticles with charge $+e$ and spin $1/2$, but enclosing a non-Luttinger volume, as originally described in S. Sachdev, PRB **49**, 6770 (1994). The theory was based on the ancilla model of doped Mott insulators proposed by Ya-Hui Zhang and S. Sachdev, Physical Review Research **2**, 023172 (2020), which can describe a FL* phase in a single band model, complementing the two band models in paper 3.

15. *Resonant thermal Hall effect of phonons coupled to dynamical defects*, Haoyu Guo, D. G. Joshi, and S. Sachdev, PNAS **119**, e2215141119 (2022).
    A new model of the thermal Hall effect, based upon a resonant 'side-jump' scattering of phonons off two-level systems realized by magnetic or other impurities. Connected to experiments on correlated electron compounds in H Guo, Physical Review Research **5**, 033197 (2023) and Ataei *et al.*, Nature Physics **20**, 585 (2024).

16. *A model of d-wave superconductivity, antiferromagnetism, and charge order on the square lattice*, M. Christos, Zhu-Xi Luo, H. Shackleton, Ya-Hui Zhang, M. S. Scheurer, and S. Sachdev, Proceedings of the National Academy of Sciences **120**, e2302701120 (2023).
    Emergence of nodal Bogoliubov quasiparticles across the transition from the pseudogap metal to the d-wave superconductor, M. Christos and S. Sachdev, npj Quantum Materials **9**, 4 (2024).
    Quantum oscillations in the hole-doped cuprates and the confinement of spinons, P. M. Bonetti, M. Christos and S. Sachdev, PNAS **121**, e2418633121 (2024).
    These papers describe the low temperature fate of the FL* pseudogap metal of the cuprates (paper 14). An important experimental constraint is that the low temperature phases with antiferromagnetic, superconducting and/or charge order must be qualitatively the same as the corresponding phases obtained from the Fermi liquid. Our work proposes that the spin liquid of the FL* phase is the SU(2) gauge theory of the π-flux spin liquid, dual to the $\mathbb{CP}^1$ spin liquid (paper 5), and this spin liquid undergoes confinement at low temperature. This is shown to lead to a d-wave superconductor with 4 gapless Dirac points along the diagonals of the square lattice Brillouin zone (as proposed in S. Chatterjee and S. Sachdev, PRB **94**, 205117 (2016)), even in cases where this region of the Brillouin zone has no Fermi surfaces in the normal state (as can be the case in the electron-doped cuprates). The SU(2) gauge theory also has charge order instabilities at an equal footing with d-wave superconductivity, and leads to states similar to those discussed in paper 7 and M. Vojta and S. Sachdev, PRL **83**, 3916 (1999). The resulting charge ordered state was argued to account for quantum oscillations at high magnetic fields, after accounting for the spinons of the FL* phase.

IV. ULTRACOLD ATOMS

17. *Mott insulators in strong electric fields*, by S. Sachdev, K. Sengupta, and S. M. Girvin, PRB **66**, 075128 (2002).

This paper predicted that a tilted Bose-Hubbard model will have spontaneous Ising density wave order. This was observed by J. Simon *et al.*, Nature **472**, 307 (2011) and F. Meinert *et al.* PRL **111**, 053003 (2013).

18. *Competing density-wave orders in a one-dimensional hard-boson model*, P. Fendley, K. Sengupta, and S. Sachdev, PRB **69**, 075106 (2004).
This paper introduced the 'FSS model', a model of interacting hard-core bosons or qubits, related to the model in paper 17. A special case is the popular 'PXP model' considered by many later. The FSS model also describes the blockade of Rydberg states in arrays of trapped atoms; the phase diagram predicted in this paper was observed by H. Bernien, *et al.*, Nature **551**, 579 (2017) and A. Keesling, A. Omran, H. Levine, H. Bernien, H. Pichler, Soonwon Choi, R. Samajdar, S. Schwartz, P. Silvi, S. Sachdev, P. Zoller, M. Endres, M. Greiner, V. Vuletić, and M. D. Lukin, Nature **568**, 207 (2019). The FSS model has also been proposed as a realization of universal quantum computation by Cesa and Pichler, PRL **131**, 170601 (2023).

19. *Complex density wave orders and quantum phase transitions in a model of square-lattice Rydberg atom arrays*, R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, and S. Sachdev, Physical Review Letters **124**, 103601 (2020).
Quantum Phases of Matter on a 256-Atom Programmable Quantum Simulator, S. Ebadi, Tout T. Wang, H. Levine, A. Keesling, G. Semeghini, A. Omran, D. Bluvstein, R. Samajdar, H. Pichler, Wen Wei Ho, Soonwon Choi, S. Sachdev, M. Greiner, V. Vuletić, and M. D. Lukin, Nature **595**, 227 (2021).
Prediction and observation of the phase diagram of square lattice Rydberg atom arrays. This provided the first experimental realization of the Ising quantum critical point in 2+1 dimensions.

20. *Quantum phases of Rydberg atoms on a kagome lattice*, R. Samajdar, Wen Wei Ho, H. Pichler, M. D. Lukin, and S. Sachdev, Proceedings of the National Academy of Sciences **118**, e2015785118 (2021).
This paper proposed that the FSS model of trapped Rydberg atoms can realize the phases of the quantum dimer model, including the $\mathbb{Z}_2$ spin liquid, and explored the case of the kagome lattice. An improved realization on the ruby lattice was subsequently proposed by R. Verresen *et al.*, Phys. Rev. X **11**, 031005 (2021). Quantum correlations of the $\mathbb{Z}_2$ spin liquid were observed on the ruby lattice of Rydberg atoms by G. Semeghini, H. Levine, A. Keesling, S. Ebadi, Tout T. Wang, D. Bluvstein, R. Verresen, H. Pichler, M. Kalinowski, R. Samajdar, A. Omran, S. Sachdev, A. Vishwanath, M. Greiner, V. Vuletic, M. D. Lukin, Science **374**, 1242 (2021).